ATLAS EXPERIMENT
http://atlas.ch

CMS

Top quark Physics at the Large Hadron Collider

past, present, future from 7 to 13 TeV collisions

INFN and Dipartimento di Fisica
Università di Napoli "Federico II"
Seminar
27th April 2016

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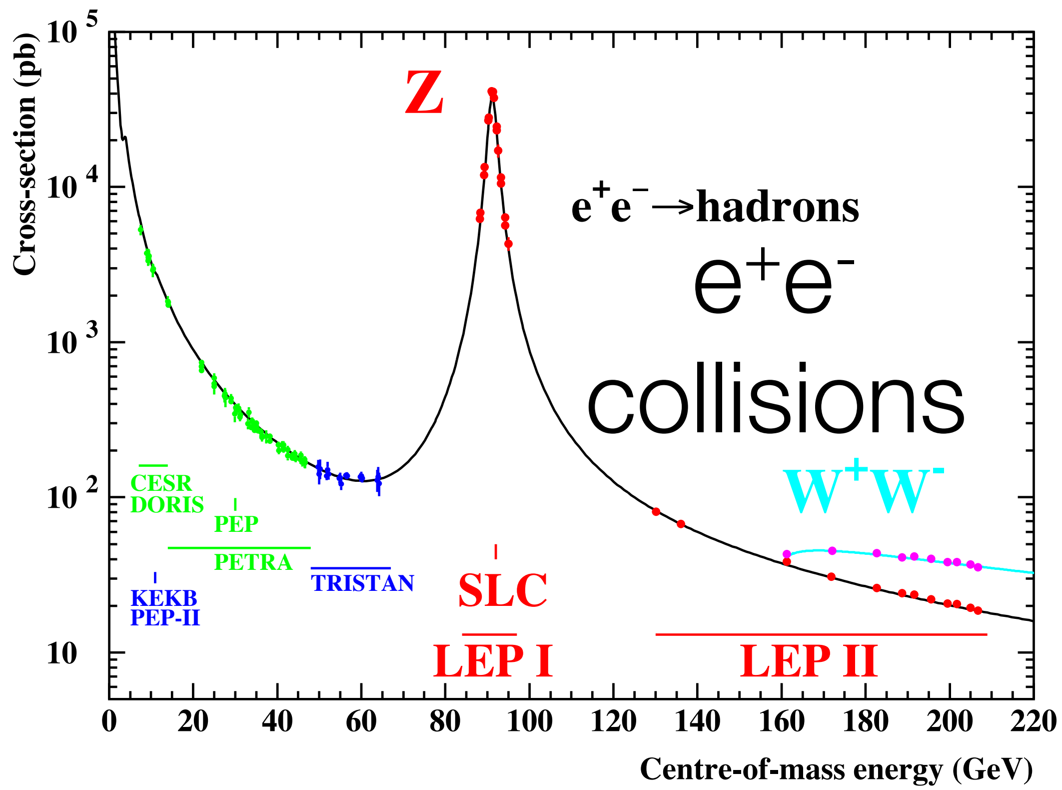
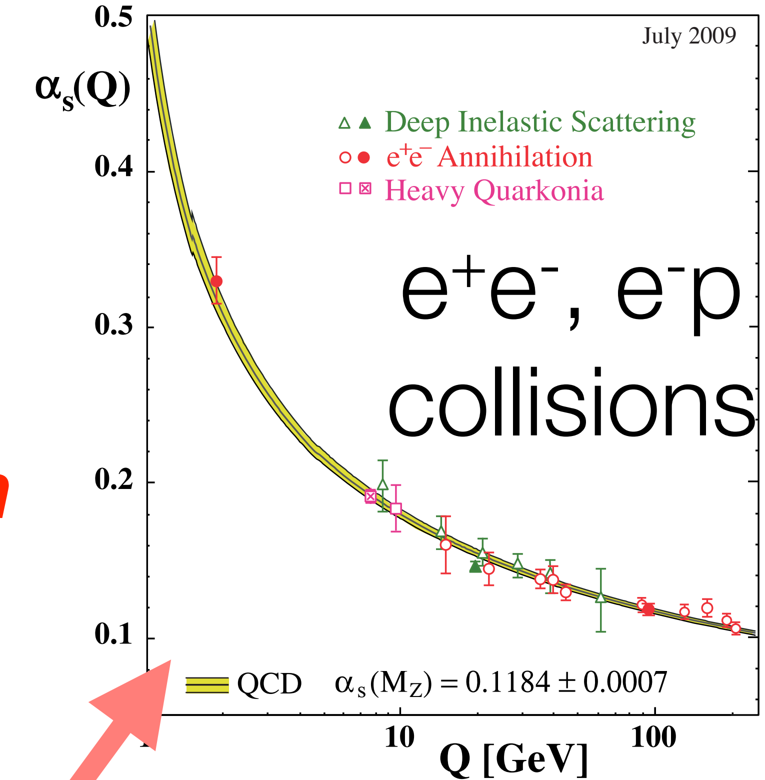
Outline

- **Why top quark?**
- **The tools of the trade**
  - **LHC:** a top factory at work
  - **The ATLAS and CMS detectors**: top observers
- Measuring **top quark production: top pair,** *single top*
  - **The emergence of boosted tops**
- Measuring the **top quark property:**
  - **mass**
- **Conclusions**

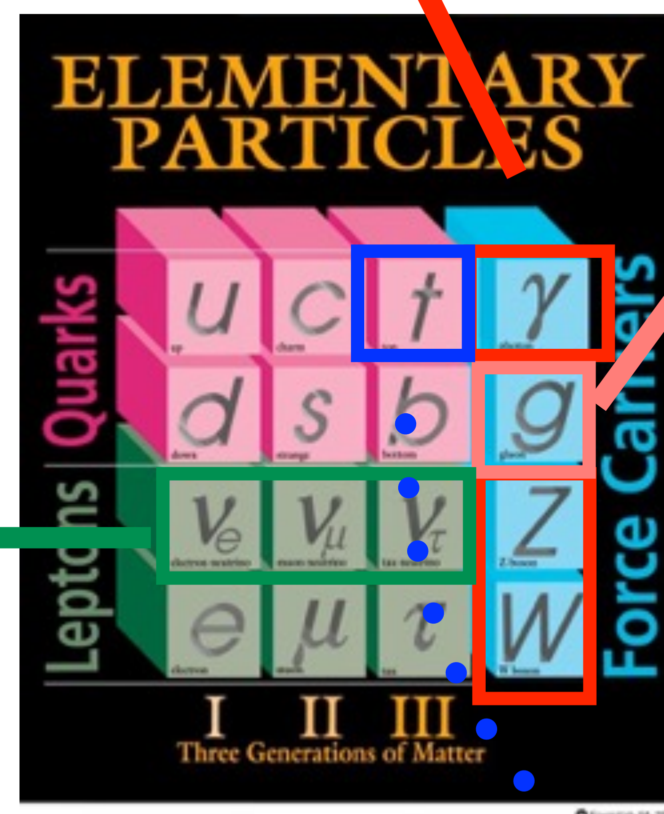
Standard (model) **successes** *at colliders*

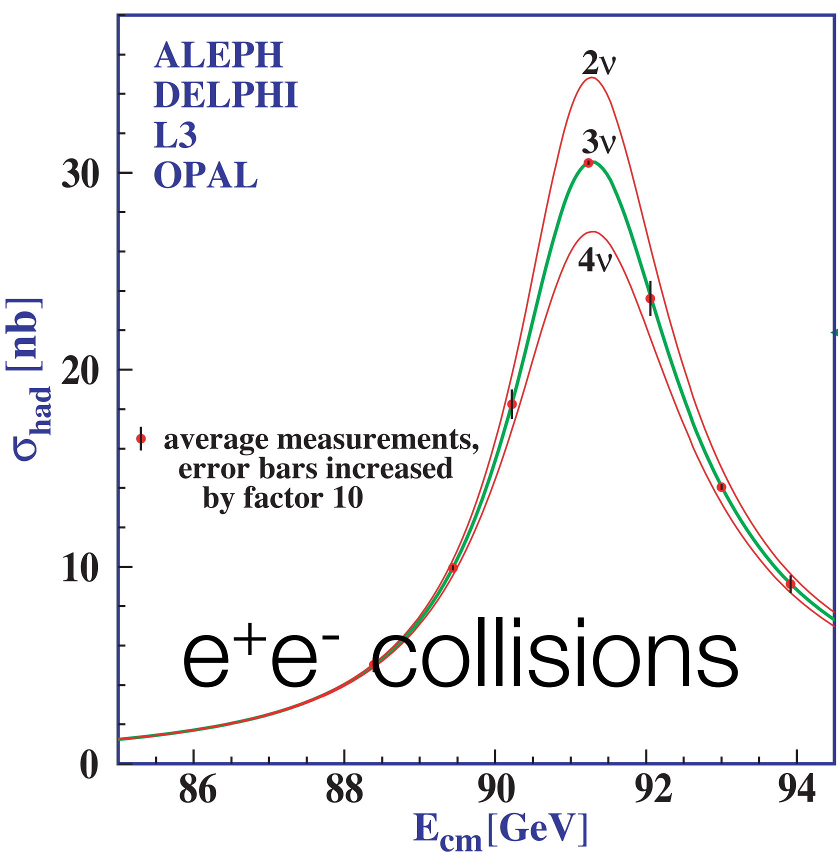




Electromagnetic force unified to Weak: electrons annihilate to W, Z, in addition to photons

Strong interaction strength changes with momentum exchange

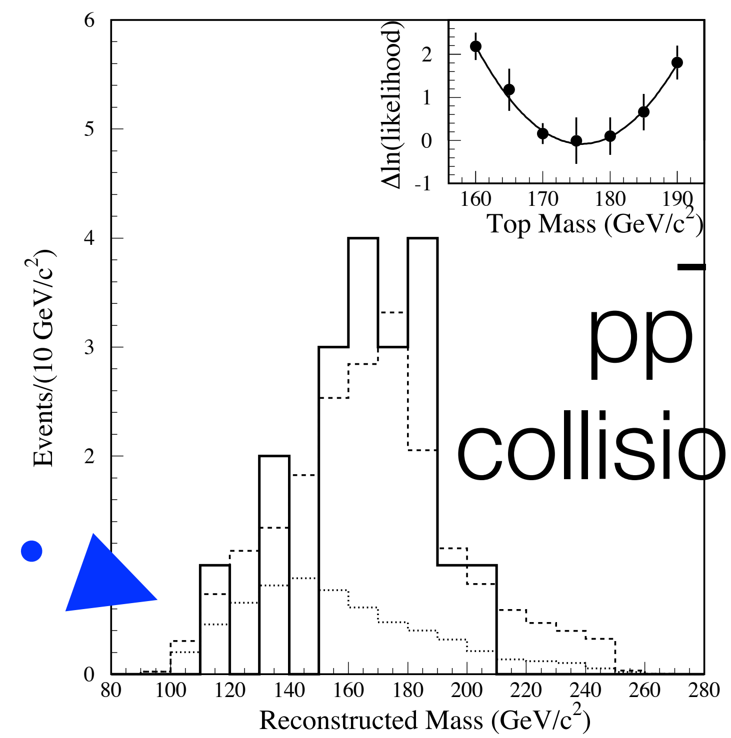




there are only 3 standard neutrinos

The known micro-world

a quick (biased) selection..



Top quark is found

Standard (model) **questions**

See for instance arXiv:0312096v1[hep-ph]

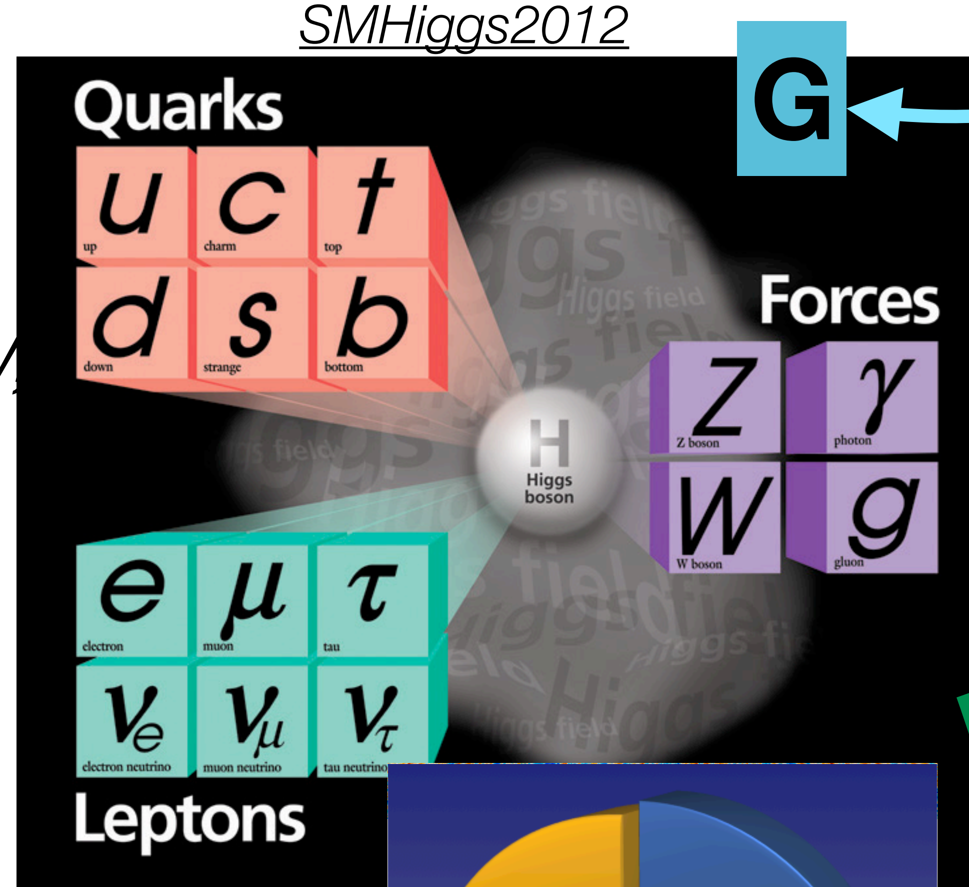
- *What is the **origin of mass**? Why are symmetries of **forces** different from those of **particles**?*

***Higgs,** SuperSymmetry*
New Strong forces..

- *How is **gravity** incorporated?*

Quantum gravity
Extra dimensions...

SymmetryMagazine SMHiggs2012



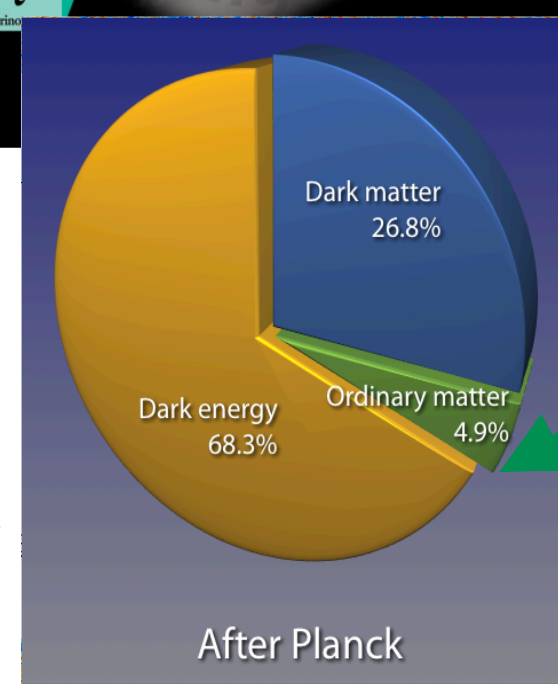
- *Why **3 generations of matter** with different quantum numbers ?*

4th generation...?

- *Why **different forces** (ranges, strengths)?*

String theory..

(P. Natoli, Cosmology with Planck, LaThuile 2014)



- ***What accounts for the energy balance of the universe?***

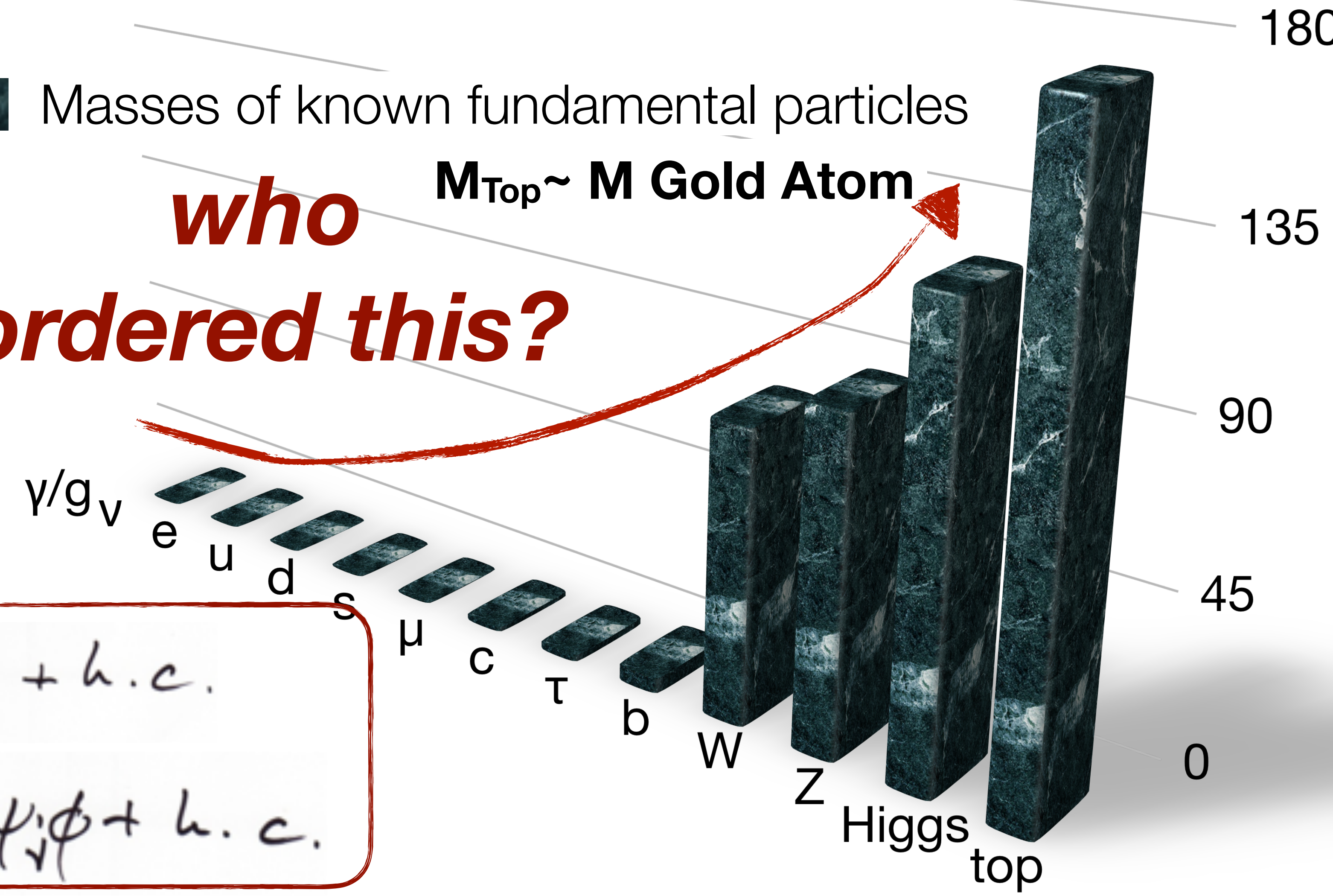
Dark matter, Dark energy...

"Special" reasons

top is most massive known **constituent** of matter

Masses of known fundamental particles

who ordered this?



$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi) + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$L_W \sim g^2 (v+H)^2 W^+_\mu W^{-\mu}$$

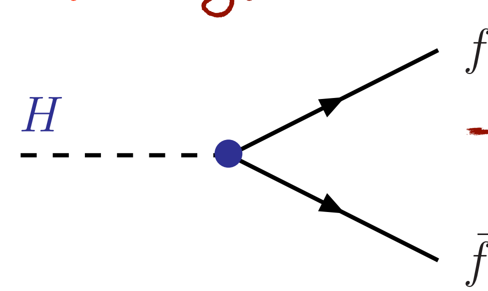
$$M_W = \frac{1}{2} g_2 v = \left(\frac{\sqrt{2} g^2}{8 G_\mu}\right)^{1/2}$$

$$v = \frac{1}{(\sqrt{2} G_\mu)^{1/2}} \rightarrow v \sim 246 \text{ GeV} \rightarrow$$

$$L_{top} = m_t t_L t_R / \sqrt{2} + y_t H t_L t_R / \sqrt{2}$$

mass term — interaction term

$$m_t = y_t v / \sqrt{2}$$



$m_{t,obs} \sim 173$ GeV

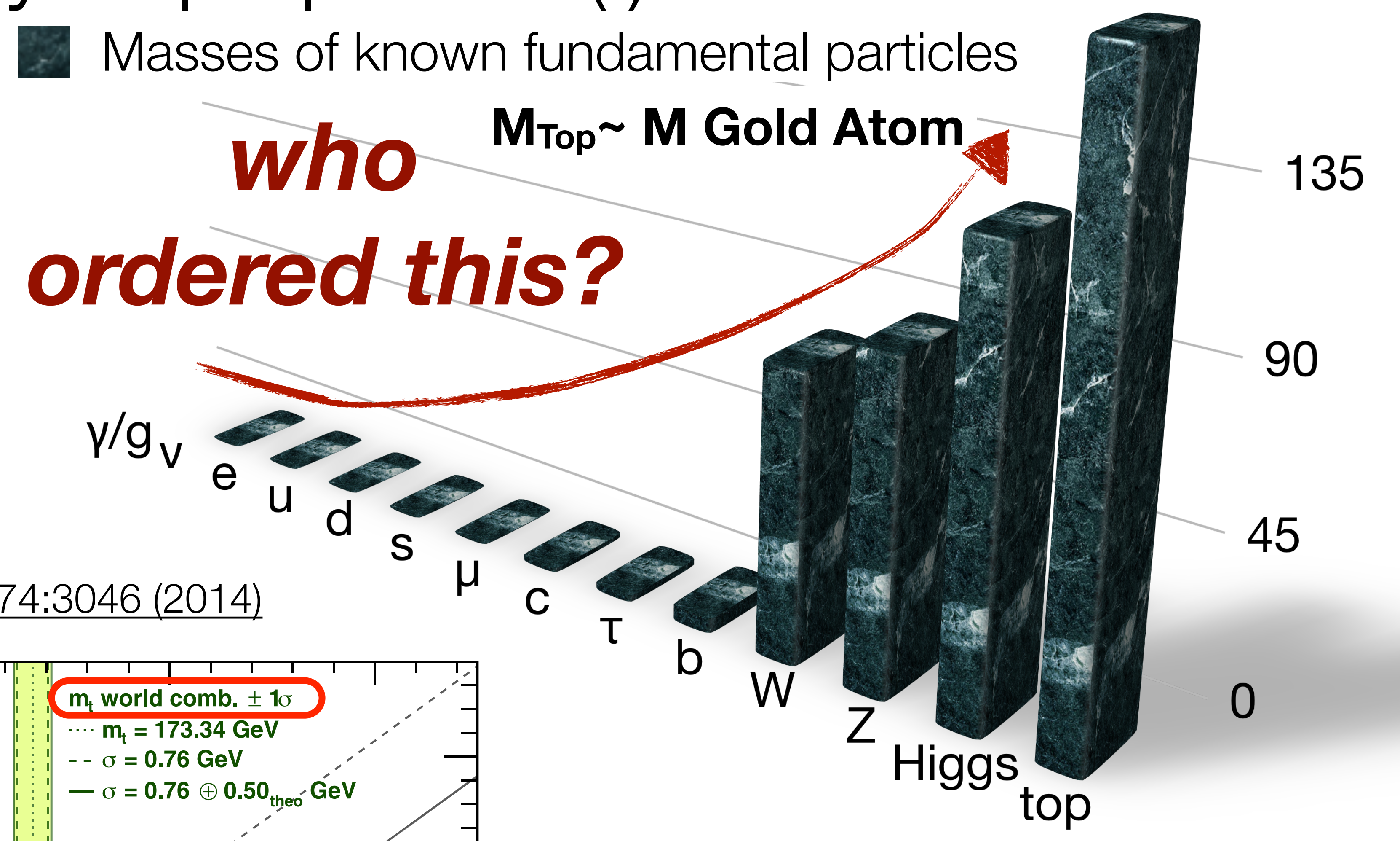
→ **largest (unmeasured) coupling y_t to Higgs boson**

Is y_t~1? Is it SM Higgs?
Measure y_t

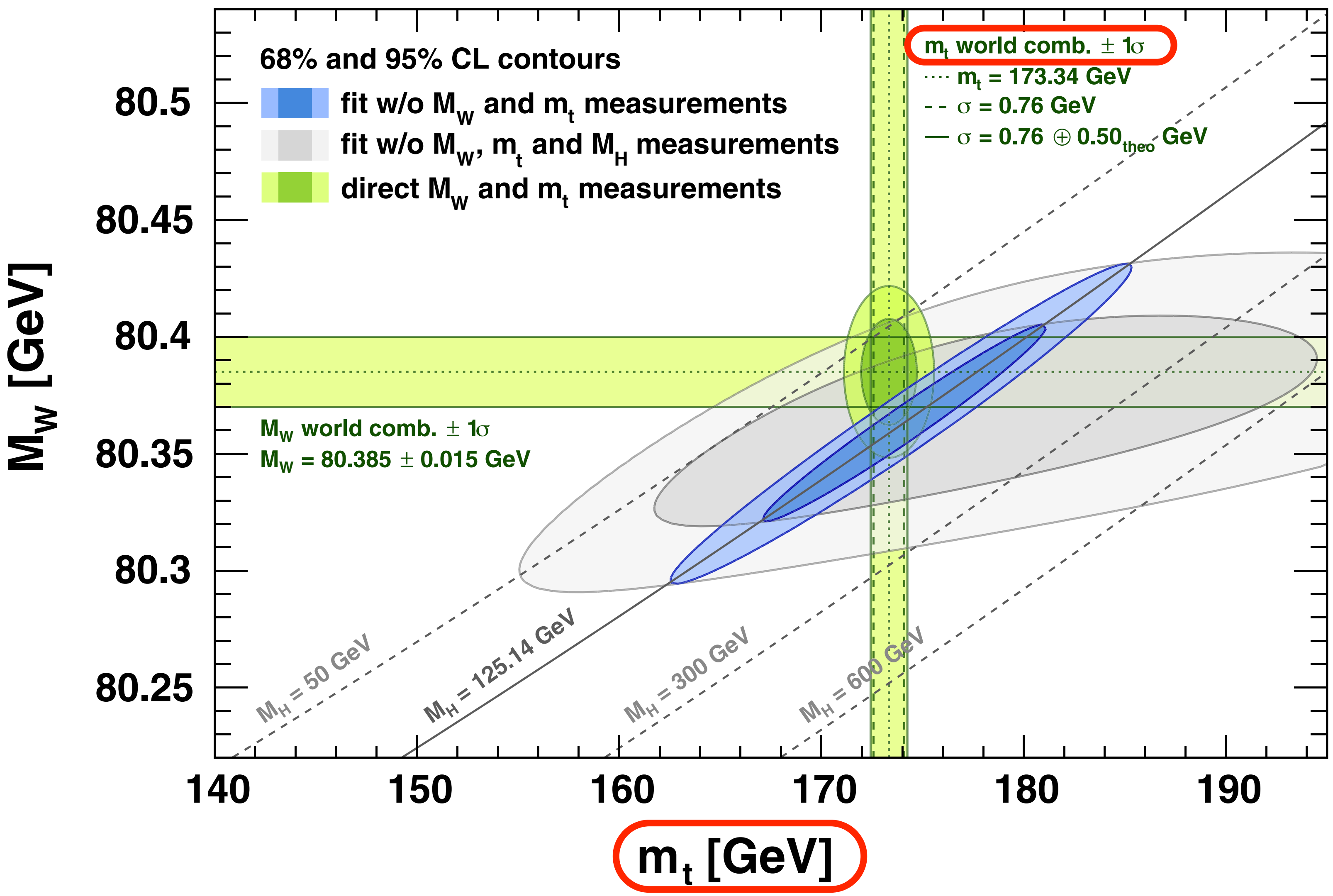
Why Top quark? (I)

“Special” reasons

top is most massive known **constituent** of matter



The GFitter Group, Eur. Phys. J. C 74:3046 (2014)



largest (unmeasured) coupling y_t to Higgs boson

Is y_t~1? Is it SM Higgs?

Measure y_t

Why Top quark? (I)

"Standard" reasons

see JHEP07(2012)022

heavy = mass of quark m_q is so large that $\alpha_s(m_q^2)$ is in perturbative regime

top-quark

"lives" less than "time to make hadrons" less than "time to decorrelate spins"

$1/m_t$ < $1/\Gamma_t$ < $1/\Lambda$ < m_t/Λ^2

Production time < Lifetime < Hadronization time < Spin decorrelation time

(see R.K.Ellis@TOP2012)

no top-antitop meson is observed , **spin information** is preserved in decay products

Study of production, decay, quantum numbers and couplings of bottom and top quark

precision tests of standard model strong and EWK interactions

standard candles to calibrate/ commission multi-purpose detector

information on proton composition *(gluons)*

At the foundations of SM of the measurement techniques

Why Top quark? (I)

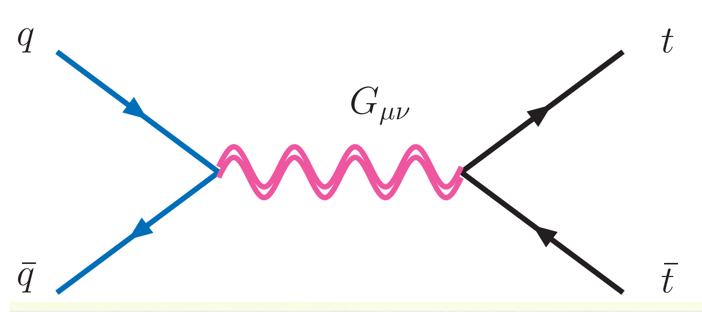
"Beyond" reason(s)

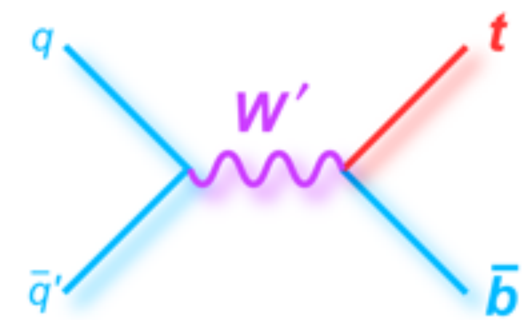
Open window on physics beyond SM

top is Ubiquitous connection to phys beyond SM

top quark mass is "special" : "**needs to be accommodated first"** i.e. many scenarios feature top quark's **significant/dominant direct/indirect coupling to new physics:** from extra dimensions to new strong forces

(figure by Geraldine Servant)





(figure from D0 top diagrams)

Ubiquitous background to searches

top quarks mimic large number of scenarios with physics beyond SM
(non standard Higgs, SUSY, new vector-like quarks,...)

LHC : a *Top* producer i.e. providing the luminosity

counter-rotating high intensity proton bunches colliding at center of mass energy (E_{cm} or $\sqrt{s}$) = 7,8, 13 TeV in 27 Km tunnel

E_{cm}(Tevatron)= 1.96 TeV

$$\mathcal{L} \propto \frac{N_1 N_2}{\sigma^2}$$

Key parameters:

- N_i = bunch intensity
- n_b = number of bunches
- σ = colliding beam size

Ad maiora..

design: **E_{CM}=14TeV** , lumi ***$10^{34}cm^{-2}\ s^{-1}$***

(~30 times Tevatron pp collider)

RUN2 (ongoing)

E_{cm} =13 TeV

(14 to be decided later)

2016 ***∫Ldt ~25 fb-1***

2015 **peak lumi: $5.22 \cdot 10^{33}\ cm^{-2}\ s^{-1}$**

∫Ldt ~4.3 fb^{-1} /exp

RUN1

2012 **E_{cm} =8 TeV**

peak lumi: $7.7 \cdot 10^{33}\ cm^{-2}\ s^{-1}$

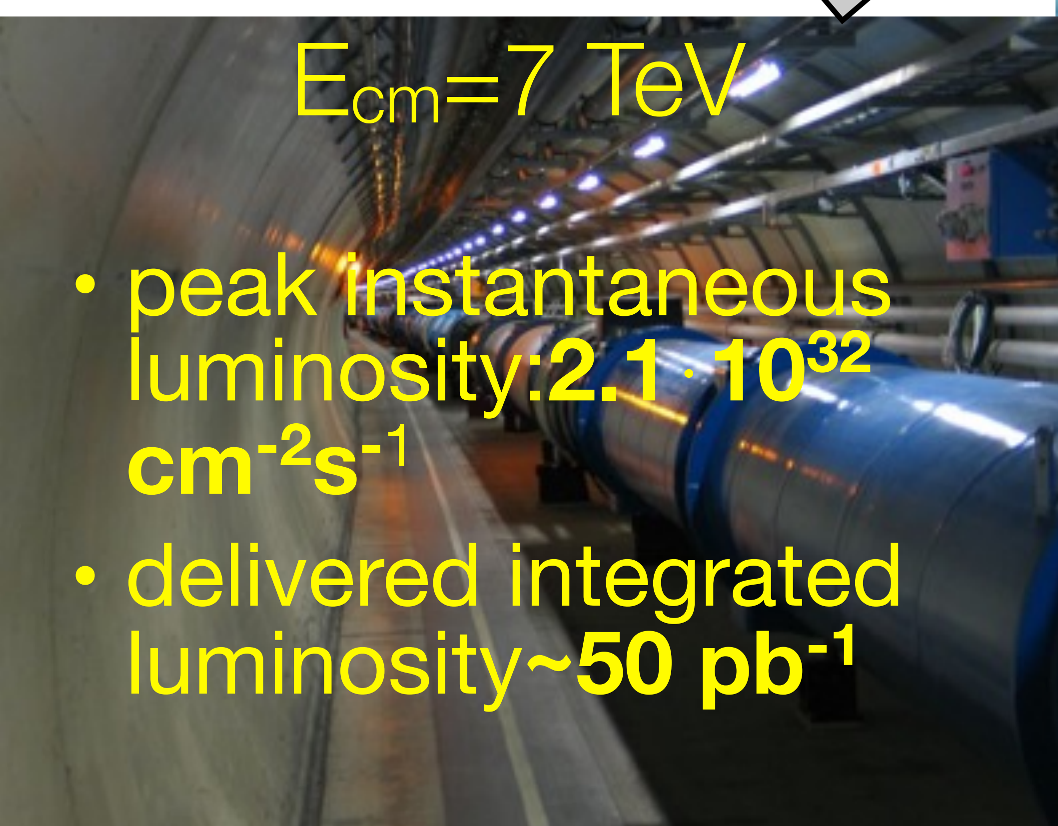
∫Ldt ~22 fb^{-1} /exp

2011 **E_{cm} =7 TeV**

peak lumi $2 \cdot 10^{33}\ cm^{-2}\ s^{-1}$

∫Ldt ~5.6 fb^{-1} /exp

2010



E_{cm}=7 TeV

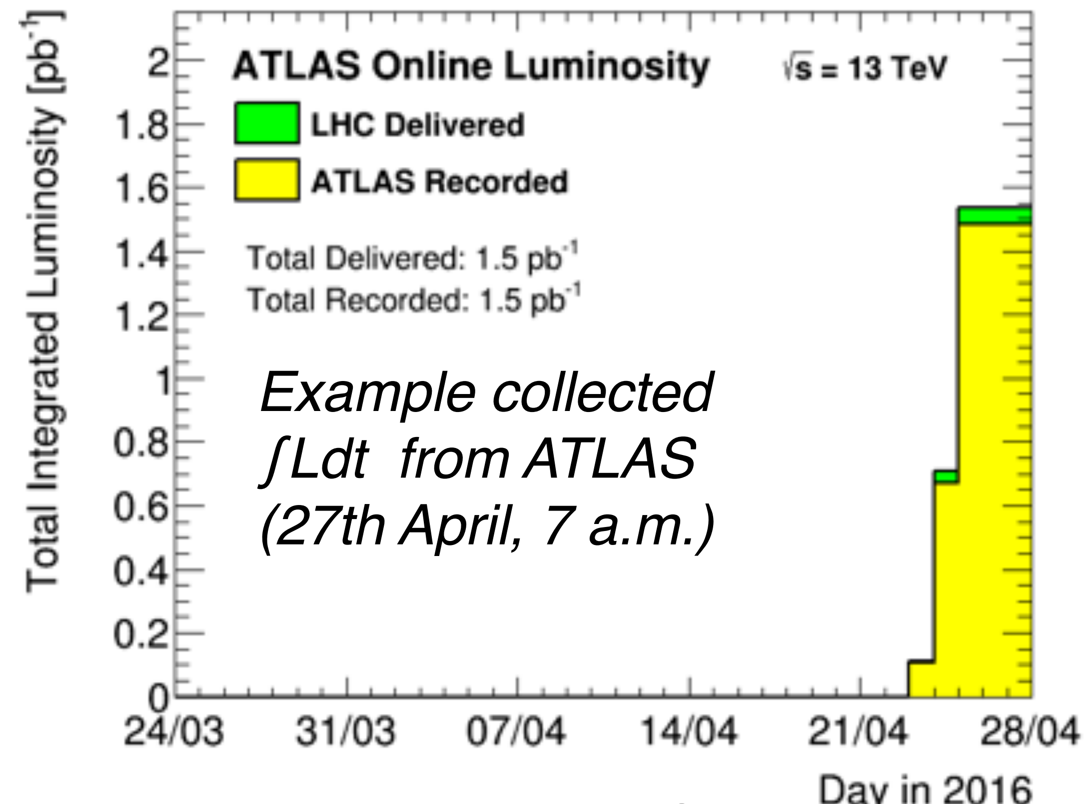
- peak instantaneous luminosity:**$2.1 \cdot 10^{32}$ $cm^{-2}s^{-1}$**
- delivered integrated luminosity**~50 pb^{-1}**

$N_{events}(\Delta t)$= ***∫Ldt*** * cross section

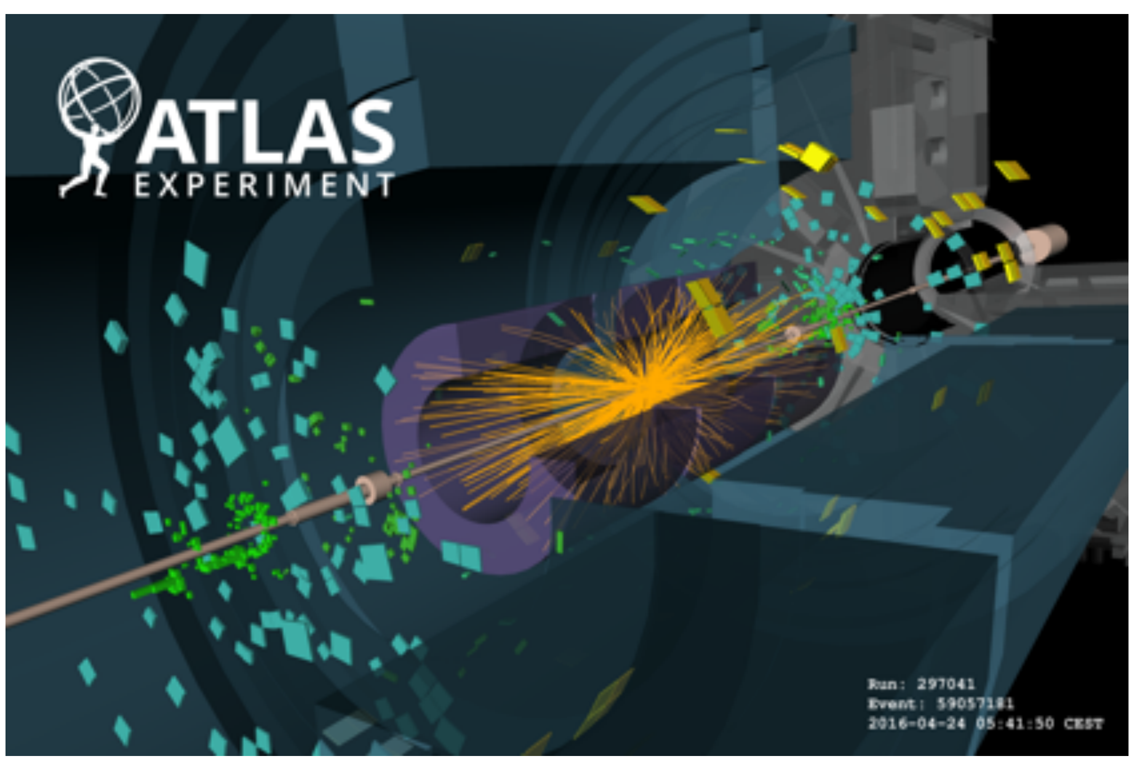
LHC status as of today: low intensity collisions @ $\sqrt{s}$ =13 TeV

- Stable beams delivered by LHC over the week-end: first low intensity collisions from Saturday 23rd April at $\sqrt{s}$ = 13 TeV
- **Using 12 bunches** (~10^{11}p/bunch) per beam achieving $L_{int,max}$ ~3.6 10^{31}cm^{-2} s^{-1}
- From early may increase N bunches. **Goal: 2736 bunches** to achieve design lumi: $L_{int,max}$ 1 10^{34}cm^{-2} s^{-1}

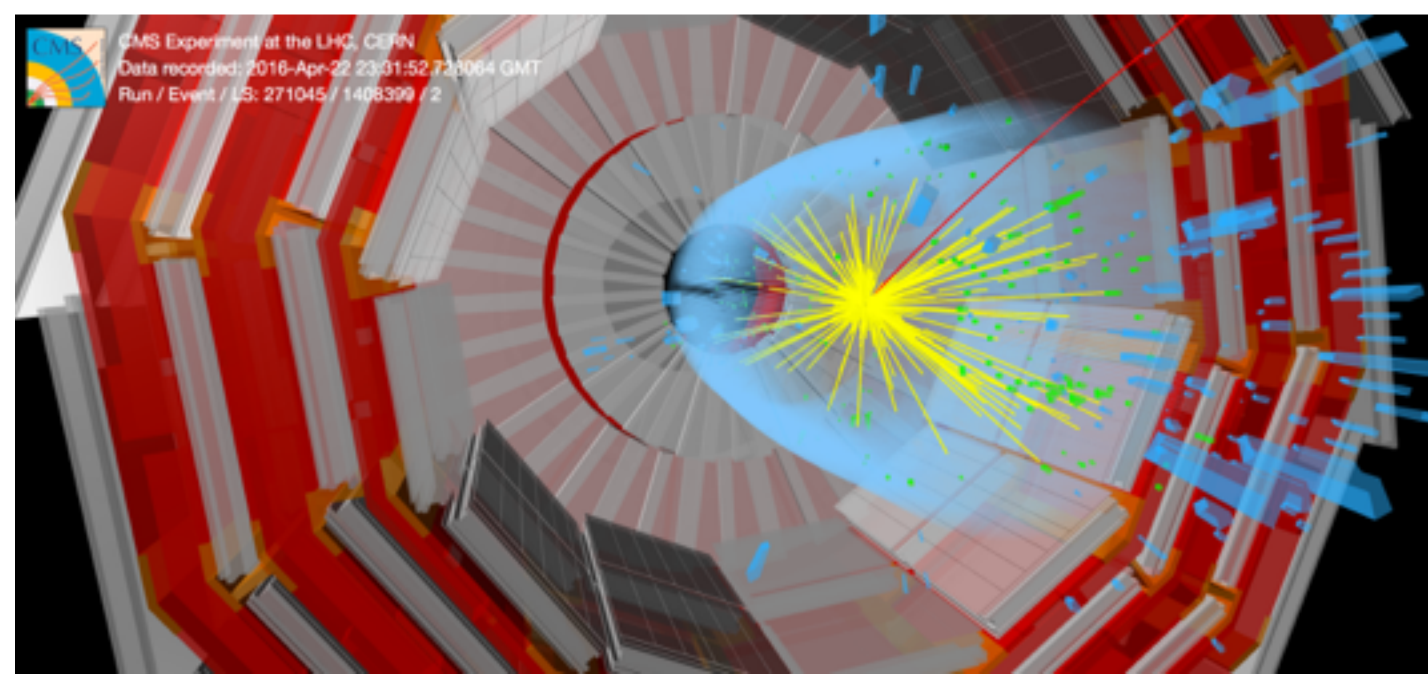
ATLAS Data Summary Public Page



ATLAS Event at 13 TeV - First 2016 Stable Beams



CMS Event at 13 TeV - First 2016 Stable Beams



Outlook

In 2015 operation was established **with 25 ns beams at 6.5 TeV**. Half of the design luminosity was reached with significant margin for improvements.

We expect to reach **design luminosity in 2016**, with the potential for more improvements in the years to come.

- *First beam injection around Easter.*

With at least 30 fb^{-1} expected per year, the target of **100 fb^{-1} for Run 2** is well within reach.

In 2016 LHC will operate at 6.5 TeV. Now that the 'quench cost' of operation at 7 TeV is better known, an energy increase can be considered in the coming years. To be agreed between machine and experiments.

Thank you for your attention!

15.03.2016 Moriond WS - La Thuile

Parameter	2015	2016
Peak luminosity (10^{34} cm^{-2}s^{-1})	0.51	1.0
Integrated per 150 days (fb^{-1})	--	~30

LHC in 2016

(J Wenninger, Moriond EWK 2016)

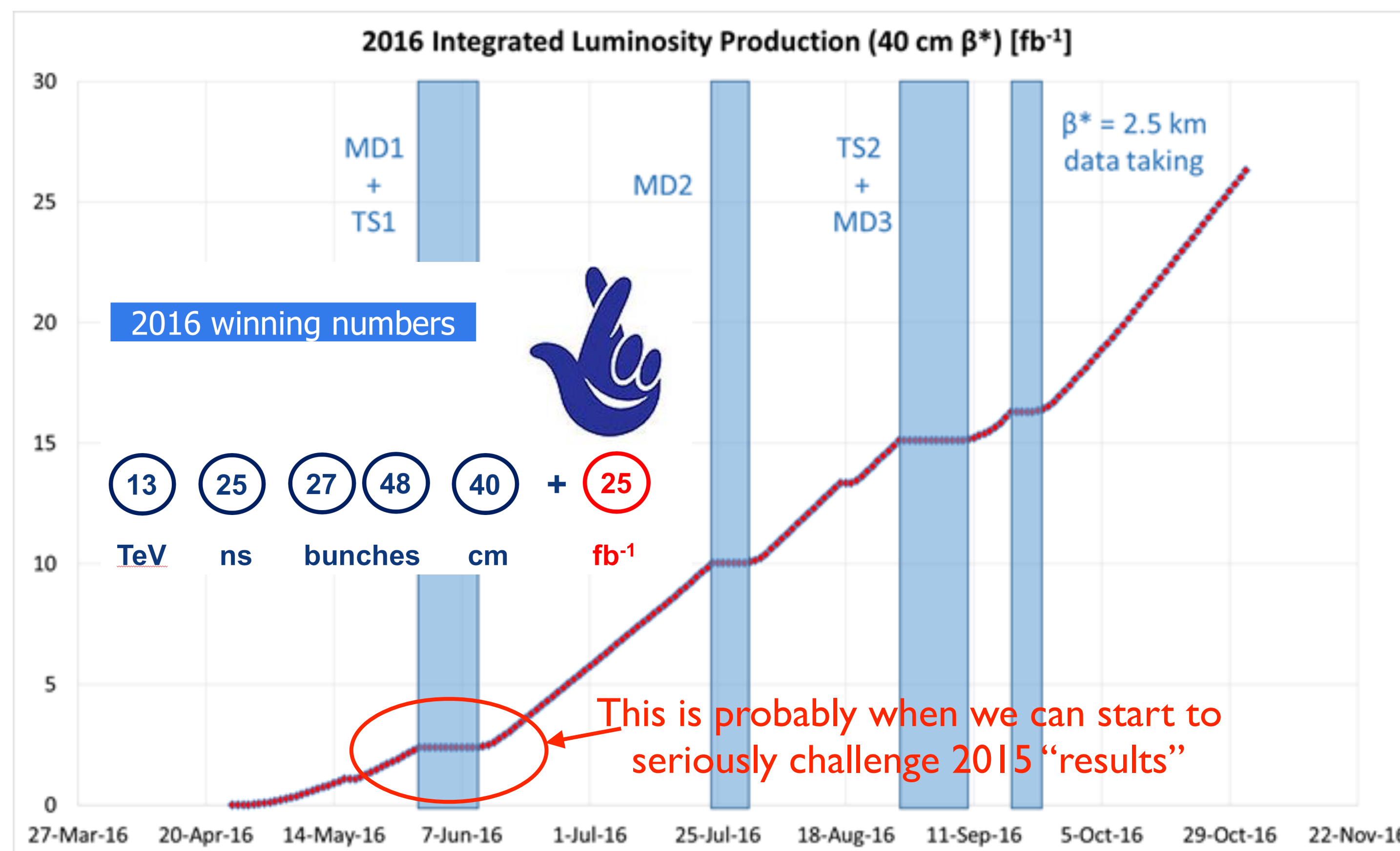
(Luca Malgeri Exp Summary @ Moriond QCD)

The 1232 main dipole magnets had to be trained for 6.5 TeV operation, 150 training quenches were required to bring the LHC to 6.5 + e TeV.

- *Dominated by the magnets of firm 3.*

With this new data, the **estimate for 7 TeV is ~300-400 additional quenches**.

LHC prospects for 2016



L. Malgeri - Moriond QCD 2016 - Exp. Summary 69

LHC prospects for later

(Luca Malgeri Exp Summary @ Moriond QCD)

LHC goal for **2016 and for Run 2 and 3**

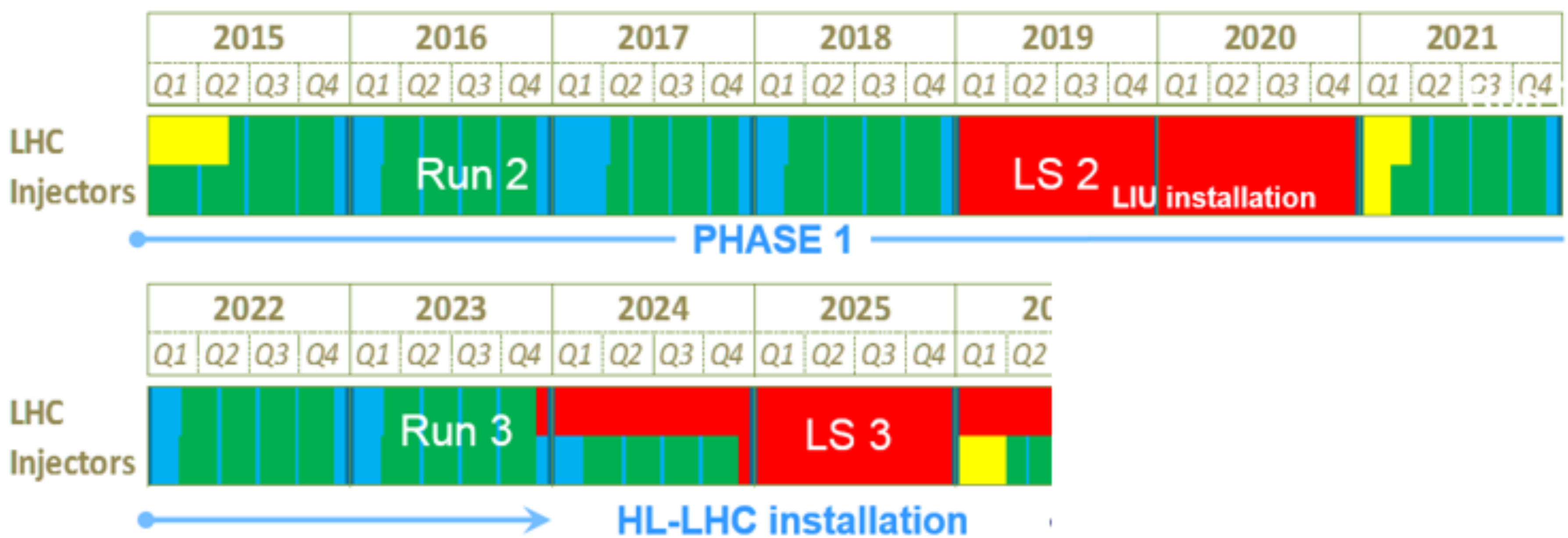
Integrated luminosity goal:

2016 : $\sim$25 fb^{-1} at 13 TeV c.m

Run2: $\sim$100 fb^{-1}

Prepare for (or go to) 14 TeV operation

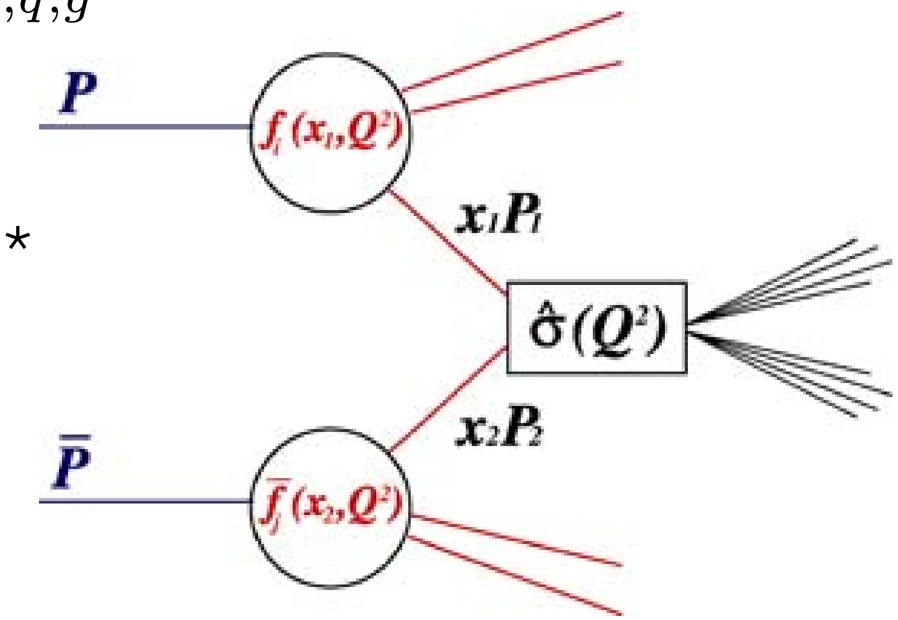
300 fb^{-1} before LS3



L. Malgeri - Moriond QCD 2016 - Exp. Summary 70

Top quark @ LHC: the cross section(I)

$$\sigma^{t\bar{t}}(\sqrt{s}, m_t) = \sum_{i,j=q,\bar{q},g} \int \mathrm{d}x_i \mathrm{d}x_j f_i(x_i, \mu^2) \bar{f}_j(x_j, \mu^2) \; \hat{\sigma}^{ij\to tt}(\rho, m_t^2, x_i, x_j, \alpha_s(\mu^2), \mu^2)$$



	LHC(14)	LHC(7)	Tev(1.9)
gg	~90%	~85%	~10%
qq	~10%	~15%	~90%

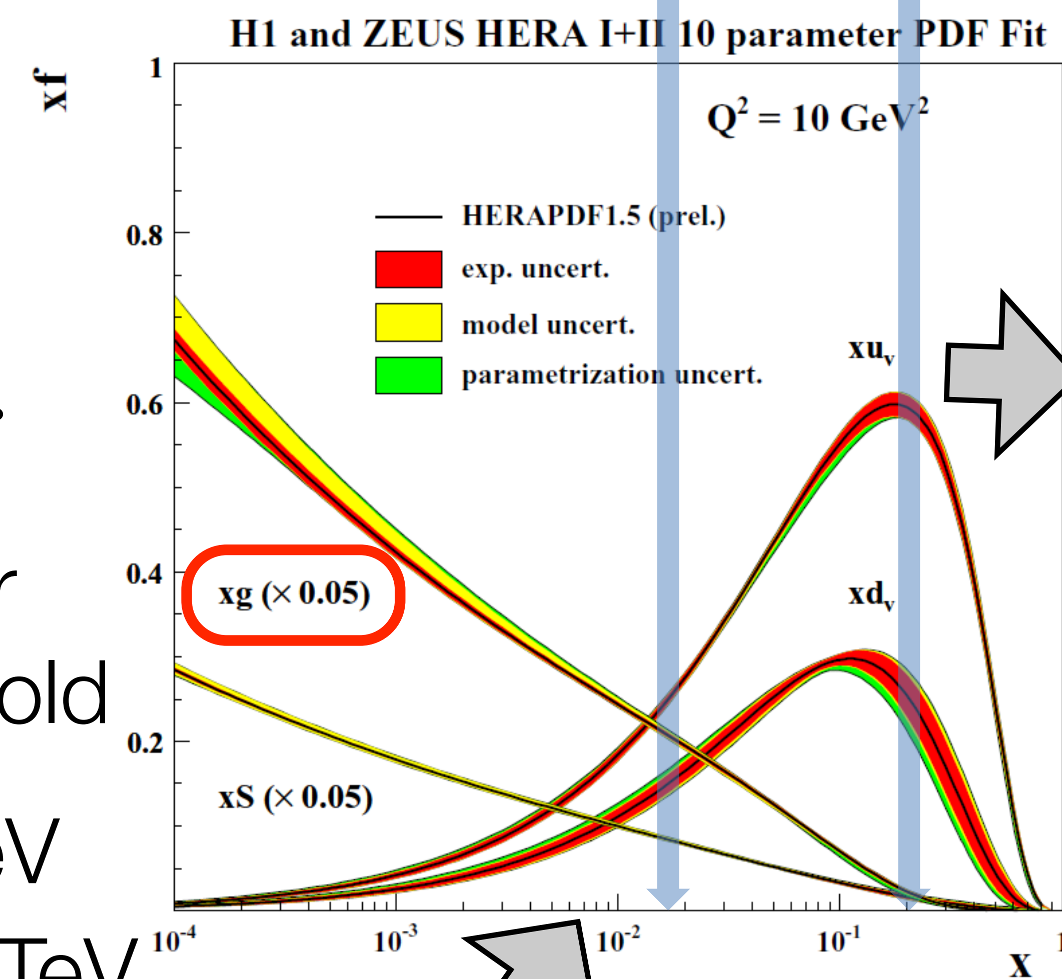
$N_{events}(\Delta t)$= ***∫Ldt*** * cross section

To produce $t\bar{t}$

~massless partons

$$\hat{s} \geq 4m_t^2 \Rightarrow x_i x_j = \hat{s}/s \geq 4m_t^2/s.$$

$f_i(x)$ falls with larger x ⇒ typical $x_i x_j$ near threshold



$$\Rightarrow x \approx \frac{2m_t}{\sqrt{s}} =$$

0.19 @ Tevatron √s=1.8 TeV

0.18 @ Tevatron √s=1.96 TeV

(0.048, 0.043, 0.026) @ LHC with √s=(7, 8,13) TeV

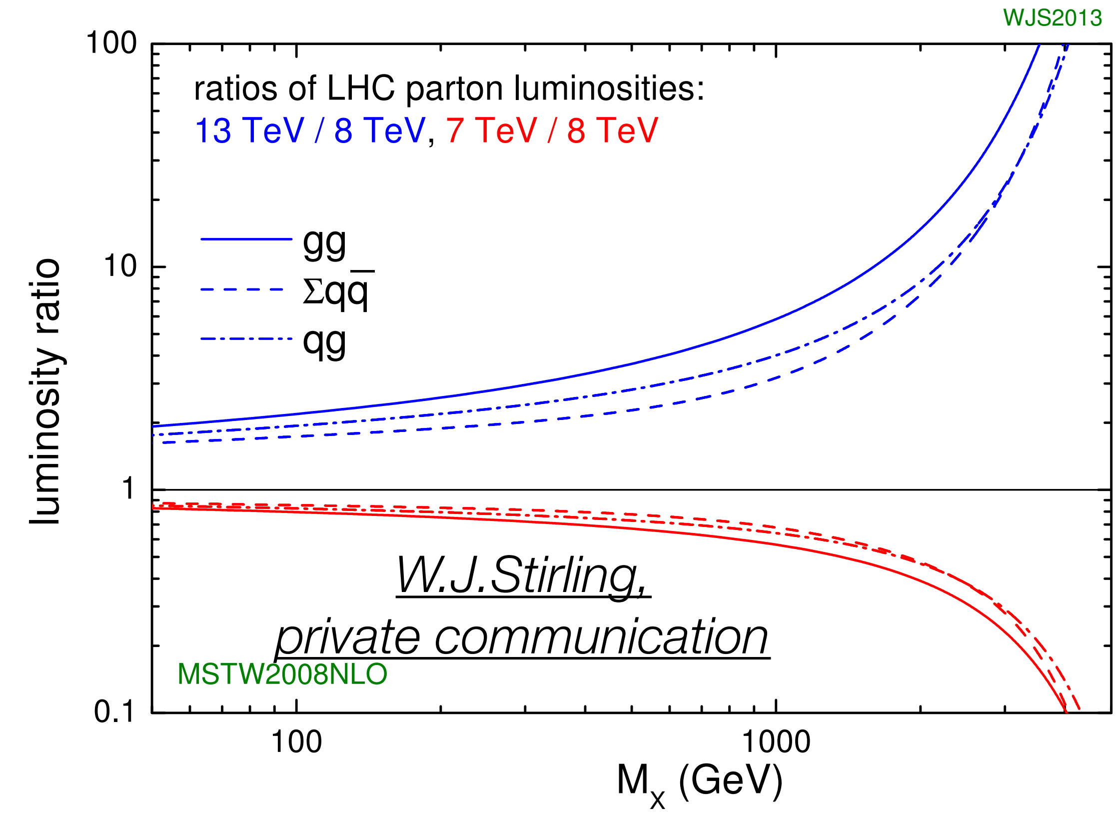
Top quark @ LHC: production (I)

(Campbell et al, Rept.Prog.Phys.70:892007)

$$\sigma = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat\sigma_{ij} = \sum_{i,j} \int \left(\frac{d\hat s}{\hat s}\, dy\right) \left(\frac{dL_{ij}}{d\hat s\, dy}\right) (\hat s\, \hat\sigma_{ij}) \sim \sum_{i,j} \frac{\Delta \hat s}{\hat s} \left(\frac{dL_{ij}}{d\hat s}\right) (\hat s\, \hat\sigma_{ij})$$

$$\frac{dL_{ij}}{d\hat s\, dy} = \frac{1}{s} \frac{1}{1+\delta_{ij}} [f_i(x_1,\mu) f_j(x_2,\mu) + (1 \leftrightarrow 2)]$$

- Different **x-range and center of mass** dependence incorporated in **Parton luminosities**→
  - **gg→X** dominated processes **grow more than qq →X** ones
  - **larger gains at high multi-TeV masses** ~up to O(100)



Magano, Rojo, JHEP{1208},2012:10

$R^{th,nnpdf}$ = 14TeV to 8 TeV xsec ratios

Cross Section	$R^{\rm th,nnpdf}$	$\delta_{\rm PDF}(\%)$	δ_{α_s} (%)	$\delta_{\rm scales}$ (%)
$t\bar t/Z$	2.12	$\pm$ 1.3	$-0.8 - 0.8$	$-0.4 - 1.1$
$t\bar t$	3.90	$\pm$ 1.1	$-0.5 - 0.7$	$-0.4 - 1.1$
Z	1.84	$\pm$ 0.7	$-0.1 - 0.3$	$-0.3 - 0.2$
W^+	1.75	$\pm$ 0.7	$-0.0 - 0.3$	$-0.3 - 0.2$
W^-	1.86	$\pm$ 0.6	$-0.1 - 0.3$	$-0.3 - 0.1$
W^+/W^-	0.94	$\pm$ 0.3	$-0.0 - 0.0$	$-0.0 - 0.0$
W/Z	0.98	$\pm$ 0.1	$-0.1 - 0.0$	$-0.0 - 0.0$
ggH	2.56	$\pm$ 0.6	$-0.1 - 0.1$	$-0.9 - 1.0$
$t\bar t(M_{tt} \ge 1$ TeV$)$	8.18	$\pm$ 2.5	$-1.3 - 1.1$	$-1.6 - 2.1$
$t\bar t(M_{tt} \ge 2$ TeV$)$	24.9	$\pm$ 6.3	$-0.0 - 0.3$	$-3.0 - 1.1$
$\sigma_{\rm jet}(p_T \ge 1$ TeV$)$	15.1	$\pm$ 2.1	$-0.4 - 0.0$	$-1.9 - 2.4$
$\sigma_{\rm jet}(p_T \ge 2$ TeV$)$	182	$\pm$ 7.7	$-0.3 - 0.2$	$-5.7 - 4.0$

- **Cross sections in "tails" increase differently** from (more rapidly than the inclusive value

thanks to K. Suruliz, TOP2013

Top quark @ LHC: production (II)

pp collisions

probing lower x than Tevatron → (abundant) gluon fusion dominated

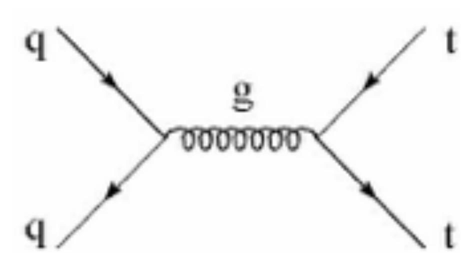
	Tevatron	LHC(7)	LHC(14)
gg	~10%	**~85%**	~90%
qq	~90%	**~15%**	~10%

LO representative

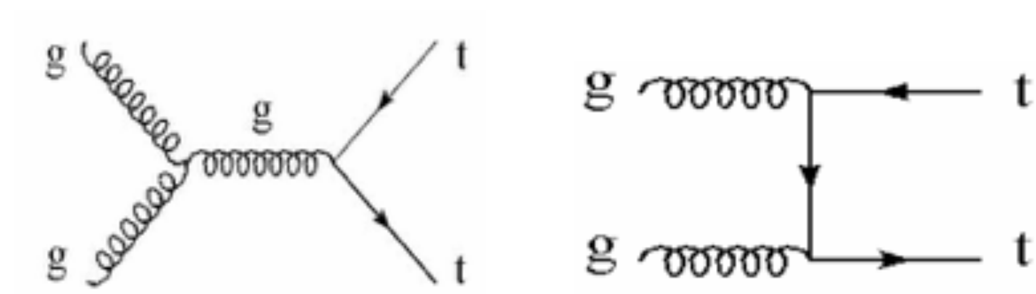
m_{top}= 172.5

top pairs: strong

qq annihilation



gluon fusion



At Tevatron

$\sigma_{t\bar{t}} \sim 7$ pb
$\sigma_t \sim 3.5$ pb

Czakon,Mitov,Fiedler 2013

NNLO+NNLL accuracy

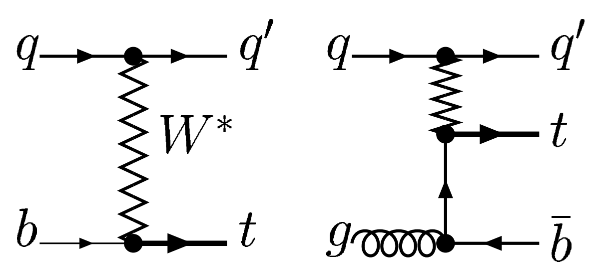
$\delta\sigma_{tt}/\sigma_{tt}$ ~4%

σ_{7TeV} (pb)	**$172^{+4.4}_{-5.8}{}^{+4.7}_{-48}$**
σ_{8TeV} (pb)	**$245^{+6.2}_{-8.4}{}^{+6.2}_{-6.4}$**
σ_{13TeV} (pb)	**$832^{+20}_{-29}{}^{+35}_{-35}$**

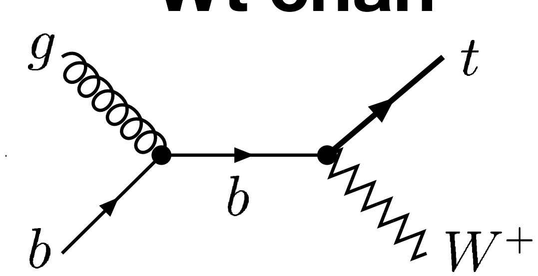
R(13/8) ~ 3.3

single top: electroweak

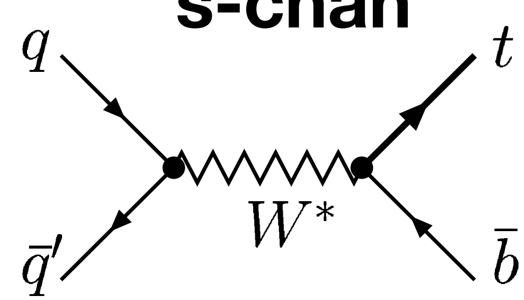
t-chan



Wt chan



s-chan



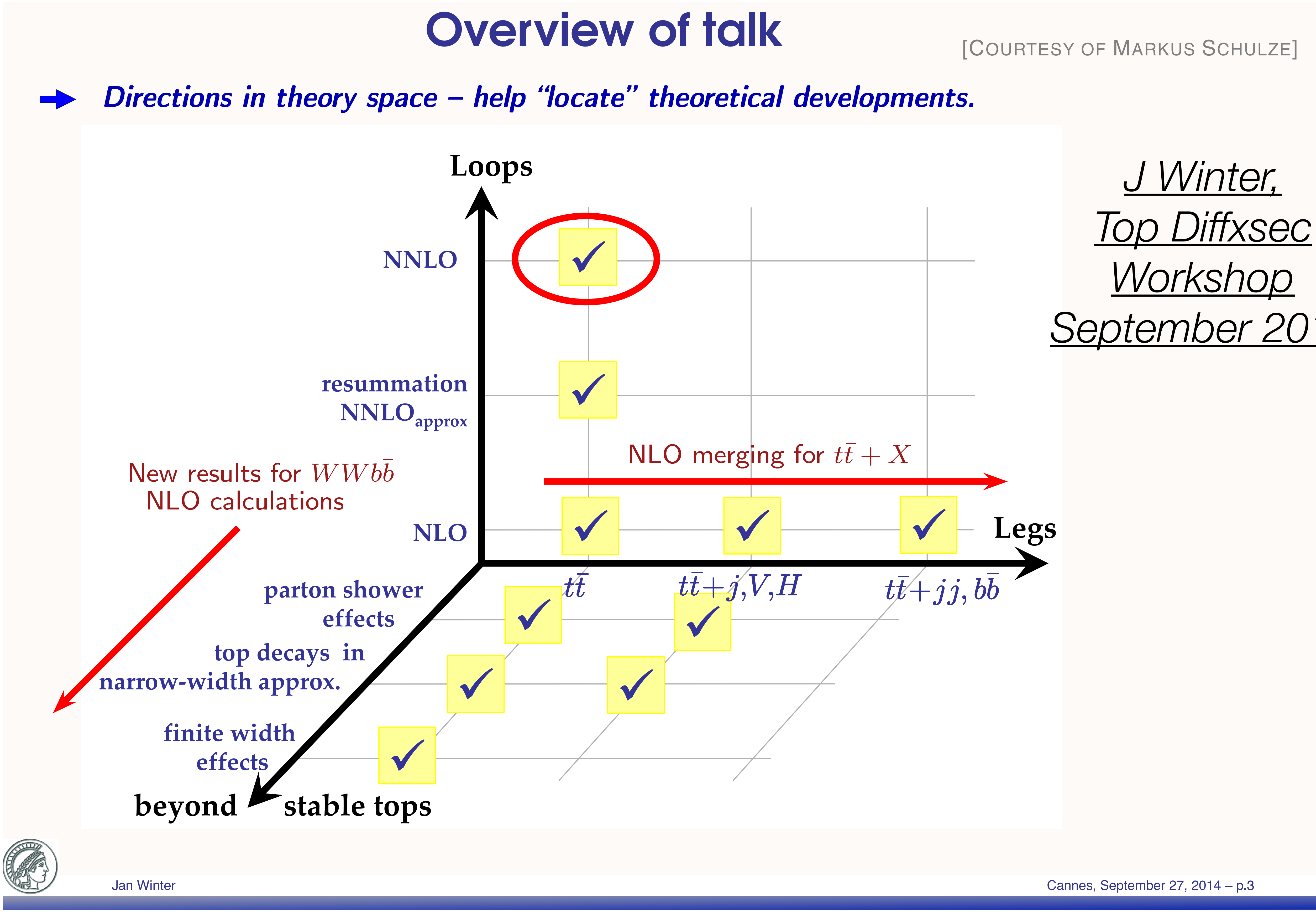
	t-chan	Wt chan	s-chan
σ_{7TeV} (pb)	**64.6±2.4**	**15.7±1.1**	**4.6±0.2**
σ_{8TeV} (pb)	**87.8±3.4**	**22.4±1.5**	**5.6±0.2**
σ_{13TeV} (pb)	**~213**	**~71.7**	**~10.9**

Kidonakis 2010,2011

approx NNLO

$\delta\sigma_t/\sigma_t$ ~2 to 7%

From present to future directions in top phys. predictions

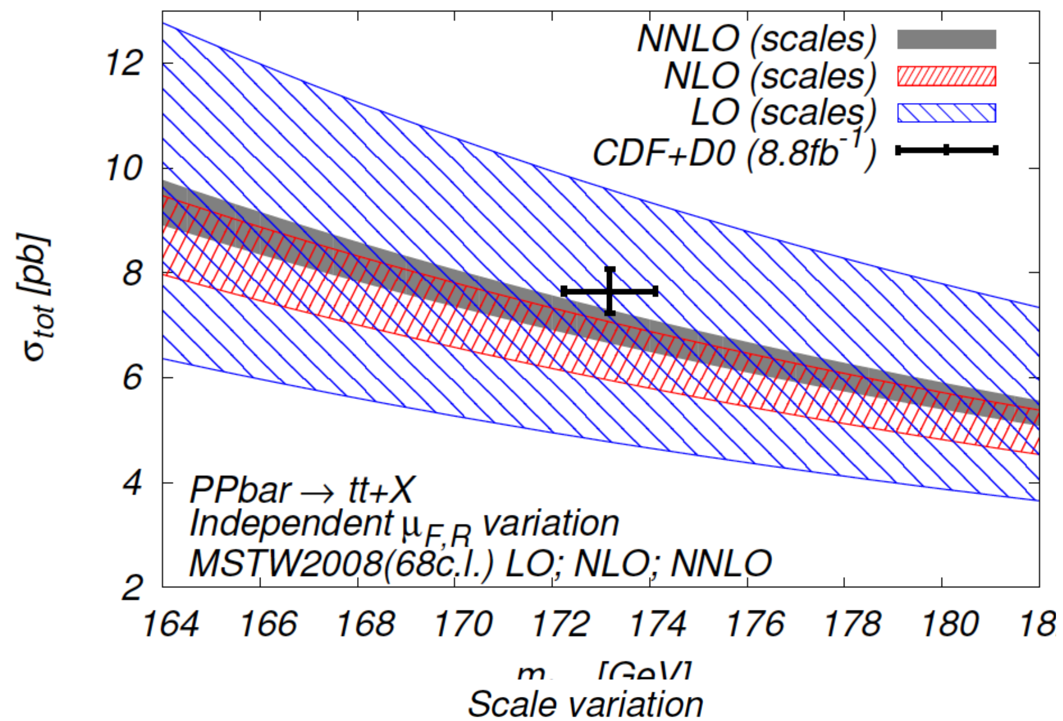


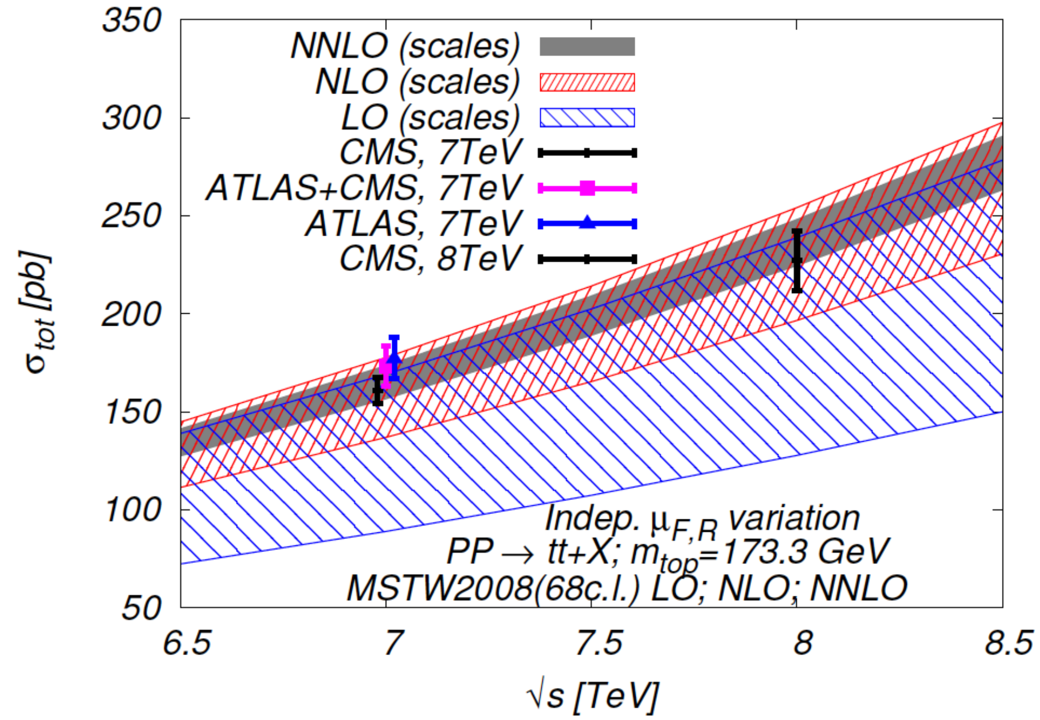
J Winter,
Top Diffxsec
Workshop
September 2014

The NNLO revolution: $t\bar{t}$ inclusive cross section

Czakon,Fedler,Mitov PRL 110.252004

- NNLO QCD calculations are available for $t\bar{t}$ production vs $\sqrt{s}$

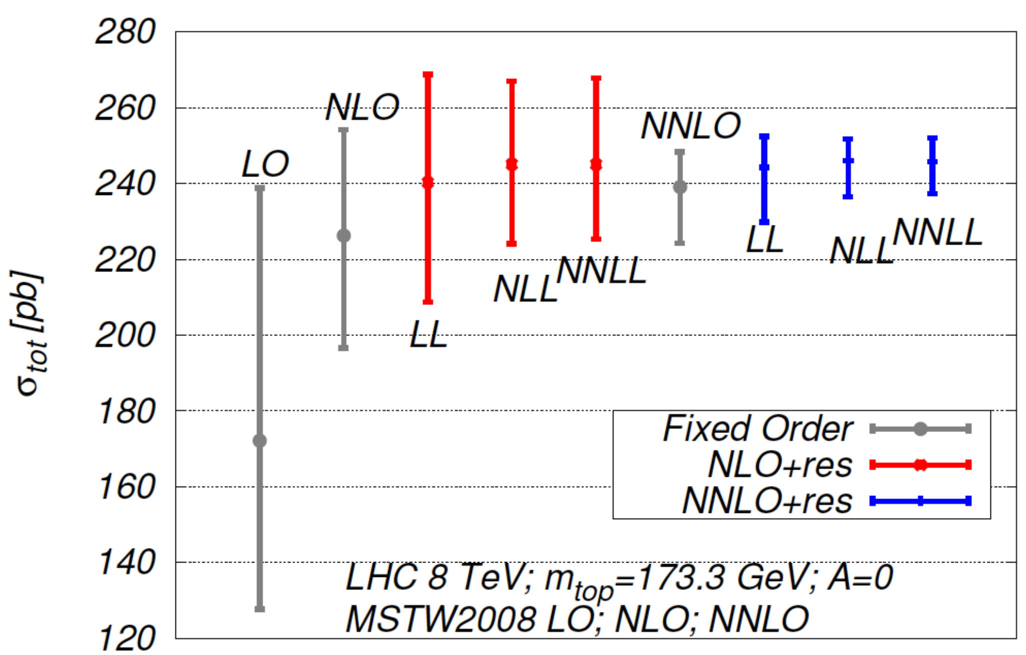




Czakon @ TOP2014

Inclusive $t\bar{t}$ cross section

Scale variation



Scales	~ 3%
pdf (at 68%cl)	~ 2-3%
α_S (parametric)	~ 1.5%
m_{top} (parametric)	~ 3%

Soft Gluons resummation makes a difference

5% -> 3% CONSIDER ANY THEORY UPDATE FROM Top2015 and Moriond ?

Differential $t\bar{t}$ cross section is now also available!! (see further)

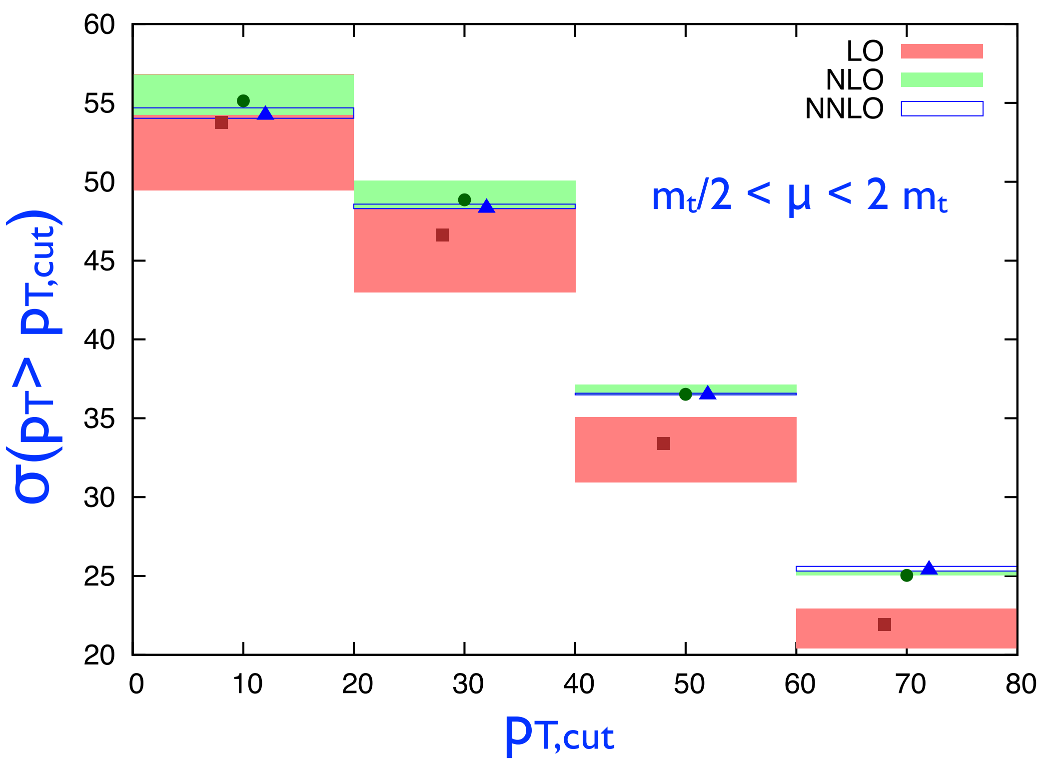
The NNLO revolution: single top t-channel @ $\sqrt{s}$ = 8 TeV

F. Caola @ Moriond QCD2015

t-channel single-top@NNLO: LHC8 results

$$\sigma_{\mathrm{LO}} = 53.77 + 3.03 - 4.33 \text{ pb}$$

$$\sigma_{\mathrm{NLO}} = 55.13 + 1.63 - 0.90 \text{ pb}$$



PERCENT-LEVEL CONTROL ON THE CROSS-SECTION ACHIEVED

$$\sigma_{\mathrm{NNLO}} = 54.2^{+0.5}_{-0.2} \text{ pb}$$

- Contrary to NLO, results stable in the full spectrum
- Improved scale dependence
- K-factor small but not constant
- Similar results for antitop
- t/tbar ratio extremely stable -> PDF test?

[Brucherseifer, FC, Melnikov (2014)]

Future: compare with fiducial cross section at particle level (reduce extrapolations).

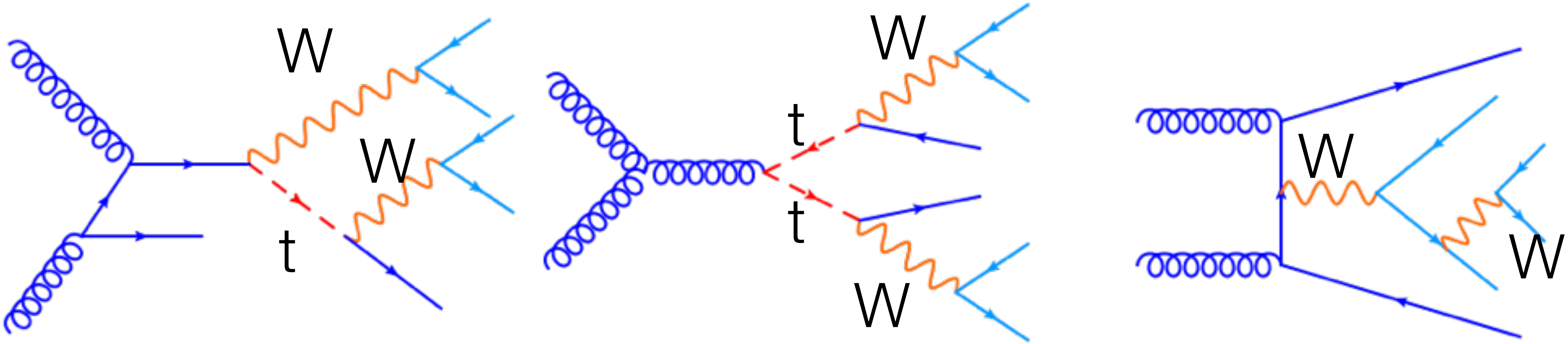
Need to:

- combine production with available NNLO decay chains
- combine with parton shower & hadronization

Towards realistic final-states NLO for $t\bar{t}$ & single top quark

- At NLŌ tt, Wt and WW share the same final state so one needs WWbb @NLO

(graphs by F. Caola, CERN)



it is there now!!

- results provided recently by two groups:

[Frederix, arXiv:1311.4893] [Cascioli, Kallweit, Maierhöfer, Pozzorini, arXiv:1312.0546]

Future @ NLO

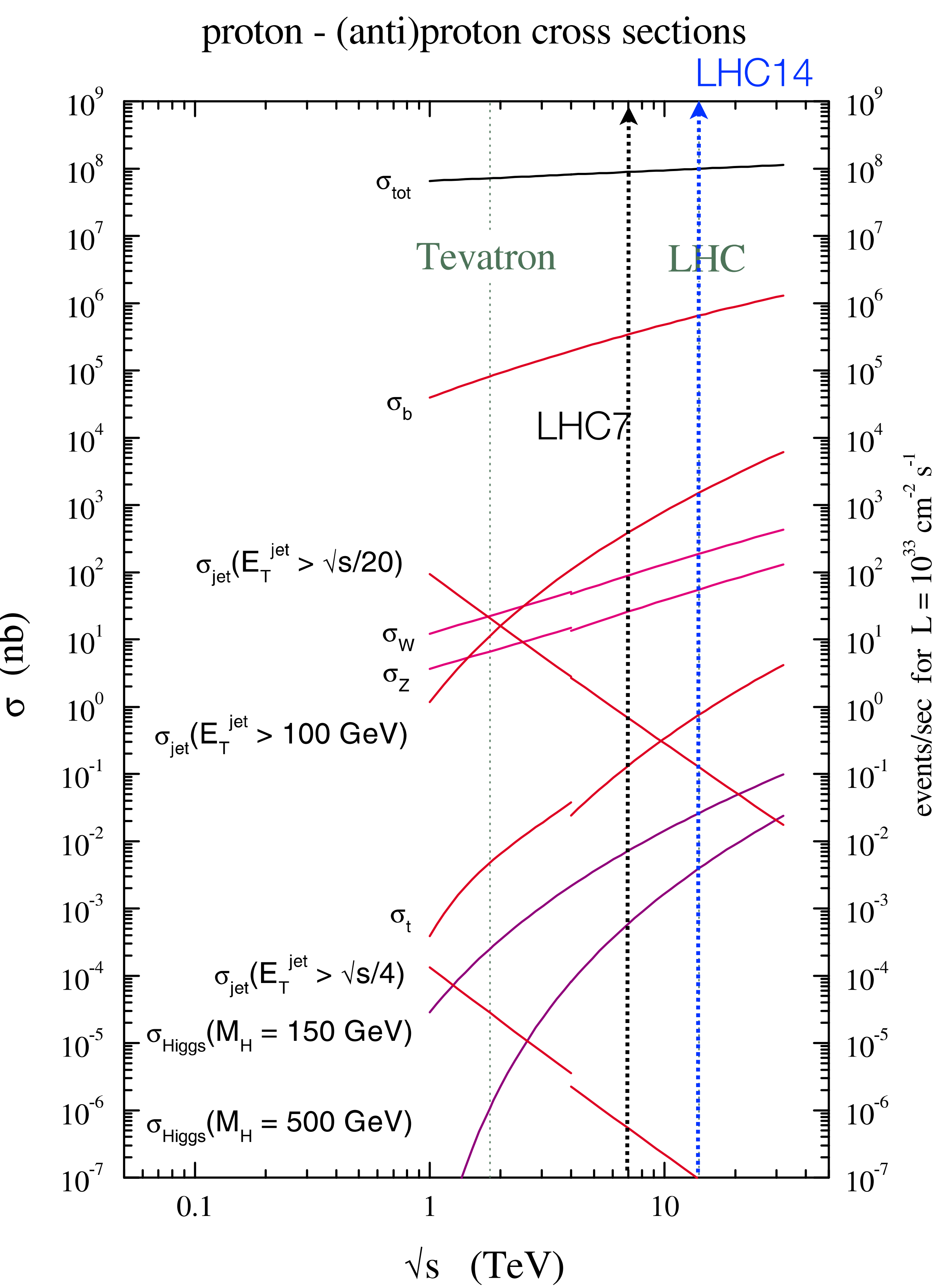
WWbb final state with doubly resonant ($t\bar{t}$), singly resonant (Wt) and non resonant interfering contributions

\+

single top t- & s-channel

Future: to be matched to Parton Shower & Hadronization

Top @ LHC: in the context



t and $t\bar{t}$ cross section

√s(TeV)	σ_{tt}(pb)	σ_t(pb)
1.96(pp)	~7	
7(pp)	~172	~85
8(pp)	~245	~115
13(pp)	~830	~296
14(pp)	~900	~338

$t\bar{t}$(t) Rate at L= $10^{33}cm^{-2}\ s^{-1}$

0.17 (0.08)Hz
0.24 (0.12)Hz
0.83 (0.30)Hz
0.90 (0.33)Hz

~8.3M (~3M) $t\bar{t}$(single top) events with 10 fb^{-1} with √s = 13 TeV LHC

~5.4M (~0.96 M) $t\bar{t}$ events produced by LHC in 2012 (2011)

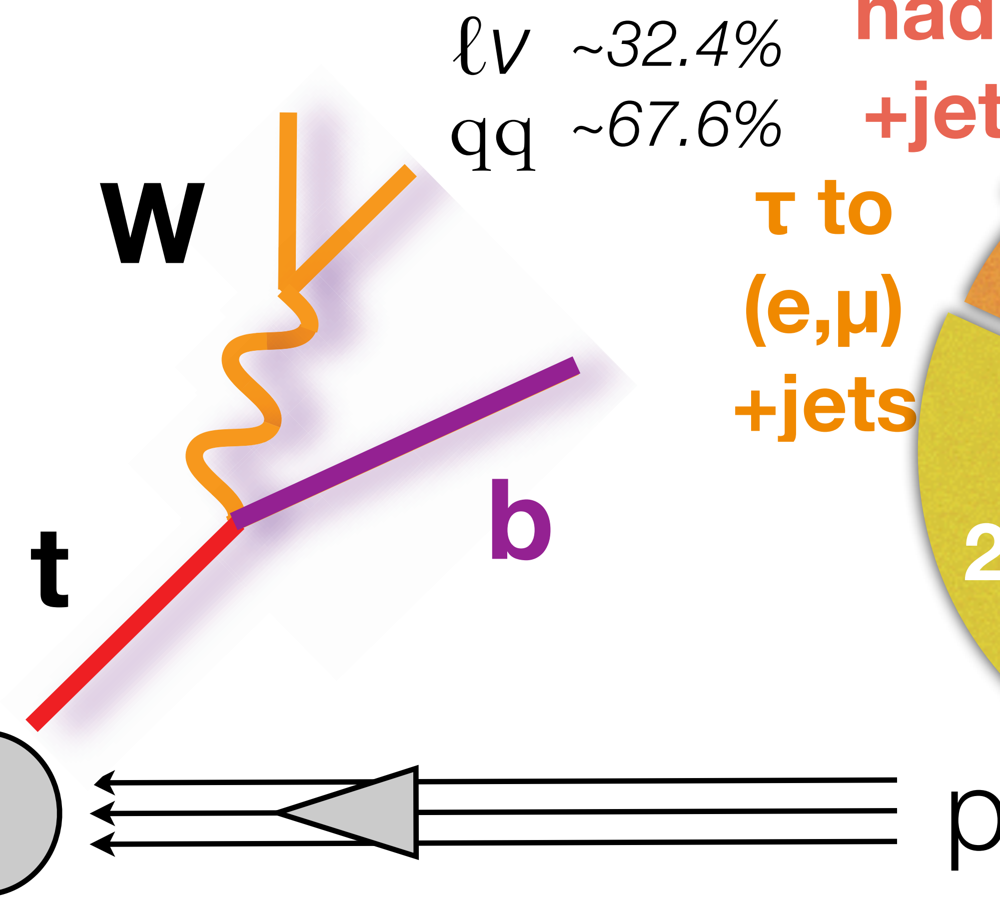
~2.5M (0.47 M) single top events produced by LHC in 2011 (2012)

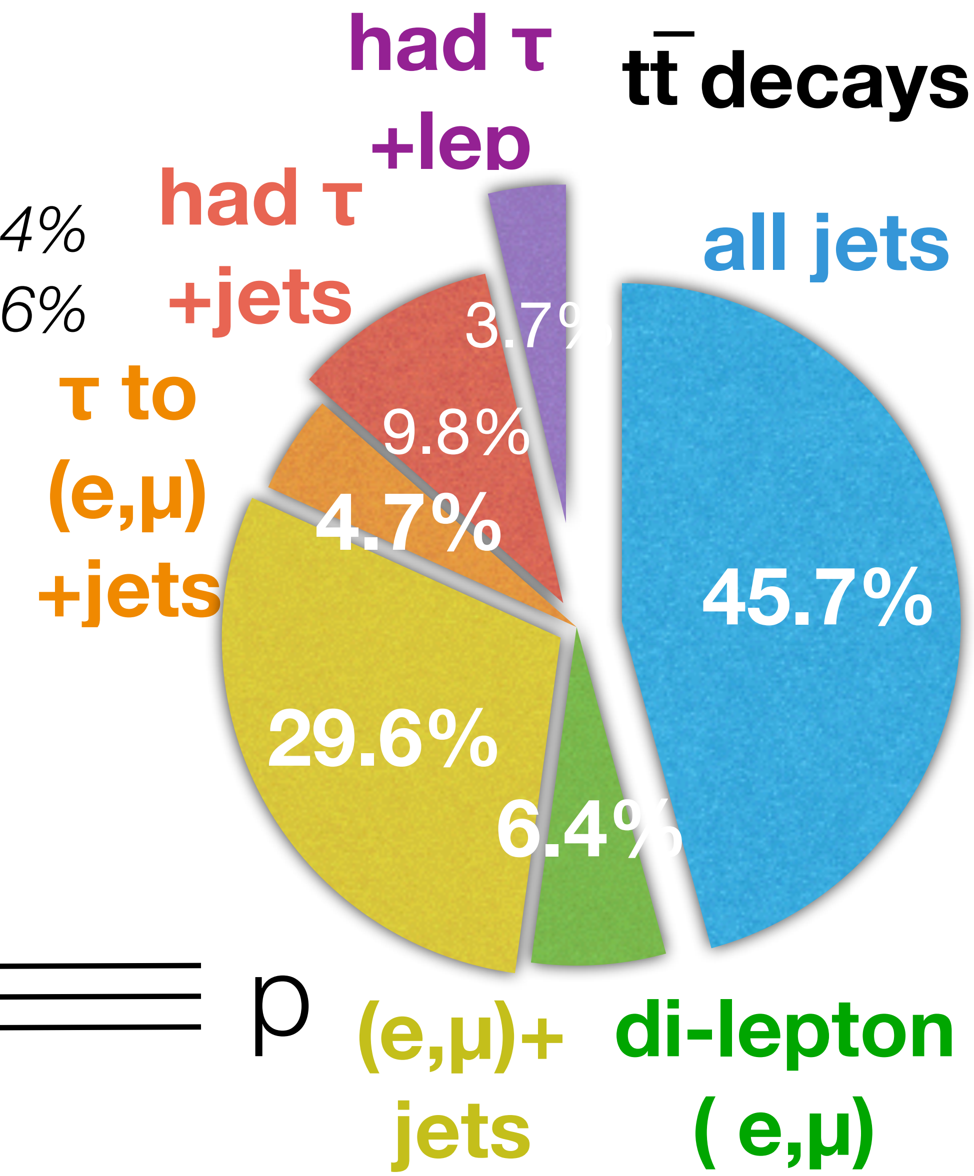
LHC is a TOP FACTORY

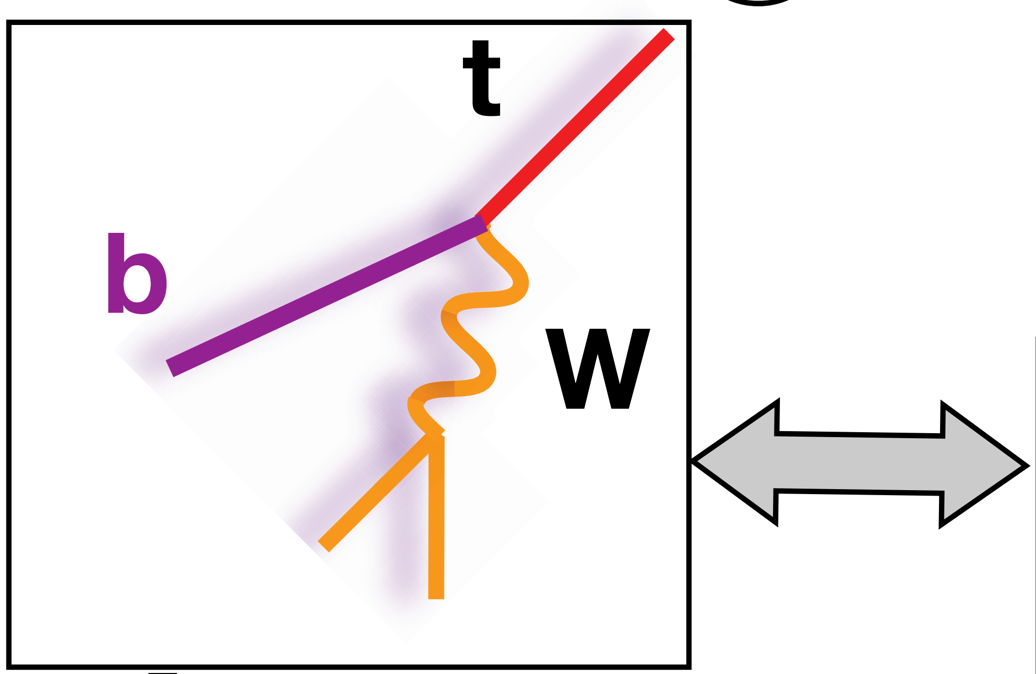
Tevatron (lower energy collider): ∫Ldt =9.4 fb^{-1} on tape, expect ~ $6.6 \cdot 10^4$ $t\bar{t}$ events

Final state signatures

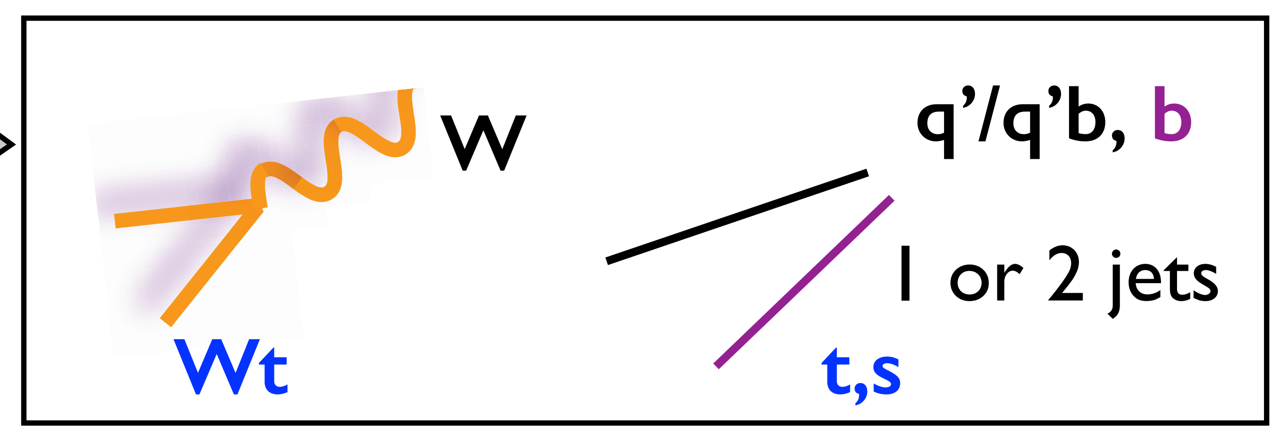
- **High P_T jets of hadrons**
- **b-jets**
- **1 to 2 high P_T leptons**
- **Missing energy**







single top



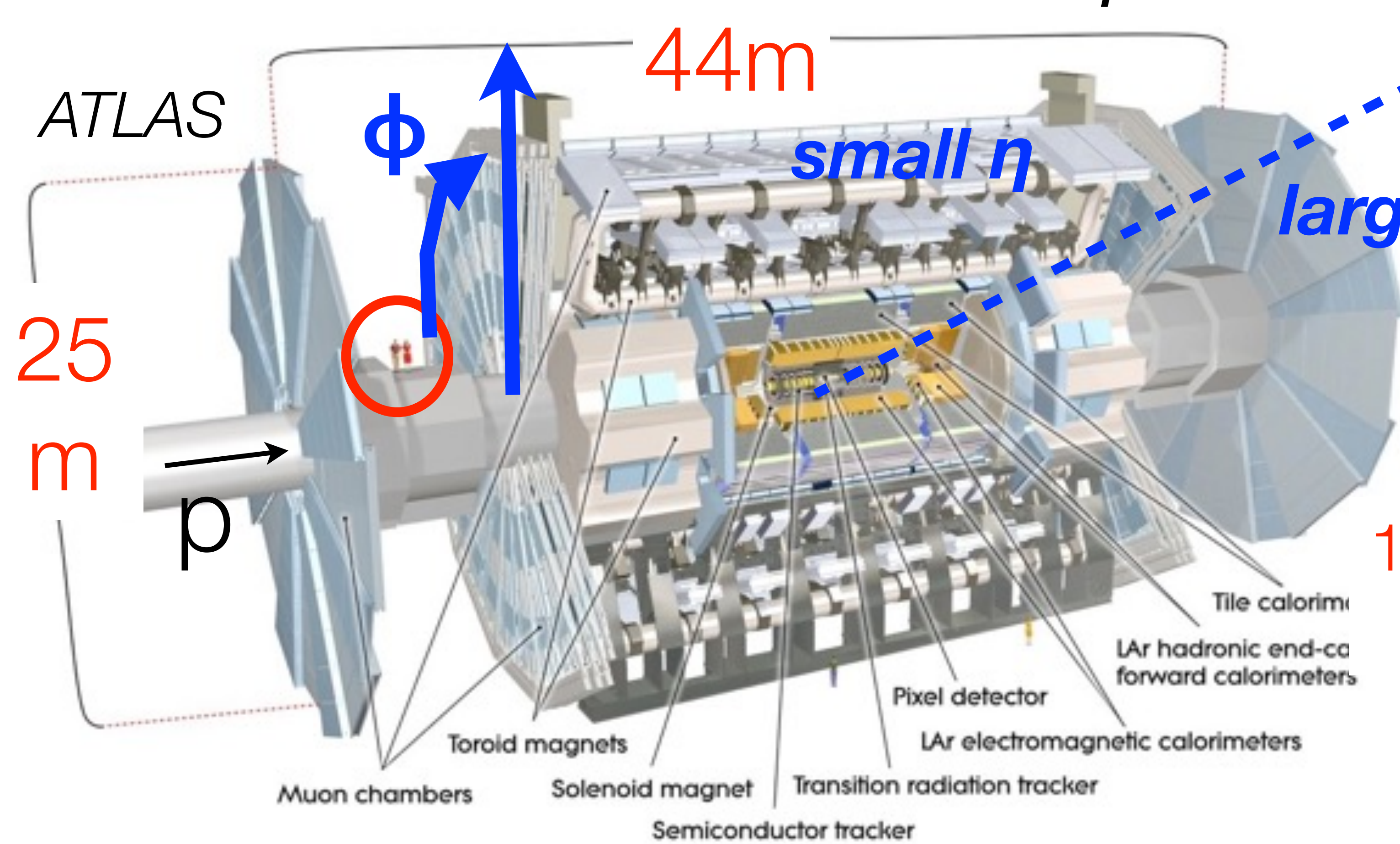
bkgs_tt̄: W/Z(+jets), single top, QCD, Di-bosons

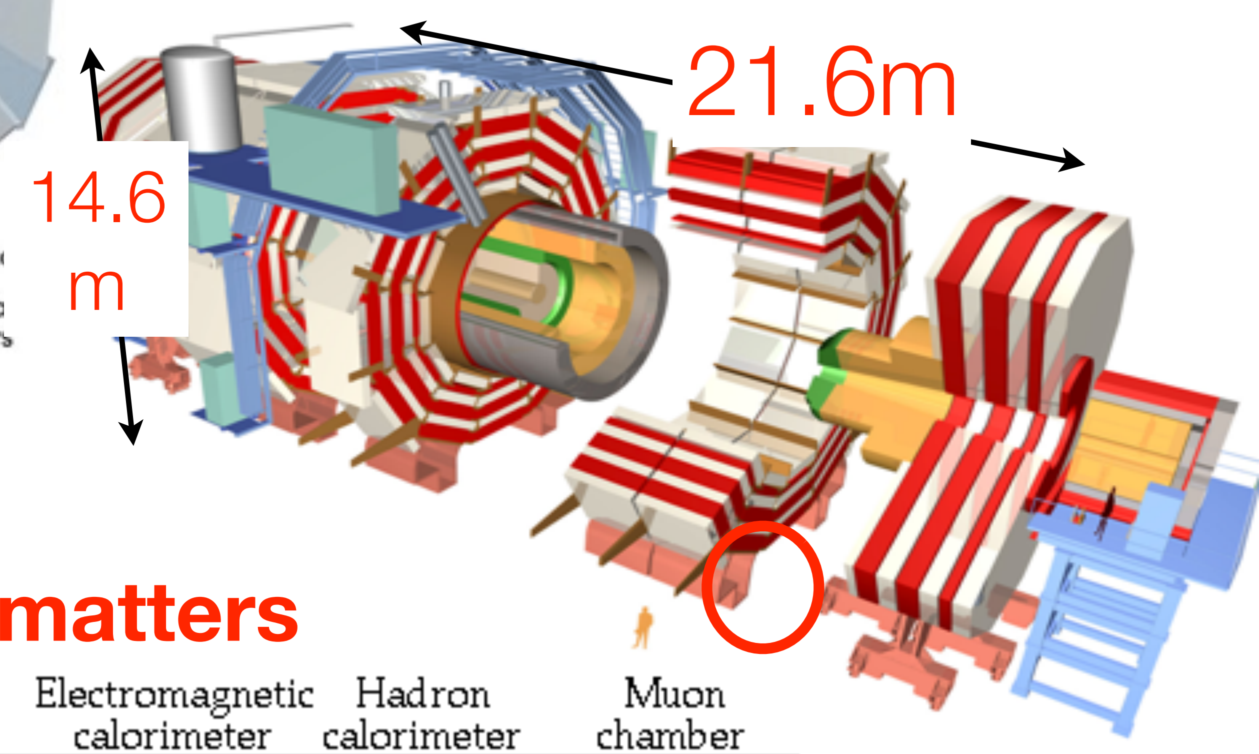
bkgs_single_t: tt̄ + same bkgs_tt̄

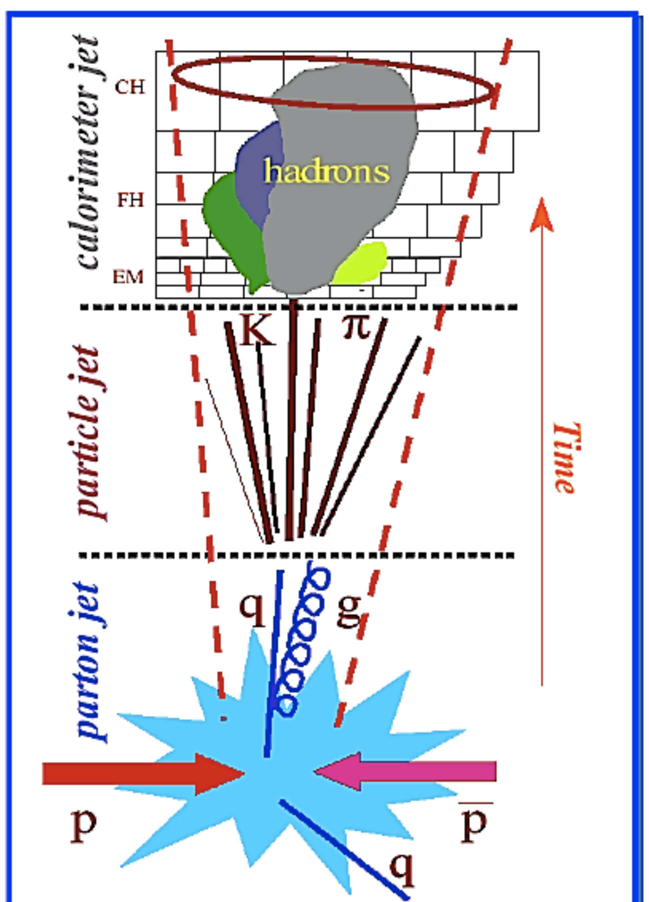
ATLAS & CMS: *Top* observers

2 trigger levels for event selection
(ATLAS had 3 in the past)

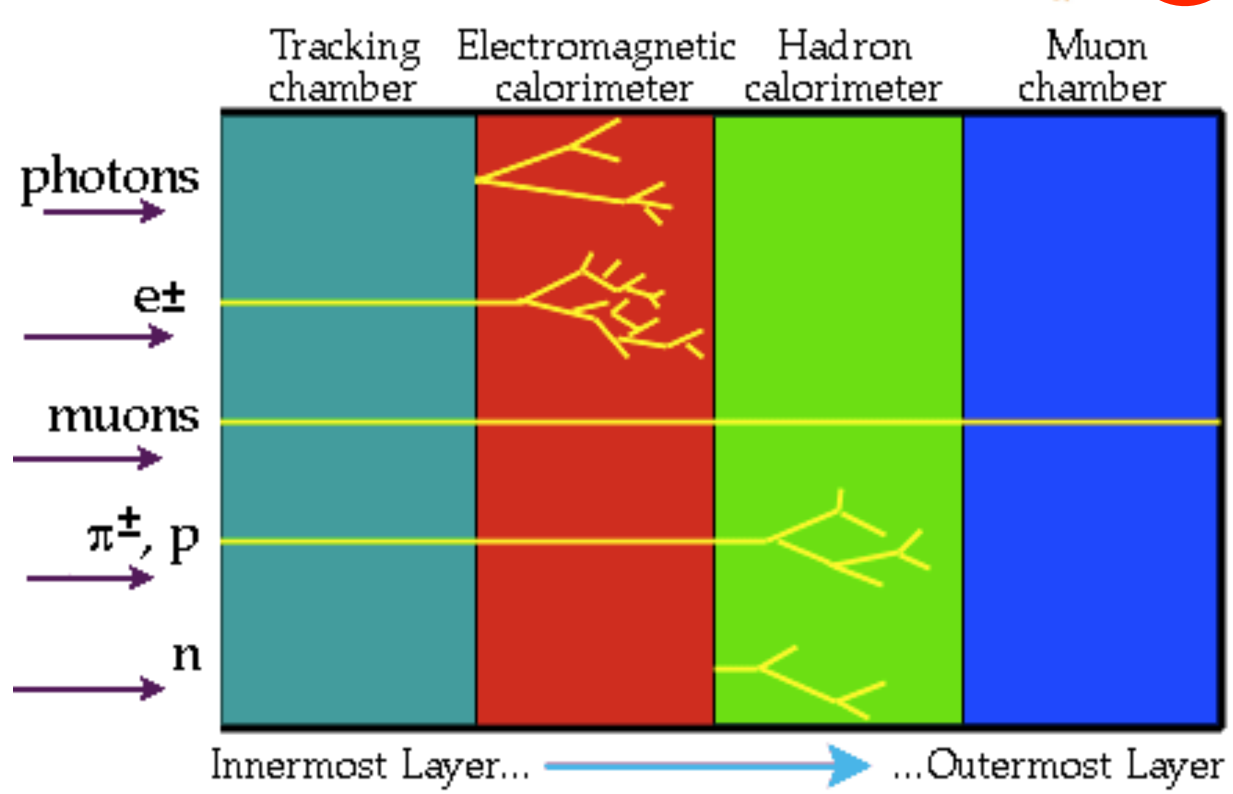
η = pseudorapidity =-ln (tan(θ/2))





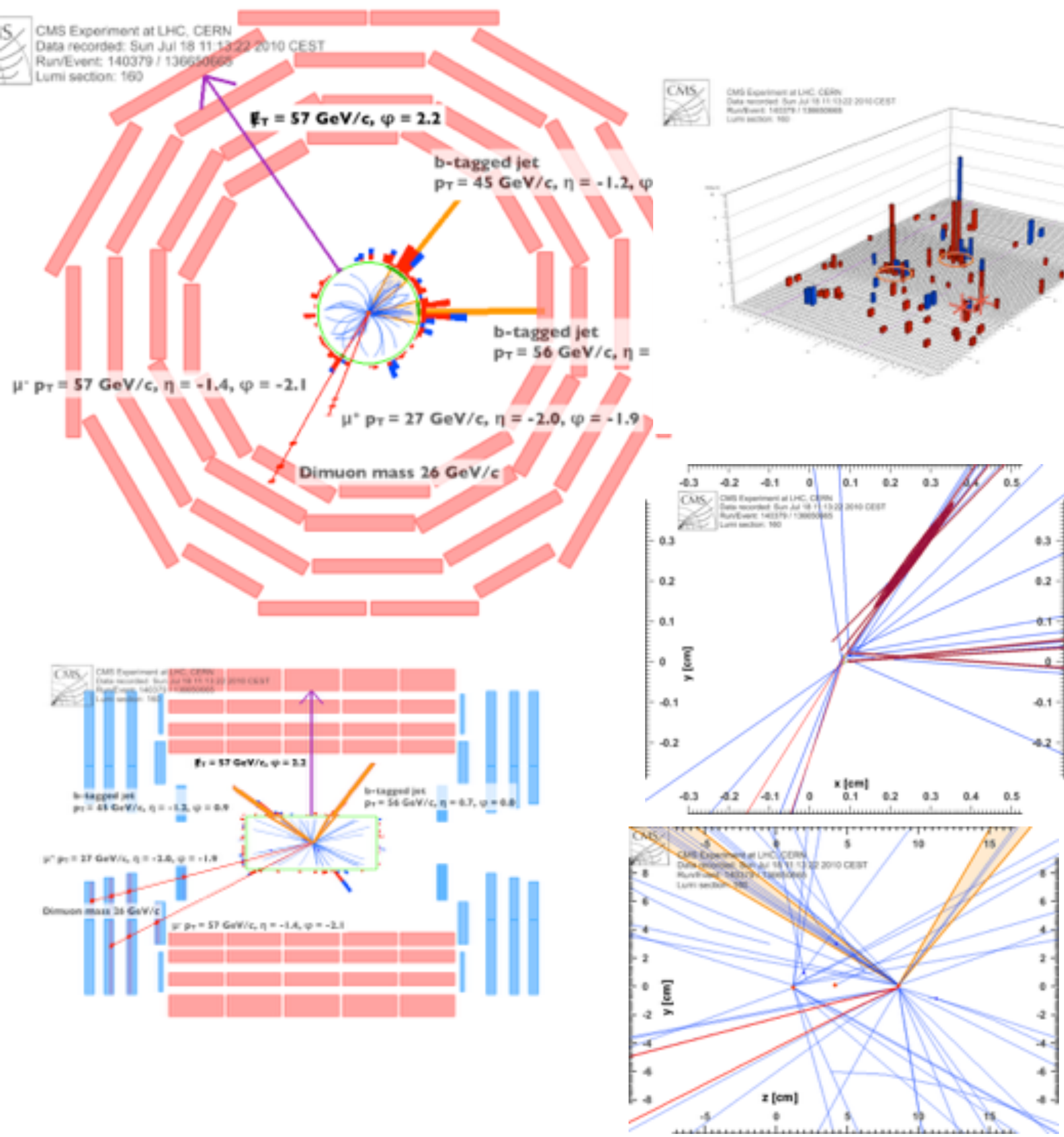


size matters



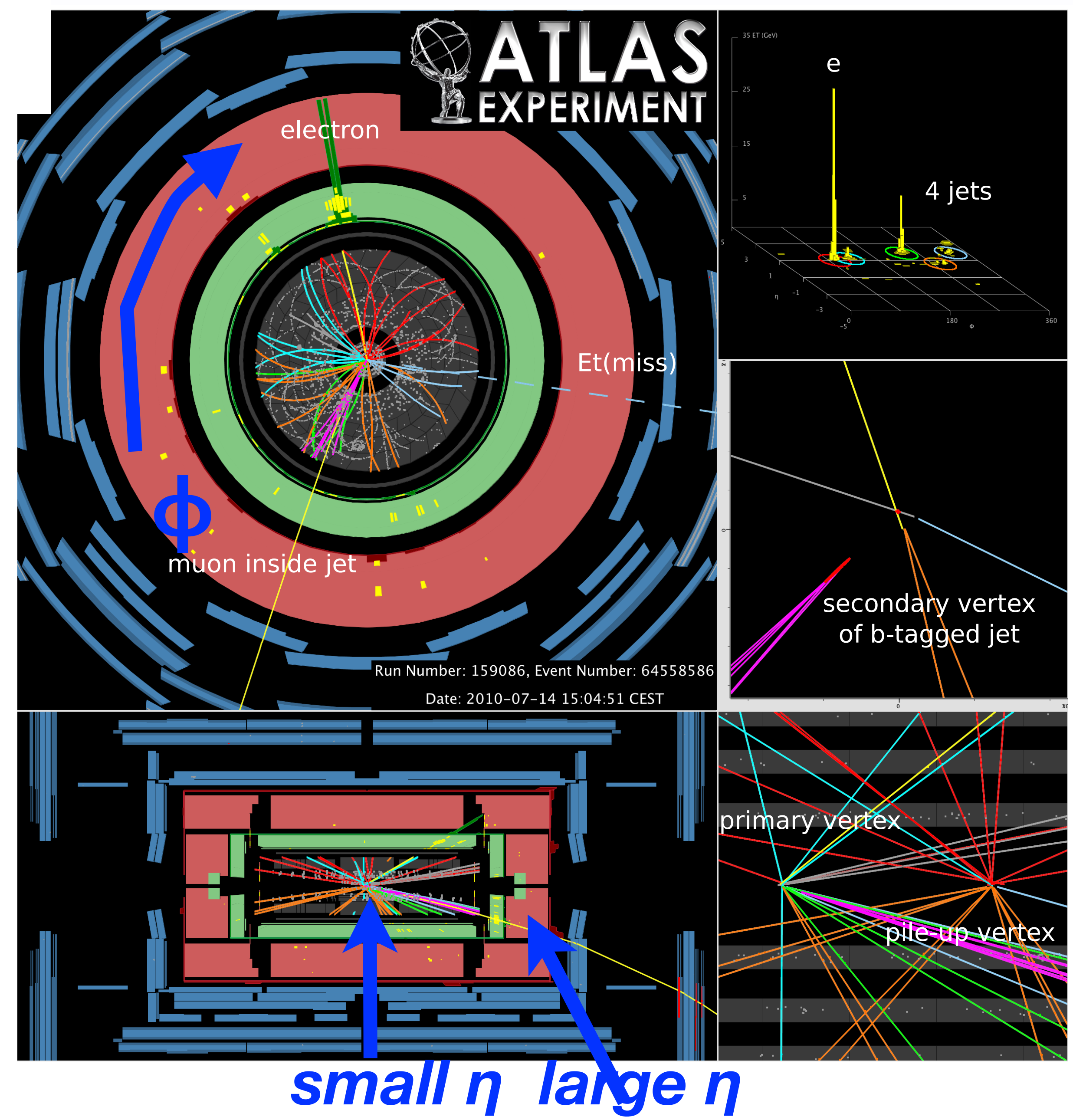
ATLAS and CMS: *Top observers.....*

Top quark events are real commissioning tool: full detector at play!!



di-lepton (μμ+jets) candidate

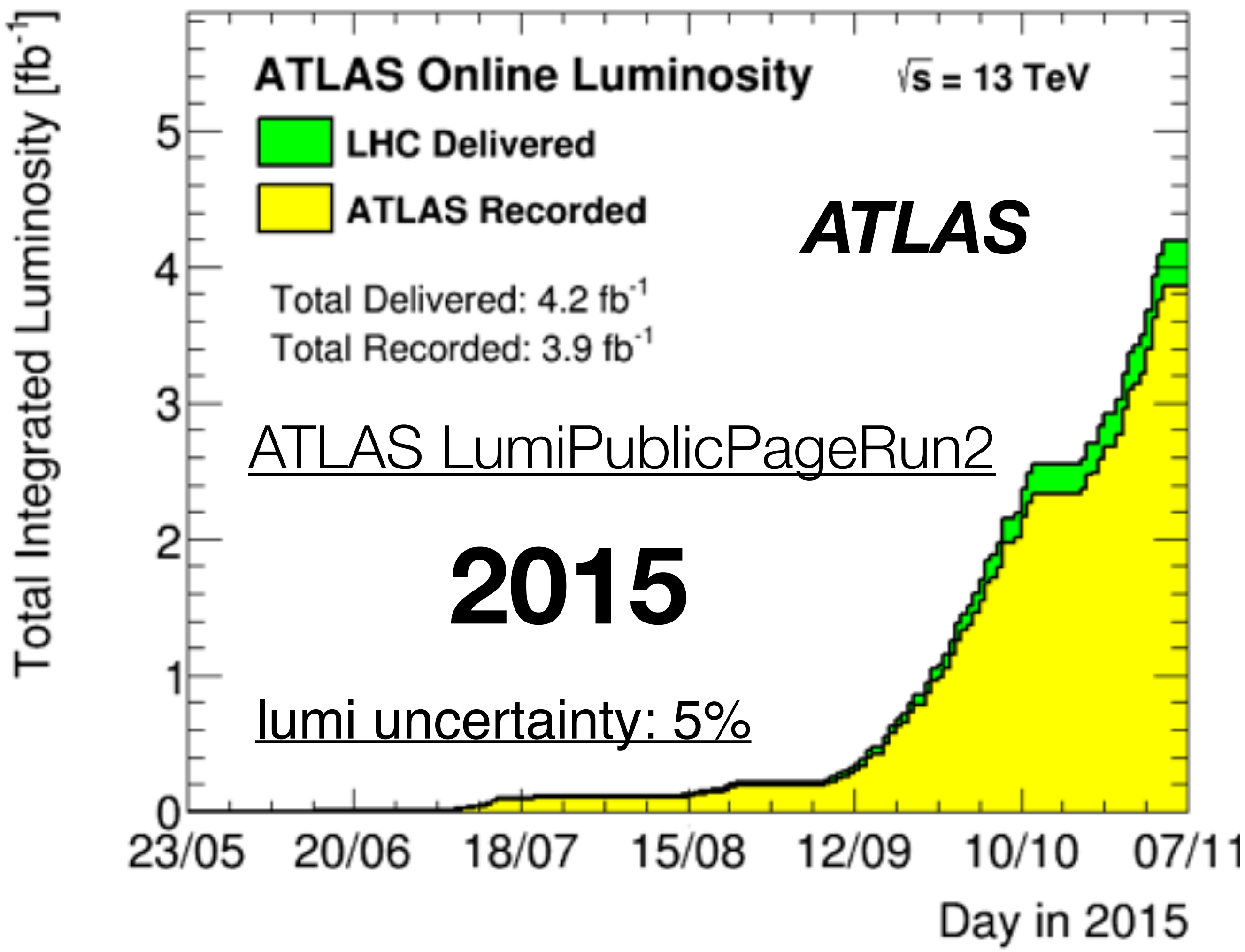
e+jets candidate

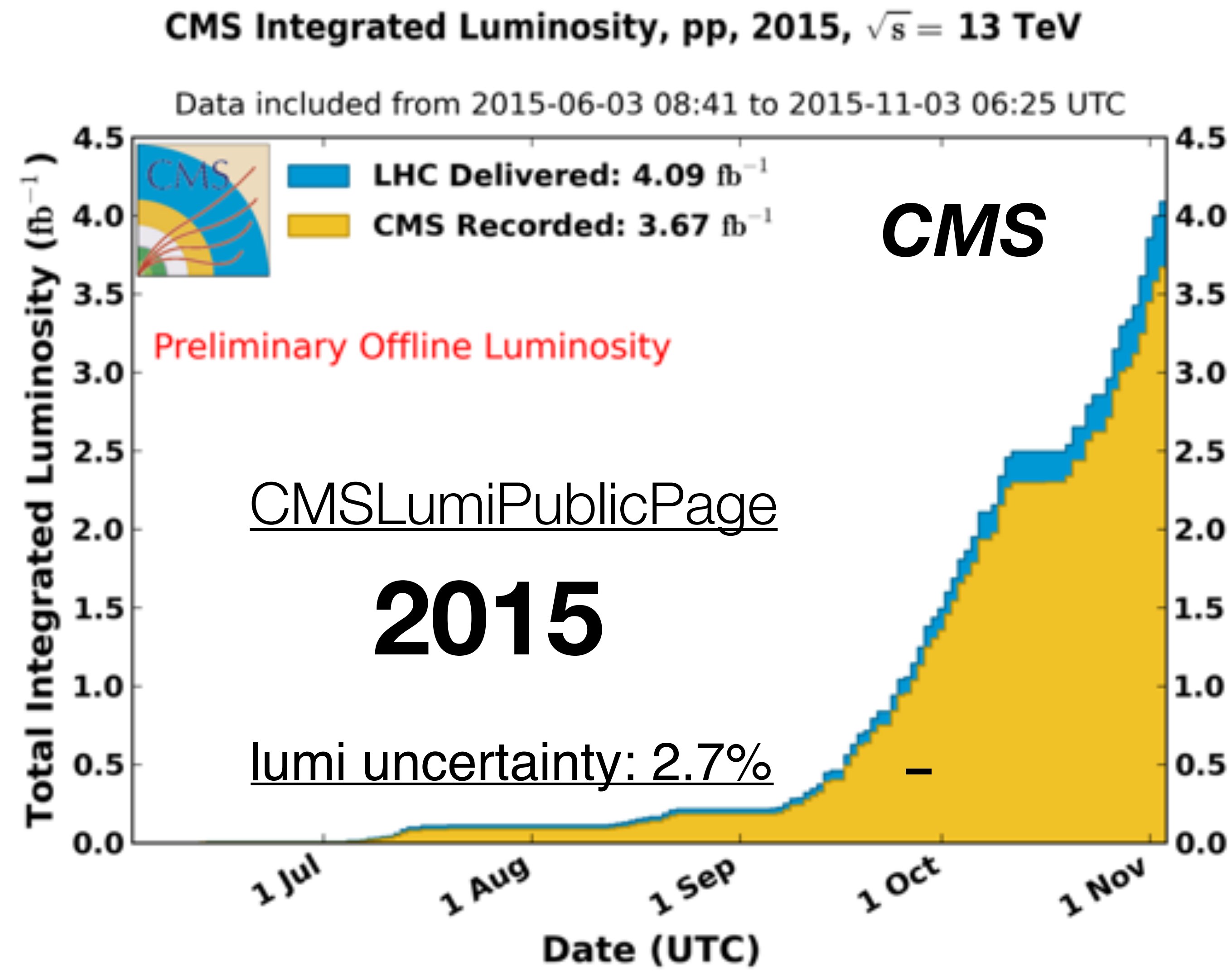


…with excellent data taking performance

Analyses use : ~4.5-5 fb^{-1} @7TeV , ~20-21 fb^{-1} @8TeV ~2.6 to 3.2 fb^{-1} @ 13 TeV

$N_{events}(\Delta t) = \int L dt$ * cross section





	2010	2011	2012
Delivered	0.0481	5.46	22.8
Recorded	0.0450	5.06	21.3
Uncertainty	3.4%	1.8%	2.8%

	2010	2011	2012
Delivered	0.04422	5.51	23.30
Recorded	0.04076	5.41	21.79
Uncertainty	4%	2.2%	2.6%

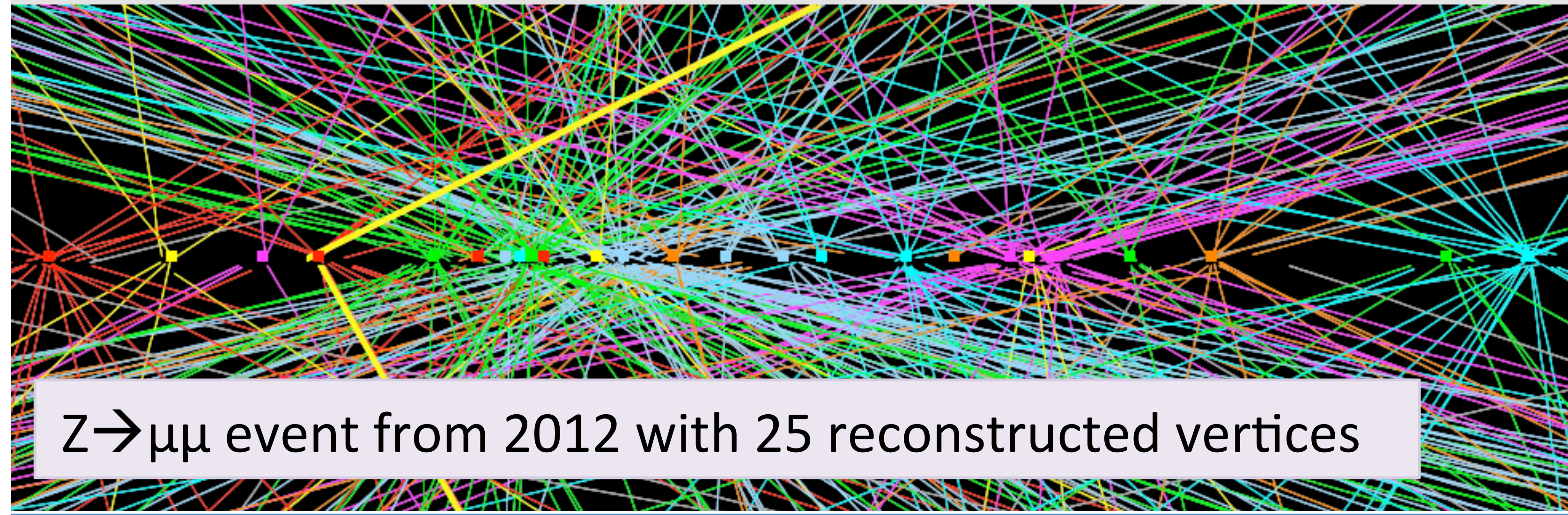
Data sample for first top paper~3 pb^{-1}

...In a harsh environment

[ATLAS LumiPublicPage](#)

- Running with 50ns bunch spacing (instead of 25ns)
  - → double pile-up for same luminosity
- Has to be fought and mitigated at all levels:
  - Trigger, reconstruction of physics objects, isolation cuts, etc.
  - Data processing: CPU time for reconstruction…

M. Aleksa TOP2012

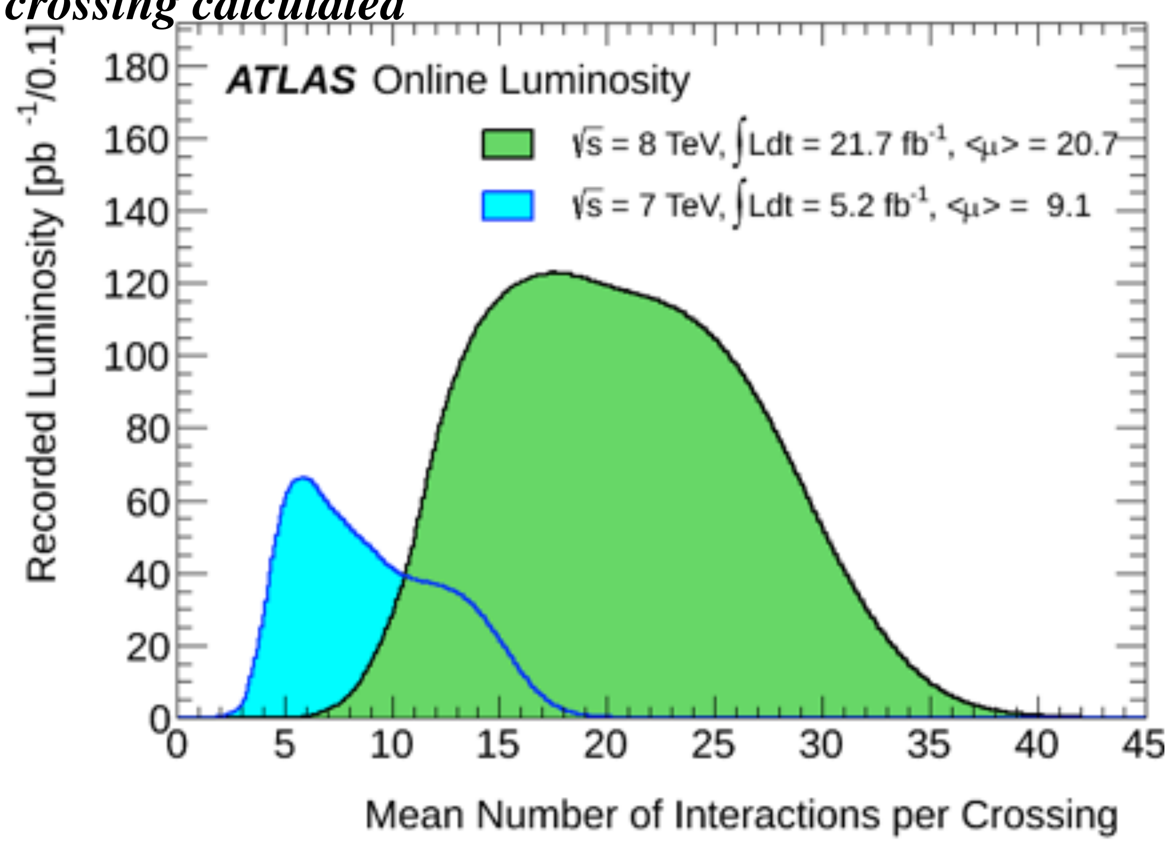


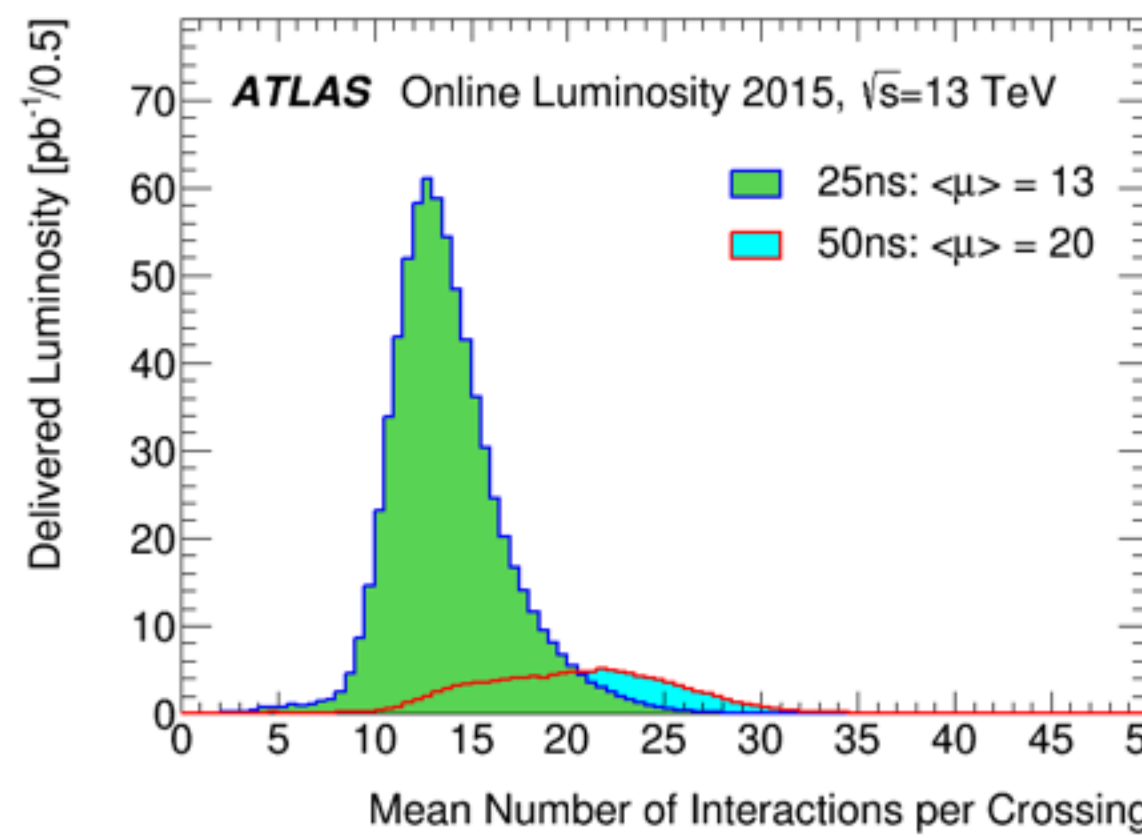
Z→μμ event from 2012 with 25 reconstructed vertices

Number of Interactions per Crossing

Shown is ***the luminosity-weighted distribution of the mean number of interactions per crossing for the 2011, 2012 and the 2015 data.***

The integrated luminosities and the mean mu values are given in the figure. The mean number of interactions per crossing corresponds ***the mean of the poisson distribution on the number of interactions per crossing calculated for each bunch.***





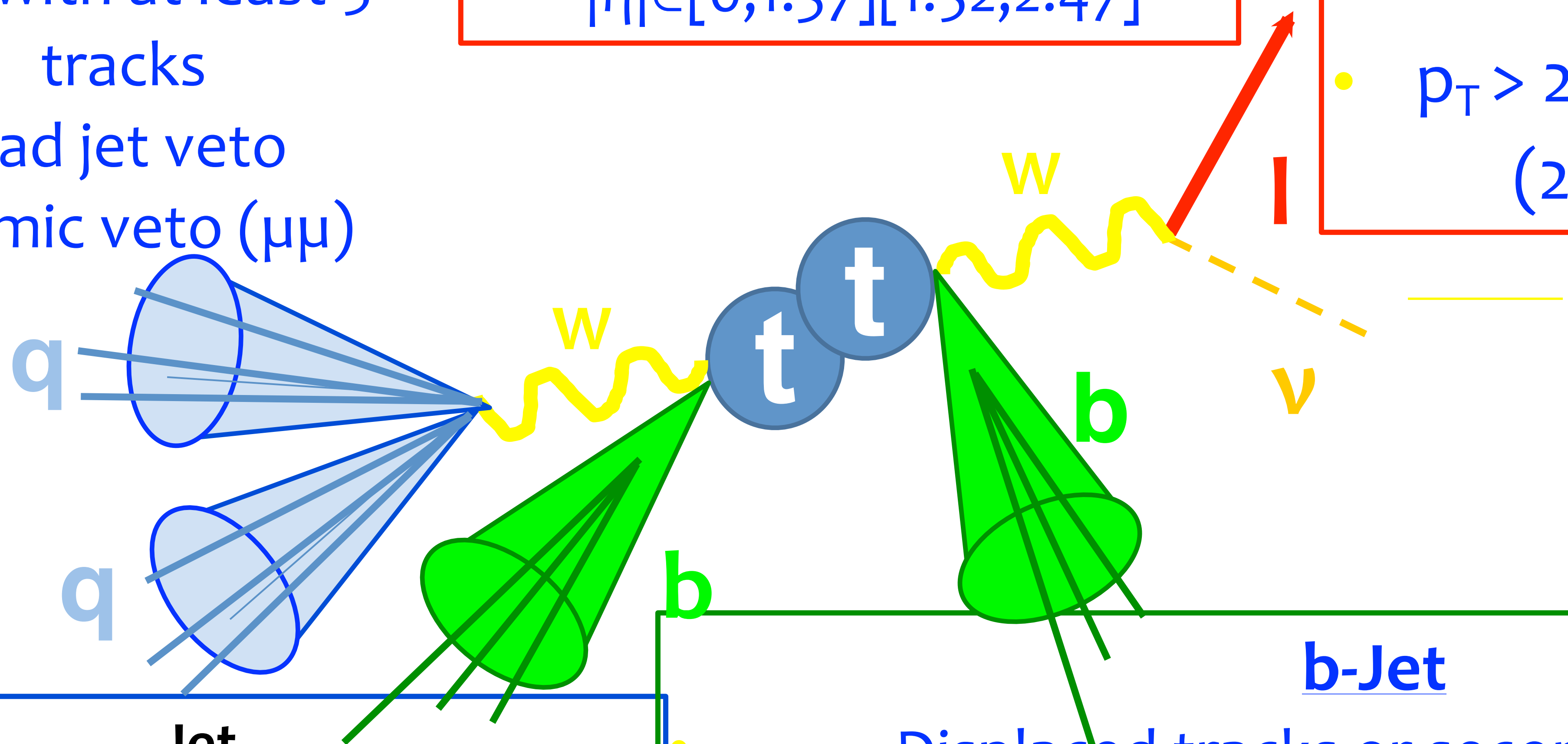
Selection/Ingredients for top quark pairs/single-top

ATLAS (CMS is similar)

Event cleaning
- Good run conditions
- Primary vertex (PV)with at least 5 tracks
- Bad jet veto
- Cosmic veto (μμ)

Electron
- Good isolated calo object
- Matched to track
- E_T>25 GeV
- $|\eta| \in [0;1.37][1.52;2.47]$

Muon
- Segments in tracker and muon detector
- Calo and track isolation
- $p_T > 20$ GeV $|\eta| < 2.5$ (2.1 for CMS)

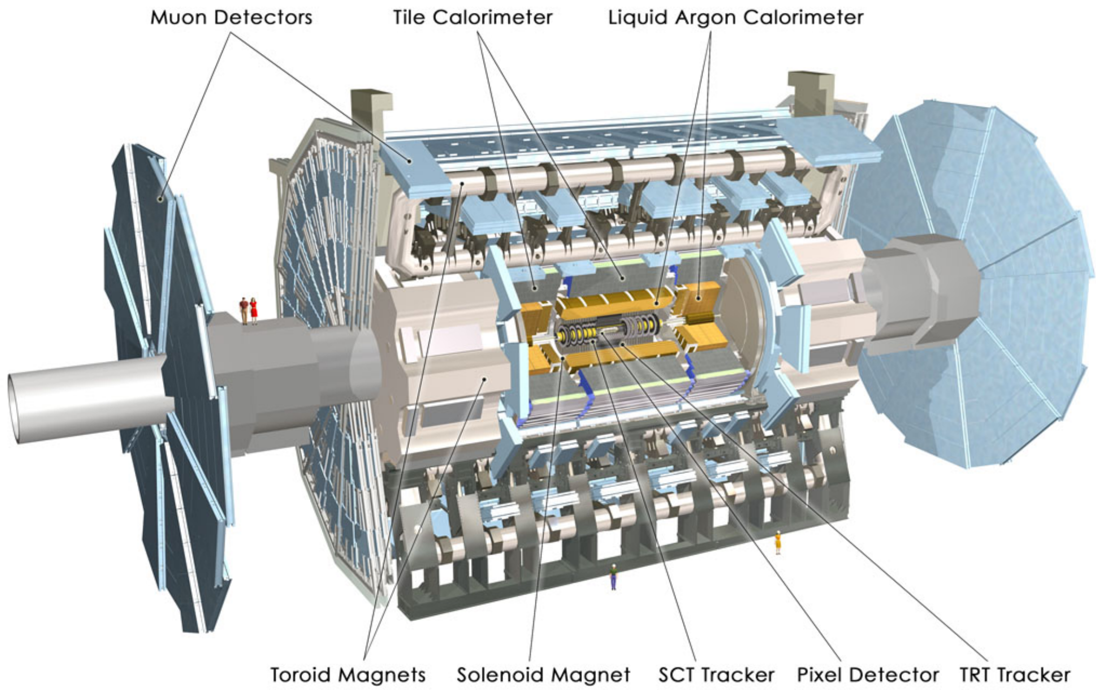


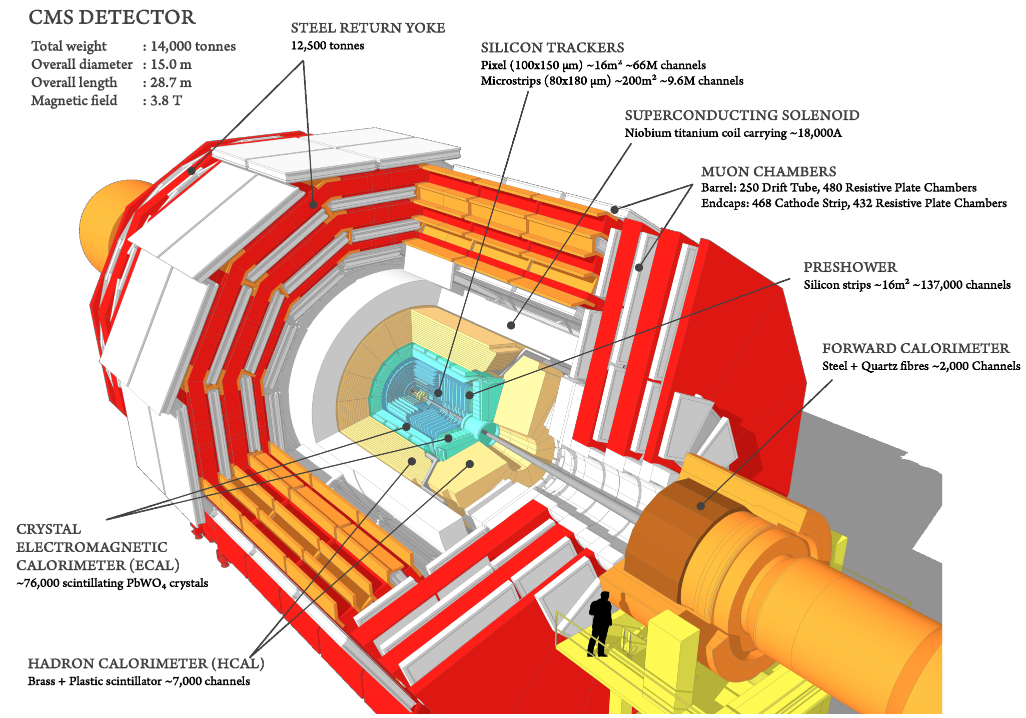
Jet
- Topological clusters, Anti-k_T (R=0.4)
- MC Calibration checked w/data
- $p_T > 25$ (20) GeV (30 for CMS), $|\eta| < 2.5$
- (large JVF $=\sum_{\text{jet trk in PV}} p_T / \sum_{\text{jet trk}} p_T$ vs pile-up jets, CMS: use particle flow to remove charged hadrons not from prim vertex)

b-Jet
- Displaced tracks or secondary lepton
- SV0: reconstruct sec.vertex
- JetProb: track/jet compatibility with prim. vertex
- IP3D+SV1 +/or JetFitter: advanced lkl/NN taggers

Beyond Run2

Towards the HL-LHC: detector upgrade strategies





Consolidate detectors, address operational issues, prepare for high pileup

Phase 0

2013-2014

- complete muon coverage, improve muon trigger, new smaller radius beam pipes
- CMS : Replace HCAL forward PMTs and outer HPD → SiPM
- ATLAS : Diamond beam monitor, additional pixel layer

Mantain / improve performance at high pileup

Phase I

2018-2019

- CMS: new pixels, HCAL SiPMs, electronics, and L1-Trigger
- ATLAS: L1 trigger improvement, fast track trigger at L2, new muon small wheels

Mantain / improve performance at extreme pileup : sustain rate + radiation doses

Phase II

2023-2024

- New inner detector, new calorimeter electronics, muon extension, trigger and DAQ upgrade
- CMS: track trigger, replace endcap calorimeters
- ATLAS: replace inner tracker, new forward calorimeter

(P Ferreira da Silva @TOP2014)

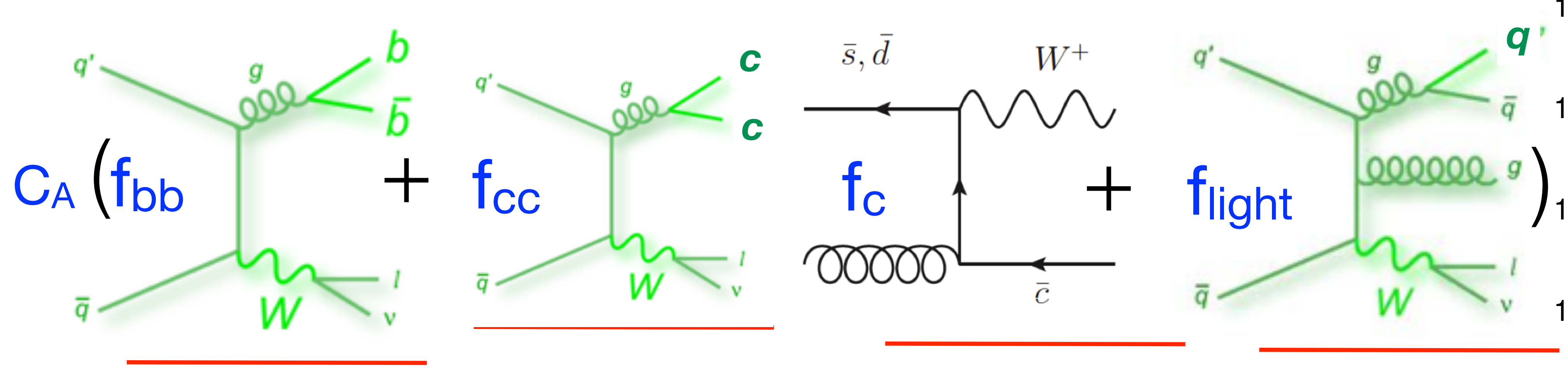
Data-driven Backgrounds - (*single lepton+jets*) - **example from run1**

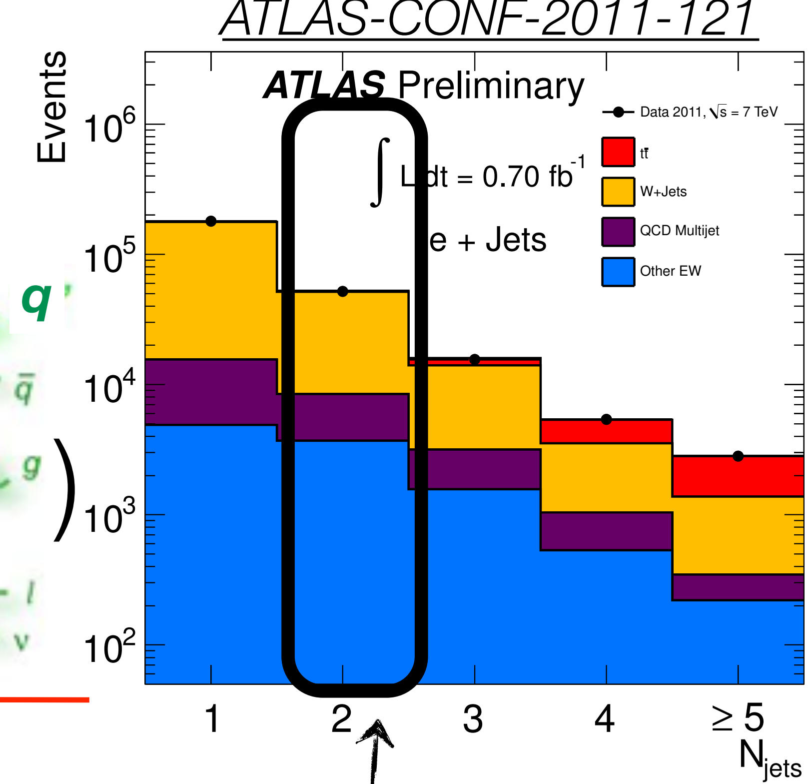
ATLAS-CONF-2011-121

- ***W+jets***

simulated shapes

data-driven overall norm and flavour fractions





2. Derive f_{xx} from data

1. Apply **standard single lepton selection**, excluding b-tagging **and** replacing jet requirements by $\mathbf{N_{jet} = 2}$, **≧1 b-tag;**
2. **Derive K_{xx} from matrix equation involving D_{W^+} (D_{W^-}) observed in 2-jet bin,** after bkg subtraction

$$\begin{pmatrix} C_A \cdot (N^{b\bar{b}}_{MC,W^-} + N^{c\bar{c}}_{MC,W^-}) & C_A \cdot N^{c}_{MC,W^-} & C_A \cdot N^{light}_{MC,W^-} \\ (f_{b\bar{b}} + f_{c\bar{c}}) & f_c & f_{light} \\ C_A \cdot (N^{b\bar{b}}_{MC,W^+} + N^{c\bar{c}}_{MC,W^+}) & C_A \cdot N^{c}_{MC,W^+} & C_A \cdot N^{light}_{MC,W^+} \end{pmatrix} \cdot \begin{pmatrix} K_{b\bar{b},c\bar{c}} \\ K_c \\ K_{light} \end{pmatrix} = \begin{pmatrix} D_{W^-} \\ 1.0 \\ D_{W^+} \end{pmatrix}$$

known from MC & ***from step 1*** *unknown* *observed*

3. **Derive C_A as in step 1** but in r_{MC} use K_{xx} from step 2 keeping relative ratios between K_{xx} to derive a new prediction for $N_{MC,W^+}/N_{MC,W^-}$

Data-driven Backgrounds

(tt single lepton+jets, single top t,s-chan)

- ***Fake leptons***

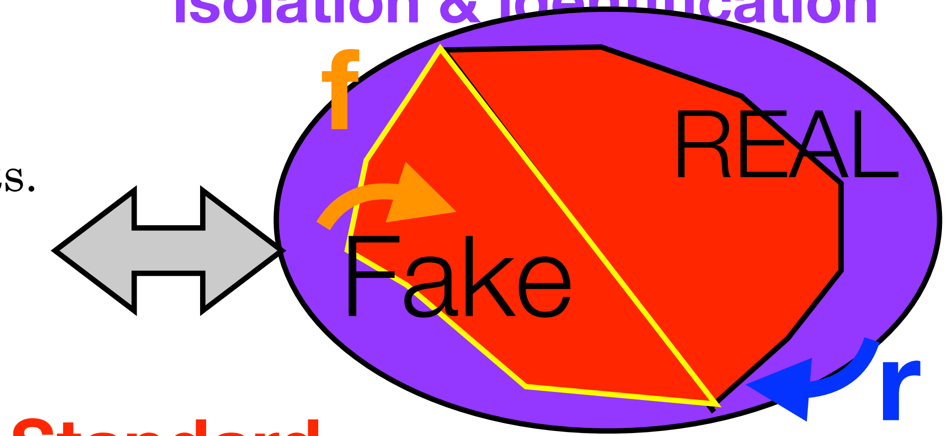
- ***Matrix method*** **(J Boudreau, Top2012)**

$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}},$$
$$N^{\text{std}} = r N^{\text{loose}}_{\text{real}} + f N^{\text{loose}}_{\text{fake}}$$

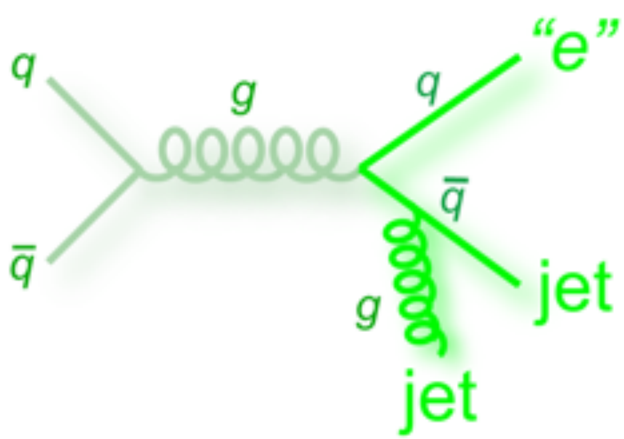
r is the marginal efficiency of standard cuts.
f is the same, for background sources

Both can be measured in pure or background event subtracted samples

Loose selection=relax lepton isolation & identification



Standard selection



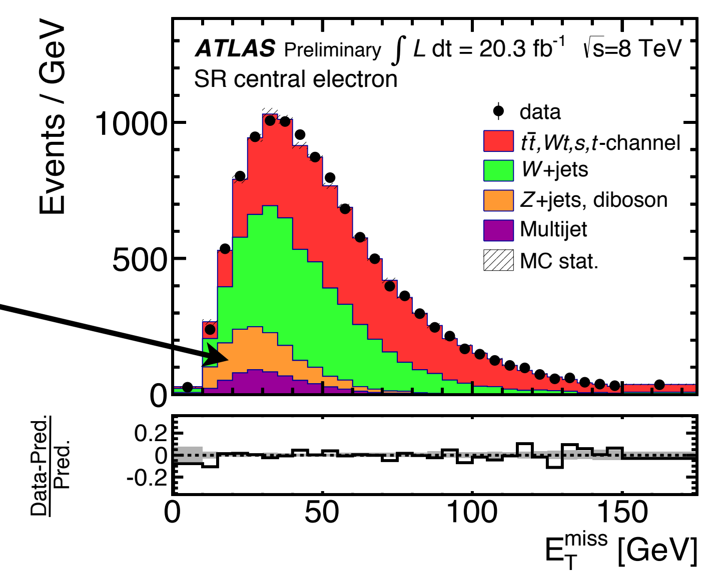
"Fake" leptons: mis-id jets, $\gamma \rightarrow e^+e^-$, non-prompt leptons (b/c-decays), punch-through had

- ***Jet template***

Shape from jet triggered events with 1 high em. content jet.

Normalize by fitting low E_T^{miss} shape to data and extrapolate

ATLAS-CONF-2014-007



- ***SS extrapolation*** *(tt di-lepton, Wt single top)*

In $e^+\mu^-$ ($e^-\mu^+$) Opposite Sign dilepton events,1 o2r 2 b-tag

Simulation: fakes dominate events with Same Sign (SS) leptons $e^-\mu^-$ ($e^+\mu^+$)

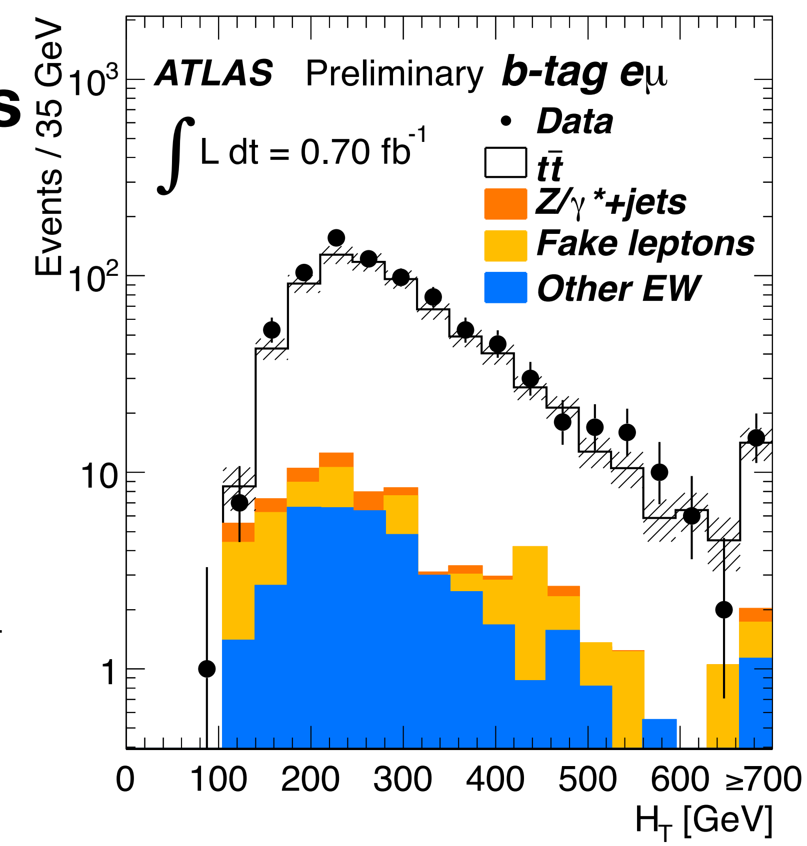
Fakes Rate in SS ~ OS

$$N_{\text{fakes}}(\text{OS}) = [\text{Data(SS)} - \text{NonFakeBkg(SS)}] \frac{\text{MC (OS)}}{\text{MC (SS)}}$$

MC= tt with 1 had W, W+jets, W+ γ +jets, t-chan single top, Dibosons (negligible)

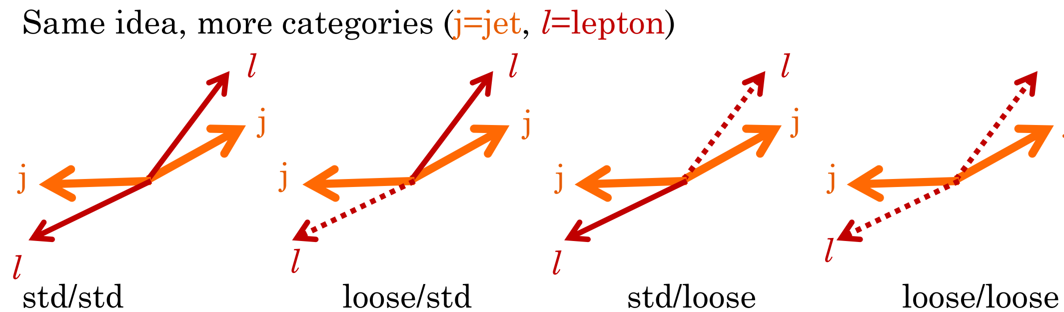
Data Driven Backgrounds *(tt di-lepton, Wt single top)*

ATLAS-CONF-2011-100



- ***Fake leptons** : generalize single lepton estimate*
  - Get **r** and **f** : **probability** for **loose** “fake” and real **leptons *to pass standard sel.*** ← **control samples** enriched with real (in Z window) or **“fake” (low E_T^{miss})** leptons
  - **Combine** with **N(di-lep)** for **all loose “fake” & real** pairs→**fake standard lepton content**

di-lep topologies



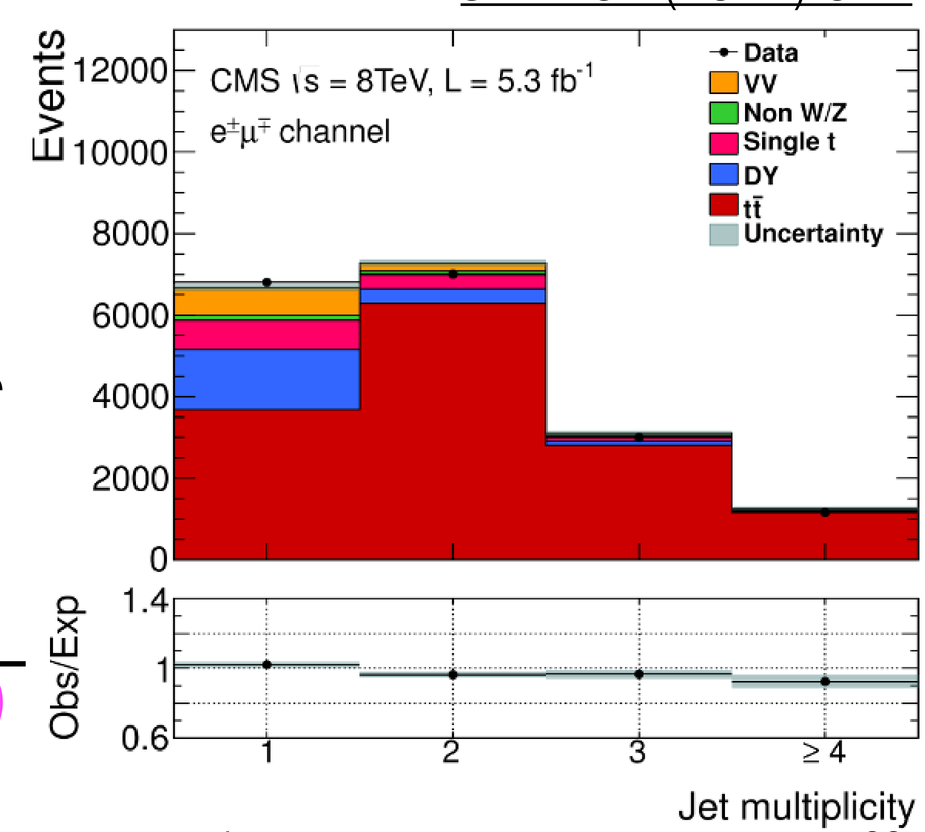
(J Boudreau, Top2012)

loose, standard

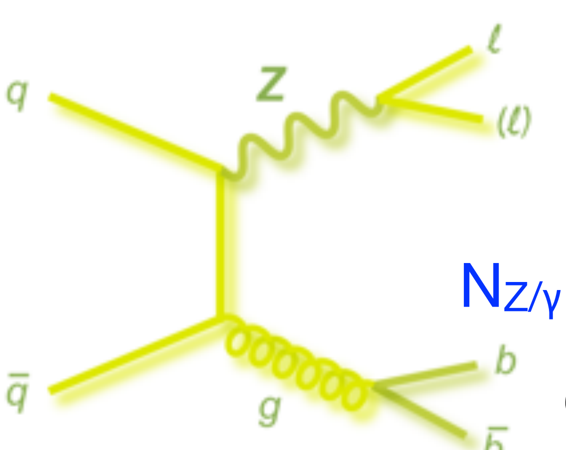
$$\begin{pmatrix} N^{l,l} \\ N^{l,s} \\ N^{s,l} \\ N^{s,s} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ r_2 & f_2 & r_2 & f_2 \\ r_1 & f_1 & r_1 & f_1 \\ r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \end{pmatrix} \circ \begin{pmatrix} N^{l,l}_{r,r} \\ N^{l,l}_{r,f} \\ N^{l,l}_{f,r} \\ N^{l,l}_{f,f} \end{pmatrix}$$

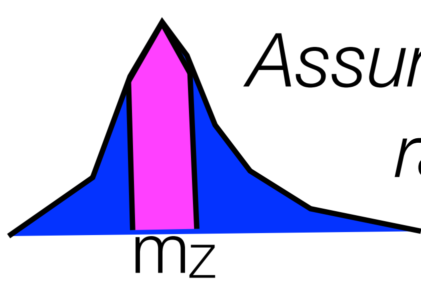
real,fake in loose

JHEP02 (2014) 024



- ***Z/γ* bkg (ee, μμ)***





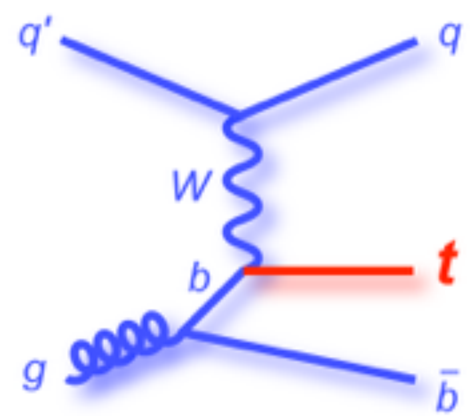
Assume constant Zdata/Z MC ratio in/out Z window

$$N_{Z/\gamma}(SR) = [\mathbf{Data}(CR) - NonZBkg(CR)] \frac{MC_{Z/\gamma}(SR)}{\mathbf{MC_{Z/\gamma}(CR)}}$$

CR (SR)=in (out of) Z mass window

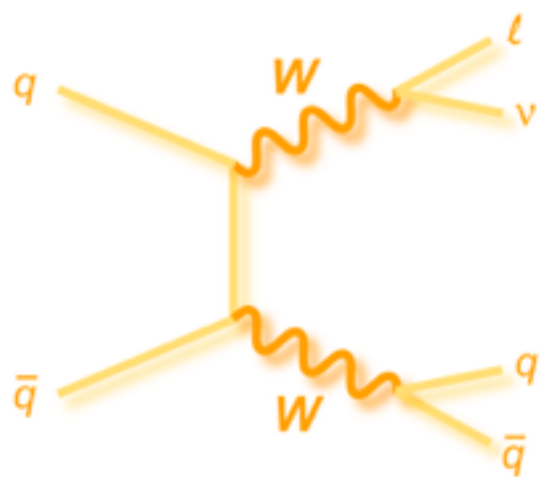
Simulated Backgrounds *(all final states)*

- **Single top**



Simulated shape+ rate set to approx NNLO

- **Di-bosons (WW,WZ,ZZ)**



Simulated shape+ rate set to SM

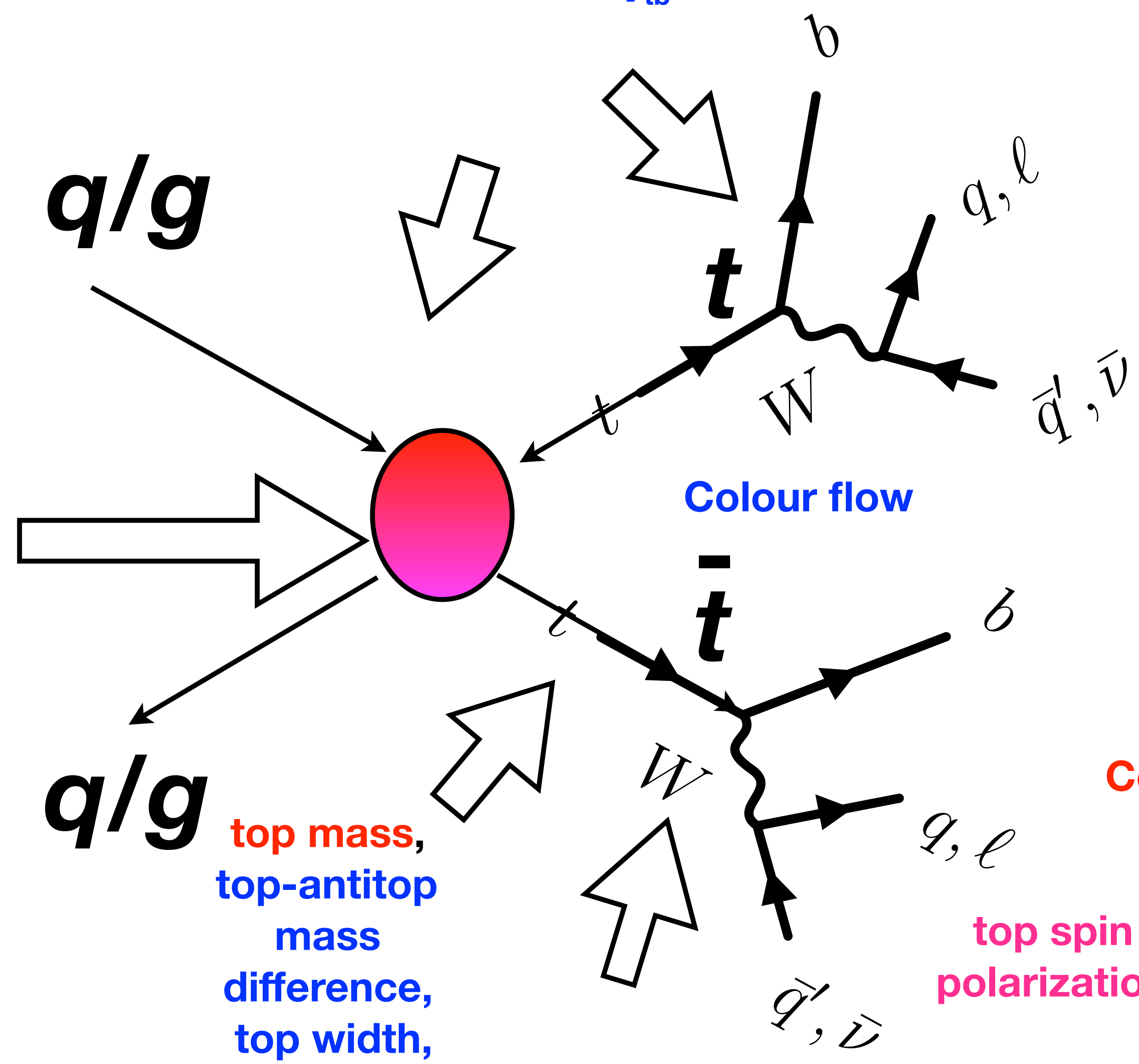
normalizations=fit parameters, estimates are starting points for fit

What we study about the top quark

inspired by figure
by D. Chakraborty

Discuss

briefly touch upon



Branching Fractions
V_{tb}

Production cross section double and single top

Resonant production & New phys

Production kinematics

top mass, top-antitop mass difference, top width, spin, charge lifetime

Colour flow

W helicity
Wtb coupling,V(tb)

Spin correlation

Charge asymmetry

Coupling to Higgs W,Z,photon

top spin polarization

Measurement of top cross sections: $\sigma_{t\bar{t}}$ and σ_t

or

how many top quarks have we got?

top pair and single top production

important test of SM
related to fundamental parameters of SM: m_{top} and alpha_s
sensitive to new physics

$N_{observed} = N_{bkg} + \int L dt \ * \ \sigma_{tt \text{ or } t} \ *$ **detection/extrapolation efficiency**

Start to combine results at the LHC...

How is cross section (σ) measured? The Extrapolation

- **Particle level, fiducial phase space**
- Object definition at generator level: based on stable particles after radiation & hadronization
- Phase space definition closely follows the (detector-level) event selection

neutrinos are used to define E_T^{miss}

Leptons: from W decay (not from hadron)+ "dressed" with non-measurable FSR

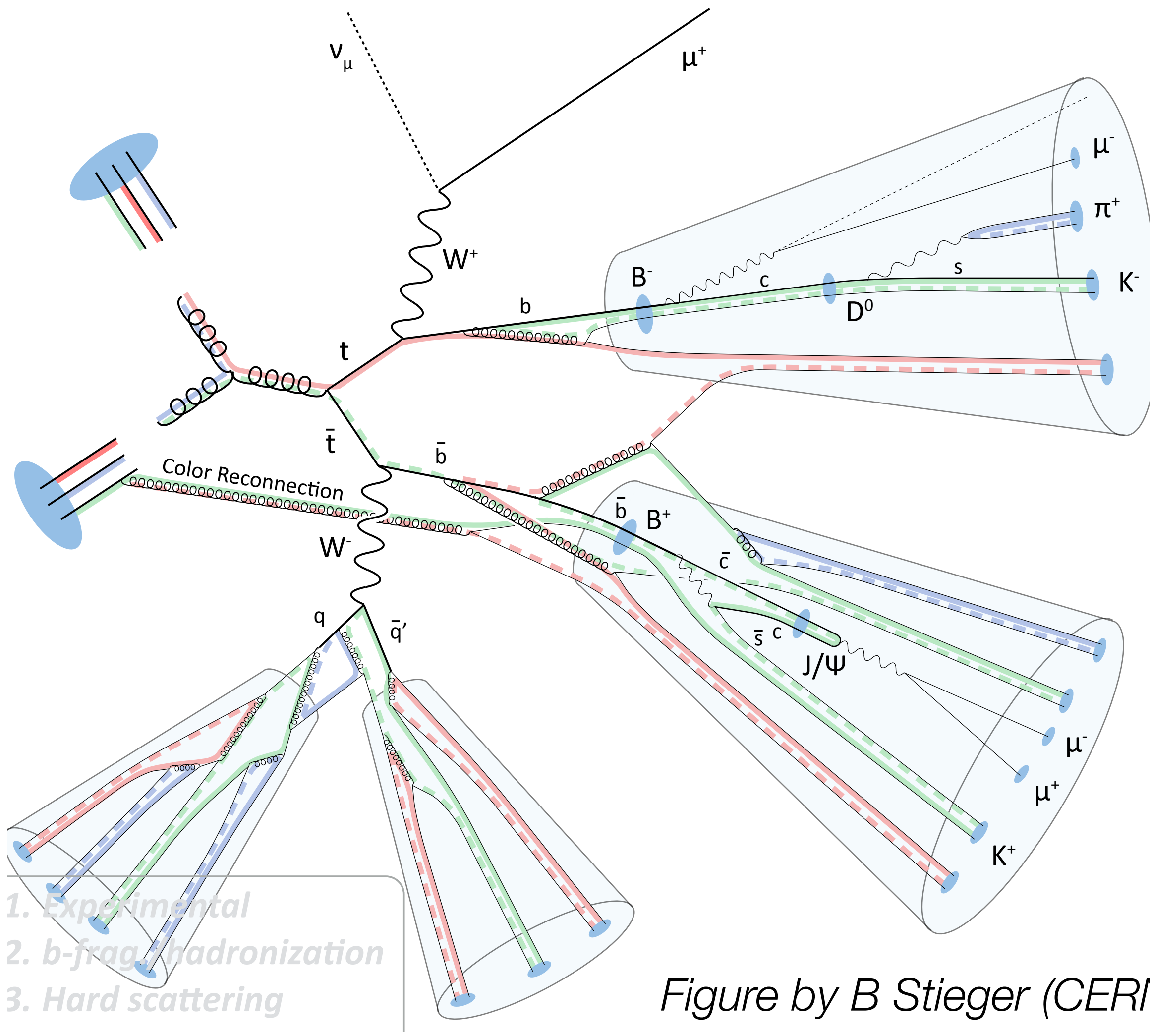


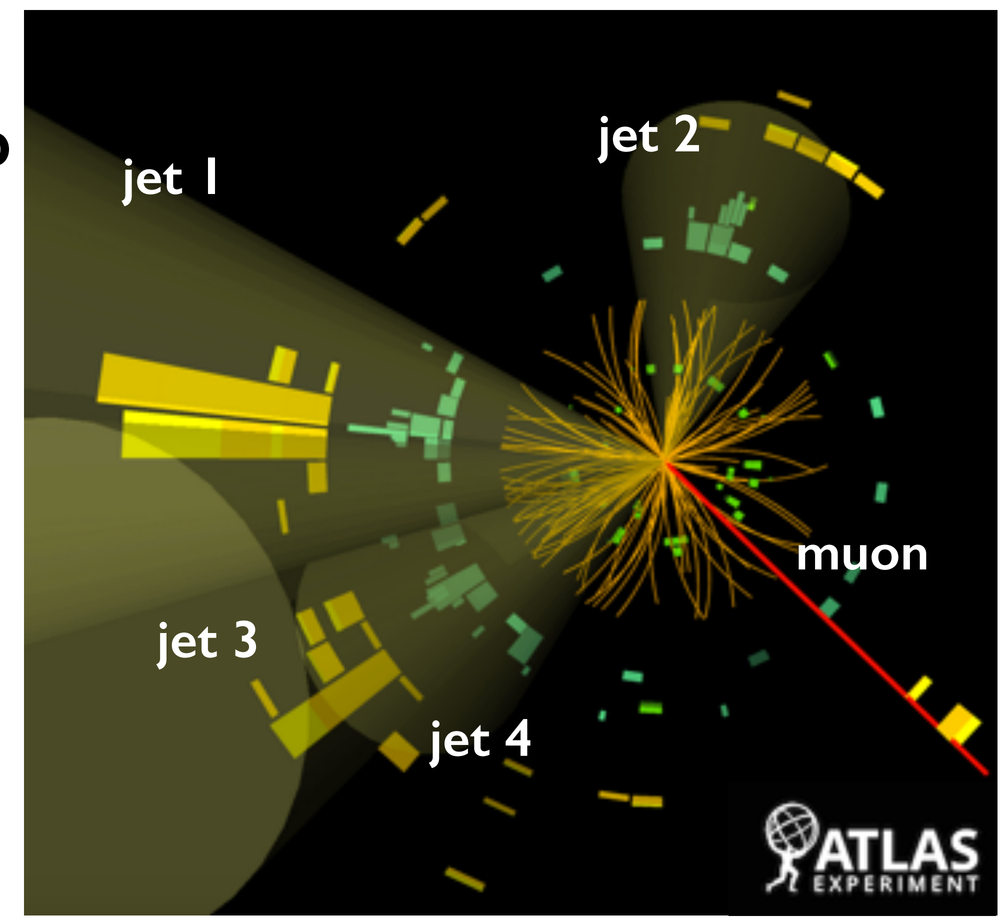
Figure by B Stieger (CERN)

b-jets: contains any of the decay products of a B-hadron

essential clues

- **Detector Level**

Correct to



Jets: anti-kT algorithm (as for reco jets), cluster all but prompt particles (i.e, ν, μ from hadron decays are inside jets)

How is cross section (σ) measured? The Extrapolation

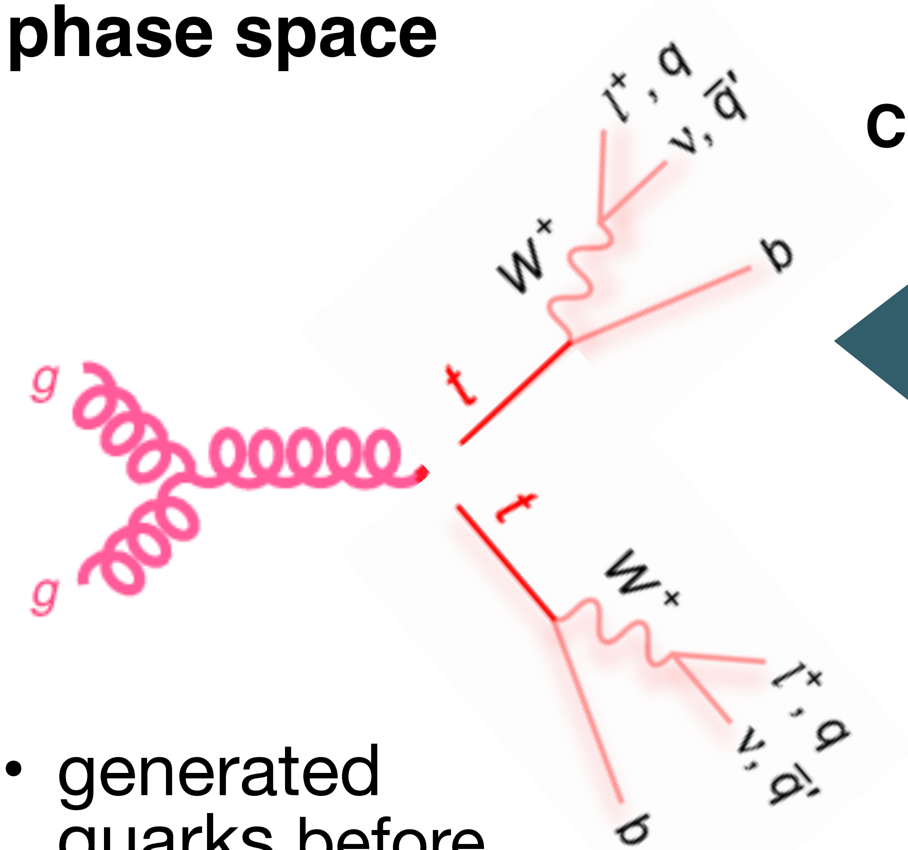
essential clues

- **Particle level, fiducial phase space**
- Object definition at generator level: based on stable particles after radiation & hadronization
- Phase space definition closely follows the (detector-level) event selection

Leptons: from W decay
(not from hadron)+ "dressed" with non-measurable FSR

neutrinos are used to define E_T^{miss}

- **Parton level, full phase space**



Correct to

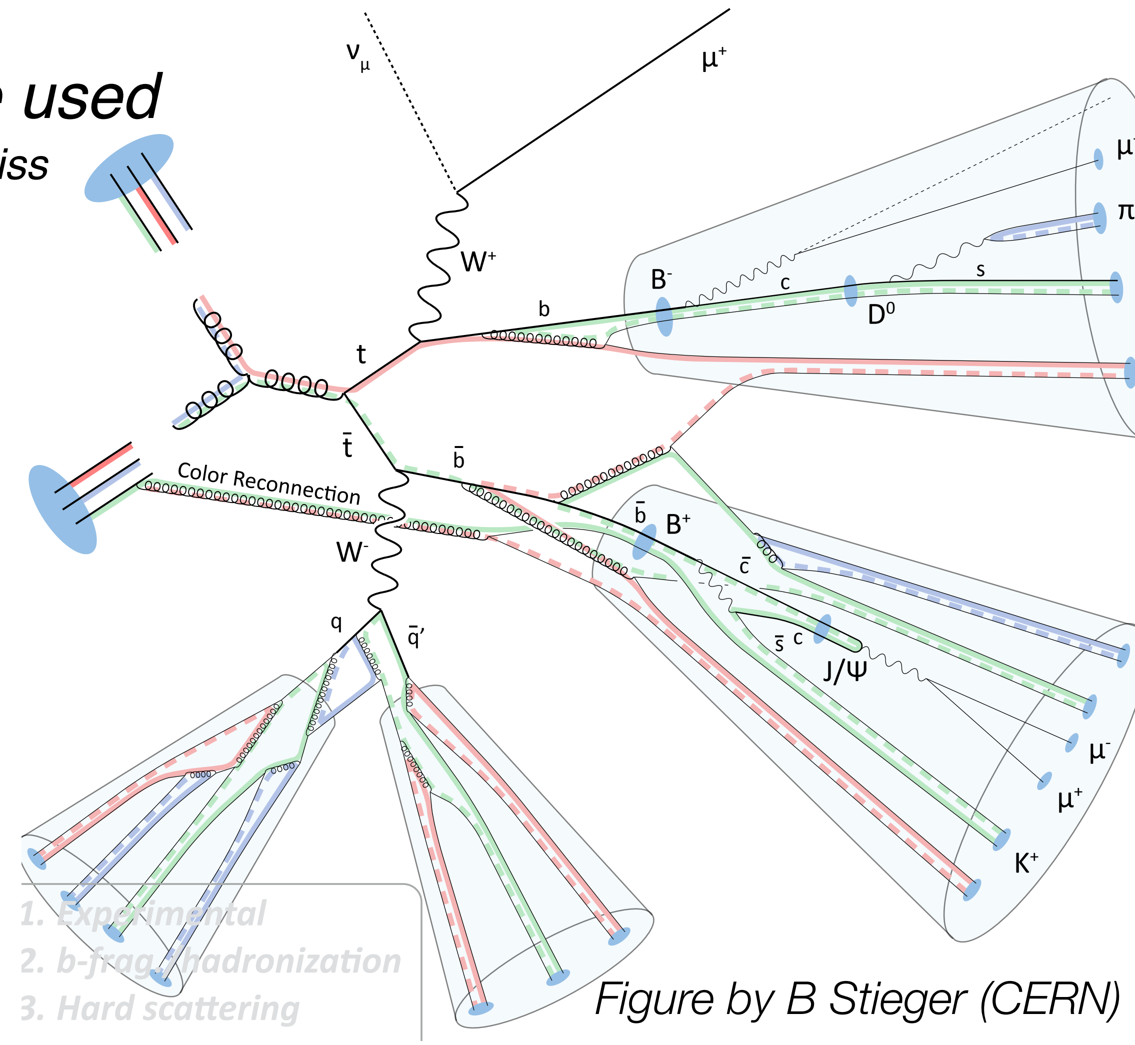


Figure by B Stieger (CERN)

b-jets: contains any of the decay products of a B-hadron

- generated quarks before decay and after QCD radiation

Jets: anti-kT algorithm (as for reco jets), cluster all but prompt particles (i.e, ν, μ from hadron decays are inside jets)

How is cross section (σ) measured? The Extrapolation

$$\sigma_{t\bar{t}}^{fid\,/\,total} = \frac{N_{evt}}{\mathcal{E} \times \mathcal{A} \times Br \times \mathcal{L}} \Rightarrow \sigma_{t\bar{t}}^{total} = \frac{\sigma_{t\bar{t}}^{fid}}{\mathcal{A} \times Br}$$

$$\mathcal{E} = \frac{N_{RECO}}{N_{GEN}^{Cut}} = \frac{1+2}{1+3}$$

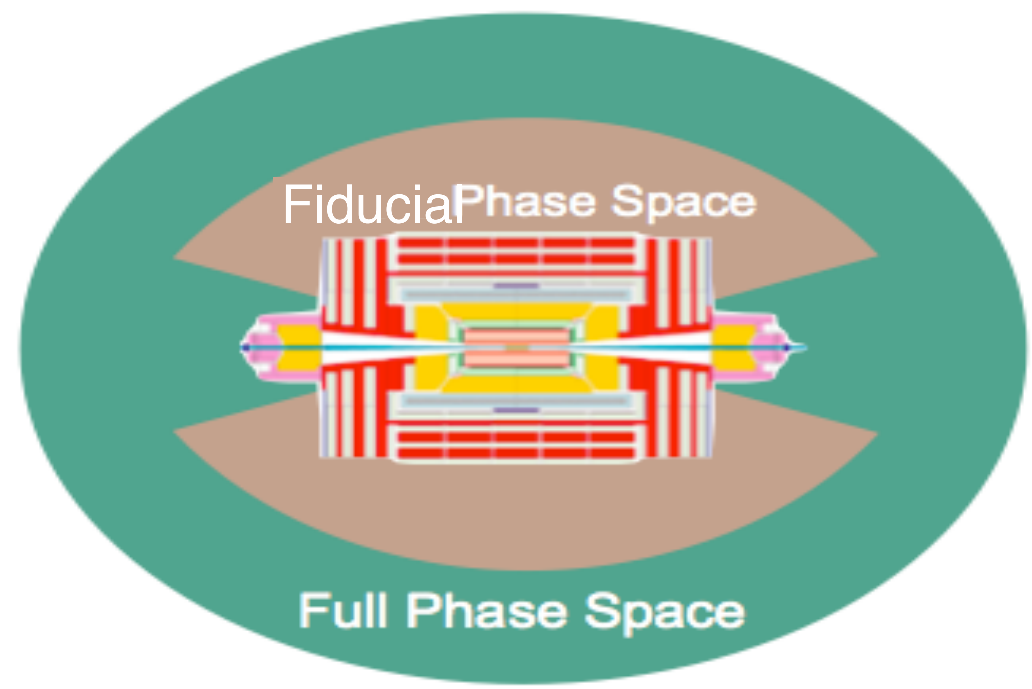
$$\mathcal{A} = \frac{N_{GEN}^{Cuts}}{N_{GEN}} = \frac{1+3}{1+2+3+4}$$

Reco

1	2	3	4
Pass Reco, Pass PL	**Pass Reco**, Fail PL	Fail Reco Pass PL	Fail Reco, Fail PL

3 *to correct to*

essential clues



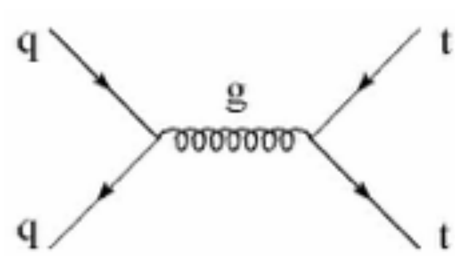
- ***Particle level, fiducial phase space:*** durable connection with theory
  - Store & compare results with evolving predictions: <u>**R**obust **I**ndependent **V**alidation of **E**xperiment and **T**heory</u>
  - usually reduced modelling uncertainties
- ***Parton level :*** Comparison with highest order QCD calculations, so far only available in production

Top specific!

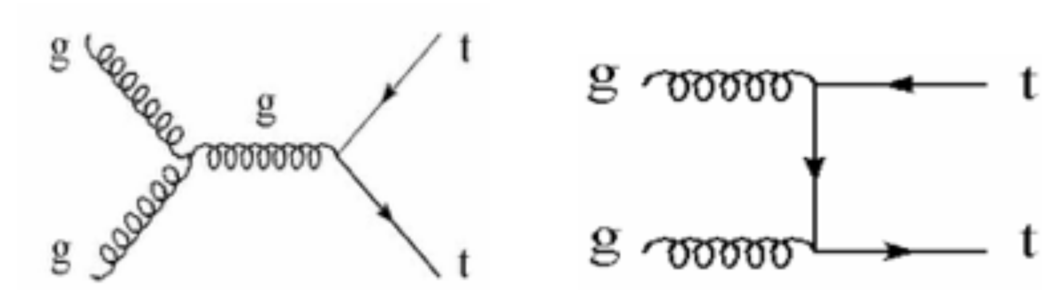
- ***Dilepton e channel: emerging as the most precise***
  - ***low bkg , reduction of syst uncertainties from jets***

top pair production

qq annihilation



gluon fusion



Dominant production scheme

Inclusive σ_{tt} : dilepton - $\sqrt{s}$ =7,8,13 TeV

$\int Ldt \sim$ **4.6 fb^{-1}** *(2011)*
$\int Ldt \sim$ **20.3 fb^{-1}** *(2012)*
$\int Ldt \sim$**3.2 fb^{-1}** *(2015)*

ℓνℓνbb

- **Require opposite sign (OS) eμ,** no H_T,E_T^{miss} cuts, no lep isolation *minimal use of jet/E_T^{miss} info*
- **Bkg: single top** (Wt) *(from simul.)*, **data-driven fake leptons** *(extrapolated from same sign lep. sample)*, **Z +jets** *(extrapolated from Z→μ⁺μ⁻ sample)*
- **Simultaneous fit for σ_{tt} and ε_b, efficiency to select, reco and b-tag a jet in** 1-b-tag and 2 b-tag samples→**minimize jet & b-tag syst**

from simulation

$$N_1 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{bkg}$$
$$N_2 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{bkg}$$

Measure σ_{tt} (parton level) & σ_{fid} (particle level,)

$$\epsilon_{e\mu} = A_{e\mu}G_{e\mu} \qquad C_b = \epsilon_{bb}/\epsilon_b{}^2$$

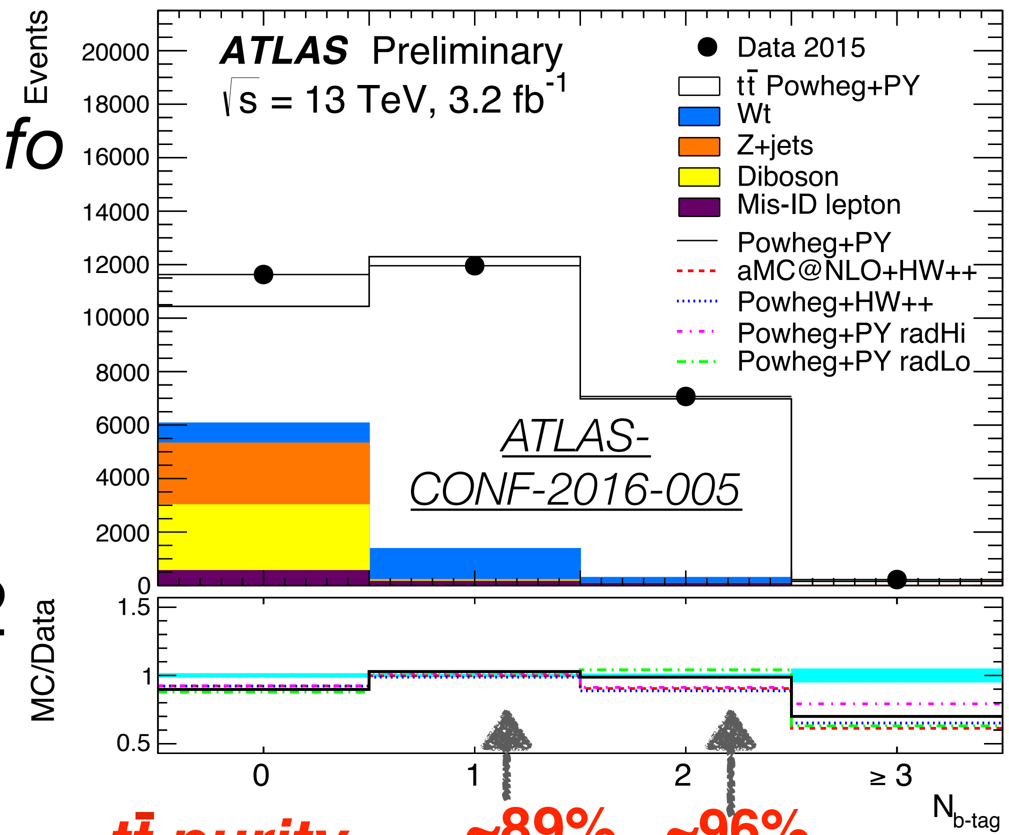
$A_{e\mu}$= *fraction of tt ev. with 1* **eμ** *"dressed" pair from W*

b-jet is tagged with b-hadron

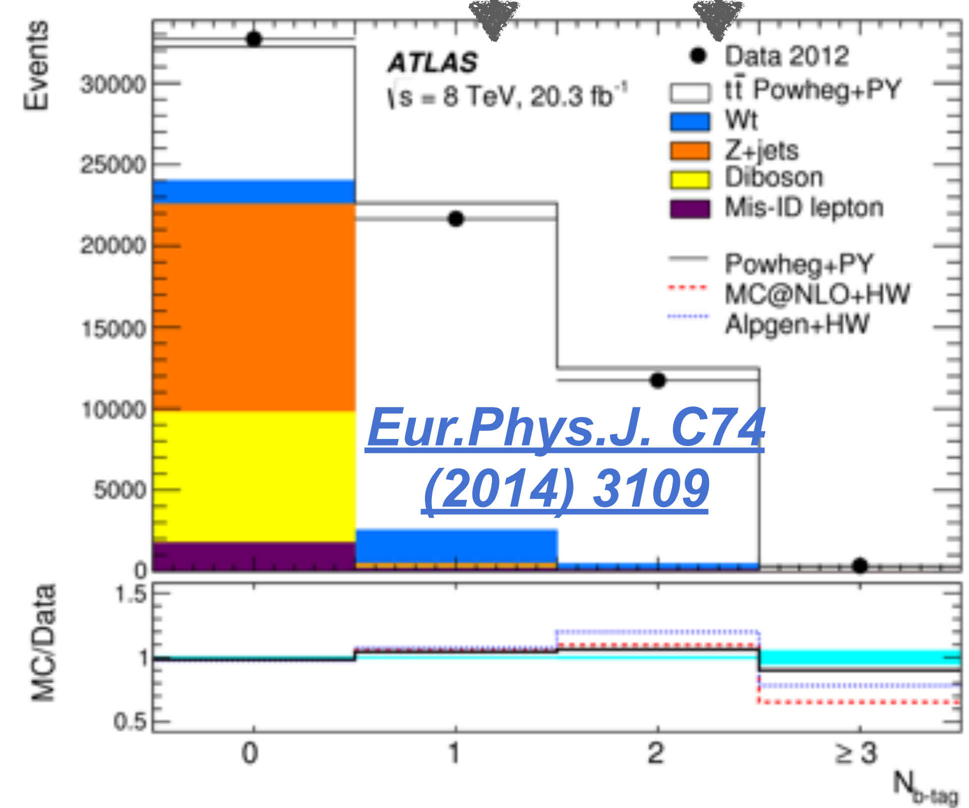
$G_{e\mu}$= **eμ** *reco efficiency*

$$\sigma_{t\bar{t}}^{\mathrm{fid}} = A_{e\mu}\sigma_{t\bar{t}},$$

$$\sigma_{t\bar{t}}\epsilon_{e\mu} \longrightarrow \sigma_{t\bar{t}}^{\mathrm{fid}}G_{e\mu}$$



tt̄ purity **~89%** **~96%**



Inclusive σ_{tt} : dilepton - $\sqrt{s}$ =13 TeV

$\int L dt$ ~3.2 **fb^{-1}** *(2015)*

ATLAS-CONF-2016-005

ℓνℓνbb

$$\sigma_{t\bar{t}} = 803 \pm 7\ (\text{stat}) \pm 27\ (\text{syst}) \pm 45\ (\text{lumi}) \pm 12\ (\text{beam})\ \text{pb}$$

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~6.7%

$$\sigma^{\text{fid}}_{t\bar{t}} = 11.12 \pm 0.10\ (\text{stat}) \pm 0.28\ (\text{syst}) \pm 0.62\ (\text{lumi}) \pm 0.17\ (\text{beam})\ \text{pb}$$

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~6.3%

Uncertainty	**$\delta\sigma_{tt}/\sigma_{tt}$(%)**	
	Particle	Parton
Int. Luminosity	5.5	
Statistical	0.9	
Trigger/sel	0.7	
tt NLO Modelling	0.6	0.8
tt Hadronisation	1.9	2.8
Bkg	0.9	
Total	6.3	6.7

fiducial space is O(1%) of full space

- **Dominated by "External" Systematic effects:** *Luminosity*

Inclusive σ_{tt} : dilepton - $\sqrt{s}$ =7 & 8 TeV

$\int Ldt \sim$ **20.3 fb^{-1}** *(2012)*
$\int Ldt \sim$**3.2 fb^{-1}** *(2015)*

[Eur.Phys.J. C74 (2014) 3109](#)

(J Brochero @ TOP2014)

Total Cross Section

$$\sigma^{\mu e}_{t\bar{t}}(\sqrt{s}{=}7\,\mathrm{TeV}) = 182.9 \pm 3.1(\mathrm{stat.}) \pm 4.2(\mathrm{syst.}) \pm 3.6(\mathcal{L}) \pm 3.3(\mathrm{beam})\,\mathrm{pb}$$

$$\sigma^{\mu e}_{t\bar{t}}(\sqrt{s}{=}8\,\mathrm{TeV}) = 242.4 \pm 1.7(\mathrm{stat.}) \pm 5.5(\mathrm{syst.}) \pm 7.5(\mathcal{L}) \pm 4.2(\mathrm{beam})\,\mathrm{pb}$$

$$R_{t\bar{t}} = 1.326 \pm 0.024(\mathrm{stat.}) \pm 0.015(\mathrm{syst.}) \pm 0.049(\mathcal{L}) \pm 0.001(\mathrm{beam})$$

p_T^ℓ (GeV)	$\lvert\eta^\ell\rvert$	Fiducial cross section (including $W \to \tau \to \ell\nu$) $\sqrt{s} = 7$ TeV (pb)	$\sqrt{s} = 8$ TeV (pb)
> 25	< 2.5	$2.615 \pm 0.044 \pm 0.056 \pm 0.052 \pm 0.047$	$3.448 \pm 0.025 \pm 0.069 \pm 0.107 \pm 0.059$
> 30	< 2.4	$2.029 \pm 0.034 \pm 0.043 \pm 0.040 \pm 0.036$	$2.662 \pm 0.019 \pm 0.054 \pm 0.083 \pm 0.046$

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~3.9%

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~4.2%

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	
$\sqrt{s}$	7 TeV	8 TeV
Data statistics	1.69	0.71
$t\bar{t}$ modelling and QCD scale	1.46	1.26
Parton distribution functions	1.04	1.13
Background modelling	0.83	0.83
Lepton efficiencies	0.87	0.88
Jets and b-tagging	0.58	0.82
Misidentified leptons	0.41	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	2.27	2.26
Integrated luminosity	1.98	3.10
LHC beam energy	1.79	1.72
Total uncertainty	3.89	4.27

fiducial space is O(1%) of full space

- **Dominated by "External" Syst:**
  Lumi and E_b, then tt modelling & scales

$$R^{Theory}_{t\bar{t}}(7/8\,\mathrm{TeV}) =$$
$$1.430 \pm 0.013(\mathrm{PDF} + \alpha_s) + \pm 0.001(\mathrm{scale})$$

$$\frac{d\sigma_{t\bar{t}}}{dm_t} = -0.28\%\ \mathrm{per\ GeV}$$

← *useful to compare with theory*

Using top quarks as gluon luminometers

ATLAS-CONF-2015-049

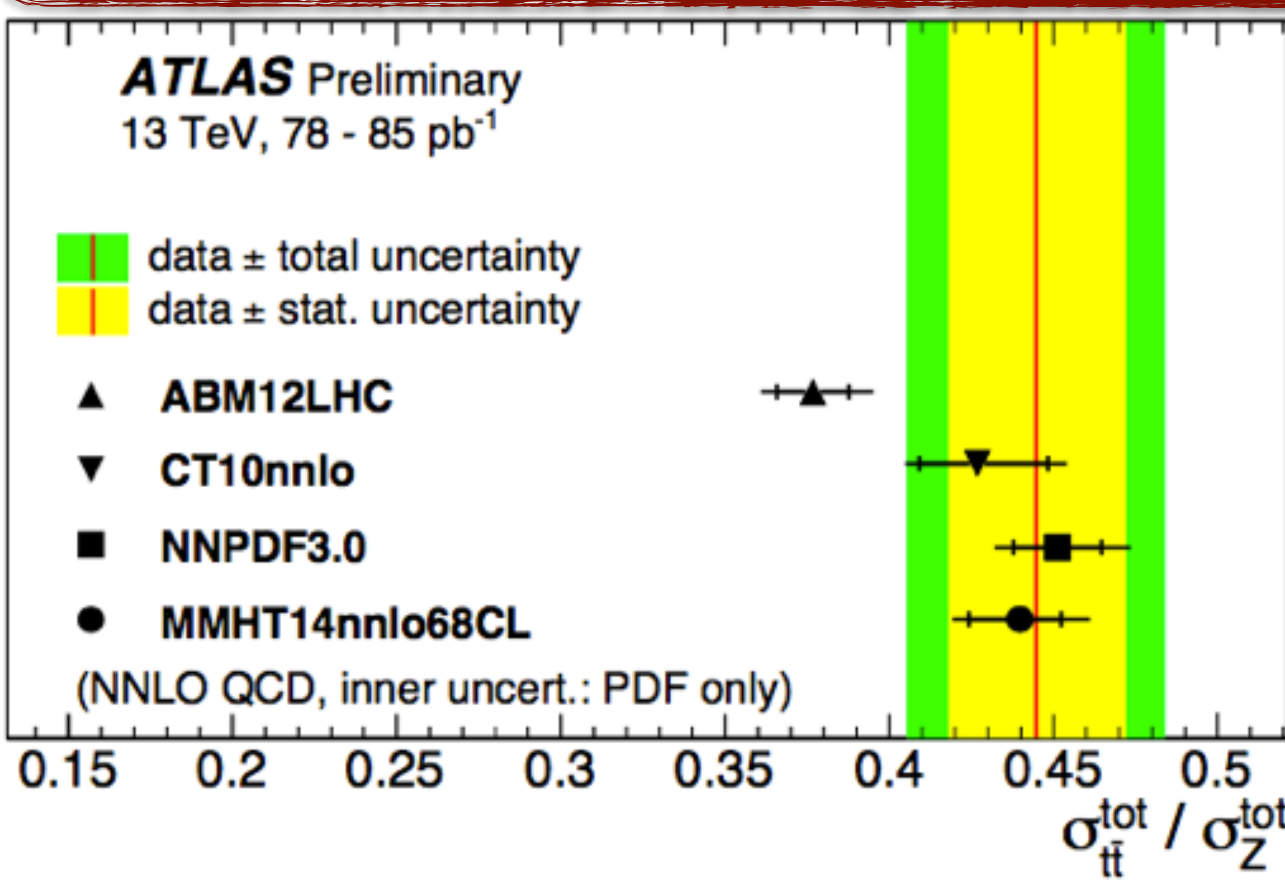
- **Ratios of cross sections are expected to cancel out some of the systematic uncertainties**
  - compare to SM predictions : test parton luminosities, search for new physics effects
- **Ratio to Z production tests qq/gg ratio**

Possibly replace with CMS precise measurement..

  - improves on luminosity (1%), trigger/lepton selection efficiencies (2.2%)
  - uncertainties in Z/tt modelling and backgrounds are similar

(Pedro Ferreira da Silva @ Moriond 2016)

$$R_{t\bar{t}/Z}^{\text{CT10nnlo}} = 0.427^{+0.022}_{-0.013}\ (\text{PDF})\ ^{+0.012}_{-0.016}\ (\text{QCD scale})\ ^{+0.005}_{-0.004}\ (\alpha_s)$$



- **PDF predictions tested mostly compatible with data**
  - 2σ tension with prediction based on ABM12LHC (smaller gg density)

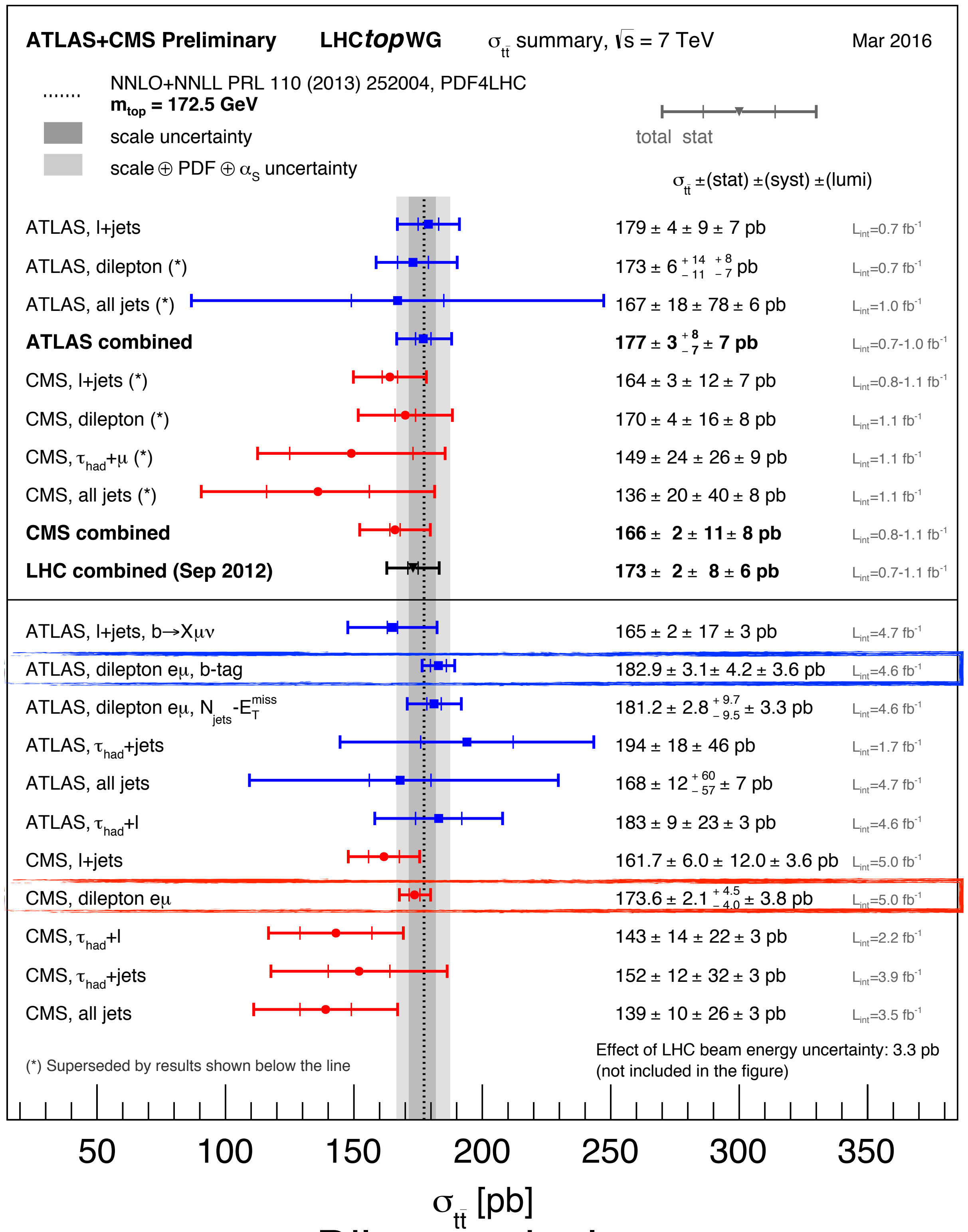
Still large room to explore different ratios in Run 2, also at different $s^{1/2}$, to constraint further PDFs

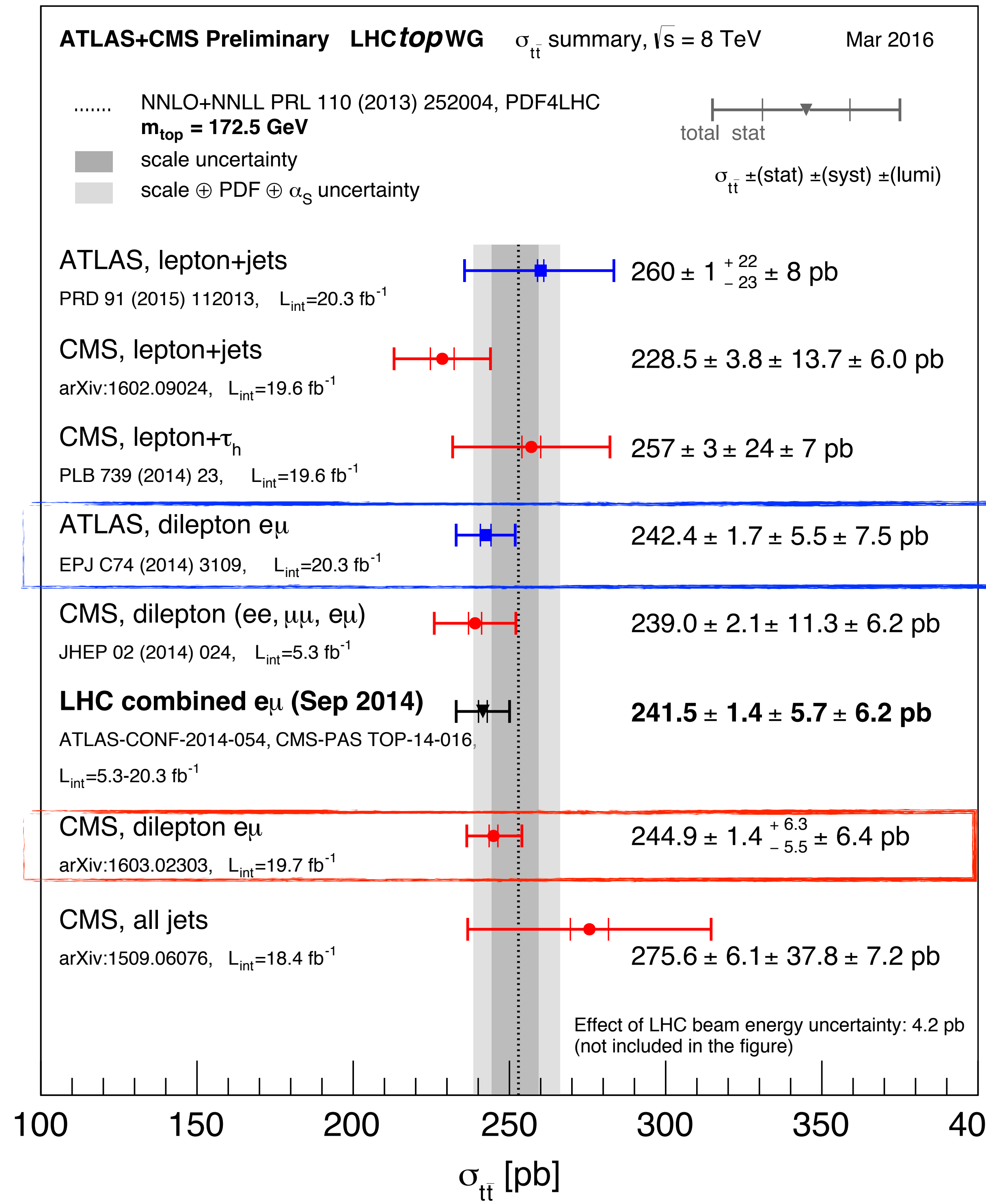
Inclusive σ_{tt} - Summary at $\sqrt{s}$ = 7 & 8 TeV

Systematics dominated, similar to/smaller than theory uncertainty

Fair agreement with NNLO +NNLL over all final states

ATLAS & CMS Public summary plots





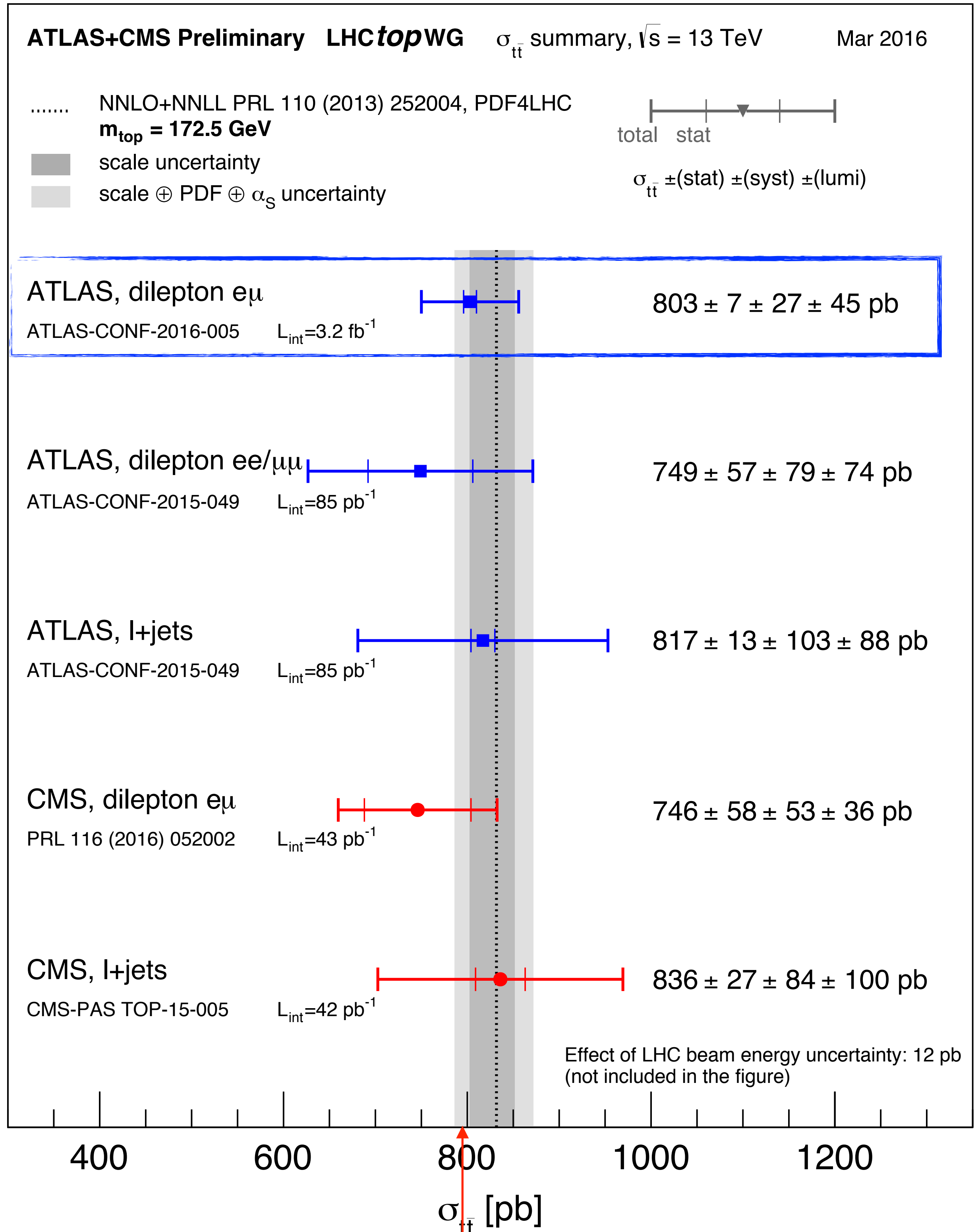
Dilepton single measurements achieve **$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~3 (~3.7%)%** at 7 (8) TeV

Improving upon past LHC combinations that achieved **$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~5.8(3.5)%** at 7 (8) TeV

Inclusive σ_{tt} - Summary at $\sqrt{s}$ = 13 TeV

Systematics dominated

- Dilepton results lead in precision (again)
- Good agreement with NNLO +NNLL



at 13 TeV uncertainties are already as low as **$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~6.5%**

ATLAS & CMS Public summary plots

CMS-PAS-TOP-16-005

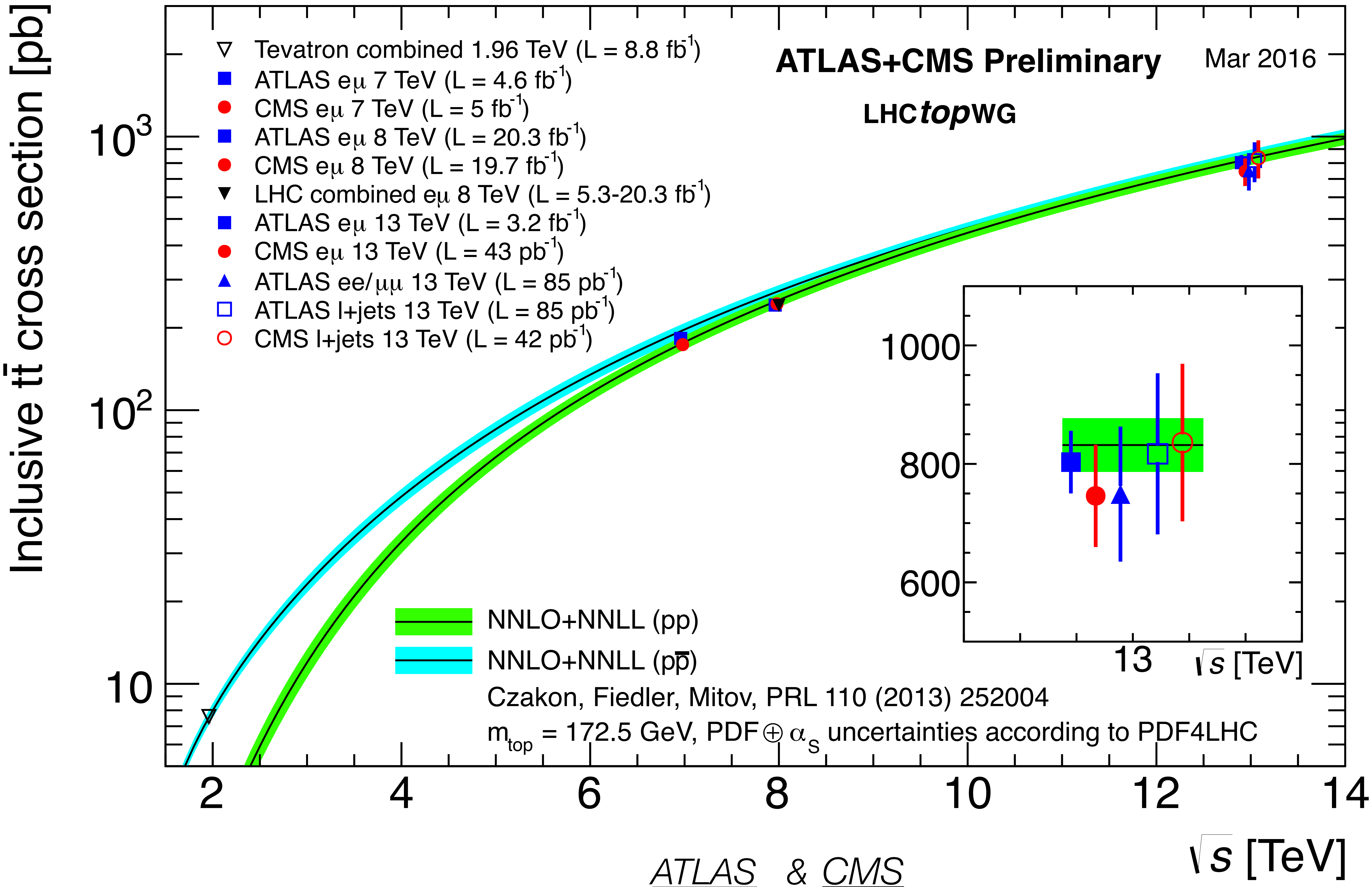
$$\sigma_{t\bar{t}} = 793 \pm 8\,(\mathrm{stat}) \pm 38\,(\mathrm{syst}) \pm 21\,(\mathrm{lumi})\,\mathrm{pb}$$

∫Ldt ~2.2 **fb^{-1}** *(2015)*

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~5.6%

Inclusive σ_{tt} vs $\sqrt{s}$ - LHC & Tevatron

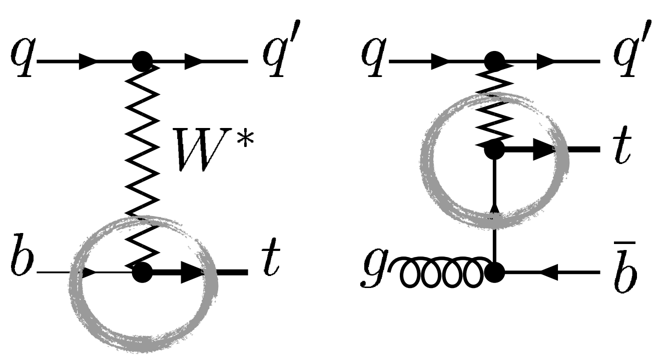
good agreement with NNLO+NNLL over 2 orders of magnitude



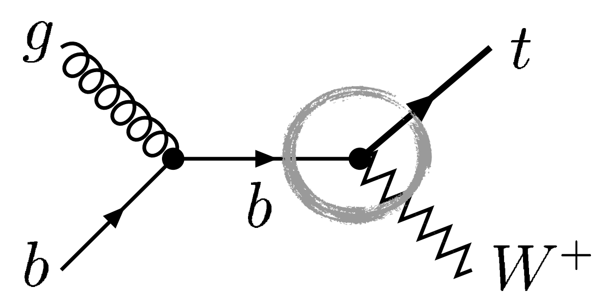
ATLAS & *CMS*
Public summary plots

Single top production

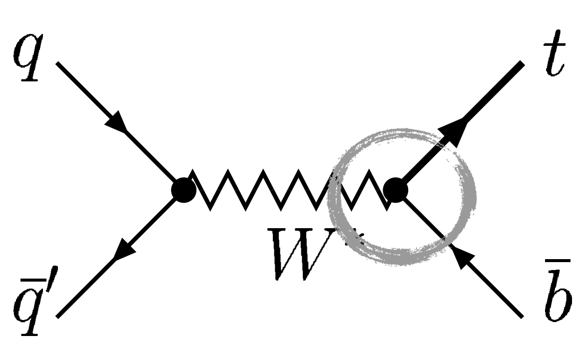
t-chan



Wt chan



s-chan



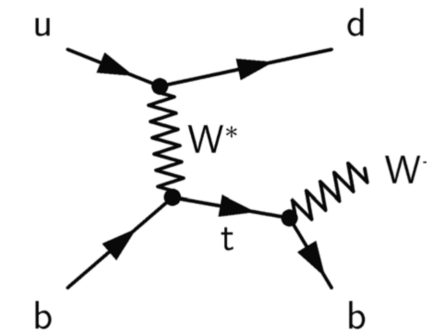
cross section ~ $|f_{\mathrm{LV}} \cdot V_{tb}|^2$

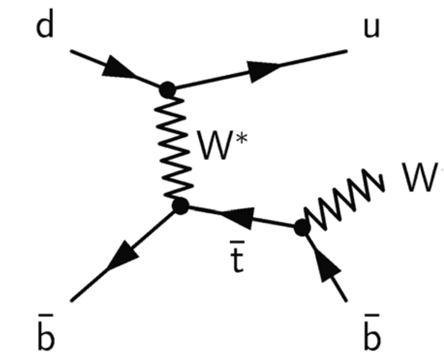
left handed form factor   CKM matrix element

only direct determination of $|f_{\mathrm{LV}} \cdot V_{tb}|$

explore PDF for u and d quark separately

Inclusive σ_t : t-chan @ $\sqrt{s}$ = 13 TeV

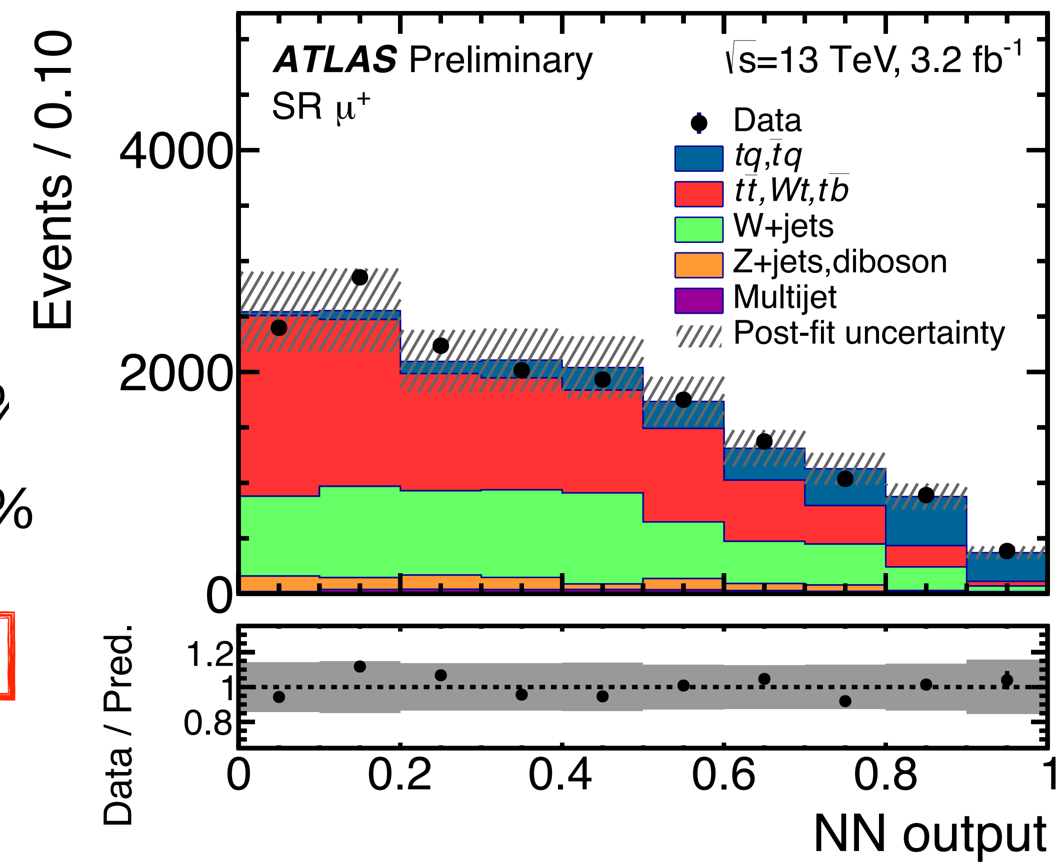




- **1 isol.** μ, **2 jets** with |η|<3.5, large E_T^{miss} and $m_T(W)^* \rightarrow$ fake lep. veto, **1 b-tag,** *additional lepton iso*
- Bkg: *simulated* $t\bar{t}$/Wt/s-chan, W/Z+jets, **data-driven fake lep** (*sample with inverted muon quality cuts)*
- **Extract number of t-chan events,** ν_t**, by binned max. likelihood fit** *of* **Neural Network output** to data
  - **Computational scheme for pattern recognition**
  - **Train on expectation from 10 kinematic variables** *(jet-lep &jet-b masses, jet η,top/W-jet angles..)*
- **Calculate cross section** σ_t **with full phase space efficiency**

ATLAS-CONF-2015-079

$\int L dt$ = **3.2 fb^{-1}** *(2015)*



$$\sigma(tq) = 133 \pm 6\,(\text{stat.}) \pm 24\,(\text{syst.}) \pm 7\,(\text{lumi.})\ \text{pb}$$
$$\sigma(\bar{t}q) = 96 \pm 5\,(\text{stat.}) \pm 23\,(\text{syst.}) \pm 5\,(\text{lumi.})\ \text{pb}$$

$\delta\sigma_t/\sigma_t$ ~19%

$\delta\sigma_t/\sigma_t$ ~25%

$$|f_{LV} \cdot V_{tb}| = 1.03 \pm 0.02\,(\text{stat.}) \pm 0.11\,(\text{syst.}) \pm 0.02\,(\text{theor.}) \pm 0.03\,(\text{lumi.})$$

if f_{LV} =1 & $|V_{tb}|$ in [0,1] → $|V_{tb}| > 0.78$ at 95 % CL

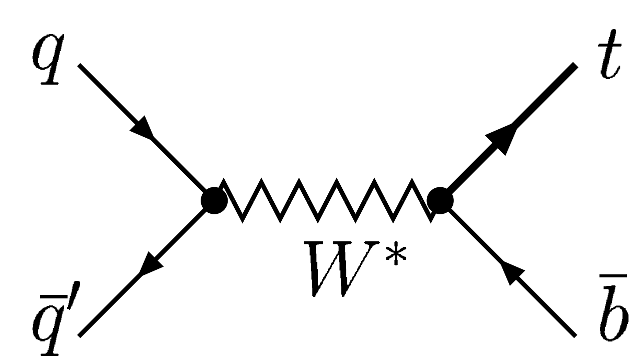
syst dominated

t-chan generator~11-15%, b-tag efficiency~7%,

$$^*m_T(W) = \sqrt{2\left[p_T(\ell)E_T^{miss} - \vec{p}_T(\ell)\cdot\vec{E}_T^{miss}\right]},$$

Inclusive and fiducial σ_t: s-chan $\sqrt{s}$ = 8 TeV

(Marina Cobal @ La Thuile 2016)

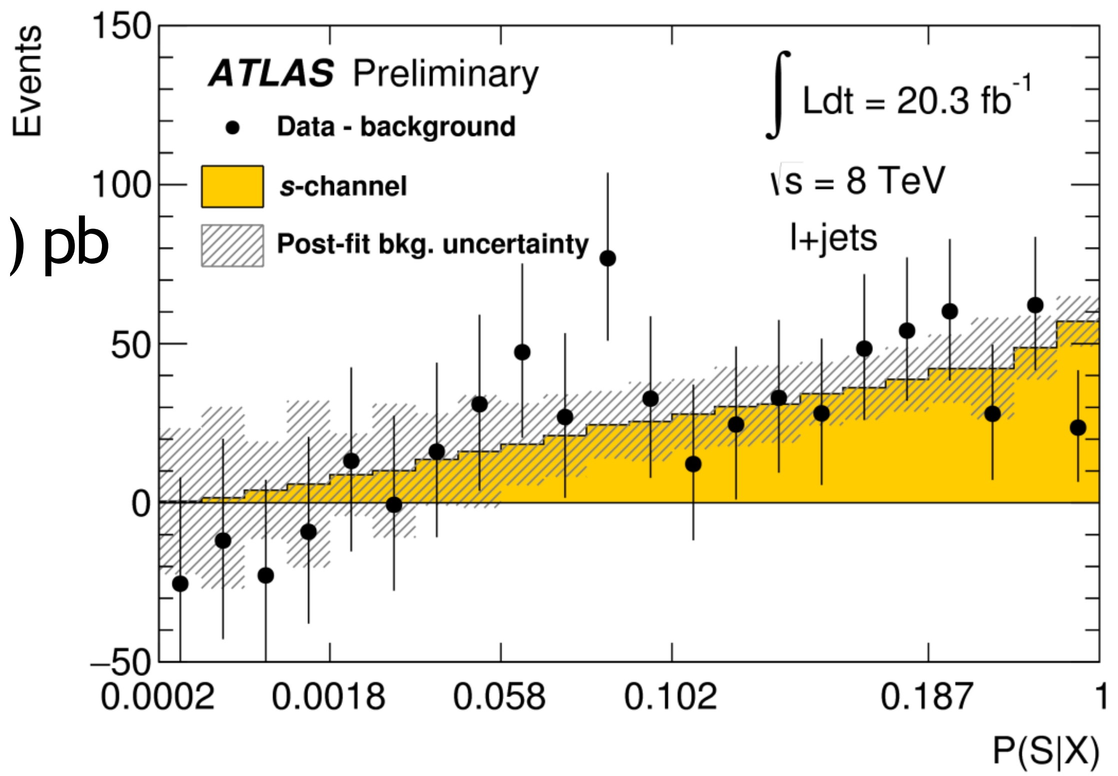


σ(t) in the s-channel @ 8 TeV

- Lepton+jets selection with 2 b-jets and large ETMiss
- Build Matrix Element discriminant for each selected event
- s-channel vs t-channel, tt, W+jets
- Template fit in signal and control regions

This one from ATLAS

σ = 4.8 ±1.1(stat.)$^{-2.0}_{+2.2}$(syst.+lumi.) pb

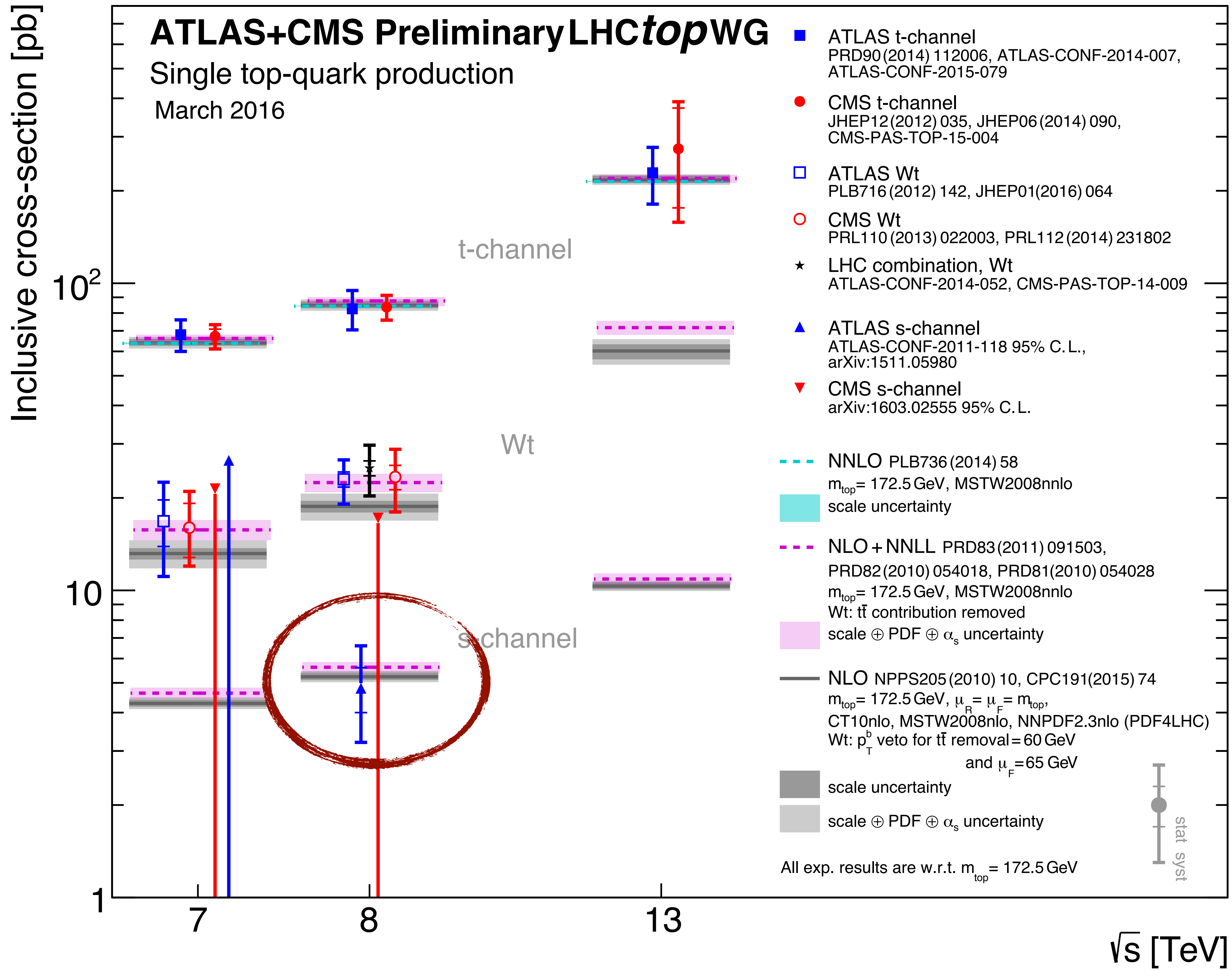


Observed (expected) significance: 3.2σ (3.9σ)

First evidence of single-top s-channel production at the LHC!

7 7

Inclusive σ_t - Summary at $\sqrt{s}$ = 7 & 8 TeV



All results consistent with approx NNLO predictions

t-channel and Wt channels are observed at LHC,

evidence for s-channel *(observed at Tevatron in 2014 PRL112 231803 (2014))*

ATLAS & CMS Public summary plots

- ATLAS + CMS t-chan combination at $\sqrt{s}$ = 8 TeV

$\int Ldt$ = **5.8 (5.0) fb^{-1}** *(2012))*

CMS-PAS-TOP-12-002

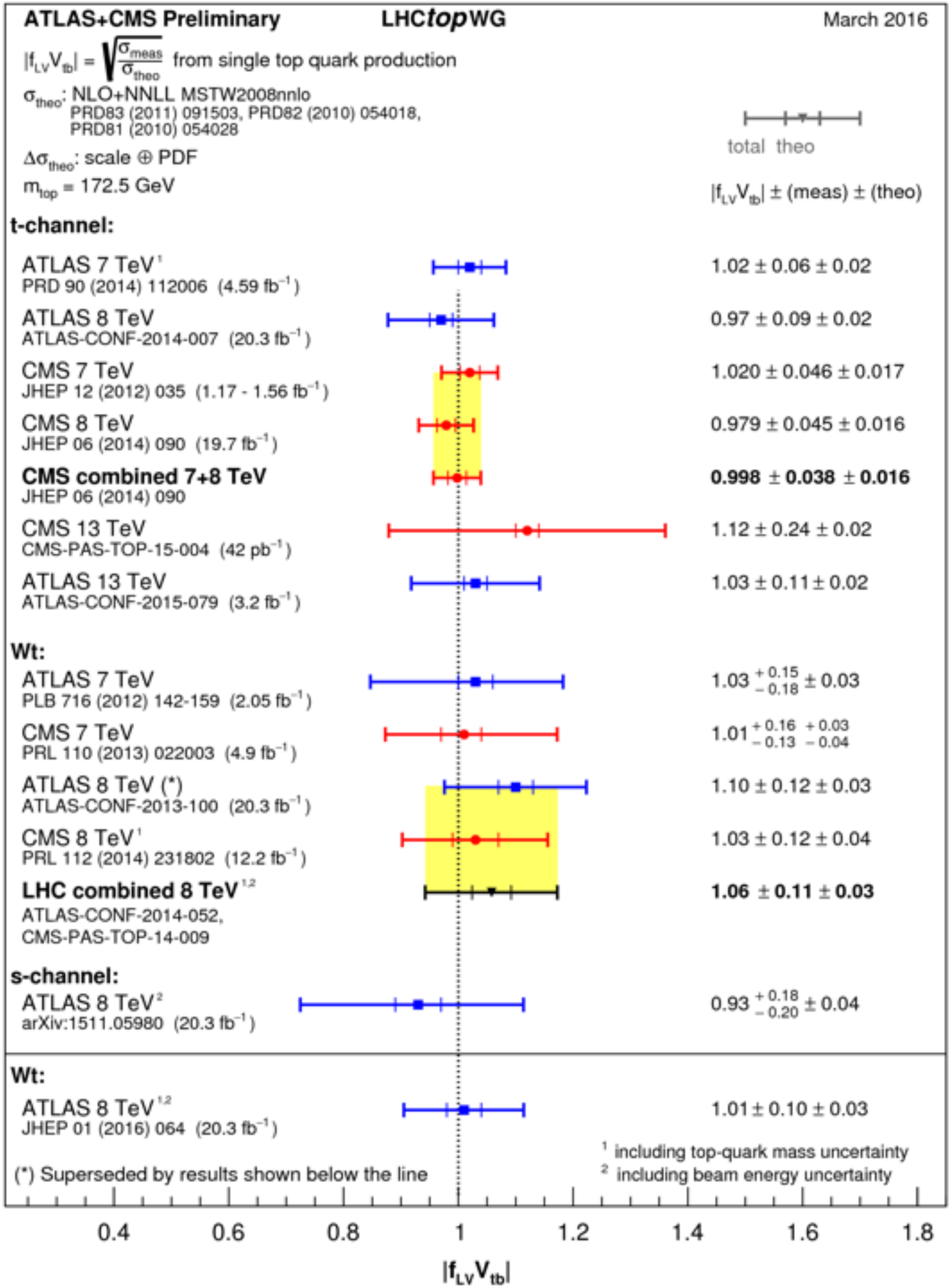
ATLAS-CONF-2013-098

$$\sigma_{\text{t-ch.}} = 85 \pm 4\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 3\,(\text{lumi.})\,\text{pb}$$

$\delta\sigma_t/\sigma_t$ ~14%

$|f_{\mathrm{LV}} \cdot V_{tb}|$

summary

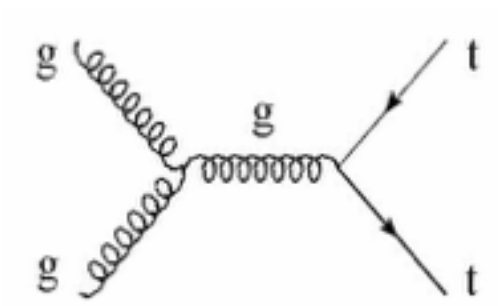


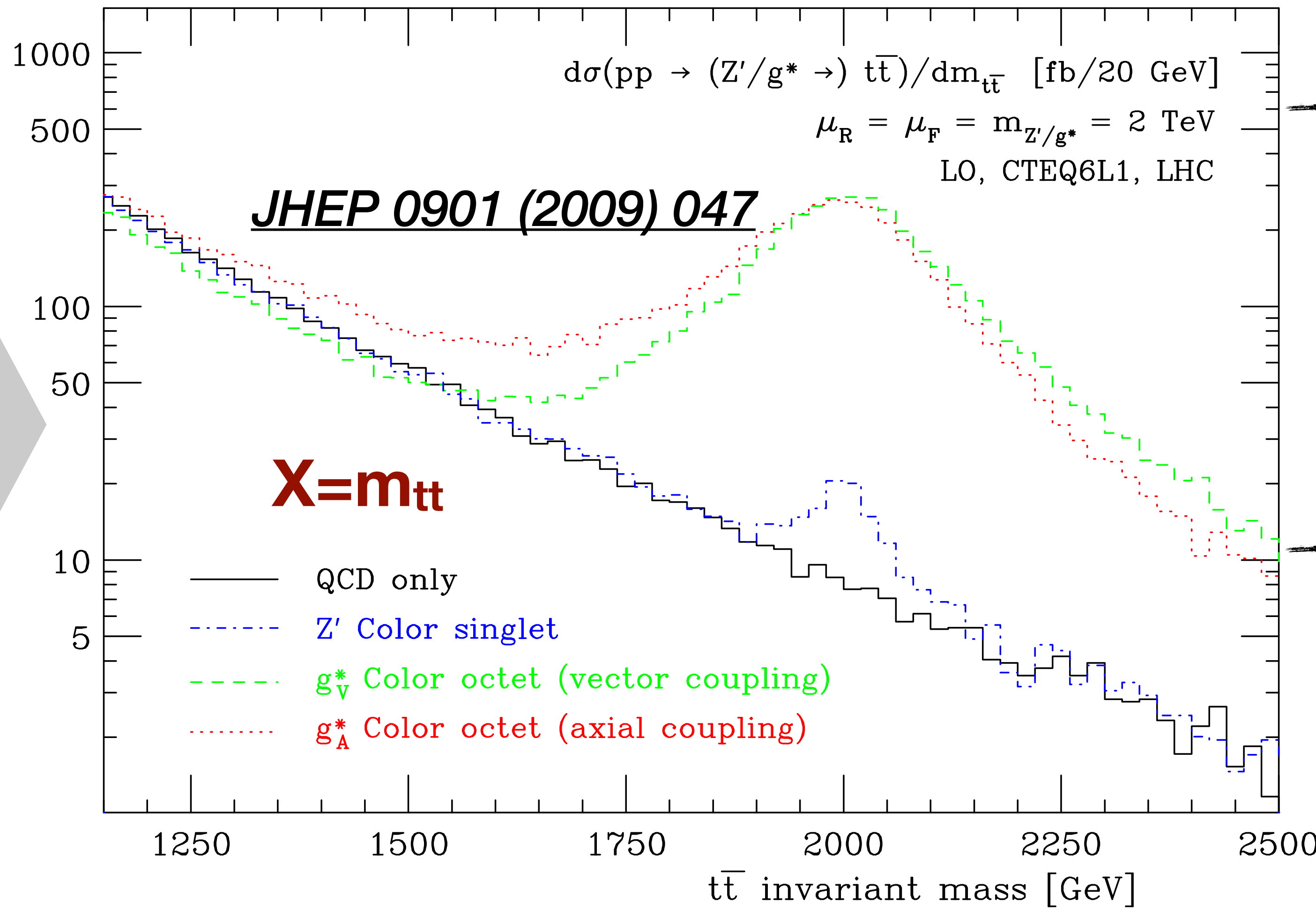
ATLAS & CMS
Public summary plots

To explore **elusive and/or heavy new physics** with top quarks **@LHC**

Measure $d\sigma_{tt}/dX$

- **LHC is a top factory**





→ **sensitive to many new physics models**

complement specific searches

→ explore kinematics → **reduce t/t$\bar{t}$ modelling uncertainties**

probe parton dist. functions (high x gluon)

↓

use **new reconstruction/recognition techniques**

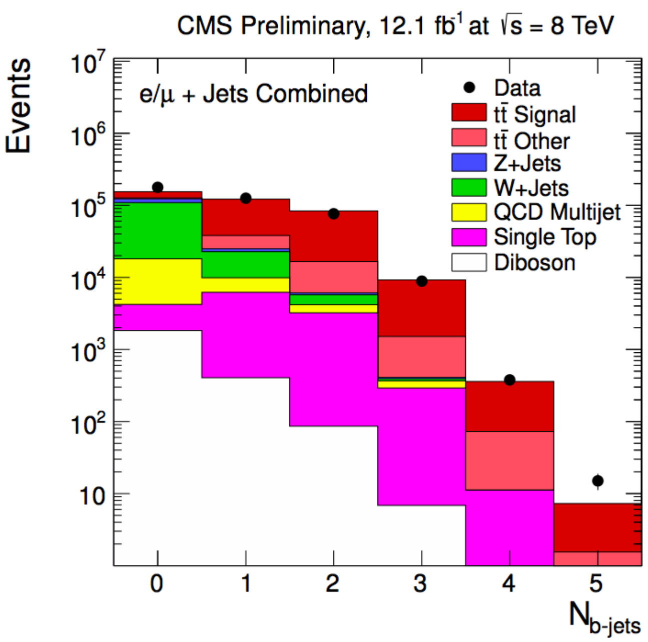
provide info on Parton Dist Functions

high energy gluons

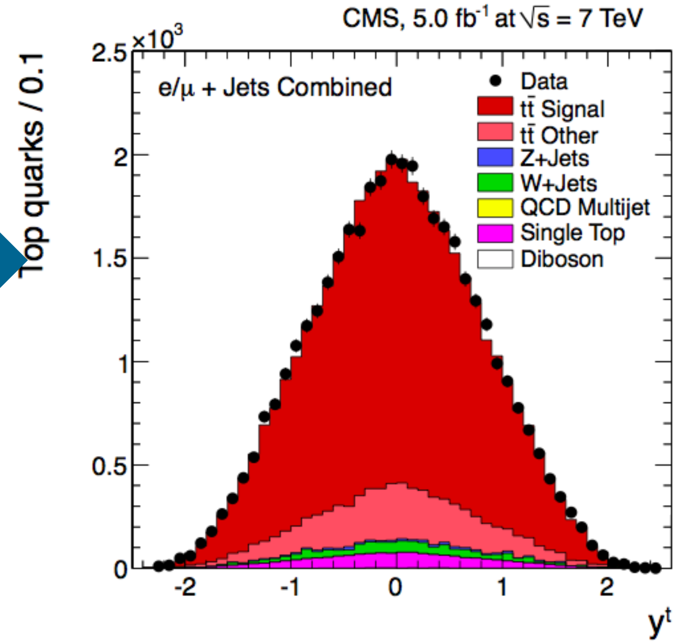
Going differential for $\sigma_{t\bar{t}}$!

Measure σ(tt̄) as a function of kinematic distributions of **top, top pairs, b-jets, leptons, and lepton pairs**

(1) Event selection



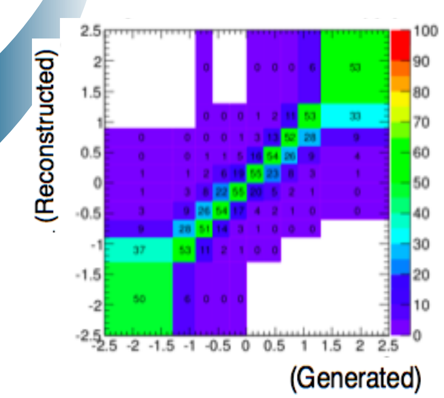
(2) tt̄ kinematic reconstruction



(3) Bin-wise cross section measurement

- Subtract background
- Unfolding: correct for detector effects and acceptance

$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\rm Data} - N^i_{\rm BG}}{\Delta^i_{\rm X}\epsilon^i L}$$

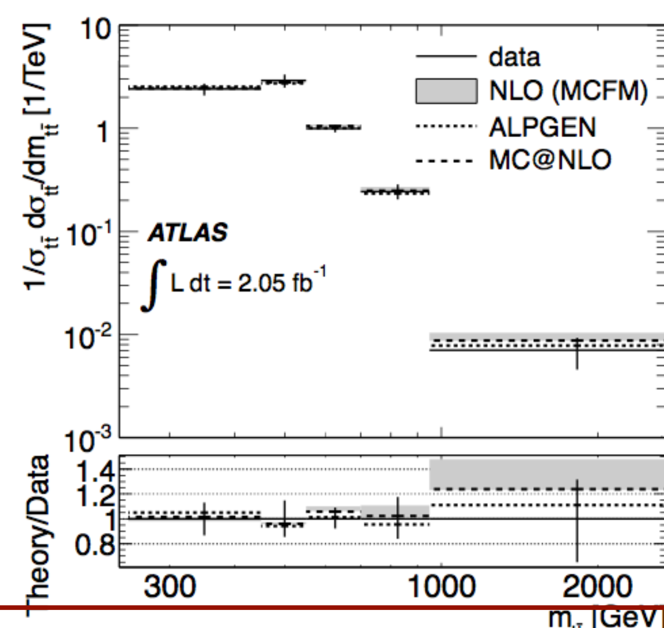


Response matrix

Migrations due to det resolution & biases

(4) Differential tt̄ cross sections

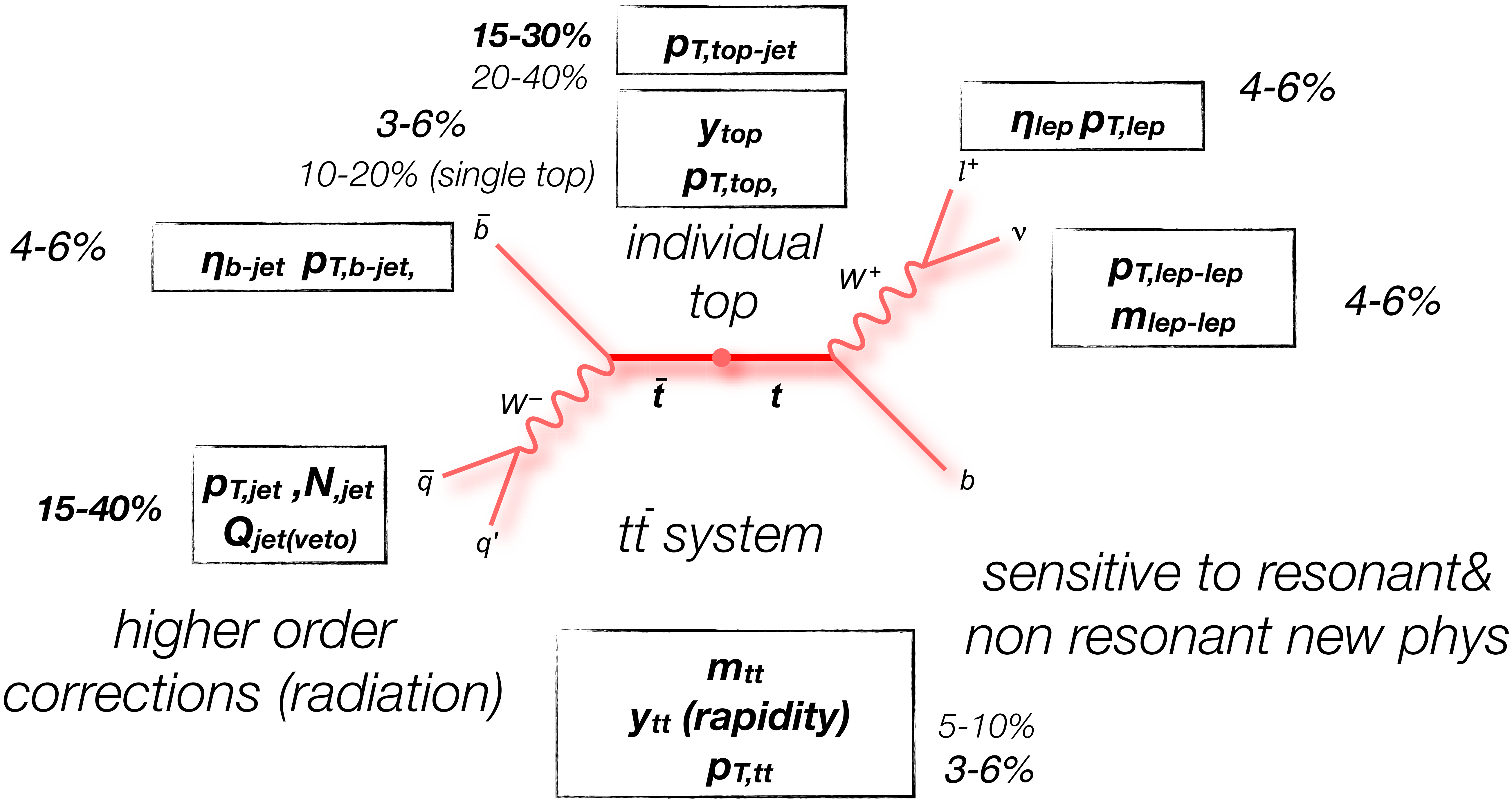
- Normalised to in-situ measured σ(tt̄)
- 'Visible' or extrapolated to full phase space
- Compare to theory predictions



What we measured *(up to now)* in Run1: ***X in $d\sigma_{(tt/t)}/dX$***

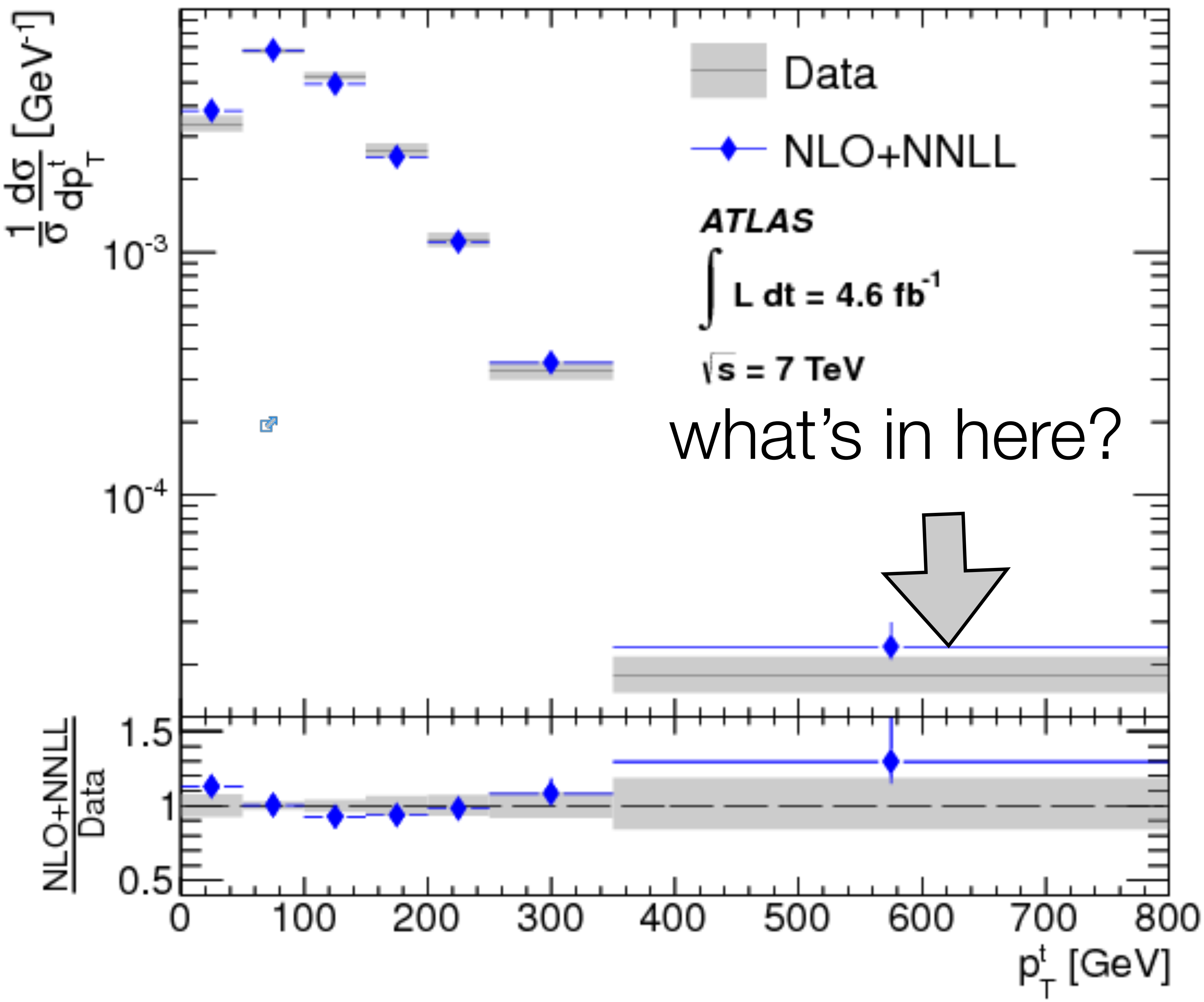
Overview of current results at LHC

- Increasing variety of differential cross section results
  - More measurements in fiducial PS, exploiting particle-level object definition and pseudo-top
  - Pioneering results in boosted regime, first absolute differential cross sections appearing



Exploring top quark p_T : the emergence of boosted tops

Phys. Rev. D 90, 072004



Exploring top quark p_T : the emergence of boosted tops

ΔR(i,j from X→i,j) ~ $2m_X(i,j)/p_{T,X}$

Reduced efficiency for "resolved" reco

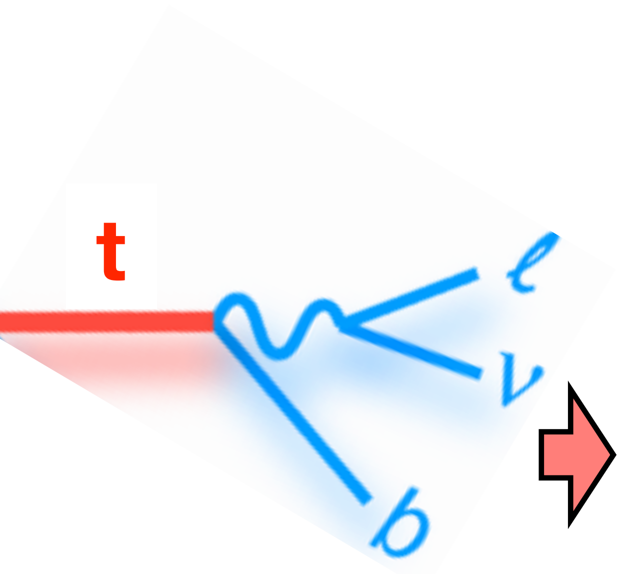
M_{tt}

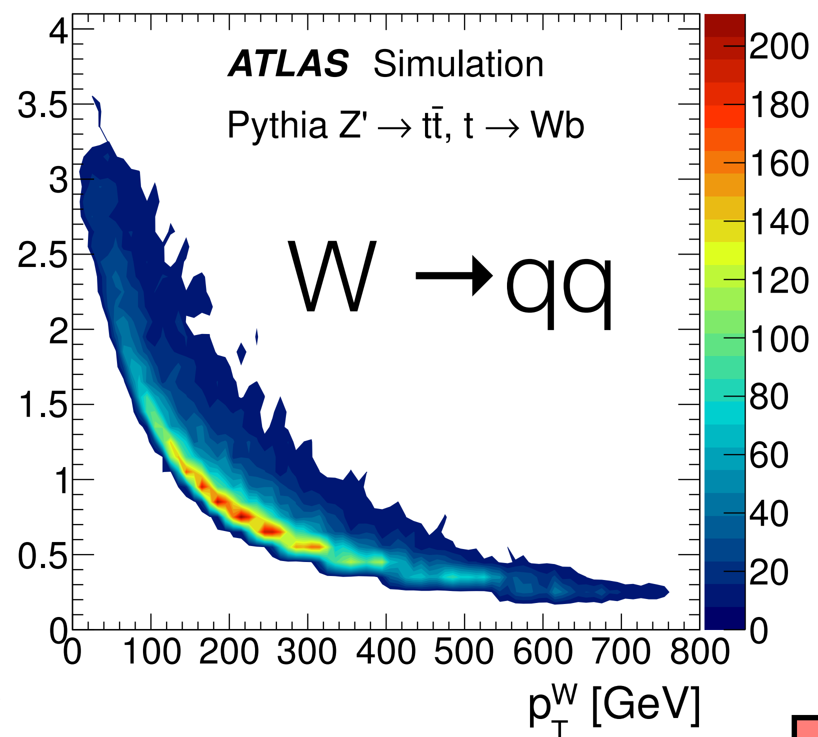
P_T^{Top}

*M_{tt} =1 TeV & anti-k_T (R=0.4): **86% resolved***

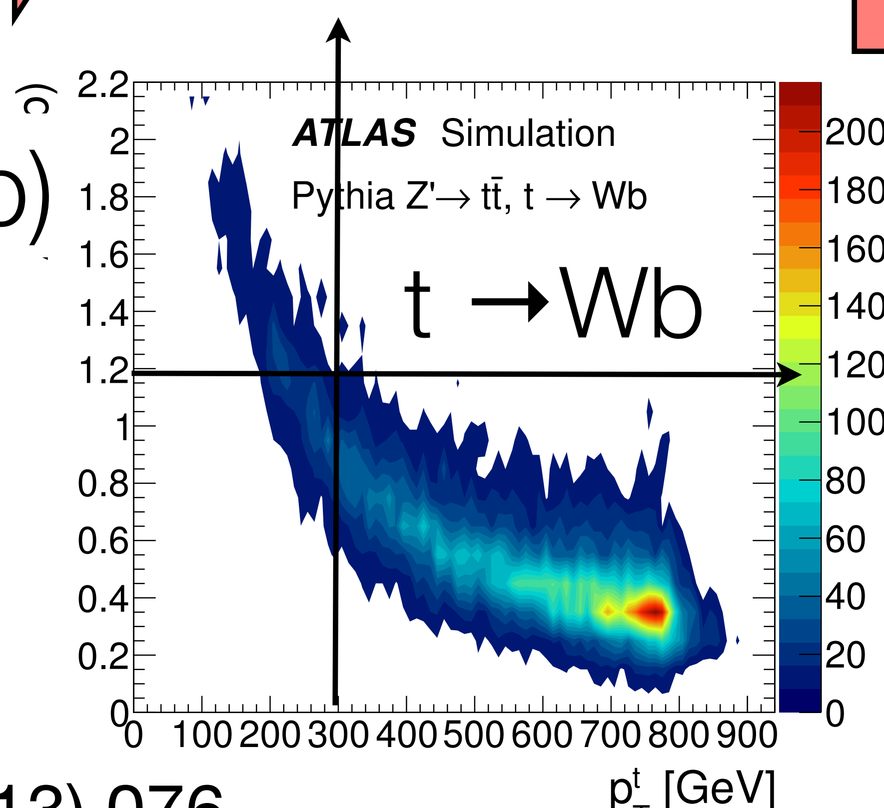
*M_{tt} =2 TeV & antikt (R=0.8): **60% boosted***

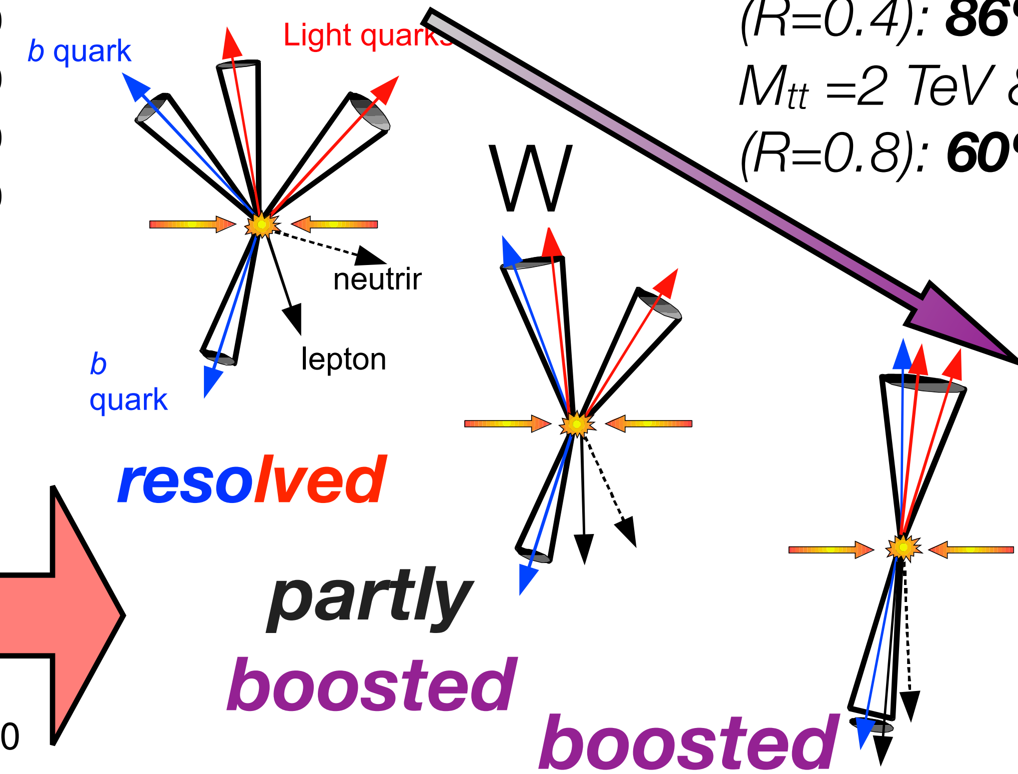
ΔR(q,q)





ΔR(W,b)





For ΔR=0.8, M_{tt} ~1.7 TeV, P_T ~600 GeV

*Need to **distinguish top-jet from light q-, gluon**-initiated jets: **di-jets** bkg **overwhelming** fully had tt decays*

Pile up & soft activity degrade identification & energy estimate

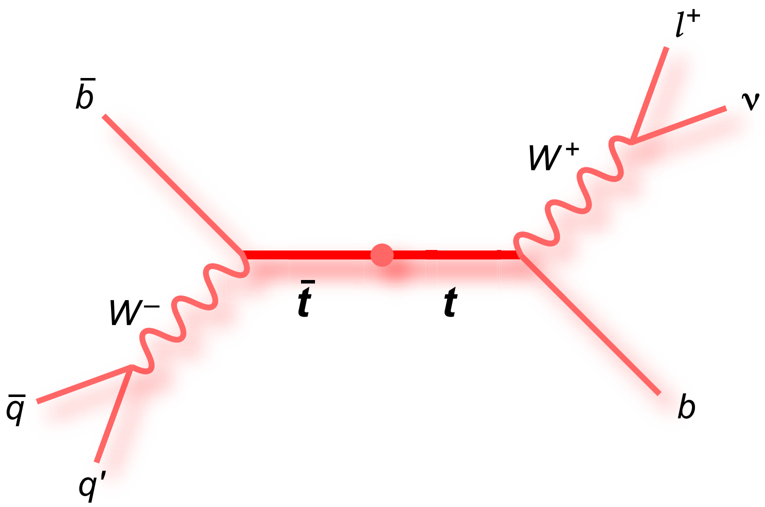
JHEP 1309 (2013) 076

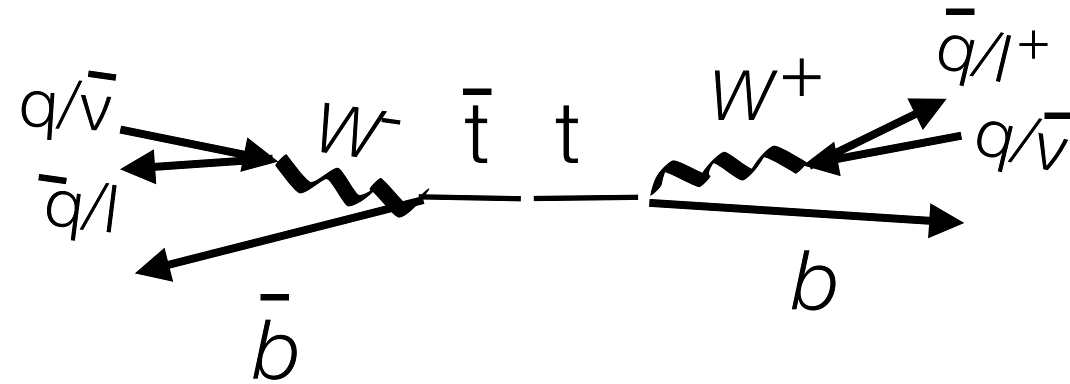
Exploring top quark p_T : the emergence of boosted tops

$d\sigma_{tt,t}/dp_{T,top(-jet)}$

"Resolved" — *map p_T* → "Boosted"

Parton





reduce extrapolation

Particle

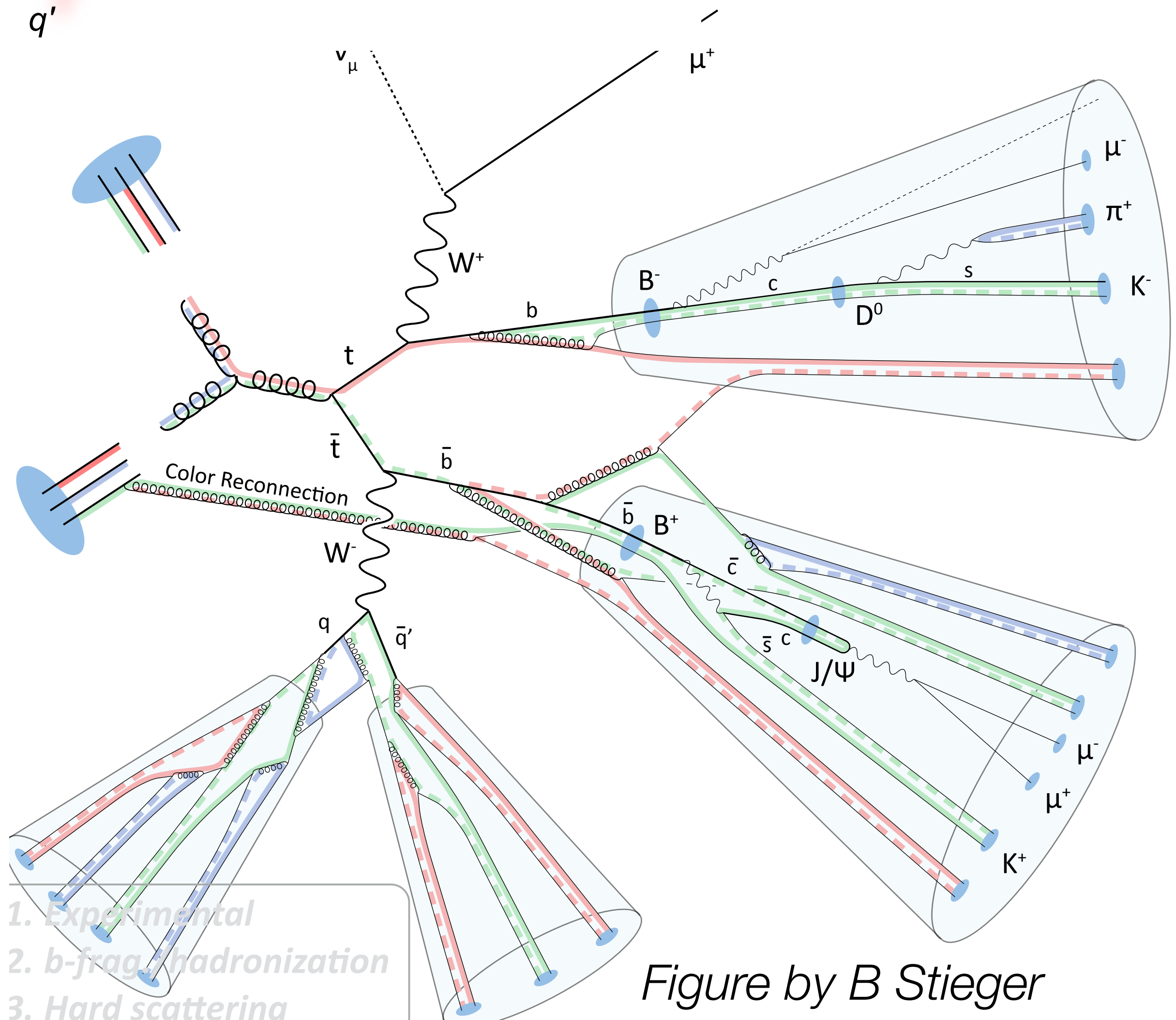
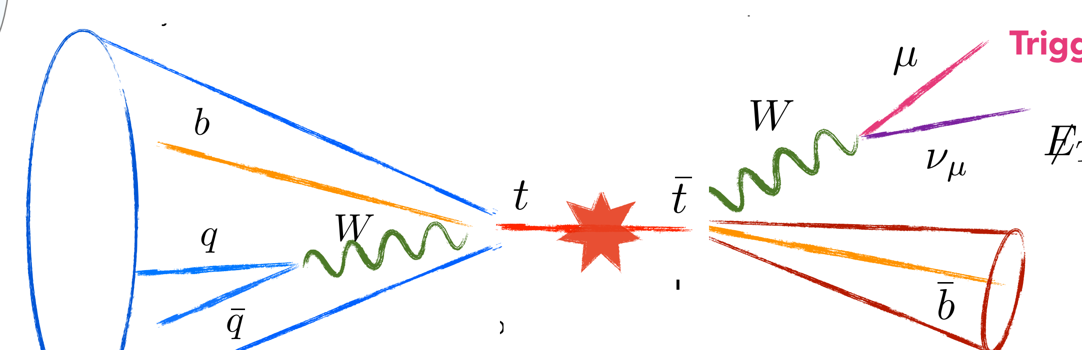
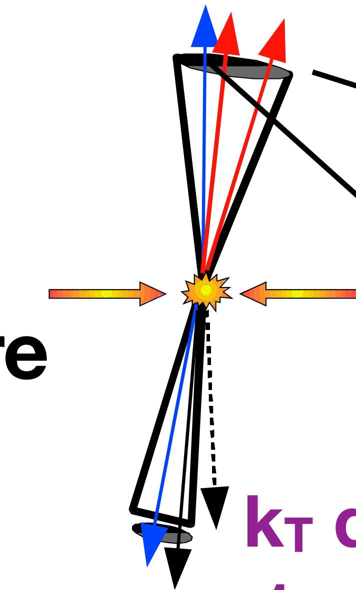


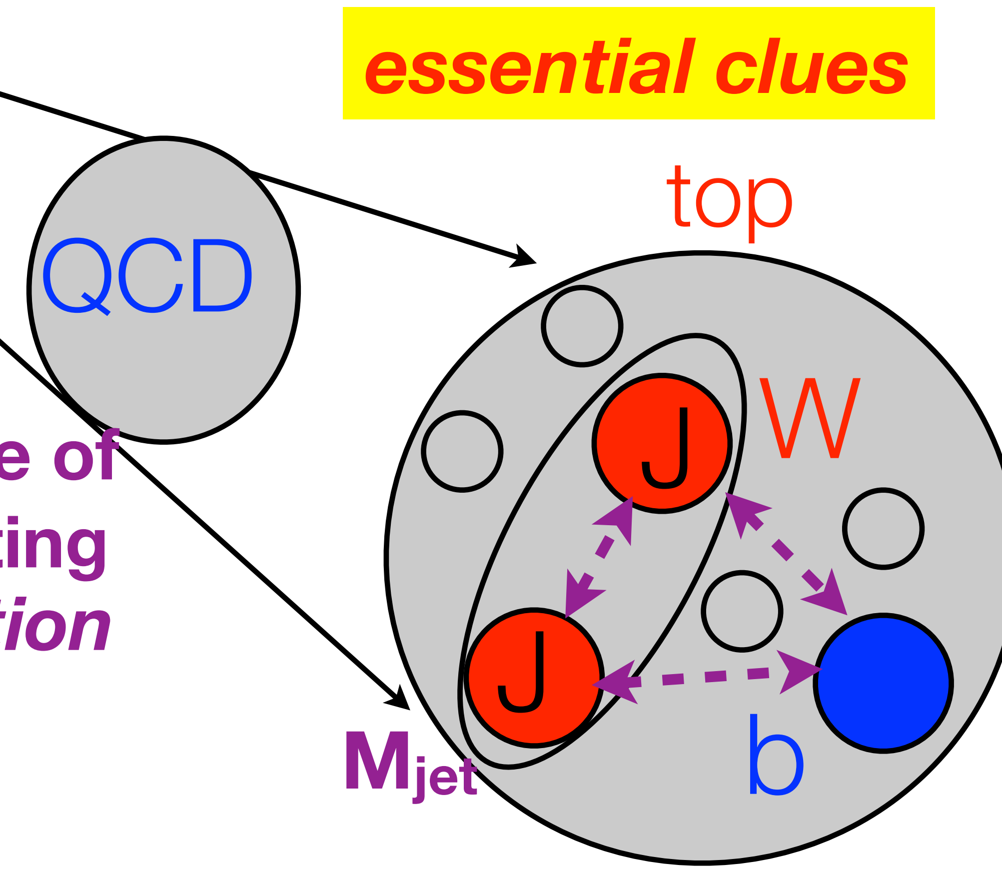
Figure by B Stieger (CERN)



(figure by A Ovcharova (UCSB))

How **to tag** a boosted hadronic top quark? (I)





Look into the jet substructure

(see Jose Juknevich, TOP2013)

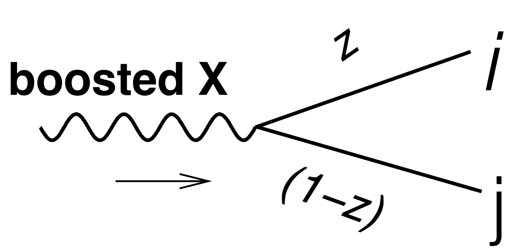
kT distance of 1→2 splitting

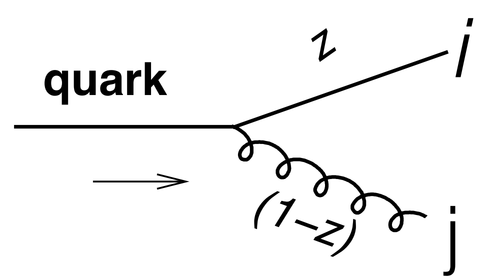
Basic

*Use **jet mass** and **product of p_T* angular separation** of two hardest jet constituents from jet algorithm*

- Splitting scales (ATLAS tagger) Butterworth, Cox, Forshaw (hep-ph/021098)
  - Read off k_T scales of the (next-to-)next-to-last clusterings
  - Place cuts on jet mass and splitting scales

$$p_t = p_{ti} + p_{tj} \qquad z = p_{tj}/p_t$$





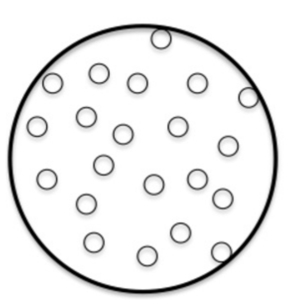
in collinear soft limit

$$d_{ij} = z^2 p_t^2 \Delta R_{ij}^2 \simeq \frac{z}{(1-z)} m^2$$

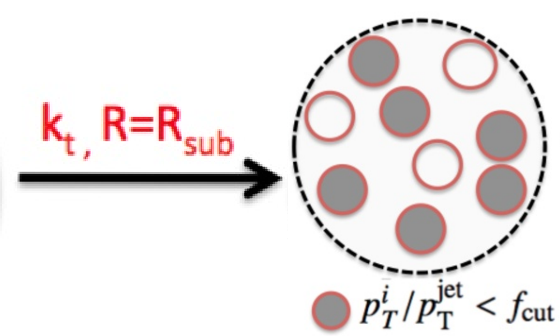
small QCD splitting prob → large √d(i,j)

$P(z) \propto 1$ $\qquad P_{gq} \propto \frac{1+(1-z)^2}{z}$

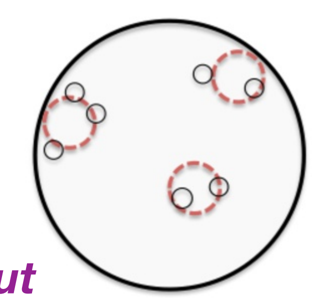
*To do also on **trimmed jets** i.e deprived of soft jet constituents*



Cluster with anti-kT



reject subjets with → ***$p_{T,subjet}/p_{T,jet} < f_{cut}$***



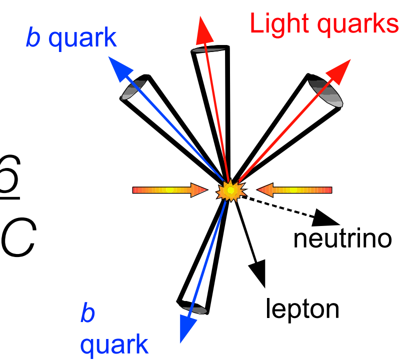
R=0.2 f=0.3

Differential $d\sigma_{tt}/dp_{T,top(-jet)}$: l+jets @ $\sqrt{s}$ = 8 TeV

$\int Ldt$ = **4.7 fb^{-1}** *(2011)*

Eur. Phys. J. C 75 (2015) 542

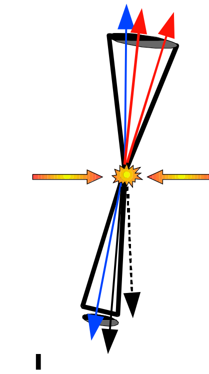
arxiv:1511.04716
submitted to EPJC



- 1 isolated (e,μ), symmetric E_T and m_T^W cuts, **≥ 4 central jets,**
- ≥1 b-tag or =2 btags

$\int Ldt$ = **20.3 fb^{-1}** *(2012)*

Phys Rev D 93 032009 (2016)



- ***Lep top:*** 1 p_T dep.-isolated (e,μ) , E_T^{miss} + (closest) R=0.4 jet to lep. with *ΔR(lep,jet)<1.5*
- ***Had top :*** *≥ 1 R=1.0* ***trimmed jet*** *with* ***large p_T*** *≥ 300 GeV,* ***large m_{jet}****>100 GeV,* ***large k_T (1 →2) scale*** *(> 40 GeV)*
- ***top quarks in opposite hemisphere*** *→ Δϕ(lep,had top-jet)>2.3, ΔR(lept b-jet, had top-jet)>1.5*

- *Bkg:data driven W+jets & fakes, single top & diboson from MC*
- ≥1 b-tag jet

kine-fit top

- **Reconstruct tt decay products from jets + lepton+ E_T^{miss} by kinematic fit** *(m_t,m_W constraint)* → assign jets
- ***Had top*** = 3 assigned jets from lkl

pseudo-top

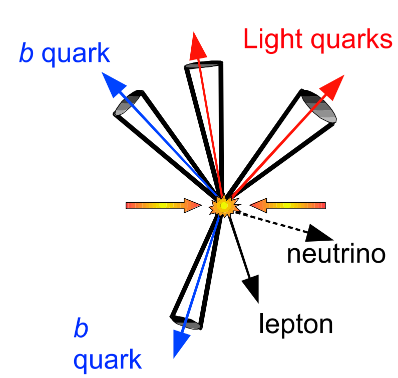
- **Assume 2 highest p b-jets come from tt decay**
- ***Lep top:*** W boson = lep+ E_T^{miss} +,*m_W constraint* + b-jet with min ΔR(b-jet,lept)
- ***Had top :*** W boson= ***2*** *non* ***b-tagged jets*** *with mass closest to M_W* + **other b-jet**

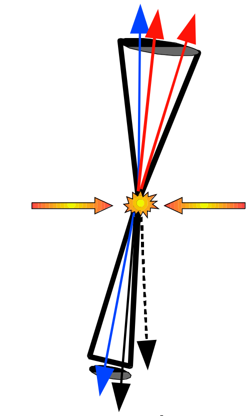
top-jet

- **Had top = Had top jet**

reduce combinatorial bkg

Differential $d\sigma_{tt}/dp_{T,top(-jet)}$: l+jets $\sqrt{s}$ = 8 TeV





$\int Ldt$ = **19.7 fb^{-1}** *(2012)*

Eur. Phys. J. C 75 (2015) 542

kine fit
hadronic top

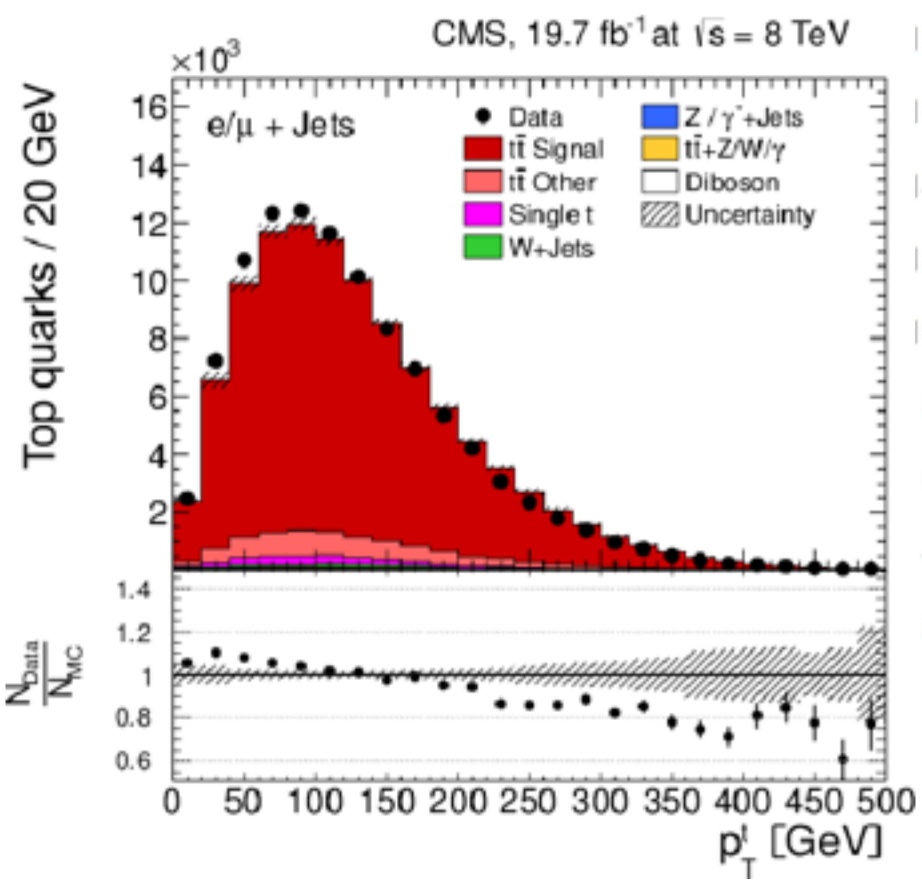
arxiv:1511.04716 submitted to EPJC

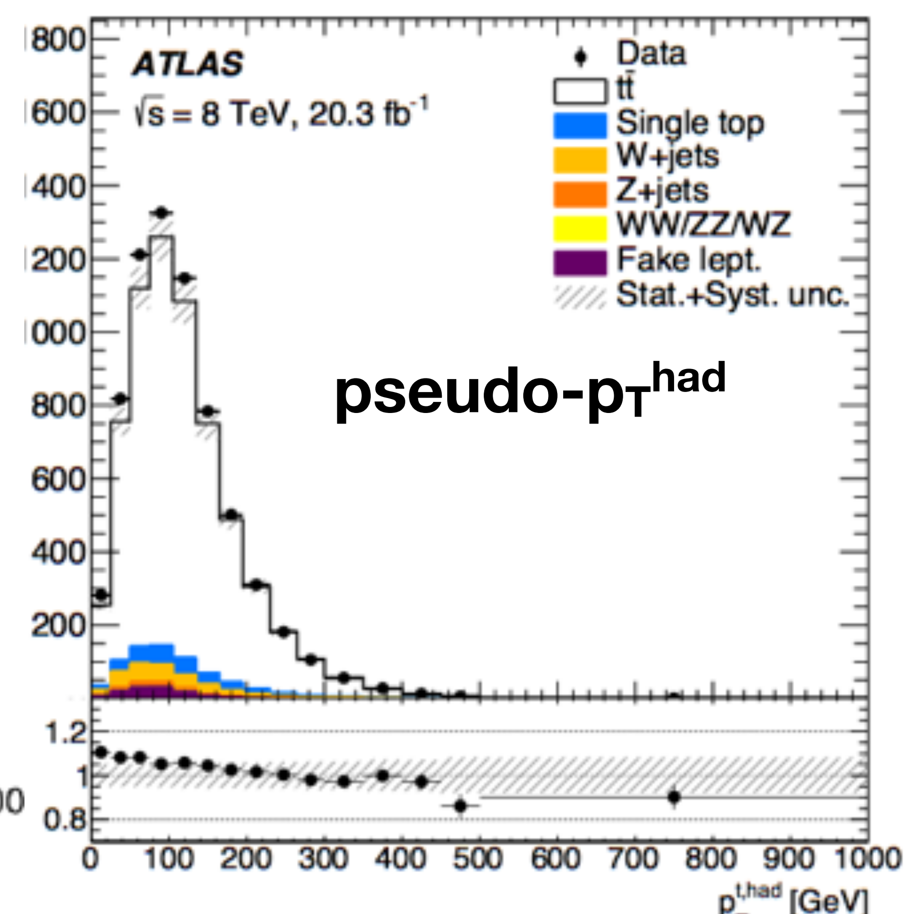
pseudo-top

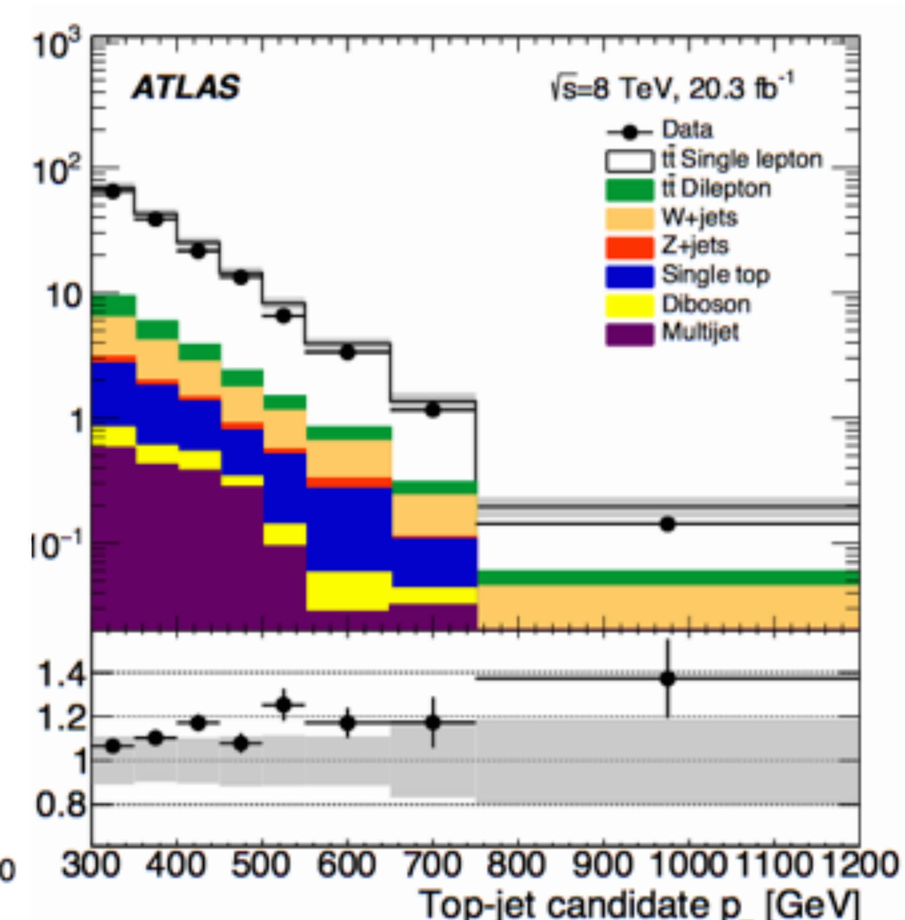
$\int Ldt$ = **20.3 fb^{-1}** *(2012)*

Phys Rev D 93 032009 (2016)

hadronic top-jet







~64k ev,
~79% pure signal $t\bar{t}$

~200k sel events,
~84% pure signal $t\bar{t}$

~8k selected events,
85% tt-pure

$d\sigma_{tt}/dp_{T,top(-jet)}$ l+jets: unfolding - $\sqrt{s}$ =8 TeV $\int L dt$ = 20.3 fb^{-1} (2012)

Phys Rev D 93 032009 (2016)

- **Particle level** *(regularized unfolding, linearity tests)*

Reco — *selected out*

Pass Reco, Pass PL	Pass Reco, Fail PL	Fail Reco Pass PL	Fail Reco, Fail PL

to correct to

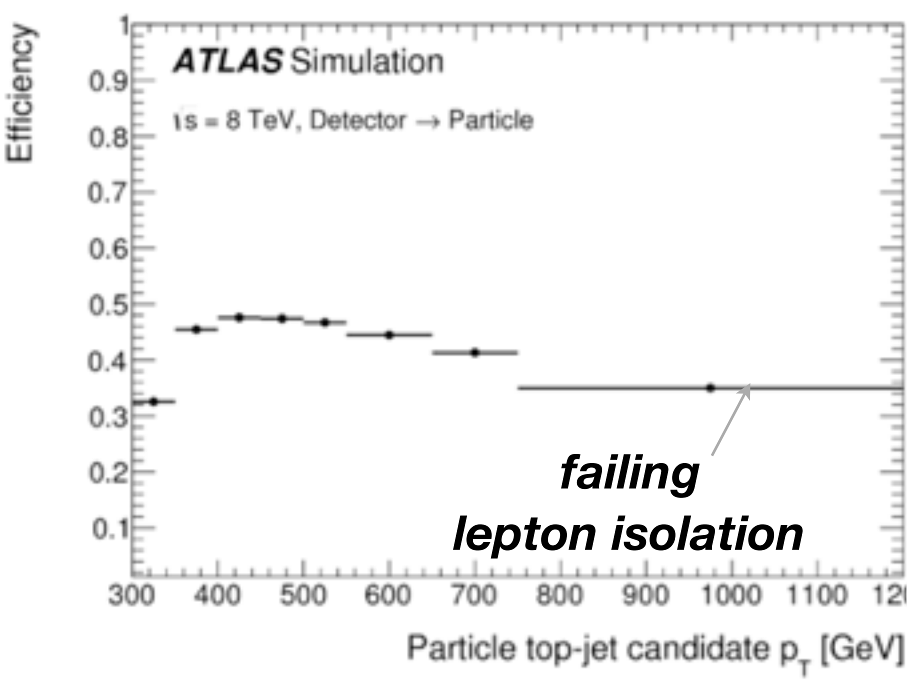
similar (simpler) formulas for parton level

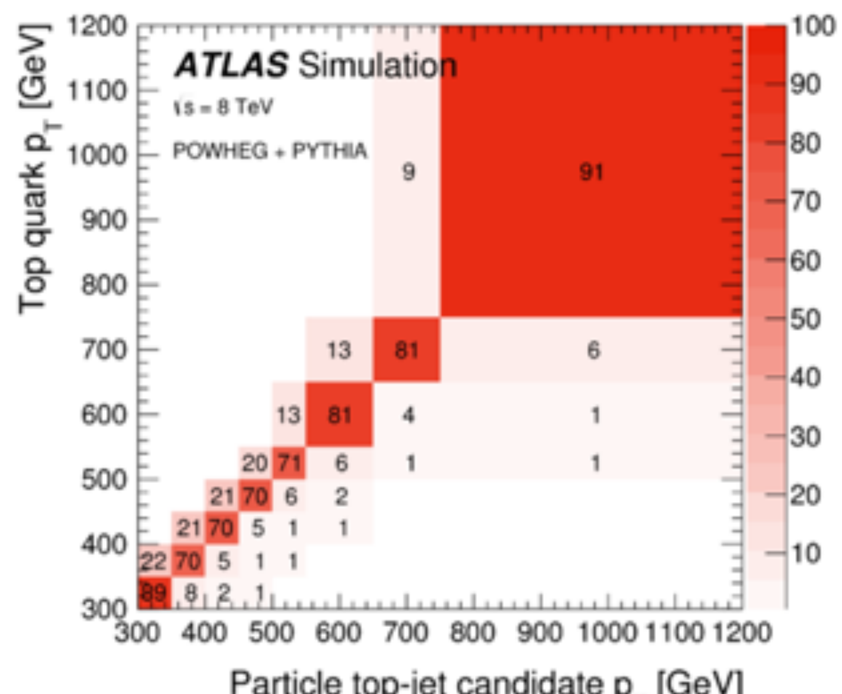
$$\frac{d\sigma_{t\bar{t}}}{dp_{\mathrm{T,ptcl}}}(p^{i}_{\mathrm{T,ptcl}}) = \frac{1}{\Delta p^{i}_{\mathrm{T,ptcl}}\mathcal{L} f^{i}_{\mathrm{ptcl!reco}}} \cdot \sum_{j} M^{-1}_{ij}\, f^{j}_{\mathrm{reco!ptcl}} f_{t\bar{t},\ell+\mathrm{jets}} (N^{j}_{\mathrm{reco}} - N^{j}_{\mathrm{reco,bgnd}})$$

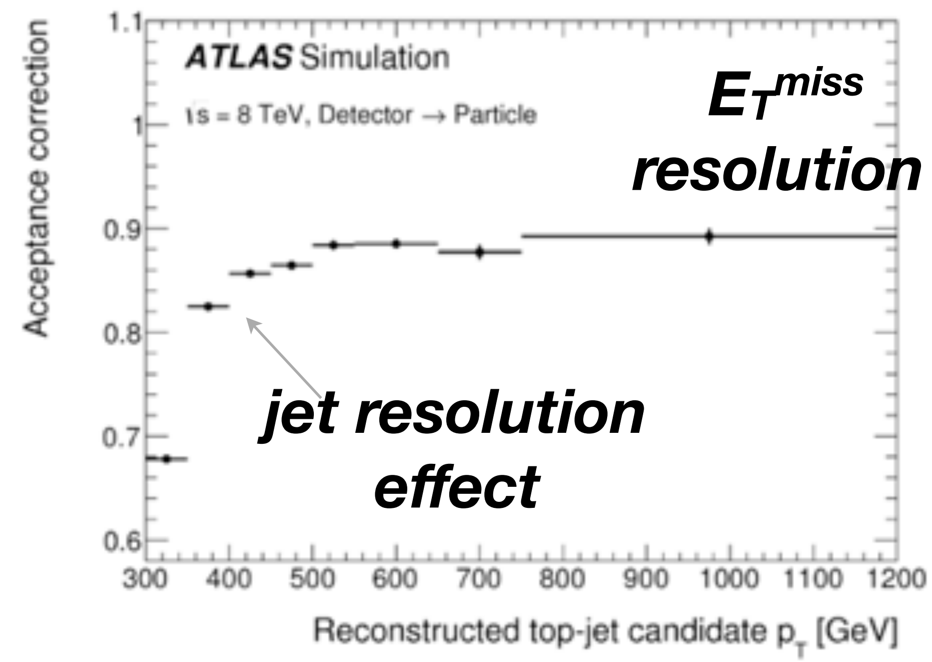
events that pass particle & reco / events that pass particle → restore **Fail Reco Pass PL**

unfold at level of **Pass Reco, Pass PL**

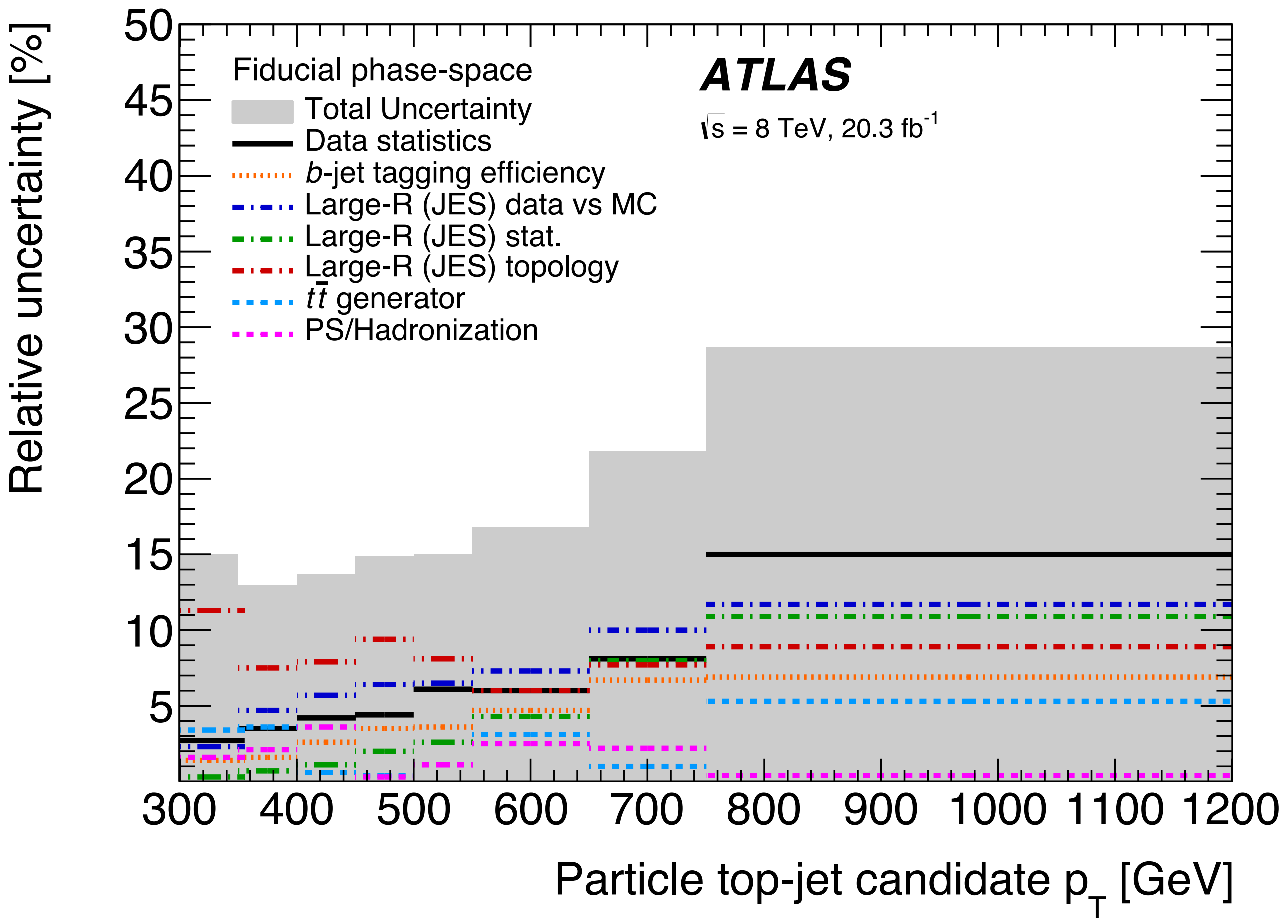
events that pass reco & part / events that pass reco → take **Pass Reco, Fail PL** away







Differential $d\sigma_{tt}/dp_{T,top(-jet)}$ l+jets: Uncertainties- $\sqrt{s}$ =7& 8 TeV



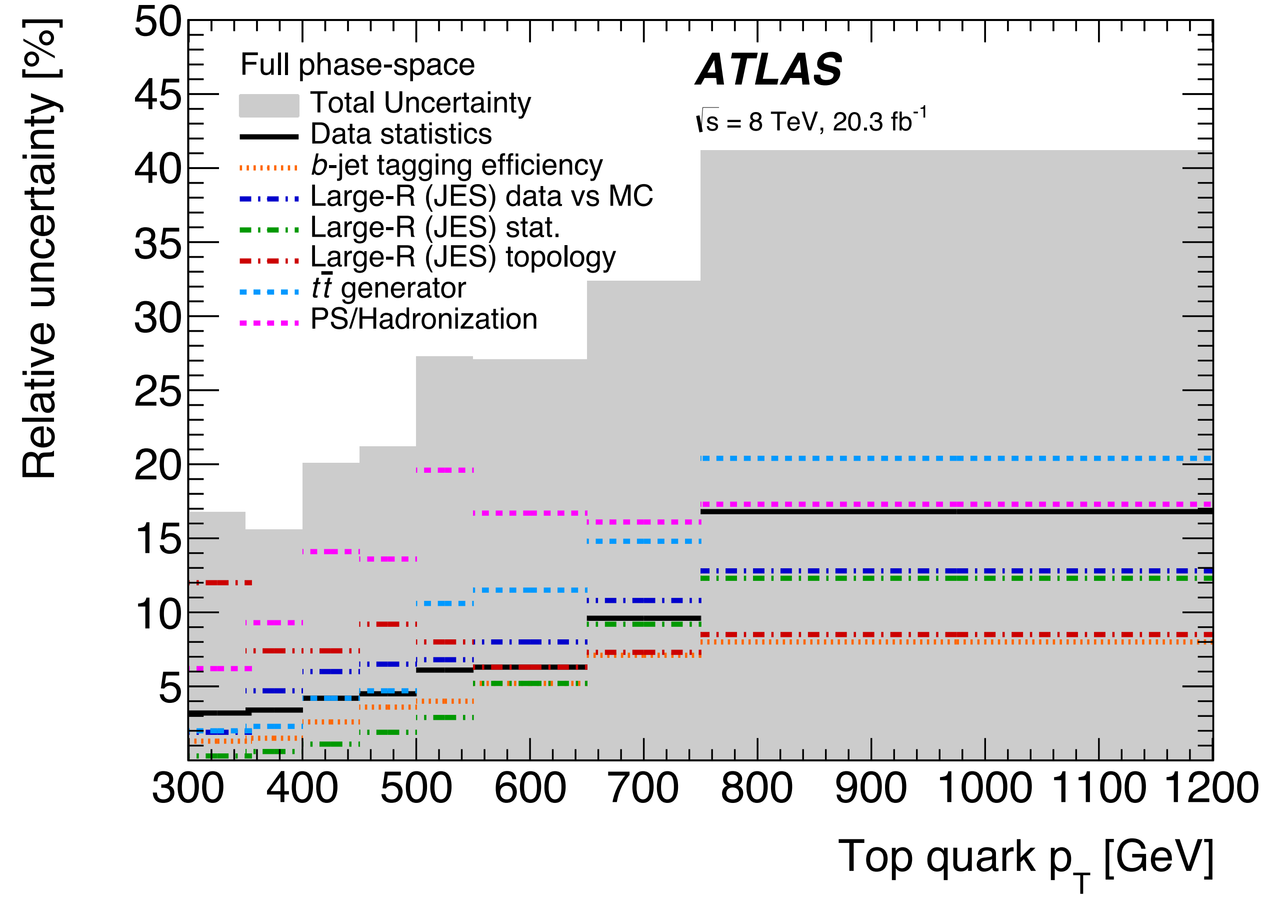
Phys Rev D 93 032009 (2016)

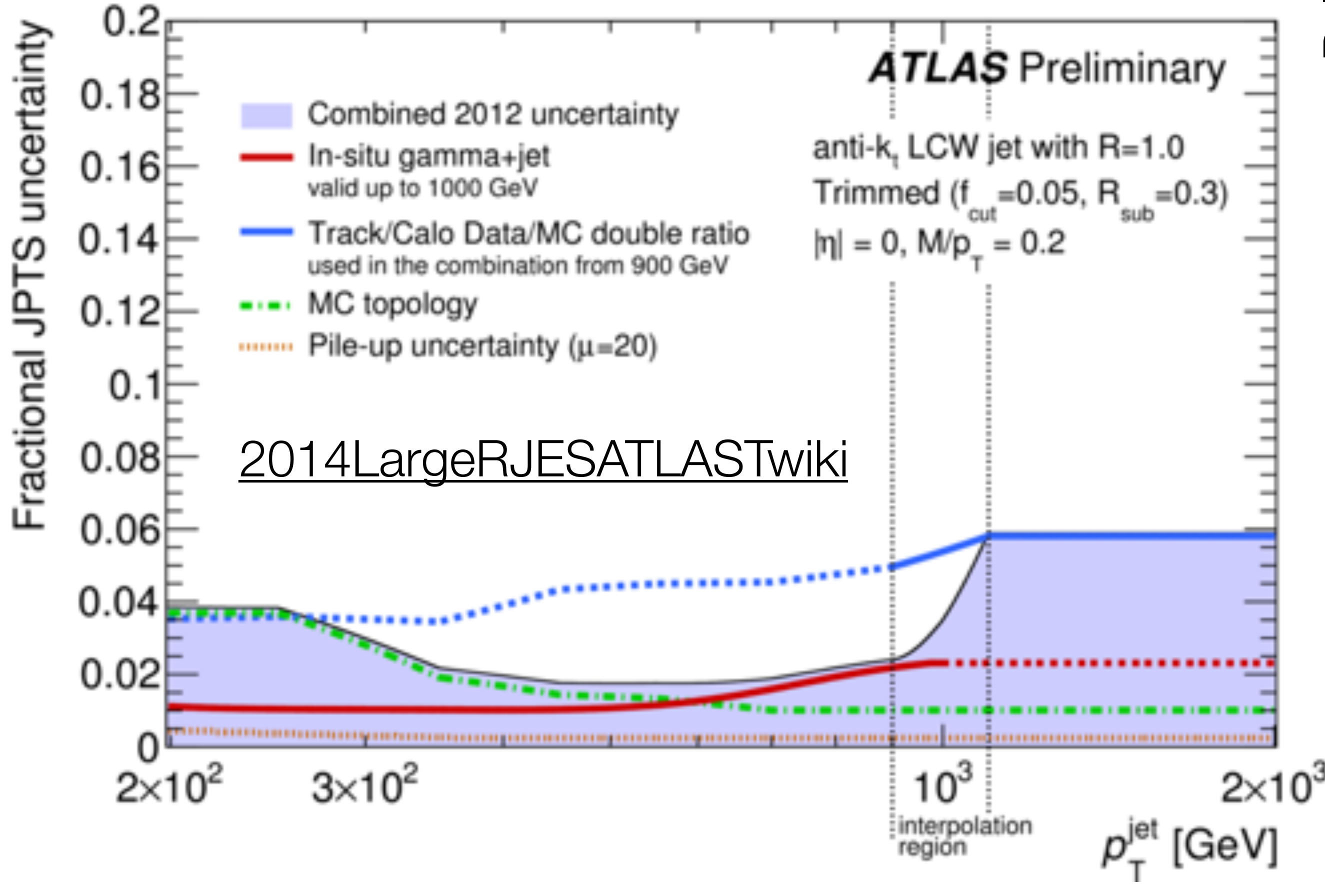
$\int Ldt$ = **20.3 fb^{-1}** (2012)

example at 8 TeV boosted

syst estmate

$\Delta d\sigma/dX(i) = d\sigma/dX\ (i)^{meas}$ (pseudodata) - $d\sigma/dX\ (i)^{generated}$





- Jets are dominant uncertainty
- Comparison of data to prediction derives p-value for χ^2 variable built with the full stat+syst covariance matrix

$d\sigma_{tt}/dp_{T,top(-jet)}$ l+jets

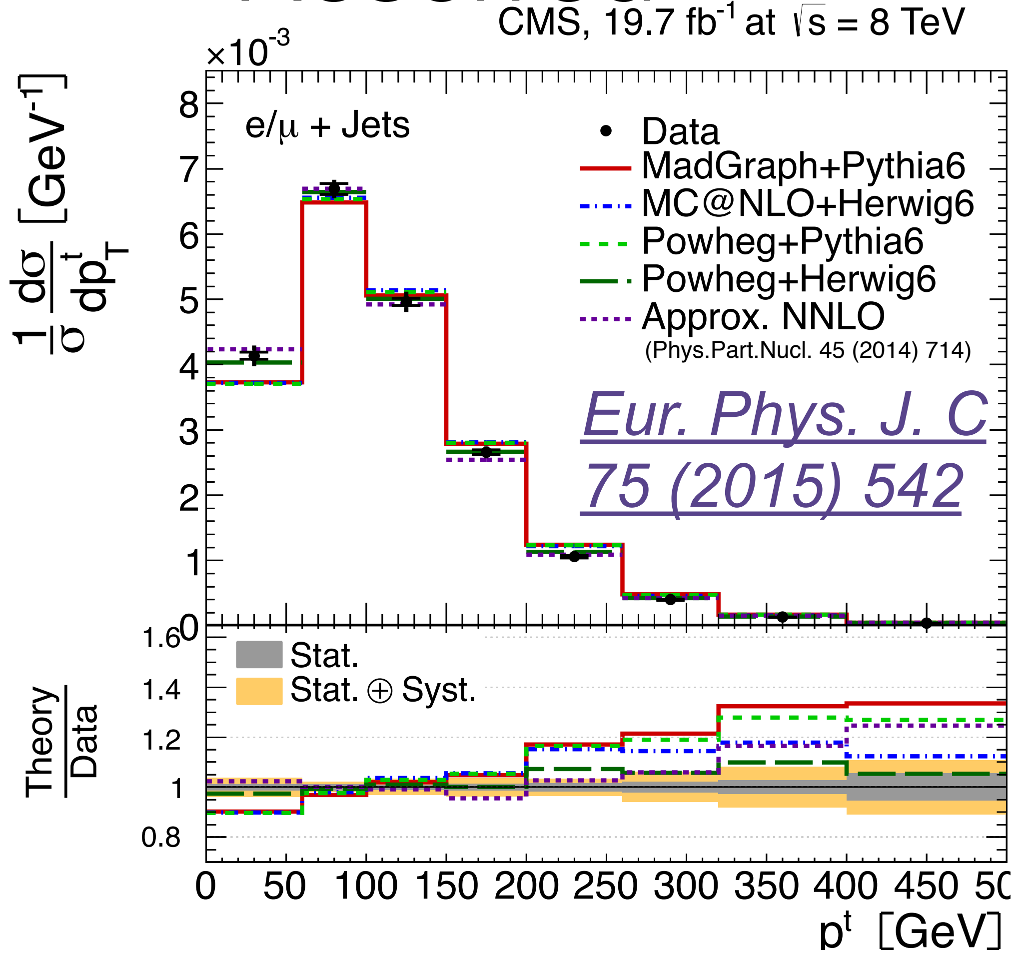
"Resolved" **Results** Boosted

Parton

$\sqrt{s}$ =8 TeV

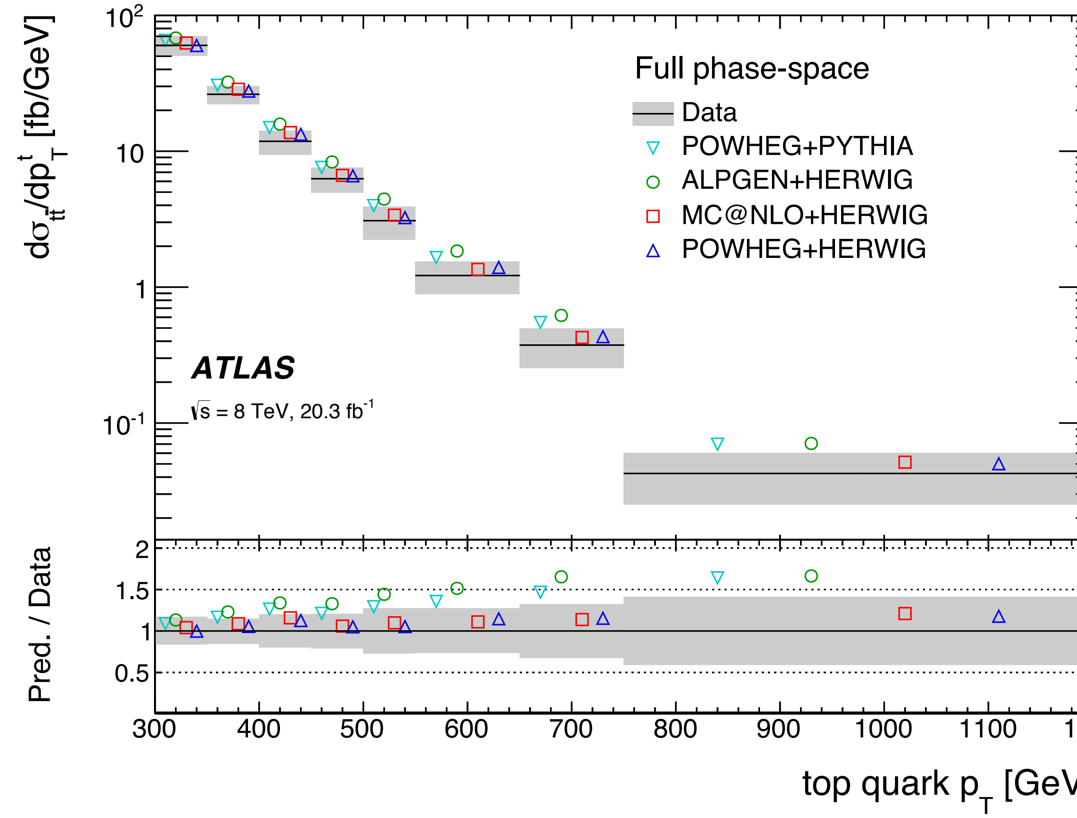
- **$d\sigma/dp_T$(data) < $d\sigma/dp_T$ (NLO predictions)** effect enhanced in boosted regime
- MC hierarchy qualitatively similar

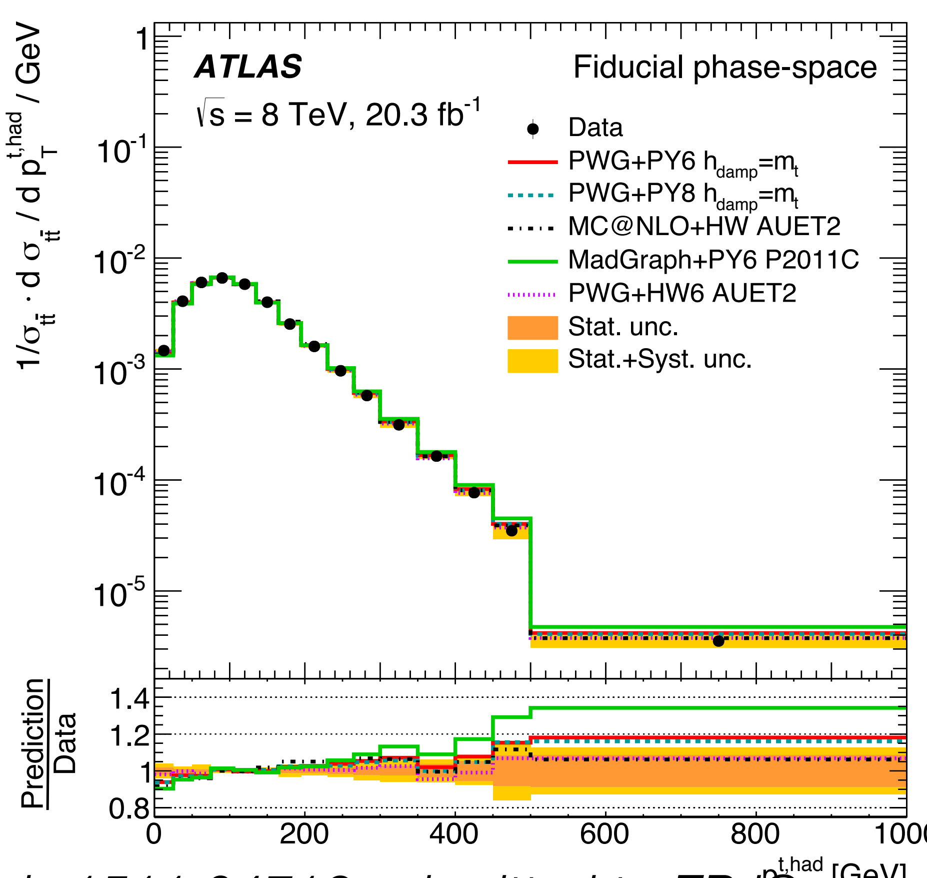
Particle



Eur. Phys. J. C 75 (2015) 542

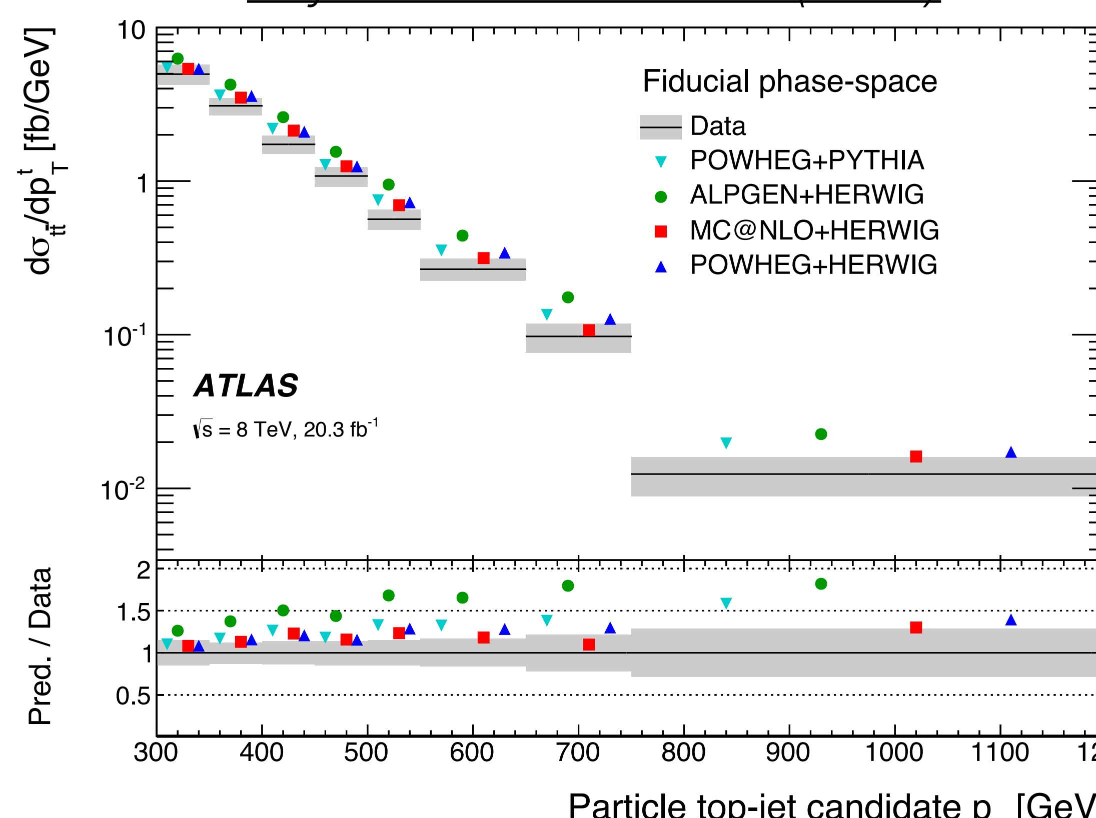
Phys Rev D 93 032009 (2016)





arxiv:1511.04716 submitted to EPJC

Phys Rev D 93 032009 (2016)



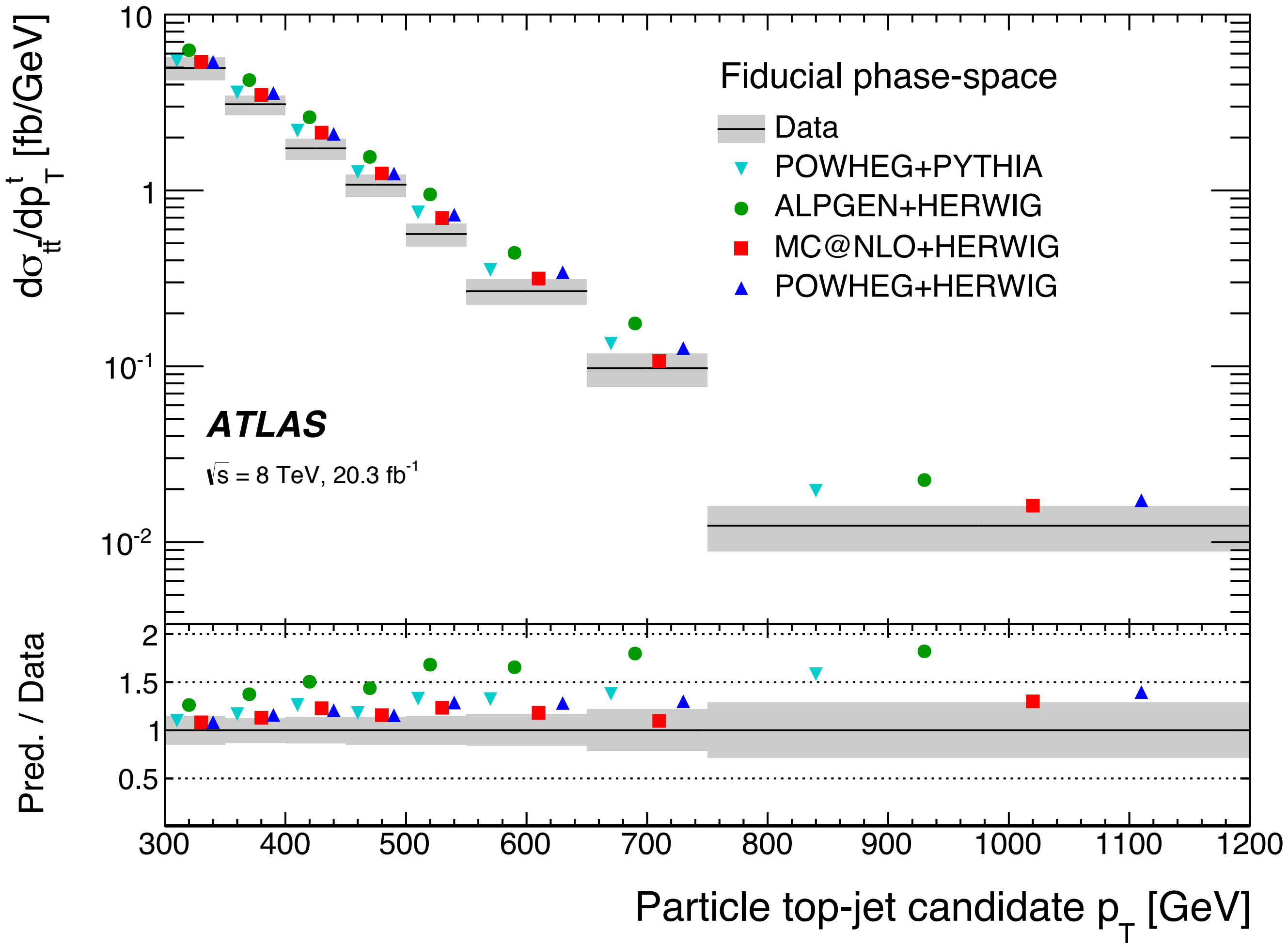
Quantitative assessment of “**boosted**” **dσ_{tt}/d$p_{T,top}$**

Phys Rev D 93 032009 (2016)

TABLE III. Correlation matrix between the bins of the particle-level differential cross-section as a function of $p_{T,ptcl}$.

$p_{T,ptcl}$ [GeV]	300–350	350–400	400–450	450–500	500–550	550–650	650-750	750-1200
300–350	1.00	0.83	0.79	0.79	0.72	0.63	0.58	0.51
350–400	0.83	1.00	0.83	0.80	0.76	0.74	0.67	0.60
400–450	0.79	0.83	1.00	0.87	0.79	0.78	0.77	0.63
450–500	0.79	0.80	0.87	1.00	0.89	0.76	0.77	0.66
500–550	0.72	0.76	0.79	0.89	1.00	0.84	0.75	0.62
550–650	0.63	0.74	0.78	0.76	0.84	1.00	0.89	0.71
650–750	0.58	0.67	0.77	0.77	0.75	0.89	1.00	0.87
750–1200	0.51	0.60	0.63	0.66	0.62	0.71	0.87	1.00

Quantitative assessment of "boosted" $d\sigma_{tt}/dp_{T,top}$



Phys Rev D 93 032009 (2016)

vector of (dσ/dX (i)[meas] - dσ/dX (i)[predicetd])

$$\chi^2 = V^T \cdot \mathrm{Cov}^{-1} \cdot V,$$

Cov is the full estimate of the covariance matrix (syst+stat)

χ^2 Table for particle level results vs MC predictions

MC generator	PDF	χ^2	p-value
POWHEG+PYTHIA $h_{damp} = m_{top}$ + Electroweak corr.	CT10	9.8	0.28
POWHEG+PYTHIA $h_{damp} = m_{top}$	CT10	13.0	0.11
POWHEG+PYTHIA $h_{damp} = \infty$	CT10	15.6	0.05
POWHEG+PYTHIA $h_{damp} = m_{top}$	HERAPDF	9.4	0.31
POWHEG+PYTHIA $h_{damp} = \infty$	HERAPDF	10.9	0.21
POWHEG+HERWIG	CT10	8.2	0.41
MC@NLO+HERWIG	CT10	12.3	0.14
ALPGEN+HERWIG	CTEQ6	33.1	$5.9 \cdot 10^{-5}$

Significant discrepancy

Table 6: Values of χ^2 and a p-value, computed for 8 degrees of freedom, obtained from the covariance matrix of the measured cross-section for various predictions. Electroweak corrections are applied only to the first prediction.

Measurement of $1/\sigma_{tt}\, d\sigma_{tt}/dX$ @$\sqrt{s}$ = 8 TeV

example χ^2 Table : particle level results vs MCs

ATLAS EXPERIMENT

Resolved

arxiv:1511.04716 submitted to EPJC

Variable	PWG+PY8 CT10 $h_{damp} = m_t$ χ^2/NDF	p-value	MC@NLO+HW CT10 AUET2 χ^2/NDF	p-value	PWG+PY6 CT10 $h_{damp} = m_t$ χ^2/NDF	p-value	PWG+HW6 CT10 $h_{damp} = \infty$ χ^2/NDF	p-value	MadGraph+PY6 MadGraph+PY6 P2011C χ^2/NDF	p-value
p_T^t	11/14	0.72	25/14	0.04	12/14	0.59	3.1/14	1.00	35/14	<0.01
R_{Wt}	20/11	0.05	24/11	0.01	25/11	0.01	4.2/11	0.96	60/11	<0.01
$\chi^{t\bar{t}}$	27/9	<0.01	40/9	<0.01	24/9	<0.01	58/9	<0.01	240/9	<0.01
$\lvert y^{t\bar{t}}\rvert$	110/17	<0.01	77/17	<0.01	100/17	<0.01	110/17	<0.01	210/17	<0.01
$m^{t\bar{t}}$	7.9/10	0.64	4.6/10	0.92	3.8/10	0.95	6.7/10	0.75	21/10	0.02
$y_{boost}^{t\bar{t}}$	83/15	<0.01	56/15	<0.01	76/15	<0.01	80/15	<0.01	160/15	<0.01
$\lvert p_{out}^{t\bar{t}}\rvert$	2.4/5	0.79	9.0/5	0.11	8.8/5	0.12	11/5	0.05	3.3/5	0.66
$\lvert y^t\rvert$	22/17	0.18	11/17	0.88	20/17	0.27	15/17	0.60	13/17	0.72
$p_T^{t\bar{t}}$	1.3/5	0.93	2.6/5	0.75	3.1/5	0.68	4.2/5	0.52	2.9/5	0.71
$H_T^{t\bar{t}}$	8.2/14	0.88	12/14	0.59	13/14	0.52	2.3/14	1.00	38/14	<0.01
$\Delta\phi^{t\bar{t}}$	0.8/3	0.84	24/3	<0.01	5.0/3	0.17	17/3	<0.01	19/3	<0.01

Table 3: Comparison between the measured fiducial phase-space normalized differential cross-sections and the predictions from several MC generators. For each variable and prediction a χ^2 and a p-value are calculated using the covariance matrix of each measured spectrum. The number of degrees of freedom (NDF) is equal to $N_b - 1$ where N_b is the number of bins in the distribution.

individual top variables *kinematic tt variables* *tt system variables*

$$\chi^2 = V_{N_b-1}^T \cdot \mathrm{Cov}_{N_b-1}^{-1} \cdot V_{N_b-1},$$

vector of ($d\sigma/dX$ (i)^{meas} - $d\sigma/dX$ (i)^{predicetd})

N_b= number of bins

Cov is the full estimate of the covariance matrix (syst+stat)

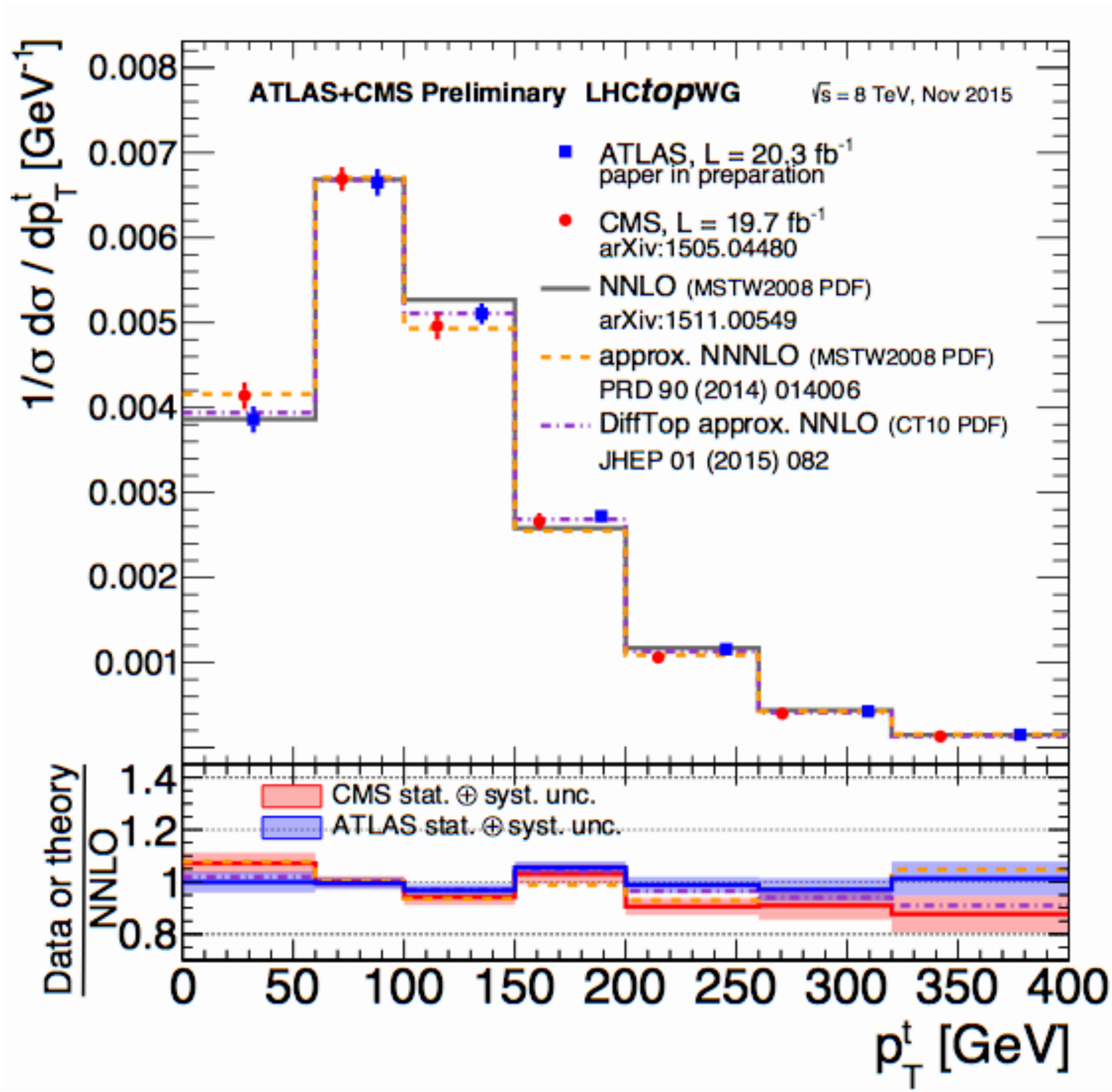
ATLAS vs CMS *vs Theory (I)* :$1/\sigma_{tt}\, d\sigma_{tt}/dp_{T,top}$ @ $\sqrt{s}$ = 8 TeV

parton level

ATLAS & CMS
Public summary plots

- **ATLAS & CMS measurements are generally consistent with each other and all predictions**
  - CMS shows slight slope

Qualitative statement, no statistical test performed yet



Latest differential: $d\sigma_{tt}/dN_{jets}$ @ $\sqrt{s}$ = 13 TeV

Global event description I

ATLAS-CONF-2015-065

NEW PAS-TOP-16-011

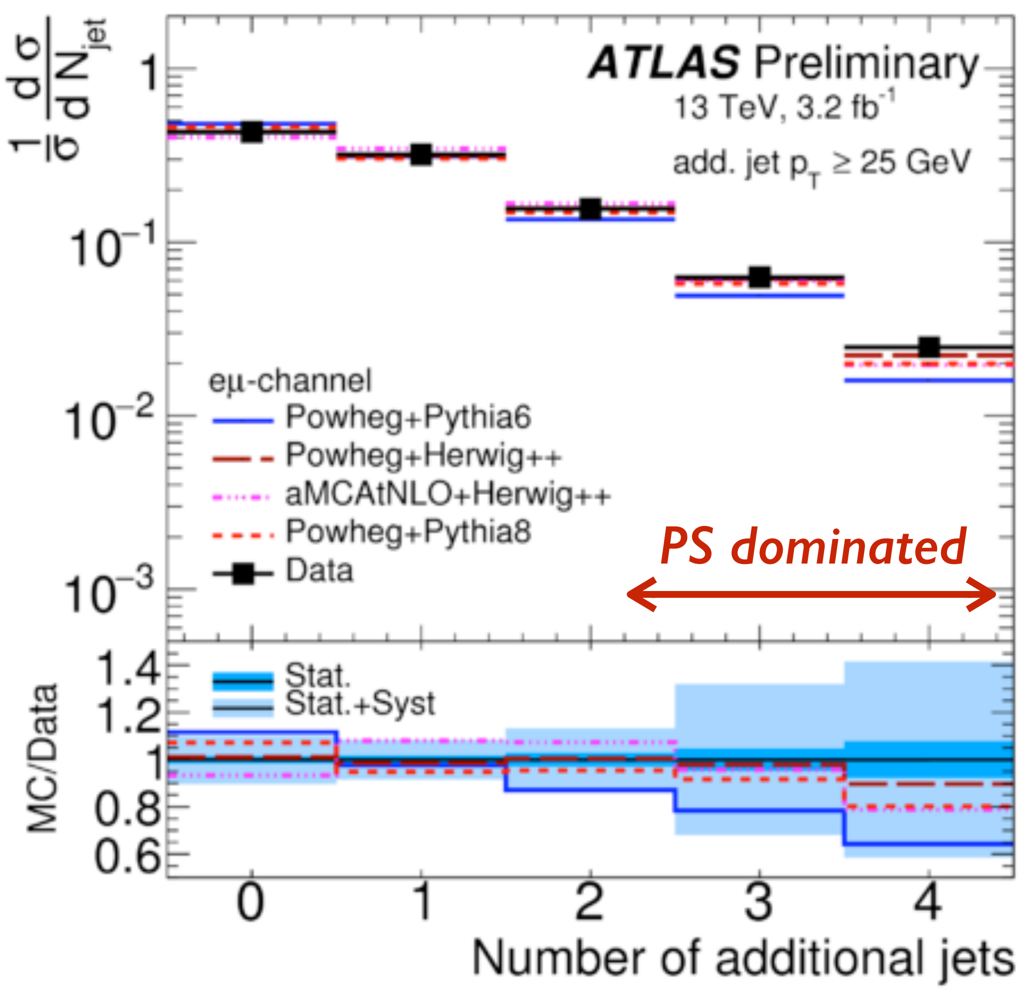
16

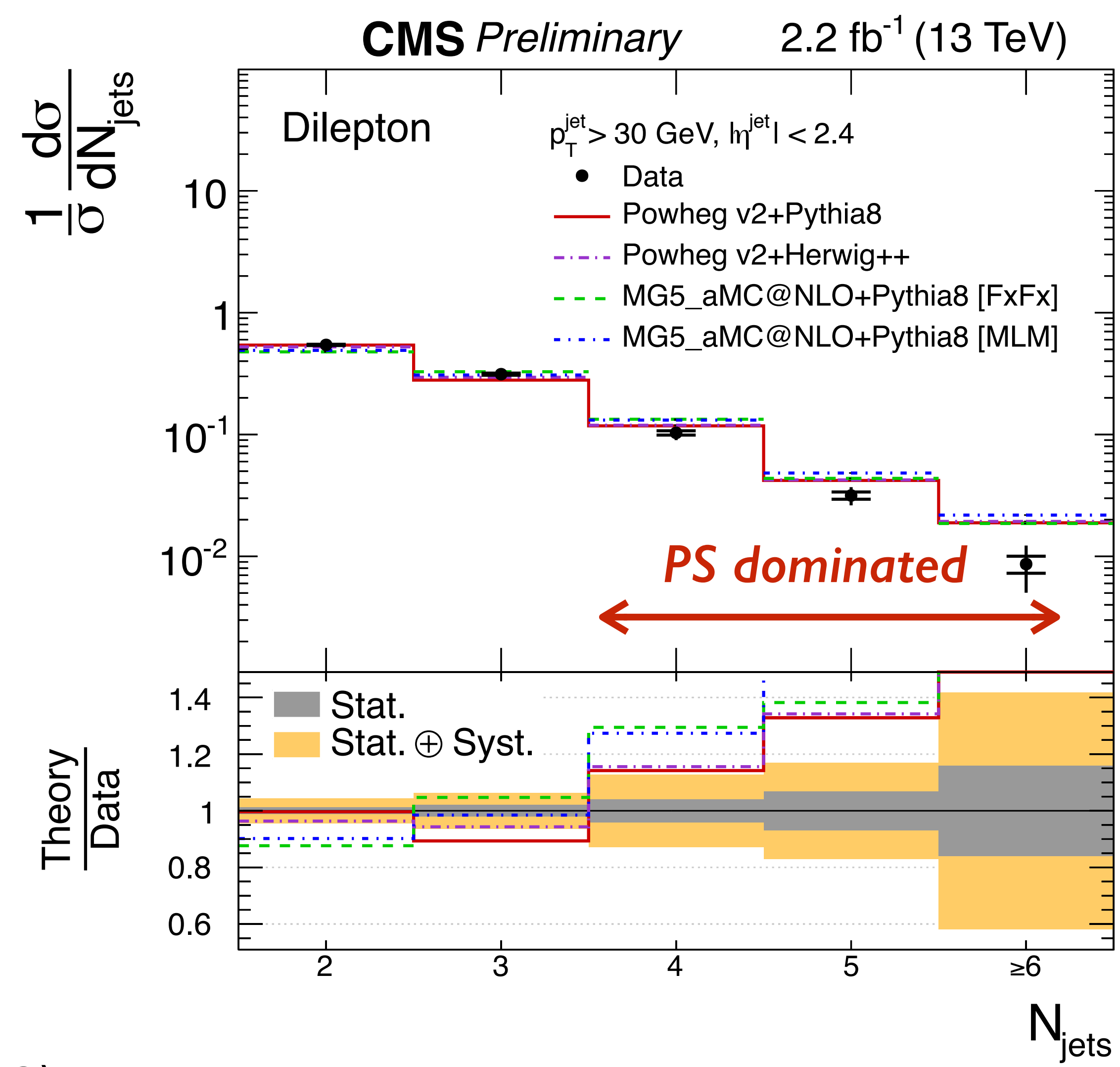
- **Extra jet emissions are mostly regulated by the Parton Shower generators**
  - sensitive to matching to matrix-element generators and to shower model
  - predictions from modern generators in agreement with each other within <15%
  - however in extreme regions observe discrepancies which need to be tuned further

PAS-TOP-16-011

Dilepton channel

tt+jets is dominant bkg to tt+Higgs & new phys





(Pedro Ferreira da Silva @ Moriond 2016)

Latest differential: $1/\sigma_{tt}\ d\sigma_{tt}/dp_{T,top}$ @ $\sqrt{s}$ = 13 TeV

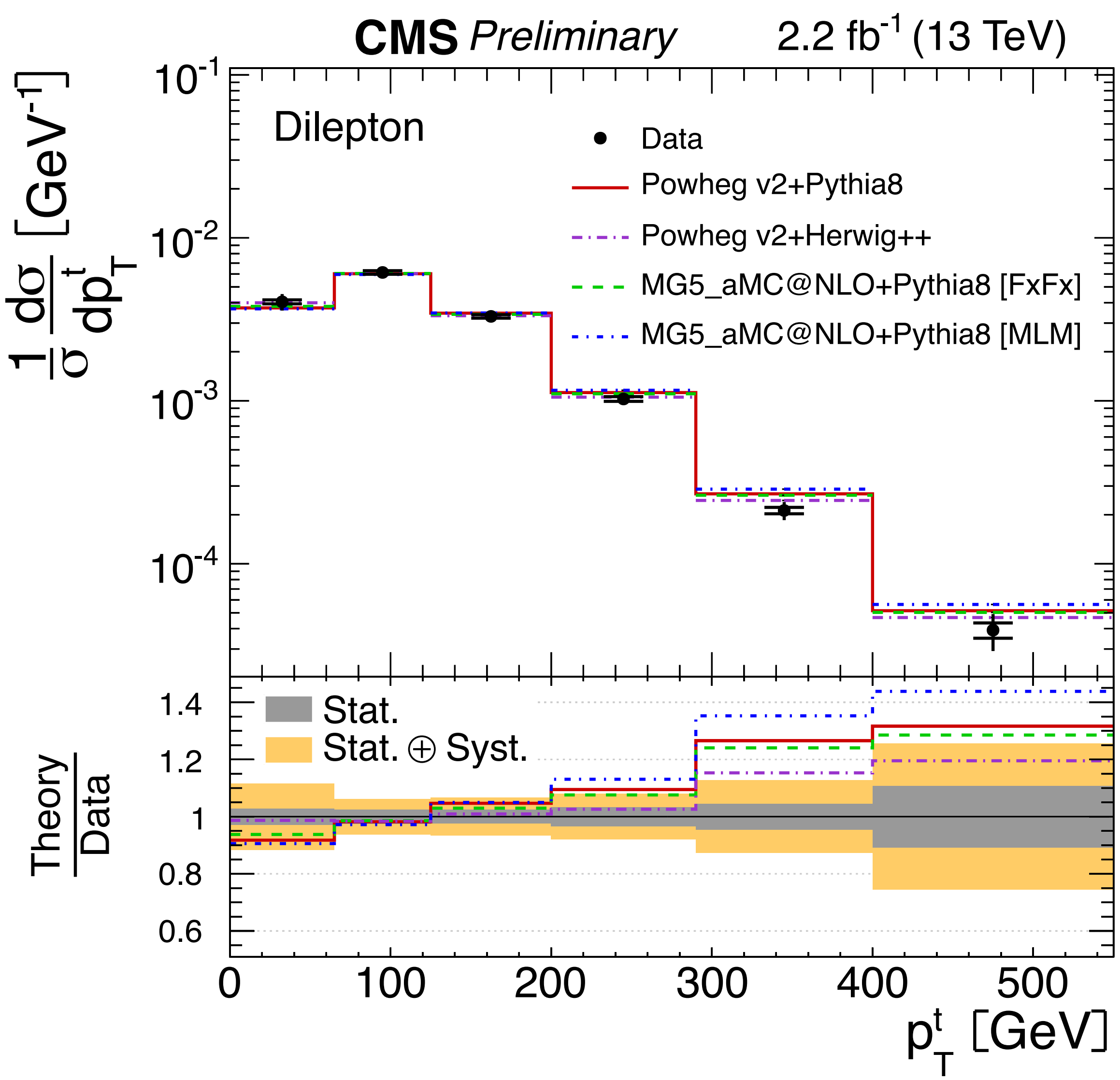
- dilepton selection: 2 OS **lep (e^+e^-,$\mu^+\mu^-$,$e^\pm\mu^\mp$),≥ 2 jets, ≥1 b-tag**
  - bkg: **data-driven Z+jets,** (tW), diboson, tt+V **fake leptons***(from simul.)*
- Subtract bkg, unfold *(regularized) to parton level* & derive $1/\sigma_{tt}\ d\sigma_{tt}/dp_{T,top}$
- Combine results of different channels

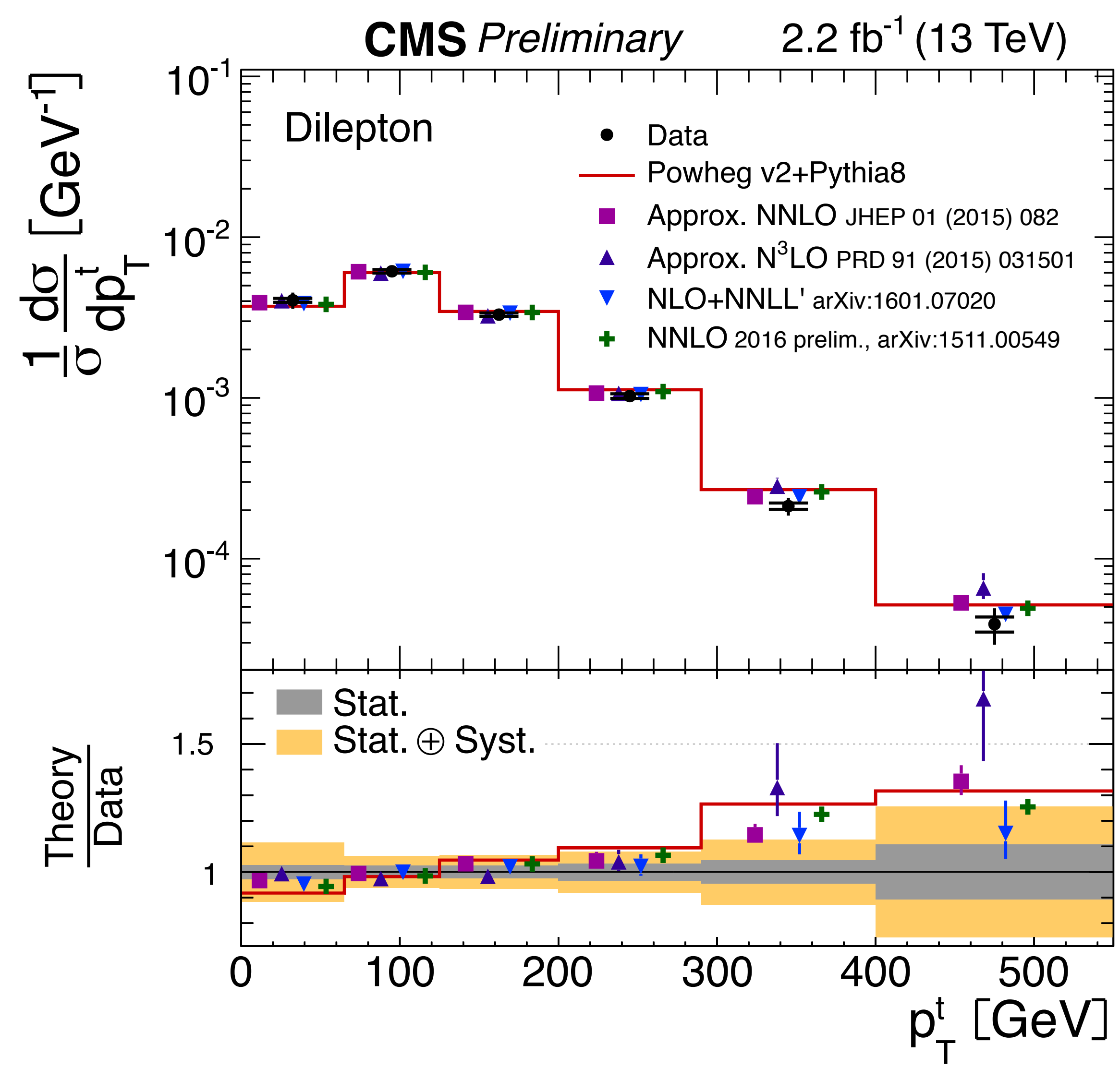
$d\sigma/dp_T$(data)

- **< $d\sigma/dp_T$ (MC predictions),** similar to 7 & 8 TeV
- best description by POWHEG+HW+

qualitative

- ***reasonably described by all fixed order calculations***





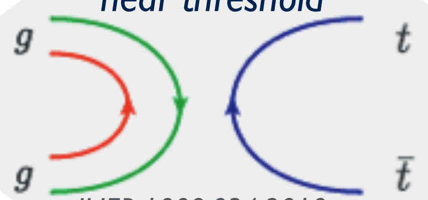
Latest differential: $d\sigma_{tt}/dm_{tt}$ @ $\sqrt{s}$ = 13 TeV (I)

dilepton selection

Towards probing precisely the measured tt invariant mass

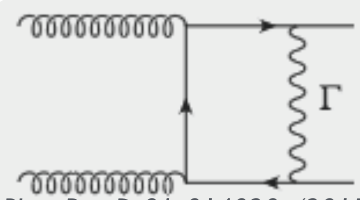
NEW PAS-TOP-16-011 18

Test QCD production modes near threshold



JHEP 1009:034,2010

Test EW corrections (Z,γ,H)

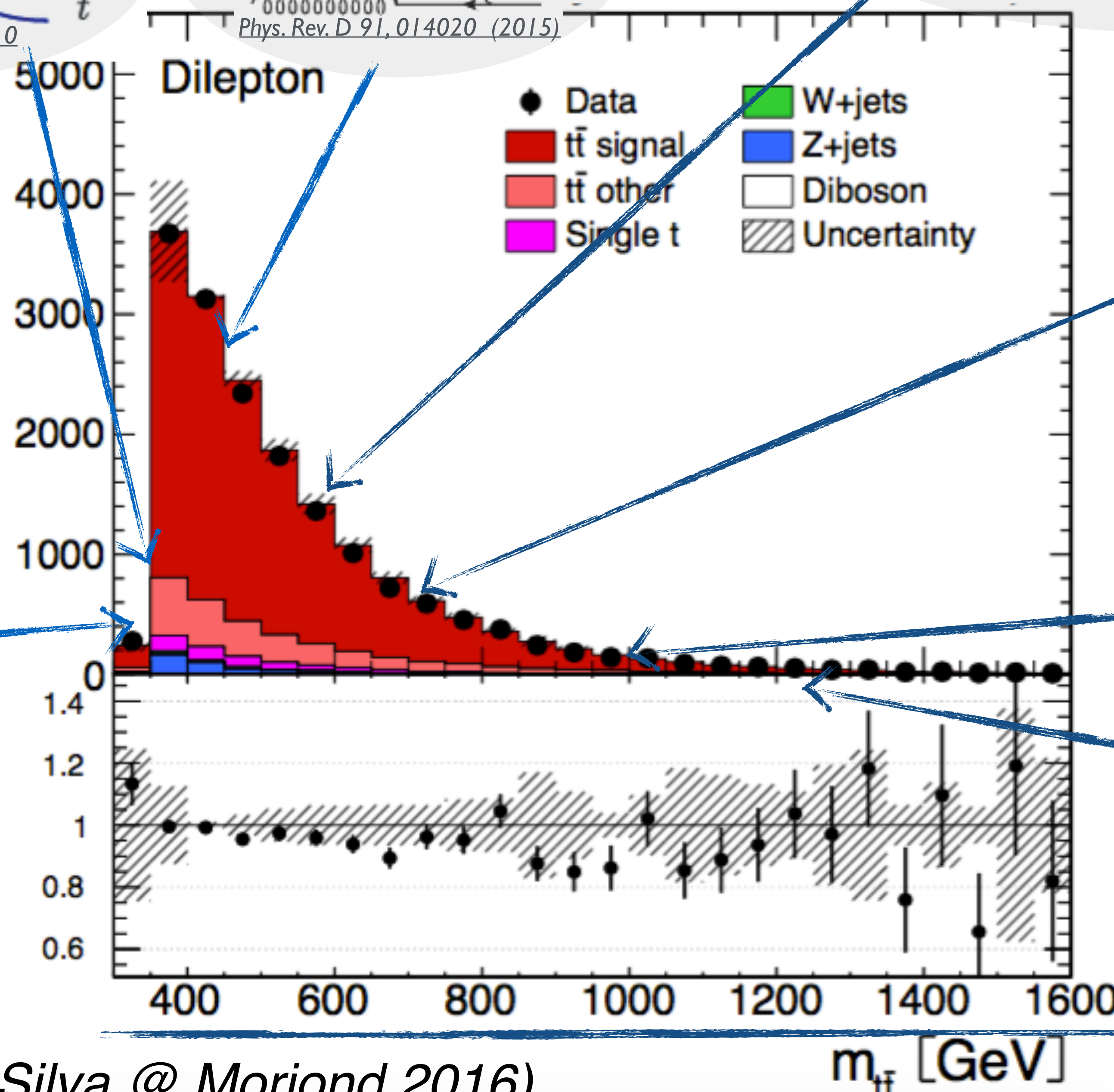


Phys. Rev. D 91, 014020 (2015)

Rate/shape reproduced within uncertainties

Elusive signs of new physics

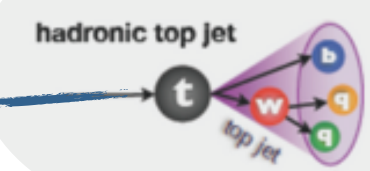
PRD 90, 014008 (2014) 10.1007/JHEP01(2015)092



Bump hunting

X→tt

Entering the boosted regime



Pole mass scan?

$$\frac{\Delta m_t}{m_t} \sim 1.2 \cdot \frac{\Delta < m_{t\bar{t}} >}{< m_{t\bar{t}} >}$$

JHEP 0901:047,2009

PDFs, α_S at high x

Top mass running?

$$m_t = m_t(\mu)$$

(Pedro Ferreira da Silva @ Moriond 2016)

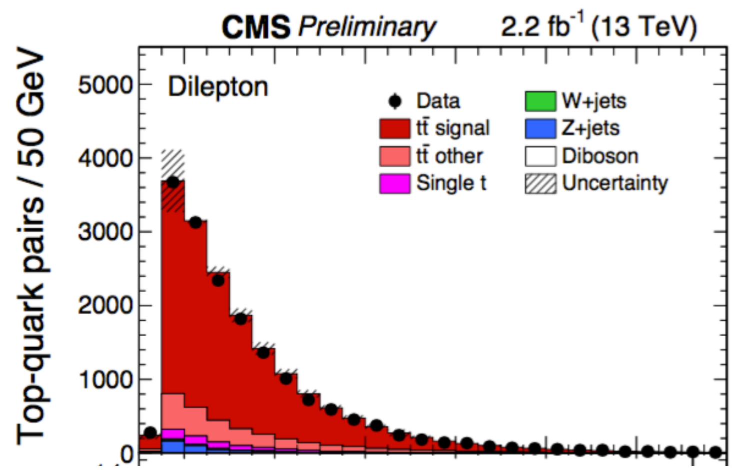
Latest differential: $d\sigma_{tt}/dm_{tt}$ @ $\sqrt{s}$ = 13 TeV (I)

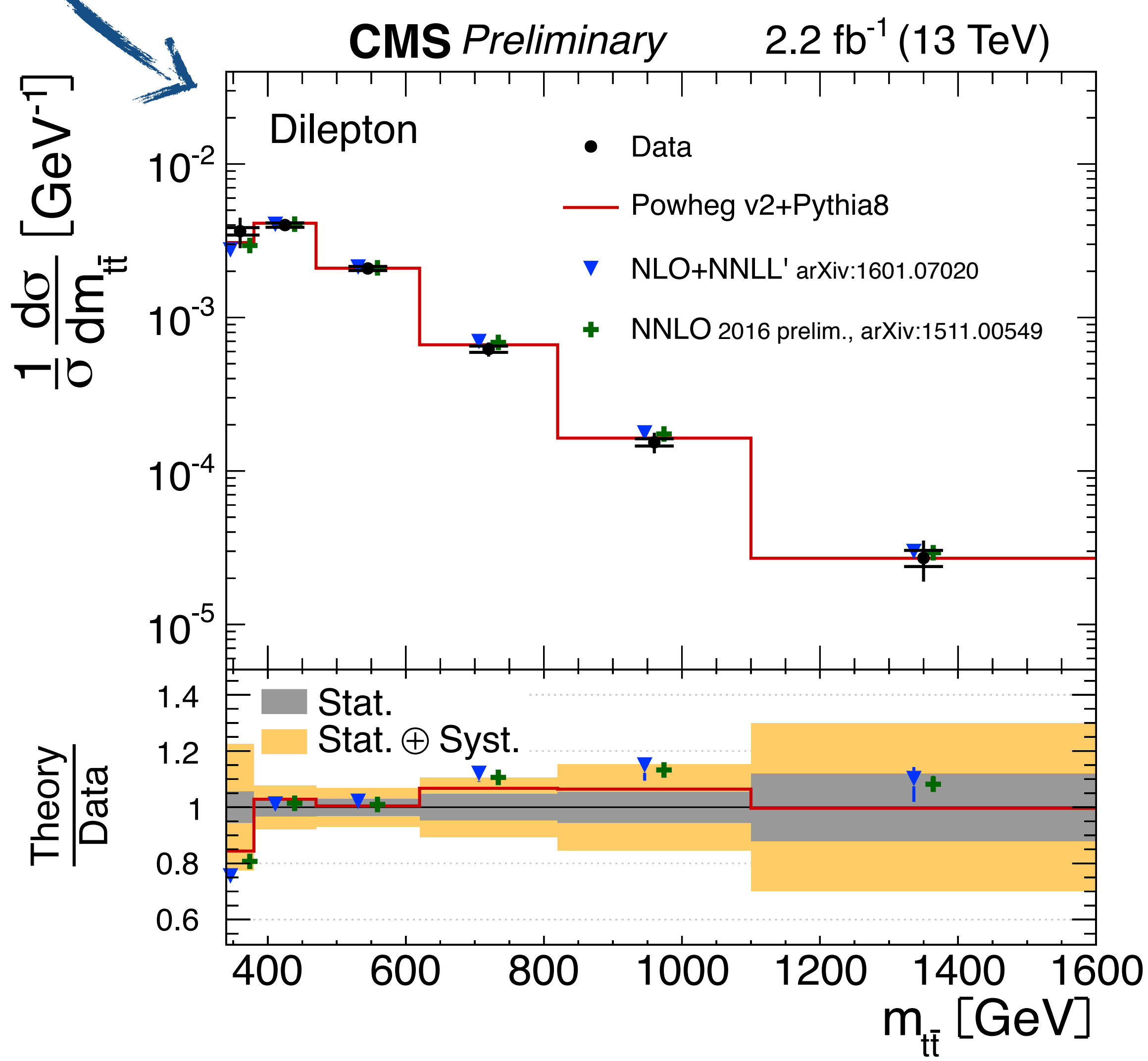
Probing the measured tt invariant mass

dilepton selection

NEW PAS-TOP-16-011 19

Give my interpretation???





Rate/shape reproduced within uncertainties

- **Precise measurements** of M(tt) and others **depends crucially on the understanding of ME+PS-based predictions**
- Current uncertainty at the level of 5-20%
  - ambiguity in data shape corrections
  - dominated by different MC models
- **Largest contributions** from choice of
  - hadronizer (Pythia8 vs Herwig++)
  - NLO generator (aMC@NLO vs Powheg)

⇒ complement with alternative measurements to constrain PS related uncertainties (e.g. underlying event, jet activity, etc.)

- Experimentally jet energy scale unc. dominant

(Pedro Ferreira da Silva @ Moriond 2016)

$t\bar{t}$ & t cross section prospects for 13 TeV

- Increase in luminosity & cross section will enhance signal, backgrounds, possibly better S/B; even though samples are already extremely pure
- More **particle level** vs parton level **measurements**
- **More differential cross section measurements**
  - test uncharted territory (high N_{jets} , high p_T), top p_T crucial for searches
  - **focused syst studies as above in each diffxsec bin interplay with bin and unfolding optimization**
  - **enhance selection efficiency in more boosted configurations by tagging high transverse momentum massive objects**
- Combinations will improve uncertainty by including uncorrelated uncertainties
- Measurements are dominated by systematic uncertainties 2 strategies
  - **Reduce syst uncertainties by measuring differential distributions that are sensitive to alternative models tune ambiguities, discard un-tunable models**
    - ❖ generator modelling: crucial harmonization in LHC to achieve combined result
    - ❖ ISR/FSR
    - ❖ Fragmentation: tune simulation/hadronization models
    - ❖ improve PDF measurements particularly high x gluons and feed-it back
  - **De-sensitize analysis to sys uncertainty: use ingenuity and intuition to develop new cuts, reconstructions schemes**

Measurement of top quark mass, m_t

i.e.

the defining property

The Top mass (I)

Phys.Rept. 504 (2011) 145-233

- Remember the SM Lagrangian $m_t = y_t v/\sqrt{2}$

$$L_{Higgs,fermions} = \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \rightarrow L_{top} = m_t t_L t_R/\sqrt{2} + y_t H t_L t_R/\sqrt{2}$$

provides CKM matrix — mass term — interaction term

- At LO, $m=m_{bare}$ in SM Lagrangian, **beyond LO m_{top} depends on renormalization scheme**

- **Rapidity of convergence in perturbative regime depends on renormalization scheme** (even if results don't)
- QCD is only asymptotically convergent : scheme should be acceptable in non pert regime too + no infinite order in perturbative regime

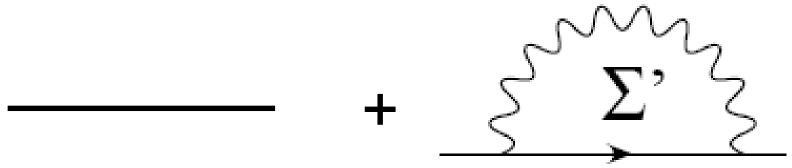
Typical renormalization schemes

- **Long distance** scheme ~ **Pole mass**: real part of pole position in complex momentum space; imagine taking free particle to infinity, and measuring mass (impossible for QCD, top is coloured and confined); closer to collider measurement
- **Short distance** ~ **Minimal Subtraction (MS):** subtract the divergent term of corrections + universal constant; do not touch finite part.
- Mass difference between any two schemes is calculable as perturbative series in α_s

$$m_{pole} = \overline{m}(\overline{m})\left(1 + \frac{4}{3}\frac{\overline{\alpha}_s(\overline{m})}{\pi} + 8.28\left(\frac{\overline{\alpha}_s(\overline{m})}{\pi}\right)^2 + \cdots\right) + O(\Lambda_{QCD})$$

- *Difference involves integral of alpha_s over a region where it becomes large so the series does not converge : the ambiguity is of order Λ_{QCD}*

essential clues



$$= p - m^0 - \Sigma(p, m^0, \mu)$$

$$\Sigma(m^0, m^0, \mu) = m^0 \left[\frac{\alpha_s}{\pi\epsilon} + \ldots \right] + \Sigma^{\rm fin}(m^0, m^0, \mu)$$

$\overline{\text{MS}}$ scheme:

$$m^0 = \overline{m}(\mu) \left[1 - \frac{\alpha_s}{\pi\epsilon} + \ldots \right]$$

→ $\overline{m}(\mu)$ is pure UV-object without IR-sensitivity

→ Useful scheme for $\mu > m$

→ Far away from a kinematic mass of the quark

A. Hoang (TOPLHCWG, Jan 2015)

Pole scheme:

$$m^0 = m^{\rm pole} \left[1 - \frac{\alpha_s}{\pi\epsilon} + \ldots \right] - \Sigma^{\rm fin}(m^{\rm pole}, m^{\rm pole}, \mu)$$

→ Absorbes all self energy corrections into the mass parameter

→ Close to the notion of the quark rest mass (kinematic mass)

→ Renormalon problem: infrared-sensitive contributions from < 1 GeV that cancel between self-energy and all other diagrams cannot cancel.

→ Has perturbative instabilities due to sensitivity to momenta < 1 GeV (Λ_{QCD})

Should not be used if uncertainties are below 1 GeV !

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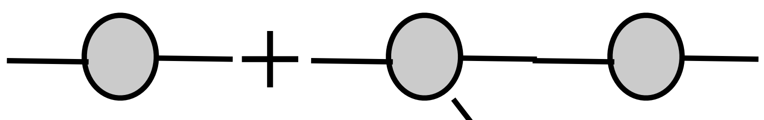
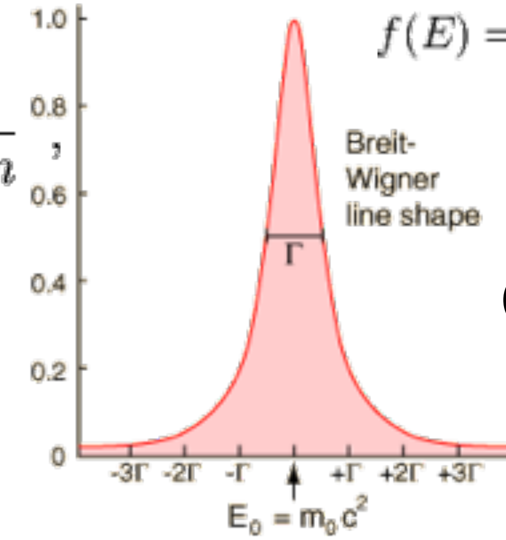
TOP LHC WG, Jan 12 - 13, 2015

What is top mass and how is it measured? the Pole

propagator to amplitude: higher order corrections

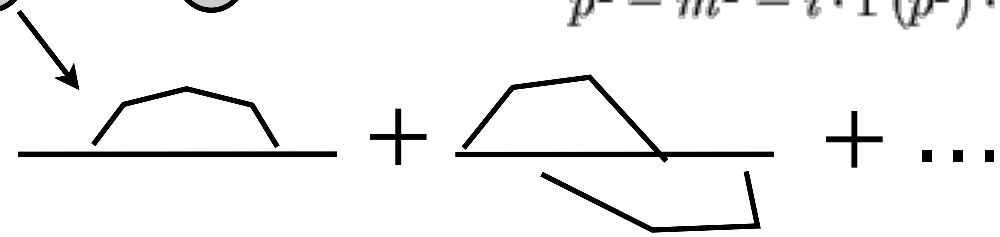
$$\frac{1}{p^2 - m^2} \cdot$$  $$+ \cdots = \frac{1}{p^2 - m^2 - i \cdot \Gamma(p^2) \cdot m},$$



$$f(E) = \frac{k}{(E^2 - M^2)^2 + M^2\Gamma^2}.$$

⊗ Detector

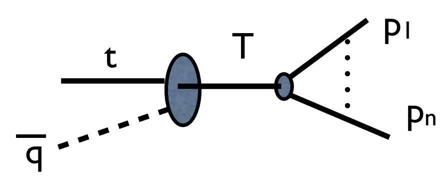
1 part irreducible: cannot be split in two by removing a single line



Definition

Definition of m_{top} from top decays

If Γ_{top} were < 1 GeV, top would hadronize before decaying. Same as b-quark

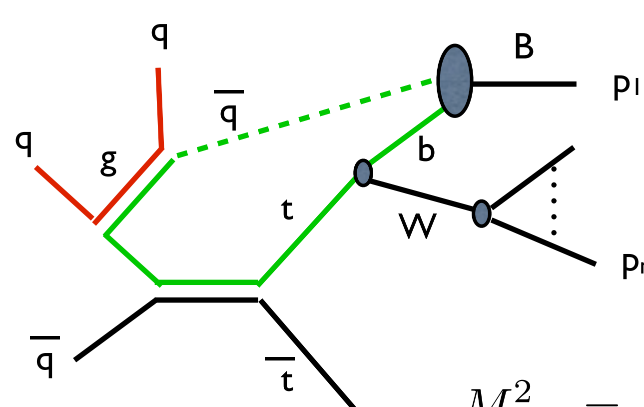


$$m_T^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

m_t = $F_{lattice/potential\ models}$ (m_T, α_{QCD})

essential clues

But Γ_{top} is > 1 GeV, top decays before hadronizing. Extra antiquarks must be added to the top-quark decay final state in order to produce the physical state whose mass will be measured



$$M_{exp}^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

As a result, M_{exp} is not equal to m^{pole}_{top}, and will vary in each event, depending on the way the event has evolved.

The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_{top})$~ 1 GeV

Goal:
- correctly quantify the systematic uncertainty
- identify observables that allow to validate the theoretical modeling of hadronization in top decays
- identify observables less sensitive to these effects

- The parameter of the Breit-Wigner for a resonance : **property of a distribution.**

(M. Mangano, TOP2013)

Theory tools to measure the MC mass

essential clues

1)

A. Hoang (TOPLHCWG, Jan 2015)

The relation between MC mass and field theoretical mass can be made more precise by measuring the MC mass using a completely independent hadron level QCD prediction of a mass-dependent observable.

Need:

- Accurate analytic QCD predictions beyond LL/LO with full control over the quark mass dependence
- Theoretical description at the hadron level for comparison with MC at the hadron level

di-jet events

Start work on b-hadron mass as a test case

Observable: Thust in e+e-

$$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{n} \cdot \vec{p}_i|}{Q}$$

$$\stackrel{\tau \to 0}{\approx} \frac{M_1^2 + M_2^2}{Q^2}$$

SUMMARIZE

Compare MC with SCET (pQCD, summation, hadronization effects) @ NNLL for Thrust

2)

G Corcella http://arxiv.org/pdf/1409.8592.pdf

- For quark making hadrons well defined calculation exists to obtain pole or MS mass
- Force MC to generate a fictitious T hadron
- relate T mass to standard top decays

Theory tools to measure the MC mass : latest

essential clues

A. Hoang @ Moriond 2016

Conclusions & Outlook

- First serious precise MC top quark mass calibration based on e^+e^- 2-jettiness: preliminary results.
- NNLL+NLO QCD calculations based on an extension of the SCET approach concerning massive quark effects (all large logs incl. Ln(m)'s summed systematically).
- The Monte Carlo top mass calibration in terms of MSR mass with perturbative error O(500 MeV) appears feasible at NNLL+NLO
- Intrinsic MC error seems O(100 MeV).

Outlook:

- Full verified error analysis @ NNLL+NLO on the way
- Calibration for other MC generators
- Heavy jet mass, C-parameter (NNLL), pp-2 jettiness analysis (NLL) w.i.p.
- NNNLL+NNLO (2jettiness) w.i.p
- Mass (+ Yukawa coupling) conversions w. QCD + electroweak

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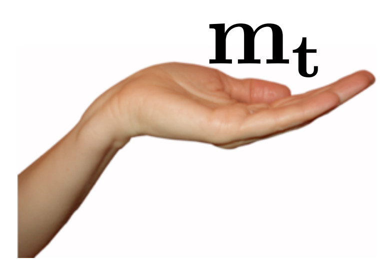
51st Recontre de Moriond, EW Session, La Thuile, March 12-19, 2016

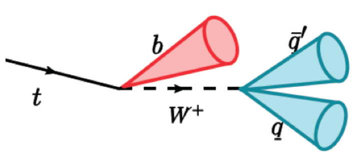
Extraction of the top mass:



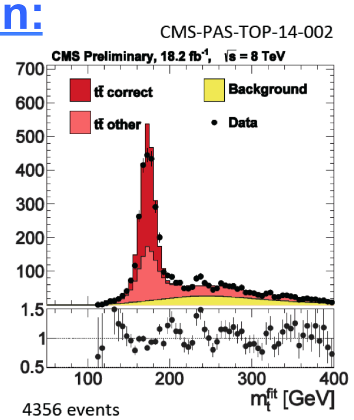
André H. Hoang's proposal:

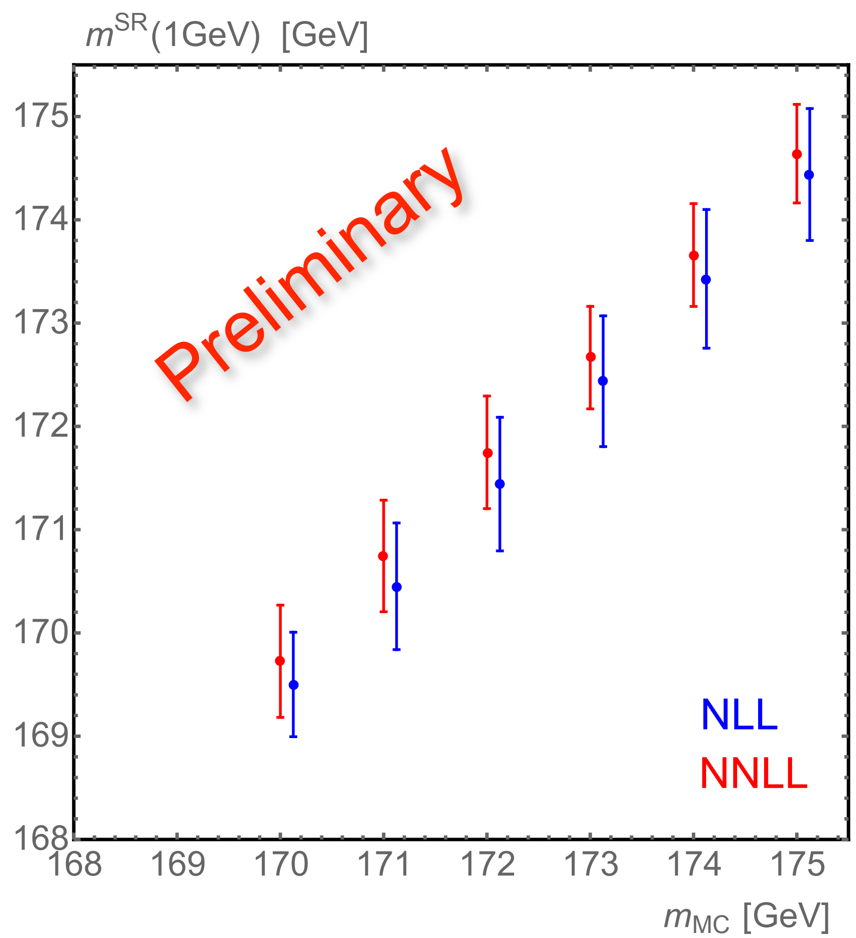
LHC+Tevatron

Direct Reconstruction:



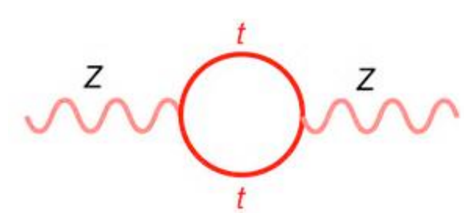
kinematic mass determination





error O(500 MeV)

useful for precision tests of the SM!



(G. Cortiana's CERN seminar, 2nd July 2013)

Higgs potential stability

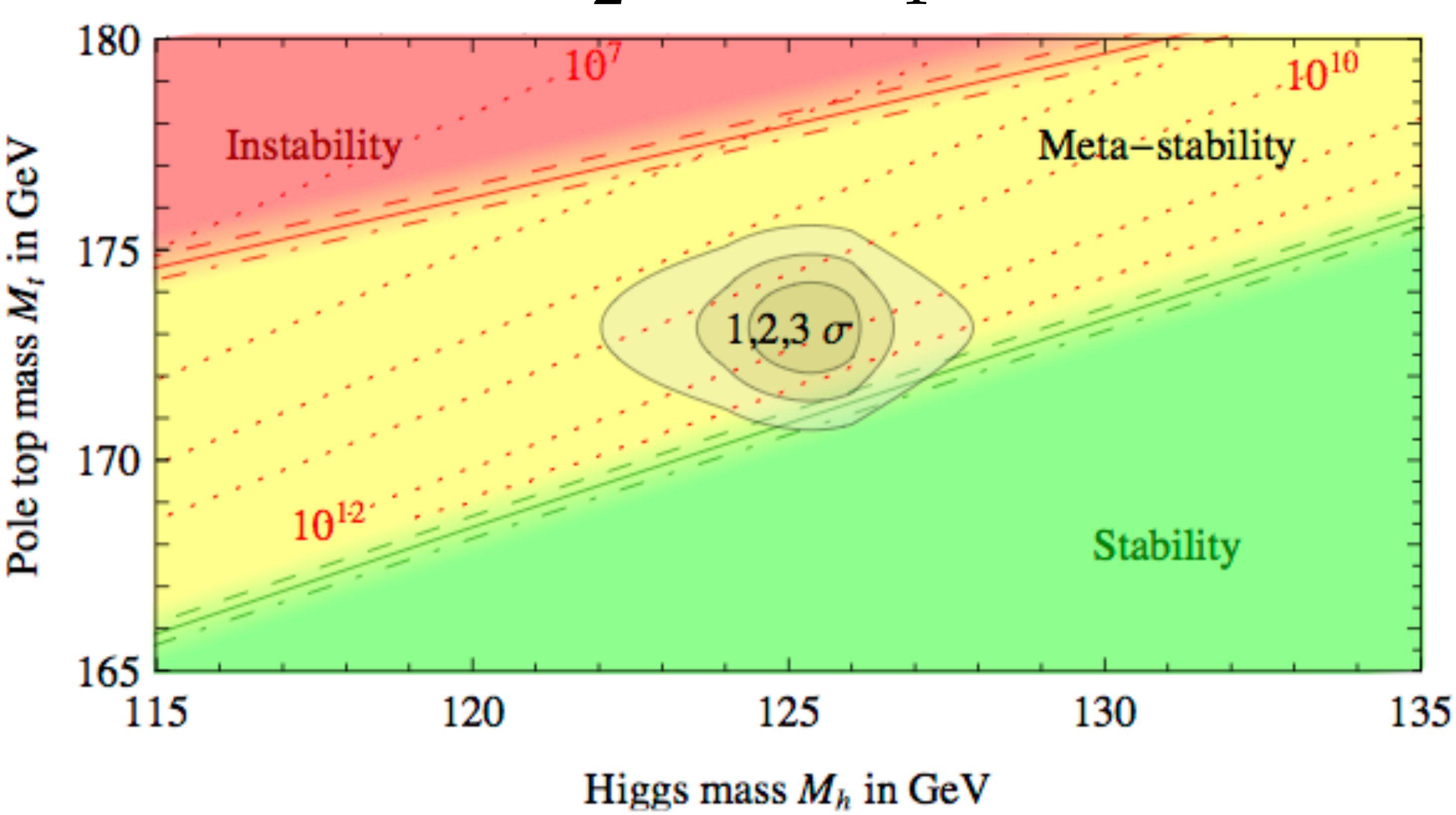
IF SM is valid up to the Planck scale

- The current experimental values of m_H and m_{top} are very intriguing from the theoretical point of view:
  - the Higgs quartic coupling could be rather small, vanish or even turn negative at a scale slightly smaller than the Planck scale.
  - if λ(μ)>0

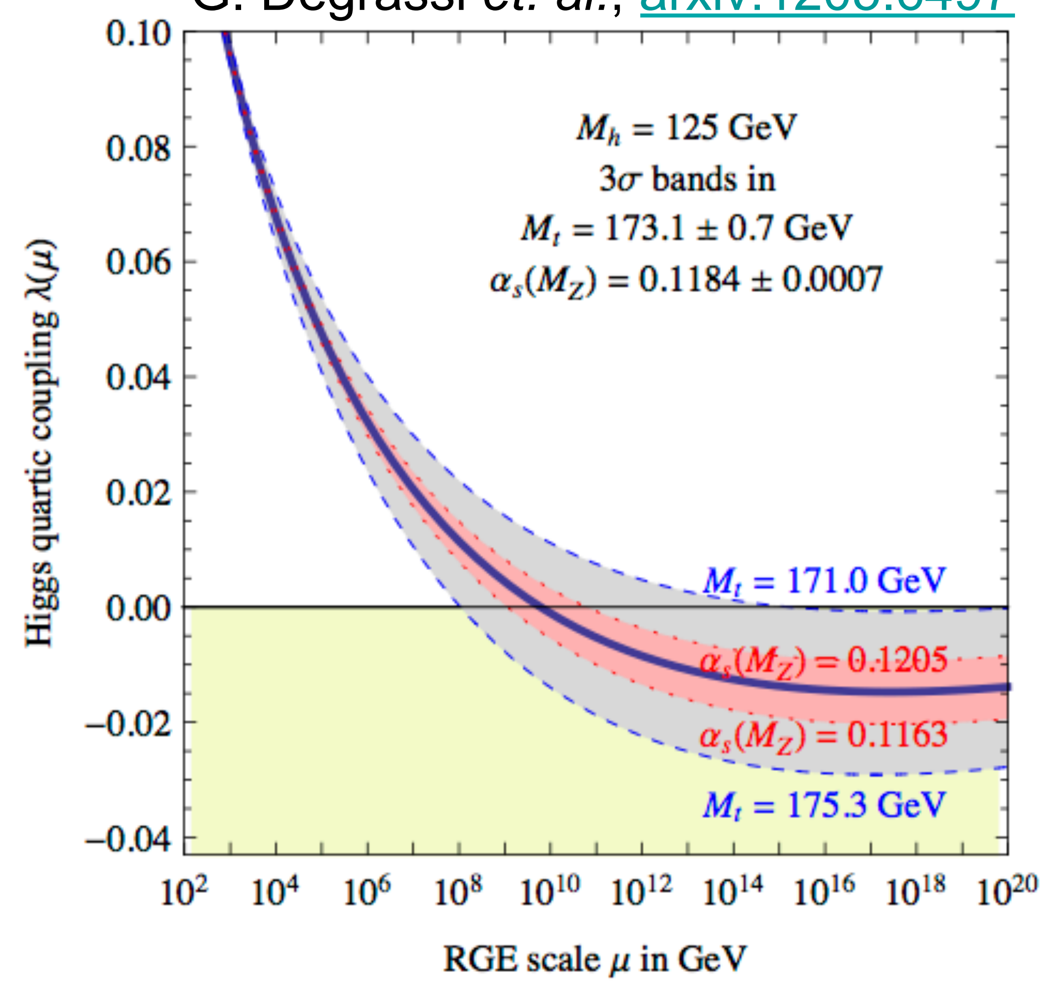
    the electroweak vacuum is a global minimum
  - if λ(μ) <0

    the electroweak vacuum becomes metastable (does not become unstable over the age of the universe)

$$V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$



G. Degrassi *et. al.*, arxiv:1205.6497



- Even in the absence of direct evidences for new physics at the LHC, the experimental information on m_H and m_{top} gives us useful hints on the structure of the theory at very short distances
- Renewed interest for precision m_{top} measurements

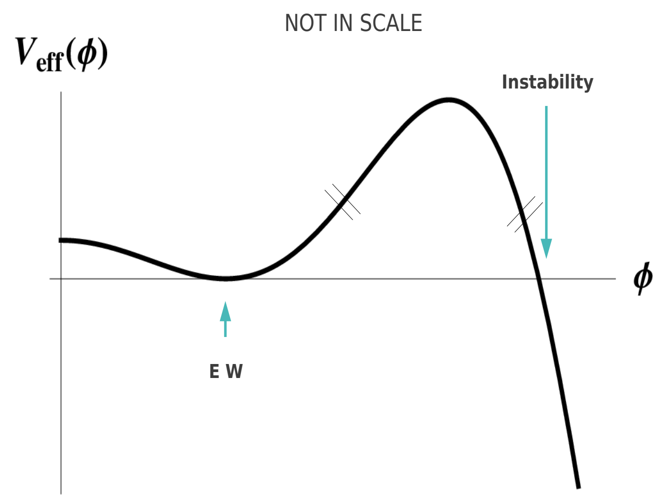
G. Cortiana 42

.. or how stable is the instability?

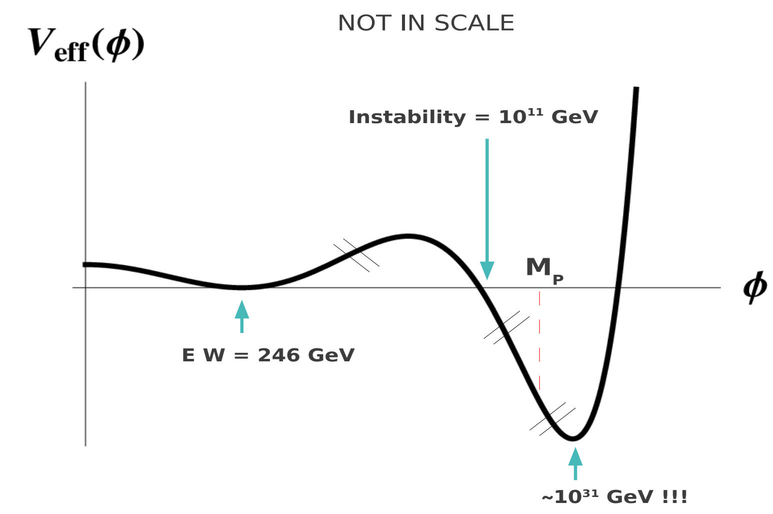
V Branchina, @ Moriond 2015

Top loop-corrections to the Higgs Effective Potential

destabilize the electroweak vacuum...



Probably worth to know that for $M_H \sim 126$ GeV and $M_t \sim 173$ GeV



New minimum at $\phi^{(2)}_{min} \sim 10^{30}$ GeV !!!

SM Effective Potential extrapolated well above M_P !!!

Remember : you normally hear... "assume SM valid up to M_P"

Does this make any sense ??? Is this a problem or not ???

To make sense out of this potential, people have (had??) arguments ..

1. New Physics Interactions that appear at the Planck scale M_P eventually stabilize the potential around M_P ...

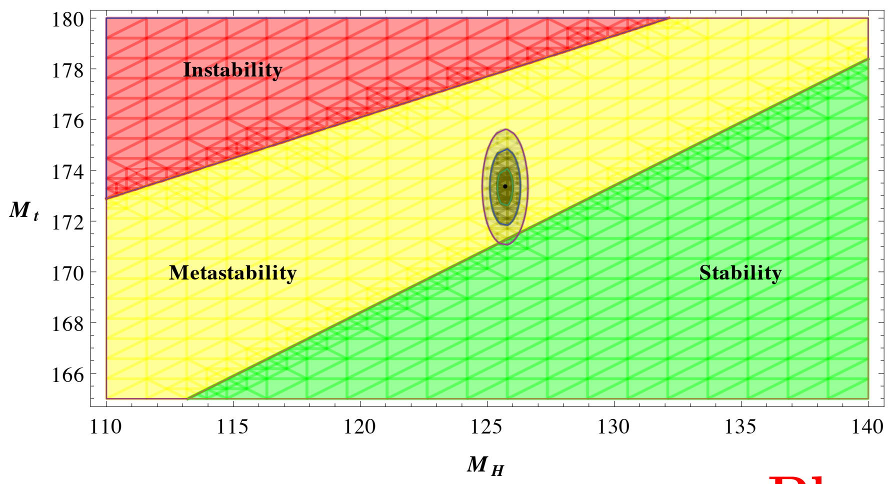
... meaning that if you take into account the presence of these new physics interactions at M_P, given in terms of higher order operators as

$$\frac{\phi^6}{M_P^2}\ , \quad \frac{\phi^8}{M_P^4}\ , \dots$$

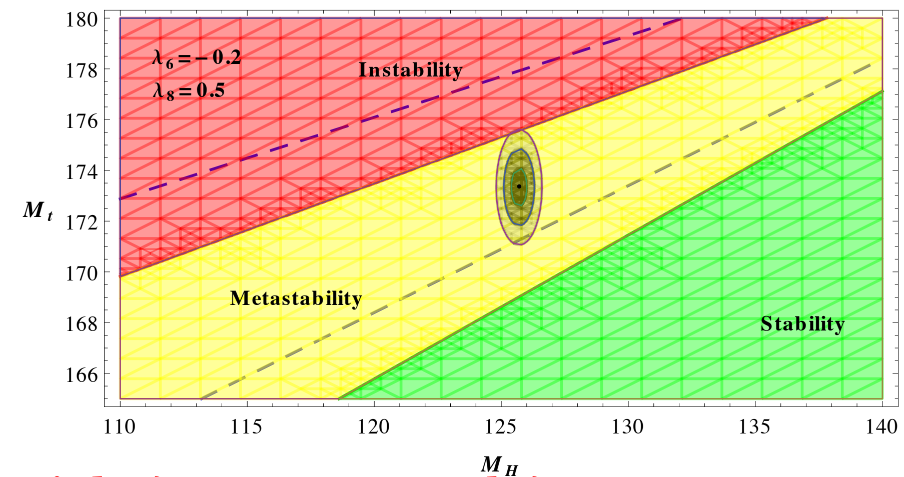
these terms stabilize the Higgs potential around M_P...

"Precision Measurements of M_t"

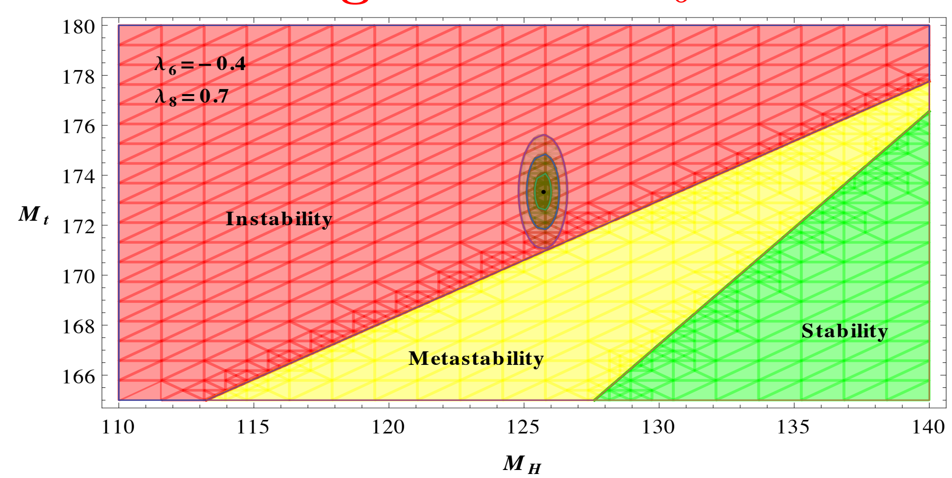
Phase diagram with $\lambda_6 = 0$ and $\lambda_8 = 0$ - Literature case



Phase diagram with $\lambda_6 = -0.2$ and $\lambda_8 = 0.5$



Phase diagram with $\lambda_6 = -0.4$ and $\lambda_8 = 0.7$

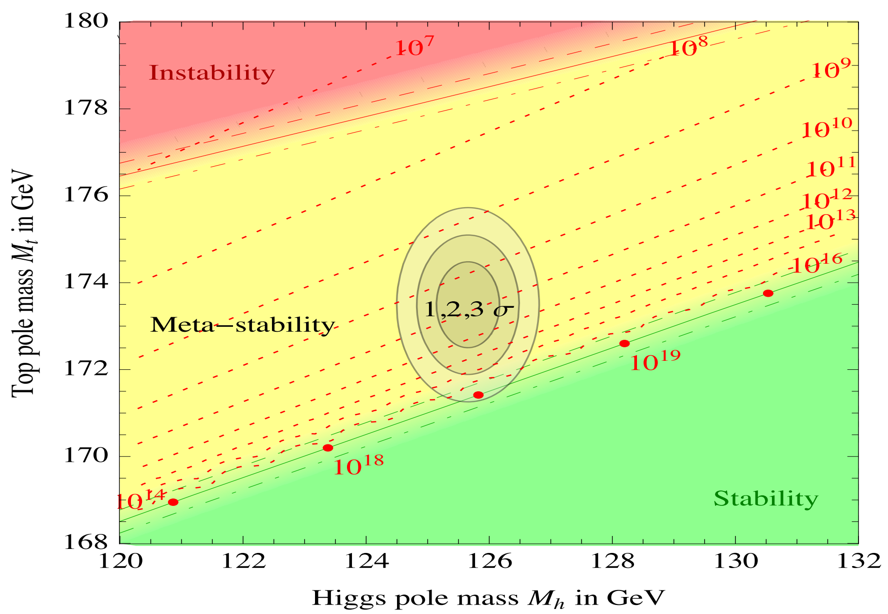


Precision measurements of M_t (and M_H) cannot discriminate between stability, metastability or criticality ... The knowledge of M_t and M_H alone is not sufficient to decide of the EW vacuum stability condition. We need informations on NEW PHYSICS in order to asses this question ...

.. or how stable is the instability?

V Branchina, @ Moriond 2015

The Phase Diagram

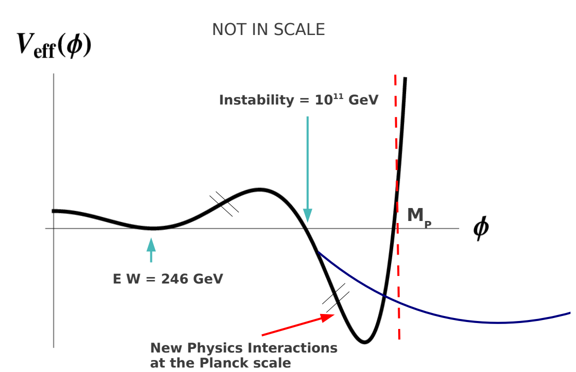


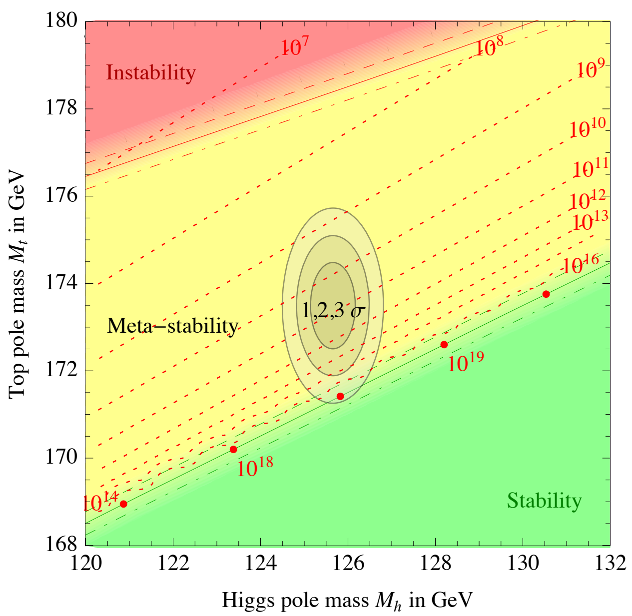
in not Universal !

… one out of different possibilities ..

The two statements :

(1) - There should be new physics at the Planck scale that stabilizes the potential





(2) - The stability phase diagram in independent on this new physics

Cannot be true at the same time

measuring the top quark mass, m_{top}

standard & “alternative” measurements

What is top mass and how is it measured?

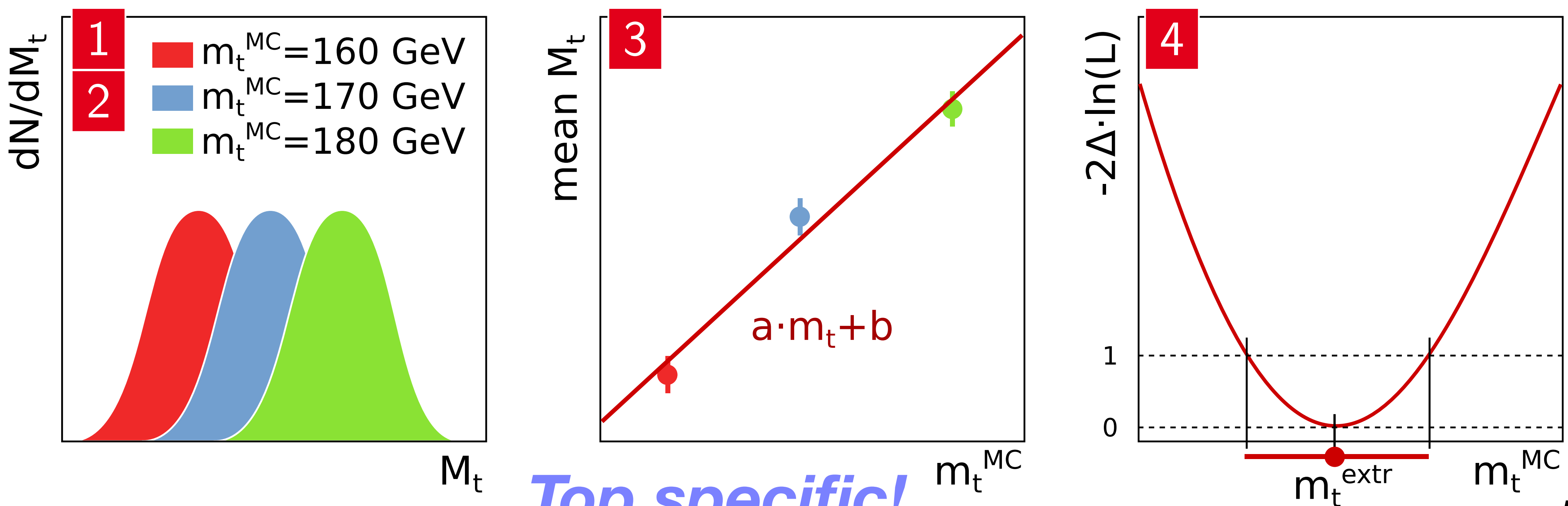
essential clues

Techniques

1. **Select** $t\bar{t}$ events
2. Construct **observable that is sensitive to m_{top}**
3. **Parametrize** observable in m_t using MC simulation
4. **Fit** to data, extract mass
   - **Compare predicted distribution of observable with measured one as a function of top mass associated to observable. D**istance is "measured" by -log(likelihood) to be **minimized.**

➡ **measured m is parameter of predicted distribution**

‣ *template method, ideogram method, matrix element, end-point...*



(images by B. Stieger (CERN))

Top specific!

Uncertainties

- Most precise methods **need full event reconstruction**: what jets to use and assign to quark, missing energy due to neutrinos in final state
- Precision measurement dominated by systematic uncertainties: mostly jet & theory related. **Develop techniques to constrain uncertainties from data or make analysis less sensitive or insensitive.**

What is top mass and how is it measured? **essential clues**

Standard Techniques

(see B. Kehoe, Int.J.Mod.Phys.A23:353-470,2008)

Different (ways to find)/(format for) the likelihood as function of m_{top}

Given

$$p_{evt}(x|m_t,\alpha,f) = f p_{top}(x|m_t,\alpha) + (1-f)p_{bkg}(x|\alpha)$$

$$-\ln L(x_1 ... x_n|m_t,\alpha,f) = -\sum_{i=1}^{n} \ln p_{evt}(x|m_t,\alpha,f).$$

x= vector of observable quantities (jets, leptons,..)

α=vector of scale factors/ nuisance parameters

Template Method

$p_{top}(x|m_t,\alpha)$ ***Prob to observe x*** *given* m_t ***from fully simulated events*** *(sometimes parametrized)*

Matrix element method : Convolution of matrix element with transfer functions

$$p_{sig}(x|m_t,\alpha) = \frac{1}{\sigma_{t\bar{t}}(m_t)} \int dz d\bar{z} f(z) f(\bar{z}) d\sigma_{t\bar{t}}(y,m_t) W(x|y,\alpha),$$

$$d\sigma_{t\bar{t}}(y,m_t) = \frac{|\mathcal{M}|^2}{x\bar{x}s} d\Phi_6,$$

LO ***matrix element*** *for* $q\bar{q} \to t\bar{t} \to \ell\nu b q\bar{q}'\bar{b}$

Prob to observe x *given parton momentum y, scale a parametrized* ***from full simulation***

Ideogram Method Convolution of analytical parametrizations for theory & detector

signal-bkg discriminant

least square for reconstruction

$$p_{sig}(o|m_t,\alpha) = \tilde{p}_{sig}(D) \sum_{i=1}^{24} \exp\left(-\frac{\overline{X}_i}{2}\right) \left[f \int G(m_i,m',\sigma_i) B(m',m_t) dm' + (1-f) S(m_i,m_t) \right]$$

Prob of "correct" jet- parton assignment from full simulation

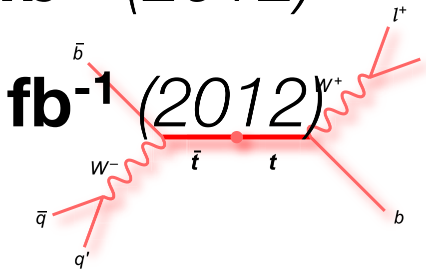
Gaussian *with mean m' and width*

Breit Wigner *mean m' and witdth*

Measuring top mass @ $\sqrt{s}$ = 7 & 8 TeV

$\int L dt$ = **19.7 fb^{-1}** *(2012)*

$\int L dt$ = XXX **fb^{-1}** *(2012)*



<u>*Phys. Rev. D 93, 072004 (2016)*</u>

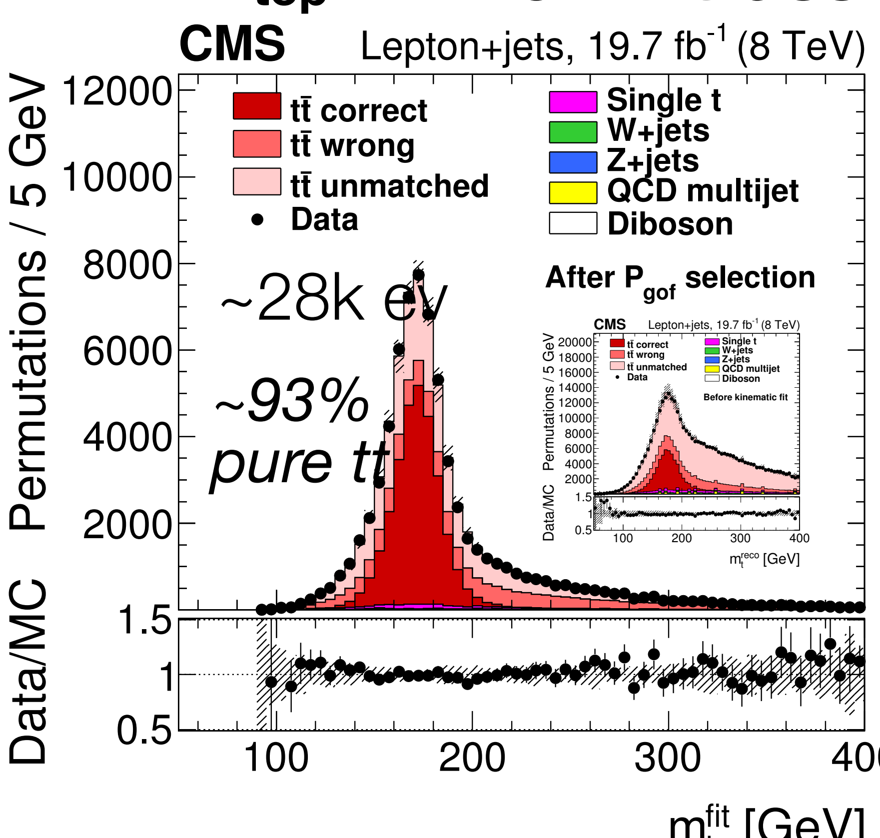
- **Select *ℓ+jets*, *all jets* and *dilepton* events**
  - *1 lepton (e,μ), ≥4 jets, 2 b-tags OR*
  - *2 Opp. Sign ℓℓ(e,μ), ≥2 jets, high E_T^{miss} + veto $m_{\ell\ell}$ around m_Z, eμ: high H_T OR*
  - *≥6 high p_T jets, 2 b-tags*

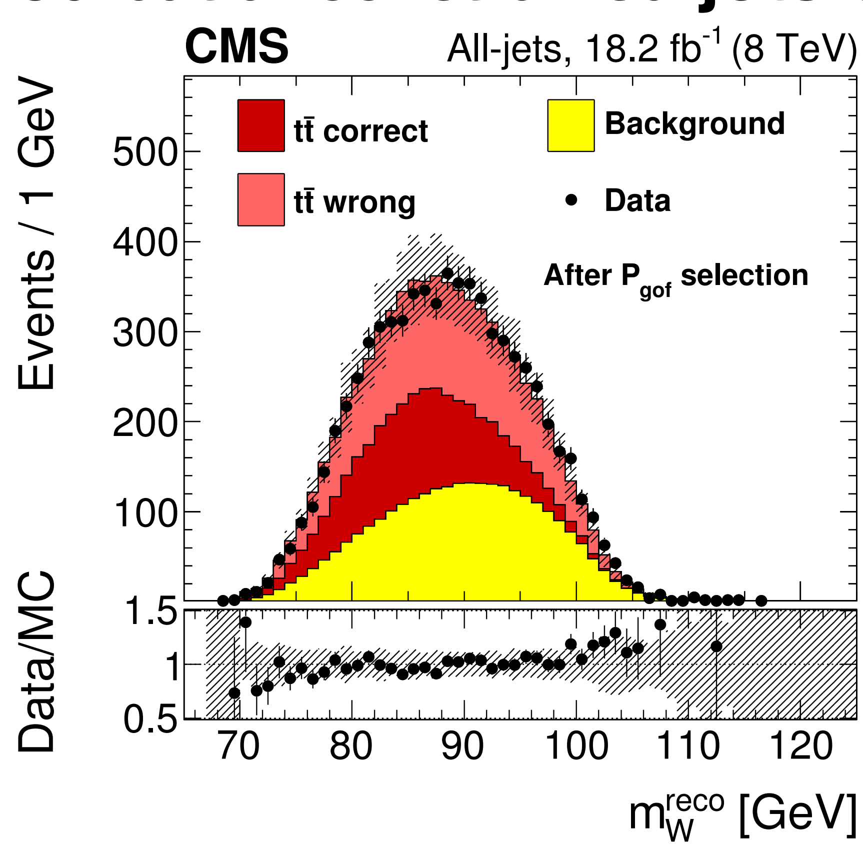
bkg: data driven multi-jets (all jets) W+jets+fake leptons; single top, Z+jets,dibosons from simul.

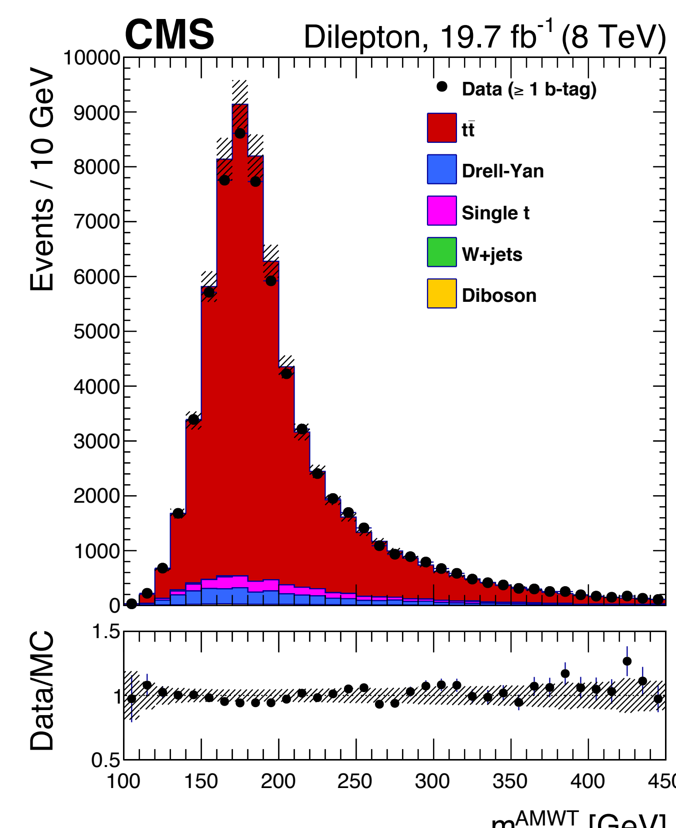
Reconstruct m_{top}-sensitive variable

- ***ℓ+jets* or *all jets***: derive tt topology with LO **kinematic fit** *($m_{top,HAD}$= $m_{top,LEP}$,m_W constraint)* **→ assign 4 or 6 jets**
  - keep event if P_{fit}>0.2 or (**>0.1 & DR(bb)> 2.0**)
- ***dilepton*** **: Assign b-jets to top,** impose 4-mom conservation, M_W and m_{top} hypo→ get neutrinos 4-mom. + weight depending on resolution and E(ℓ)→ **Keep assignment with max. weight**

- **m_{top}^{reco} from fit-assigned *but unconstrained* jets or from kine solution**







Measuring top mass @ $\sqrt{s}$ = 8 TeV

$\int Ldt$ = **19.7 fb^{-1}** *(2012)*

Phys. Rev. D 93, 072004 (2016)

- (***ℓ+jets*** ***or*** ***all jets***)
- **Build simulated prob. density function (pdf/templates)** of **m_{top}^{reco}** as a function of
- ***dilepton***

- **m_{top}, JSF:** *global jet en. scale factor,* **jet-parton assignment** in kine fit

- **m_{top}**

Σ_i P_i [f P_{sig}()+(1-f_{sig})P_{bkg}]

- **For each event derive**

- **ideogram (= event likelihood) for m_{top}^{reco}** from **pdfs** & kine-fit info: function of **m_{top}, JSF**

- **event likelihood for m_{top}^{reco}** from pdfs: function of **m_{top},**

- **Maximize likelihood of *data set*** *as function of*

$$\mathcal{L}\left(\text{sample}|m_t,\text{JSF}\right) = \prod_{\text{events}} \mathcal{L}\left(\text{event}|m_t,\text{JSF}\right)^{w_{\text{event}}}$$

sum of goodness of fit less weight to incorrect permutations

product of ev, lkl

1D

m_{top},

JSF=1

2D

m_{top}, JSF

hybrid

ideogram → ideogram·P(JSF)

P(JSF) = Gauss(1,width of Jet Energy Correction)

m_{top},

JSF=1

Measuring top mass @ $\sqrt{s}$ = 8 TeV

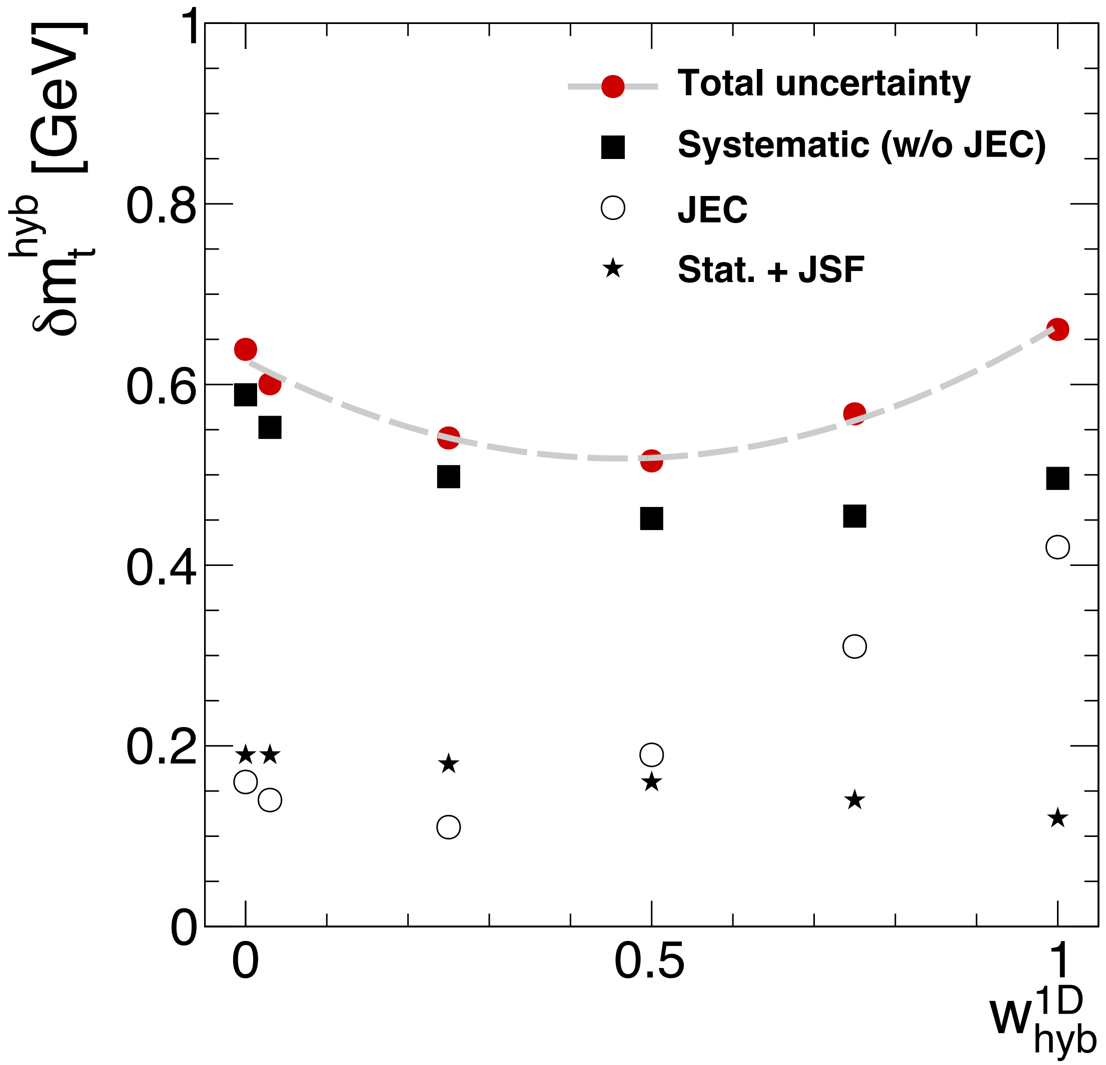
$\int Ldt$ = **19.7 fb^{-1}** *(2012)*

Phys. Rev. D 93, 072004 (2016)

- Hybrid is the most precise method: includes more info about JSF

- Found anti-correlated uncertainties between 1D and 2D fits
  - JEC, JER, pileup, radiation, top p_T, ...
- Reason: Flat JSF overcorrects for uncertainties that mostly affect the light jets (due to flavor- and/or p_T-depency)
- Methods for improvement:
  - Use p_T-dependent JSF (CDF)
  - BLUE combination of 1D and 2D (ATLAS)
  - Weigh down JSF constraint
  - Add external JES constraint (D0, CMS)
- Trade-off between JEC and other unc., minimum in-between

(M. Seidel , LHCTopWG meeting,17th Nov 2015)



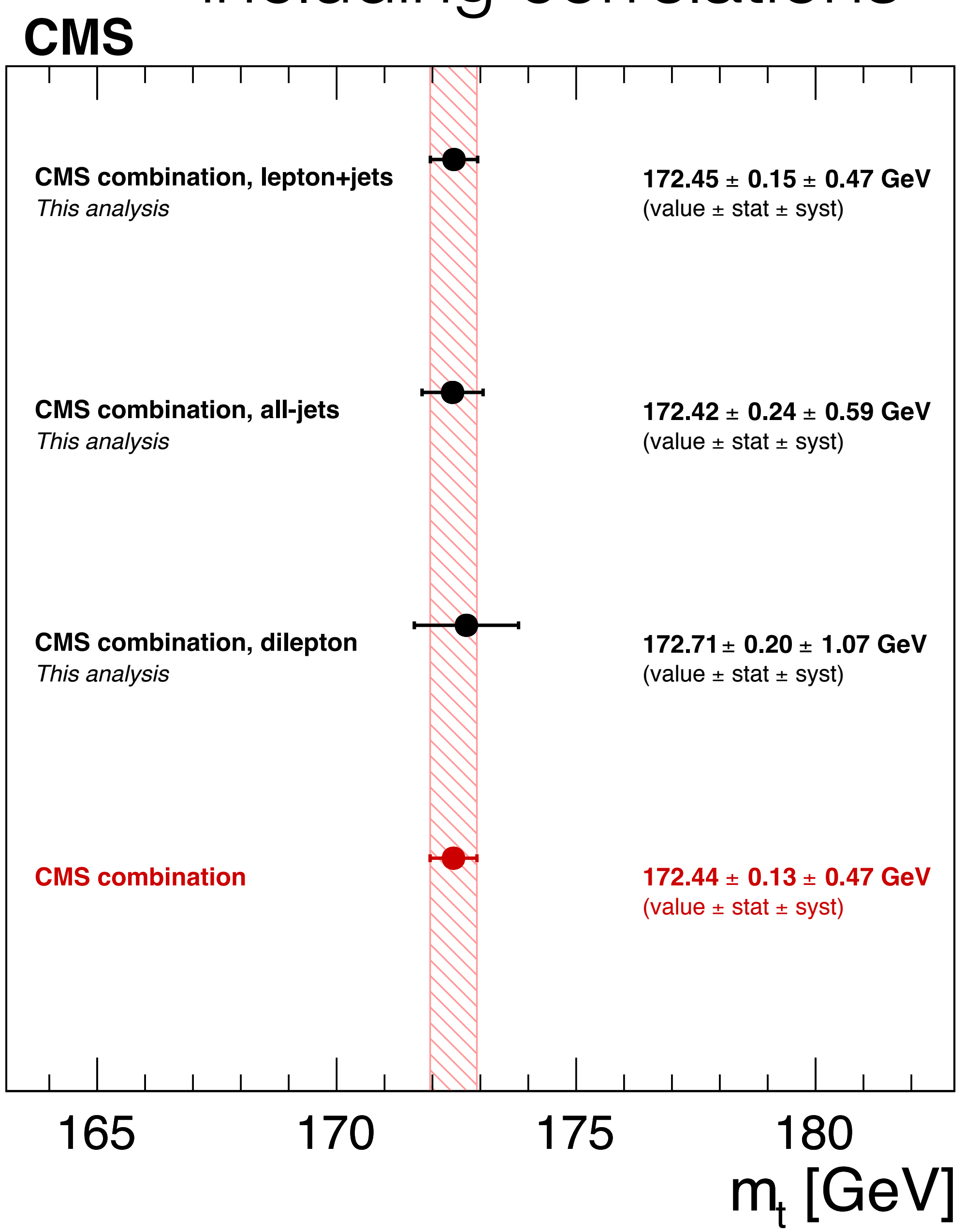
2D ←hybrid→ 1D

Measuring top mass @ $\sqrt{s}$ = 7 & 8 TeV

Phys. Rev. D 93, 072004 (2016)

$\int L dt$ = **19.7 fb^{-1}** (2012)

Combine 3 measurements @ 8 TeV with 4 results at 7 TeV: use BLUE including correlations



$m_t = 172.44 \pm 0.13\,(\text{stat}) \pm 0.47\,(\text{syst})$ GeV with $\chi^2/\text{ndf} = 2.5/6$

$\delta m_{top} / m_{top}$ ~0.28%

TABLE IX. Category breakdown of systematic uncertainties for the combined mass result. The uncertainties are expressed in GeV.

Combined m_t result	δm_t(GeV)
Experimental uncertainties	
Method calibration	0.03
Jet energy corrections	
–JEC: intercalibration	0.01
–JEC: *in situ* calibration	0.12
–JEC: uncorrelated nonpileup	0.10
Lepton energy scale	0.01
E_T^{miss} scale	0.03
Jet energy resolution	0.03
b tagging	0.05
Pileup	0.06
Backgrounds	0.04
Trigger	< 0.01
Modeling of hadronization	
JEC: flavor	0.33
b jet modeling	0.14
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	0.10
ME-PS matching threshold	0.08
ME generator	0.11
Top quark p_T	0.02
Modeling of soft QCD	
Underlying event	0.11
Color reconnection modeling	0.10
Total systematic	0.47
Statistical	0.13
Total Uncertainty	0.48

First M_{top} World average

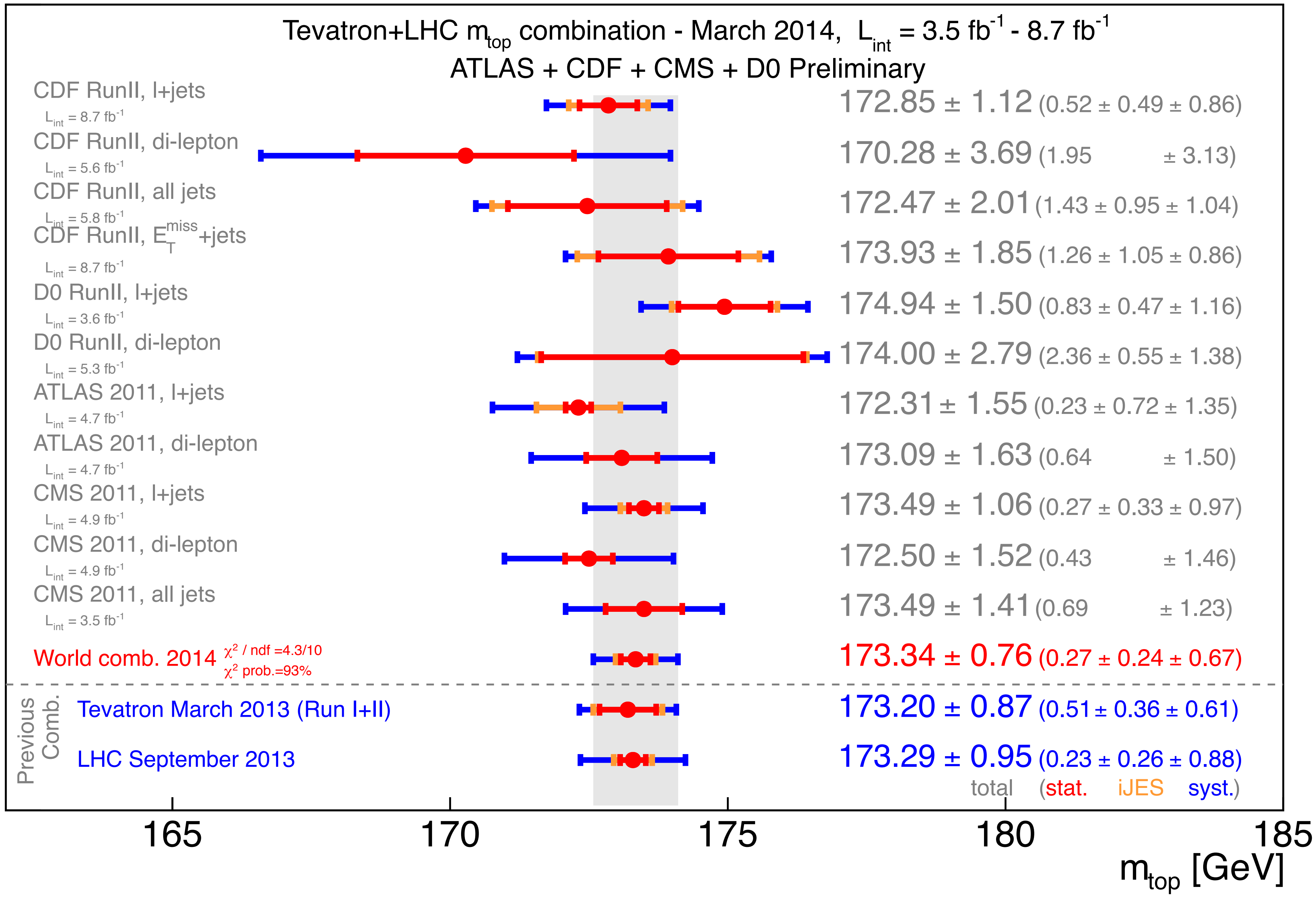
- **First combination** of m_{top} from **1.96 TeV $p\bar{p}$ & 7 TeV pp** collisions

arxiv:1403.4427[hep-ex]

- Tevatron: up to 8.7/fb
- LHC: up to 4.9/fb
- Use most precise measurement in each channel by each experiment

- **δm_{top} reduced** by
  - 28% w.r.t. most precise single input
  - 13% w.r.t to previous most precise combination

- **Systematics dominated**
  - tt modelling
  - energy scale of light and b-



m_{top} = 173.34± 0.27(stat) ± 0.71(syst) GeV

δm_{top} /m_{top} ~0.44%

First M_{top} World average : uncertainties & correlations

GeV

Uncertainty	World Combination
m_{top}	173.34
Stat	0.27
iJES	0.24
stdJES	0.20
flavourJES	0.12
bJES	0.25
MC	0.38
Rad	0.21
CR	0.31
PDF	0.09
DetMod	0.10
b-tag	0.11
LepPt	0.02
BGMC	0.10
BGData	0.07
Meth	0.05
MHI	0.04
Total Syst	0.71
Total	0.76

arxiv:1403.4427[hep-ex]

- Major effort to classify **uncertainties** & define

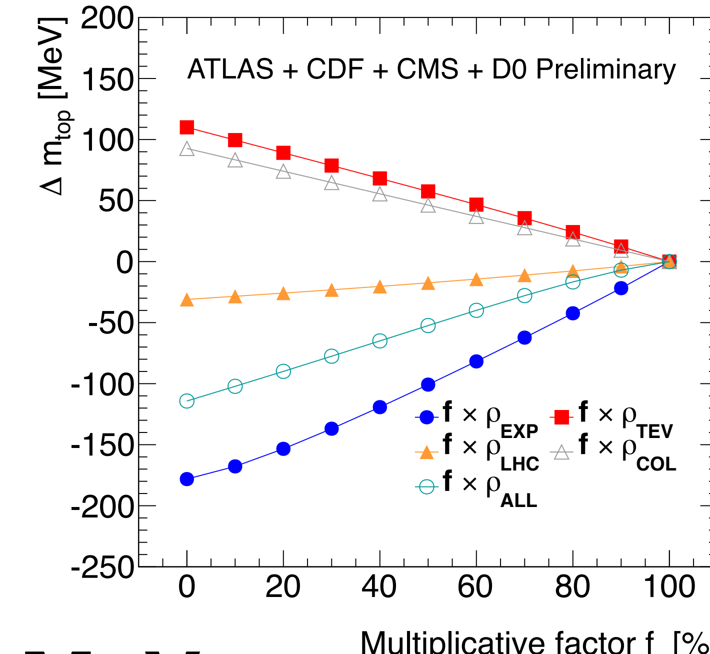
within same experiment *within same collider* *between colliders*

11 input columns combined with

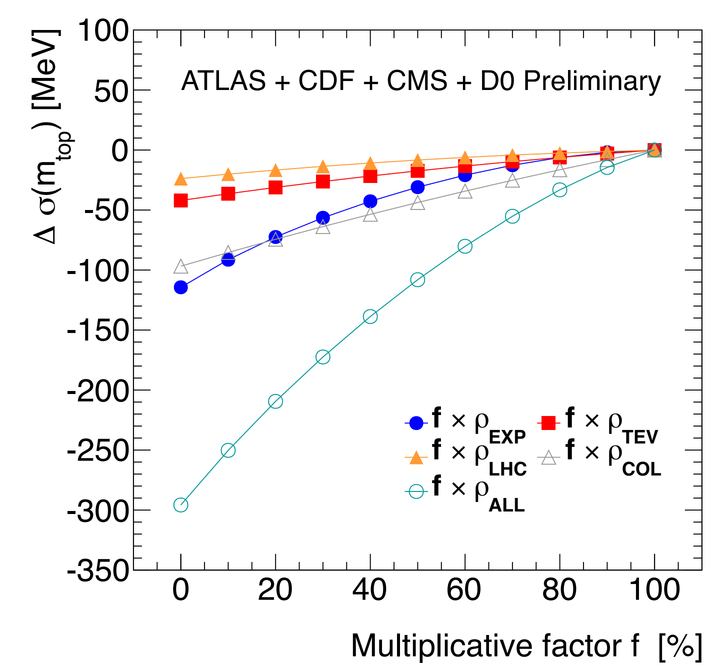
	ρ_{EXP}				ρ_{LHC}	ρ_{TEV}	ρ_{COL}	
	ρ_{CDF}	ρ_{D0}	ρ_{ATL}	ρ_{CMS}			$\rho_{ATL-TEV}$	$\rho_{CMS-TEV}$
Stat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iJES	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
stdJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
flavourJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
bJES	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5
MC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rad	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
CR	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PDF	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
DetMod	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
b-tag	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
LepPt	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
BGMC[†]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
BGData	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MHI	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0

- Vary correlation scenarios **(m_{top} ,δm_{top}) stable** within uncertainties

MeV

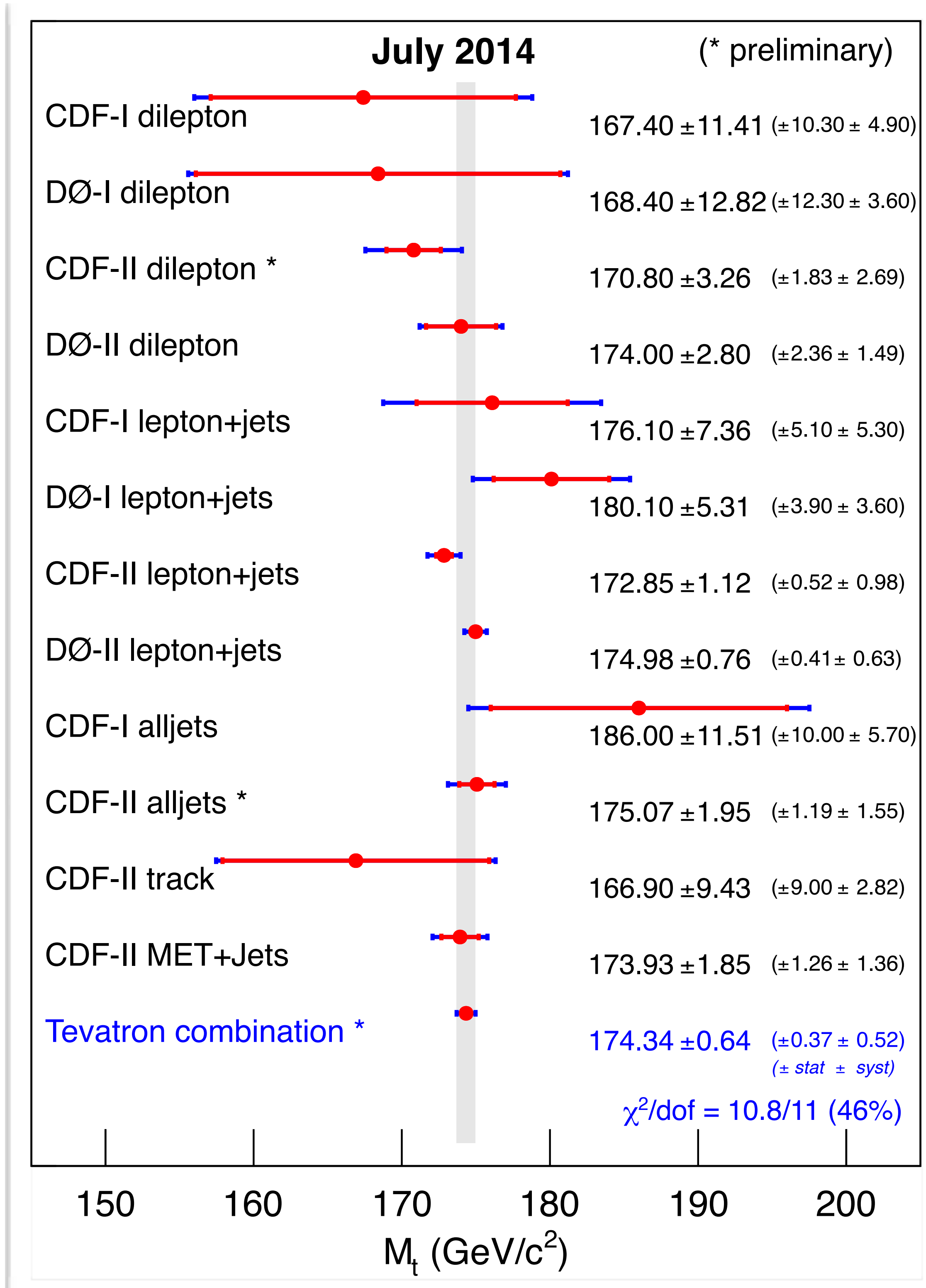


MeV



Tevatron M_{top} combination

http://arxiv.org/abs/1407.2682

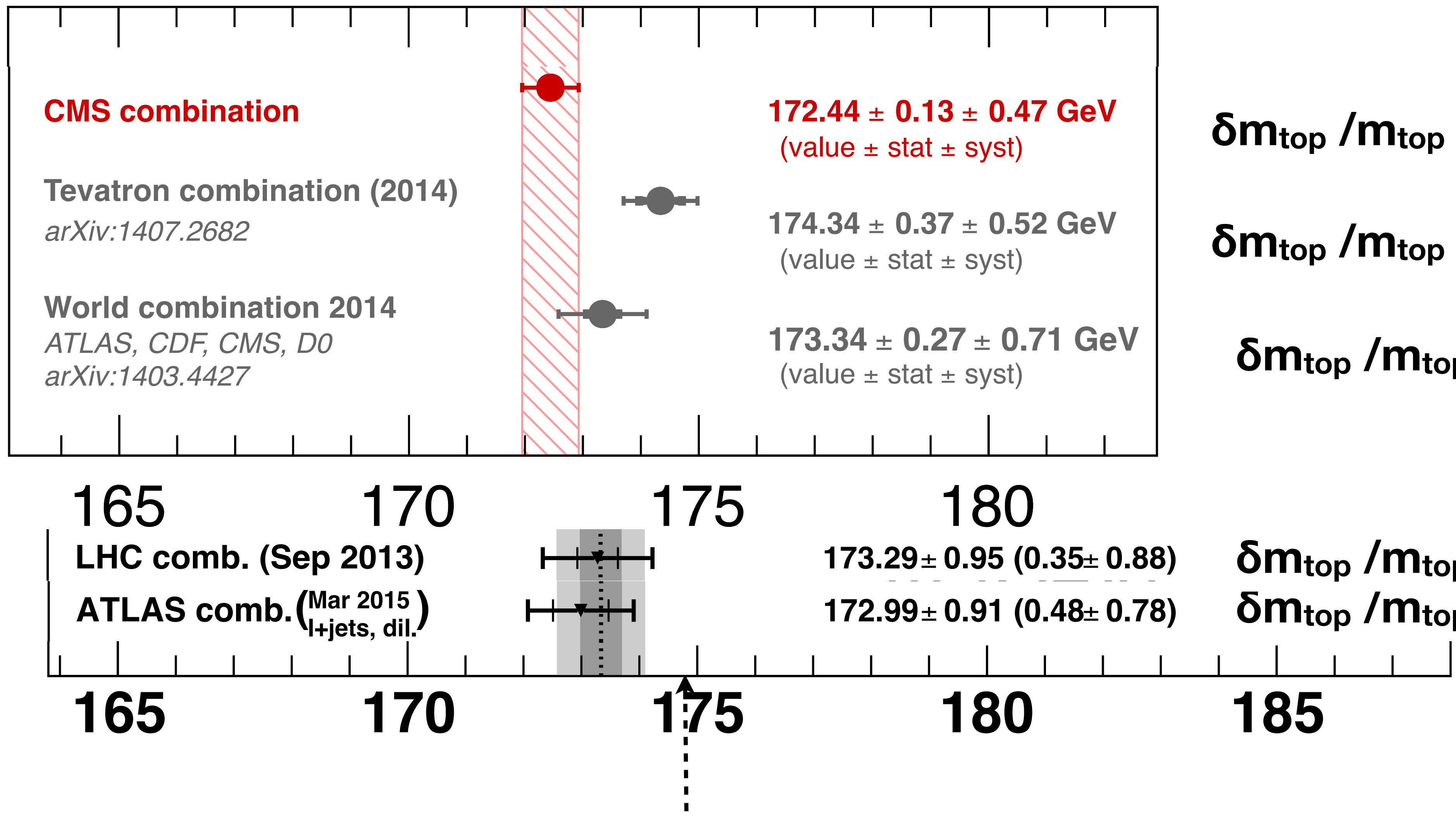


$\delta m_{top} / m_{top}$ ~0.36%

Global most precise M_{top} picture (Mar 2016)

CMS Combination (Sept 2015)
latest D0 (Jan 2015)
ATLAS Run1 (Mar 2015)
World (March 2014),
Tevatron (July 2014),
LHC (Sept 2013)

LHC is not including latest from CMS + new in 2014-2015



$\delta m_{top} / m_{top}$ ~0.28%

$\delta m_{top} / m_{top}$ ~0.36%

$\delta m_{top} / m_{top}$ ~0.44%

$\delta m_{top} / m_{top}$ ~0.54%

$\delta m_{top} / m_{top}$ ~0.52%

D0 latest (Jan 2015) $m_t = 174.98 \pm 0.58\,(\mathrm{stat}+\mathrm{JES}) \pm 0.49\,(\mathrm{syst})\ \mathrm{GeV}$ **$\delta m_{top} / m_{top}$ ~0.43%**

Measure m_{top}^{pole} from σ_{tt} - dilepton - $\sqrt{s}$ =7 & 8 TeV

A=ATLAS, C=CMS

ℓνℓνbb

$\int L dt$ ~ **20.3 fb^{-1}** *(2012)*
$\int L dt$ ~ **4.6 fb^{-1}** *(2011)*

Eur.Phys.J. C74 (2014) 3109
Phys. Lett. B 728 (2014) 496-517
Phys. Lett. B 738 (2014) 526 (Corrigendum)

Idea

- $\sigma_{t\bar{t}}$ depends on m_{top}^{pole} →Comparing the $\sigma_{t\bar{t}}^{meas}$ (m_{top}^{MC}) to predictions expressed as $\sigma_{t\bar{t}}^{theo}$ (m_{top}^{pole}) allows determination of m_{top}^{pole}

Identify $m_{top}^{pole} = m_{top}^{MC} \pm$ 1 GeV (propagate uncertainty)

&

Assume that σ_{tt} is not affected by non SM physics

The theory part

- $\sigma_{t\bar{t}}^{theo}$ (m_{top}^{pole}) is determined by calculating $\sigma_{t\bar{t}}^{theo}$ at NNLO+NNLL for different m_{top}^{pole} values & parametrizing the result

(A) $$\sigma_{t\bar{t}}^{\text{theo}}(m_t^{\text{pole}}) = \sigma(m_t^{\text{ref}}) \left(\frac{m_t^{\text{ref}}}{m_t^{\text{pole}}}\right)^4 (1 + a_1 x + a_2 x^2) \qquad \begin{aligned} m_t^{\text{ref}} &= 172.5 \text{ GeV} \\ x &= (m_t^{\text{pole}} - m_t^{\text{ref}})/m_t^{\text{ref}} \end{aligned}$$

(C) third-order polynomial in m_{top}^{pole} divided by $(m_{top}^{pole})^4$

Measure m_{top}^{pole} from σ_{tt} $\sqrt{s}$ =7 & 8 TeV *A=ATLAS, C=CMS*

$\ell\nu\ell\nu bb$

$\int L dt$ ~ **4.6 fb^{-1}** *(2011)* & **20.3 fb^{-1}** *(2012)* Eur.Phys.J. C74 (2014) 3109

The Experimental part

- Standard dilepton selection: 2 OS lept (e^+e^-, eμ, μμ) (C) or (eμ(A)
  - C: *≥2 jets, high E_T^{miss} + veto $m_{\ell\ell}$ around m_Z, eμ: high H_T*
  - *A:no cuts on N_{jet}, E_T^{miss}, H_T*

- **Extract σ_{tt} (m_{top}^{MC}) by**
  - ***C***: correcting bkg-subtracted N_{tt} with lumi and efficiency

$$\sigma_{t\bar{t}} = \frac{N - N_B}{\mathcal{A} \cdot \mathcal{L}}$$

- ***A***:simultaneous fit for σ_{tt} and ε_b, efficiency to select, reco and b-tag a jet in 1-b-tag and 2-b-tag samples

$$N_1 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{bkg}$$
$$N_2 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{bkg}$$

Phys. Lett. B 728 (2014) 496-517

Phys. Lett. B 738 (2014) 526 (Corrigendum)

change m_{top}^{MC}→ event kinematic properties of $t\bar{t}$ change→ acceptances/efficiencies (A, $\varepsilon_{\mu\nu}$) & single top bkg (N_B ,$N_{i,B}$) vary correction yield→ $\sigma_{t\bar{t}} = \sigma_{t\bar{t}}(m_{top}^{MC})$

Measure m_{top}^{pole} from σ_{tt}

Eur.Phys.J. C74 (2014) 3109
Phys. Lett. B 728 (2014) 496-517
Phys. Lett. B 738 (2014) 526 (Corrigendum)

$\int L dt$ ~ **4.6 fb^{-1}** *(2011) &* **20.3 fb^{-1}** *(2012)*

ℓνℓνbb

A=ATLAS, C=CMS

- **Extracting m_{top}^{pole}** *by incorporating theory and experimental uncertainties*

1. **Determine Bayesian prior $f_{th}(\sigma_{t\bar{t}}$ (m_{top}^{pole}))=prob. of $\sigma_{t\bar{t}}$ as function of m_{top}^{pole}**

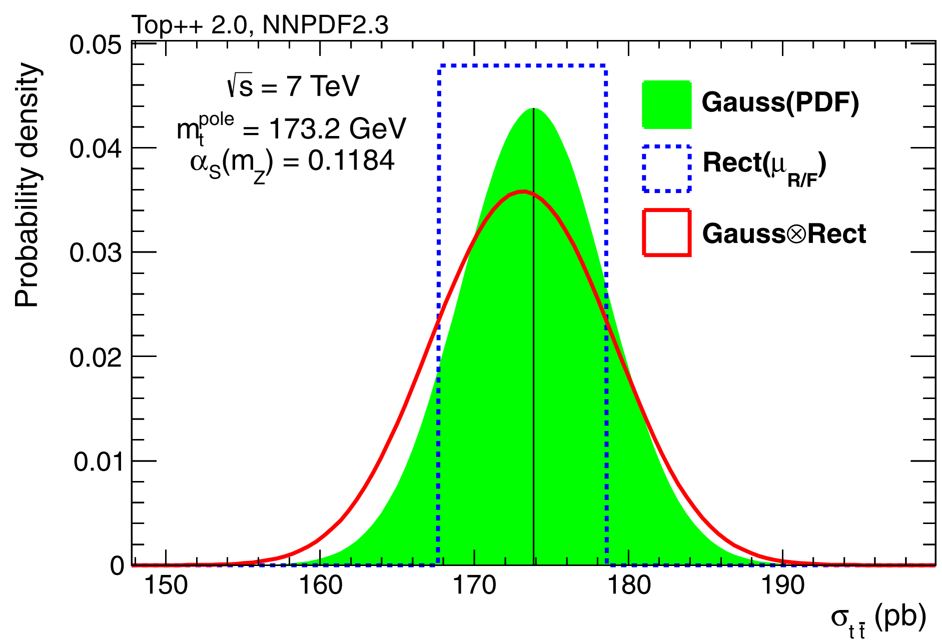
CMS

Gaussian in σ_{tt} with std.dev = PDF uncertainty

⊗

constant over ren/fact scale variation range of σ_{tt}, zero elsewhere

=



$$\frac{1}{2(\sigma_{t\bar{t}}^{(h)} - \sigma_{t\bar{t}}^{(l)})}\left(\mathrm{erf}\left[\frac{\sigma_{t\bar{t}}^{(h)} - \sigma_{t\bar{t}}}{\sqrt{2}\delta_{\mathrm{PDF}}}\right] - \mathrm{erf}\left[\frac{\sigma_{t\bar{t}}^{(l)} - \sigma_{t\bar{t}}}{\sqrt{2}\delta_{\mathrm{PDF}}}\right]\right)$$

$\sigma_{t}^{(h),(l)} = \sigma_{tt}^{(h),(l)}\,(m_{top}^{pole})$

ATLAS

$$G(\sigma'_{t\bar{t}}|\sigma_{t\bar{t}}^{\mathrm{theo}}(m_t^{\mathrm{pole}}),\, \rho_{\mathrm{theo}}^{\pm})$$

Asymmetric Gaussian in $\sigma_{t\bar{t}}$ with mean $\sigma_{t\bar{t}}^{theo}$ (m_{top}^{pole}) and stand dev = quadrature sum of PDF+α_S and scale variations

2. **Multiply by exp. likelihood $f_{exp}(\sigma_{tt}^{meas}(m_{top}^{pole}))$ σ_{tt}^{meas} as a function of m_{top}^{pole}**

(A,C)

$$G(\sigma'_{t\bar{t}}|\sigma_{t\bar{t}}(m_t^{\mathrm{pole}}),\, \rho_{\mathrm{exp}})$$

Gaussian in $\sigma_{t\bar{t}}$ with mean $\sigma_{t\bar{t}}^{meas}$ (m_{top}^{pole}) and stand dev = exp uncertainty

3. **Find likelihood for** m_{top}^{pole} by **marginalizing the posterior with respect to $\sigma_{t\bar{t}}$**

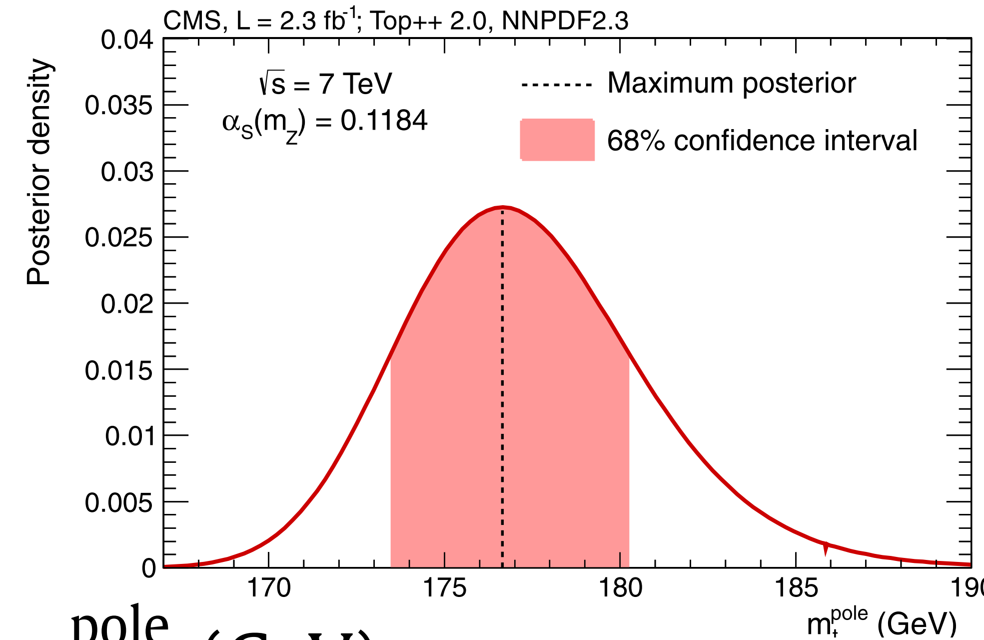
$$\mathscr{L}(m_{top}^{pole}) = \int f_{th}(\sigma_{t\bar{t}},\, m_{top}^{pole})\, f_{exp}(\sigma_{t\bar{t}},\, m_{top}^{pole})\, d\sigma_{t\bar{t}}$$

4. **Derive m_{top}^{pole} value & interval** : symmetric interval around max of $\mathscr{L}(m_{top}^{pole})$

Measure m_{top}^{pole} from σ_{tt}

Phys. Lett. B 738 (2014) 526 (Corrigendum)
Phys. Lett. B 728 (2014) 496-517

$\int L dt$ ~ **4.6 fb^{-1}** *(2011)* & **20.3 fb^{-1}** *(2012)*



Systematic uncertainties

CMS

	m_t^{pole} (GeV)	Uncertainty on m_t^{pole} (GeV)						
		Total	$\sigma_{t\bar{t}}^{meas}$	PDF	α_S	$\mu_{R,F}$	E_{LHC}	m_t^{MC}
ABM11	172.7	$^{+3.9}_{-3.5}$	$^{+2.8}_{-2.5}$	$^{+2.2}_{-2.0}$	$^{+1.0}_{-1.0}$	$^{+0.7}_{-0.7}$	$^{+0.8}_{-0.8}$	$^{+0.4}_{-0.3}$
CT10	177.0	$^{+4.3}_{-3.8}$	$^{+3.2}_{-2.8}$	$^{+2.4}_{-2.0}$	$^{+0.8}_{-0.8}$	$^{+0.9}_{-0.9}$	$^{+0.9}_{-0.9}$	$^{+0.5}_{-0.4}$
HERAPDF1.5	179.5	$^{+4.3}_{-3.8}$	$^{+3.5}_{-3.0}$	$^{+1.7}_{-1.5}$	$^{+1.2}_{-1.1}$	$^{+0.9}_{-0.8}$	$^{+1.0}_{-1.0}$	$^{+0.6}_{-0.5}$
MSTW2008	177.9	$^{+4.1}_{-3.6}$	$^{+3.4}_{-2.9}$	$^{+1.6}_{-1.4}$	$^{+0.9}_{-0.9}$	$^{+0.9}_{-0.9}$	$^{+0.9}_{-0.9}$	$^{+0.5}_{-0.5}$
NNPDF2.3	176.7	$^{+3.8}_{-3.4}$	$^{+3.1}_{-2.8}$	$^{+1.5}_{-1.3}$	$^{+0.7}_{-0.7}$	$^{+0.9}_{-0.9}$	$^{+0.9}_{-0.9}$	$^{+0.5}_{-0.4}$

Table 2
Results obtained for m_t^{pole} by comparing the measured $t\bar{t}$ cross section to the NNLO + NNLL prediction with different NNLO PDF sets. The total uncertainties account for the full uncertainty on the measured cross section ($\sigma_{t\bar{t}}^{meas}$), the PDF and scale ($\mu_{R,F}$) uncertainties on the predicted cross section, the uncertainties of the $\alpha_S(m_Z)$ world average and of the LHC beam energy (E_{LHC}), and the ambiguity in translating the dependence of the measured cross section on the top-quark mass value used in the Monte Carlo generator (m_t^{MC}) into the pole-mass scheme.

Measure m_{top}^{pole} from σ_{tt}

$\int Ldt \sim$ **4.6 fb^{-1}** *(2011)* & **20.3 fb^{-1}** *(2012)*

Eur.Phys.J. C74 (2014) 3109

Systematic uncertainties

ATLAS

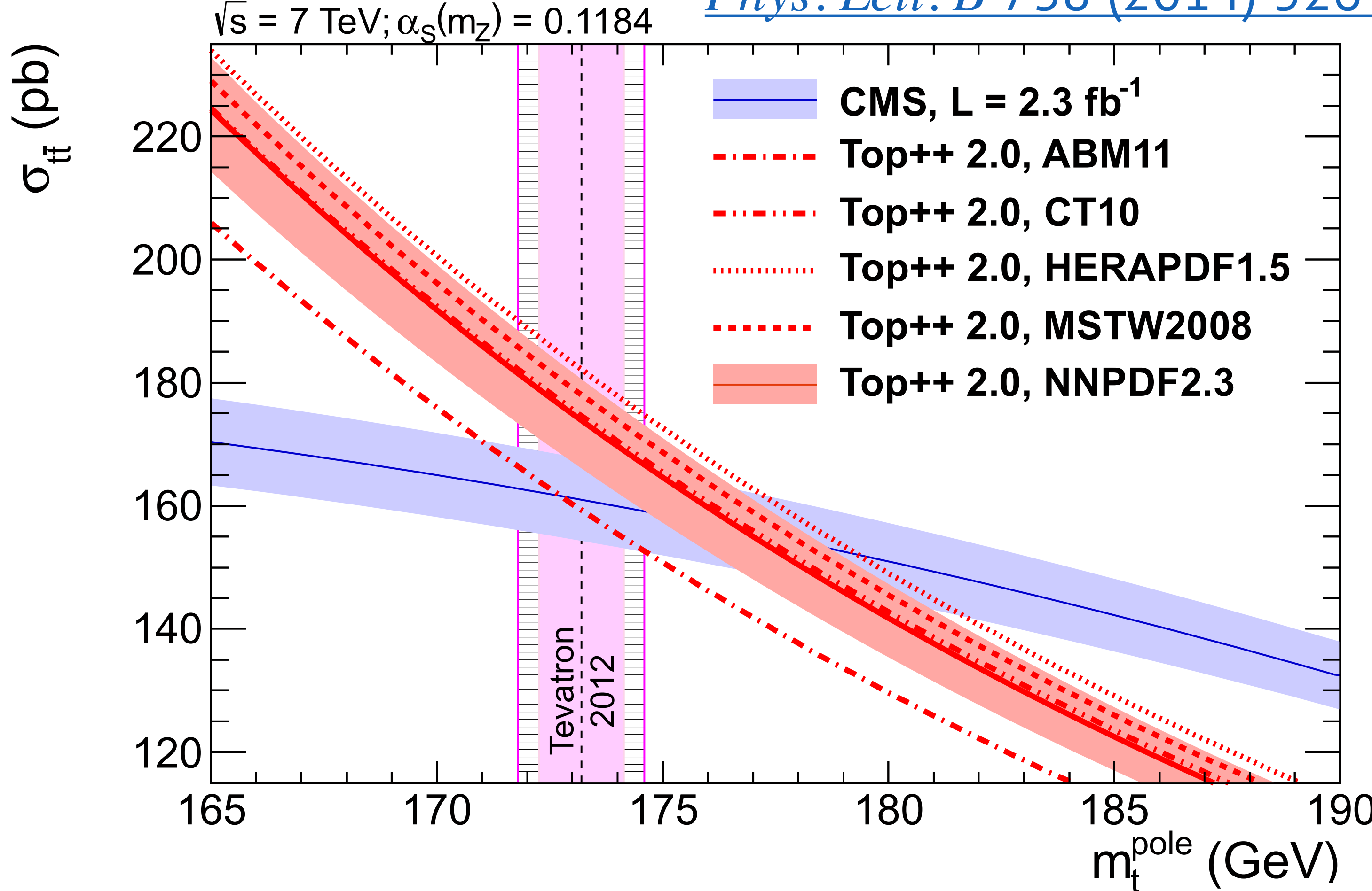
Table 6 Measurements of the top quark pole mass determined from the $t\bar{t}$ cross-section measurements at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV using various PDF sets

PDF	m_t^{pole} (GeV) from $\sigma_{t\bar{t}}$	
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
CT10 NNLO	171.4 ± 2.6	174.1 ± 2.6
MSTW 68 % NNLO	171.2 ± 2.4	174.0 ± 2.5
NNPDF2.3 5f FFN	$171.3^{+2.2}_{-2.3}$	174.2 ± 2.4

Table 7 Summary of experimental and theoretical uncertainty contributions to the top quark pole mass determination at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV with the CT10 PDF set

Δm_t^{pole} (GeV)	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
Data statistics	0.6	0.3
Analysis systematics	0.8	0.9
Integrated luminosity	0.7	1.2
LHC beam energy	0.7	0.6
PDF+α_s	1.8	1.7
QCD scale choice	$^{+0.9}_{-1.2}$	$^{+0.9}_{-1.3}$

[Phys. Lett. B 738 (2014) 526 (Corrigendum)](#)



Measure m_{top}^{pole} from σ_{tt}

CMS

use results from NNPDF 2.3

(preferred because of stability against change of PDF parametrization)

$$m_t^{pole} = 176.7^{+3.8}_{-3.4}$$

inner solid= initial uncertainty on $m_{top}^{Tevatron}$

external: m_{top}^{meas} /m_{top}^{pole} difference

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ATLAS

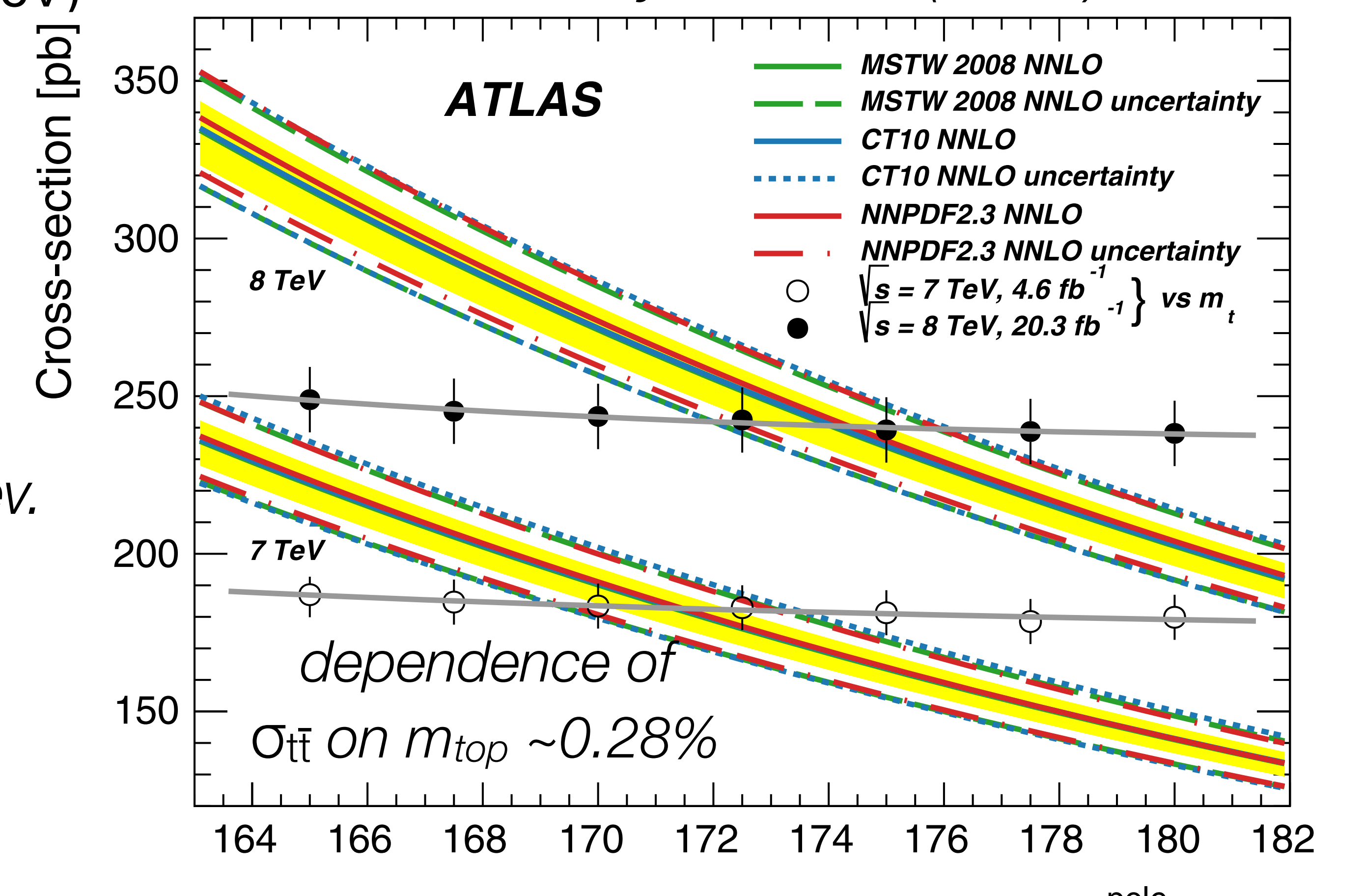
use envelope of PDF errors for PDF uncertainty (PDF4LHC prescription)

$$m_t^{pole} = 171.4 \pm 2.6 \text{ GeV } (\sqrt{s} = 7 \text{ TeV})$$
$$m_t^{pole} = 174.1 \pm 2.6 \text{ GeV } (\sqrt{s} = 8 \text{ TeV})$$

lumi is uncorrelated; consistent within 1.7 st. dev.

Maximize product of likelihoods at E_{cm}=7 and 8 TeV : same correlations as for cross section + fully correlated theory uncertainties

$$m_t^{pole} = 172.9^{+2.5}_{-2.6} \text{ GeV}$$



Prediction uncertainty bands include renormalization scale, factorization scale and PDF

Pole mass extraction

CMS added 8 TeV data!

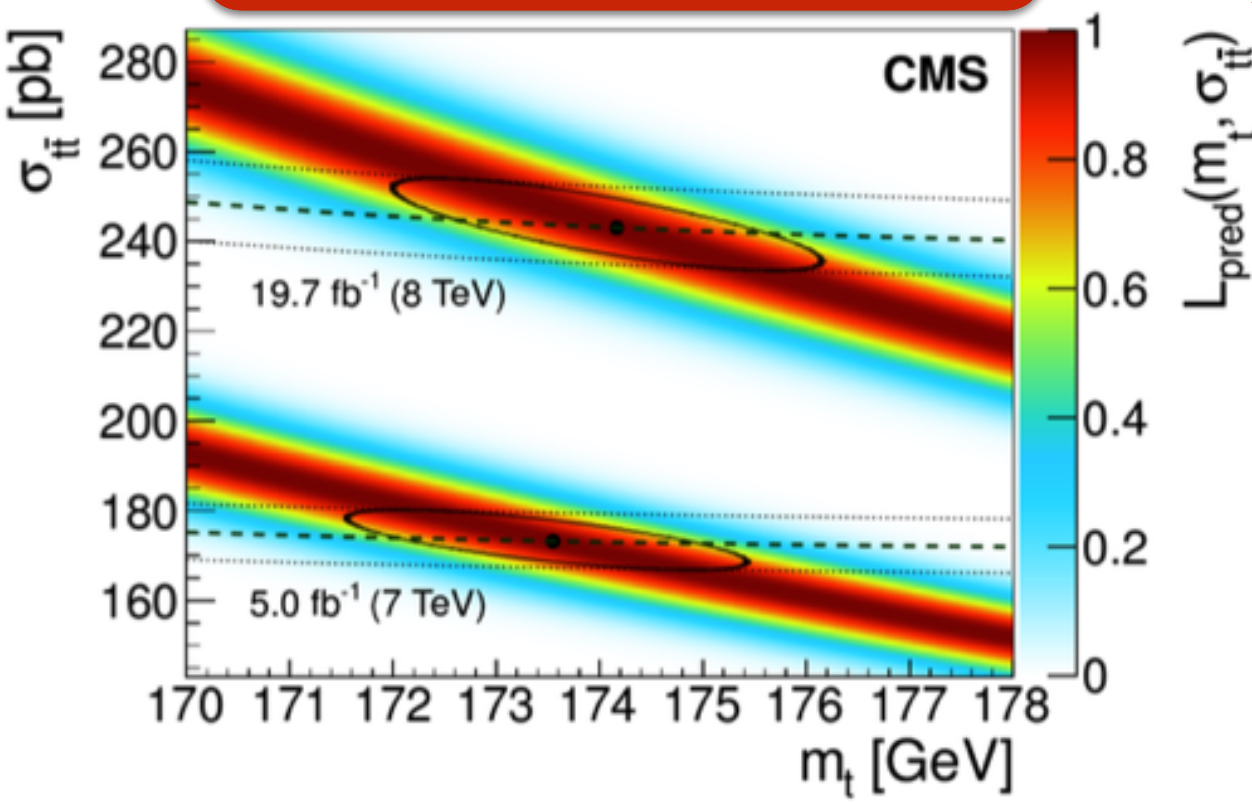
used most updated PDF

- Top mass extraction at fixed order scheme
  - need full phase space extrapolation
  - benefits from loose selections ⇒ flat acceptance
  - assume α_s and PDF and compare to theory

$$m_t^{\text{pole}} = 173.8^{+1.7}_{-1.8}\ (\text{GeV})$$

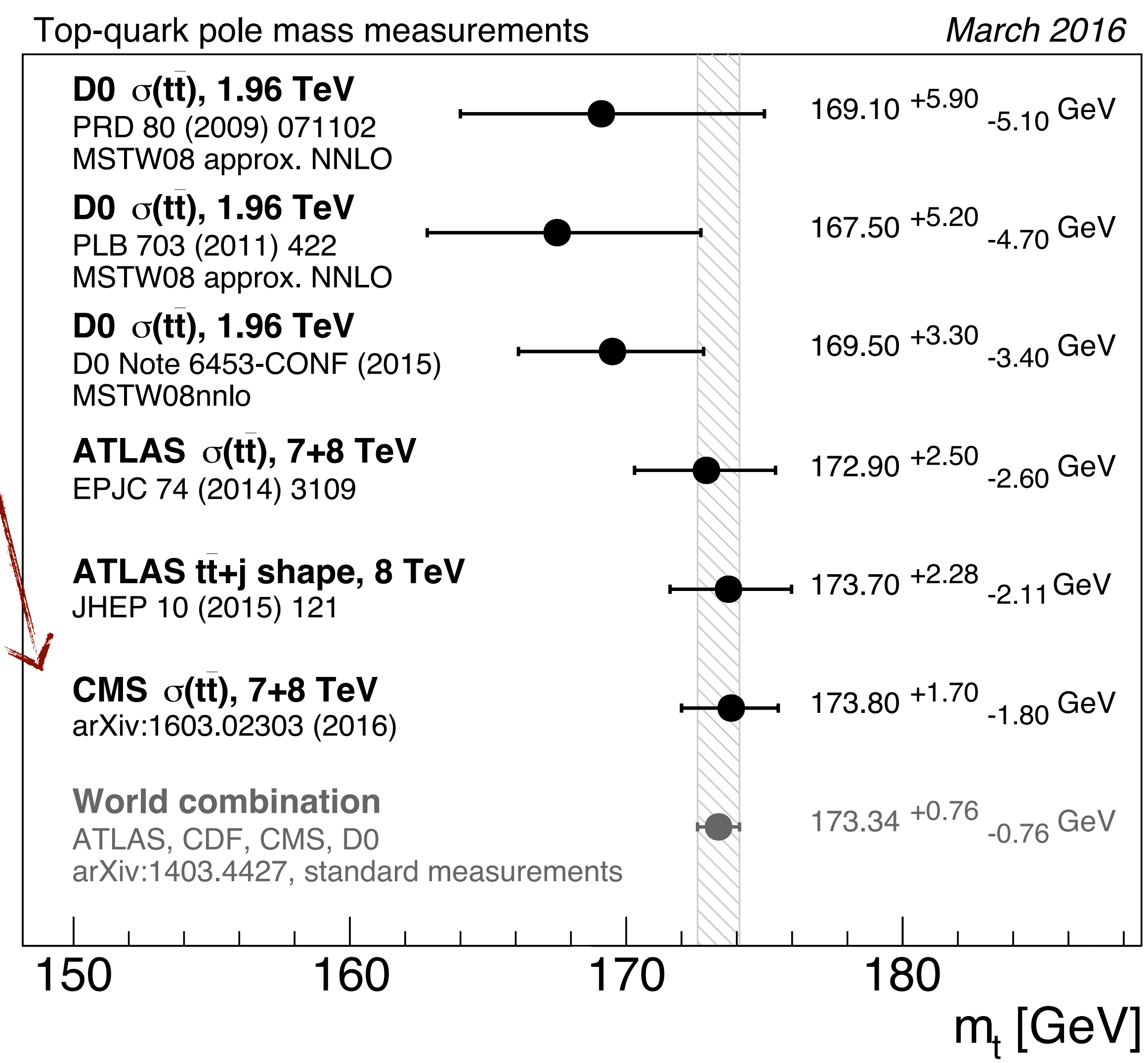
Δm/m=1%

NEW arXiv:1603.02303 *sub to JHEP*



- How far do we need go experimentally?
  - assuming current $\delta\sigma_{th}^{NNLO} \approx 5.5\%$ PRL110 (2013) 252004
  - may reach $\delta m_t^{pole} \approx 0.5\%$ if $\delta\sigma_{exp} \approx 2\%$

For more details on top mass see - B. Stieger's talk



(Pedro Ferreira da Silva @ Moriond 2016)

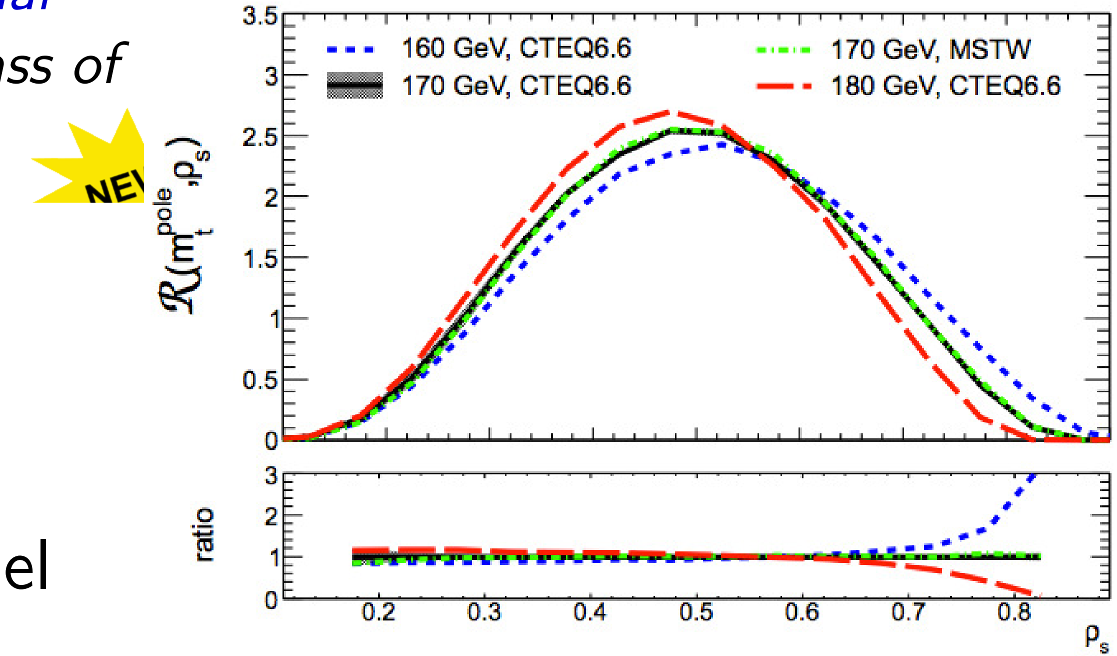
M_{top} alternative measurements (II)

$\Rightarrow$ *exploit m_t^{pole} dependence of normalised $t\bar{t}$+1-jet differential cross-section, as a function of the inverse of the invariant mass of $t\bar{t}$+1-jet system*

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1-\text{jet}}} \frac{d\sigma_{t\bar{t}+1-\text{jet}}}{\rho_s}(m_t^{pole}, \rho_s)$$

$\sqrt{s} = 7$ TeV (L = 4.6 fb^{-1}), ℓ+jets channel

Eur.Phys.J C73 (2013) 2438



▷ kinematical event reconstruction to identify W- and t-candidates, "additional jet" with $p_T > 50\,\mathrm{GeV}$

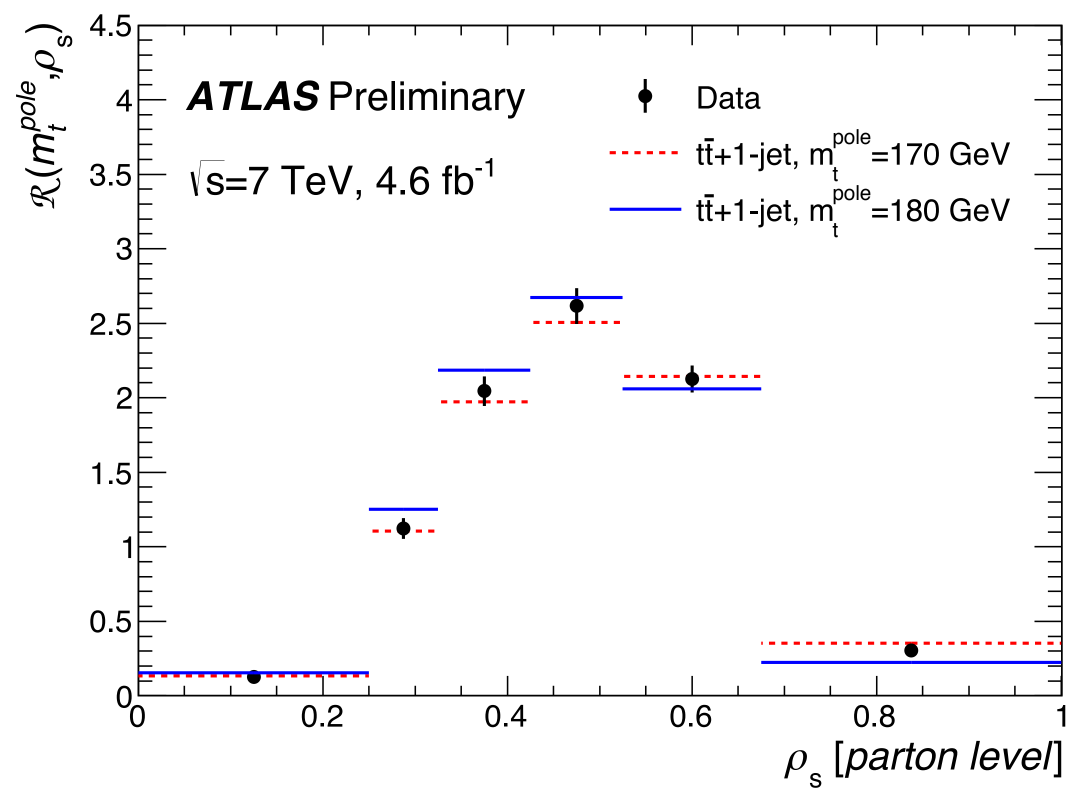
▷ regularised matrix unfolding to correct for detector effects *& extract shape of R*

▷ fit with NLO+PS prediction:

$$m_t^{\rm pole} = 173.7 \pm 1.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})\,^{+1.0}_{-0.5}(\text{theo.})\,\text{GeV}$$

- ▷ dominant sources of systematic uncertainty:
  - ▷ JES: 0.94 GeV
  - ▷ ISR/FSR: 0.72 GeV
  - ▷ proton PDF: 0.54 GeV

ATLAS-CONF-2014-053



(see S. Adomeit, TOP2014)

M_{top} alternative measurements (III)

- **in single top events**
  - enriched single top sample with template method
  - ATLAS-CONF-2014-055
  - $m_t = 172.2 \pm 0.7\,(\text{stat.}) \pm 2.0\,(\text{syst.})$ GeV

- **Kinematic endpoint**
  - ▷ use transverse mass of $t\bar{t}$ pair

$$M_{T2} \equiv \min_{\mathbf{p}_T^{\nu a} + \mathbf{p}_T^{\nu b} = \mathbf{p}_T^{miss}} \{\max(m_T^a, m_T^b)\}$$

  - use only components perpendicular to the boost of the $t\bar{t}$ pair:

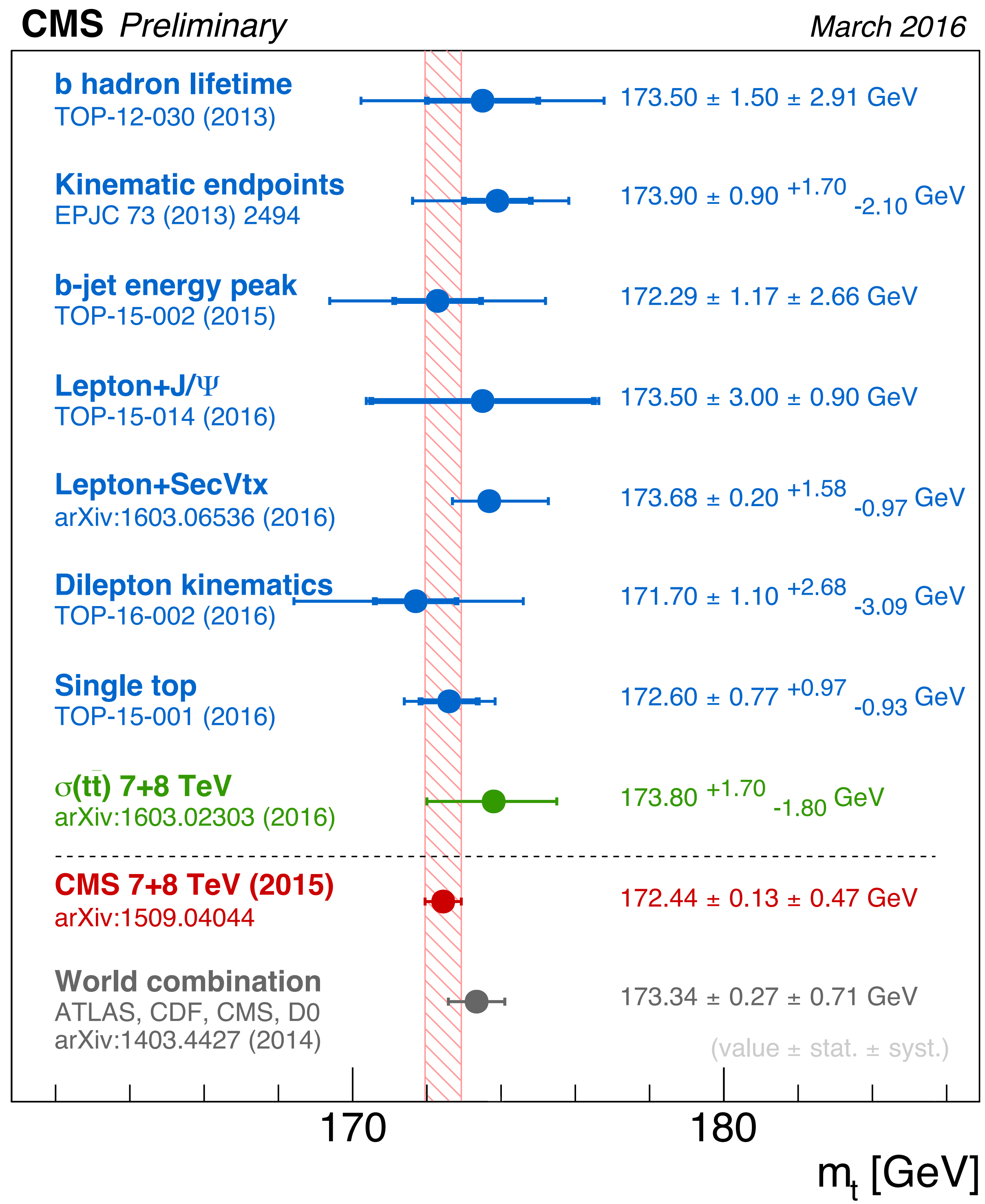
$$M_{T2} \to M_{T2\perp} \equiv \mu_{bb}$$

  - ▷ endpoint: $\mu_{bb}^{max} = m_t$

- **Dependence on B-hadron lifetime**
  - no Monte Carlo
  - ▷ lifetime and (transverse) decay length (L_{xy}) of B-hadrons from the top decay depend ~linearly on m_t
  - ▷ similarly, p_T of the charged leptons from the W boson decay can be used

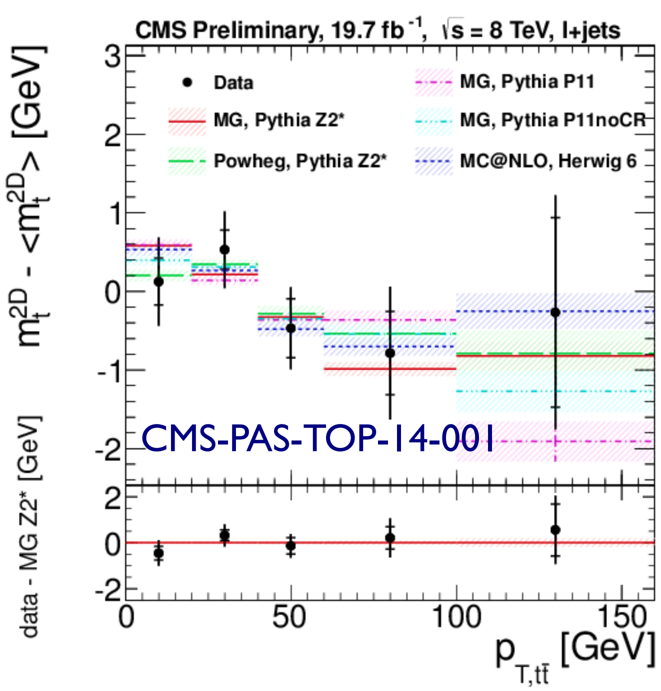
- **J/Psi final state**
  - independent of jet scaling factor
  - ▷ select $t\bar{t}$ events with $b \to J/\Psi$ $(+J/\Psi \to \ell\ell)$
  - ▷ exploit m_t dependence of $M_{J/\Psi+\ell}$ (Phys. Lett. B 476 (2000) 73)

(see S. Adomeit, TOP2014)

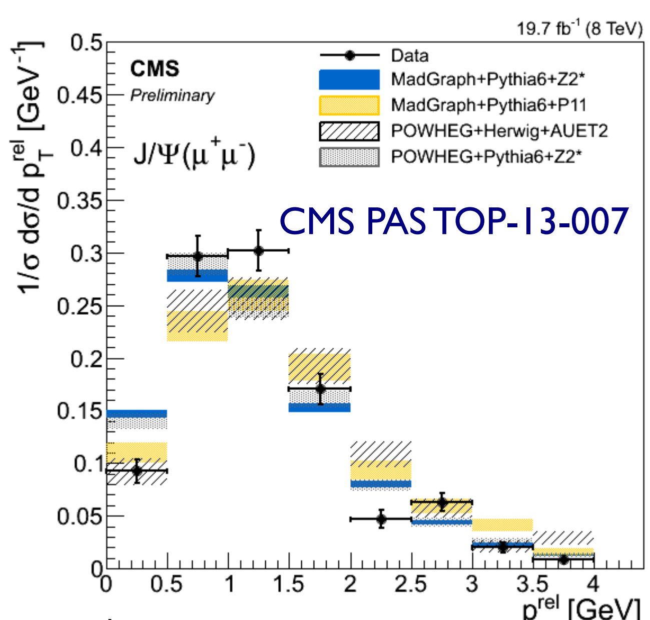


- The most ~~fundamental~~ ~~crucial~~ ~~interesting~~ ambiguous parameter of the standard model
- Most **measurements rely on** an intrinsic **calibration to** a LO/NLO **MC** definition
  - may assume that ambiguity can in principle be resolved up to $O(\Lambda_{QCD})$ – *see A. Hoang's talk*
  - e.g. measure mass in MC, use observables calculated in well defined schemes, use short-range definition
  - from the experimental point of view **Run 2 and HL-LHC have potential for more precise m_t**

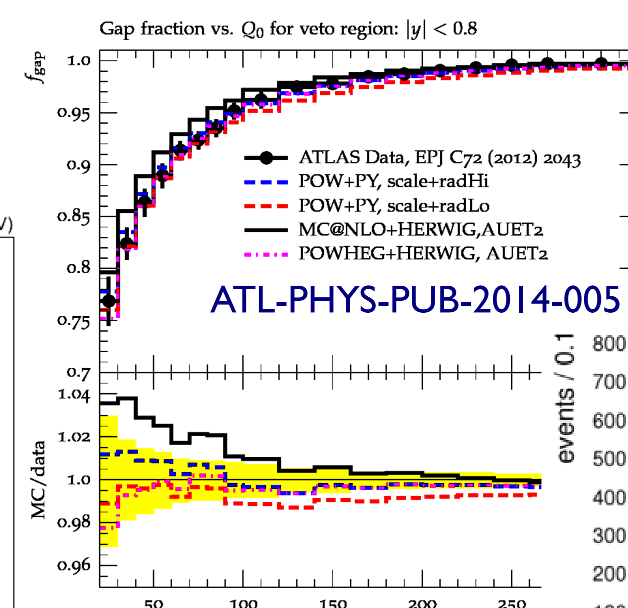
Diff. m_t measurements
constrain in-situ main uncertainties



Measurements of the UE and fragmentation in tt:
tune signal model with data

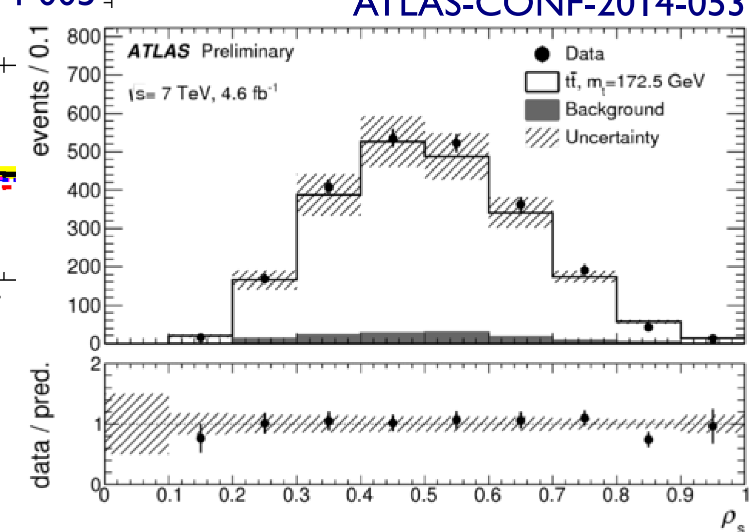


Measurements of radiation in tt
constrain pQCD signal model uncertainties



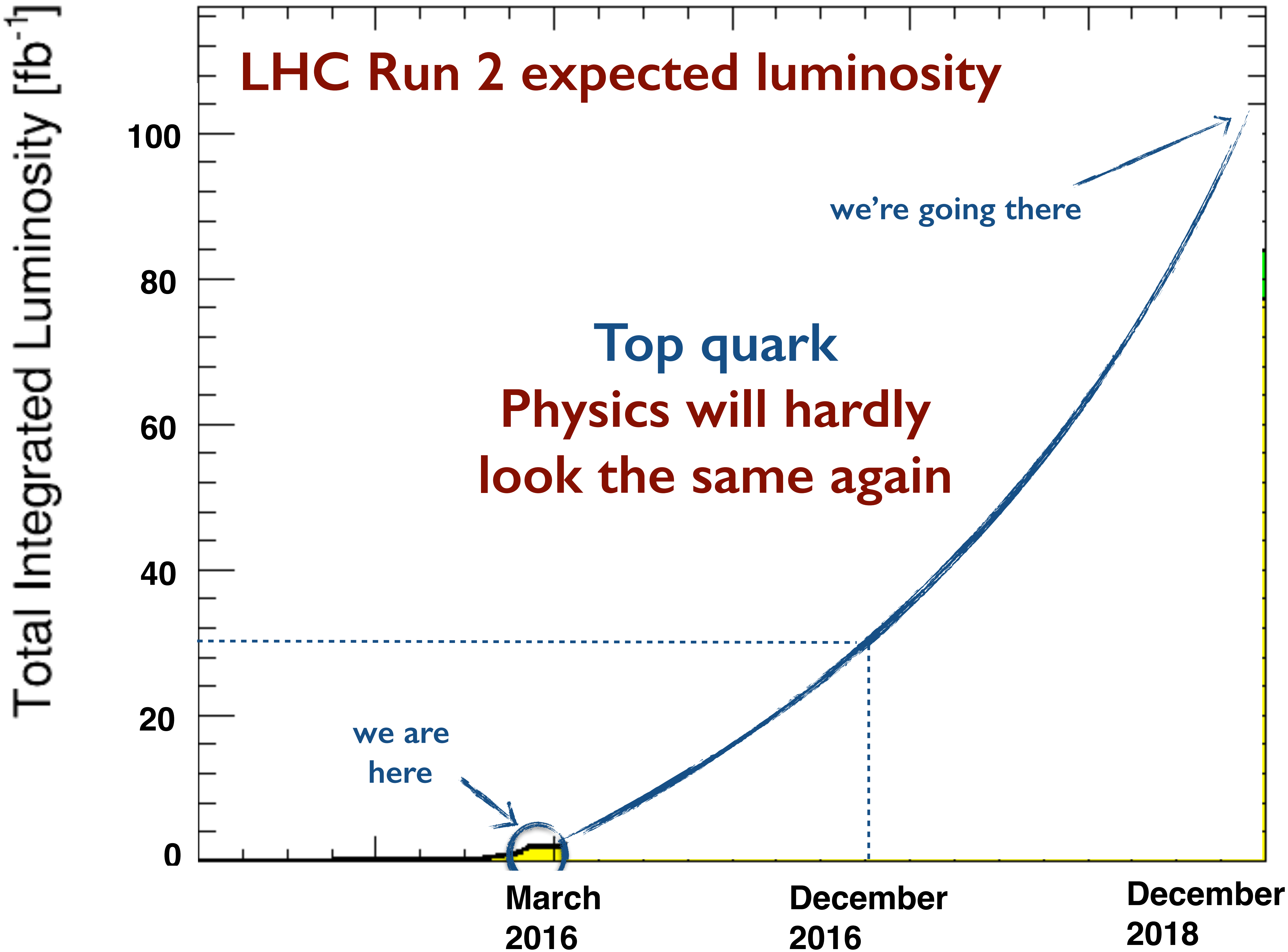
$$f(Q_0) = \frac{n(Q_0)}{N}$$

Alternative methods
Improve precision on "theory safe" observables, profit from high stats and also NNLO signal modelling



(P. Ferreira da Silva @ Top2014)

Significant words by Pedro…



(Pedro Ferreira da Silva @ Moriond 2016)

Conclusions and Outlook

- **Top analysis is in full swing** thanks to the combined performance of LHC & detectors: **a very rich program is under way.**
- *By exploiting the LHC top quark factory* (~6 (~4)M tt, ~3 (1.5)M single top events produced by LHC @ √s=8 (13) TeV) **ATLAS & CMS are testing top strong and electroweak inclusive production at unprecedented precision at new energies centre**
  - **$\delta\sigma_{tt}/\sigma_{tt}$** ~O(3.5 to 5%) compared to ~4% prediction uncertainty (NNLO+NNLL)
  - **$\delta\sigma_{t}/\sigma_{t}$** : s-chan, t-chan and Wt observed. $|V_{tb}|$ consistent with 1 at 4% level
- **Differential cross sections measurements test SM tt production and complement new physics searches in completely new phase space** with O(5%) to O(40)% relative unc. Expect higher reach in Multi TeV region with reduced syst uncertainties, due to parametrization/understanding of more phase space corners & improvement in MC generators (NNLO).
- The **top mass** is measured at O(0.5)% level. sub-GeV precision if progress is made on syst uncertainties exploiting differential info.
- Spin determination in top quark production (tt spin correlations) and decay (W polarization, Wtb vertex properties) are consistent with SM
- **Direct determination of top** quark **coupling to bosons is consistent with SM even if with limited number of events . Measurement of the coupling to the** the newly found **Higgs** boson is still limited by number of events. Run2 expects observation with high luminosity.
- **New physics** connected to top quark by resonances/asymmetries and top rare decays to Higgs boson **is being searched in previously unexplored 2-3 TeV/O(0.1) pb regions** of mass and cross sections: reach to be extended in multi-TeV region with pile-up mitigation techniques & improved syst uncertainties

References and useful workshops

TOP Workshop series

- TOP2015:8th International Workshop on Top Physics
- TOP2014:7th International workshop on Top Physics
- TOP2013: 6th International workshop on Top physics
- Top2012: 5th International workshop on Top physics

LHC TopWG agenda

LHC & Tevatron experiments public results

- Top Public results from ATLAS
- Top Public results from CMS
- Top Public results from CDF
- Top Public results from D0

Additional (useful) references

- A. Quadt, *Top quark physics at hadron colliders*, Eur. Phys. J. C 48, 835–1000 (2006) DOI 10.1140/epjc/s2006-02631-6
- A J,. Khun, *Theory of Top Quark Production and Decay*, http://arxiv.org/abs/hep-ph/9707321v1
- S Willembrock,*THE STANDARD MODEL AND THE TOP QUARK*, http://arxiv.org/abs/hep-ph/0211067v3
- Chris Quigg, *Top-ophilia*,FERMILAB-FN-0818-T

and references therein