Standard Model Measurements at the Tevatron

- Introduction
- Jet correlations
- Top physics
- W mass
- Conclusions & Outlook

Fermilab

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DESY Hamburg

January 8th, 2013

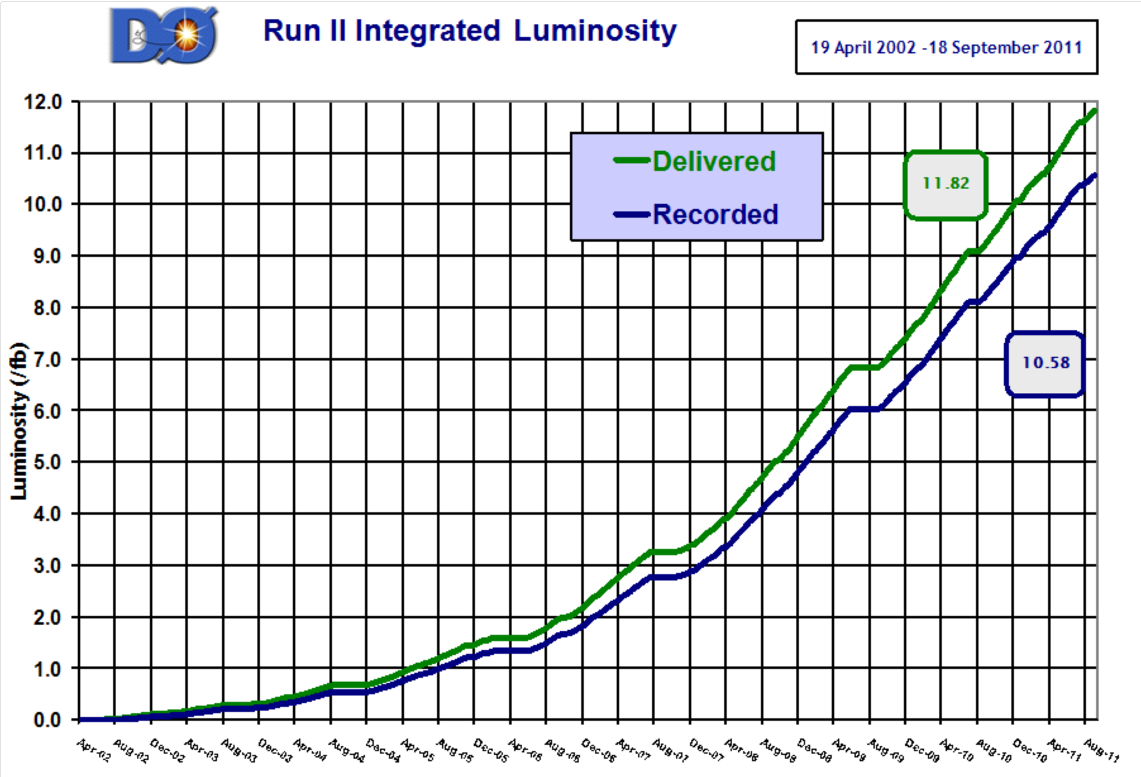
The Midwest

Scale: DESY → LHC (~1050 km)

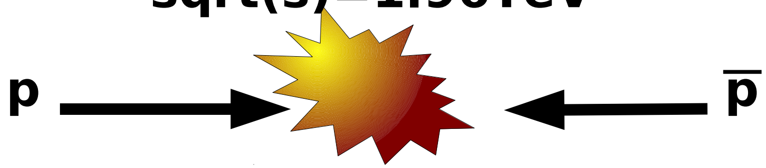
- Fermilab is located near Chicago
- Endless Corn fields to the west,
  Lake Michigan to the east...

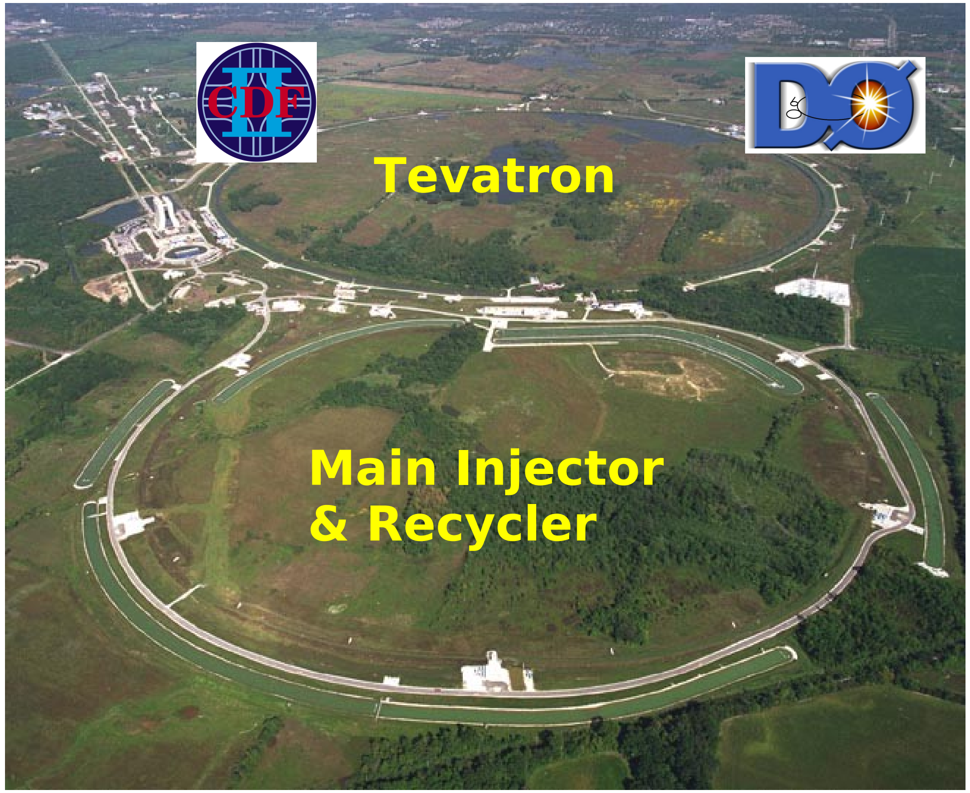
The Tevatron

- Integrated luminosity:



sqrt(s)=1.96TeV





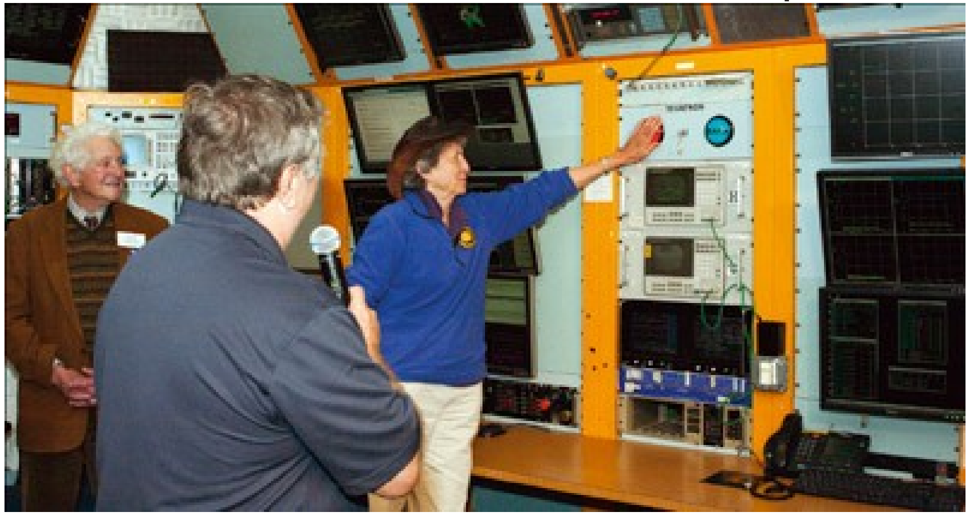
- Initial luminosities: 3 – 4 x 10^{32} $cm^{-2}s^{-1}$
- Δt = 396ns
- ~12fb^{-1}/experiment delivered → ~10 fb^{-1}/experiment collected

Thanks to the Accelerator Division!

The Tevatron

- <u>Shutdown 30th of September 2011:</u>

Main Control room: H. Edwards dumps beams



At DØ control room:

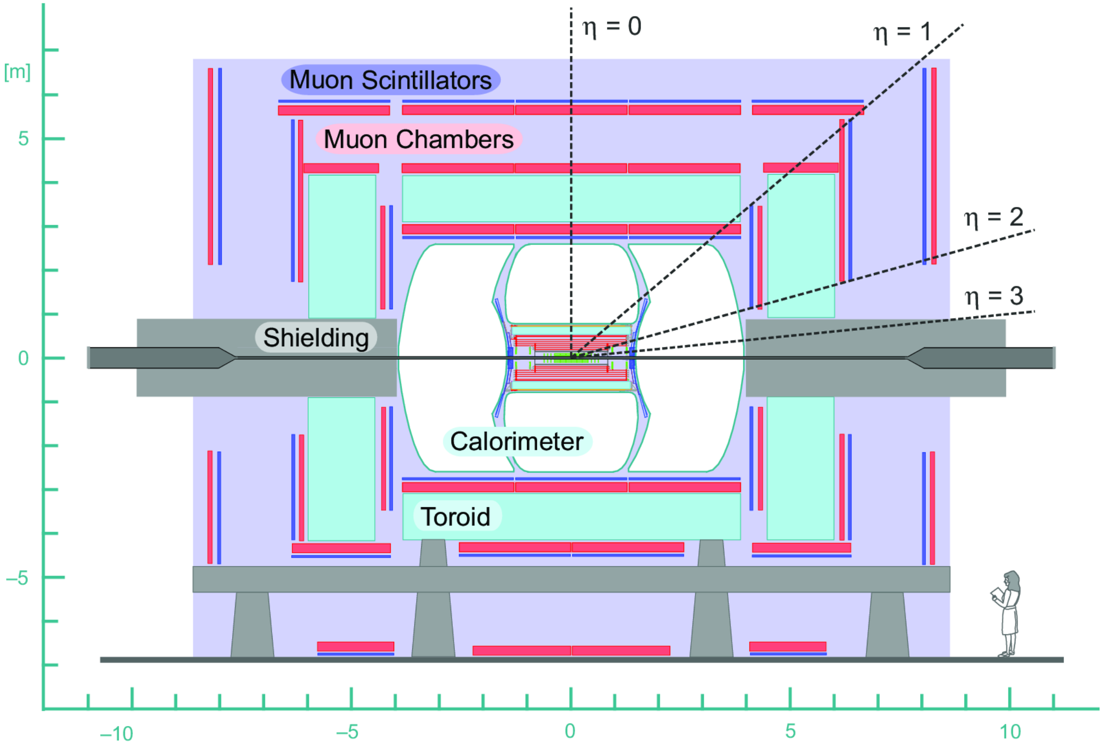
– Bill Lee and George Ginther
  (Run and technical Coordinator)
– DØ RunII data taking finally ends
  after ~10 years

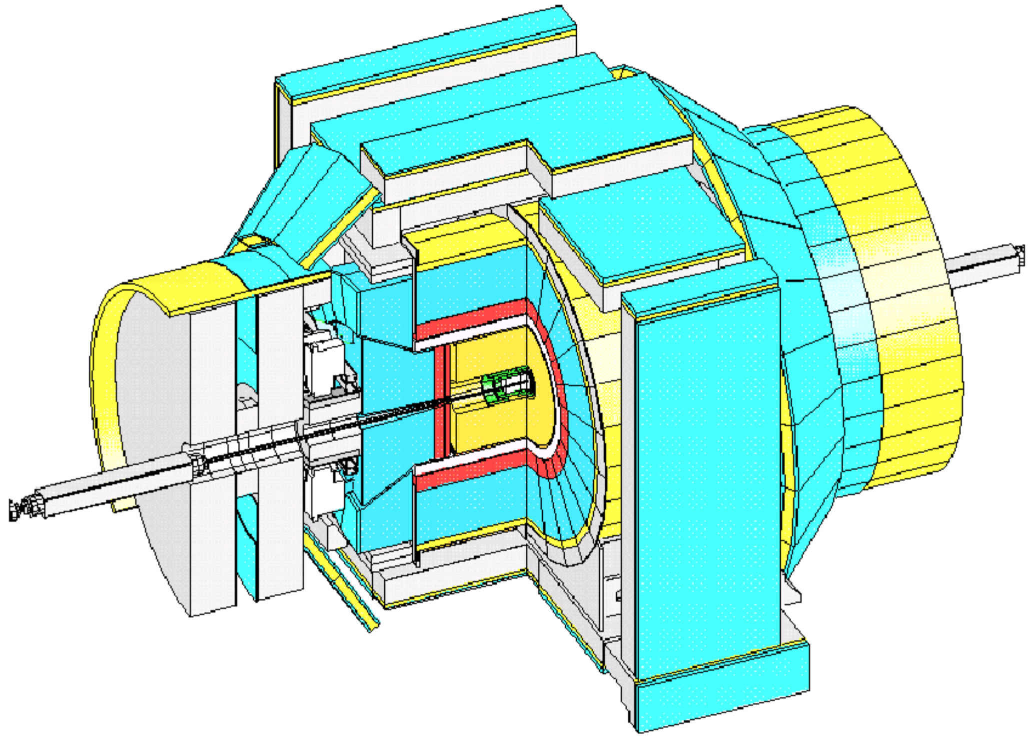
Thanks to the Accelerator Division, Shifters and Experts!

The Experiments: CDF & DØ

General purpose 4π detectors:

- **Tracker**: Detection and momentum measurement for charged particles
- **Calorimeter**: Identification and energy measurement of jets and electrons
- **Muon system**: Identification and momentum measurement of muons





- Similar calorimeter and tracker coverages
- Detectors are of comparable strength in Tevatron Run II !

Jet Correlations

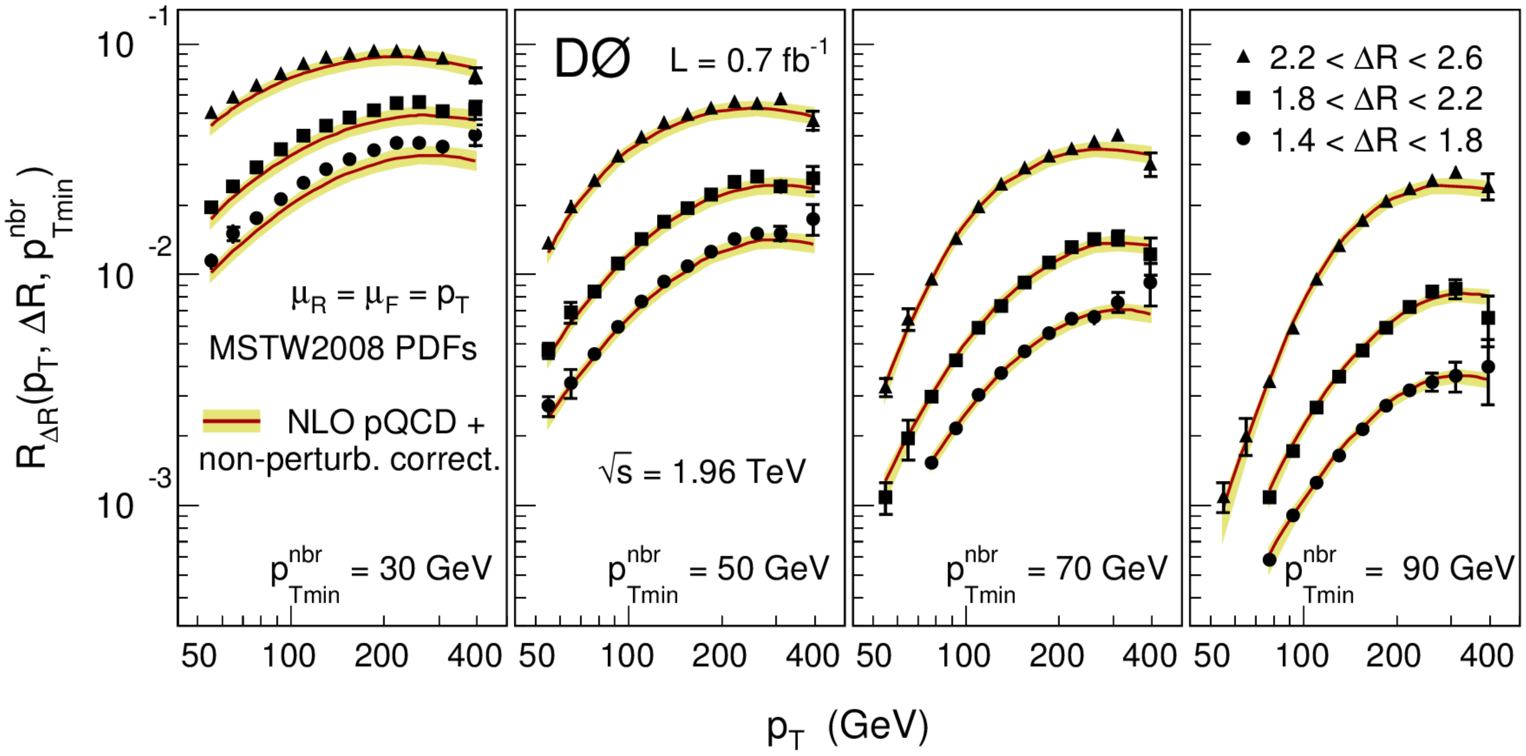
Phys.Let.B 718 , 56 (2012)

- Triple differential measurement of the average number of neighboring jets per jet:

$$R_{\Delta R}(p_T, \Delta R, p_{T\min}^{\text{nbr}}) = \frac{\sum_{i=1}^{N_{\text{jet}}(p_T)} N_{\text{nbr}}^{(i)}(\Delta R, p_{T\min}^{\text{nbr}})}{N_{\text{jet}}(p_T)}$$

$N_{\text{nbr}}^{(i)}$ is number of neighboring jets with minimum p_T and ΔR (using Δy and $\Delta\varphi$)

- Reduced experimental Uncertainties
- Well described by pQCD for $p_T^{\text{nbr}} > 50$ GeV



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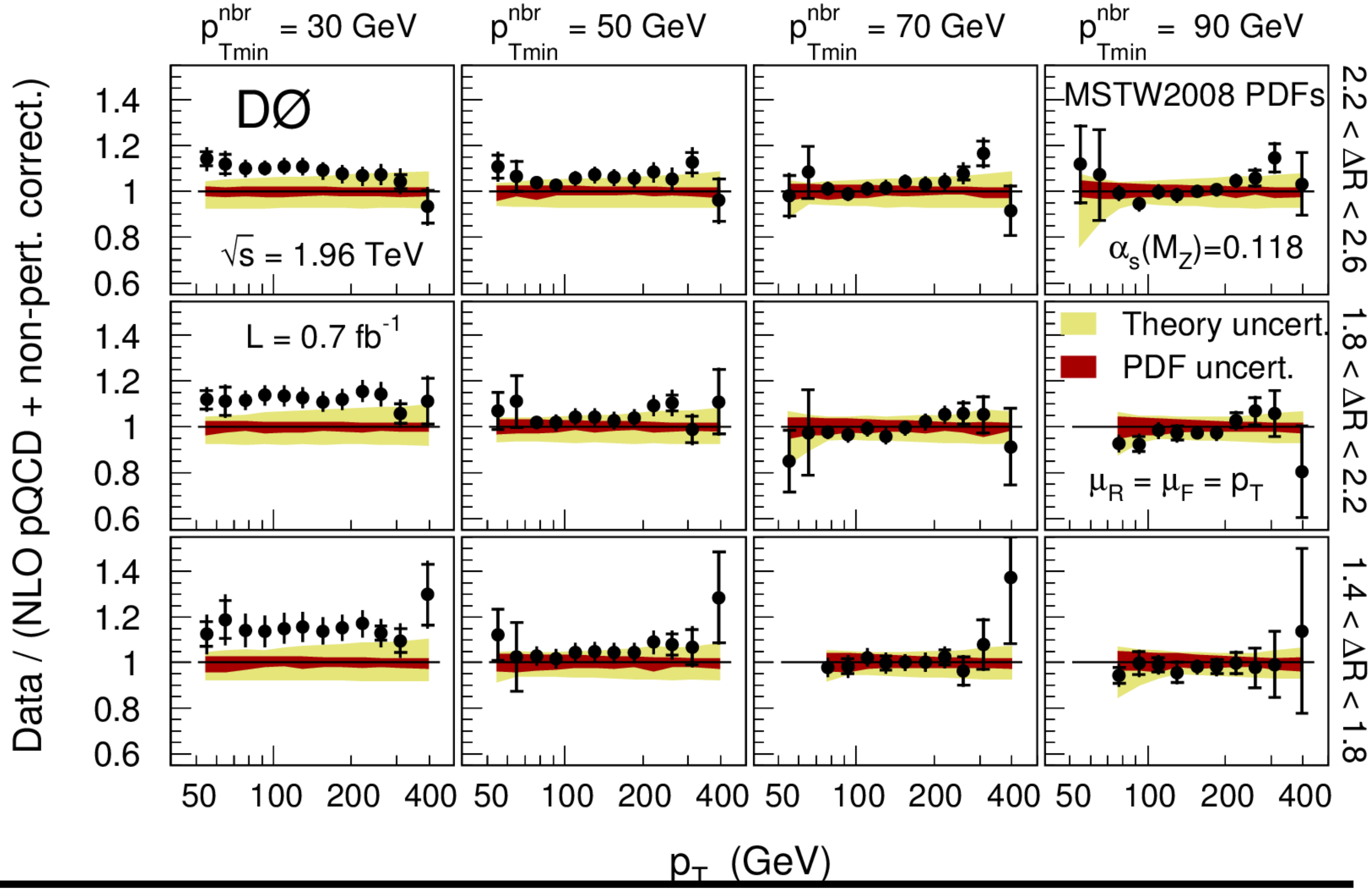
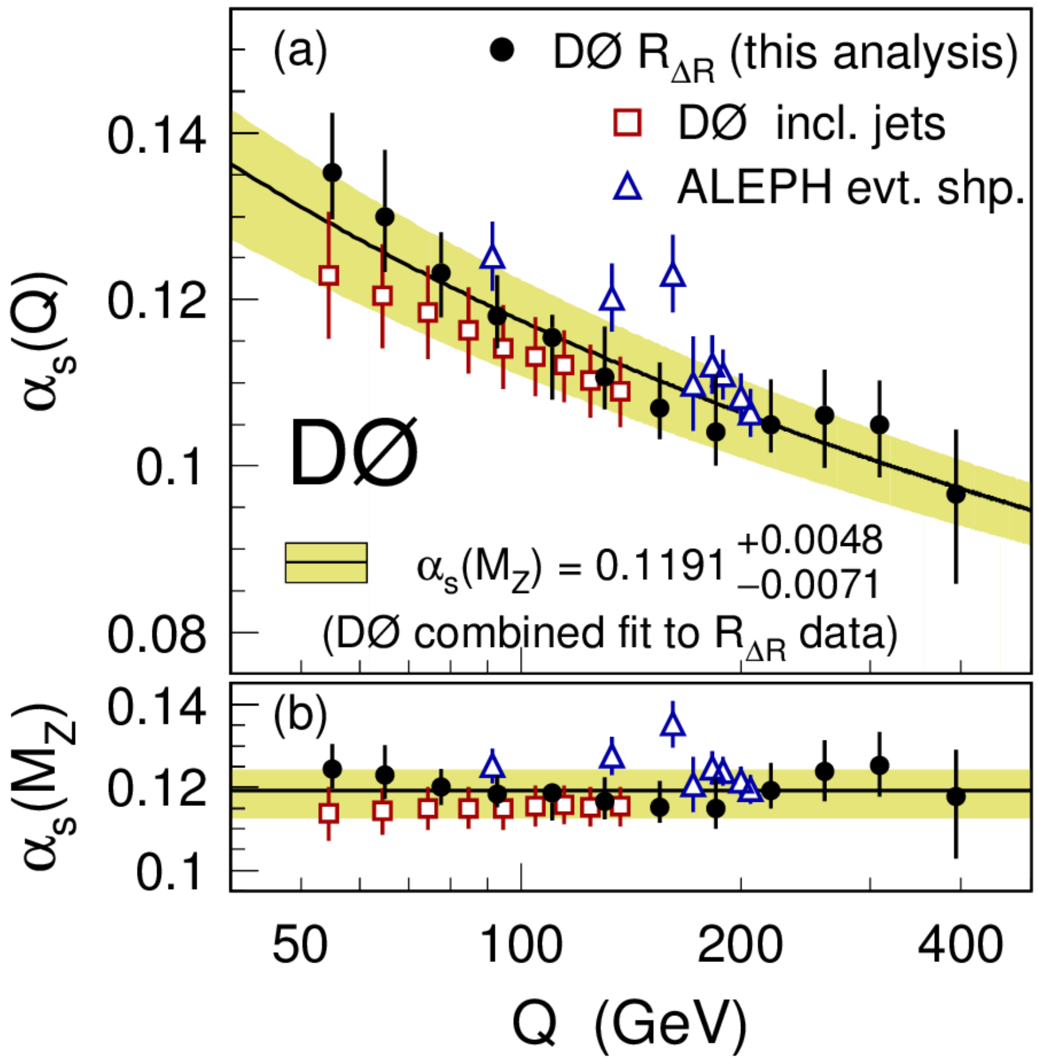


DØ Jet Correlations

Phys.Let.B 718 , 56 (2012)

- $R_{\Delta R}$ allows to probe α_s up to high scales of 400 GeV
- $\alpha_S(M_Z)$ is determined using data with p_T^{nbr} = 50, 70, 90 GeV
  (Integrated over p_T and ΔR)
- Reject p_T^{nbr} = 30 GeV region



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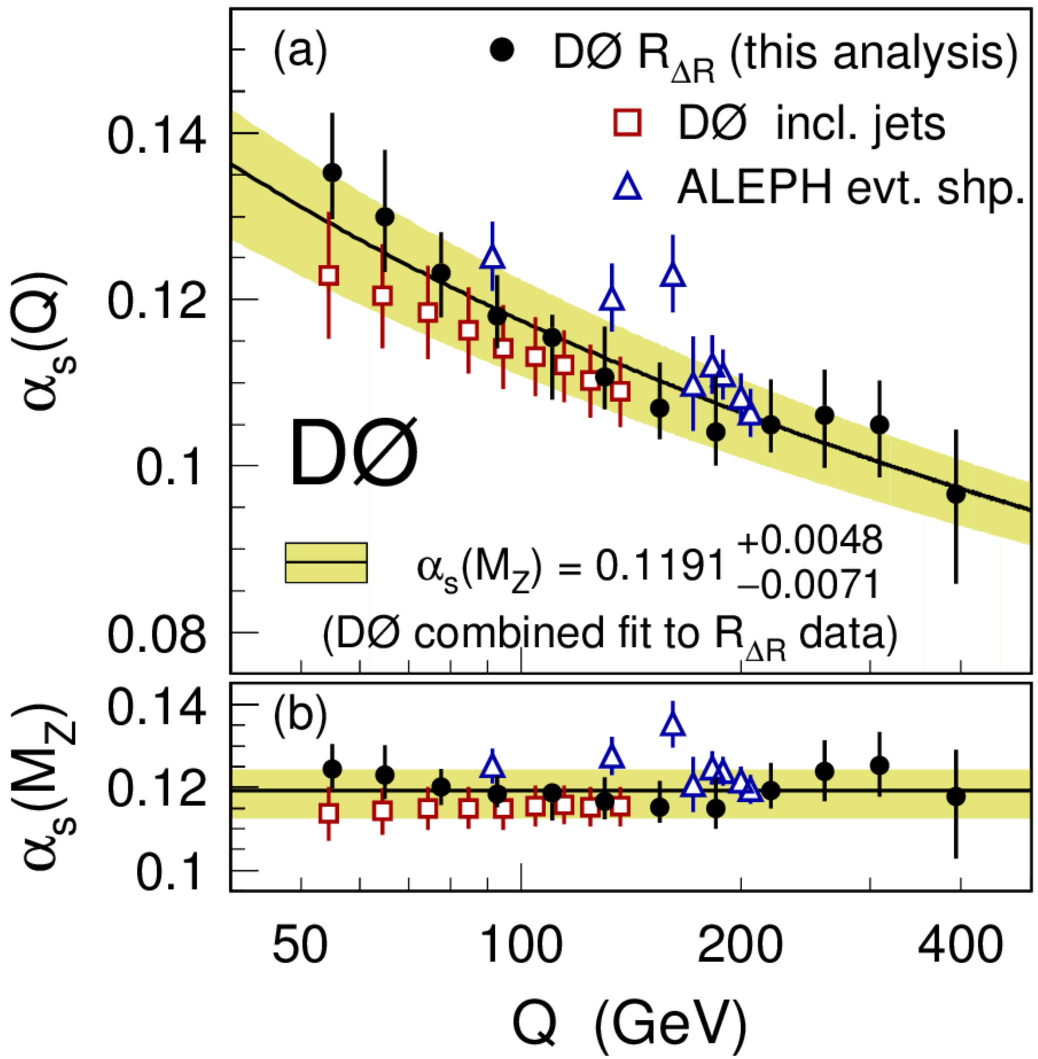
$\alpha_s(M_Z) = 0.1191 \pm {}^{0.0048}_{0.0071}$

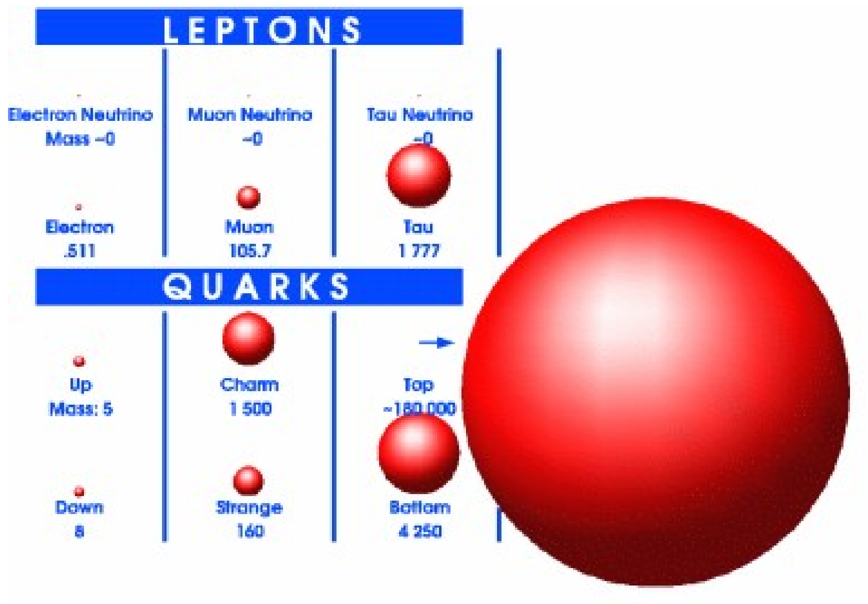


- High experimental precision with reduced uncertainties due to non-perturbative corrections, increased scale dependencies
  → Need NNLO for 2, 3 jets

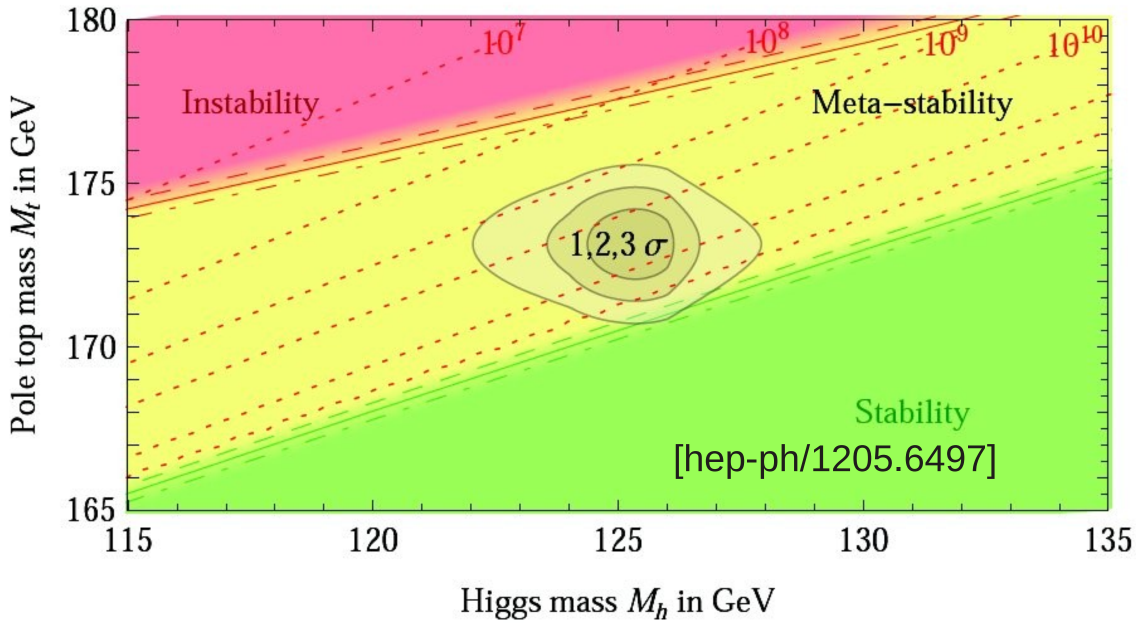
$\alpha_s(M_Z)$	Total uncertainty	Statistical	Experimental correlated	Non-perturbative corrections	MSTW2008NLO uncertainty	PDF set	$\mu_{R,F}$ variation
0.1191	${}^{+4.8}_{-7.1}$	±0.3	${}^{+0.7}_{-0.9}$	${}^{+0.2}_{-0.1}$	${}^{+1.0}_{-0.5}$	${}^{+0.0}_{-2.4}$	${}^{+4.6}_{-6.6}$

Top – Introduction

- Top is the heaviest fundamental particle discovered so far:
  → m_t = 173.2 ± 0.9 GeV
- Top plays special role in EWSB ?
  → Yukawa coupling ~1
- Lifetime: $\tau \approx 5\text{x}10^{-25}\,\text{s} << \Gamma_{QCD}$
  → Observe bare quark



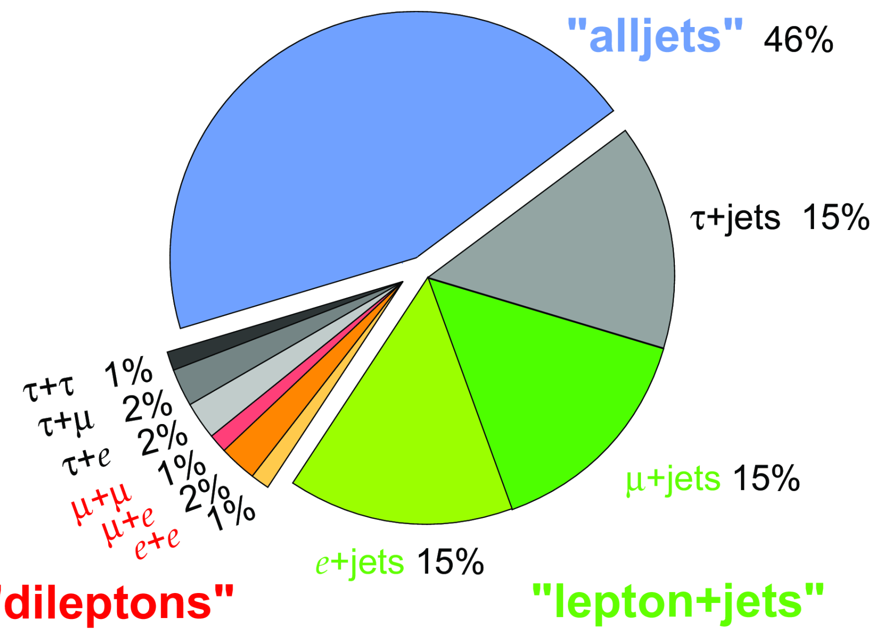
- → Recent Higgs-like boson discovery at ATLAS & CMS
  → If SM is "valid" up to the Planck-scale:

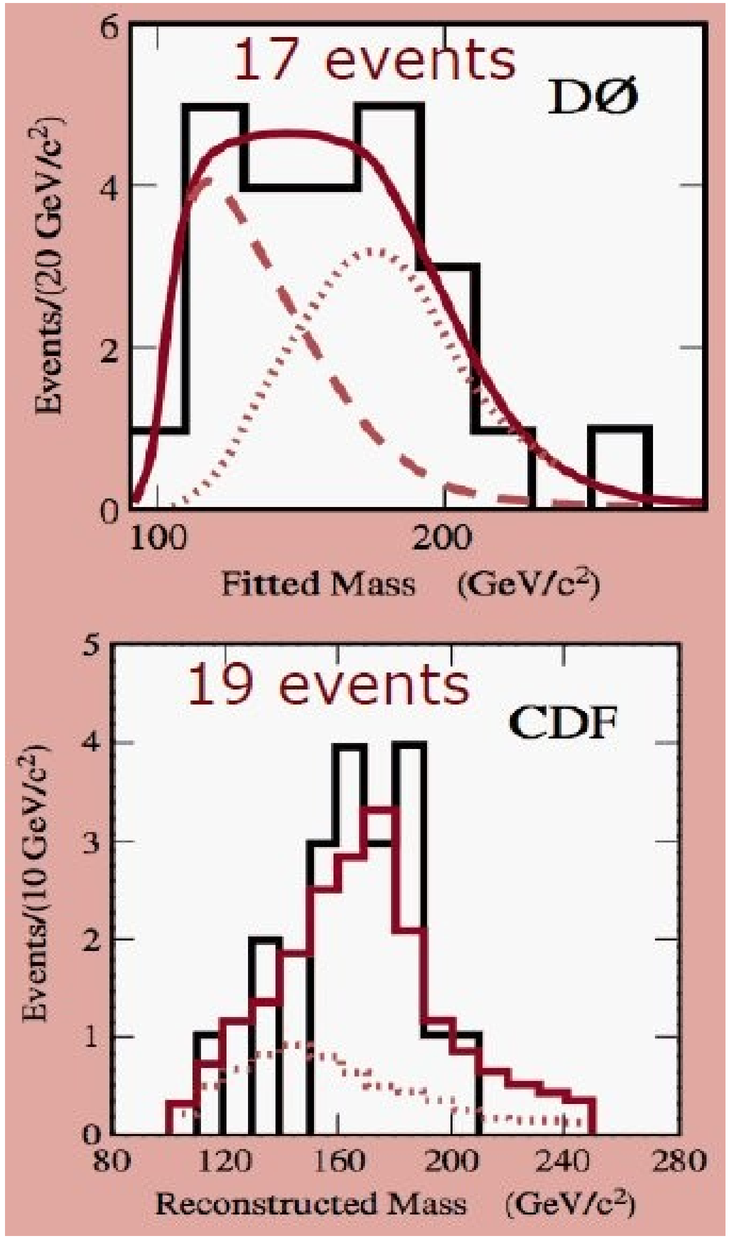


DØ Top – Introduction

- Needed as Isospin partner of b-quark
- Discovered in 1995 by CDF and DØ using ~120pb^{-1}
- Charge: +2/3e
- SM top quark, ~100% decay into Wb

Top Pair Branching Fractions

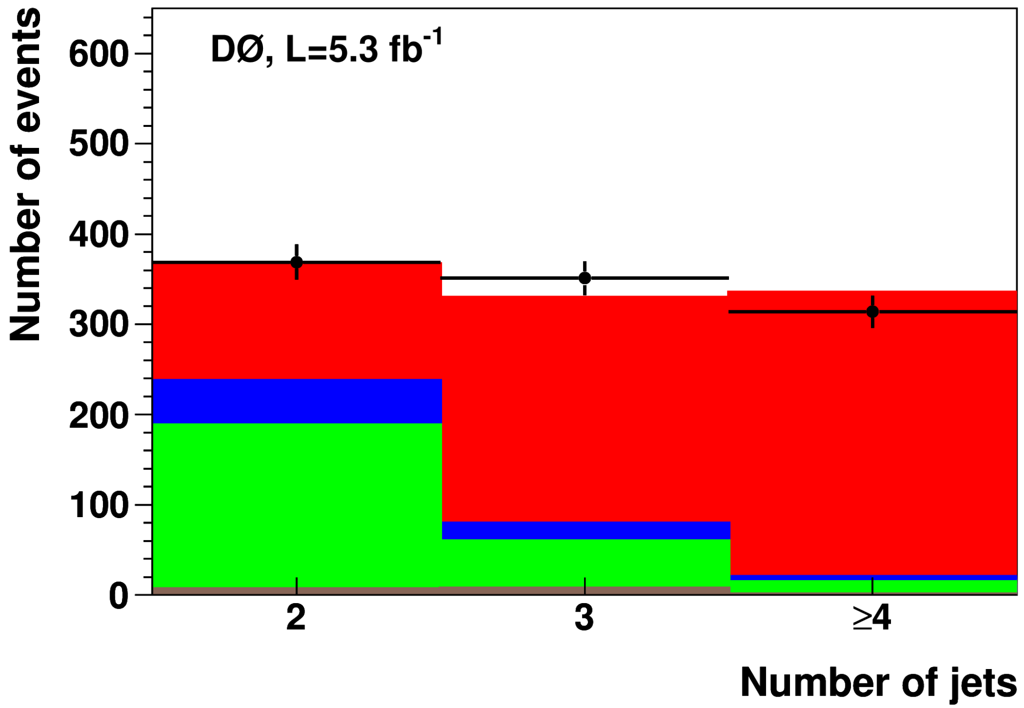




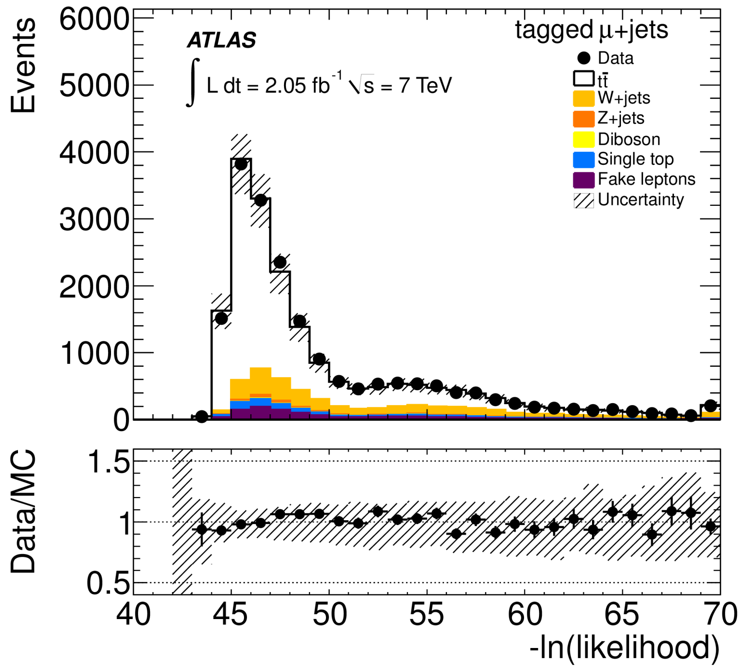
- Samples classified according to W-decay: dilepton ($\ell\ell$), lepton+jets (ℓ+jets), all jets

- Can Tevatron compete ?

Tevatron RunII (large statistics):

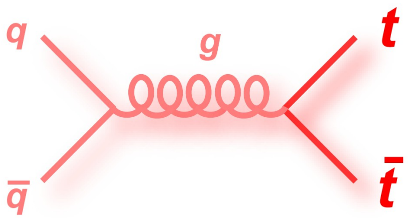
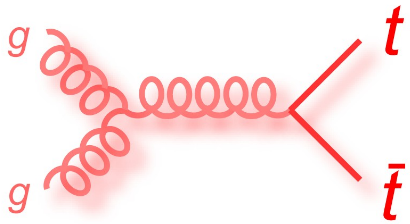
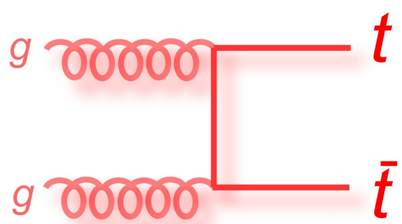


Top factory:

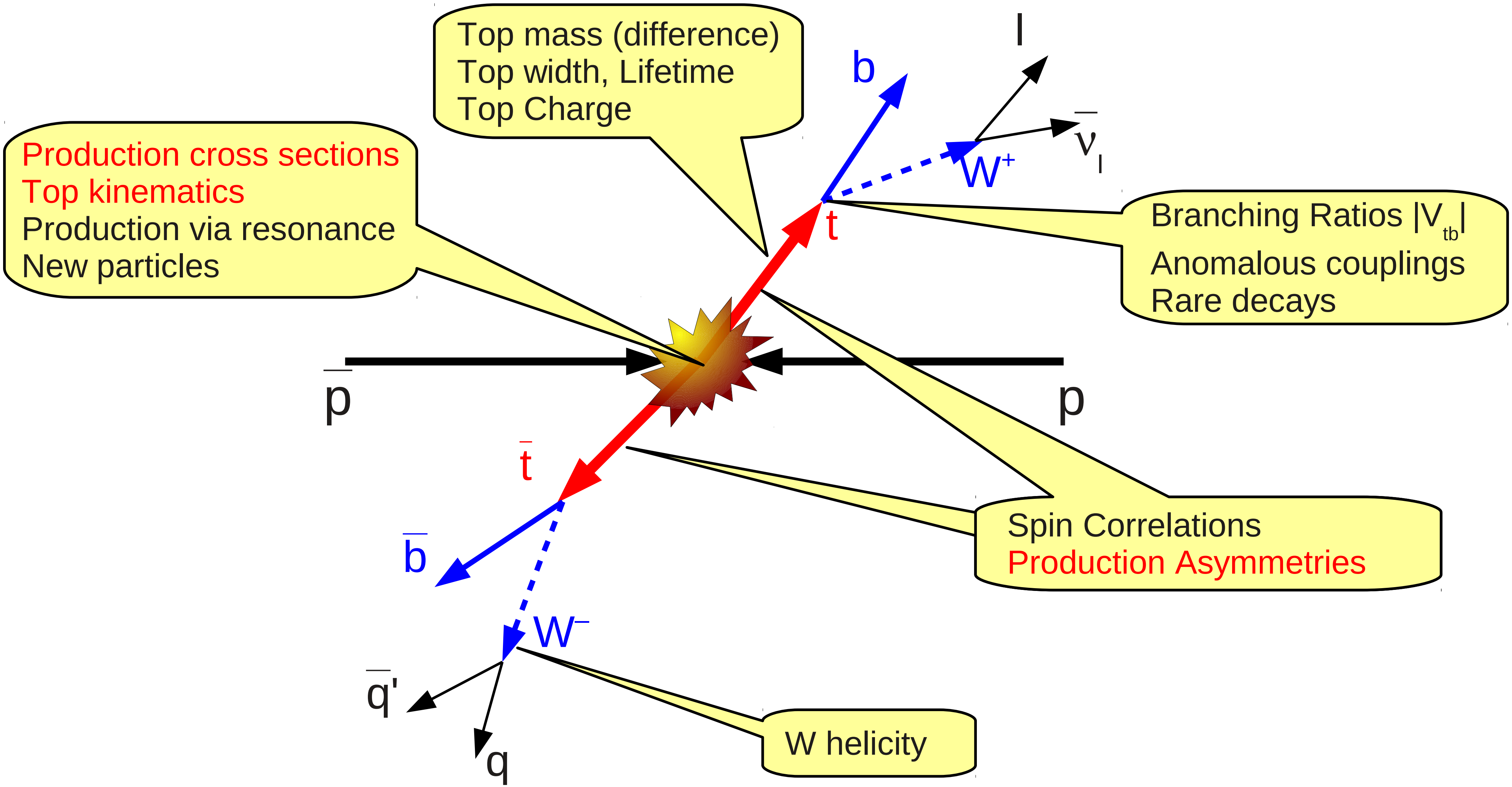


Top – Introduction

- Can Tevatron compete ? Differences between the machines helps:
  - center-of-mass energy → different parton x of the initial state
  - $p\bar{p}$ versus pp machine

Tevatron: (1.96 TeV)		LHC: (7/8 TeV)
~85%		~15% (~10%, 14 TeV)
~15%	 	~85% (~90%, 14 TeV)

- Differential and inclusive cross-sections
- Forward-backward asymmetries
- Systematically limited measurements, like top mass


Top mass (difference)
Top width, Lifetime
Top Charge
Production cross sections
Top kinematics
Production via resonance
New particles
b
l
$\bar{\nu}_l$
W^+
t
Branching Ratios $|V_{tb}|$
Anomalous couplings
Rare decays
$\bar{p}$
p
$\bar{t}$
$\bar{b}$
Spin Correlations
Production Asymmetries
W^-
$\bar{q}'$
q
W helicity

Tevatron Combination

CDF and DØ Electroweak working group (TevEWWG):

- CDF inputs: 4 measurements, up to 8.8 fb^{-1}
- DØ inputs: 2 measurements, up to 5.4 fb^{-1}
- use Best Linear Unbiased Estimator (BLUE)
- 10 sources of correlated systematic uncertainties
  → either 0% (detector, statistics) or 100% (luminosity) assumed
- CDF has a weight of 60%, DØ comes with 40%

First preliminary Tevatron cross-section combination:

$\sigma\,(p\bar{p} \to t\bar{t})$ at $\sqrt{s} = 1.96$ TeV, assuming $m_t = 172.5$ GeV/c^2

$$7.65\ \pm 0.20\,(stat)\ \pm 0.29\,(syst)\ \pm 0.22\,(lumi)\,\text{pb}$$
$$= 7.65\ \pm 0.42\,\text{pb} \qquad (rel.\ 5.5\%)$$

- Best prediction at NNLO+NNLL (MSTW2008)

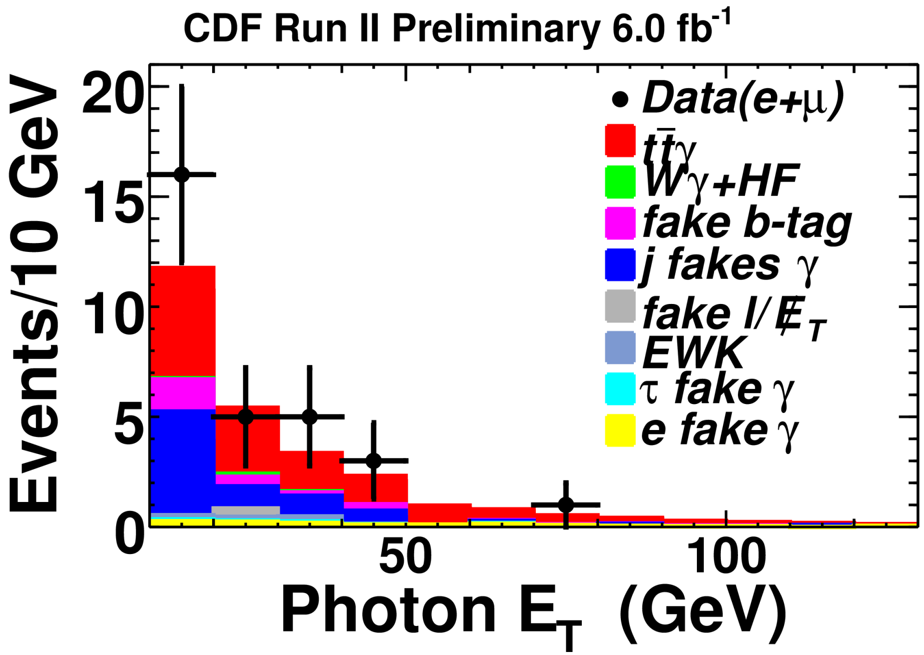
$$\sigma_{\text{tot}}^{\text{res}} = 7.067\ {}^{+0.143\,(2.0\%)}_{-0.232\,(3.3\%)}\ [\text{scales}]\ {}^{+0.186\,(2.6\%)}_{-0.122\,(1.7\%)}\ [\text{pdf}]$$

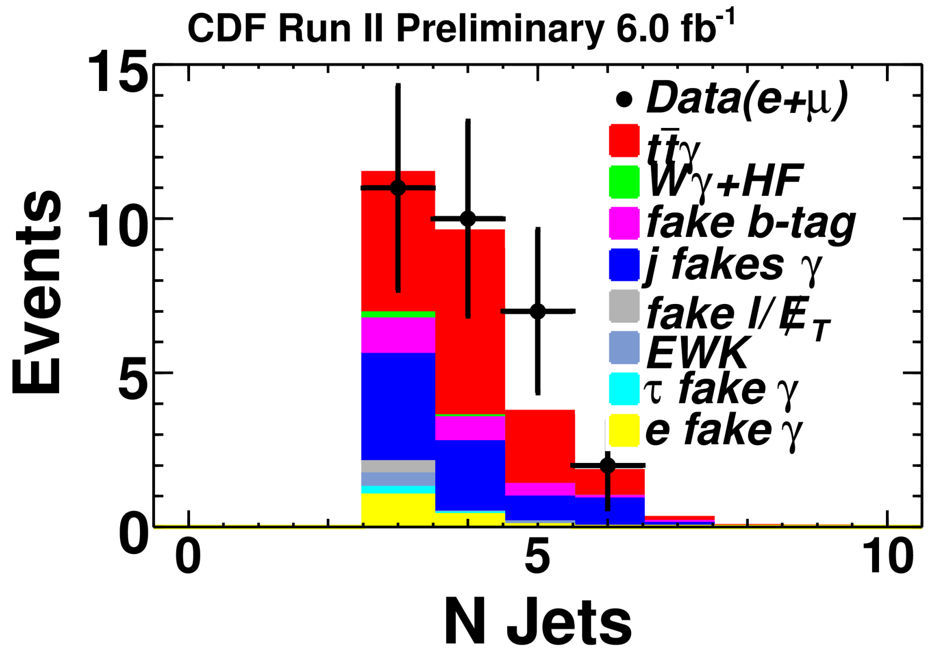
arxiv:1204.5201

Evidence for $t\bar{t}\gamma$

- Final selection yields:

$t\bar{t}\gamma$, Isolated Leptons, Tight Chi2 on Photons			
Standard Model Source	$e\gamma b \not{E}_T$	$\mu\gamma b \not{E}_T$	$(e+\mu)\gamma b \not{E}_T$
Total SM Prediction	$16.7 \pm 2.2(tot)$	$10.3 \pm 1.9(tot)$	$26.9 \pm 3.4(tot)$
Observed in Data	17	13	30





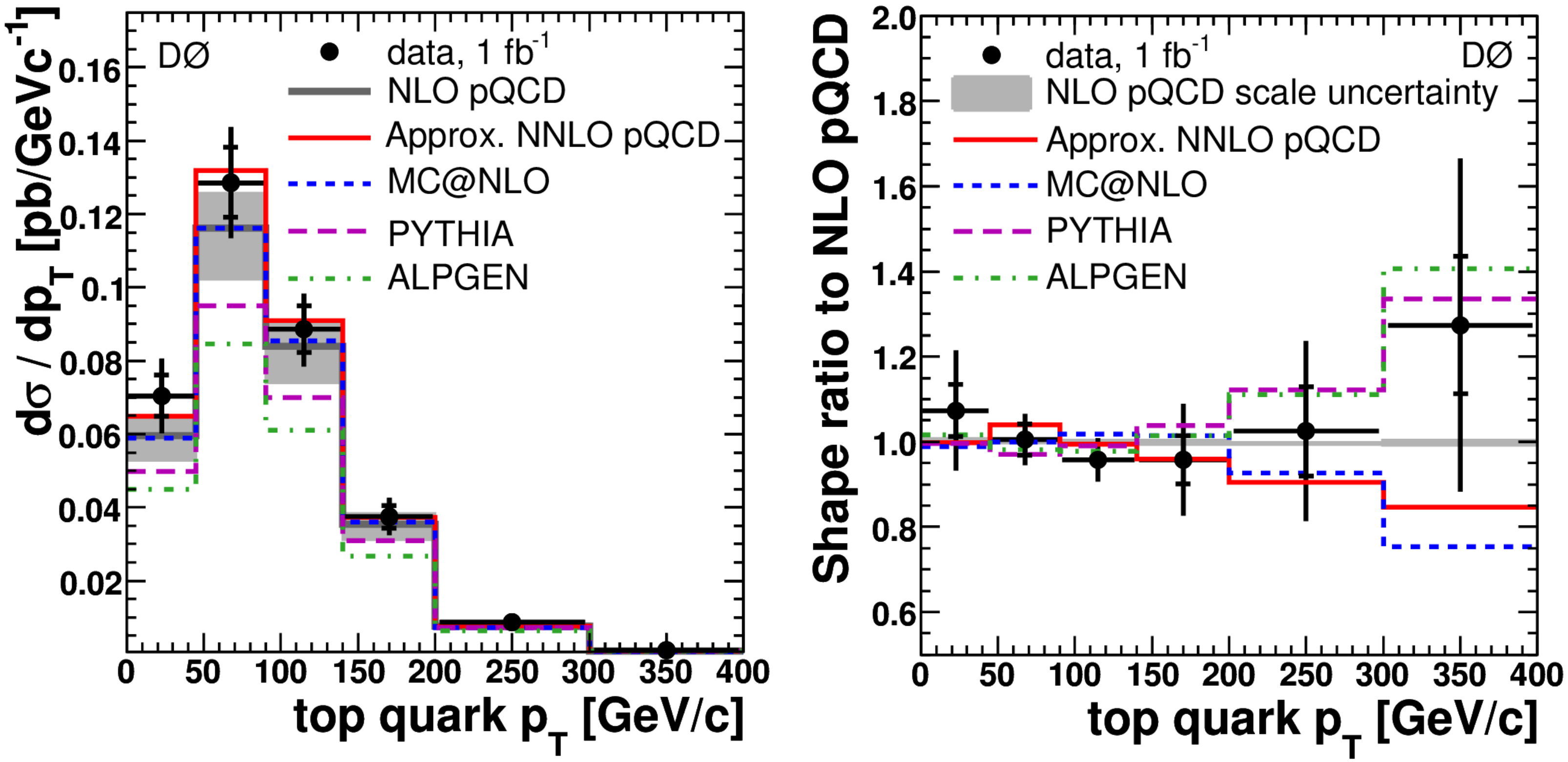
- Probability of background alone to mimic observed signal is: 3 s.d.

$$\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.07(\text{stat}) \pm 0.04(\text{sys.}) \ \pm 0.01 \ (\text{lum.}) \ \text{pb}$$

$$R = \frac{t\bar{t}\gamma}{t\bar{t}} = 0.024 \pm 0.009(\text{stat.}) \pm 0.001(\text{sys.})$$

- In good agreement to SM

Differential cross section



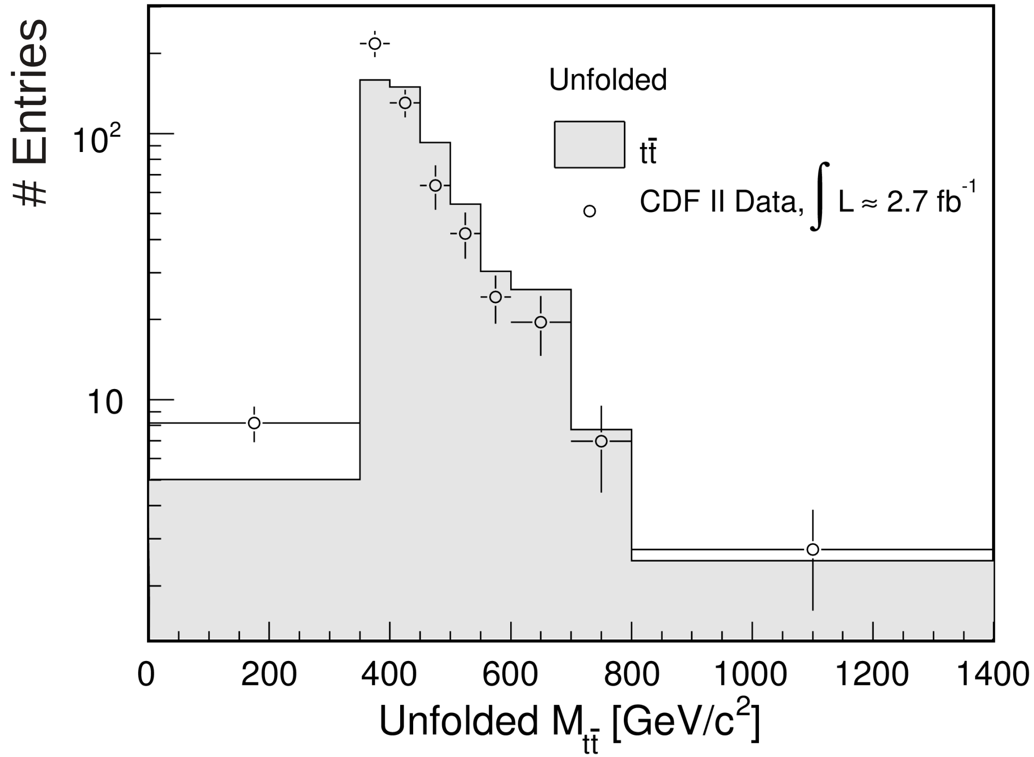
Phys. Lett. B 693, 515 (2010),
arXiv.org:1001.1900

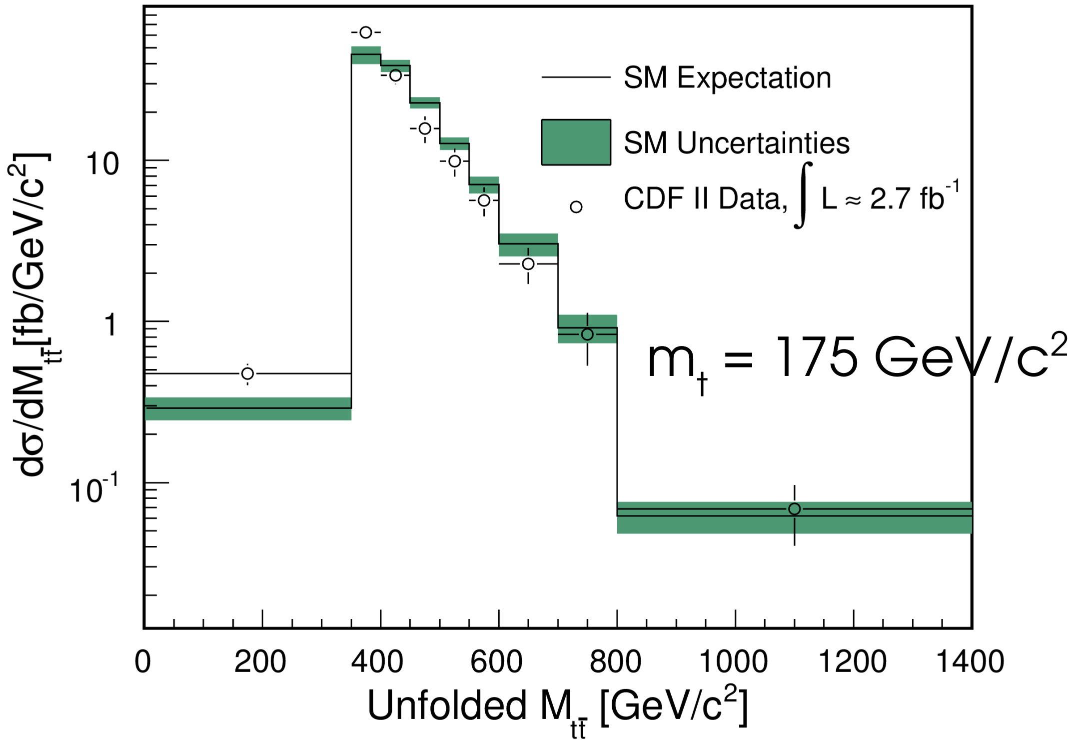
- Largest shape uncertainty: Jet energy scale (1.5-5%)
- All use: CTEQ61 with $\mu_{r/f} = m_t$, except approx. NNLO pQCD uses MSTW08
- Integrated cross section: $\sigma = 8.31 \pm 1.28$ (stat.) pb

→ Normalization nicely described by pQCD (N)NLO, however offset for PYTHIA, ALPGEN. Shape is reasonable described by all predictions

Differential cross section

- Correct for detector effects & finite resolution by regularized unfolding





- Dominant systematics: JES 2-8% and at high M($t\bar{t}$) PDF up to 18%
- Integrated cross section: σ = 6.9 ± 1.0 (stat.+JES) pb

→ Invariant mass distribution of the $t\bar{t}$ system is described by SM

PRL 108, 261603 (2012)

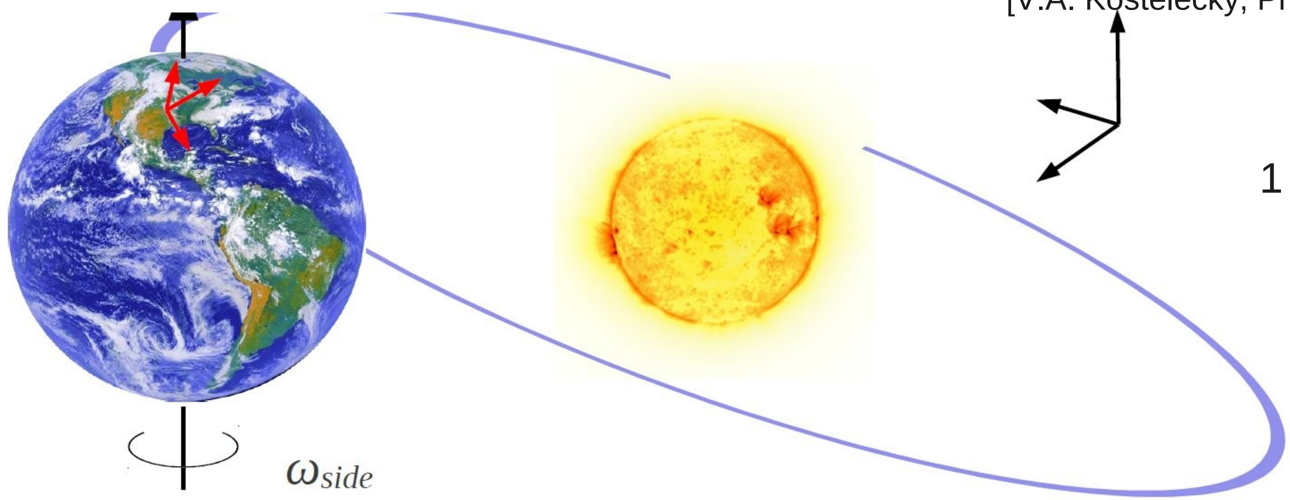
Lorentz Invariance Violation

- Search for a time dependent $t\bar{t}$ cross section
- Standard Model Extension (SME): adds terms for Lorentz Invariance violation (LIV) to the matrix element:

$$|\mathcal{M}|^2_{\mathrm{SME}} = PF\bar{F} + (\delta P_p)F\bar{F} + (\delta P_v)F\bar{F} + P(\delta F)\bar{F} + PF(\delta\bar{F}).$$

$$\sigma(t) \approx \sigma_{\mathrm{ave}}\left[1 + f_{\mathrm{SME}}(t)\right]$$

[D. Colladay and V.A. Kostelecky, Phys. Rev. D 58, 116002 (1998)]
[V.A. Kostelecky, Phys. Rev. D 69, 105009 (2004)]



1 Solar day ≈ 0.997 sidereal days

$$c_{L(R)}^{\mathrm{Apparatus}} = \hat{\mathrm{R}}\left(\omega_{side} t\right)_{(\mathrm{Sun}\rightarrow\mathrm{Apparatus})} c_{L(R)}^{\mathrm{Sun}}$$

- SME predicts cross section dependence on sidereal time (relative to fixed stars) as the orientation of the detector changes with the rotation of the earth
- $c_{L(R)}$ are different components of SME matrices

Lorentz Invariance Violation

PRL 108, 261603 (2012)

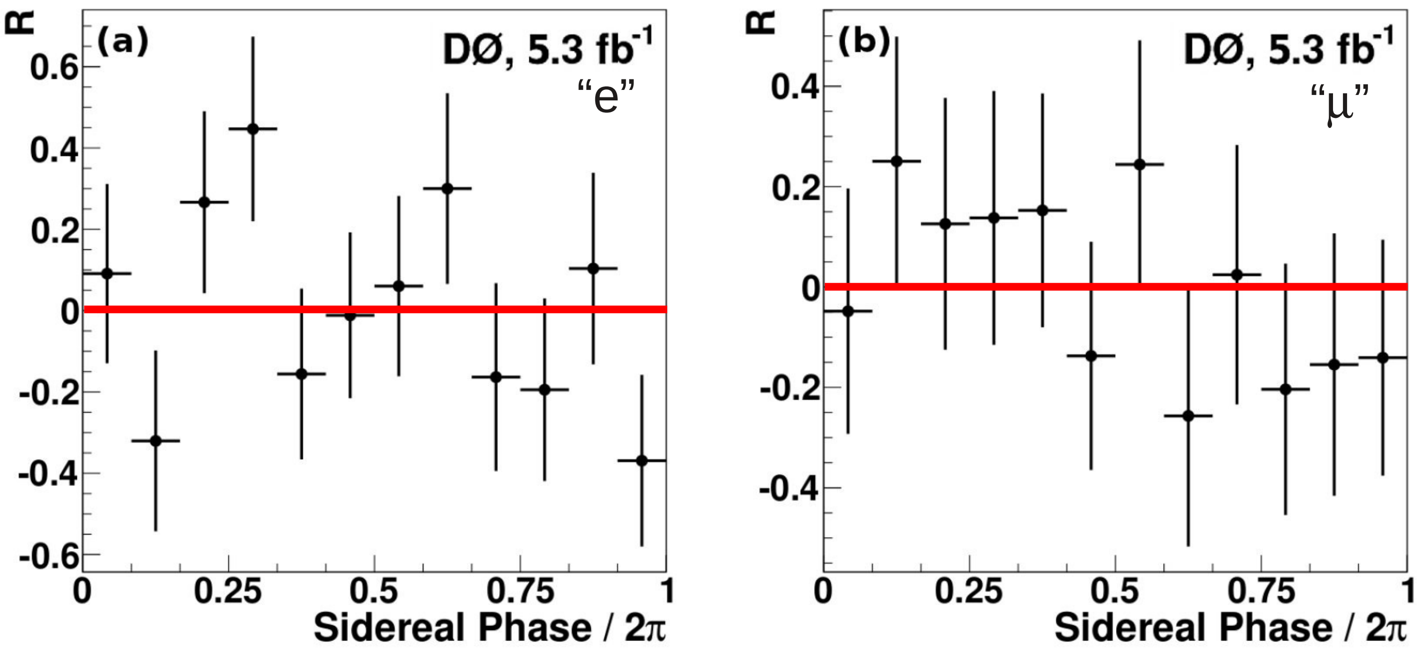
- Use lepton+jets $t\bar{t}$ selection with: ≥ 4jets, exactly one b-tag and $\not\!\!E_T$
- Other ingredients: 'Timestamp' of data at production, signal fraction f_S
- Data corresponds to August 2002 to June 2009
- Ratio R_i expected to be flat in SM (−), i.e. no time dependence

$$R_i \equiv \frac{1}{f_S}\left(\frac{N_i/N_{S+B}}{\mathcal{L}_i/\mathcal{L}_{\rm int}} - 1\right)$$

Sidereal phase bin i

Total integrated luminosity

Integrated Luminosity per bin



PRL 108, 261603 (2012)

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- c_U (right-handed) and c_Q (left-handed)

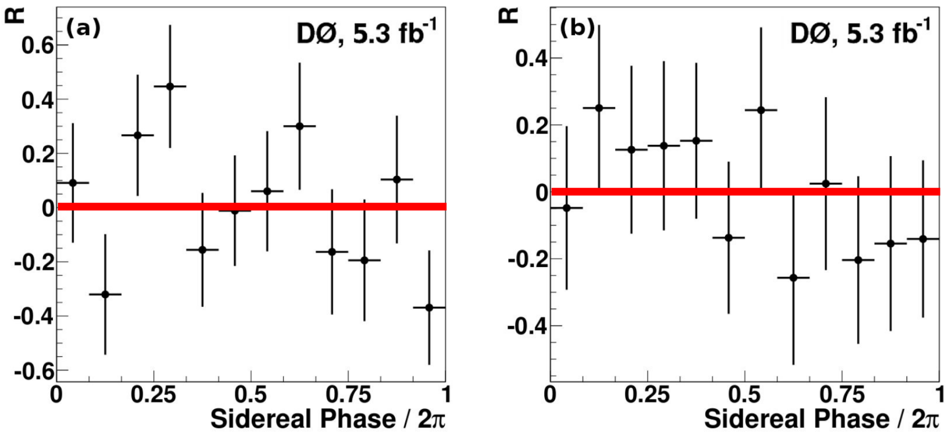

TABLE IV: Limits on SME coefficients at the 95% C.L., assuming $(c_Q)_{\mu\nu} \equiv 0$.

Coefficient	Value ± Stat. ± Sys.	95% C.L. Interval
$(c_U)_{XX33}$	$0.10 \pm 0.09 \ \pm 0.02$	$[-0.08, +0.27]$
$(c_U)_{YY33}$	$-0.10 \pm 0.09 \ \pm 0.02$	$[-0.27, +0.08]$
$(c_U)_{XY33}$	$0.04 \pm 0.09 \ \pm 0.01$	$[-0.14, +0.22]$
$(c_U)_{XZ33}$	$-0.14 \pm 0.07 \ \pm 0.02$	$[-0.28, +0.01]$
$(c_U)_{YZ33}$	$0.01 \pm 0.07 \ \pm < 0.01$	$[-0.13, +0.14]$

TABLE III: Limits on SME coefficients at the 95% C.L., assuming $(c_U)_{\mu\nu} \equiv 0$.

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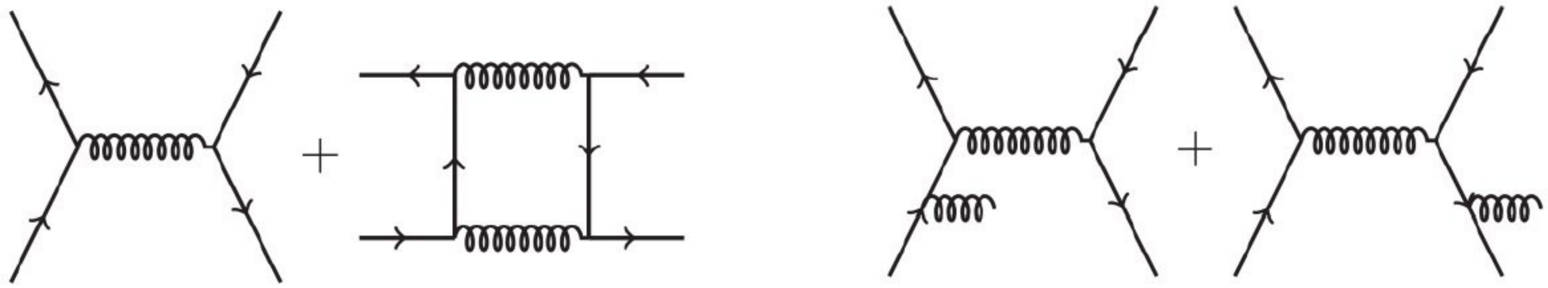
$(c_Q)_{YY33}$	$0.12 \pm 0.11 \ \pm 0.02$	$[-0.11, +0.34]$
$(c_Q)_{XY33}$	$-0.04 \pm 0.11 \ \pm 0.01$	$[-0.26, +0.18]$
$(c_Q)_{XZ33}$	$0.15 \pm 0.08 \ \pm 0.02$	$[-0.01, +0.31]$
$(c_Q)_{YZ33}$	$-0.03 \pm 0.08 \ \pm 0.01$	$[-0.19, +0.12]$

→ No indication for time dependence of $t\bar{t}$ cross-section.
First constraints on LIV in top sector (and for a bare quark)

A_{FB} measurements

- Interference starts with NLO QCD



- Tevatron this is a forward-backward asymmetry because of initial state: $q\bar{q}$ vs. gg (fwd-bwd symmetric)
- Difference between rapidities of the top-quarks is a measure of the asymmetry

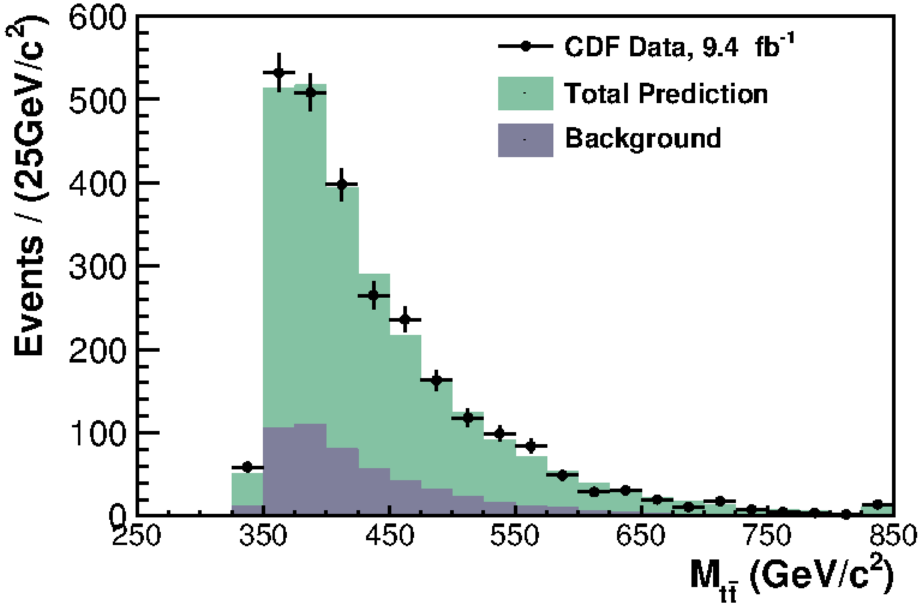
- Measure $\Delta y \equiv y_t - y_{\bar{t}}$ and define asymmetry:

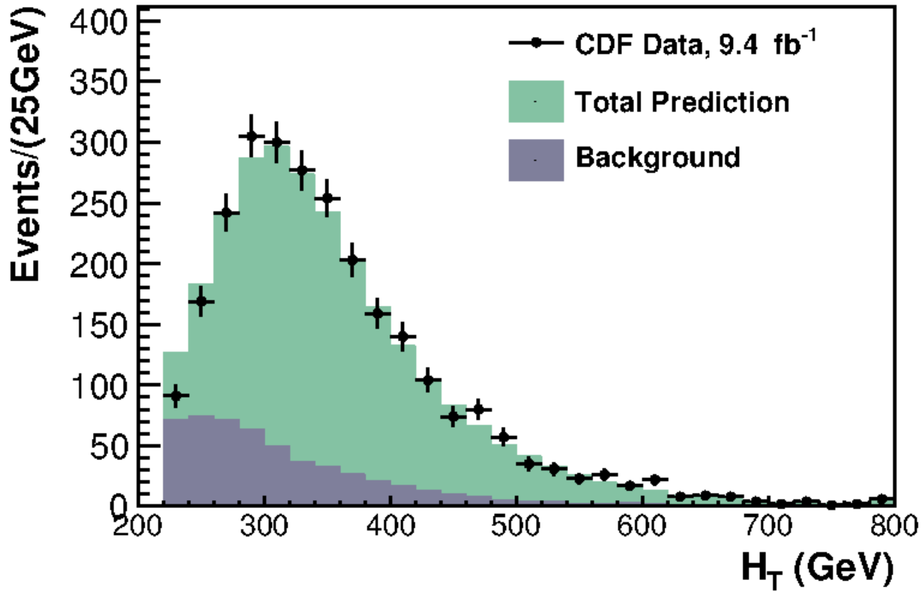
$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

→ Inclusive NLO prediction (QCD+EWK): A_{fb} = 6.6 ± 2.0 %

A_{FB} measurements

- Lepton+jets decay channel
- Full reconstruction of $t\bar{t}$ pair using kinematic fitter:
  → constrain m(W) and m(t), choose best solution
- NLO model: Powheg





- Nicely described
- Unfold detector effects to have result at parton level

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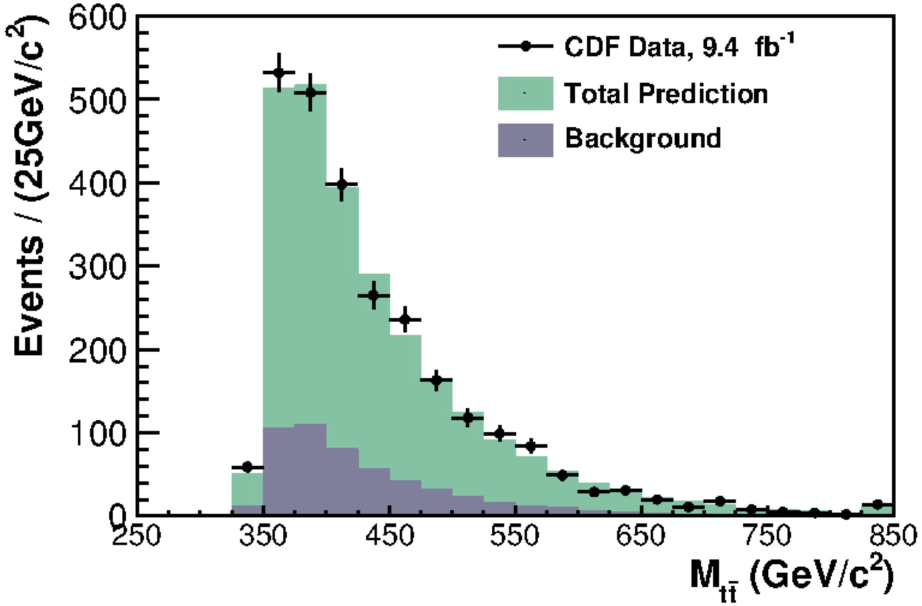
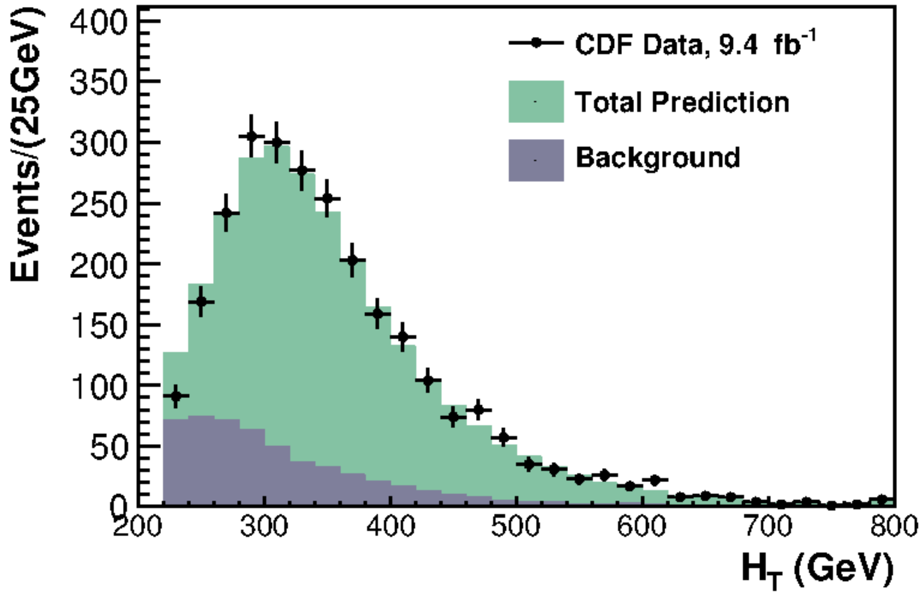


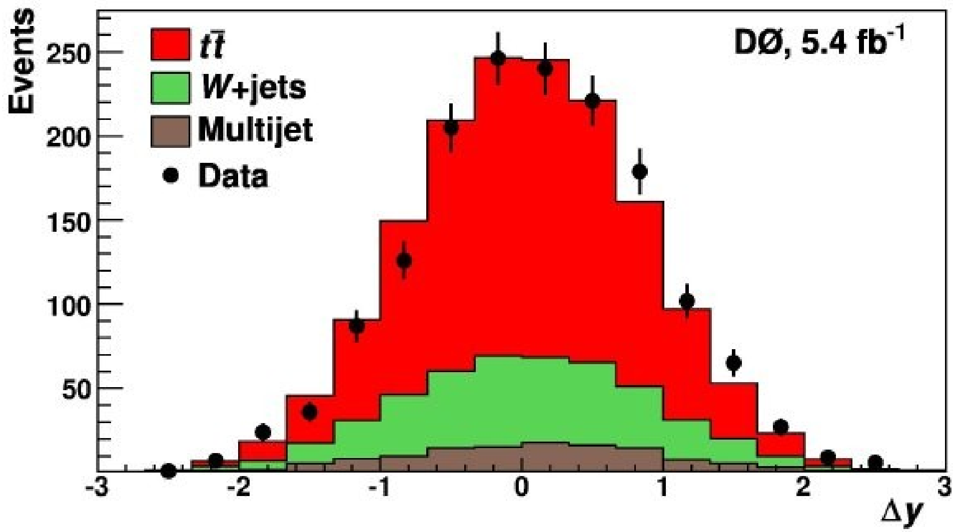


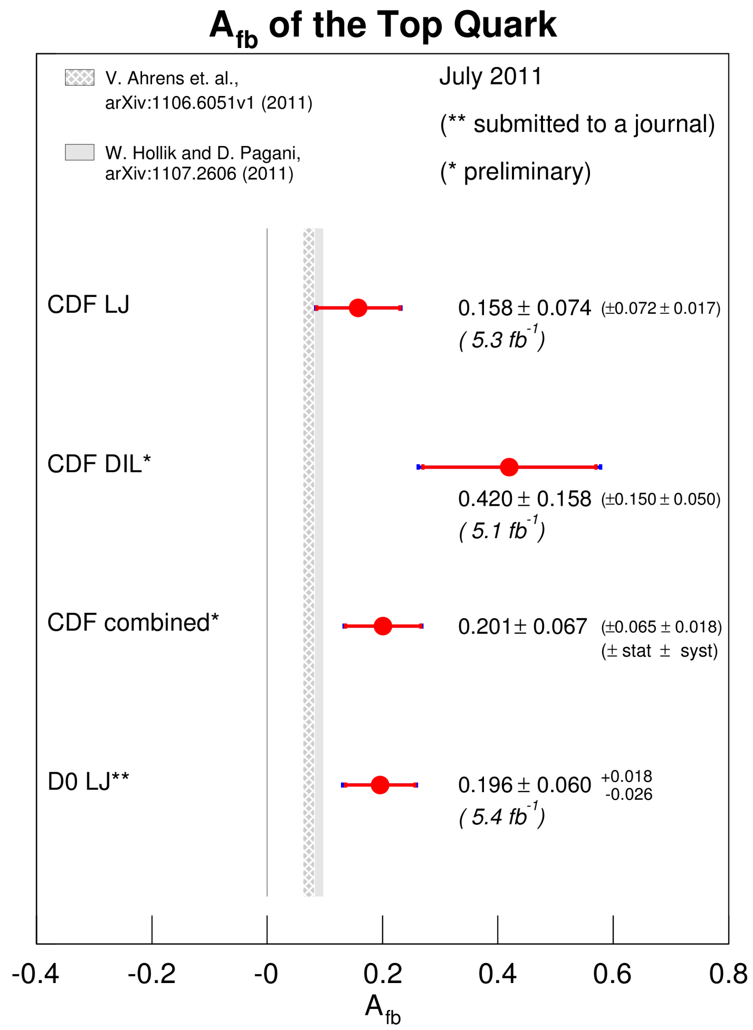
- Nicely described
- Unfold detector effects to have result at parton level

- Results: **A_{fb} parton = (16.2 ± 4.7)%** compare with **A_{fb} NLO = (6.6 ± 2.0)%**

A_{FB} measurements

- DØ measured asymmetry in lepton+jets decay channel as well
- Unfolded detector effects → asymmetry at parton level
- Kinematic fitter provides best solution





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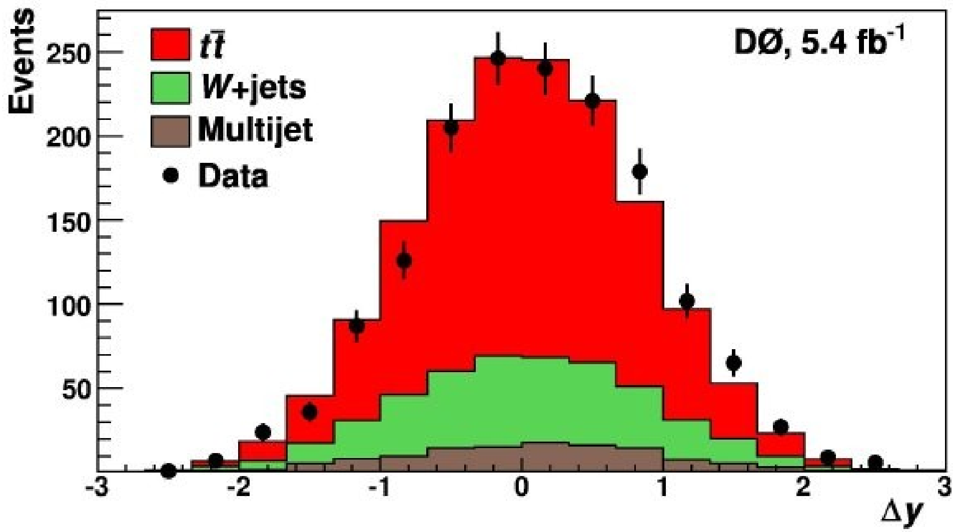
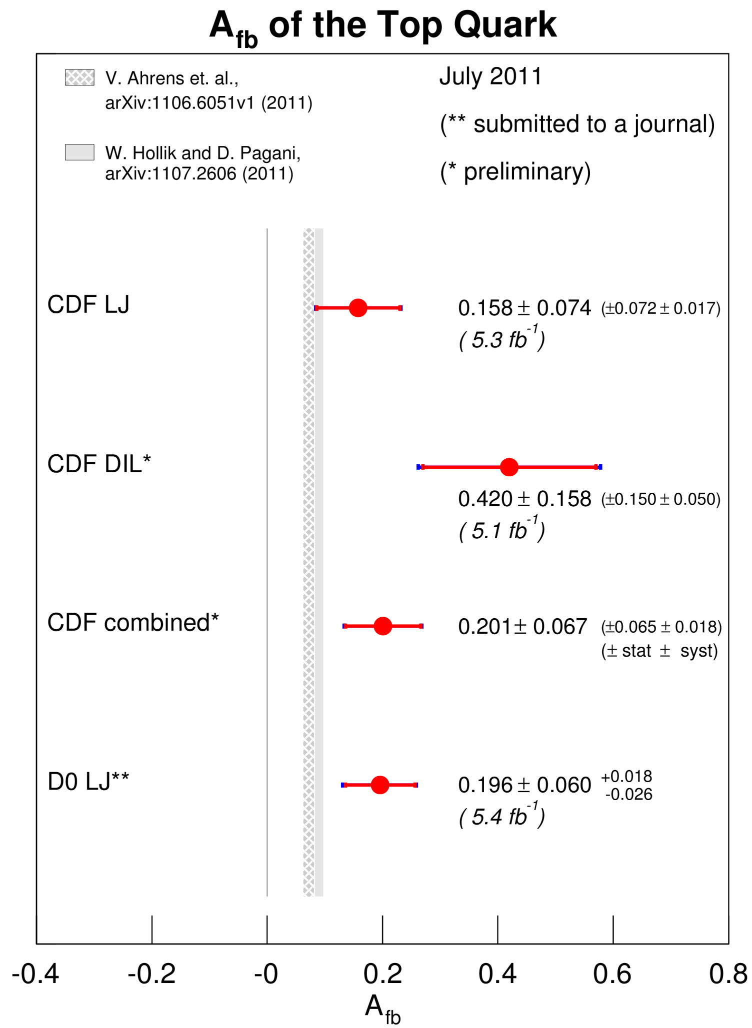


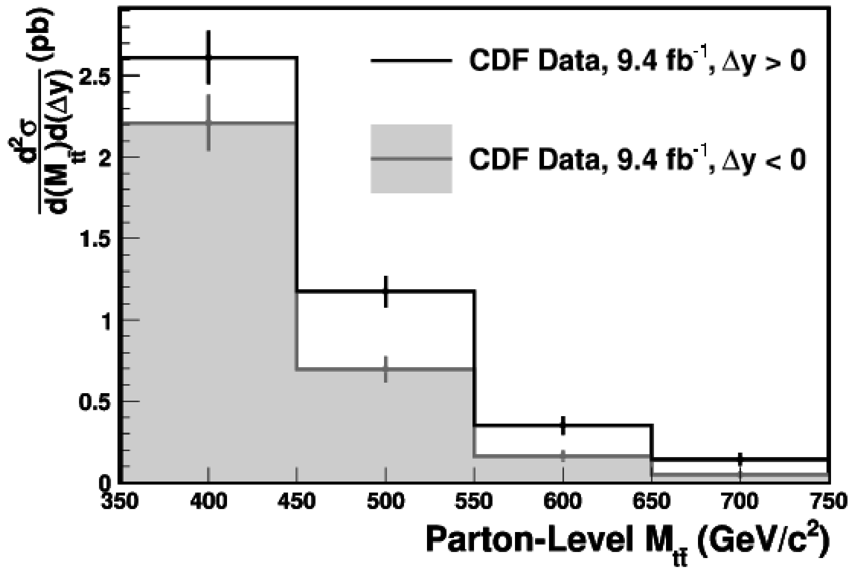


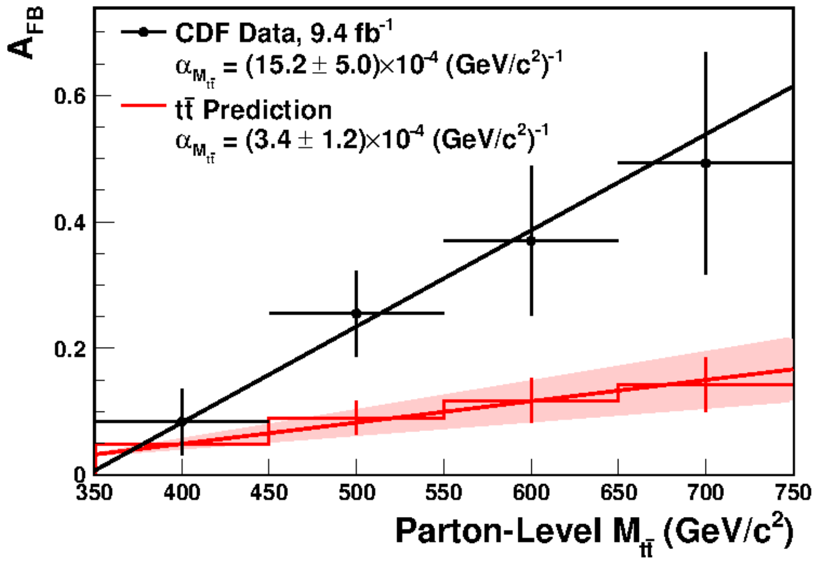
- Results: A_{fb} **parton = (19.6 ± 6.6)%**

  compare with A_{fb} **NLO = (6.6 ± 2.0)%**

A_{FB} measurements

- Kinematic dependencies (double-differential cross sections)

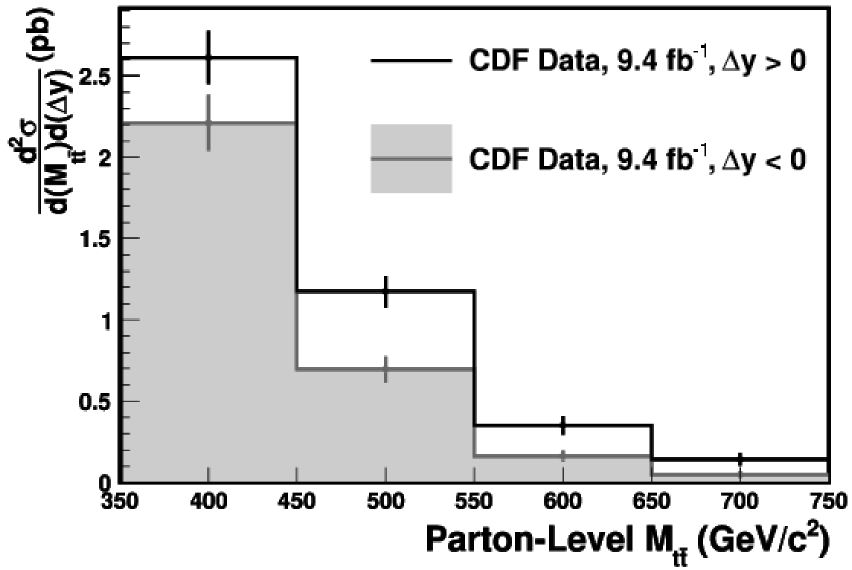


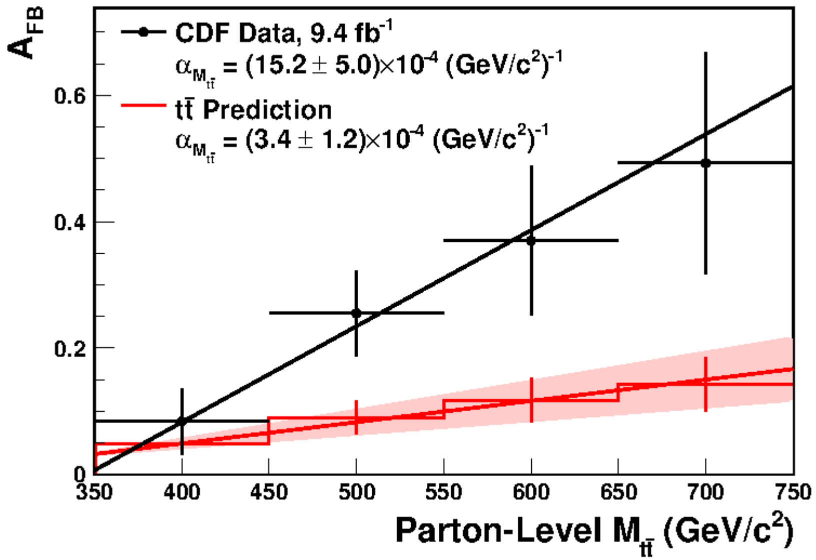


- Slope is 2.5 s.d. away from prediction

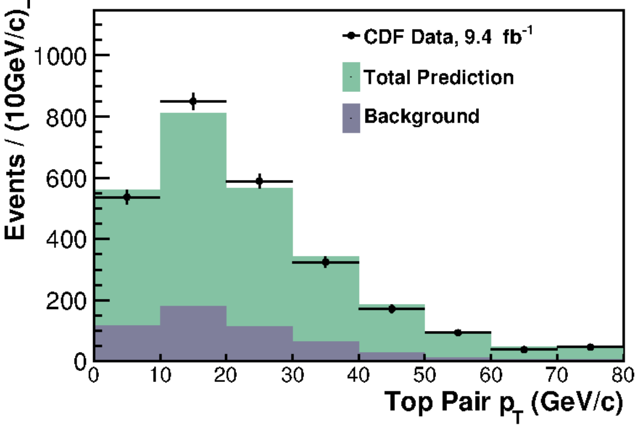
A_{FB} measurements

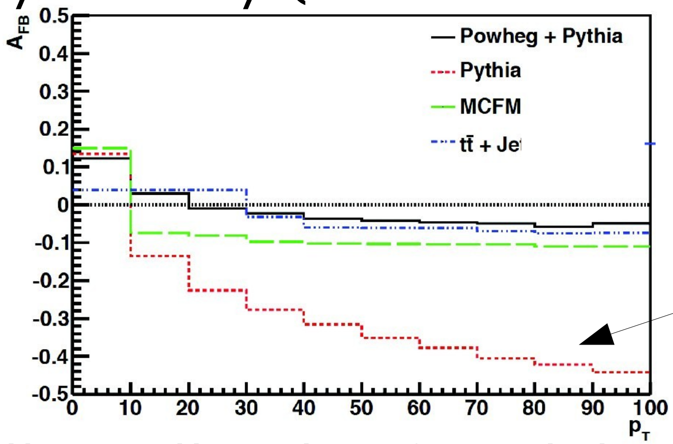
- Kinematic dependencies (double-differential cross sections)





- Slope is 2.5 s.d. away from prediction
- $p_T(t\bar{t})$ dependence of asymmetry (first noted in DØ analysis)





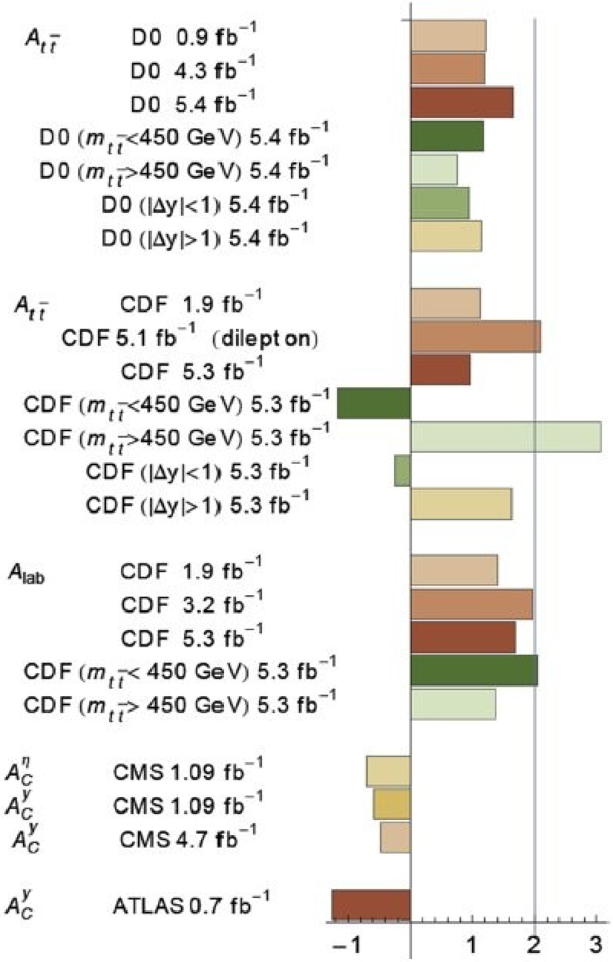
→ Strong dependence in case of Pythia

→ NLO QCD smaller

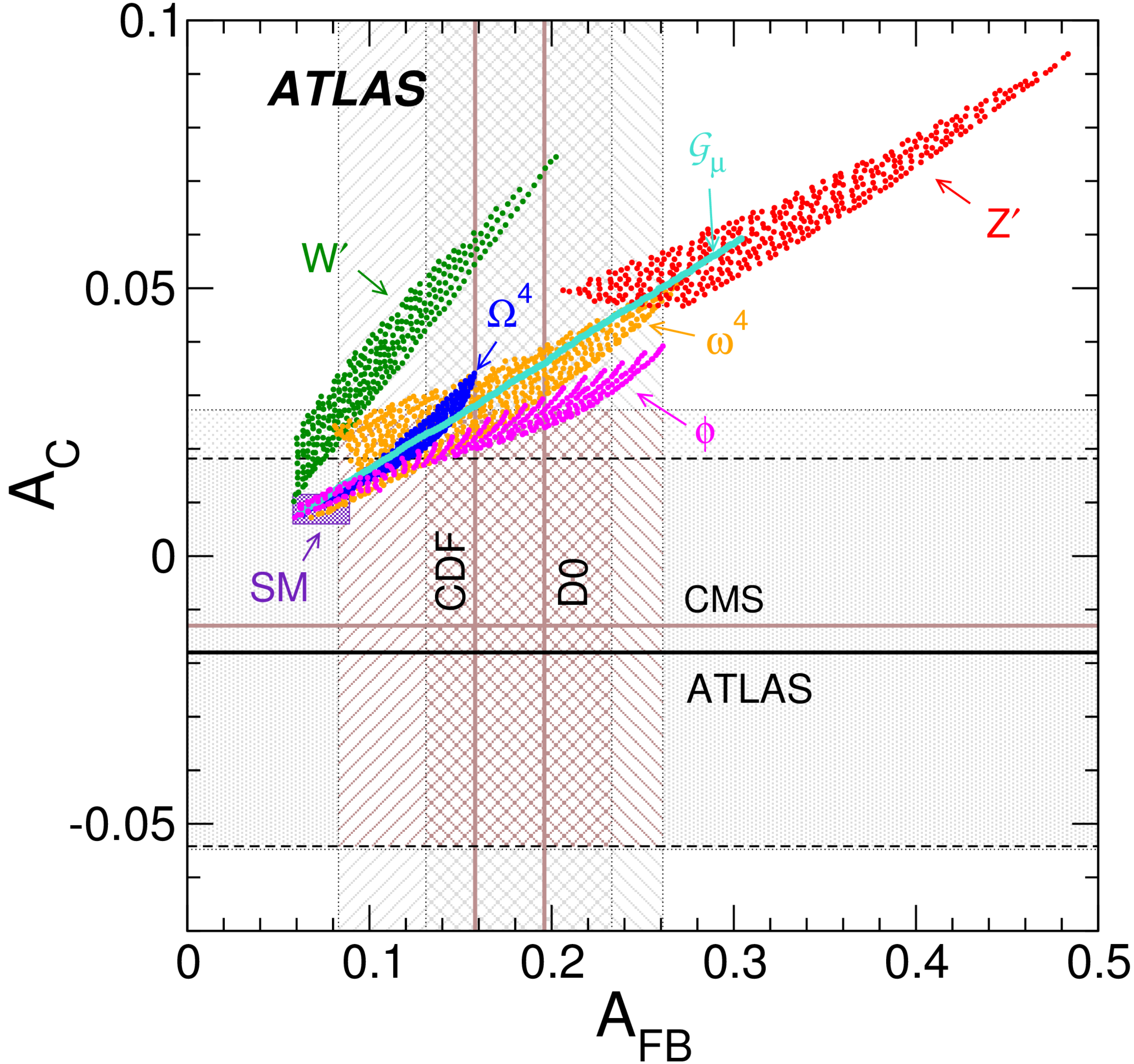
- Remains a puzzling situation, still lots of work to do...

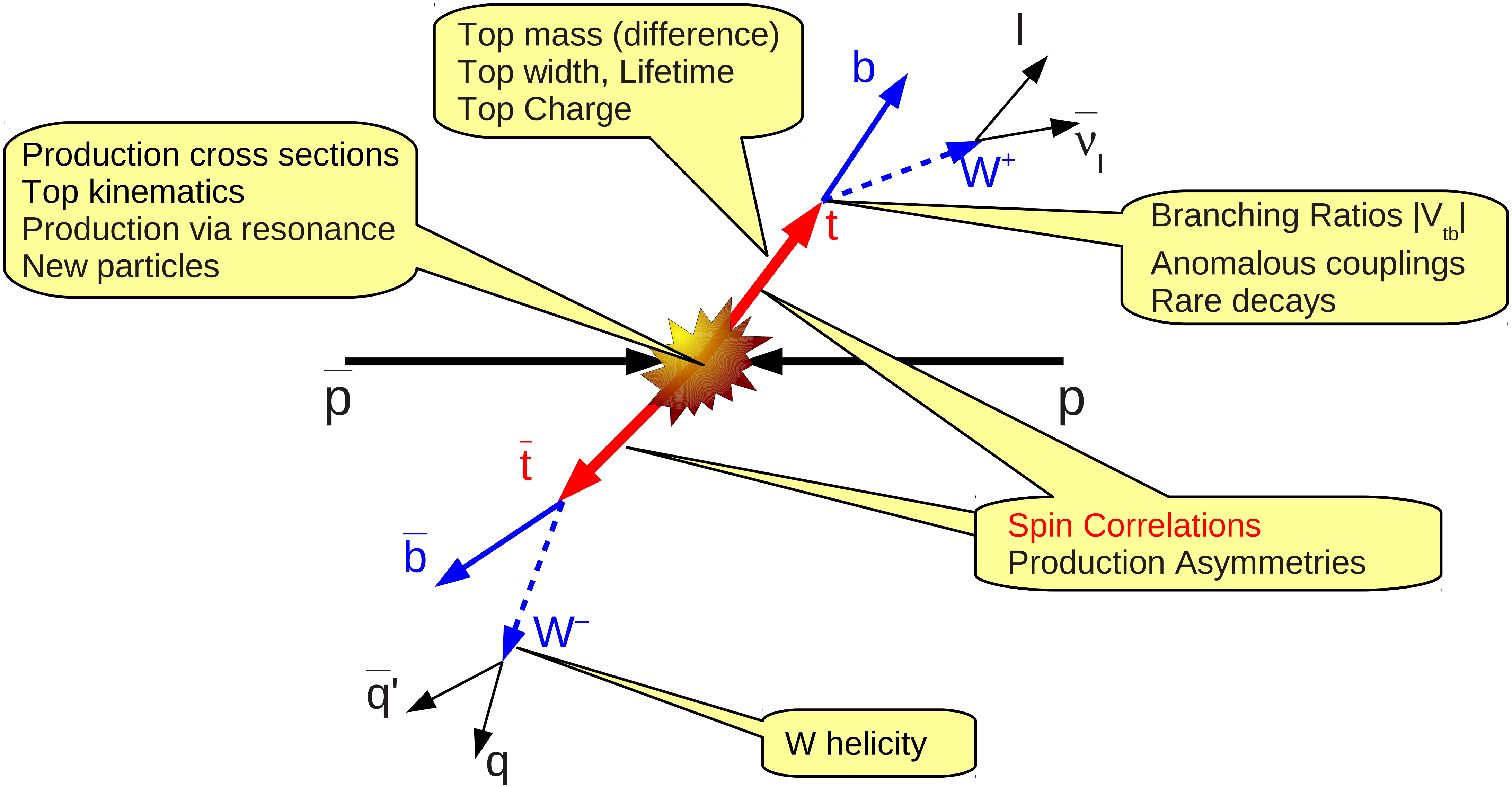
A_{FB} measurements

- Complimentary information from Tevatron and LHC
- Remains a puzzle for now...



Taken from G. Rodrigo (Moriond EW)




Top mass (difference)
Top width, Lifetime
Top Charge
Production cross sections
Top kinematics
Production via resonance
New particles
b
l
$\bar{\nu}_l$
W^+
t
Branching Ratios $|V_{tb}|$
Anomalous couplings
Rare decays
$\bar{p}$
p
$\bar{t}$
$\bar{b}$
Spin Correlations
Production Asymmetries
W^-
$\bar{q}'$
q
W helicity

Spin correlations

- Very short lifetime prevents spins from being affected by the fragmentation process: Spin correlations affect decay products
- Production is different at Tevatron vs. LHC → measure both !

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

- NLO QCD predicts: C = 0.78 + 0.03 – 0.04
- Use matrix element approach:

$$P_{\rm sgn}(x;H) = \frac{1}{\sigma_{\rm obs}}\int f_{\rm PDF}(q_1)\, f_{\rm PDF}(q_2) {\rm d}q_1 {\rm d}q_2 \times \frac{(2\pi)^4\, |\mathcal{M}(y,H)|^2}{q_1 q_2 s}\, W(x,y)\, {\rm d}\Phi_6$$

→ 30% improvement

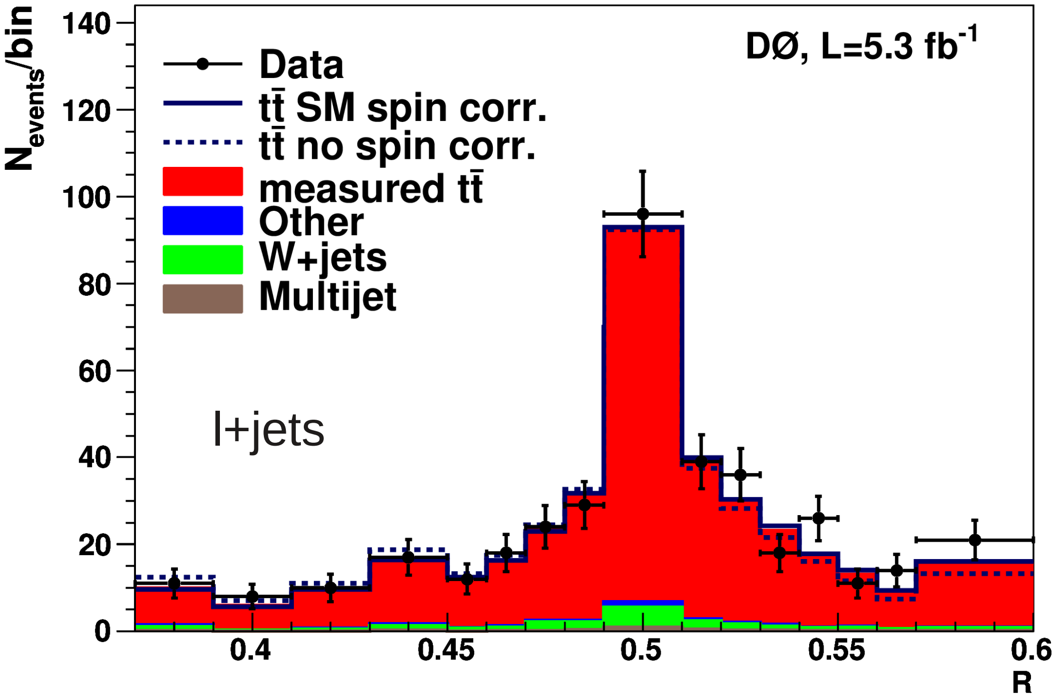
- Probabilities are used to form discriminant:

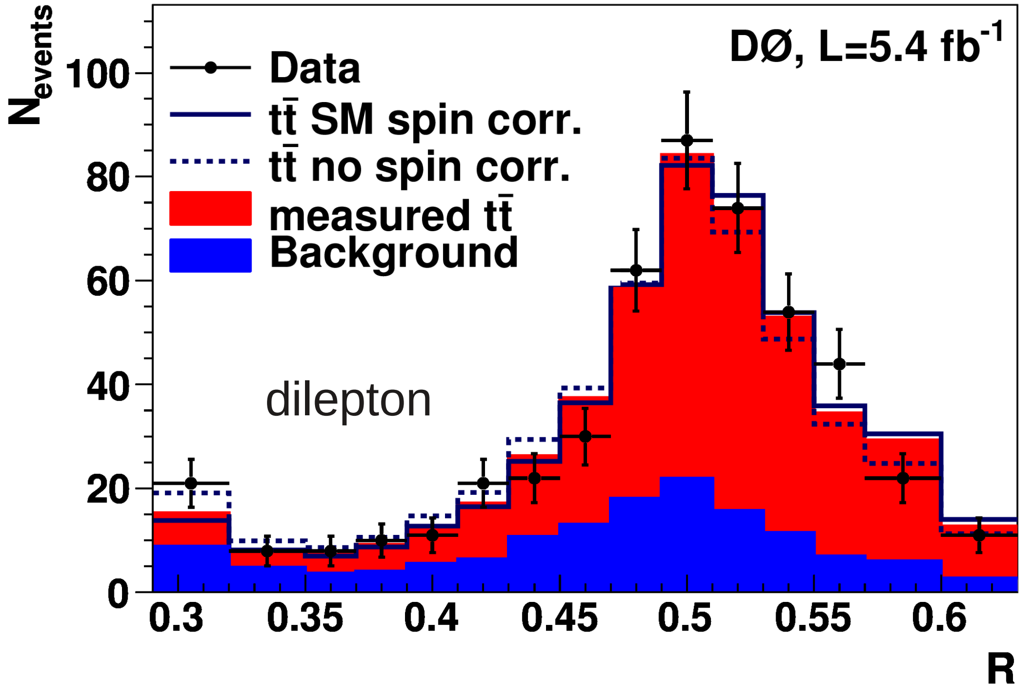
$$R = \frac{P_{\rm sgn}(x;H=c)}{P_{\rm sgn}(x;H=u) + P_{\rm sgn}(x;H=c)}$$

[PLB 700, 17 (2011)]

Spin correlations

- Very short lifetime prevents spins from being affected by the fragmentation process: Spin correlations affect decay products
- Use MC@NLO samples with and w/o spin correlations

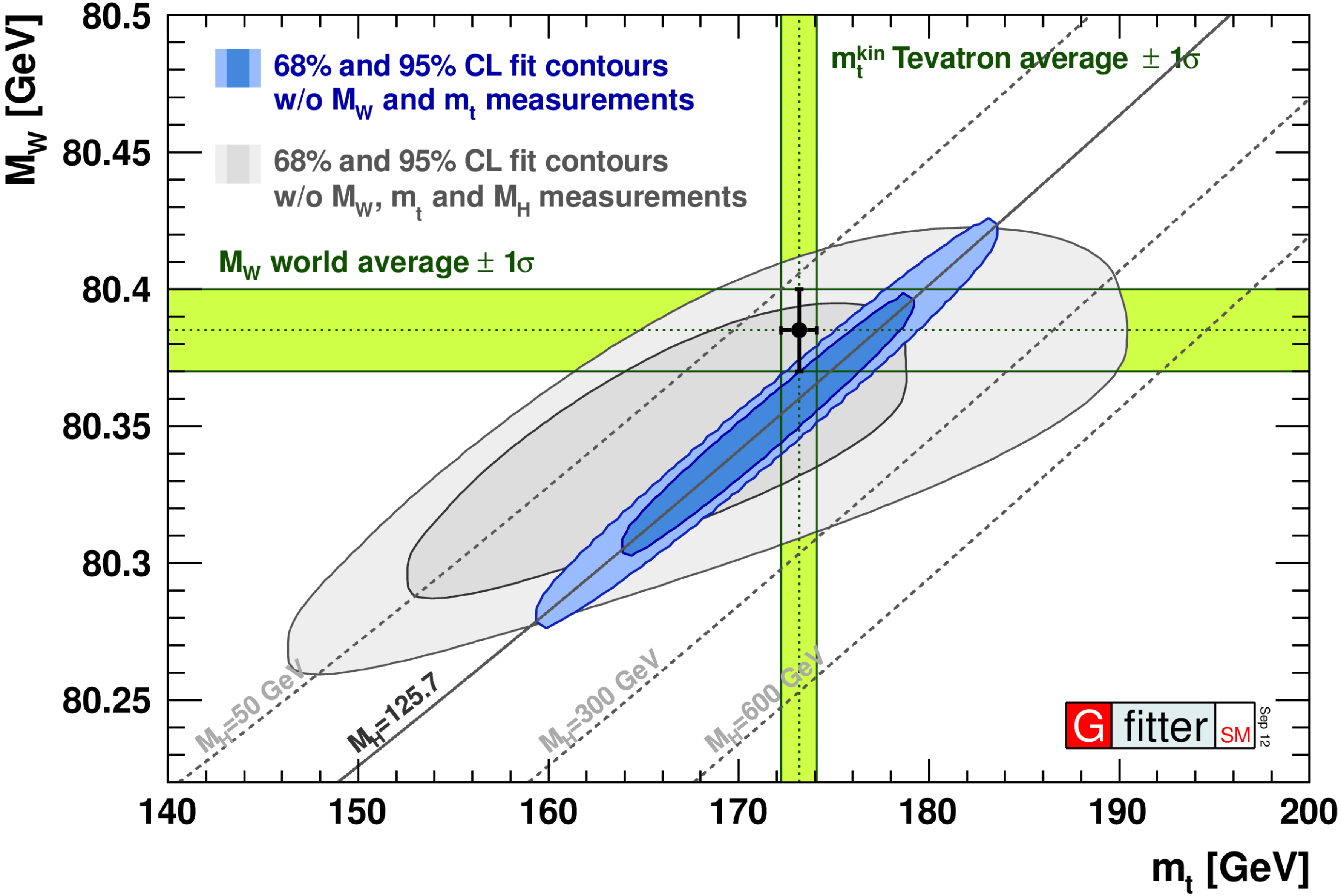




- l-jets: 1.15 ± 0.43 (stat + sys) Dilepton: 0.74 ± 0.41 (stat + sys)
- DØ combination: 0.85 ± 0.29 (stat + sys) → 3.1 s.d. for spin correlation

W mass ↔ top quark mass

GFitter [arxiv:1209.2716]



Top mass: Methods

The measurements discussed today are based on:

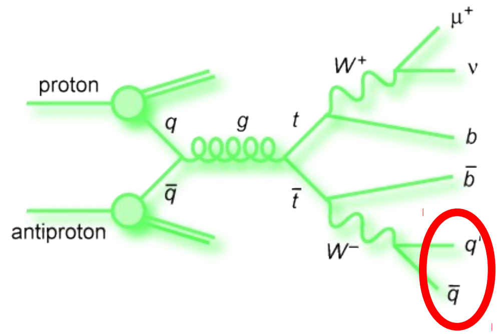
- Template method
- Matrix Element method

→ Template method: Few assumptions, fast
  - Pick a set of variables sensitive to m_t, e.g. m_t^{reco}
  - Create "templates" = distributions of m_t using MC: m_t^{reco}

→ Matrix element method: Precise, slow
  - Calculate Probability on event-by-event basis

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

- Both methods use the 'in-situ' JES calibration to reduce JES uncertainty, use W boson mass constrain



Top mass: Template

- Final state categories: 0,1,2 b-tags x loose,tight jet criteria
- Reconstruct event kinematics by minimizing:

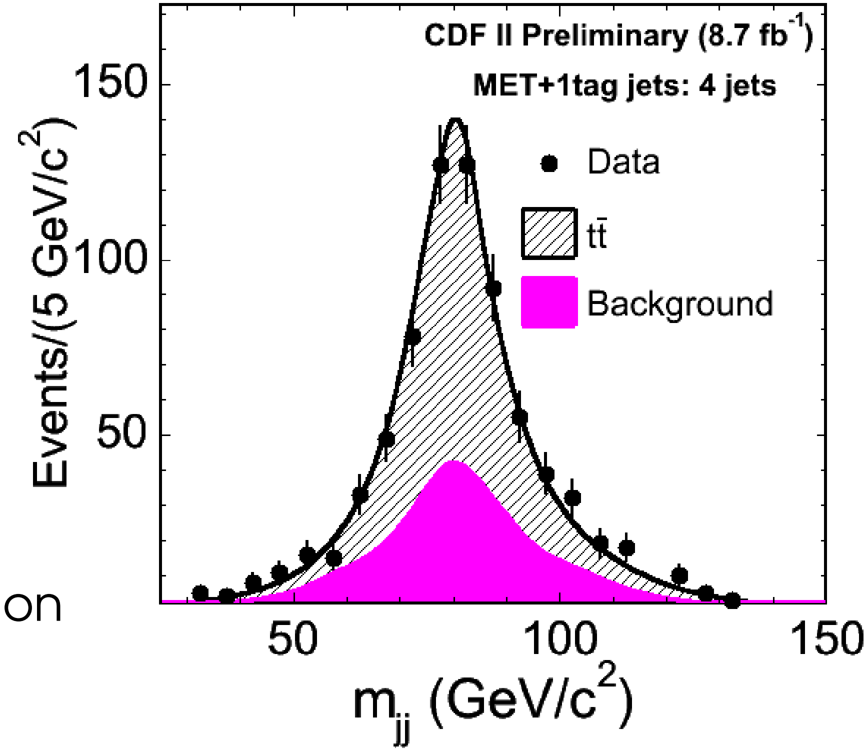
$$\chi^2 = \sum_{i=4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_T^{UE,meas})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b,missing} - M_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{bjj} - M_t^{reco})^2}{\Gamma_t^2}$$

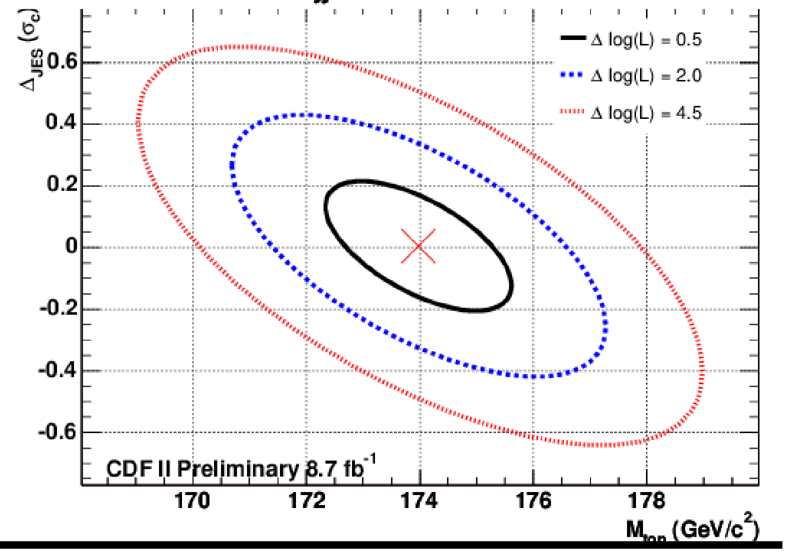
'wrong' combination

- 3D template fit of m_{jj}^{reco}, m_t^{reco1}, m_t^{reco2}
- Largest uncertainties:
  - Signal modeling: hadronization + UE, color reconnection
  - Detector modeling: JES, b-jet energy scale

→ m_t = 172.85 ± 1.10 (stat+sys) GeV

Precision of 0.6% !



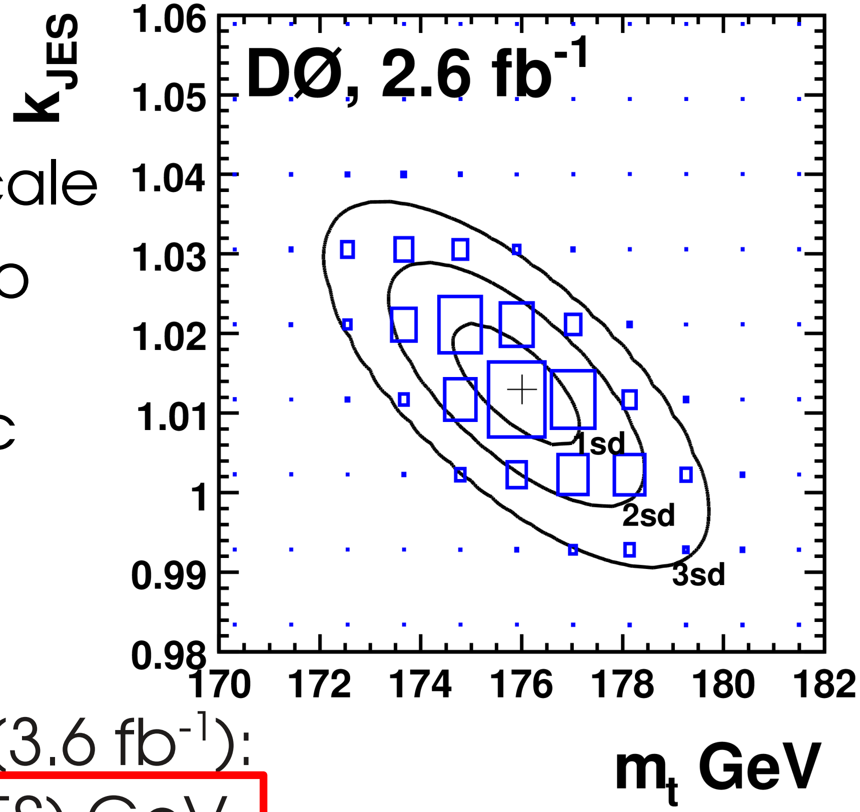


Mass of the Top Quark

- Matrix Element method (ME) calculates event probability densities (PD) from differential cross sections and detector resolutions:

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

- The Transferfunction relates the PD of measured set x to the partonic set y
- k_{JES} is a global factor for the Jet Energy Scale
- Selection of l+jets events, use b-tagging to increase purity of the sample
- Measurement is dominated by systematic uncertainty



→ Most precise DØ mass measurement (3.6 fb^{-1}):

m_t = 174.9 ± 0.8 (stat.) ± 1.2 (sys.+JES) GeV

Precision of 0.9% !

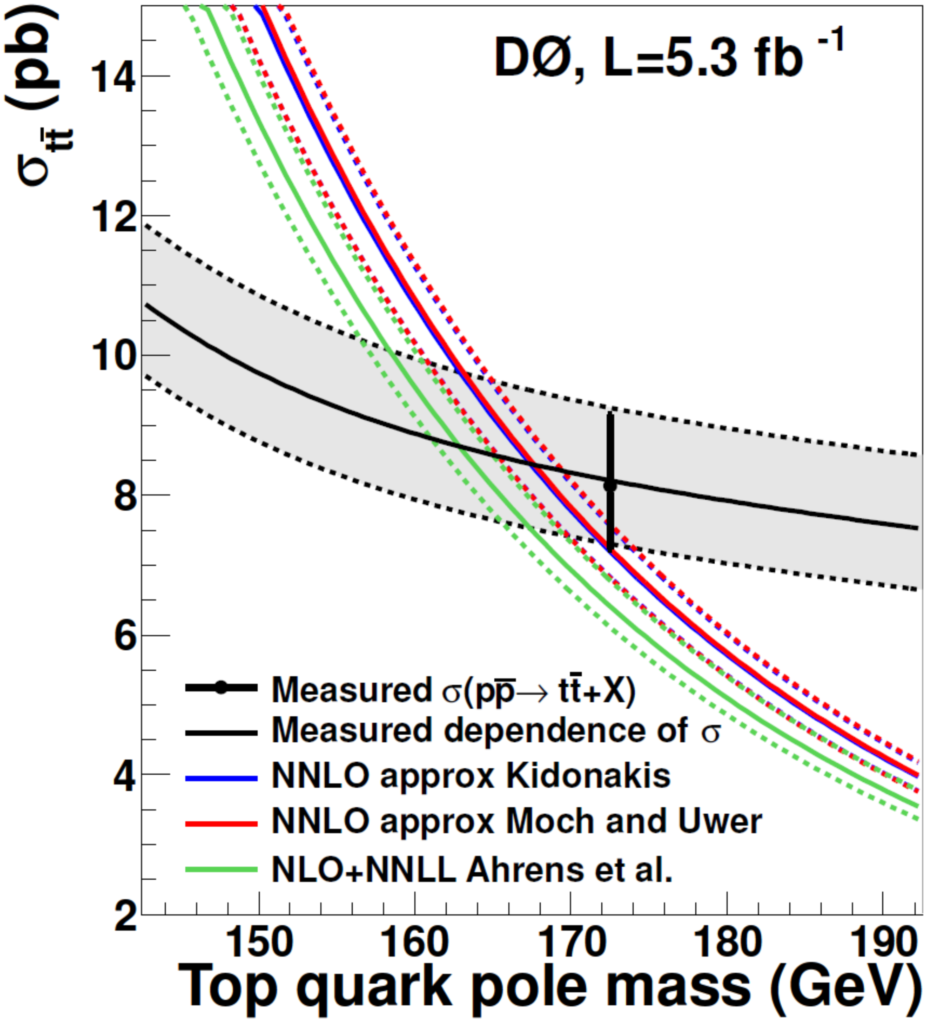
Mass of the Top Quark

- Mass is convention dependent:

Depends on the renormalization scheme

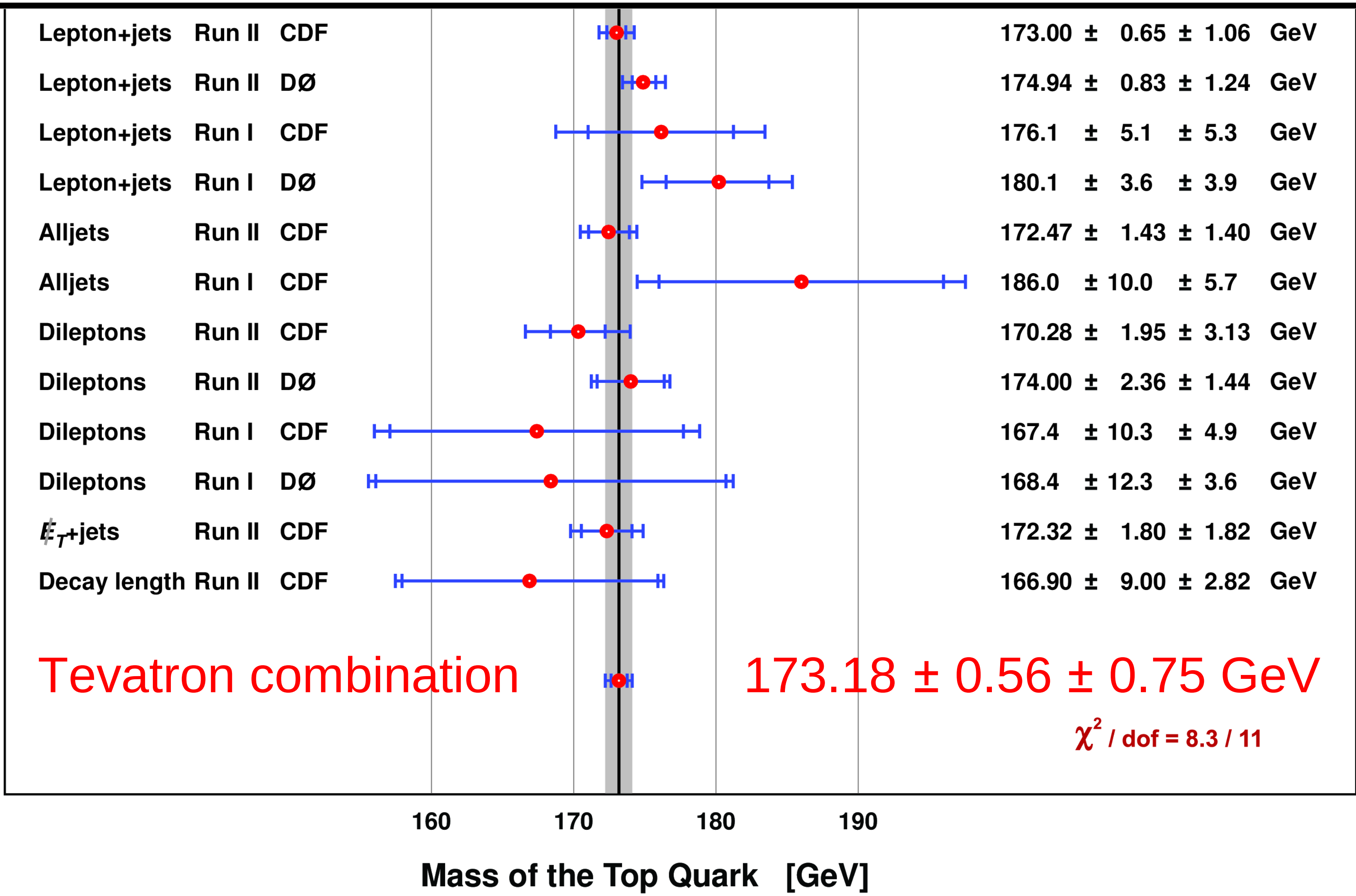
- Direct mass measurement is close to the pole mass
- Derive m_t^{pole} from intersection of measured $\sigma_{t\bar{t}}$ and theoretical predictions:

Theoretical prediction	m_t^{pole} (GeV)	Δm_t^{pole} (GeV)
MC mass assumption	$m_t^{MC} = m_t^{pole}$	$m_t^{MC} = m_t^{\overline{MS}}$
NLO [11]	$164.8^{+5.7}_{-5.4}$	-3.0
NLO+NLL [12]	$166.5^{+5.5}_{-4.8}$	-2.7
NLO+NNLL [13]	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO [14]	$167.5^{+5.2}_{-4.7}$	-2.7
Approximate NNLO [15]	$166.7^{+5.2}_{-4.5}$	-2.8

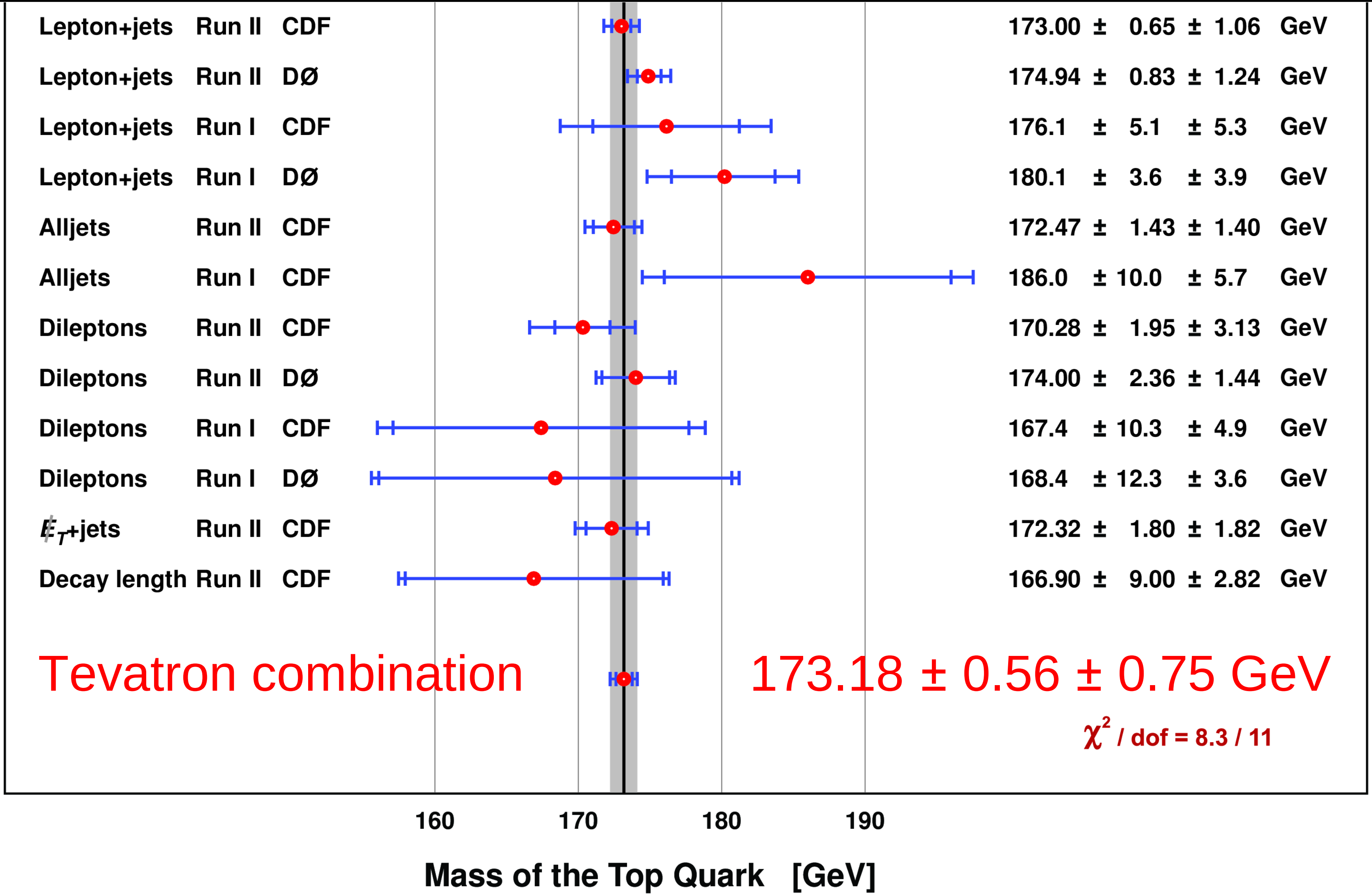


→ $m_t = 167.5 + 5.4 - 4.7$ GeV

Tevatron combination



Tevatron combination



Remarkable agreement !

LHC June 2012 173.3 ± 0.5 ± 1.3 GeV

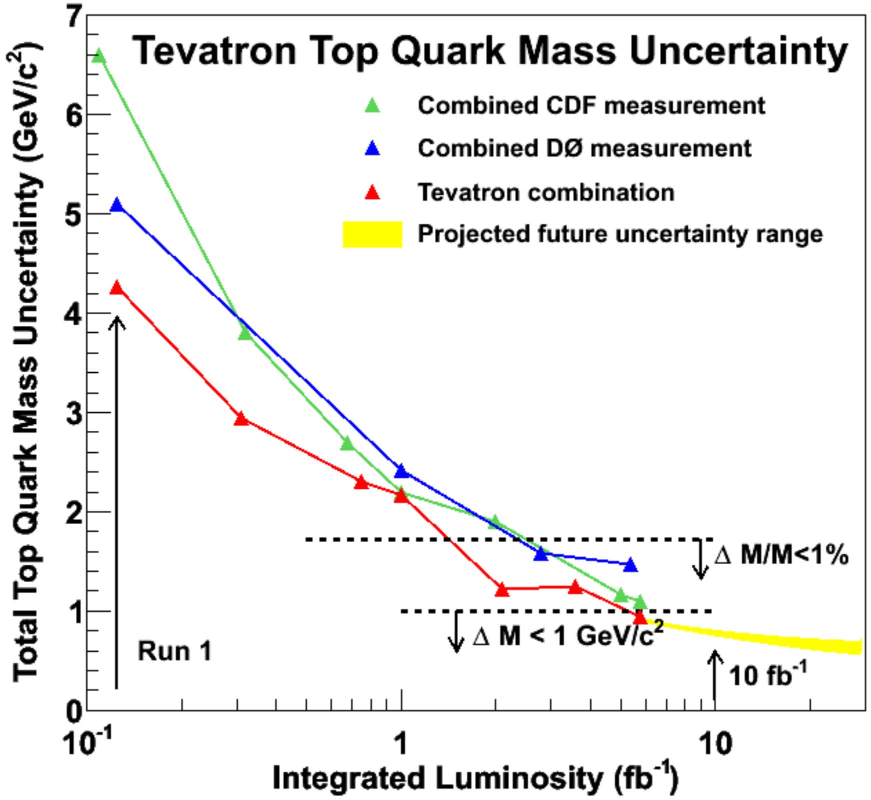
Top mass: Uncertainties!

→ Some overlap in systematic uncertainties

- Estimation of higher order effects:
  - Factorization and Renormalization uncertainties overlap with ISR/FSR uncertainties, differential cross section distributions might help
- MC parton showers: PT versus Q2 ordered → O(500 MeV) difference ?!
  - Jet shapes studies, differential distributions, …

Skands, Wicke:
[hep-ex:0807.3248]

- Improvements in uncertainties: ~25%



→ Fundamental limit:

- Already of the same order of Λ_{QCD}
- Ultimately threshold scan at ILC

W mass

- CDF and DØ measurements use binned likelihood fits to extract M_W
- CDF calibration done by:
  - Momentum scale from $J/\psi \rightarrow \mu\mu$, $\Upsilon \rightarrow \mu\mu$, $Z \rightarrow \mu\mu$ mass fits
  - E/p distribution in $W \rightarrow e\nu$ to calibrate calorimeter energy scale
- DØ calibration done by:
  - $Z \rightarrow ee$ invariant mass and angular distribution (electron energy scale α and offset β

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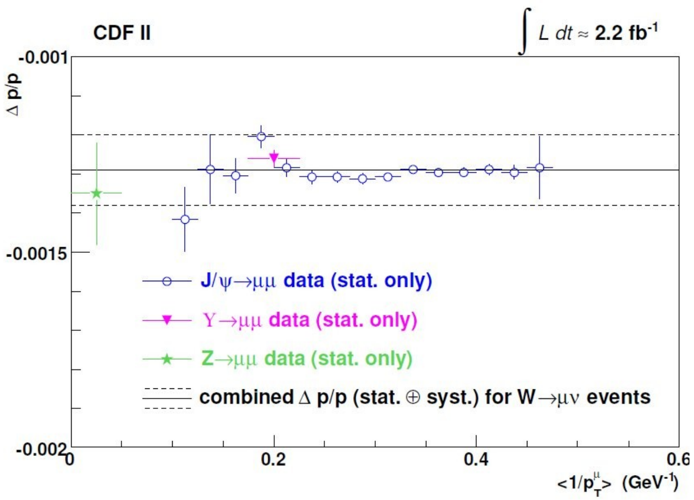
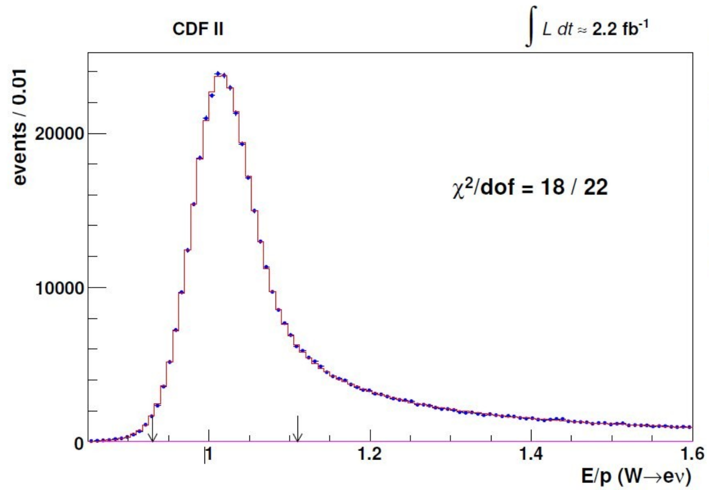
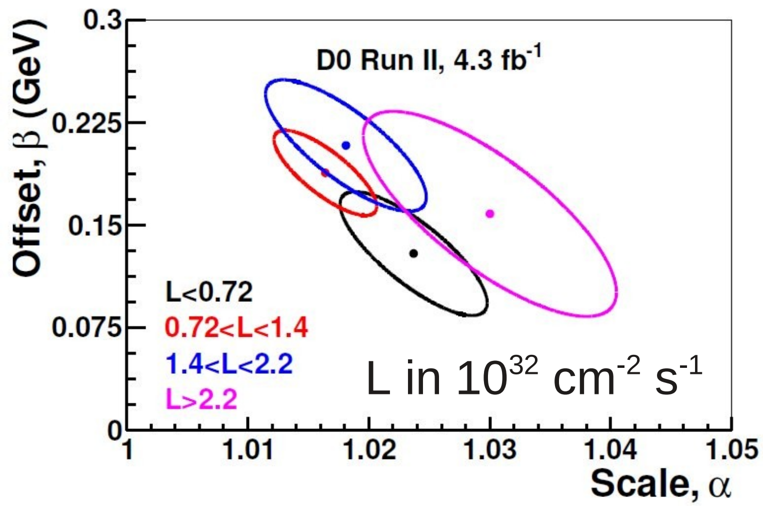






- CDF momentum scale and DØ energy scale precision ~ 0.01% !

W mass

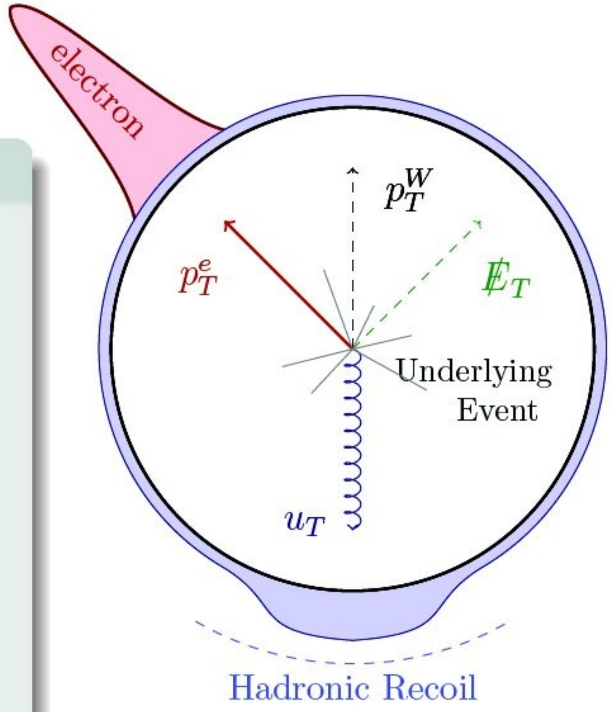
- CDF and DØ measurement cuts:

CDF analysis

- Analyzed $2.2\, fb^{-1}$.
- Uses $W \to e\nu$ and $W \to \mu\nu$ decay channels.
- Central leptons $|\eta| < 1$ with $30 < p_T < 55\, GeV$
- Missing transverse energy $30 < \not{E}_T < 55\, GeV$
- Transverse mass $60 < m_T < 100\, GeV$
- Hadronic recoil momentum $u_T < 15\, GeV$

DØ analysis

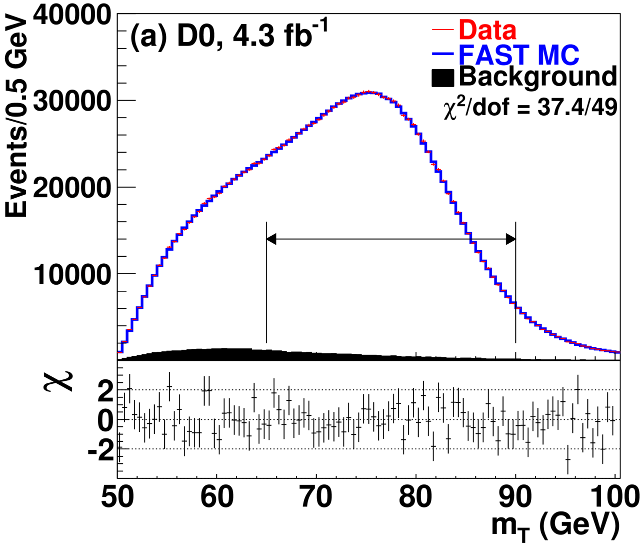
- Analyzed $4.3\, fb^{-1}$ ($1\, fb^{-1}$ analyzed before)
- Uses $W \to e\nu$ decay channel.
- Central electrons $|\eta| < 1.05$ with $p_T > 25\, GeV$
- Missing transverse energy $\not{E}_T > 25\, GeV$
- Transverse mass $50 < m_T < 200\, GeV$
- Hadronic recoil momentum $u_T < 15\, GeV$

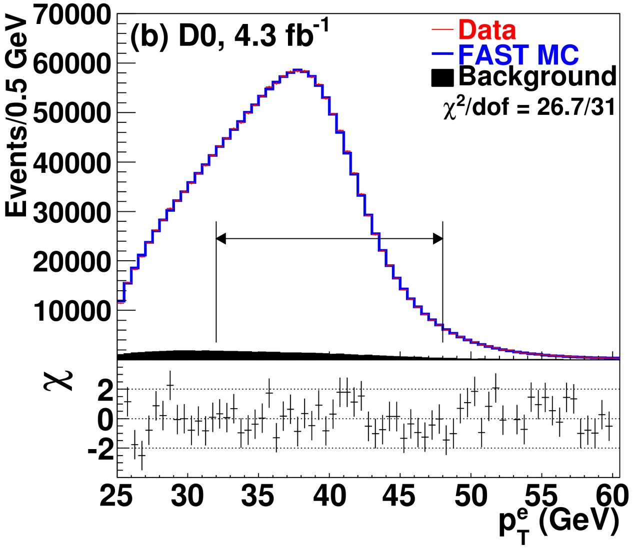


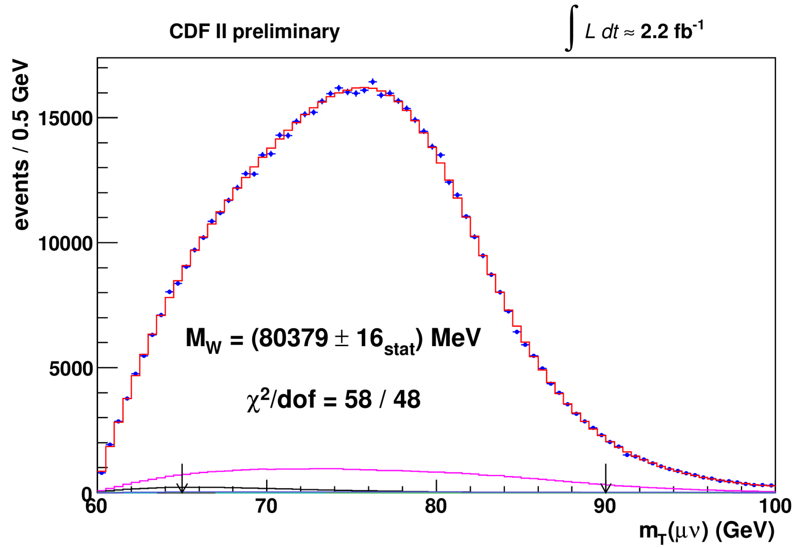
- Number of selected events:

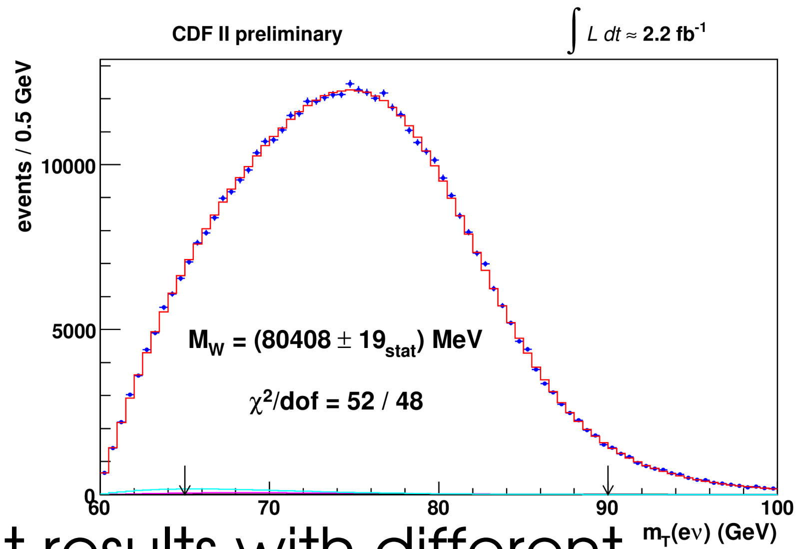
	$W \to e\nu$ candidates	$W \to \mu\nu$ candidates	Total
CDF $2.2\, fb^{-1}$	$470,126$	$624,708$	$1,094,834$
DØ $4.3\, fb^{-1}$ ($+1\, fb^{-1}$)	$1,677,394$	–	$1,677,394$ $2,177,224$

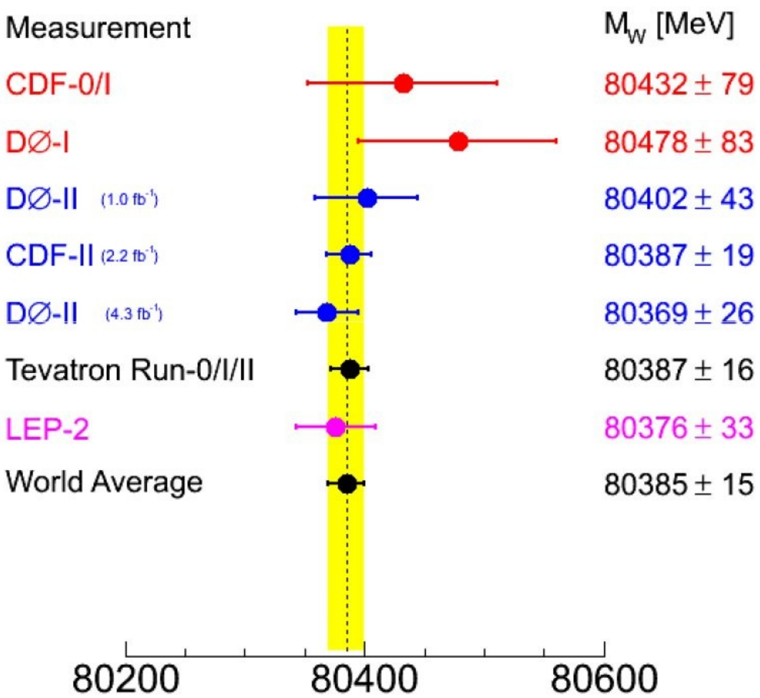
W mass











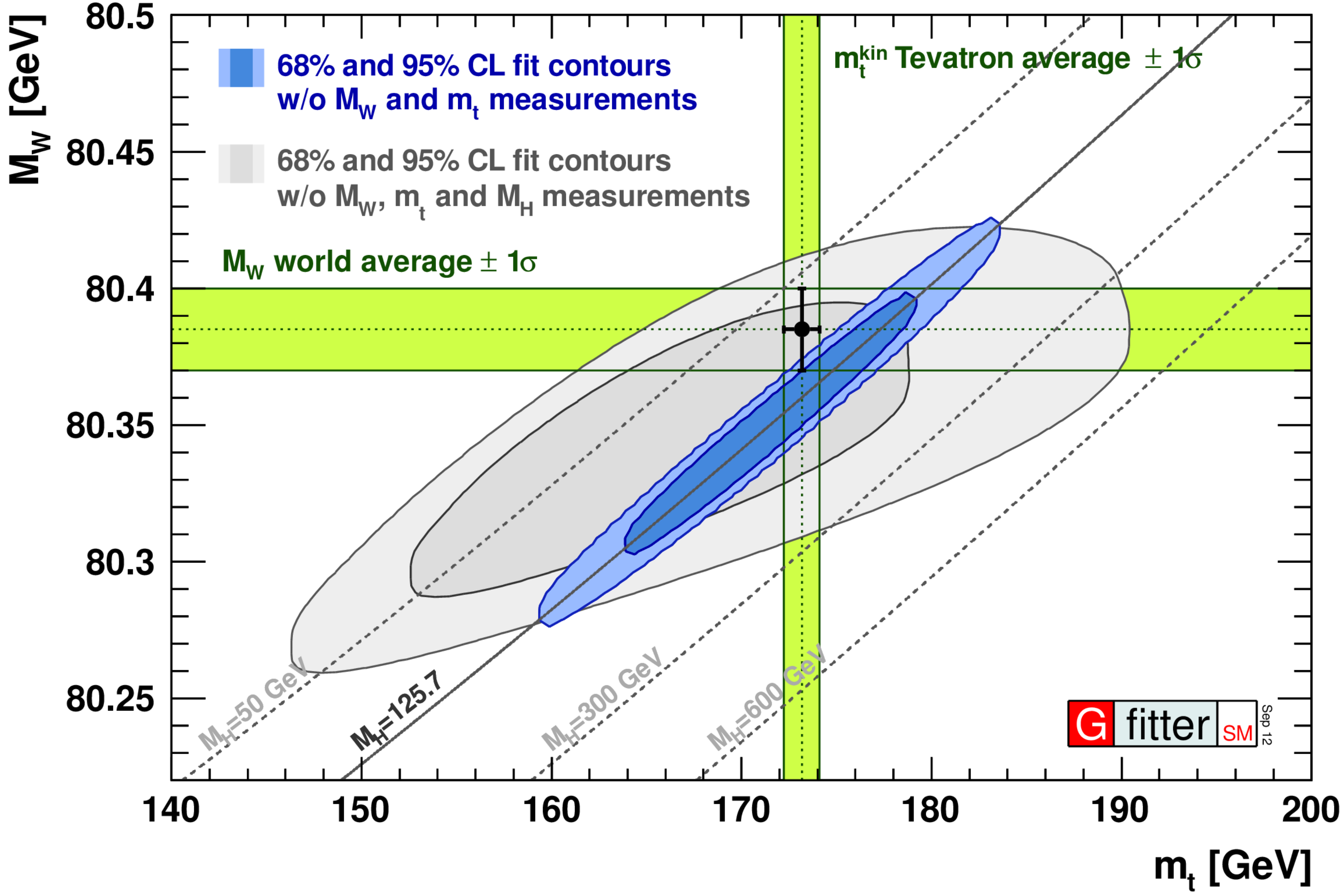
Very consistent results with different detectors and experimental measurement strategies !

W mass

Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	2	3	
Recoil Model			5
Efficiency Model			1
Background	3	4	2
W production and decay model – Not statistically driven.			
PDF	10	10	11
QED	4	4	7
Boson p_T	3	3	2

W mass ↔ top quark mass

GFitter [arxiv:1209.2716]



Conclusions & Outlook

- Presented recent Standard Model measurements at the Tevatron:
  - Self consistency of SM
  - Many results not yet with final data set, updates expected soon
  - Tevatron top physics program can compete with LHC !

Outlook:

- More precise results in the near future, *but:*
  - Concentrate on results which are **competitive or complimentary** to LHC
  - Puzzling situation AFB

http://www-d0.fnal.gov/Run2Physics/top/index.html

http://www-cdf.fnal.gov/physics/new/top/top.html

Summary – Overview

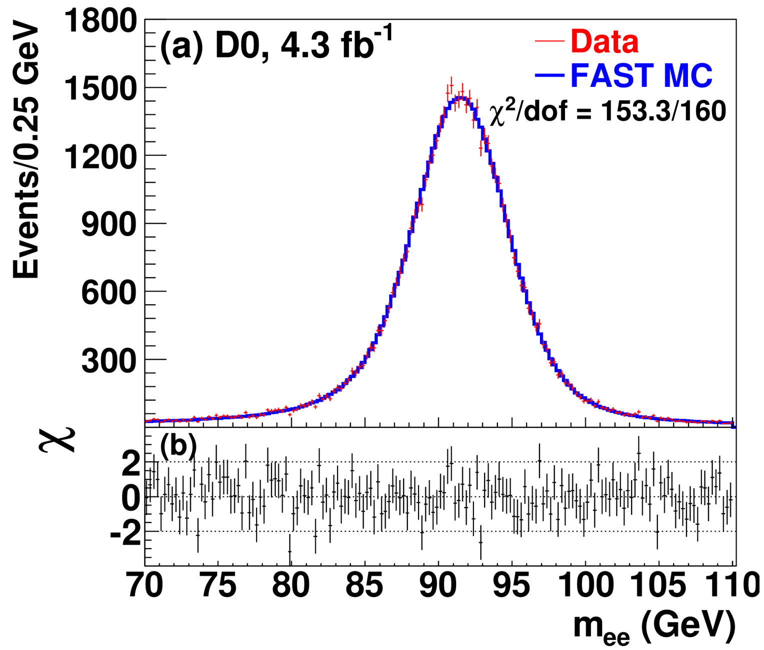
Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\|V_{tb}\|$	CDF: $\|V_{tb}\| = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\|V_{tb}\| = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3

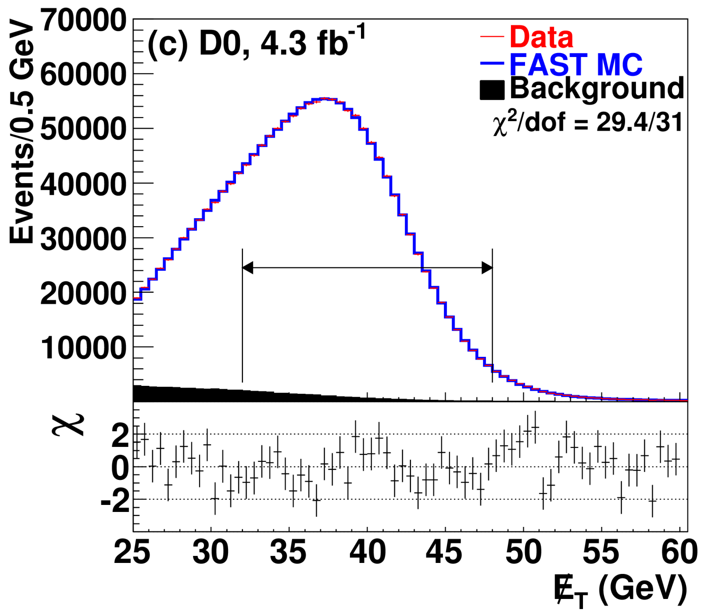
Table by F. Deliot Autum 2011

Backup

W mass

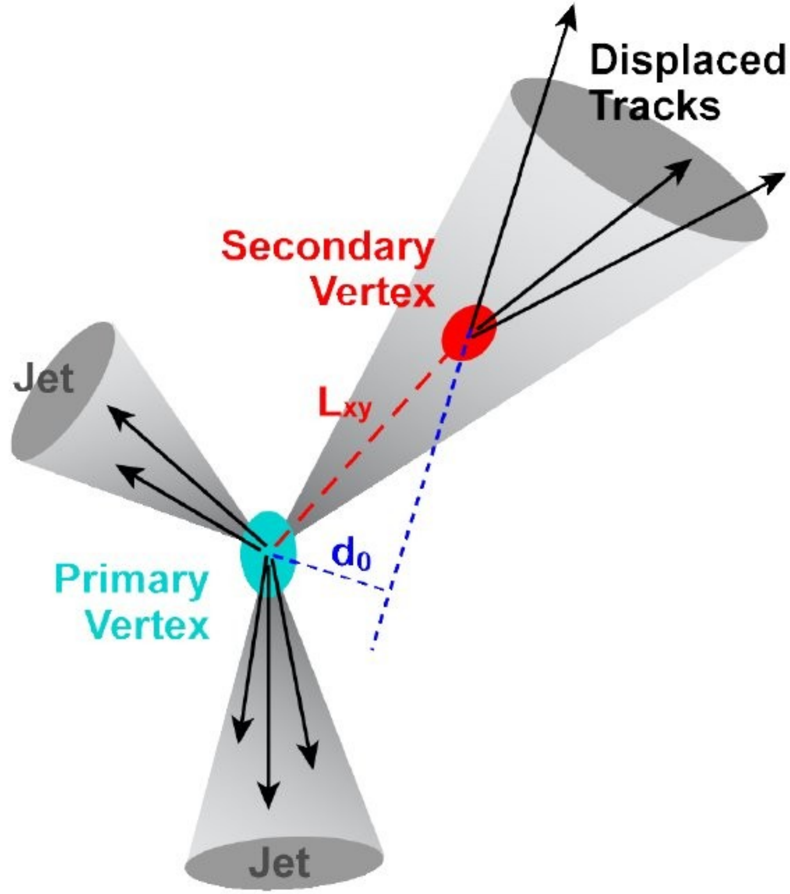
Source	ΔM_W (MeV) m_T	p_T^e	$\not\!\!E_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29





b-tagging

- *b*-quarks hadronize before decaying into a *c*-quark:
  - Long-lived *B* hadrons decay some millimeters away
  - Identify a displaced vertex from the decay tracks
  - soft *e* or μ is produced (11% each)



- CDF Secondary Vertex Tagger searches for two or more tracks with large impact parameter (d0) pointing to a displaced vertex
- DØ Neural Network tagger combines the information from a secondary vertex and two impact parameter taggers

Cross section measurement

- Compare the observed number of events (N^{data}) with prediction
- Cross section is measured as:

$$\sigma = (N^{data} - N^{bg}) / BR \cdot A \cdot \varepsilon \cdot L$$

- or maximize Poisson likelihood based on N^{data} using N^{pred}:

$$L(\sigma) = P(N^{data}, N^{pred})$$

- $t\bar{t}$ pair production tests QCD prediction, can also be used search for new physics

<u>A recipe:</u>

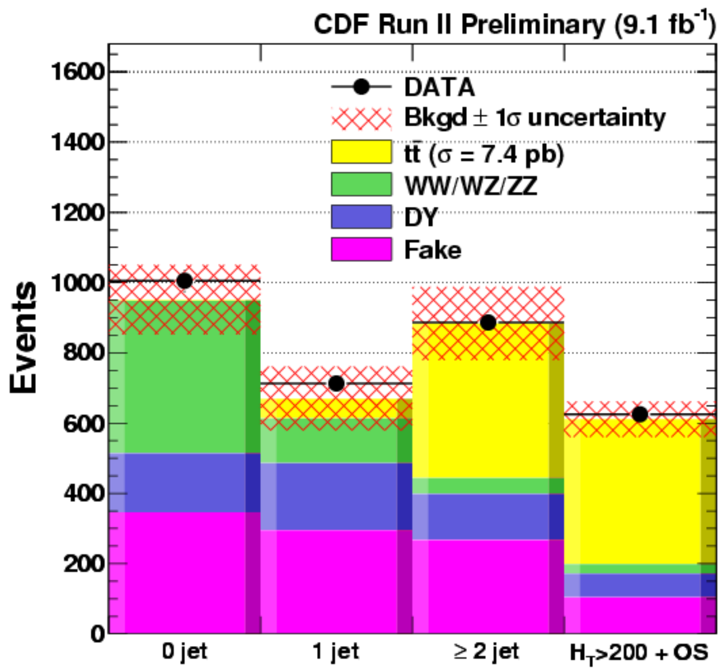
- ℓ+1,2 jets as control, 3 and ≥ 4 jet bins for measurement.
- Require at least one jet as a b-jet using a NN-based tagger.
- Require an isolated lepton and large missing transverse energy.
- Largest physics background: W/Z+jets; include di-boson, single-top.
- Include NLO/LO scale factors.
- Multi-jet background from data

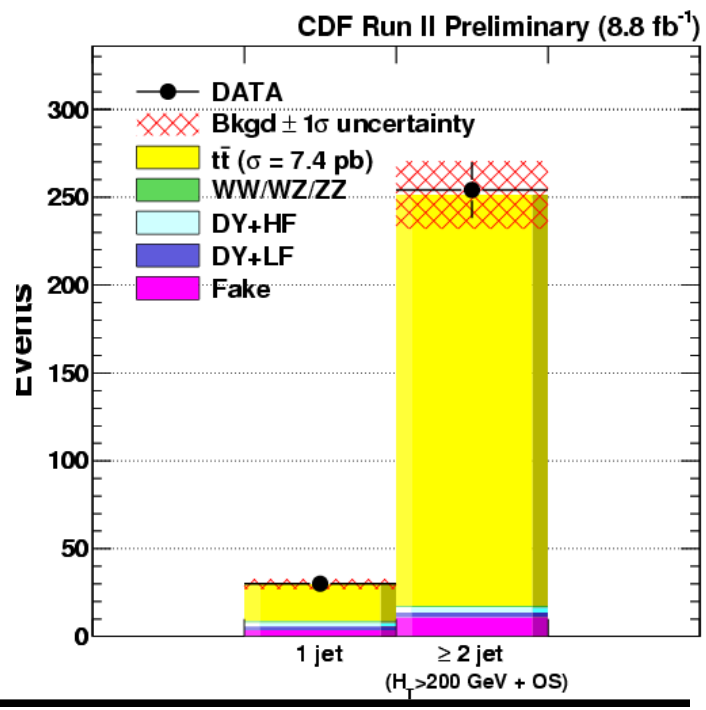
Cross section measurement

- 625 candidate events in 9.1 fb^{-1} with 198 expected background evts:
  $\sigma = 7.66 \pm 0.46$ (stat) ± 0.66 (syst) ± 0.47 (lumi) pb (rel: 12.2%)
- 254 candidate events with b-tagged jets in 8.8 fb^{-1} with 17 bg evts:
  $\sigma = 7.47 \pm 0.50$ (stat) ± 0.53 (syst) ± 0.46 (lumi) pb (rel: 11.5%)
- Best prediction at NNLO+NNLL (MSTW2008)

<u>Leading uncertainties:</u>

- background modeling
  (1st measurement)
- b-tagging
  (2nd measurement)





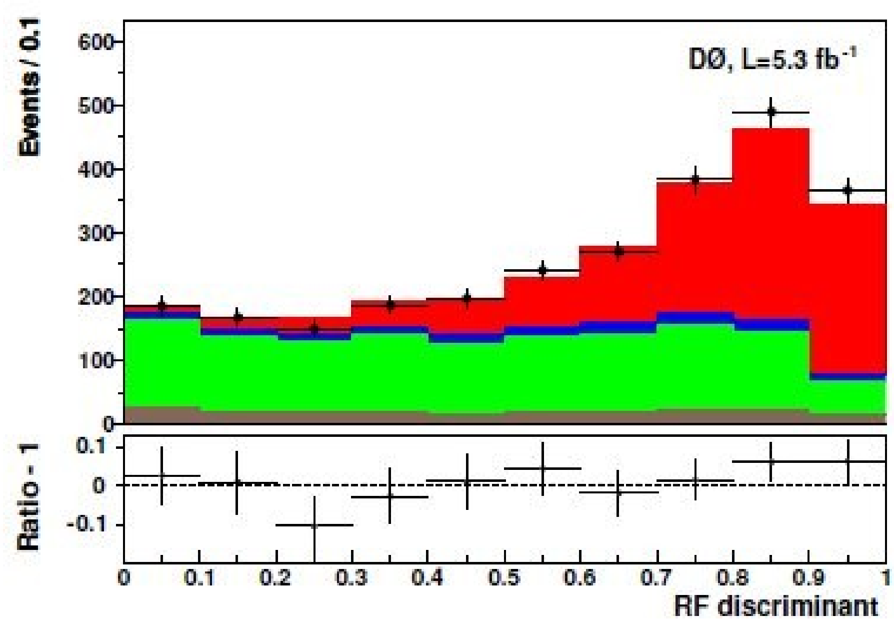
Cross section measurement

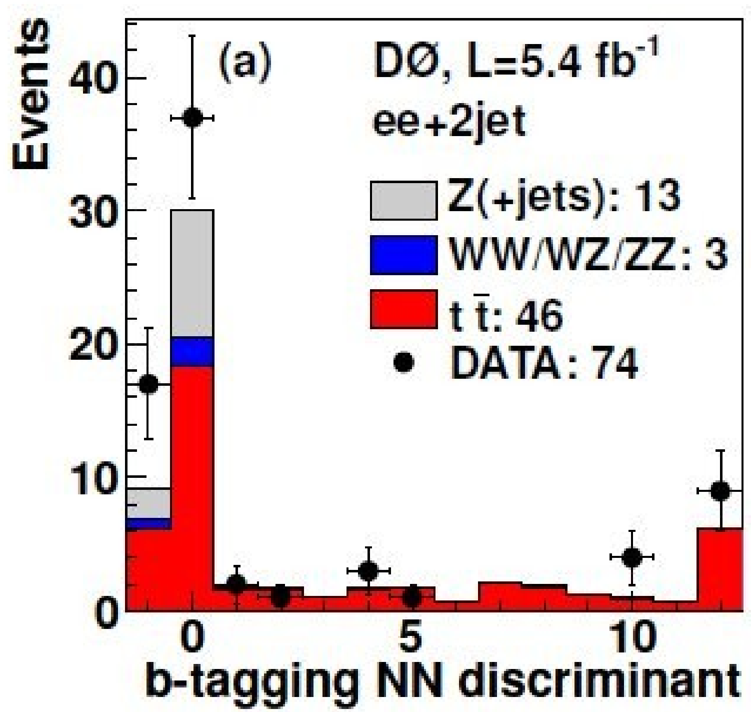
l+jets final state in 5.3 fb^{-1}:

- Discriminant using topological info
- Event count, by number of b-tags
- Combine both in likelihood (→ fit uncertainties)

dilepton final state in 5.4 fb^{-1}:

- Likelihood based on b-tagging discriminant distribution (→ fit uncertainties)
- Merges 2-jet events and 1-jet events (eμ only)





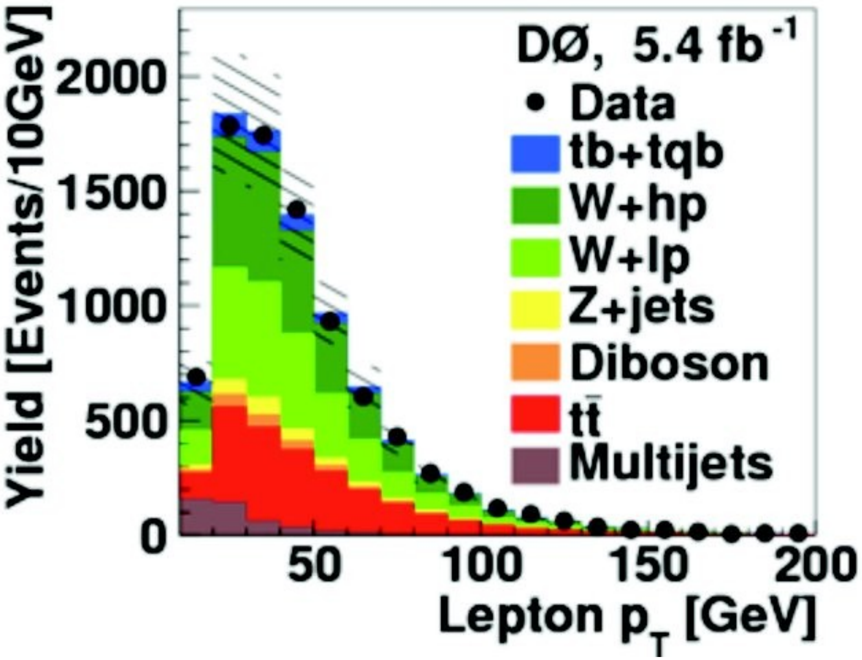
σ = 7.87 + 0.77 – 0.64 pb (rel: 9.1%)

σ = 7.90 + 0.78 – 0.69 pb (rel: 9.4%)

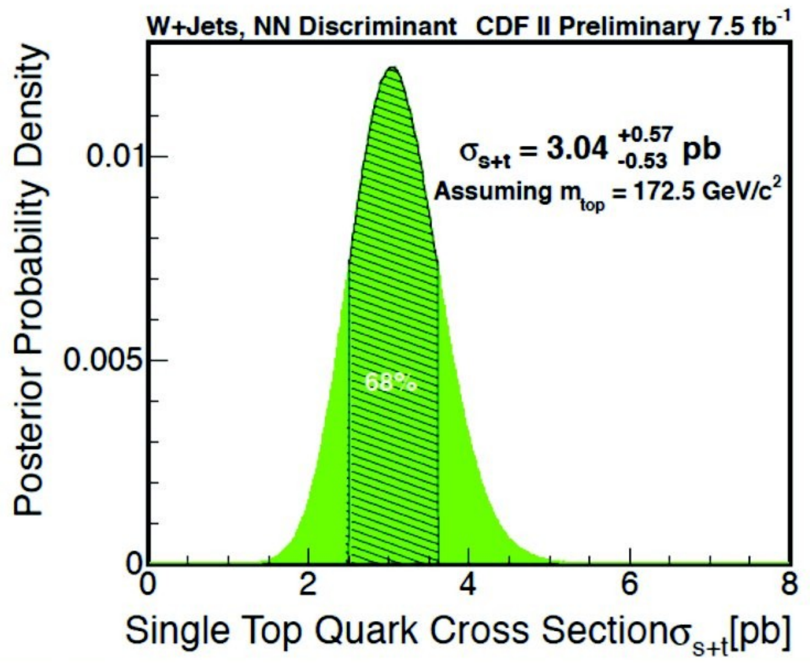
Cross section measurement

Observation of single top quark production in 2009

- 5 s.d. by CDF and DØ
- Very challenging channel at the Tevatron:
  - Small signal
  - Overwhelmed by background with similar signature
  - "Counting" does not work
    → multivariate techniques !



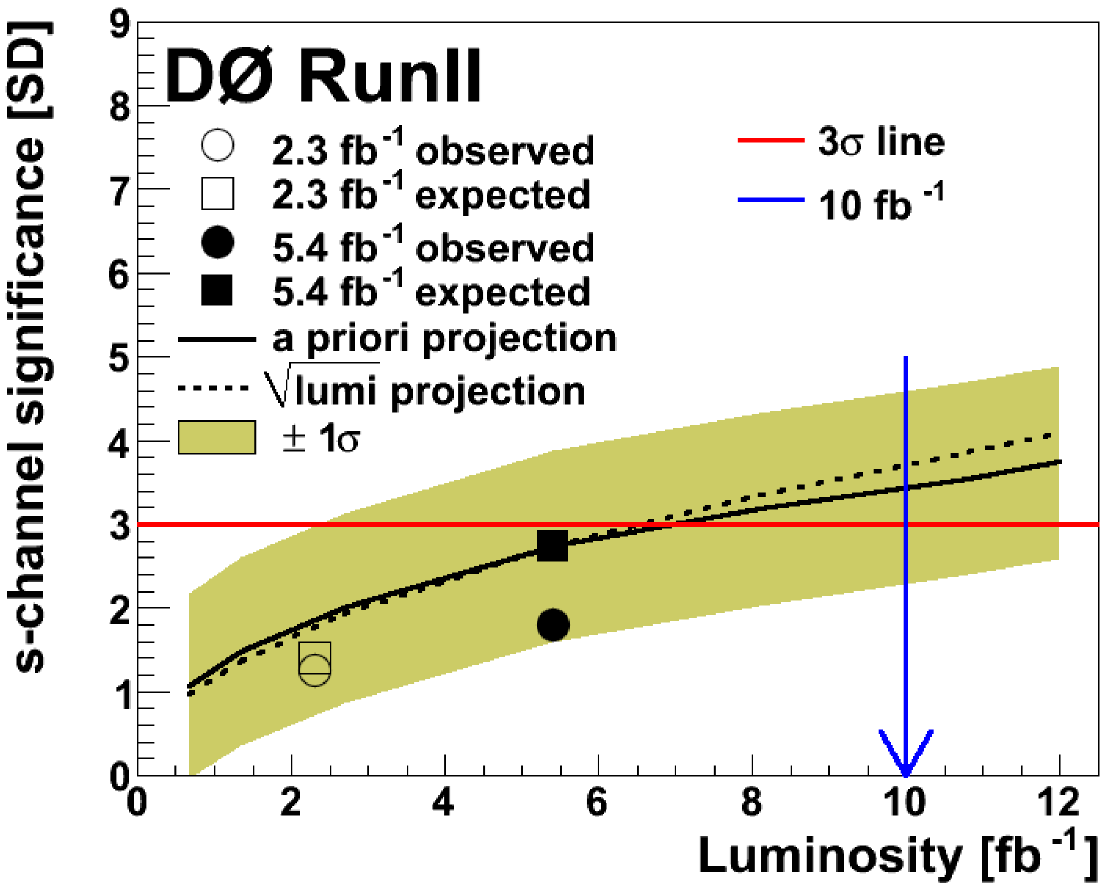
Bayesian approach (flat prior):

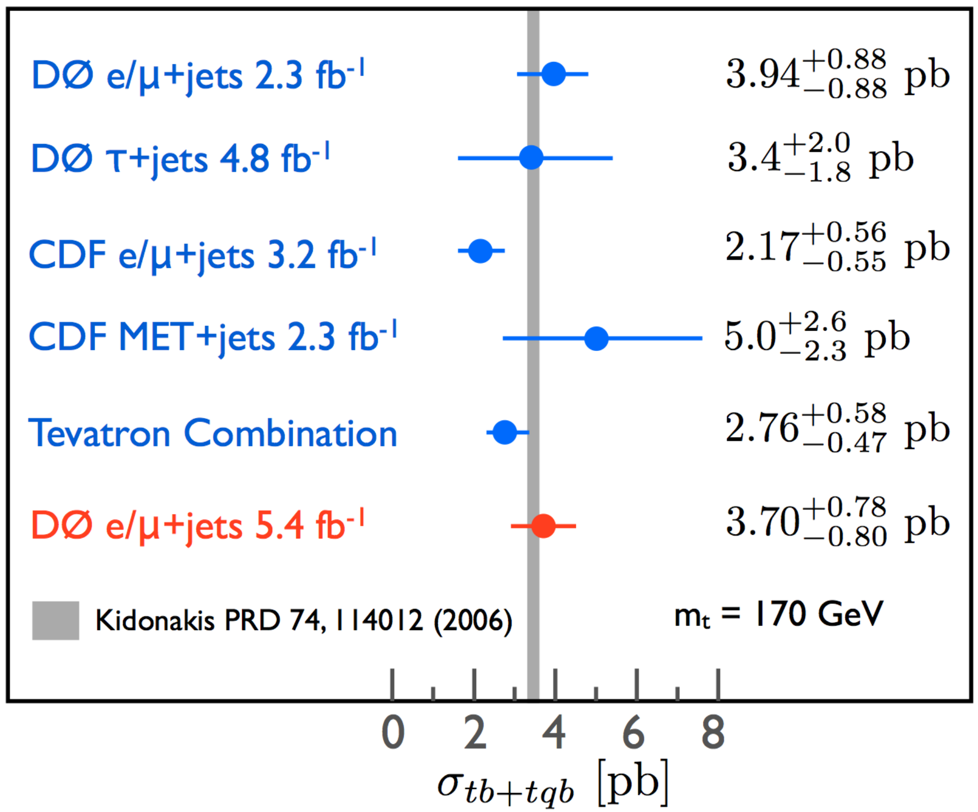


Cross section measurement

Projection for Run II using full data set:

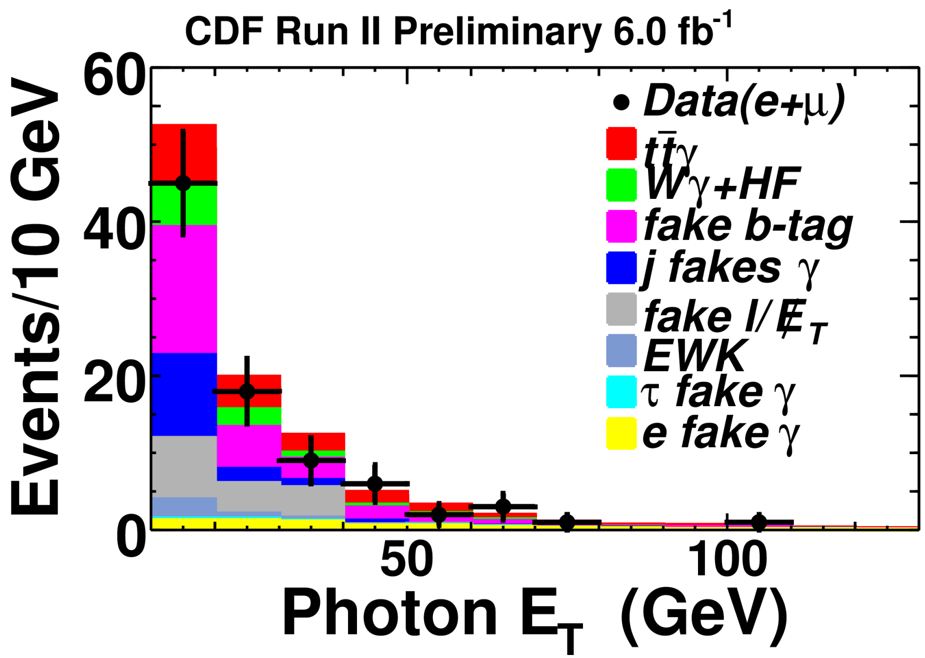
- Single experiment: 3 – 3.5 s.d. possible
- Combination at least 4 s.d.

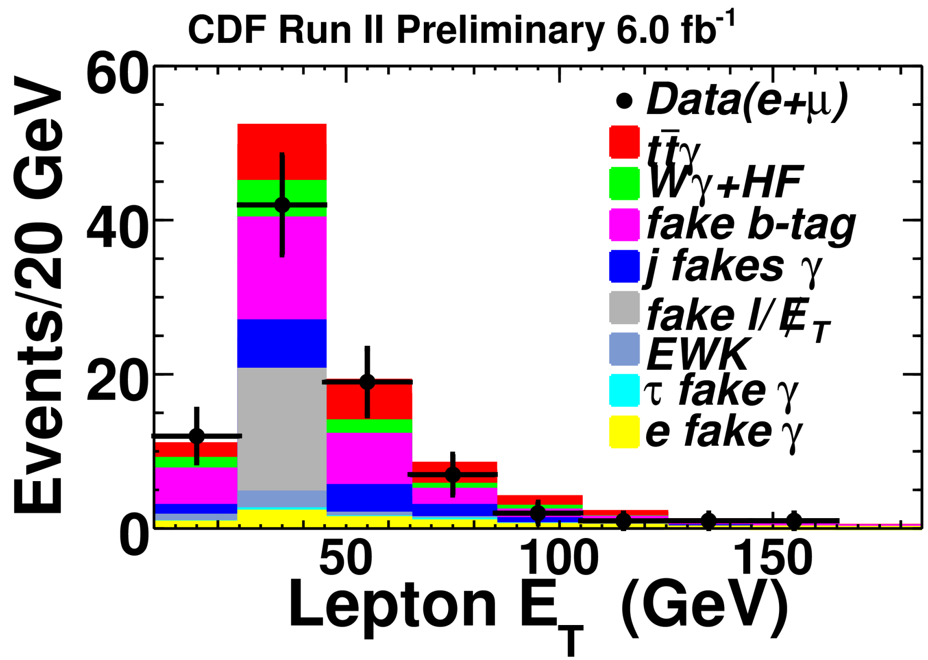




Evidence for $t\bar{t}\gamma$

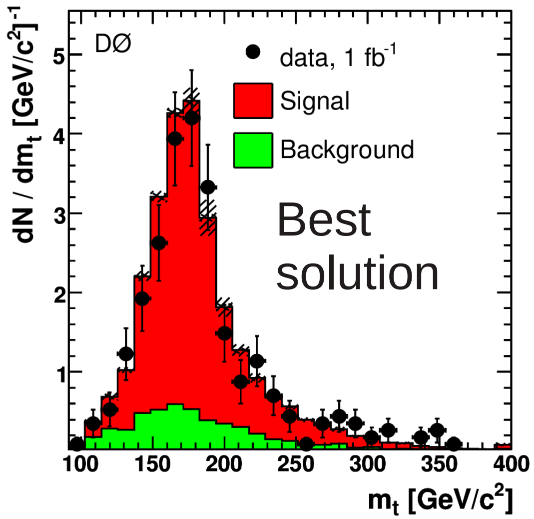
- l+jets channel (at least 3 jets, one *b*-tag and $\not\!\!E_T$) + photon
- Fake photons by jets: no isolation cuts, use Z → ee events to extrapolate isolation shape to used cuts at higher isolation values
- Fake photons by electrons: use Z → ee events, where a high E_T photon is radiated from one of the electrons



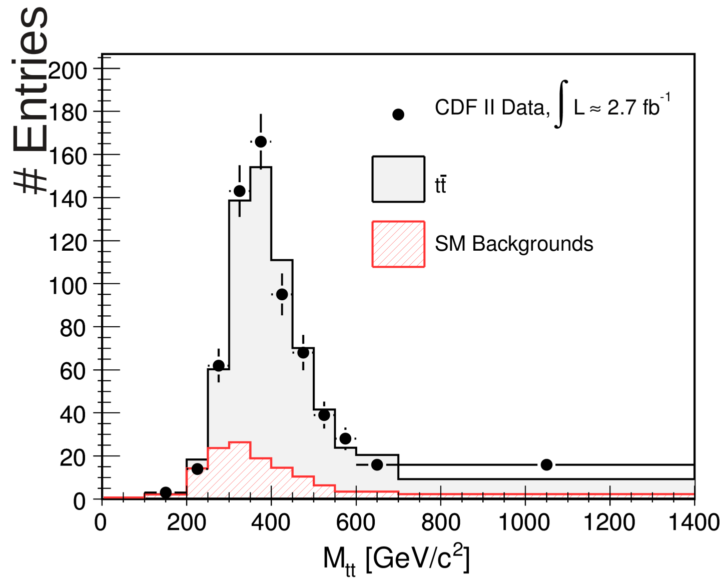


Differential cross section

- Isolated lepton p_T > 20 GeV/c
- $\not{E}_T(e)$ > 20 GeV, $\not{E}_T(\mu)$ > 25 GeV
- 4 jets p_T > 20 GeV/c,
  $p_T^{lead.jet}$ > 40 GeV/c
- | η(jet) | <2.5 and at least 1 *b*-tag



- Isolated lepton p_T > 20GeV/c
- $\not{E}_T$ > 20 GeV
- 4 jets p_T > 20 GeV/c
- | η(jet) | <2.0 and at least 1 *b*-tag
- MC uses CTEQ5L, m_t = 175 GeV/c^2



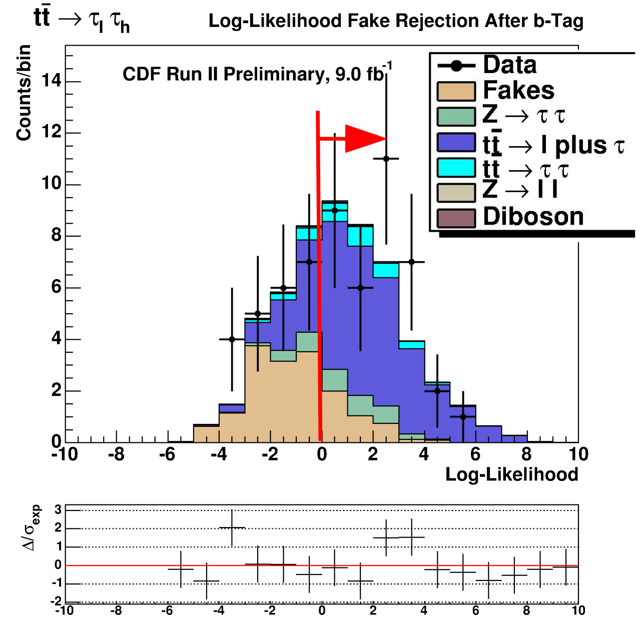
- W → q'q to constrain Jet Energy Scale (JES)
- Reconstruct invariant mass of $t\bar{t}$ system: $M(t\bar{t})$
- Associate leptons and jets with top quarks by constrained kinematic fit: Takes unreconstructed ν into account, W boson mass is 80.4 GeV/c^2

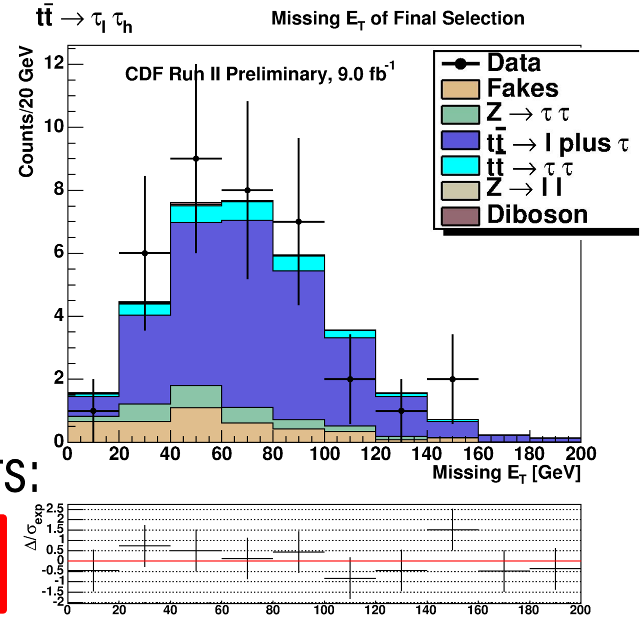
Measurement $BR(t \to b\tau\nu_\tau)$

CDF Conf. note

- More details on the cross section measurement:
  - CDF Conf. note
- e or μ originating from τ or W decay
- Selection uses kinematic + *b*-tag + log-likelihood cuts
  - log-L: , $m_T(\ell + \not{E}_T)$, $E_T(3^{\rm rd}$ lead. jet)
- Removes most of the fake contribution, yields:

$t\bar{t} \to \tau_\ell \tau_h + X$	Events of Final Selection		
Process	**Muon Sample**	**Electron Sample**	**Total**
Fakes	$1.80{\pm}0.31^{+0.13}_{-0.31}$	$2.20{\pm}0.64^{+0.18}_{-0.48}$	$4.01{\pm}0.71^{+0.31}_{-0.80}$
$Z/\gamma^* \to \tau\tau$	$1.12{\pm}0.07 \pm 0.25$	$1.41{\pm}0.08 \pm 0.29$	$2.53{\pm}0.11 \pm 0.53$
$Z/\gamma^* \to \ell\ell$	$0.10{\pm}0.03 \pm 0.03$	$0.03{\pm}0.01 \pm 0.01$	$0.13{\pm}0.03 \pm 0.04$
Diboson	$0.09{\pm}0.02 \pm 0.03$	$0.09{\pm}0.02 \pm 0.03$	$0.17{\pm}0.03 \pm 0.05$
$t\bar{t} \to \tau\ell + X$	$10.56{\pm}0.08 \pm 1.34$	$13.73{\pm}0.10 \pm 1.75$	$24.29{\pm}0.13 \pm 3.09$
$t\bar{t} \to \tau\tau + X$	$1.07{\pm}0.03 \pm 0.14$	$1.37{\pm}0.03 \pm 0.18$	$2.44{\pm}0.04 \pm 0.32$
Total Expected	$14.7{\pm}0.3^{+1.6}_{-1.7}$	$18.8{\pm}0.6^{+2.1}_{-2.1}$	$33.6{\pm}0.7^{+3.7}_{-3.8}$
Observed	12	24	36



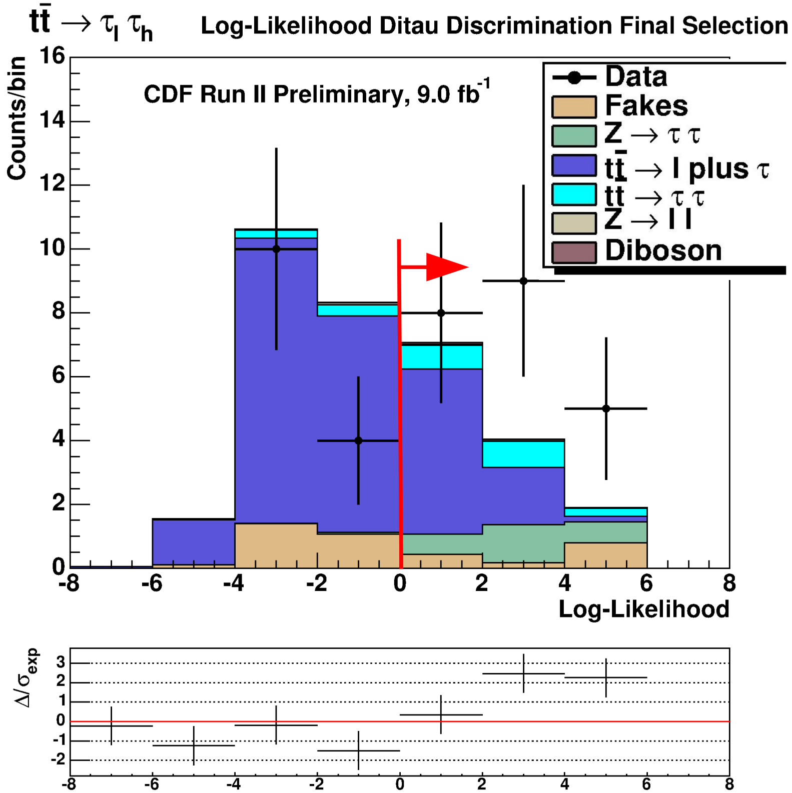


- BR measured from decays to single- and di-tau events:

$$BR(t \to \tau\nu b) = 0.120 \pm 0.030(stat.)^{+0.022}_{-0.019}(syst.) \pm 0.007(lum.)$$

Measurement $BR(t \to b\tau\nu_\tau)$

- Resulting sample is further separated to measure $R(t \to b\tau\nu_\tau)$ from only di-tau decays
- Log-likelihood based on:
  - $m_T(\ell + \not{E}_T)$, $\Delta\phi(\not{E}_T, \ell)$, $E_T(\ell)$



- SM expectation: $BR(W \to \ell\nu) = (10.80 \pm 0.09)$
  (average over e, μ, τ decay modes)

- R measured from decays of only di-tau events:

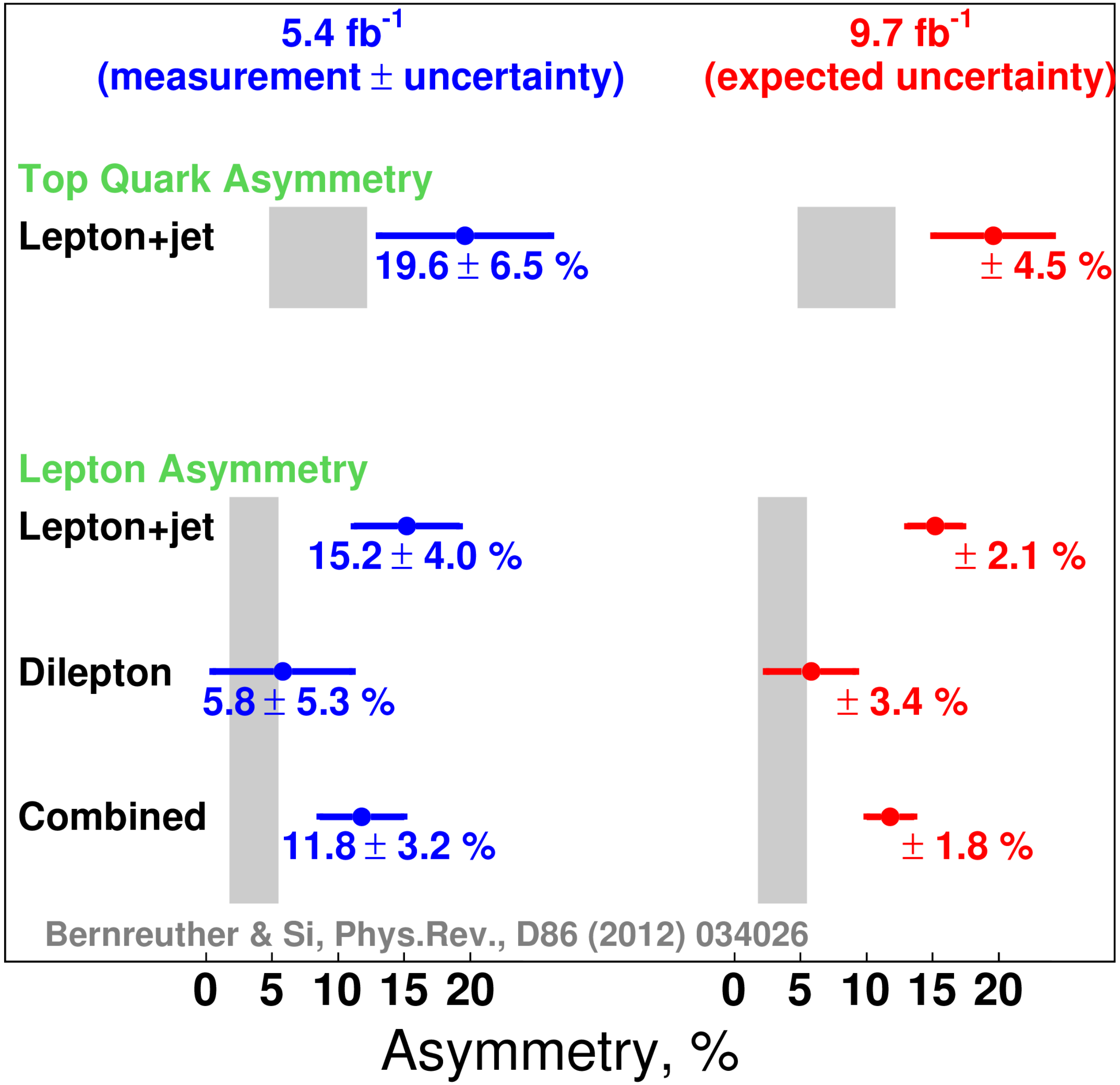
$$BR(t \to \tau\nu b) = 0.098 \pm 0.022(stat.) \pm 0.014(syst.)$$

- Single- and di-tau result in good agreement, as well as to SM expectation

A_{FB} measurements

- **Puzzling situation !** → Need higher order QCD predictions

- Expected uncertainties for full data set
- Latest prediction at NLO (QCD+EWK)
- Lots of work still to do...



Mass of the Top Quark

- Top Mass Measurement is dominated by systematics
- Total systematic error close to be below 1GeV, already only 0.7%

Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
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
Modeling of detector:	
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
Method:	
Multijet contamination	±0.14
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

Measurement of R

CDF Conf. note 10887

Lepton+Jets, 1b Tag	CDF Preliminary 8.7fb^{-1}		
Process	3 Jets	4 Jets	≥5 Jets
$t\bar{t}$	800 ± 67	777 ± 64	260 ± 21
STopS	30 ± 2	6.5 ± 0.5	1.5 ± 0.1
STopT	48 ± 5	10± 1	2.1 ± 0.2
WW	33 ± 4	8 ± 1	2.4 ± 0.3
WZ	9.9 ± 0.9	1.9 ± 0.2	0.6 ± 0.1
ZZ	1.8 ± 0.2	0.46 ± 0.04	0.12 ± 0.01
Z+jets	31 ± 3	9.1 ± 0.9	2 ± 0.2
W+bb	291 ± 118	74 ± 30	17 ± 7
W+cc	167 ± 68	47 ± 20	12 ± 5
W+c	87 ± 35	17 ± 7	4 ± 2
Mistags	303 ± 42	74 ± 14	17 ± 6
Non-W	125 ± 50	35 ± 29	10 ± 9
Total Prediction	1928 ± 243	1061 ± 93	330 ± 28
Observed	1844	1088	339

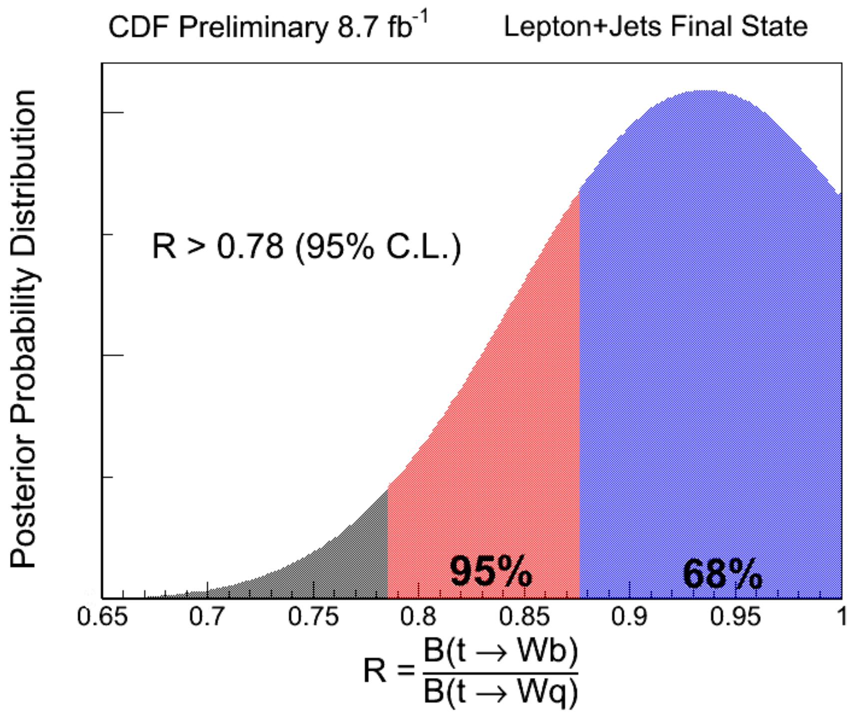
Lepton+Jets, 2b Tag	CDF Preliminary 8.7fb^{-1}		
Process	3 Jets	4 Jets	≥5 Jets
$t\bar{t}$	216 ± 30	271 ± 36	97 ± 13
STopS	9 ± 1	2.0 ± 0.3	0.47 ± 0.06
STopT	9 ± 1	2.7 ± 0.4	0.60 ± 0.09
WW	0.9 ± 0.2	0.5 ± 0.1	0.22 ± 0.04
WZ	1.8 ± 0.3	0.27 ± 0.04	0.07 ± 0.01
ZZ	0.4 ± 0.1	0.14 ± 0.02	0.01 ± 0.00
Z+jets	2.1 ± 0.2	0.77 ± 0.08	0.29 ± 0.03
W+bb	48 ± 20	14 ± 6	4 ± 2
W+cc	5 ± 2	2 ± 1	0.8 ± 0.4
W+c	3 ± 1	0.8 ± 0.4	0.2 ± 0.1
Mistags	5 ± 1	1.7 ± 0.4	0.6 ± 0.2
Non-W	6 ± 3	0.1 ± 1.5	0.1 ± 1.5
Total Prediction	306 ± 40	296 ± 38	104 ± 13
Observed	275	273	126

Measurement of R

CDF Conf. note 10887

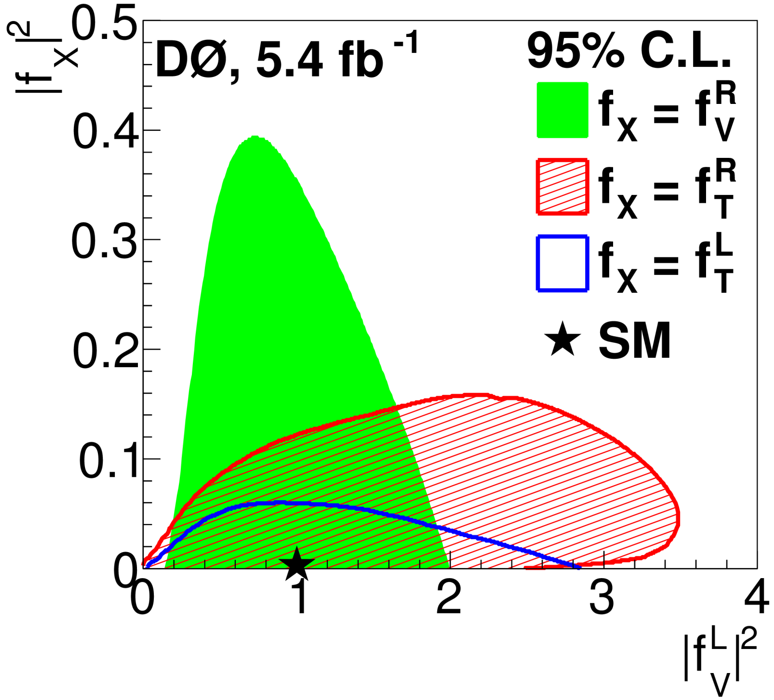
Lepton + Jets		CDF Preliminary 8.7 fb^{-1}
Source	$+\delta\sigma_{p\bar{p}\to t\bar{t}}$ (pb)	$-\delta\sigma_{p\bar{p}\to t\bar{t}}$ (pb)
Statistical	0.29	-0.29
Jet Energy Scale	0.46	-0.41
ISR/FSR	0.22	-0.21
Luminosity	0.44	-0.39
Background Normalization	0.78	-0.66
Top Mass	0.33	-0.32
Others	0.18	-0.15
Squared Sum	1.08	-0.96

Lepton + Jets		CDF Preliminary 8.7 fb^{-1}
Source	$+\delta R$	$-\delta R$
Statistical	0.043	-0.043
Jet Energy Scale	0.016	-0.019
ISR/FSR	0.006	-0.006
b-tagging	0.078	-0.073
Background Normalization	0.056	-0.052
Others	0.005	-0.005
Squared Sum	0.098	-0.092

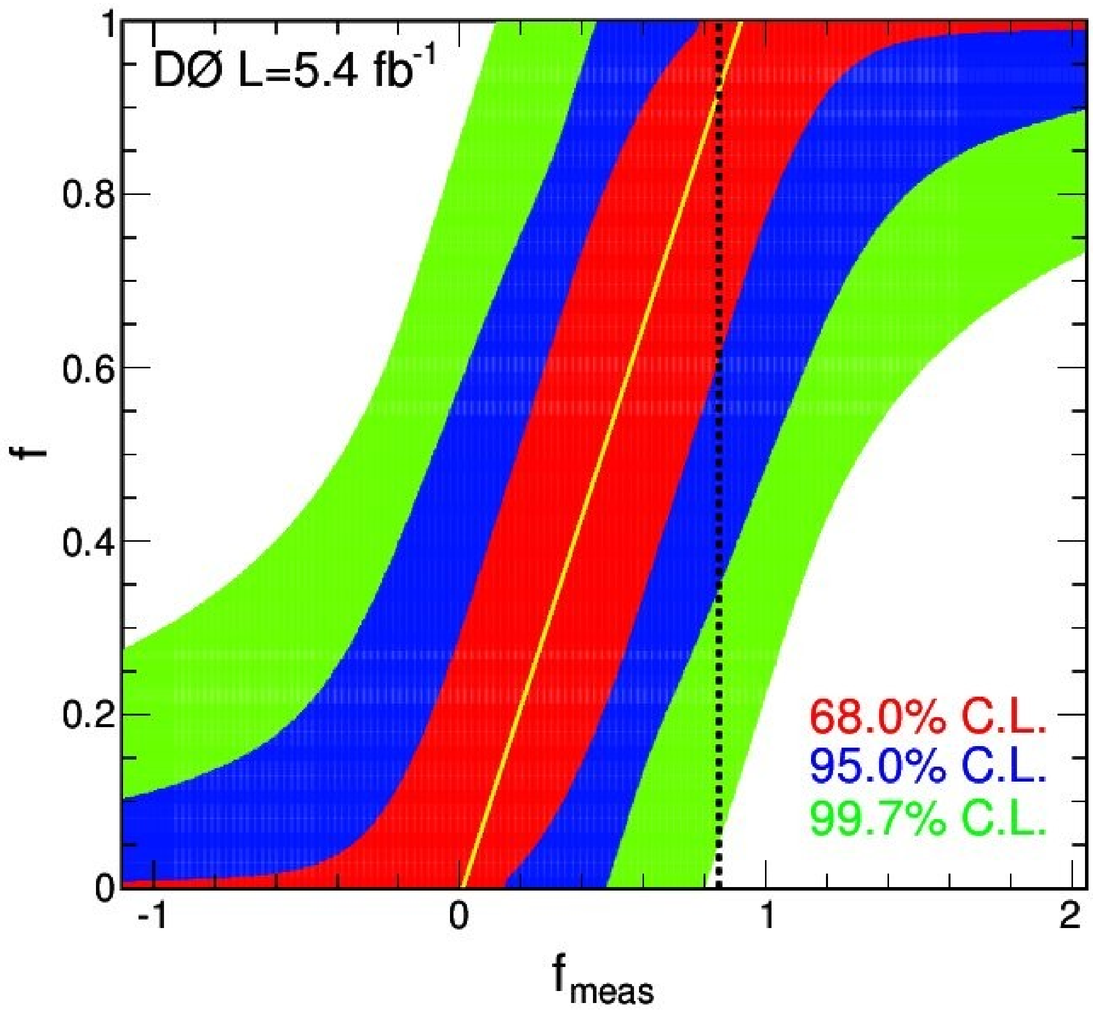


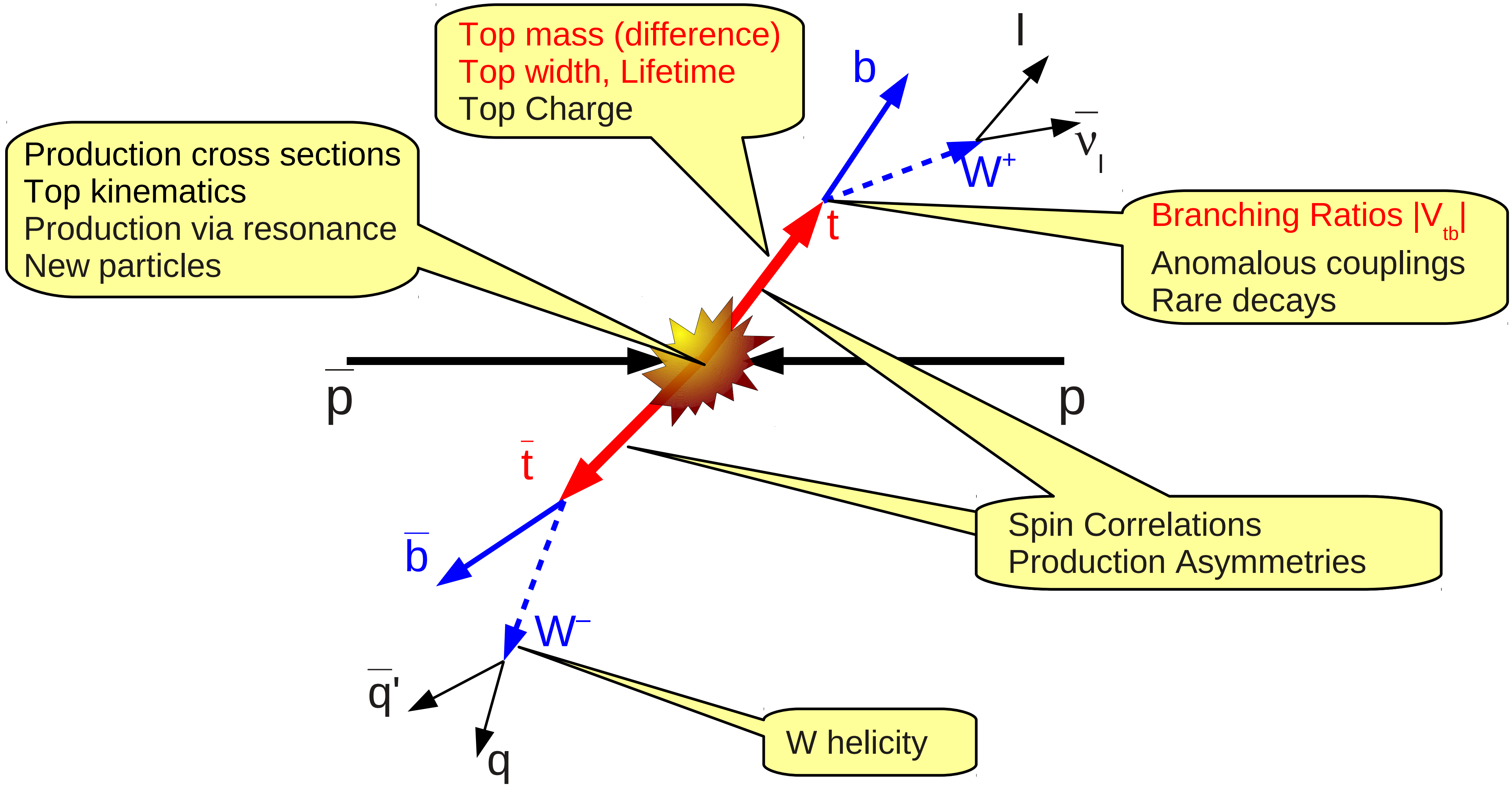
Anomalous couplings

-



Spin correlations

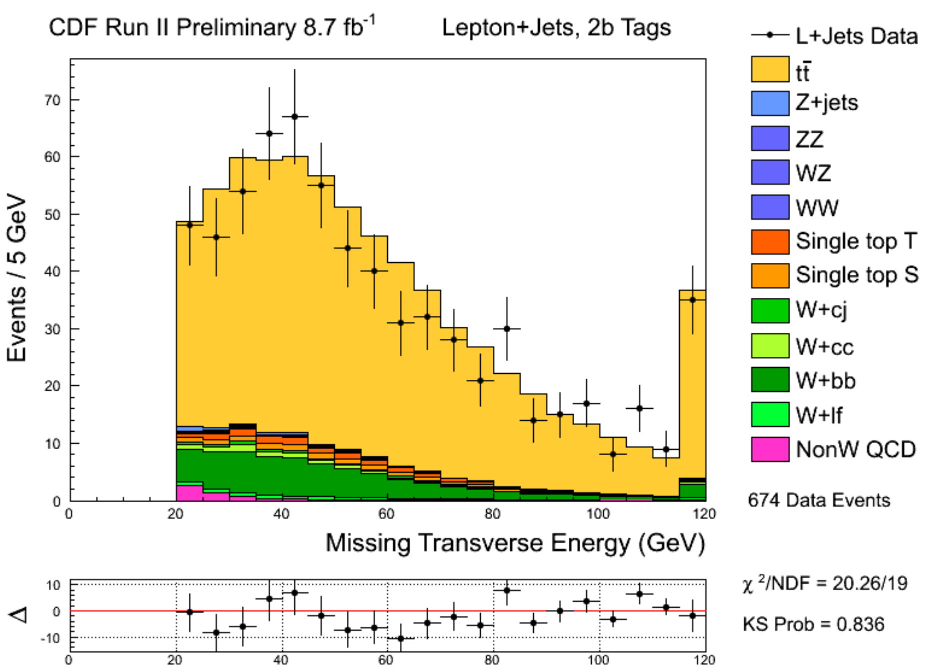


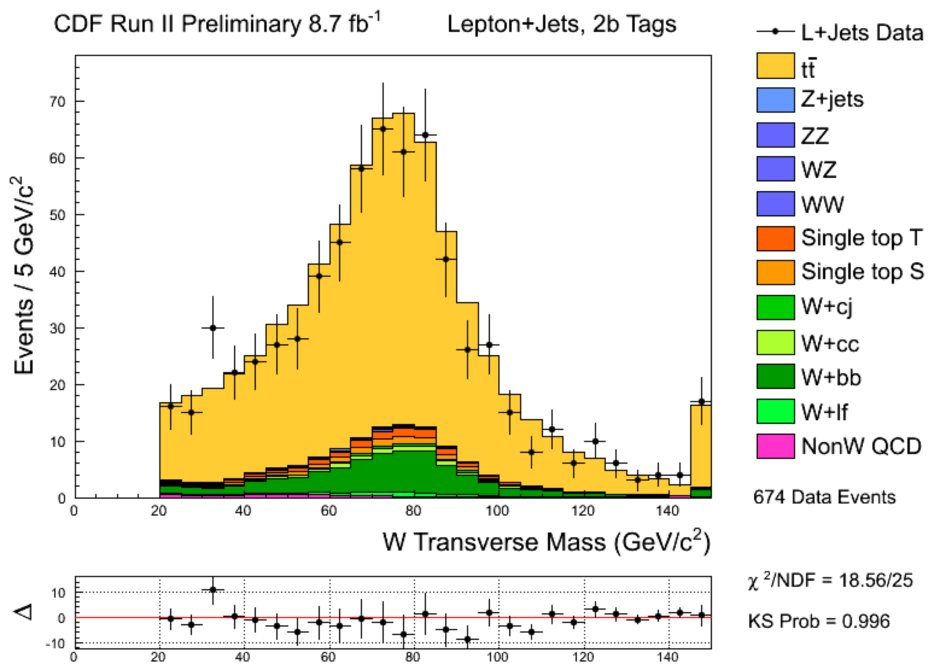

Top mass (difference)
Top width, Lifetime
Top Charge
Production cross sections
Top kinematics
Production via resonance
New particles
b
l
W+
ν̄l
t
Branching Ratios |Vtb|
Anomalous couplings
Rare decays
p̄
p
t̄
b̄
Spin Correlations
Production Asymmetries
W−
q̄'
q
W helicity

Measurement of R

CDF Conf. note 10887

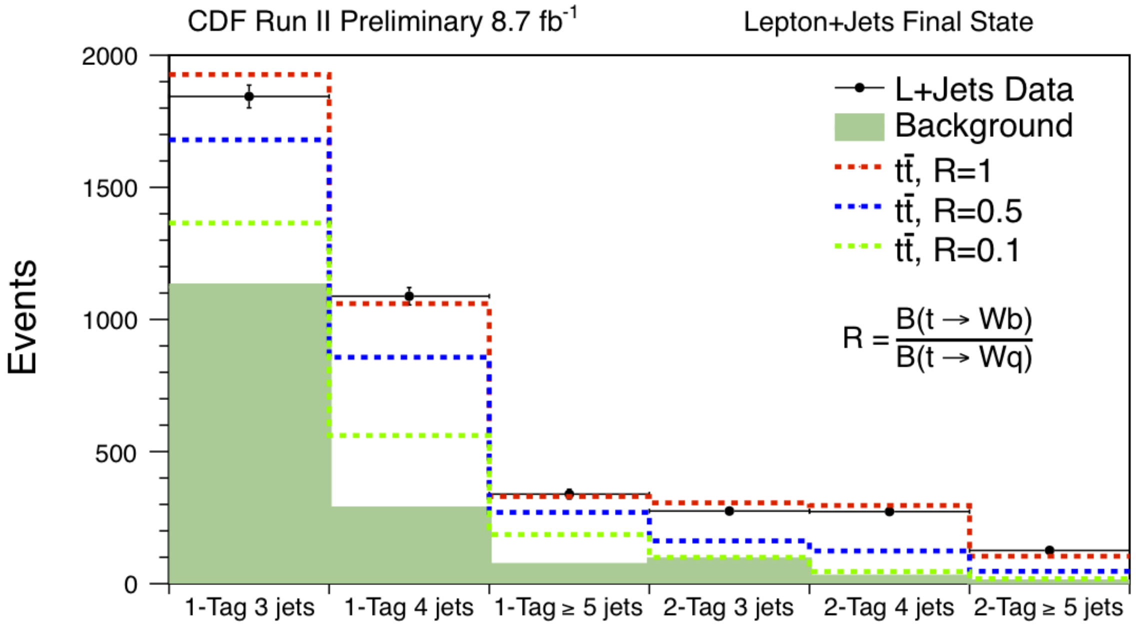
- Use lepton+jets $t\bar{t}$ selection with: ≥ 3jets, exactly one, two b-tag and $\not{E}_T$
- Uses full CDF RunII data sample !
- Example control distribution shown for 2 *b*-tags – nicely described





- Measure $R = \frac{\mathcal{B}(t\rightarrow Wb)}{\mathcal{B}(t\rightarrow Wq)}$ from different jet and *b*-tag bins

Measurement of R

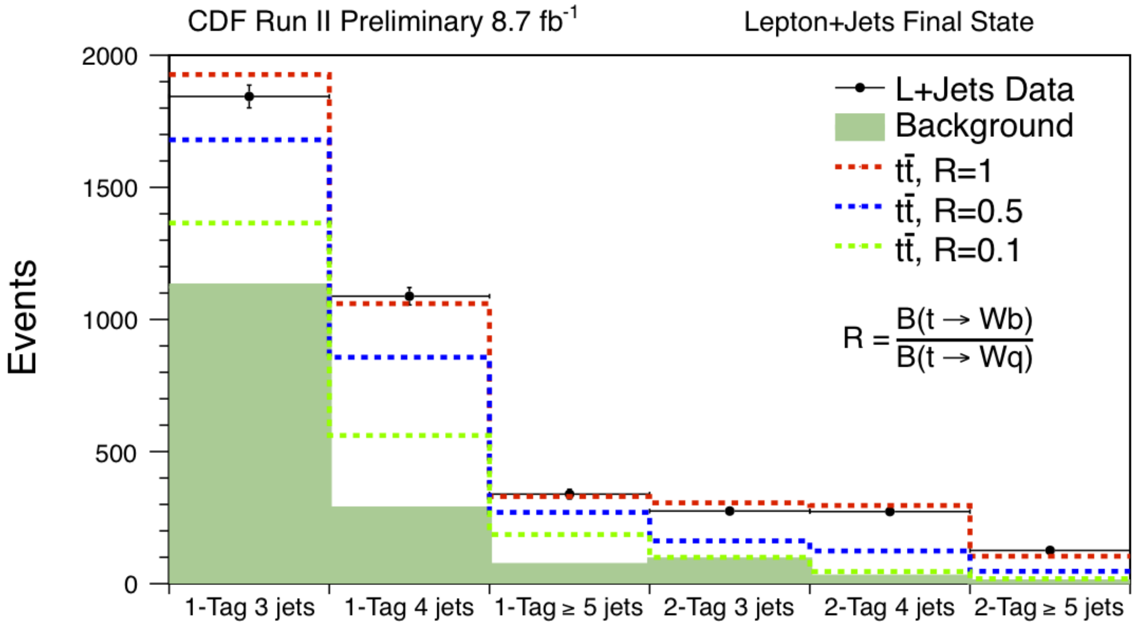


- Distribution shows example values of R
- Simultaneous negative log-likelihood fit to R and $\sigma(p\bar{p} \rightarrow t\bar{t})$:

$$\mathcal{L} = \prod_i \mathscr{P}\left(\mu^i_{exp}(R, \sigma_{p\bar{p}\rightarrow t\bar{t}}, x_j) | N^i_{obs}\right) \prod_j G\left(x_j | 0, 1\right)$$

Measurement of R

CDF Conf. note 10887

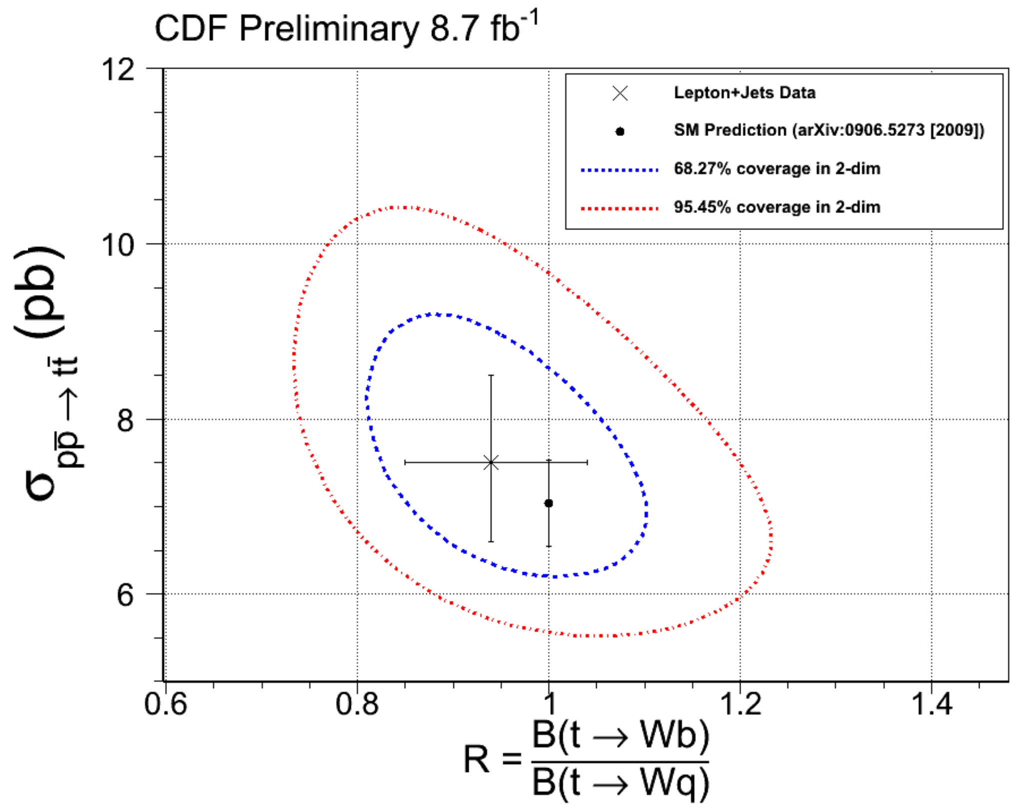


	Value (stat+syst)
$\sigma_{p\bar{p}\to t\bar{t}}$ (pb)	7.5 ± 1.0
R	0.94 ± 0.09
$\lvert V_{tb}\rvert$	0.97 ± 0.05

- Assume 3 Generations and Unitarity

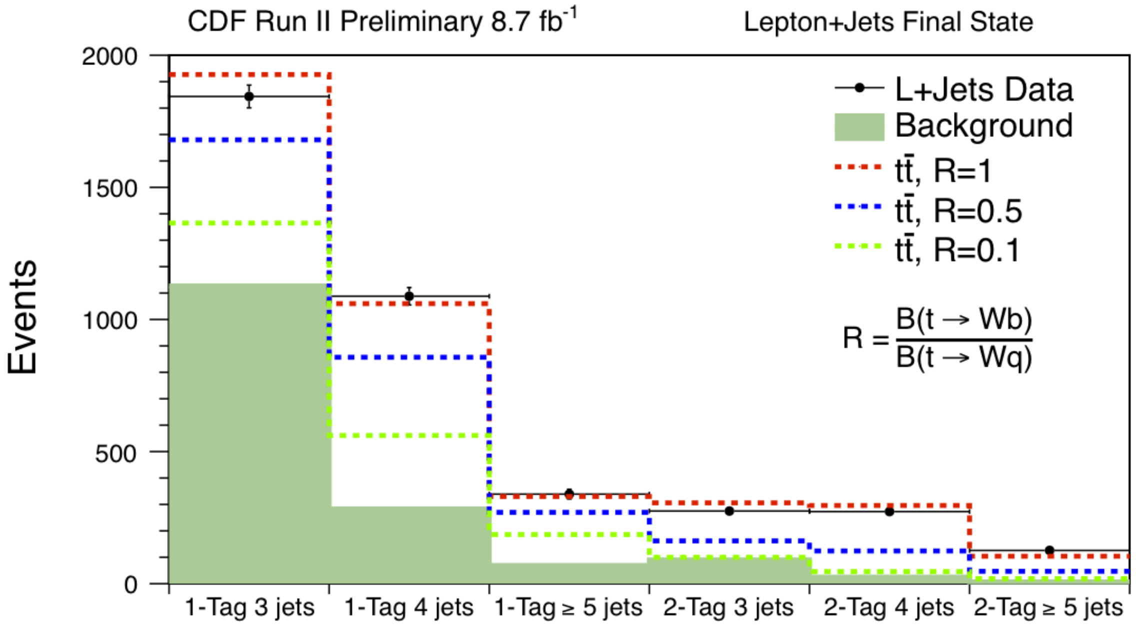
- Distribution shows example values of R
- Simultaneous negative log-likelihood fit to R and $\sigma(p\bar{p} \to t\bar{t})$:

$$\mathcal{L} = \prod_i \mathscr{P}\left(\mu^i_{exp}(R, \sigma_{p\bar{p}\to t\bar{t}}, x_j) | N^i_{obs}\right) \prod_j G\left(x_j | 0, 1\right)$$



Measurement of R

CDF Conf. note 10887



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	Value (stat+syst)
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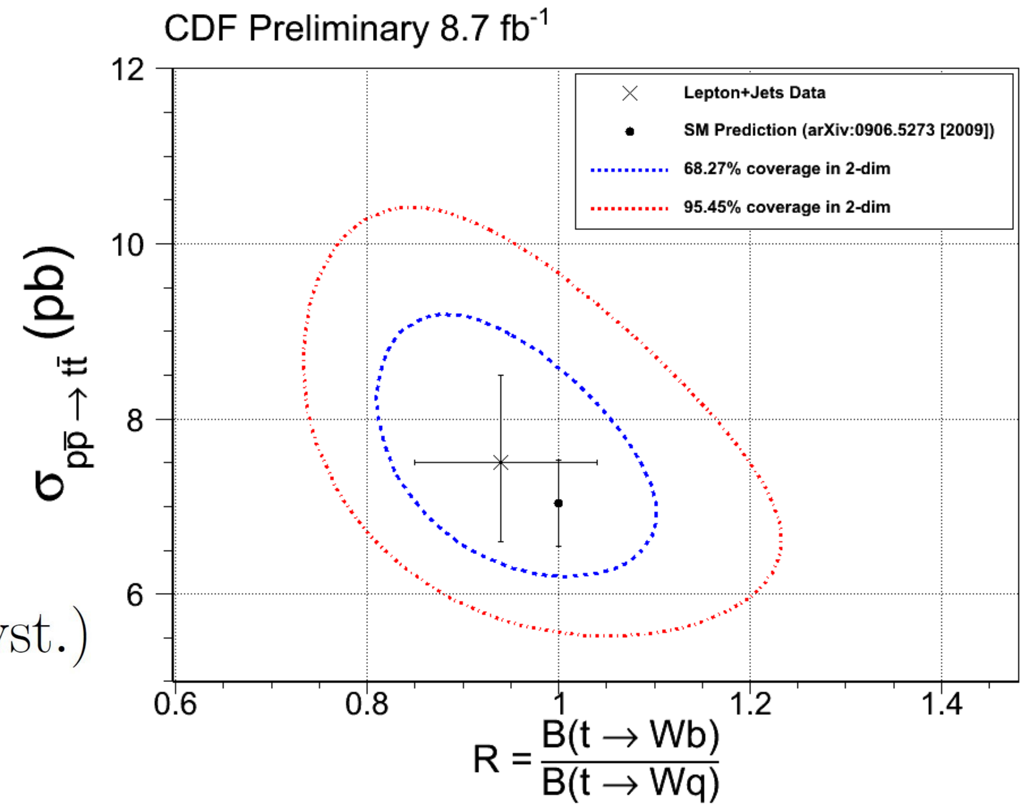

- D0: $R = \frac{\mathcal{B}(t\rightarrow Wb)}{\mathcal{B}(t\rightarrow Wq)} = 0.90 \pm 0.04\ (\text{stat.} + \text{syst.})$

  PRL 107, 121802 (2011)
- CMS: 0.98 ± 0.04 (TOP-11-029)
- Results agrees with other measurements and SM expectation

Width of the Top Quark

PRD 85, 091104 (2012)

- Fundamental property of the top quark:
  Γ_t and lifetime $\tau_t = 1/\Gamma_t$
- Total width:

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}$$

→ $\Gamma(t \to Wb)$: Use t-channel single top cross section measurement

→ $\mathcal{B}(t \to Wb)$: BR measured using $t\bar{t}$ decays

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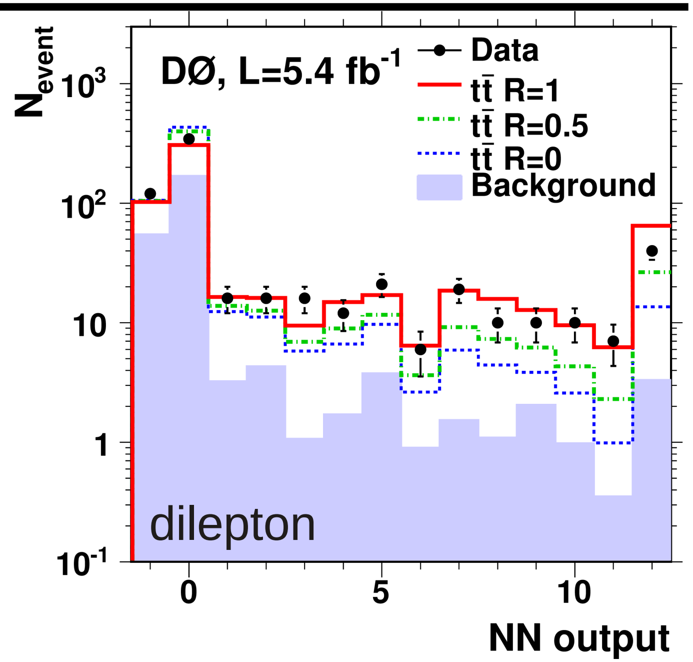
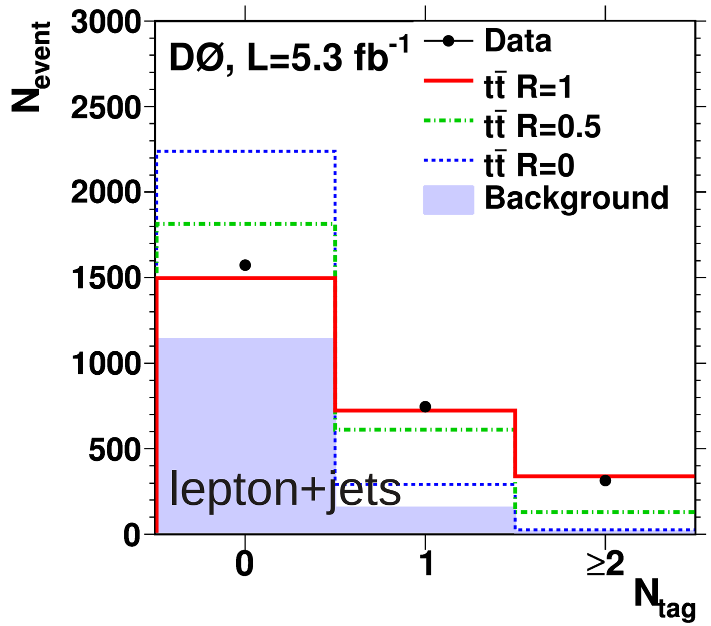
PLB 705, 313 (2011)

$\mathcal{B}(t \to Wb)$ → BR measured using $t\bar{t}$ decays
PRL 107, 121802 (2011)

- Result of BR measurement in $t\bar{t}$ production:

$$R = \frac{\mathcal{B}(t\to Wb)}{\mathcal{B}(t\to Wq)} = 0.90 \pm 0.04\,(\text{stat.} + \text{syst.})$$





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PLB 705, 313 (2011)

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PRL 107, 121802 (2011)

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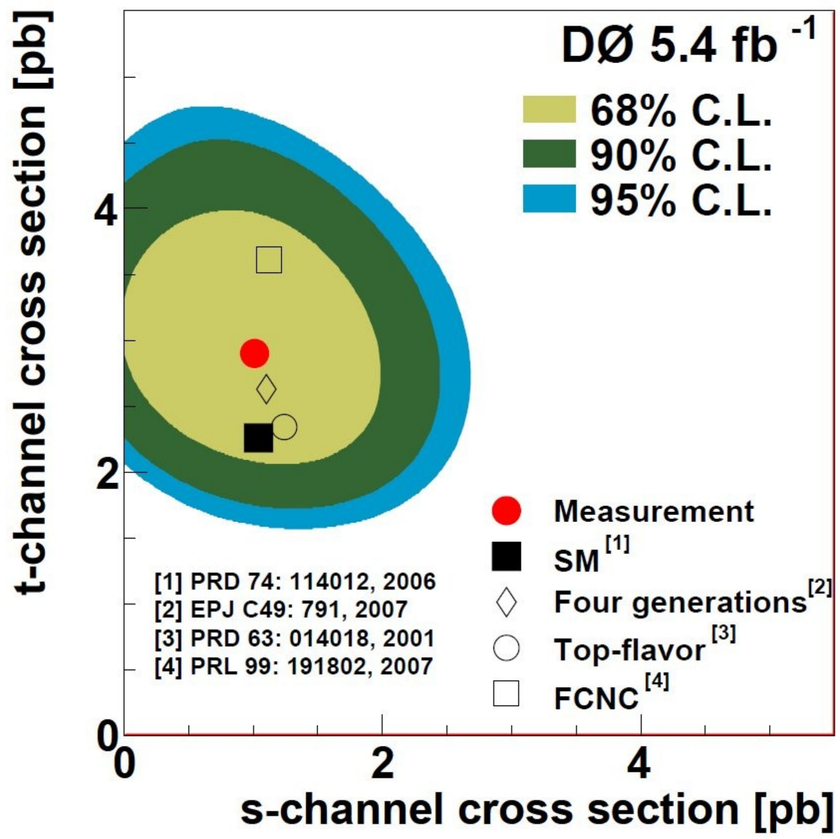


- Result of t-channel single top cross section measurement:

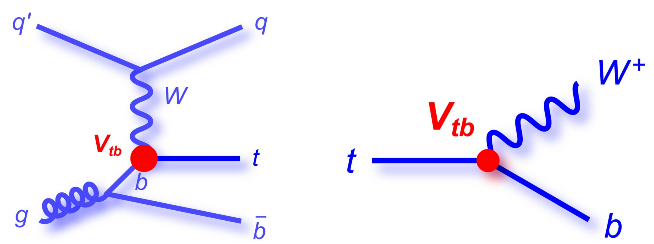
→ $$\sigma(p\bar{p} \to tqb + X) = 2.90 \pm 0.59(\text{stat} + \text{syst})\ \text{pb}$$

Width of the Top Quark

PRD 85, 091104 (2012)

- Total width: $\Gamma_t = \dfrac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}$ From t-channel single top cross section measurement / BR measured using $t\bar{t}$ decays

- Assume same coupling in production and decay:

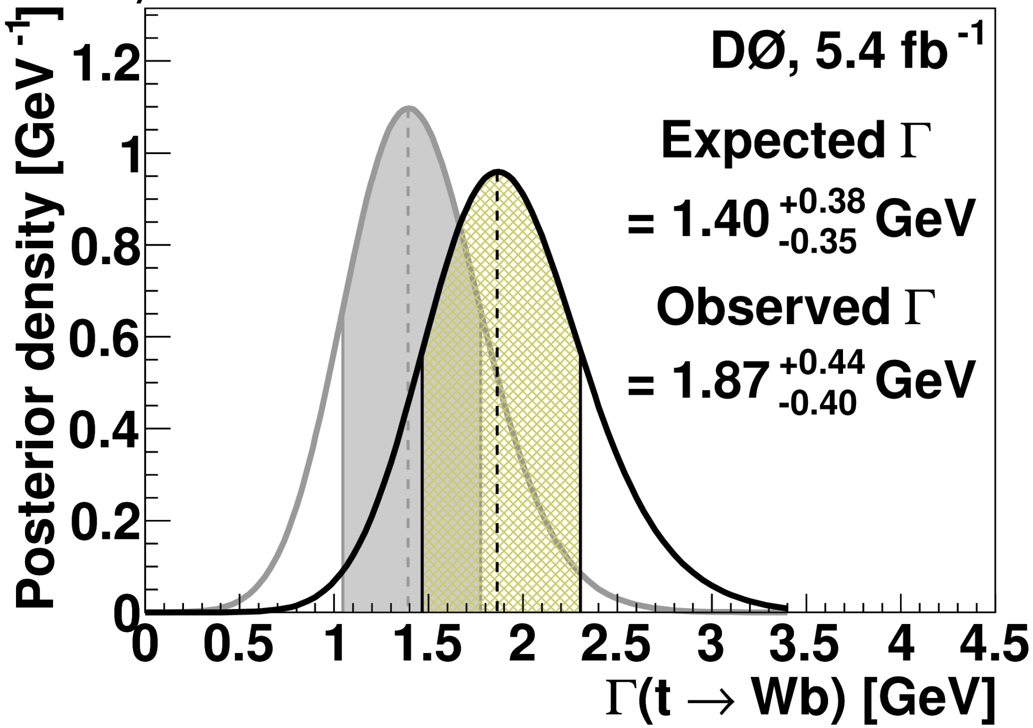


- Extract partial decay width from:

Only SM processes: 1.33 GeV

$$\Gamma(t \to Wb)_{m(t)=172.5\ \mathrm{GeV}} = \sigma(t\text{–channel}) \frac{\Gamma(t \to Wb)_{\mathrm{SM}}}{\sigma(t\text{–channel})_{\mathrm{SM}}}$$

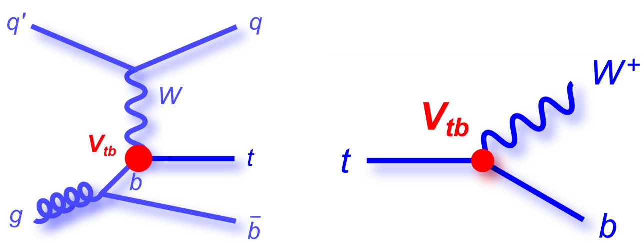
2.14 ± 0.18 pb



Width of the Top Quark

PRD 85, 091104 (2012)

- Total width: $\Gamma_t = \dfrac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}$ From t-channel single top cross section measurement; BR measured using $t\bar{t}$ decays
- Assume same coupling in production and decay:

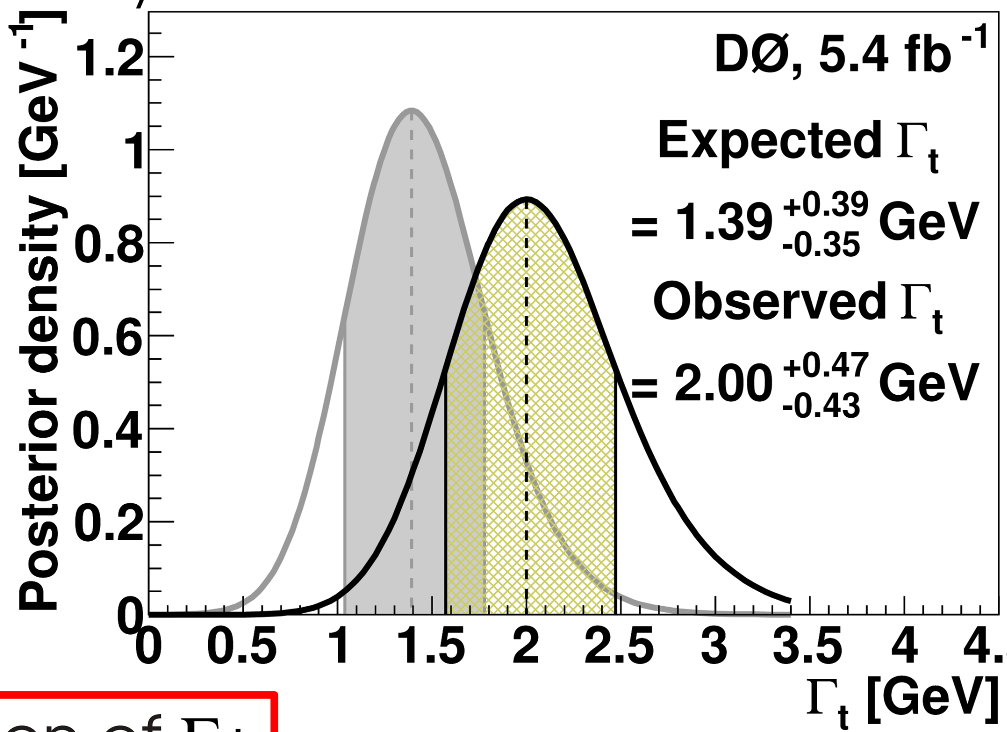


- Extract partial decay width from:

Only SM processes: 1.33 GeV

$$\Gamma(t \to Wb)_{m(t)=172.5\ \mathrm{GeV}} = \sigma(t\text{–channel}) \frac{\Gamma(t \to Wb)_{\mathrm{SM}}}{\sigma(t\text{–channel})_{\mathrm{SM}}}$$

2.14 ± 0.18 pb



Most precise (indirect) determination of Γ_t:

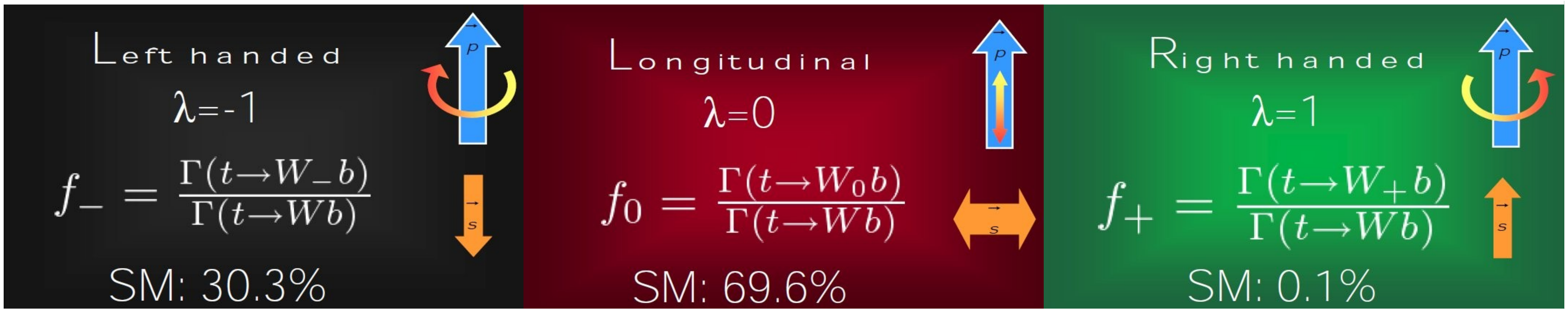
$\Gamma_t = 2.00 \pm^{0.47}_{0.42}$ GeV $\to$ $\tau_t = 3.29 \pm^{0.90}_{0.63} \cdot 10^{-25}$ s

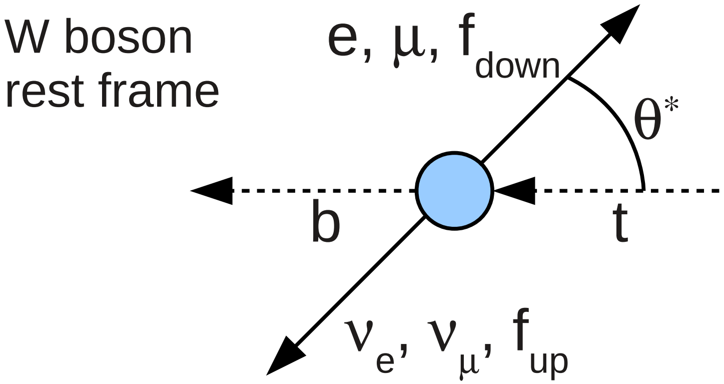
CDF (direct measurement from reconstructed mass distribution):

Γ_t < 7.6 GeV @95% C.L. PRL 105 232003

W helicity

- Experimental precision not good enough → no strong constraint for left-handed and longitudinal case, but tiny prediction for right-handed helicity state → contributions due to new physics ?
- Direct test of the “V – A” nature of weak interaction





W helicity

- Direct test of the "V – A" nature of weak interaction
- Use $\cos(\theta^*)$ to distinguish between helicity states
- Fit templates to f_x distributions

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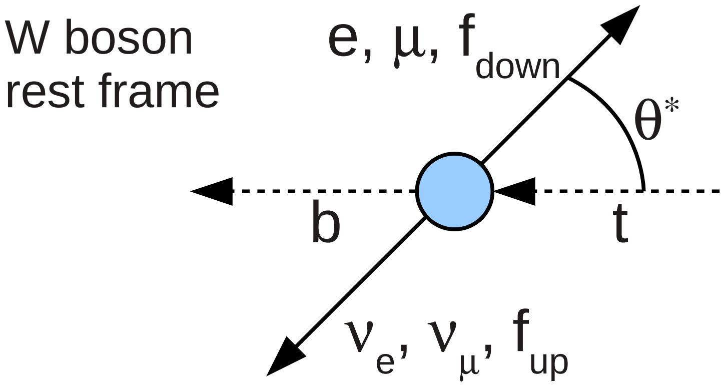
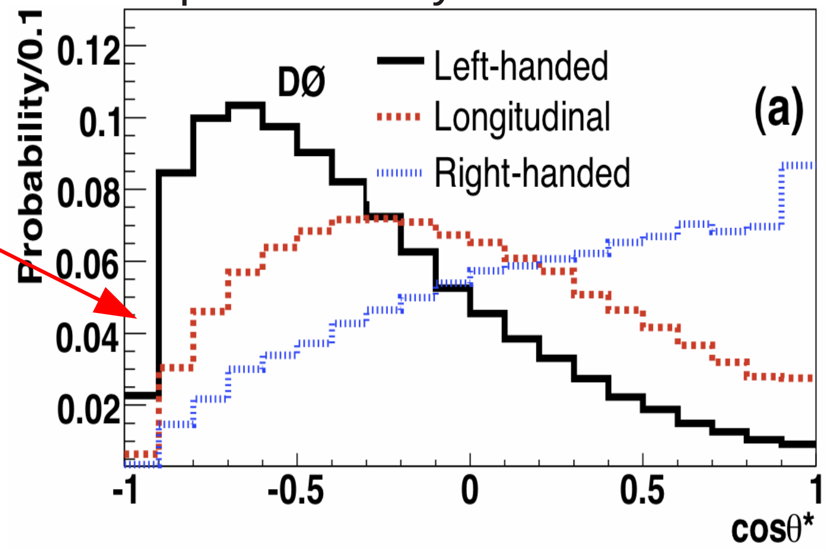
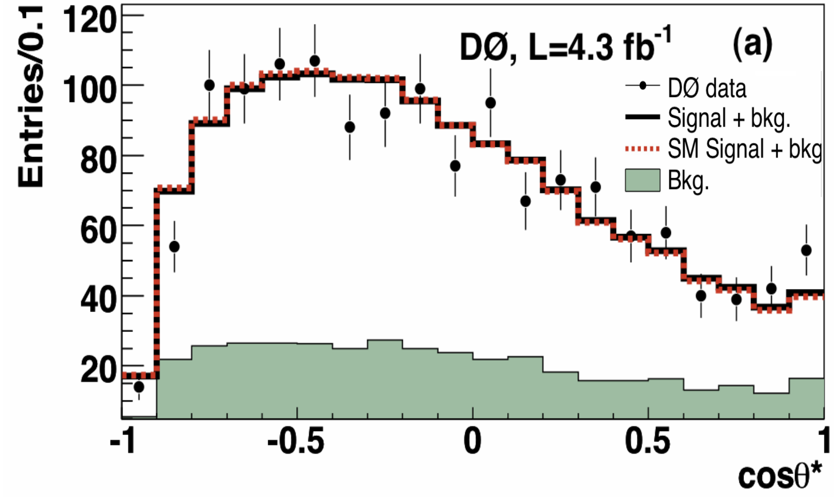


Acceptance:
lepton within b-jet

Leptonic Decay of W:





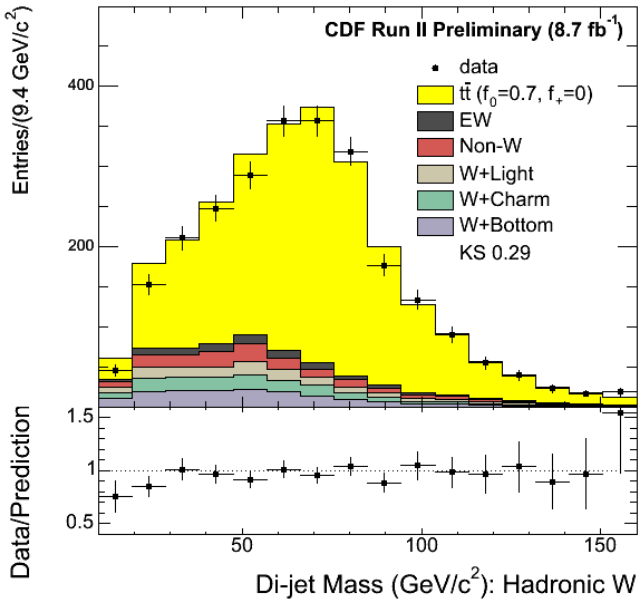
→ Result consistent with SM:

$$f_0 = 0.669 \pm 0.078\ (\text{stat.}) \pm 0.065\ (\text{syst.})$$
$$f_+ = 0.023 \pm 0.041\ (\text{stat.}) \pm 0.034\ (\text{syst.})$$

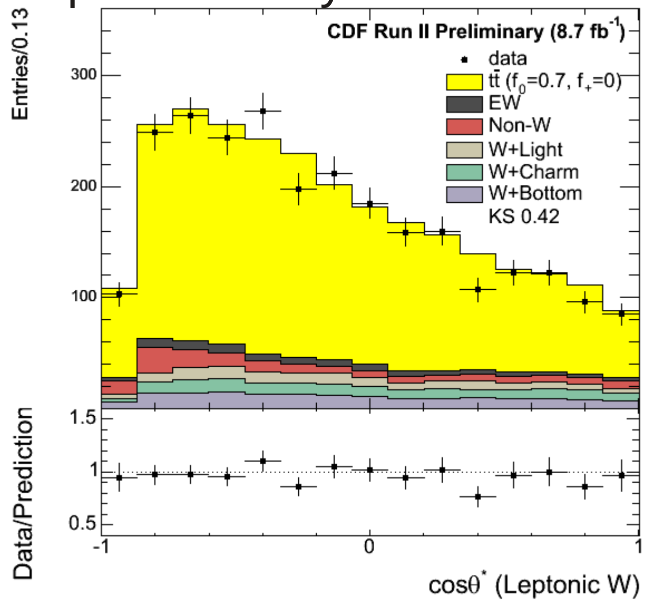
W helicity

- Use matrix element approach for W helicity measurement
- Calculates an event probability based on the best jet-parton assignments:

Hadronic Decay of W:



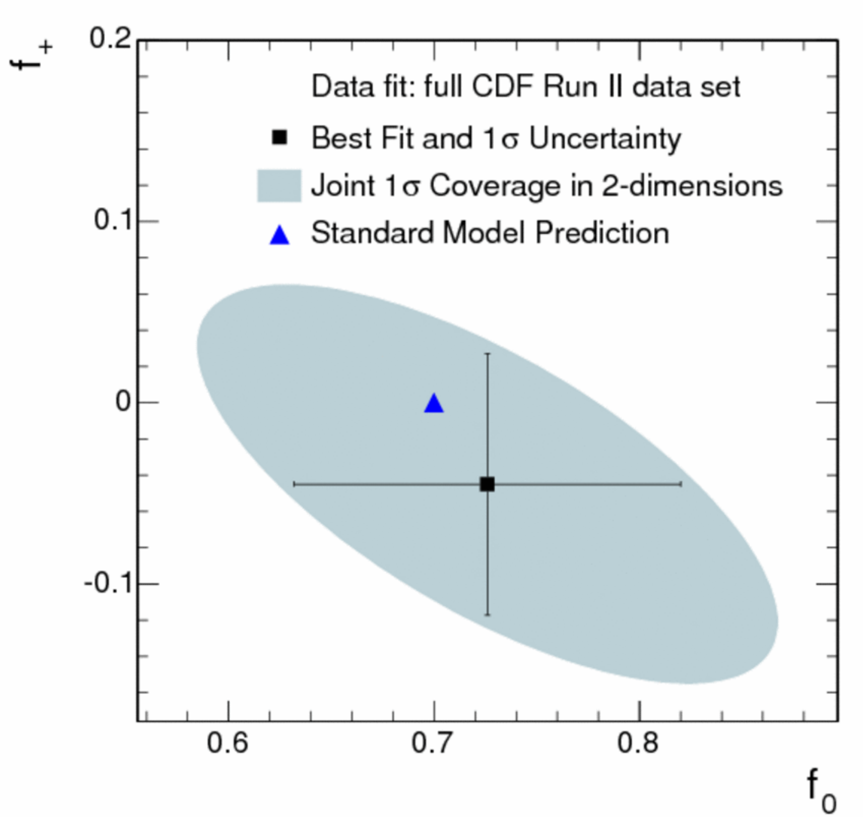
Leptonic Decay of W:

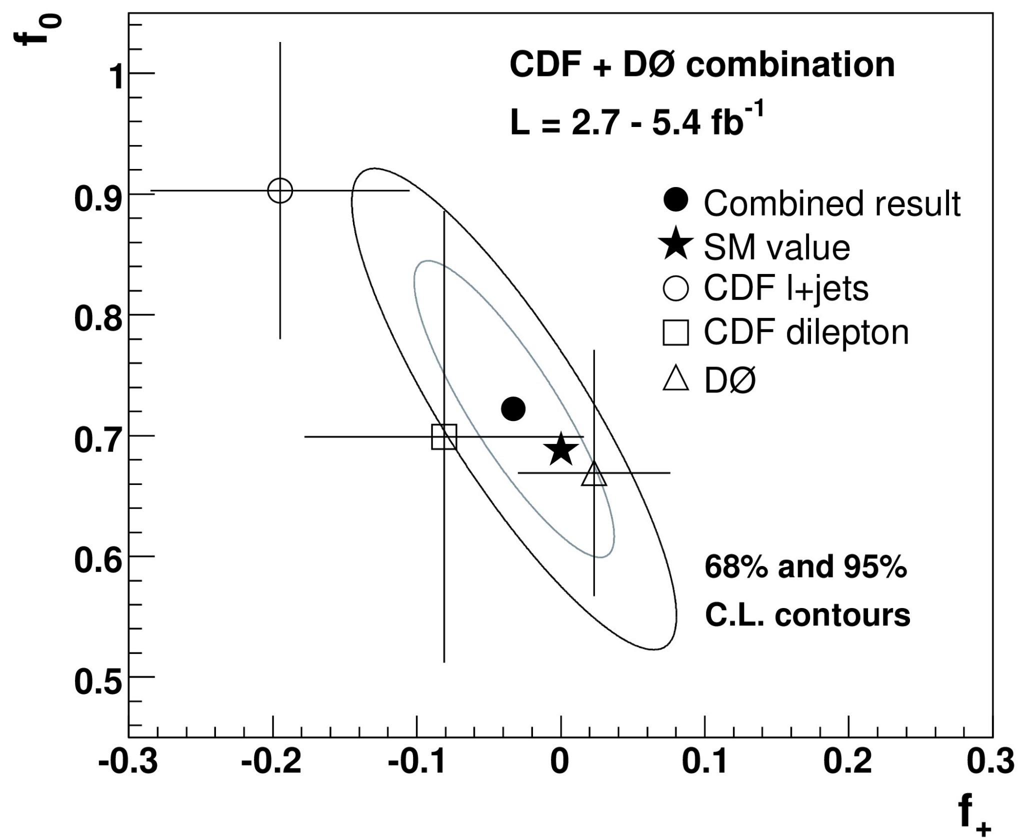


- ME likelihood is not full answer:
  - Only leading order (missing diagrams)
  - Events w/o correct assignment → Calibrate using ensemble tests

W helicity

- Use matrix element approach for W helicity measurement





→ Result consistent with SM:

f_0 = 0.726 ± 0.066 (stat) ± 0.067 (syst)
f_+ = -0.045 ± 0.043 (stat) ± 0.058 (syst)

f_0 = 0.683 ± 0.042 (stat) ± 0.040 (syst)
f_+ = -0.025 ± 0.024 (stat) ± 0.040 (syst)

other fixed to SM