7. Physics of the Top Quark

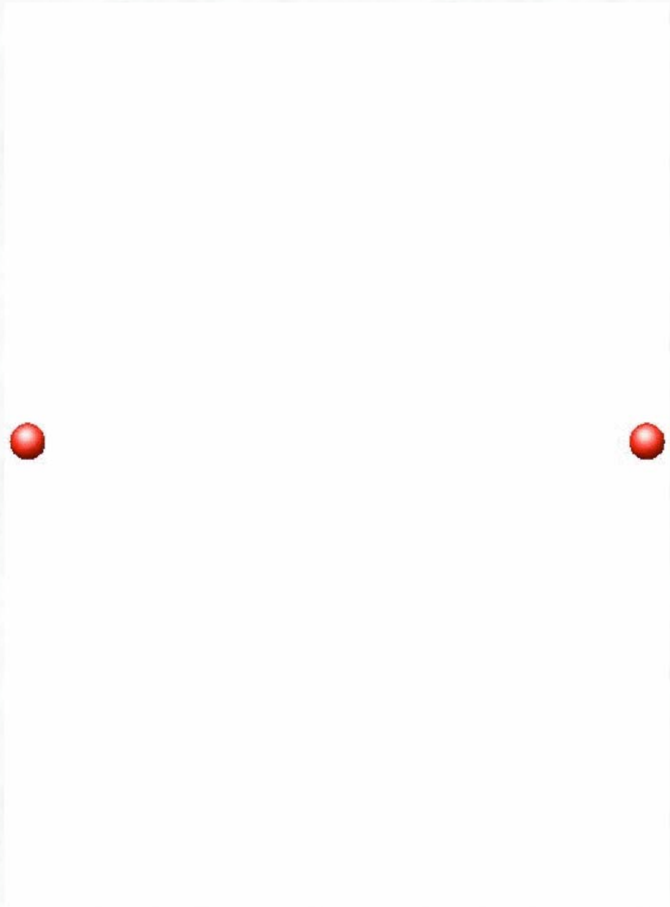
7.1 Introduction (The top quark in the Standard Model)

7.2 Top quark production at the Tevatron

7.3 First results on top quark production
from the LHC

7.4 Top-quark mass measurements
(Tevatron and LHC)

7.5 Constraints on the Standard Model



7.1 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

What do we know about the top quark?

- The top quark is the heaviest know fermion

  m_t ~173 GeV (from experiment)

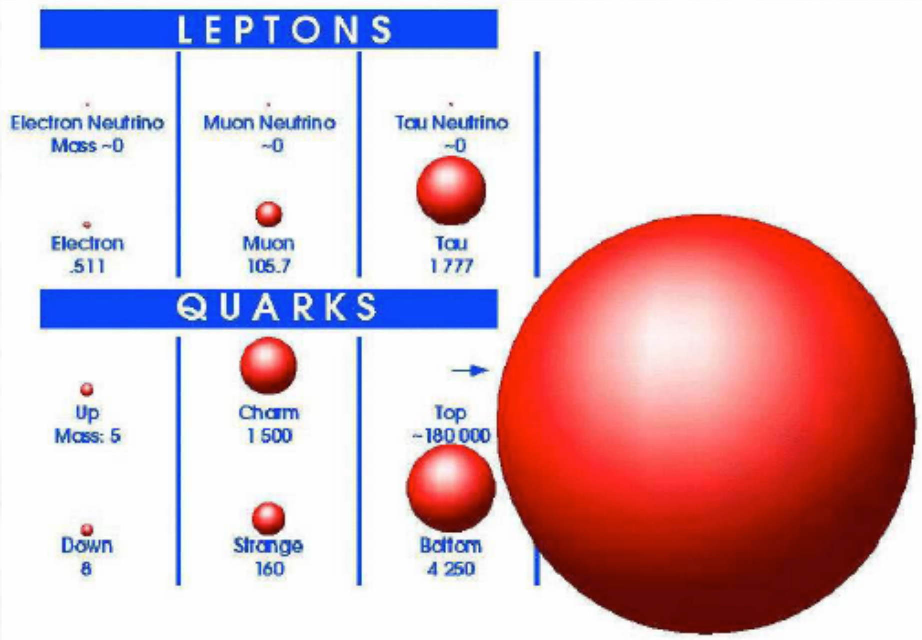
- Lifetime $\tau \sim 5\ 10^{-25}$ s
  (theory, Standard Model decays)

  no hadronisation, behaves like a quasi-free quark !

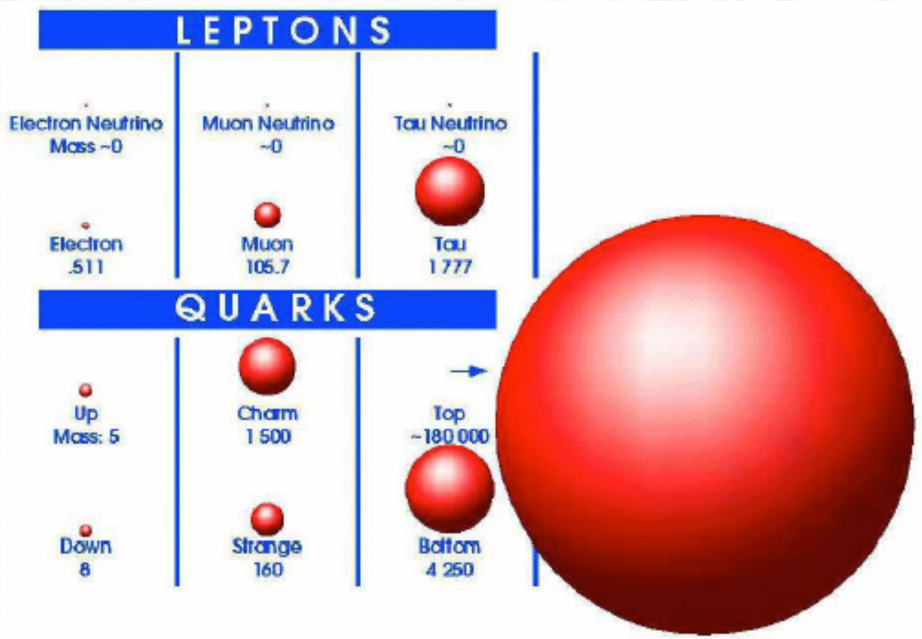
- Predominant decays:
  t $\rightarrow$ Wb (BR ~100%)

  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 ??

$$M_t = \frac{1}{\sqrt{2}} \lambda_t v$$

$$\Rightarrow \lambda_t = \frac{M_t}{173.9\ \mathrm{GeV}/c^2}$$

- 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

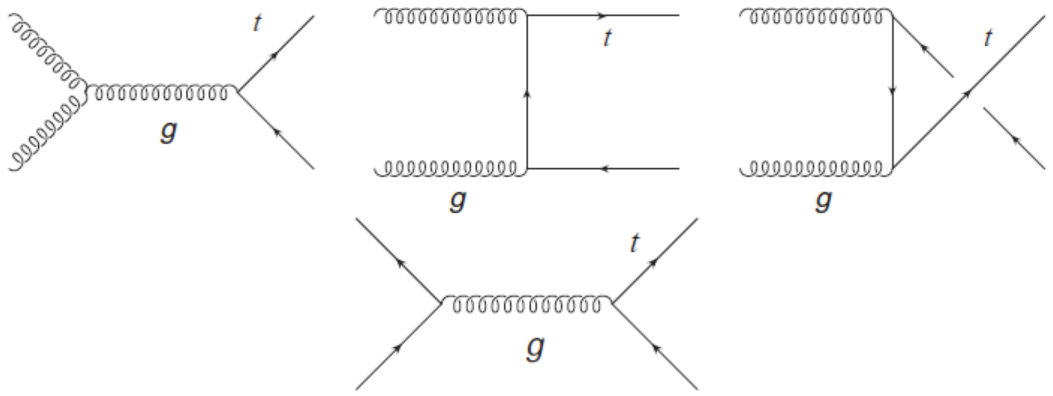


Figure 9.3 Top-quark pair production in the Born approximation.

- NLO corrections completely known
- NNLO partly known

approximate NNLO 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)

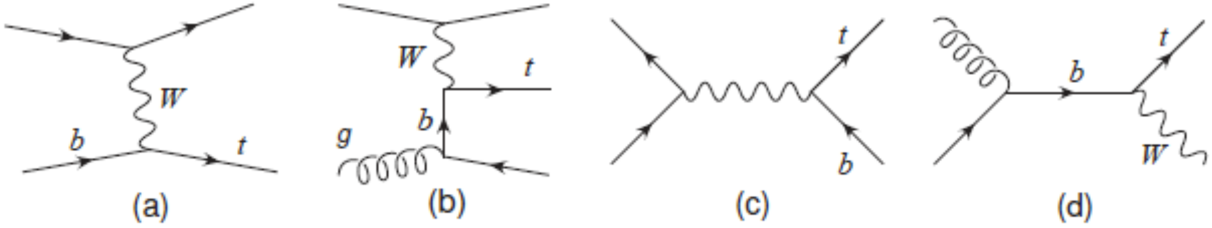
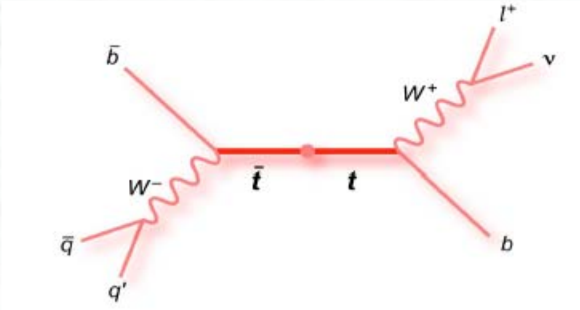


Figure 9.5 Representative Feynman diagrams for the three single top-quark production modes. The graphs show single top-quark production; the diagrams for single antitop-quark production can be obtained by interchanging quarks and antiquarks.

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:

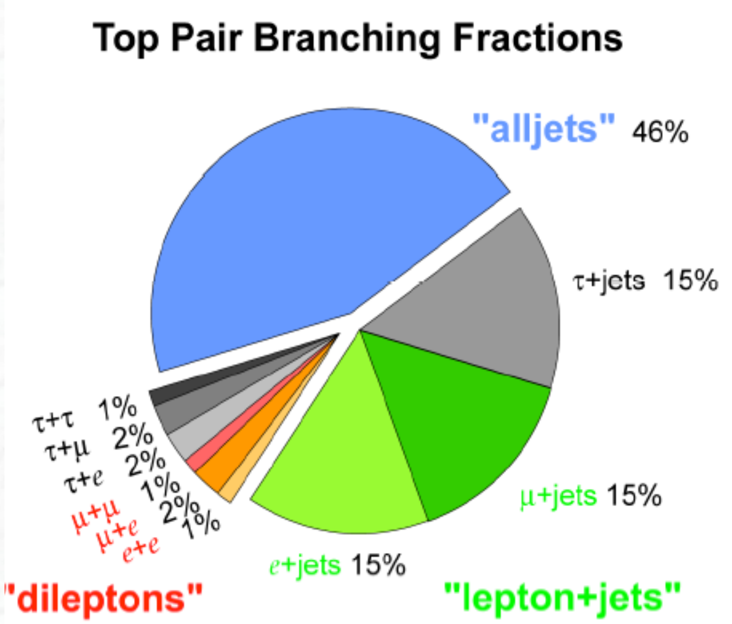
Both W's decay via $W \rightarrow \ell\nu$ (ℓ=e or μ; 4%)

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%)



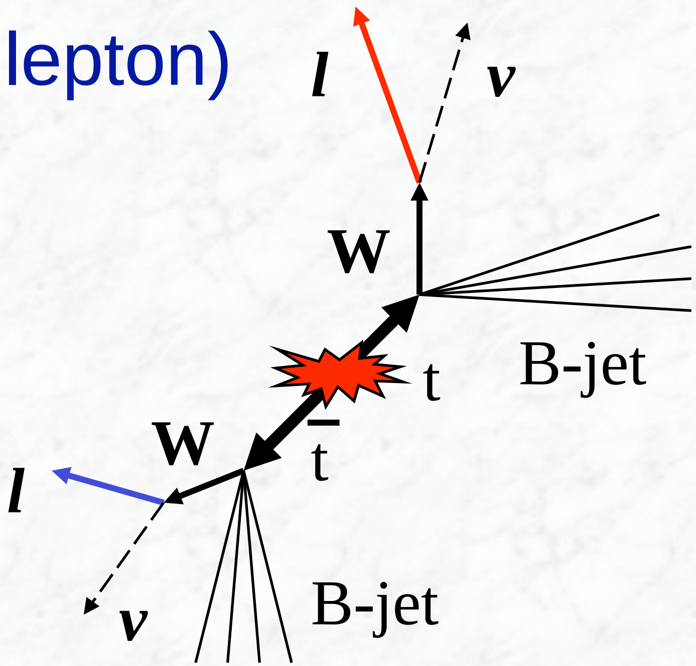
Important experimental signatures: : - Lepton(s)

- Missing transverse momentum
- b-jet(s)

7.2 Measurement of Top Quark production

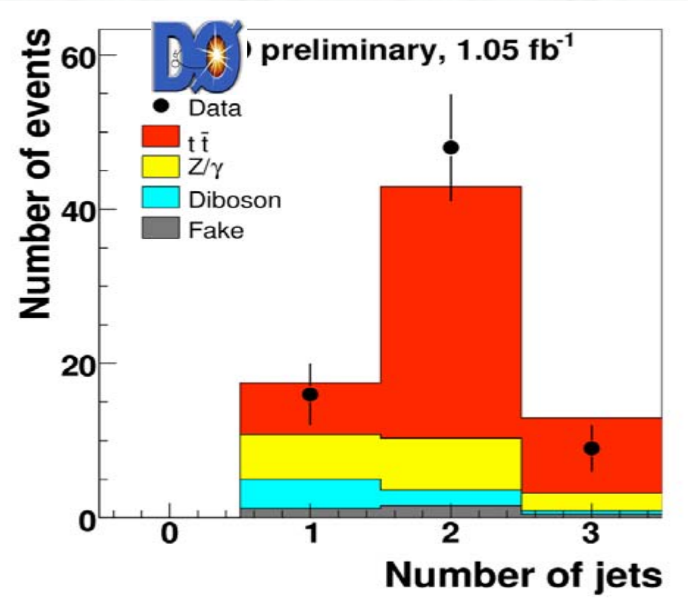
at the Tevatron

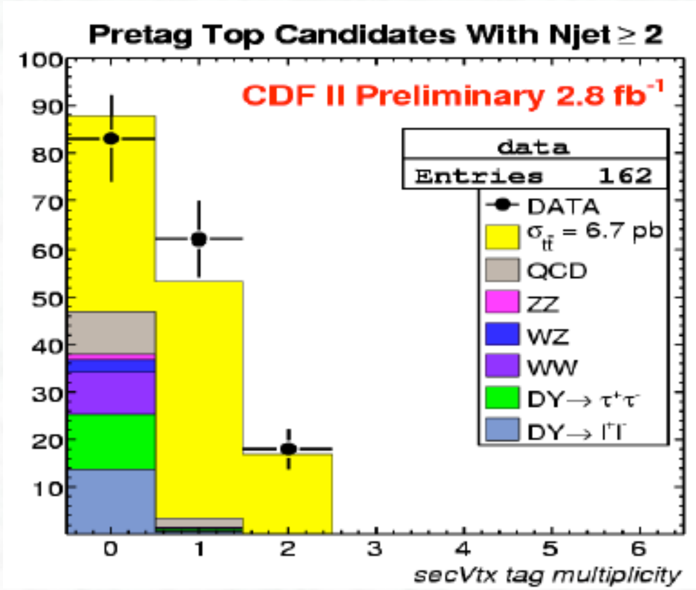
tt cross section (dilepton)



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

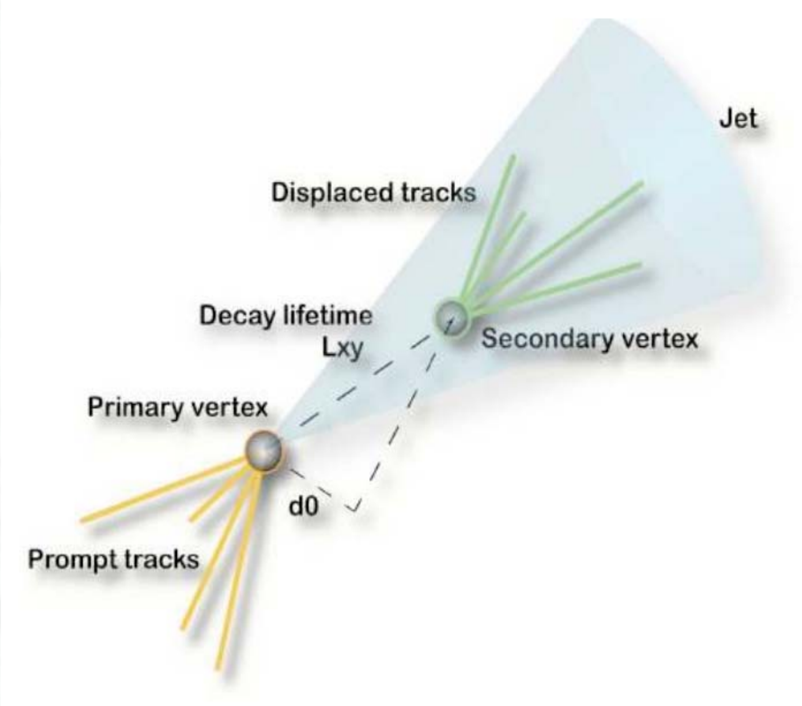
ee,eμ and μμ combined

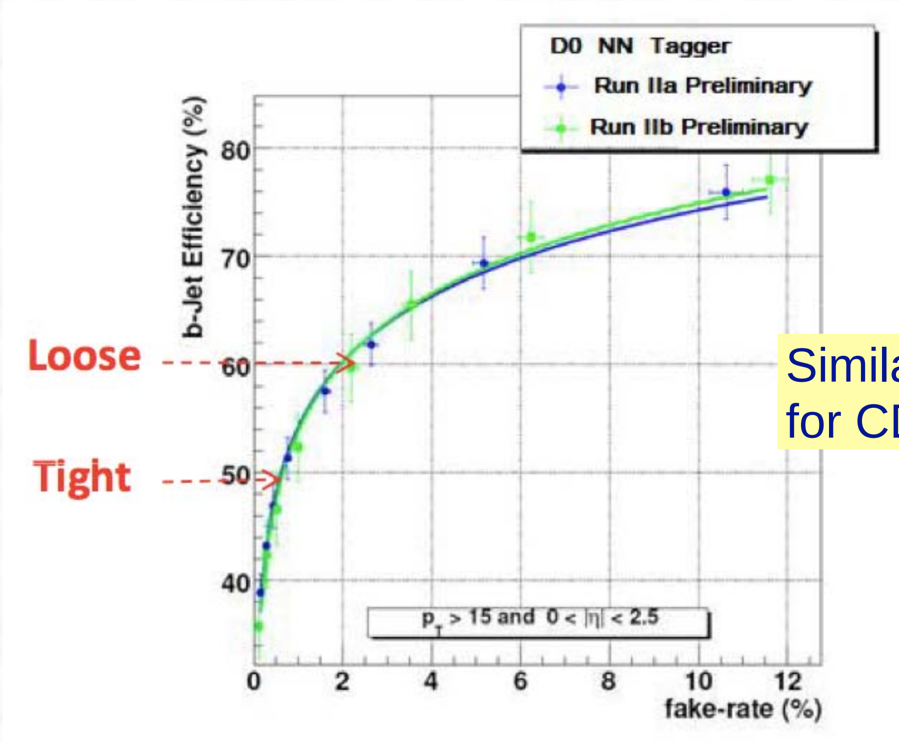




Top quark is needed to describe the
b-jet multiplicity distribution in dilepton events

Tevatron b-tagging performance





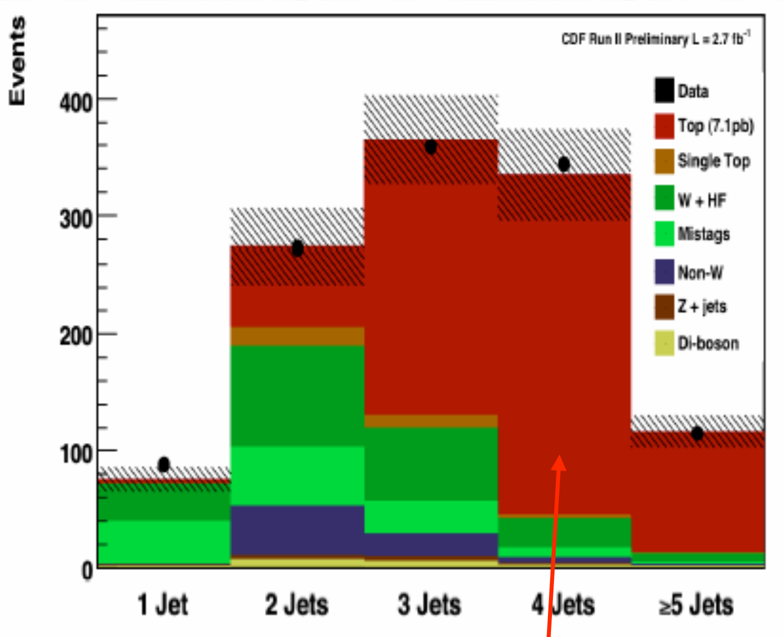
Similar for CDF

Neural networks are used for optimal combination of tagging information

$t\bar{t}$ cross section (lepton + jets) (including b-tagging)

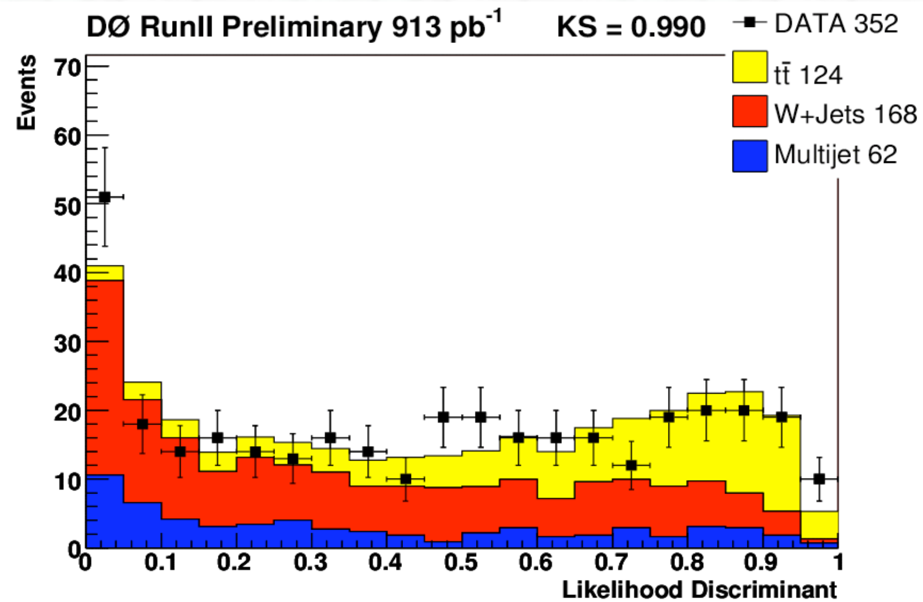
<u>b-tag selection:</u>

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



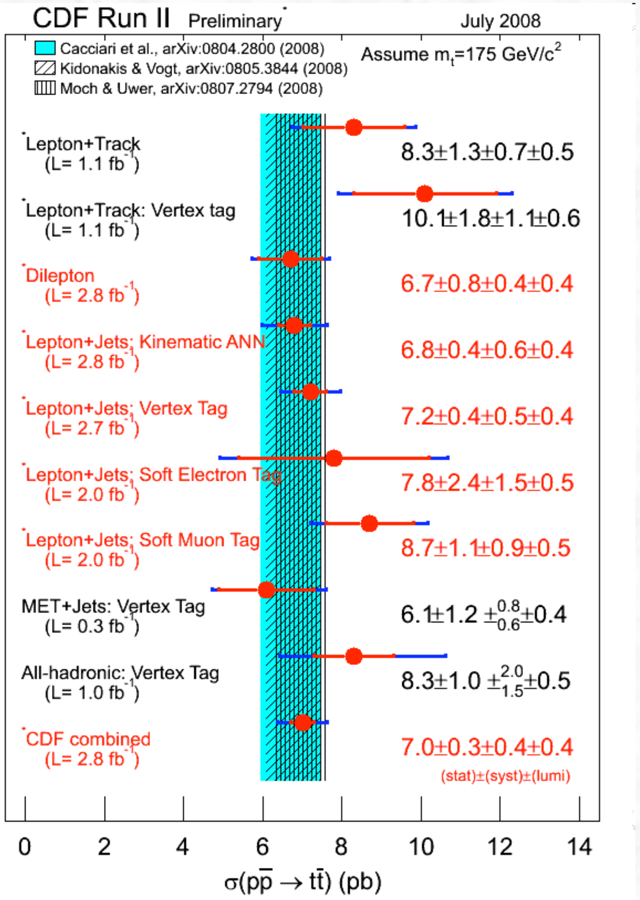
<u>Kinematic selection:</u>

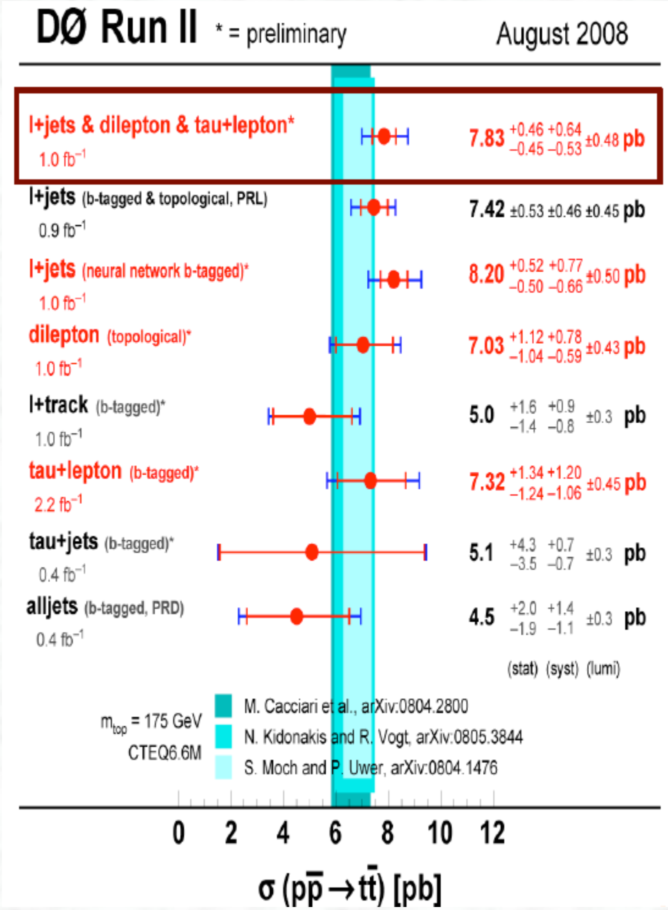
- One high P_T lepton (e, μ)
- Significant E_T^{miss}
- $\geq$ 4 jets
- Likelihood discriminant ($t\bar{t}$ vs. W+jets)



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

tt cross section summary from the Tevatron





Summary of syst. uncertainties

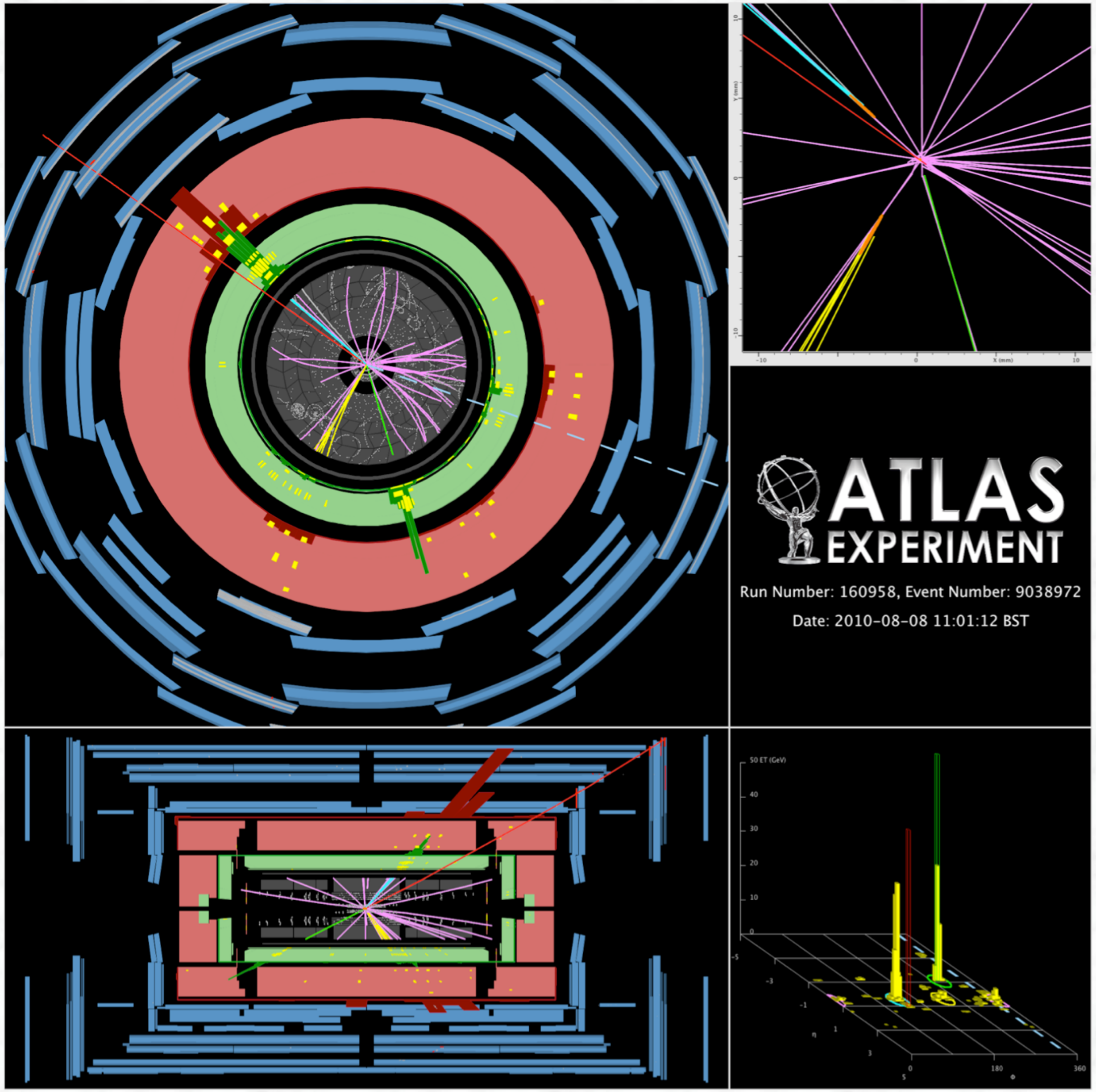
b-tag analysis (2.7 fb^{-1}):

SYSTEMATIC	Δ σ pb	Δ σ / σ %
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}

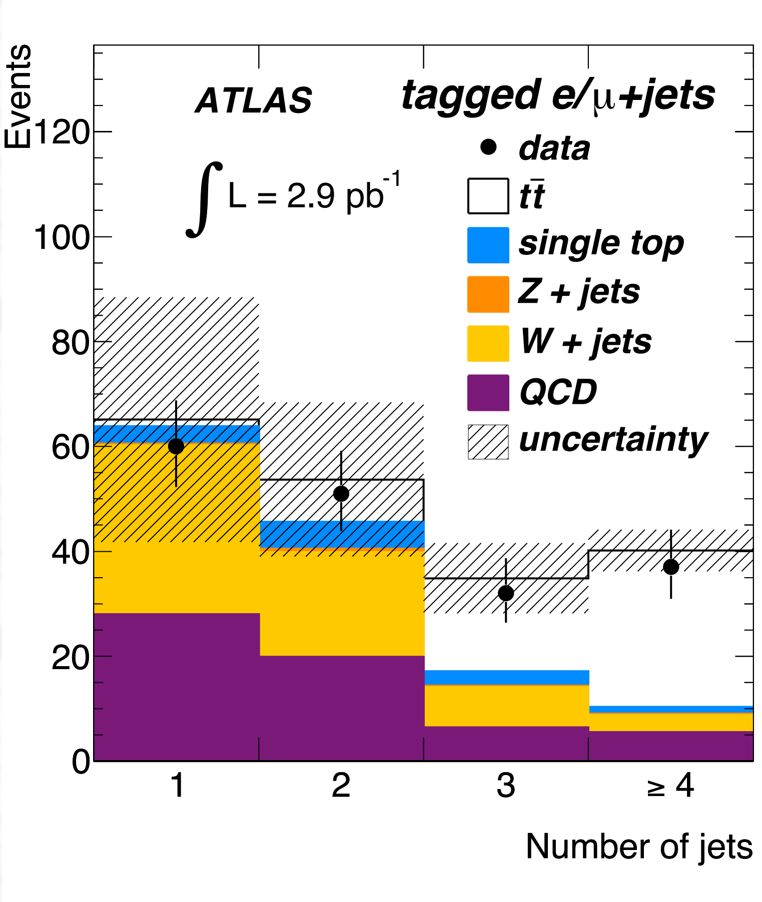
Good agreement:
- among various exp. measurements (two experiments)
- and with NLO + LL QCD prediction
- Systematic uncertainties at the 10% level (luminosity, b-tagging)

7.3 First measurements 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 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:

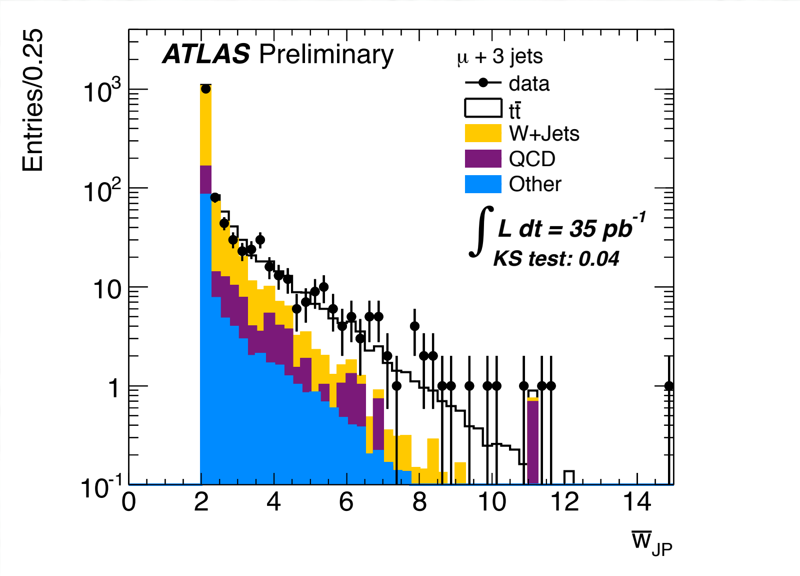
ATLAS experiment, L = 35 pb^{-1} (data from 2010)

Table 1: Selected events in the electron (top) and muon (bottom) channels split up according to jet multiplicity. The uncertainties quoted are statistical and systematic.

Electron Channel	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
$t\bar{t}$	14.3 ± 2.9	61 ± 9	116 ± 13	111 ± 16	82 ± 12
W+jets	9000 ± 1900	2300 ± 700	580 ± 250	140 ± 90	41 ± 26
QCD multijets	290 ± 140	123 ± 62	62 ± 31	13 ± 7	8 ± 4
Single Top	36 ± 4	42 ± 5	22 ± 4	7.8 ± 1.8	3.1± 0.7
Z+jets	65 ± 14	62 ± 20	32 ± 14	12 ± 8	6 ± 4
Diboson	35.3 ± 2.8	30.1 ± 2.4	9.3 ± 1.5	2.2 ± 0.5	0.4± 1
Total Predicted	9400 ± 1900	2700 ± 800	830 ± 250	290 ± 90	141 ± 29
Data Observed	9481	2552	781	273	127

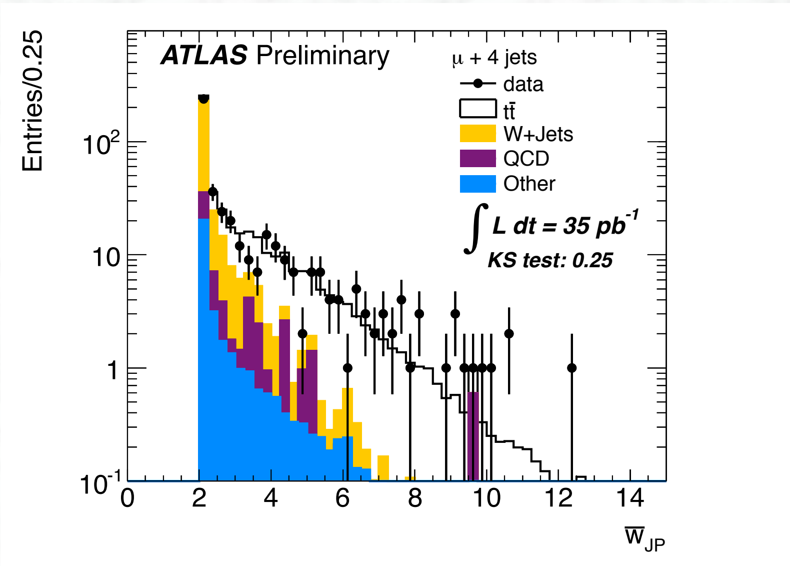
Muon Channel	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
$t\bar{t}$	19 ± 4	81 ± 12	161 ± 18	158 ± 22	115 ± 16
W+jets	19000 ± 4000	4600 ± 1500	1100 ± 500	250 ± 150	70 ± 40
QCD multijets	520 ± 160	287 ± 86	121 ± 36	30 ± 10	20 ± 6
Single Top	57 ± 7	64 ± 8	32 ± 6	11.1± 2.5	4.0± 0.9
Z+jets	770 ± 160	250 ± 80	69 ± 30	19 ± 12	6 ± 4
Diboson	63 ± 5	55 ± 4	16.1 ± 2.6	3.4± 0.7	0.6± 0.1
Total Predicted	20000 ± 4000	5300 ± 1500	1500 ± 500	470 ± 160	210 ± 50
Data Observed	20583	5228	1356	448	205

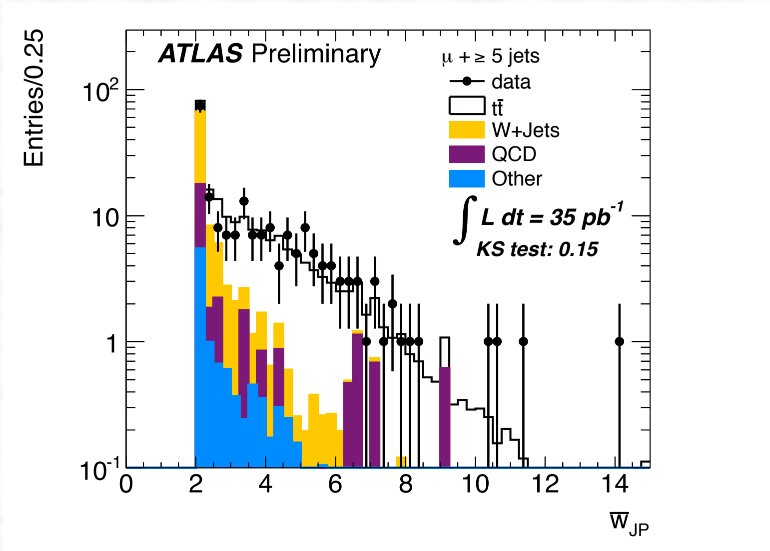
b-tag requirements, higher integrated luminosity



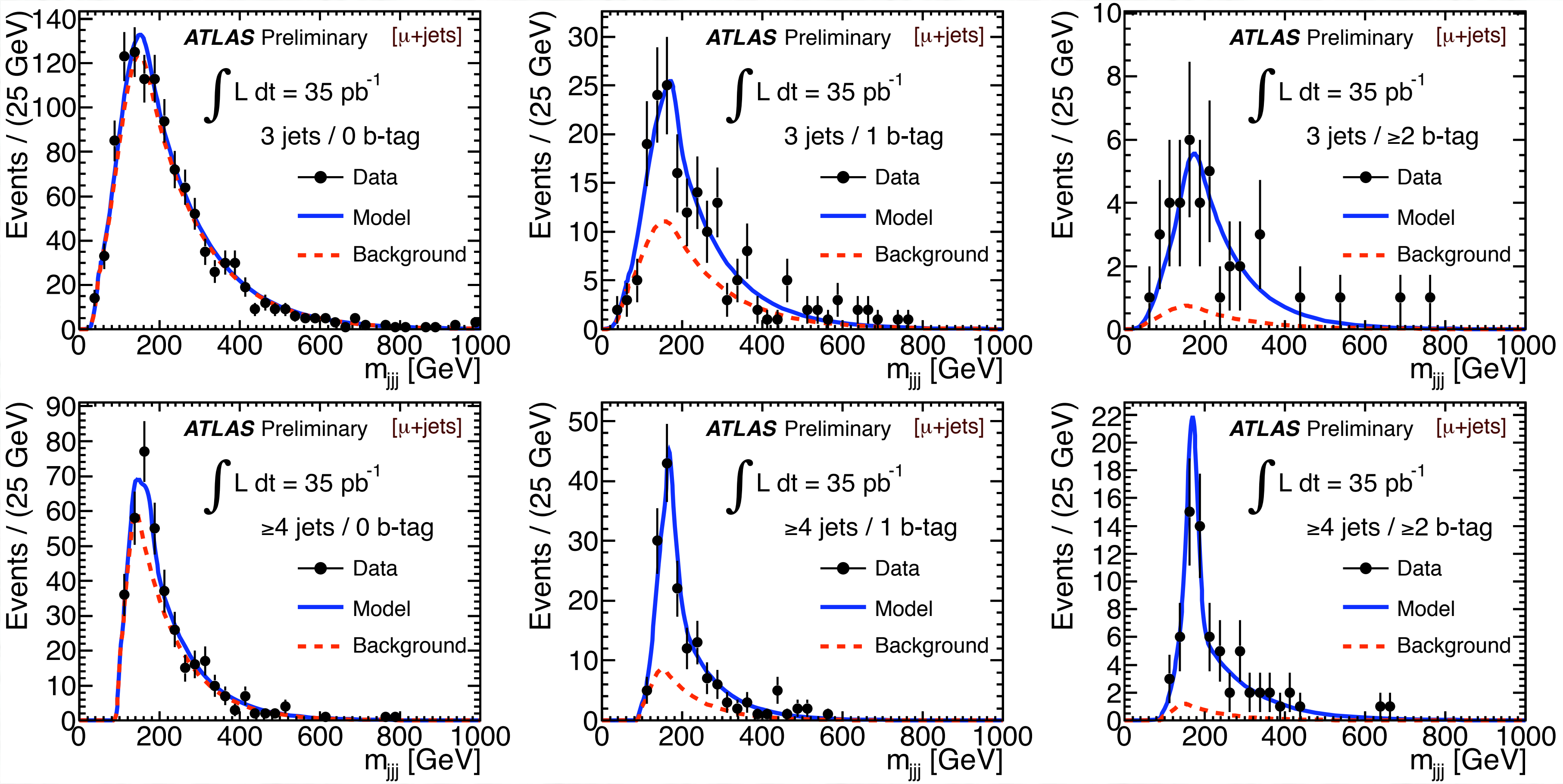
Distribution of the b-tagging discriminant in events with at least 3 jets;

tt component dominated the 4 and 5 jet bins





Description of the invariant mass distributions in the l-had channel



- Top fractions increase with number of b-tags
- Good description for all jet-multiplicity and b-tag combinations
- Data are consistent with top quark production with mass of 173 GeV

CMS tt signals in the di-lepton channel

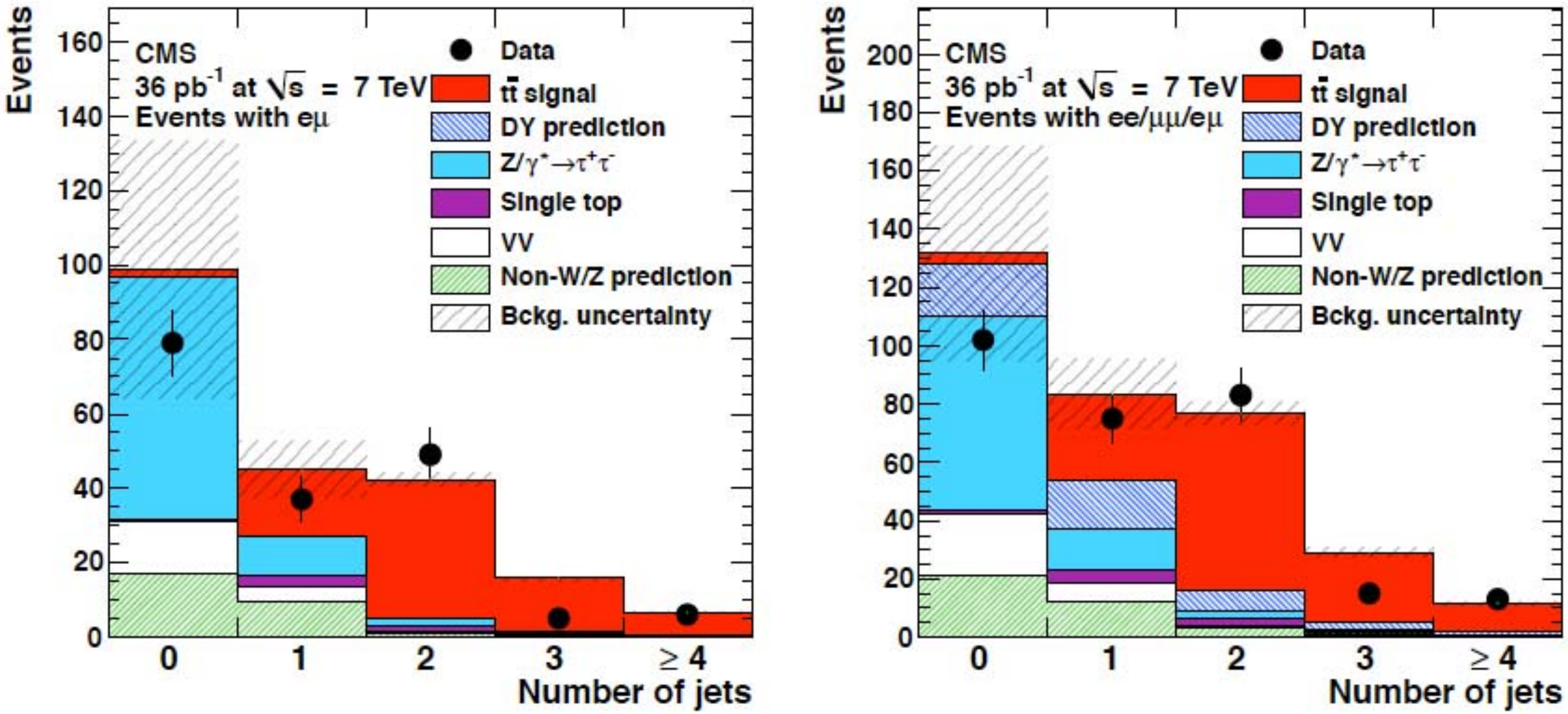


Figure 3: Number of events passing the full dilepton selection criteria without a b tag (points), as a function of the jet multiplicity for $e^{\pm}\mu^{\mp}$ (left) and all dileptons (right). There is no $\not\!\!E_T$ requirement for the $e^{\pm}\mu^{\mp}$, and a requirement of $\not\!\!E_T > 30\,\text{GeV}$ for the e^+e^- and $\mu^+\mu^-$. The expected distributions for the $t\bar{t}$ signal and the background sources are shown by the histograms. The Drell–Yan and non-W/Z lepton backgrounds are estimated from data, while the other backgrounds are from simulation. The total uncertainty on the background contribution is displayed by the hatched region.

CMS tt signals in the di-lepton channel

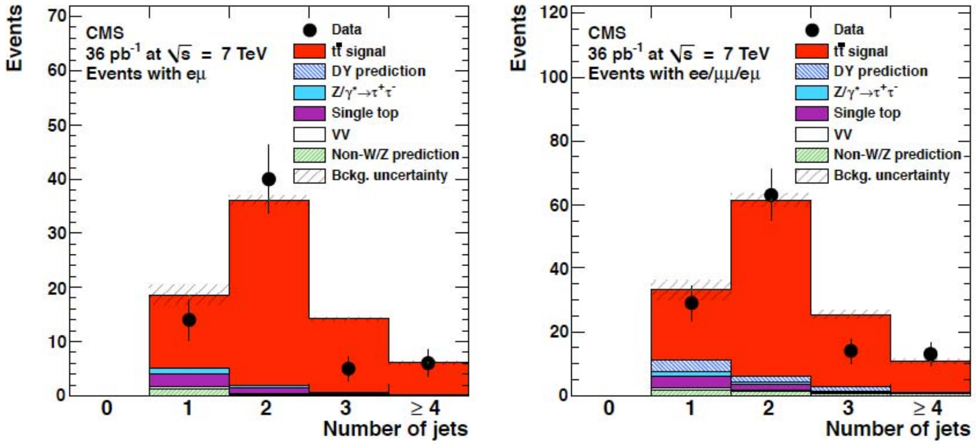


Figure 4: Jet multiplicity for events passing full dilepton selection criteria with at least one b-tagged jet, otherwise the same as in Fig. 3.

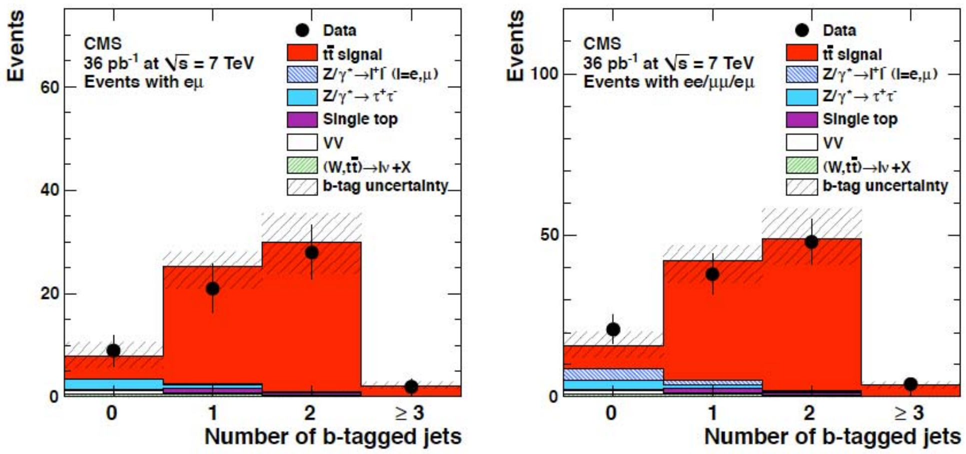


Figure 5: Multiplicity of b-tagged jets in events passing full dilepton selection criteria with at least two jets compared to signal and background expectations from simulation. The uncertainty on the number of signal events corresponding to the uncertainty in the selection of b-tagged jets is displayed by the shaded area. The distributions are for $e^{\pm}\mu^{\mp}$ (left) and all (right) final states combined.

CMS tt signals in the di-lepton channel

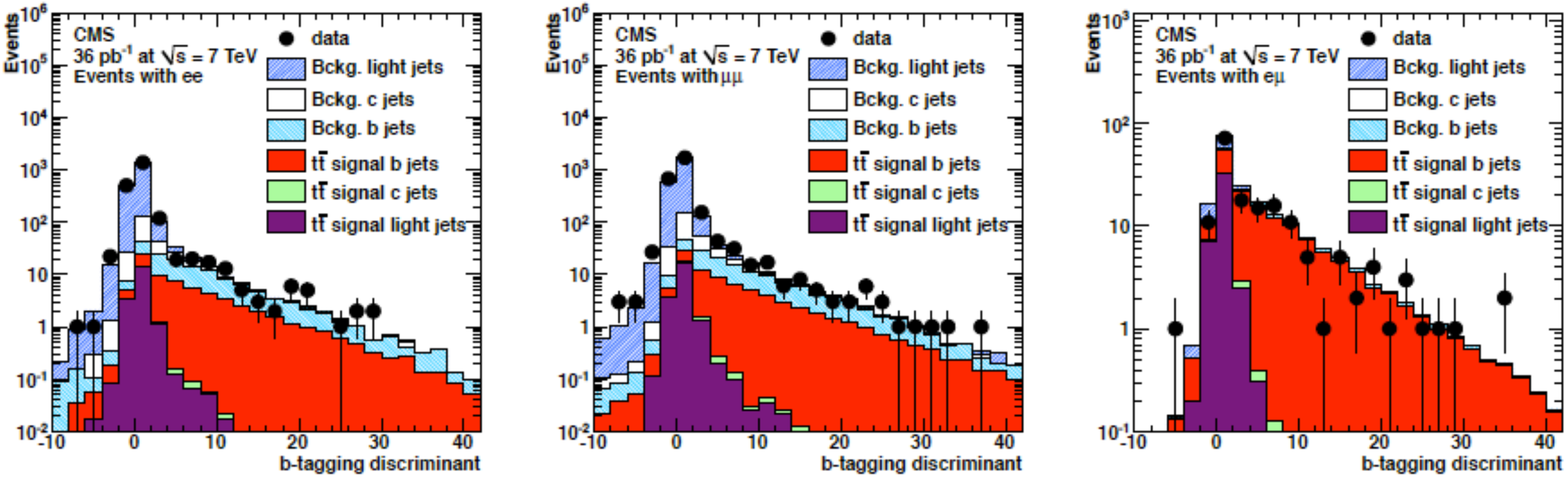
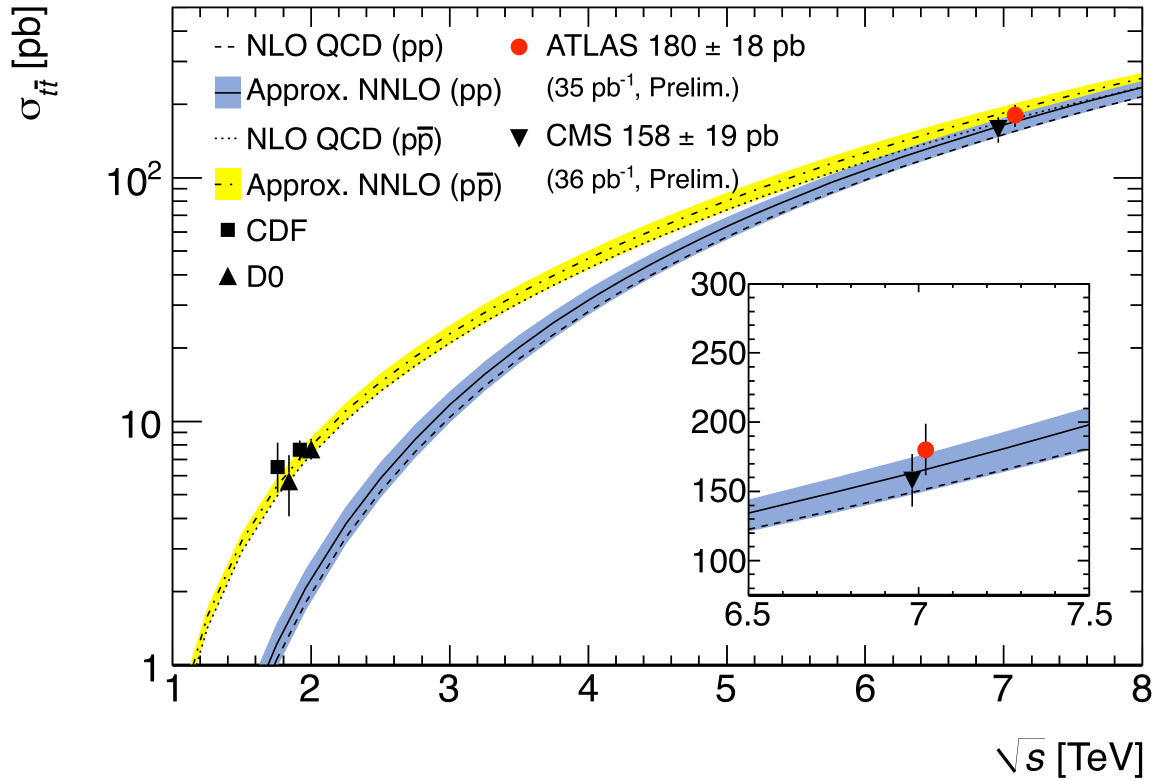
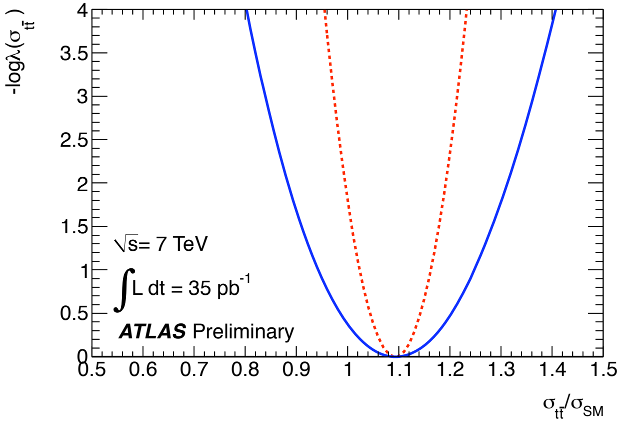


Figure 1: Distribution of the b-tagging discriminant in events with at least one jet and two oppositely charged leptons in data (points), compared to signal and background expectations from simulation (histograms) for e^+e^- (left), $\mu^+\mu^-$ (centre), and $e^\pm\mu^\mp$ (right). The simulated contributions are normalised to the SM predicted values without additional corrections. All background contributions are combined and displayed separately, based on the flavour of the simulated jet.

Top cross section measurements based on 2010 data from ATLAS and CMS

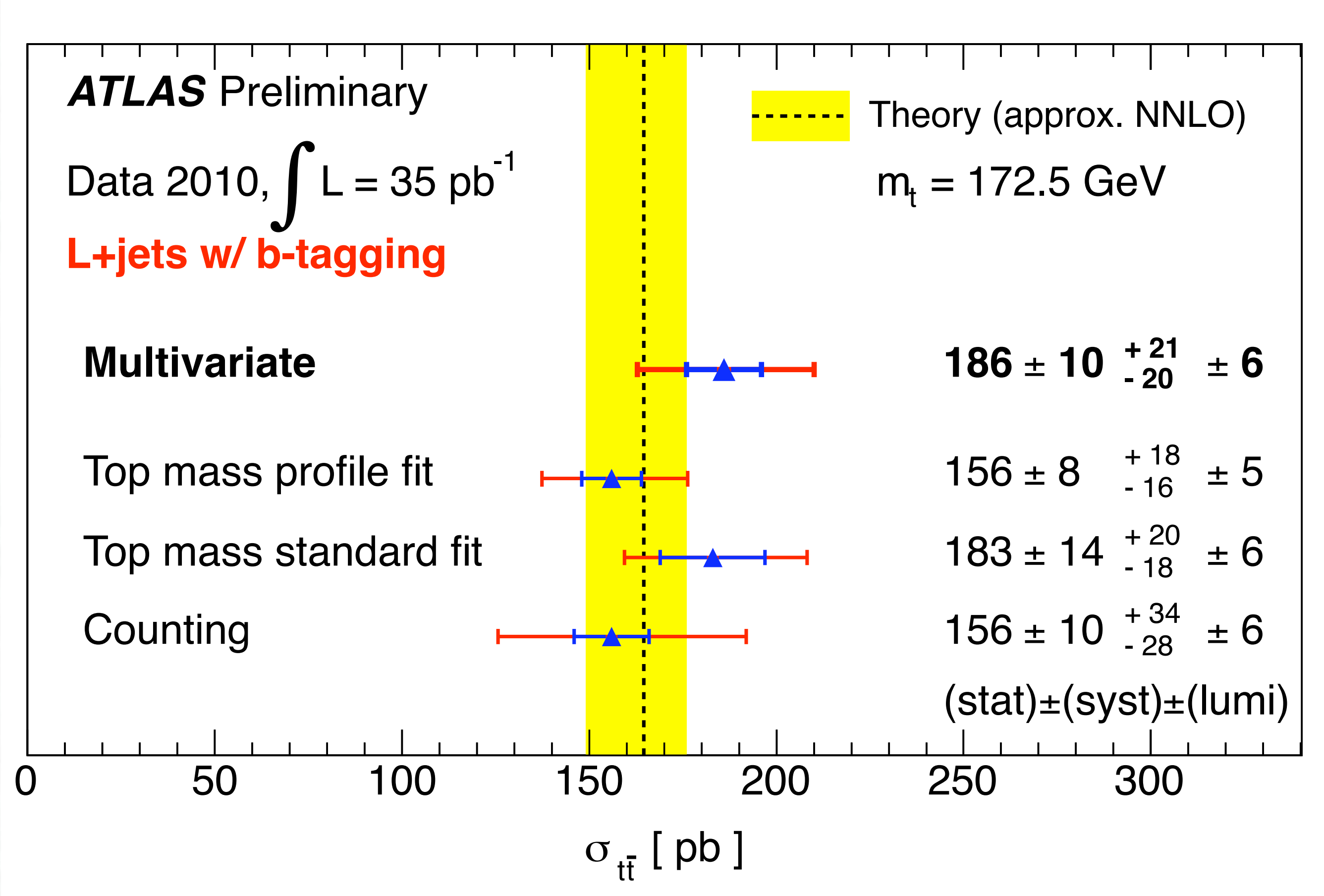




Best fit (ATLAS) gives a slightly higher cross-section than the expected approx. NNLO QCD value, but consistent within 1 σ (red: likelihood, stat errors only; blue: stat + syst. uncertainties)

- Results between the two experiments are consistent
- Perturbative QCD calculations are in agreement with the obtained results

Summary of ATLAS cross section measurements



Perturbative QCD calculations (approx. NNLO) describe the data well

7.4 Top-quark mass measurement

Top mass measurements

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

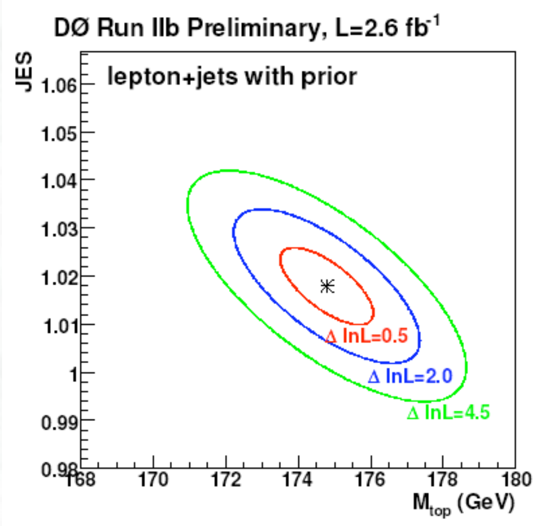
  → template methods,…
  matrix element method…

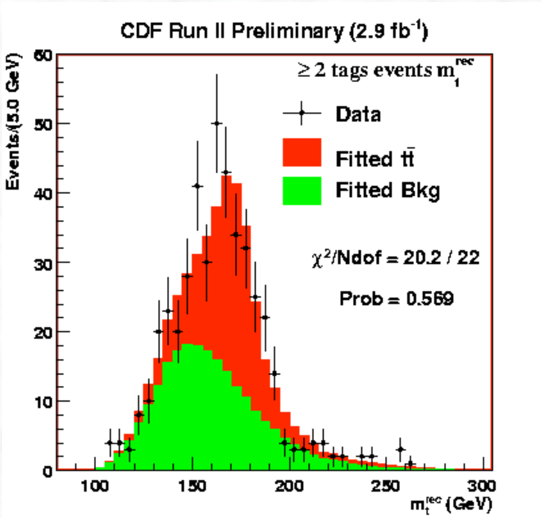
<u>Most precise single measurements</u>:

m_{top} = 172.1 ± 0.9 (stat) ± 1.3 (syst) GeV/c^2 (CDF)

m_{top} = 173.7 ± 0.8 (stat) ±1.6 (syst) GeV/c^2 (DØ)

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

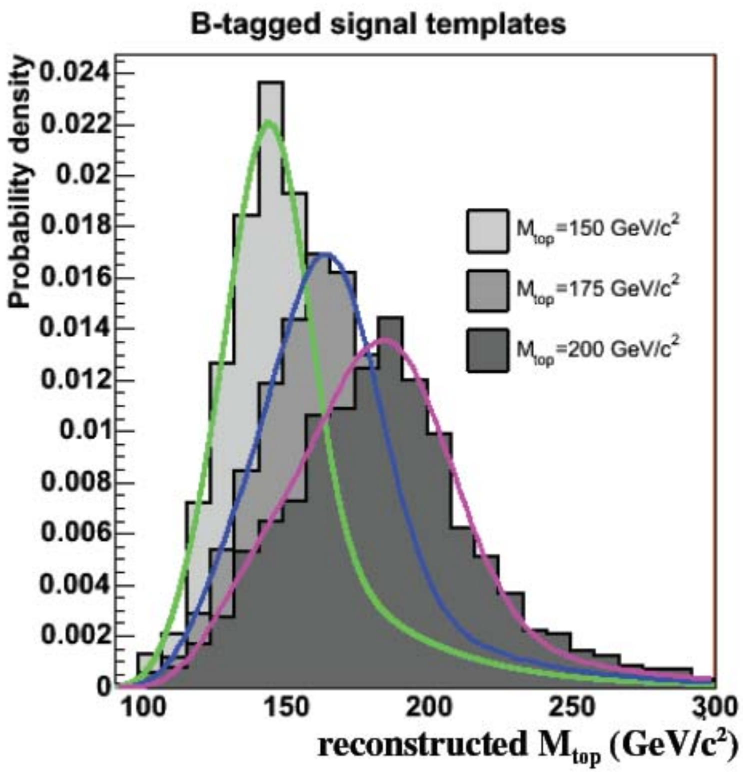




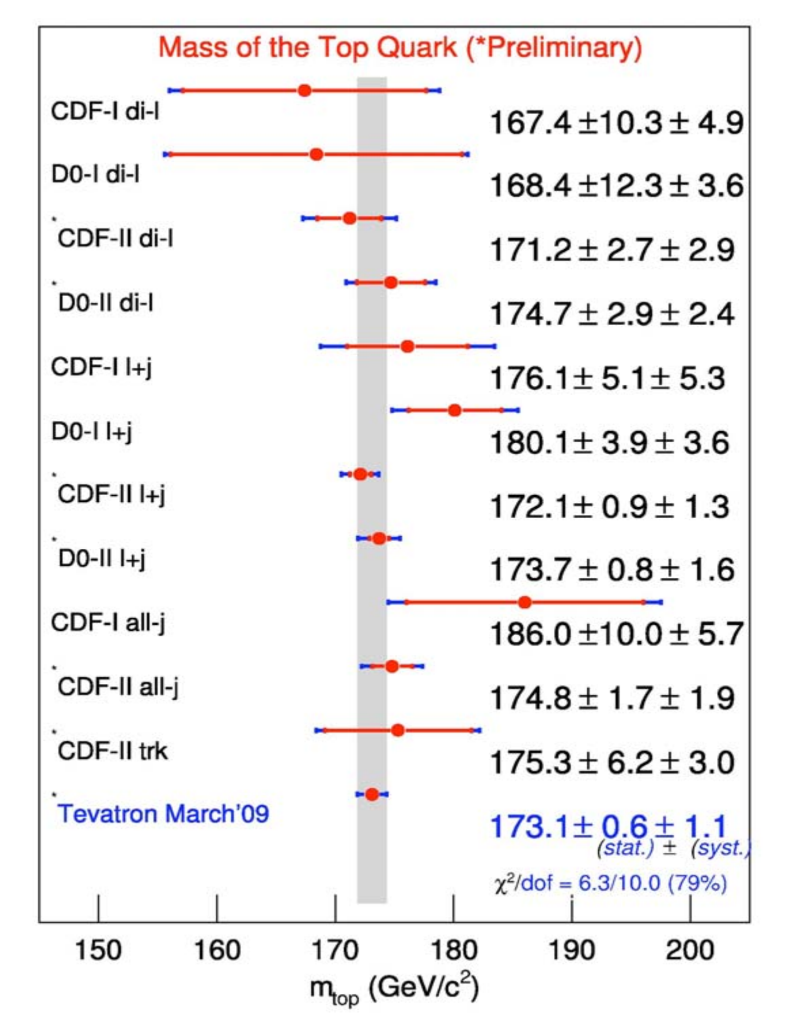
full hadronic channel

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

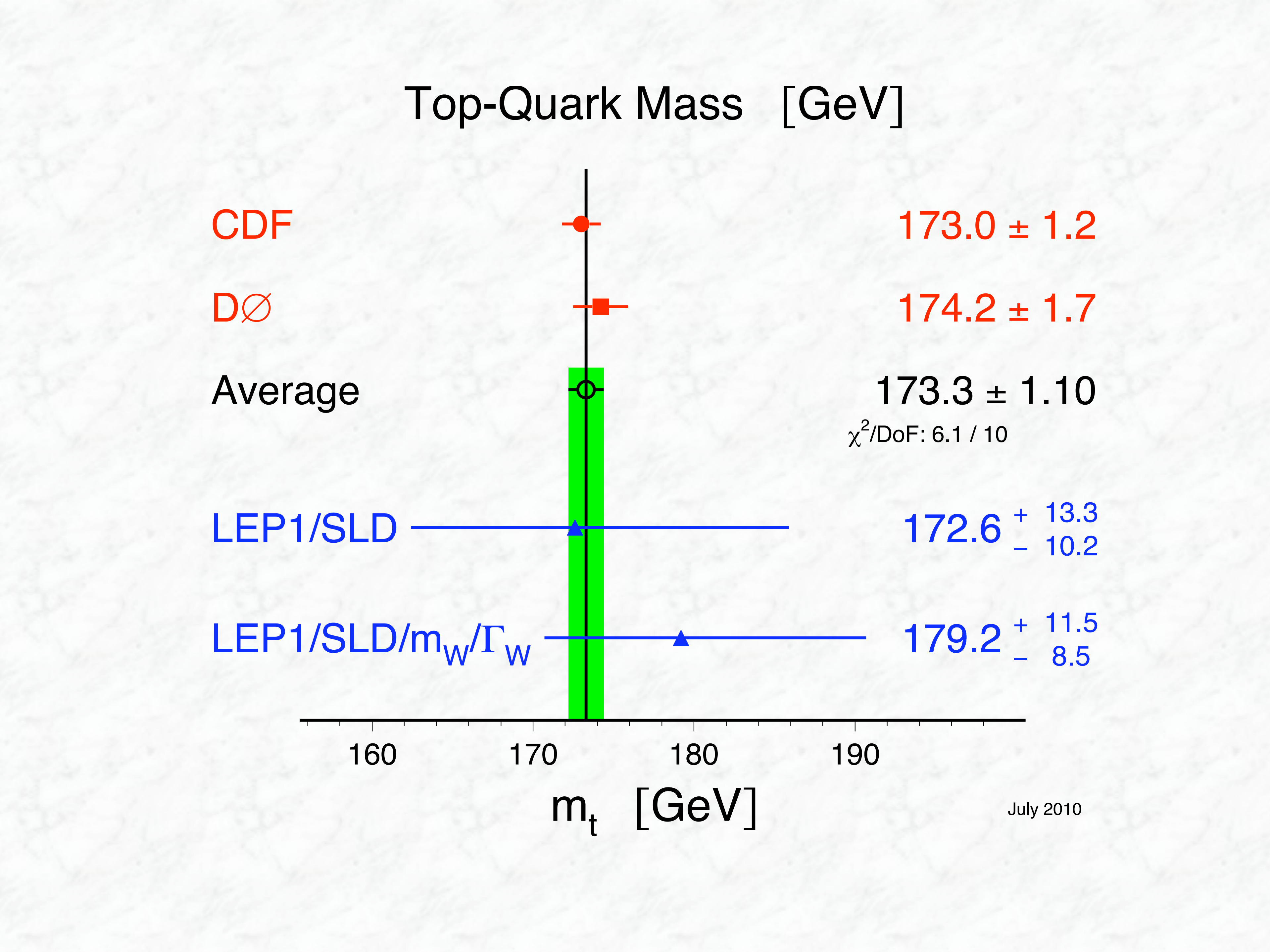


Summary of present results and future prospects



Expected LHC precision for 10 fb^{-1}:
(Combination of several methods, maybe somewhat conservative)

< ~ 1 GeV/c^2

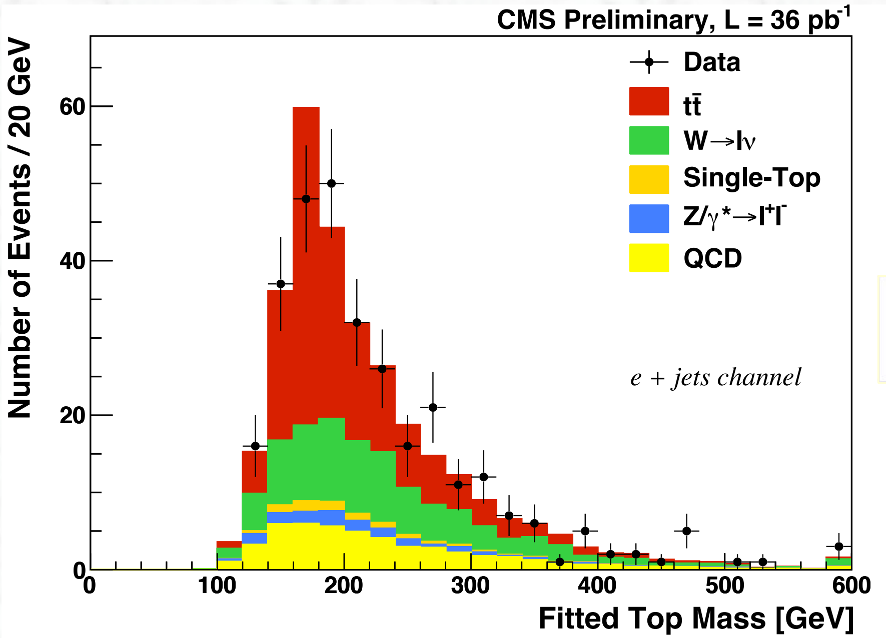


Top-Quark Mass [GeV]
CDF
173.0 ± 1.2
DØ
174.2 ± 1.7
Average
173.3 ± 1.10
χ2/DoF: 6.1 / 10
LEP1/SLD
172.6 + 13.3 − 10.2
LEP1/SLD/mW/ΓW
179.2 + 11.5 − 8.5
160
170
180
190
mt [GeV]
July 2010

First top quark mass measurements from CMS

CMS, 06.06.2011

- Use lepton + jet channel
- Full 2010 data set
- 637 candidate events selected



Top quark mass after the fit of the e+jets selected sample for an integrated luminosity of 36/pb after applying the event selection and requesting at least one solution with chi2<10.

$$m_t = 173.4 \pm 1.9(\mathrm{stat}) \pm 2.7(\mathrm{syst})\ \ \mathrm{GeV}.$$

Already impressive precision reached at that early stage of the experiment !

Estimated error compared to expectations from Monte Carlo simulations:

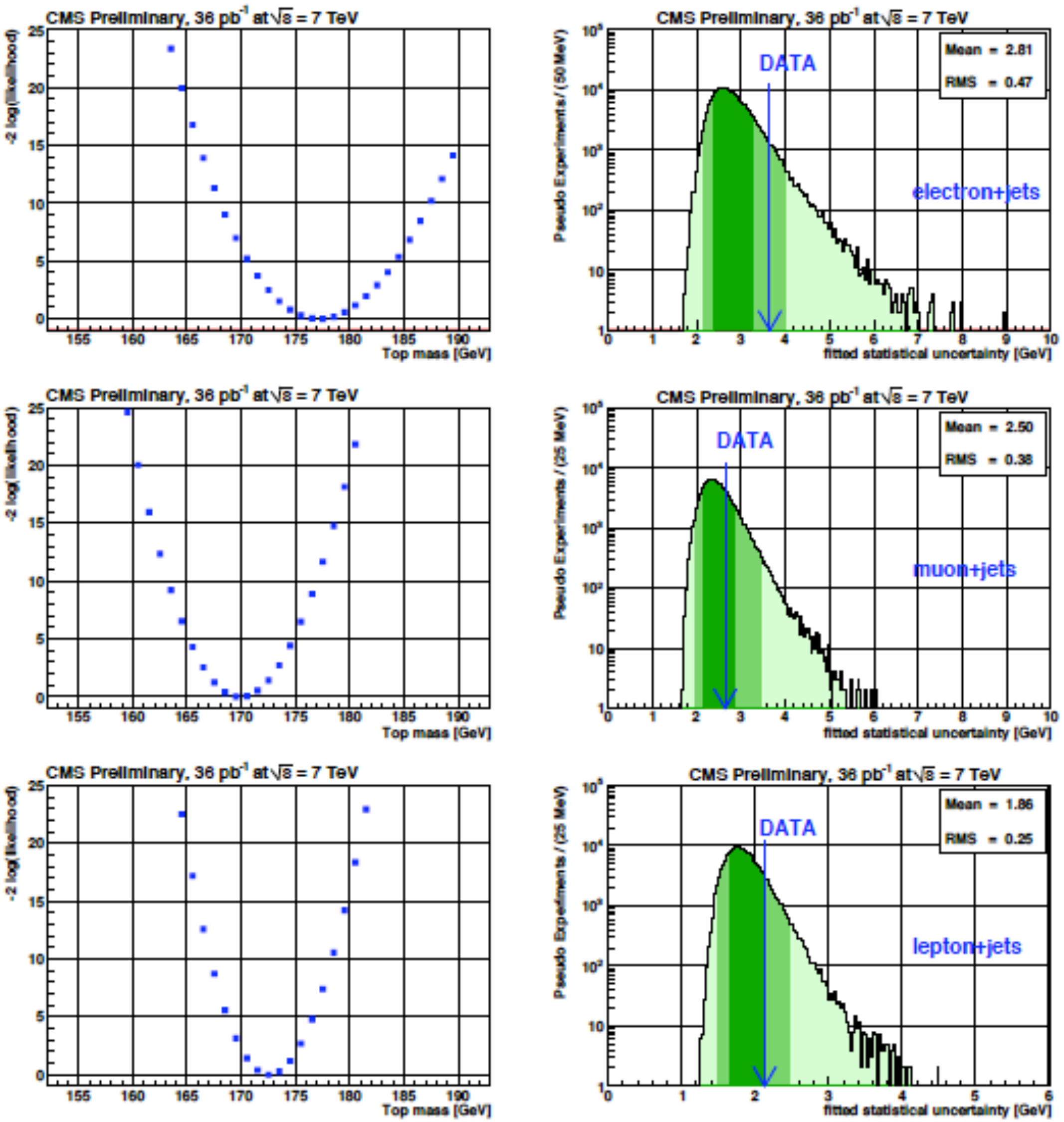
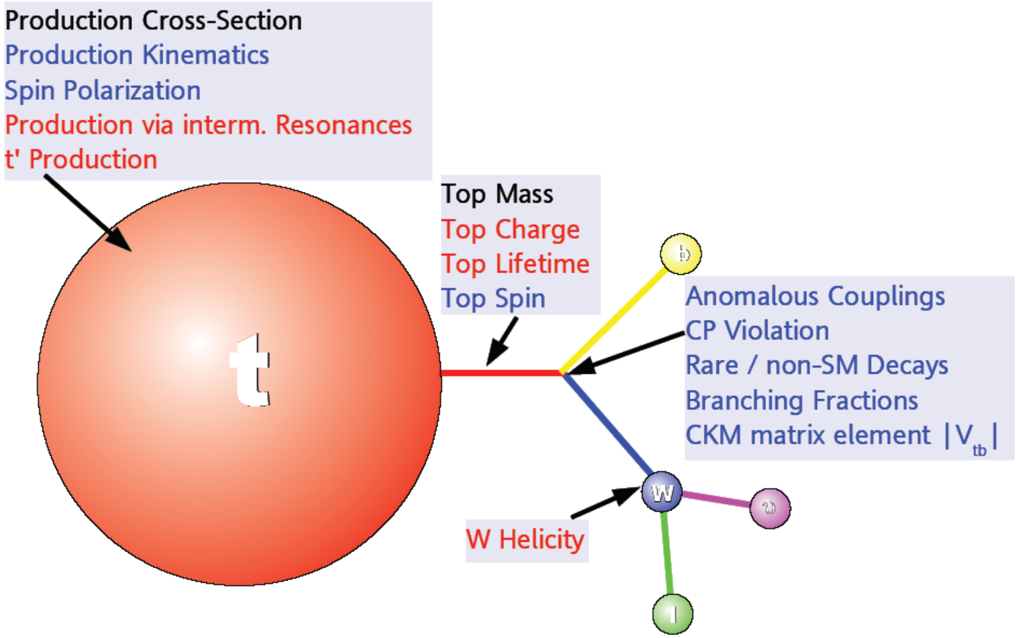
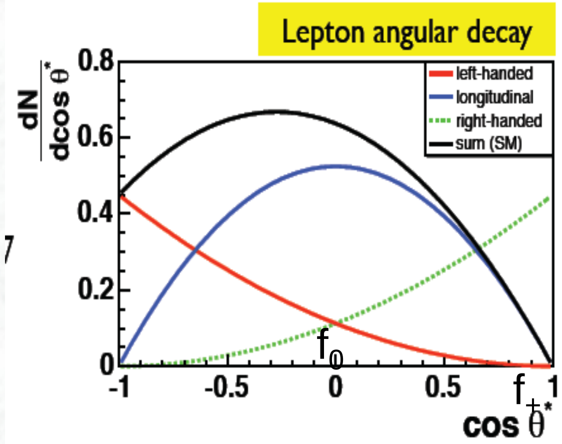


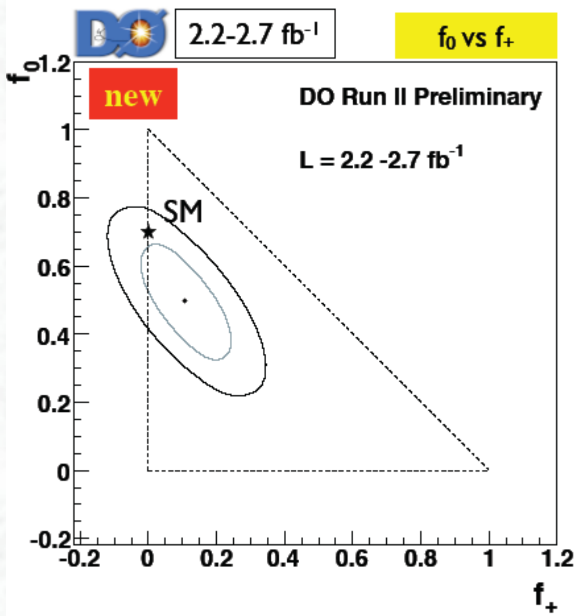
Figure 7: Likelihood as a function of the top quark mass from the fit to the data (left) and the estimated uncertainty compared to the expectation from MC pseudo-experiments (right), for the electron+jets (top), muon+jets (middle), and the combined lepton+jets channel (bottom).



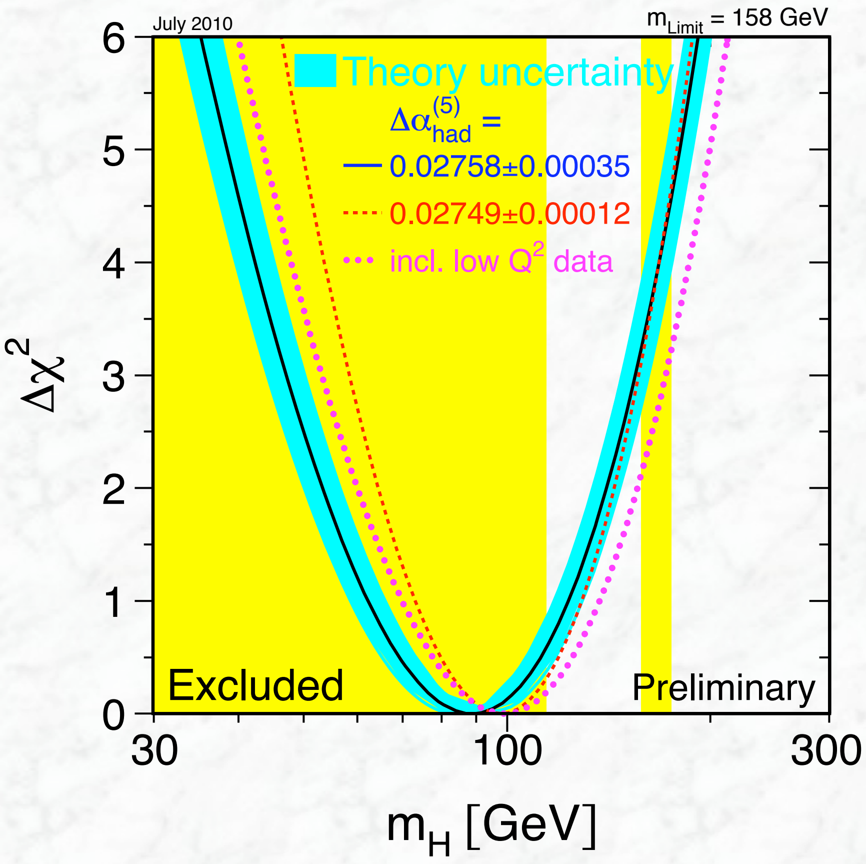
Other top properties

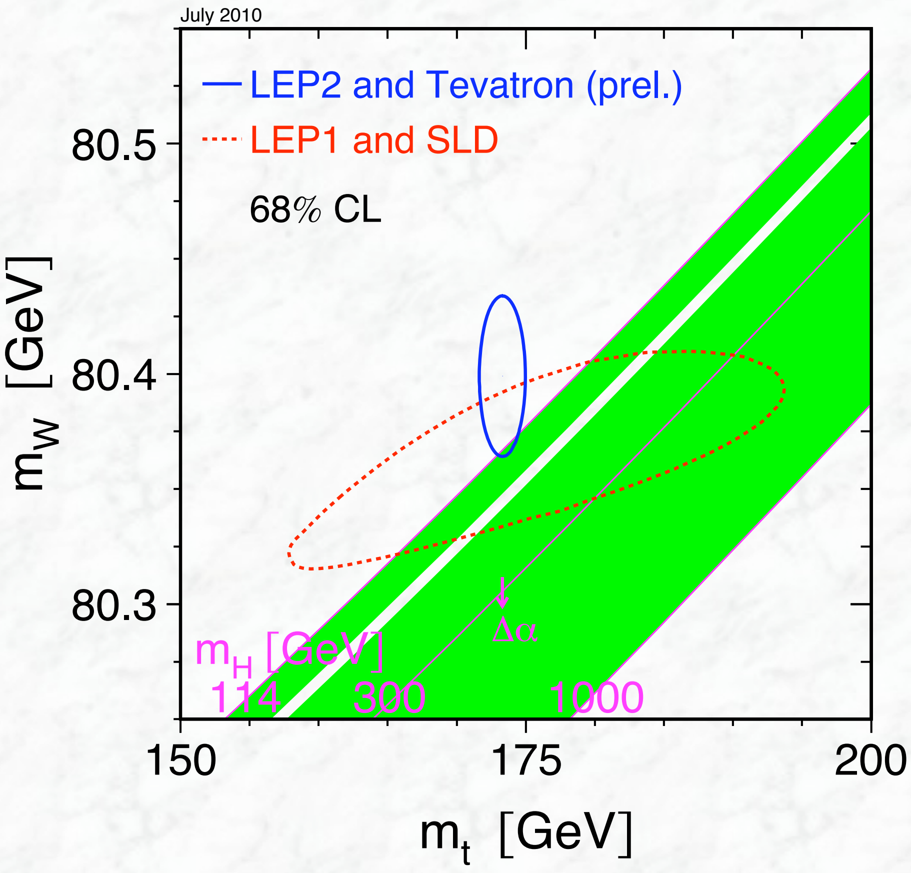


	Tevatron Result	luminosity (fb^{-1})
Mass	173.1 ± 1.1 GeV	~ 5.0
W helicity	CDF: $f_0 = 0.66 \pm 0.16$, $f_+ = -0.03 \pm 0.07$ DØ: $f_0 = 0.49 \pm 0.14$ $f_+ = 0.11 \pm 0.08$	1.9 2.2 – 2.7
Charge Lifetime $\mathbf{V_{tb}}$ BR(t→Wb) / BR(W→Wq) BR (t → Zq)	rule out Q = +4/3 (90.% C.L.) Γ_t < 13.1 GeV (95%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

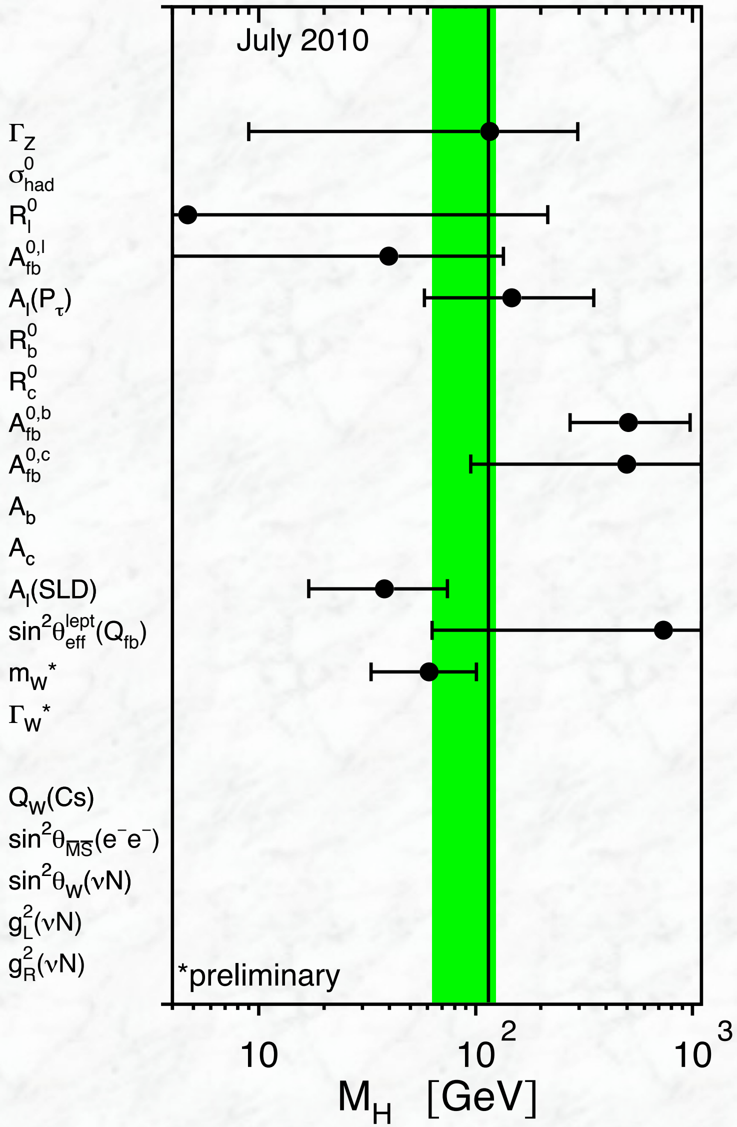


7.5 Constraints on the Standard Model

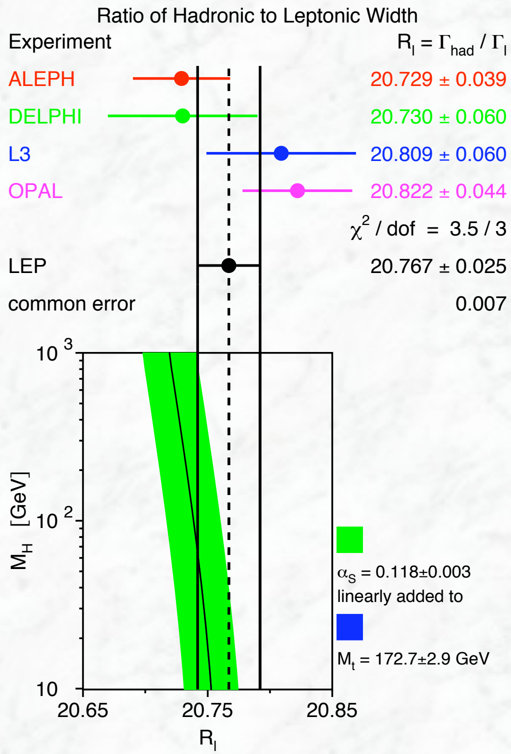


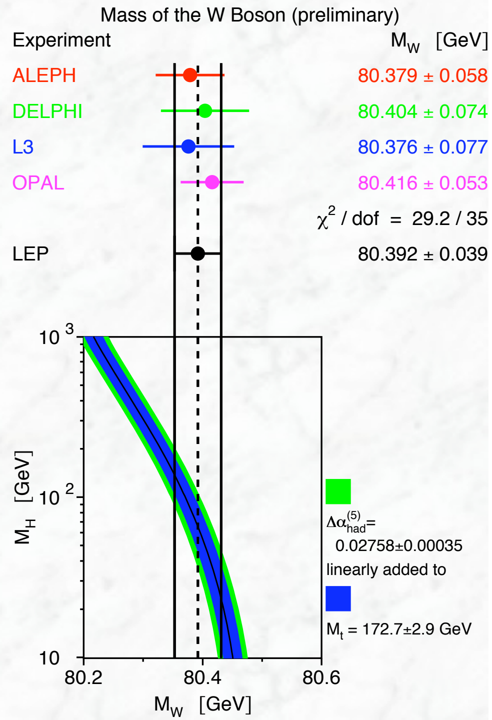


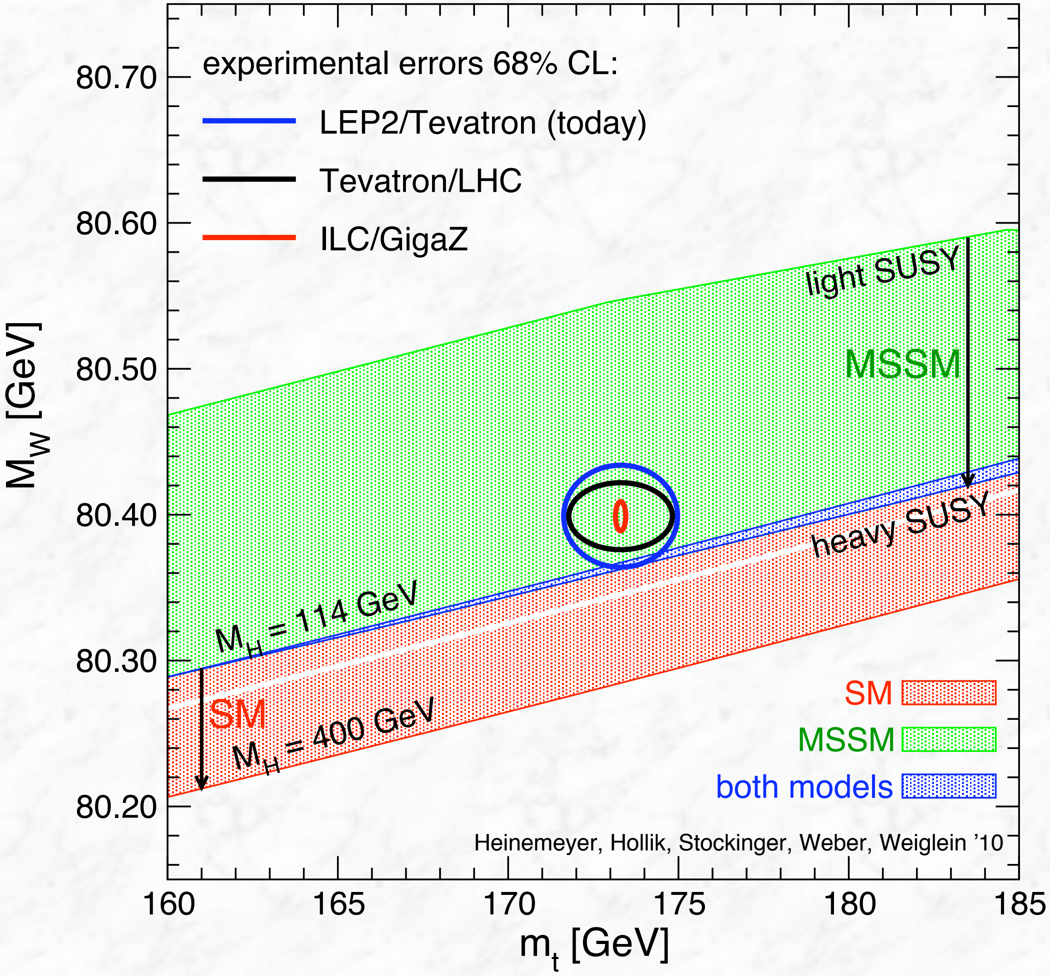
Best estimate for the Higgs boson mass from the different electroweak observables:



Examples: R_l and m_W







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