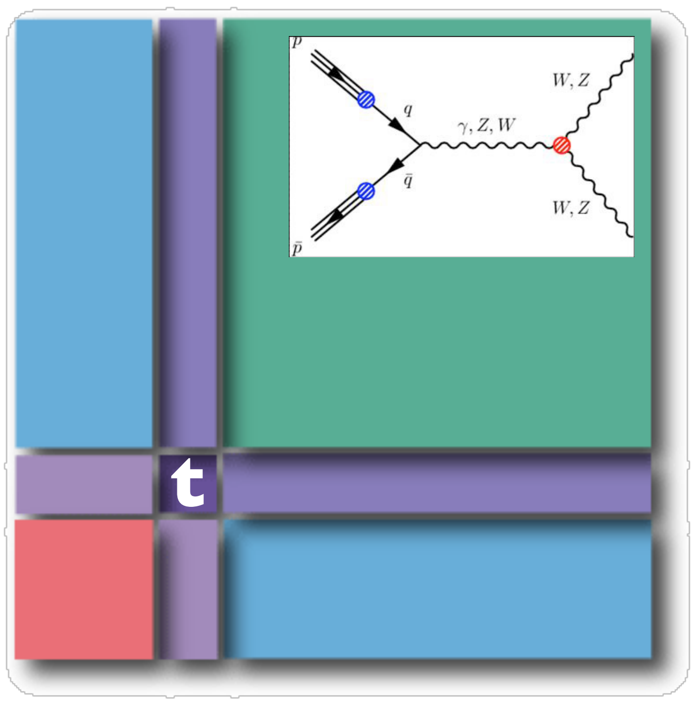
Precision EWK & Top Physics at Colliders



Prof. Robin Erbacher
University of California, Davis

46th SLAC Summer Institute
SLAC - July 2018

Comparison of collider samples

Samples of W, Z and top-pair events at the different colliders

	LEP	Tevatron	LHC
Particles	e^+e^-	p-pbar	pp
√s (GeV)	88-209 GeV	1.8-1.96 TeV	7-13 TeV
Int. L/ expt	200-700 pb^{-1}	2-10 fb^{-1}	5-300 fb^{-1}
Typical $\langle\mu\rangle$	<<1	~1-10	20-40
# W→lv /expt	10k	~1-2M	10M (in 5 fb^{-1})
# Z→ll / expt	0.5M	~100k	1M (in 5 fb^{-1})
# ttbar / expt	-	10^5	10^7

LEP e+e- collider

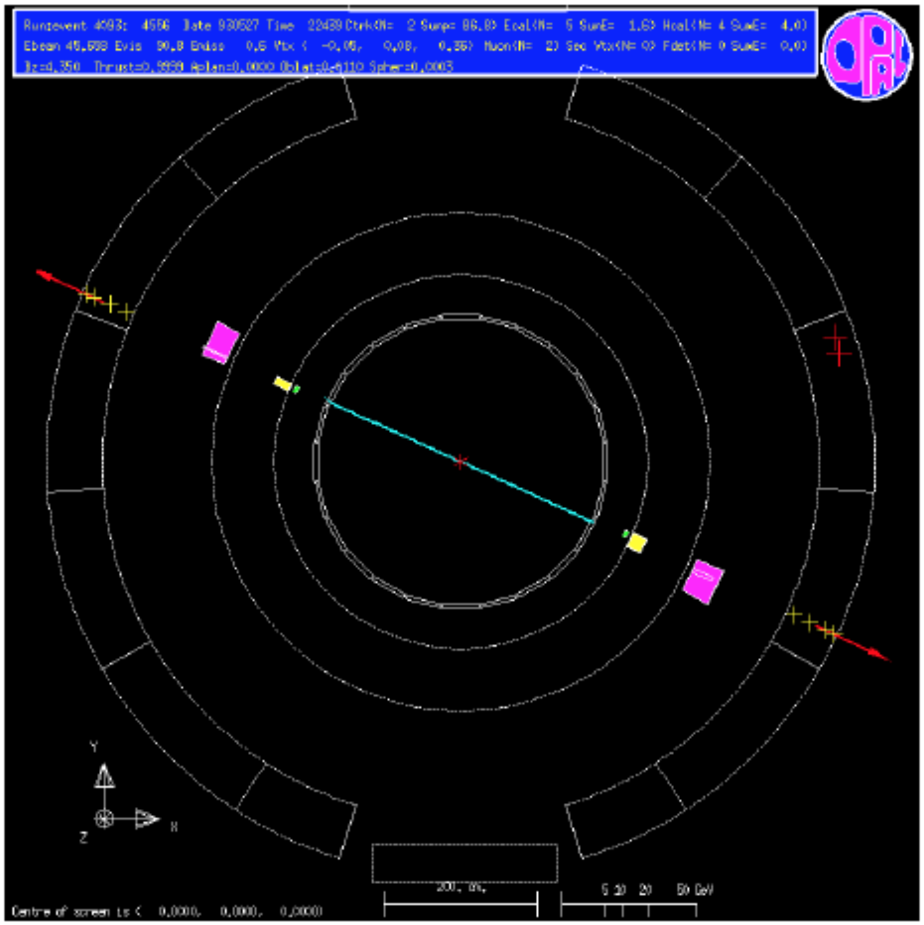
- Very clean e^+e^- events, Ws only produced in pairs, full event reconstruction, limited data samples, no top quarks

Tevatron/LHC

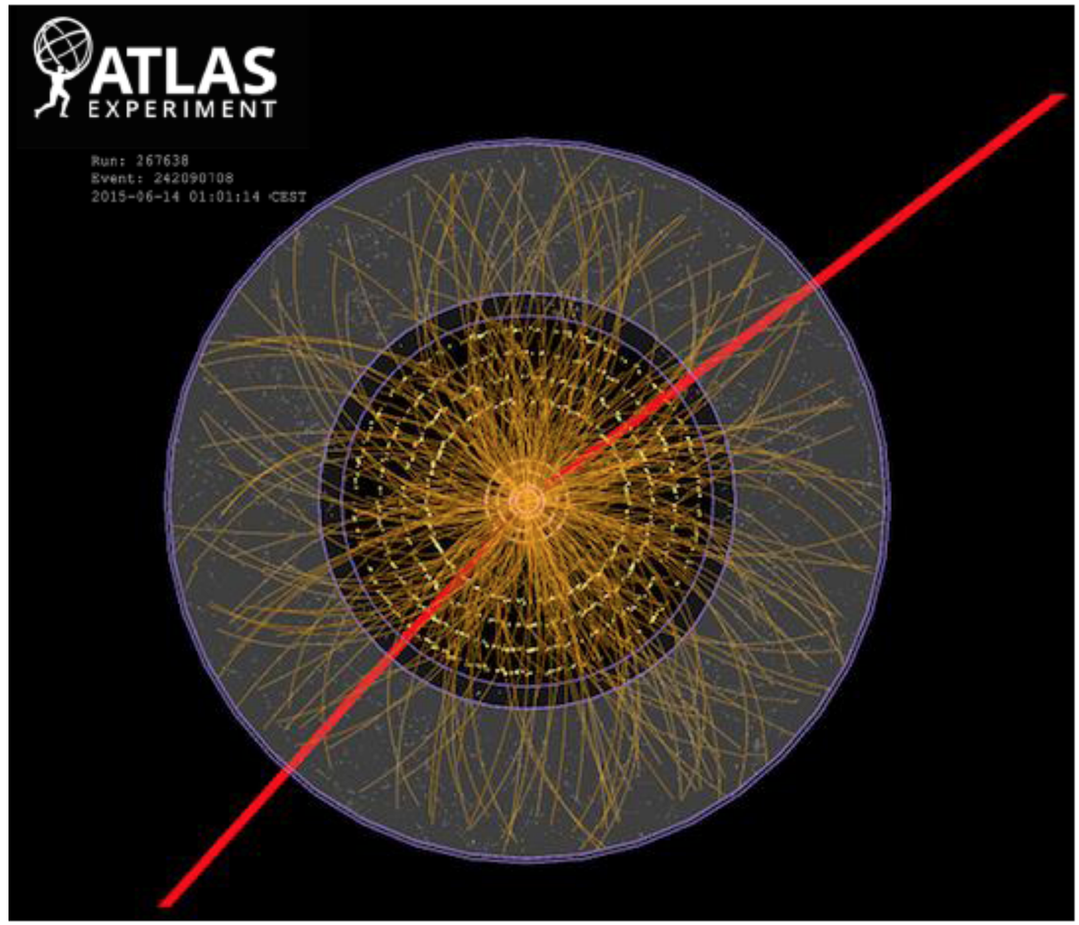
- Larger samples, pileup and underlying event, no complete reconstruction, tops

Comparison of collider challenges

LEP (Opal) $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ event from 1993



LHC (ATLAS) 13 TeV $pp \rightarrow Z \rightarrow \mu^+\mu^-$ event from 2015



Lecture Outline

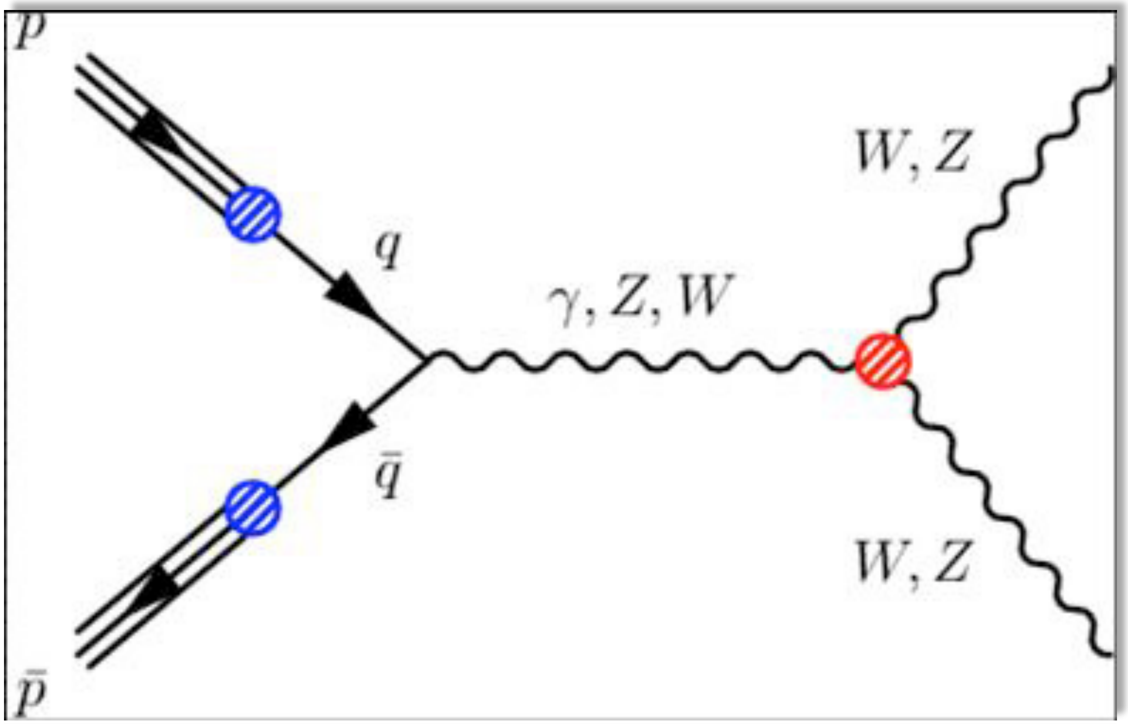
Electroweak Physics

- W/Z Production
- Multibosons & SM deviations
- EWK Parameters: W mass, $\sin^2\theta_{eff}$

Top Physics

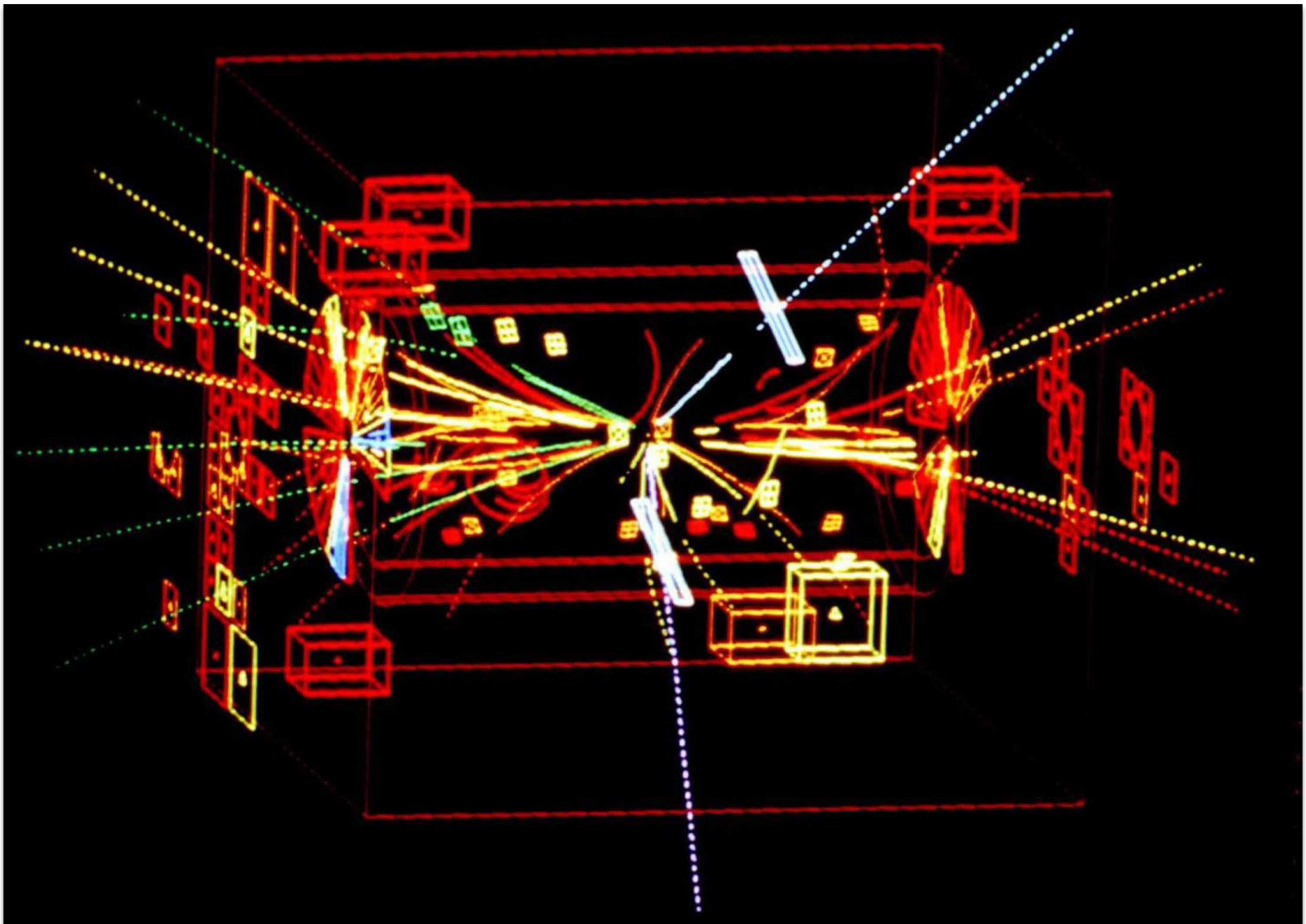
- Top Production
- EWK Single Top Production
- Some top properties
- Top quark Mass

Electroweak Physics



One of the first Z events found in UA1

- 1983 - UA1 and UA2 announced first observation of Z boson

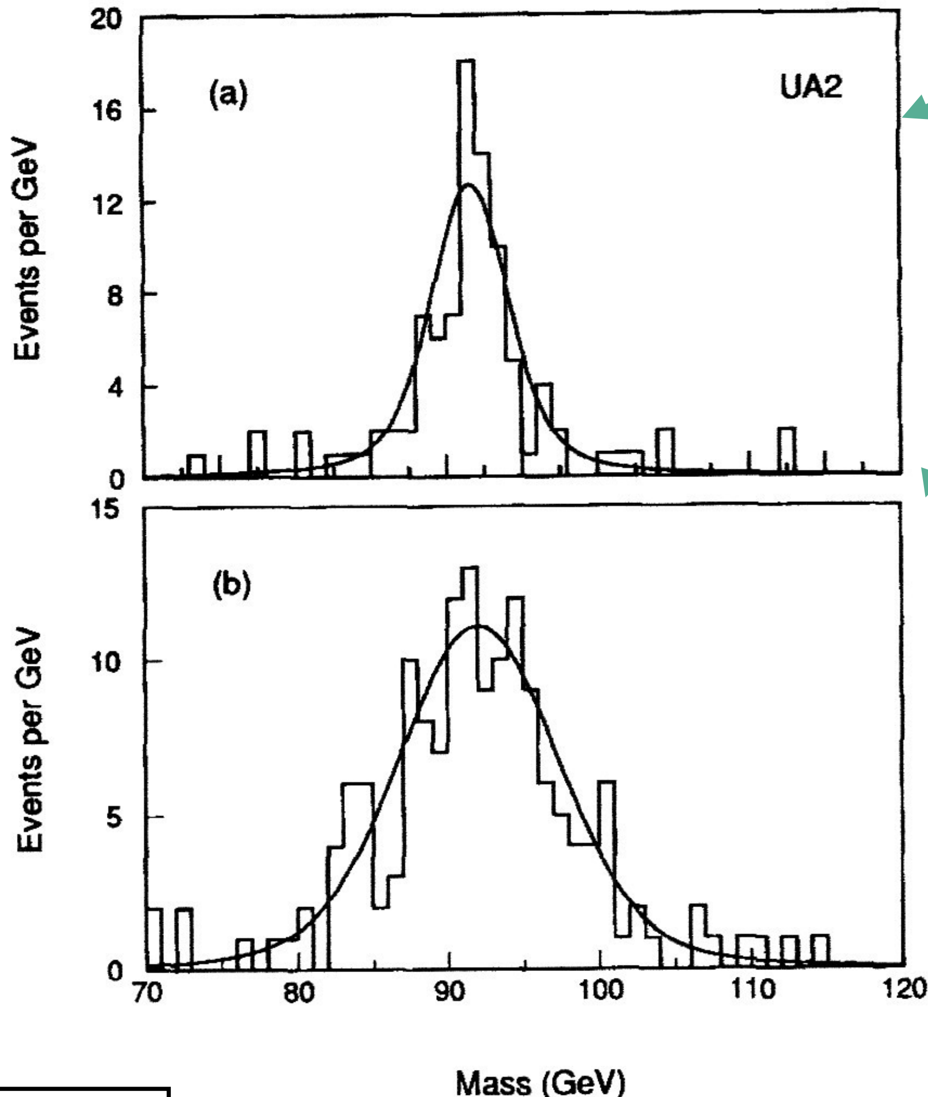


First W/Z observations at UA1 and UA2

$$u+\bar{d} \rightarrow W^+ \qquad \bar{u}+d \rightarrow W^-$$

SpS

$$u+\bar{u} \rightarrow Z \qquad d+\bar{d} \rightarrow Z$$



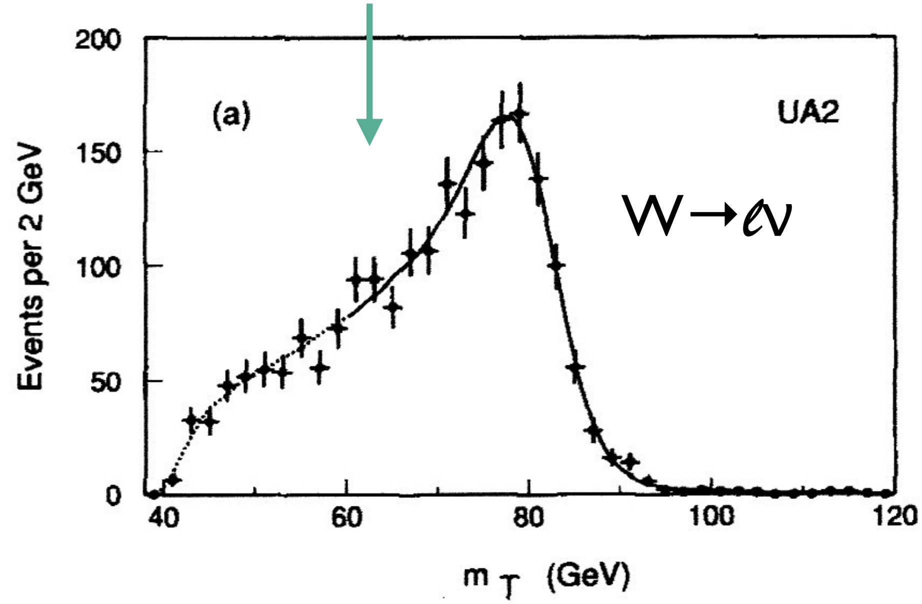
Z boson results from UA2

$$(M_{ee}c^2)^2 = (E_1+E_2)^2 - (\vec{p}_1+\vec{p}_2)^2c^2$$

(for $Z \rightarrow e^+e^-$, $M_{ee}=M_Z$)

W boson results from UA2

m_T ("transverse mass"): invariant mass of the electron – neutrino



see P. Jenni lecture

[UA1, PLB126, 398 (1983)
UA2, PLB129, 130 (1983)]

Z Mass(LEP)

- the Z mass is one of the best known fundamental parameters in physics:

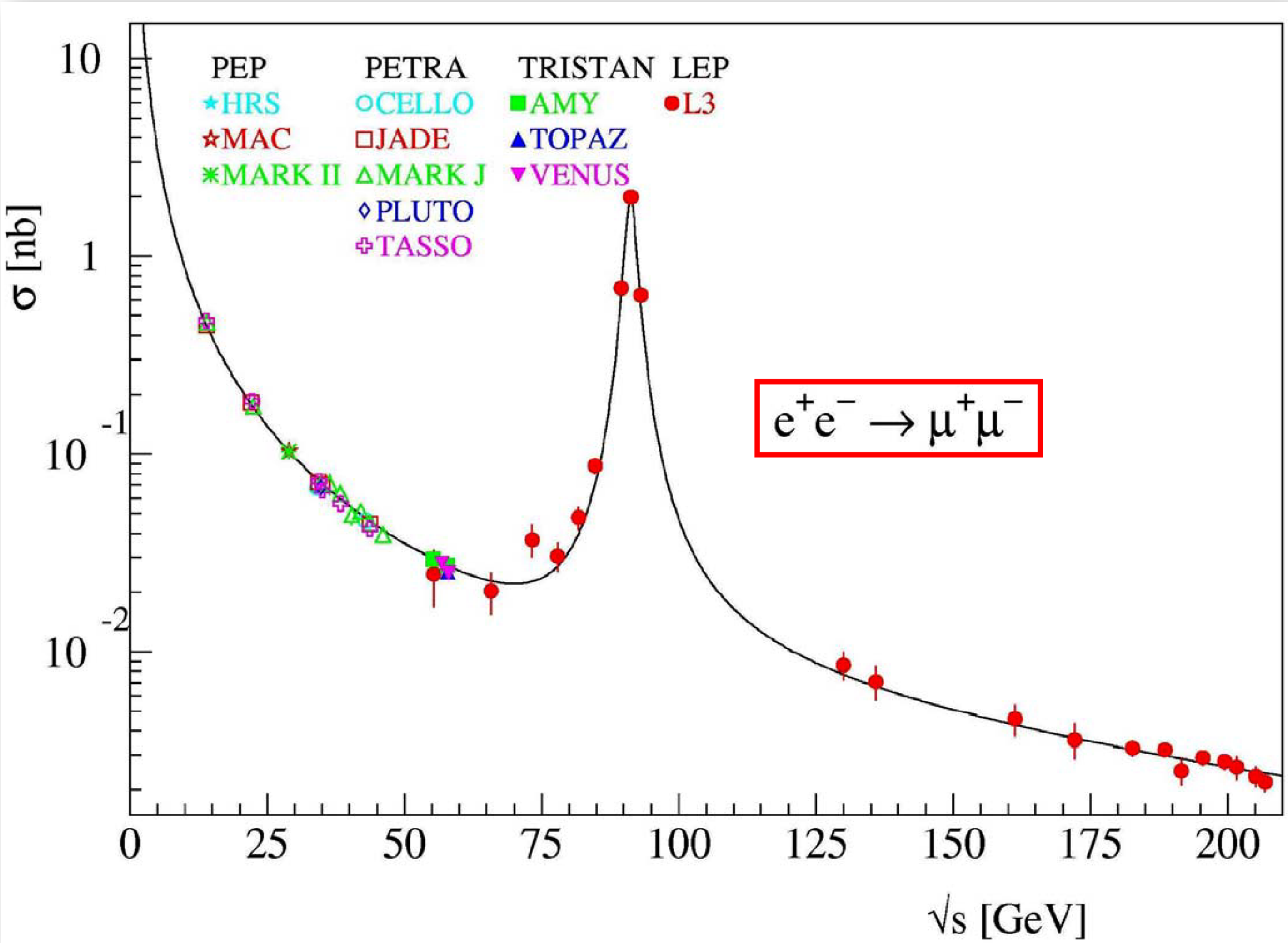
$$m_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}/c^2$$

- took years of painstaking work to overcome concrete expansion, passing trains, even the phase of the moon
- Z lineshape suffers from large radiative corrections* so the theoretical input is crucial

see also A. Freitas, L. Evans lectures

* Mainly due to top loops!

Mapping out the Z region

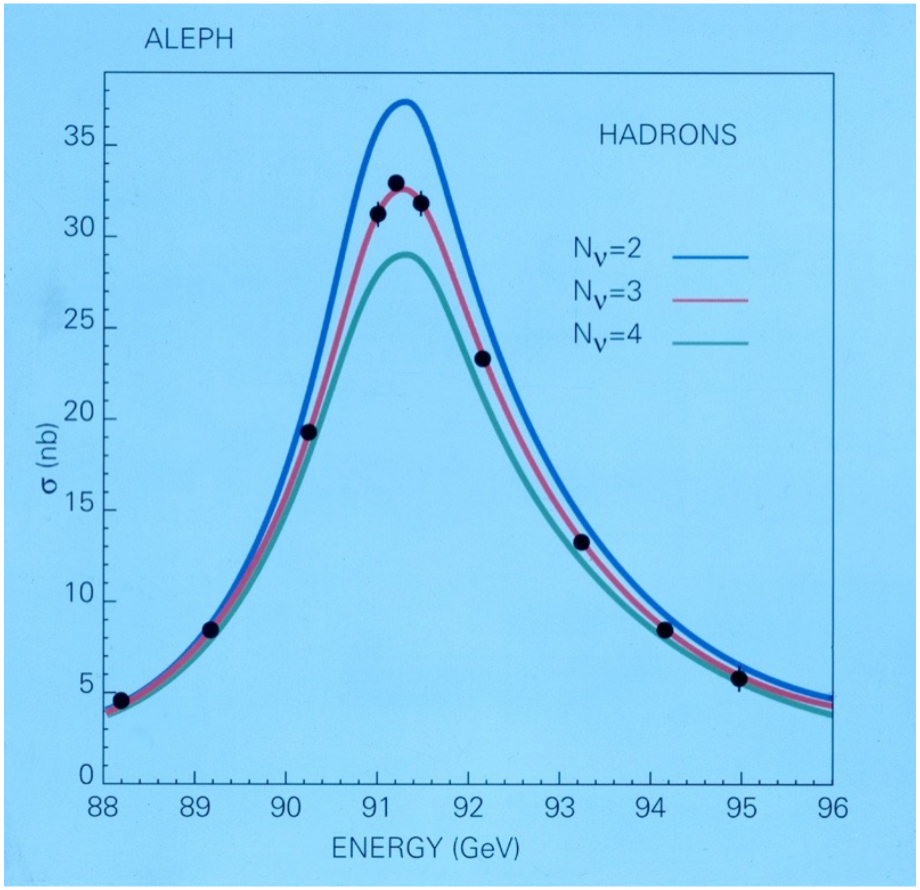


Plot shows the rate for ee → μμ below, at, and above the Z pole from a dozen experiments at different colliders.

Awesome.

Z Width (LEP)

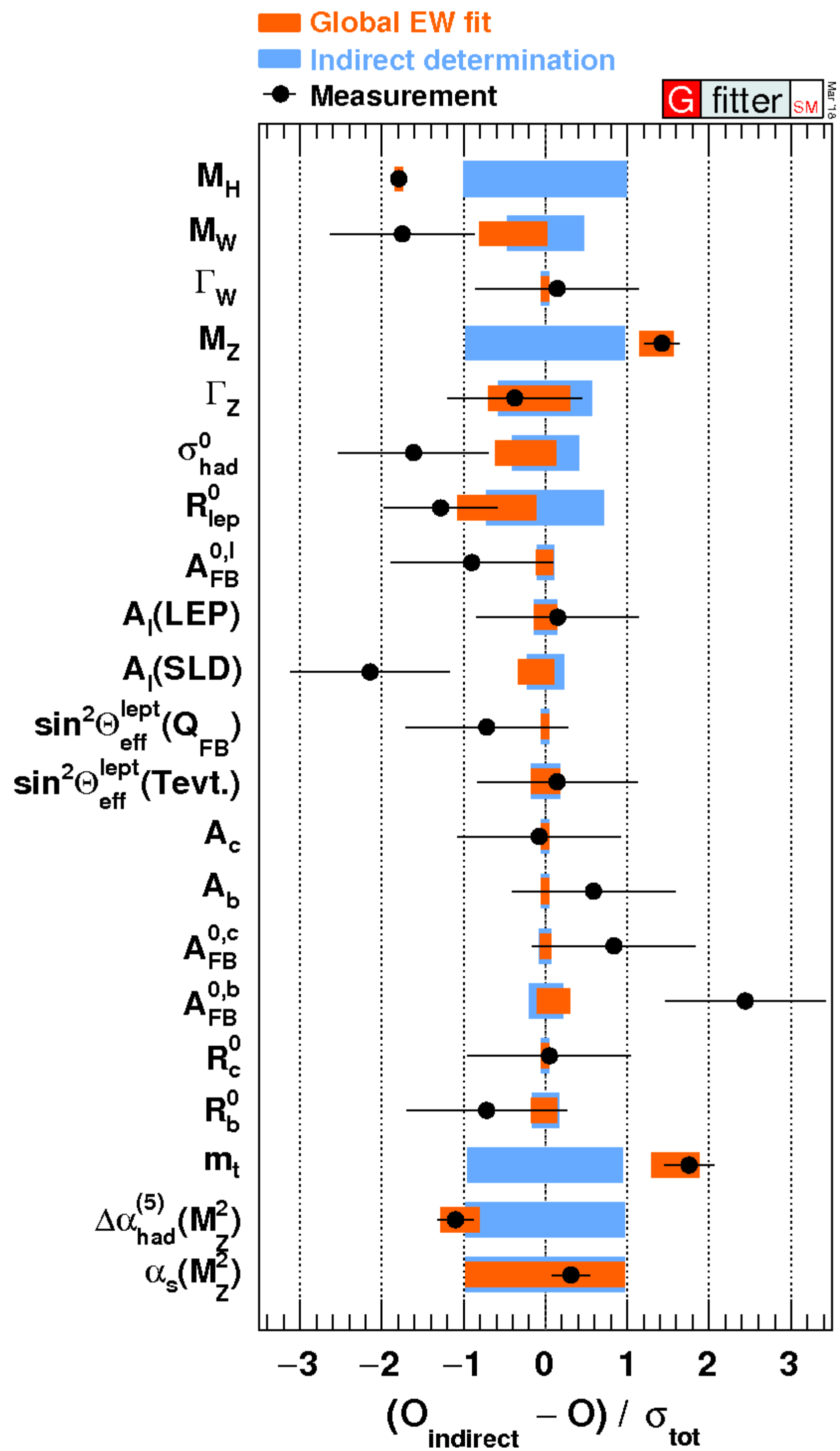
- The production cross section for ee→Z depends on the Z total width
- Any deviation from the SM width could be due to extra neutrinos!
- Within weeks the LEP experiments had ruled out a fourth light neutrino definitively



measured and predicted Z lineshape after radiative corrections, for different numbers of light neutrino flavors: $N_\nu = 2.99 \pm 0.011$

Current Global Electroweak Fit

<u>Fit:</u>



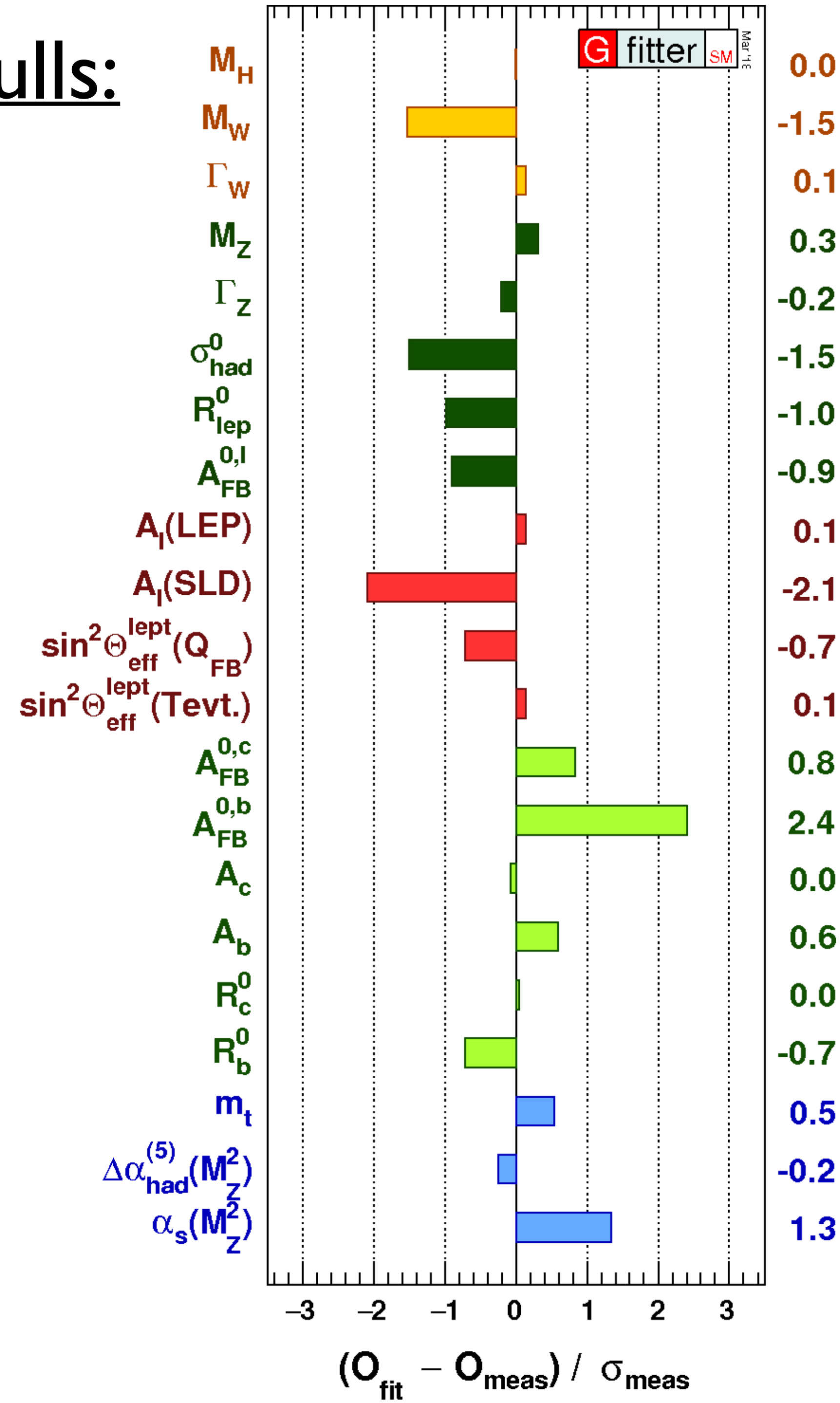
Latest from Gfitter March 2018

arXiv:1803.01853

see also A. Freitas lecture

Current Global Electroweak Fit

Pulls:



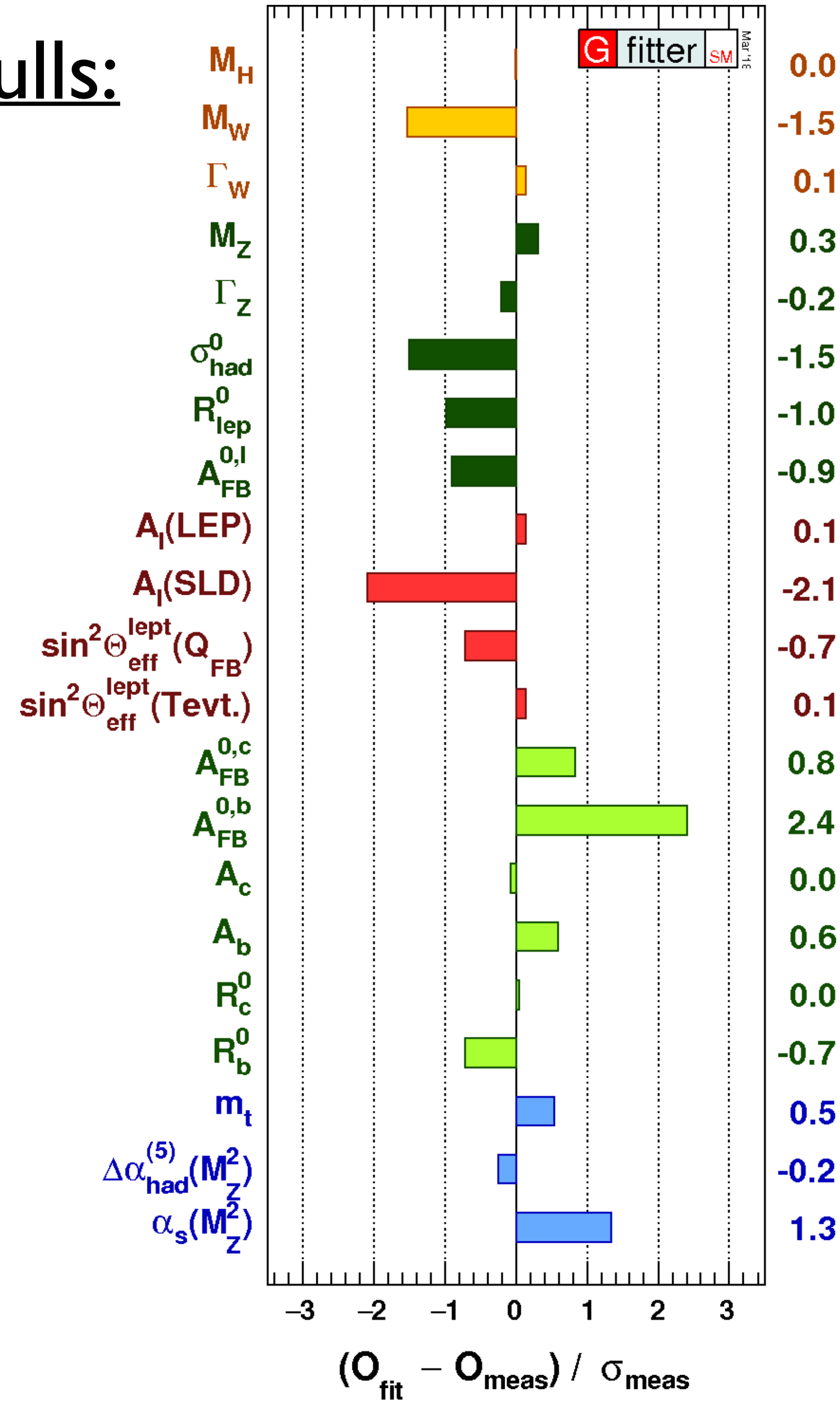
Latest from Gfitter March 2018

- χ^2_{min} 18.6 for 15 degrees of freedom
- Pulls all within 2.5σ
- p-value of 0.23

arXiv:1803.01853

Current Global Electroweak Fit

Pulls:



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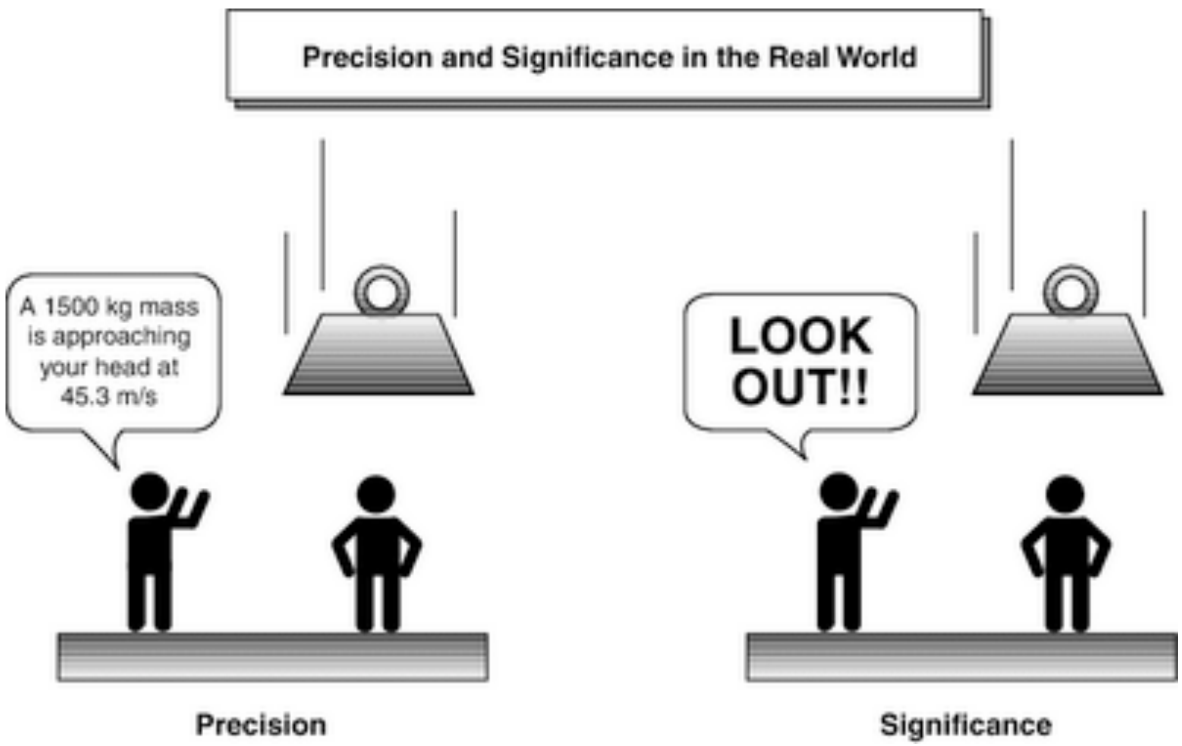
What next?

arXiv:1803.01853

What next?

Current Global Electroweak Fit

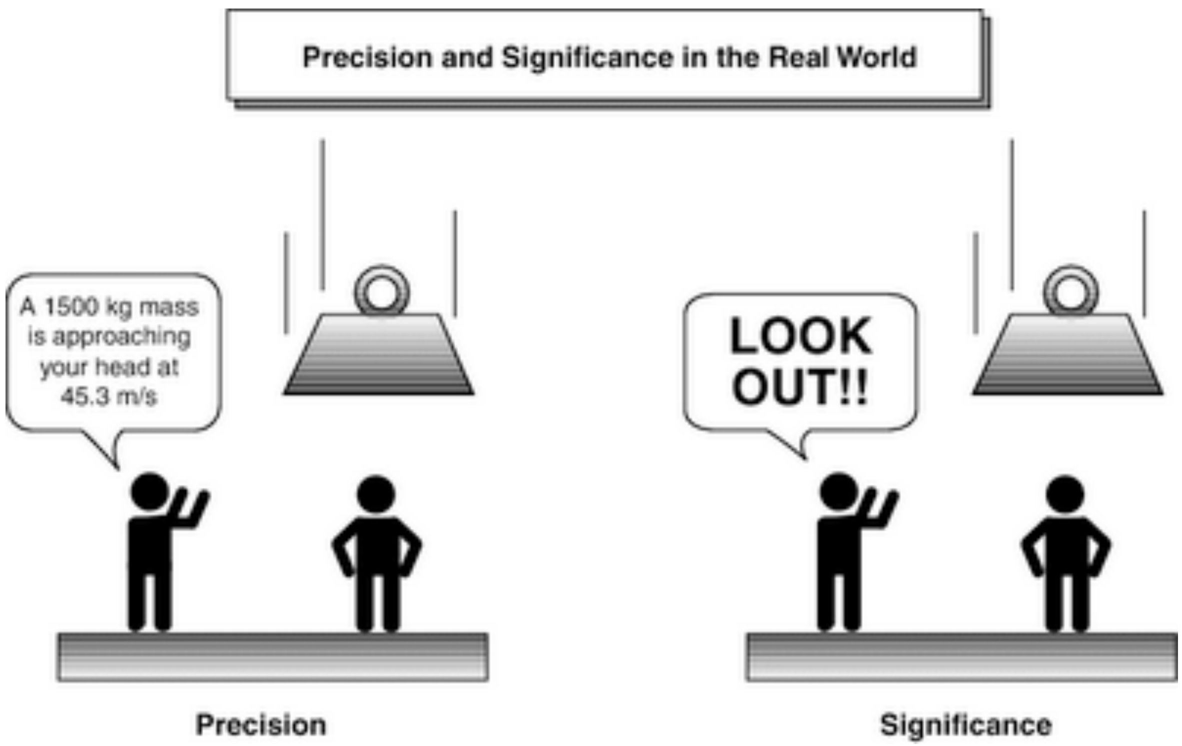
More Precision!



What next?

Current Global Electroweak Fit

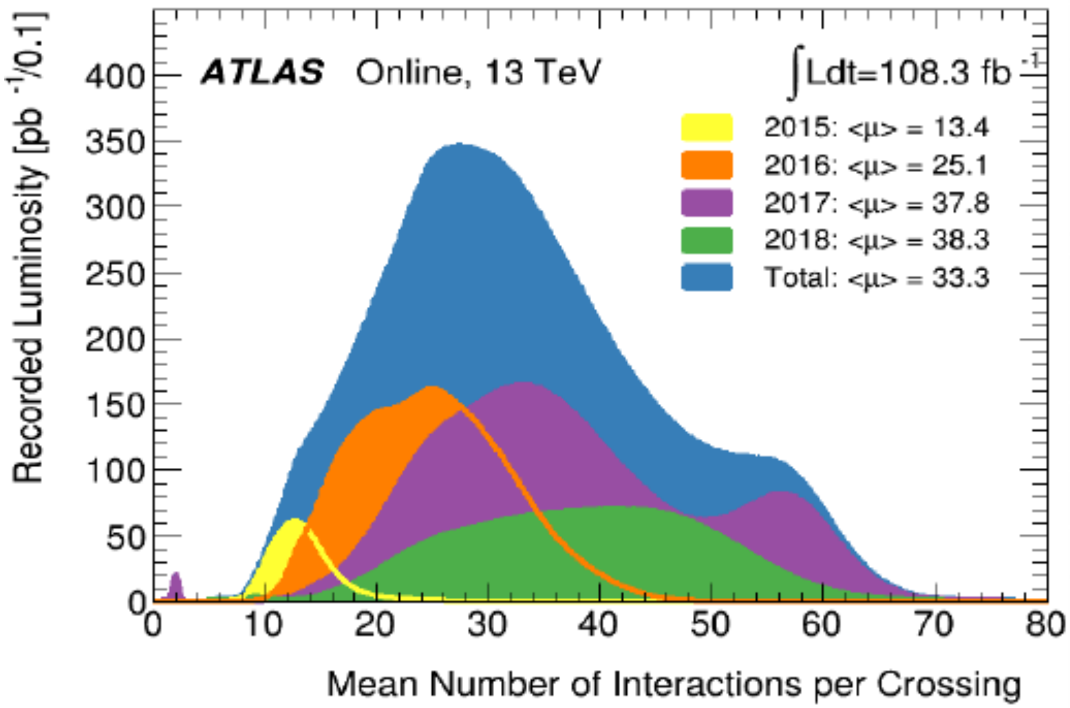
More Precision!



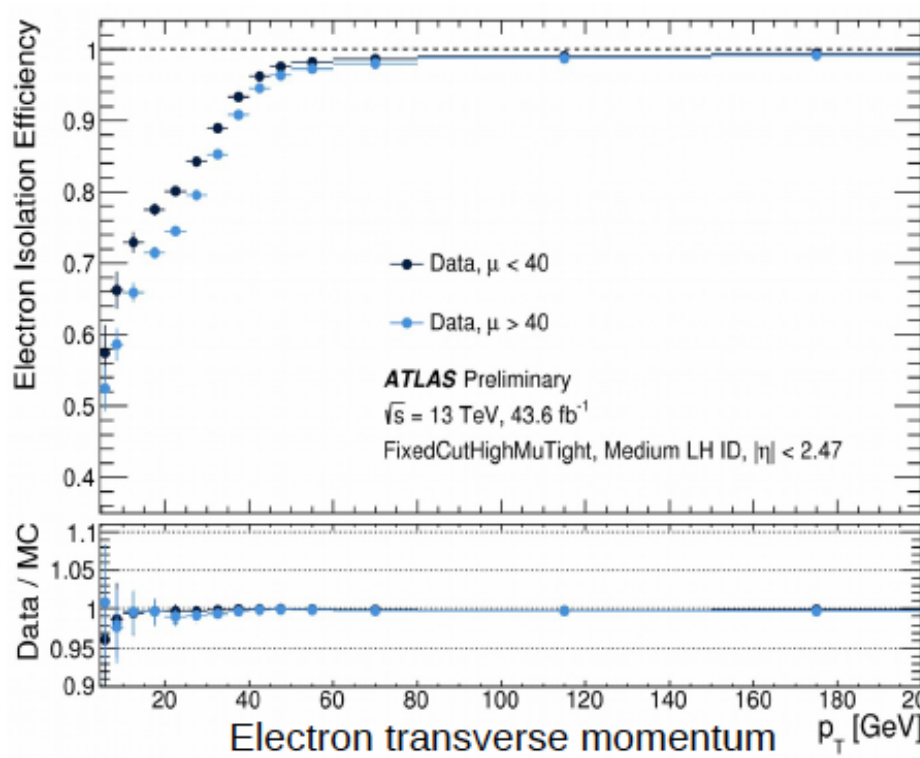
- Study W,Z thoroughly: differential distributions
- Improve precision parameters: W mass, $A_{FB}(\ell)$ (weak mixing angle)…
- Precision theory & PDF constraints
- WW scattering
- Look for new physics -- anomalous couplings

Challenges at the LHC

Interactions per bunch crossing



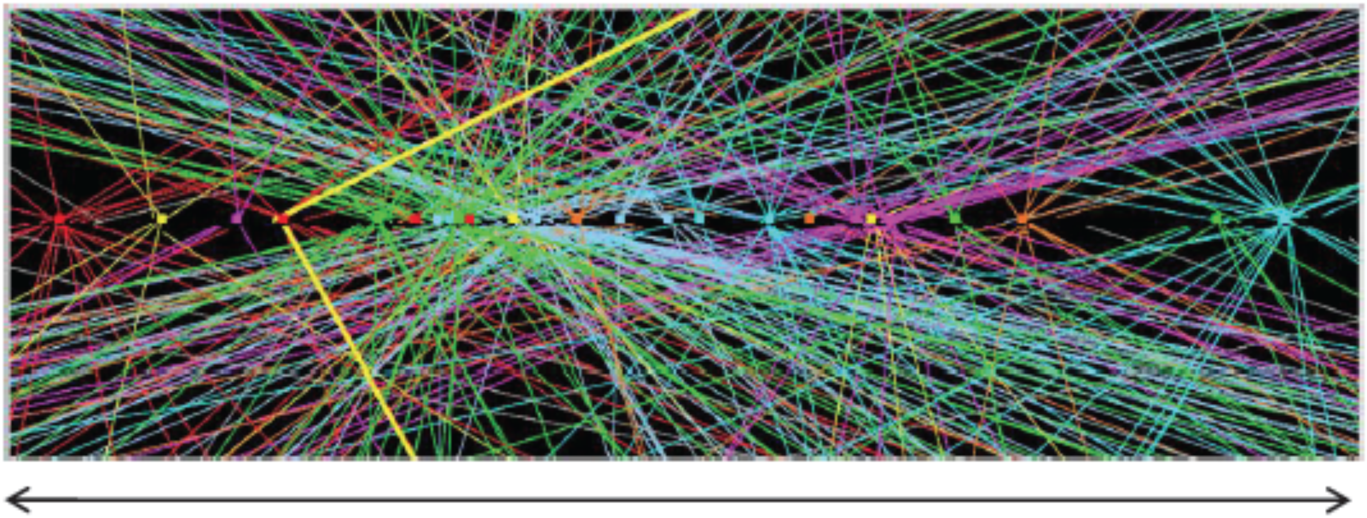
Electron isolation efficiency



- Large pile-up (additional interactions) causes performance degradation.
- Performance loss is modeled well by Monte Carlo simulation.
- Powerful pile-up mitigation techniques developed.

Challenges at the LHC

Z→μμ event with ~25 reconstructed vertices



20 cm

Effects of pileup

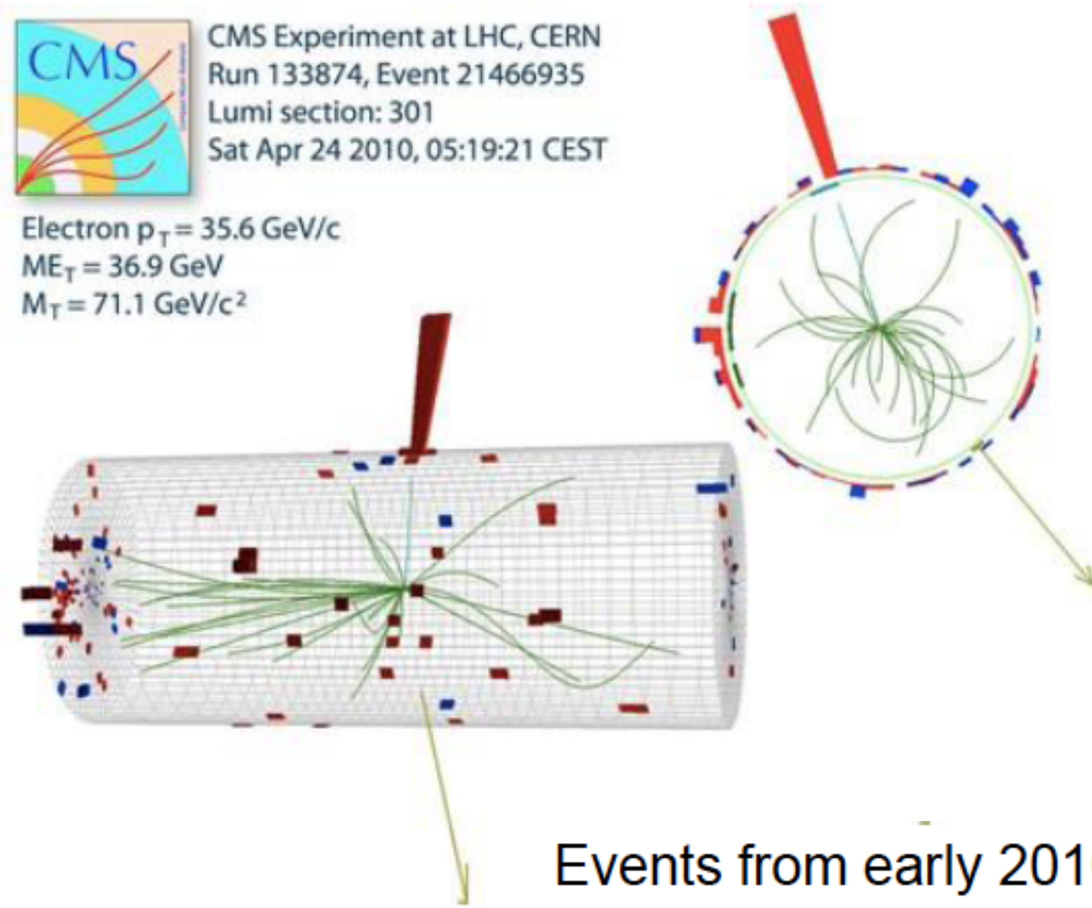
- Deterioration of jet and E_T^{miss} resolution, additional pileup jets
  - Higher trigger thresholds
- Additional jets from pileup
- Misidentification of primary vertex
- Pileup-dependent efficiencies, even for leptons

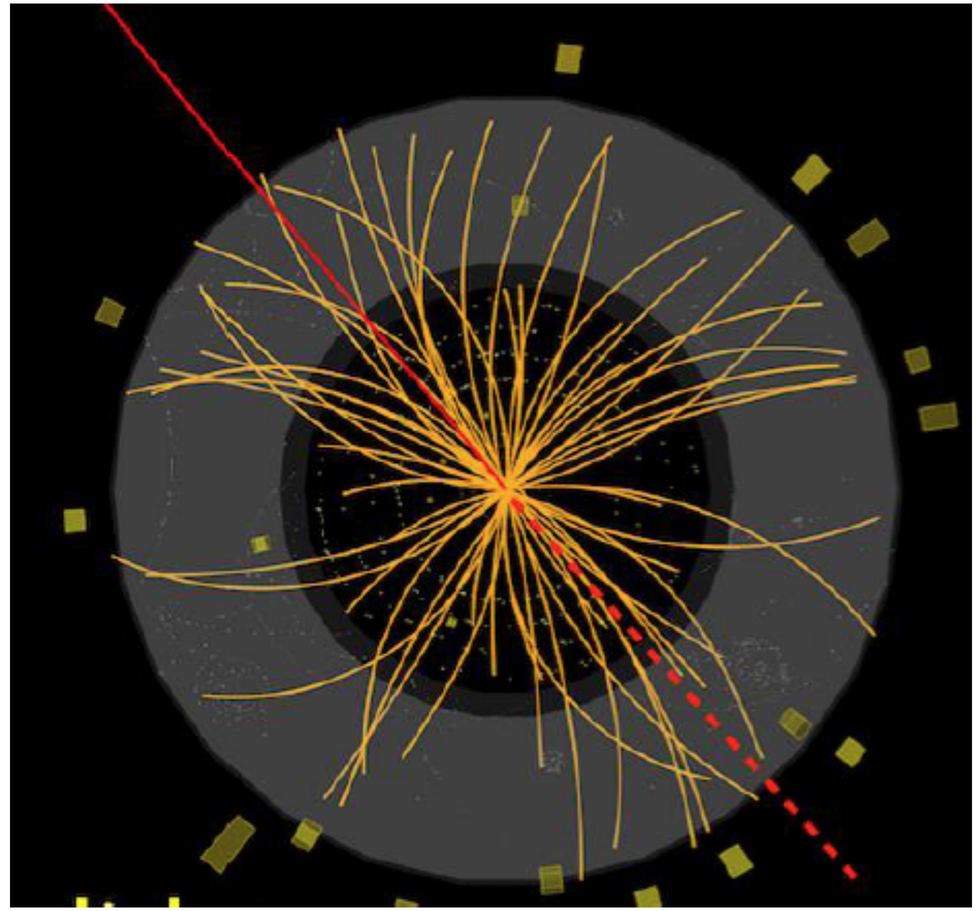
Pileup mitigation techniques

- Particle flow (jets, E_T^{miss}, isolation)
- Jet-area based pileup corrections

PUPPI (pile-up per particle id)

Vector Boson Production





ATLAS EXPERIMENT

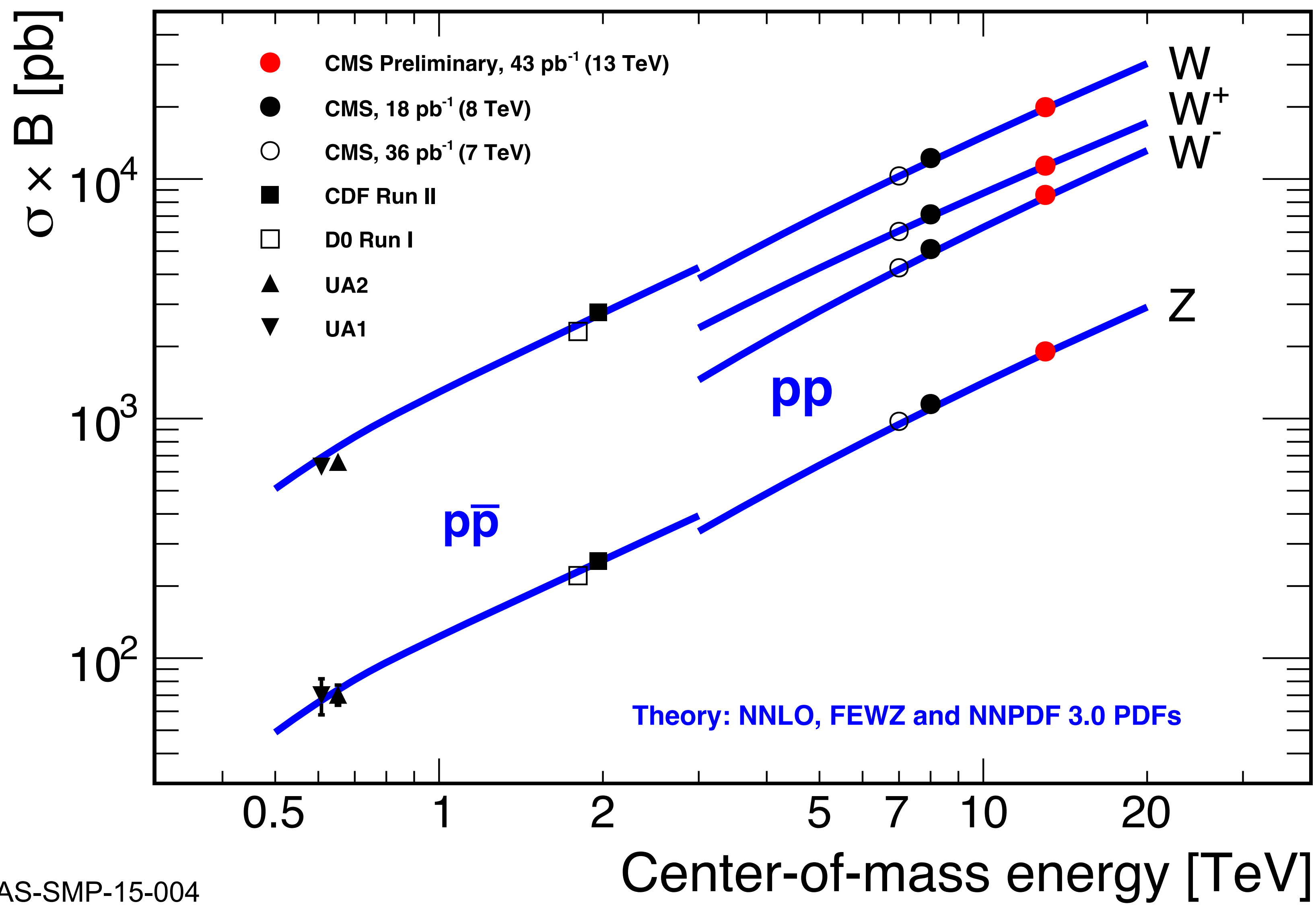
$p_T(\mu-) = 40$ GeV
$\eta(\mu-) = 2.0$
$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV

Events from early 2010

- Very little pileup, but still see tracks from underlying event accompanying the W boson production

Vector Boson Production

hadron colliders

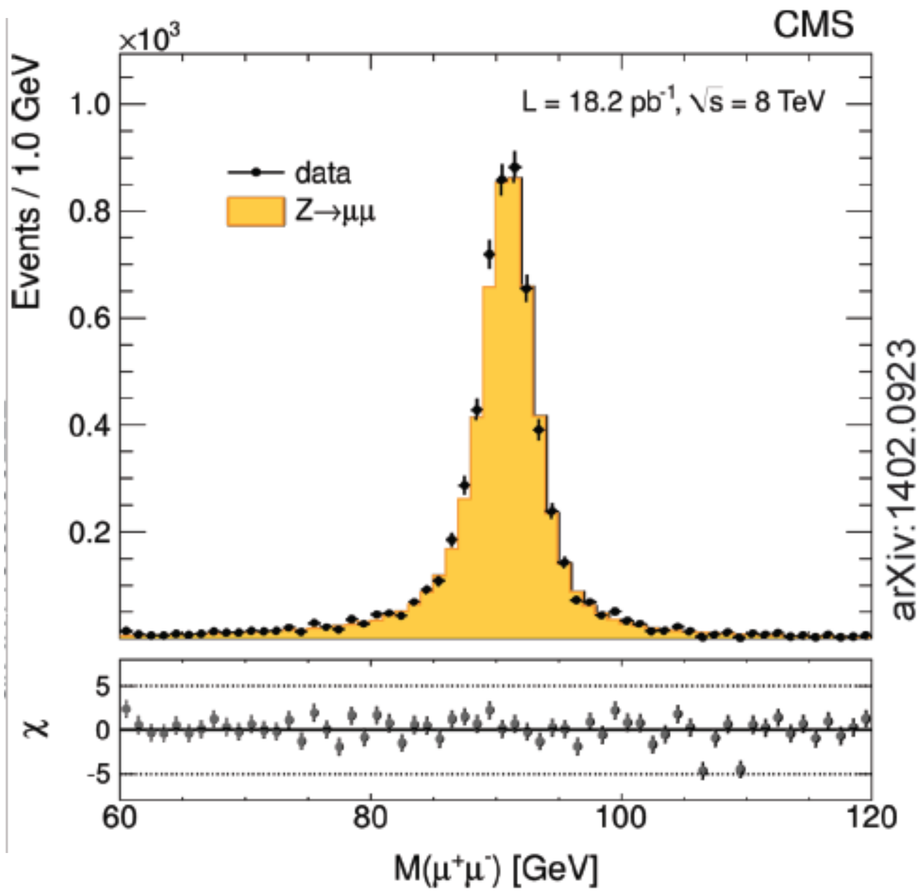


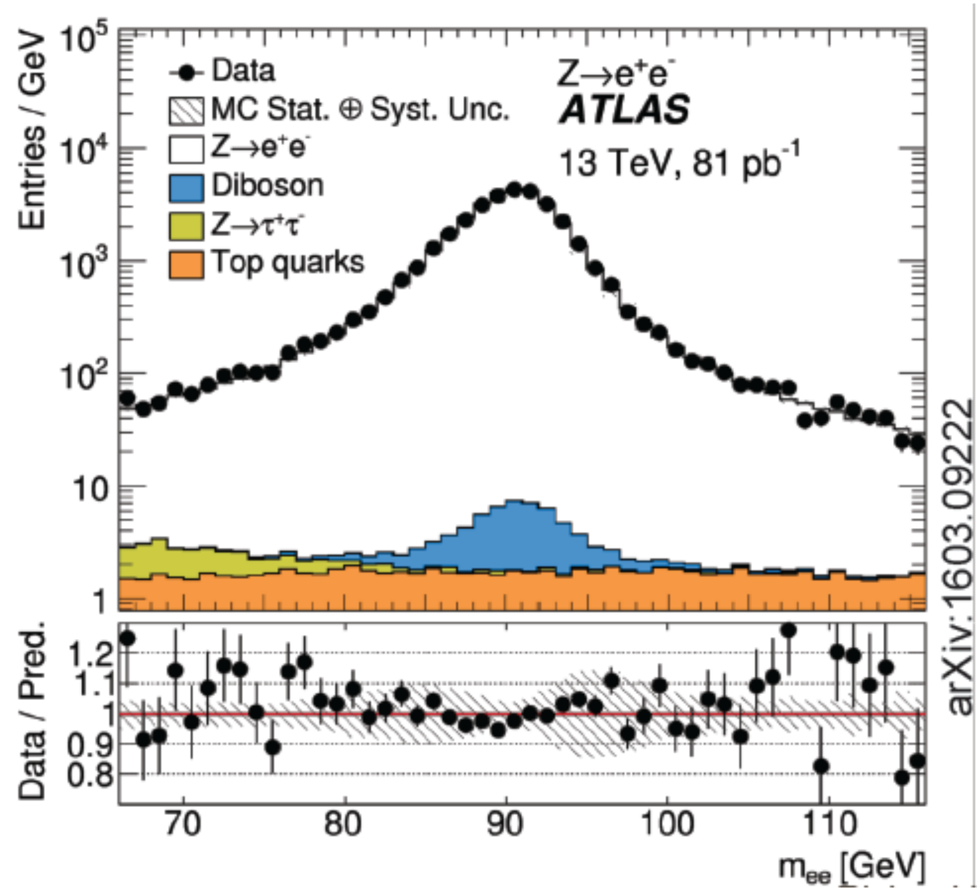
CMS-PAS-SMP-15-004

Z→ee Z→μμ samples

Even small samples (<100 pb^{-1}) lead to 10^4-10^5 Z→ll event samples

- Inclusive cross-section analyses do not need the full data statistics
- Early analyses done with both Run-1 and Run-2 data

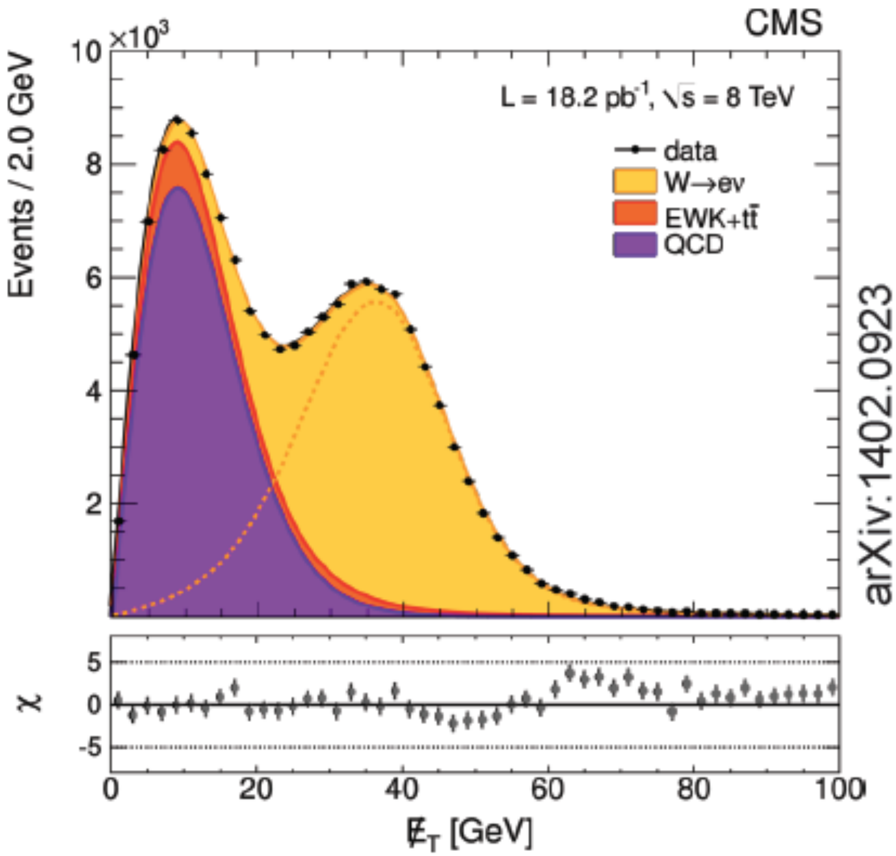


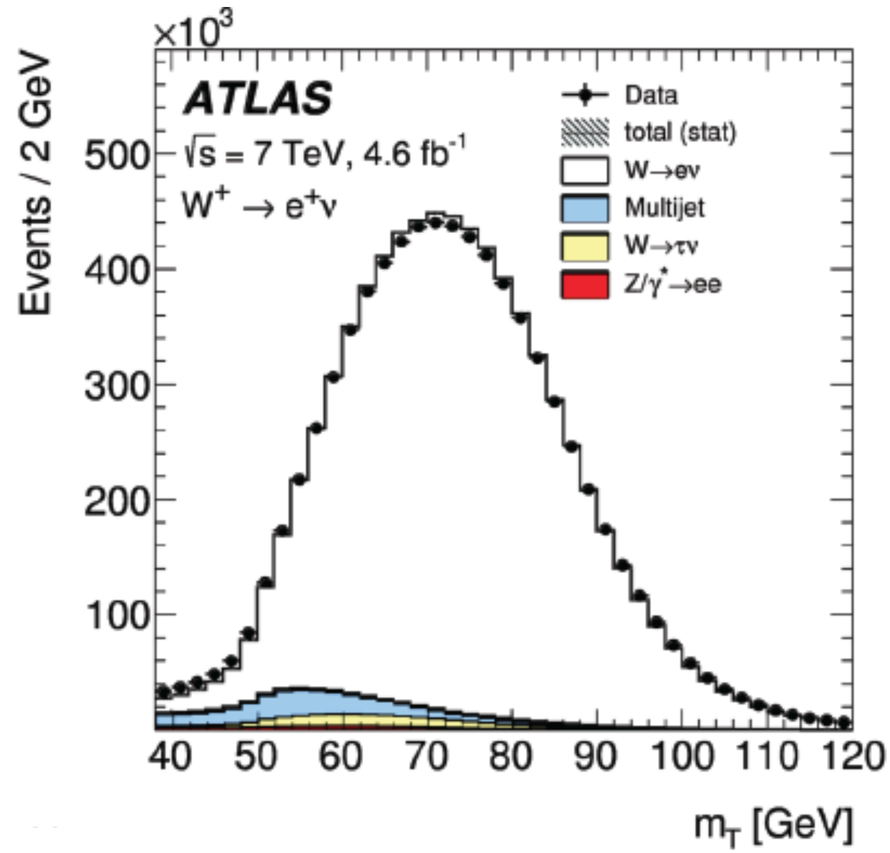


W→eν W→μν samples

W selections also require the use of E_T^{miss} to measure the neutrino p_T

- Cannot fully reconstruct the W boson mass as the neutrino p_Z is not measured
- Use the transverse mass m_T: $m_T = \sqrt{2 p_T^\ell p_T^{miss}(1 - \cos\Delta\phi)}$,





$$m_T = \sqrt{2 p_T^\ell p_T^{miss}(1 - \cos\Delta\phi)},$$

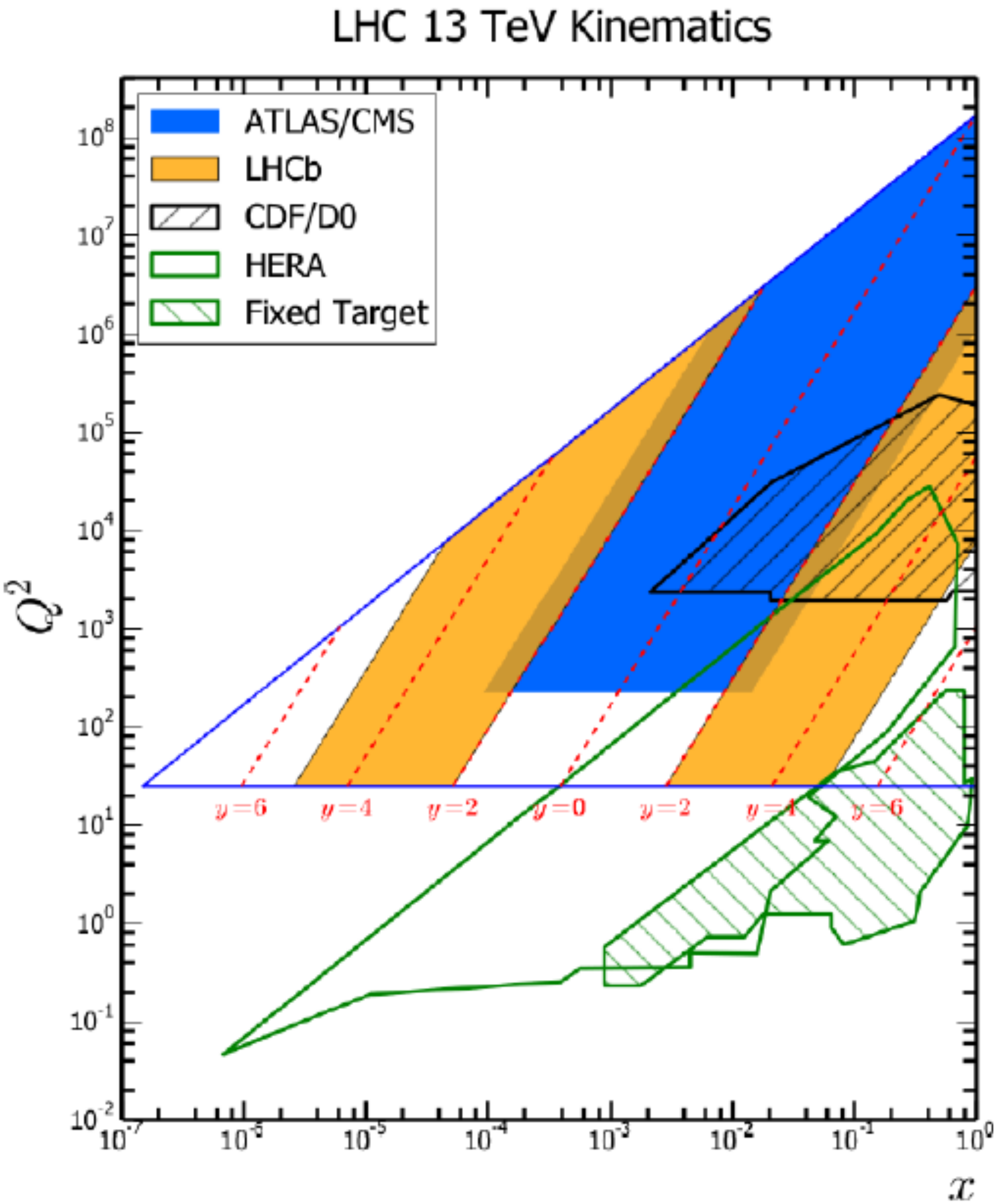
R. Hawkings HCPSS17

Electroweak Bosons at LHCb

Complementary phase space for EWK tests:

- W / Z cross sections in the forward region
- Access to parton distribution functions (PDFs) at known high-x and unexplored low-x.
- PDFs parametrized by:

$$Q^2 = M^2, x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$



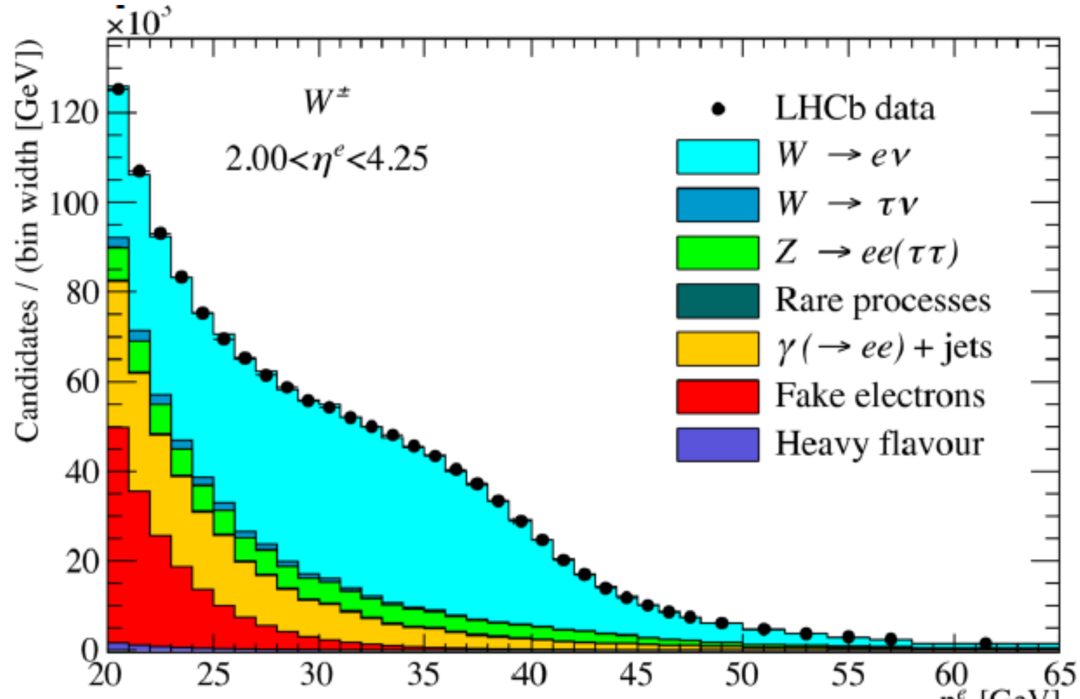
LHCb is aiming for precise measurements of EWK parameters: EWK mixing angle, W mass, …

Krokovny ICHEP18

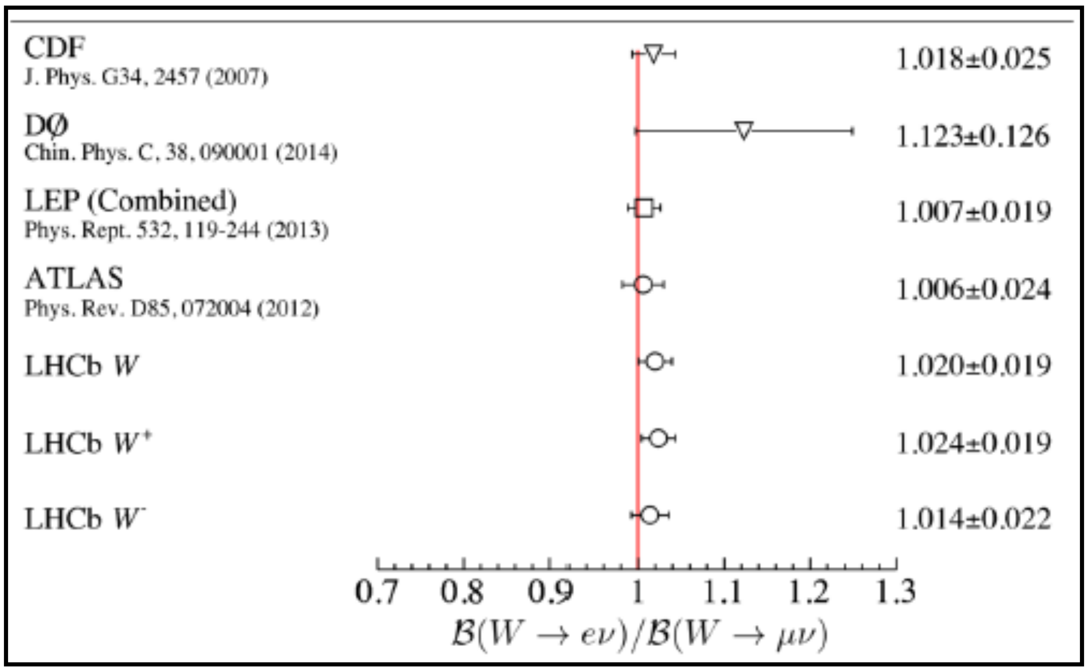
Electroweak Bosons at LHCb

Forward W production at $\sqrt{s}$= 8 TeV

- $p_T^e >$ 20 GeV
- $2.0 < \eta^e < 4.25$



JHEP 10 (2016) 030



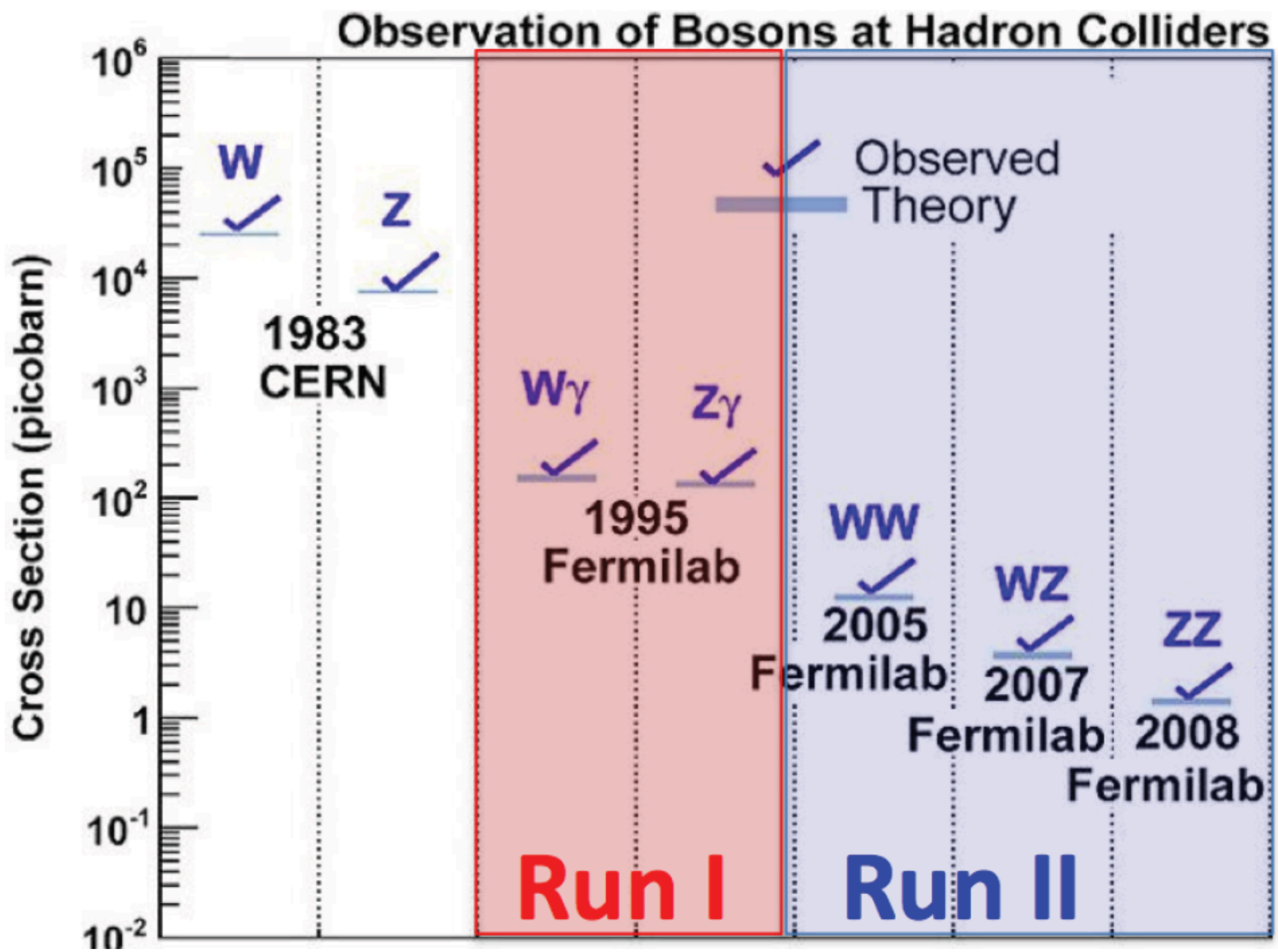
W yield extracted from fit to electron p_T distribution.

$\sigma(W^+ \rightarrow e^+\nu)$ = (1124.4 ± 2.1 ± 21.5 ± 11.2 ± 13.0) pb
$\sigma(W^- \rightarrow e^-\nu)$ = (809.0 ± 1.9 ± 18.1 ± 7.0 ± 9.4) pb
Uncertainties: statistics, systematic, energy, luminosity

$B(W \rightarrow e\nu) / B(W \rightarrow \mu\nu)$ = 1.020 ± 0.002 ± 0.019

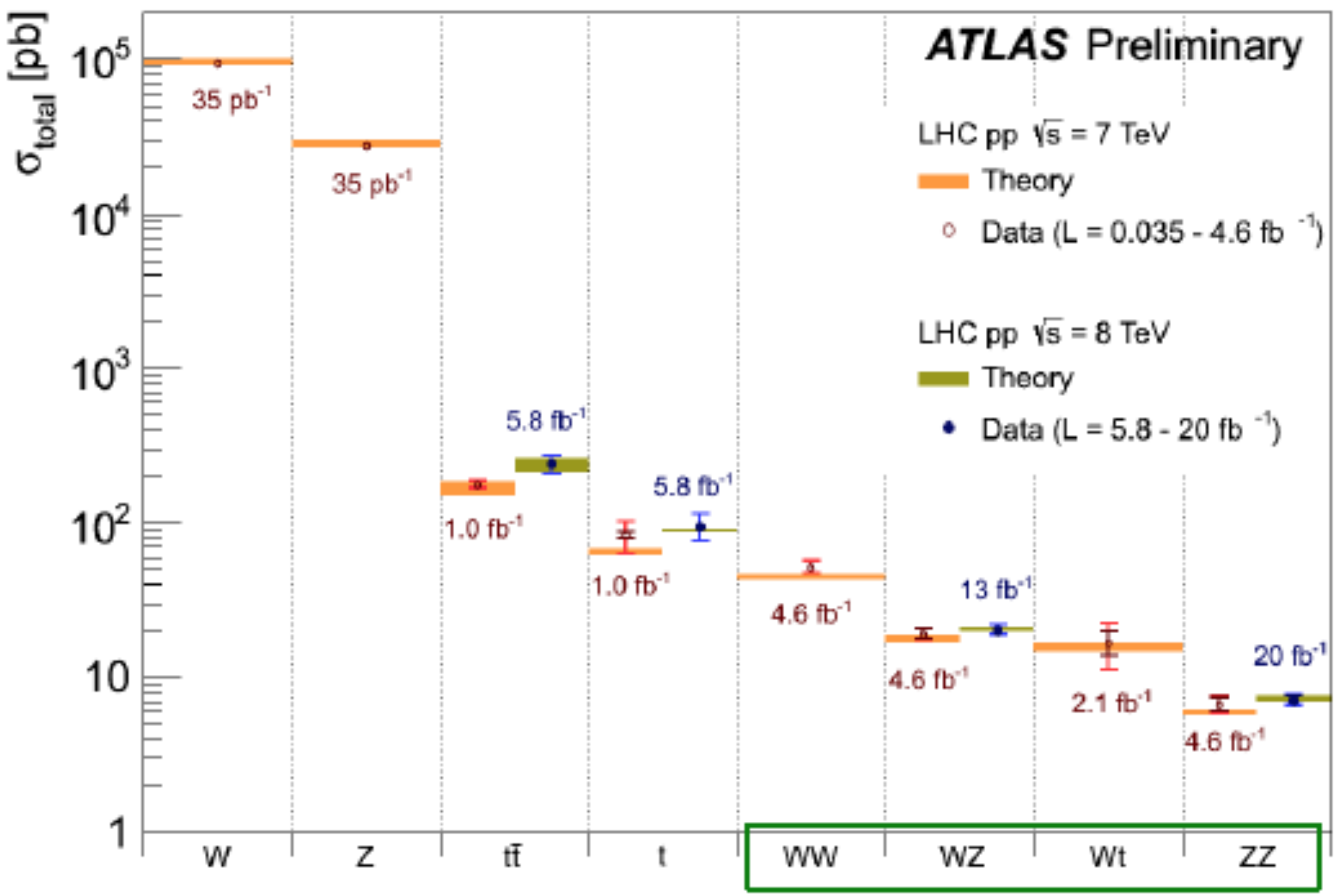
Diboson Production

Tevatron diboson discoveries!



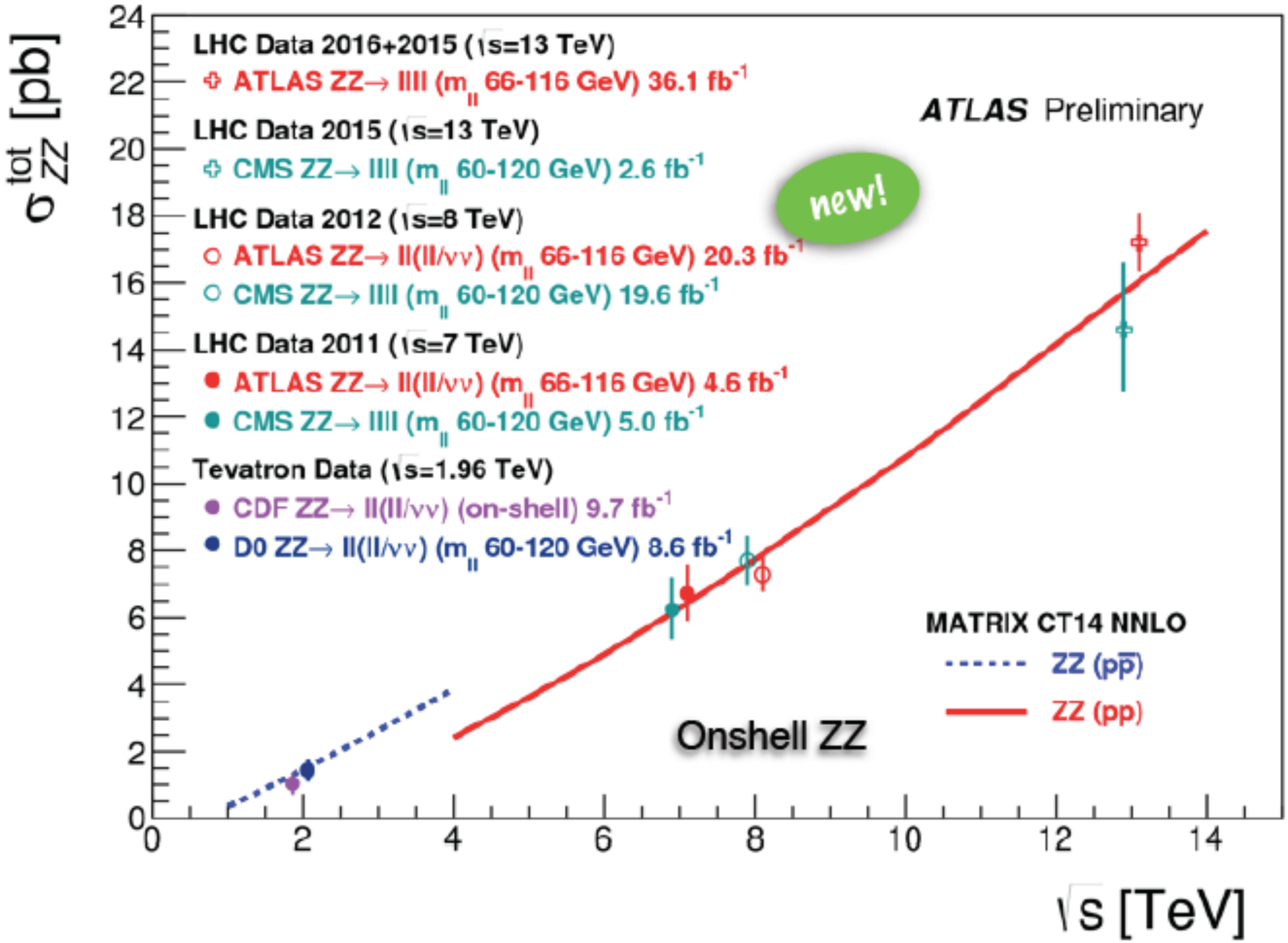
Precision at the LHC, Even with high pile-up!

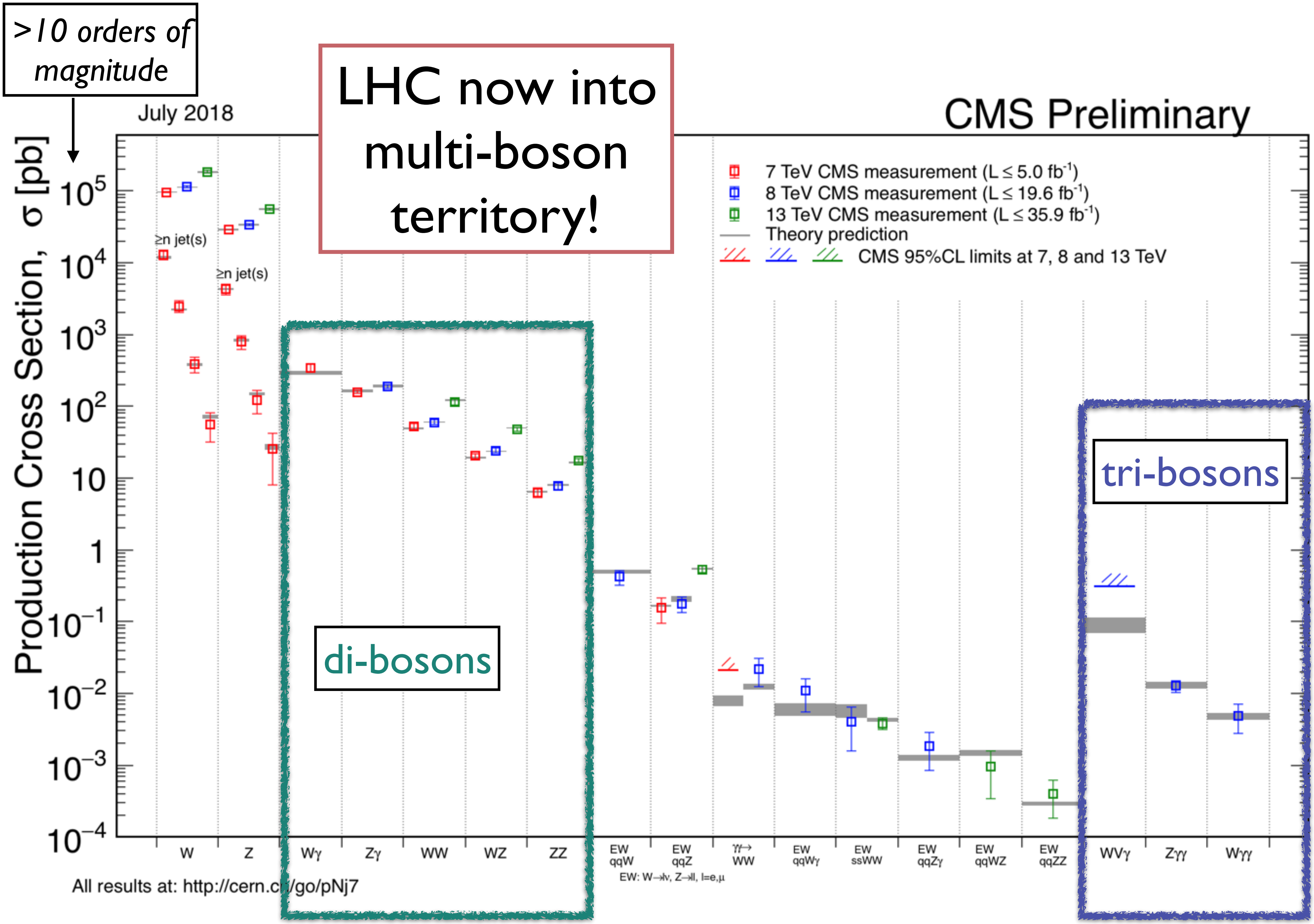
Diboson Production



Example: ZZ production

Diboson Production




>10 orders of magnitude
LHC now into multi-boson territory!
July 2018
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 35.9 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
di-bosons
tri-bosons
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→WW
EW qqWγ
EW ssWW
EW qqZγ
EW qqWZ
EW qqZZ
WVγ
Zγγ
Wγγ
EW: W→lν, Z→ll, l=e,μ
All results at: http://cern.ch/go/pNj7

Multi-boson: Production of combinations of W, Z, and γs

Multi-boson Production

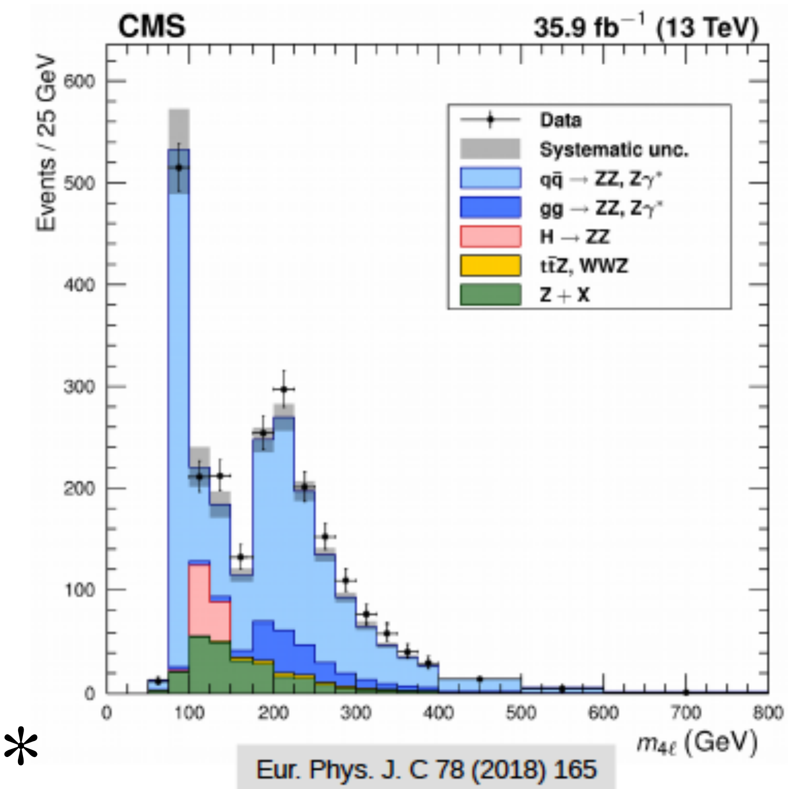
Common signatures:

- High-p_T isolated electrons, muons, γs.
- Missing energy (or p_T) due to neutrinos from $W \to \ell\nu$ or $Z \to \nu\nu$.
- High-p_T jets.

Common backgrounds:

- Real leptons from heavy flavor decays. *
- Mis-identified jets that mimic leptons. *
- Poorly reconstructed missing E_T. *
- Other bosons.

* use sidebands for data-driven backgrounds



ZZ→4ℓ production at CMS

Physics with Multi-bosons

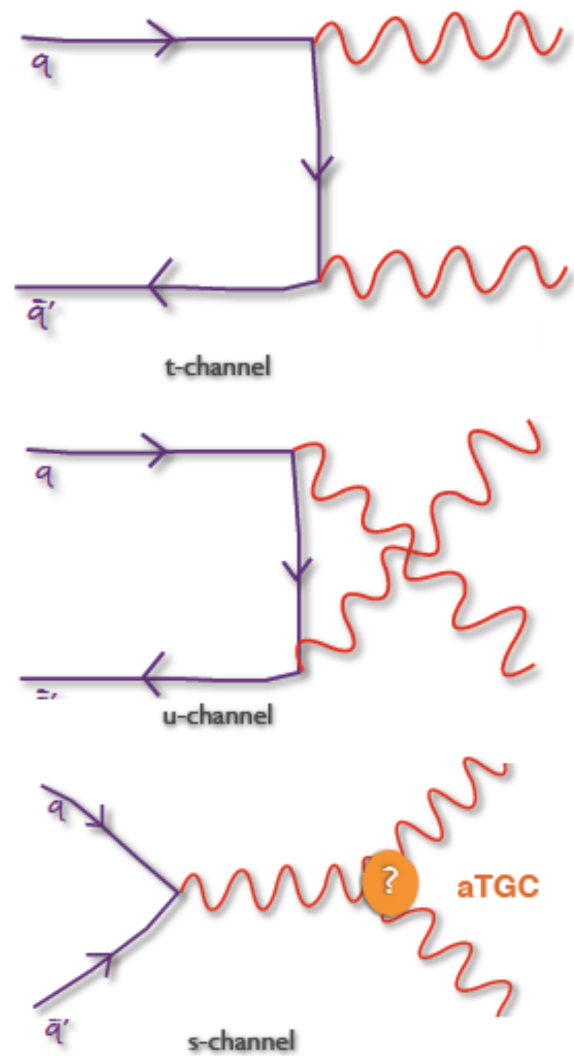
Why the interest in multi-bosons?

Direct tests of EWK SM at TeV scale

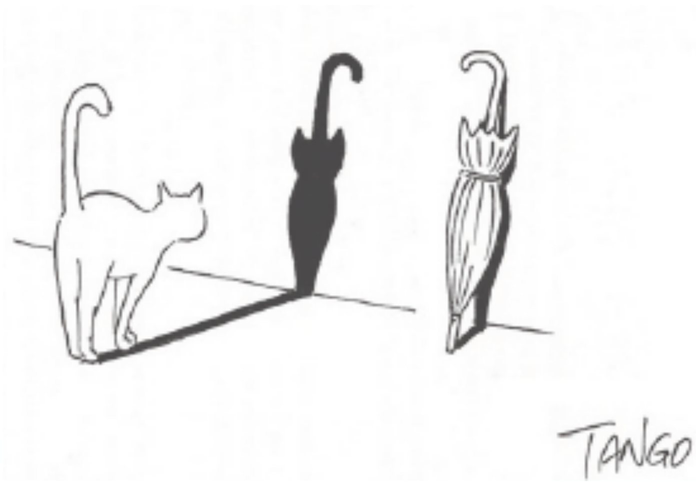
- Fiducial, total, and differential cross sections
- Test NLO EWK corrections and NNLO QCD calculations
- Irreducible backgrounds to Higgs and beyond-Standard-Model (BSM) searches

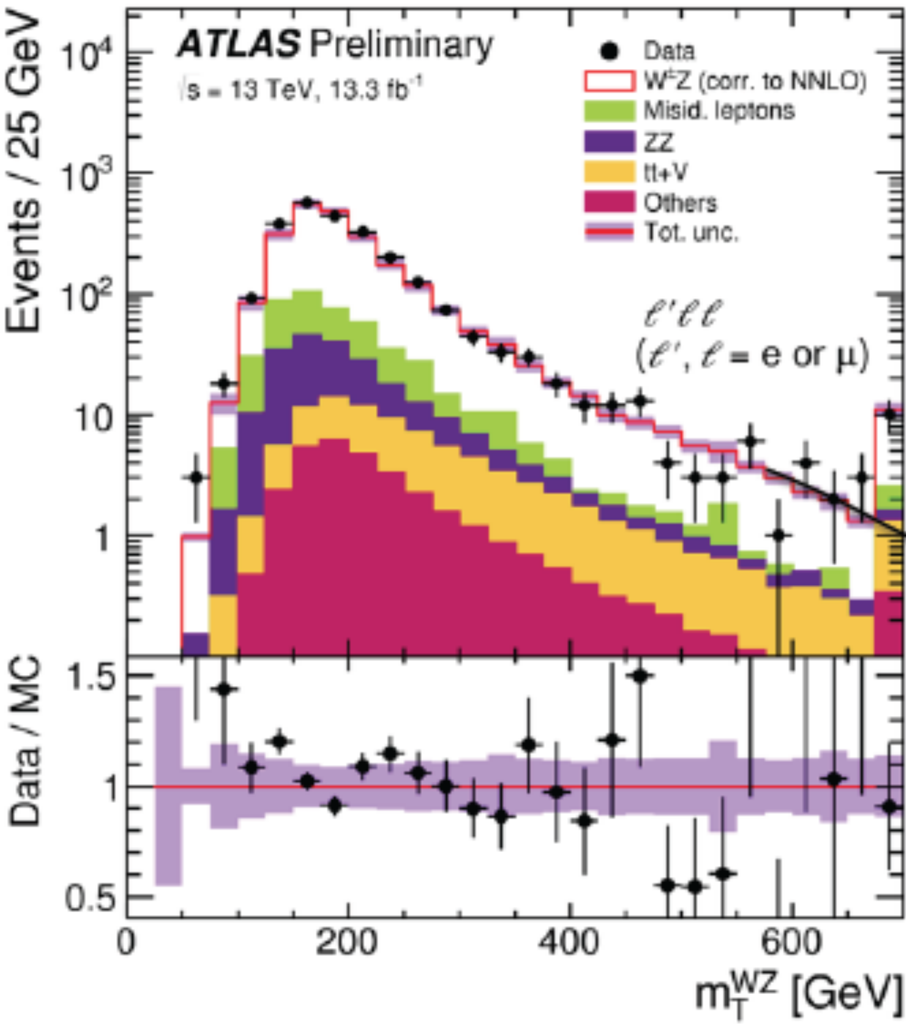
Sensitive to new EWK physics

- Look for anomalous triple gauge couplings (aTGCs) and quartic gauge couplings (aQGCs)

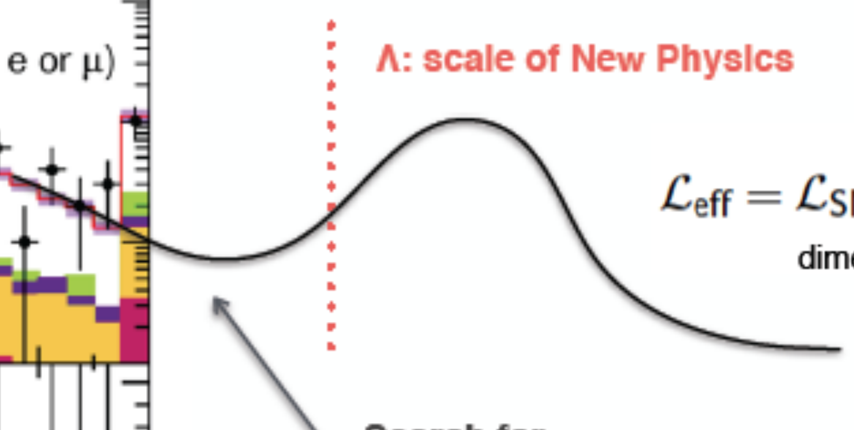


Anomalous Gauge Couplings





Breaking the SM leads to a theory with an effective range of validity



Λ: scale of New Physics

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

dimension d

Search for deviations in tails, modified cross sections

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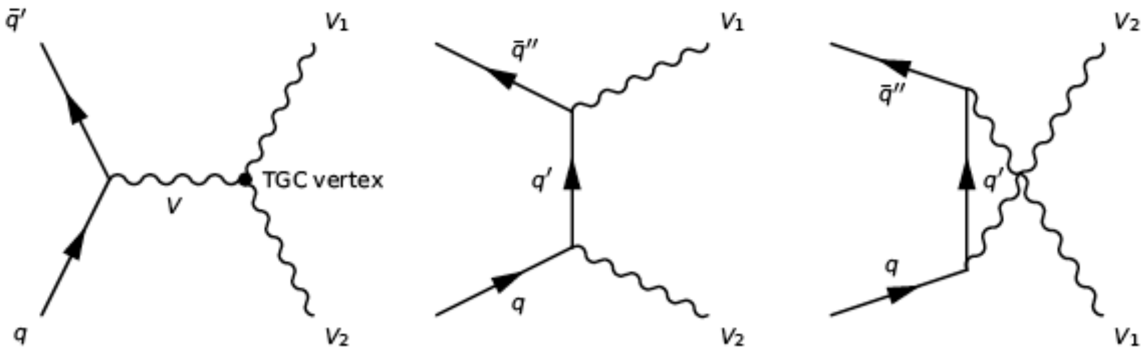
aTGCs: Precision test of the SM

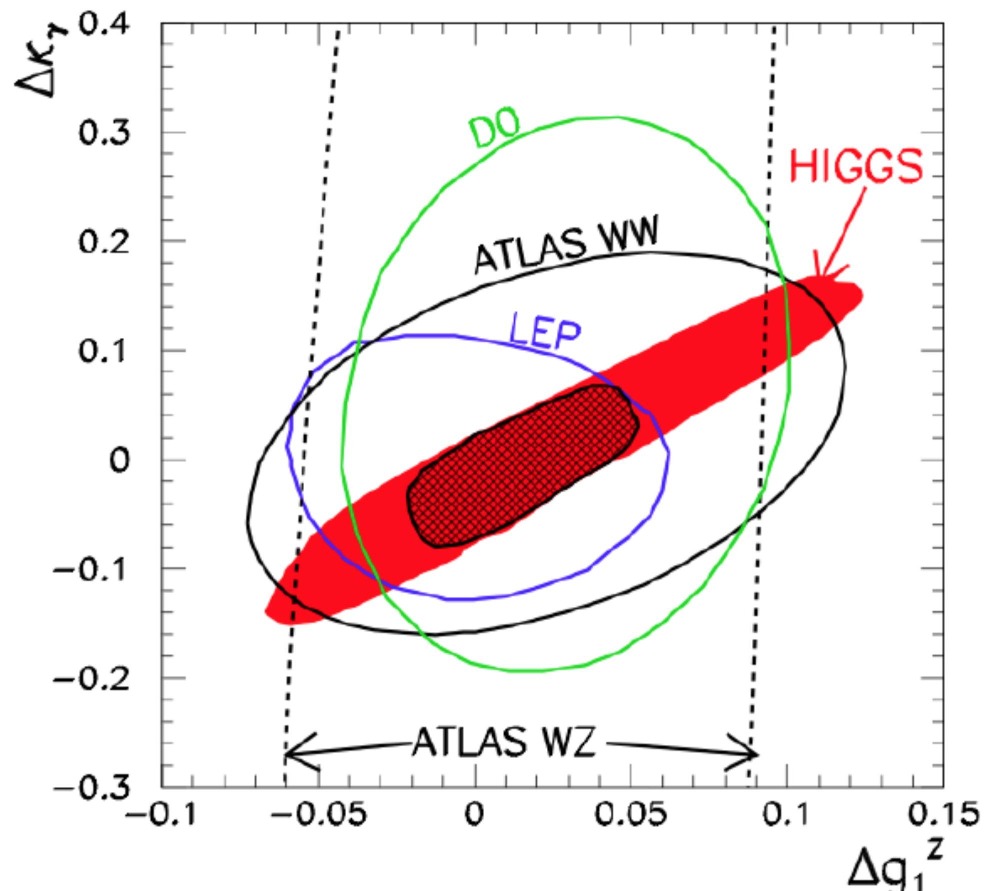
Anomalous Triple Gauge Couplings



Coupling	Parameters	Channels
$WW\gamma$	$\lambda_\gamma, \Delta\kappa_\gamma$	WW
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	WW,WZ
$Z\gamma Z$	f_4^Z, f_5^Z	ZZ
ZZZ	f_4^γ, f_5^γ	ZZ

All "parameters" = zero in SM.

Complementary approach to direct new physics searches, using coupling deviations



Corbett et al
arXiv:1304.1151

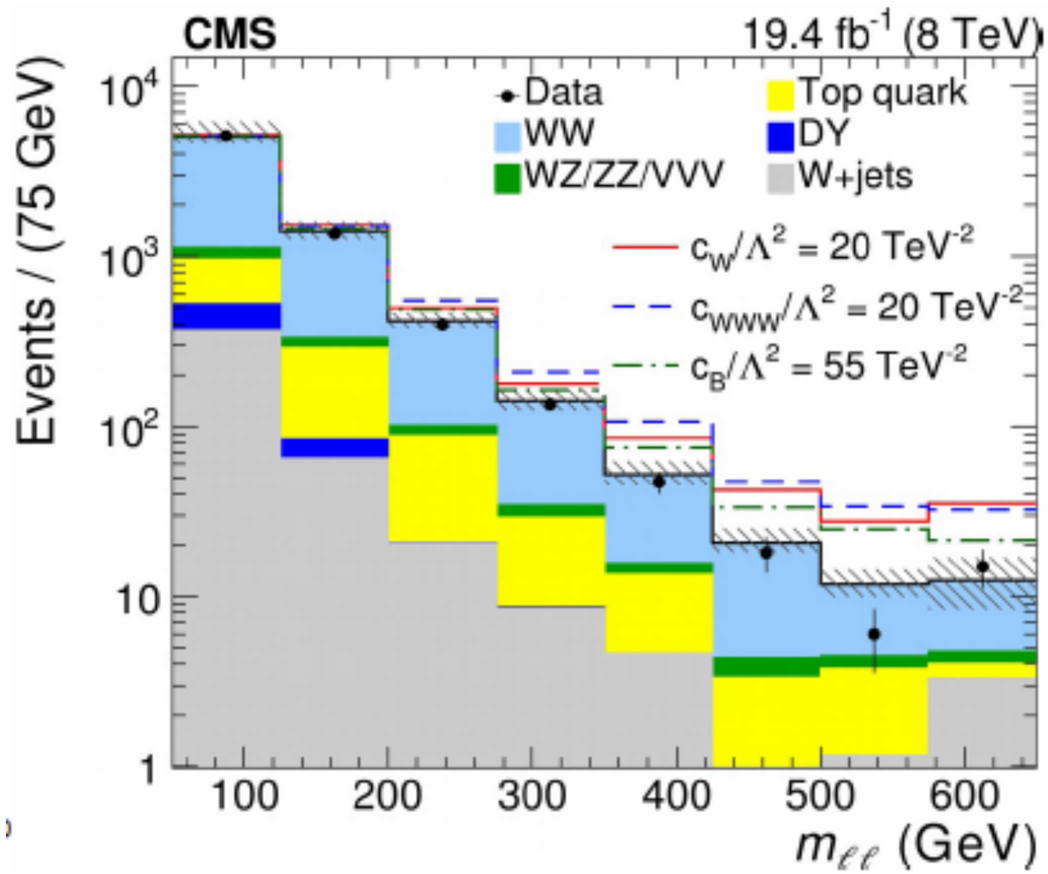
Several possible strategies

- Effective vertex approach used in CMS ZZ analysis [Nucl.Phys.B282(1987)253]
- Effective lagrangian approach → CMS WV analyses [Phys.Rev.D41(1990)2113]
- Effective field theory approach → CMS WW, VBS, triboson [Phys.Rev.D48(1993)2182]

Anomalous Triple Gauge Couplings

Example from CMS

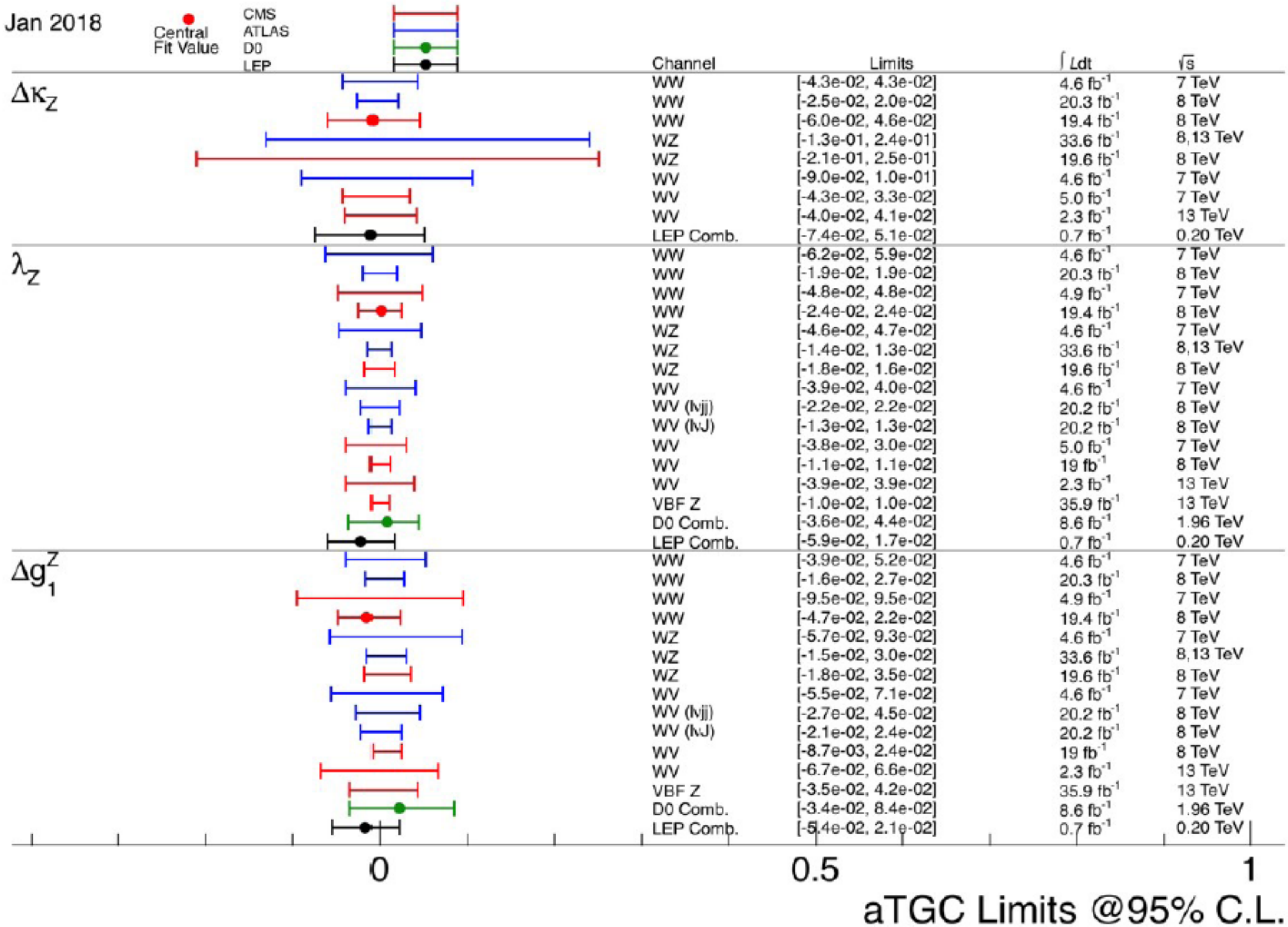
- Look in tails of distns (m_{VV}, $m_{\ell\ell}$, m_{jj}, $p_{T,V}$….)
- Vary 1-2 terms at a time (uncorrelated)



Bellan ICHEP18

Sensitivity is channel-dependent;
slightly better than LEP for charged case

charged aTGC limits



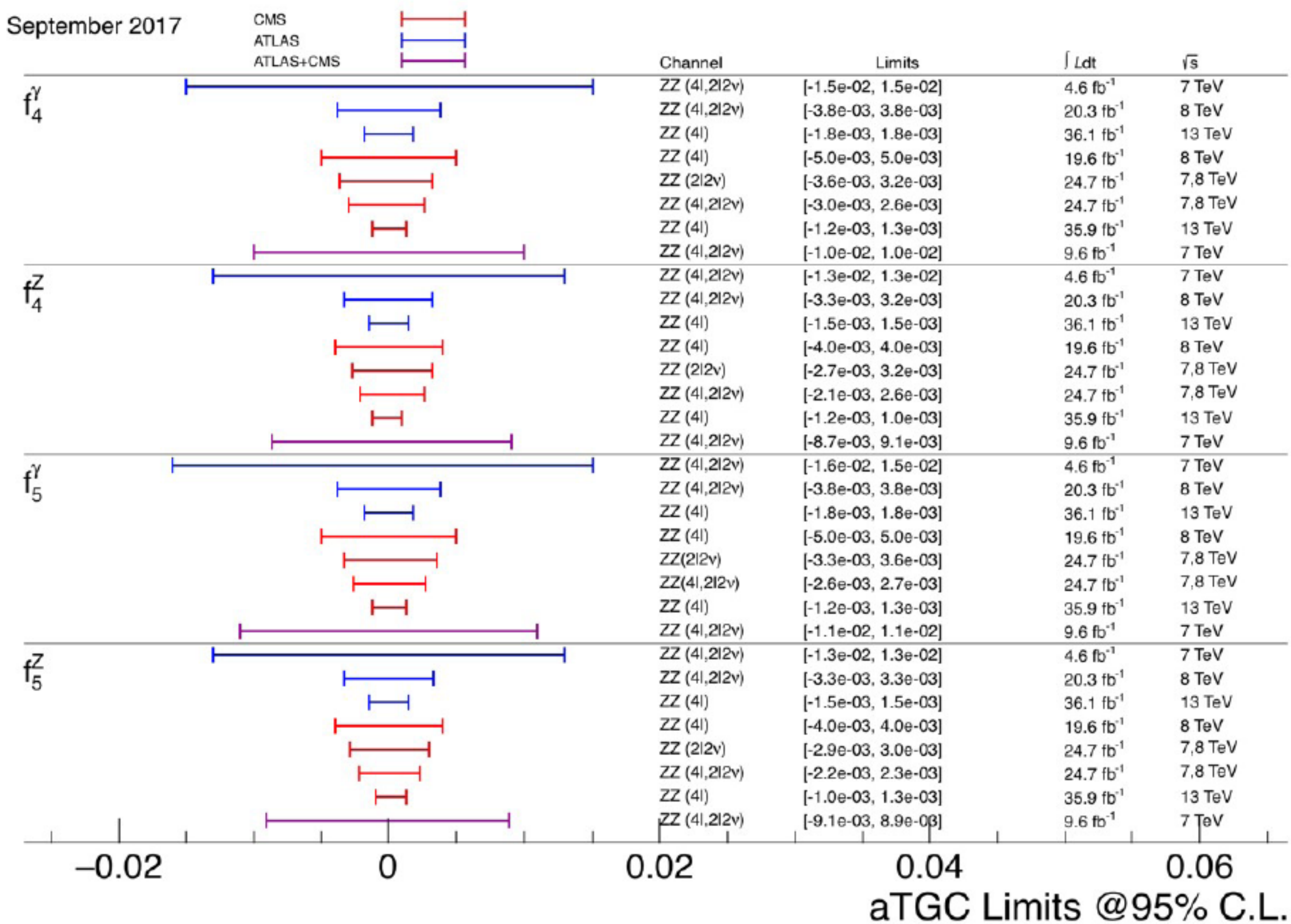
ATLAS 13TeV results

Coupling strength	Expected 95% CL [$\times 10^{-3}$]	Observed 95% CL [$\times 10^{-3}$]
f_4^γ	−2.4, 2.4	−1.8, 1.8
f_4^Z	−2.1, 2.1	−1.5, 1.5
f_5^γ	−2.4, 2.4	−1.8, 1.8
f_5^Z	−2.0, 2.0	−1.5, 1.5

new!

neutral aTGC limits

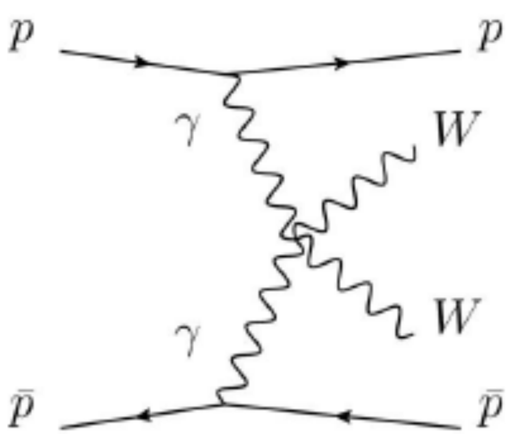
LHC limits much stronger than LEP for neutral case

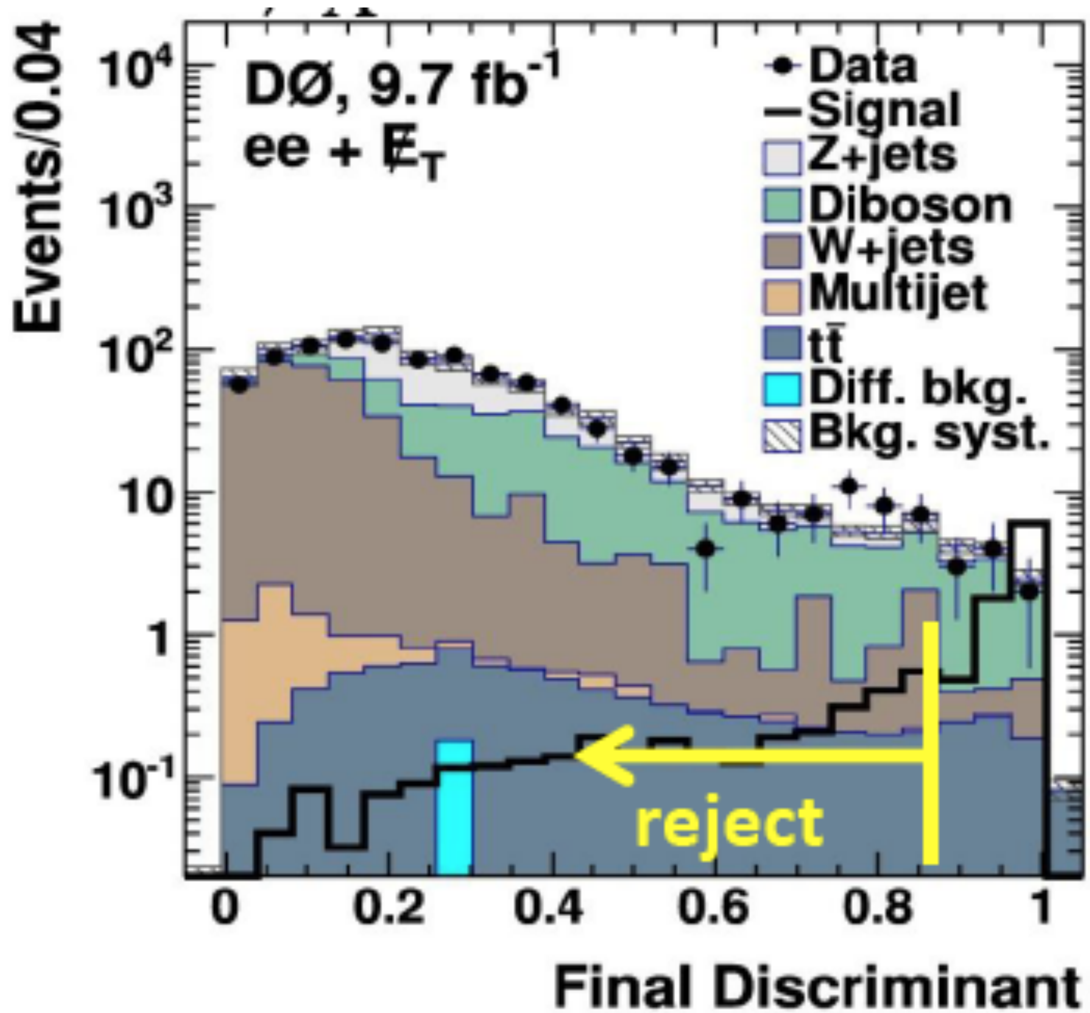


BSM models (eg- extra dimensions):
10-100x cross section enhancement

Anomalous Quartic Gauge Couplings

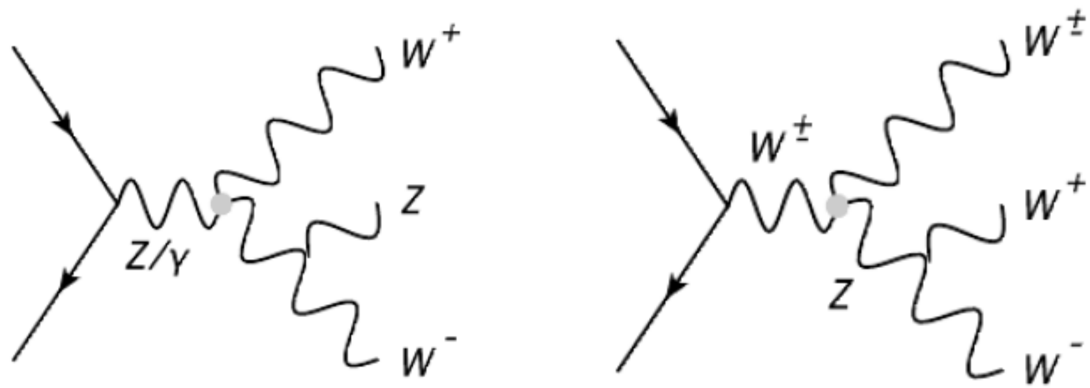
photon-initiated





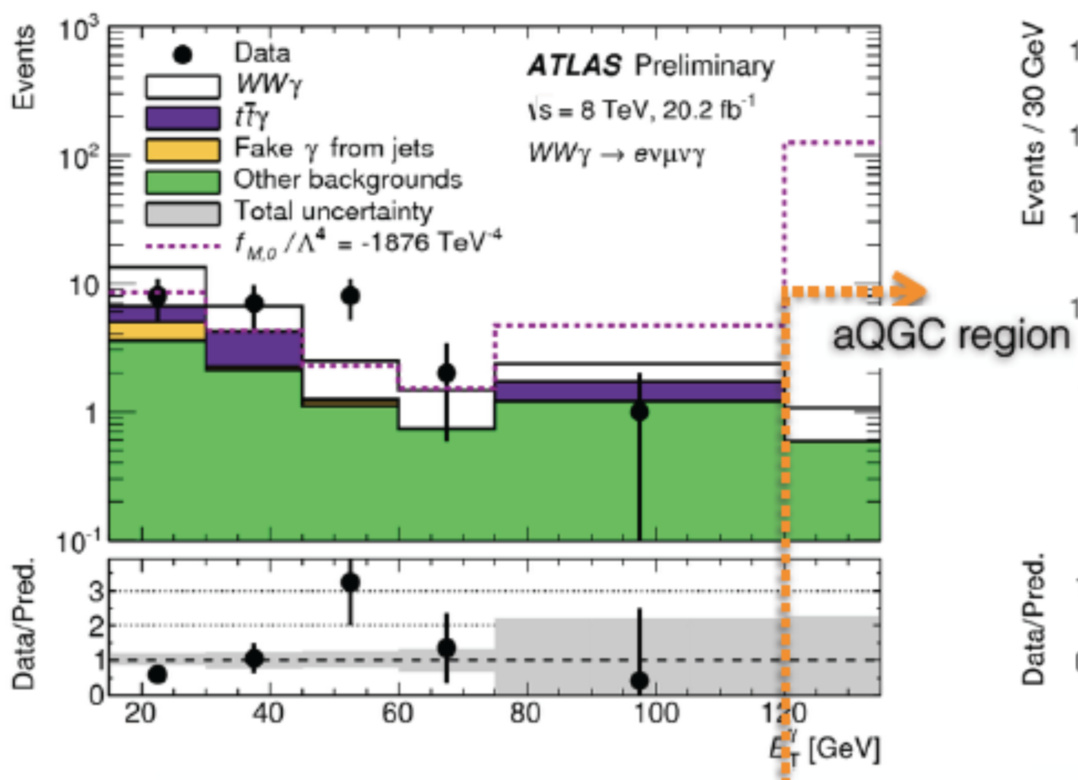
Limits first set by Tevatron on anomalous terms in Lagrangian.

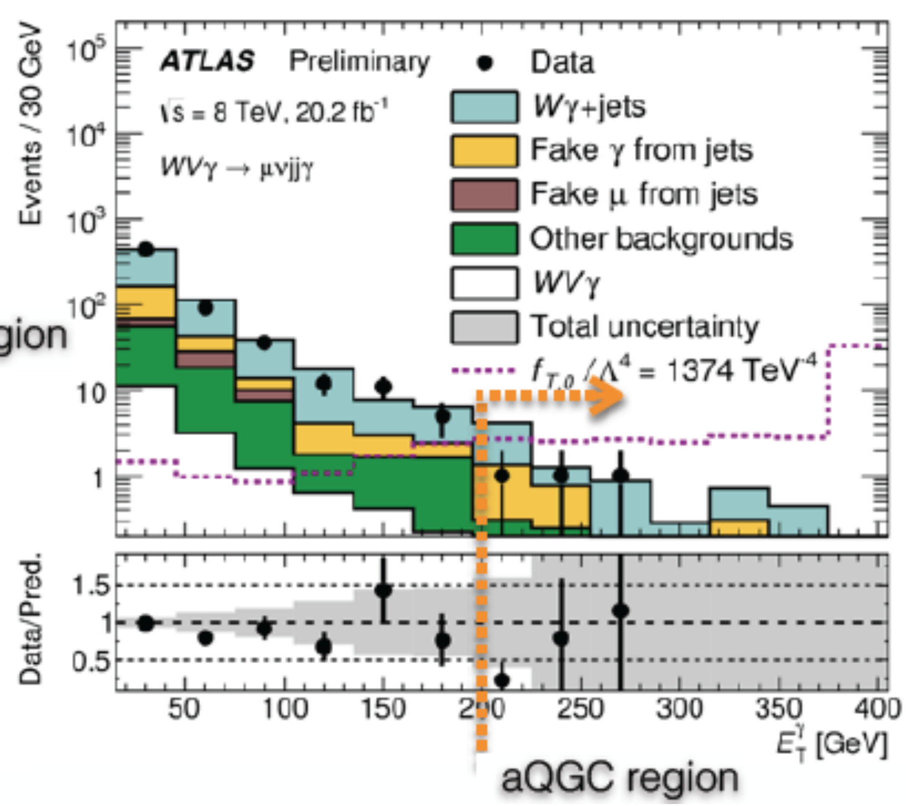
aQGCs at the LHC



Constraints are obtained using dibosons and tribosons

aQGC fits use a more restrictive phase space: higher S/B but low statistics





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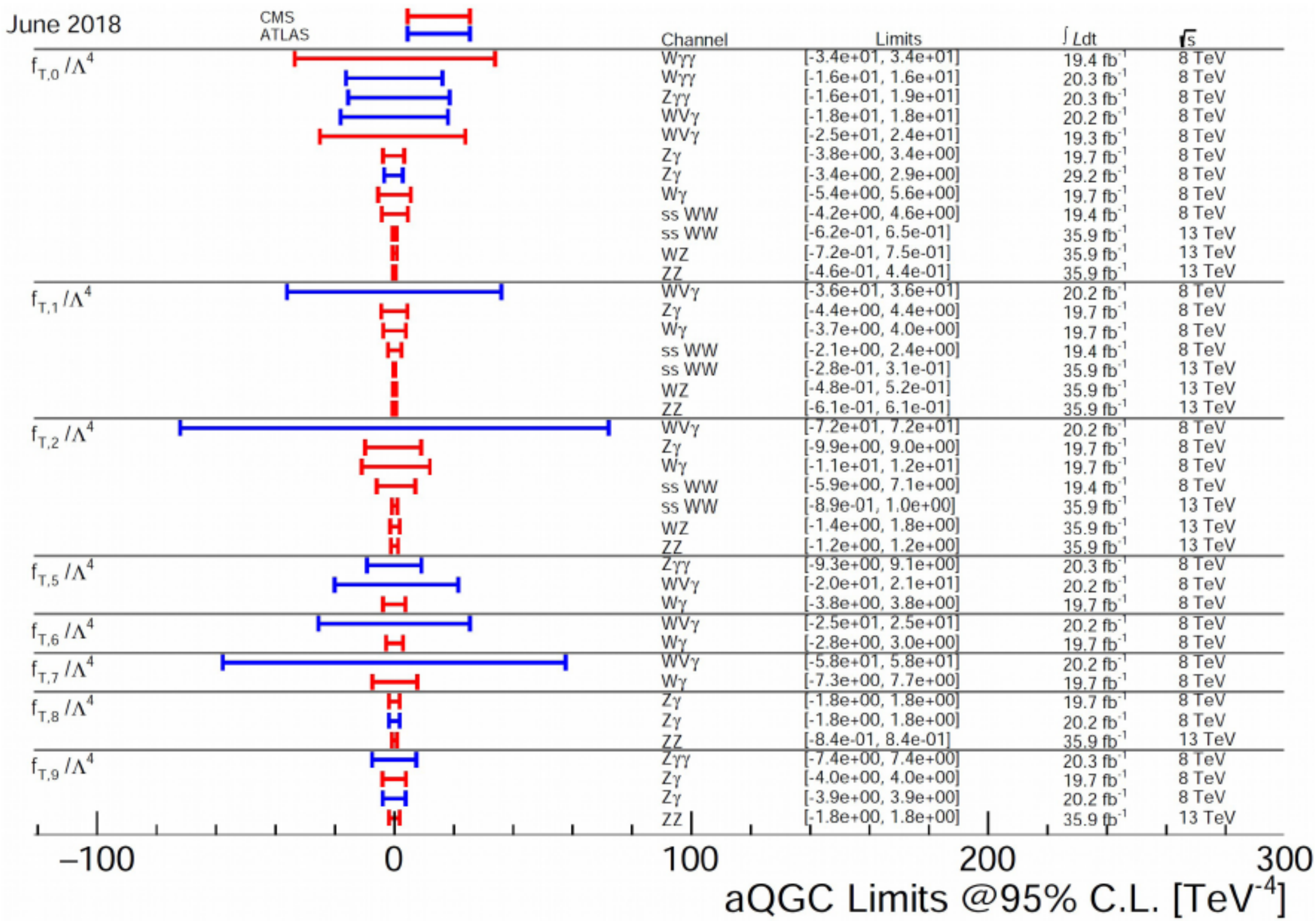
aQGC summary

dim 8 transverse parameters

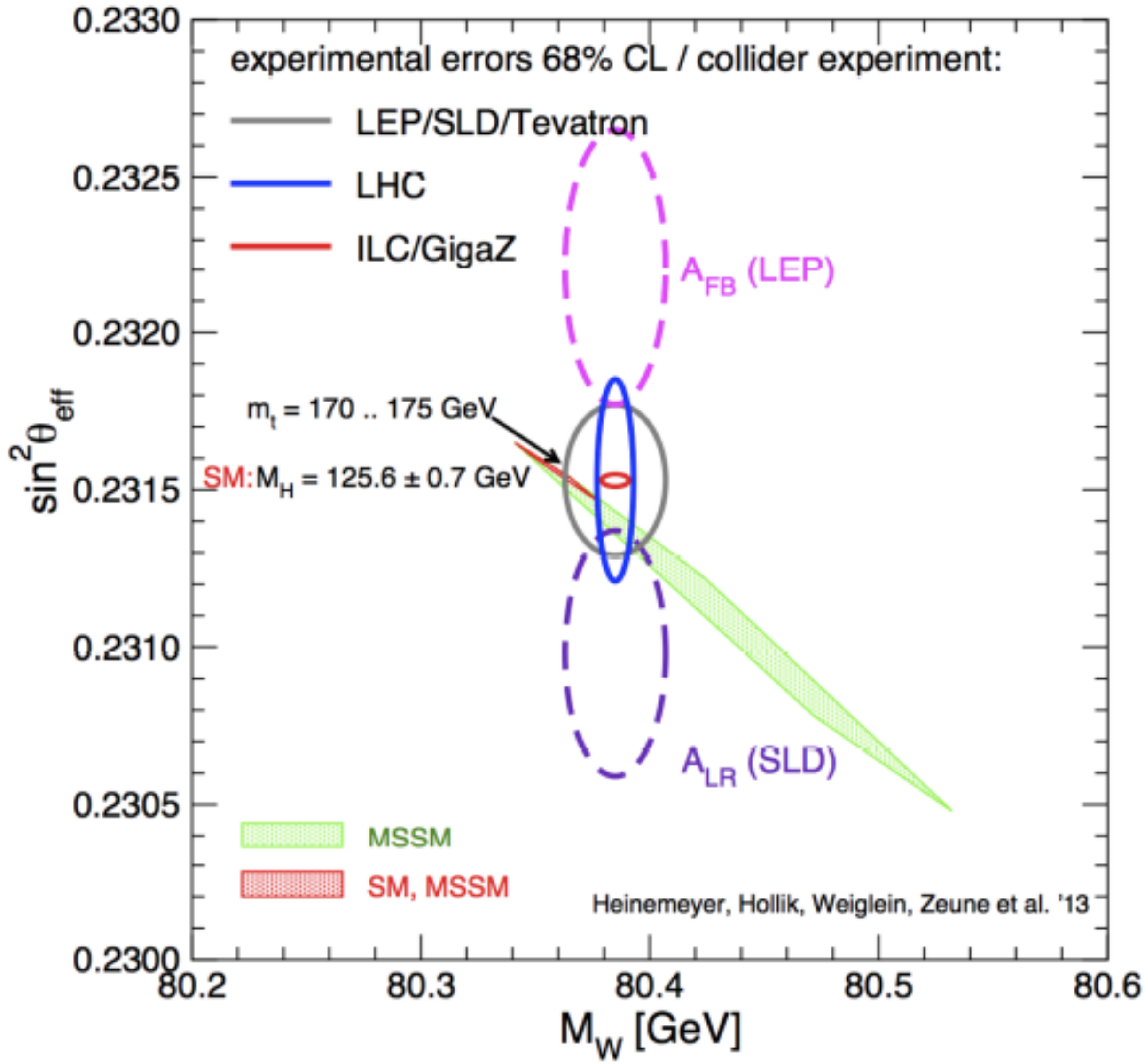
aQGCs at the LHC



Vector Boson Scattering

Hot topic for EWSB, mentioned by P. Jenni

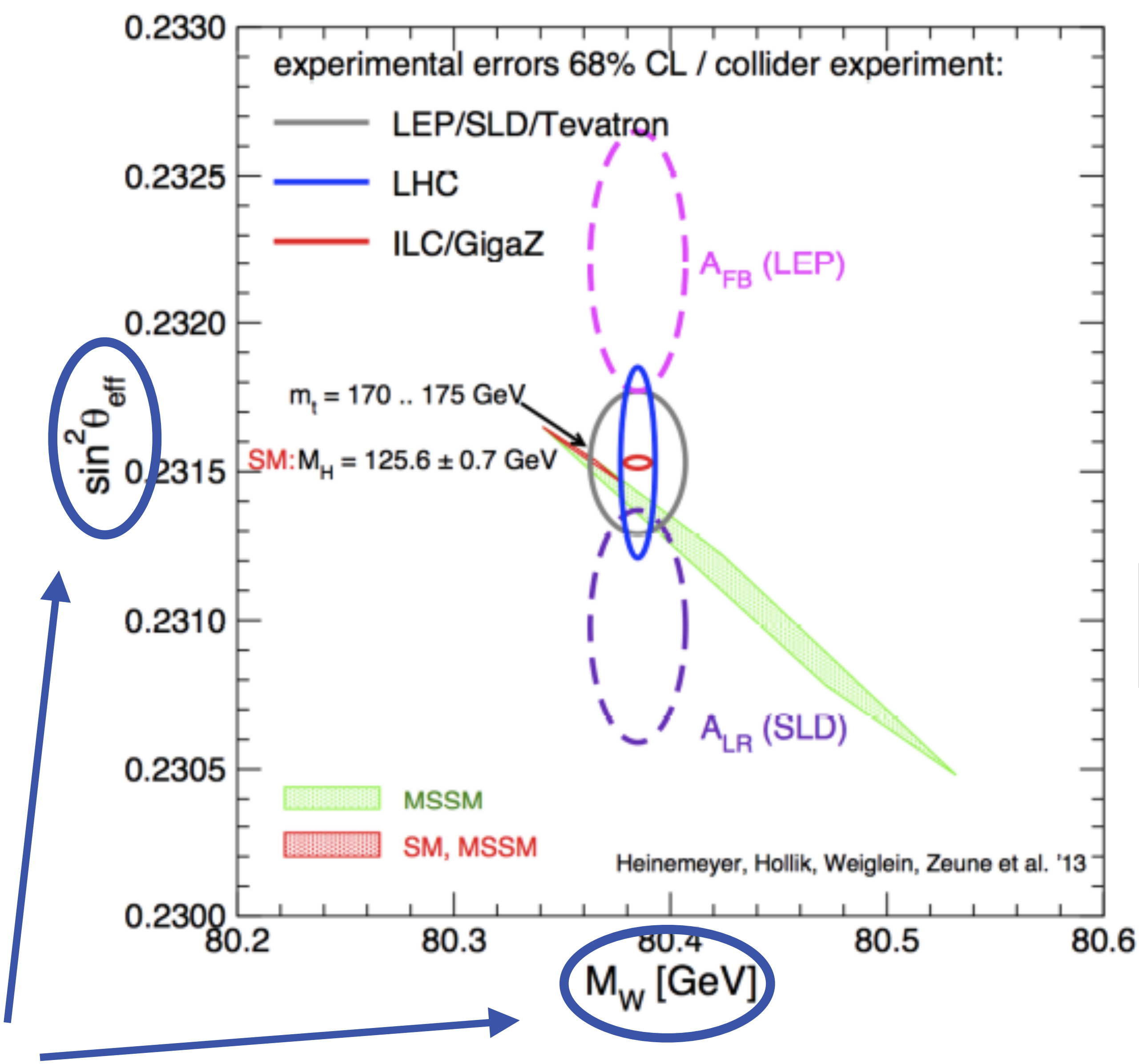
Precision Electroweak Observables



Good discussion in 2013 Snowmass proceedings (Kotwal, Wackeroth, et al.)

See yesterday's lectures by Freitas, Marciano

Precision Electroweak Observables



Good discussion in 2013 Snowmass proceedings (Kotwal, Wackeroth, et al.)

See yesterday's lectures by Freitas, Marciano

Both predicted precisely in SM. BSM predictions, too.

$\sin^2\theta_{eff}$

See yesterday's lectures by Freitas, Marciano

- Important EWK observable

$$\sin^2\theta_W \approx 1 - M_W^2 / M_Z^2$$

- Radiative corrections → Measure the "effective" angle

$$\sin^2\theta_{eff}^{lept} = \mathrm{Re}[k_l(m_Z^2, \sin^2\theta_W)]\sin^2\theta_W$$

- Indirect measure of W mass:

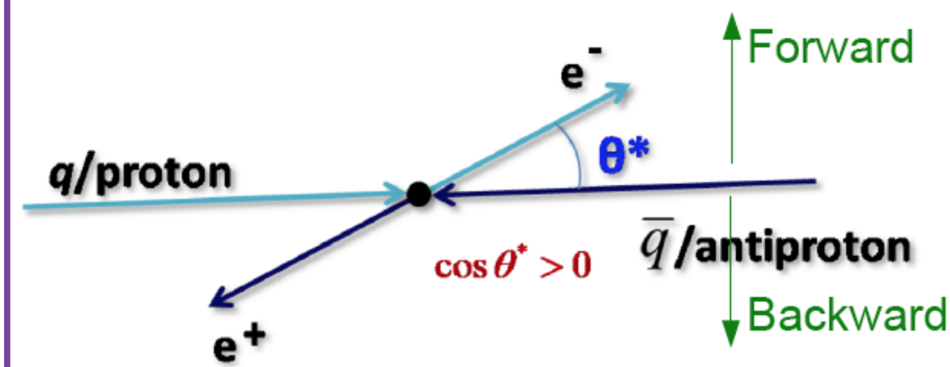
$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{1-\Delta r}$$

V-A nature of EWK interaction:

$$g_v^f = I_3^f - 2Q_f \sin^2\theta_W$$

$$g_a^f = I_3^f$$

$$q\bar{q} \rightarrow Z/\gamma^* \rightarrow e^+e^-$$

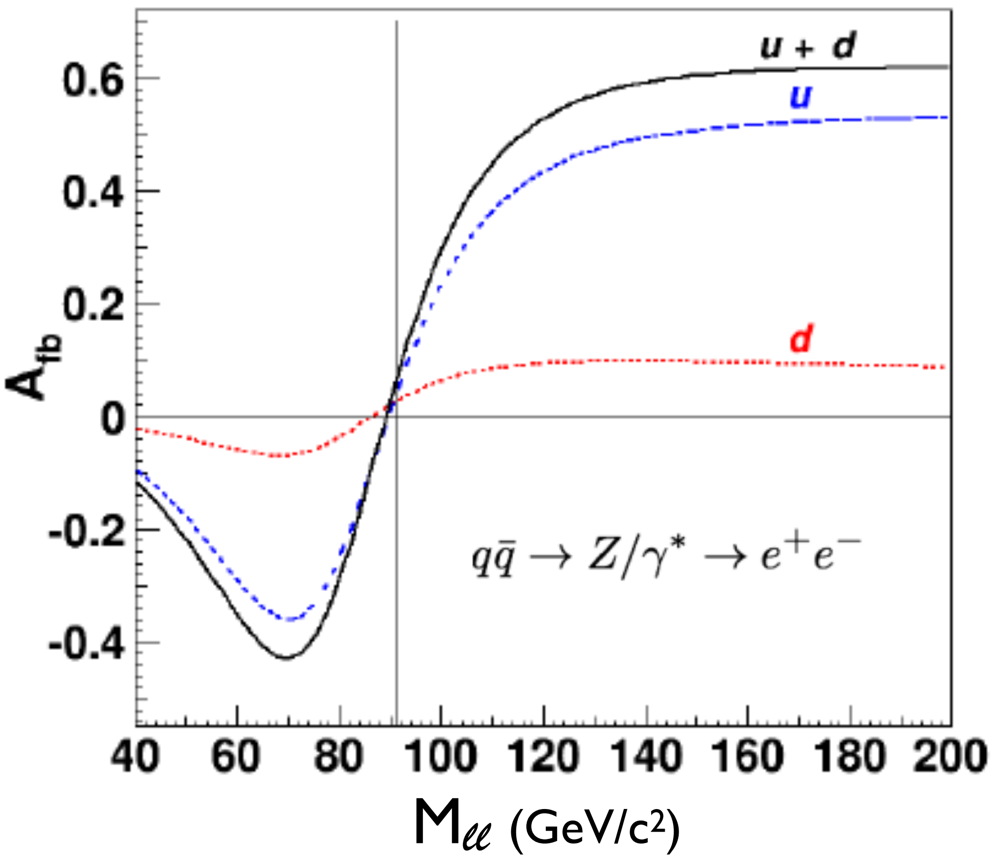


"forward-backward asymmetry"

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$\sin^2\theta_{eff}$

- LEP/SLD best measurement.
- Tevatron still more precise than LHC: better p-p_{bar} PDF uncertainty. (Just published!)



Measure at the Z pole so Z/γ interference minimal

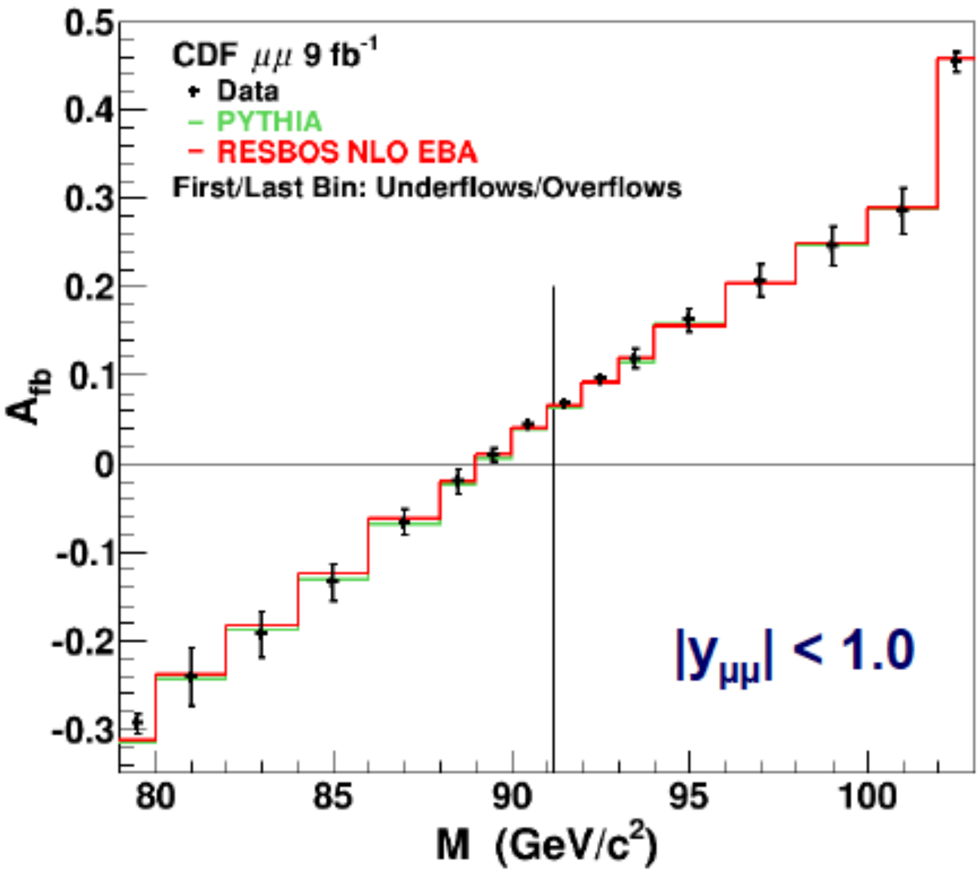
Tevatron

Measurement recipe:

- Measure A_{fb} in bins of lepton pair invariant mass
- Compare to MC templates of $A_{fb}(M_W, \sin^2\theta_W)$
- Corrections to data/simulation
- Extract $\sin^2\theta_{eff}$ by χ^2 comparison

$\sin^2\theta_{eff}$

CDF ee, μμ



CDF: PRD 89, 072005 (2014)
PRD 93 112016 (2016)

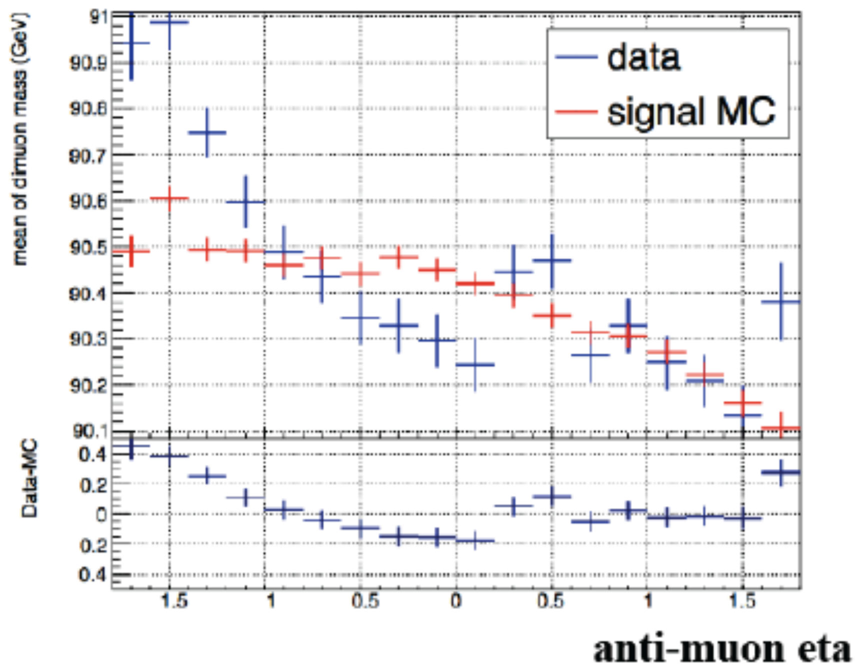
- Asymmetry measurements corrected for direct fits to calculations: "angular weighted event sums method"
- Matrix unfolding of detector effects and QED FSR smearing: residual bias ~few %
- Templates: POWHEG-BOX(NLO), NNPDF 3.0(NNLO) PDFs, Pythia 6.4
- Higher order QCD effect corrections to gen events; EWK radiative corrections needed.

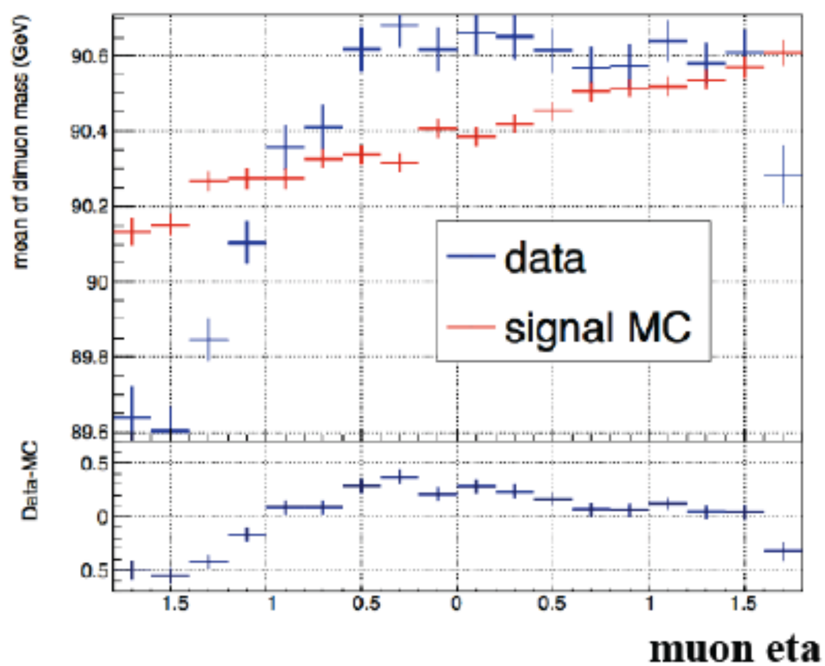
$\sin^2\theta_{eff}$

D0 ee, μμ

- Simulation/Templates: Pythia 6.323 (CTEQ6L1), ALPGEN; NNPDF (2.3,3.0) w/ NLO PDFs

before calibration:





- Main challenge in D0 μμ: A_{FB} v. $M_{\mu\mu}$ sensitive to p_μ charge-dep.
- Solution: charge eta solenoid polarity dependent calibration
  - data/MC calibrated at gen level separately: $P_{corr} = \alpha(q,\eta,S) \cdot P_{obs}$
  - req. consistent mean M_z in each charge-eta-solenoid category

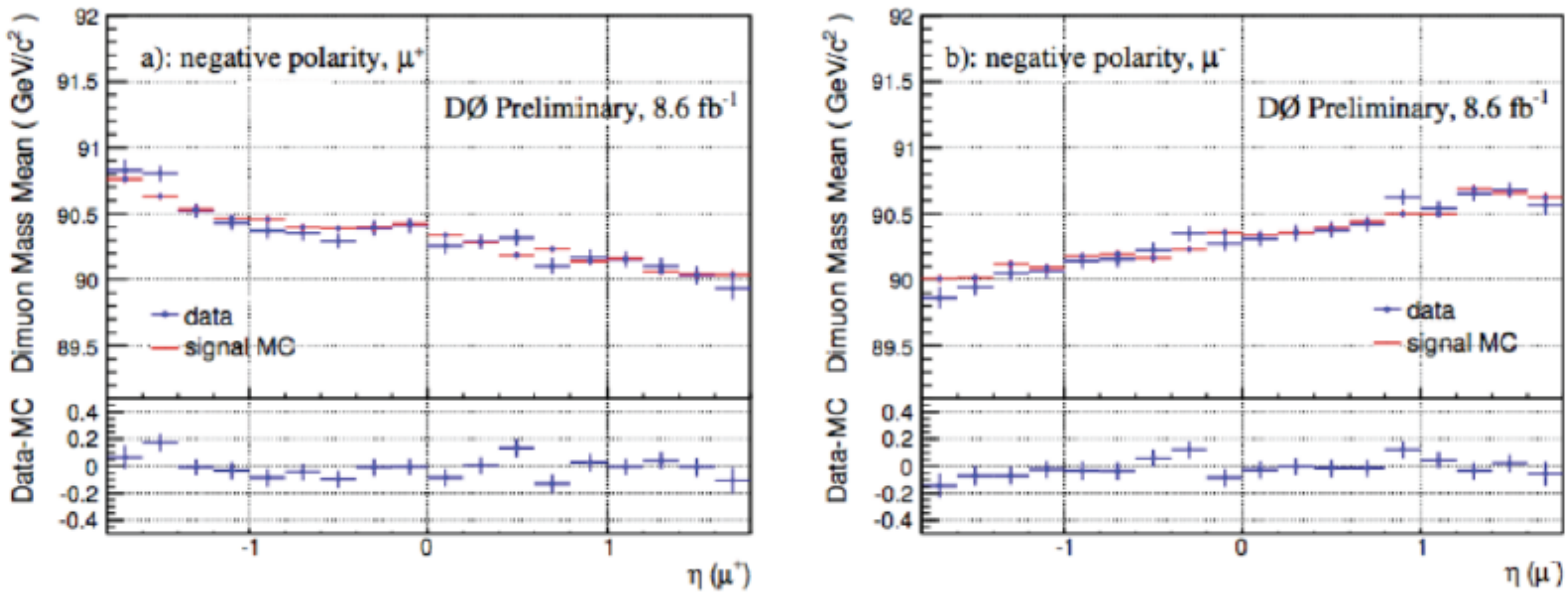
Quinn Blois2018

$\sin^2\theta_{eff}$

after calibration:

D0 ee, μμ

- Simulation/Templates: Pythia 6.323 (CTEQ6L1), ALPGEN; NNPDF (2.3,3.0) w/ NLO PDFs



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Quinn Blois2018

$\sin^2\theta_{eff}$

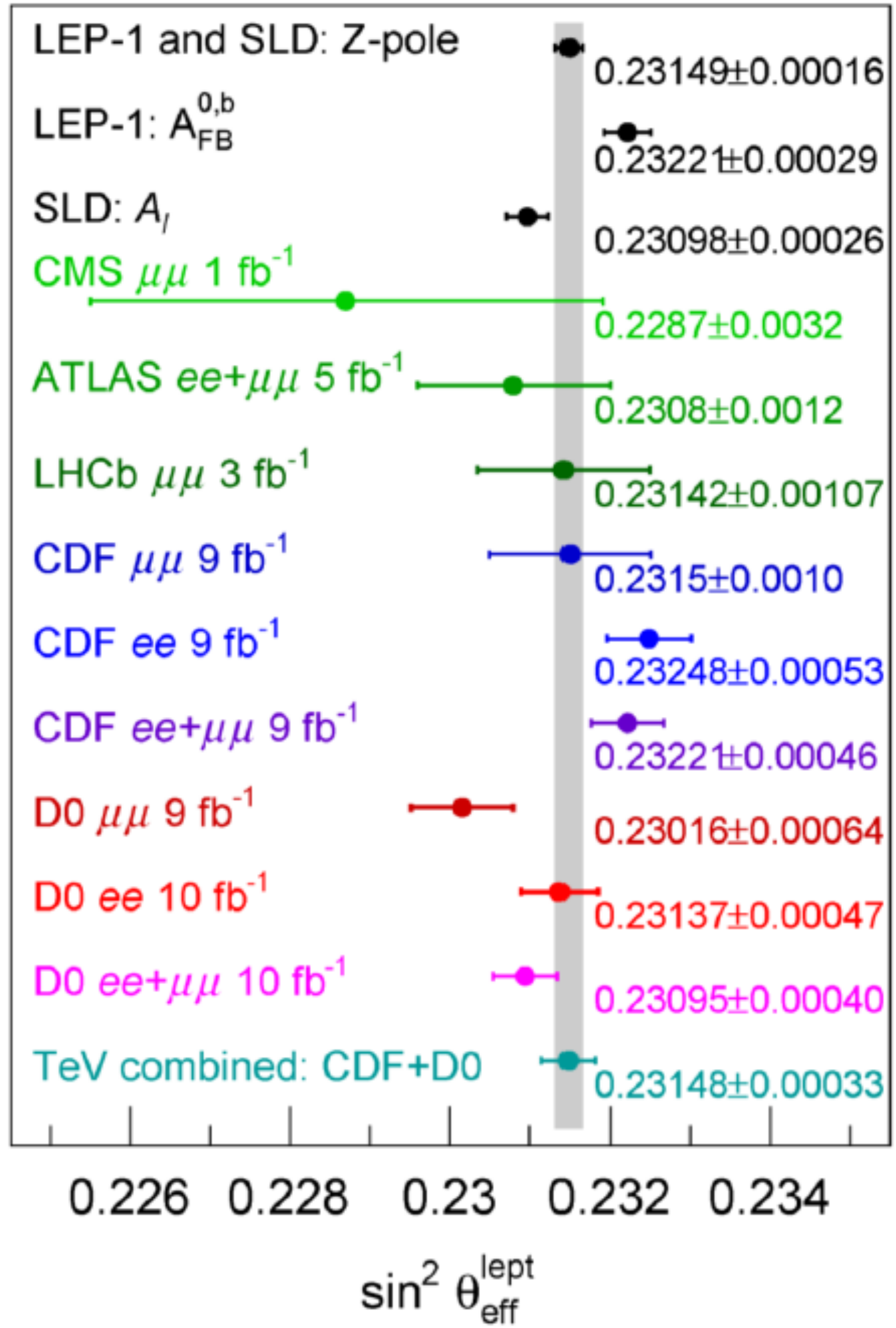
Tevatron combination just published:

$$\sin^2\theta^l_{eff} = 0.23148 \pm 0.00027\,(\text{stat}) \pm 0.00005\,(\text{syst}) \pm 0.00018\,(\text{PDF})$$

- Weight CDF/D0 0.42/0.58
- χ^2 probability 2.6%

Phys. Rev. D97, 112007

New LHC ATLAS result, but not quite as sensitive yet.



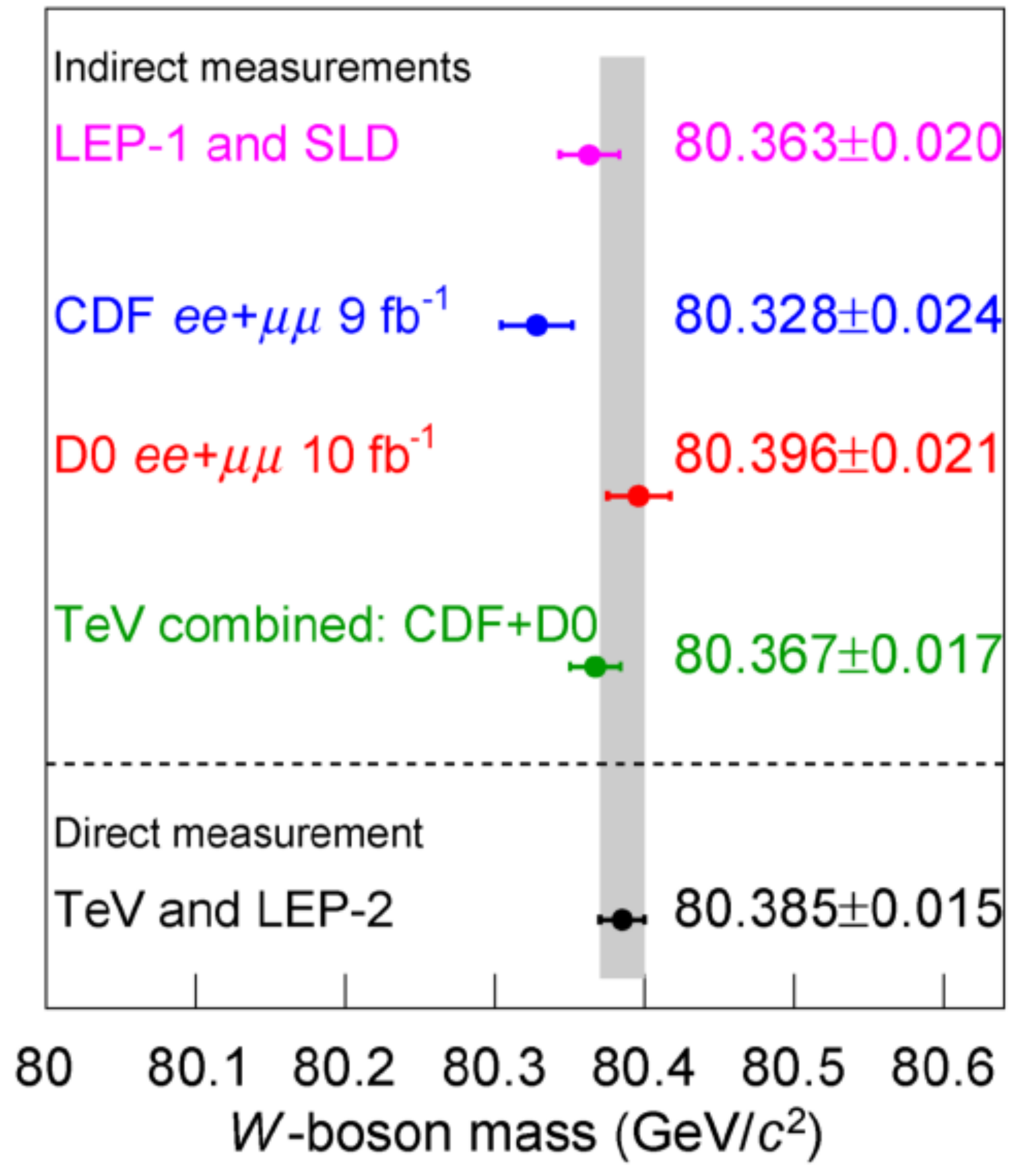
read these plots carefully: correlated points!

$\sin^2\theta_{eff}$: W mass

Can extract W mass

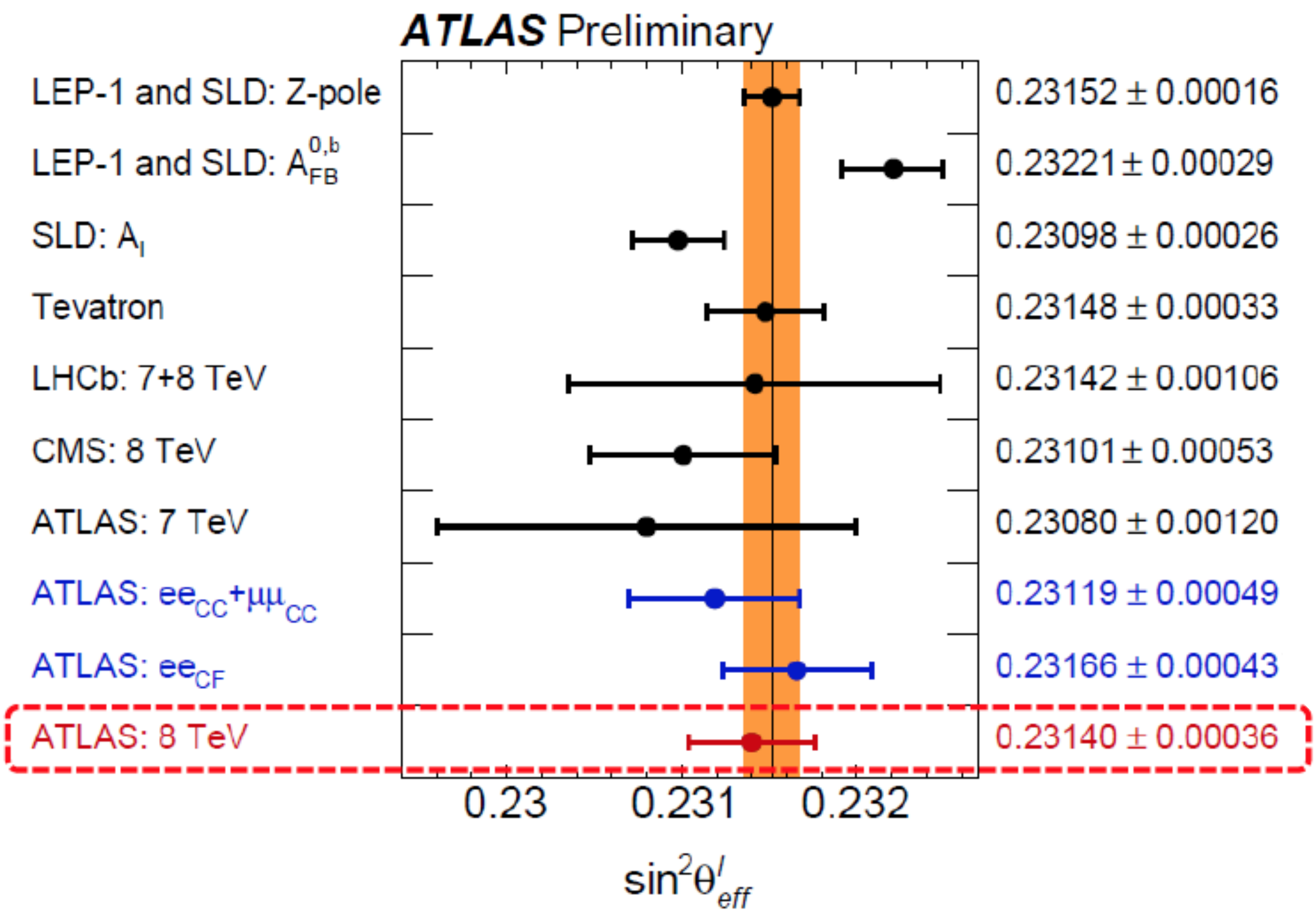
Tevatron combination:

$$M_W = 80.367 \pm 0.014\ (\text{stat}) \pm 0.010\ (\text{syst})\ \text{GeV}/c^2$$



$\sin^2\theta_{eff}$

New ATLAS Result at 8 TeV approaching Tevatron sensitivity



Test compatibility in 20 rapidity bins/channels: $9ee_{cc}+9\mu\mu_{cc}+2ee_{cf}$ and with varying PDF sets.

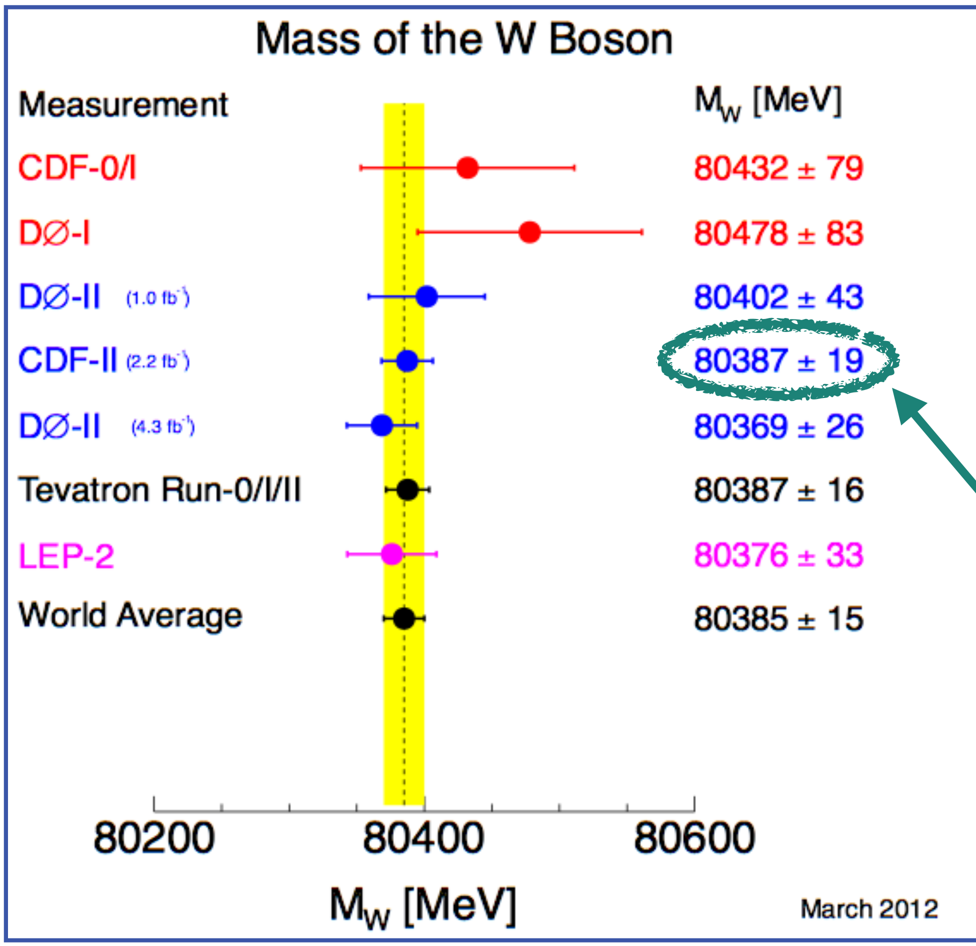
ATLAS-CONF-2018-037

W boson mass

The mass of the W boson M_W provides a precise test of the SM.

See lecture by Freitas

$$M_W^2 = \pi\alpha_{EM} / \sqrt{2}G_F \sin^2\vartheta_W$$



Precision measurements at LEP (e+e-), but statistics limited.

Tevatron: pioneered precision W mass at hadron colliders. Abundant production, but complicated systematics.

Until last year, most precise hadron collider measurement was from CDF (2012).

W Mass Measurement Strategy

Measurement requires control of different issues:

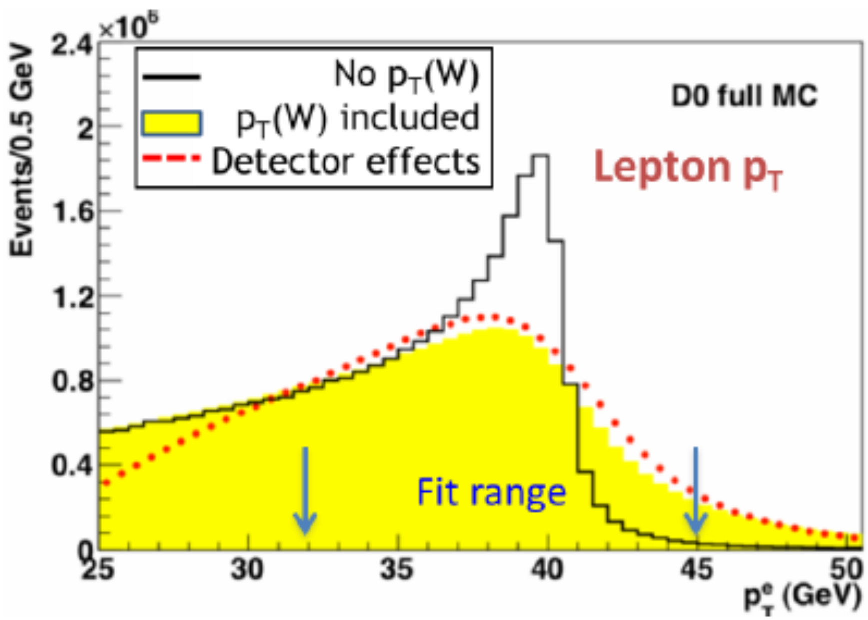
- Experimental: lepton momentum scale, hadronic recoil resolution
- Theoretical: PDF, QCD (boson p_T, polarization), QED (FSR)

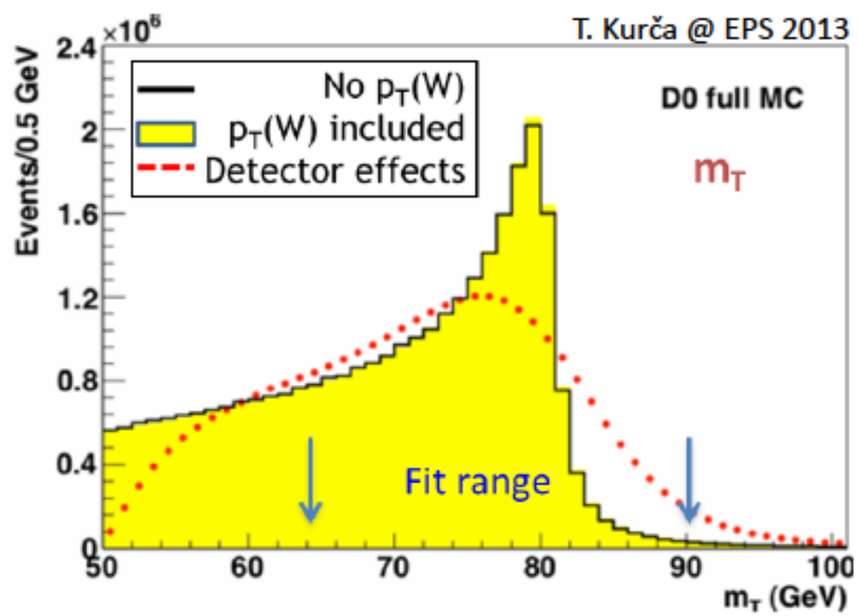
<u>Template analysis</u>: Compare data/MC using one of the observables

$\vec{p}_T^{\,l}$ - most affected by p_T^W uncertainties

$\vec{p}_T^{\,\mathrm{miss}}$ - most affected by detector resolution issues

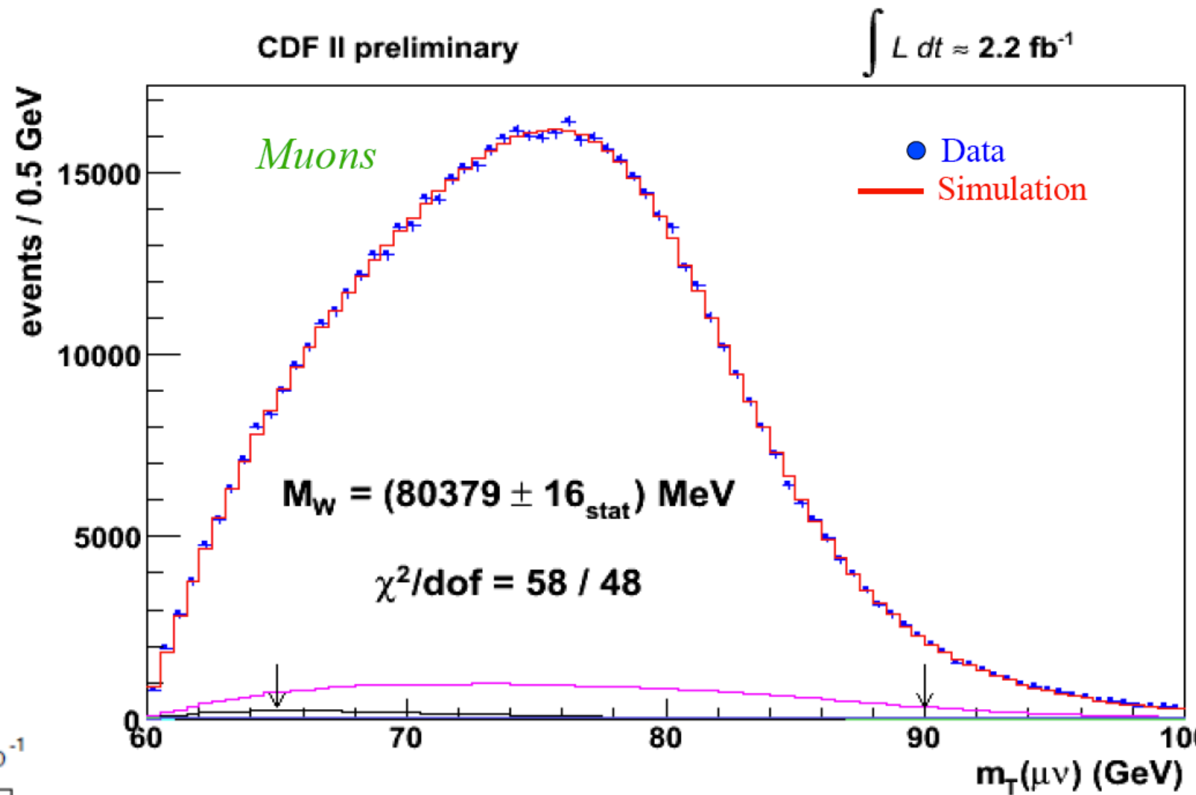
m_T - compromise between TH and EXP errors (*arXiv:1106.0396*)

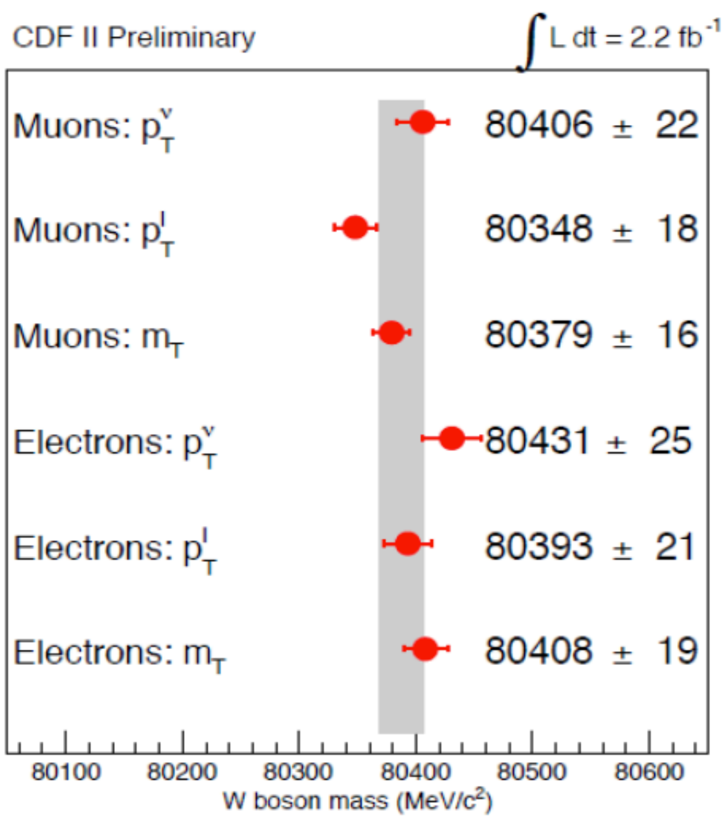




Perrozzi ICHEP16

W boson mass





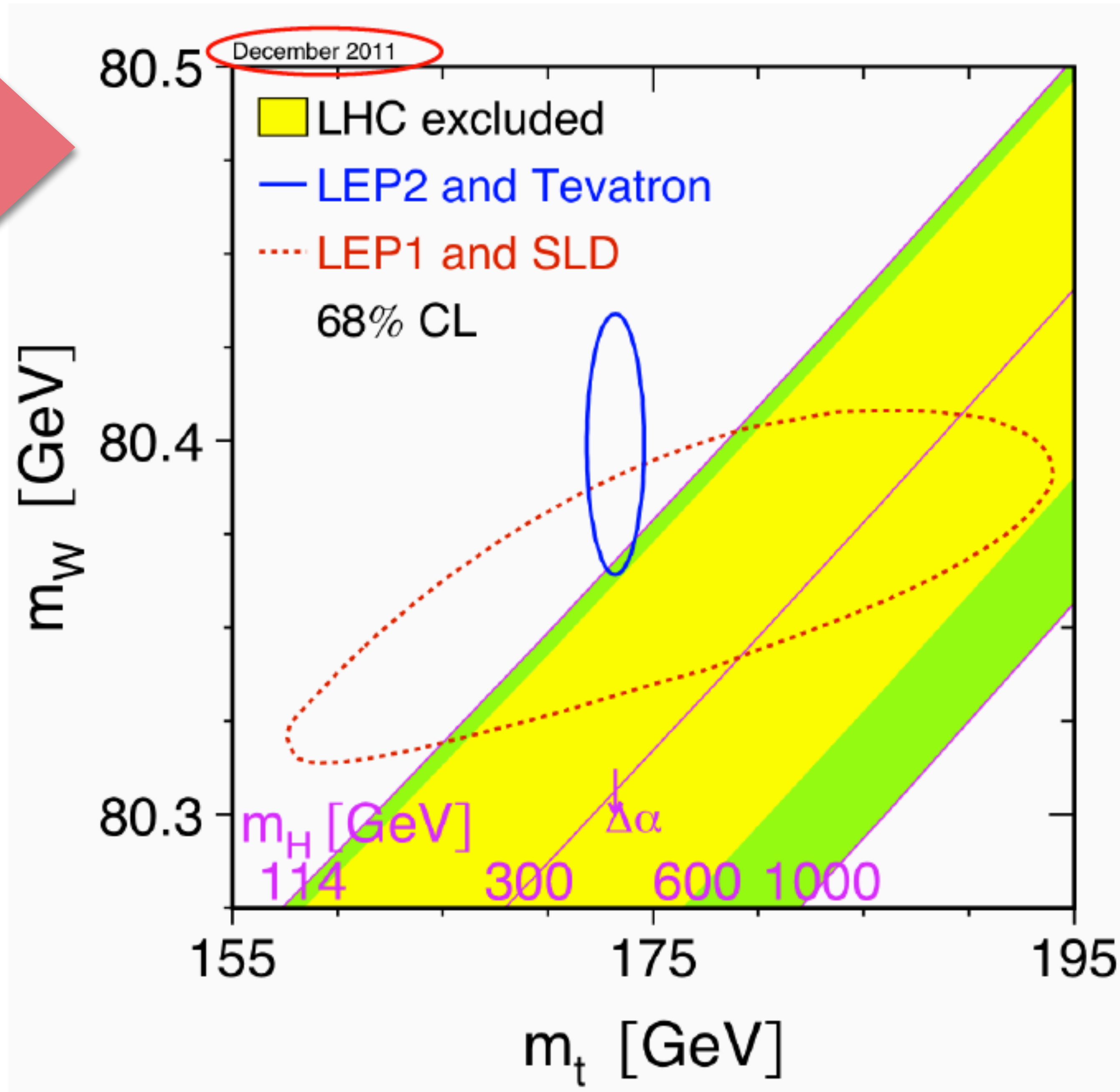
CDF measurement:

Used three observables from muons & electrons:

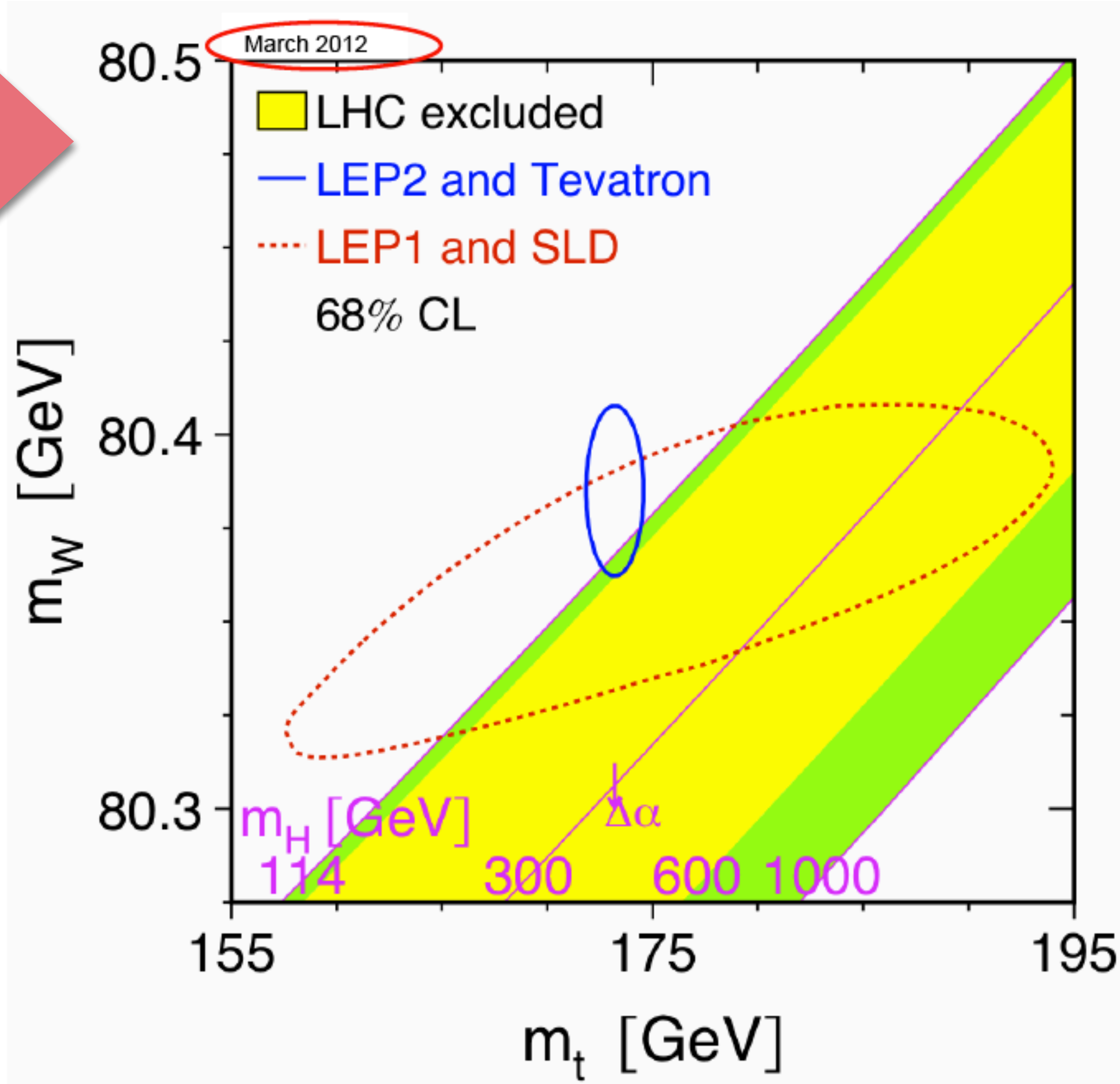
lepton p_T, neutrino p_T (p_T^{miss}), and transverse mass m_T

All combined (6 fits):
M_W=80387 ± 19 MeV **$P(\chi^2)$=25%**

W boson mass


December 2011
LHC excluded
LEP2 and Tevatron
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
600
1000
Δα
155
175
195
m_t [GeV]

W boson mass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m_H [GeV]
114
300
600
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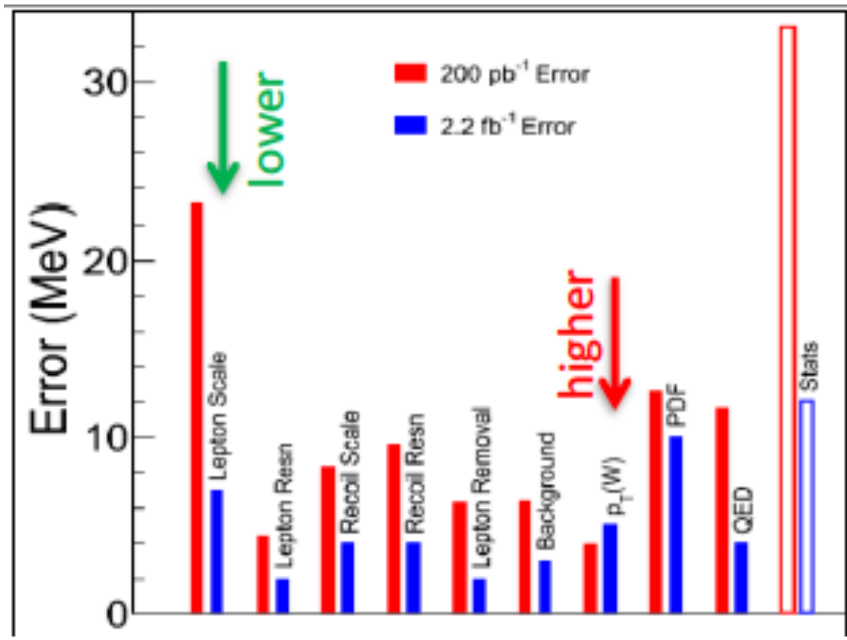
155
175
195
m_t [GeV]

Tevatron Uncertainties

Experimental (decrease w/ stats) v. Theoretical (don't)

Source	CDF	Uncertainty
Lepton energy scale and resolution		7
Recoil energy scale and resolution		6
Lepton tower removal		2
Backgrounds		3
PDFs		10
$p_T(W)$ model		5
Photon radiation		4
Statistical		12
Total	combination	19



Source (D0)	Public. 2009 (1.0 fb^{-1})		Public. 2012 (4.3 fb^{-1})
Statistical	23		13
Experimental syst.			
Electron energy scale	34	→	16
Electron energy resolution	2	lower	2
EM shower model	4		4
Electron energy loss	4		4
Hadronic recoil	6		5
Electron ID efficiency	5		1
Backgrounds	2		2
Subtotal experimental syst.	35		18
***W* production and decay model**			
PDF	9	→	11
QED	7	higher	7
boson p_T	2		2
Subtotal W model	12		13
Total systematic uncert.	37		22
Total	**44**		**26**

combination: 23

CDF, PRD 89 (2014) 072003, arXiv:1203.0275v1 [hep-ex], 2.2 fb^{-1}

D0, PRD 89 (2014) 012005 , arXiv:1310.8628v2 [hep-ex], 4.3 fb^{-1}

Perrozzi ICHEP16

W Mass at the LHC

Advantages:

- Statistical precision: 7 TeV (~4.5 fb^{-1}) < 10 MeV/channel; 8 TeV (~20 fb^{-1}) < 5 MeV/channel
- Large calibration samples: 1-2M (@7 TeV) of $Z \rightarrow ee/\mu\mu$ events
- Large fiducial (detector— pseudo rapidity) coverage
- MC template built with full detector simulation with latest calibration conditions and detector description.

Challenges:

- Higher pile-up environment→affects hadronic recoil resolution & calibration
- Higher energy regime (2 TeV v. 7/8/13 TeV), p-p v. p-pbar: larger systematics?
- W+ and W- production not symmetric: charge-dependent analysis.

W Mass: Event Observables

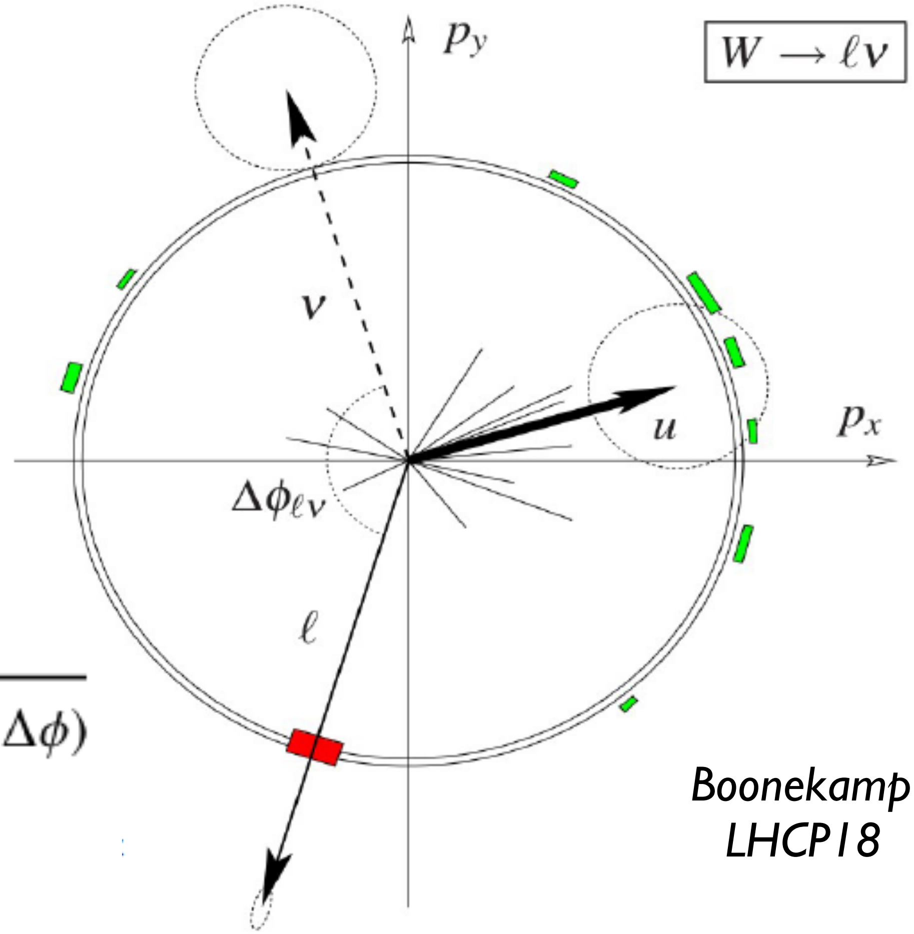
- Main signature is single e,μ: $\overrightarrow{p_T}^l$
- Recoil: sum of "all else" in calo/ tracker; a measure of $p_T^{W,Z}$:

$$\vec{u}_{\rm T} = \sum_i \vec{E}_{{\rm T},i} + \ldots$$

- Derived quantities:

p_T^l

$$\vec{p}_{\rm T}^{\rm miss} = -\left(\vec{p}_{\rm T}^{\ell} + \vec{u}_{\rm T}\right), \quad m_{\rm T} = \sqrt{2 p_{\rm T}^{\ell} p_{\rm T}^{\rm miss} (1 - \cos\Delta\phi)}$$



Boonekamp LHCP18

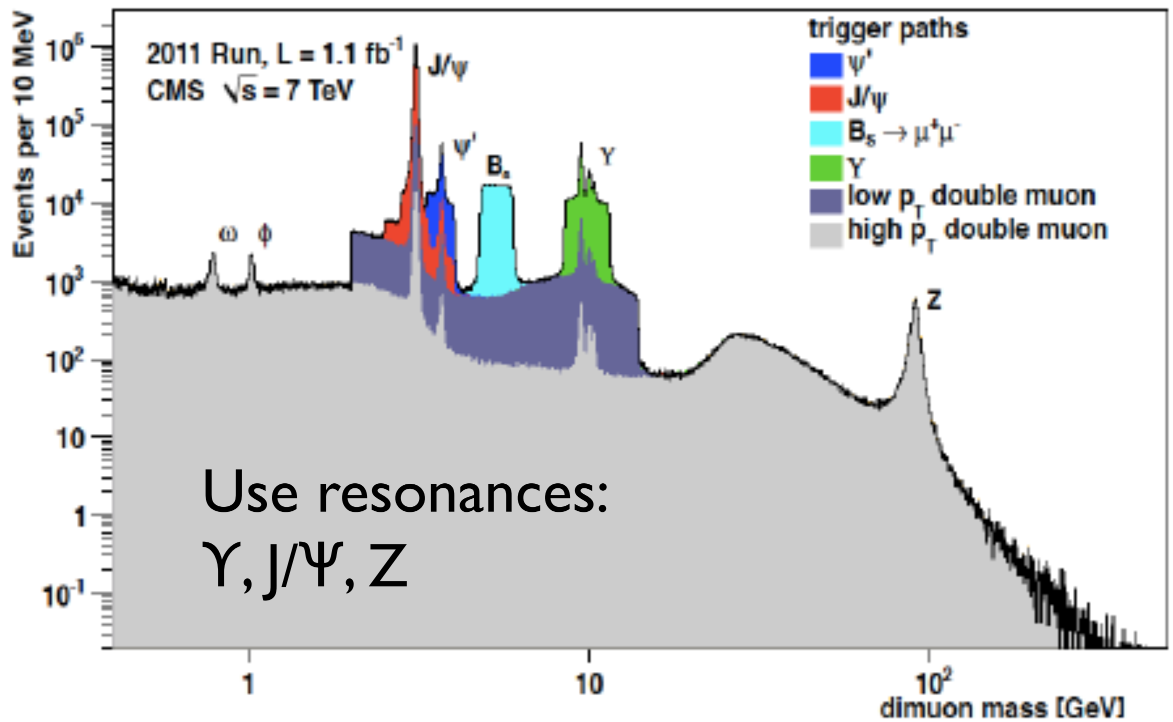
- Typical W event kinematics:

($M_W \sim 80$ GeV)

- $p_T^l > 30$ GeV $\quad p_T^{miss} > 30$ GeV
- $m_T > 60$ GeV $\quad u_T < 30$ GeV

W mass at LHC

Example: Lepton momentum calibration



- At low boson p_T:

$$m_T \sim 2p_T^{\mu} + p_T^{W}$$

For 10 MeV on m_W, need 10^{-4} on $\vec{p}_T^{\,l}$ ~40 GeV); 10^{-3} on p_T^W (~5GeV)

CMS PAS SMP-14-007

Calibrate muon curvature (1/pT) using J/ψ, Y at 7 TeV

Use a physically motivated calibration model to cover the whole p_T spectrum

$$k^c = (A + 1)k + qM + \frac{k}{1 + k\epsilon \sin\theta}$$

magnetic field misalignment material

W mass at LHC

Example: Lepton calibration from Zs:

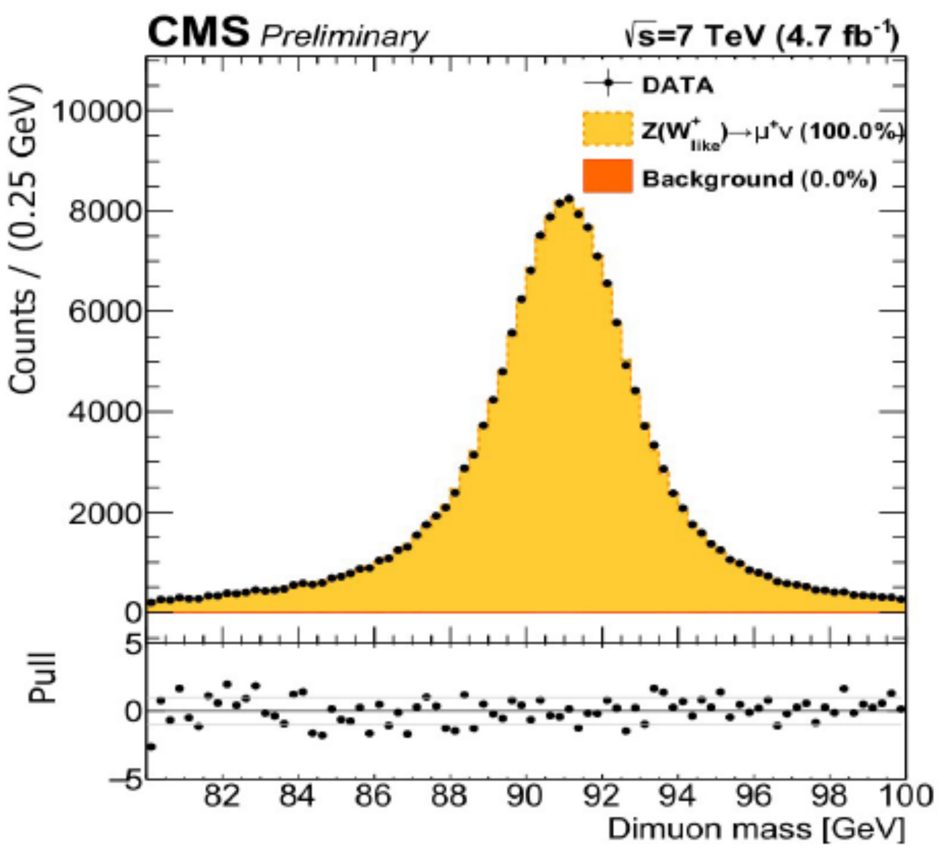
W-like muon : $|\eta|<0.9$, $p_T^l > 30$ GeV

W-like "neutrino" : $|\eta|<2.1$, $p_T^l > 10$ GeV

$u_T < 15$ GeV

Improves W modeling but other systematics needed:

- PDFs in W production
- Z → W extrapolation
- Background

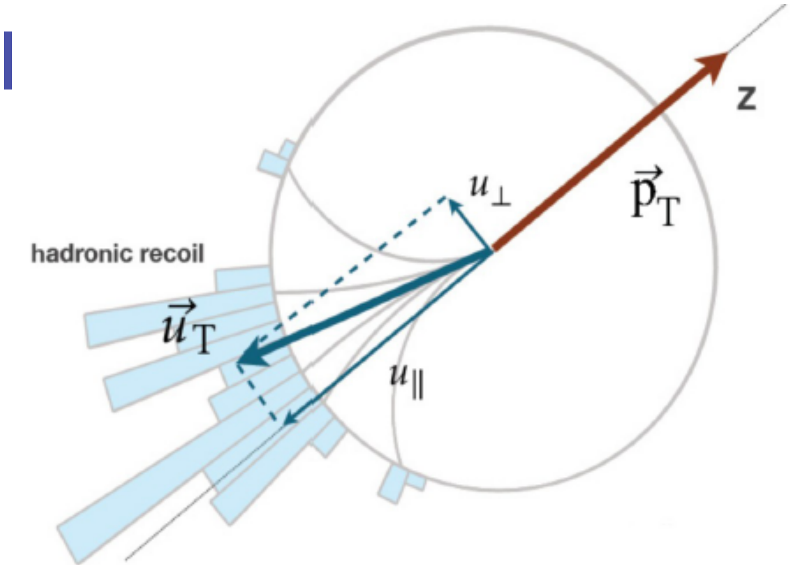


Systematic source	W-like	W
PDF	skip	✓ YES
Boson PT	skip	✓ YES
Boson PT W/Z extrapolation	NO	✓ YES
EWK correction	skip	✓ YES
Polarization	skip	✓ YES
μ momentum scale	✓ YES	✓ YES
μ tr-iso-id efficiency	✓ YES	✓ YES
Missing et scale/resolution DATA/MC agreement	✓ YES	✓ YES
MET W/Z extrapolation	NO	✓ YES
Background to 1 lepton	NO	✓ YES

W mass at LHC

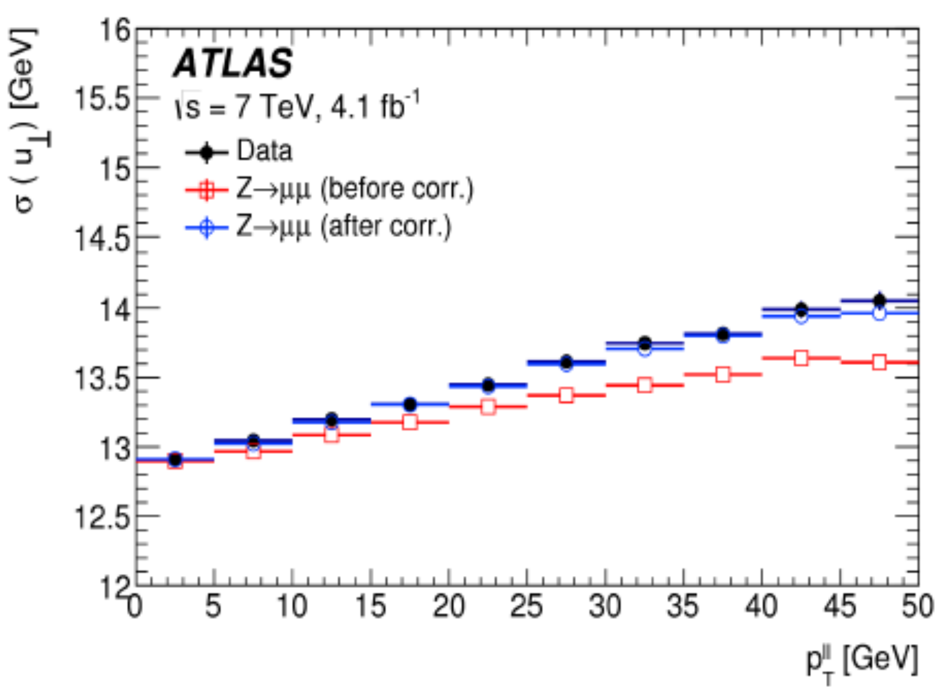
Example: Recoil calibration

momentum balance in transverse plane



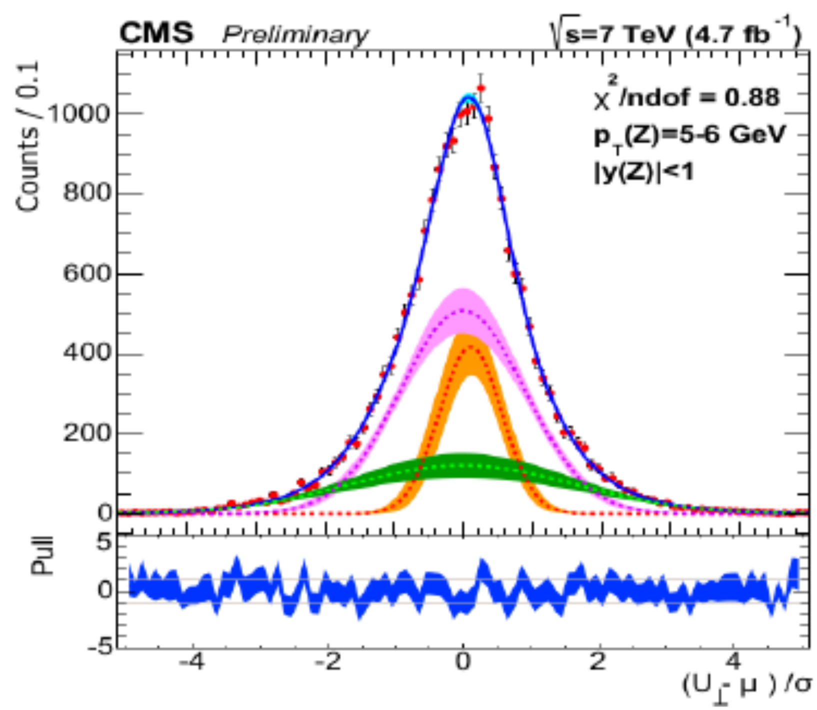
ATLAS: Calorimeter clusters

- Good response, sub-optimal resolution
- no pile-up mitigation



CMS: Calorimeter clusters

- Weaker response; better resolution
- Good pile-up robustness



W mass at LHC

Example: Theory + Support measurements

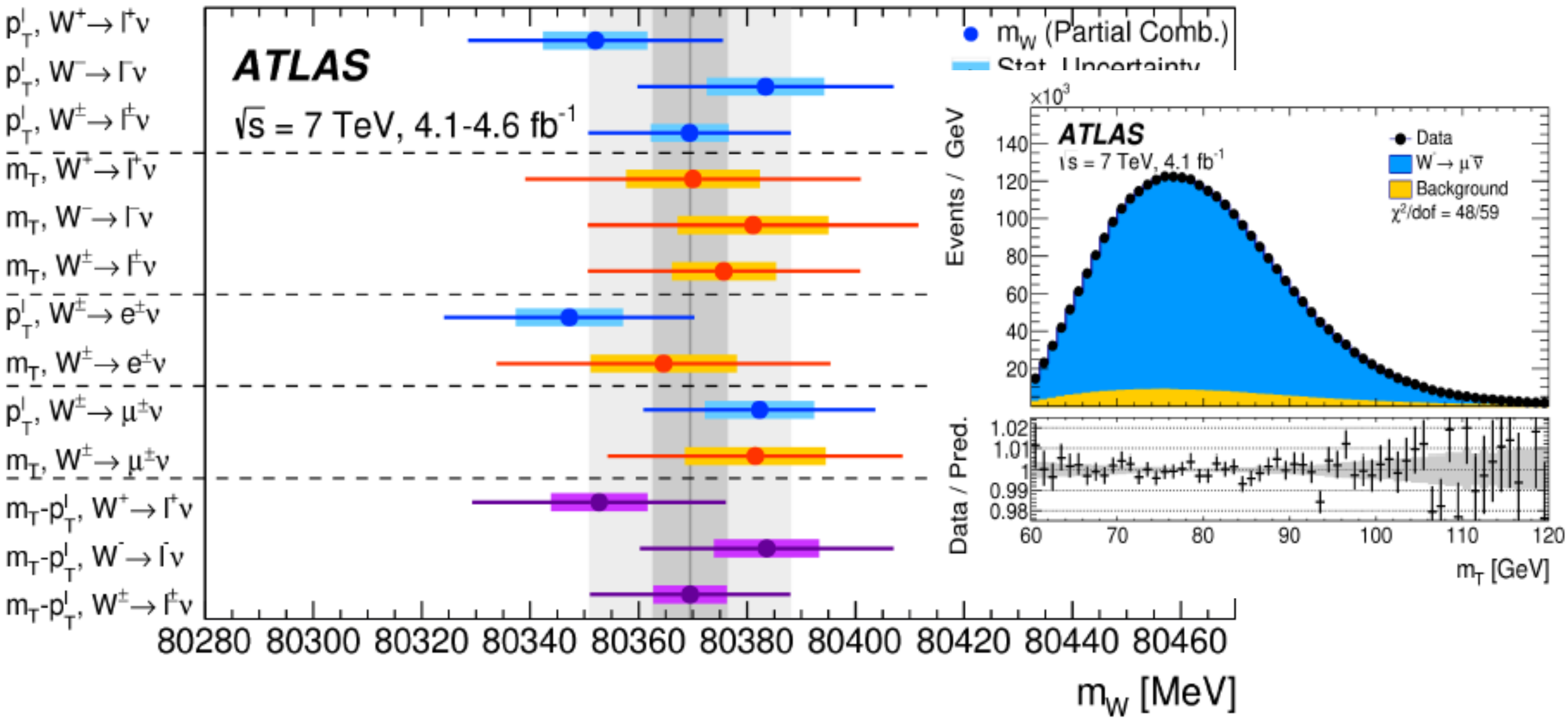
Electroweak corrections:

- Baseline simulation : “improved Born” : use physical values for G_μ, m_Z, m_W, $\alpha_{QED}(m_Z)$, $\sin^2\theta_W$ + FSR (multiple photon emissions)
- Optimal theory : NLO EW + FSR (multiple photon emissions)

QCD uncertainties:

Distribution	*Theory*	*Data*
Rapidity	PDFs	$\sigma_{W,}$ σ_Z $d\sigma_W/d\eta_{l,}$ $d\sigma_Z/dy_{ll}$
p_T	pQCD + p_T resummation	$d\sigma_Z/dp_T^Z$
Decay angle	Spin correlations	$A_i^Z(p_T, y)$

First W Mass Result from ATLAS!

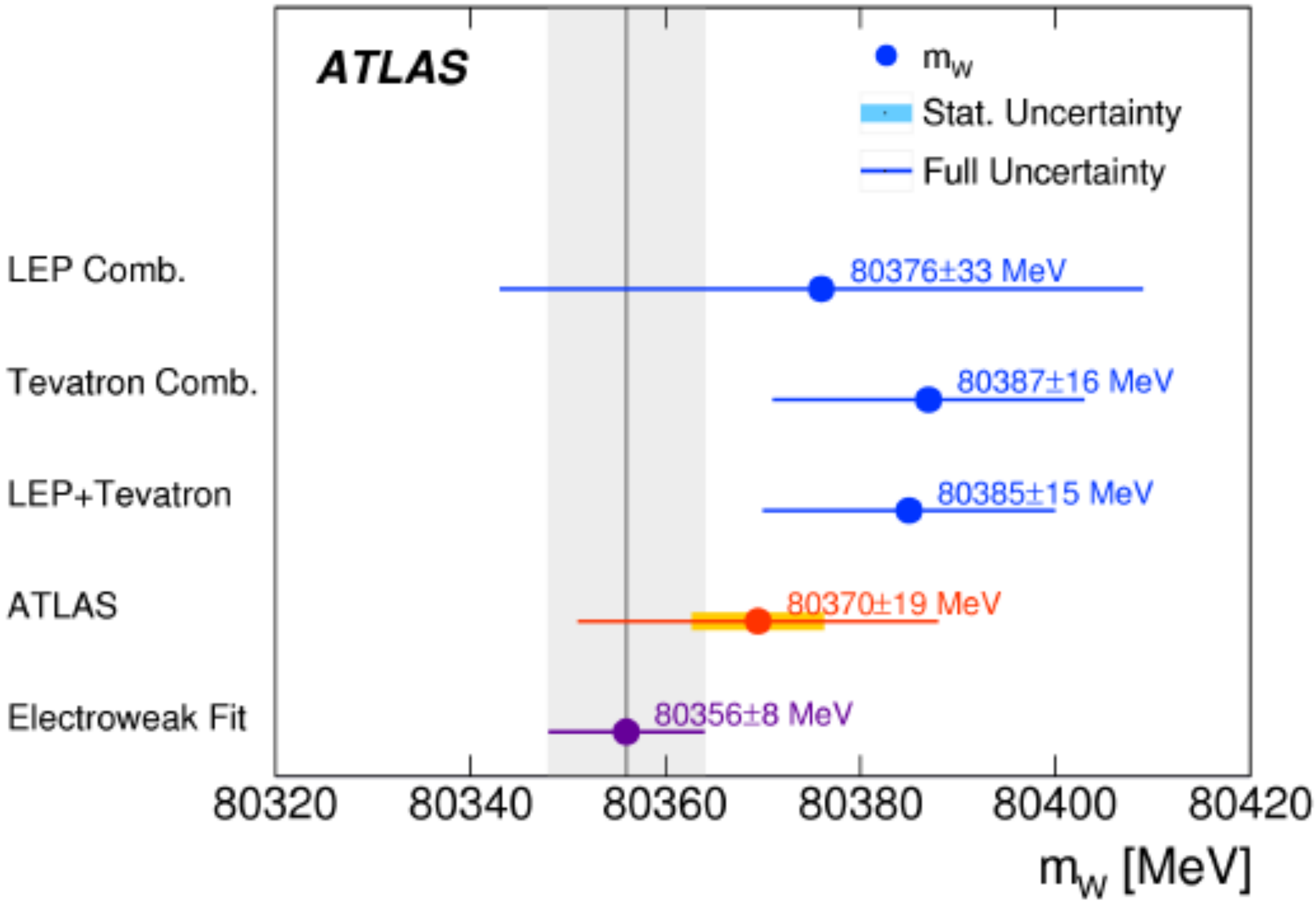


$m_W = 80.370 \pm 0.007\,(\text{stat.}) \pm 0.011\,(\text{exp.syst.}) \pm 0.014\,(\text{mod.syst.})$ GeV

$= \underline{80.370 \pm 0.019 \text{ GeV}}$

δm_W (mod.syst) ~ 6 (EW) ⊕ 8 (QCD) ⊕ 9 (PDF) MeV

W Mass Consistency with SM

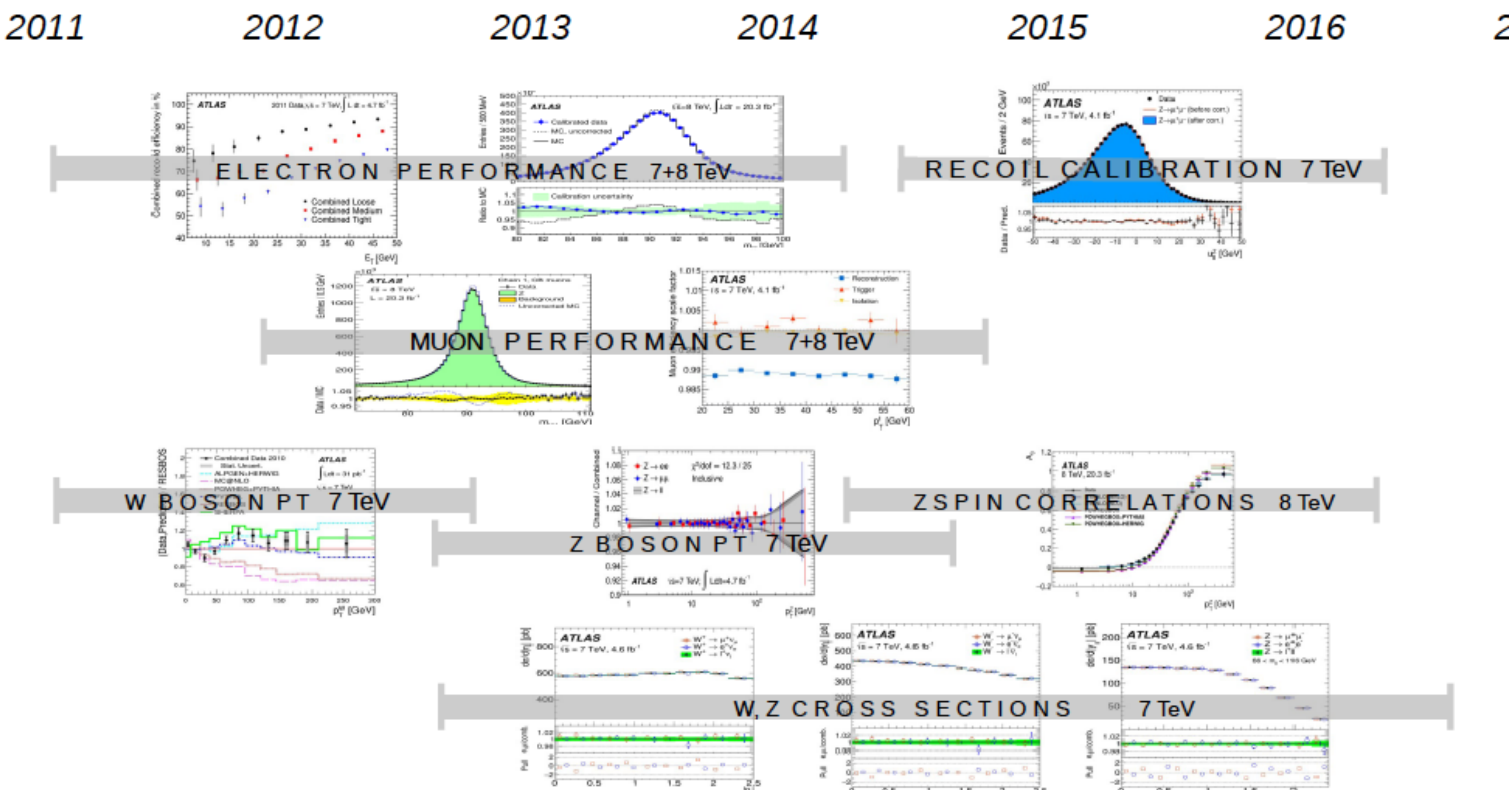


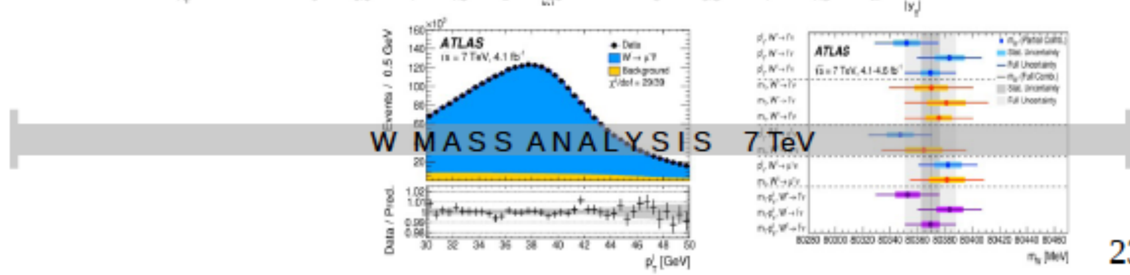
SM prediction for m_W, assuming

m_H = 125.09 ± 0.24 GeV

m_t = 172.84 ± 0.70 GeV

Many Inputs to the ATLAS analysis

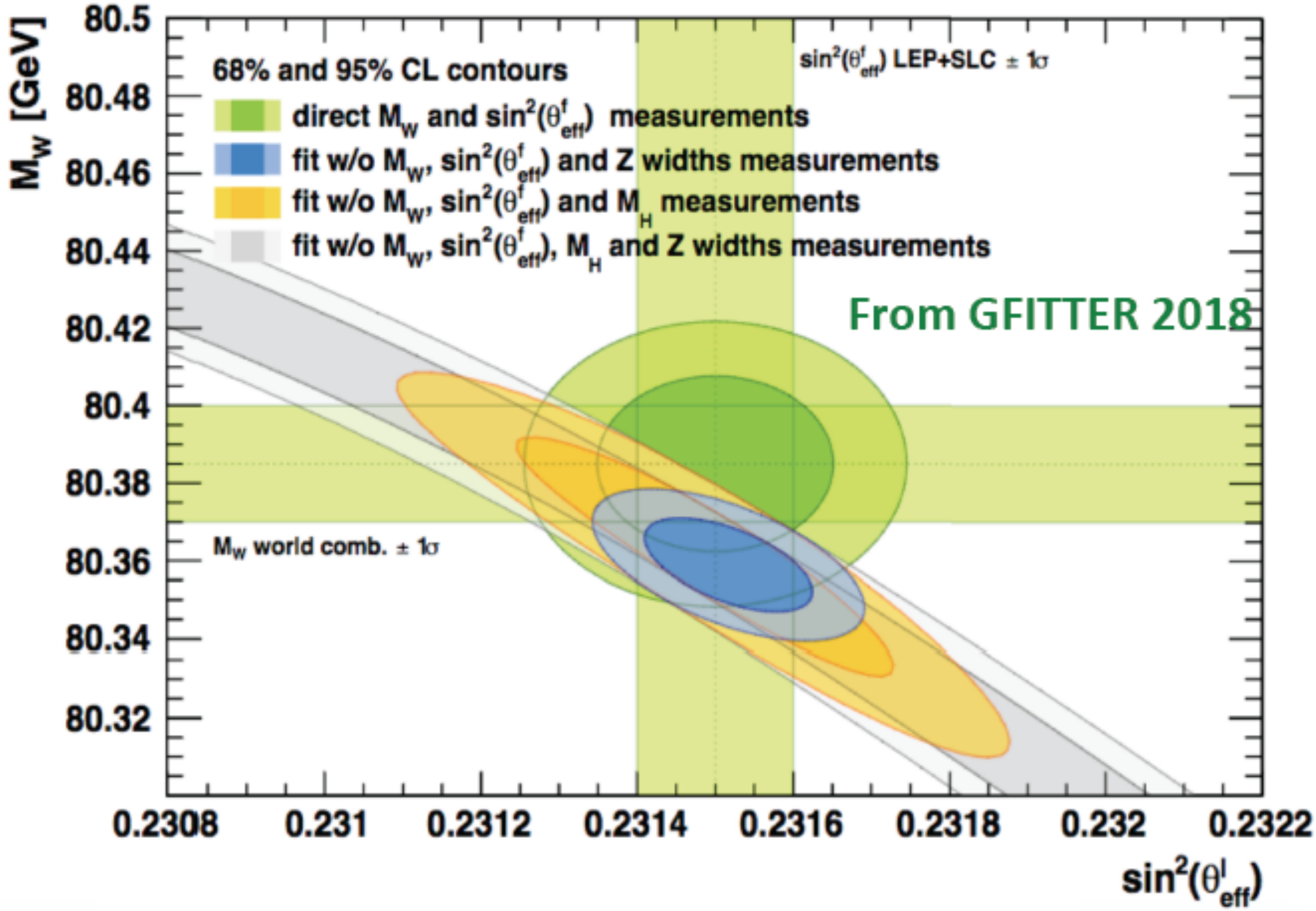




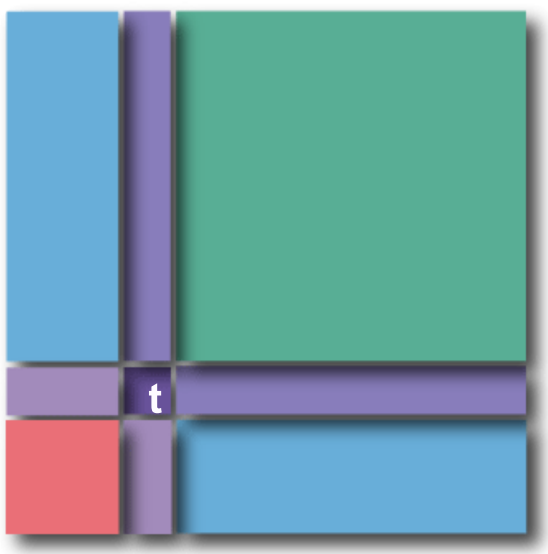
many measurements
by CMS & ATLAS
needed to understand
data and detectors

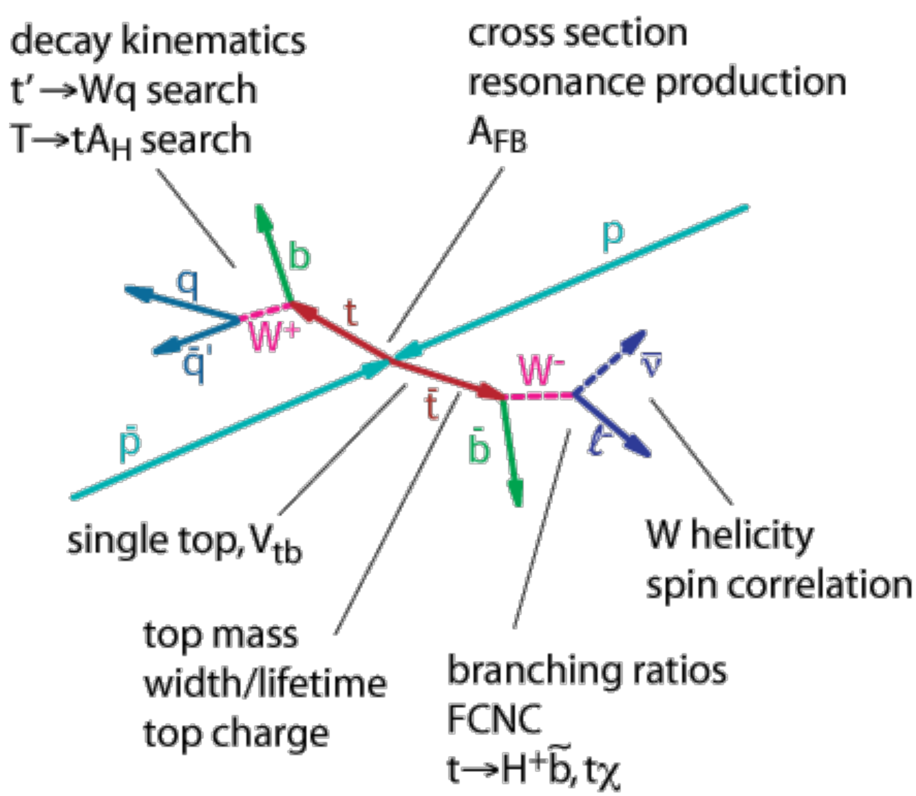
W mass at LHC

$\sin^2\theta_{eff}$



Top Quark Physics





Quark discoveries

$\begin{pmatrix} u \\ d \end{pmatrix}$

- Quarks (u,d,s) were postulated in 1964 by Gell-Mann and Zweig, discovered in 1968

- The charm quark c was discovered in 1974 by Brookhaven and SLAC

$\begin{pmatrix} c \\ s \end{pmatrix}$

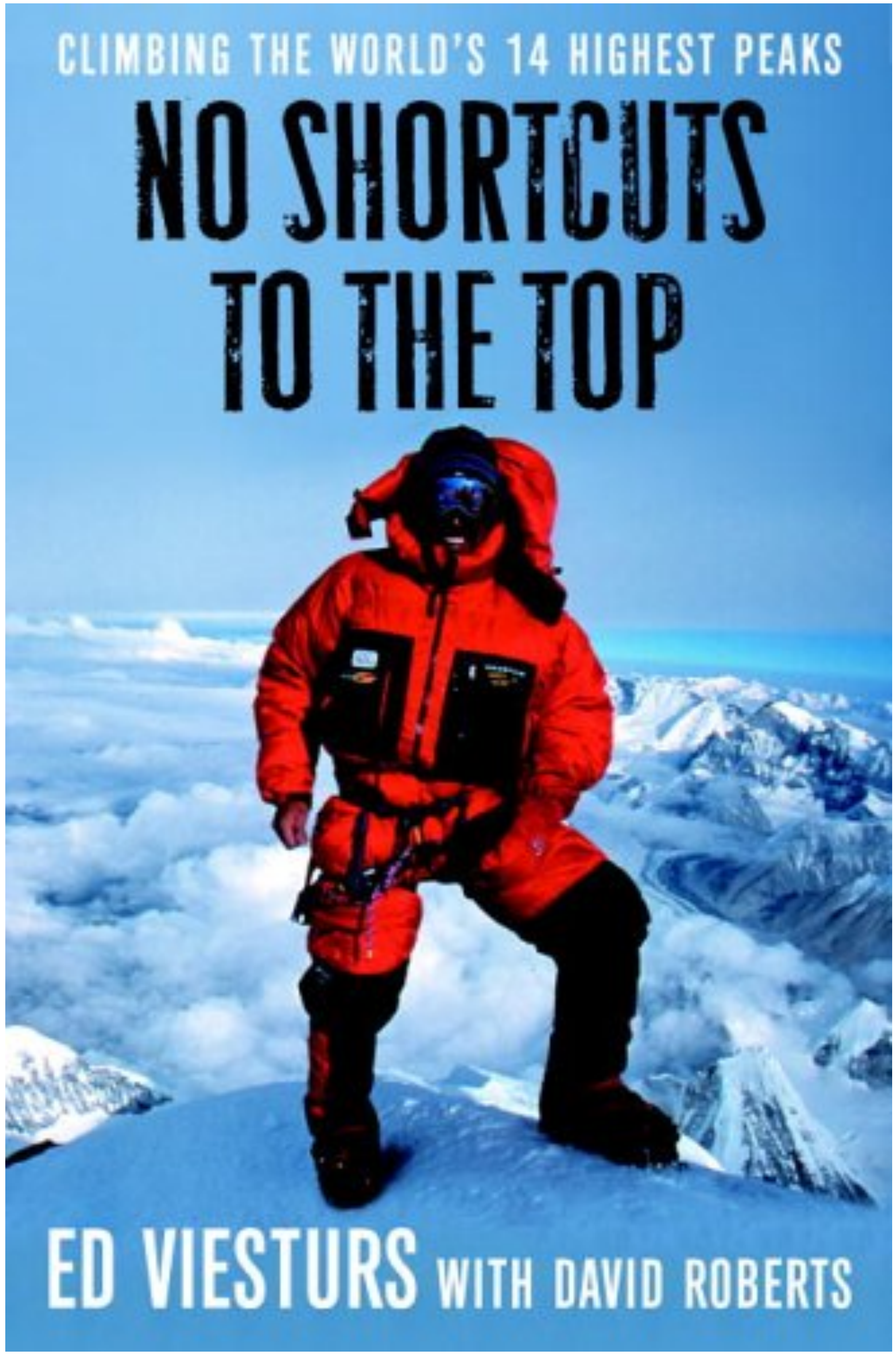
$\begin{pmatrix} \cdots \\ b \end{pmatrix}$

- The bottom b quark was discovered In 1977 at Fermilab

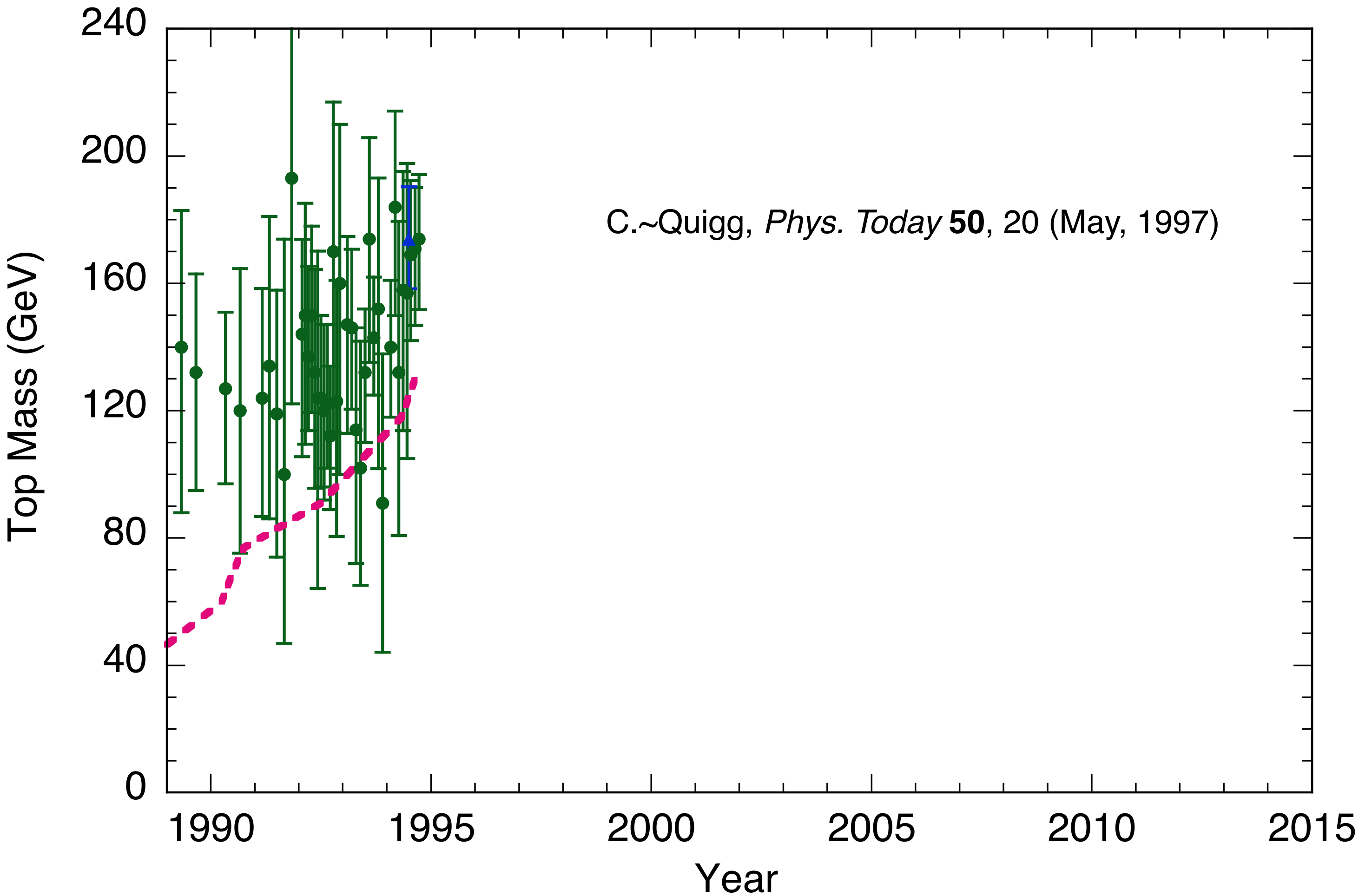
The bottom quark needed a partner... => top!

search for the top was on!

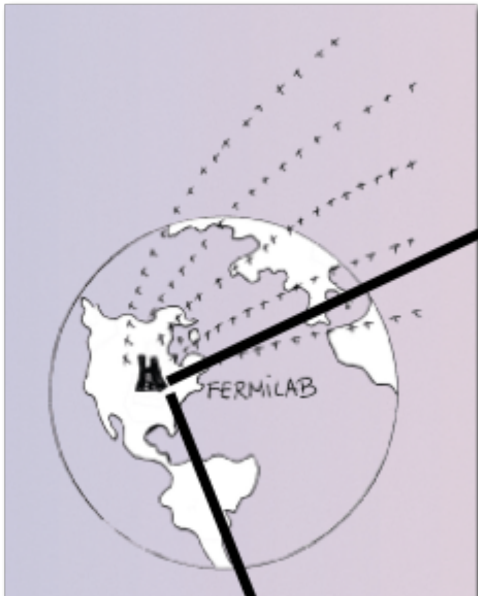
- 1976: Discovery of Upsilon (Fermilab)
  - Contains a 5th quark - the b-quark
  - From family structure of SM
    - Expect a 6th quark - race to find it
- Petra (e+e-) at DESY, Hamburg, $m_t > 23.3$ GeV (1984)
- Tristan (e+e-) in Japan: $m_t > 30.2$ GeV (late 1980s)
- UA1@SPS at CERN: $m_t > 44$ GeV (1988)
- LEP (e+e-) at CERN: $m_t > 45.8$ GeV (1990)
- UA2@SPS: $m_t > 69$ GeV


CLIMBING THE WORLD'S 14 HIGHEST PEAKS
NO SHORTCUTS TO THE TOP
ED VIESTURS WITH DAVID ROBERTS

Indirect constraints on top quark



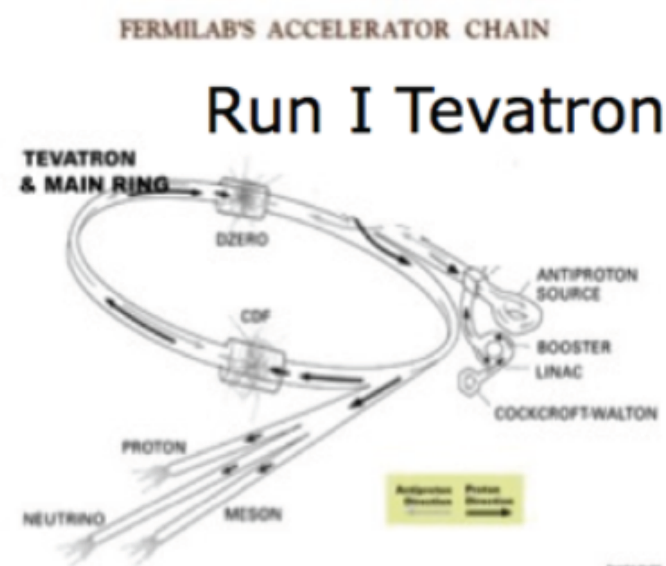
Fermilab's Tevatron



more in L. Evans' & P. Jenni's lectures

search for the top at the Tevatron

- **1984/85**: Tevatron collider commissioned and dedicated
- October **1985**:
  First collisions recorded by CDF
  - DØ: still in construction
- 1987: CDF Run–0
- **1992**: First collisions by DØ
- **Run I (1.8 TeV): 1992–1996**
  - **1995: Discovery of the top quark!**
  - In total ~120pb^{-1} per experiment
  - DØ: more focused on calorimetry
  - CDF: more focused on tracking



more in
P. Jenni's lecture

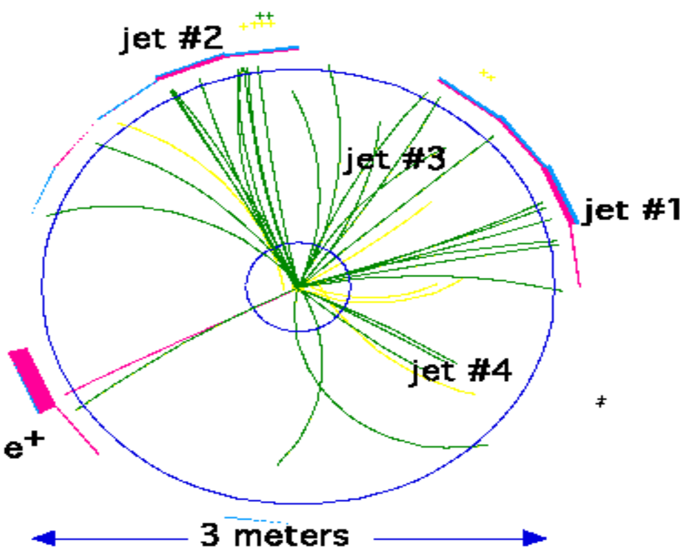
Eureka!

Physicists Discover Top Quark

News Release - March 2, 1995

PHYSICISTS DISCOVER TOP QUARK

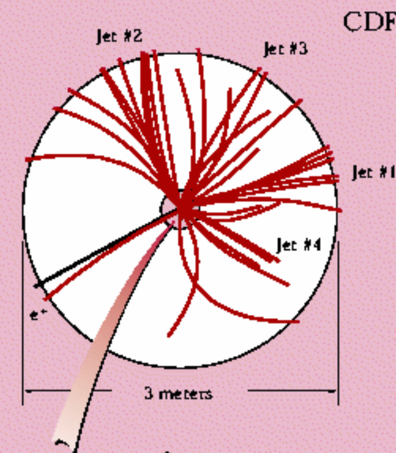
Batavia, IL--Physicists at the Department of Energy's Fermi Natic
subatomic particle called the top quark, the last undiscovered qua
sought the top quark since the discovery of the bottom quark at Fe
of the structure of matter.

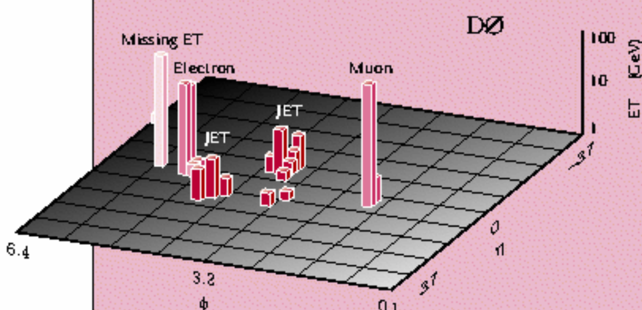


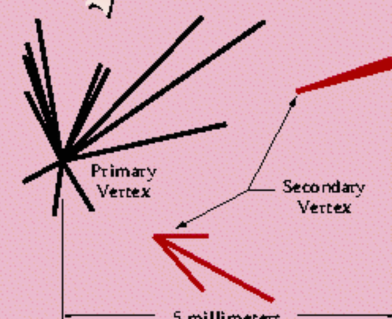
Tracking View

CDF AND DØ RESULTS

THE RESULTS FROM THE TWO COLLABORATIONS were remarkably similar. CDF found 6 dilepton events with a background of 1.3; 21 single-lepton events in which 27 cases of a *b* quark tag by the vertex detector (with 6.7 background tags expected); and 22 single-lepton events with 23 cases of a *b* tag through leptonic decay (with 15.4 background tags expected). DØ found 3 dilepton events (0.65 background events); 8 single-lepton events with topological tagging (1.9 background events); and 6 single-lepton events with *b*-to-lepton tags (1.2 background events). A particularly striking example of a dilepton event with very energetic electron, muon, and missing E_T (due to the neutrinos), plus two jets, is shown below from the DØ data. The plot shows the detector unfolded on to a plane, with the energy of the various objects indicated by the height of the bars. This event has a very low probability to be explained by any known background. The probability that background fluctuations could explain the observed signal was one-in-a-million for CDF and two-in-a-million for DØ—sufficiently solid that each experiment was able to claim the observation of the top independently.





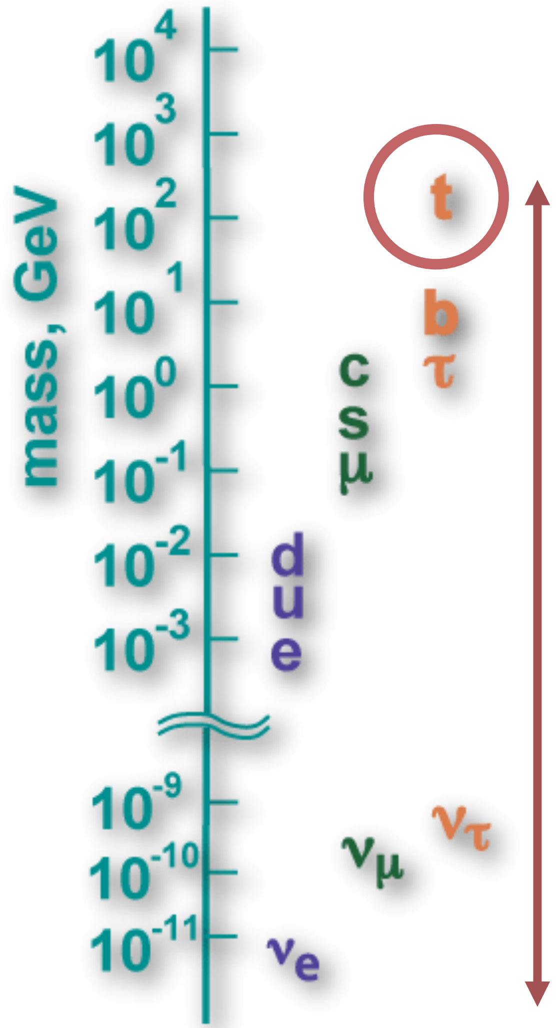


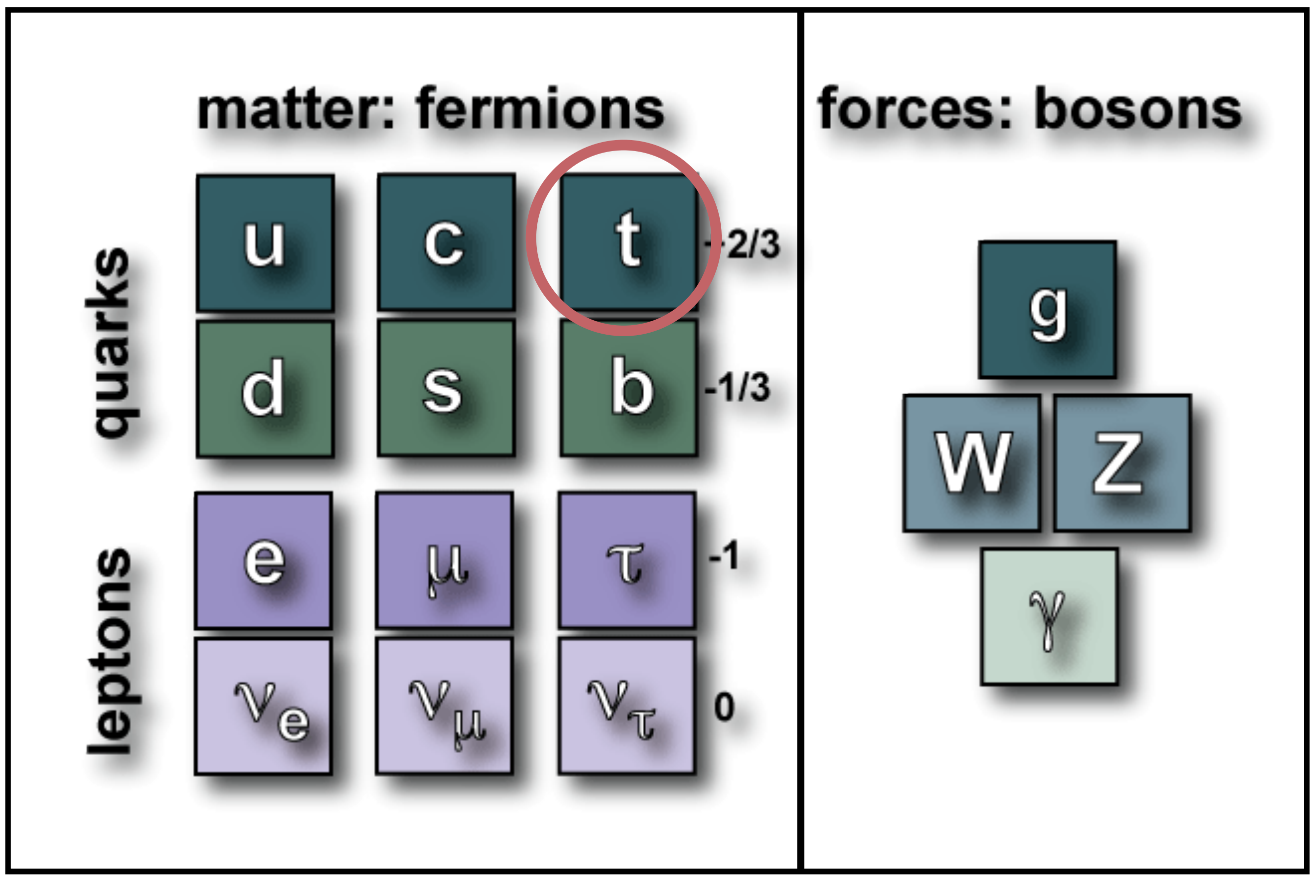
Additional studies helped to establish that the new signal

by the need to identify the correct combination of jets with parent quarks in the decay and to accommodate the tendency of the strong interaction to generate additional jets. The two experiments obtained consistent results for this

Top found at a peculiarly high mass

Periodic Table of the Particles





5 orders of magnitude!

- needed as isospin partner of bottom quark

- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom

Is the top quark standard??

- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?

- short lifetime: $\tau \sim 5 \cdot 10^{-25}s \ll \Lambda^{-1}_{QCD}$: decays before fragmenting
→ observe “naked” quark

Tevatron became the only place to study top through Run 1 and most of Run 2…

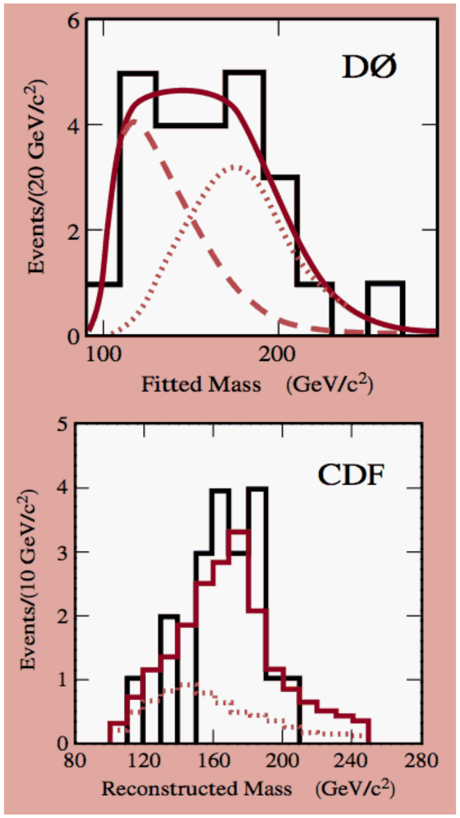
Flagship program:
many LHC measurements pioneered at Fermilab

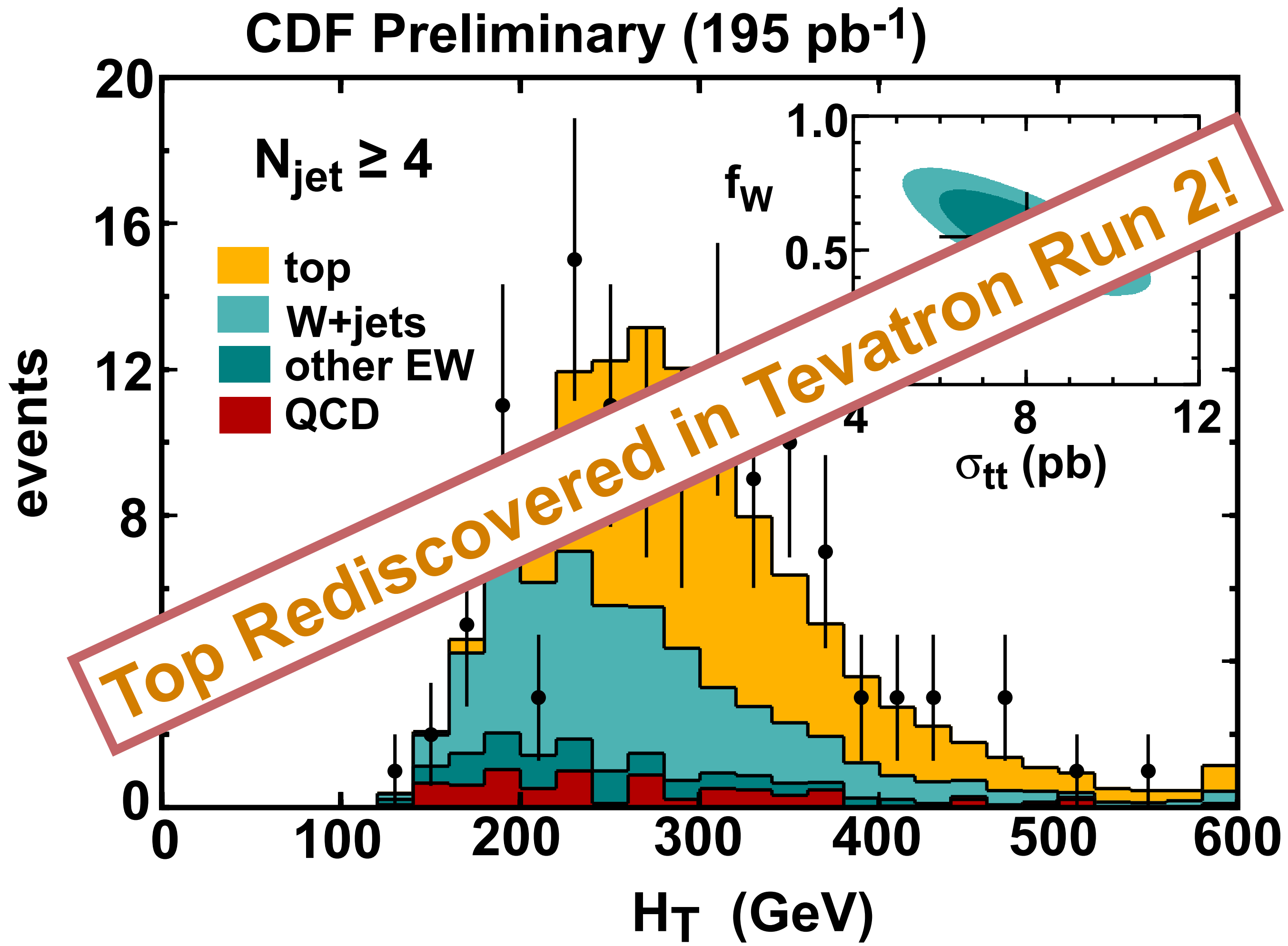
Top Quarks have been one of the most sexy things to study...

When Trish discovers Ned works exclusively with top quarks, she will be putty in his hands.

...until Higgs! (but related)

Tevatron
Run I Top



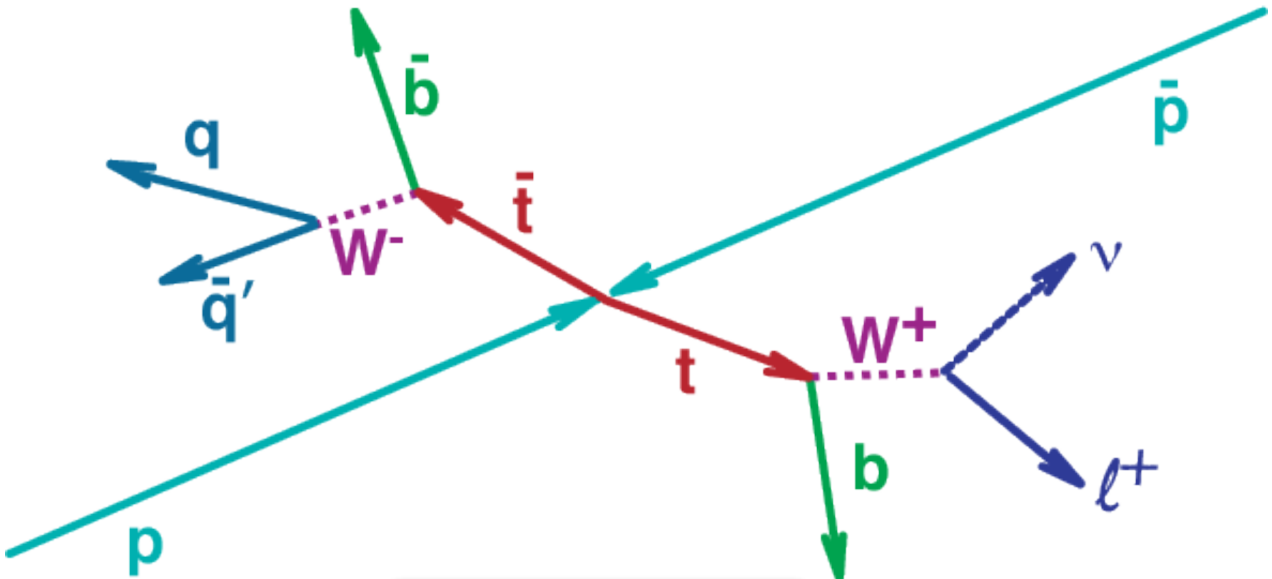


Top Event Decays

- W helicity (V-A)
- Branching ratios
- Top to charged higgs
- Top sample (W+HF)
- FCNC

Top Quark Production

- Mechanism
- Top Pair Cross Section
- Ewk Production (single top)
- Forward-backward asymmetry
- Resonances decaying to top
- stop or t' production



Top Properties

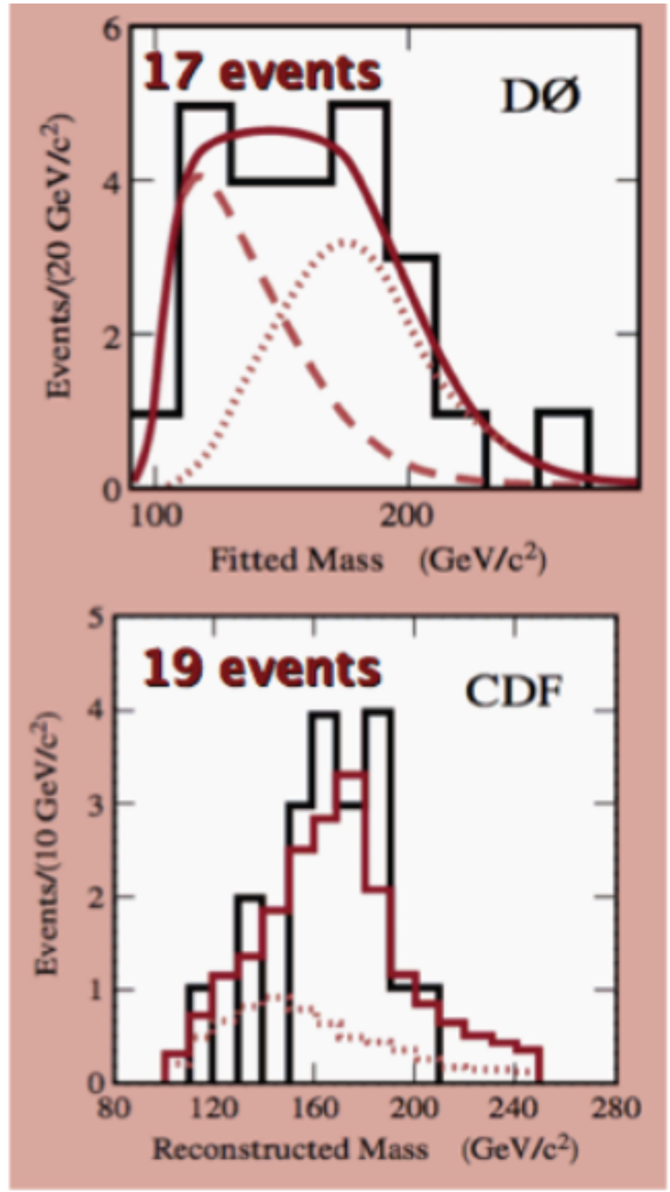
- Top Mass
- Top Quark Width
- Charge of Top Quark
- Mt – Mtbar & CPT

sample of
many things
to study!

Discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

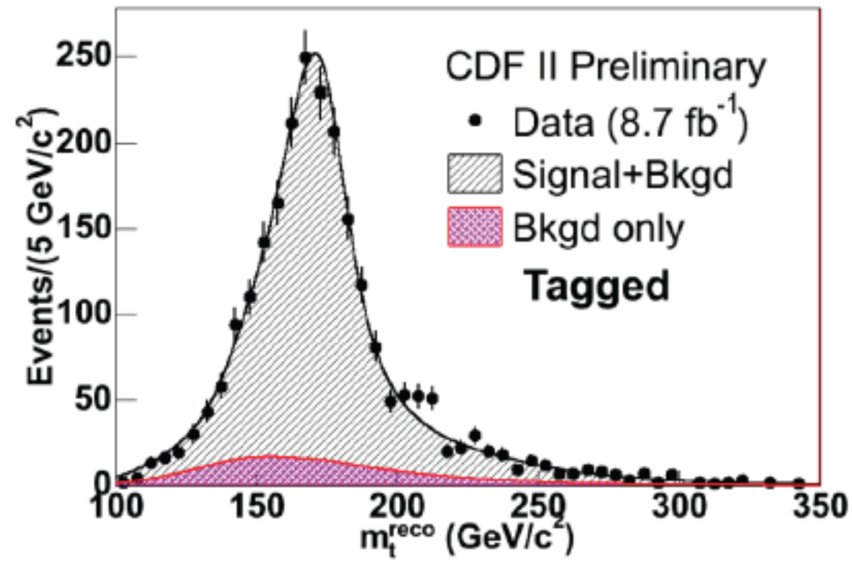
handfuls of events

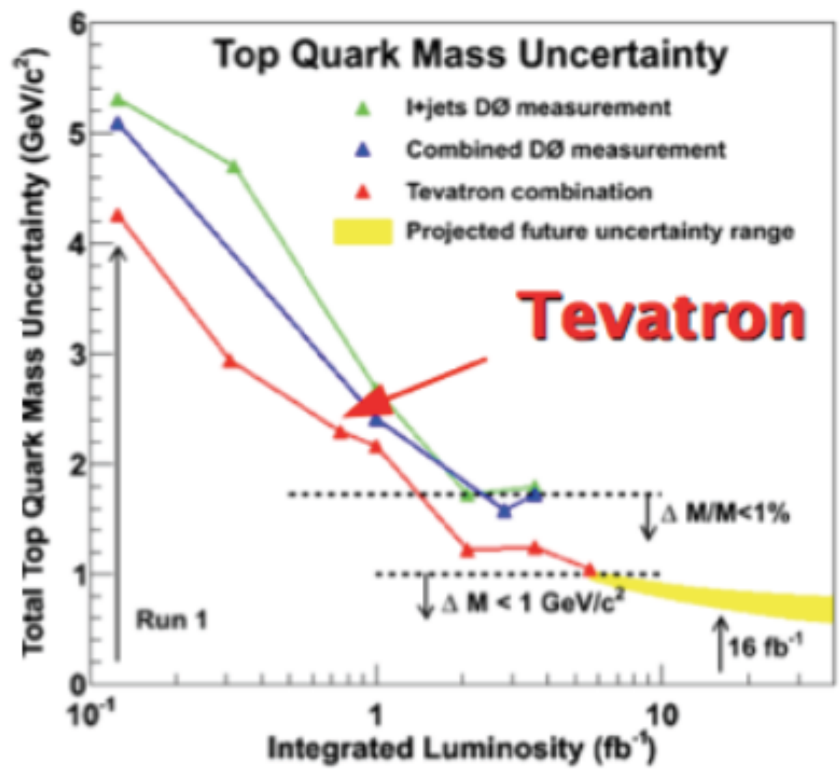


1995, CDF and DØ experiments, Fermilab

Tevatron Run 2

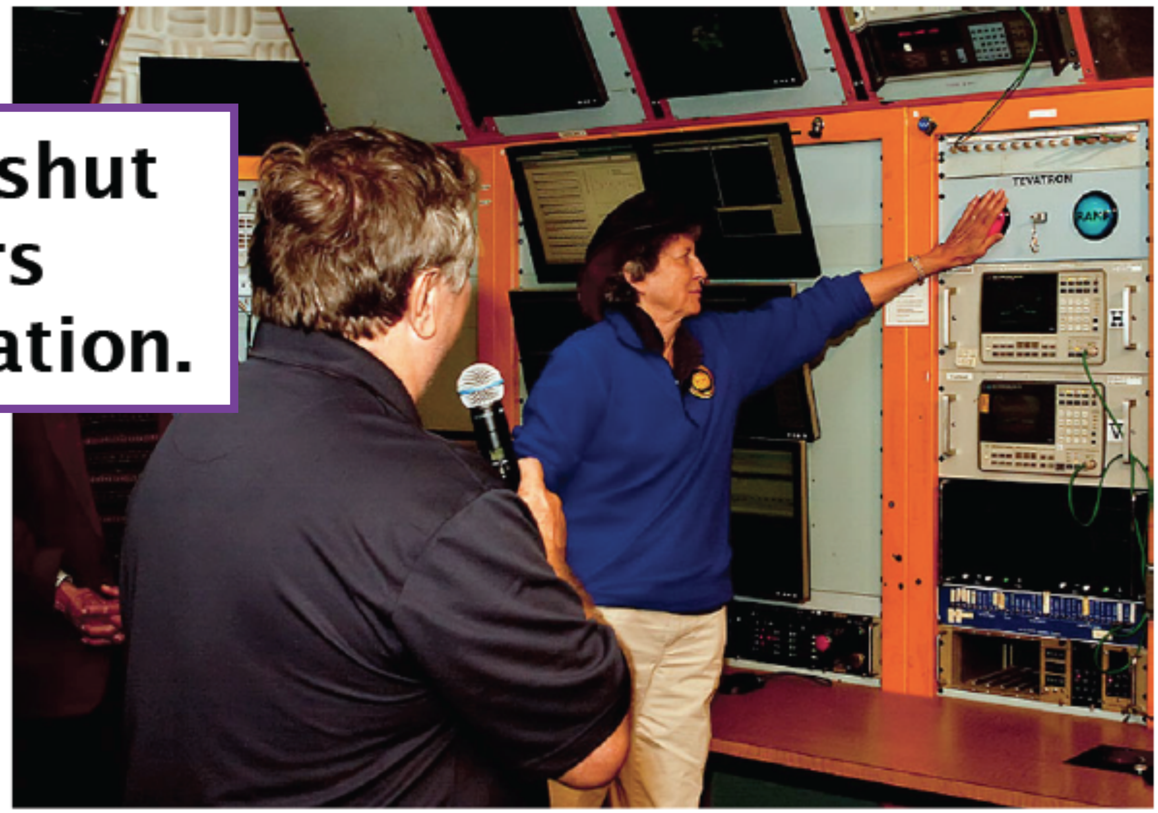
1000s of events





Then in 2010... enter the LHC!

see details in
L. Evans' &
P. Jenni's lectures



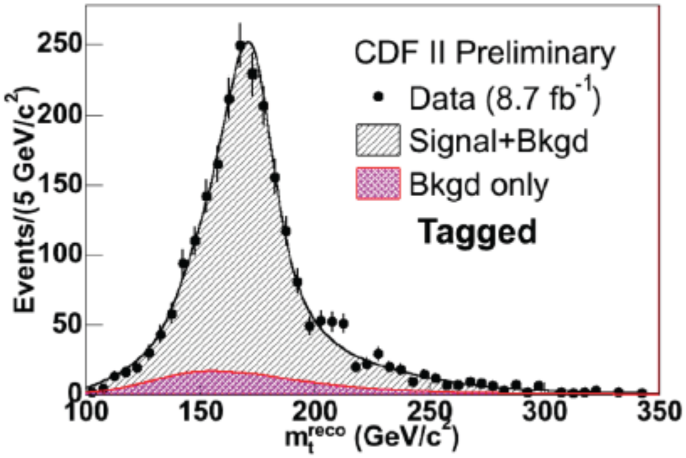
Tevatron complex shut down after 26 years of successful operation.

b. 10-13-85
d. 09-30-11

First 13 TeV Collisions!

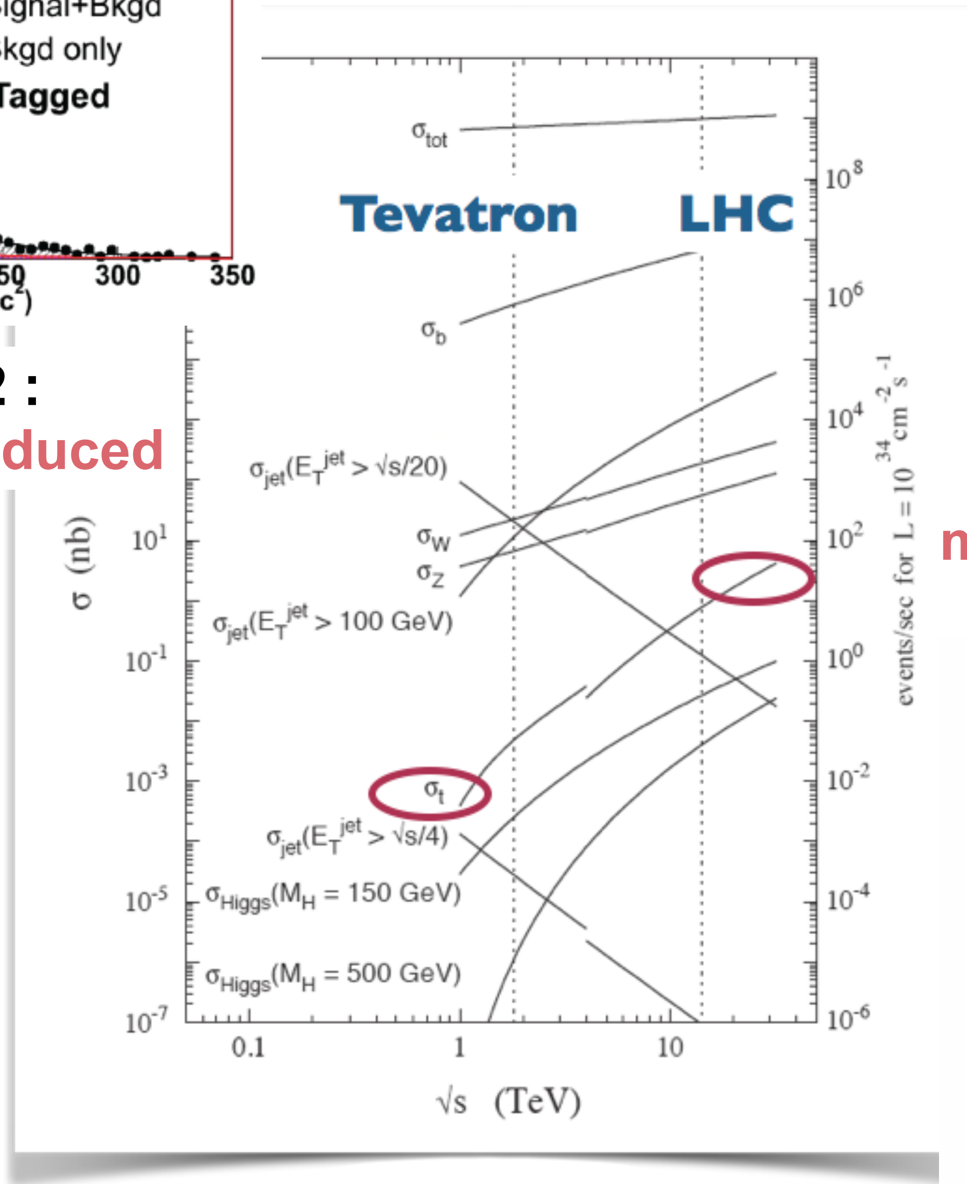
LHC Run 2 begins

June 3, 2015



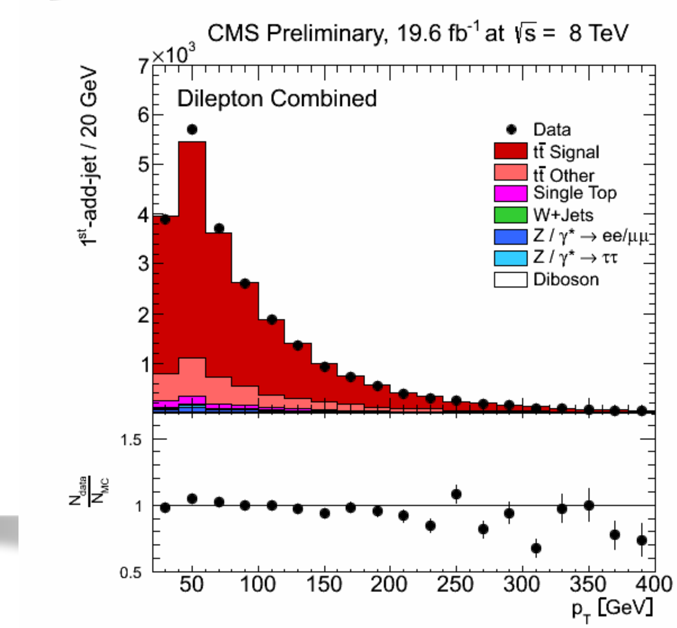
Tevatron Run 2 :

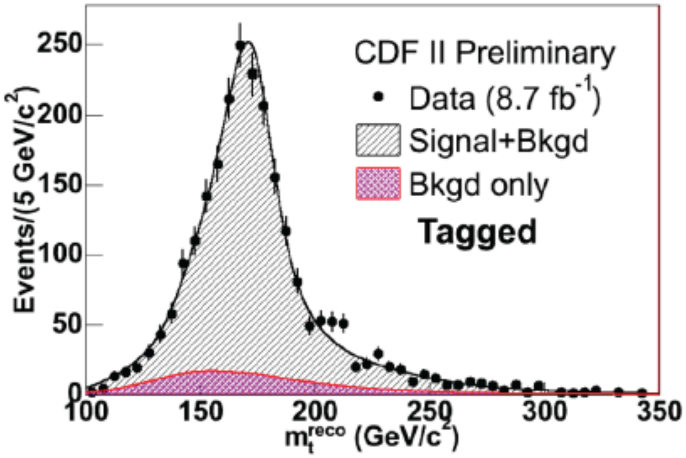
~100k tops produced



LHC Run 1:

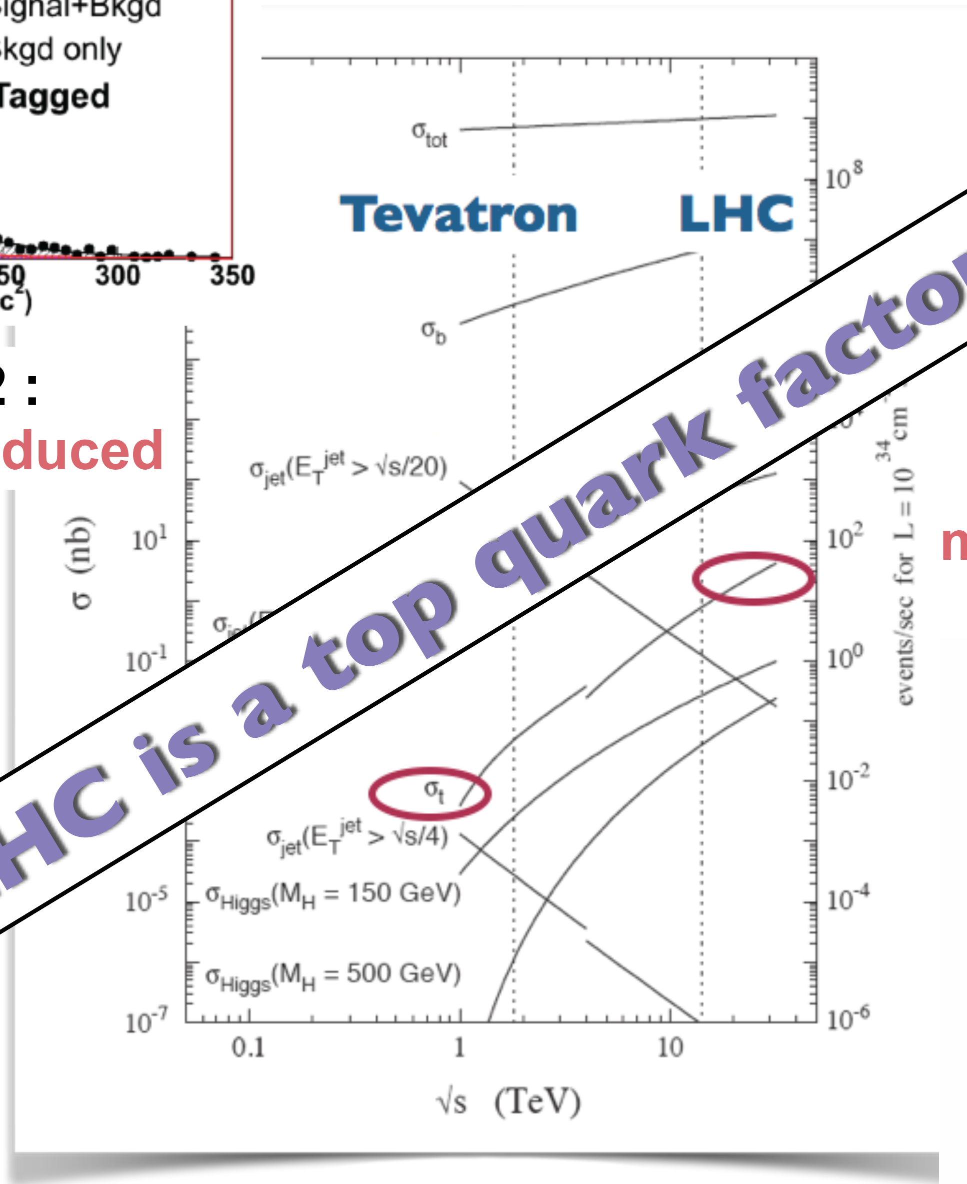
millions tops produced





Tevatron Run 2 :

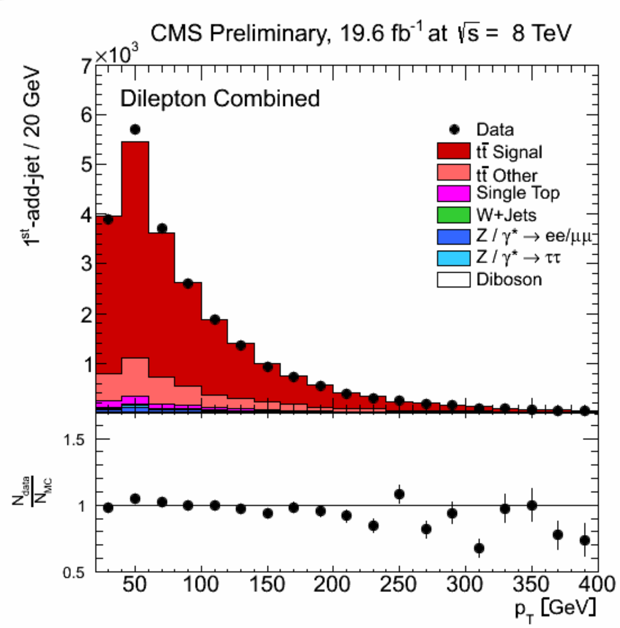
~100k tops produced



LHC is a top quark factory!

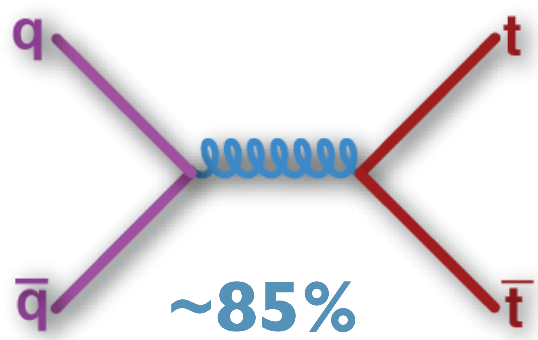
LHC Run 1:

millions tops produced

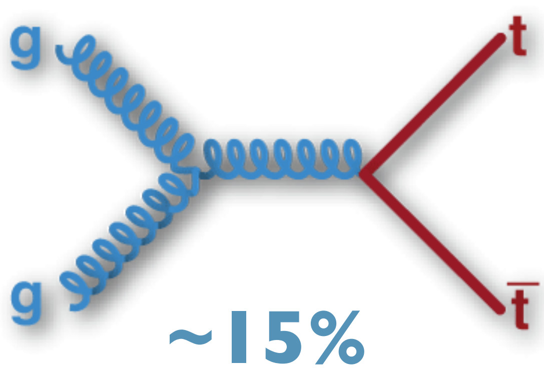


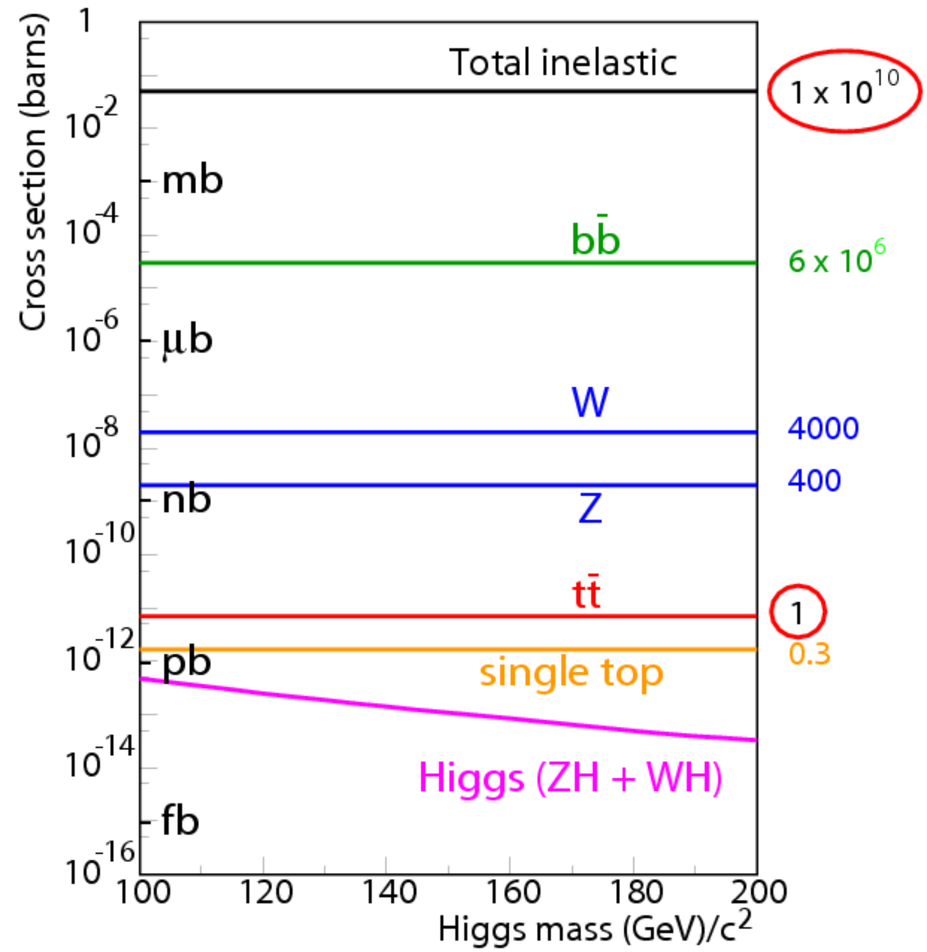
Tevatron: Top Pair Production

How is Top Produced?



strong pair production

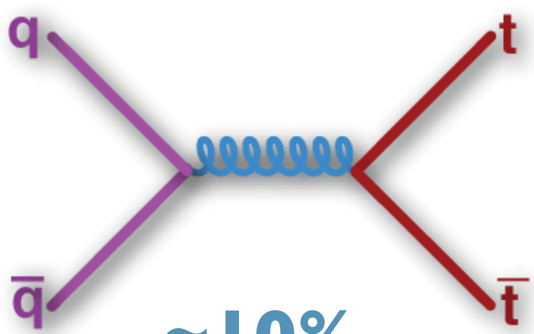




One top pair each 10^{10} inelastic collisions at $\sqrt{s}$ = 1.96 TeV

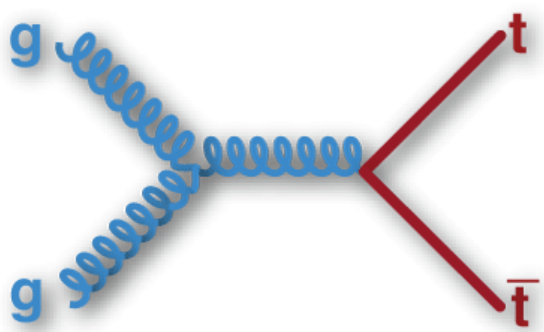
LHC (13 TeV): Top Pair Production

How is Top Produced?

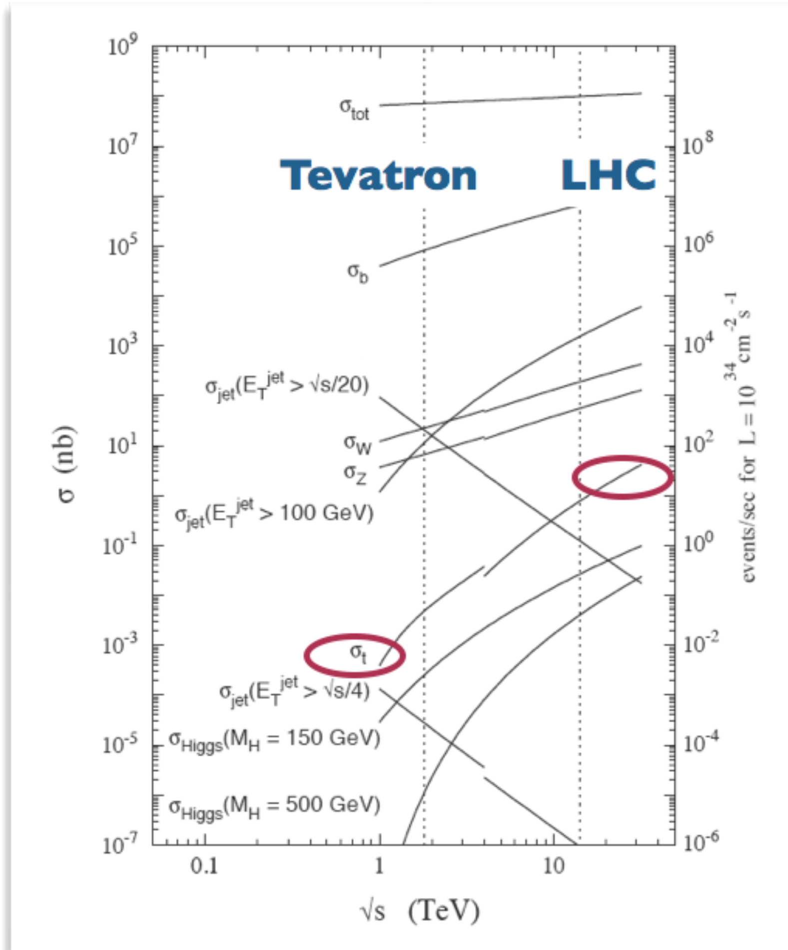


~10%

strong pair production



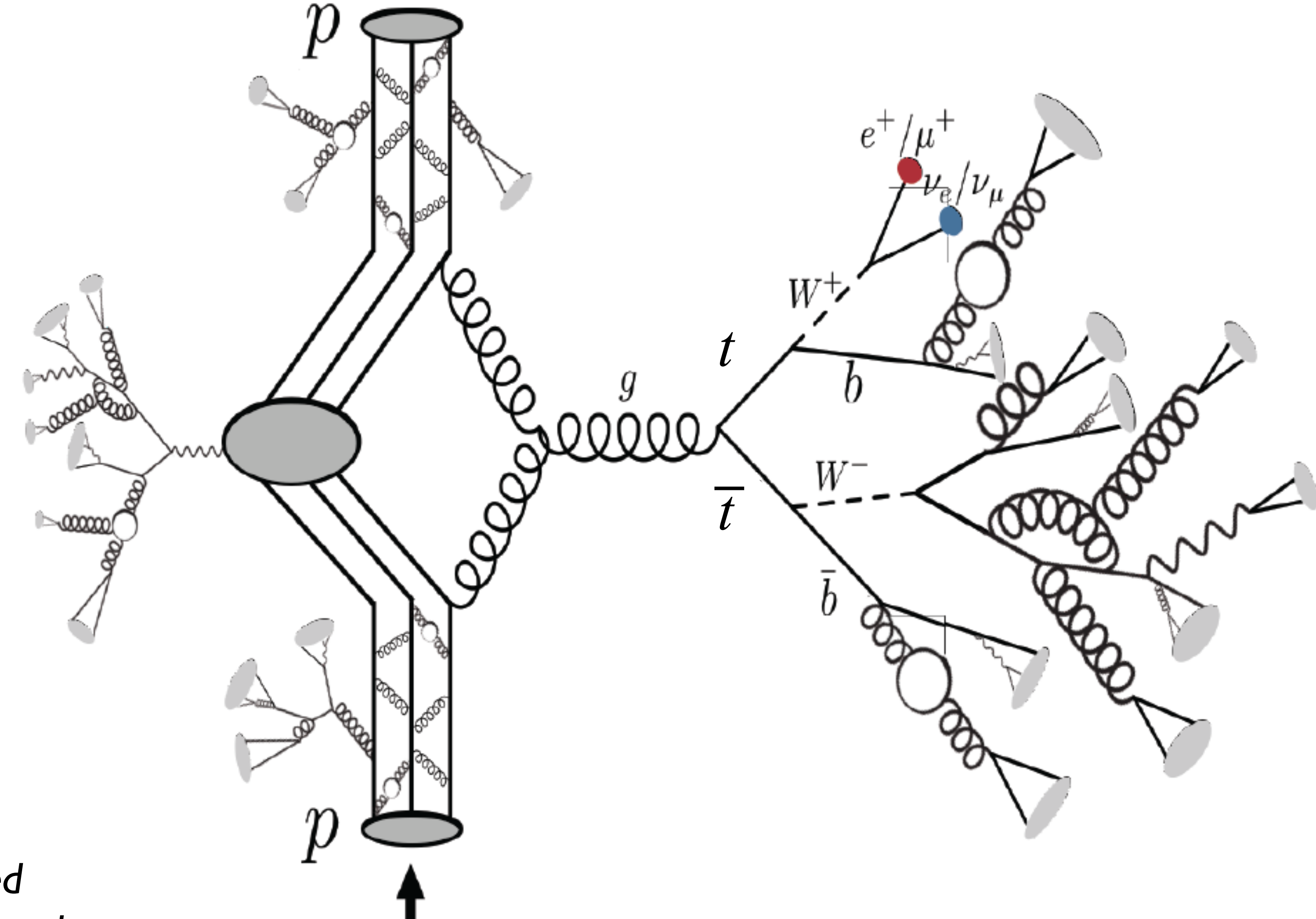
~90%



One top pair each 10^8 inelastic collisions at $\sqrt{s}$ =13 TeV

Actually things can get more complicated…

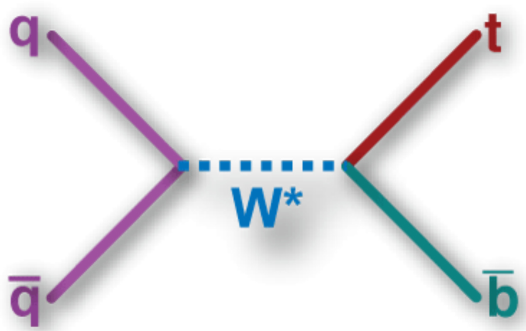
How is Top Produced?



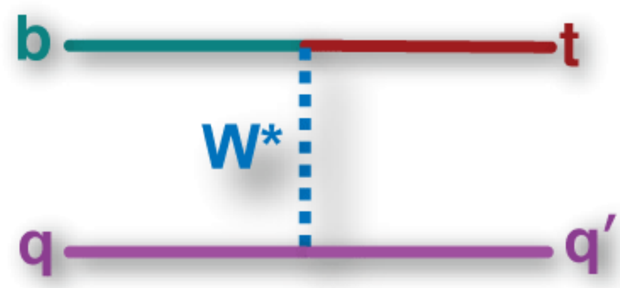
QCD covered by J. Butterworth

Electroweak Single Top Production

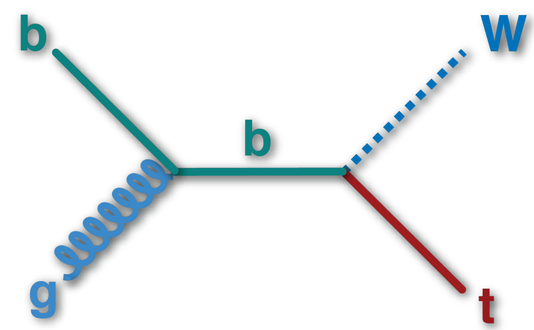
How else is top produced?



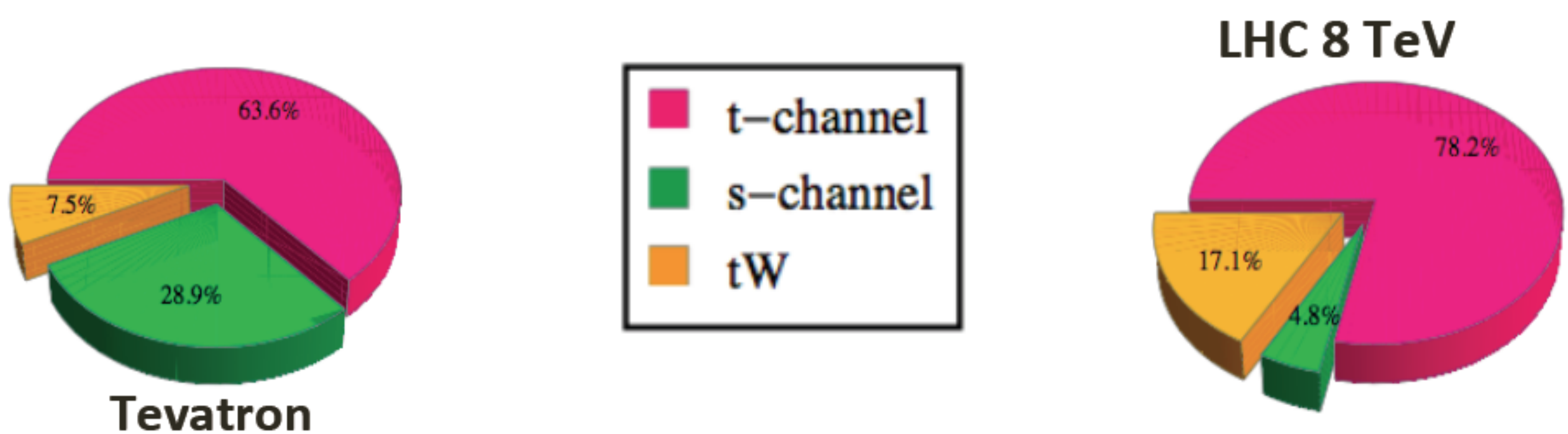
s-channel



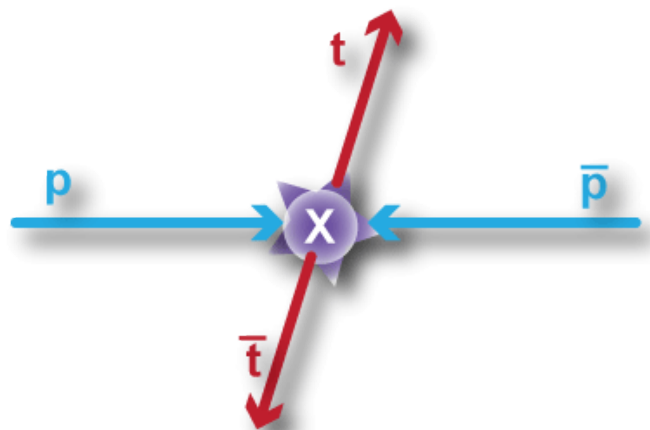
t-channel



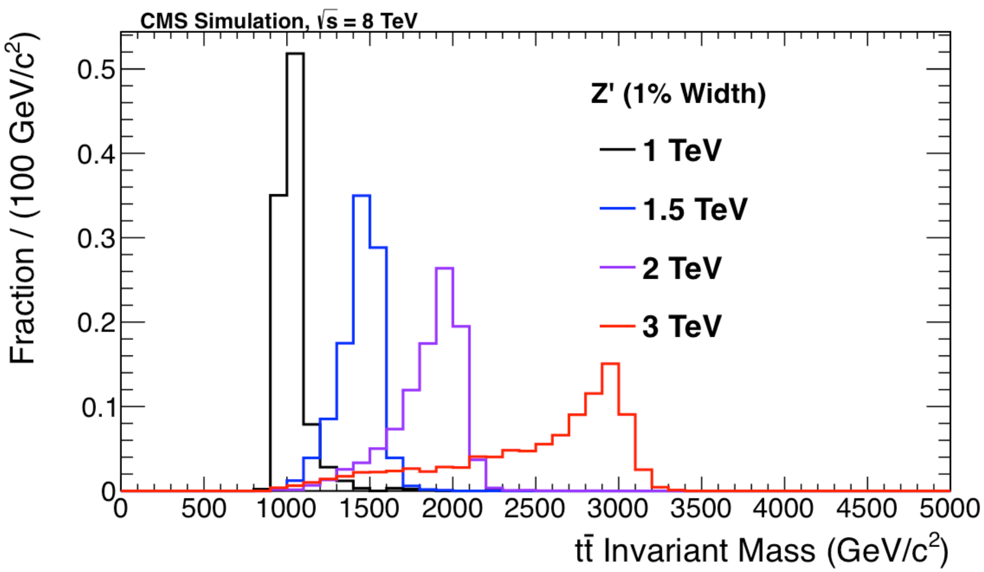
Wt-production

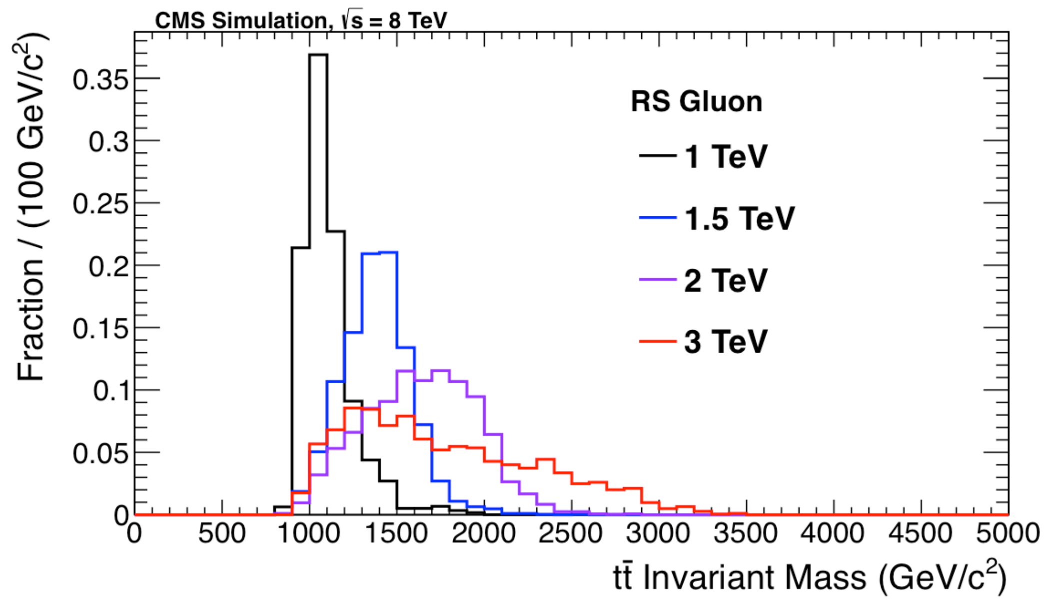


How else is top produced?



tt resonances popular in composite & extra dimensions models

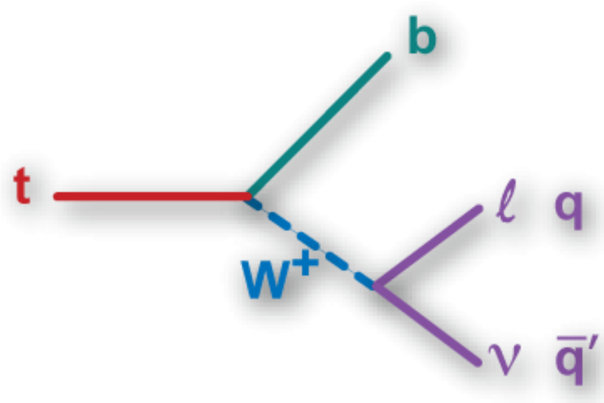




$Z' \rightarrow tt$, $\Gamma/m_{Z'}$ =1%, 10%, xs∝width
but SM couplings

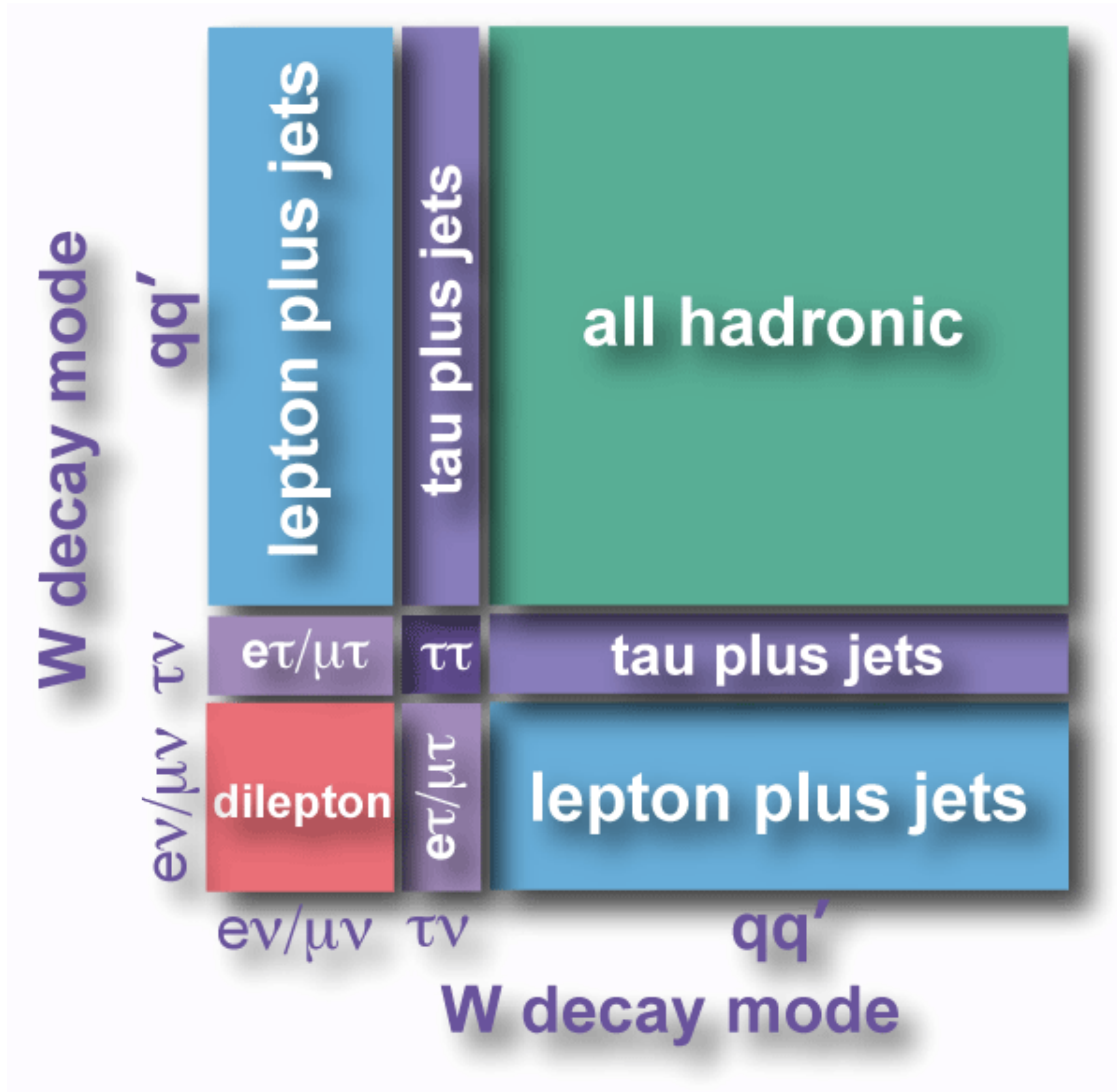
RS KK gluon→tt

How does Top decay?

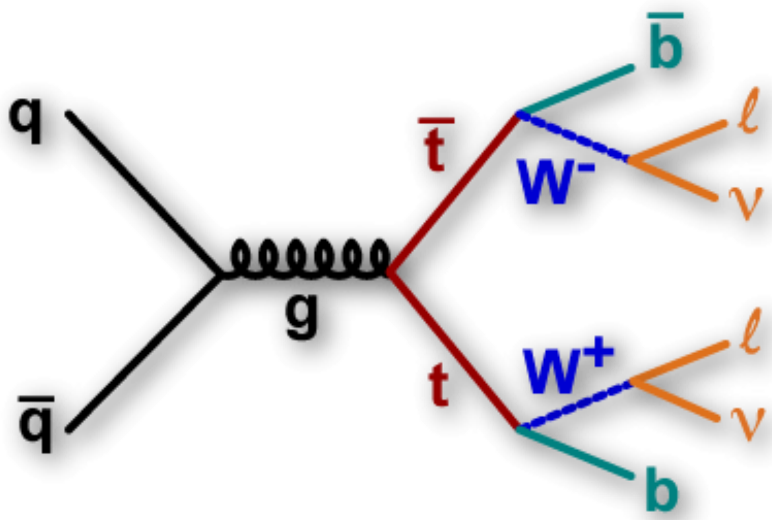


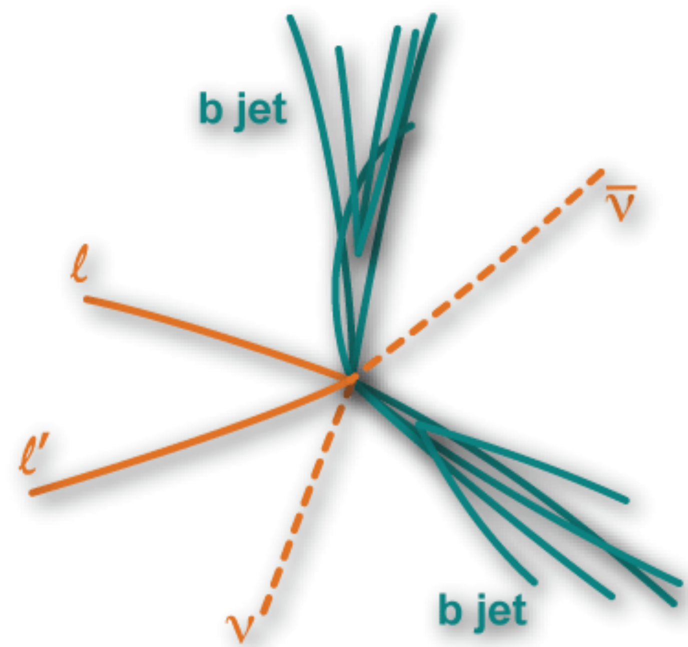
t→Wb ~ 100%

Categorize top pair final states based on W decays



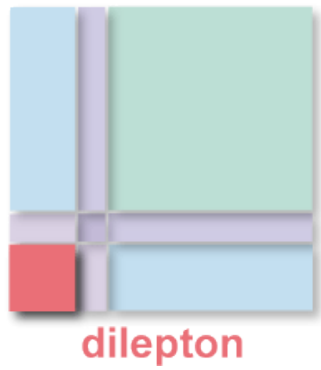
Dilepton Decay Mode

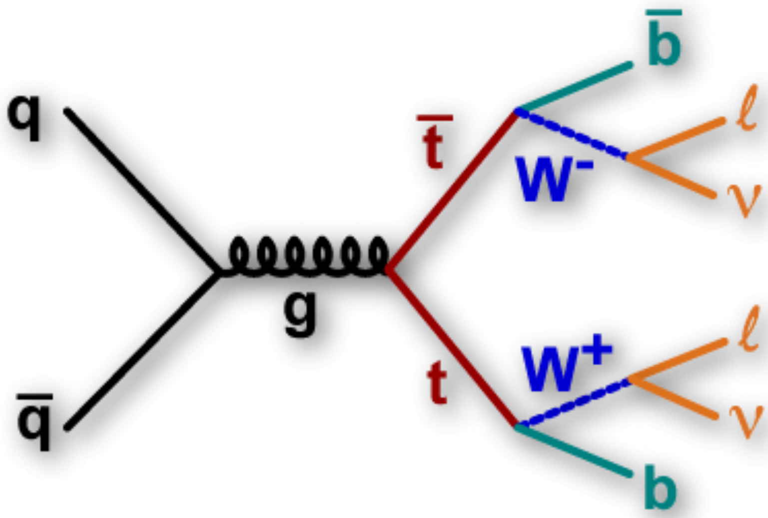


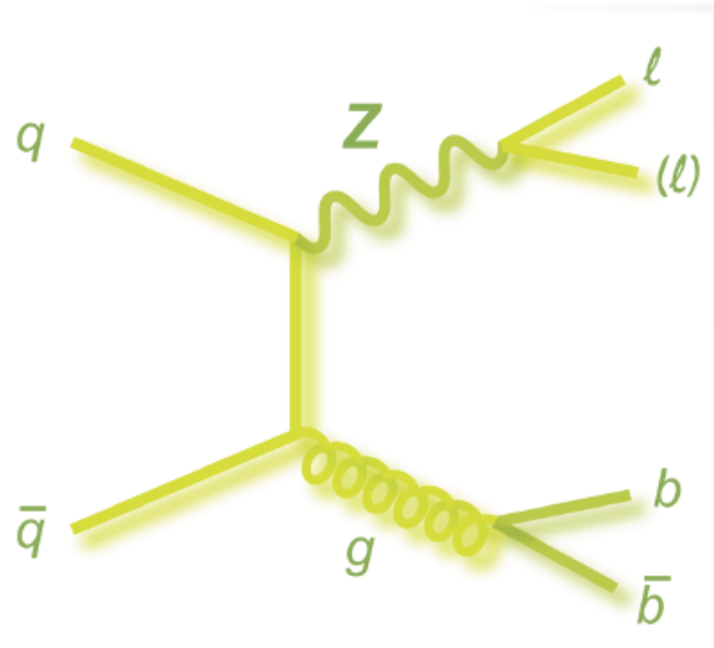


e/μ *BR* 6%

Dilepton Decay Mode







Event selection:

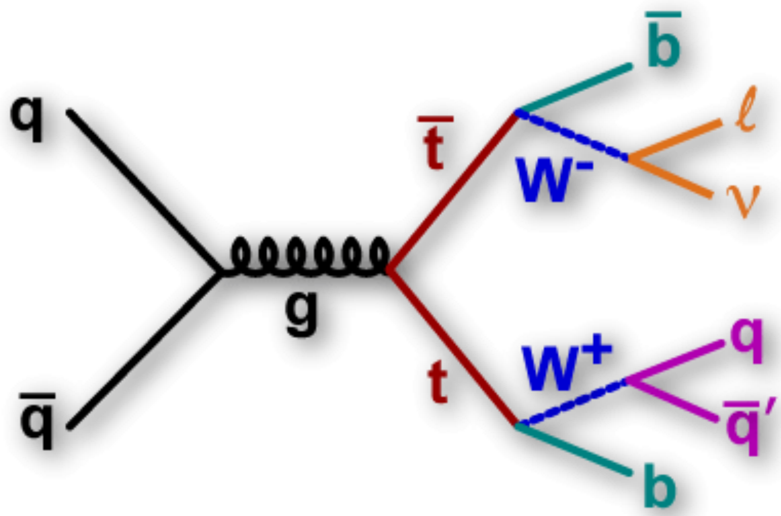
- 2 leptons (e,μ)
- MET (2ν)
- b-jets

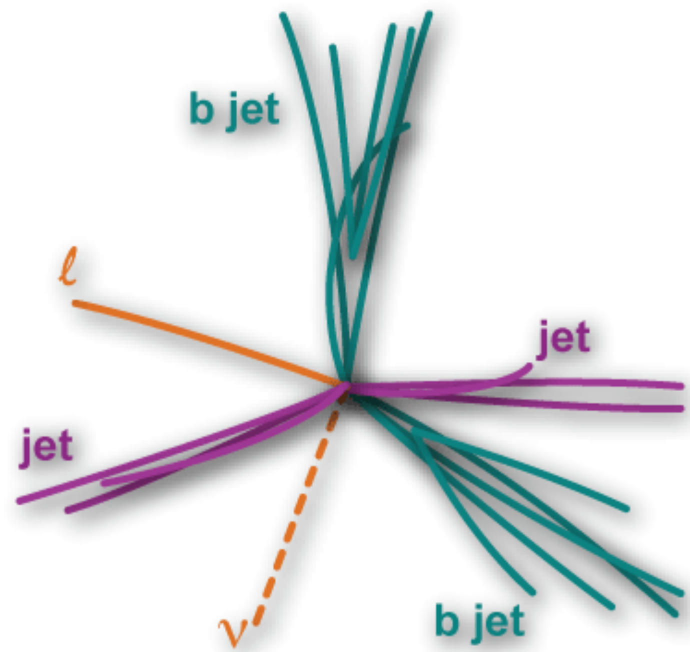
Main Backgrounds

- Z + jets
- single top
- dibosons
- QCD "fakes"

lepton plus jets

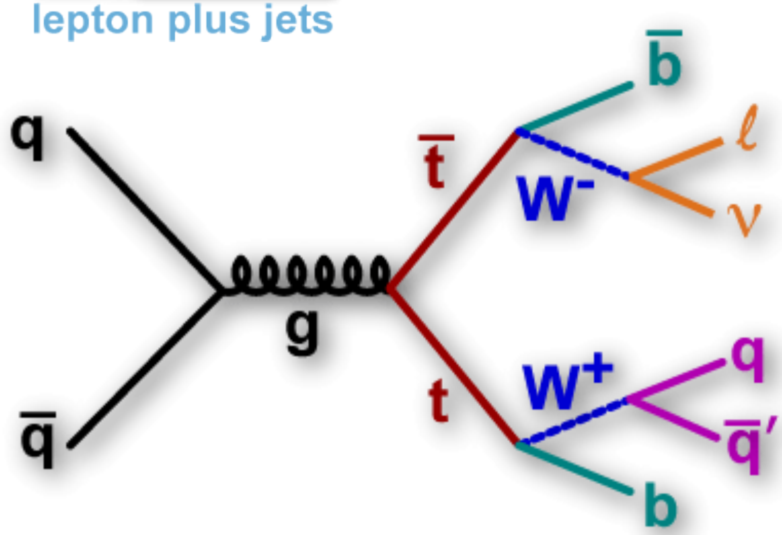
Lepton+Jets Decays

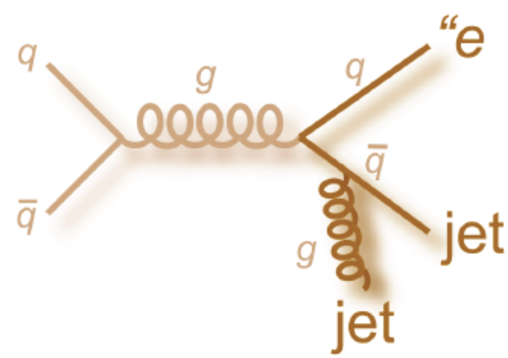


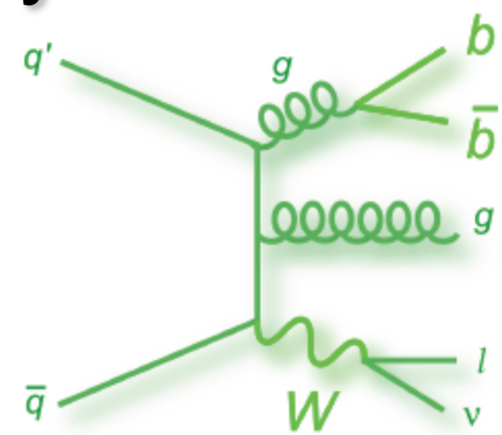


e/μ+jet *BR* 34%

Lepton+Jets Decays







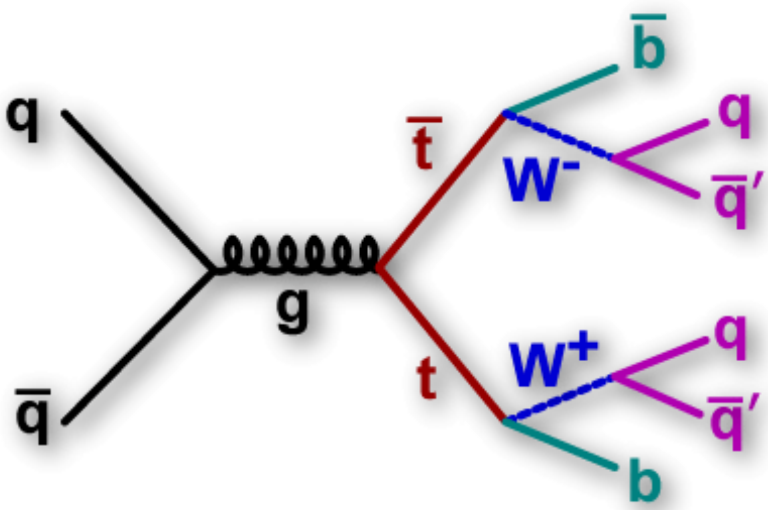
Event selection:

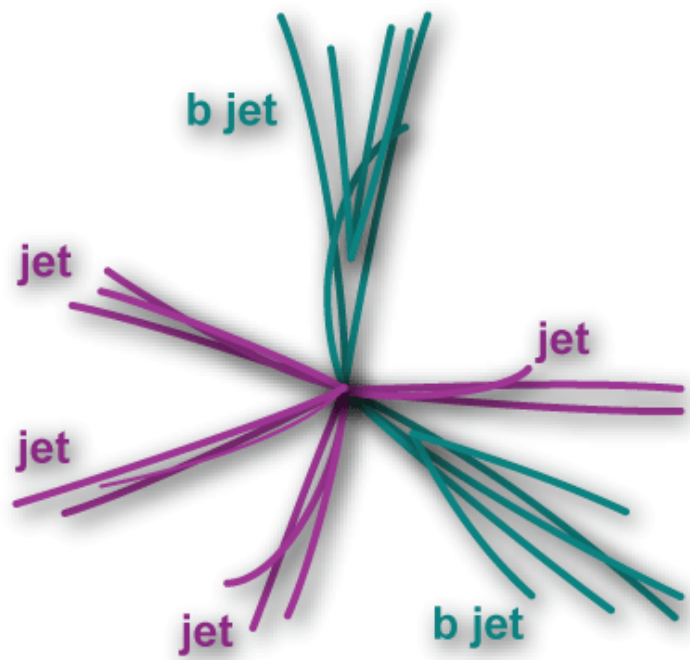
- 1 lepton (e or μ)
- MET (1ν)
- b-jets
- 2 jets

Main Backgrounds

- W + jets
- single top
- dibosons
- Z + jets
- QCD "fakes"

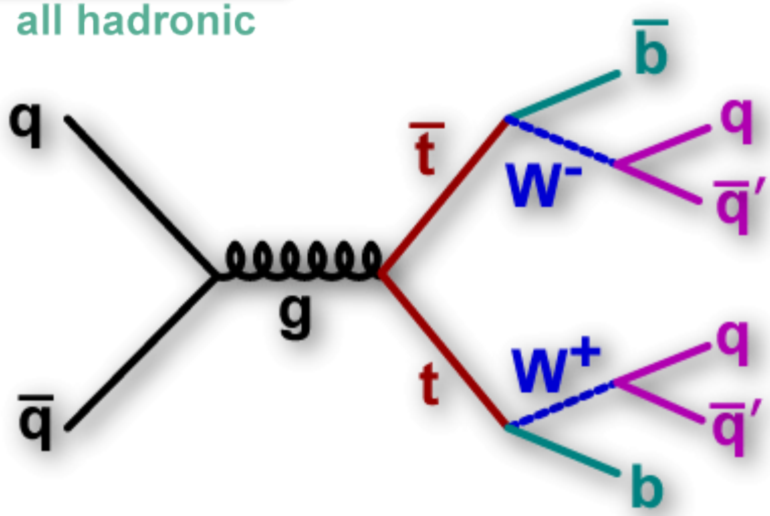
All-Hadronic Decays

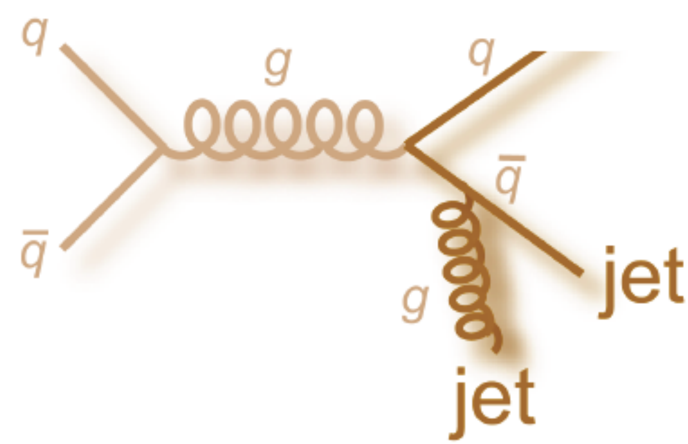




all jets *BR* 46%

All-Hadronic Decays





Event selection:

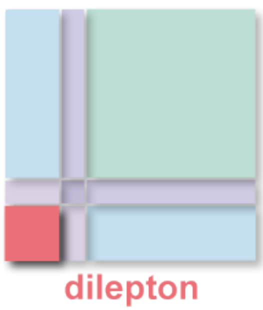
- 0 leptons (veto)
- no MET
- >4 jets
- b jets

Main Backgrounds

- QCD "fakes"

Pros and cons by final state channel:

- fairly good branching ratio (statistics)
- decent S/B ratio
- one ν so can fully reconstruct t-tbar system

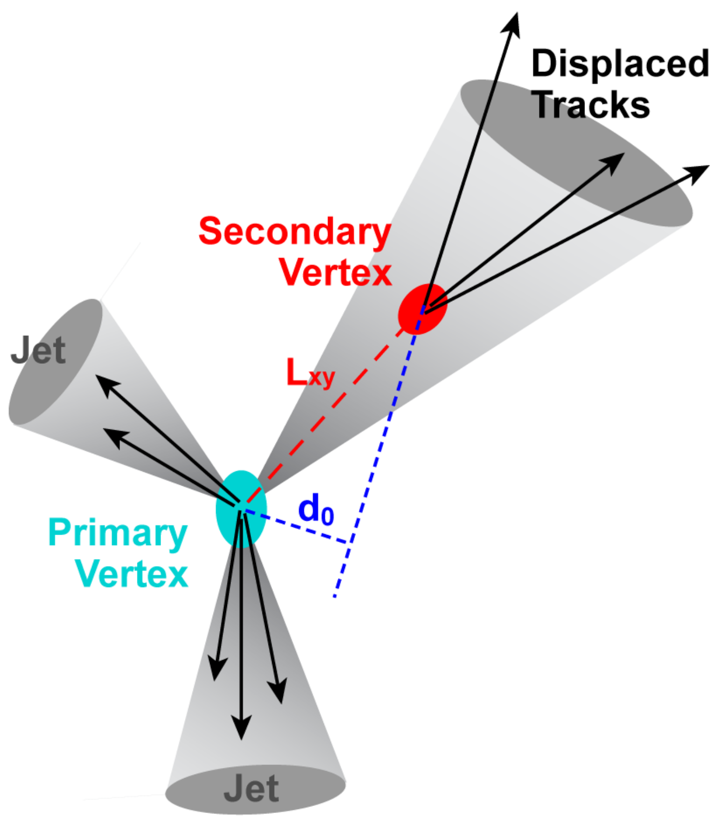


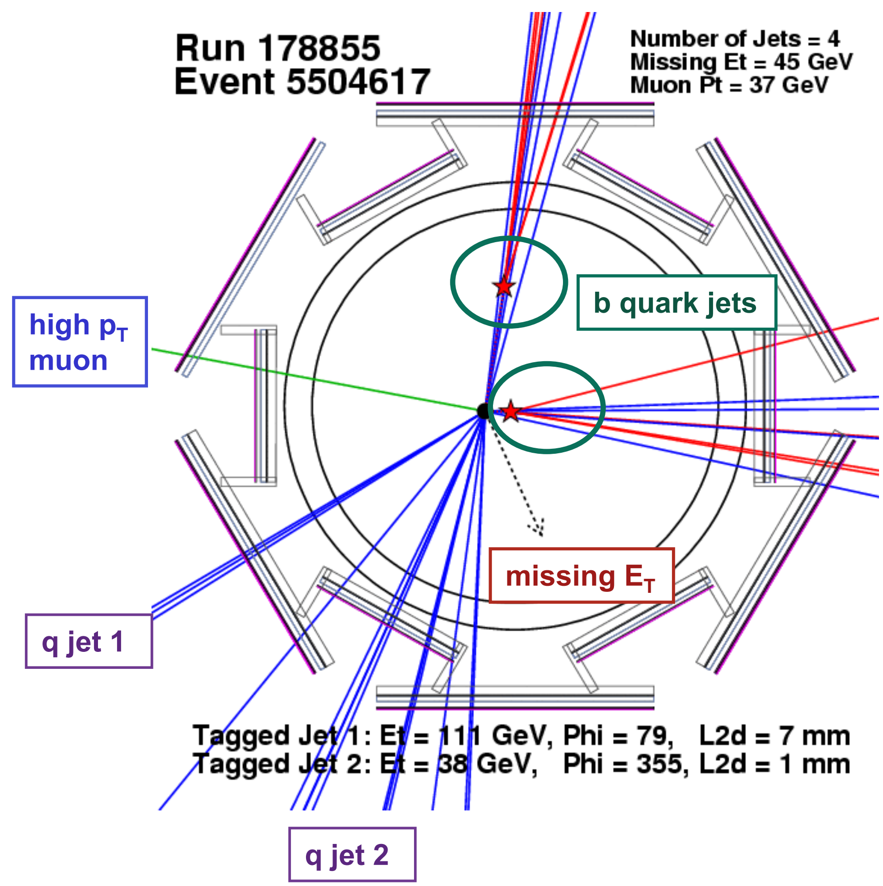
- smallest branching ratio, but…
- highest S/B ratio
- $2\nu \rightarrow$ reconstruction of t-tbar system ambiguous

- highest branching ratio, but…
- lowest S/B ratio
- QCD backgrounds difficult but dominant
- combinatorics of t-tbar reconstruction complex

b-quark lifetime: cτ~450 μm
can travel ~3 mm before decaying

"Tagging" b-quark jets

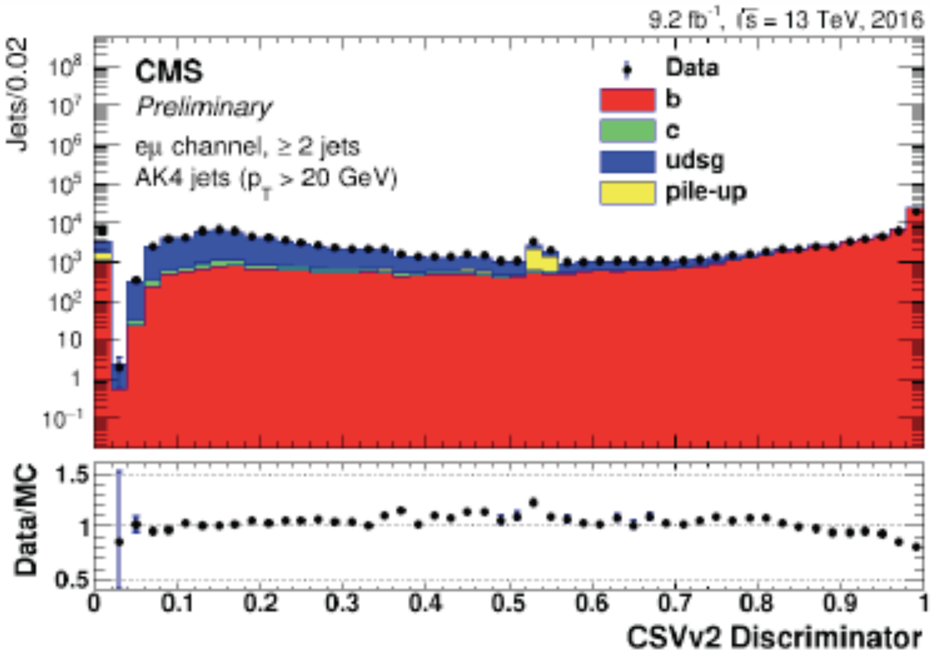




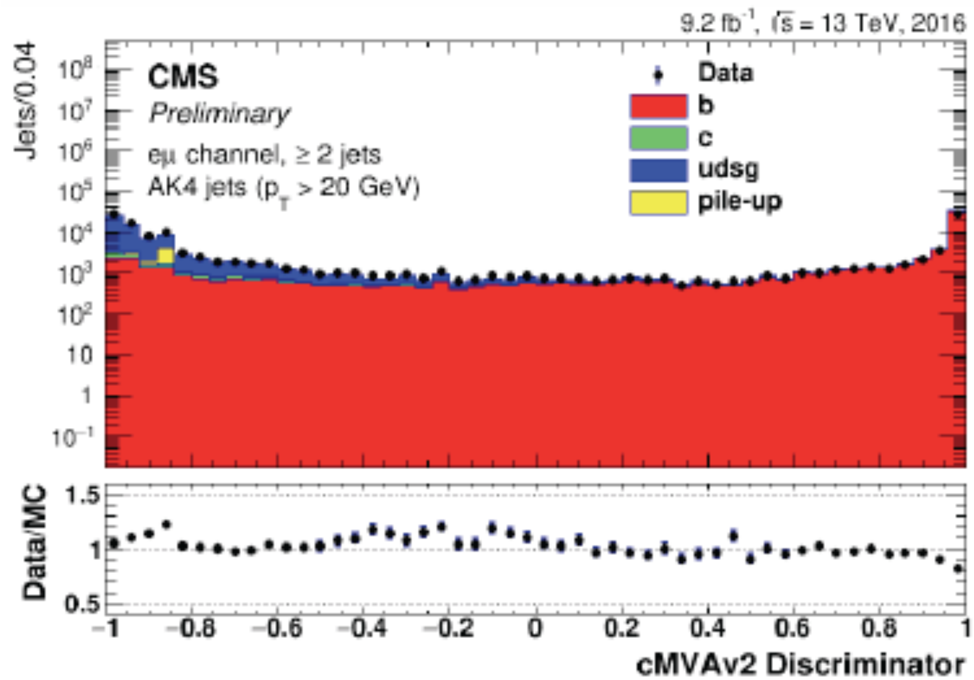
- secondary vertex tagging
  - use silicon tracking
- soft lepton tagging
  - low p_T lepton inside jet from b,c $\rightarrow \ell \nu X$ decay

Multi-variate b-tagging at LHC

"Tagging"
b-quark jets



cMVAv2 (top pair selection):
- boosted decision tree (BDT)
- jet probability and soft lep tags



CSVv2 (top pair selection):
- neural network with inputs from "inclusive vertex finder"
- tight, med, loose working pts

New: Deep neural networks

NNLO and MC generators

Another time…

Top Production Cross Section

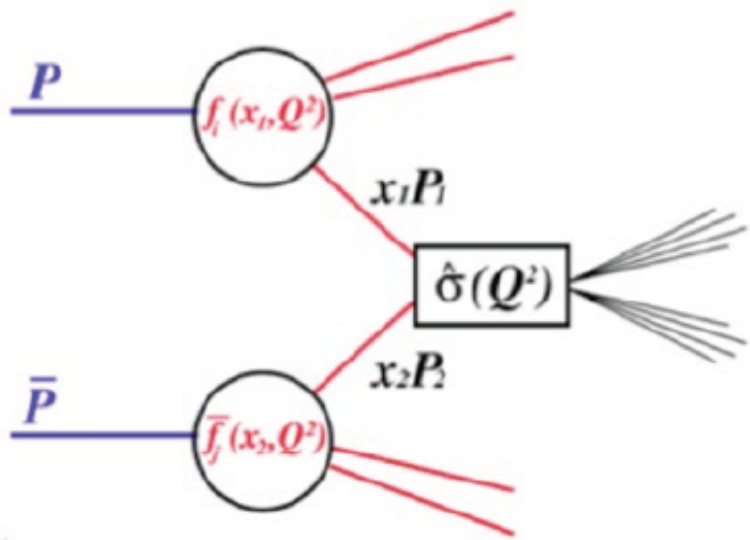
What is a cross section?

Geiger and Rutherford

differential cross section $d\sigma/d\Omega$: Probability of a scattered particle in a given quantum state per unit solid angle $d\Omega$

integrated cross section: $\sigma = \int [d\sigma/d\Omega] \, d\Omega$

Cross section calculation



$$\sigma = \sum_{i,j=q,\bar{q},g} \int dx_1\, dx_2\, f_i(x_1,Q^2) \cdot \bar{f}_j(x_2,Q^2) \cdot \hat{\sigma}(Q^2)$$

Sum over incoming partons i, j

Momentum fraction for incoming parton

PDF for incoming parton i

"partonic" cross section

QCD covered by J. Butterworth

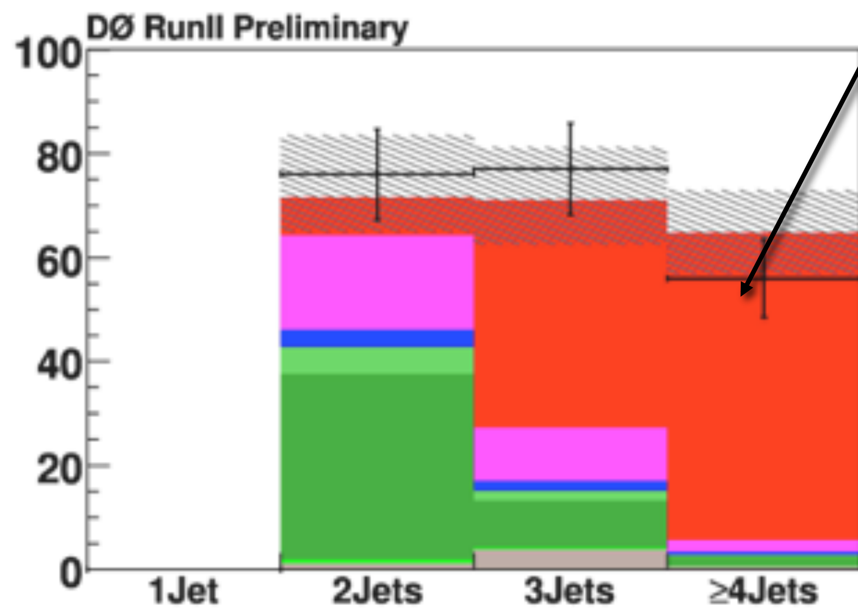
How do we measure the cross section?

$$\sigma(tt) = \frac{N_{events} - N_{background}}{\mathcal{L}uminosity * \varepsilon}$$

Why measure the Top Pair Production Cross Section:

- As QCD predicts?
- Only SM top?
- By heavy particles?

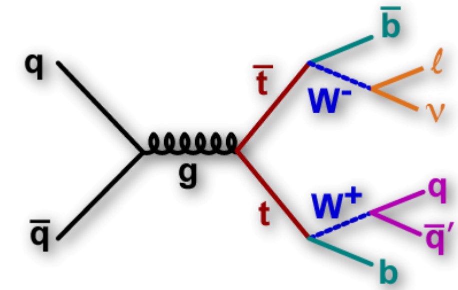
t-tbar!



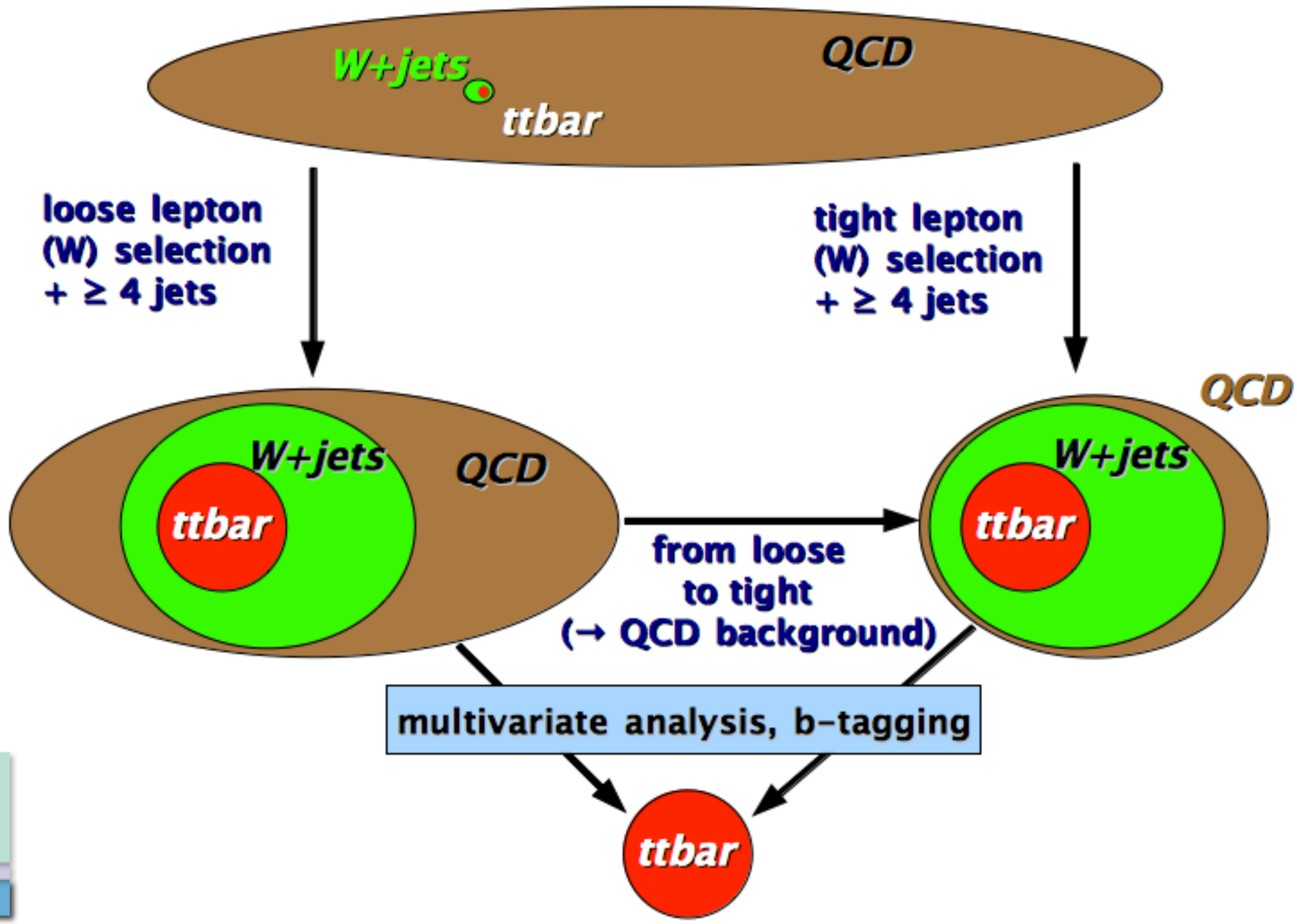
counting experiment

lepton plus jets

How do we measure the cross section?

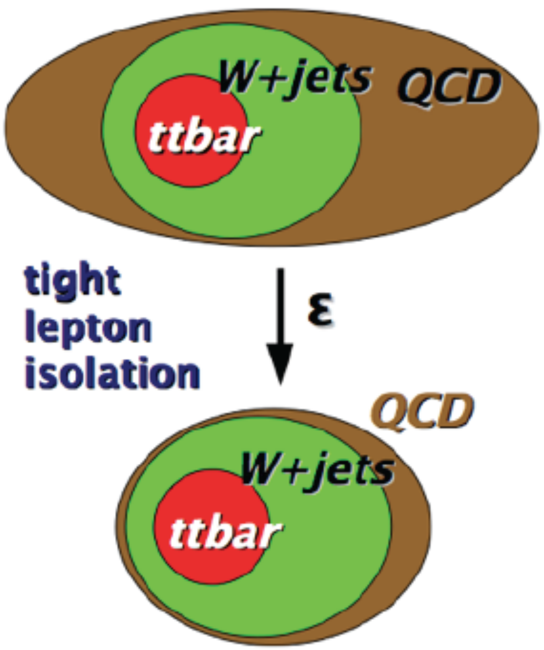


triggered sample: isolated e/μ



lepton plus jets

How do we measure the cross section?



determining QCD from data:

matrix method

$$N_{loose} = N_{QCD} + N_{W+ttbar}$$

$$\downarrow \varepsilon \qquad \varepsilon_{QCD} \downarrow \qquad \varepsilon_{W+ttbar} \downarrow$$

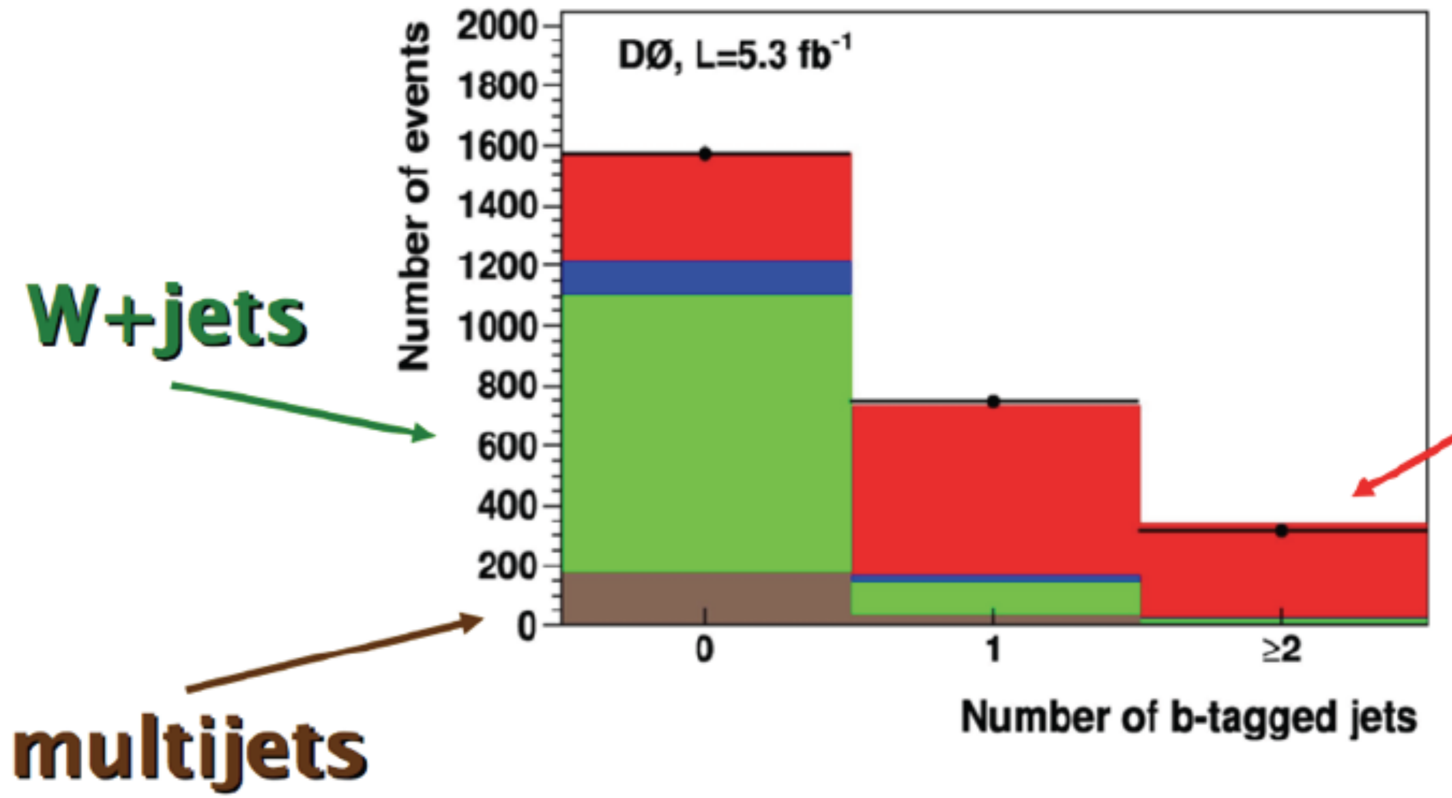
$$N_{tight} = \varepsilon_{QCD} * N_{QCD} + \varepsilon_{W+ttbar} * N_{W+ttbar}$$

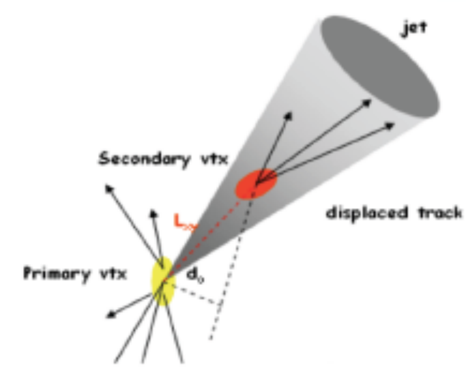
- N_{loose} and N_{tight}: signal datasets
- ε_{QCD} from independent QCD multi-jet dataset *(e.g. low MET sideband)*
- $\varepsilon_{W+ttbar}$ from W+jets MC simulation, normalized to data
- Solve for N_{QCD} and $N_{W+ttbar}$
- Determine multi-jet QCD entirely from data!

How do we measure the cross section?

Counting Experiment

b-tagging: powerful tool to reduce background



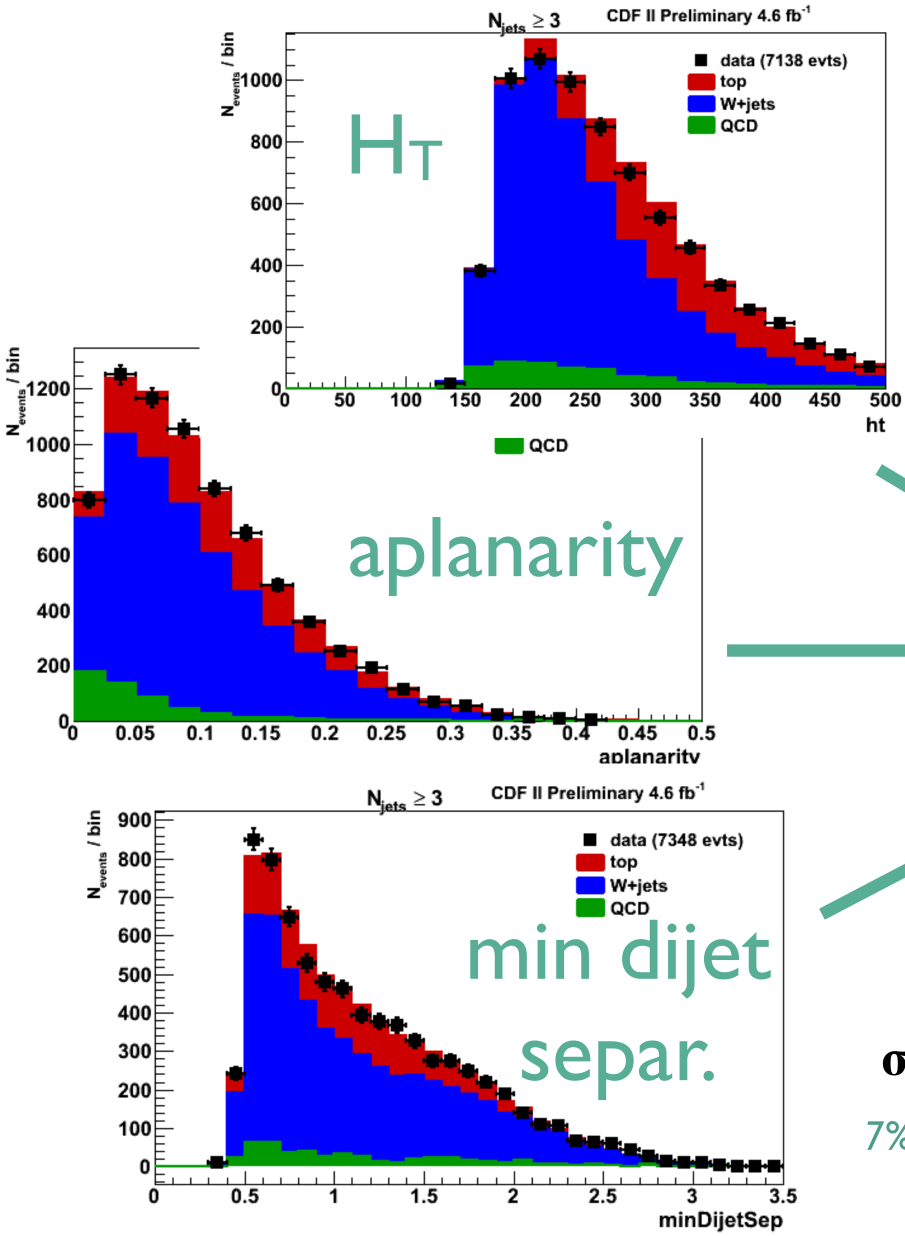


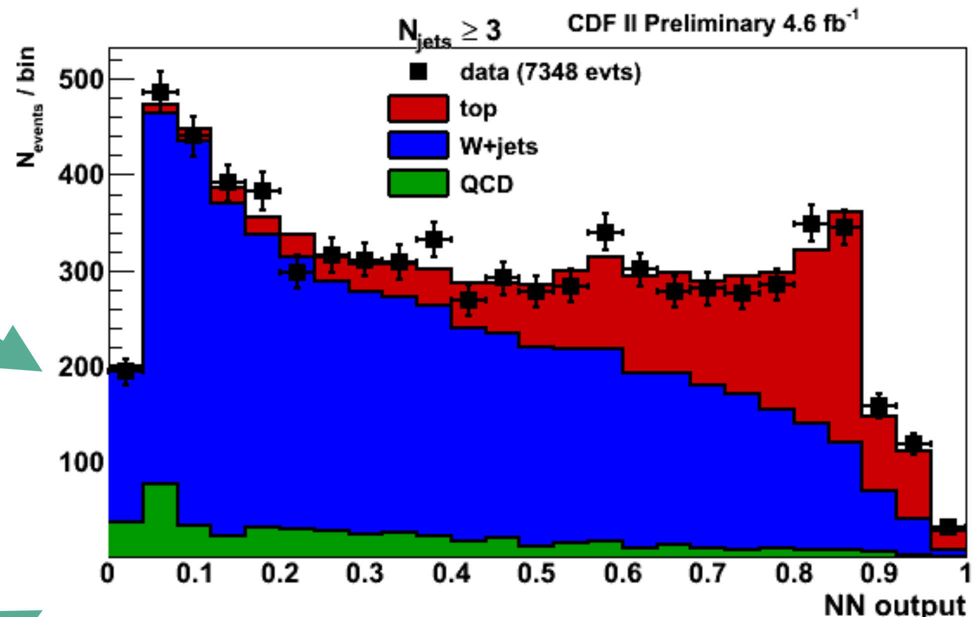
$\sigma_{t\bar{t}} = 8.13^{+1.02}_{-0.90}$ (stat+syst+lumi) pb

m_{top} = 172.5 GeV

How do we measure the cross section?

Multivariate techniques using event topologies





Neural Net

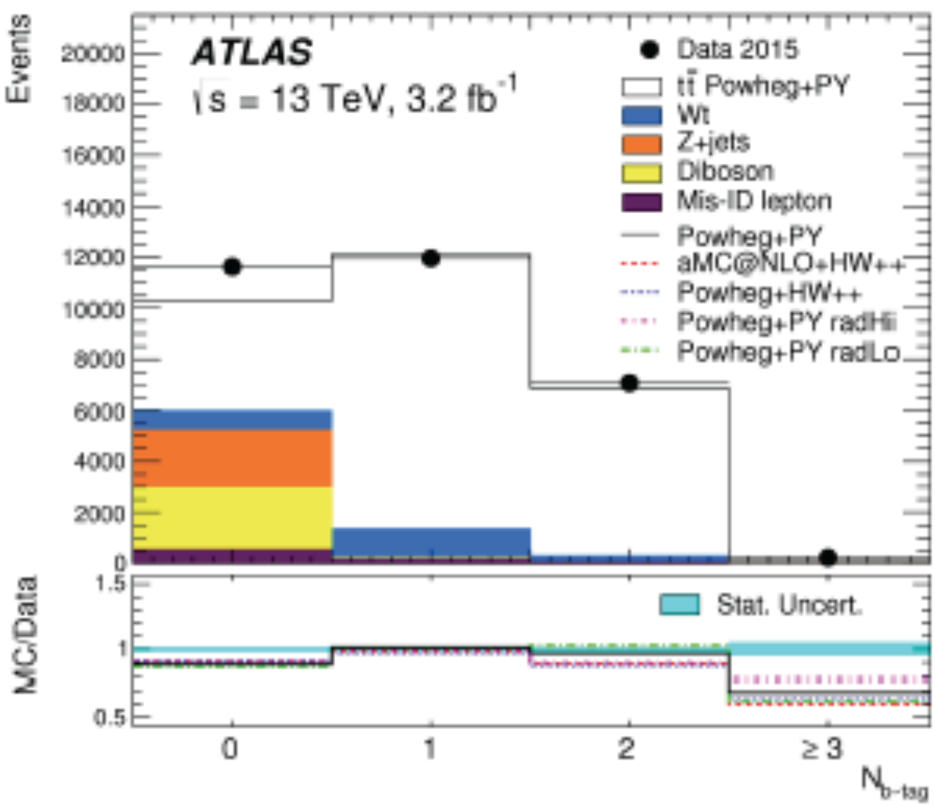
$$\sigma_{ttbar} = 7.82 \pm 0.38(\text{stat}) \pm 0.37(\text{syst}) \pm 0.15\ (\text{theory})\ \text{pb}$$

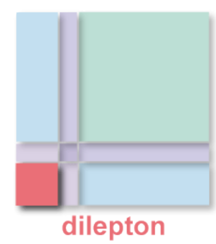
7% relative uncertainty better than 10% Run 2 goal and theory at the time

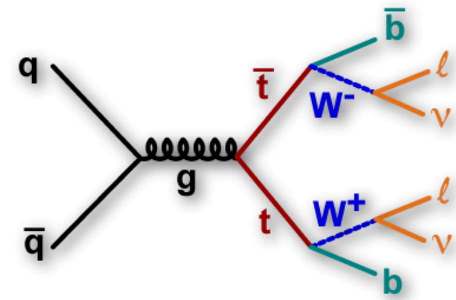
How do we measure the cross section?

New ideas: Extract both σ and b-tag efficiency εb

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







Event counts	N_1	N_2
Data	11958	7069
Single top	1140 ± 100	221 ± 68
Dibosons	34 ± 11	1 ± 0
$Z(\rightarrow \tau\tau \rightarrow e\mu)$+jets	37 ± 18	2 ± 1
Misidentified leptons	164 ± 65	116 ± 55
Total background	1370 ± 120	340 ± 88

- Selection requires one electron, one muon and one or more b-tagged jets (70% eff).
- B-tagging efficiency absorbs systematic uncertainties due to b-tagging and BJES.
- Dominant uncertainties from hadronisation.

$$\sigma_{t\bar{t}}^{\text{meas.}} = 818 \pm 8\ (\text{stat}) \ \pm 27\ (\text{syst}) \ \pm 19\ (\text{lumi}) \ \pm 12\ (\text{beam})\ \text{pb}$$
$$\sigma_{t\bar{t}}^{\text{NNLO}} = 832^{+40}_{-46}\ \text{pb}$$
$$\epsilon_b = 0.559 \pm 0.004\ (\text{stat}). \ \pm 0.003\ (\text{syst}).$$
$$\epsilon_b^{MC} = 0.549$$

How do we measure the cross section?

Strategy and trade-offs: optimizing uncertainties

D0 optimized technique for stat uncertainty

CDF reduced 6% lumi uncertainty to 2% theory uncertainty by normalizing by Z cross section

Uncertainty (pb)	CDF	D0	Tevatron
Statistics	**0.31**	**0.20**	**0.20**
All systematics	**0.39**	**0.56**	**0.36**
Signal model *	0.21	0.13	0.18
Luminosity (inel)*	0.05	0.30	0.15
Luminosity (det)	0.06	0.35	0.14
Detector model	0.17	0.22	0.13
Jet model	0.21	0.11	0.13
Bkg theory *	0.10	0.08	0.10
Z normalization	0.13	N/A	0.08
Bkg data	0.08	0.06	0.05
Method	0.01	0.07	0.03

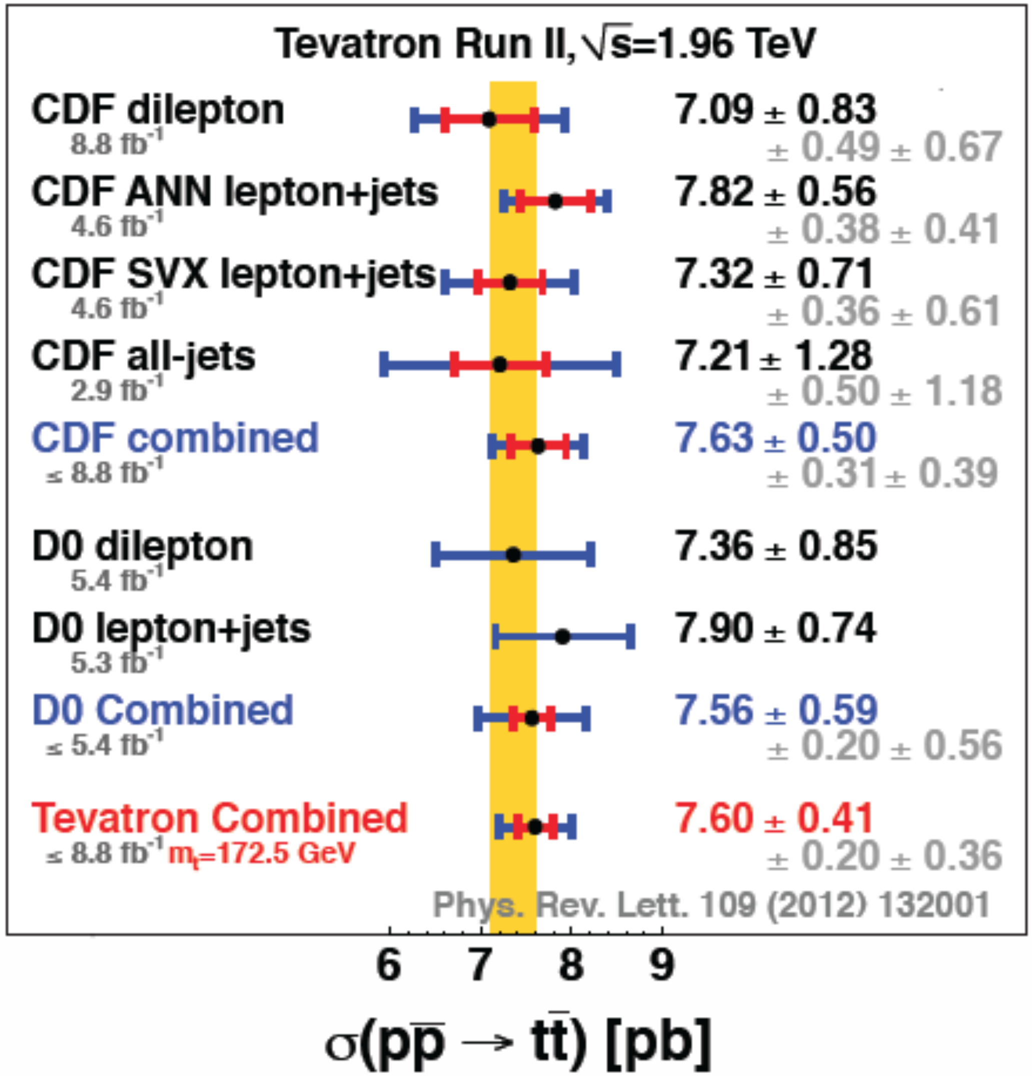
How do we measure the cross section?

example menu of uncertainties at the LHC

$\sqrt{s}$ Uncertainty (inclusive $\sigma_{t\bar{t}}$)	7 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	7 TeV $\Delta C_b/C_b$ (%)	7 TeV $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	8 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	8 TeV $\Delta C_b/C_b$ (%)	8 TeV $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			1.69			0.71
$t\bar{t}$ modelling	0.71	−0.72	1.43	0.65	−0.57	1.22
Parton distribution functions	1.03	-	1.04	1.12	-	1.13
QCD scale choice	0.30	-	0.30	0.30	-	0.30
Single-top modelling	-	-	0.34	-	-	0.42
Single-top/$t\bar{t}$ interference	-	-	0.22	-	-	0.15
Single-top Wt cross-section	-	-	0.72	-	-	0.69
Diboson modelling	-	-	0.12	-	-	0.13
Diboson cross-sections	-	-	0.03	-	-	0.03
Z+jets extrapolation	-	-	0.05	-	-	0.02
Electron energy scale/resolution	0.19	−0.00	0.22	0.46	0.02	0.51
Electron identification	0.12	0.00	0.13	0.36	0.00	0.41
Muon momentum scale/resolution	0.12	0.00	0.14	0.01	0.01	0.02
Muon identification	0.27	0.00	0.30	0.38	0.00	0.42
Lepton isolation	0.74	-	0.74	0.37	-	0.37
Lepton trigger	0.15	−0.02	0.19	0.15	0.00	0.16
Jet energy scale	0.22	0.06	0.27	0.47	0.07	0.52
Jet energy resolution	−0.16	0.08	0.30	−0.36	0.05	0.51
Jet reconstruction/vertex fraction	0.00	0.00	0.06	0.01	0.01	0.03
b-tagging	-	0.18	0.41	-	0.14	0.40
Misidentified leptons	-	-	0.41	-	-	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	1.56	0.75	2.27	1.66	0.59	2.26
Integrated luminosity	-	-	1.98	-	-	3.10
LHC beam energy	-	-	1.79	-	-	1.72
Total uncertainty ($\sigma_{t\bar{t}}$)	1.56	0.75	3.89	1.66	0.59	4.27

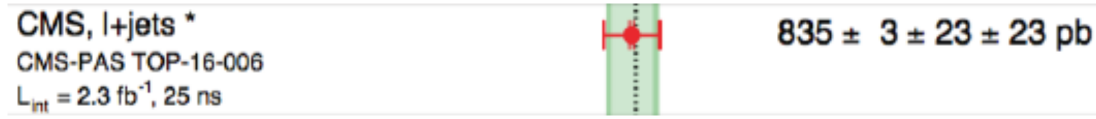
Tevatron top cross section summary

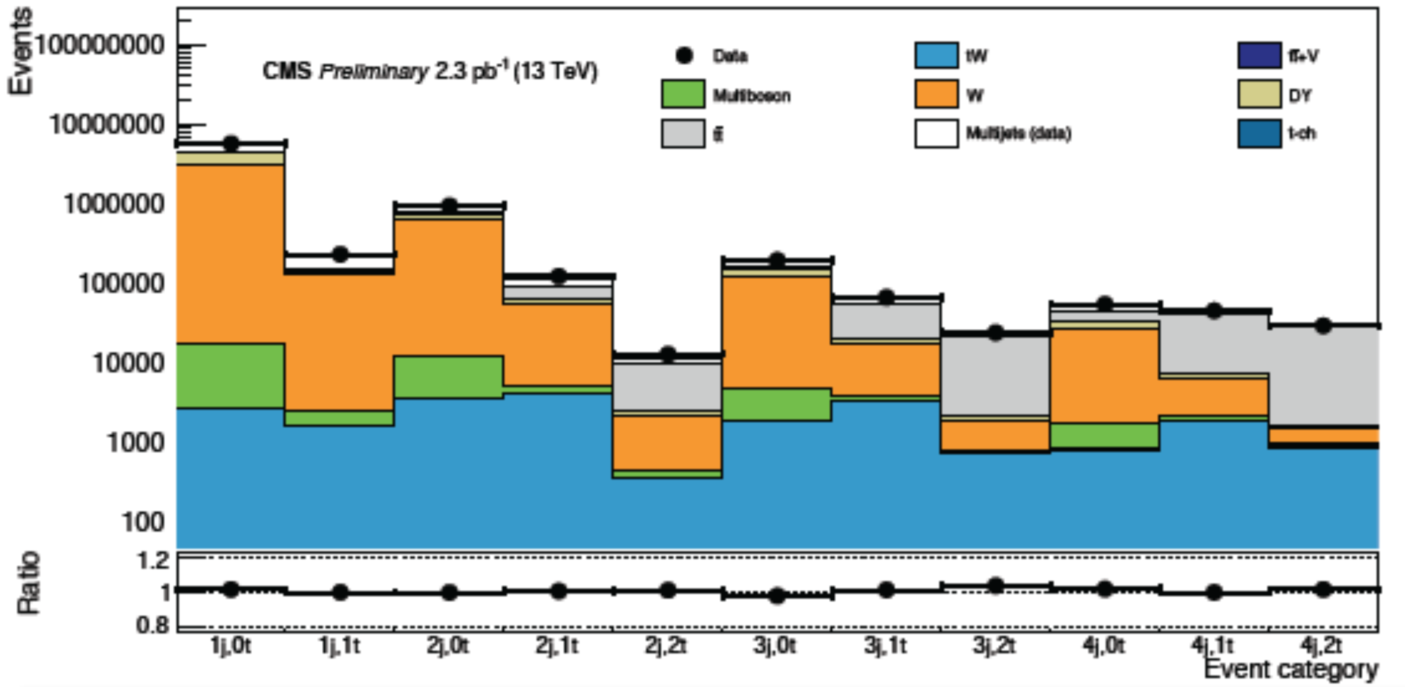
NNLO+NNLL



Good agreement with NNLO+NNLL

How do we measure the cross section?





TOP-16-006 –
e/μ +jets channel at 13 TeV

- Shape fit in 44 lepton charge (b) jet multiplicity categories.
- In-situ constraints on systematics
- Total uncertainty ~ **3.9%**

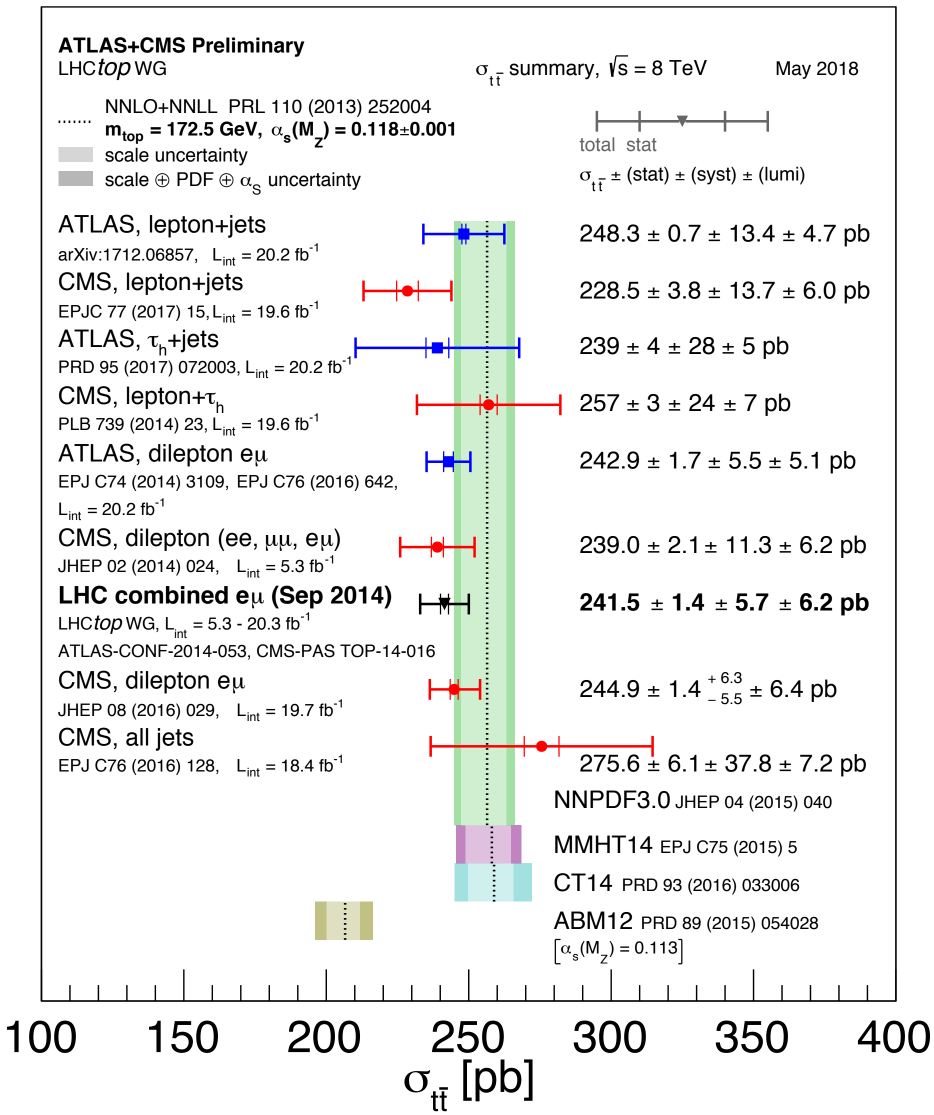
- Most precise **13 TeV** CMS measurement so far
- Largest uncertainties:
  - W+jets bkg. modelling
  - Luminosity
- Extraction of M_{top} (pole)

$$m_t = 172.3^{+2.7}_{-2.3}\,\text{GeV}$$

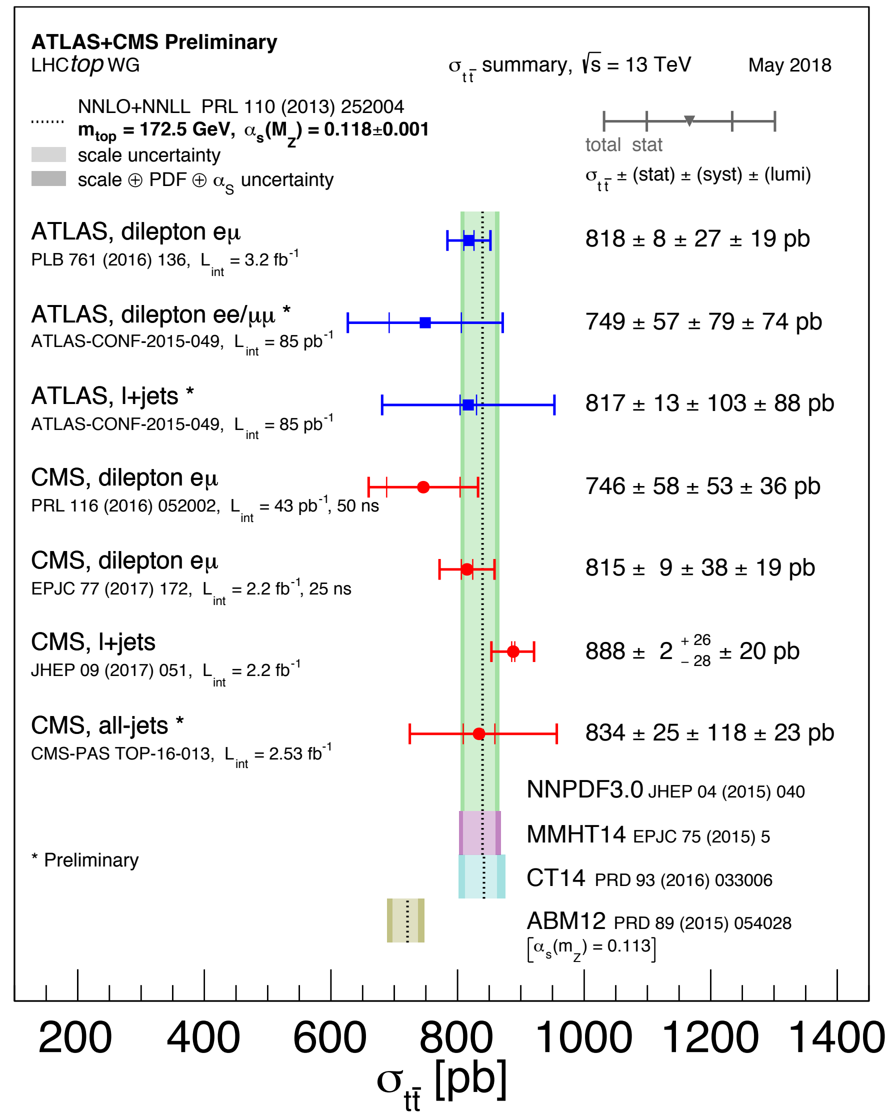
...

All channels measured: look for the unexpected!

ATLAS & CMS 8 TeV

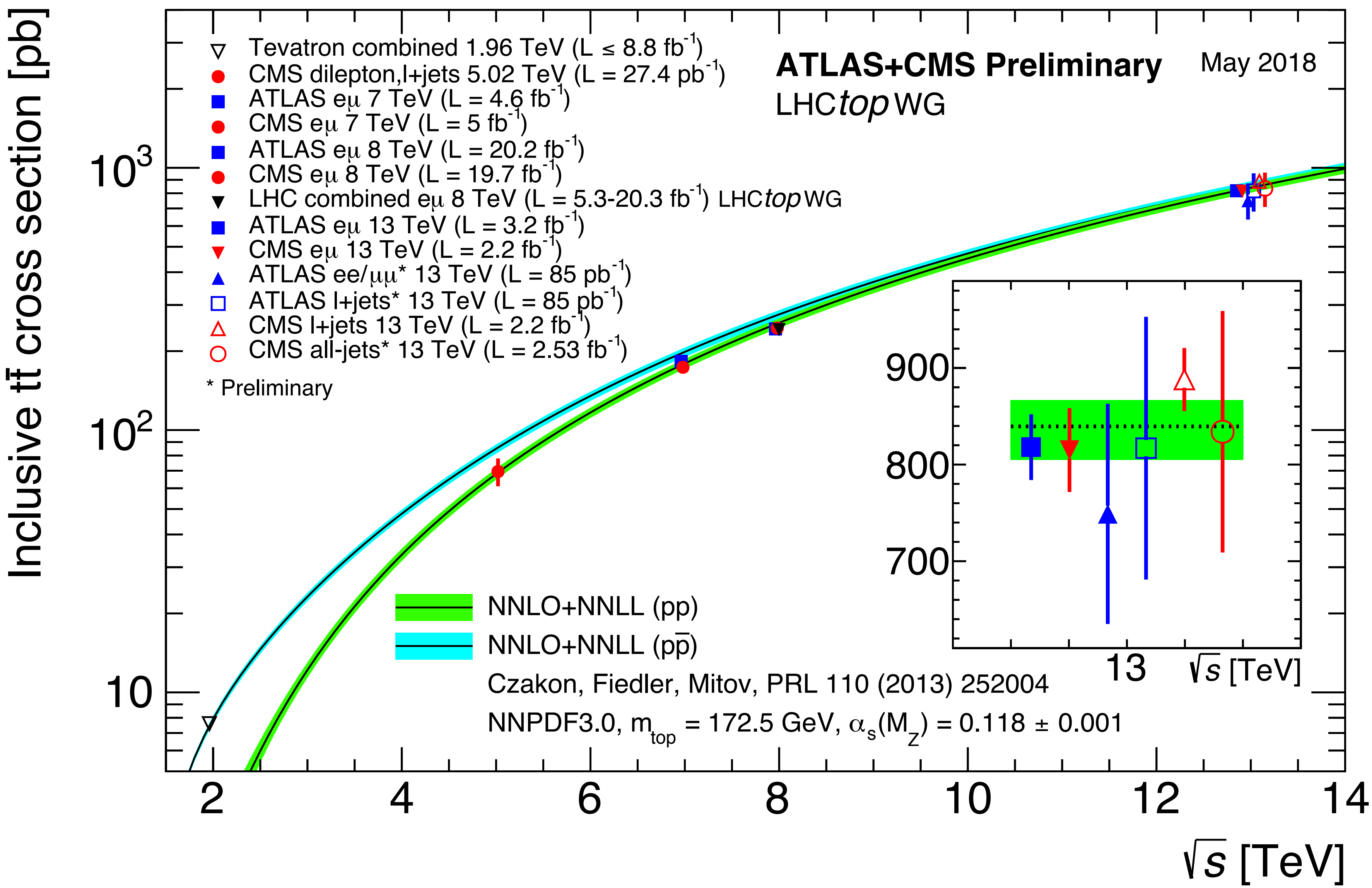


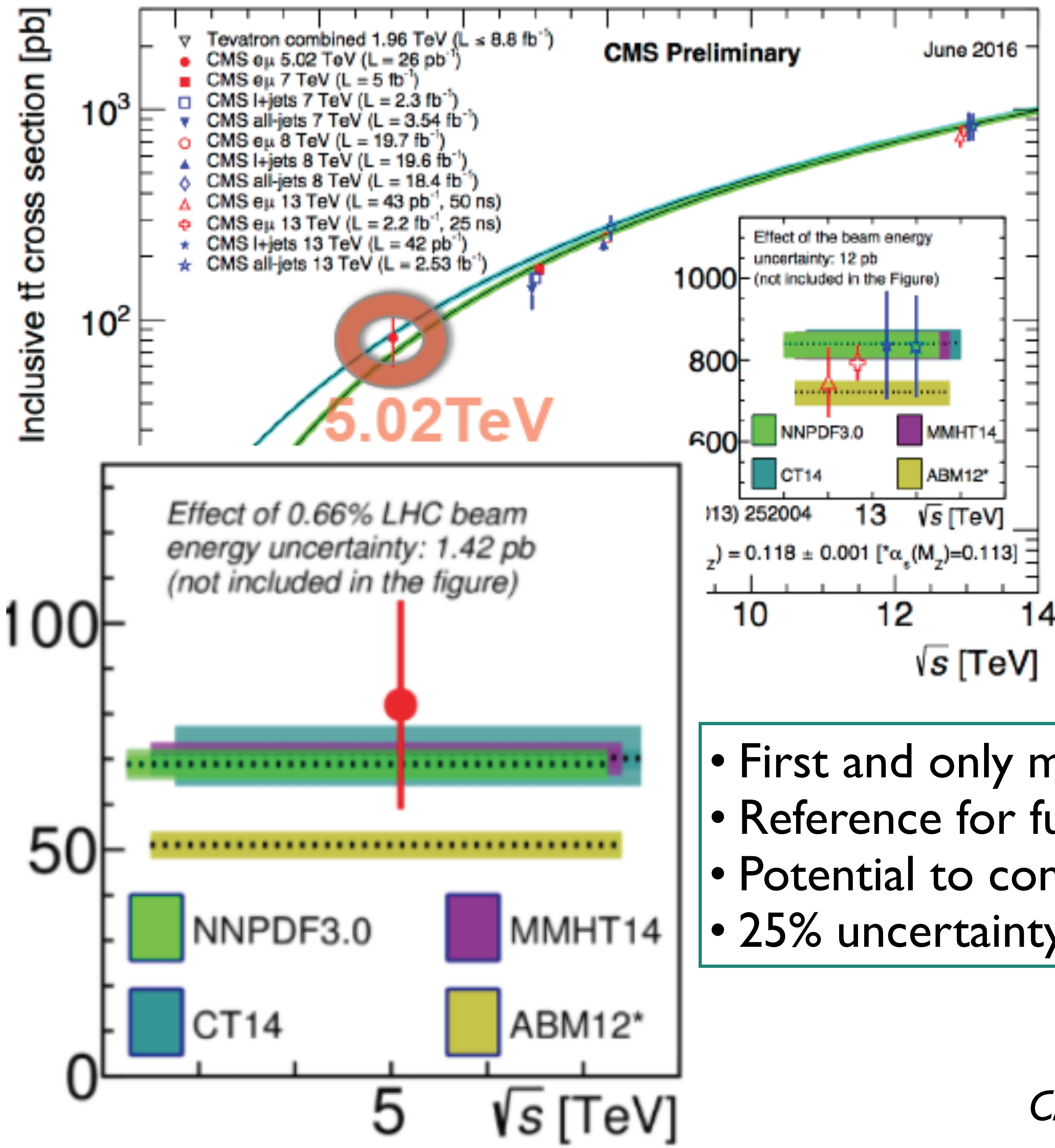
ATLAS & CMS 13 TeV



Measurement precision comparable to theory

Tevatron and LHC results consistent with NNLO+NNLL over a large range of CM energies



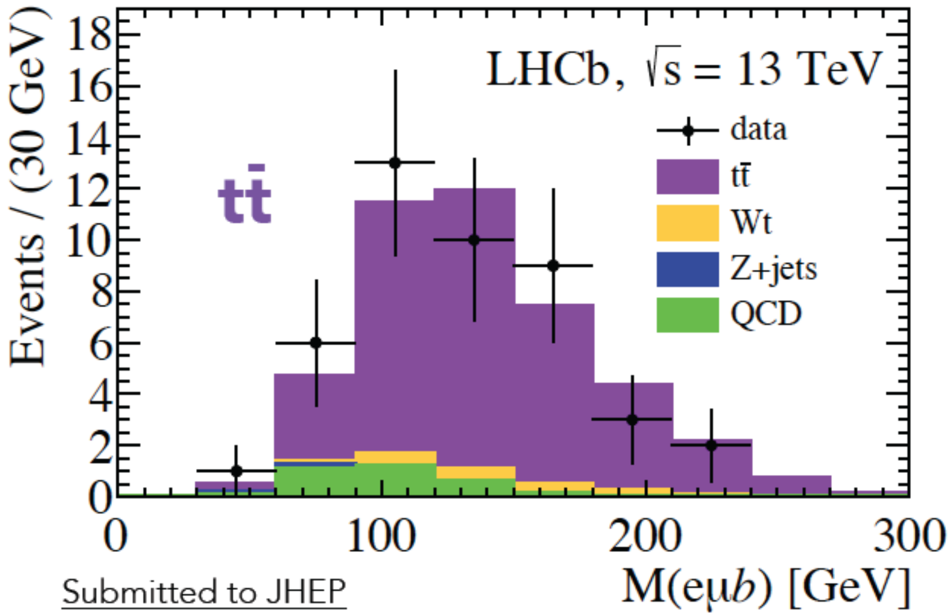


CMS: special run at $\sqrt{s}$ = 5 TeV

- First and only measurement at this energy
- Reference for future heavy ion analysis
- Potential to constrain high-x gluon PDF
- 25% uncertainty dominated by stats

CMS-TOP-16-015

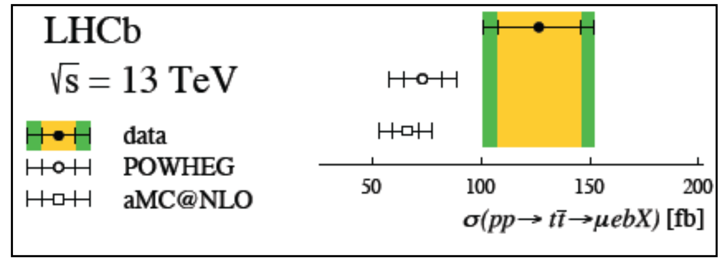
Top quarks measured at LHCb and in CMS p-Pb!



Submitted to JHEP

Forward top production at LHCb

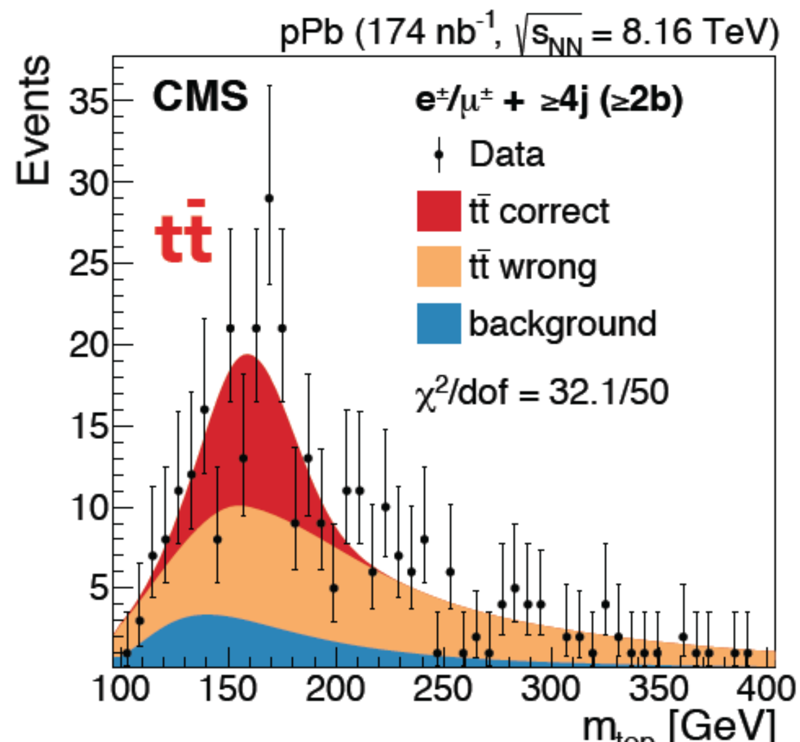
$2<|\eta|<4.5$



$\sigma_{tt,\,fid}$ = 45±8 nb

Observation of tops in p-Pb collisions

- Precise probe of nuclear gluon density
- σ_{tt} = 45±8 nb, consistent with predictions



PRL 119 (2017) 242001

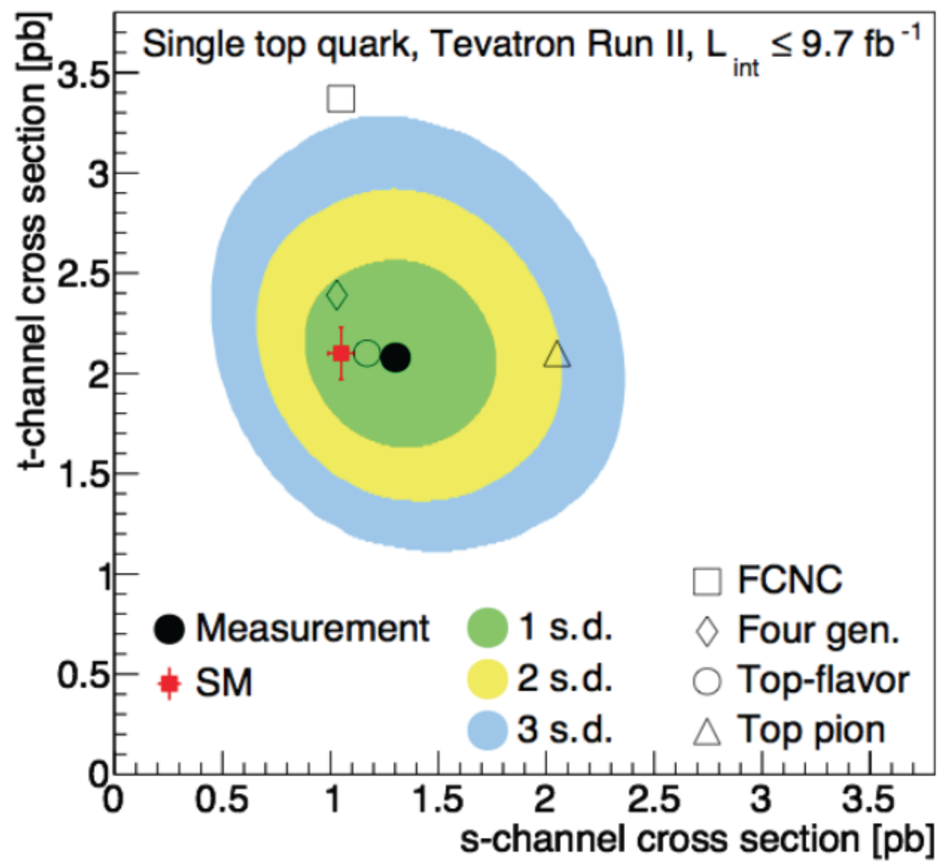
Electroweak Single Top Production

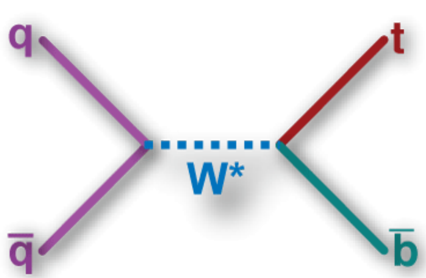
Searches for Single top at the Tevatron

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- direct measurement of $|V_{tb}|$
- sensitive to new physics models

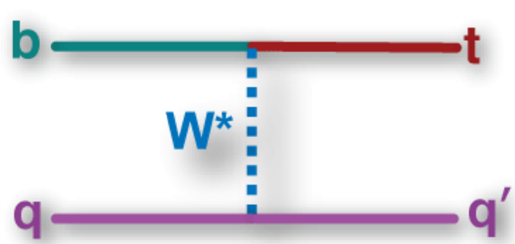
Single top quark production as a window to physics beyond the standard model
Timothy M.P. Tait, C.-P. Yuan
Published in **Phys.Rev. D63** (2000) 014018
e-Print: hep-ph/0007298



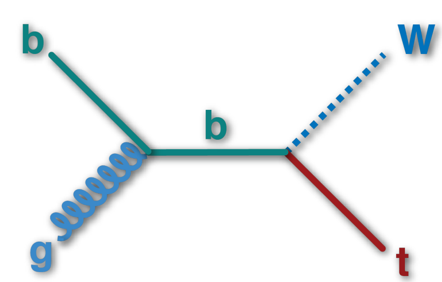


s-channel

only at Tevatron so far



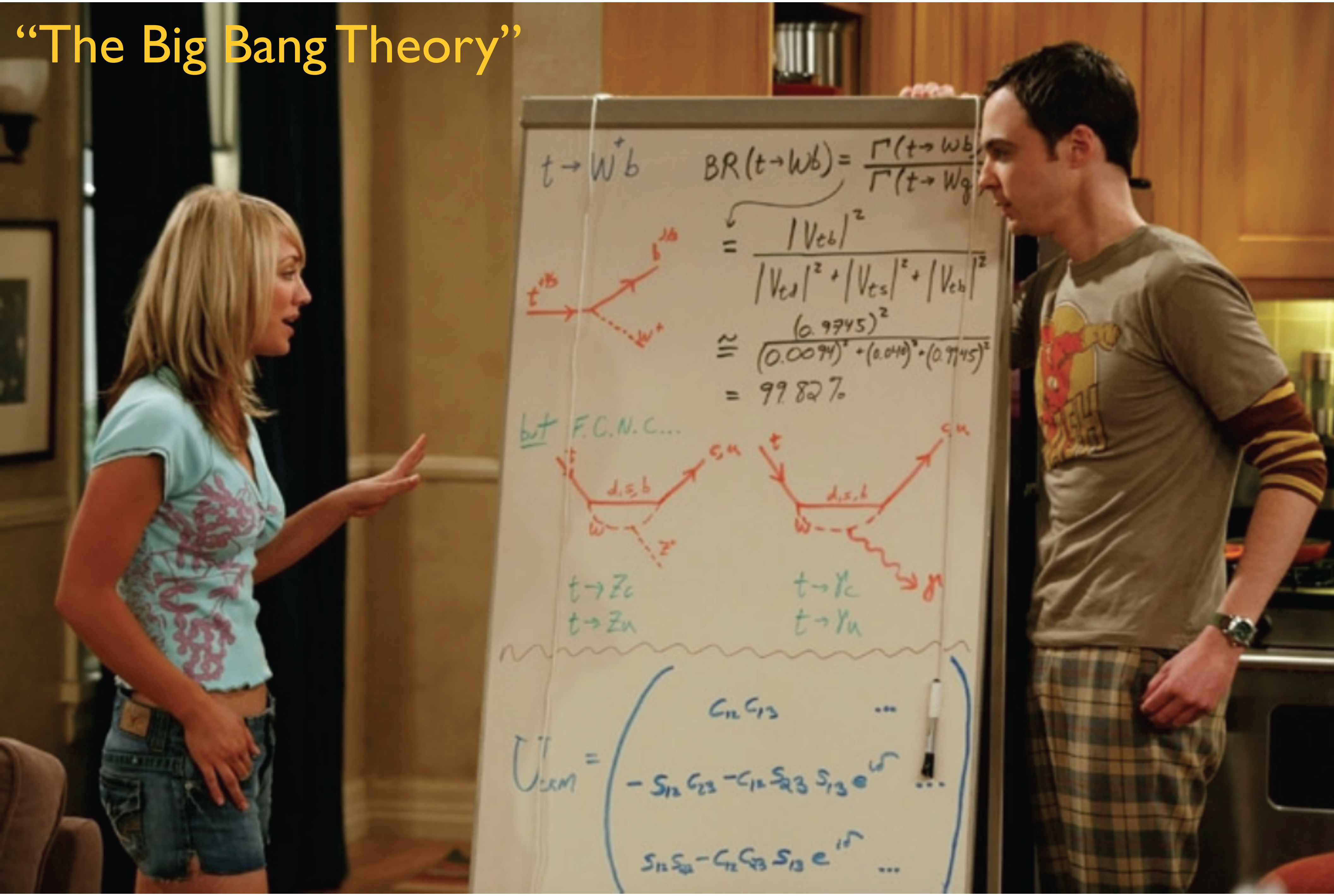
t-channel



Wt-production

only at LHC

“The Big Bang Theory”

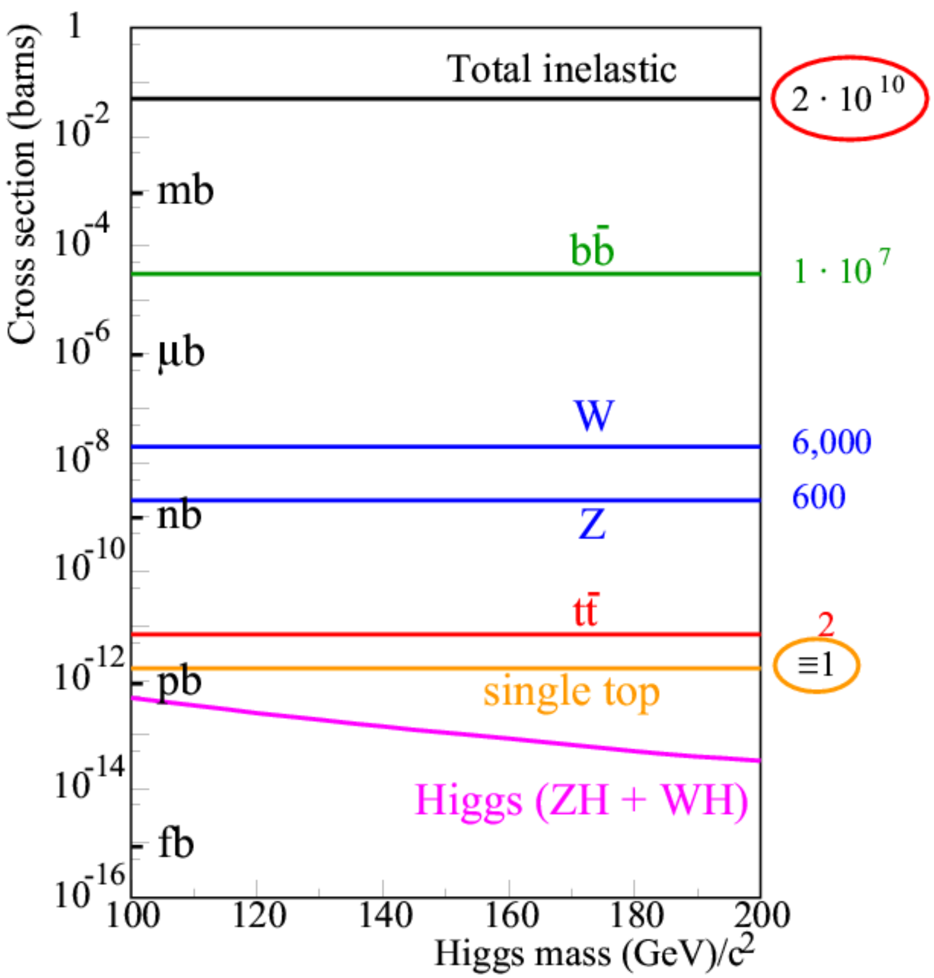


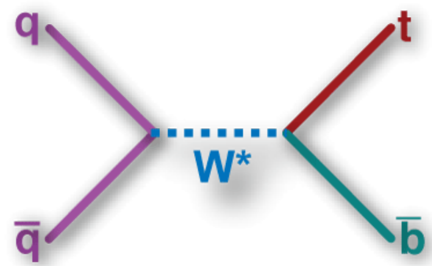
Searches for Single top at the Tevatron

Single top backgrounds much larger than signal: Only ~2 jets! (QCD dijet events)

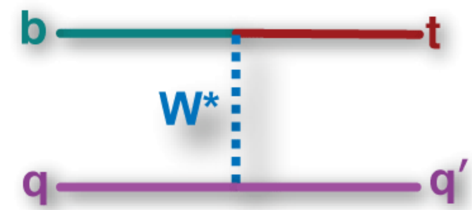
=> Statistically & systematically challenging

(Good exercise for Higgs searches!)





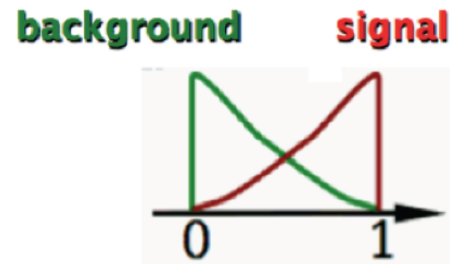
s-channel
1.05 ± 0.06 pb

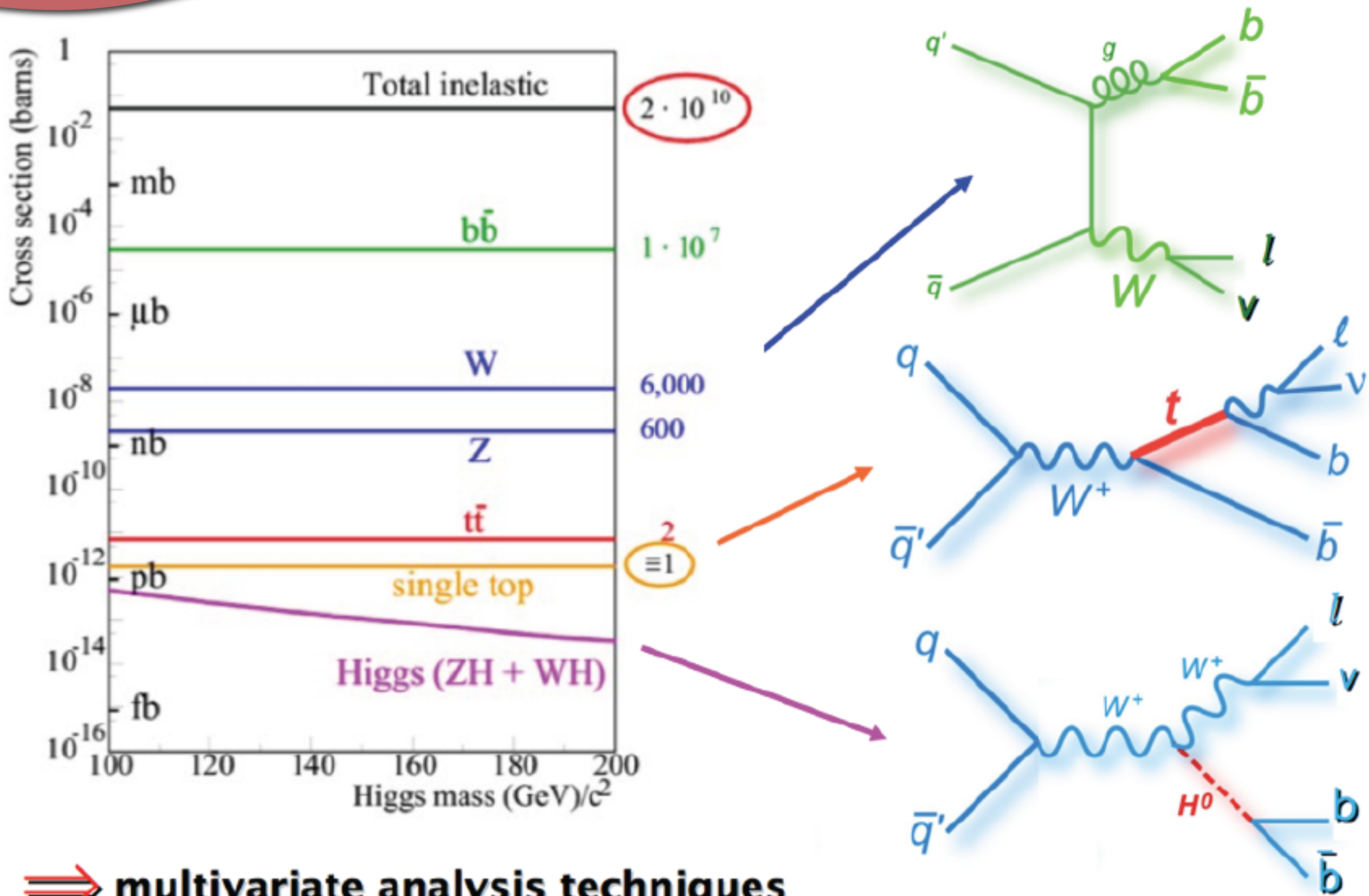


t-channel
2.12 ± 0.16 pb

Searches for Single top at the Tevatron

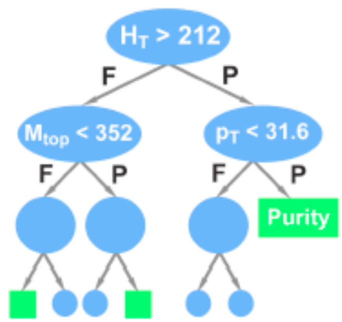
low cross section,
challenging backgrounds!
best S/B 1/200 before b-tag



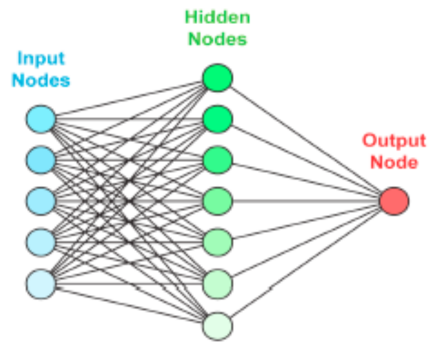


⇒ **multivariate analysis techniques**

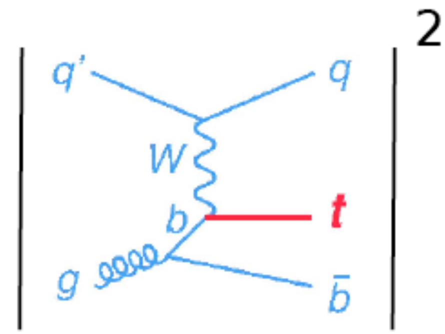
Decision Trees



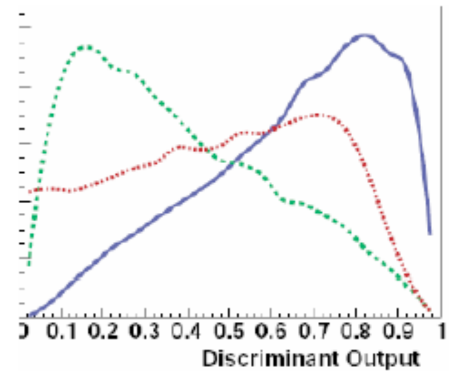
Neural Networks



Matrix Elements



Likelihoods

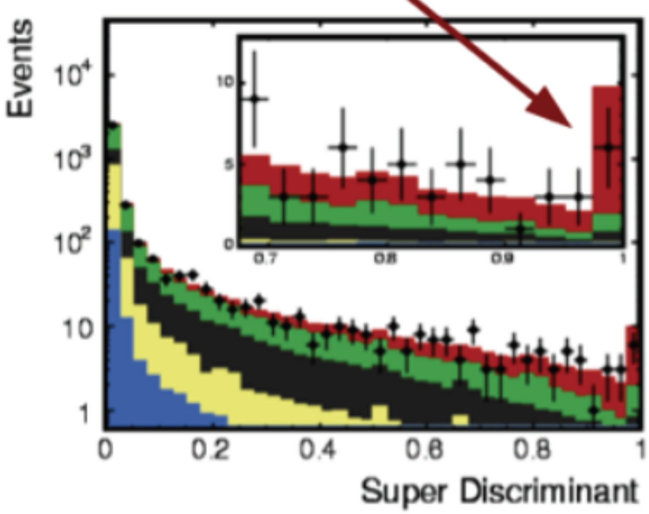


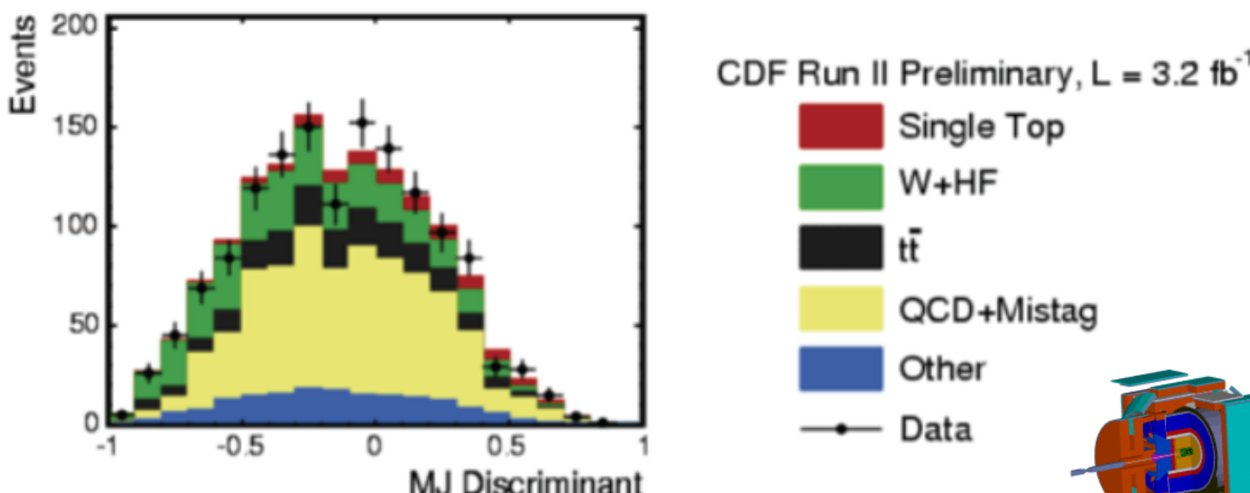
Combined up to 8 different analysis channels

single top

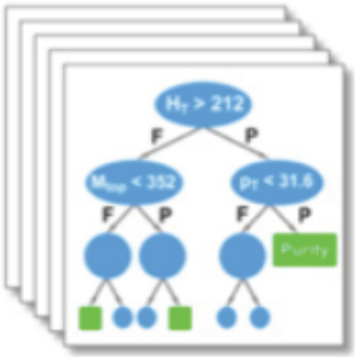
- **$\not{E}_T$+jets selection :**

recover badly reconstructed e, μ; include τ

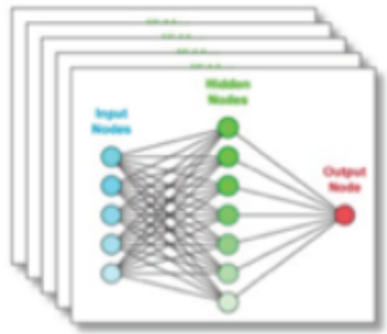




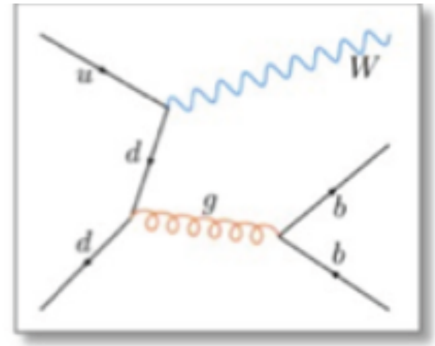
boosted decision trees



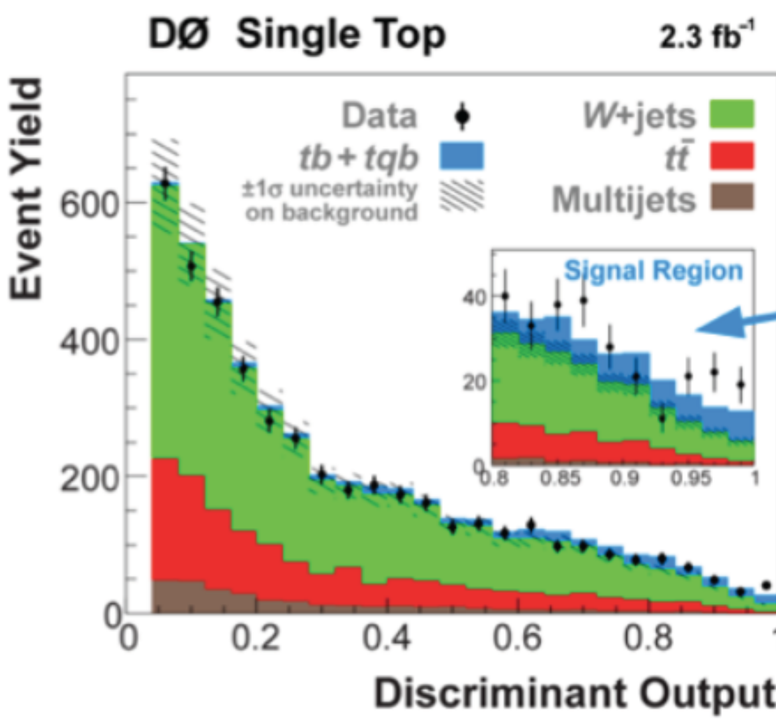
neural nets



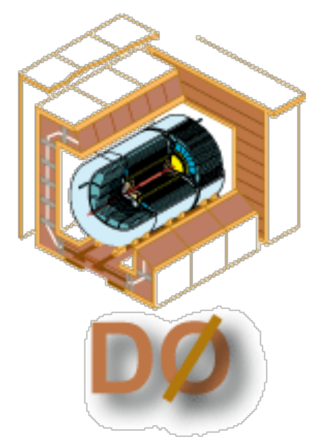
matrix elements



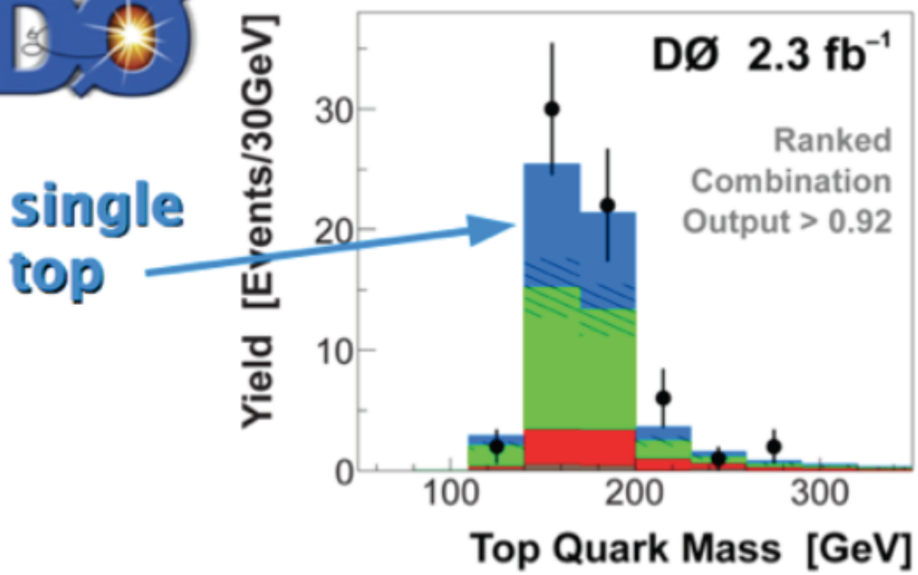
Combined up to 12 different analysis channels

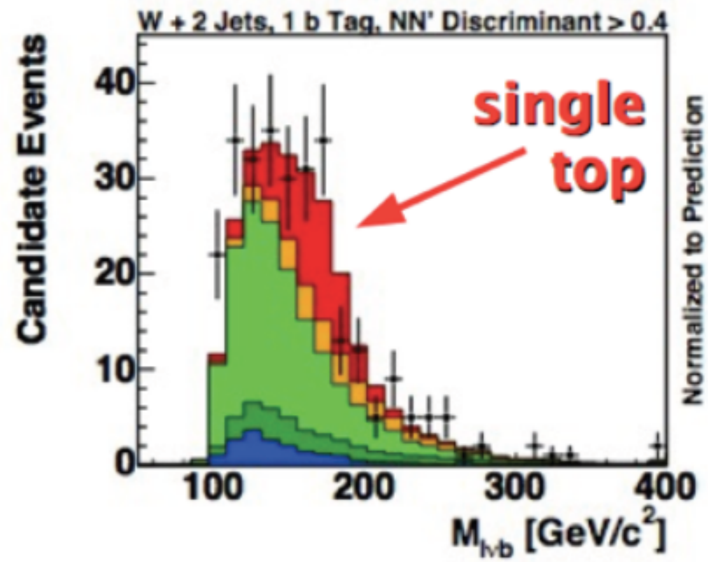


single top



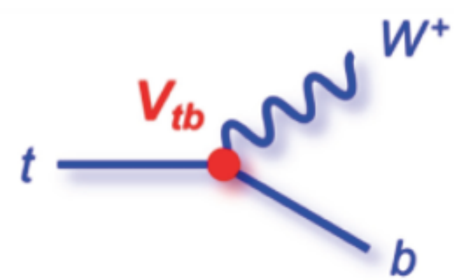
Single Top Discovered!





Single Top Cross Section	Signal Significance Expected	Signal Significance Observed
DØ 2.3 fb^{-1} arXiv:0903.0850 m_{top} = 170 GeV		
3.94 ± 0.88 pb	4.5 σ	5.0 σ
CDF 3.2 fb^{-1} arXiv:0903.0885 m_{top} = 175 GeV		
$2.3^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ

⇒ **observation with 5.0σ!**



DØ: $|V_{tb}| = 1.07 \pm 0.12$

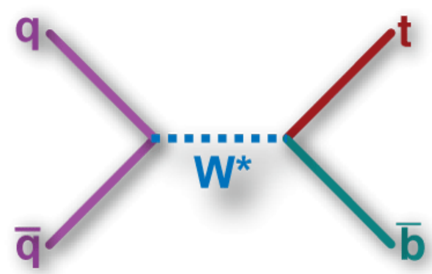
CDF: $|V_{tb}| = 0.91 \pm 0.13$

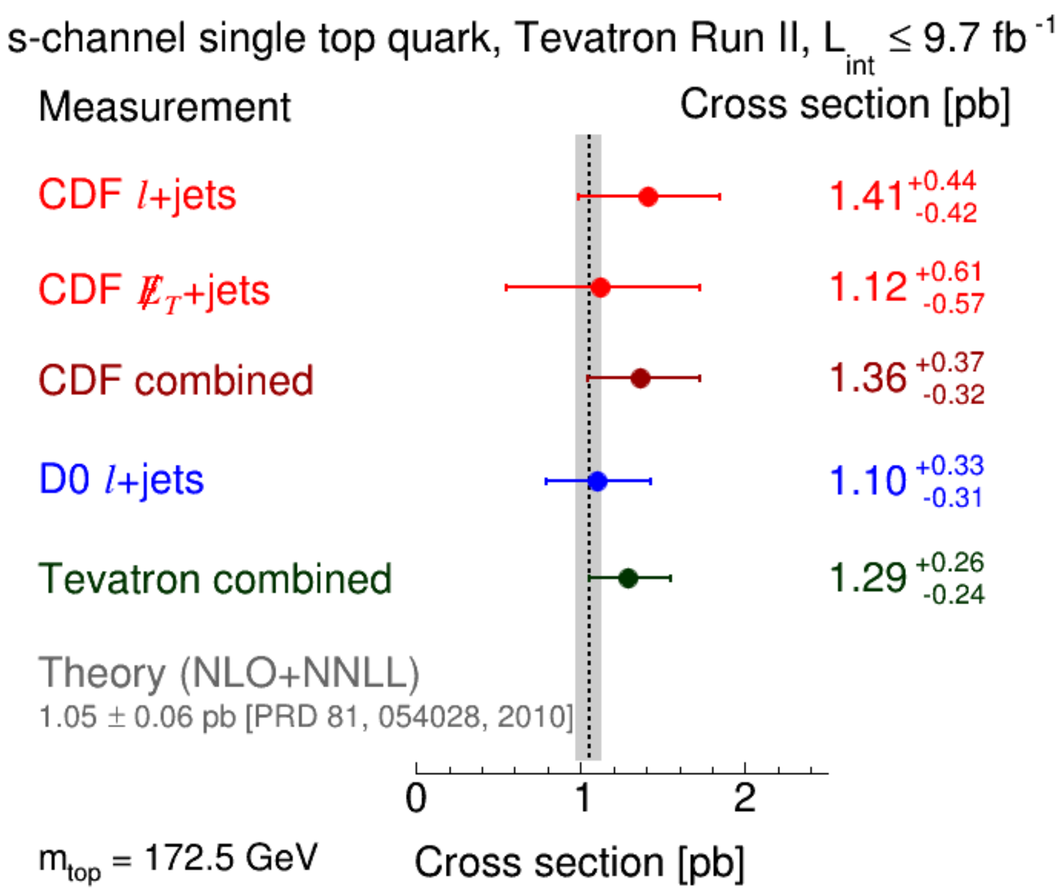
Single Top Discovered!

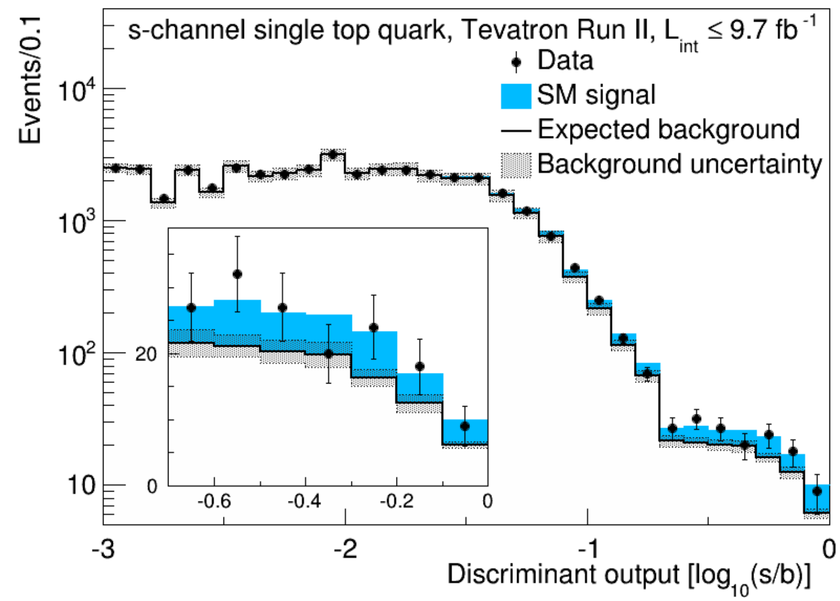
2009

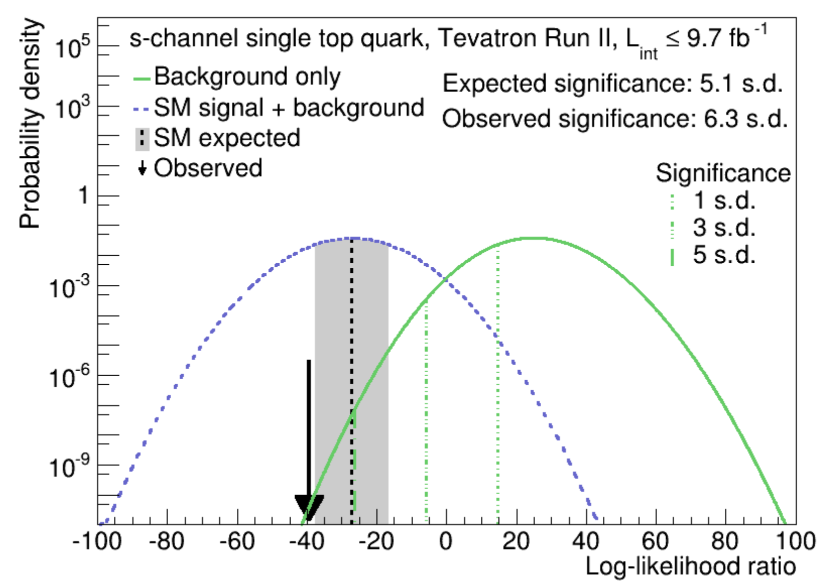
Single top at the Tevatron

Observation of the s-channel in 2014

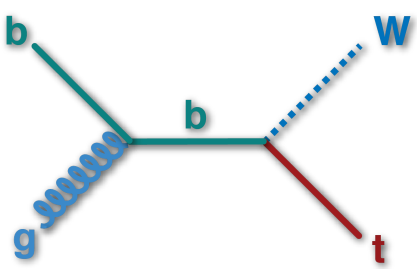




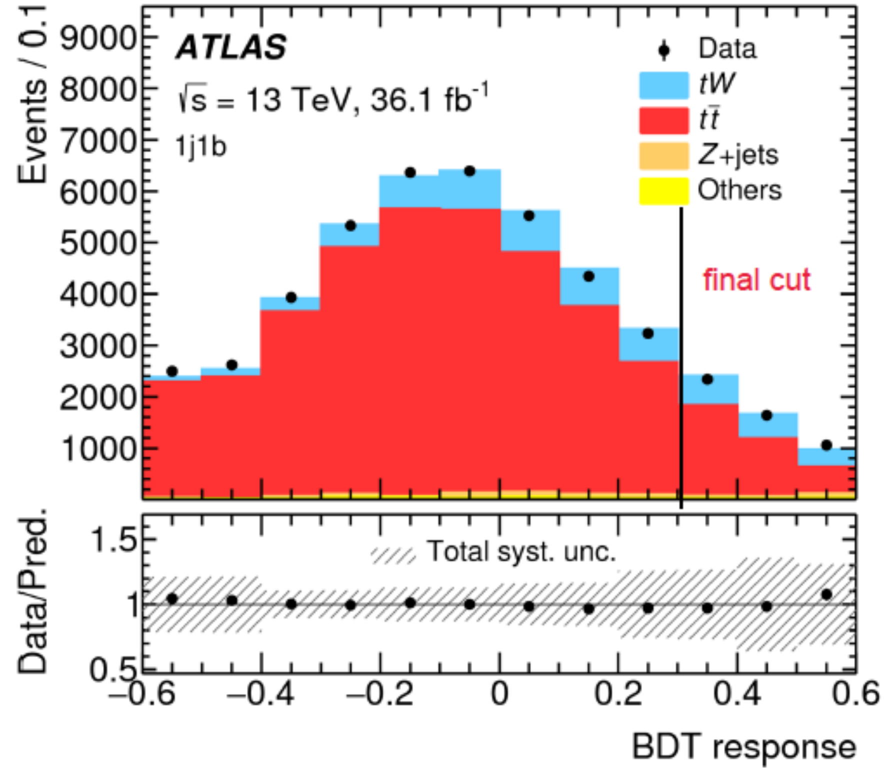




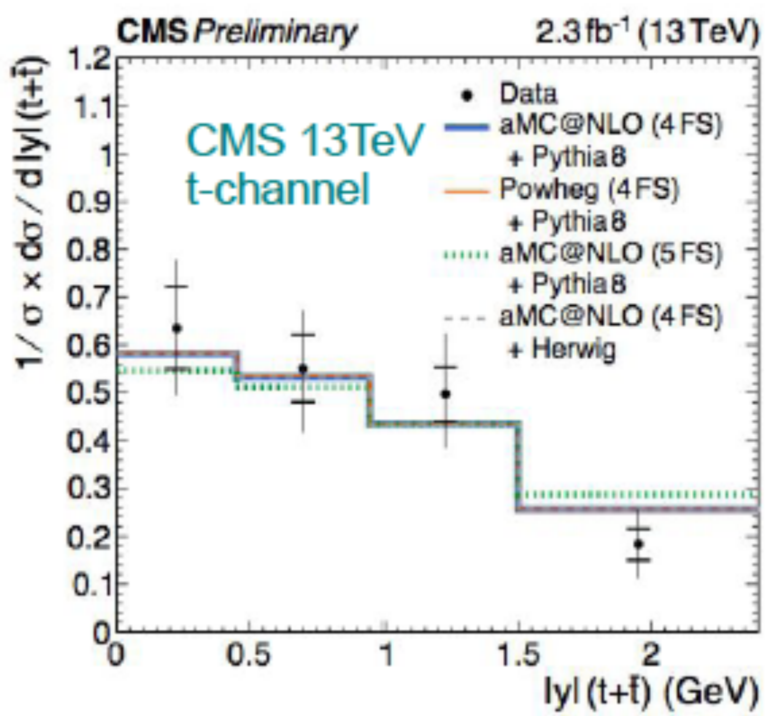
Recent results: Single top at the LHC

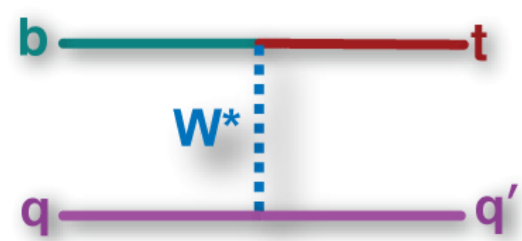


ATLAS 13 TeV Wt channel



Full program of single top studies

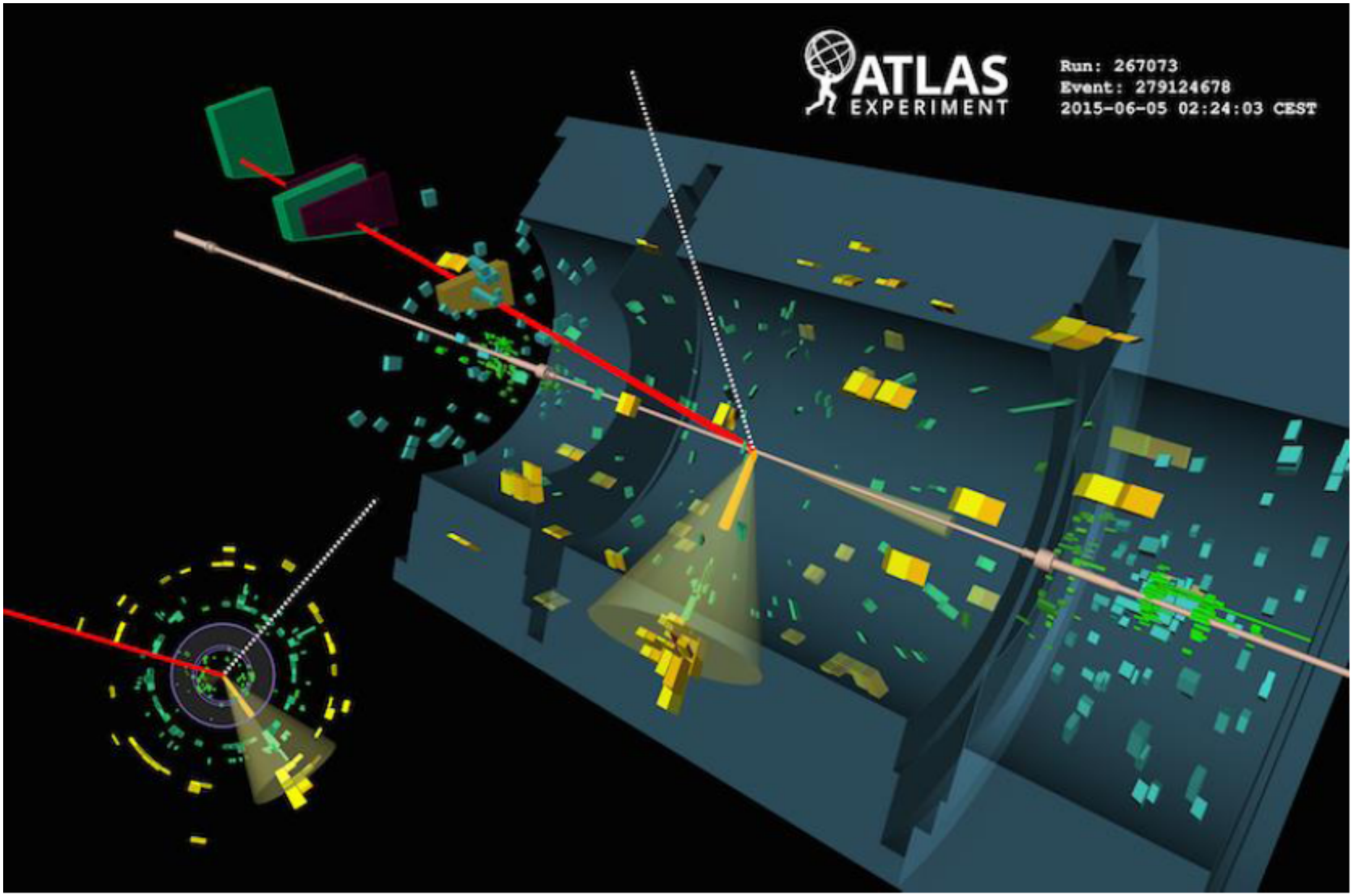




CMS 13 TeV t-channel

Recent results: Single top at the LHC

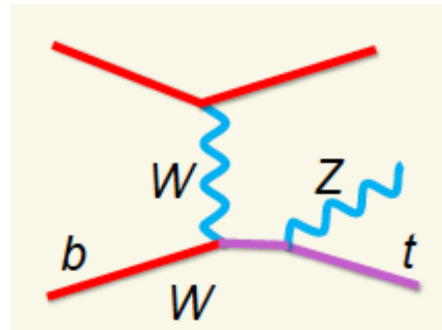
t-channel candidate at ATLAS

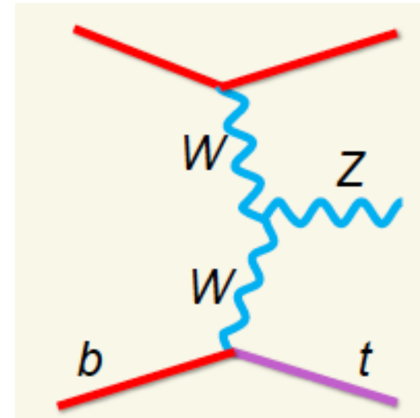


Recent results: Single top at the LHC

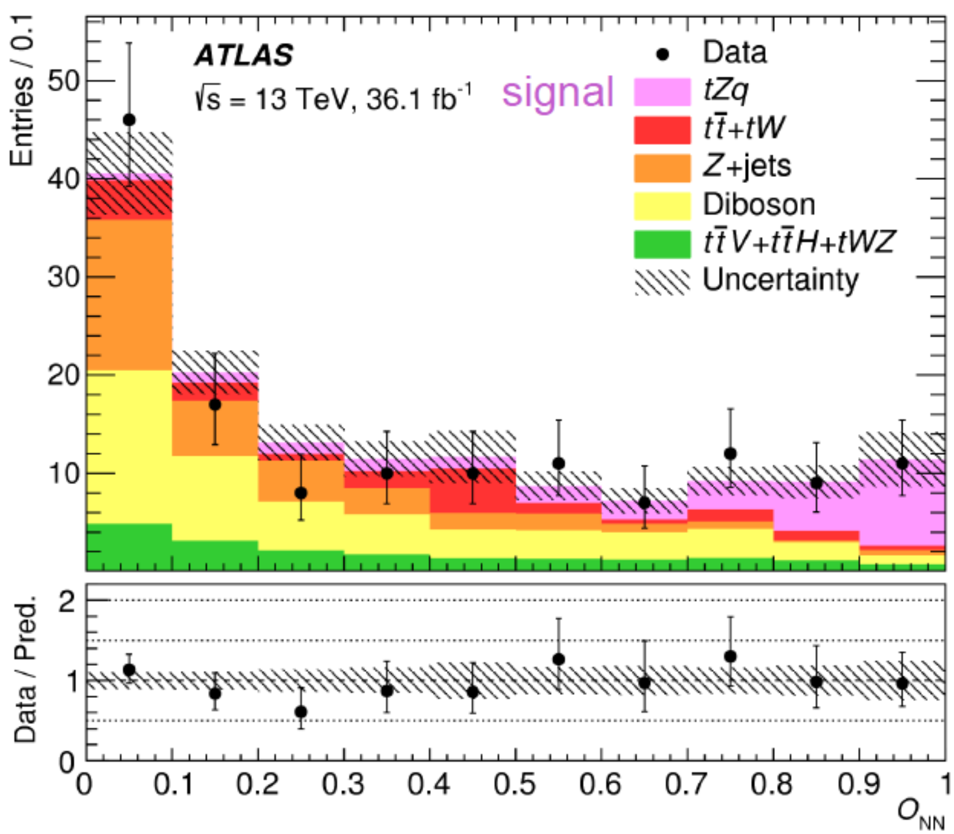
NEW!

tZq channel
(rare SM process)





Sensitive to *WWZ* and *tZ* coupling
→ Not seen before
→ Background to *tH* channel



Signal obtained in Likelihood fit
Background also fitted with constrains according to uncertainties

σ=600±170 (stat.)±140 (syst.) fb
(theory NLO 800fb ±7% (scale))

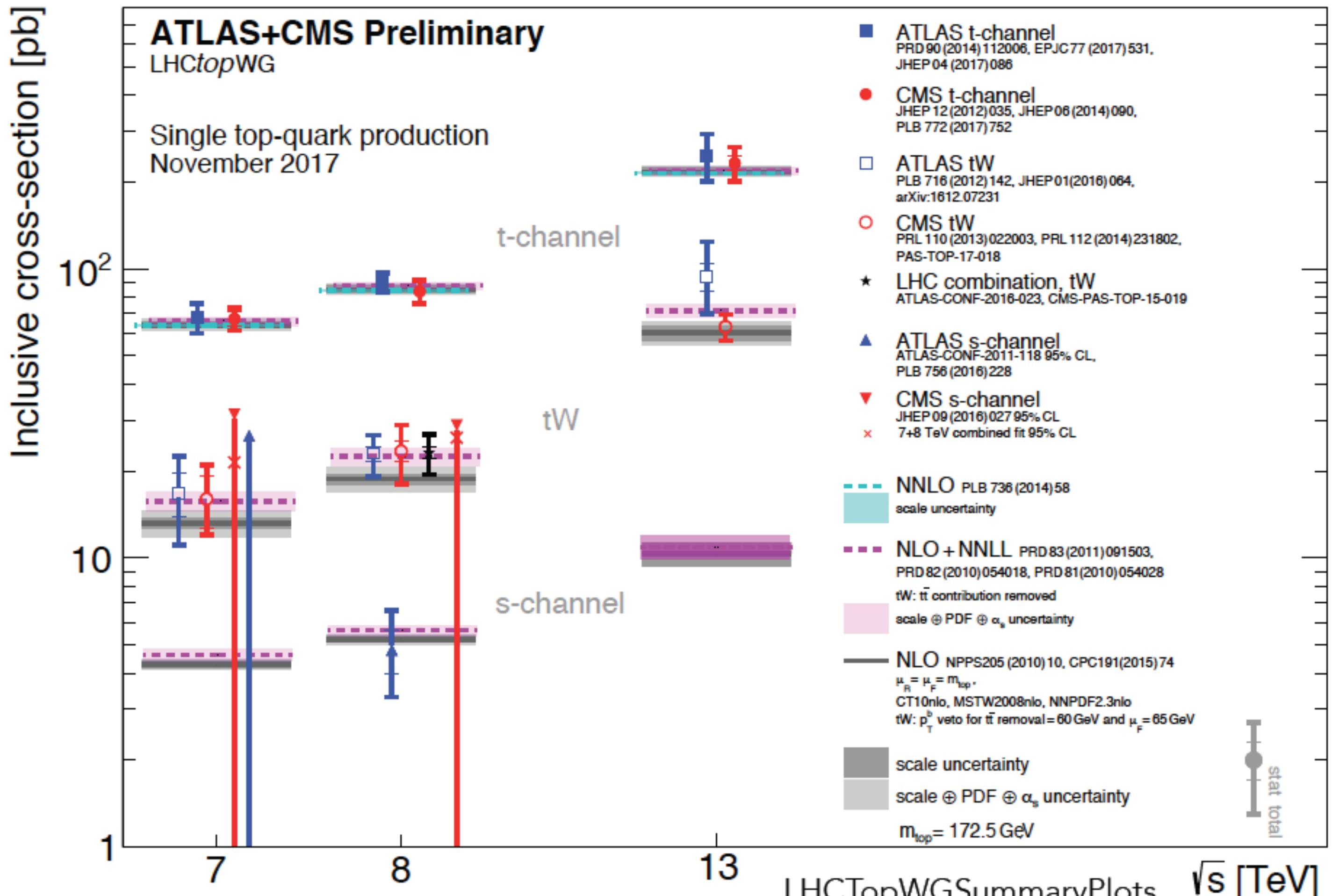
Significance 4.2 (5.4 expected)

EVIDENCE

PLB 780 (2018) 557

Latest on single top results

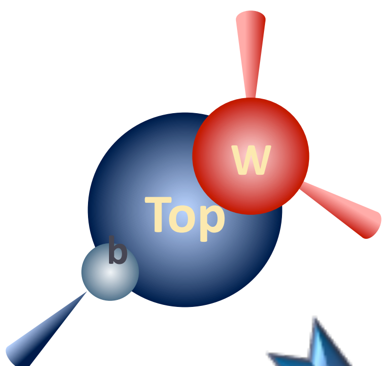
LHC: recently observed t-channel and t-W, getting closer to s-channel!

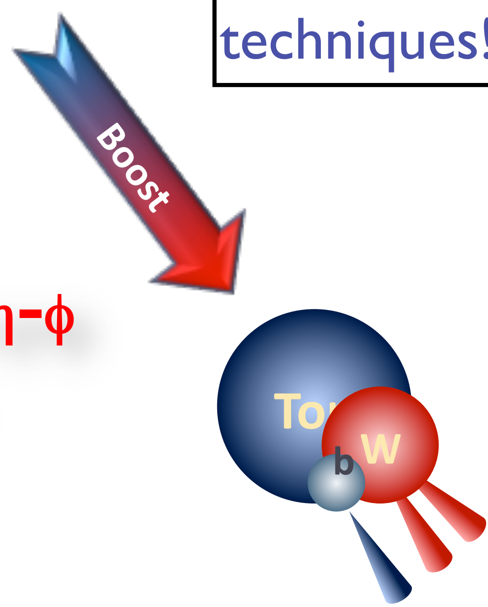


LHCTopWGSummaryPlots

Boosted Top Quarks

- QCD top production at high CM, together with searches for High mass particles give Lorentz-boosted SM final states.
- **Boosted top quark** reconstruction is a thriving industry, relevant for measurements and searches.

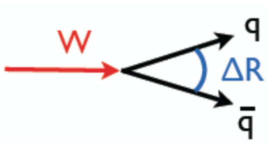




Distinct top quark signatures become merged like QCD jets: need substructure techniques!

ΔR: separation in η-ϕ

$\Delta R \sim 2m/p_T$



$p_T > 400$ GeV

Boosted Top Quarks

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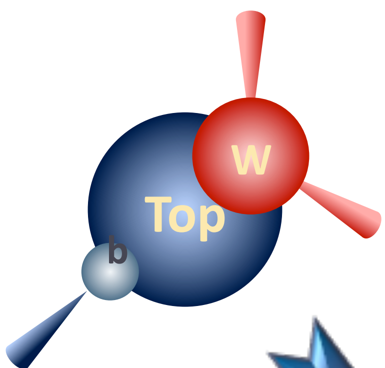
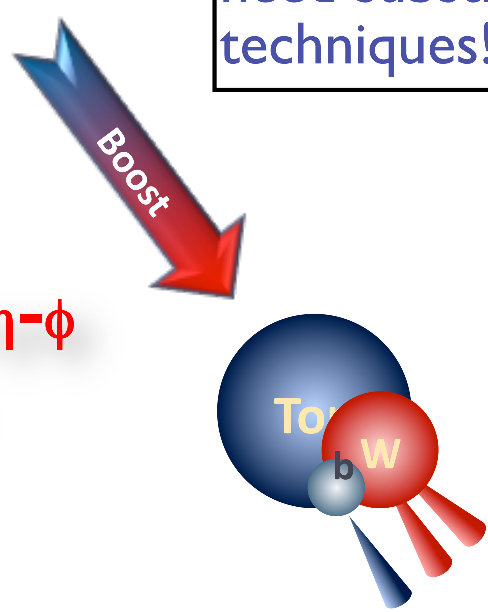


Distinct top quark signatures become merged like QCD jets: need substructure techniques!



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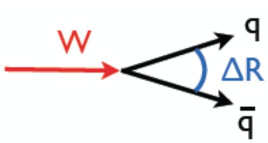
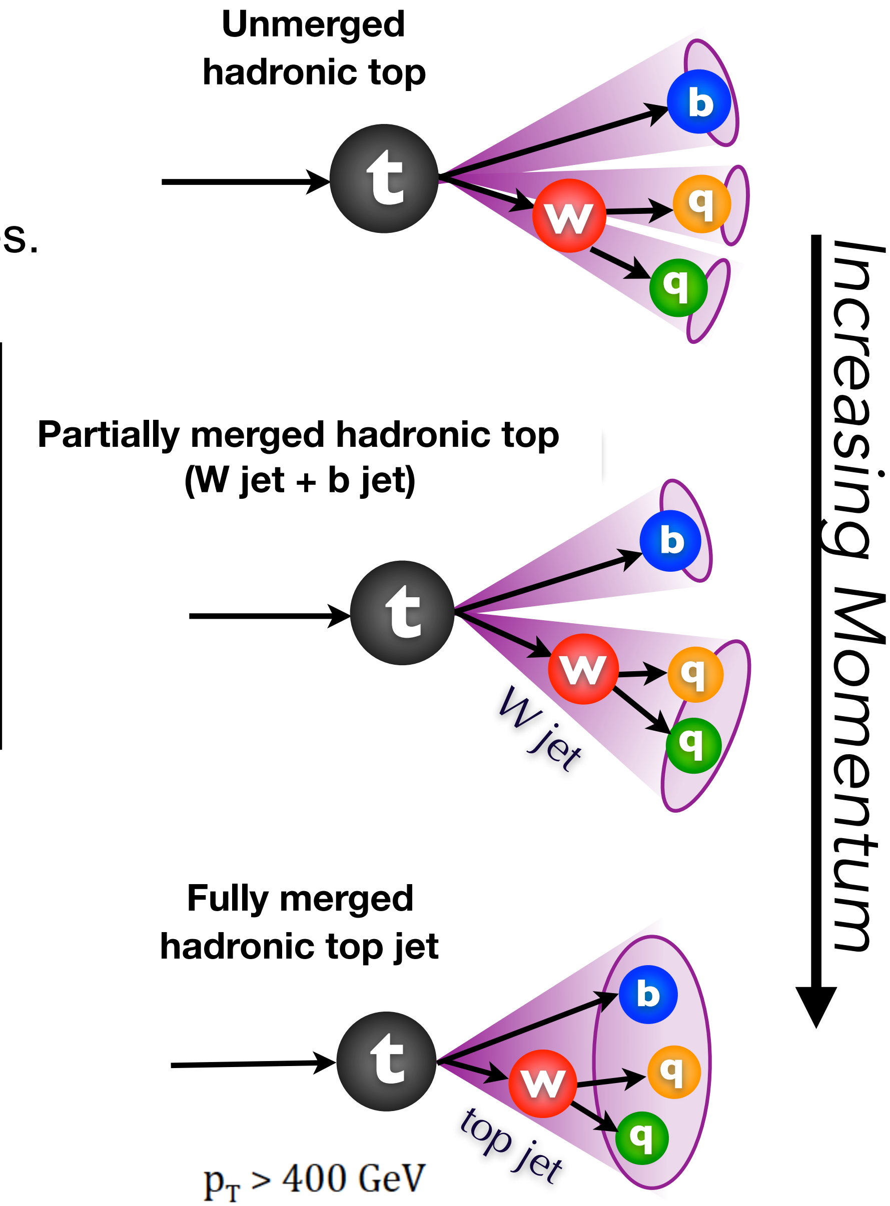
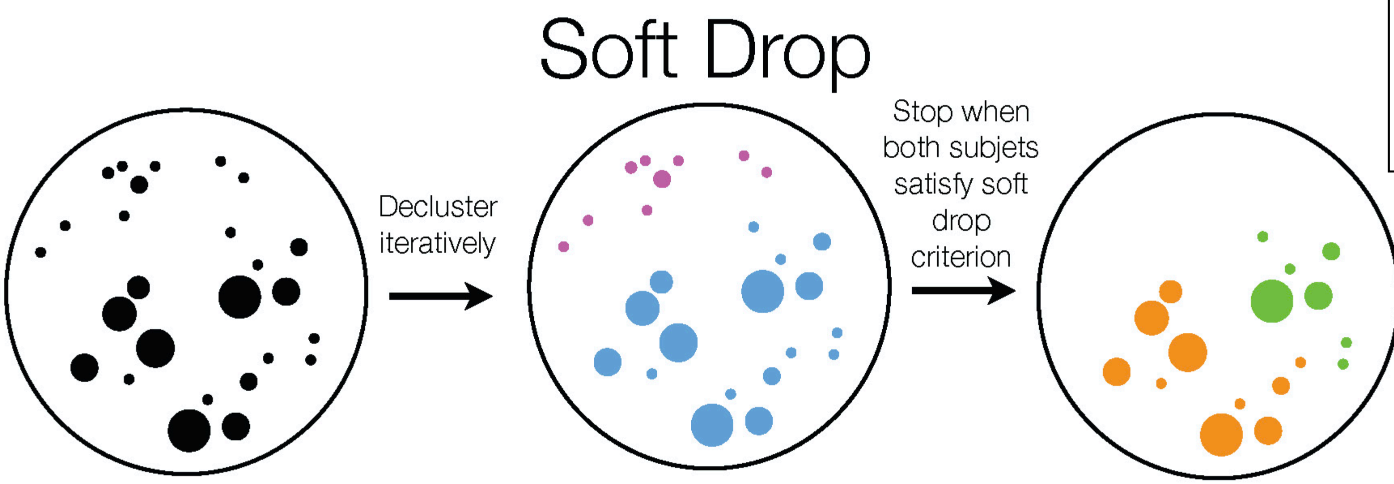




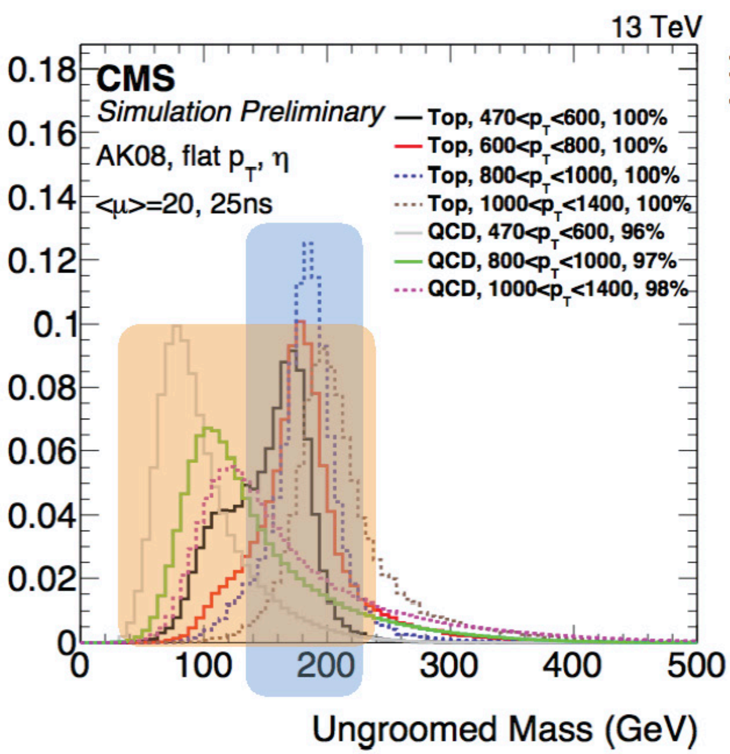
Grooming helps discern Boosted tops

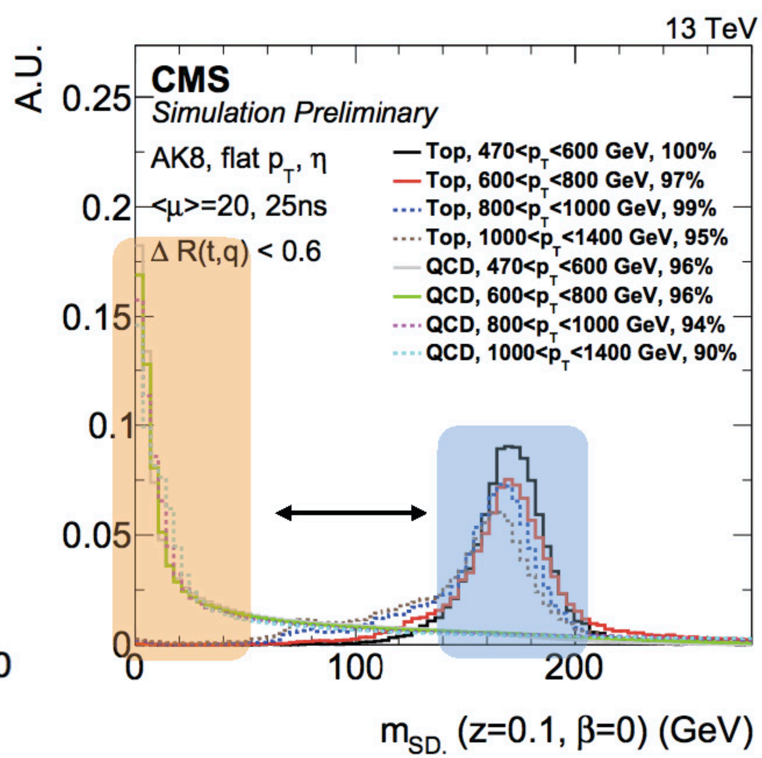


Softdrop condition

$$\frac{min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z(\Delta R_{12}/R_0)^\beta$$

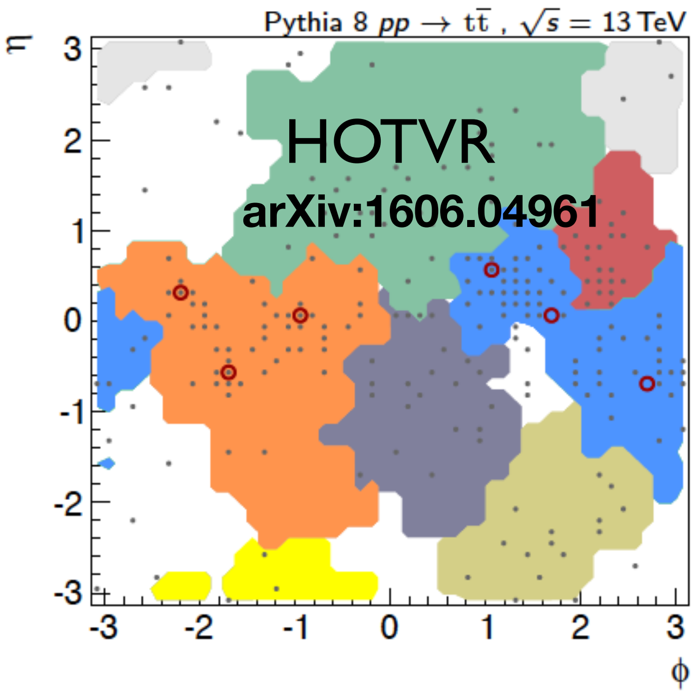
arXiv:1402.2657
0802.2470v2

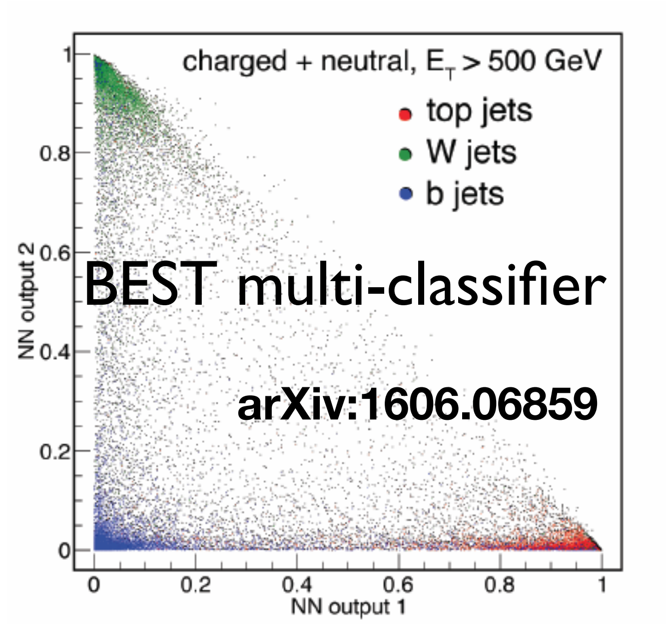




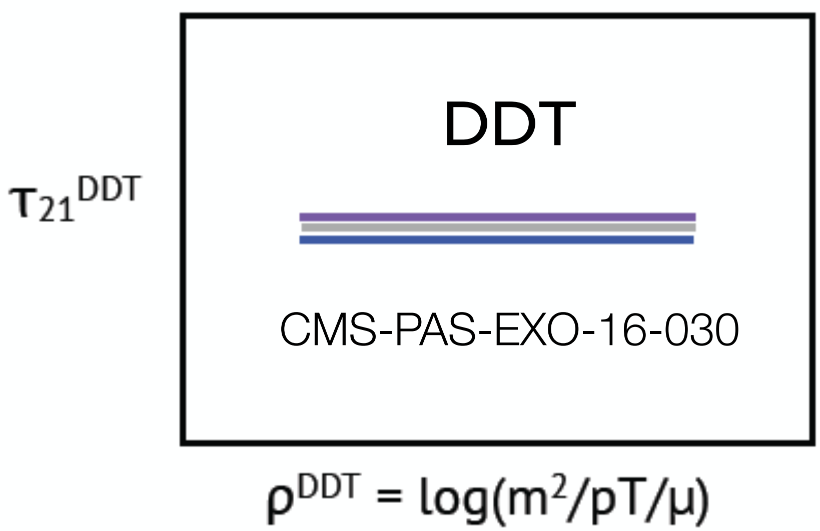
Merged-top separation from QCD after grooming

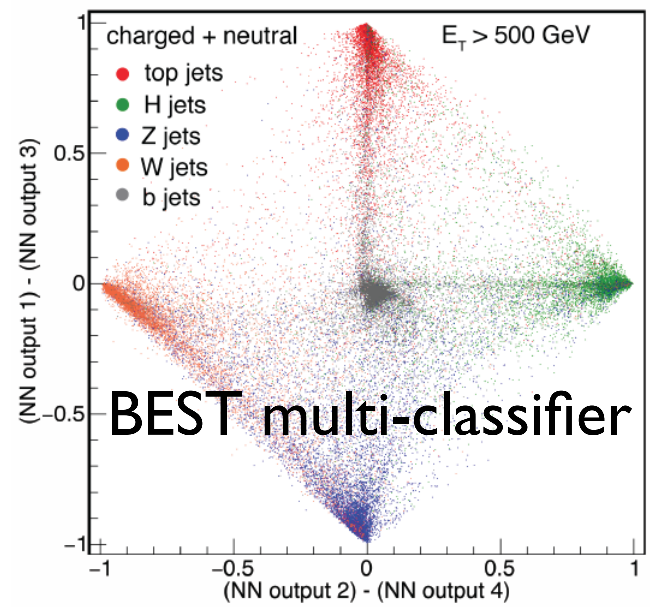
Future for top-tagging



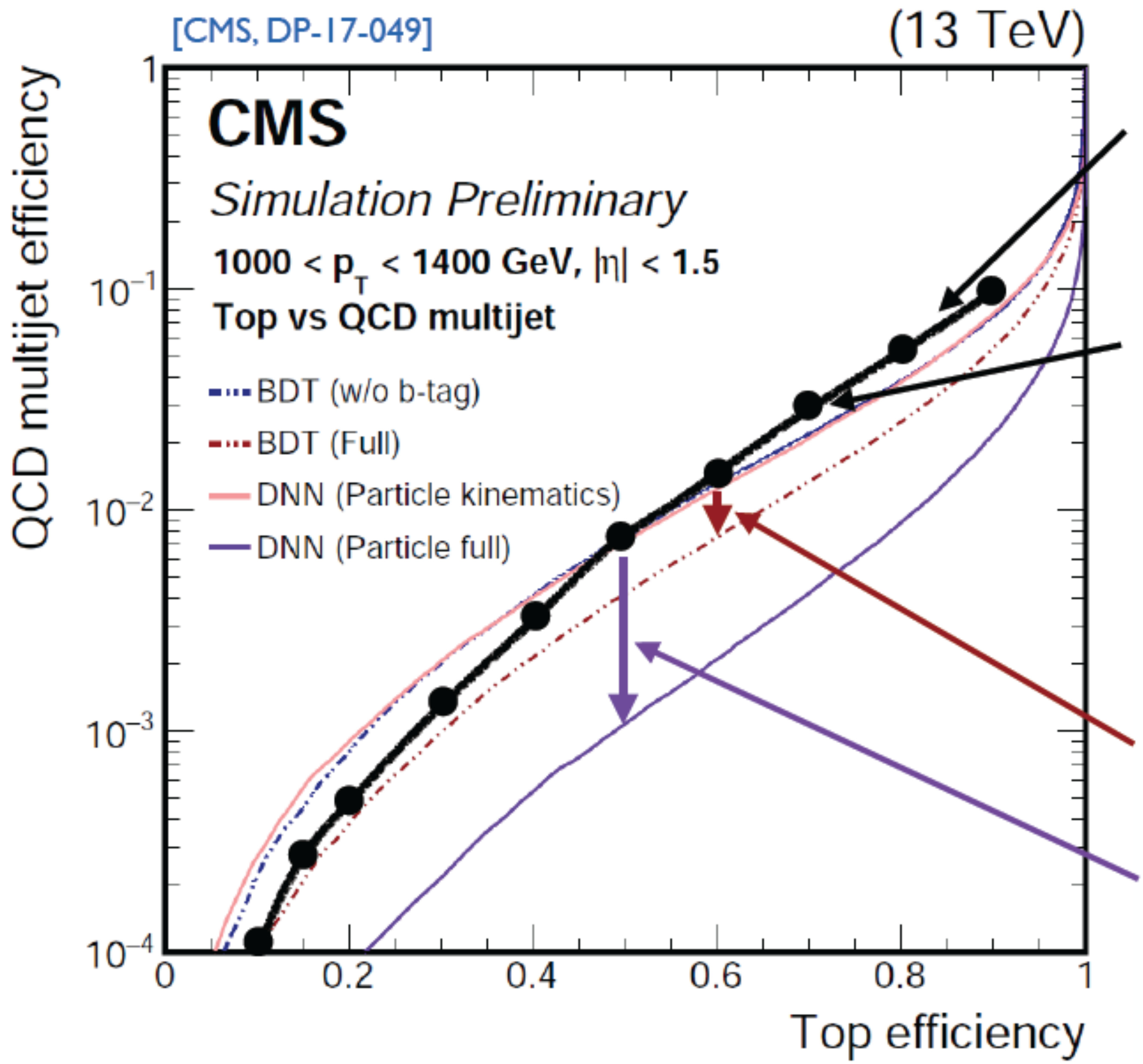


PUPPI





Top tagging improvements



soft drop mass, $\tau_{3/2}$, subjet b
[CMS-PAS-JME-15-002]

today's standard

2-3% misidentification at 70% signal efficiency

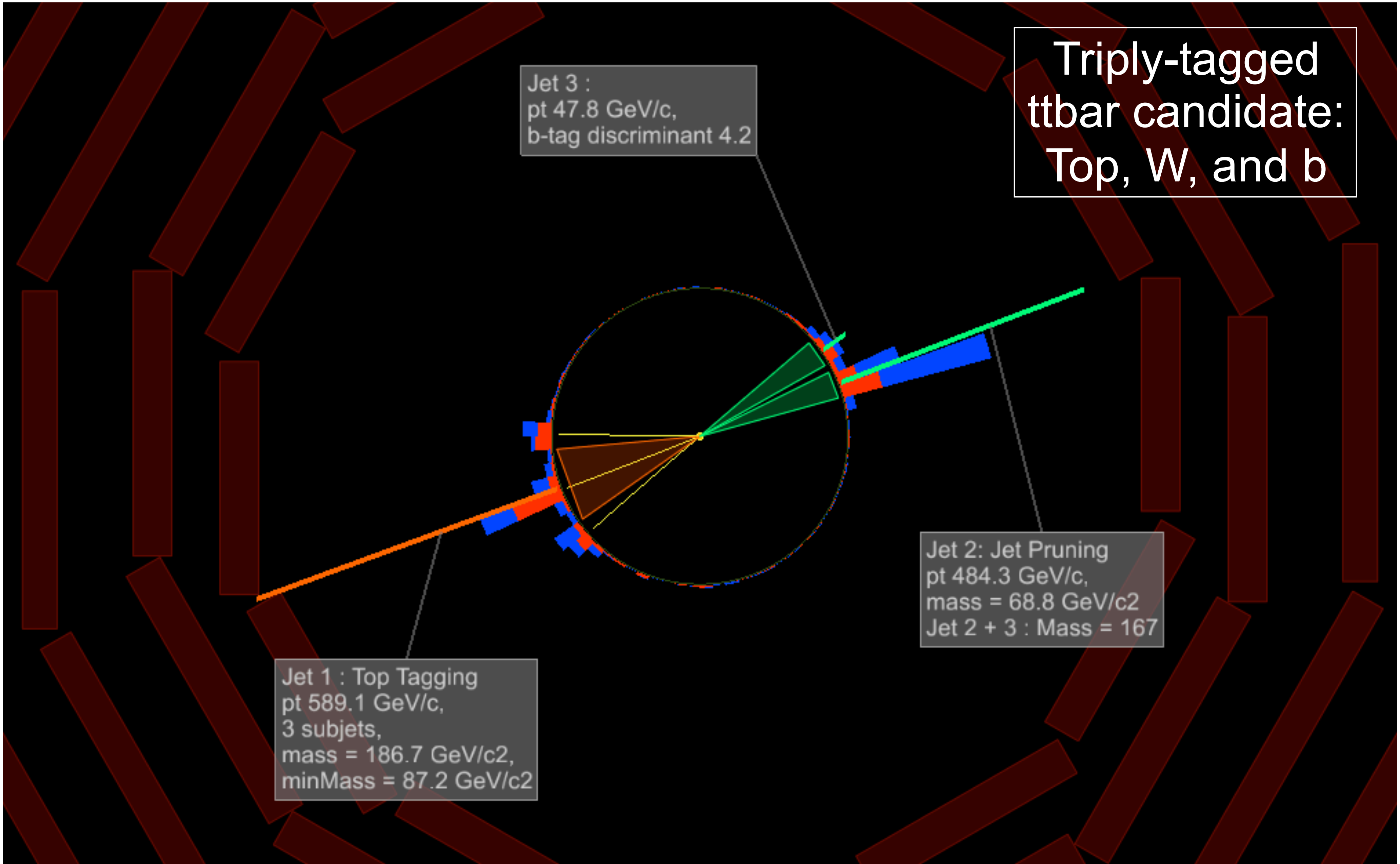
A prime example for machine learning

gain from a BDT

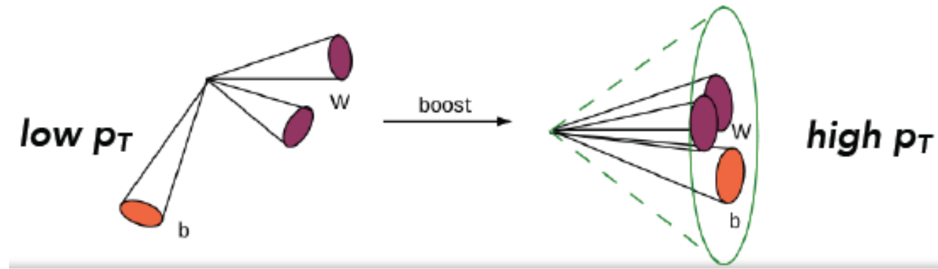
gain from a deep neural network

[see also ATL-PHYS-PUB-2017-004]

Candidate Top Quark Jets

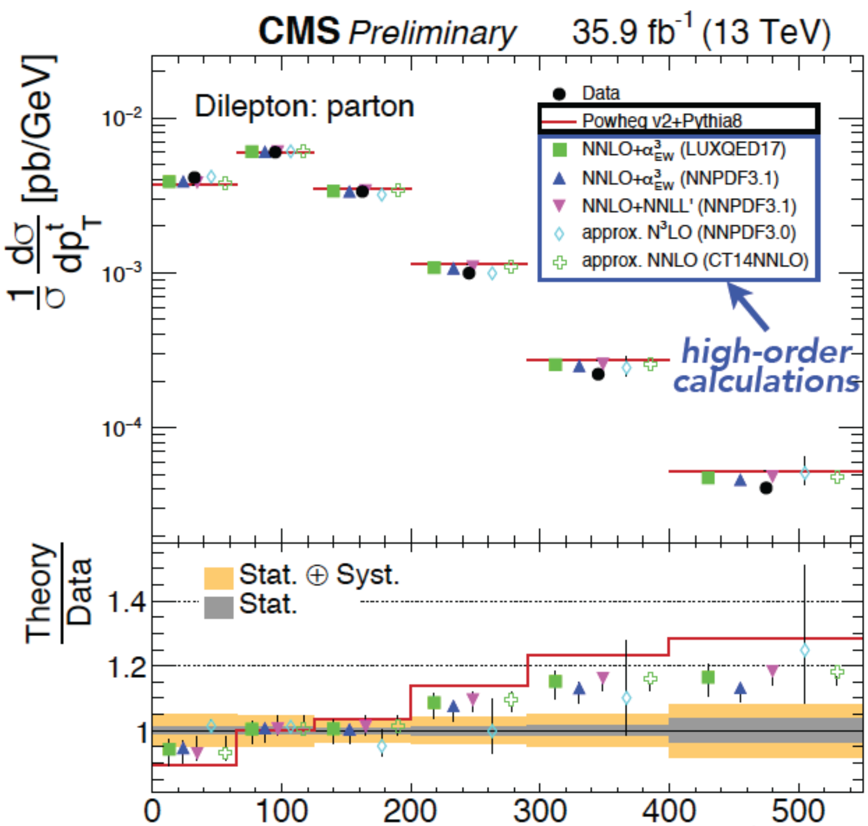


Top Differential Measurements

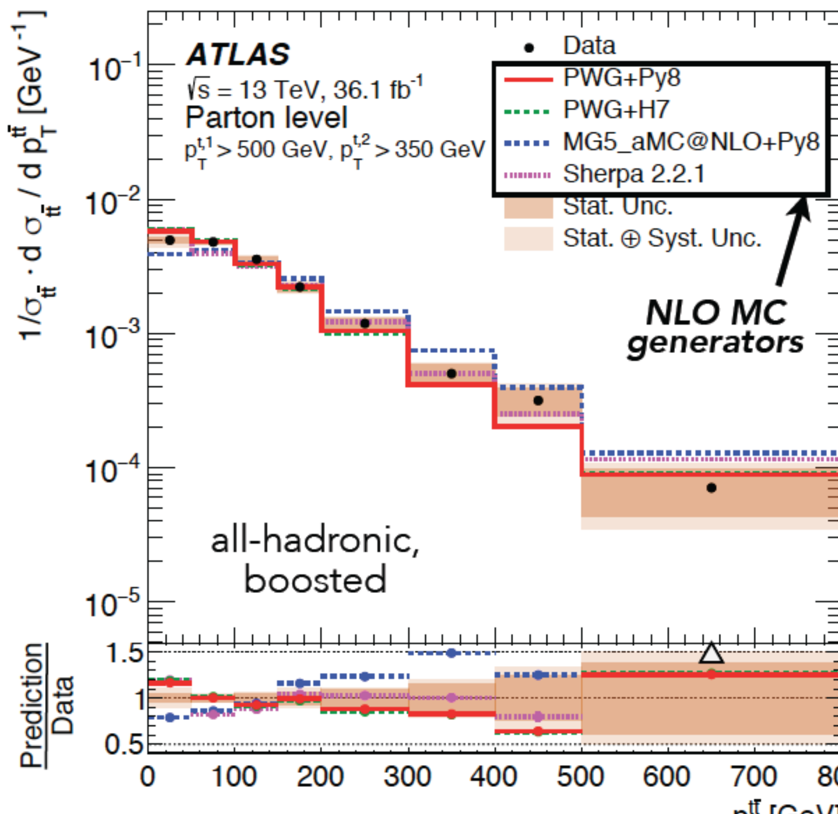


Anything different at high pT?

- *Abundance of measurements vs kinematic variables*
- *Test theory predictions, constrain SM parameters (m_{top}, α_S), constrain PDFs*
- *Sensitive to new physics*



CMS-PAS-TOP-17-014

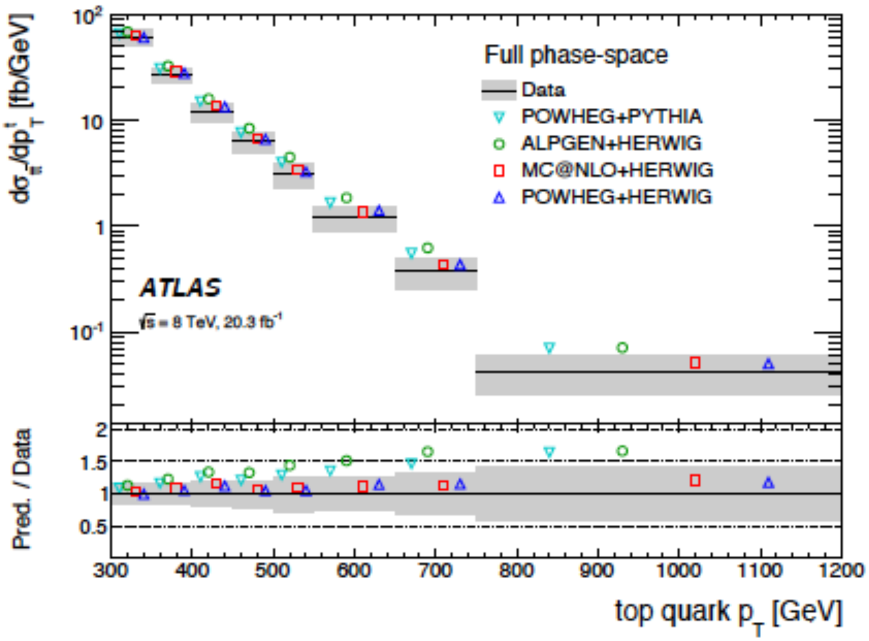


Submitted to PRD

Boosted differential top pair xs

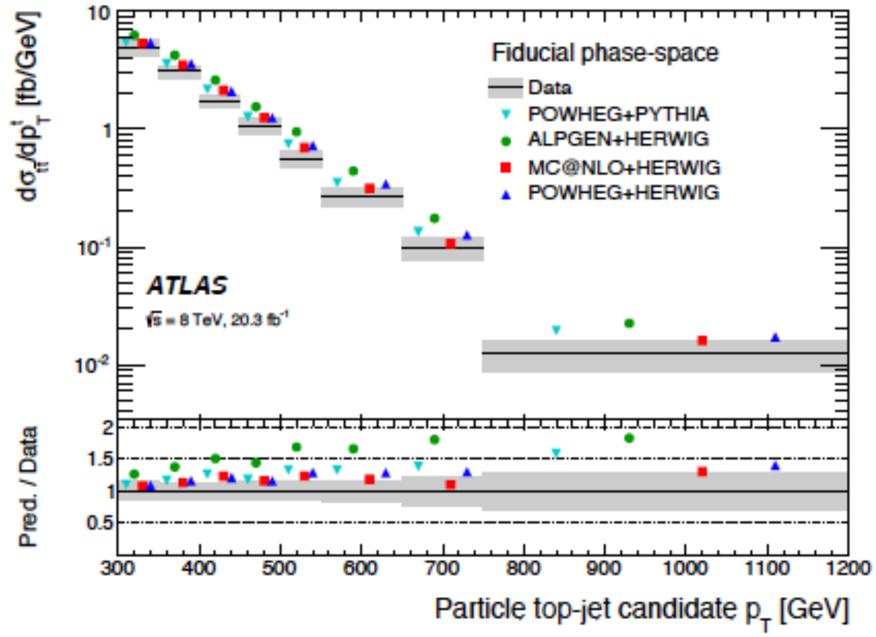
Anything different at high pT?

- p_T>300, trimmed large-R (1.0) jets
- m_{jet} > 100 GeV, substructure selection
- largest jet is hadronic top candidate



ATLAS: Phys. Rev. D 93, 032009 (2016)

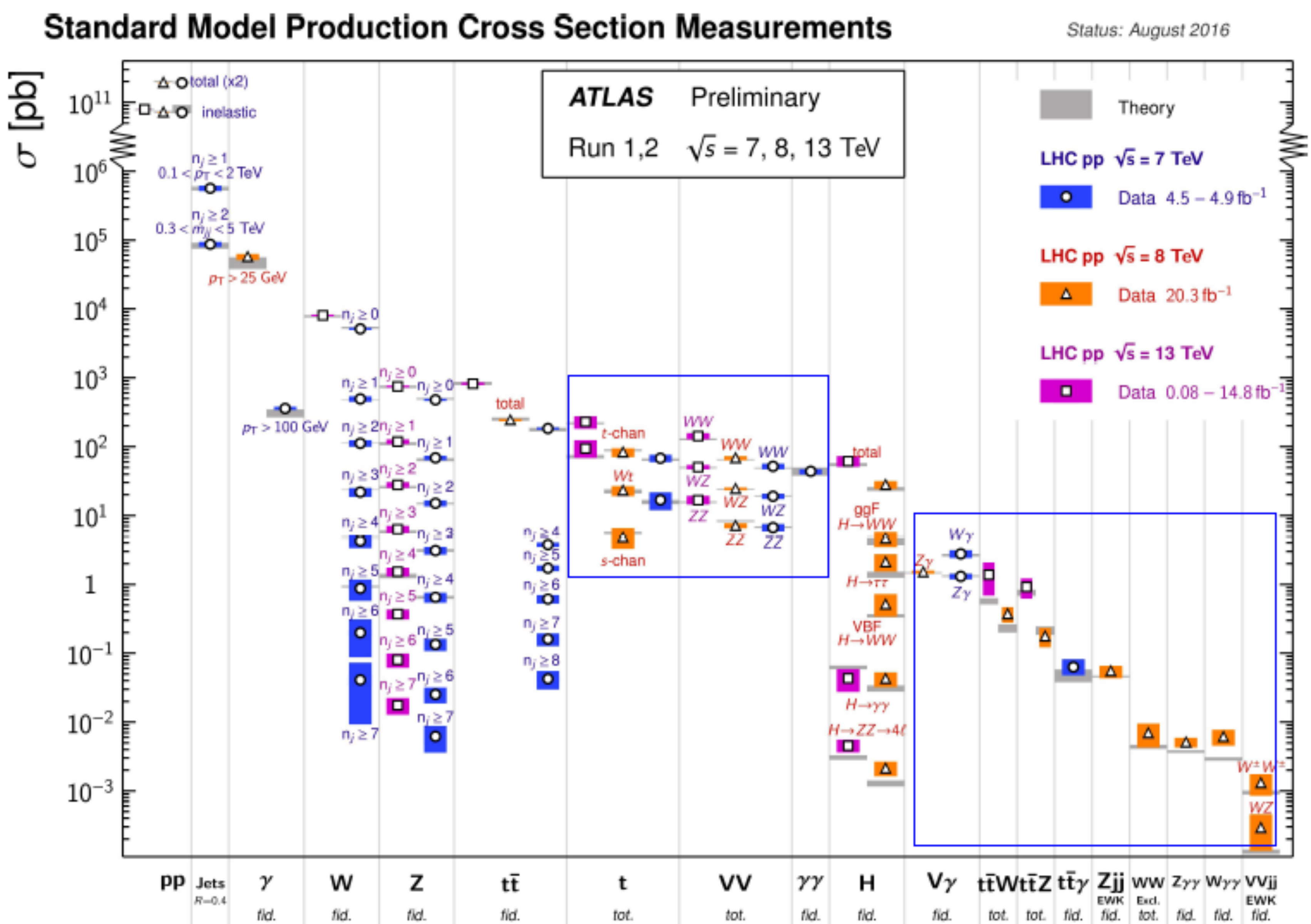
CMS: arXiv:1605.00116



- 13-29% uncertainty, large-R JES dominates
- parton-level result relies on MC: larger systematics
- same trend as resolved analysis:

ATLAS-CONF-2015-065

Down to smaller cross sections: tt+V



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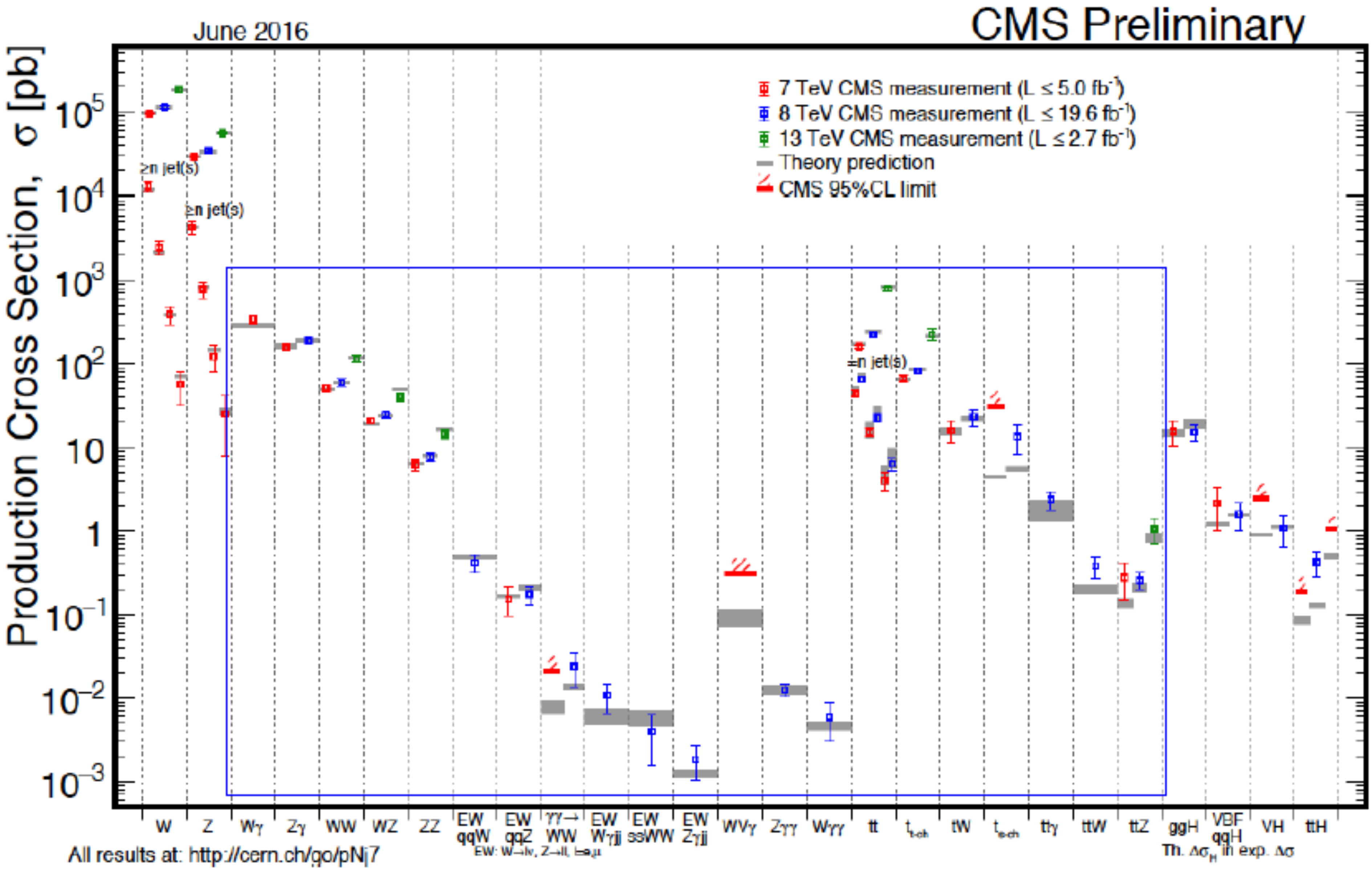
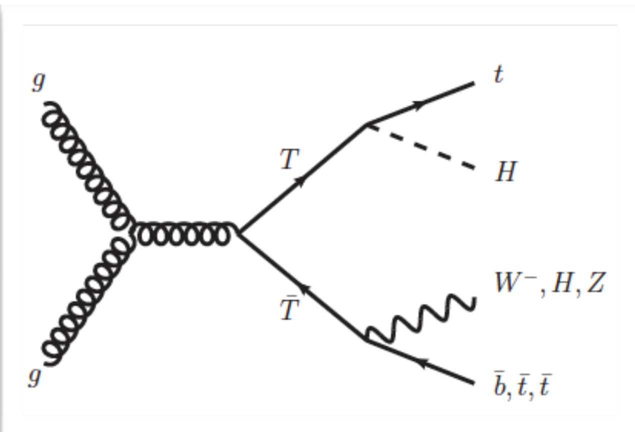


TT→tH+X and 4-top production

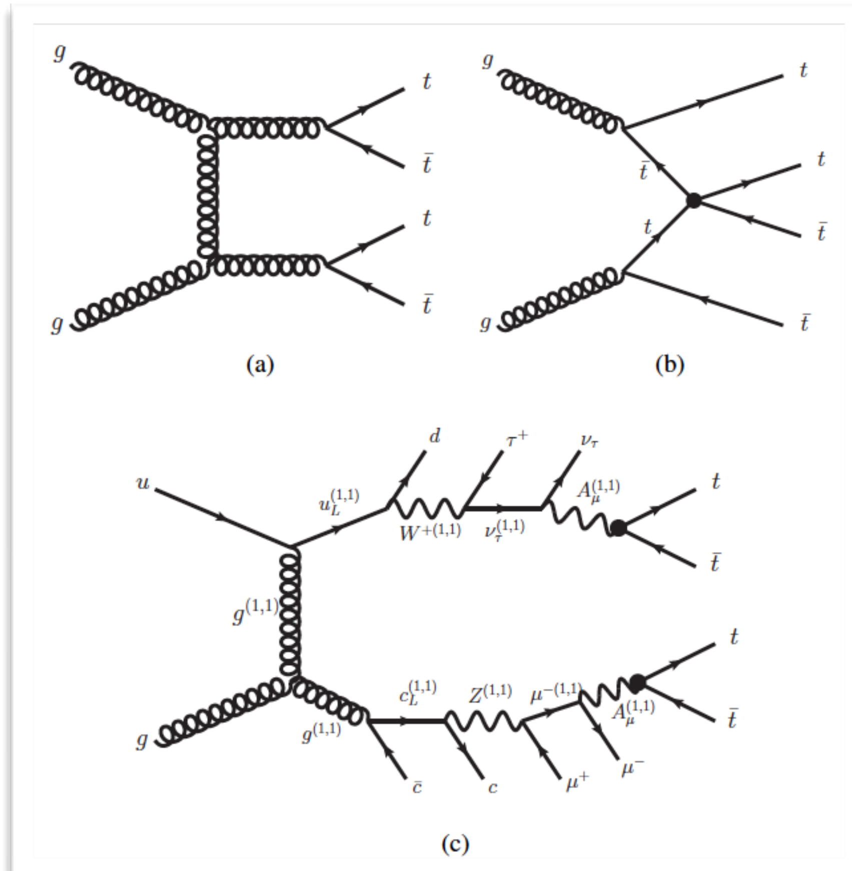
leading TT production diagram



ATLAS-CONF-2016-013

- Many final states: 11 search channels!

4 tops (SM and BSM)



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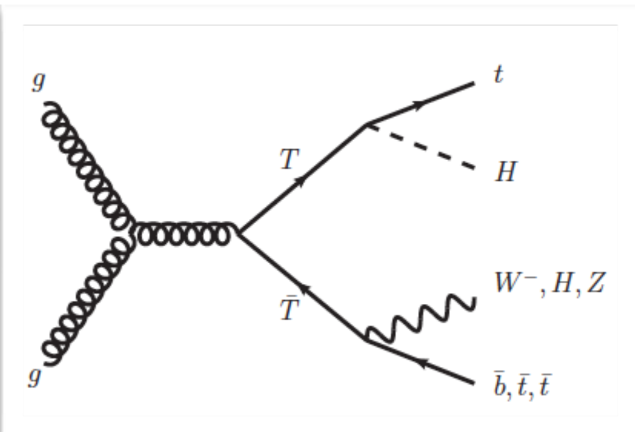
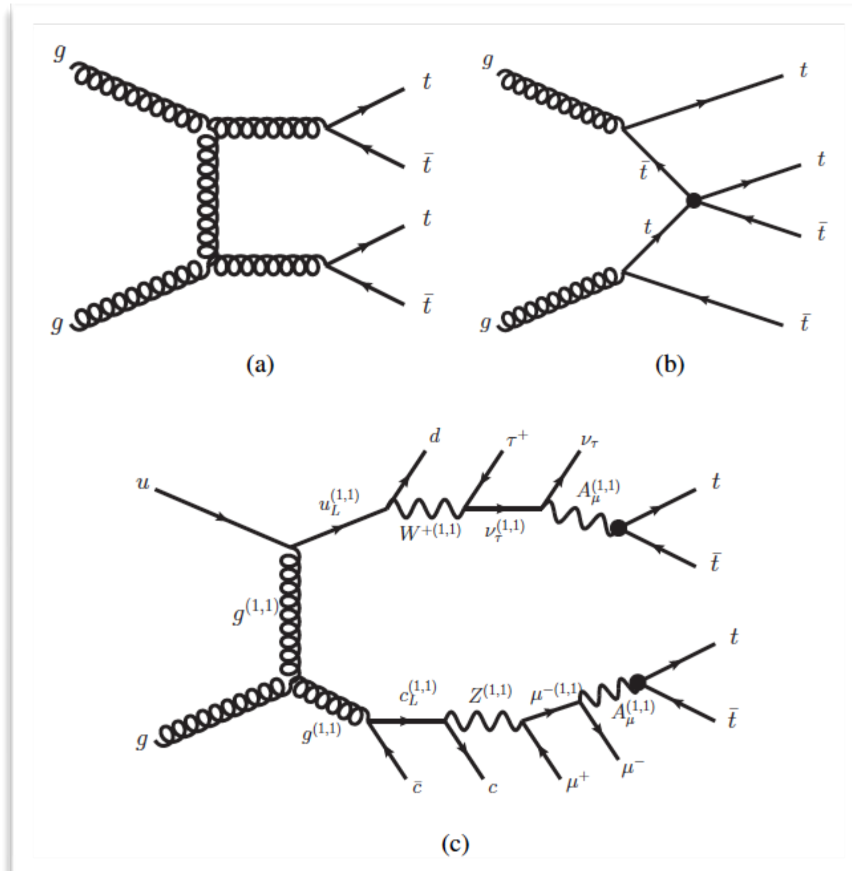


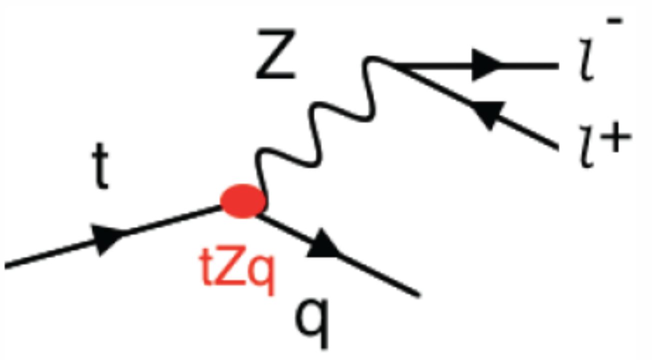
ATLAS-CONF-2016-013

4 tops (SM and BSM)



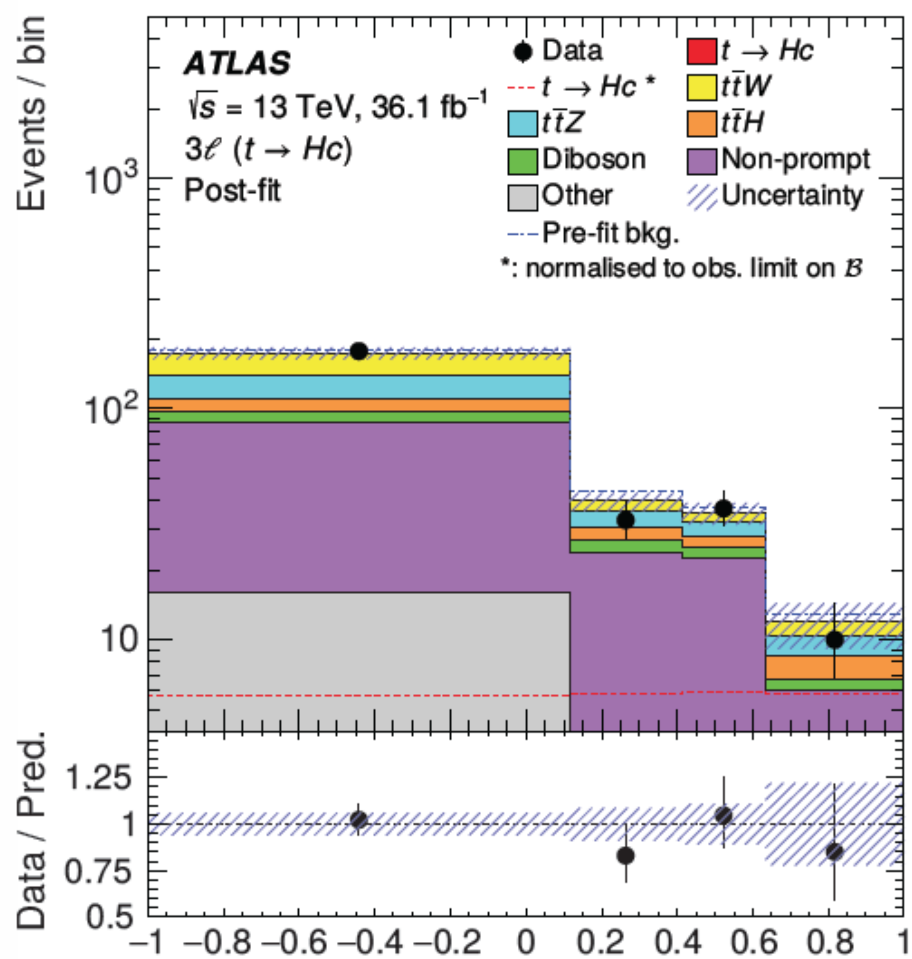
- Many final states: 11 search channels!
- Search for VLQ pair production TT decays to tH and bW, tH, tZ
- Final state also sensitive to 4-top production in the SM and BSM models
- Compositeness, RS extra dimensions, colored scalars, UED.

FCNC searches



Example of recent result (ATLAS)

tHq, H→WW/ZZ/γγ

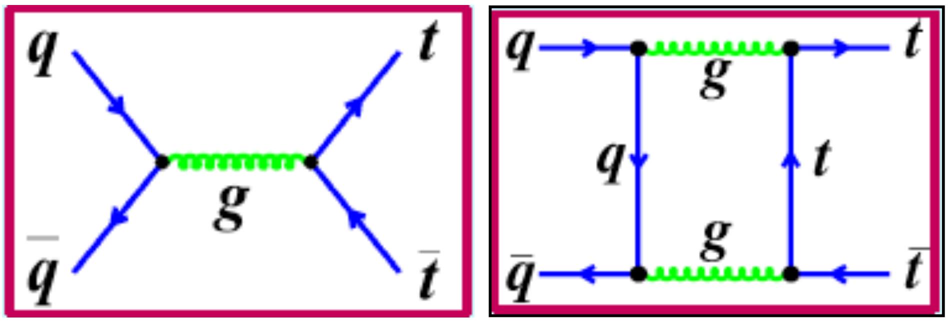


Submitted to PRD

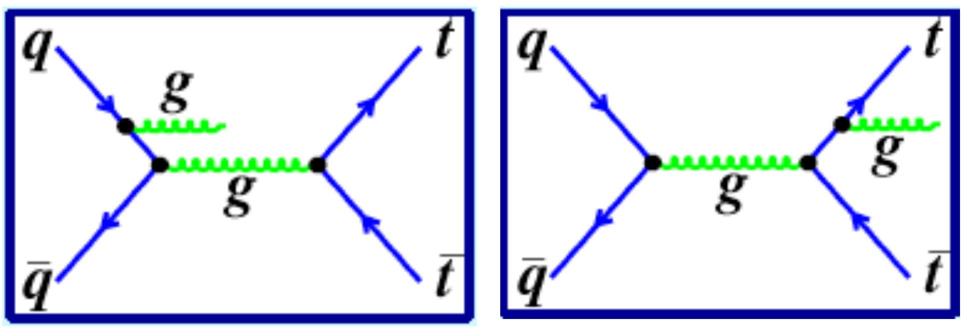
Top Production Asymmetry

Top Forward-Backward Production Asymmetry A_{fb}

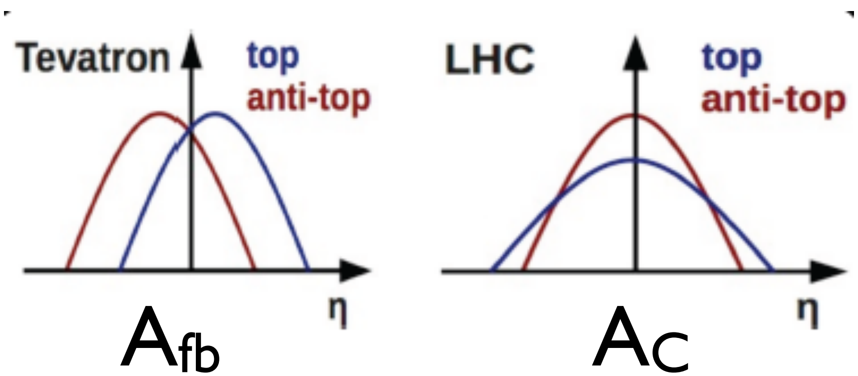
J. Kuhn, *et al.*



Tevatron: $q\bar{q}$ diagram interferences

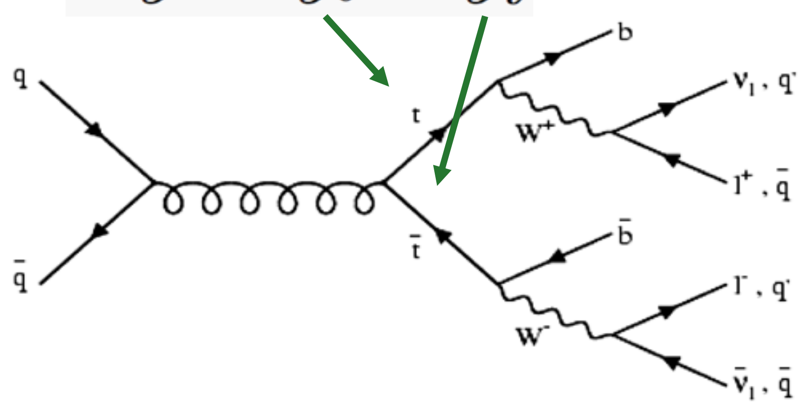


Reduced Asymmetry in tt+jet -- Uwer, *et al.*



No asymmetry expected at LO, but 4-6% expected at NLO in parton frame

$$\Delta y \equiv y_t - y_{\bar{t}}$$



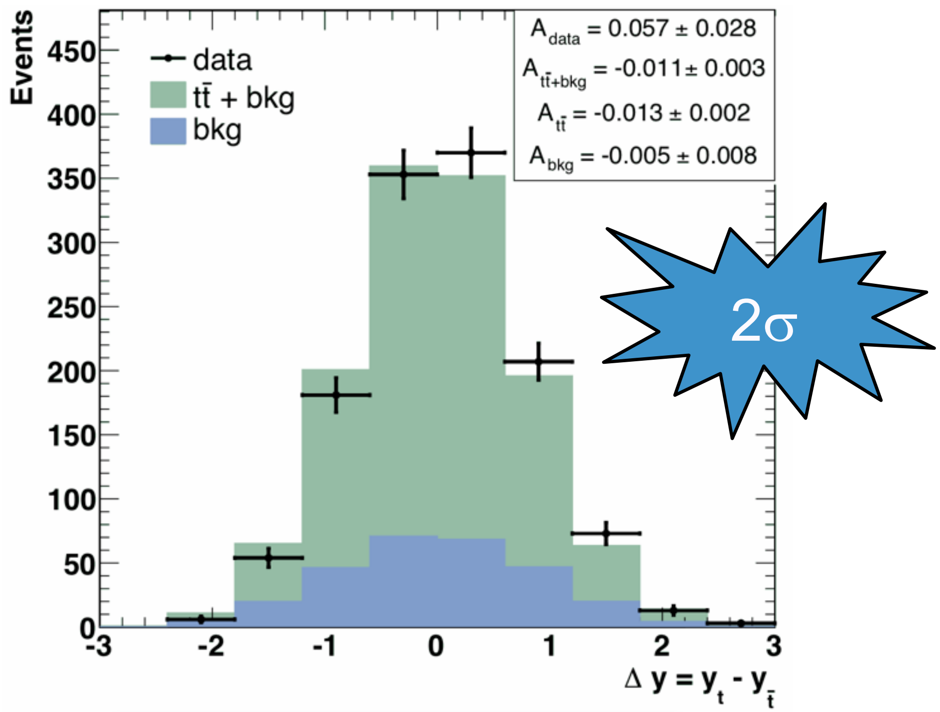
$$A_{\rm FB}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}$$

Top A_{fb}

First measurements produced some excitement— larger asymmetries than QCD predicted.

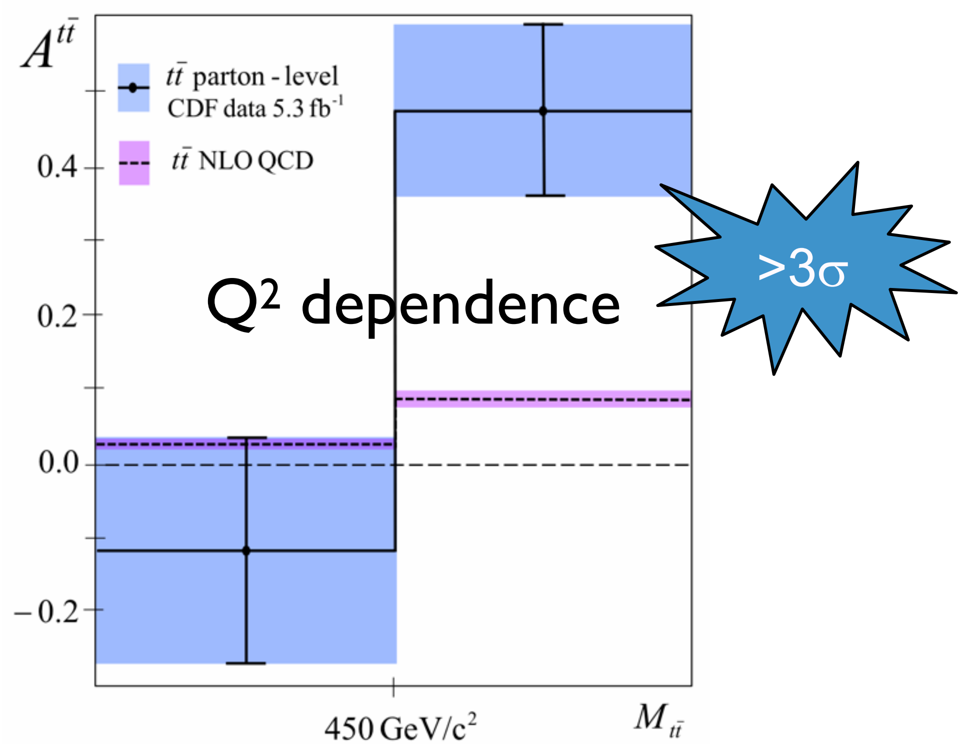
Both CDF and D0:
Discrepancies from Theory, multiple channels

New physics, Z′ or color octets, could enhance A_{fb}!



$A_{fb}=15 \pm 5$ %
(Parton Level: Fully corrected for reconstruction)

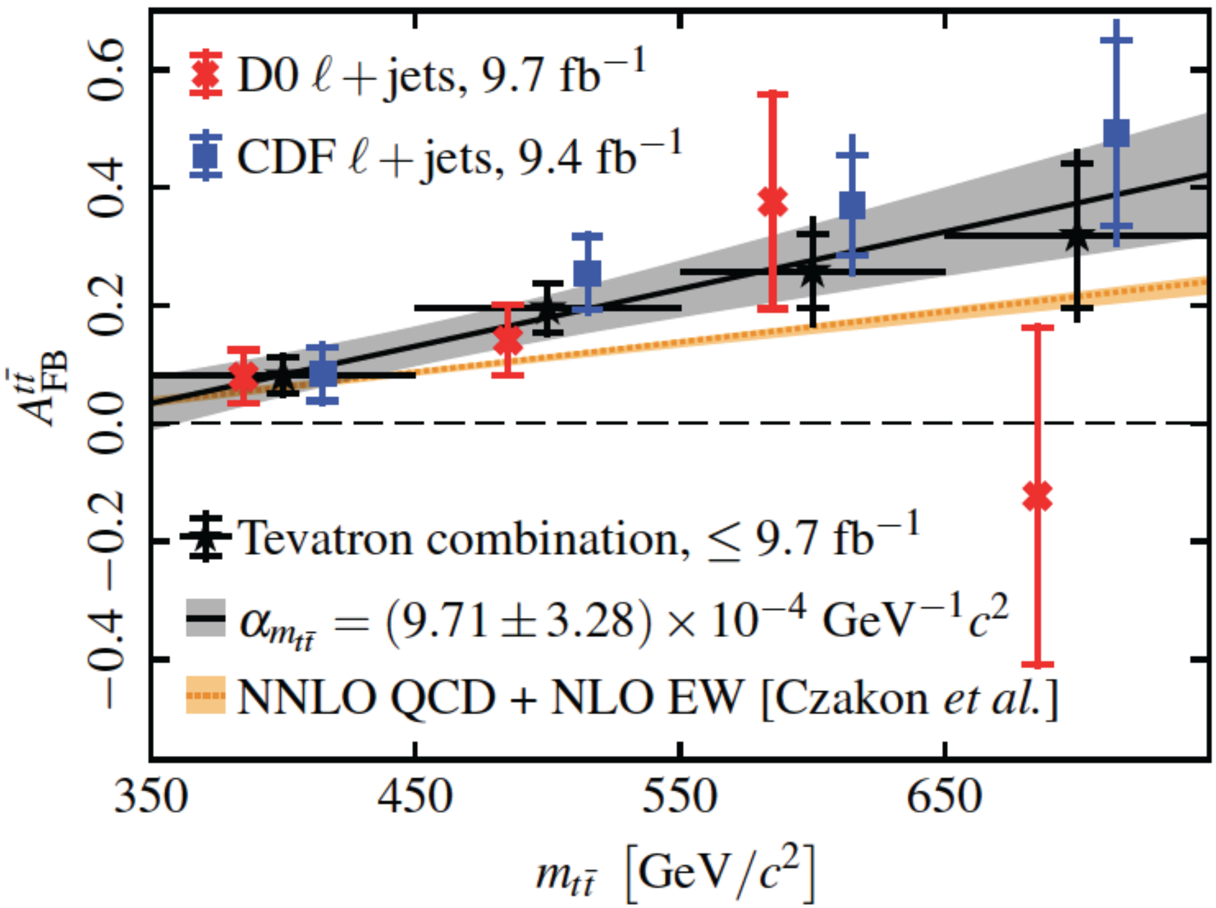
mc@nlo prediction: 6 ± 1%



color octet models studied

Top A_{fb}

- Forward-backward asymmetry, A_{FB}(tt) @ Tevatron
  - Combination of final CDF/D0 results
  - Use rapidity difference & resulting asymmetry between decay leptons



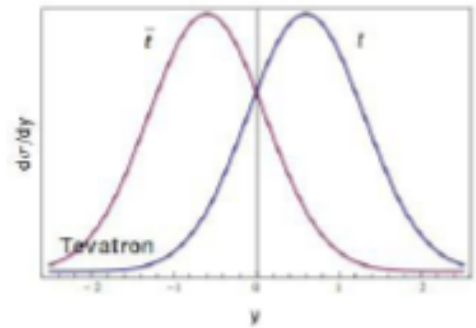
Agreement improved: statistics and QCD met in the middle

current status:

Agreement within 1.3σ

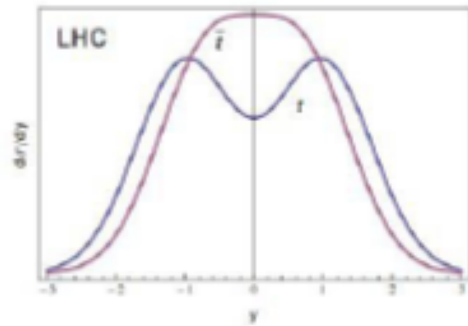
PRL 120, 042001 (2018)

Boosted top pair charge asymmetry



$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$$

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

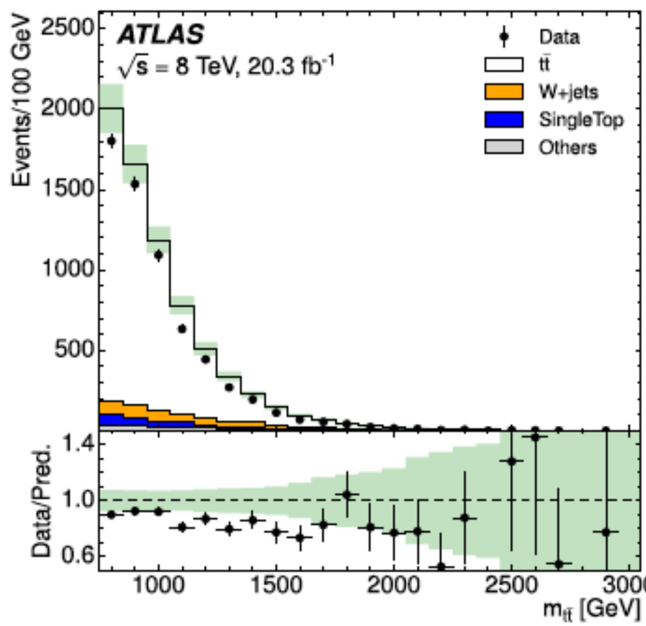


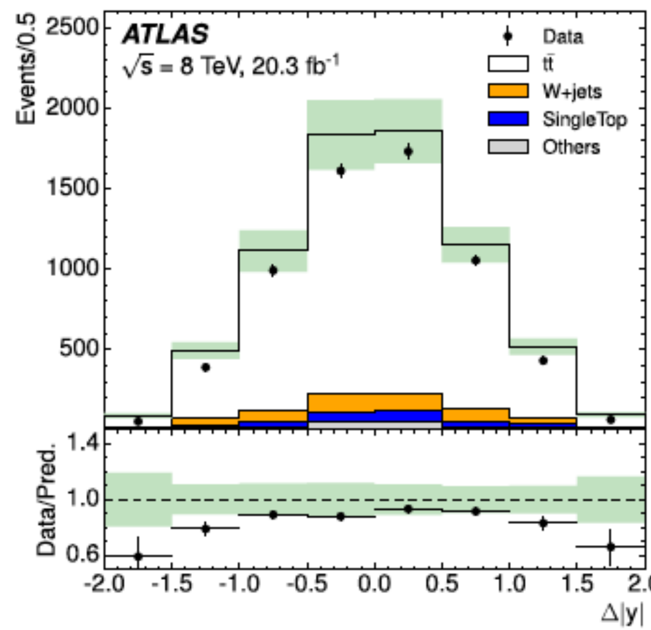
$$A_C = \frac{N(\Delta|y|>0)-N(\Delta|y|<0)}{N(\Delta|y|>0)+N(\Delta|y|<0)}$$

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

- tt production gives charge asymmetry at NLO due to interference: qq v. gg
- LHC - Tevatron: complementary for searches for new physics

detector-level distributions

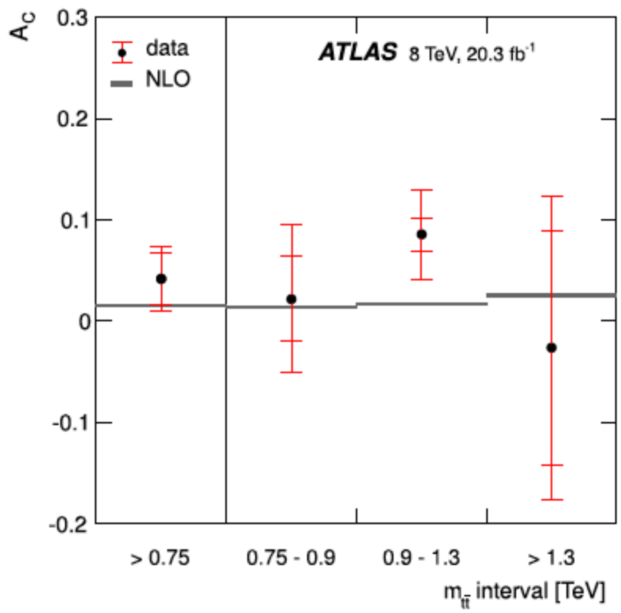


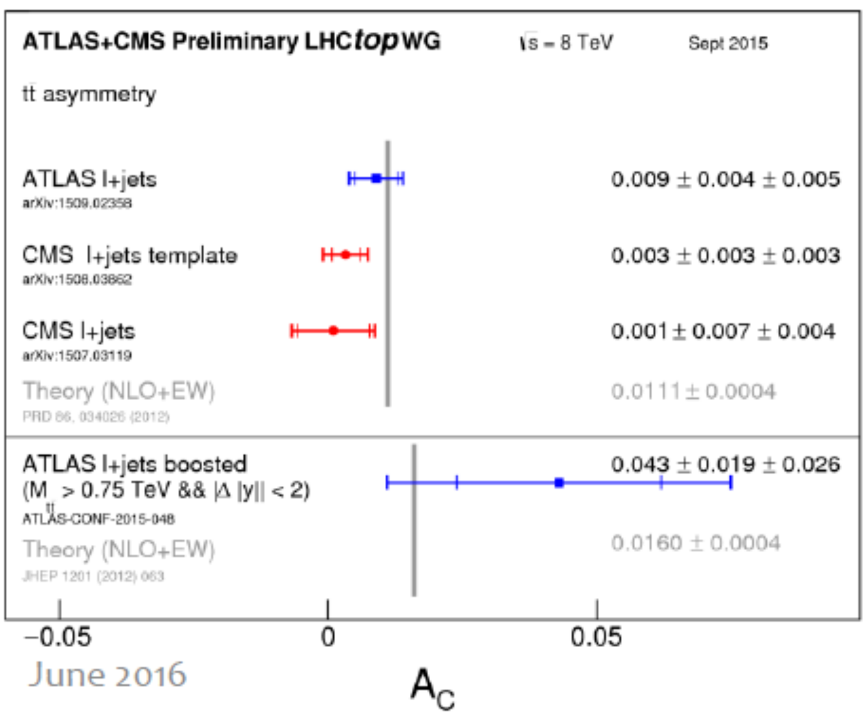


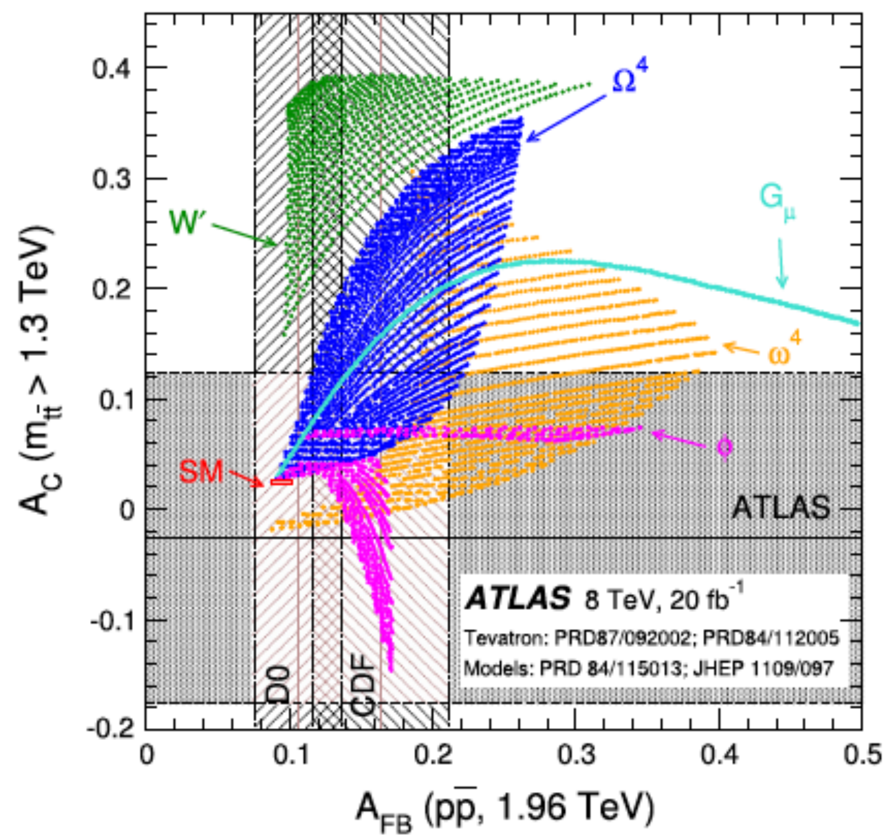
Physics Letters B (2016), Vol. 756, pp. 52-71

Boosted top pair charge asymmetry

- differential distributions sensitive to new physics, such as axi-gluons, especially at high m_{tt}
- boosted: m_{tt} >0.75 TeV



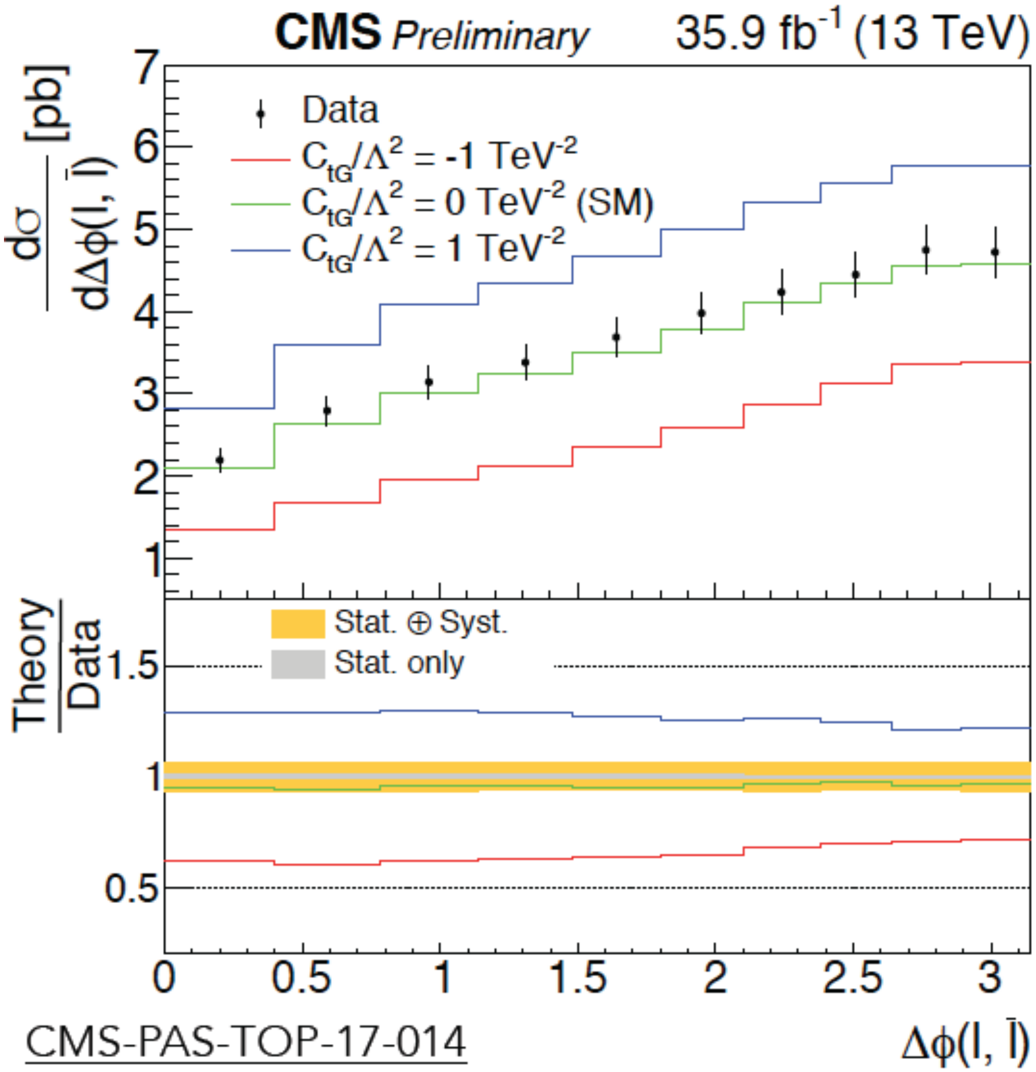




Physics Letters B (2016), Vol. 756, pp. 52-71

New Physics? Use Effective Field Theories

- Assume scale of new physics >> that probed in direct searches → constrain new physics contributions due to higher-order operators using **ETFs**



CMS-PAS-TOP-17-014

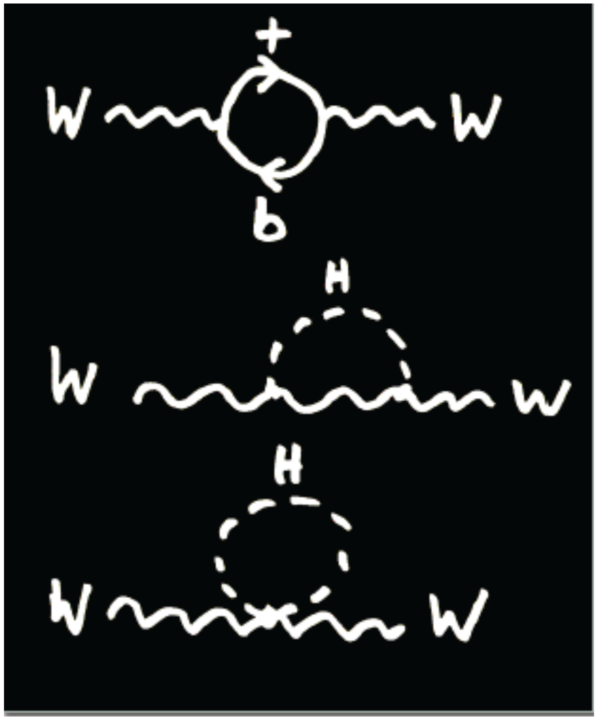
- Recent example
  - *Differential cross section to constrain top chromo-magnetic dipole moment*

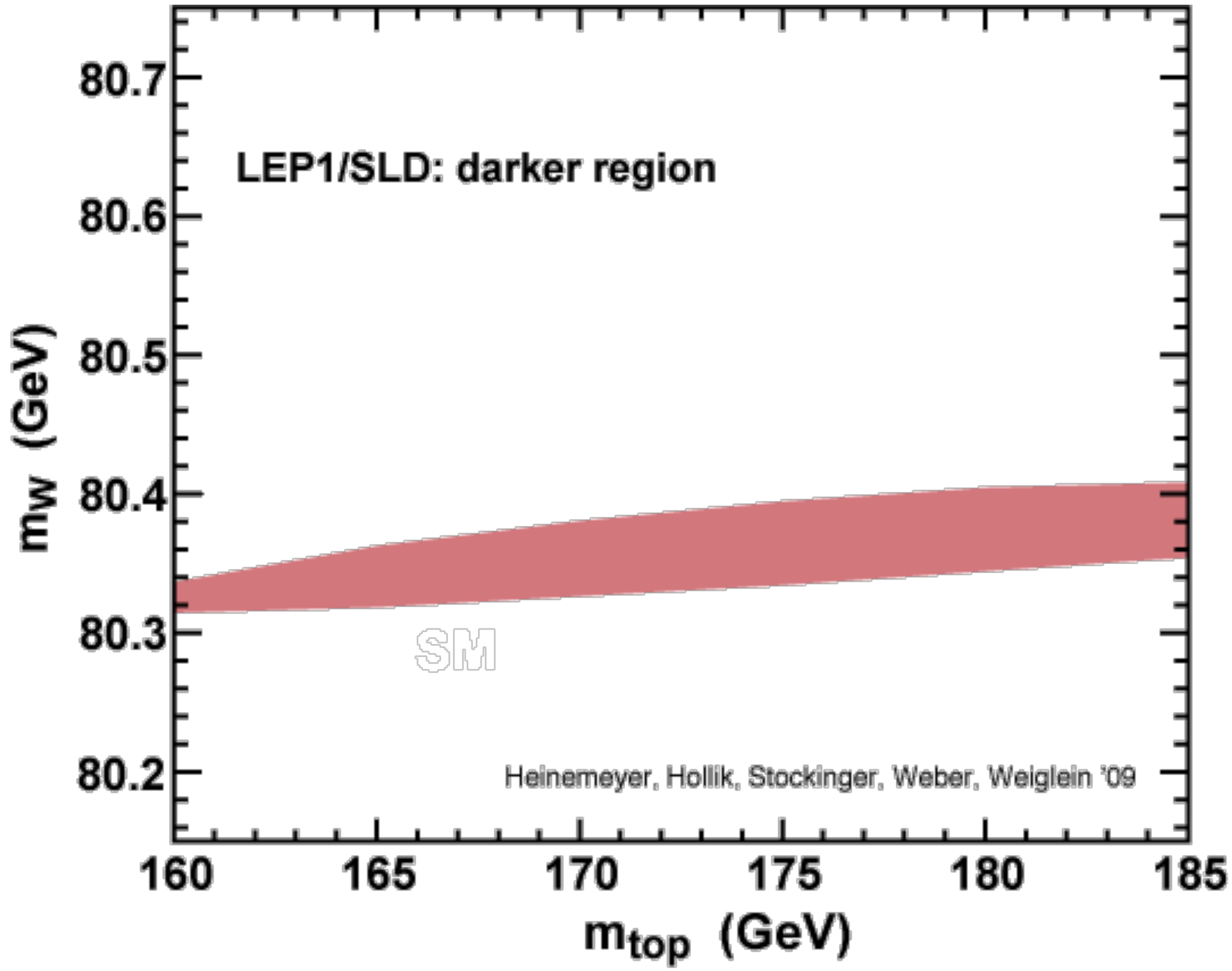
$-0.06 < C_{tG}/\Lambda^2 < 0.41$	**CMS-PAS-TOP-17-014**
$-0.89 < C_{tG}/\Lambda^2 < 0.43$	CMS 8 TeV diff. x-sec
$-0.42 < C_{tG}/\Lambda^2 < 0.30$	CMS 8 TeV incl. x-sec
$-0.32 < C_{tG}/\Lambda^2 < 0.73$	Tevatron incl. x-sec

Top Mass Measurements

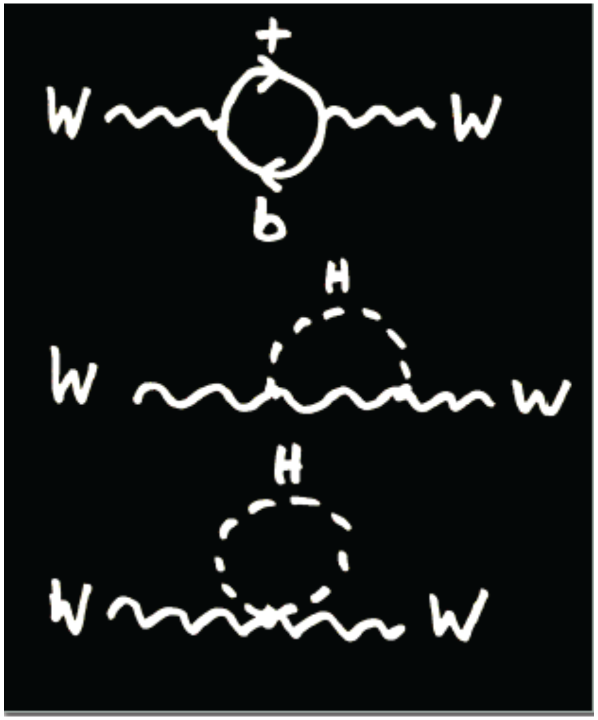
Important EWK parameter

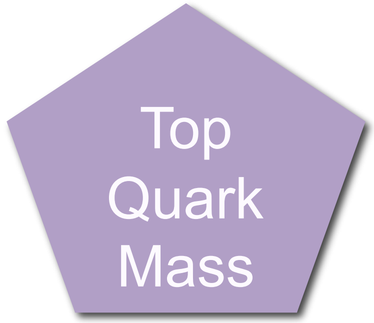
Top Quark Mass

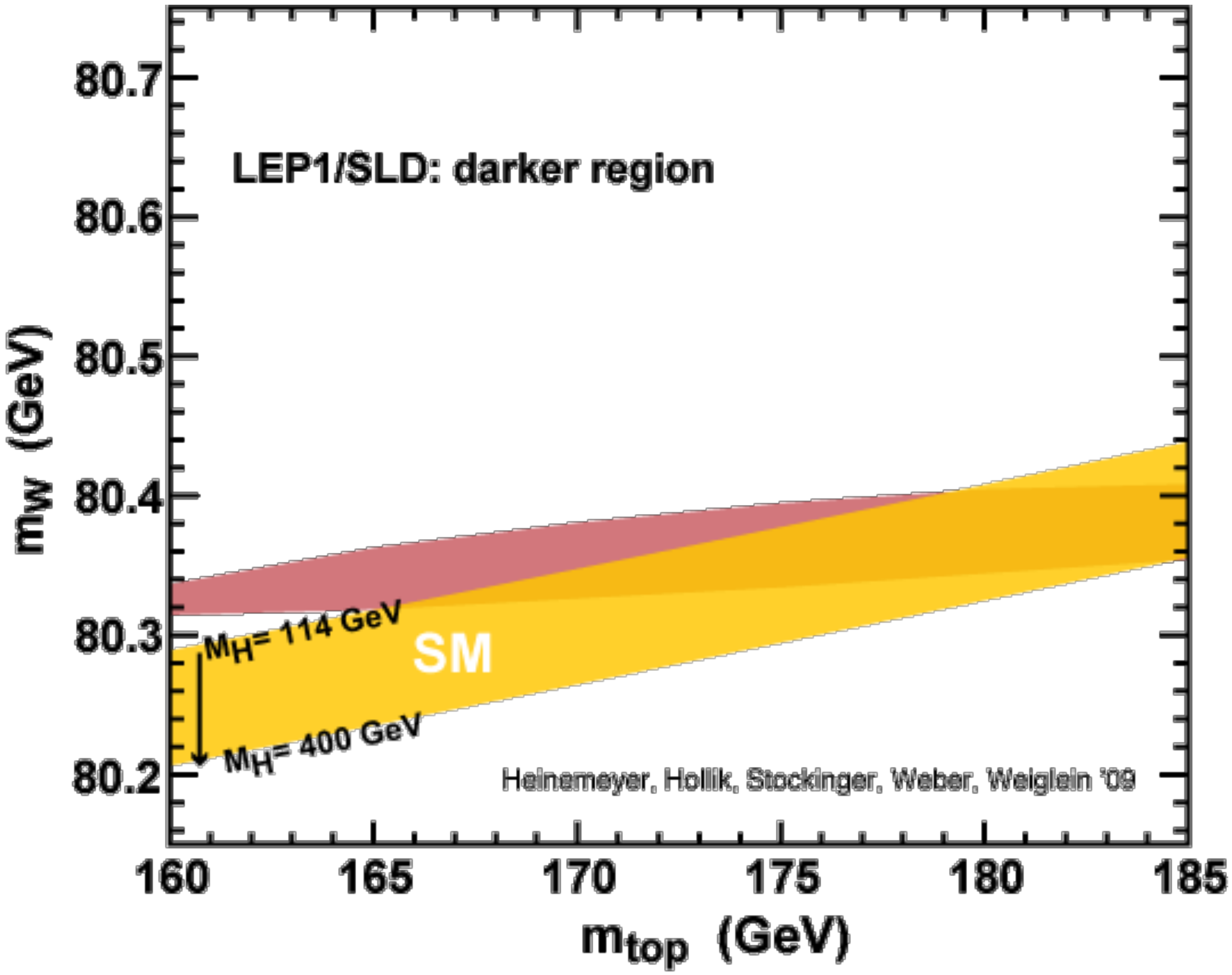


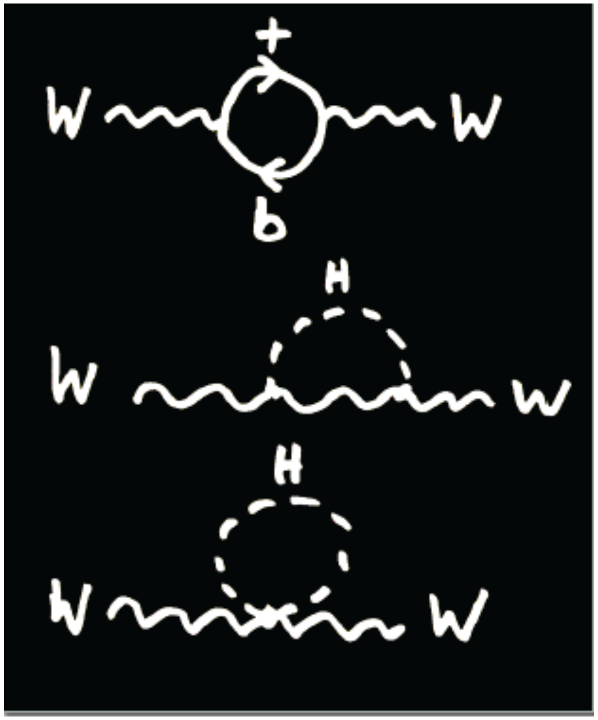


Important EWK parameter



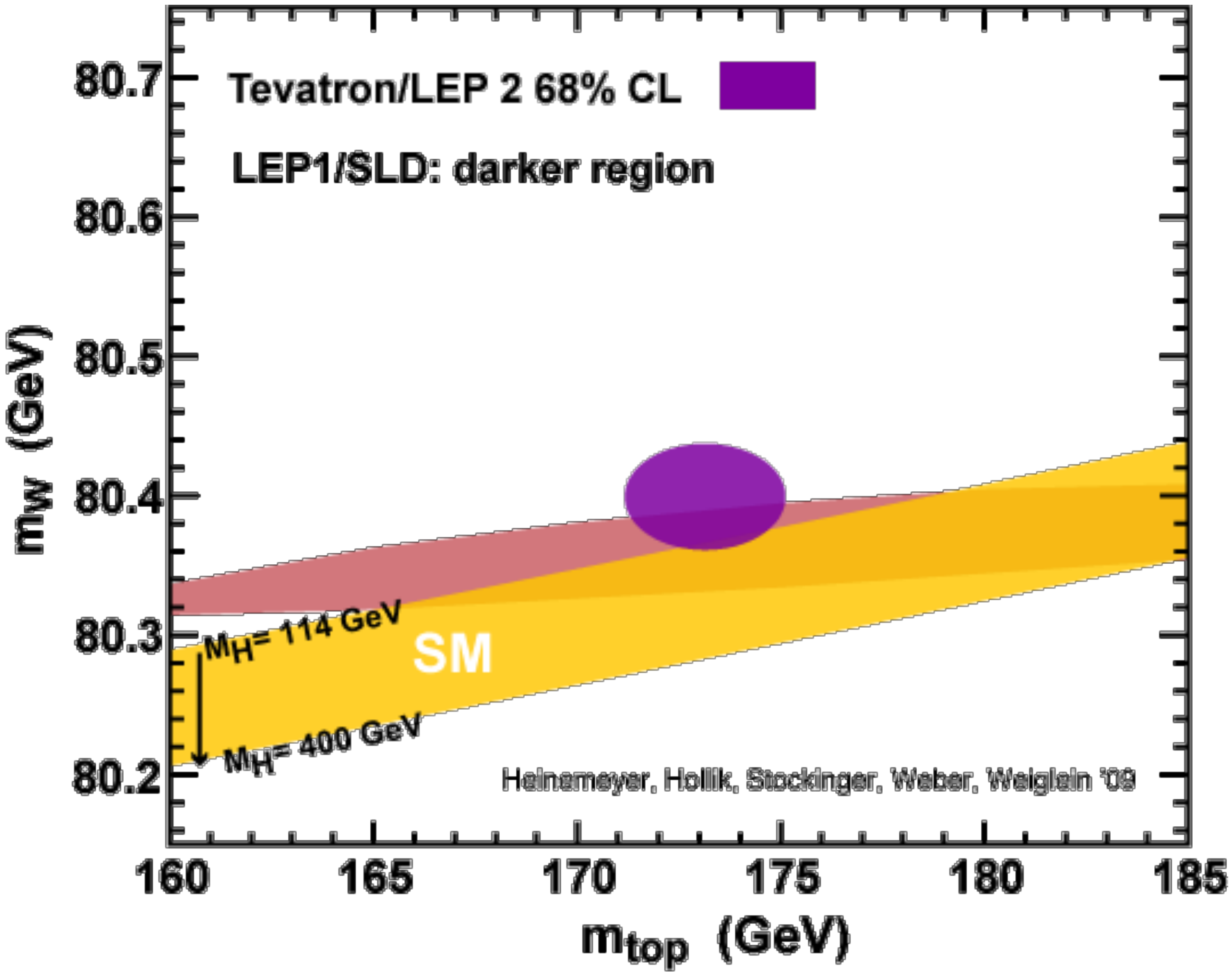






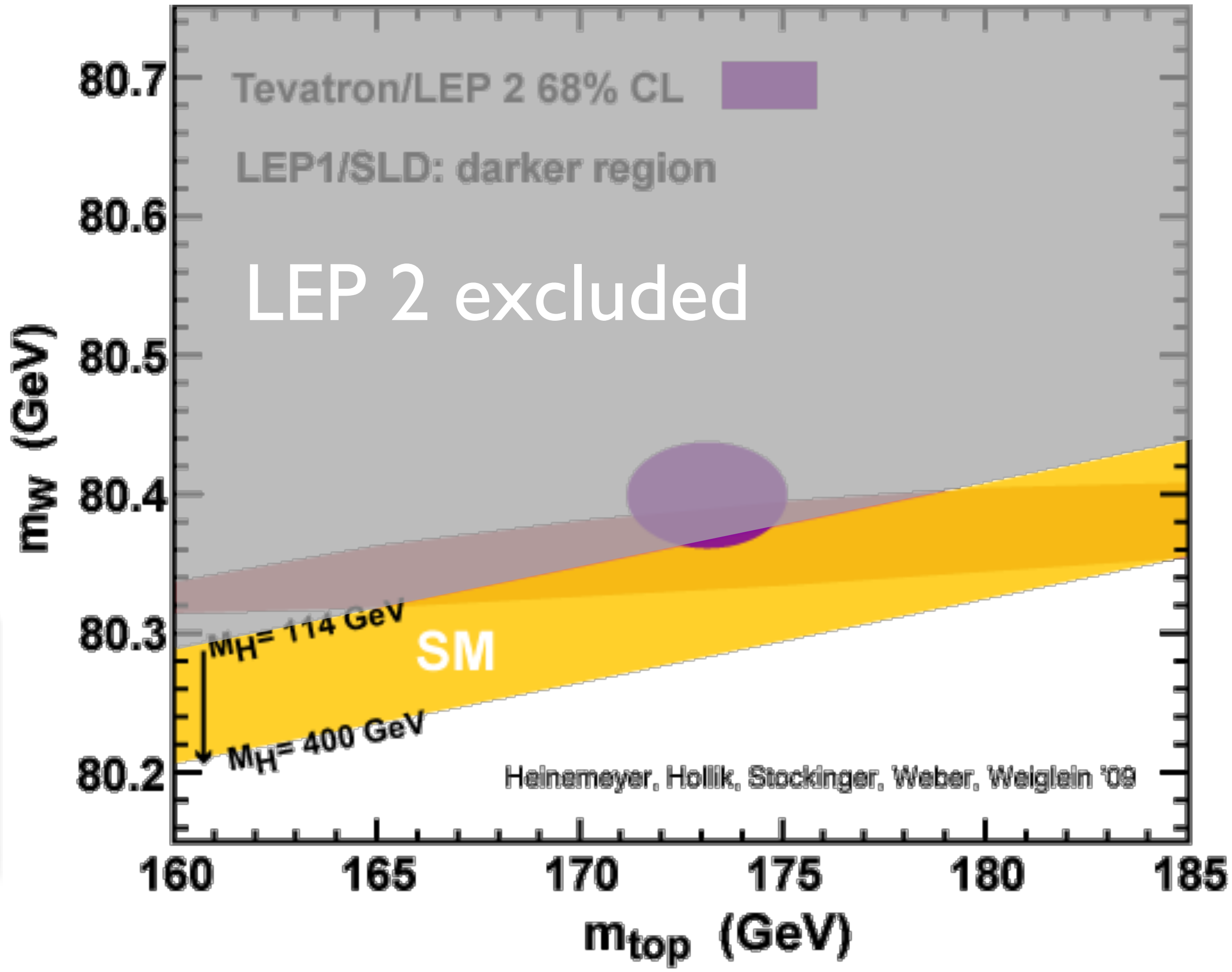
Top
Quark
Mass

Important EWK parameter



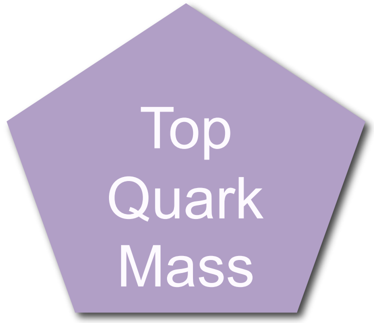
Top Quark Mass

Where is the Higgs?

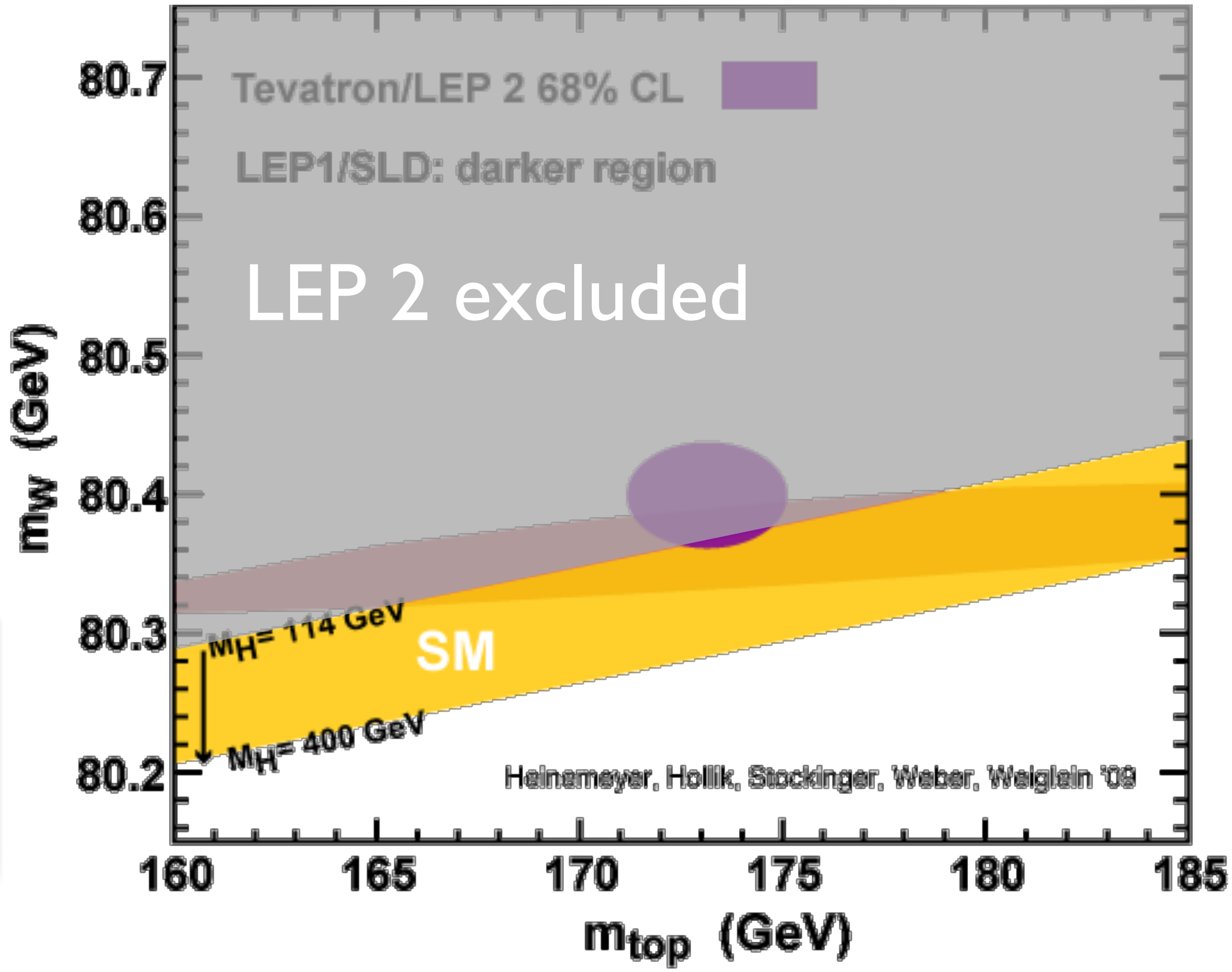


$$m_H = 87 \pm^{35}_{26} \text{ GeV}$$
$$m_H < 157 \text{ GeV} @ 95\% \text{C.L.}$$
$$m_H > 114 \text{ GeV(direct)}$$

W and top quark mass tells us Higgs mass

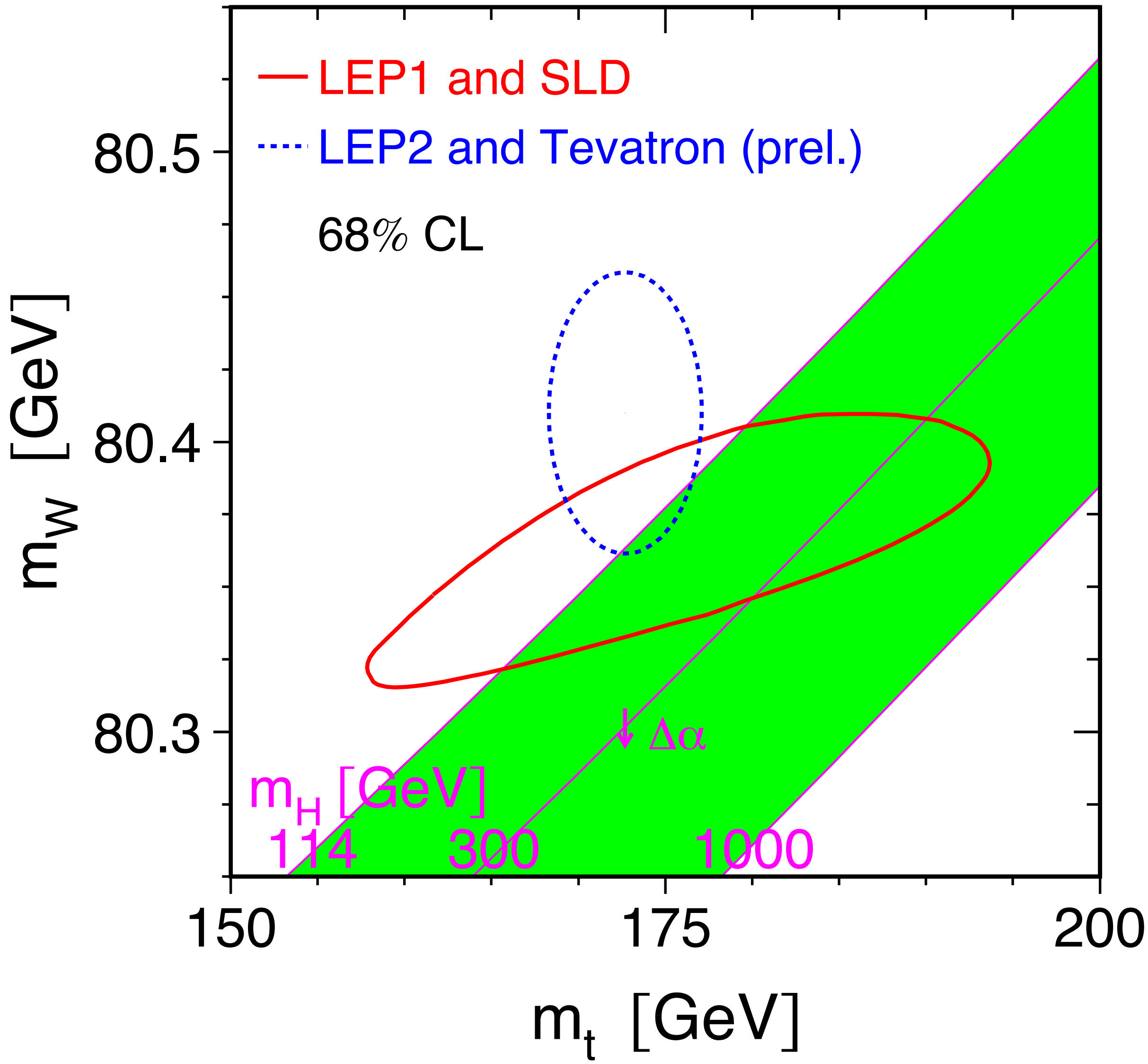


Where is the Higgs?

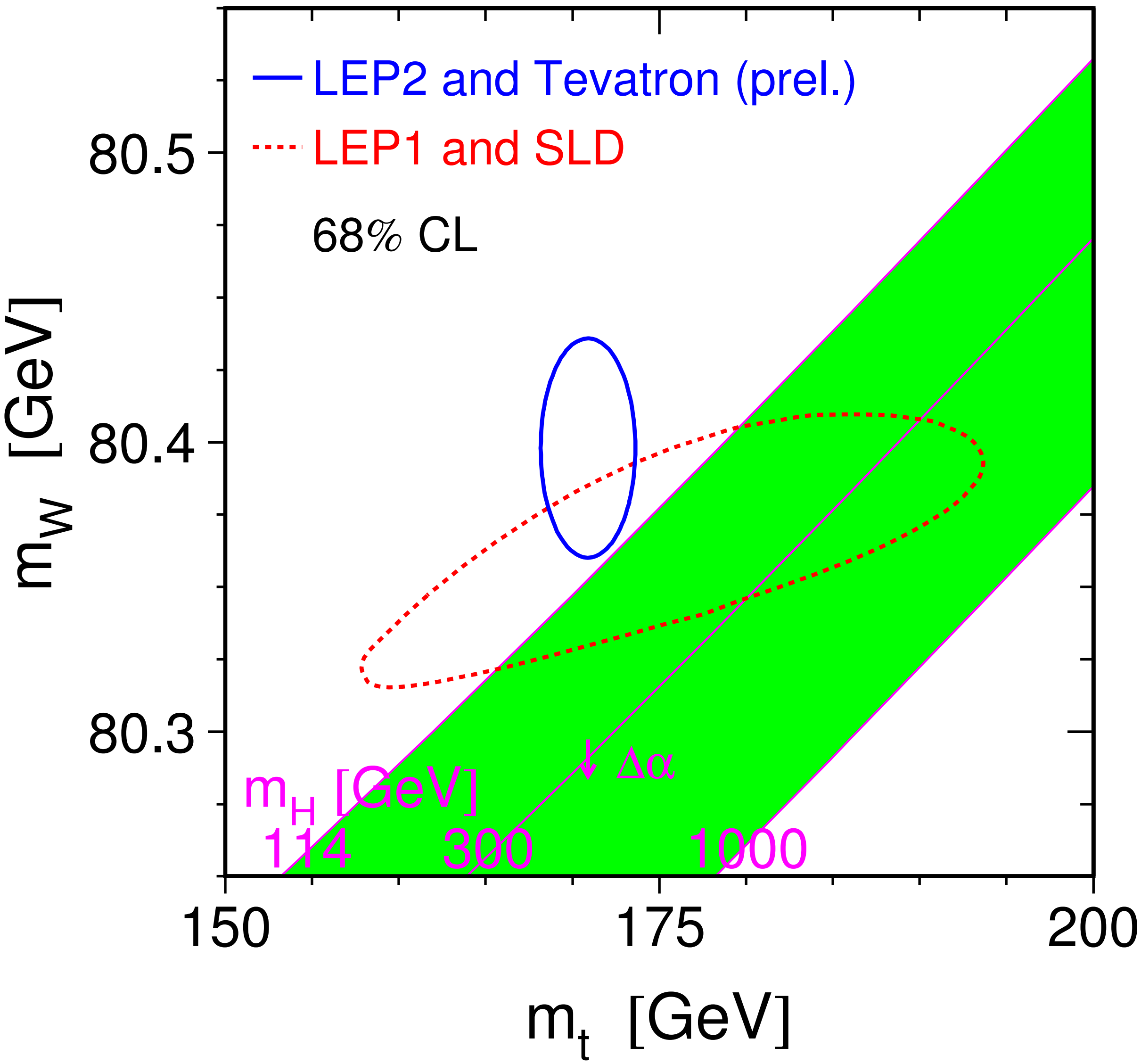


$$m_H = 87 \pm^{35}_{26} \text{ GeV}$$
$$m_H < 157 \text{ GeV} @ 95\% \text{C.L.}$$
$$m_H > 114 \text{ GeV(direct)}$$

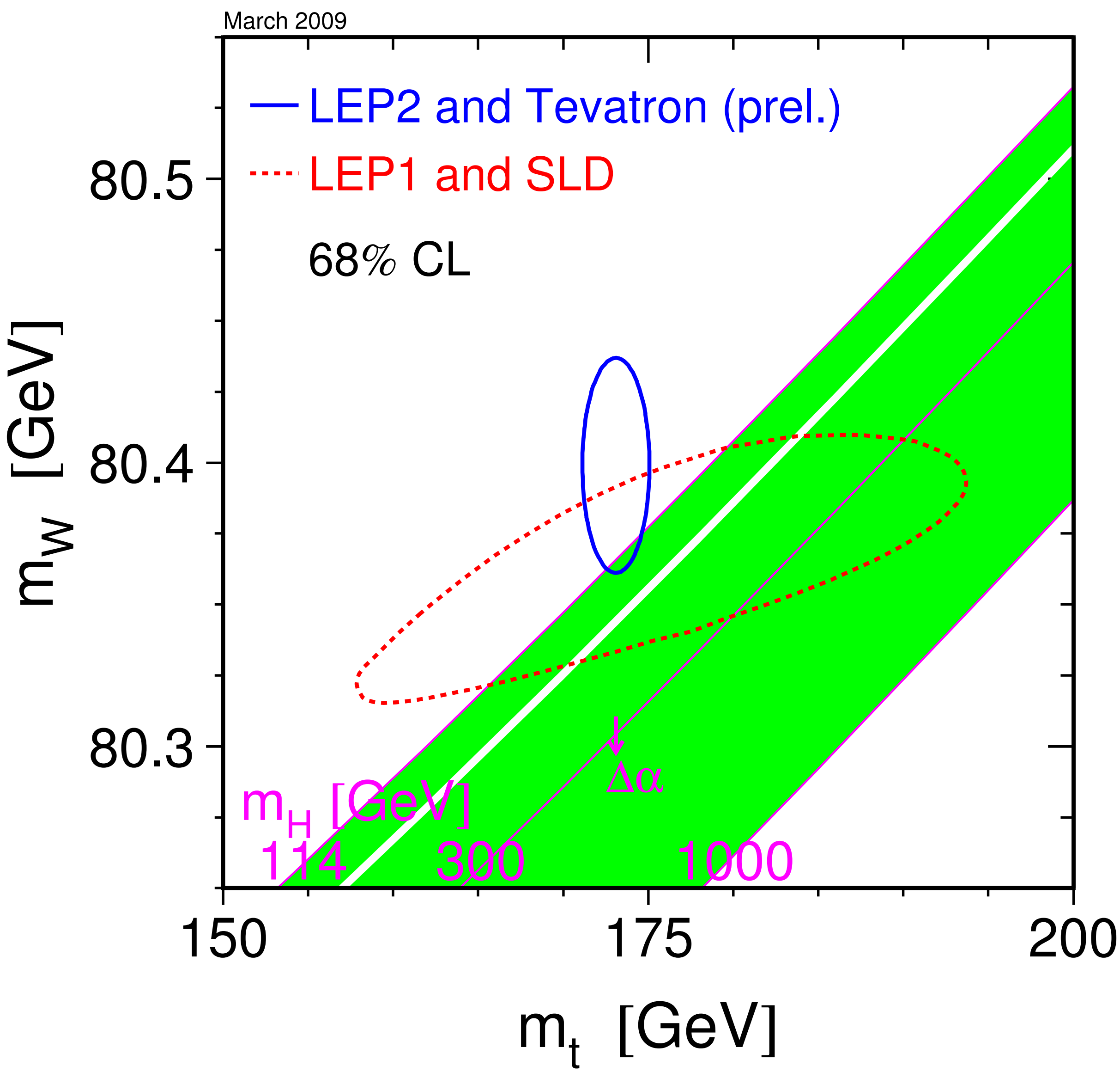
W and top quark mass tells us Higgs mass



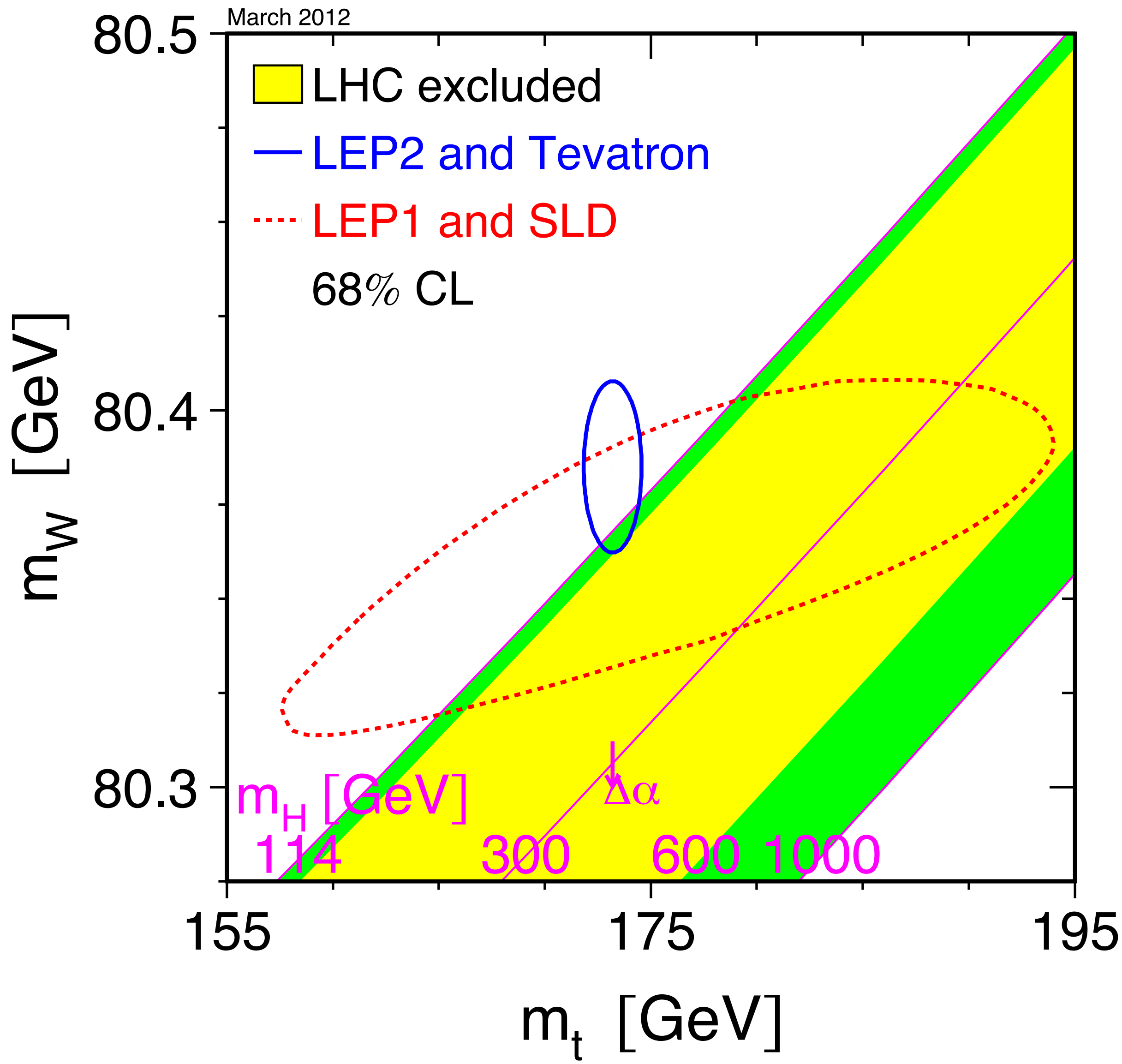
LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
80.5
80.4
80.3
m_W [GeV]
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]



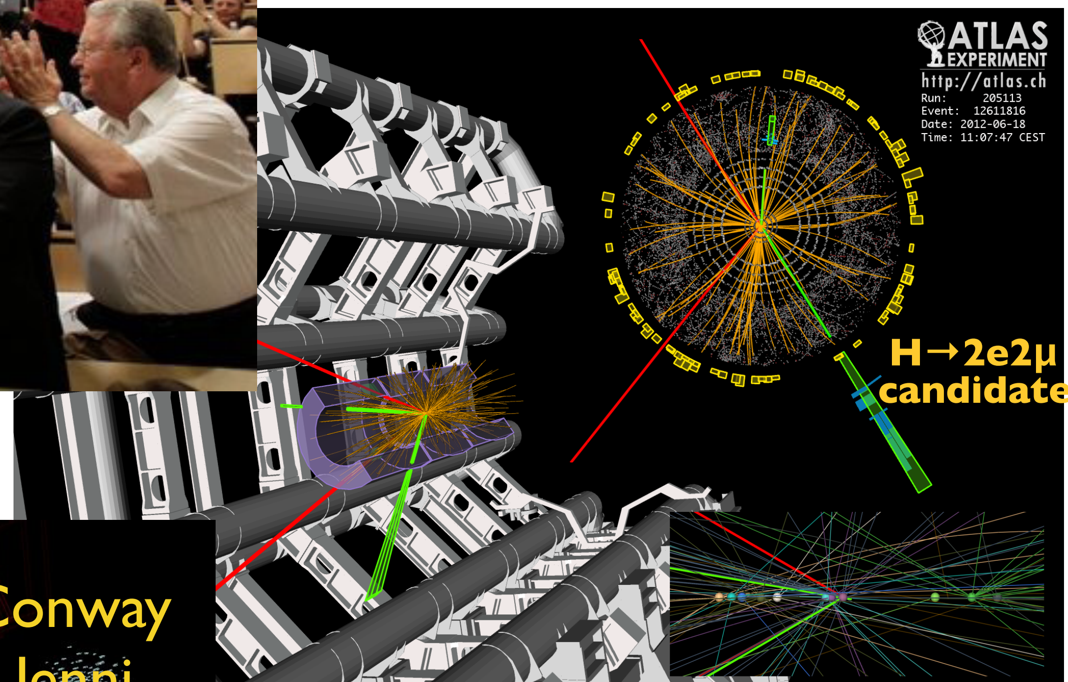
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]

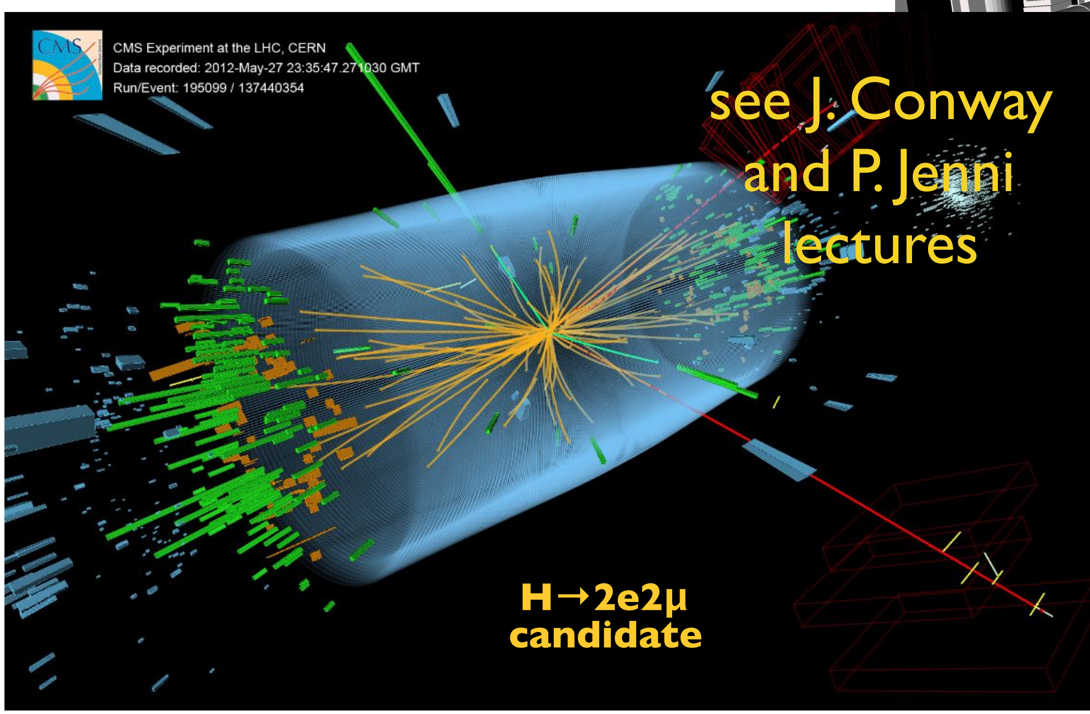


March 2009
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
Δα
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]

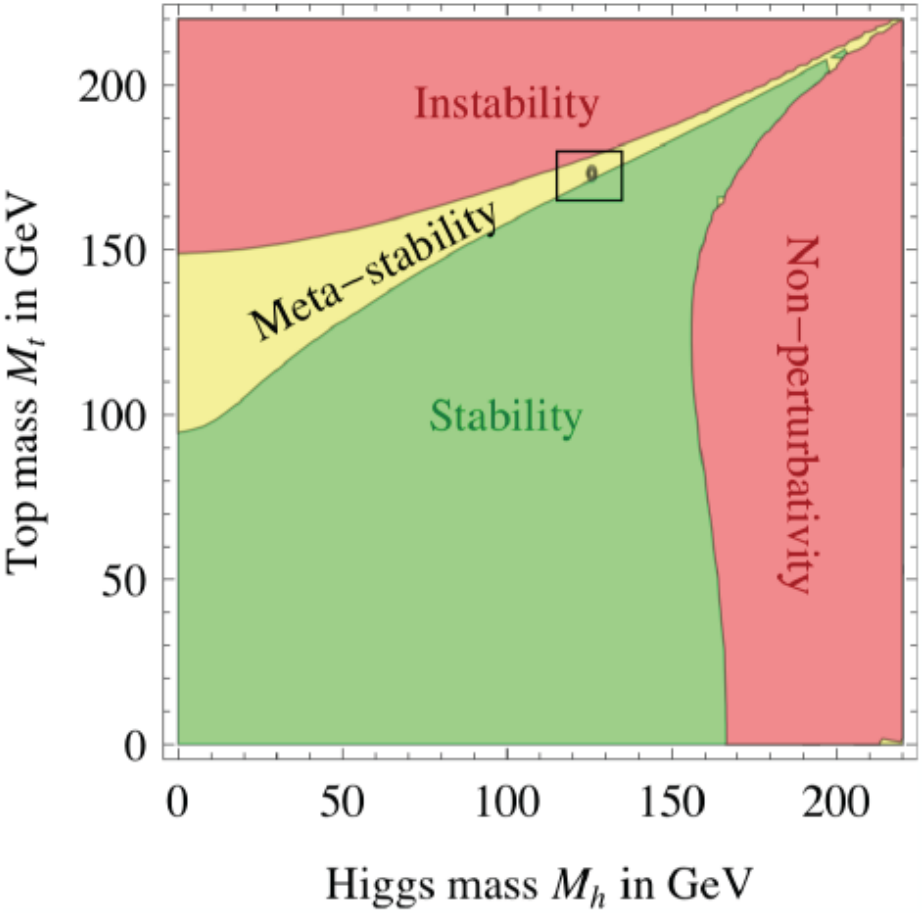

March 2012
LHC excluded
LEP2 and Tevatron
LEP1 and SLD
68% CL
m_H [GeV]
114
300
600
1000
Δα
80.5
80.4
80.3
m_W [GeV]
155
175
195
m_t [GeV]

Higgs is Discovered! 2012





theory: 1964
design: 1984
construction: 1998
collisions: 2010



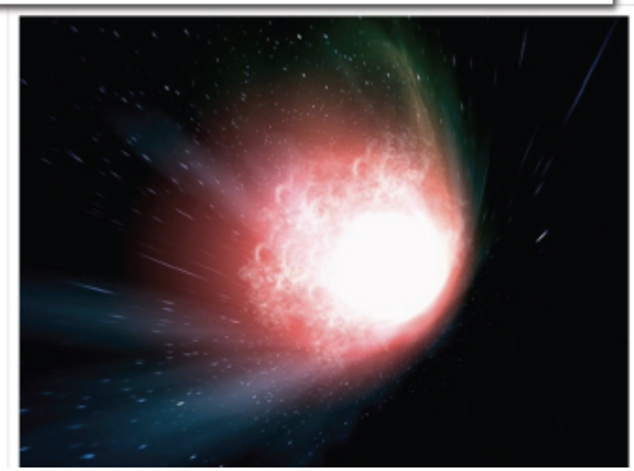
Top Quark Mass

- Stability of the EW vacuum is an important property of the SM
- Measurements of the top mass and Higgs mass for the first time allow us to infer properties of the vacuum we live in!

$$M_h > 129.6\,\mathrm{GeV} + 2.0(M_t - 173.34\,\mathrm{GeV}) - 0.5\,\mathrm{GeV}\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007} \pm 0.3\,\mathrm{GeV}$$

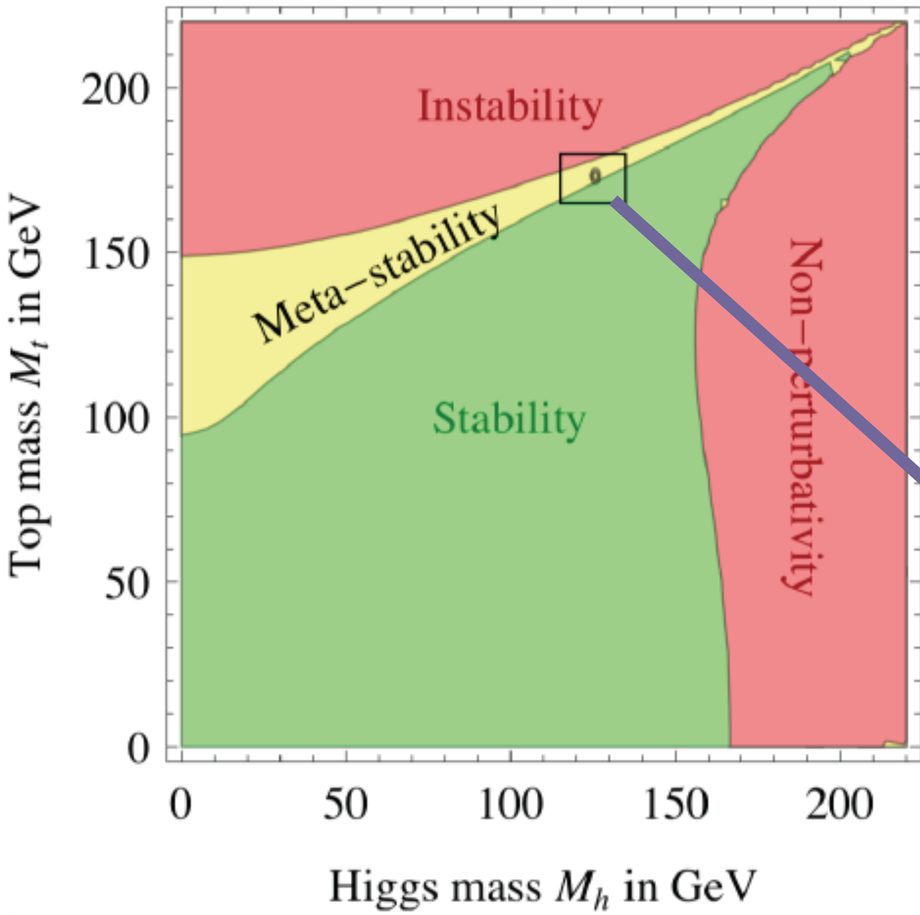
Will our universe end in a 'big slurp'?

nbcnews.com



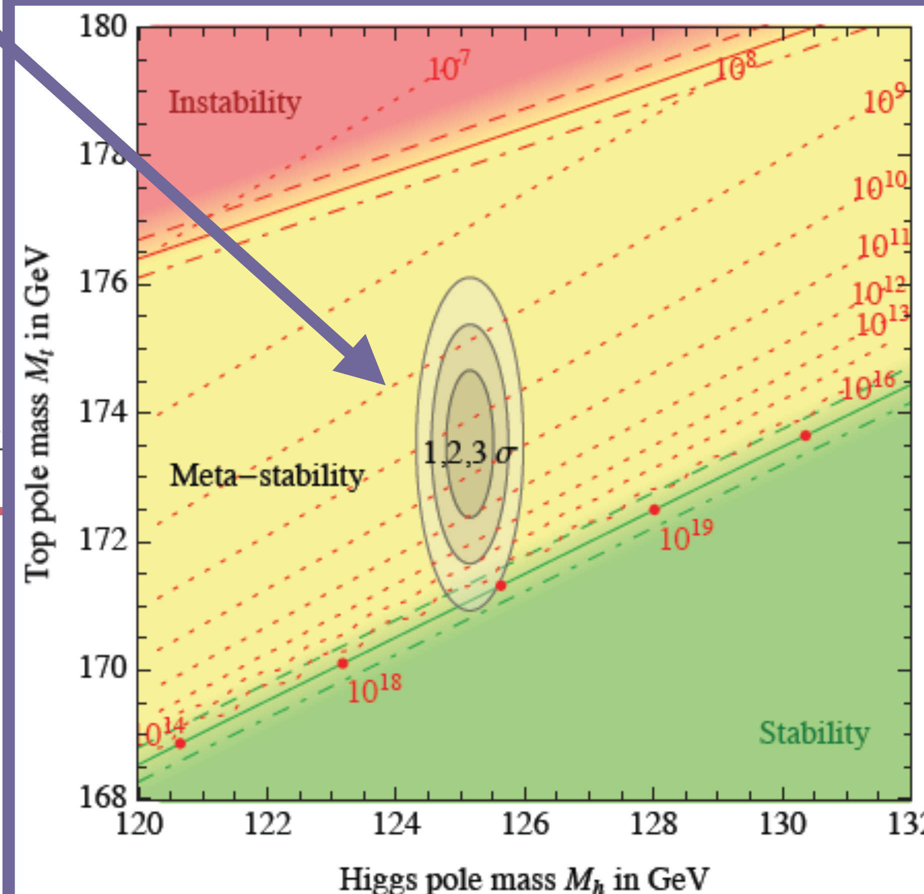
- A fine-tuned situation: vacuum on the verge of being either stable or unstable. ~1-2 GeV in either mass could tip the scales. (But new physics could possibly change this scenario.)
- What mass are we measuring?? Pole mass or MC mass?

arXiv:1307.3536



Top Quark Mass

- Stability of the EW vacuum is an important property of the SM

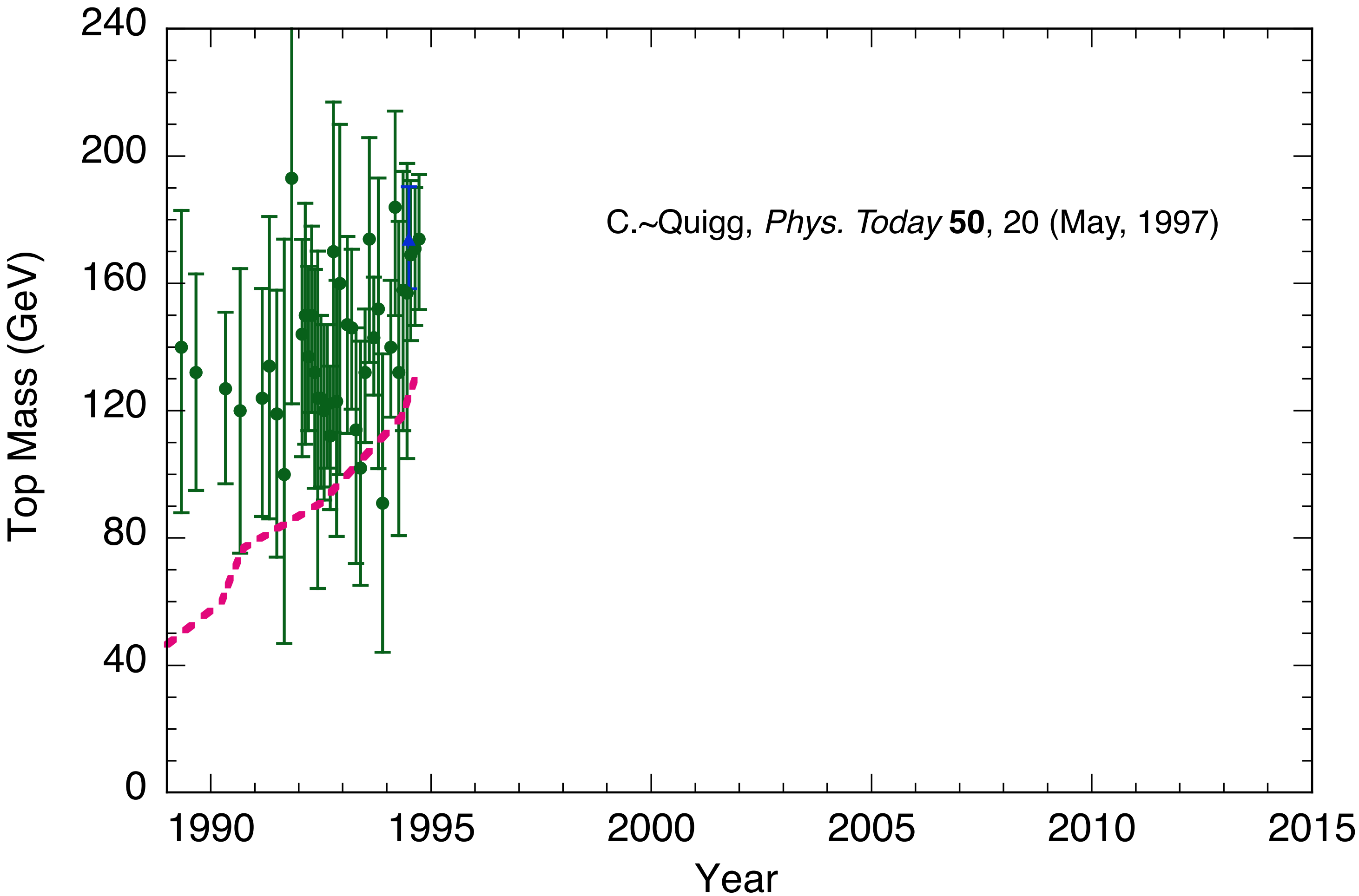


$$M_h > 129.6\,\mathrm{GeV} + 2.0(M_t - 173.34\,\mathrm{GeV}) - 0.5\,\mathrm{GeV}\,\frac{\alpha_3(M_Z) - 0.1}{0.0007}$$

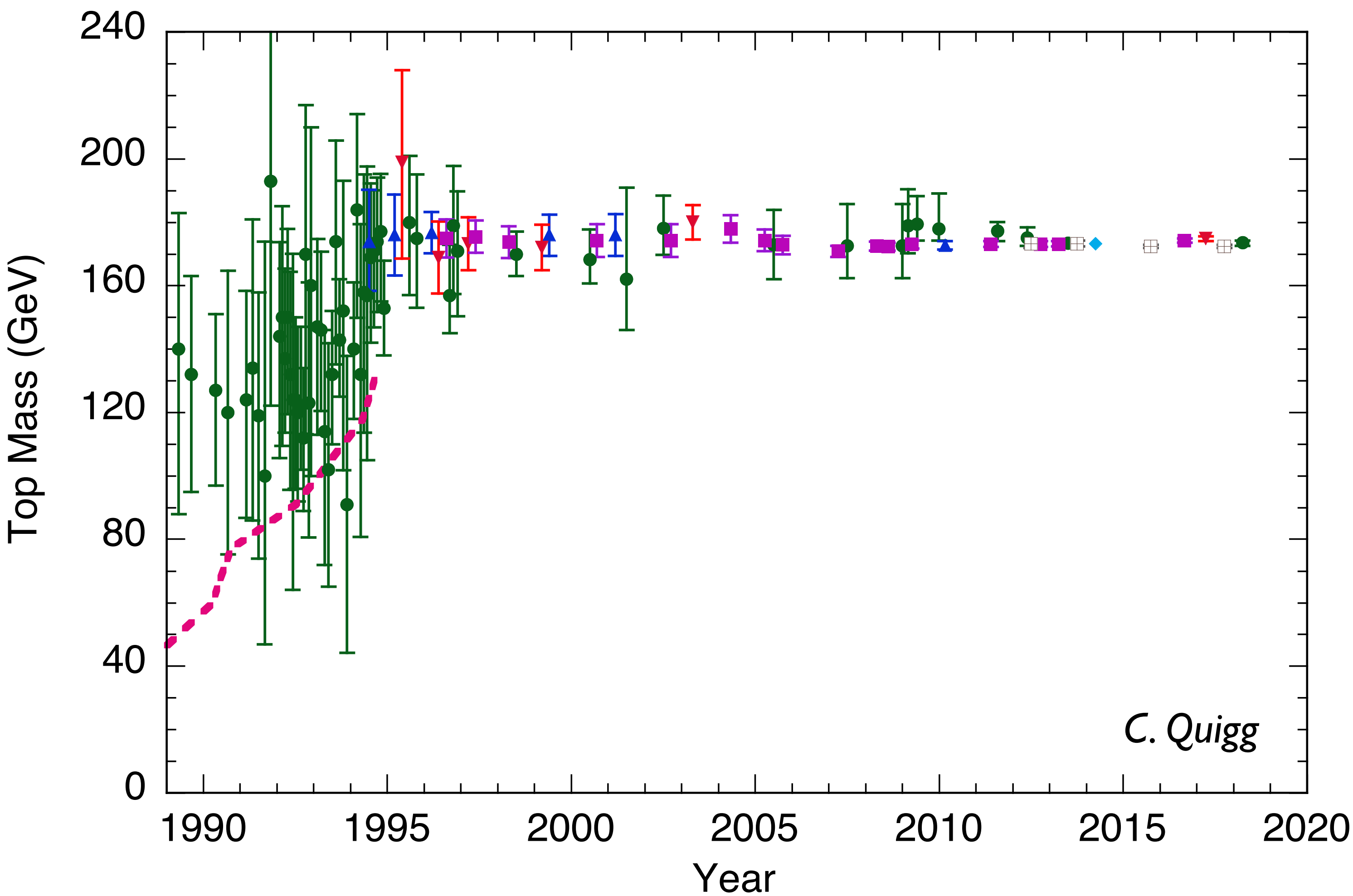
- A fine-tuned situation: vacuum on the verge of being either stable or unstable. ~1-2 GeV in either mass could tip the scales. (But new physics could possibly change this scenario.)
- What mass are we measuring?? Pole mass or MC mass?

arXiv:1307.3536

Indirect Constraints on Top Quark Mass



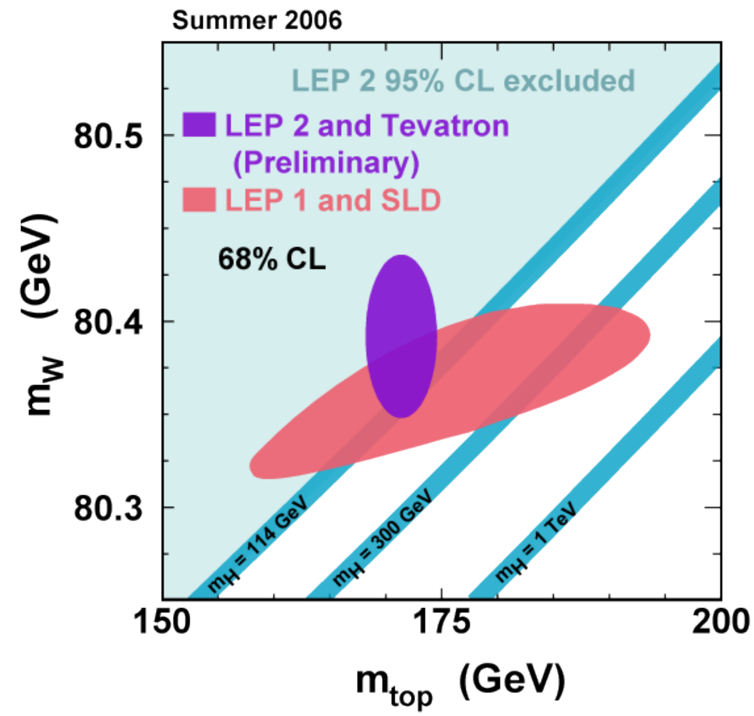
Evolution of Top Mass Measurements and Constraints



C.~Quigg, *Phys. Today* **50**, 20 (May, 1997); extended version: arXiv:hep-ph/9704332, and updates via private communication.

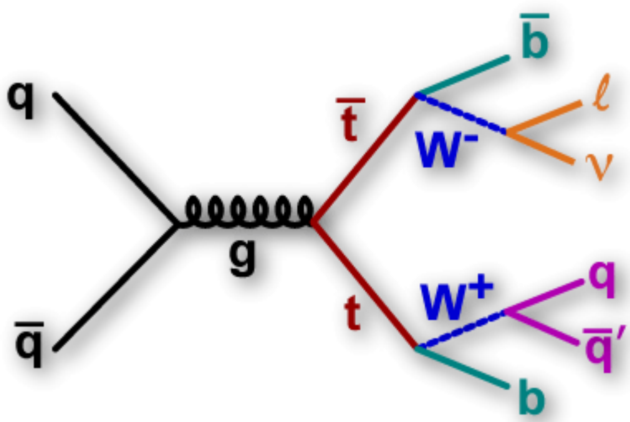
Top Quark Mass

- Important EWK parameter
- Key role in BSM physics models
- Constrains the Higgs mass
- Heavy: Unexpected role in EWSB?

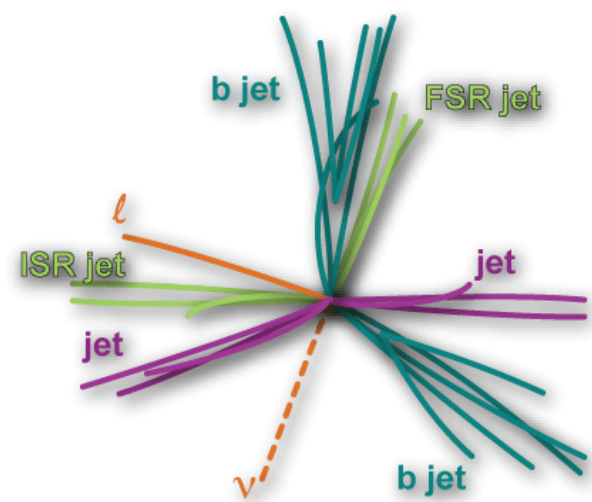


Challenges: combinatorics, b-tagging efficiencies, jet energy scale.

Solutions: sophisticated analyses, in-situ W→jj calibration



What a theorist sees…

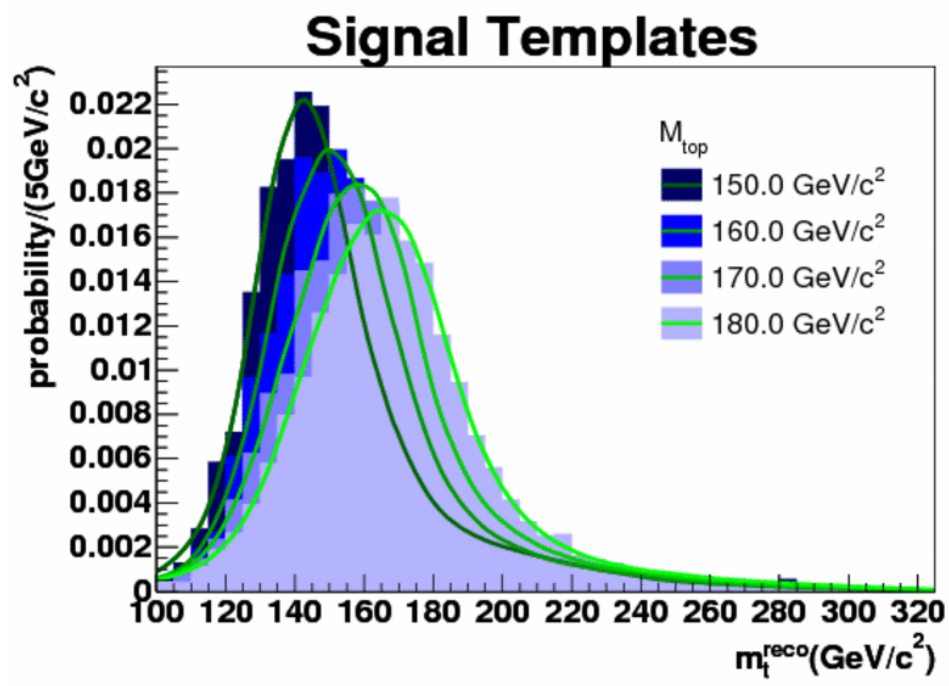


What an experimentalist sees

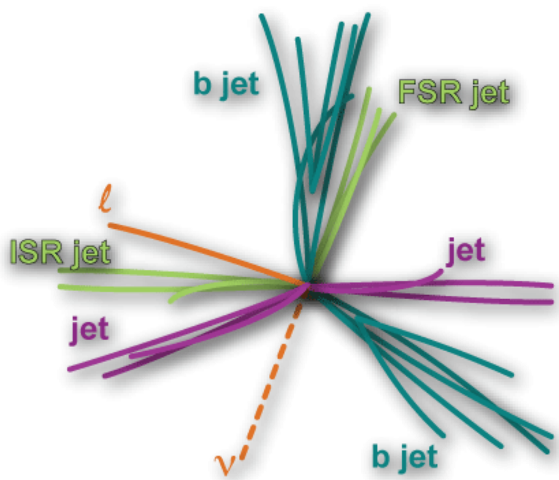
Template: measure most quantities in an event and reconstruct the mass

How we measure the top quark mass?

- p_T leptons
- E_T jets
- missing E_T
- b-tags



difficult combinatorics:



minimize the chi-square:

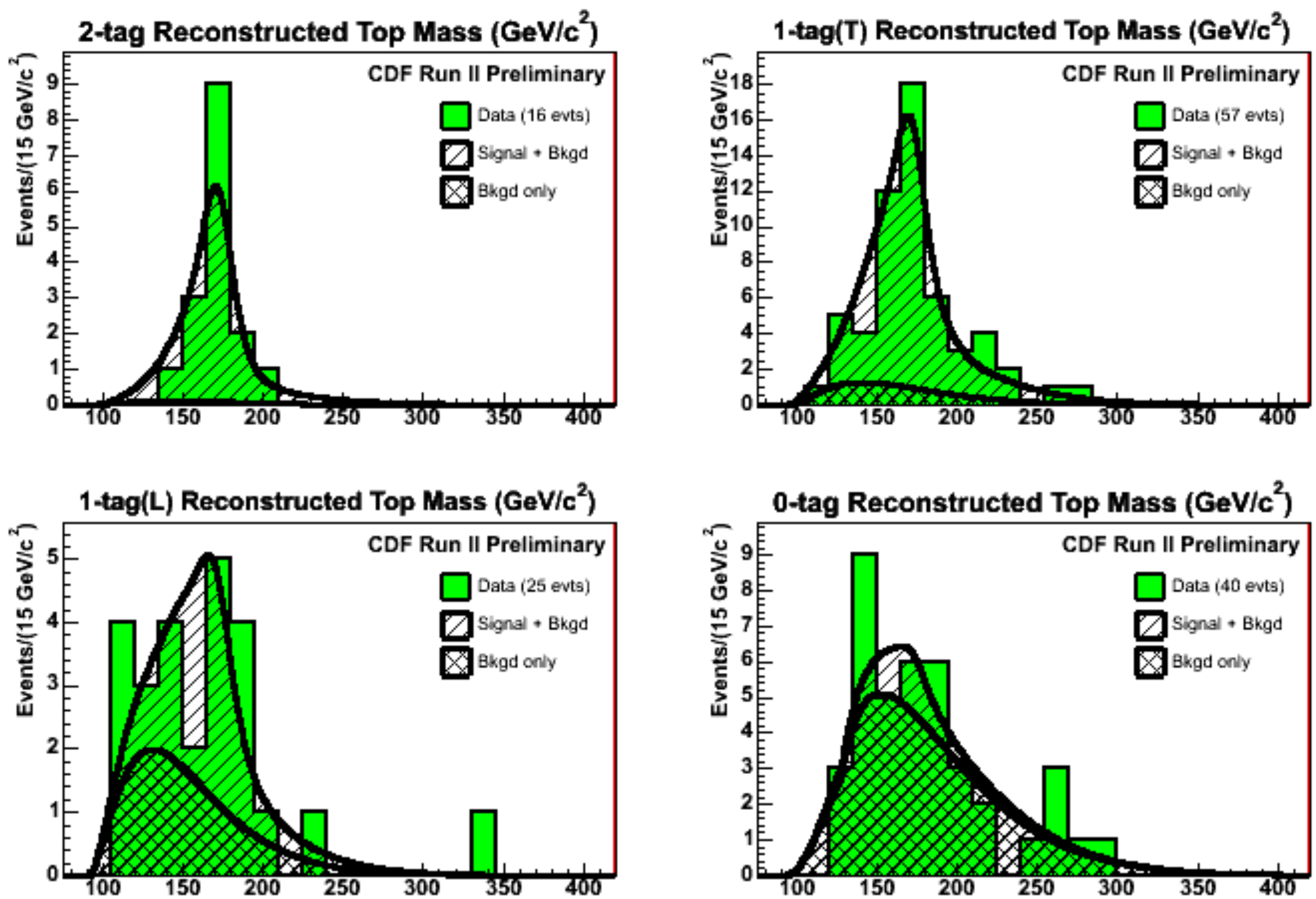
$$\chi^2 = \Sigma_{i=\ell,4jets}\frac{(p_T^{i,fit}-p_T^{i,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y}\frac{(U_j^{fit}-U_j^{meas})^2}{\sigma_j^2}$$
$$+\frac{(M_{jj}-M_W)^2}{\Gamma_W^2}+\frac{(M_{\ell\nu}-M_W)^2}{\Gamma_W^2}+\frac{(M_{bjj}-m_t^{reco})^2}{\Gamma_t^2}+\frac{(M_{b\ell\nu}-m_t^{reco})^2}{\Gamma_t^2}$$

How we measure the top quark mass?

Template: measure most quantities in an event and reconstruct the mass

early Tevatron Run 2 example:

spring 2005



Better sensitivity by splitting in S/B bins, in this case, number of b-tags

How we measure the top quark mass?

Template: one of the largest systematic uncertainties: Jet energy scale (JES)

JES calibrations are complicated!

Quark/gluon produced from p-p (p-pbar) interaction.

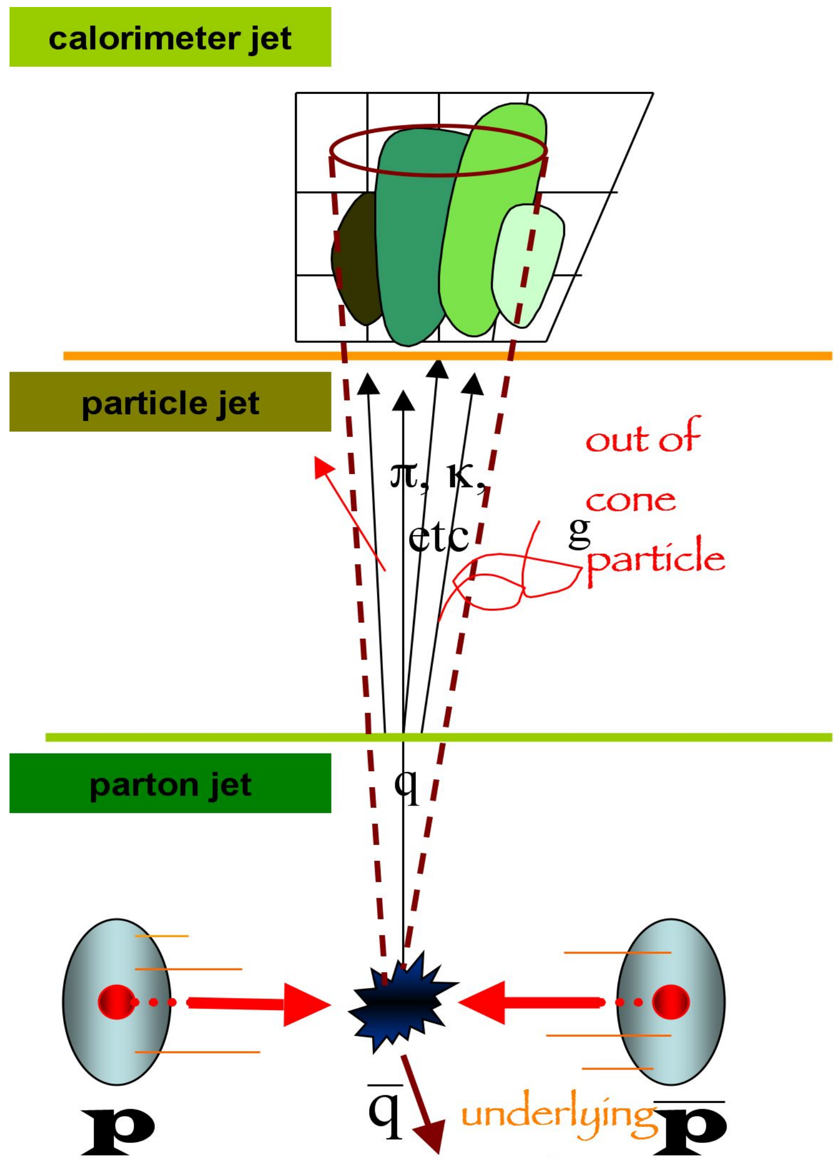
Fragmentation into hadrons.

Jet clustering algorithm (adds towers inside cone).

Fraction of energy is outside of cone.

Underlying event contributes to energy inside of cone.

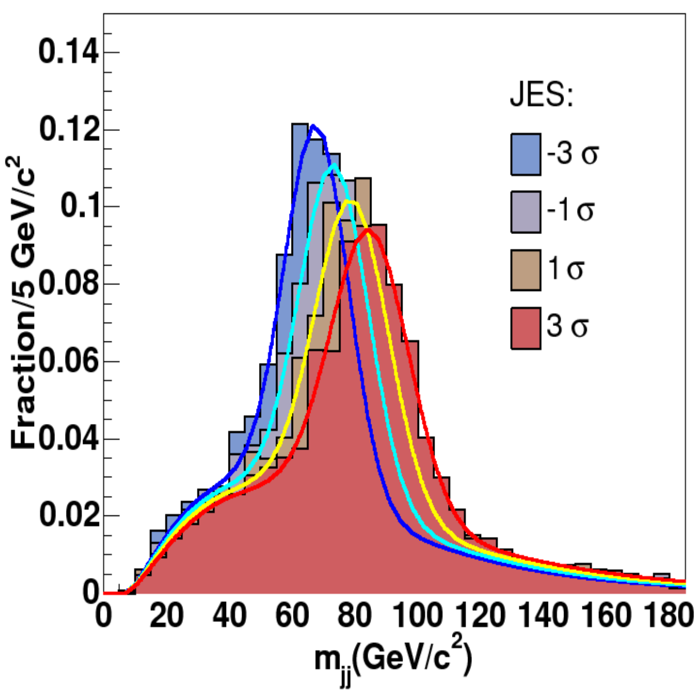
⇒Need to get original parton energy!



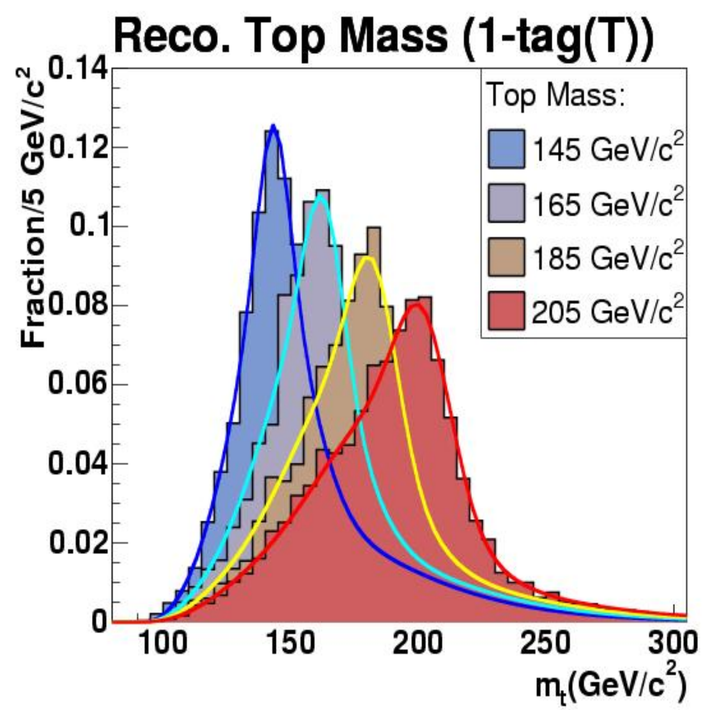
How we measure the top quark mass?

Template: one of the largest systematic uncertainties: Jet energy scale (JES)

Creative solution: fit for the JES using known W mass peak



↔



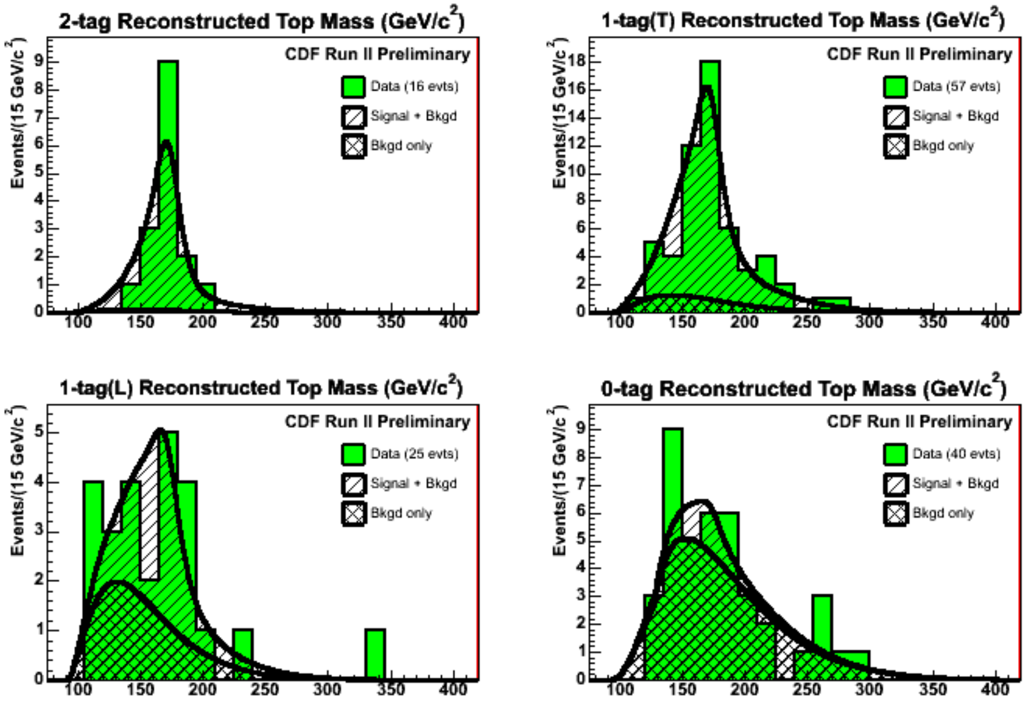
in-situ JES calibration with W→jj

same data: same JES, reduced systematics

First in-situ JES calibration at Tevatron

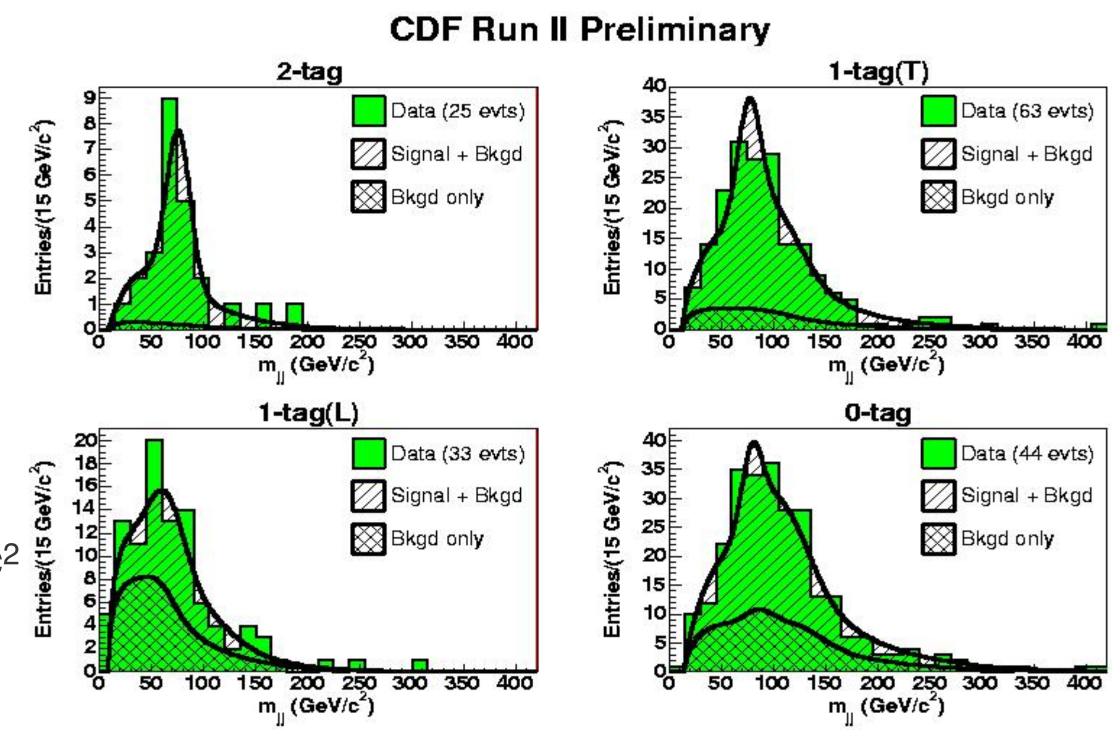
With 138 candidate ttbar events:

M_{top}= 173.2 +/- 2.8 (stat.) +/- 3.4 (syst.) GeV/c



before in-situ Wjj calibration

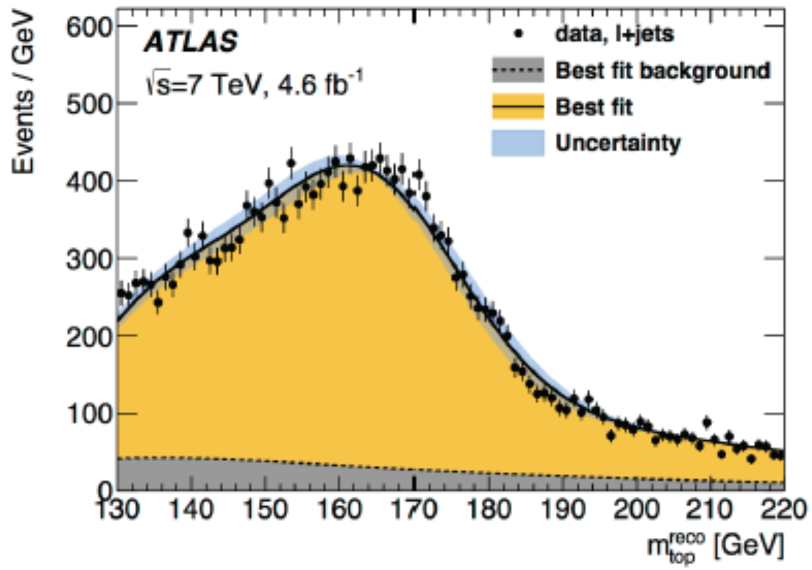
after in-situ Wjj calibration



With the same data as previously:

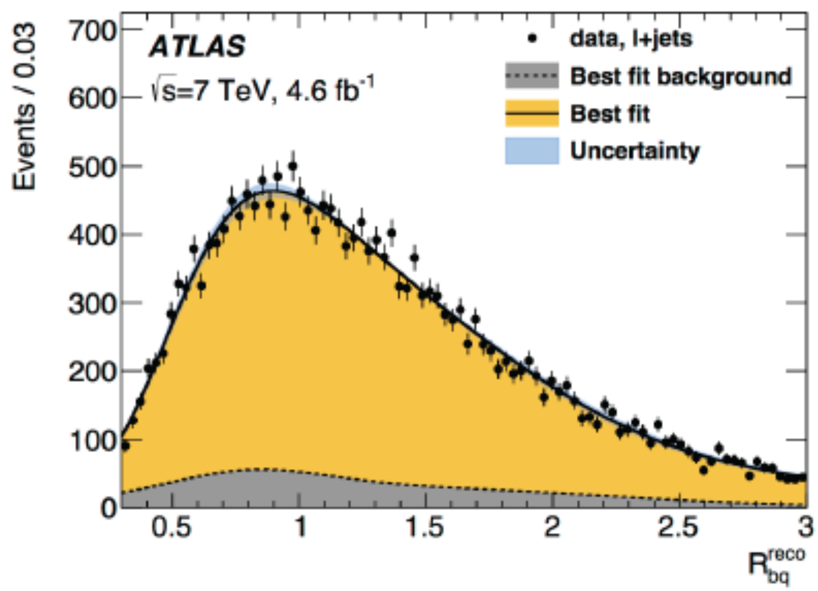
M_{top}= 173.5 +/- 2.7 (stat.) +/- 2.8 (syst.) GeV/c^2

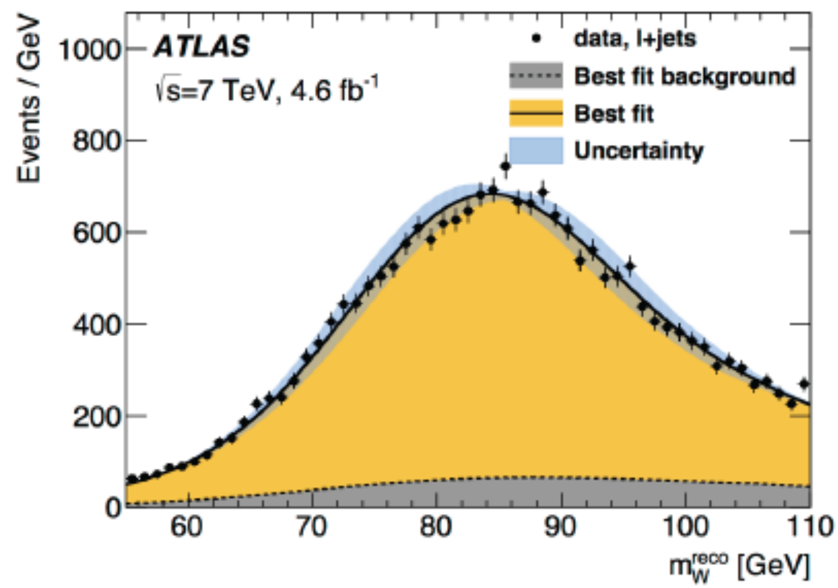
ATLAS 3D in-situ calibration:



- 3D template fit in l+jets
- Reconstruct the top pairs using kinematic likelihood fit to select combination of assignments that best fits ttbar hypothesis

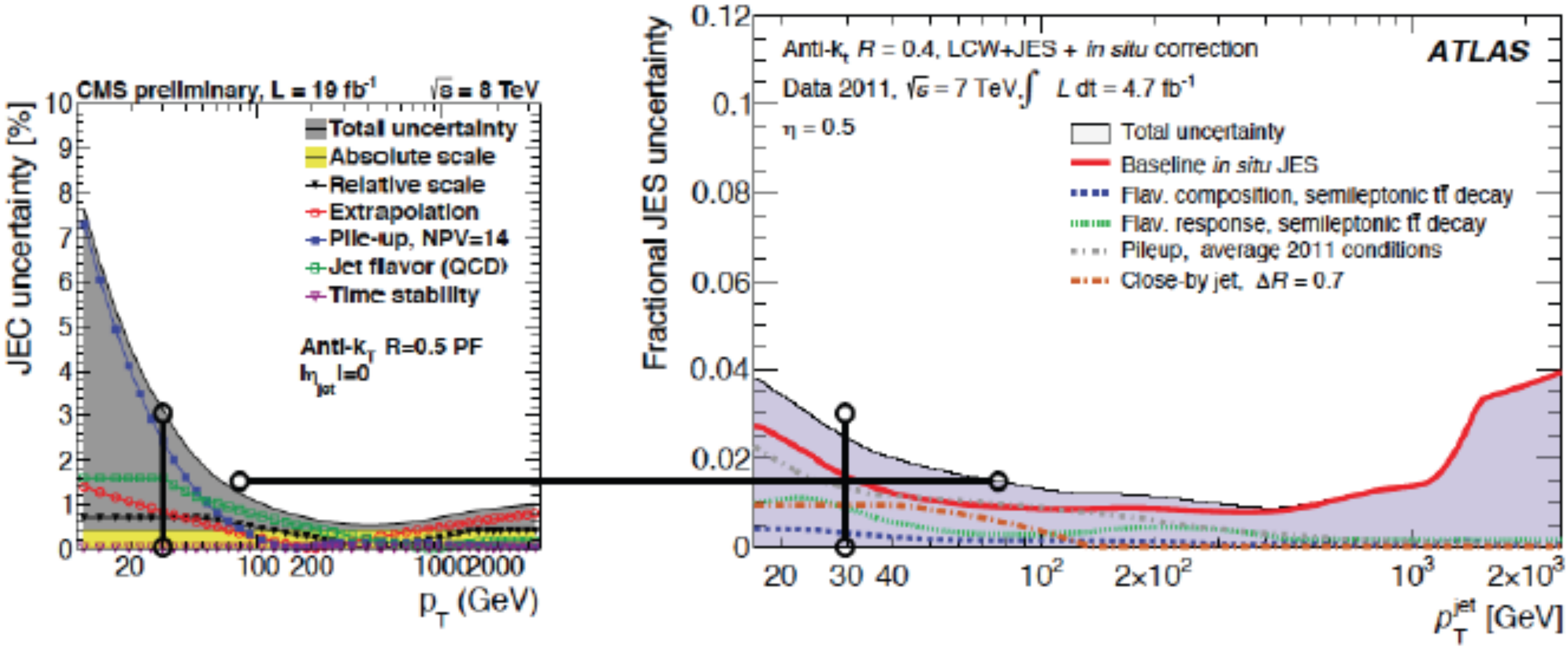
fit W→jj JES and ratio b/q JES





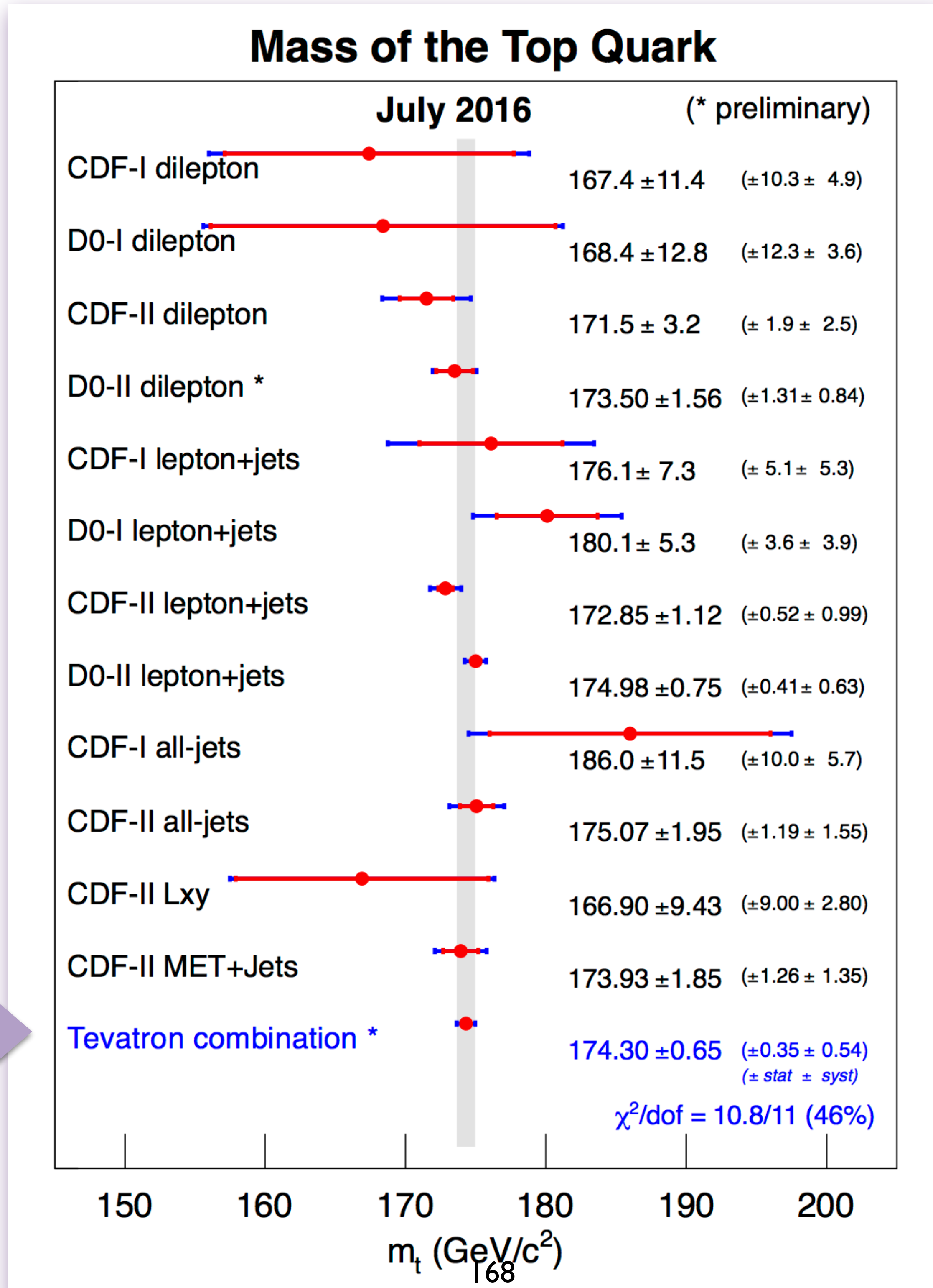
How we measure the top quark mass?

LHC JEC/JES Uncertainties



Top Quark Mass

Tevatron combination



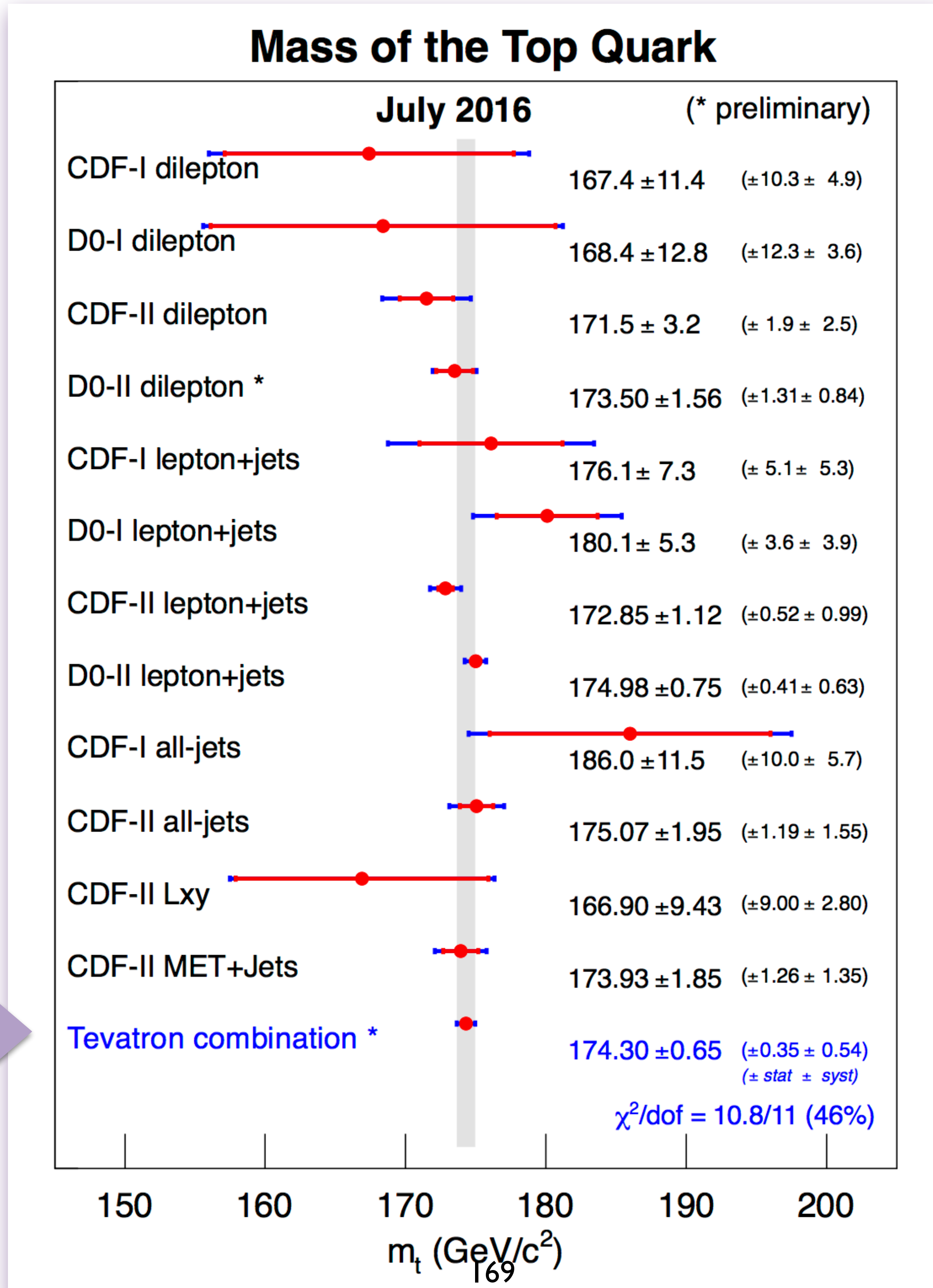
<4% relative uncertainty

arXiv: 1608.01881

latest here:
https://tevewwg.fnal.gov/top/

Top Quark Mass

Tevatron combination

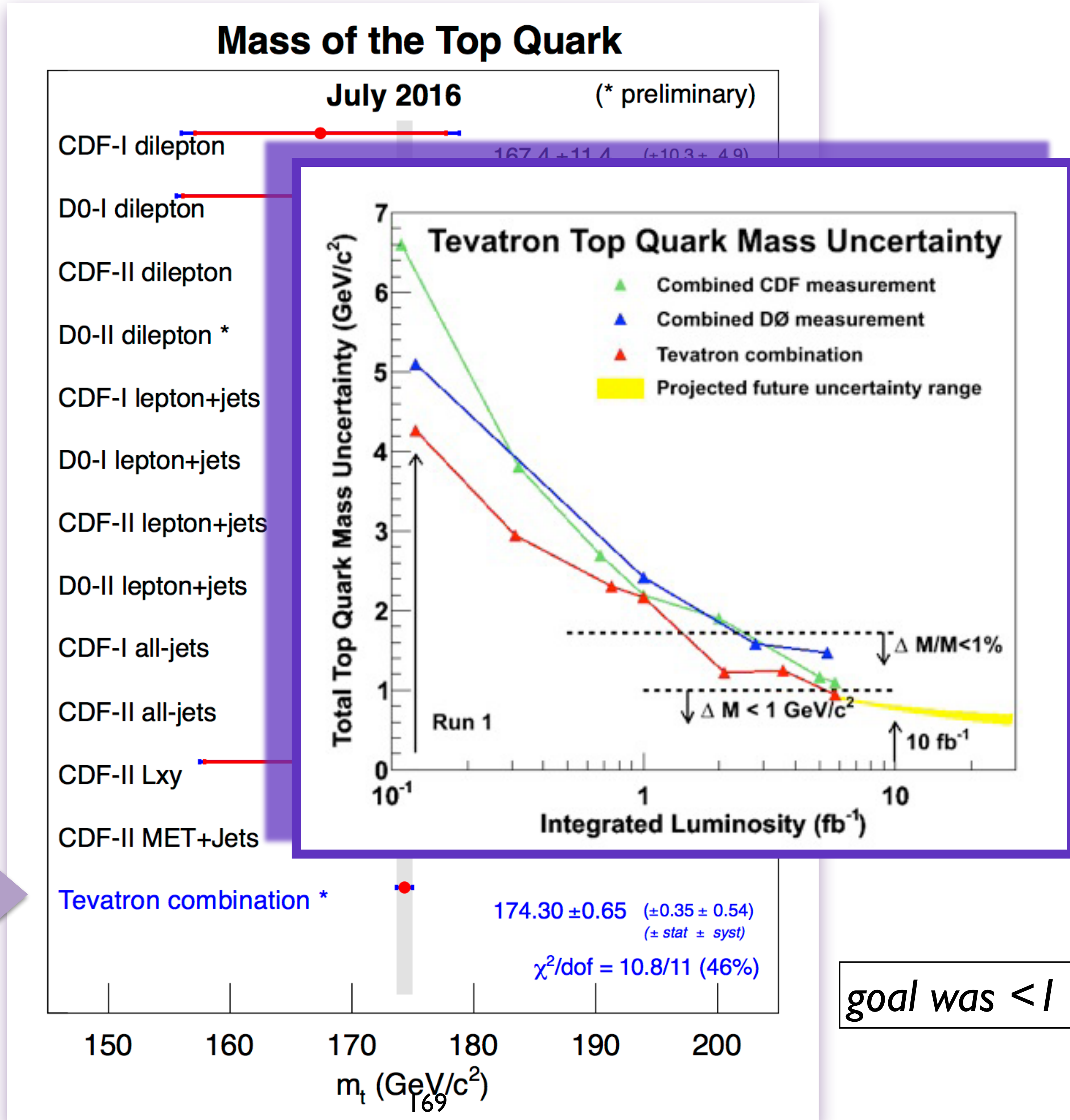


<4% relative uncertainty

goal was <1 GeV

Top Quark Mass

Tevatron combination



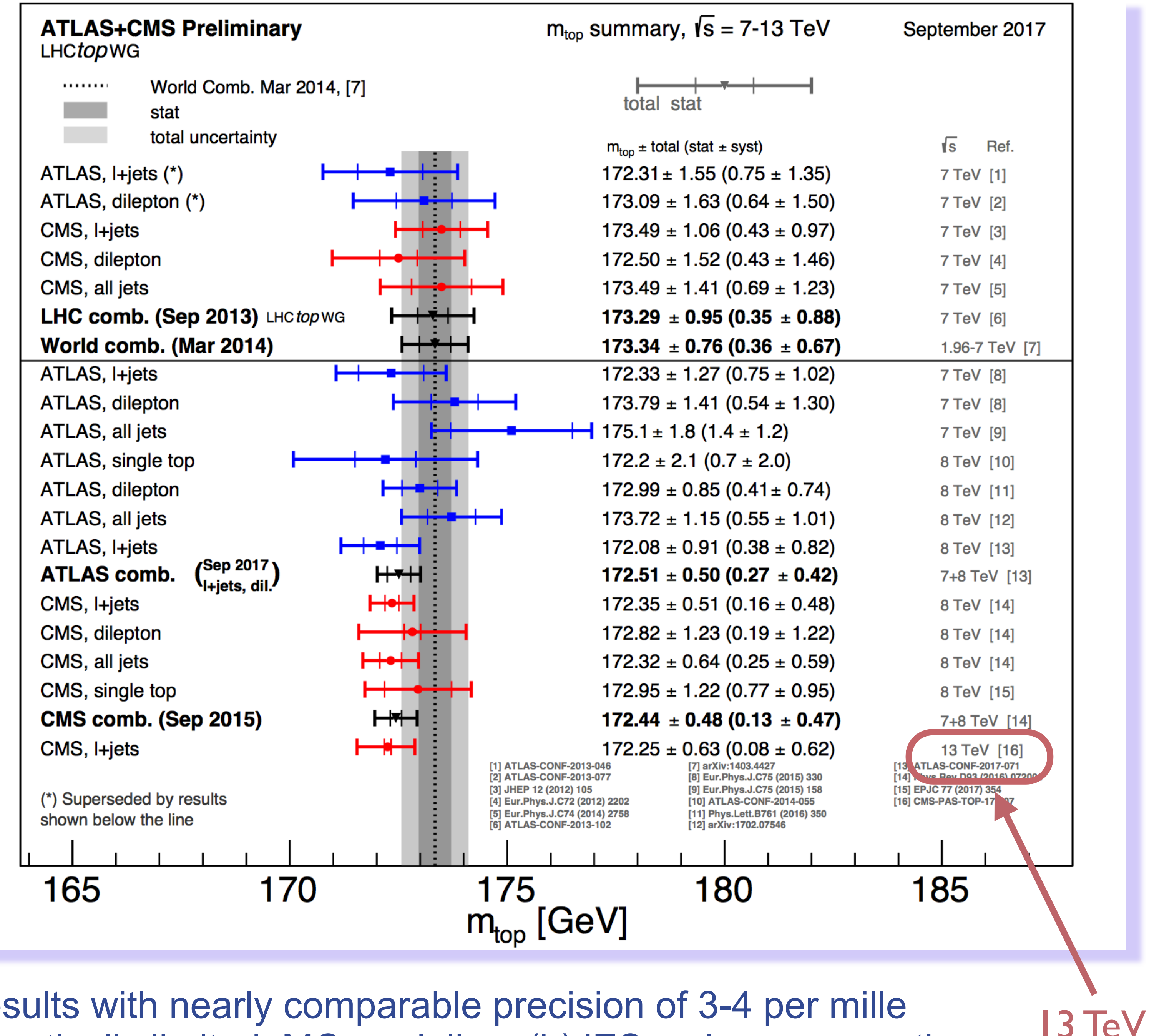
<4% relative uncertainty

goal was <1 GeV

Top
Quark
Mass

ATLAS and CMS combined: direct measurements

<3% relative uncertainty

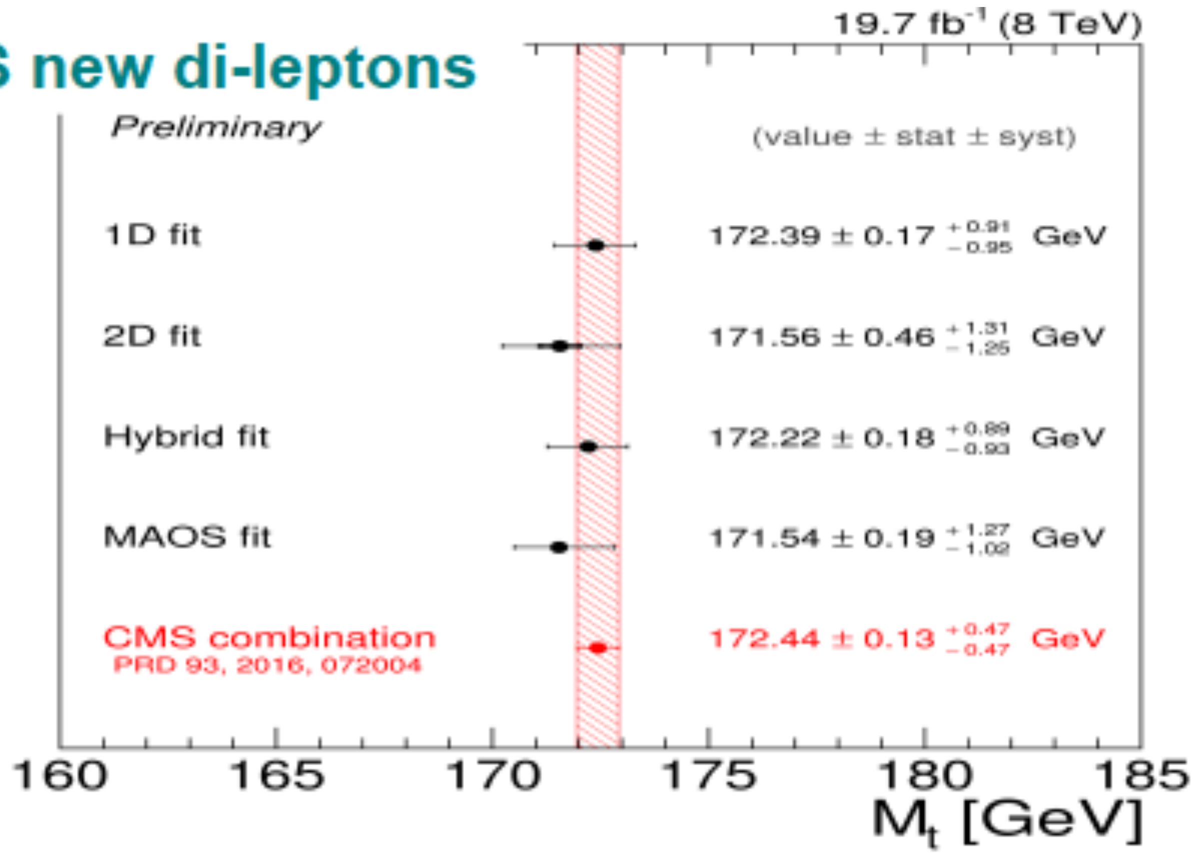


LHC and Tevatron results with nearly comparable precision of 3-4 per mille
LHC top mass systematically limited: MC modeling, (b)JES, color reconnection
Template/Matrix element methods → Monte Carlo top mass parameter

Top Quark Mass

Since LHC is a top quark factory, it's all about controlling systematics

CMS new di-leptons

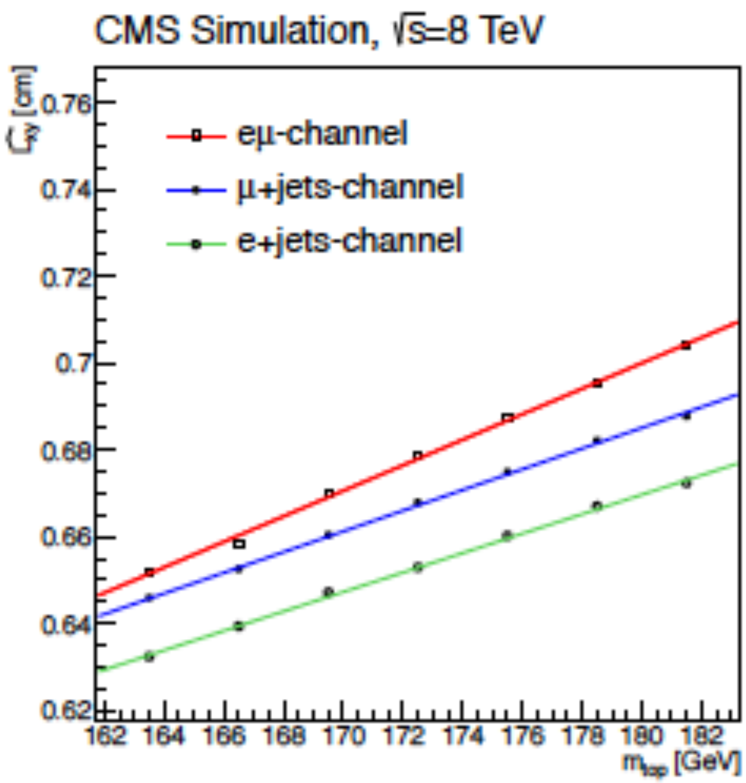


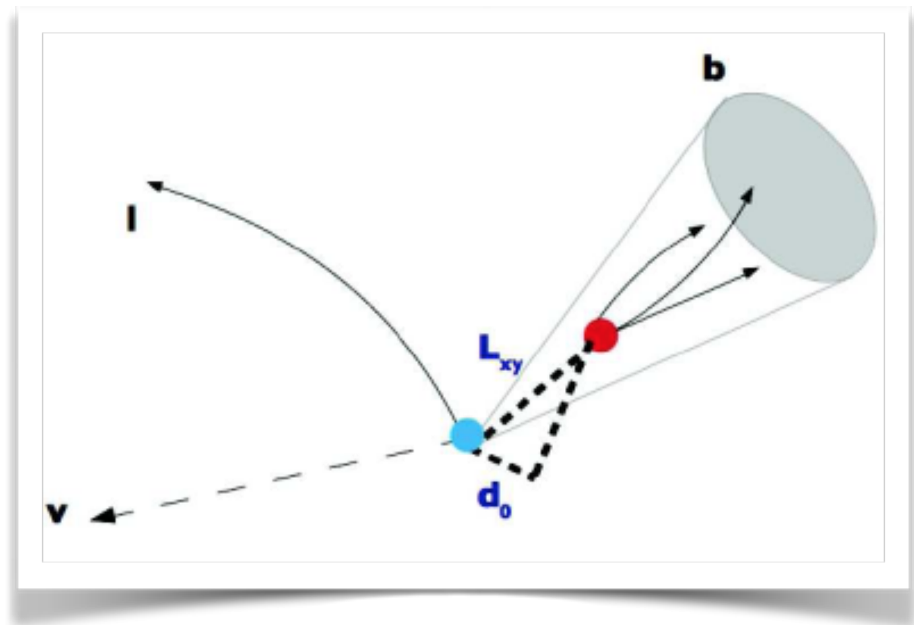
new approaches with complementary systematics can constrain combined systematics

CMS, $19.7 fb^{-1}$, dileptons, 1D, 2D, hybrid, $m_{bl}+m_{T2}$, ,MAOS $m_{bl\nu}+m_{T2}$,
$M_{top} = 172.22 \pm 0.18 \; {}^{+0.89}_{-0.93}$
CMS-PAS-TOP-15-008

Top Quark Mass

New Ideas: b-lifetime

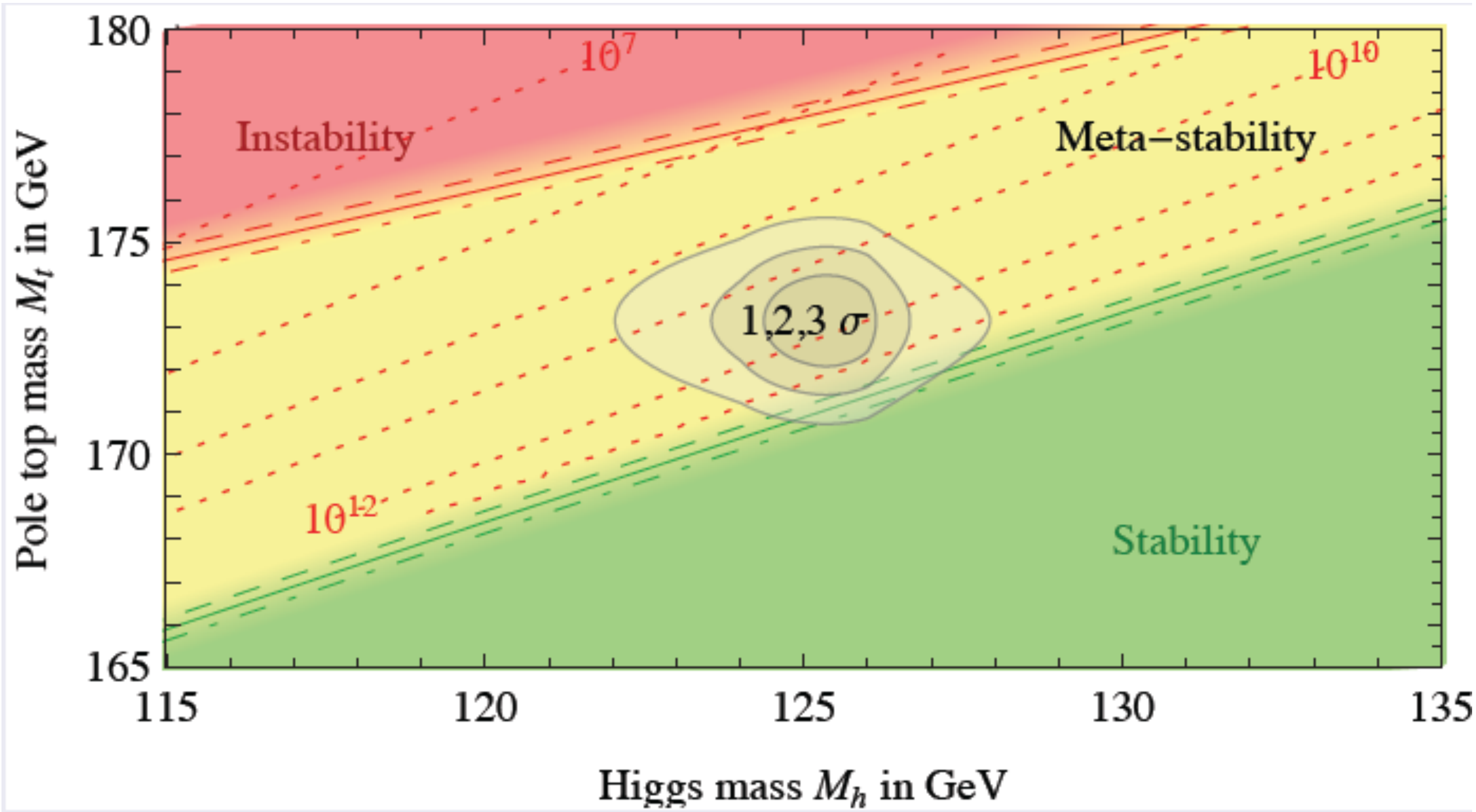




$$L_{xy} = \gamma_b \beta_B \tau_B \approx 0.4 \cdot \frac{m_t}{m_B} \beta_B \tau_B.$$

First used in CDF, systematics complementary (no jets).
L_{xy} distribution gives M_{top}.

Vacuum Stability



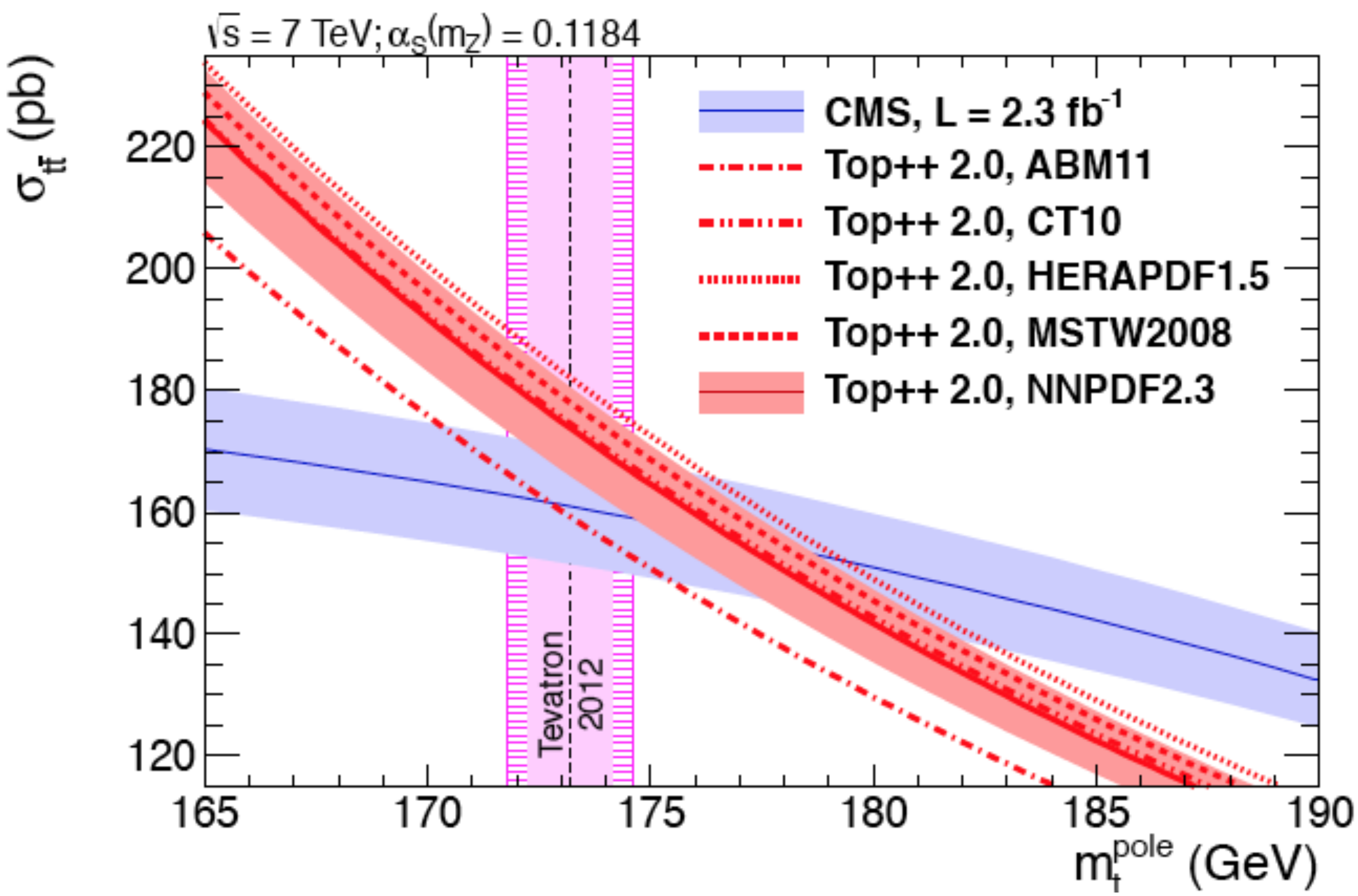
arXiv:1307.3536

150 MeV $\delta(M_H)$ ~ 100 MeV $\delta(M_t)$

Are we measuring the pole mass?

Top Quark Mass

Top mass from σ_{tt}

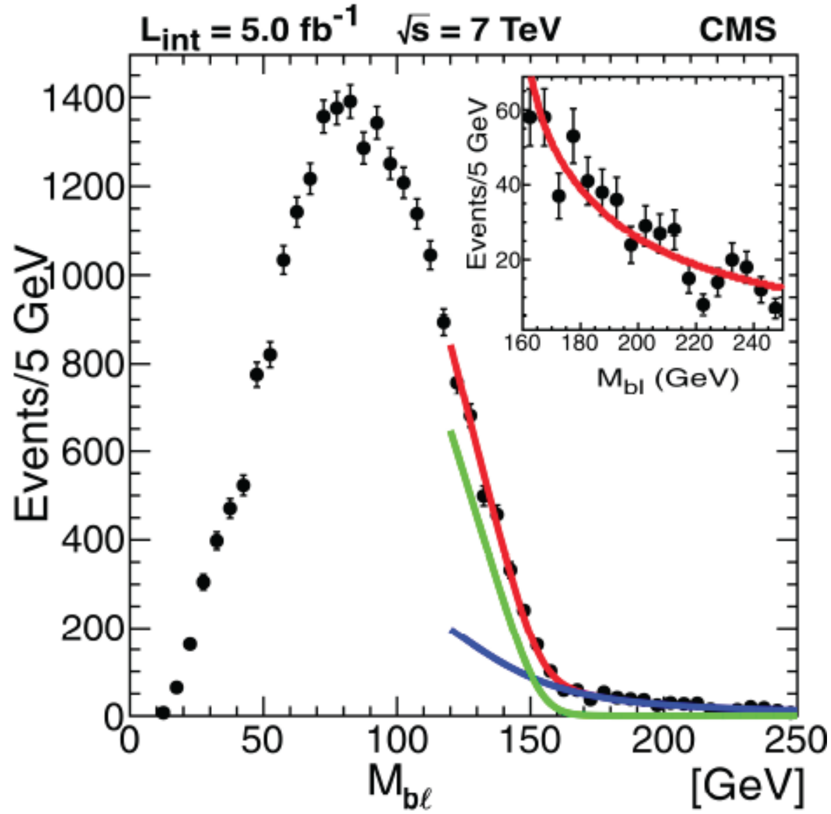


Compare precise σ_{tt} for different m_t to NNLO prediction ($\alpha_{s(PDG)}$).

done first at D0

Top Quark Mass

What M_t do we measure?



Normally, "MC" mass

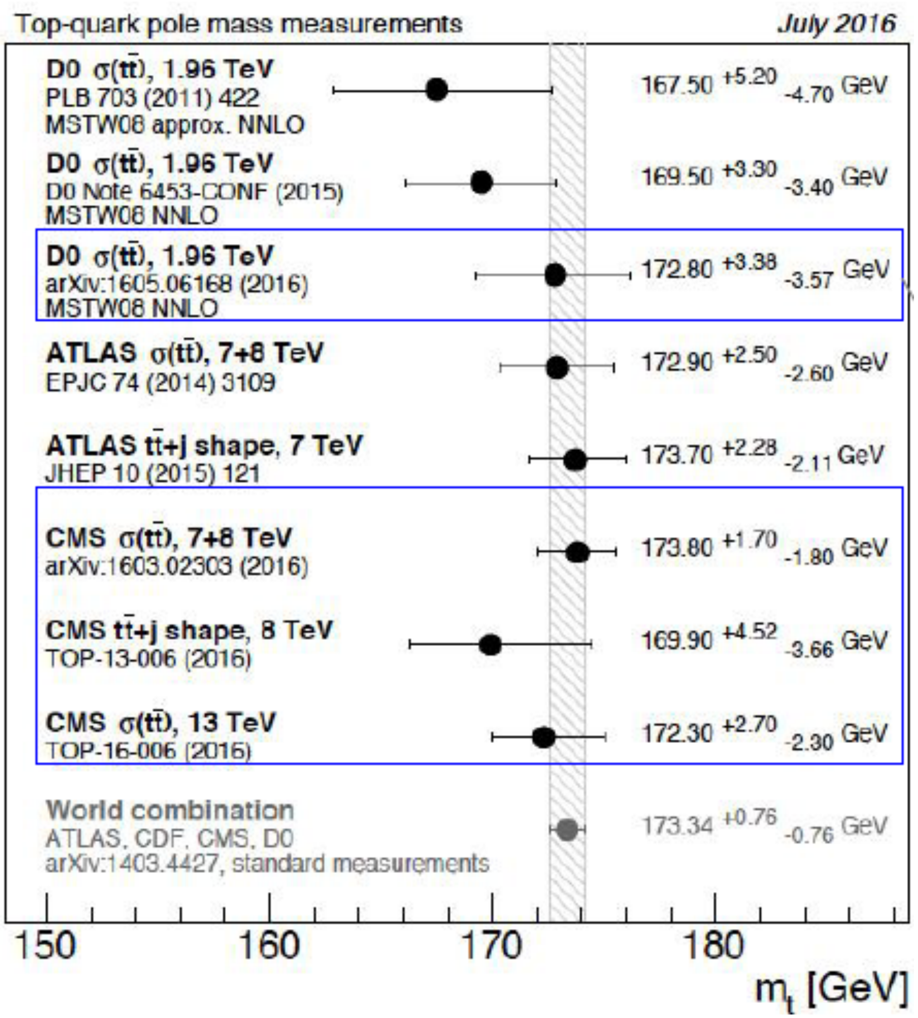
(uncertain hadronic activity)

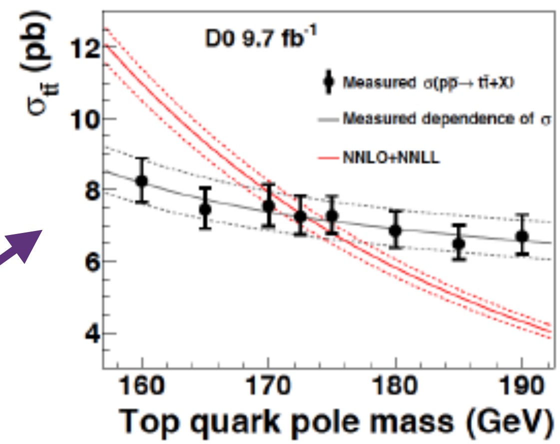
Idea: "Endpoints" of transverse distributions:

- Can fit to shapes independent of MC/theory
- Very sensitive to M_{top}
- CMS: fit to M_{T2}, M_{WT}, $M_{b\ell}$

Top Quark Mass

Pole mass vs Monte-Carlo mass measurements





Direct top mass measurements:

- Monte-Carlo mass m_t^{MC}
- precision 0.5 GeV

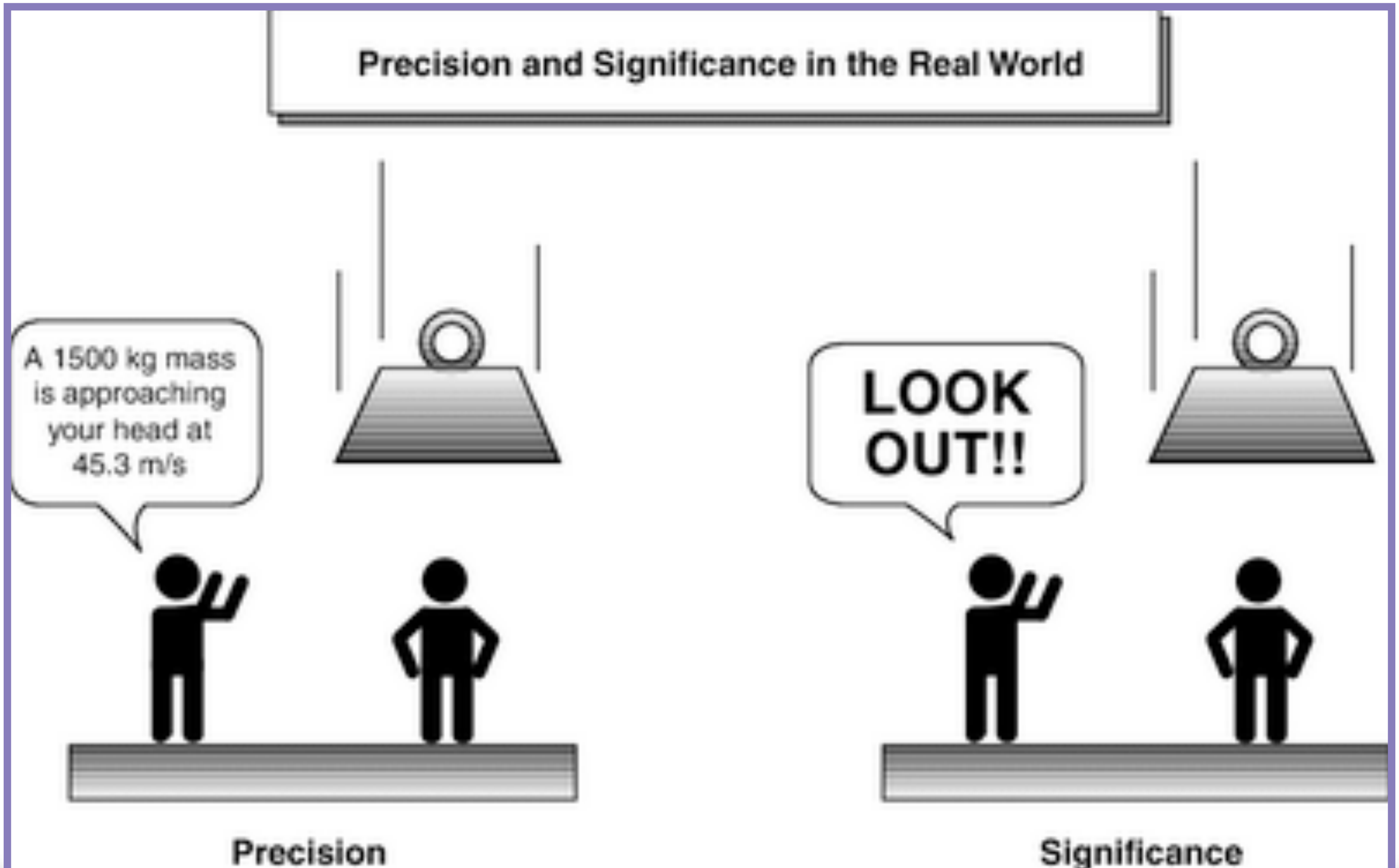
Expect $m_t^{MC} - m_t^{pole} \sim 1$ GeV

→ Calibrate m_t^{MC}

→ Indirect measurements of m_t^{pole}: compatible with measured m_t^{MC} within precision of ±2 GeV

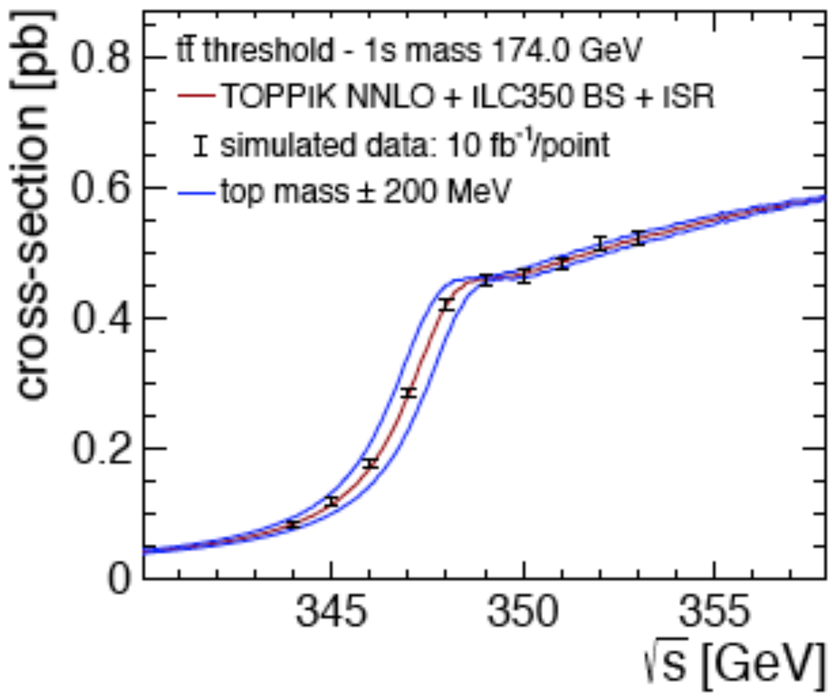
Top Quark Mass

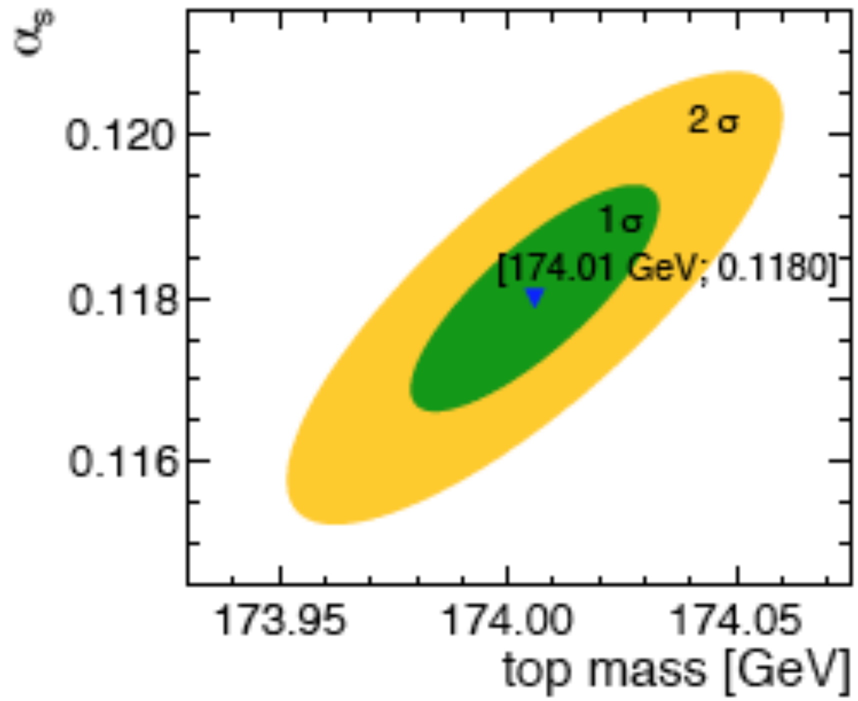
What's next? Even more precision! (HL-LHC, ILC)



Top Quark Mass

Linear collider threshold scans

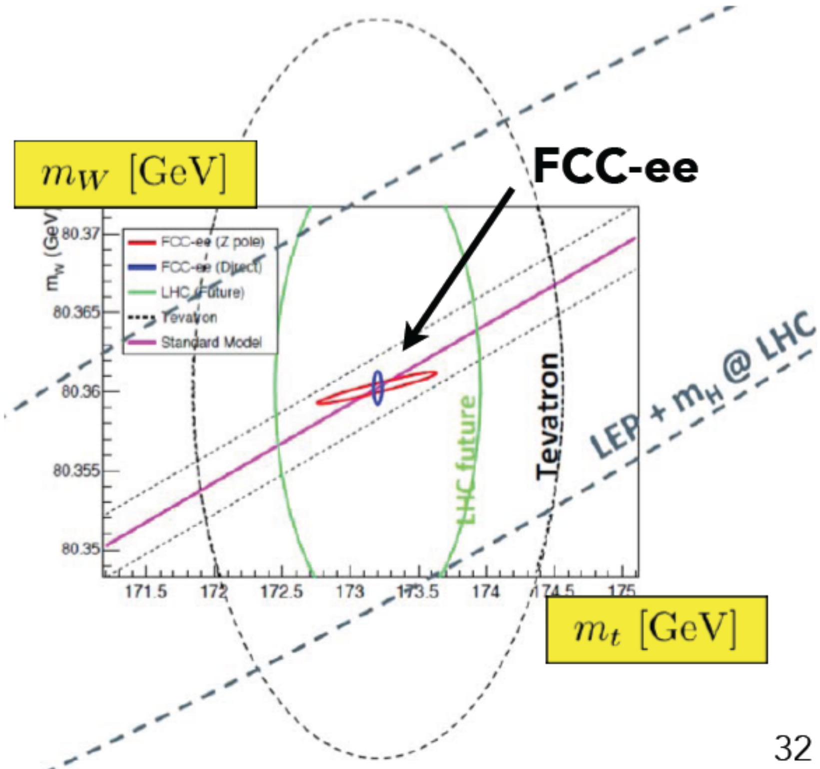


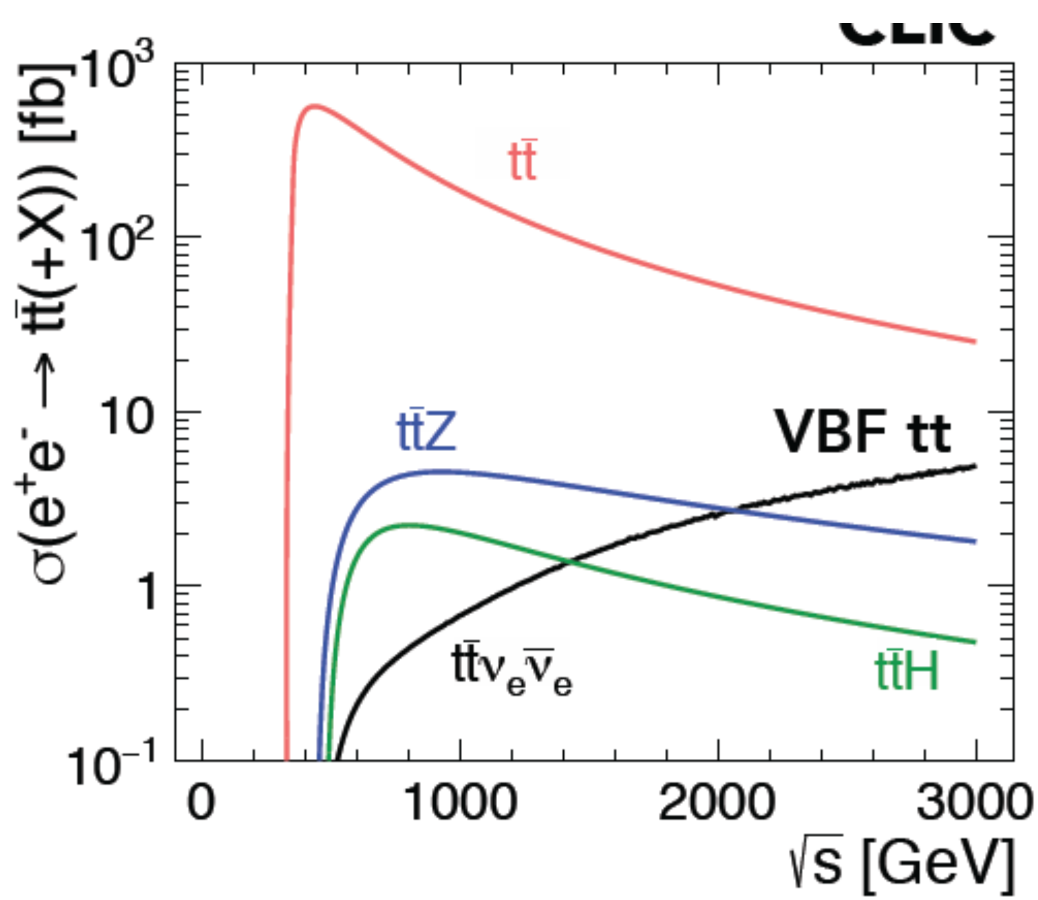


Snowmass top ILC white paper

Analytical theory predictions.
Expected precision < 100 MeV.

Top/EW @ future colliders





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future colliders: L-T. Wang

Summary

- I didn't have time to do justice to the many and varied topics in top physics. Many "Top"-ics not covered!
- Measurements of top properties are becoming precise: top spin correlations, W helicity, t-tbar mass difference.
- If there is no new physics found at 13 TeV, precision EWK and top measurements will be one of the ways to access new physics at higher scales: FCNC, EWK parameters, top mass, EFTs, new couplings.

Welcome to hadron collider precision!