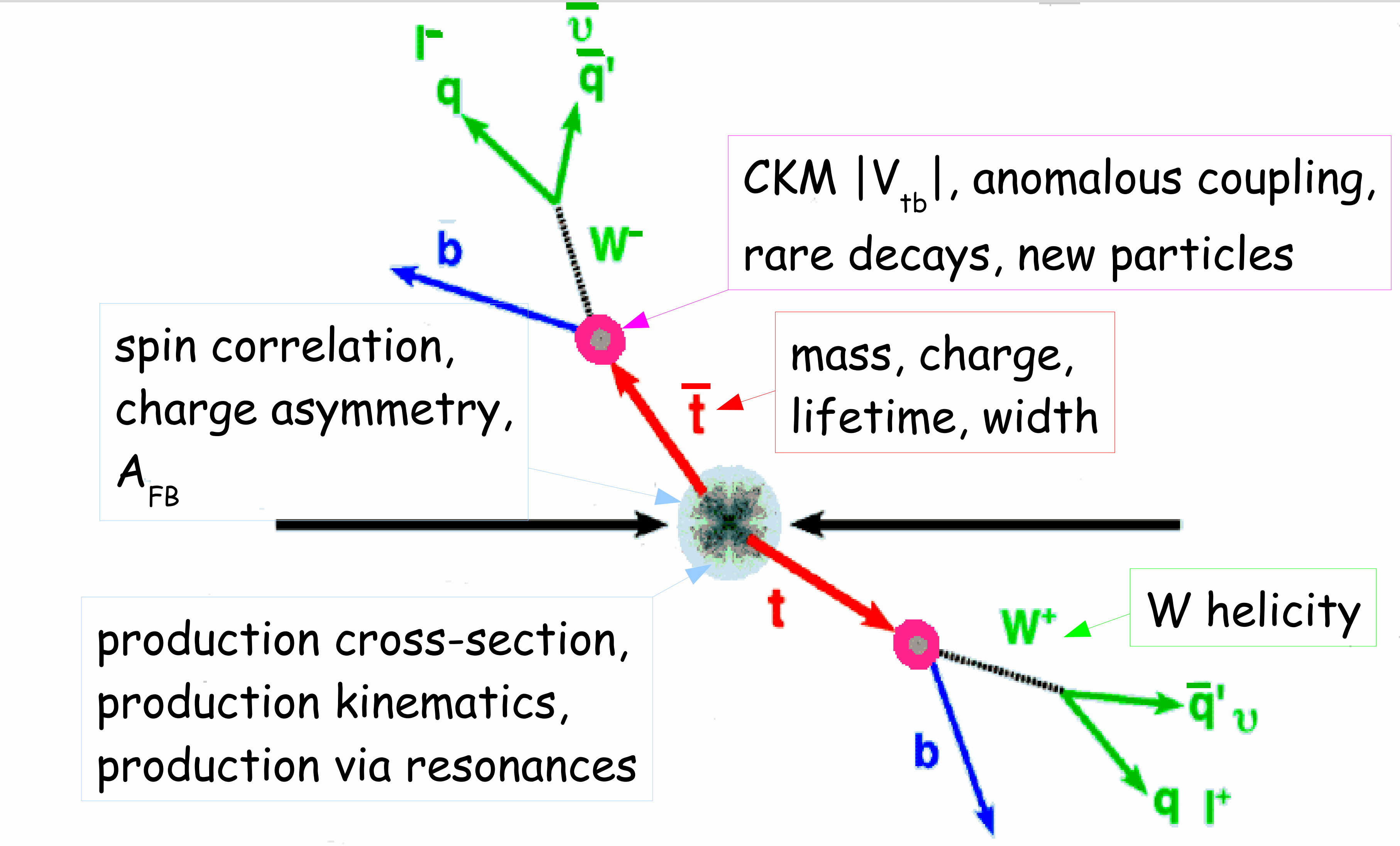
Top Quark Properties



Top Quark Introduction

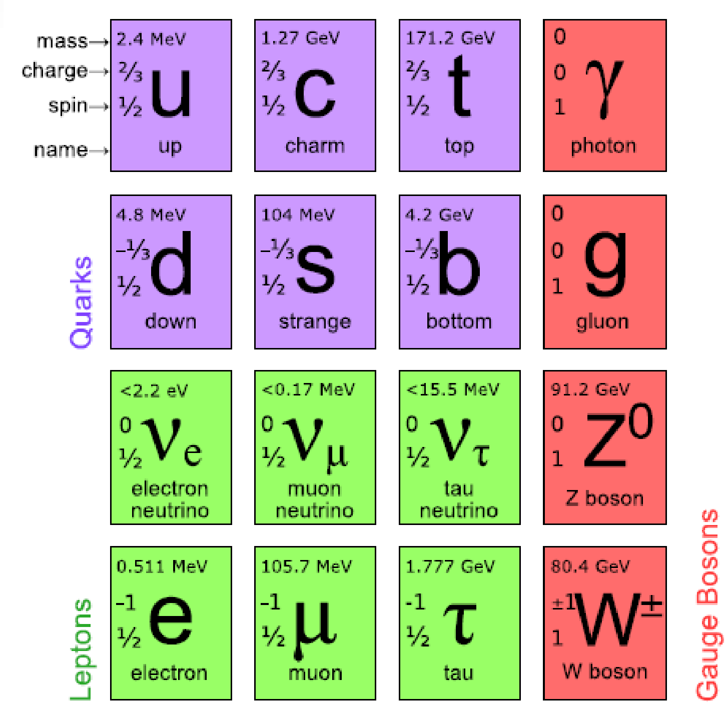
The last quark discovered. Precision SM measurements predict its existence and its mass.

In particular the asymmetry backward-forward of b-jets produced in e+e- annihilation at the Z resonance can be easily explained assuming that the b quark is in an SU(2) doublet with the top quark

Precision electroweak fits constrained the mass: 178^{+8+17}_{-8-20} GeV

The top discovery dates 1995 by the two experiments at the Tevatron Collider.

We are now in the era of precision top measurements

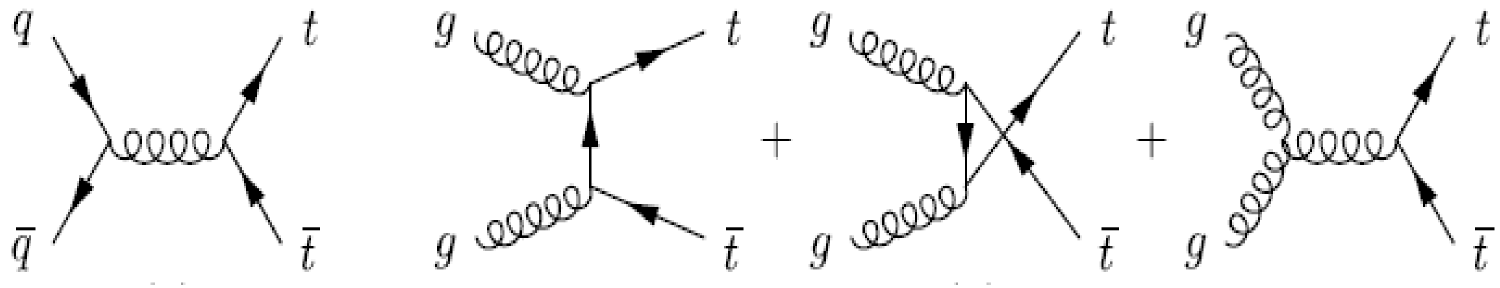


Top Quark Cross Sections

$$\sigma(pp \to t\bar{t} + X) = \sum_{i,j} \int dx_i dx_j \times F_i(x_i,\mu) F_i(x_j,\mu) \hat{\sigma}_{ij}(x_i, x_j, m_{top}^2, \mu^2)$$

$m_{top}/2 < \mu < 2m_{top}$ since the mass is so large the calculation can be performed with the perturbative QCD

At LO the diagrams that contribute are



LHC: 80% gluon fusion 20% $q\bar{q}$

Tevatron: 85% $q\bar{q}$ 15% gluon fusion

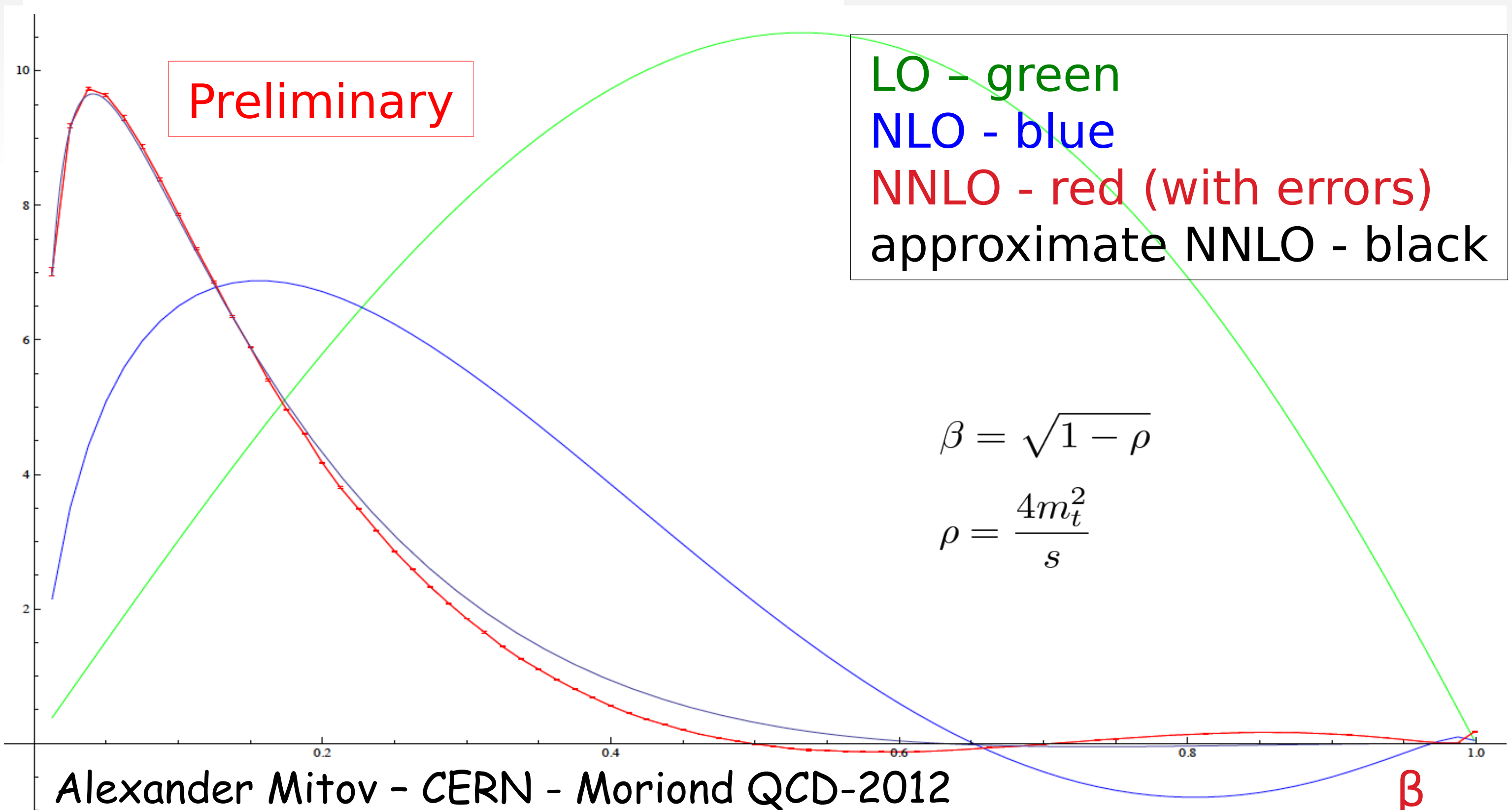
NLO calculations available.

Top Quark Cross Sections high order

NLO calculations are important: ~50%

Since not everything is in agreement with the theoretical expectations theoreticians are calculating also the NNLO corrections

$$\hat{\sigma}_{q\bar{q}\to t\bar{t}}(\beta) = \frac{\alpha_S^4(m_t)}{m_t^2}\left\{\mathrm{LO} + \mathrm{NLO} + \mathrm{NNLO}\right\}$$



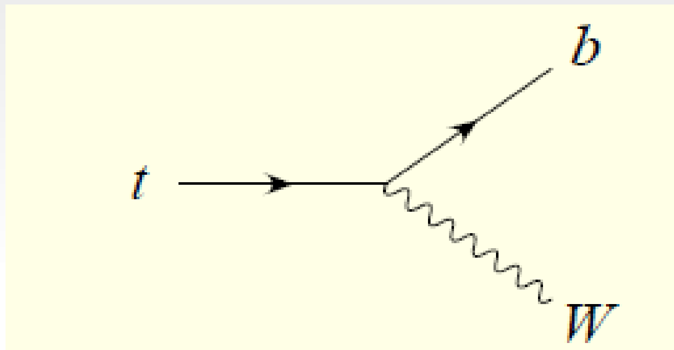
Alexander Mitov – CERN - Moriond QCD-2012

Top Quark Decay

Quark top decay before it can form a bound state

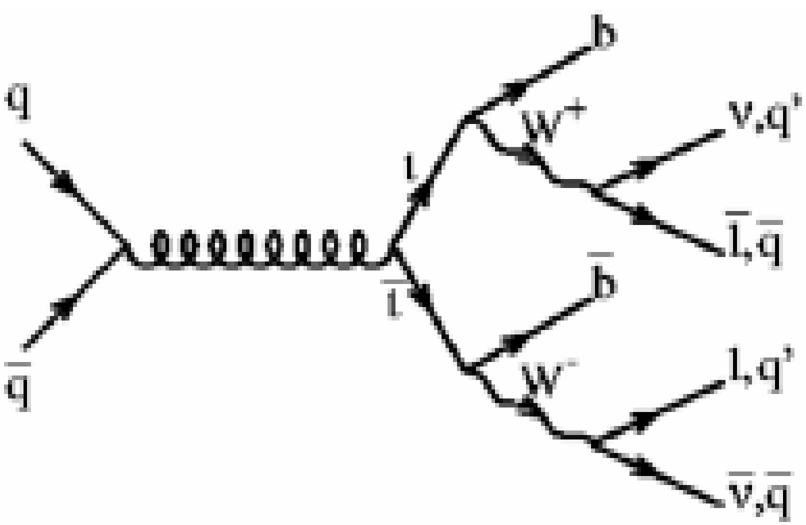
$\tau_t \simeq 10^{-25}$ sec compare to $\tau_{QCD} \simeq 10^{-24}$ sec

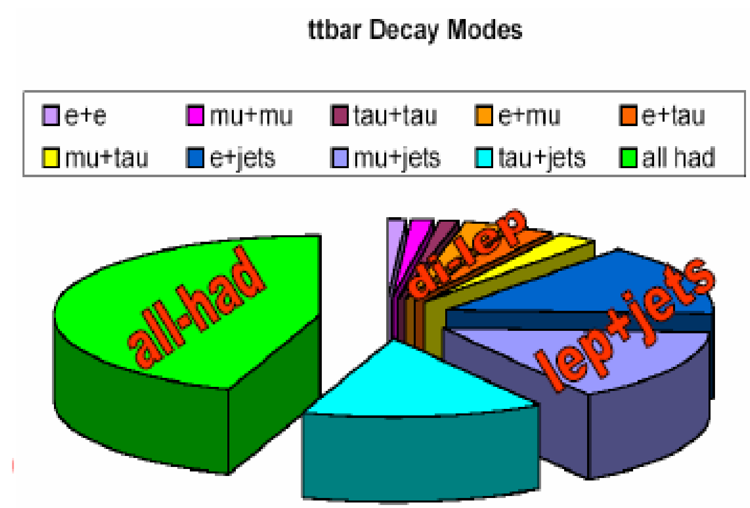
It decays predominantly



$$t \to bW^+ \begin{cases} W^+ \to l^+ \nu_l \\ W^+ \to q\bar{q}' \end{cases}$$

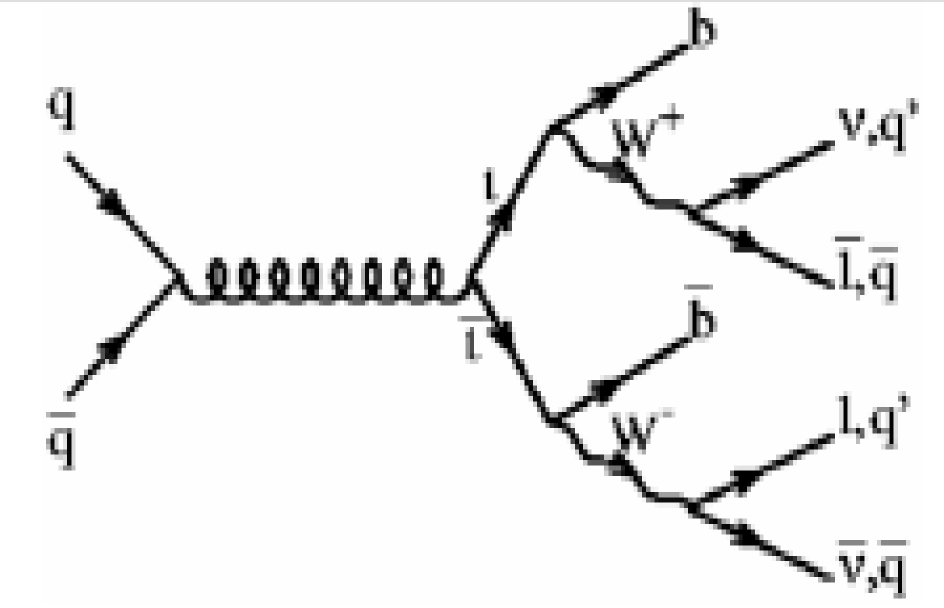
The event is



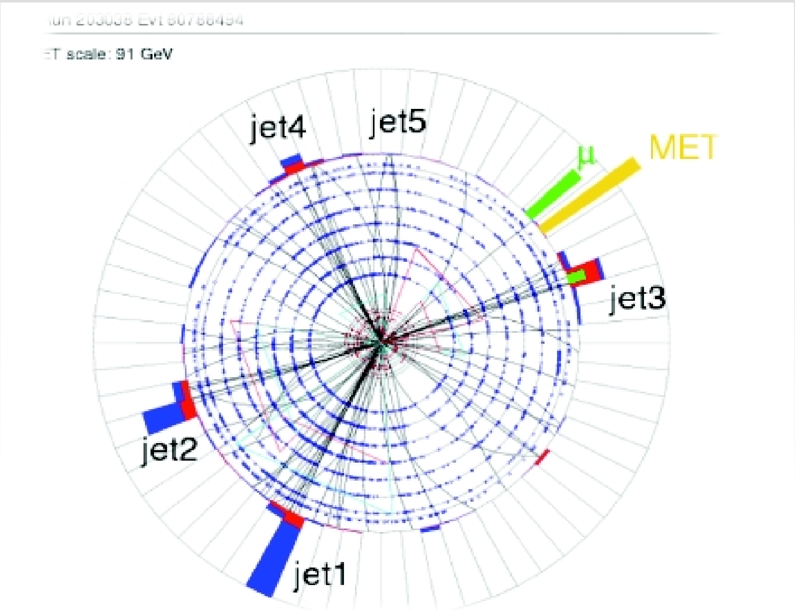


Top Quark Reconstruction

Theory



Detector



Events classified depending on the W decay:

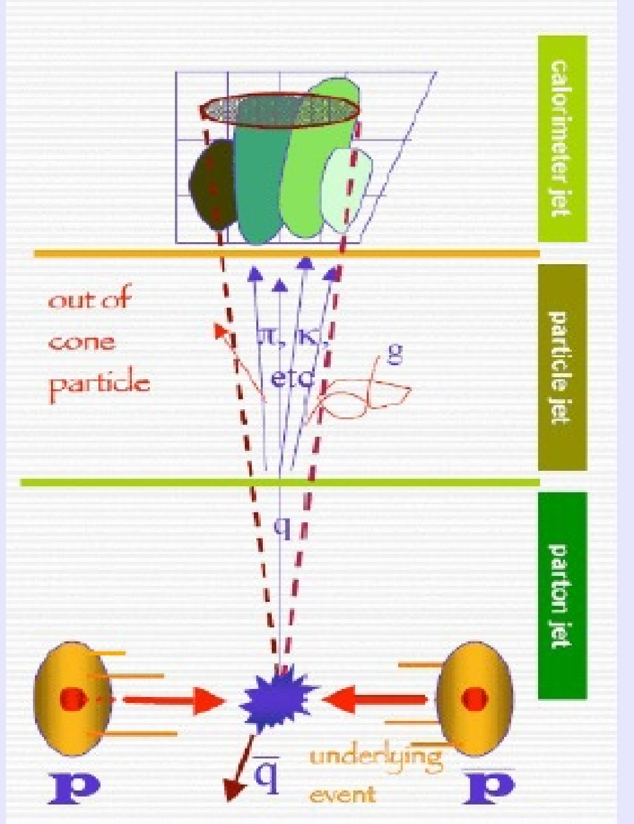
- Di-lepton: low yield, low background, well defined leptonic signature, neutrinos → MET
- Lepton+jets: higher yield, moderate background, lepton signature + MET + jets
- All hadronic: highest yield, huge background, only jets

Top Quark Events Reconstruction: Common tools

Final states always with jets and b-quark in jets.

1. Reconstruct jets
2. Use b-tag algorithm to determine if the jet is originated by a b-quark

1.



Use cone algorithm

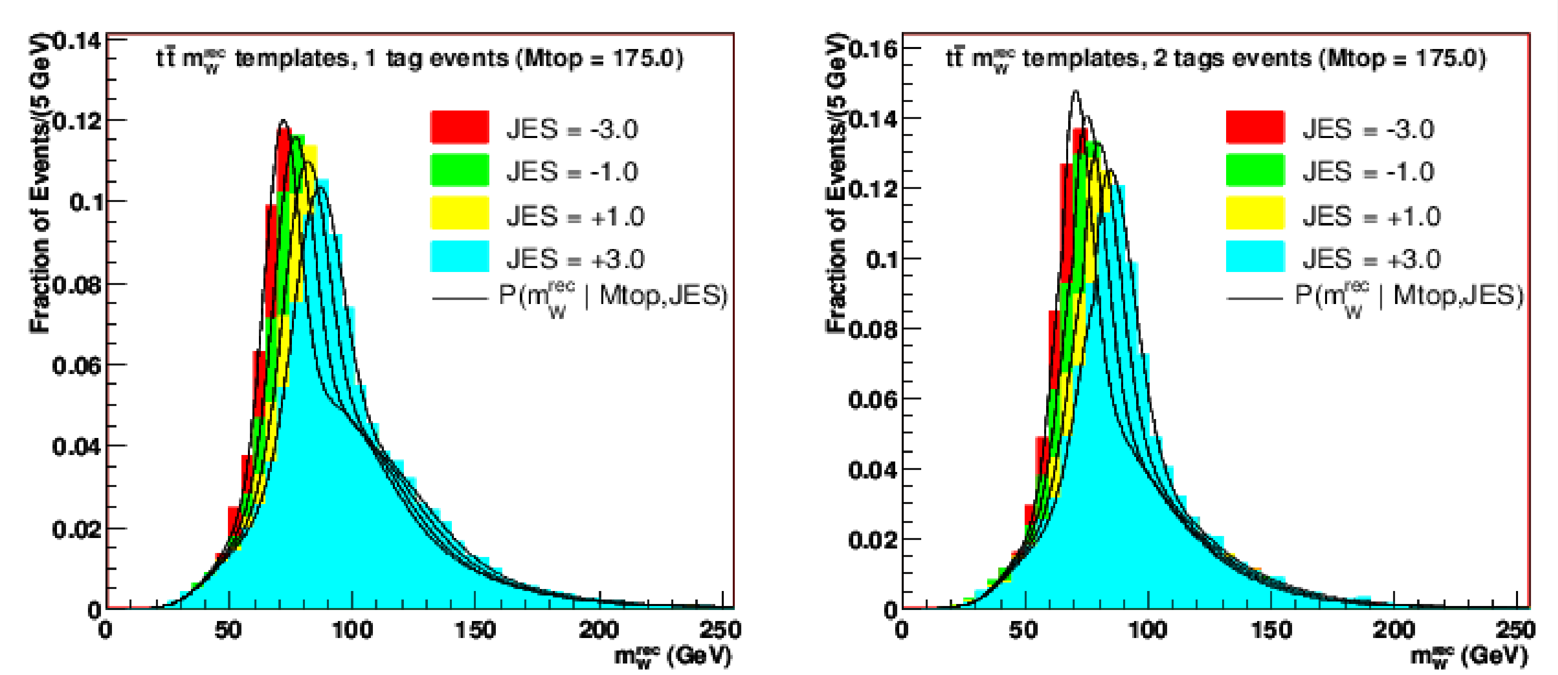
Jet Energy Scale (JES) is one of the major source of uncertainty (see discussion on jet reconstruction)

Top analysis now use a new method to determine the energy scale: the "in situ" calibration.

Common Tools: “In situ” Energy Calibration

In the decay channels where both Ws decay in hadrons it is possible to leave the JES as free parameter and fit the W mass.

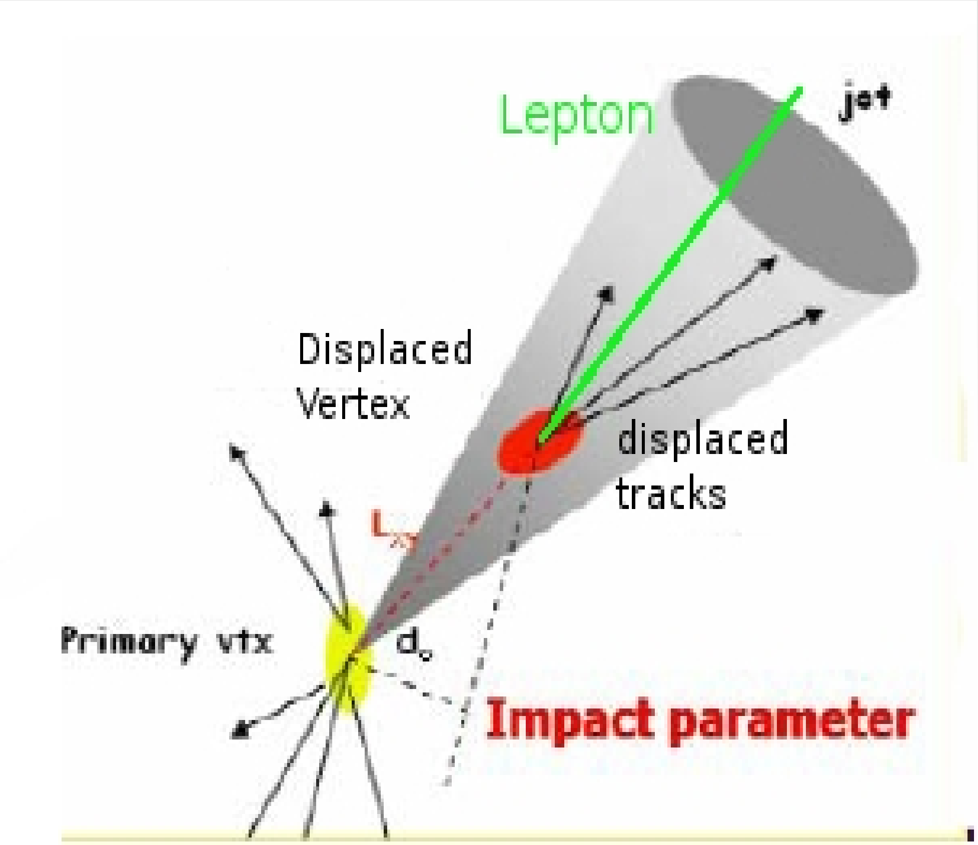
Templates with different JES are produced and the W mass is fitted



$$\chi^2 = \frac{\left(M_{jj}^{a} - M_{W}^{rec}\right)^2}{\Gamma_W} + \frac{\left(M_{jj}^{b} - M_{W}^{rec}\right)^2}{\Gamma_W}$$

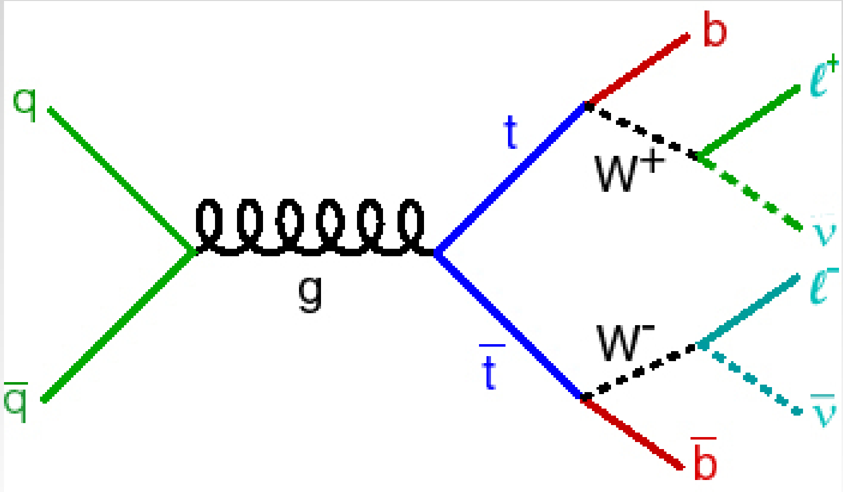
Top Quark Reconstruction:Common tools

2. Use b-tag algorithm to determine if the jet is originated by a b-quark



- Select tracks with high impact parameter respect to primary vertex
- Request at least 2 tracks
- Fit the tracks to identify a secondary vertex
- Cut on decay lenght L_{xy} to be compatible with the distance traveled by a b-hadron

Top Quark Decay Selections

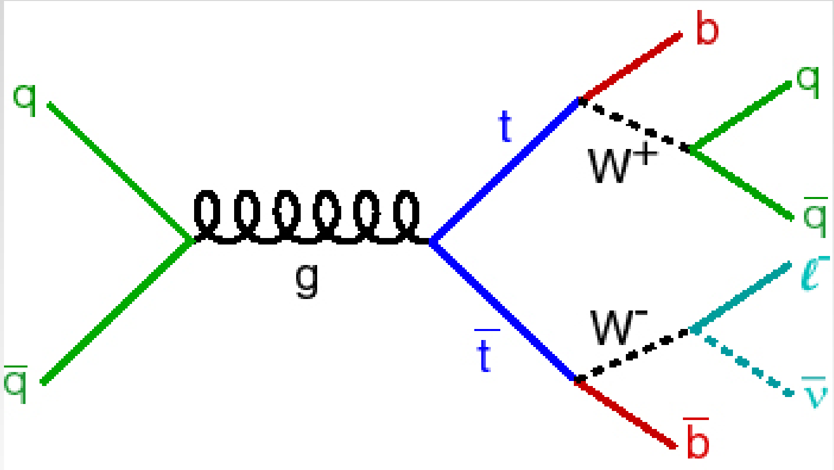


Requirements:

- two high P_T opposite charge isolated leptons
- at least 2 high E_T jets
- at least one vertex b-tag
- Significant MET

Major Backgrounds

- Process with 2 leptons in the final state: Drell-Yan Z/γ^*, WW,WZ,ZZ
- QCD: fake leptons



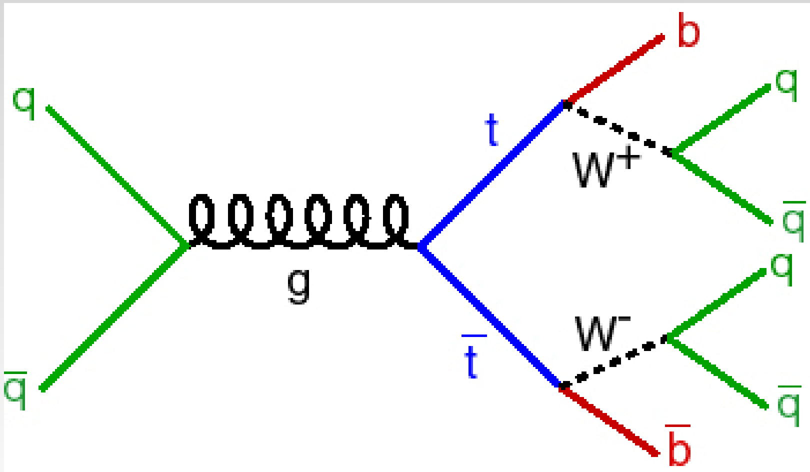
Requirements:

- one high P_T isolated leptons
- at least 4 high E_T jets
- at least one b-tag
- Significant MET

Major Background

- Process with 1 lepton + jets in the final state: W+jets
- Other contributions from non-W

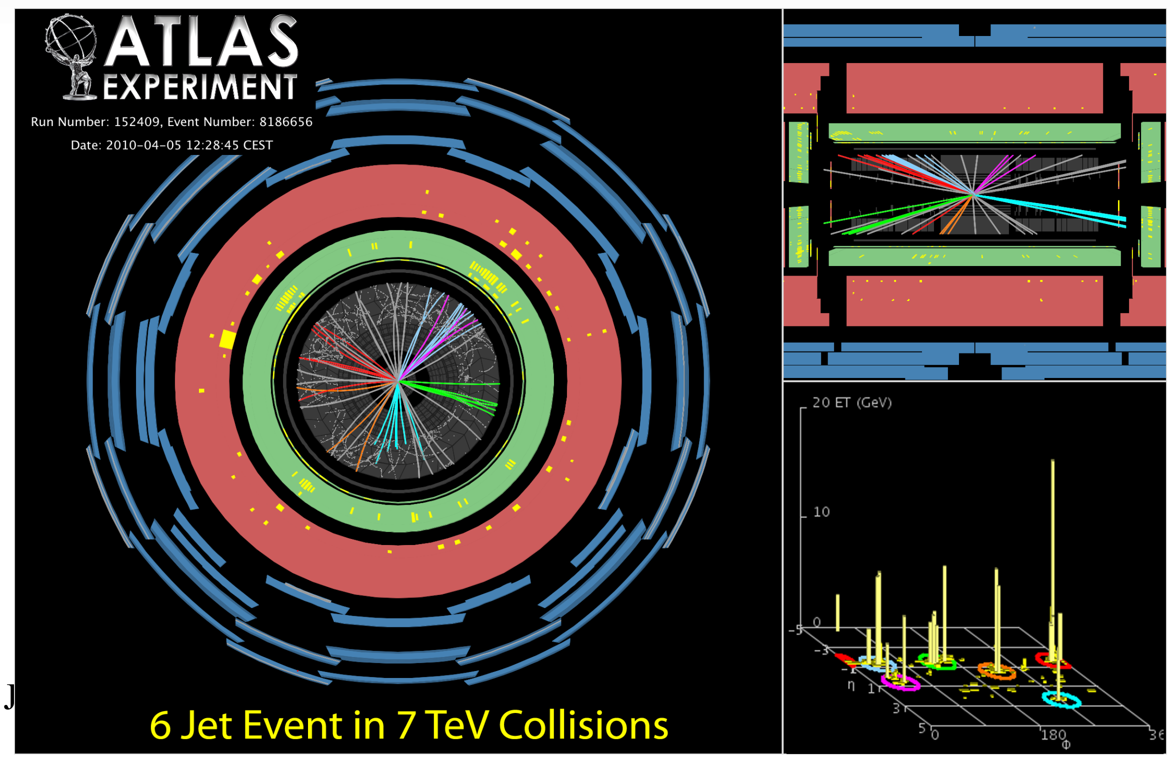
Top Quark Decay Selections



Requirements:

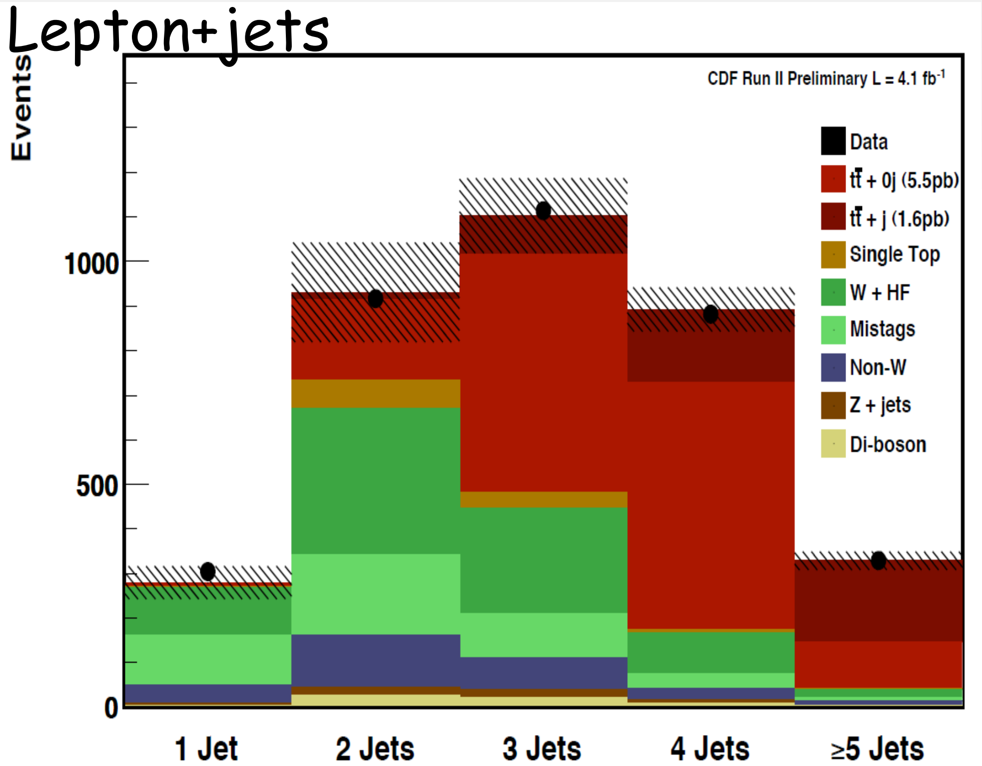
- at least 6 high E_T jets
- at least one b-tag
- Small MET
- No leptons

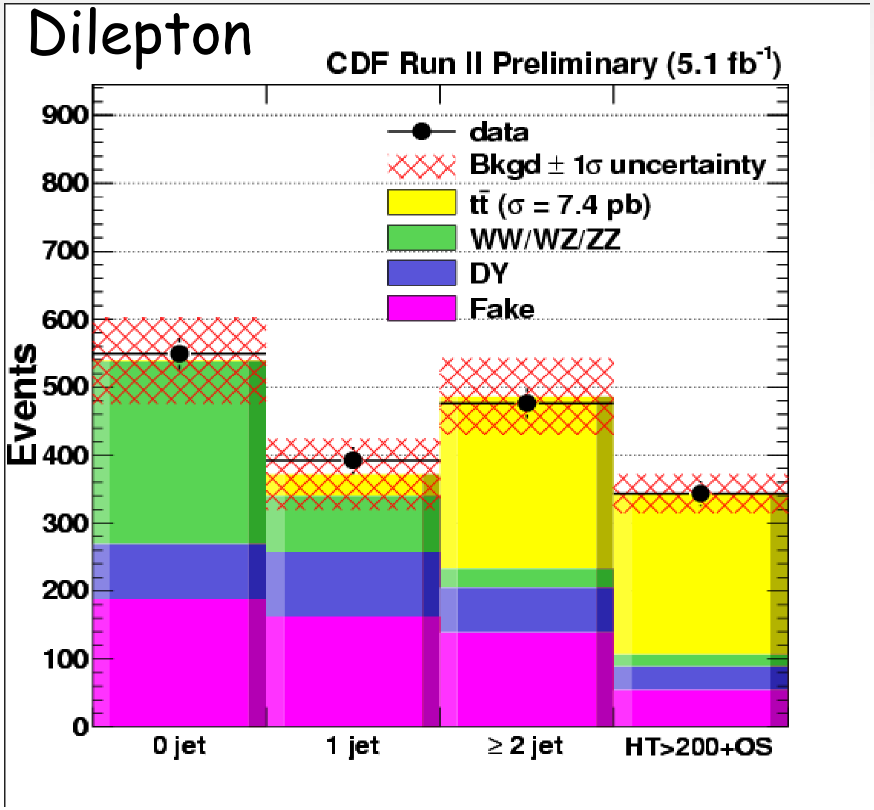
Dominant Background: QCD multi-jets



Top Quark Event count

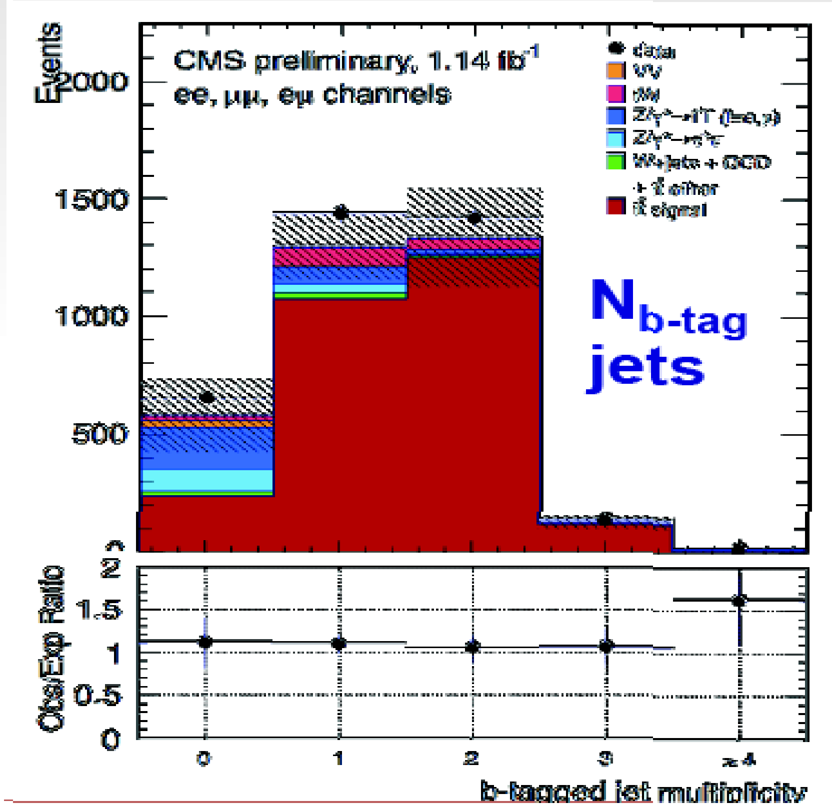
In order to count the number of top-anti-top event candidates the number of events is plotted versus the n umber of jets per event. In each bin the contribution of signal and background is different.

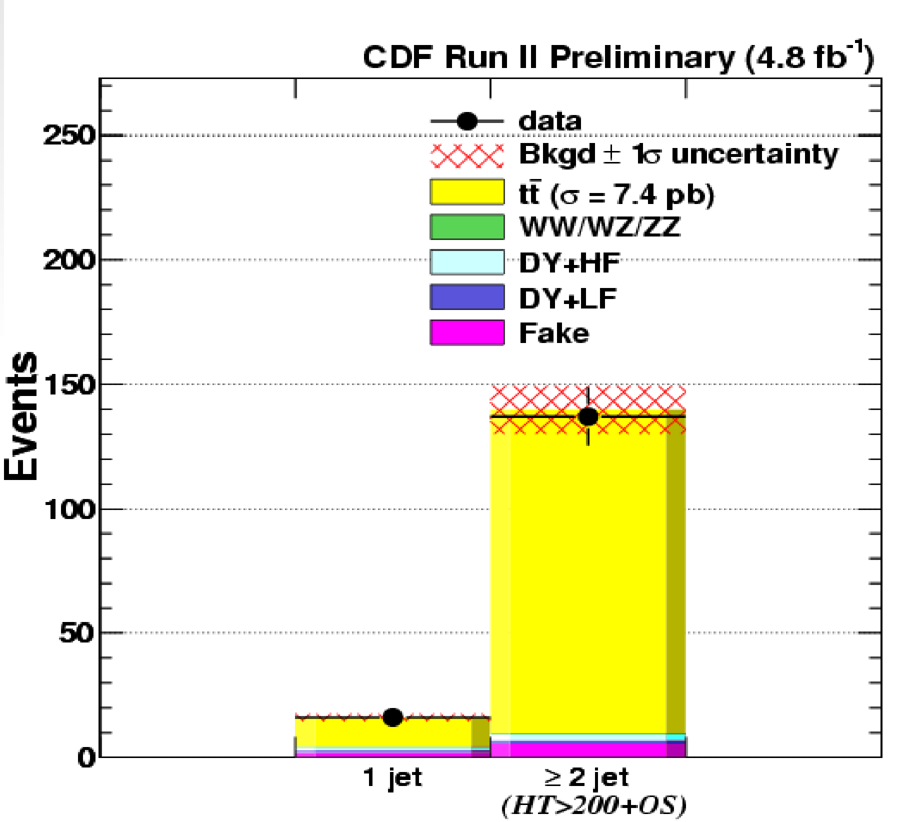




Top Quark Event count - 2

In order to increase the purity of the sample the number of b-tagged jets are counted or at least 2 b-jets are required.

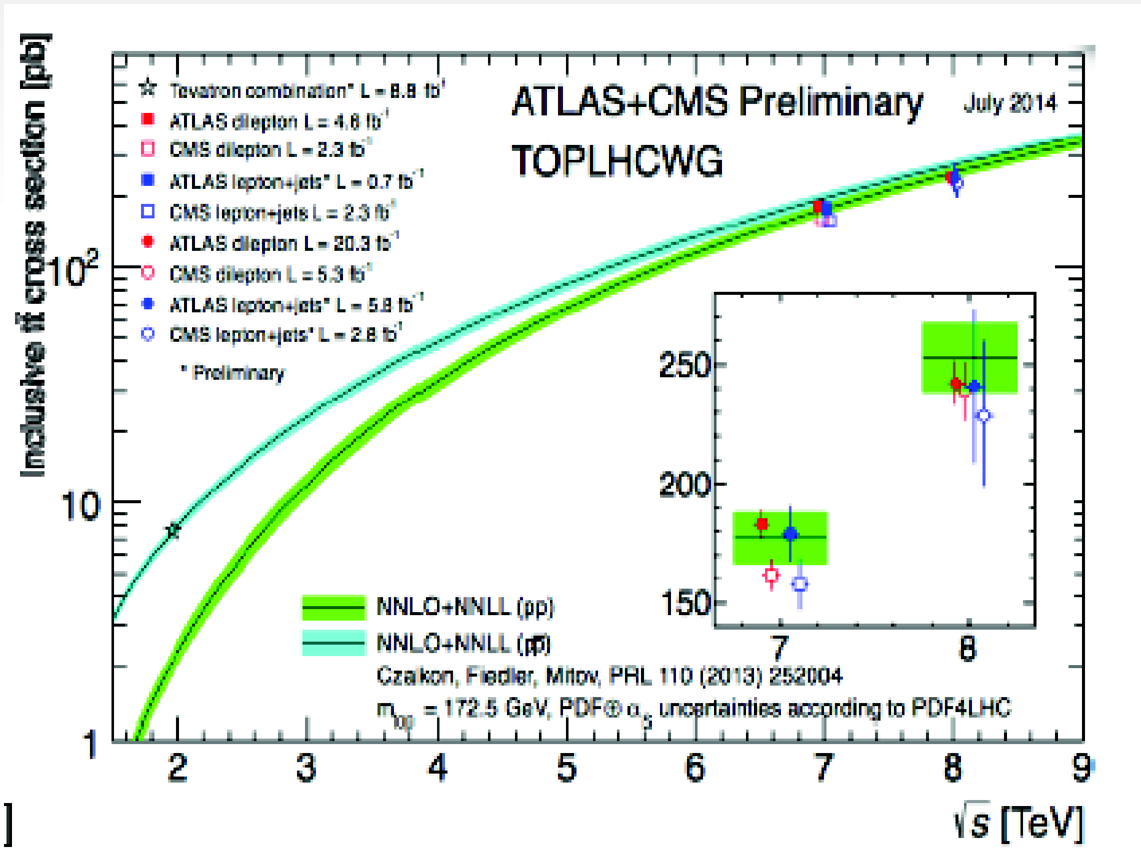




Top Quark Cross Section

$$\sigma_{tt} = \frac{N_{Data} - N_{Background}}{Acc \int L dt}$$

Inserting the number of signal and background events in the formula and knowing luminosity and efficiency on signal we have the cross section



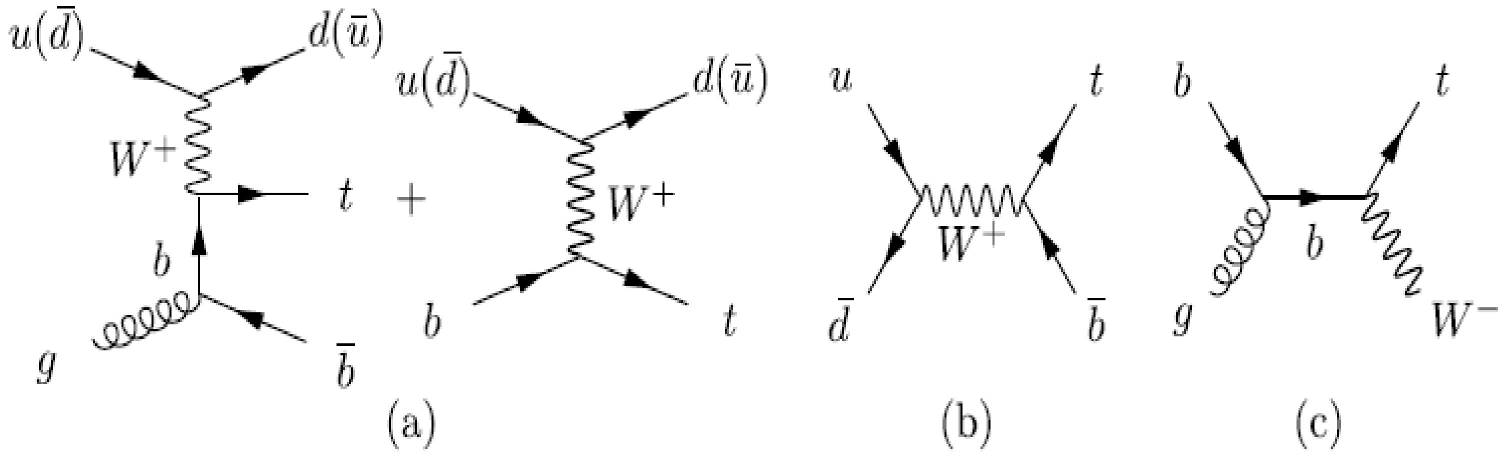
Good agreement with the expectations

]

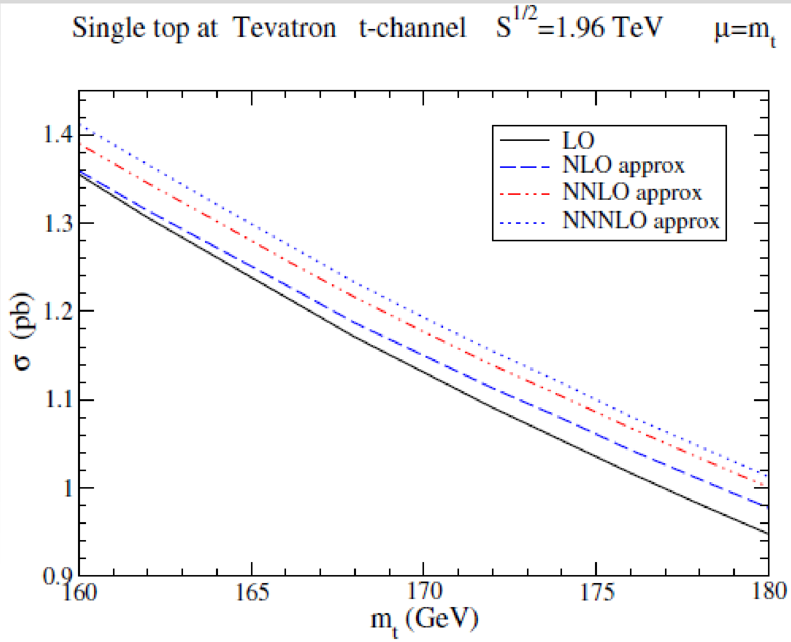
Single Top Quark

Top can be produced also via electroweak interaction involving a vertex Wtb. There are three different production models depending on the Q^2 of the W:

1. t-channel: a virtual W-boson interact with b-quark (sea quark) (a)
2. s-channel: a virtual W boson $q^2>(m_{top}+m_b)^2$ is produced by the fusion of 2 quark of SU(2) isospin doublet (b)
3. W-associated production: top quark is produced with a real W-boson starting from a sea b-quark and gluon (c)



Single Top Quark Expected Cross Section

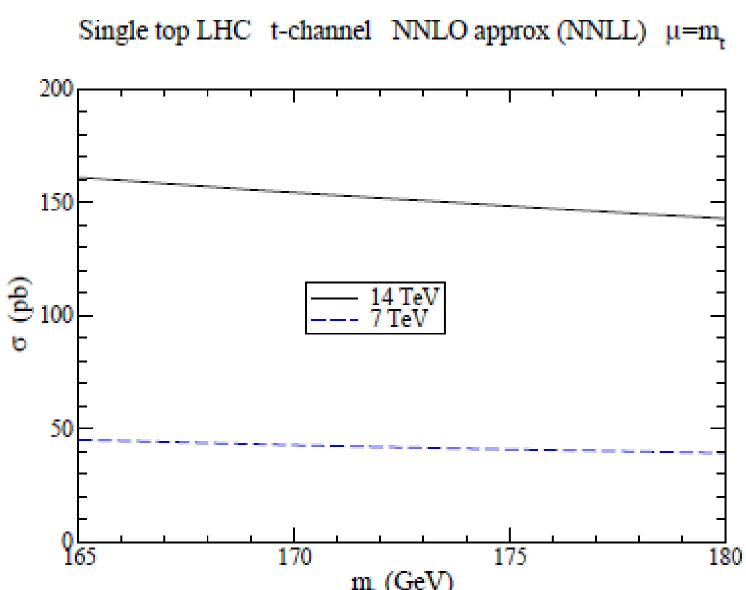


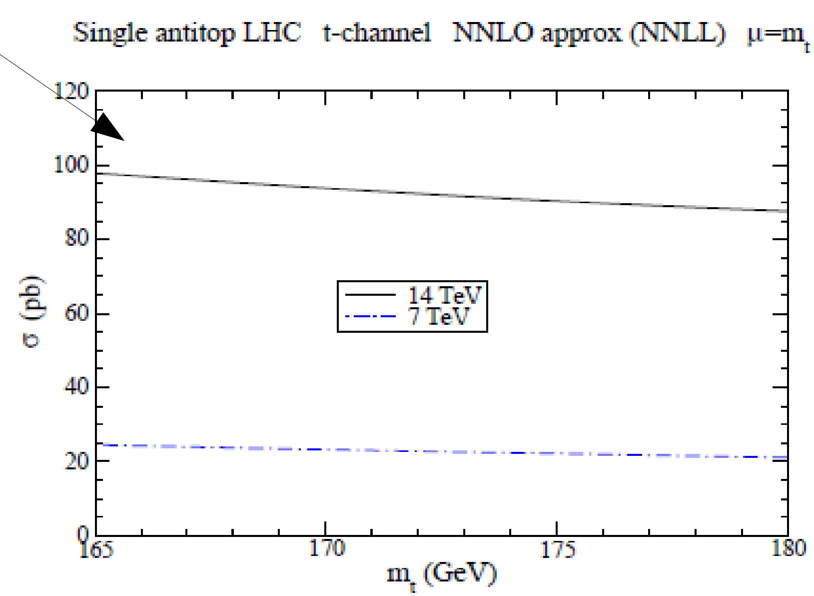
Single top cross section t-channel

Dominate at Tevatron and LHC

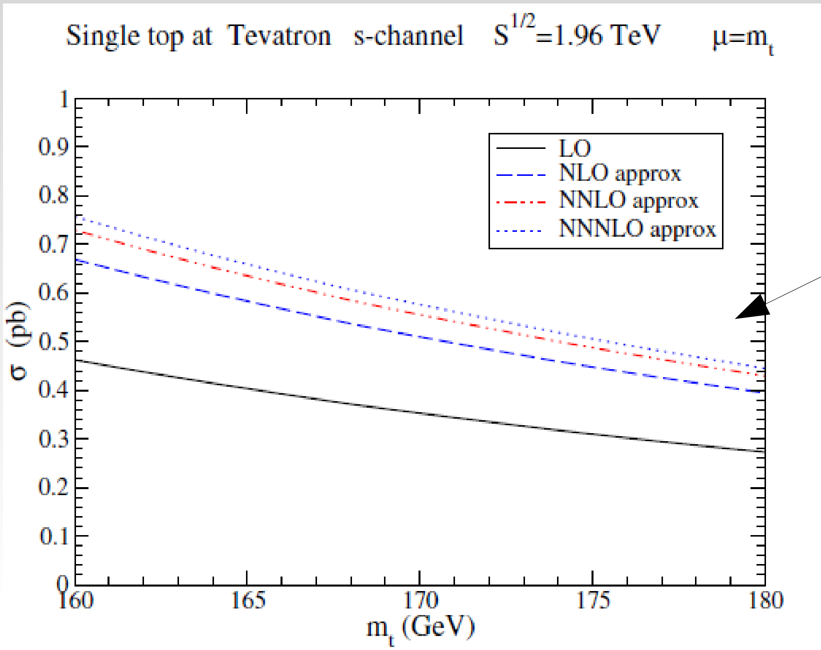
PRD74,114012,(2006)

LHC





Single Top Quark Expected Cross Section

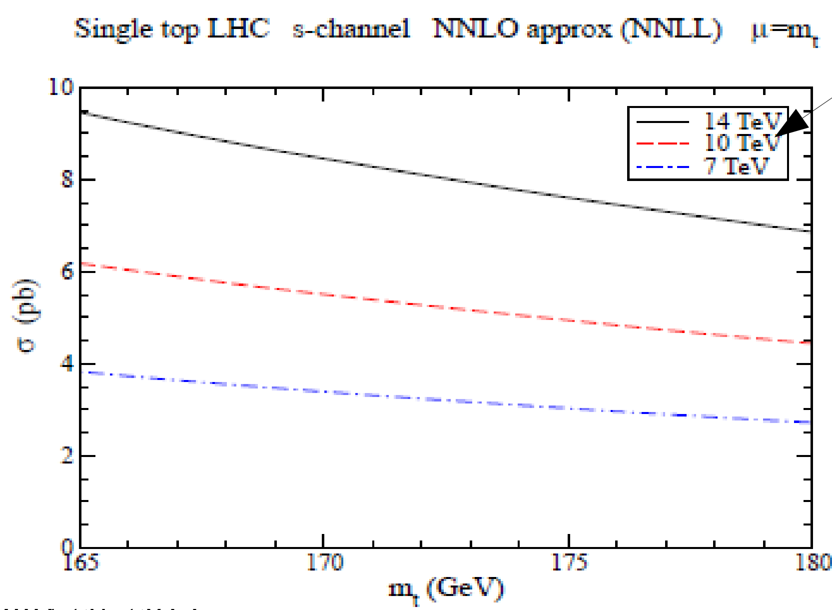


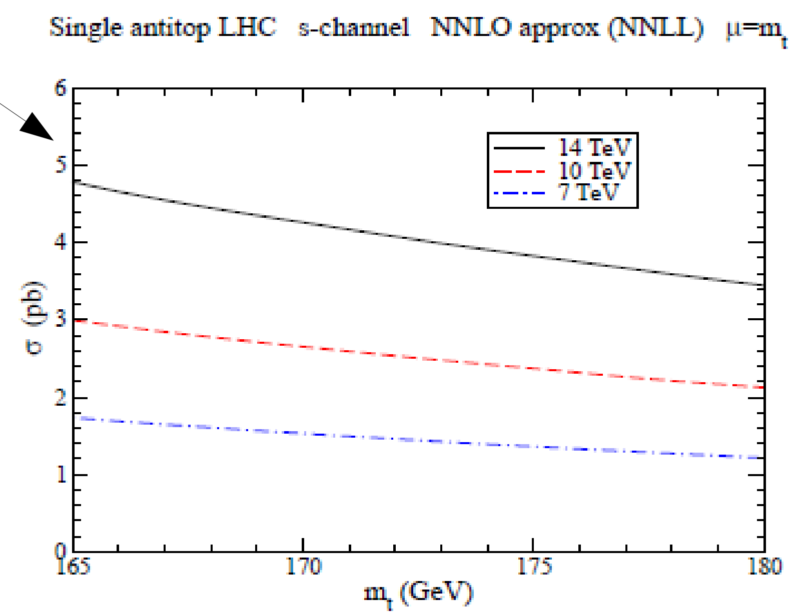
Single top cross section s-channel

Tevatron

PRD74,114012,(2006)

LHC

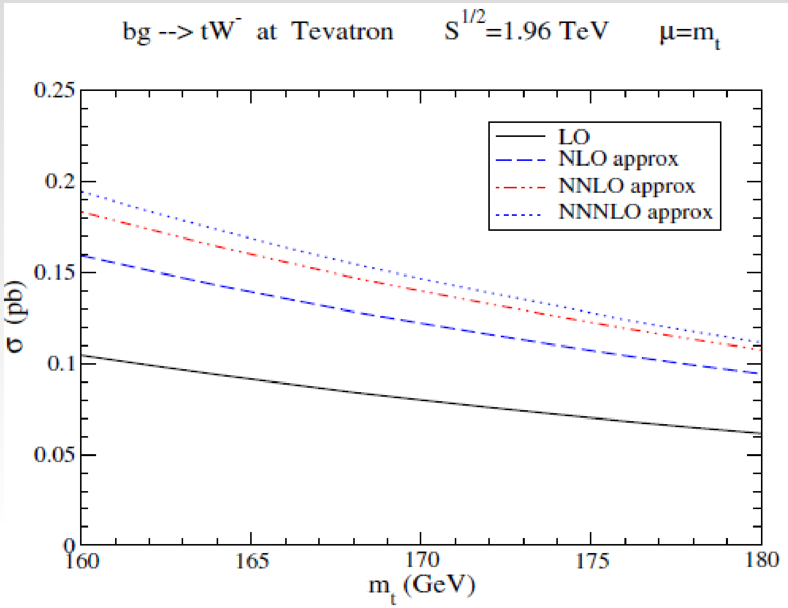


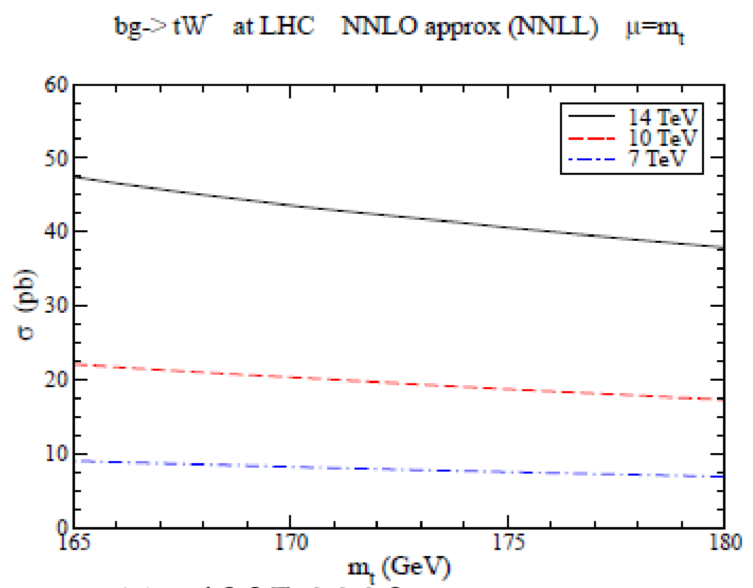


arXiv:1005.3330

Single Top Quark Expected Cross Section

PRD74,114012,(2006)



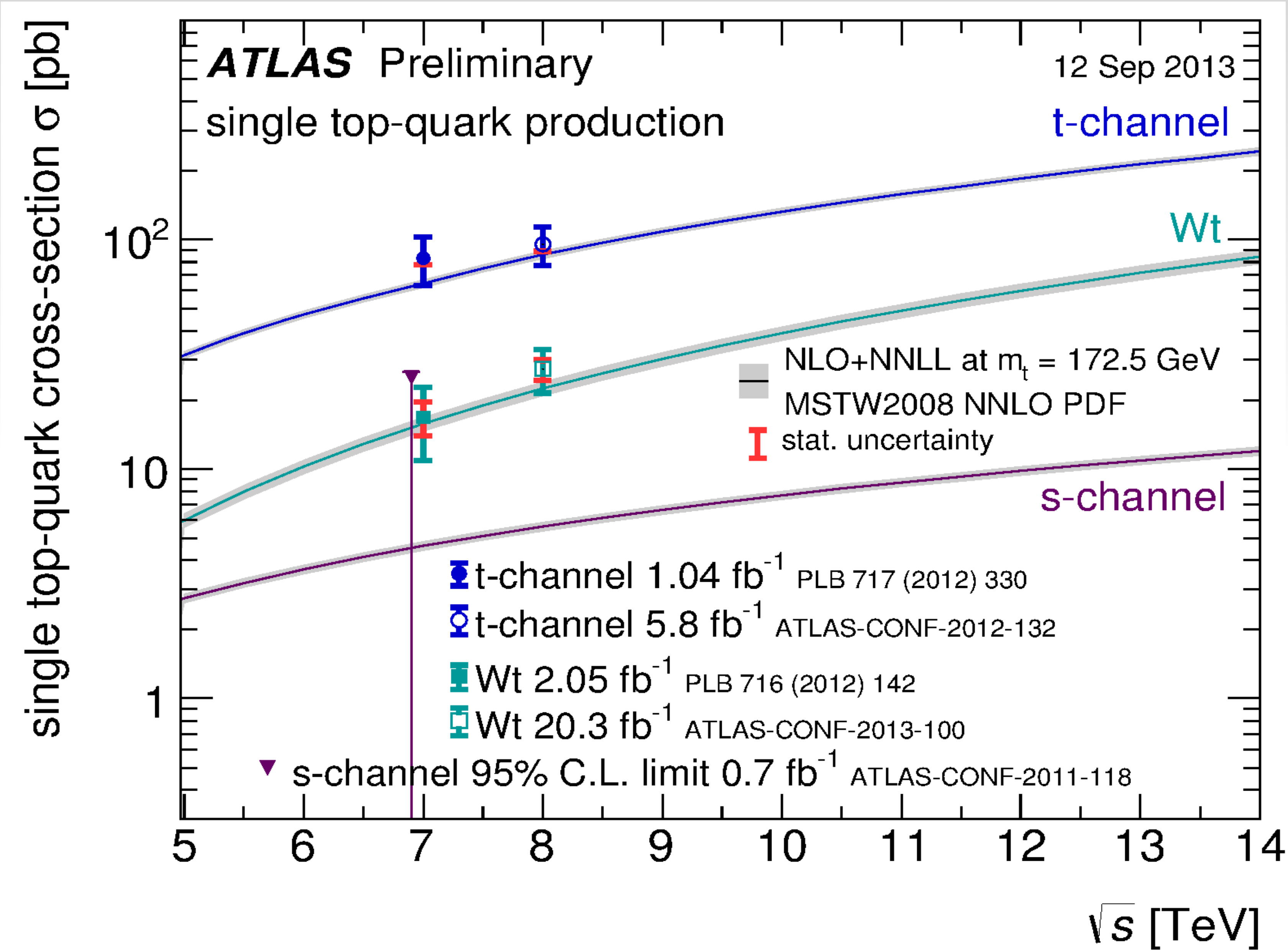


arXiv:1005.3330

Single top cross section:
Wt associated production

Not enough sensitivity at Tevatron

Single Top Quark Expected Cross Section



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:

$$\chi^2 = \frac{\left(m_{jj}^{(1)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jj}^{(2)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jjb}^{(1)} - m_t^{rec}\right)^2}{\Gamma_t^2} + + \frac{\left(m_{jjb}^{(2)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{\left(p_{T,i}^{fit} - p_{T,i}^{meas}\right)^2}{\sigma_i^2}$$

mjj = invariant mass of two light jets

mjjb = invariant mass of three jets

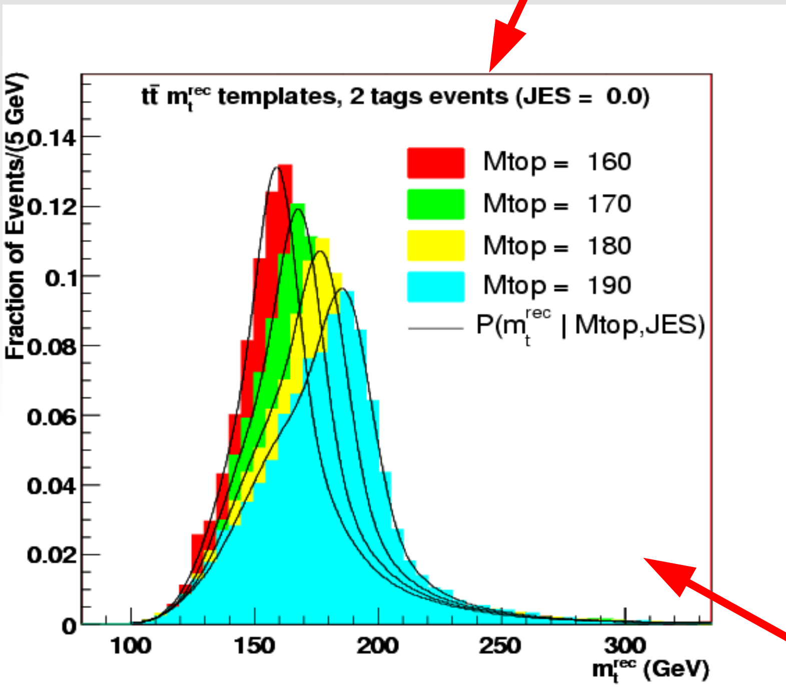
P_T^{fit} =top transv. momentum

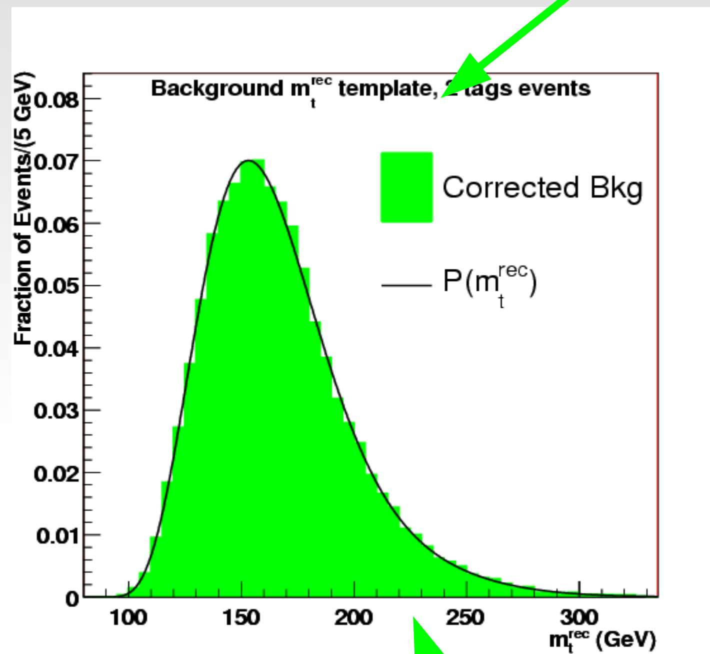
For each permutation we obtain m_t^{rec} this forms the template for signal (MC) and background (data)

Top Quark Mass Measurement: Template Method

Signal template: Monte Carlo data

Background template: data





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

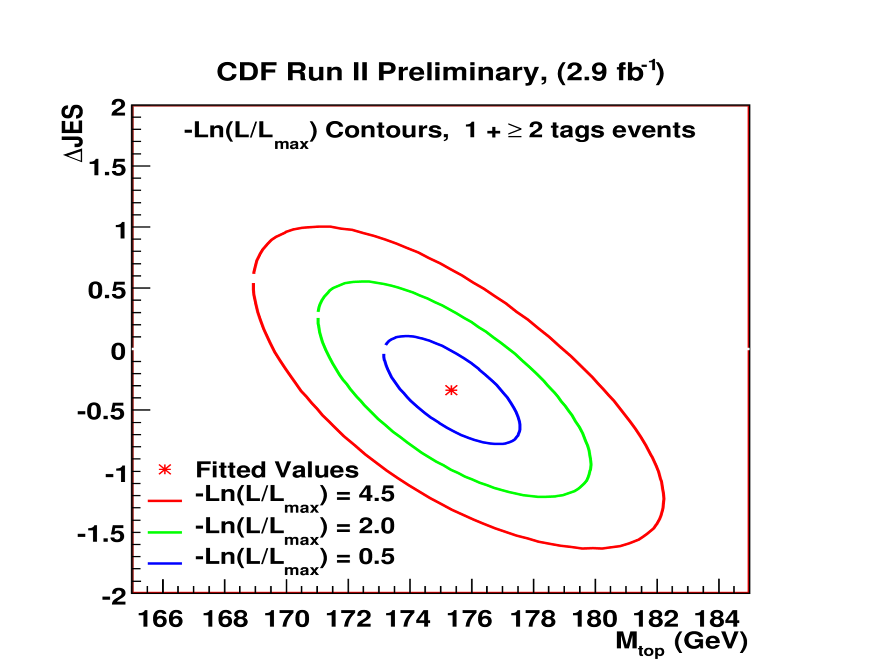
$$\mathcal{L}_{M_{top}} = \prod_{i=1}^{N_{obs}} \frac{n_s \cdot P_{sig}^{m_t^{rec}}(m_{t,i} \mid M_{top}, JES) + n_b \cdot P_{bkd}^{m_t^{rec}}(m_{t,i})}{n_s + n_b}$$

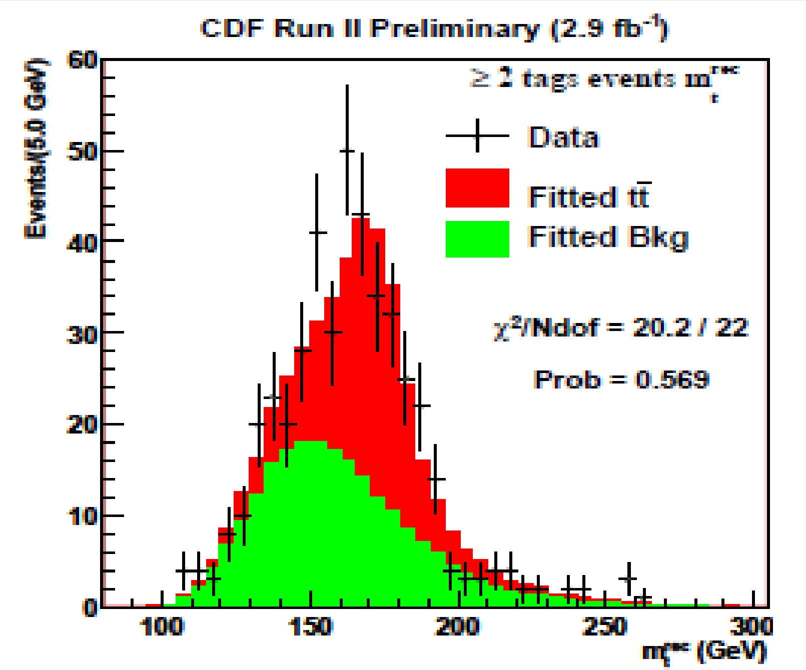
The 2 free parameters are: top mass and JES

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

Top Quark Mass Measurement: Template Method

Tevatron all hadronic decay channel

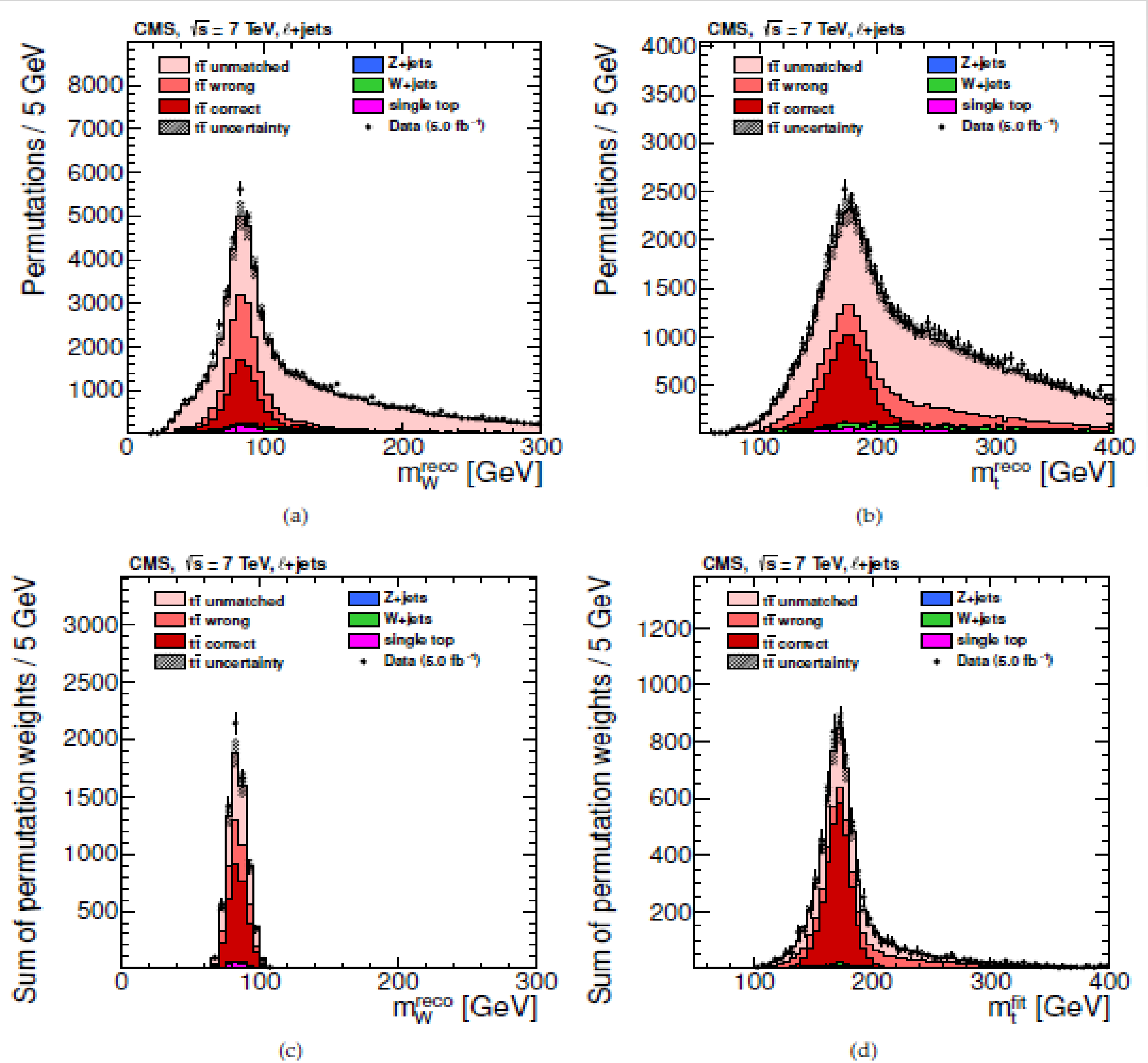




Top Quark Mass Measurement: Template Method

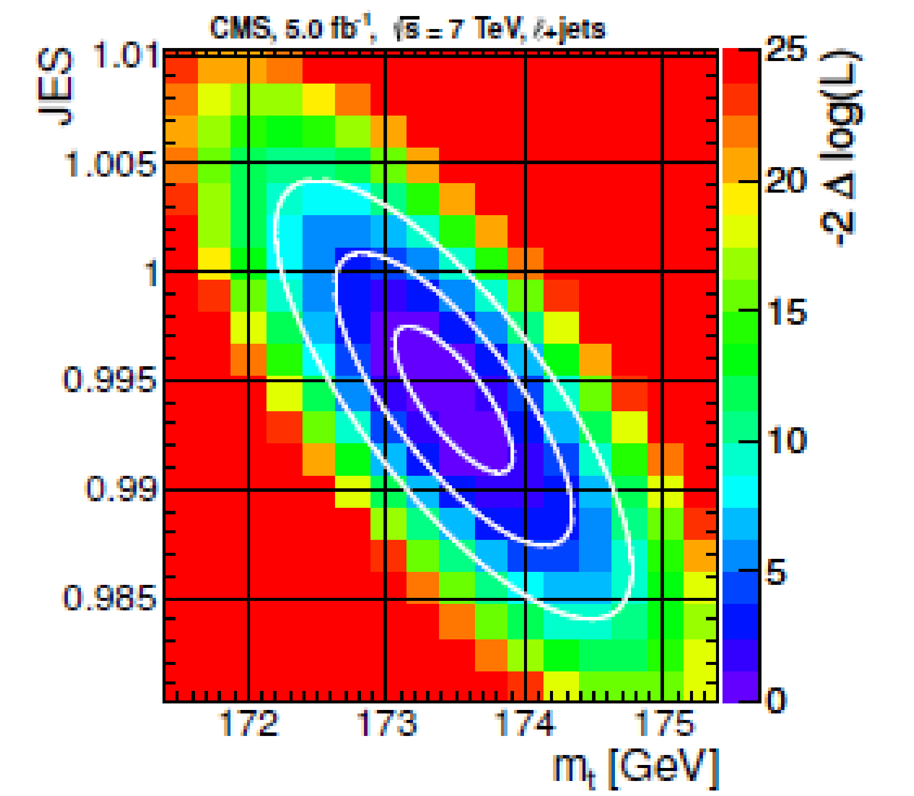
LHC- CMS
μ/e+jets
decay channel

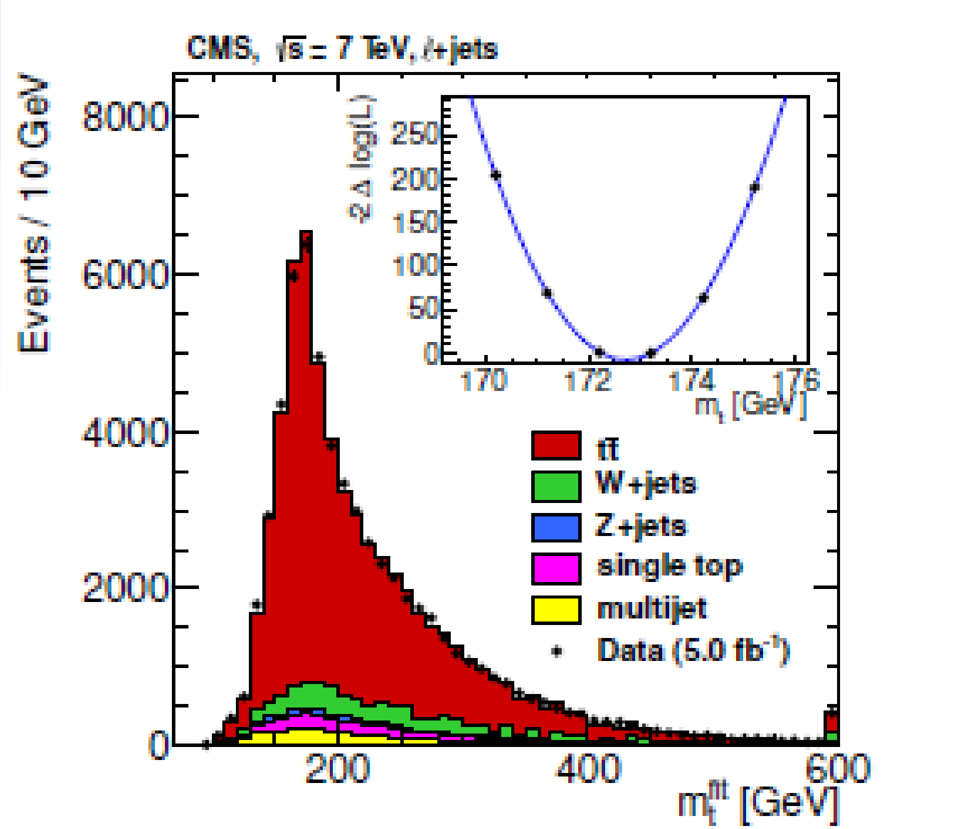
Comparison of M_W and M_t^{reco} before and after the constrain



Top Quark Mass Measurement: Template Method

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





Top Quark Mass Measurement: Matrix Element

Observables: measured momenta of jets and leptons

Question: for an observed set of kinematic variables x what is the most probable top mass

Method: start with an observed set of events of given kinematics and find maximum of the likelihood, which provides the best measurement of top quark mass

Our sample is a mixture of signal and background

$$P_{evt}(x, m_t) = f_{top} \cdot P_{\mathrm{sgn}}(x, m_t) + (1 - f_{top}) \cdot P_{bkg}(x)$$

$P_{bkg}(x)$ depends on the decay channel

$$P_{\mathrm{sgn}}(x; m_t) = \frac{1}{\sigma(m_t)} \int d^n\sigma(y; m_t)\, dq_1\, dq_2\, f(q_1)\, f(q_2)\, W(x, y)$$

Top Quark Mass Measurement: Matrix Element

probability to observe a set of kinematic variables *x* for a given top mass

$$P_{sgn}(x;m_t) = \frac{1}{\sigma(m_t)} \int d^n\sigma(y;m_t)\, dq_1\, dq_2\, f(q_1)\, f(q_2)\, W(x,y)$$

$d^n\sigma$ is the differential cross section
Contains **matrix element** squared

W(x,y) is the probability that a parton level set of variables ***y*** will be measured as a set of variables ***x***.
Parton Energy ↔ Jet Energy

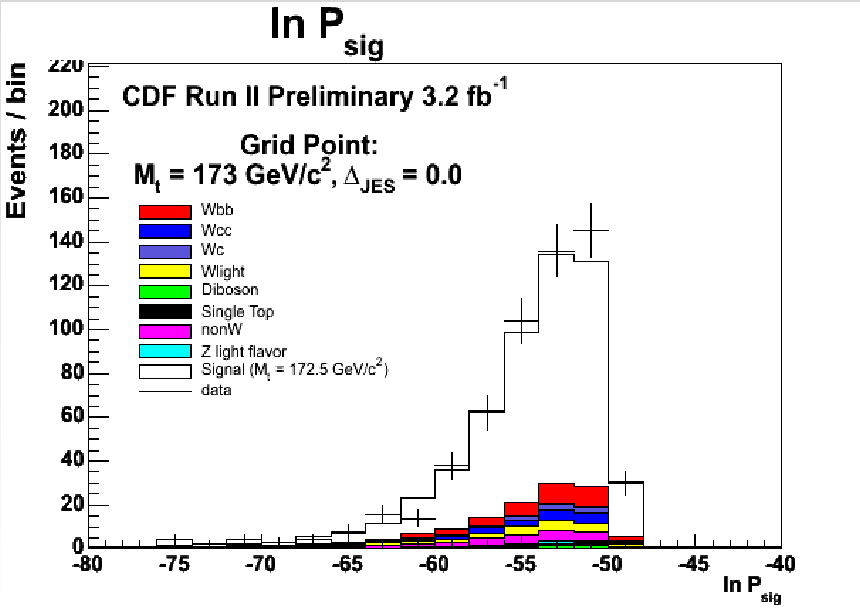
Normalization depends on m_t
Includes acceptance effects

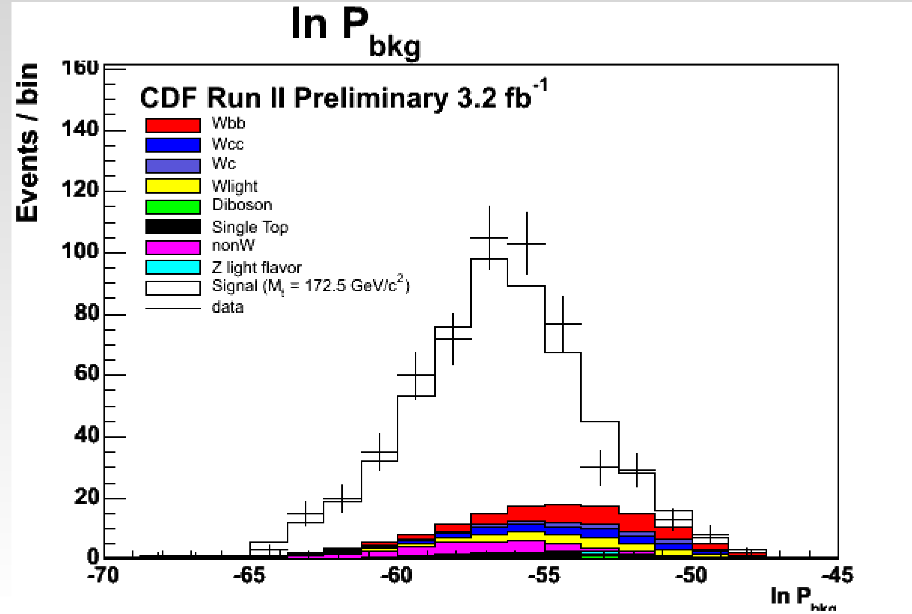
f(q) is the probability distribution than a parton will have a momentum ***q***

Integrate over unknown:
kinematical variable q_1, q_2 of initial states parton and final states parton y
Approximations: LO matrix element and
qq->tt process only (no gluon fusion – 15%)

In a similar way is constructed $P_{bkg}(x)$

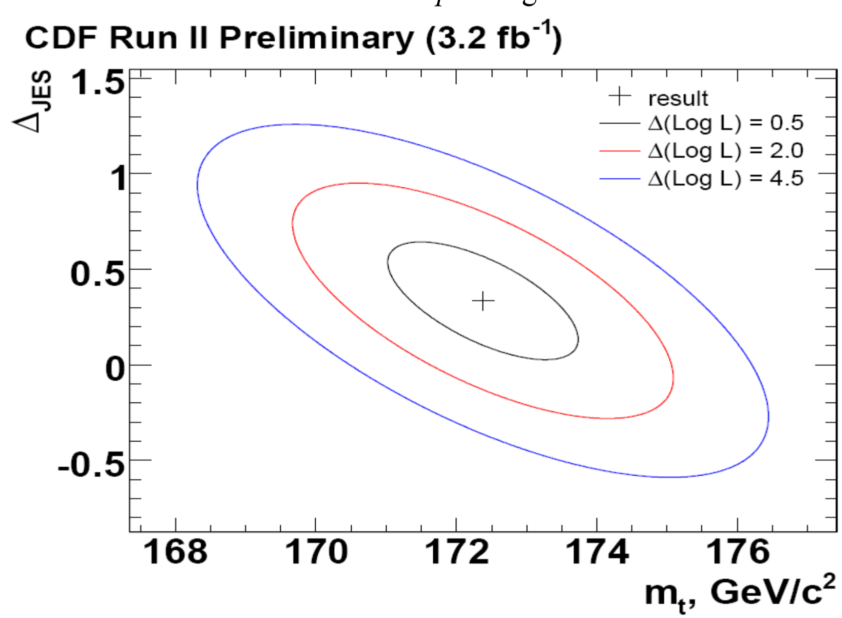
Top Quark Mass Measurement with Matrix Element





Then the likelihood which uses is minimized to obtain

$$P_{evt}(x, m_t) = f_{top} \cdot P_{sgn}(x, m_t) + (1 - f_{top}) \cdot P_{bkg}(x)$$



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

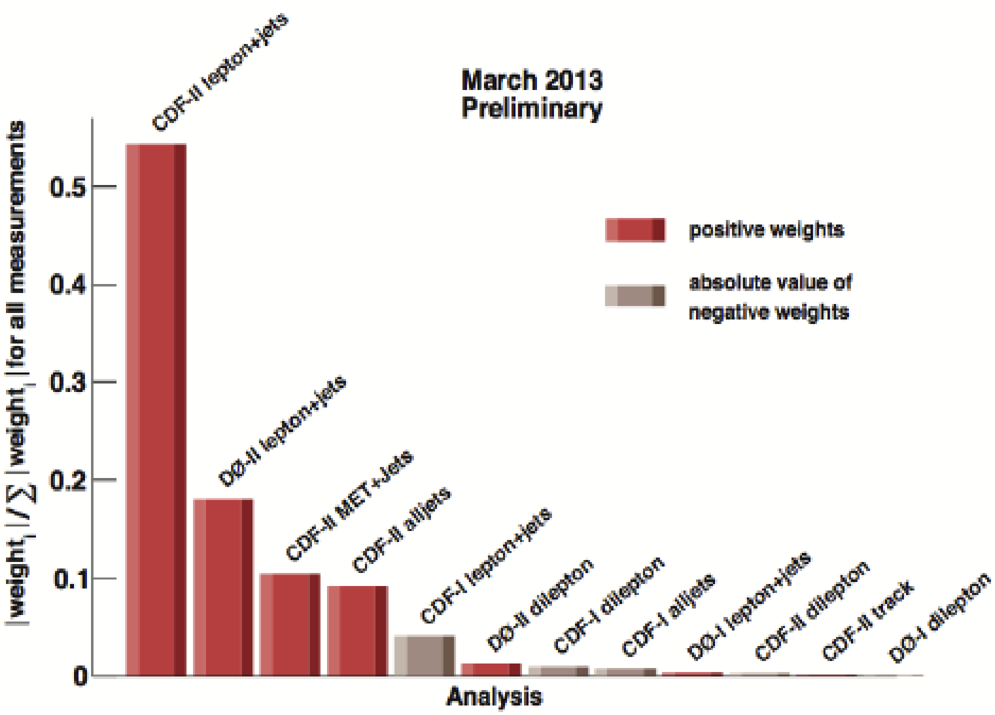
Top Quark Mass Combination Results Tevatron

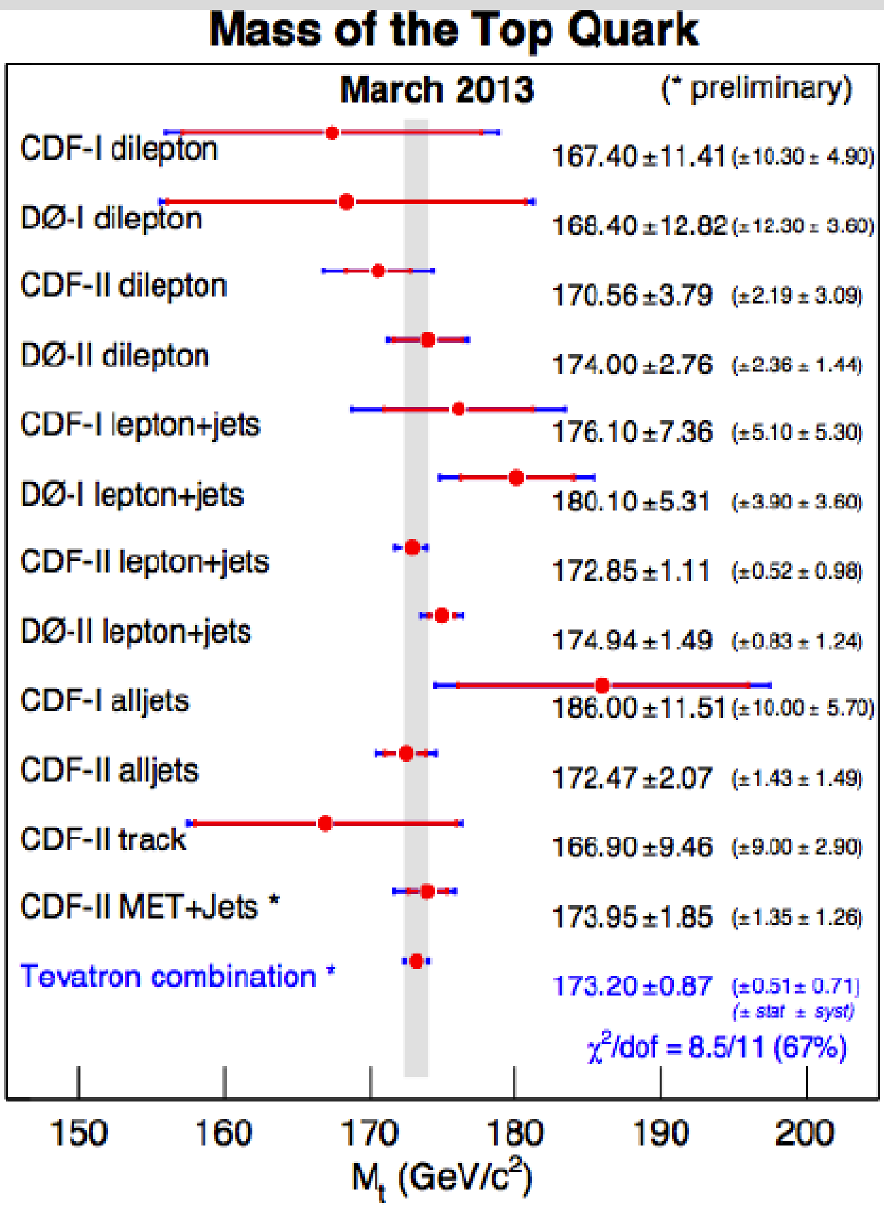
- Measured with 0.5% precision

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

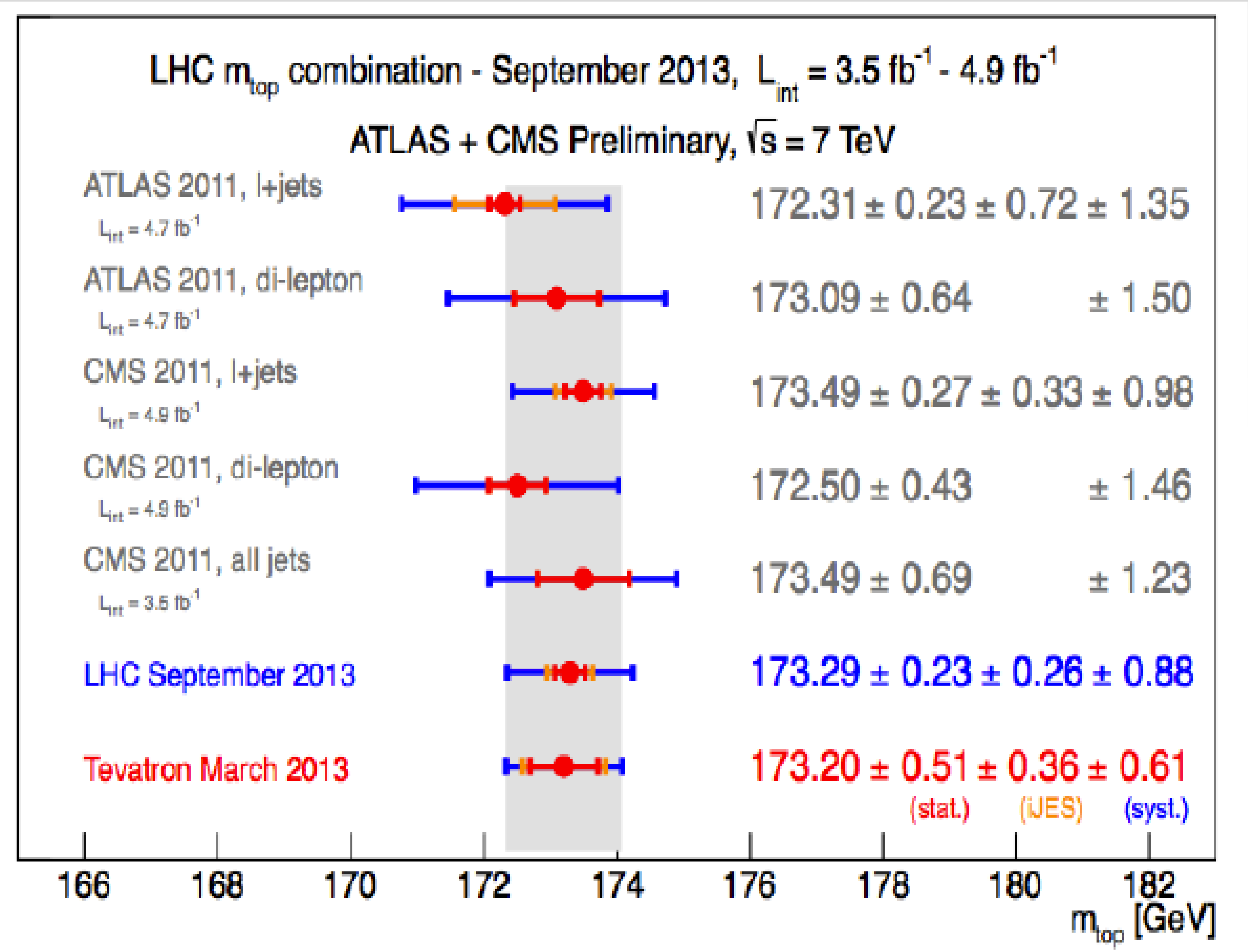
χ^2 /ndf=8.5/11 corresponds to 67% probability

Individual pulls within 1.5σ

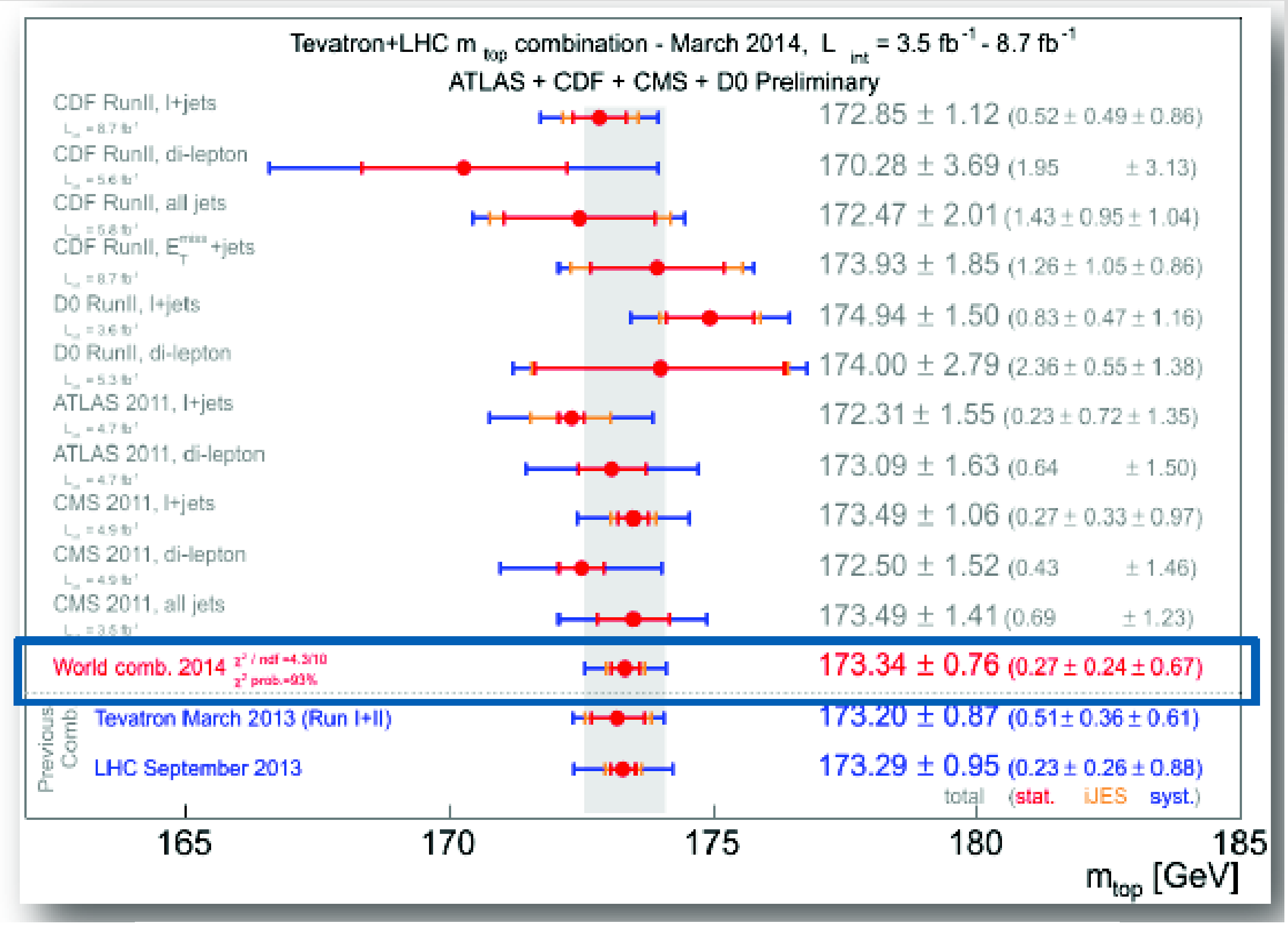




Top Quark Mass Combination Results LHC



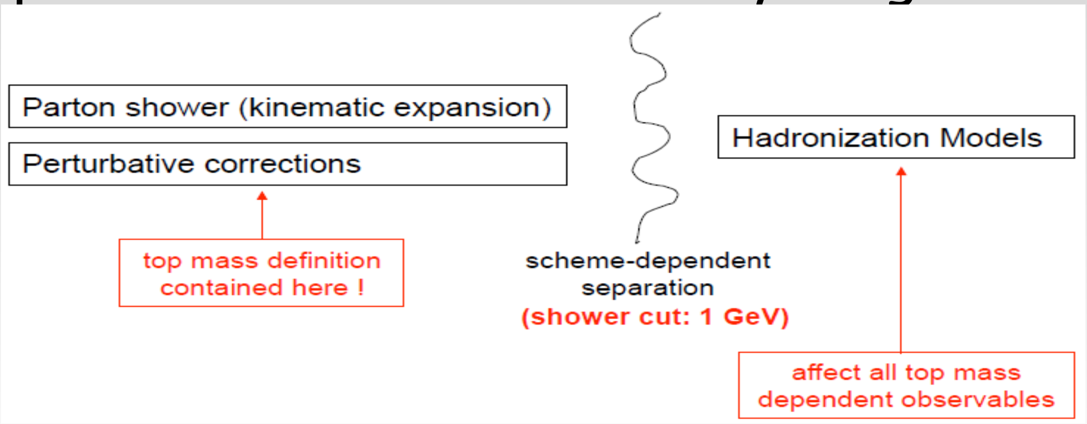
First World Top Quark Mass Combination



$$m_{top} = 173.34 \pm 0.27\ (\text{stat}) \pm 0.71\ (\text{syst})\ \text{GeV}$$ (0.44% !!)

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 ($i\frac{p+m}{p^2-m^2+i\epsilon}$), 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:

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

Parameters a, b determined from data

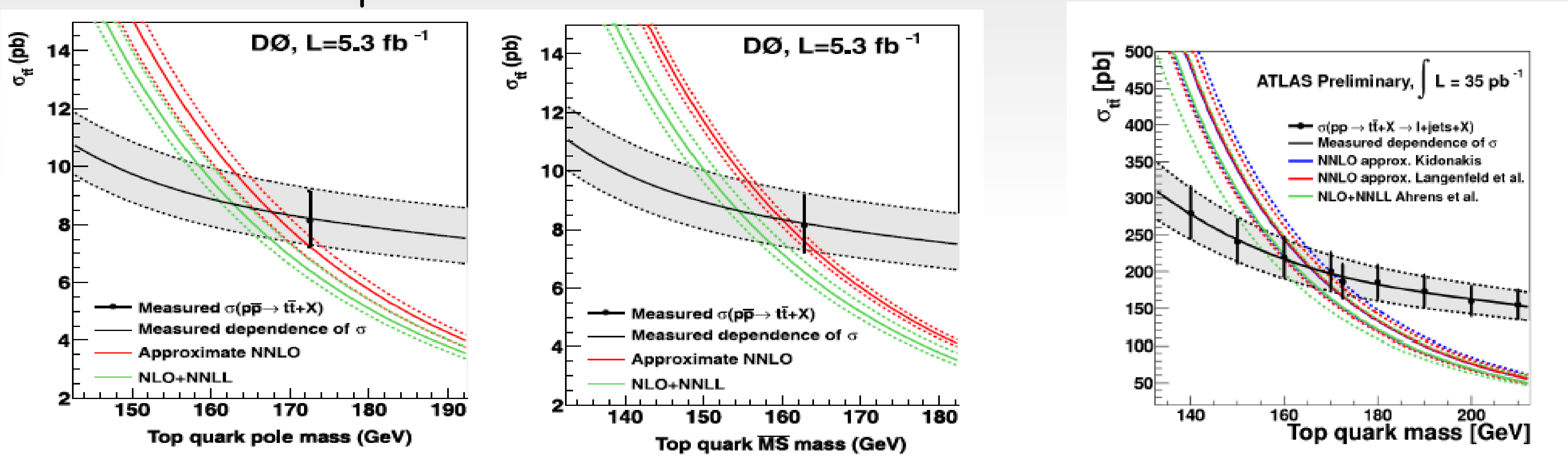
m_0=170 GeV

Top Quark Mass Measurement from Cross Section

Mtop is determined from the joint likelihood

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

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 %

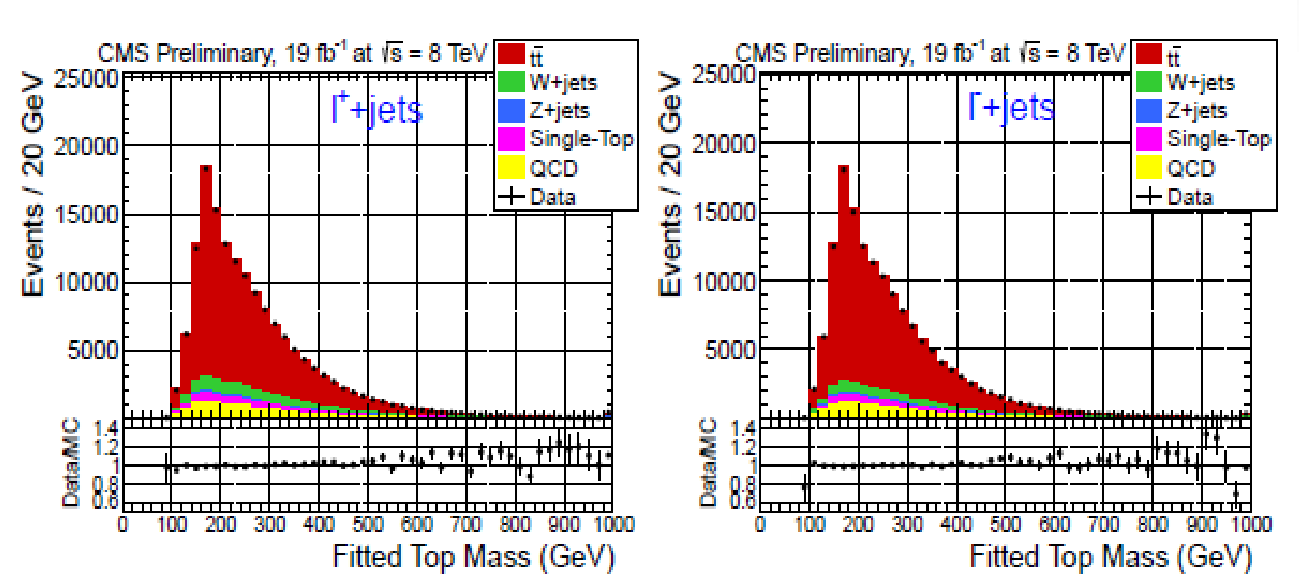
→ CMS: $m_t^{pole} = 176.7\ ^{+3.8}_{-3.4}$ - precision: ~ 2%

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.



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

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 $\Delta m_{reco} = -Q_{lepton} \times dm_{reco}^{min}$

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

$$\Delta \mathrm{M}_{\mathrm{top}} = -1.95 \pm 1.11\ (\mathrm{stat}) \pm 0.59\ (\mathrm{syst})\ \mathrm{GeV}/c^2$$
$$= -1.95 \pm 1.26\ \mathrm{GeV}/c^2.$$