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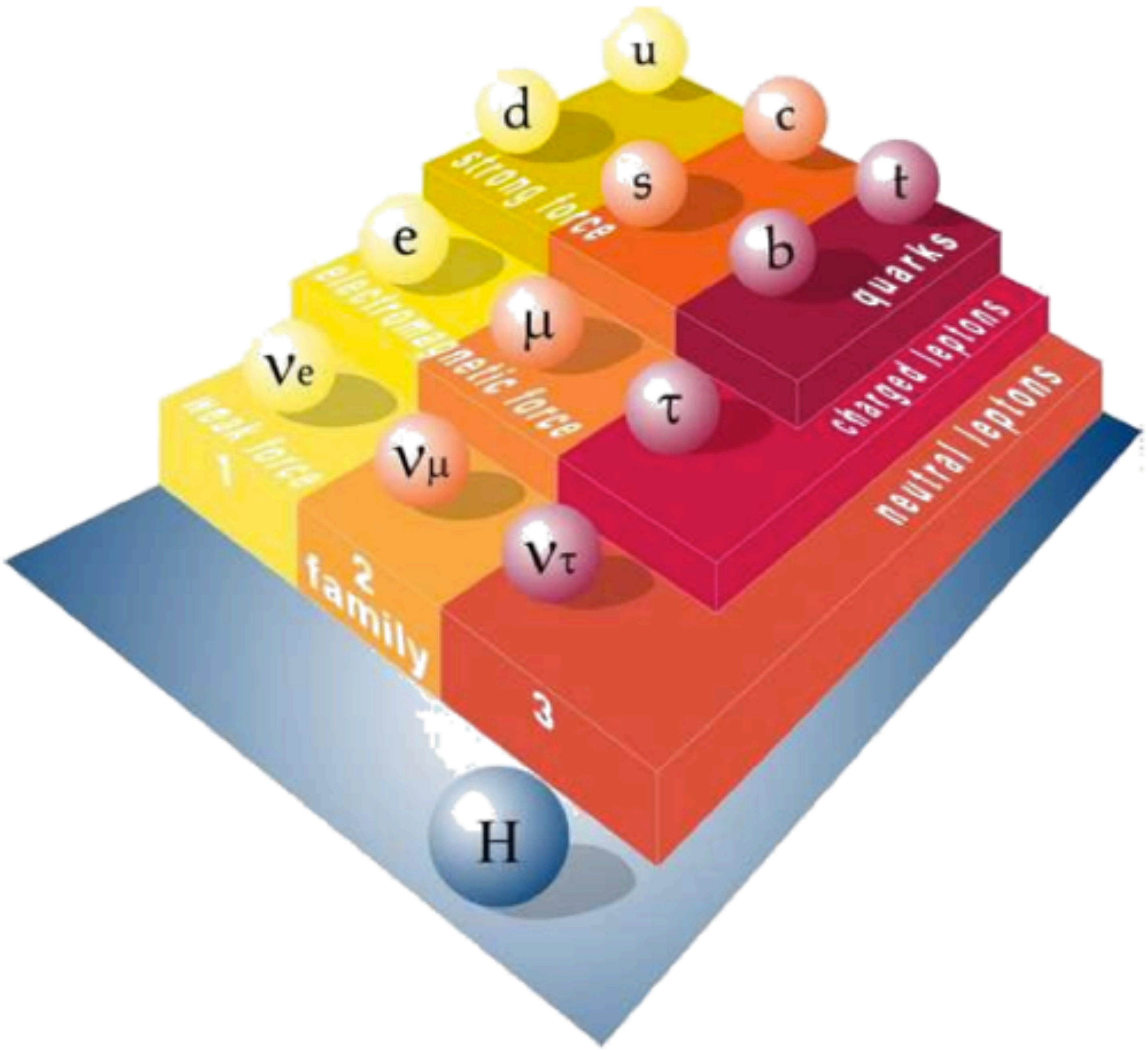
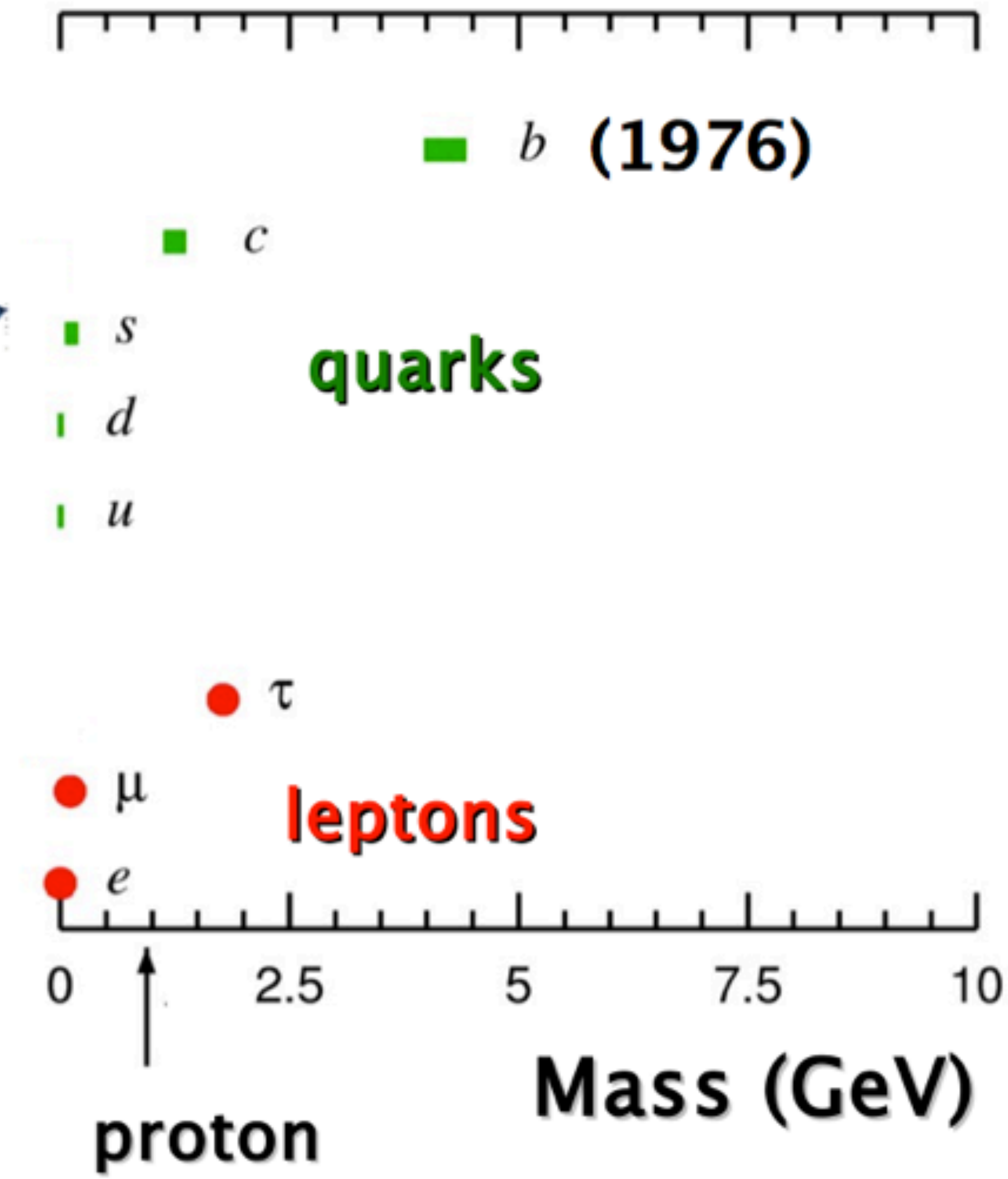
Top Quark Physics

Mark Owen
The University of Manchester

HASCO Summer School 2013

Recap This Morning





neutrino masses $\ll$ 1 eV

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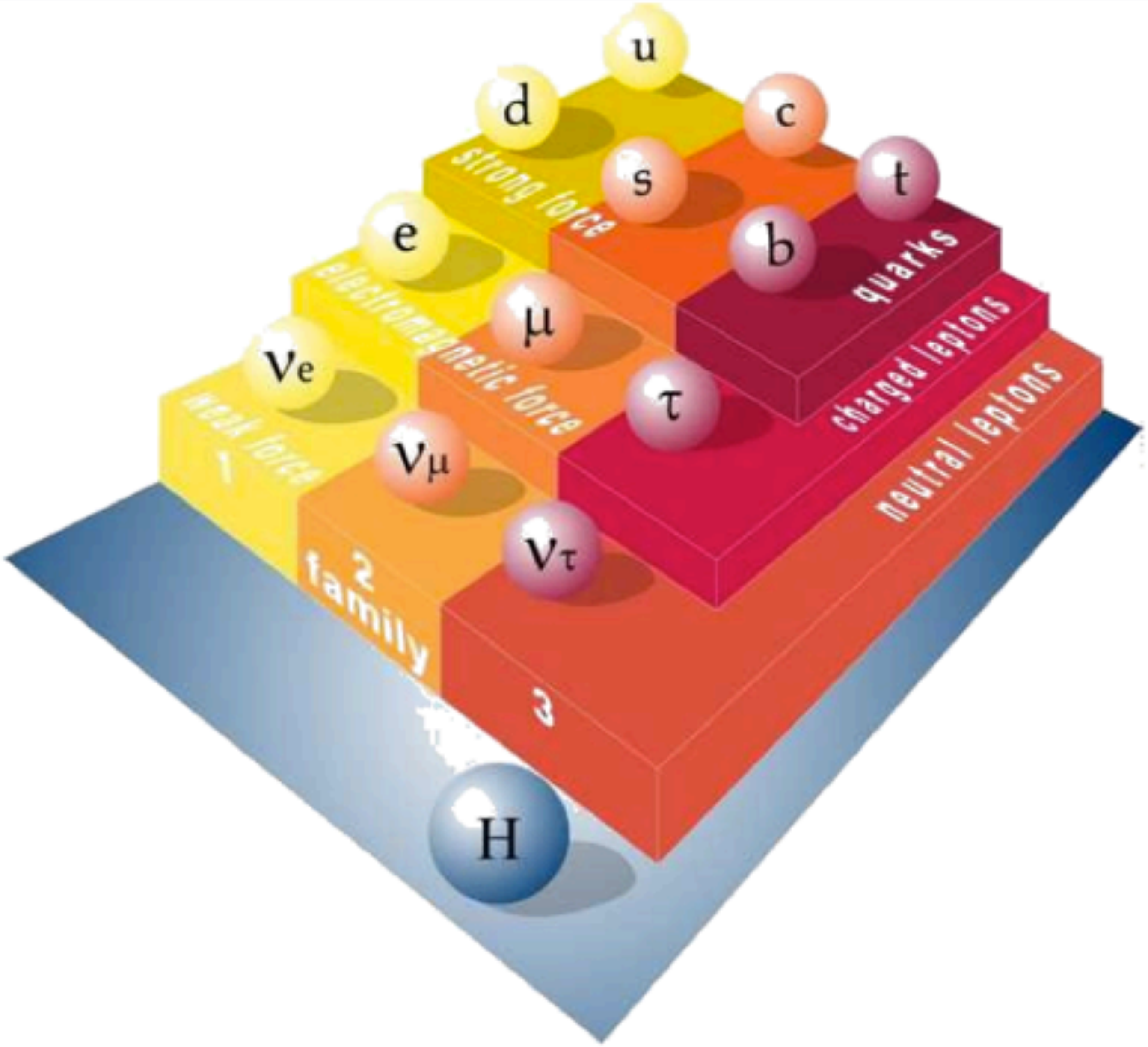
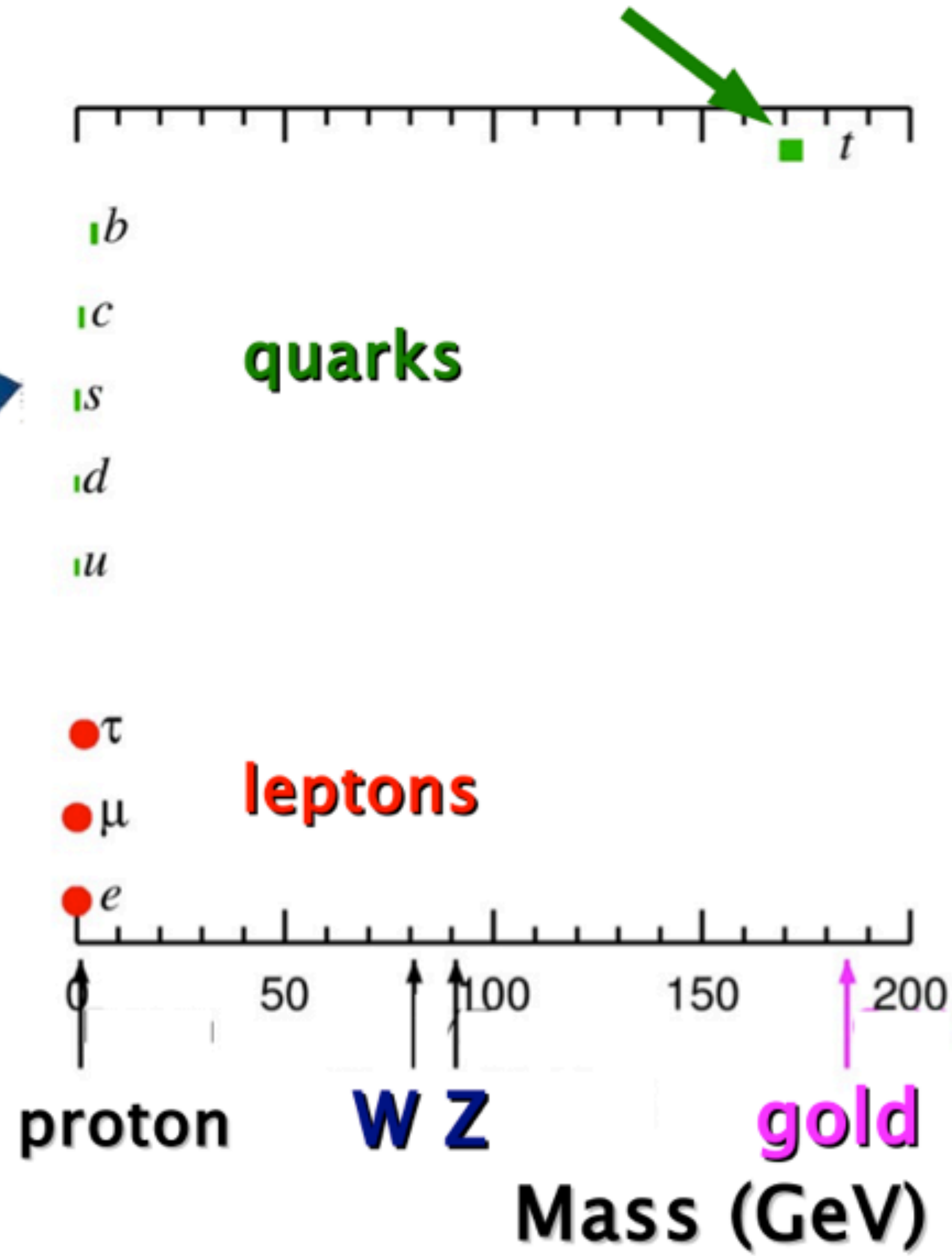
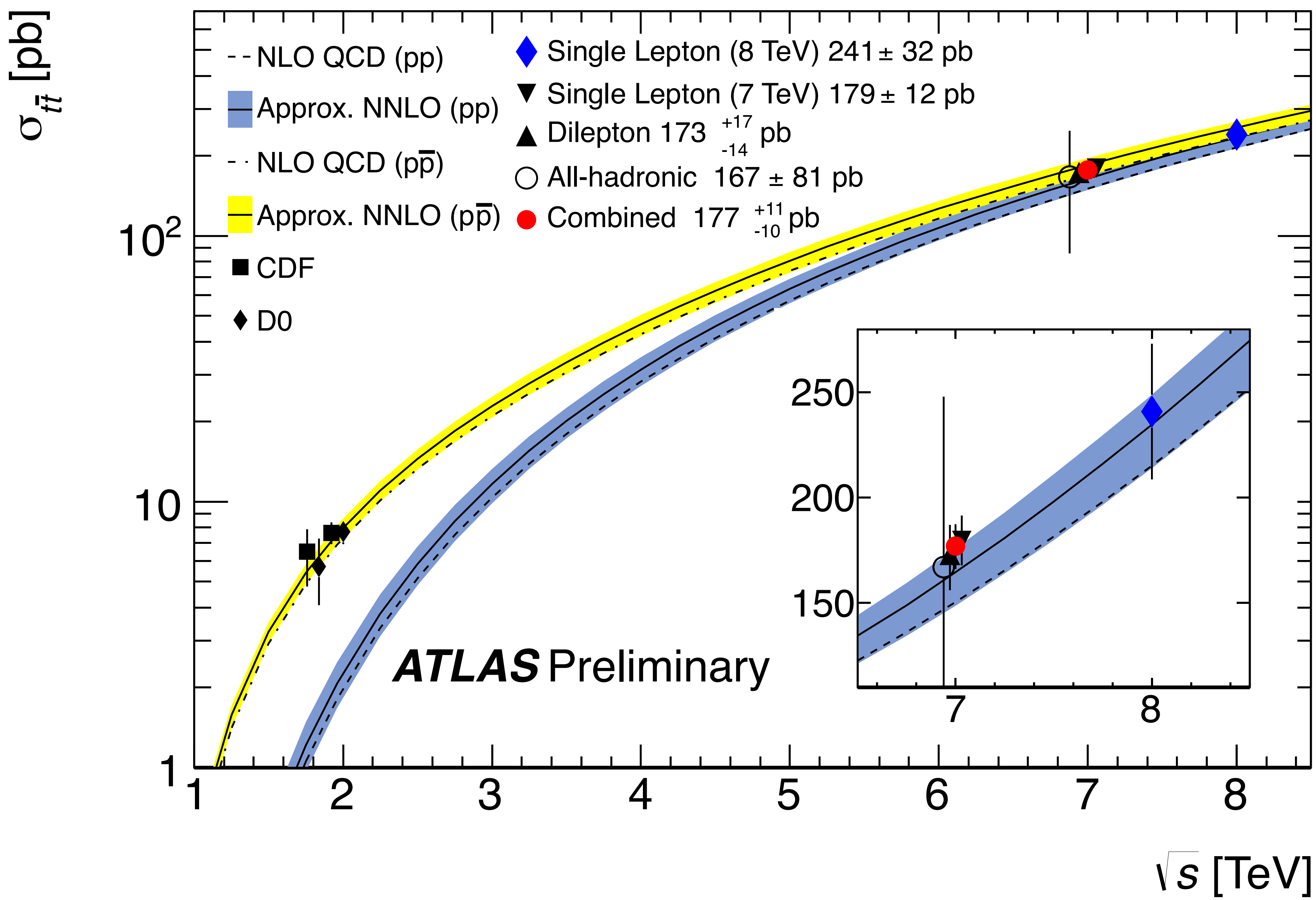


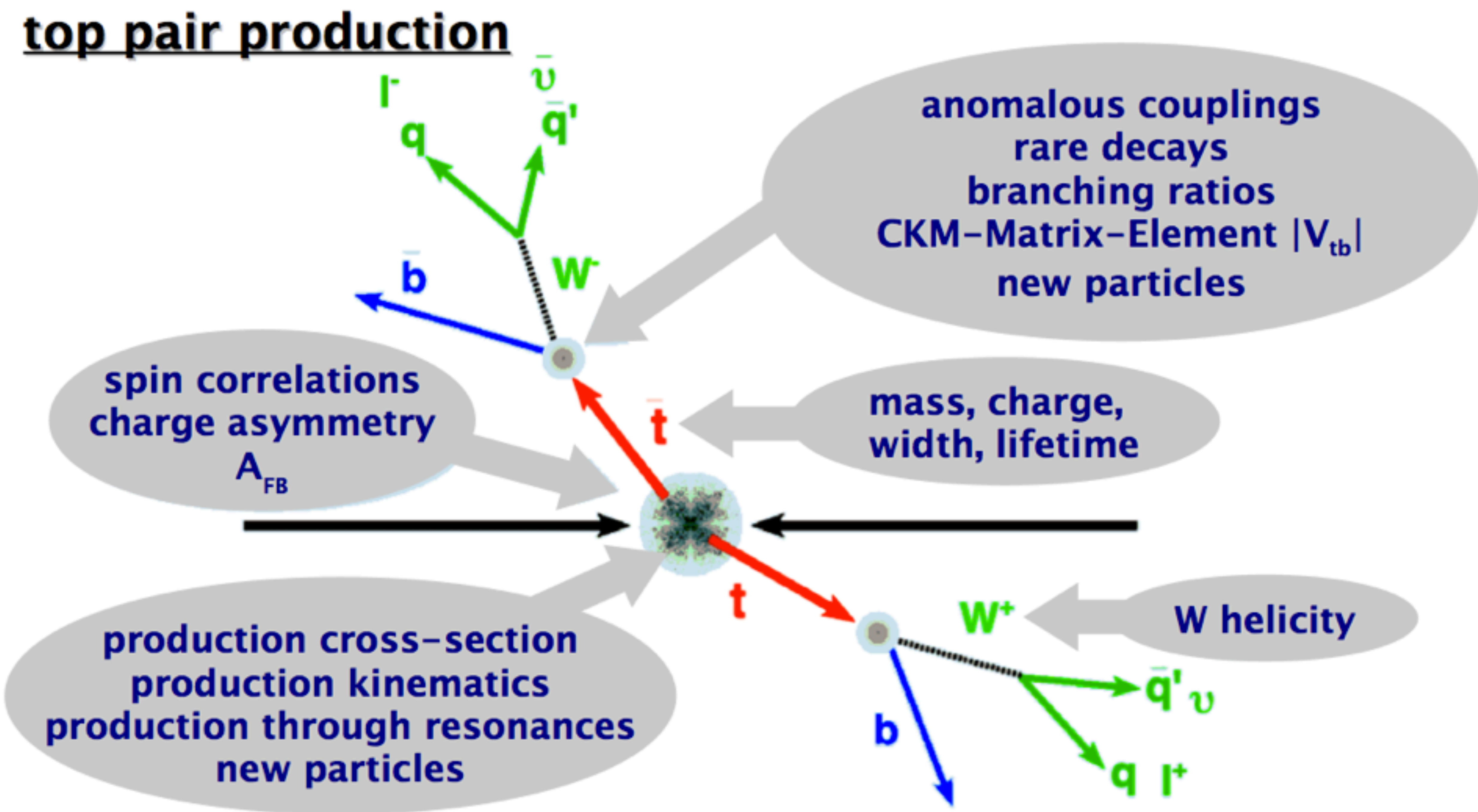


Recap This Morning



- Now want to measure top quark properties:
  - Is this the top quark predicted by the SM?

Top Quark Properties



single top production production cross section, CKM–Matrix–Element $|V_{tb}|$, anomalous couplings, searches for new particles

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Top Properties:

Top quark mass

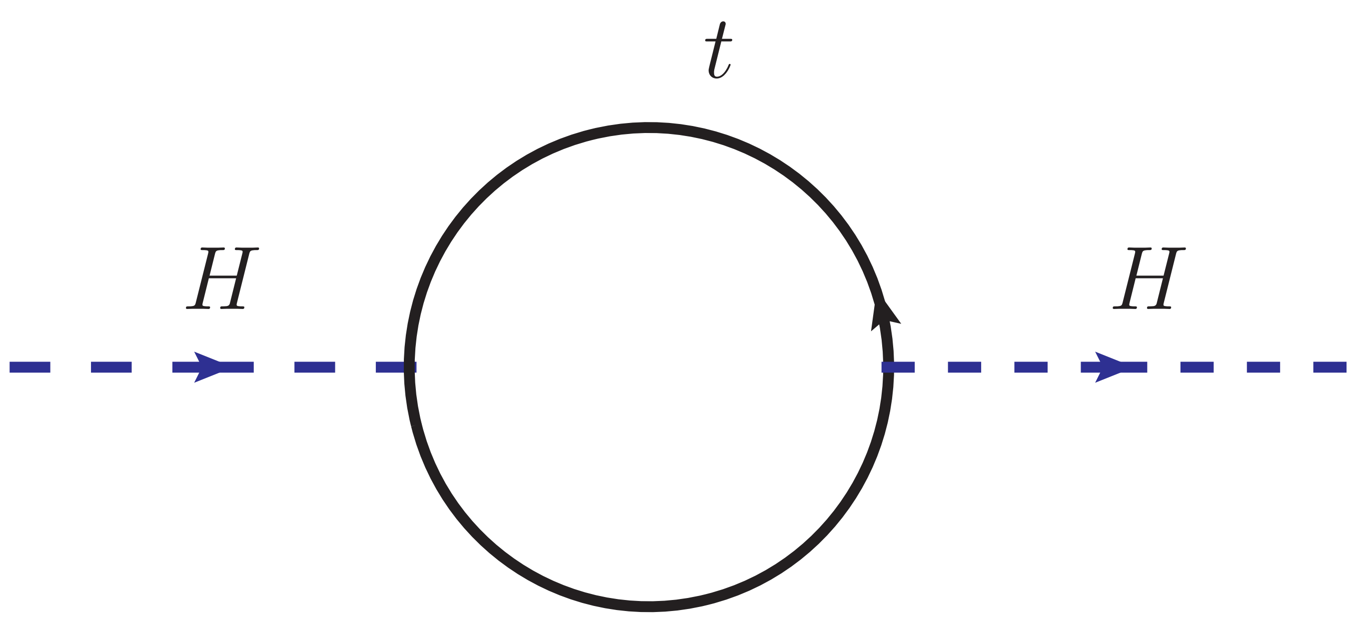
Top spin correlations

Forward-backward asymmetry

Boosted tops

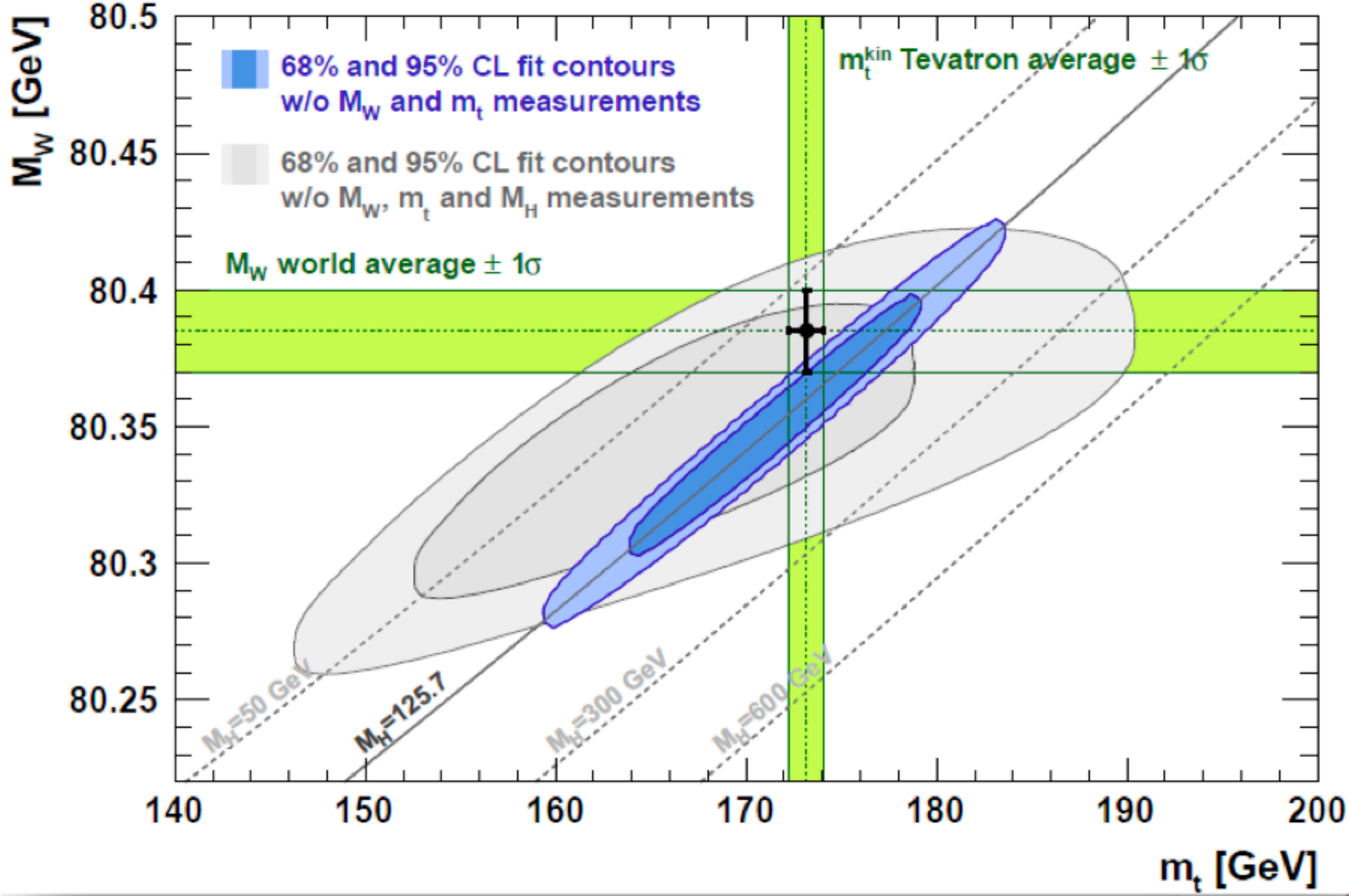
Top Quark Mass

- Free parameter in SM - must be measured in experiment.
- Enters other SM observables through loop corrections.
- Prior to Higgs discovery, important to predict Higgs mass in SM.
- Now, vital to test self-consistency of the SM.



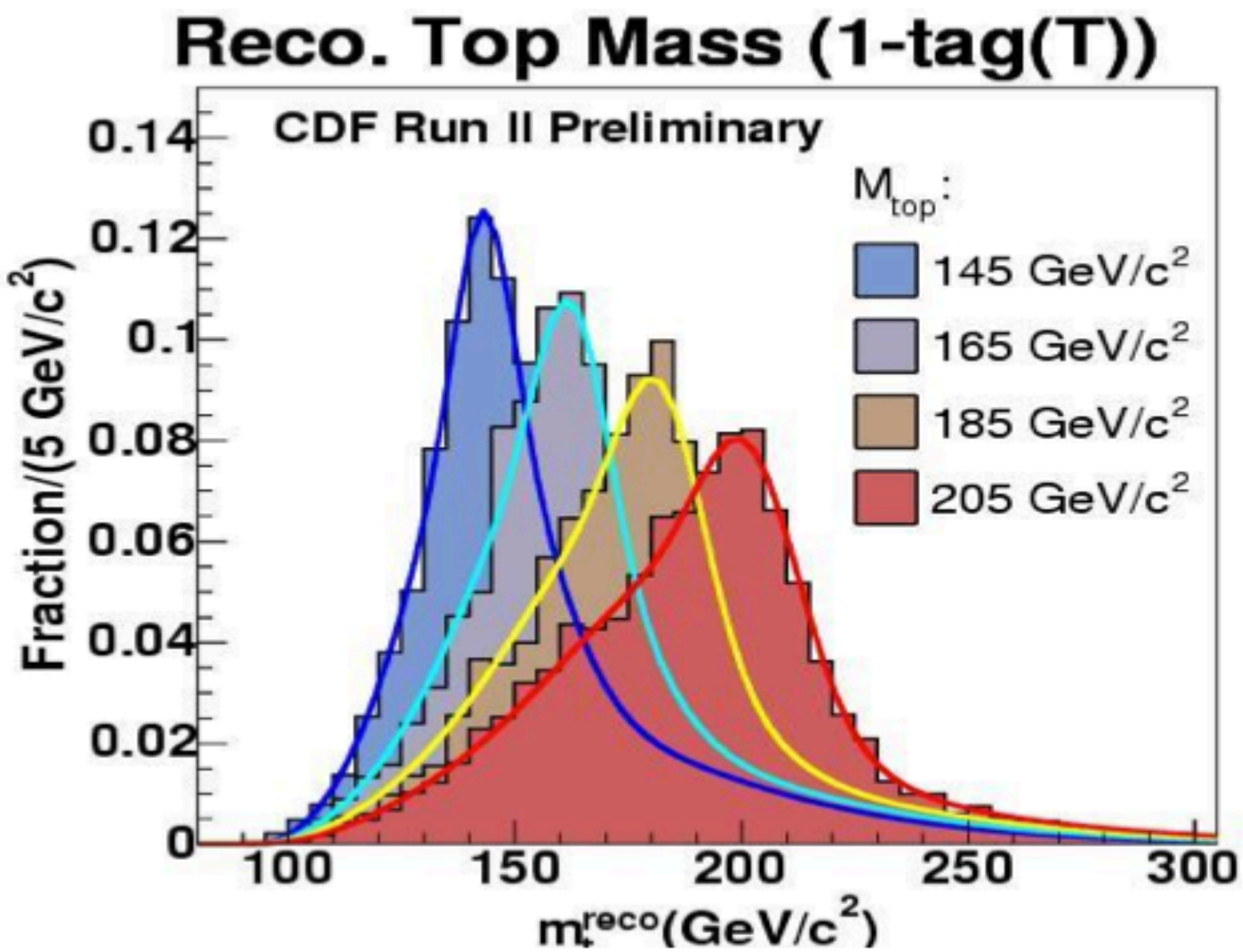
Top Quark Mass

- Now, vital to test self-consistency of the SM:



Measuring the Top Mass

- Simplest technique - template method:
  - Choose variable correlated to top mass.
  - Compare data to MC simulations with different top mass & fit.

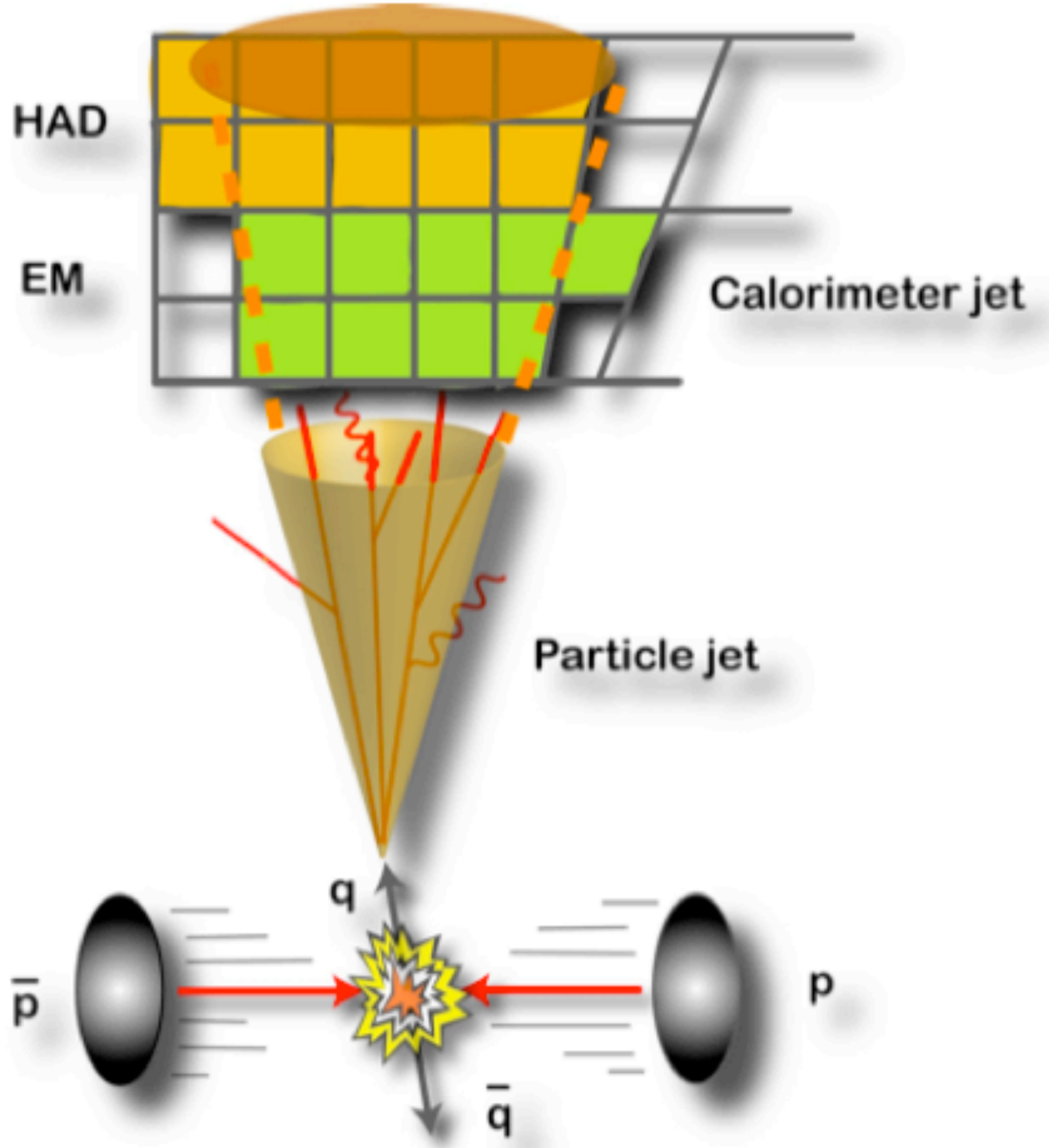


Invariant mass of three jets - one from the b-jet, two from the W decay.

Measuring the Top Mass

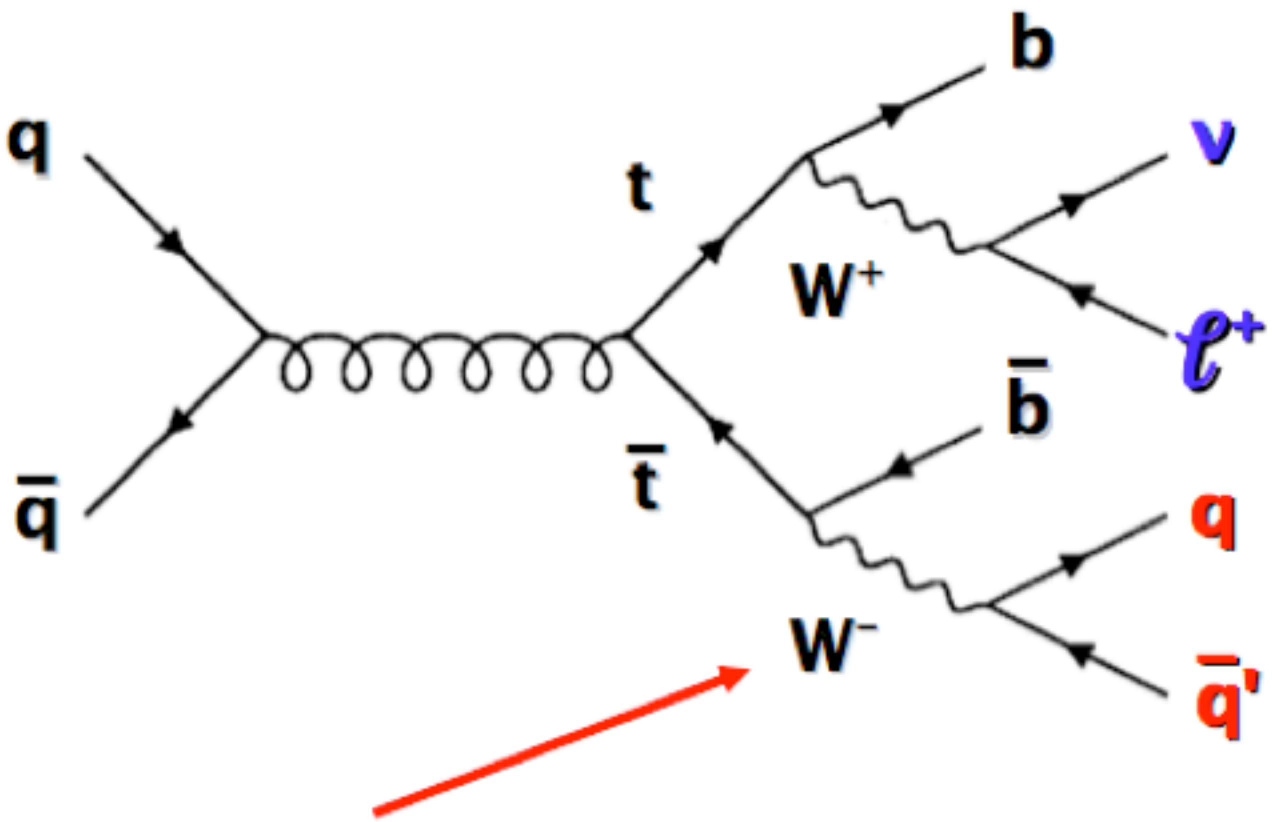
- Analysis highly sensitive to jet energy scale.
  - Data & MC differ by x%, then top mass from 3 jets is biased by $(1.0x)^3$.

ATLAS: JES calibration back to particle jets, then correct to parton level using MC corrections.

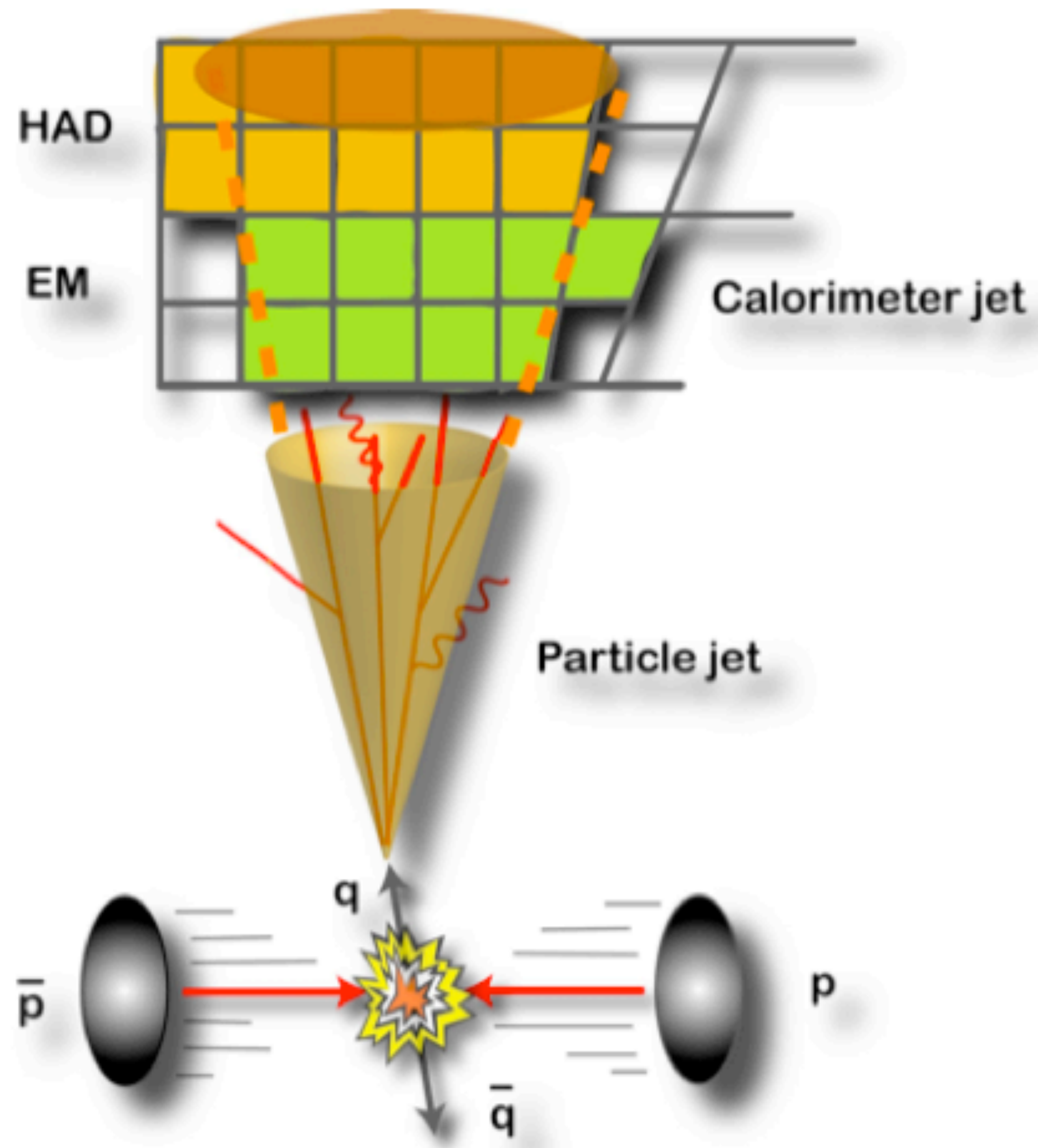


Measuring the Top Mass

- Can fit JES while measuring top quark mass by using W mass:

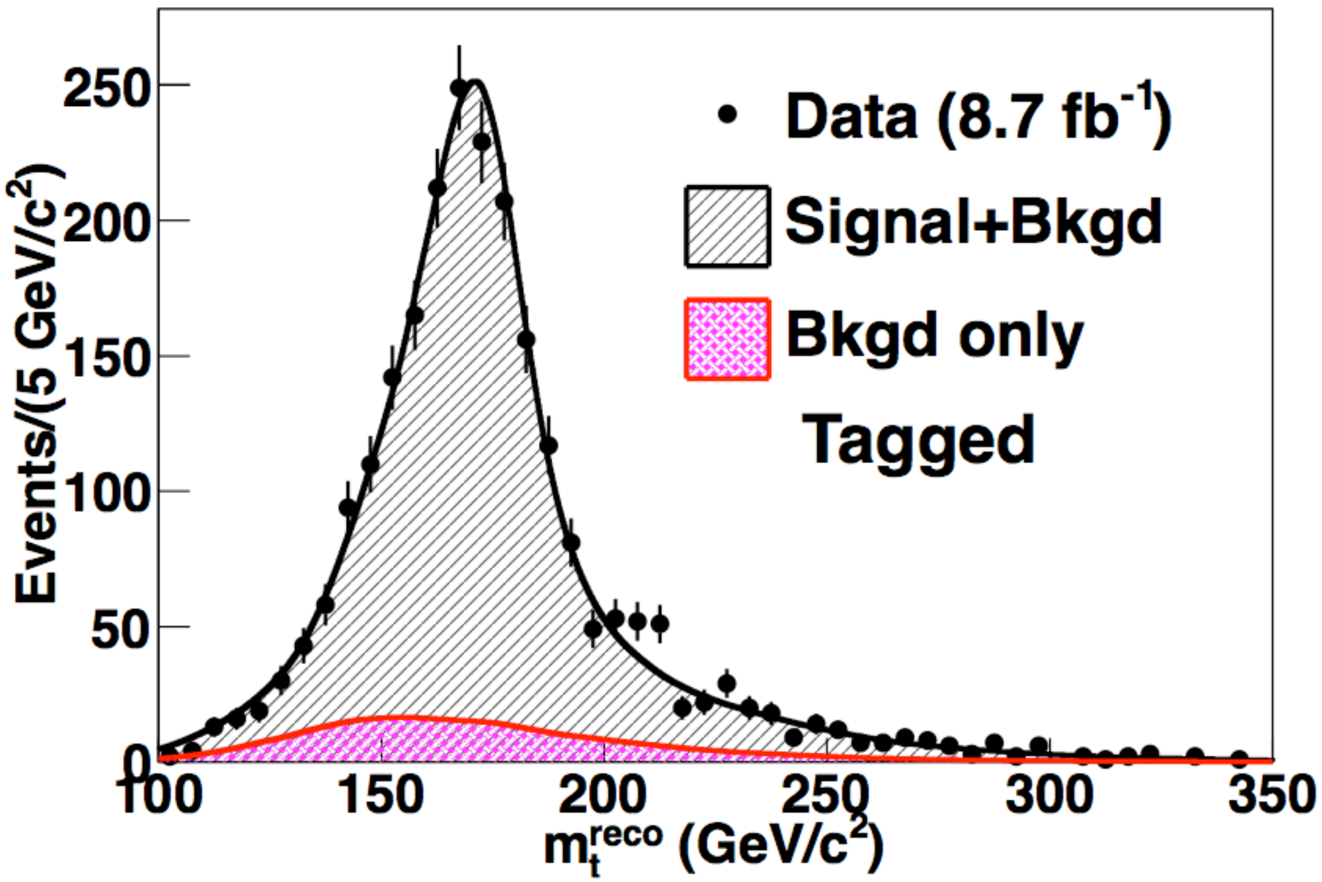


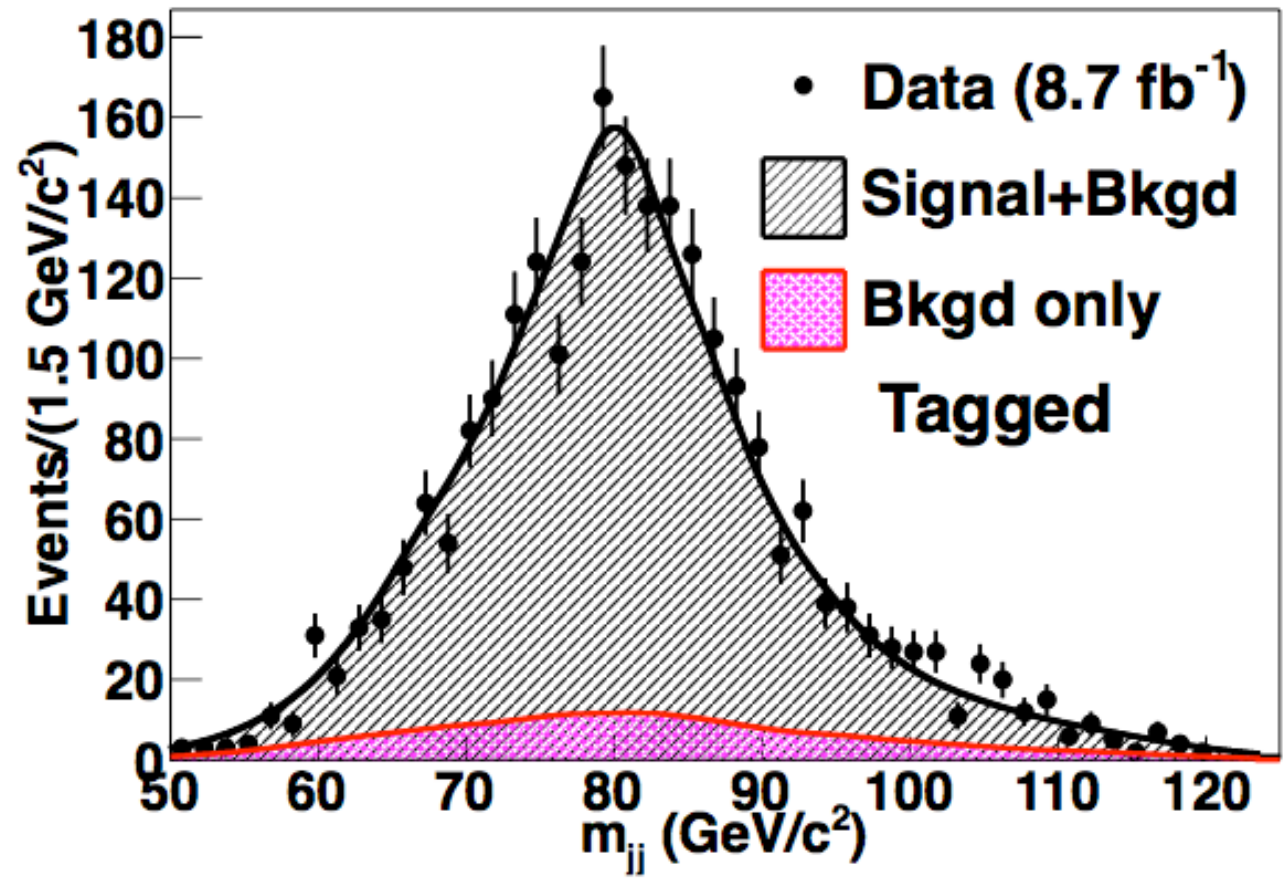
W mass constrains jet energy scale



Measuring the Top Mass

- Single best measurement from Tevatron:





Measuring the Top Mass

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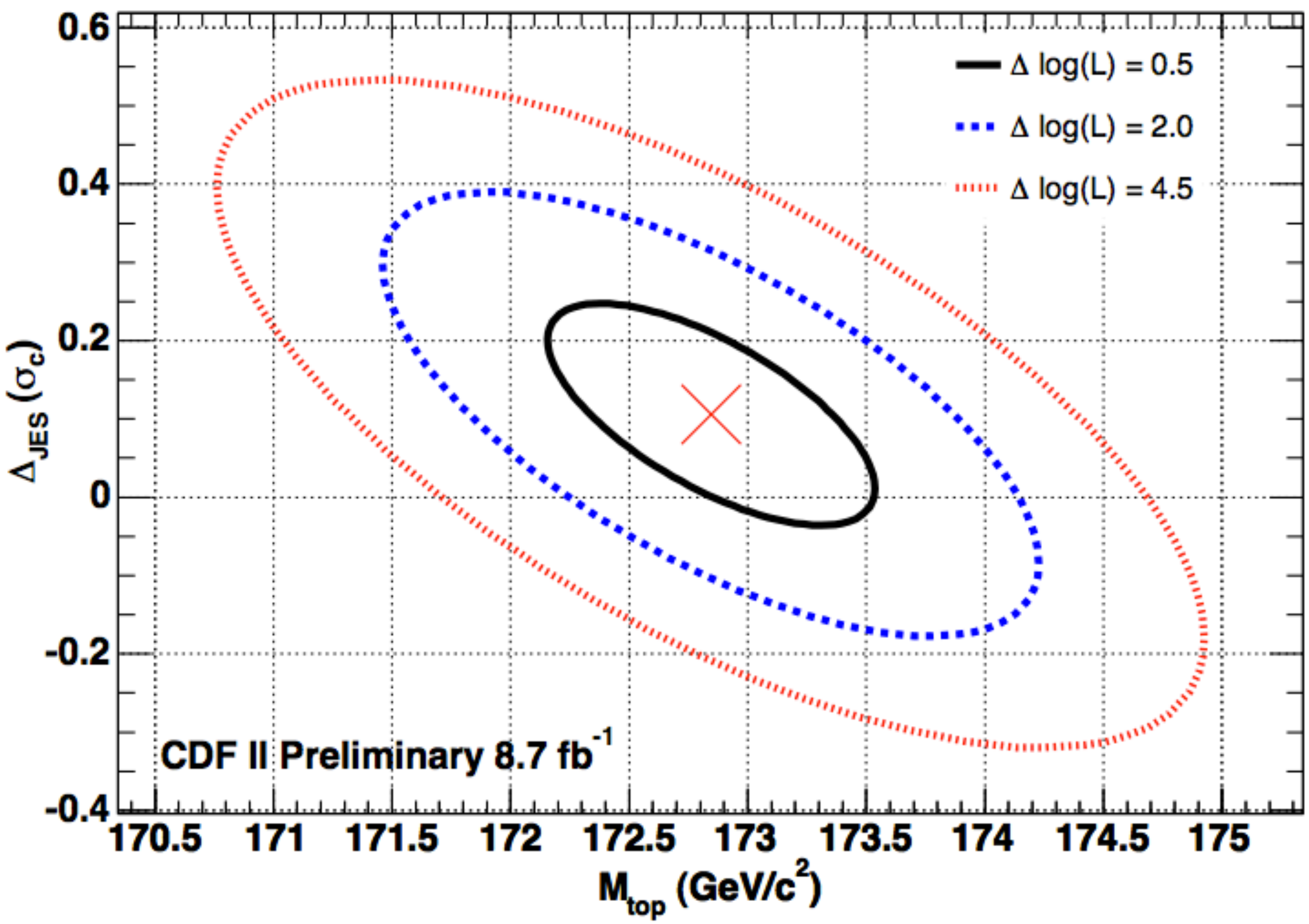
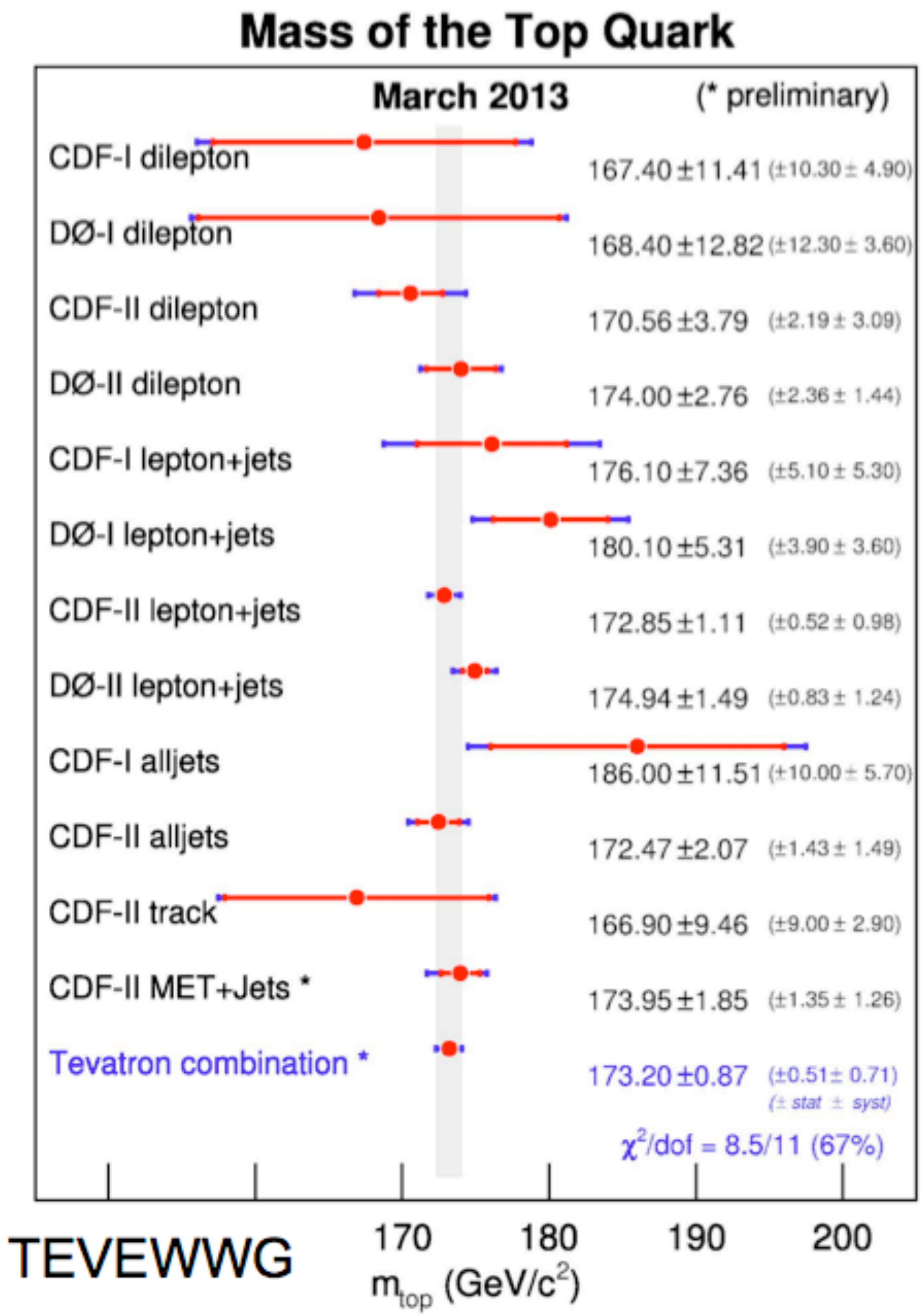


m_{top} = 172.85 ± 0.71 (stat) ± 0.85 (syst) GeV
172.85 ± 1.11 GeV

Tevatron Combination

- Combine top mass measurements from CDF & D0:

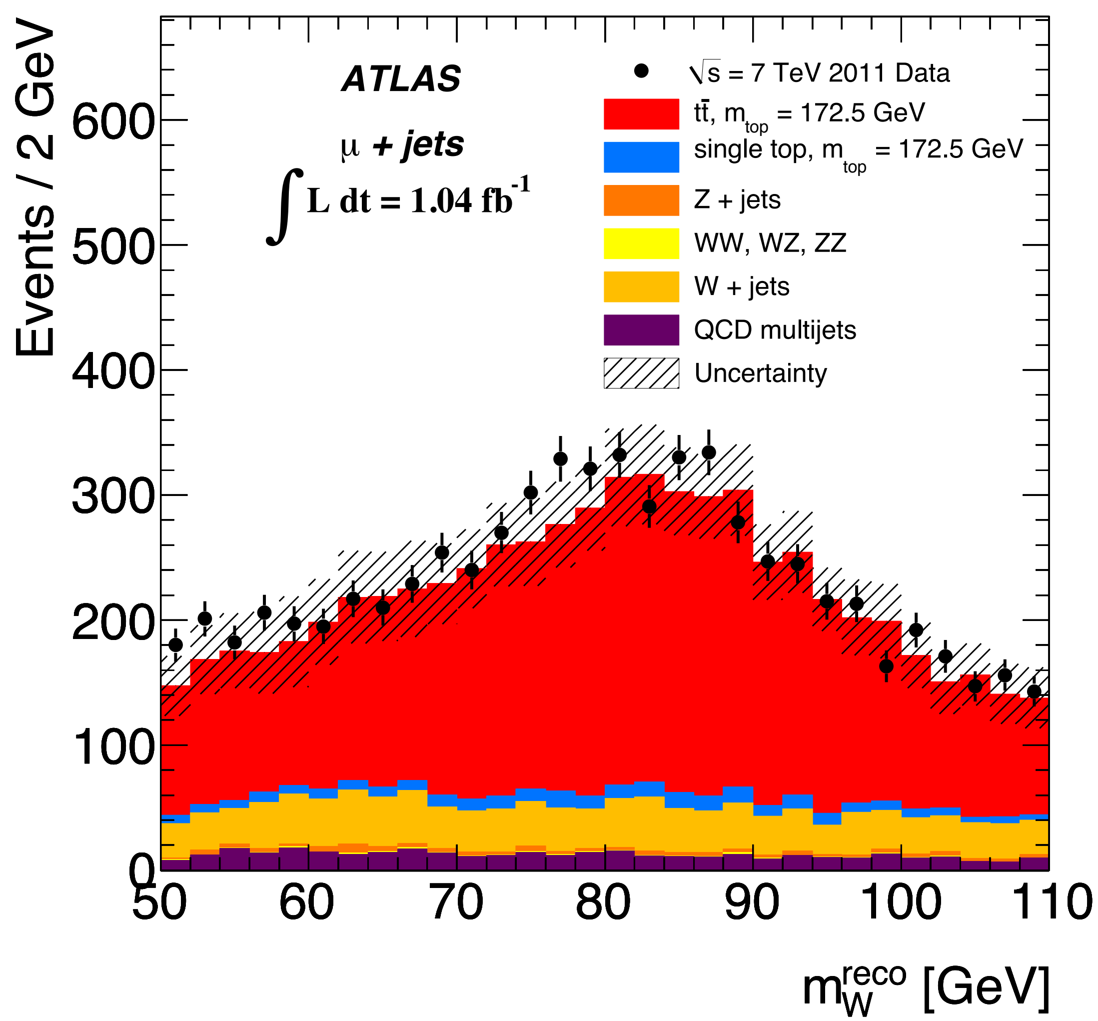


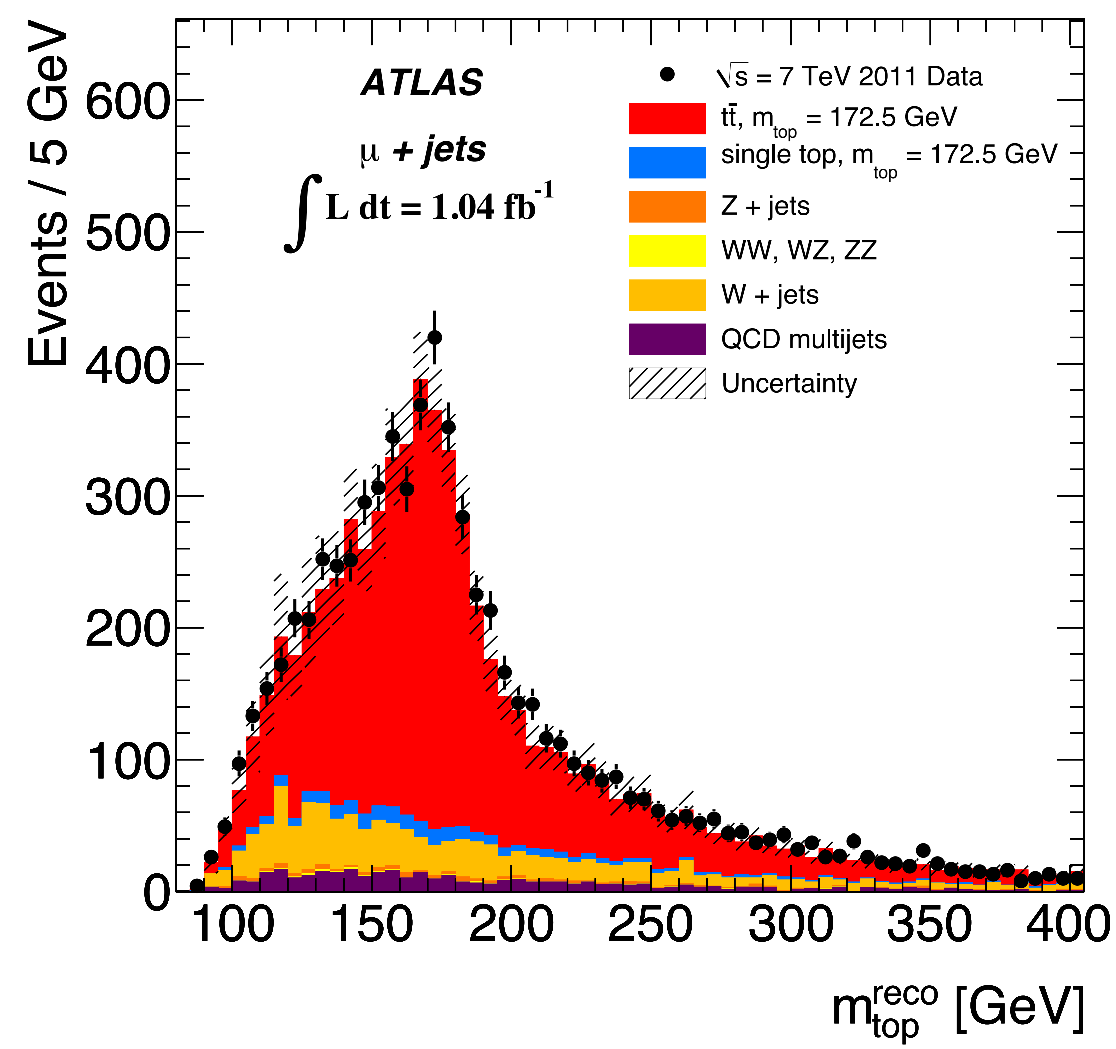
ATLAS Top Mass

- Discuss two ATLAS top mass measurements, both with lepton +jets events:
  - Eur.Phys.J. C72 (2012) 2046 - analysis with 1 fb^{-1} 7 TeV data.
  - ATLAS-CONF-2013-046 - analysis with 5 fb-1 7 TeV data.
- Try to illustrate how we make progress (i.e. reduced uncertainties).

ATLAS Top Mass

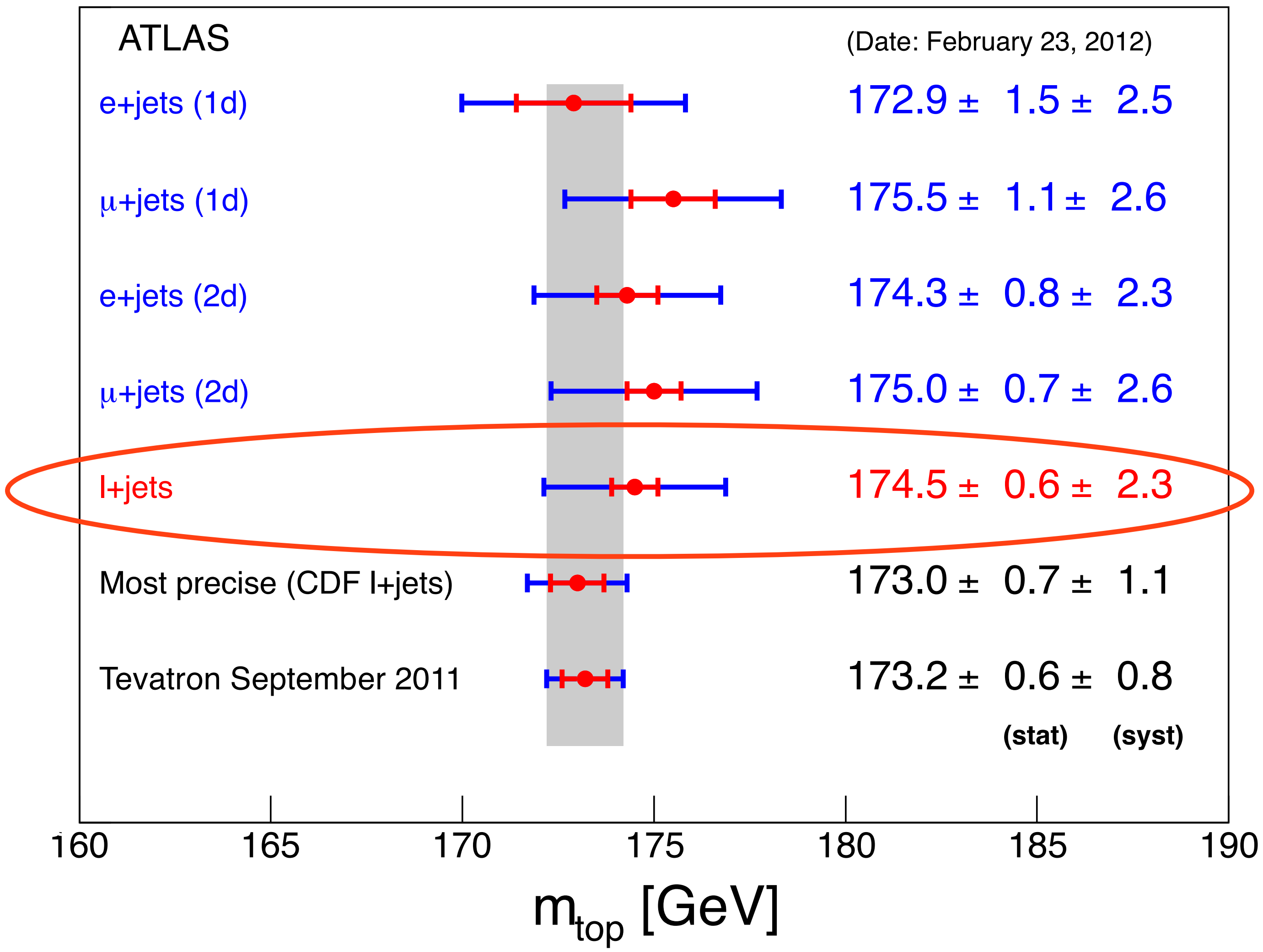
- 1 fb^{-1} analysis:
  - Reconstruct m(top) from three jets - two jets from W boson, one jet from b-jet.
  - Calibrate JES using W boson mass.





ATLAS Top Mass

- 1 fb^{-1} results:



ATLAS Top Mass

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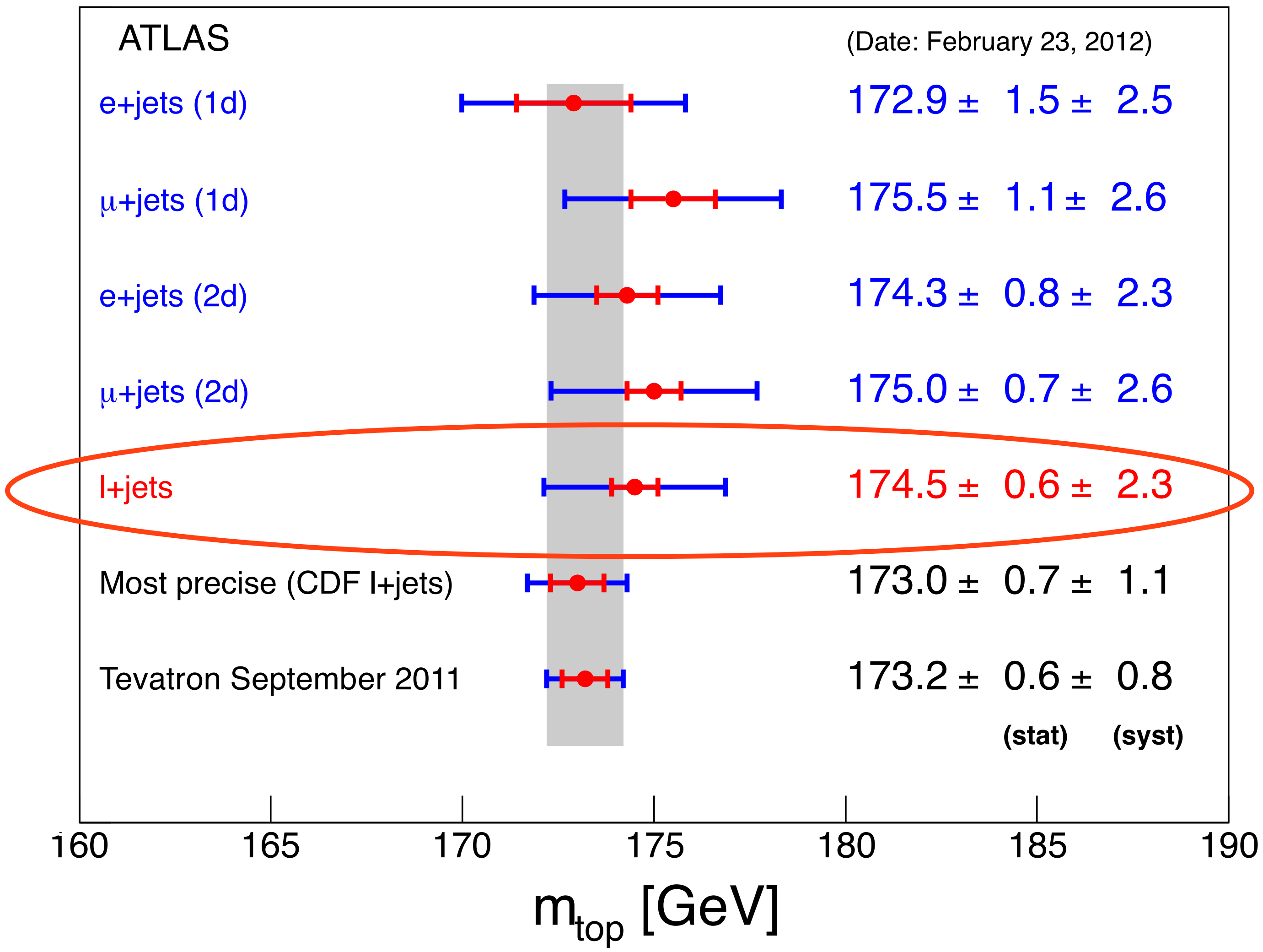
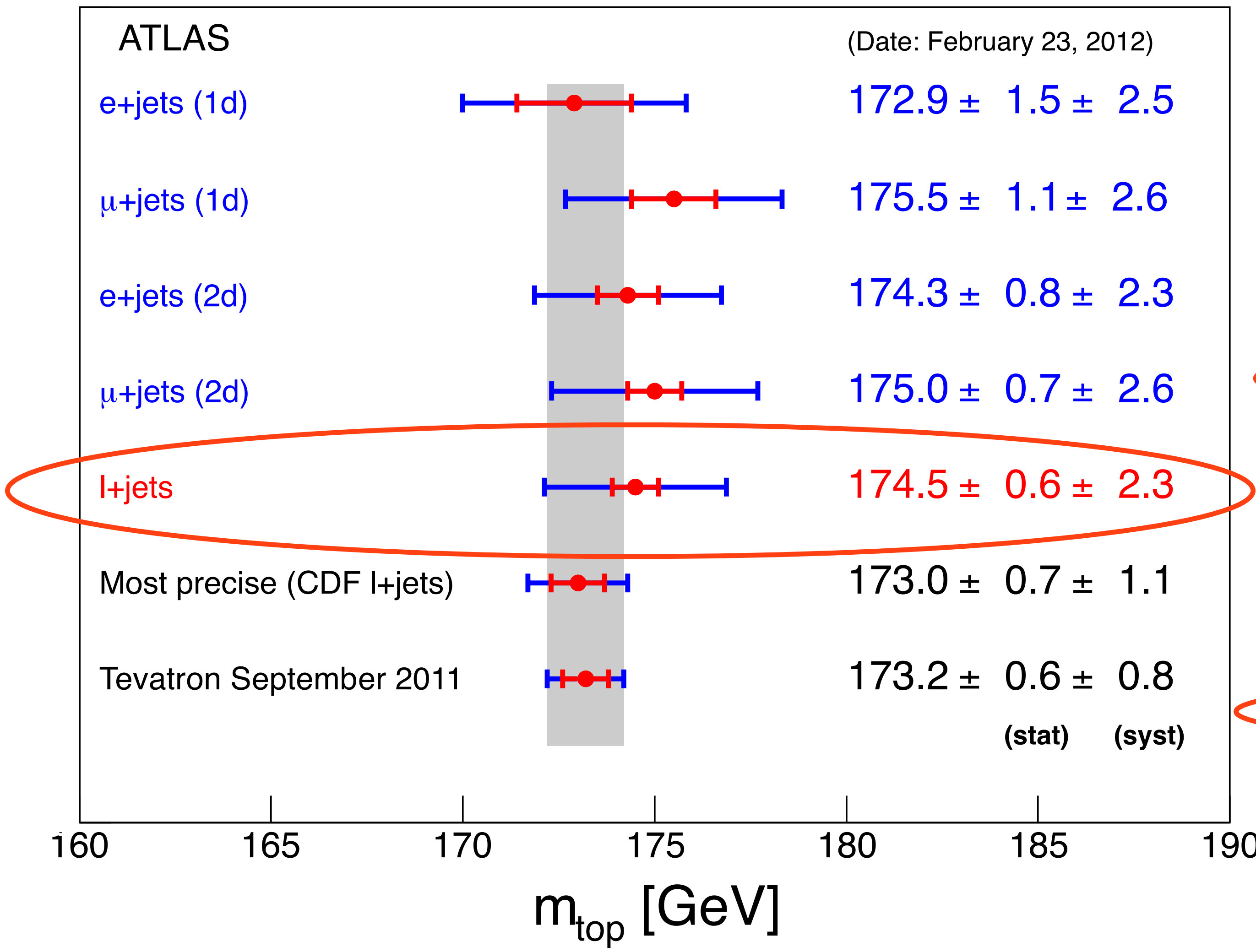


	2d
Measured value of $m_{\rm top}$	174.53
Data statistics	0.61
Jet energy scale factor	0.43
Method calibration	0.07
Signal MC generator	0.33
Hadronisation	0.15
Pileup	< 0.05
Underlying event	0.59
Colour reconnection	0.55
ISR and FSR (signal only)	1.01
Proton PDF	0.10
W+jets background normalisation	0.37
W+jets background shape	0.12
QCD multijet background normalisation	0.20
QCD multijet background shape	0.27
Jet energy scale	0.66
b-jet energy scale	1.58
b-tagging efficiency and mistag rate	0.29
Jet energy resolution	0.07
Jet reconstruction efficiency	< 0.05
Missing transverse momentum	0.13
Total systematic uncertainty	2.31
Total uncertainty	2.39

ATLAS Top Mass

- 1 fb^{-1} results:



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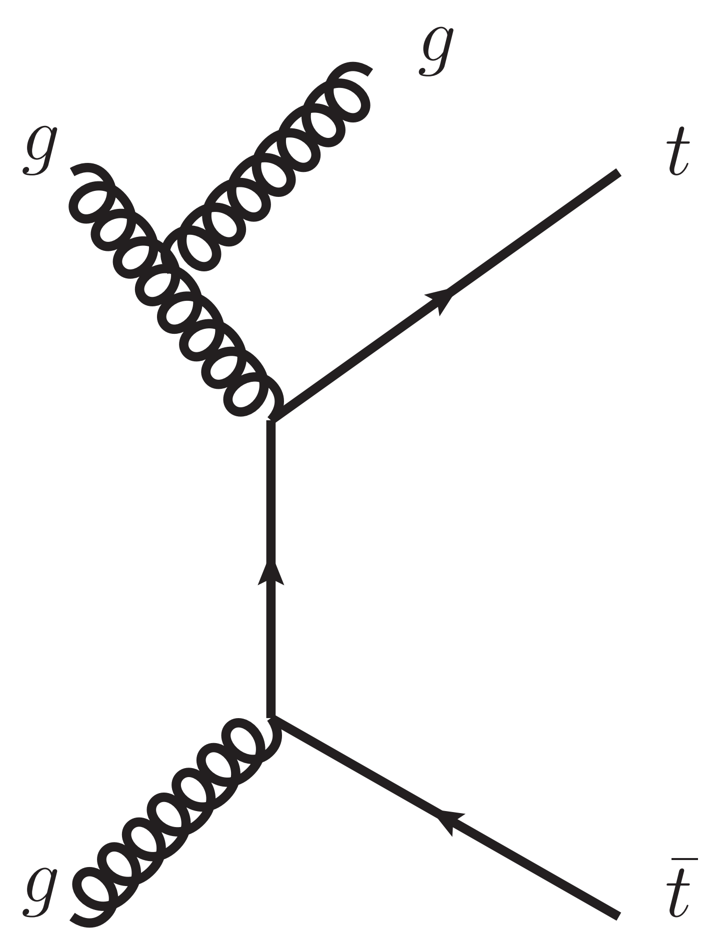
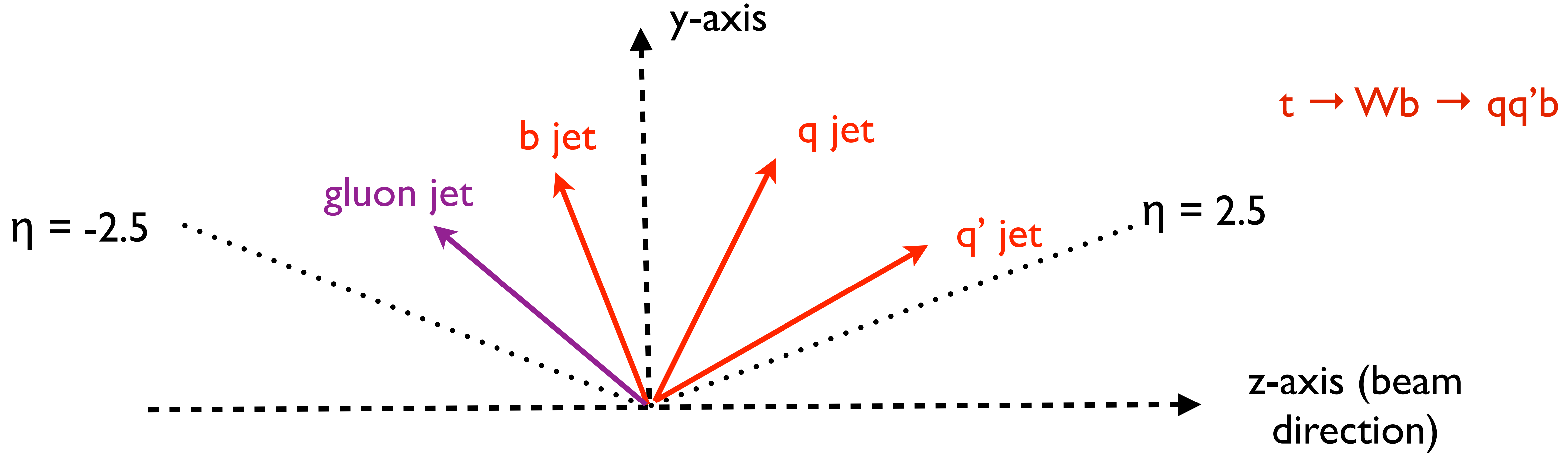
ISR on Top Mass

- ISR = initial state radiation - mainly gluon jets.
- Top reconstruction variable needs the three jets originating from the top decay.
- If we have additional jets - harder to pick the correct jet for the top reconstruction.
  - Events with 'wrong' jets will have a different shape for the reconstructed mass distribution.



ISR on Top Mass

- Events with additional jets more likely to be incorrectly assigned.



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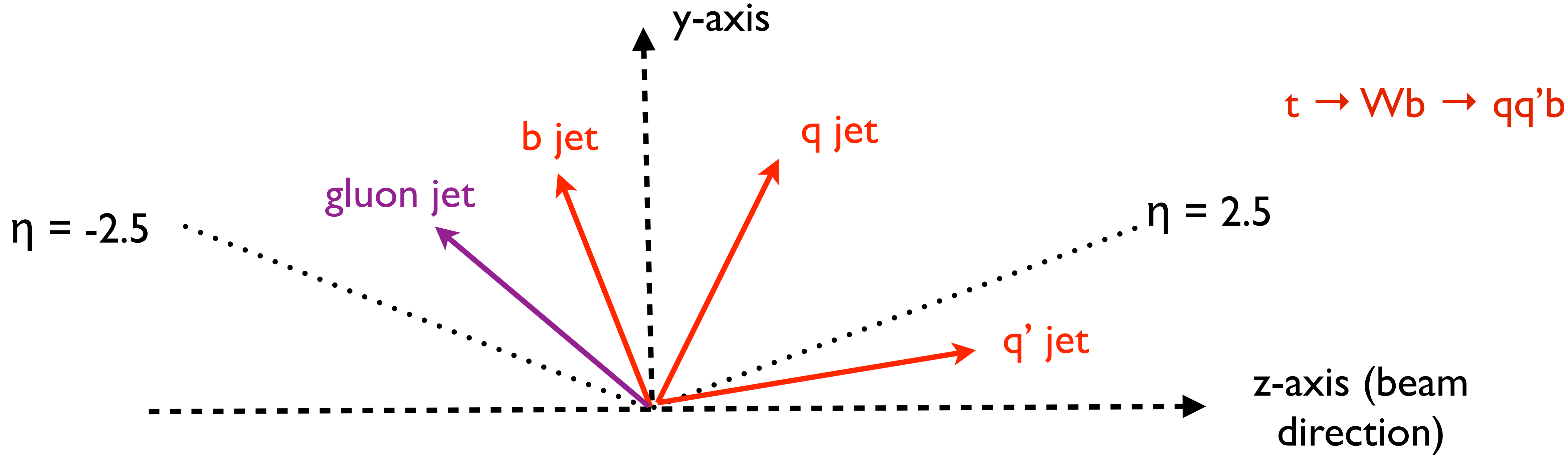

ISR on Top Mass

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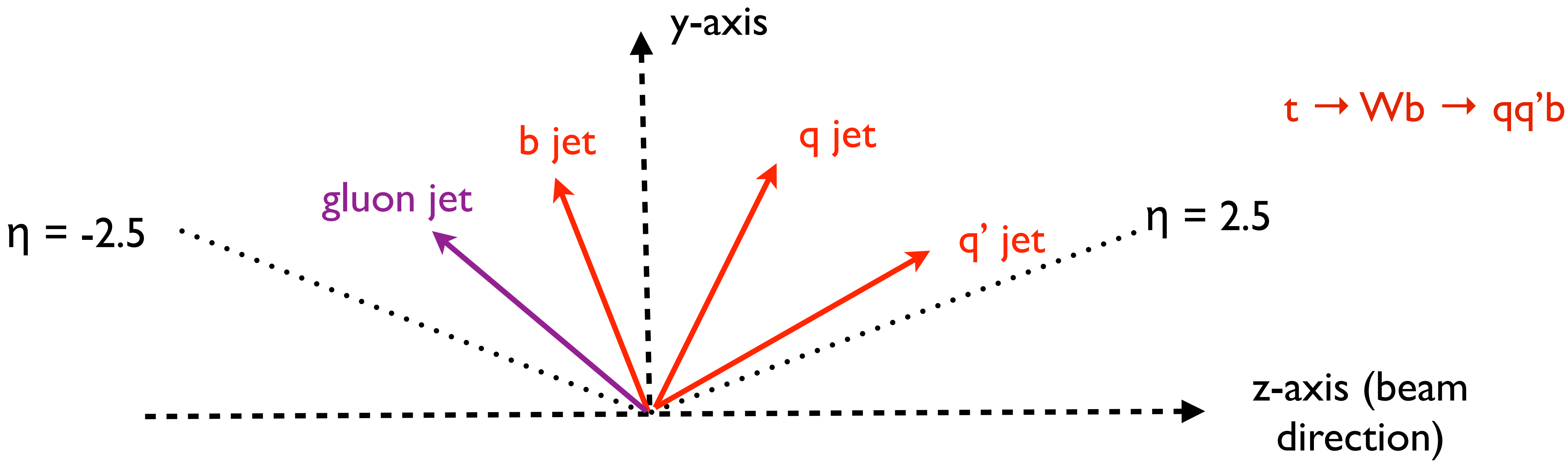
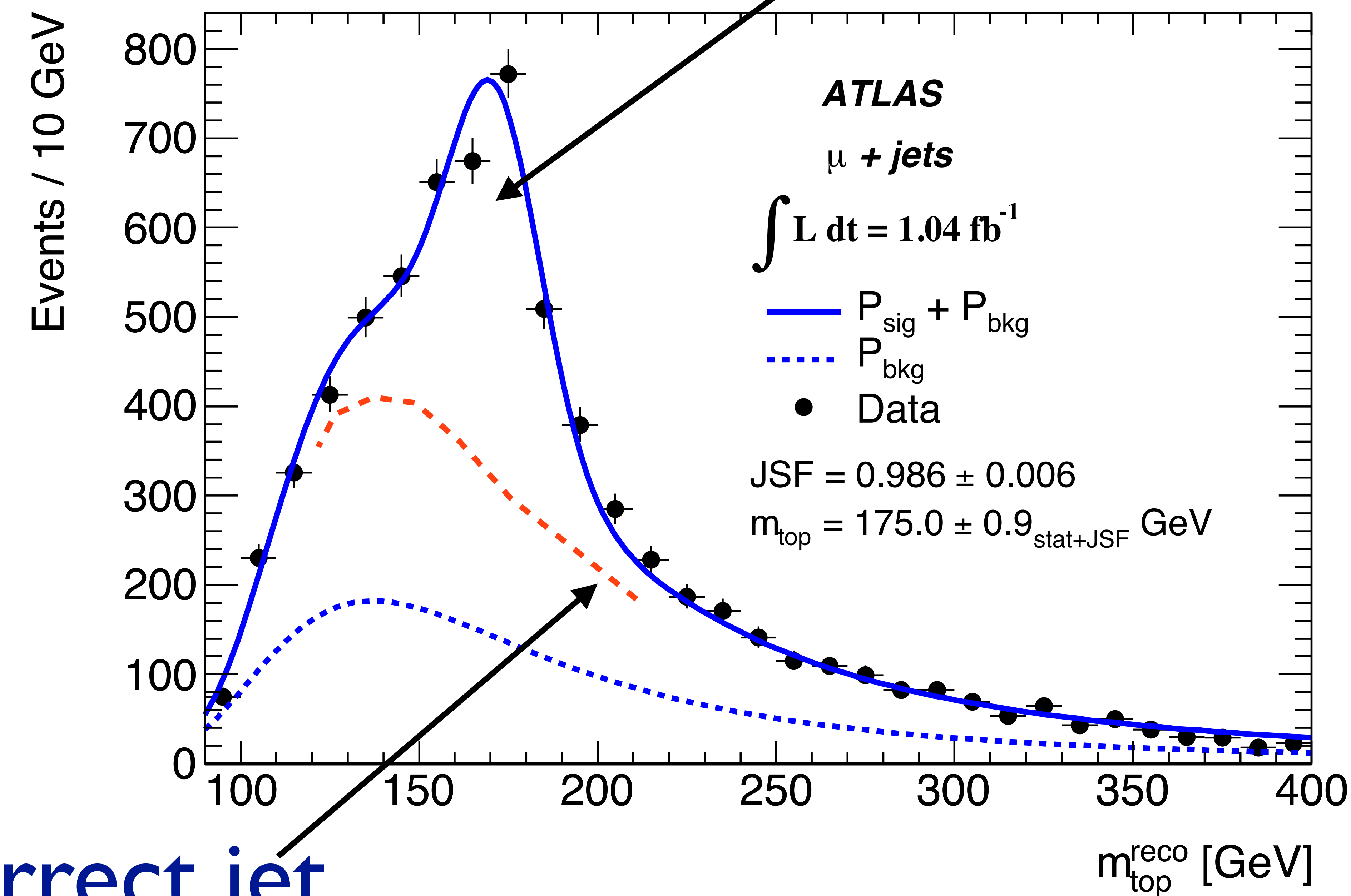


- Observed 3-jet mass distribution has 3 components:
  - ttbar events with correctly assigned jets
  - ttbar events incorrectly assigned jets
  - Background events

ISR on Top Mass

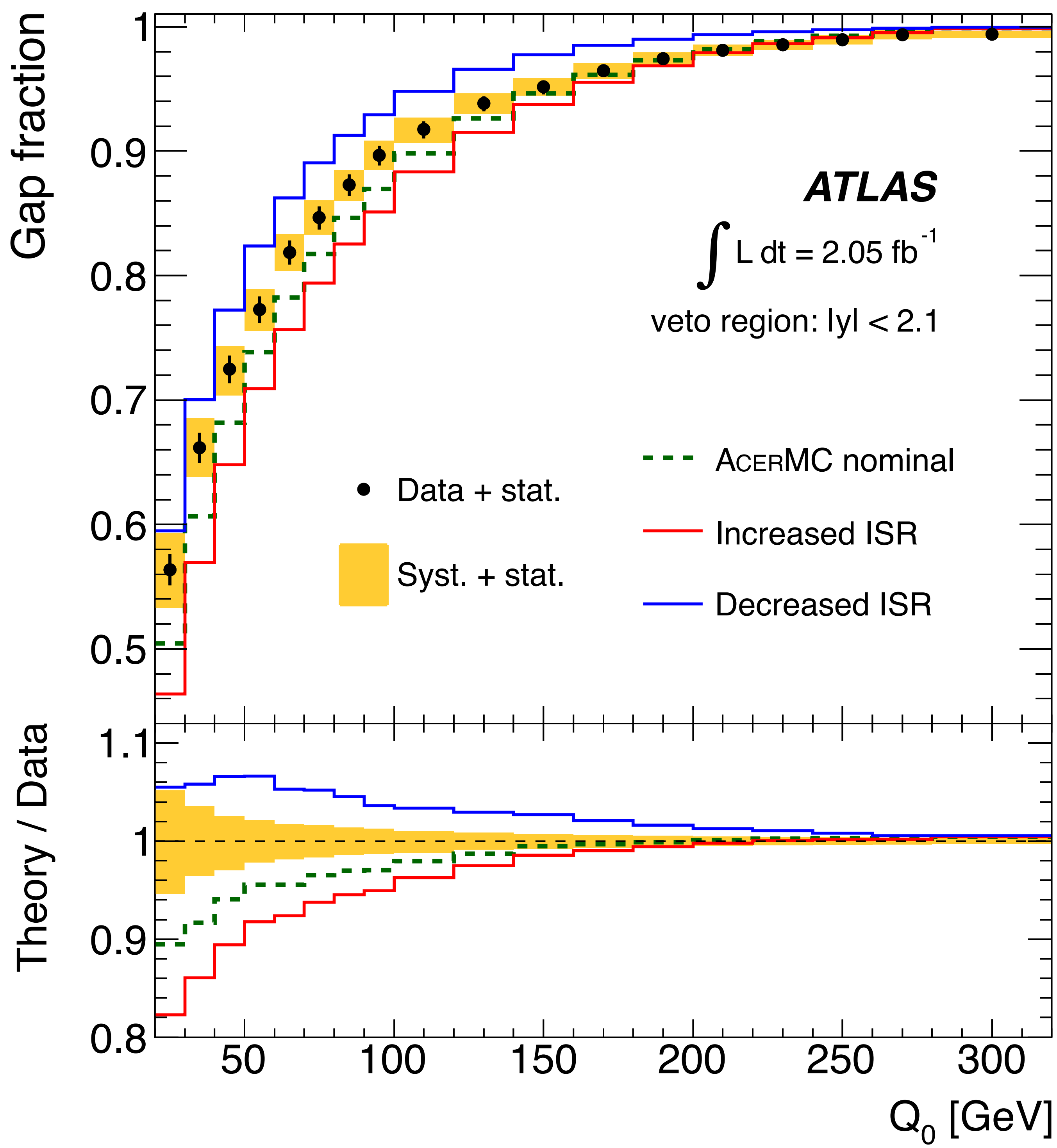
Correct assignment



Incorrect jet assignment

Reducing the Uncertainty

- Remember the jet veto measurement from this morning:



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

$n(Q_0) = \text{Number of } t\bar{t} \text{ events with no jet with } p_T > Q_0$

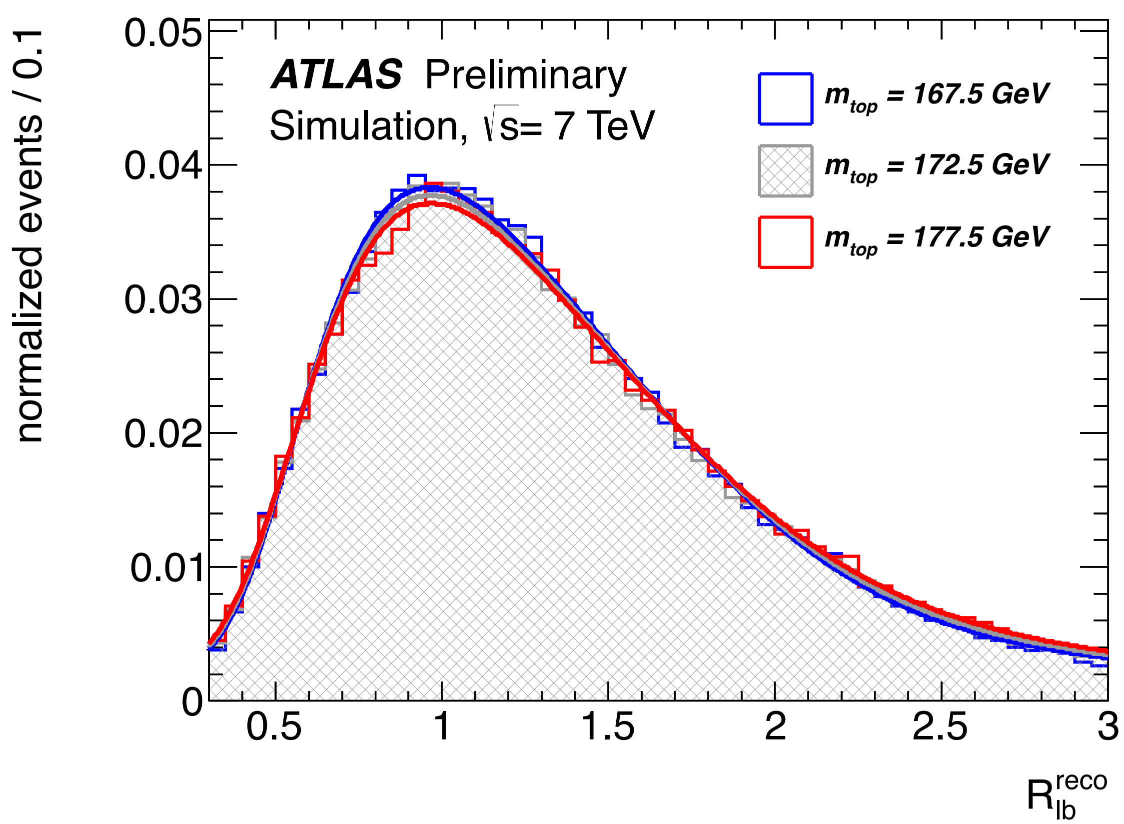
$N = \text{Total number of } t\bar{t} \text{ events}$

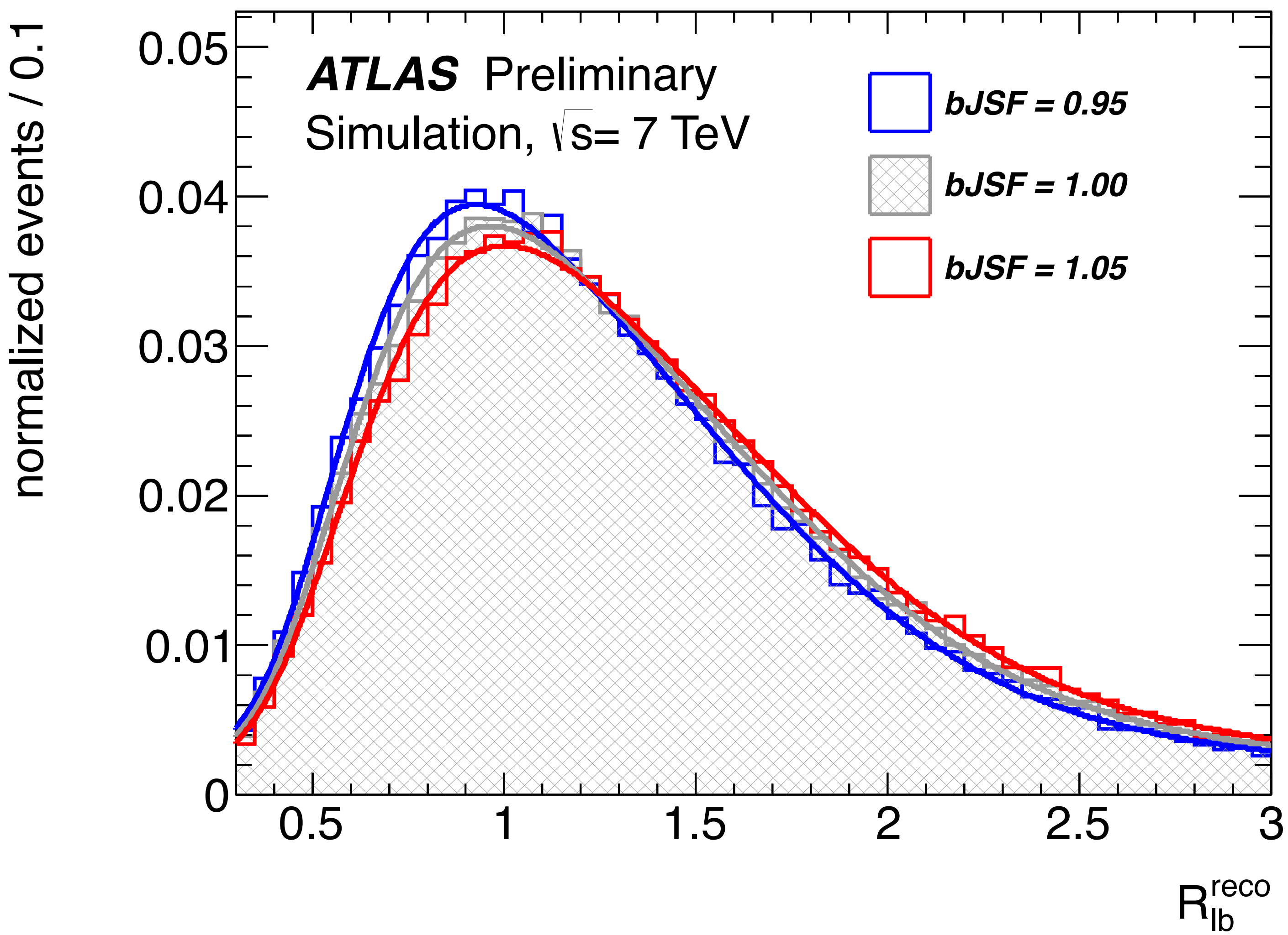
Expect reduced uncertainty with updated measurement!

B-jet energy scale

- W boson constrains the jet energy scale - but cannot give information of difference between b-quark and light-quark jets.
- Need some additional information to constrain b-jet energy scale - use ratio of b-jet and light-jets in the top sample:

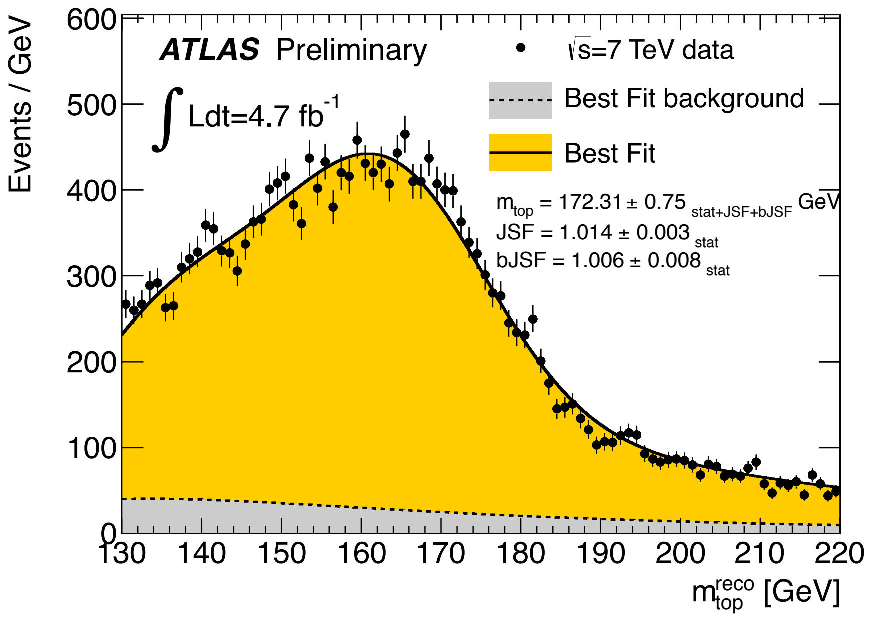
$$R_{\mathrm{lb}}^{\mathrm{reco,2b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}}},$$

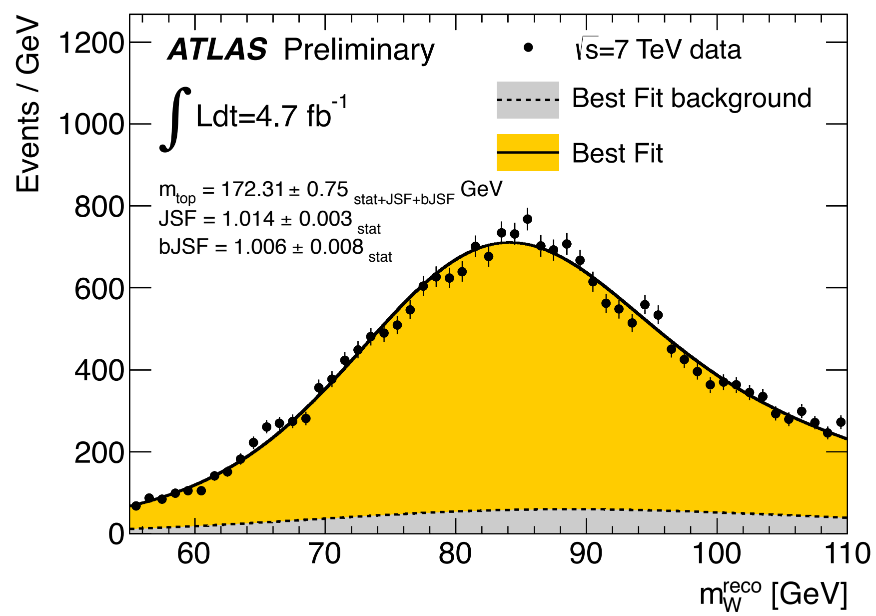


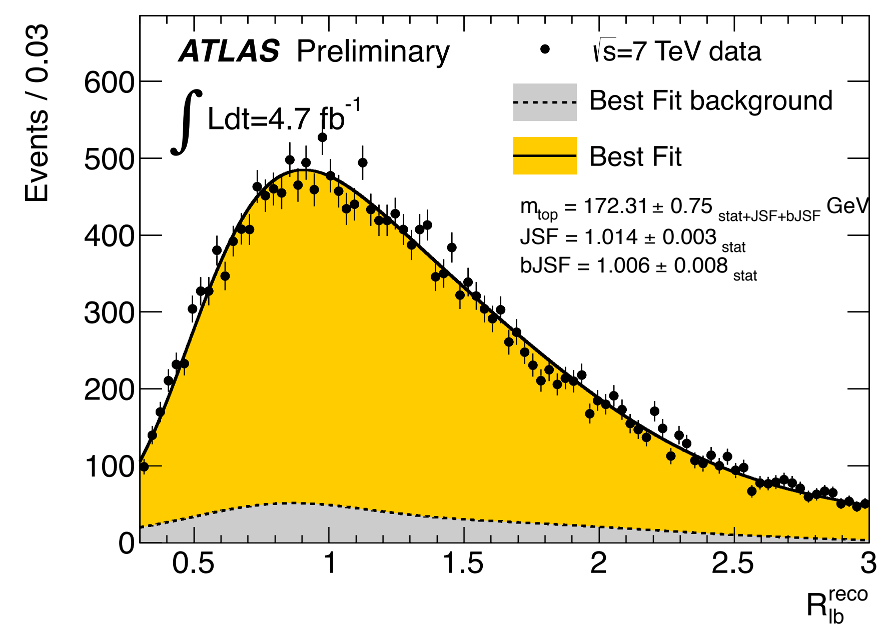


ATLAS 5 fb^{-1} analysis

- Reconstruct m(top) from fit to lepton + jet events.
- Make 3D fit to m(top), m(W) and R_{lb} - constrain both JES and bJES while extracting the top mass.







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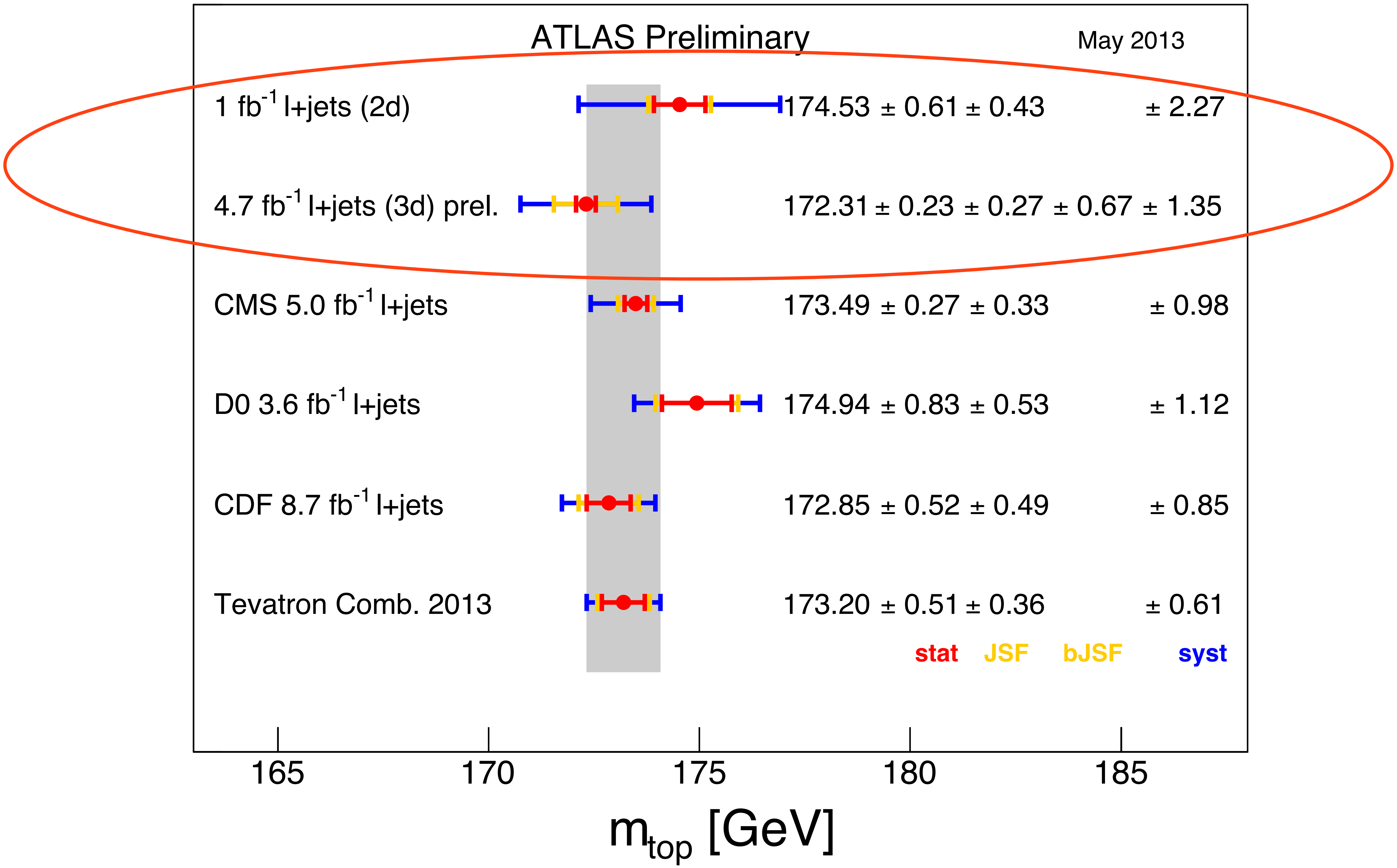
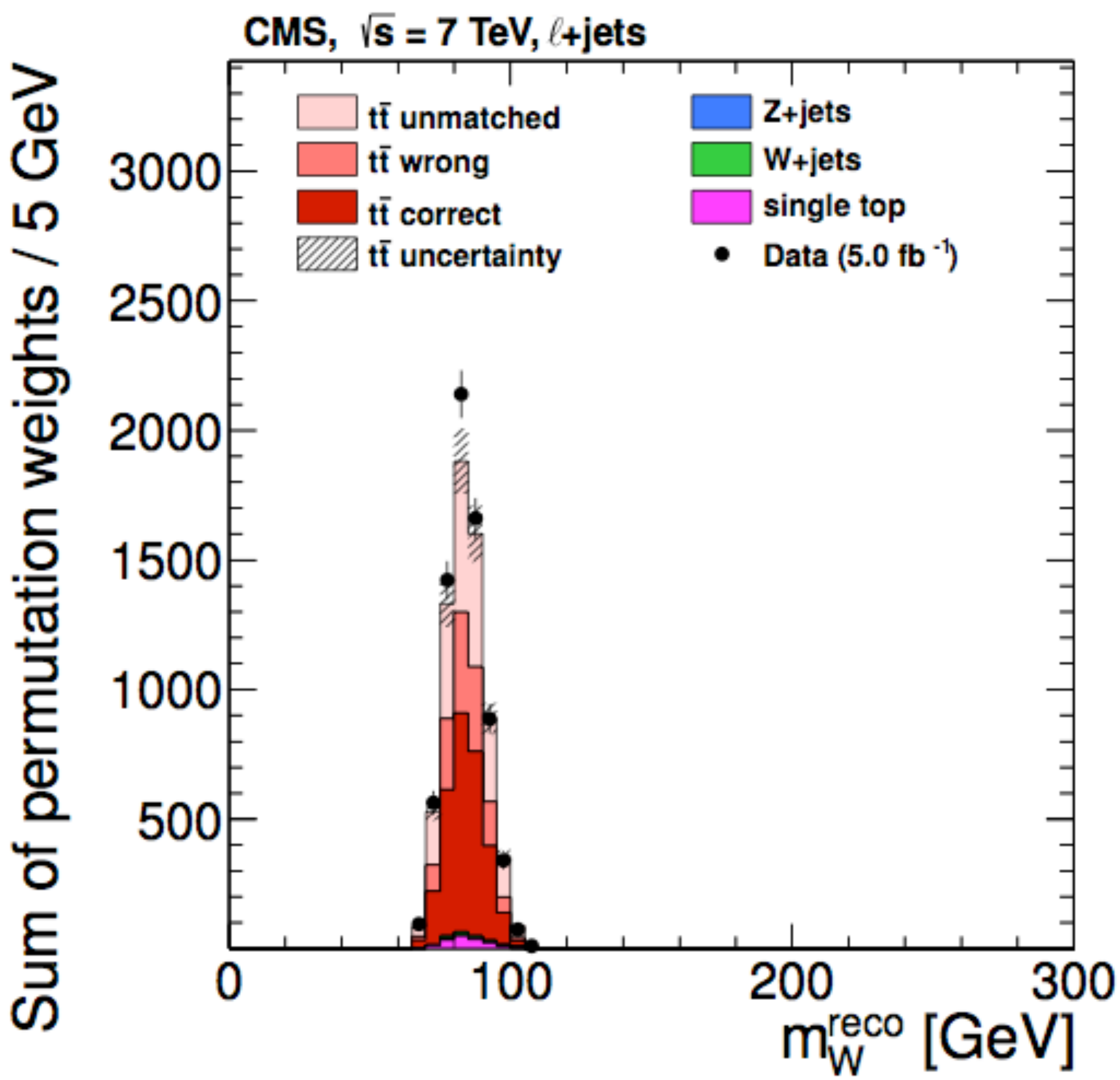
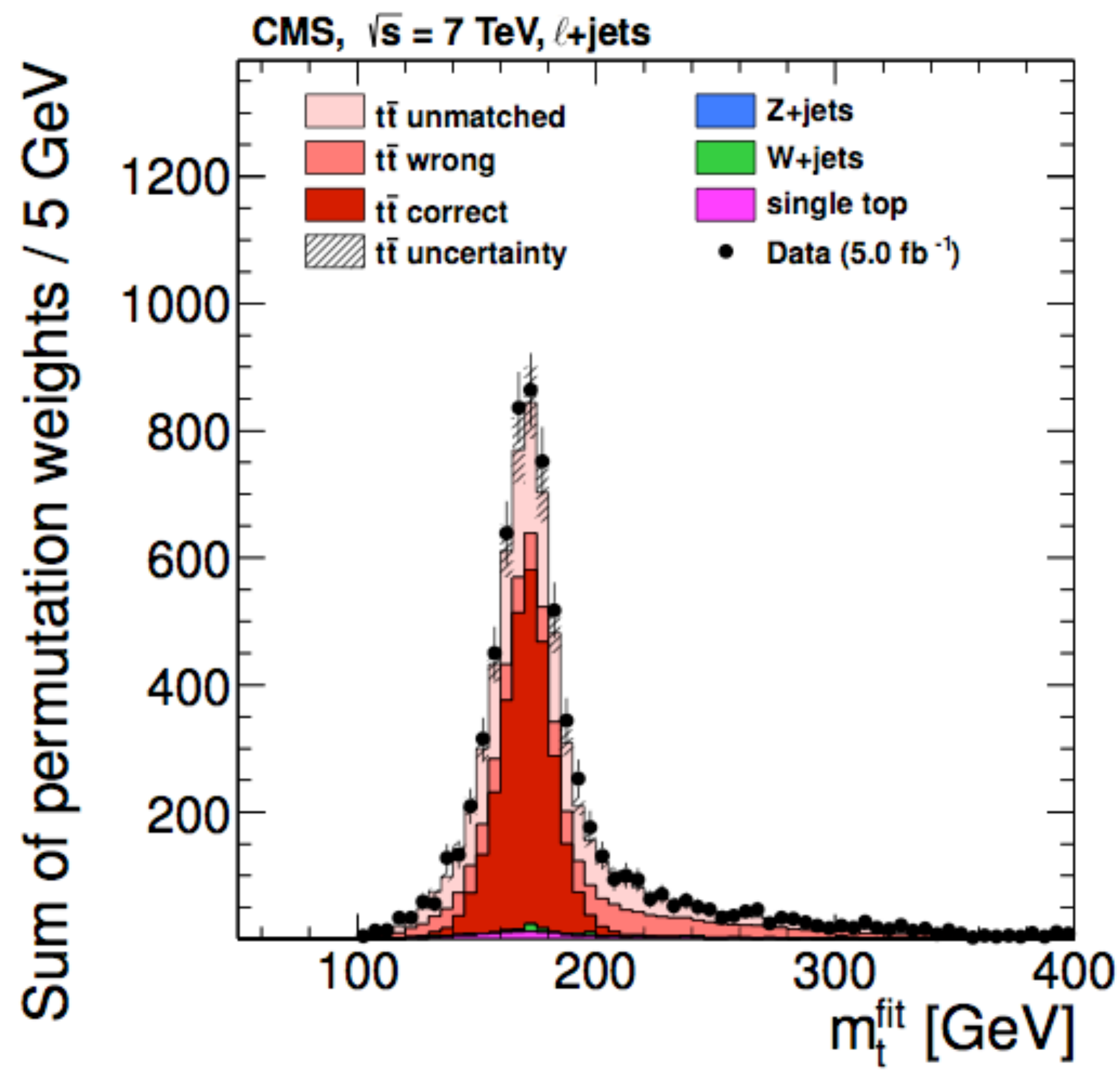


Total uncertainty reduced from 2.5 to 1.4 GeV

CMS Top Mass

- Top mass from kinematic fit to the ttbar system - then 2D fit constraining the JES using W boson mass.





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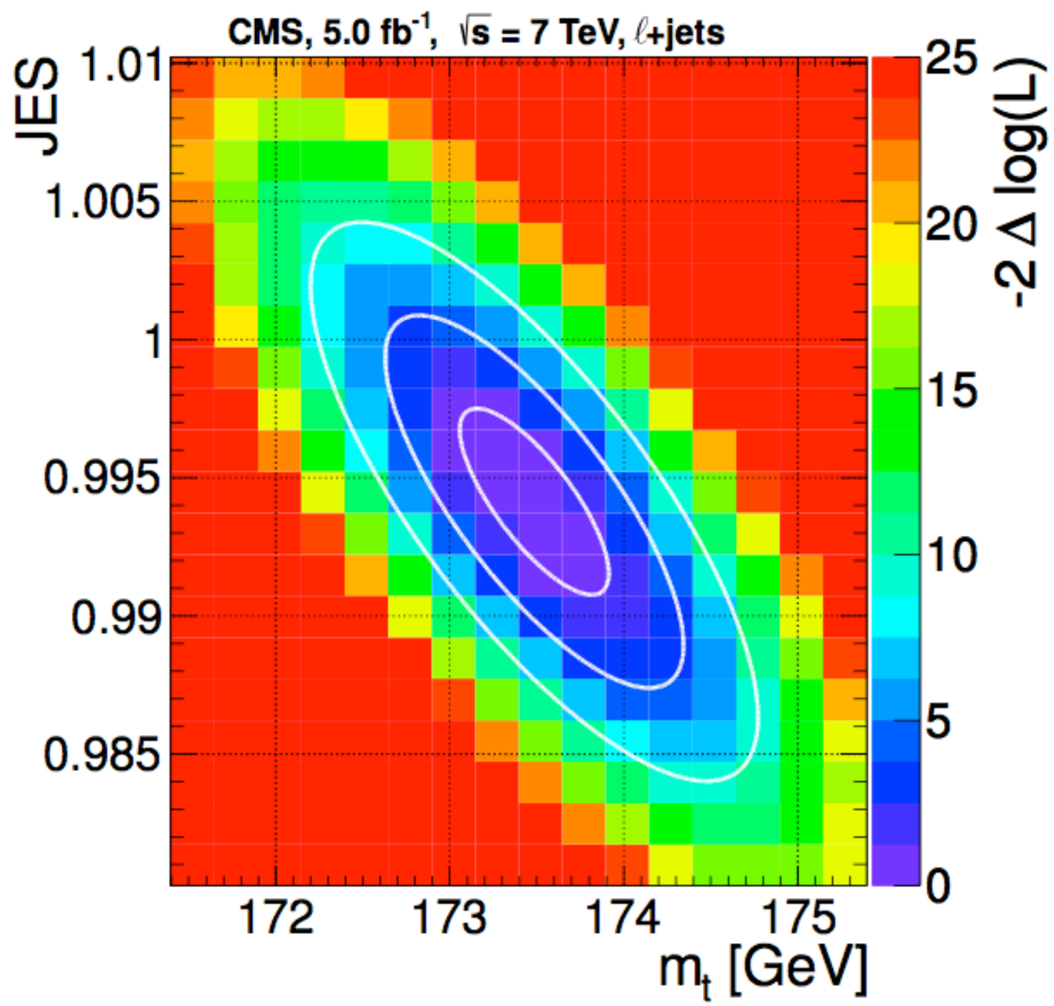
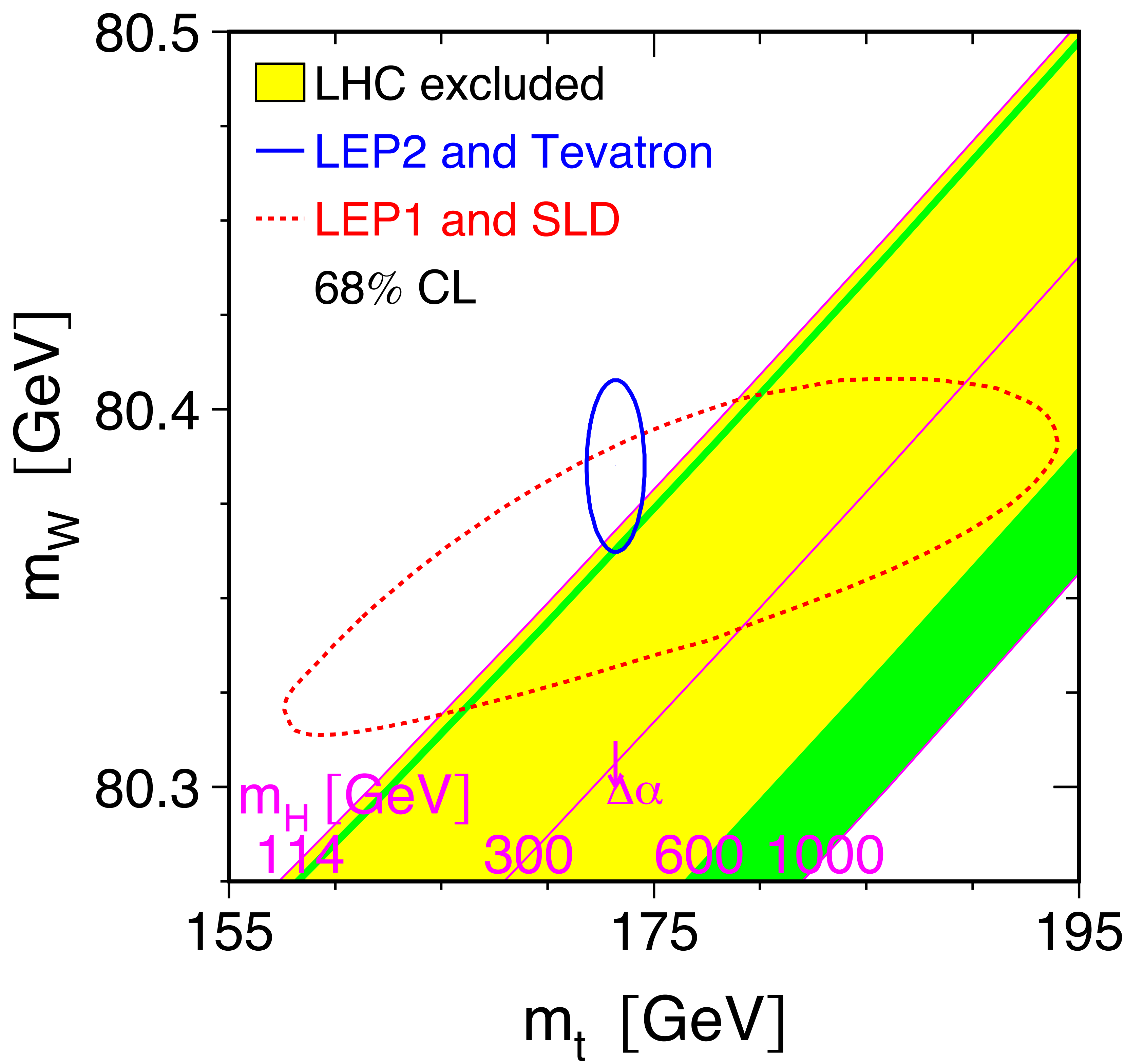


$$m_t = 173.49 \pm 0.43\,(\text{stat.+JES}) \pm 0.98\,(\text{syst.})\,\text{GeV},$$

$$\text{JES} = 0.994 \pm 0.003\,(\text{stat.}) \pm 0.008\,(\text{syst.}).$$

Single best measurement to date.

SM Consistency



Improved m_W is essential

Top Properties:

Top quark mass

Top spin correlations

Forward-backward asymmetry

Boosted tops

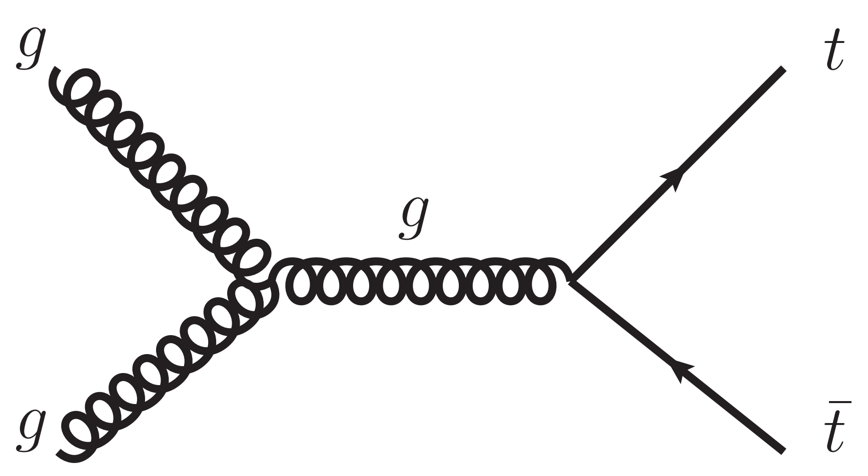
Top Pair Spin Correlations

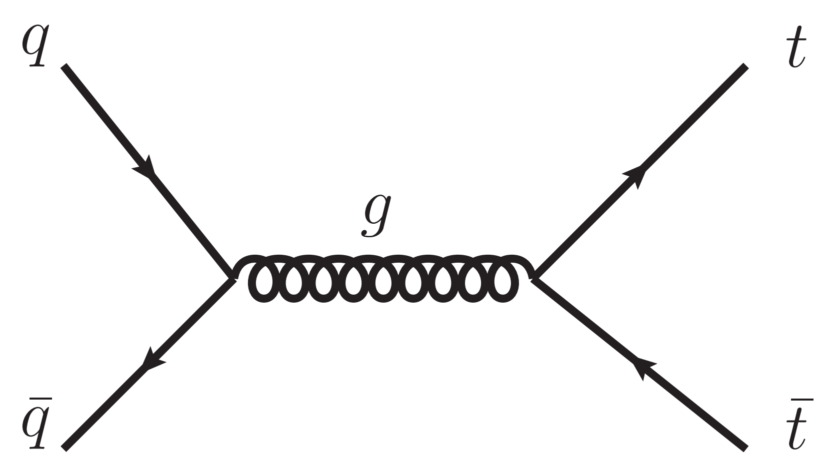
- Want to test if top quark is really spin-1/2 particle.
- Top quark pair production: spins of top and anti-top are correlated due to the QCD production mechanism.
- Top quark decays before hadronizing - spin information transferred to the decay products.
- Measure spin correlation:

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

Top Pair Spin Correlations

- Measure spin relative to a quantization axis:
  - Helicty basis: Measure relative to top (anti-top) direction.
  - Beam basis: Measure relative to the beam line.
- Correlation is different for the different production modes:





Top Pair Spin Correlations

- Helicity basis:

$$\beta = \frac{|p|}{E}$$

$$\sum_{LL,\ RR} |\mathcal{M}(q\bar{q} \to t\bar{t})|^2 = 8g^4\ (1-\beta^2)\sin^2\theta^*,$$ →0 for β→1

$$\sum_{LR,\ RL} |\mathcal{M}(q\bar{q} \to t\bar{t})|^2 = 8g^4\ (1+\cos^2\theta^*).$$

$$\sum_{LL,\ RR} |\mathcal{M}(gg \to t\bar{t})|^2 = \frac{16}{3}g^4\ \mathcal{Y}(\beta,\cos\theta^*)\ (1-\beta^2)(1+\beta^2+\beta^2\sin^4\theta^*),$$

→0 for β→1

$$\sum_{LR,\ RL} |\mathcal{M}(gg \to t\bar{t})|^2 = \frac{16}{3}g^4\ \mathcal{Y}(\beta,\cos\theta^*)\ \beta^2\sin^2\theta^*(1+\cos^2\theta^*).$$

A→-1 for β→1 for qq & gg

Mahlon & Parke, arXiv:hep-ph/9512264

Top Pair Spin Correlations

- Helicity basis:

$$\beta = \frac{|p|}{E}$$

$$\sum_{LL,\ RR} |\mathcal{M}(q\bar{q} \to t\bar{t})|^2 = 8g^4\ (1-\beta^2)\sin^2\theta^*,$$

$$\sum_{LR,\ RL} |\mathcal{M}(q\bar{q} \to t\bar{t})|^2 = 8g^4\ (1+\cos^2\theta^*).$$

Not suppressed for $\beta \to 0$

$$\sum_{LL,\ RR} |\mathcal{M}(gg \to t\bar{t})|^2 = \frac{16}{3} g^4\ \mathcal{Y}(\beta, \cos\theta^*)\ (1-\beta^2)(1+\beta^2+\beta^2\sin^4\theta^*),$$

$$\sum_{LR,\ RL} |\mathcal{M}(gg \to t\bar{t})|^2 = \frac{16}{3} g^4\ \mathcal{Y}(\beta, \cos\theta^*)\ \beta^2\sin^2\theta^*(1+\cos^2\theta^*).$$

Suppressed for $\beta \to 0$

Different behaviour for $\beta \to 0$

Mahlon & Parke, arXiv:hep-ph/9512264

Top Pair Spin Correlations

- NLO prediction:

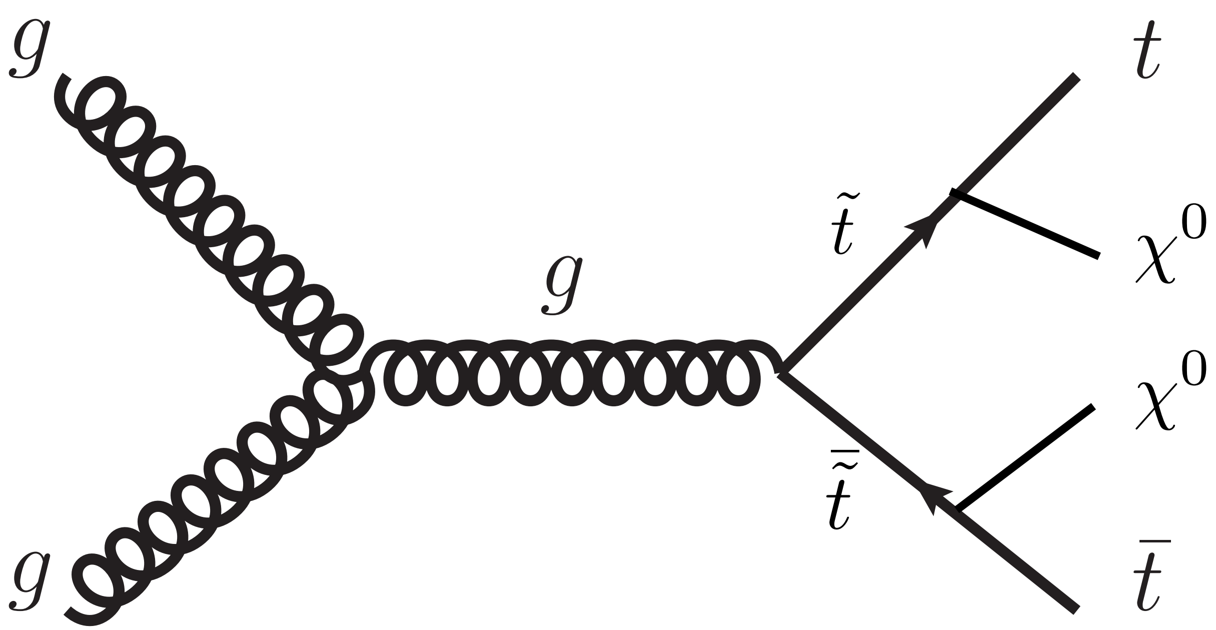
Axis	A at Tevatron	A at LHC (14 TeV)
Beam	0.79	0
Helicity	-0.37	0.33

LHC & Tevatron are complimentary!

Bernreuther & Zong-Guo, arXiv:1003.3926

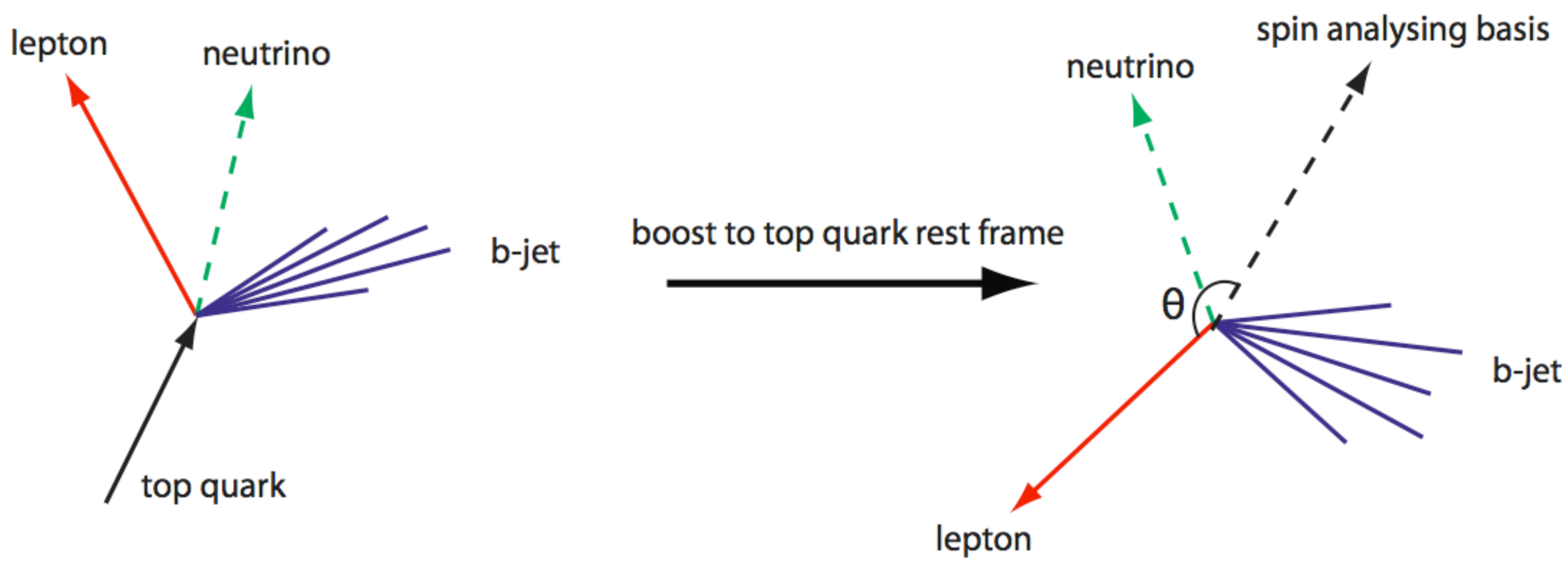
Top Pair Spin Correlations - Why?

- New physics could modify the spin correlation from SM prediction:



Top Pair Spin Correlations

- Need to measure angular distribution of top decay products:

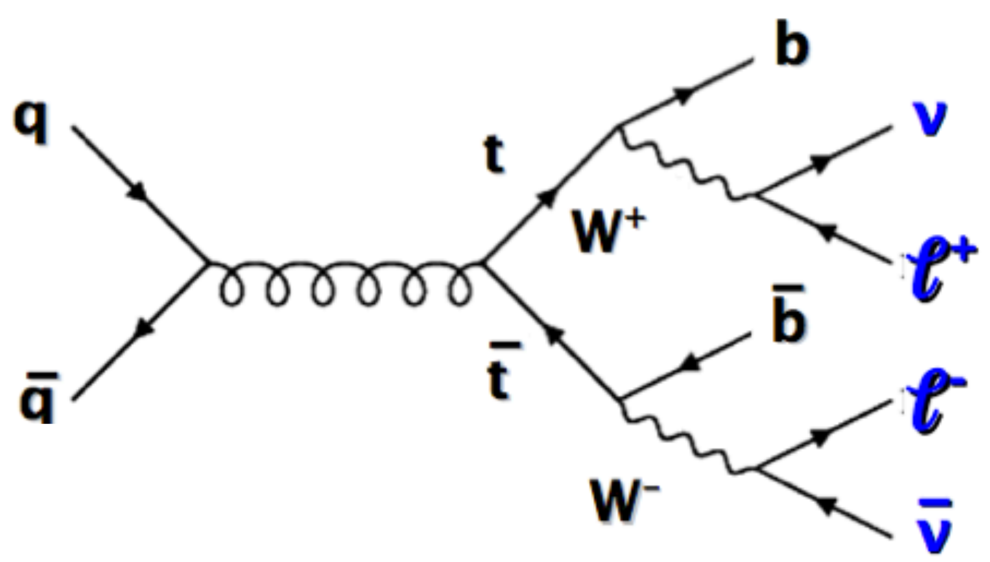


$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2} = \frac{1}{4}\left(1 - C\cos\theta_1\cos\theta_2\right)$$
$$\text{where } C = A\alpha_1\alpha_2$$

	b-quark	W^+	l^+	$\bar{d}$-quark or $\bar{s}$-quark	u-quark or c-quark
α_i (LO)	-0.41	0.41	1	1	-0.31
α_i (NLO)	-0.39	0.39	0.998	0.93	-0.31

Top Pair Spin Correlations

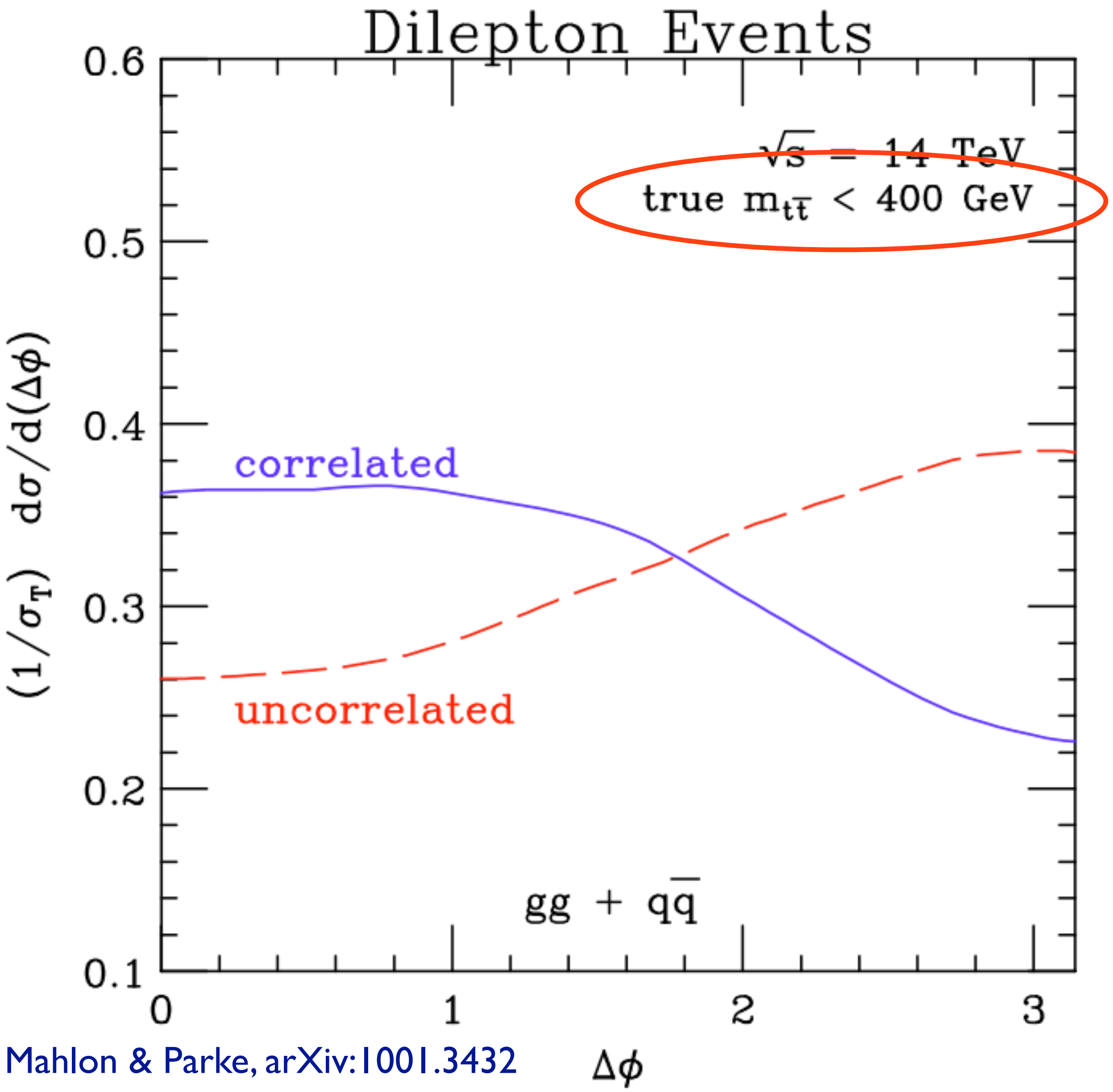
- Want to use dileptons high polarization power, but need to reconstruct the top direction:



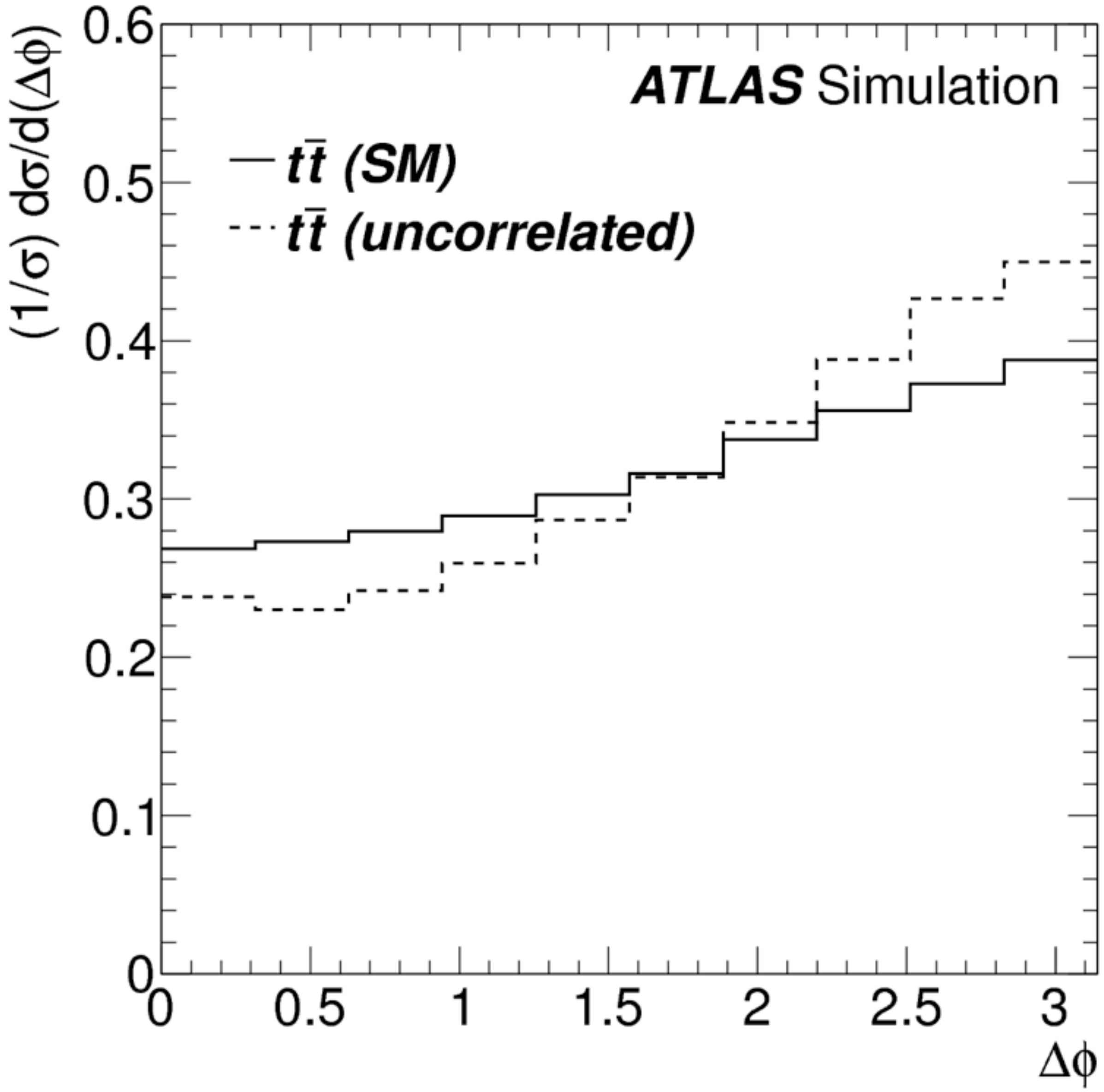
- Two neutrinos in final state - but only measure total missing transverse momentum in the detector.
  - Full reconstruction subject to significant uncertainties.
  - Simpler method with smaller uncertainties available?

Top Pair Spin Correlations

- LHC: azimuthal angular difference between leptons in lab frame is sensitive to spin correlations.
  - Simple to measure - small experimental systematic uncertainties.

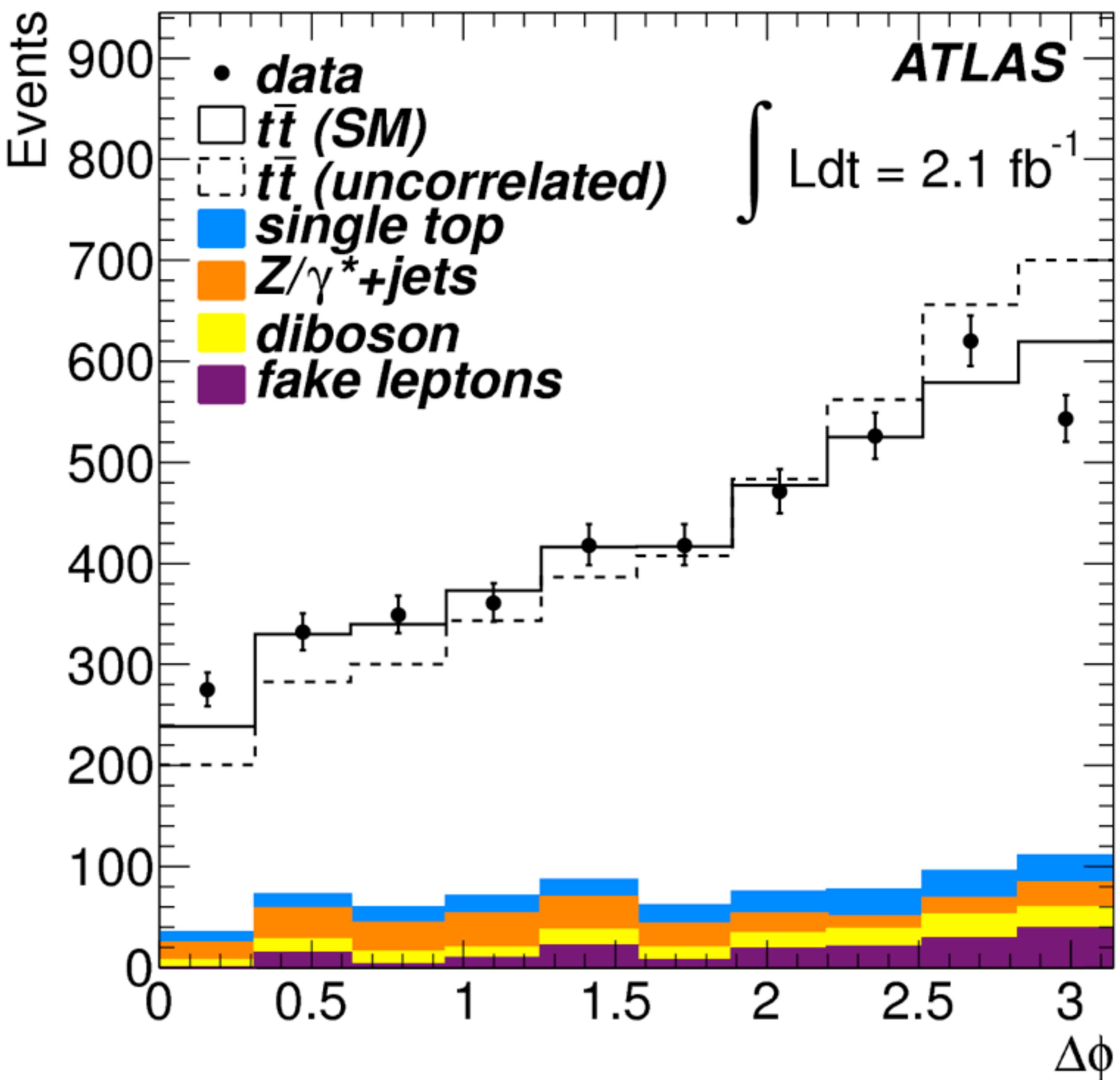


Mahlon & Parke, arXiv:1001.3432



Top Pair Spin Correlations

- ATLAS: Fit to azimuthal angular difference to extract correlation strength.



PRL 108, 212001 (2012)

MANCHESTER 1824

Top Pair Spin Correlations

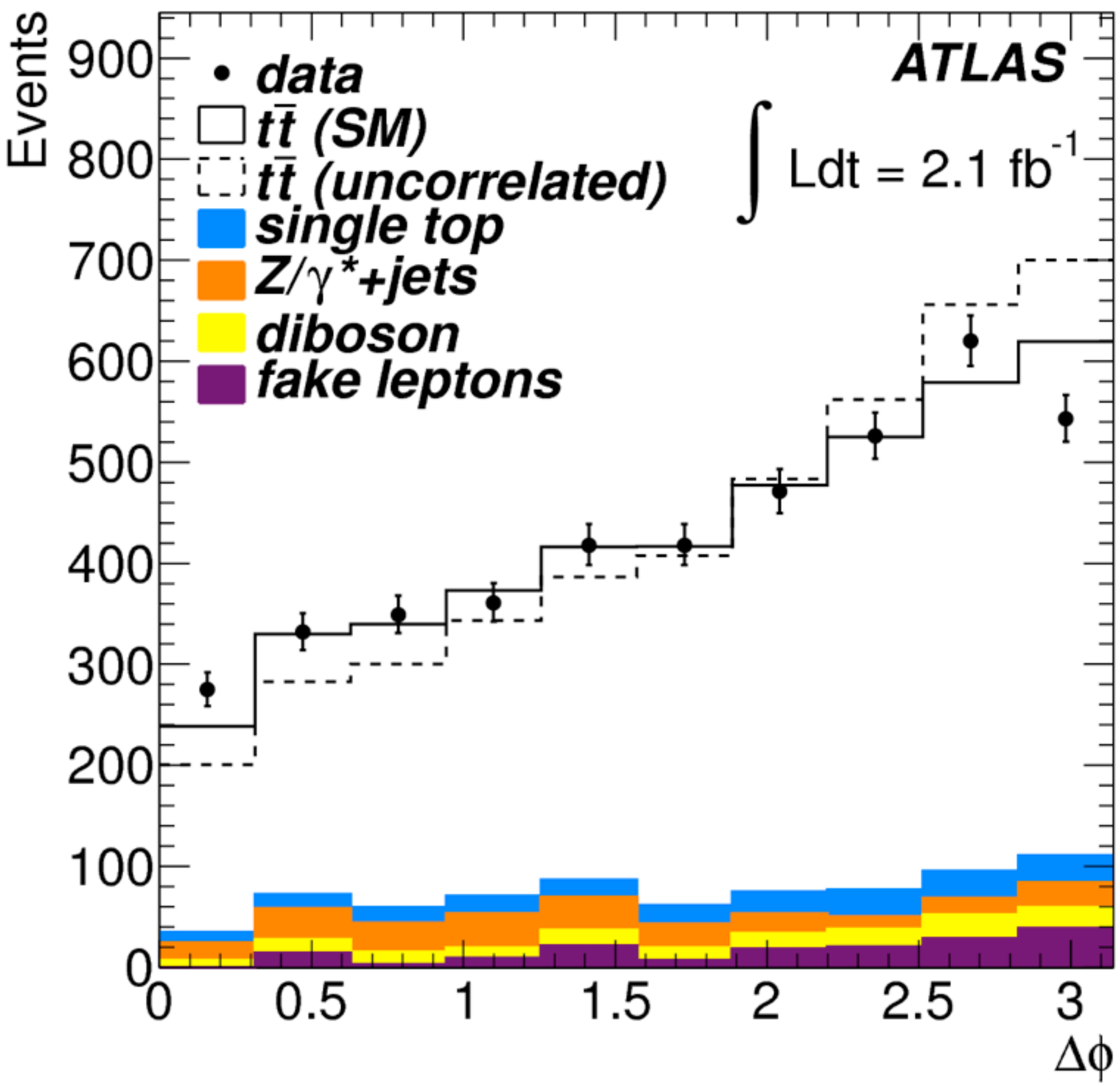
- ATLAS: Fit to azimuthal angular difference to extract correlation strength.

$$f^{SM} = 1.30 \pm 0.14\,(\text{stat})\,{}^{+0.27}_{-0.22}\,(\text{syst})$$

(=1 for SM)

$$C_{helicity} = 0.40\,{}^{+0.09}_{-0.08}$$

(=0.32 in NLO QCD)



First observation of non-zero spin correlations (5.1σ)!

Data consistent with SM top with spin 1/2 & NLO QCD.

PRL 108, 212001 (2012)

The University of Manchester

MANCHESTER 1824

Top Properties:

Top quark mass

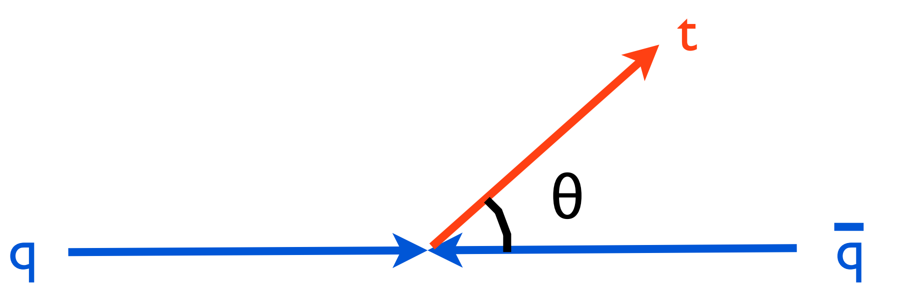
Top spin correlations

Forward-backward asymmetry

Boosted tops

Forward Backward Asymmetry

- Forward-Backward asymmetry (Tevatron):
  - Compare number of tops emitted in p direction with number of tops emitted in anti-p direction.
  - Equivalent to charge asymmetry: number of top emitted in p direction compared with anti-tops in p direction.



$$\hat{A}_{FB}(\cos\theta) = \frac{N_t(\cos\theta) - N_t(-\cos\theta)}{N_t(\cos\theta) + N_t(-\cos\theta)}$$

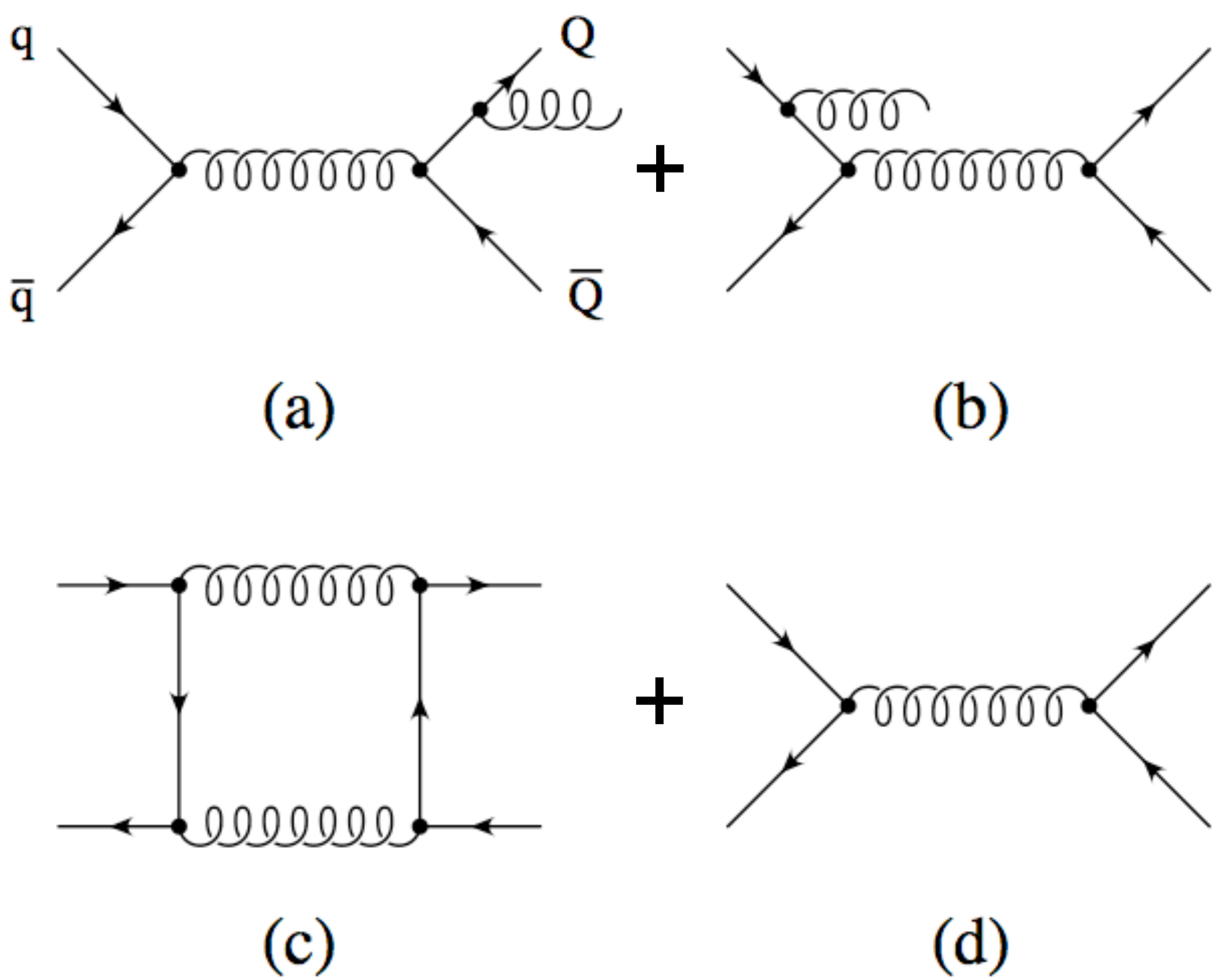
CP conservation:

$$N_{\bar{t}}(\cos\theta) = N_t(-\cos\theta)$$

$$\hat{A}_{C}(\cos\theta) = \frac{N_t(\cos\theta) - N_{\bar{t}}(\cos\theta)}{N_t(\cos\theta) + N_{\bar{t}}(\cos\theta)}$$

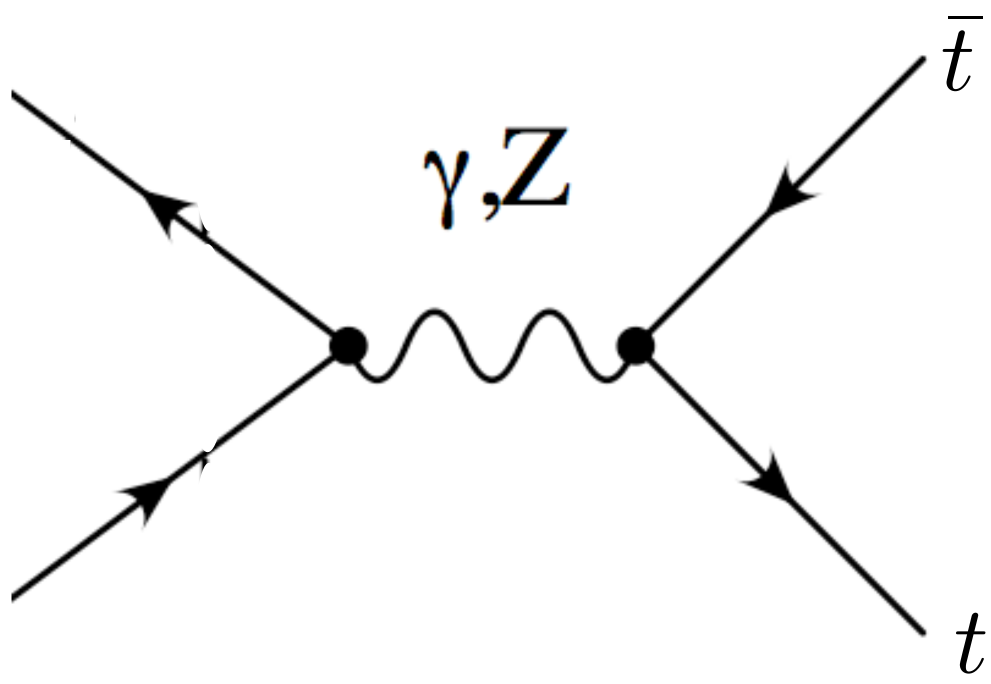
Forward Backward Asymmetry in SM

- Leading order: qq / gg → top pairs - no AFB.
- Asymmetry arrises at NLO through interference between diagrams:

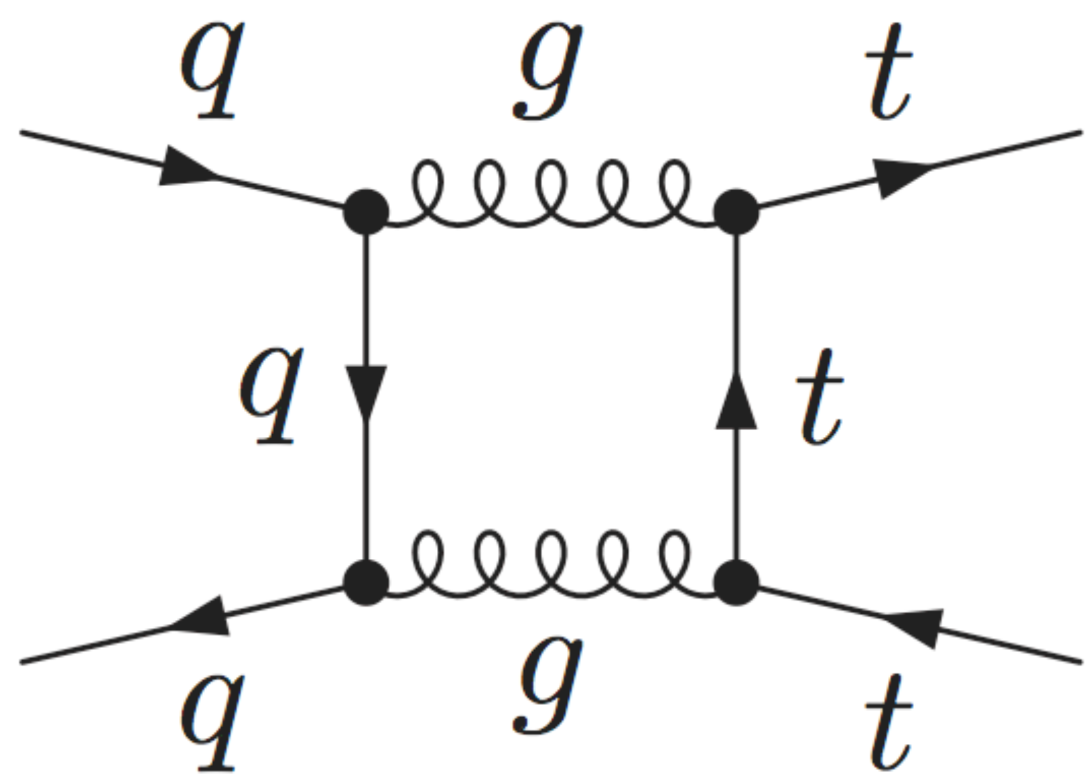


Forward Backward Asymmetry in SM

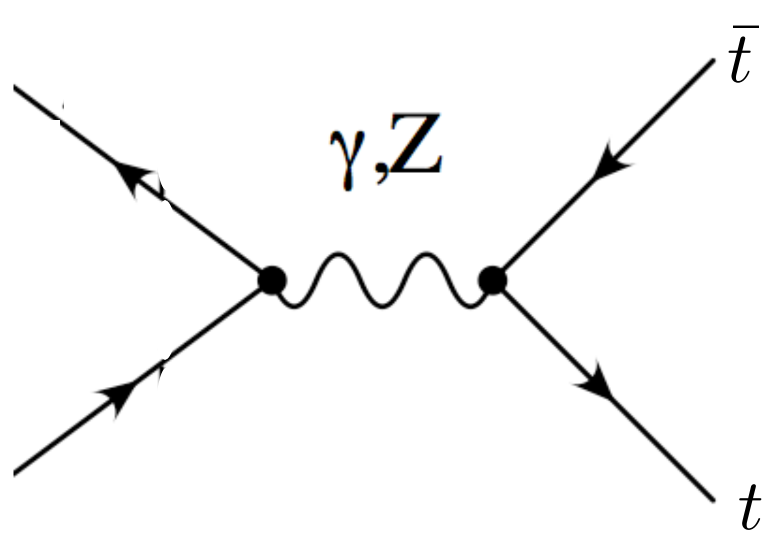
- Additional contribution from electroweak production interfering with NLO QCD:

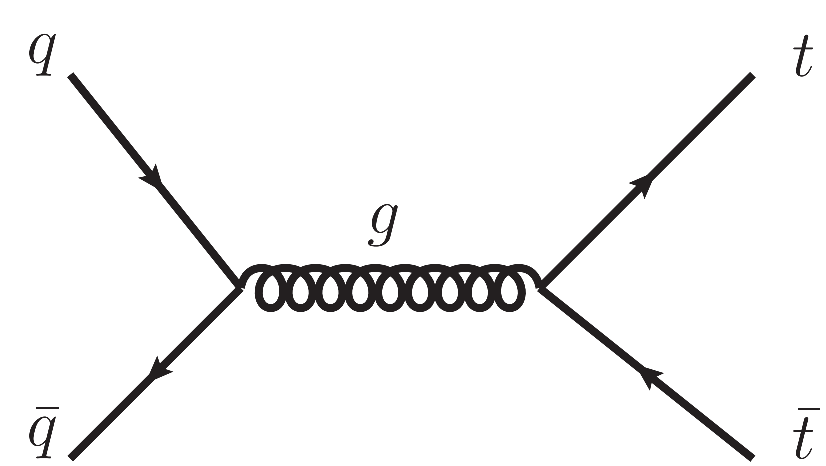


+



- Q: Why no interference between:



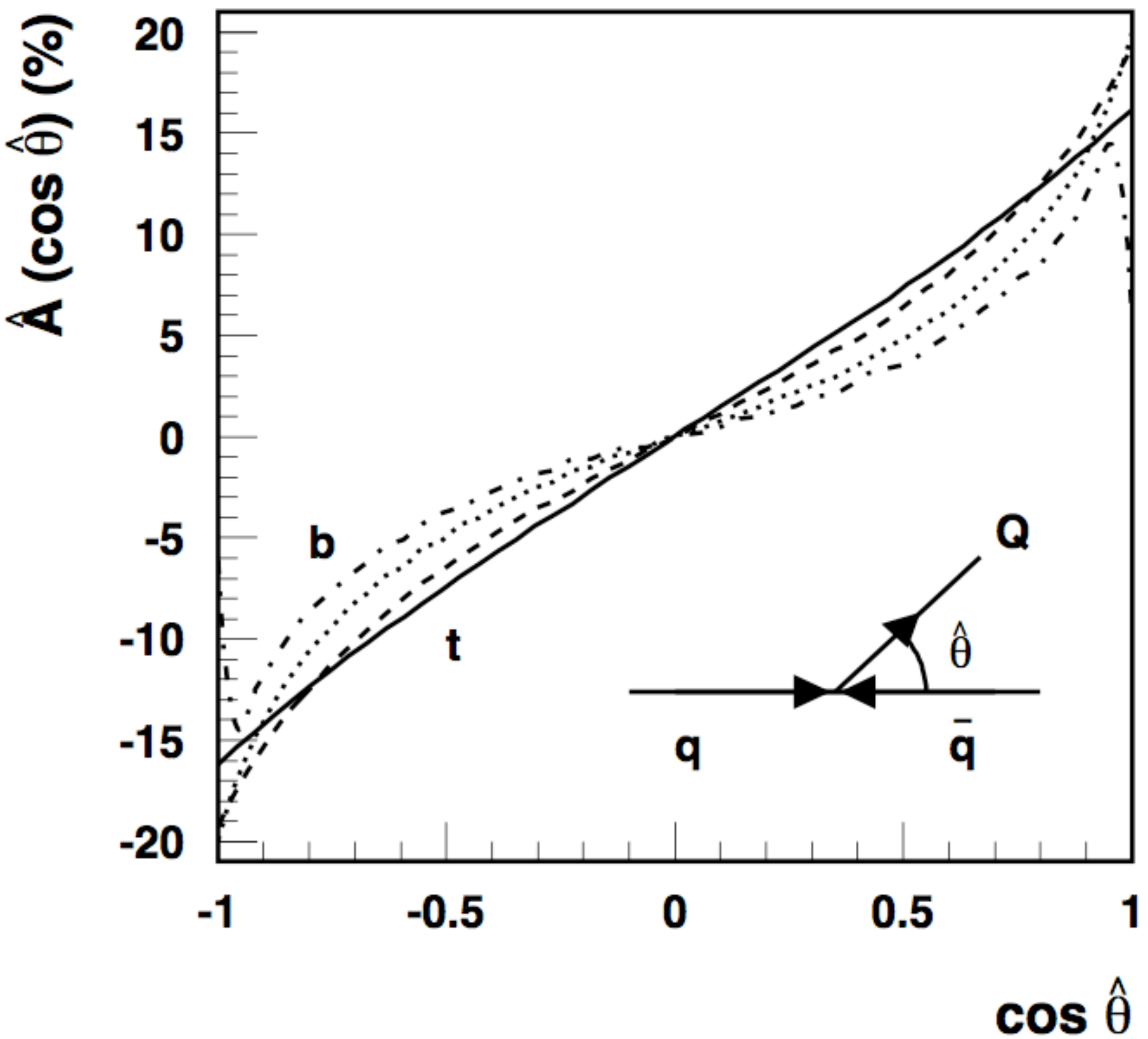


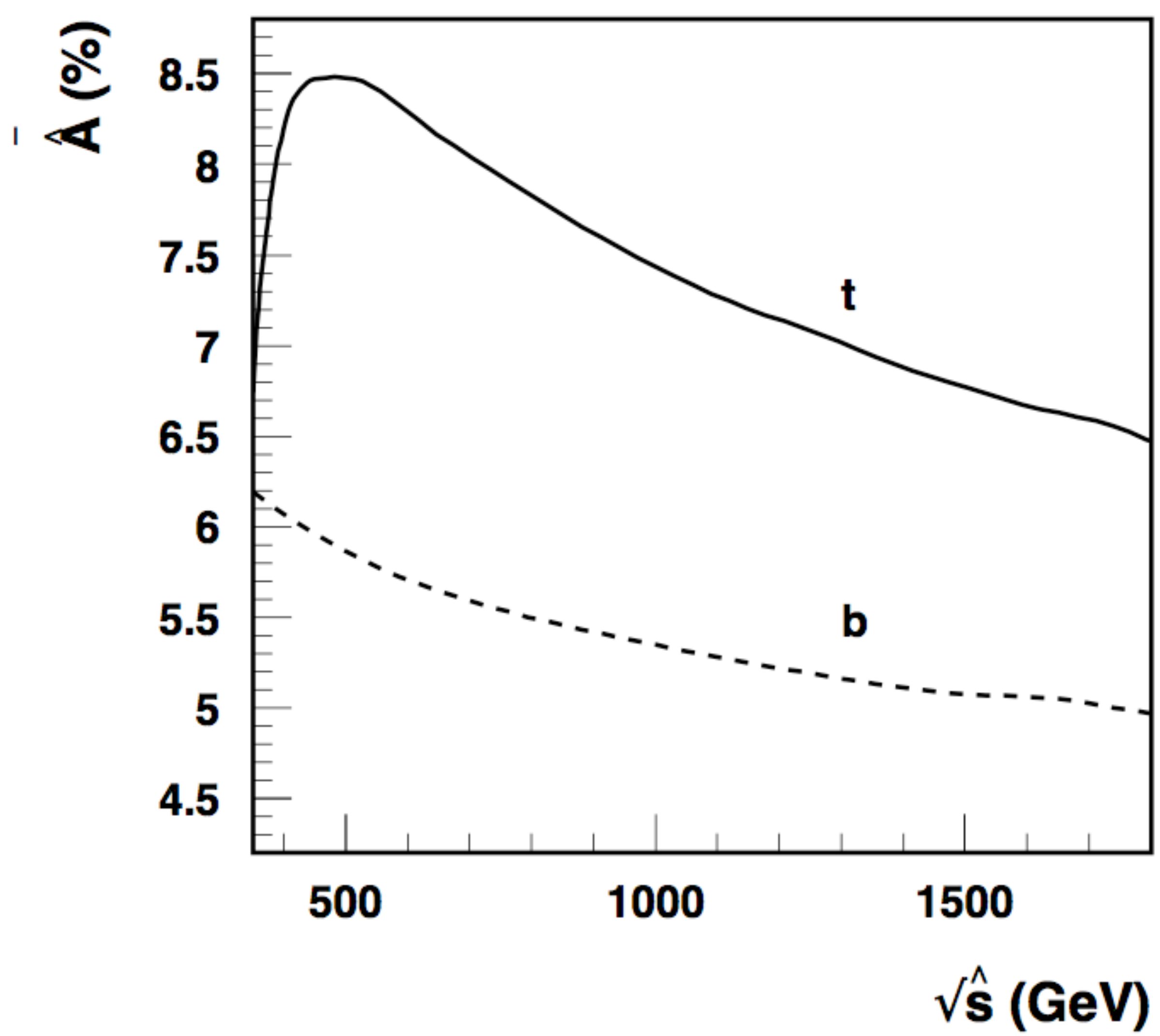
Forward Backward Asymmetry in SM

- SM prediction:

$$\hat{A}(\cos\theta) = \frac{N_t(\cos\theta) - N_{\bar{t}}(\cos\theta)}{N_t(\cos\theta) + N_{\bar{t}}(\cos\theta)}$$

$$\bar{\hat{A}} = \frac{N_t(\cos\theta \geq 0) - N_{\bar{t}}(\cos\theta \geq 0)}{N_t(\cos\theta \geq 0) + N_{\bar{t}}(\cos\theta \geq 0)}$$

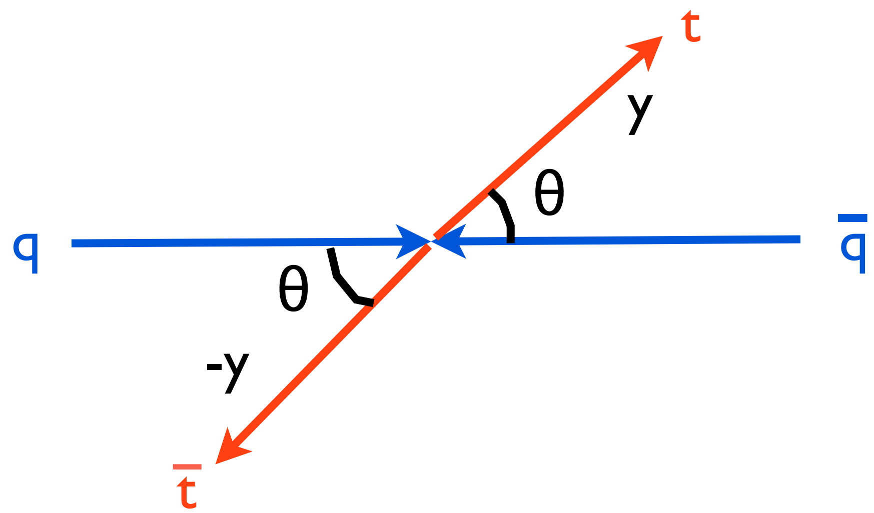




Kuhn & Rodrigo, Phys.Rev. D59 (1999) 054017

Measuring Forward Backward Asymmetry

- Forward-backward asymmetry also visible in asymmetry in difference in rapidity between tops:



$$\mathrm{y} = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

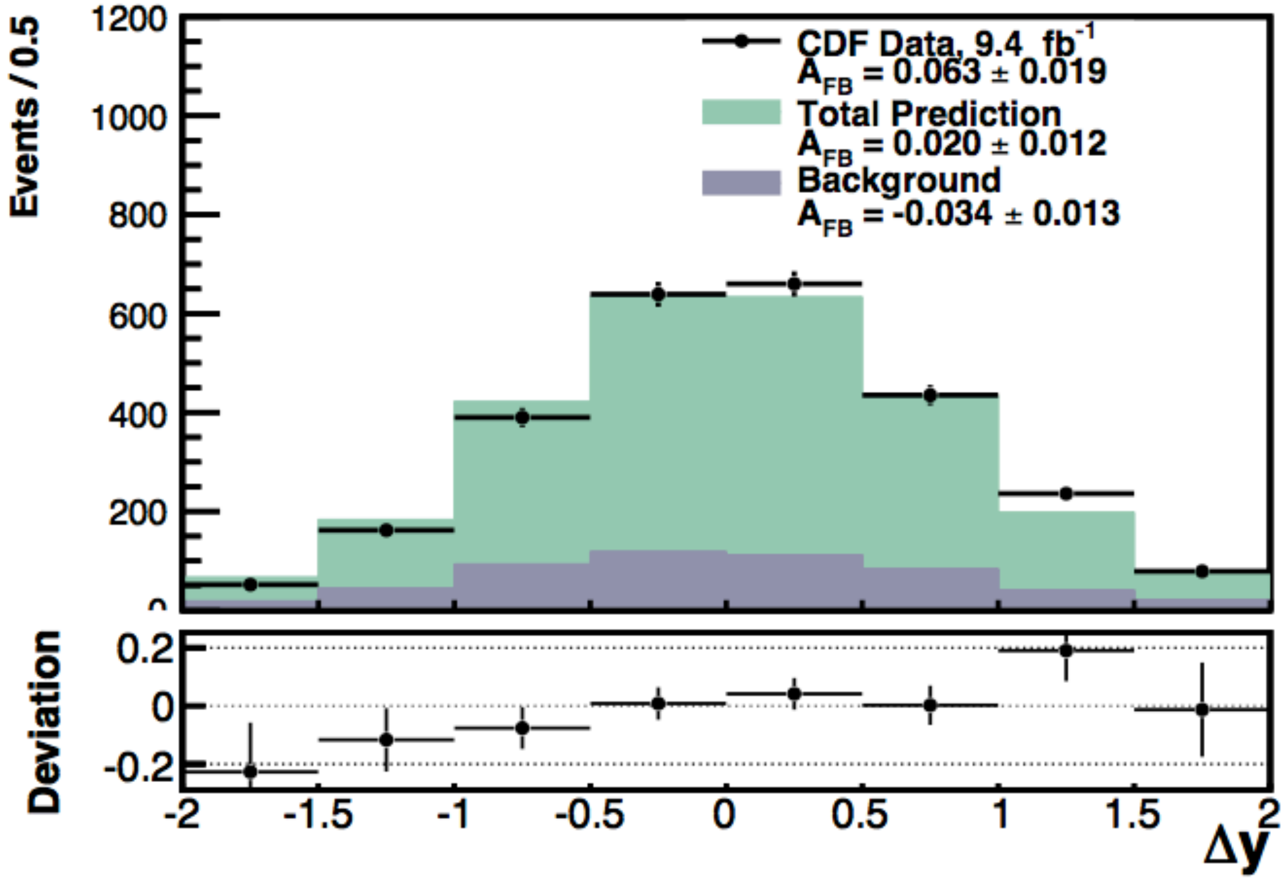
partonic CMF: $\Delta y = y_t - y_{\bar{t}} = 2y$

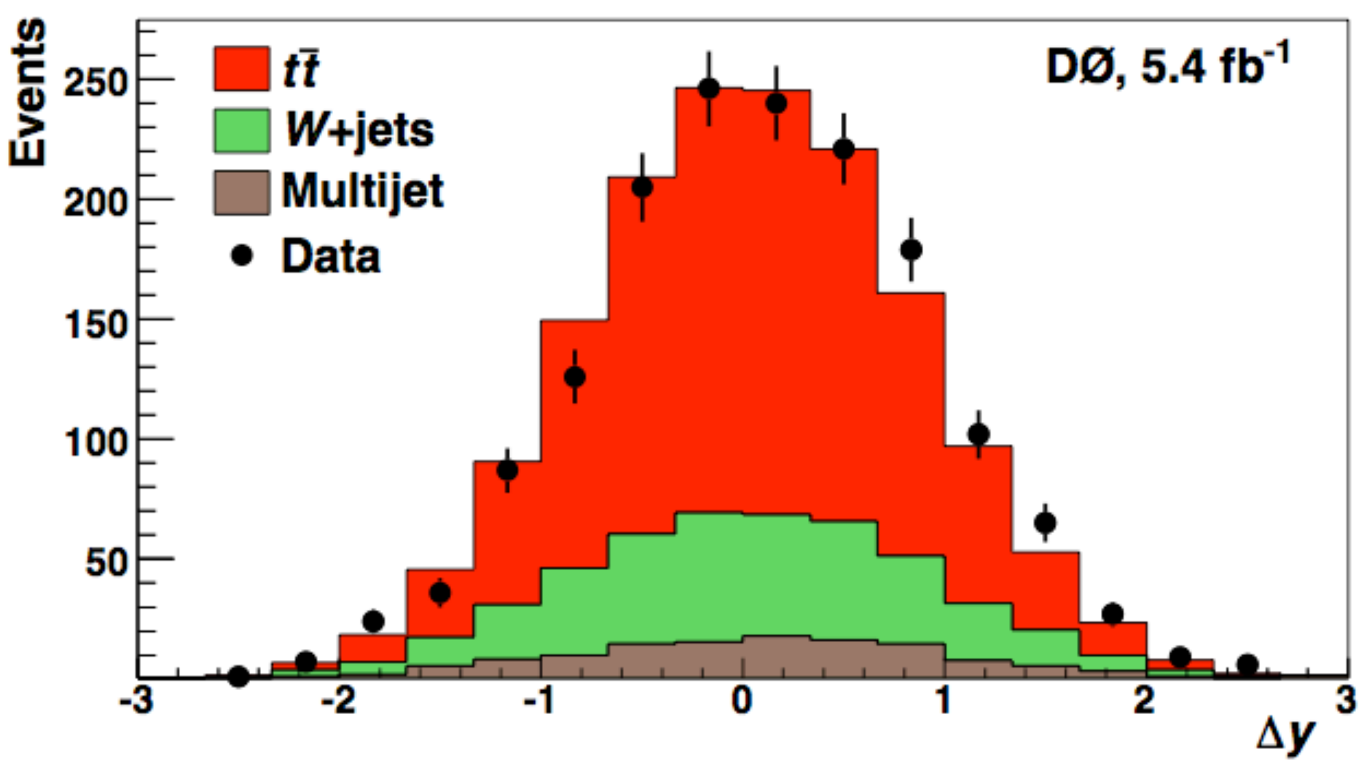
- Differences in rapidity are invariant under lorentz boosts
  - Measure asymmetry for Δy in lab frame:

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

Tevatron Afb

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





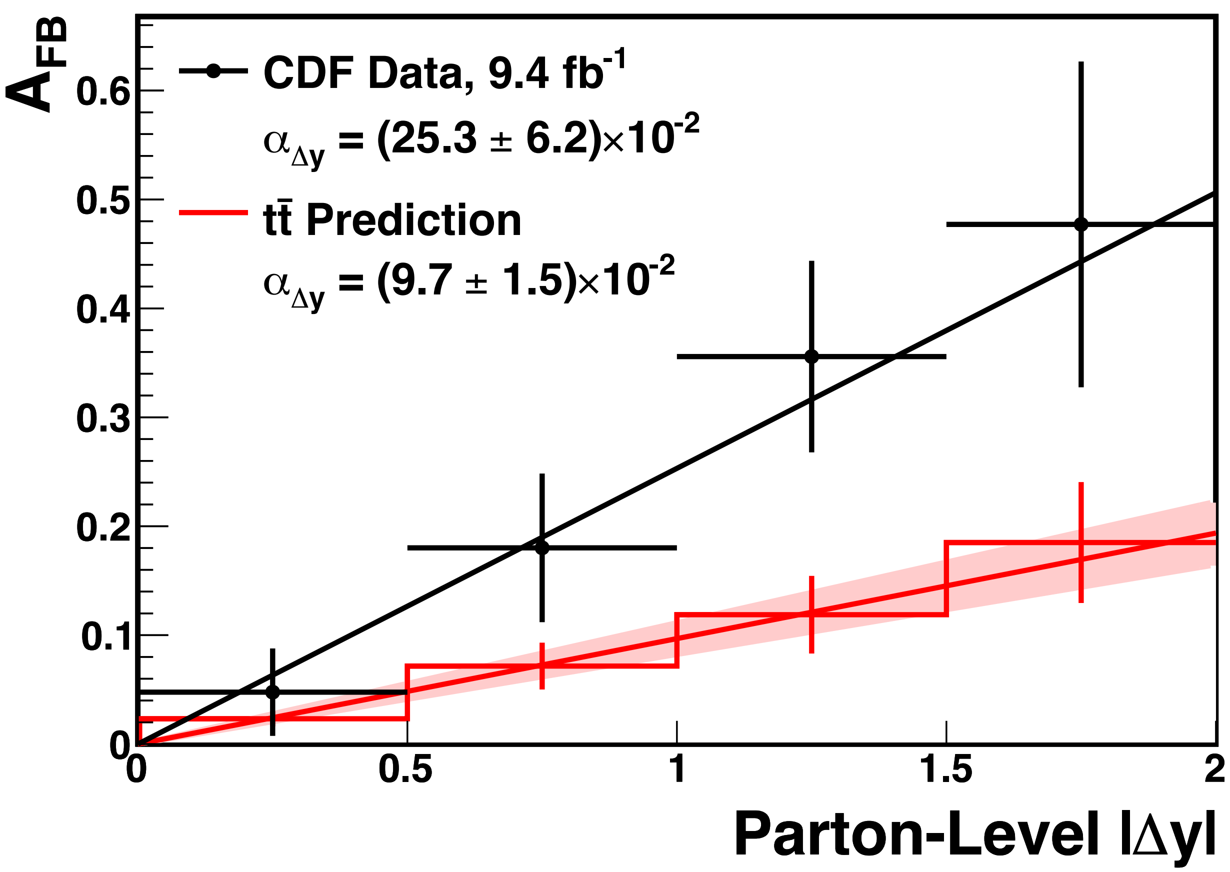
A_{FB} = 0.164 ± 0.047

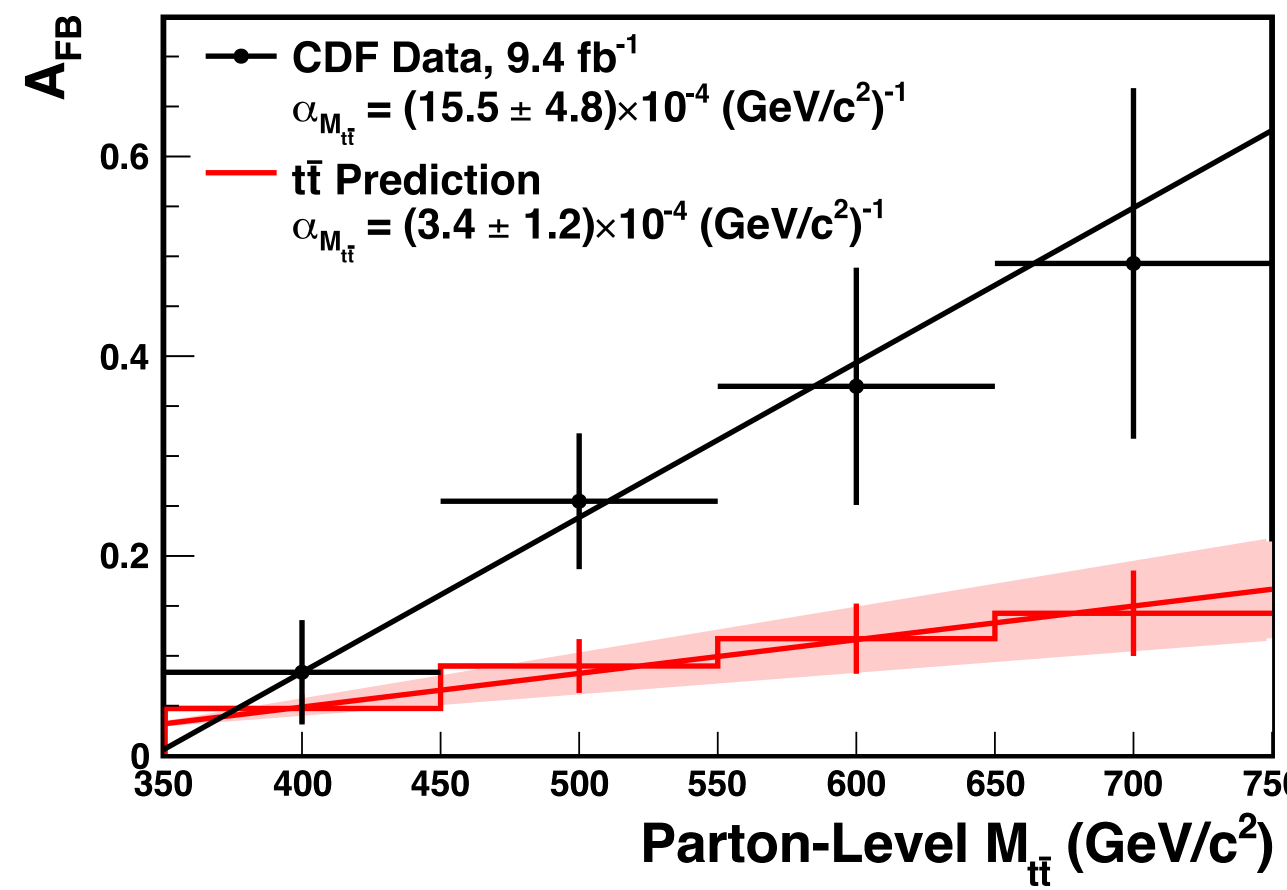
A_{FB} = 0.196 ± 0.065

$A_{FB}(SM) \approx$ 0.05-0.09

CDF Afb

- Significant dependence on mass and rapidity seen in CDF analysis:

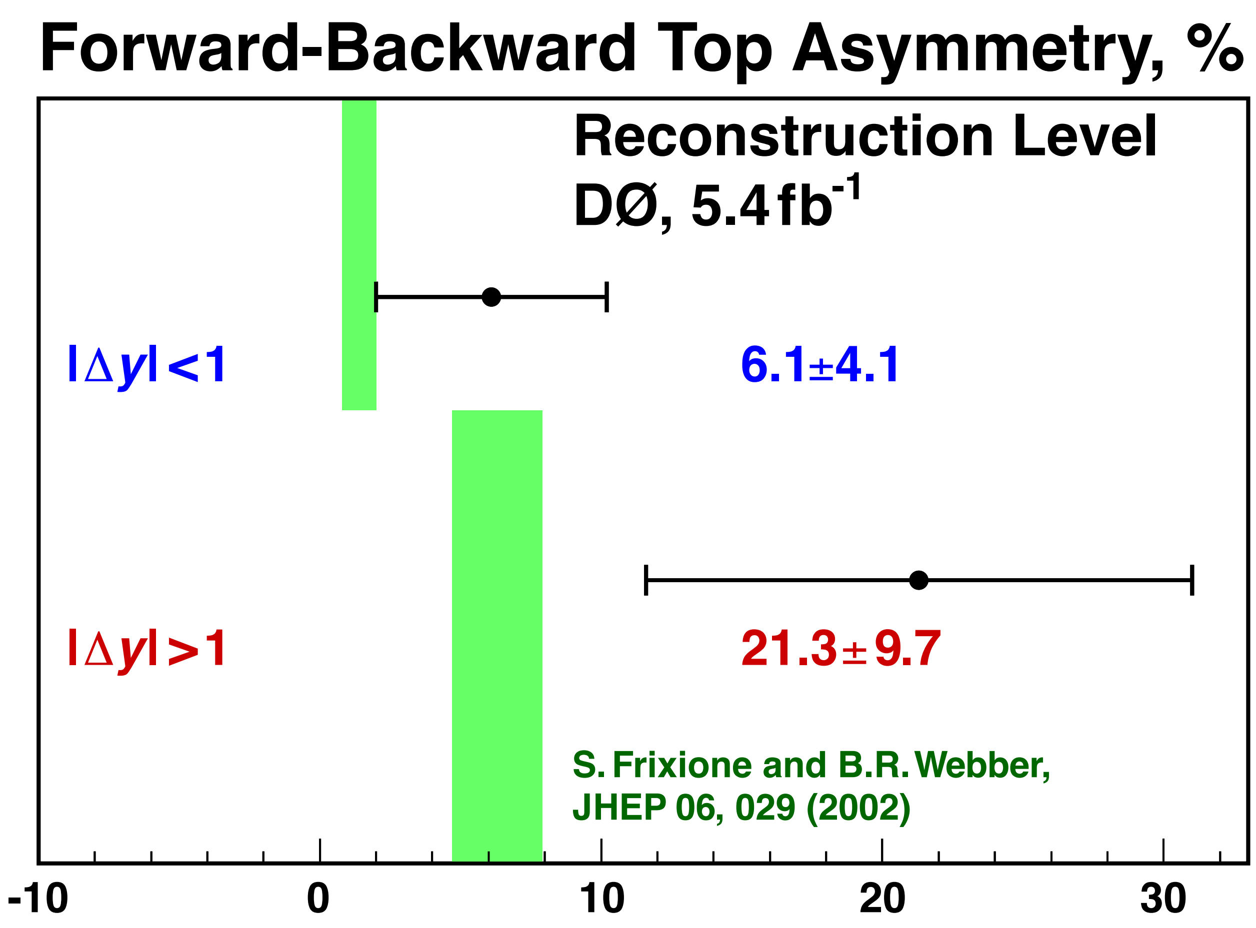


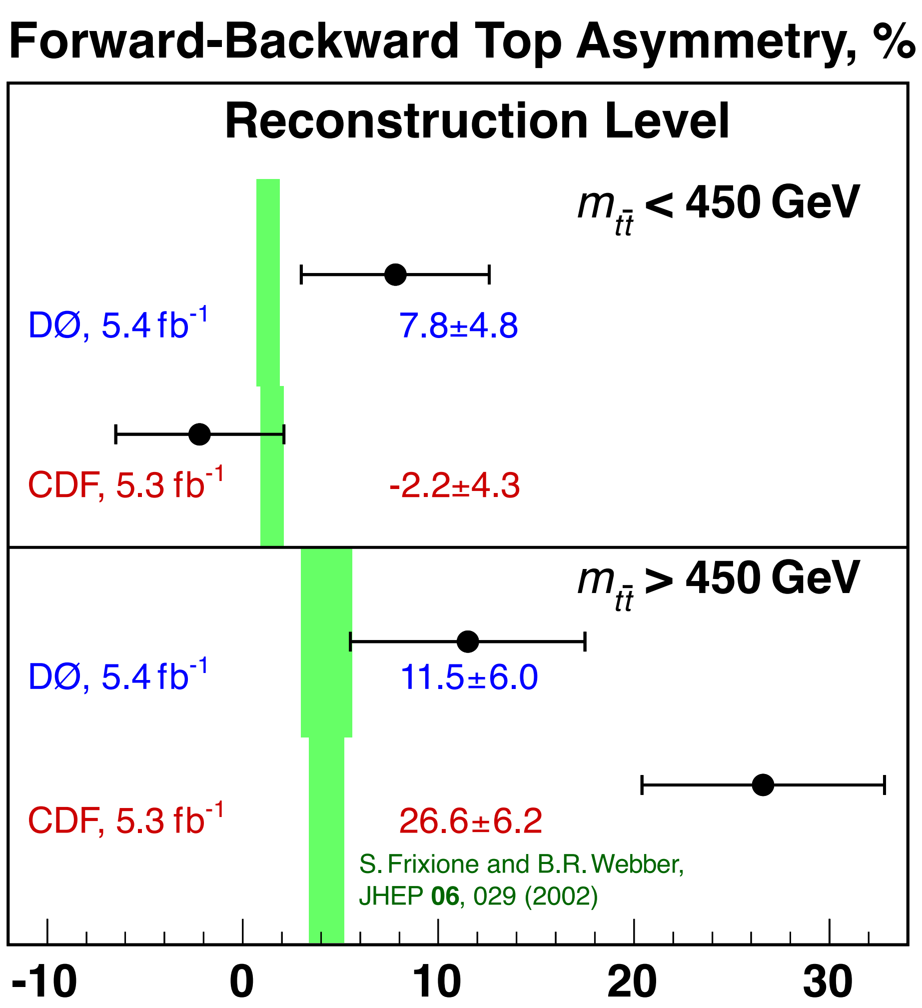


2.8σ & 2.4σ disagreement with SM prediction

D0 Afb

- Significant dependence on mass and rapidity in D0 analysis is not statistically significant:

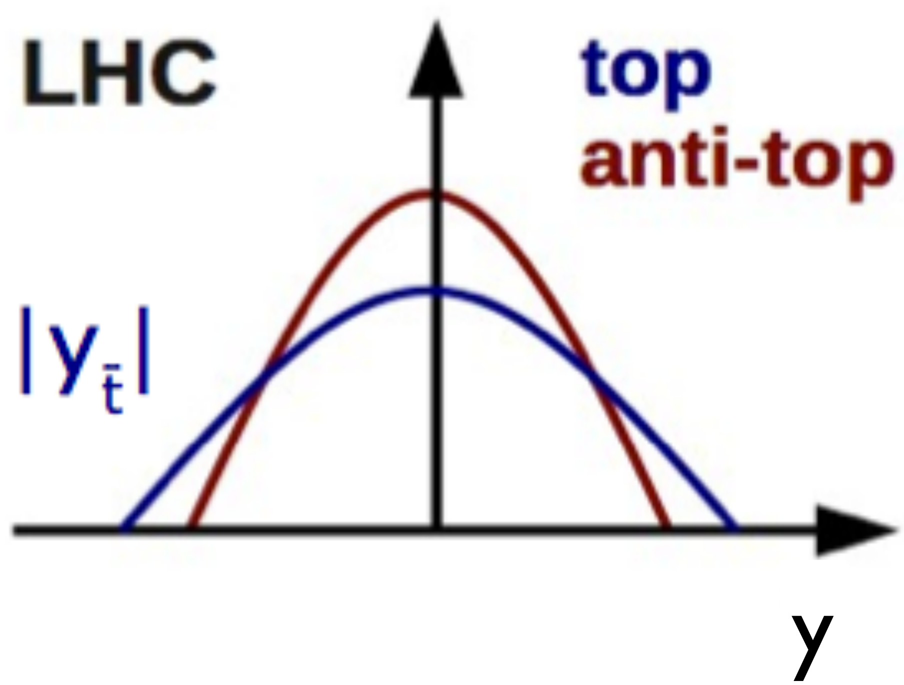




Need to investigate with LHC data!

Asymmetry at LHC

- Two difficulties at LHC for measuring Afb:
  - LHC dominated by gluon-gluon fusion - while asymmetry comes from interference of quark anti-quark diagrams.
  - Collisions are symmetric (proton-proton) - cannot define asymmetry in same way.
- Same physics can be seen in 'charge asymmetry':



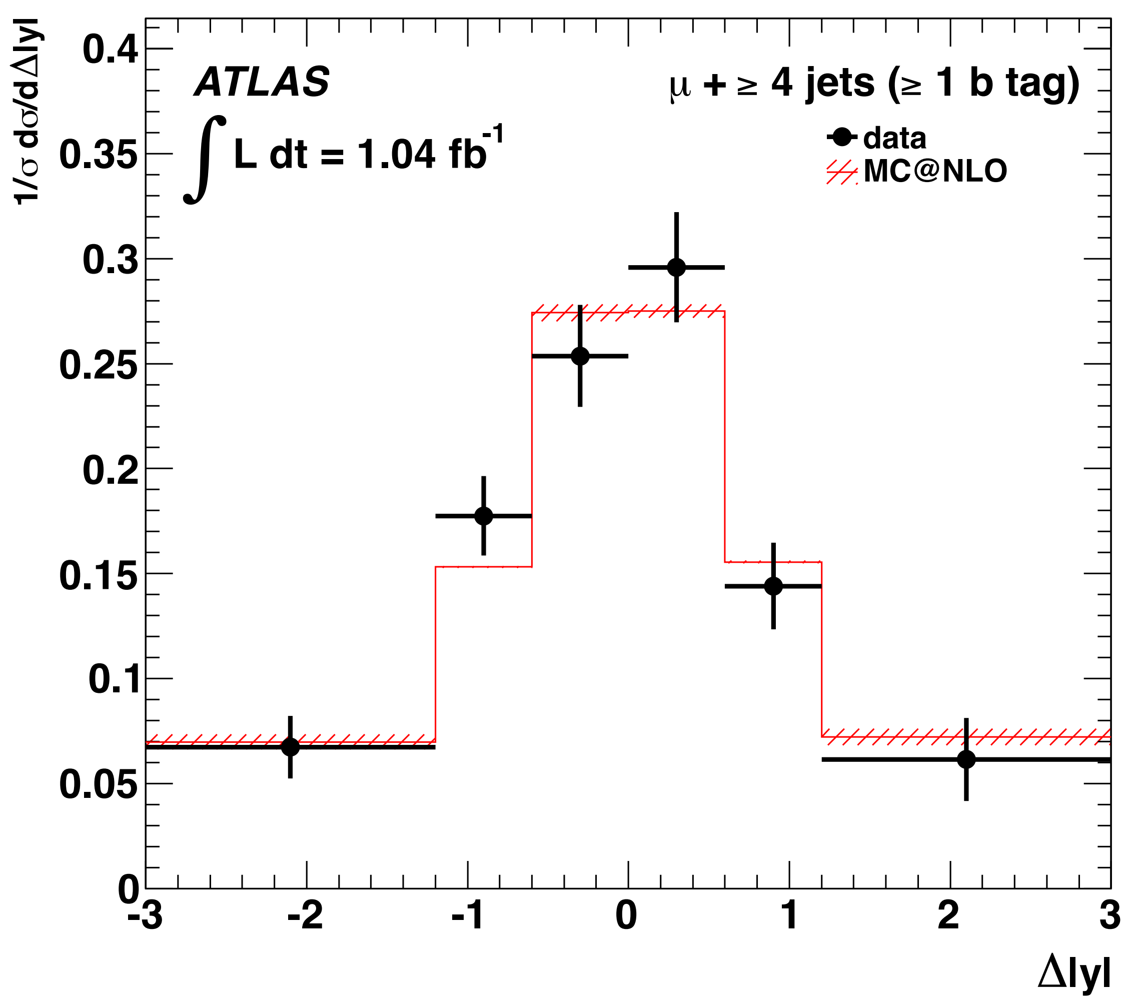
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

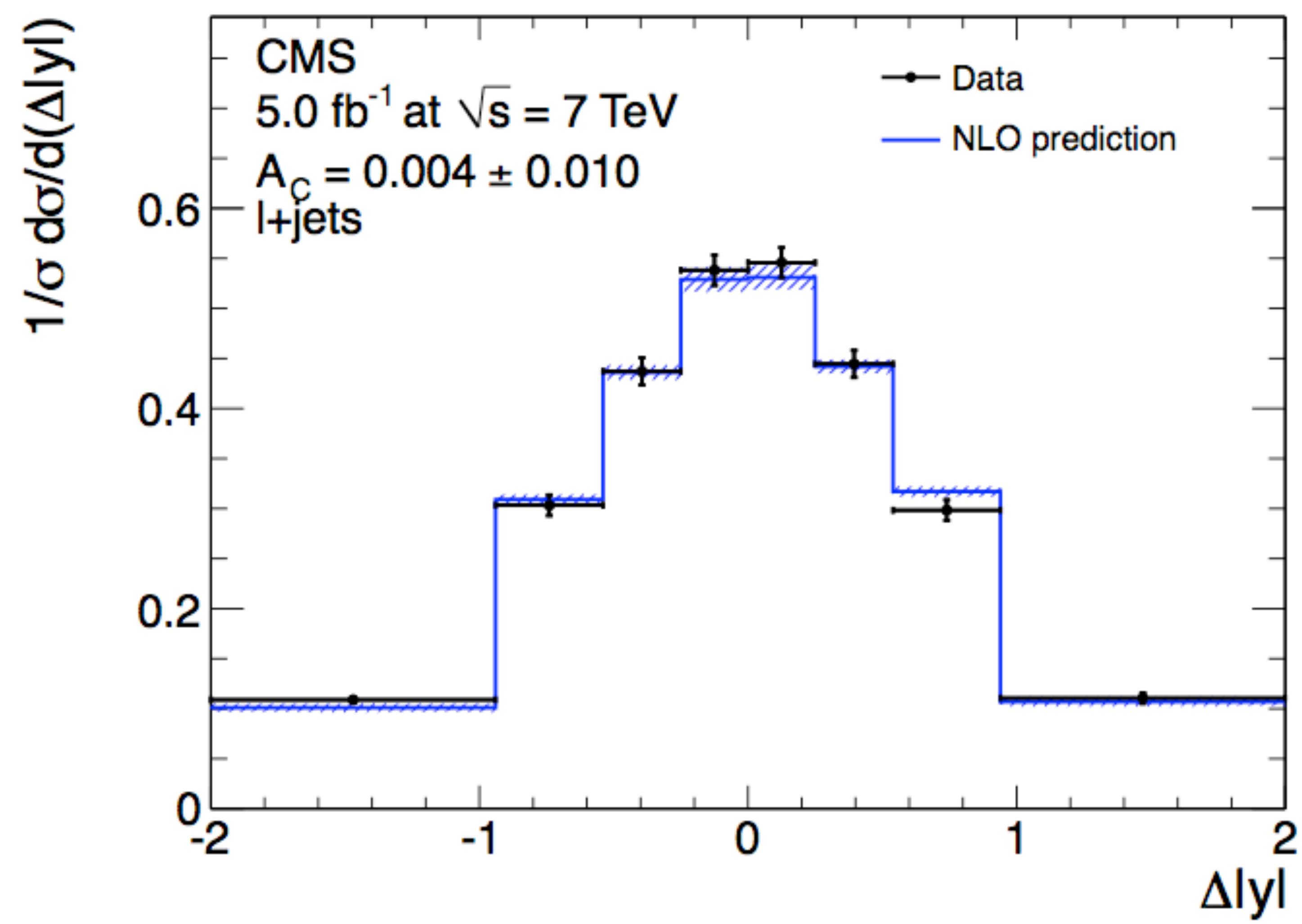
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

Asymmetry at LHC

- ATLAS & CMS measurements:

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





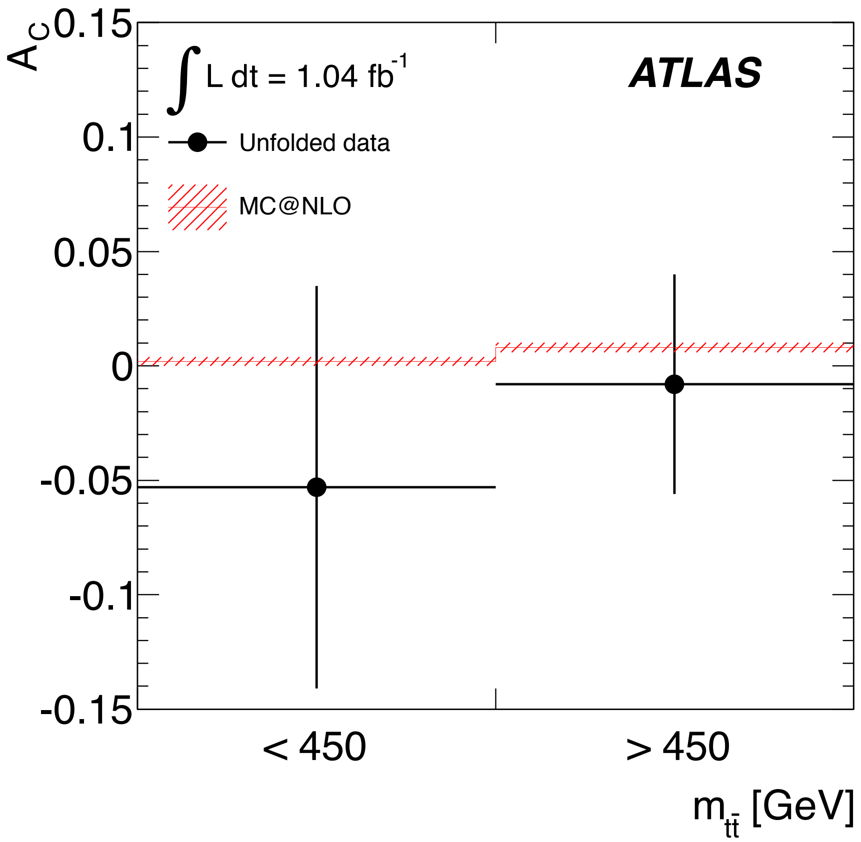
$A_C = -0.019 \pm 0.037$

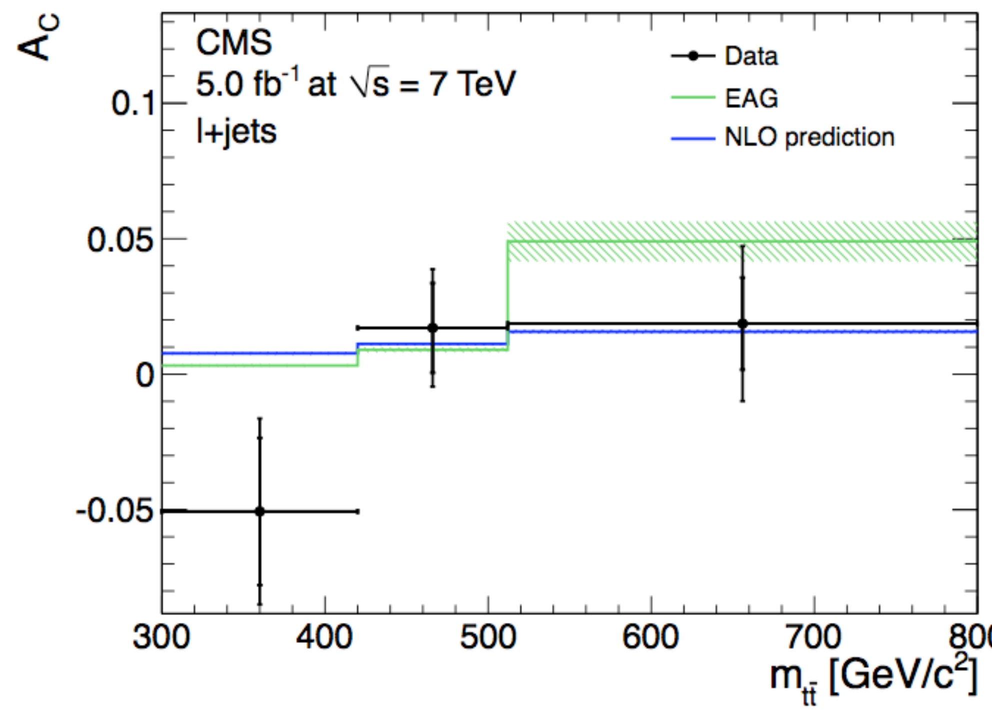
$A_C = 0.004 \pm 0.01$

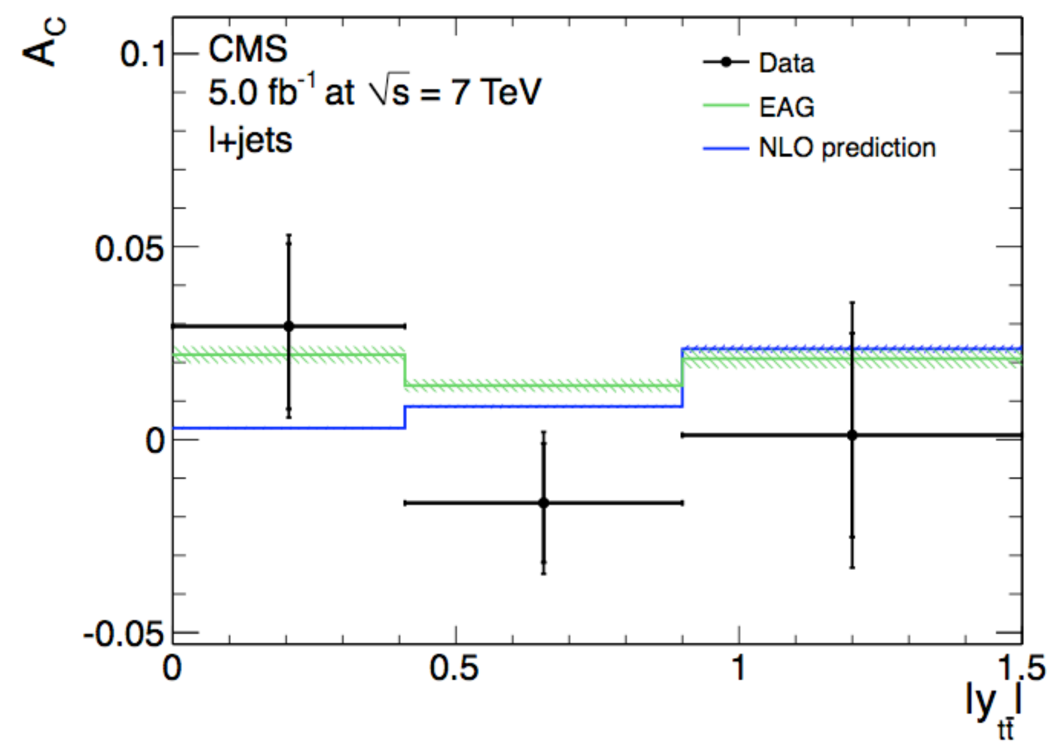
Good agreement with SM

Asymmetry at LHC

- ATLAS & CMS measurements vs invariant mass & rapidity of ttbar system:



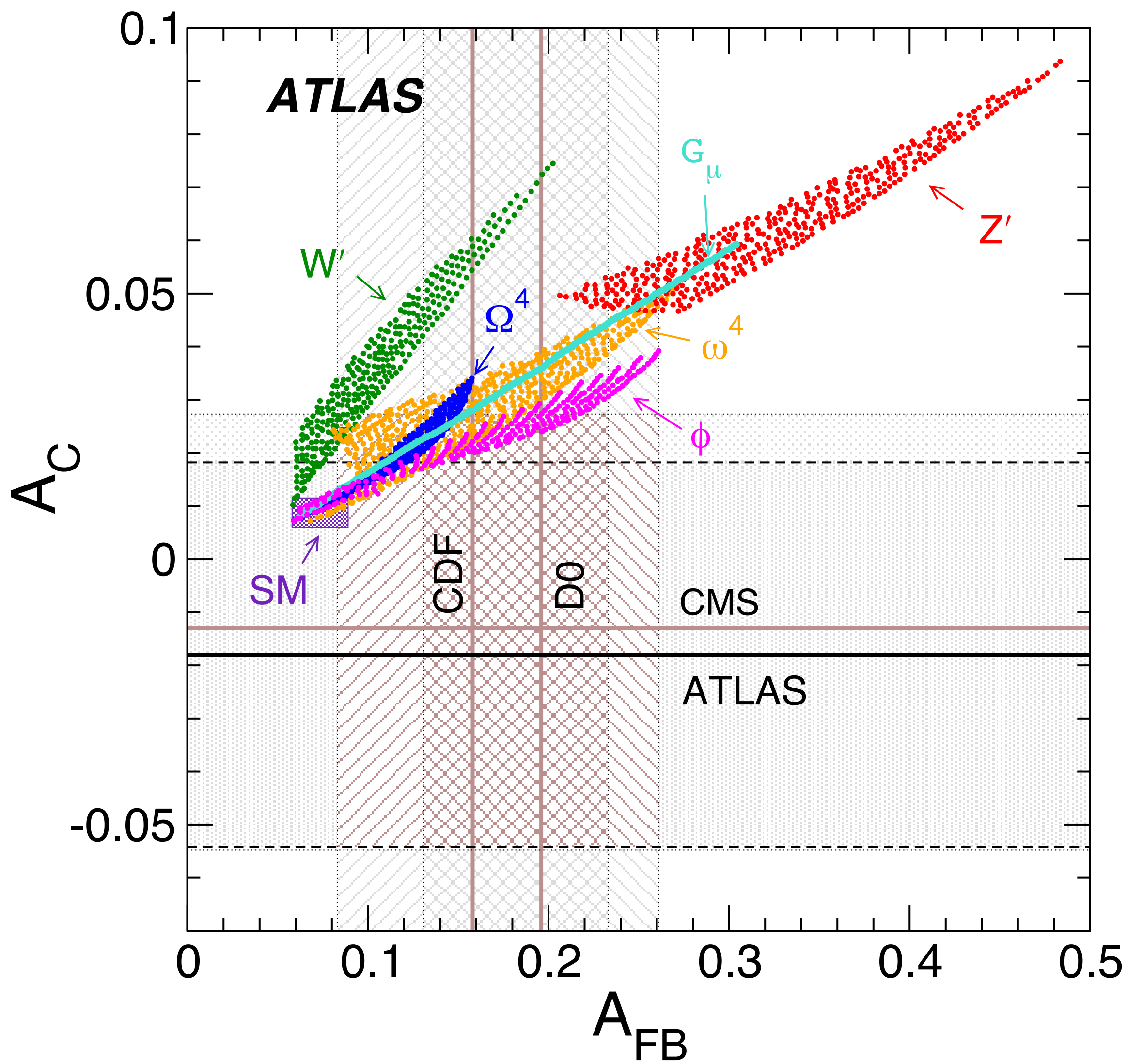




Good agreement with SM

Tevatron vs LHC

- Tevatron & LHC measure different quantities - can only compare in the context of real new physics models:



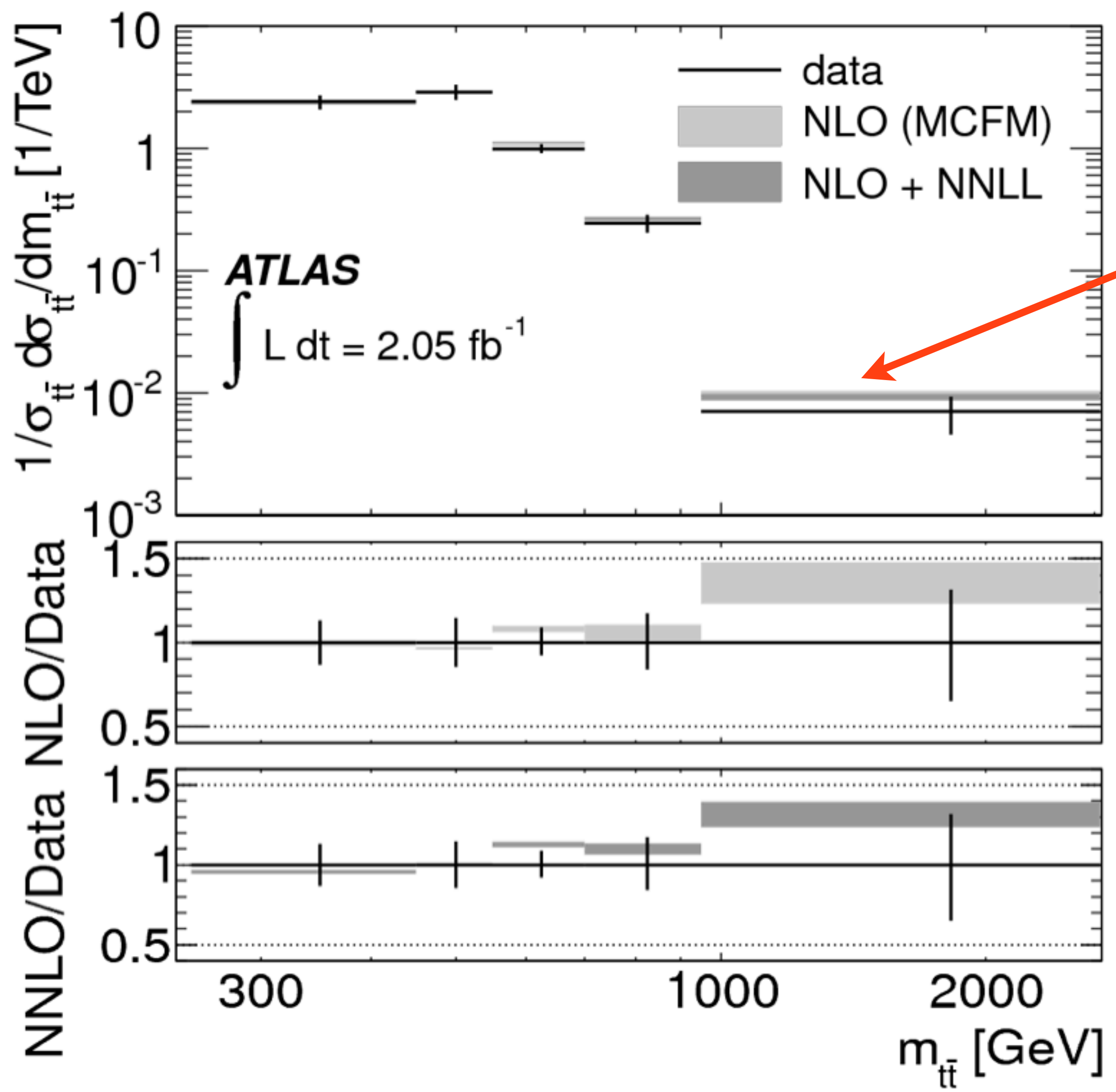
- Some models are excluded - some survive (‘natural selection’!).
- More data & more differential measurements needed.

Top Properties:

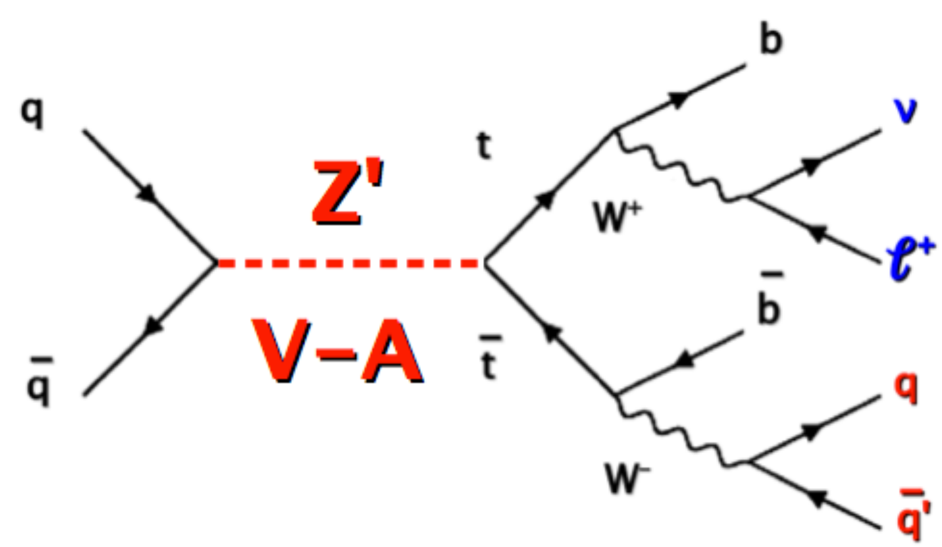
Top quark mass
Top spin correlations
Forward-backward asymmetry
Boosted tops

High pT tops

- Recall the differential measurement of the invariant mass of top pairs:

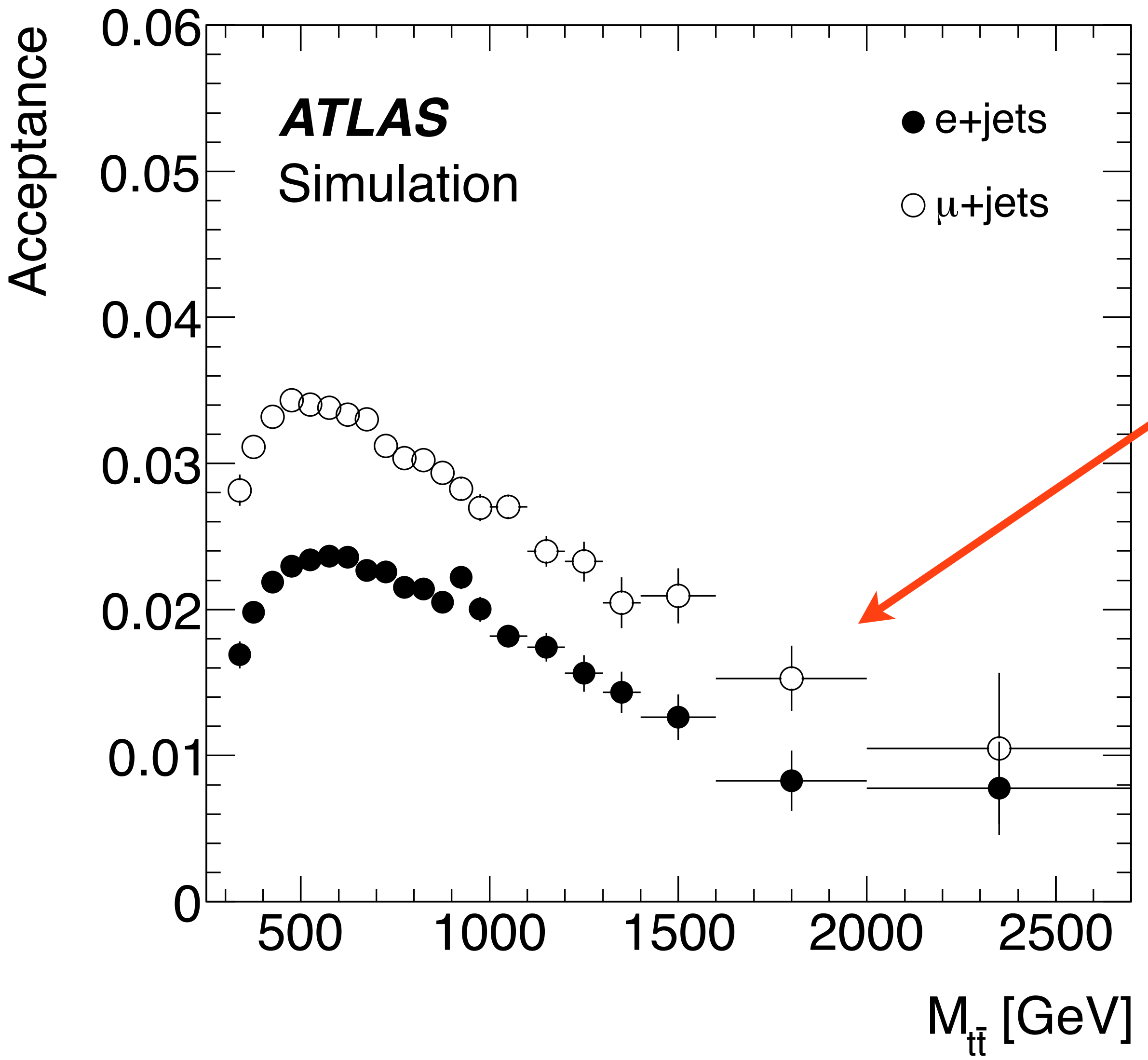


Could see new physics at high invariant mass.



High pT tops

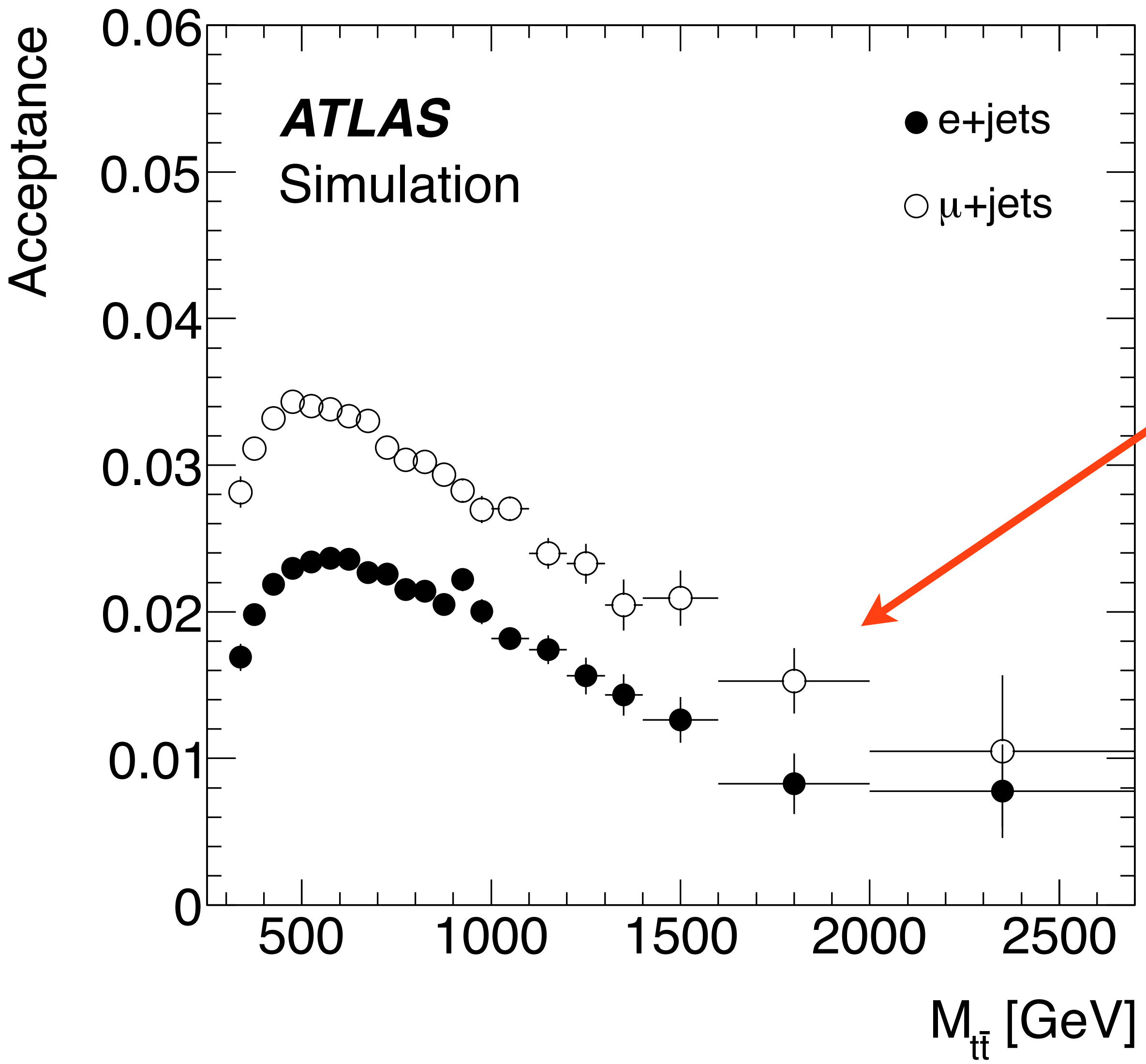
- Efficiency to select top events in ATLAS analysis:



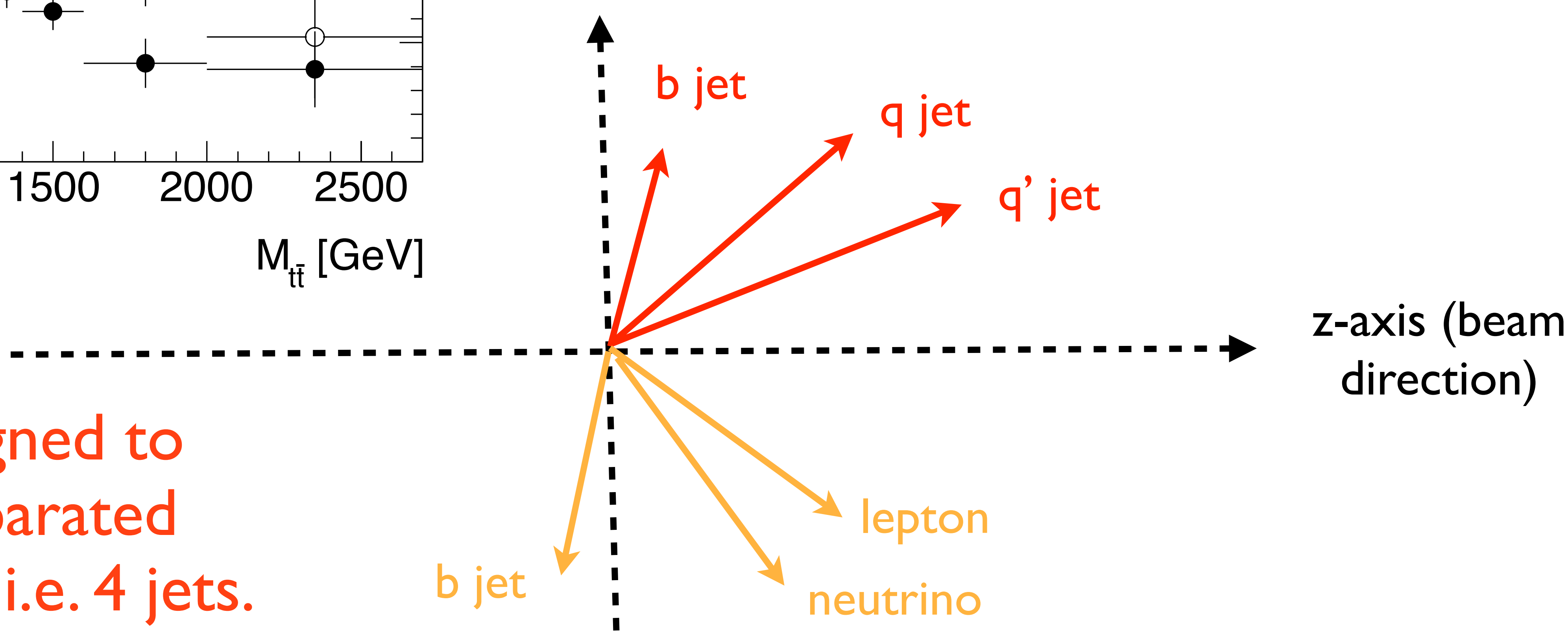
Efficiency drops at high mass!

High p_T tops

- Efficiency to select top events in ATLAS analysis:



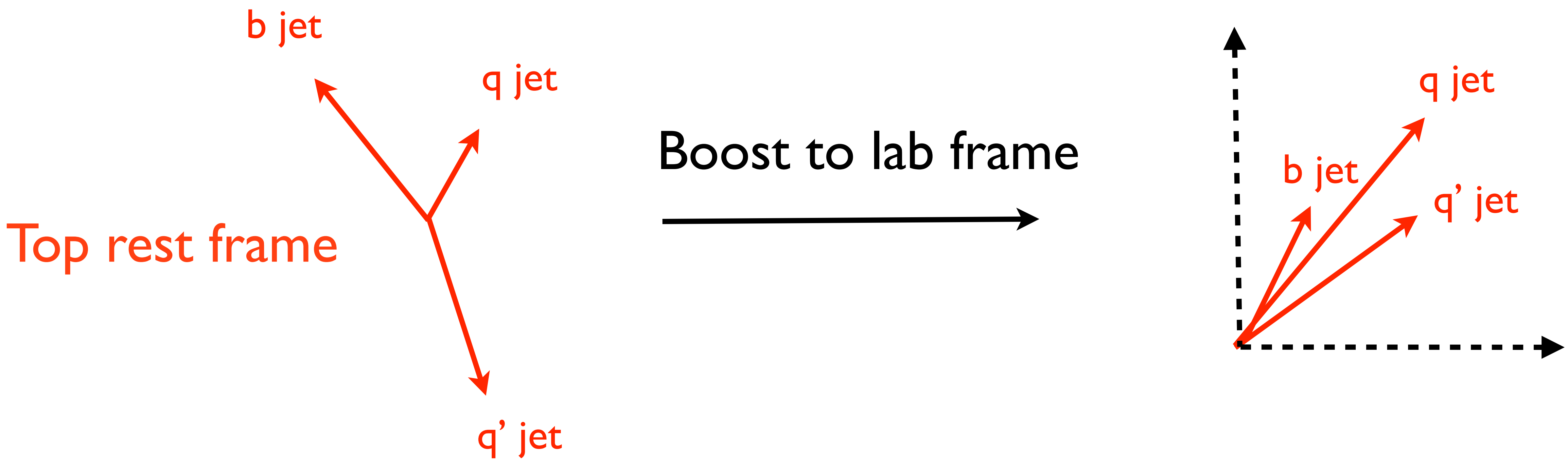
Efficiency drops at high mass!



Selection designed to select well separated decay products - i.e. 4 jets.

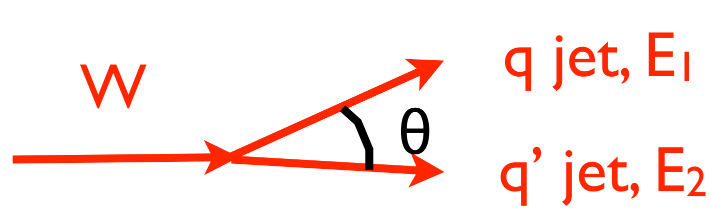
High p_T tops

- High mass, means large momentum tops - significant boost for decay products:



- Decay products not necessarily now in three separate jets.

For two body decay:

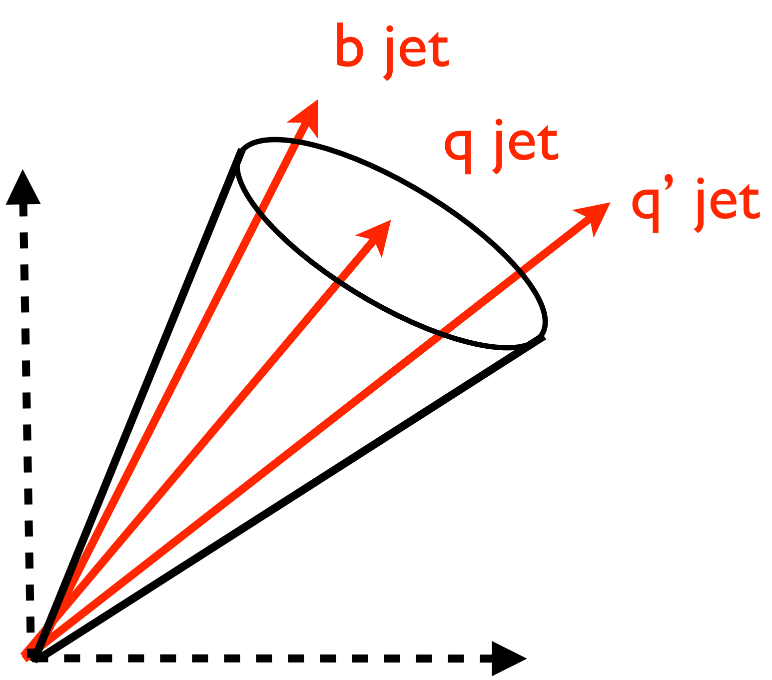


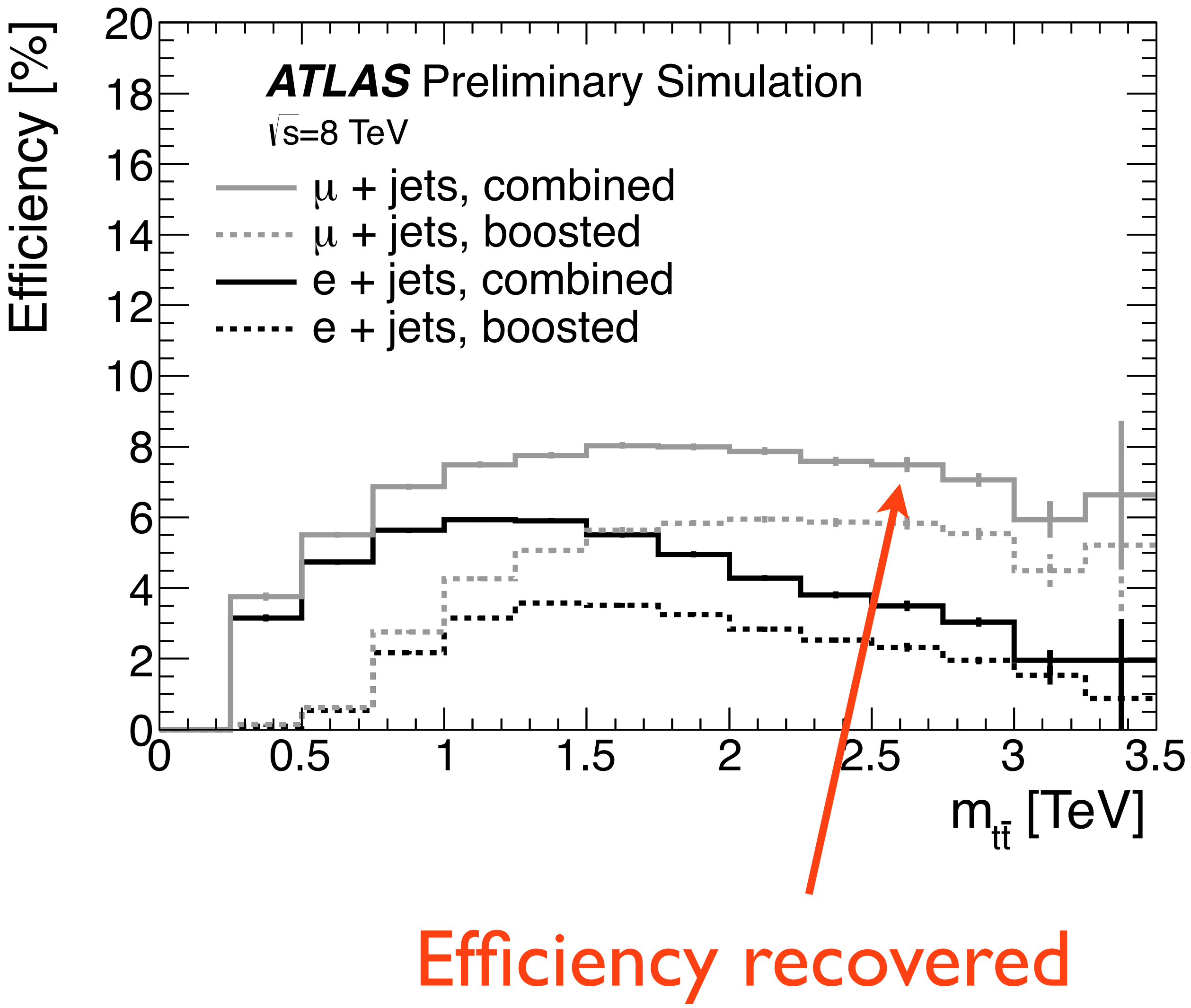
$$\theta \sim \frac{m_W}{\sqrt{E_1 E_2}}$$

(for small angles)

High p_T tops

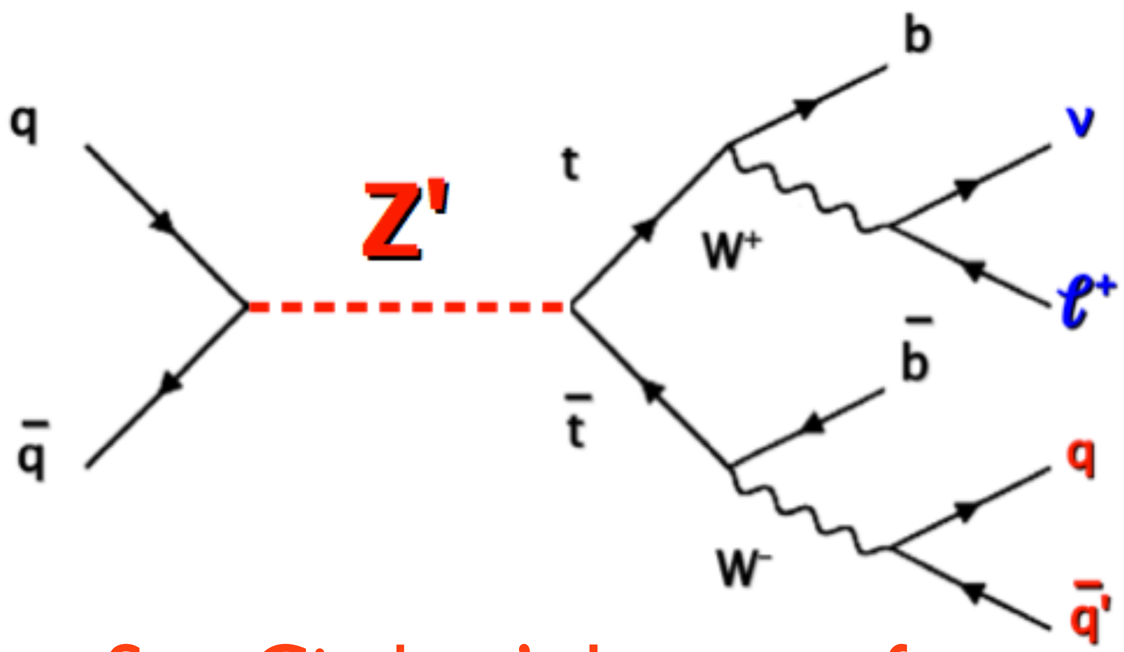
- Solution: Look for a single large-radius jet containing all the top decay products:



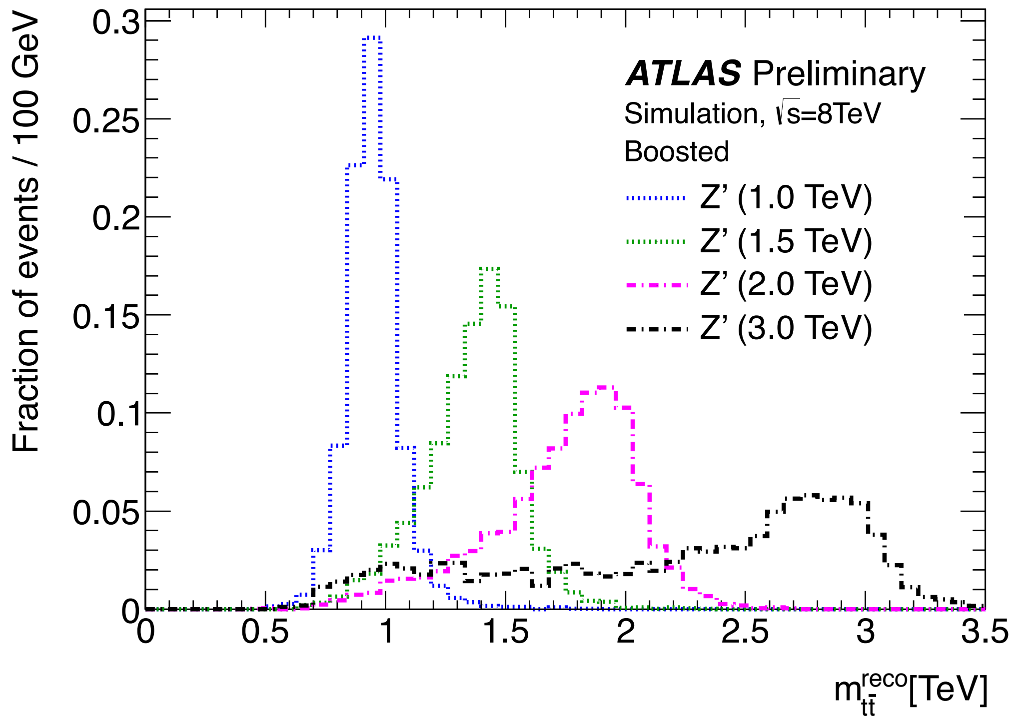


High p_T tops

- Physics with high pT tops - so far mainly searches:



See Cigdem's lectures for dedicated searches with top



- Interesting to start making measurements of boosted tops at high p_T and compare with QCD calculations.

Summary

- Top quark provides a unique window on QCD & EW physics.
- Many ongoing analyses - all try to ask the question: is the top quark we see the quark predicted in SM:
    - Top mass: so far consistent with W & Higgs boson masses.
    - Spin correlations: first non-zero observation from ATLAS - we really see a ‘bare’ quark before it decays.
    - Forward-backward asymmetry: Some deviation from SM in Tevatron experiments - not confirmed by LHC measurements.
- So far top looks SM like.
- 8 TeV LHC data sample still under analysis - lots of interesting results still to come & then more tops to come at 14 TeV.

Thanks to C. Schwanenberger for the graphics!

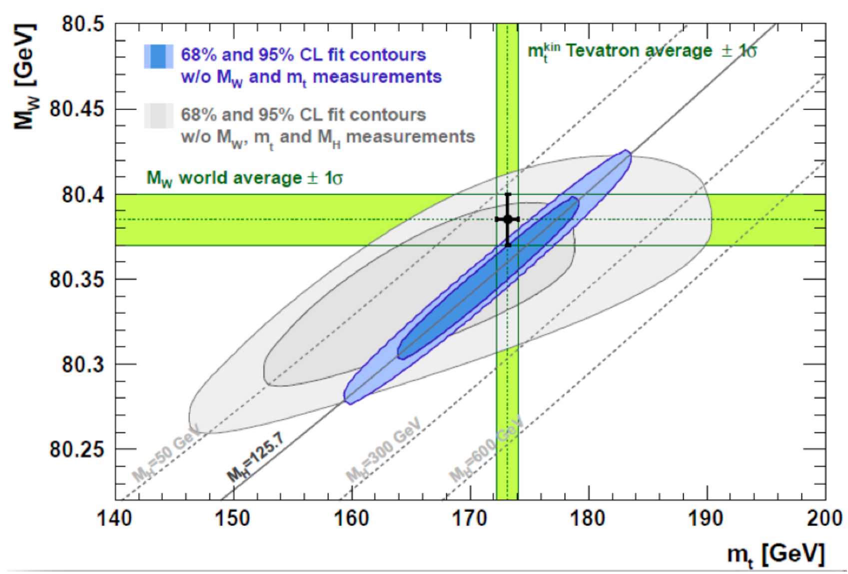
Backup

What mass do we measure?

- Top mass (or top Yukawa coupling) is free parameter in SM:

$$\mathcal{L}_t = \frac{f_t v}{\sqrt{2}} \left(\bar{t}_L t_R + \bar{t}_R t_L \right) \qquad\qquad m_t = -\frac{f_t v}{\sqrt{2}}$$

- At NLO mass becomes dependent on the renormalisation scale, μ.
- Concept of mass is scheme dependent - e.g. for the EW fit a particular renormalisation scheme is used.



What mass do we measure?

- Can write relations between the schemes:

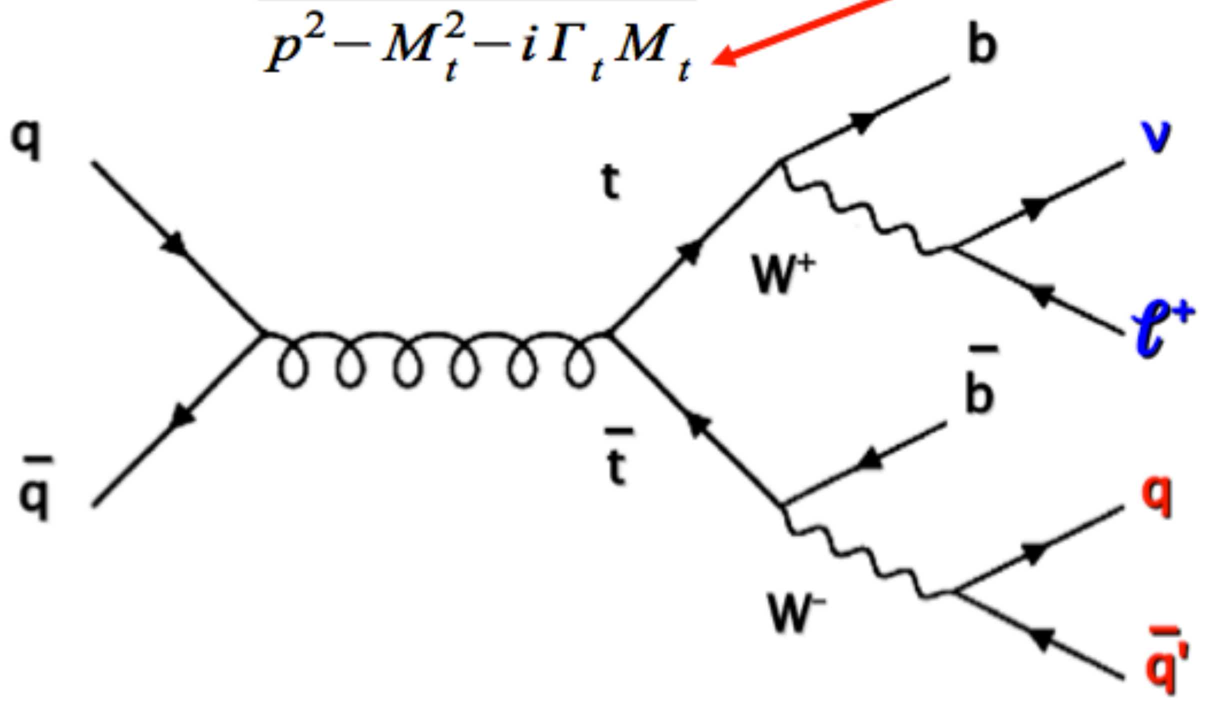
hep-ph/0001002

$$\overline{m}_t \equiv m_t^{\overline{\rm MS}}(m_t) = \frac{M_t}{1+\frac{4}{3\pi}\alpha_s(M_t)}$$

$\overline{\rm MS}$ scheme

pole mass

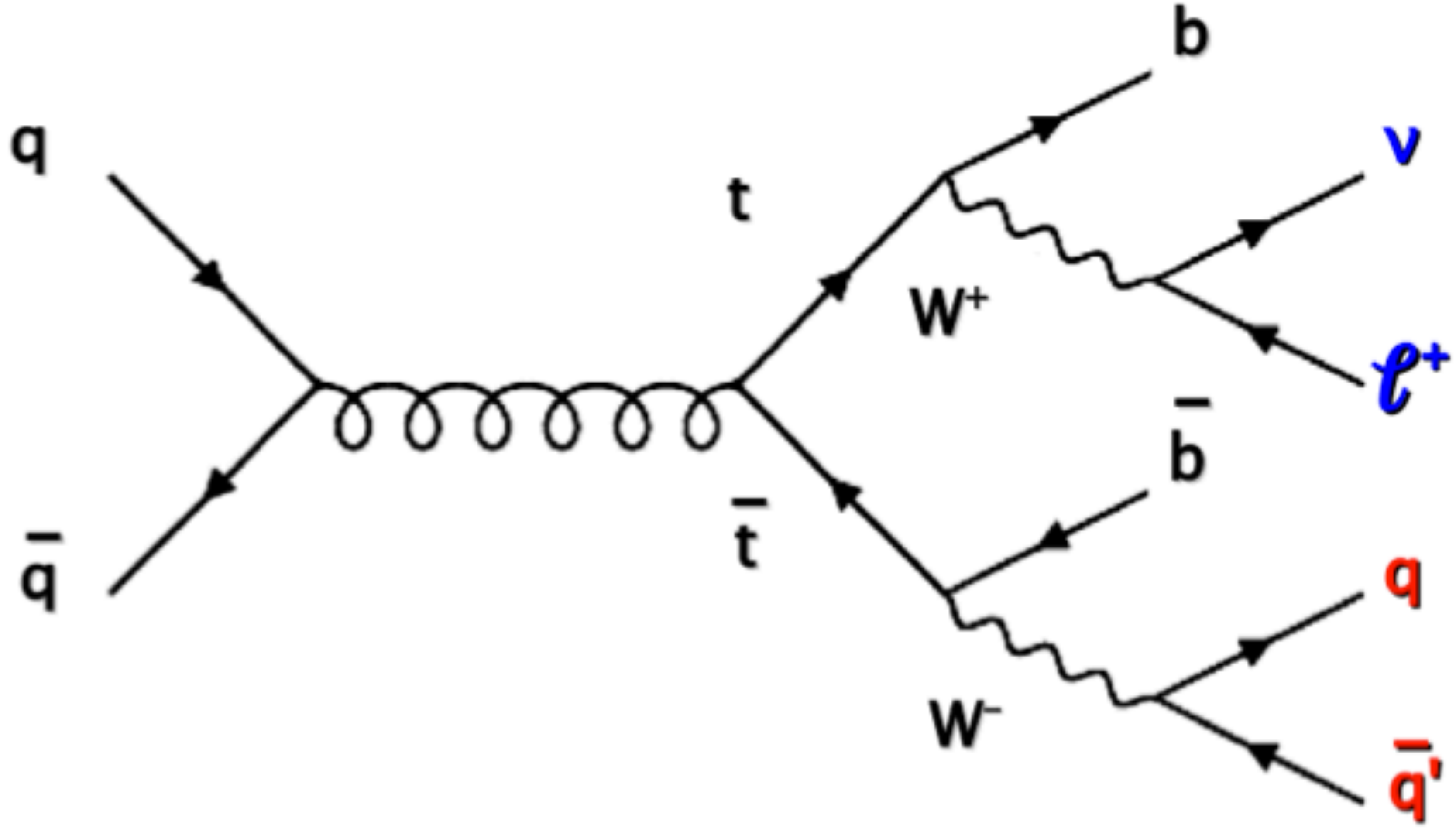
$$\frac{1}{p^2 - M_t^2 - i\Gamma_t M_t}$$



Need to know which scheme the MC uses.

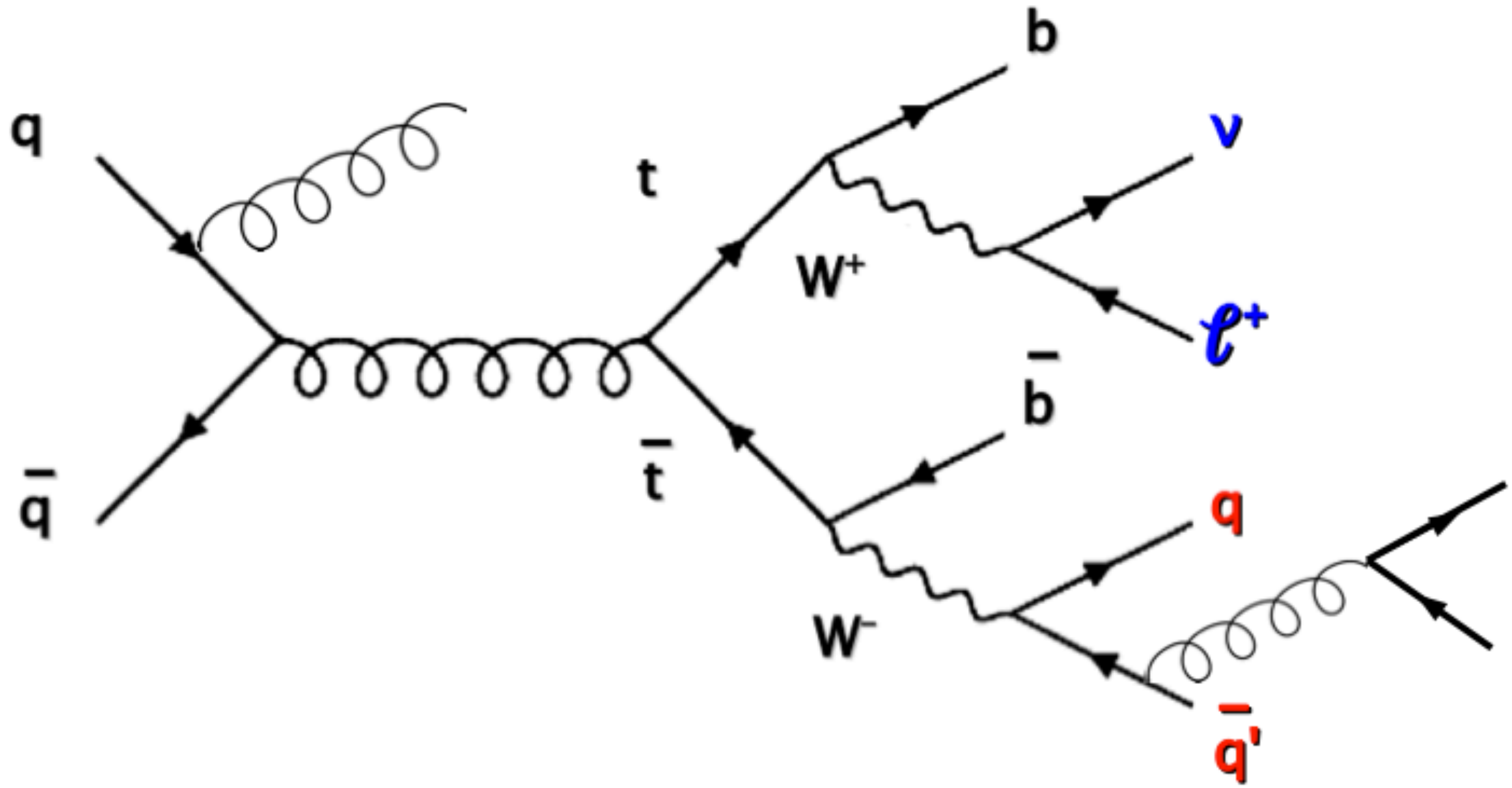
Which top mass is in LO MC?

- matrix element in LO QCD



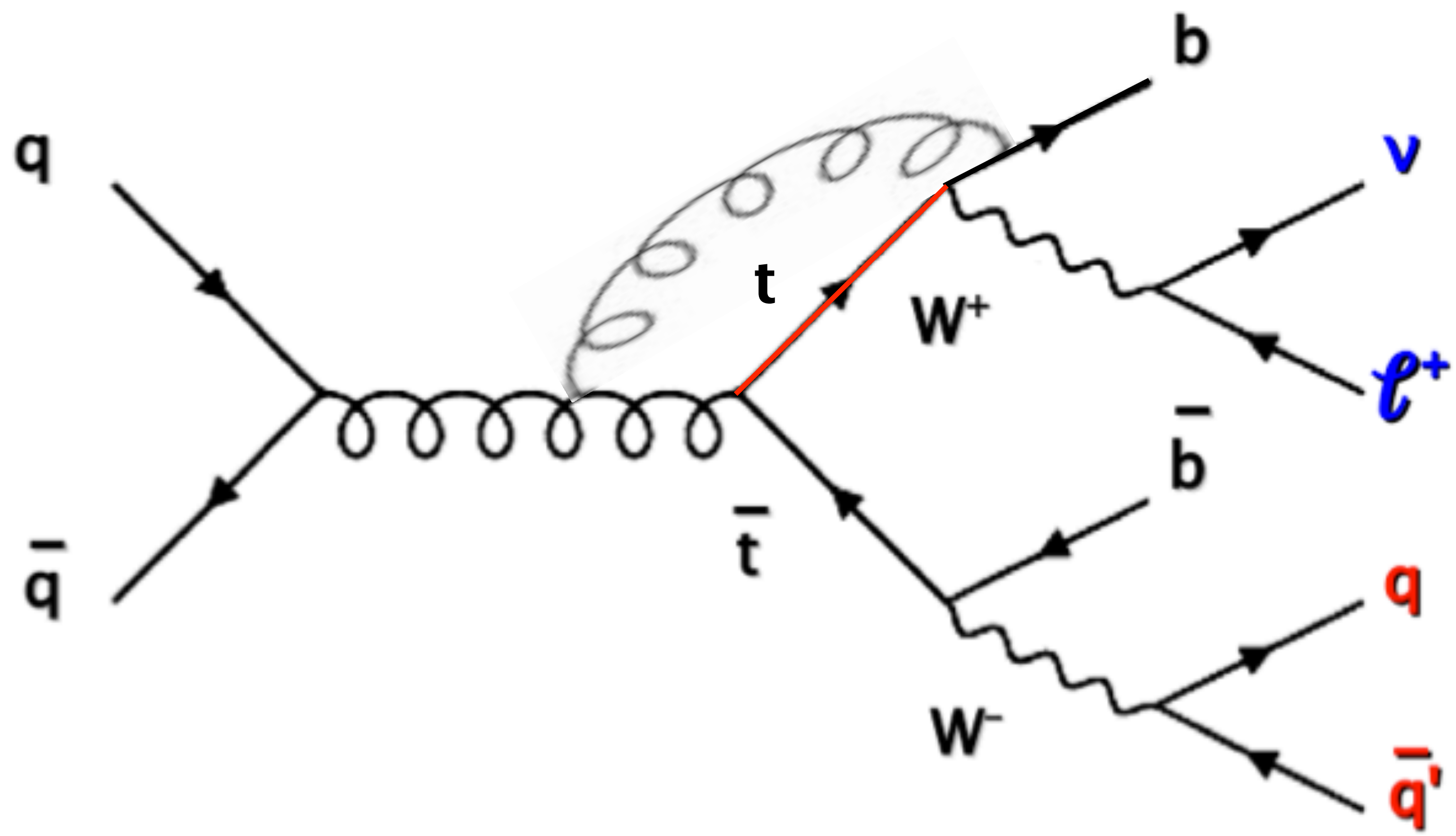
Which top mass is in LO MC?

- **matrix element in LO QCD**



- Parton shower approximates higher orders - but only for soft / collinear emissions.
- No 'answer' to what top mass is in the MC - arguments it is close to the pole mass.

Which top mass is in NLO MC?



- Need to include diagrams as above - but not included in 'standard' MC@NLO / Powheg.
- Recent NLO calculation for full WbWb final state should help (but dilepton mode only...)