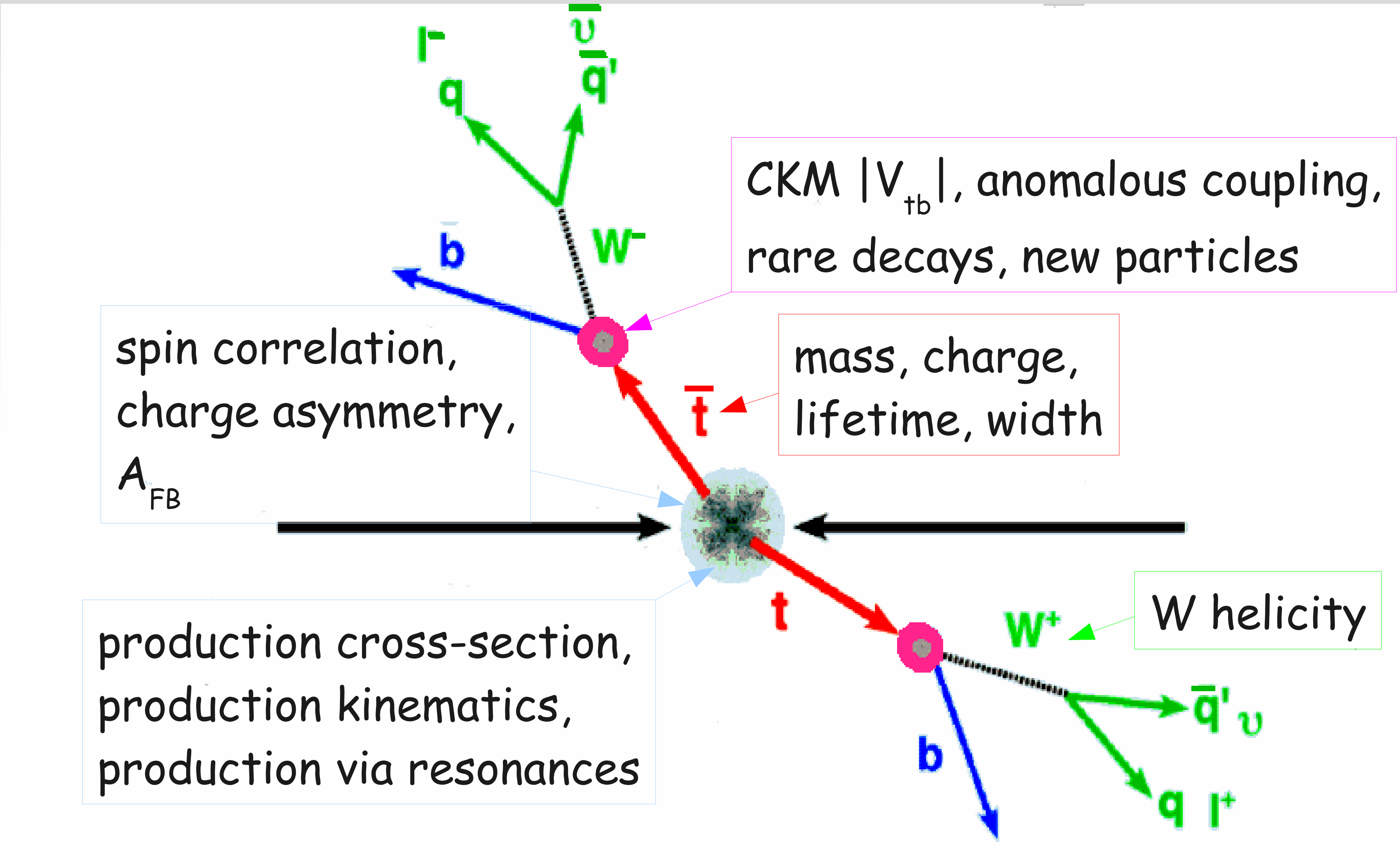
Top Quark Properties



Top Quark Mass Measurement

- Possible to measure the quark mass
- Important ingredient for SM precision tests: $B \to X_s \gamma$ and $K_L \to \pi^0 \nu\nu$
- Help verify the Higgs sector due to the relationship with W and H
- Measure the mass from the reconstructed decay products has low precision due to the presence of jets and neutrino. Use other methods.

Template method

- Choose an observable, x, sensitive to m_T
- x can be: lepton Pt, reconstructed top mass, decay length
- Predict the x distribution as a function of m_T using Monte Carlo
- For each event evaluate the likelihood for each m_T value
- Maximize the likelihood for the entire sample

Matrix Element

- Use all information from the event integration over the least known variables

Top Quark Mass Measurement: Template Method

Method: build top mass and JES template for signal and background
Use the templates as pdf in the Likelihood. Extract top mass and JES

Hadronic decay channel

Reconstruct the event kinematic by minimizing:

$$\chi^2 = \frac{\left(m_{jj}^{(1)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jj}^{(2)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jjb}^{(1)} - m_t^{rec}\right)^2}{\Gamma_t^2} + + \frac{\left(m_{jjb}^{(2)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \sum_{i=1}^{n} \frac{\left(p_{T,i}^{fit} - p_{T,i}^{meas}\right)^2}{\sigma_i^2}$$

mjj = invariant mass of two light jets

mjjb = invariant mass of three jets

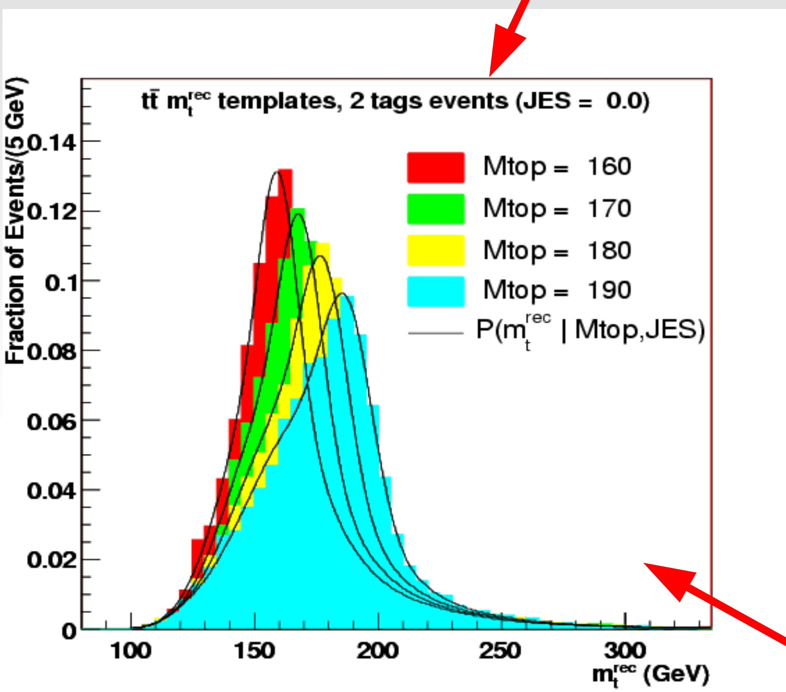
P_T^{fit} =top transv. momentum

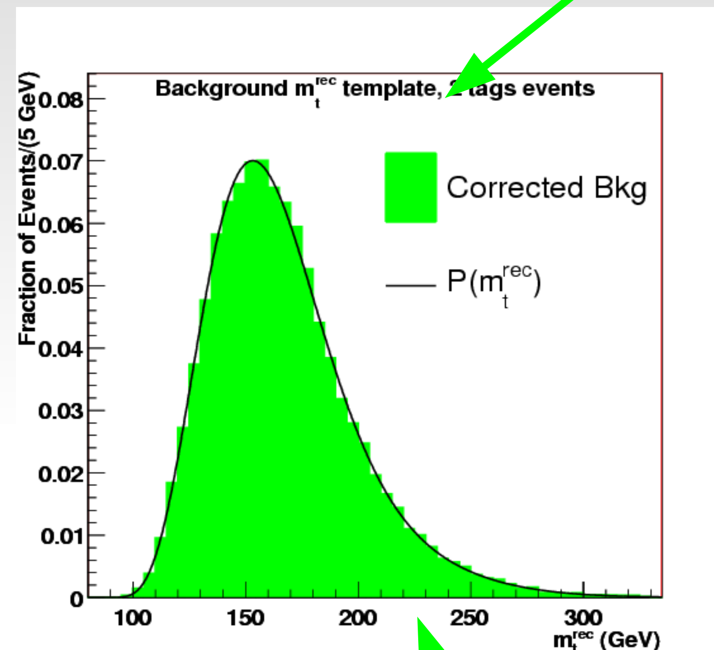
For each permutation we obtain m_t^{rec} this forms the template for signal (MC) and background (data)

Top Quark Mass Measurement: Template Method

Signal template: Monte Carlo data

Background template: data





$$L_{tot} = L_{M_{top}} + L_{JES}$$

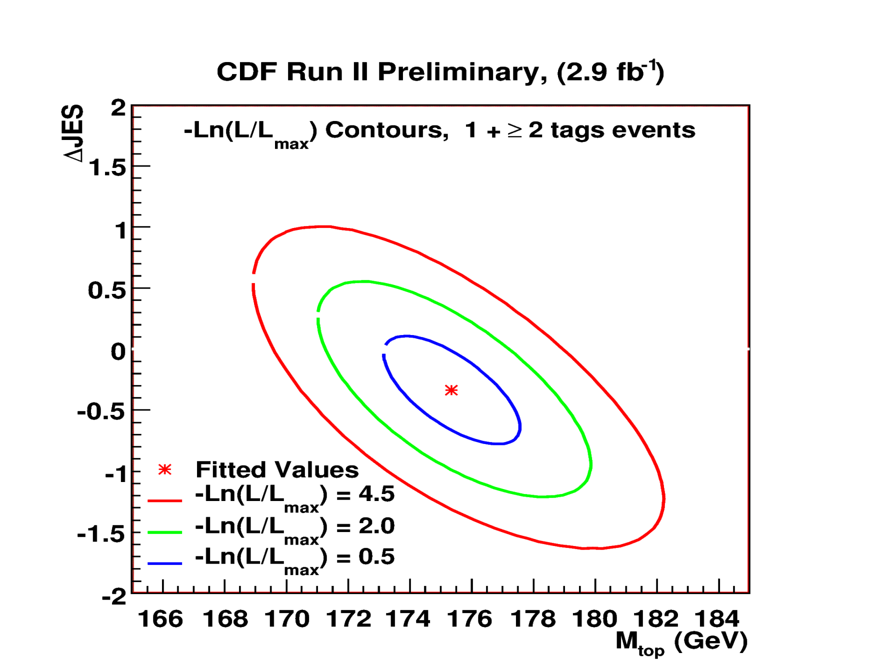
$$\mathcal{L}_{M_{top}} = \prod_{i=1}^{N_{obs}} \frac{n_s \cdot P_{sig}^{m_t^{rec}}(m_{t,i} \mid M_{top}, JES) + n_b \cdot P_{bkd}^{m_t^{rec}}(m_{t,i})}{n_s + n_b}$$

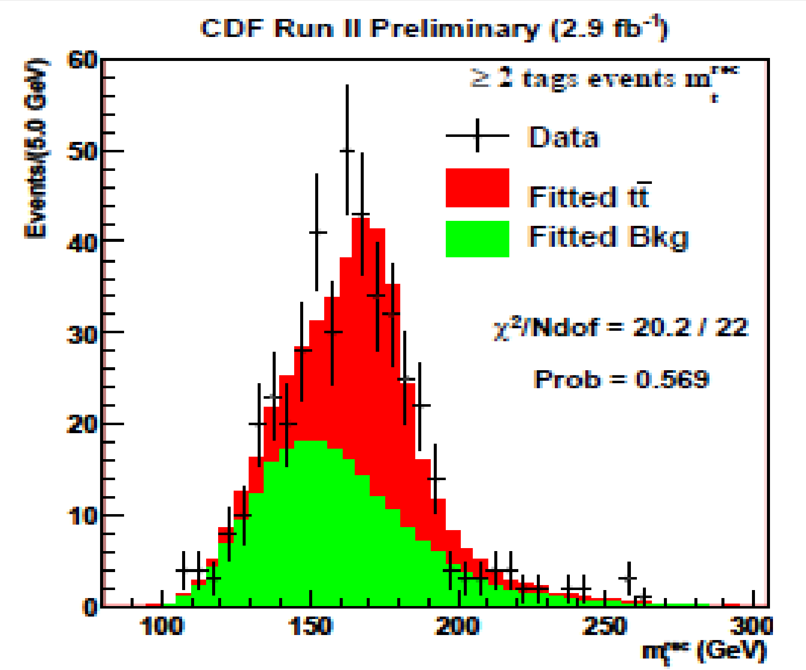
$$\mathcal{L}_{JES} = \prod_{i=1}^{N_{obs}} \frac{n_s \cdot P_{sig}^{m_W^{rec}}(m_{W,i} \mid M_{top}, JES) + n_b \cdot P_{bkd}^{m_W^{rec}}(m_{W,i})}{n_s + n_b}$$

The 2 free parameters are: top mass and JES

Top Quark Mass Measurement: Template Method

Tevatron all hadronic decay channel





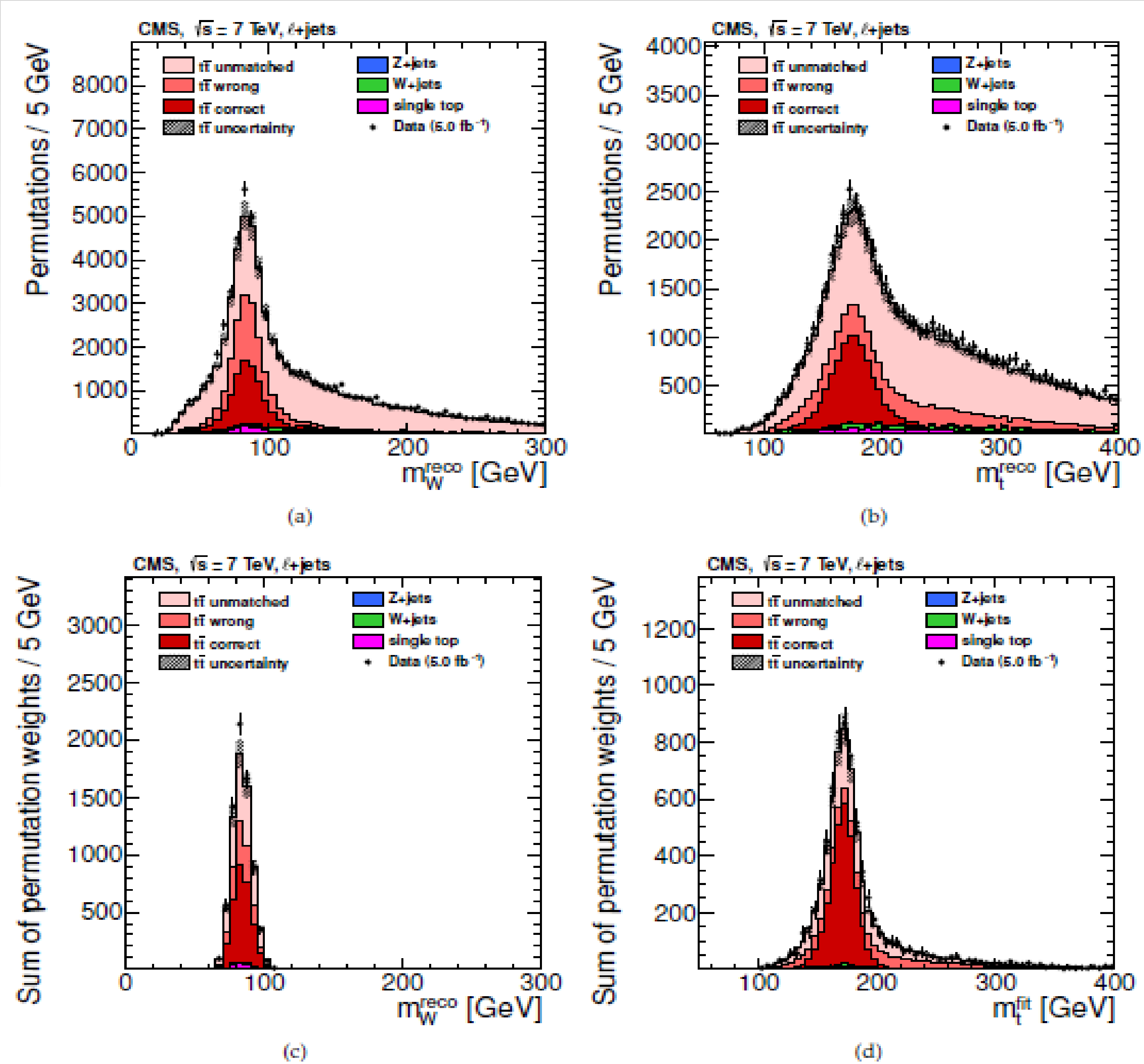
Top Quark Mass Measurement: Template Method

LHC- CMS

μ/e+jets

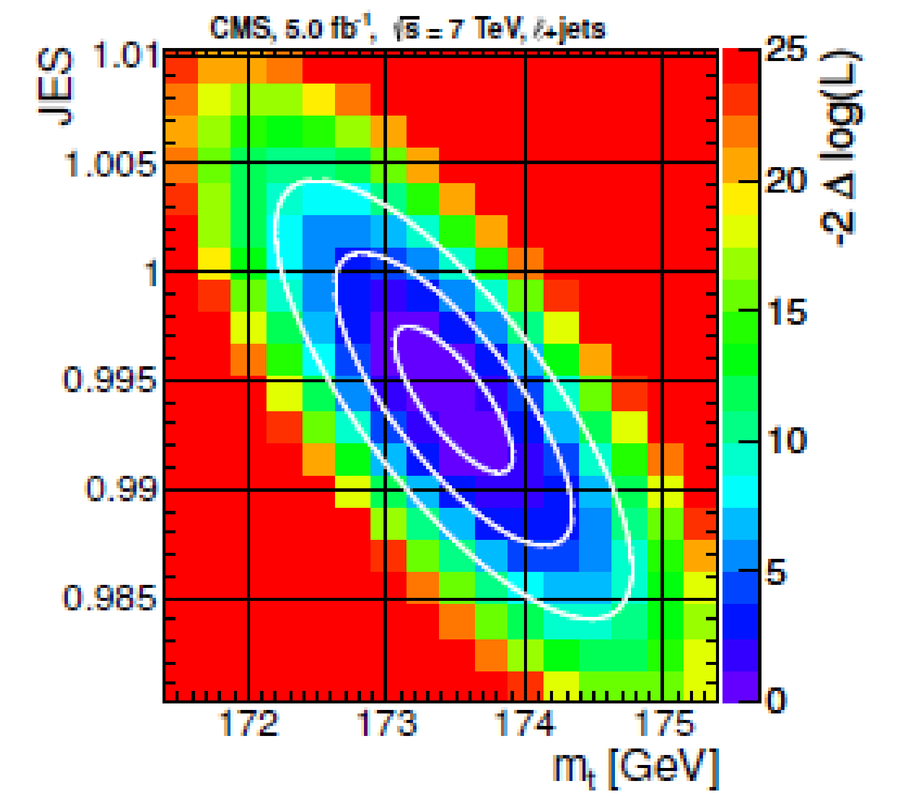
decay channel

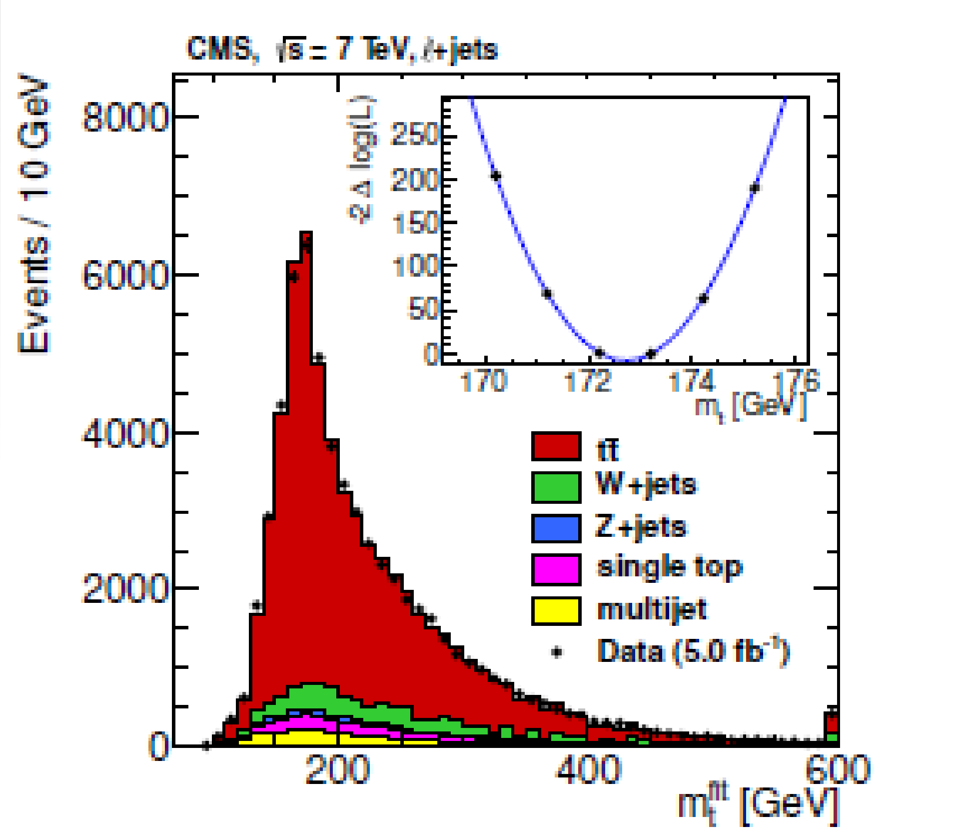
Comparison of M_W and M_t^{reco} before and after the constrain



Top Quark Mass Measurement: Template Method

LHC- CMS μ/e+jets decay channel - Results





Top Quark Mass Combination

ATLAS

- Dileptons ATLAS-CONF-2013-077

  $173.09 \pm 0.64_{stat} \pm 1.50_{syst}$ GeV

- Lepton+jets ATLAS-CONF-2013-046

  $172.31 \pm 0.23_{stat} \pm 1.53_{syst}$ GeV

CMS

- Dileptons EPJC 72 (2012) 2202

  $172.50 \pm 0.43_{stat} \pm 1.46_{syst}$ GeV

- Lepton+jets JHEP 12 (2012) 105

  $173.49 \pm 0.27_{stat} \pm 1.03_{syst}$ GeV

- All jets arXiv:1307.4617, *sub. to EPJC*

  $173.49 \pm 0.69_{stat} \pm 1.30_{syst}$ GeV

Only quoting results used in grand combinations

CDF

- Dileptons
  - Run I PRL 82 , 271 (1999): $167.4 \pm 10.3_{stat} \pm 4.9_{syst}$
  - Run II PRD 83 , 111101 (2011): $170.28 \pm 1.95_{stat} \pm 3.09_{syst}$
- Lepton+jets
  - Run I PRD 63, 032003 (2001): $176.1 \pm 5.1_{stat} \pm 5.3_{syst}$
  - Run II PRL 109 152003: $172.85 \pm 0.52_{stat} \pm 0.98_{syst}$
- All jets
  - Run I PRL 79, 1992–1997 (1997): $186.0 \pm 10.0_{stat} \pm 5.7_{syst}$
  - Run II PLB 714, 24 (2012): $172.47 \pm 1.43_{stat} \pm 1.49_{syst}$
- Lxy
  - Run II PRD 81, 032002 (2010): $166.90 \pm 9.0_{stat} \pm 2.90_{syst}$
- MEt
  - Run II PRD 88, 011101(R) (2013): $173.95 \pm 1.26_{stat} \pm 1.35_{syst}$

D0

- Dileptons
  - Run I PRD 60 , 052001: $168.4 \pm 12.3_{stat} \pm 3.6_{syst}$
  - Run II PRD 86 , 051103 (2012): $174.00 \pm 2.36_{stat} \pm 1.44_{syst}$
- Lepton+jets
  - Run I Nature 429 , 638 (2004): $180.1 \pm 3.6_{stat} \pm 3.9_{syst}$
  - Run II PRD 84, 032004 (2011): $174.94 \pm 0.83_{stat} \pm 1.24_{syst}$

Top Quark Mass Combination Method

Best Linear Unbiased Method (BLUE)
- Linear combination of all measurements
- Set of coefficients (weights) minimizes final uncertainty (optimal
- Individual uncertainties and correlations are into account for the final uncertainty

Correlations are very important:
- For correlated measurements may yield negative weights for less precise measurements
- Major correlations sources: JES (light quark and b quark jets) and theoretical model

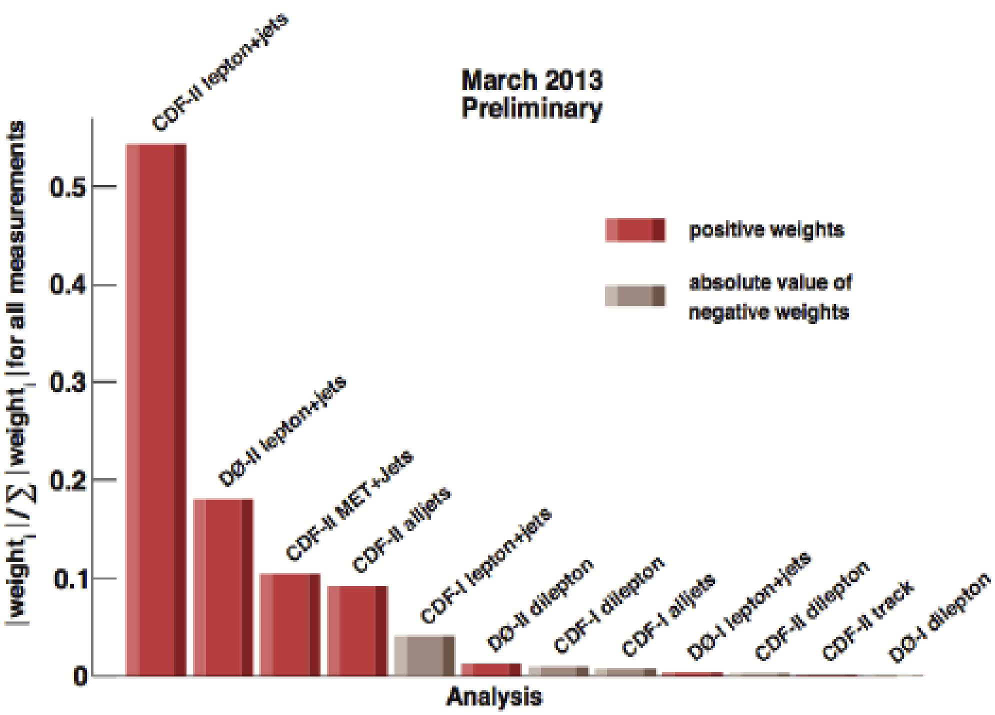
Top Quark Mass Combination Results Tevatron

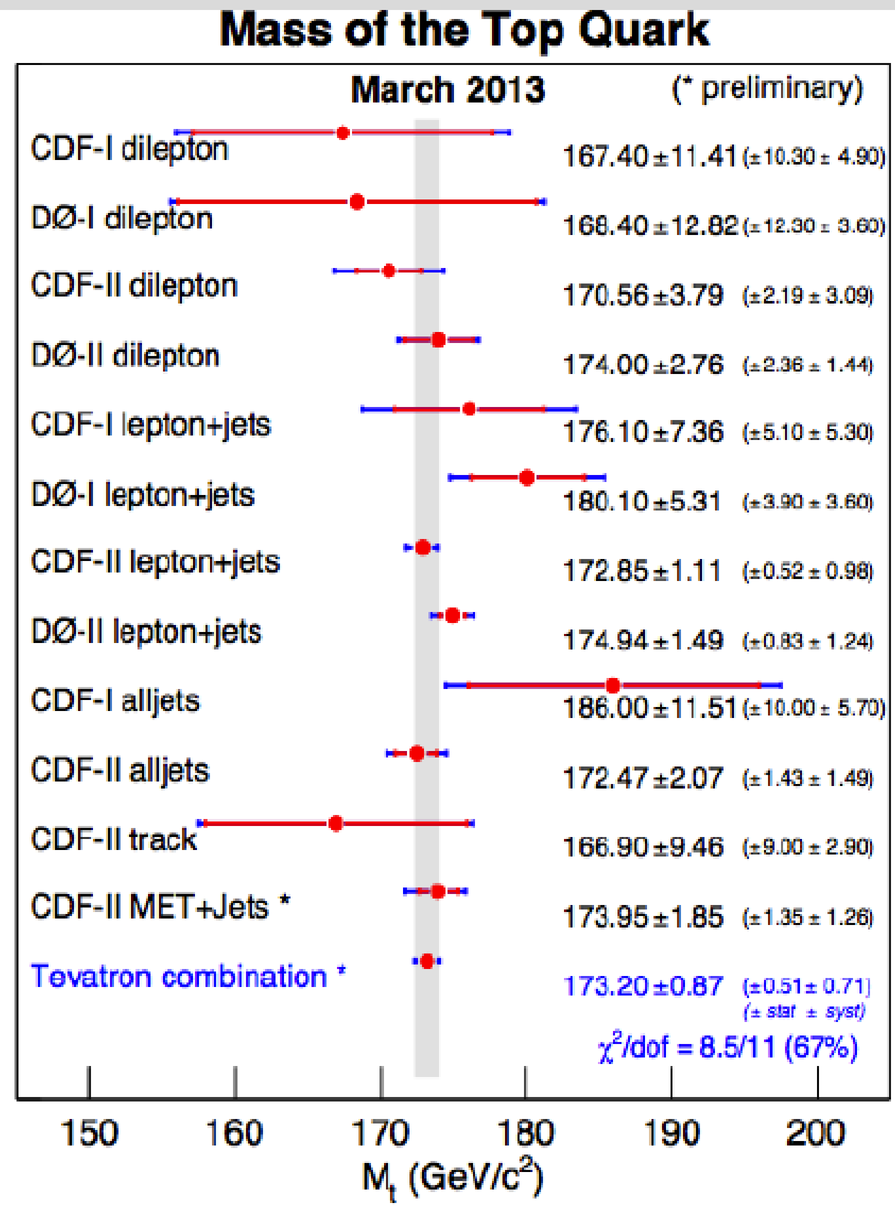
- Measured with 0.5% precision

$$M_t = 173.20 \pm 0.51\,(\text{stat}) \pm 0.71\,(\text{syst})\ \text{GeV}$$

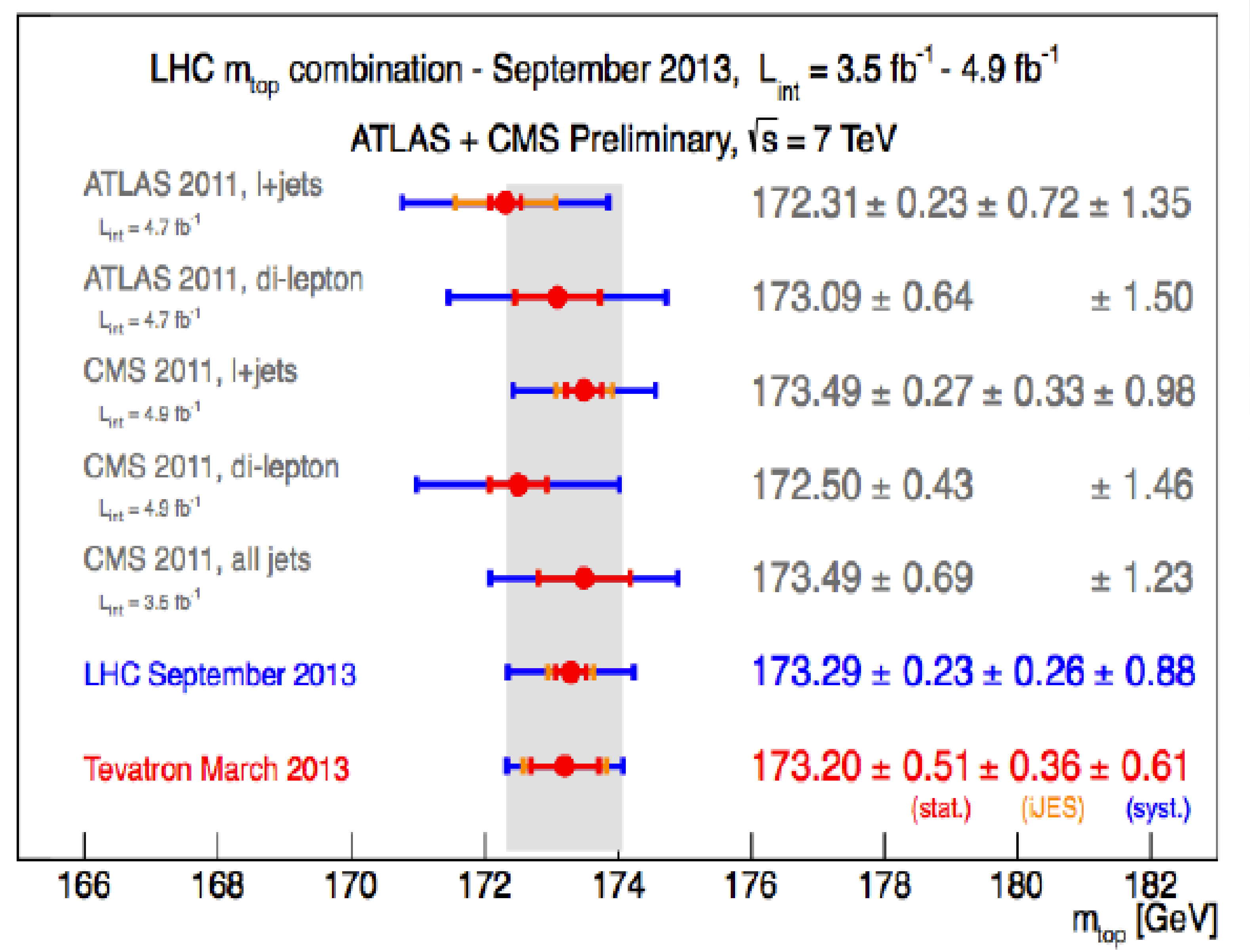
χ^2 /ndf=8.5/11 corresponds to 67% probability

Individual pulls within 1.5σ



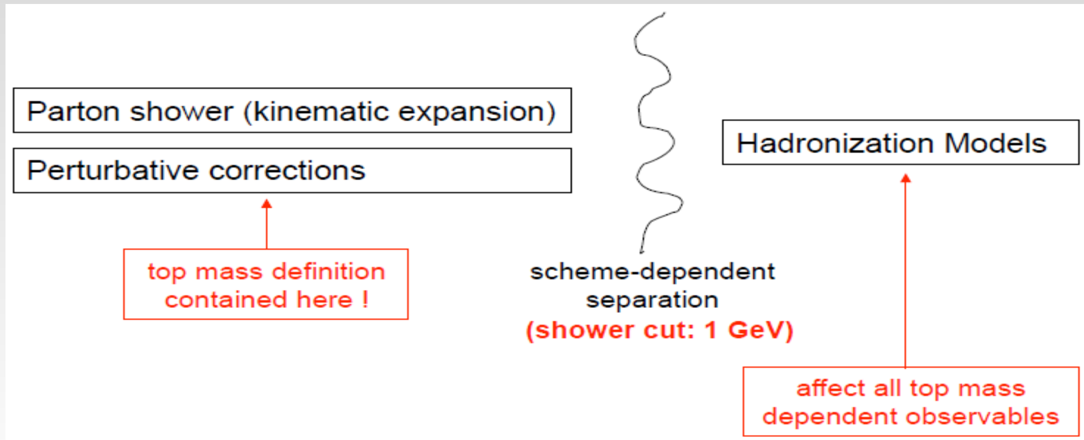


Top Quark Mass Combination Results LHC



Top Quark Mass: What are we measuring?

- Direct Mtop measurements make heavy usage of Monte Carlo



- So we measure the Monte Carlo top mass! What is in the Monte Carlo?
- Masses in Quantum Field theory:

  Pole mass: based on the concept of free particle, usable only in perturbation theory ($i\frac{\not p+m}{p^2-m^2+i\epsilon}$), does not apply to quark

  MS (Mass Scheme): m_{top}^{pole} + corrections due to the interaction

  Conclusion $m_{top}^{MC}(R_{sc}) = m_{top}^{pole} - R_{sc}\, c\left[\frac{\alpha_s}{\pi}\right]$ $R_{sc} \approx 1\, GeV$ Shower cut-off

Detailed discussion: http://arxiv.org/abs/0808.0222v2

Top Mas Measurements from jets and the Tevatron Top-Quark Mass A. H. Hoang, I. W. Stewart and https://indico.desy.de/getFile.py/access?contribId=30&sessionId=9&resId=0&materialId=slides&confId=7095

Top Quark Mass Measurement from Cross Section

- The top quark mass can be extracted from the cross section measurement using final states that have weak dependence on the top mass. The measured cross section is compared to the NNLO theory prediction where the top mass is a parameter and can be defined in a not ambiguous way
- This measurement is a important QCD test where the σ(m_{top}^{pole}) is verified.
- Method used:
  - The theoretical cross section as function of m_{top}^{pole} is calculated using different NNLO approximation.
  - Cross section parametrization is extracted from data:

$$\sigma_{t\bar{t}}(m_t^{\mathrm{MC}}) = \frac{1}{(m_t^{\mathrm{MC}})^4}\left[a + b(m_t^{\mathrm{MC}} - m_0) + c(m_t^{\mathrm{MC}} - m_0)^2 + d(m_t^{\mathrm{MC}} - m_0)^3\right].$$

Parameters a, b determined from data

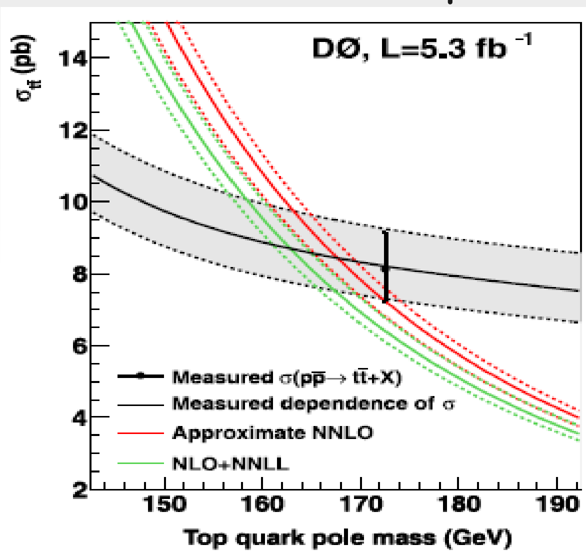
m_0=170 GeV

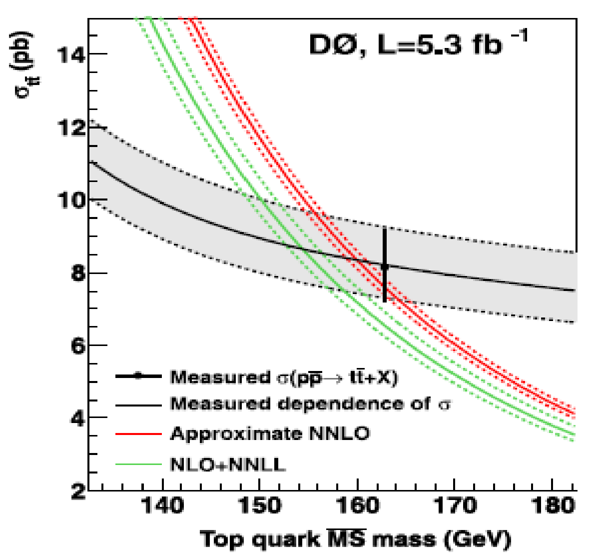
Top Quark Mass Measurement from Cross Section

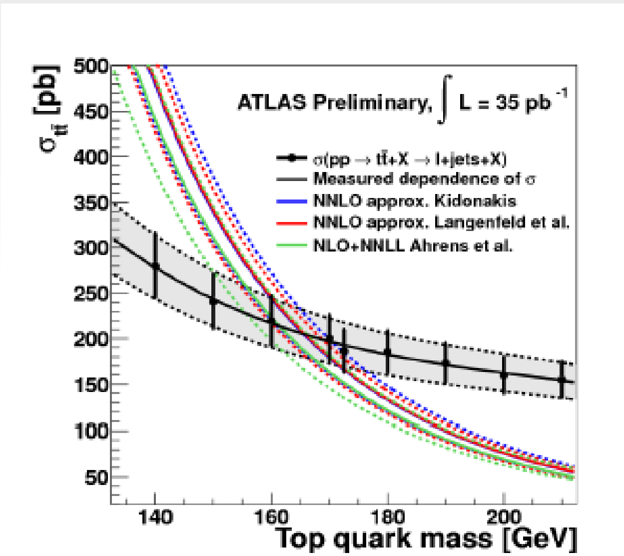
Mtop is determined from the joint likelihood

$$L(m_t) = \int f_{\mathrm{exp}}(\sigma|m_t)\left[f_{\mathrm{scale}}(\sigma|m_t) \otimes f_{\mathrm{PDF}}(\sigma|m_t)\right] d\sigma$$

Experimental function   Theoretical function







→ D0: $m_t^{pole} = 167.5\ ^{+5.4}_{-4.9}$ - precision: ~ 3%

inputs: experimental: ~ 12%, theory: ~ 3%

→ ATLAS: $m_t^{pole} = 166.4\ ^{+7.8}_{-7.3}$ - precision: ~ 4.5%

inputs: experimental: ~ 13% , theory: ~ 5 %

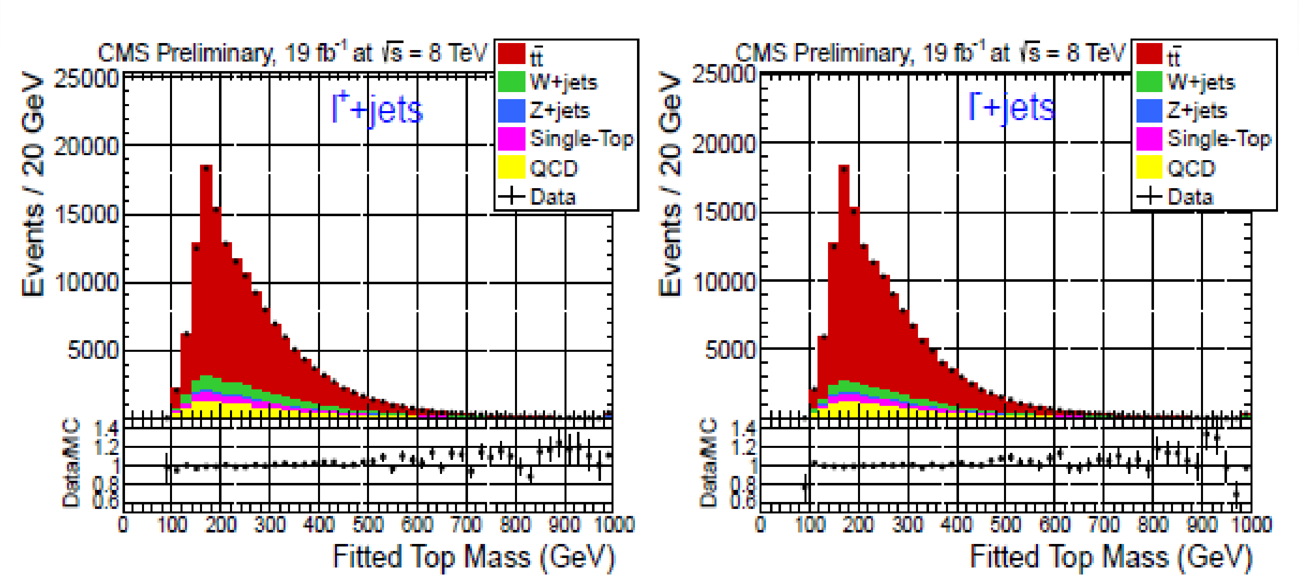
→ CMS: $m_t^{pole} = 176.7\ ^{+3.8}_{-3.4}$ - precision: ~ 2%

inputs: experimental: ~ 4 %, theory: ~ 4 %

Top-anti-Top Quark Mass Difference

With the top quark is possible to test the CPT invariance in the quark system. The data used to measure the mass is also fitted for the mass difference Δm.

CMS measure the m_{top} and $m_{anti\text{-}top}$ by applying analysis separately to l^-+jets events and to l^++jets events, and take the difference of the two extracted values.



$$\Delta m_t = -272 \pm 196\ (\text{stat.})\ \text{MeV}.$$

Top-anti-Top Quark Mass Difference

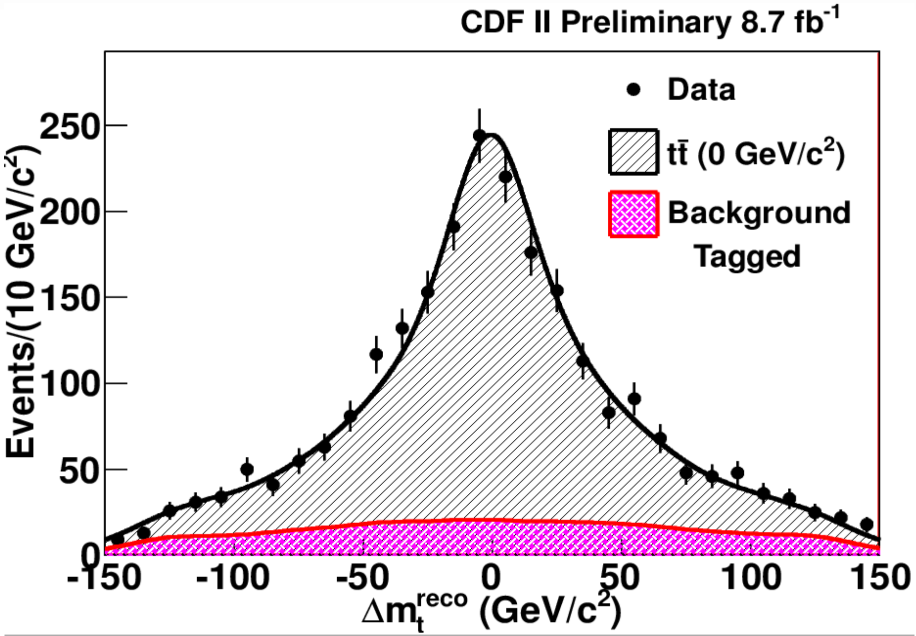
With the top quark is possible to test the CPT invariance in the quark system. The data used to measure the mass is also fitted for the mass difference Δm.

Tevatron measure Δm.

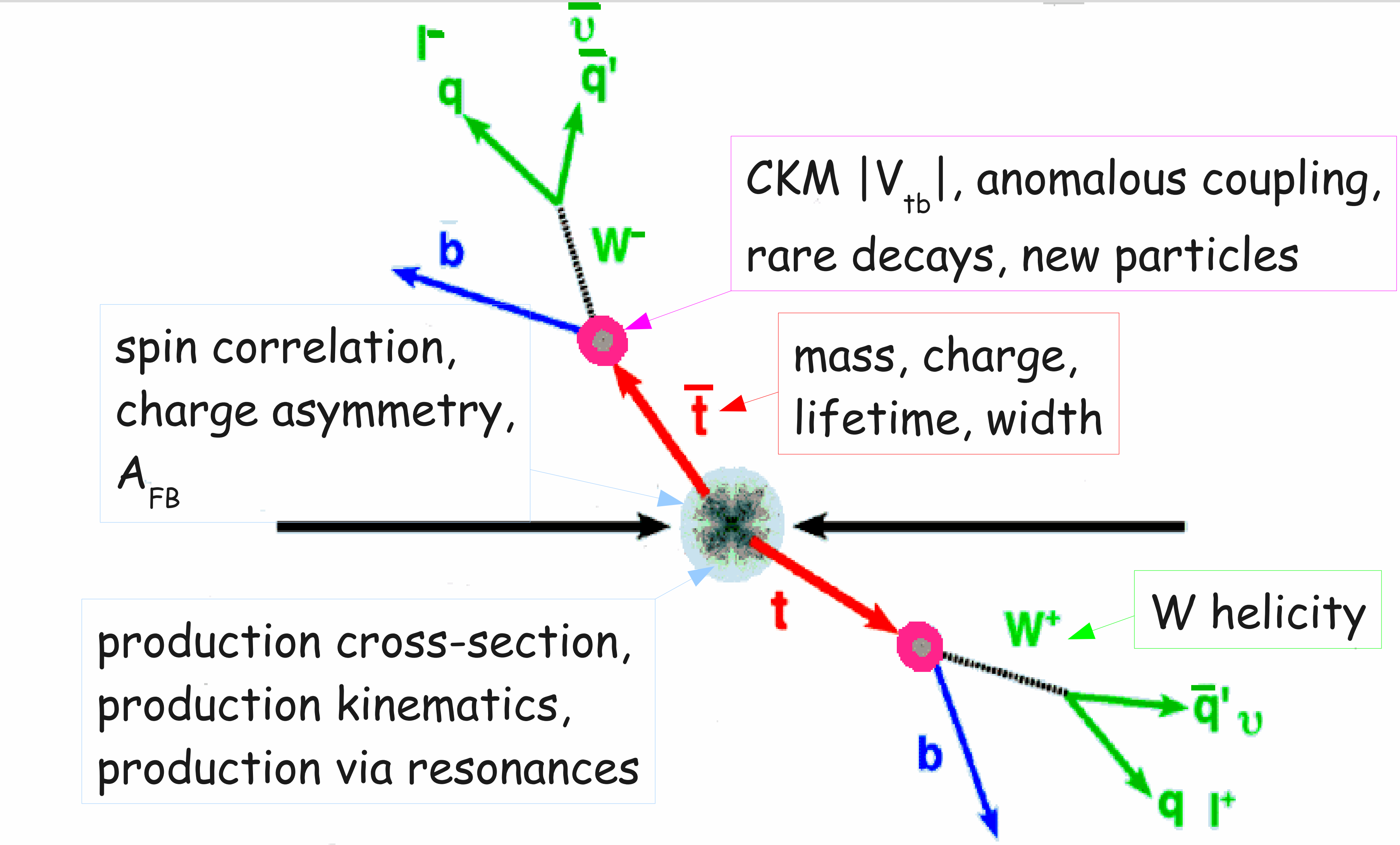
The t and t-bar flavor determination is done using the electric charge of the lepton (Q_{lepton}), defining $\Delta m_{reco} = -Q_{lepton} \times dm_{reco}^{min}$

$$
\begin{aligned}
\chi^2 &= \Sigma_{i=\ell,4jets}(p_T^{i,fit} - p_T^{i,meas})^2/\sigma_i^2 \\
&+ \Sigma_{k=x,y}(U_{T_k}^{fit} - U_{T_k}^{meas})^2/\sigma_k^2 \\
&+ (M_{jj} - M_W)^2/\Gamma_W^2 + (M_{\ell\nu} - M_W)^2/\Gamma_W^2 \\
&+ \{M_{bjj} - (\overline{M}_{top} + dm_{reco}/2)\}^2/\Gamma_t^2 \\
&+ \{M_{b\ell\nu} - (\overline{M}_{top} - dm_{reco}/2)\}^2/\Gamma_t^2,
\end{aligned}
$$

$$
\begin{aligned}
\Delta M_{top} &= -1.95 \pm 1.11\ (\text{stat}) \pm 0.59\ (\text{syst})\ \text{GeV}/c^2 \\
&= -1.95 \pm 1.26\ \text{GeV}/c^2.
\end{aligned}
$$



Top Quark Properties



CKM V_{tb} measurement: Introduction

- In the SM SU(2)xU(1) quarks and leptons are assigned to be left-handed doublets and right-handed singlet
- Quark mass eigenstates are not the same as the weak eigenstates, the matrix relating these bases defined for 6 quarks and parametrized by Kobayashi and Maskawa by generalization of 4 quark case described by the Cabibbo angle
- By convention, the matrix is often expressed in terms of a 3x3 unitary matrix, V, operating on the charge -1/3 quark eigenstates (d,s,b):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Elements depend on 4 real parameters (3 angles and 1 CPV phase)
V_{CKM} is the only source of CPV in the SM

CKM V_{tb} measurement

V_{tb} can be measured using top events in two different way:

1. indirect, by using $t\bar{t}$ events
2. direct with single-top events

1. the ratio R= $\frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$ is obtained from

events with 0, 1 and 2 tags (two different taggers are used)

$$N_{00} = n_0 + (1-\varepsilon_l)(1-\varepsilon_s)n_1 + (1-\varepsilon_l)^2(1-\varepsilon_s)^2 n_2 + F_{00}$$

$$N_{01} = \varepsilon_l(1-\varepsilon_s)n_1 + \varepsilon_l(2-\varepsilon_l)(1-\varepsilon_s)^2 n_2 + F_{01}$$

$$N_1 = \varepsilon_s n_1 + 2\varepsilon_s(1-\varepsilon_s)n_2 + F_1$$

$$N_2 = \varepsilon_s^2 n_2 + F_2$$

Number of background events

$$n_0 = N_{top}[a_0 + (1-R)a_1 + (1-R)^2 a_2]$$

$$n_1 = N_{top}[Ra_1 + 2R(1-R)a_2]$$

$$n_2 = N_{top}R^2 a_2$$

Number of $t\bar{t}$ events

$\epsilon_{s,l}$ a_i Tagging efficiency and acceptance

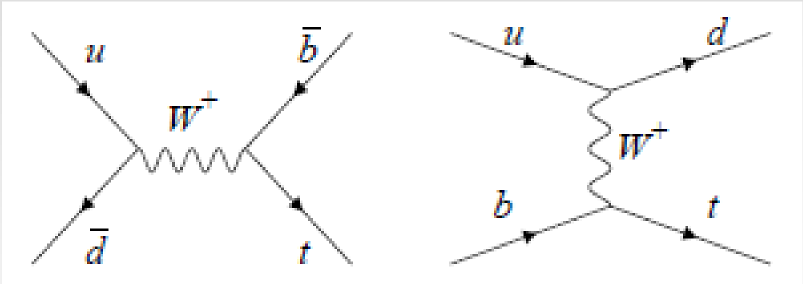
$R=0.94^{+0.31}_{-0.24}$

Three generation unitarity → denominator=1

$V_{tb}=0.97^{+0.16}_{-0.12}$

CKM V_{tb} measurement

2. Single top production is dominated by s and t channel



The cross section μ $|V_{tb}|^2$ from which it can be extracted:

$$|V_{tb}|^2_{\text{measured}} = \sigma^{\text{measured}}_{s+t} |V_{tb}|^2_{\text{SM}} / \sigma^{\text{SM}}_{s+t}$$

With the assumption that $t \rightarrow Wb$, $|V_{tb}|^2 >> |V_{td}|^2 + |V_{ts}|^2$

With the measured cross section

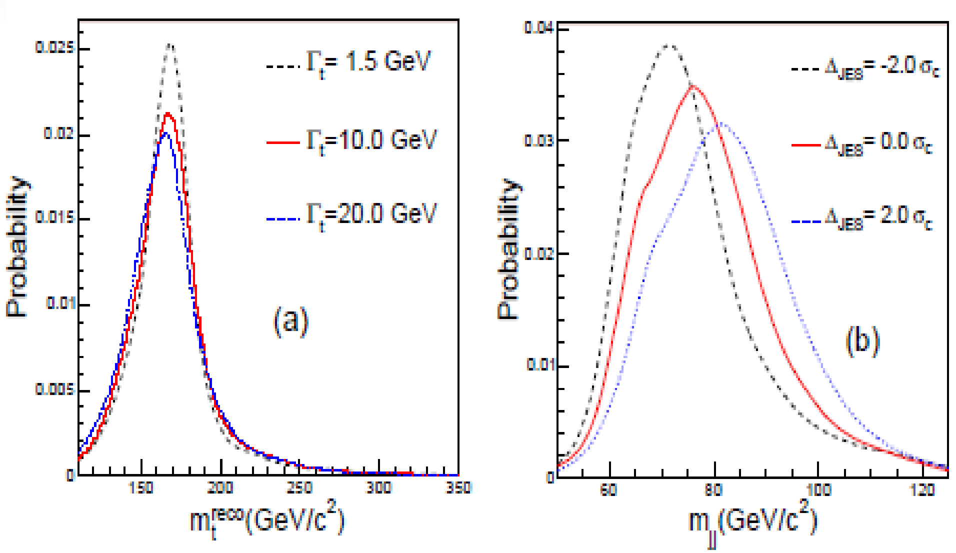
$$|V_{tb}| = 0.91 \pm 0.11(\text{stat.+syst.}) \pm 0.07(\text{theory})$$

Top Quark Width and Lifetime

At LO the total top width $\Gamma_t^0 = |V_{tb}|^2 G_F m_t^3 / 8\pi\sqrt{2}$

If $|V_{tb}| \approx 1$ $\Gamma_t^0 = 1.3\ GeV$ assuming m_{top}=172.5 GeV which correspond to a lifetime of 5×10^{-25} s. Deviation from the expected value could indicate new physics.

In events lepton+jets two observable are used : m_t^{reco} and m_{jj} and reconstructed for each event as function of Γ and ΔE

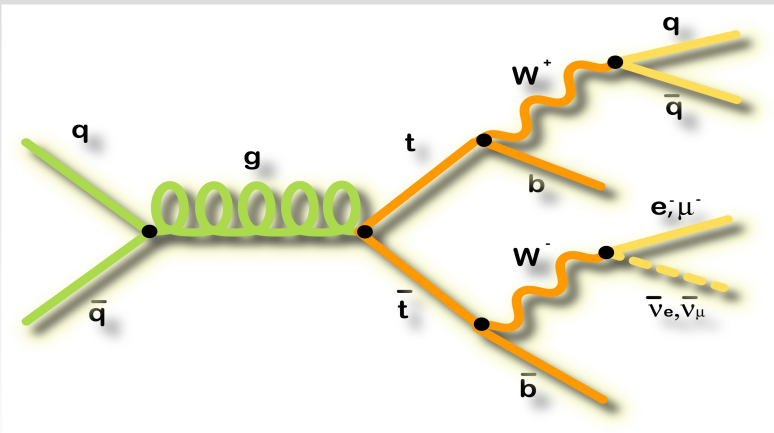


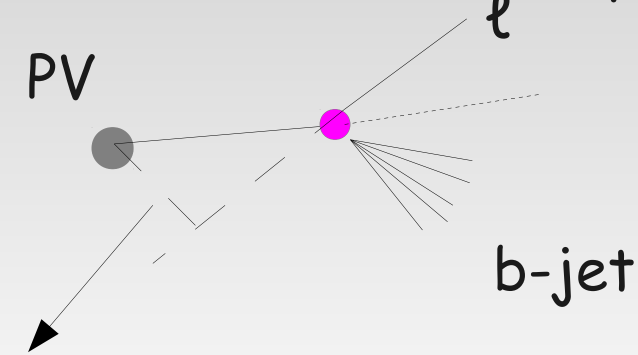
A likelihood, built using these template is minimized from which is extracted

Γ_t<7.6 GeV @95 CL

Top Quark Width and Lifetime

Top quark candidate are reconstructed in events with lepton + jets



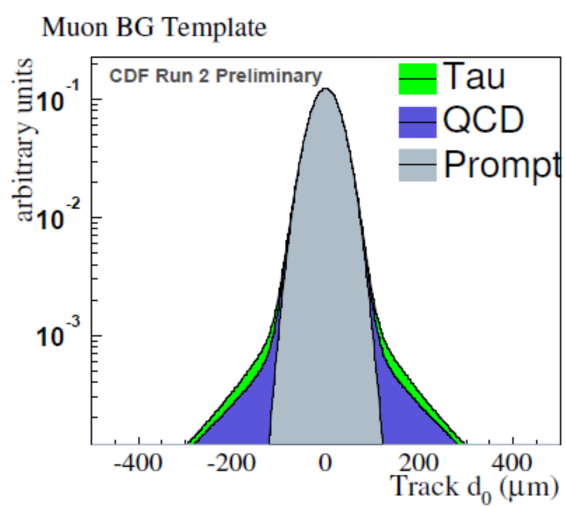


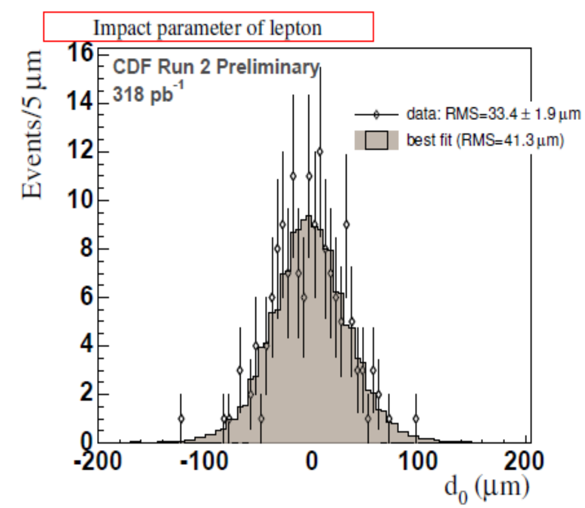
$$\delta = \beta \gamma c t \sin(\theta)$$

The impact parameter distribution is proportional to the lifetime.

The measured impact parameter distribution has several components:

- detector resolution
- background
- top quark





$c\tau < 52.5\mu m$

$\rightarrow 17.5 \times 10^{-14} s$

Top Quark Charge

In the SM top quark is supposed to have charge +2/3, $t \rightarrow W^+b$ but for long time its charge was not measured.

In hep-ph/9810531 it is proposed an exotic 4th generation model: what has been observed it is not the SM top but a particle of this family decaying $t \rightarrow W^-b$ with charge -4/3. In this scenario the top quark has mass ~230 GeV.

Top quark charge measurement: $t \rightarrow W^+b$ lepton+jets

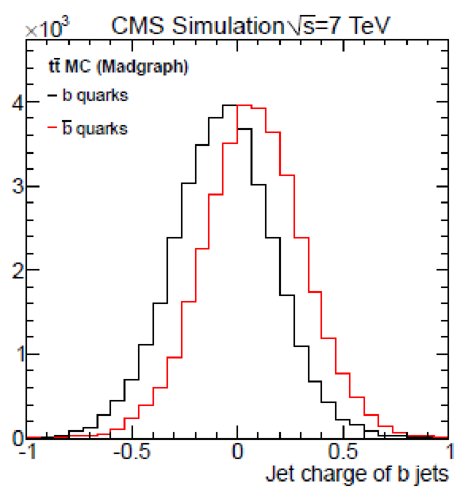
1. infer the charge of the W by using the charge of the lepton
2. determine the charge of the b jet:
   a. jet charge method: for each b-tagged jet loop over all tracks, evaluated Q

$$Q_{b-jet} = \frac{\sum_i q_i \cdot (\vec{p}_i \cdot \hat{a})^x}{\sum_i (\vec{p}_i \cdot \hat{a})^x}$$

x = weighting factor

$\hat{a}$ = jet axis

$\vec{p}_i$ = track momentum

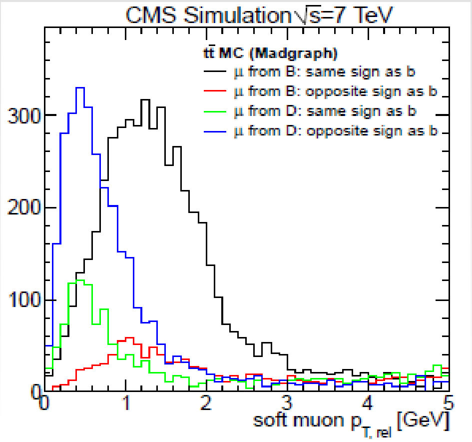


Jet charge method is calibrated on MC and data, it has high efficiency but low purity: efficiency~98% purity~60%

Top Quark Charge - 2

b. soft lepton method: b → ℓ⁻

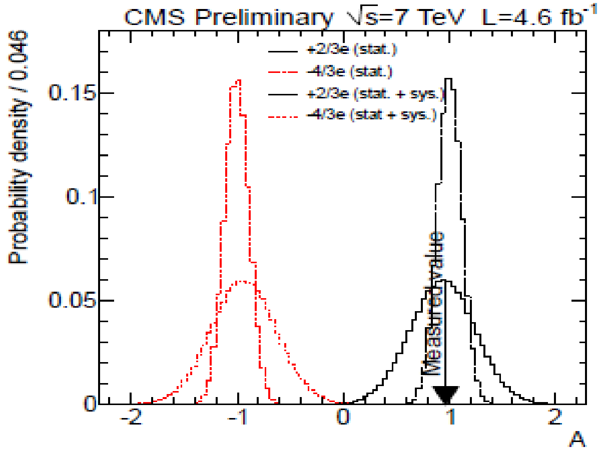
identify a lepton with low momentum inside the b-jet



use $p_{T,rel}$ to distinguish lepton from b and charm

3. pair W and b to form "right" top: fit three jets invariant mass, one b-tagged, the best combination → the candidate top.

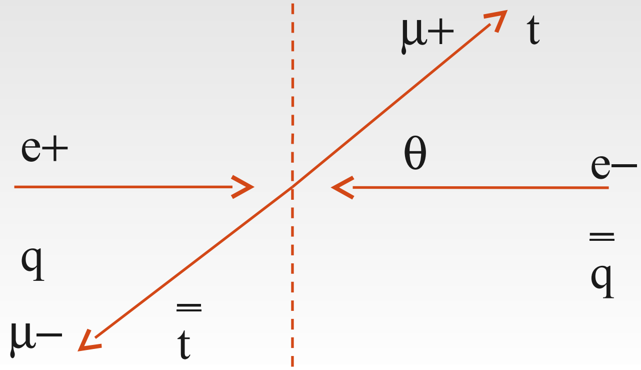
The other b-jet is paired to the W.



Exotic top-quark model is excluded at 99%CL

Top anti-Top Quark Charge Asymmetry

At LO the number of top quark produced at a given angle is expected to be almost equal to the number of anti-top quark produced at the same angle.



$$A = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

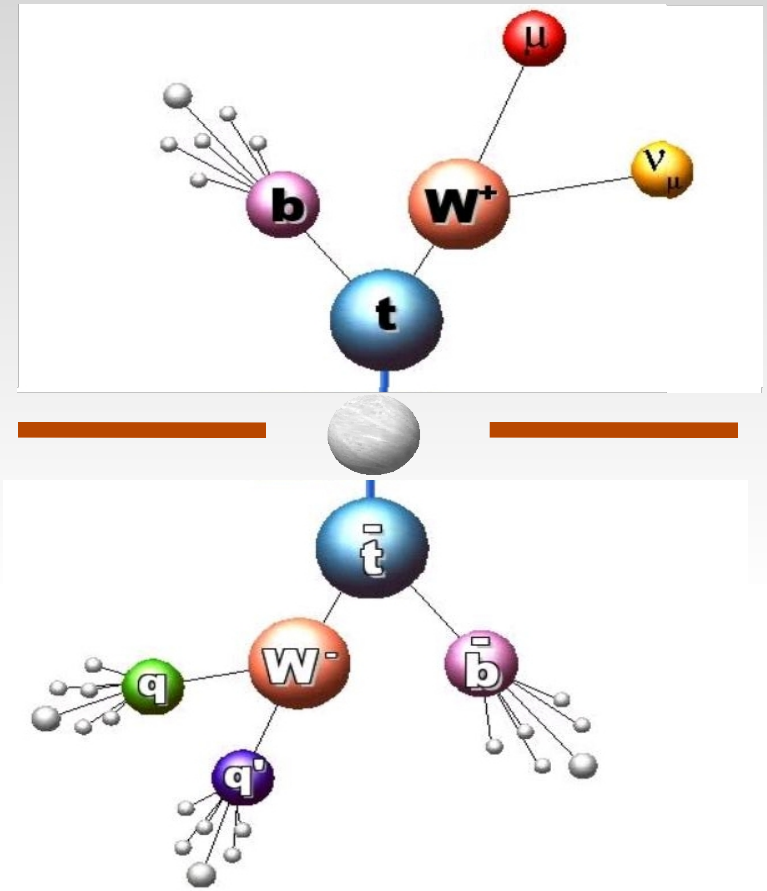
In analogy to the muon production asymmetry for the $t\bar{t}$ system it is possible to defined the asymmetry using the rapidity, in lepton+jets events

$\Delta y = y_t - y_{\bar{t}} = q_l (y_{leptonic} - y_{hadronic})$ rapidity difference invariant to z-boost

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

Asymmetry as function of Δy is the same in the lab and $t\bar{t}$ frame

Top anti-Top Quark Charge Asymmetry



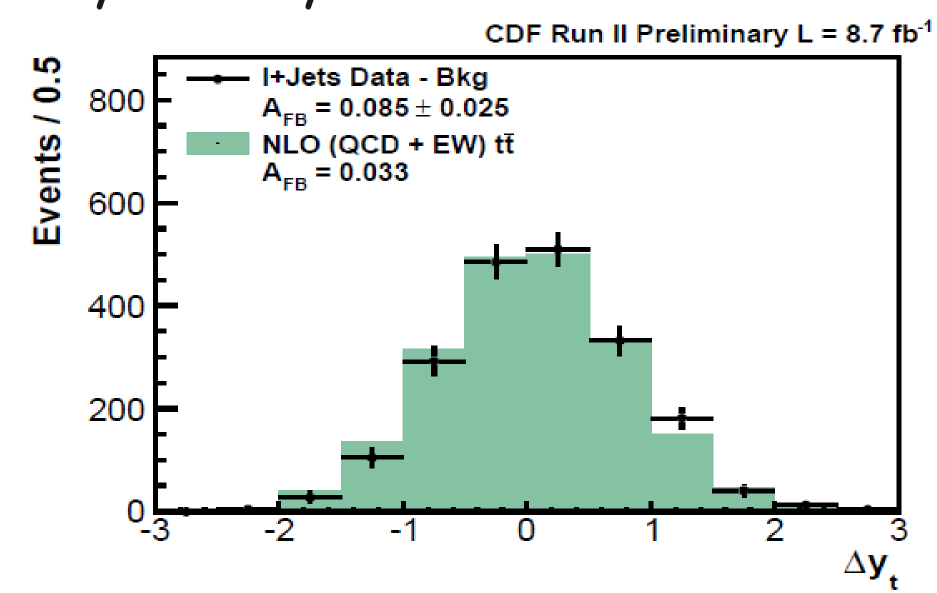
Usual requirements for the lepton+jets reconstruction.
The charge of the lepton determine which reconstructed quark is top.
Lepton angles are very well measured.

The SM predictions are calculated by using different Monte Carlo

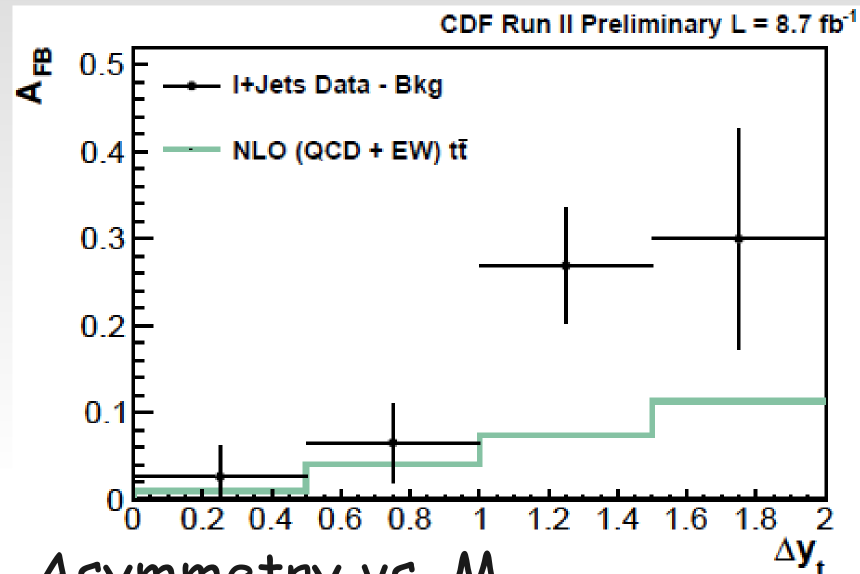
	MC@NLO	POWHEG	MCFM
Inclusive	0.067	0.066	0.073
$\lvert\Delta y\rvert < 1$	0.047	0.043	0.049
$\lvert\Delta y\rvert > 1$	0.130	0.139	0.150
$M_{t\bar{t}} < 450$ GeV/c^2	0.054	0.047	0.050
$M_{t\bar{t}} > 450$ GeV/c^2	0.089	0.100	0.110

Top anti-Top Quark Charge Asymmetry

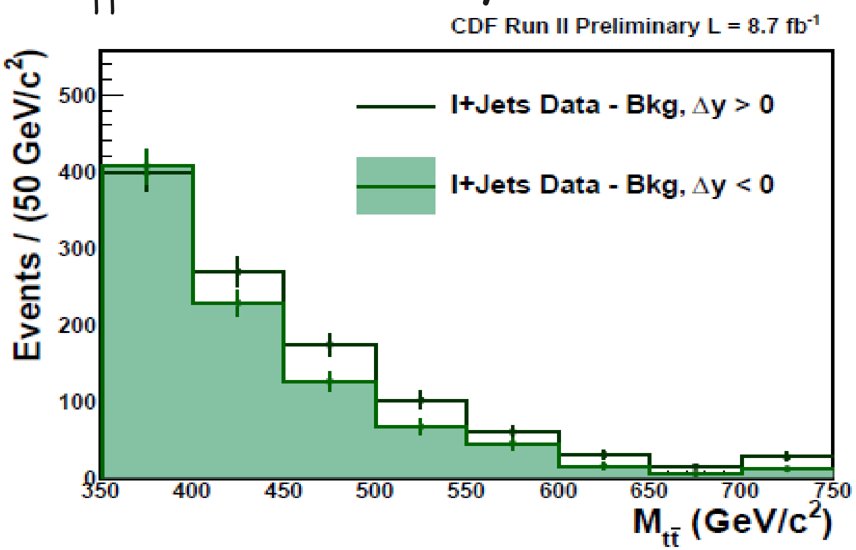
Asymmetry



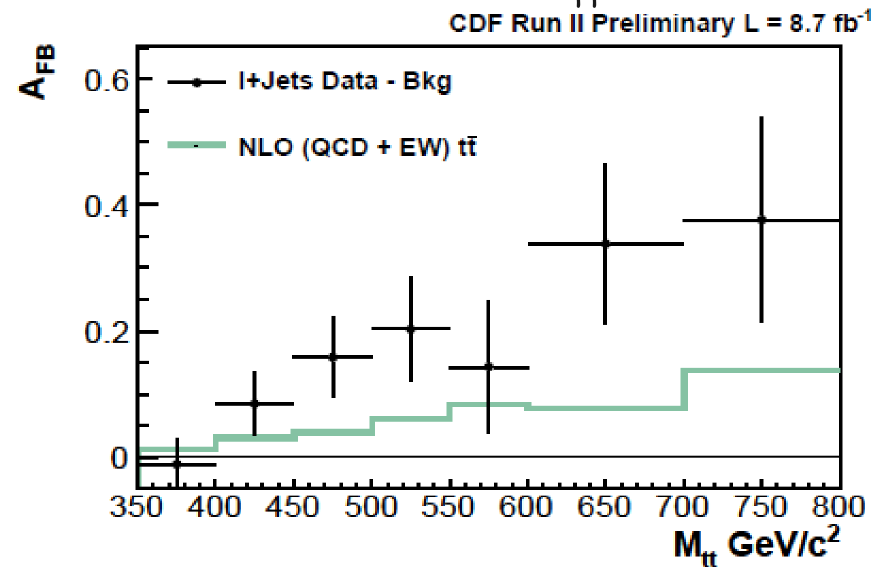
Asymmetry vs. Δy



M_{tt} for events Δy<0

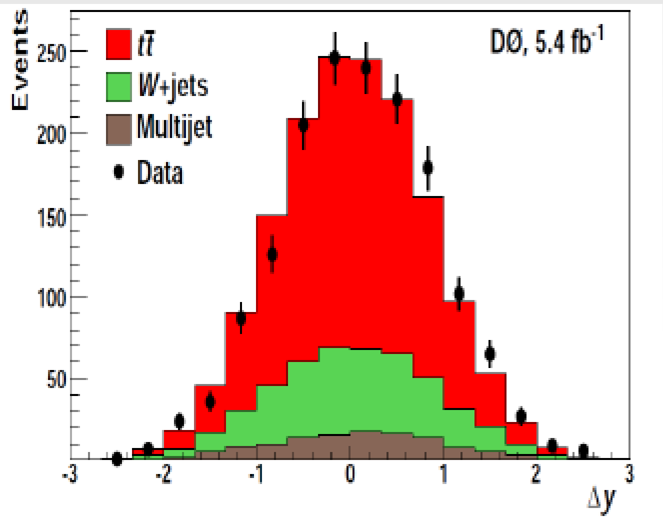


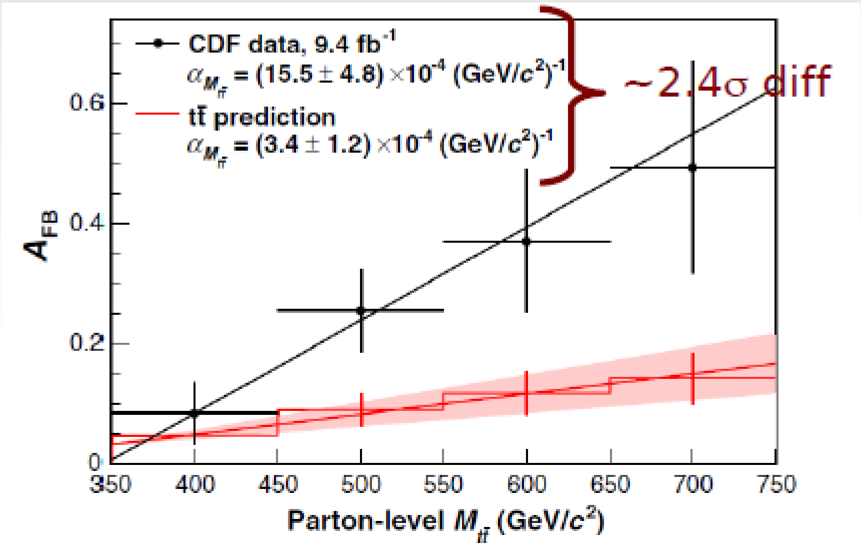
Asymmetry vs. M_{tt}



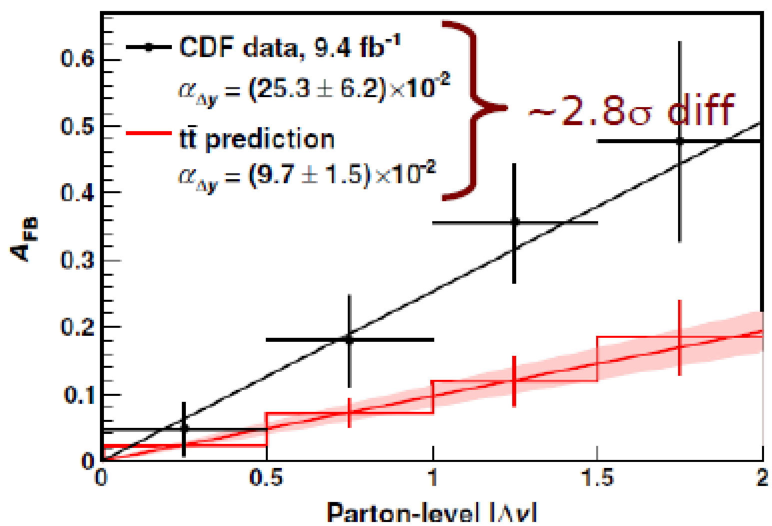
Top anti-Top Quark Charge Asymmetry

In order to compare the measured asymmetry directly to theory Prediction we have to go back to the parton level asymmetry. This is done with the "unfolding" procedure.





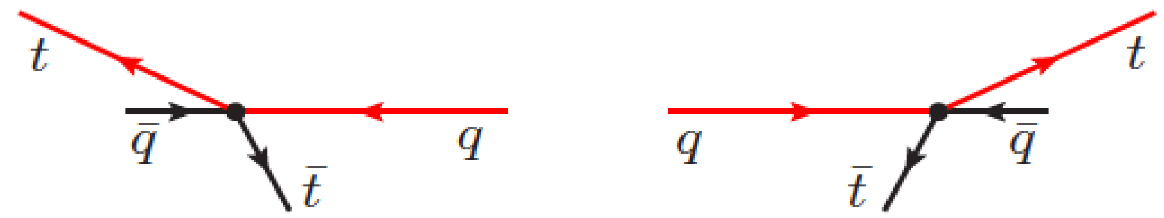
D0 is performing the measurement on full statistics using l+jets and di-leptons decay channels



Top anti-Top Quark Charge Asymmetry @ LHC

Differences respect to Tevatron:

1. large fraction of $t\bar{t}$ is produce by gluon fusion and the asymmetry is present only in $q\bar{q}$ initial states
2. at LHC quarks are mainly valence quarks while anti-quarks are sea quarks and the larger average momentum of the valence quarks produce an excess of top quark produced in the forward region

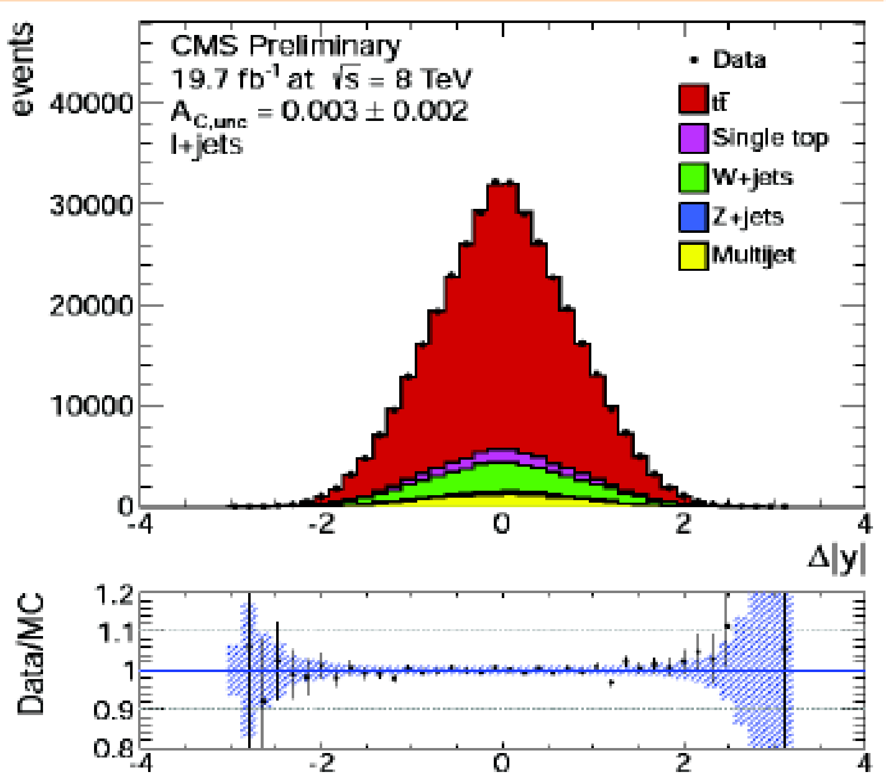


The expected asymmetry A(theory) = 0.0115 ± 0.0006

Top anti-Top Quark Charge Asymmetry @ LHC

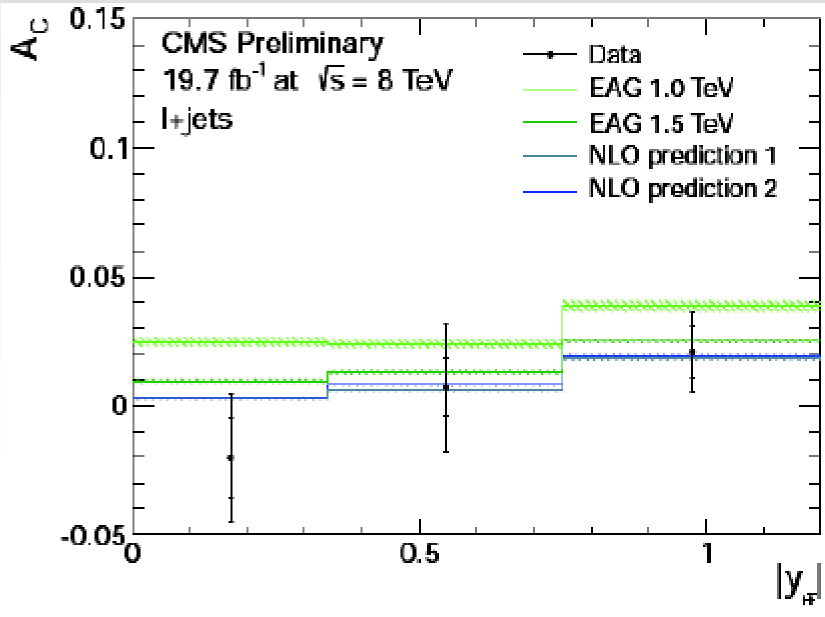
The asymmetry is based on the fully reconstructed four-momenta of t and $\bar{t}$ in each event

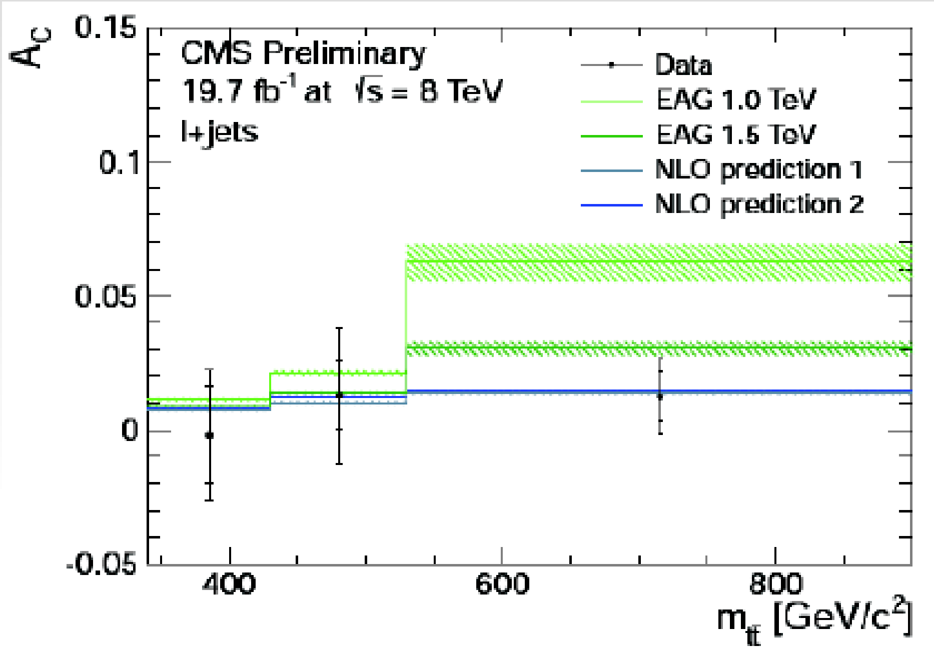
The reconstructed four-vectors are used to obtain the inclusive and differential distributions of Δy and the charge asymmetry is calculated by counting the entries with Δy>0 and the entries with Δy<0



Top anti-Top Quark Charge Asymmetry @ LHC

After the unfolding



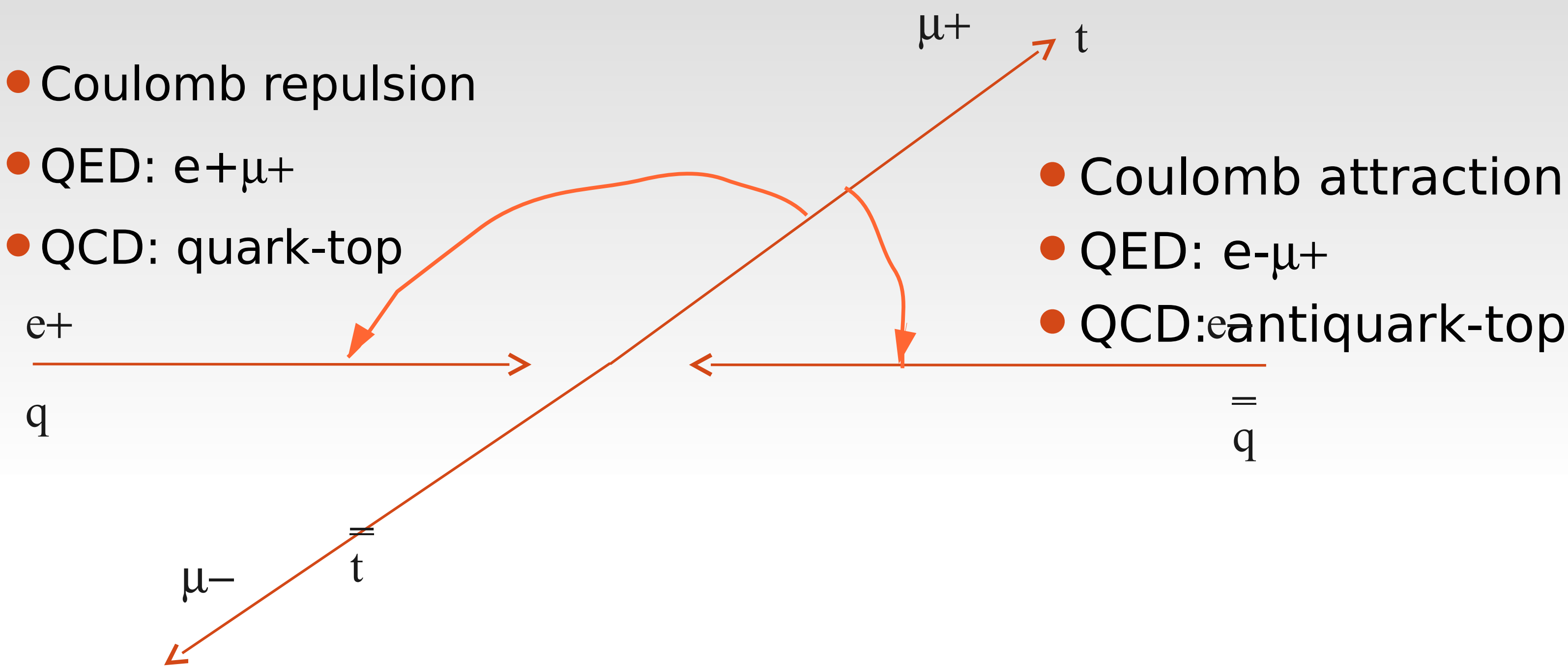


$$A_C^{t\bar{t}} = 0.050 \pm 0.043(\mathrm{stat})^{+0.010}_{-0.039}(\mathrm{syst})$$

No disagreement with SM.

Many other measurements of CMS and Atlas show no deviation from SM

Top anti-Top Quark Charge Asymmetry Meaning



New kind of interactions to explain the $t\bar{t}$ asymmetry

- gluon interferes with an axial object arising from an extended strong gauge group or extra-dimensions
- objects with flavor violating couplings create an asymmetry via a u/d → t flavor change into the forward Rutherford peak.