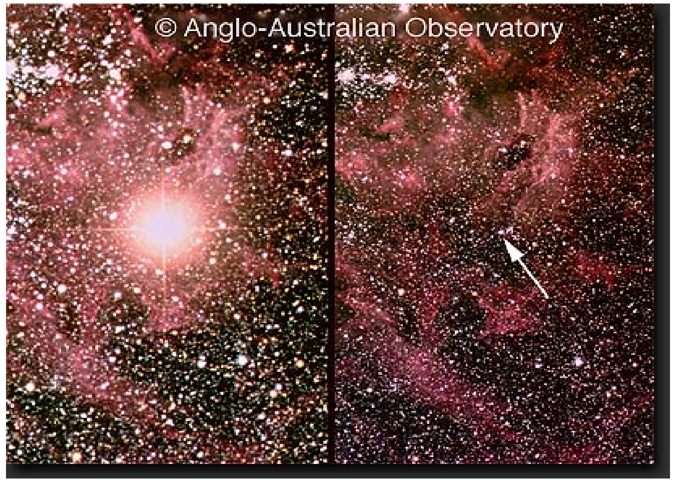
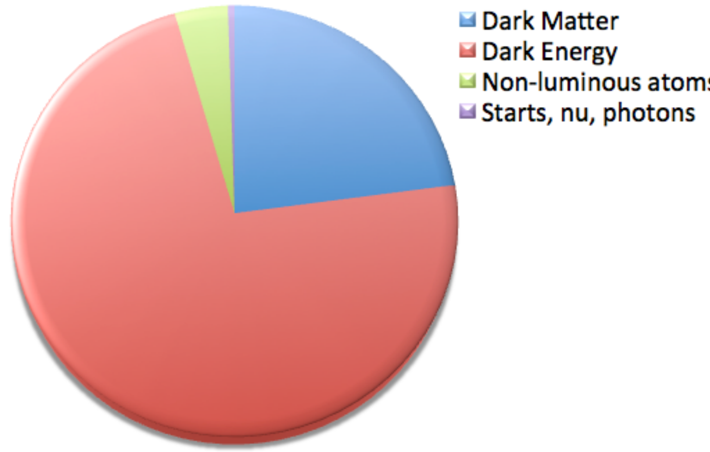
The Top Quark

M. Cobal and G. Panizzo

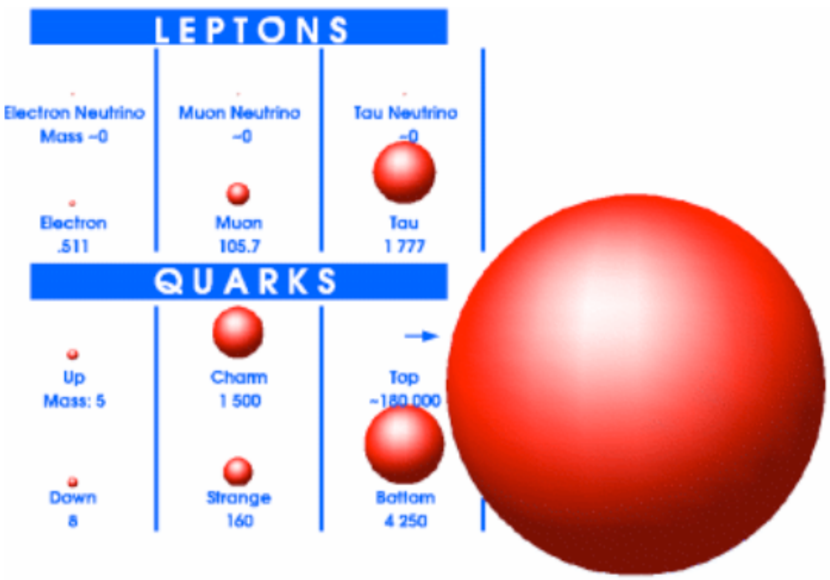
credits: L. Cerrito

The Standard Model vs. our Universe





There are indications that New particles, Forces, or a new Space-Time structure are waiting to be uncovered…



New Physics at O(TeV)

↕

Dynamics of the heaviest particle:
the top quark

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hic sunt futura

The Top quark

After 1977 we had:

Quarks	u	c	
	d	s	b
Leptons	e	μ	τ
	ν_e	ν_μ	ν_τ

Obviously one missing 'top' t

Also good theoretical reasons for complete 'doublets'.

Searched in vain at e^+e^- machines, PETRA, PEP, LEP etc – ruling out any new quarks at their energies → top mass > 45 GeV/c^2 (half LEP1 energy).

The Top quark discovery

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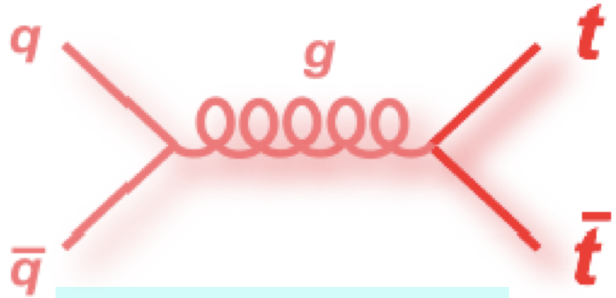
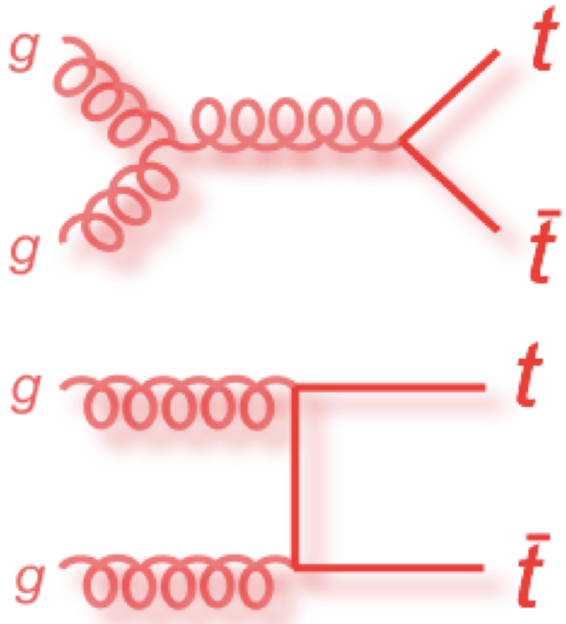
The sixth quark was found in 1994 at Fermilab. The first evidence came from the CDF experiment in proton/antiproton collisions at the energy of 1.8 TeV.

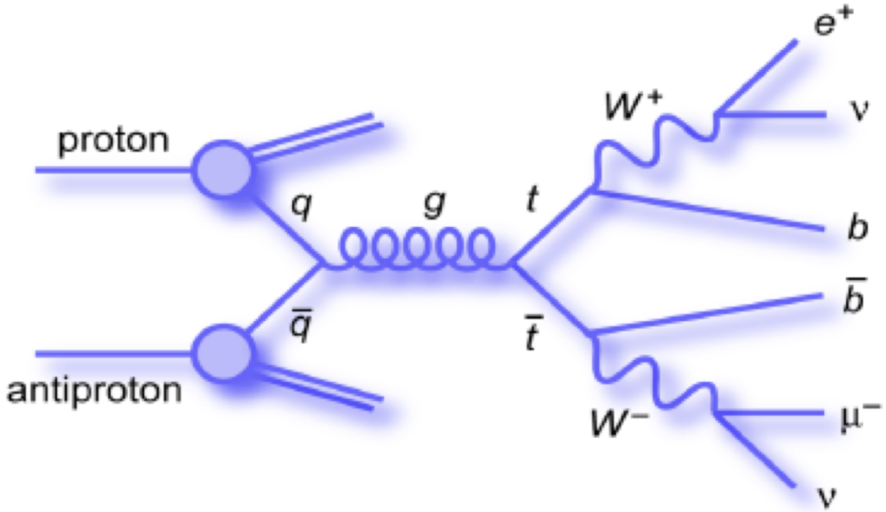


Quark annihilation

Typical Feynman diagrams for production

Gluon-gluon fusion





Topology of a top event

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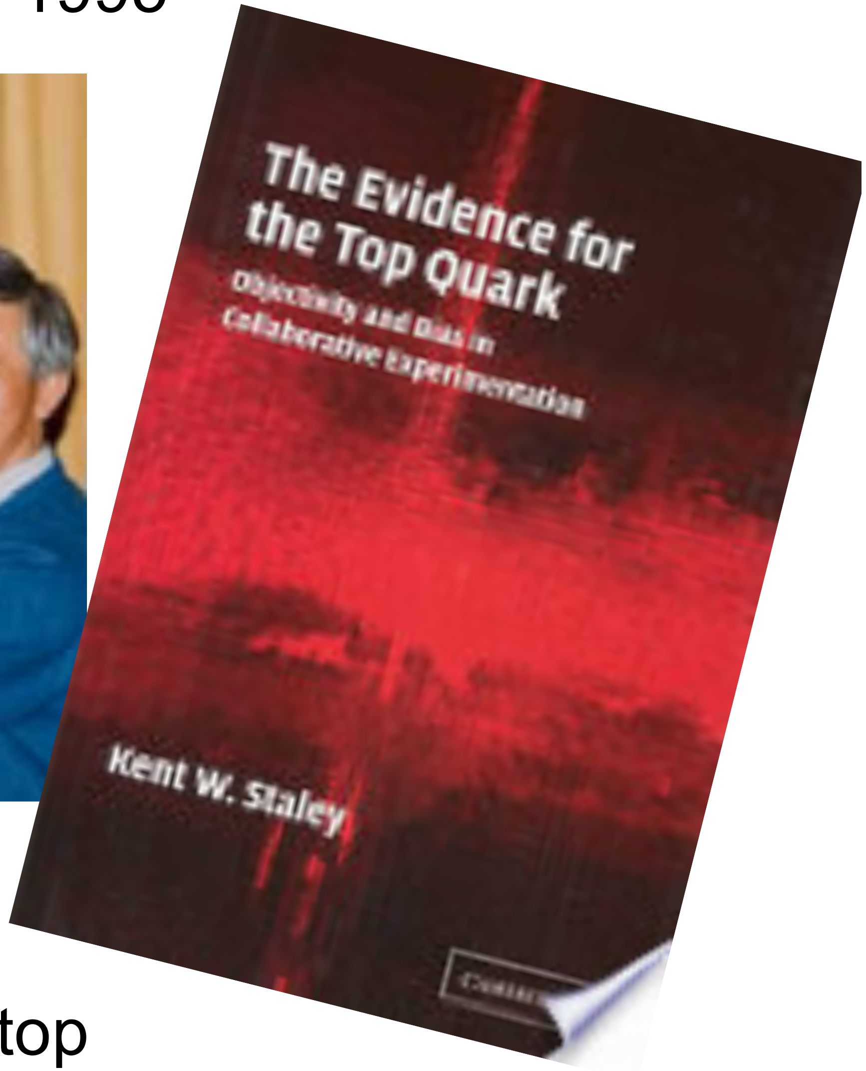
Moriond Conference

France 1995



The full story of top discovery in two books!

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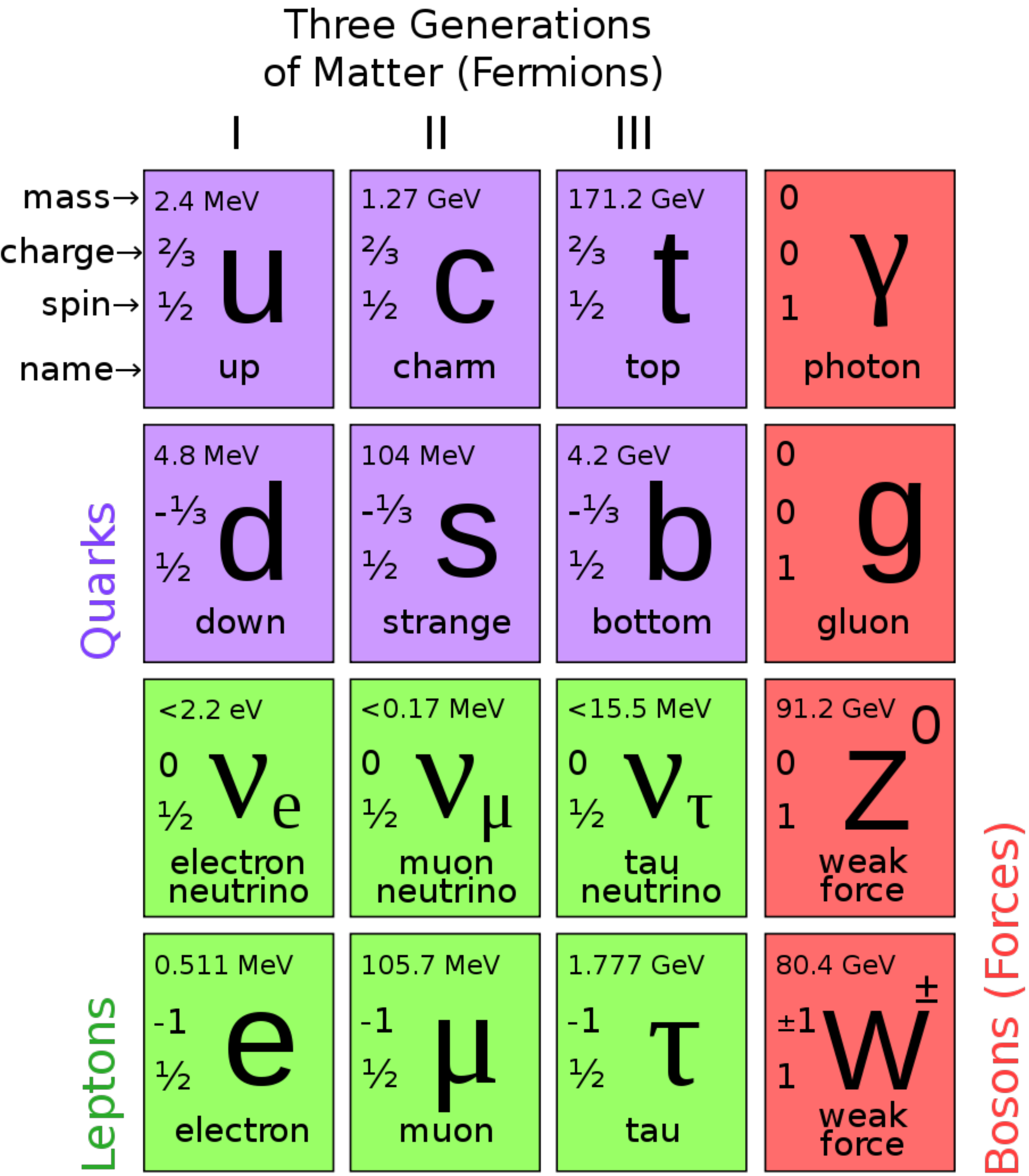
Virgin Islands Summer School

US 1994

Brief introduction to top quarks



Top Quark:

- Particle type: weak isospin partner of the bottom quark
- Spin: +1/2
- Mass: approximately 173 GeV/c^2
- Width: ~1.5 GeV/c^2 or ~10^{-24} s
- Couplings: Strong (color triplet), EM (Q=+2e/3), Weak ($I_{3,L}$=+1/2)
- Decay: almost exclusively to W+b

Top quark discovery: 1995

The search for top lasted almost two decades. Its heavy mass delayed discovery.

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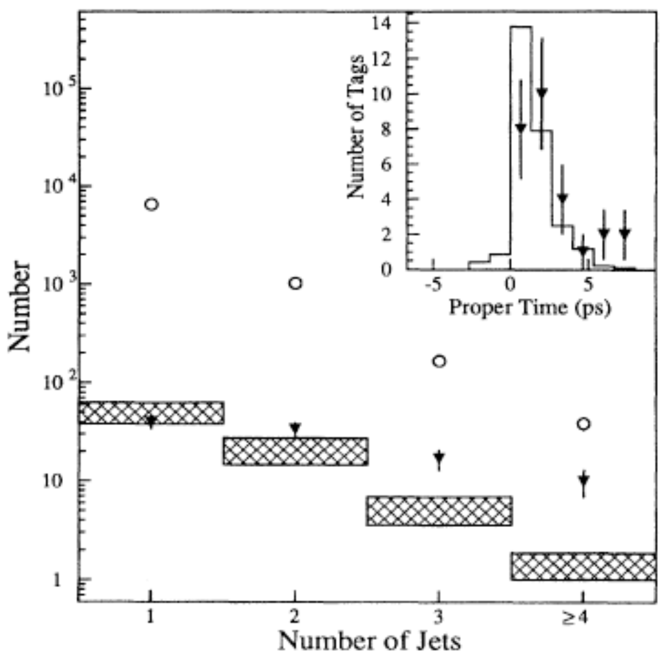
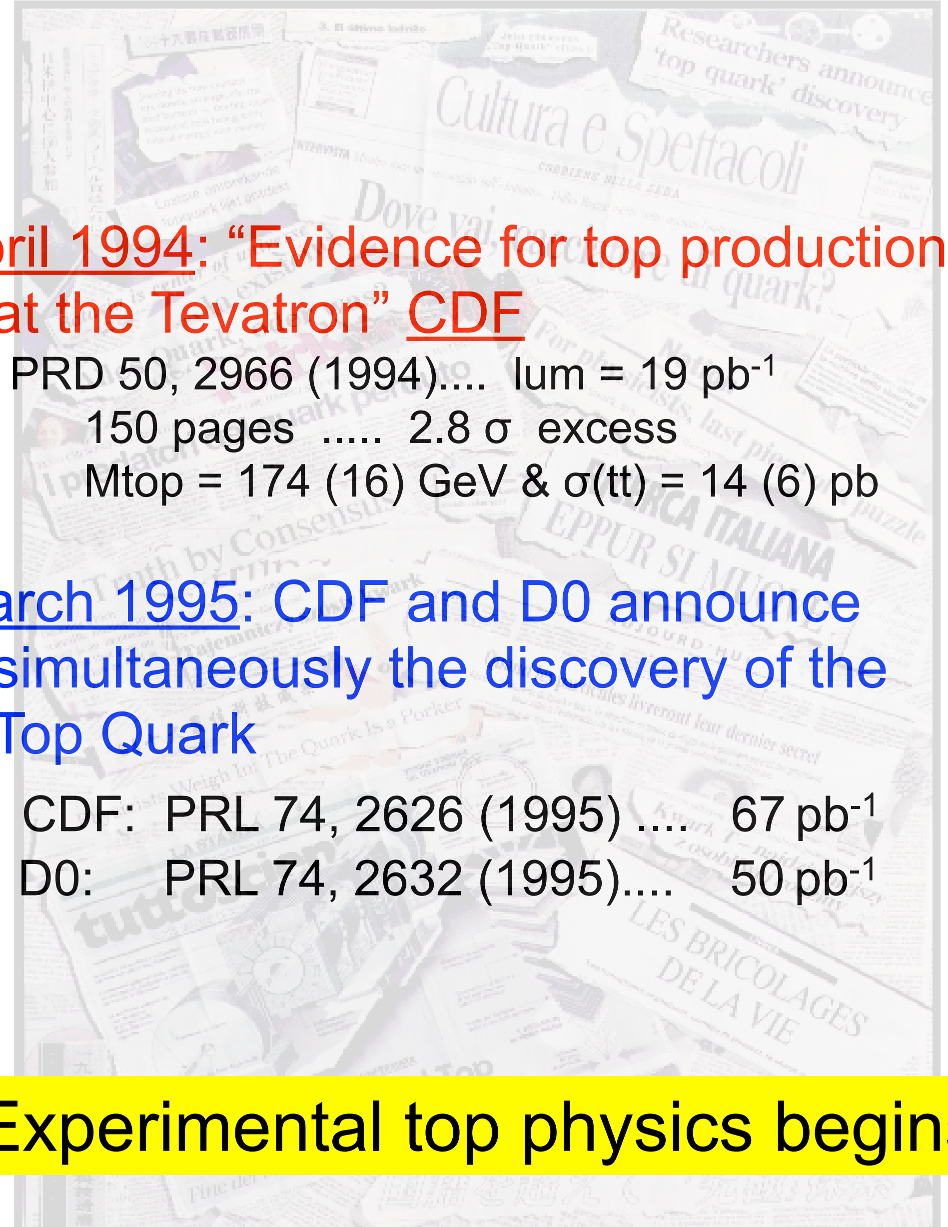


FIG. 1. Number of events before SVX tagging (circles), number of tags observed (triangles), and expected number of background tags (hatched) versus jet multiplicity. Based on the excess number of tags in events with ≥3 jets, we expect an additional 0.5 and 5 tags from $t\bar{t}$ decay in the 1- and 2-jet bins, respectively. The inset shows the secondary vertex proper time distribution for the 27 tagged jets in the $W+$ ≥3-jet data (triangles) compared to the expectation for b quark jets from $t\bar{t}$ decay.



April 1994: "Evidence for top production at the Tevatron" CDF

PRD 50, 2966 (1994).... lum = 19 pb^{-1}

150 pages ..... 2.8 σ excess

Mtop = 174 (16) GeV & σ(tt) = 14 (6) pb

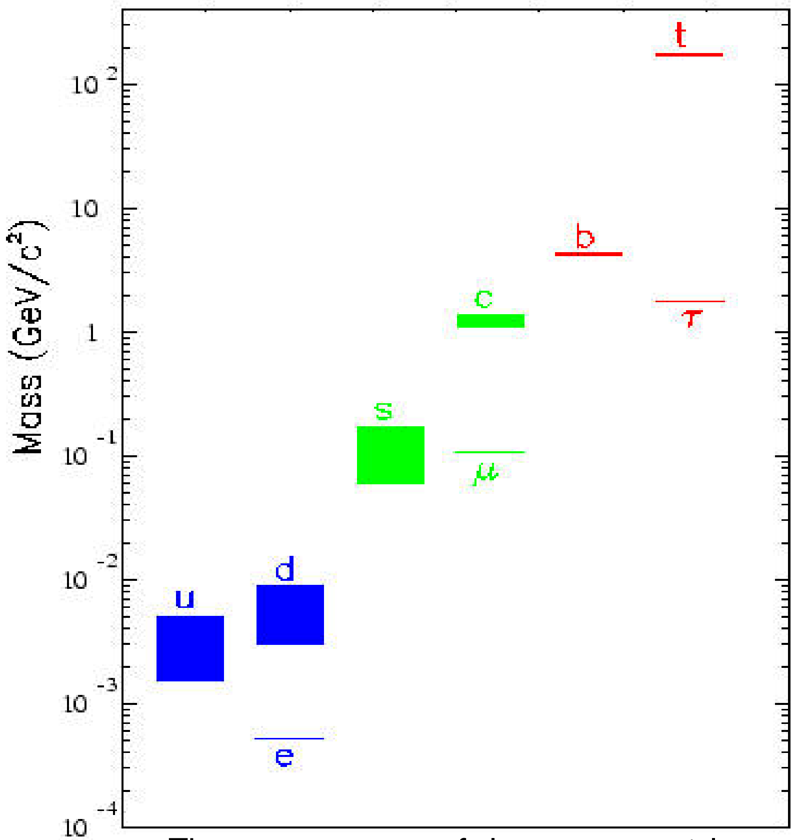
March 1995: CDF and D0 announce simultaneously the discovery of the Top Quark

CDF: PRL 74, 2626 (1995) ....   67 pb^{-1}

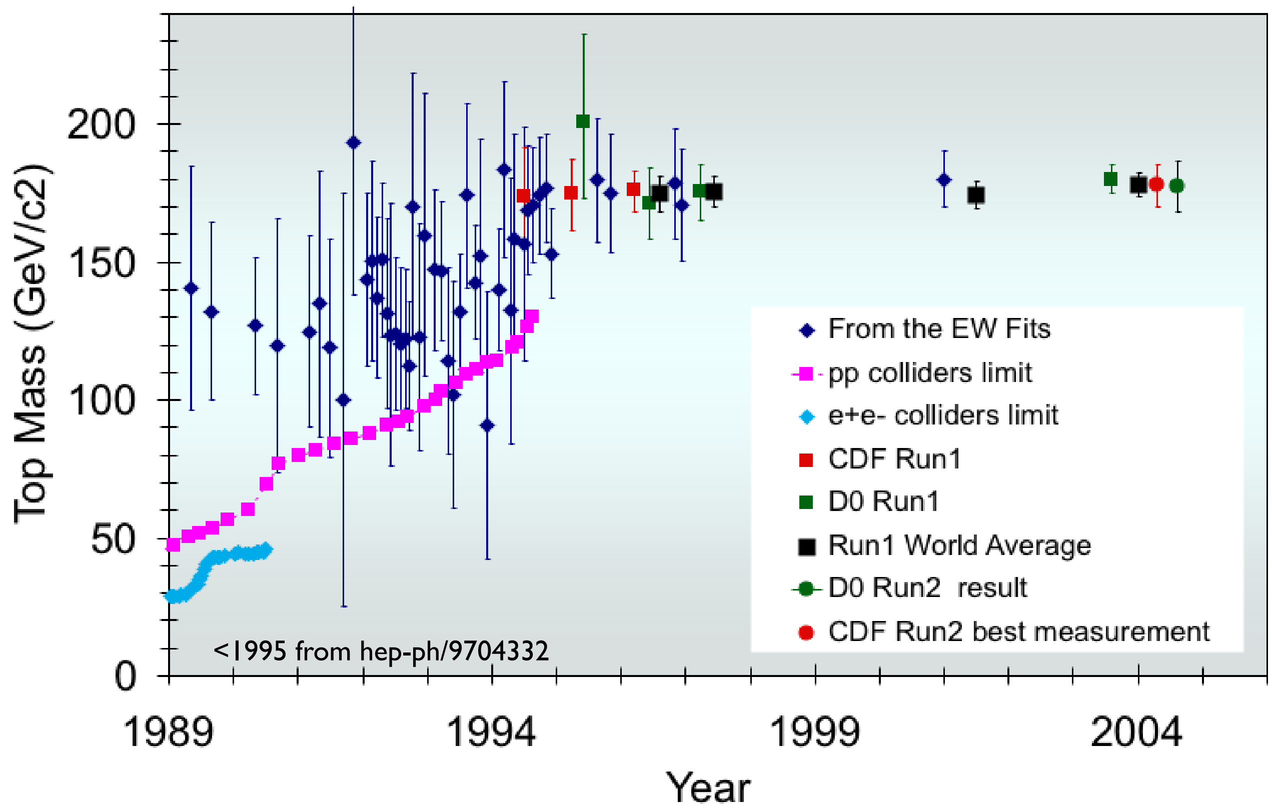
D0:   PRL 74, 2632 (1995)....   50 pb^{-1}

Experimental top physics begins

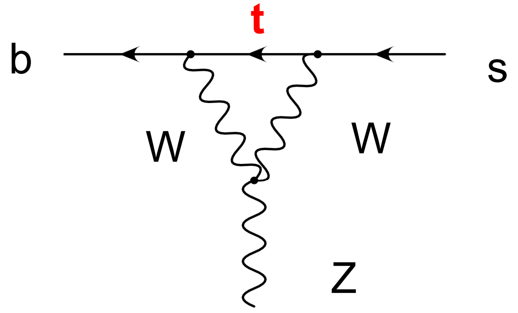
Top in the standard model: mass



The mass spectrum of elementary particles

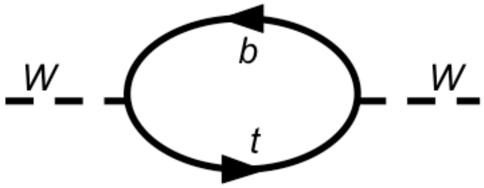


A free parameter… but experimental evidence suggested a large-ish top mass before its discovery because of e.g. FCNC in K and B



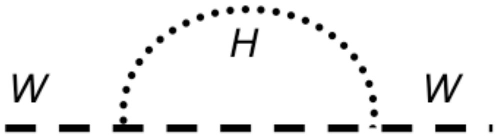
Top in the standard model: mass

Radiative corrections to the W mass calculation:



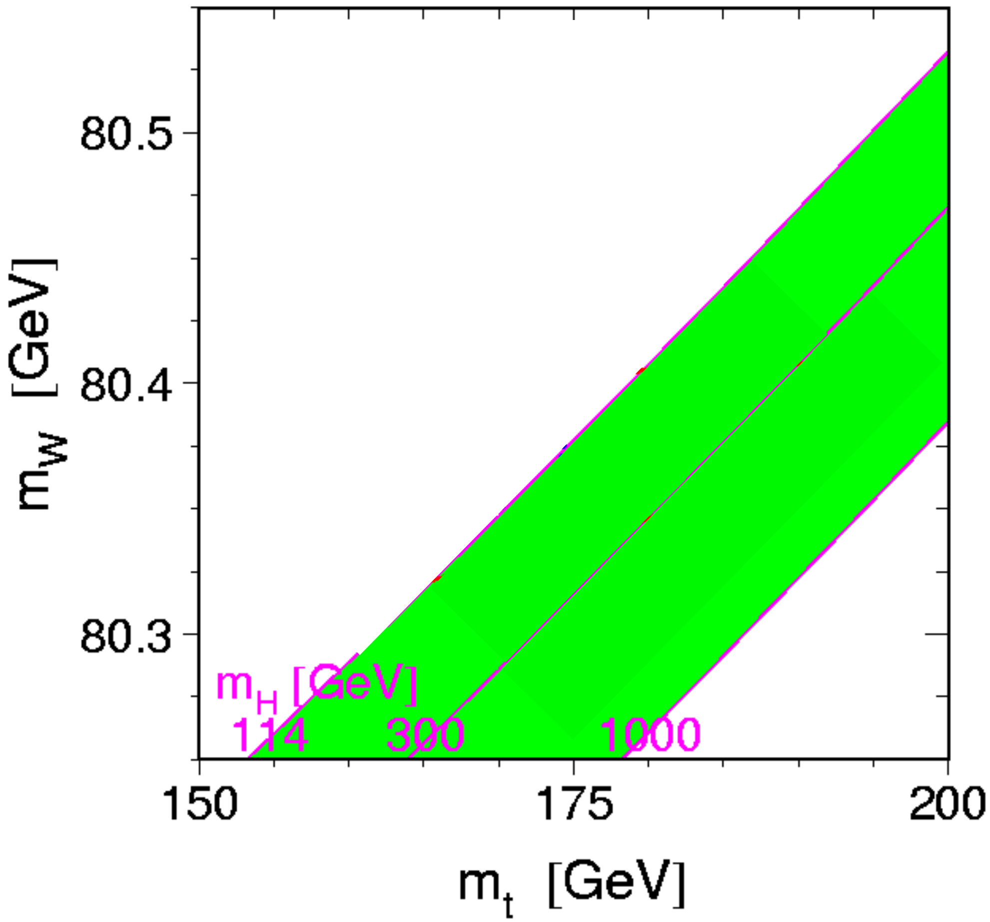
Quadratic in the top mass:

$$\Delta M_W \propto M_t^2$$



Logarithmic in the Higgs mass:

$$\Delta M_W \propto \ln(M_H)$$



The top mass enters many EW parameters, with sizeable corrections.

Top in the standard model: lifetime

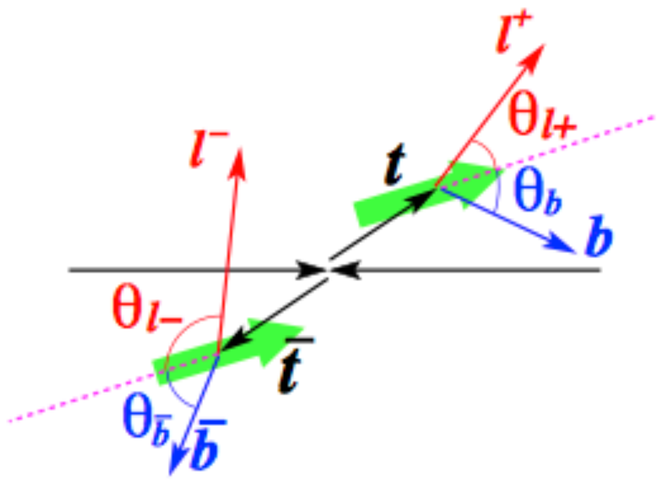
The large width of the top quark implies a very short decay time:

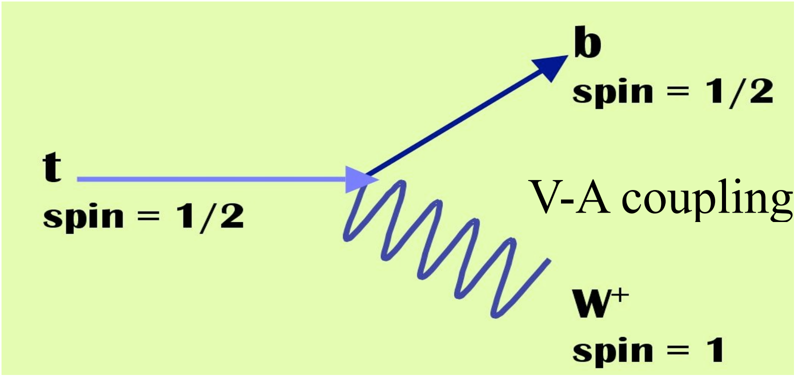
$\Gamma_t \approx 1.5 \text{ GeV}$ corresponding to $\tau \approx 5 \cdot 10^{-25} \text{ s}$

This is one order of magnitude larger than the hadronization scale:

$\Lambda \approx 0.2 \text{ GeV}$ or $\tau \approx 10^{-24} \text{ s}$

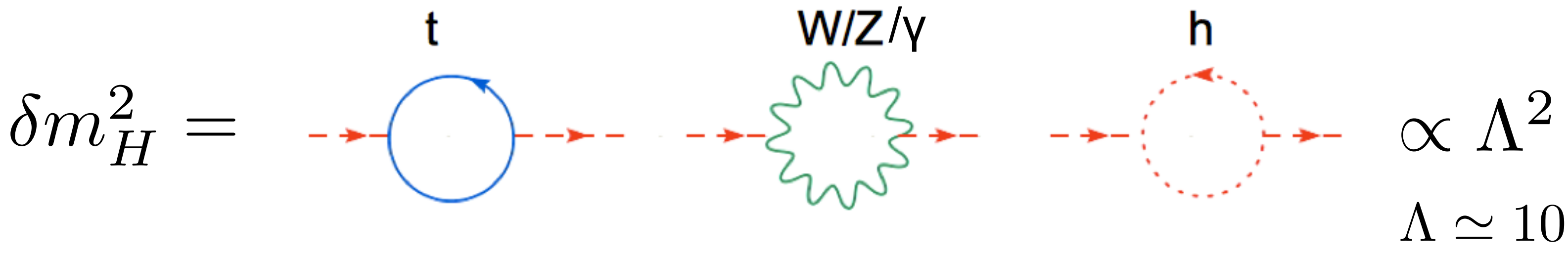
top is the only quark which is created and decays as a free quark

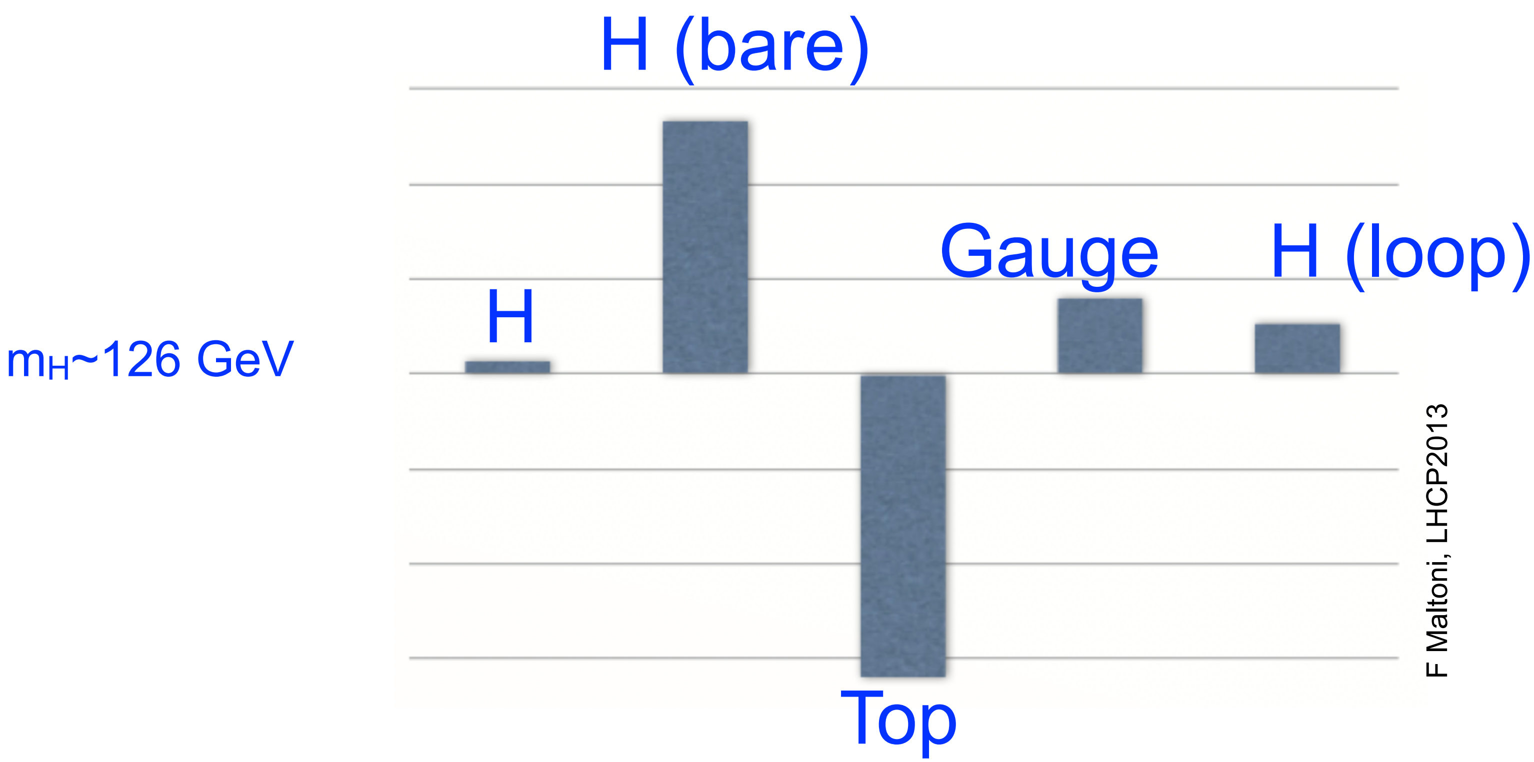




The Higgs "Naturalness" Problem

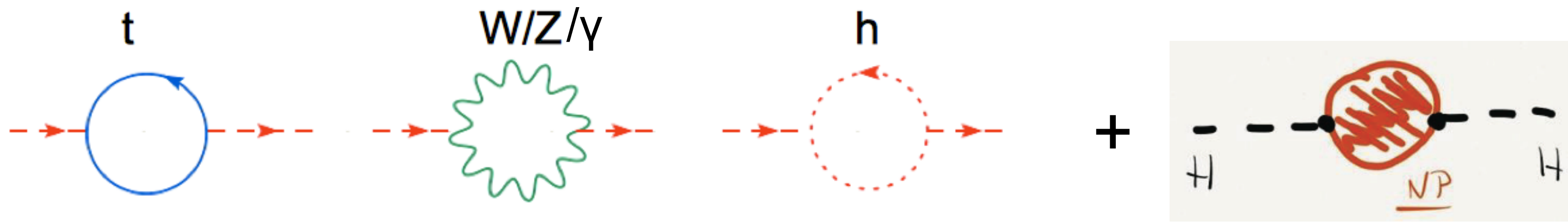
Radiative corrections to the Higgs boson mass diverge with the SM cut-off energy (Λ)





The large top quark mass (173 GeV/c^2) gives "un-naturally" large corrections.

Possible Discoveries: a Revolution

$\delta m_H^2 =$ 

$= \log\Lambda$ or finite Λ=O(TeV)

Most Natural theories of physics Beyond the Standard Model (BSM) foresee modifications of the top dynamics at O(TeV)

Models with partners of the top:

new scalars/vectors, possibly strongly coupled with the top. e.g. SUSY.
Cancel the divergence

Models with compositeness and strong dynamics:

top bound states, top is not elementary, e.g. Technicolour.
New dynamics at ~TeV

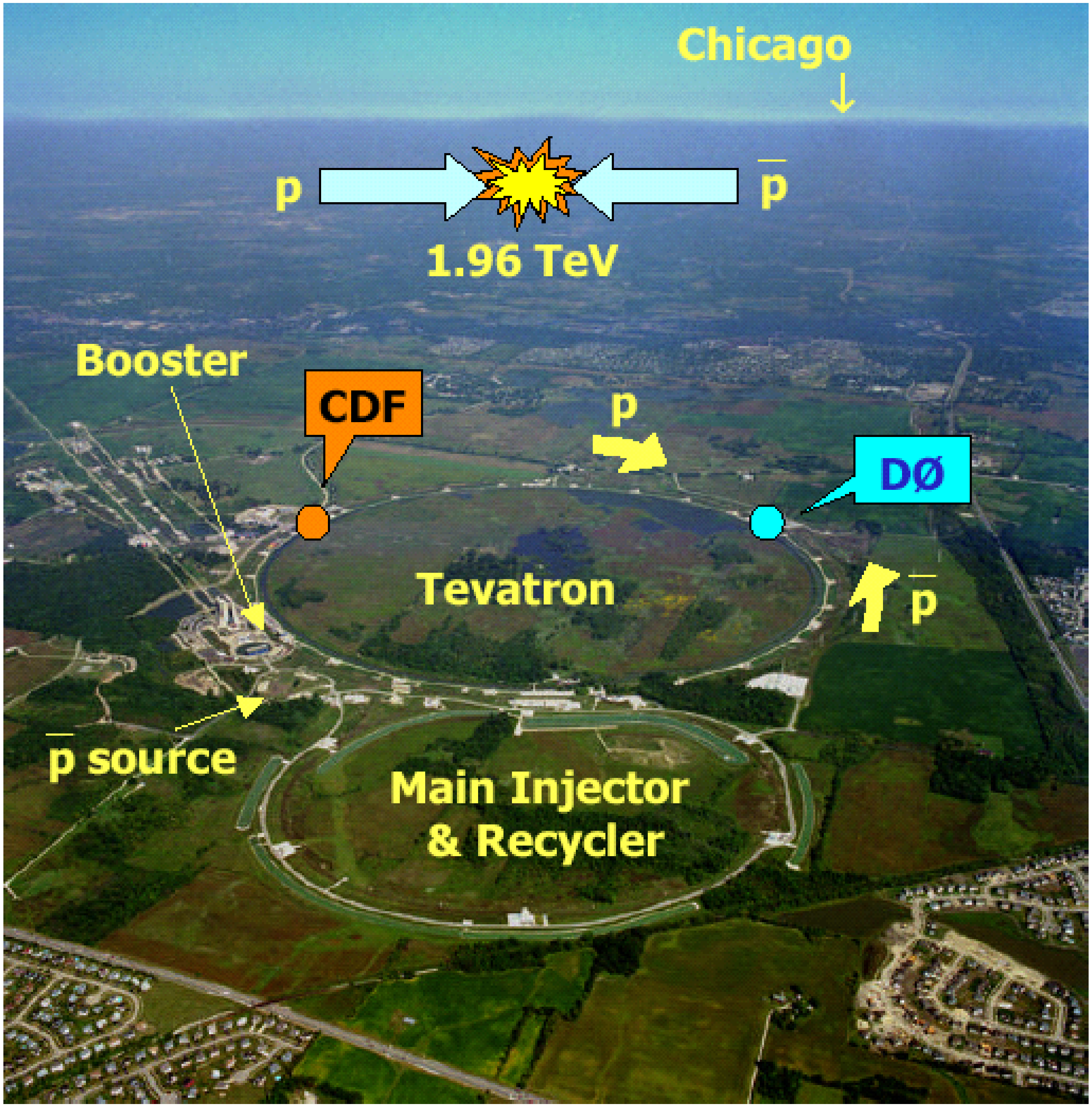
New space-time structure:

Extra dimensions. e.g. Kaluza-Klein theories.
Lower the cut-off Λ

We TALK of top quark physics,

but we're THINKING of physics beyond the standard model (BSM)

The Fermilab Tevatron



Protons - Antiprotons

- Run I: 1992-96 ($\sqrt{s}$=1.8 TeV, ~110 pb^{-1})
- Run II: 2000-11 ($\sqrt{s}$=1.96 TeV, ~10 fb^{-1})
- 396 ns bunch spacing
- Peak luminosities: 3 – 4 x 10^{32} $cm^{-2}s^{-1}$

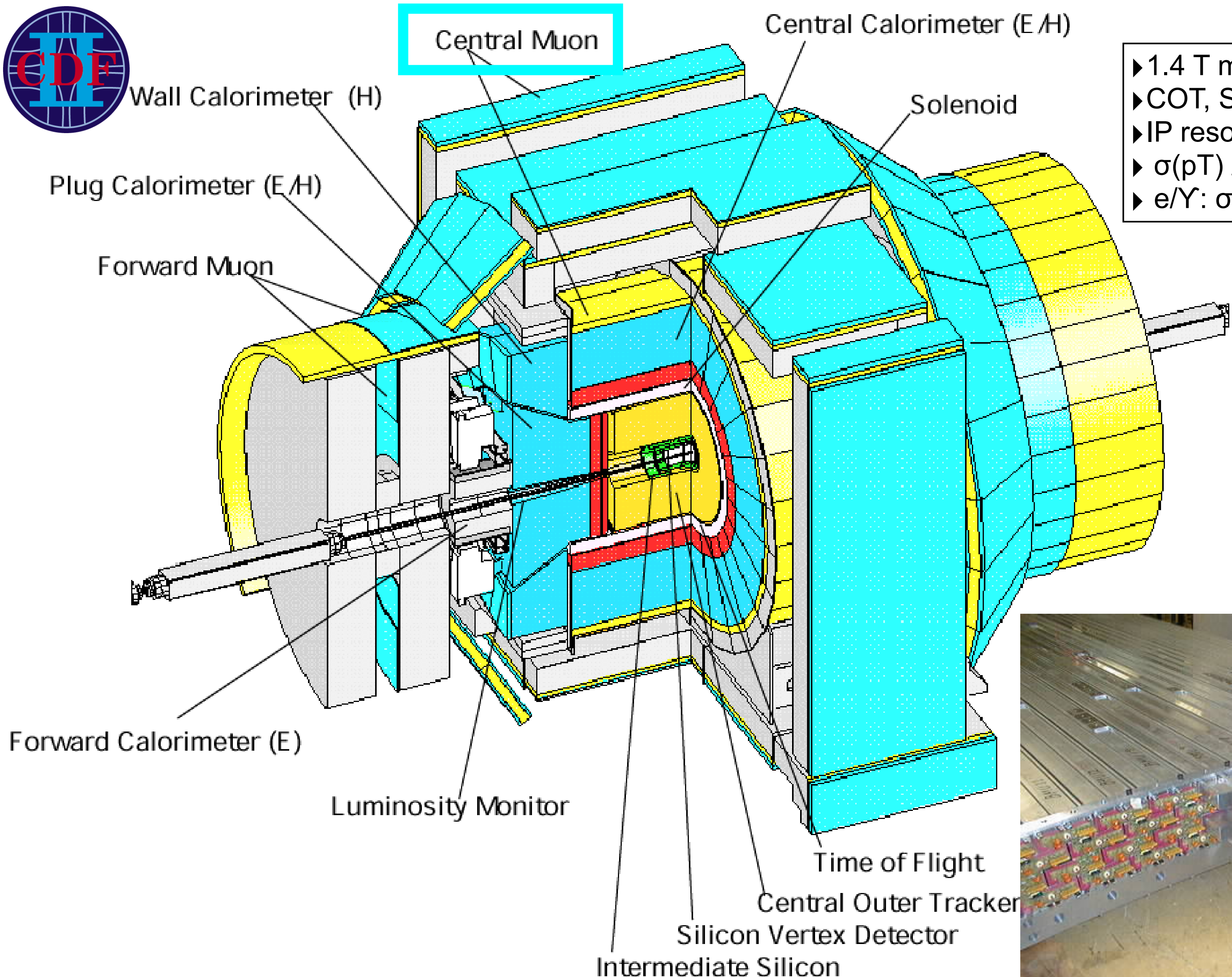
Ceased operations in 2011

The Large Hadron Collider

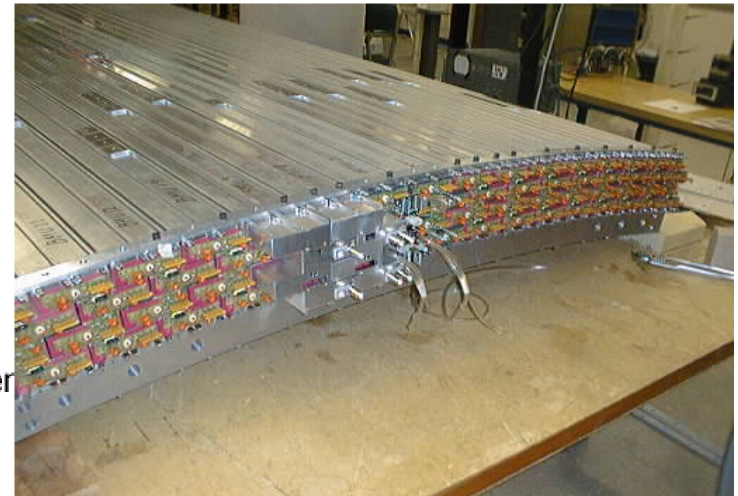
Protons - Protons

- Run I: 2010-12 $\sqrt{s}$=7(8) TeV, ~5 (20) fb^{-1})
- Run II: 2015-18 ($\sqrt{s}$=13-14TeV, ~75-100 fb^{-1})
- 25/50 ns bunch spacing
- Peak luminosities (<2012): ~7×10^{33} $cm^{-2}s^{-1}$

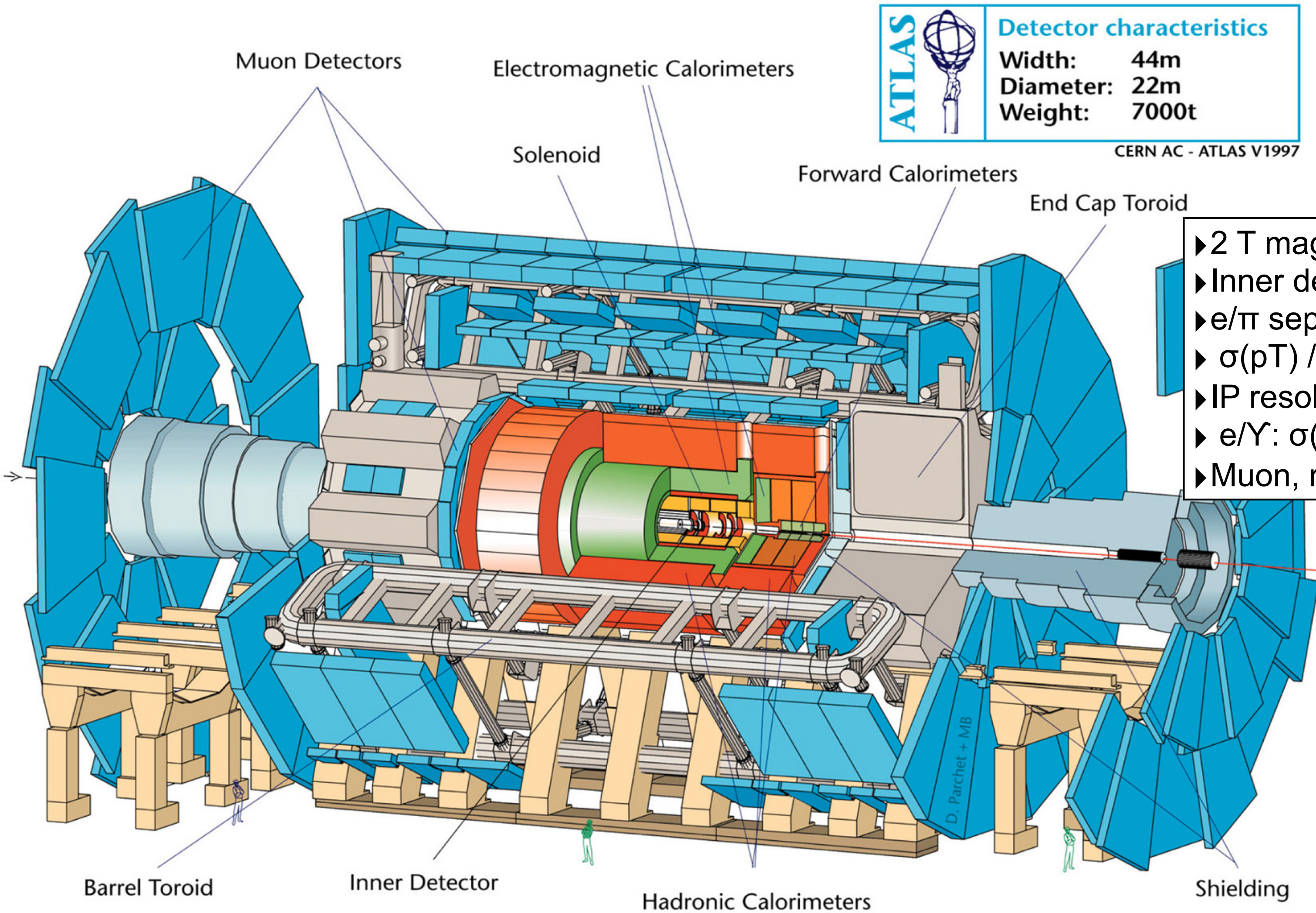
The CDF Detector at FNAL



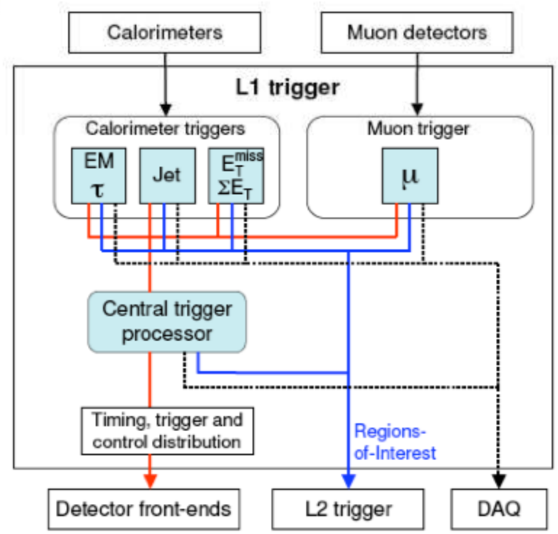
- 1.4 T magnetic field
- COT, SVX: $|\eta|<1$, $|\eta|<2$
- IP resolution: 40 μm
- $\sigma(p_T) / p_T = 0.07\%\ p_T\ [\mathrm{GeV/c}]^{-1}$
- e/γ: $\sigma(E)/E = 13.5\% / \sqrt{E_T} \oplus 2\%$


CDF muon chambers

The ATLAS detector at the LHC

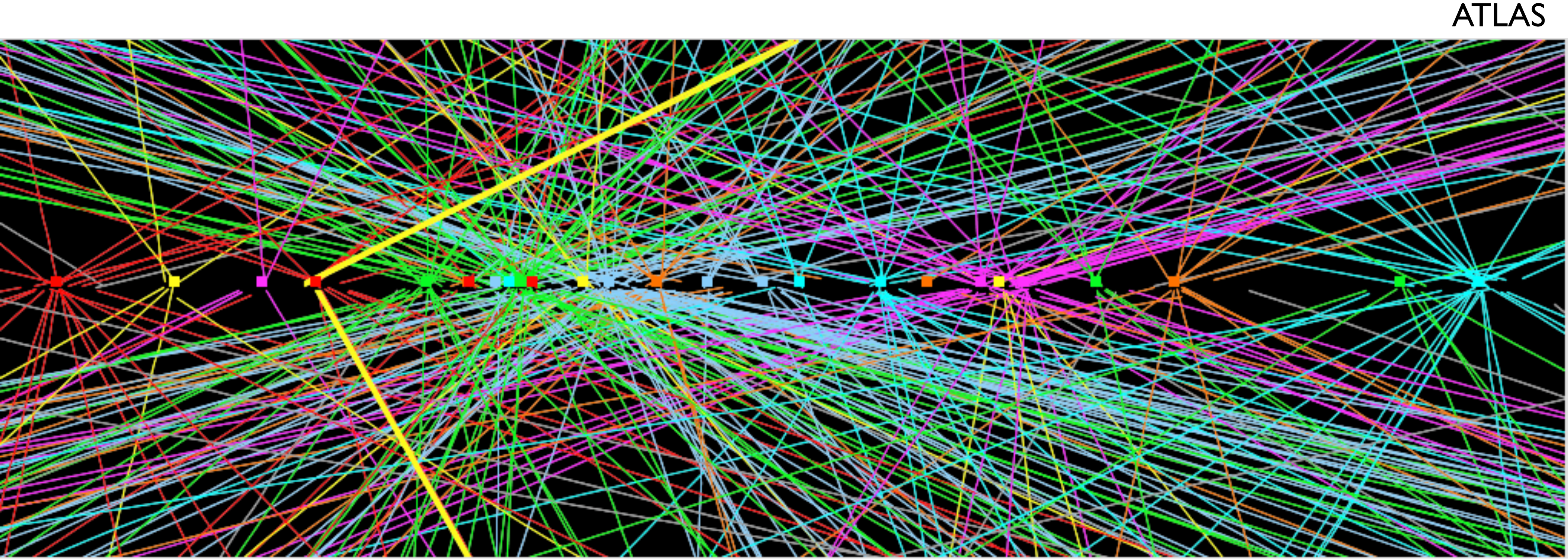


- 2 T magnetic field for ID
- Inner detectors $|\eta|<2.5$
- e/π separation
- $\sigma(pT) / pT = 0.038\%\ pT \oplus 1.5\%\ [GeV/c]^{-1}$
- IP resolution: ~22μm
- e/ϒ: $\sigma(E)/E = 10\% / \sqrt{E} \oplus 1\%$
- Muon, resolution <10% up to ~1 TeV



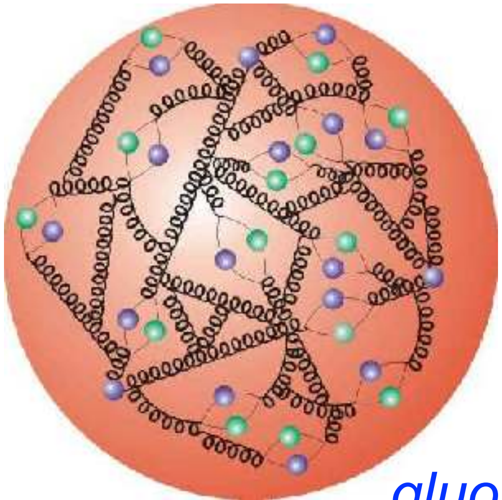
R Achenbach *et al* 2008 *JINST* **3** P03001

Candidate Z event with 25 pp interactions

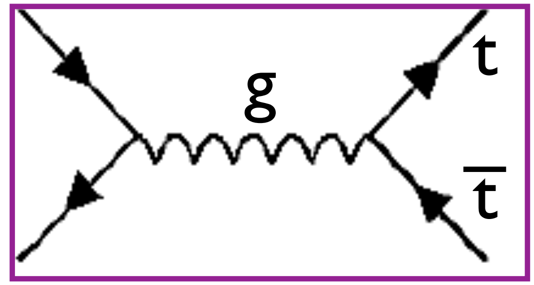



ATLAS & CMS
LHC

Pair production of top in hadronic collisions

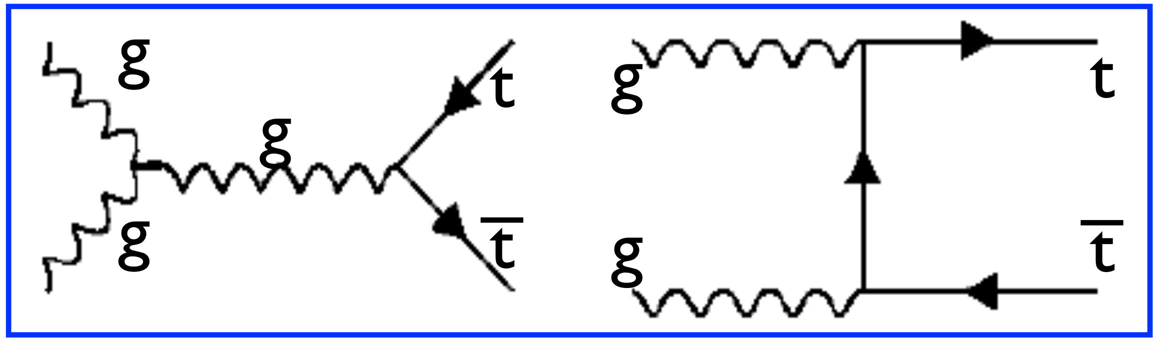


quark annihilation
(~85% at the Tevatron)



NOTE: Production through virtual Z and γ are much smaller

gluon fusion
(~90% at the LHC)



Expected production rates

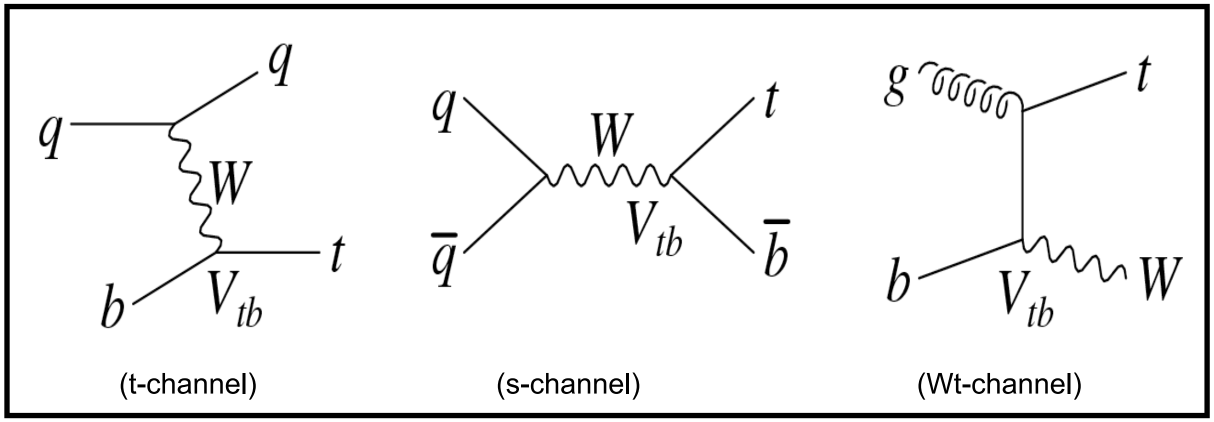
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

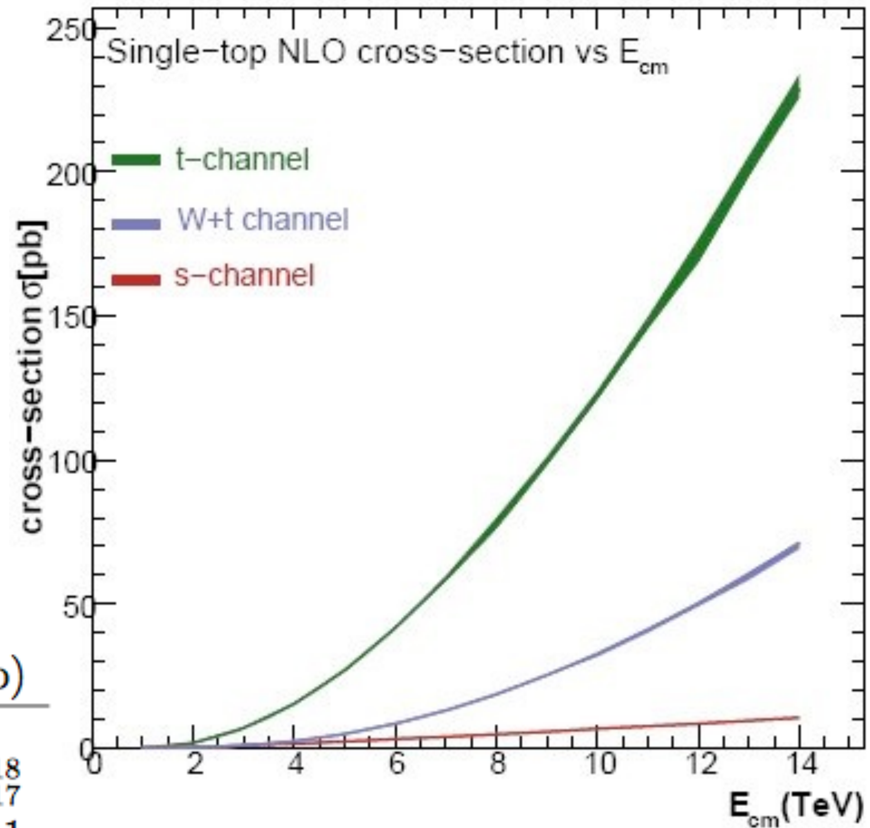
- ~70k *tt* @ Tevatron
- ~6M *tt* @ LHC8
- ~100M/y @ LHC14
- theory precision: ~3-4%$\oplus$3%(Δm_t)

Computed with: Top++ et. al.NNLO+NNLL, mt=173.3 GeV, arXiv:1303:6524 (2013)

Single production of top in hadronic collisions

Single (EWK production):





Expected production rates

LHC 7 TeV	$\sigma(t)$ (pb)	$\sigma(\bar{t})$ (pb)	$\sigma(t)+\sigma(\bar{t})$ (pb)
t-channel	$43.0^{+1.6}_{-0.2} \pm 0.8$	$22.9 \pm 0.5^{+0.7}_{-0.9}$	$65.9^{+2.1+1.5}_{-0.7-1.7}$
s-channel	$3.14 \pm 0.06^{+0.12}_{-0.10}$	$1.42 \pm 0.01^{+0.06}_{-0.07}$	$4.56 \pm 0.07^{+0.18}_{-0.17}$
tW	$7.8 \pm 0.2^{+0.5}_{-0.6}$	$7.8 \pm 0.2^{+0.5}_{-0.6}$	$15.6 \pm 0.4 \pm 1.1$

Kidonakis, arXiv:1210.7813 [hep-ph] (2012), m_t=173 GeV/c^2

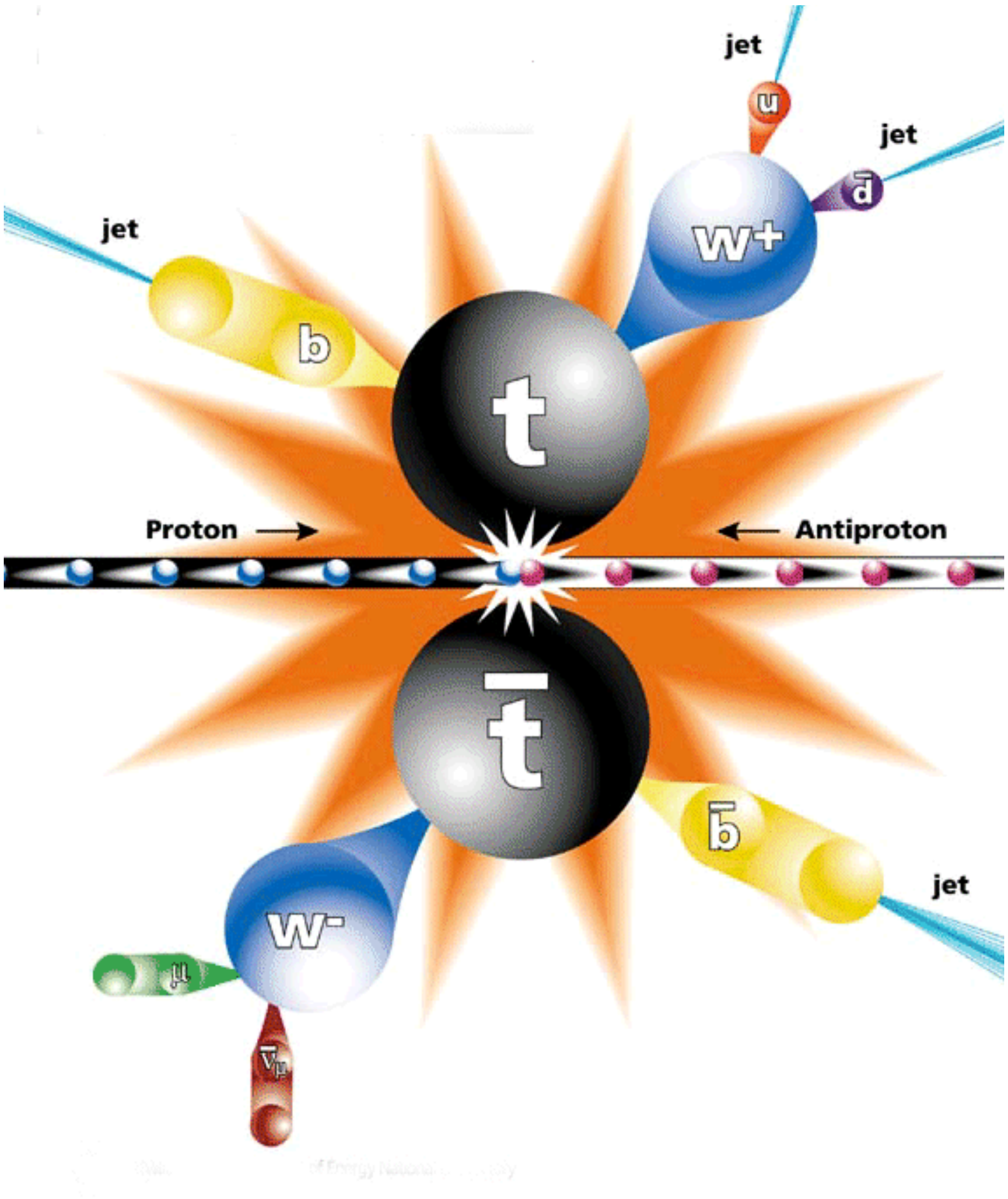
Tevatron	σ(pb)
s-ch	1.05 ± 0.05 [a]
t-ch	2.08 ± 0.08 [b]
Wt-ch	0.25 ± 0.03 [c]

Kidonakis, arXiv:1001.5034, 1103.2792, 1005,4451 [hep-ph], m_t=173 GeV/c^2

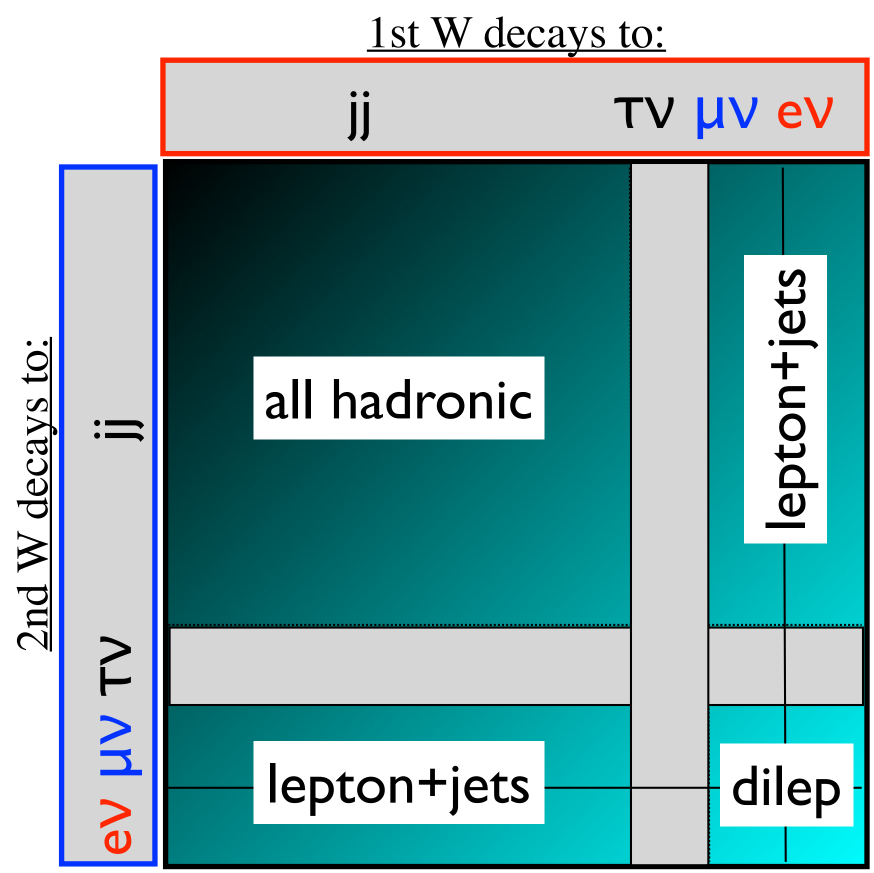
Rates ~70% lower than pair production.

Top decay and event classification

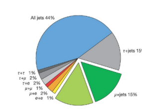
$|V_{tb}|\sim 1$, and $M_t > M_W + M_b$ $\Rightarrow$ $t \to Wb$ almost exclusively.



tt event classification:



Br(W→leptons) = 1/3
Br(W→quarks) = 2/3

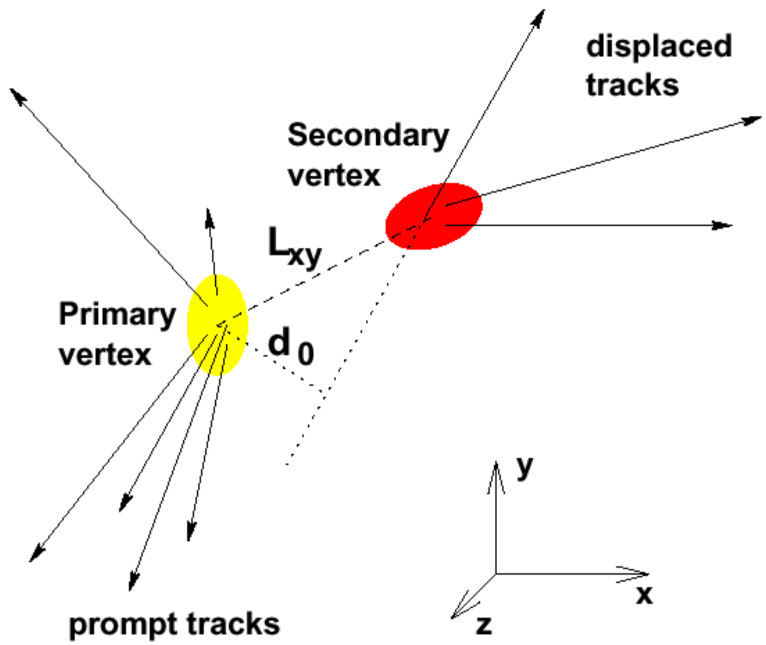


b-quark identification

B hadrons in top events..

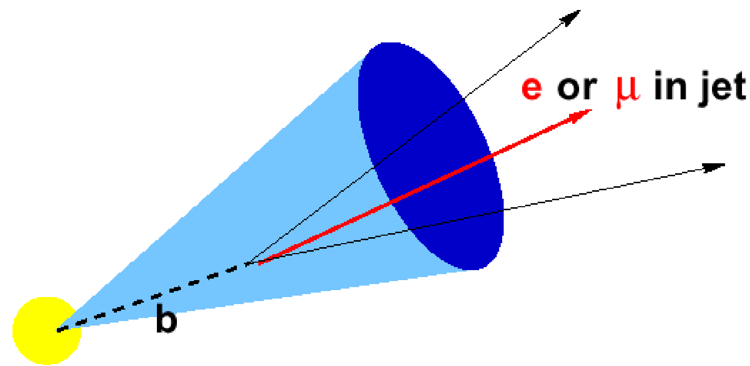
are long-lived and massive

Detect secondary vertices



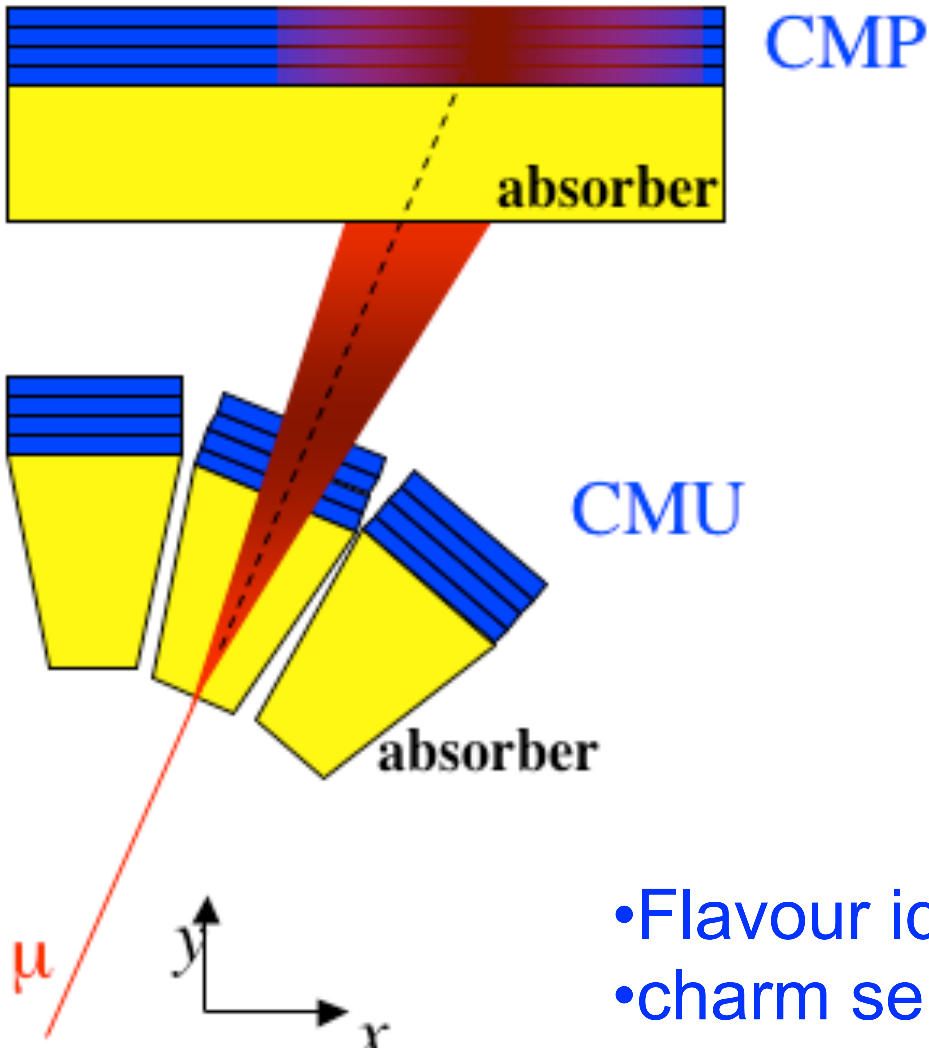
may decay semileptonically

Identify muons in jets



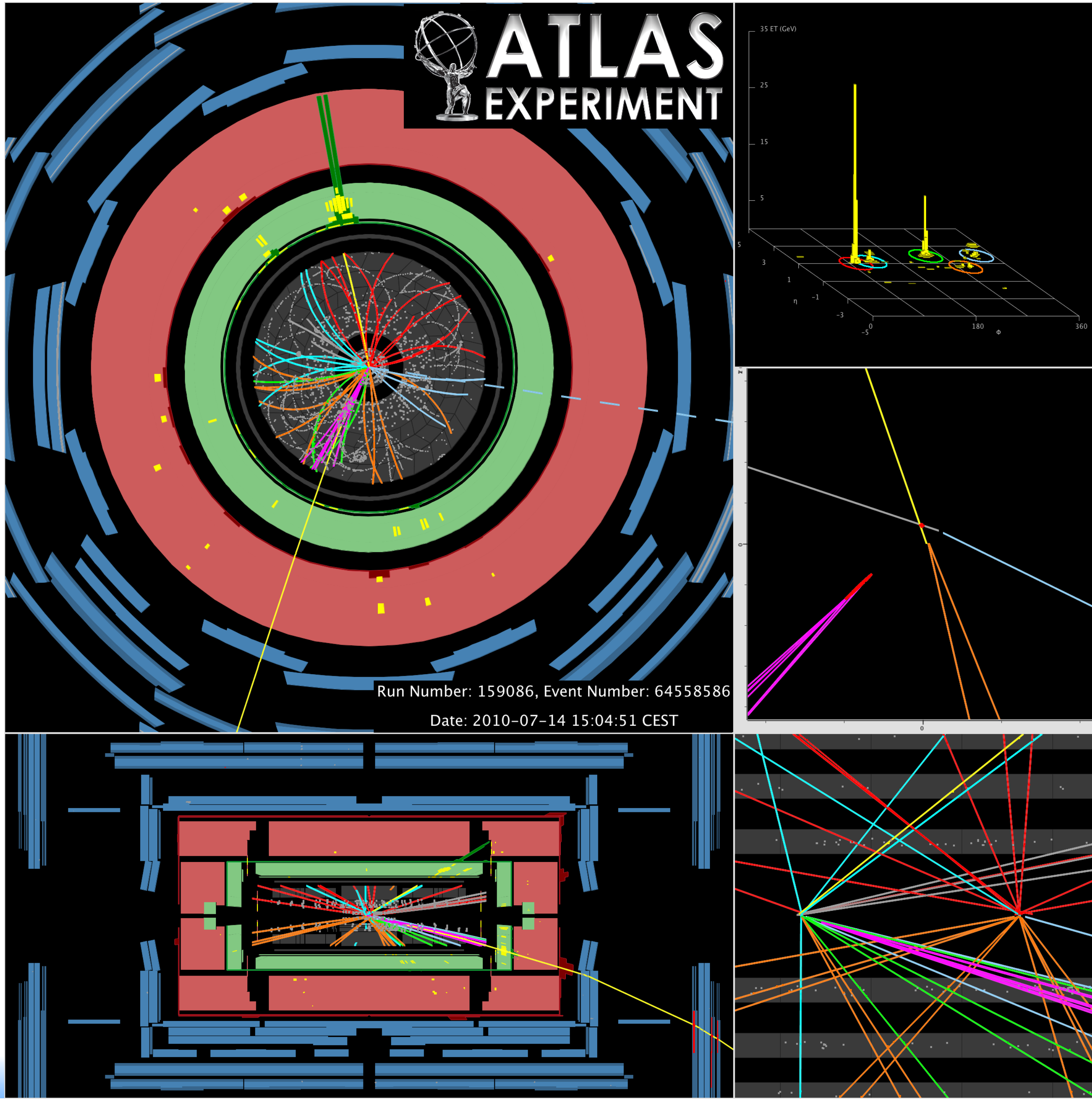
- $b \to \ell\nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell\nu s$ (BR $\sim$ 20%)

Working with soft muons (CDF)

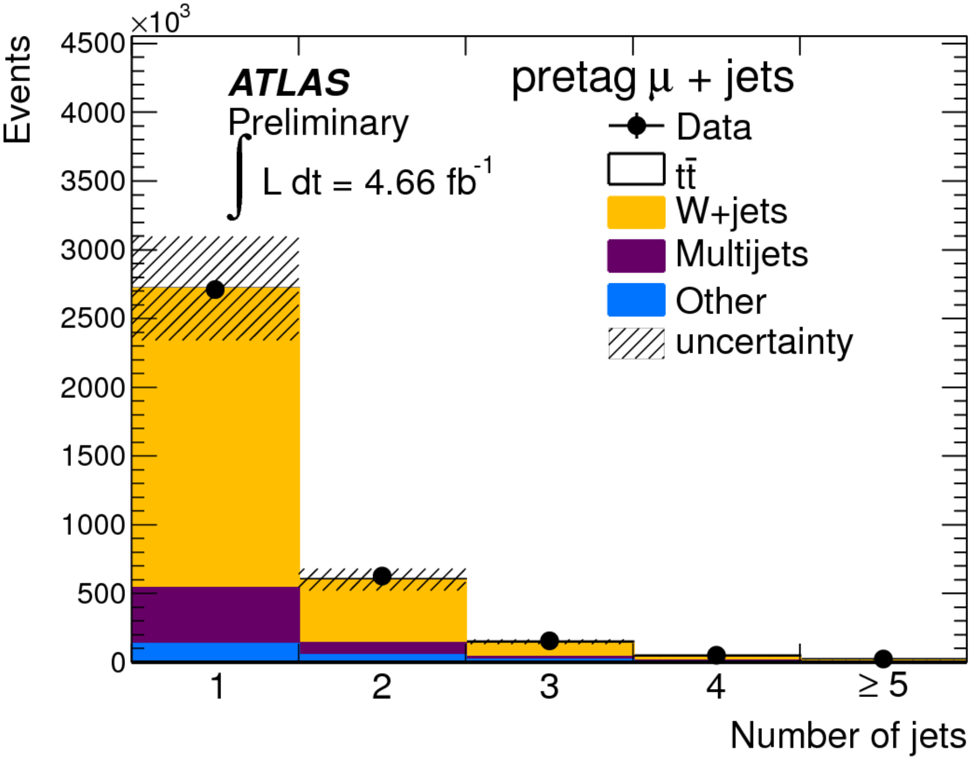


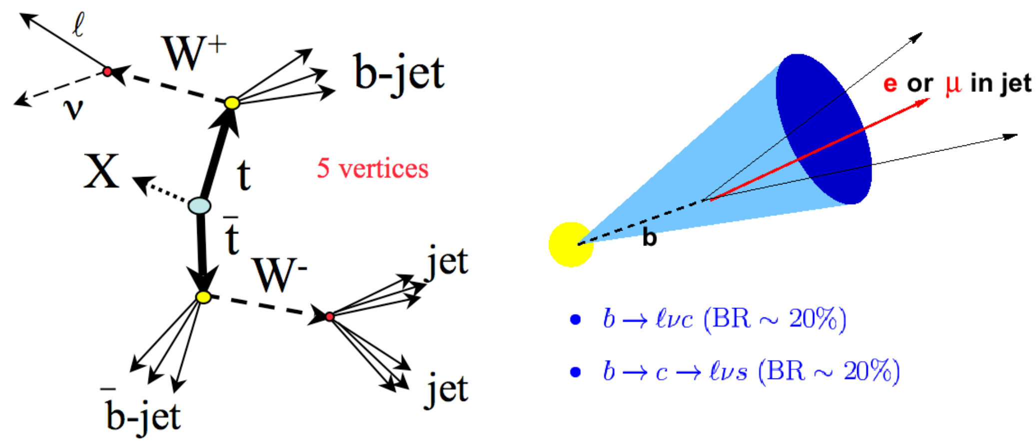
- Flavour identification
- charm sensitivity
- different/low systematics

Candidate top quark pair event

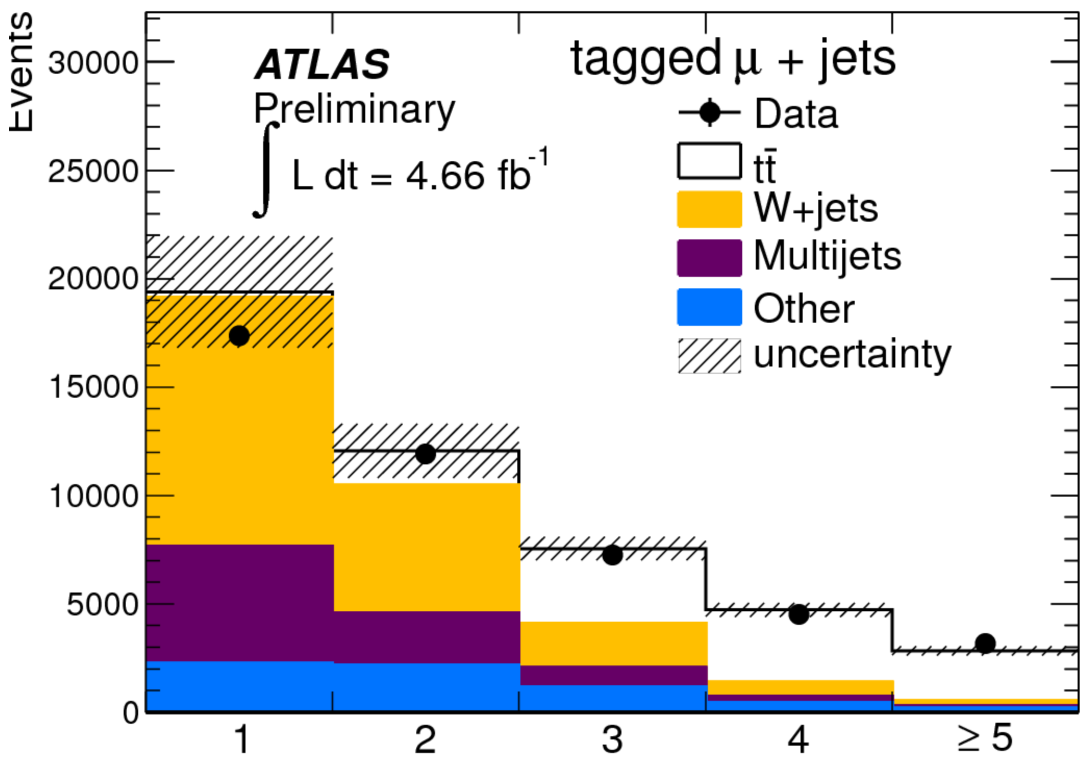


Identification of top pairs: single lepton ch.



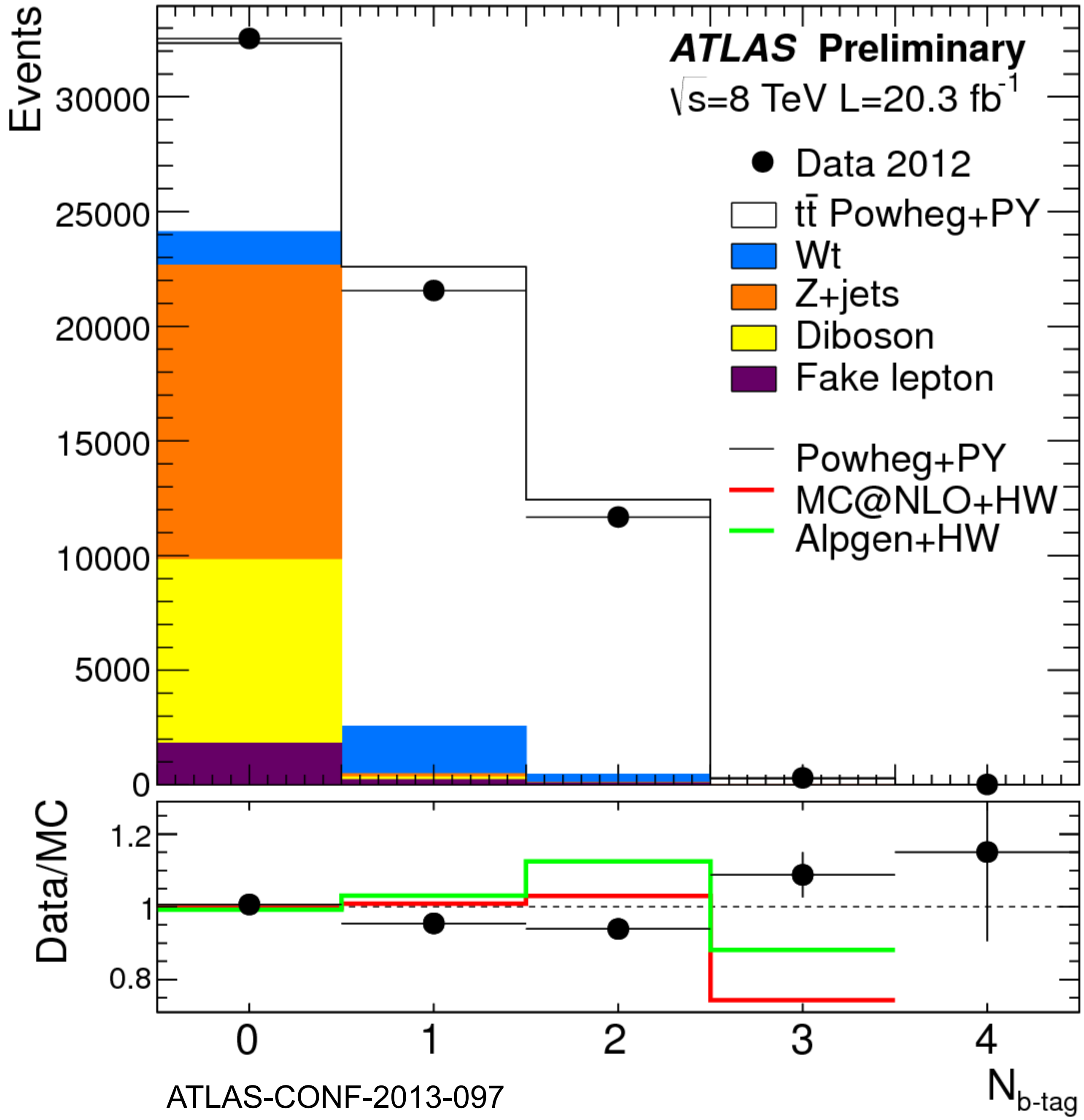


- $b \to \ell\nu c$ (BR ~ 20%)
- $b \to c \to \ell\nu s$ (BR ~ 20%)

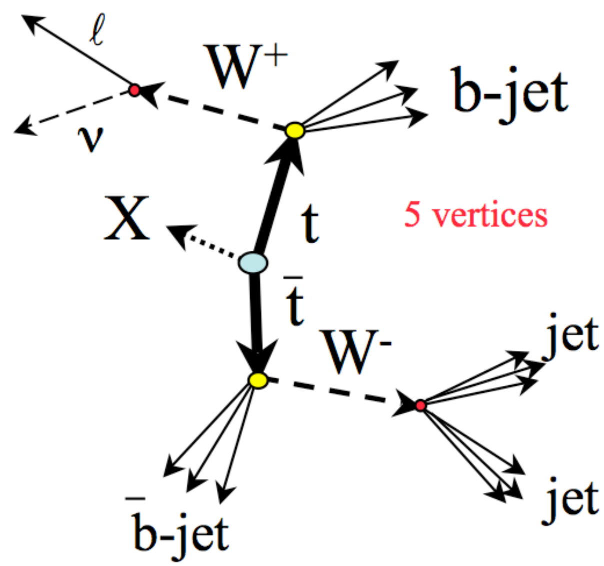


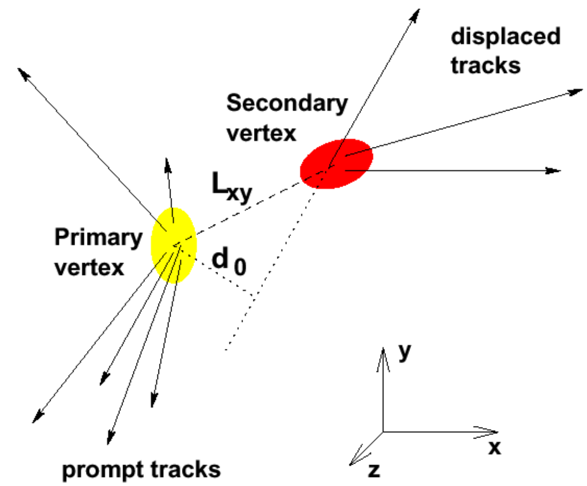
L. Cerrito *et al.*, ATLAS-CONF 056 (2012)

Identification of top pairs: dilepton channel

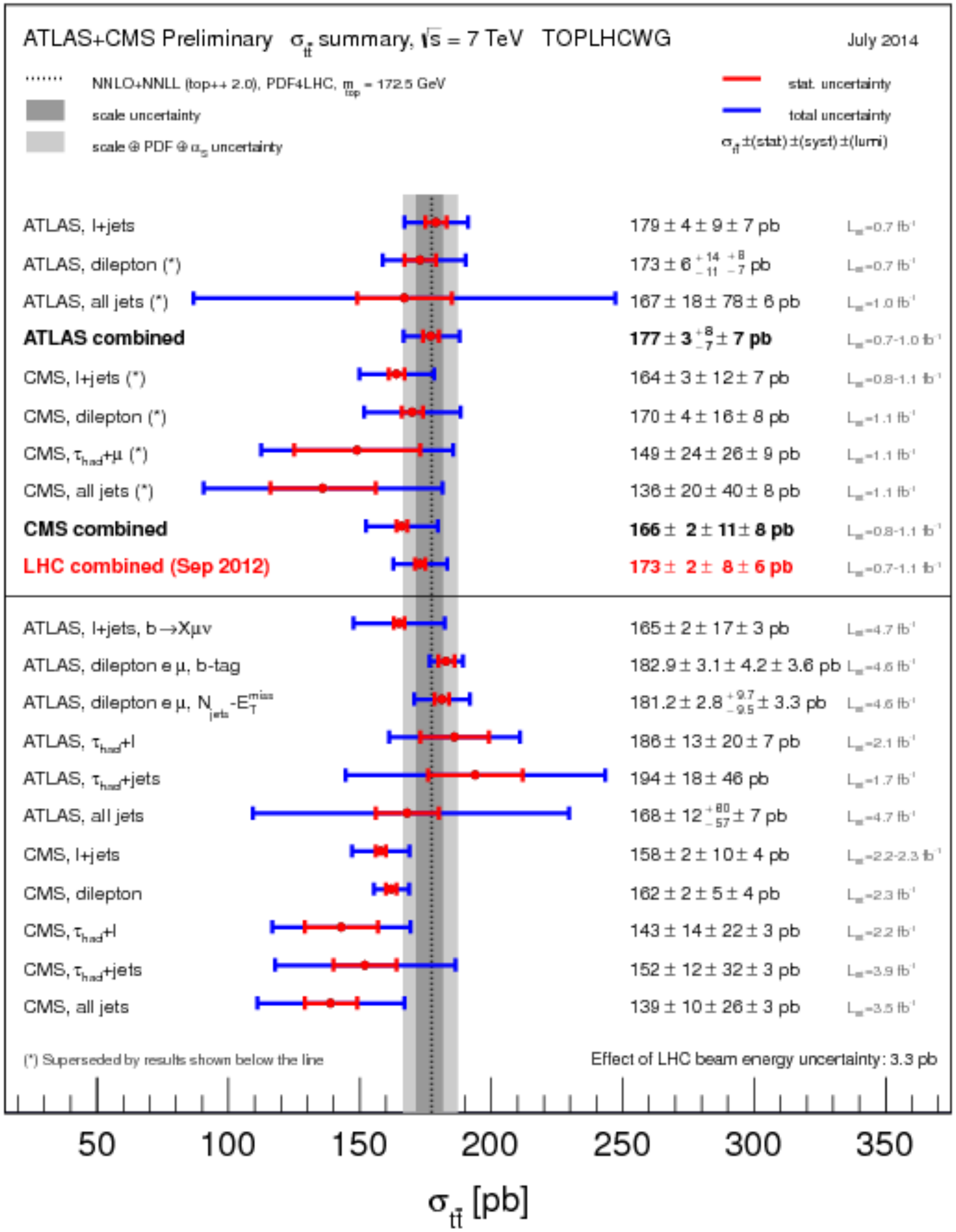


ATLAS-CONF-2013-097



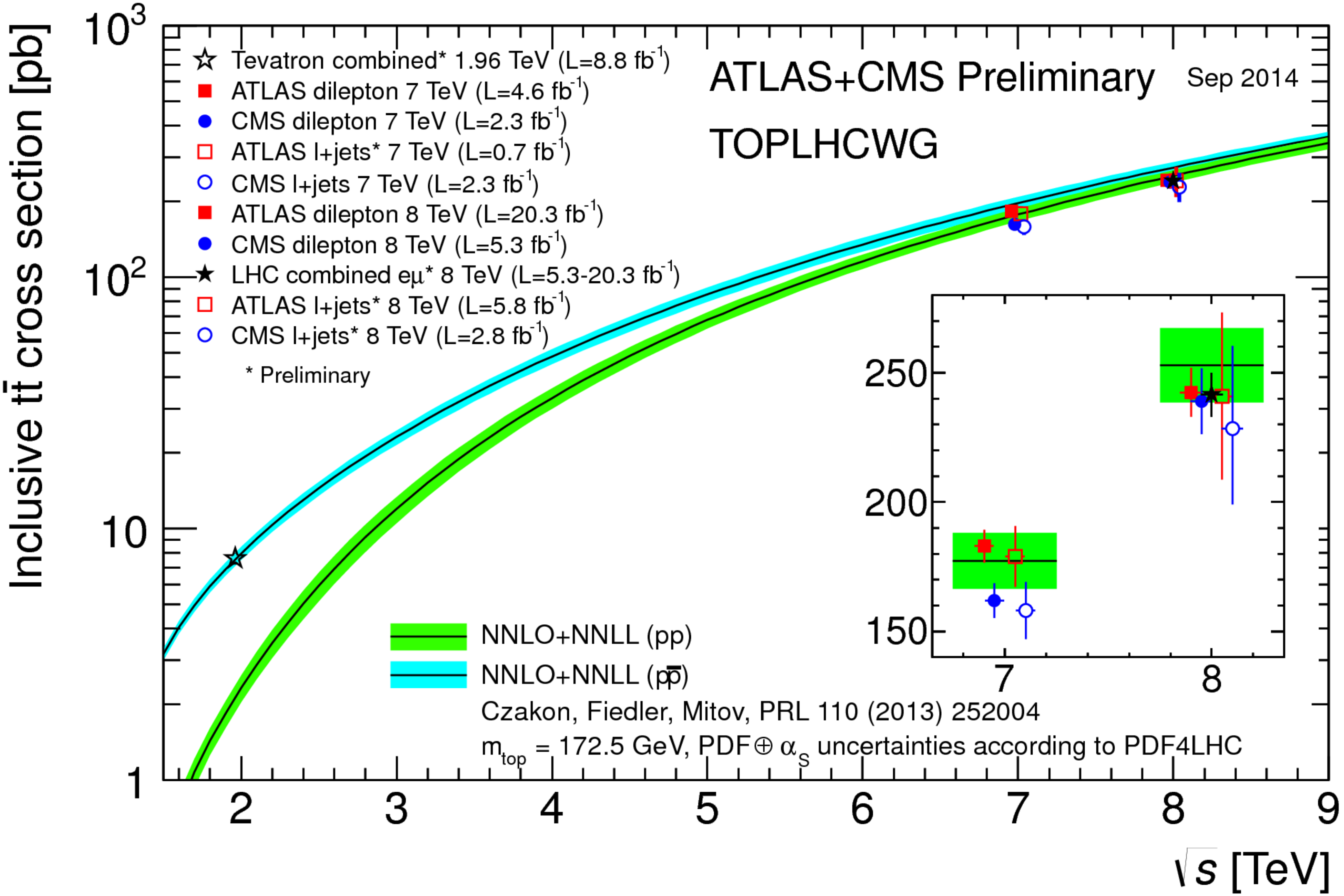


LHC 7 TeV Pair production summary

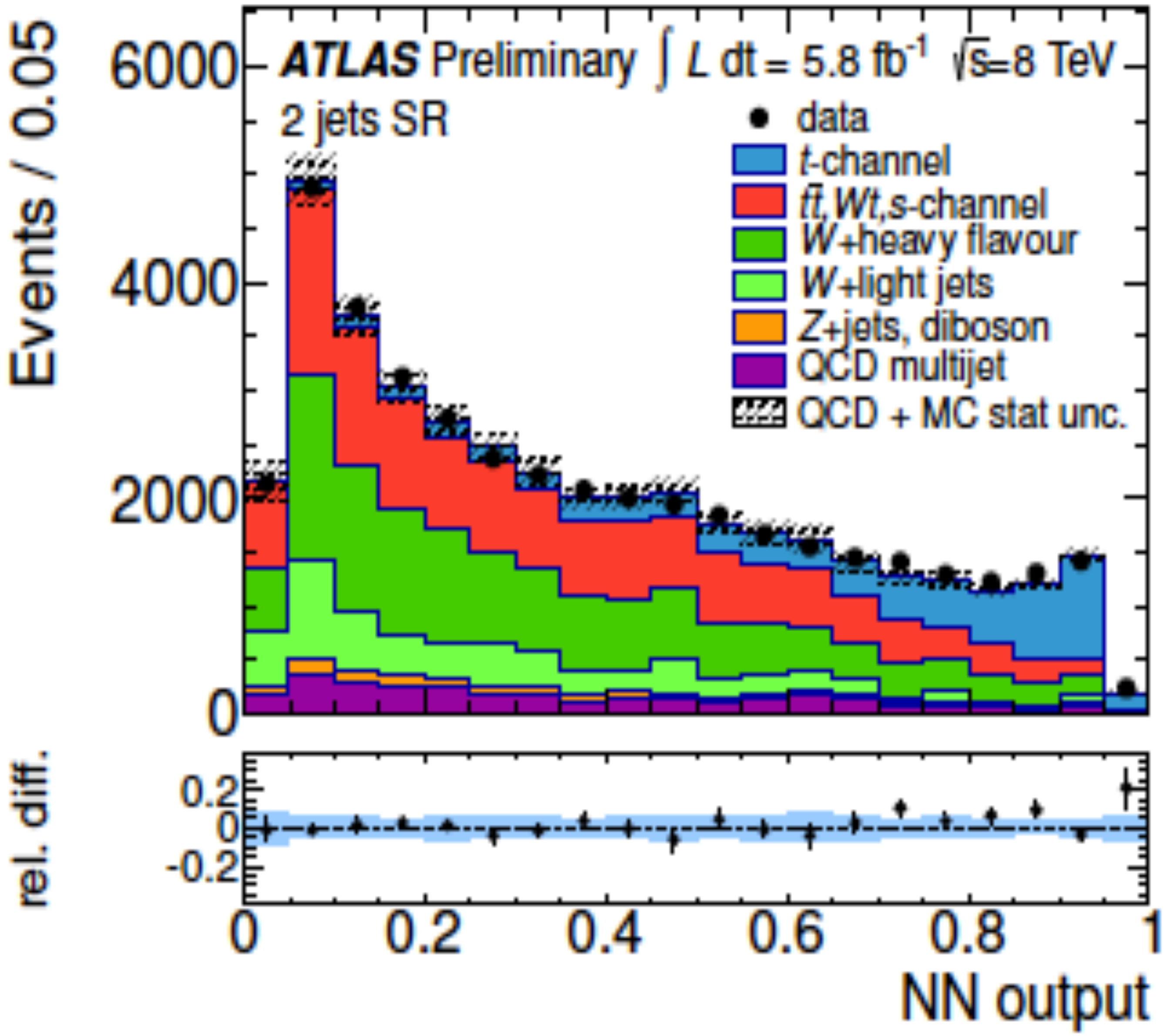


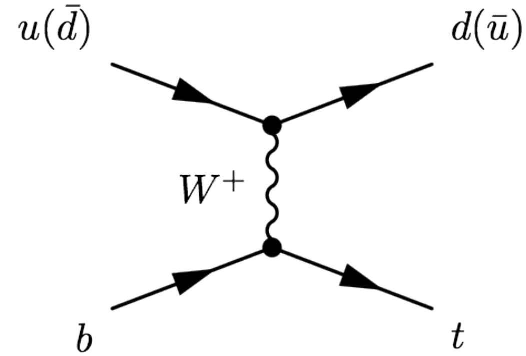
- Combined precision ~6%, is similar to theory uncertainty.
- New measurements approach the ~4% precision
- Agreement between channels within uncertainties (individual precisions 4% to 40%)

Tevatron/LHC pair production summary

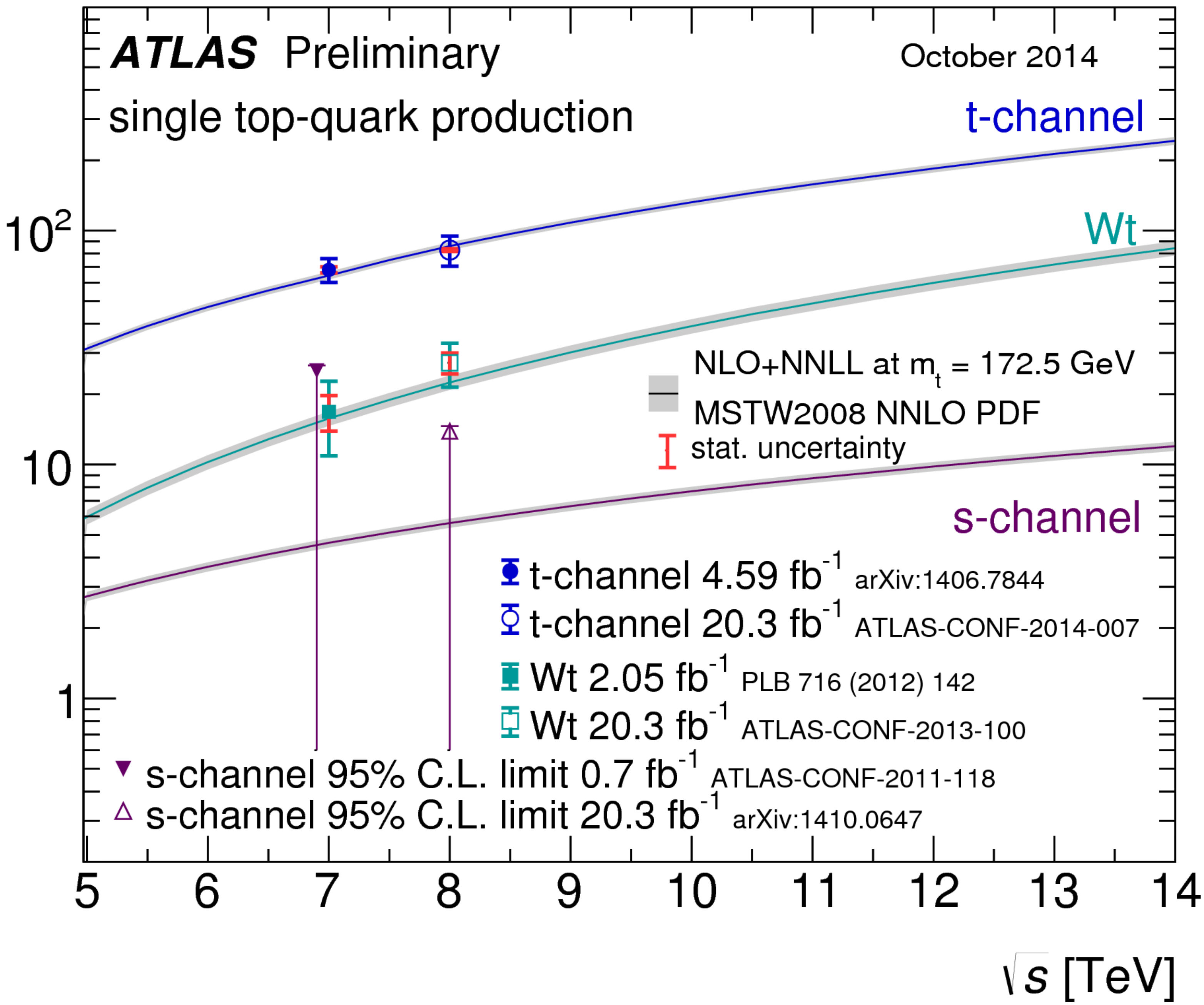


Single top


ATLAS Preliminary ∫ L dt = 5.8 fb-1 √s=8 TeV
2 jets SR
data
t-channel
tt̄,Wt,s-channel
W+heavy flavour
W+light jets
Z+jets, diboson
QCD multijet
QCD + MC stat unc.
Events / 0.05
6000
4000
2000
0
rel. diff.
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
NN output

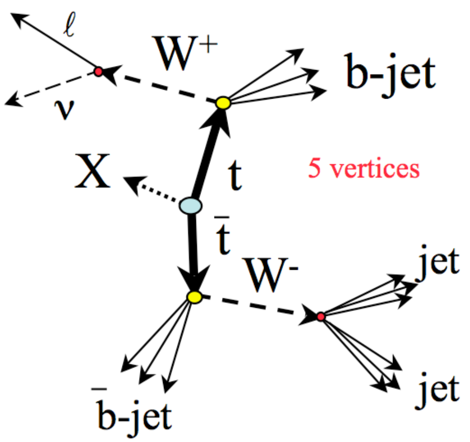

$u(\bar{d})$
$d(\bar{u})$
W^+
b
t

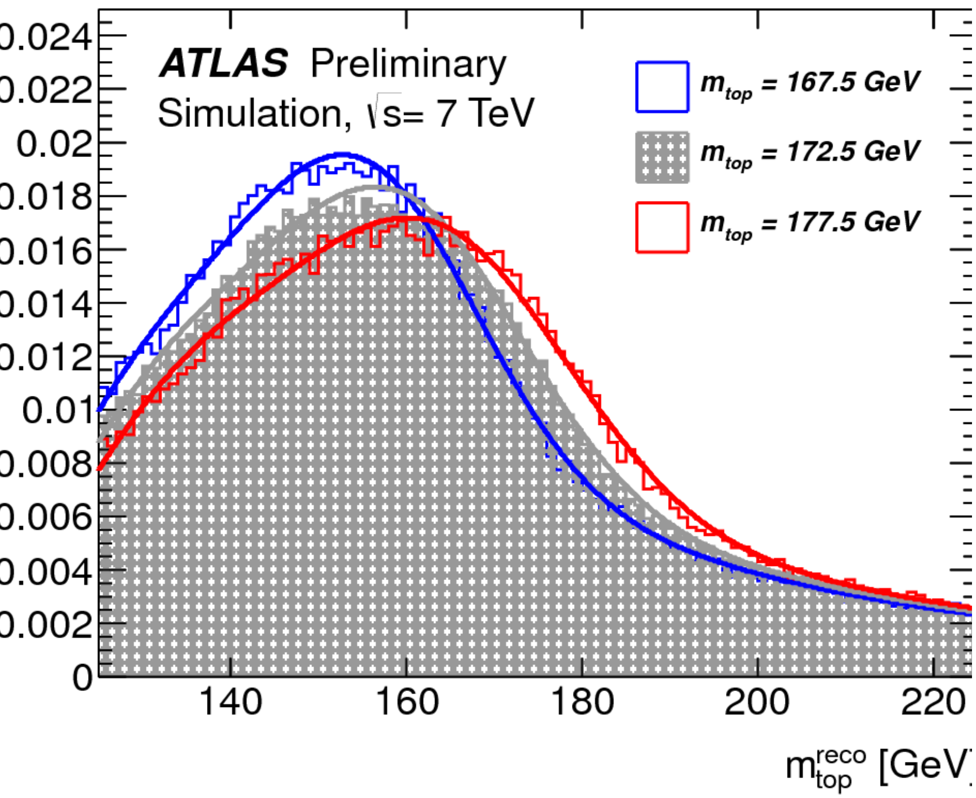
ATLAS single top production summary

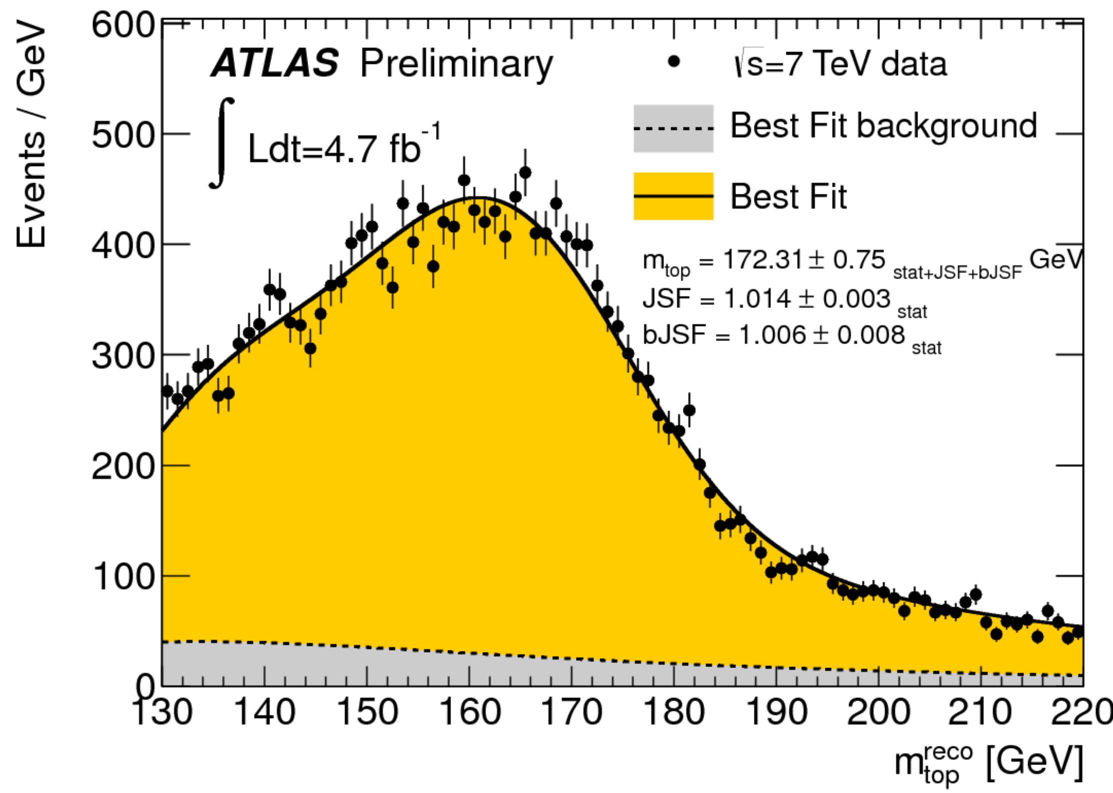


- Precision of ~12-30%, still larger than theory uncertainty. (4% for t-ch, 8% for Wt)

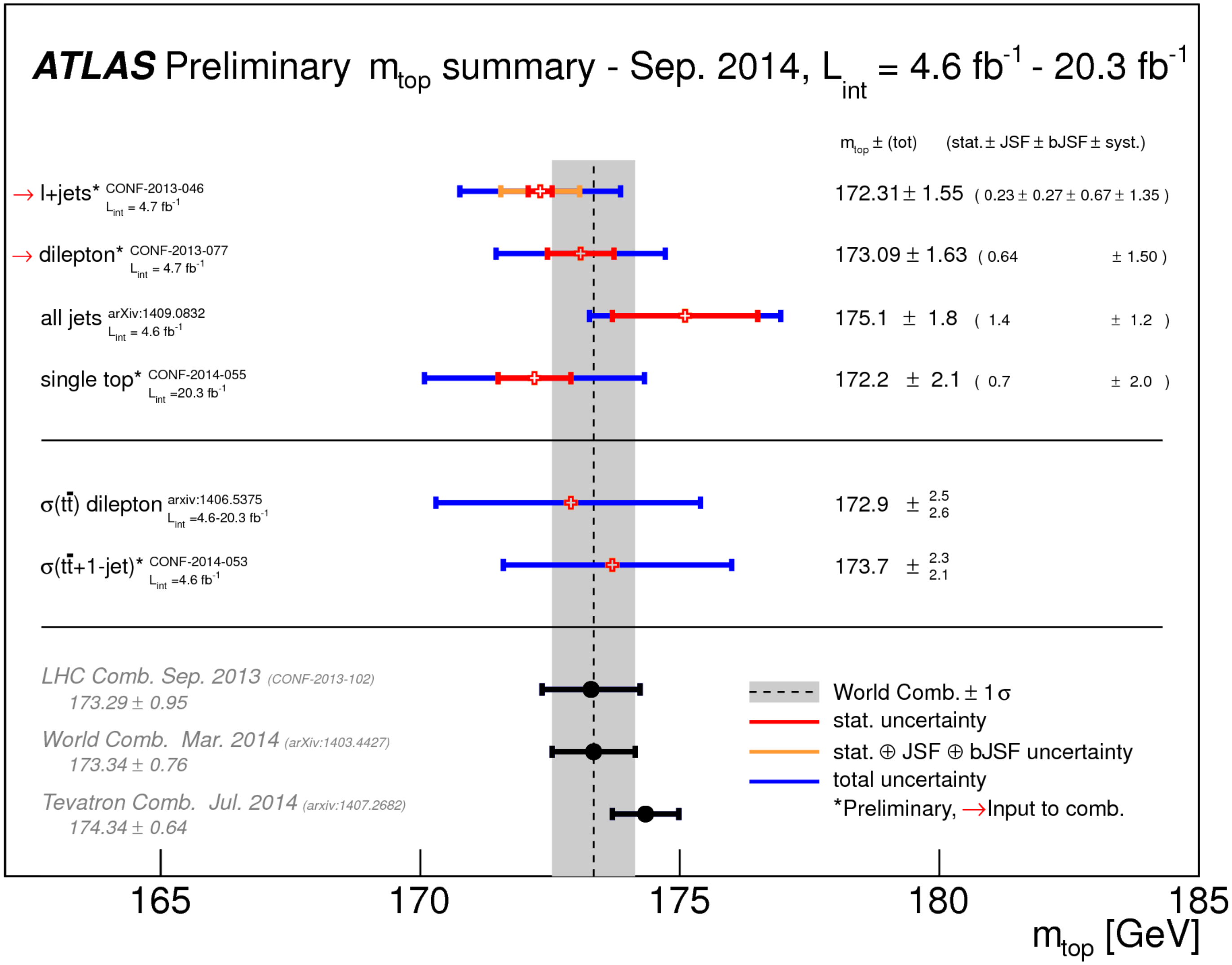
Top quark mass reconstruction





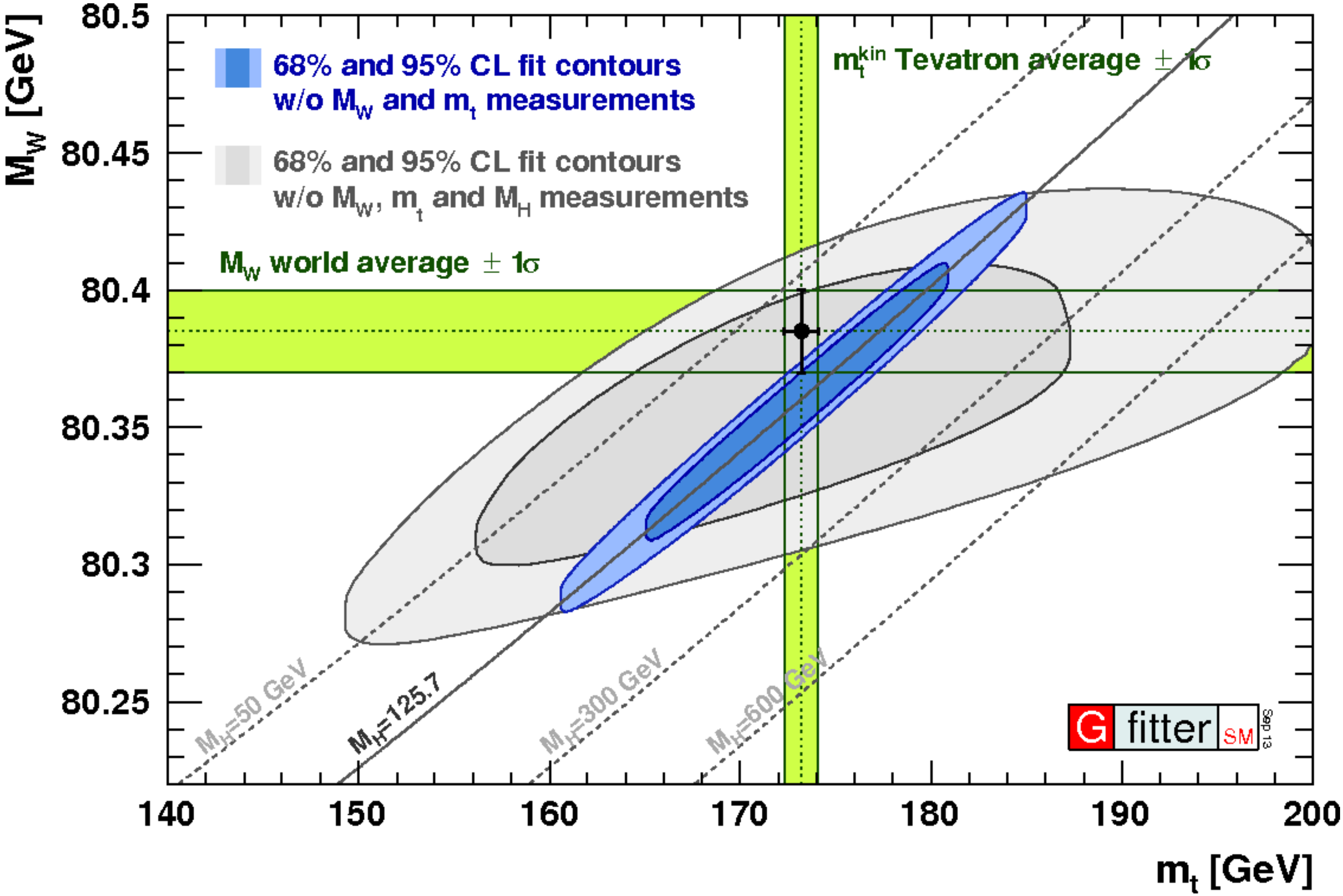


Top quark mass



- LHC combined precision of ±0.9 GeV (~0.5%)
- Best precision of an individual measurement (ATLAS): ~±1.5 GeV
- Measurements in different channels are consistent

M_W vs M_t vs M_h



68% and 95% CL fit contours
w/o M_W and m_t measurements
68% and 95% CL fit contours
w/o M_W, m_t and M_H measurements
M_W world average ± 1σ
m_t^kin Tevatron average ± 1σ
M_H=50 GeV
M_H=125.7
M_H=300 GeV
M_H=600 GeV
G fitter SM
Sep 13
80.5
80.45
80.4
80.35
80.3
80.25
M_W [GeV]
140
150
160
170
180
190
200
m_t [GeV]

Top mass and SM vacuum stability

arXiv:1205.6497 [hep-ph]

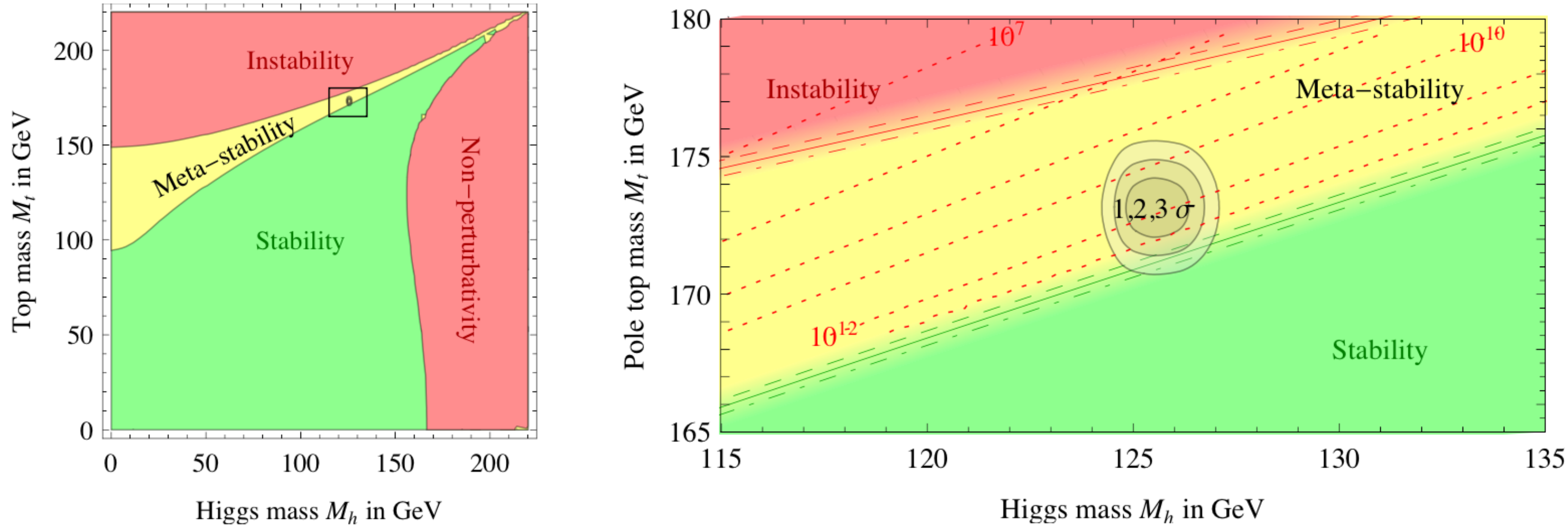
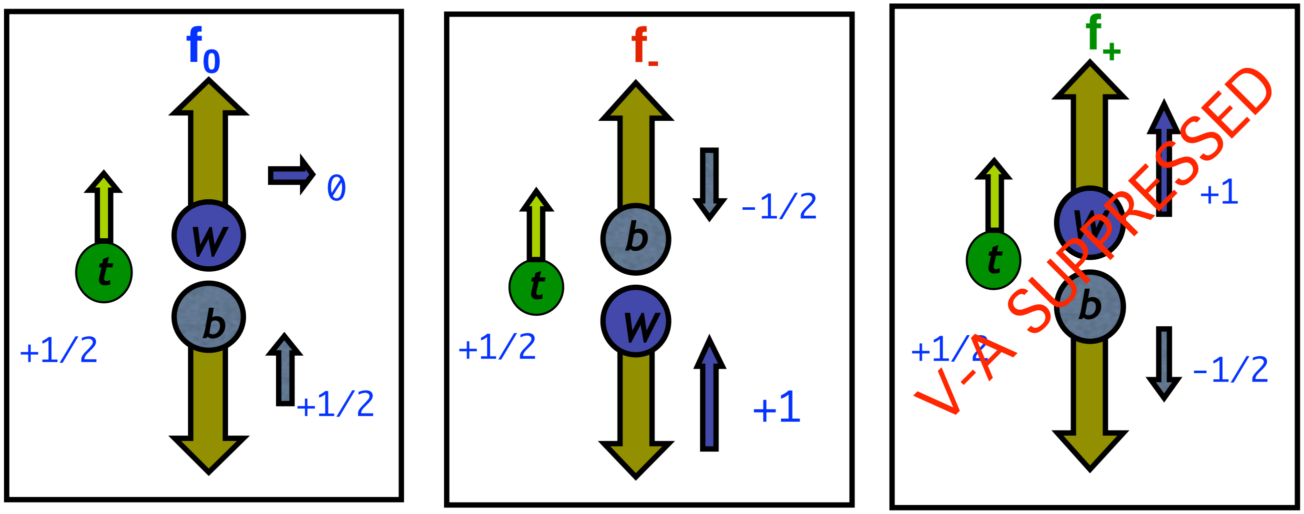


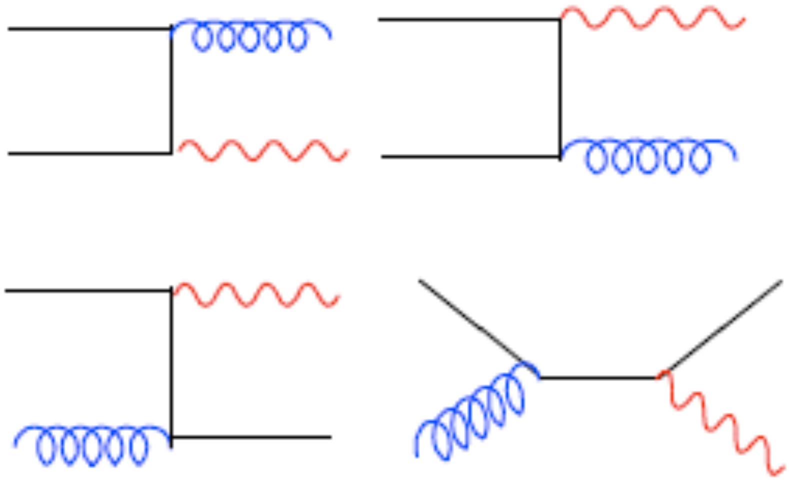
Figure 5: *Regions of absolute stability, meta-stability and instability of the SM vacuum in the* M_t–M_h *plane (upper left) and in the* λ–y_t *plane, in terms of parameter renormalized at the Planck scale (upper right).* **Bottom**: *Zoom in the region of the preferred experimental range of* M_h *and* M_t *(the gray areas denote the allowed region at 1, 2, and 3σ). The three boundary lines correspond to* $\alpha_s(M_Z) = 0.1184 \pm 0.0007$, *and the grading of the colors indicates the size of the theoretical error. The dotted contour-lines show the instability scale* Λ *in* GeV *assuming* $\alpha_s(M_Z) = 0.1184$.

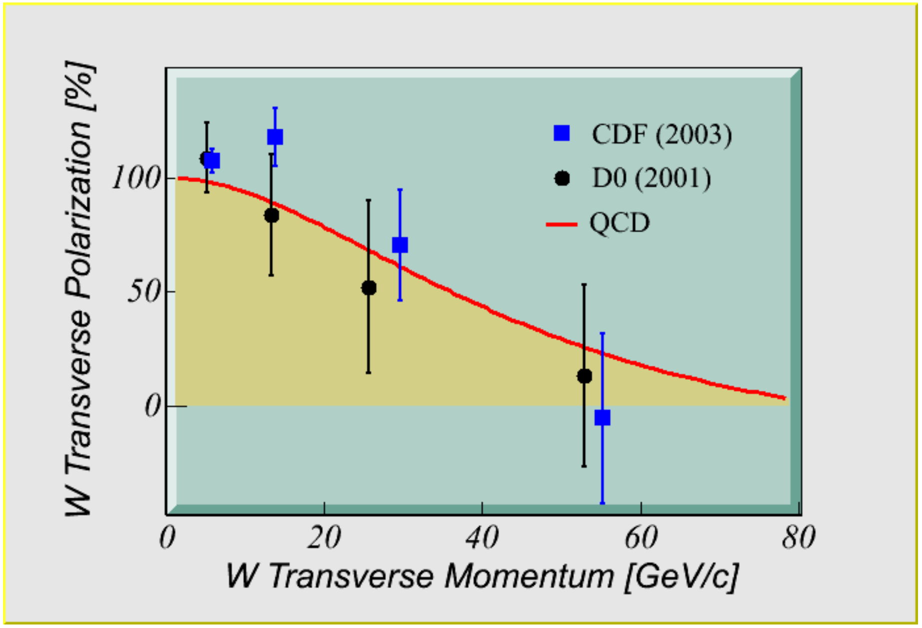
Polarization of W in top decays



$$f_0 = \frac{M_t^2 / 2M_W^2}{1 + M_t^2 / 2M_W^2} \cong 0.7$$

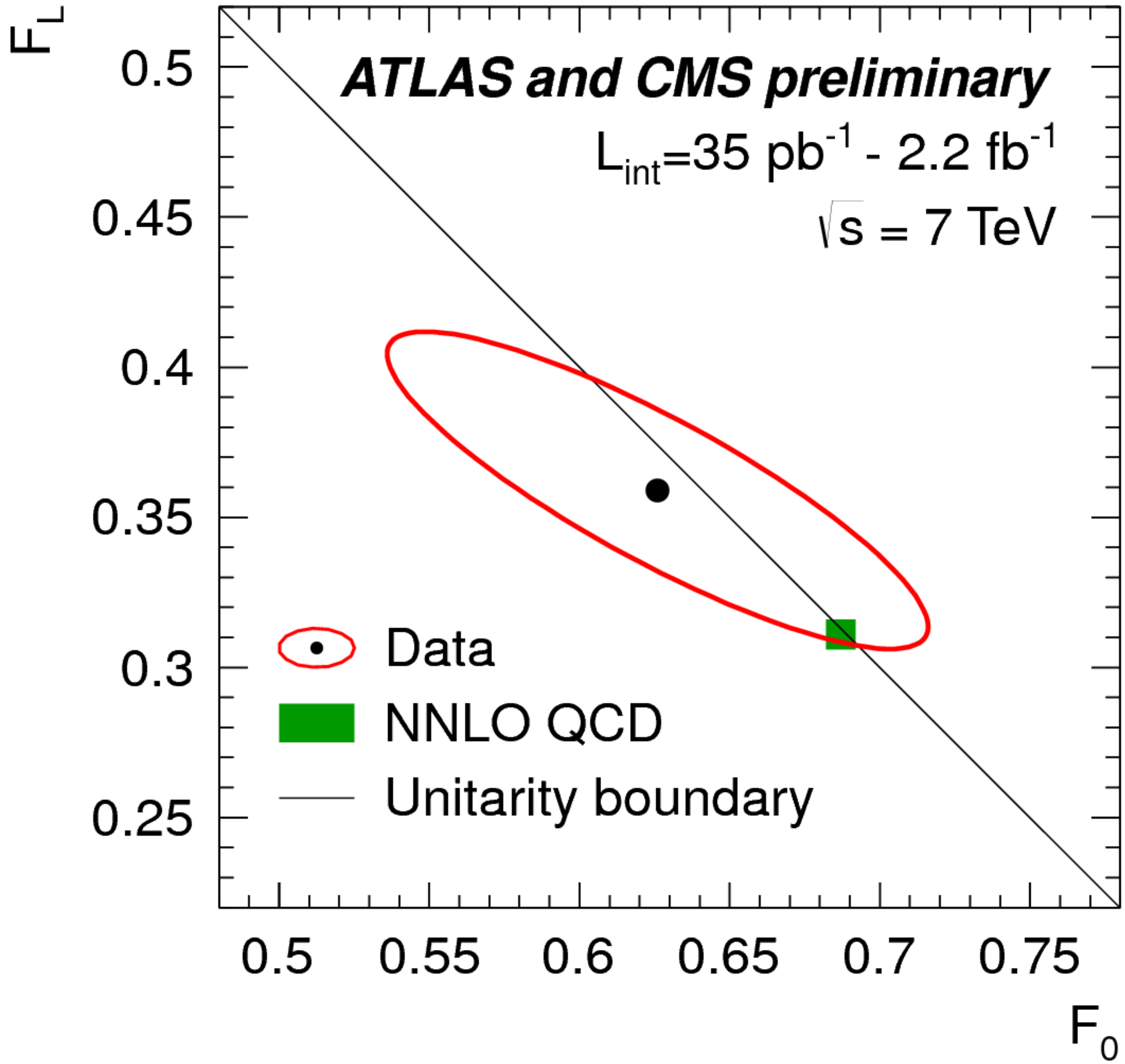
Phys. Rev. D 81 (2010) 111503





L Cerrito et al, Physical Review D 70, 032004, 2004.

Polarization of W in top decays

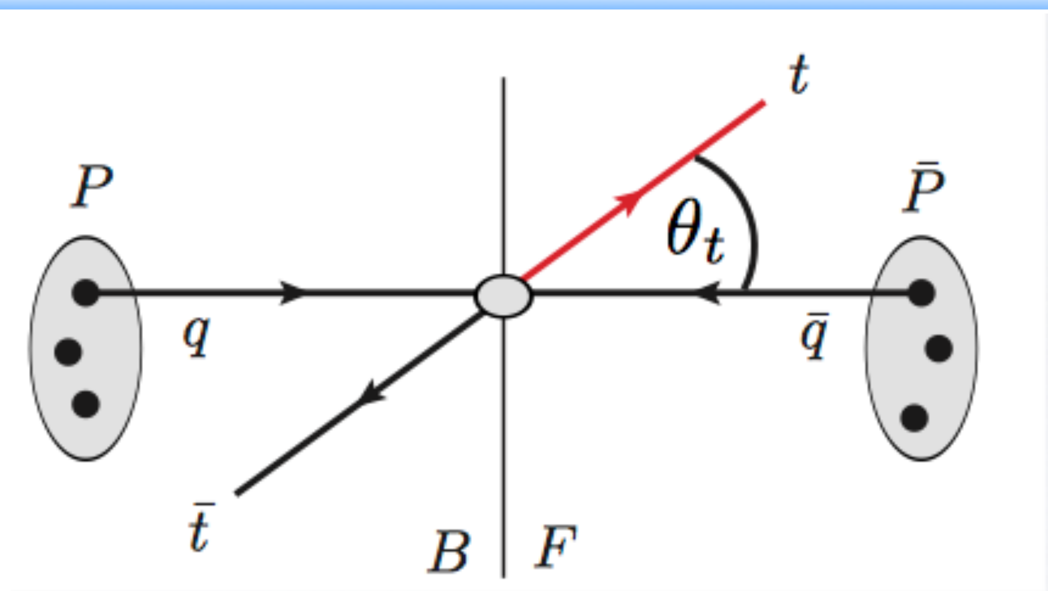


ATLAS-CONF-2013-033

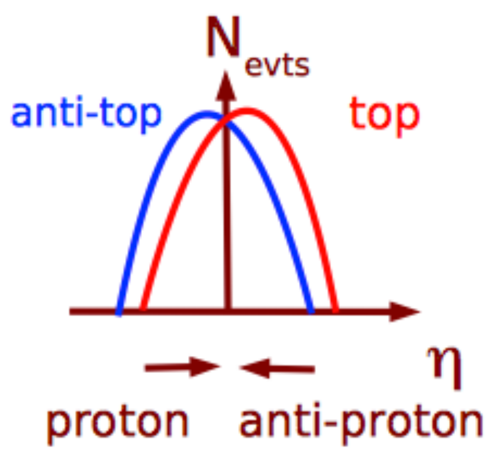
(68% C.L. contour)

- Precision of ~15%

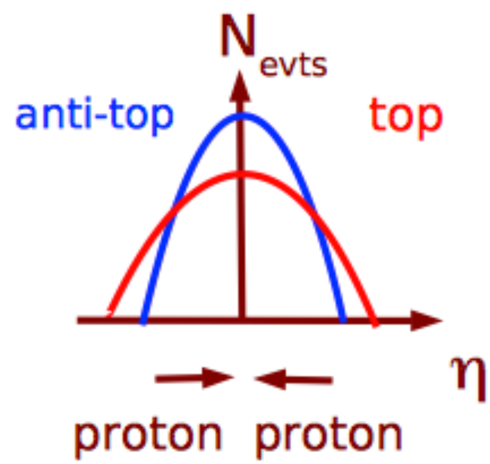
Top pair F/B asymmetry



Tevatron



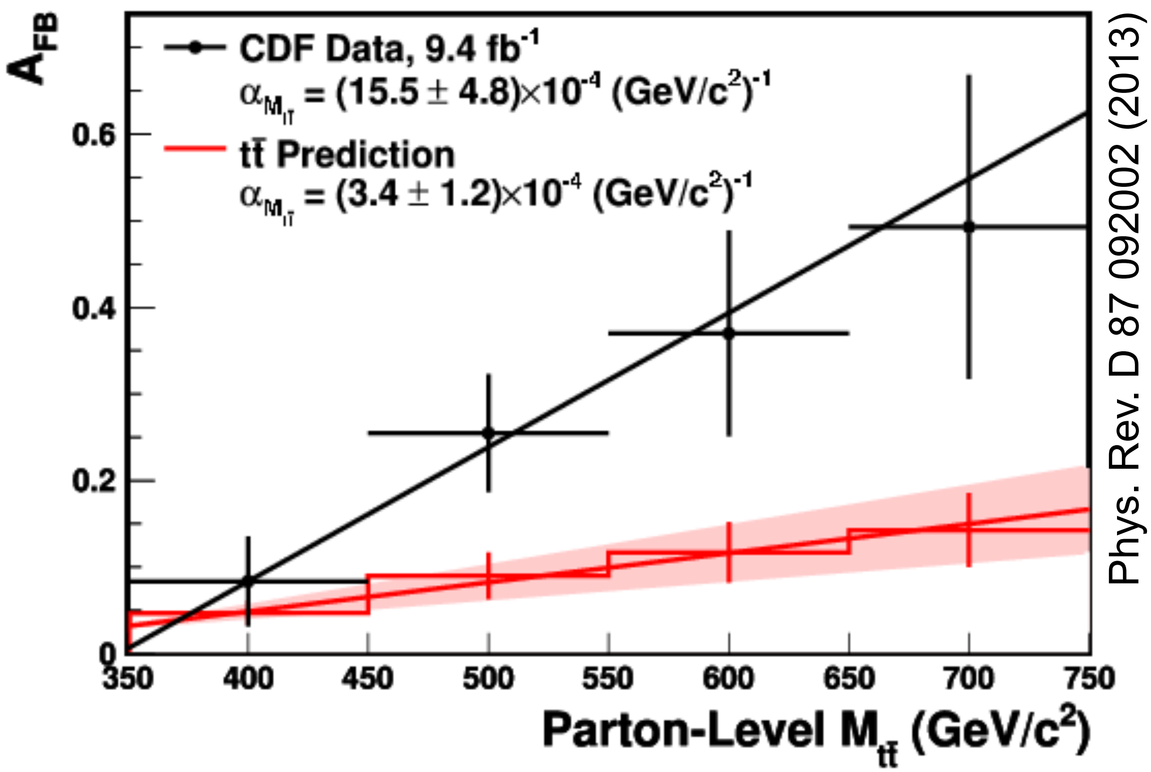
LHC



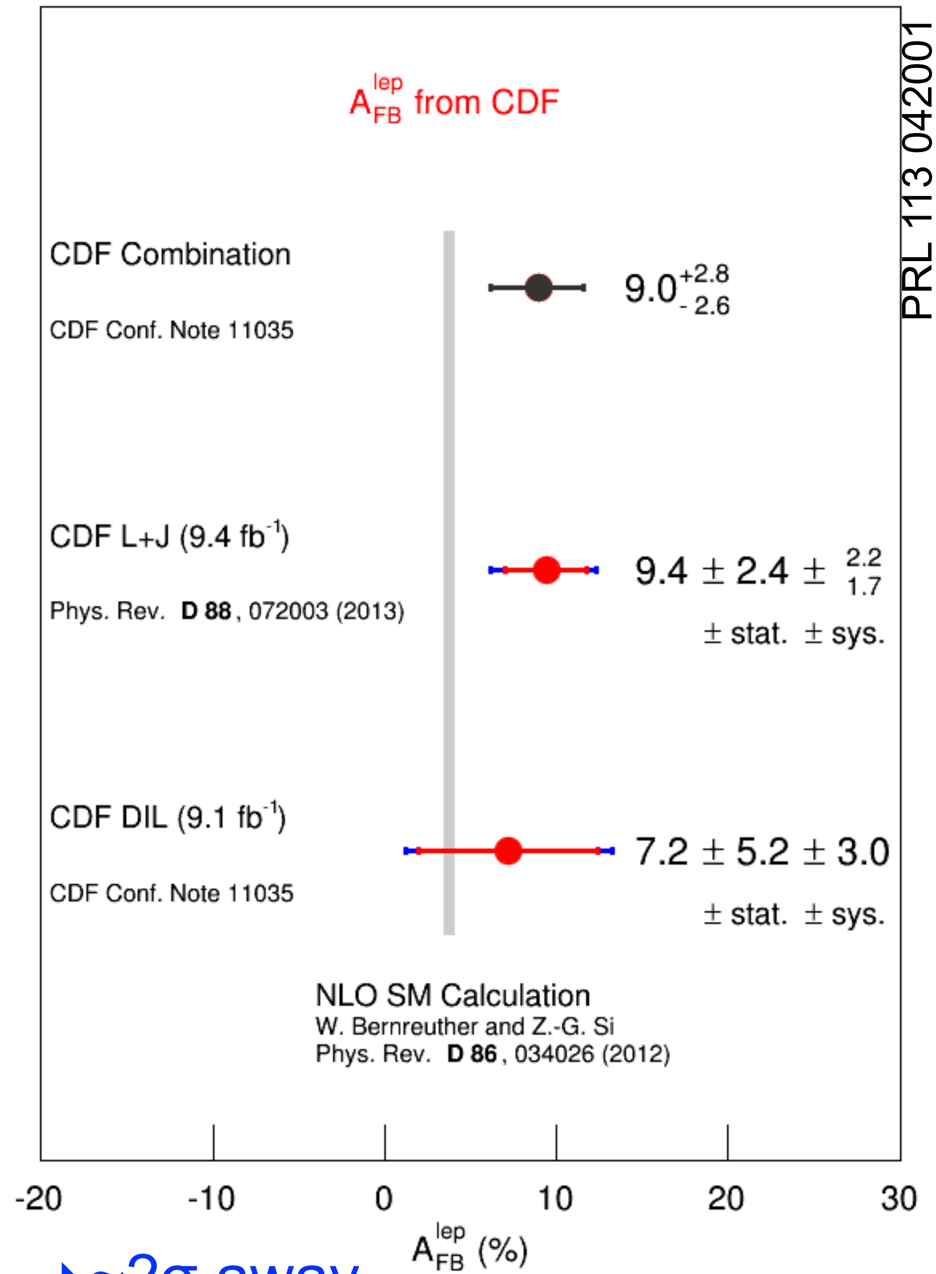
+gg dilution !

Arises at higher than tree-level order in the *qq→tt* process (NLO): [Khun, Rodrigo, PRD 59 054017]

Top pair F/B asymmetry



- ~2.4 σ away



- ~2σ away

A note on statistics

5σ

1/1.7M Discovery

A note on statistics

5σ

1/1.7M Discovery

3σ

1/370 Evidence

A note on statistics

5σ  1/1.7M Discovery

3σ  1/370 Evidence

2σ  1/22 “tension”

A note on statistics

5σ  1/1.7M Discovery

3σ  1/370 Evidence

2σ  1/22 “discrepancy”

A note on statistics

5σ  1/1.7M Discovery

3σ  1/370 Evidence

2σ  1/22 “deviation”

A note on statistics

5σ

1/1.7M Discovery

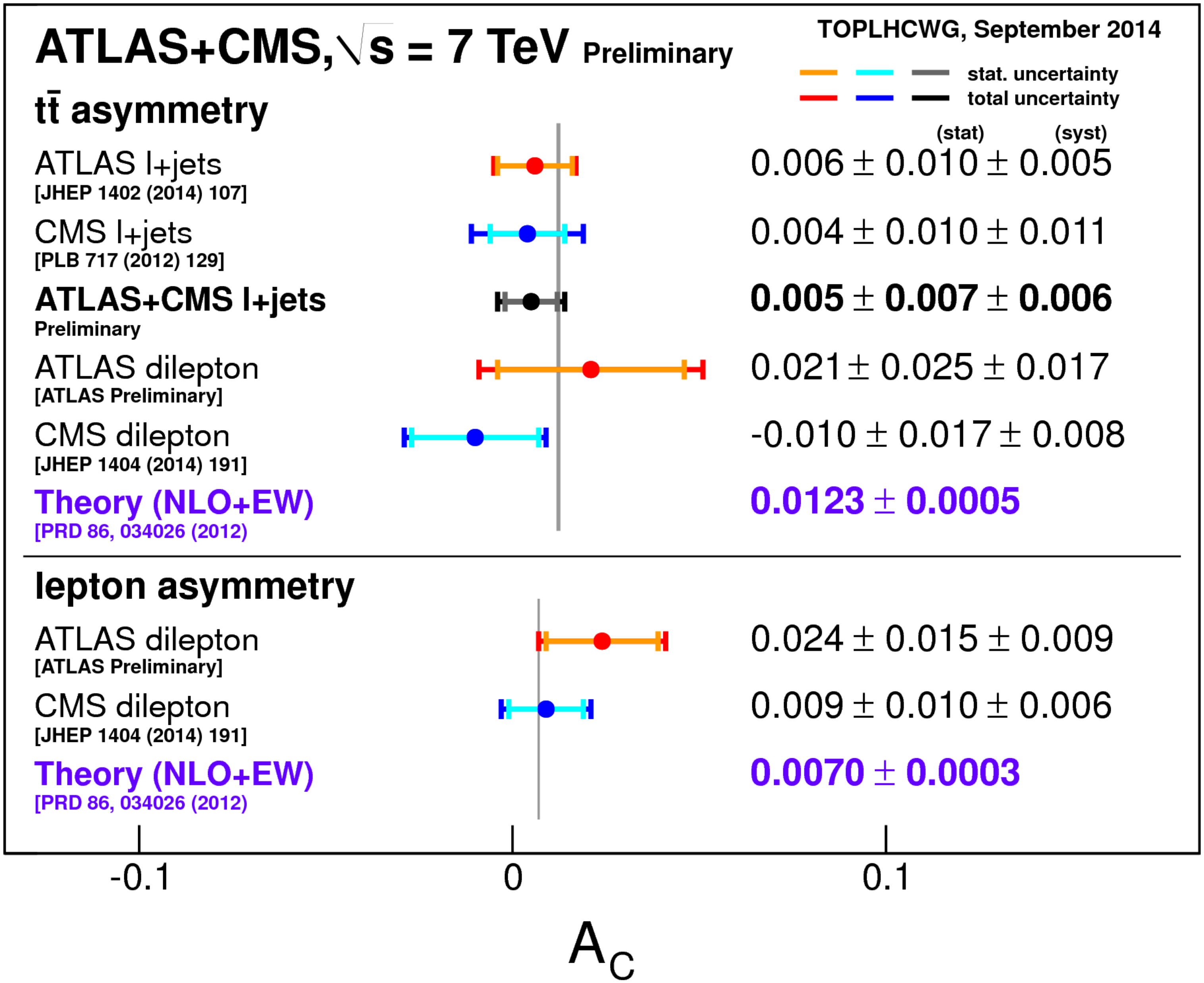
3σ

1/370 Evidence

2σ

1/22 “significantly larger/smaller”

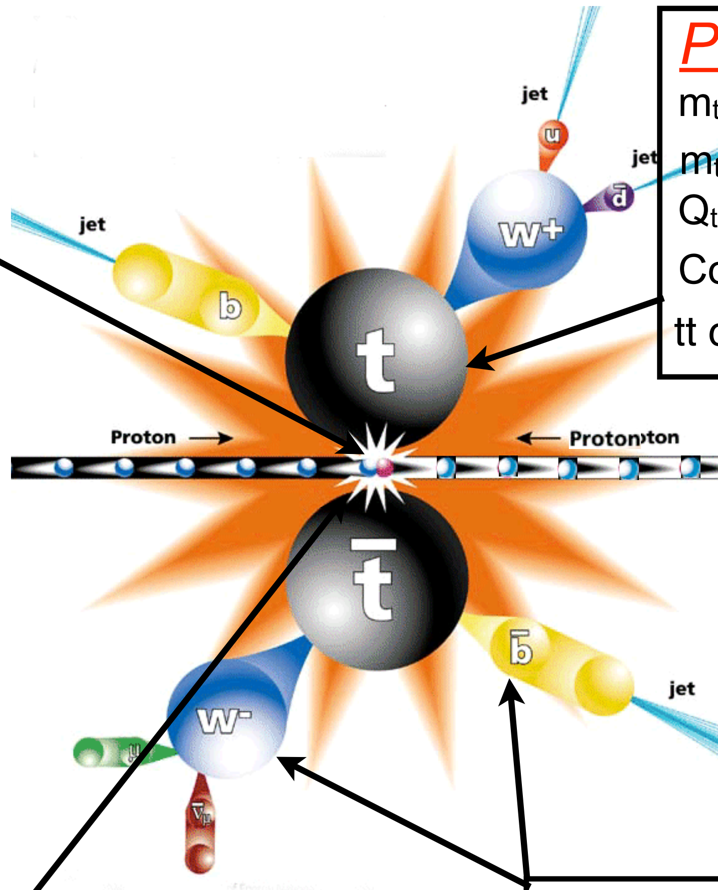
Top pair Charge asymmetry



Summary of ATLAS top physics

Production Rates

σ_{tt} (dilepton ch. 7(8) TeV)……±4(4)%
σ_{tt} (single lep. ch) 7(8) TeV)..±7(13)%
σ_{tt} (hadronic channel)………….±35%
σ_{tt} (τ+jets)……………………… ±27%
σ_{tt} (e,μ+τ)……………………… ±15%
σ_{tt} combined……………………… ±6%
σ_{tt} (ttZ)………………………… <0.7 pb
σ_{tt} (ttγ)……………………………±41%
Differential σ_{tt}, jet veto………… obs.
Differential σ_{tt}, N_{jets}………………up to 5
$\sigma_{t,\ t\text{-channel}}$, $|V_{tb}|$, 7(8)TeV……..12(15)%
$R=\sigma_{t,}/\sigma_{tbar,\ t\text{-channel}}$………………… ±12%
$\sigma_{t,\ Wt\text{-channel}}$…7(8)TeV…………±34(21)%
$\sigma_{t,\ s\text{-channel}}$.. 7(8)TeV…………<26(15) pb
$\sigma_{t,\ FCNC}$ x B(W→lν)………………<2.5 pb



Properties

m_{top} (precision)………………±0.5%
m_{top} (additional methods)… > ±1%
Q_{top}…………………………… not 4/3e
Correlation of t-tbar spins..~6σ
tt charge asymmetry……… ±1%

New Physics in production

tt+E_{Tmiss}, ………. m_T>0.42 TeV
Resonant tt, …… $m_{Z'}$>2.5 TeV
Resonant tb, ….. $m_{W'}$>1.7 TeV
T→tH………. m_T>~700 GeV

Decay

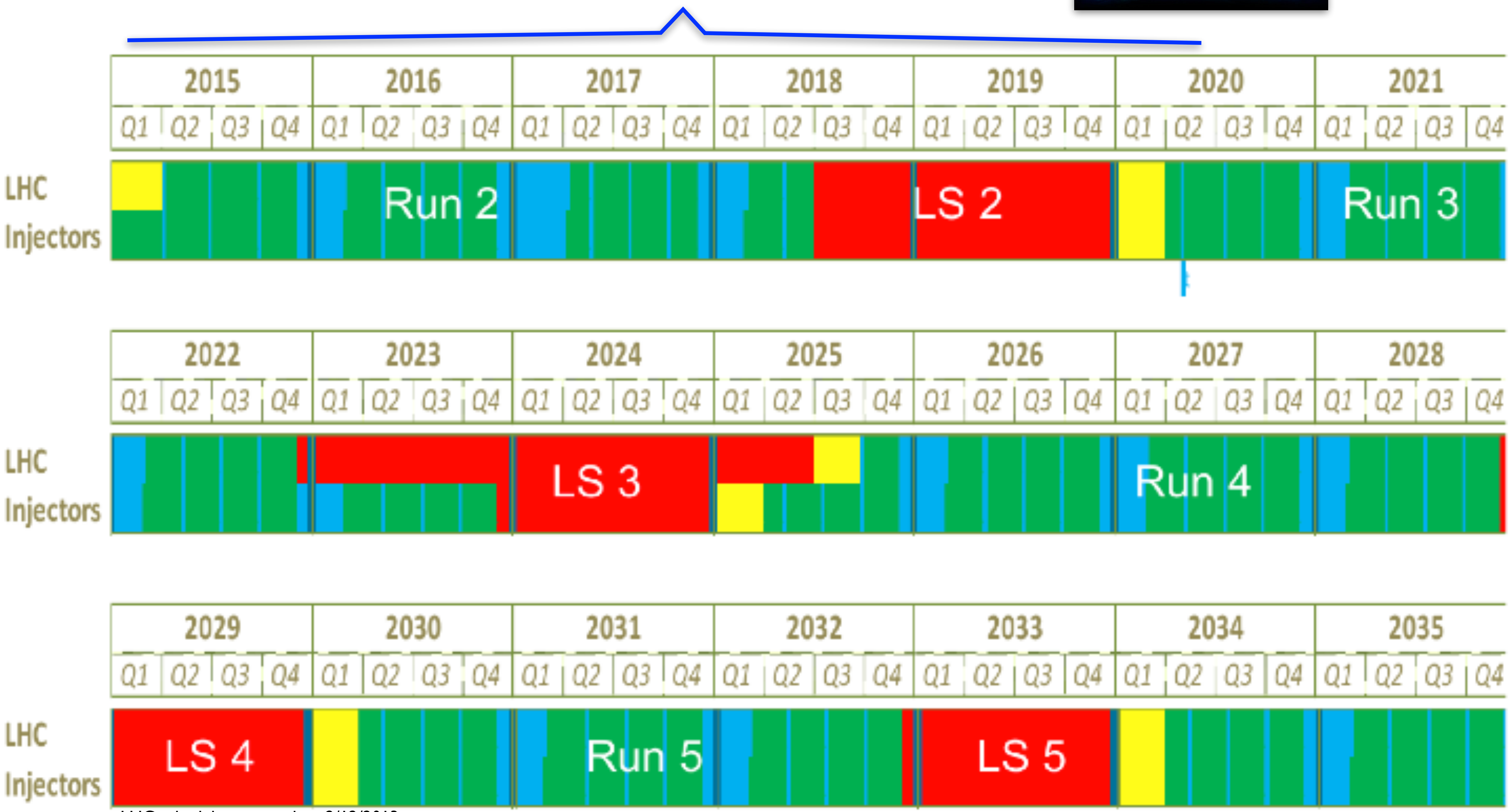
Helicity of W bosons…….. ~±15%
FCNC in decay (t→Zq)….. <0.73%
FCNC in decay (t→Hc)…. <0.83%


Has anyone seen
new physics?

LHC schedule

LHC Run 2

- Collision energy: $\sqrt{s}$=13–14 TeV
- Accumulated Data: ~100 fb^{-1}
- Top Quarks: x15-20 Run I sample

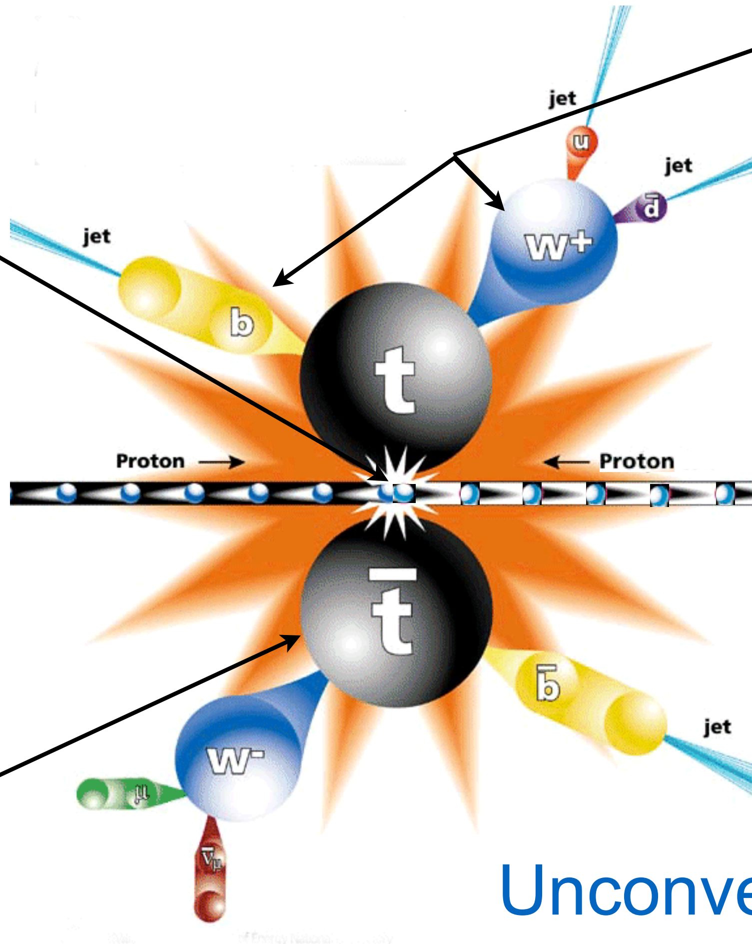


LHC schedule approved on 2/12/2013

5 Selected Measurements in Top Dynamics

ttZ: vs p_T^Z, vs $\Delta\varphi(l^+l^-)$
First couplings measurement

Resonances in top pairs with di-lepton events
Sensitivity up to 3-3.5 TeV



Exclusive Flavour Changing Neutral Current decay $t \to Zc$
BR sensitivity improved by x6 and first exclusive measurement

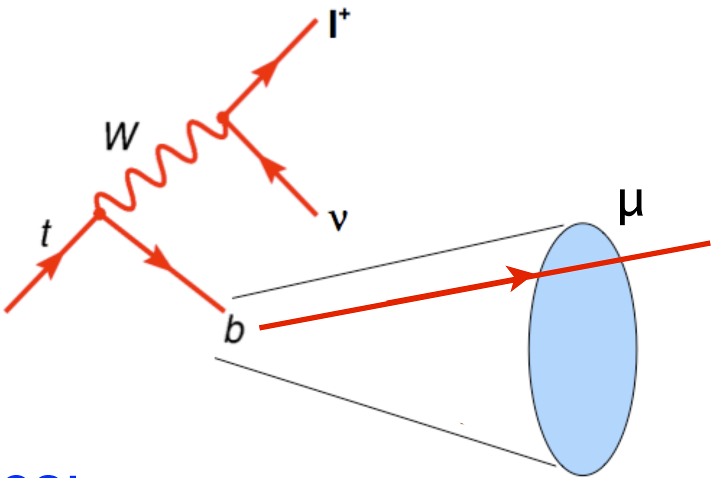
CP violation in B from top quarks
First measurement

Mass of top quark with leptonic endpoints
Improvement of 40%

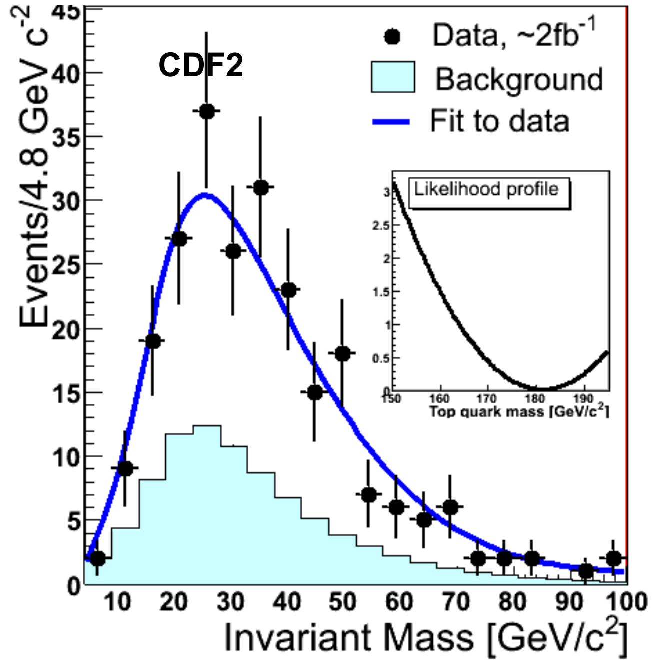
Unconventional Techniques
New Channels
New Observables

n1: Top Quark Mass

Objective: Top quark pole mass determined with a precision of ≈ ±500 MeV



L. Cerrito *et al.*, PRD 79, 052007 (2009)



Novelties:

The observable used; reduced systematics

Dataset Required:

20 fb^{-1} @ 13-14 TeV

State of the Art:

±800 MeV (Sep 2014) w. JES

Target Uncertainties:

Source	Δm_{top} [MeV]
Statistical uncertainty	300
Top quark production and decay modelling	300
Background modelling	150–200
ISR/FSR, PDF	$\lesssim 200$
Leptons' momentum calibration	$\lesssim 100$
Total	500

Table 1: Top mass (m_{top}) measurement: breakdown of expected statistical and systematic uncertainties.

n2: CPV in B from Top Quarks

Objective: Probing for the first time CP violation in B from top pairs.

$$A^{ss}_{\rm sl} \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = r_b A^{b\ell}_{\rm mix} + r_c (A^{bc}_{\rm dir} - A^{c\ell}_{\rm dir}) + r_{c\bar{c}}(A^{bc}_{\rm mix} - A^{c\ell}_{\rm dir}),$$

$$A^{os}_{\rm sl} \equiv \frac{N^{+-} - N^{-+}}{N^{+-} + N^{-+}} = \tilde{r}_b A^{b\ell}_{\rm dir} + \tilde{r}_c (A^{bc}_{\rm mix} + A^{c\ell}_{\rm dir}) + \tilde{r}_{c\bar{c}} A^{c\ell}_{\rm dir},$$

Dataset Required:

~50 fb^{-1} @ 13-14 TeV

Novelties:

First measurement

State of the Art:

No measurement

Target Sensitivities:

$$A^{b\ell}_{mix} = \frac{\Gamma(b \to \bar{b} \to \ell^+ X) - \Gamma(\bar{b} \to b \to \ell^- X)}{\Gamma(b \to \bar{b} \to \ell^+ X) + \Gamma(\bar{b} \to b \to \ell^- X}, \quad \approx 7\text{x}10^{-3}$$

$$A^{b\ell}_{dir} = \frac{\Gamma(b \to \ell^- X) - \Gamma(\bar{b} \to \ell^+ X)}{\Gamma(b \to \ell^- X) + \Gamma(\bar{b} \to \ell^+ X)}, \quad \lesssim 0.3\%$$

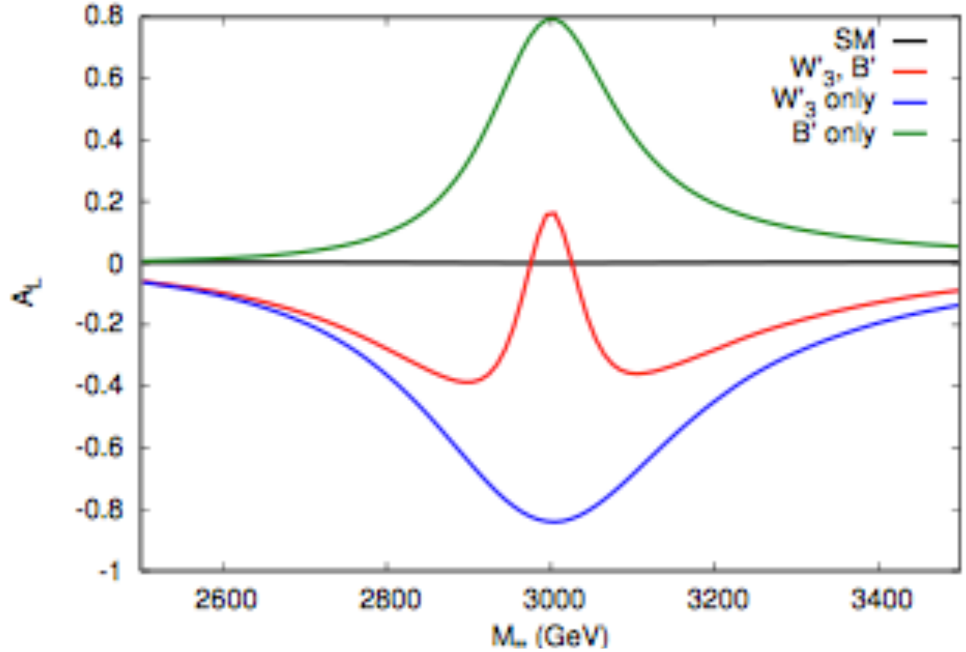
$$A^{c\ell}_{dir} = \frac{\Gamma(\bar{c} \to \ell^- X_L) - \Gamma(c \to \ell^+ X_L)}{\Gamma(\bar{c} \to \ell^- X_L) + \Gamma(c \to \ell^+ X_L)}, \quad \lesssim 0.3\%$$

$$A^{bc}_{dir} = \frac{\Gamma(b \to c X_L) - \Gamma(\bar{b} \to \bar{c} X_L)}{\Gamma(b \to c X_L) + \Gamma(\bar{b} \to \bar{c} X_L)}, \quad \lesssim 0.3\%$$

PHYS. REV. LETT. 110,232002 (2013)

n3: BSM Resonances in Top Pairs

Objective: Search for a *broad* TeV-scale resonance (X') decaying to top pairs and disentangle possible degenerate states



arxiv:1304.4494 [hep-ph] (2013)

Novelties:

- First use of top di-lepton channel
- Scan of spin polarisation *vs.* V_T

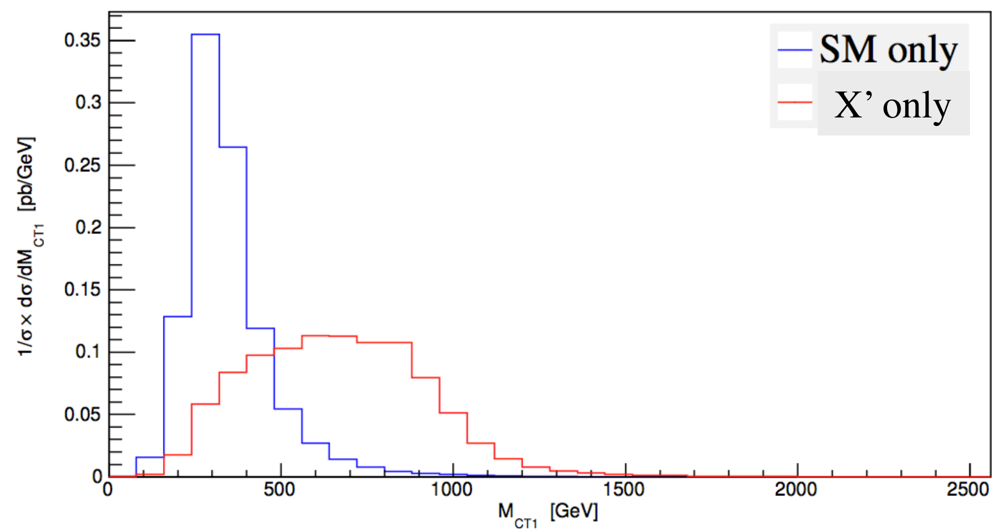
Dataset Required:

~70-100 fb^{-1} @ 13-14 TeV

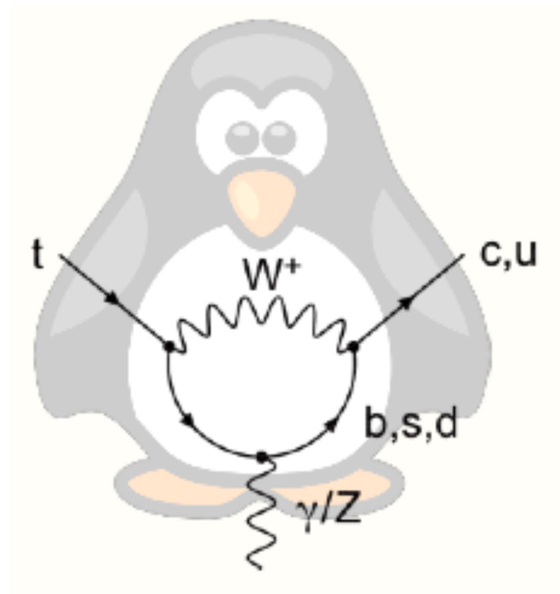
State of the Art:

Mass X' ≳ 2.5 TeV

Target Sensitivity: ~3-3.5 TeV



n4: FCNC Decay $t \to Zc$



Objective: First search for the exclusive $t \to Zc$ decay

Novelties:

- Explicit charm tagging $c \to \mu + X$
- top mass constraints

Dataset Required:

~100 fb^{-1} @ 13-14 TeV

State of the Art:

BR $(t \to Zq) < 6 \times 10^{-4}$

Target Sensitivity: BR $(t \to Zc) \lesssim 1 \times 10^{-4}$

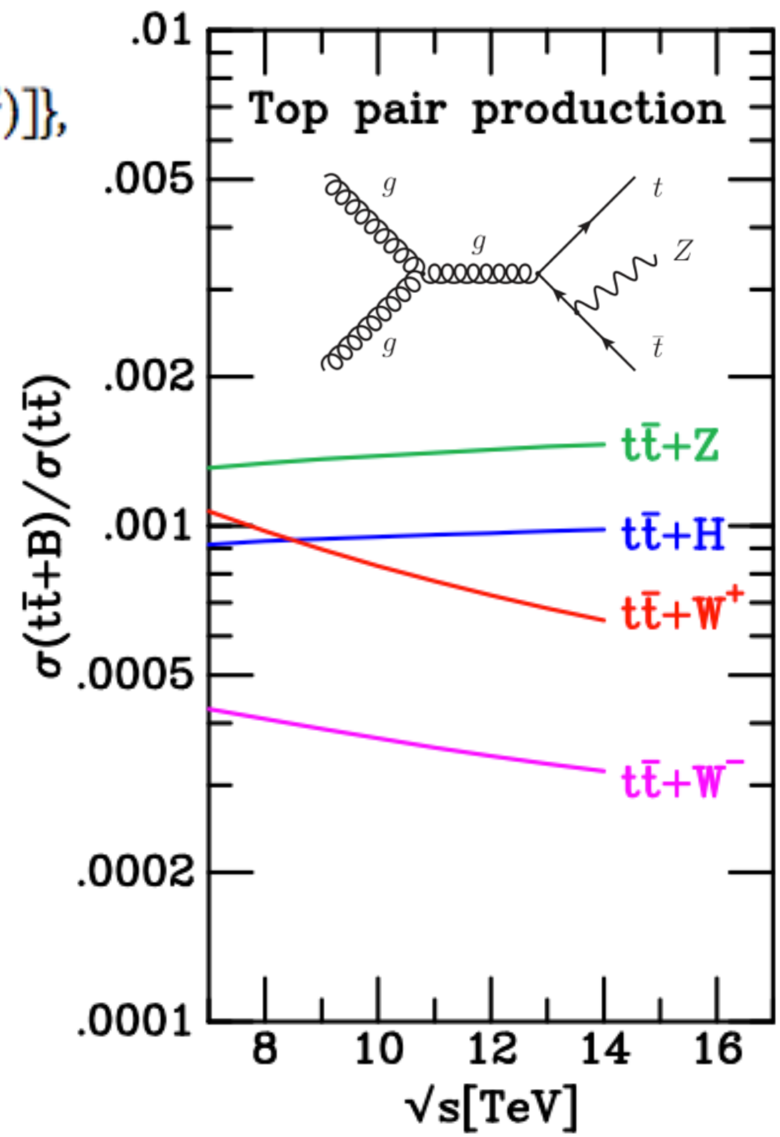
	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

Figure 4: Branching ratios for top FCN decays in the SM, models with Q = 2/3 quark singlets (QS), a general two-Higgs doublet model (2HDM), a flavour-conserving (FC) 2HDM, in the MSSM and with R parity violating SUSY[14].

n5: *ttZ* Couplings

Objective: First search for anomalous Vector (Axial Vector) ttZ couplings

$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\{\gamma_\mu[F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)] + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu[iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)]\},$$



Novelties:

- Production binned in p_T^Z
- Binned in di-lepton opening angle

Dataset Required:

~100 fb^{-1} @ 13-14 TeV

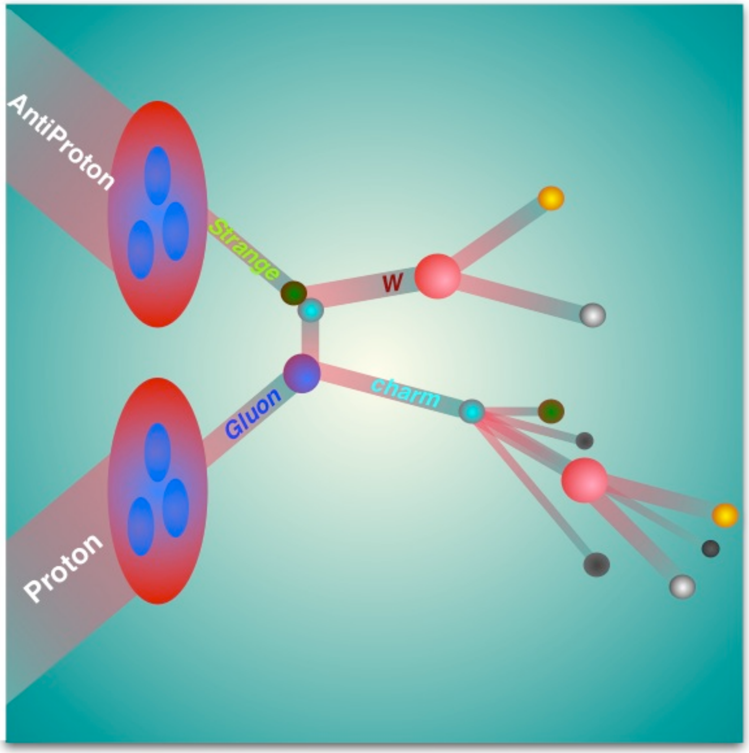
State of the Art:

No direct limit on couplings. *ttZ* observed

Target Sensitivity: ~80% on Vector,
~20% on AV

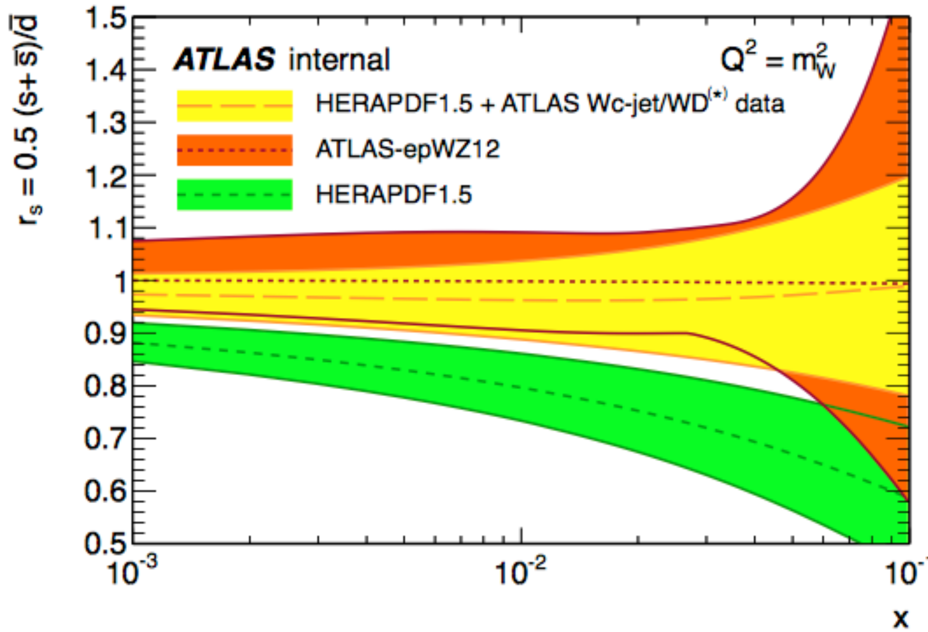
Unexpected directions

pp→W+charm

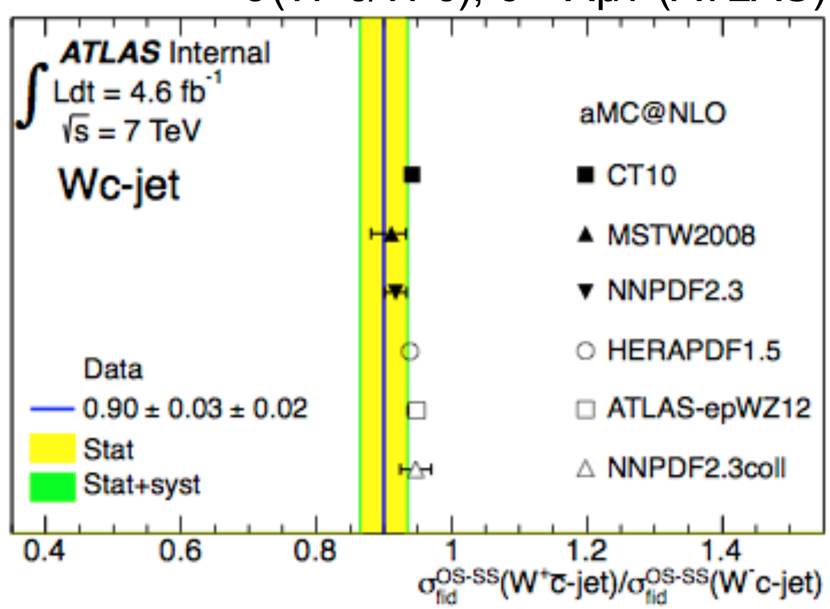


L .Cerrito, CDF, Phys. Rev. Lett. 110, 071801 (2013)

L. Cerrito, CDF, Phys. Rev. Lett. 100, 091803 (2008)



σ(W⁺c/W⁻c), c→Xμν (ATLAS)



L. Cerrito *et al.*, JHEP05 068 (2014)

Summary

- Top quarks are central to many scenarios of physics beyond the standard model (BSM)
- Top physics properties and dynamics has so far indicated SM behaviour on all observables (modulo A_{FB} somewhat)
- The LHC and HL-LHC will give an extraordinary amount of top quark data: accessing processes of O(fb)
- Proposed a few measurements for the period 2015-2020, which might point to BSM.