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Top quark properties at the Tevatron

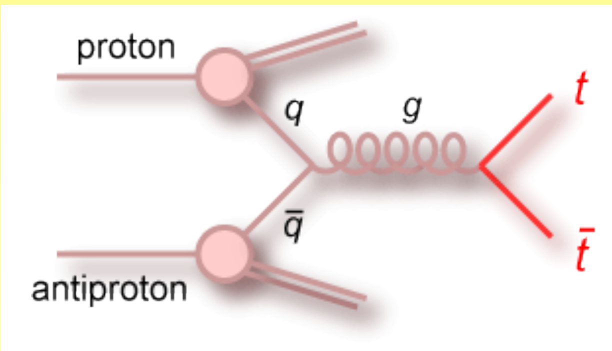
Frédéric Déliot
CEA/Irfu-Saclay

on behalf of the CDF and D0 collaborations

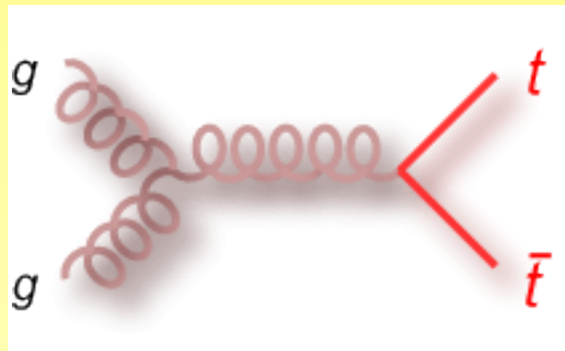
Les rencontres de physique de la vallée d'Aoste, 27 February 2014

Top quark production at the Tevatron

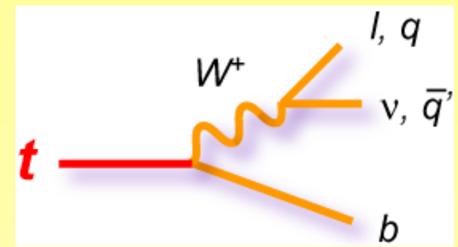
- Mainly pair production via QCD



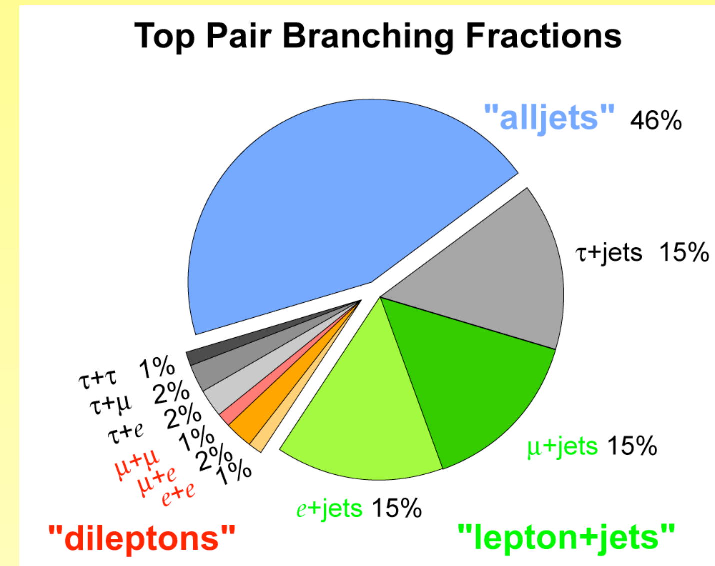
~ 85 %



~ 15 %



B(t➔Wb) ~ 100 %



- theoretical computations:
  Mt = 172.5 GeV, $\sigma(t\bar{t}) \approx 7.35$ pb (NNLO), $\Delta\sigma/\sigma \sim 4$ %

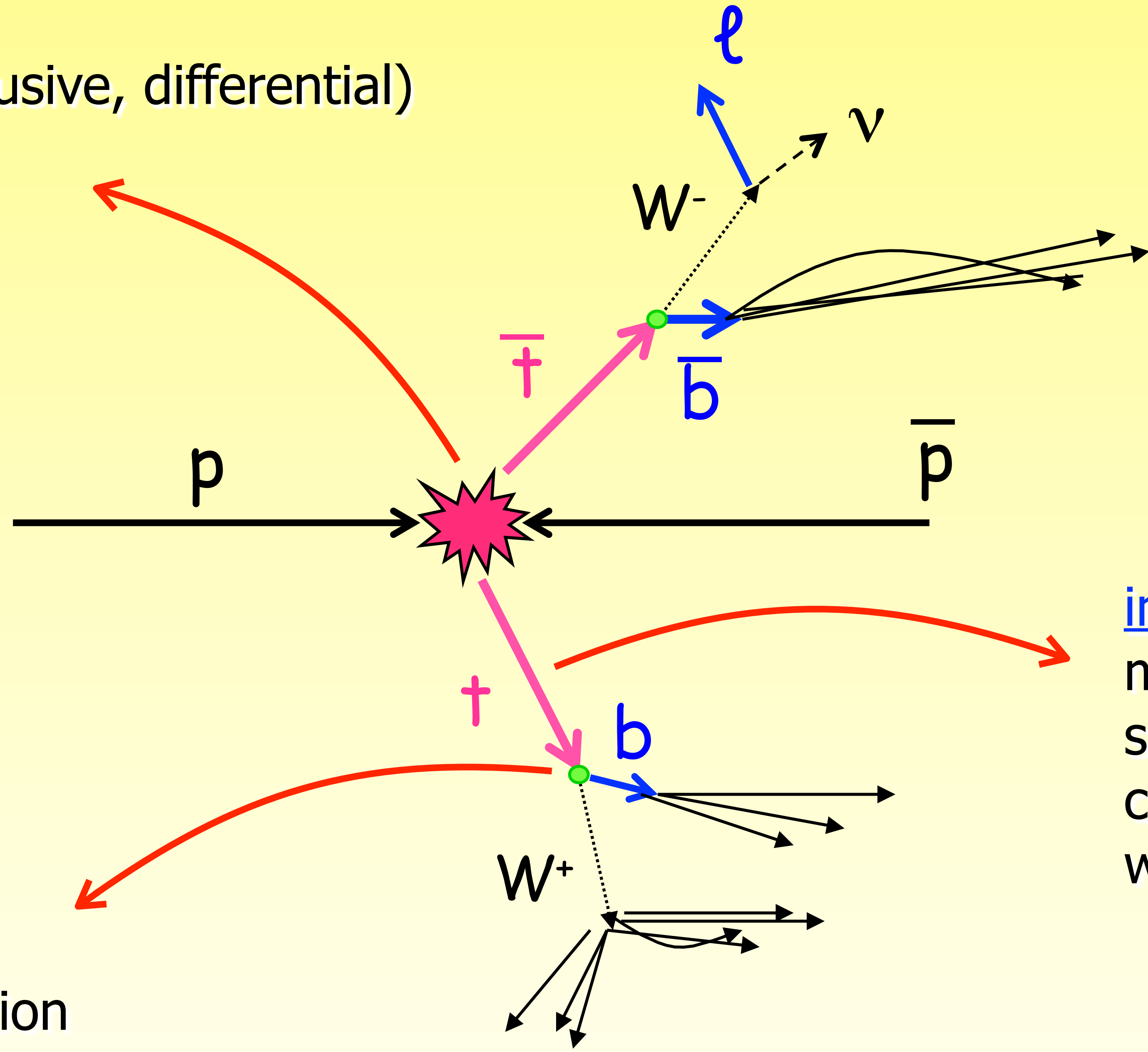
Calculation	$\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{\mathrm{scale}}$ (pb)	$\Delta\sigma_{\mathrm{PDF}}$ (pb)
NLO	6.85	$^{+0.37}_{-0.77}$	$^{+0.19}_{-0.13}$
NLO+NLL	7.09	$^{+0.28}_{-0.51}$	$^{+0.19}_{-0.13}$
NNLO+NNLL	7.35	$^{+0.11}_{-0.21}$	$^{+0.17}_{-0.12}$

computed with top++
M. Czakon, P. Fiedler, A. Mitov, PRL 110 252004 (2013)

We have a large sample of $t\bar{t}$ events with the full Tevatron dataset mainly produced by $q\bar{q}$ (~7.5 kevts observed per experiment)

Top quark properties from $t\bar{t}$ events

production:
cross sections (inclusive, differential)
charge asymmetry
top polarization

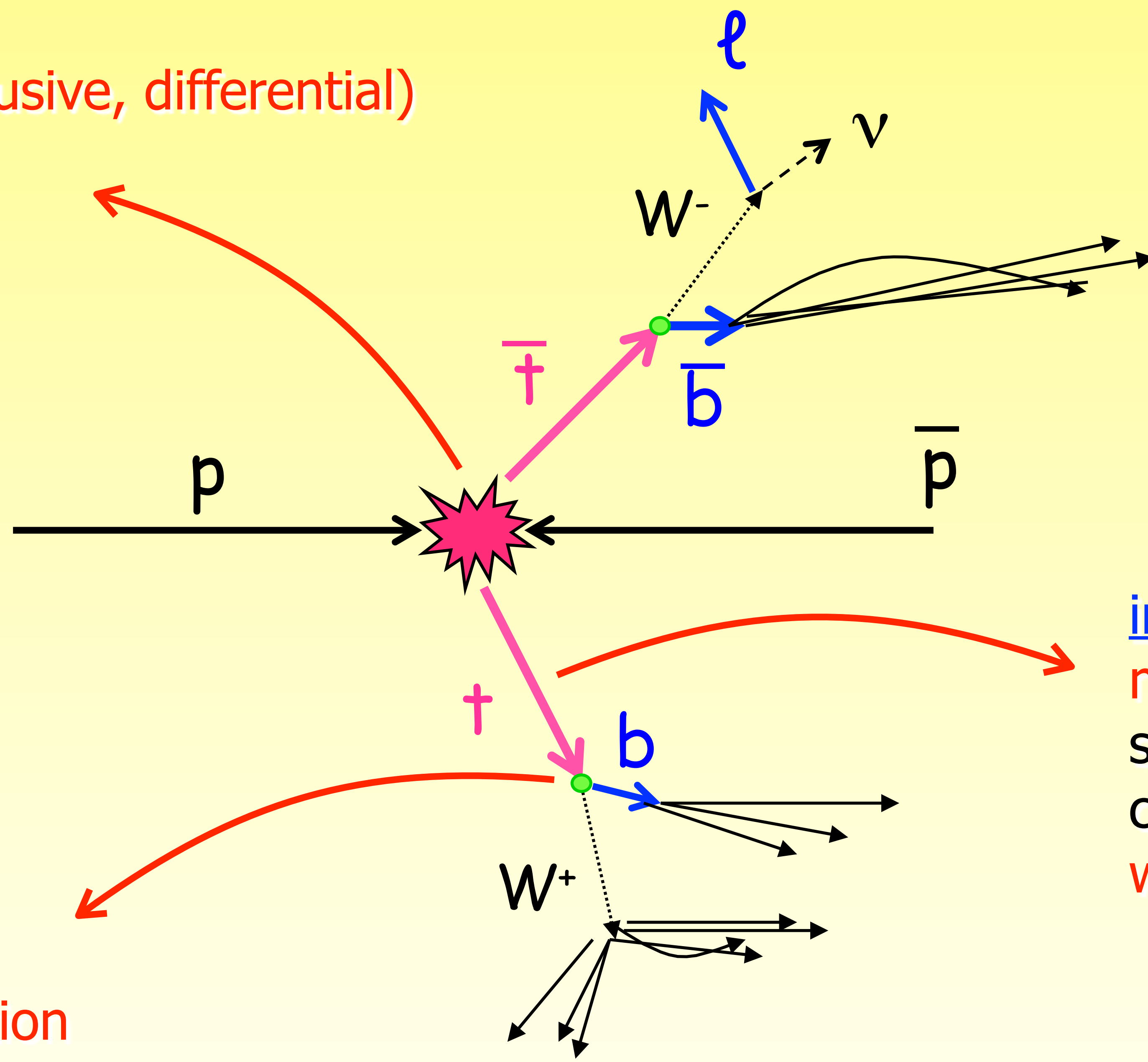


intrinsic:
mass
spin correlation
charge
width

decay:
W helicity
branching fraction

Does the heaviest elementary particle behave as expected ?

Top quark properties from $t\bar{t}$ events



production:
cross sections (inclusive, differential)
charge asymmetry
top polarization

intrinsic:
mass
spin correlation
charge
width

decay:
W helicity
branching fraction

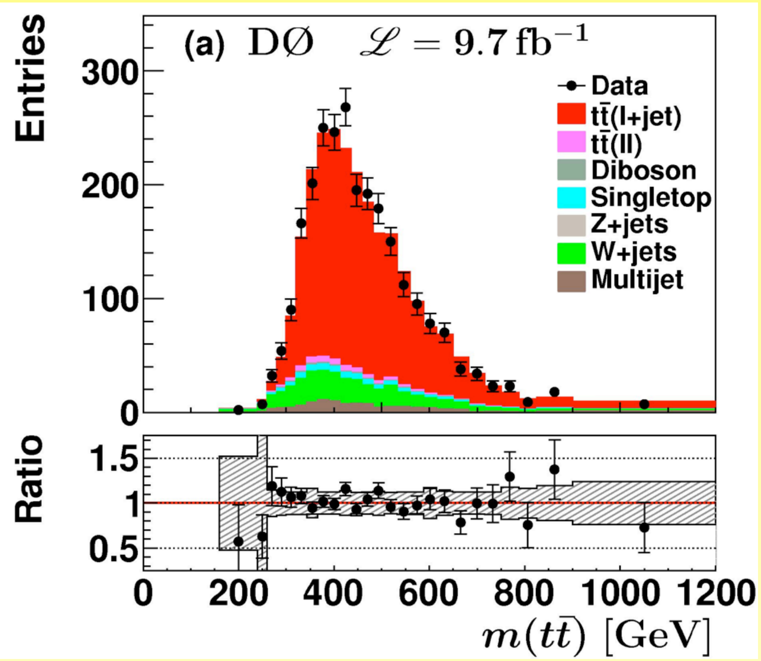
This talk will focus on the latest results

$t\bar{t}$ cross sections

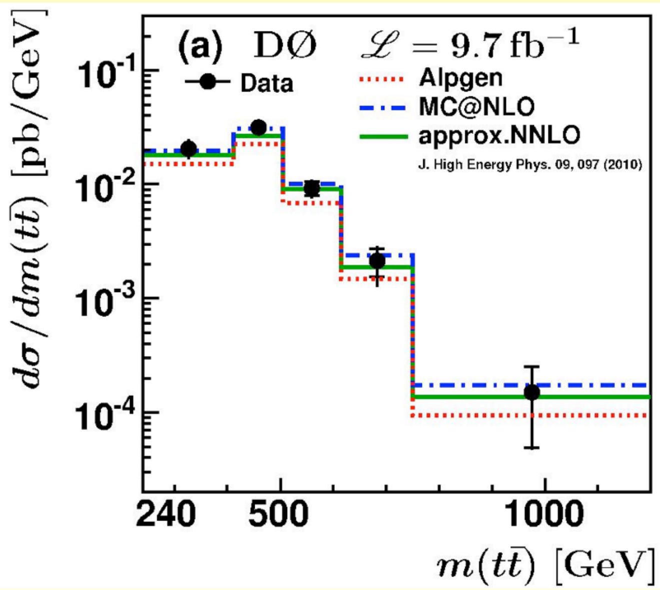
Differential $t\bar{t}$ cross section

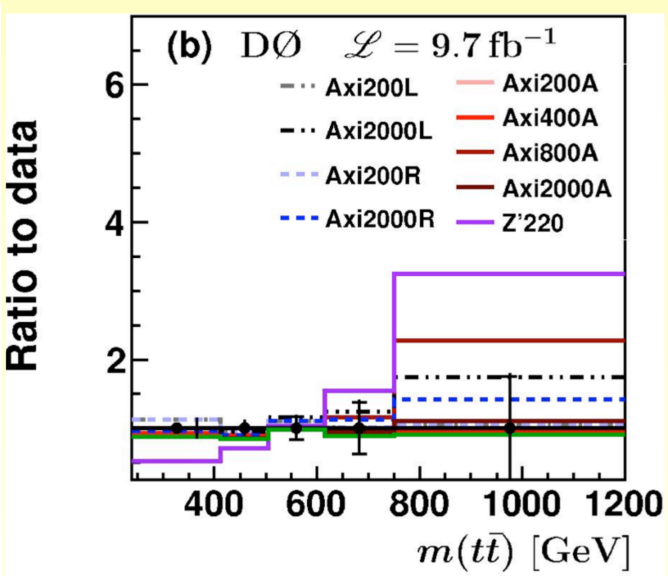
arXiv:1401.5785, submitted to PRD

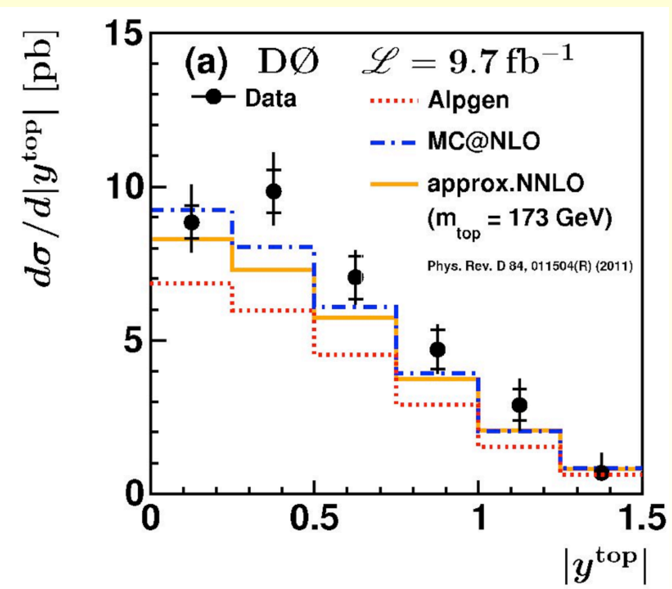
- stringent tests of QCD in the top quark sector
  - → allowed by the large $t\bar{t}$ statistics
  - → crucial to understand the QCD modeling
    (new physics search, $t\bar{t}$ charge asymmetry)
- l+jets channel with 1 b-tag
  - → measurements vs m_{tt}, $p_T(t)$, $|y(t)|$
    normalized to the NNLO inclusive cross section
  - → $t\bar{t}$ final state reconstructed with a X^2 method,
    corrected to parton-level using regularized matrix unfolding

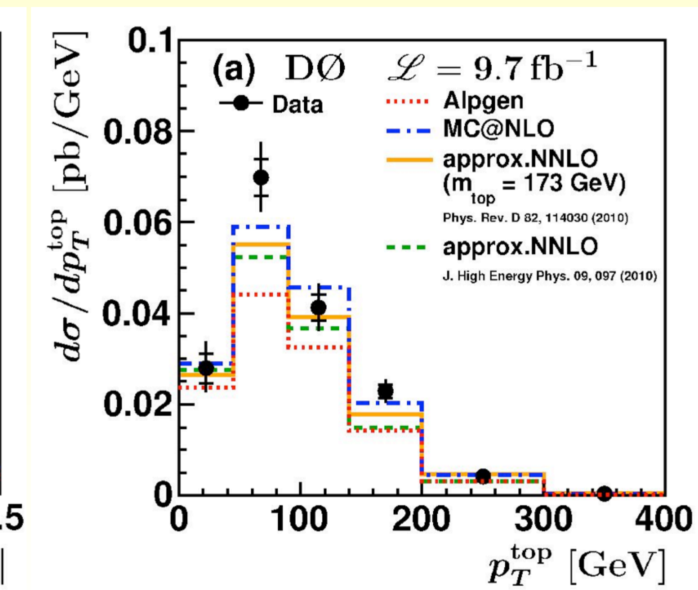


Source of uncertainty	Uncertainties, % δ_{incl}	$\lvert\delta_{\text{diff}}\rvert$
Signal modeling	$^{+5.2}_{-4.4}$	4.0 – 14.2
PDF	$^{+3.0}_{-3.4}$	0.9 – 4.4
Detector Modeling	$^{+4.0}_{-4.1}$	3.1 – 13.7
Sample composition	±1.8	2.8 – 9.2
Regularization strength	±0.2	0.8 – 2.1
Integrated luminosity	±6.1	6.1 – 6.1
Total systematic uncertainty	$^{+9.6}_{-9.3}$	8.5 – 23.1









Typical uncertainty: ~ 9 %
Overall good agreement with the predictions

Tevatron $t\bar{t}$ cross section combination

arXiv:1309.7570, accepted by PRD

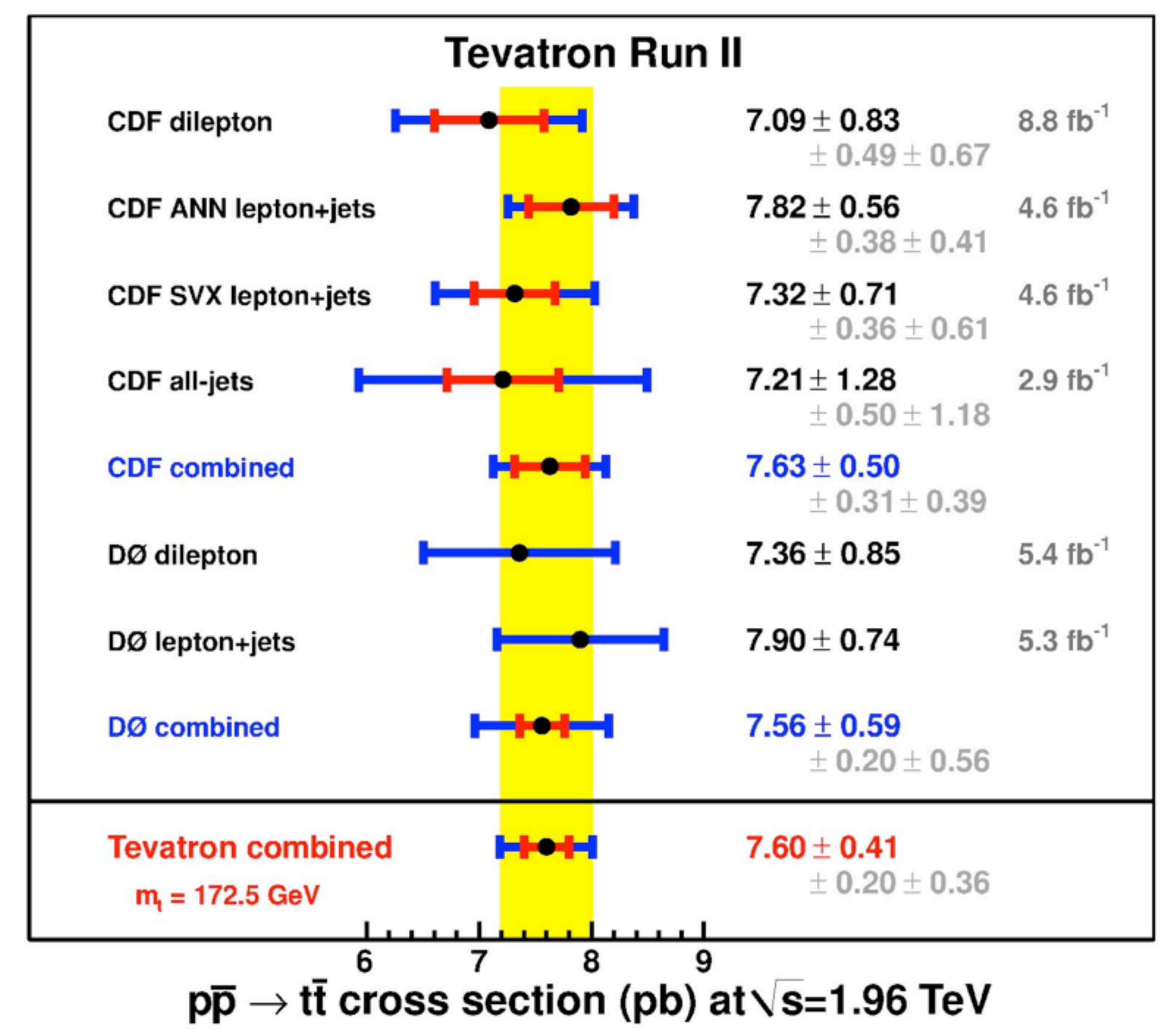
- First Tevatron combination of inclusive $t\bar{t}$ cross sections

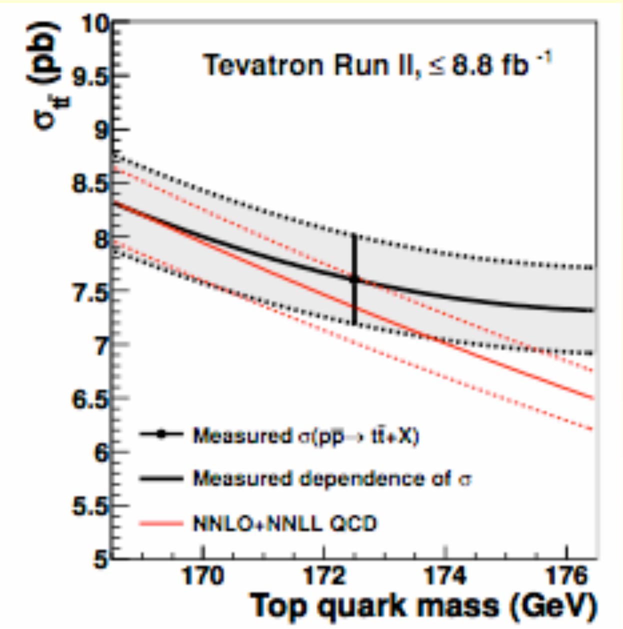
➔ combination of 6 measurements:

* CDF: 2 l+jets, dilepton, alljets

* D0: l+jets, dilepton

	CDF	D0		Tevatron
Central value of $\sigma_{\bar{t}t}$	7.63	7.56		7.60
Sources of systematic uncertainty			Correlation	
Modeling of the detector	0.17	0.22	NO	0.13
Modeling of signal	0.21	0.13	YES	0.18
Modeling of jets	0.21	0.11	NO	0.13
Method of extracting $\sigma_{t\bar{t}}$	0.01	0.07	NO	0.03
Background modeled from theory	0.10	0.08	YES	0.10
Background based on data	0.08	0.06	NO	0.05
Normalization of Z/γ^* prediction	0.13	–	NO	0.08
Luminosity: inelastic $p\bar{p}$ cross section	0.05	0.30	YES	0.15
Luminosity: detector	0.06	0.35	NO	0.14
Total systematic uncertainty	0.39	0.56		0.36
Statistical uncertainty	0.31	0.20		0.20
Total uncertainty	0.50	0.59		0.41





weights: CDF 60%, D0 40%

X^2 = 0.01/1, Prob = 92%

Total uncertainty: 5.4 %

improvement: 18% wrt CDF, 30% wrt D0

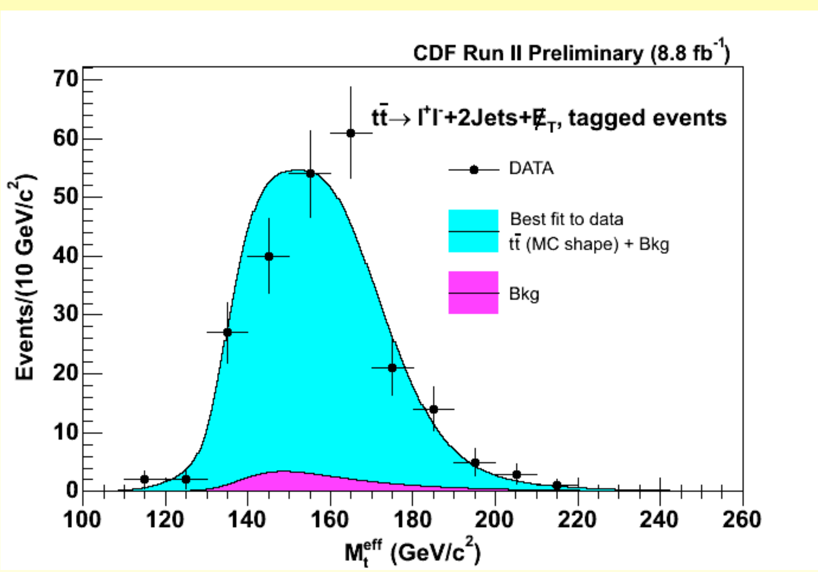
Intrinsic properties

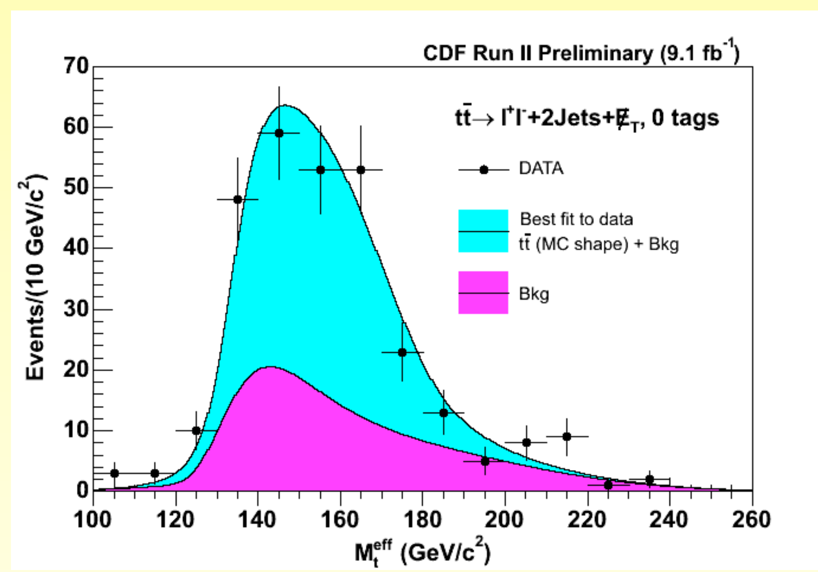
Dilepton top-quark mass

- Measurement with the full Tevatron dataset
  - ➔ statistics is no longer the limiting uncertainty, this analysis also optimized the influence of jet energy scale
- template analysis using an hybrid variable

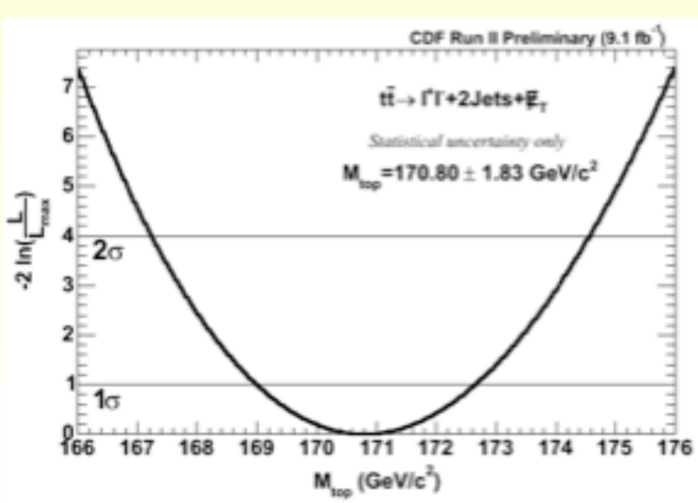
$$M_t^{eff} = w \cdot M_t^{reco} + (1-w) \cdot M_t^{alt}$$

  - ➔ M_t^{reco}: reconstructed top mass (neutrino Φ weighting)
  - ➔ M_t^{alt}: based only on lepton 4-momenta and jet directions: $M_t^{alt} \equiv \sqrt{\frac{\langle l_1, b_1 \rangle \cdot \langle l_2, b_2 \rangle}{E_{b_1} E_{b_2}}} + 120\ \mathrm{GeV}$
  - ➔ optimization of the uncertainty: w = 0.7





CDF Run II Preliminary (9.1 fb^{-1})	
M_{top} Measurement in the $t\bar{t}$ Dilepton Final State	
Source	Uncertainty (GeV/c^2)
Jet energy scale	2.42
NLO effects	0.64
Monte Carlo generators	0.49
Lepton energy scale	0.36
b-jet energy scale	0.34
Initial and final state radiation	0.33
Background modeling	0.33
Luminosity profile (pileup)	0.30
Color reconnection	0.24
gg fraction	0.24
Parton distribution functions	0.21
MC statistics	0.19
b-tagging	0.05
Total systematic	2.69
Statistical	1.83
Total	**3.25**



$$M_{top} = 170.80 \pm 1.83\ (\mathrm{stat.}) \pm 2.69\ (\mathrm{syst.})\ \mathrm{GeV}$$

10% improved uncertainty compared to the latest CDF result in this channel

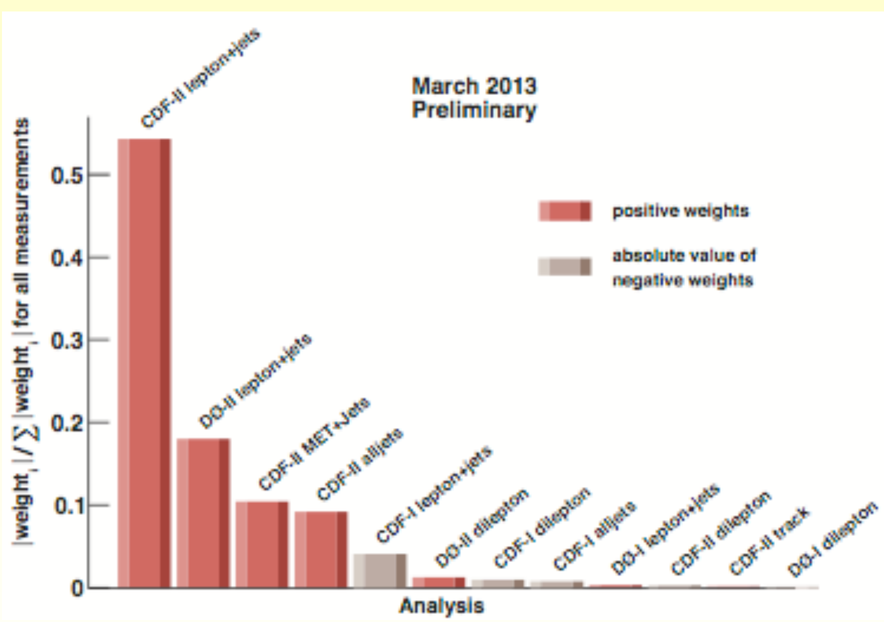
Tevatron top mass combination

arXiv:1305.3929

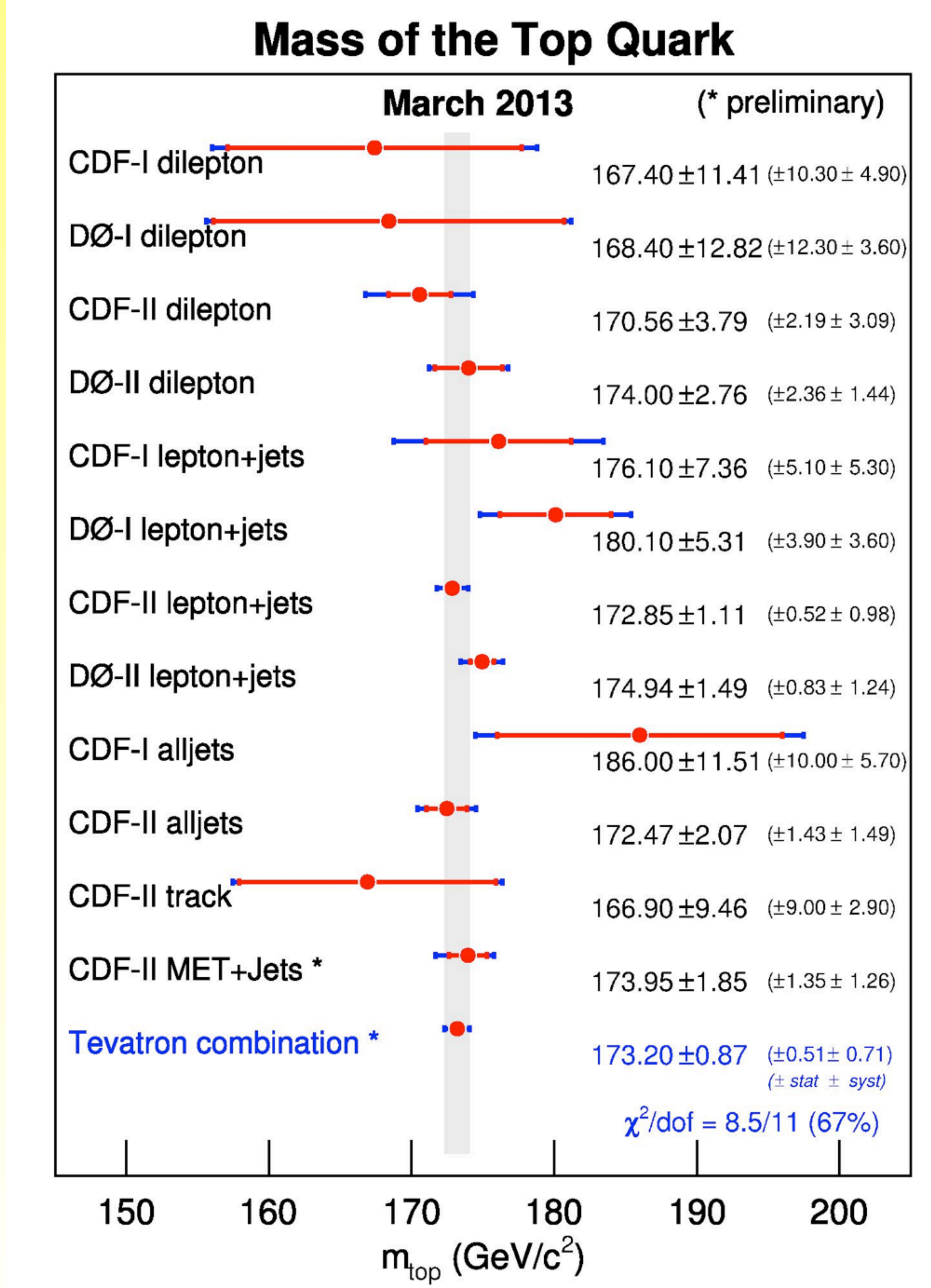
- Combination of 11 measurements
  - ➔ 5 from Run I, 7 from Run II

M_t	173.20
In situ light-jet calibration (iJES)	0.36
Response to $b/q/g$ jets (aJES)	0.09
Model for b jets (bJES)	0.11
Out-of-cone correction (cJES)	0.01
Light-jet response (2) (dJES)	0.15
Light-jet response (1) (rJES)	0.16
Lepton modeling (LepPt)	0.05
Signal modeling (Signal)	0.52
Jet modeling (DetMod)	0.08
Offset (UN/MI)	0.00
Background from theory (BGMC)	0.06
Background based on data (BGData)	0.13
Calibration method (Method)	0.06
Multiple interactions model (MHI)	0.07
Systematic uncertainty (syst)	0.71
Statistical uncertainty (stat)	0.51
Total uncertainty	0.87

precision of 0.5%



Combination with LHC measurements underway



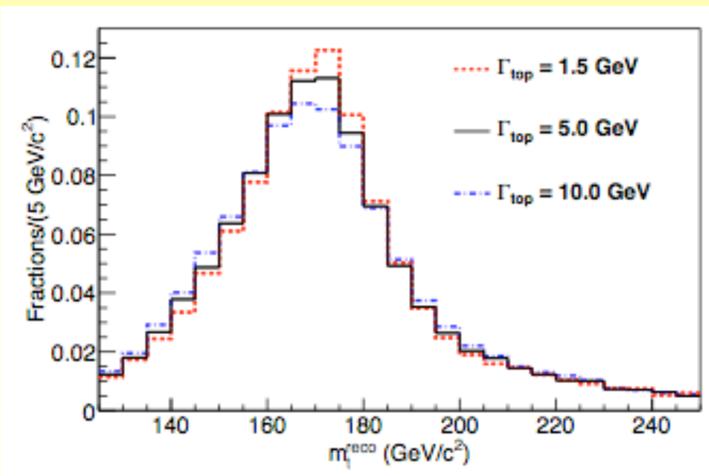
Top-quark width

- The top quark has the largest decay width of the known fermions
  - → NNLO QCD: Γ_t = 1.32 GeV (±1%), can be used to extract V_{tb}
  - → non standard width would indicate non-SM top decays

- CDF direct measurement
  - → fit the data with template of M_t^{reco} and M_{jj}
  - → the width of M_t^{reco} is used to extract Γ_t

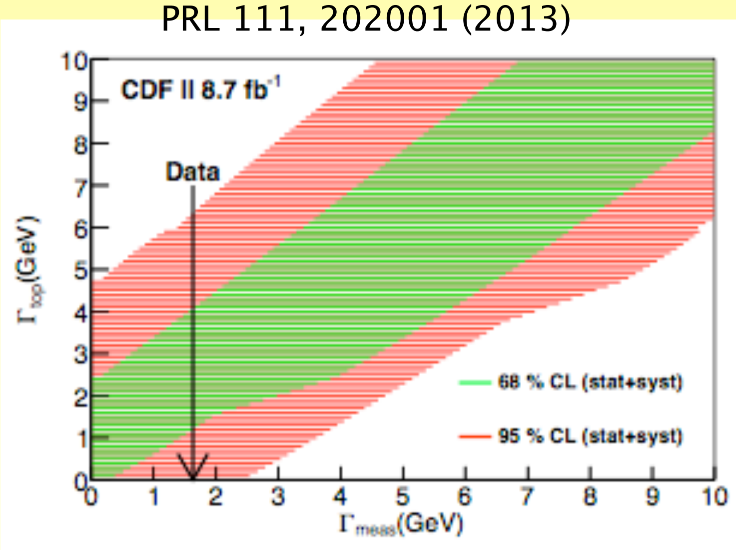
$$1.10 < \Gamma_{top} < 4.05 \text{ GeV}$$ at 68% CL

M_{jj} constrains the JES uncertainty



Source	Uncertainty (GeV)
Jet resolution	0.56
Color reconnection	0.69
Event generator	0.50
Higher-order effects	0.21
Residual jet-energy scale	0.19
Parton distribution functions	0.24
b-jet energy scale	0.28
Background shape	0.18
Gluon fusion fraction	0.26
Initial- and final-state radiation	0.17
Lepton energy scale	0.03
Multiple hadron interaction	0.23
Total systematic uncertainty	1.22

PRL 111, 202001 (2013)

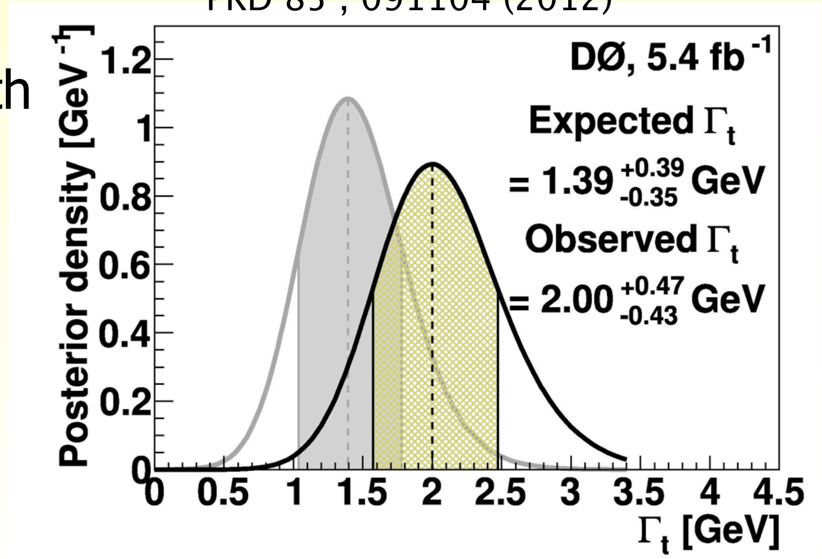


- D0 indirect determination
  - → using the t-channel single top cross section to extract the partial top width
  - → using the branching ratio B(t→Wb) (see next slide) to get the total width
  - → based on the assumption that the coupling in t-channel and in top decay are the same

$$\Gamma_t = \frac{\sigma(t\text{-channel})\,\Gamma(t\to Wb)_{SM}}{\mathcal{B}(t\to Wb)\,\sigma(t\text{-channel})_{SM}}$$

$$\Gamma_t = 2.00^{+0.47}_{-0.43}\ \text{GeV}$$

PRD 85 , 091104 (2012)



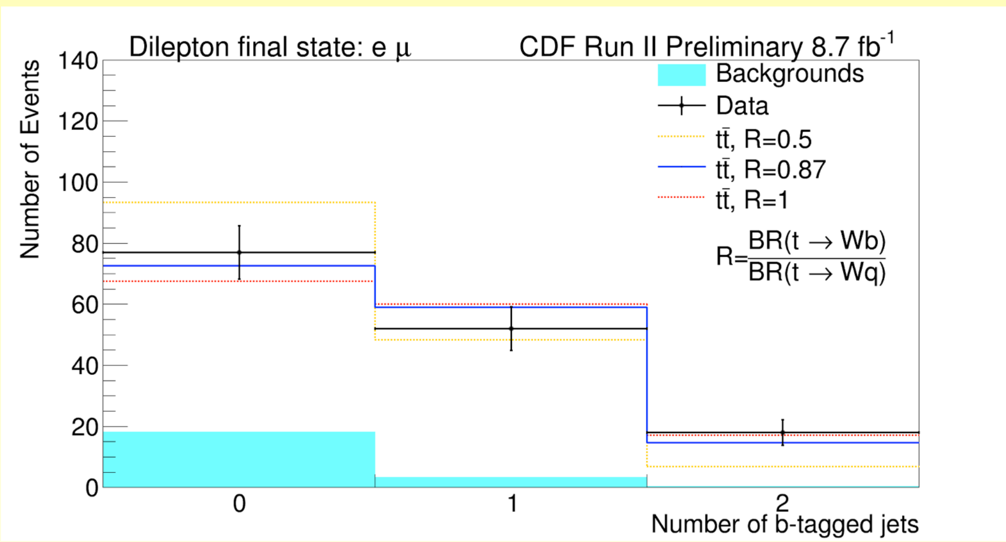
Decay properties

Top-quark branching fraction

- Comparing $t\bar{t}$ cross section measurements vs number of b-tag jets
  - ➔ indirect measurement of V_{tb}
  - ➔ test of existence of a 4th quark family

$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

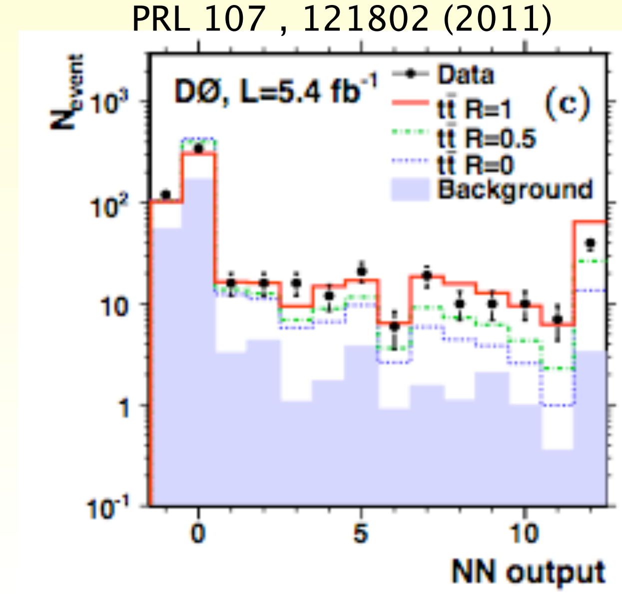
- Latest CDF measurement in the dilepton channel
  - ➔ several bins in lepton flavour and number of b-tags
  - ➔ R is extracted using a likelihood fit with nuisance parameters to constrain the systematic uncertainties



CDF Run II Preliminary, $\mathcal{L}$=8.7 fb^{-1}

Parameter	Result
$R = \frac{BR(t\to Wb)}{BR(t\to Wq)}$	0.87 ± 0.07
$\lvert V_{tb}\rvert$	0.93 ± 0.04

PRL 107 , 121802 (2011)

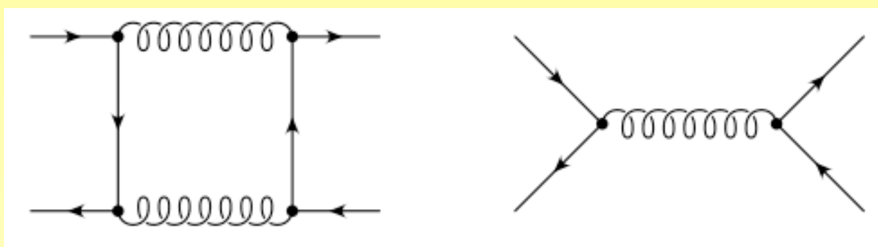


- D0 combined measurement in the l+jets and dilepton channel
  - ➔ fit together R and the $t\bar{t}$ cross section $R = 0.90 \pm 0.04$ (stat+syst)

$t\bar{t}$ asymmetries

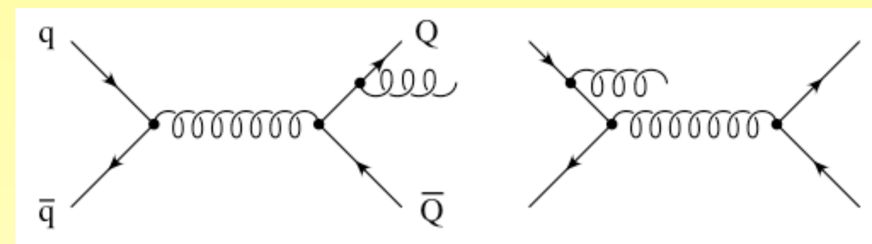
Top-antitop charge asymmetry

- At NLO, QCD predicts an asymmetry for $t\bar{t}$ produced via $q\bar{q}$ initial state
  - ➔ the top quark is predicted to be emitted preferably in the direction of the incoming quark
  - ➔ gg remains symmetric
  - ➔ this asymmetry can be modified by new physics (Z', axigluons, ...)

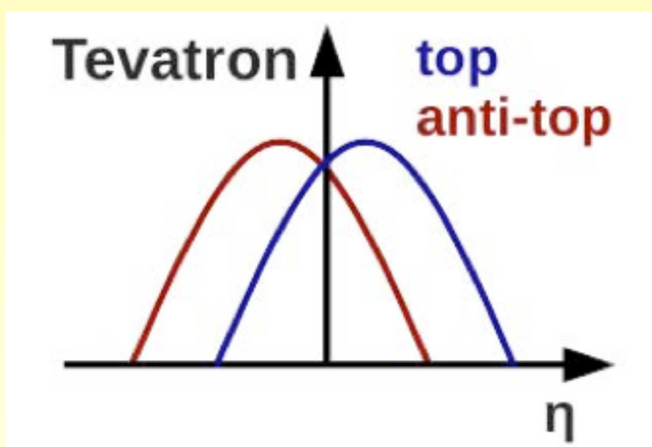


positive asymmetry

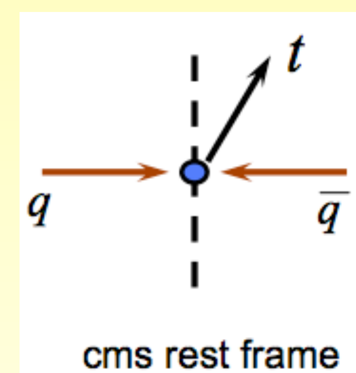
+



negative asymmetry



forward-backward asymmetry



~ LAB frame at the Tevatron

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

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

the lepton from the top-quark decay can also be used as asymmetry observable (lepton-based asymmetry)

Lepton-based asymmetry in the dilepton channel

see Z. Hong's talk at the YSF yesterday

- Lepton-based asymmetry
  - ➔ advantage: no need to reconstruct the $t\bar{t}$ final state, sensitive to top-quark polarization
  - ➔ drawback: dilution of the produced asymmetry
    (w/o polarization effects, ~ half of the prediction for the $t\bar{t}$-based asymmetry)
  - ➔ relation between lepton-based and $t\bar{t}$-based asymmetry is model-dependent
- In the dilepton channel
  - ➔ two possible observables

$$A^{\ell}_{\rm FB} = \frac{N(q\times\eta>0) - N(q\times\eta<0)}{N(q\times\eta>0) + N(q\times\eta<0)}$$

$$A^{\ell\ell} = \frac{N(\Delta\eta>0) - N(\Delta\eta<0)}{N(\Delta\eta>0) + N(\Delta\eta<0)}$$

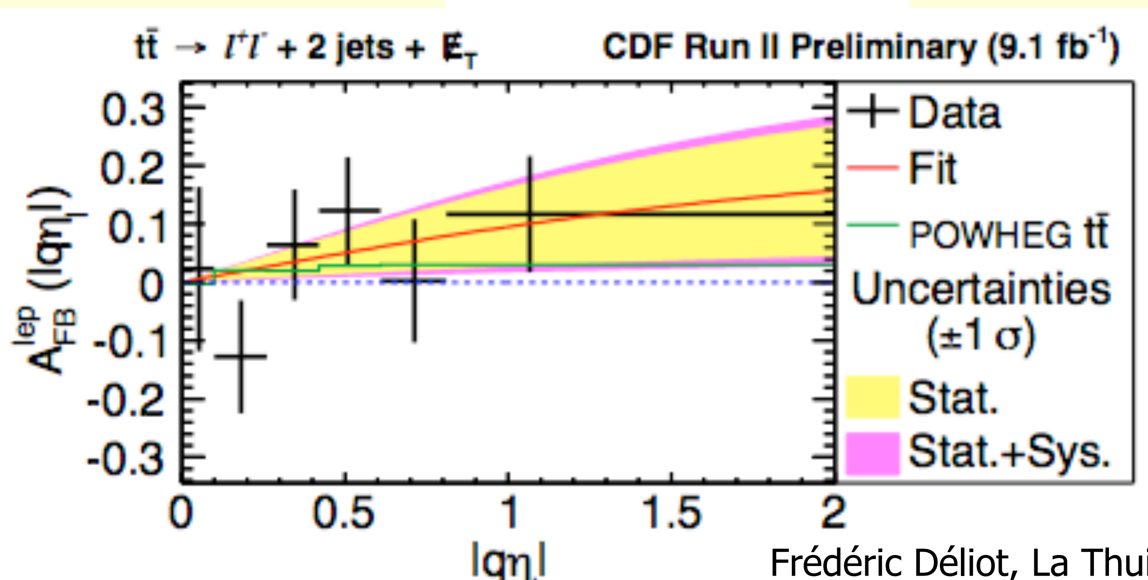
- Measurement at CDF
  - ➔ decompose the observable into the symmetric and asymmetric part
  - ➔ the asymmetric part is parametrized as: $A(|q\eta_l|) = a\cdot\tanh[\frac{1}{2}\cdot|q\eta_l|]$
  - ➔ the symmetric part is taken from MC at the generated level (almost model independent)
  - ➔ leptons are well measured: no bin migration due to detector effects

$$A^{lep}_{FB} = 0.072 \pm 0.052({\rm stat.}) \pm 0.030({\rm sys.}) = 0.072 \pm 0.060$$

SM: $A^{\rm lep}_{\rm FB} = 0.038 \pm 0.003$

$$A^{\Delta\eta}_{\rm FB} = 0.076 \pm 0.072({\rm stat.}) \pm 0.037({\rm sys.}) = 0.072 \pm 0.081$$

SM: $A^{\Delta\eta}_{\rm FB} = 0.048 \pm 0.004$



CDF Run II Preliminary (9.1 fb^{-1})

Source of Uncertainty ($A^{\rm lep}_{\rm FB}$)	Value
Backgrounds	0.029
Asymmetric Modeling	0.006
Jet Energy Scale	0.004
Symmetric Modeling	0.001
Total Systematic	0.030
Statistical	0.052
Total Uncertainty	0.060

Lepton-based asymmetry in the l+jets channel

- Only one observable based only on leptons:
  ➔ same methodology as in the dilepton channel:
  * decomposition in the symmetric and asymmetric parts
  * fit the asymmetric part which allows to extrapolation outside the detector acceptance

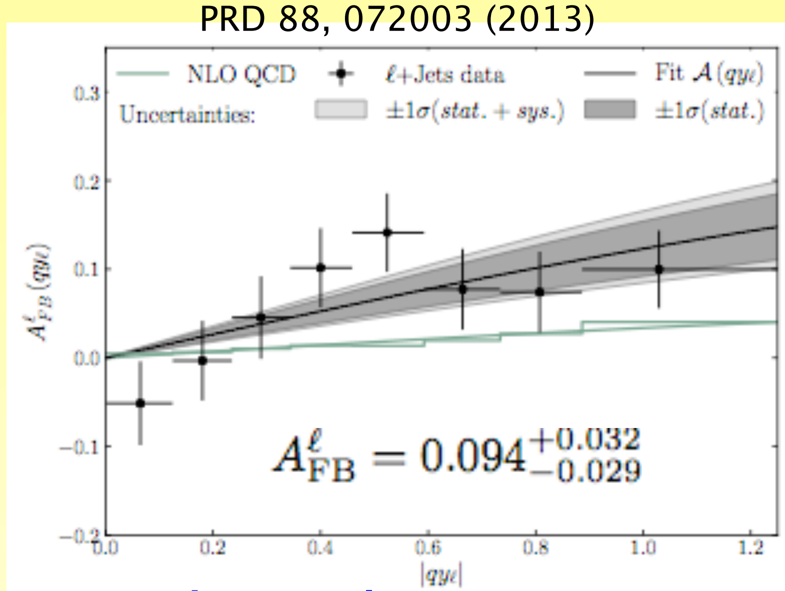
$$A^{\ell}_{\rm FB} = \frac{N(qy_\ell > 0) - N(qy_\ell < 0)}{N(qy_\ell > 0) + N(qy_\ell < 0)}$$

$$\mathcal{S}(qy_\ell) = \frac{N(qy_\ell) + N(-qy_\ell)}{2}$$

$$\mathcal{A}(qy_\ell) = \frac{N(qy_\ell) - N(-qy_\ell)}{N(qy_\ell) + N(-qy_\ell)}$$

SM: $A^{\rm lep}_{\rm FB} = 0.038 \pm 0.003$

PRD 88, 072003 (2013)



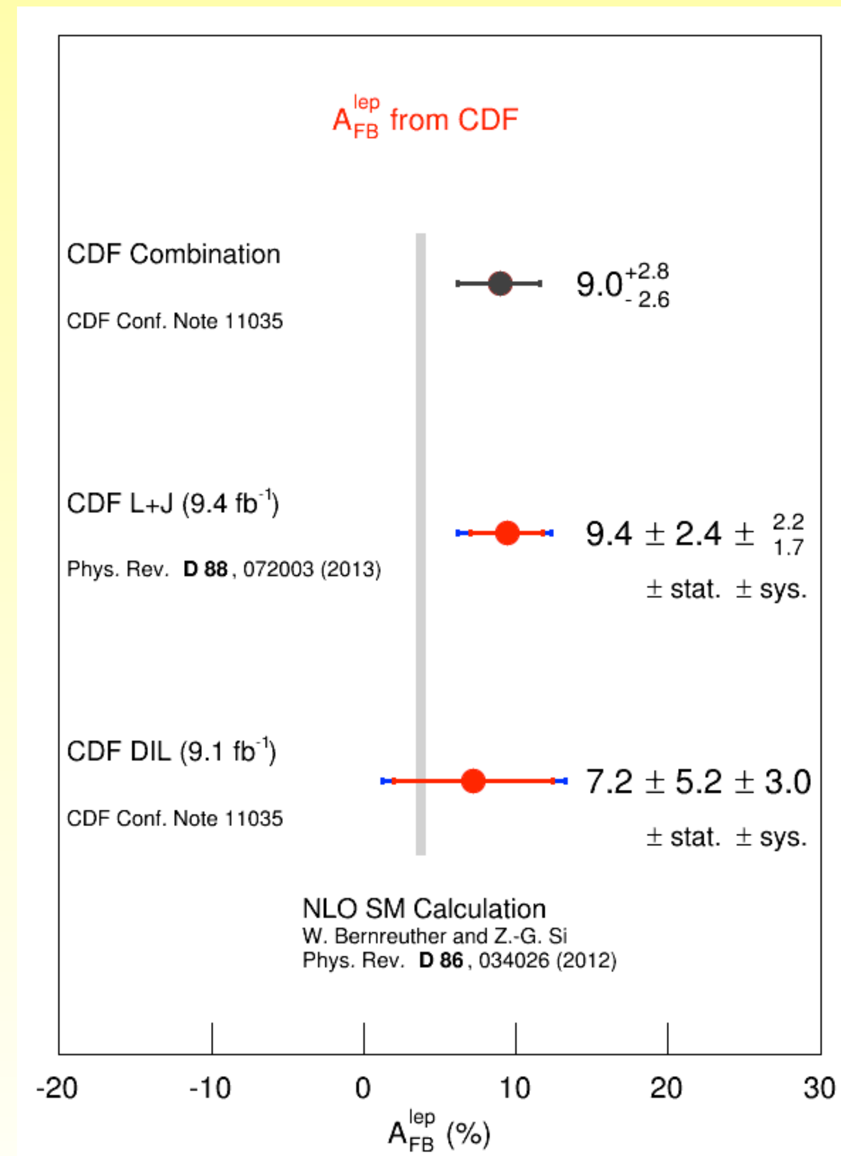
- Combination with the dilepton channel
  ➔ using the BLUE method

$A^{\rm lep}_{\rm FB} = 0.090^{+0.028}_{-0.026}$

2 σ larger than SM predictions

CDF Run II Preliminary

Source of uncertainty	L+J (9.4fb^{-1})	DIL (9.1fb^{-1})	Correlation
Backgrounds	0.015	0.029	0
Recoil modeling (Asymmetric modeling)	+0.013 −0.000	0.006	1
Symmetric modeling	-	0.001	
Color reconnection	0.0067	-	
Parton showering	0.0027	-	
PDF	0.0025	-	
JES	0.0022	0.004	1
IFSR	0.0018	-	
Total systematic	+0.022 −0.017	0.030	
Statistics	0.024	0.052	0
Total uncertainty	+0.032 −0.029	0.060	



Lepton-based asymmetry in the dilepton channel

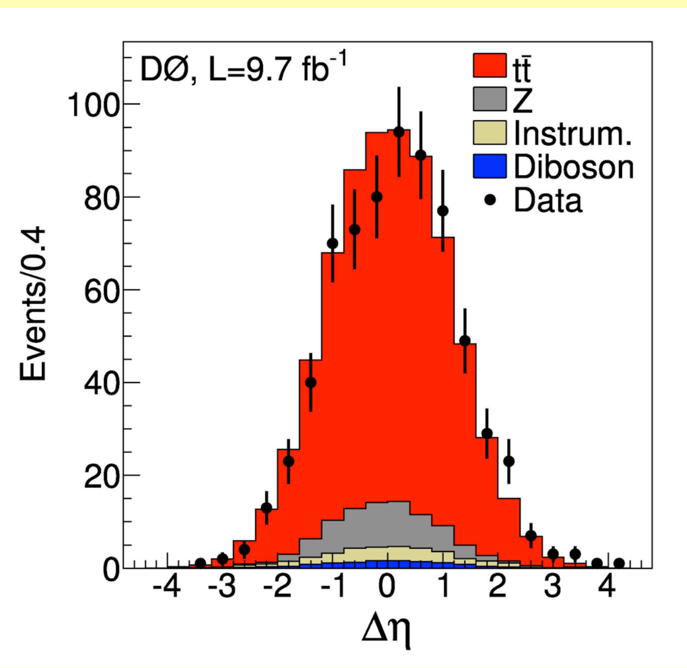
PRD 88, 112002 (2013)
see A. Chapelain's talk at the YSF yesterday

- Method

➔ correct for selection effects (no migration across bins) within the fiducial region after background subtraction

➔ then extrapolate to the full acceptance using MC

$$A^{\ell}_{\mathrm{FB}} = \frac{N(q\times\eta>0)-N(q\times\eta<0)}{N(q\times\eta>0)+N(q\times\eta<0)} \qquad A^{\ell\ell} = \frac{N(\Delta\eta>0)-N(\Delta\eta<0)}{N(\Delta\eta>0)+N(\Delta\eta<0)}$$

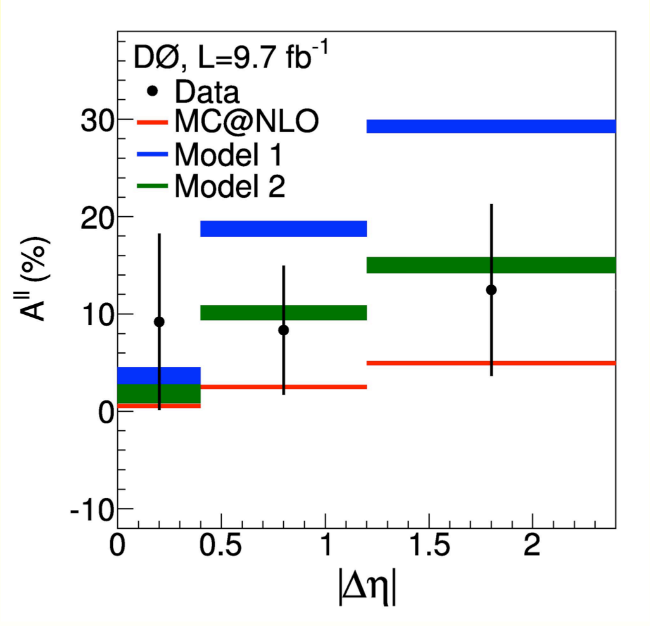


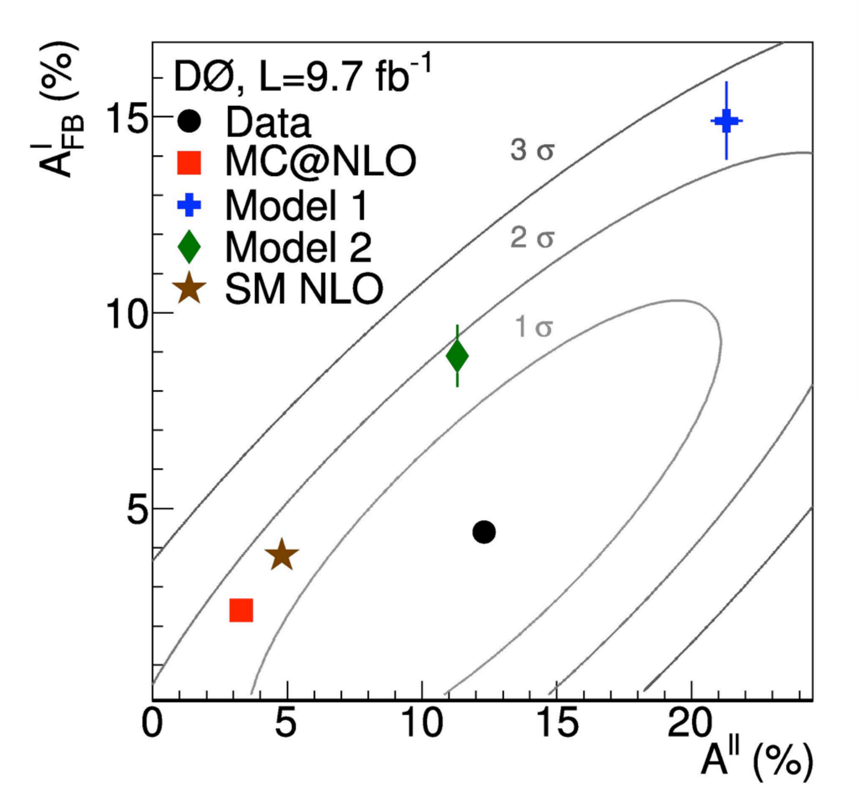
systematics:

	Corrected A^{ℓ}_{FB}	Corrected $A^{\ell\ell}$	Extrapolated A^{ℓ}_{FB}	Extrapolated $A^{\ell\ell}$
Source				
Object ID	0.54	0.50	0.59	0.60
Background	0.66	0.74	0.72	0.88
Hadronization	0.52	0.62	0.62	0.92
MC statistics	0.19	0.23	0.23	0.37
Total	1.02	1.12	1.14	1.46

$$A^{\ell}_{\mathrm{FB}} = (4.4 \pm 3.7\ (\mathrm{stat}) \pm 1.1\ (\mathrm{syst}))\%,$$
$$A^{\ell\ell} = (12.3 \pm 5.4\ (\mathrm{stat}) \pm 1.5\ (\mathrm{syst}))\%.$$

$A^{\ell}_{\mathrm{FB}}/A^{\ell\ell} = 0.36 \pm 0.20$ SM: 0.79 ± 0.10





Lepton-based asymmetry in the l+jets channel

- No need for full $t\bar{t}$ reconstruction

  ➔ use the l+3jets in addition to l+≥4jets:

$$A^{\ell}_{\rm FB} = \frac{N(q\times\eta>0)-N(q\times\eta<0)}{N(q\times\eta>0)+N(q\times\eta<0)}$$

  increase $t\bar{t}$ statistics but with higher background, reduce the acceptance corrections

  ➔ study the dependence vs $t\bar{t}$ kinematics looking at the measurement vs lepton p_T

- Method

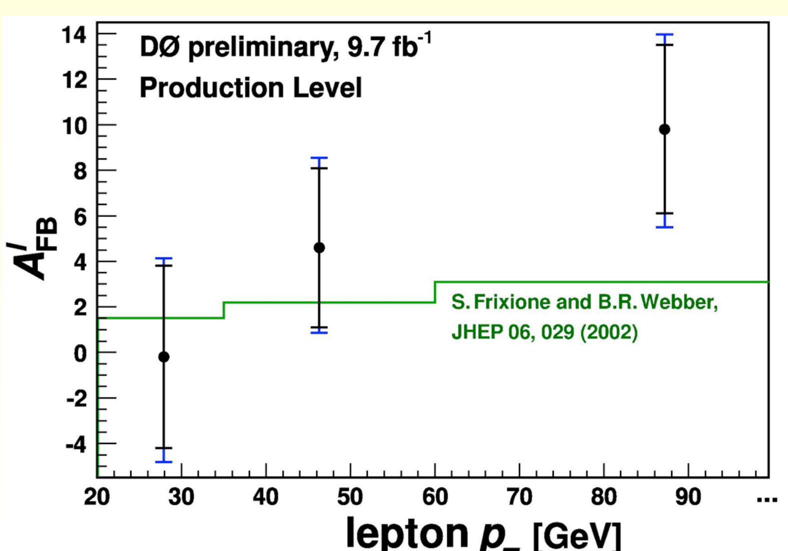
  ➔ likelihood to discriminate $t\bar{t}$ fitted together with the asymmetry

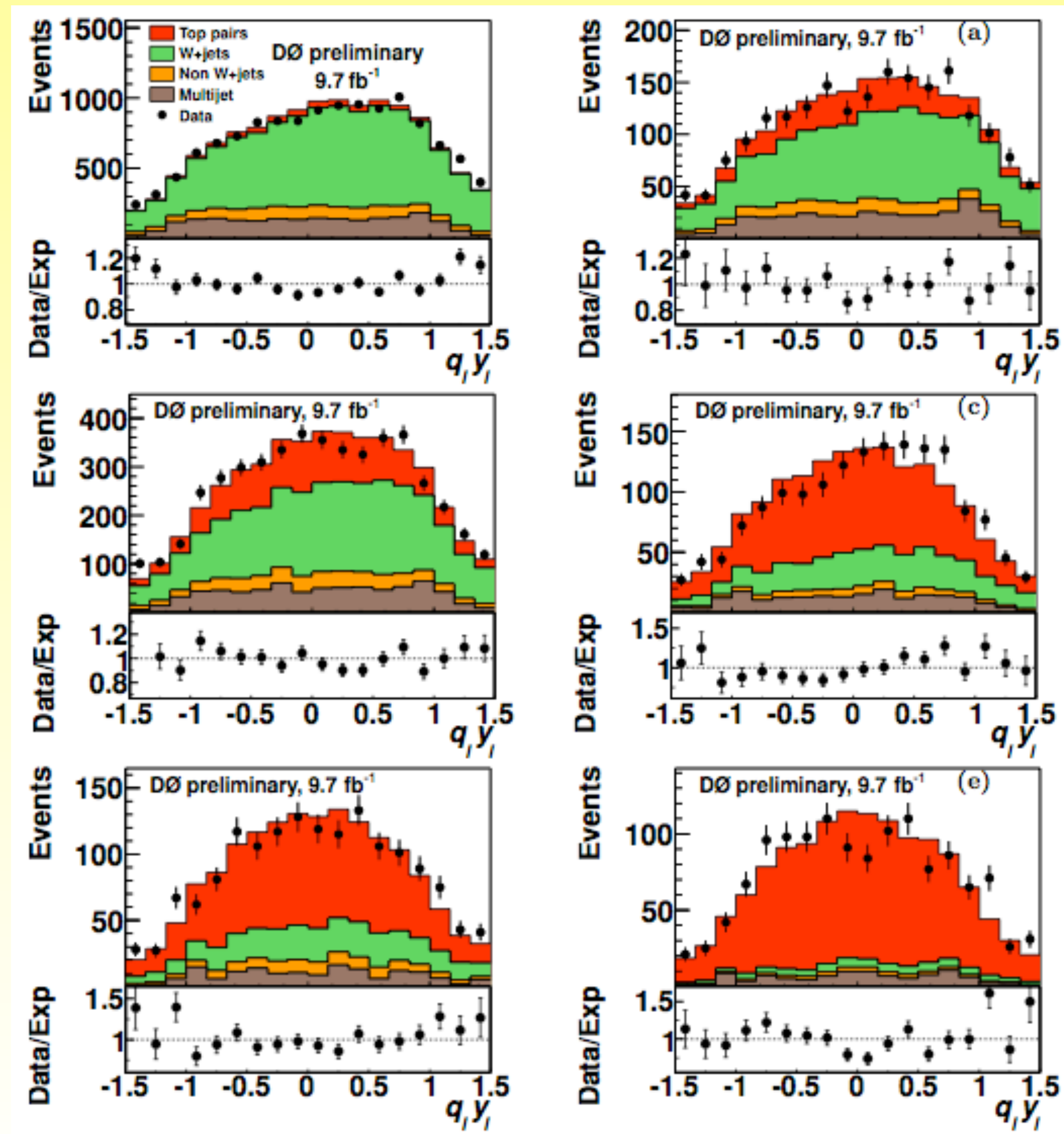
  ➔ calibration the W+jets asymmetry using control region (l+3jets, no b-tag)

  ➔ unfold for acceptance effects

  A_{FB} ($|y_l|<1.5$)= $4.7 \pm 2.3\,(\text{stat.})^{+1.1}_{-1.4}\,(\text{syst.})$

  SM (MC@NLO): A_{FB} =2.3 %



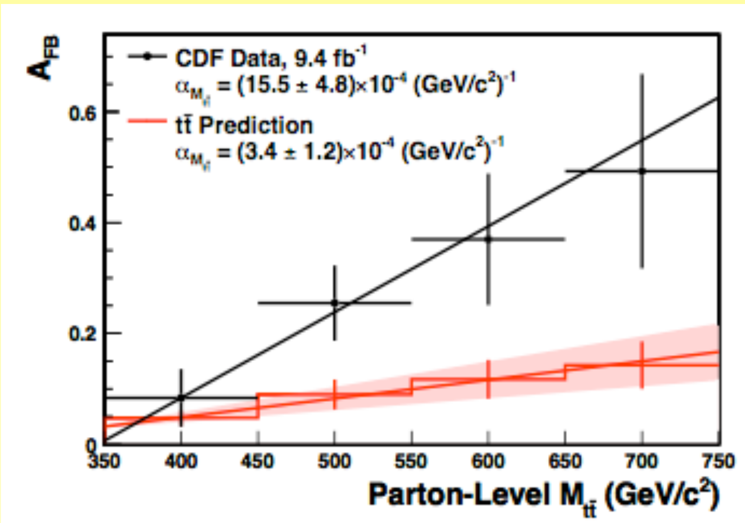


$t\bar{t}$-based asymmetry

- Method
  - ➔ reconstruct the $t\bar{t}$ final state in the l+jets channel (X^2 based fit)
  - ➔ background subtraction (~ 20% of the selection sample)
  - ➔ correct to parton-level using matrix inversion unfolding (SVD) in 2D

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

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



PRD 87, 092002 (2013)

Correction level	Inclusive A_{FB}	Slope $\alpha_{\Delta y}$	Slope $\alpha_{M_{t\bar{t}}}$
Reconstruction	0.063 ± 0.019	$(11.4 \pm 2.5) \times 10^{-2}$	$(8.9 \pm 2.3) \times 10^{-4}$ (GeV/c^2)$^{-1}$
Background-subtracted	0.087 ± 0.026	$(15.5 \pm 3.3) \times 10^{-2}$	$(10.9 \pm 2.8) \times 10^{-4}$ (GeV/c^2)$^{-1}$
Parton	0.164 ± 0.047	$(25.3 \pm 6.2) \times 10^{-2}$	$(15.5 \pm 4.8) \times 10^{-4}$ (GeV/c^2)$^{-1}$

slope: 2.4 σ different from the SM prediction: (3.4±1.2)x10^{-4}

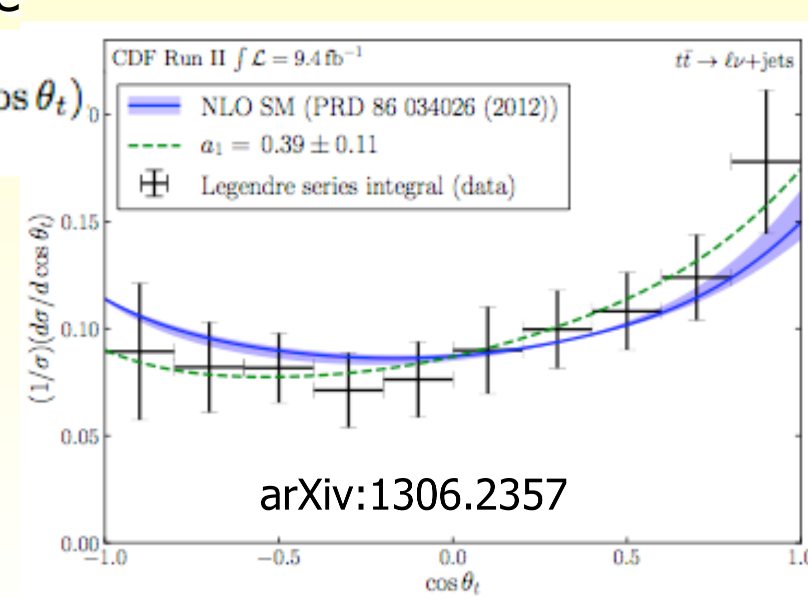
- Additional informations: measurement of the $d\sigma/d\cos\theta_t$
  - ➔ full shape of the differential cross section instead of 2 bins ($\cos\theta_t$ >0 and $\cos\theta_t$)

  θ_t is the angle between the top and the incoming proton in the $t\bar{t}$ rest frame

  - ➔ decomposition in series of Legendre polynomials (l≤8): $\frac{d\sigma}{d(\cos\theta_t)} = \sum_{\ell=0}^{\infty} a_\ell P_\ell(\cos\theta_t)$

ℓ	a_ℓ (obs)	a_ℓ (pred)
1	0.40 ± 0.12	$0.15^{+0.07}_{-0.03}$
2	0.44 ± 0.25	$0.28^{+0.05}_{-0.03}$
3	0.11 ± 0.21	$0.030^{+0.014}_{-0.007}$
4	0.22 ± 0.28	$0.035^{+0.016}_{-0.008}$
5	0.11 ± 0.33	$0.005^{+0.002}_{-0.001}$
6	0.24 ± 0.40	$0.006^{+0.002}_{-0.003}$
7	-0.15 ± 0.48	$-0.003^{+0.001}_{-0.001}$
8	0.16 ± 0.65	$-0.0019^{+0.0003}_{-0.0003}$

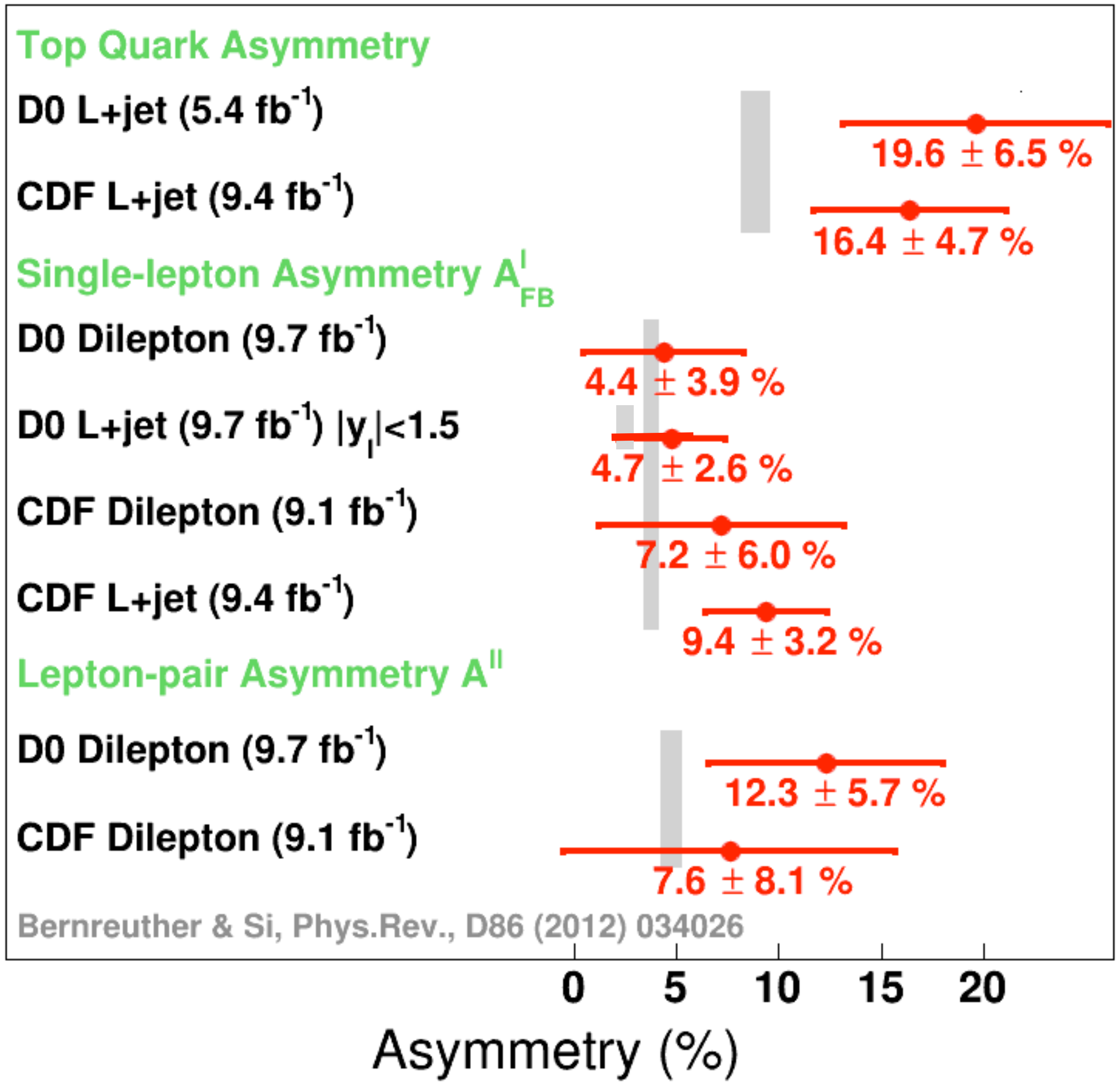
CDF observed discrepancy is in a_1



Summary of the charge asymmetries at the Tevatron

- inclusive asymmetries
  - ➔ lepton-based asymmetries:
    rather good agreement with the QCD predictions
  - ➔ $t\bar{t}$-based asymmetries:
    slightly higher than predictions

- differential measurements
  - ➔ CDF sees an excess in the asymmetry slopes
    vs $M_{t\bar{t}}$ and $|\Delta y|$ (2-3 σ)
  - ➔ not seen in D0 with 5.4 fb^{-1}



Conclusion

- Top-quark physics is one of the highlights of the Tevatron physics program

  ➔ almost 20 years after its discovery during Run I, a lot of the top-quark properties have now been scrutinized at the Tevatron

- Still a lot of activities in the top quark sector at the Tevatron

  ➔ finalize the measurements with the full dataset

  ➔ focus on measurements complementary to LHC (charge asymmetry, spin correlation) or competitive with the LHC (mass, $t\bar{t}$ and single top cross sections)

  ➔ CDF/D0 combination + first combination with the LHC