Recent results from the Tevatron

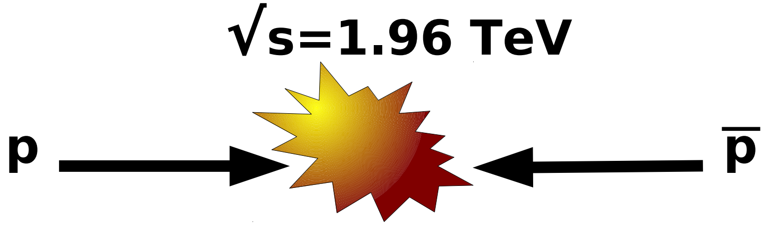
(excluding Higgs)

- Introduction
- Heavy Flavor & QCD
- EW & Top quark
- Conclusions & Outlook

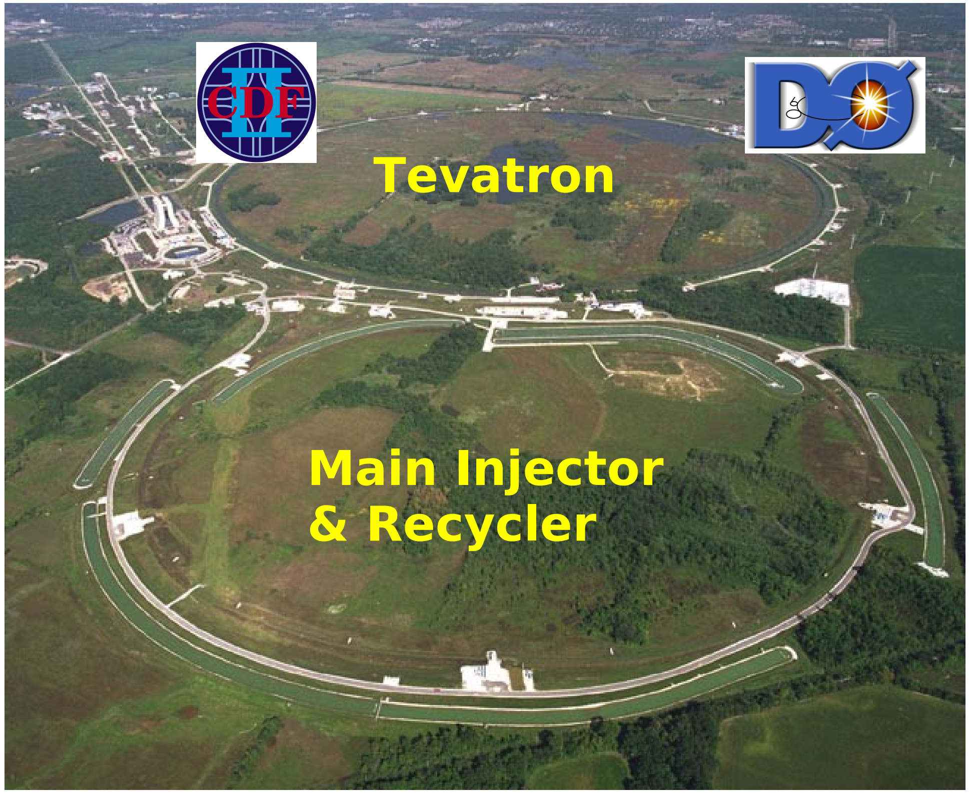
Andreas Jung

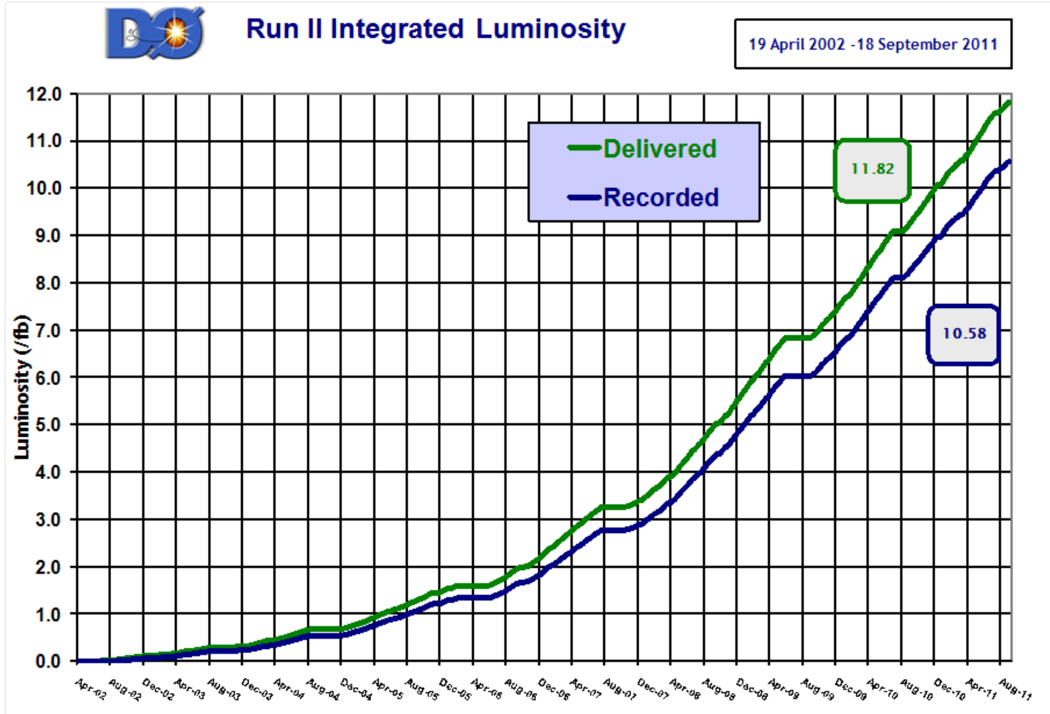
46th Annual Fermilab Users Meeting June 12th, 2013

Tevatron – Introduction



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

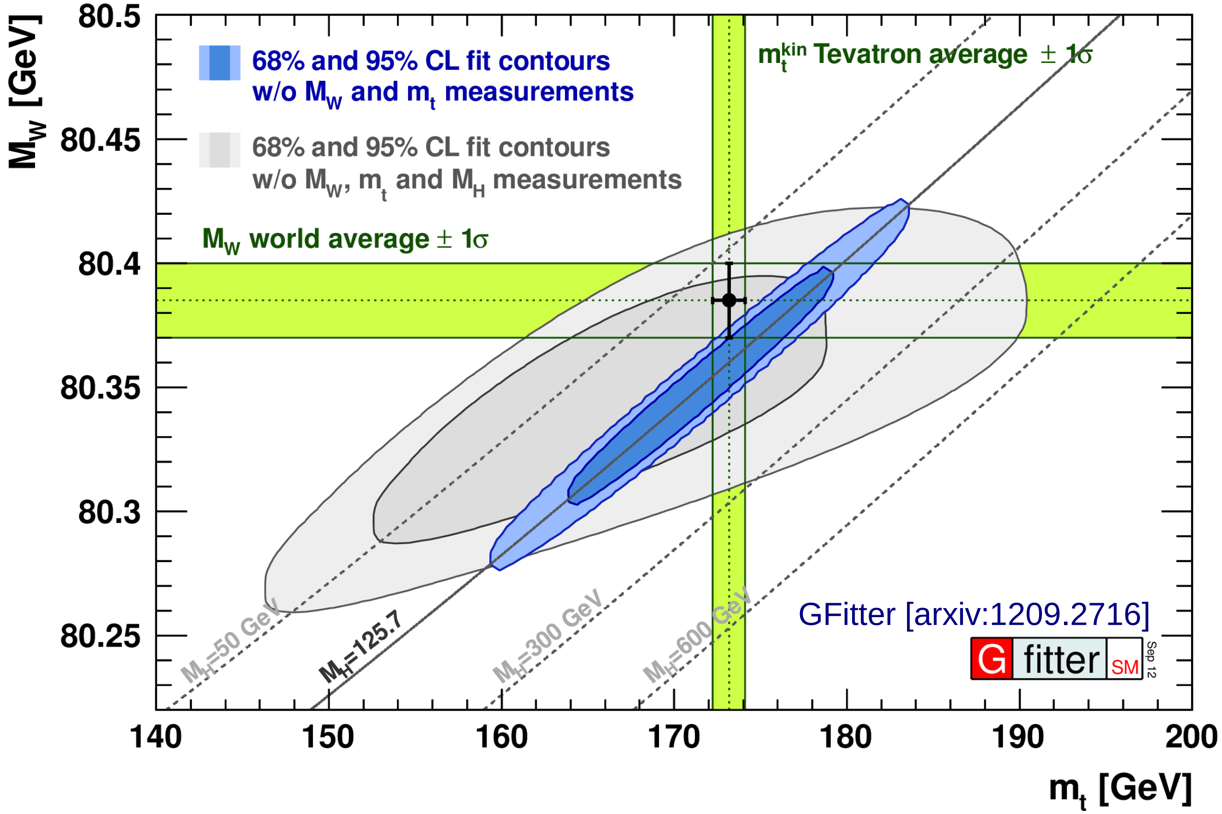


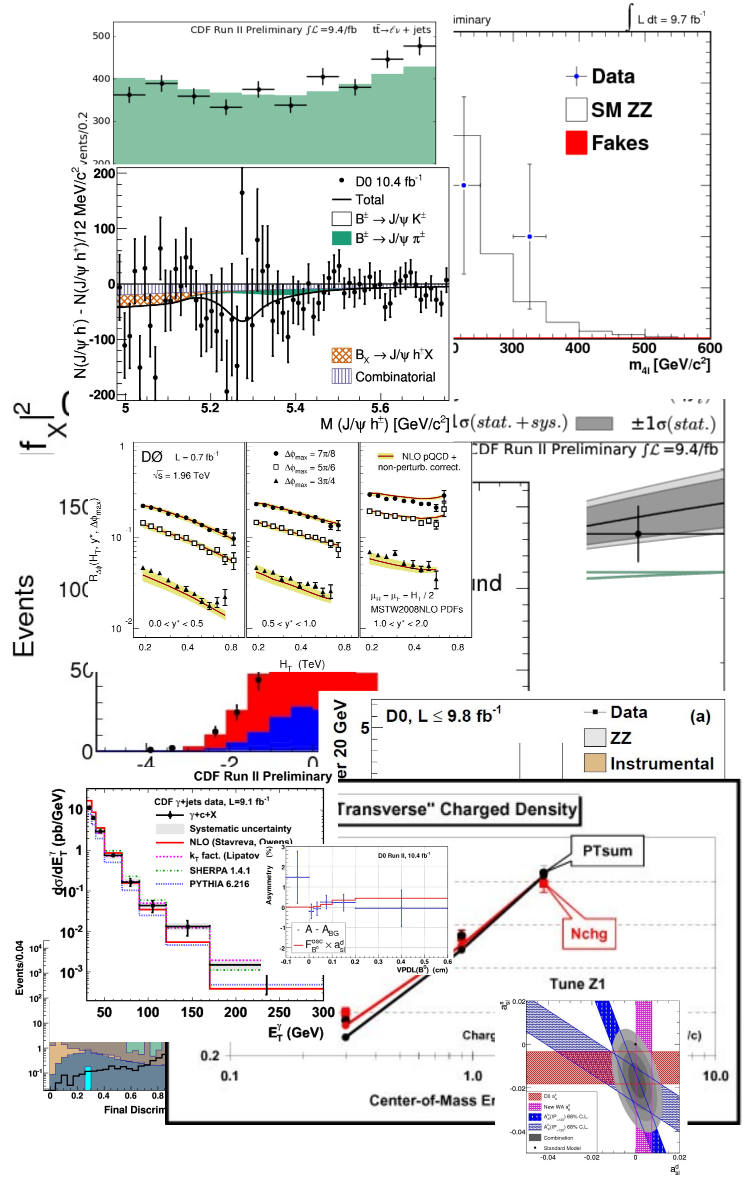


Big thanks to the Accelerator Division!

Tevatron – Strengths

- Worlds largest $p\bar{p}$ data set for a long time
- Well understood detectors
- Initial state allows for unique measurements
- Less pile-up effects





Tevatron: → **High precision m_W and m_t measurements**

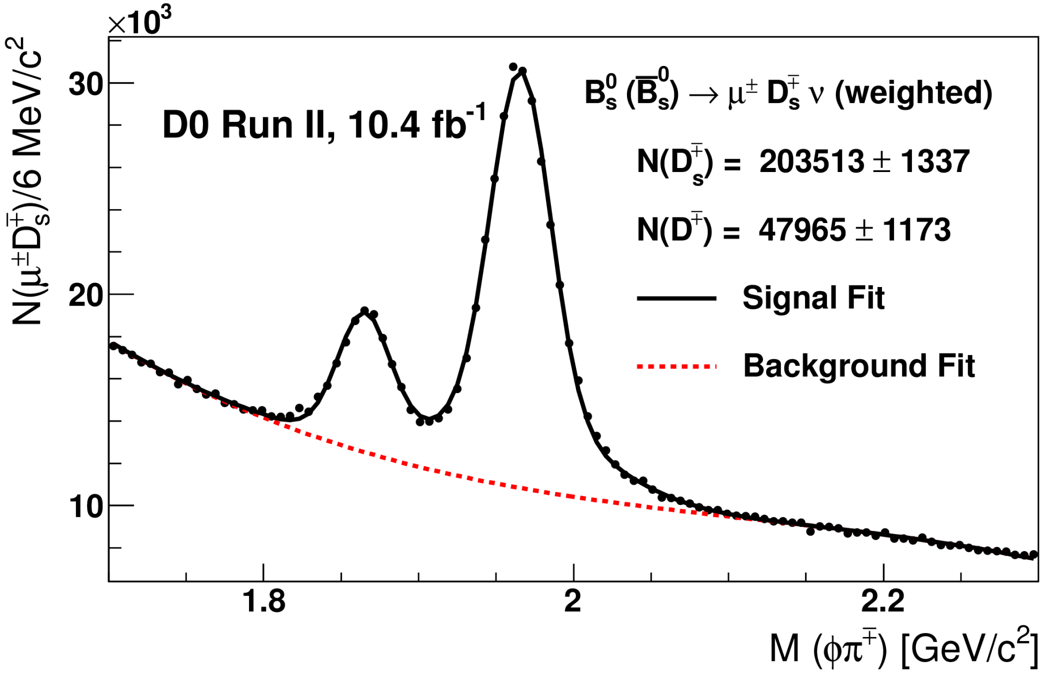
Heavy Flavor

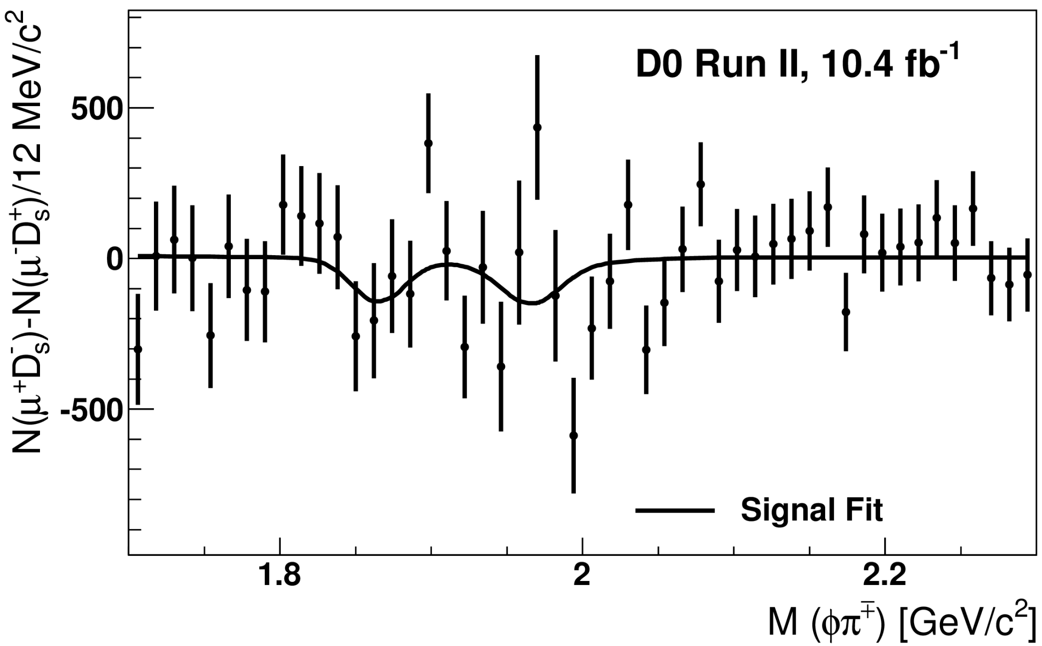
CP Asymmetries (D0)

- Tevatron: Initial state is CP symmetric
- D0 observes large asymmetry in like-sign dimuons: 3.9 s.d.
- Semileptonic mixing asymmetry:
- Measure a_{sl}^{s} in $B_s^0 \rightarrow D_s \mu X$
- Ability to reverse polarity of magnets in D0

$$a_{sl}^{q} = \frac{N(\mu^+ D^-_{(s)}) - N(\mu^- D^+_{(s)})}{N(\mu^+ D^-_{(s)}) + N(\mu^- D^+_{(s)})}$$

Phys. Rev. Lett. 110, 011801 (2013)



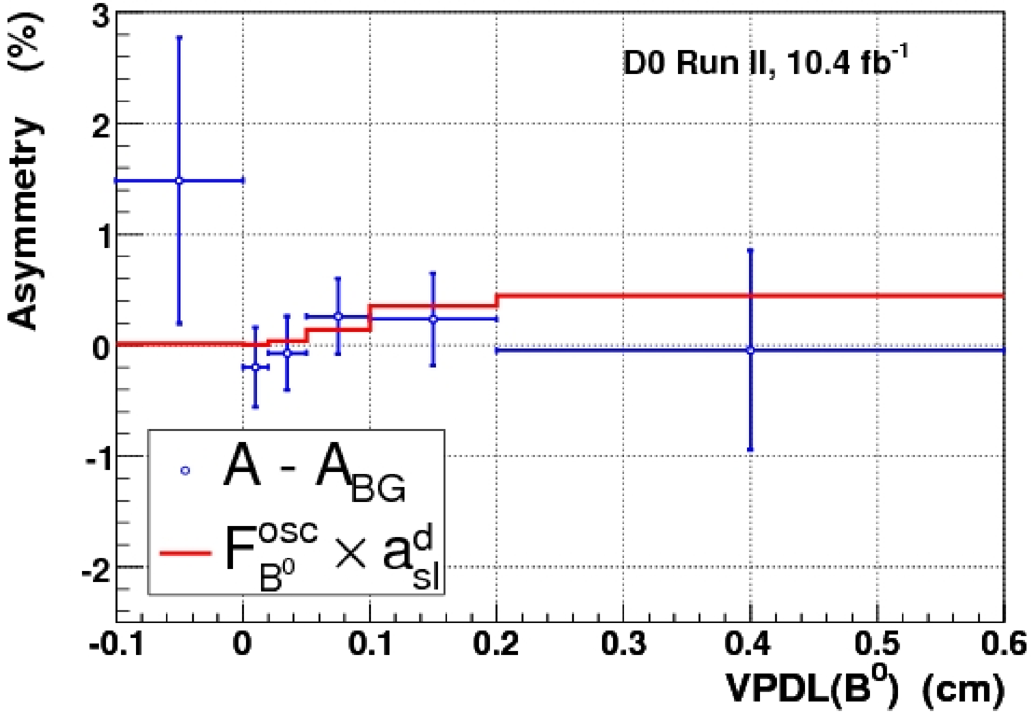


$\boxed{a_{sl}^{s} = (-1.12 \pm 0.74\ (\text{stat}) \pm 0.17 (\text{syst}))\%}$

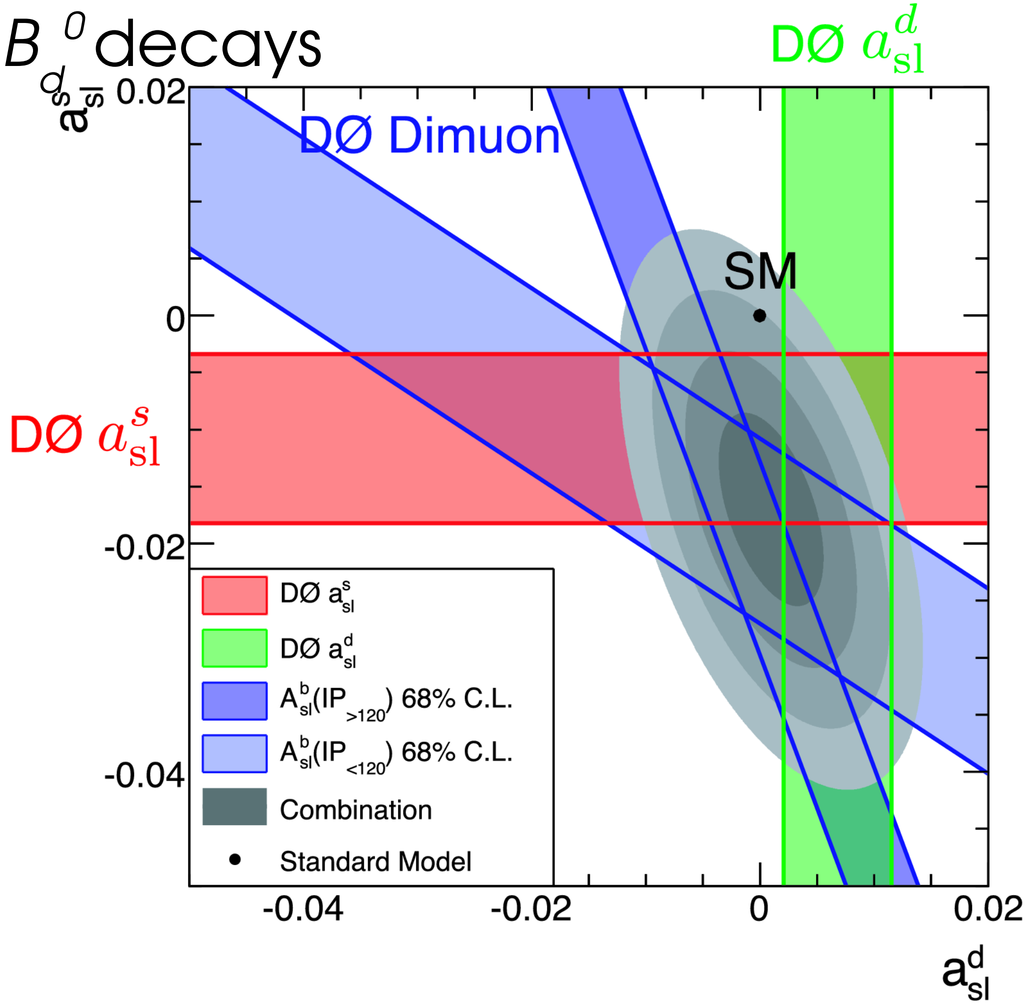
(also measured by LHCb, compatible with SM and D0)

CP Asymmetries (D0)

- Tevatron: Initial state is CP symmetric
- D0 observes large asymmetry in like-sign dimuons: 3.9 s.d.
- Measure a_{sl}^s in $B_s^0 \to D_s \mu X$ and a_{sl}^d in B^0 decays



Phys. Rev. D 86, 072009 (2012)



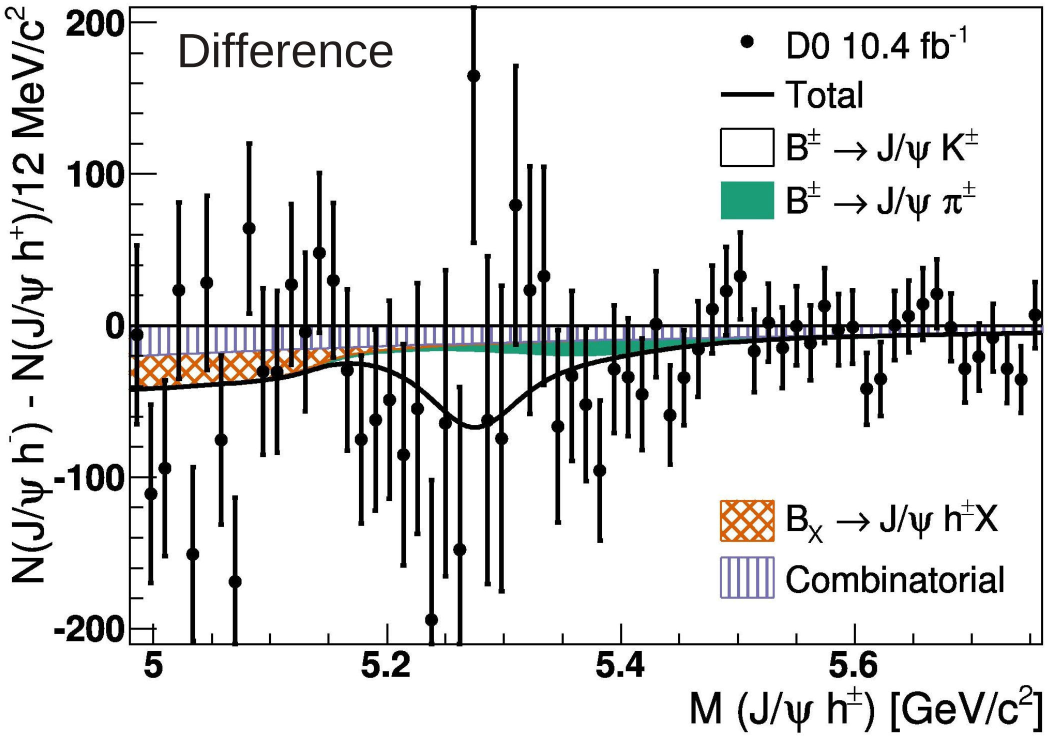
$\boxed{a_{sl}^d = (\,0.68 \pm 0.45\ (\text{stat}) \pm 0.14(\text{syst}))\%}$

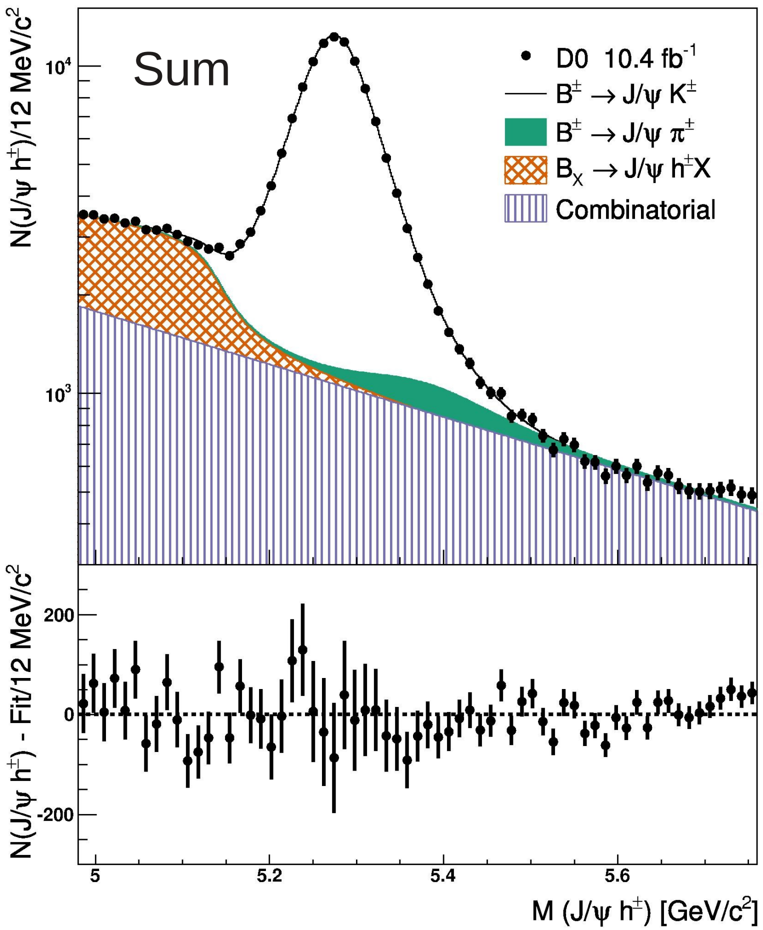
$\to a_{s,d}^{sl}$ both compatible with SM and Dimuon result

CP Asymmetries (D0)

- Measure direct CP-violating charge asymmetry in decays of: $B^{\pm} \rightarrow J/\psi K^{\pm}$ and $B^{\pm} \rightarrow J/\psi \pi^{\pm}$ (expect very small CP violation)
- Special ability to reverse polarity of magnets in D0
- **Most precise measurement of $B^{\pm} \rightarrow J/\psi K^{\pm}$**

D0 [arxiv:1304.1655]





$A^{J/\psi K} = (0.59 \pm 0.37)\%$ $A^{J/\psi \pi} = (-4.2 \pm 4.5)\%$

Result is consistent with 0

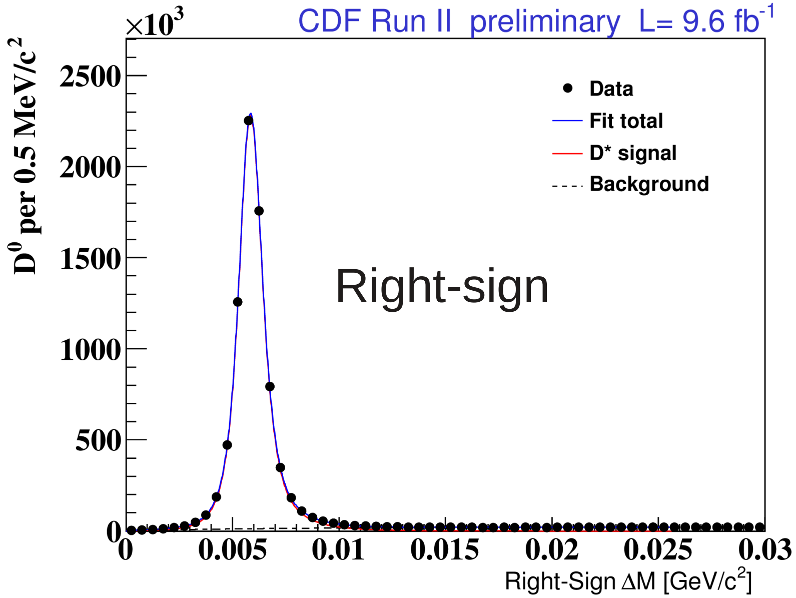
$D\bar{D}$ mixing (CDF)

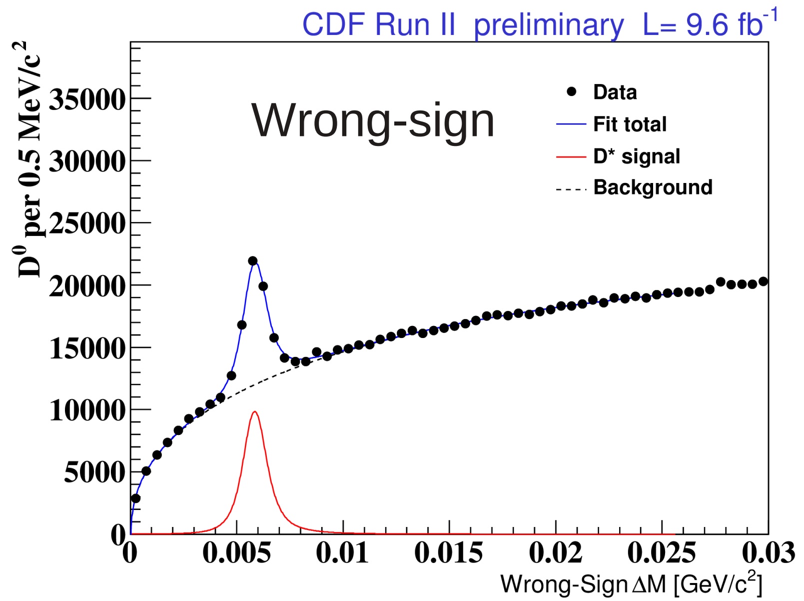
CDF note

- Study $D\bar{D}$ system by measuring:

$$D^* \rightarrow D^0\pi^+ \begin{cases} (K^-\pi^+)\pi^+ & \text{Right-sign} \\ (K^+\pi^-)\pi^+ & \text{Wrong-sign} \end{cases}$$

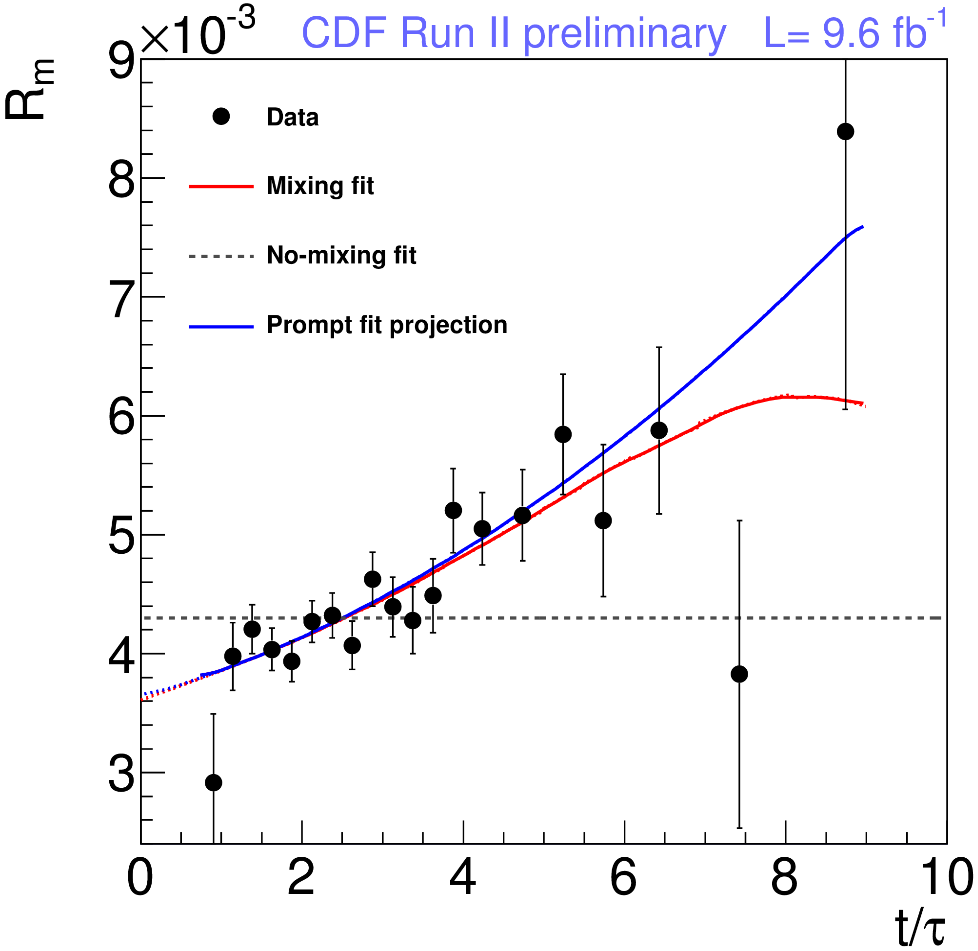
- Explicitly reconstruct D^* and subsequent D^0 meson decay
- Reject misidentified D^* by employing particle ID for kaon & pion cut
- Use impact parameter of D^0 to estimate contribution from B decays

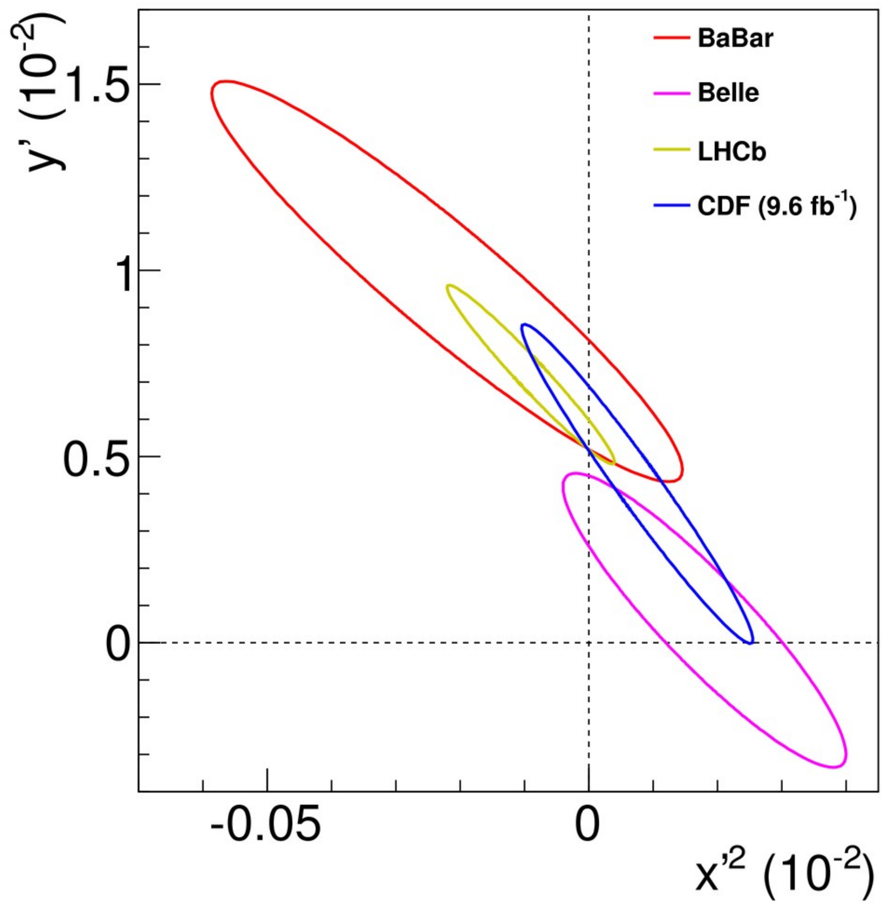




$D\bar{D}$ mixing (CDF)

CDF note





t/τ – normalized proper decay time

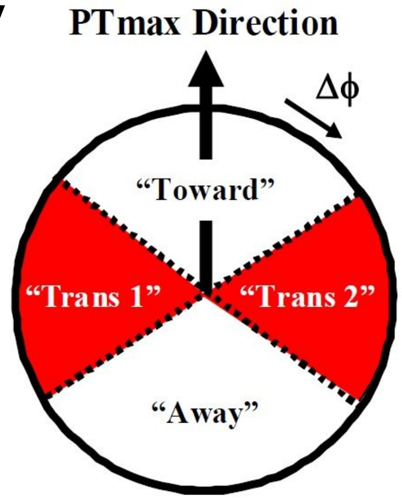
R_m – ratio of WS/RS D* decays

Observe $D^0 - \overline{D^0}$ mixing at 6.1 s.d.

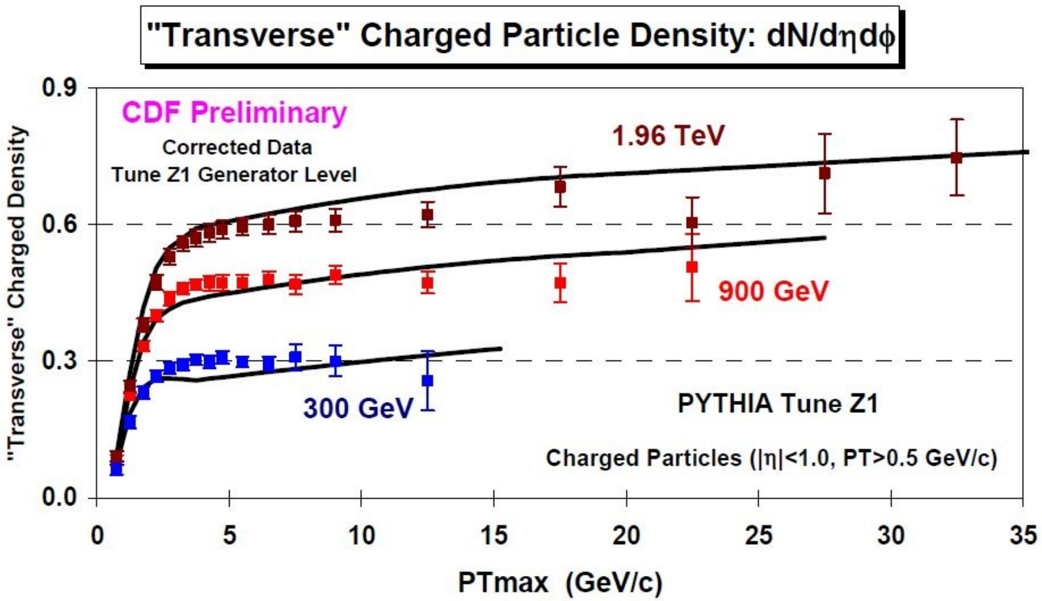
QCD

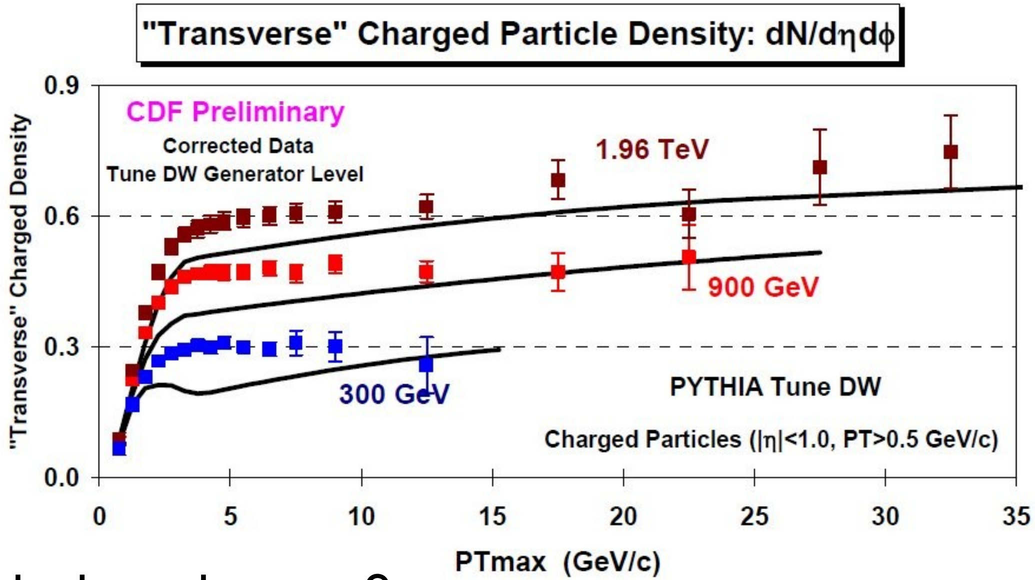
Underlying Event (CDF)

- Make use of the **Tevatron energy scan** just before shutdown !
- Underlying event structure in **√s=0.3, 0.6 and 1.96 TeV**
- Leading charged particle defines three regions:



CDF webpage

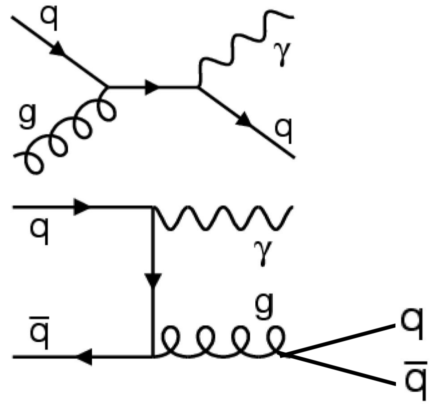




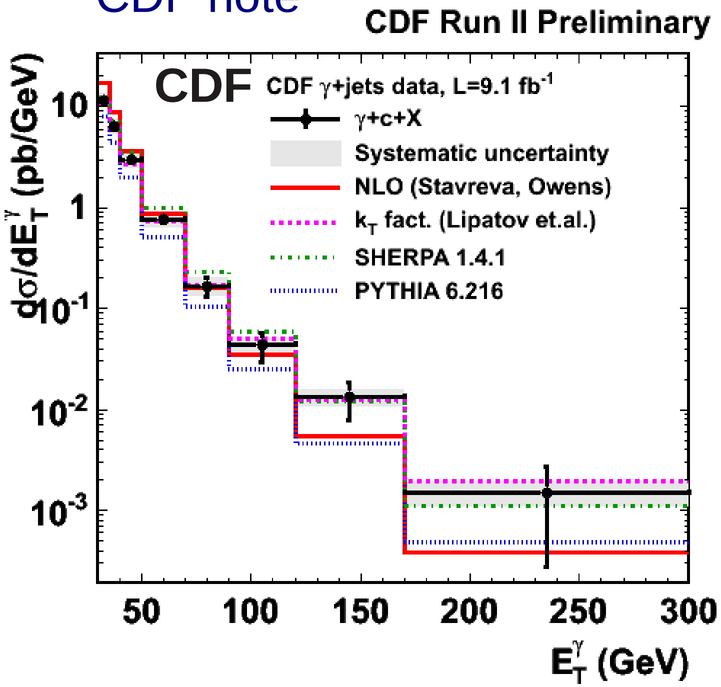
Extensive studies of underlying event structures & comparisons to various MC tunes

γ, W, Z + HF (CDF, D0)

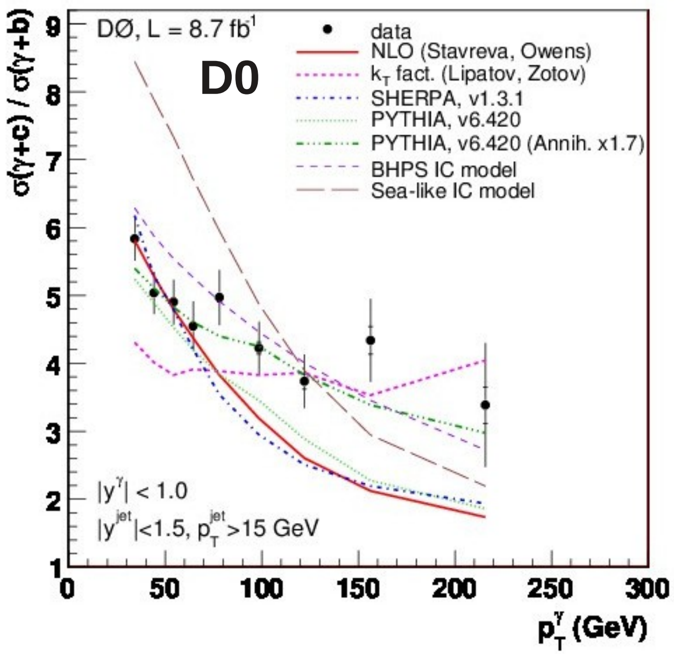
- Extensive studies of γ, W, Z + HF production used for validation of background models used in searches or measurements
- γ + HF production: sensitive to *c*, *b* and *g* content
- Compton scattering at low E_T, gluon splitting at high E_T



CDF note



Phys. Lett. B 719, 354 (2013)



- Compared to data NLO prediction is lower at higher E_T (effectively LO $g \rightarrow q\bar{q}$)

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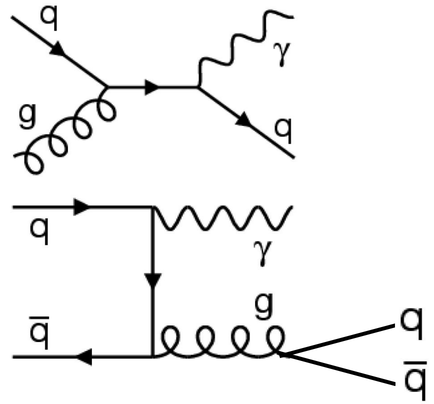
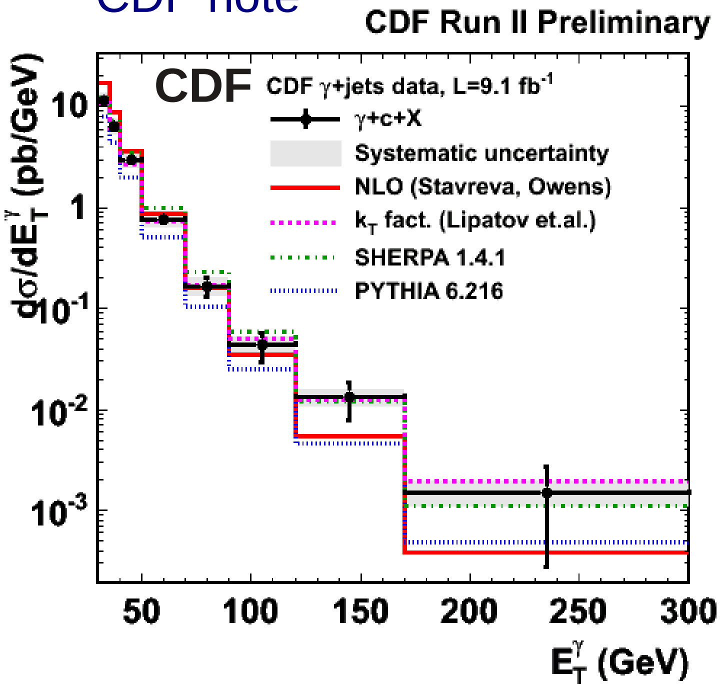


CDF note



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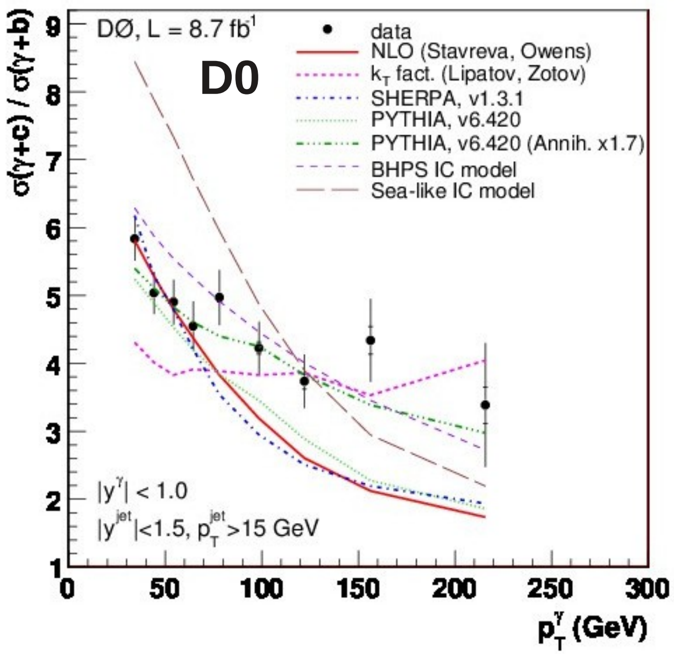
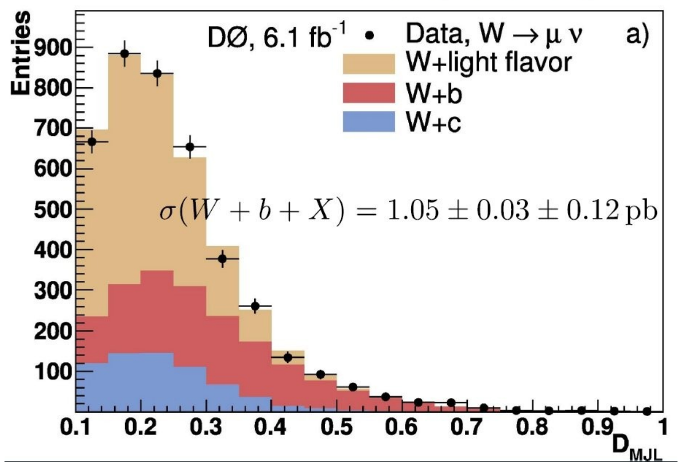


D0: PLB 718, 1314 (2013)



Phys. Lett. B 718, 1314 (2013)

- Compared to data NLO prediction is lower at higher E_T (effectively LO $g \rightarrow q\bar{q}$)
- *W + b + X:* Cross section agrees with NLO QCD (MCFM)

3 jet / 2 jet ratios (D0)

- Sensitive to α_s, test pQCD, advantage: systematic uncertainties cancel
- $R_{3/2}$: inclusive 3/2 jet ratios — D0 [arxiv:1209.1140]
- $R_{\Delta R}$: # of neighboring jets / # inclusive jets — Phys. Lett. B 718, 56 (2012)
- **First measurement of jet azimuthal decorrelations $R_{\Delta\varphi}$** — Phys. Lett. B 721, 212 (2013)

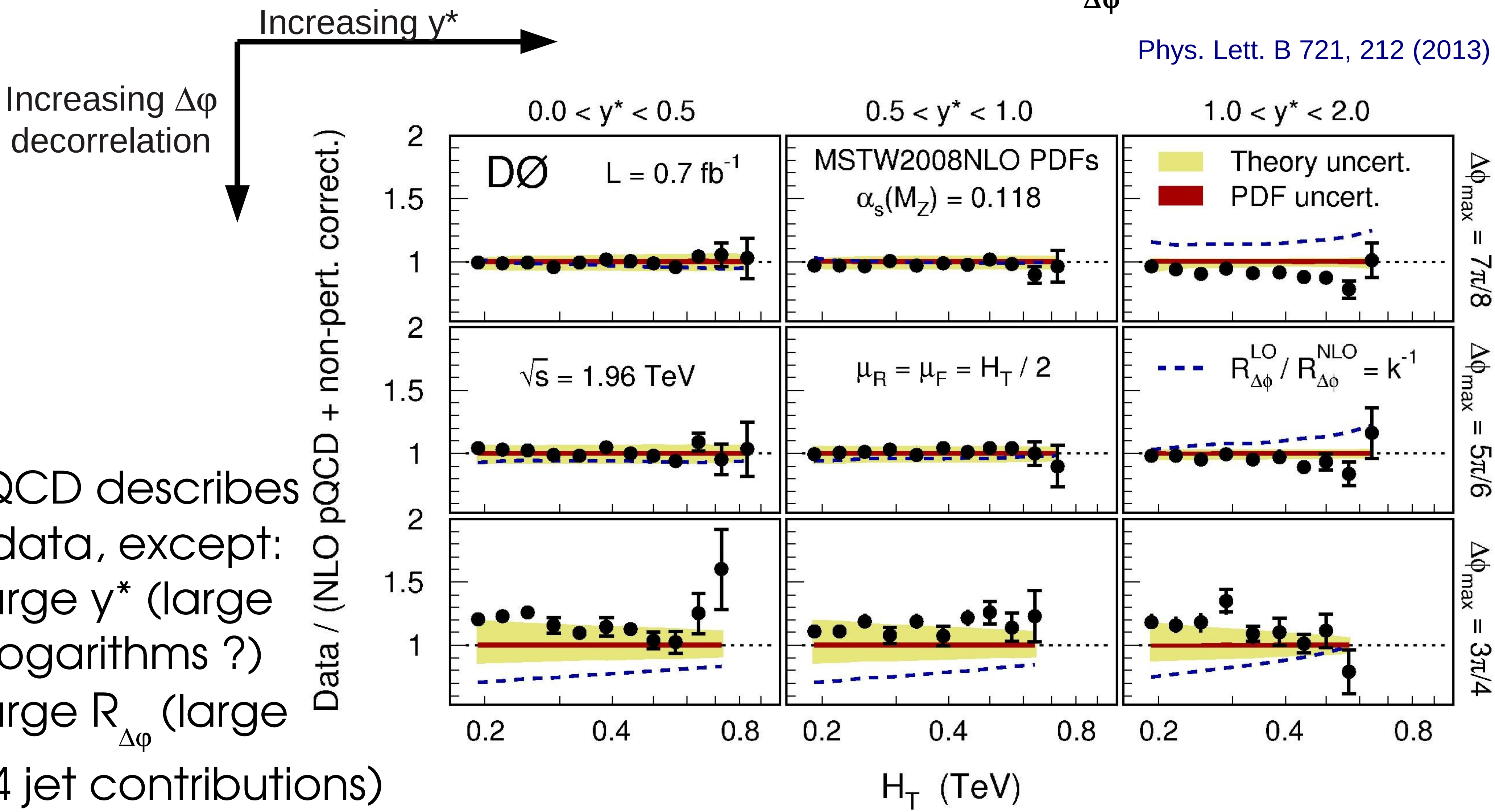
$$R_{\Delta\phi}(H_T, y^*, \Delta\phi_{\max}) = \frac{\dfrac{d^2\sigma_{\text{dijet}}(\Delta\phi_{\text{dijet}} < \Delta\phi_{\max})}{dH_T\,dy^*}}{\dfrac{d^2\sigma_{\text{dijet}}(\text{inclusive})}{dH_T\,dy^*}}$$

- Test perturbative QCD in a large phase space

3 jet / 2 jet ratios (D0)

- Sensitive to α_S, test pQCD, advantage: systematic uncertainties cancel
- **First measurement of jet azimuthal decorrelations $R_{\Delta\varphi}$**

Phys. Lett. B 721, 212 (2013)



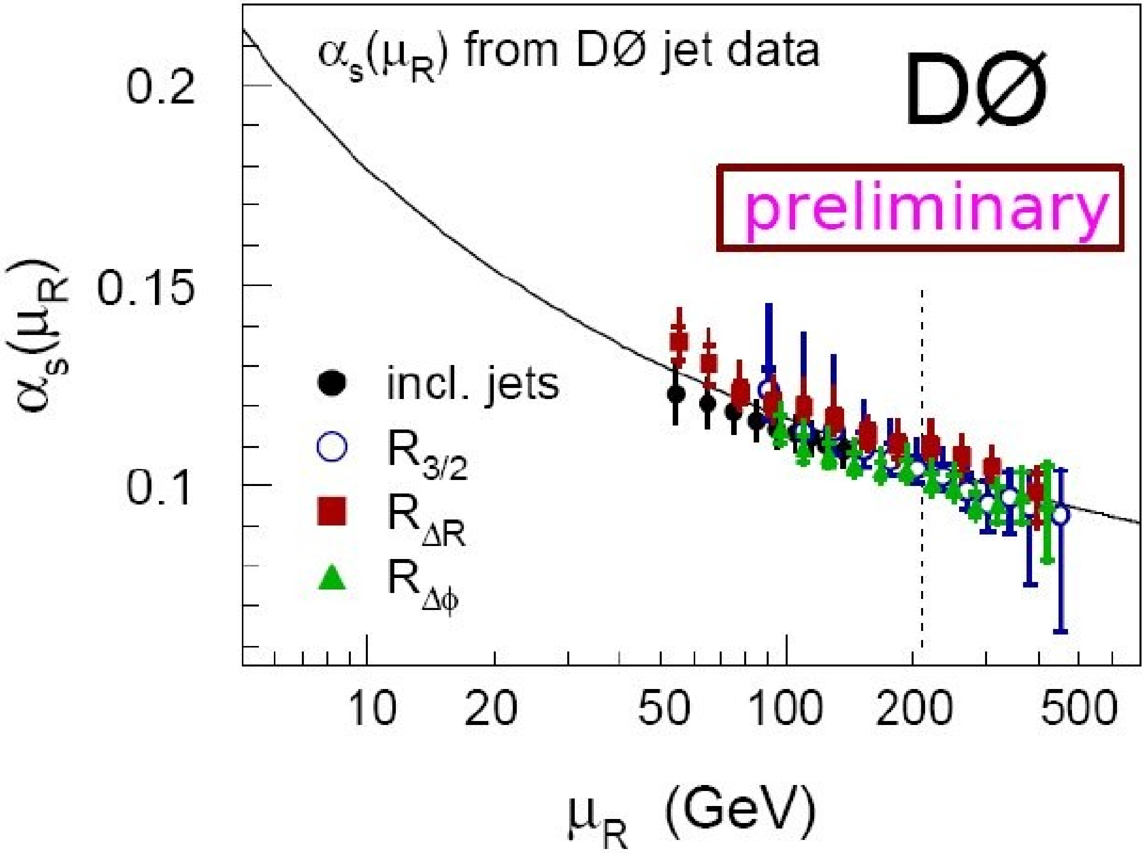
- pQCD describes data, except:
  - → large y* (large logarithms ?)
  - → large $R_{\Delta\varphi}$ (large 4 jet contributions)

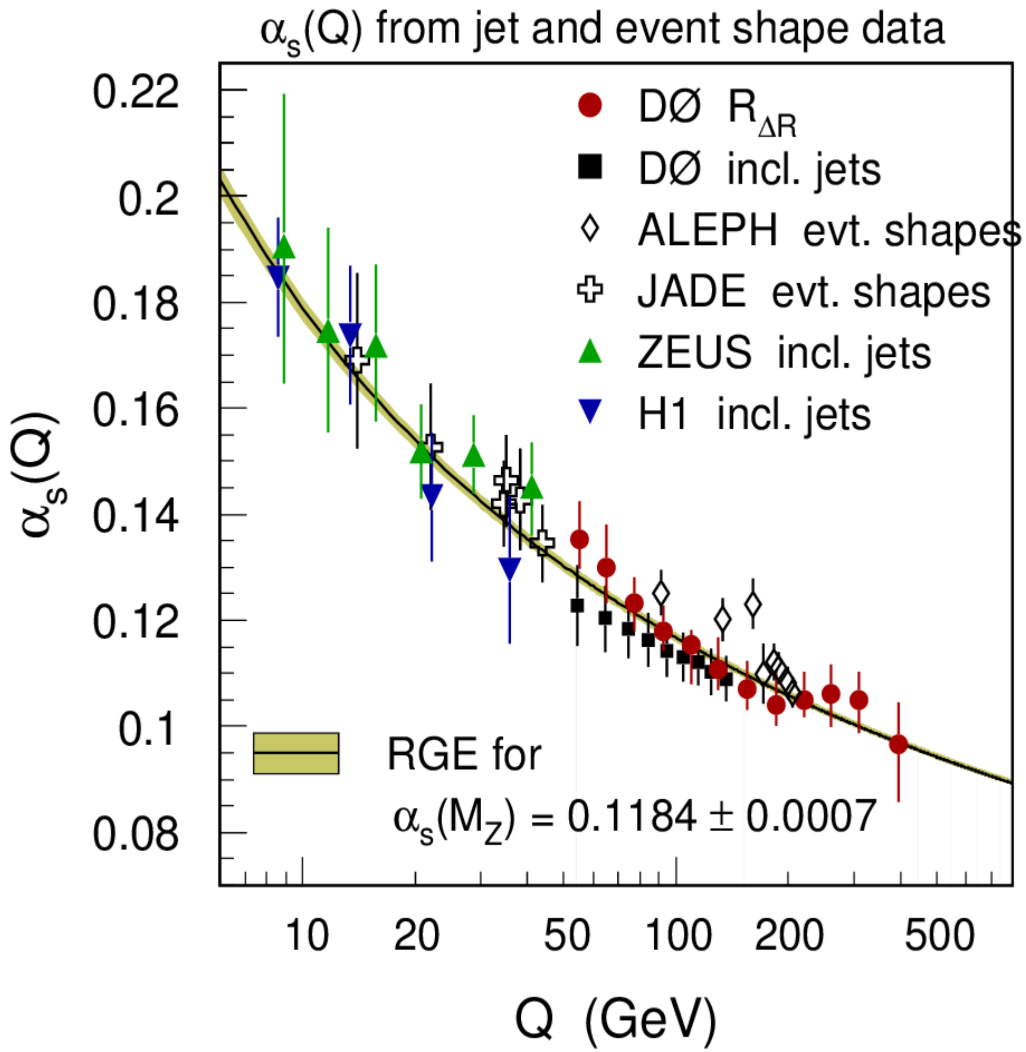
Strong coupling (D0)

- R_X allows **probing α_s up to high scales of 400 GeV !**

Phys. Lett. B 721, 212 (2013)

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





Data follows predicted decreasing slope by RGE

Electroweak

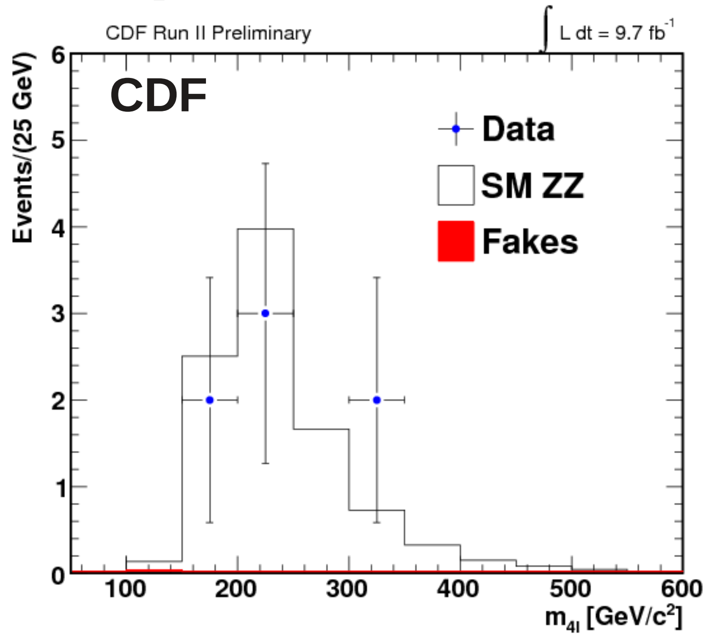
ZZ production (CDF)

- $ZZ \to \ell\ell\ell'\ell'$ SM cross section σ= 1.43 ± 0.10 pb
- Measurement with very small SM background
- Ratio to SM:

$$\frac{\sigma(p\bar{p} \to ZZ)}{\sigma_{SM}} = 0.73^{+0.31}_{-0.24}(\text{stat.})^{+0.08}_{-0.05}(\text{syst.})$$

- Combine $ZZ \to \ell\ell\ell'\ell' + ZZ \to \ell\ell\nu\nu$: $\sigma = 1.38^{+0.28}_{-0.27}$ pb

  CDF note (ZZ)



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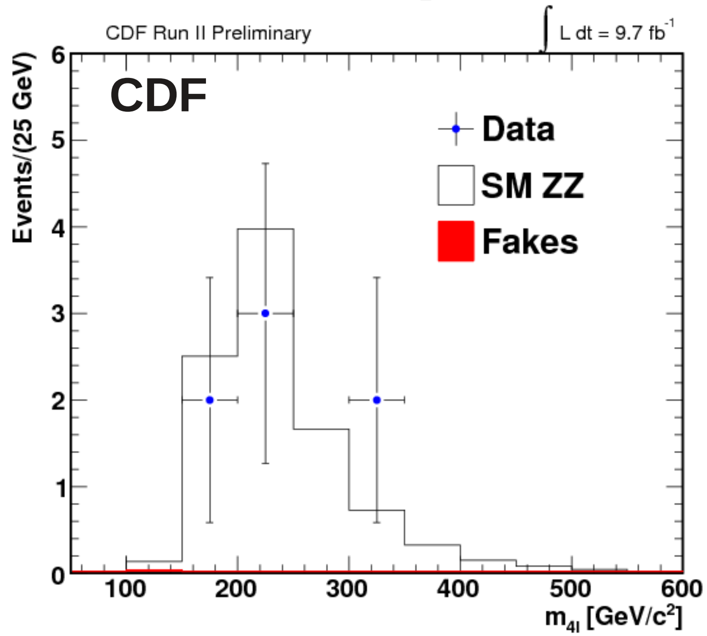
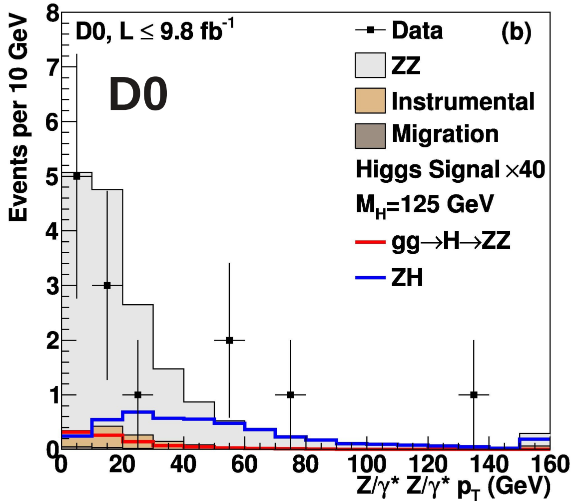


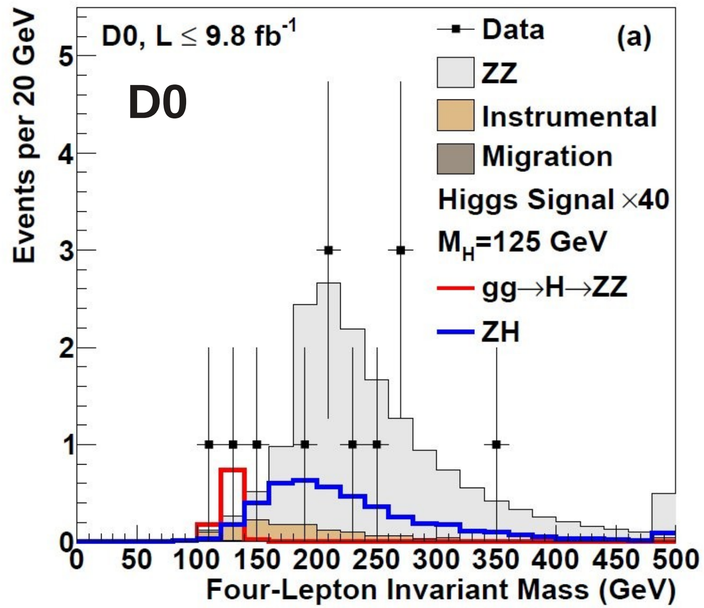
- Same approach as in CDF, combined D0 measurement:

σ= 1.32 $^{+0.29}_{-0.25}$(stat) ± 0.12 (syst) ± 0.04 (lumi) pb

D0 [arxiv:1304.5422]

Very good agreement between experiments and with SM

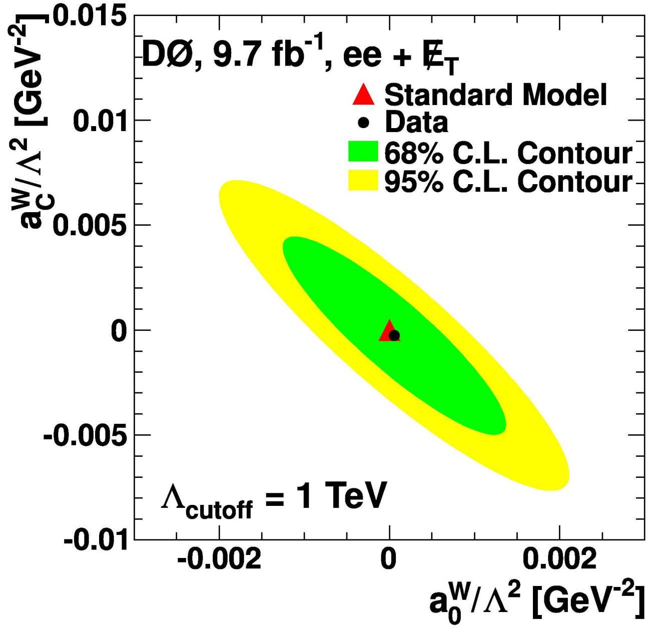


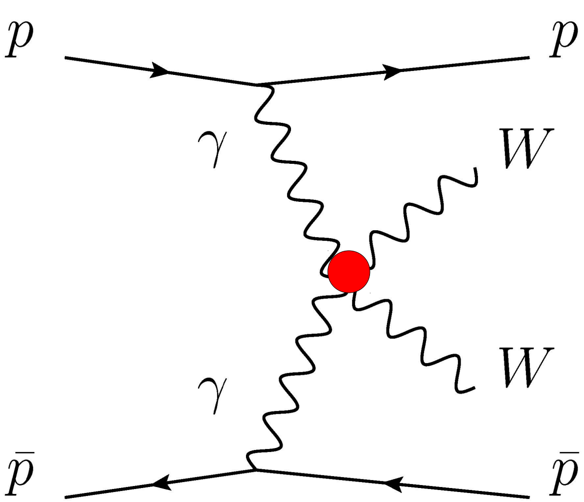


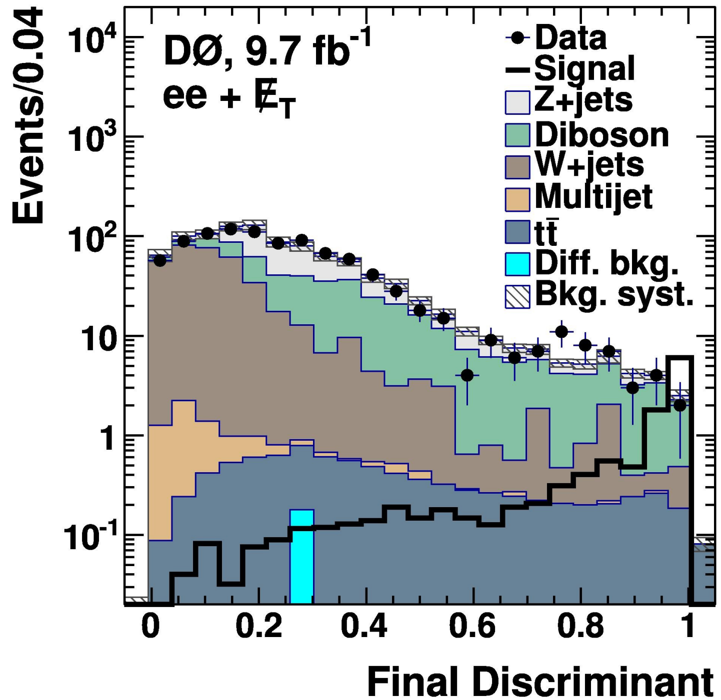
AQGC (D0)

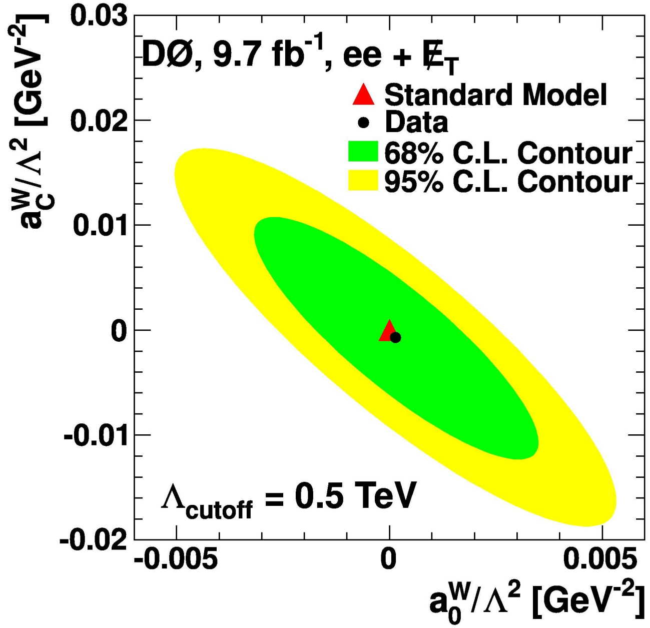
- Search for **A**nomalous **Q**uartic **G**auge **C**ouplings
  → sensitivity to beyond SM contributions
- Very small SM cross section $\sigma_{p\bar{p} \to WW\gamma\gamma} = 3$ fb
- Unitarity would be violated if AQGC exist
- Introduce a form factor Λ (scale of new physics)
- Final discriminant does not show excess of data
  → **First limits from Tevatron on AQGC**

D0 [arxiv:1305.1258]





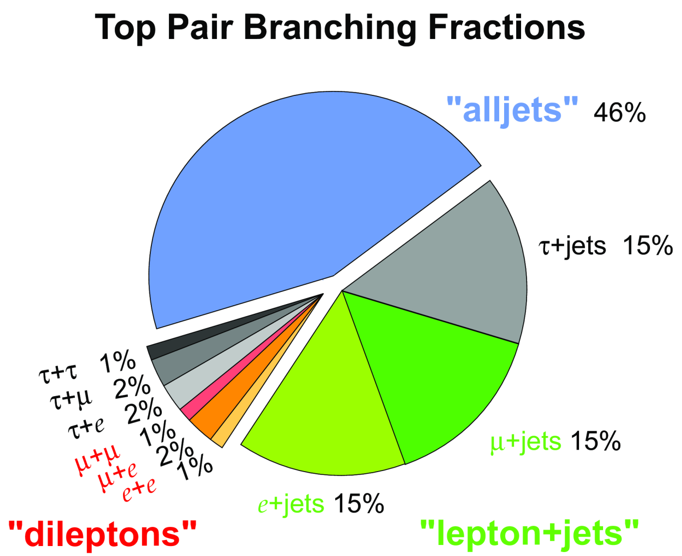




Top

Top introduction

- Top is the heaviest fundamental particle discovered so far:
  - → m_t = 173.2 ± 0.9 GeV
- Top plays special role in EWSB ?
  - → λ_t = 0.995 ± 0.005
- Lifetime: $\tau \approx 5\text{x}10^{-25}$ s << Γ_{QCD}
  - → **Observe bare quark**
- Different decay channels:



Top production (CDF, D0)

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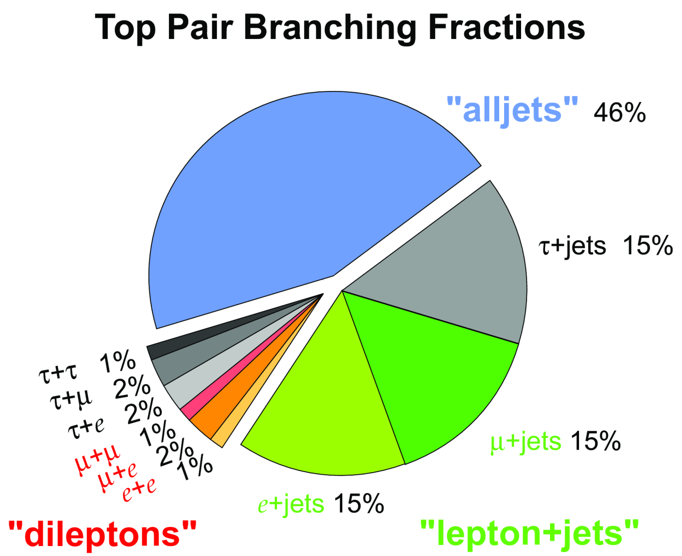
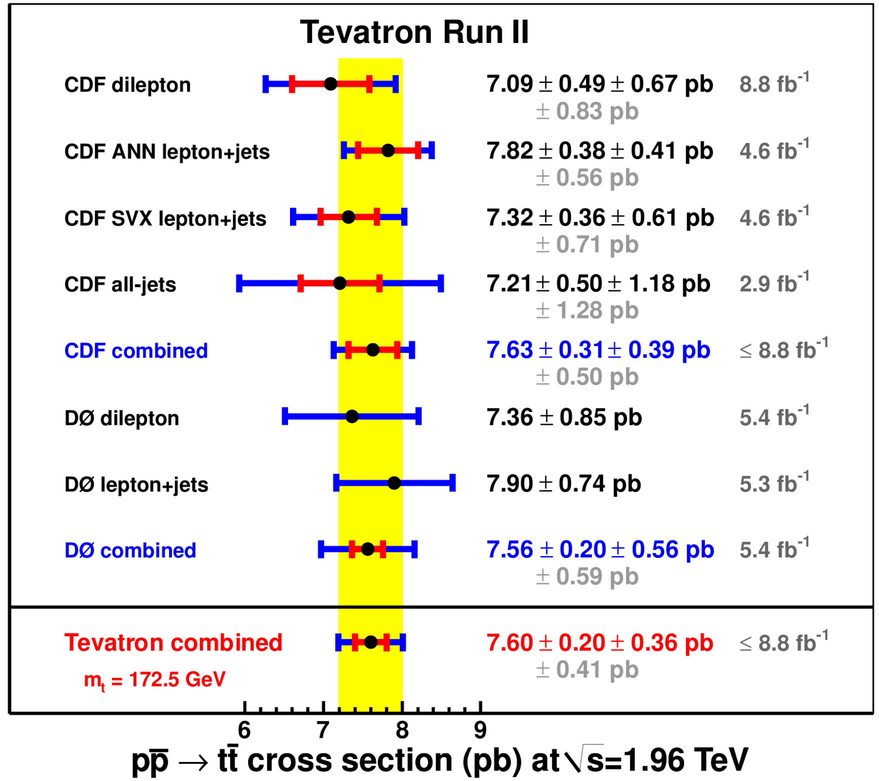


Production cross section:

- CDF inputs: 4 measurements, < 8.8 fb^{-1}
- D0 inputs: 2 measurements, < 5.4 fb^{-1}
- Correlations taken into account

Tevatron note

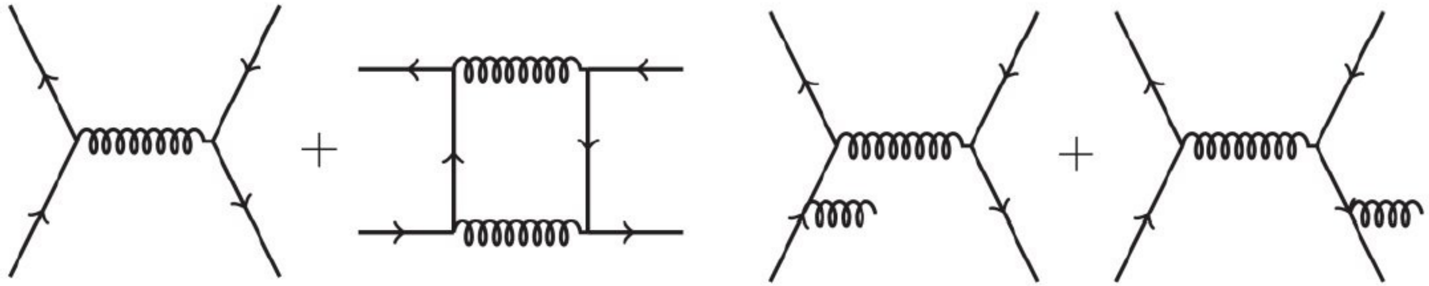


5.4% experimental precision !

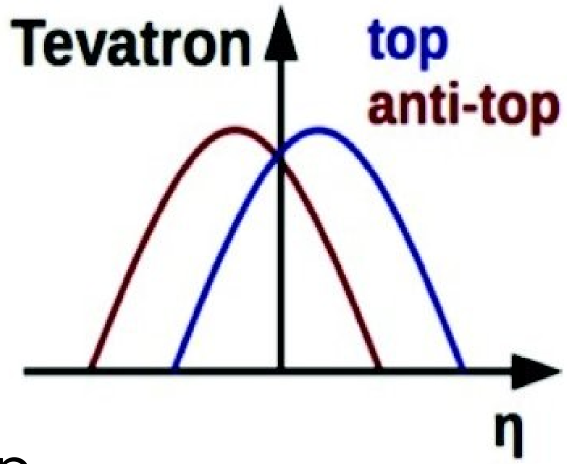
(Best Theory has precision of 4%)

Asymmetry – Recab

- Interference appears at NLO QCD:



Positive asymmetry   Negative asymmetry

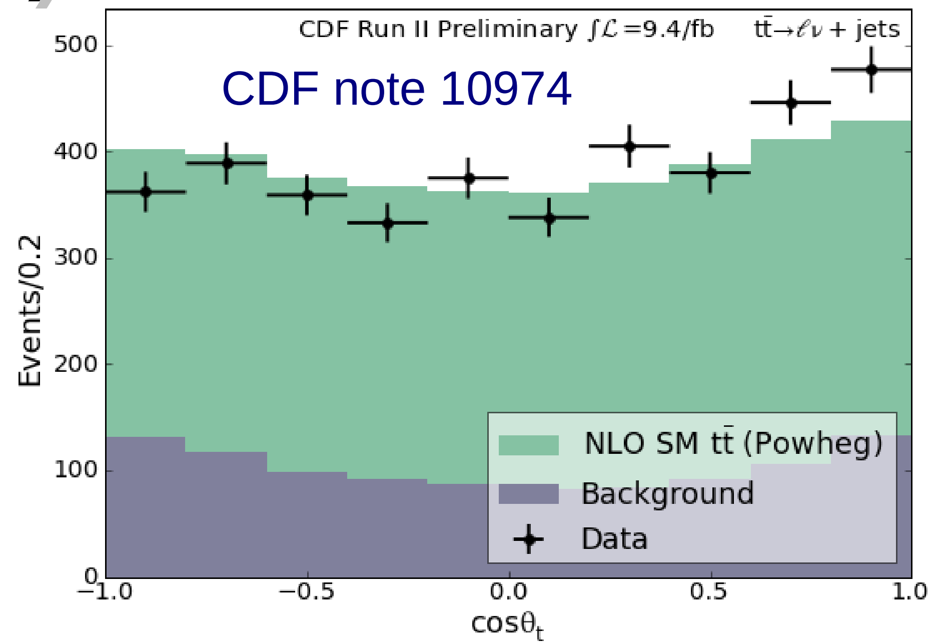


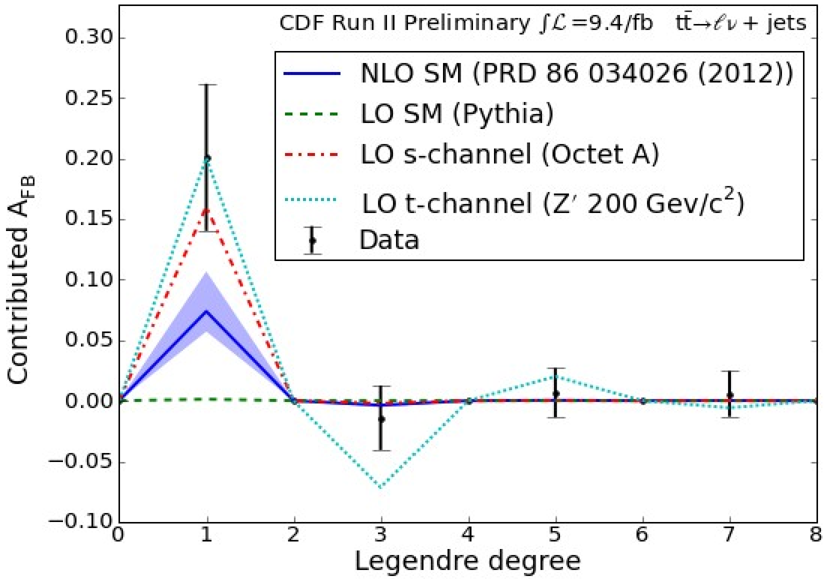
- This is a forward-backward asymmetry at Tevatron
  → initial state: $q\bar{q}$ vs. gg (fwd-bwd symmetric)
- SM prediction at NLO (QCD+EWK):
  $\mathbf{A_{fb} = (6.6 \pm 2.0)\%}$
- **Large positive or negative asymmetry**
  would indicate physics beyond SM:
  → Axi-gluons (s-channel), *Z'* (t-channel)

- Current CDF & D0 measurements show ~2 s.d. deviation
  → **Goal: Be less inclusive, more differentially !**

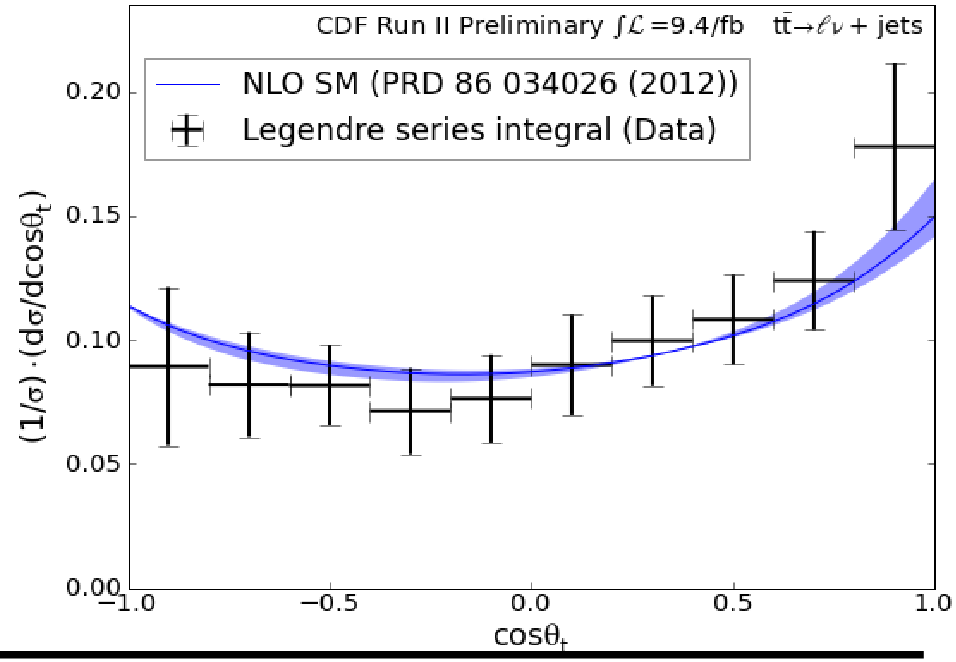
Top asymmetry (CDF)

- Analyze the **shape of the differential cross section: cos(θ_t)**
- Make an expansion in Legendre polynomials: $\frac{d\sigma}{d\cos\theta_t} = \sum_\ell a_\ell P_\ell(\cos\theta_t)$
- New physics contributes differently





Coefficient a_1 of linear term ($a_1\cos\theta_t$) 2.1 s.d. from NLO



Lepton asymmetry (D0)

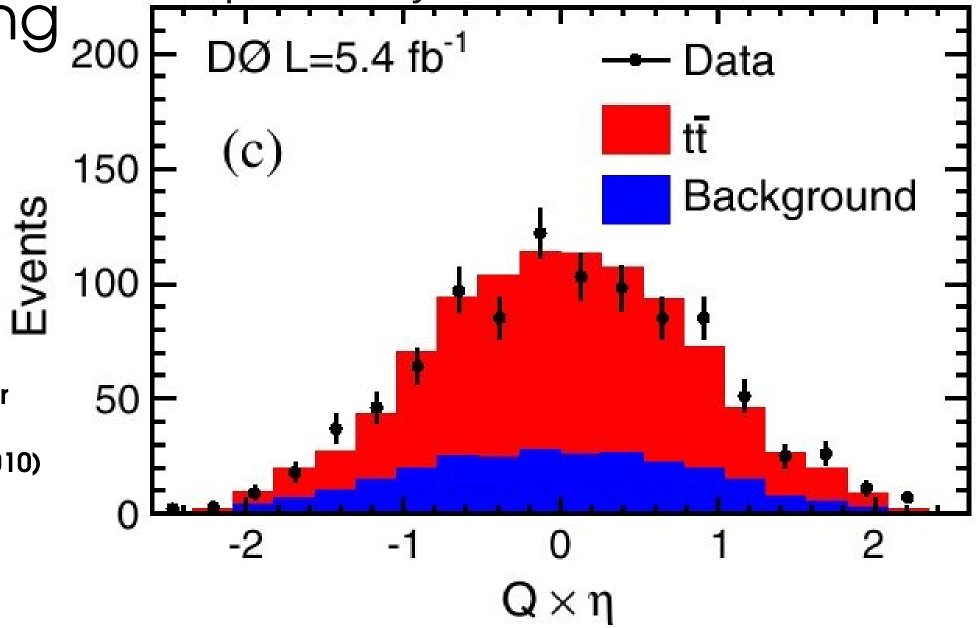
- Leptonic asymmetries are not facing additional difficulties of reconstructing top quark object:

$$A^{\ell}_{\mathrm{FB}} = \frac{N_\ell(Q\cdot\eta > 0) - N_\ell(Q\cdot\eta < 0)}{N_\ell(Q\cdot\eta > 0) + N_\ell(Q\cdot\eta < 0)}$$

Theory: $A_{fb}^{l} = (4.7 \pm 0.1)\%$ MC@NLO + higher order QCD+EW corrections (Nucl.Phys. B837, 90 (2010))

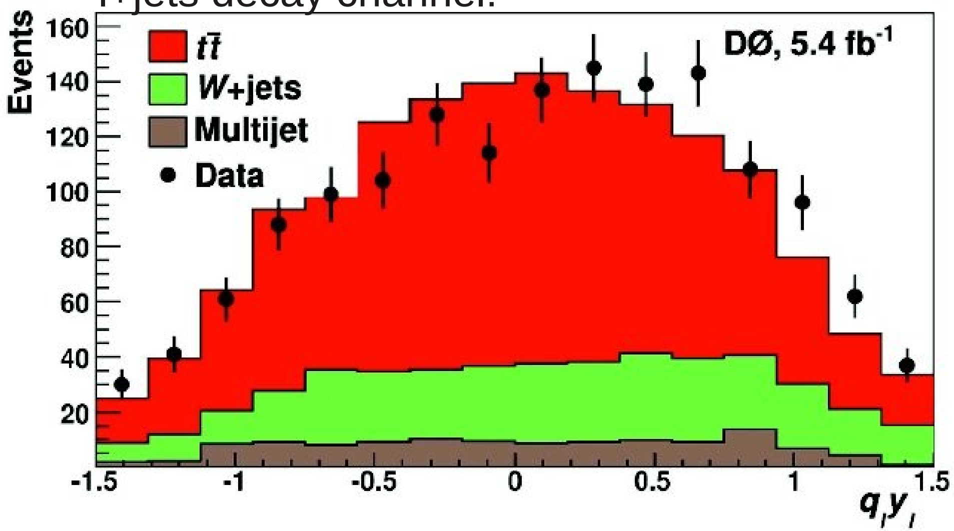
Phys. Rev. D 87, 011103(R) (2013)

Dilepton decay channel:



- Correct data by efficiency & acceptance: $A_{fb}^{l} = (5.8 \pm 5.3)\%$
- Measurement in l+jets: $A_{fb}^{l} = (15.2 \pm 4.0)\%$

l+jets decay channel:



- Combination:

$\boxed{A_{fb}^{l} = (11.8 \pm 3.2)\% \rightarrow 2.2\text{ s.d.}}$

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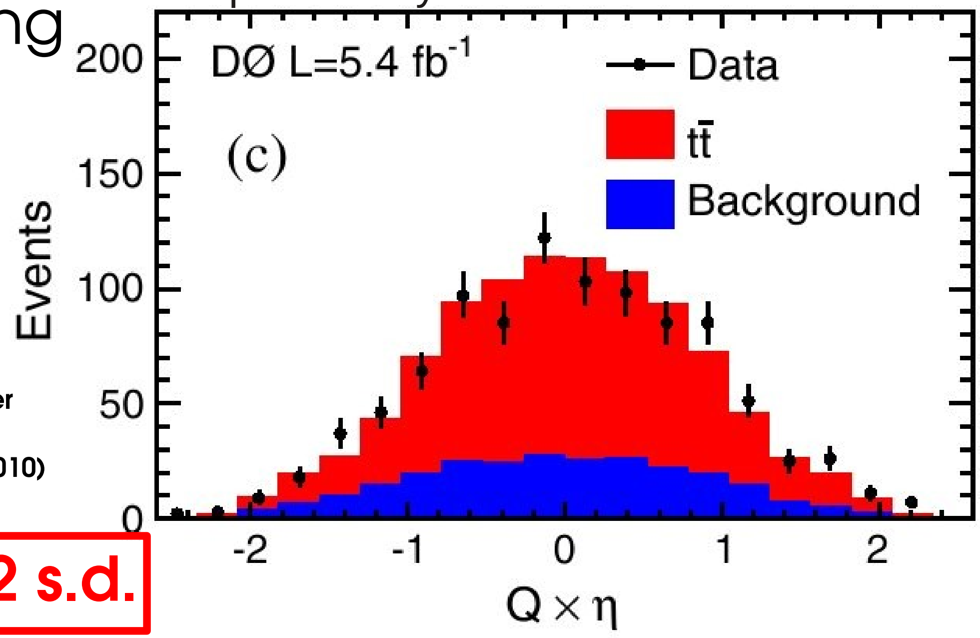
$$A^{\ell}_{\rm FB} = \frac{N_\ell(Q\cdot\eta>0) - N_\ell(Q\cdot\eta<0)}{N_\ell(Q\cdot\eta>0) + N_\ell(Q\cdot\eta<0)}$$

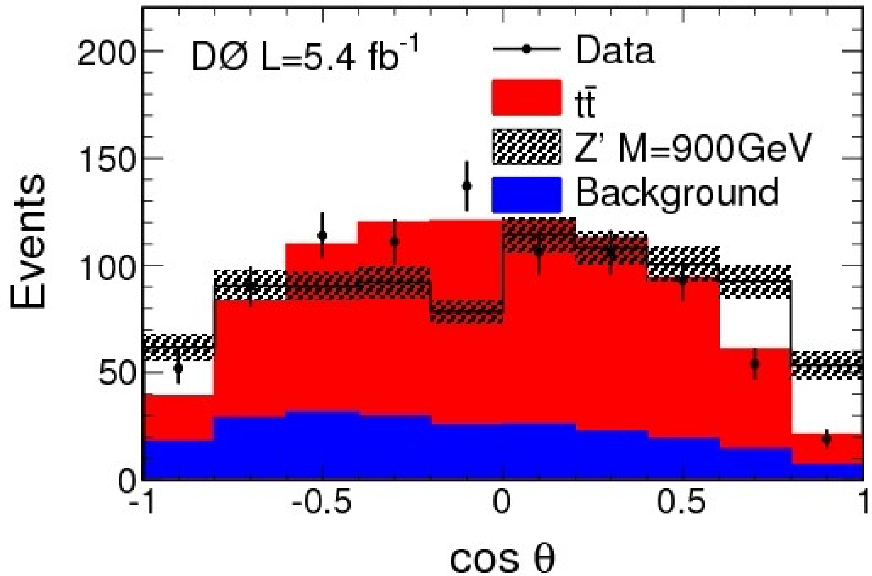
Theory: $A_{fb}^{l} = (4.7 \pm 0.1)\%$ MC@NLO + higher order QCD+EW corrections (Nucl.Phys. B837, 90 (2010)

- Combination: $\boxed{A_{fb}^{l} = (11.8 \pm 3.2)\% \rightarrow 2.2 \text{ s.d.}}$

Phys. Rev. D 87, 011103(R) (2013)

Dilepton decay channel:



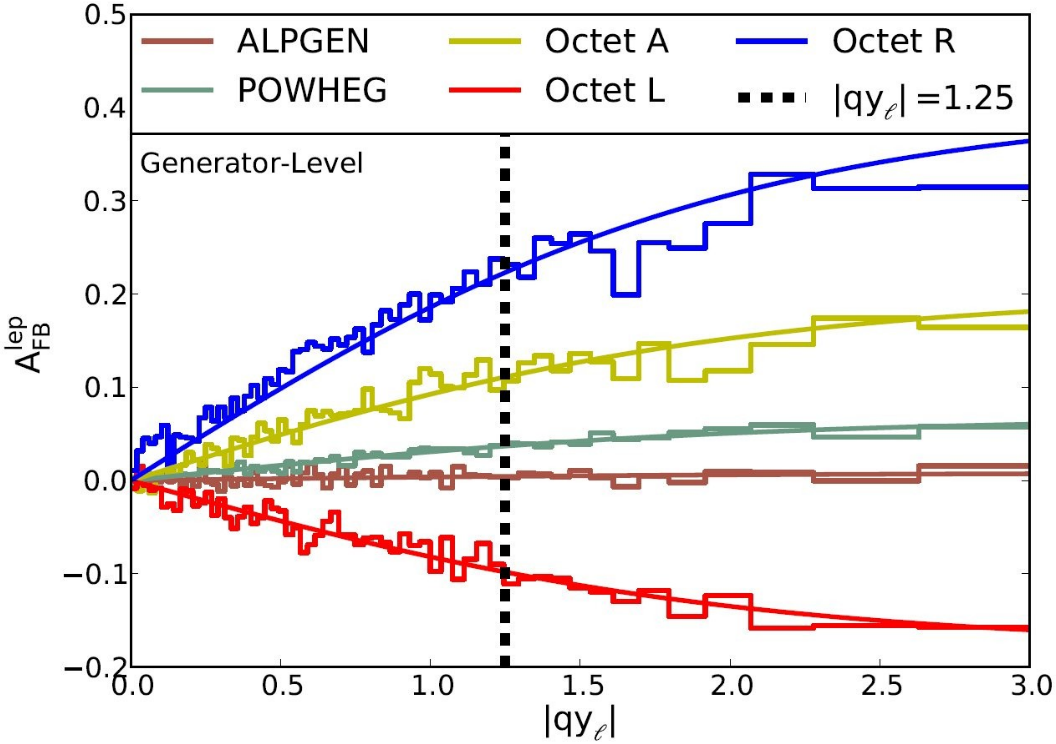


Orthogonal information by looking at the polarization: Described by SM

Lepton asymmetry (CDF)

- More information by **measuring A_{FB}^{lep} differentially** as a function of $|qy_{lep}|$
- New physics contributions with different slope

CDF note 10975

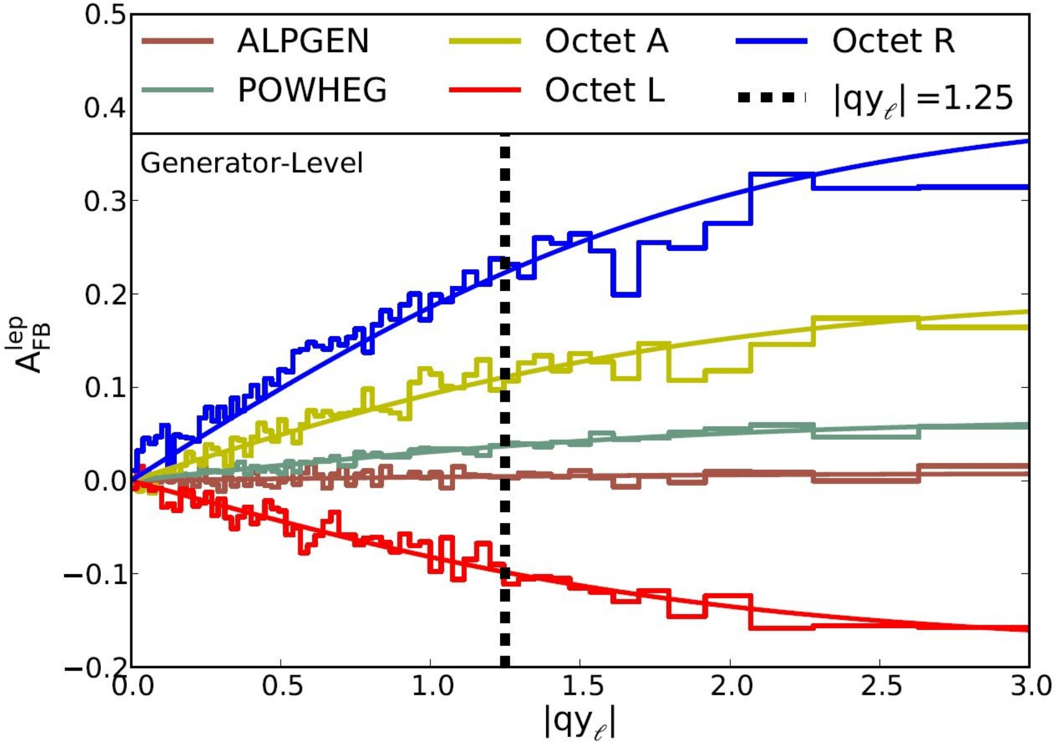


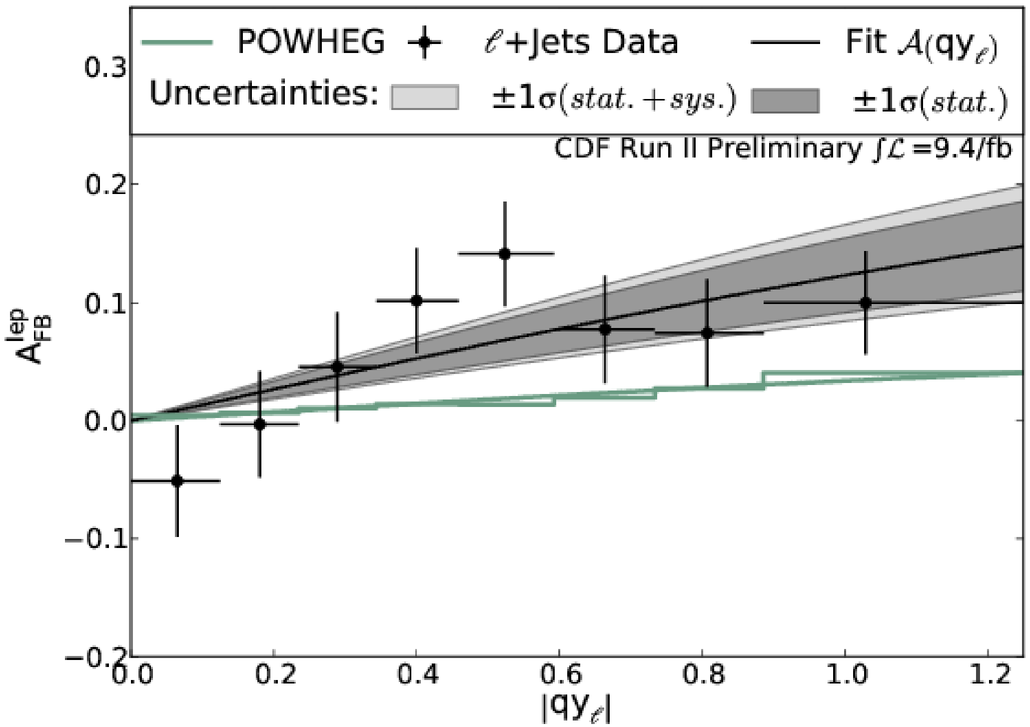
Lepton asymmetry (CDF)

- More information by **measuring A_{FB}^{lep} differentially** as a function of $|qy_{lep}|$
- New physics contributions with different slope

CDF note 10975

- Correct data by efficiency & acceptance: $\boxed{A_{fb}^{l}\ \text{parton} = (9.4 \pm^{3.2}_{2.9})\%}$





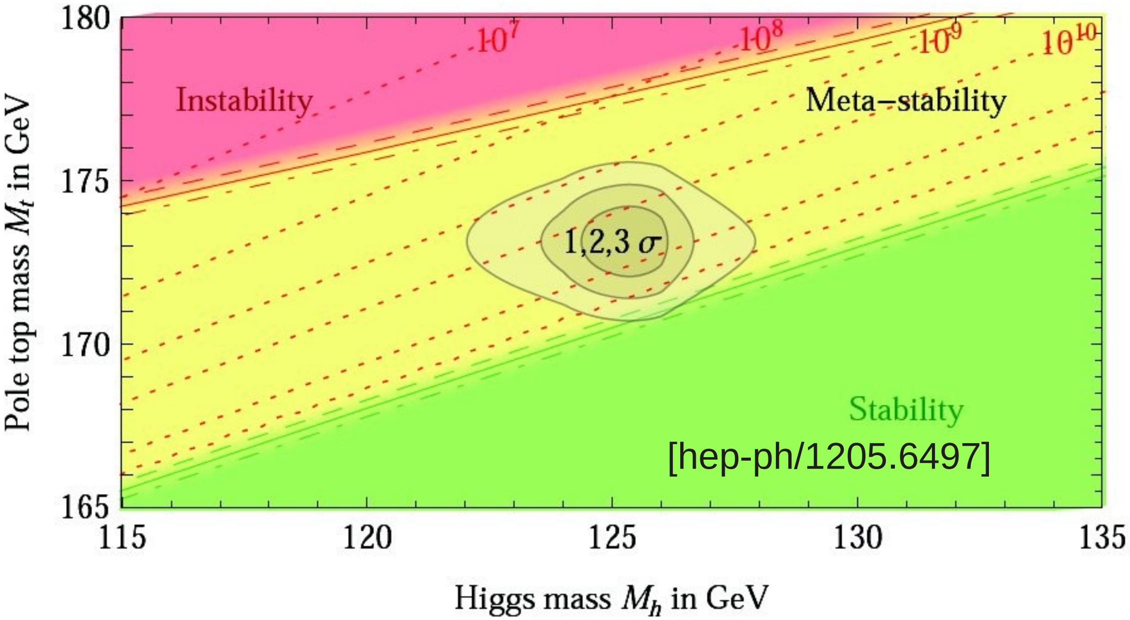
- Puzzling situation...
- STAY TUNED ! More updates to come very soon !

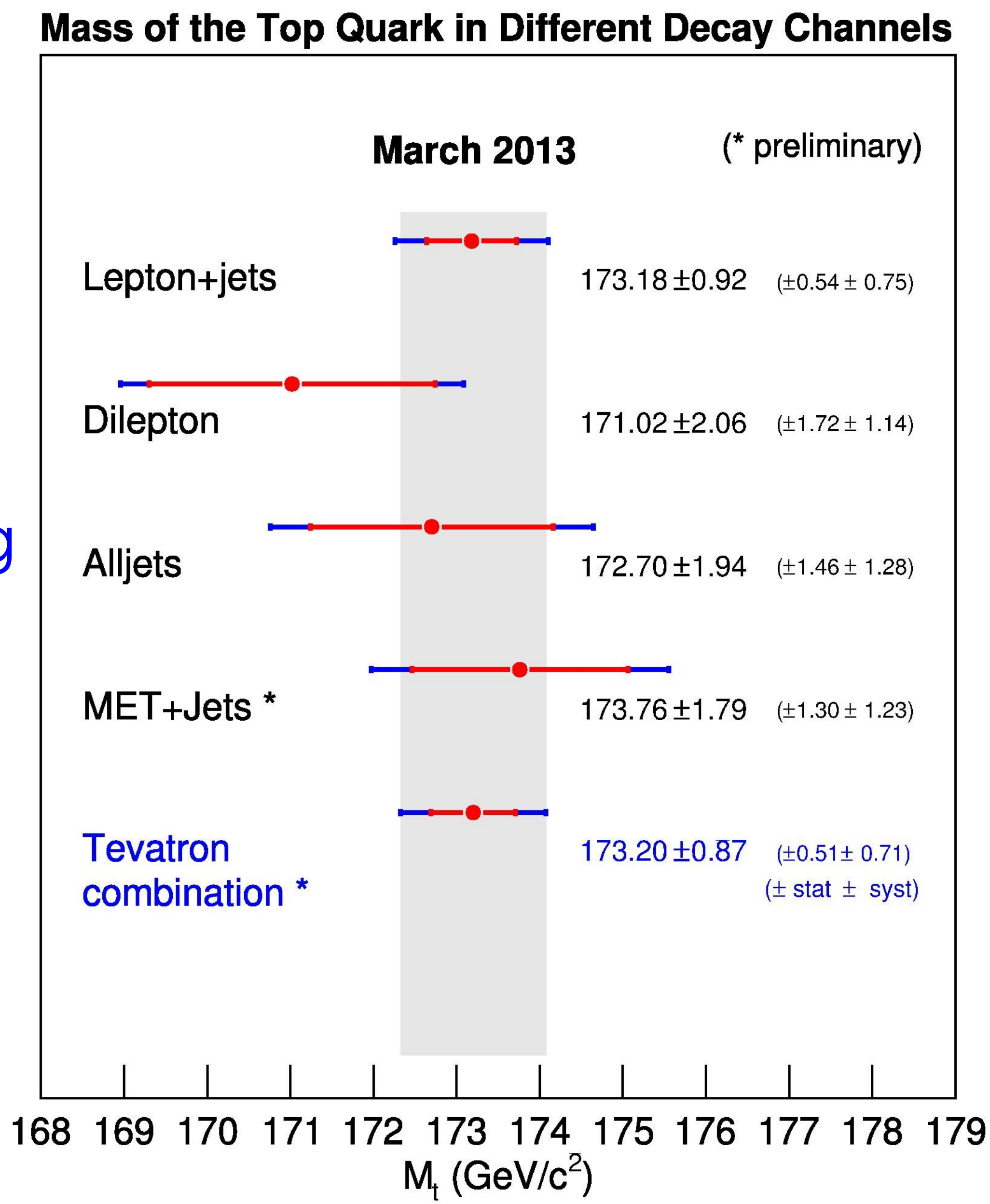
Mass (CDF, D0)

- Tevatron combination of 12 top quark mass measurements
- Worlds most precise top mass measurement:

  m_t = 173.20 ± 0.87 GeV/c^2
  (Precision of 0.5% !)

- Further improvements & results using full data set to come in near future !





Tevatron [arXiv:1305.3929]

Summary & Conclusion

- Presented recent results from the Tevatron (excluding Higgs):
  - **Unique data set** at $\sqrt{s}=1.96$ TeV of $p\bar{p}$ data
  - Tevatron experiments with innovative & unique results !
  - Building up the **legacy of the Tevatron**:
    → **High precision m_W and m_t measurements**
  - Still significant results not yet with final data set

D0 Physics Results   CDF Physics Results

Outlook:

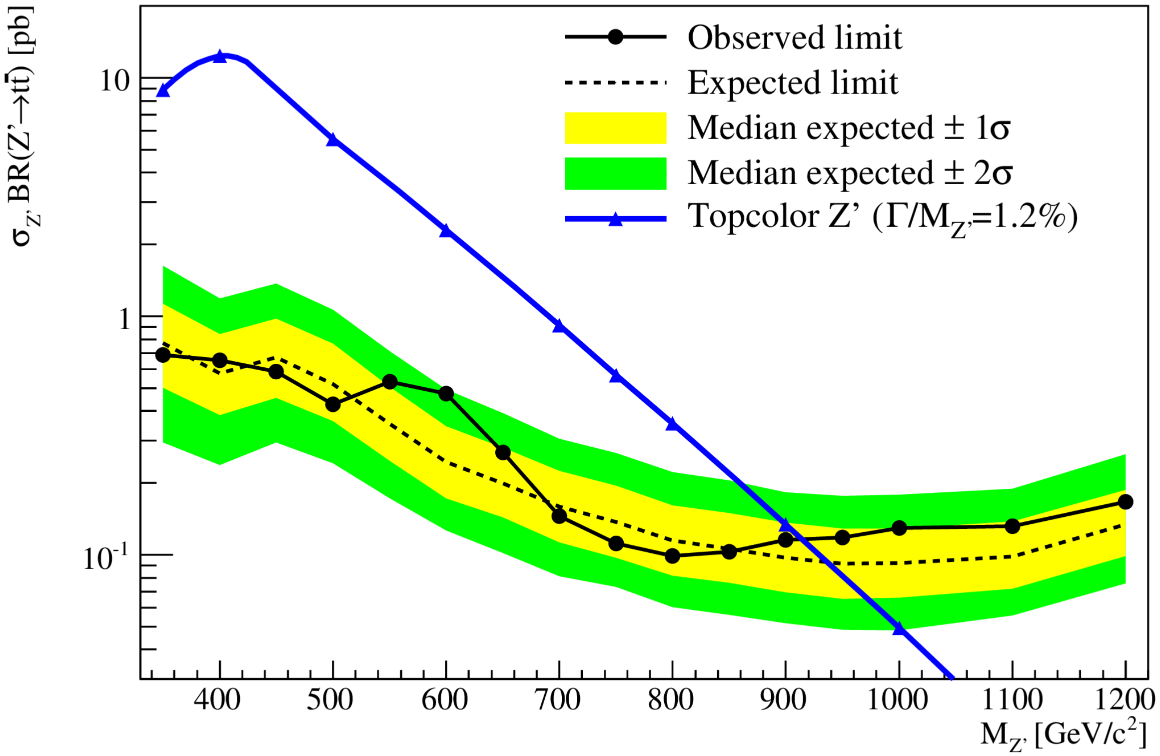
- Concentrate on results which are **competitive or complementary** to LHC
- Anomalies in top A_{FB}, heavy flavor CP violation

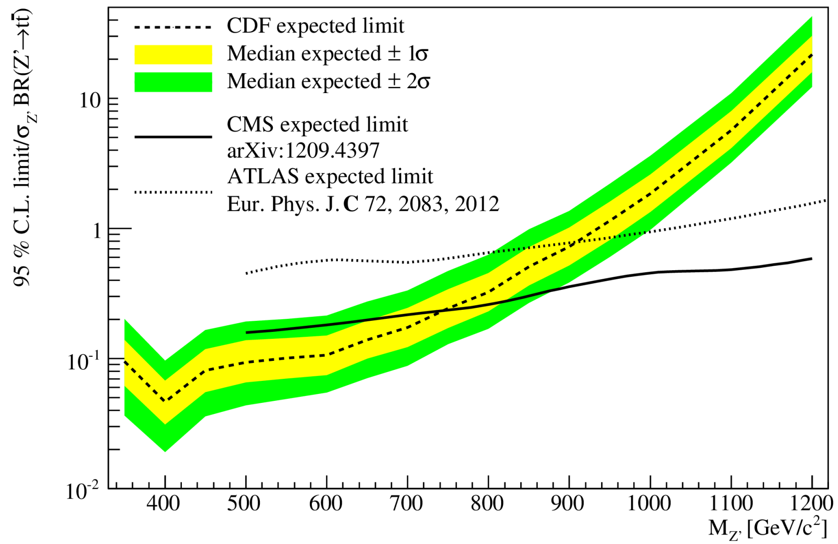
Backup

Search for Z' (CDF)

- Top Forward-backward asymmetry can be explained by a Z'
- Limit on leptophobic Z' > 915 GeV
- Tevatron more sensitive at low masses

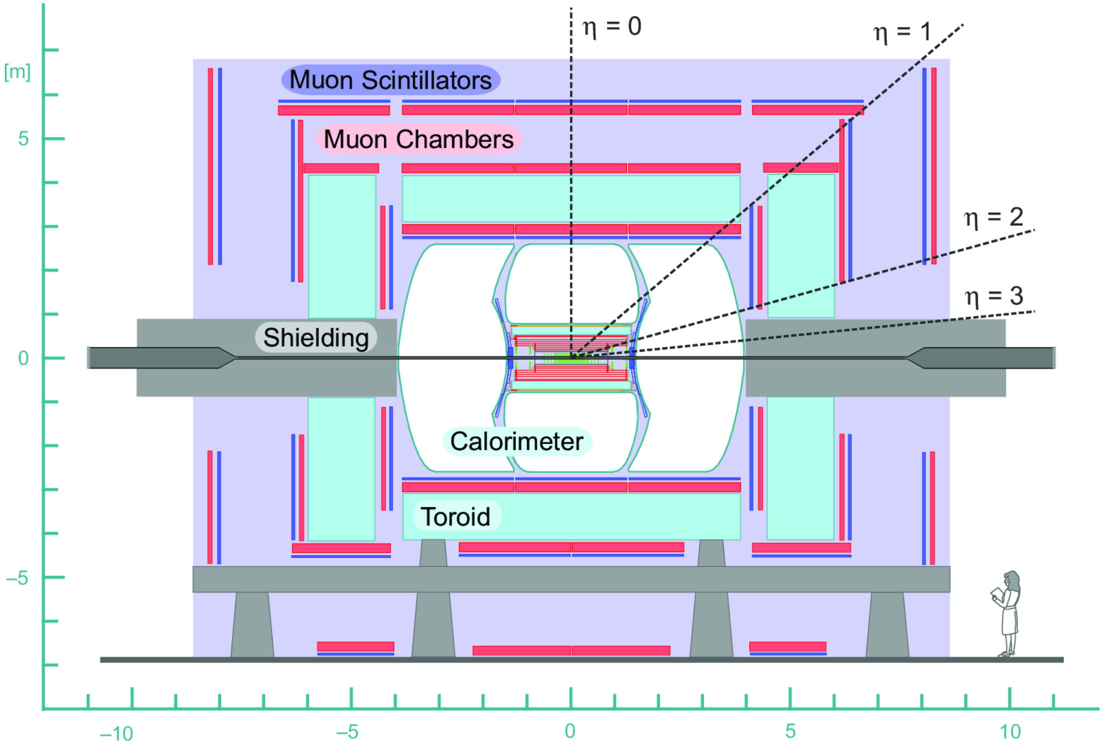
CDF note

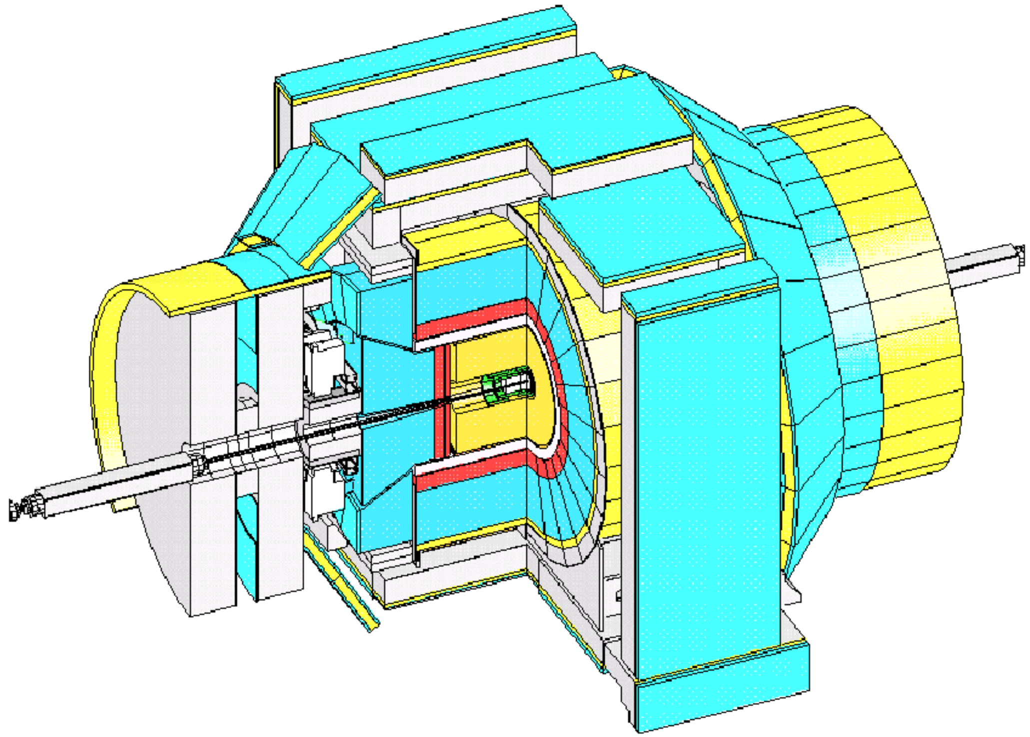




General purpose 4π detectors:

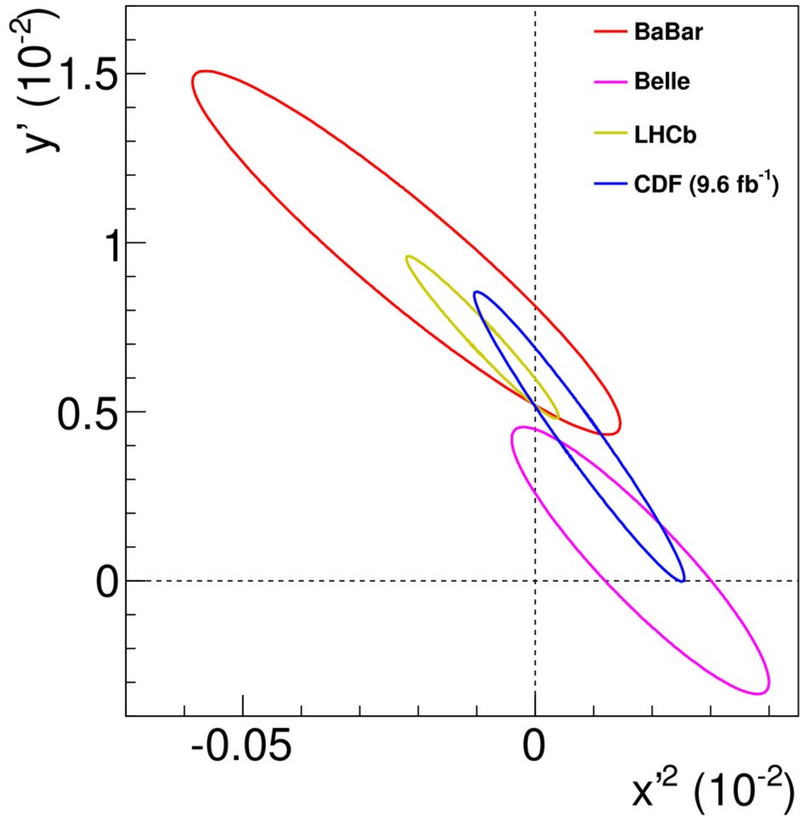
- **Tracker**: Detection and momentum measurement for charged particles
- **Calorimeter**: Identification and energy measurement of jets and electrons
- **Muon system**: Identification and momentum measurement of muons





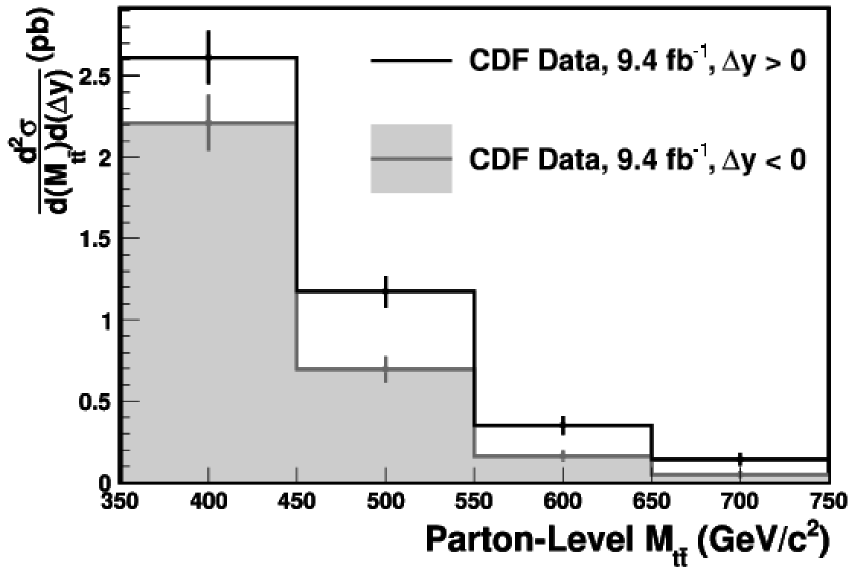
- Similar calorimeter and tracker coverages
- Detectors are of comparable strength in Tevatron Run II

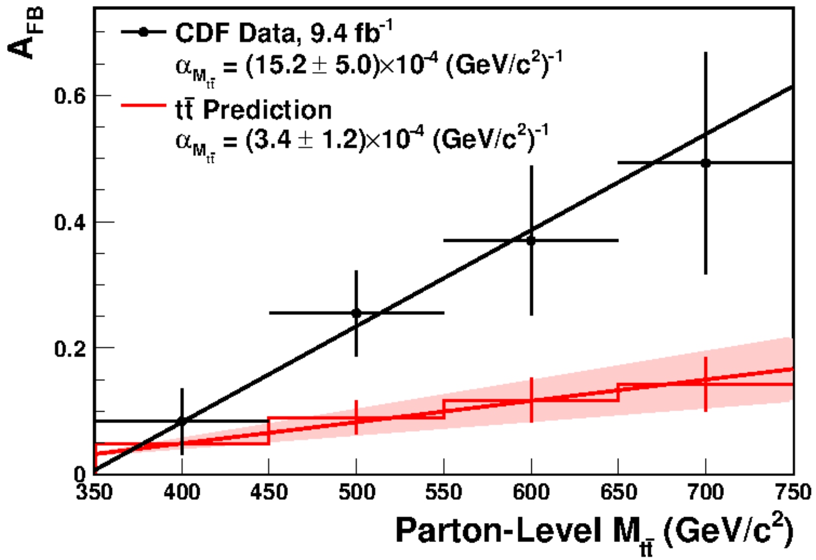
Additional plots



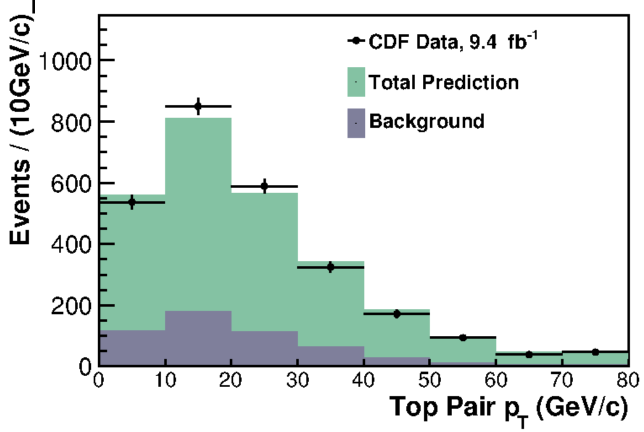
Top – Asymmetries

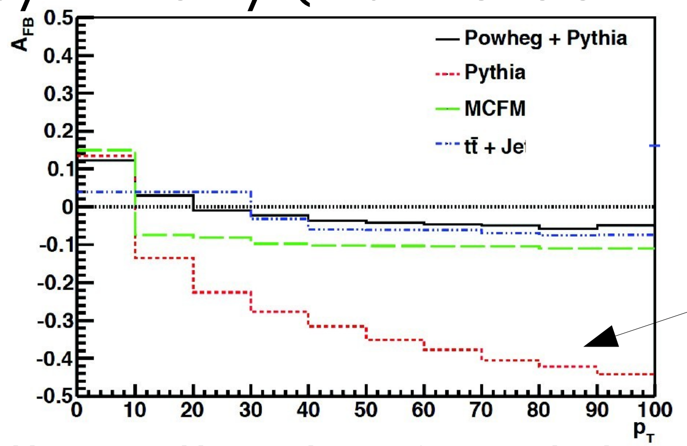
- Kinematic dependencies (double-differential cross sections)





- Slope is 2.5 s.d. away from prediction
- $p_T(t\bar{t})$ dependence of asymmetry (first noted in D0 analysis)



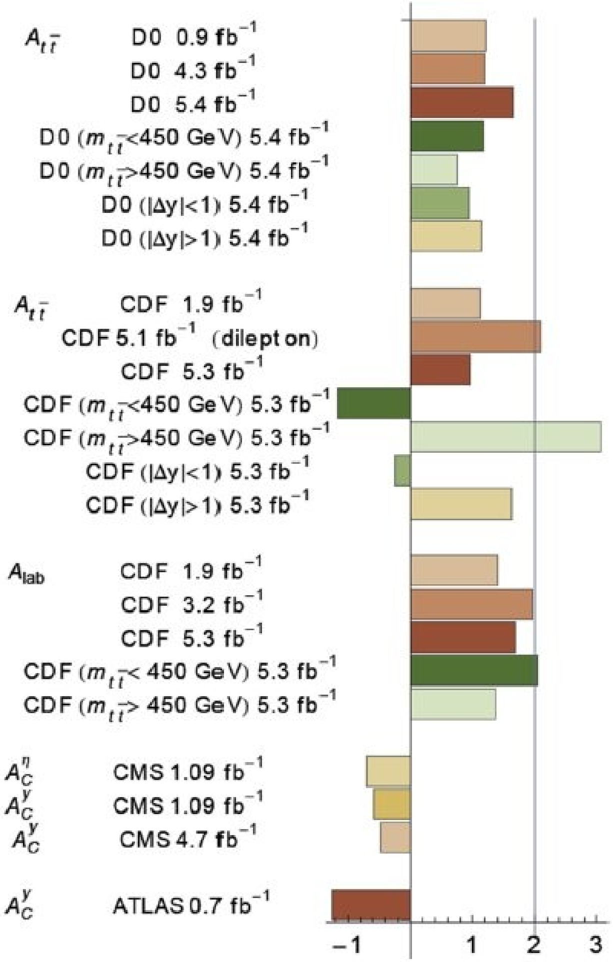


→ Strong dependence in case of Pythia
→ NLO QCD smaller

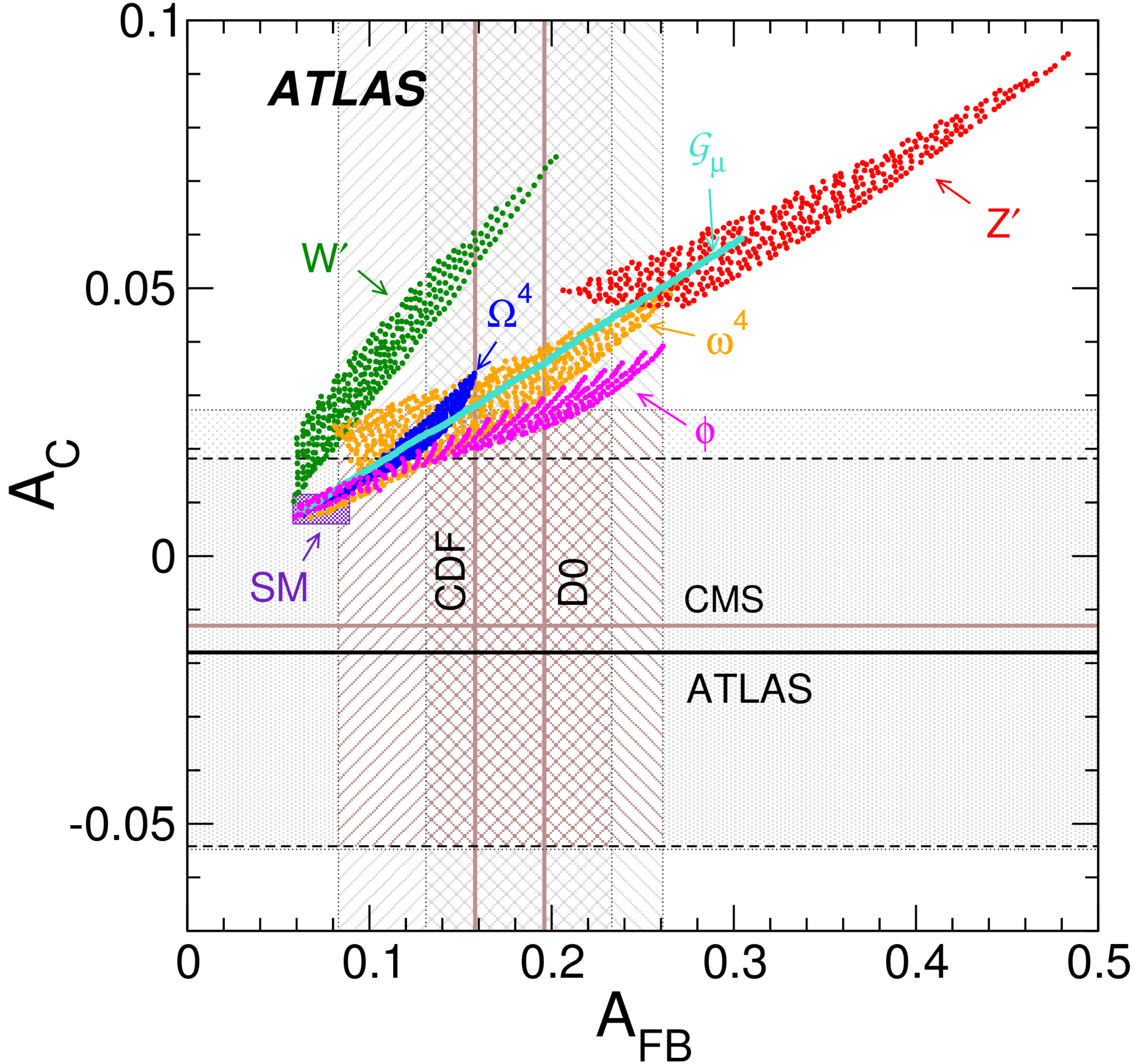
- Remains a puzzling situation, still lots of work to do...

Top – Asymmetries

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



Taken from G. Rodrigo (Moriond EW)



Top mass: template

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

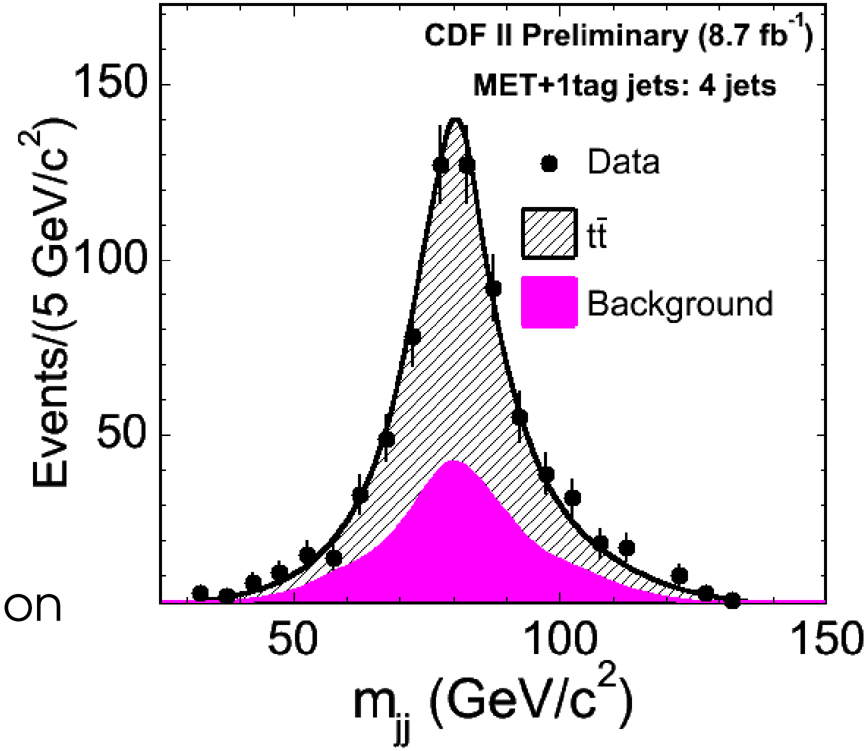
$$\chi^2 = \sum_{i=4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_T^{UE,meas})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b,missing} - M_t^{\mathrm{reco}})^2}{\Gamma_t^2} + \frac{(M_{bjj} - M_t^{\mathrm{reco}})^2}{\Gamma_t^2}$$

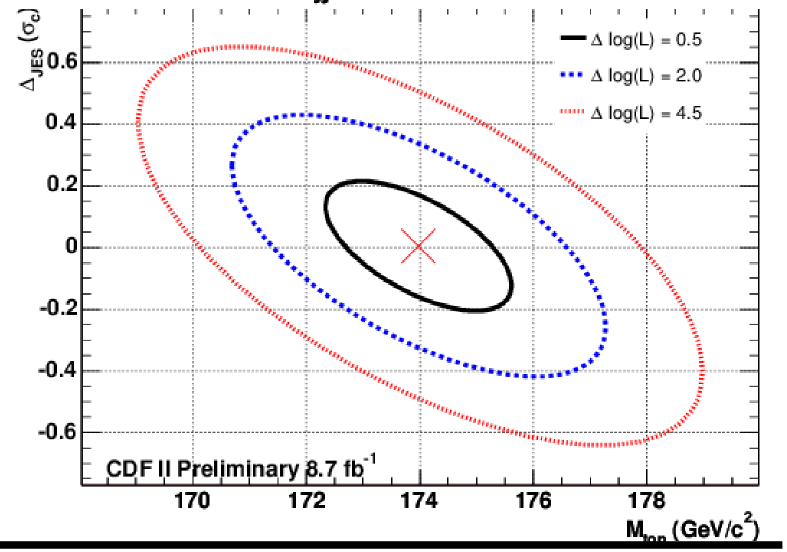
'wrong' combination

- 3D template fit of m_{jj}^{reco}, m_t^{reco1}, m_t^{reco2}
- <u>Largest uncertainties:</u>
  - 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% !



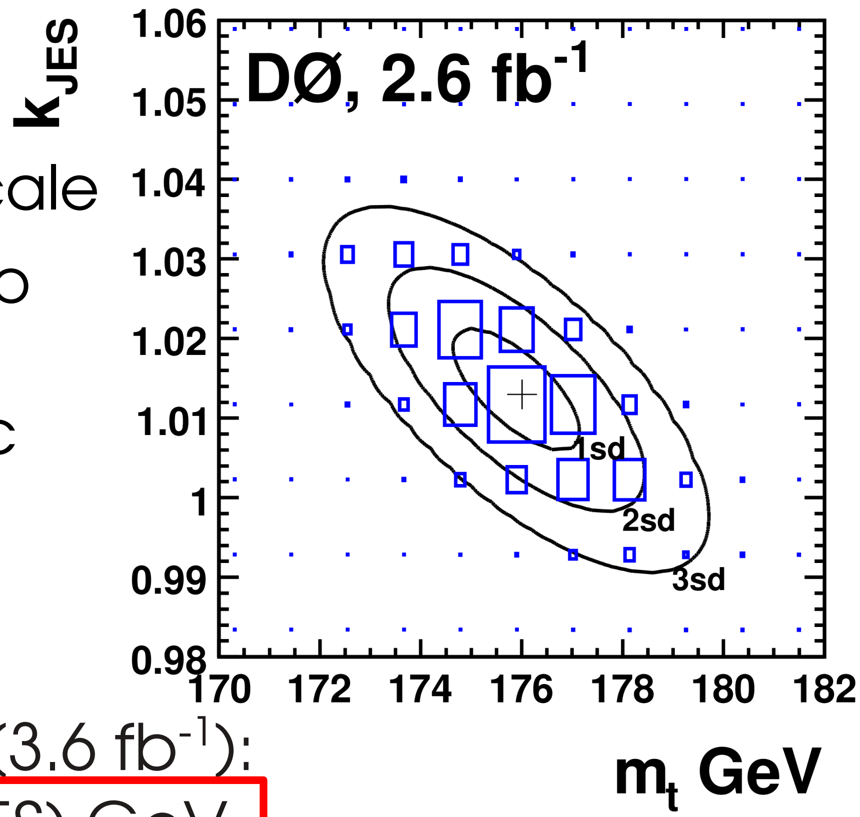


DØ Top mass: ME method

- 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

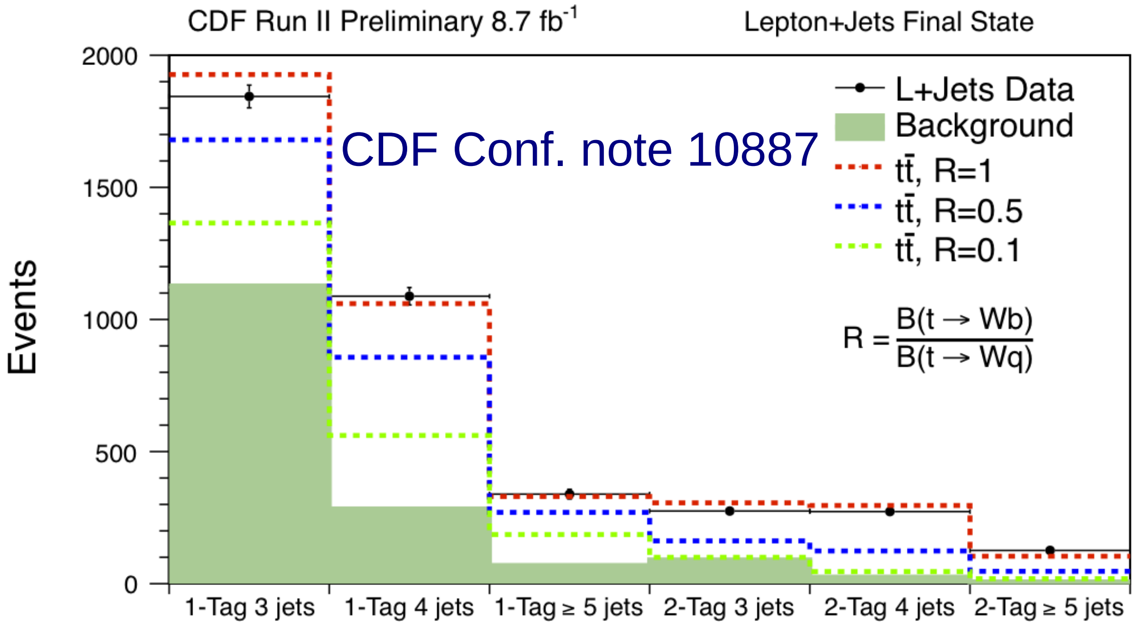


→ Most precise DØ mass measurement (3.6 fb^{-1}):

$\boxed{m_t = 174.9 \pm 0.8 \text{ (stat.)} \pm 1.2 \text{ (sys.+JES) GeV}}$

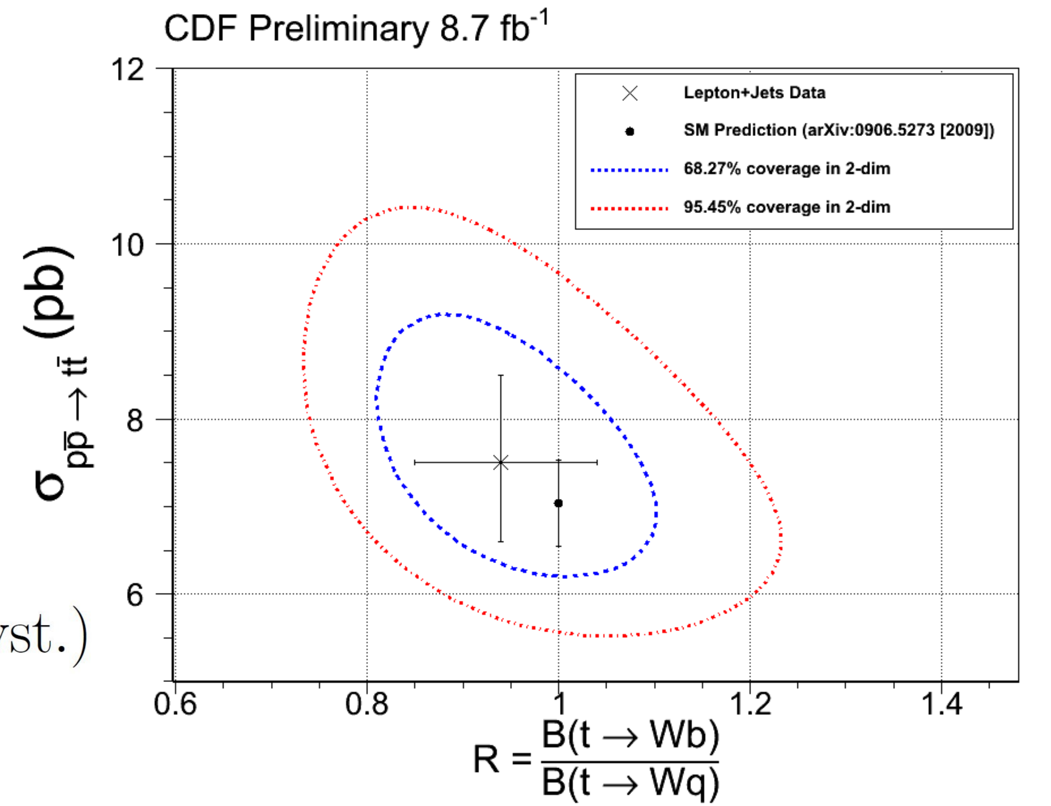
Precision of 0.9% !

Measurement of R



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

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



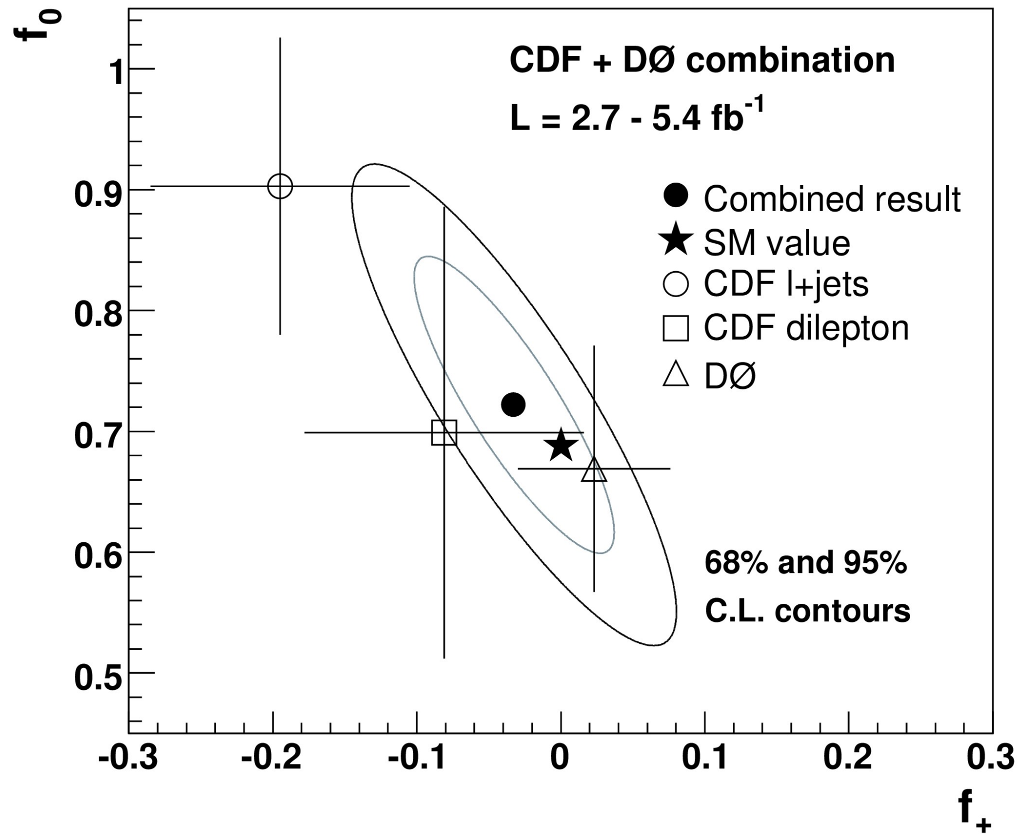
	Value (stat+syst)
$\sigma_{p\bar{p}\to t\bar{t}}$ (pb)	7.5 ± 1.0
R	0.94 ± 0.09
$\lvert V_{tb} \rvert$	0.97 ± 0.05

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

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

W helicity

- Direct test of the "V – A" nature of weak interaction
- Use matrix element approach for W helicity measurement



→ Result consistent with SM:

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

$f_0 = 0.683 \pm 0.042$ (stat) ± 0.040 (syst)
$f_+ = -0.025 \pm 0.024$ (stat) ± 0.040 (syst)
other fixed to SM