Top quark physics at the Tevatron

- (Introduction)
- Production
- Mass
- Asymmetries
- Conclusions & Outlook

Andreas Jung (Fermilab) for the CDF, DØ collaboration

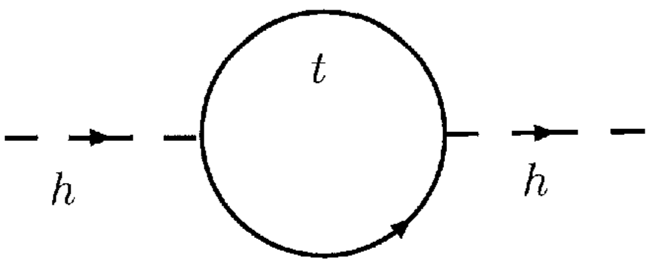
Fermilab
50th Rencontres de Moriond EW
March 14th – 21th 2015, La Thuile

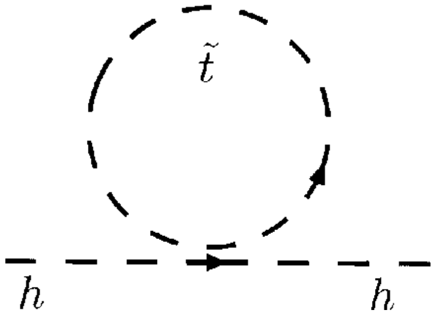
Happy birthday!

Discovered 1995 at CDF/D0

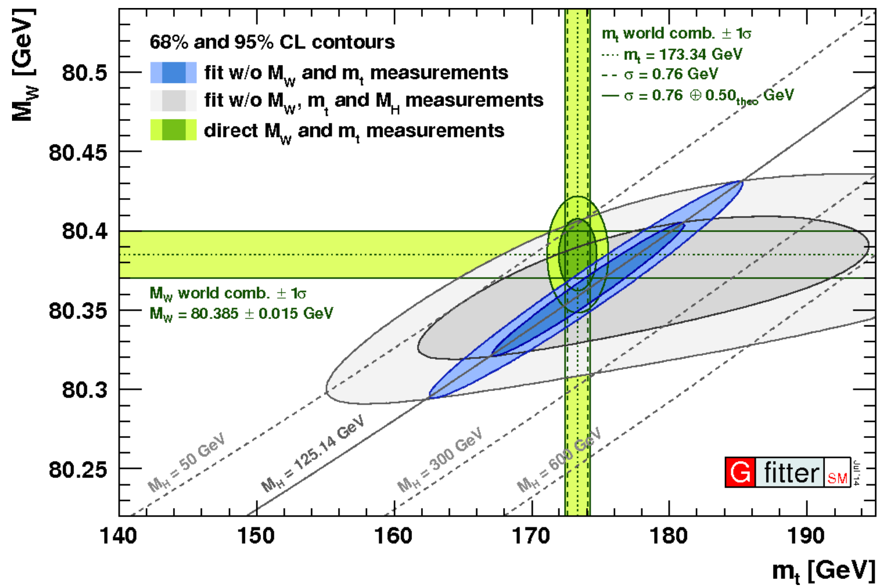
The top quark

- Top is the heaviest fundamental particle discovered so far
  → m_t **= 174.34 ± 0.76 GeV**
- Lifetime: $\tau \approx 5\text{x}10^{-25}$ s << Γ_{QCD}
  → **Observe bare quark properties**
- Large Yukawa coupling to Higgs boson
  → $\lambda_t \sim 1$ special role in electroweak symmetry breaking ?
- SM self-consistency test, “fate of the universe”, Hierarchy problem
  → **Window to new physics**

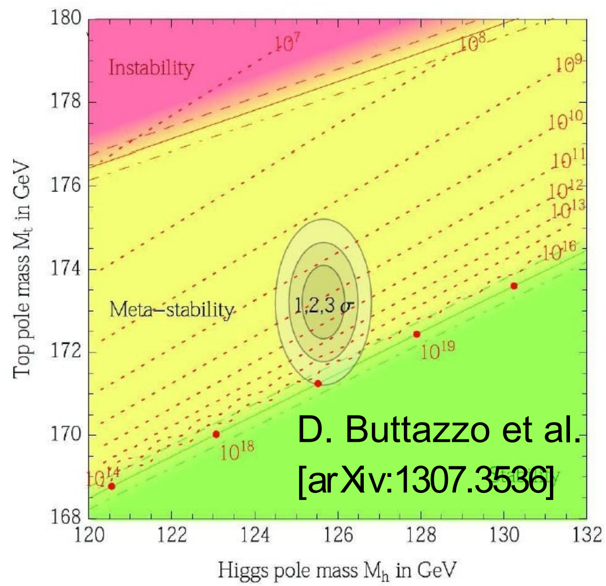




- Stringent SM self-consistency test



- “Fate of the Universe”

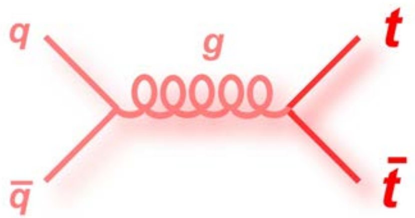


Production modes

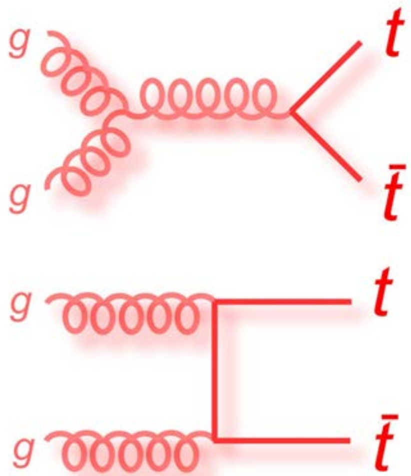
- Theoretical production cross sections (NNLO):

[Kidonakis]

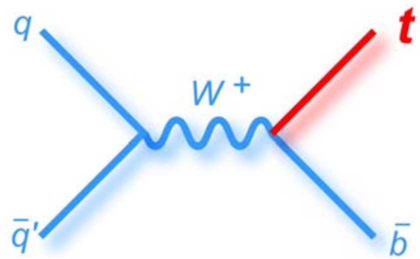
	Pairs	Single top quarks		
	$t\bar{t}$ [pb]	tb [pb]	tqb [pb]	tW [pb]
TEV	7.24	**1.04**	2.26	0.30
LHC8	248.50	**5.55**	87.20	11.50



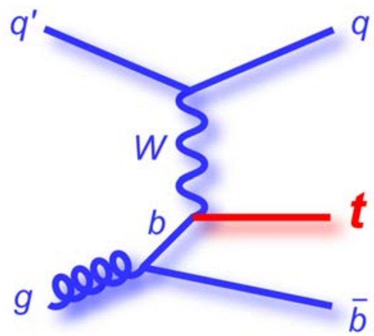
$q\bar{q}$ annihilation



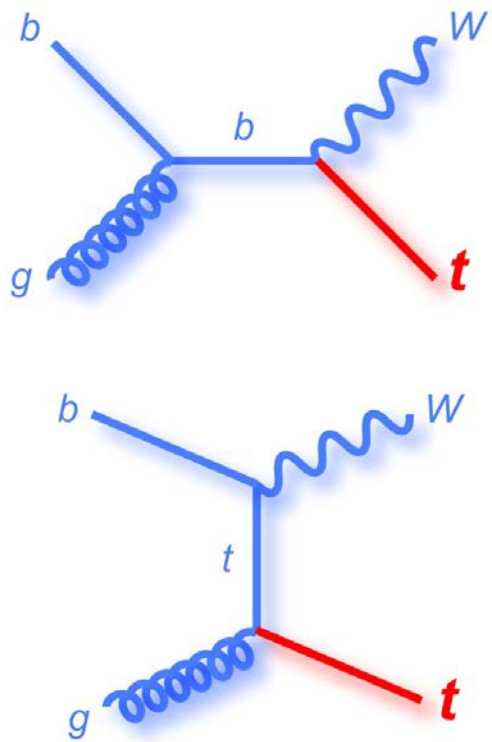
gg fusion



s-channel



t-channel



tW-channel

Tevatron can **compete and is complementary** ($p\bar{p}$ versus pp)

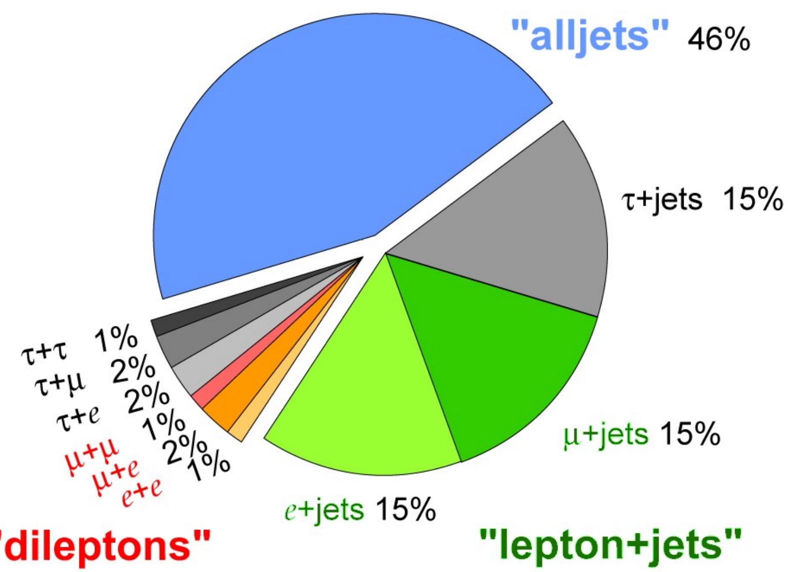
- Tevatron vs. LHC:
  (1.96 TeV 7/8 TeV)

$q\bar{q}$: ~85% ~15/13% (~10%, 14 TeV)

gg: ~15% ~85/87% (~90%, 14 TeV)

→ **Tevatron is *the* $q\bar{q}$ machine**

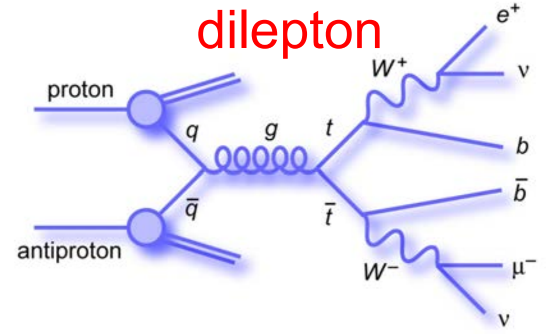
Top Pair Branching Fractions



$t \rightarrow Wb$ ~ 100%

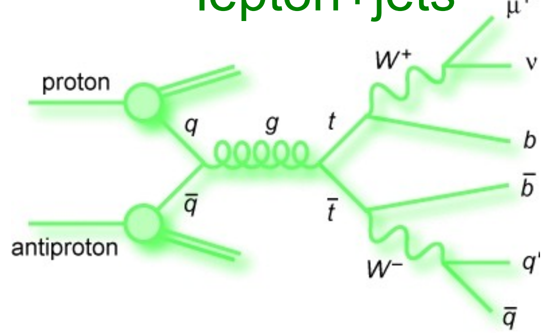
different W decay channels:

dilepton

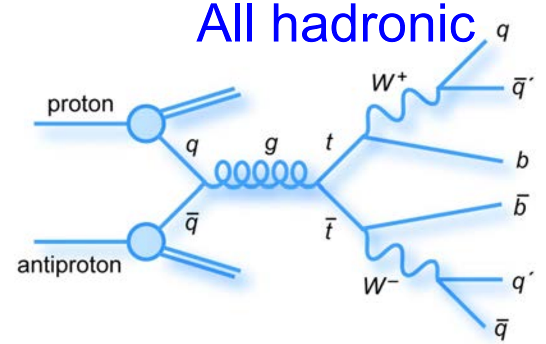


BR, bg decrease

lepton+jets

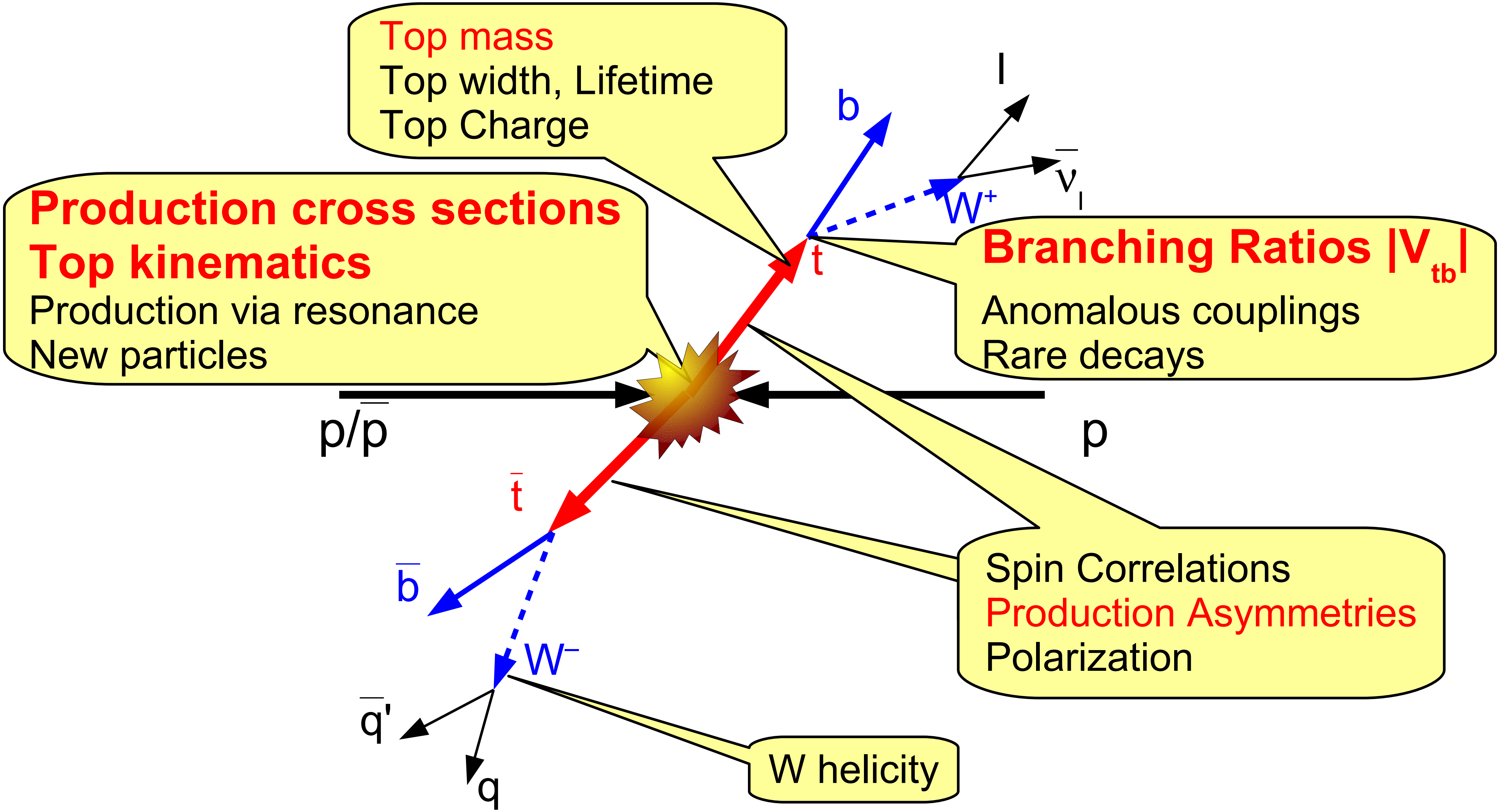


All hadronic



BR, bg increase

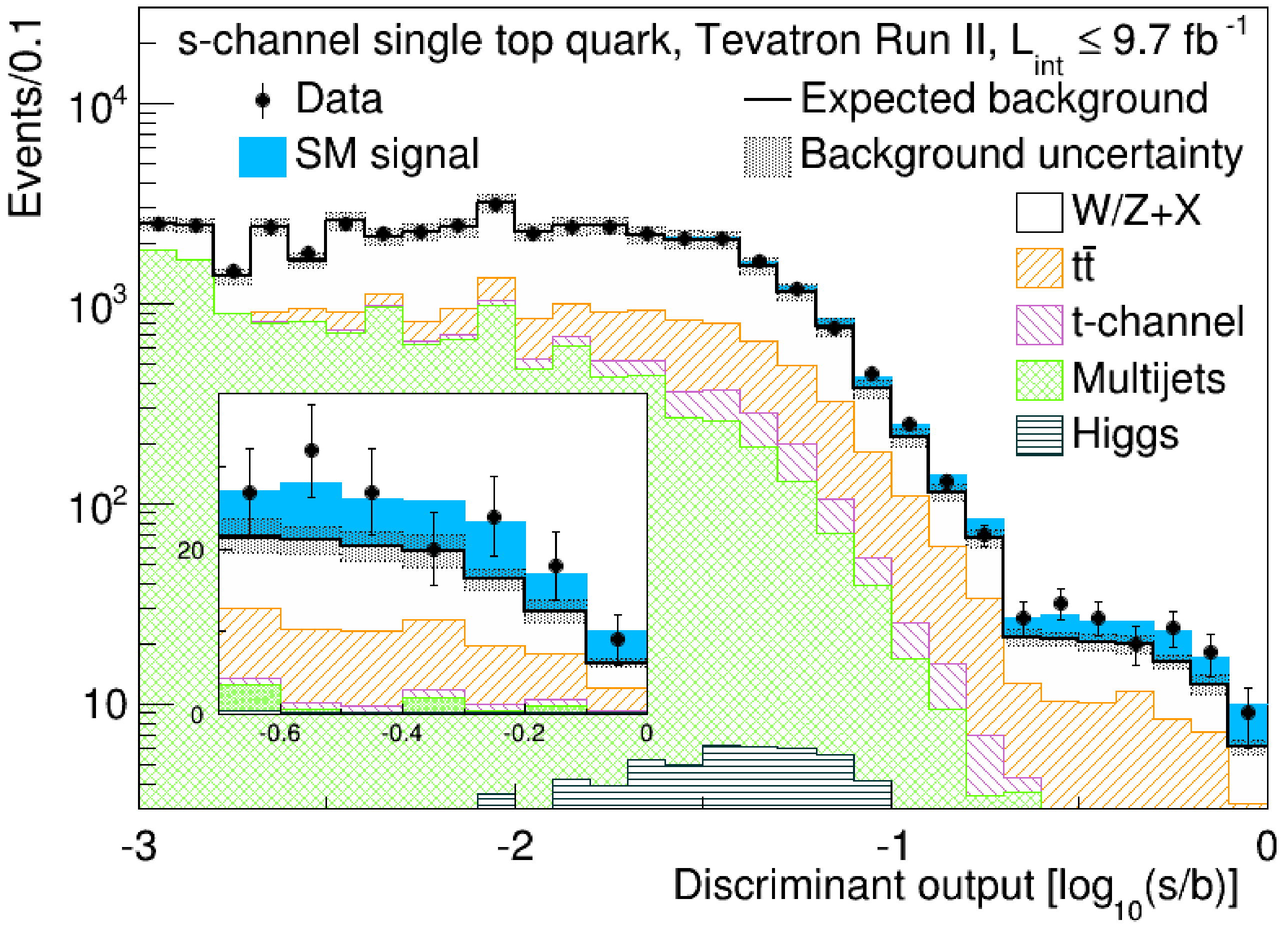
Content

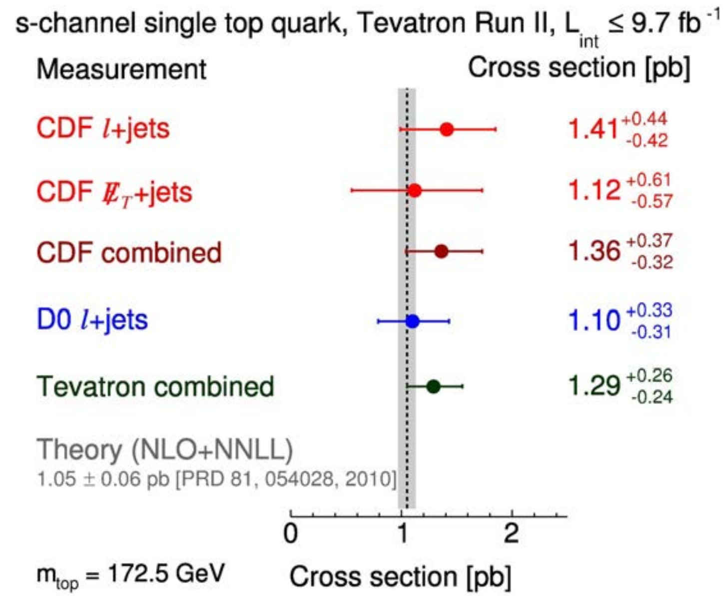


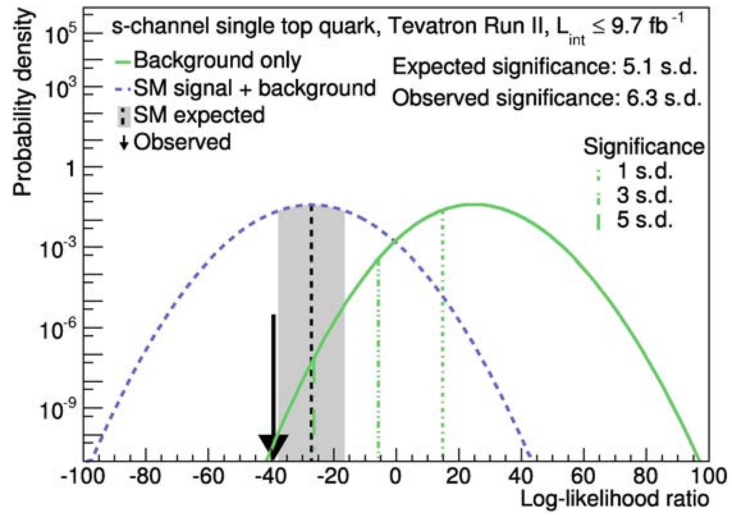
→ **Selection of results, focus on most recent and/or precise results**

Single top production

- Combine CDF (l+jets and MET+jets) & D0 discriminants (l+jets)
- Include all systematic uncertainties and correlations
- **First observation of s-channel single top (6.3 s.d.)** Phys. Rev. Lett. 112, 231803 (2014)

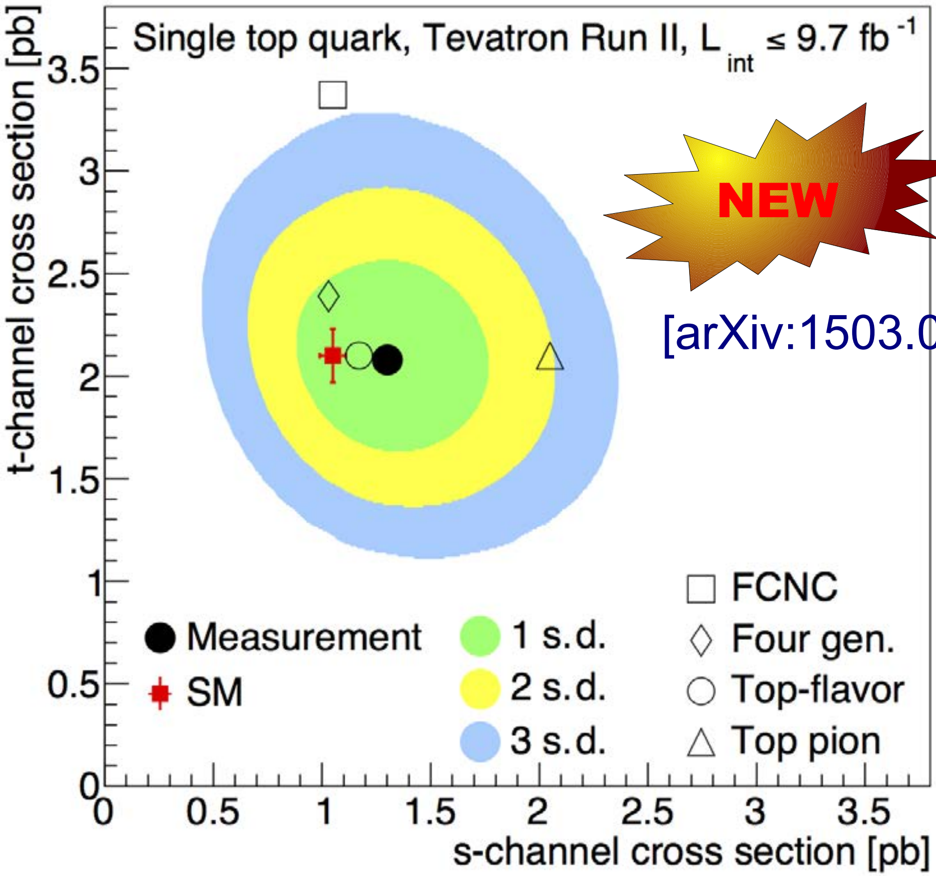






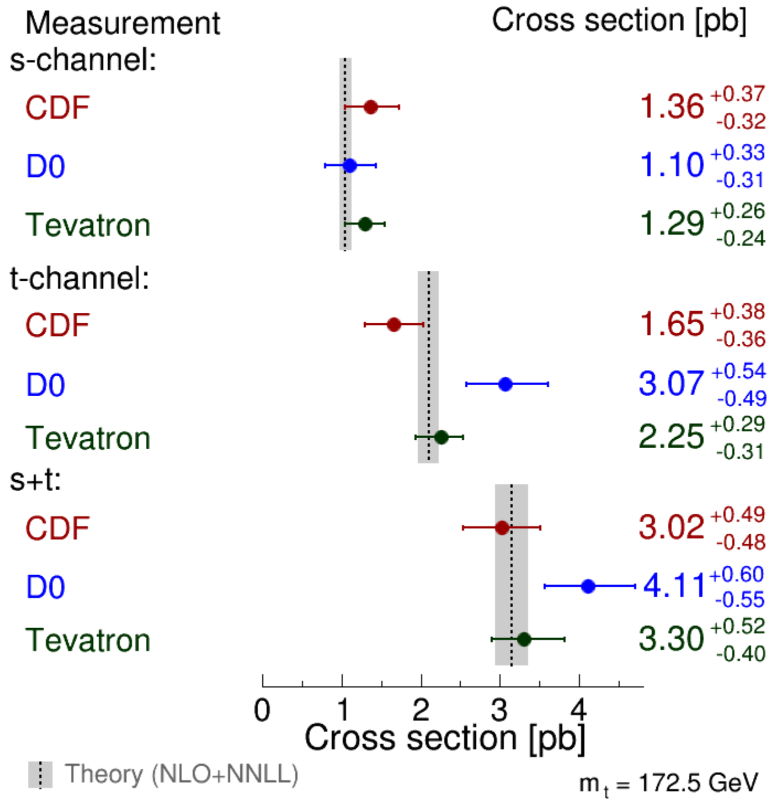
Single top production

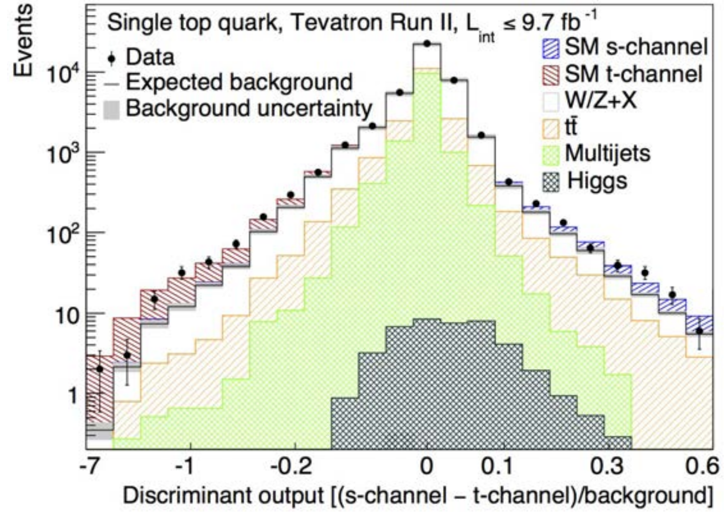
- Employ *s*-, *t*-channel discs for combination
- Not assuming σ_s/σ_t SM value
- Agreement with the SM, no indications for non-SM contributions



NEW

[arXiv:1503.05027]

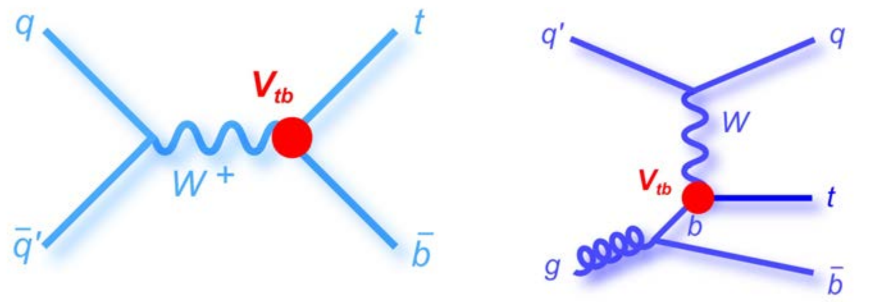




Single top production

- Measure CKM matrix element V_{tb}

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

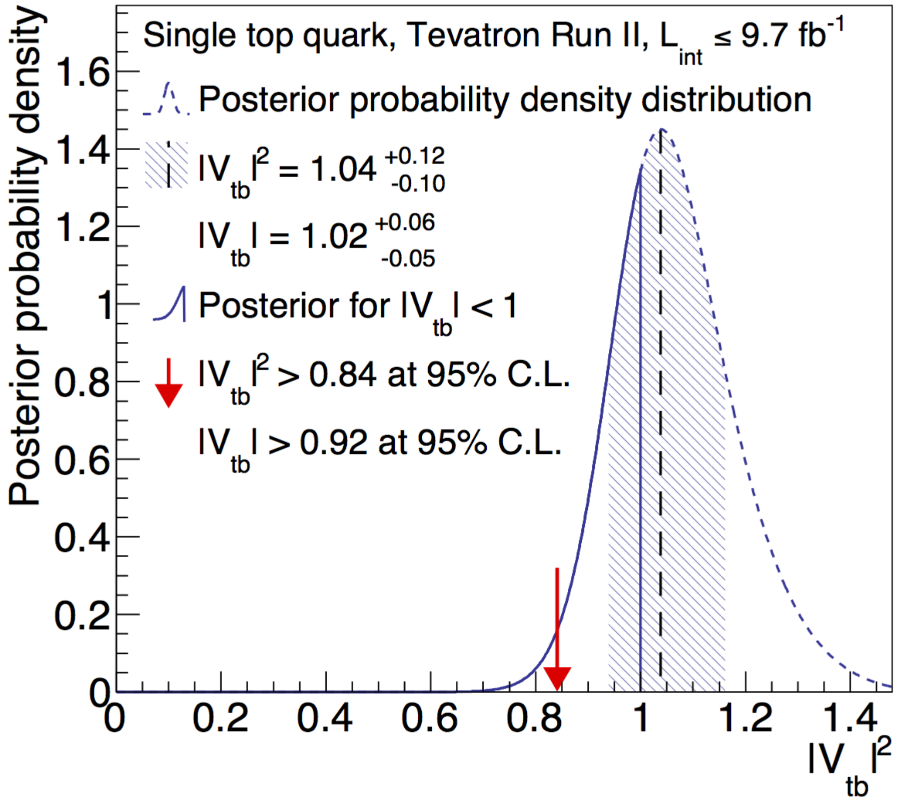


- Do not assume: 3 generations, unitarity, SM ratio of s- to t-channel
- Assume: SM top decay, Pure V-A interaction, CP conservation

→ $|V_{tb}| > 0.92$ at 95% C.L.
$|V_{tb}| = 1.02\ ^{+0.06}_{-0.05}$

NEW

[arXiv:1503.05027]



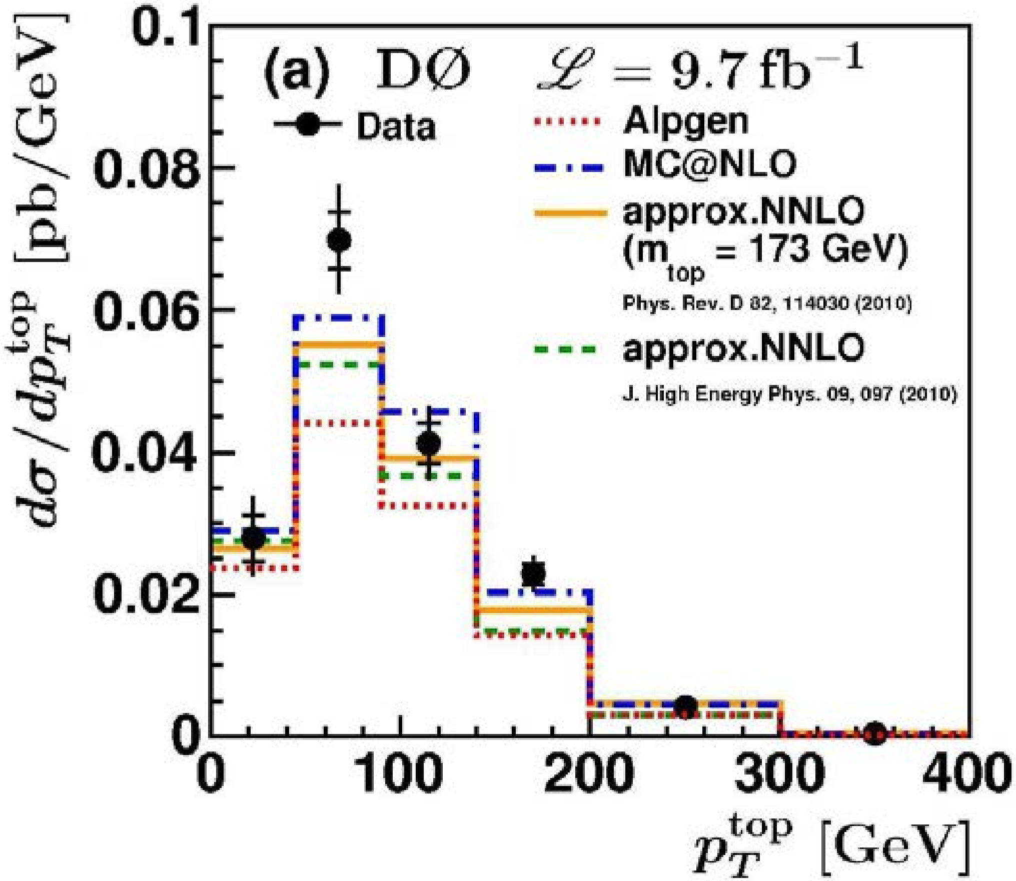
- **Concludes** single top Tevatron program

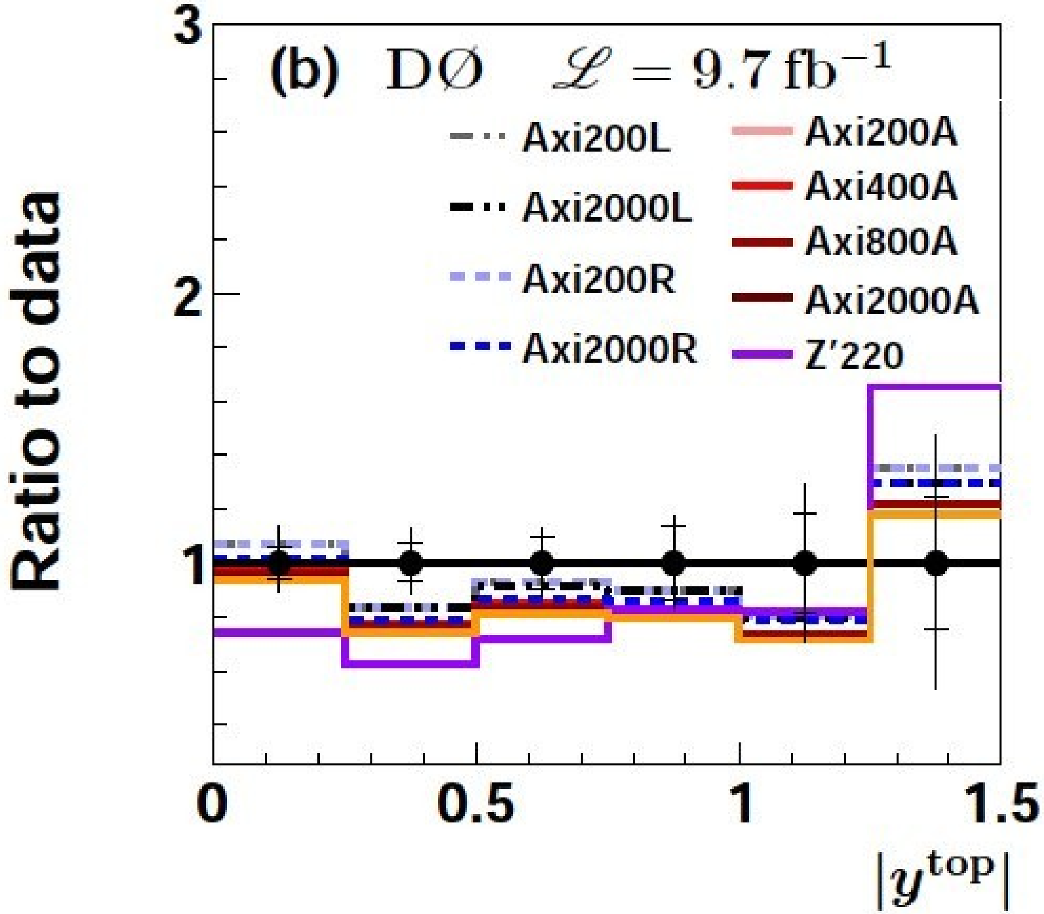
Differential cross sections

- Detailed studies & tests of pQCD
- Measured: $m(t\bar{t})$, $p_T(t/\bar{t})$ and $|y(t/\bar{t})|$
- Corrected to parton level via matrix unfolding

Phys. Rev. D 90, 092006 (2014)

Stringent tests of QCD
Study new physics models: no signs





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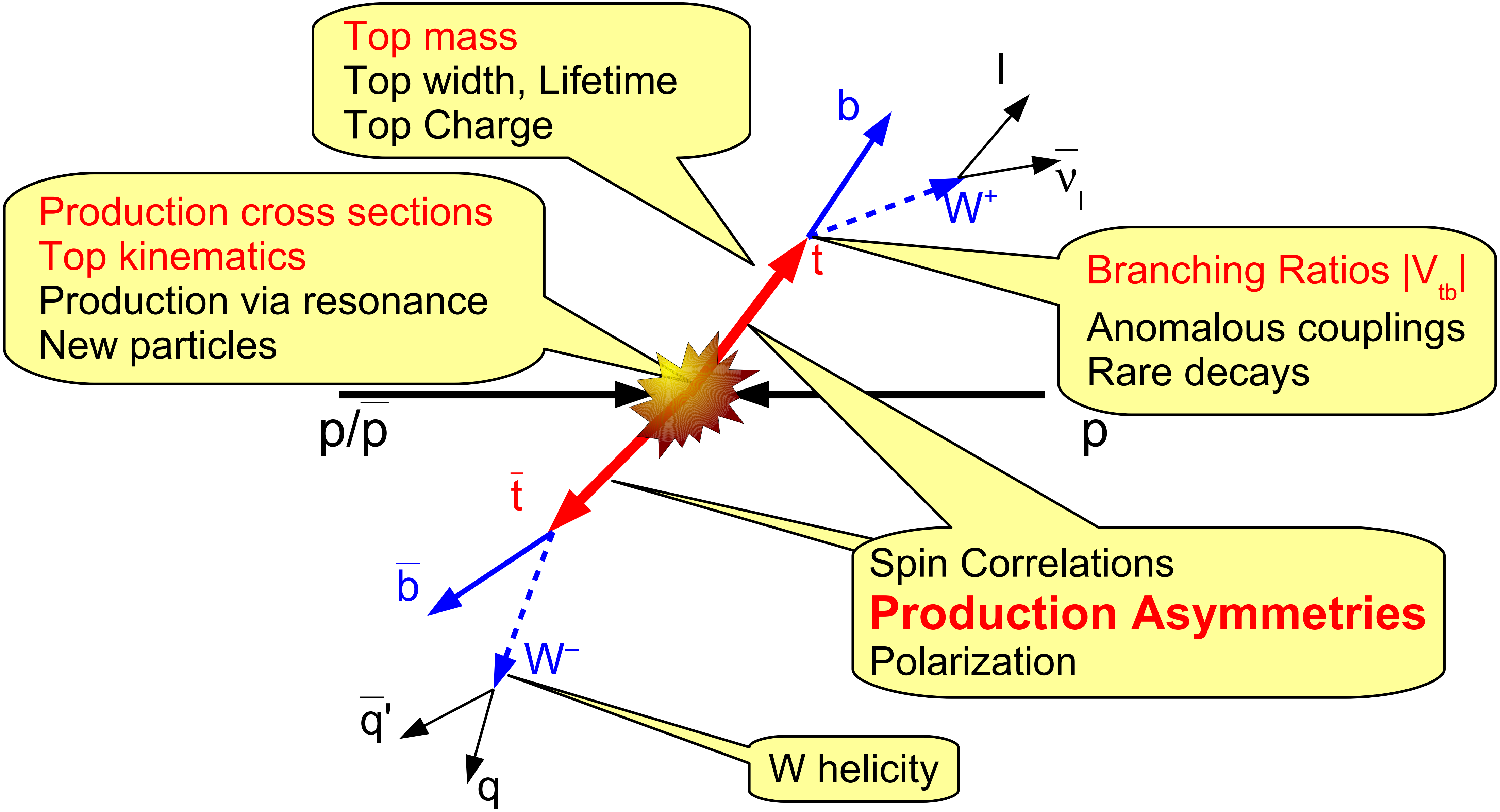


→ **Selection of results, focus on most recent and/or precise results**

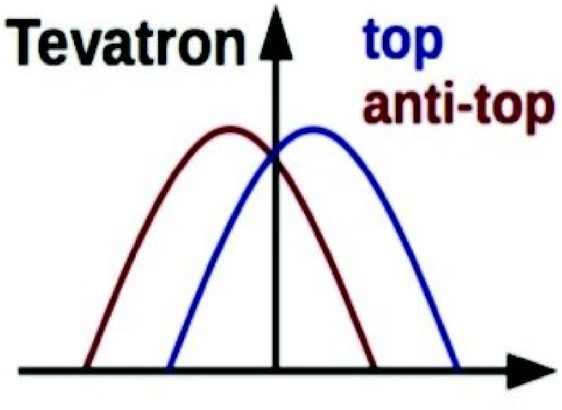
Top quark asymmetries

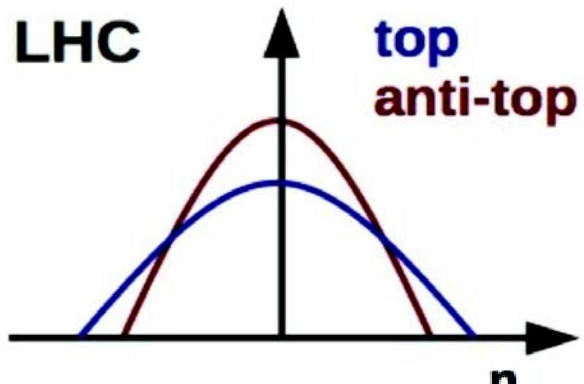
- Interference appears at NLO QCD
  - → Only occurs in $q\bar{q}$ initial state; *gg* is fwd-bwd symmetric
- This is a forward-backward asymmetry at Tevatron
- At LHC only anti-quarks from sea → $\bar{t}$ more central

<u>SM predictions at NLO (QCD+EWK)</u>

→ Tevatron: **A_{FB} ~ 8-9 %** vs. LHC: **A_c ~ 1 %**

→ **<u>Update:</u> 10% at NNLO+NNLL**





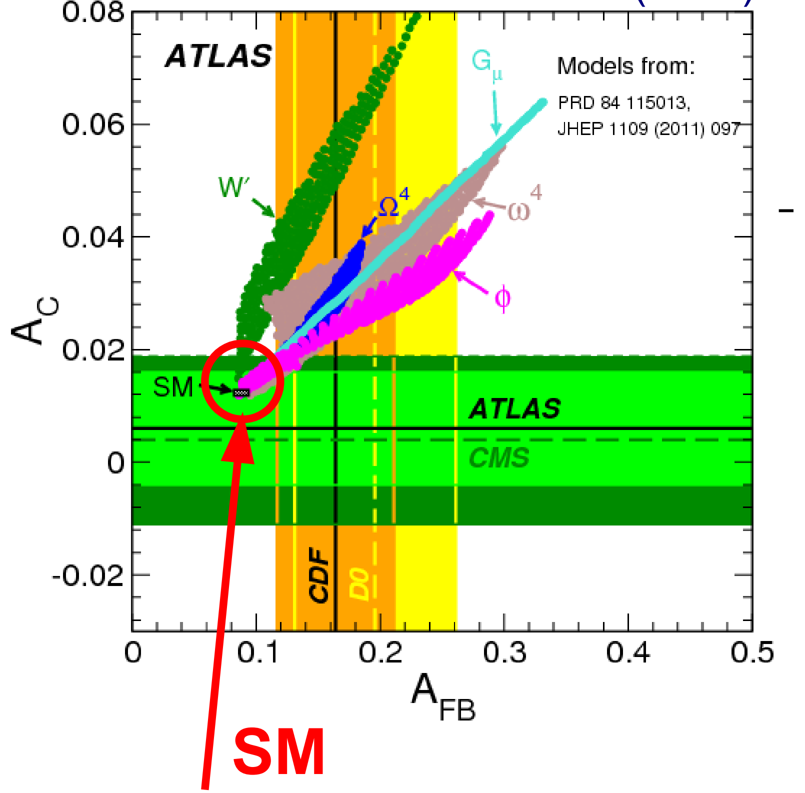
$\Delta y = y_t - y_{\bar{t}}$ η

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

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

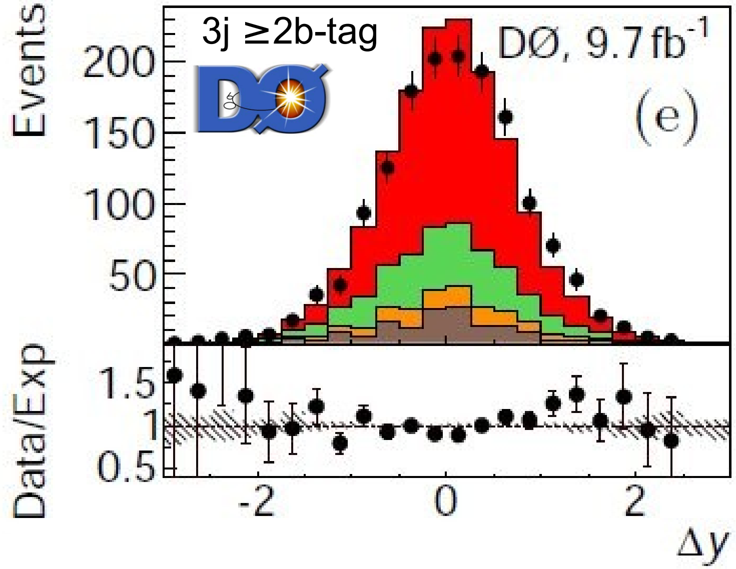
$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$

JHEP 1402 (2014)



Top quark asymmetries

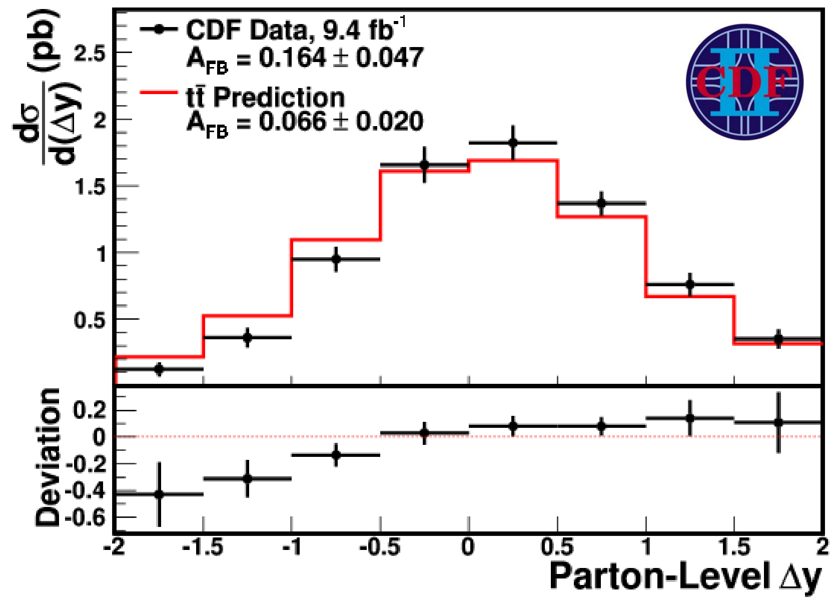
- D0 larger phase space, improved object identifications, new top quark reco
- Combine several channels (different purity) & unfold to parton level



- SM @NNLO+NNLL: ~10% (Czakon, Mitov, et al.)

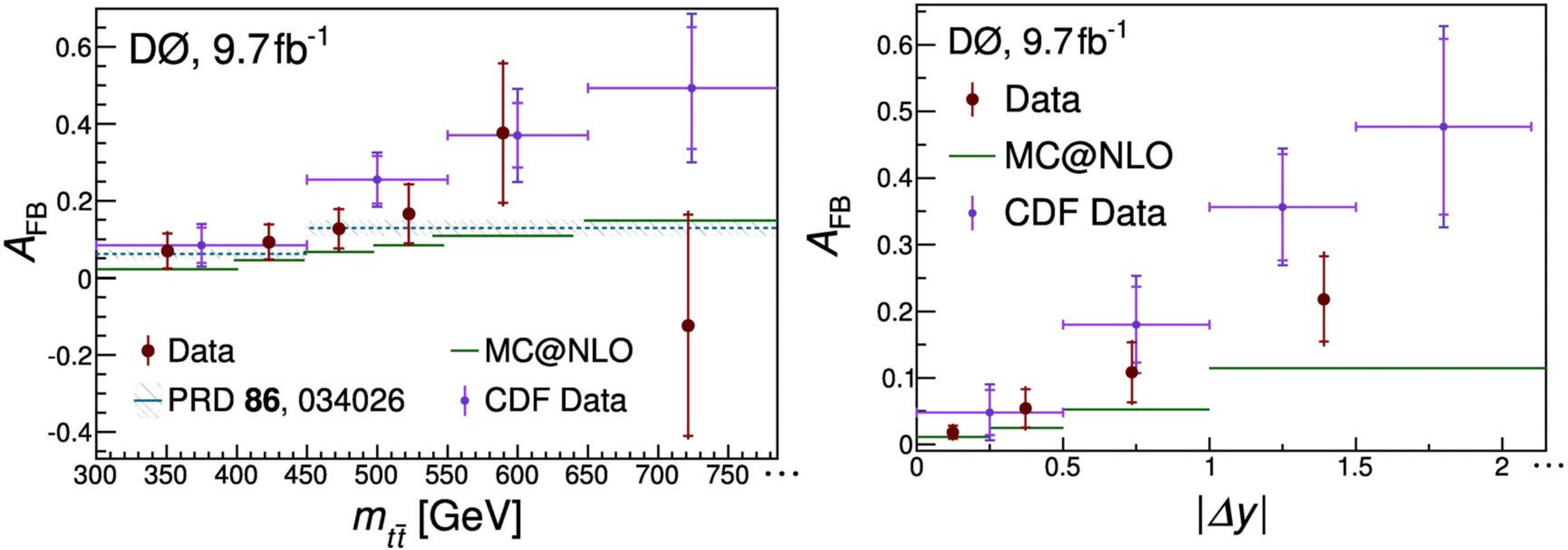
→ *D0:* A_{FB} = 10.6 ± 3.0 (tot.) %
Phys. Rev. D 90 072011 (2014)
→ D0 agrees with SM within uncertainties

→ *CDF:* A_{FB} = 16.4 ± 4.5 (tot.) %
PRD 87 092002 (2012)
→ CDF higher than SM predictions



Top quark asymmetries

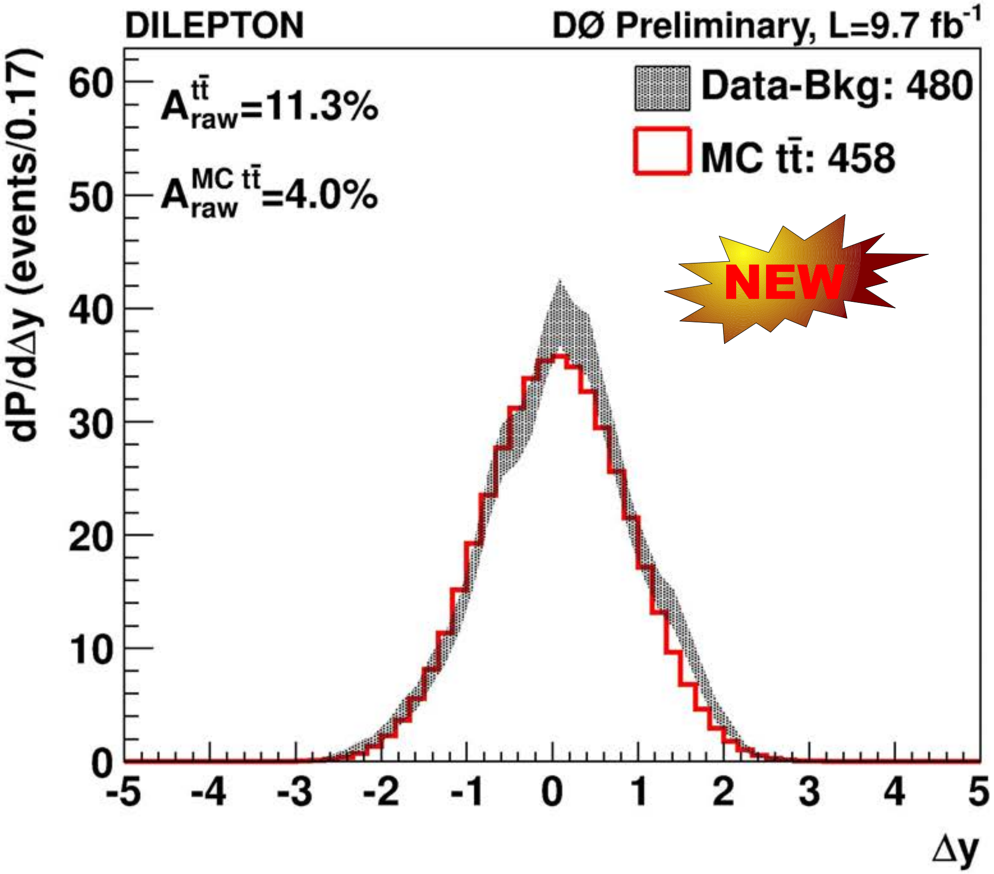
- CDF and D0 measure the kinematic dependence of A_{FB}



- Kinematic dependencies larger than "currently" predicted by SM
- Good agreement of D0 data with most recent pQCD @NNLO

Top quark asymmetries

- New measurement by D0 in the dilepton channel employing the matrix element method: D0 Conf. note 6445
  → assign a likelihood per event for most probably Δy (x) value
- Systematic uncertainties dominated by signal modeling, in particular hadronization & showering, and method calibration

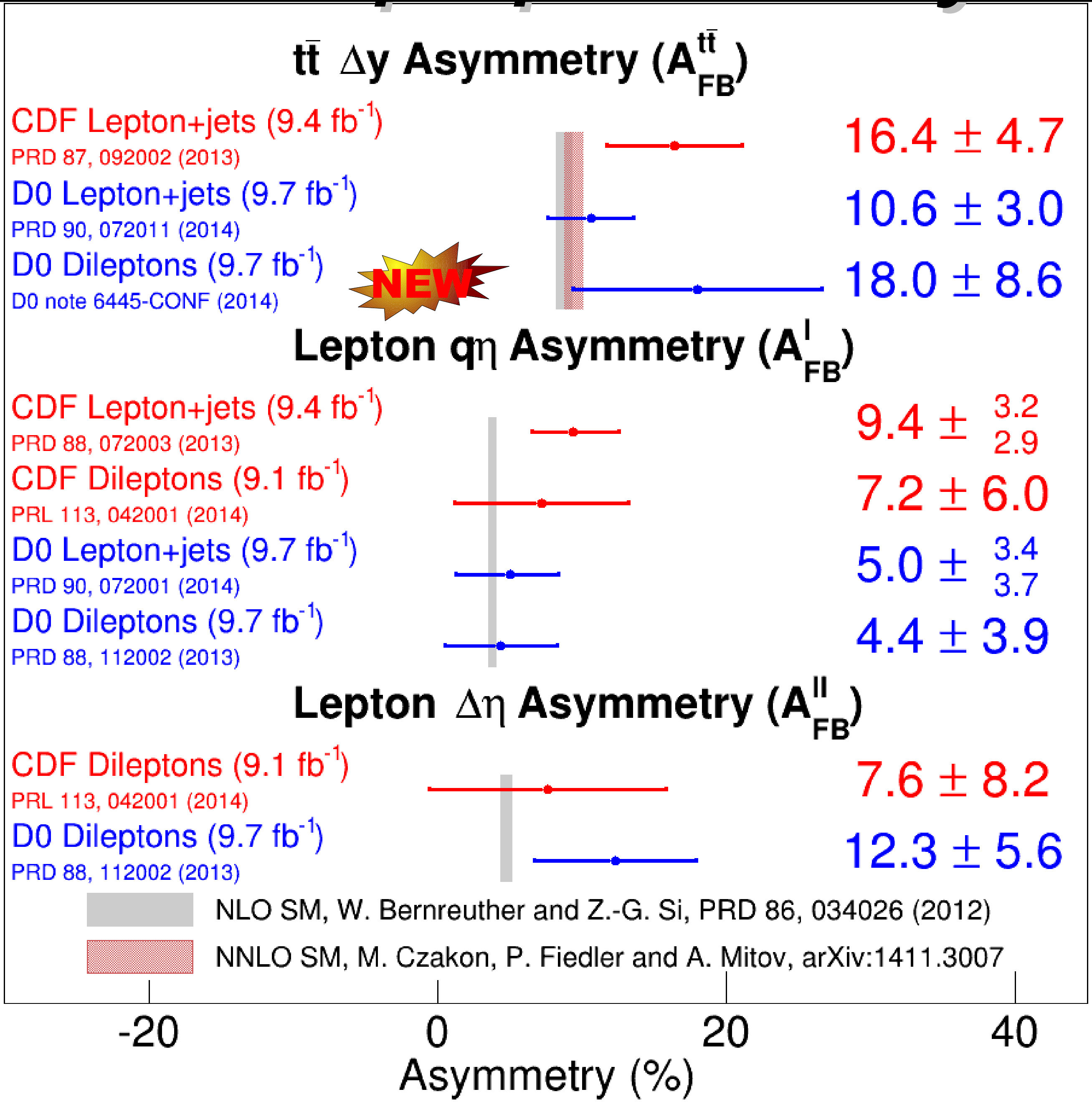


Test SM or test for BSM, but need to consider unknown polarization in calibration

→ A_{FB} = 18.0 ± 6.9 (tot.) %

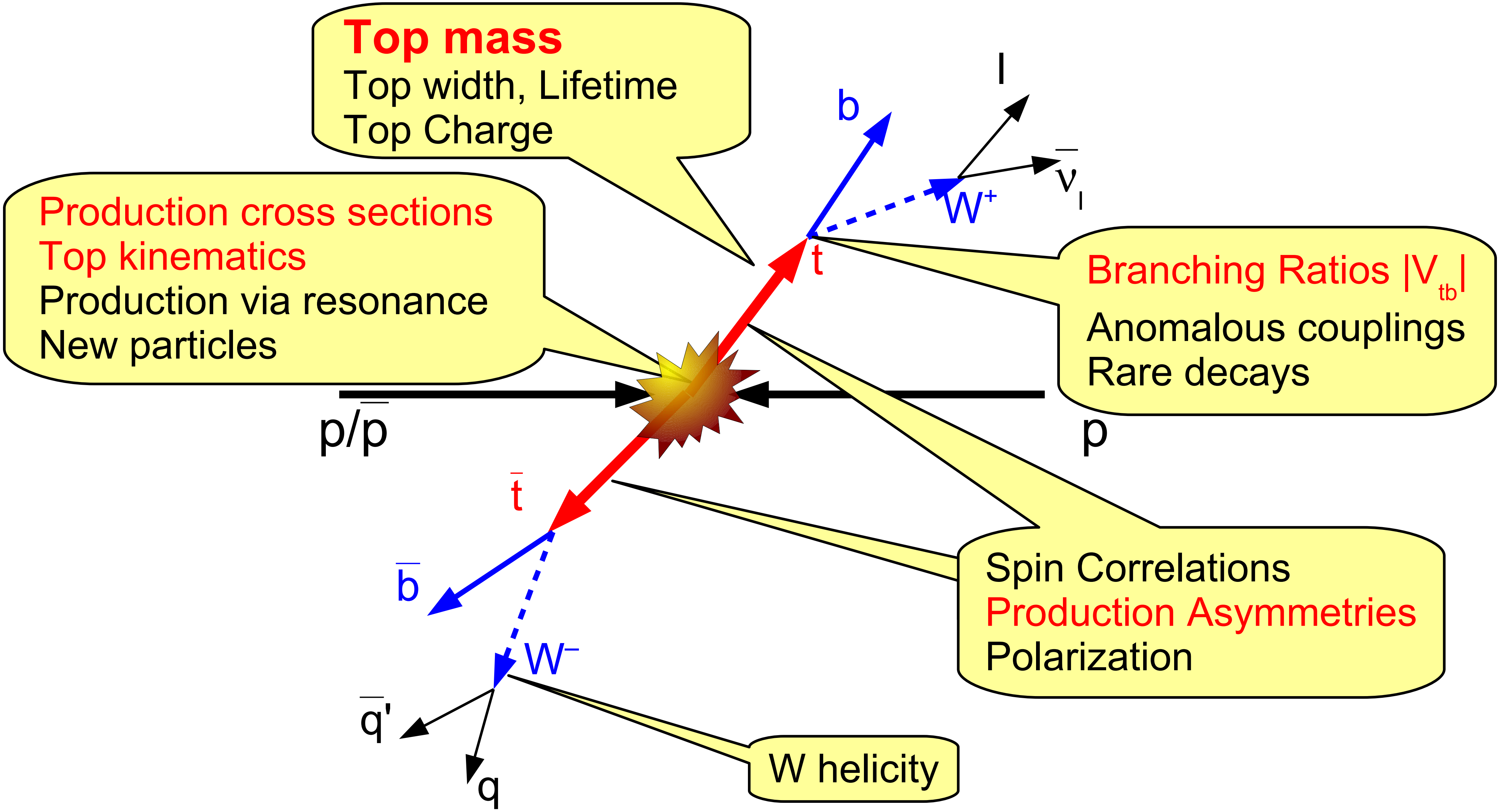
A_{FB} = 18.0 ± 6.9 (tot.) ± 5.1(model) %

Top quark asymmetries



- All Tevatron results use full data sets
- Expect final results and Tevatron combination very soon
- Agreement with latest theory predictions

Content



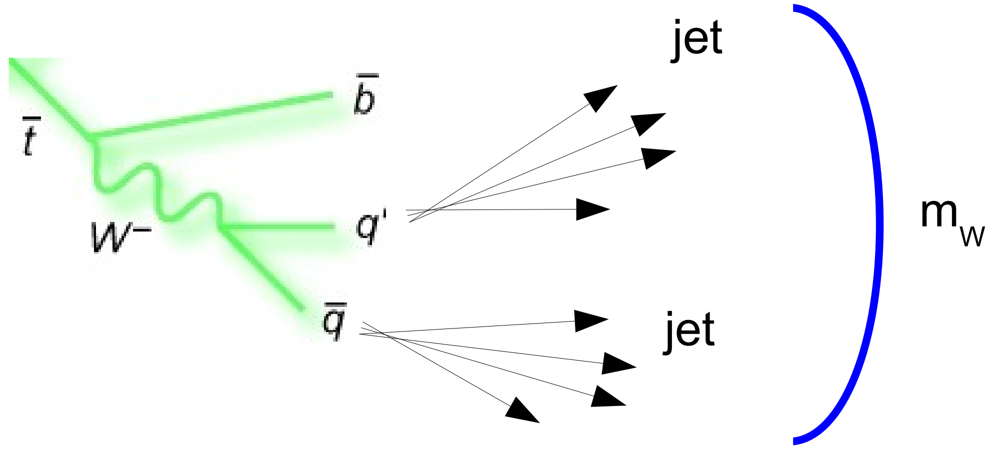
→ **Selection of results, focus on most recent and/or precise results**

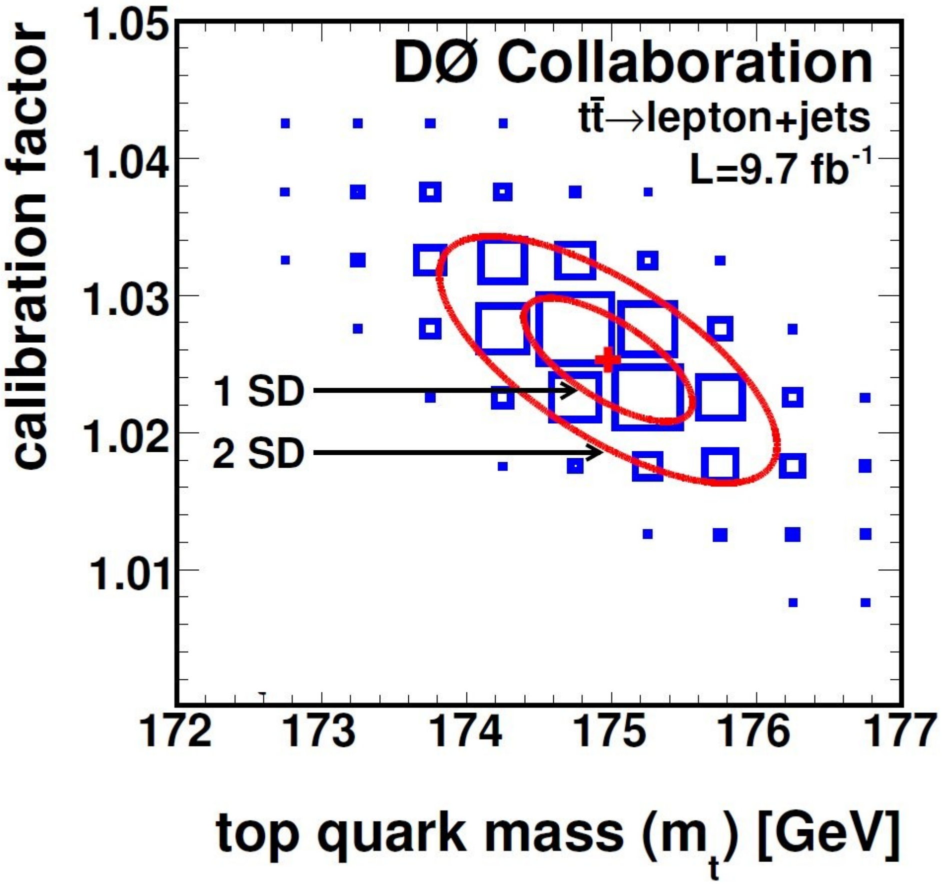
m(t): matrix element method

- Use full event kinematic information by applying matrix element method
- 2D measurement of a calibration factor and the mass
- lepton+jets decay channel

Phys. Rev. Lett. 113, 032002 (2014)

- In-situ calibration by constraining hadronic decay of *W* to known *W* mass





m(t): matrix element method

Single-most precise measurement !

→ m_t = 174.98 ± 0.58 (stat.) ± 0.49 (syst) GeV

m_t = 174.98 ± 0.76 (total) GeV $\delta m_t/m_t$ = 0.43%

Phys. Rev. Lett. 113, 032002 (2014)

Most precise LHC measurement by CMS: m_t = 172.04 ± 0.77 GeV ($\delta m_t/m_t$ = 0.45%)

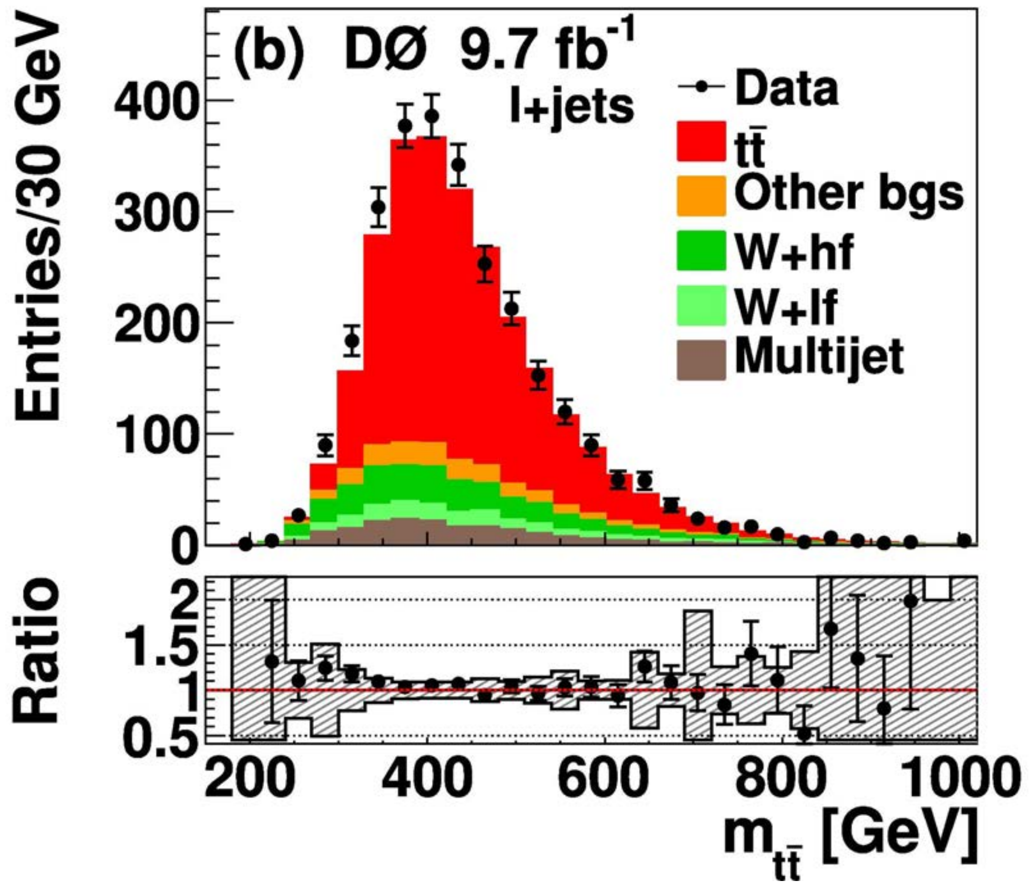
Systematic uncertainties:

- Signal model & jet energy scale
- Statistical component:
  0.25 → 0.05 GeV

- **Detailed PRD**, e.g. cross-check of the b-quark jet energy scale:
  - R_{bl} = 1.008 ± 0.0195 (stat.) $\pm^{0.037}_{0.031}$ (syst.)
  - Subm. to PRD [arXiv:1501.07912]

NEW

Applying results (σ, JSF, m_t) to MC:



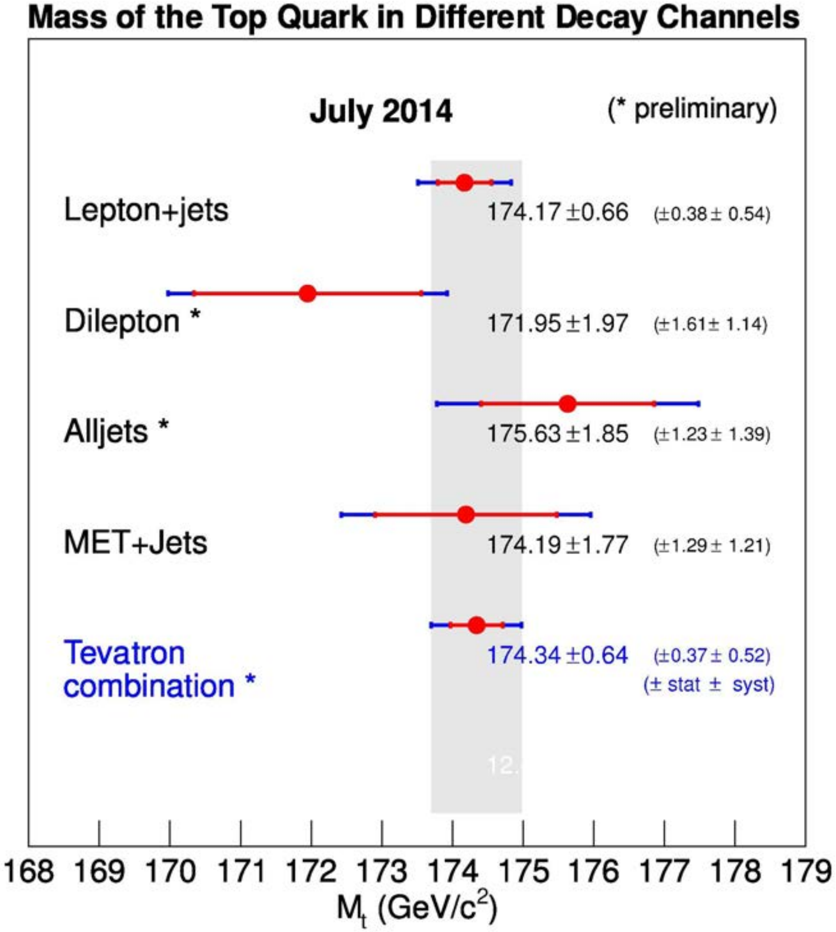
Most precise CDF measurement:
m_t = 172.85 ± 1.12 (total) GeV
$\delta m_t/m_t$ = 0.65% PRL 109 152003

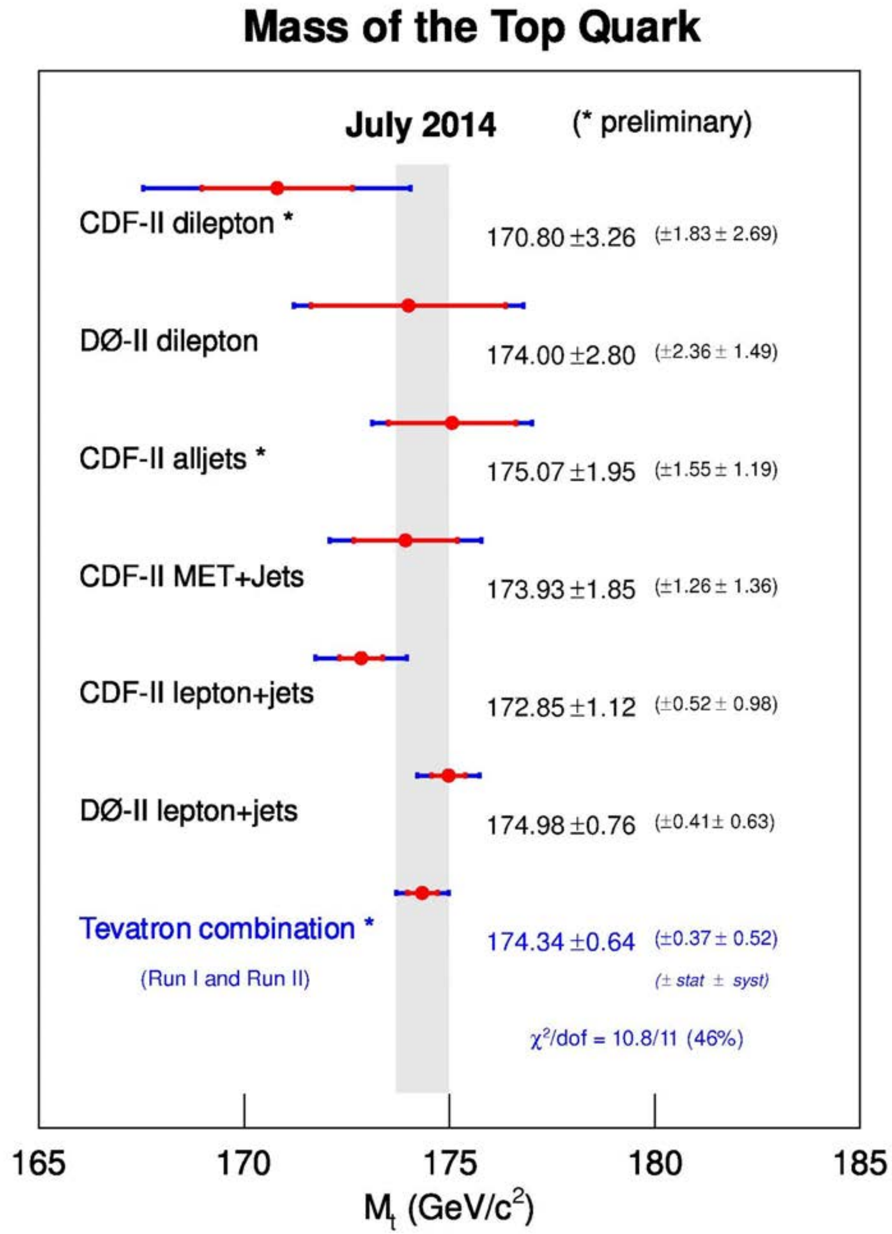
m(t): Tevatron combination

- Latest Tevatron combination
- Using BLUE, include correlations

→ $m_t = 174.34 \pm 0.64$ GeV (stat. + JES + syst.) $\delta m_t/m_t = 0.37\%$

[arXiv:1407.2682]





Tevatron Legacy & Outlook

- Finished Tevatron single top program, including First Observation of *s*-channel single top quark production
- Detailed measurements of differential top pair production
- Top quark Asymmetry ?
  → D0 close to SM, CDF larger than SM, both agree as well.
- Precision measurements of the top quark mass:

$$m_t = 174.34 \pm 0.64 \text{ (tot.) GeV} \qquad \delta m_t/m_t = 0.37\%$$

- **Expect more results to come...**

Only small limited selection of results shown, more information:

CDF Top Web pages D0 Top Web pages

Thank you

Backup

m(t): matrix element method

Modifications compared to the previous ME result:

Phys. Rev. D 84, 032004 (2011)

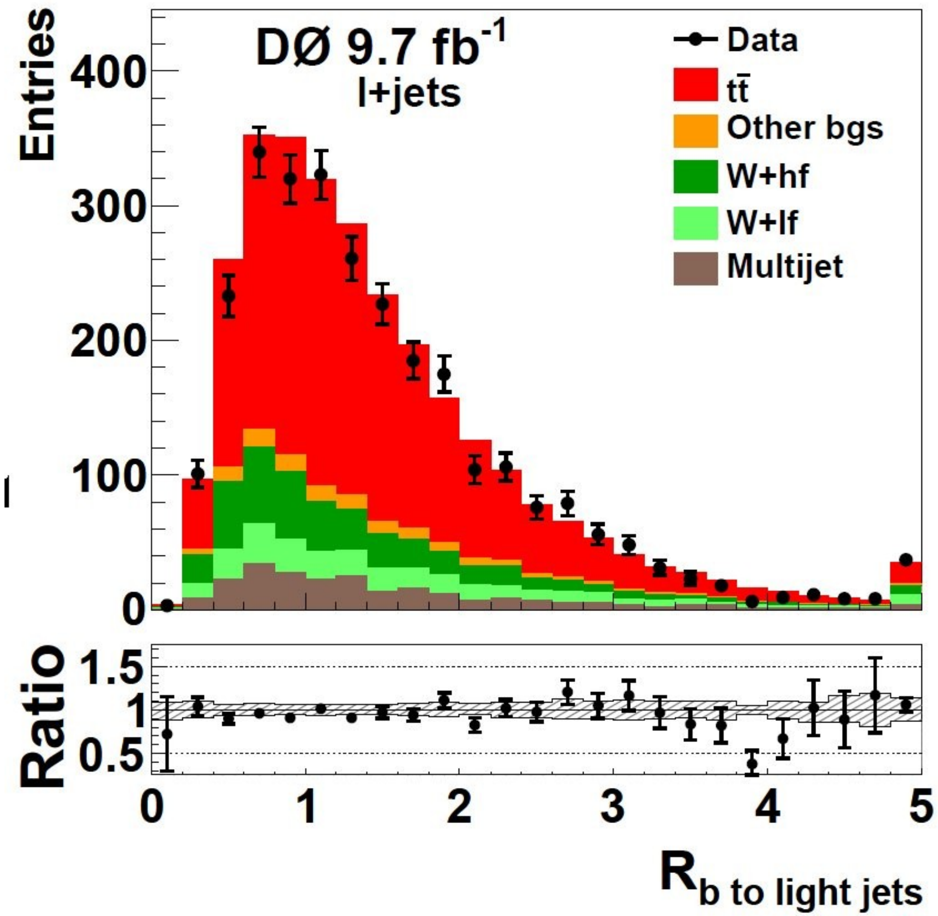
- More data 3.6/fb → 9.7/fb
- Improved object IDs (e, μ, b)
- Accelerated ME method

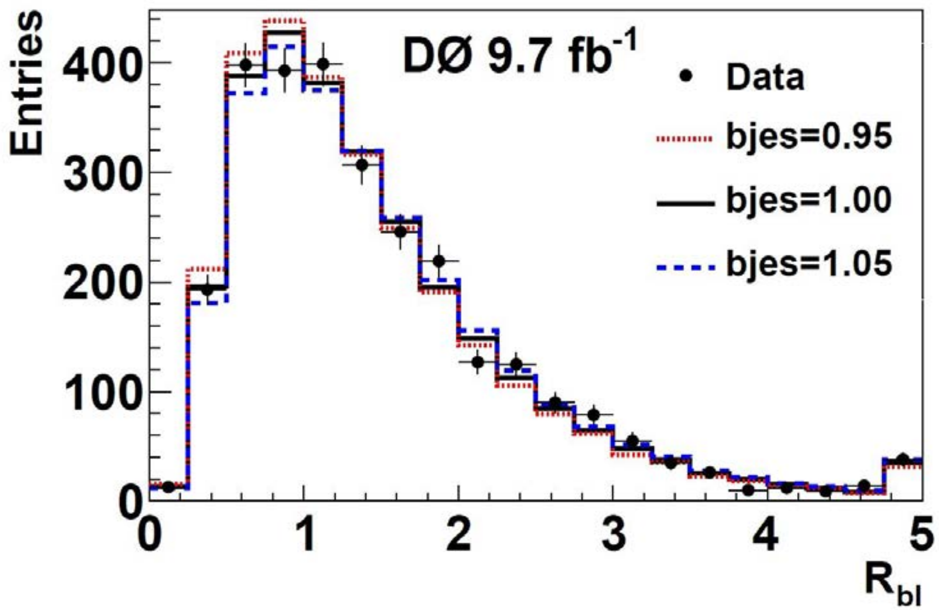
→ Typical statistical uncertainty:
~0.25 GeV → ~ 0.01 – 0.05 GeV

- Factorize out previously double-counted effects

- Signal model uncertainties are dominant

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections	$+0.15$
Initial/final state radiation	± 0.09
Hadronization and UE	$+0.26$
Color reconnection	$+0.10$
Multiple $p\bar{p}$ interactions	-0.06
Heavy flavor scale factor	± 0.06
b-jet modeling	$+0.09$
PDF uncertainty	± 0.11
Detector modeling:	
Residual jet energy scale	± 0.21
Flavor-dependent response to jets	± 0.16
b tagging	± 0.10
Trigger	± 0.01
Lepton momentum scale	± 0.01
Jet energy resolution	± 0.07
Jet ID efficiency	-0.01
Method:	
Modeling of multijet events	$+0.04$
Signal fraction	± 0.08
MC calibration	± 0.07





1 b-tag:

$$R_{bl} = \frac{p_T^{bjet1}}{(p_T^{ljet1} + p_T^{ljet2})/2}$$

2 b-tags:

$$R_{bl} = \frac{p_T^{bjet1} + p_T^{bjet2}}{p_T^{ljet1} + p_T^{ljet2}}$$

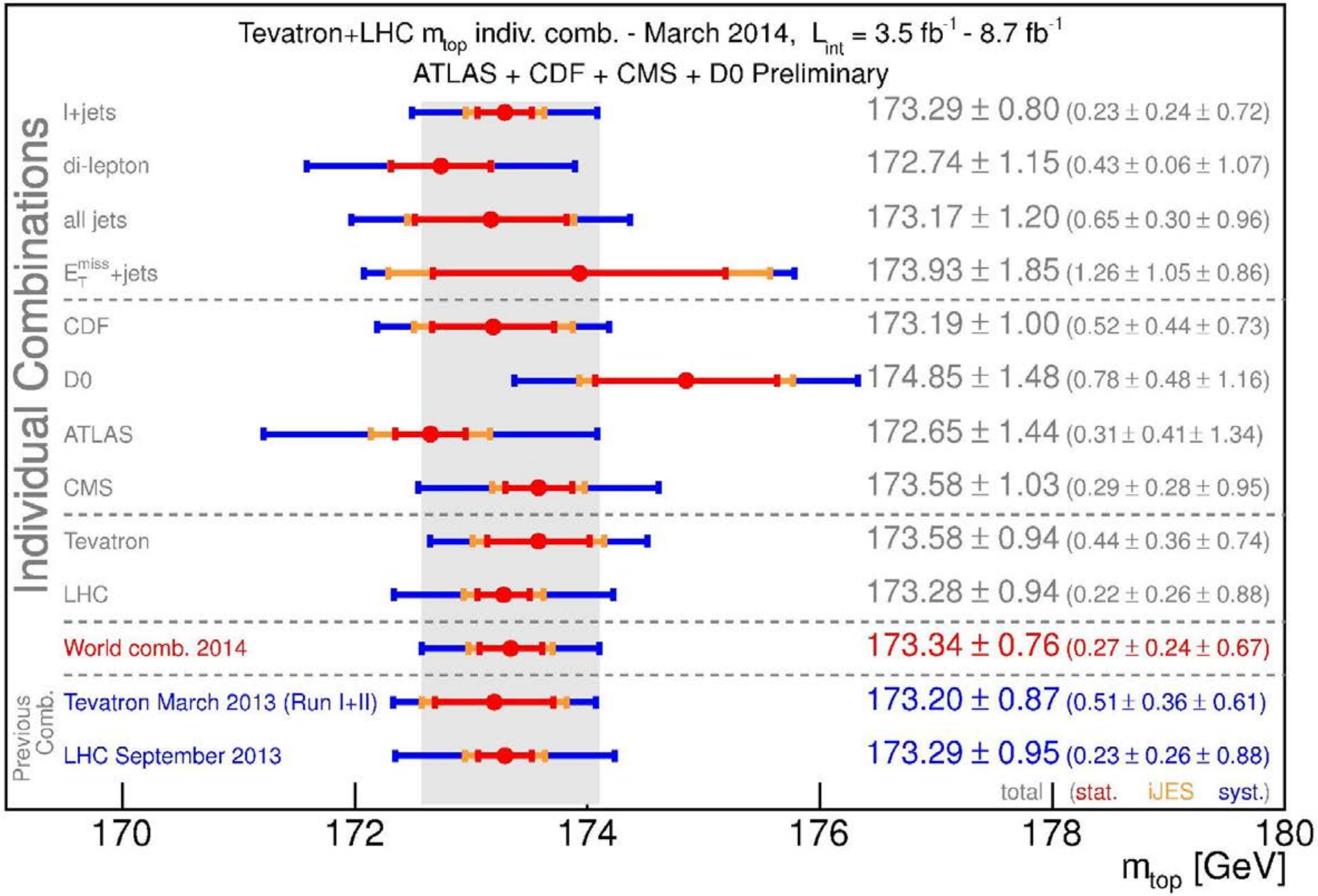
- Measure ratio of *b*-jets to light jets – sensitive to *b*-JES ('ATLAS method')
- Template fit including dominant systematic uncertainties

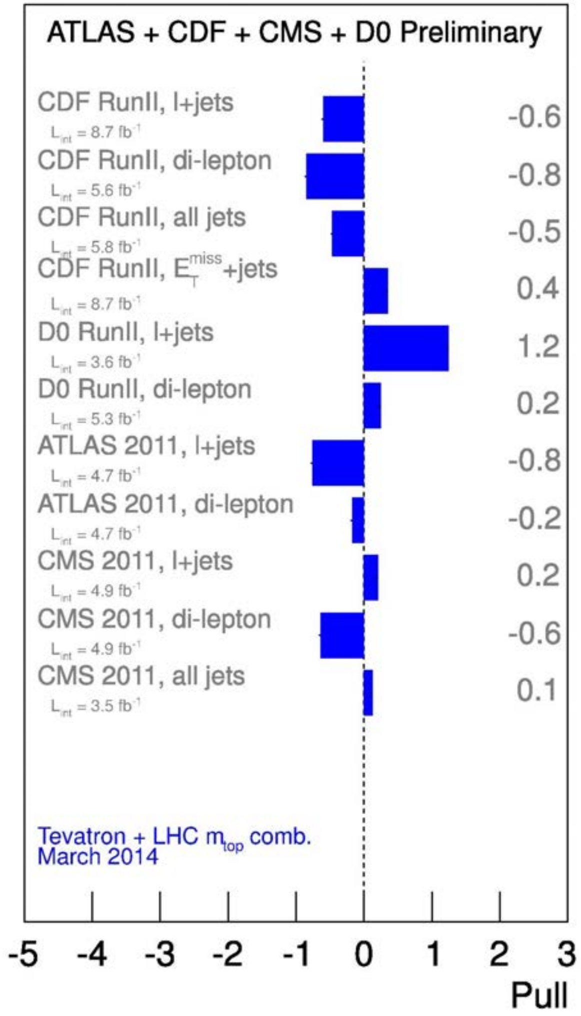
$R_{bl} = 1.008 \pm 0.0195\ (\text{stat.}) \pm^{0.037}_{0.031}\ (\text{syst.})$

- Important cross-check of *b*-JES; after all corrections applied ~ 1.

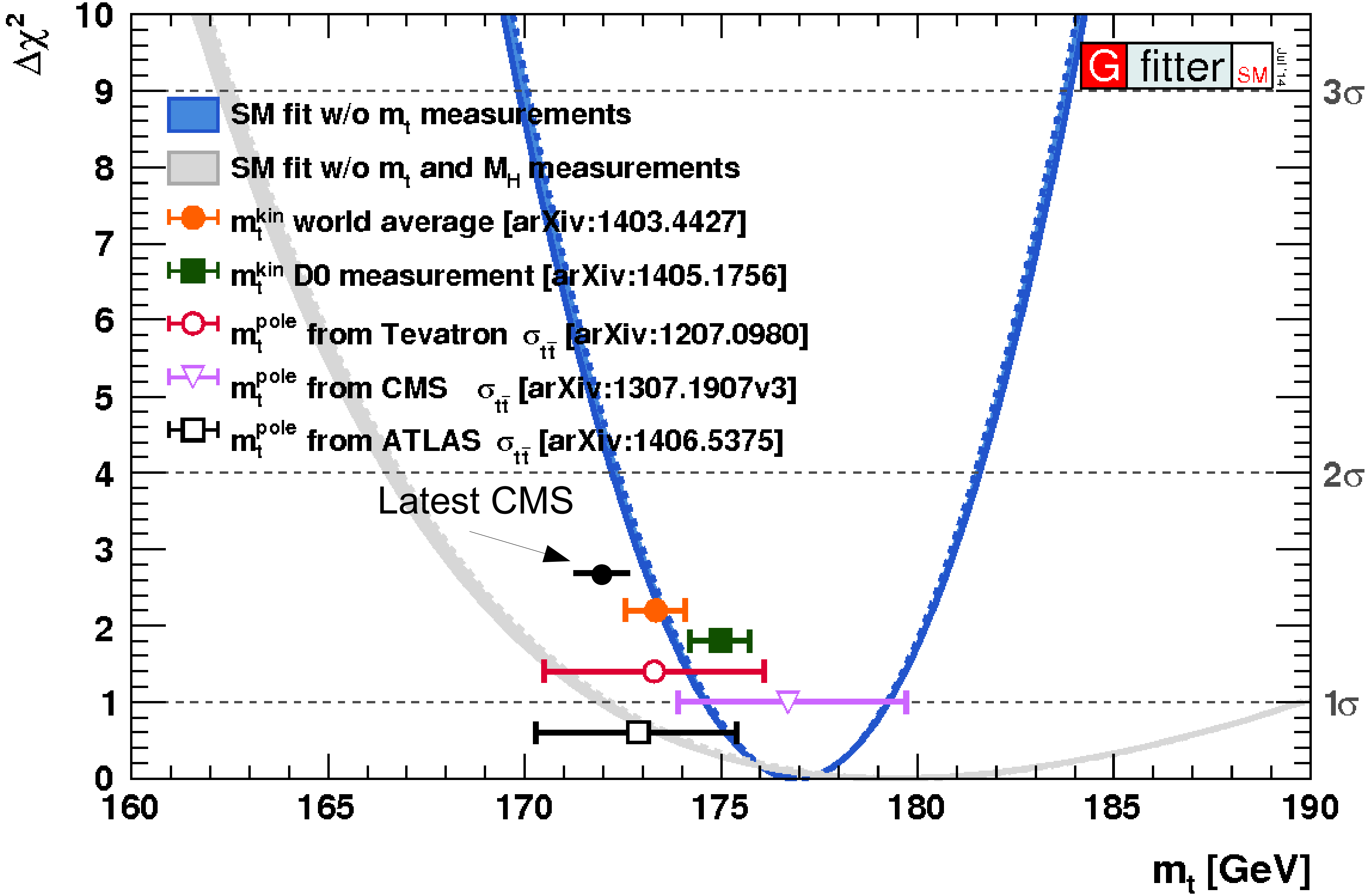
World combination

- First World Combination of top mass measurements [arxiv:1403.4427]
- Detailed study of inter-experiment & inter-collider correlations





→ m_t = 173.34 ± 0.76 (stat. + JES + syst.) GeV — 0.44% rel. unc.



→ Internal D0-CMS study group to understand differences & correlations of systematic uncertainties, effort is towards new world combination

m(t): matrix element method

Updates compared to last publication/measurement:

- More data 3.6/fb → 9.7/fb (full Run II)
- Improved object IDs (*e*, μ, *b*)
- Faster method:
  - Random number generation
  - Modify treatment of kJES
    → Verified that method gets same result as with "old" method, but factor of
    ~ 100 faster
  - Allowed **dramatic increase** in MC statistics

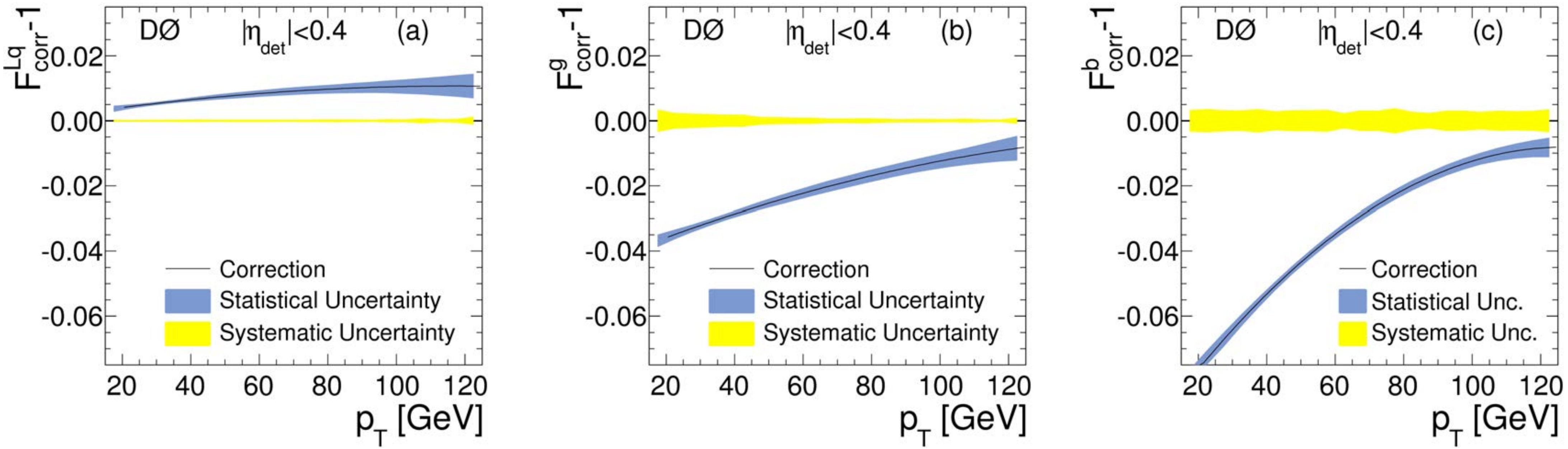
→ Typical statistical uncertainty:
~0.25 GeV → ~ 0.01 – 0.05 GeV

Higher-order effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color reconnection	±0.28
Multiple $p\bar{p}$ interactions	±0.07
Modeling of background	±0.16
W+jets heavy-flavor scale factor	±0.07
Modeling of b jets	±0.09
Choice of PDF	±0.24
Residual jet energy scale	±0.21
Data-MC jet response difference	±0.28
b-tagging efficiency	±0.08
Trigger efficiency	±0.01
Lepton momentum scale	±0.17
Jet energy resolution	±0.32
Jet ID efficiency	±0.26

Phys. Rev. D 84, 032004 (2011)

m(t): Single Particle Response

- Improves MC description of jets and reduces sample-dependency
- Resulting F_{corr} for different jet flavors and their uncertainties



- Small correction to light quarks (*u*,*d*,*s*,*c*), several % for *g* and *b* quarks
- Without that correction, the measurement (see 1\fb result) suffers an uncertainty for the b/light response ratio of 0.83 GeV, by far dominant source

Phys. Rev. Lett. 101, 182001 (2008)

m(t): methods

- **Matrix Element method** (leading order) calculates event probability densities from dσ/dX

$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum \underbrace{d\sigma(y, m_t)}_{\text{LO ME}} \, dq_1 dq_2 \, \underbrace{f(q_1) f(q_2)}_{\text{PDFs}} \, \underbrace{W(y, x, k_{\mathrm{JES}})}_{\text{Transfer function}}$$

- **Ideogram method** event likelihood based on Breit-Wigner (signal) convoluted with detector resolutions

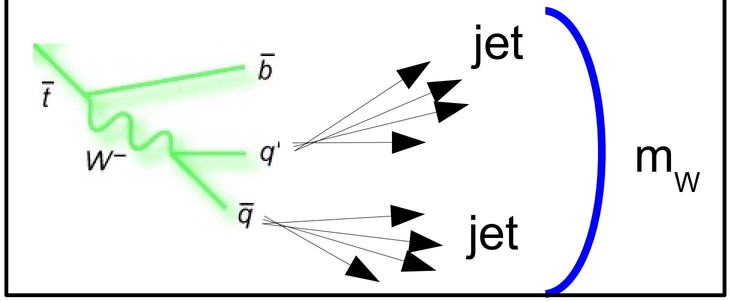
$$\mathcal{L}\,(\text{sample}|m_t, \text{JSF}) \;=\; \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{gof}}\,(i) \left(\sum_j f_j P_j(m_{t,i}^{\text{fit}}|m_t, \text{JSF}) \times P_j(m_{W,i}^{\text{reco}}|m_t, \text{JSF}) \right) \right)^{w_{\text{event}}}$$

- **Template method** compares histograms in data to simulations (including detector resolutions)

- Depend on MC → We measure "MC mass"

- **Alternative methods** ("End-point", J/ψ , "σ")

W boson fully reconstructed:
→ In-situ calibration, Constrain reconstructed m_W to m_W



m(t): single particle response

- JES does not distinguish quark and gluon jets
- Employ γ+jets events to calibrate response in MC to data
- Derive a correction factor F_{corr} for MC:

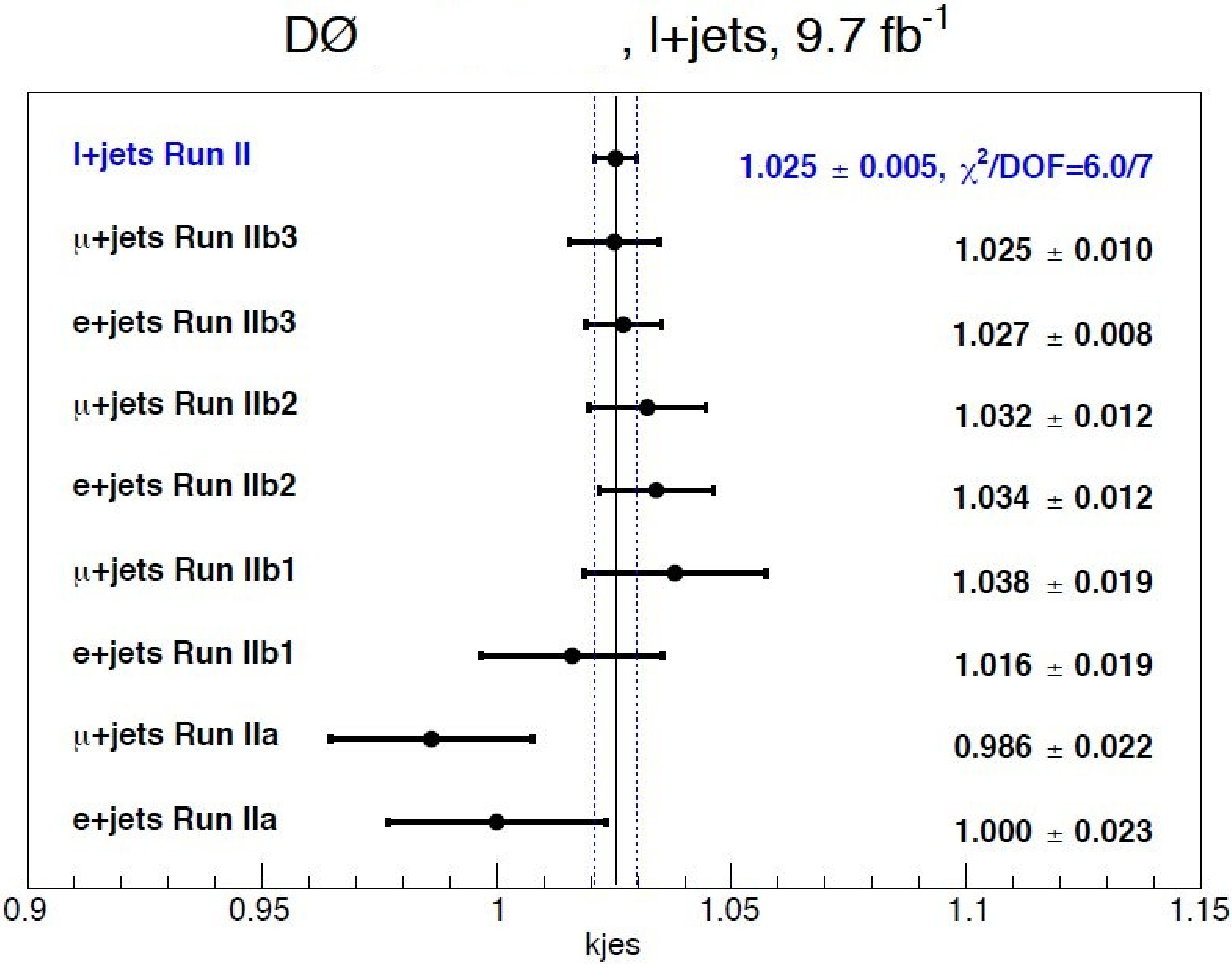
$$F_{\mathrm{corr}} = \frac{1}{\langle F \rangle_{\gamma+\mathrm{jet}}} \cdot \frac{\sum_i E_i \cdot R_i^{\mathrm{data}}}{\sum_i E_i \cdot R_i^{\mathrm{MC}}}$$

• Response in calorimeter for data or MC for particle *i* inside particle jet
• Matching with $dR < 0.25$

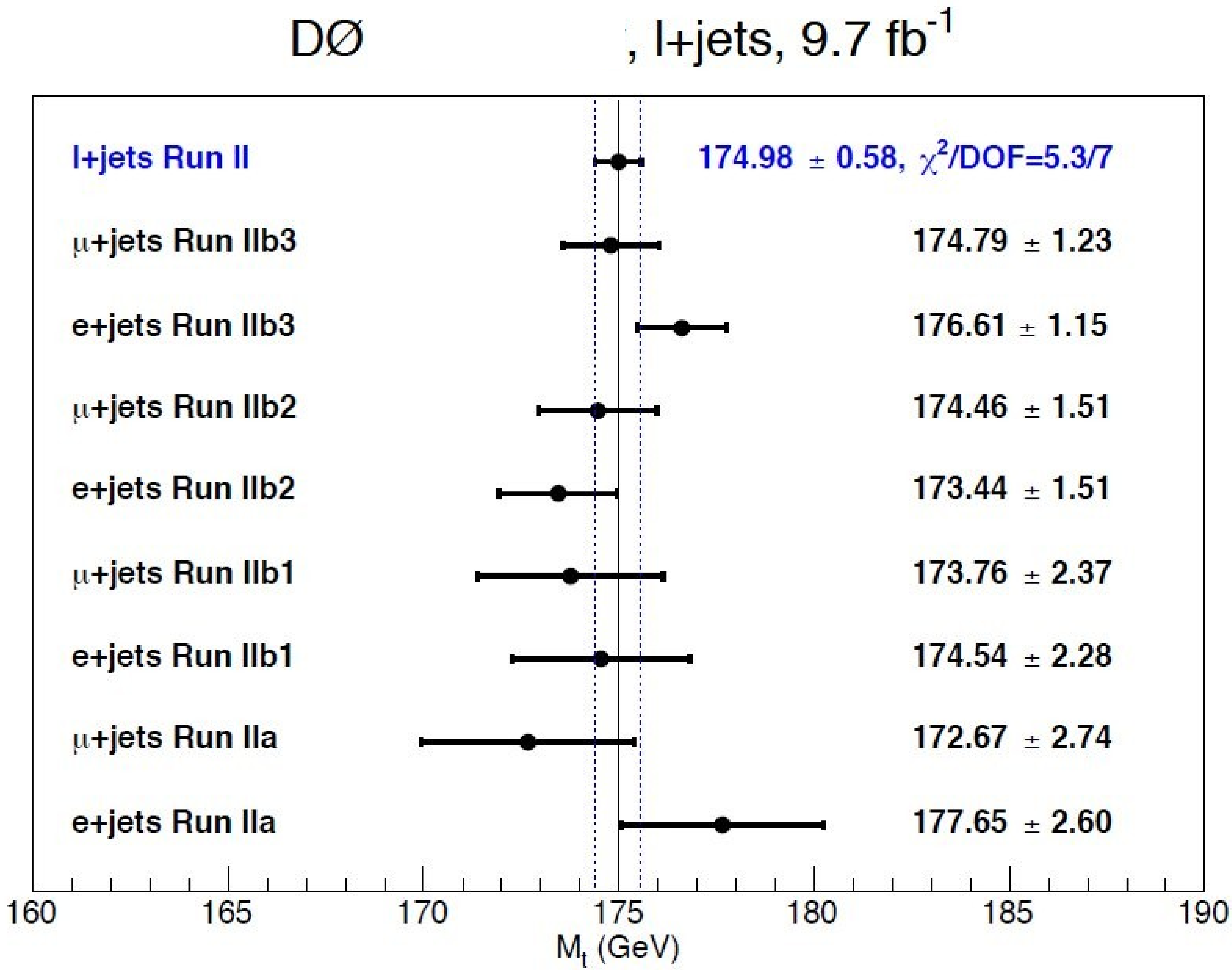
- Preserves standard JES calibration
- <u>Calibration by using:</u>
  - Reconstructed jet p_T with offset correction: p_T^{corr}
  - p_T of EM cluster with tight photon ID: p_T^{γ}
  - Calibrate ratio $p_T^{corr} / p_T^{\gamma}$

Assuming the single particle composition as in MC

m(t): matrix element method

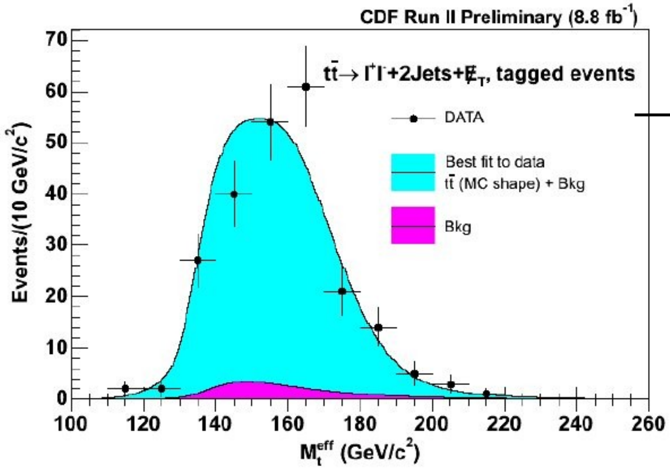


m(t): matrix element method



m(t): template method

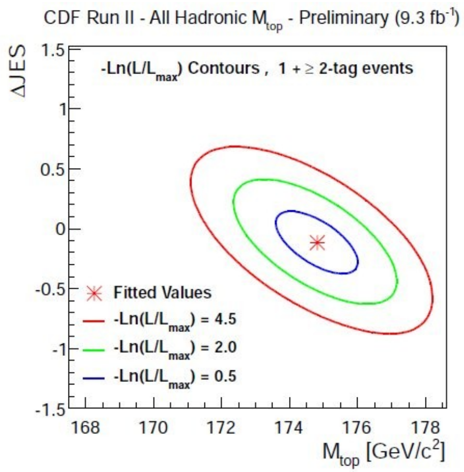
- Dilepton decay channel using Hybrid method to reduce JES uncertainty
  - $m_t^{eff} = w\, m_t^{reco} + (1-w)\, m_t^{alt}$, with:
    m_t^{reco} sensitive to true m_t (nW
    less sensitive to m_t
    but does not use jet energies

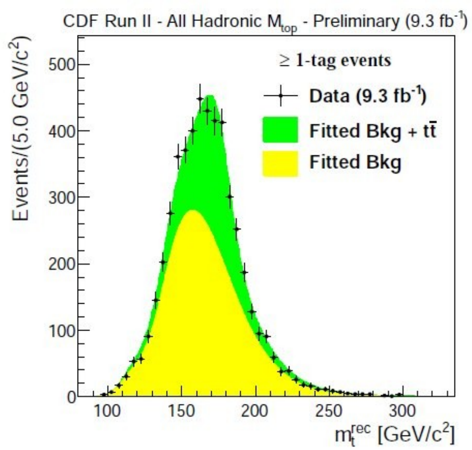


→ m_t^{alt}

→ m_t = 170.80 ± 1.83 (stat. + JES) ± 2.69 (syst.) GeV 1.9 % rel. unc.

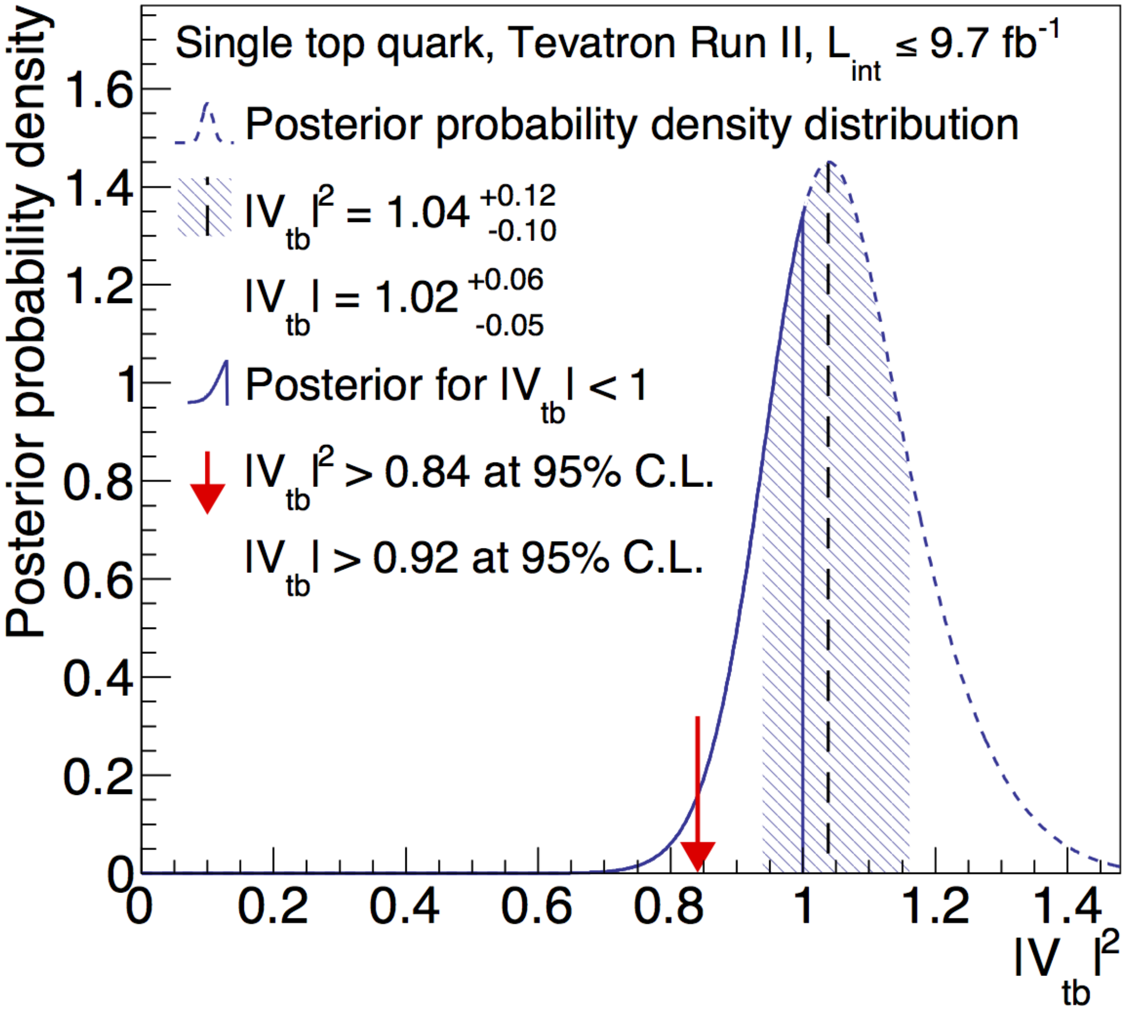
- All-hadronic decay channel:
  - Data driven bg model
  - S/B ~ 1 for ≥ 2 *b*-tags
  - For each event reconstruct *W* mass and *t* mass by minimizing χ^2
  - Hadronic *W decay* for in-situ JES cal.

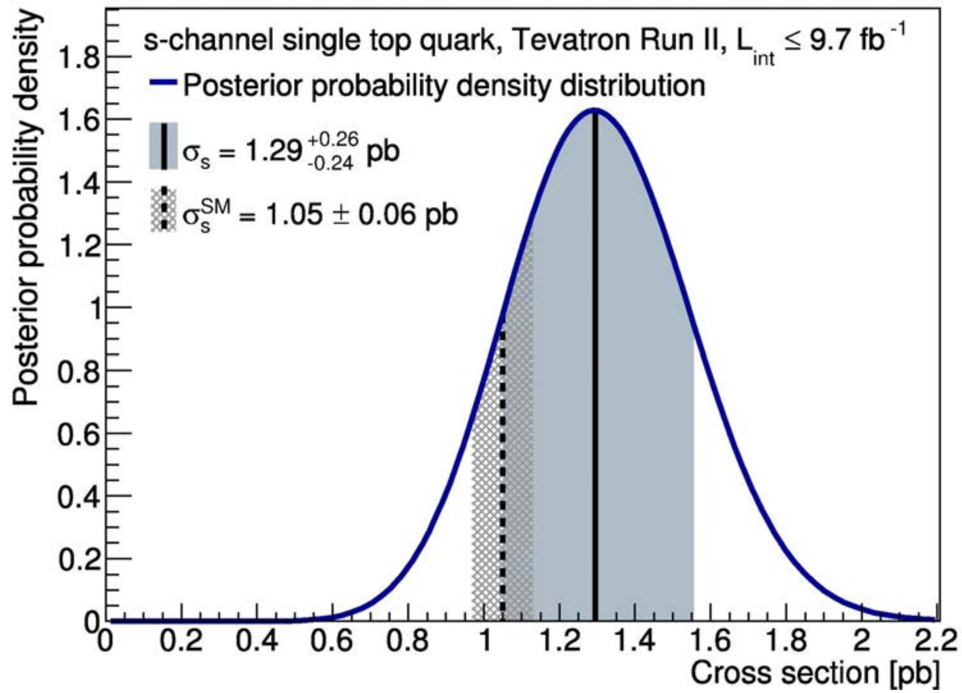




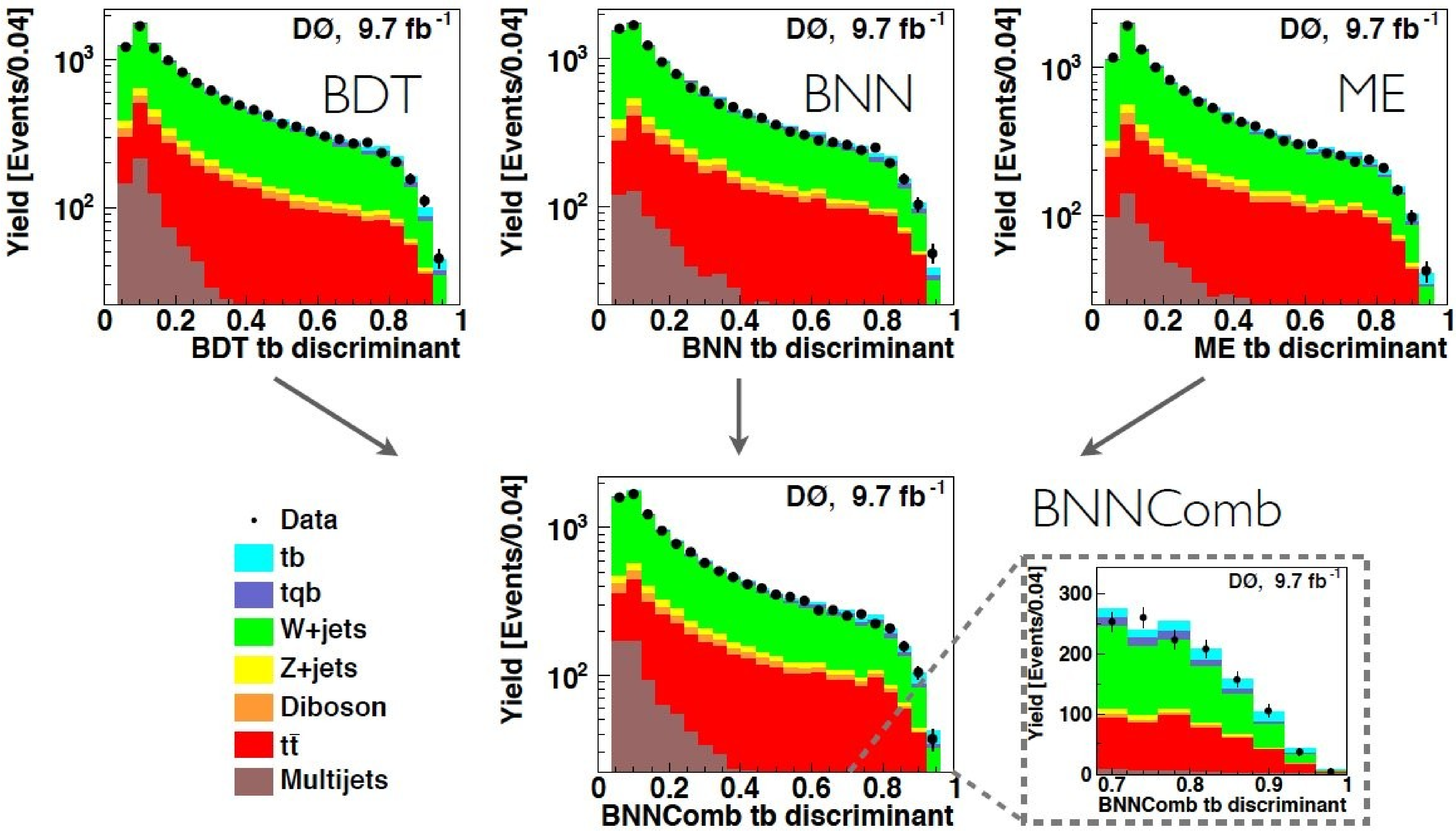
→ m_t = 175.07 ± 1.19 (stat. + JES) ± 1.56 (syst.) GeV 1.1 % rel. unc.

Single top production





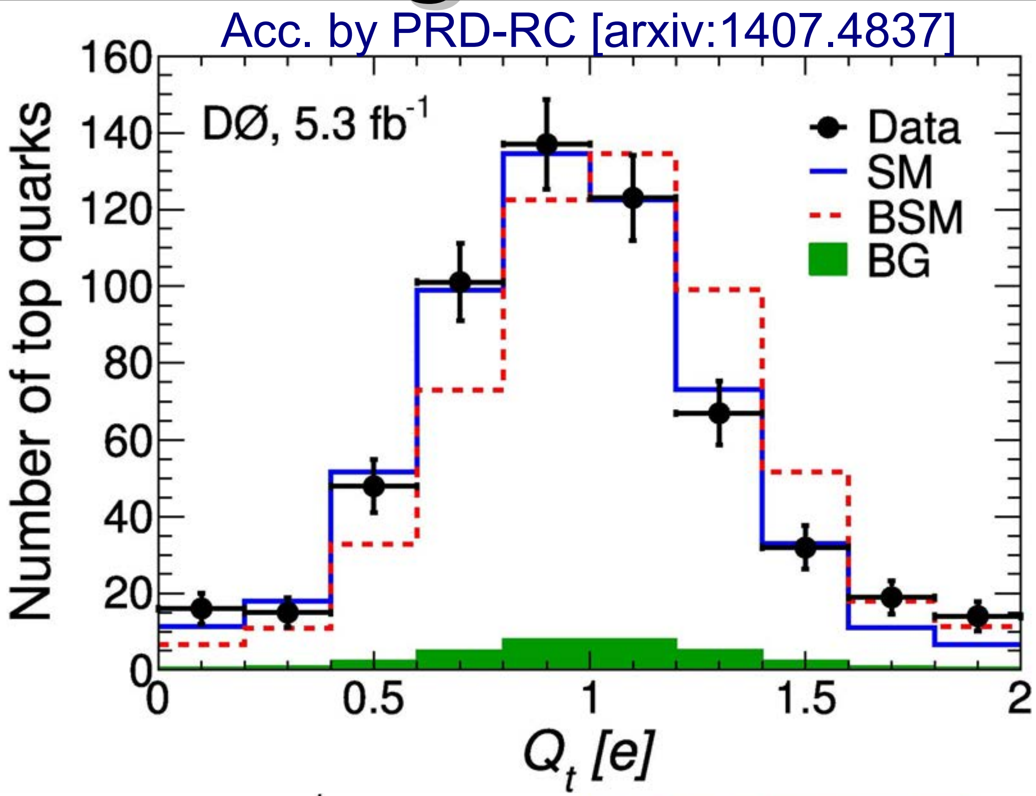
Single Top production

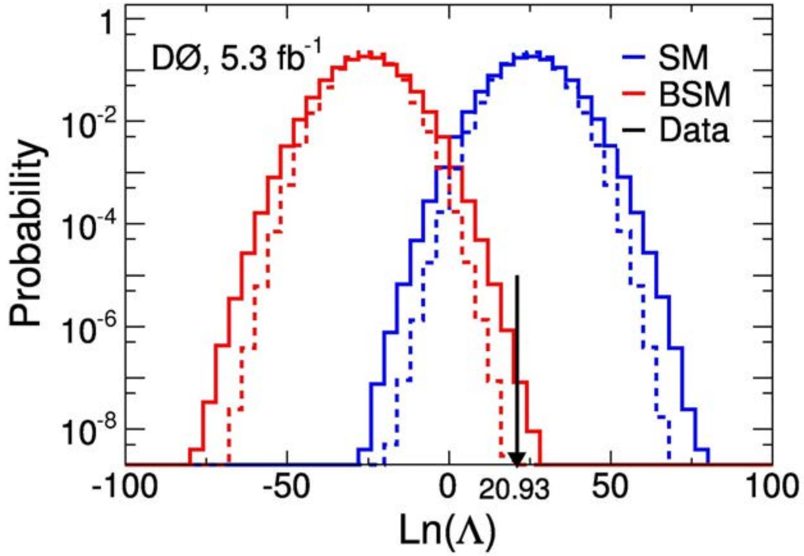


Top quark charge

- Fully reconstruct top pairs in lepton+jets decay channel
- Identify *b*-jet charge by jet charge algorithm
- Exclude -4/3 hypothesis with 5 s.d.

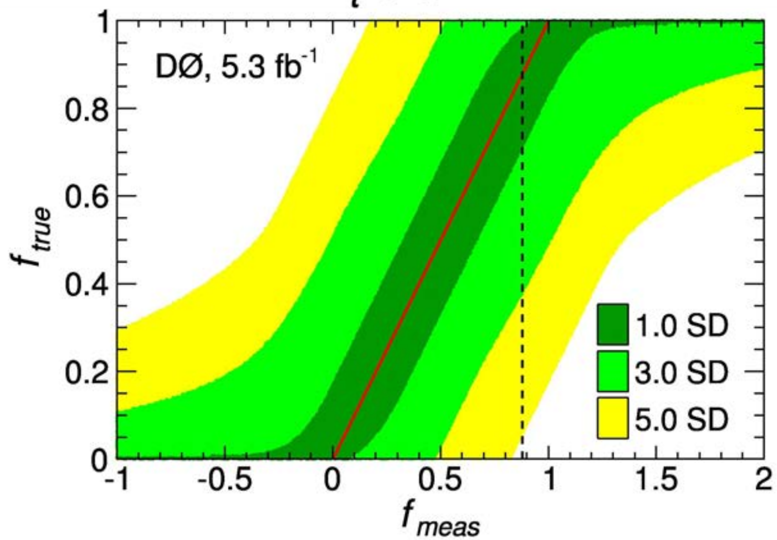
Acc. by PRD-RC [arxiv:1407.4837]





- Fraction of BSM quarks

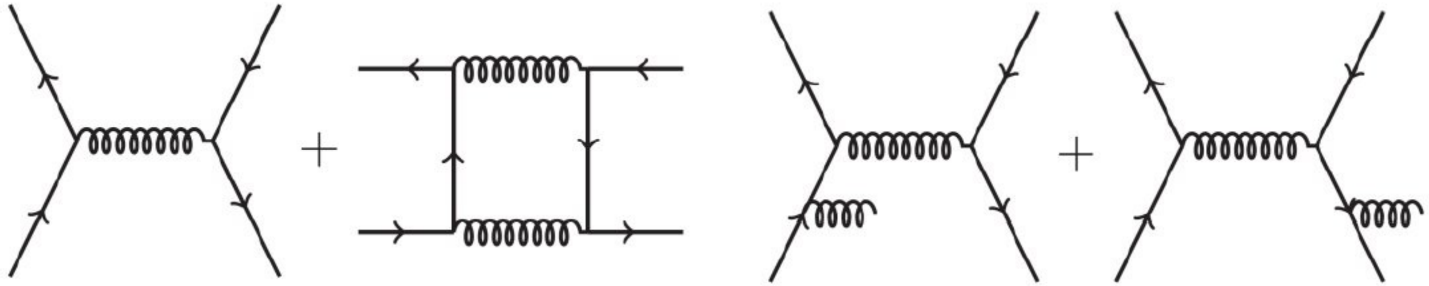
→ F_{BSM} < 0.46 @ 95% C.L.



- Confirmed earlier measurements

Top quark asymmetries

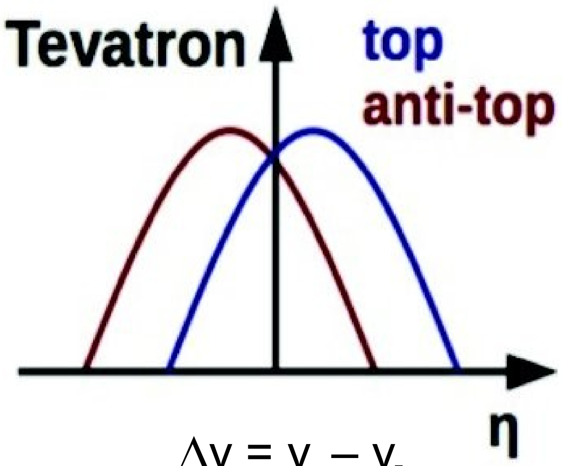
- <u>Interference appears at NLO QCD:</u>



Positive asymmetry   Negative asymmetry

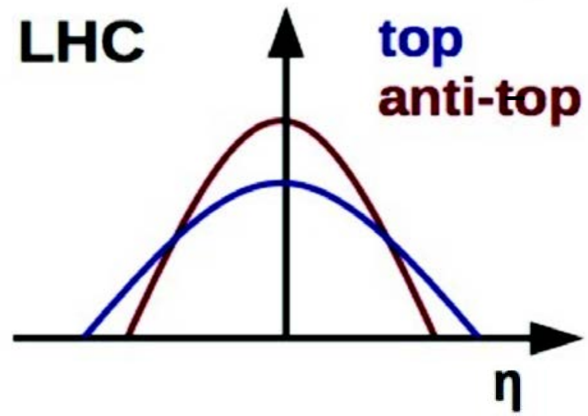
→ Only occurs in $q\bar{q}$ initial state; *gg* is fwd-bwd symmetric

- This is a forward-backward asymmetry at Tevatron
- No valence anti-quarks at LHC → $\bar{t}$ more central



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

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



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

- <u>SM predictions at NLO (QCD+EWK)</u>

→ Tevatron: $\mathbf{A_{FB}}$ **~ 8-9 %** vs. LHC: $\mathbf{A_C}$ **~ 1 %**

→ **<u>Update:</u> 10% at NNLO+NNLL**

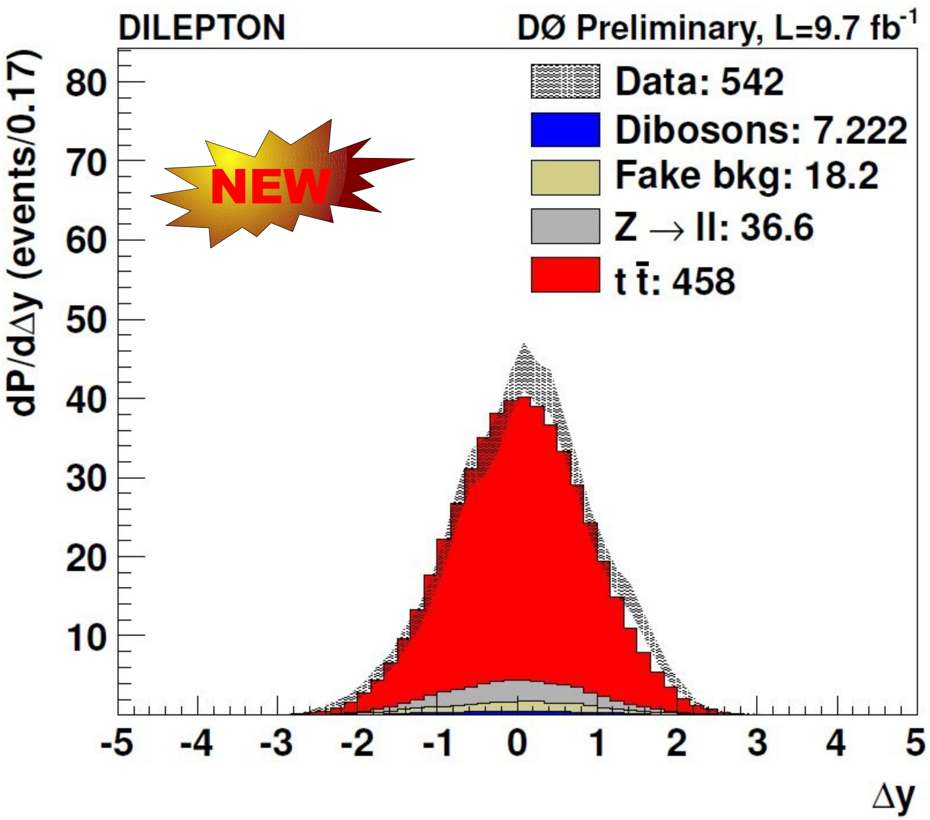
- Experimentally: Asymmetries based on <u>decay leptons</u> or fully <u>reconstructed top quarks</u>

"easier"

"harder"

Top quark asymmetries

- New measurement by D0 in the dilepton channel employing the matrix element method: D0 Conf. note 6445
  → assign a likelihood per event for most probably Δy (x) value

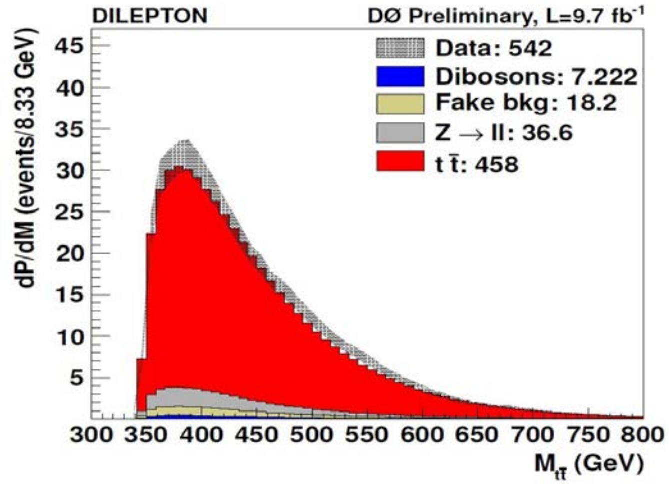


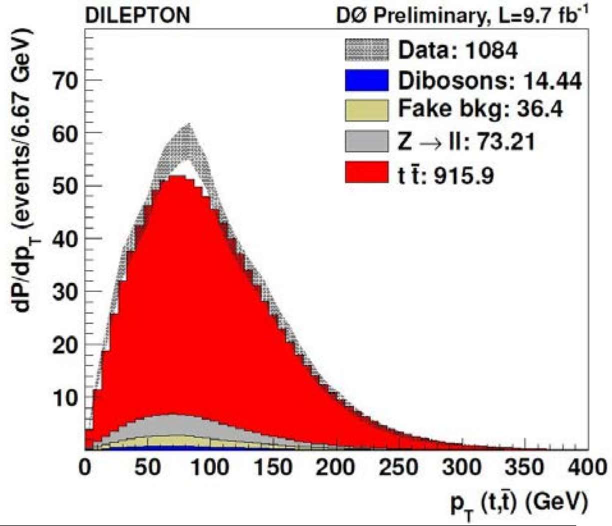
- Control distributions show reasonable data modeling by MC → extract asymmetry

Top quark asymmetries

- New measurement by D0 in the dilepton channel employing the matrix element method:
  → assign a likelihood per event for most probably Δy (x) value

Source of uncertainty	Uncertainty on $A_{FB}^{t\bar{t}}$ (%)
Detector modeling	
jet energy scale	0.14
jet energy resolution	0.17
flavor-dependent jet response	0.03
b-tagging	0.11
Signal modeling	
ISR/FSR	0.32
forward/backward ISR	0.36
hadronisation and showering	→ 1.08
higher order correction	0.80
PDF	0.60
Background model	
fake background normalization	0.35
fake background shape	0.35
background normalization	0.53
Calibration	
$\Delta y_{t\bar{t}}$ model	→ 2.7
calibration statistics	0.4
Total	3.3





Differential cross sections

- Detailed studies & tests of pQCD
- Corrected to parton level via matrix unfolding

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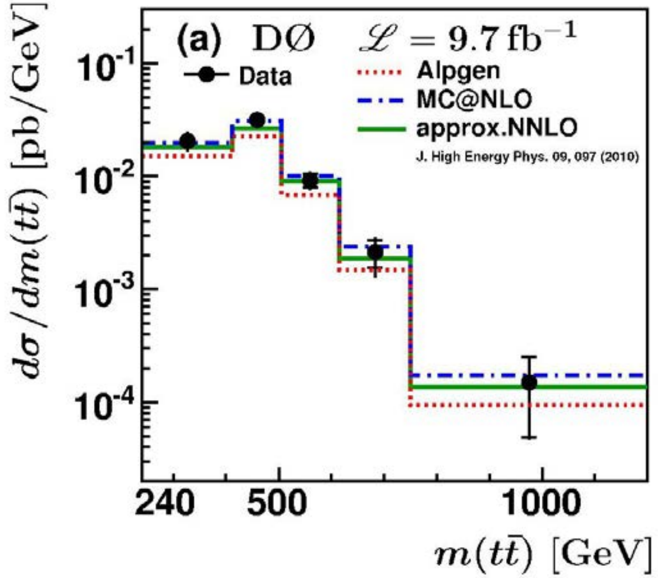
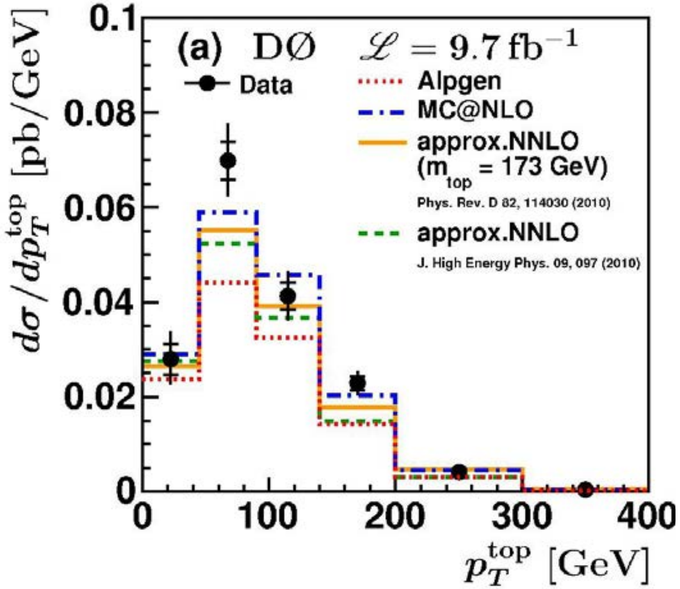
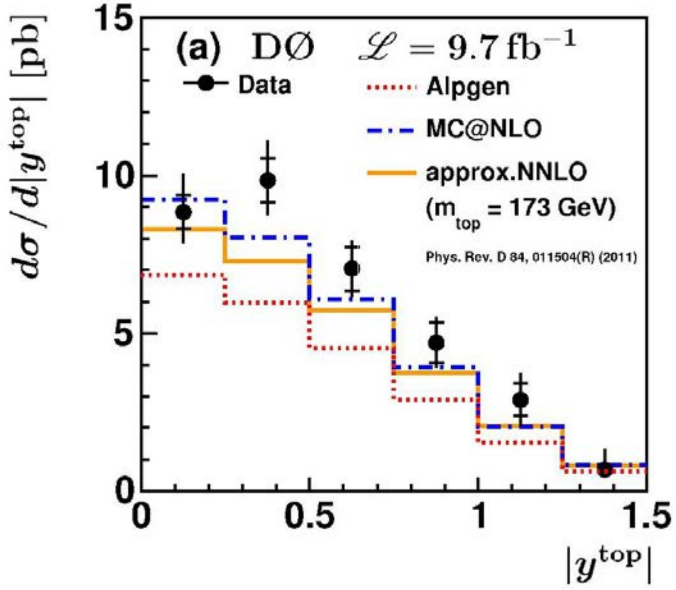
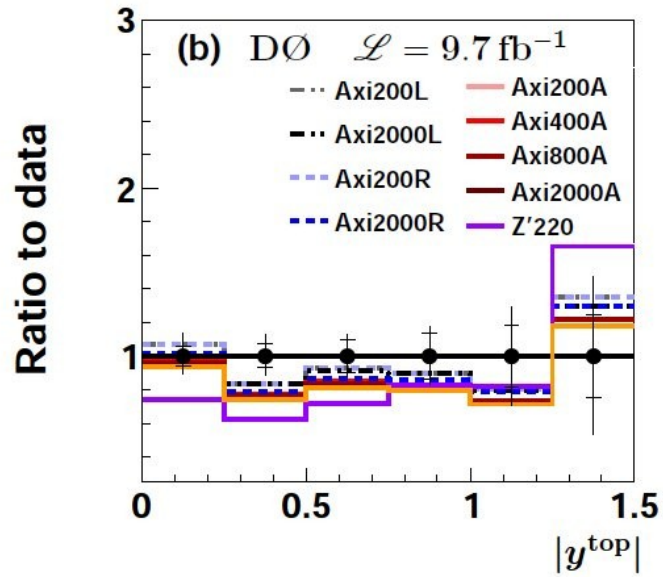






Stringent tests of QCD
Study new physics models: no signs



Axigluons and Z'

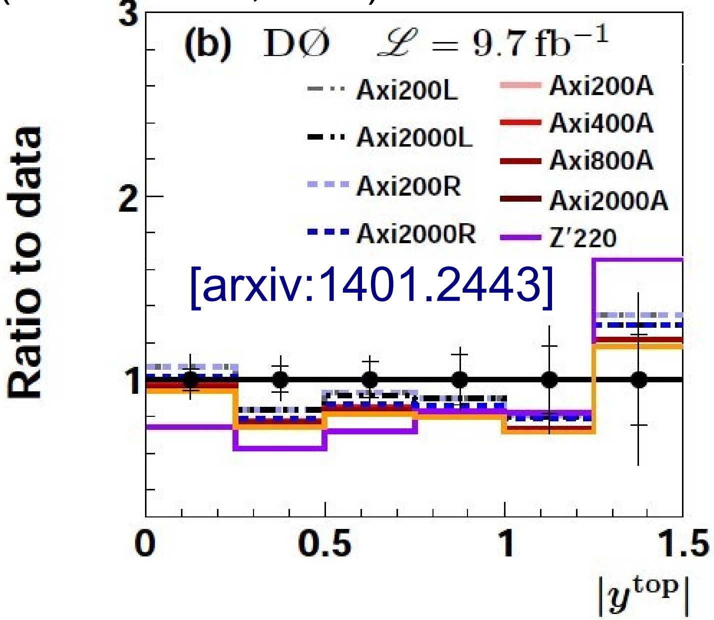
- Various axi gluon models with different couplings, differential cross section predictions (A. Falkowicz, et al.)

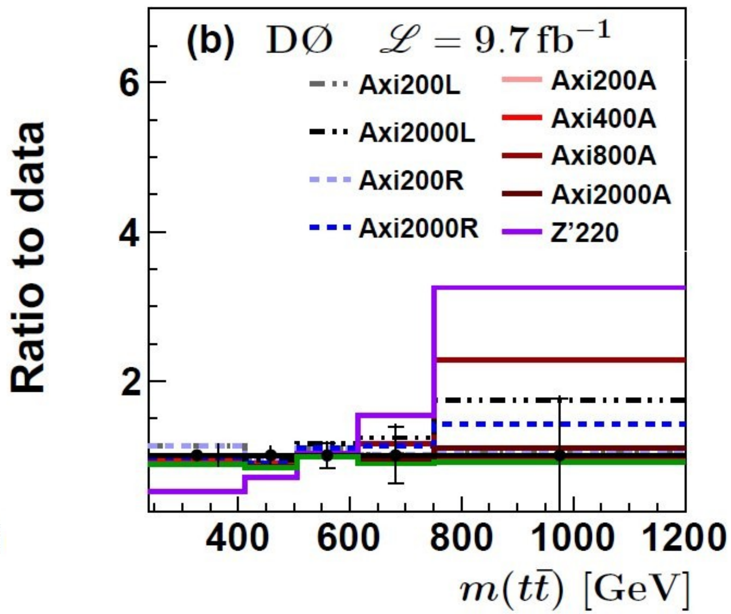
- Compare various models to unfolded cross section data using full covariance matrix:

$$\chi^2 = \sum_{i,j} (y-\mu)_i \cdot \mathrm{cov}^{-1}_{i,j} \cdot (y-\mu)_j$$

- Models with masses of 0.2 to 2 TeV for L (left), R (right), A (axial)
- Models are constrained by σ(tt), A_{FB} and high tail of dσ/dm(tt) at Tevatron and LHC

- Some models are in tension with the presented data !
  → Z', some axi gluons

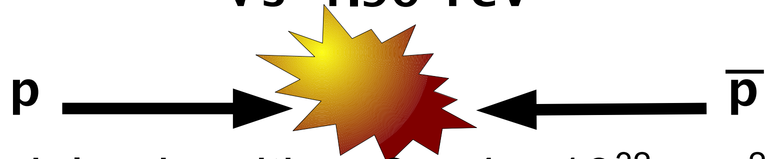




	$M(t\bar{t})$ $[\chi^2/ndf]$	p_T^{top} $[\chi^2/ndf]$	$\lvert y^{top}\rvert$ $[\chi^2/ndf]$
axi200L	0.96	1.07	1.20
axi200R	0.96	1.07	1.20
axi200A	0.85	3.55	3.88
axi400A	0.44	2.65	3.26
axi800A	0.97	2.86	3.23
axi2000L	0.58	1.27	3.78
axi2000R	0.43	1.94	2.75
axi2000A	0.88	3.56	4.11
Z'220	4.95	8.27	7.48

Tevatron data adds sensitivity at low mass
→ specific models constrained

$\sqrt{s}$=1.96 TeV



- Peak luminosities: 3 – 4 x 10^{32} $cm^{-2}s^{-1}$
- ~10 fb^{-1}/experiment recorded
- Tevatron shutdown September 2011