Physics at the LHC
Lecture 5: The Standard Model at the LHC (II)

Klaus Mönig, Sven Moch

(klaus.moenig@desy.de, sven-olaf.moch@desy.de)

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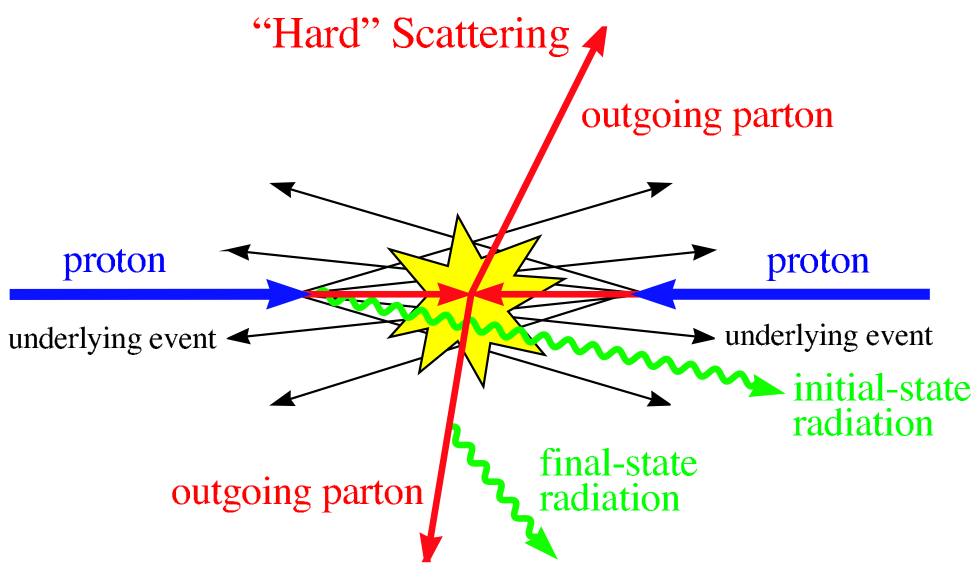
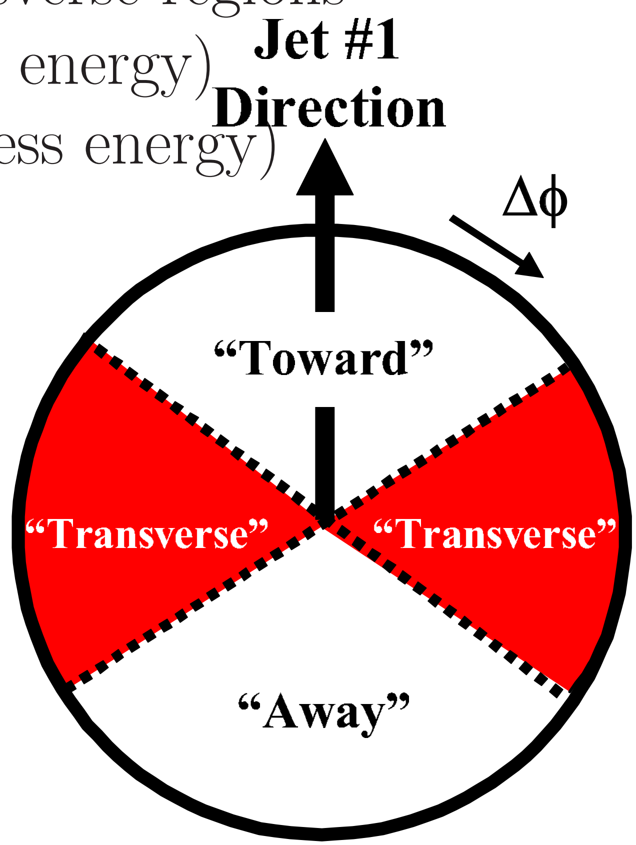
The underlying event

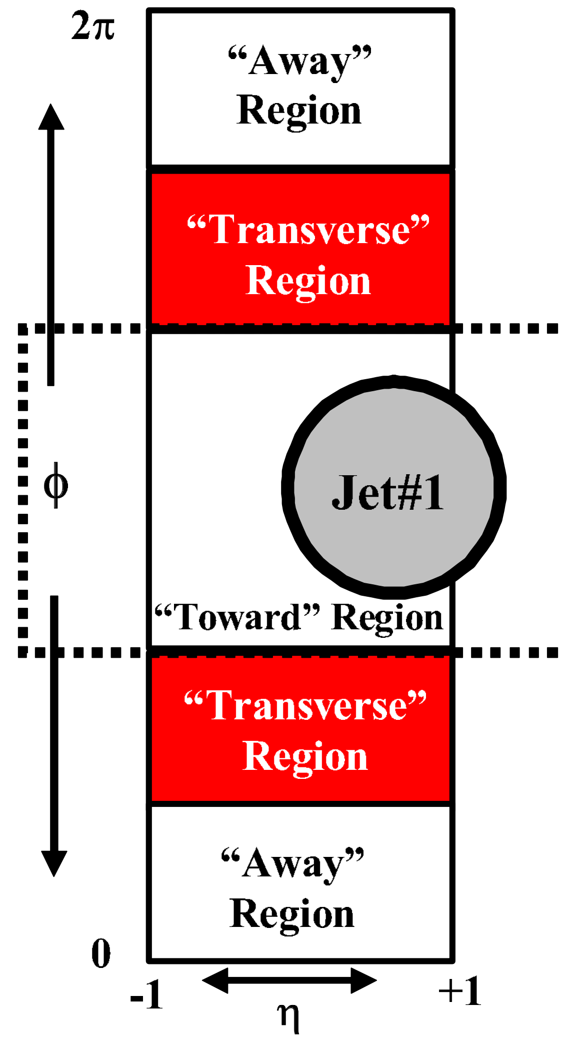
- At the LHC the parton-parton cross section integrated over the PDFs exceeds the proton-proton cross section
- This is interpreted as several parton-parton scatterings during one in-elastic pp event
- There are indications that the hard partons concentrate in the core of the event
- For this reason the underlying event does not simply look like minimum bias



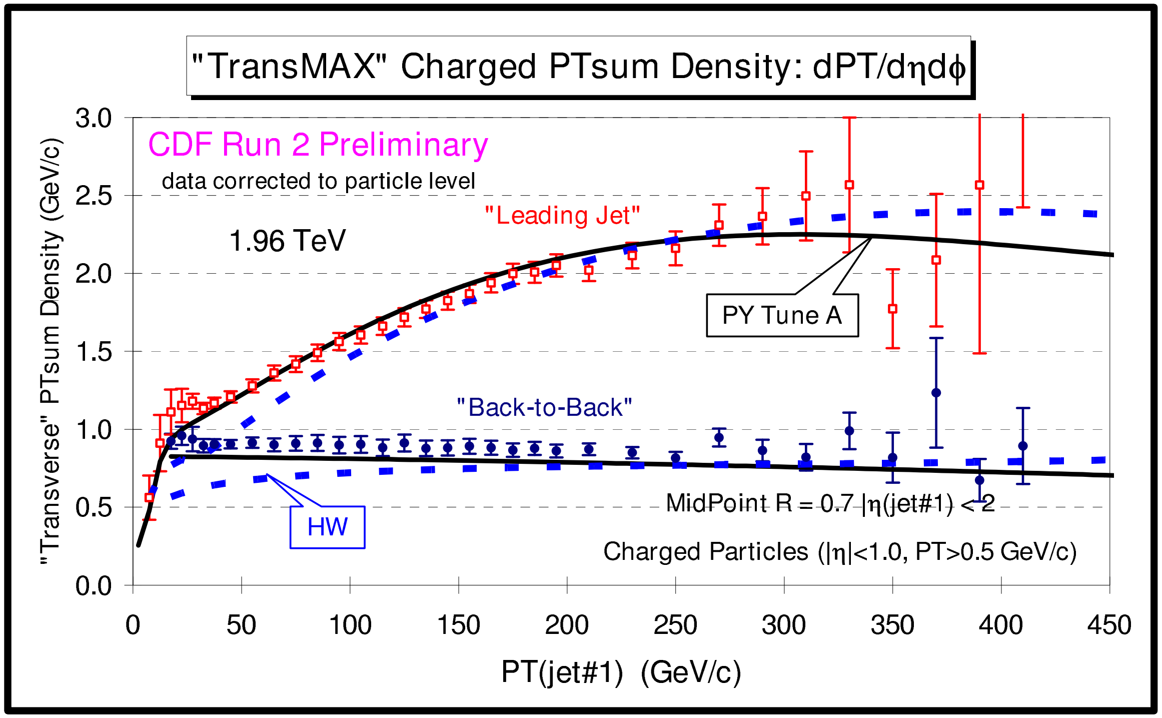
Analysis of the underlying event:

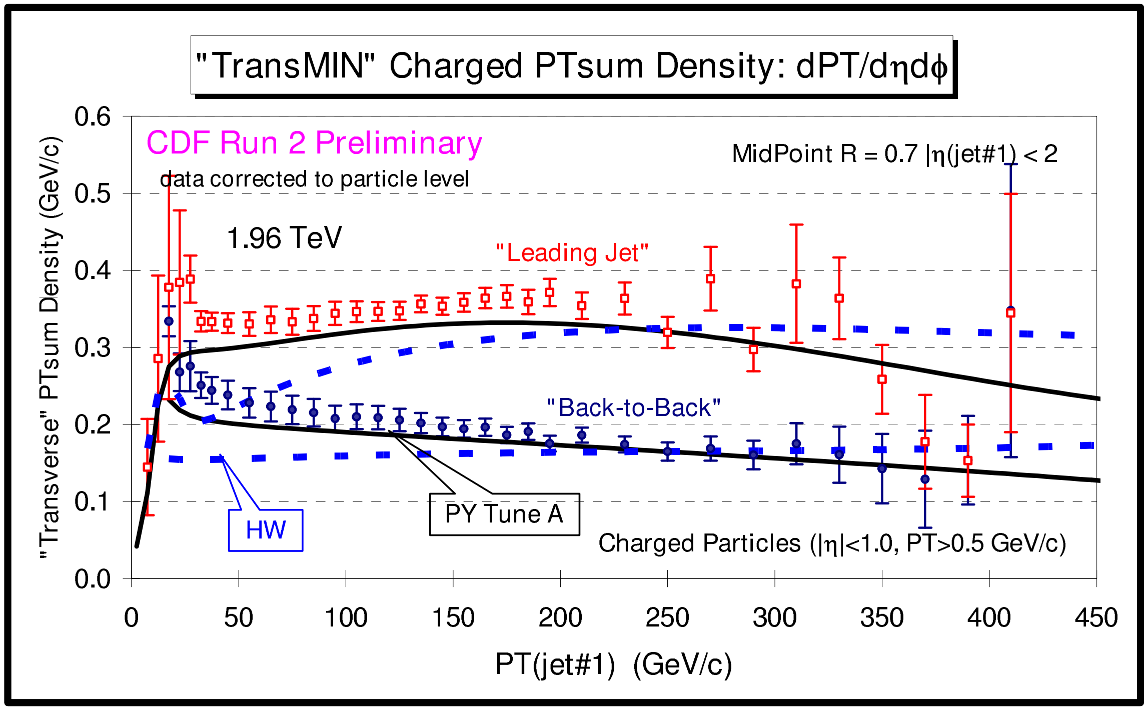
- 2-jet events are back-to-back
- Select events with one hard jet
- The opposite region should contain the 2nd jet
- Look into the transverse regions TRANSmax (more energy) and TRANSmin (less energy)



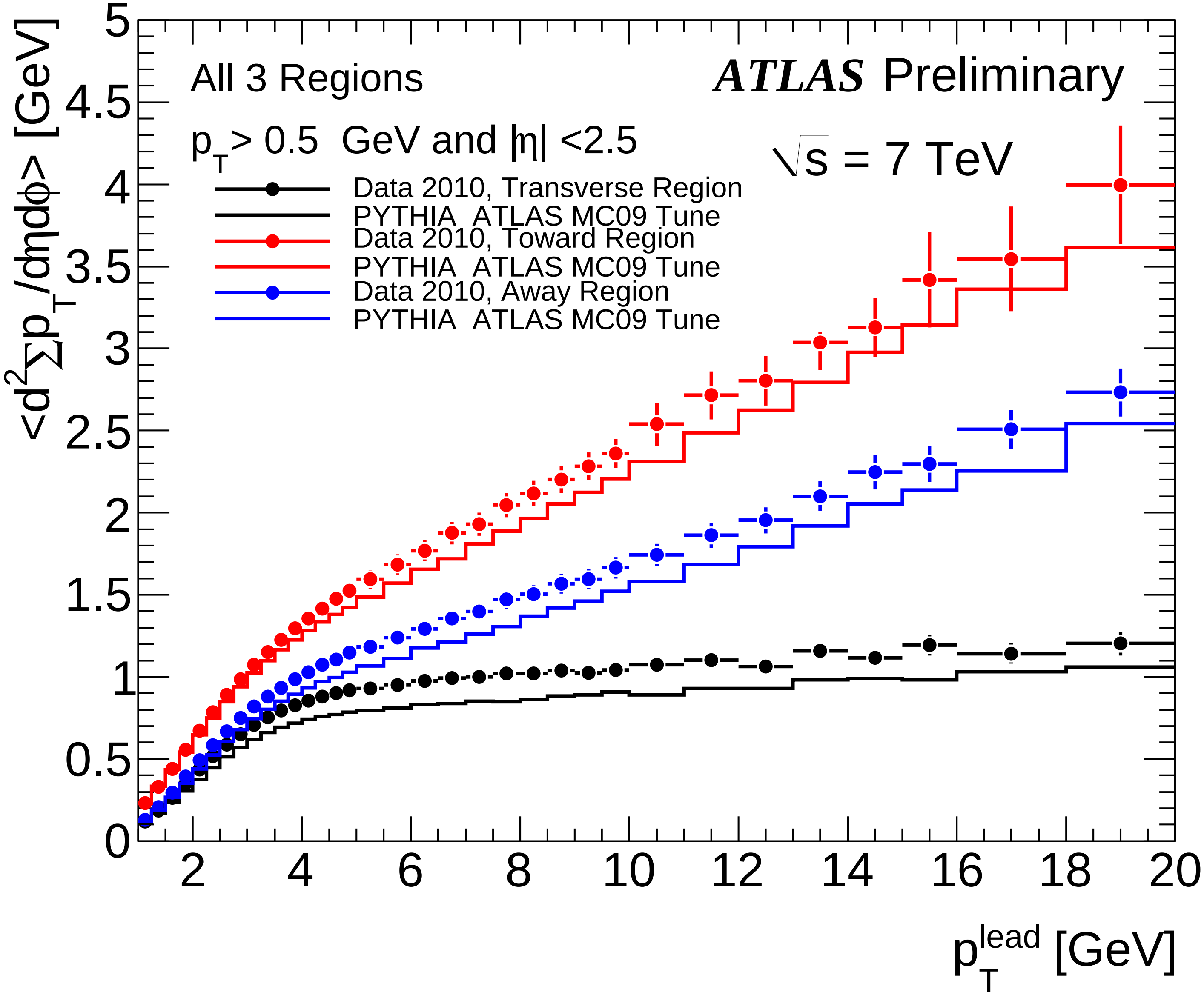


- Generators without multi-parton interactions cannot describe the data
- However generators with UE can be tuned to agree with the data
- Warning: it cannot be expected that the Tevatron tunes describe the LHC data





LHC studies with charged tracks have started, calorimeter-jets will follow



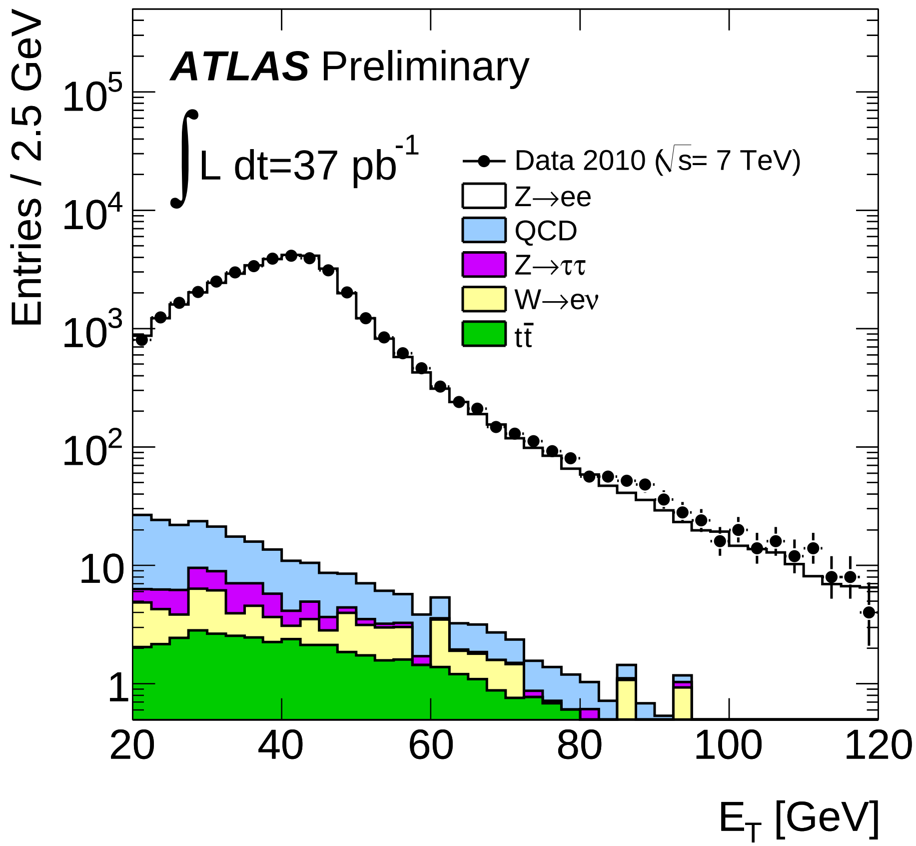
Gauge bosons at the LHC

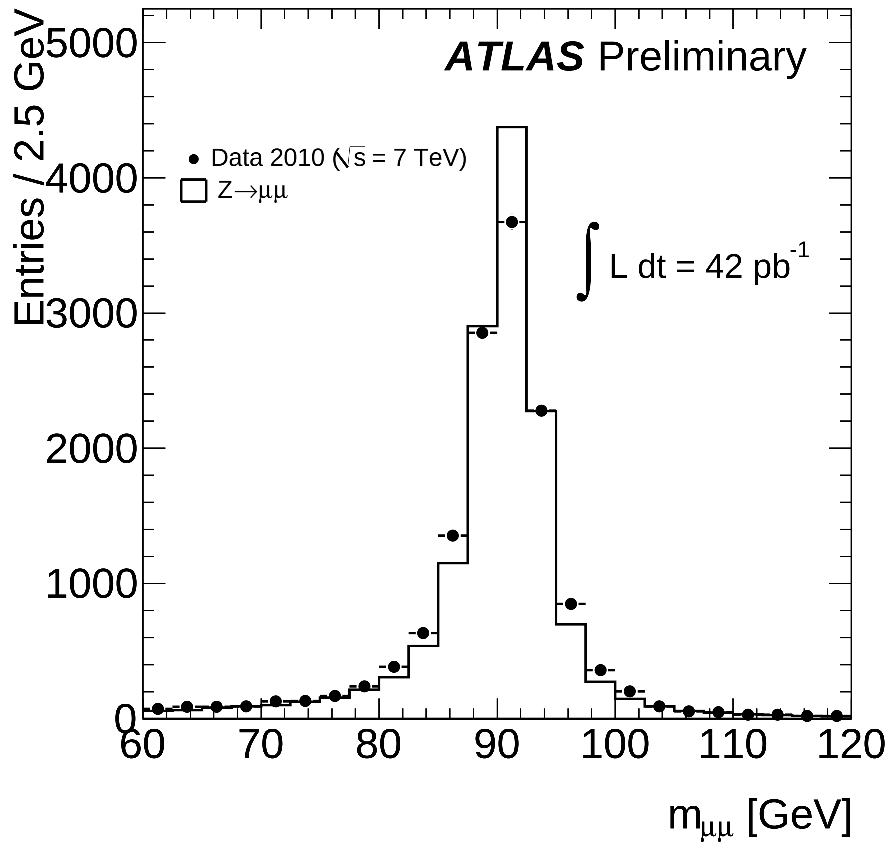
- Gauge bosons are produced via quark-antiquark annihilation
- The quarks are in a regime where the PDFs are well known from HERA
- Theoretical predictions should thus be possible to a few %
- Experimentally only the leptonic decays of W and Z are visible
- Expected cross sections at 7 TeV: $\sim 10\,\mathrm{nb}$ for $pp \to W \to \ell\nu$, $\sim 0.8\,\mathrm{nb}$ for $pp \to Z \to \ell^+\ell^-$

Event selection

$Z \to \ell^+\ell^-$:

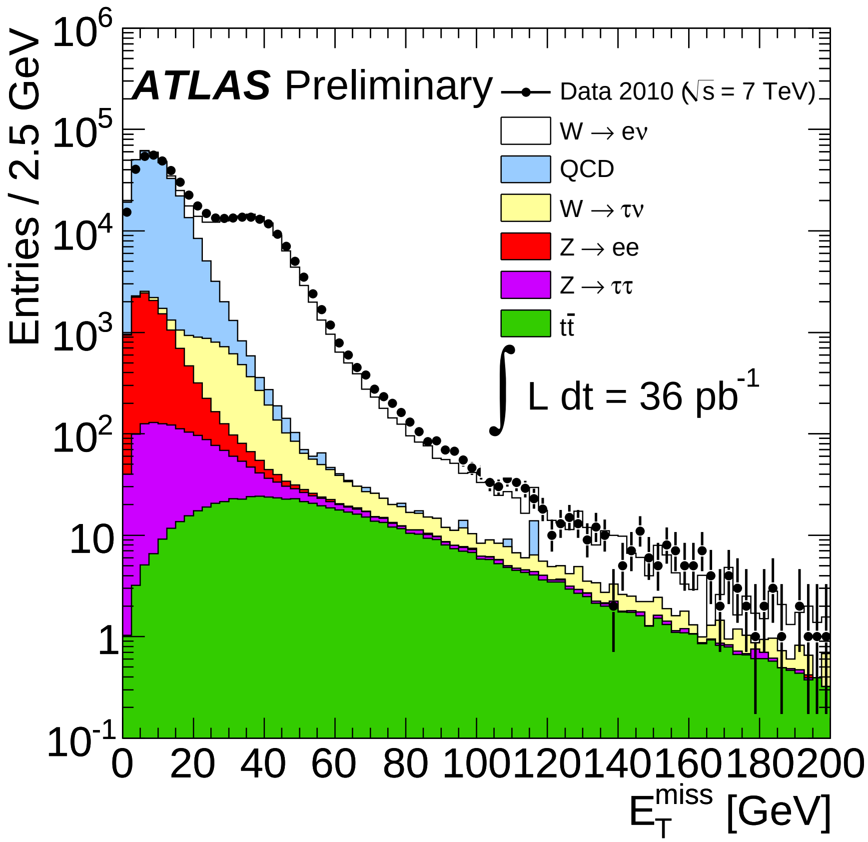
- Just need two loosely defined leptons and invariant mass cut

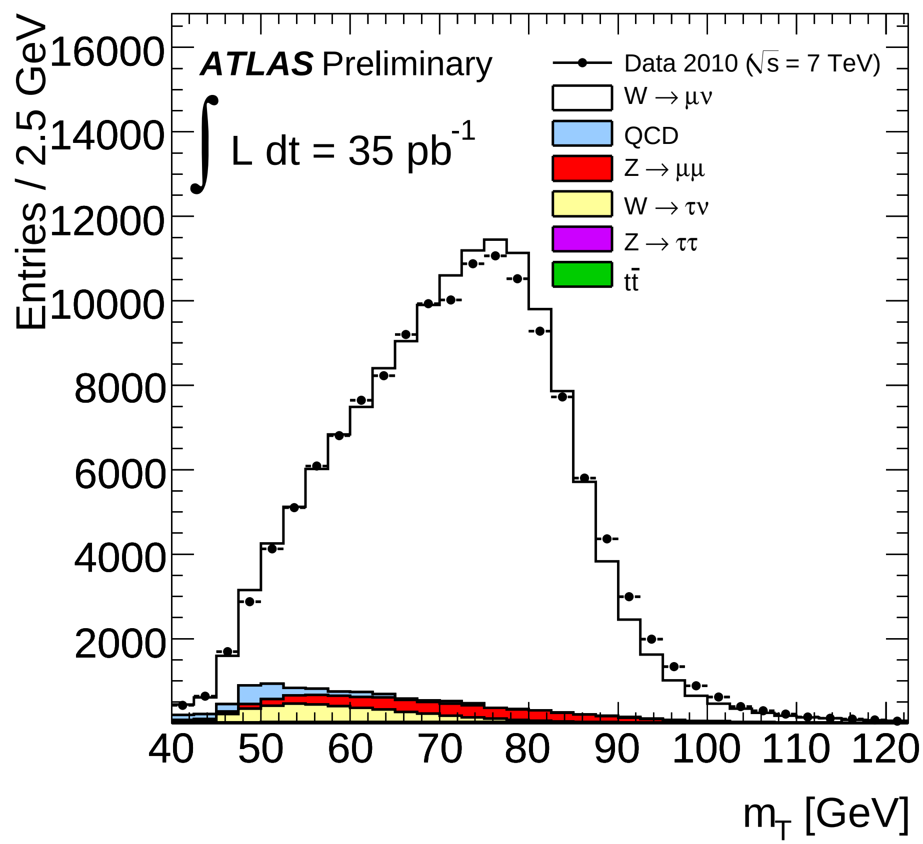




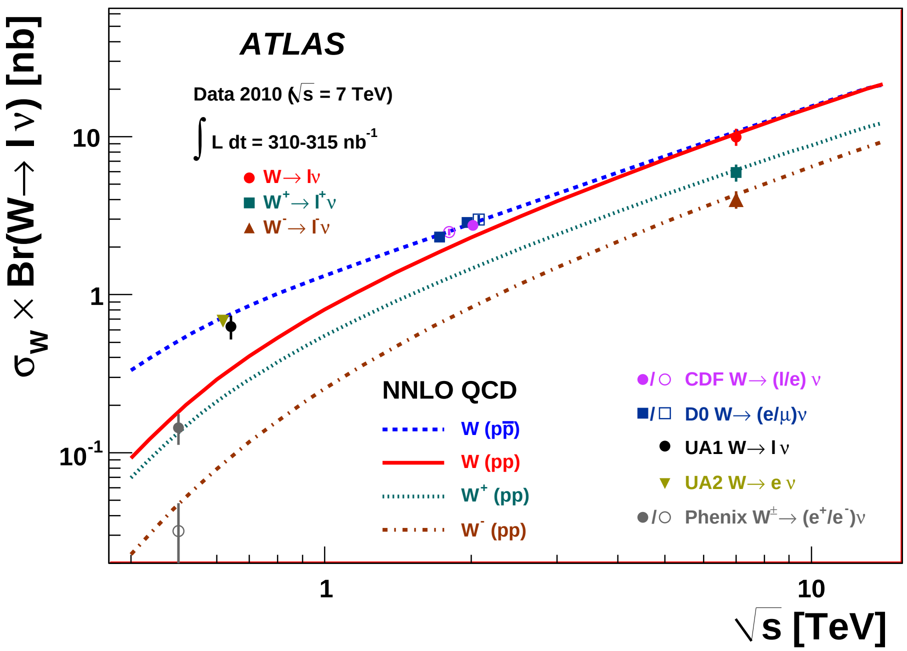
$W \to \ell\nu$

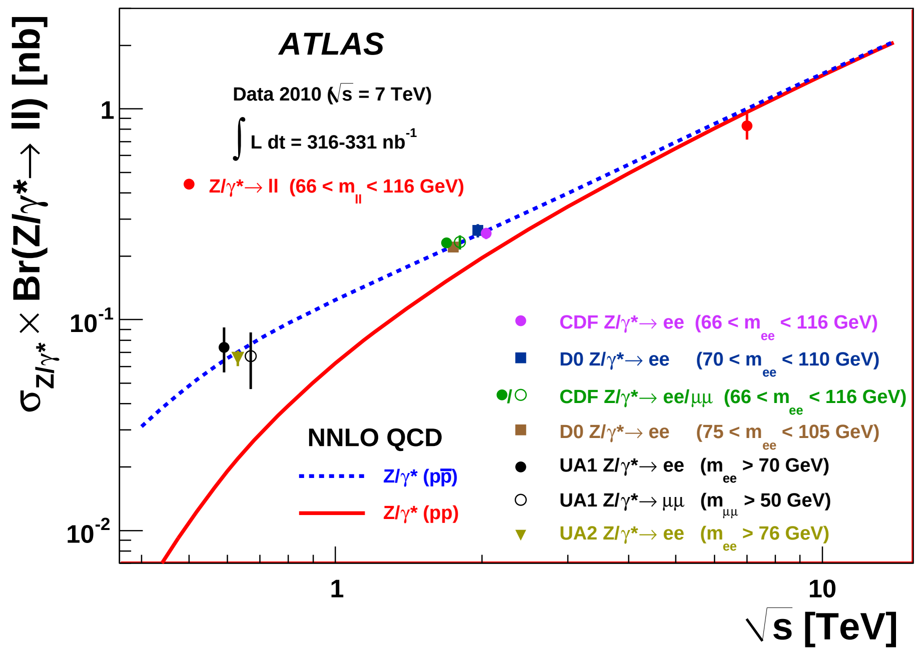
- Need one high p_t lepton with stricter requirements (fakes!)
- Missing E_T largely suppresses QCD background
- Final selection from transverse mass





W,Z cross sections agree well with theory





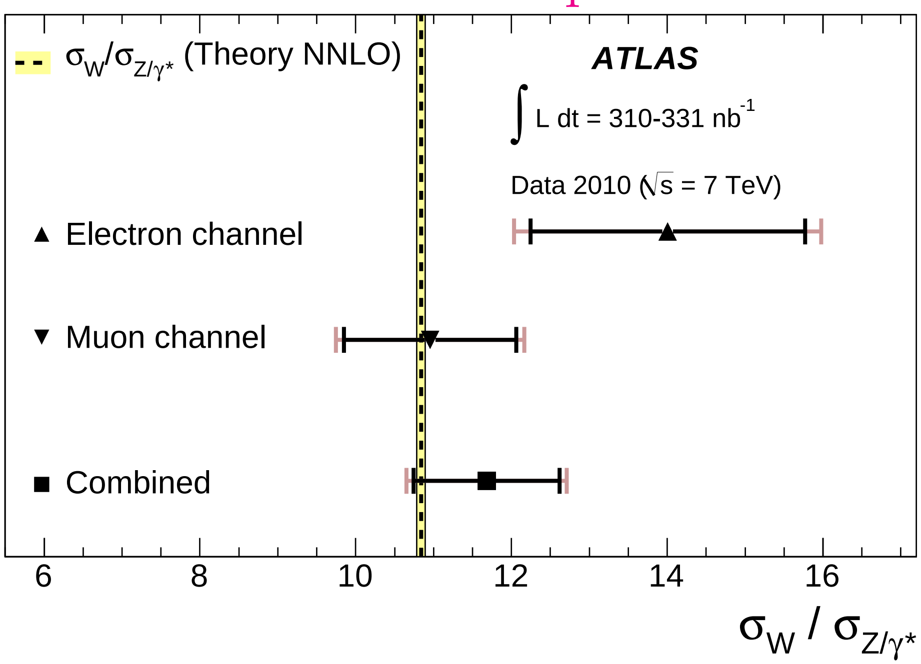
This is a stringent test of QCD

The calculations are so precise that it may even be used as luminosity monitor

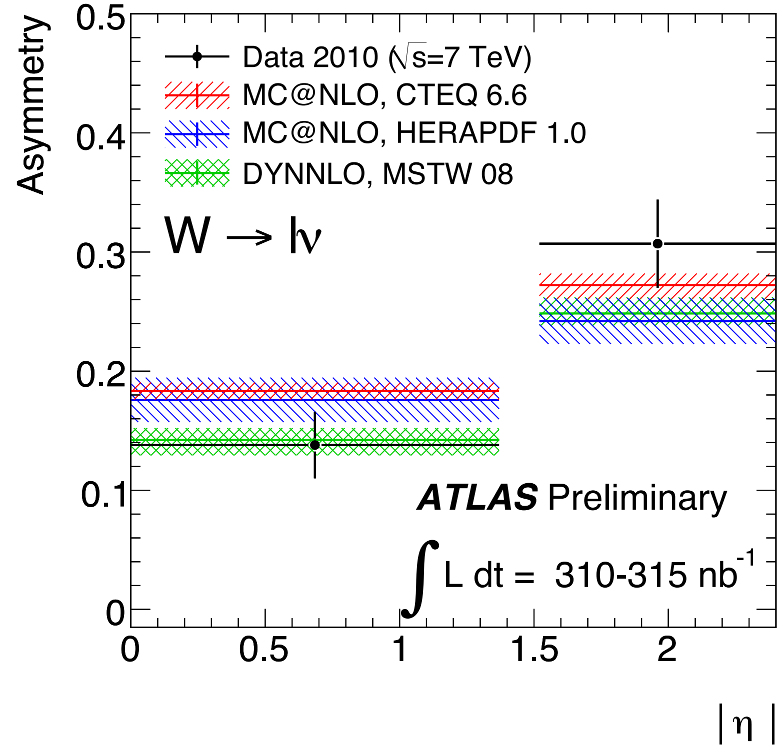
W,Z ratios

- Ratios are a better test of the theory calculations since luminosity and some other systematics drop out.
- In a pp machine also the ratio W^+/W^- is $\neq 1$ because a proton contains more u- than d-quarks
- The ratios may be used to constrain PDF fits

Ratio of W and Z production

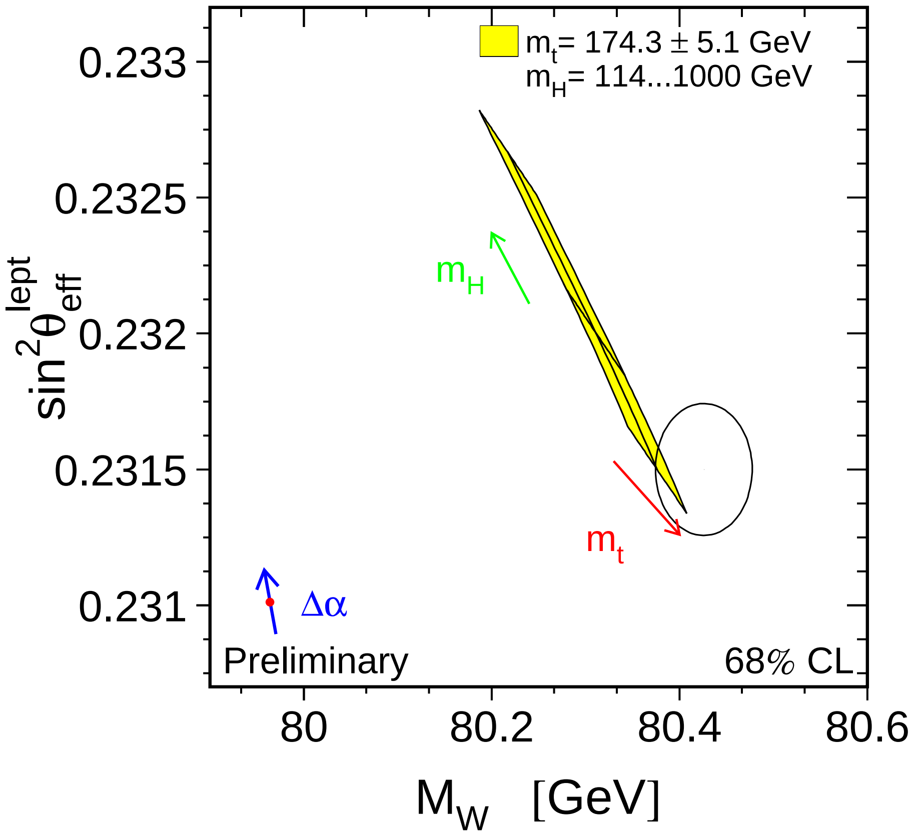


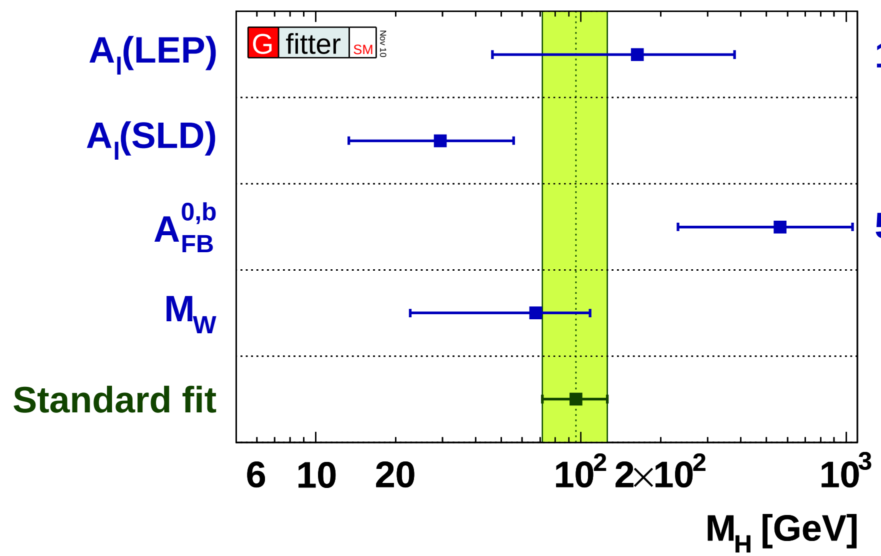
$W^+ - W^-$ asymmetry



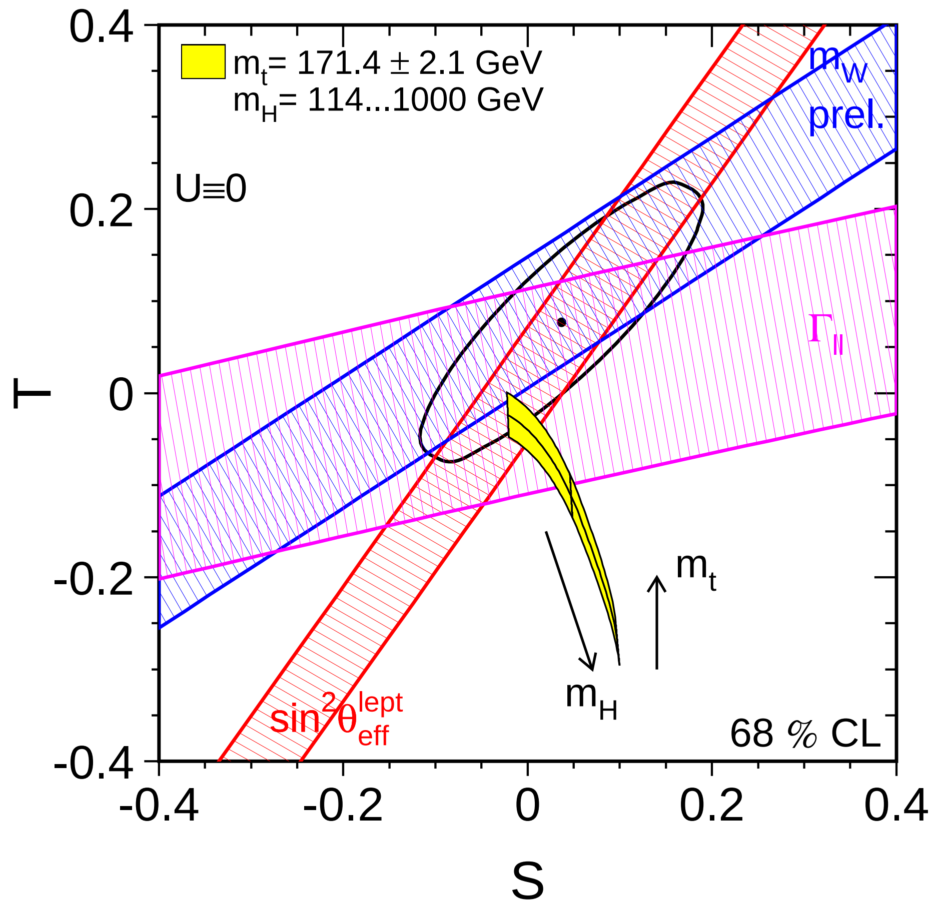
Measurement of the W-mass

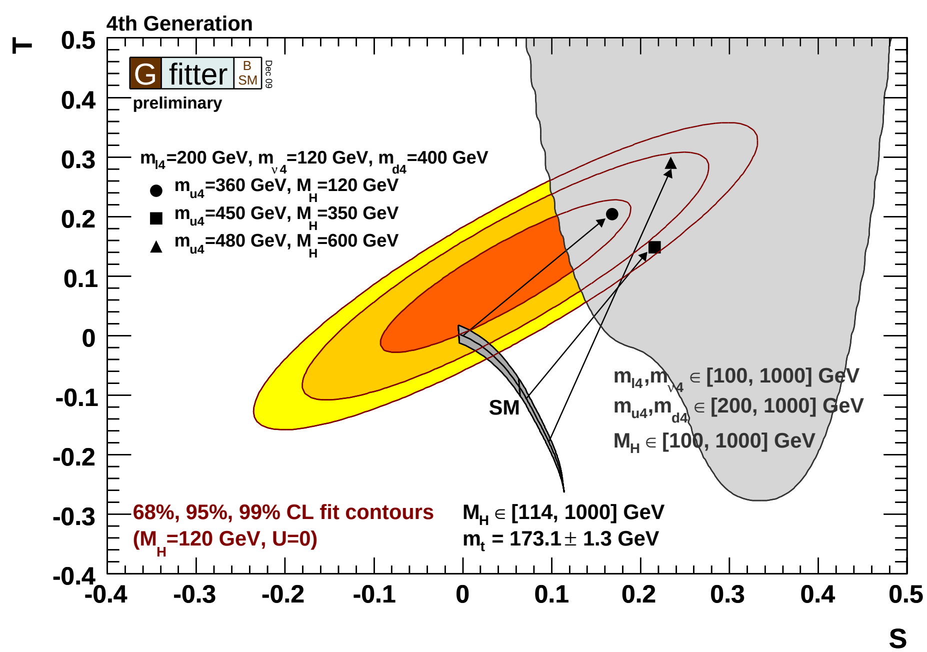
- The W-mass is (together with $\sin^2\theta^l_{eff}$) one of the precision measurements to constrain the Standard Model
- It is known to 30 MeV from LEP and to similar precision from the Tevatron





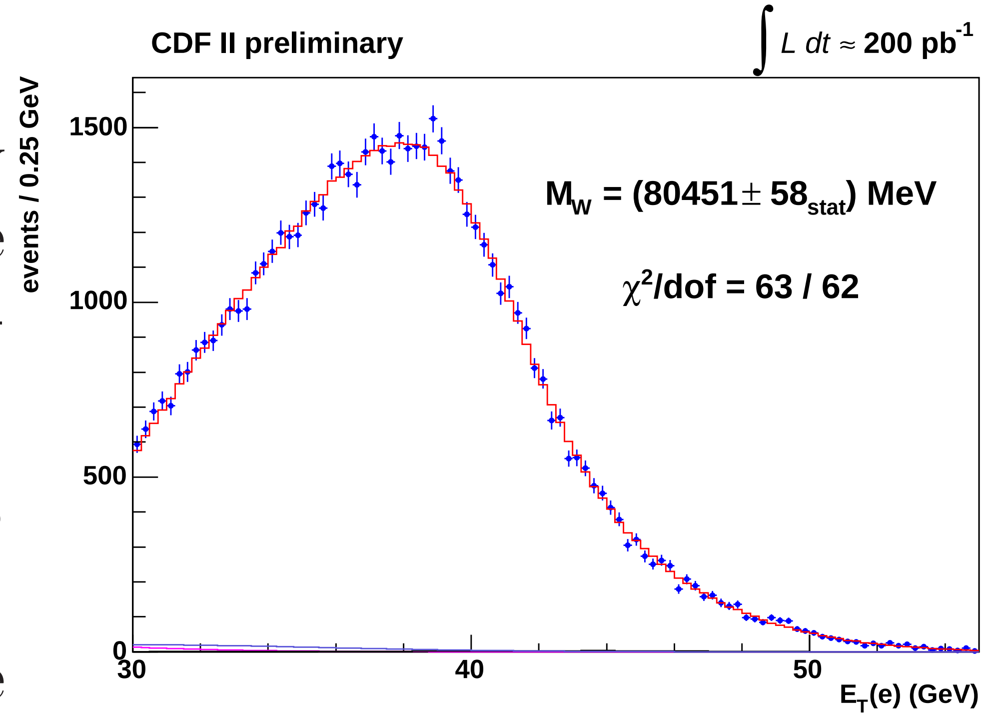
In new physics models with more free parameters m_W is complementary to $\sin^2\theta^l_{eff}$

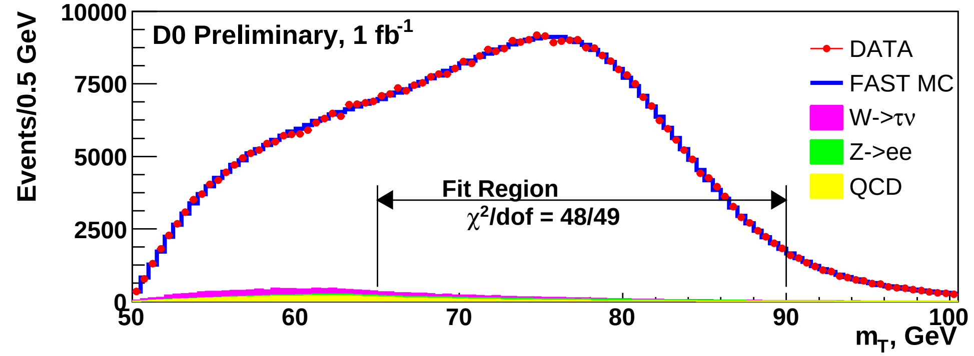


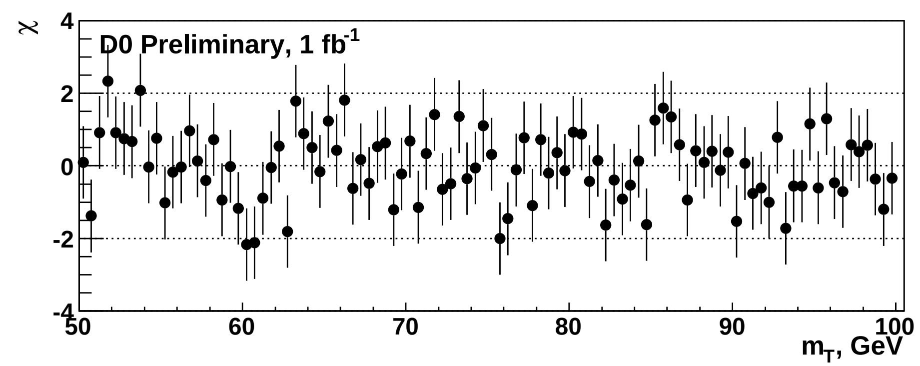


Measurement strategy:

- Cannot reconstruct mass, only transverse momentum of ν can be reconstructed using hadronic recoil
- In principle p_t-lepton is sensitive, however uncertainties from $p_t(W)$
- Can be cured using transverse mass
- Main uncertainty from lepton energy-scale (and jet energy scale)
- Can be calibrated using Z-production
- At Tevatron limited by Z-statistics
- Estimated precision at LHC between 15 and 5 MeV



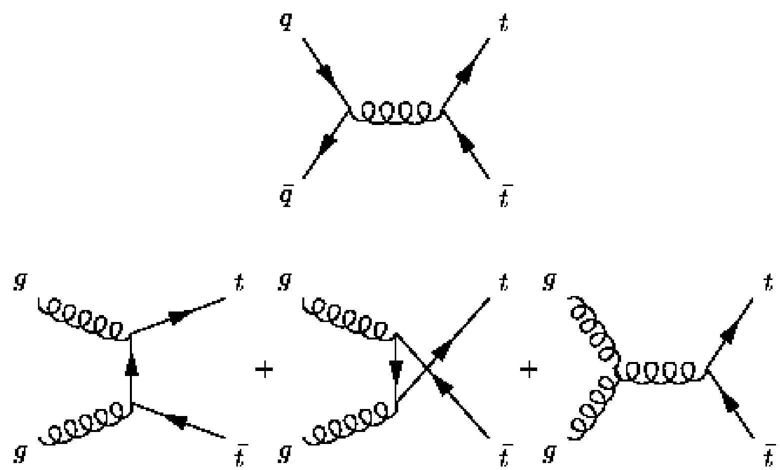




Top-quarks at the LHC

Top pair production:

- $q\bar{q}$ and gg, gg largely dominates at LHC



Top cross section at 14 TeV $\sim$ 800 pb
$\Rightarrow$ 80 000 000 events in 100 fb^{-1}
($\sigma_t \sim$ 170 pb at 7 TeV)

Top decays: $t \to bW$ (99.8%) with

$$\begin{array}{ll} W \to q\bar{q} & 2/3rd \\ W \to \ell\nu,\ \ell = e,\mu & 2/9th \\ W \to \tau\nu & 1/9th \end{array}$$

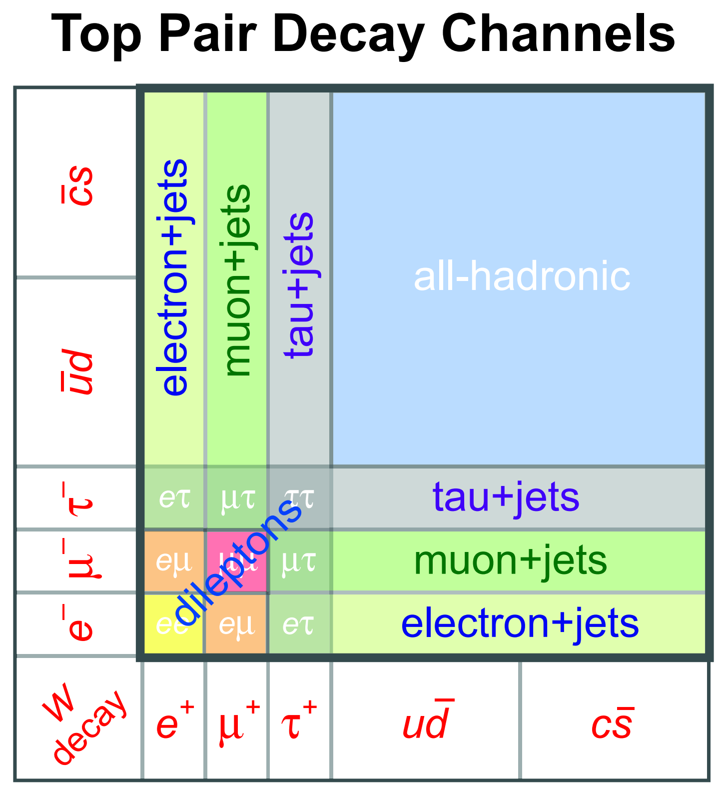
(Rest is $t \to s, d\,W$)

➠ Always have jets in top events

➠ Always have b-quarks

This means for $t\bar{t}$ events:

- 45% 2 b-jets + 4 light jets
  - everything can be reconstructed
  - however large pairing ambiguities
  - large QCD backgrounds



- 30% 2 b-jets, 2 light jets, 1ℓ , 1ν
  - the neutrino can be reconstructed with a 2-fold ambiguity using the W-mass
  - pairing ambiguities are less
  - lepton strongly suppresses QCD background
- 5% 2 b-jets, 2ℓ , 2ν
  - clean samples
  - however few constraints for reconstruction
- Rest contains τs ➠ difficult

Intermezzo: b-tagging at colliders

- b-quarks decay semileptonically with $BR(b \to \ell X) = 2 \times 10\%$
  - can be used for b-tagging
  - however low efficiency from the beginning
  - leptons inside jets where fake rate is high
- b-quarks have significant lifetime ($c\tau \sim 0.5$mm)
  - e.g. flight distance of 50 GeV B-meson: $\sim$ 5mm
  - impact parameter w.r.t. primary vertex: $\sim 500\mu$m
  - resolution of modern vertex detectors: $\sim 10\mu$m

  ➠ can use vertexing for b-tagging

Impact parameter methods

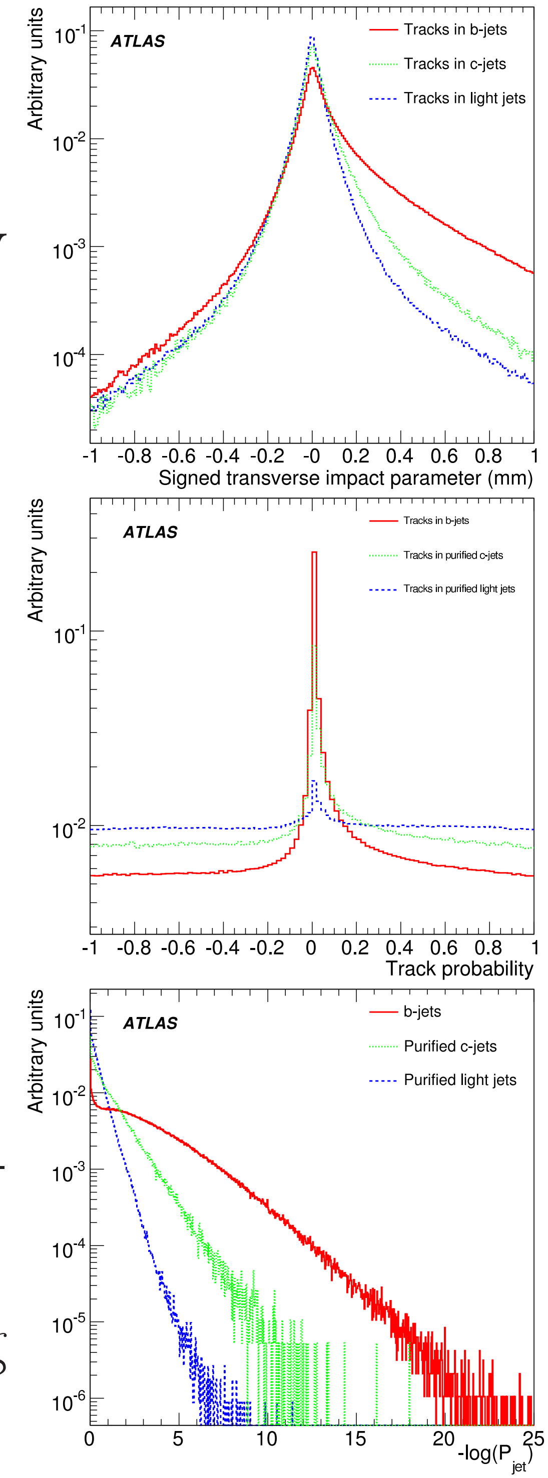
- Signed track impact parameter gives already good sensitivity for b-tagging
- Calculate probability for optimal use

$$\mathcal{P}_i = \int_{d_i/\sigma_{d,i}}^{\infty} \mathcal{R}(x)dx$$

- Tracks in a jet/event can be combined

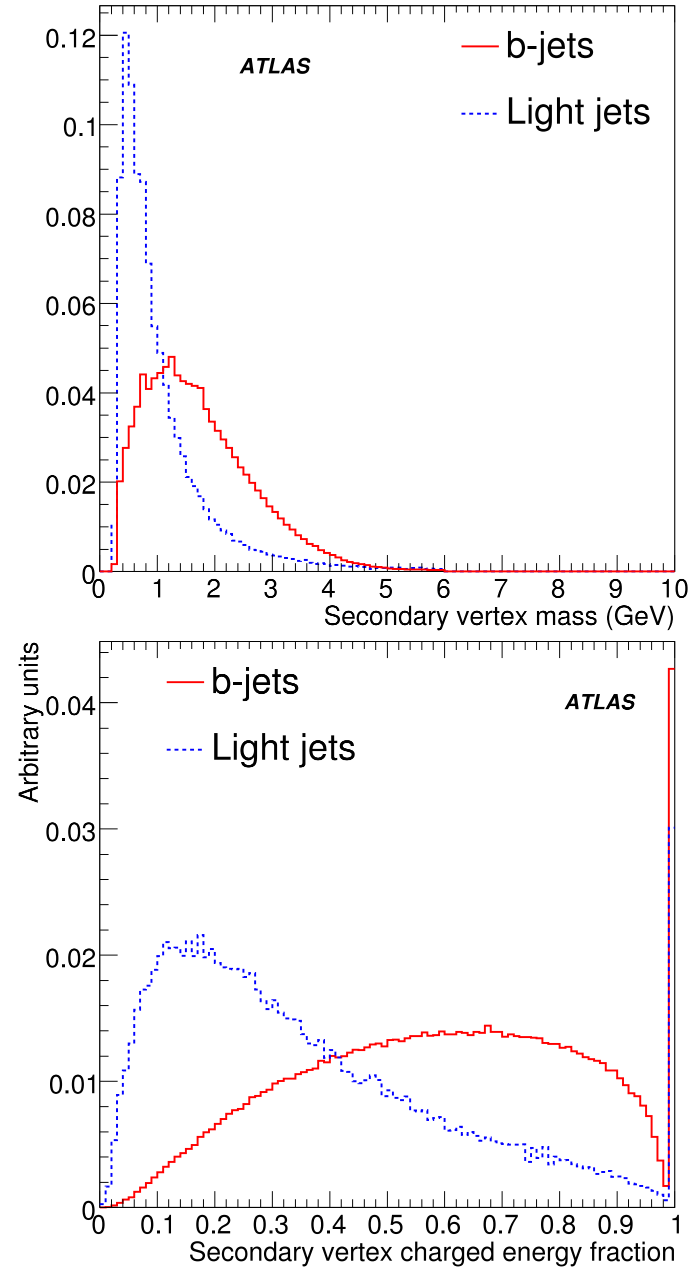
$$\mathcal{P}_0 = \prod_i^N \mathcal{P}_i \qquad \mathcal{P} = \sum_0^{N-1} \frac{(-\ln \mathcal{P}_0)^j}{j!}$$

- In principle this method gives an optimal separation of b- and light jets
- However very sensitive understanding of tracking

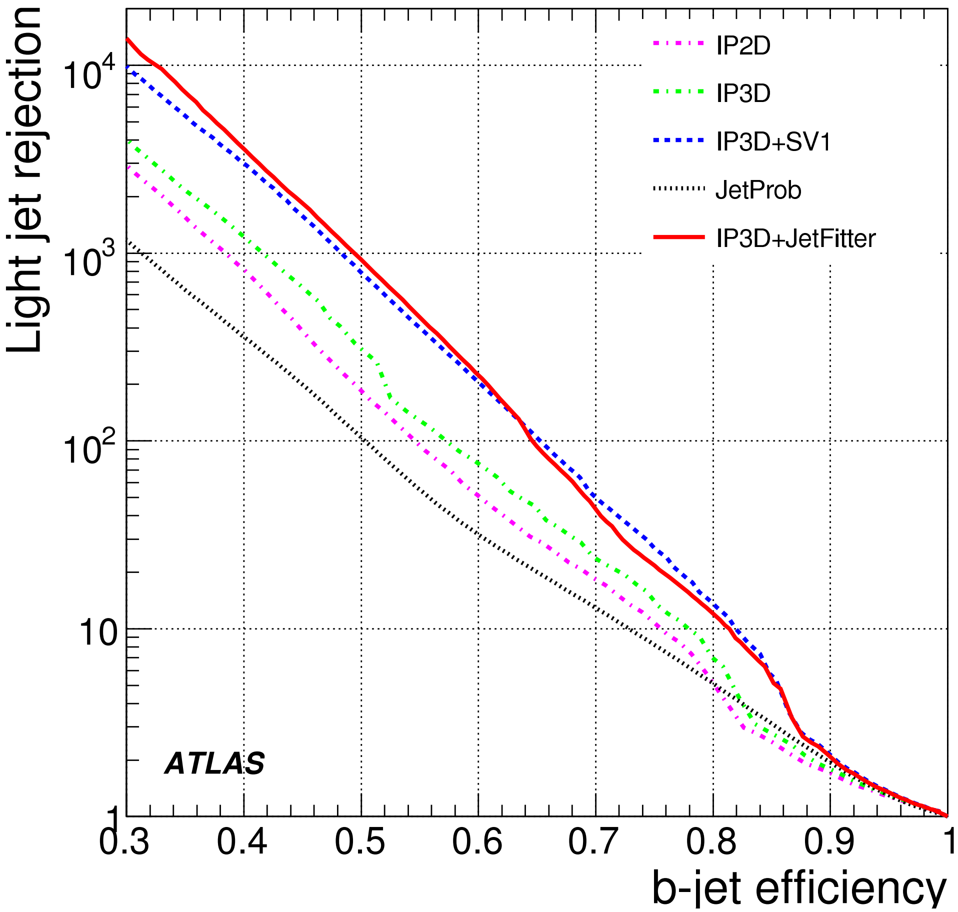


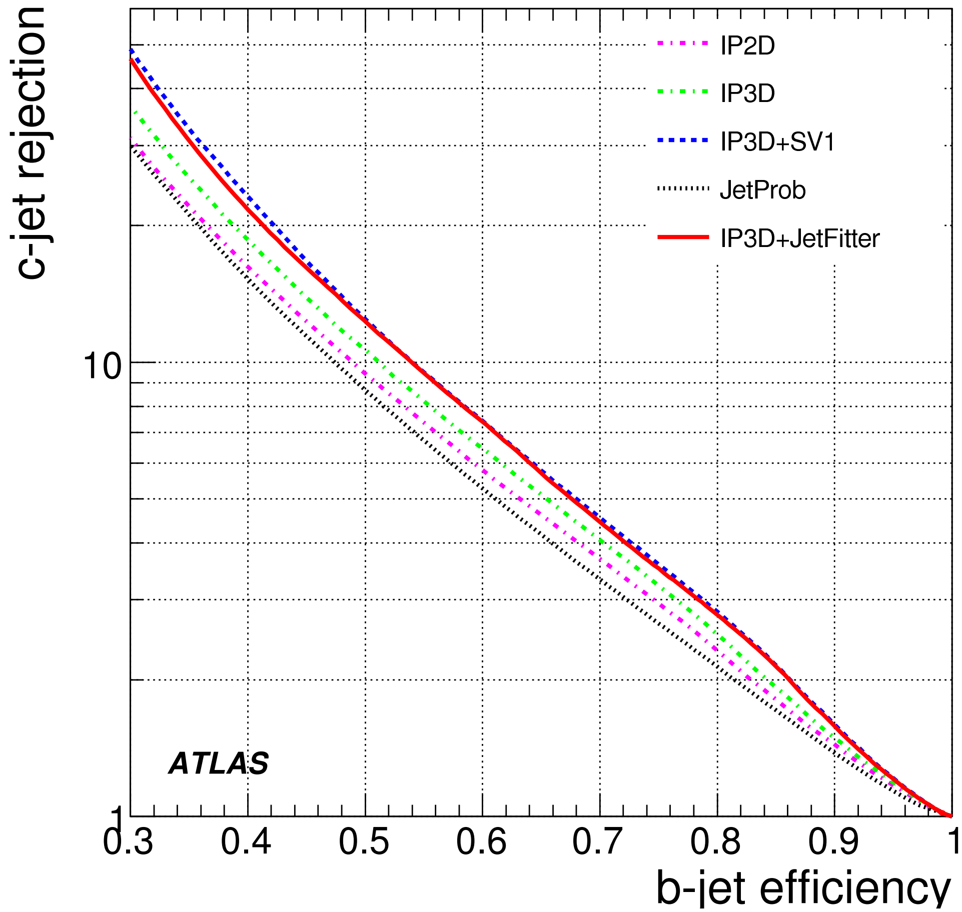
Enhancement/alternative: secondary vertices

- Secondary vertices are not faked so easily by reconstruction problems
- The vertex mass gives a good separation especially to c-quarks
- The energy of the fitted particles normalised to the jet energy makes use of the hard b-fragmentation (average B energy is $\sim 80\%$ of jet energy)



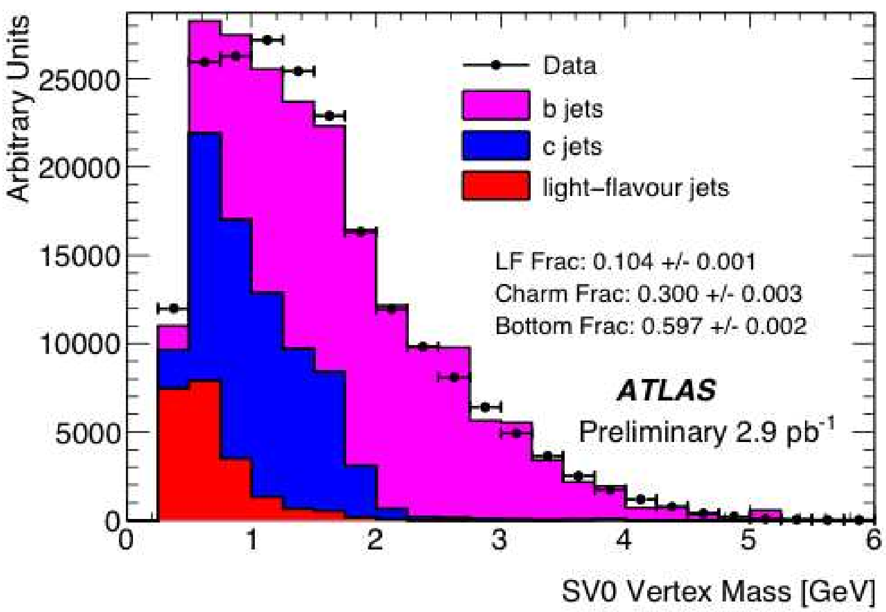
With the available methods e.g. a light quark rejection of 10^3 and a c-quark rejection of 10 can be achieved for 50% b-efficiency ($t\bar{t}$ events)

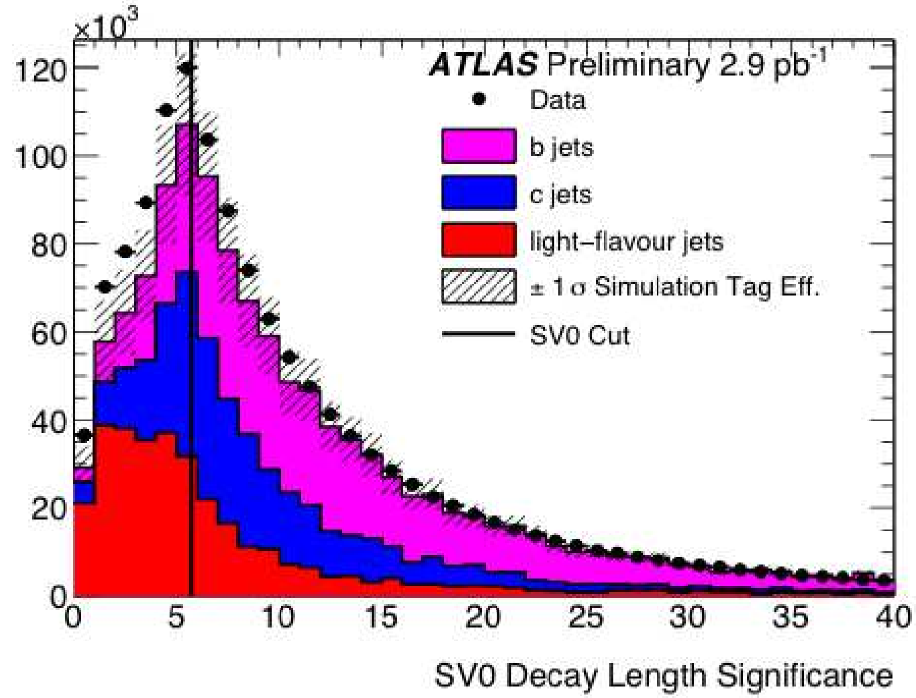




B-tagging in 2010

- Sophisticated methods require good detector understanding
- Prefer simple methods for startup
- User secondary vertex tagger





Selection of $t\bar{t}$ events

Concentrate on mixed decays:

- $E_{T,miss} > 20\,\text{GeV}$ (neutrino!)
- 1 isolated lepton with $P_T > 20\,\text{GeV}$
- 2 b-jets with $p_T > 40\,\text{GeV}$ and ≥ 2 light jets with $p_T > 40\,\text{GeV}$

(At the beginning of data taking b-tagging can be dropped at the price of a larger background)

Hadronic W reconstruction

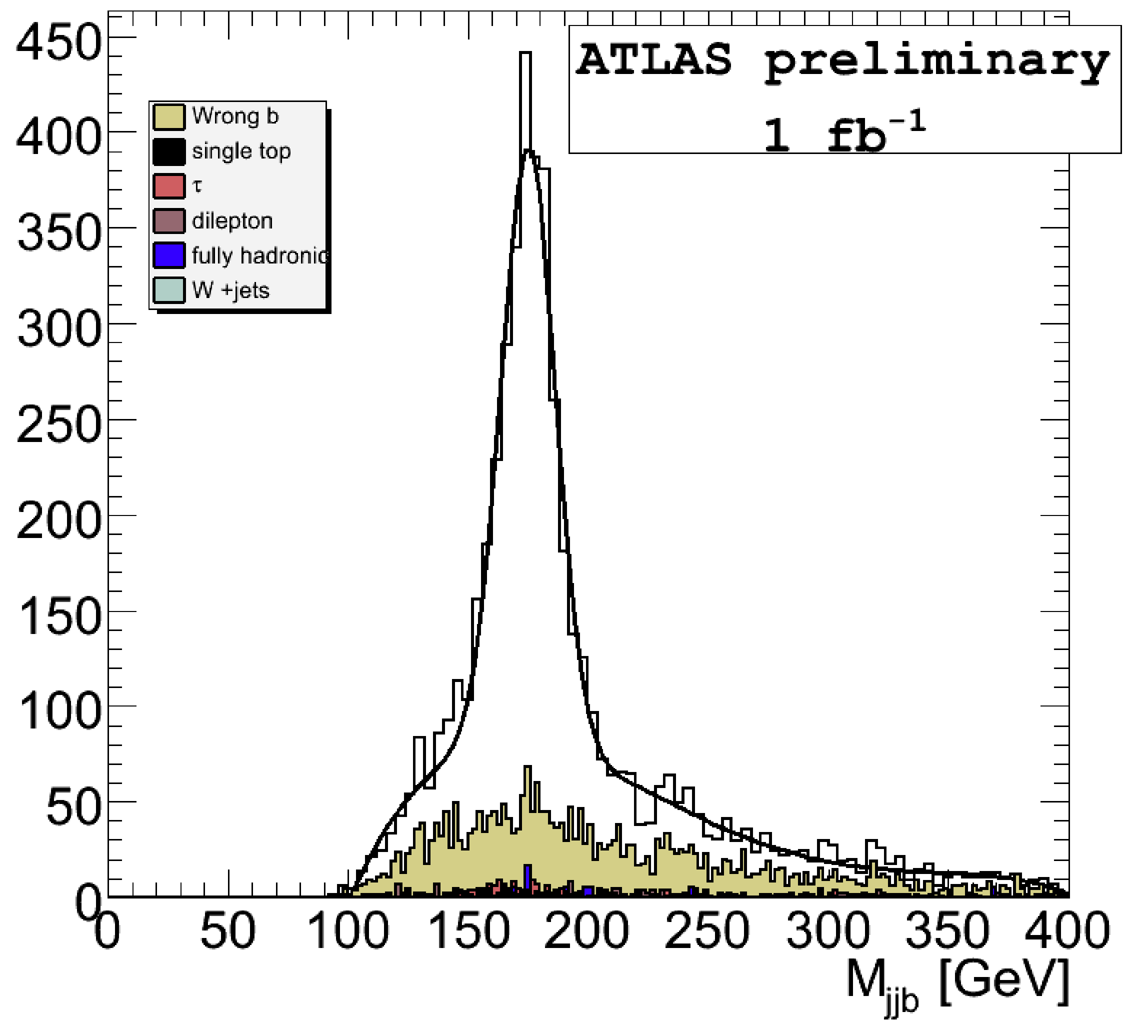
- Accept light jet pair if consistent with m_W at 3σ
- Rescale jets to m_W using a χ^2 technique
- Cut again on jet-jet mass around m_W

W-b association

- Take the combination with minimal ΔR

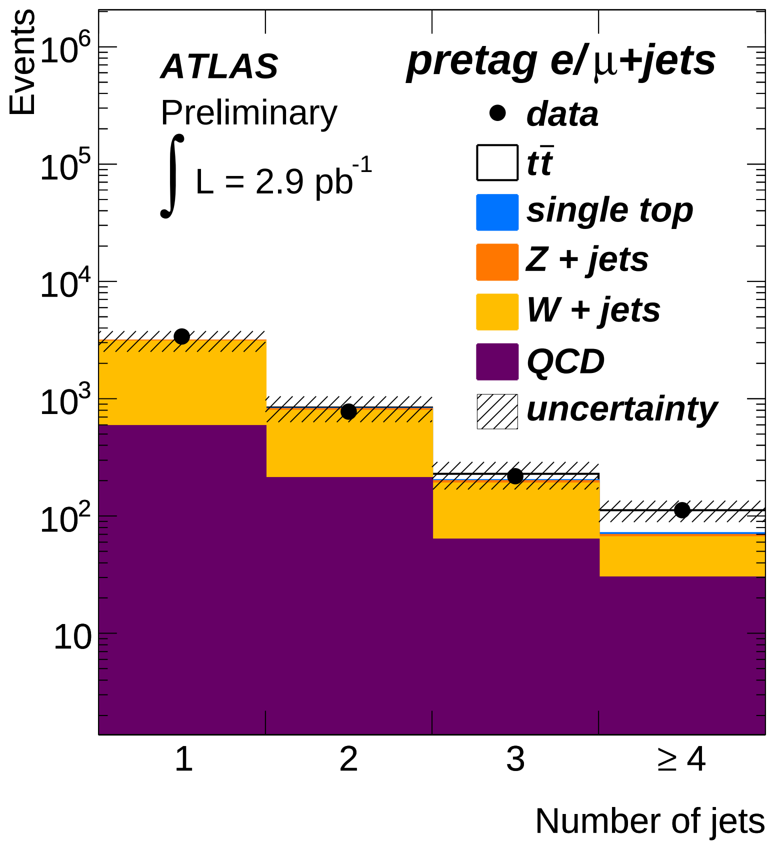
Top mass distribution for the top-mass analysis

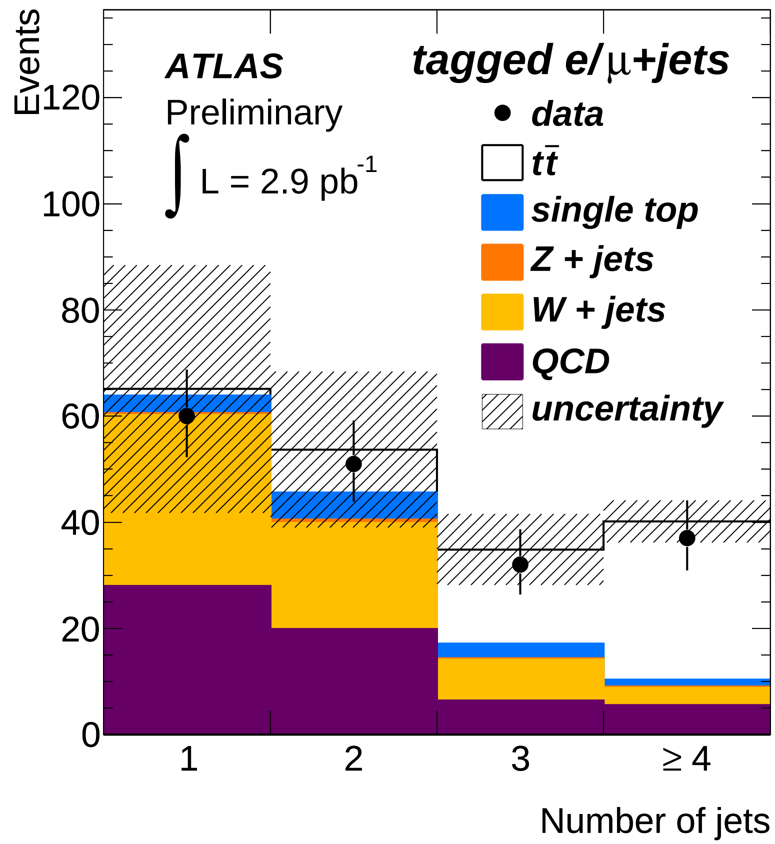
- Selected top-sample has very little non-$t\bar{t}$ background
- For mass determination most serious background is combinatorial background



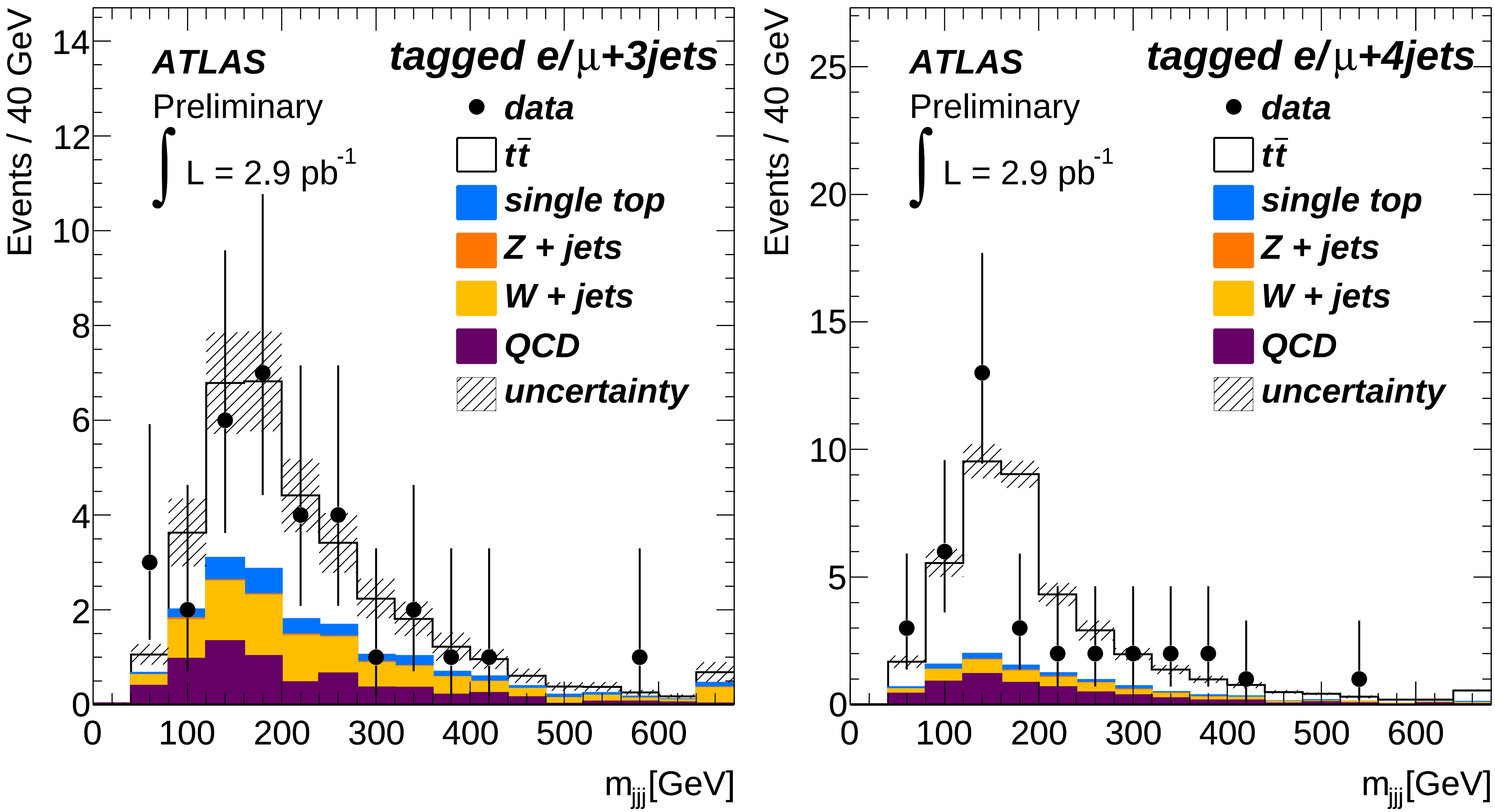
Top quarks at 7 TeV

- Semileptonic analysis:
  - Cut on $p_T^\ell > 20\,\text{GeV}$, $E_{T,miss} > 20\,\text{GeV}$, $m_T + E_{T,miss} > 60\,\text{GeV}$
  - Require 1 b-tag and take signal from events with 4 jets with $p_T > 25\,\text{GeV}$

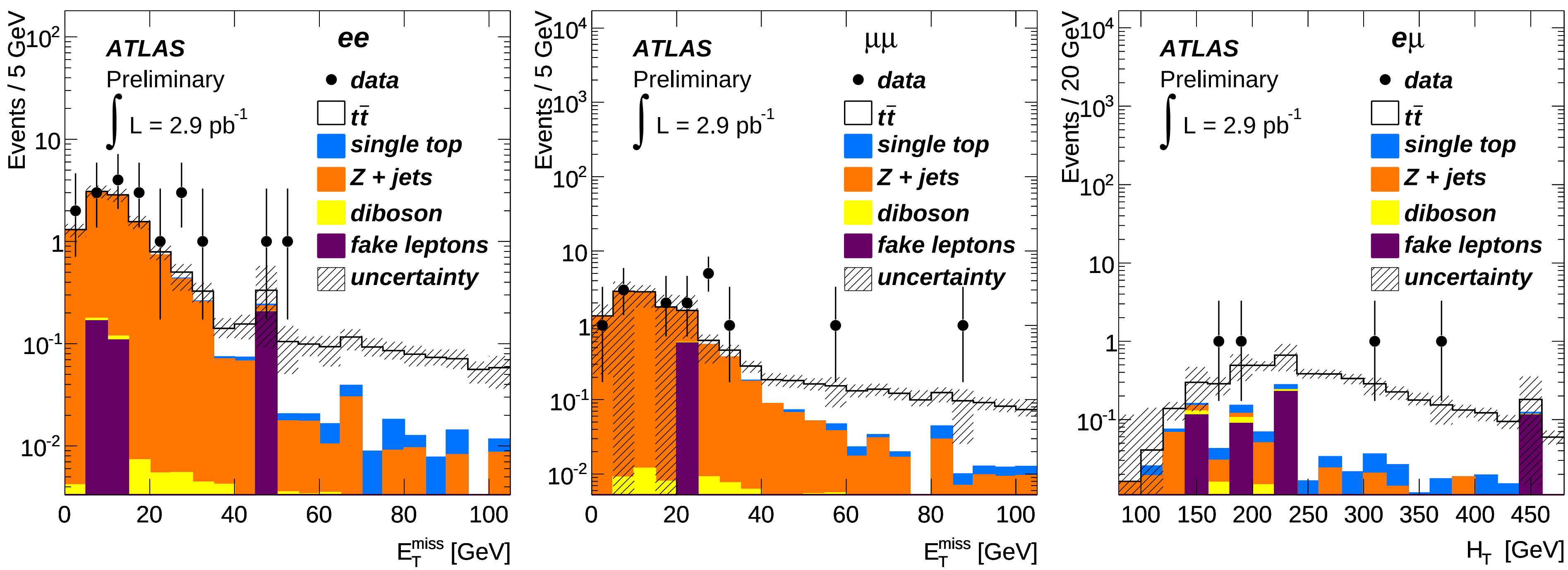




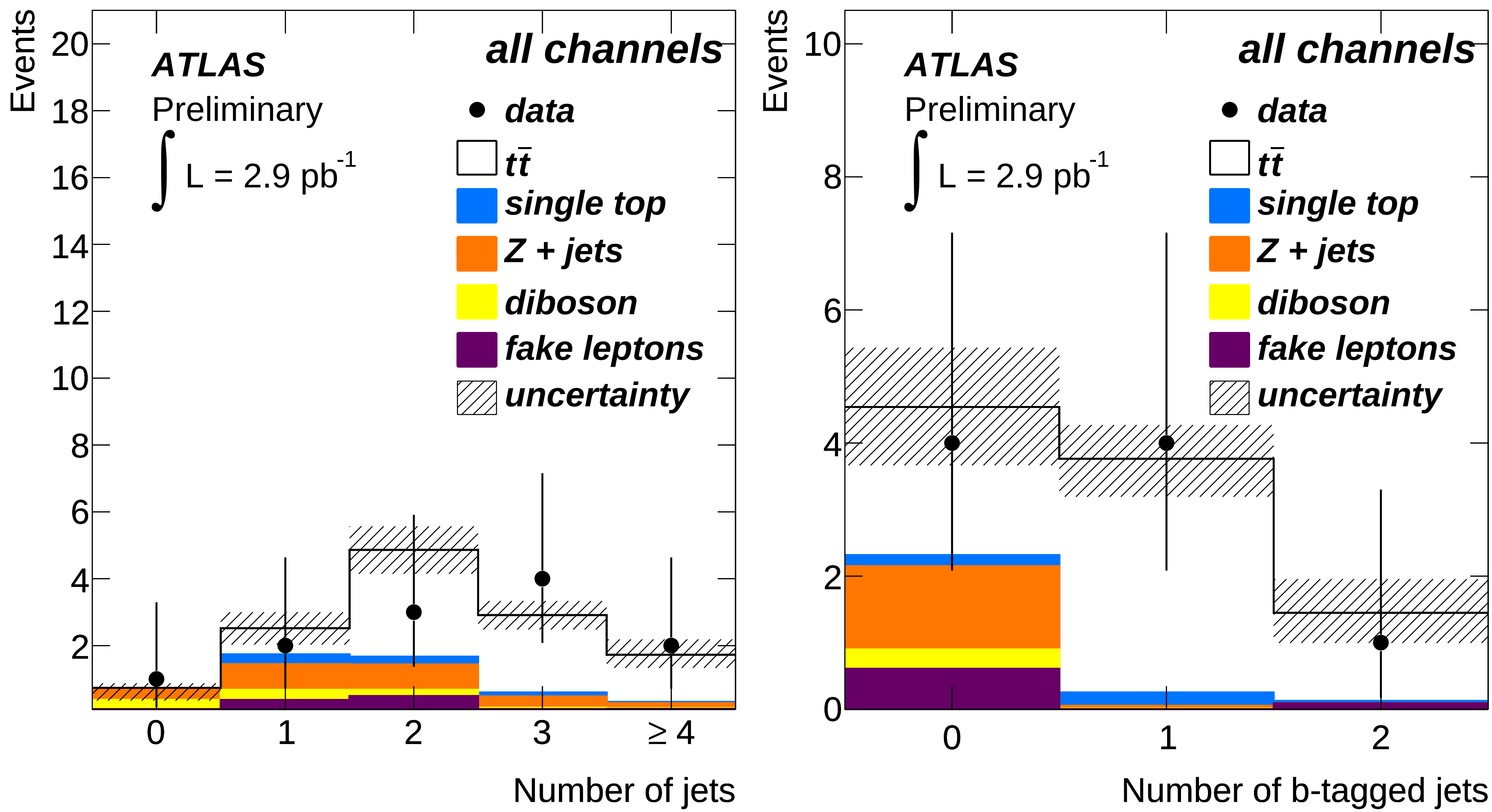
3-jet mass combinations peak at top-mass as expected



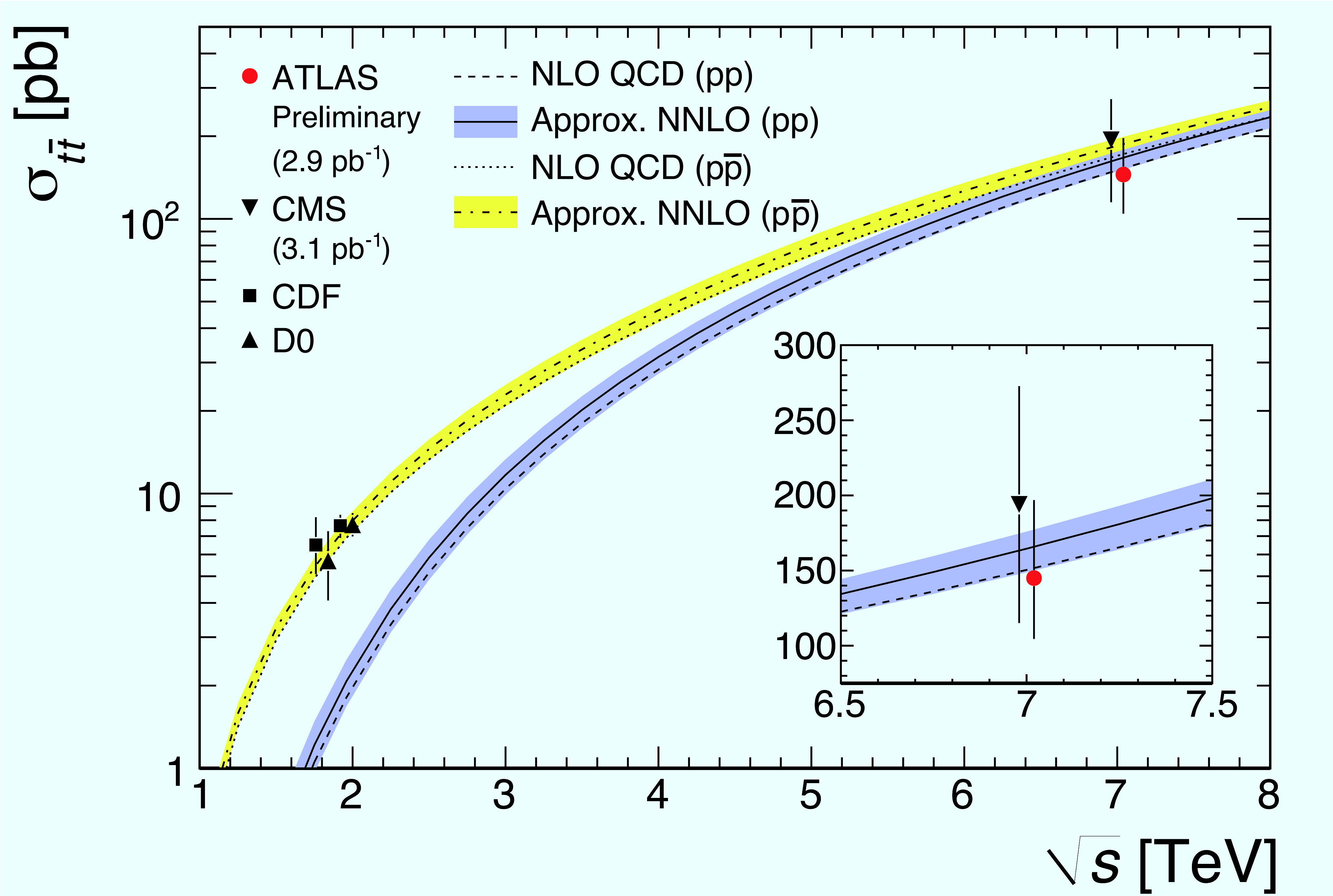
- Dilepton analysis:
  - ee ($\mu\mu$): require $E_{T,miss} > 40\,(30)$ GeV
  - eμ: scalar sum of transverse energy $H_T > 150$ GeV
  - no b-tagging needed



Jet and b-jet distributions agree with expectation



Measured cross section agrees well with SM prediction

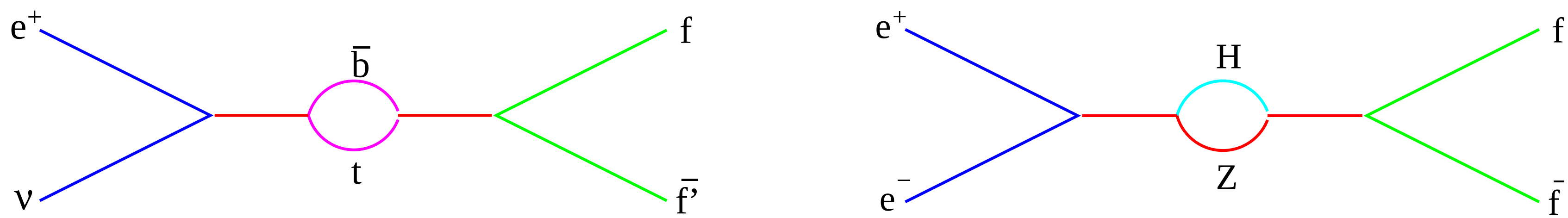


Measurements of the top-quark mass

Why is the top mass interesting?

SM:

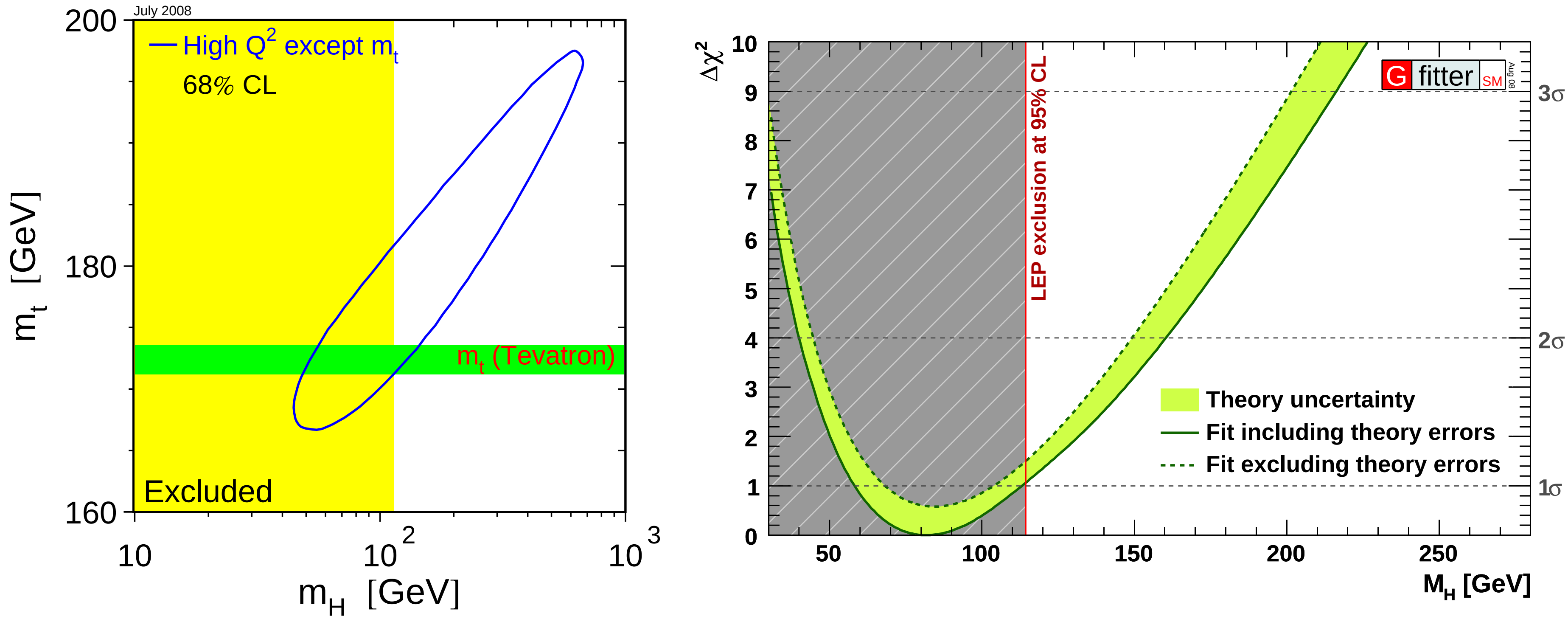
- Electroweak precision data are affected by loop corrections



e.g. $m_{\mathrm{W}}^2 = \frac{1}{2} m_{\mathrm{Z}}^2 \left(1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_{\mathrm{F}} m_{\mathrm{Z}}^2} \frac{1}{1 - \Delta r}} \right)$

- Can be used e.g. to constrain m_{H}
- Top-quarks corrections are quadratic ➡ need to be known to get useful results

For this need m_t measurement of $\mathcal{O}(1\,\mathrm{GeV})$



Beyond SM

- Some models like SUSY predict the Higgs mass from the model parameters
- Here the m_t corrections can be of order $\Delta m_H/\Delta m_t \sim 1$

➡ In principle a much better top mass is needed

Current uncertainty from the Tevatron: $\Delta m_{\mathrm{t}} = 1.2\,\mathrm{GeV}$

This does not yet include

- errors from colour reconnection effects
- uncertainties from the mass definition

which might add up again to $1\,\mathrm{GeV}$

Expectation at the LHC: $\Delta m_{\mathrm{t}} \lesssim 1\,\mathrm{GeV}$

- totally dominated by systematics
- largest experimental uncertainty: energy scale of b-jets
- errors from QCD might be of similar size

Search for rare top decays

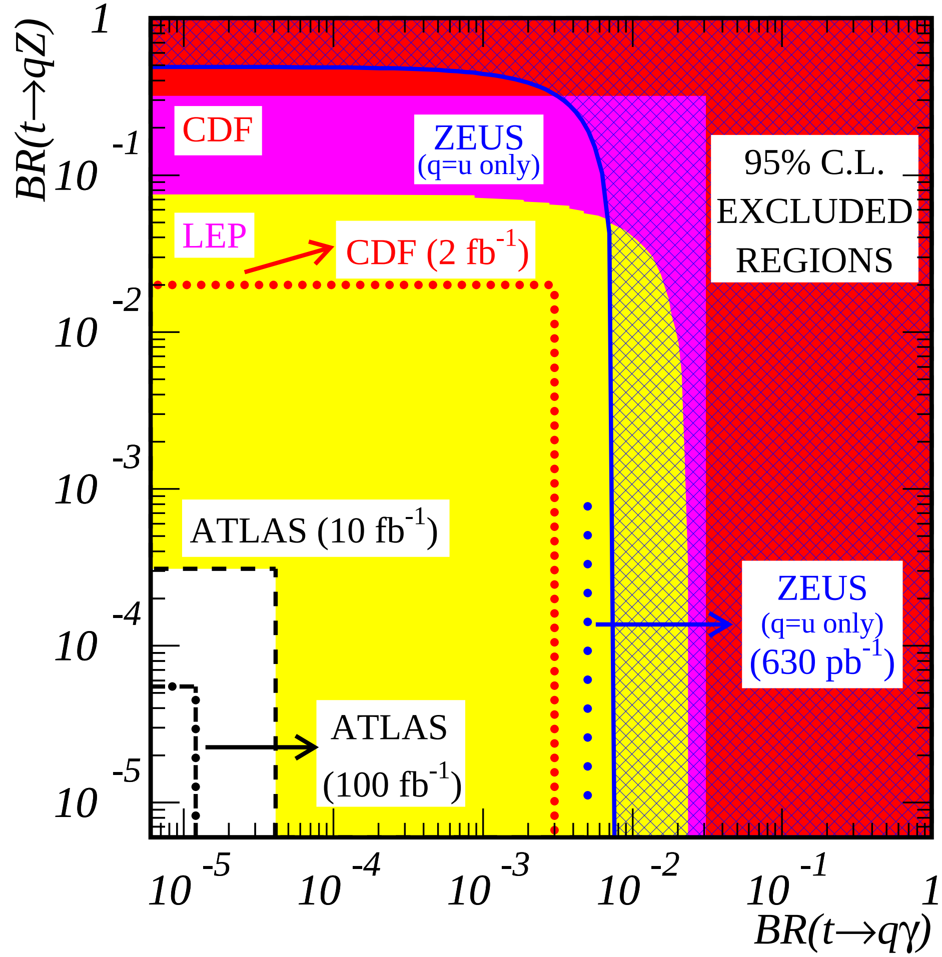
The SM predicts FCNC top decays ($t \to Zq$, γq, gq) on the 10^{-14} – 10^{-12} level

In some new physics scenarios 10^{-4} can be reached

Example for a $t \to Zq$, $Z \to \ell\ell$ selection:

Description of Cuts	Signal $t \to Zq$ ε (%)	Background Processes Z+jets Nevt	$Z+W$ Nevt	tt Nevt
Preselection 3 leptons, 2 jets	80.2	3.7×10^5	2941	11.7×10^5
3 leptons, $p_T^\ell > 20$ GeV/c	43.3	945	1778	1858
$\not{p}_T > 30$ GeV	32.7	80	1252	1600
2 jets, $P_T^{jet} > 50$ GeV/c	19.8	31	225	596
$m_Z \pm 6$ GeV	16.8	24	180	29
one b-tag	8.2	10	28	10
$m_t \pm 24$ GeV	6.1	0	2	5

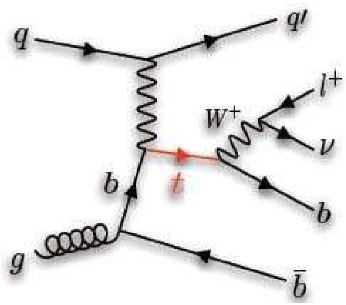
Even the LHC can only scratch the interesting region!



Measurement of single top production

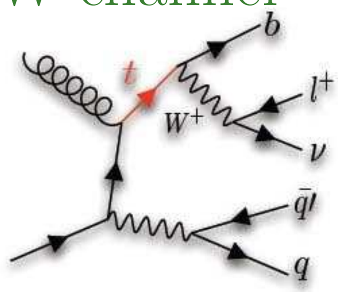
Feynman graphs

t-channel



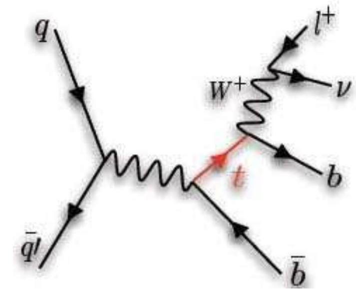
$\sigma = 260\,\mathrm{pb}$

W-channel



$\sigma = 60\,\mathrm{pb}$

s-channel

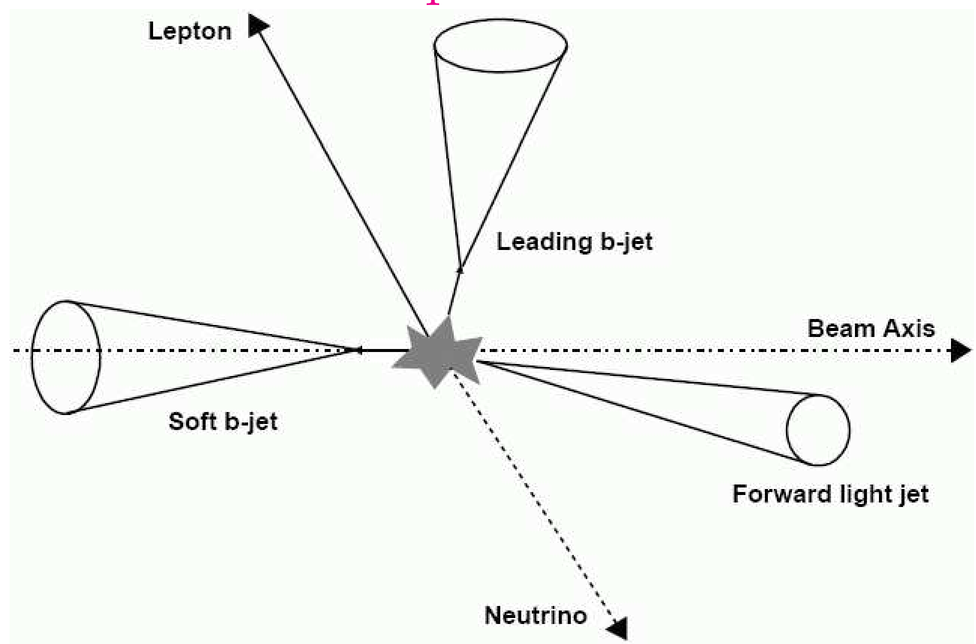


$\sigma = 10\,\mathrm{pb}$

All channels are sensitive to V_{tb}

t-channel analysis

- Special cuts for event topology
- Main background is $t\bar{t}$ and some W+jets
- Sample analysis gave $\varepsilon = 1.4\%$ and S/B=0.8



- Statistical error no problem, however systematics can be in 20% region

Conclusions of 5th lecture

- Standard Models measurements test QCD end EW theory
- The large statistics allows precision test
- SM measurements are important to understand backgrounds for new physics searches
- However they can also test new physics directly using loop corrections