Intrinsic top quark properties - top mass, charge and polarization

DIS2013

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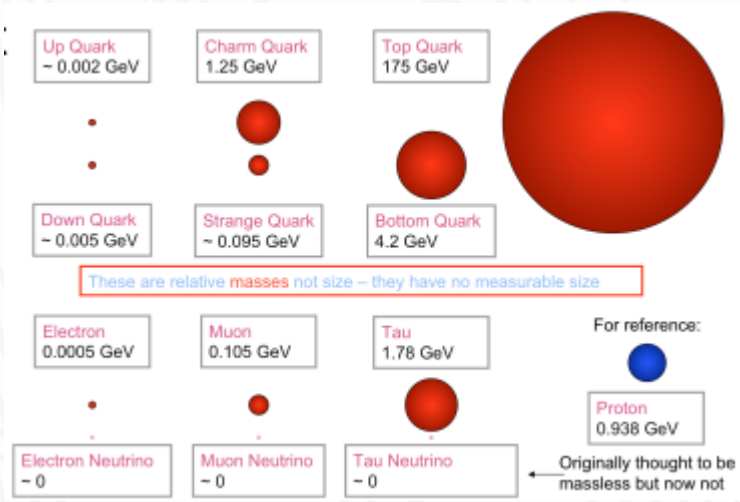
for the ATLAS collaboration

Outline

- Top Properties in brief
- Production at LHC & decay
- Mass
- Charge
- W polarization in top decay
- Summary

Top Overview

- Top is the heaviest fundamental particle ($m_{top} = 173.2 \pm 0.9\ GeV$)[1].
- It decays faster [$\sim 0.5 \cdot 10^{-24} s$] than its hadronization time [$\sim 3 \cdot 10^{-24} s$] →unique possibility to study a bare quark
- Top mass is a fundamental SM parameter and it provided an indirect Higgs mass constraint
- Many BSM scenarios predict heavy particle strongly coupling with the top
- Dominant background in most BSM scenarios.



[1] FERMILAB-PUB-12-336-E

Production at LHC & decay

10.1103/PhysRevD.83.091503, CERN-PH-TH/2013-056, TTK-13-08

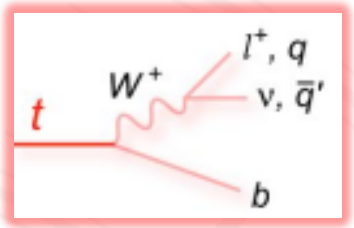
Production at $\sqrt{s} = 7TeV$

- Top pair production (**strong interaction**) $\sigma_{t\bar{t}} = 172.0^{+0.9}_{-1.2}\ pb$
  - 85% $gg \rightarrow t\bar{t}$
  - 15% qq $\rightarrow t\bar{t}$

- Single top production (**weak interaction**):
  - t-ch: $64.6^{+2.7}_{-2.0}\ pb$
  - s-ch: $4.6 \pm 0.2\ pb$
  - Wt: $15.7 \pm 1.1\ pb$

Decay

- $BR_{SM}(t \rightarrow bW) \approx 100\%$



- Top pair decay in different channels grouped in: all hadronic, l+jets and dileptonic

LHC top factory: $5fb^{-1}$ @ $\sqrt{s} = 7TeV$ + $20fb^{-1}$ @ $\sqrt{s} = 8TeV$ ⟶ per experiment
5,600,000 top pairs and 2,700,000 single top events

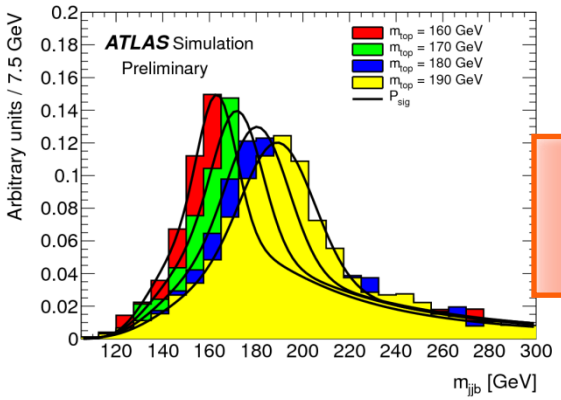
Top Mass

- ℓ+jets channel
- Fully Hadronic Channel
- Combination

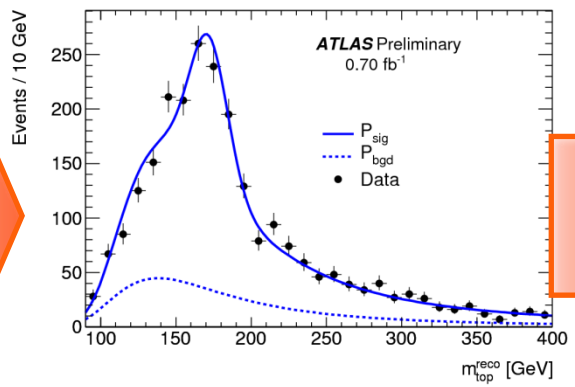
Top Mass

Template Method

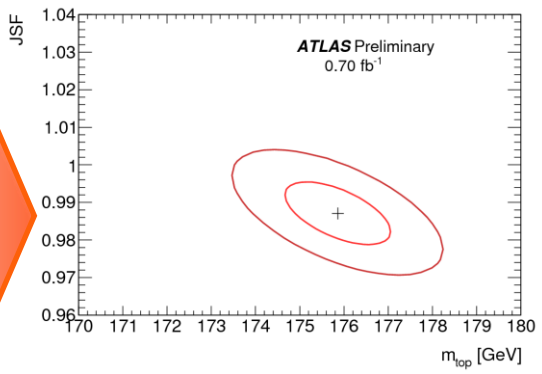
General technique used in many of the following analysis (not only top mass)



Generate some template MC kinematic distributions varying one or more variables.



Interpolate all template distributions to have a Probability Density Function (PDF) distribution for signal (and background).



Perform a likelihood fit of data using the estimated PDF .

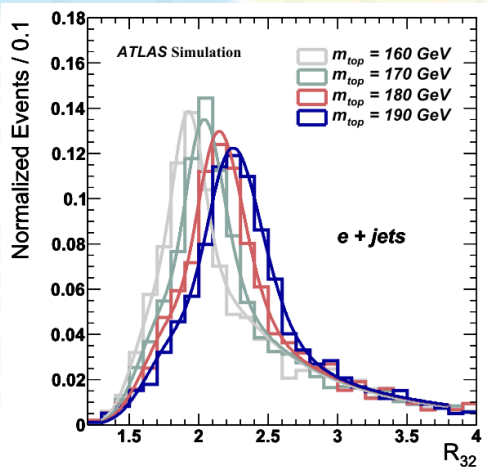
Top Mass – Template Method

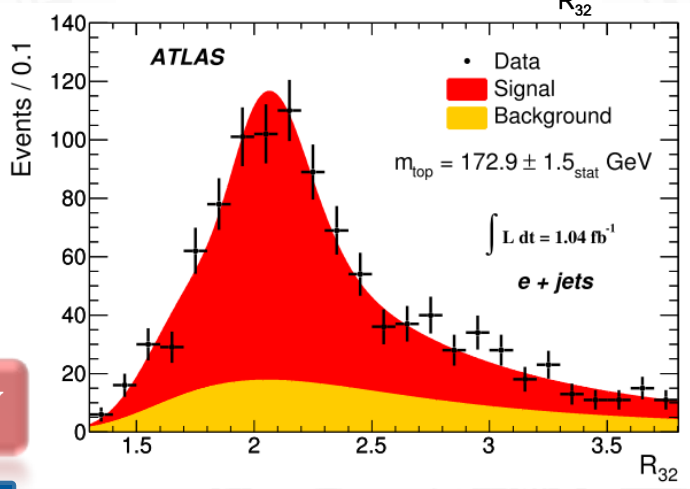
$t\bar{t}$ ℓ+jets channel

$\mathcal{L}$=1.04 fb^{-1}

1D-analysis

- Based on the observable $R_{32} = \frac{m_{top}^{had}}{m_W^{had}}$ to extract m_{top}
- W and top mass reconstructed using a kinematic fit based on the $t\bar{t}$ process likelihood. (70% eff.)
- Fit R_{32} with 2Gauss + Landau → PDF
- Algorithm performance tested via pseudo-experiments





1D $m_{top} = 174.4 \pm 0.9_{stat} \pm 2.5_{syst}\ GeV$

Main Systematics: JES, b-tag, I/FSR, hadronisation

Eur.Phys.J. C72 (2012) 2046

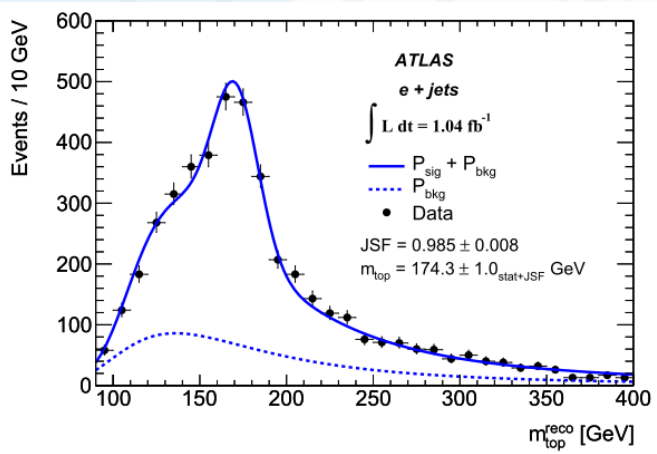
Top Mass – Template Method

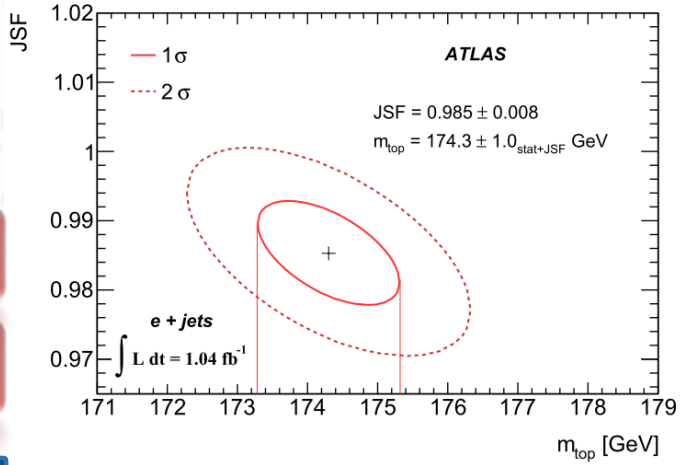
$t\bar{t}$ ℓ+jets channel

$\mathcal{L}$=1.04 fb^{-1}

2D-analysis

- Evaluate m_{top} and Jet Scale Factor(JSF) at the same time using 2 dim. likelihood fit
- m_{top} uncertainty includes part of JES, I/FSR, … contributions.
- Use a kinematic fit with a χ^2 minimization
- Template sample varying m_{top}[160-190] GeV and JSF [0.9-1.1]





1D	$m_{top} = 174.4 \pm 0.9_{stat} \pm 2.5_{syst}\ GeV$
2D	$m_{top} = 174.5 \pm 0.6_{stat} \pm 2.3_{syst}\ GeV$

Main Systematics: JES, b-tag, I/FSR, hadronisation

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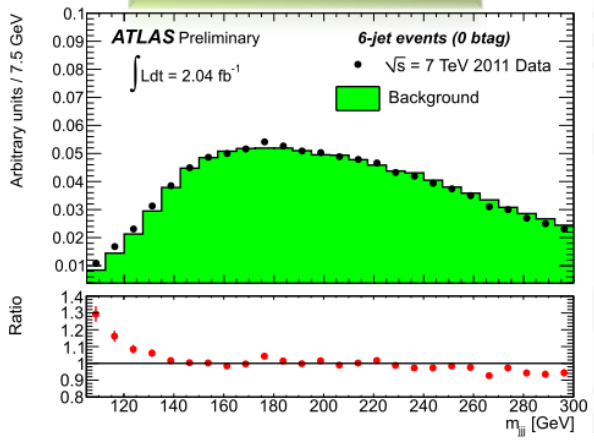
Top Mass – Template Method

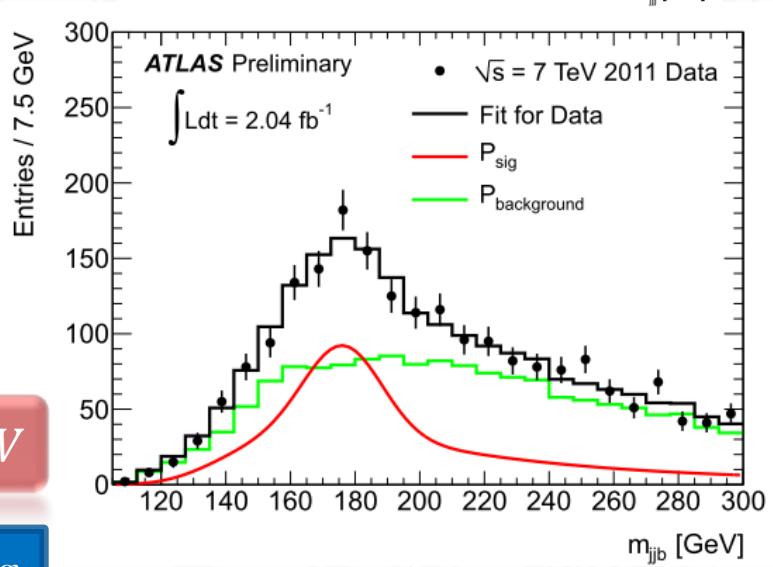
$t\bar{t}$ fully had channel

$\mathcal{L}$=2.04 fb^{-1}

- Background only from combinatorial and multi-jet events.
- Multi-jets PDF via data driven estimation
- Event Mixing Algorithm: event with N° jets = 5 ✚ the 6th jet (ordered by p_T) from events with ≥ 6
- Top mass evaluated from a binned likelihood fit

Validation Sample





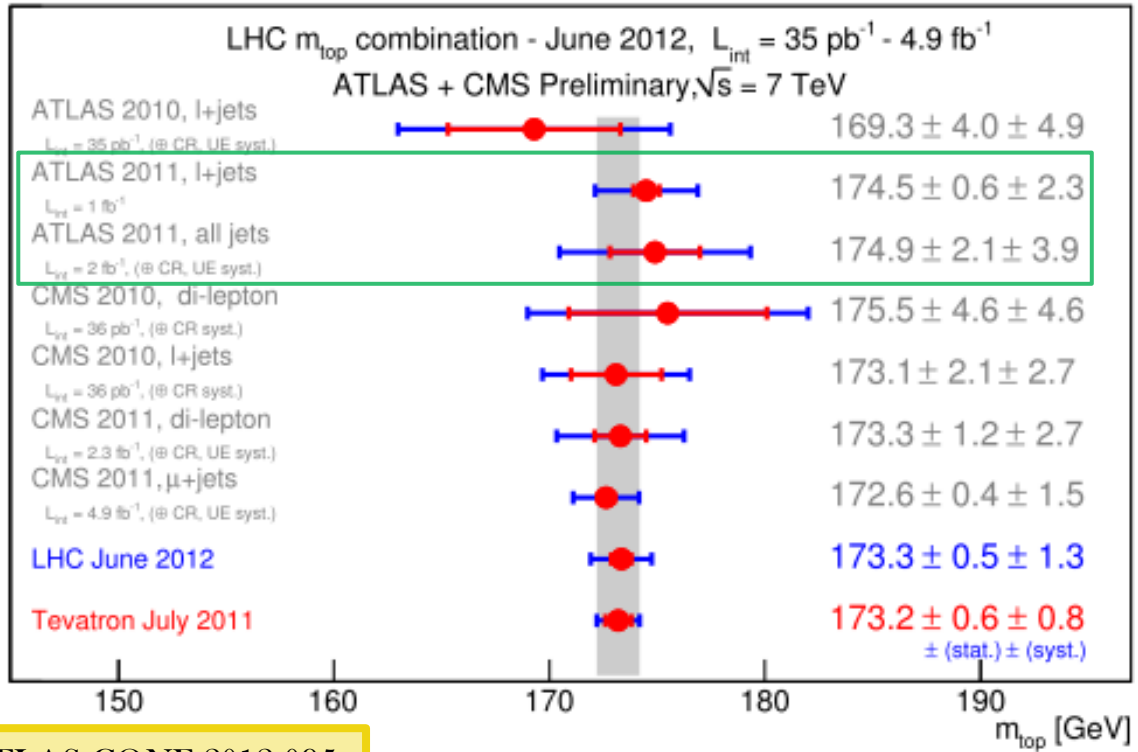
All Had. $m_{top} = 174.9 \pm 2.1_{stat} \pm 3.8_{syst}\ GeV$

Main Systematics: JES, b-tag, I/FSR, bkg modelling

ATLAS-CONF-2012-030

Top Mass - Combination

- ATLAS + CMS combination is performed using the Best Linear Unbiased Estimator (**BLUE**) method



ATLAS-CONF-2012-095

- LHC precision: 0.8%
- Tevatron precision: 0.6%

Tevatron has smaller systematics contribution

$\mathcal{L}_{Tevatron}$=8.7 fb^{-1}

Top Charge

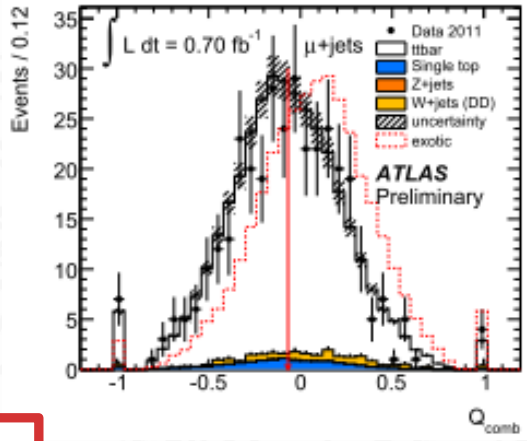
Top Charge

$t\bar{t}$ ℓ+jets channel

$\mathcal{L}$=0.7 fb^{-1}

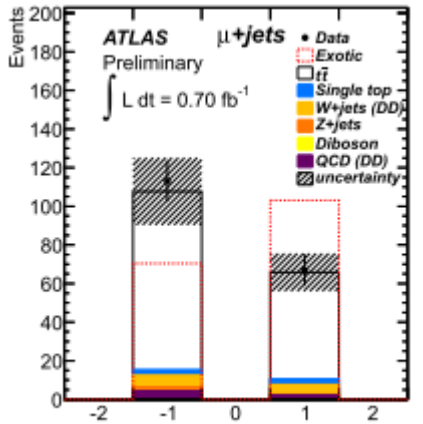
Test exotic hypothesis of a -4/3 charged top quark

- **Track charged weighting technique**:
  - b_{jet} charge as $Q_{bjet} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p_i}|^{1/2}}{\sum_i |\vec{j} \cdot \vec{p_i}|^{1/2}}$
  - Consider at most 10 highest p_T charged tracks in a R=0.25 cone around b → decrease pileup



$Q_{comb} = Q_{bjet} \cdot Q_\ell$

- **Soft lepton technique:**
  - Consider muonic b decay BR($b \to \mu + \nu + X$)=11%
  - μ inside b cone → the same sign of the b
  - Main bkg from $b \to c \to \mu + \nu + X$(BR=10%).μ has opposite sign than b. Rejected with a $p_T^{rel}(\mu)$ cut.



ATLAS-CONF-2011-141

Exotic Top quark excluded at more than **5σ**

Main Systematics: MC modelling, I/FSR

W polarization in Top decay

W polarization in Top decay

$t\bar{t}$ ℓ+jets & $\ell\ell$ channel

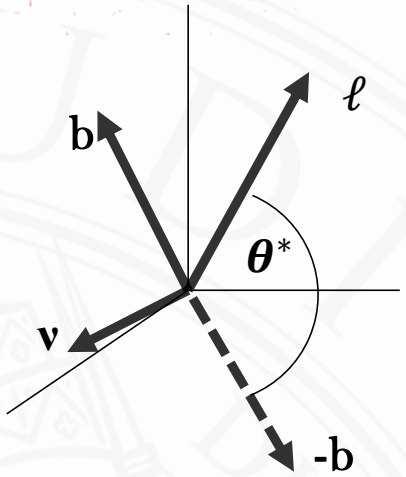
$\mathcal{L}$=1.04 fb^{-1}

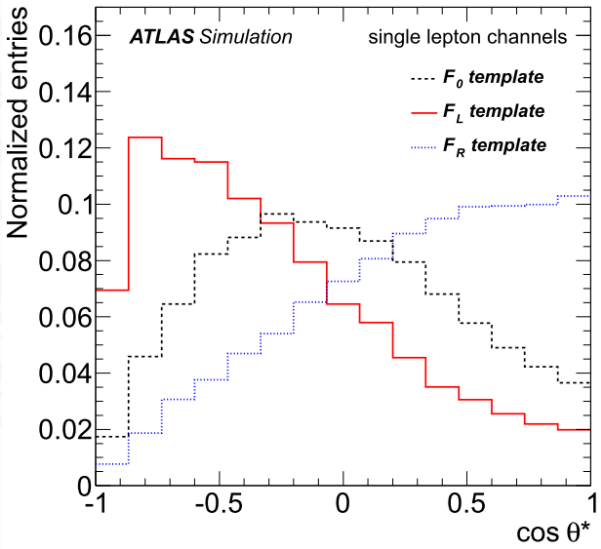
- Measure the W angular distribution
- Polarization is an important test of the SM
- Consider only angular distribution wrt θ^* in the **W rest frame.**
- Angular distribution parameterized with 3 variables

$$\frac{1}{\sigma}\frac{d\sigma}{\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F_0 + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$

with

$$F_0 + F_L + F_R = 1$$





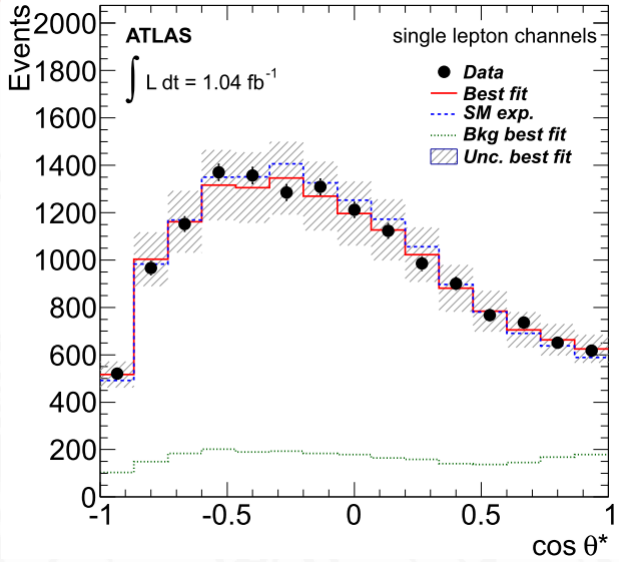
JHEP 1206 (2012) 088

W polarization in Top decay

$t\bar{t}$ ℓ+jets & $\ell\ell$ channel

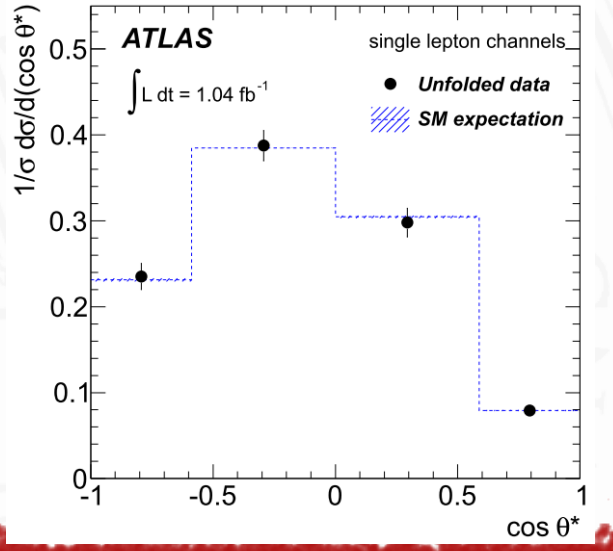
$\mathcal{L}$=1.04 fb^{-1}

- **Cos θ^* distribution fit**
  - PDF from template with 3 different polarization values
  - Binned likelihood fit.



- **Asymmetry distribution**
  - $A_{\pm}$ related with polarization variables F_0, F_L and F_R.
  - $A_{\pm} = \frac{N(\cos\theta^* > z) - N(\cos\theta^* < z)}{N(\cos\theta^* > z) + N(\cos\theta^* < z)}$

    $with \quad z = \pm(1 - 2^{2/3})$



W polarization in Top decay

Results:

$F_0 = 0.67 \pm 0.03_{stat} \pm 0.06_{syst}$

$F_L = 0.32 \pm 0.02_{stat} \pm 0.03_{syst}$

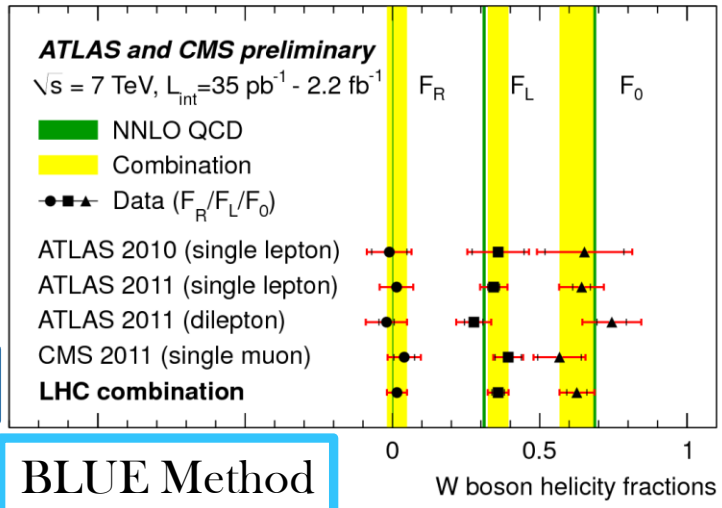
$F_R = 0.01 \pm 0.01_{stat} \pm 0.04_{syst}$

SM prediction

$F_0 = 0.687 \pm 0.005$

$F_L = 0.311 \pm 0.005$

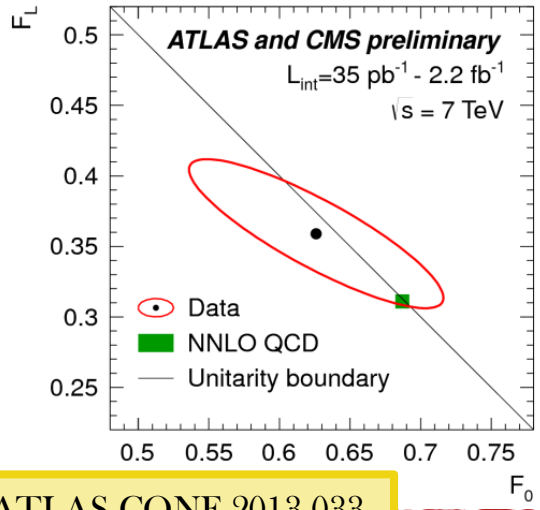
$F_R = 0.0017 \pm 0.0001$



Main Systematics: JES, lepton mismatch, specific method uncert.

CMS & ATLAS combination

BLUE Method



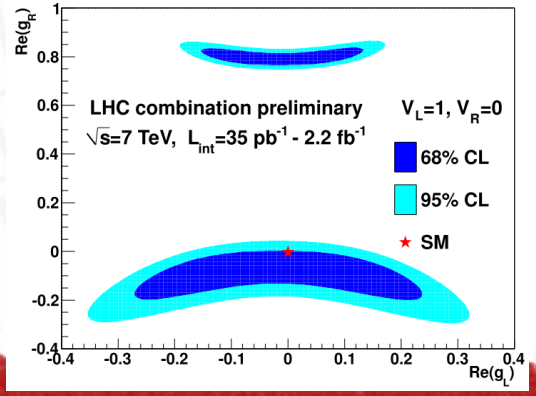
ATLAS-CONF-2013-033

Electroweak Lagrangian for Wtb vertex

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.},$$

$$V_L = V_{tb} + C_{\phi q}^{(3,3+3)}\frac{v^2}{\Lambda^2}, \quad V_R = \frac{1}{2}C_{\phi\phi}^{33*}\frac{v^2}{\Lambda^2},$$

$$g_L = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}, \quad g_R = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}.$$



Summary

Top properties very important in order to test SM validity:

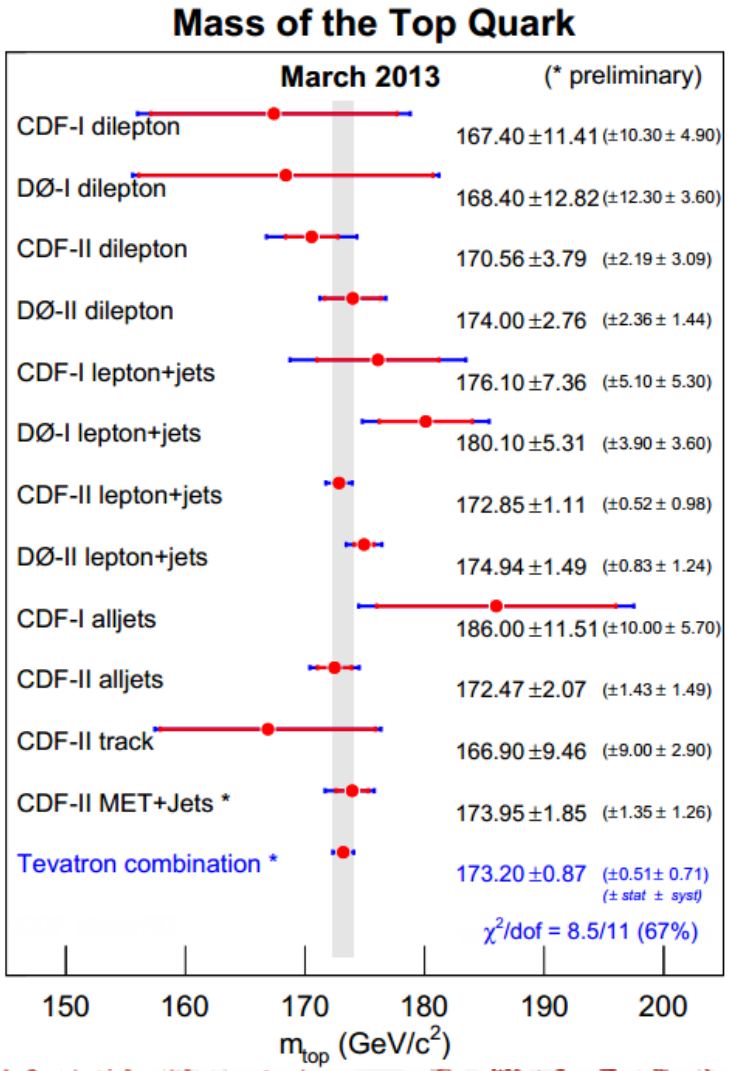
- Top Mass in ℓ+jets and all hadronic channel and ATLAS+CMS combination is presented (precision 0.8%). Results in agreement with theory.
- Exotic top with charge -4/3 is excluded at more than 5σ.
- W polarization in top decay (and combination with CMS) is in agreement with theoretical prediction. No BSM structures observed in Wtb vertex.

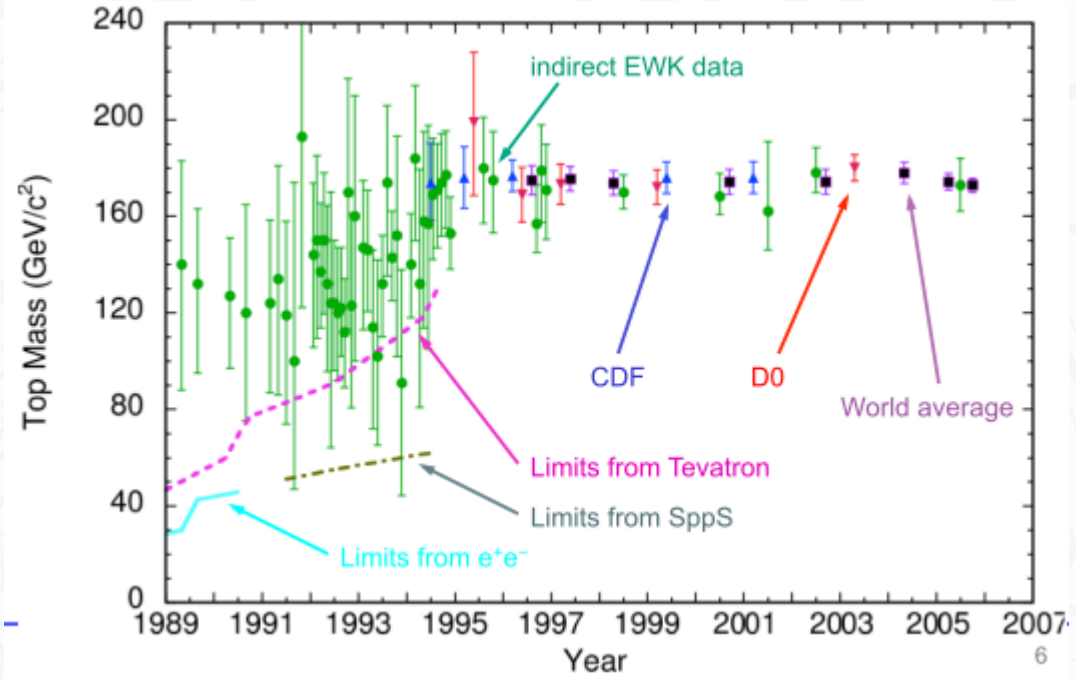
All results compatible with SM and Tevatron results


Thanks for the attention

Backup Slide

Top Mass

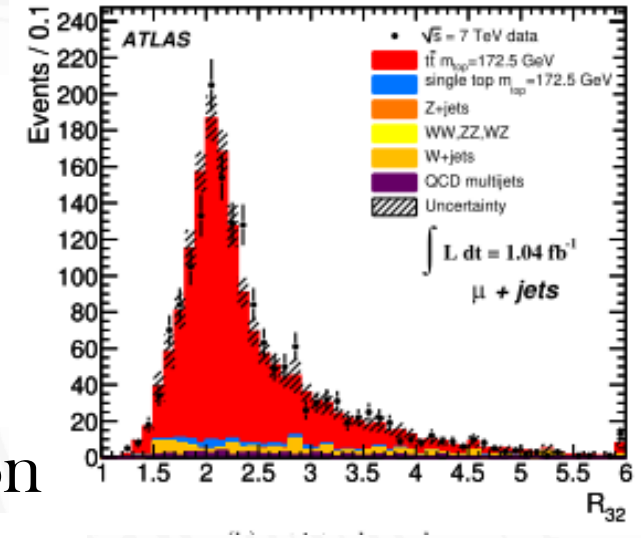

Mass of the Top Quark
March 2013
(* preliminary)
CDF-I dilepton
167.40 ±11.41 (±10.30 ± 4.90)
DØ-I dilepton
168.40 ±12.82 (±12.30 ± 3.60)
CDF-II dilepton
170.56 ±3.79 (±2.19 ± 3.09)
DØ-II dilepton
174.00 ±2.76 (±2.36 ± 1.44)
CDF-I lepton+jets
176.10 ±7.36 (±5.10 ± 5.30)
DØ-I lepton+jets
180.10 ±5.31 (±3.90 ± 3.60)
CDF-II lepton+jets
172.85 ±1.11 (±0.52 ± 0.98)
DØ-II lepton+jets
174.94 ±1.49 (±0.83 ± 1.24)
CDF-I alljets
186.00 ±11.51 (±10.00 ± 5.70)
CDF-II alljets
172.47 ±2.07 (±1.43 ± 1.49)
CDF-II track
166.90 ±9.46 (±9.00 ± 2.90)
CDF-II MET+Jets *
173.95 ±1.85 (±1.35 ± 1.26)
Tevatron combination *
173.20 ±0.87 (±0.51± 0.71)
(± stat ± syst)
χ²/dof = 8.5/11 (67%)
150
160
170
180
190
200
m_top (GeV/c²)


Top Mass (GeV/c²)
240
200
160
120
80
40
0
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Year
indirect EWK data
CDF
D0
World average
Limits from Tevatron
Limits from SppS
Limits from e⁺e⁻

Top Mass – Template Method

- DiTop mass likelihood fit to find mtop and mW: transfer func.(T), Breit-Wigner (B) distributions, and aweight W btag =0.48

$$
\begin{aligned}
L = & \mathcal{T}\left(E_{\mathrm{jet}_1}|\hat{E}_{b_{\mathrm{had}}}\right)\cdot\mathcal{T}\left(E_{\mathrm{jet}_2}|\hat{E}_{b_\ell}\right)\cdot\mathcal{T}\left(E_{\mathrm{jet}_3}|\hat{E}_{q_1}\right)\cdot \\
& \mathcal{T}\left(E_{\mathrm{jet}_4}|\hat{E}_{q_2}\right)\cdot\mathcal{T}\left(E_x^{\mathrm{miss}}|\hat{p}_{x,\nu}\right)\cdot\mathcal{T}\left(E_y^{\mathrm{miss}}|\hat{p}_{y,\nu}\right)\cdot \\
& \left\{\begin{array}{ll}\mathcal{T}\left(E_e|\hat{E}_e\right) & e\text{+jets}\\ \mathcal{T}\left(p_{\mathrm{T},\mu}|\hat{p}_{\mathrm{T},\mu}\right) & \mu\text{+jets}\end{array}\right\}\cdot \\
& \mathcal{B}\left[m(q_1\,q_2)|m_W,\Gamma_W\right]\cdot\mathcal{B}\left[m(\ell\,\nu)|m_W,\Gamma_W\right]\cdot \\
& \mathcal{B}\left[m(q_1\,q_2\,b_{\mathrm{had}})|m_{\mathrm{top}}^{\mathrm{reco,like}},\Gamma_{\mathrm{top}}\right]\cdot \\
& \mathcal{B}\left[m(\ell\,\nu\,b_\ell)|m_{\mathrm{top}}^{\mathrm{reco,like}},\Gamma_{\mathrm{top}}\right]\cdot W_{\mathrm{btag}}\,.
\end{aligned}
$$



- Binned likelihood for mTop evaluation

$$\mathcal{L}_{\mathrm{shape}}(R_{32}|m_{\mathrm{top}}) = \prod_{i=1}^{N_{\mathrm{bins}}}\frac{\lambda_{\mathrm{i}}^{N_{\mathrm{i}}}}{N_{\mathrm{i}}!}\cdot e^{-\lambda_{\mathrm{i}}}\,,$$

$$\mathcal{L}_{\mathrm{bkg}}(R_{32}) = \exp\left\{-\frac{(n_{\mathrm{bkg}}-n_{\mathrm{bkg}}^{\mathrm{pred}})^2}{2\sigma^2_{n_{\mathrm{bkg}}^{\mathrm{pred}}}}\right\}\,,$$

$$\mathcal{L}(R_{32}|m_{\mathrm{top}}) = \mathcal{L}_{\mathrm{shape}}(R_{32}|m_{\mathrm{top}})\times\mathcal{L}_{\mathrm{bkg}}(R_{32})\,,$$

with:

$$\lambda_{\mathrm{i}} = (N-n_{\mathrm{bkg}})\cdot P_{\mathrm{sig}}(R_{32}|m_{\mathrm{top}})_i + n_{\mathrm{bkg}}\cdot P_{\mathrm{bkg}}(R_{32})_i\,,$$

$$N = \sum_{i}^{N_{\mathrm{bins}}} N_{\mathrm{i}} = n_{\mathrm{sig}} + n_{\mathrm{bkg}}\,.$$

Top Mass – Template Method

Selection: ttbar l+jets

$\mathcal{L}$=1.04 fb^{-1}

2D-analysis

- To find reco top and W mass kinematic fit minimizing chi2 (-0.06 correlation)

$$\chi^2 = \sum_{i=1}^{2} \left[\frac{E_{\mathrm{jet},i}(1-\alpha_i)}{\sigma(E_{\mathrm{jet},i})}\right]^2 + \left[\frac{M_{\mathrm{jet,jet}}(\alpha_1,\alpha_2) - m_W}{\Gamma_W}\right]^2$$

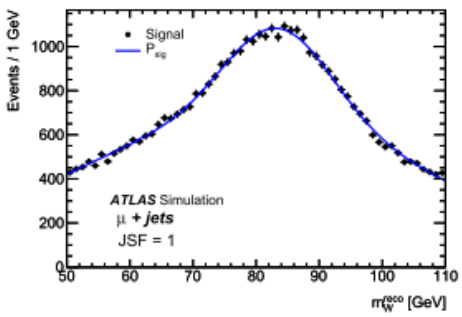
- Fit 2 gauss for mW
- Fit guass+landau for mTop
- Unbinned 2 dim likelihood to get mTop

$$\mathcal{L}_{\mathrm{shape}}(m_{\mathrm{W}}^{\mathrm{reco}}, m_{\mathrm{top}}^{\mathrm{reco}} | m_{\mathrm{top}}, \mathrm{JSF}, n_{\mathrm{bkg}}) = \prod_{i=1}^{N} P_{\mathrm{top}}(m_{\mathrm{top}}^{\mathrm{reco}} | m_{\mathrm{top}}, \mathrm{JSF}, n_{\mathrm{bkg}})_i \times P_{\mathrm{W}}(m_{\mathrm{W}}^{\mathrm{reco}} | \mathrm{JSF}, n_{\mathrm{bkg}})_i \quad ,$$

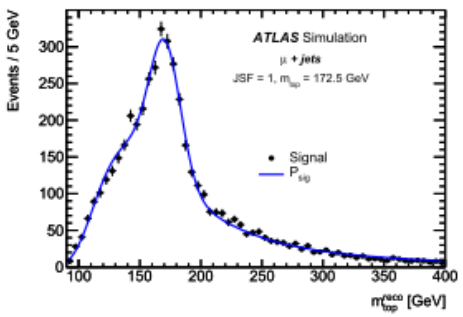
with:

$$P_{\mathrm{top}} = (N - n_{\mathrm{bkg}}) \cdot P_{\mathrm{top}}^{\mathrm{sig}}(m_{\mathrm{top}}^{\mathrm{reco}} | m_{\mathrm{top}}, \mathrm{JSF})_i + n_{\mathrm{bkg}} \cdot P_{\mathrm{top}}^{\mathrm{bkg}}(m_{\mathrm{top}}^{\mathrm{reco}} | m_{\mathrm{top}}, \mathrm{JSF})_i \ ,$$

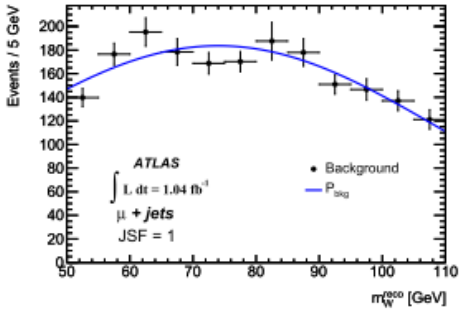
$$P_{\mathrm{W}} = (N - n_{\mathrm{bkg}}) \cdot P_{\mathrm{W}}^{\mathrm{sig}}(m_{\mathrm{W}}^{\mathrm{reco}} | \mathrm{JSF})_i + n_{\mathrm{bkg}} \cdot P_{\mathrm{W}}^{\mathrm{bkg}}(m_{\mathrm{W}}^{\mathrm{reco}} | \mathrm{JSF})_i \ .$$

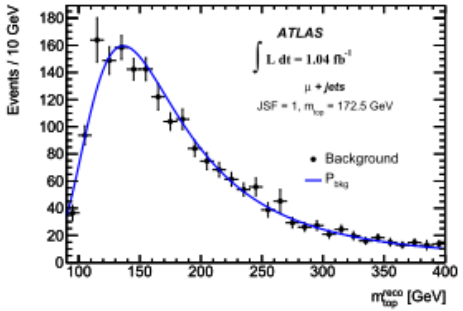


(a) μ+jets channel



(b) μ+jets channel





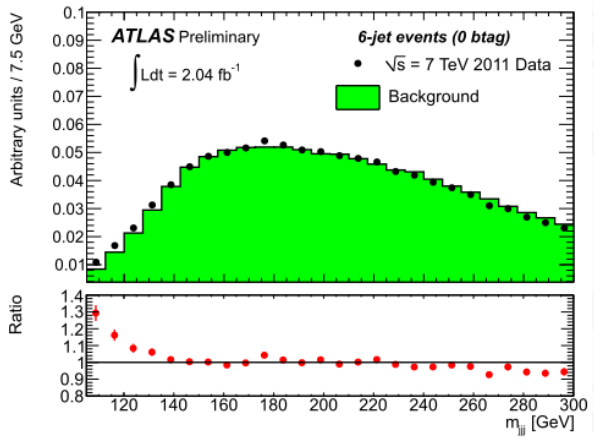
Top Mass – Fit Method

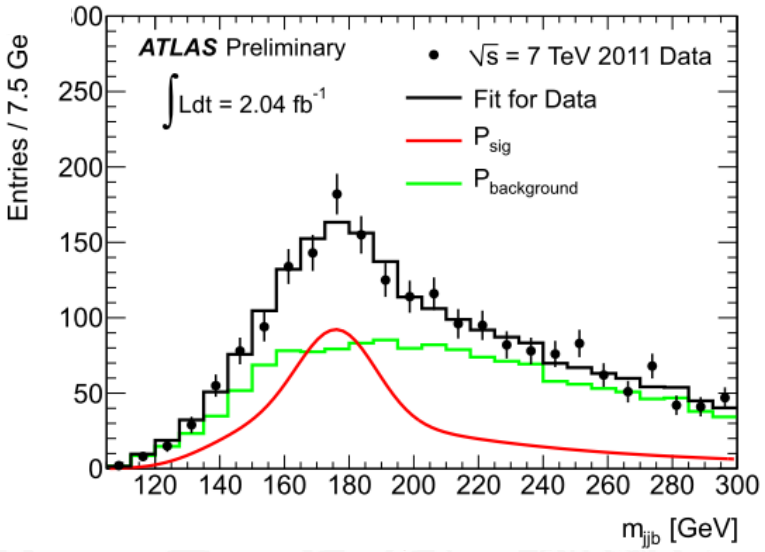
$t\bar{t}$ fully had channel

$\mathcal{L}$=2.04 fb^{-1}

- Event reconstructed with kinematic fit with chi2 minimization

$$\chi^2 = \frac{(m_{j_1,j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_1,j_2,b_1} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_3,j_4} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3,j_4,b_2} - m_t)^2}{\sigma_t^2}$$





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Top Charge

$t\bar{t}$ ℓ+jets channel

$\mathcal{L}$=0.7 fb^{-1}

- Exotic hypothesis of -4/3 top quark tested

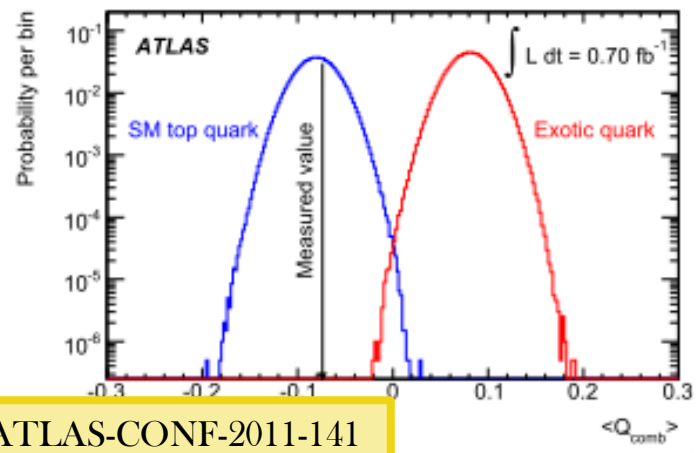
SM

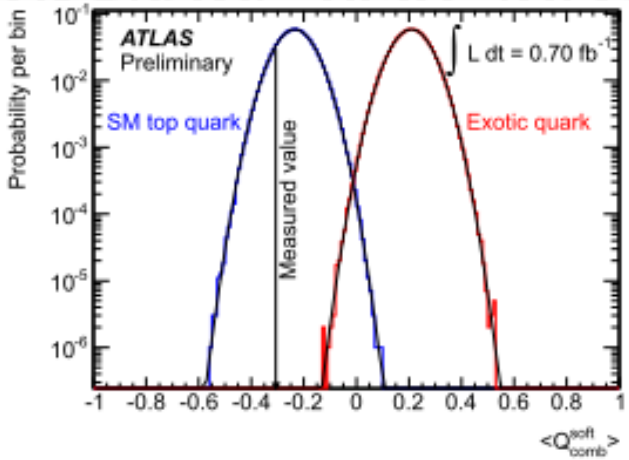
$t^{(2/3)} \rightarrow b^{(-1/3)} + W^{(+1)}, W^{(+1)} \rightarrow \ell^{+} + \nu_{\ell}$

$\tilde{t}^{(-4/3)} \rightarrow b^{(-1/3)} + W^{(-1)}, W^{(-1)} \rightarrow \ell^{-} + \bar{\nu}_{\ell}$

Exotic

- Evaluated $< Q_{comb} >$ for SM and exotic top via pseudo-experiments





Exotic Top quark excluded at more than **5σ**

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Top Polarization

Selection: ttbar l+jets & ll

$\mathcal{L}$=1.04 fb^{-1}