Legacy Top Quark Properties With Full Tevatron Data Set

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for the D0 collaboration

Joint Experimental-Theoretical Physics Seminar
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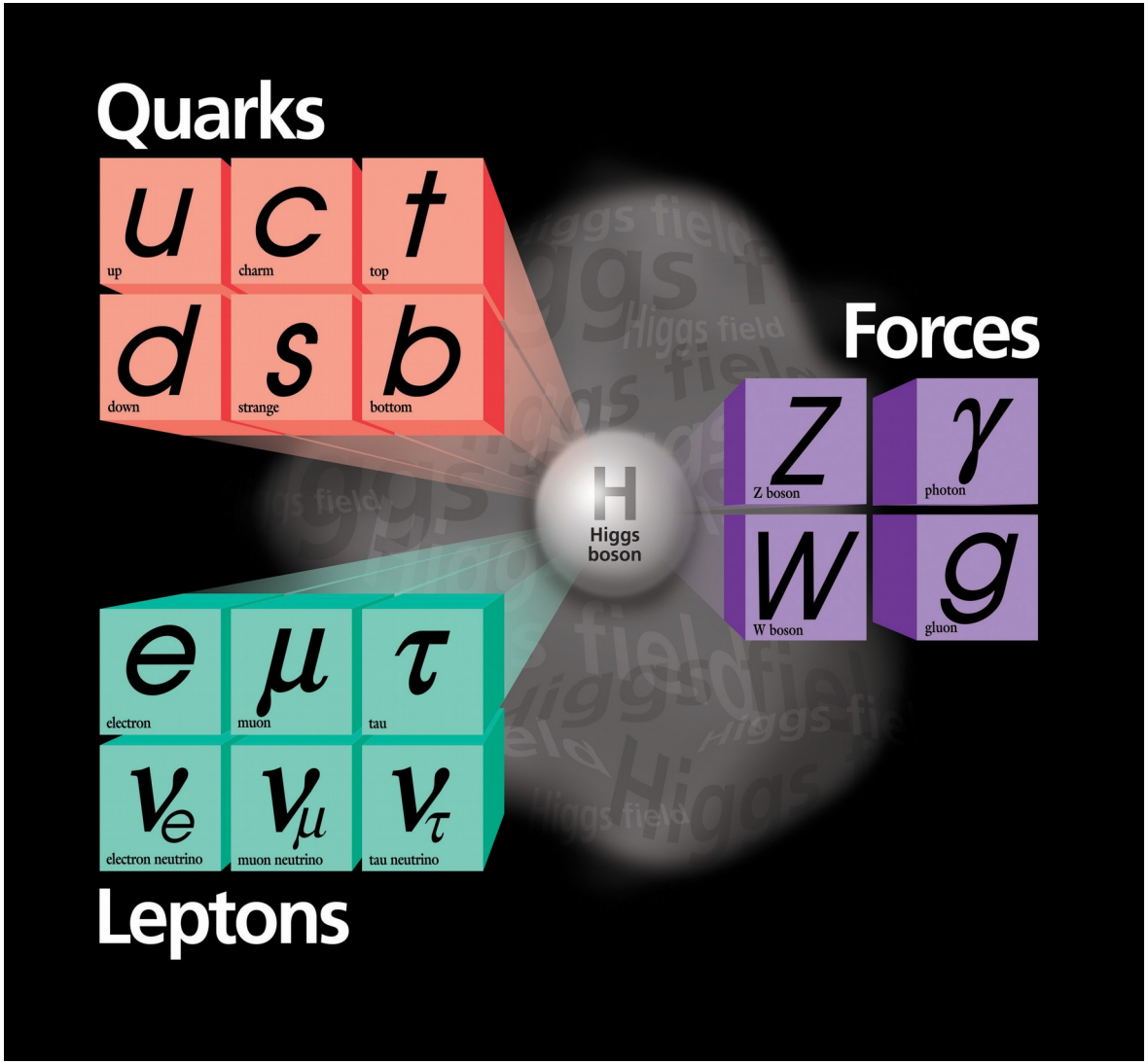
Content

- Top quark mass.
  - Direct measurements and combinations.
  - Top quark pole mass measurement.
- Spin correlation.
- Polarization.
- $t\bar{t}$ asymmetry Tevatron combination.

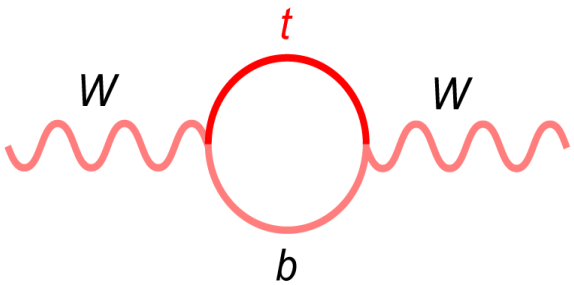
Introduction

- Top is the heaviest particle of the SM.
- Very fast decay, ~$5 \cdot 10^{-25}$s, before hadronization → bare quark measurements.
- Top quark coupling to the Higgs boson close to unity → special role in the electroweak symmetry breaking mechanism?
- Good candidate to search for the new physics.

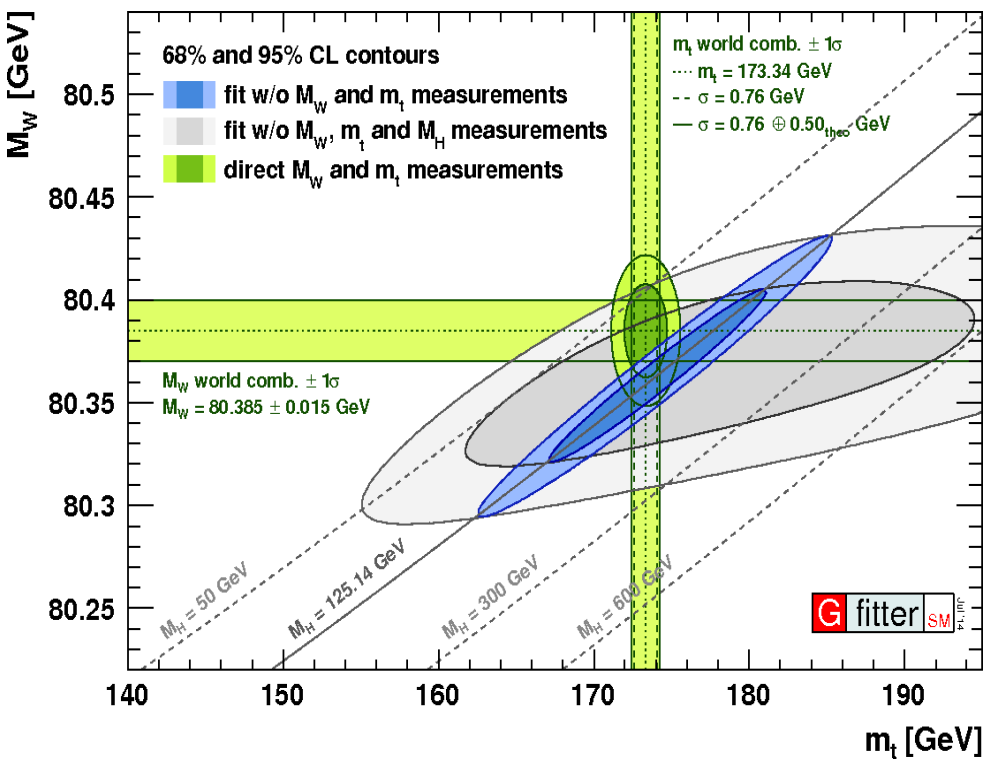


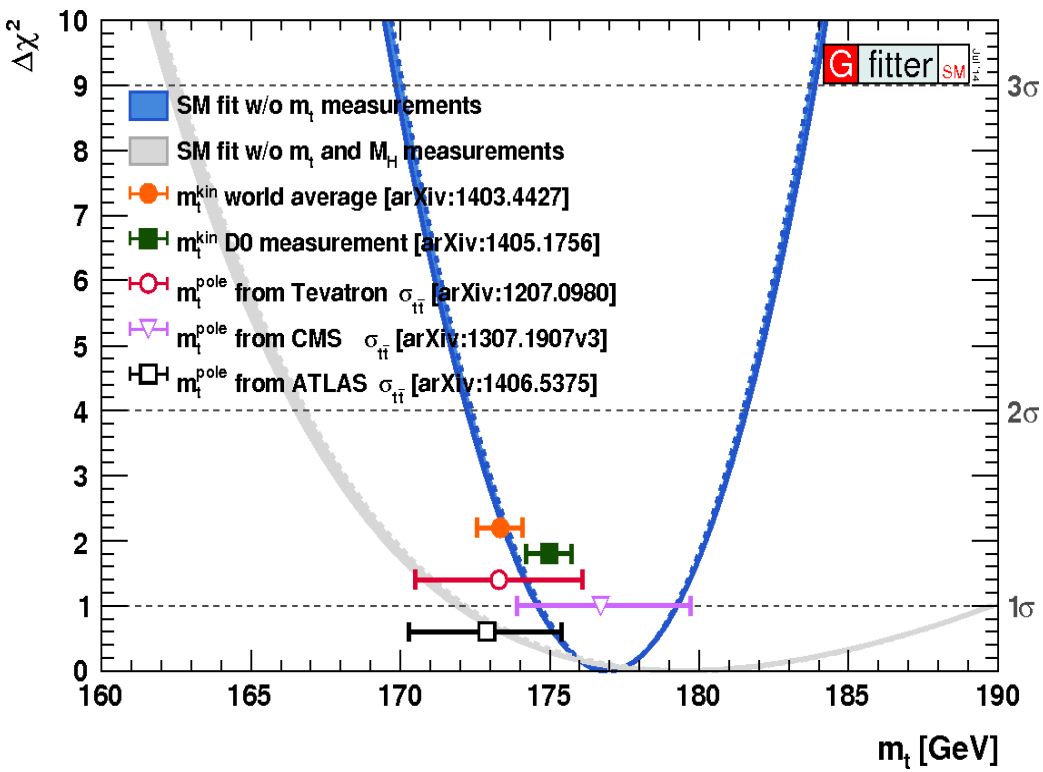
Precision measurements → SM cross-check

- Bare quark mass measurements → precise calculation of the W mass correction



$$M_W^2 = M_Z^2 \left\{ \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2}G_\mu M_Z^2}\left[1 + \Delta r(M_W, M_Z, M_H, m_t, \ldots)\right]} \right\}$$





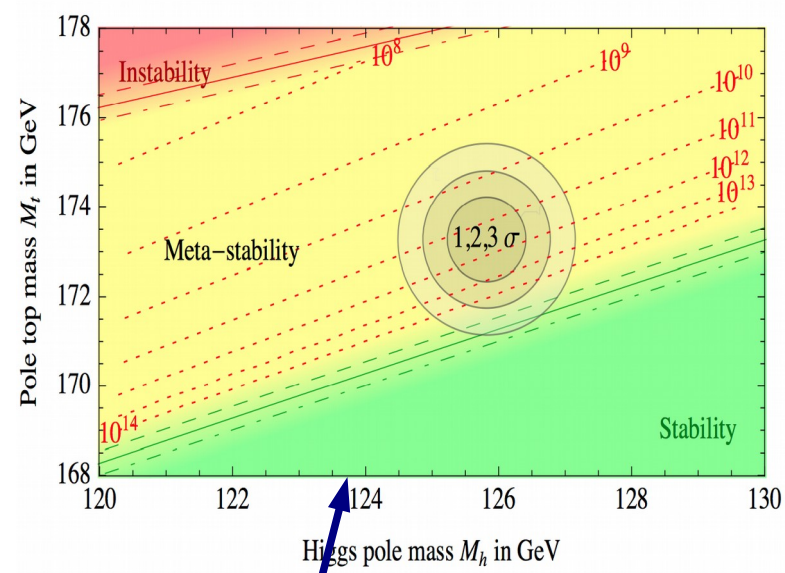
Another SM cross-check: EW vacuum stability

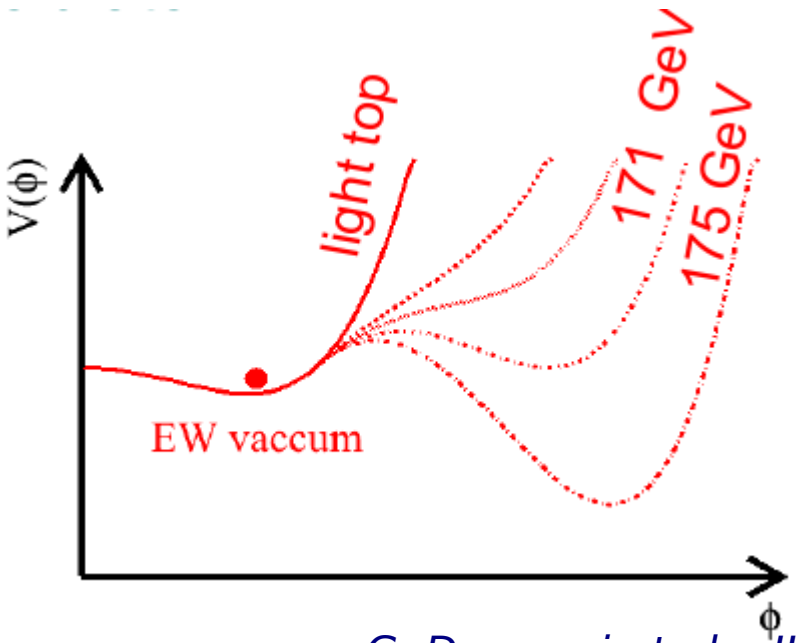
- SM scalar potential: $V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$

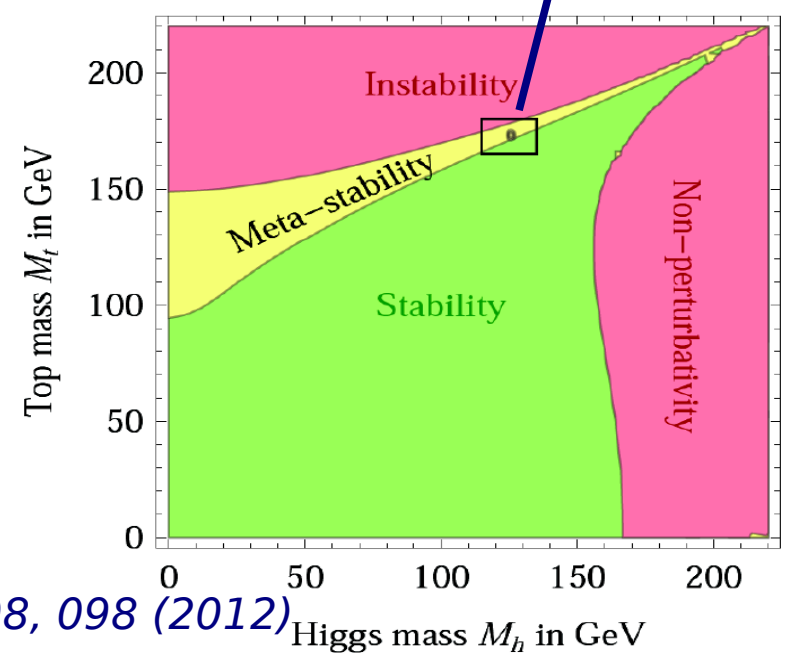
- Higgs quartic coupling corrections depends mainly on the top quark mass

$$\lambda(\mu) = \frac{G_\mu M_H^2}{\sqrt{2}} + \Delta\lambda(\mu)$$

renormalization scale

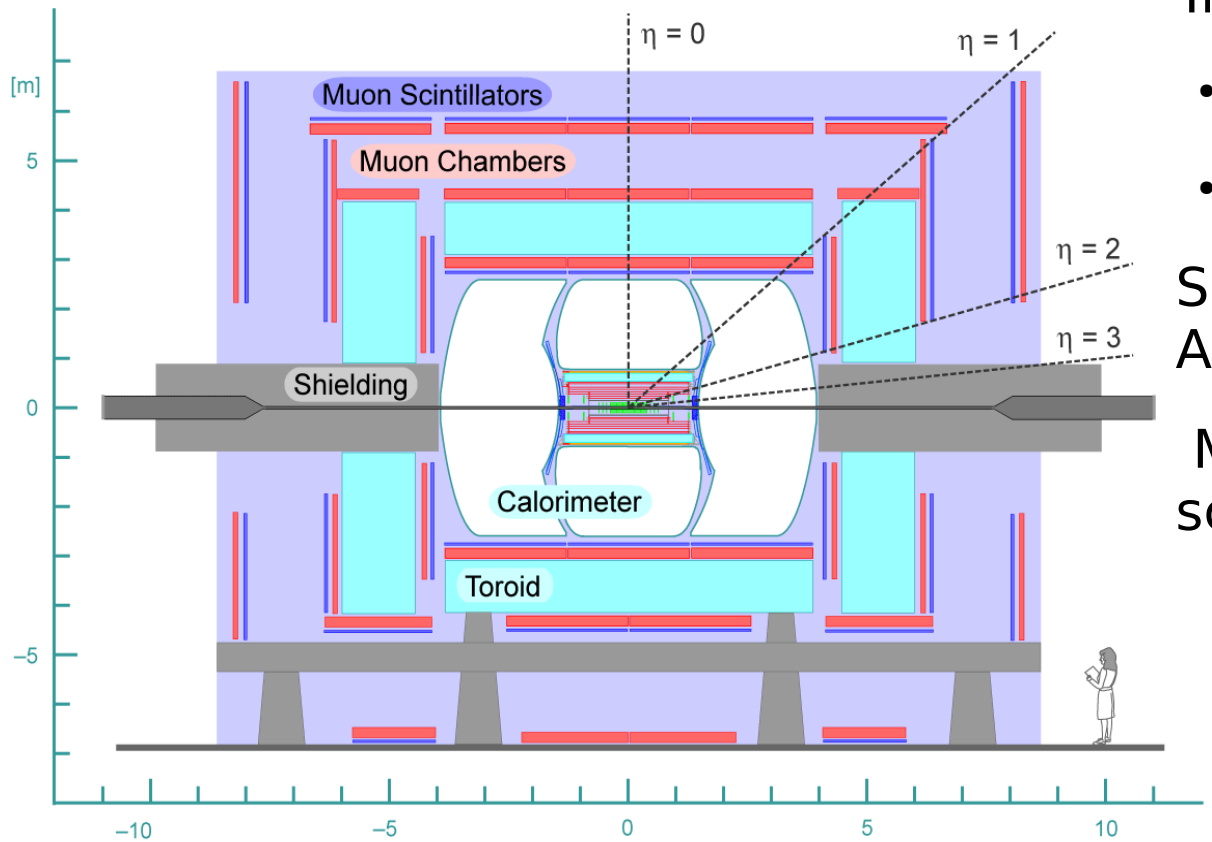






G. Degrassi et al., JHEP 1208, 098 (2012)

D0 Detector

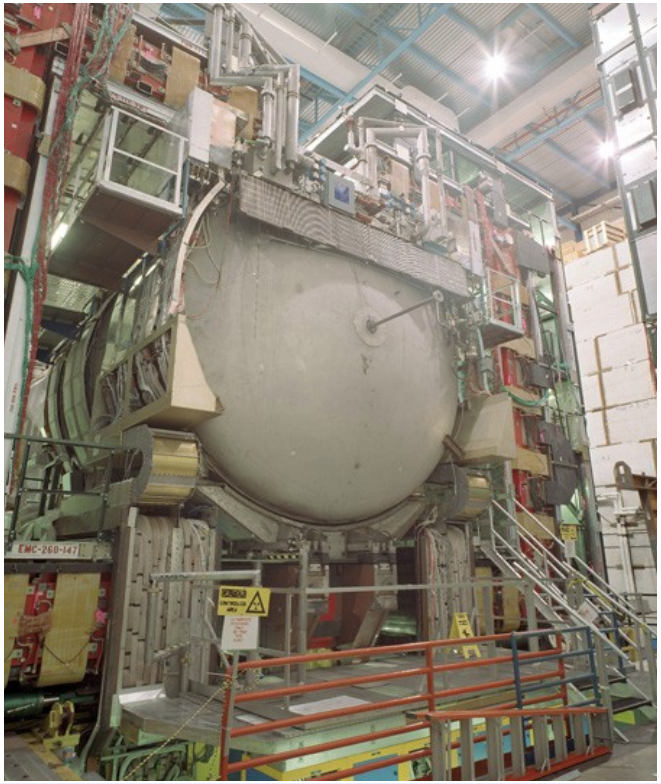


Tracking with 2 Tesla solenoid

- Silicon tracker (|η|<3.0, r~10cm)
- Fiber tracker (|η|<1.7, r~50 cm)

Sampling Calorimeter with liquid Ar / Uranium

Muons: drift chambers + scintillators

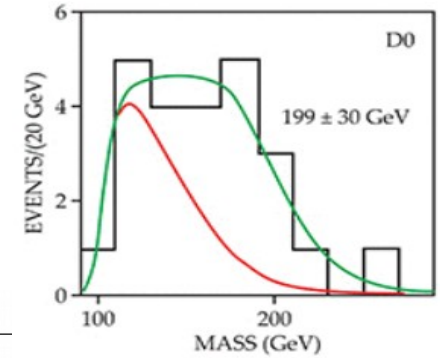


Typical Coverage

- Muons: |η| < 2
- Electrons: |η|<1.1 and 1.5<|η|<2.5
- Jets: |η|< 2.5

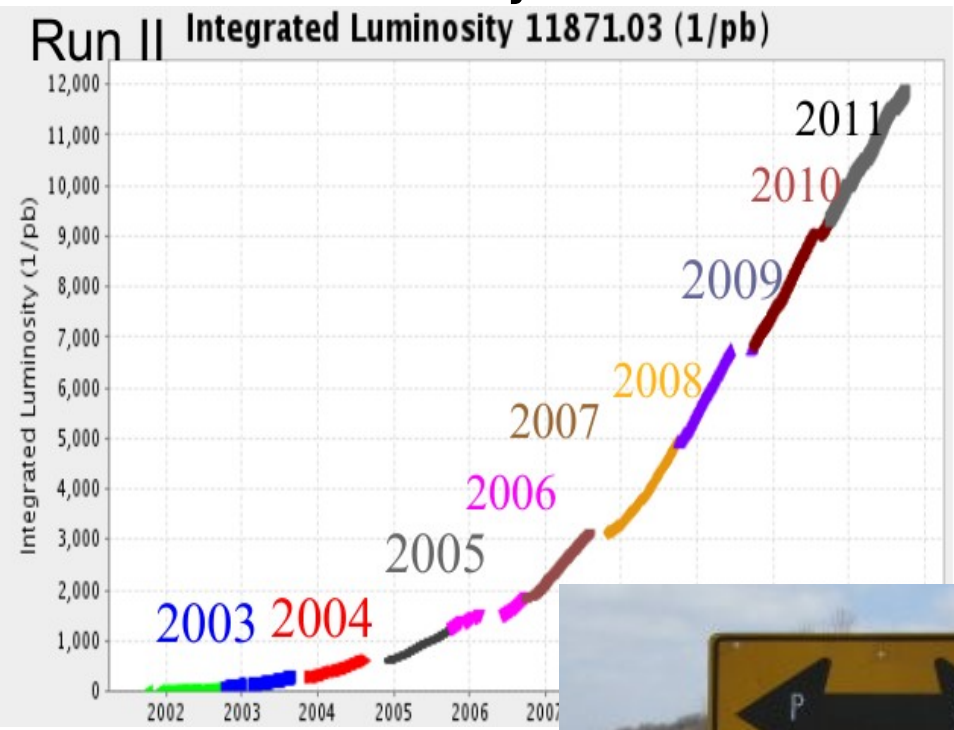
Data Set

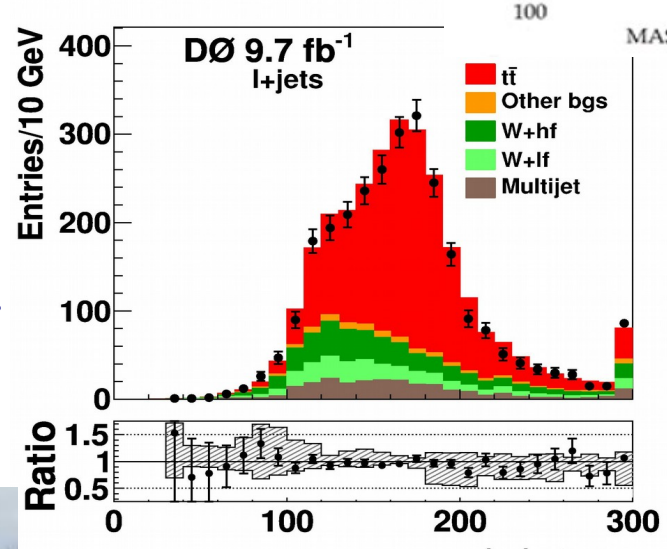
Top quark discovery:
Tevatron Run I (1995)

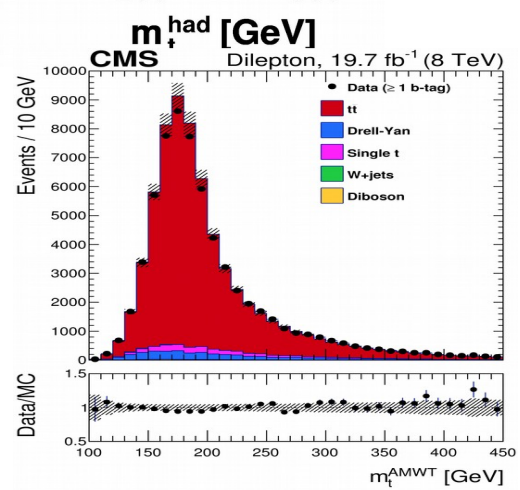


Tevatron Run II data taking (2001-2011):

- ~12 fb^{-1} delivered per experiment
- ~9.7 fb^{-1} for analysis

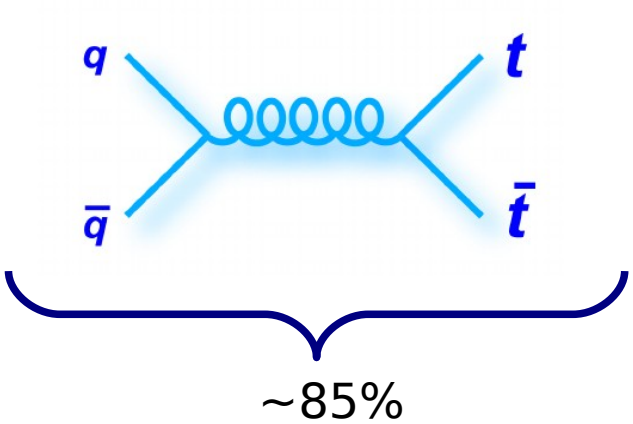


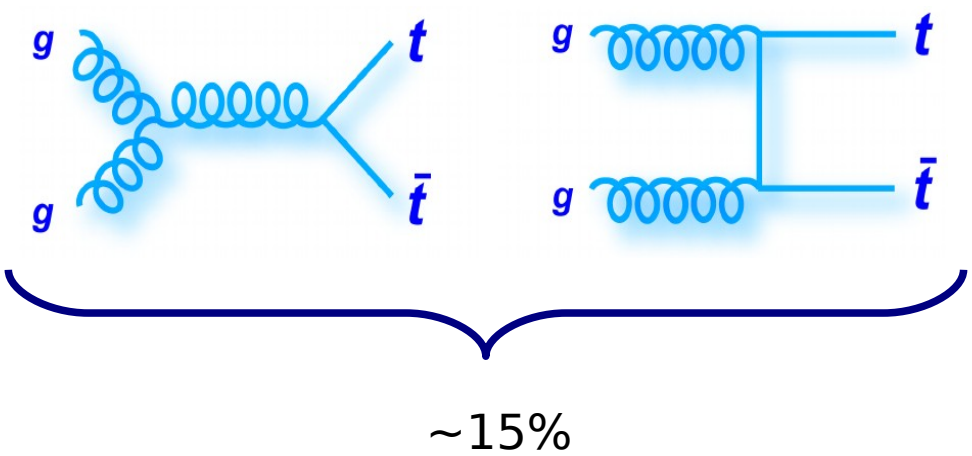




- $p\bar{p}$ collisions
- $\sqrt{s} = 1.96$ TeV

Top Quark Production





LHC
Gluon fusion: 80 – 90%
Quark annihil: 20 – 10%

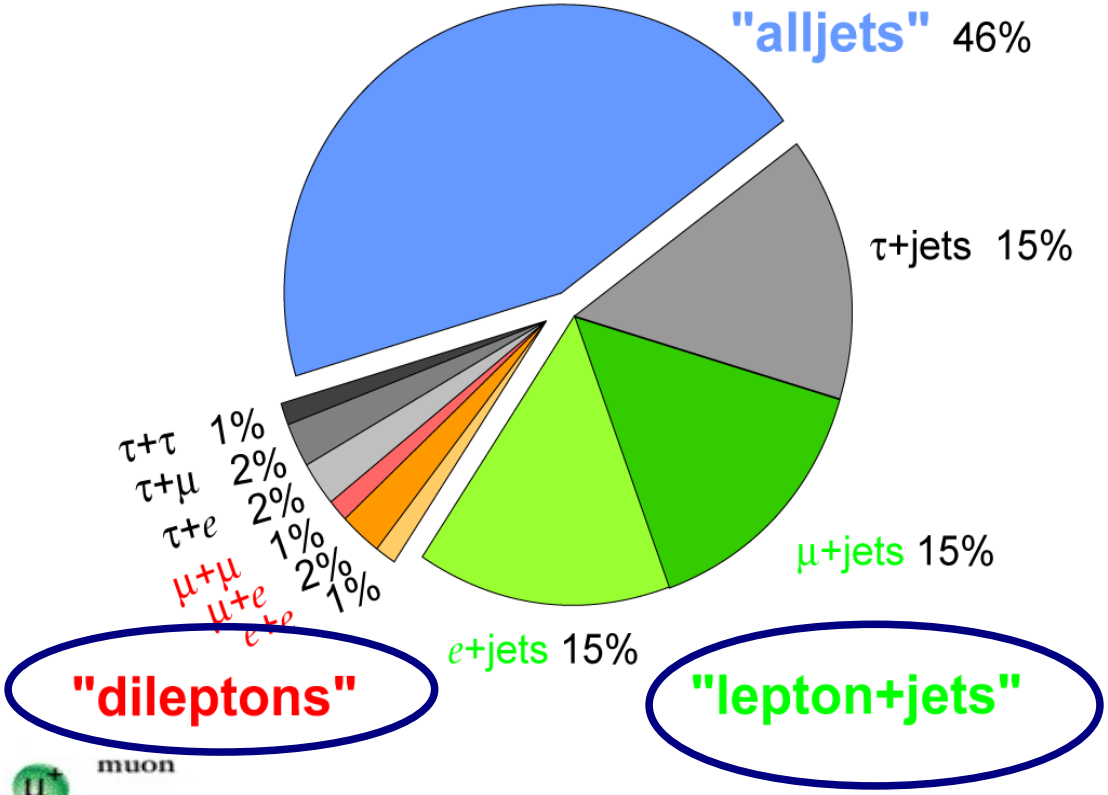
- At the Tevatron top mostly produced in pairs
  - We will not discuss the EW, single-top production today
- Mostly the $q\bar{q}$ annihilation → a unique data set for the top quark studies.
- Cross-section (NNLO +NNLL QCD for $m_t = 172.5\ \mathrm{GeV}$):

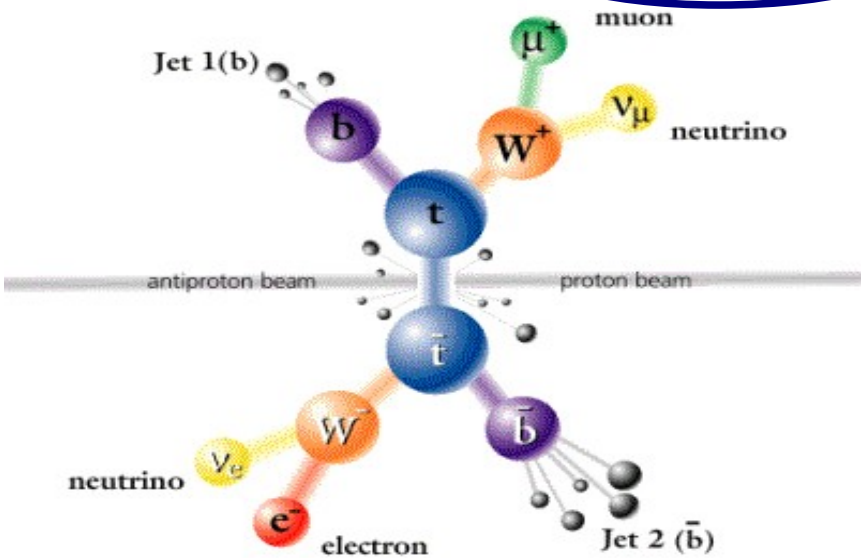
$$\sigma_{t\bar{t}} = 7.35^{+0.23}_{-0.27}\ \mathrm{pb}$$

Czakon,Fiedler and Mitov, PRL **110** (2013) 252004
Czakon and Mitov, Comput. Phys. Commun. **185** (2014) 2930

Top Pair Production Signatures

- Top decays into Wb (99.8%).
  - W→ eν or μν or τν or jets.
- $t\bar{t}$ event signature:
  - high momenta leptons and jets
  - large angular separation
  - Significant missing transverse momentum
  - Use b-quark jets identification to improve selection purity





Typical Event Selections

Lepton + Jets

- Trigger: single lepton and lepton+jets
- Isolated electron or muon
  - $p_T > 20$ GeV
  - $|\eta(\mu)| < 2.0$, $|\eta(e)| < 1.1$
- At least 3 jets pT>20 GeV
- Missing transverse momentum > 20 GeV
- Additional selections:
  - Use of the b-jet identification
  - Event kinematic selections

Dileptons

- Trigger: dileptons
- Two isolated leptons (electrons and/or muons)
  - $p_T > 15$ GeV
  - $|\eta(\mu)| < 2.0$
  - $|\eta(e)| < 1.1$ and $1.5<|\eta(e)| <2.5$
- At least 2 jets pT>20 GeV
- Missing transverse momentum > 20 GeV
- Additional selections:
  - Use of the b-jet identification
  - Event kinematic selections

Signal vs Background

- $t\bar{t}$ simulation: Alpgen + Pythia (parton showering + hadronization)
  - Systematic uncertainty studies: MC@NLO+ Herwig, different Pythia versions
- Acceptance 10-20% (4 – 6 reconstructed objects in the final state)

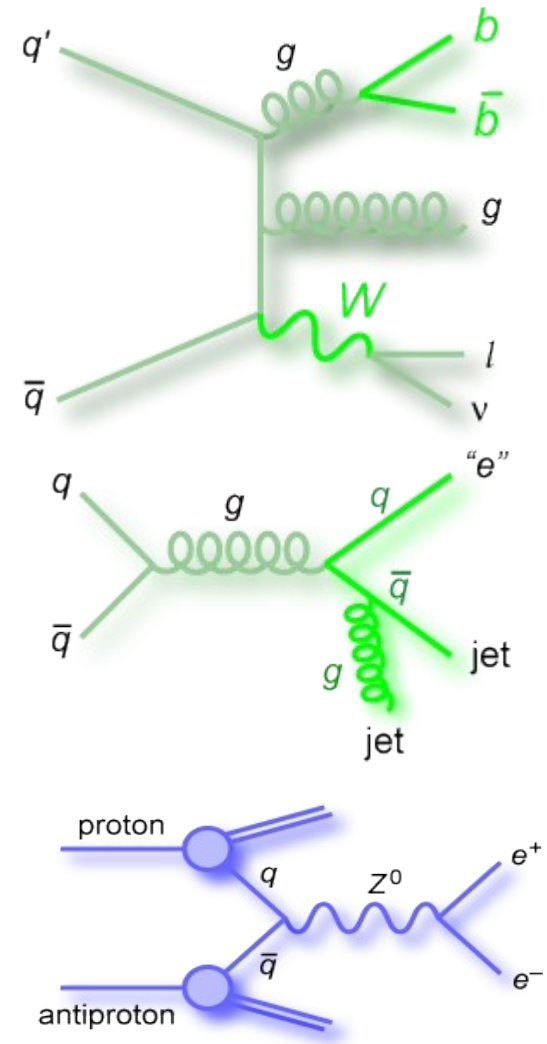
Backgrounds

Lepton + Jets

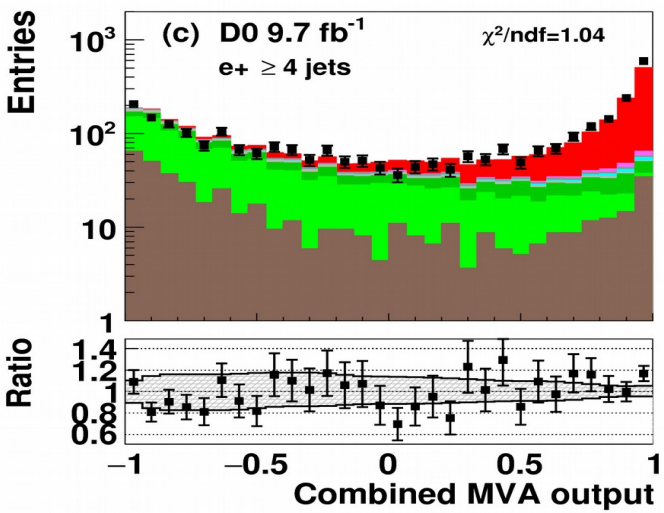
- W+jets (Wbbj, Wccj, Wjjj)
- Multijet events with misidentified leptons
- Dibosons (WW, WZ, ZZ) +jets

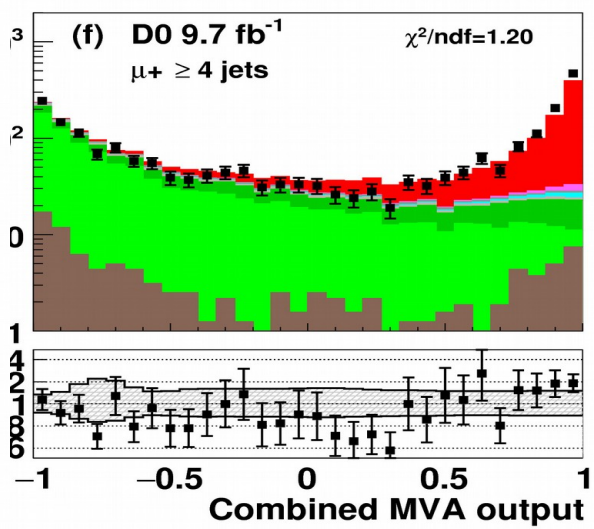
Dileptons

- Z → μμ, ee, ττ + jets
- Dibosons (WW, WZ, ZZ) + jets
- W+jets and multijet events with misidentified leptons

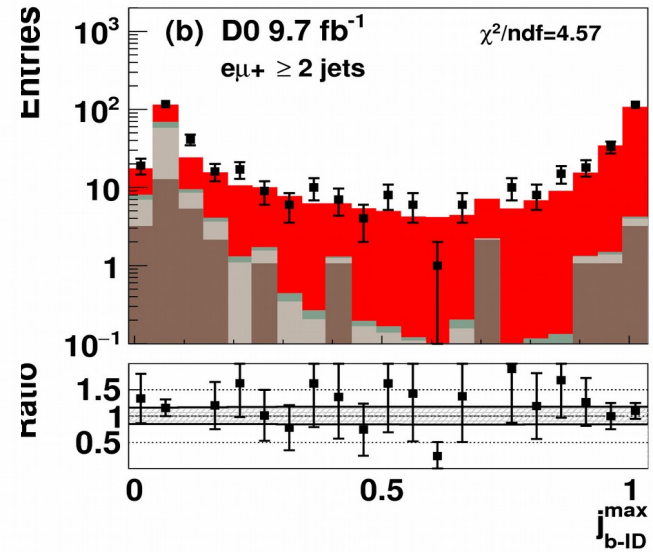


Cross-Section Measurements





Lepton + Jets



Dileptons

- Use multivariate discriminant (topological + b-tagging) in six l+jets channels and b-tagging discriminant in four dilepton channels.
- Use the likelihood profiling technique to reduce systematic uncertainty and fit discriminant distributions simultaneously in all channels.

$$\sigma_{t\bar{t}} = 7.26 \pm 0.13(\text{stat.})^{+0.57}_{-0.50}(\text{syst.})\text{pb}$$

Phys. Rev. D 94, 092004 (2016)

Precision: 7.5%

Theory: $\sigma_{t\bar{t}} = 7.35^{+0.23}_{-0.27}$ pb

Matrix Element Technique

- Allow to improve the statistical precision of the result by using the maximum available information and by associating the event-by-event statistical weight, depending on the event "precision".

$$P(x,H) \sim \int d^6\sigma(y,H) W(x,y) f_{PDF}(q_1) f_{PDF}(q_2) dq_1 dq_2$$

Hypothesis

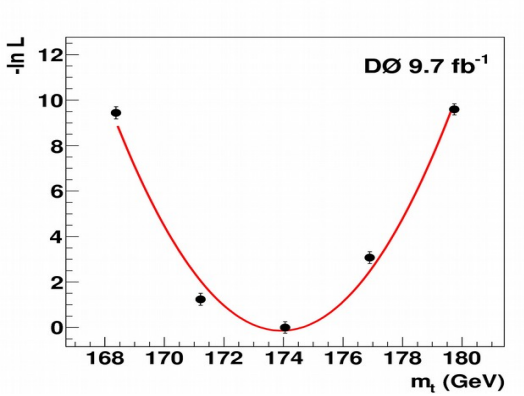
Diff. xsection with LO ME

Detector response (Transfer Function)

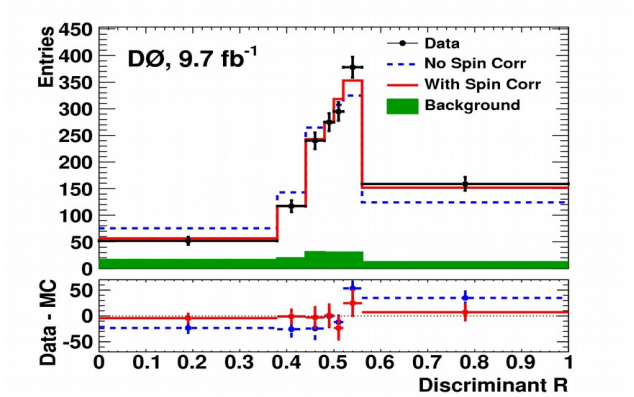
PDFs

- Sum over all possible jet-parton assignments with
- Use MC integration technique to integrate over 6-10 dimensions → CPU consuming

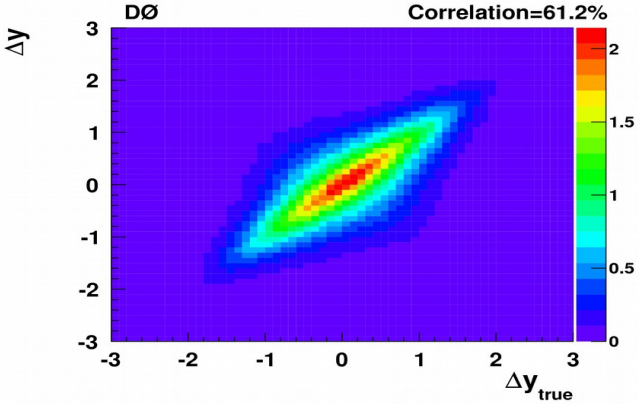
Mass Measurement



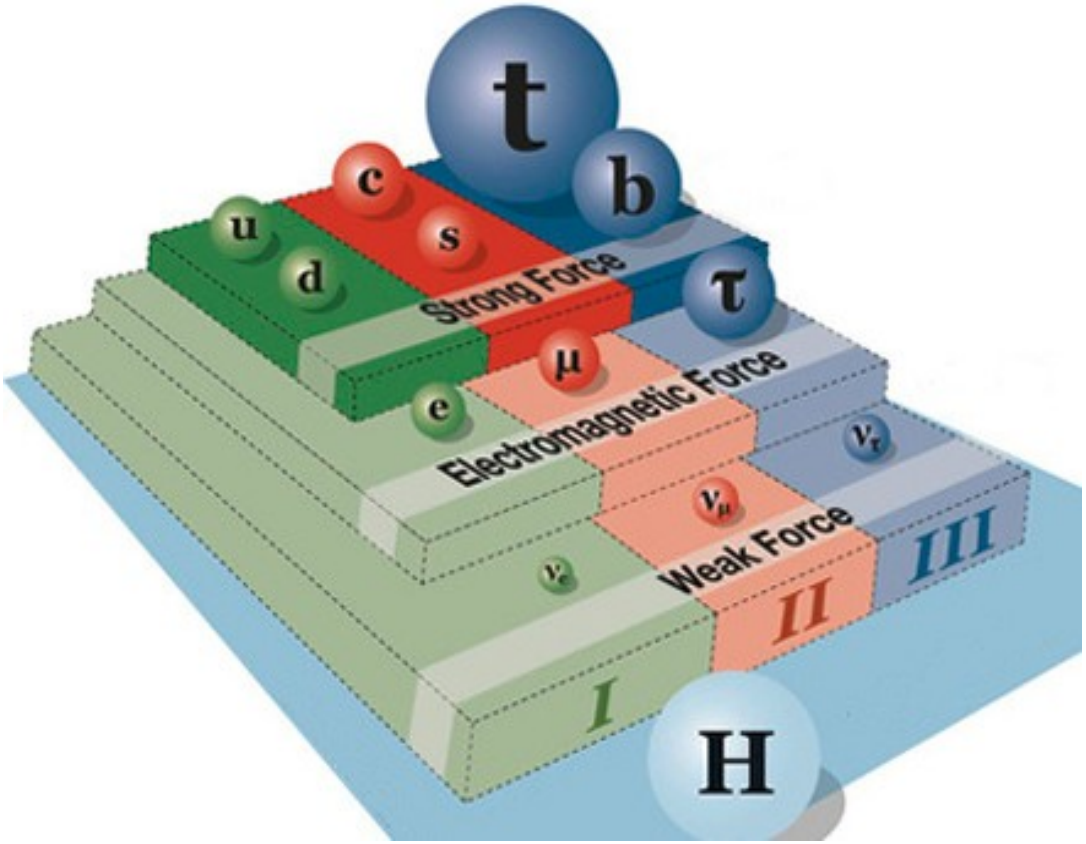
Spin Correlation



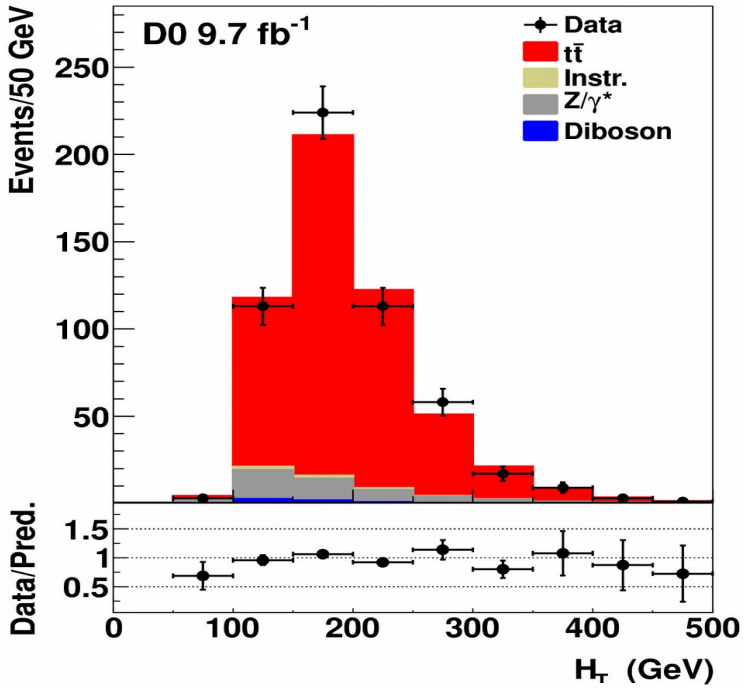
Asymmetry and Polarization in Dilepton Channel



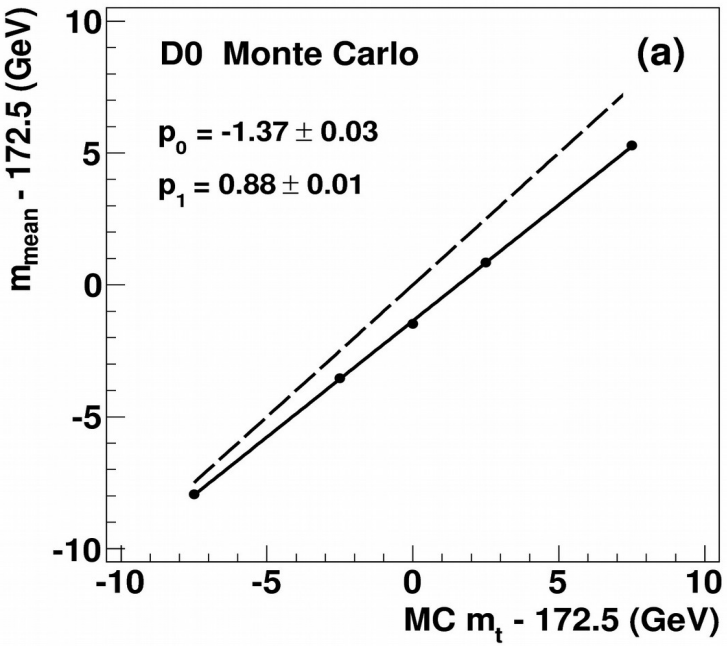
Top Quark Mass

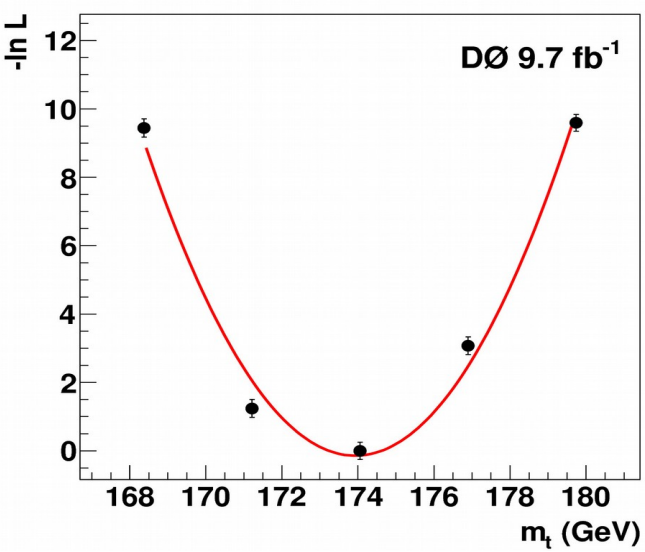


ME Mass Measurement in the Dilepton Channel



MC calibration





- Propagate JES in-situ correction factor from the l+jets channel to the dilepton ⇒ reduction of the JES related uncertainty

$$m_t = 173.93 \pm 1.61(\text{stat}) \pm 0.88(\text{syst})\ \text{GeV}$$

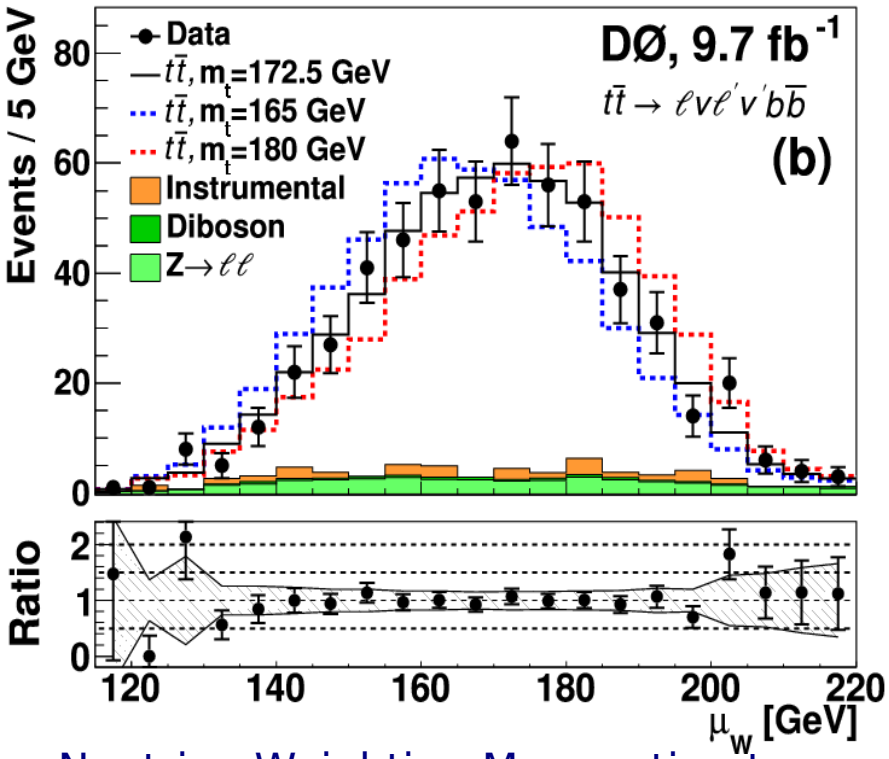
Phys. Rev. D 94 032004 (2016)

Precision: 1.1%

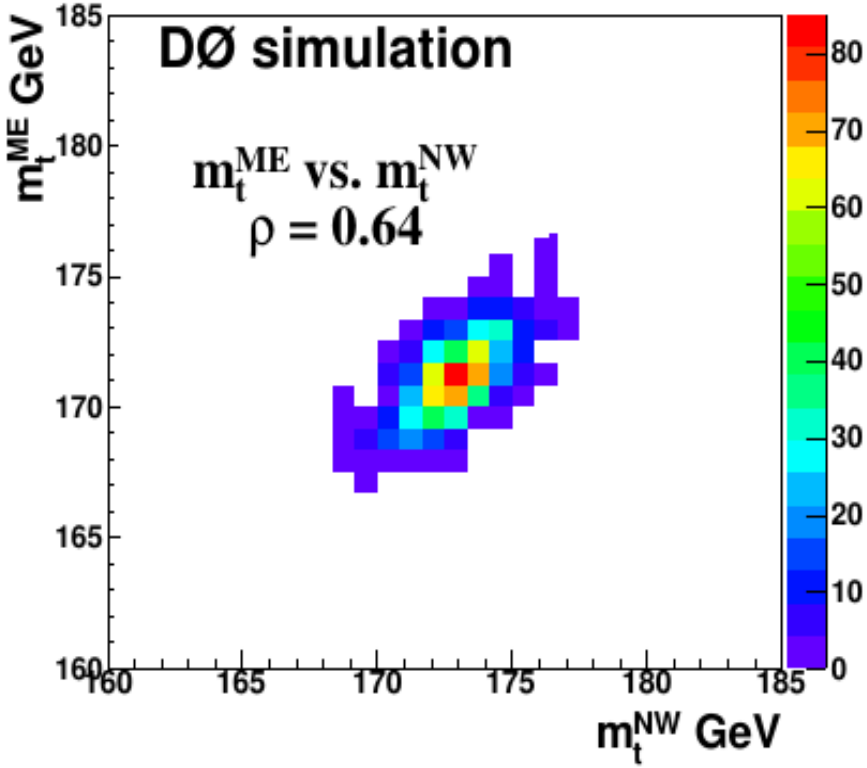
D0 Top Quark Mass Combination: Dilepton Channel

- Matrix Element dilepton measurement: $173.93 \pm 1.61(\text{stat}) \pm 0.88(\text{syst})$ GeV
  Phys. Rev. D 94 032004 (2016)

- Neutrino Weighting dilepton measurement: $173.32 \pm 1.36(\text{stat}) \pm 0.85(\text{syst})$ GeV
  Phys. Lett. B 752, 18 (2016)



Neutrino Weighting Mass estimator



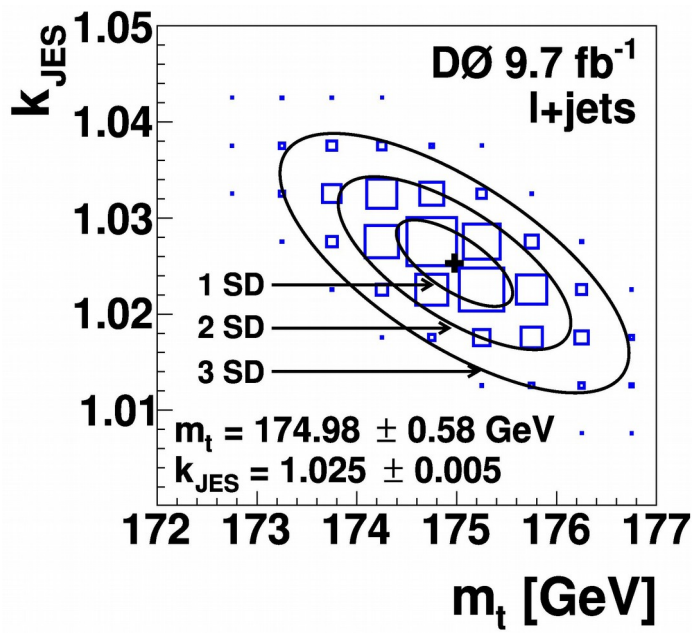
$$m_t = 173.50 \pm 1.31(\text{stat}) \pm 0.84(\text{syst}) \text{ GeV}$$

D0 Conference Note 6485 (2016)

Precision: 0.9%

D0 Top Quark Mass Combination: Uncertainties

- l+Jets measurement
- Use W-boson mass as an additional constrains for the JES correction factor.



$$174.98 \pm 0.41(\text{stat}) \pm 0.63(\text{syst})\ \text{GeV}$$

	ℓ+jets, GeV	$\ell\ell$, GeV	ℓ+jets/$\ell\ell$, GeV
m_t	174.98	173.50	174.95
In situ light-jet calibration	0.41	0.47	0.41
Response to $b/q/g$ jets	0.16	0.28	0.16
Model for b jets	0.09	0.13	0.09
Light-jet response	0.21	0.31	0.21
Lepton modeling	0.01	0.08	0.01
Signal modeling	0.35	0.43	0.35
Jet modeling	0.07	0.14	0.07
b-tag modeling	0.10	0.22	0.10
Background from theory	0.06	0.00	0.06
Background based on data	0.09	0.08	0.09
Calibration method	0.07	0.14	0.07
Multiple interactions model	0.06	0.07	0.06
Systematic uncertainty	0.63	0.84	0.64

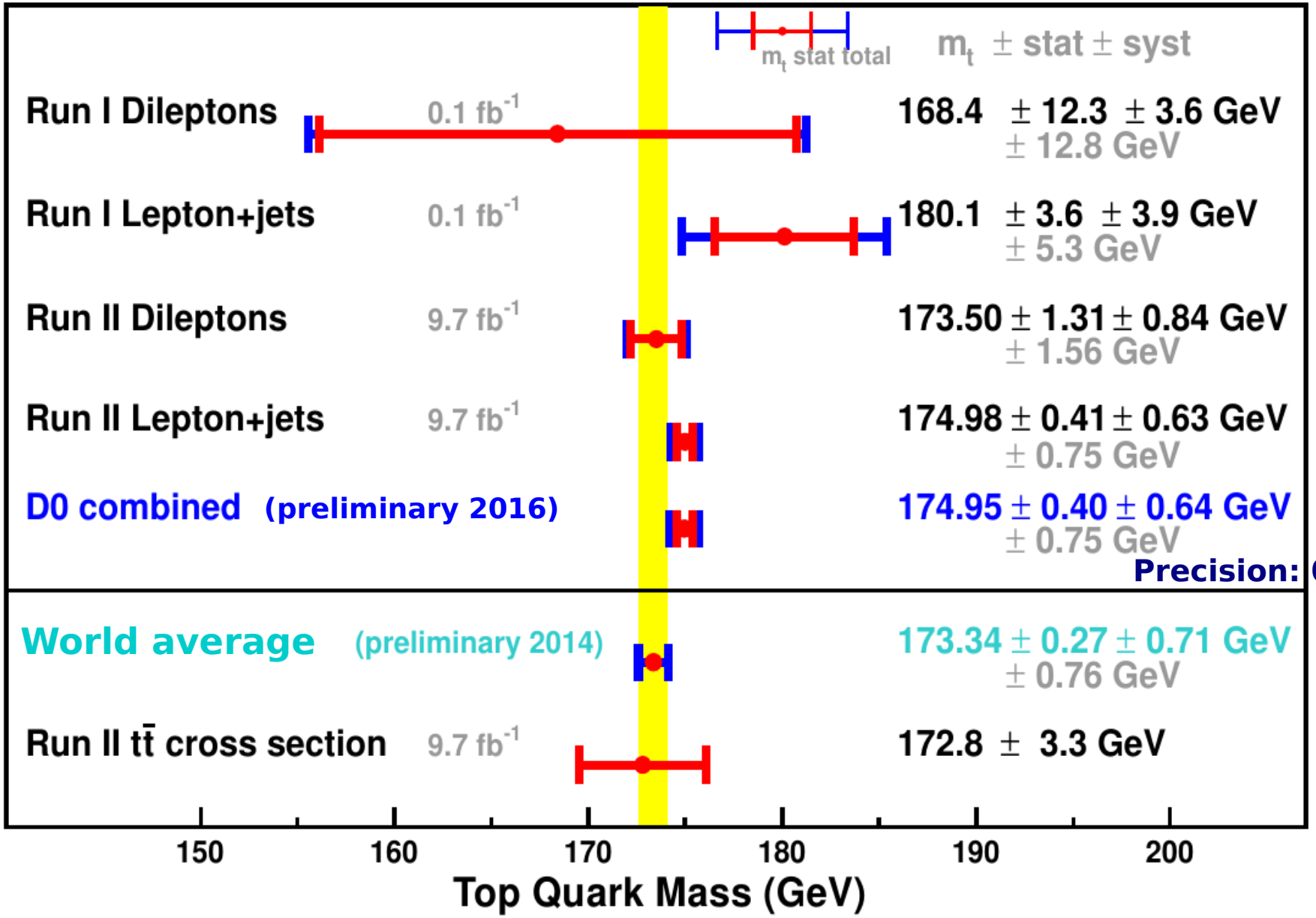
Phys. Rev. D 91, 112003 (2015)

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

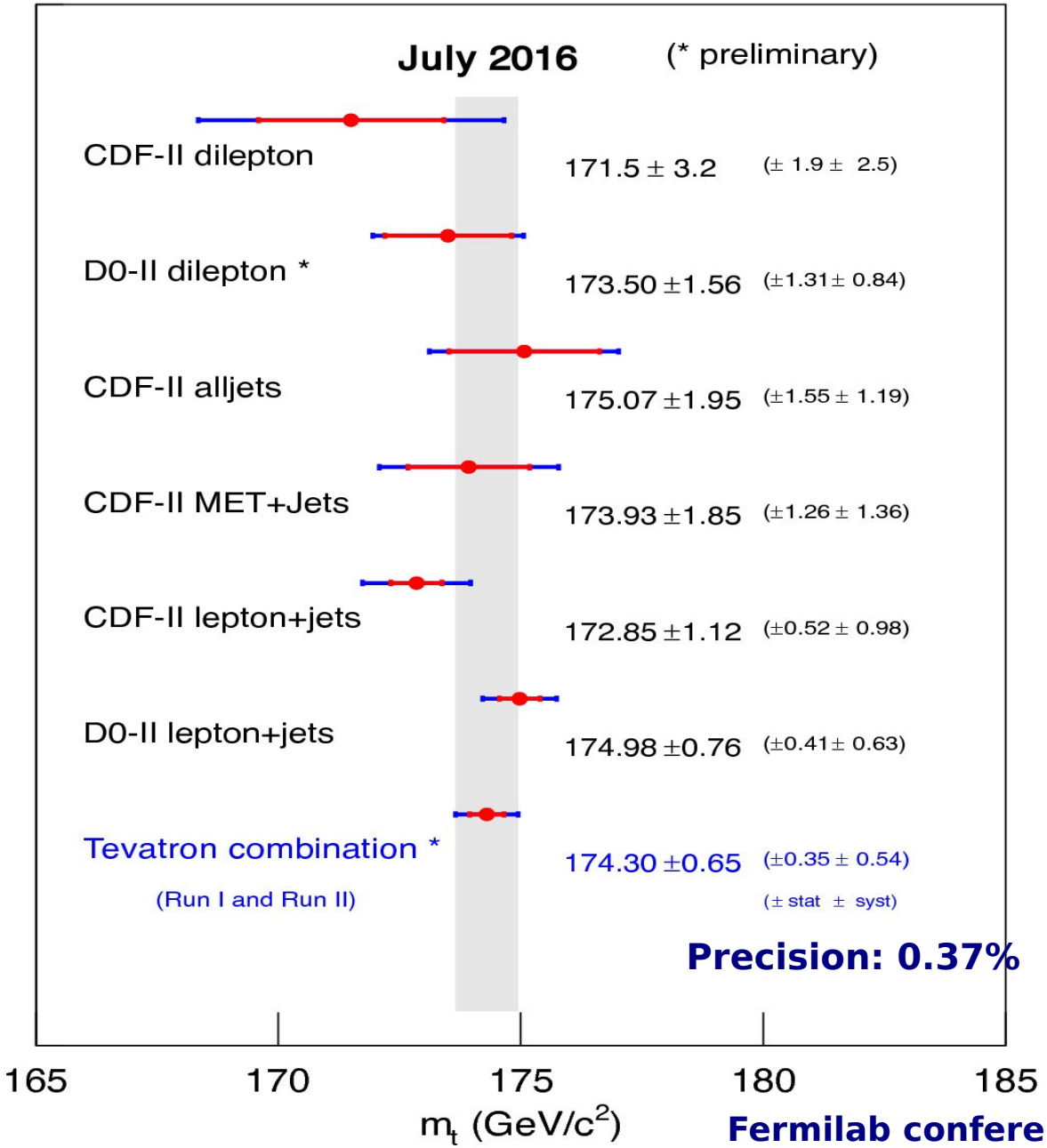
D0 Conference Note 6485 (2016)

D0 Top Mass Combination

D0 Conference Note 6485 (2016)
Final D0 paper is in preparation



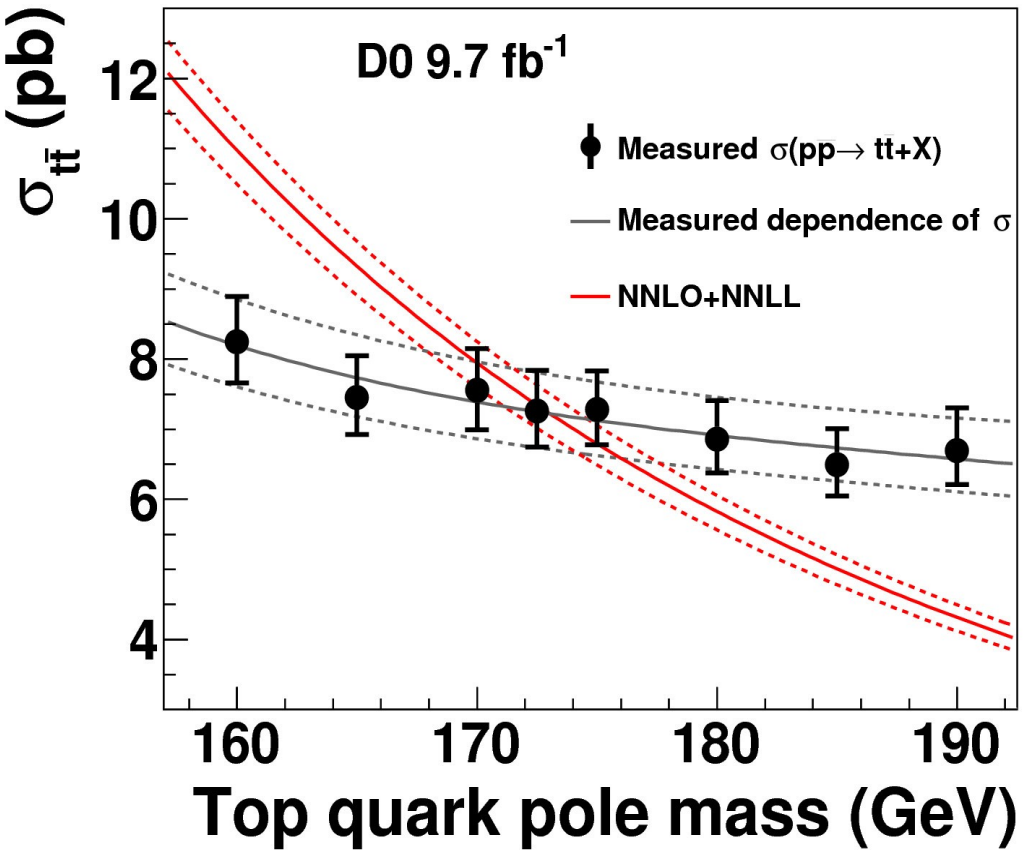
Tevatron Mass Combination



Fermilab conference note
FERMILAB-CONF-16-298-E

Indirect Top Mass Determination

- Due to the presence of long range effects in QCD, the MC mass relation to "well defined" theoretical mass definitions could be established with a precision ~ O(0.5 GeV).
- It is useful to measure the top quark mass in the well defined scheme using "indirect" approaches.
- D0 uses the comparison of measured and theoretical inclusive cross sections as a function of top pole mass.



$$m_t = 172.8 \pm 1.1(\text{theo.})^{+3.3}_{-3.1}(\text{exp.})\ \text{GeV}$$

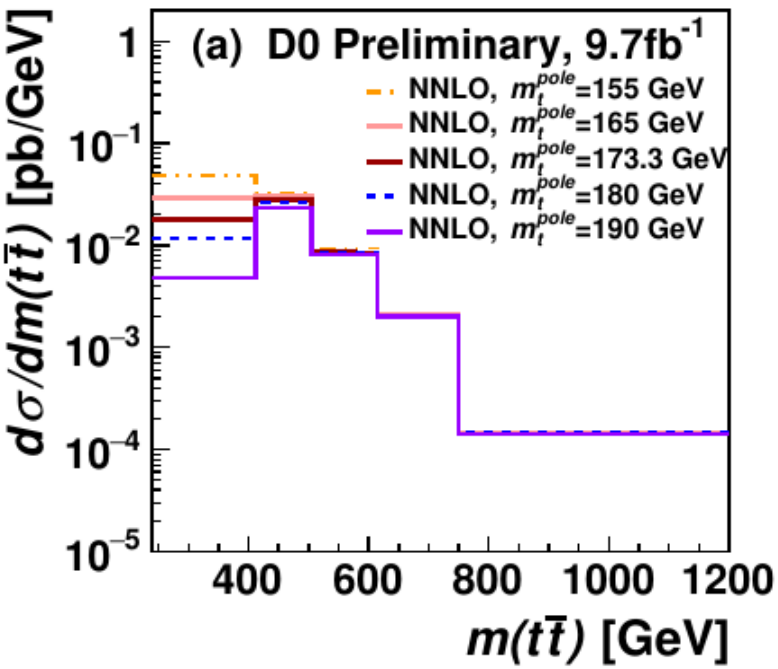
Precision: 1.9%

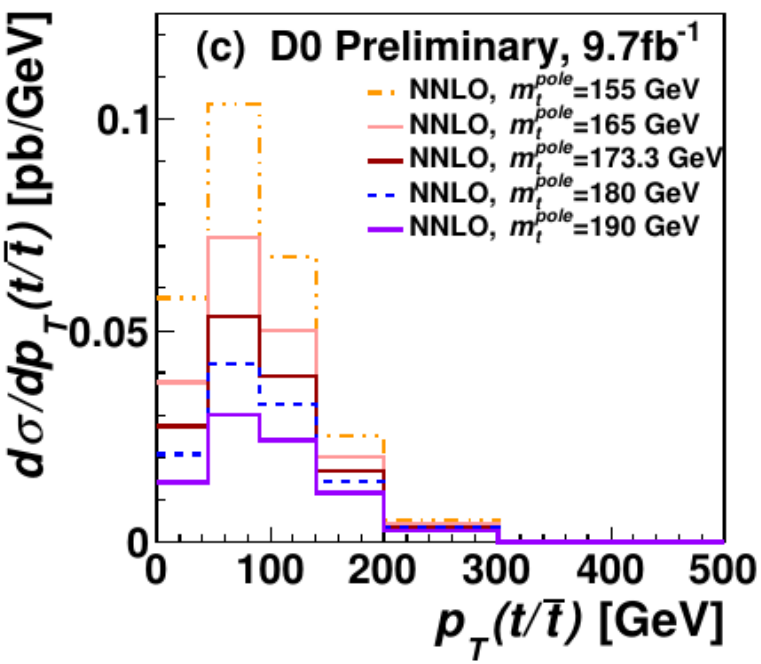
Phys. Rev. D 94, 092004 (2016)

New Idea: Mass from Differential Cross-Section

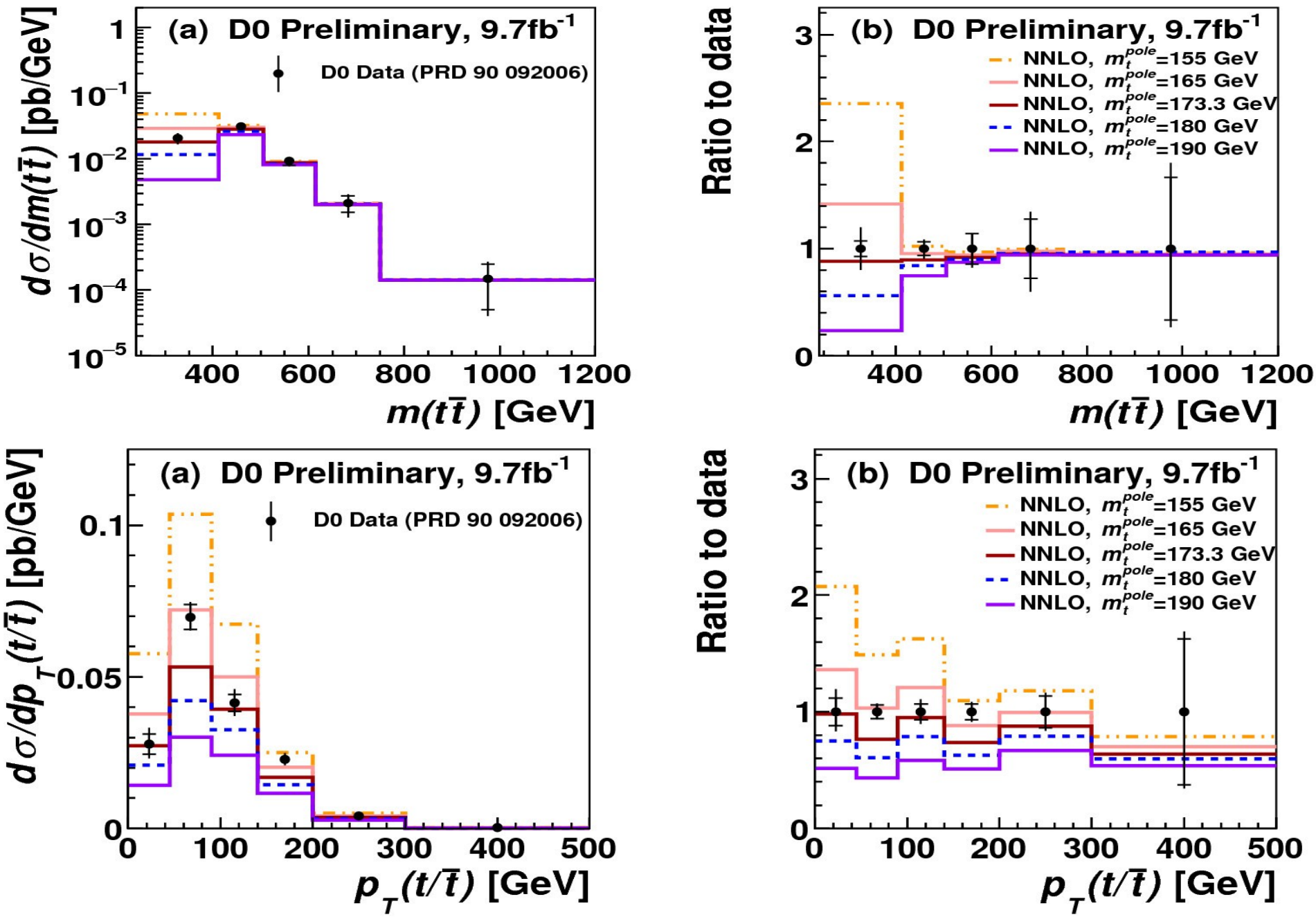
- Top quark momentum and the $t\bar{t}$ invariant mass distributions are sensitive to the top quark mass
- Expect improvement compare to the extraction from total cross-section
- Use the D0 lepton+jets measurement: **Phys. Rev. D 90, 092006 (2014)**
- Compare differential distributions to NNLO QCD calculation which use the pole mass definition:

Czakon, Fiedler, Heymes and Mitov, JHEP 1605, 034 (2016)



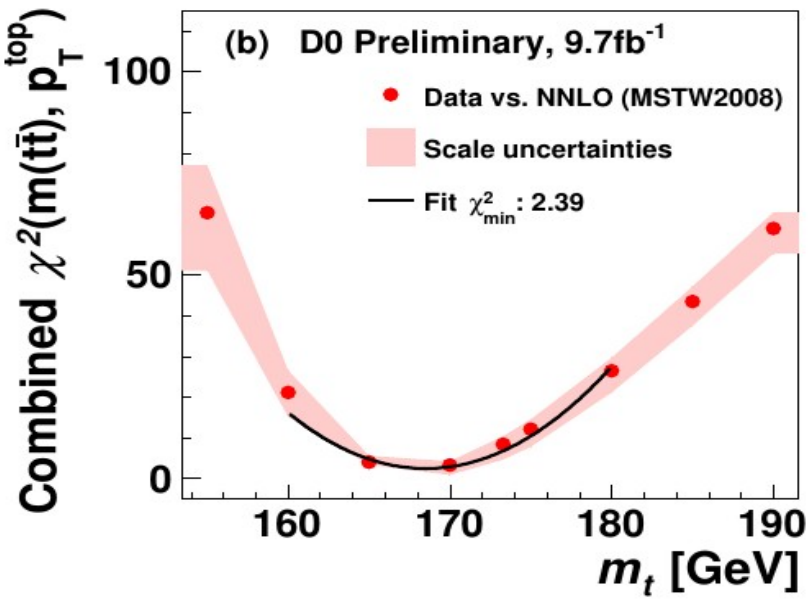


Pole Mass From Differential Cross-Section

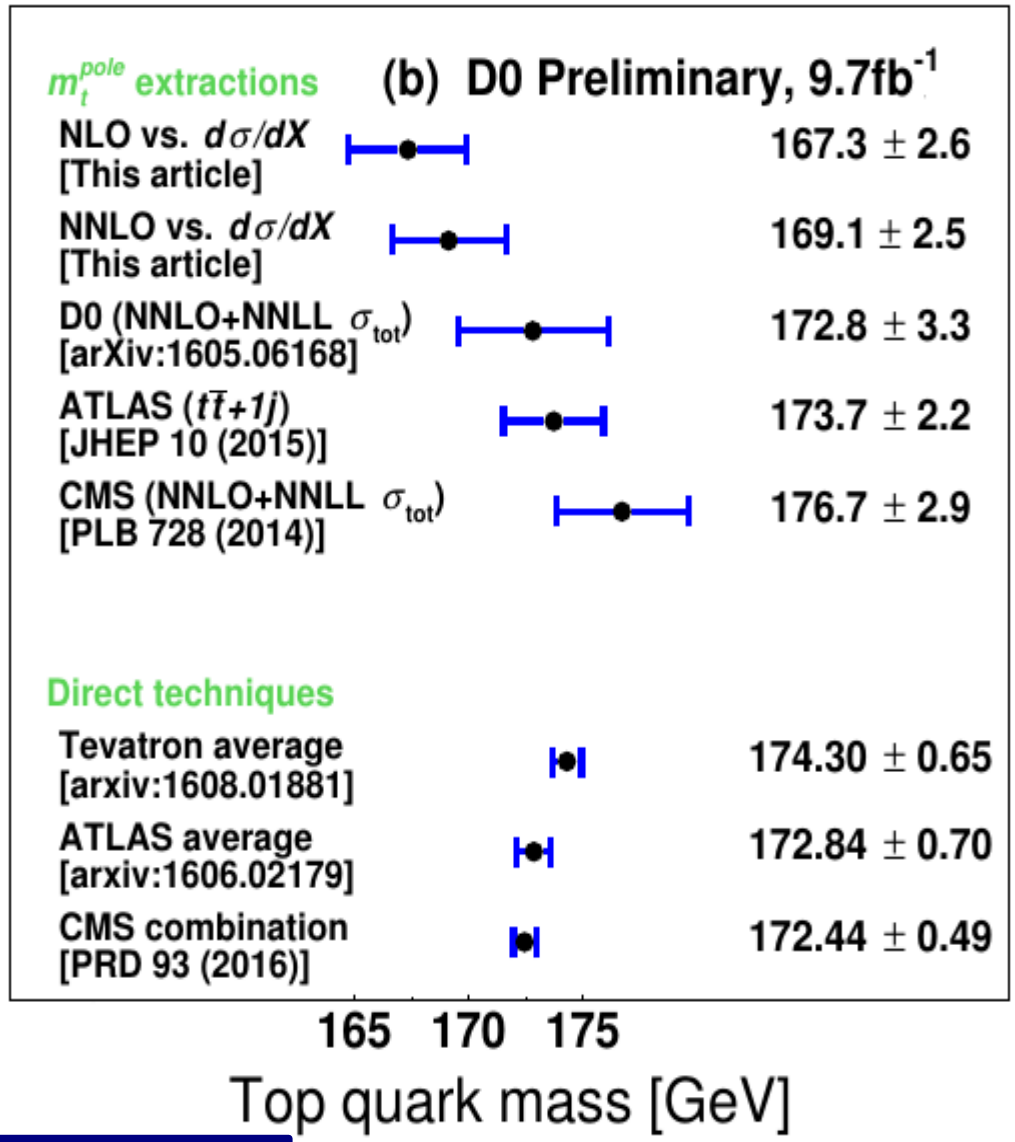


Pole Mass From Differential Cross-Section: Results

- Use the χ^2 formalism to measure the mass
- The full 2-D correlation matrix is used.



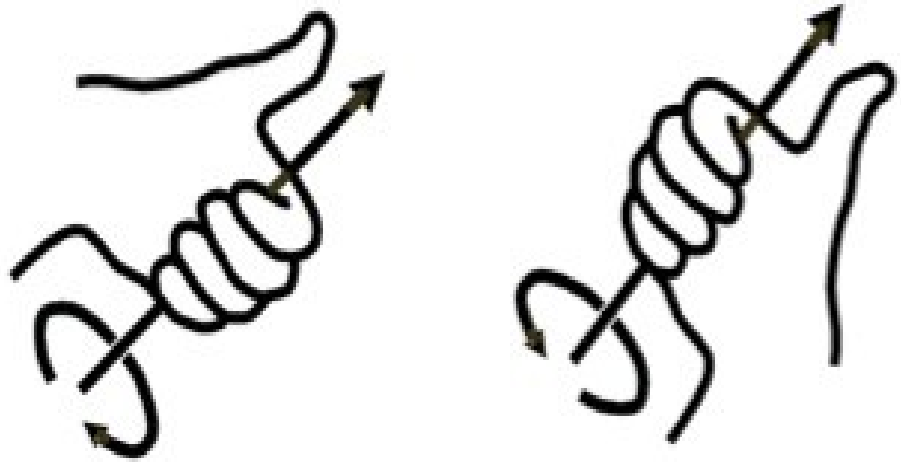
D0 Conference Note 6473 (2016)



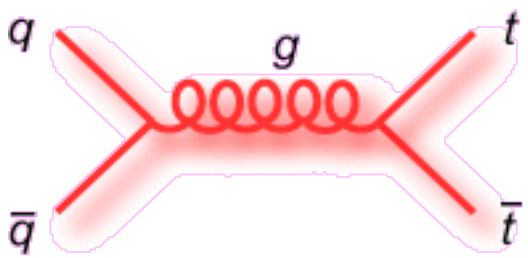
$$m_t = 169.1 \pm 1.4(\text{theo.}) \pm 2.2(\text{exp})\ \text{GeV}$$

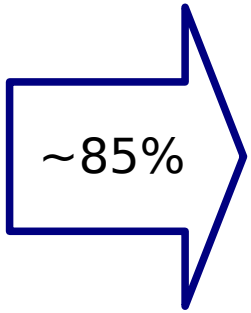
Precision: 1.5%

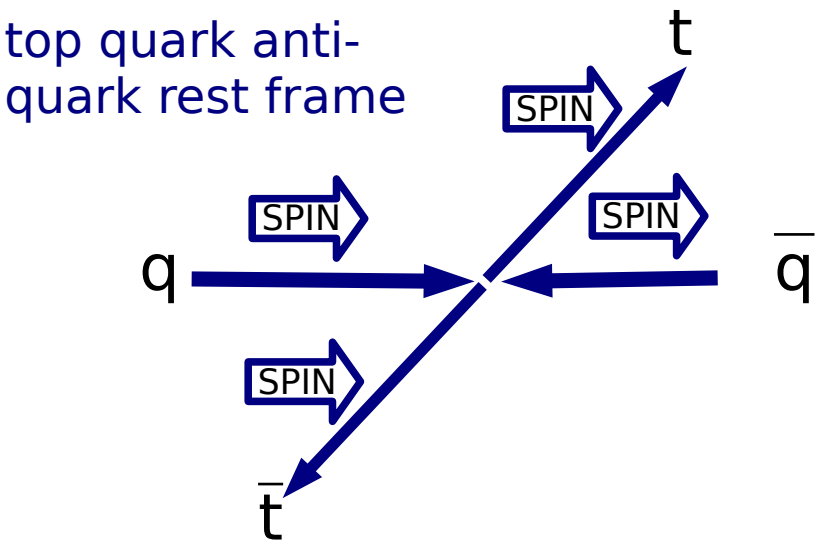
Top Quark Spin Properties



Spin Correlation



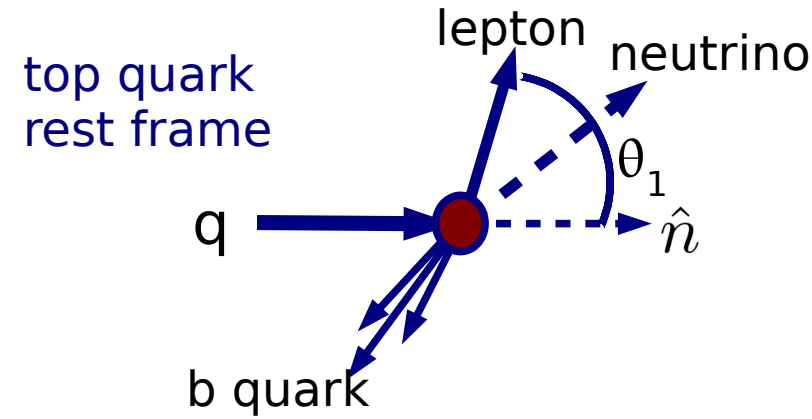




- Due to the short life-time (10^{-25} sec) of the top quark, it decays before depolarization, so the spin information transmitted to the decay products (W boson, b quark).
- Top quark and antiquark have very small polarization in the SM.
- For the quark anti-quark annihilation at Tevatron the spin correlation is close to 1.0 at the optimal basis.
  - Allow to verify the QCD calculation.
  - Different correlation → new physics.

Spin Correlation: Formalism

$$O_{\hat{n}_1,\hat{n}_2} = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) - \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)},$$



Polarization

Spin Correlation Coefficient

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{1,\hat{n}_1}\, d\cos\theta_{2,\hat{n}_2}} = \frac{1}{4}(1 + k_1 P_{\hat{n}_1}\cos\theta_{1,\hat{n}} \pm k_2 P_{\hat{n}_2}\cos\theta_{2,\hat{n}} - k_1 k_2 O_{\hat{n}_1\hat{n}_2}\cos\theta_{1,\hat{n}}\cos\theta_{2,\hat{n}})$$

Spin analyzing power coefficients

Spin quantization axes

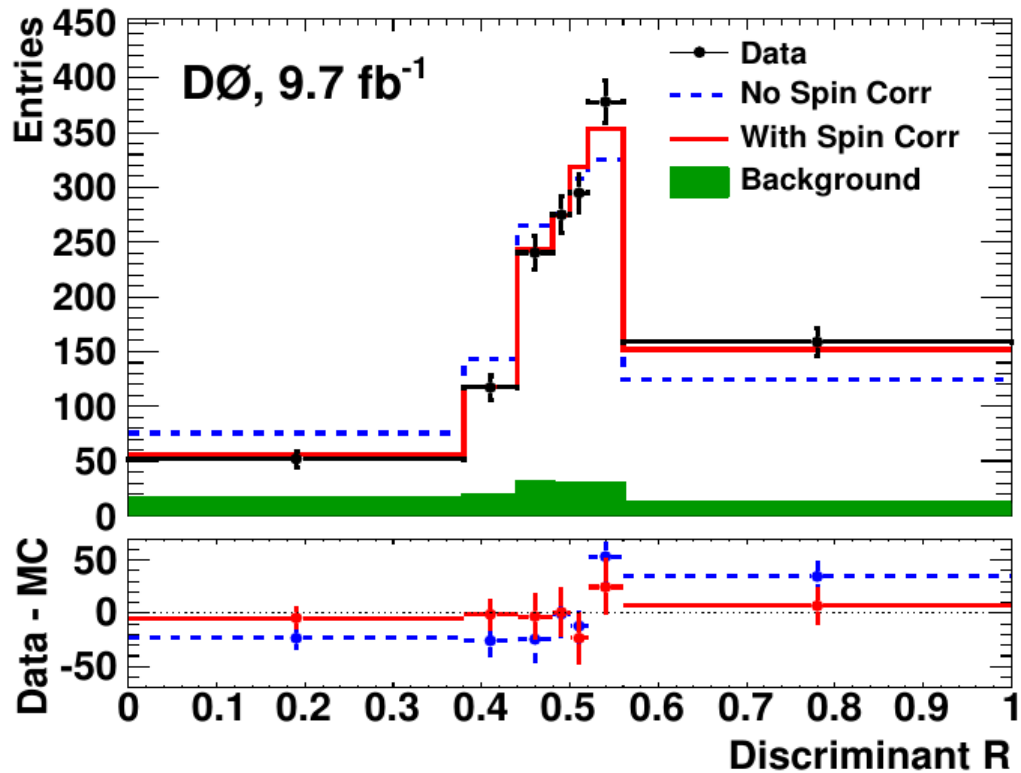
	LO	NLO
$O_{\text{off-diagonal}}$	0.93	$0.80^{+0.1}_{-0.2}$

Bernreuther, Brandenburg, Si and Uwer, Nucl. Phys. B 690, 81 (2004)
W. Bernreuther and Z.-G. Si, Nucl. Phys. 837, 90 (2010).

Spin Correlation: Measurement

- l+jets and dileptons channels.
- Use ME probabilities → calculate discriminant R.
- Use MC@NLO generators for 2 samples: with SM spin correlation and null spin correlation → constructs templates.
- Fit the R-distribution in data and determine the fraction (f) of events with SM spin correlation.

$$R(x) = \frac{P_{t\bar{t}}(x, \mathrm{SM})}{P_{t\bar{t}}(x, \mathrm{SM}) + P_{t\bar{t}}(x, \mathrm{null})}$$



$$O_{\mathrm{off}}^{\mathrm{meas}} = O_{\mathrm{off}}^{\mathrm{mc@nlo}} \cdot f = 0.89 \pm 0.16\ (\mathrm{stat}) \pm 0.15\ (\mathrm{syst})$$

non-zero spin correlation: 4.2 SD

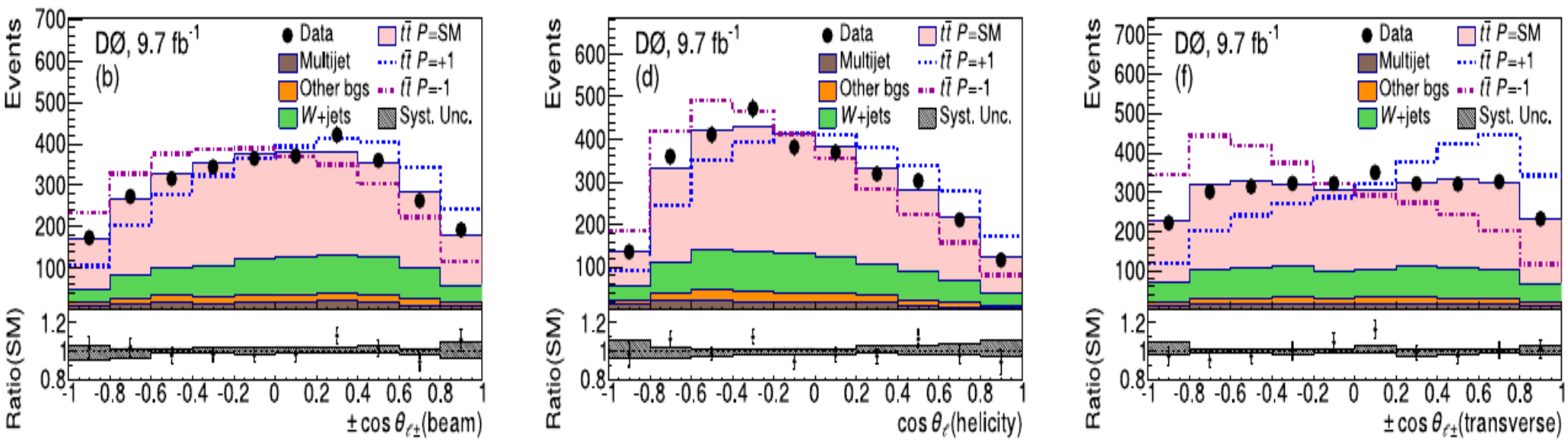
Phys. Lett. B 757, 199 (2016)

Polarization: l+jet channel

- Study polarization in three bases
  - Beam basis: use proton beam direction boosted in $t\bar{t}$ rest frame as quantization axis
  - Helicity basis: use $t\bar{t}$ axis in $t\bar{t}$ rest frame
  - Transverse basis: use cross product (beam axis x top direction) in $t\bar{t}$ rest frame

    The first measurement of the transverse polarization!

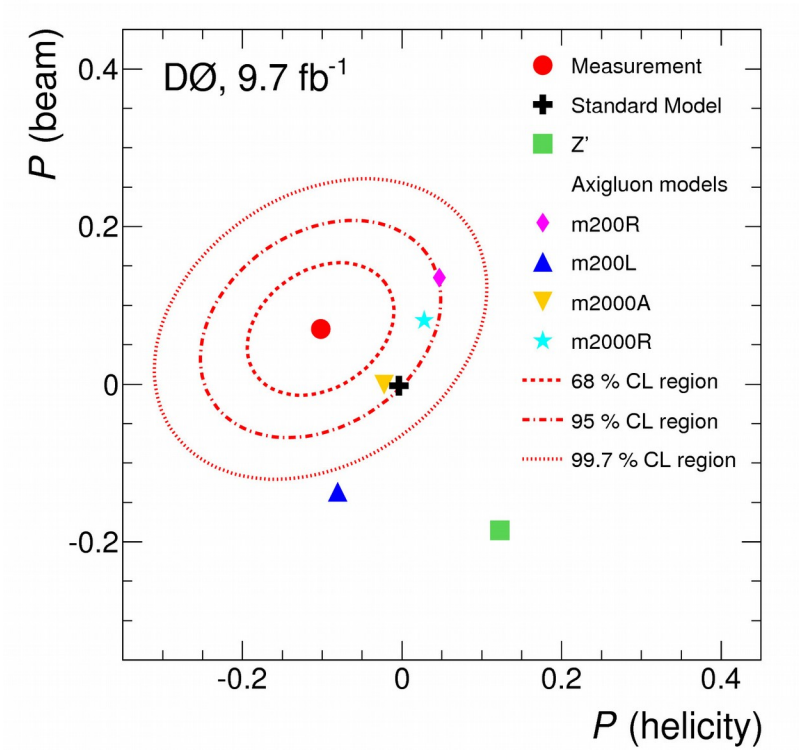
- SM expectations for all three bases are close to zero.
- Use the template based method

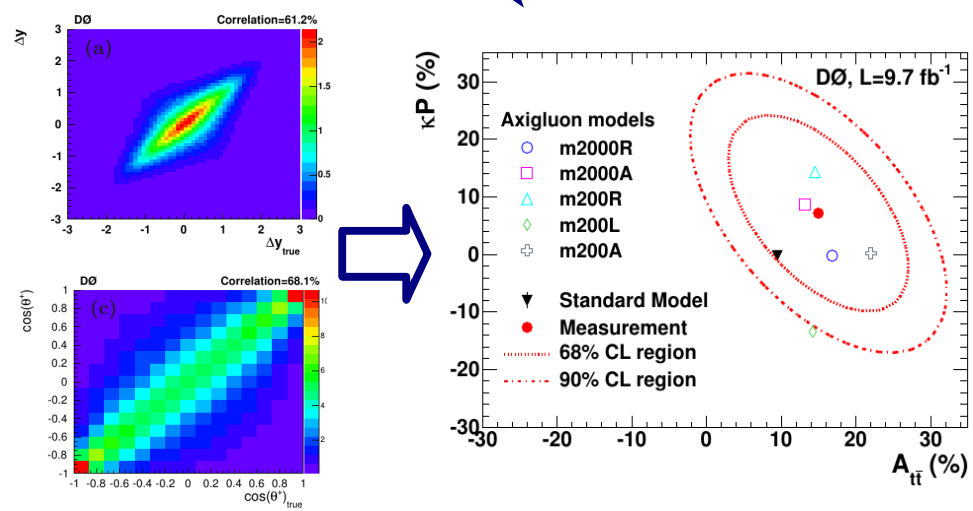


Polarization: l+jets Results

Phys. Rev. D 95, 011101(R) (2017)

Axis	Measured polarization	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Beam - D0 comb.	$+0.081 \pm 0.048$	-0.002
Helicity	-0.102 ± 0.061	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$



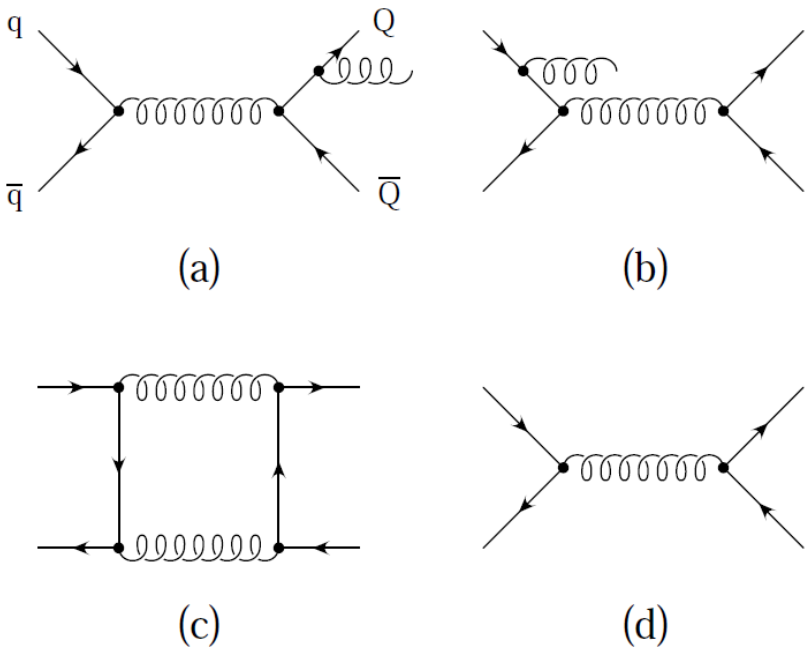


Phys. Rev. D 92, 052007 (2015)

Top Quark Production Asymmetry

Asymmetry

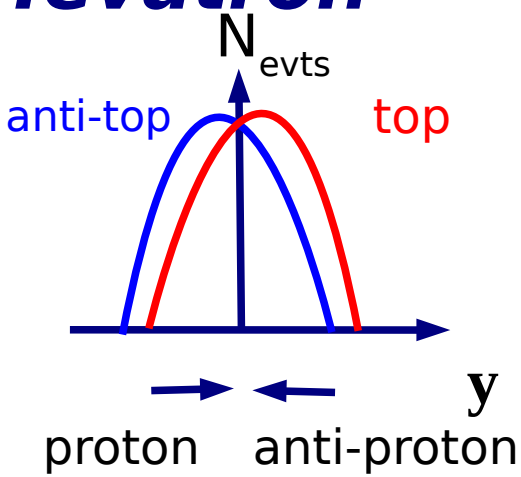
- In $p\bar{p}$ collisions the produced top quark and antiquark can show a forward-backward asymmetry:
  - LO: kinematic distributions in production are charge symmetric
  - NLO 2→2 (interference between Born and box diagrams), LO 2→3: expect (5—10)% asymmetry (higher order corrections are small)
  - NLO 2→3 (ISR/FSR interference): has the negative asymmetry and reduce expected asymmetry significantly ⇒ strong dependence from phase space region
- SM asymmetry is small, ~9.5% (NNLO), so it is a sensitive variable to test the new physics contributions.



Czakon, Fiedler and Mitov,
Phys. Rev. Lett. **115**, 5, 052001 (2015)

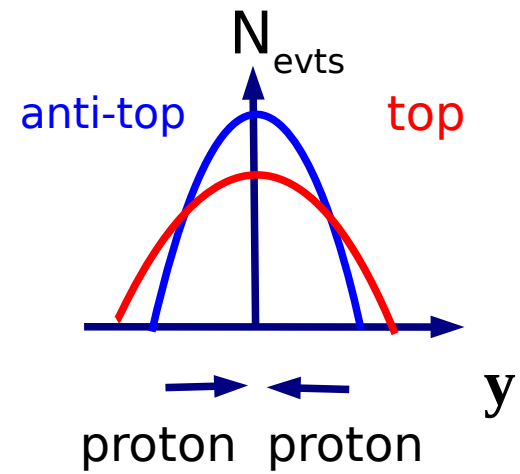
Asymmetry Studies at Tevatron

Tevatron



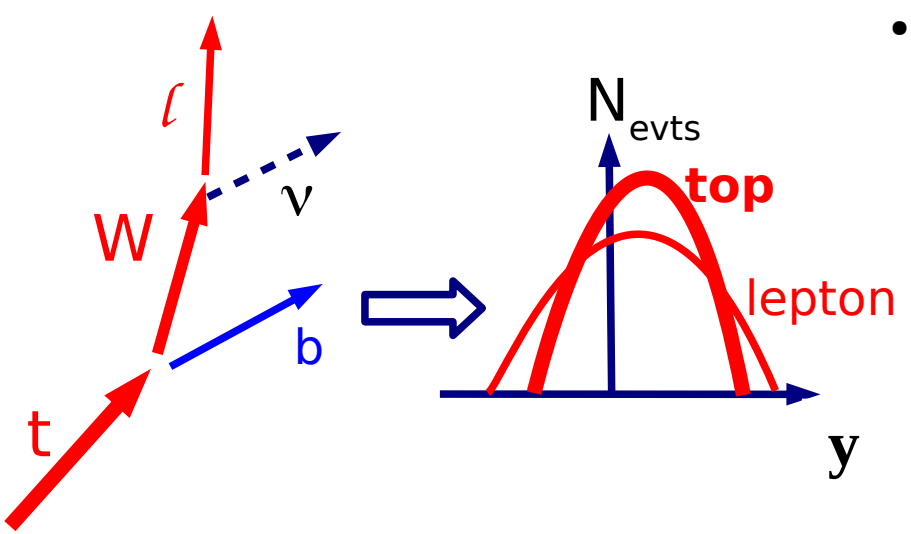
- Forward-backward asymmetry at the Tevatron → ~10%
- Charge asymmetry at the LHC → ~ 1%

LHC



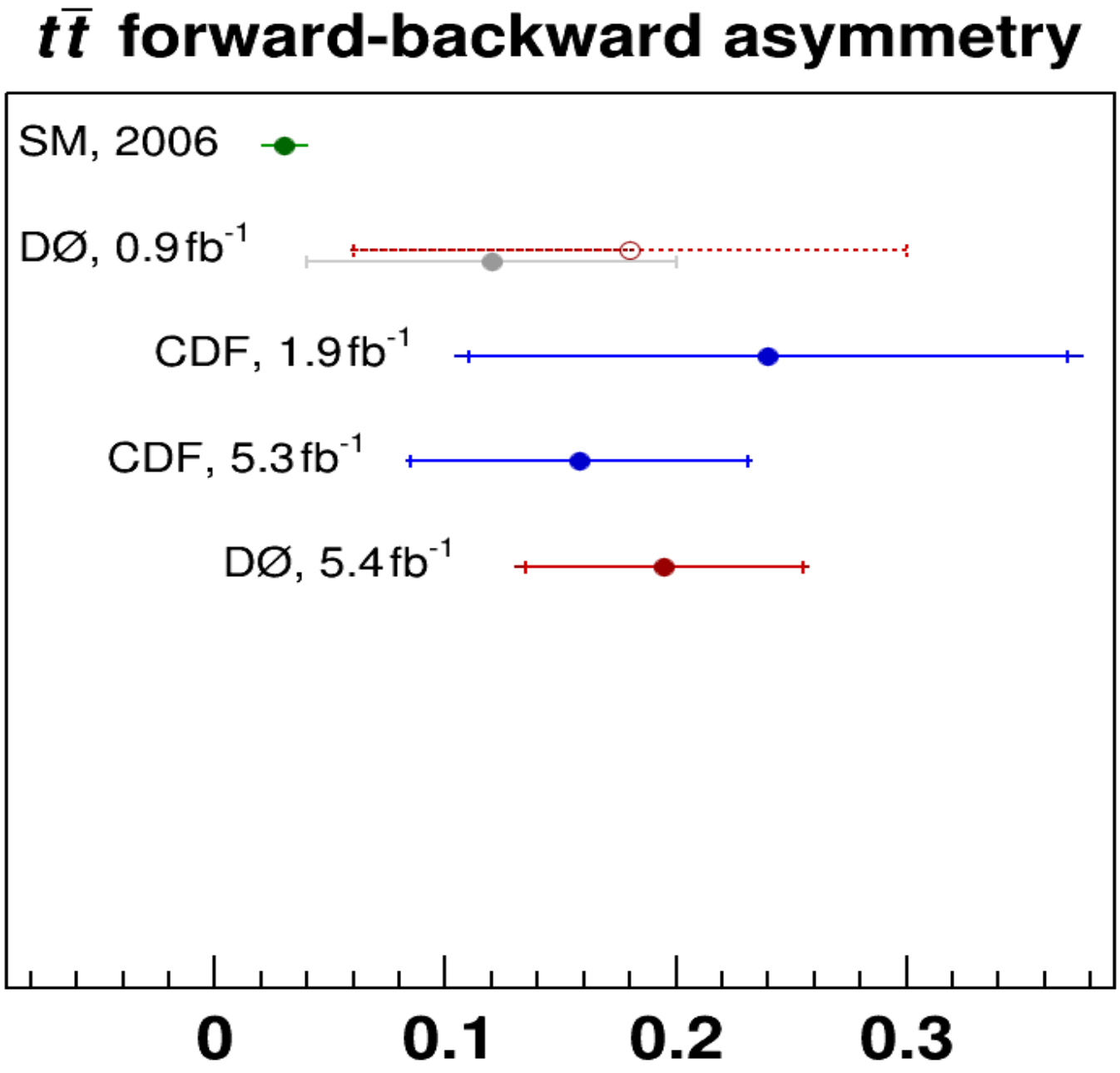
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

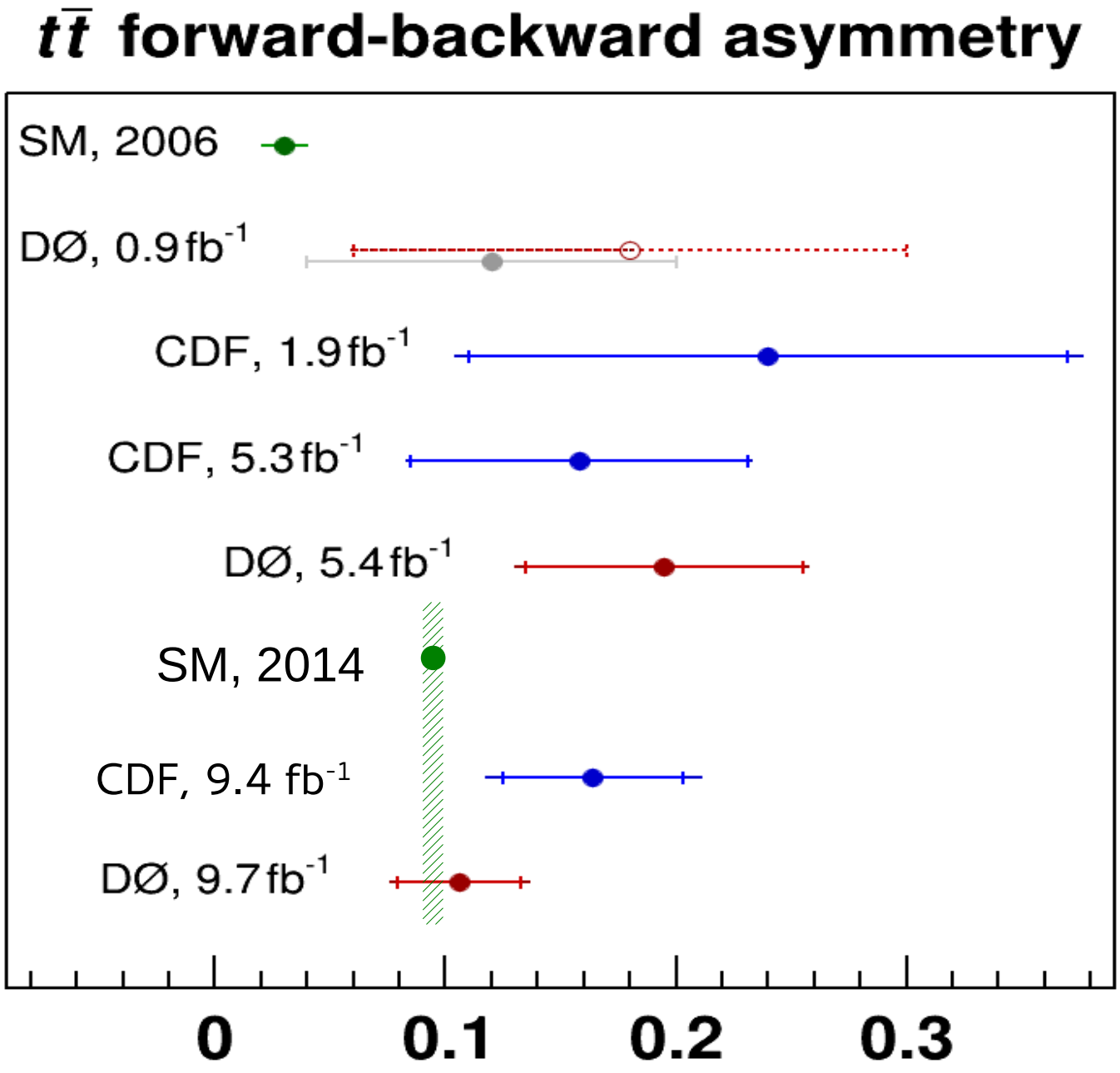


- Asymmetries measurement:
  - Reconstruction of the dy distribution
  - Background subtraction
  - A_{top}: unfolding, A_{lep}: correction
  - A_{lep} affected by the top polarization
  - $A_{lep} \sim A_{top}/2$ at 1.96 TeV

Forward-Backward Asymmetry: History

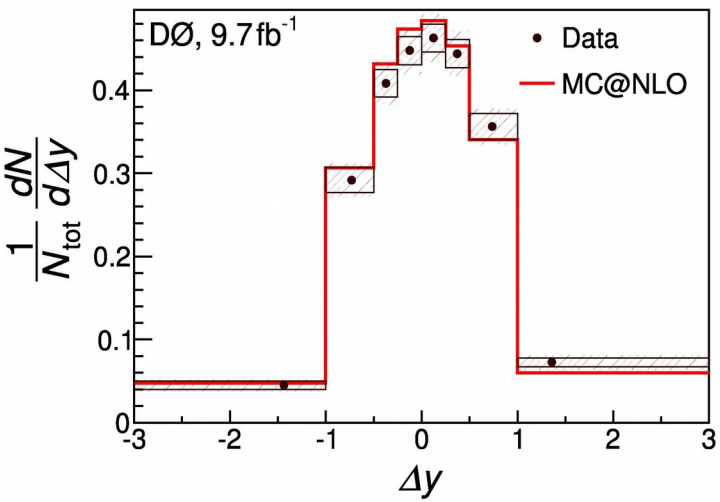


Forward-Backward Asymmetry: History



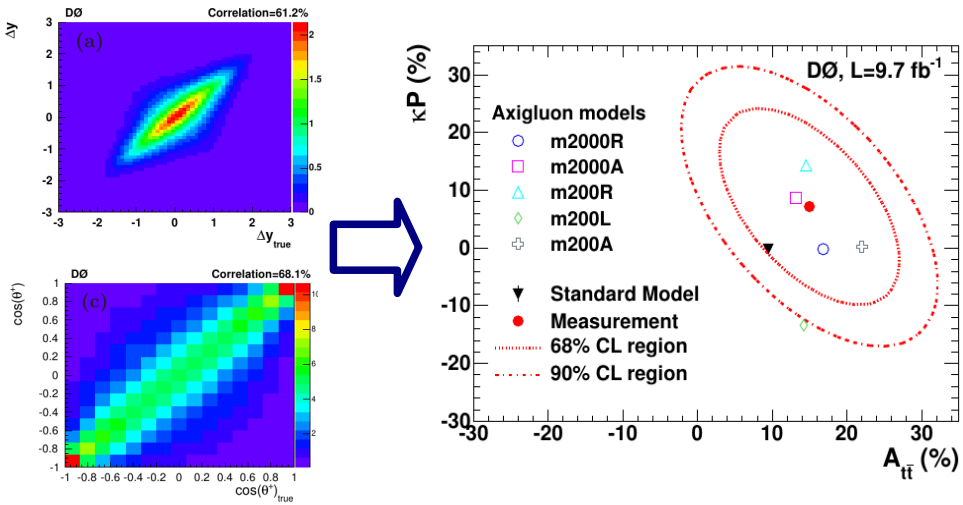
Forward Backward Asymmetry at D0

$t\bar{t}$ asymmetry in l+jets channel



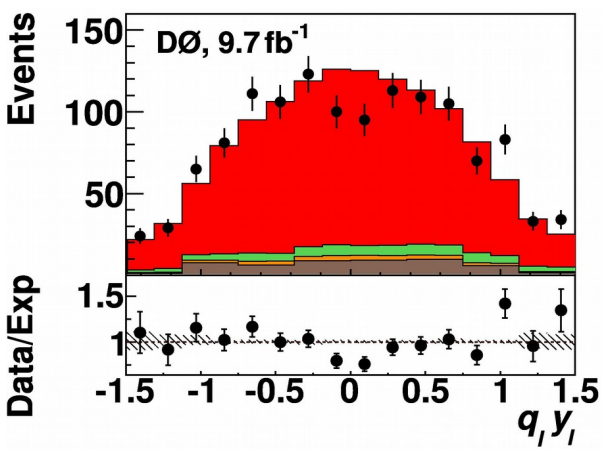
Phys. Rev. D 90, 072011 (2014)

$t\bar{t}$ asymmetry in diepton channel



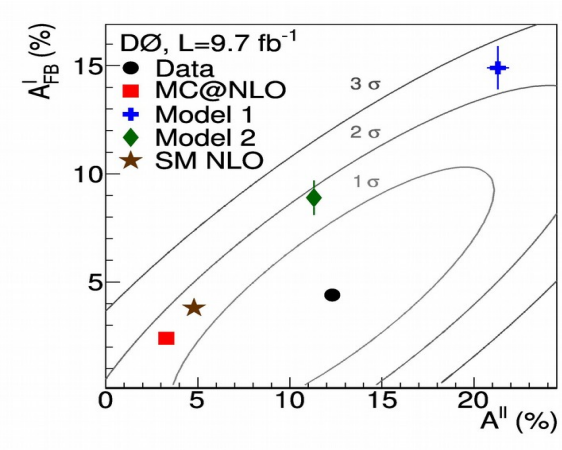
Phys. Rev. D 92, 052007 (2015)

Leptonic asymmetry in l+jets channel



Phys. Rev. D 90, 072001 (2014)

Leptonic asymmetry in l+jets channel

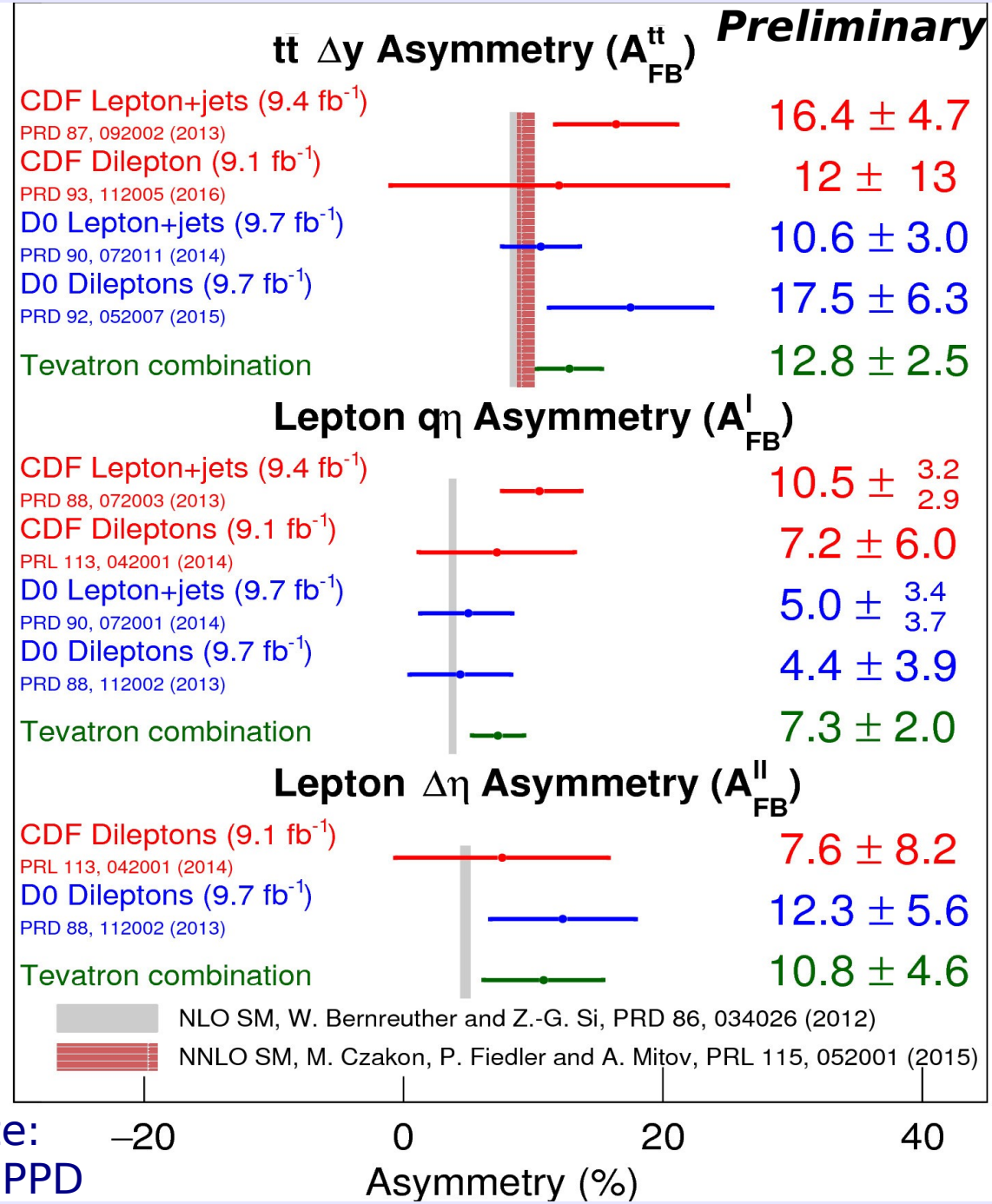


Phys. Rev. D 88, 112002 (2013)

Asymmetry: Tevatron Combination

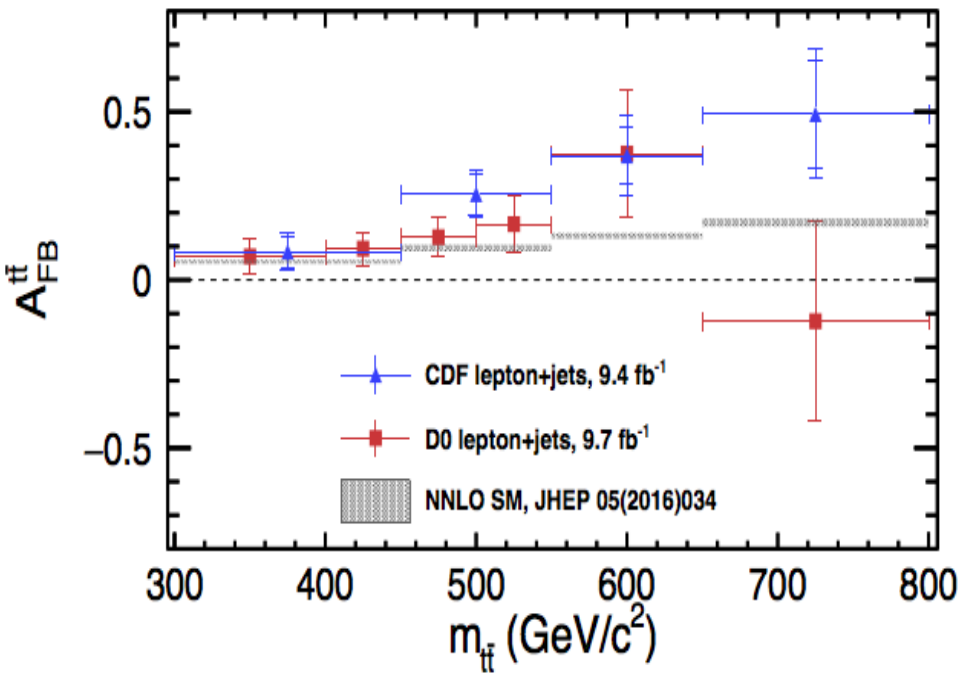
- Use BLUE to combine measurements
- Standardize and combine systematic uncertainties.
  - All results are limited by the statistical uncertainty
- Consistency:
  - $t\bar{t}$ asymmetry vs NNLO prediction: **1.3 SD**
  - Lepton $q\eta$ asymmetry vs NLO prediction: **1.6 SD**
  - Lepton $\Delta\eta$ asymmetry vs NLO prediction: **1.3 SD**

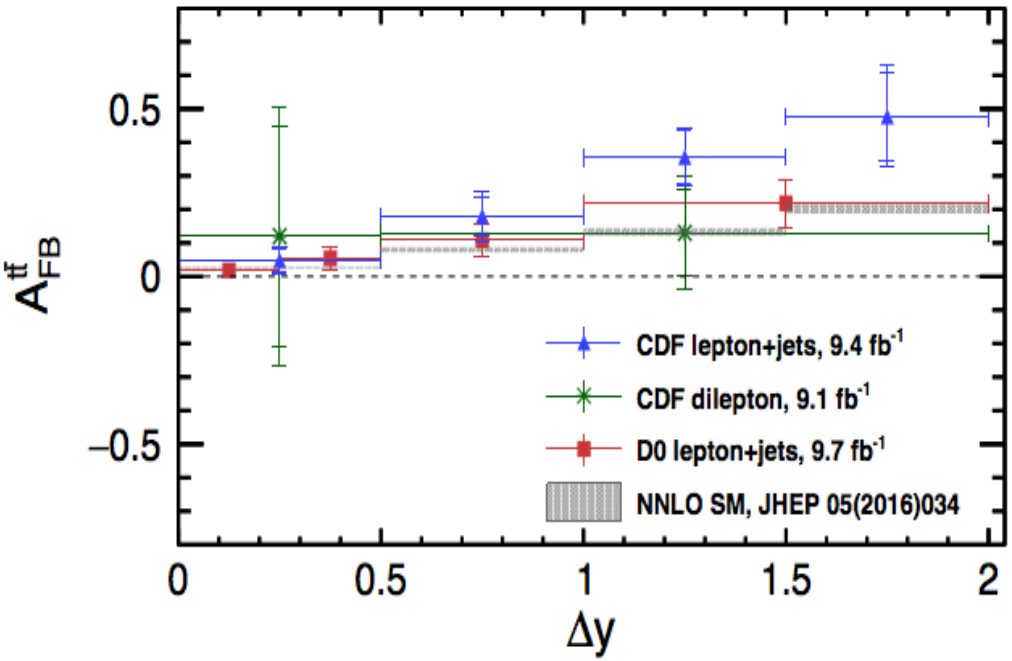
Note: the three asymmetry measurements are correlated!



Fermilab Conference Note: FERMILAB-CONF-16-386-PPD

Asymmetry: work in progress

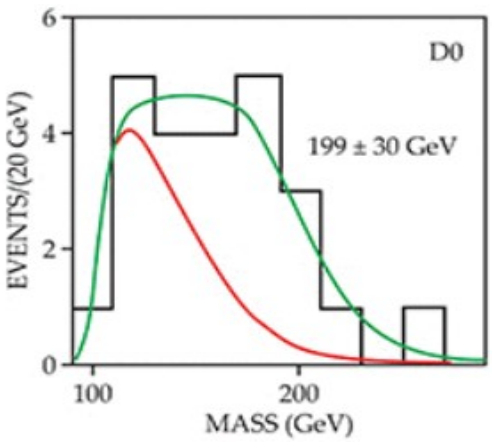




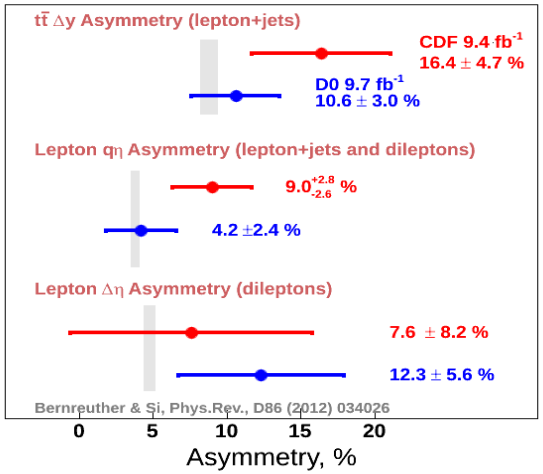
- Work on the differential asymmetry combination
  - Determine the combination bins
  - Account for the bin-to-bin correlations
  - Combine the systematic uncertainties

Conclusion: D0 & Tevatron Top Studies

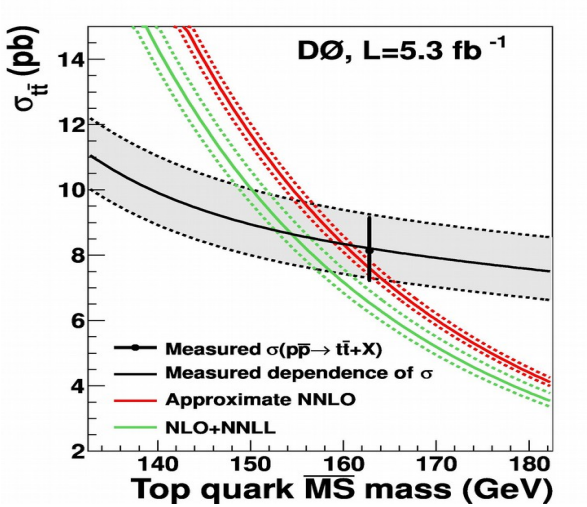
1995: Top Quark Discovery



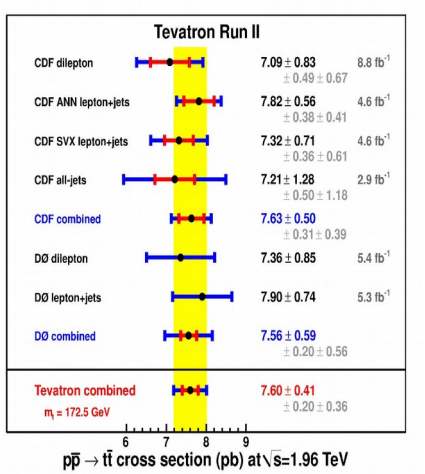
$t\bar{t}$ asymmetry



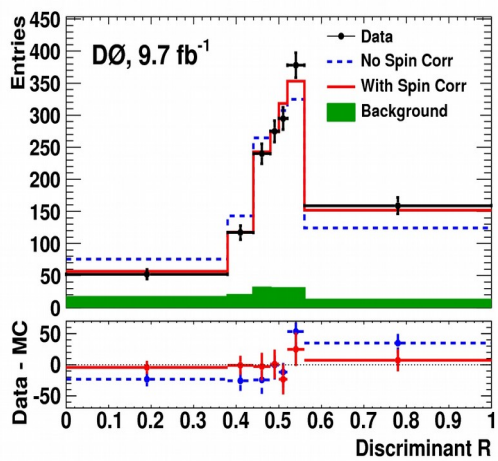
Pole and $\overline{MS}$ top quark mass



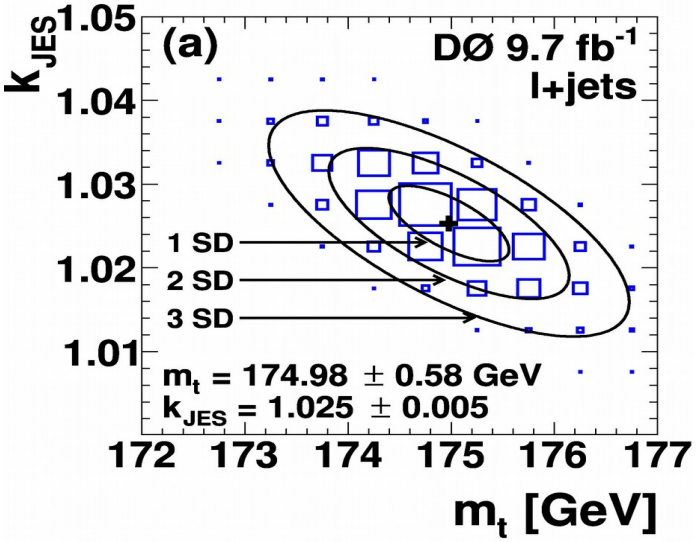
$t\bar{t}$ cross section



spin correlation

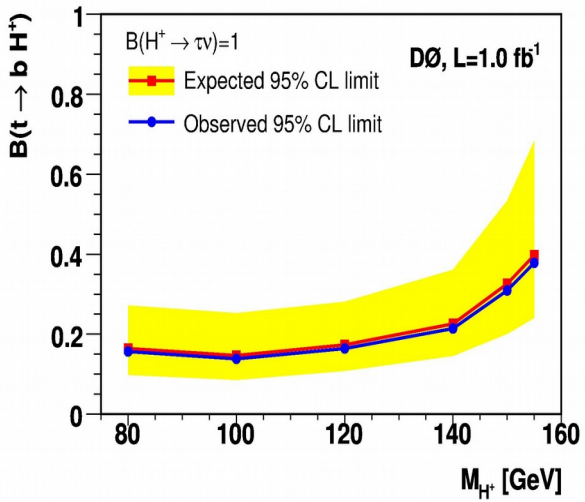


mass measurement with a precision 0.4%!

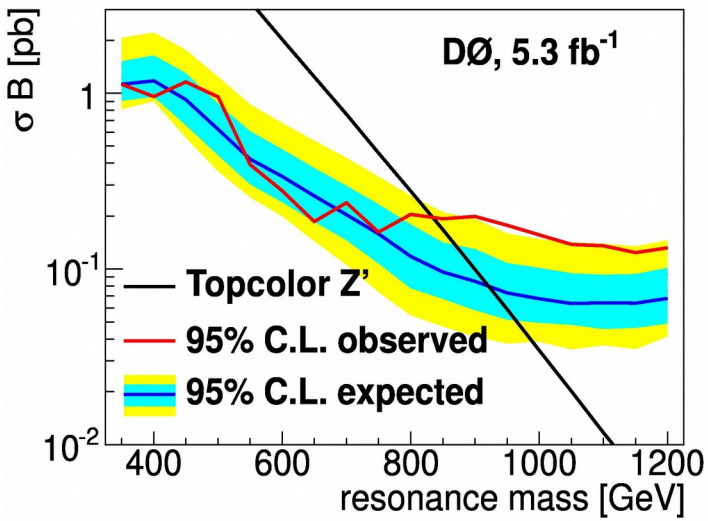


Conclusion: D0 & Tevatron Top Studies

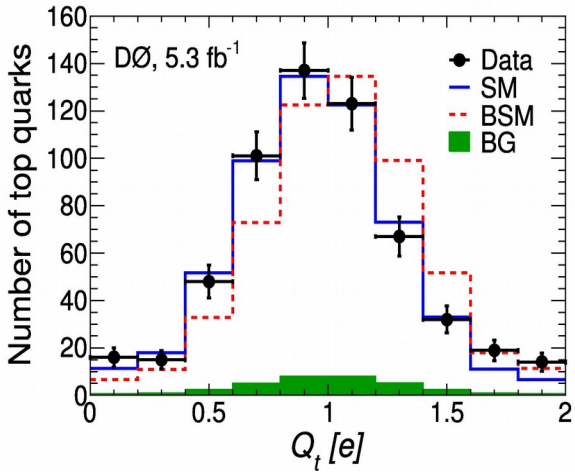
Charge Higgs



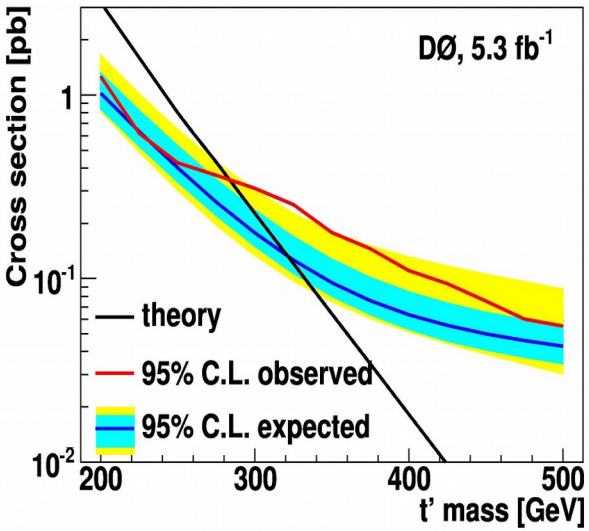
$t\bar{t}$ resonances



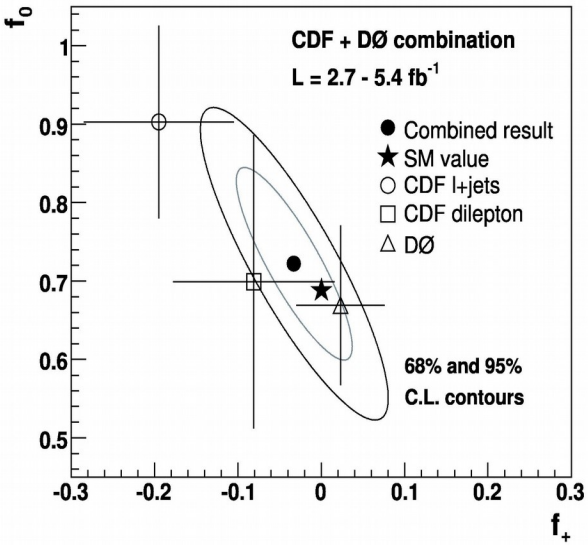
top quark electric charge



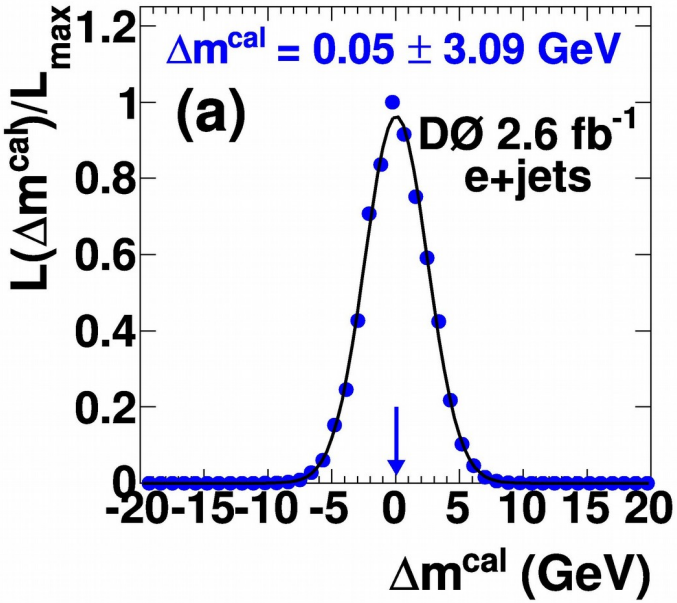
4 generation t' search



W boson helicity

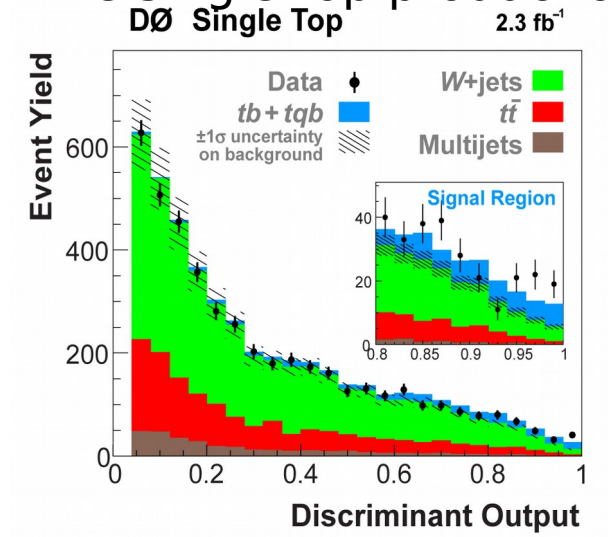


Mass difference between t and $\bar{t}$

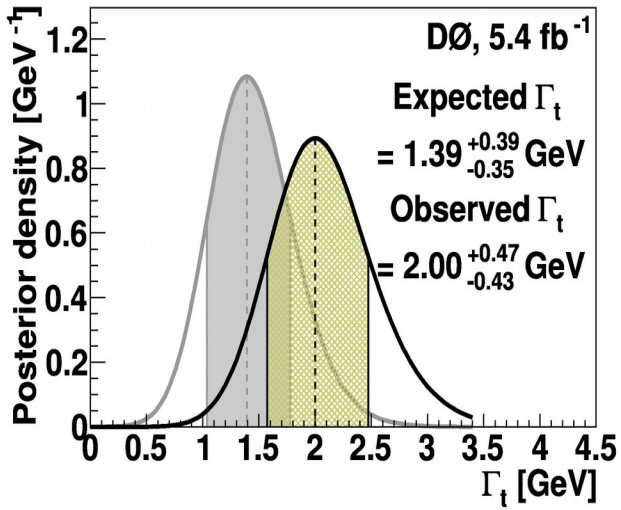


Conclusion: D0 & Tevatron Top Studies

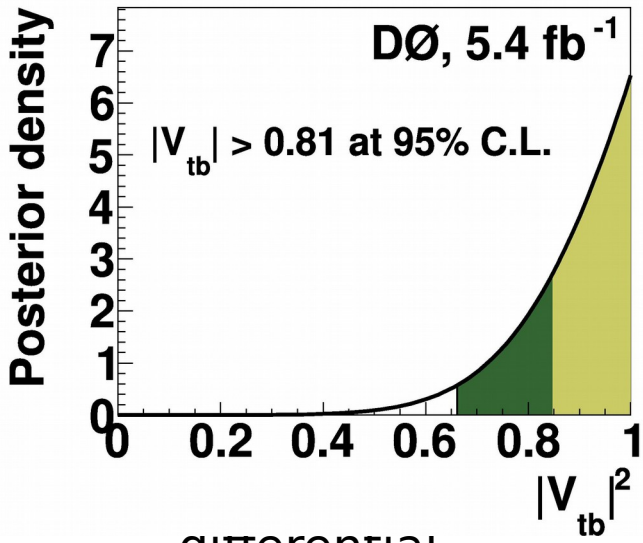
2009: observation of the single top production.



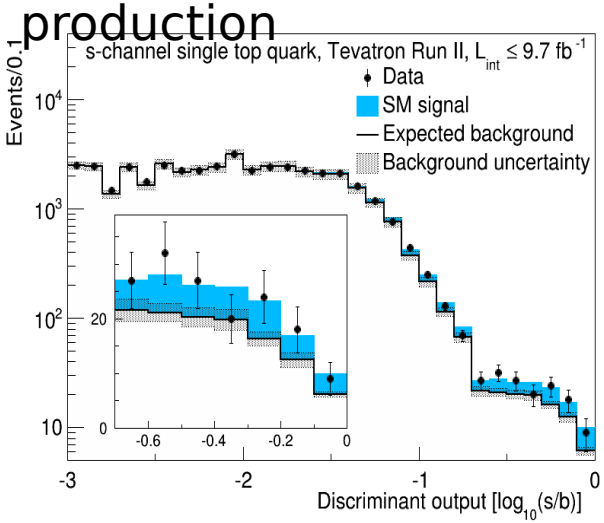
Top quark width



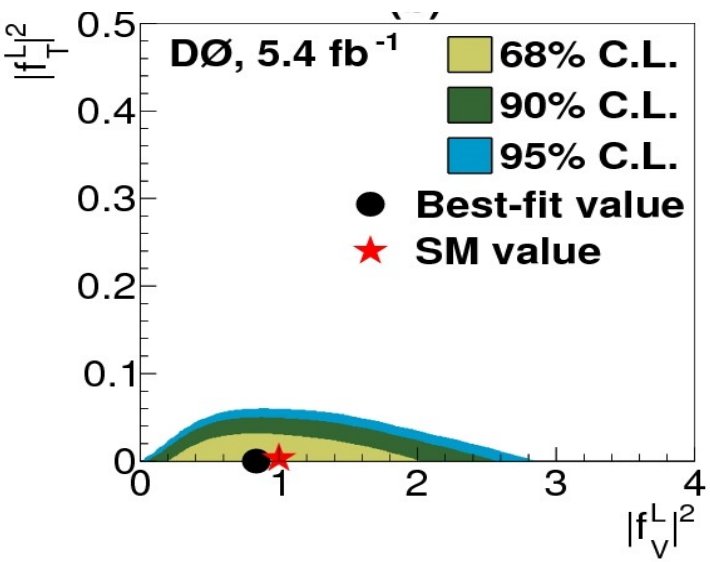
V_{tb} matrix element



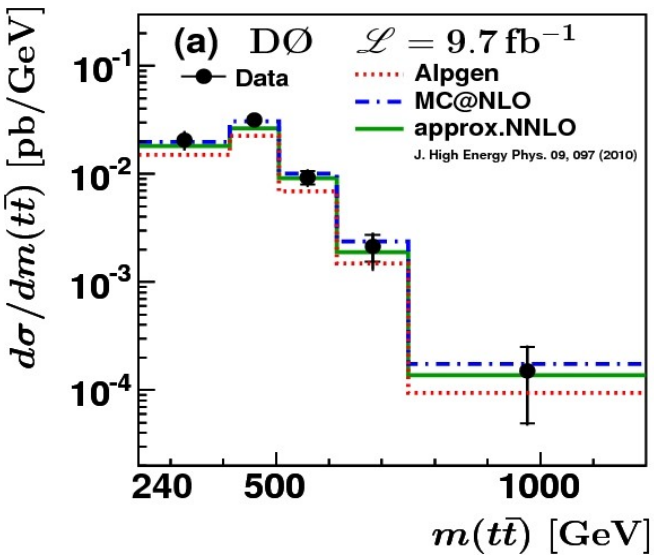
2014: observation of s-channel single top production



Anomalous top quark couplings



differential cross-section



The DØ Collaboration

Fermilab

Congratulations
FERMILAB!

Additional Materials

D0 l+jet measurements, 9.7 fb^{-1}

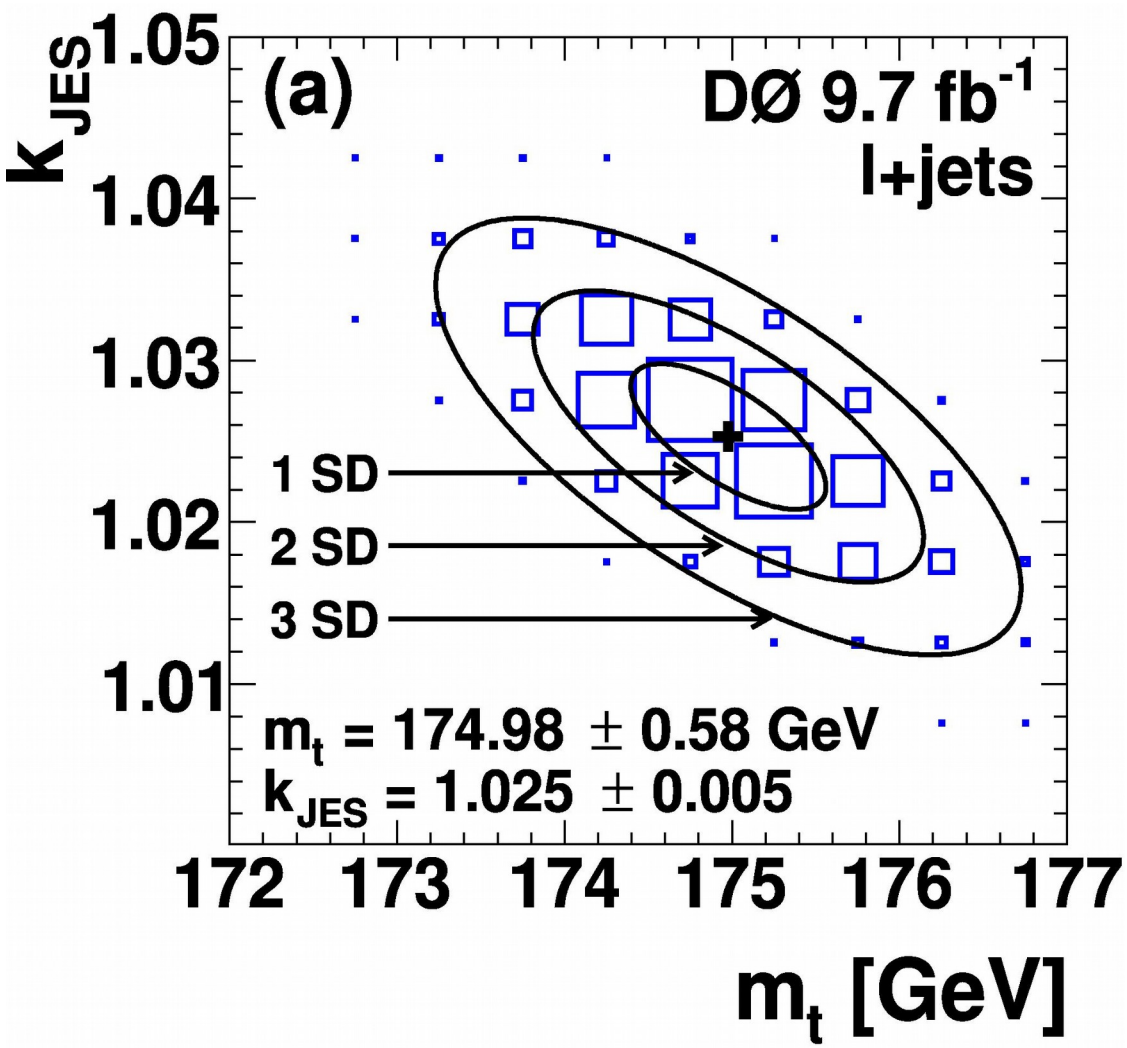
- Full D0 data set.
- Selections
  - Exactly one electron or muon with $p_T > 20$ GeV, $|\eta_e| < 1.1$, $|\eta_\mu| < 2.0$
  - Exactly four jets $p_T^{leading} > 40$ GeV, $p_T > 20$ GeV
  - One or more b-tagged jets (efficiency ~ 65%, mistag rate ~5%)
  - MET < 20 GeV + topological cuts

- Simulation
  - $t\bar{t}$: Alpgen +Pythia (D0 modified tune A), CTEQ 6L1 PDFs
  - W+jets : Alpgen+Pythia
  - W+cc, W+bb: Alpgen+Pythia
  - Multijets events : from data

Contribution	e+jets			μ+jets		
$t\bar{t}$	918.11	±	3.63	824.88	±	3.48
W+jets	77.85	±	2.13	101.03	±	2.93
W+HF	125.98	±	2.12	162.21	±	2.81
Multijet	144.41	±	24.19	48.17	±	16.11
Other backgrounds	97.75	±	0.51	79.24	±	0.94
Expected	1364.10	±	24.65	1215.53	±	17.00
Observed	**1502**			**1286**		

Expected signal fraction ~68%

Results



m_{top} = 174.98 ± 0.41(stat) ±0.41(JES) ±0.49(syst) GeV

Precision: 0.44%

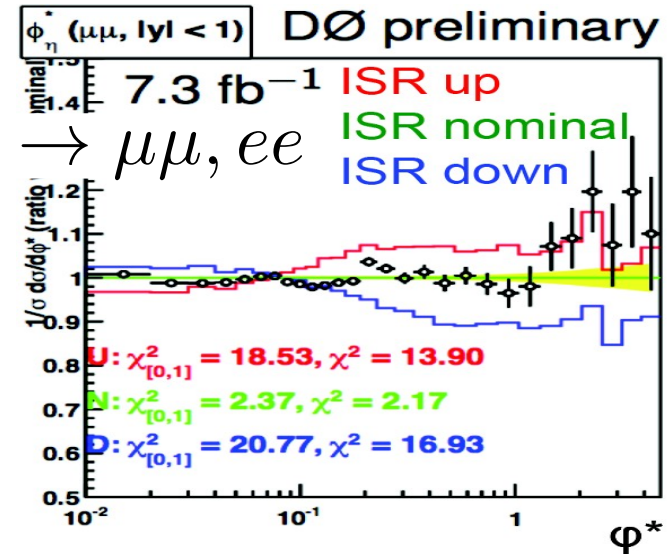
Systematic Uncertainties Estimation

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections	+0.15
Initial/final state radiation	±0.09
Hadronization and underlying event	+0.26
Color reconnection	+0.10
Multiple $p\bar{p}$ interactions	−0.06
Heavy flavor scale factor	±0.06
b quark jet modeling	+0.09
Parton distribution functions	±0.11
Detector modeling:	
Residual jet energy scale	±0.21
Flavor-dependent response to jets	±0.16
b tagging	±0.10
Trigger	±0.01
Lepton momentum scale	±0.01
Jet energy resolution	±0.07
Jet identification efficiency	−0.01
Method:	
Modeling of multijet events	+0.04
Signal fraction	±0.08
MC calibration	±0.07
Total systematic uncertainty	±0.49
Total statistical uncertainty	±0.58
Total uncertainty	±0.76

MC@NLO +Herwig – Alpgen + Herwig

Vary renormalisation scale in Alpgen by 1.5

$Z \to \mu\mu, ee$



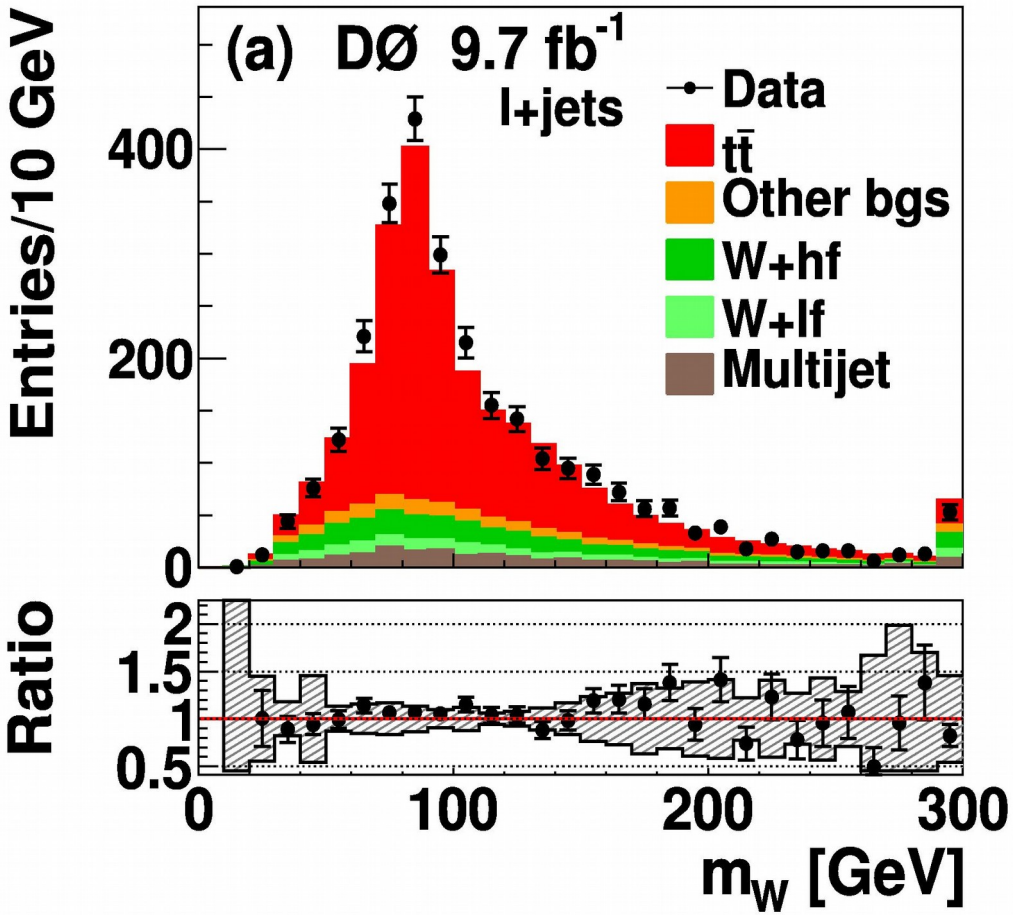
Alpgen +Herwig – Alpgen + Pythia
for particle-level jets

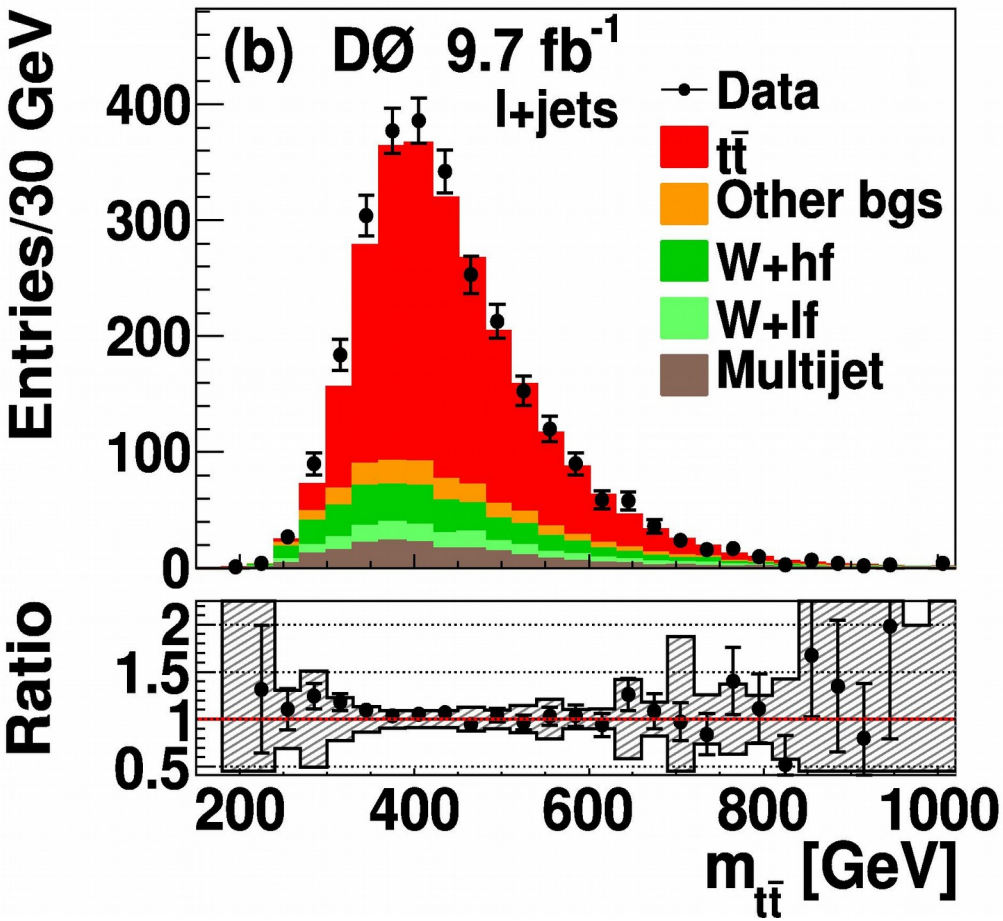
Pythia, Perugia 2011 – Perugia 2001NOCR

Phys. Rev. D 91, 112003 (2015)

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

D0 l+jet measurements, 9.7 fb^{-1}





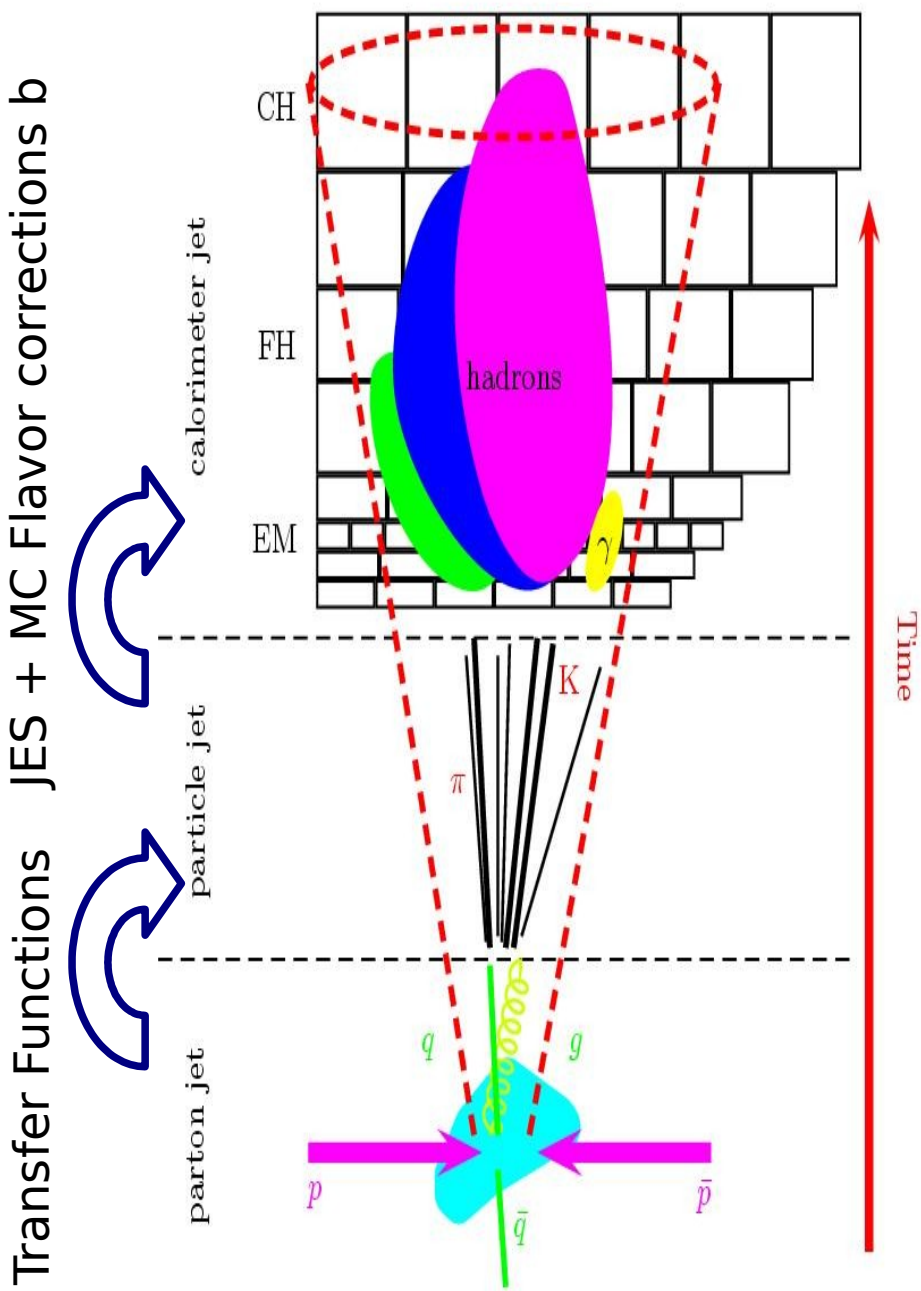
JES at D0

- Jet Energy Scale: correct reconstructed jet energy to the particle level
  - Absolute JES
  - Separately measured for data and MC

$$E_{jet} = \frac{E_{meas} - E_{offset}}{R_{esponse} \cdot S_{howring}}$$

- Flavor dependent correction : different response correction for gluon, light quark, b-quarks (b-JES)
  - Tune the single particle response difference between data and MC in γ+jets and dijets events

$$F_{corr} = \frac{1}{<F>_{\gamma+jet}} \frac{\Sigma_i E_i R_i^{data}}{\Sigma_i E_i R_i^{MC}}$$



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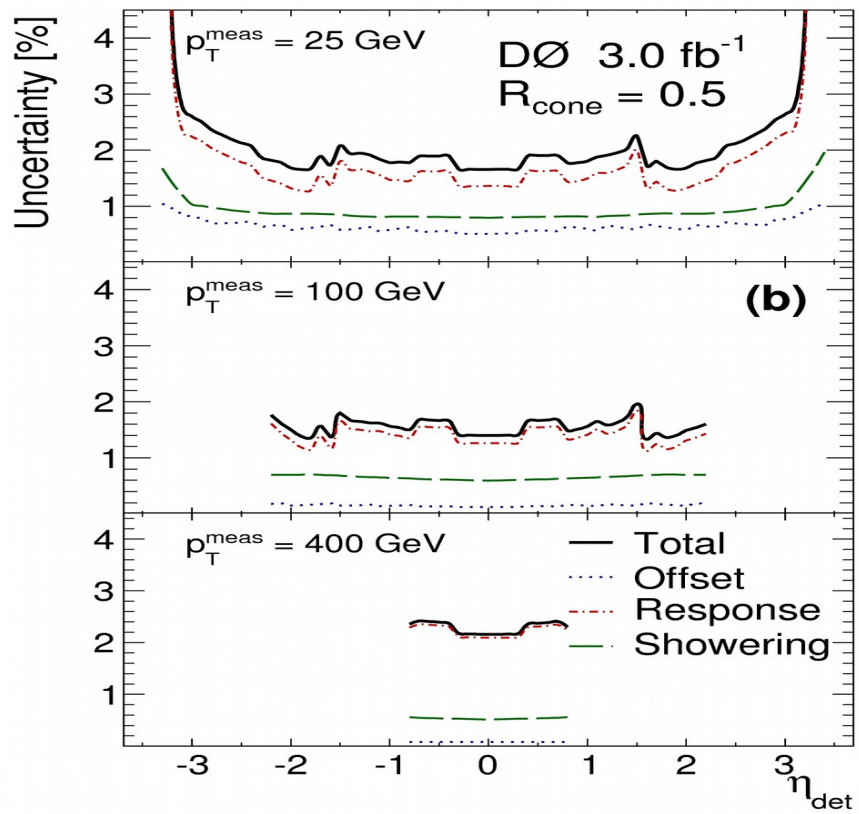
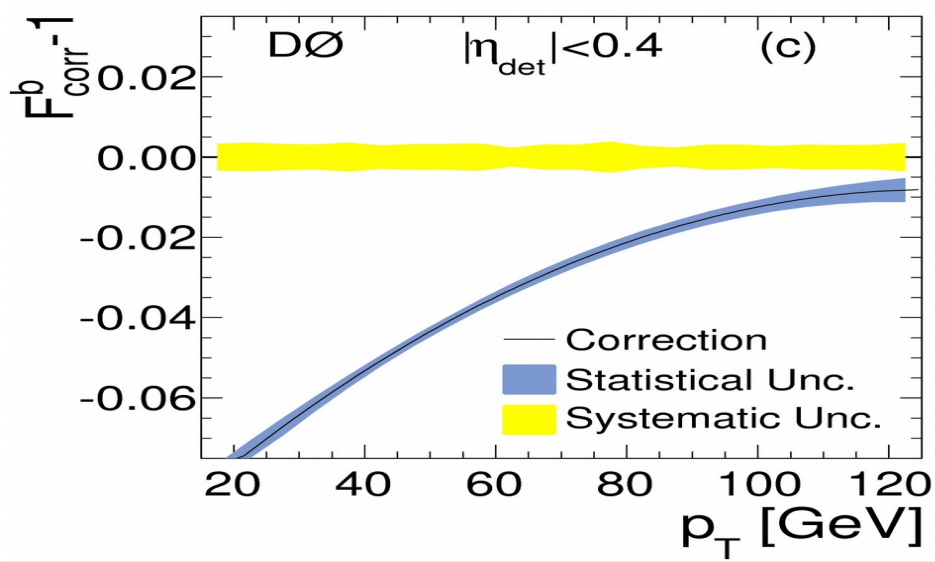
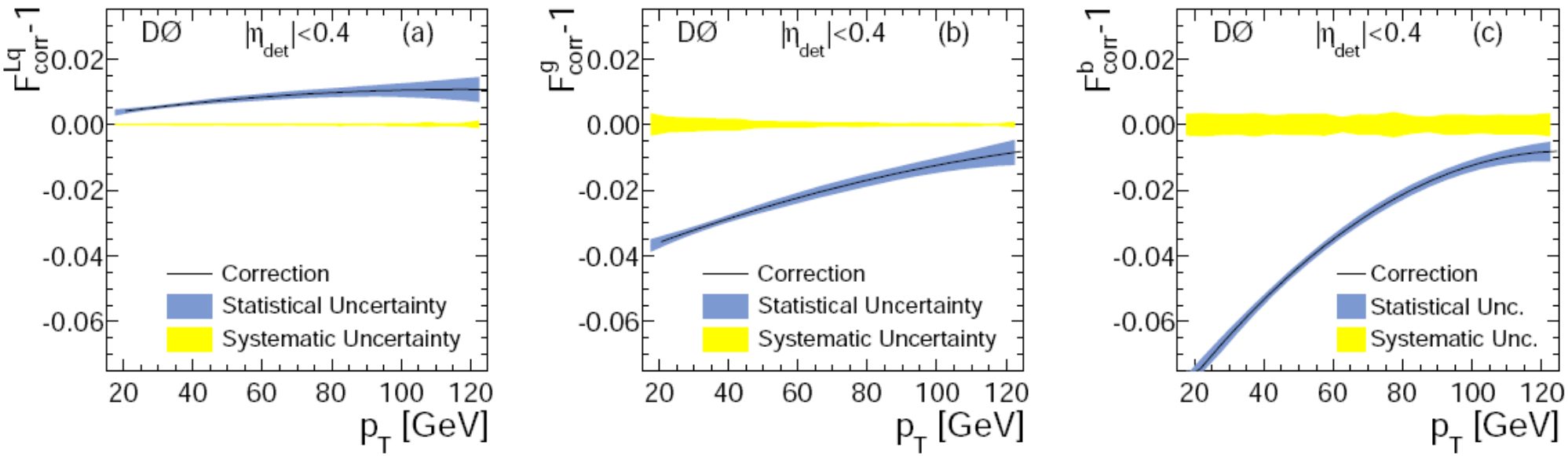




D0 b-JES


DØ
$|\eta_{det}|<0.4$
(a)
$F^{Lq}_{corr}-1$
Correction
Statistical Uncertainty
Systematic Uncertainty
p_T [GeV]
DØ
$|\eta_{det}|<0.4$
(b)
$F^{g}_{corr}-1$
Correction
Statistical Uncertainty
Systematic Uncertainty
p_T [GeV]
DØ
$|\eta_{det}|<0.4$
(c)
$F^{b}_{corr}-1$
Correction
Statistical Unc.
Systematic Unc.
p_T [GeV]

Spin Correlation and Gluon Fraction

$$O = (1 - f_{gg})O_{q\bar{q}} + f_{gg}O_{gg} \ .$$

Assuming $O_{q\bar{q}} \approx 1$, the gluon fraction becomes

$$f_{gg} \approx \frac{1 - O}{1 - O_{gg}}, \qquad O_{gg} = -0.36 \pm 0.02$$

$$\boxed{f_{gg} = 0.08 \pm 0.12(\text{stat}) \pm 0.11(\text{syst}) = 0.08 \pm 0.16(\text{stat+syst})}$$