Top quark phenomenology at the LHC

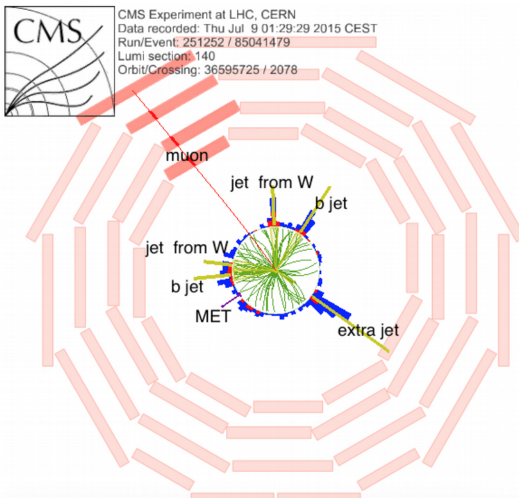
LFC 2017: old and new strong interactions
from LHC to Future Colliders

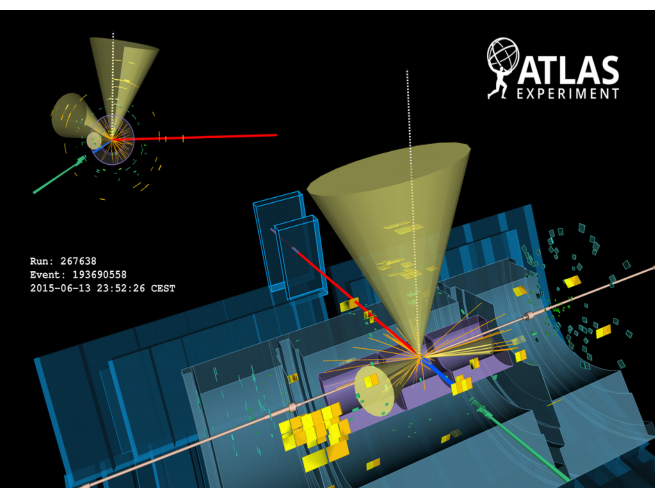
ECT, Villa Tambosi, Villazzano (Trento)
13/9/2017

Alberto Orso Maria Iorio

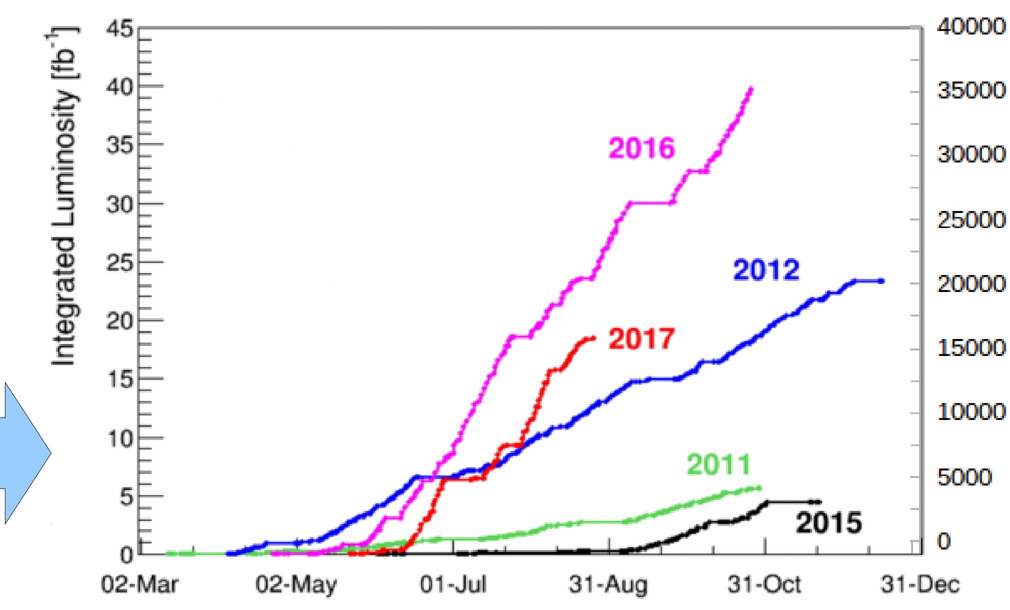
Top quarks at LHC and beyond

LHC: a top quark factory? **Yes indeed...**





x10³ top quark pairs at 13 TeV pp



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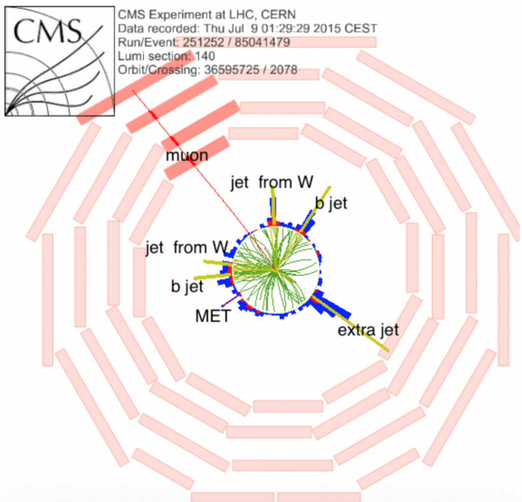
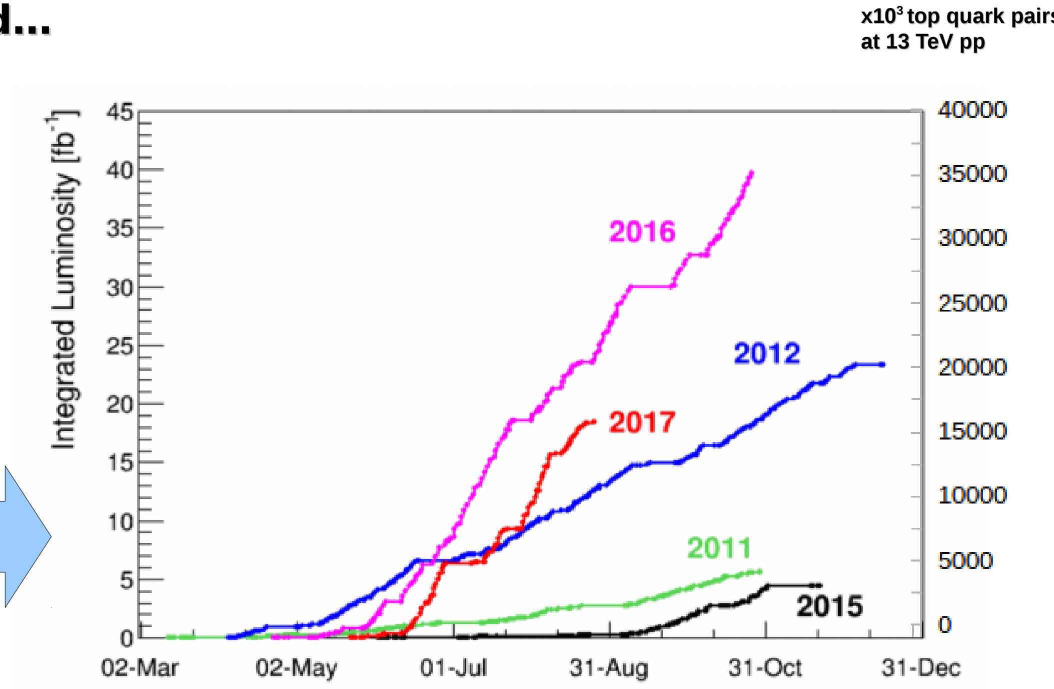
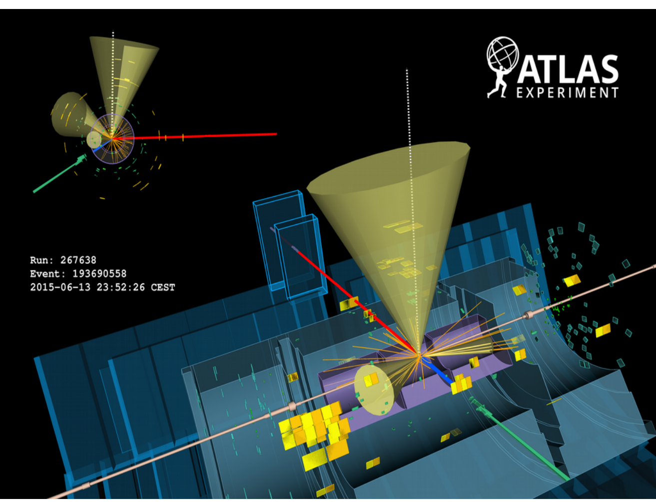






→ top quarks are part of our toolbox for studying SM and BSM

Pert. QCD, PDF, hadronisation → cross sections, decay properties
Coupling properties → α_S, top quark polarisation, w-helicity
Fundamental parameters → Top quark mass, charge, Vtb
Search for new physics → Associated production, FCNC.

Outline

- **Introduction on top quark:**
  - production mechanisms
  - detection channels

- **Top quark measurements:**
  - strong production:
    - inclusive measurements and interpretation
    - differential measurements and properties
    - MC tuning and PDF measuremetns
  - electroweak single top production
  - top quark mass
  - spin properties

More results can be found here:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
https://lhcb.web.cern.ch/lhcb/Physics-Results/LHCb-Physics-Results

DISCLAIMER! The top quark physics at LHC is an ever-growing and expanding field: there is a plethora of aspects that for brevity couldn't be summarized here

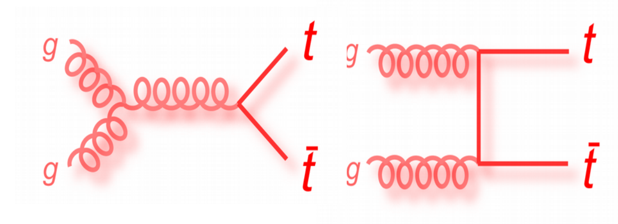
→ Additional material, including projections and

top-quark production in the standard model @LHC

Production mechanism… | **…cross section…** | **…LO diagrams**

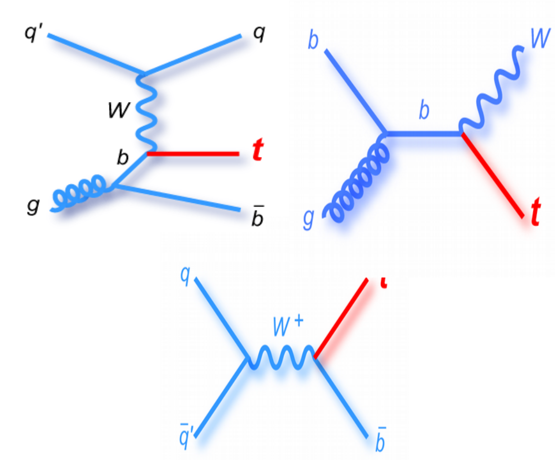
- **tt pairs** via strong interaction:
  - dominant at the LHC and Tevatron
  - depends on α_S
  - sensitive to pdf

LO ∝ $(\alpha_s/m_{top})^2$
pp collisions @7/8/13 TeV:
~172/246/830 pb

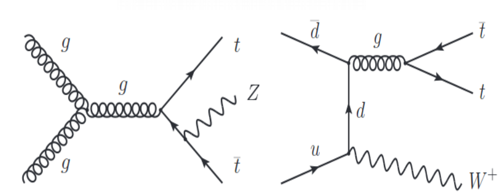


- **single-tops:**
  - weak charged current interactions
  - *t*-, *s*-channel and W-associated
  - tWb vertex in production
  - Sensitive to Vtb

LO ∝ $(\alpha^*|V_{tb}|)^2$
pp collisions @7/8/13 TeV:
~ 66/85/217 pb (*t*-ch.)
~ 15/22/72 pb (tW)
~ 4.4/5.5/11 pb (*s*-ch.)

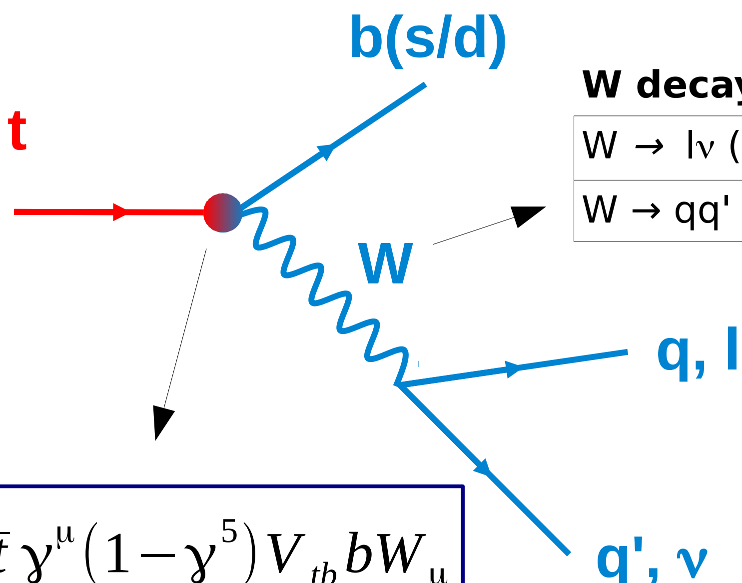


- **top + X :**
  - top pair and single top + W, Z,γ…
  - way to probe neutral current vertices involving top quark

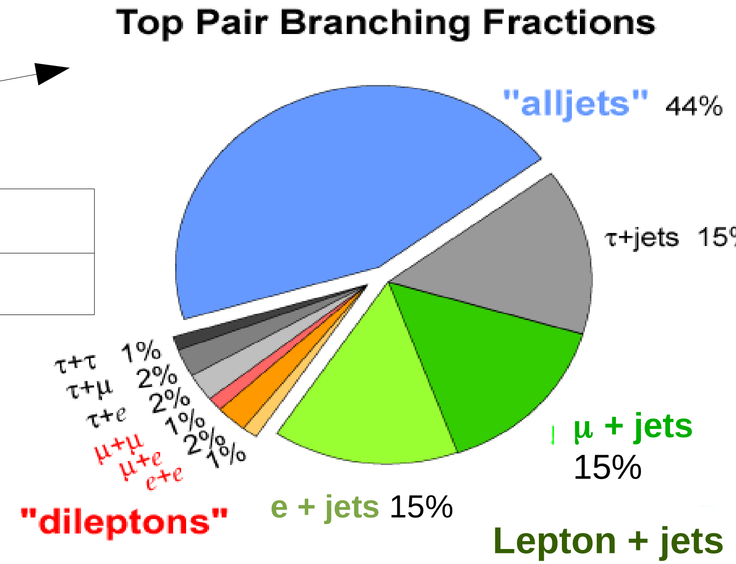


top-quark decays

- **Main mechanism is electroweak: no hadronisation**



W decay:	BR:
W → lν (any)	0.32
W → qq' (any)	0.68



$$\frac{-ig}{2\sqrt{2}}\bar{t}\,\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}\,b\,W_{\mu}$$

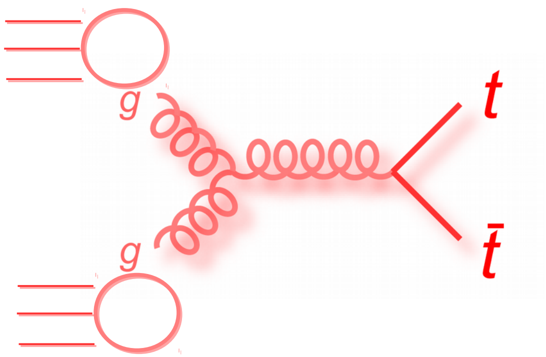
- Electroweak **tWb vertex:**
  - V-A: **polarization** of the products and defined **W-helicity**
  - CKM matrix element $|V_{tb}|\sim 1 \rightarrow \Gamma(t \rightarrow b) >> \Gamma(t \rightarrow s,d)$

$1/m_{toq}$		$1/\Gamma_t$		$1/\Lambda$		m_t/Λ^2
production	<	lifetime	<	hadronization	<	spin decorrelation

tt production

Top quark pairs physics snapshot

Pair production: what can we learn?



→ PDF α_S M_{top}
→ Spin correlations

→ Pert. QCD at higher orders
→ PS tuning

→ Top width
→ M_{top} from decays
→ V-A in decays

→ Model for hadronisation

For each of our measurements:
- **How sensitive** are we?
- Where can we **push the envelope**?

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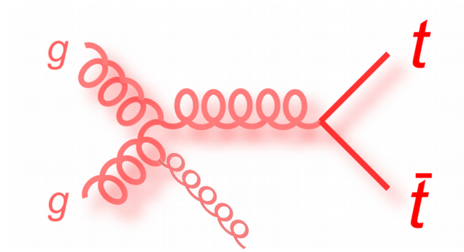

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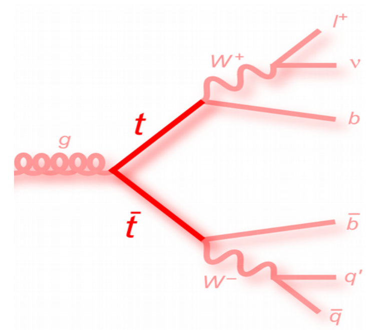

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→ M_{top} from decays
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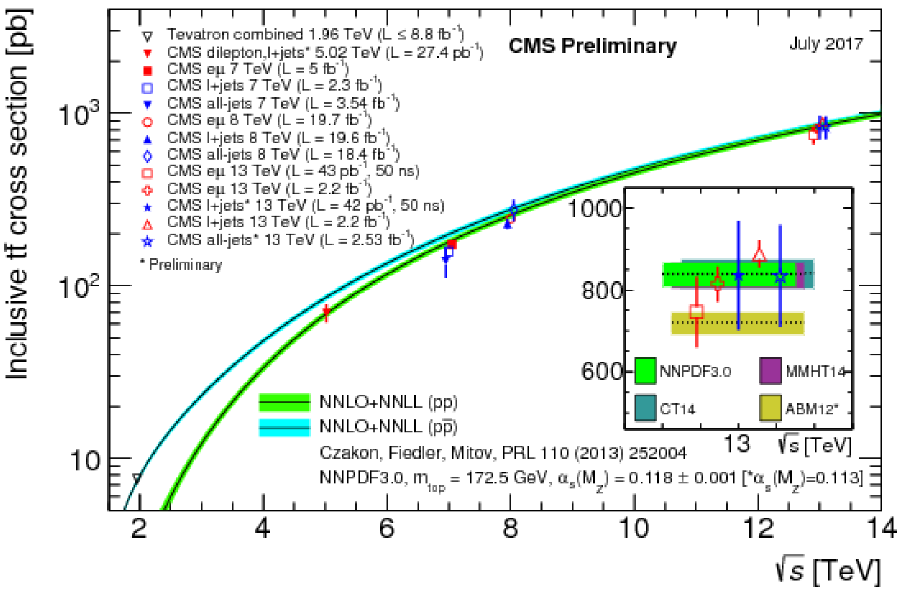
PDF, as and Mtop through inclusive measurements:

- **tt** inclusive measurement now reached ~1-2% precision
- Measurements **across energies:**



ATLAS-CONF-2017-054

8 TeV
248.3 ±0.7(stat) ±12.8(syst) ±4.7 (lumi) **Atlas**
244.9 ±1.4(stat) $^{+6.3}_{-5.5}$ (syst) ±6.4 (lumi) **CMS**

J. High Energy Phys. 08 (2016) 029

Phys. Lett. B761 (2016) 136

13 TeV
818 ±8(stat) ±27(syst) ±19 (lumi) **Atlas**
888 ±2(stat) ±28 (syst) ±20 (lumi) **CMS**

arXiv:1701.06228

- Relevant common uncertainties:

→ luminosity, lepton efficiency,background normalisation **CMS**
→ MC Modeling, luminosity, lepton efficiency **Atlas**

Measurements interpretation: top-quark pole mass

- **Re-interpretation of cross section measurements:**

- top mass m_{top} parameter in the MC :depends on the renormalisation scheme used

- can be taken from the cross section parametrisation (example from cms)

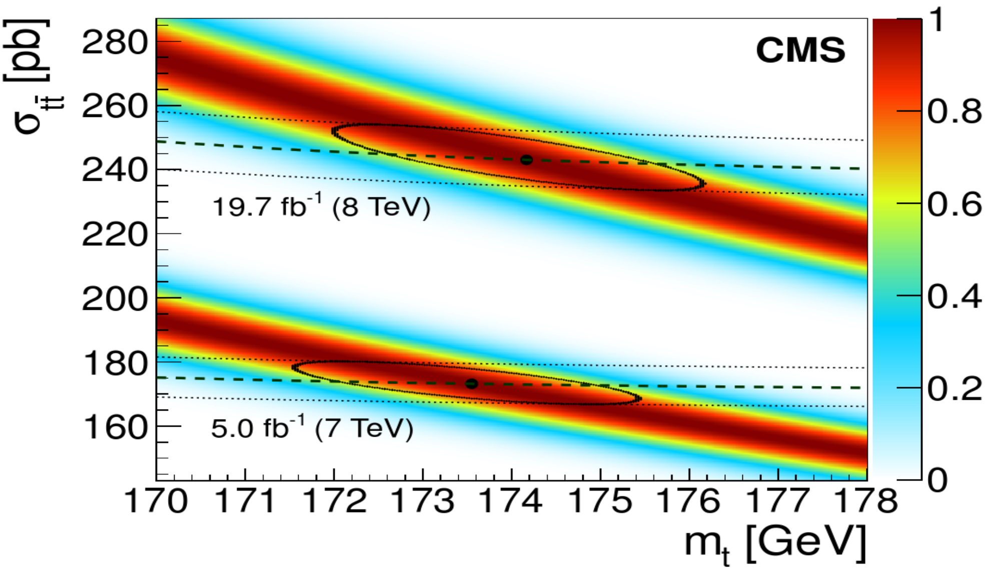
- uncertainties from cross section measurement: luminosity, background yield, lepton reconstruction

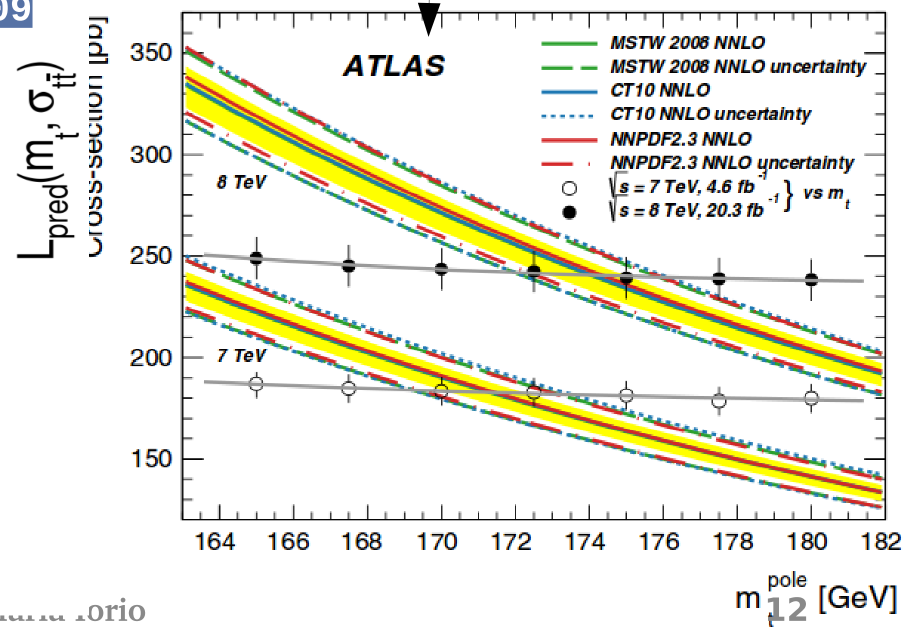
$$\sigma_{t\bar{t}}(7\,\mathrm{TeV}, m_t^{MC}) = \exp\left[-0.1718\,(m_t^{MC}/\mathrm{GeV} - 178.5)\right] + 170.9\,\mathrm{pb}$$

$$\sigma_{t\bar{t}}(8\,\mathrm{TeV}, m_t^{MC}) = \exp\left[-0.1603\,(m_t^{MC}/\mathrm{GeV} - 185.4)\right] + 237.0\,\mathrm{pb}$$

JHEP 08(2016)029

Eur.Phys.J.C74 (2014)3109





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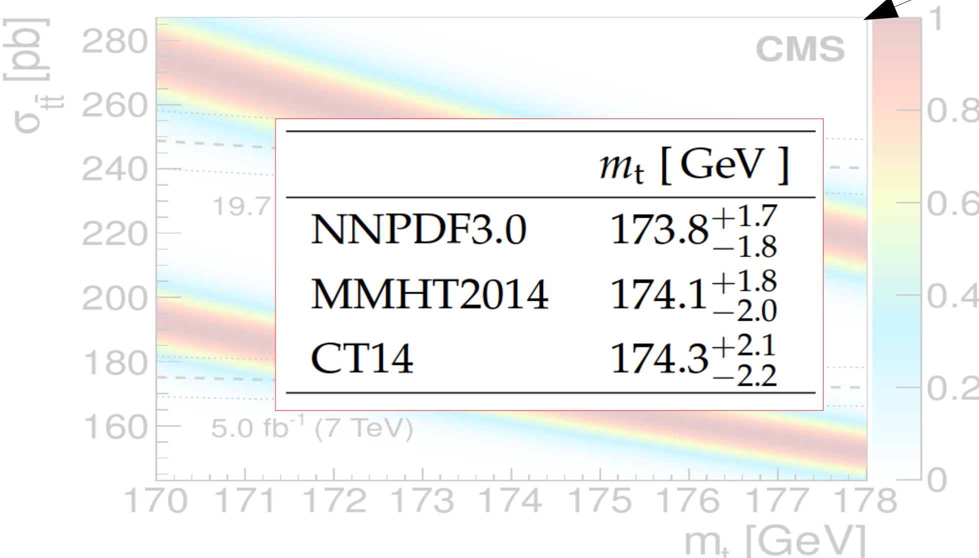
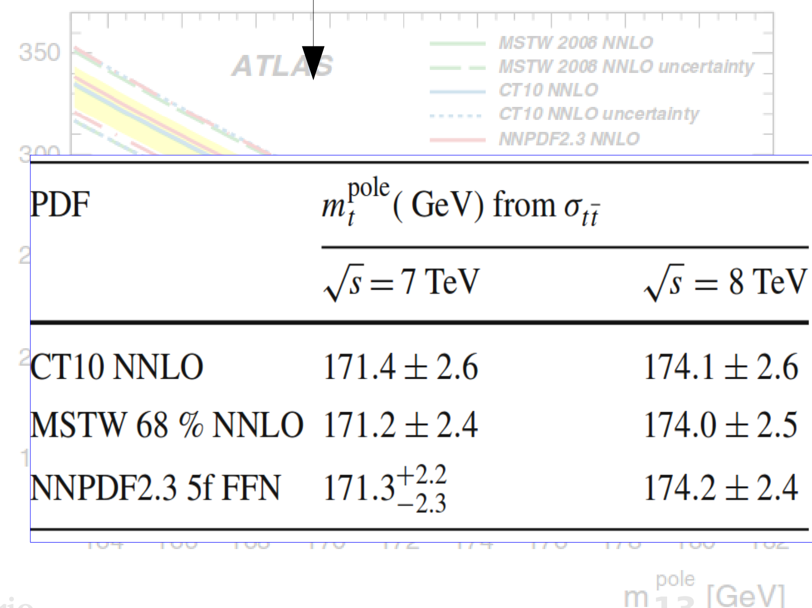


	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$



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

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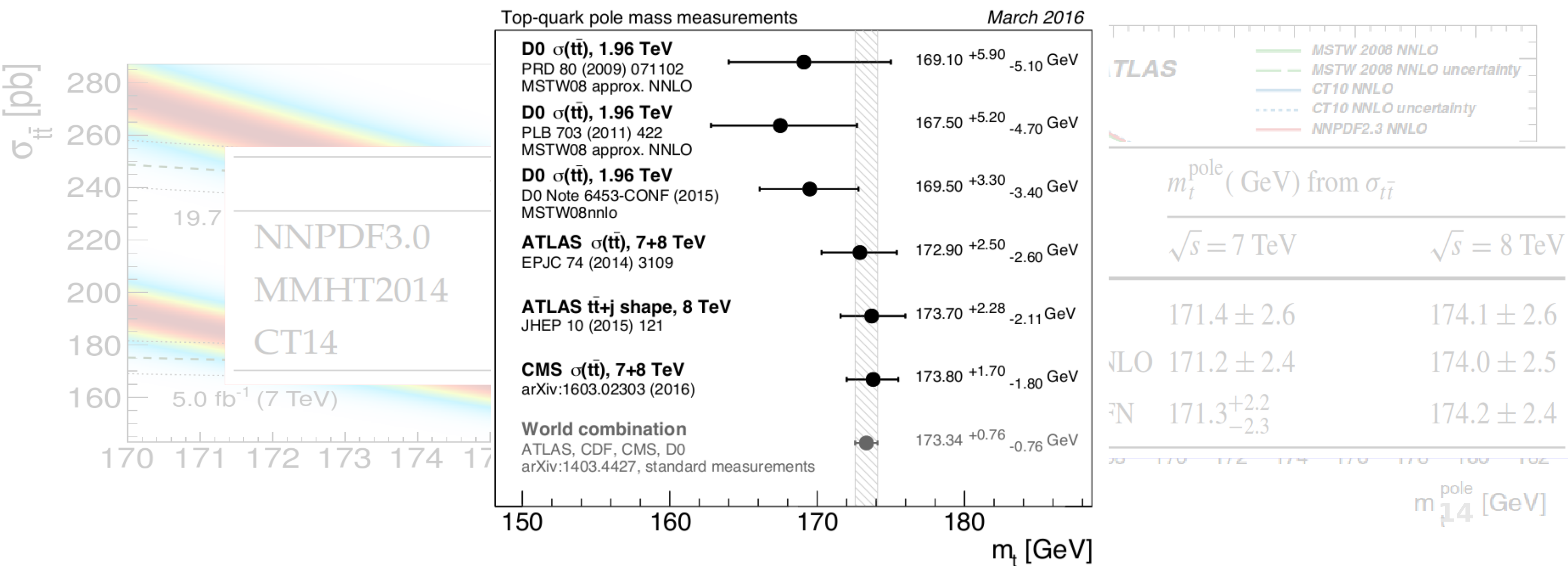
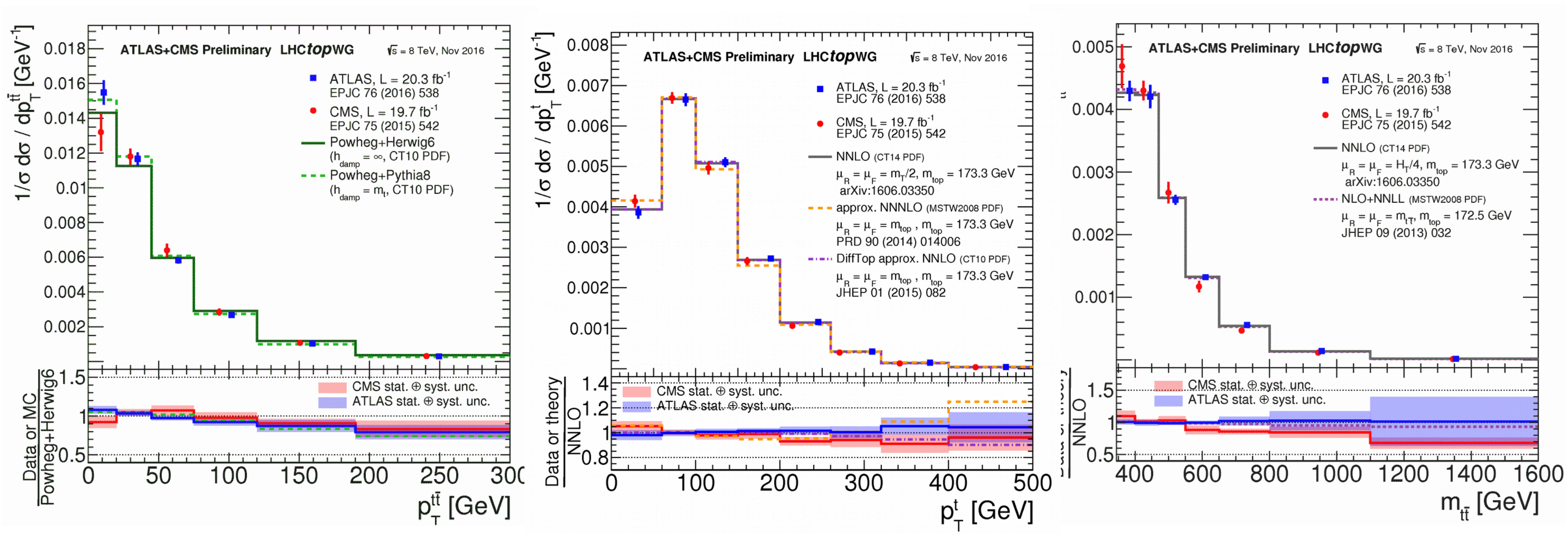


Differential measurements: the tt - pt conundrum

- Discrepancy in **top quark pair system pt spectrum** seen across the years,

→ present since the early years: no clear explanation yet.

→ Difference in rapidity as well.



- CMS adds a reweighting for the top pair momentum

- Atlas finds out slightly harder spectra for the top P_T and m_{tt}

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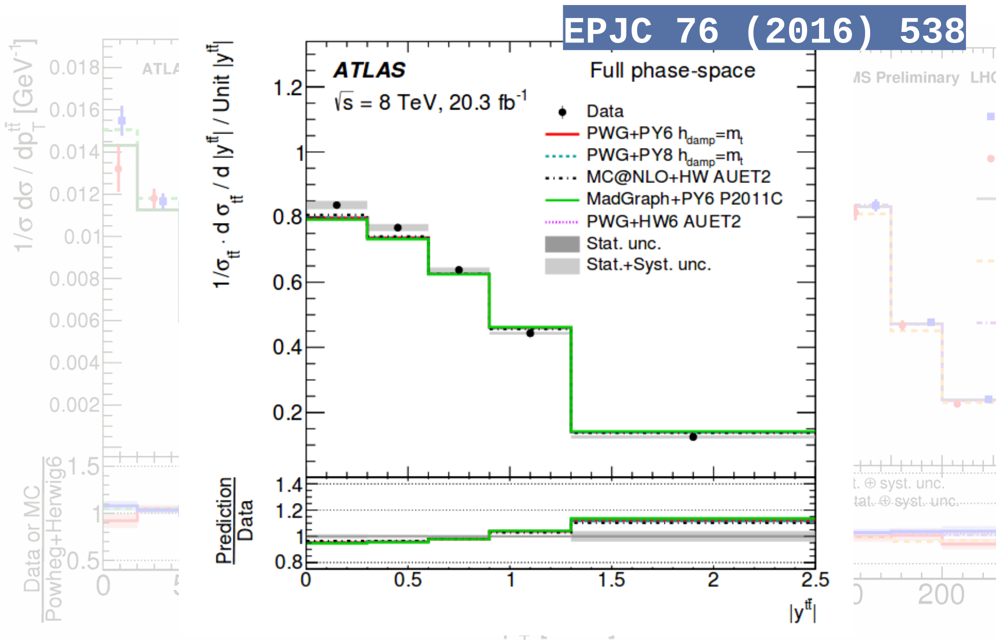

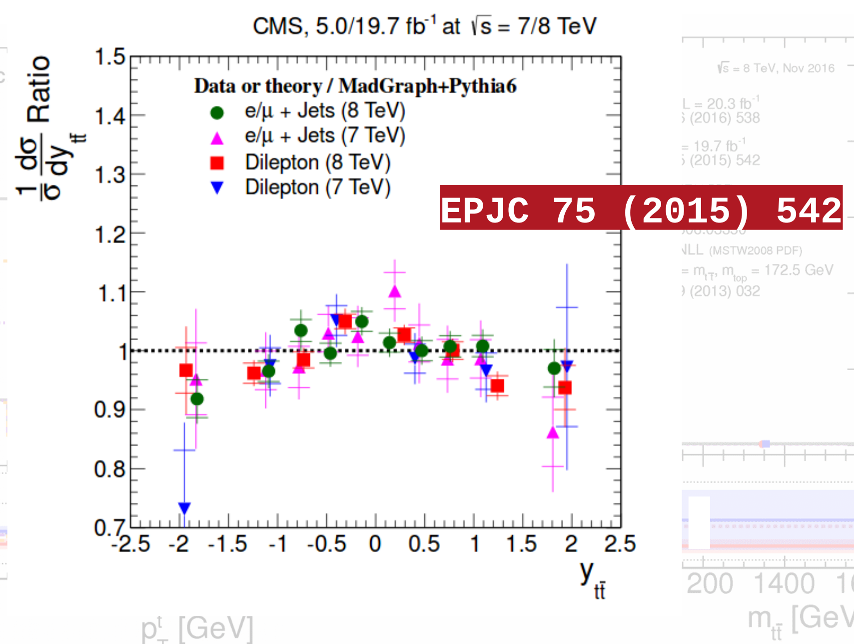

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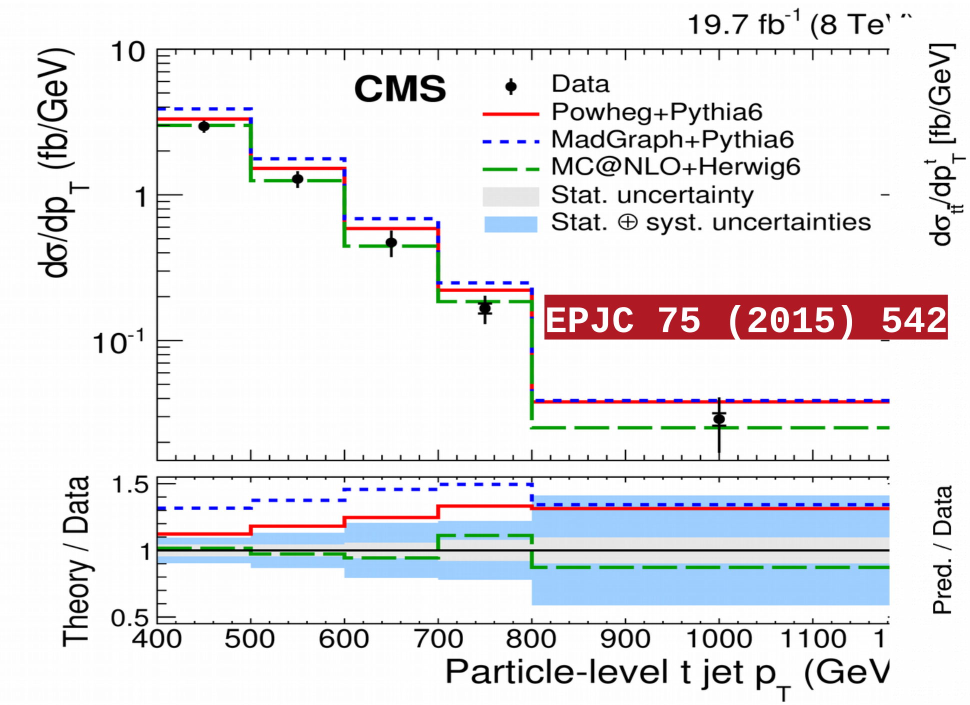
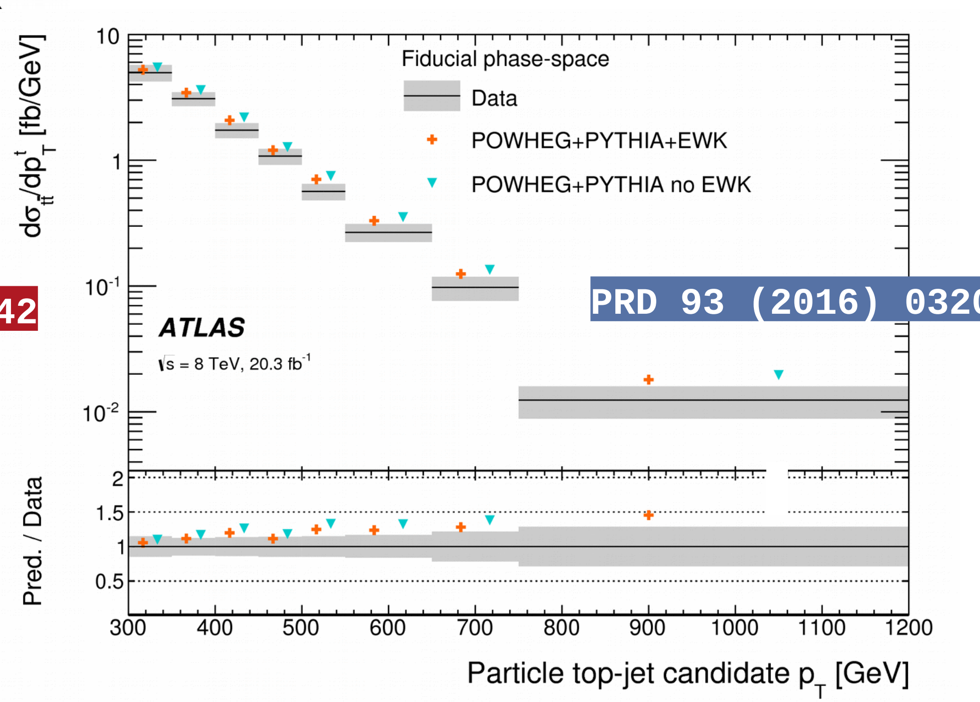
Differential measurements:
tt pt for boosted top quarks

- In boosted topologies (top quarks clustered into an AK8 jet) the trend **is present as well**.
- Measurements at 13 TeV to confirm the trend.

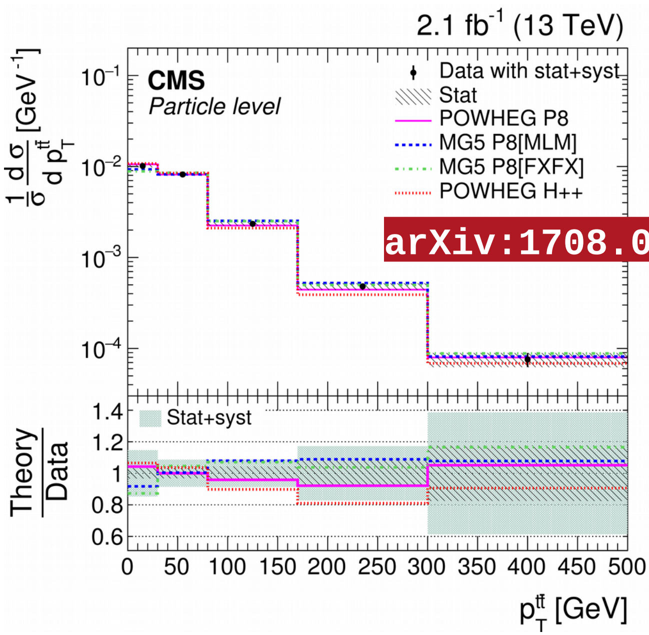




- At 13 TeV will be even more important.

→ Crucial for new physics searches as well!

Differential measurements @13 TeV



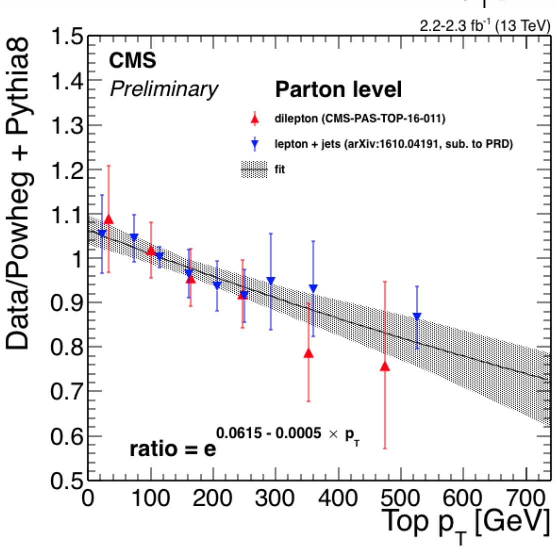
arXiv:1708.07638

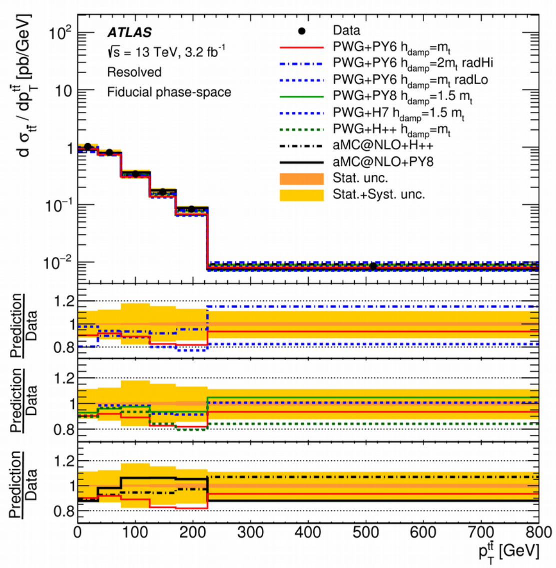
- Measurements from 2015, low statistics data set
→ still enough to be used for model tuning

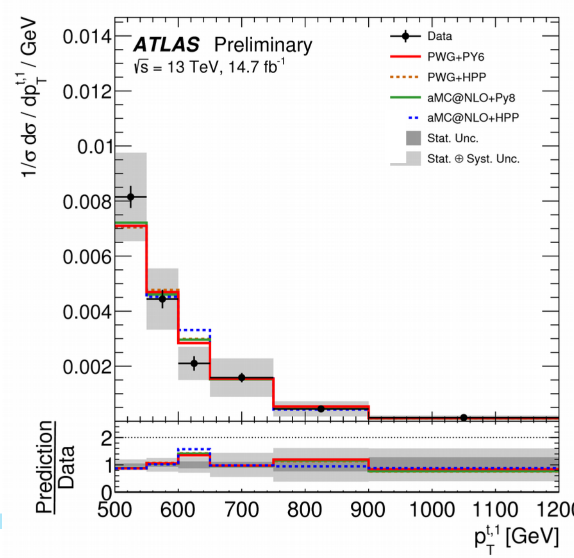
- Higher precision will exploit 2016 data

- Similar trends for top pt and highly boosted regime

arXiv:1708.00727







Differential measurements and PDFs

- **Differential distributions** can be used for pdf constraints → double differential to improve sensitivity

- highest impact is on **high-x gluon PDF**

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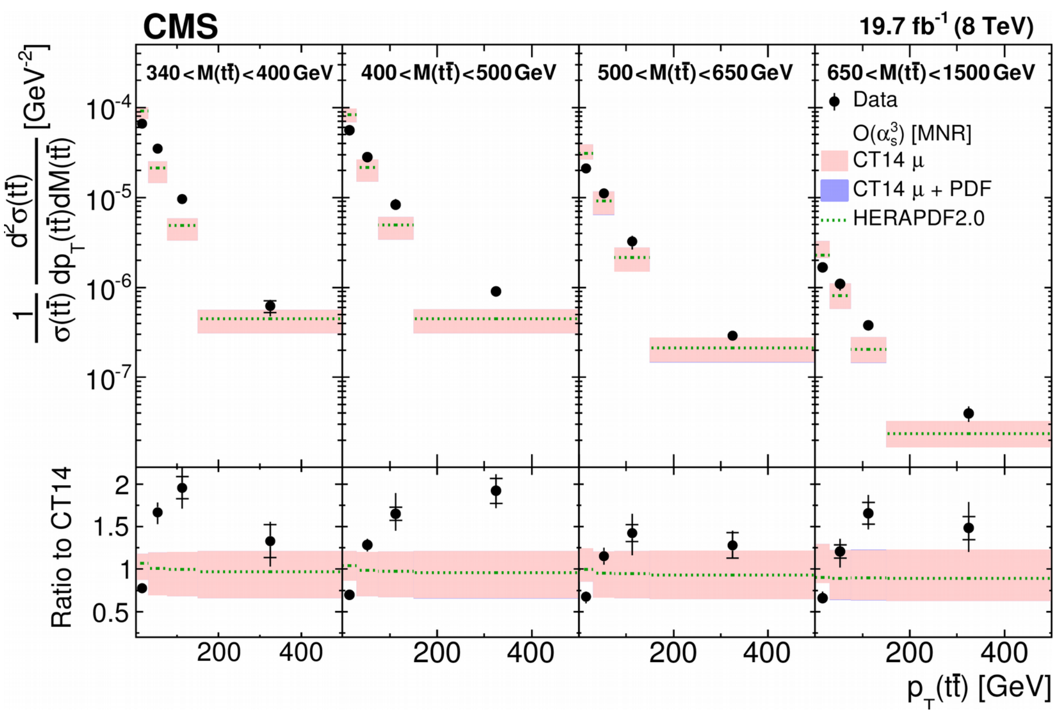
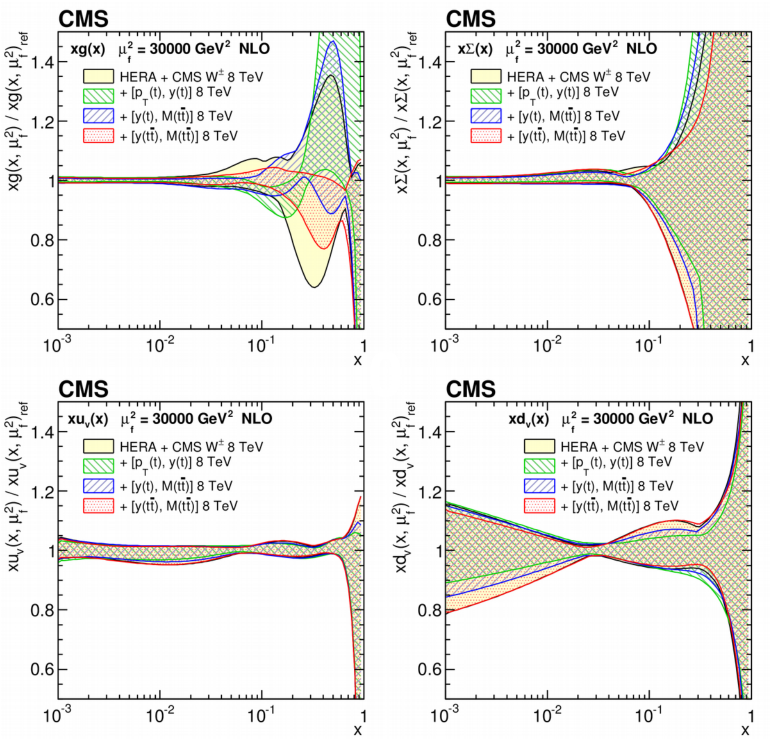
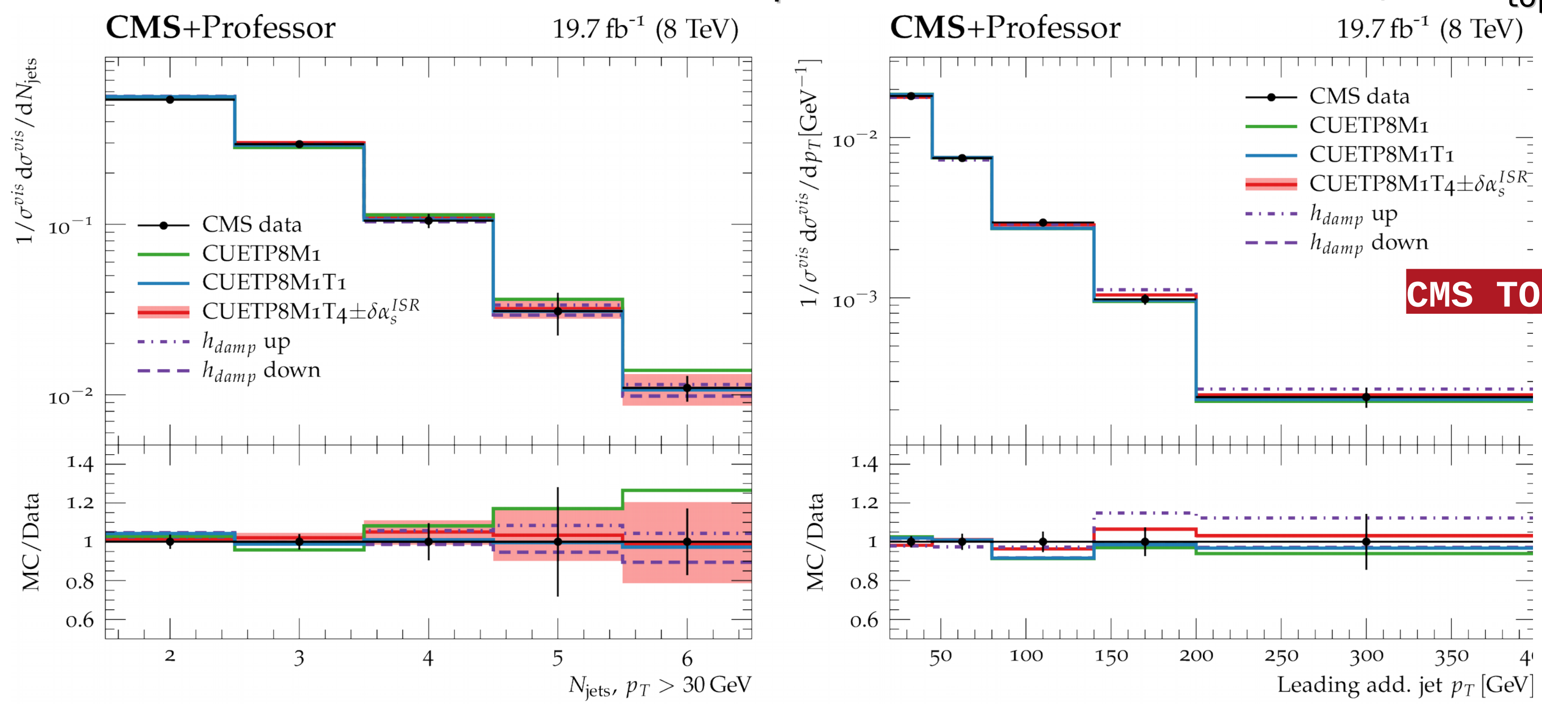




Use of tt events for MC tuning

- Jet multiplicity discrepancy with initial configuration of Run-I: POWHEG + Pythia8 with **CUETP8M1** α^{ISR}= 0.1365, hdamp = 172.5 GeV (== m_{top})
- New tunes developed with: **CUETP8M1T4** α^{ISR}= 0.1108 +0.0, hdamp = 1.581 +0.658-0.585 GeV (== m_{top})



(a) (b)

CMS TOP-16-021

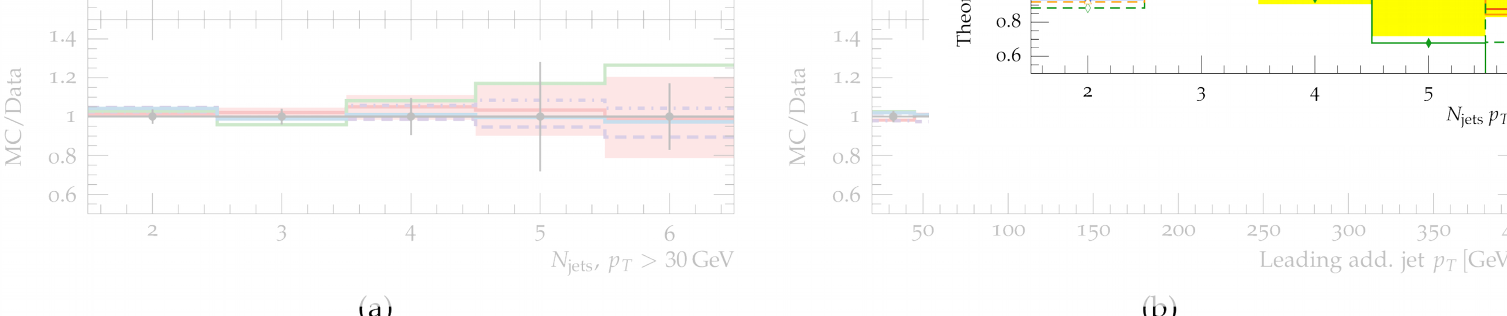
Use of tt events for MC tuning

- Previous default:

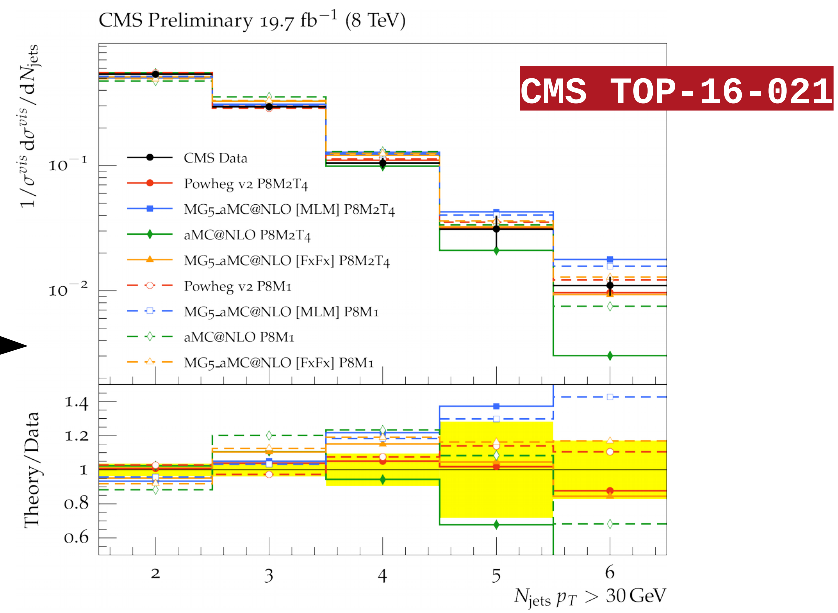
CUETP8M1 α^{ISR}= 0.1365, hdamp = 172.5 GeV (== m_{top})

- New tunes:

CUETP8M1T4 α^{ISR}= 0.1108 +0.0, hdamp = 1.58



	CUETP8M1	CUETP8M2T4
Tune	pp 14	pp 14
Tune	ee 7	ee 7
MultipartonInteractions ecmPow	0.2521	0.2521
SpaceShower:alphaSvalue	0.1365	0.1108
PDF pSet LHAPDF6	NNPDF23_lo_qed_as_0130	NNPDF30_lo_as_0130
MultipartonInteractions:pT0Ref	2.40	2.20
MultipartonInteractions:expPow	1.6	1.6
ColourReconnection:range	1.8	6.6



- After this is done, further PYTHIA tuning is performed with PROFESSOR, for the UE, obtaining the parameter used in **CUETP8M2T4**

Single-top production

The single-top production: top in the the electroweak sector

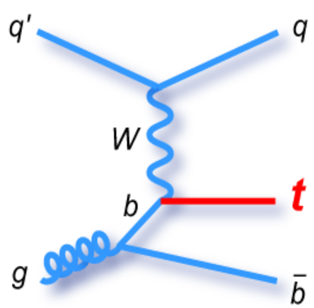
∘ **All ingle-top quark processes:**

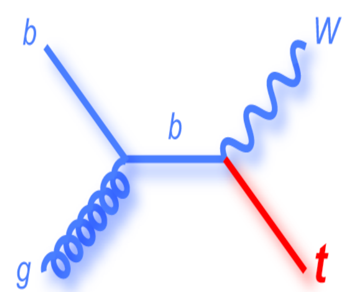
- tWb vertex in production

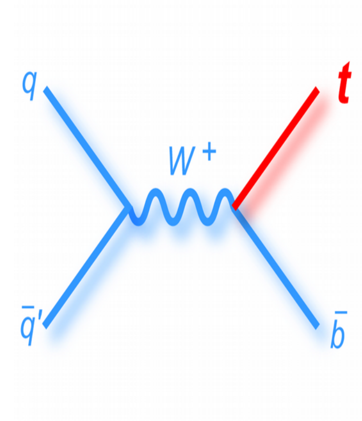
- Top is produced polarised

- non SM couplings can appear in cross section and properties

- All channels cross sections: proportional to $|V_{tb}|^2$



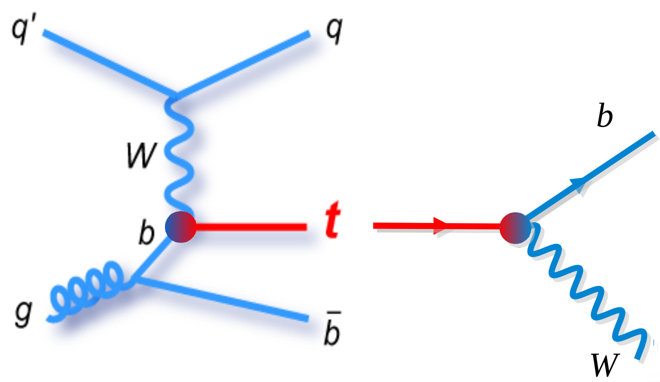




	***t*-channel**	**W associated (tW)**	***s*-channel**
LHC pp @7 TeV(1)(2)	63.9±0.2.7 pb	15.7±1.2 pb	4.29±0.18 pb
LHC pp @8 TeV(1)(2)	85.2±2.2 pb(3)	22.4±1.5 pb	5.24±0.21 pb
LHC pp @13 TeV(1)(2)	217.0±8.4 pb	84.4±4.4 pb	10.32±0.38pb

(1): LHCTopWG: calculations with HATOR, see also https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec
(2): N. Kidonakis Phys. arXiv:1205.3453
(3): M. Burcherseifer, F.Caola, K. Melnikov: arXiv:1404.7116 All with top mass = 172.5 GeV

t-channel Single top production:



- **Most abundant single-top ($\sigma\sim$ 1/3 x σ(tt)):**

- measurement of Vtb in production!

EPJC 77 (2017) 531

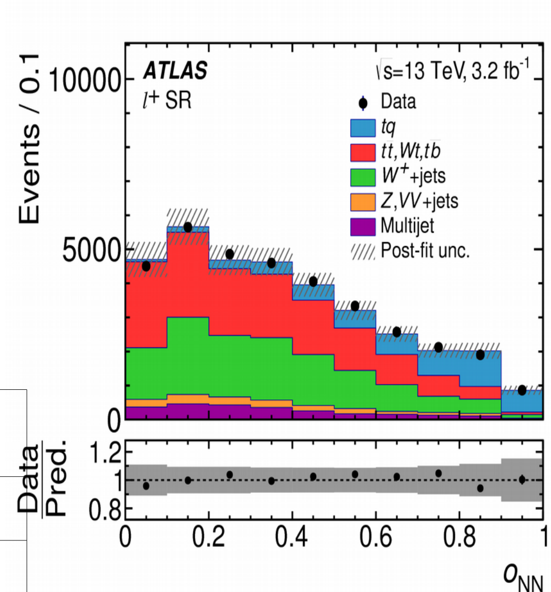
arXiv:1610.00678

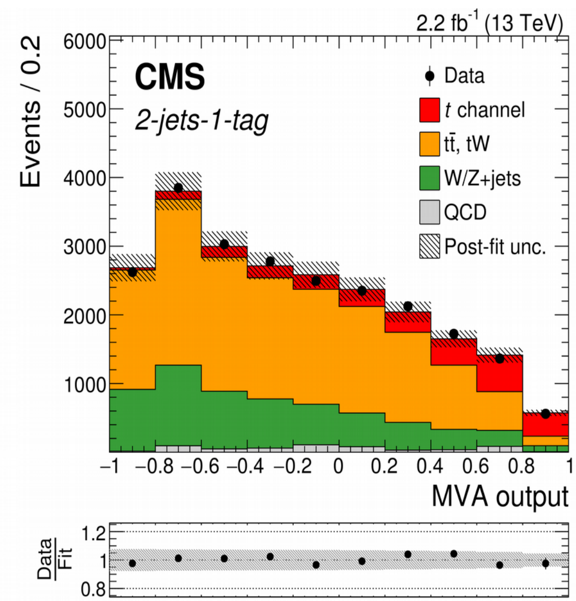
- **Inclusive cross sections:**

→ leptonic only decay channels (1 lepton + 2-3 jets)
→ MVA use for s/b rejection
→ main systs: signal Q2 scale and modeling

$|V_{tb}| = \sqrt{(\sigma_{t\text{-ch.}}/\sigma_{t\text{-ch}}})$:

	Atlas	CMS
7 TeV	1.02±0.07	1.02±0.05
8 TeV	0.97±0.09	0.978±0.04
13 TeV	1.07±0.09	1.05±0.07



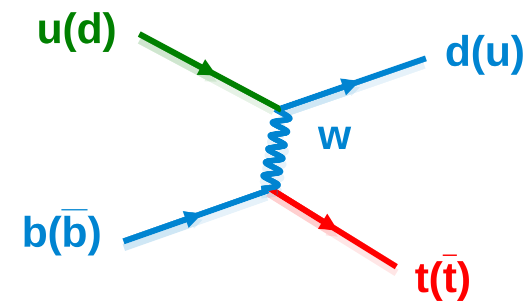


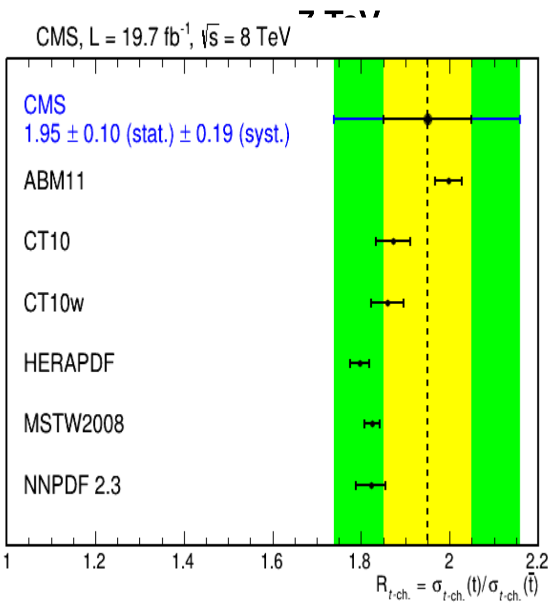
t-channel single-top: charge ratio measurement

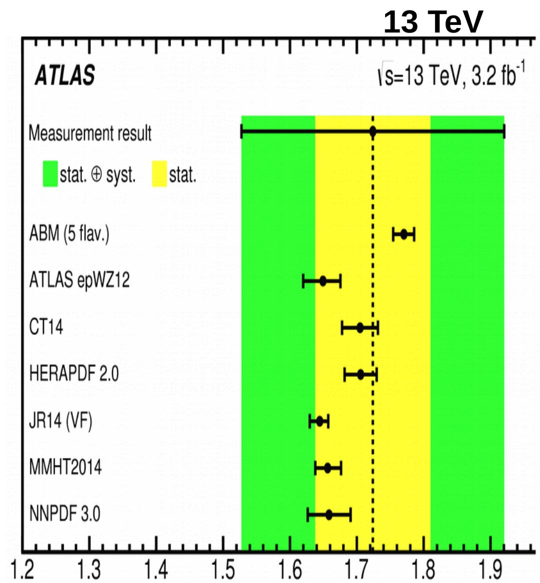
- **Asymmetry in top production :**

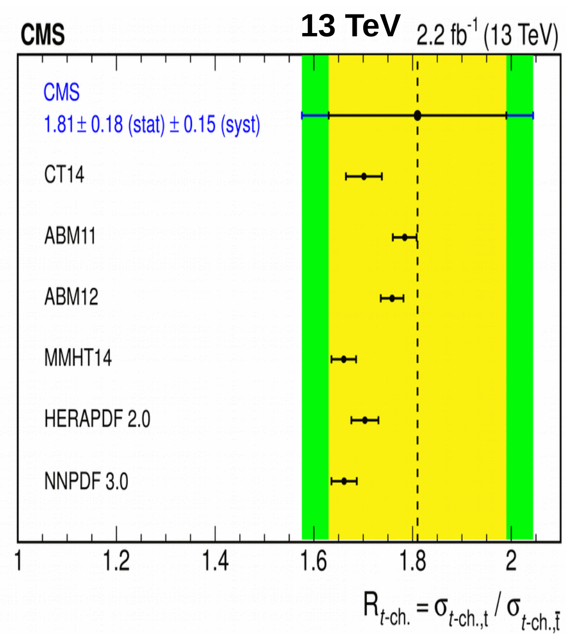
- stems from valence quark composition:
σ(top)/σ(antitop) ~2

- can be inferred directly from lepton sign









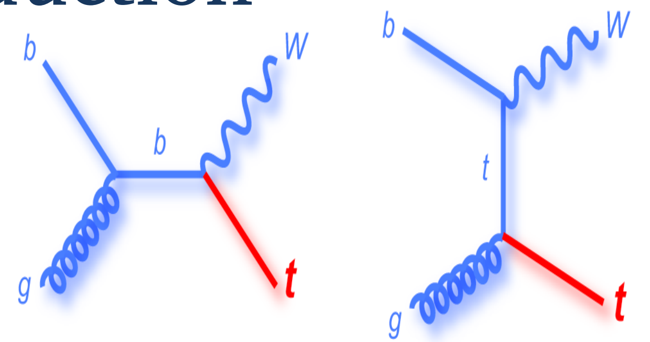
JHEP 06(2014)090 EPJC 77 (2017) 531 arXiv:1610.00678

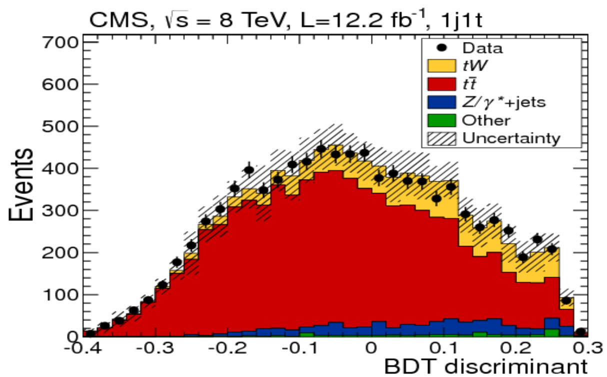
The single-top quark W-associated production

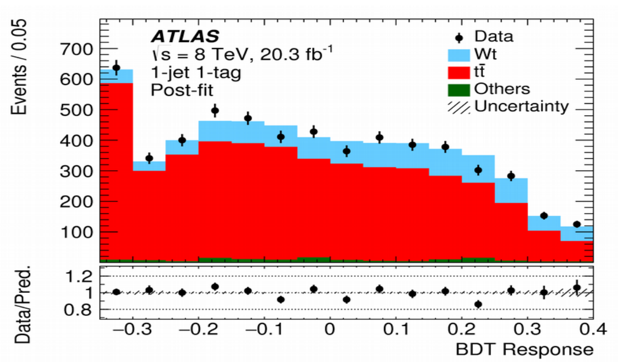
- **First measurements at LHC with 8 TeV:**

- 2 opposite sign isolated leptons in the final state

$\sigma_{(8\ TeV)}$ **[pb] = 23.0 ± 3.6(Atlas)/23.4 ± 5.4 (CMS)**





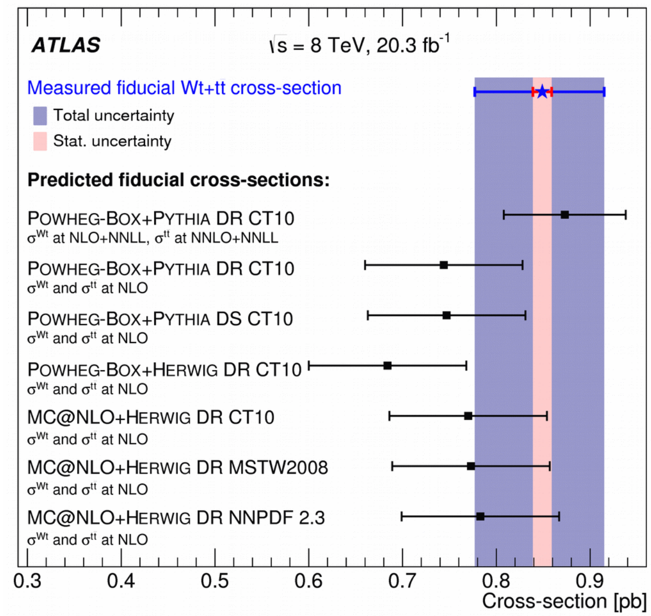


- **tt – tW interference:**

– Simulation deals with it with subtraction of diagrams

- Difference in second b pt can be used to differentiate fiducial measurements →

- **WbWb:** next step is to use proper simulation of the interference



JHEP01(2016)064 PRL 112,231802

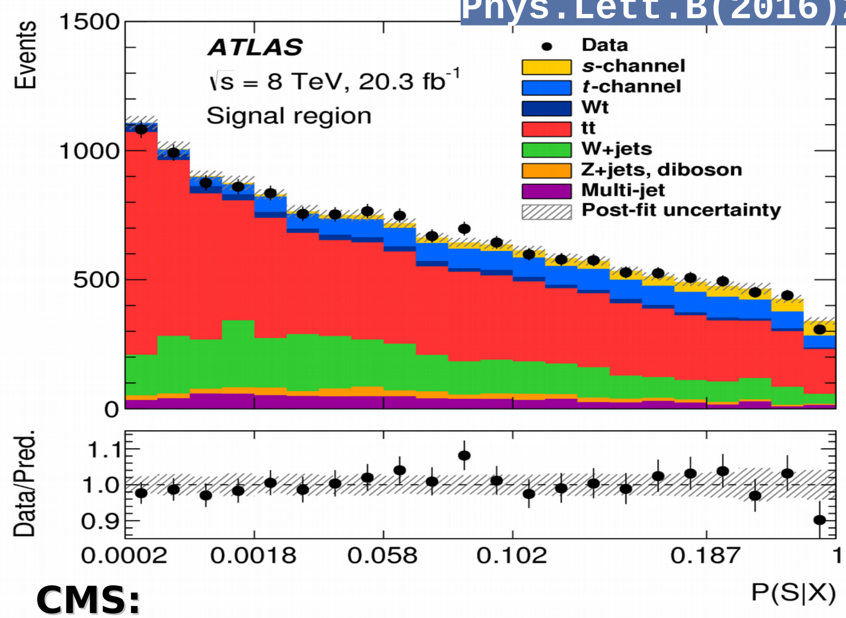
Single-top in the s-channel

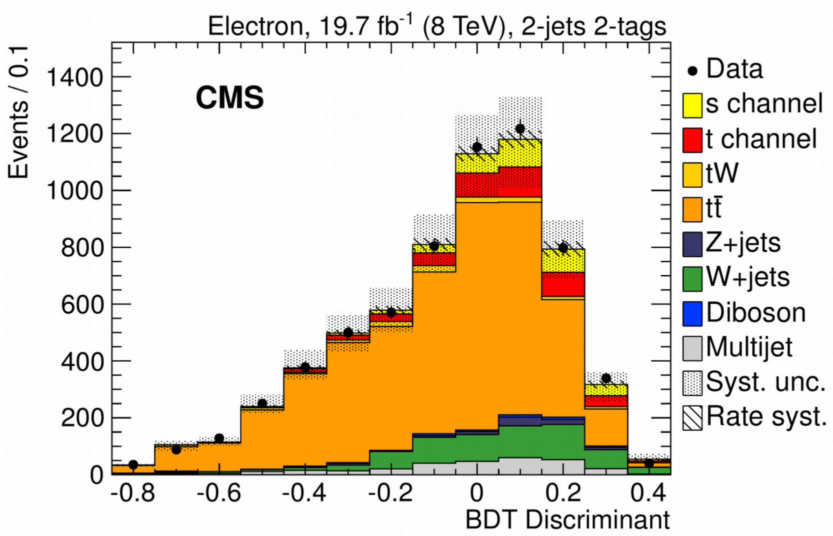
- **First evidence of s-channel:** →
- selection on 1 lepton and 2 b-tagged jets
- using matrix element method to maximize discrimination
- profile likelihood fit including systematics

$$\sigma_s = 4.8 \pm 0.8(\text{stat.})^{+1.6}_{-1.3}(\text{syst.})\ \text{pb}$$

Statistical significance (expected)/observed:
(3.9)3.2 standard deviations

Phys.Lett.B(2016)228-246





arXiv:1603.02555

CMS:

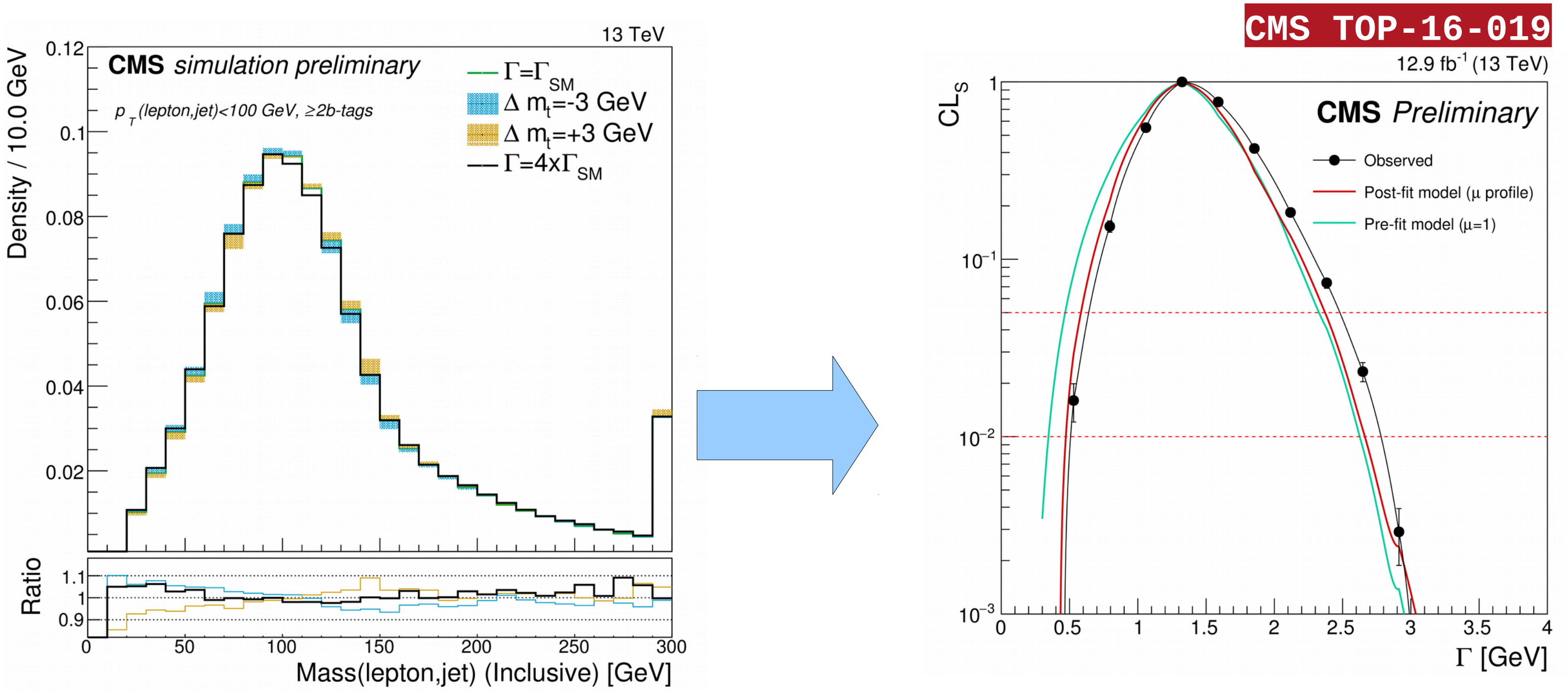
- **s-channel at 7 + 8 TeV:**
- uses MVA analysis to discriminate from backgrounds
- signal strength correlated amongst two energies
- No profiling of systematics
- Main systematics: background modeling

$$\sigma_s = 7.1 \pm 8.1\,(\text{stat} + \text{syst})\ \text{pb}, \quad 7\,\text{TeV};$$
$$\sigma_s = 13.4 \pm 7.3\,(\text{stat} + \text{syst})\ \text{pb}, \quad 8\,\text{TeV}.$$

Top quark properties

Top quark width

- **Top quark width** can affect top decay distributions e.g. Mlb **:**



→ 4 categories are studied for (non)boosted events with 1(>=2) b-jets

→ Derive a limit on 0.26 < G < 2.4 @95% cl

Top quark polarisation: *t*-channel single top

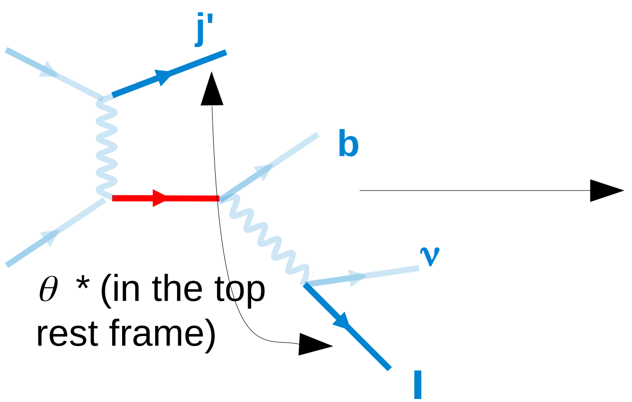
- Distribution stems from **V-A coupling:**

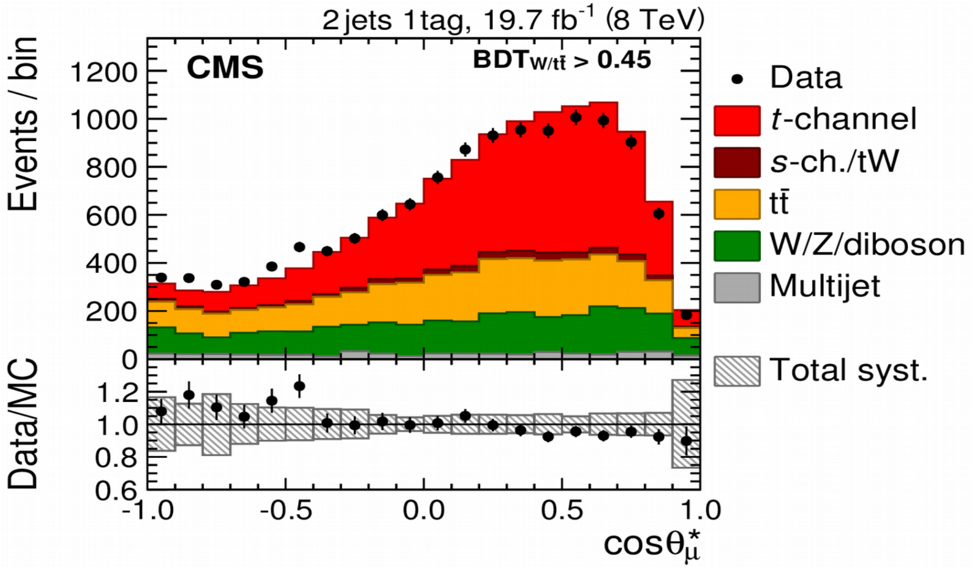
$$\frac{d\Gamma}{d\cos\theta_X} = \frac{\Gamma}{2}(1 + P_t\alpha_X\cos\theta_X) \equiv \Gamma(\frac{1}{2} + A_X\cos\theta_X)$$

- θ_X = angle between decay product X and top quark spin axis
- A_X = spin asymmmetry, from top quark polarisation

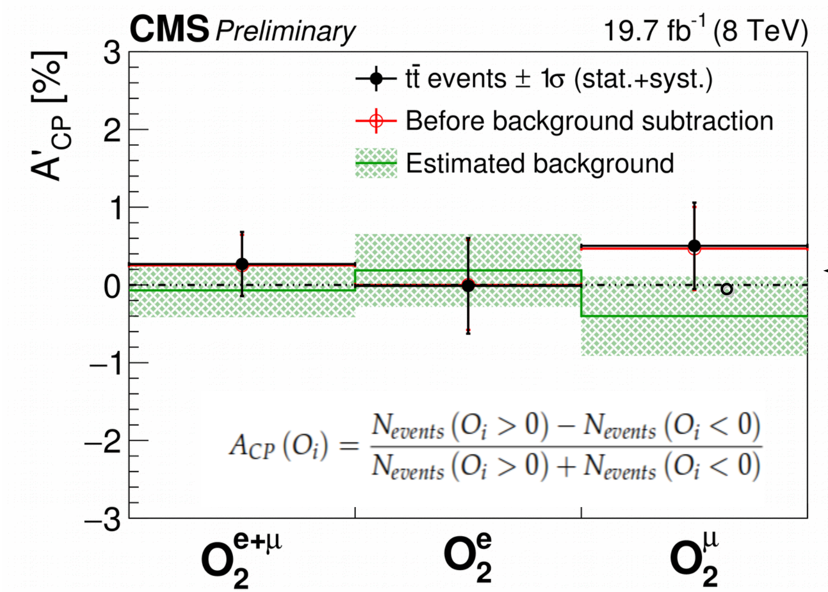
- **Can measure:** θ^* leptonic decays:

J.High Energy Phys.04(2016)073





CP violating top quark physics



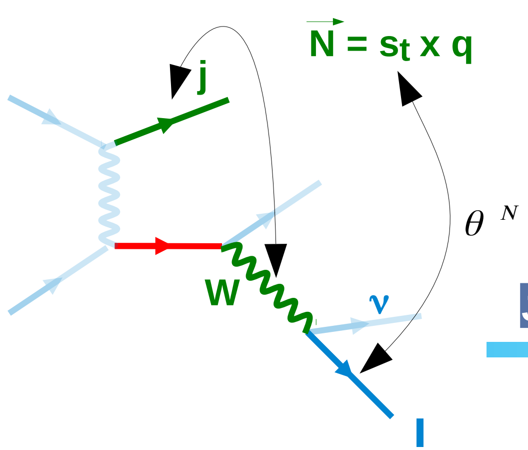
- **CP violation in tt**

- **Four observables** dthat display asymmetry if CP violation is present

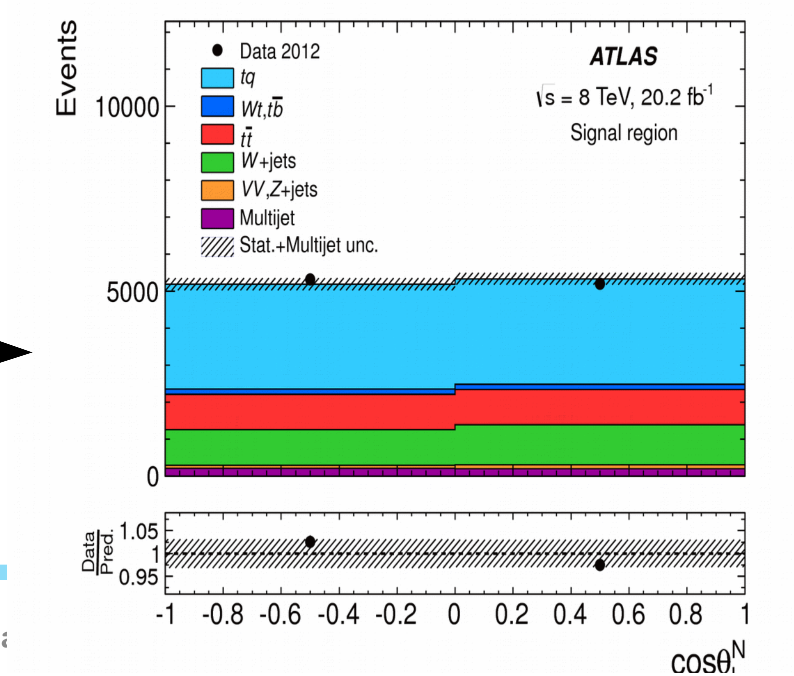
- Measurements in l + jets at 8 TeV

JHEP 03 (2017) 101

- **In single top events:** CP violation in production



JHEP04 (2017) 124



Alberto Orso Mari

top quark mass

Top mass: overview

High precision, systematic dominated measurement:

- Needs time and precise knowledge of the data set!

→ Best measurements at 7-8 TeV

→ Combinations allow to gain over systematics

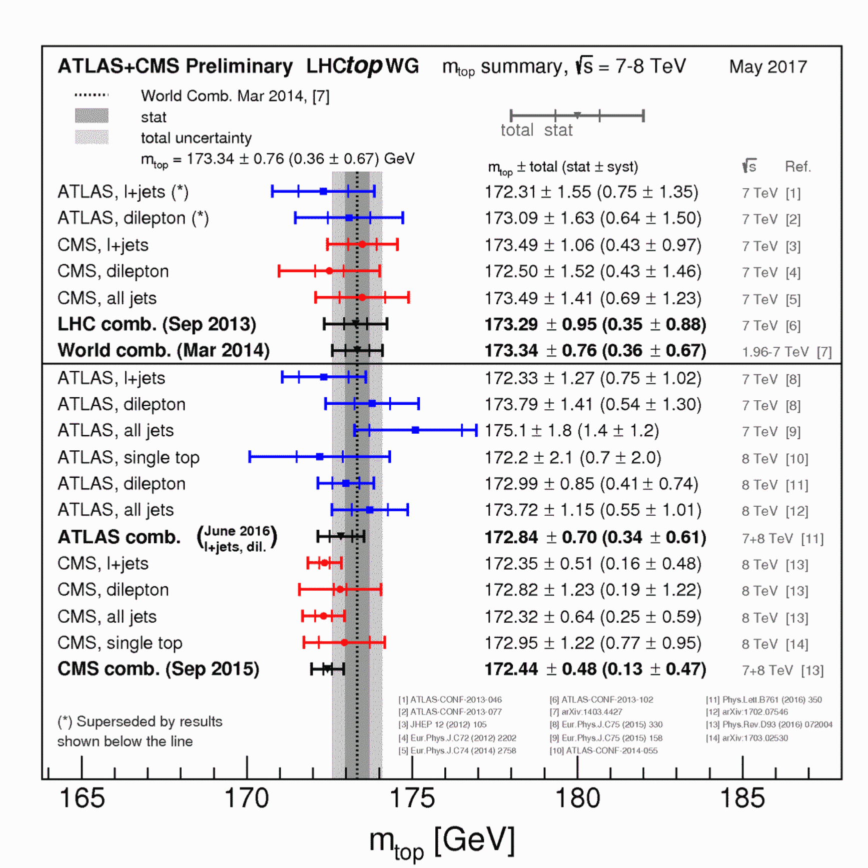
- **World combination**:

173.34 ±0.36(stat) ±0.67(syst) GeV

- **Single experiment combinations** :

172.84 ±0.34(stat) ±0.61(syst) GeV **Atlas**

172.44 ±0.13(stat) ±0.47(syst) GeV **CMS**



Top mass vs systematics: "standard" approaches

∘ Standard top mass measurements: tt pairs,

→ Have to cope with jet energy scale calibration

→ In particular: b – flavoured jets!

∘ **Most common approach**:
derive in-situ jet energy scale with top mass

Notable case: lepton + jet analysis

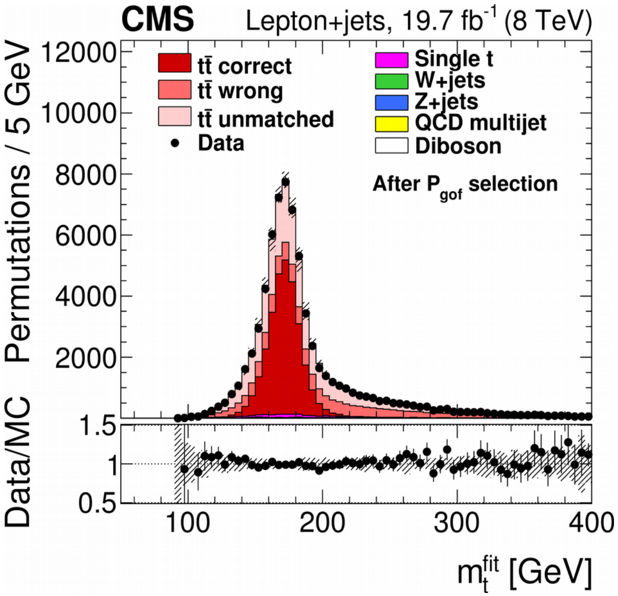
→ 1 lepton + 4 jets selection

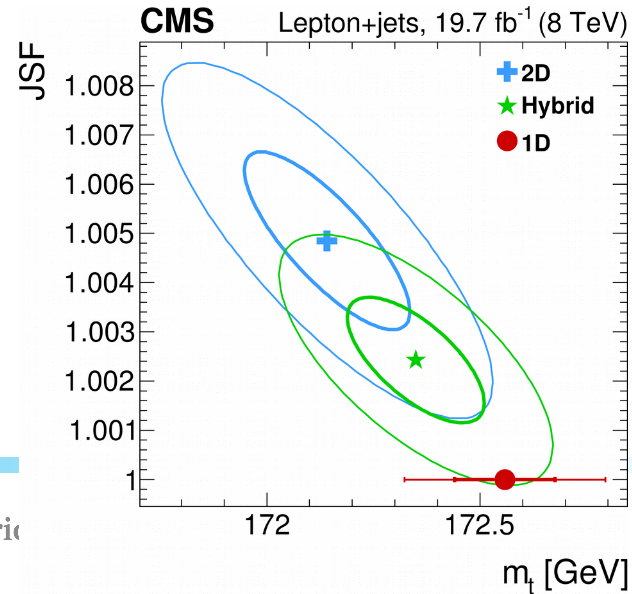
→ m_{top} from kinematic fit used as observable

→ Fit performed taking into account all permutations

→ Different parameter factorisation possible

PRD 93 (2016) 72004





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PRD 93 (2016) 72004

Lepton+jets channel	m_t fit type: 2D δm_t^{2D} (GeV)	2D δJSF	1D δm_t^{1D} (GeV)	hybrid δm_t^{hyb} (GeV)
Experimental uncertainties				
Method calibration	0.04	0.001	0.04	0.04
Jet energy corrections				
– JEC: Intercalibration	<0.01	<0.001	+0.02	+0.01
– JEC: In situ calibration	−0.01	+0.003	+0.24	+0.12
– JEC: Uncorrelated non-pileup	+0.09	−0.004	−0.26	−0.10
– JEC: Uncorrelated pileup	+0.06	−0.002	−0.11	−0.04
Lepton energy scale	+0.01	<0.001	+0.01	+0.01
E_T^{miss} scale	+0.04	<0.001	+0.03	+0.04
Jet energy resolution	−0.11	+0.002	+0.05	−0.03
b tagging	+0.06	< 0.001	+0.04	+0.06
Pileup	−0.12	+0.002	+0.05	−0.04
Backgrounds	+0.05	< 0.001	+0.01	+0.03
Modeling of hadronization				
JEC: Flavor-dependent				
– light quarks (u d s)	+0.11	−0.002	−0.02	+0.05
– charm	+0.03	<0.001	−0.01	+0.01
– bottom	−0.32	<0.001	−0.31	−0.32
– gluon	−0.22	+0.003	+0.05	−0.08
b jet modeling				
– b fragmentation	+0.06	−0.001	−0.06	<0.01
– Semileptonic b hadron decays	−0.16	<0.001	−0.15	−0.16
Modeling of perturbative QCD				
PDF	0.09	0.001	0.06	0.04
Ren. and fact. scales	+0.17 ± 0.08	−0.004 ± 0.001	−0.24 ± 0.06	−0.09 ± 0.07
ME-PS matching threshold	+0.11 ± 0.09	−0.002 ± 0.001	−0.07 ± 0.06	+0.03 ± 0.07
ME generator	−0.07 ± 0.11	−0.001 ± 0.001	−0.16 ± 0.07	−0.12 ± 0.08
Top quark p_T	+0.16	−0.003	−0.11	+0.02
Modeling of soft QCD				
Underlying event	+0.15 ± 0.15	−0.002 ± 0.001	+0.07 ± 0.09	+0.08 ± 0.11
Color reconnection modeling	+0.11 ± 0.13	−0.002 ± 0.001	−0.09 ± 0.08	+0.01 ± 0.09
Total systematic	0.59	0.007	0.62	0.48
Statistical	0.20	0.002	0.12	0.16
Total	0.62	0.007	0.63	0.51

Alternative approaches

∘ **Most precise measurements:** sensitive to hadronisation uncertainties, color reconnection, etc...

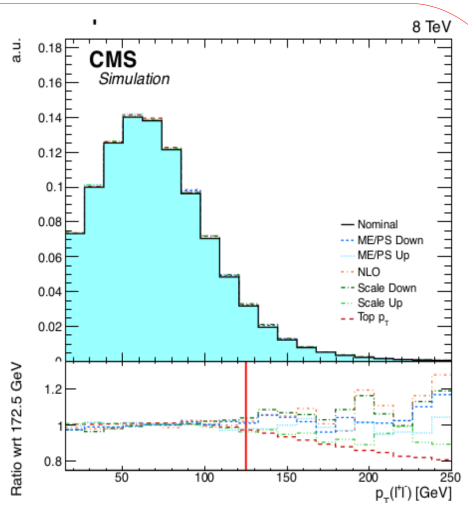
Other ideas are explored by the experiments!

- From **different observables...**

Use observables of lepton from top decay

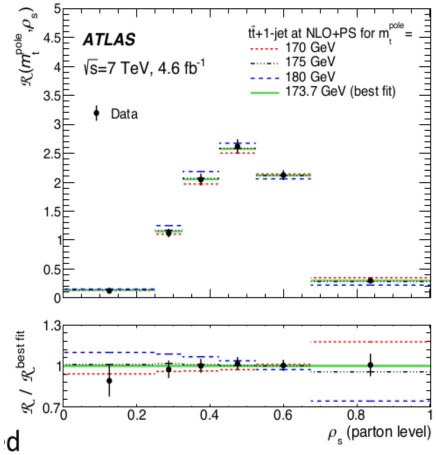
- less sensitive to hadronisation

- suggested in ArXiv:1407.2763



mt = 171.7± 1.1 (stat) ± 2.9 (syst+theo)

CMS TOP-16-002



Measure the tt + 1 jet shapes

- Can be calculated at NLO

- suggested in ArXiv:1303.6415

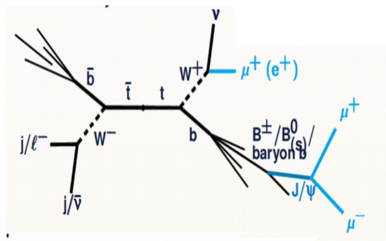
m_{top} = 173.7+2.3-2.1 GeV

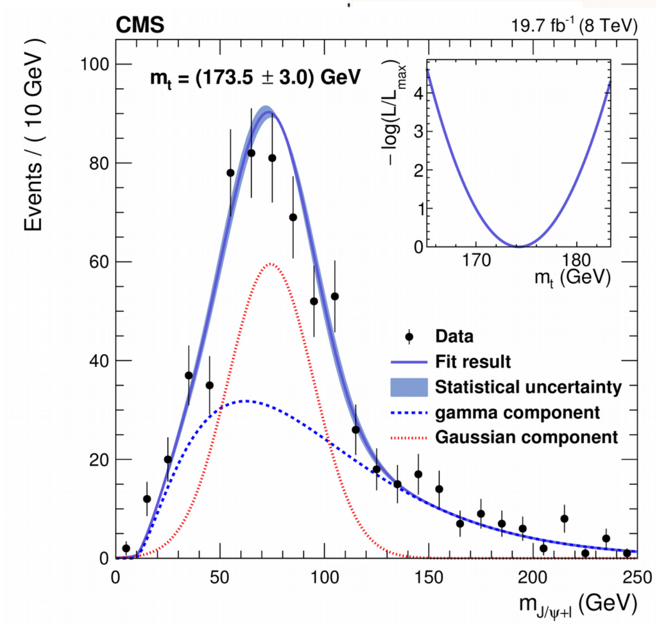
JHEP10(2015)121

Alternative approaches

... to different modes of decay or production!

Top mass from J/Psi + letpton decays:
→ Clean signature

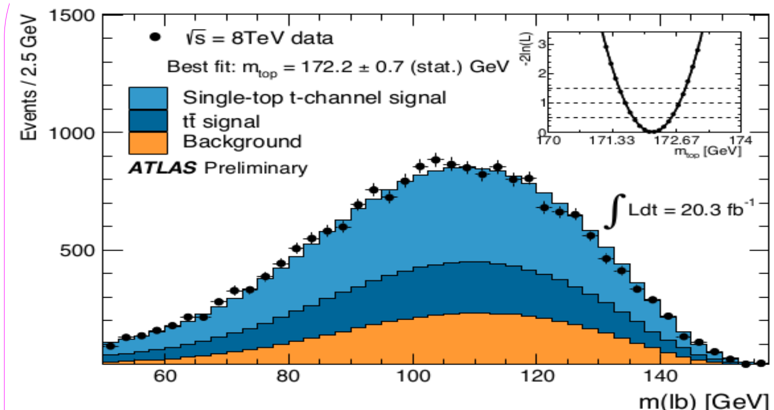




$$m_t = 173.68 \pm 0.20(\text{stat}) \, ^{+1.58}_{-0.97}(\text{syst}) \text{ GeV}$$

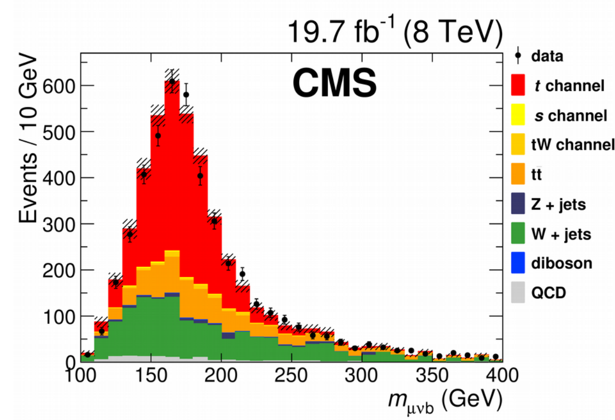
arXiv:1603.06536

Single-top topologies:



mtop = 172.2 ±2.1 GeV

ATLAS CONF-2014-055



mtop = 172.6 ±1.2 GeV

JHEP 03 (2017) 101

Top mass expectations with 14 TeV and at high-luminosity

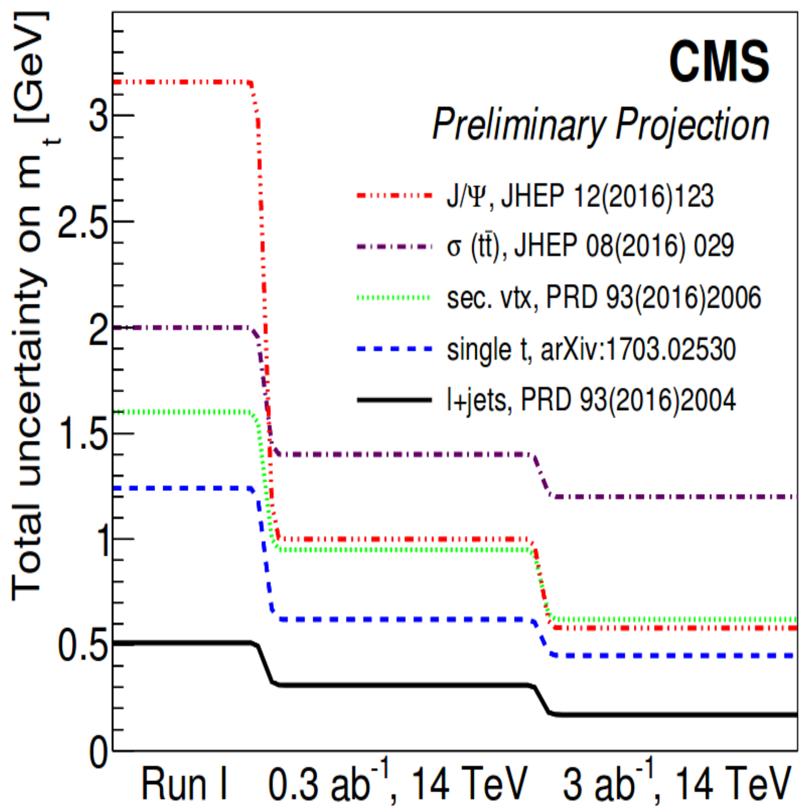
- **Top mass progress:**

- Statistics will help forconstraining backgrounds in situ

- Will be possible to have tighter cuts to select more convenient regions of the phase space

- Improvements in syst. Uncertainties understanding are expected

CMS PAS-FRT-16-006



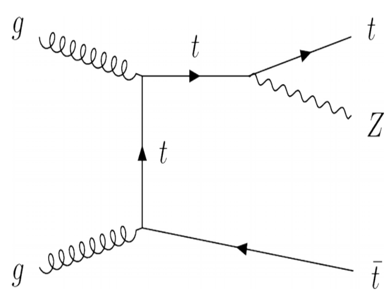
New top-related processes

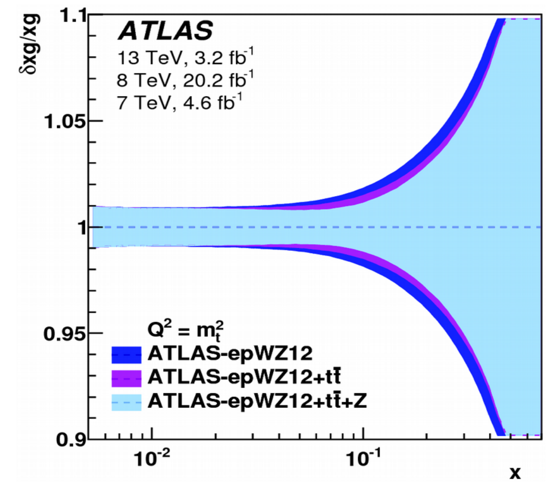
Associated production: tt + W/Z bosons

EPJC 77 (2017) 40

CMS TOP-17-005

tt+Z

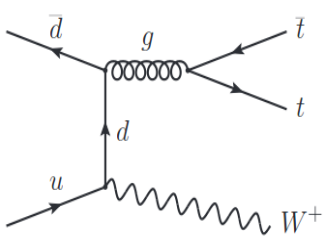




CMS and **Atlas:**
3-4 leptons and >= 2 jets → can be used in PDF constraints

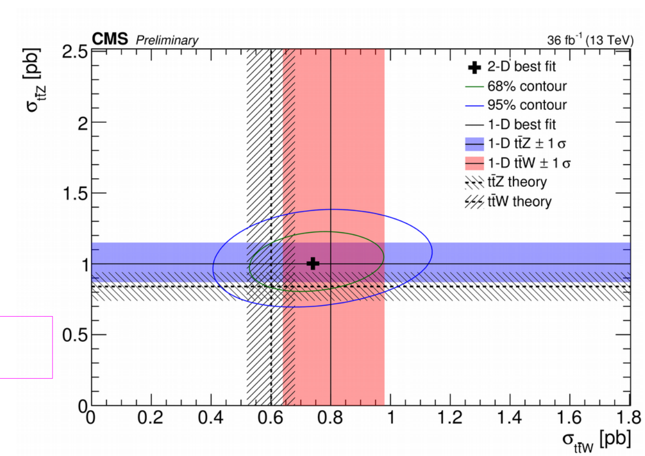
σ(tt Z) = **0.9 ± 0.3 (Atlas)** / **1.00 ± 0.14 (CMS)** pb

tt+W



At 13 TeV analysis with 2-3 leptons, >= 2 jets

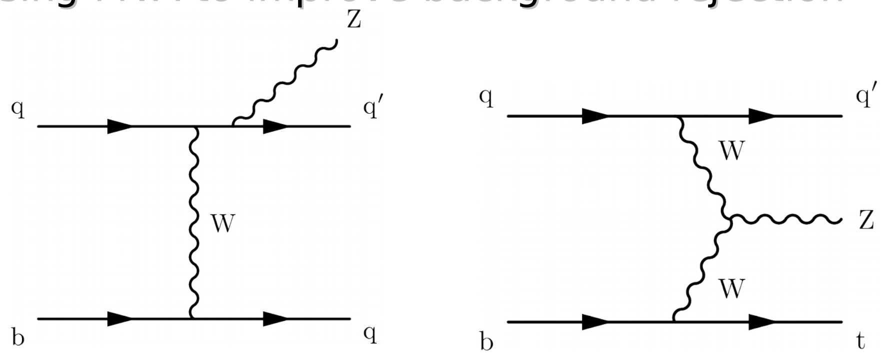
σ(tt W) = **1.5 ± 0.8 (Atlas)** / **0.80 ± 0.16 (CMS)** pb



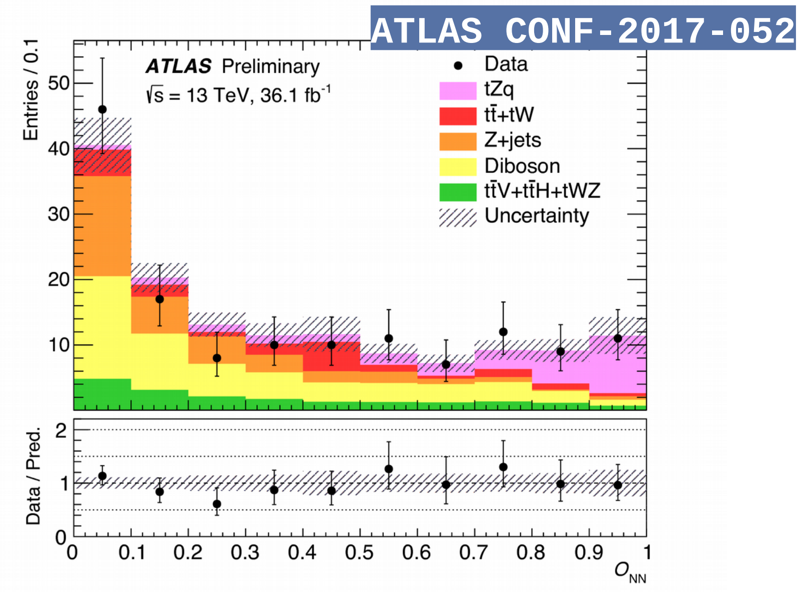
New channels: tZq

- **First evidence** at 13 TeV:

→ Channel with 3 leptons and Z resonance
→ using MVA to improve background rejection



$\sigma(tZq) =$ **600 ± 230** pb



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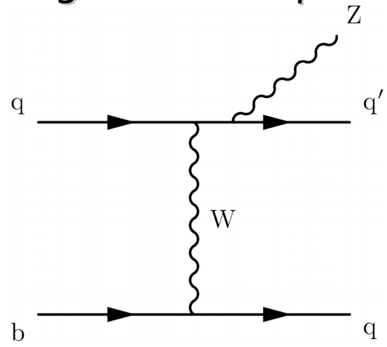

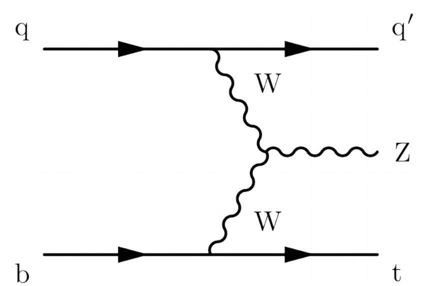

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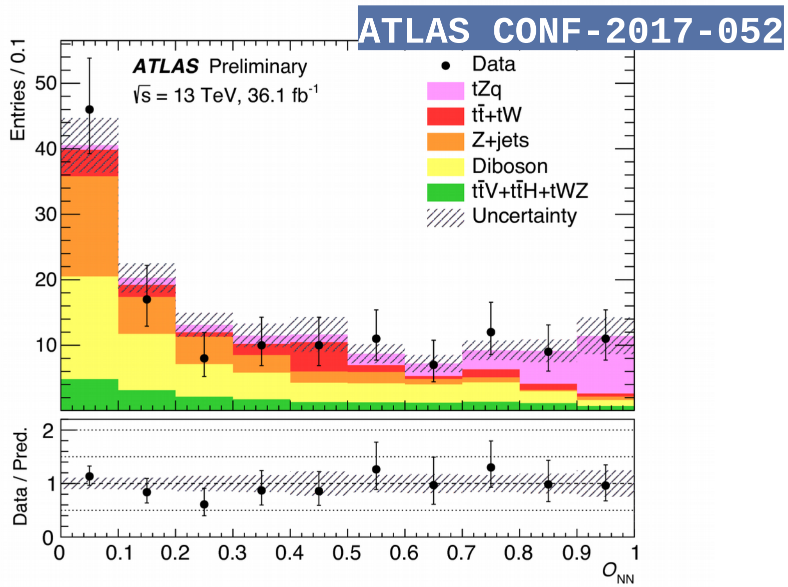
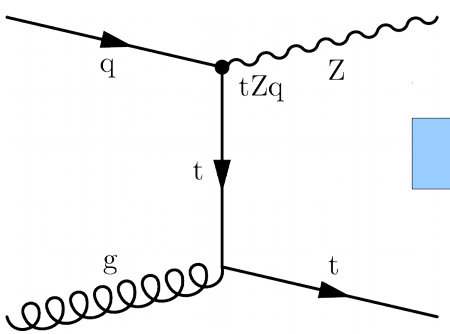
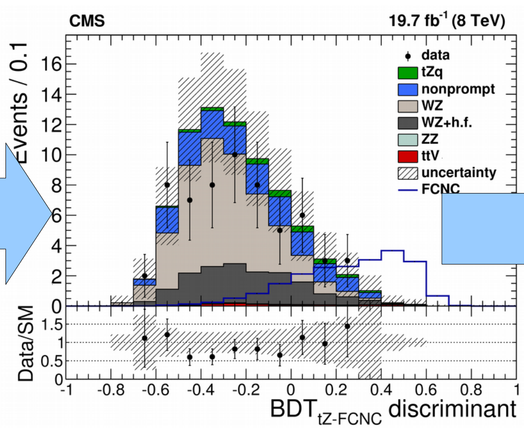
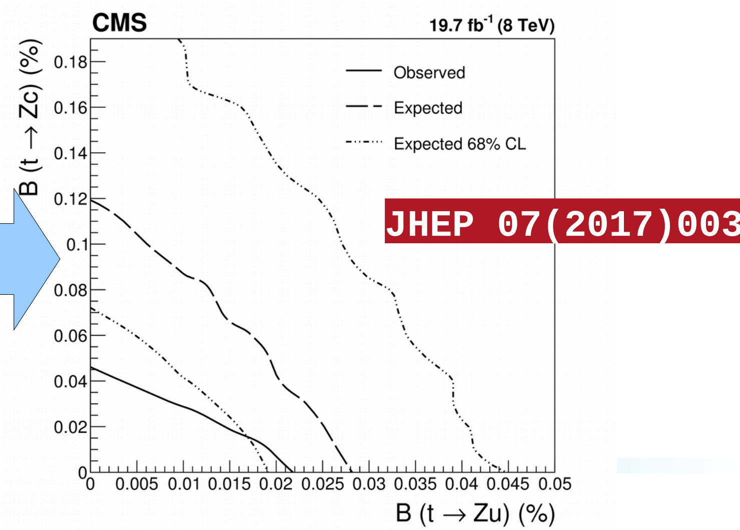


Very sensitive to FCNC BSM, both in Production and decay!







What next?

- **Standard model production** at 13 TeV has been revisited:
  → Many "old" measurements have been revamped with the experience from Run-I
  → SM has been confirmed in its core features, precision keeps improving on fundamental parameters!

- **Potential for many new measurements**:
  → Statistics will allow for exploration of the extreme regions of the phase space
  → Differential measurements in boosted topologies will massively enter the game!

- A mature enough set of measurements to **improve modelling parametrisation**:
  → PDF of gluons, especially at high x
  → Tuning of ME + PS models!

- **New interesting production modes** take spotlight:
  → ttW and ttZ as well as tZq!
  → Sensitivity to new physics!

Thanks!

Extra material

Top quarks at LHCb

Top production at LHCb in forward events

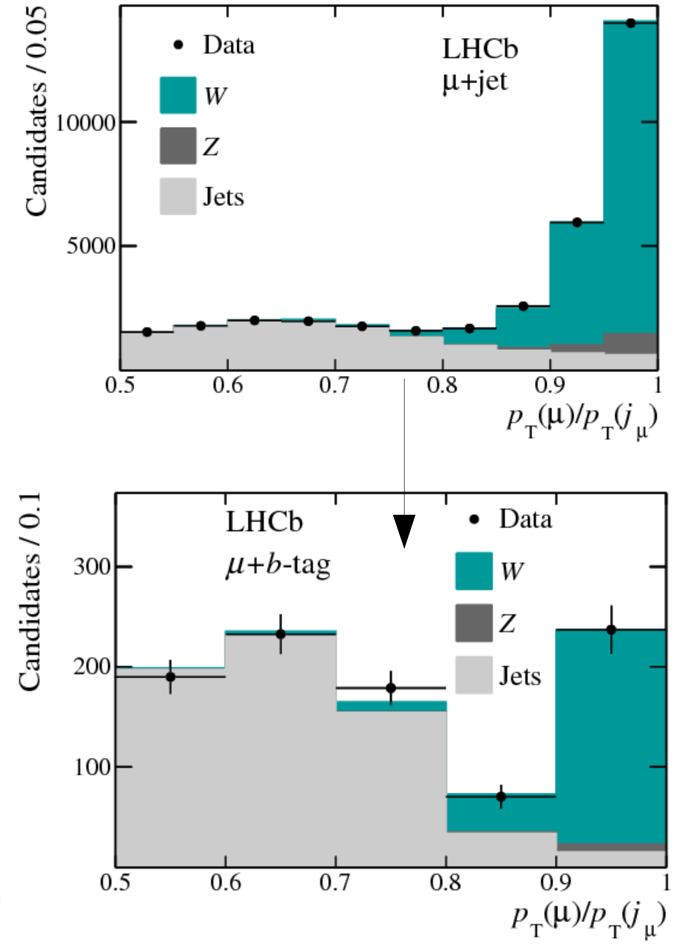
- **Measurement of top quarks at LHCb** Phys.Rev.Lett.115(2015)112001

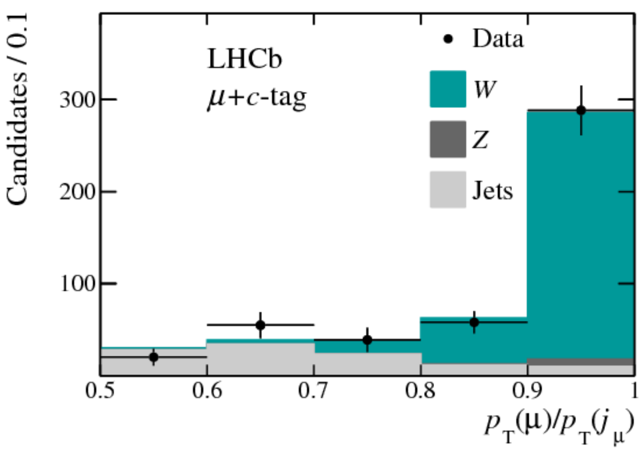
- first observation with Run-I data in asymmetric p-p collisions

- 75% ttbar / 25% single-top t-channel

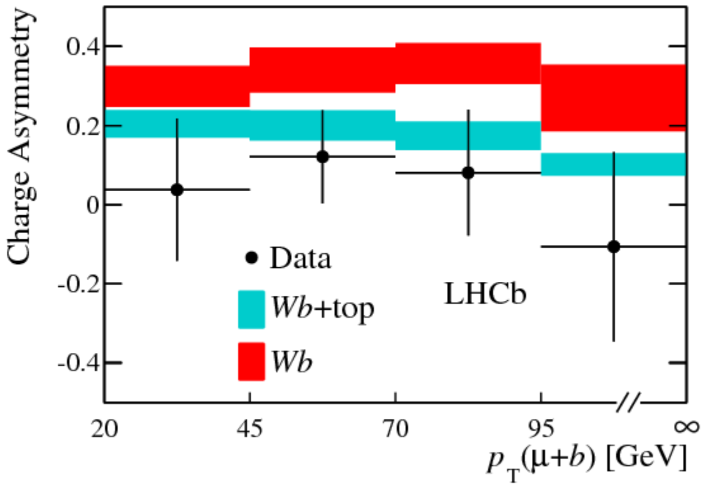
- selected events with 1 top→Wb→μνb
    - 1 muon: p_T >25 GeV ; 2.0 < η < 4.5
    - ≥ 1 jet 50 < p_T <100 GeV ; 2.2 < η < 4.2
    - jet must be b-tagged

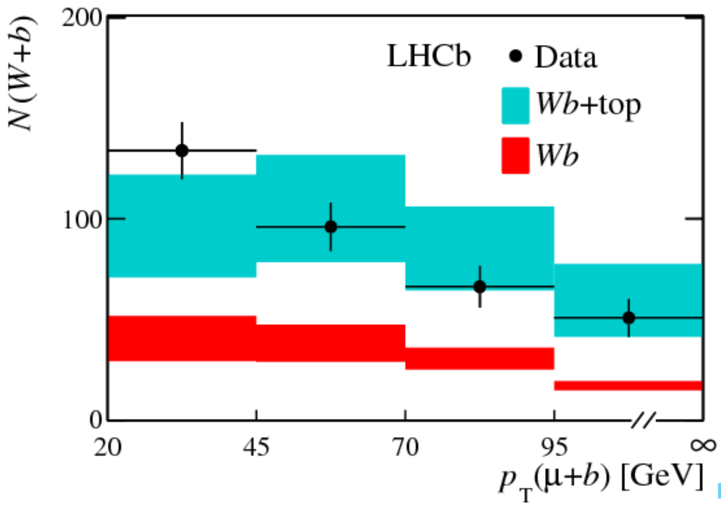
- use of the pre-tag region to reduce uncertainties
    - cross-check region with c-jets





Top production at LHCb in forward events





- **Top content extraction:**

- 2D maximum likelihood fit to charge asymmetry and event yield

- consistent with SM prediction, significance of 5.4 standard deviations

- Main uncertainties: b-tagging, theory

$$\sigma(\text{top})[7\text{ TeV}] = 239 \pm 53\,(\text{stat}) \pm 33\,(\text{syst}) \pm 24(\text{theory})\text{ fb}$$

$$\sigma(\text{top})[8\text{ TeV}] = 289 \pm 43\,(\text{stat}) \pm 40\,(\text{syst}) \pm 29(\text{theory})\text{ fb}$$

Phys.Rev.Lett.115(2015)112001

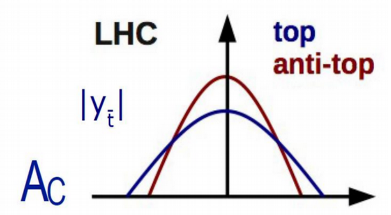
Charge asymmetry and spin correlation

Charge asymmetry in top quark pairs

- **Asymmetry in top-antitop quark production:**

- at the LHC: a difference in the rapidity spectra

- top quark is more forward than anti-top



$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

Charge asymmetry in top quark pairs

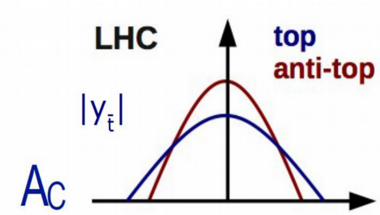
- **Asymmetry in top-antitop quark production:**

- at the LHC: a difference in the rapidity spectra

- top quark is more forward than anti-top

- **Precision measurement, at 7/8 TeV:**

- several channels exploited, including top boosted regime



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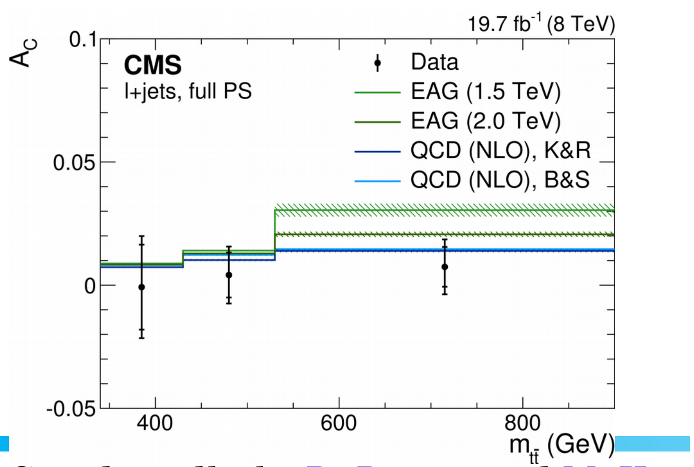
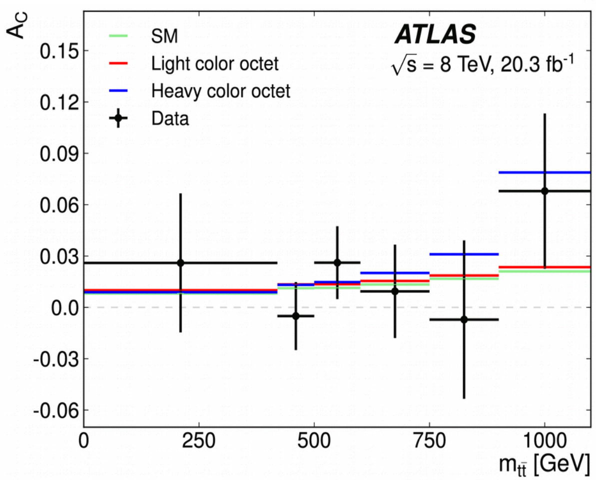
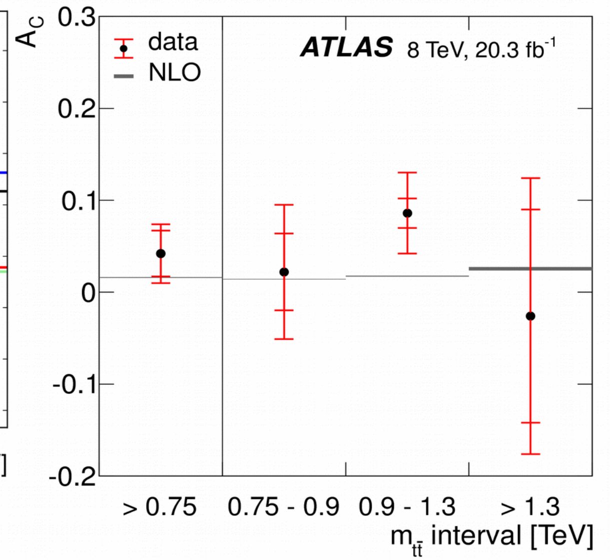
arXiv:1507.03110



Eur.Phys.J.C76(2016)87



Phys.Lett.B(2016)756,52-71



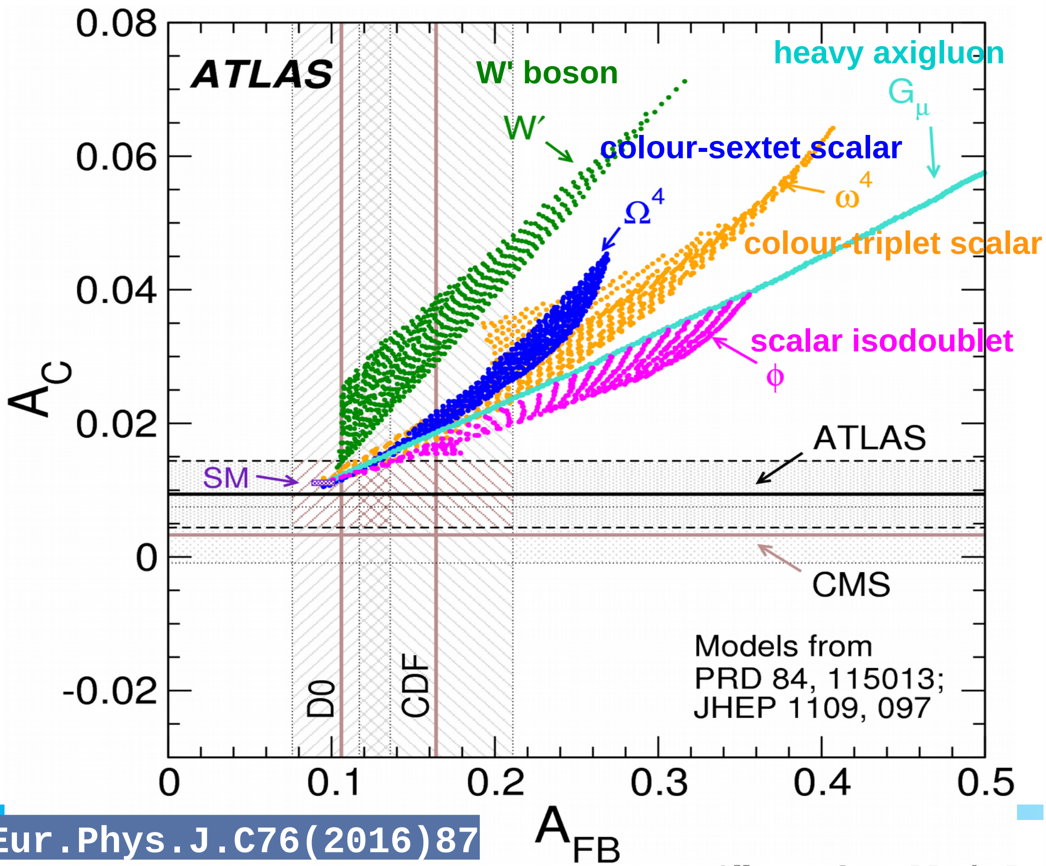
See also talks by D. Poyraz and M. Kareem

Charge asymmetry in top quark pairs

- **No significant deviation from expectation**

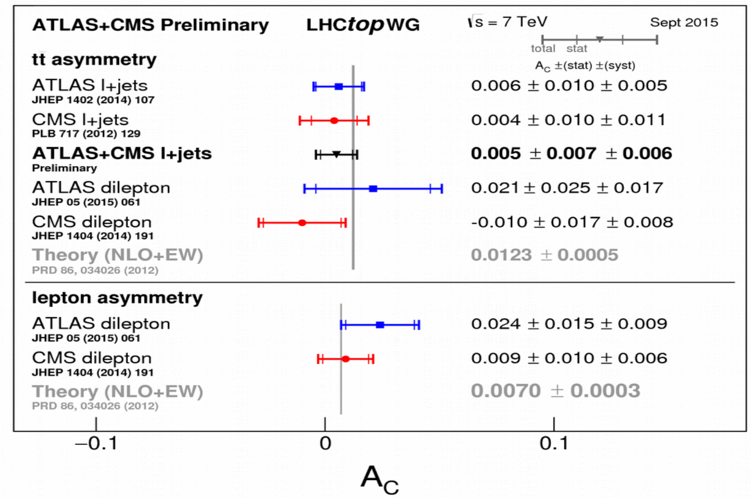
- Rich array of measurements from Atlas and CMS

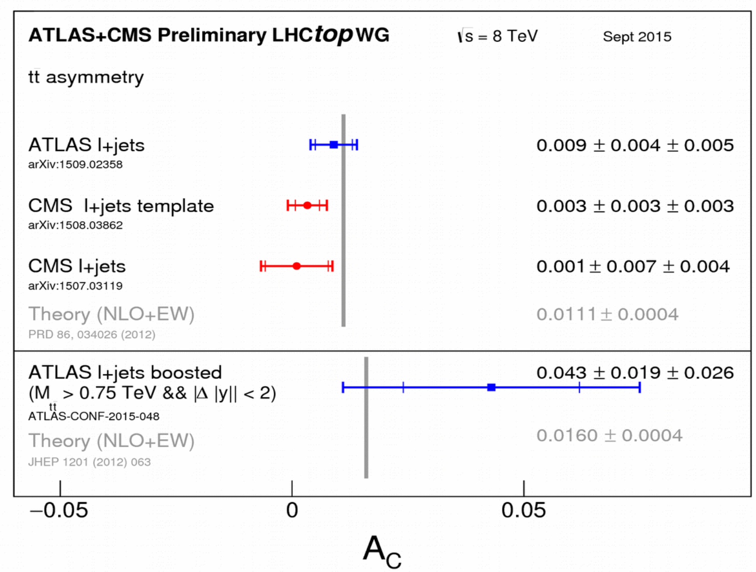
- Several BSM models can be excluded



Eur.Phys.J.C76(2016)87

LHC Top WG summary plots



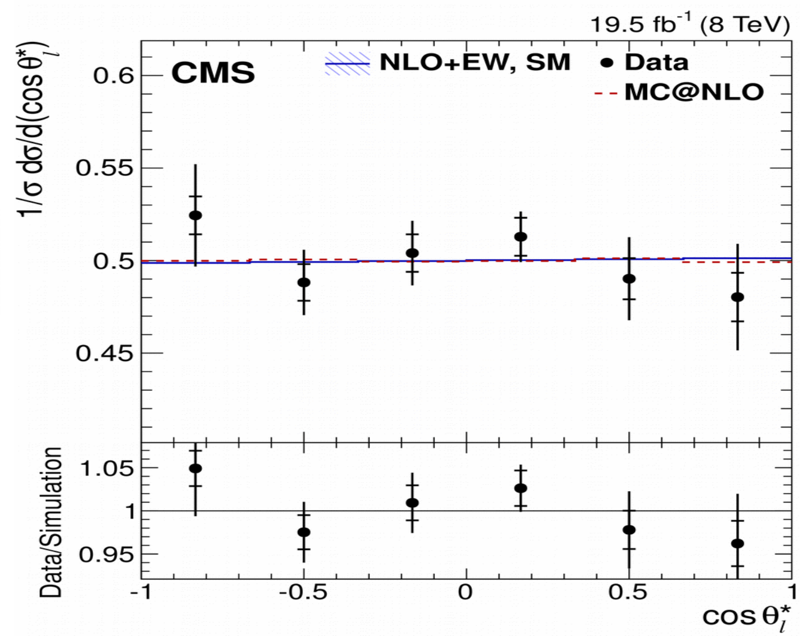


Spin correlation and top polarisation

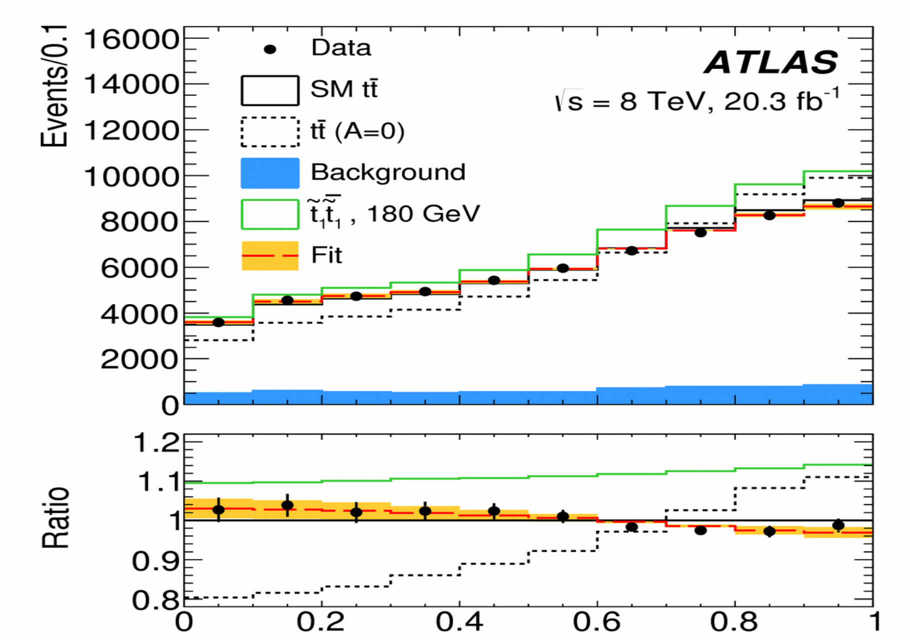
◦ **Top quarks in strong production:**
- produced unpolarised
- angular correlations stem from gluon helicities

◦ **What we do measure:**
- fraction of spin-correlated events $f_{SM} = \dfrac{N^{t\bar{t}}_{SM}}{N^{t\bar{t}}_{SM} + N^{t\bar{t}}_{Uncor}}$

- Unfolding to angular distributions → measure asymmetries



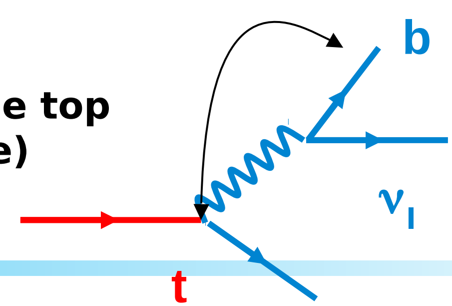
Phys.Rev.Lett.114,142001(2015)



arXiv:1601.01107

◦ **Sensitive observables:**
- angle θ* for leptonically decaying tops
- angle ϕ between leptons in dileptonic top decays

**θ_l*
(in the top frame)**



See also talks by D. Poyraz and M. Kareem

Spin correlation and top polarisation

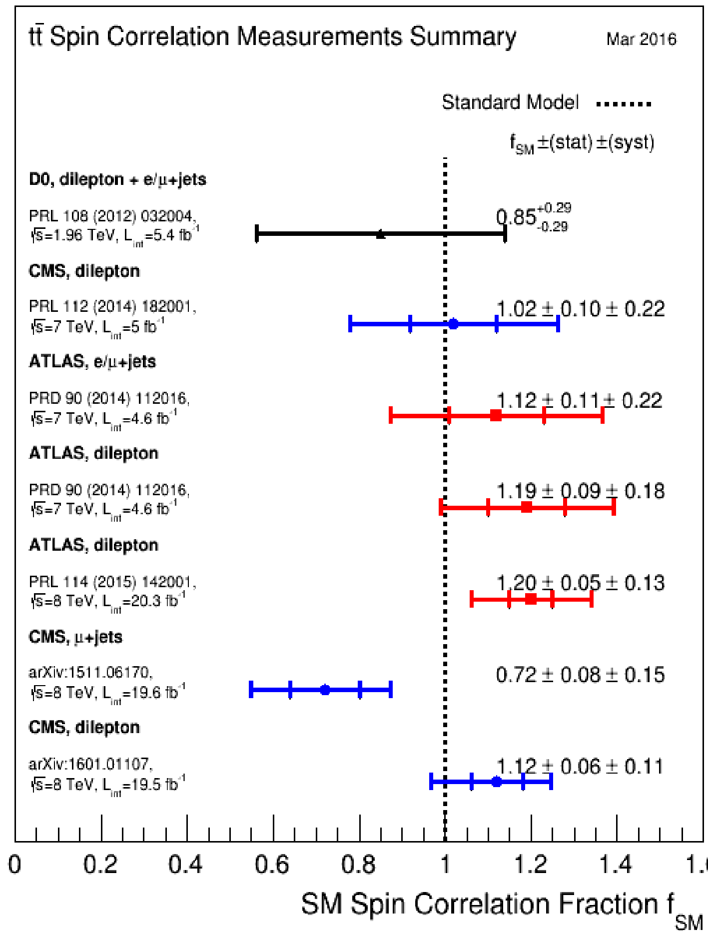
- **Several methdods explored!**

- Both dileptonic and semileptonic channels studied

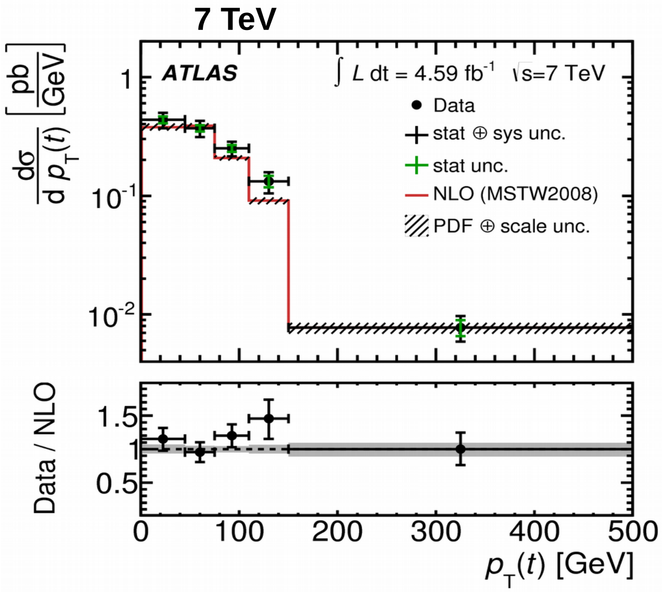
- Measurements of $\Delta\phi$, $\cos\theta^*$, etc.

- Matrix Element method

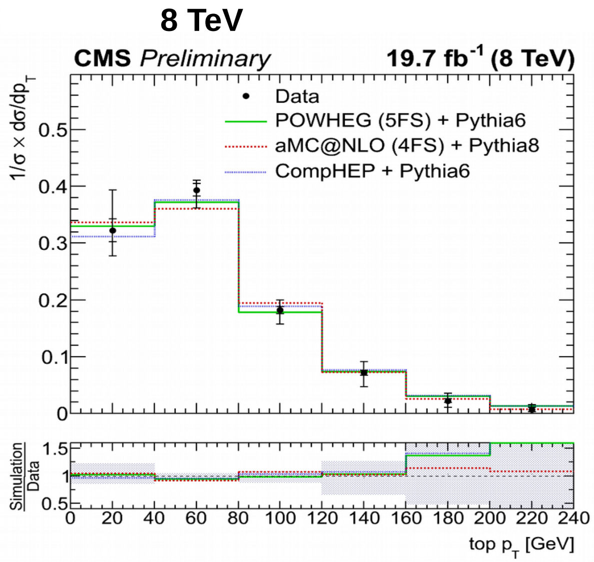
- good agreement with the standard model, two measurement show a slight tension, however less than $2\sigma_{f_{SM}}$



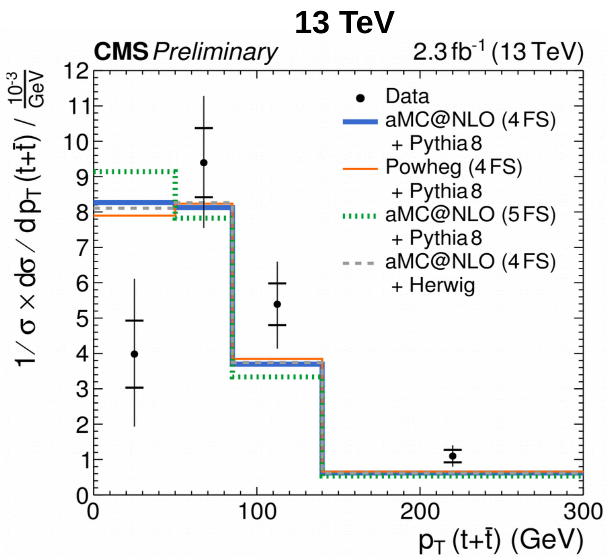
t-channel single top differential measurements



Phys.Rev.D.90,112006(2014)



CMS TOP-14-004



CMS TOP-16-004

- **Momentum and rapidity of single-top quarks**

- Same selection of inclusive analyses can be used

- Potential for signal model discrimination and MC tuning exactly as for tt!

Top BR/ width

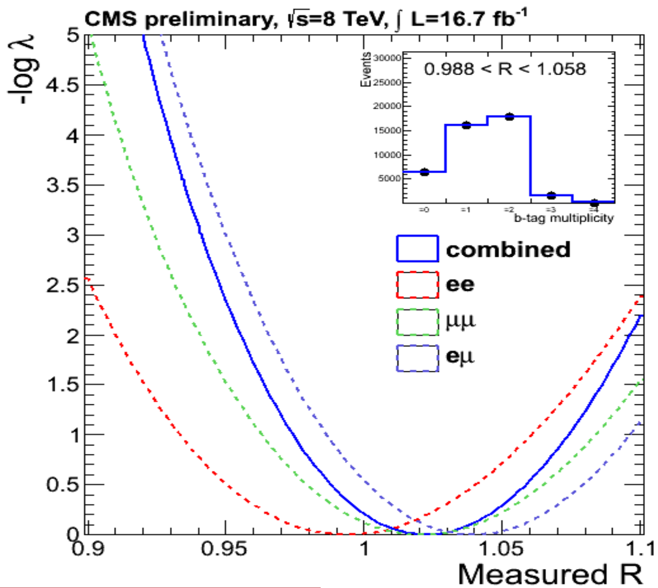
The R measurement

- **Fraction R = BR(t→Wb)/BR(t→Wq)**

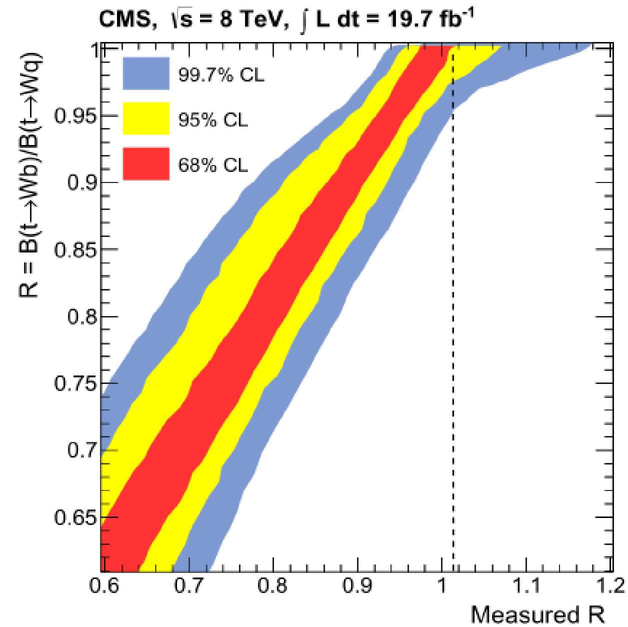
- allows measurement of $|V_{tb}|$

- Unitariety limit foresees $|V_{tb}| = 0.999146$

- Likelihood fit to jet multiplicity spectrum



PLB 736(2014)33



- Most precise measurement up to date:

$R = 1.014 \pm 0.032 \rightarrow |V_{tb}| = 1.007 \pm 0.016$;
Assuming $R < 1$: $|V_{tb}| > 0.975$ @ 95%CL

- combined with single-top cross section measurement allows to measure top width:

$$\Gamma_t = \frac{\sigma^{obs.}_{t-ch}}{B(t \rightarrow Wb)} \frac{\Gamma(t \rightarrow Wb)}{\sigma^{theo.}_{t-ch}} = 1.36^{+0.14}_{0.11}$$

Non-SM couplings / small signals

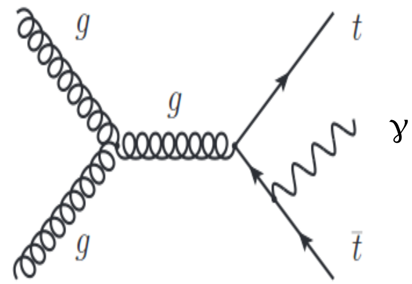
Top quark pairs + photon

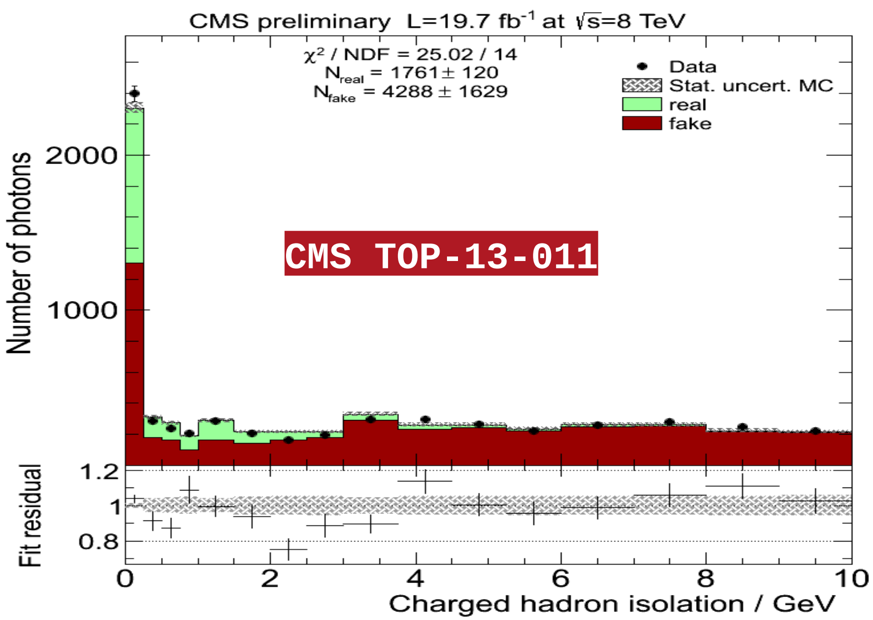
Completes the picture together with W/Z

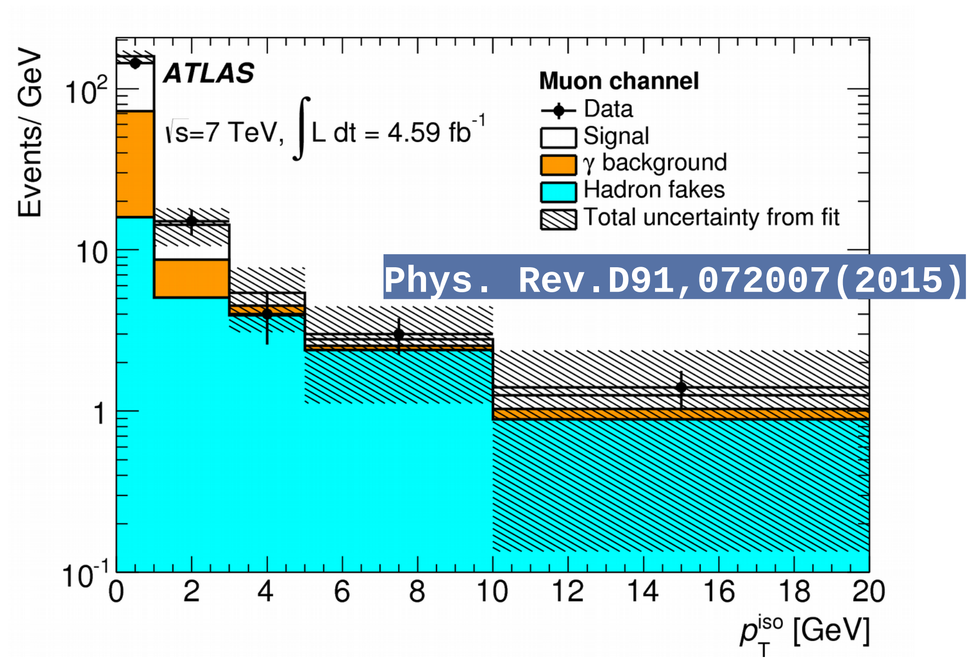
Probes **top quark charge** via the coupling

Measurements at 7 (**Atlas**) and 8 (**CMS**) TeV :

$\sigma(tt\gamma)$ = **68 ± 17 fb** at 7 TeV (48 fbexpected)
$\sigma(tt\gamma)$ = **2.4 ± 0.6 pb** at 8 TeV (1.8 pb expected)



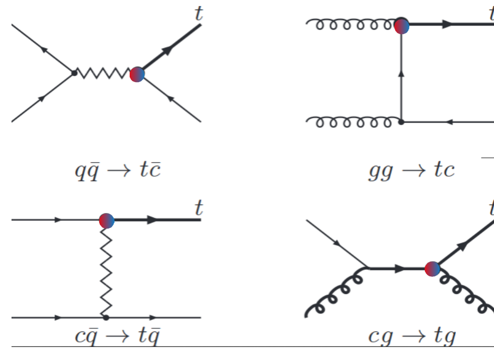


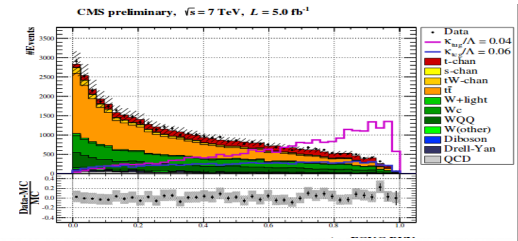


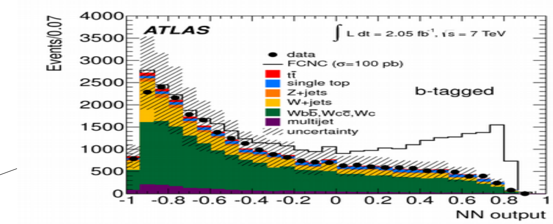
Search for non-SM couplings single-top production

- **Single-top quarks:**

- Can be produced via FCNCs together with u/q/g

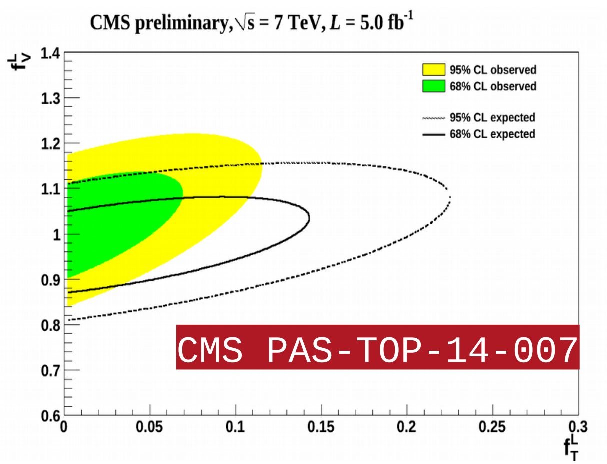




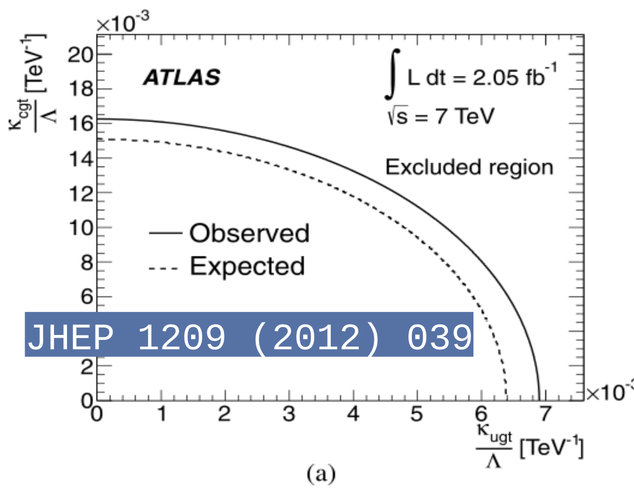


- Searched for at 7/8 TeV

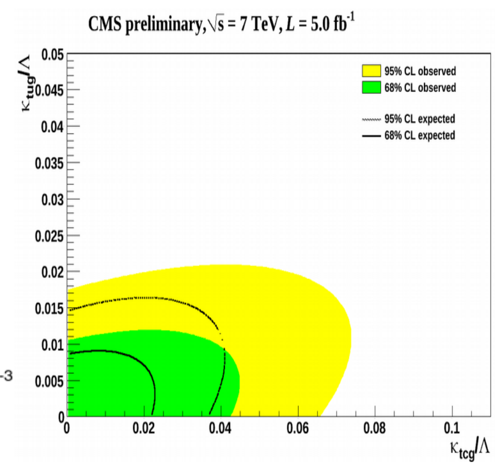
- Also, possible to search for right-handed vector components



CMS PAS-TOP-14-007



JHEP 1209 (2012) 039



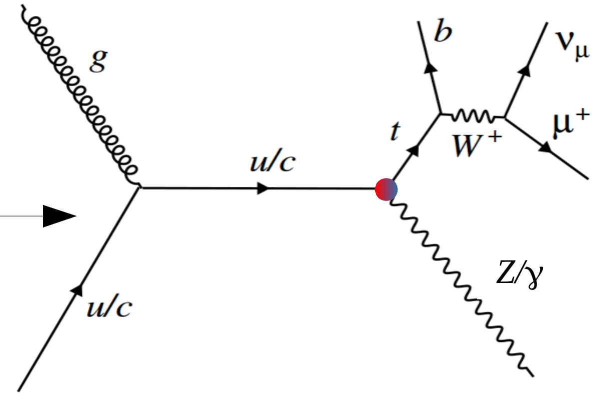
Search for non-SM couplings top associated production

- **single-top + Z/gamma production:**

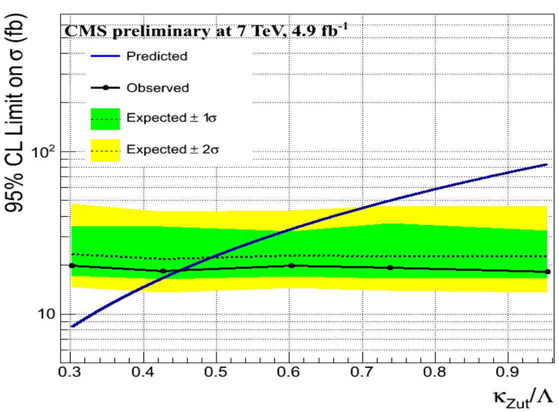
- Low cross section at LHC in the standard model (~0.2 pb/0.).

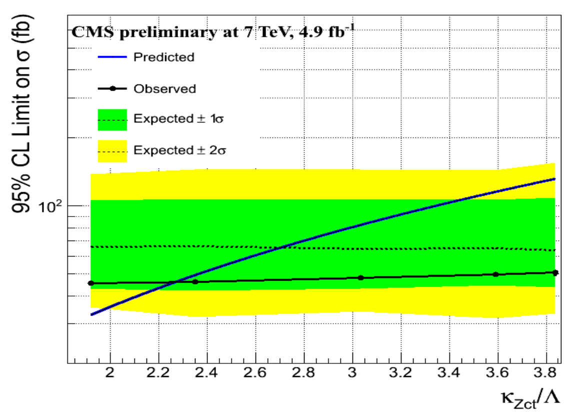
- Susceptible to enhancement from BSM FCNC

- analyses exploiting trilepton / 1 lepton + 1 photon selections

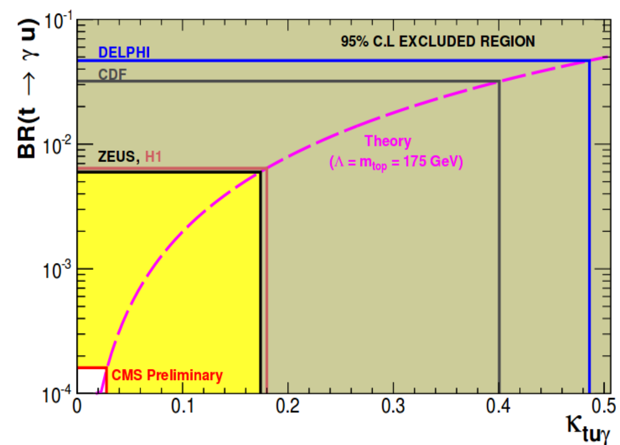


CMS PAS-TOP-12-021





CMS PAS-TOP-14-003



Prospects for the future

Run 2 top couplings:
FCNC studies @14 TeV LHC

- **FCNC in top decays:**

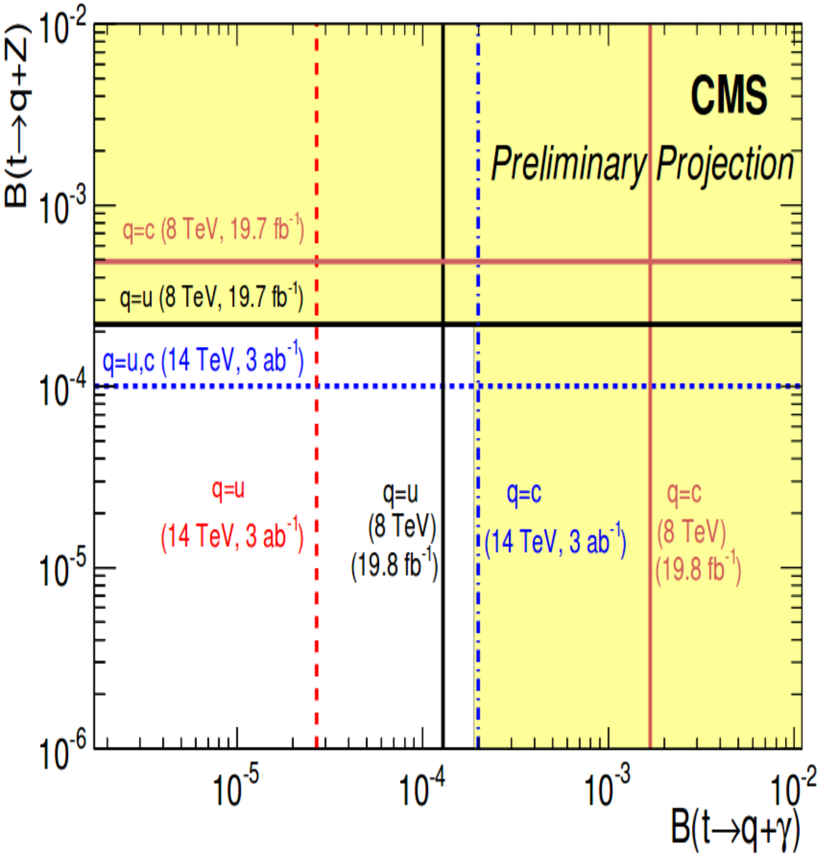
- will greatly benefit from the increase of statistics

- signal/background ratio will become far More convenient

- Will become crucial to improve or keep same performances for JES and b-tagging

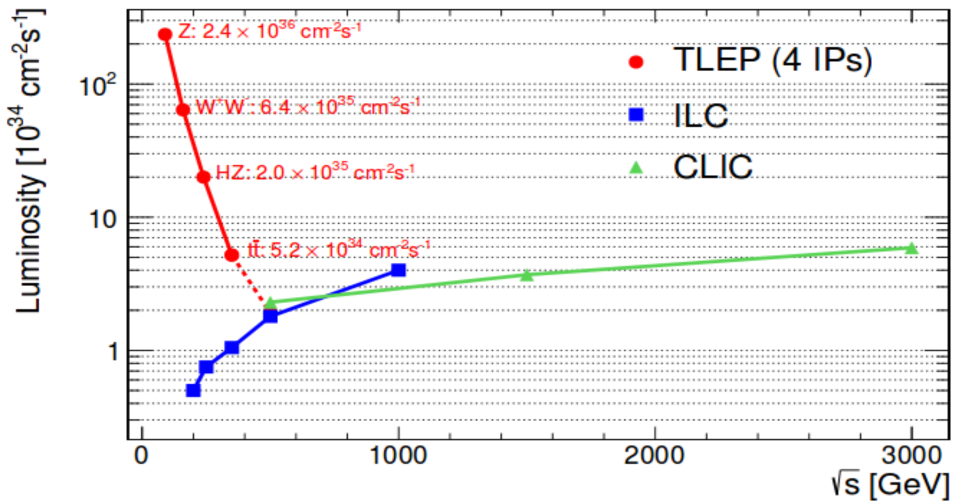
$\mathcal{B}(t \to Zq)$	$300\,\text{fb}^{-1}$ @ 14 TeV	$3000\,\text{fb}^{-1}$ @ 14 TeV
Exp. bkg. yield	26.8	268
Expected limit	$< 0.027\%$	$< 0.010\%$
$1\,\sigma$ range	$0.018 - 0.038\%$	$0.007 - 0.014\%$
$2\,\sigma$ range	$0.013 - 0.051\%$	$0.005 - 0.020\%$

CMS PAS-FRT-16-006



Note: the plot doesn't include all results presented in this talk

What are the perspectives @e+e- colliders?



- **Production of tt pairs:**

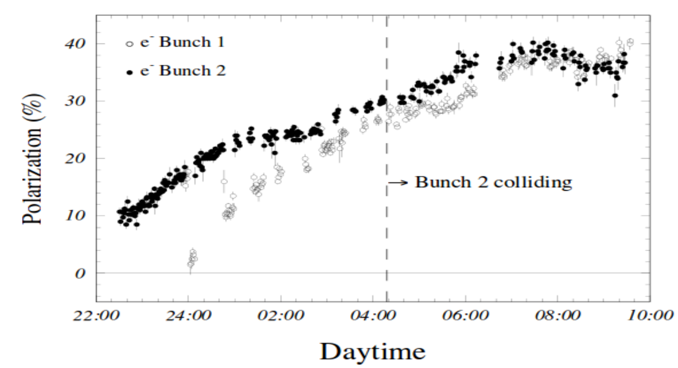
- Production with e+e- beams at 350 GeV: pure ewk process

- will need precise measurement of the beam energy

arXiv:1308.6176

- Transverse polarisation of the beam: will allow energy calibration through spin depolarization in circular e+e-.

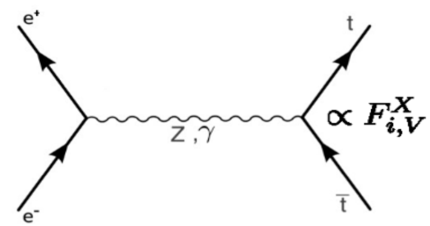
- Longitudinal polarization: can be exploited for asymmetry measurements



@TLEP : at tt threshold energy coul have polarisation ~10% in ~3 minutes, faster than @Z pole (see also arXiv:1406.0561)

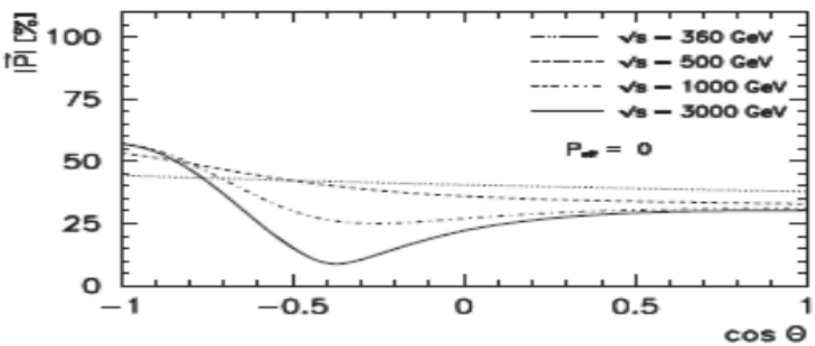
@e+e- colliders: studies with polarised beams

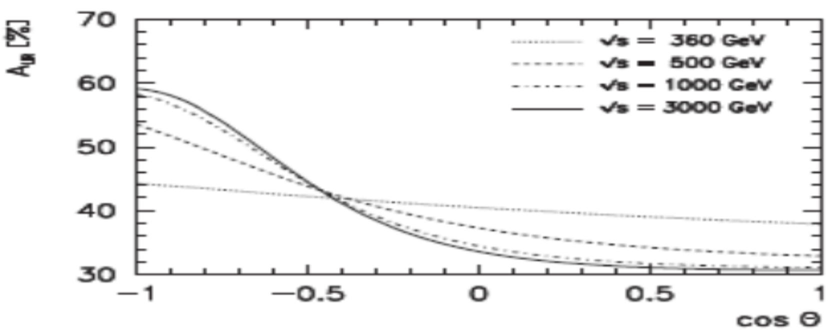
- **Top production with polarized e+e-:**



- Allow to probe features of the ewk vertex ttZ!

- Anomalous form factors might be visible at the vertex





Measurements of top production angles:

- top polarisation and forward-Backward asymmetry in production can be measured!

- They are directly sensitive to BSM Physics!

FIXME

@e+e- colliders: precision ewk tt threshold scan

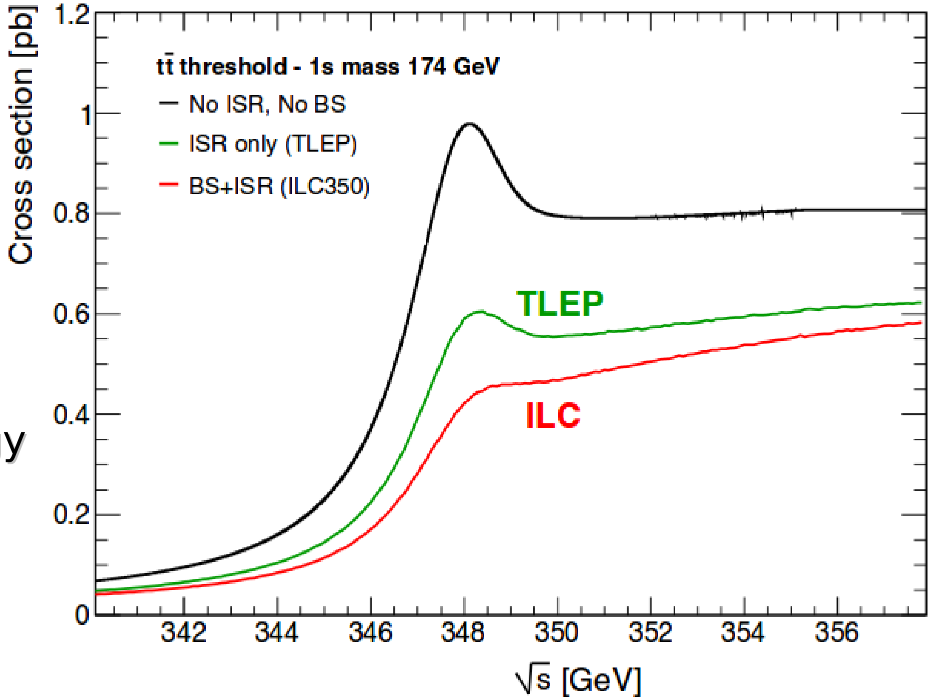
- **tt ewk production threshold:**

- High precision measurements will allow to constrain SM parameters

- top mass, decay width, and yukawa coupling to the Higgs will be measured with an unconceivable precison for LHC

- Main uncertainties: $\alpha_S(m_Z)$ and beam energy

- Experimental effort will be needed in tandem with a specific effort to reduce theoretical uncentainties on electroweak top production



arXiv:1308.6176

	m_{top}	Γ_{top}	λ_{top}
TLEP	**10 MeV**	**11 MeV**	**13%**
ILC	31 MeV	34 MeV	40%