8. Physics of the Top Quark

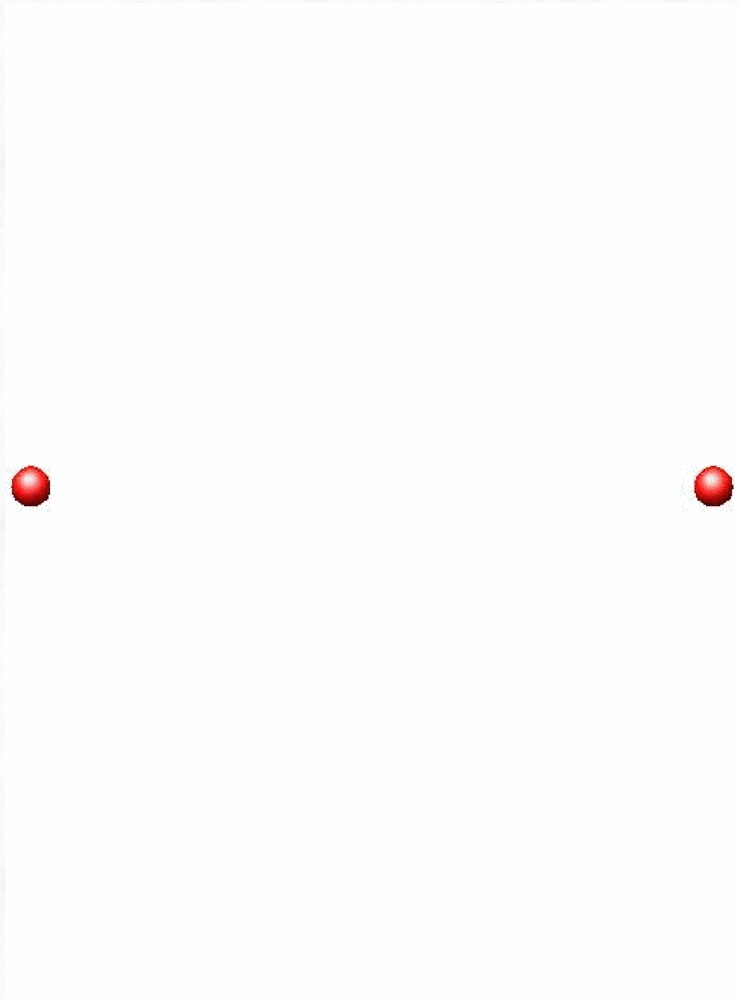
8.1 Introduction (The top quark in the Standard Model)

8.2 Top quark production at the Tevatron

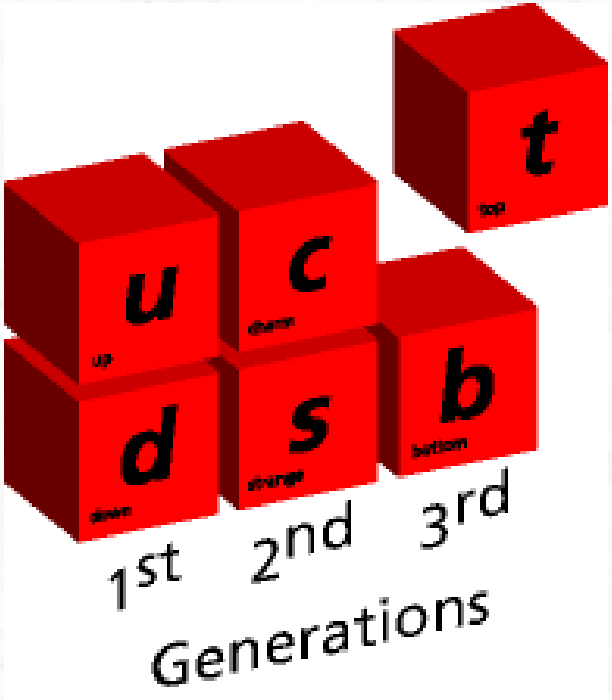
8.3 Top quark production at the LHC

8.4 Top-quark mass measurements
(Tevatron and LHC)

8.5 Constraints on the Standard Model



8.1 Introduction to Top Quark Physics



- Discovered by the CDF and DØ collaborations at the Tevatron in 1995

- Tevatron Run I top physics results are consistent
- with expectations from the Standard Model
  (Errors dominated by statistics)

- Run II top physics program profits a lot from the higher statistics

- LHC: huge production rates
  (for $\sqrt{s}$ = 7 TeV: about a factor 25 larger cross sections than at the Tevatron)

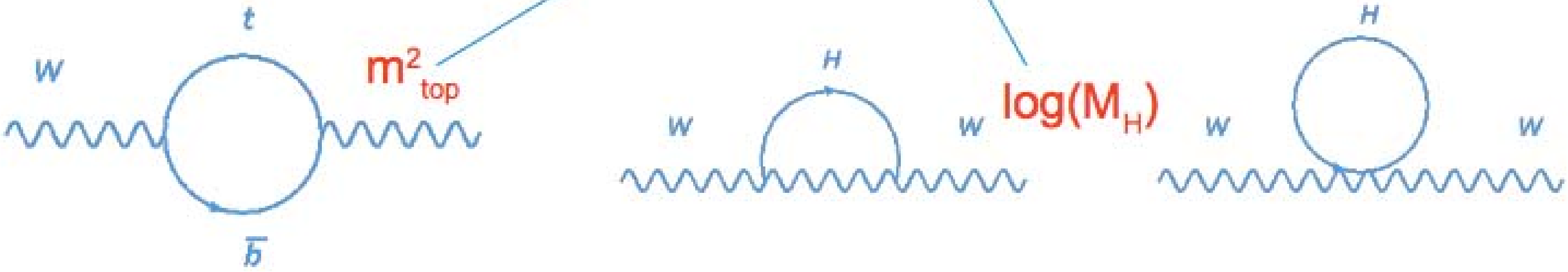
  - Better precision
  - Search for deviations from Standard Model expectations

Die Masse des W-Bosons

- Wichtiger Konsistenzest, auch wenn SM Higgs-Boson gefunden ist

$$m_W = \left(\frac{\pi \, \alpha_{EM}}{\sqrt{2} \, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \, \sqrt{1 - \Delta r}}$$

Strahlungskorrekturen
$\Delta r \sim 3\ \%$



- G_F, α_{EM} und $\sin\theta_W$ sind mit großer Präzision gemessen – nicht limitierend

What do we know about the top quark?

- The top quark is the heaviest know fermion

  m_t ~173 GeV (from experiment)

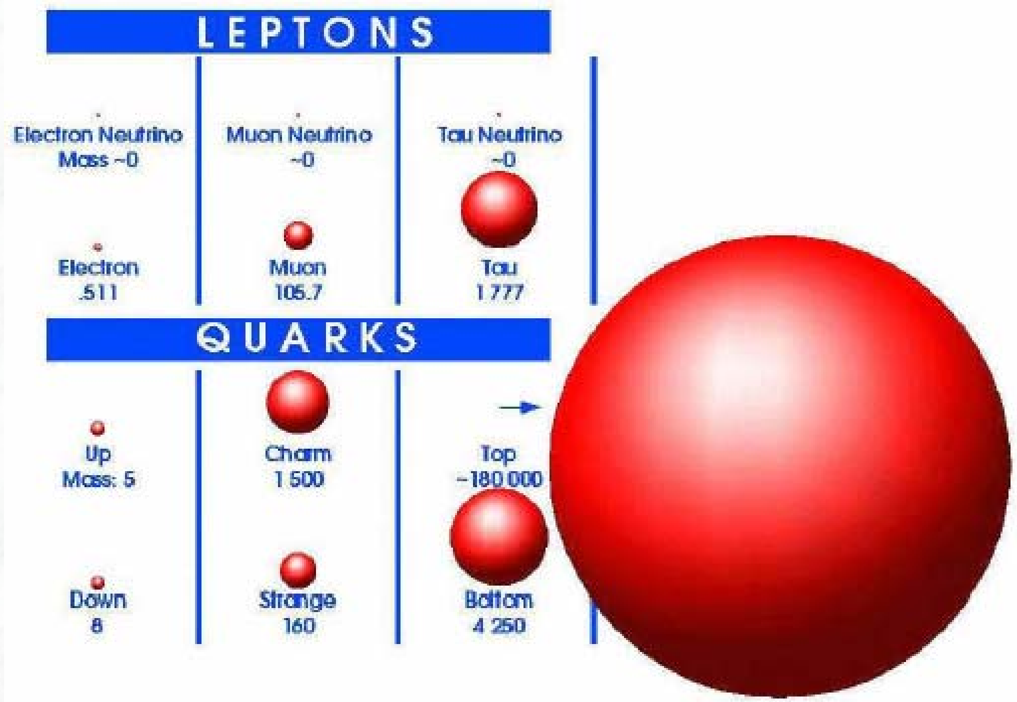
- Lifetime $\tau \sim 5\ 10^{-25}$ s (theory, Standard Model decays)

  no hadronisation, behaves like a quasi-free quark !

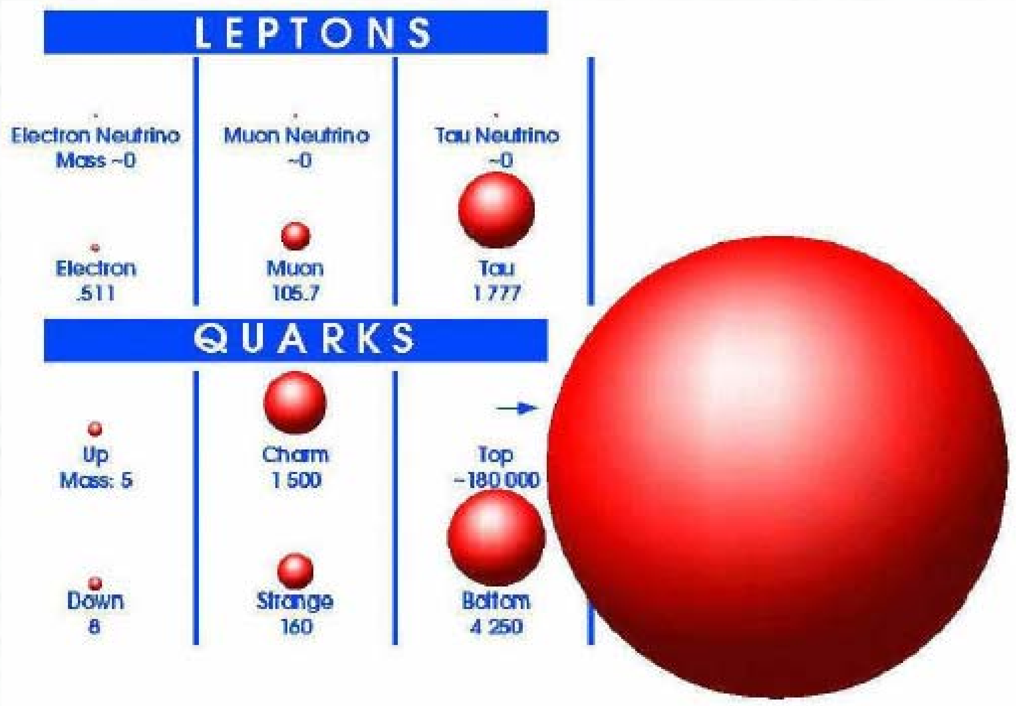
- Predominant decays: t → Wb (BR ~100%)

  largely determined from very small CKM matrix elements V_{td}, V_{ts}

- Electric charge $Q_t = +2/3$



Why is Top Quark so important ?



The top quark may serve as a window to **New Physics** related to the electroweak symmetry breaking;

Why is its Yukawa coupling ~ 1 ??

$$\boxed{\begin{aligned} M_t &= \frac{1}{\sqrt{2}}\lambda_t v \\ \Rightarrow \lambda_t &= \frac{M_t}{173.9\ \mathrm{GeV}/c^2} \end{aligned}}$$

- We still know little about the properties of the top quark:
  mass, spin, charge, lifetime, decay properties (rare decays), gauge couplings, Yukawa coupling,…

- A unique quark: decays before it hadronizes, lifetime ~10^{-25} s
  no "toponium states"
  remember: bb, bd, bs….. cc, cs….. bound states (mesons)

Top-Quark Production

Pair production: qq and gg-fusion

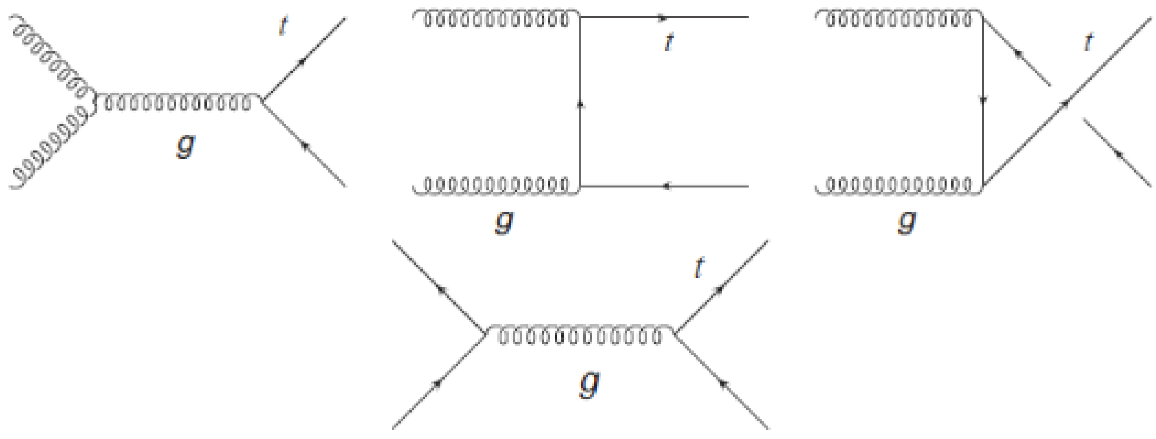


Figure 9.3 Top-quark pair production in the Born approximation.

- NLO corrections completely known (1989)
- NNLO calculated in 2013: M. Czakon et al. (PRL110(25))

NLO results:

$$\sigma_{\mathrm{LHC}} = (887^{+9}_{-33}\,(\mathrm{scale})^{+15}_{-15}\,(\mathrm{PDF}))\ \mathrm{pb} \qquad (14\ \mathrm{TeV}),$$

$$\sigma_{\mathrm{Tev}} = (7.04^{+0.24}_{-0.36}\,(\mathrm{scale})^{+0.14}_{-0.14}\,(\mathrm{PDF}))\ \mathrm{pb} \qquad (1.96\ \mathrm{TeV}).$$

	Tevatron 1.96 TeV	LHC 14 TeV
qq gg	85% 15%	5% 95%
σ (pb)	7.0 pb	887 pb

For LHC running at √s = 7 TeV, the cross section is reduced by a factor of ~5, but it is still a factor 25 larger than the cross section at the Tevatron

Single Top-Quark Production

Electroweak production of single top-quarks
(Drell-Yan and Wg-fusion)

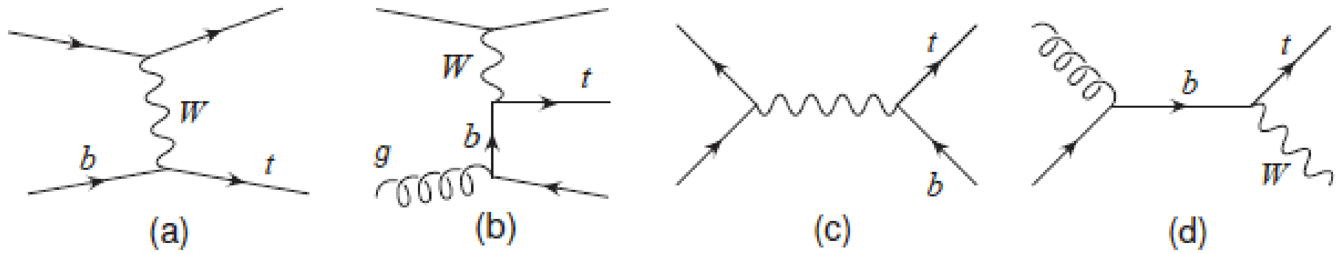
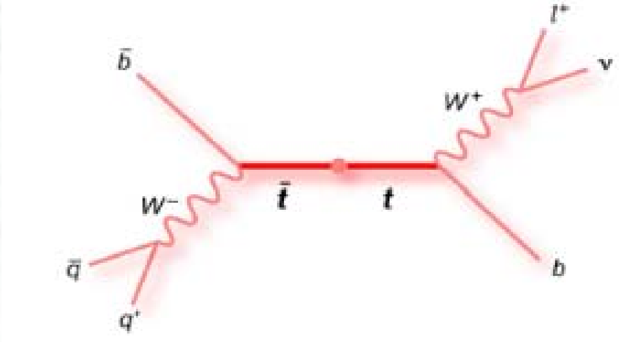


Figure 9.5 Representative Feynman diagrams for the three single top-quark production modes. The graphs show single top-quark production; the diagrams for single antitop-quark production can be obtained by interchanging quarks and antiquarks.

Process	$\sqrt{s}$	$\sigma_{tq\bar{b}}$	$\sigma_{t\bar{b}}$	σ_{Wt}
$p\bar{p} \to t/\bar{t}$	1.96 TeV	$1.86^{+0.19}_{-0.16}$ pb	1.02 ± 0.08 pb	0.25 ± 0.03 pb
$pp \to t$	14.0 TeV	149.4 ± 4.1 pb	$7.23^{+0.55}_{-0.47}$ pb	41.1 ± 4.2 pb
$pp \to \bar{t}$	14.0 TeV	88.9 ± 2.4 pb	$4.03^{+0.14}_{-0.16}$ pb	41.1 ± 4.2 pb

Table 9.2 Predicted total cross sections for single top-quark production processes at the Tevatron and the LHC. The cross sections of the t-channel process are taken from [22]. The values for s-channel and associated production are taken from [23]. All cross sections are evaluated at $m_t = 175$ GeV.

Top-Quark Decays



BR ($t \rightarrow Wb$) ~ 100%

Dilepton channel:

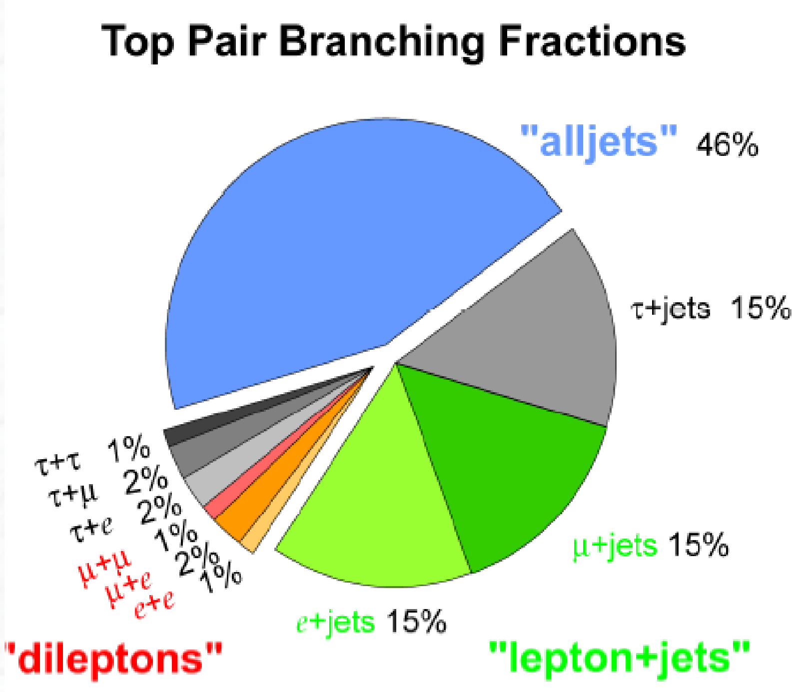
Both W's decay via $W \rightarrow \ell\nu$ (ℓ=e or μ; 4%)

Lepton + jet channel:

One W decays via $W \rightarrow \ell\nu$ (ℓ=e or μ; 30%)

Full hadronic channel:

Both W's decay via $W \rightarrow qq$ (46%)

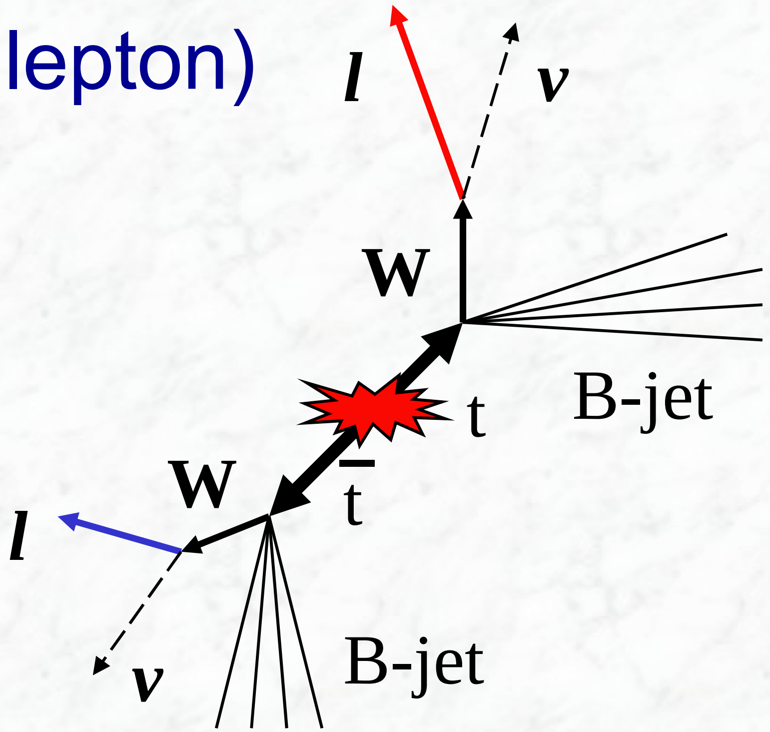


Important experimental signatures:
- Lepton(s)
- Missing transverse momentum
- b-jet(s)

8.2 Measurement of top-quark production

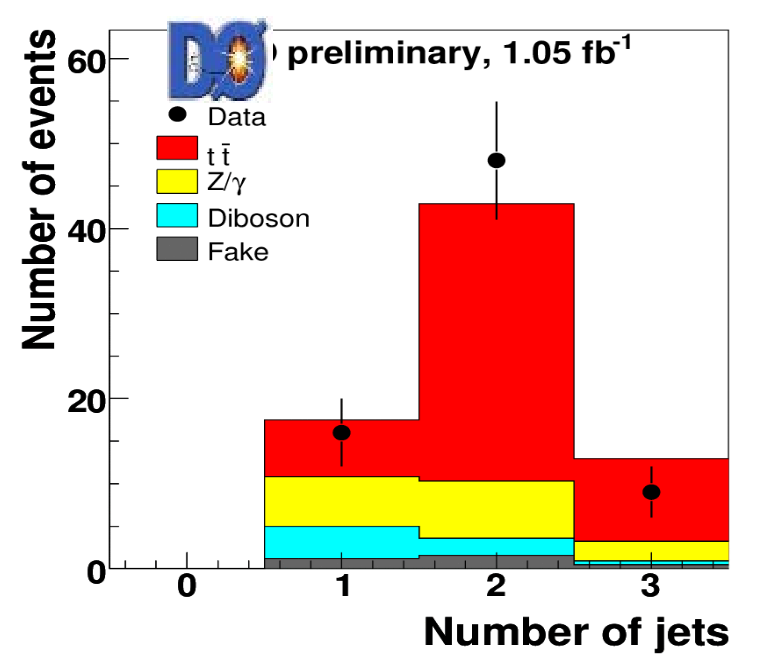
at the Tevatron

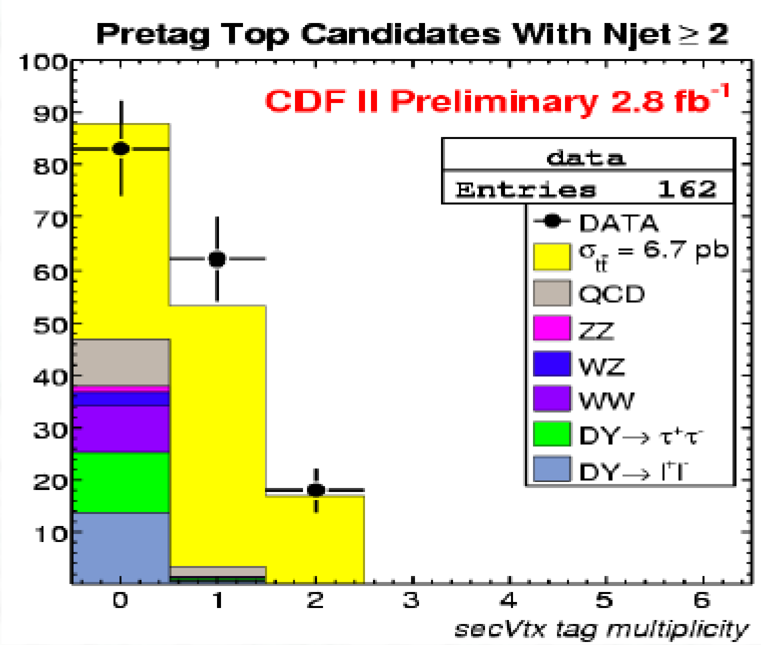
$t\bar{t}$ cross section (dilepton)



- Two high p_T leptons (opposite charge)
  ee, eμ, μμ
- Significant missing transverse momentum
- ≥ 1 jet (eμ), ≥ 2 jets (ee, μμ)

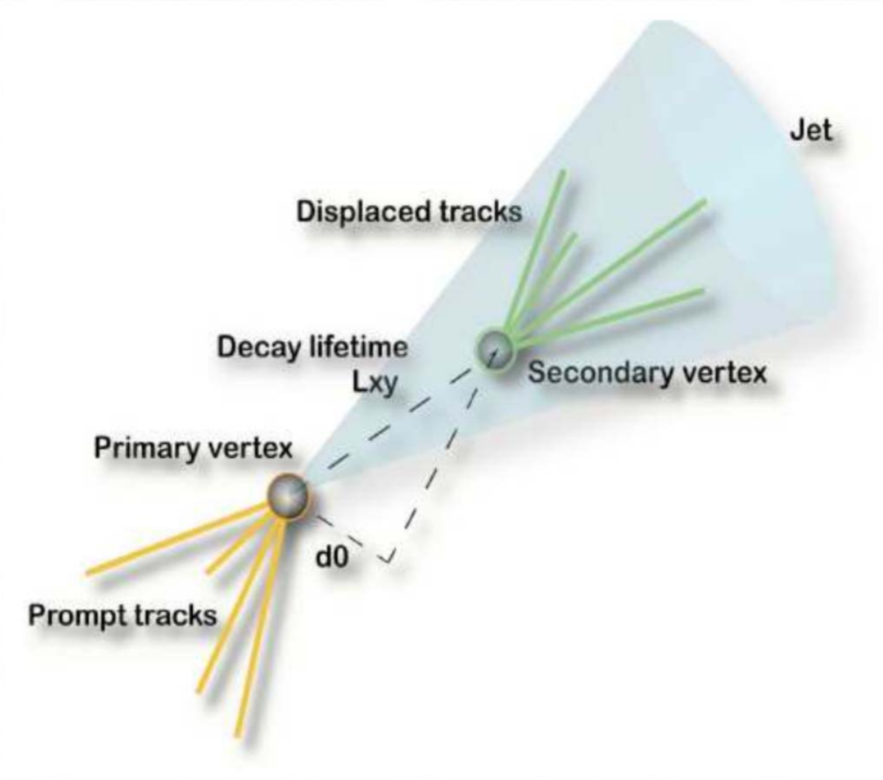
ee,eμ and μμ combined

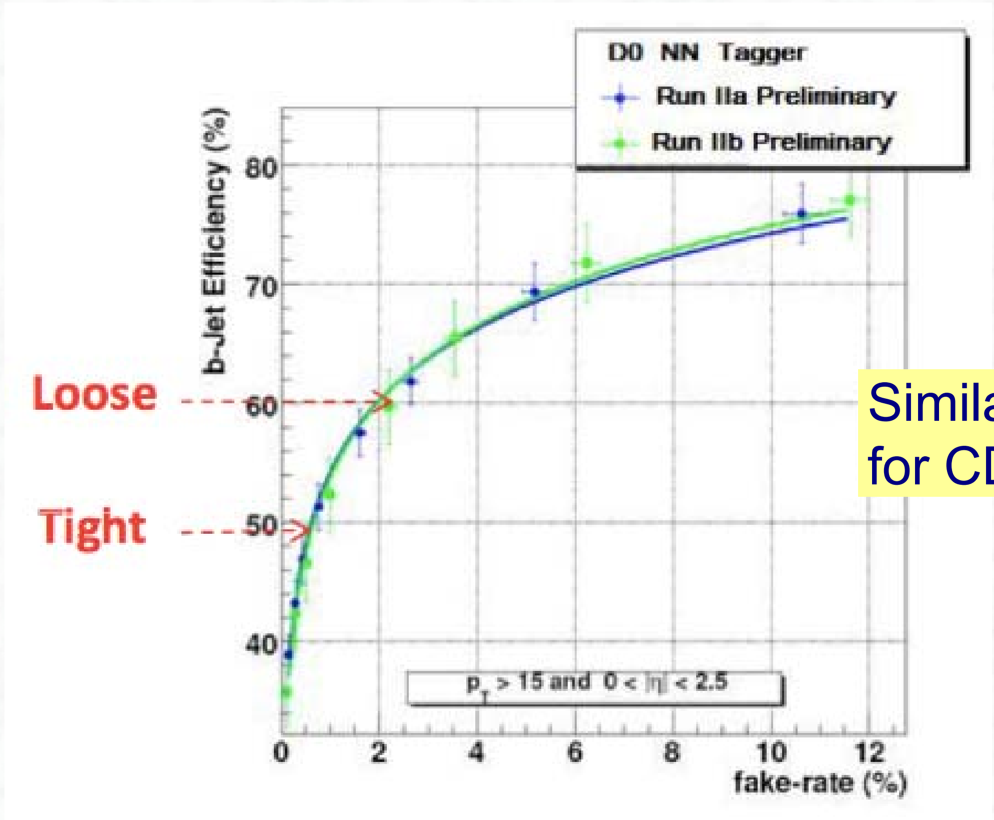




Top quark is needed to describe the
b-jet multiplicity distribution in dilepton events

Tevatron b-tagging performance





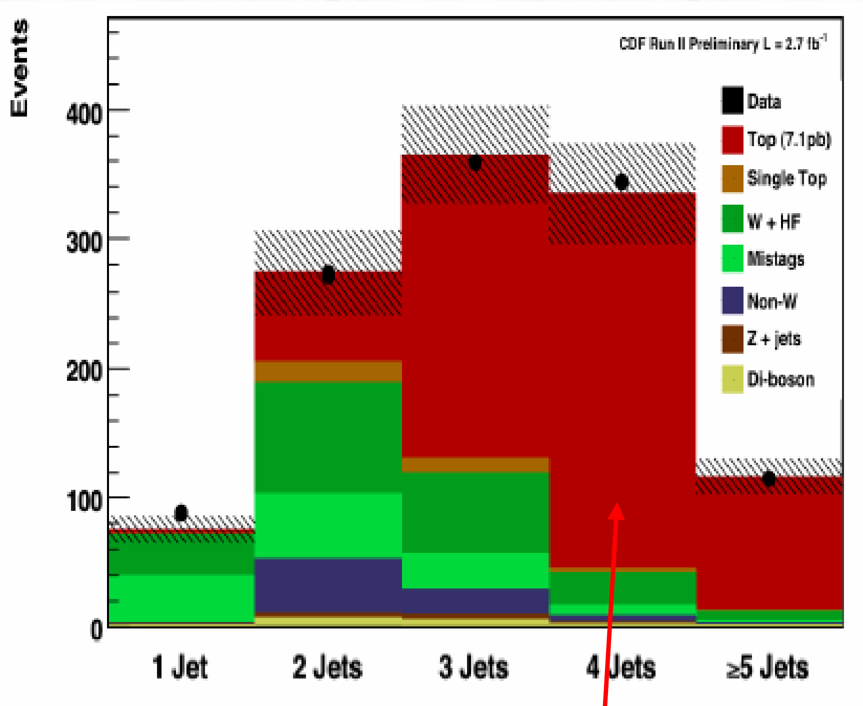
Similar for CDF

Neural networks are used for optimal combination of tagging information

tt cross section (lepton + jets)   (including b-tagging)

b-tag selection:

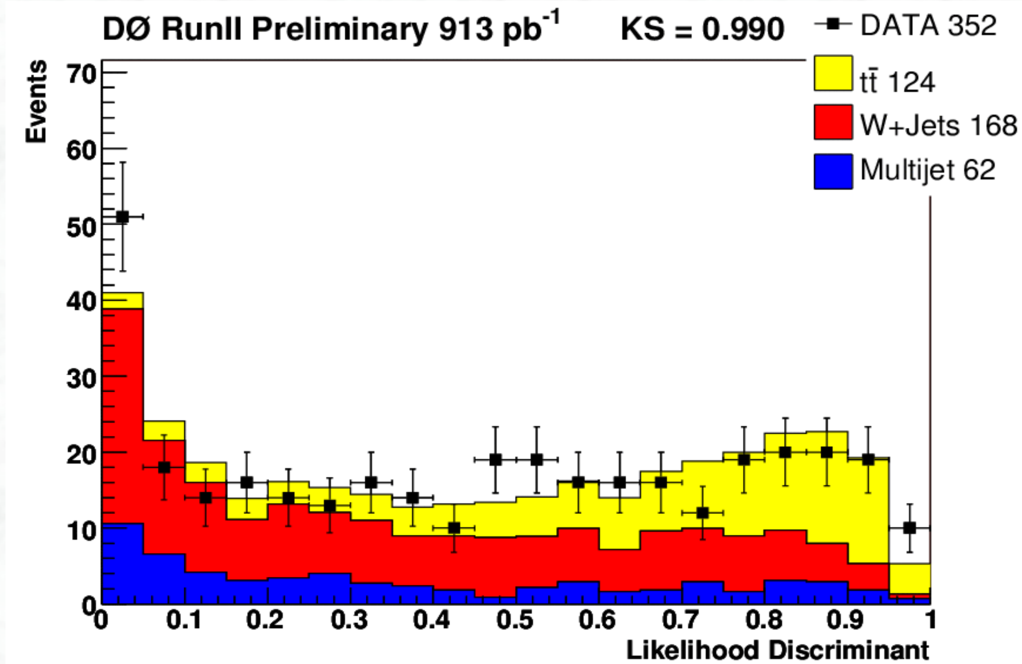
- One high-p_T lepton (e, μ)
- Significant E_T^{miss}
- $\geq$ 1 b-tagged jet



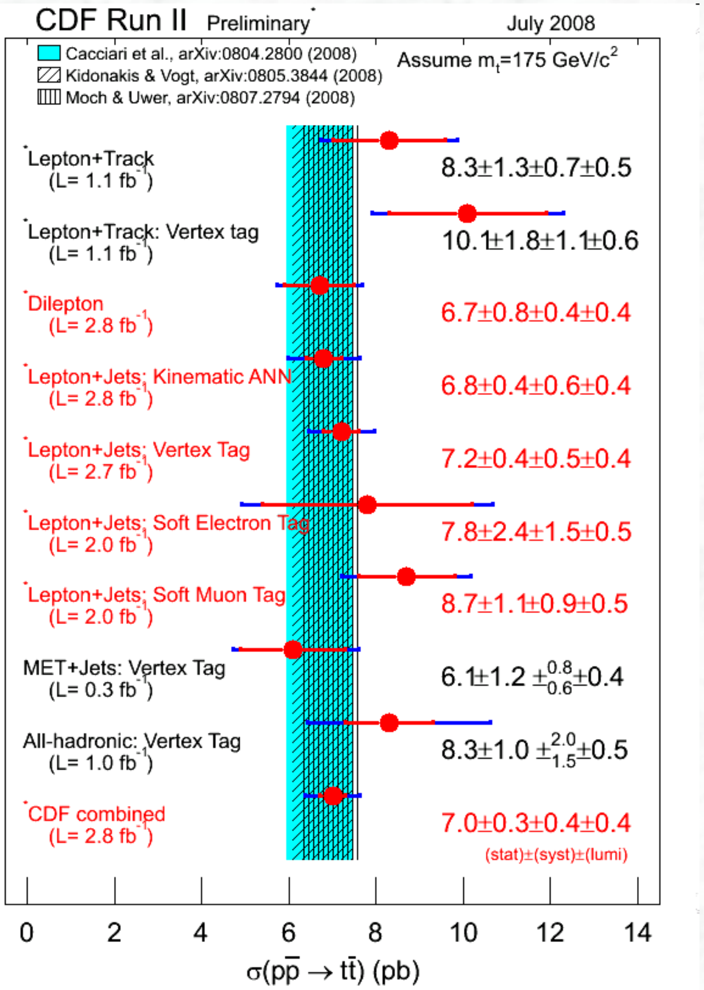
Clear excess above the W+ jet background in events with high jet multiplicity

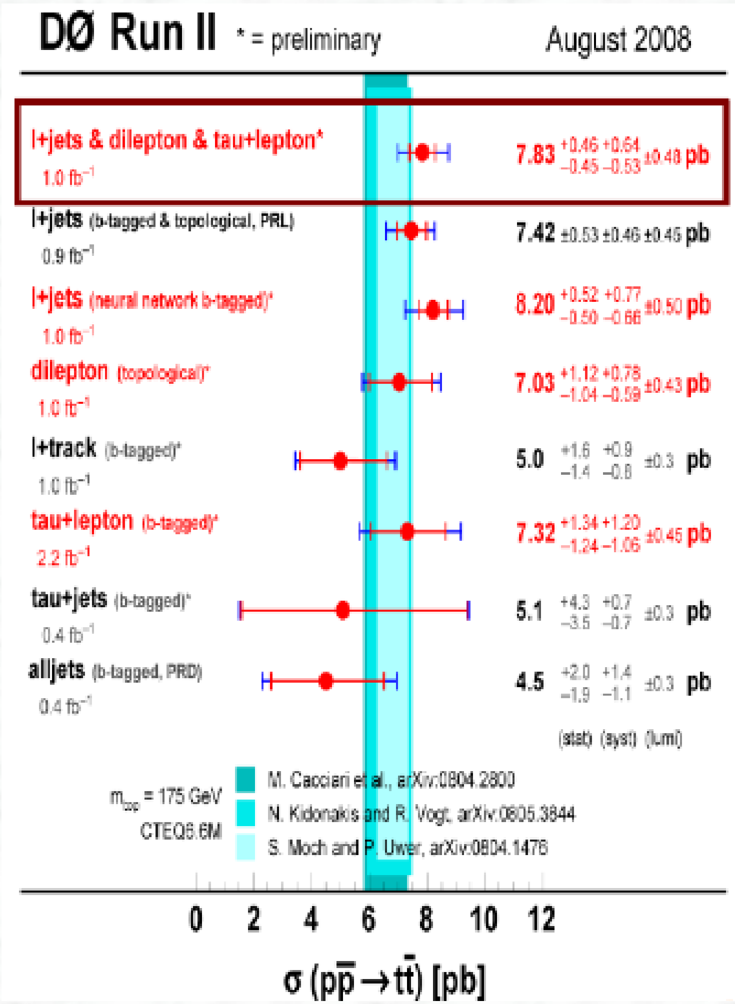
Kinematic selection:

- One high-p_T lepton (e, μ)
- Significant E_T^{miss}
- $\geq$ 4 jets
- Likelihood discriminant (tt vs. W+jets)



tt cross section summary from the Tevatron





Summary of syst. uncertainties

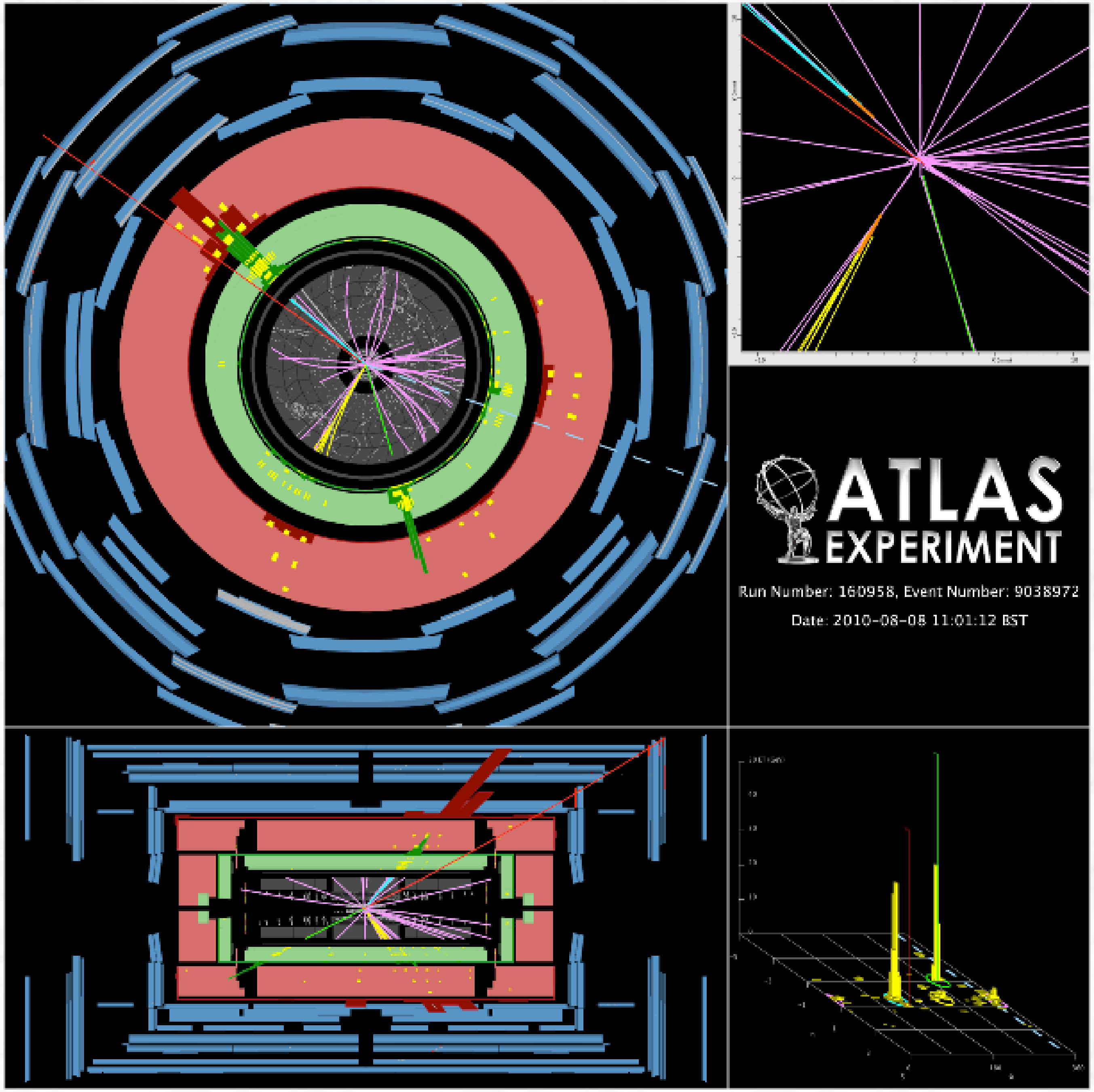
b-tag analysis (2.7 fb^{-1}):

SYSTEMATIC	$\Delta\ \sigma$ pb	$\Delta\ \sigma/\sigma$ %
JET ENERGY SCALE	0.16	2.2
BOTTOM TAGGING	0.38	5.2
CHARM TAGGING	0.08	1.1
MIS-TAGS	0.15	2.1
HEAVY FLAVOR CORRECTION	0.23	3.2
LUMINOSITY	0.42	5.8
QCD FRACTION	0.02	0.2
PARTON SHOWER MODELING	0.13	1.8
INITIAL/FINAL STATE RADIATION	0.04	0.6
TRIGGER EFFICIENCY	0.05	0.6
PDF	0.06	1.0
TOTAL	0.67	9.3

CDF Run II Preliminary L=2.7 fb^{-1}

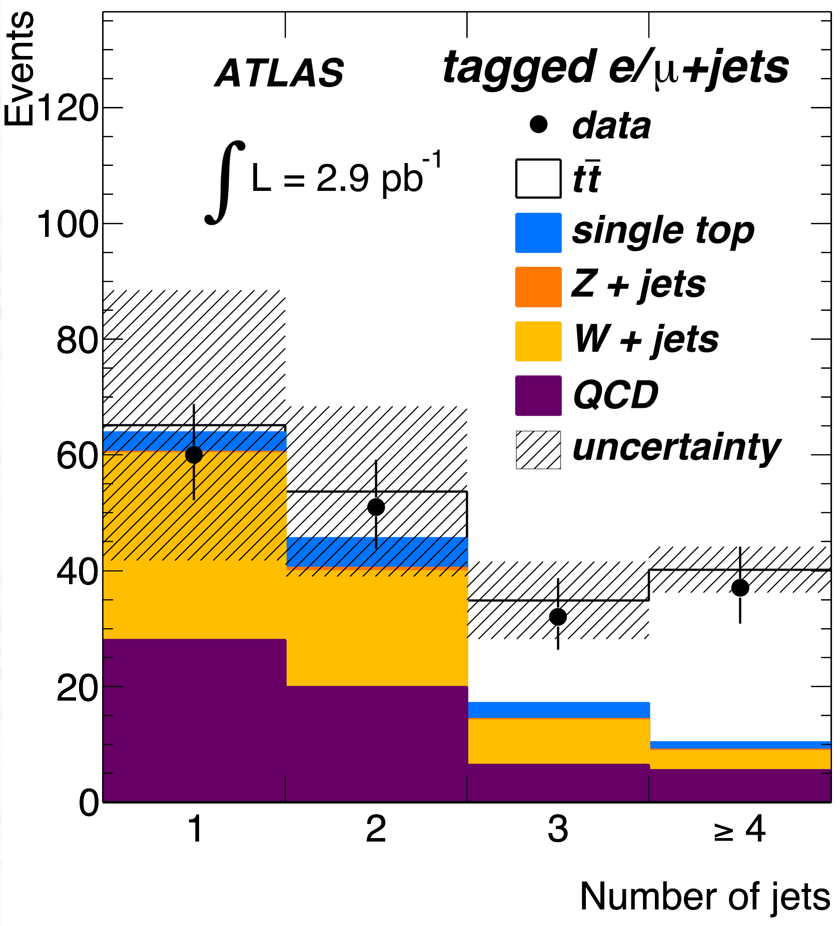
Good agreement:
- among various exp. measurements (two experiments)
- and with NLO + LL QCD prediction
- Systematic uncertainties at the 10% level
  (luminosity, b-tagging)

8.3 Measurement of Top-Quark production at the LHC



Event display of a top pair e-μ dilepton candidate with two b-tagged jets. The electron is shown by the green track pointing to a calorimeter cluster, the muon by the long red track intersecting the muon chambers, and the missing ET direction by the dotted line on the xy-view. The secondary vertices of the two b-tagged jets are indicated by the orange ellipses on the zoomed vertex region view.

First results on top-quark production from the LHC



Event Selection:

- Lepton trigger
- One identified lepton (e,μ) with p_T > 20 GeV
- Missing transverse energy: E_T^{miss} > 35 GeV (significant rejection against QCD events)
- Transverse mass: $M_T (l,\nu)$ > 25 GeV (lepton from W decay in event)
- One or more jets with p_T > 25 GeV and η < 2.5

Details on the composition of the event samples:
ATLAS experiment, L = 35 pb^{-1} (data from 2010)

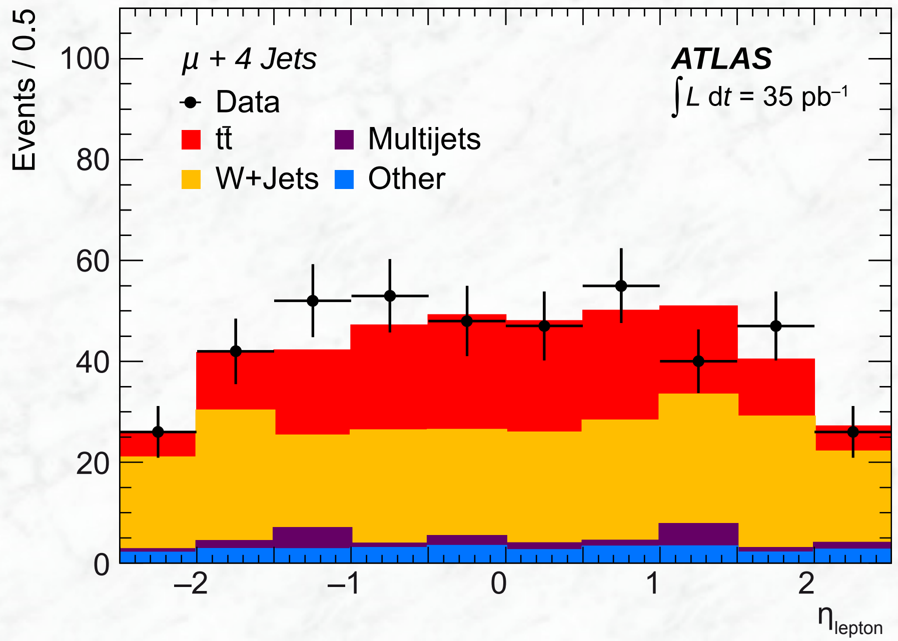
Table 1: Number of observed events in the data in the electron and muon channels after the selection cuts as a function of the jet multiplicity. The expected signal and background contributions are also given. All simulated processes are normalized to theoretical SM predictions, except the multijet background which uses the normalisation presented in Sec. 6. The quoted uncertainties include statistical, systematic and theoretical components, except for the multijet background. All numbers correspond to an integrated luminosity of 35 pb^{-1}.

Electron channel	3 jets	4 jets	≥ 5 jets
$t\bar{t}$	117 ± 16	109 ± 15	76 ± 19
W+jets	524 ± 225	124 ± 77	35 ± 23
Multijet	64 ± 32	12 ± 6	8 ± 4
Single top	21 ± 5	7 ± 3	3 ± 2
Z+jets	60 ± 28	21 ± 15	8 ± 6
Diboson	9 ± 3	1.9 ± 1.5	0.4 ± 0.8
Predicted	795 ± 236	275 ± 84	130 ± 35
Observed	755	261	123
Muon channel	**3 jets**	**4 jets**	**≥ 5 jets**
$t\bar{t}$	165 ± 22	156 ± 18	108 ± 27
W+jets	976 ± 414	222 ± 139	58 ± 38
Multijet	79 ± 24	18 ± 6	11 ± 3
Single top	31 ± 7	10 ± 4	4 ± 2
Z+jets	58 ± 26	14 ± 10	5 ± 4
Diboson	16 ± 4	3 ± 2	0.6 ± 0.8
Predicted	1325 ± 422	423 ± 143	186 ± 51
Observed	1289	436	190

Final results obtained in a >3 jet selection based on 35 pb^{-1}.

Cross section obtained by a combined fit in different jet-multiplicity regions

Distributions for different jet multiplicities



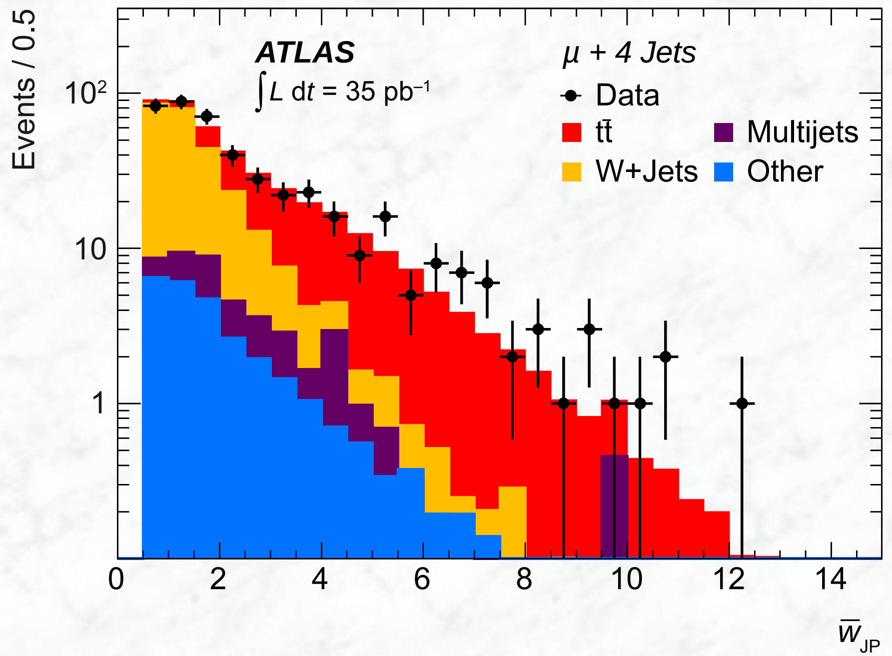
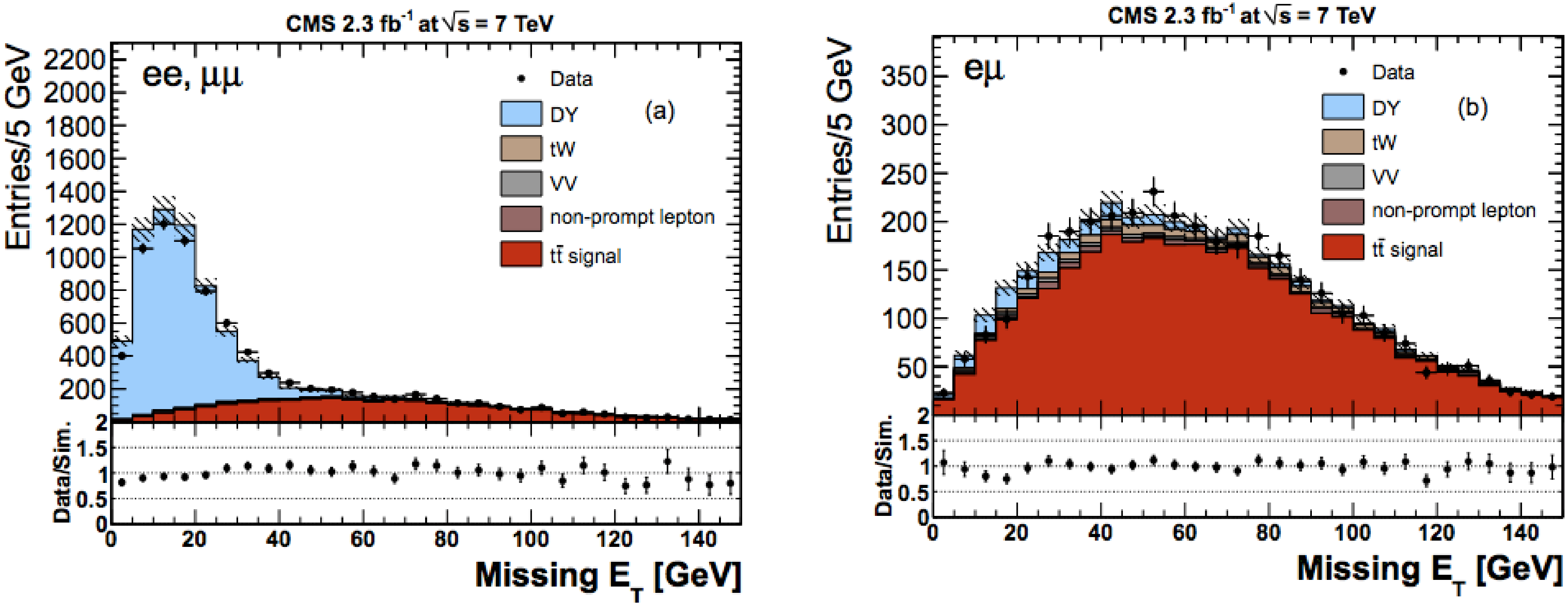


Table 2: Statistical and systematic uncertainties on the measured $t\bar{t}$ cross-section in the untagged and tagged analyses. Multijet and small backgrounds normalisation uncertainties are already included in the statistical uncertainty (a/i) in the tagged analysis. W+jets heavy-flavour content and b-tagging calibration do not apply (n/a) to the untagged analysis. The luminosity uncertainty is not included in the table.

Method	Untagged		Tagged	
Statistical Error (%)	+10.1	−10.1	+5.8	−5.7
Object selection (%)				
JES and jet energy resolution	+4.1	−5.4	+3.9	−2.9
Lepton reconstruction, identification and trigger	+1.7	−1.6	+2.1	−1.8
Background modelling (%)				
Multijet shape	+3.5	−3.5	+0.8	−0.8
Multijet normalisation	+1.1	−1.2	a/i	
Small backgrounds norm.	+0.6	−0.6	a/i	
W+jets shape	+3.9	−3.9	+1.0	−1.0
W+jets heavy-flavour content	n/a		+2.7	−2.4
b-tagging calibration	n/a		+4.1	−3.8
$t\bar{t}$ signal modelling (%)				
ISR/FSR	+6.3	−2.1	+5.2	−5.2
NLO generator	+3.3	−3.3	+4.2	−4.2
Hadronisation	+2.1	−2.1	+0.4	−0.4
PDF	+1.8	−1.8	+1.5	−1.5
Others (%)				
Simulation of pile-up	+1.2	−1.2	< 0.1	
Template statistics	+1.3	−1.3	+1.1	−1.1
Systematic Error (%)	+10.5	−9.4	+9.7	−9.0

W_{PJ} = average of $-\log_{10}$ P(b-light jet) for the two jets with lowest P(b-light jet)

CMS tt signals in the di-lepton channel



Missing E_T distribution for leptons with the same and different flavour

CMS tt signals in the di-lepton channel

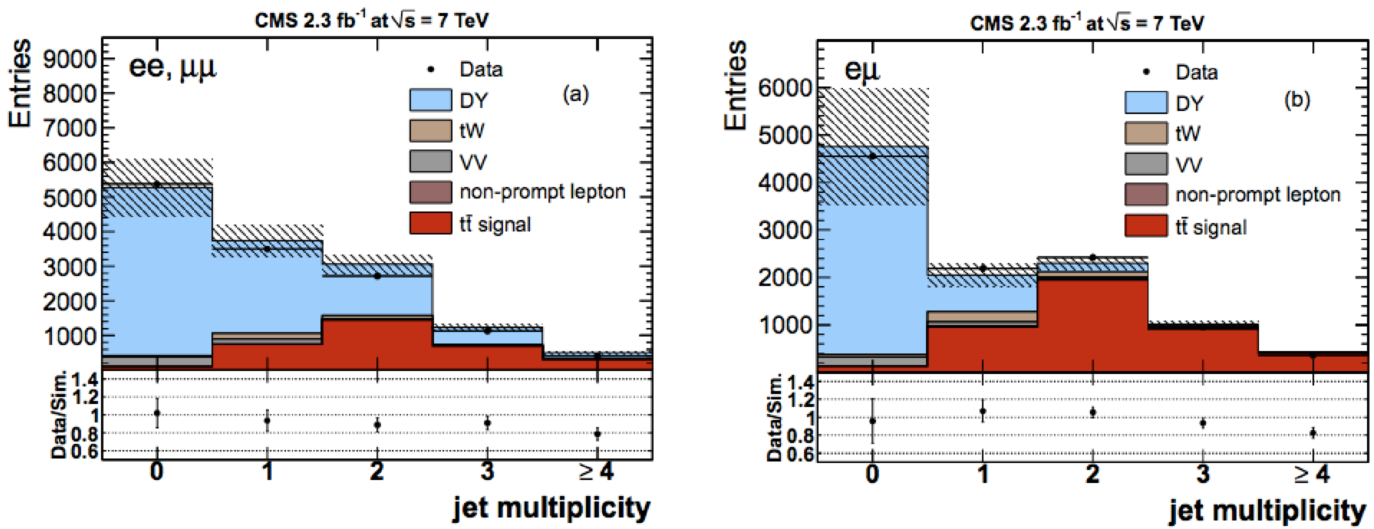


Figure 5. The jet multiplicity for events passing the dilepton and $\not{E}_T$ criteria, but before the b-tagging requirement, for (a) the sum of e^+e^- and $\mu^+\mu^-$channels, and (b) the $e^\pm\mu^\mp$ channel.

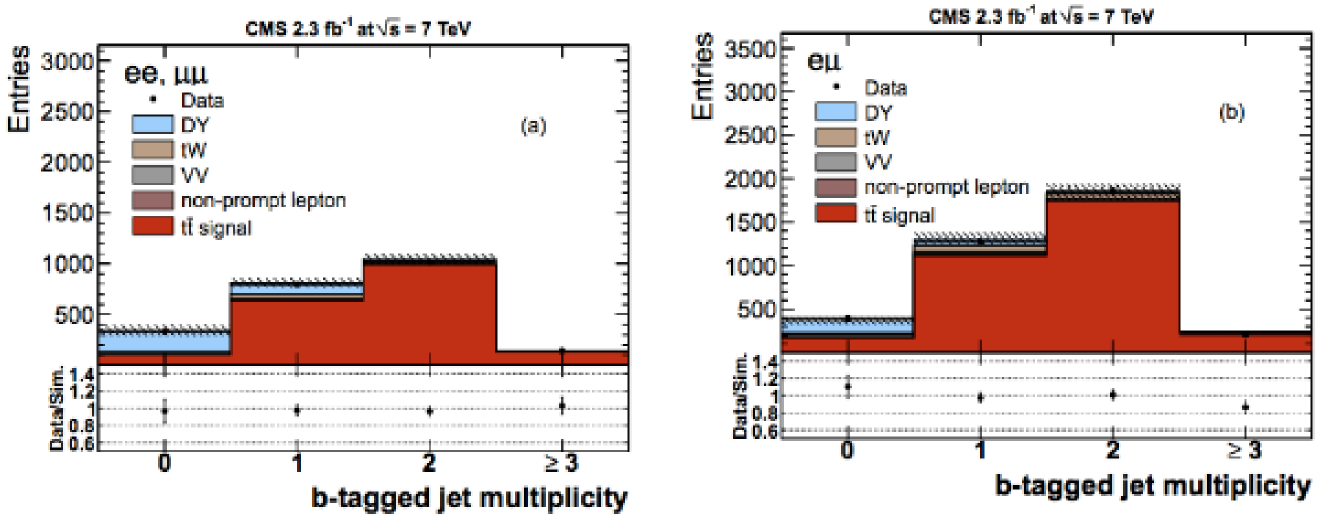
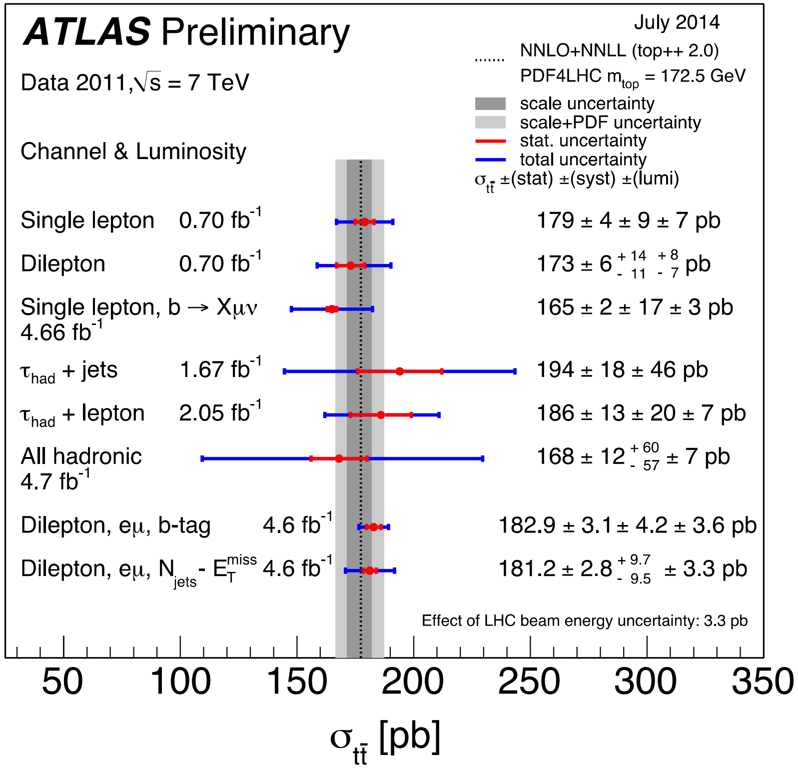
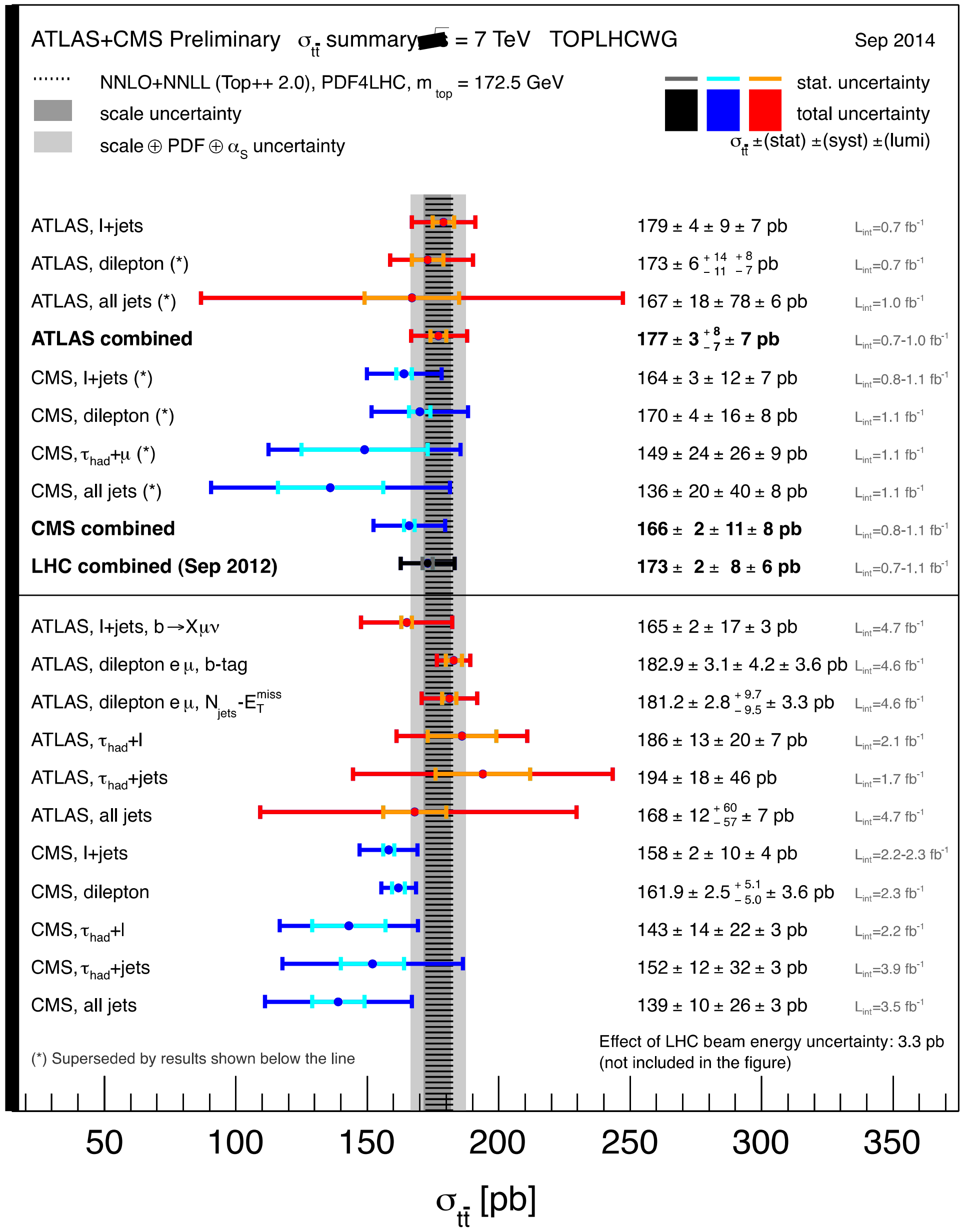


Figure 6. The multiplicity of b-tagged jets in events passing full event selections for (a) the summed e^+e^- and $\mu^+\mu^-$ channels, and (b) the $e^\pm\mu^\mp$ channels.

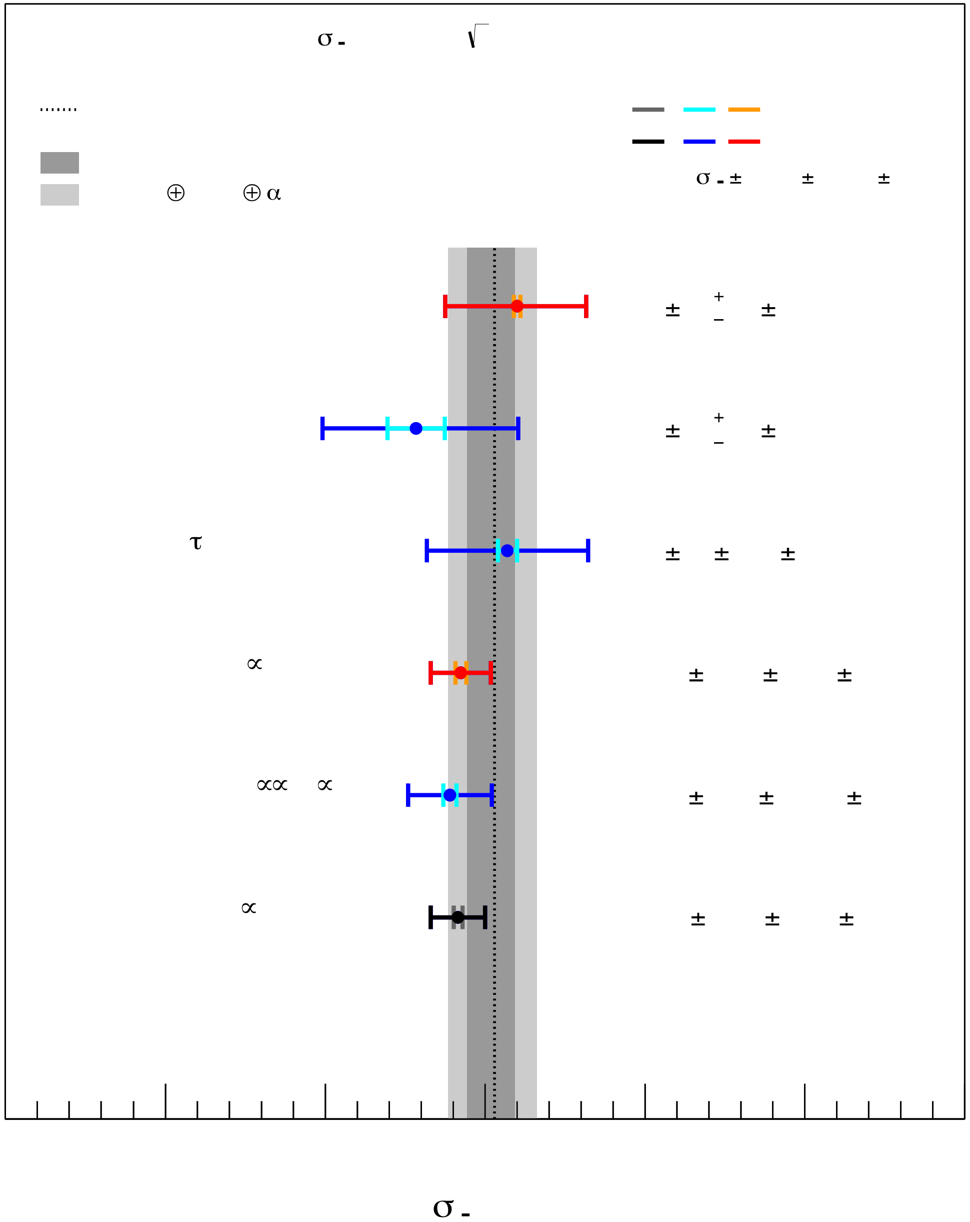
Results on tt cross-section measurements at the LHC at √s = 7 TeV





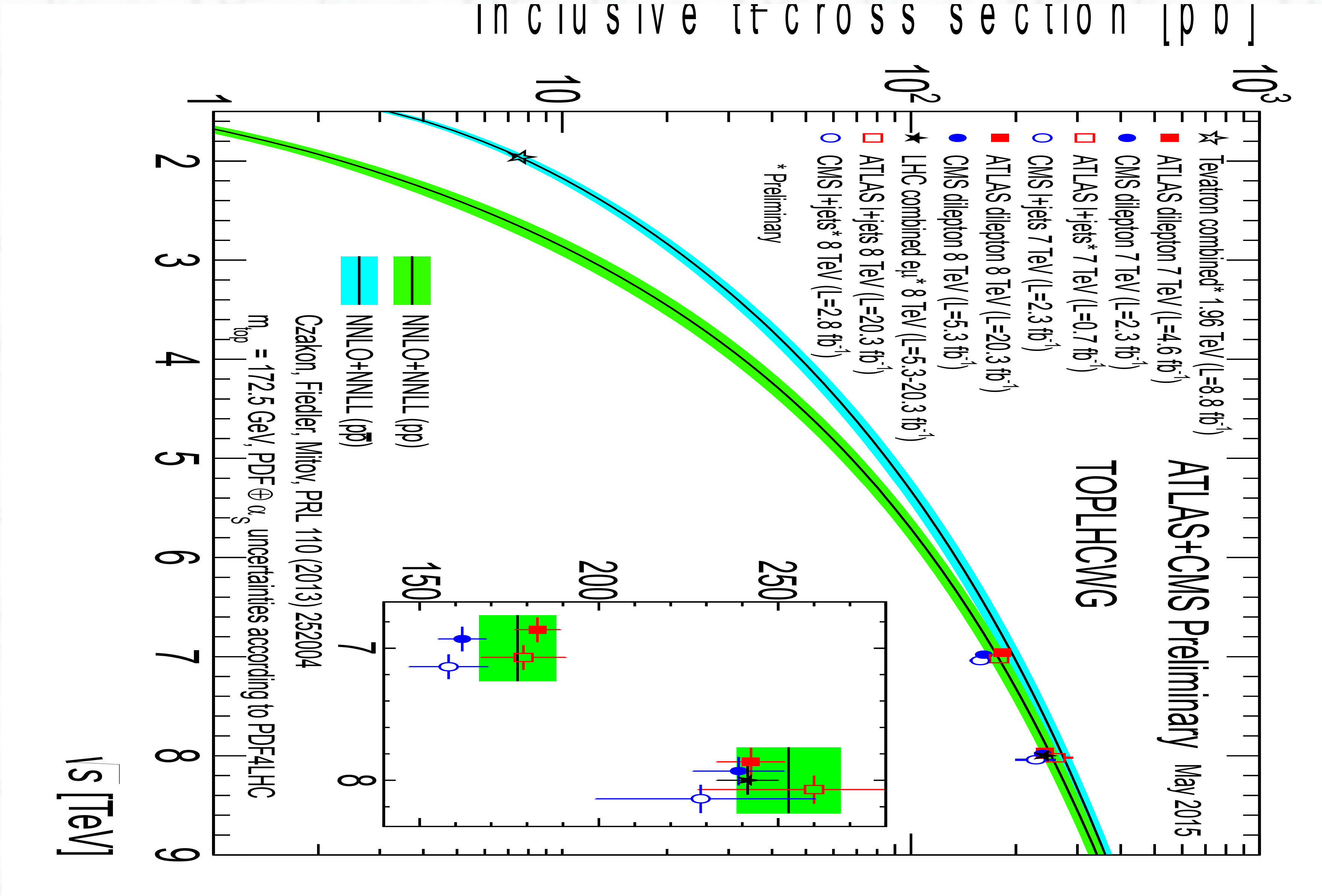
- Good agreement between exp. measurements and theoretical expectations;
- Some tension between the two experiments

Results on tt cross-section measurements at the LHC at $\sqrt{s}$ = 8 TeV

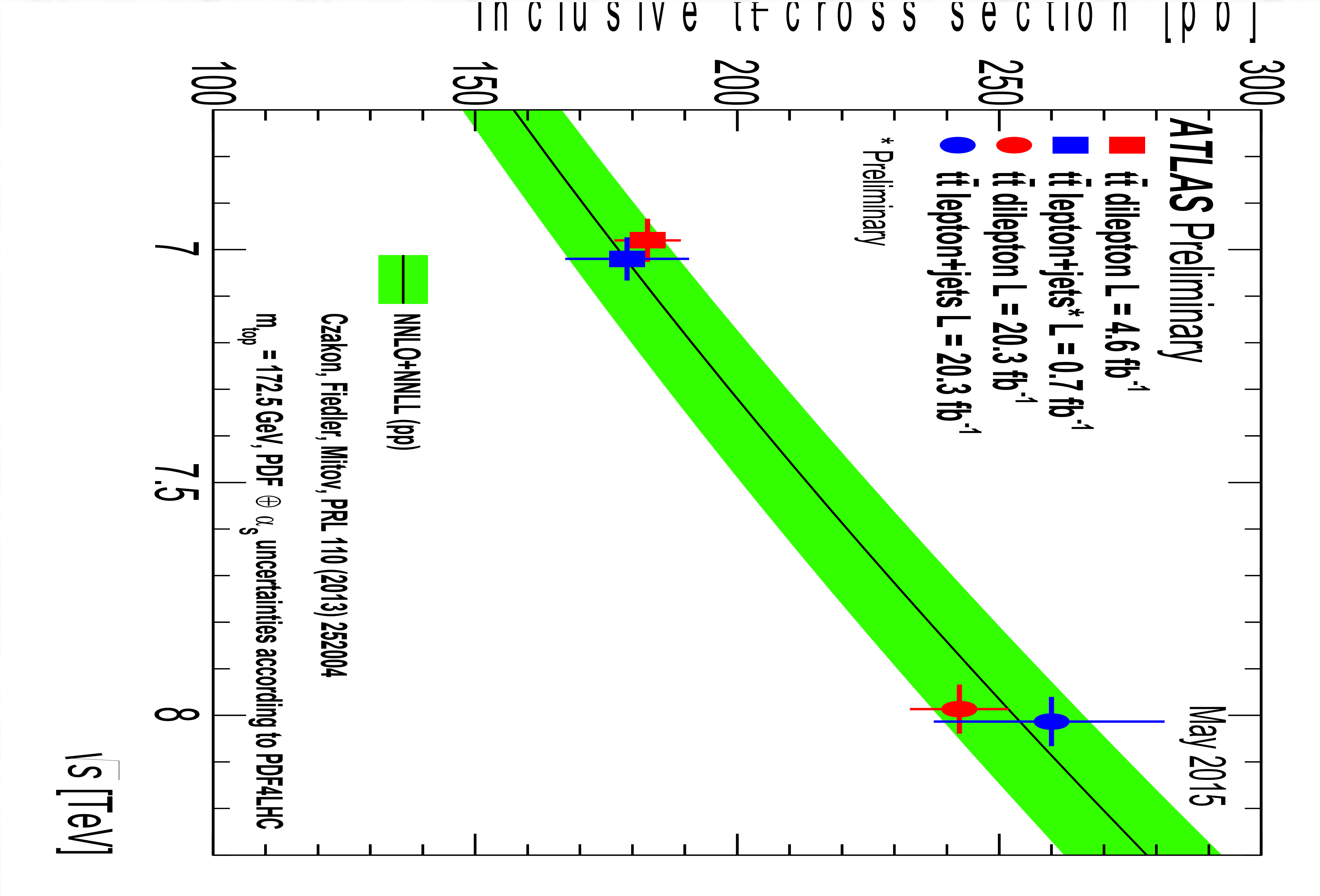


- Very recent results (May 2015)
- Again good agreement between exp. measurements and theoretical expectations
- Total cross-section uncertainty at the level of 3-4%

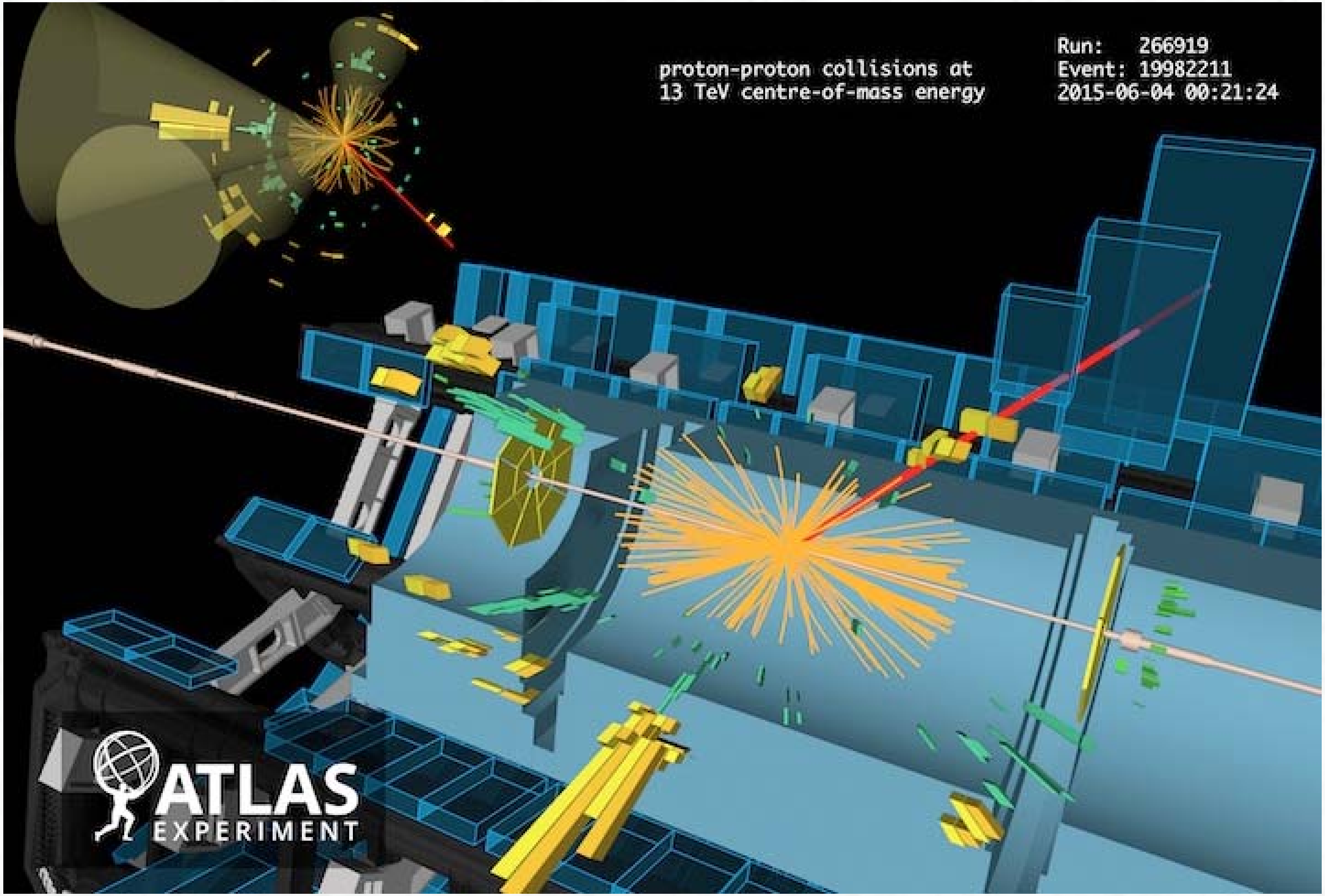
Top cross section measurements as function of √s from the ATLAS and CMS experiments



Top cross section measurements as function of √s
-ATLAS experiment-



A first tt-candidate in the ATLAS experiment at √s = 13 TeV

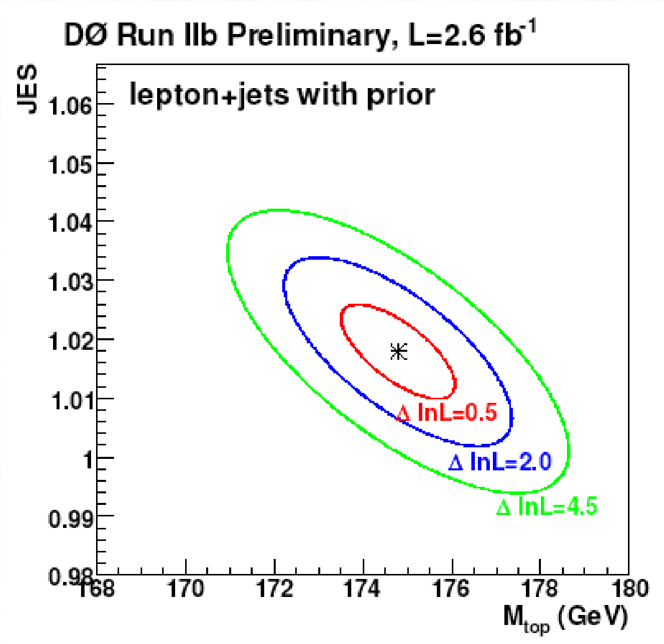


8.4 Top-quark mass measurement

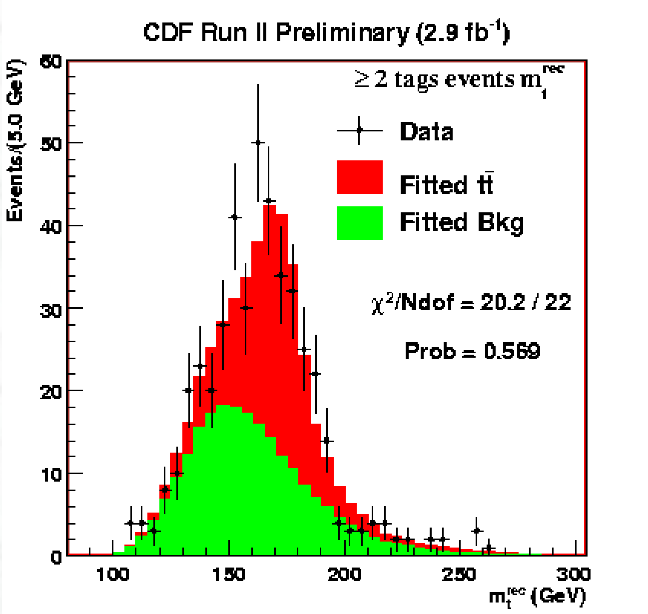
Top mass measurements

- Top mass determination:
  No simple mass reconstruction possible,
  Monte Carlo models needed

  → template methods,…
  matrix element method…



- Reduce jet energy scale systematic by using in-situ hadronic W mass in tt events
  (simultaneous determination of m_t and energy scale)



full hadronic channel

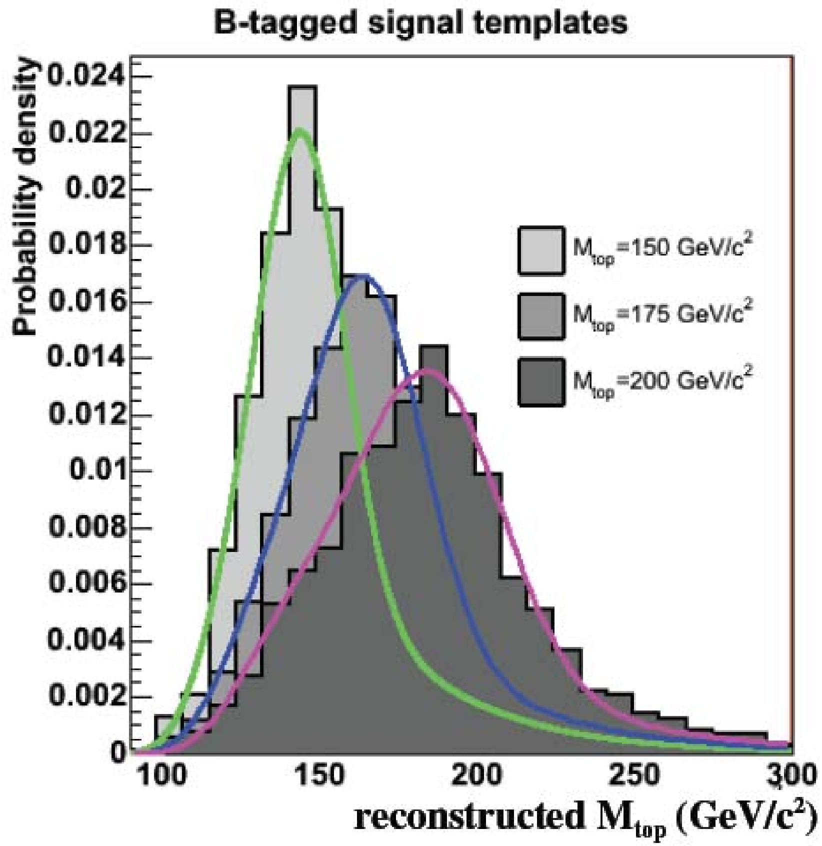
Example: template method

- Calculate a per-event observable that is sensitive to m_t

- Make templates from signal and background events

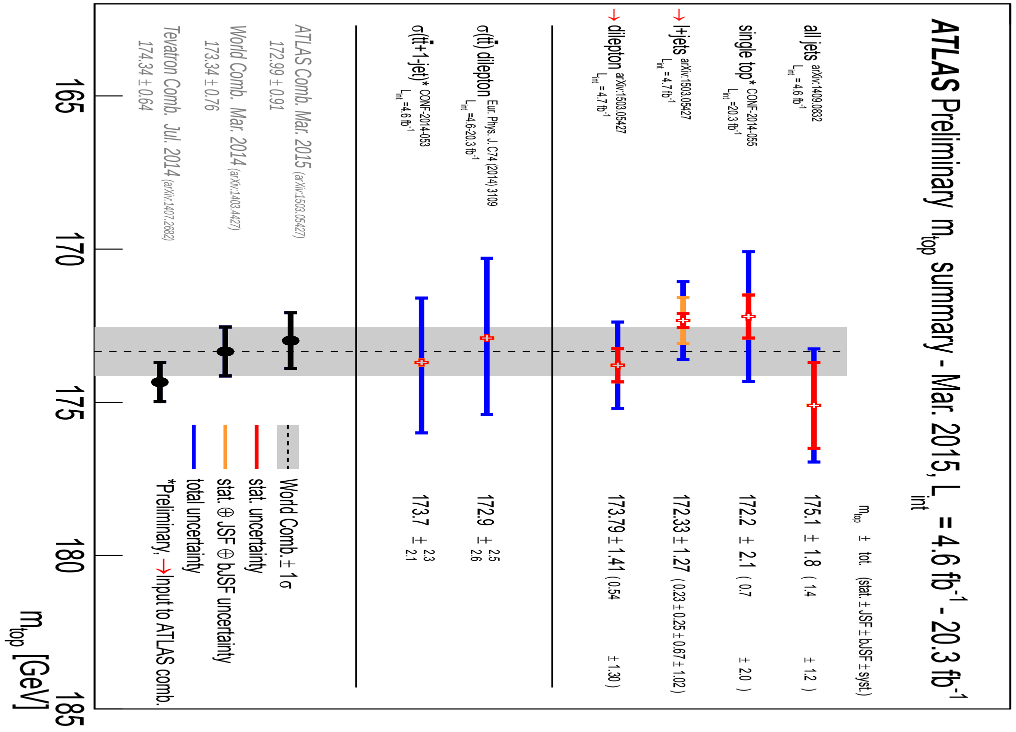
- Use pseudo-experiments (Monte Carlo) to check that method works

- Fit data to templates using maximum likelihood method

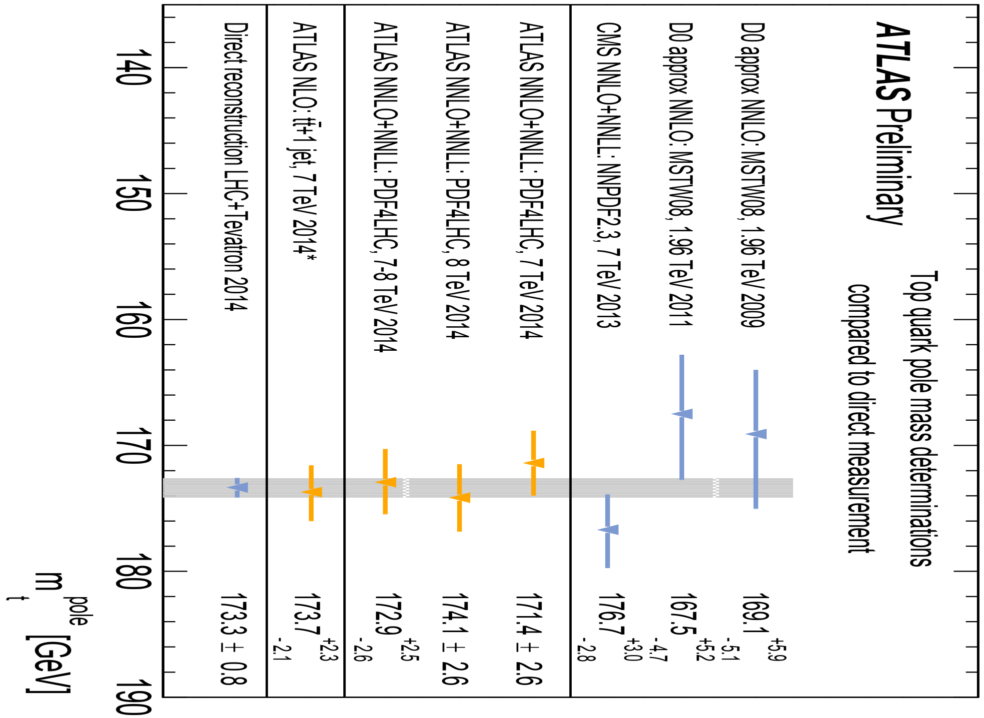


Summary of present results

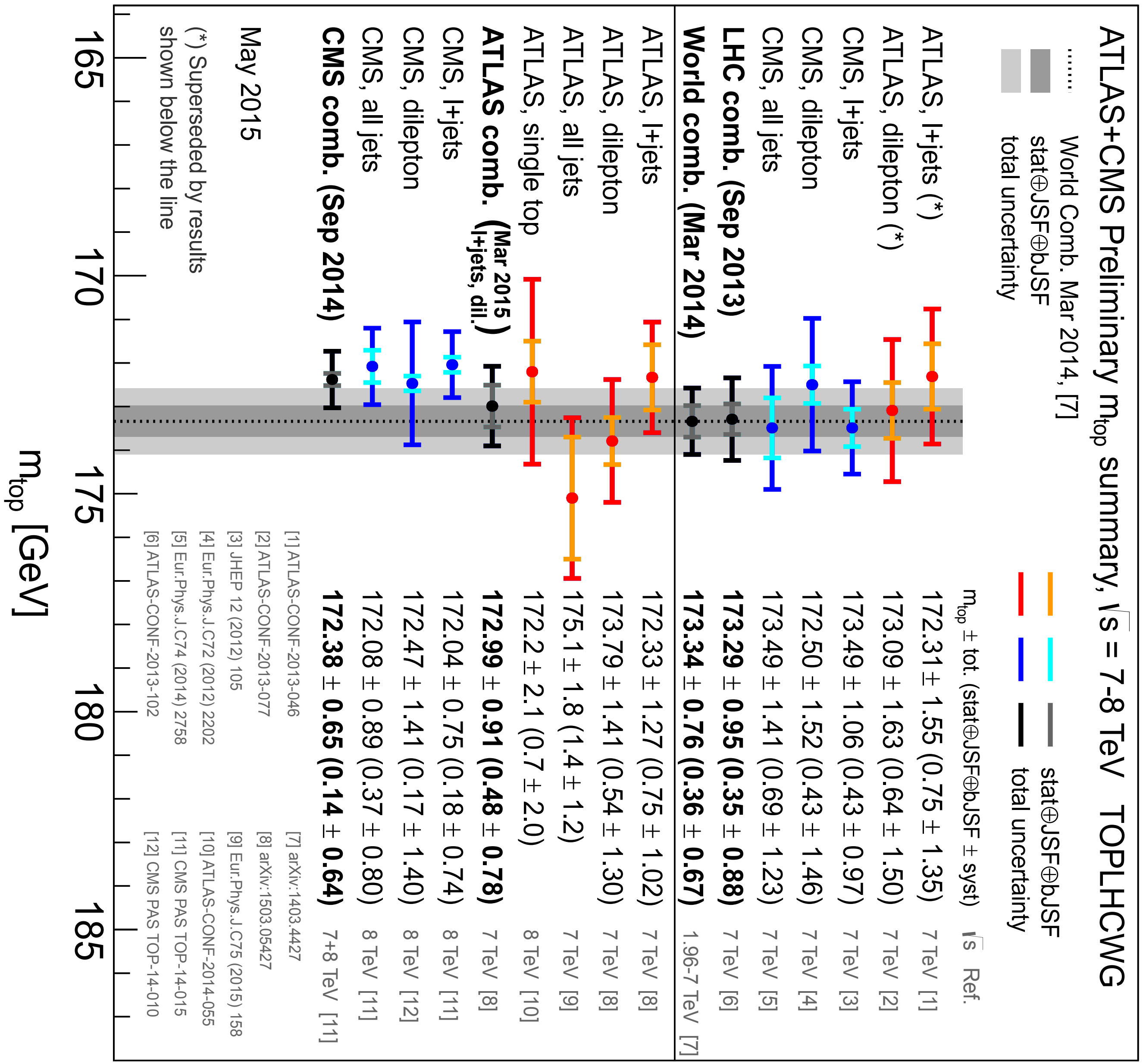
Results of ATLAS top-quark mass measurements (direct and indirect):



Results from indirect method:
m_t from cross-section measurement.
all experiments



Summary of all ATLAS and CMS results



until March 2014
(1st world combination)

updates until March 2015

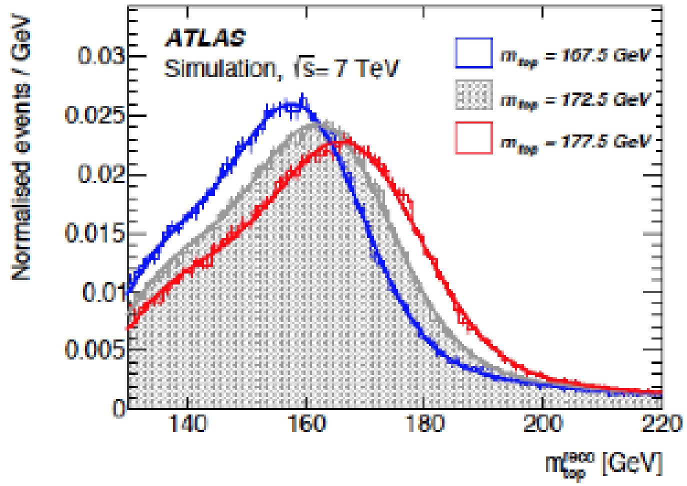
Impressive precision already reached

$\Delta m_t \sim \pm(0.3 - 0.5)\%$

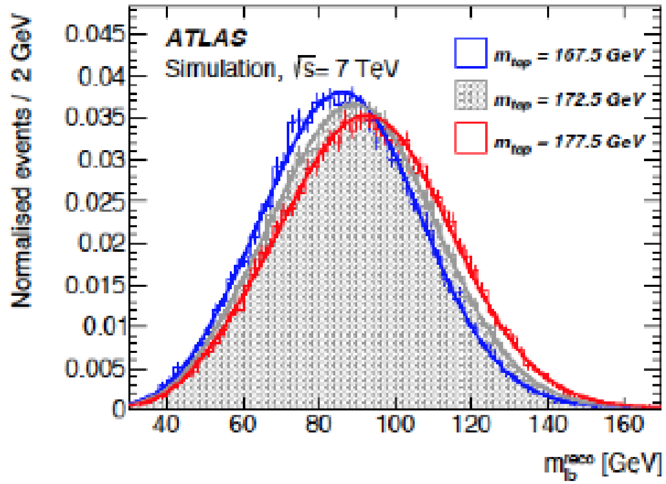
Some distributions from recent ATLAS top-quark mass measurements

l-had events (m_t^{reco})

ll events m_{bl}^{reco}

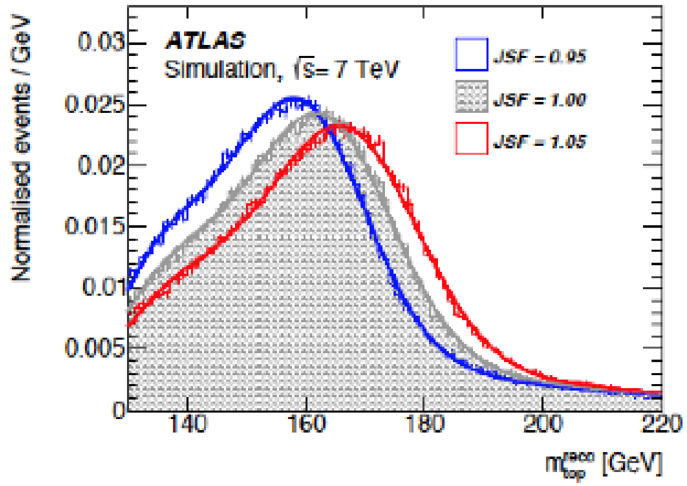


(a) $m_{\rm top}^{\rm reco}$, at least two b-tagged jets

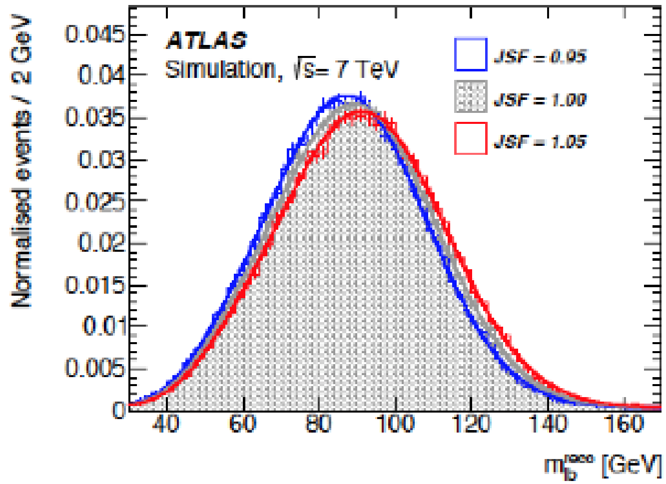


(b) $m_{\ell b}^{\rm reco}$, exactly two b-tagged jets

- sensitivity to top mass



(c) $m_{\rm top}^{\rm reco}$, at least two b-tagged jets

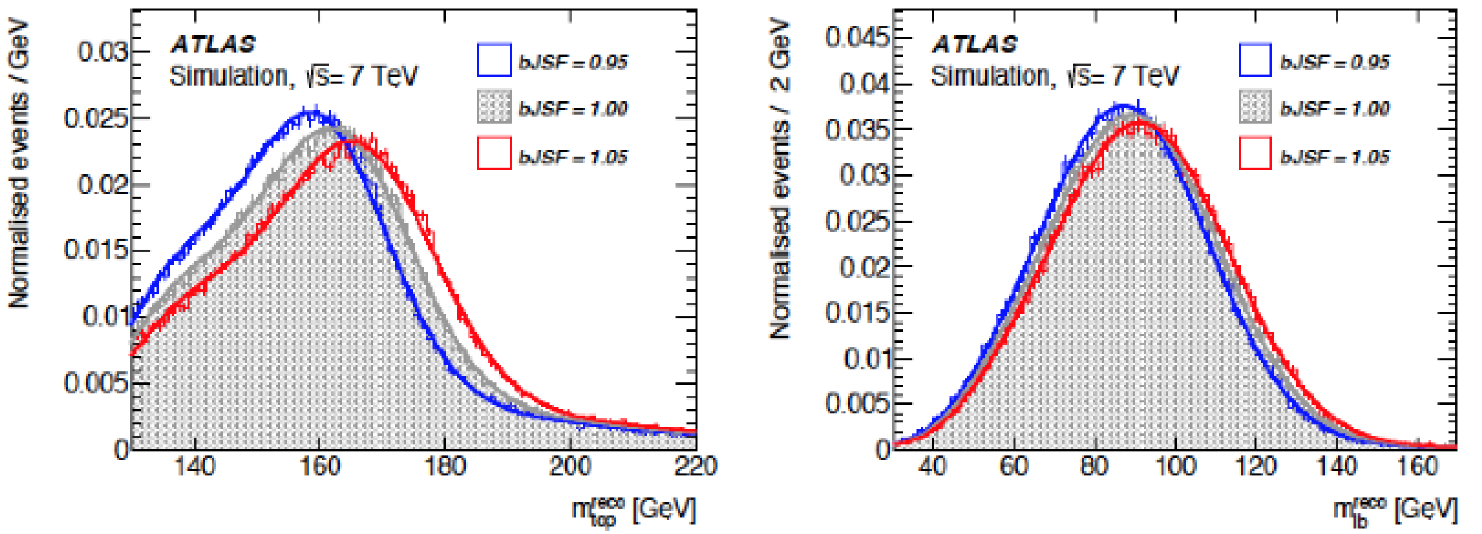


(d) $m_{\ell b}^{\rm reco}$, exactly two b-tagged jets

- sensitivity to the Jet Energy Scale (light jets) for m_t = 172.5 GeV

Some distributions from recent ATLAS top-quark mass measurements

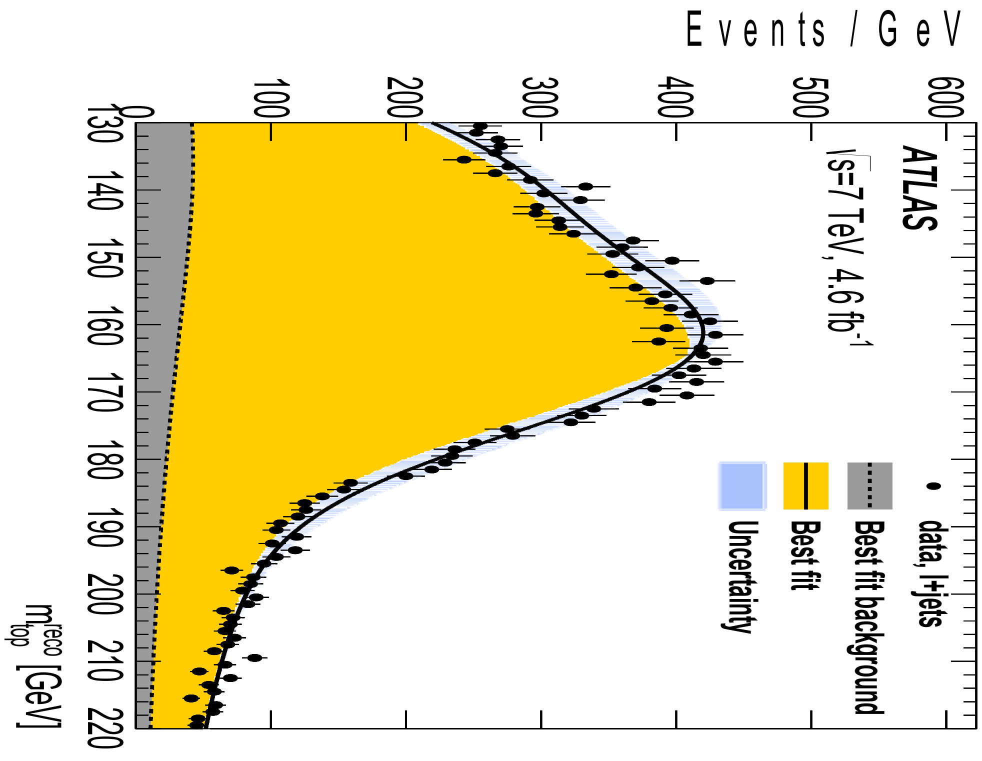
l-had events (m_t^{reco}) ll events m_{bl}^{reco}

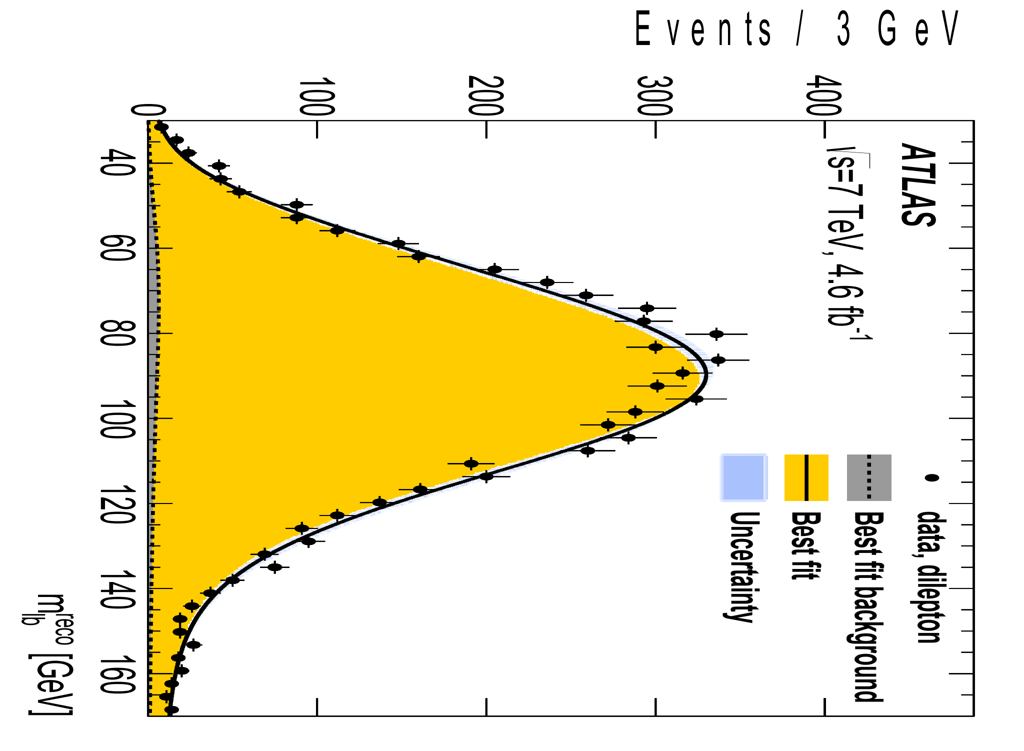


(e) m_{top}^{reco}, at least two b-tagged jets (f) $m_{\ell b}^{reco}$, exactly two b-tagged jets

- sensitivity to the b-Jet Energy Scale for m_t = 172.5 GeV

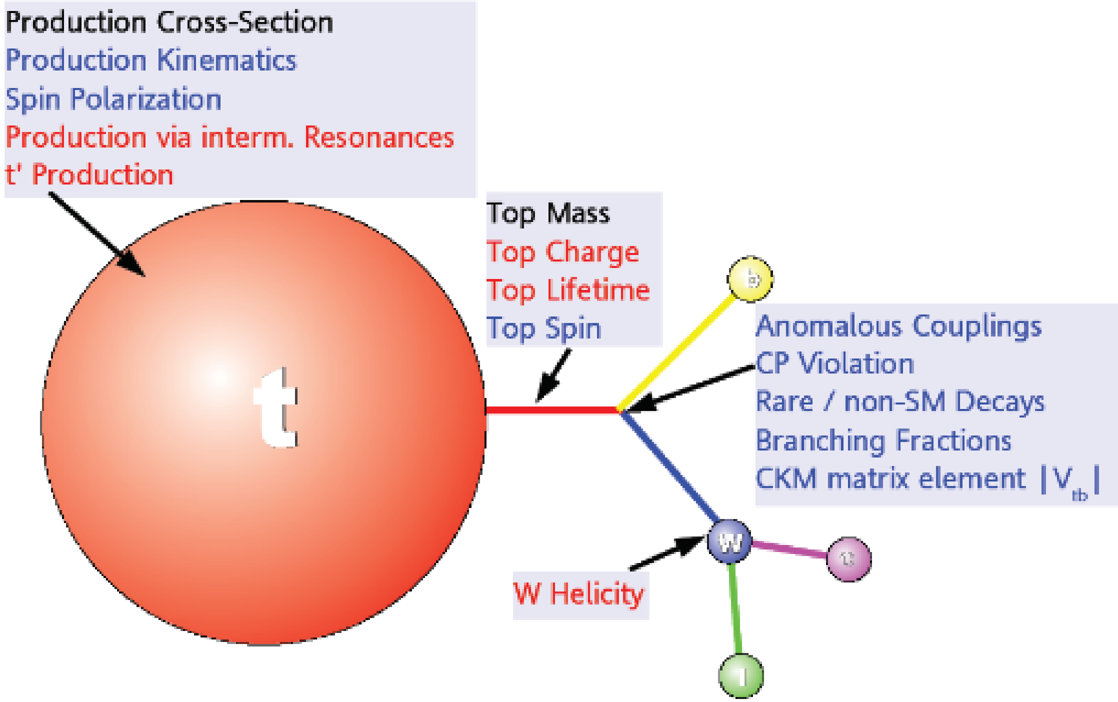
Template fits to data (ATLAS)



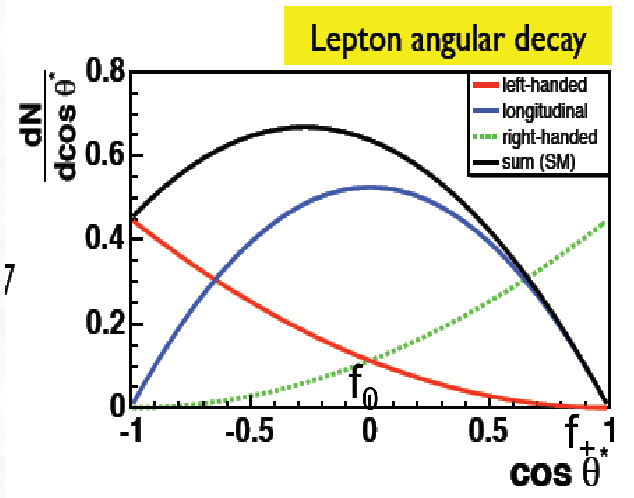


Fit results: arXiv:1503.05427

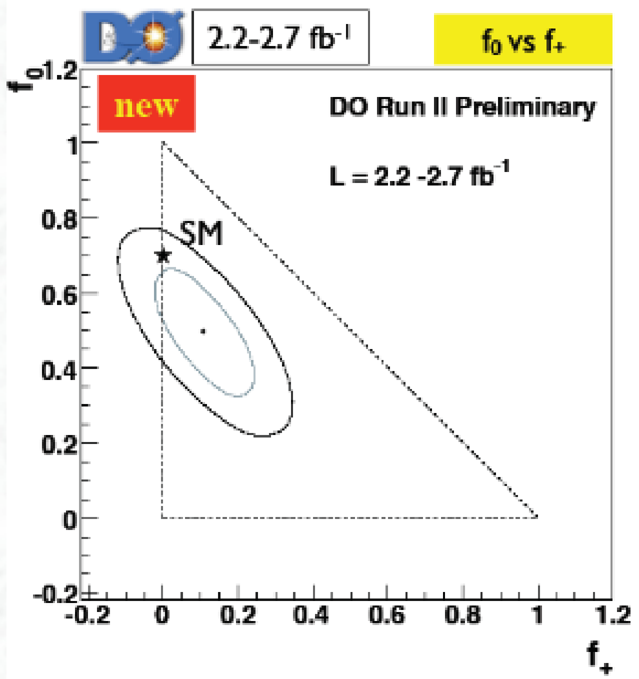
$$
\begin{aligned}
m_{\mathrm{top}}^{\ell+\mathrm{jets}} &= 172.33 \pm 0.75\ (\mathrm{stat} + \mathrm{JSF} + \mathrm{bJSF}) \pm 1.02\ (\mathrm{syst})\ \ \mathrm{GeV},\\
\mathrm{JSF} &= 1.019\ \pm 0.003\ (\mathrm{stat})\ \pm 0.027\ (\mathrm{syst}),\\
\mathrm{bJSF} &= 1.003\ \pm 0.008\ (\mathrm{stat})\ \pm 0.023\ (\mathrm{syst}),\\
m_{\mathrm{top}}^{\mathrm{dil}} &= 173.79 \pm 0.54\ (\mathrm{stat}) \pm 1.30\ (\mathrm{syst})\ \ \mathrm{GeV}.
\end{aligned}
$$



Other top properties from Tevatron



	Tevatron Result	luminosity (fb^{-1})
Mass	173.1 ± 1.1 GeV	~ 5.0
W helicity	CDF: $f_0 = 0.66 \pm 0.16$, $f_+ = -0.03 \pm 0.07$ DØ: $f_0 = 0.49 \pm 0.14$ $f_+ = 0.11 \pm 0.08$	1.9 2.2 – 2.7
Charge Lifetime V_{tb} BR(t→Wb) / BR(W→Wq) BR (t → Zq)	rule out Q = +4/3 (90.% C.L.) Γ_t < 13.1 GeV (95% C.L.) V_{tb} > 0.89 (95% C.L.) R = 0.97 (+0.09) (-0.08) < 3.7% (95% C.L.)	1.5 ~ 1.0 0.9



W-boson polarisation in top decays

- Real W bosons (spin-1 particles) produced in top-quark decays have three possible polarisation states (left-handed, right-handed or longitudinally polarised)

- Parametrised by "helicity fractions" $F_{0/L/R} = \Gamma_{0/L/R} \,/\, (\Gamma_0 + \Gamma_L + \Gamma_R)$

They can be calculated in (V-A) theory

LO results:

$$F_0 = \frac{m_t^2}{m_t^2 + 2M_W^2} \approx 0.70,$$
$$F_L = \frac{2M_W^2}{m_t^2 + 2M_W^2} \approx 0.30,$$
$$F_R = 0.$$

NLO corrections:

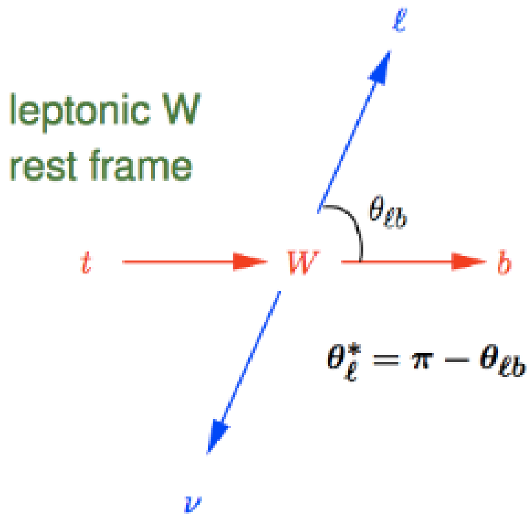
$F_0 = 0.687 \pm 0.005$
$F_L = 0.311 \pm 0.005$
$F_R = 0.0017 \pm 0.0001$

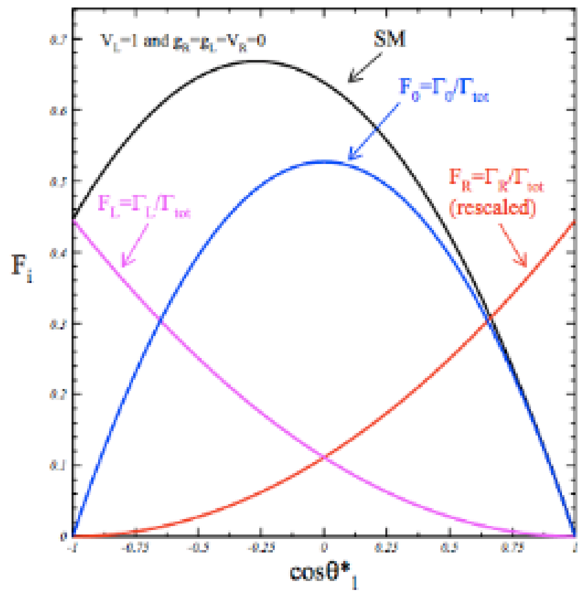
- Measurement of these fractions tests (V-A) structure of the Wtb vertex

W-boson polarisation in top decays

- Information can be extracted from the angular distributions of final-state particles;

- Consider direction of the charged lepton and b-quark in W rest frame



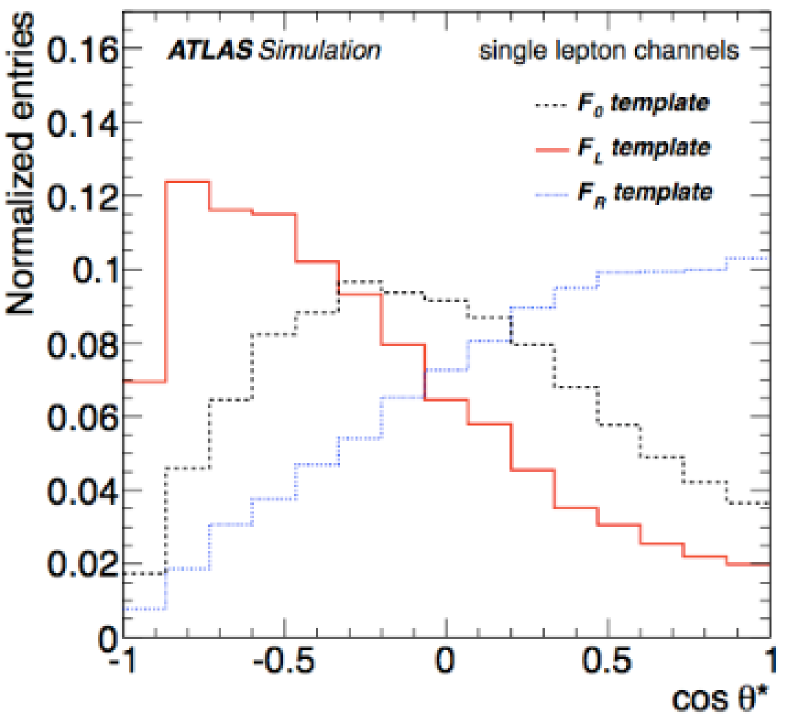


- Expected differential decay width:

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

W-boson polarisation in top decays

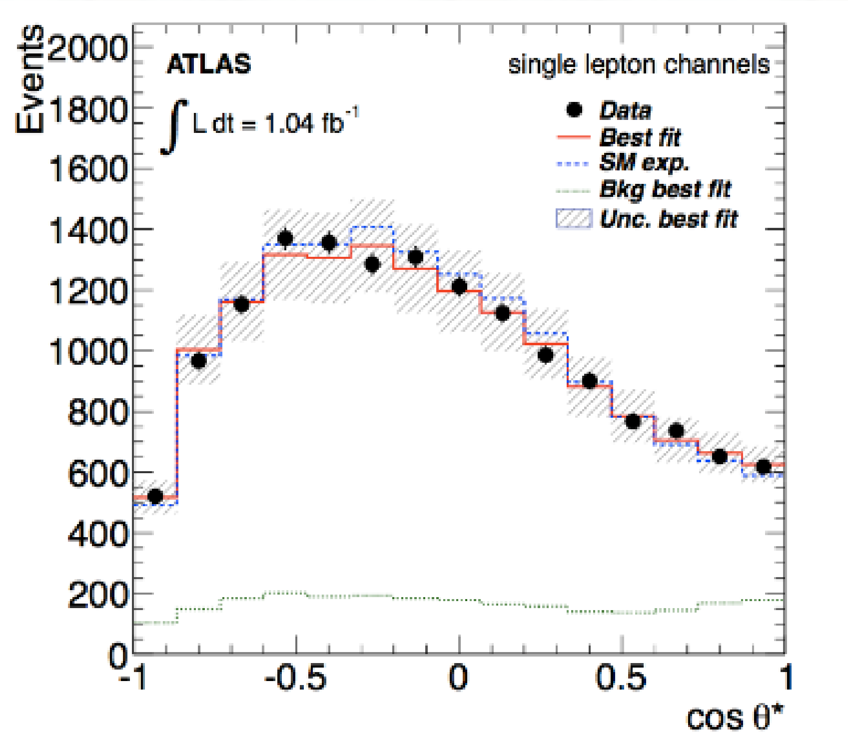
Process	Single electron	Single muon
$t\bar{t}$	4400 ± 1100	6500 ± 1400
W+jets	900 ± 700	1400 ± 1000
Z+jets	120 ± 90	140 ± 90
Diboson	14 ± 12	22 ± 12
Single top	260 ± 90	360 ± 110
Misidentified leptons	220 ± 220	500 ± 500
Total predicted	5900 ± 1300	9000 ± 1800
Data	5830	9121

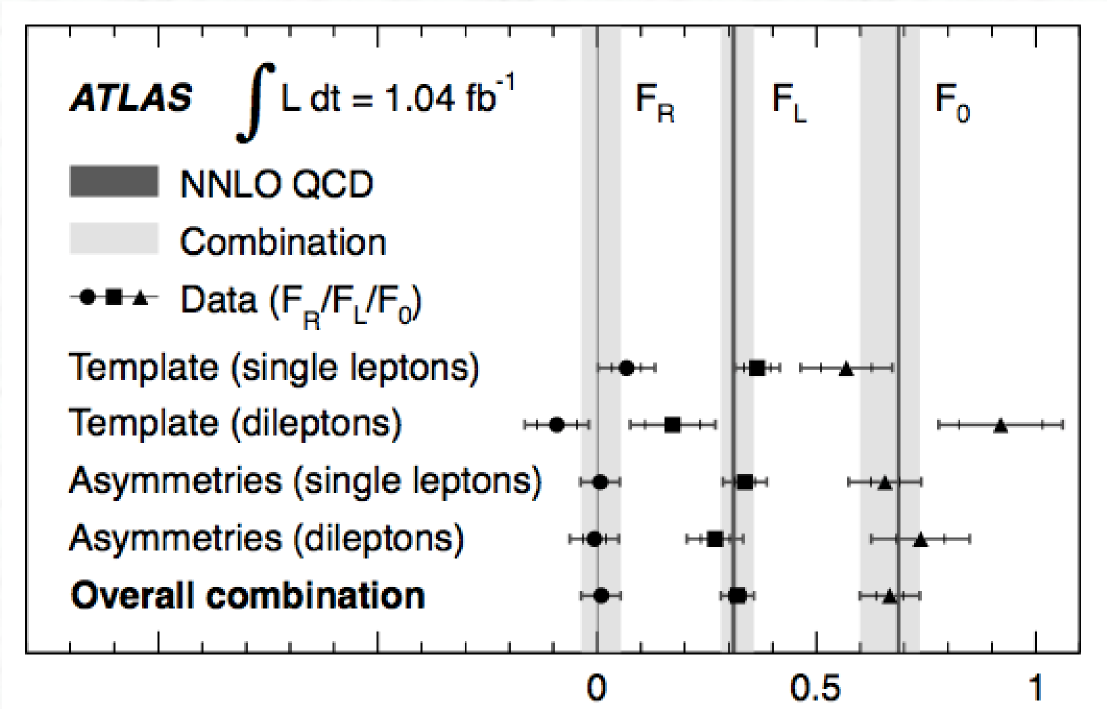


Combined fit to the final distribution with three pure helicity states templates plus three background components (W, non-prompt leptons, everything else)

W polarization in top decays

$$F_0 = 0.67 \pm 0.03\ (\text{stat.}) \pm 0.06\ (\text{syst.})\,,$$
$$F_\text{L} = 0.32 \pm 0.02\ (\text{stat.}) \pm 0.03\ (\text{syst.})\,,$$
$$F_\text{R} = 0.01 \pm 0.01\ (\text{stat.}) \pm 0.04\ (\text{syst.})\,.$$





Spin correlations

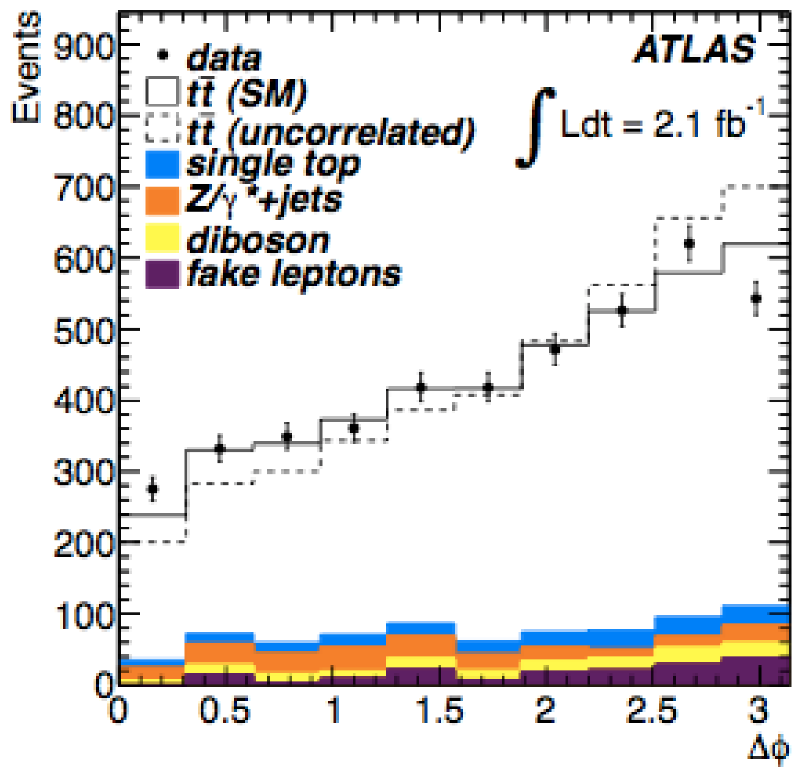
- Correlations between the top-quark and antitop-quark spins in tt production are tests of perturbative QCD and sensitive to anomalous production mechanisms

- Measurements are only possible because of the extremely short lifetime of top-quarks of $\tau_t \sim 1.5\ 10^{-25}$ s
  (Lifetime is roughly one order of magnitude smaller than time scale of hadronisation $\tau_{had} \sim 1 / \Lambda_{QCD} \sim 3\ 10^{-24}$ s

- Differences expected between gg and qq production (LHC versus Tevatron)
  gg: spins of top and antitop tend to be antiparallel
  qq: spins tend to be parallel (triplett state)

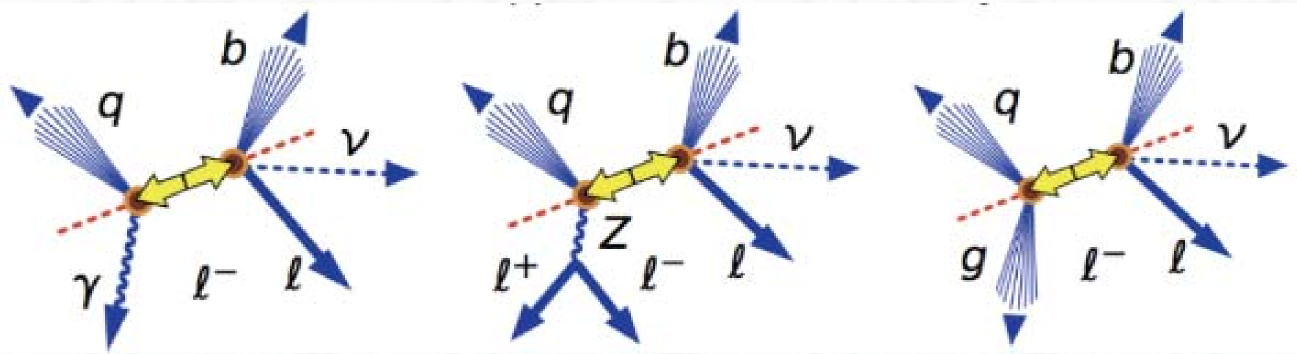
- Observed angular distributions at the LHC are consistent with presence of spin correlations as expected in the Standard Model
  $\Delta\phi$ = azimuthal difference between leptons in di-lepton events

- ATLAS analysis (2.1 fb^{-1}):
  Absence of correlations excluded at 5.1σ



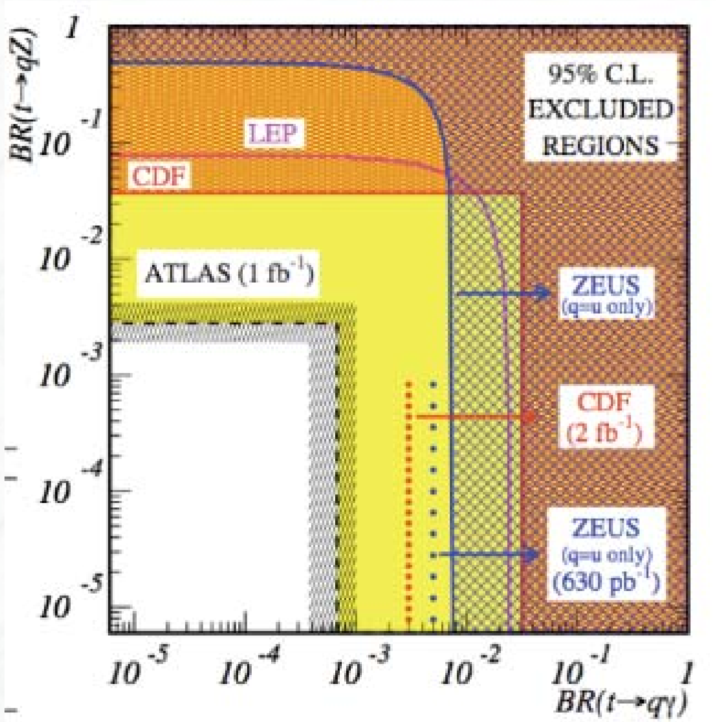
LHC sensitivity for Rare Top Quark Decays

FCNC decays into $q\gamma$, qZ and qg



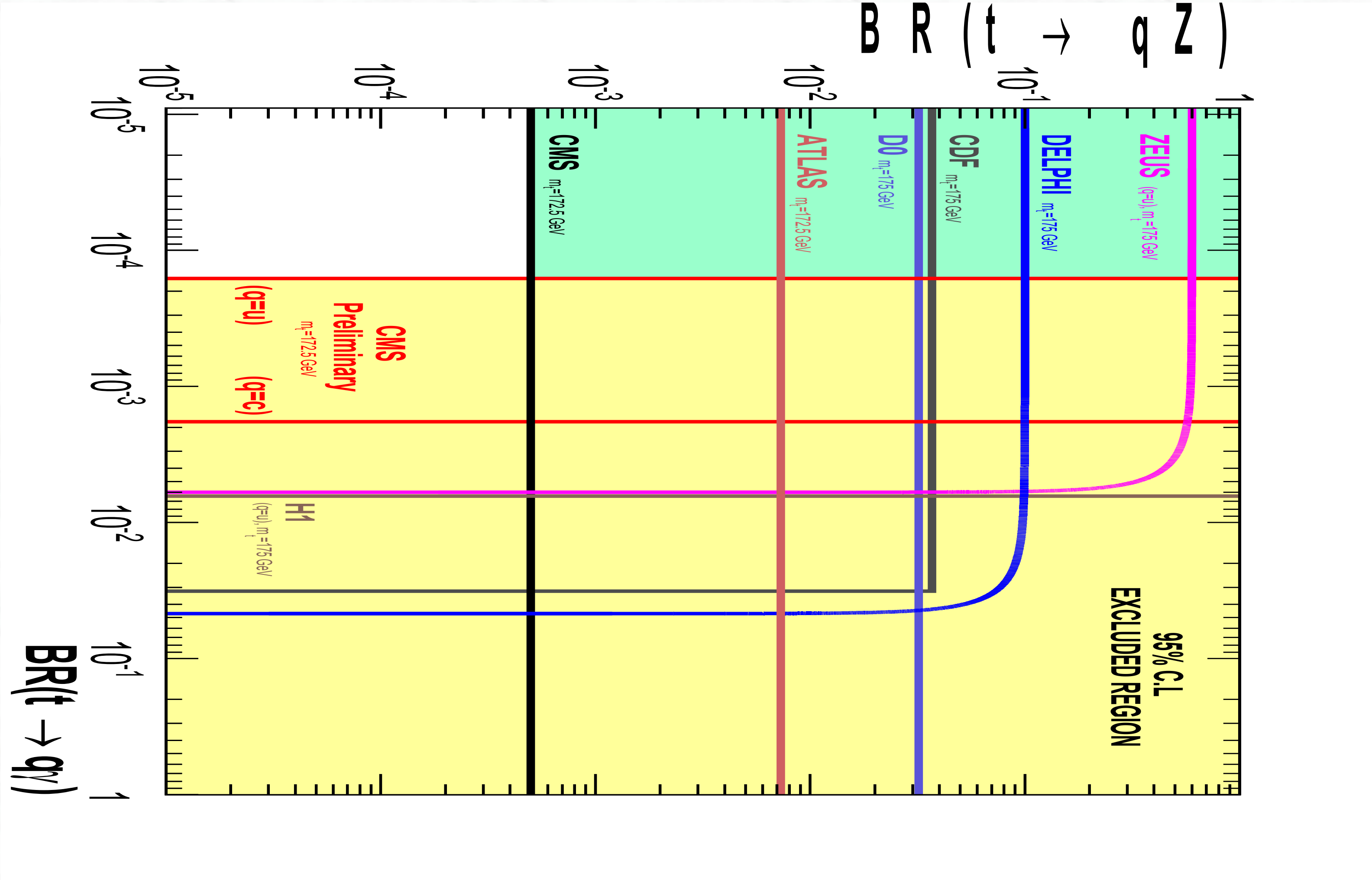
BR in Standard Model:
~ 10^{-12} for $q\gamma$ and qZ
~ 10^{-10} for qg

Process	Expected 95% C.L. sensitivity (1 fb^{-1})
$t \rightarrow q\,\gamma$	$6.8 \cdot 10^{-4}$
$t \rightarrow q\,Z$	$2.8 \cdot 10^{-3}$
$t \rightarrow q\,g$	$1.2 \cdot 10^{-2}$

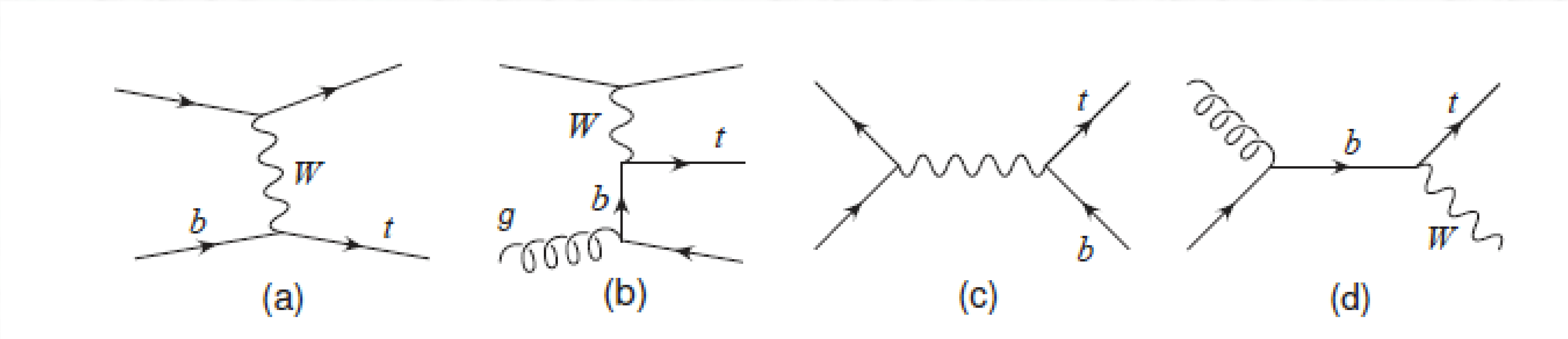


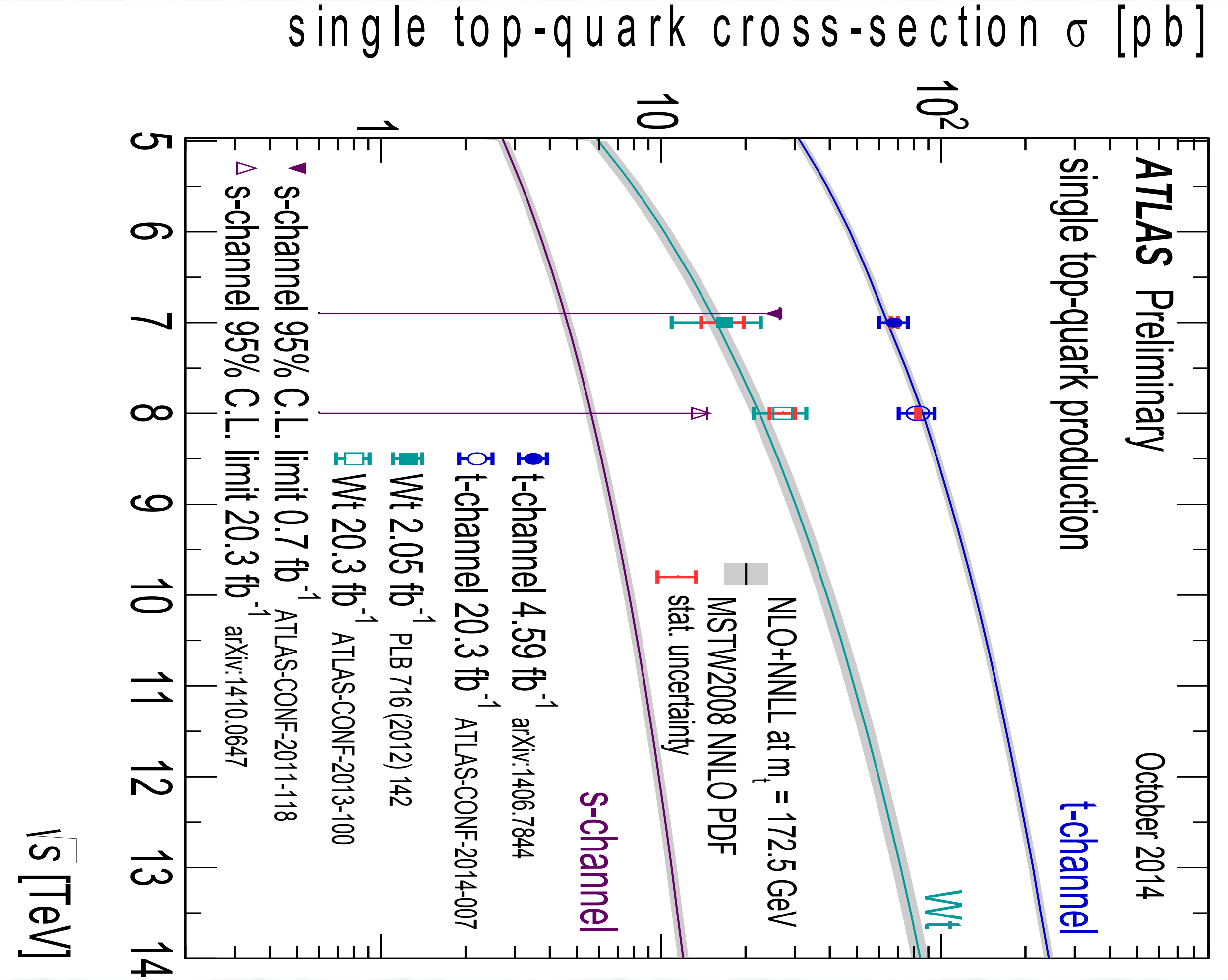
Expected 5σ discovery sensitivity for 100 fb^{-1}:
for qg and qZ final states: ~ 10^{-4}

Updated results, CMS Collaboration



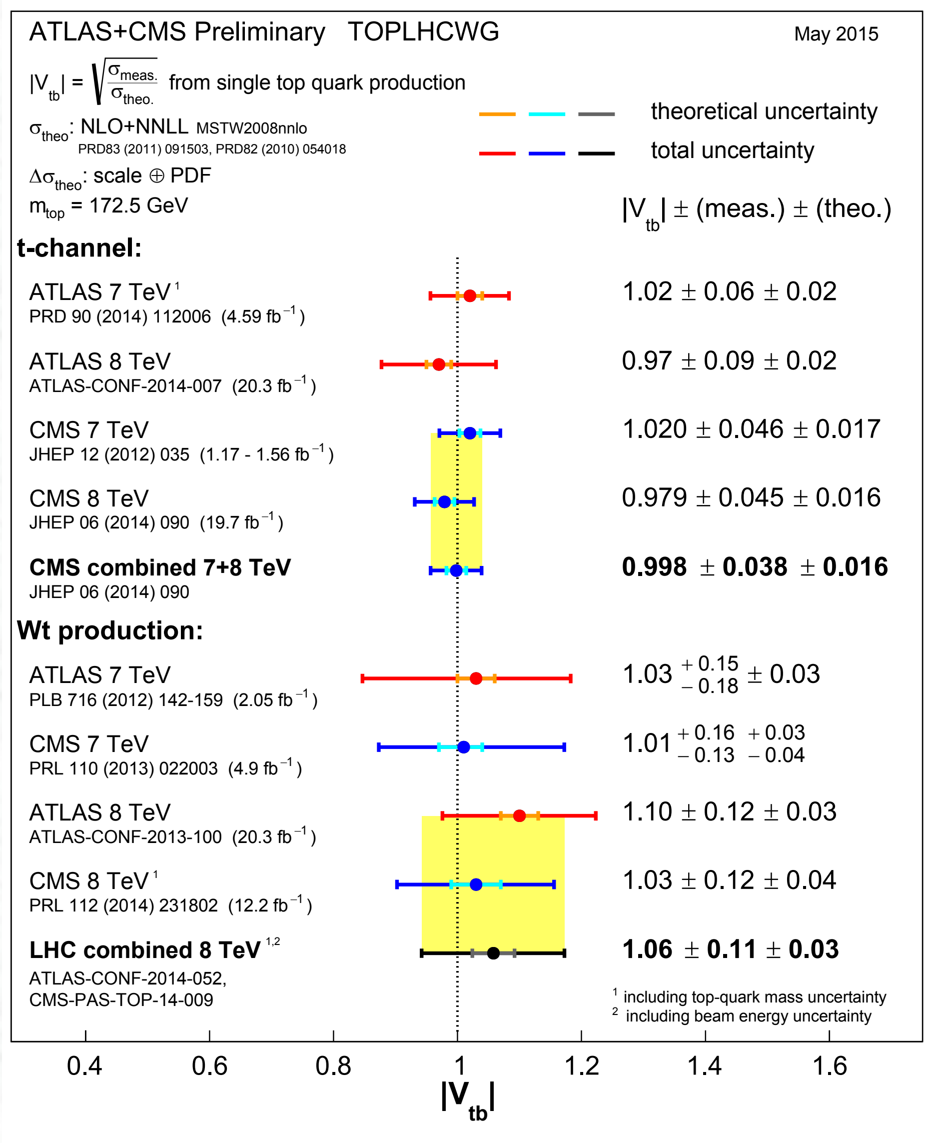
Single Top-Quark production





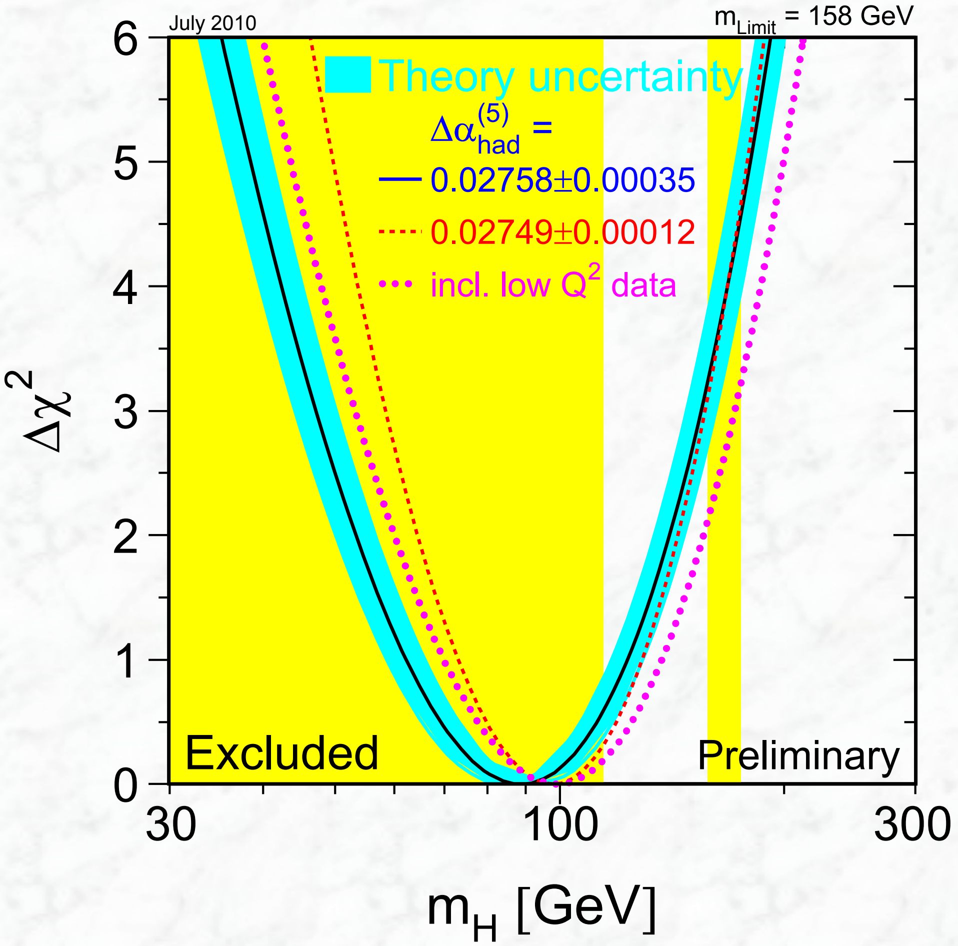
Single Top-Quark production

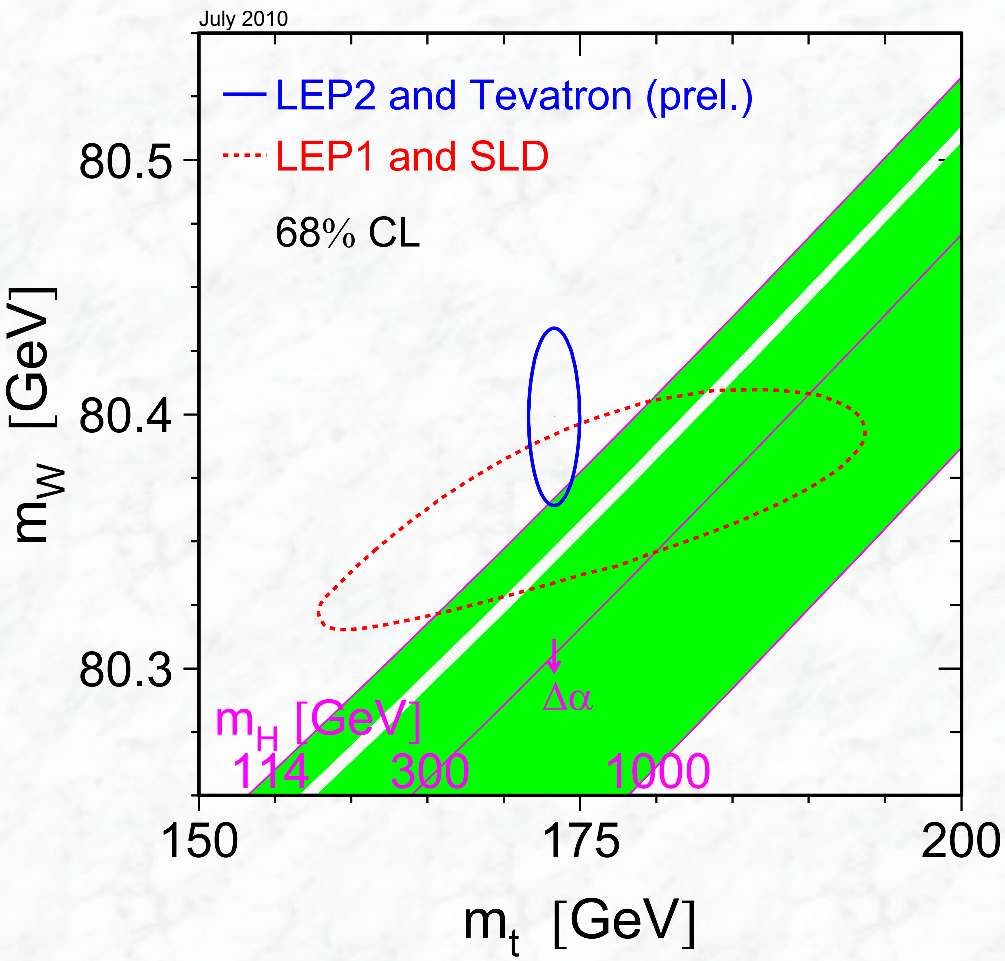
- Single top-quark production provides direct access to CKM matrix element V_{tb}



8.5 Constraints on the Standard Model

Pre – Higgs discovery: the Higgs boson mass enters logarithmically in loop corrections to the W mass



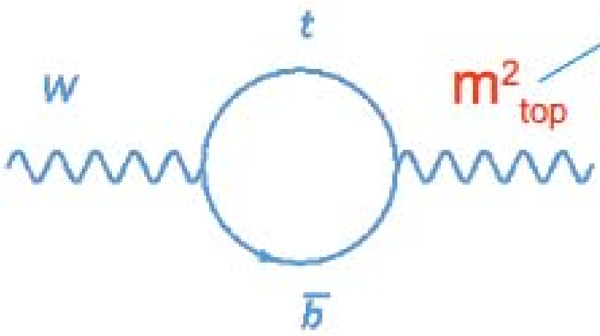


Die Masse des W-Bosons

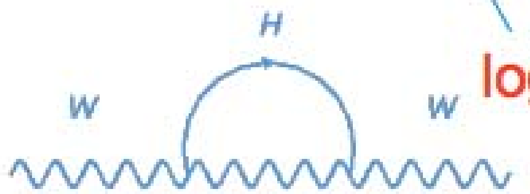
- Wichtiger Konsistenzest, auch wenn SM Higgs-Boson gefunden ist

$$m_W = \left(\frac{\pi\, \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

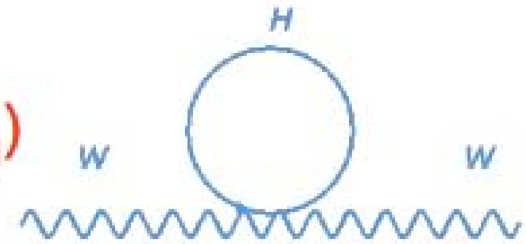
Strahlungskorrekturen
$\Delta r \sim 3$ %



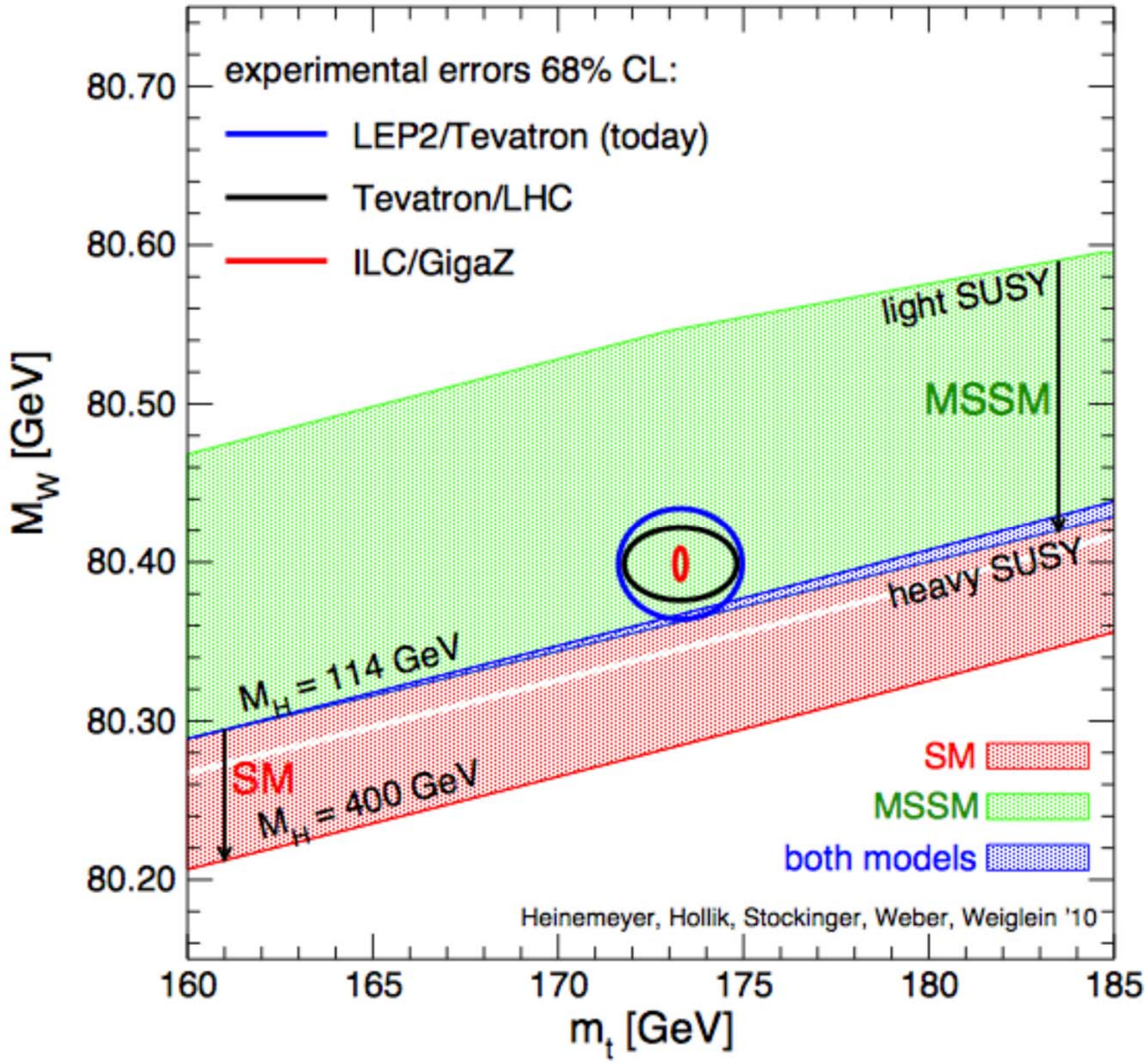
m^2_{top}



$\log(M_H)$

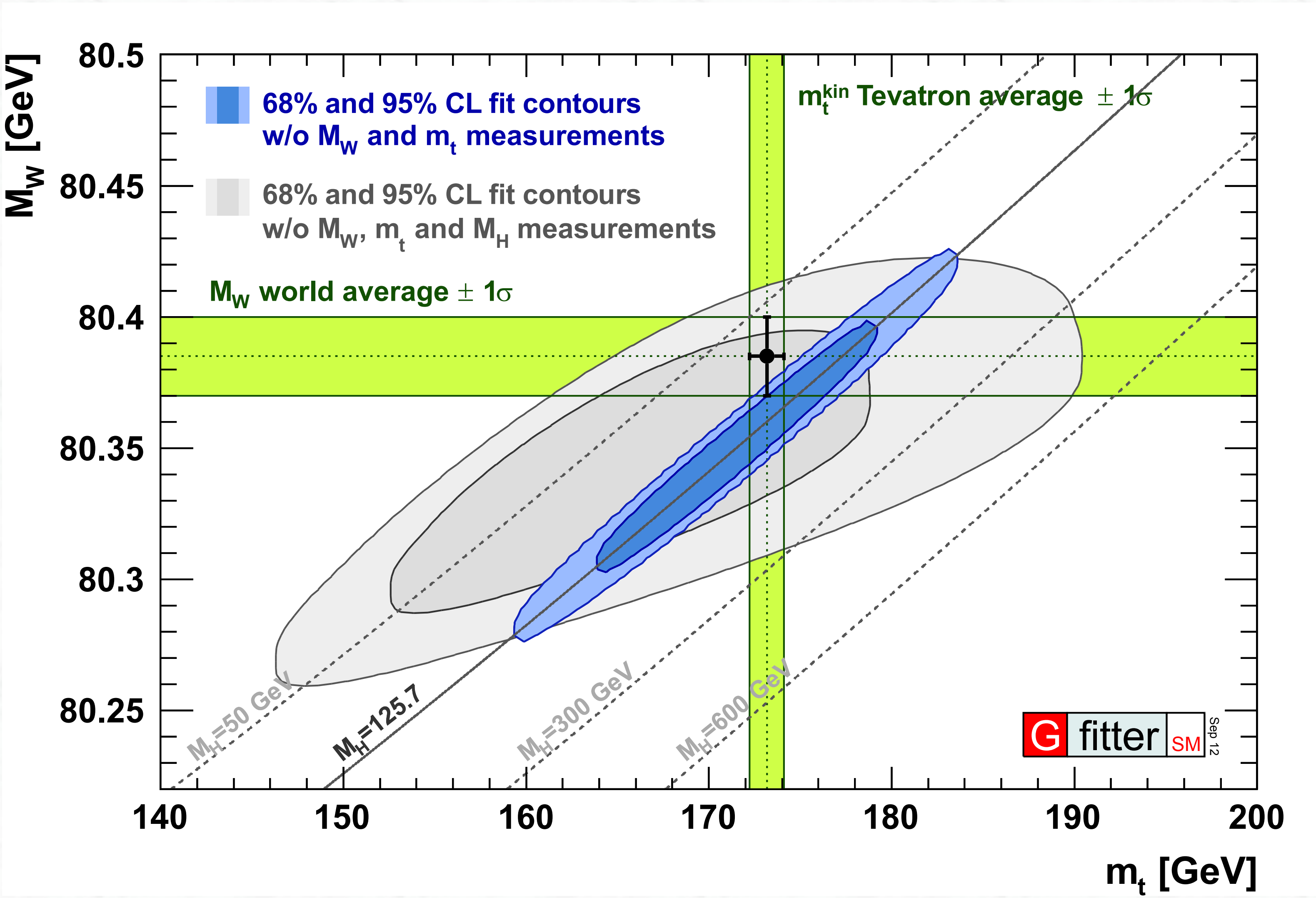


- G_F, α_{EM} und $\sin\theta_W$ sind mit großer Präzision gemessen – nicht limitierend



Predictions for future precision (including LHC), compared to the Standard Model and its Minimal Supersymmetric Extension (MSSM)

Ultimate test of the Standard Model: compare direct prediction of Higgs mass with direct observation



68% and 95% CL fit contours w/o M_W and m_t measurements
68% and 95% CL fit contours w/o M_W, m_t and M_H measurements
M_W world average $\pm 1\sigma$
m_t^{kin} Tevatron average $\pm 1\sigma$
M_H=50 GeV
M_H=125.7
M_H=300 GeV
M_H=600 GeV
G fitter SM
Sep 12
M_W [GeV]
m_t [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190
200