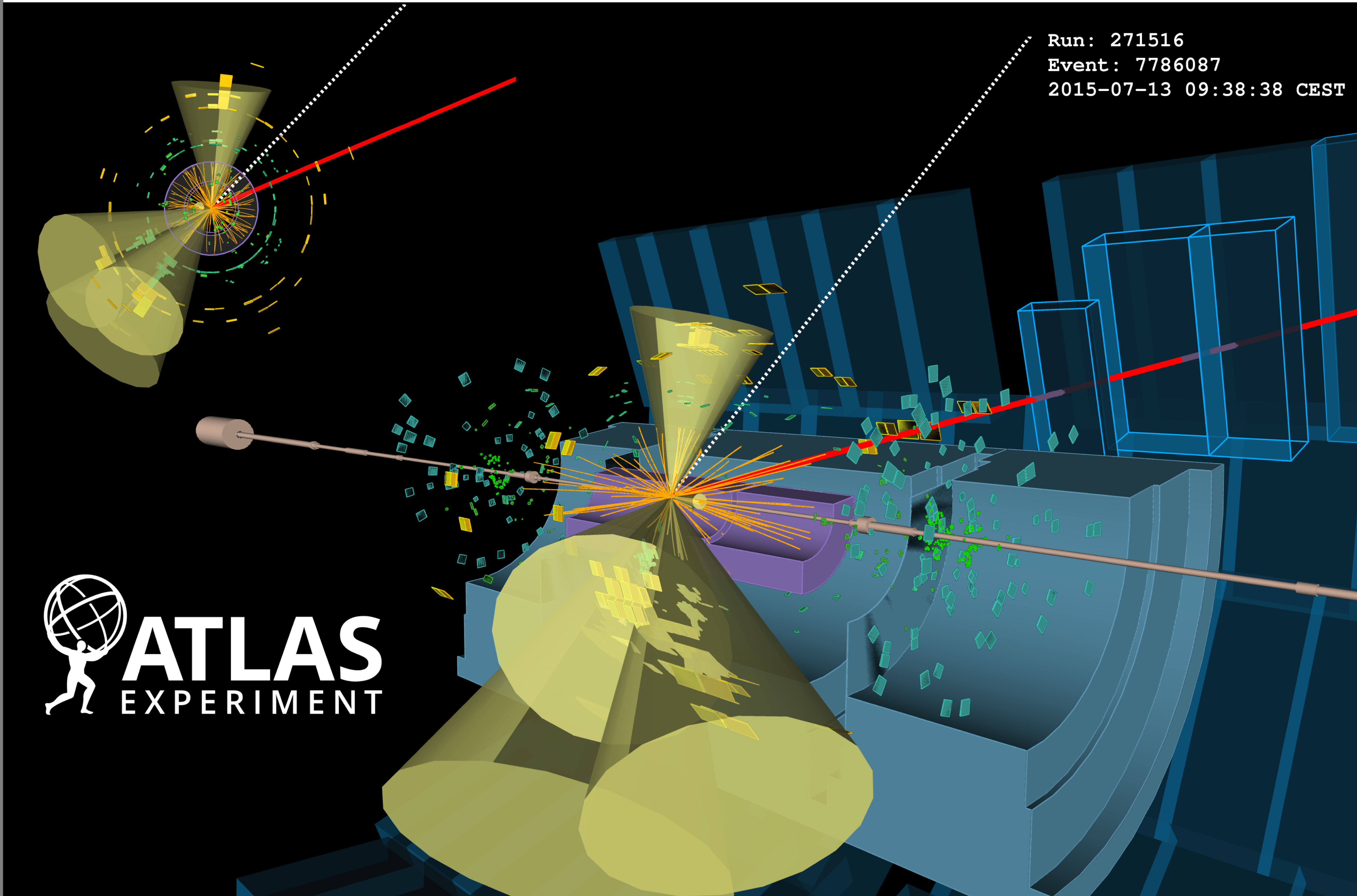
Top-Physics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2015-07-13 09:38:38 CEST
ATLAS
EXPERIMENT

Tancredi Carli (CERN)

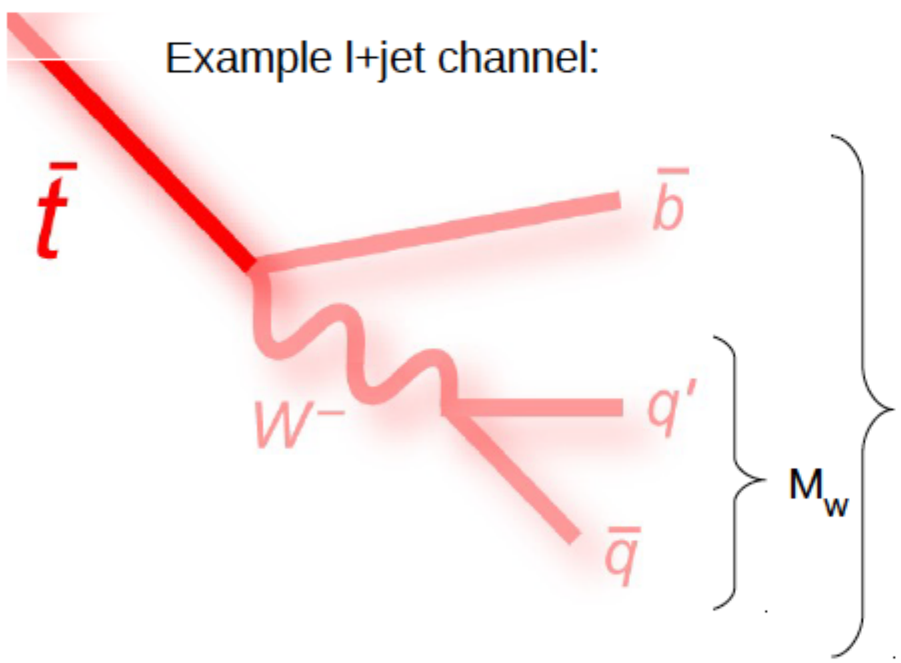
top mass measurement methods @ LHC

XXXVII INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS ICHEP 2014

Top mass measurement methods

Standard technique: Direct mass reconstruction

Example l+jet channel:



Reconstruct top decay products with kinematic fit based on likelihood (ATLAS) or chi2 (CMS)

Template method (e.g. ATLAS, CDF)
fit template of reconstructed top mass from MC to data

Ideogram method (e.g. CMS)
Likelihood function to test compatibility of event kinematics with top decay hypothesis (all good permutations are used)

Matrix element method (e.g. D0)
to calculate signal and background probability density for all parton-jet assignments as function of M_{top} and JSF

Non-standard techniques

1) NLO QCD comparison to
inclusive and tt+jet cross sections (no MC used)
→mass defined in NLO QCD calculation

2) kinematic endpoints (no MC used)

3) B-hadron lifetime

4) J/ψ final states (independent of JSF)

Exploit known M_W to constrain physics and detector effect

Fit M_{top} with n additional parameters

1D fit M_{top}

2D fit M_{top} and jet scale factor (JSF)
exploiting M_W constraint

3D fit M_{top}, JSF and bJSF (ATLAS 2013)
b-JSF relative b-to-light JSF using ratio jet from W-boson and b-jet

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Top Quark Mass

Reminder:

Radiative corrections
connect m_W, m_t, and m_H ...

Top mass measurement:

Tevatron Run II:
Top mass better than 1%
[Best measured quark mass]

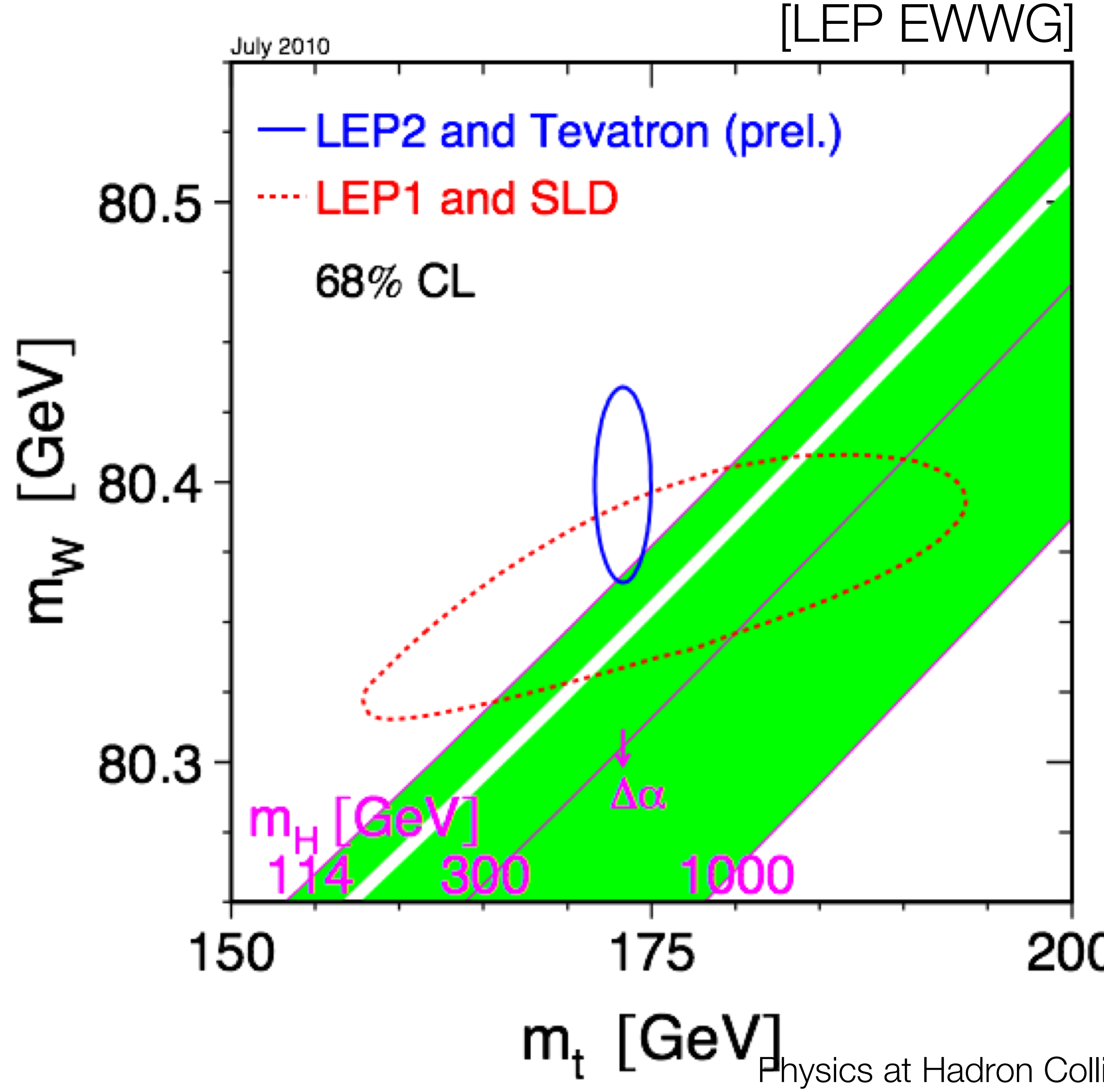
Reached after 5+ years

LHC: top mass to
better than 1 GeV

➛ very challenging

m_t = 173.3 ± 1.1 GeV

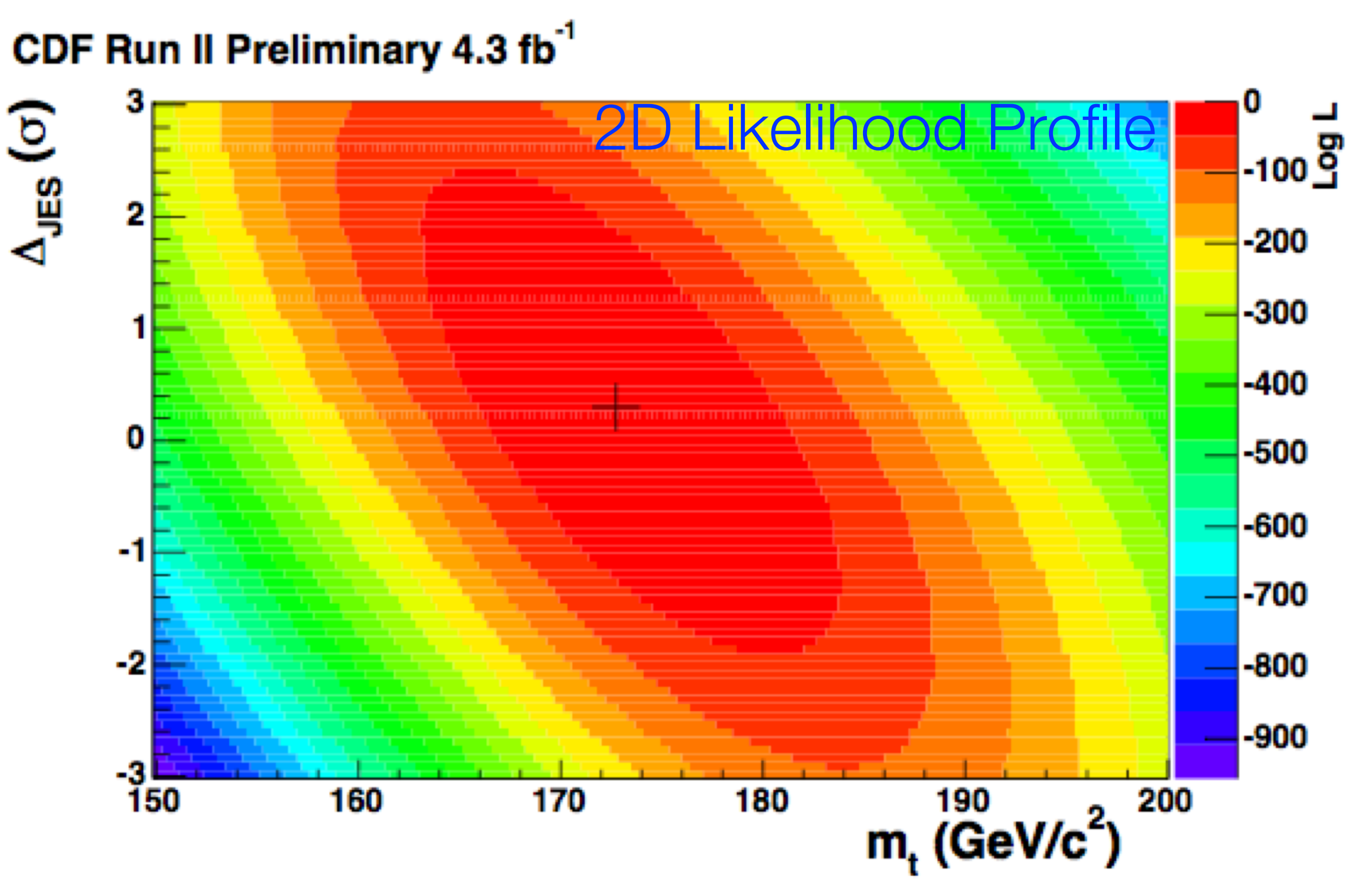
[LEP EWWG]

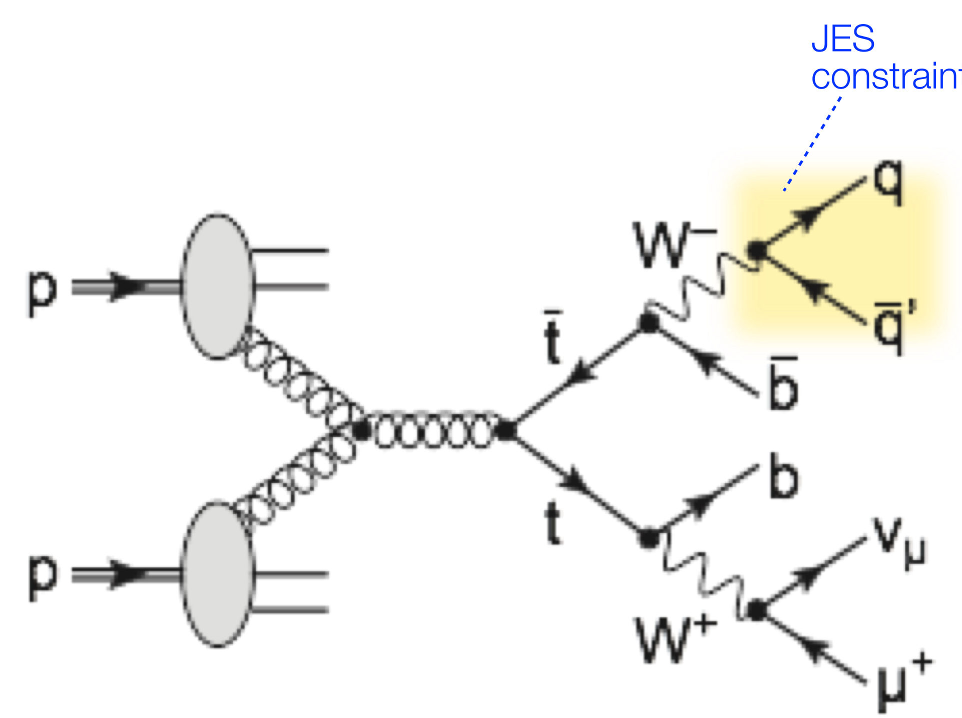


In-situ JES Calibration

Dominant uncertainty of top mass: Jet energy scale (JES)

- Idea (for lepton+jets): hadronic top decay chain contains decay W ➛ qq’ with well-known W mass [23 MeV vs. > 10 GeV]
- “In-situ JES calibration”: measure top mass and JES simultaneously [JES from known W mass]





CDF Top Mass Measurement 2009
[http://www-cdf.fnal.gov/.../mtm3_p23_public/]

Likelihood Methods

Goal: estimate parameter μ (e.g. top mass) from set of measurements $x = (x_1, x_2, \ldots)$

Known probability density distribution to observe value x_i for a given value of μ: $P(x_i|\mu)$, e.g. Poisson distribution

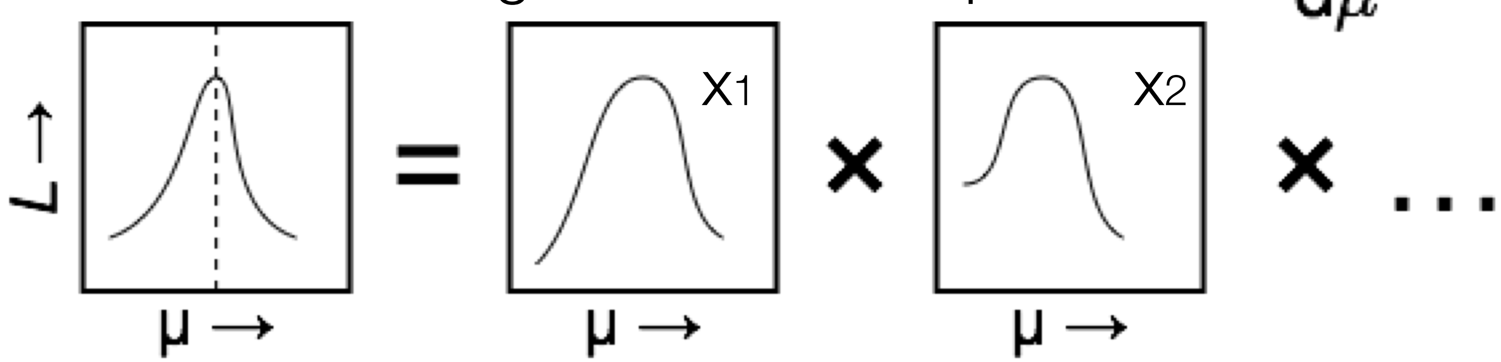
Construct joint probability ("likelihood function") for full set of measurements x by multiplying individual probabilities

$$L(\mathbf{x}|\mu) = \prod_i P(x_i|\mu)$$

Find maximum of L

Maximum likelihood method: get estimator for μ from: $\dfrac{dL(\mathbf{x}|\mu)}{d\mu} = 0$

In pictures:



In practice: minimize $-\ln L(\mathbf{x}|\mu) = -\sum_i \ln P(x_i|\mu)$

Matrix Element Technique

Matrix element technique (a.k.a. dynamic likelihood)

Idea: full parton kinematics contained in (squared) matrix element for partonic subprocess

Likelihood using matrix elements ...
best possible use of event information

First application to top quark mass in lepton+jets channel ...
[DØ, Nature 429 (2004) 638]

Restrictions:

Not all particles can be measured;
transfer function required [translation from partons to hadrons]

Only LO matrix elements for signal and most important background processes; higher order effects ignored

Numerical integration over unmeasured variables [order of 20]

CDF Top Mass Measurement – lepton + hads

1 lepton + 2 b-jets + 2 jets from W decay → 4 jets = 4x3x2 combinations

y: kinematic quantities
x: parton-level quantities

Example: CDF Top Mass Measurement ...

1 top leptonic decay +
1 top hadronic decay

Parameter to account for uncertainty in the jet energy scale
[p_T of the jets are scaled by $(1 + \Delta_{JES} \times \sigma_{jet})$]

Normalization factor
[probability = 1]

Detector acceptance

Weighting factor
[probability of consistence with tagging info]

$$L(\vec{y}\mid m_t,\Delta_{\mathrm{JES}}) = \frac{1}{N(m_t)}\frac{1}{A(m_t,\Delta_{\mathrm{JES}})}\sum_{i=1}^{24} w_i L_i(\vec{y}\mid m_t,\Delta_{\mathrm{JES}})$$

with

$$L_i(\vec{y}\mid m_t,\Delta_{\mathrm{JES}}) = \int \frac{f(z_1)f(z_2)}{FF}\,\mathrm{TF}(\vec{y}\mid \vec{x},\Delta_{\mathrm{JES}})\,|M(m_t,\vec{x})|^2\,d\Phi(\vec{x})$$

Parton level phase space ...

parton/jet assignments
[24 possibilities[]

Parton Distribution Functions; FF: flux factor

Transfer function;
probability to observe jet at momentum y for parton at x ...

Matrix element for top pair production ...

CDF Top Mass Measurement 2009
[http://www-cdf.fnal.gov/.../mtm3_p23_public/]

CDF Top Mass Measurement - 2

Example: CDF Top Mass Measurement ...

Calculate likelihood for every event ...

Acceptance Normalization

All 24 jet combinations

$$L(\vec{y} \mid m_t, \Delta_{\text{JES}}) = \frac{1}{N(m_t)} \frac{1}{A(m_t, \Delta_{\text{JES}})} \sum_{i=1}^{24} w_i L_i(\vec{y} \mid m_t, \Delta_{\text{JES}})$$

... by summing over likelihoods for all jet combinations ...

with

$$L_i(\vec{y} \mid m_t, \Delta_{\text{JES}}) = \int \frac{f(z_1) f(z_2)}{FF} \text{TF}(\vec{y} \mid \vec{x}, \Delta_{\text{JES}}) \, |M(m_t, \vec{x})|^2 \, d\Phi(\vec{x})$$

... using leading order (LO) matrix elements ...

PDFs

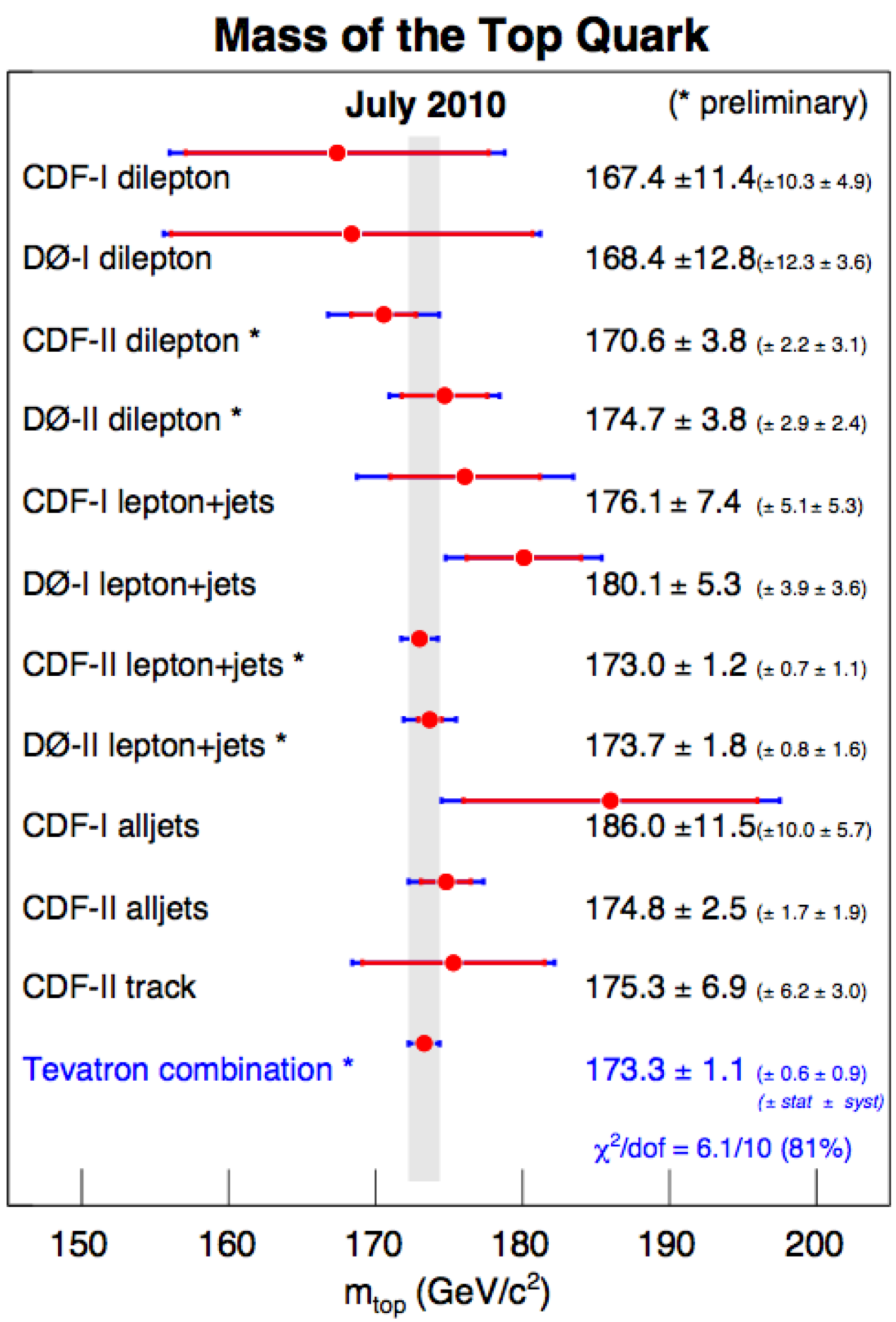
Transfer function

Matrix element & phase space

Remark: Phase space integration 19-dimensional; very CPU intensive ...

CDF Top Mass Measurement 2009
[http://www-cdf.fnal.gov/.../mtm3_p23_public/]

Tevatron Top Mass 2010



8 years of Tevatron
[Run II & Run I]

Consistency across top decay channels

Consistency across various analysis methods

Ultimate precision:

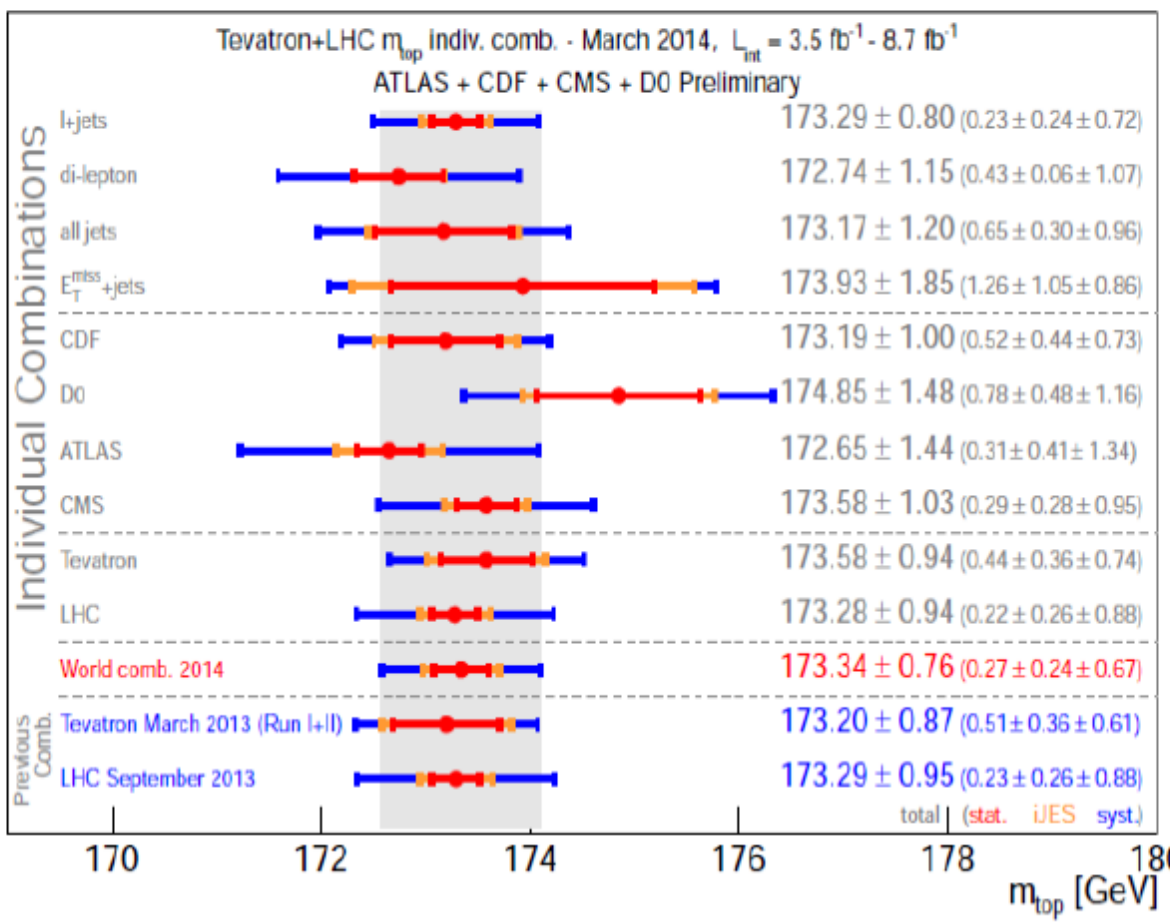
Combination of results taking all known correlations into account ...

Total uncertainty: 0.75%

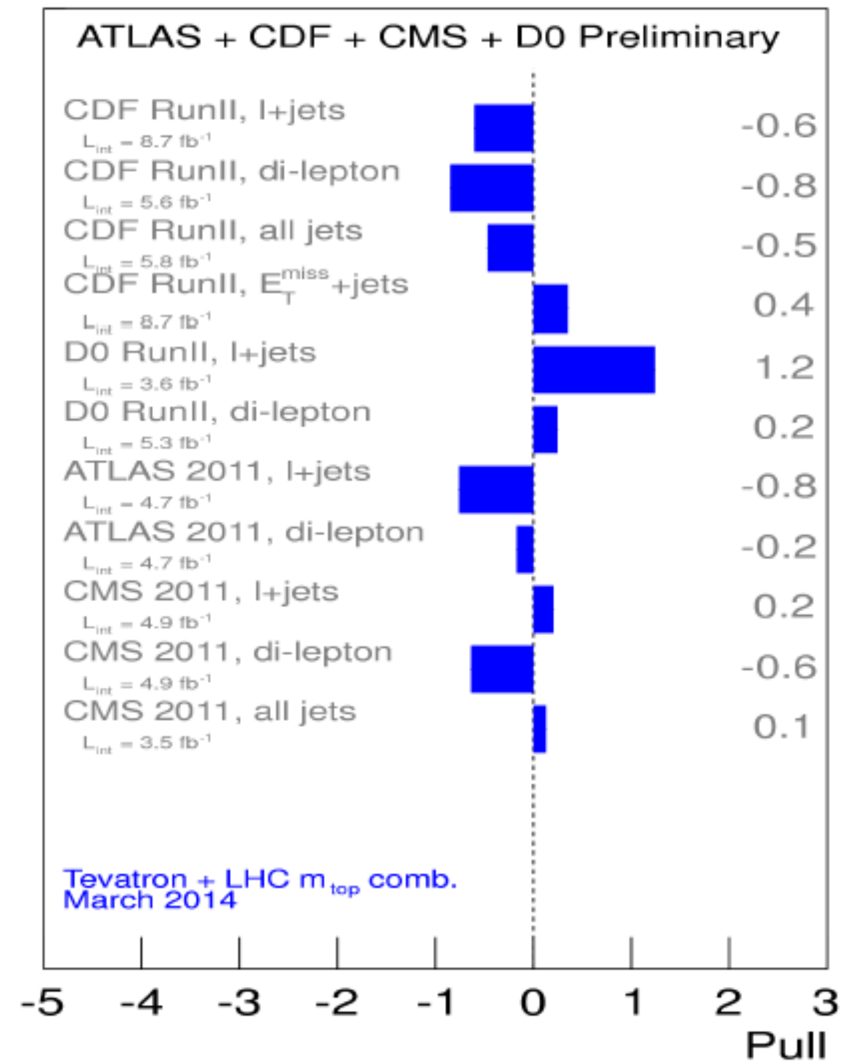
Tevatron & LHC Top Mass 2014

Top mass world average 2014

Tevatron combination November 2012 May 2013
LHC combination July 2012 September 2013
World combination March 2014 arXiv:1403.4427



Combination using BLUE



$$m_{top} = 173.34 \pm 0.27\ (\text{stat}) \pm 0.24\ (\text{iJES}) \pm 0.67\ (\text{syst})\ \text{GeV}$$

precision on M_{top} 0.44%

Consistency χ^2=4/10

Highest precision in l+jet channel
Dilepton channel good precision
Fully hadronic channel respectable

Top Mass Tevatron & LHC pdg 2017

Table 72.1: Measurements of top-quark mass from Tevatron and LHC. $\int \mathcal{L}dt$ is given in fb^{-1}. The results are a selection of both published and preliminary (not yet submitted for publication as of August 2017) measurements. For a complete set of published results see the Listings. Statistical uncertainties are listed first, followed by systematic uncertainties.

m_t (GeV/c^2)	Source	$\int \mathcal{L}dt$	Ref.	Channel
$172.99 \pm 0.48 \pm 0.78$	ATLAS	4.6	[145]	ℓ+jets+$\ell\ell$
$172.44 \pm 0.13 \pm 0.47$	CMS	19.7	[146]	ℓ+jets+$\ell\ell$+All jets
$172.35 \pm 0.16 \pm 0.48$	CMS	19.7	[146]	ℓ+jets
$172.22 \pm 0.18^{+0.89}_{-0.93}$	CMS	19.7	[152]	$\ell\ell$
$173.72 \pm 0.55 \pm 1.01$	ATLAS	20.2	[158]	All jets
$172.25 \pm 0.08 \pm 0.62$	CMS	35.9	[159]	ℓ+jets
$174.30 \pm 0.35 \pm 0.54$	CDF,DØ (I+II)	≤ 9.7	[174]	publ. or prelim.
$173.34 \pm 0.27 \pm 0.71$	Tevatron+LHC	$\leq 8.7 + \leq 4.9$	[2]	publ. or prelim.

Top Mass @ 8 TeV, CMS

New CMS top mass measurements at 8TeV

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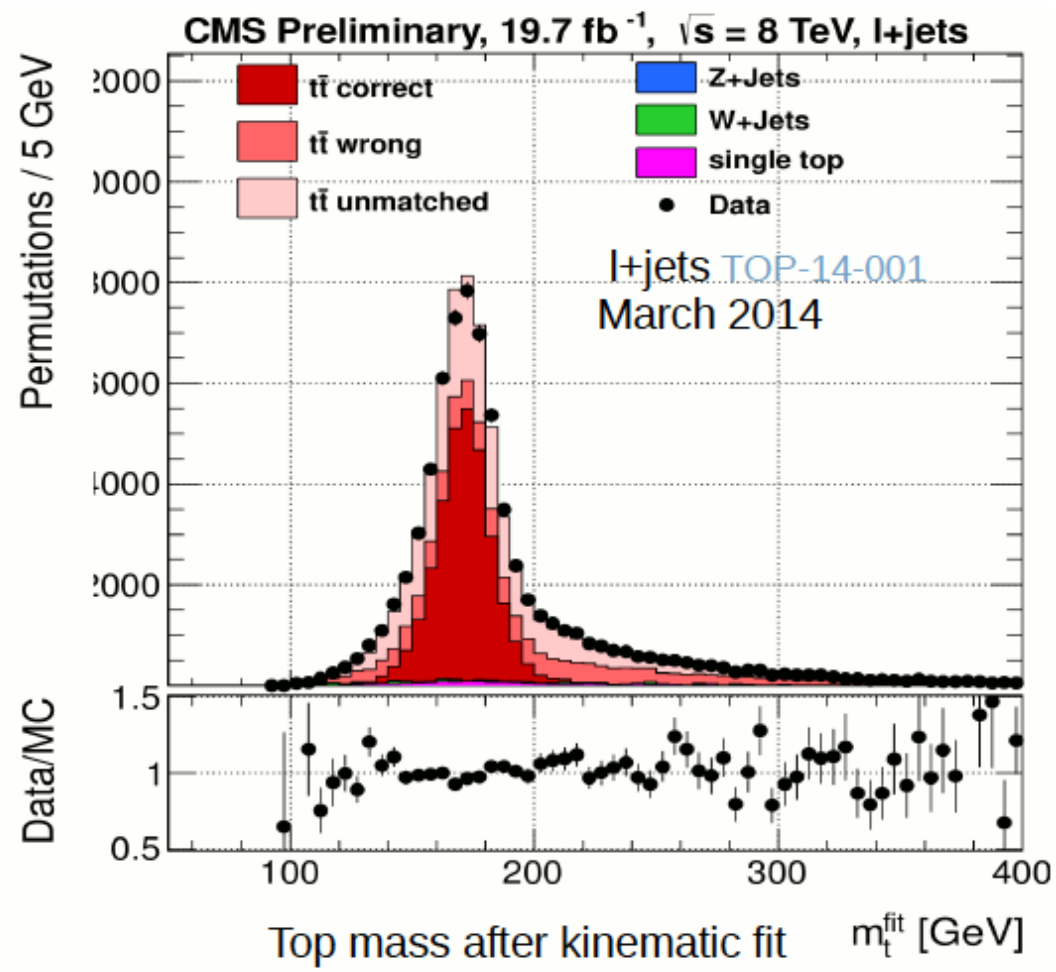
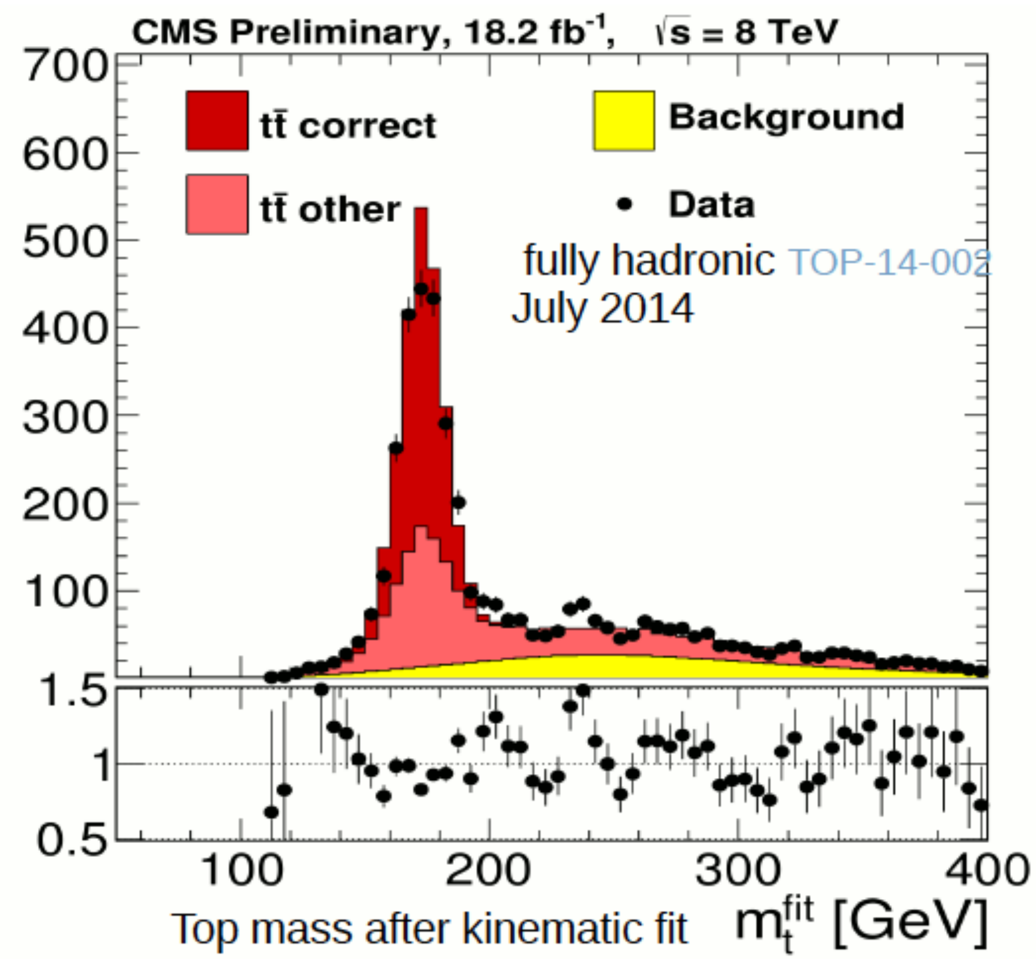
Kinematic fit to reconstruct top decay product, Ideogram method (all permutations used)
Fit M_{top} and jet scale factor exploiting M_W in l+jets and fully hadronic channel
classification using parton match in MC





$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV},$

precision: 0.45%

$m_t = 172.08 \pm 0.36\,(\text{stat.+JSF}) \pm 0.83\,(\text{syst.})\,\text{GeV},$

precision: 0.53%

Tancredi Carli (CERN)

Top Mass D0, Tevatron

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New D0 top mass measurement

D0 arXiv:1405.1756
accepted by PRL

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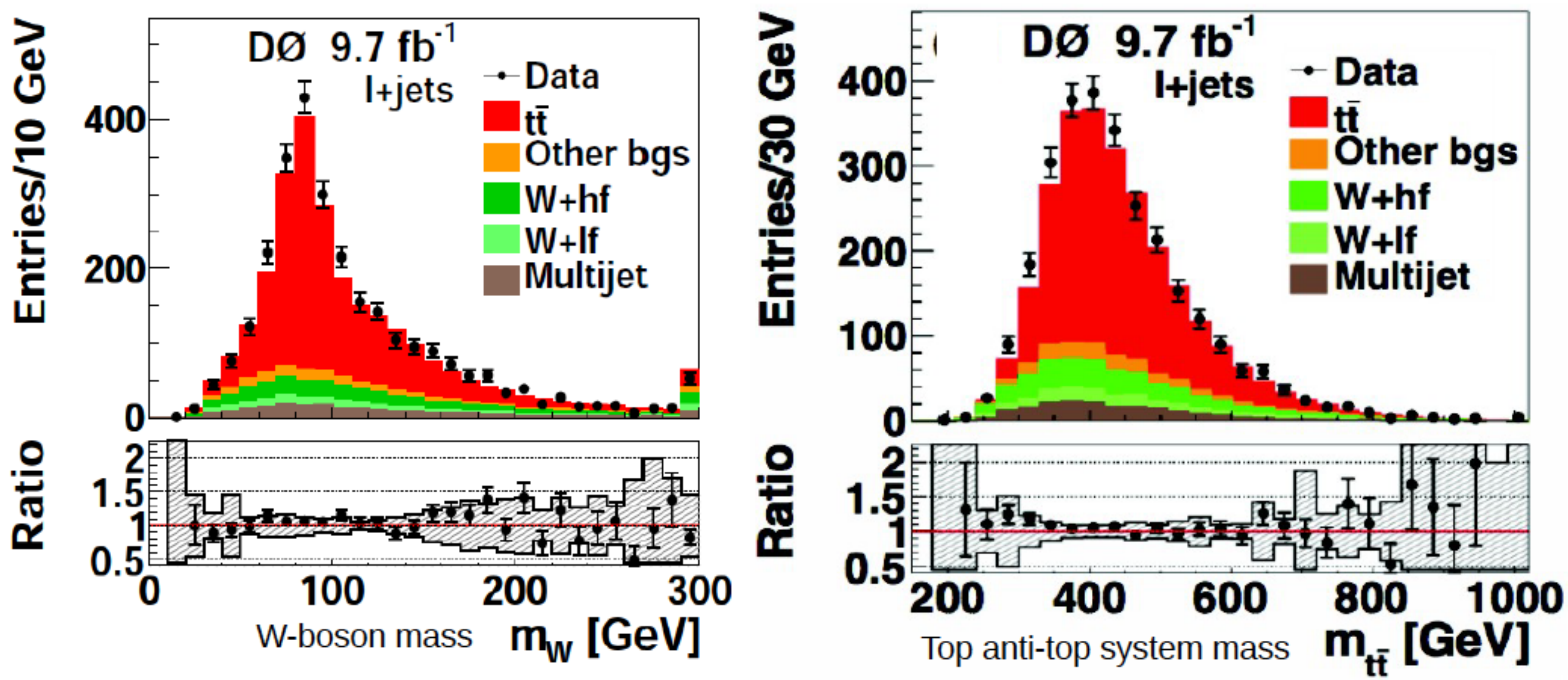
Mass of W-boson and top anti-top system after top mass fit



Select 4 jets, 1 b-tag 2500 events
Blinded analysis
Leading order matrix element to calculate signal and background probability density
2d fit M_{top} and jet scale factor (JSF) exploiting M_W constraint

$$m_t = 174.98 \pm 0.58\,(\mathrm{stat} + \mathrm{JES}) \pm 0.49\,(\mathrm{syst})\ \mathrm{GeV}$$

Recent improvements:
- faster matrix element calculation by O(100)
- large MC statistics → reduced fluctuations on systematic uncertainties to <10 MeV
- updated jet energy measurement uncertainties
- dedicated correction for b-jets
- constrain QCD radiation using Drell-Yan events

Precision 0.43%

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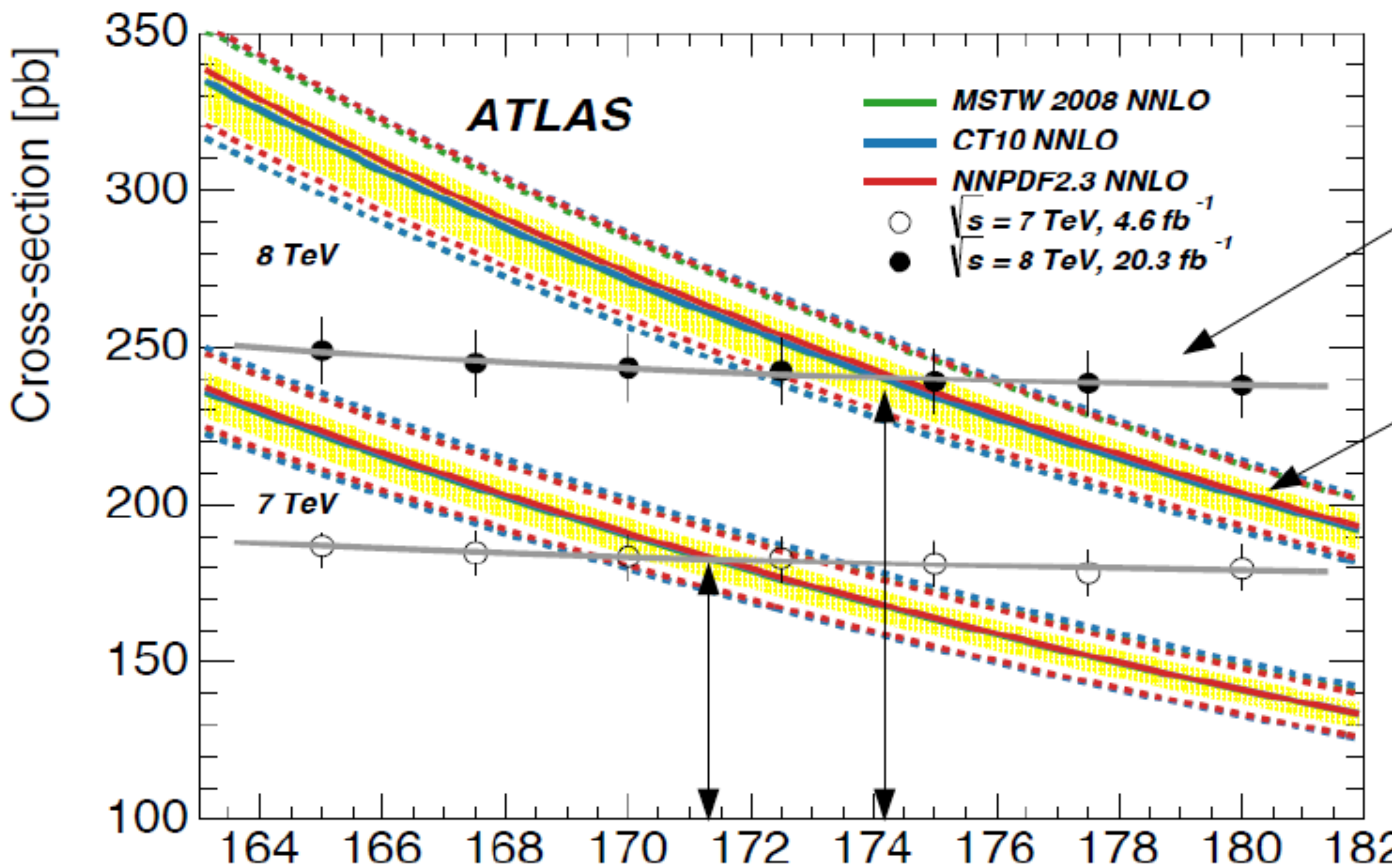
Top Mass @ LHC using Cross Sections

CMS Phys. Lett. B 728 (2013) 496
ATLAS arXiv:1406.5375

Comparing NNLO+NNLL QCD top pair cross section to data determine top mass in a well defined renormalisation scheme (here: pole mass) and theory uncertainties



M_{top} dependence of measured cross section -0.28%/GeV

NNLO+NNLL cross-section Prediction for various PDFs (band scale uncertainty)

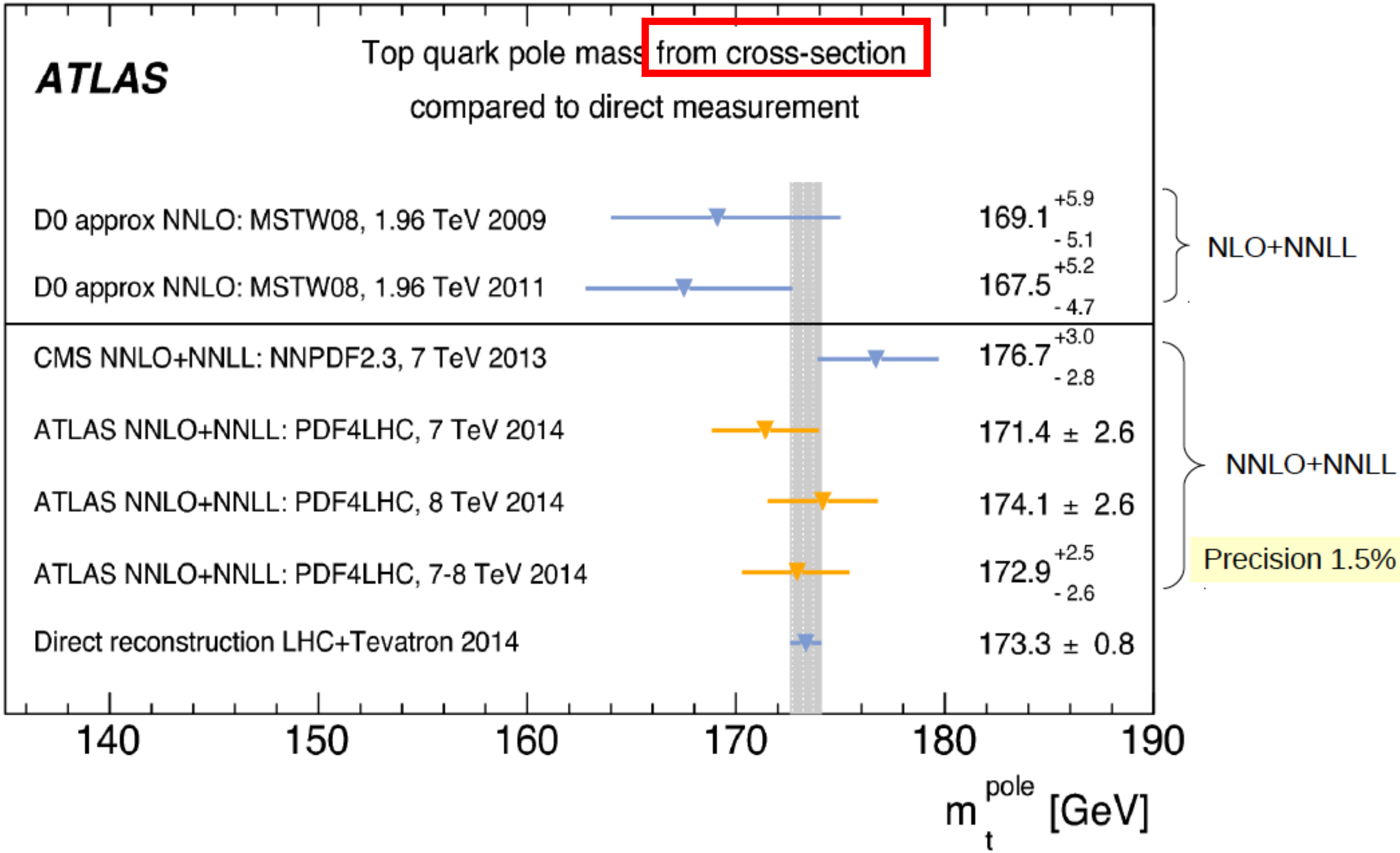
Combined result:
$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}$ GeV

$m_t^{\text{pole}} = 171.4 \pm 2.6$ GeV ($\sqrt{s} = 7$ TeV)

$m_t^{\text{pole}} = 174.1 \pm 2.6$ GeV ($\sqrt{s} = 8$ TeV)

Largest exp. syst. (luminosity) uncorrelated for 7 and 8 TeV
Results consistent within 1.7 sigma

Collection of top-mass measurements



Recently also first determination of top mass from single top cross section arXiv:1406.4403
However, low sensitivity

Recently new techniques proposed e.g. based on ttbar+jet cross section Alioli et al. EPJ C73 (2013) 2438

Top quark mass in the dilepton analysis

In the ttbar 2-lepton channel both W's decay leptonically

Pbs: pairing and guessing energies of 2 neutrinos

$$(t\bar{t} \rightarrow b\ell^+\nu\bar{b}\ell^-\bar{\nu})$$

2 neutrinos in the final state p_T^{miss} associated to the sum of momenta of 2 neutrinos.

Overcome this problem by using m_{T2}, also known as 'stransverse mass', used in topologies with 2 pair-produced particles decaying into a pair of undetected particles.

$$m_{T2}(m_{invis}) = \min_{\vec{p}_T^{(1)},\, \vec{p}_T^{(2)}} \left\{ \max\left[m_T(m_{invis}, \vec{p}_T^{(1)}), m_T(m_{invis}, \vec{p}_T^{(2)}) \right] \right\}$$

Stranverse mass - 1

$$m_{T2}(m_{\text{invis}}) = \min_{\vec{p}_T^{(1)}, \vec{p}_T^{(2)}} \left\{ \max\left[m_T(m_{\text{invis}}, \vec{p}_T^{(1)}), m_T(m_{\text{invis}}, \vec{p}_T^{(2)}) \right] \right\}$$

kinematically allowed trial values of the invisible particles' transverse momenta

$$m_T(m_{\text{invis}}, \vec{p}_T^{(i)}) = \sqrt{m_{\text{vis}}^2 + m_{\text{invis}}^2 + 2(E_T^{\text{vis}} E_T^{\text{invis}} - \vec{p}_T^{\text{vis}} \cdot \vec{p}_T^{(i)})}$$

"vis" stands for "lepton" in this case, "invis" for missing unknown neutrino energy

$$\max\left[m_T(m_{\text{invis}}, \vec{p}_T^{(1)}), m_T(m_{\text{invis}}, \vec{p}_T^{(2)}) \right]$$

means "guess" the undetected neutrino energy and pair it to each of the 2 leptons; take the larger value

Stranverse mass - 2

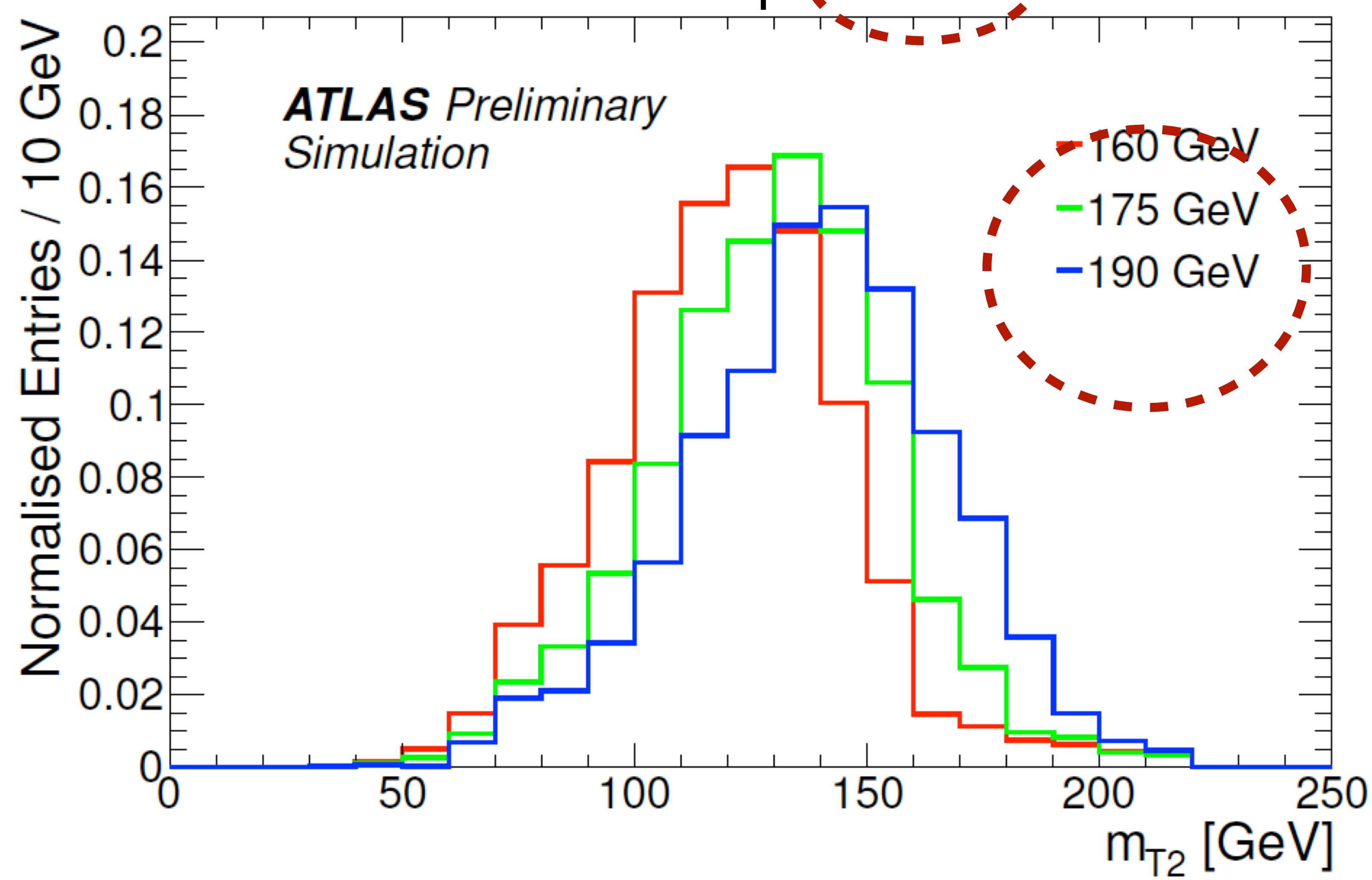
$$m_{T2}(m_{\rm invis}) = \min_{\vec{p}_T^{(1)},\, \vec{p}_T^{(2)}} \left\{ \max\left[m_T(m_{\rm invis}, \vec{p}_T^{(1)}), m_T(m_{\rm invis}, \vec{p}_T^{(2)}) \right] \right\}$$

Vary $\vec{p}_T^{(1)}, \vec{p}_T^{(2)}$ over all kinematically allowed values, constraints:

$$\vec{p}_T^{(1)} + \vec{p}_T^{(2)} = \vec{p}_T^{\rm miss}$$

$$P_{\rm vis}^{(i)} = P_{\rm lepton}^{(i)} + P_{b-{\rm jet}}^{(i)}$$

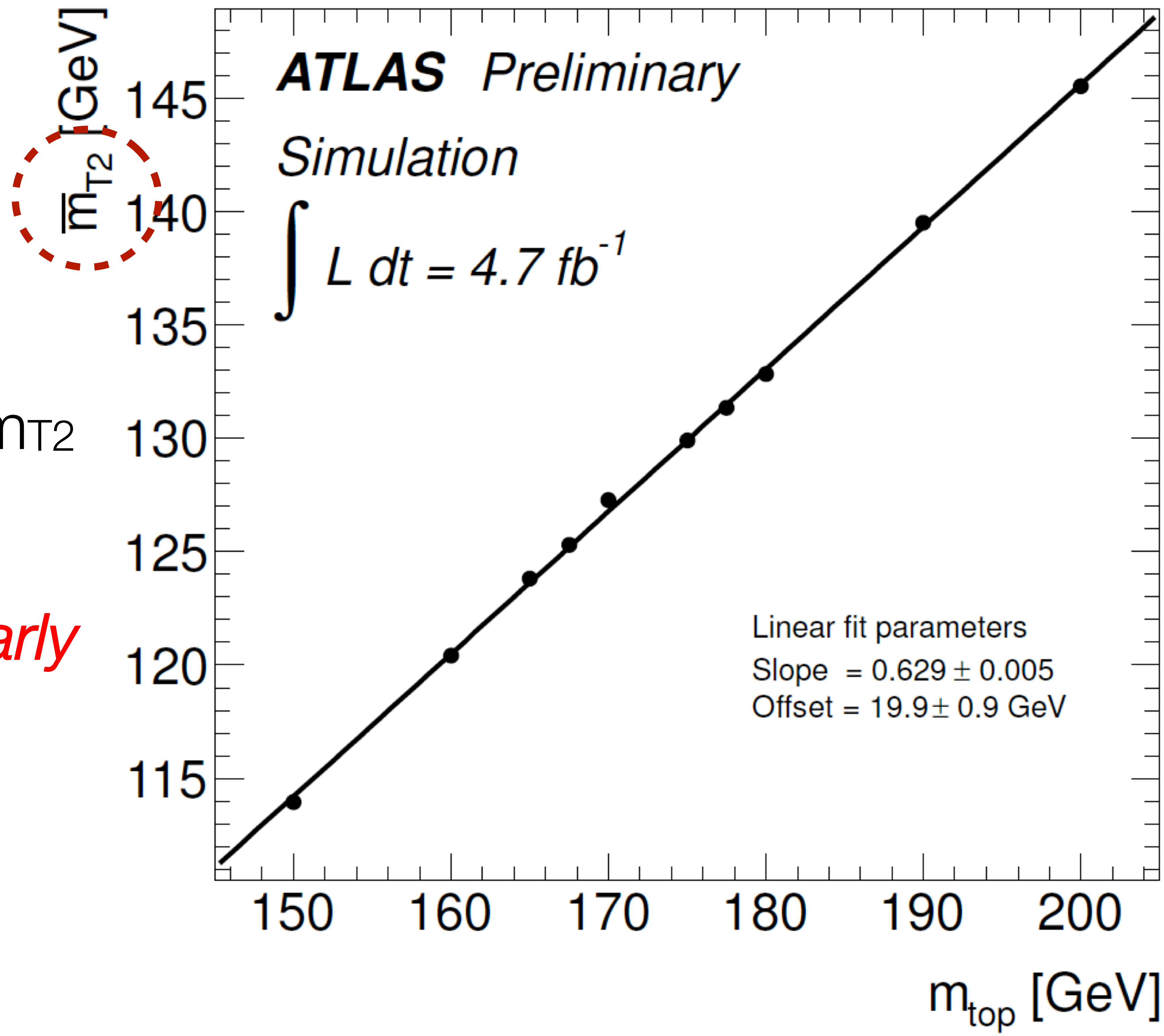
Use MC to get templates for different top mass



Stranverse mass – Closure test

Average value of m_{T2}

m_{T2} and m_{top} linearly correlated



Results on m_{top} for the 2-lepton analysis

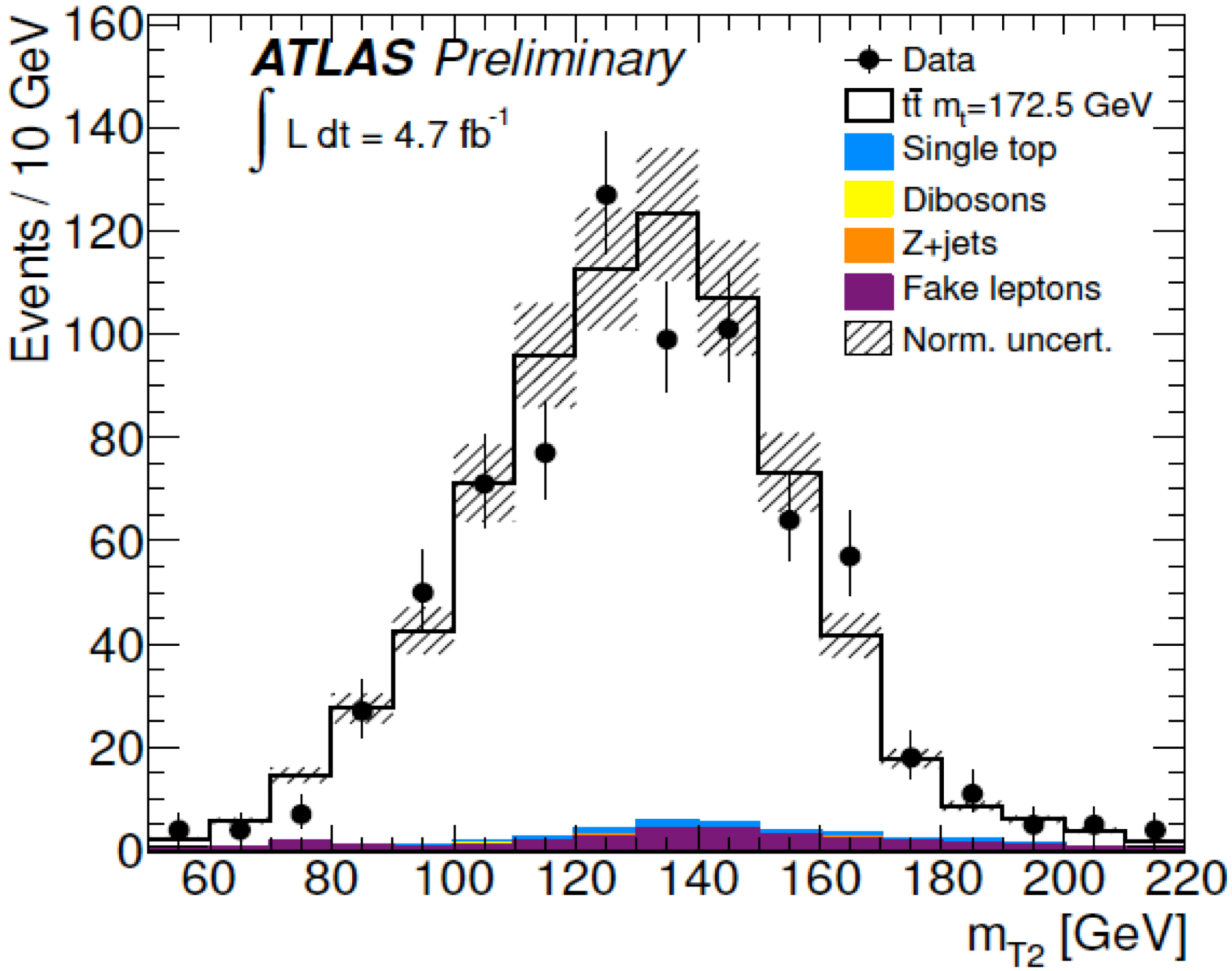


Figure 7: m_{T2} distribution of the selected events.

Source	Uncertainty [GeV]
$t\bar{t}$ generator model	−1.3 / +1.3
Parton shower	−0.9 / +0.9
Colour reconnection	−1.2 / +1.2
ISR/FSR	−0.5 / +0.5
PDF	−0.1 / +0.1
Fakes norm. and shape	−0.3 / +0.3
Calibration curve	−0.3 / +0.3
Underlying event	−0.2 / +0.2
Jet energy scale	−1.4 / +1.6
b-jet energy scale	−1.2 / +1.5
Jet energy resolution	−0.5 / +0.5
Leptons	−0.1 / +0.2
E_T^{miss} and jets	−0.1 / +0.1
b-tagging	−0.4 / +0.3
Syst. uncertainty	−2.8 / +3.1
Stat. uncertainty	−1.6 / +1.6
Total uncertainty	−3.3 / +3.5

$$m_{top} = 175.2 \pm 1.6(\text{stat.})^{+3.1}_{-2.8}(\text{syst.})\ \text{GeV}$$

Bias in m_{Top} determination

As mentioned in Section 2 the samples used to build the calibration curve are processed with ATLAS fast simulation. However, the nominal $t\bar{t}$ sample used for the analysis is generated with the full GEANT detector simulation (full simulation). The effect of using fast simulation instead of full simulation is estimated by computing the value of m_{T2} for the nominal $t\bar{t}$ sample and obtaining the top-quark mass from the calibration curve. This results in a top-quark mass of 173.7 ± 0.3 GeV where the expected value is 172.5 GeV. This observed bias of 1.2 GeV is used to correct the extracted top-quark mass from the calibration curve.

m_{Top} determination with the lepton+jets channel Best method at LHC

$$t\bar{t} \to \underbrace{\ell \nu b_\ell}_{W_1} \underbrace{q_1 q_2 b_{\mathrm{had}}}_{W_2} \text{ with } \ell = e, \mu$$

Topology: 4 jets (2 b-tagged), 1 lepton, missing energy

Description of the methods

2 different methods:

- 1 dimensional fit of "R_{32}"
- 2 dimensional fit m_{Top} & JES

Event selection:

1 lepton with p_T>25(20) GeV for electrons(muons)
E_{Tmiss}>20GeV
Njets >=4 with p_T>25GeV
At least 1 b-tagged jet

In the ratio some systematics cancel (JES)

Definition of $R_{32} \equiv \frac{m_{\mathrm{top}}^{\mathrm{reco}}}{m_{\mathrm{W}}^{\mathrm{reco}}}$

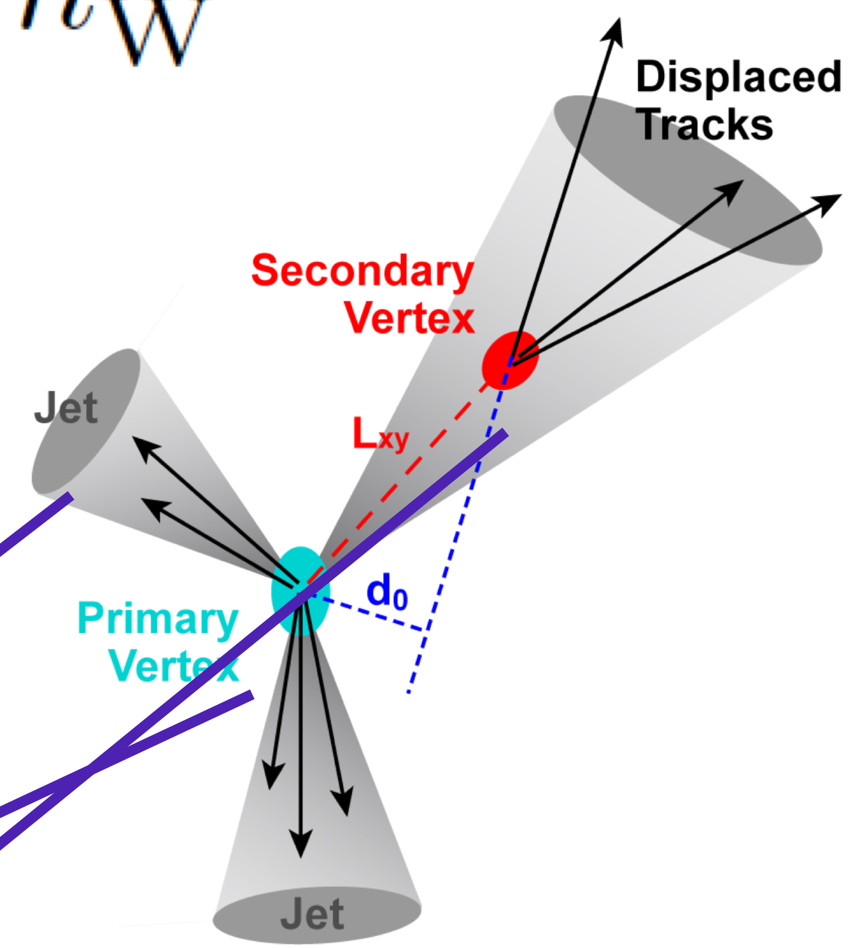
Here $m_{\mathrm{top}}^{\mathrm{reco}}$ and $m_{\mathrm{W}}^{\mathrm{reco}}$ are the per event reconstructed invariant masses of the hadronically decaying top quark and W boson, respectively.

The 1 dimensional method

$$t\bar{t} \rightarrow \ell \nu b_\ell q_1 q_2 b_{\mathrm{had}} \text{ with } \ell = e, \mu$$

$$m_{\mathrm{top}}^{\mathrm{reco}} \text{ and } m_{\mathrm{W}}^{\mathrm{reco}}$$

Problem: There are 4 jets in the event, m_W and m_{top} implies identifying which 3 jets to use. This is done with a kinematical fit which maximizes the event likelihood



$$t\bar{t} \rightarrow \ell \nu b_\ell q_1 q_2 b_{\mathrm{had}} \text{ with } \ell = e, \mu$$

The 1 dimensional method

The likelihood is defined as a product of transfer functions ($\mathcal{T}$), Breit-Wigner ($\mathcal{B}$) distributions, and a weight W_{btag} accounting for the b-tagging information:

$$L = \mathcal{T}\left(E_{\mathrm{jet}_1}|\hat{E}_{b_{\mathrm{had}}}\right) \cdot \mathcal{T}\left(E_{\mathrm{jet}_2}|\hat{E}_{b_\ell}\right) \cdot \mathcal{T}\left(E_{\mathrm{jet}_3}|\hat{E}_{q_1}\right) \cdot$$

$$\mathcal{T}\left(E_{\mathrm{jet}_4}|\hat{E}_{q_2}\right) \cdot \mathcal{T}\left(E_x^{\mathrm{miss}}|\hat{p}_{x,\nu}\right) \cdot \mathcal{T}\left(E_y^{\mathrm{miss}}|\hat{p}_{y,\nu}\right) \cdot$$

$$\begin{Bmatrix} \mathcal{T}\left(E_e|\hat{E}_e\right) & e\text{+jets} \\ \mathcal{T}\left(p_{\mathrm{T},\mu}|\hat{p}_{\mathrm{T},\mu}\right) & \mu\text{+jets} \end{Bmatrix} \cdot$$

$$\mathcal{B}\left[m(q_1\, q_2)|m_W, \Gamma_W\right] \cdot \mathcal{B}\left[m(\ell\, \nu)|m_W, \Gamma_W\right] \cdot$$

$$\mathcal{B}\left[m(q_1\, q_2\, b_{\mathrm{had}})|m_{\mathrm{top}}^{\mathrm{reco,like}}, \Gamma_{\mathrm{top}}\right] \cdot$$

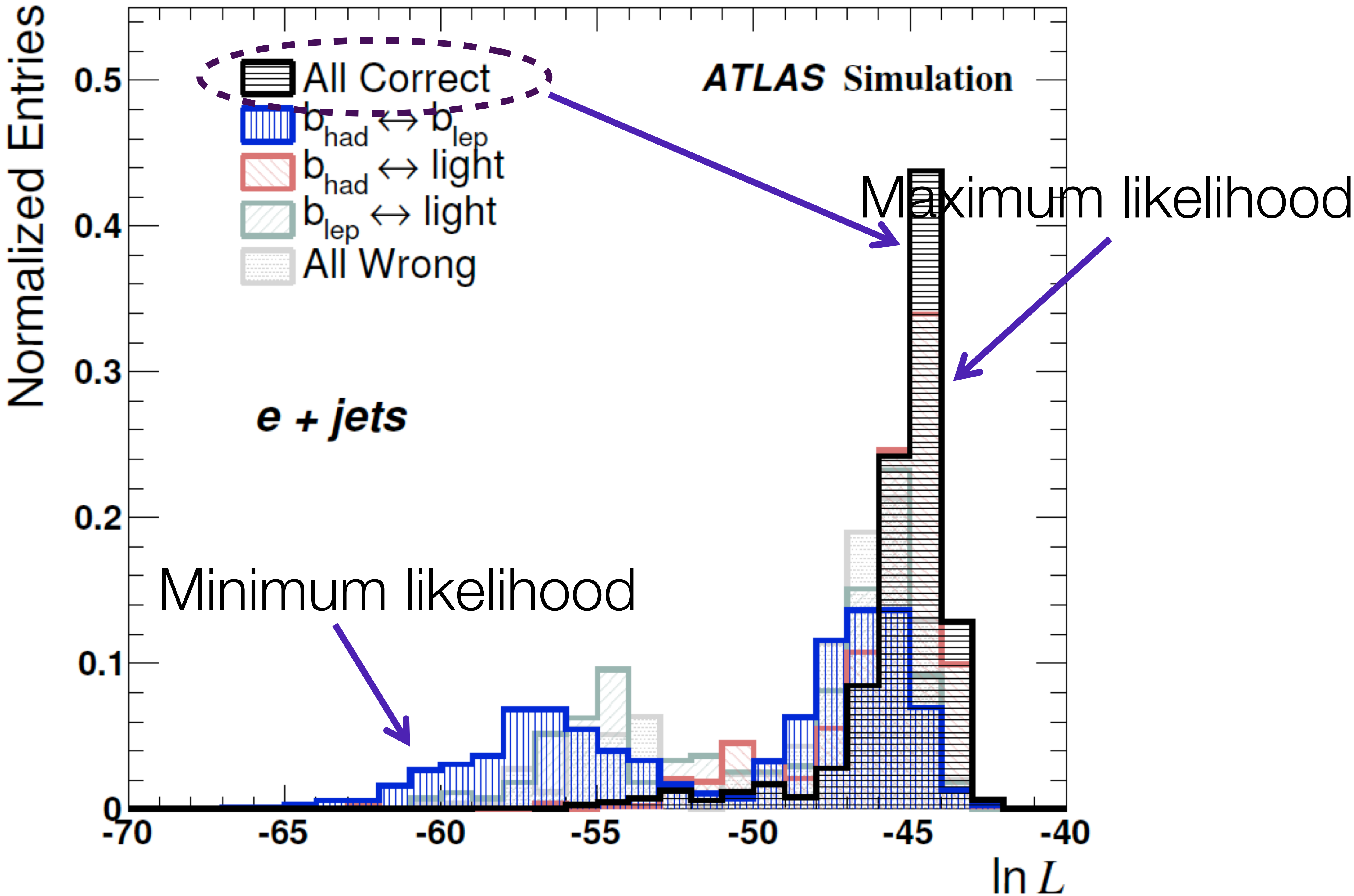
$$\mathcal{B}\left[m(\ell\, \nu\, b_\ell)|m_{\mathrm{top}}^{\mathrm{reco,like}}, \Gamma_{\mathrm{top}}\right] \cdot W_{\mathrm{btag}} \cdot$$

generator predicted quantities

Transfer function derived by MC

per event top quark mass maximizing the likelihood

The performance of the fit (using MC events where we know all the thruth)

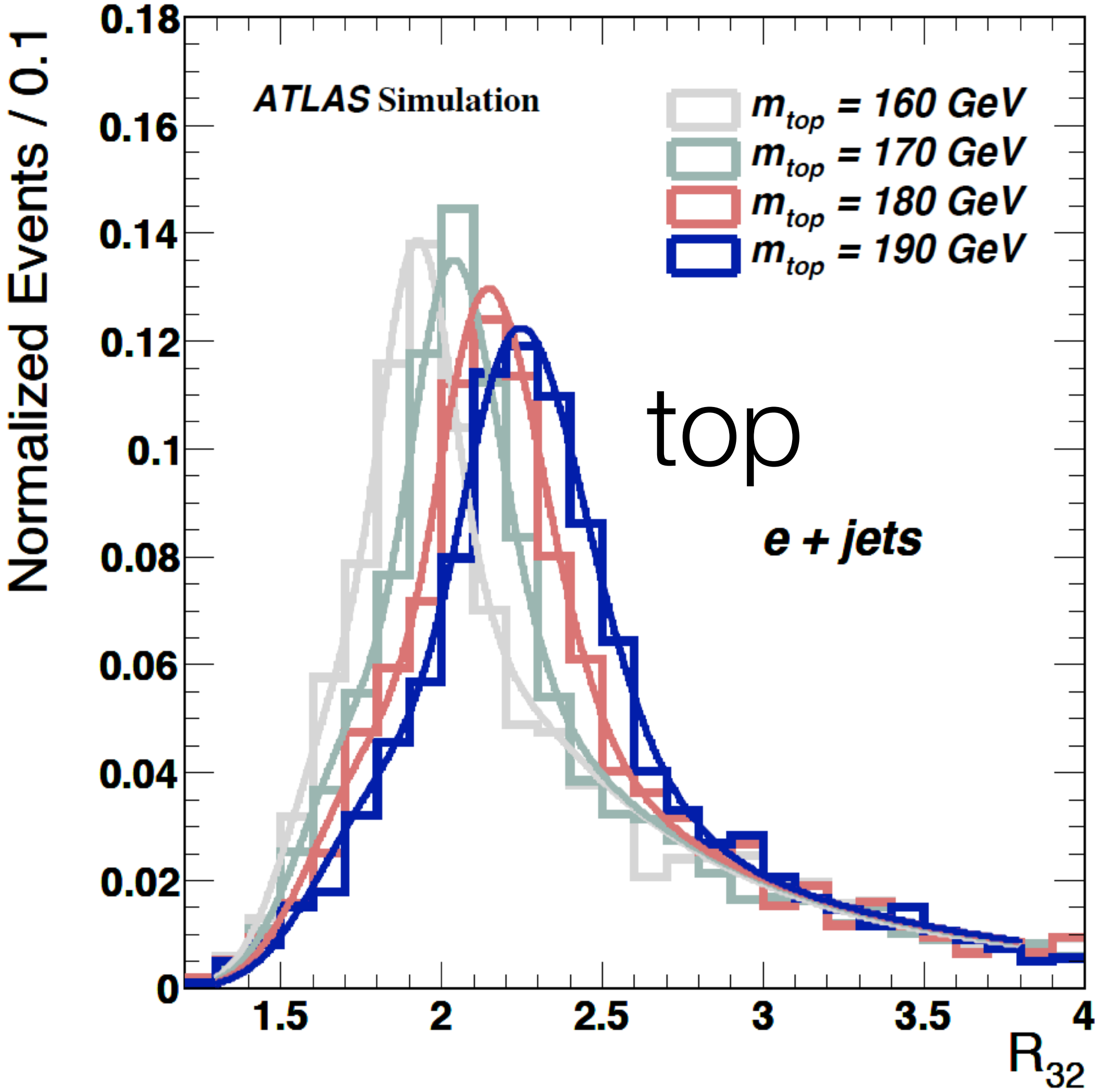


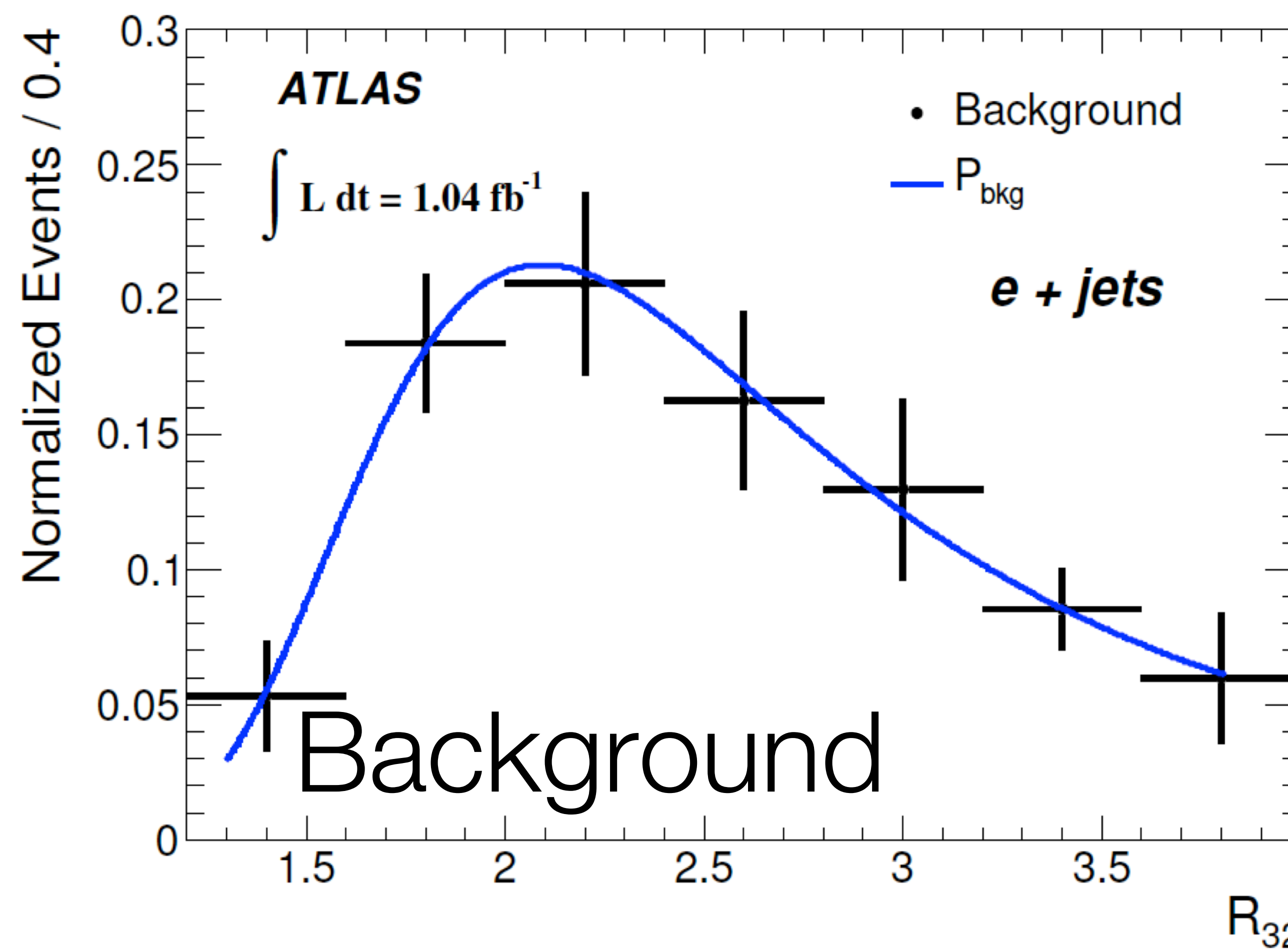
(a) e+jets channel

R_{32} is a superposition of signal and background

Once you you know the kinematics of your event you compute

$$m_{\text{top}}^{\text{reco}} \text{ and } m_{\text{W}}^{\text{reco}}$$

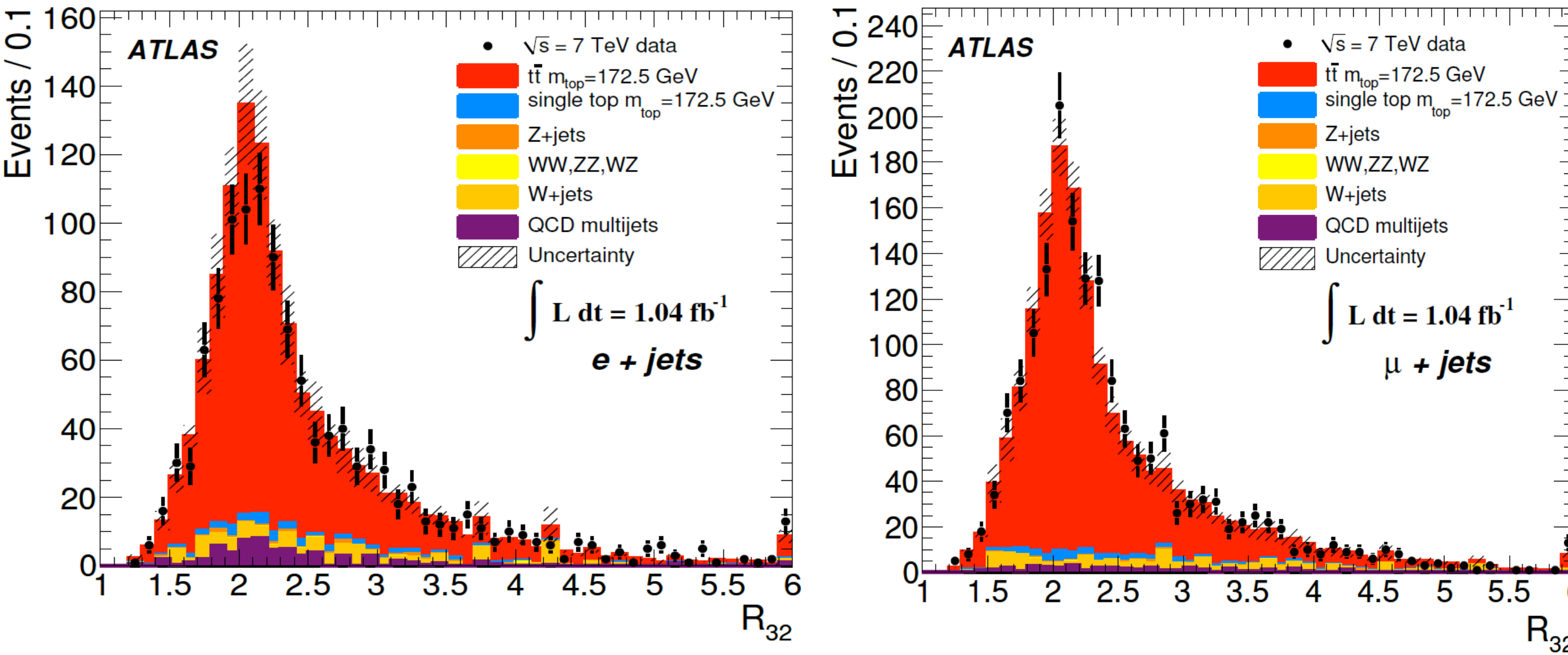




(b) e+jets channel

You can check your method using MC, check you reconstruct the same m_{top} you generated

R_{32} in data, fit the data as superposition of signal & background



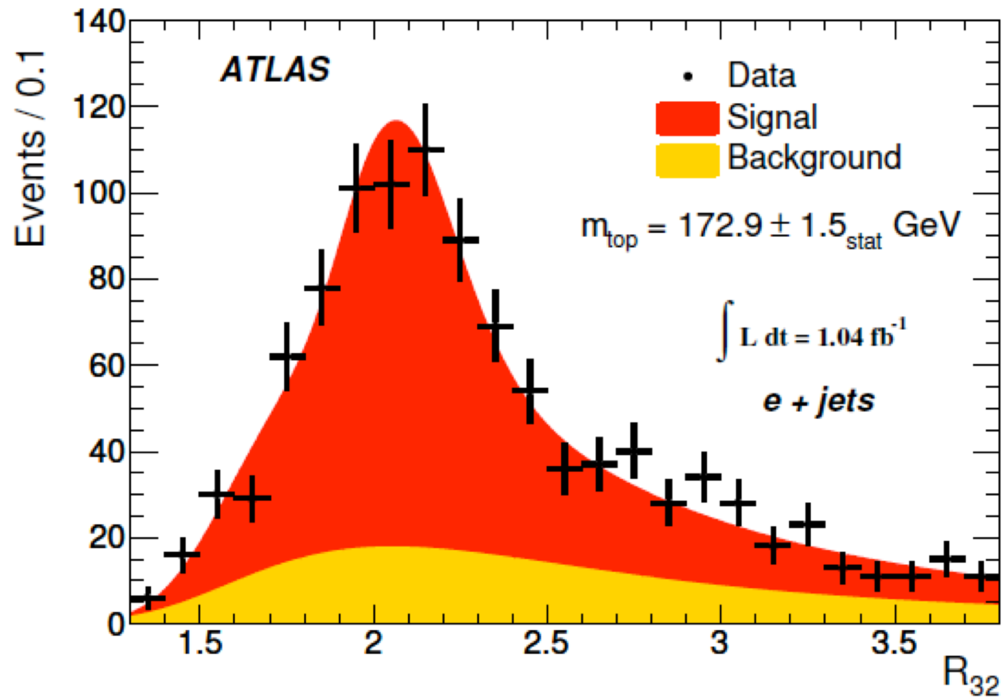
(a) e+jets channel

(b) μ+jets channel

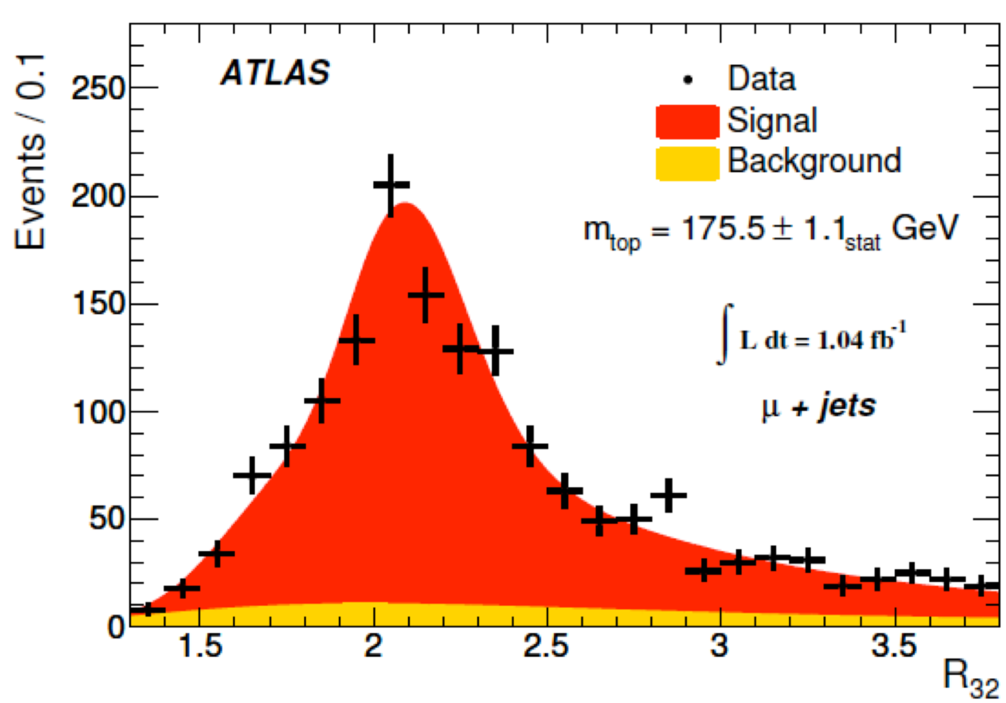
$$\mathcal{L}(R_{32}|m_{\text{top}}) = \mathcal{L}_{\text{shape}}(R_{32}|m_{\text{top}}) \times \mathcal{L}_{\text{bkg}}(R_{32})$$

2 fit parameters: m_{top} and fraction of top events

Results of the R_{32} method



(a) e+jets channel



(b) μ+jets channel

Process	1d-analysis		2d-analysis	
	e+jets	μ+jets	e+jets	μ+jets
$t\bar{t}$ signal	990 ± 40	1450 ± 50	3400 ± 200	5100 ± 300
Single top (signal)	43 ± 2	53 ± 3	190 ± 10	280 ± 20
Z+jets	12 ± 3	8 ± 3	83 ± 8	100 ± 8
$ZZ/WZ/WW$	$2 \pm <1$	$2 \pm <1$	11 ± 2	18 ± 2
W+jets (data)	80 ± 60	100 ± 70	700 ± 500	1100 ± 800
QCD multijet (data)	50 ± 50	40 ± 40	200 ± 200	400 ± 400
Signal + background	1180 ± 80	1650 ± 80	4500 ± 500	6900 ± 900
Data	1151	1724	4556	7225

$$m_{top} = 172.9 \pm 1.5_{stat} \pm 2.5_{syst}\ \text{GeV} \quad (\text{1d } e\text{+jets}),$$
$$m_{top} = 175.5 \pm 1.1_{stat} \pm 2.6_{syst}\ \text{GeV} \quad (\text{1d } \mu\text{+jets}).$$

The 2-dimensional fit

Likelihood computed for all N events

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

Fit parameters: m_{top}, JSF, % background events

with:

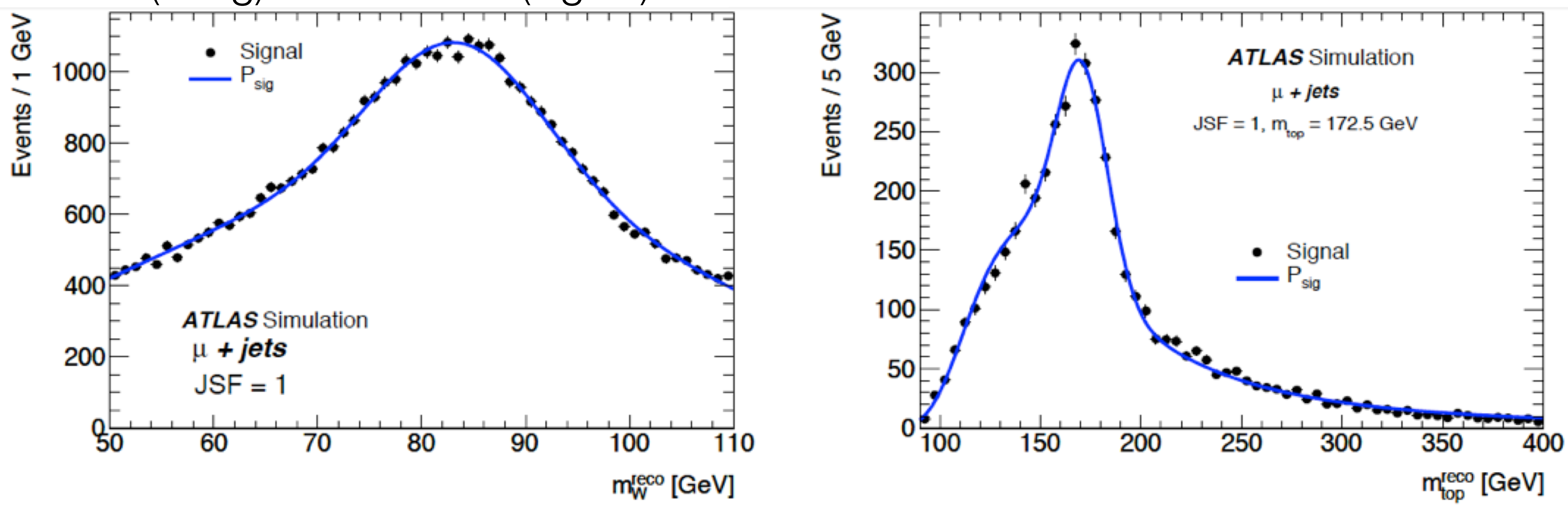
$$P_{\text{top}} = (N - n_{\text{bkg}}) \cdot P_{\text{top}}^{\text{sig}}(m_{\text{top}}^{\text{reco}} | m_{\text{top}}, \text{JSF})_i + n_{\text{bkg}} \cdot P_{\text{top}}^{\text{bkg}}(m_{\text{top}}^{\text{reco}} | m_{\text{top}}, \text{JSF})_i \ ,$$

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

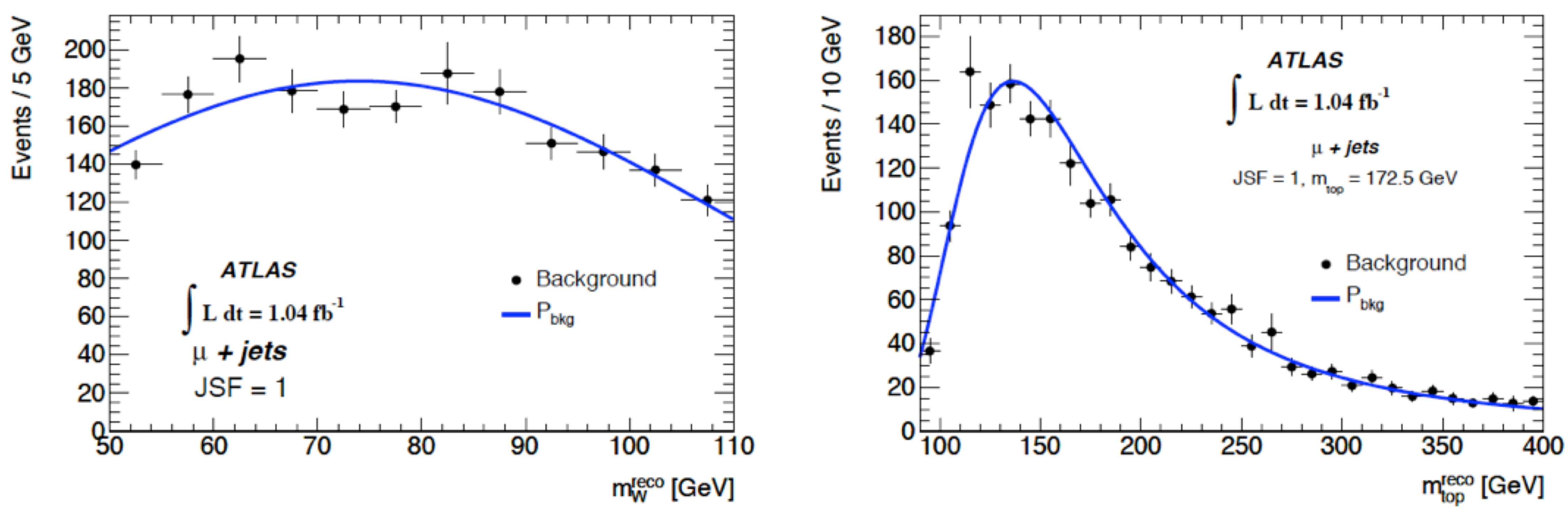
Method tested using pseudo MC experiments; good linearity found

The shapes used in the likelihood fit

analytical function fitting the MC points
Gaussian (bckg) and Landau (signal)

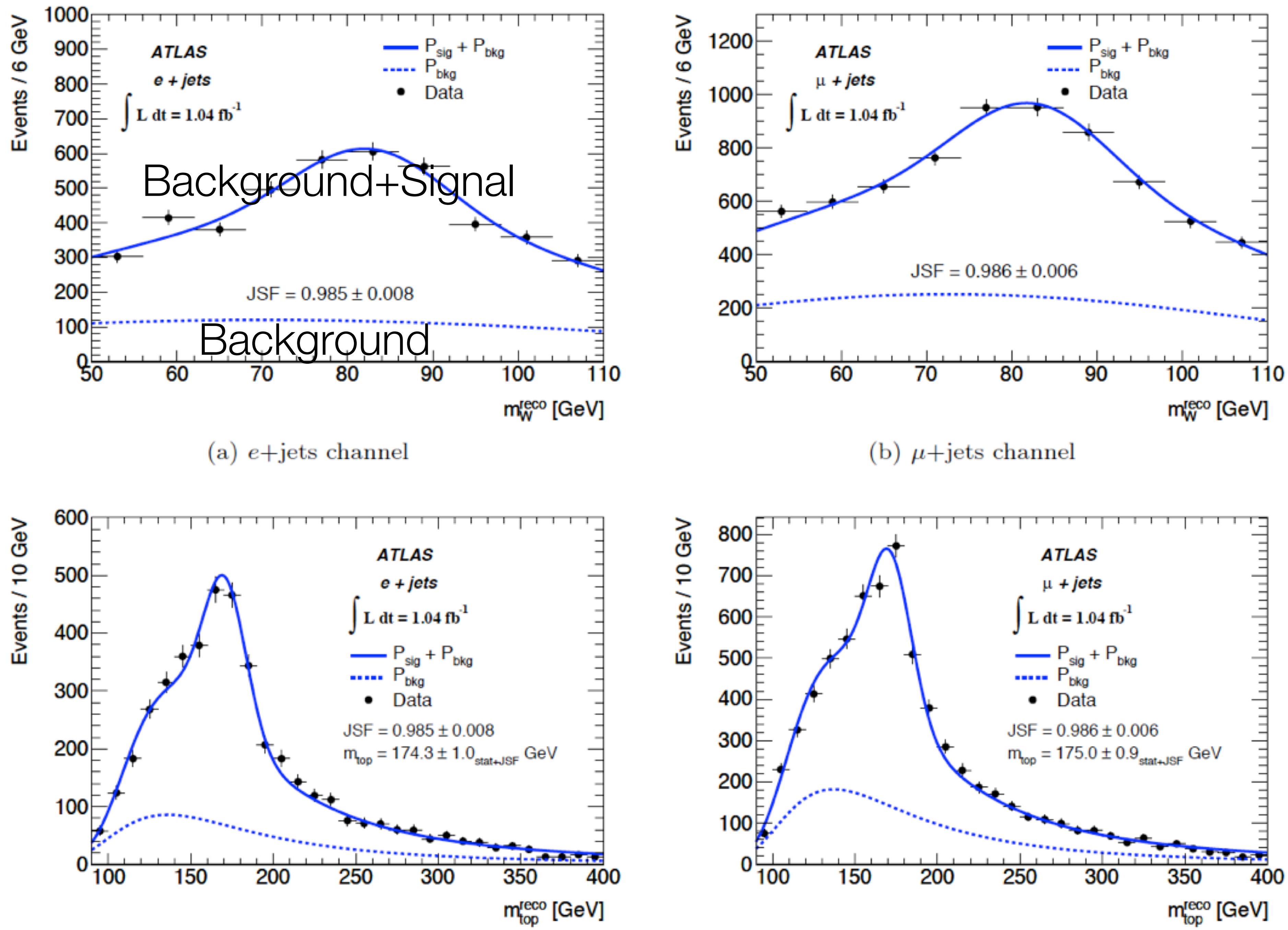


(a) μ+jets channel (b) μ+jets channel



The 2-dim fit results & summary

$$m_{\text{top}} = 174.3 \pm 0.8_{\text{stat}} \pm 2.3_{\text{syst}} \text{ GeV} \quad \text{(2d } e\text{+jets)},$$
$$m_{\text{top}} = 175.0 \pm 0.7_{\text{stat}} \pm 2.6_{\text{syst}} \text{ GeV} \quad \text{(2d } \mu\text{+jets)}.$$



Summary of the lepton+jets analysis

Fit results compatible, similar errors

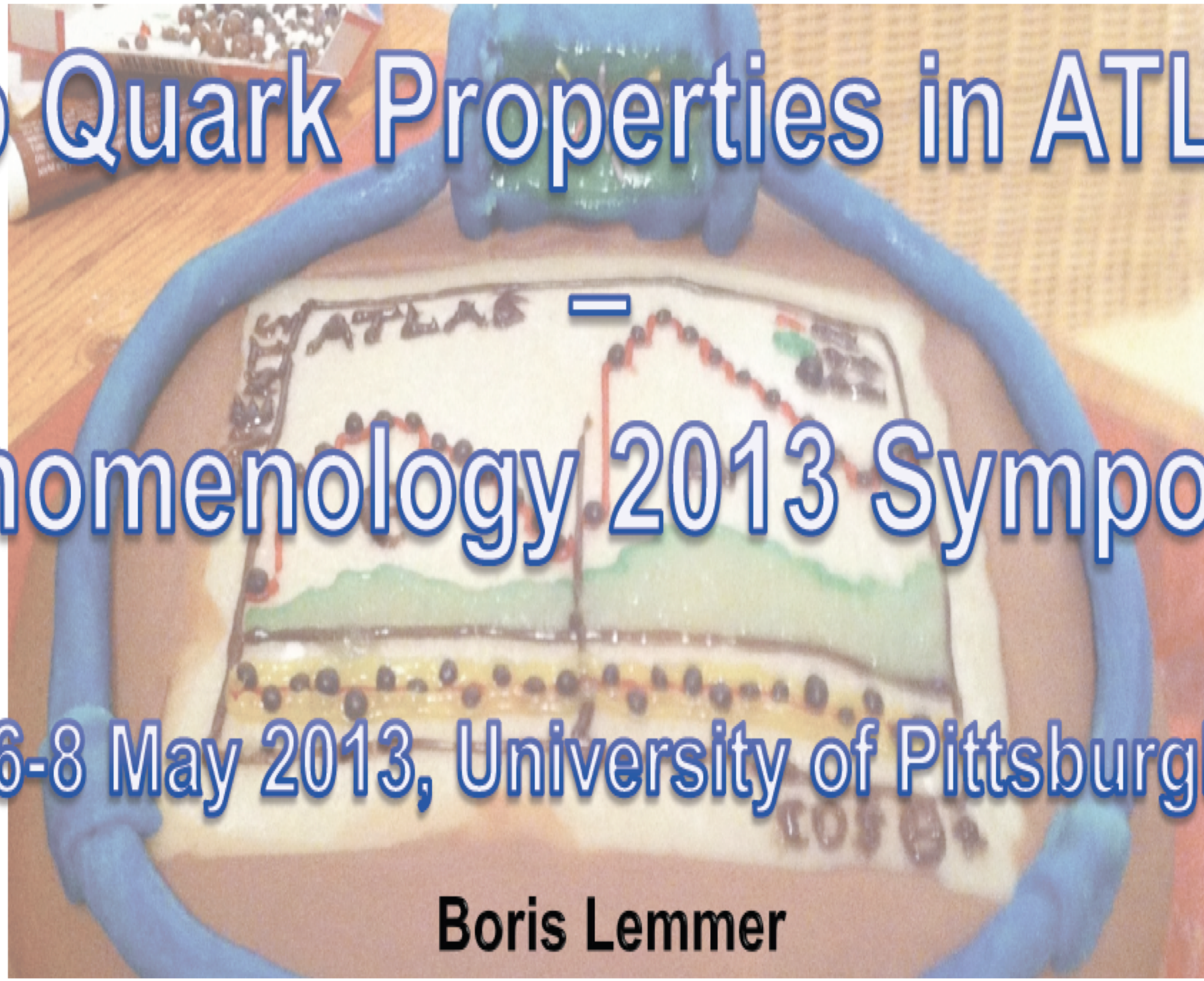
	1d-analysis		2d-analysis		Combinations		Correlation
	e+jets	μ+jets	e+jets	μ+jets	1d	2d	ρ
Measured value of m_{top}	172.93	175.54	174.30	175.01	174.35	174.53	
Data statistics	1.46	1.13	0.83	0.74	0.91	0.61	
Jet energy scale factor	na	na	0.59	0.51	na	0.43	0
Method calibration	0.07	< 0.05	0.10	< 0.05	< 0.05	0.07	0
Signal MC generator	0.81	0.69	0.39	0.22	0.74	0.33	1
Hadronisation	0.33	0.52	0.20	0.06	0.43	0.15	1
Pileup	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	1
Underlying event	0.06	0.10	0.42	0.96	0.08	0.59	1
Colour reconnection	0.47	0.74	0.32	1.04	0.62	0.55	1
ISR and FSR (signal only)	1.45	1.40	1.04	0.95	1.42	1.01	1
Proton PDF	0.22	0.09	0.10	0.10	0.15	0.10	1
W+jets background normalisation	0.16	0.19	0.34	0.44	0.18	0.37	1
W+jets background shape	0.11	0.18	0.07	0.22	0.15	0.12	1
QCD multijet background normalisation	0.07	< 0.05	0.25	0.33	< 0.05	0.20	(1)
QCD multijet background shape	0.14	0.12	0.38	0.30	0.09	0.27	(1)
Jet energy scale	1.21	1.25	0.63	0.71	1.23	0.66	1
b-jet energy scale	1.09	1.21	1.61	1.53	1.16	1.58	1
b-tagging efficiency and mistag rate	0.21	0.13	0.31	0.26	0.17	0.29	1
Jet energy resolution	0.34	0.38	0.07	0.07	0.36	0.07	1
Jet reconstruction efficiency	0.08	0.11	< 0.05	< 0.05	0.10	< 0.05	1
Missing transverse momentum	< 0.05	< 0.05	0.12	0.16	< 0.05	0.13	1
Total systematic uncertainty	2.46	2.56	2.31	2.57	2.50	2.31	
Total uncertainty	2.86	2.80	2.46	2.68	2.66	2.39	

Correlations!

$$m_{top} = 174.4 \pm 0.9_{stat} \pm 2.5_{syst}\ \text{GeV} \quad (\text{1d-analysis}),$$

$$m_{top} = 174.5 \pm 0.6_{stat} \pm 2.3_{syst}\ \text{GeV} \quad (\text{2d-analysis}).$$

Top Properties @ LHC



W Helicity from Top Decays

The angle theta* is defined as the angle between the charged lepton and -direction of the b-quark from the decay of the top quark. All boosted to the W test frame

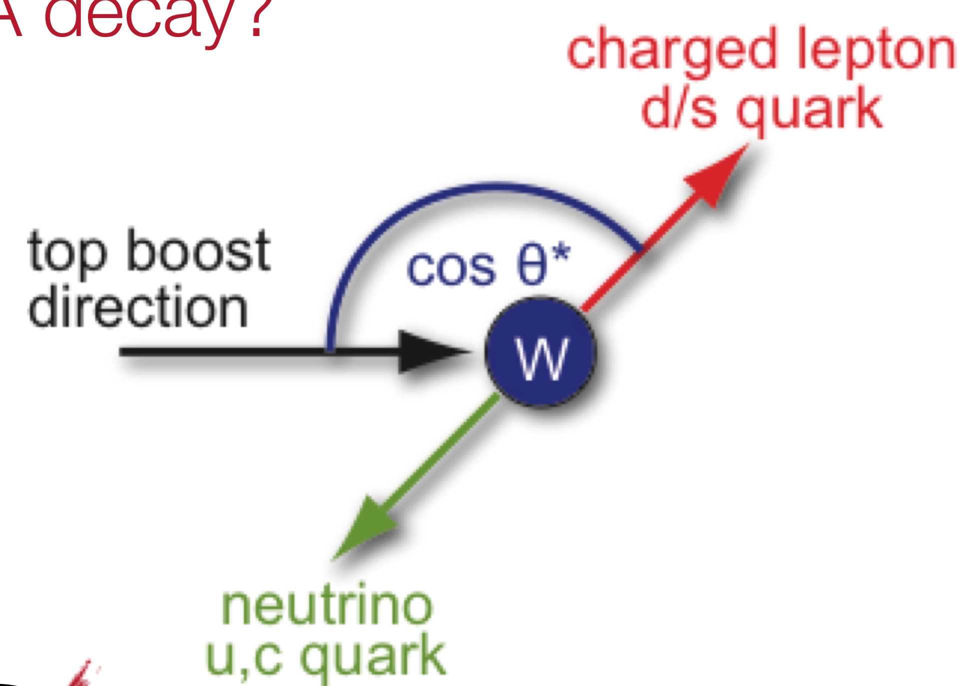
Decay t ➛ Wb governed by weak force, i.e. V–A decay?

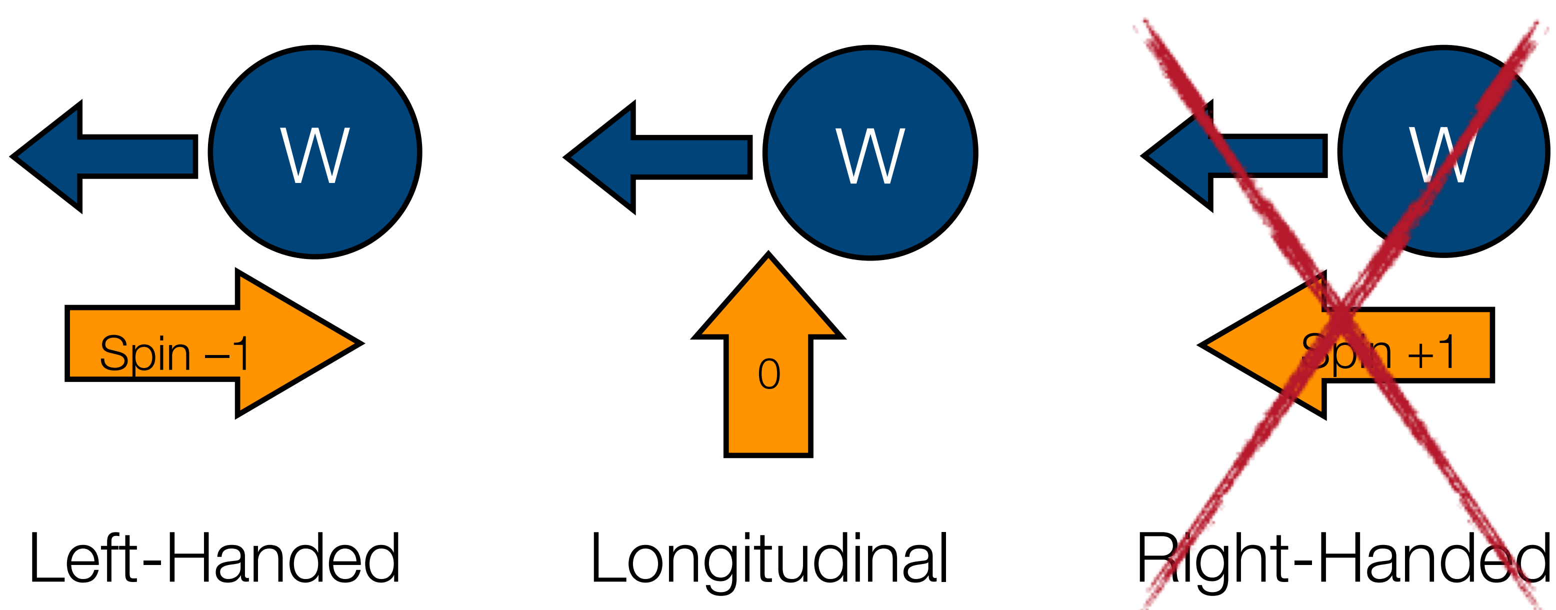
SM prediction: no "right-handed" W bosons from top decays

$$\mathcal{L}^{W}_{\rm int} = -{}^{g}/\sqrt{2}\,\mathbf{W}^{+}_{\mu}\,\bar{b}_{L}\gamma^{\mu}t_{L}$$

Observable: cos θ*

i.e. angle between lepton and top boost direction in W rest frame ...





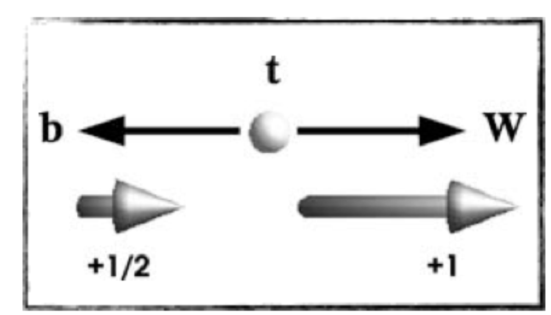


Illustration that the top mass cannot decay into a right-handed W-boson

Forbidden in Standard Model

W Helicity from Top Decays

Differential cross section decomposed into helicity states:

$$\frac{d\sigma}{d\cos\theta^*} \sim \underbrace{\frac{3}{8}(1-\cos\theta^*)^2 F_{LH}}_{\text{left-handed}} + \underbrace{\frac{3}{4}(1-\cos^2\theta^*) F_{long}}_{\text{longitudinal}} + \underbrace{\frac{3}{8}(1+\cos\theta^*)^2 F_{RH}}_{\text{right-handed}}$$

SM prediction for helicity fractions [LO, $m_b = 0$]:

$$F_{LH} = \frac{2m_W^2}{m_t^2 + 2m_W^2} \approx 0.3 \qquad F_{long} = \frac{m_t^2}{m_t^2 + 2m_W^2} \approx 0.7 \qquad F_{RH} \approx 0$$

Physical picture:

Top quark: large mass ➛ large Higgs (Yukawa) coupling

Longitudinal d.o.f. of W bosons generated by Higgs mechanism
Thus: top quark prefers to couple to longitudinal W ...

[see later]

W Helicity from Top Decays at the Tevatron

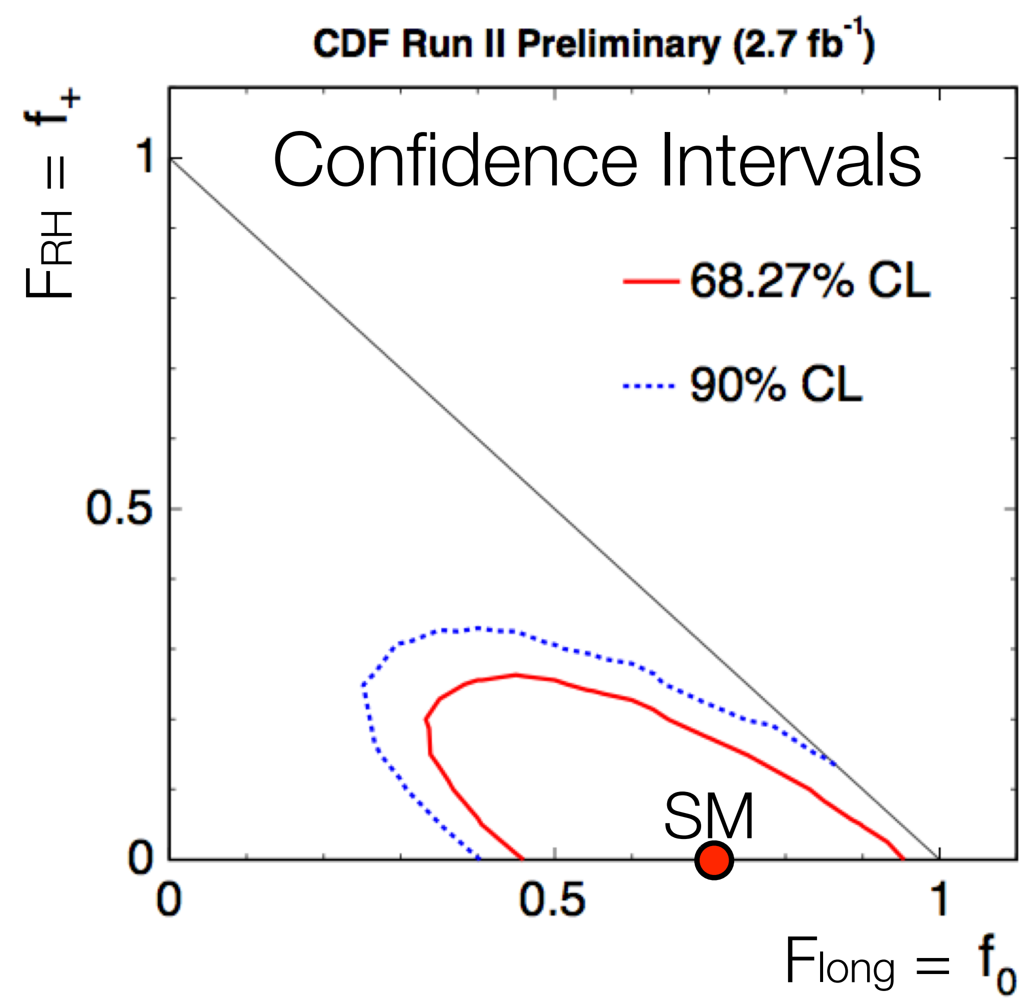
CDF result:
2D fit to F_{long} and F_{RH}

Use likelihood method

[$F_{long} + F_{RH} + F_{LH} = 1$]

$F_{long} = 0.88 \pm 0.13$ [stat.+syst.]

$F_{RH} = -0.15 \pm 0.09$ [stat.+syst.]



LHC expectations (1 fb^{-1}):

Reduce uncertainties to 0.04–0.05 [stat.+syst.]

More detailed studies of anomalous tWb couplings ...
Combination of top pair and single top measurements

[already tried at DØ: Phys. Rev. Lett. 102 (2009) 092002]

CDF; Measurement of W Helicity Fraction
[http://www-cdf.fnal.gov/physics/new/top/2008/tprop/Whel_ME/]

W-Boson polarization

W-Boson Polarization

- Probes *Wtb* vertex for anomalous couplings
- Two analyses combined:
  - Helicity fraction template fit

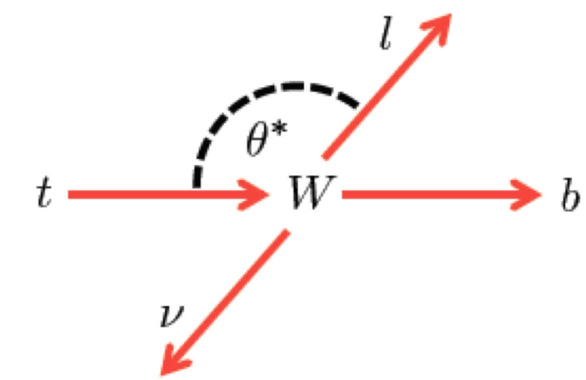
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right)F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

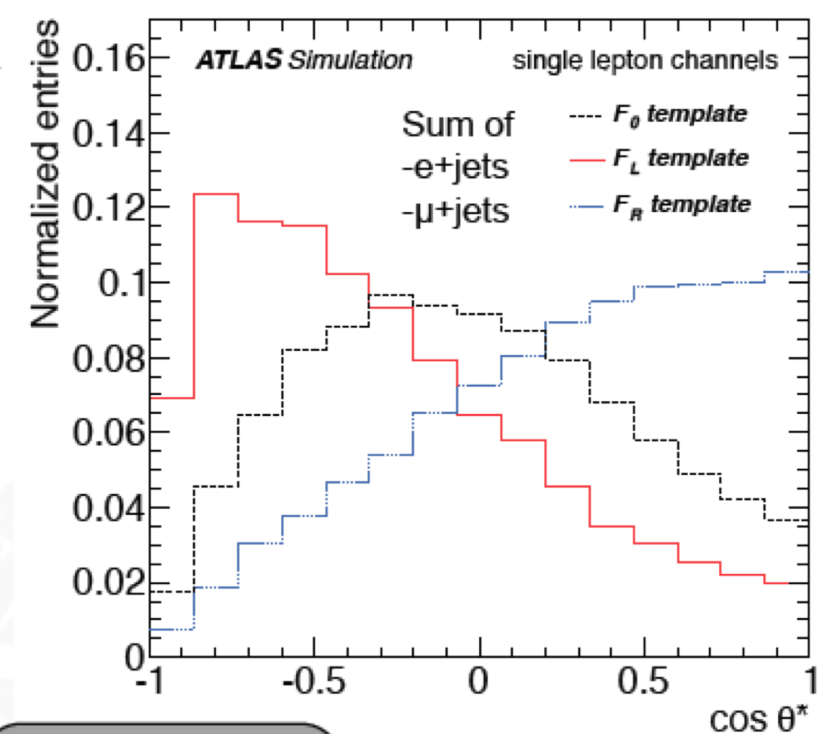
  - Angular asymmetries

$$A_\pm = \frac{N(\cos\theta^* > z) - N(\cos\theta^* < z)}{N(\cos\theta^* > z) + N(\cos\theta^* < z)}$$

- New: LHC combination (ATLAS-CONF-2013-033)

F_i: fractions of longitudinally polarized (F_0), left- (F_L) and right-handed (F_R) W-bosons





Results

- ATLAS combination
- Anomalous couplings compatible with 0

F_0 = 0.67 ± 0.03 (stat.) ± 0.06 (syst.)
F_L = 0.32 ± 0.02 (stat.) ± 0.03 (syst.)
F_R = 0.01 ± 0.01 (stat.) ± 0.04 (syst.)

JHEP 06 (2012) 088	dilepton and l+jets	1.0 fb^{-1} @ 7 TeV

NNLO pQCD*:
F_0 = 0. 687
F_L = 0.311
F_R = 0.002

[* A. Czarnecki, J.G. Korner and J.H. Piclum, Phys. Rev. D 81 (2010) 111503]

Main Systematics (F_0)

- JES (0.026)
- Fake lepton estimate (0.020)
- m_{top} (0.016)
- ISR/FSR (0.015)

Comparison data / MC of cos(theta*)

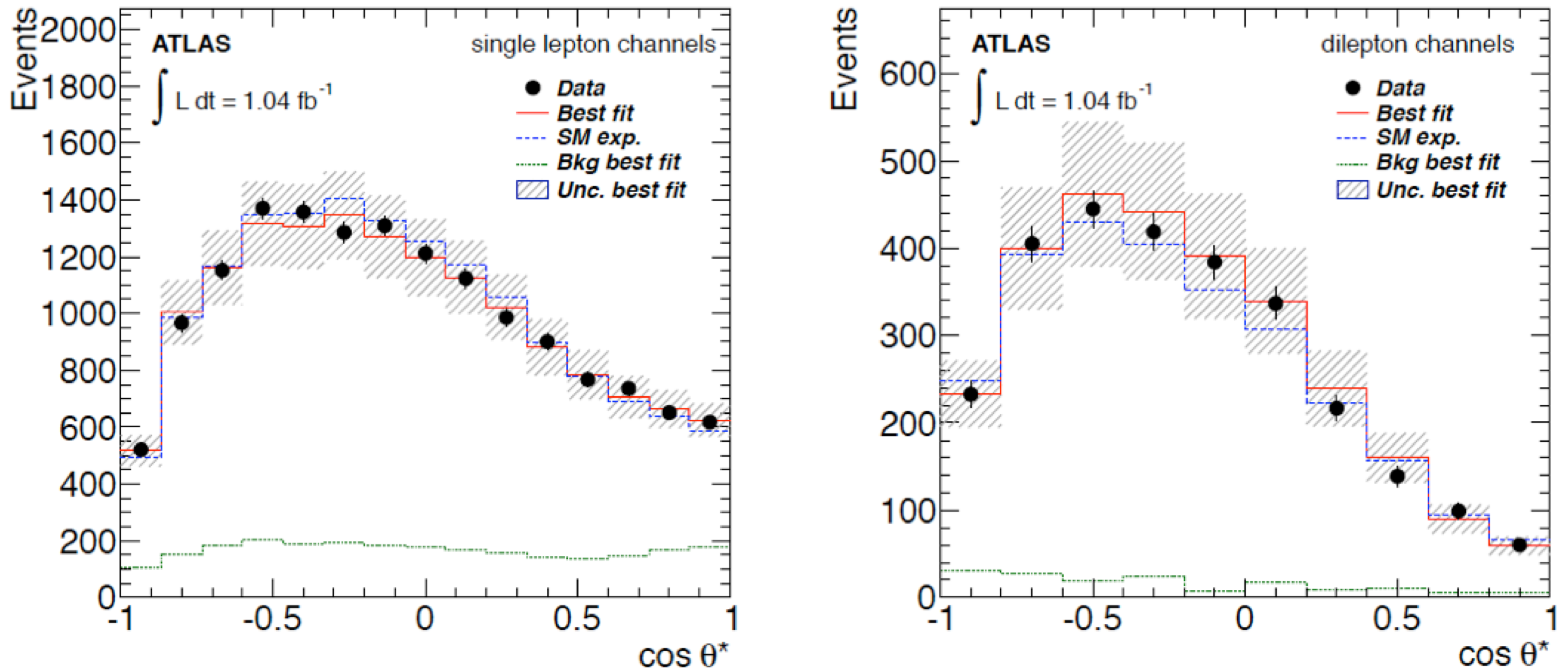


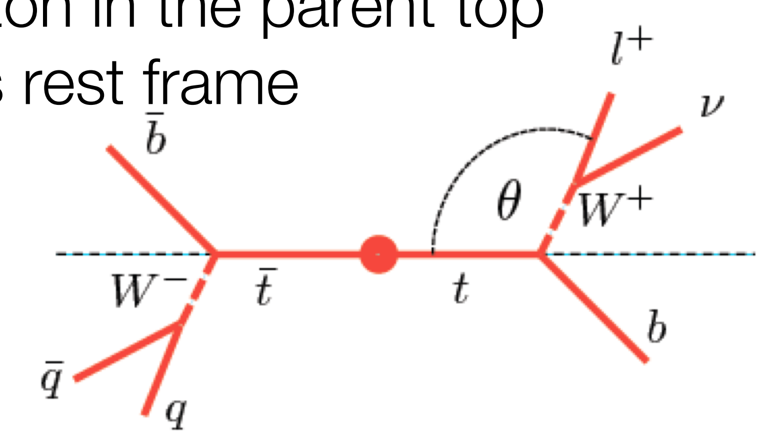
Figure 4. Distributions of the reconstructed $\cos\theta^*$ used in the template method for data (markers), fitted background (dotted line), the Standard Model prediction (dashed line) and the best fit value (solid line) for the (left) single-lepton and (right) dilepton channels. The total uncertainties on the helicity fractions for the best fit values are represented by the grey band. For the dilepton channels, each event contributed with two entries, corresponding to the two leptonic decays of the W bosons.

Top polarization

Top Polarization

- Top quarks almost unpolarized in SM
- $\cos(\theta_i)$ distributions measured via template fit
- From fit: $\alpha_i\, p$
  - α: spin analyzing power (= 1 for charged lepton)
  - p: polarization

Theta is the polar angle between the charged lepton in the parent top quark's rest frame



$$W(\cos(\theta_i)) \sim 1 + \alpha_i \cdot p \cdot \cos(\theta_i)$$

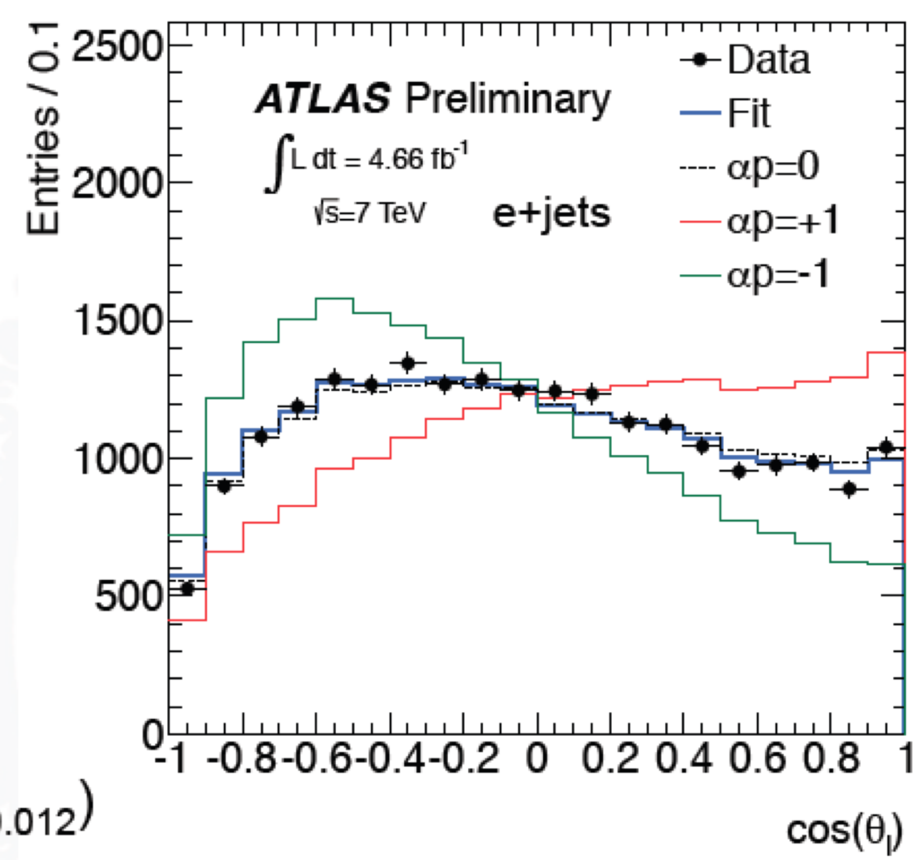
A complete reconstruction of the ttbar system is needed!

Results

- Assume CP conservation in production ($\alpha_i\, p_{top} = \alpha_j\, p_{antitop}$)

$\alpha_i\, p = -0.060 \pm 0.018$ (stat.) $^{+0.046}_{-0.064}$ (syst.)	SM: $\alpha_i\, p = 0$

ATLAS-CONF-2012-133	l+jets	4.7 fb^{-1} @ 7 TeV



Main Systematics

- Jet reconstruction ($^{+0.018}_{-0.028}$)
- Signal modeling ($^{+0.011}_{-0.012}$)

Top spin correlation

- SM description of production and decay predicts spin correlation A
- Azimuthal angle $\Delta\phi_{lab}$(analyzer$_1$, analyzer$_2$)
  [Mahlon and Parke, Phys. Rev. D 81, 074024 (2010)]
- Dilepton channel $\Delta\phi_{lab}$(lepton$_1$, lepton$_2$) :
  α_{lep}= ± 1, no full reconstruction needed
- Template fit: SM correlation, uncorrelated $t\bar{t}$ pairs

$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}} = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$

Results

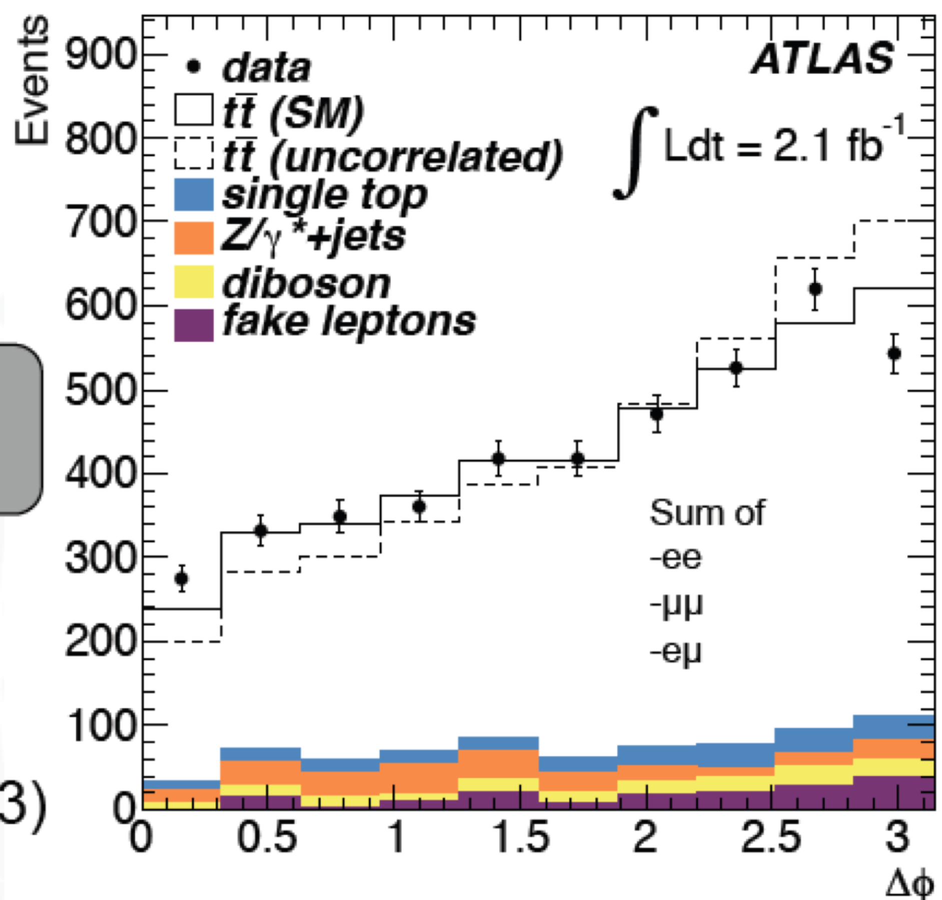
- First observation (5 σ exclusion of no spin hypothesis)

A_{hel} = 0.40 ± 0.04 (stat.) $^{+0.08}_{-0.07}$ (syst.)			SM (NLO)*: A_{hel} = 0.31
PRL 108, 212001 (2012)	dilepton	2.1 fb^{-1} @ 7 TeV	

[* Bernreuther and Zi, Nucl. Phys. B837, 90 (2010)]

Main Systematics (A_{hel})

- Jet reconstruction (0.04)
- Fake lepton estimate ($^{+0.05}_{-0.02}$)
- Template statistics (0.03)
- Signal modeling (0.02)



Top charge: is it -4/3?

- No direct measurement so far
- Instead: Exclusion of possible alternative: -4/3 *e*
- Lepton+jets channel combination:
  - Weighted jet charge method

$$Q_{\text{b-jet}} = \frac{\sum_i q_i \left|\vec{j}\cdot\vec{p}_i\right|^{\kappa}}{\sum_i \left|\vec{j}\cdot\vec{p}_i\right|^{\kappa}}$$

$$Q_{\text{comb.}} = Q_{\text{b-jet}} \cdot Q_{\text{lepton}}$$

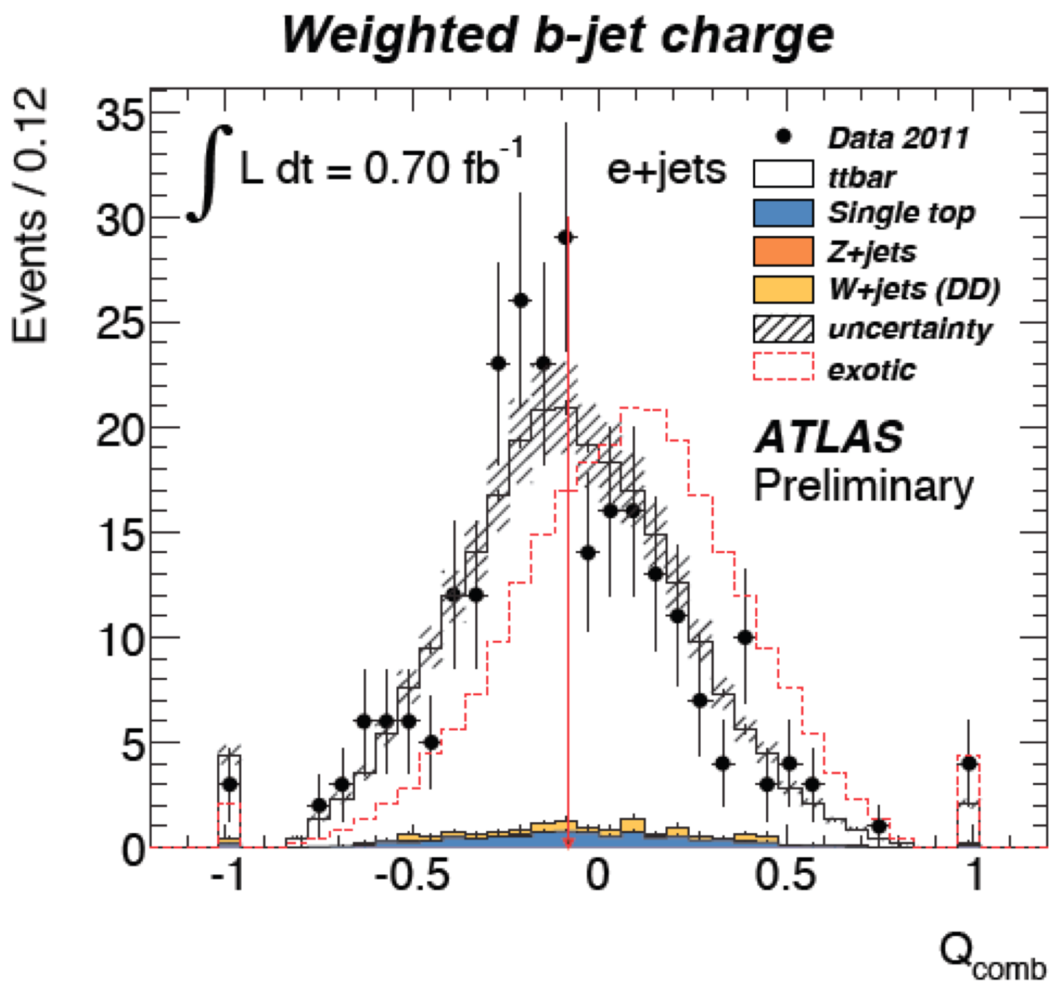
q_i : track charge

$\vec{j}$: jet axis

$\vec{p}_i$: track momentum

κ : separation tuning factor

  - Soft muon method



Result

Exotic charge of -4/3 *e* excluded by > 5 σ		
ATLAS-CONF-2011-141	l+jets	0.7 fb^{-1} @ 7 TeV

Main Systematics (<Q_{comb}> [%])

- ISR/FSR (13.8)
- Jet/E_t^{miss} reconstruction (7.2)

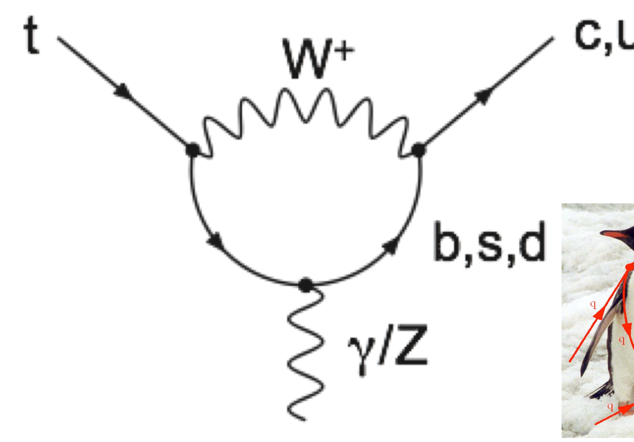
Rare Top Decays

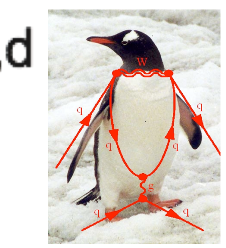
Strategy in flavor physics:

Probe high-energy phenomena via loop effects [see later]

Example:
Flavor changing neutral currents

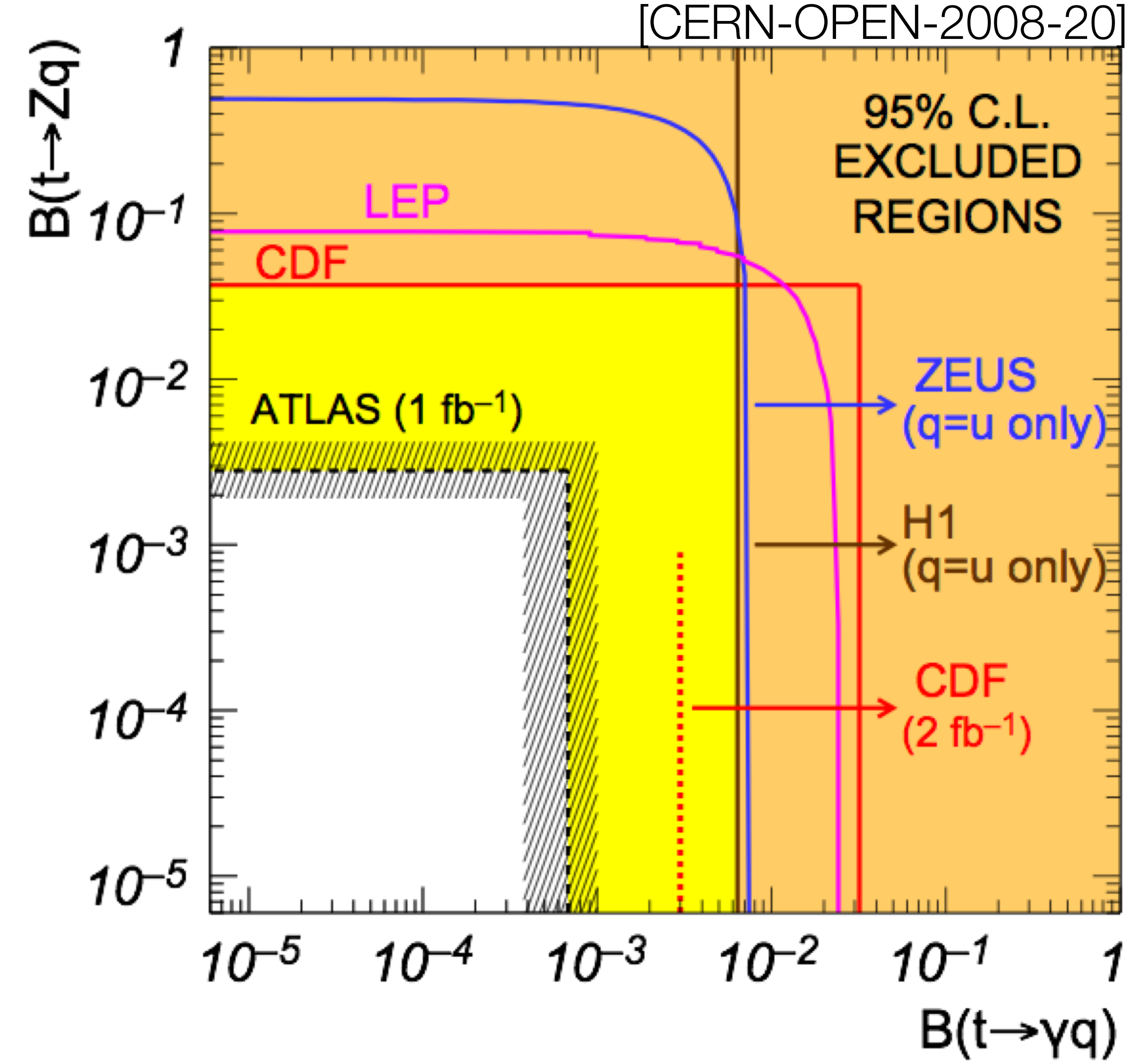
- Extremely small in the SM, e.g. $BR(t \to Zq) = 10^{-14}$
- Enhanced in many new physics scenarios, up to 10^{-4}
- Tevatron: only weak limits, e.g. $BR(t \to Zq) < 3.7 \times 10^{-2}$ [@ 95% C.L.]
- LHC: improve by 2–3 orders ...





Penguin diagram

[CERN-OPEN-2008-20]



Additional Slides

m_t vs m_W in pdg 2017

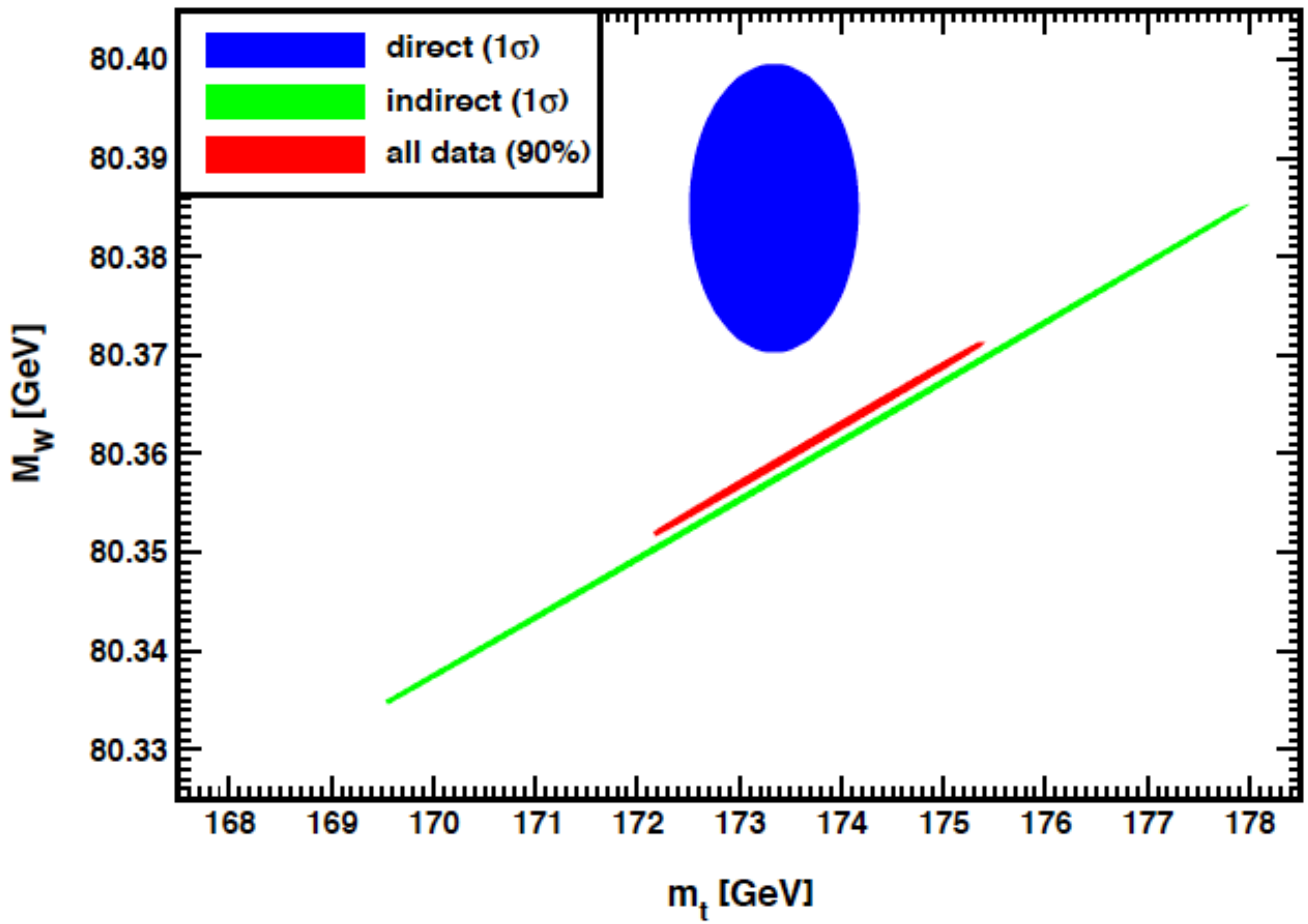


Figure 10.5: One-standard-deviation (39.35%) region in M_W as a function of m_t for the direct and indirect data, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data.