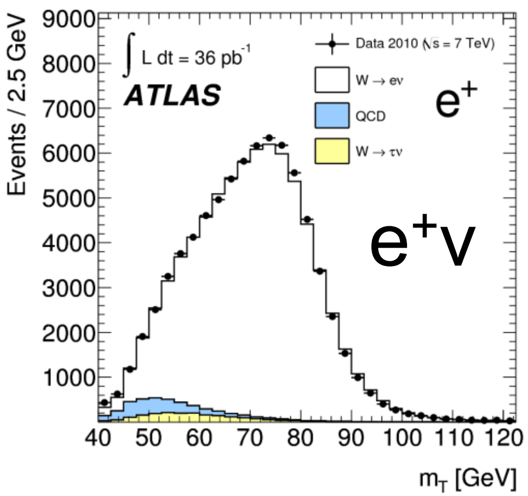
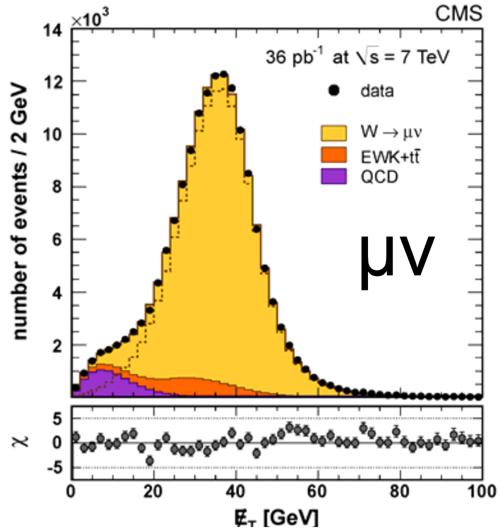
W & Z Signals

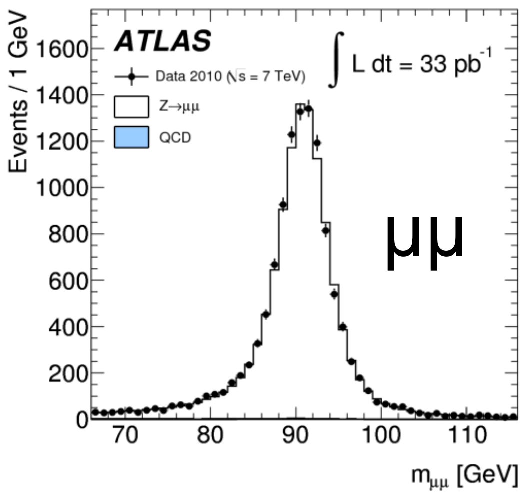
ATLAS | CMS

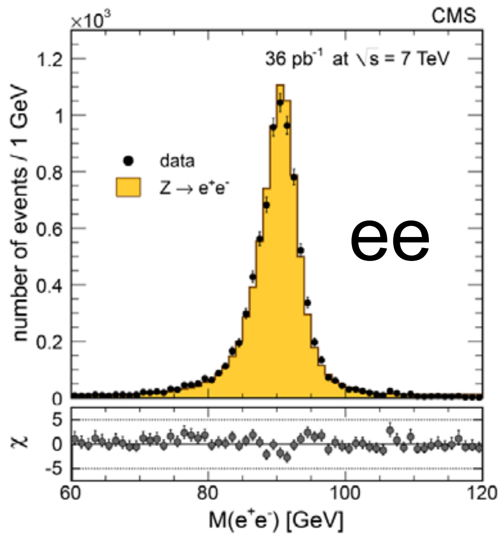
W





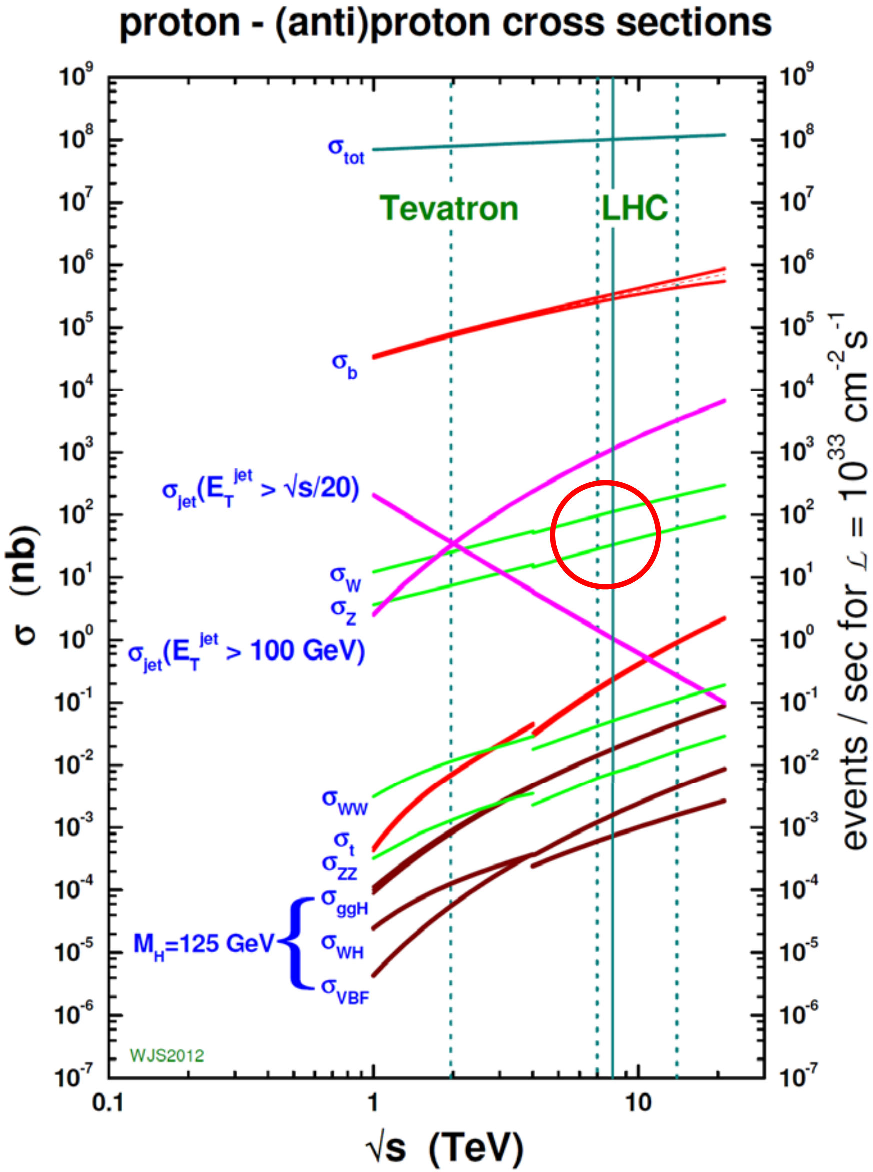
Z

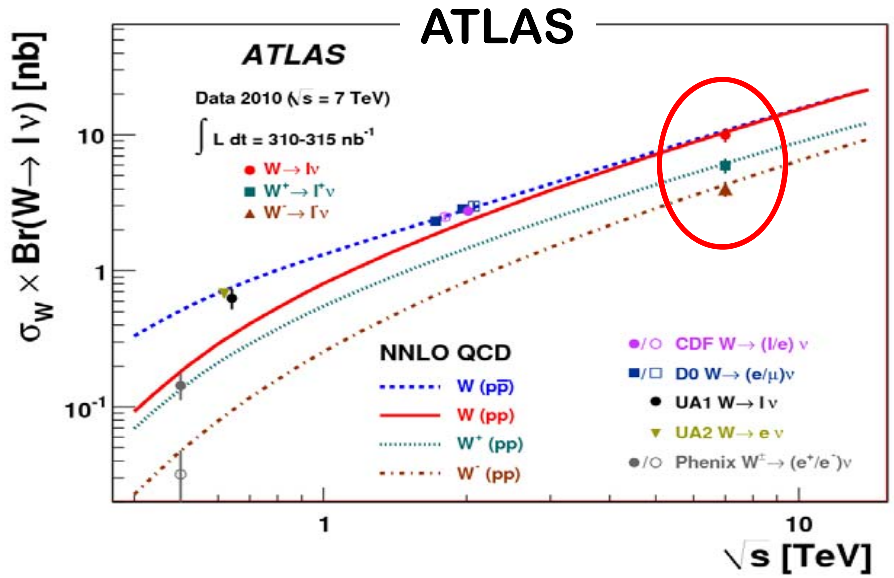


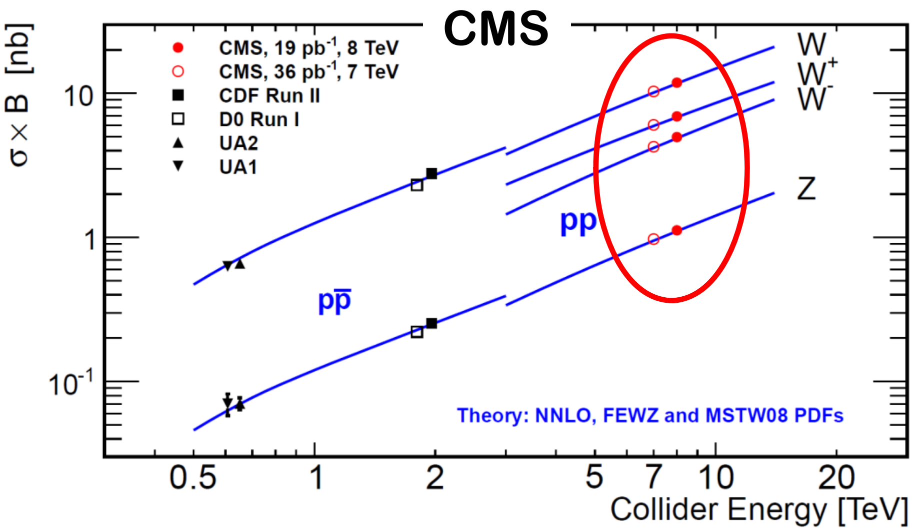


2010 data

W & Z Cross Sections





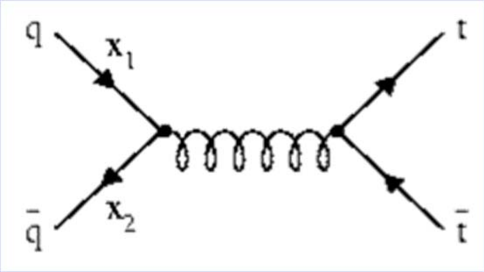


Top Quark Pair Production at the LHC

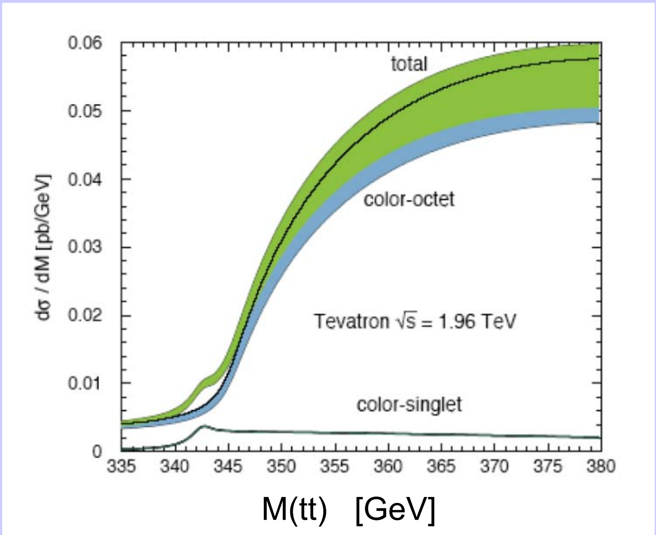
Producing Top Pairs

Tevatron (1.96 TeV)

quark annihilation



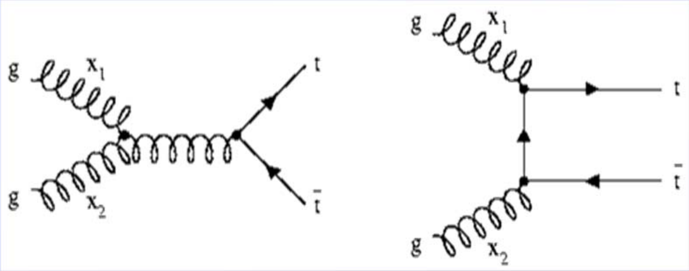
85% of the cross-section



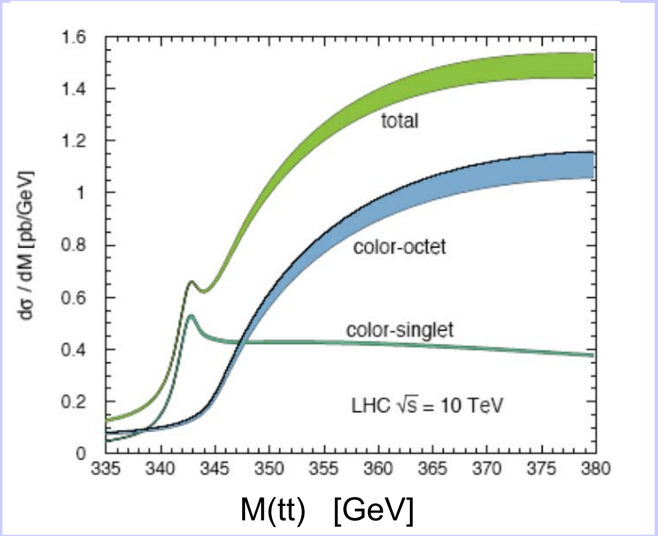
near threshold in a $^3S_1$ state
parallel spins, 100% correlation

LHC (7 TeV)

gluon fusion



80% of the cross-section

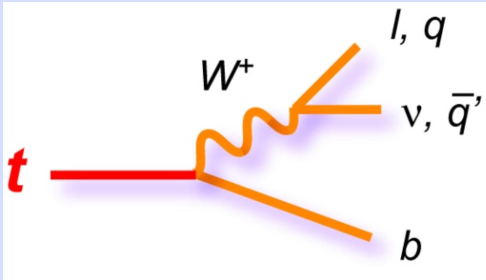


in a $^1S_0$ state, not so close from threshold
anti-parallel spins, not 100% correlated

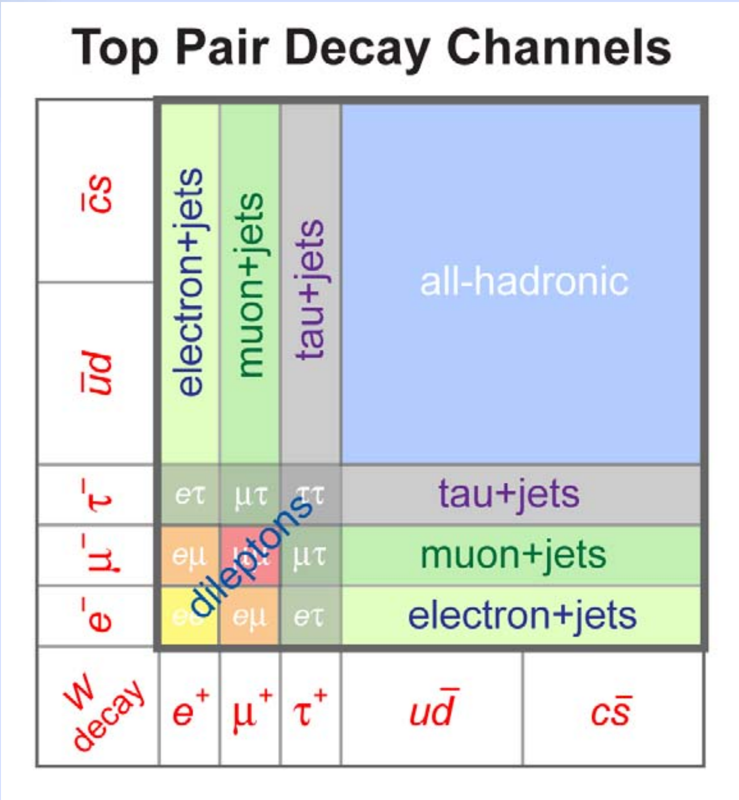
Top Pair Decay Channels

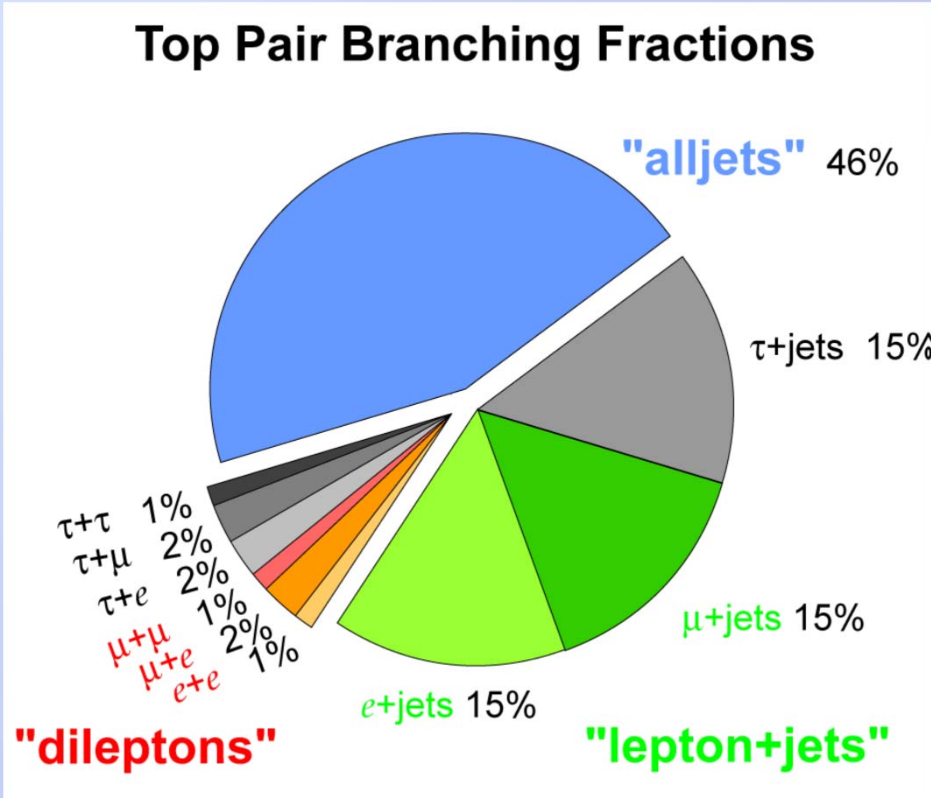
SM:

Br(t→Wb) ≈ 100%

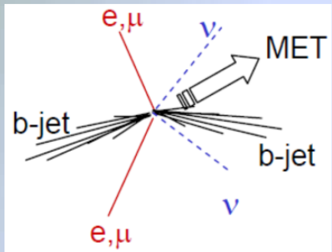


top pair rates are determined by the W branching fractions



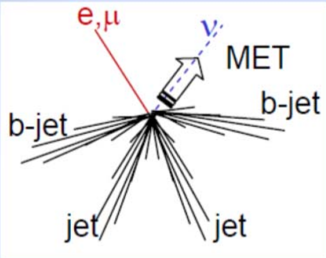


Top Pair Event Classification



Dilepton

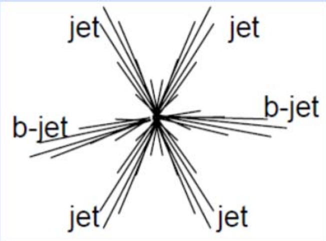
- 2 isolated oppositely-charged leptons (e or μ), 2 b-jets, large E_T^{miss}
- three channels: ee, μμ, eμ
- **BR=4.7%** (1+1+2)
- few backgrounds, mainly Z+jets



Lepton+Jets

- 1 isolated lepton (e or μ), 2 b-jets, 2 light-quark jets, some E_T^{miss}
- two channels: e+jets, μ+jets
- **BR=29.2%** (1+1)
- moderate backgrounds, mainly W+jets

at the LHC, W+jets production is charge-asymmetric



All Hadronic

- no lepton, 2 b-jets, 4 light-quark jets, no E_T^{miss}
- **BR=45.7%**
- huge QCD-multijet background

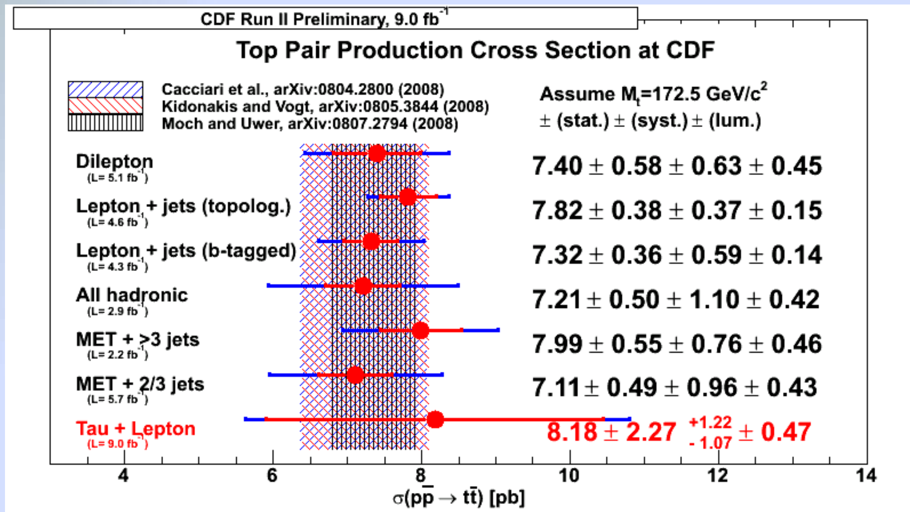
Hadronic Tau

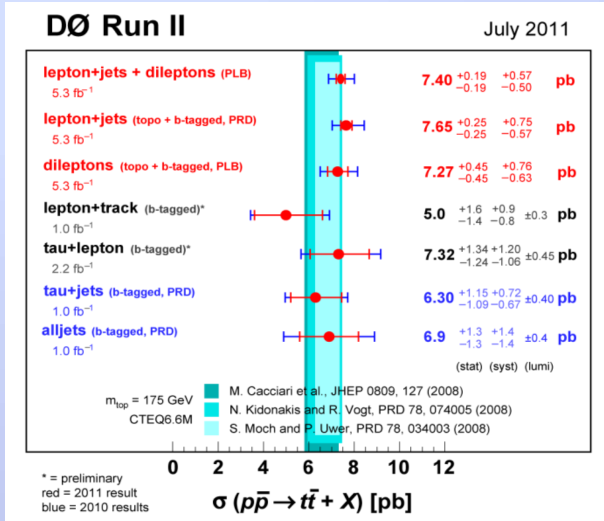
- two channels: τ+e/μ, τ+jets
- **BR=4.7%+14.6%**

dilepton and lepton+jets channels usually include contributions of e and μ from τ-lepton decays

Top Cross Section at Tevatron

Top pair production cross section in proton-antiproton collisions at $\sqrt{s}$ = 1.96 TeV





CDF Prelim (2012) | **D0 arXiv:1105.5834 (2011)**

$$\sigma_{t\bar{t}}(\text{CDF-combined}) = 7.50 \pm 0.48\ (\text{stat} + \text{syst})\ \text{pb}$$ (6.4%)

$$\sigma_{t\bar{t}}(\text{D0-combined}) = 7.56\ {}^{+0.63}_{-0.56}\ (\text{stat} + \text{syst})\ \text{pb}$$ (8%)

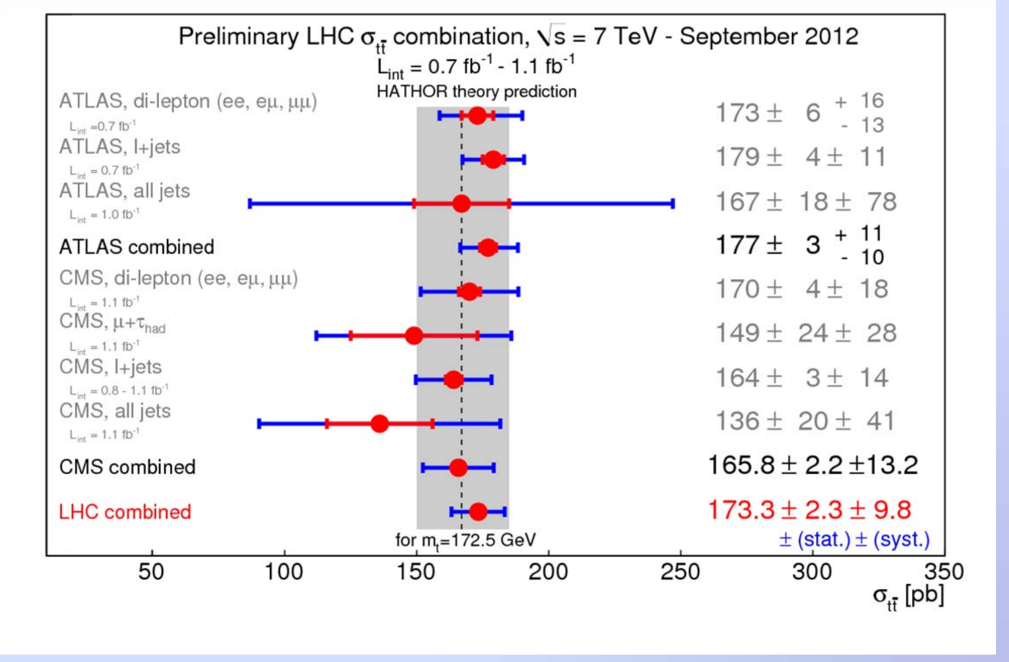
Consistency among various channels

- mains systematic uncertainties: Jet Energy Scale (JES), b-tagging, W+jets modeling

Consistency between experiments

Good agreement with SM predictions

Top Cross Section at the LHC



Theory (approx. NNLO)
σ(tt;7 TeV)= 167^{+17}_{-18} pb

(11%)

experimental result more precise than theory prediction!

ultimate limitation: JES, luminosity

ATLAS-CONF-2012-024

$$\sigma_{t\bar{t}}(\text{ATLAS-combined, 7 TeV}) = 177 \pm 3\ (\text{stat})^{+8}_{-7}\ (\text{syst}) \pm 7\ (\text{lumi})\ \text{pb}$$ **(6%)**

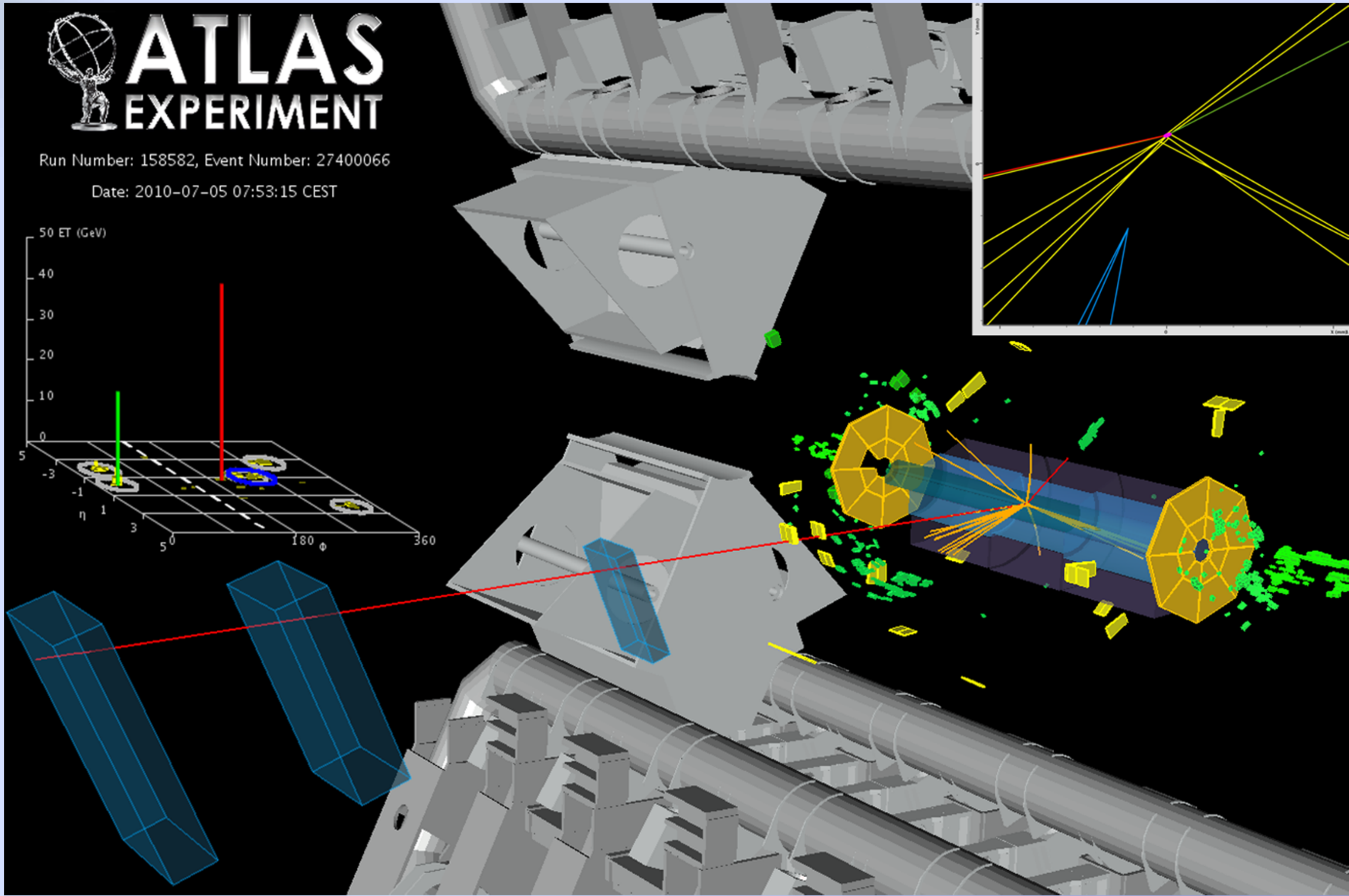
CMS-TOP-11-024

$$\sigma_{t\bar{t}}(\text{CMS-combined, 7 TeV}) = 165.8 \pm 2.2\ (\text{stat}) \pm 10.6\ (\text{syst}) \pm 7.8\ (\text{lumi})\ \text{pb}$$ **(8%)**

ATLAS-CONF-2012-134, CMS-TOP-12-003

$$\sigma_{t\bar{t}}(\text{LHC-combined, 7 TeV}) = 173.3 \pm 2.3\ (\text{stat}) \pm 9.8\ (\text{syst})$$ **(6%)**

Dilepton



ATLAS
EXPERIMENT
Run Number: 158582, Event Number: 27400066
Date: 2010-07-05 07:53:15 CEST
50 ET (GeV)
40
30
20
10
0
η
180 φ
360

ATLAS: Dilepton

ATLAS
LHC@√s=7 TeV (2011)
∫Ldt = 0.7 fb^{-1}

Standard selection
- 2 oppositely-charged leptons (e or μ)
- p_T > 25 (20) GeV for e (μ)
- at least 2 jets with p_T > 25 GeV

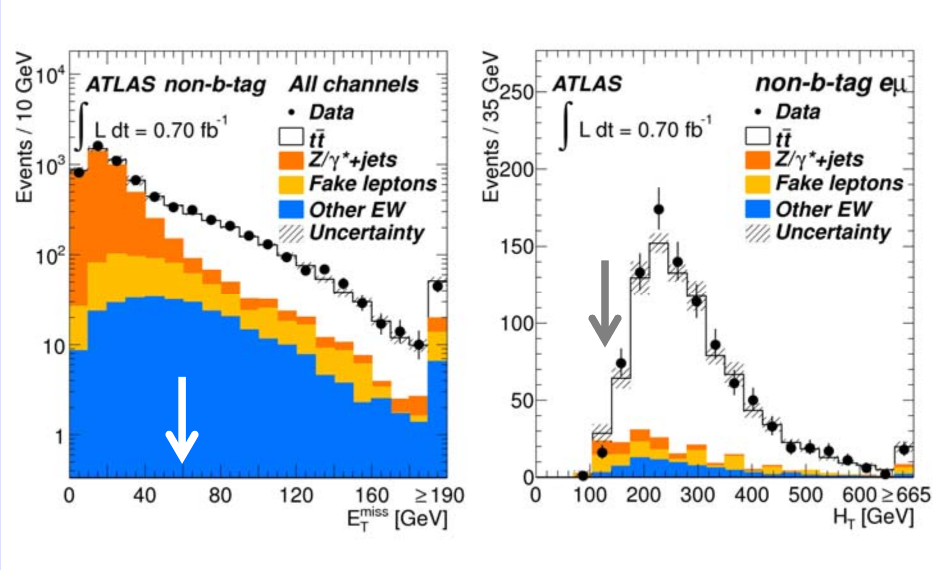
In ee and μμ channels
- Y veto: M(ll) > 15 GeV
- Z veto: | M(ll) - m_Z | > 10 GeV
- E_T^{miss} > 60 GeV

In eμ channel
- H_T > 130 GeV

Selection with b-tagging
- working point: 80% b-tagging efficiency
- ≥ 1 b-tagged jet
- E_T^{miss} > 40 GeV

Backgrounds
- data-driven estimation of fake-lepton and DY
- diboson and single-top from simulation + (N)NLO theory

JHEP 1205 (2012) 059



very pure samples of top pair events

H_T is defined as the scalar sum of the transverse energies of the two leptons and all selected jets

ATLAS: Dilepton

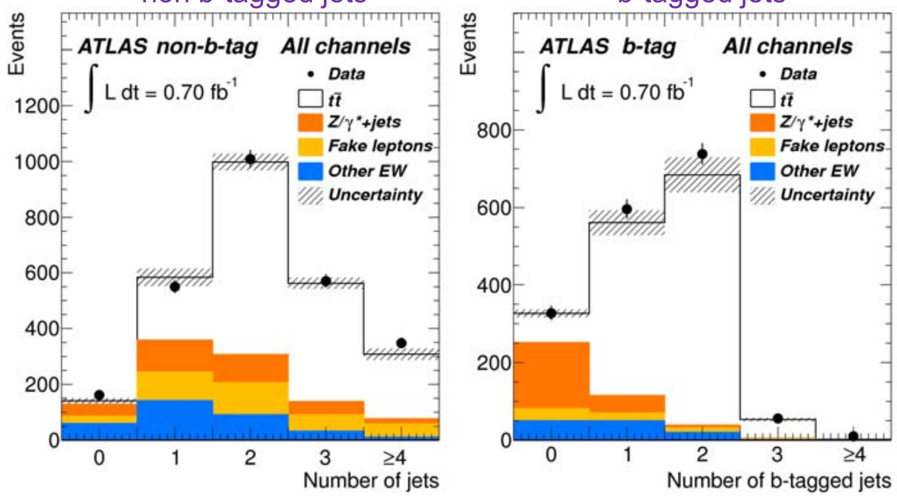
ATLAS
LHC@√s=7 TeV (2011)
$\int Ldt = 0.7\ fb^{-1}$

Signal extraction

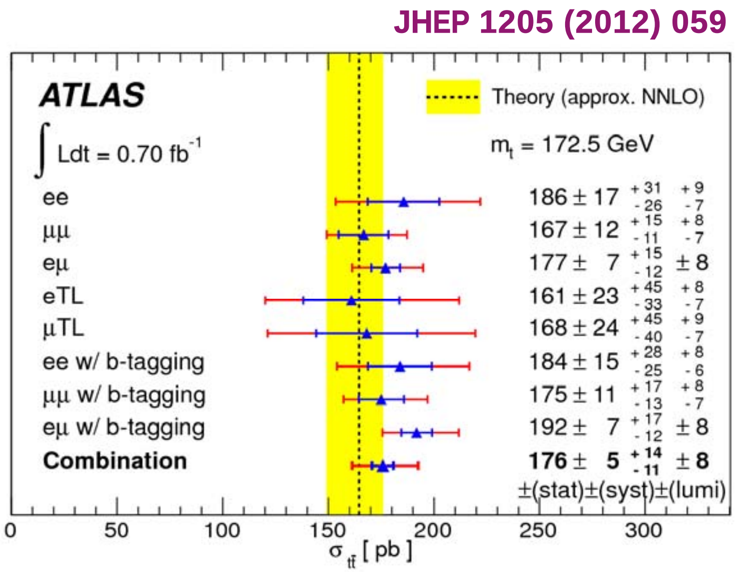
- profile likelihood in individual channels
- 1920 (1400) signal events without (with) b-tagging

Jet multiplicity in ee+μμ+eμ channels

non b-tagged jets | b-tagged jets



Combination of channels

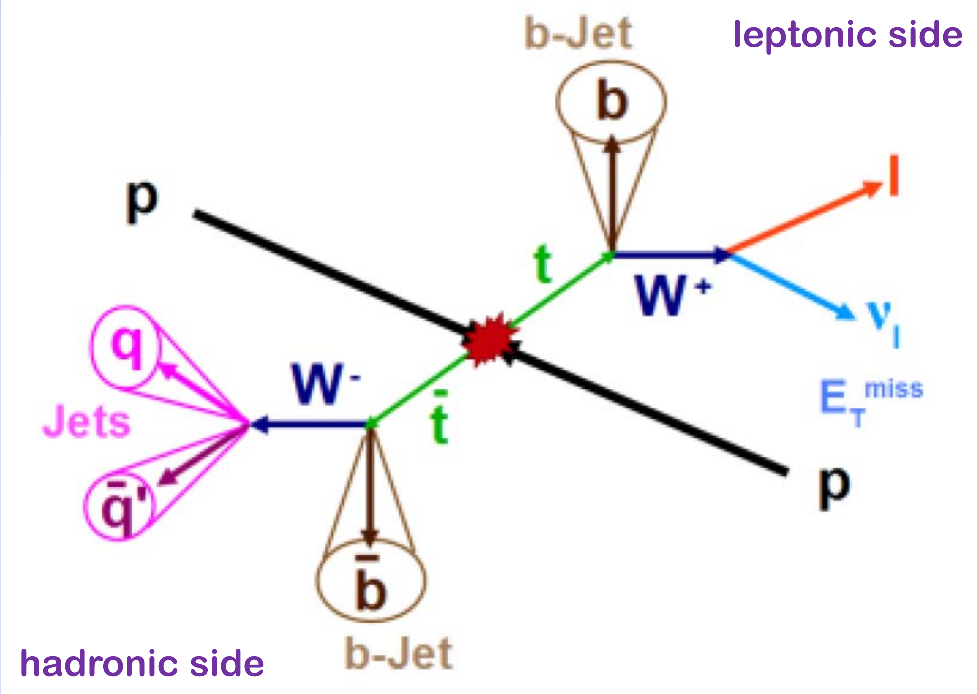


Main systematic uncertainties

- JES, E_T^{miss}, fake-leptons
- signal modeling

$$\sigma_{t\bar{t}}(\text{ATLAS-dilepton, 7 TeV}) = 176 \pm 5\ (\text{stat})^{+14}_{-11}\ (\text{syst}) \pm 8\ (\text{lumi})\ \text{pb}$$ (9%)

The Golden Mode: Lepton+Jets

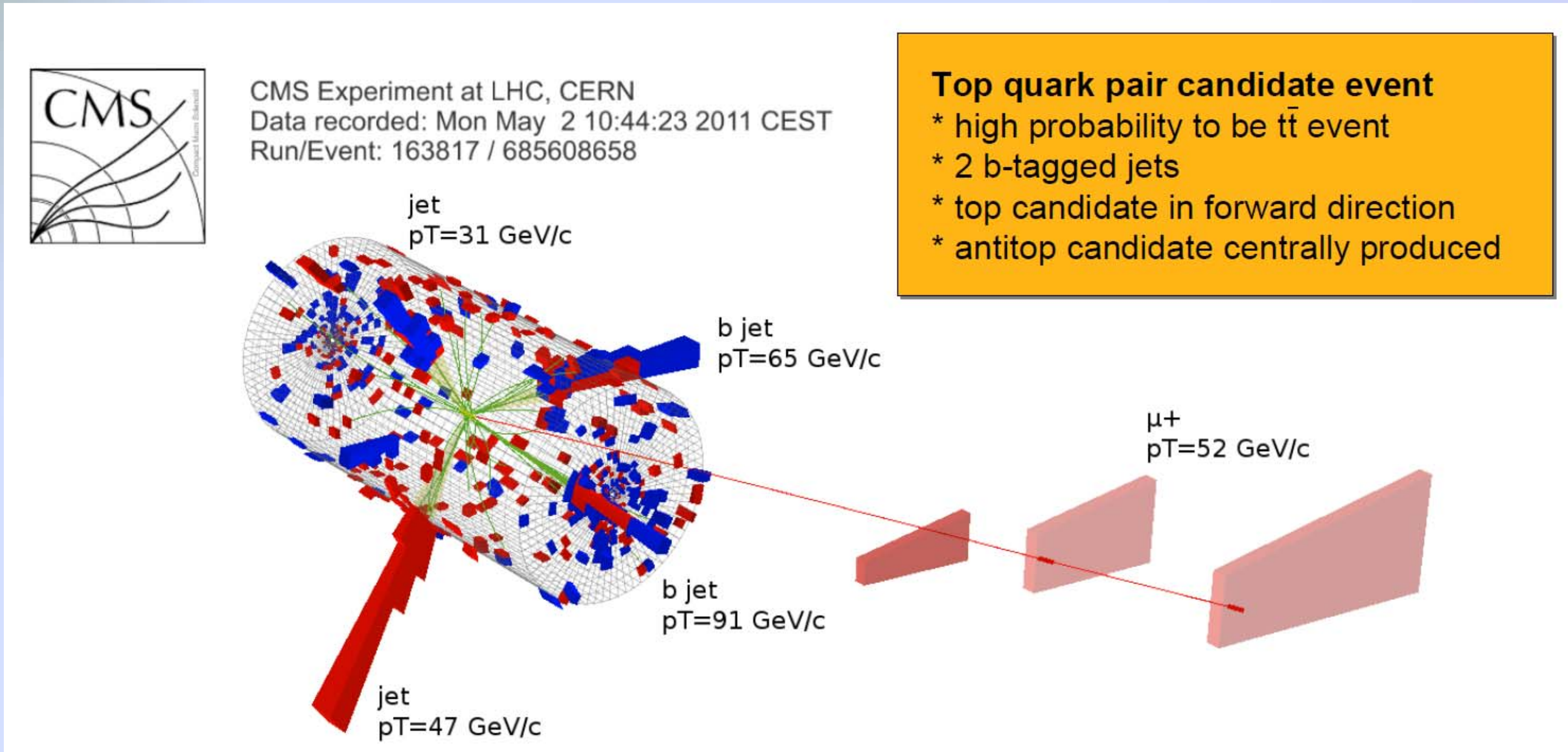


- **High rate:** 30% of top pairs
- **Low backgrounds**
  S/B > 1
- **W reconstructed in the hadronic channel:**
  in-situ constraint on the jet energy scale (JES)
- **Full reconstruction of the top quark on the hadronic side**
  direct mass measurement

But:

- **Very high jet combinatory:**
  importance of
  - efficient b-jet tagging and
  - excellent di-jet resolution

Lepton+jets


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 2 10:44:23 2011 CEST
Run/Event: 163817 / 685608658
jet
pT=31 GeV/c
b jet
pT=65 GeV/c
μ+
pT=52 GeV/c
b jet
pT=91 GeV/c
jet
pT=47 GeV/c
Top quark pair candidate event
* high probability to be tt̄ event
* 2 b-tagged jets
* top candidate in forward direction
* antitop candidate centrally produced

CMS: Lepton+Jets

CMS
LHC@$\sqrt{s}$=7 TeV (2011)
$\int L dt$ = 0.8-1.1 fb^{-1}

Selection

- exactly 1 isolated lepton (e or μ)
- p_T > 45 (35) GeV for e (μ)
- consider jets with p_T > 30 GeV
- ≥ 1 jet(s) b-tagged (SV algorithm, WP: ε~55%, mistag~1.5%)
- E_T^{miss} > 30 (20) GeV in e (μ) channel

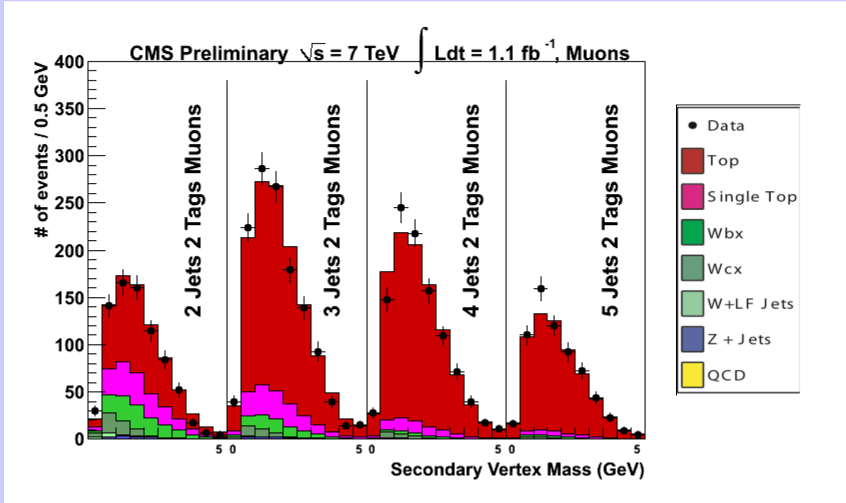
Signal extraction

- profile likelihood fit to N_{jets}, $N_{b\text{-}jets}$
  and secondary vertex mass
- determine simultaneously
  Signal, W+light-jet and W+heavy-jet
- templates from simulation (except QCD)
- nuisance parameters:
  b-tagging efficiency, light-jet mis-tagging,
  JES, W+jets factorization scale

Main systematic uncertainties

- JES, b-tagging efficiency, W+jets modeling

CMS-TOP-11-003



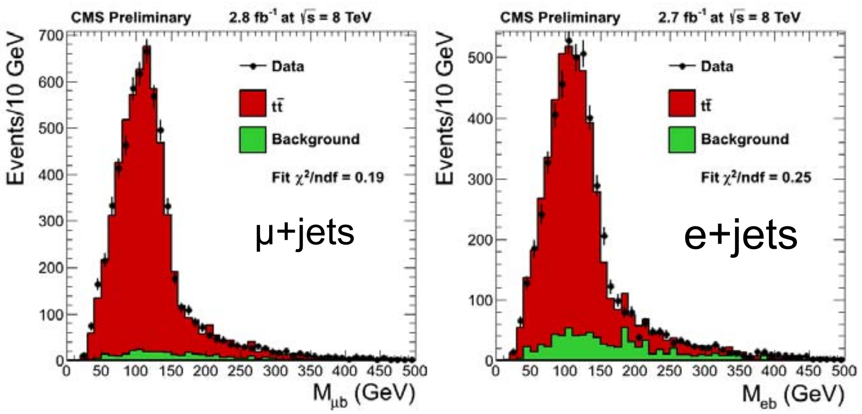
$$\sigma_{t\bar{t}}(\text{CMS-lepton+jets, 7 TeV}) = 164.4 \pm 2.8\ (\text{stat}) \pm 11.9\ (\text{syst}) \pm 7.4\ (\text{lumi})\ \text{pb}$$

(8.7%)

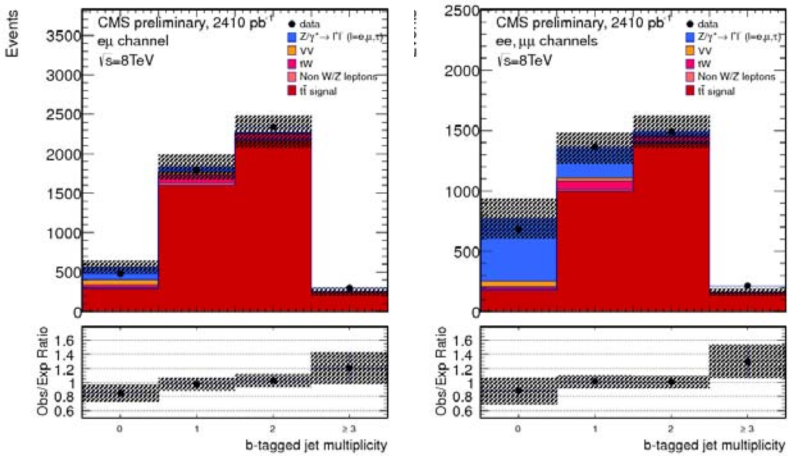
CMS: Cross Sections at 8 TeV

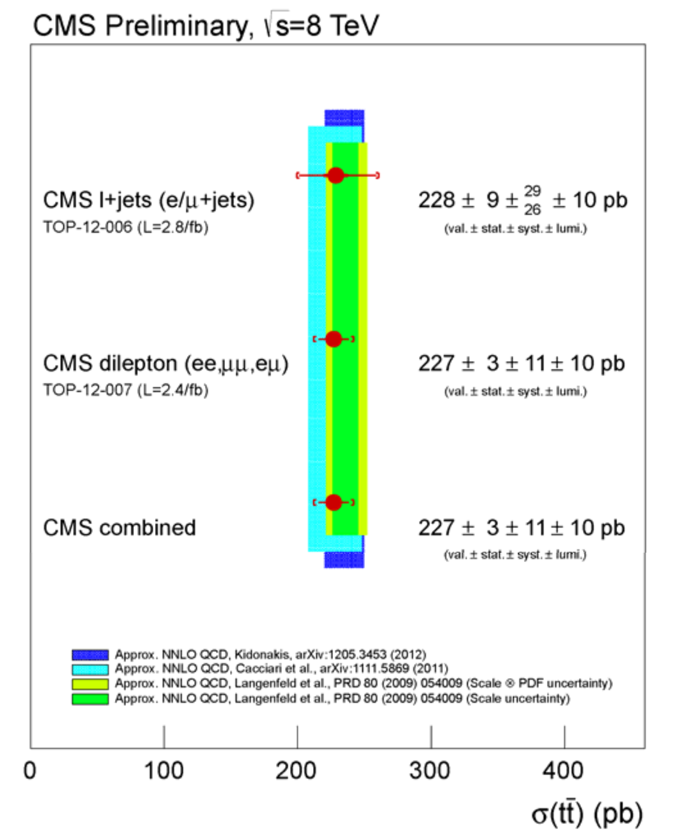
CMS
LHC@√s=8 TeV (2012)
∫Ldt = 2.4-2.8 fb^{-1}

CMS-TOP-12-006 — **lepton+jets**



CMS-TOP-12-007 — **dilepton**



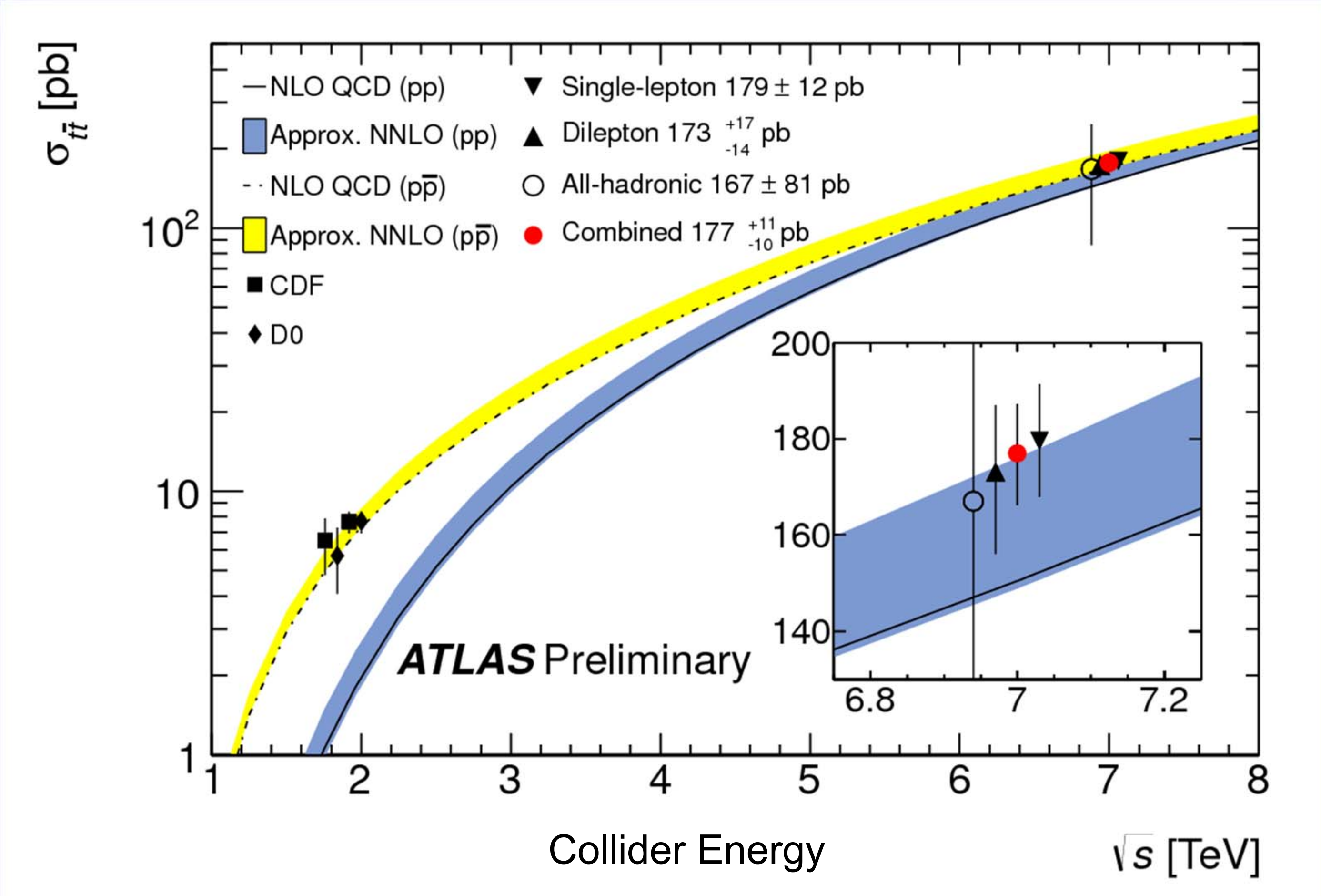


$$\sigma_{t\bar{t}}(\text{CMS-combined, 8 TeV}) = 227 \pm 3\ (\text{stat}) \pm 11\ (\text{syst}) \pm 10\ (\text{lumi})\ \text{pb}$$

(7%)

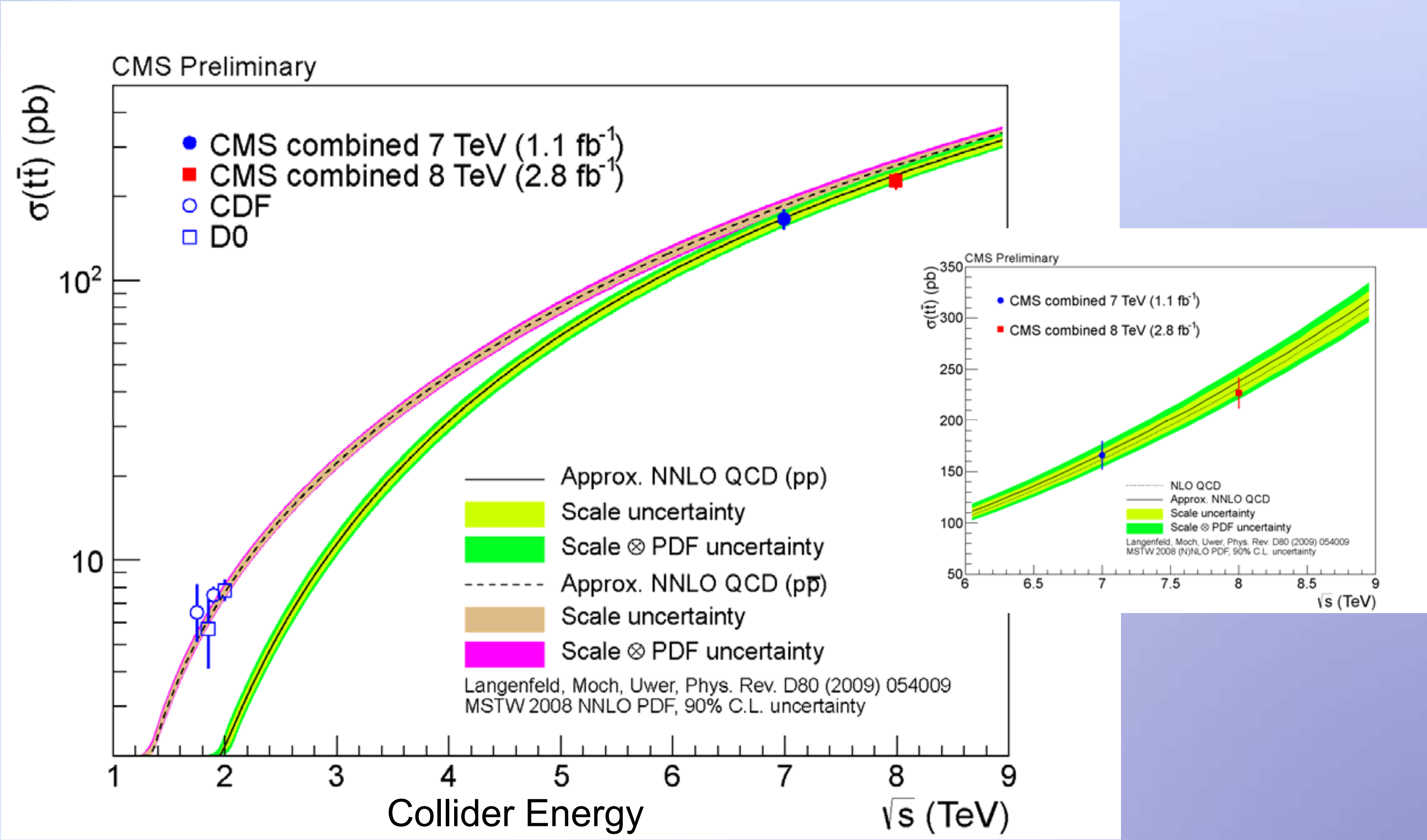
ATLAS: Cross Sections at 7 TeV

ATLAS-CONF-2012-024

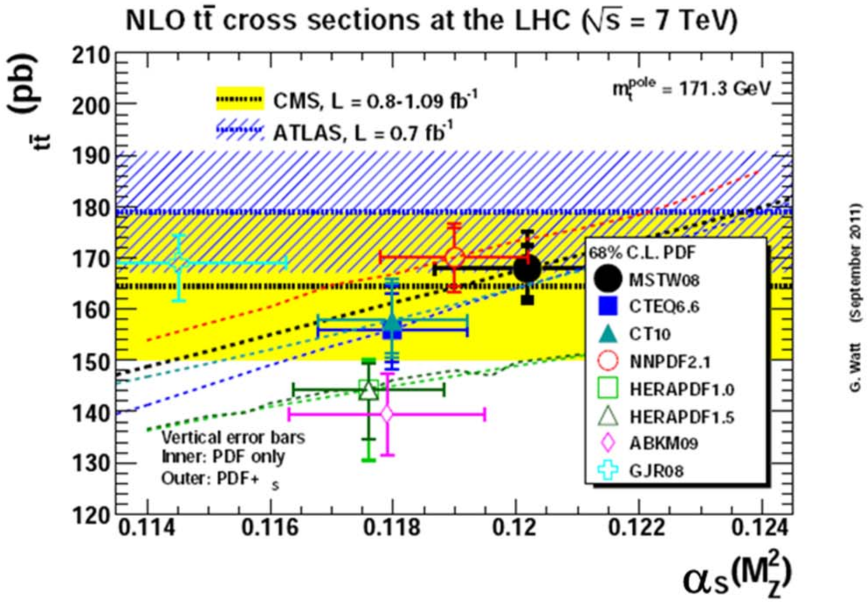


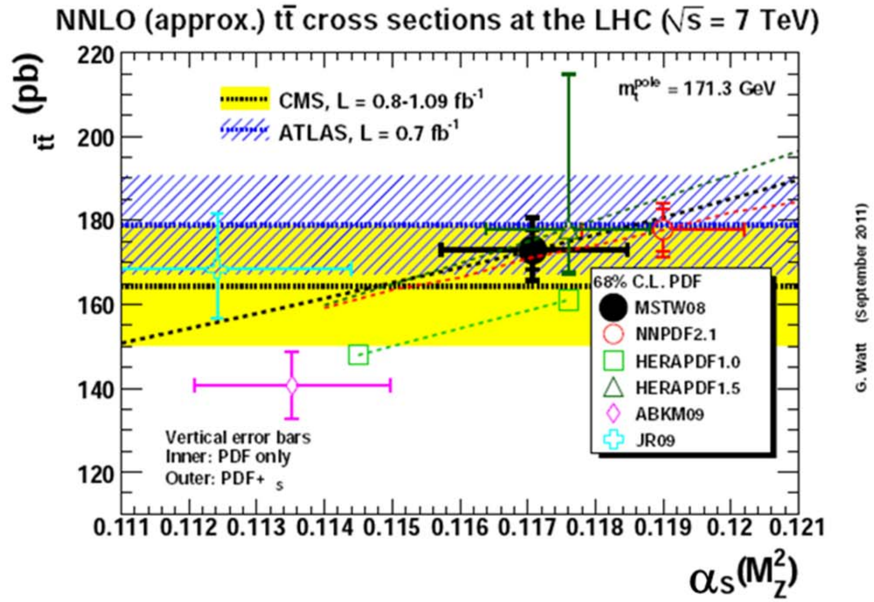
CMS: Cross Sections at 7 & 8 TeV

$\sigma(8\text{TeV})/\sigma(7\text{TeV}) = 1.41 \pm 0.11$



Top Constraints on PDFs





Top quark pair production cross section measurements at LHC are already at a level that allows some discrimination between NLO/NNLO predictions with various PDF sets

expect ultimate resolution on cross section around 5%

Spin Correlations

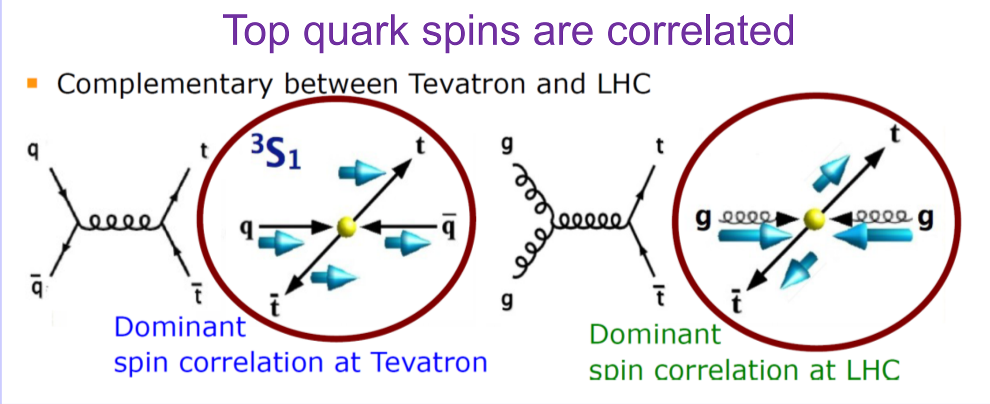
Top quark pair production property

Near threshold

- **quark annihilation:**
  parallel spins, opposite helicities
- **gluon fusion:**
  antiparallel spins, same helicities

Far from threshold

- angular momentum plays a role

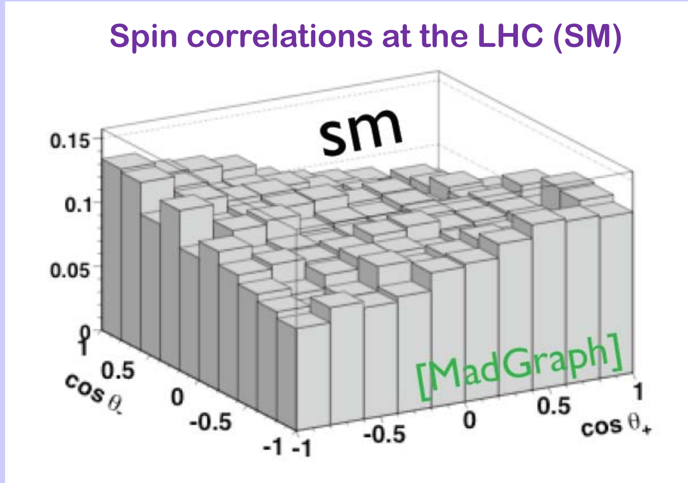


Decay before hadronization

$\rightarrow$ possibility of measuring the spin correlations from angular correlation of the decay products of the 2 top quarks

Spin analyzers from W-boson decay

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1}{2}(1 + \alpha_i \times \cos\theta_i)$$



Best spin analyzers

charged leptons and down-type quarks: α=1

(but difficult to distinguish down- from up-type quark jets)

First one needs to define the quantization axis…

Spin Correlations

Observable: Spin Correlation Coefficient

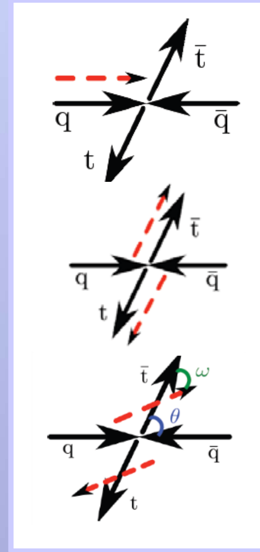
$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\downarrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\downarrow\uparrow) + N(\uparrow\downarrow)}$$

A depends on the production mechanism of the top quark pair

first, one needs to define the quantization axis…

Definitions of the spin analyzing vectors

- **Beam Basis:**
  bisector of the beams in the t-tbar CoM frame (Collins-Soper)
- **Helicity Basis:**
  direction of flight of the top quark in the t-tbar CoM frame,
  defined such that the spin analyzing vectors have opposite sign
- **LHC Maximal Basis:**
  a basis for which the correlation coefficient
  is maximal for top pairs produced by gluon fusion



$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{2}(1 + A\alpha_1\alpha_2 \times \cos\theta_1\cos\theta_2)$$

Tevatron: evidence for non-vanishing t-tbar spin correlations (but statistically limited)

SM Predictions:

- $A_{beam} = 0.78$
  in the Beam Basis at the Tevatron
- $A_{hel} = 0.31$
  in the Helicity Basis at the LHC

ATLAS: Spin Correlations

ATLAS
LHC@√s=7 TeV (2011)
∫Ldt = 2.1 fb^{-1}

PRL 108, 212001 (2012)

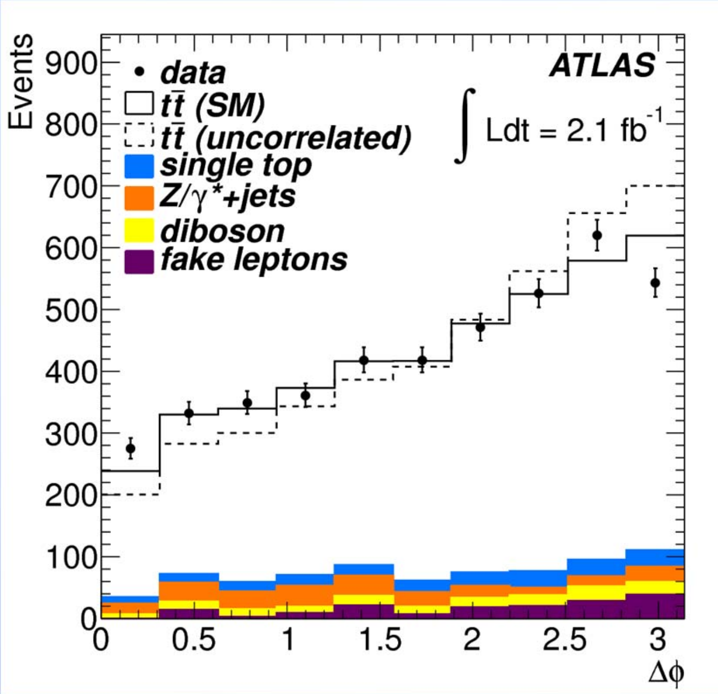
Strategy:

- use dilepton channel (standard selection)
- fit the difference in azimuthal angle between the two leptons $\Delta\phi$
- template method
- no requirement on M(t-tbar)

Hypothesis testing

- **H0:** spin correlation from Standard Model
- **H1:** uncorrelated top quark spins

results inconsistent with zero spin-correlation hypothesis at the 5.1σ level



$$A_{\rm hel} = 0.40 \pm 0.04\ ({\rm stat})^{+0.08}_{-0.07}\ ({\rm syst})$$

in good agreement with SM predictions at parton level

CMS: Top Polarization

Measurement of top polarization in the Helicity Basis

CMS
LHC@√s=7 TeV (2011)
∫Ldt = 5 fb^{-1}

CMS-TOP-12-016

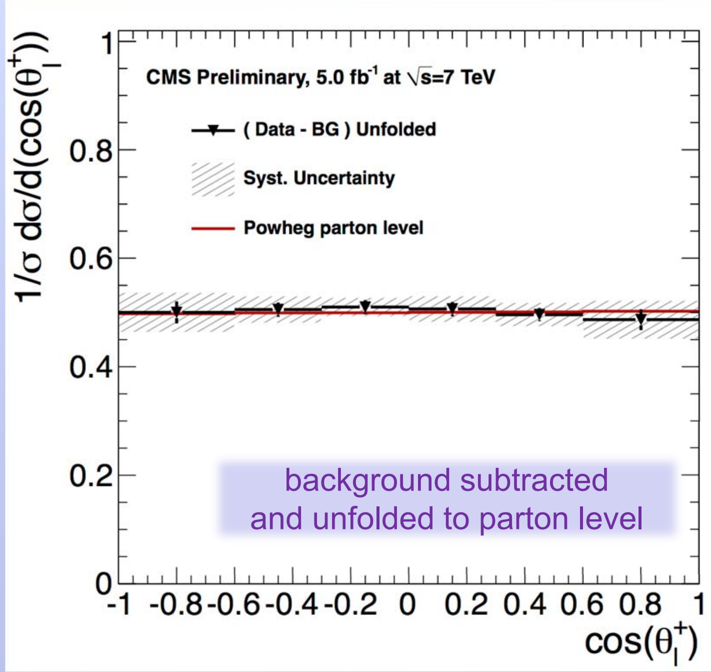
- At LHC, top pairs are produced **unpolarized** from QCD
  a small net polarization from EWK corrections
- **Top polarization**: a new observable to distinguish between models proposed to explain the large charge asymmetry at the Tevatron

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{\ell+}} = \frac{1}{2}\left(1 + 2P_{\text{top}} \times \cos\theta_{\ell+}\right)$$

Quantization axis

- direction of the top quark in the t-tbar rest frame

differential cross section as a function of the angle of the positively charged lepton with the quantization axis



background subtracted and unfolded to parton level

$$P_{\text{top}} = -0.009 \pm 0.029\ (\text{stat}) \pm 0.041\ (\text{syst})$$

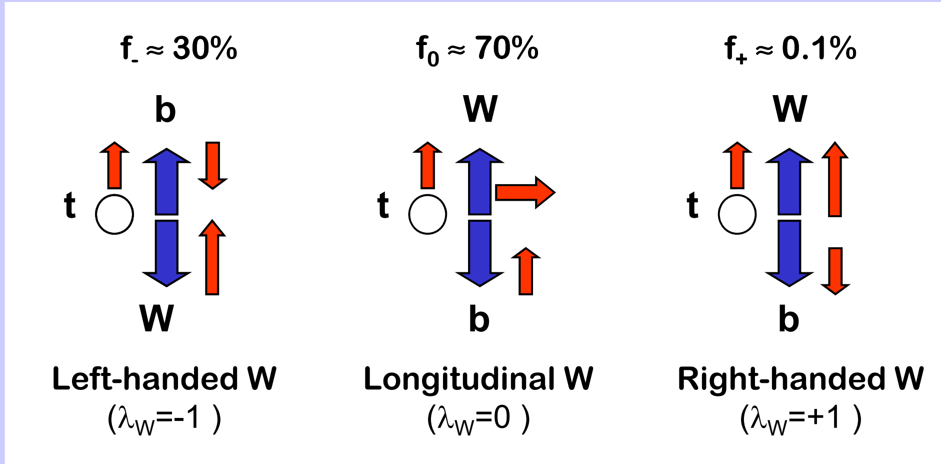
top polarization consistent with zero, as expected in SM

Test of V-A Coupling to W

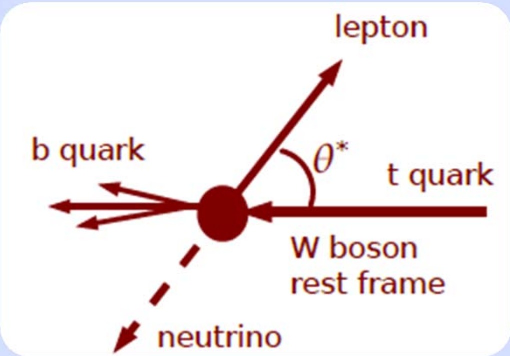
Top quark decay property

W bosons from top decays are polarized:

- longitudinal (69.6%)
- left-handed (30.3%)
- almost no right-handed (~0.1%)



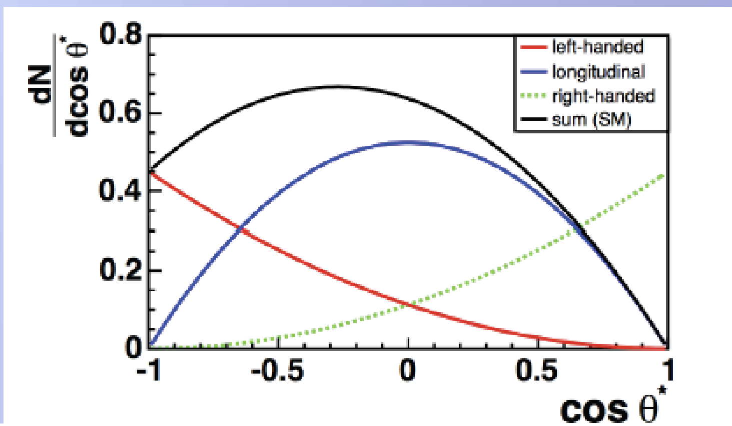
Angular distribution of the charged lepton in the W-boson rest frame



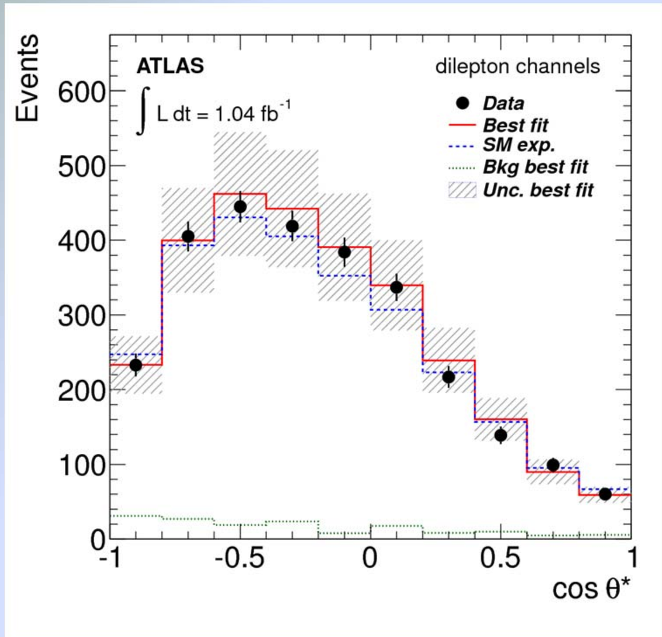
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = f_-\frac{3}{8}(1-\cos\theta^*)^2 + f_0\frac{3}{4}(1-\cos^2\theta^*) + f_+\frac{3}{8}(1+\cos\theta^*)^2$$

left-handed polarization | longitudinal polarization | right-handed polarization

direct measurement of
W-polarization in top decays
might reveal
non-standard couplings



ATLAS: W Polarization



Lepton+jets and dilepton channels

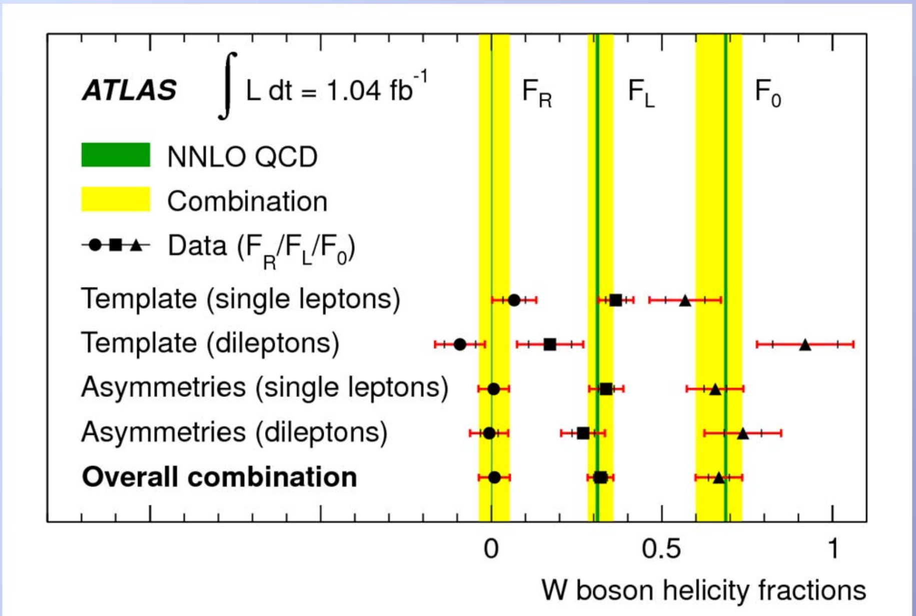
CMS
LHC@√s=7 TeV (2011)
∫Ldt = 1.04 fb-1

CMS-TOP-12-016

$$f_0 = 0.67 \pm 0.03\ (\text{stat}) \pm 0.06\ (\text{syst})$$
$$f_R = 0.01 \pm 0.01\ (\text{stat}) \pm 0.04\ (\text{syst})$$
$$f_L = 0.32 \pm 0.02\ (\text{stat}) \pm 0.03\ (\text{syst})$$

fixing f_R=0

$$f_0(f_R = 0) = 0.66 \pm 0.03\ (\text{stat}) \pm 0.04\ (\text{syst})$$

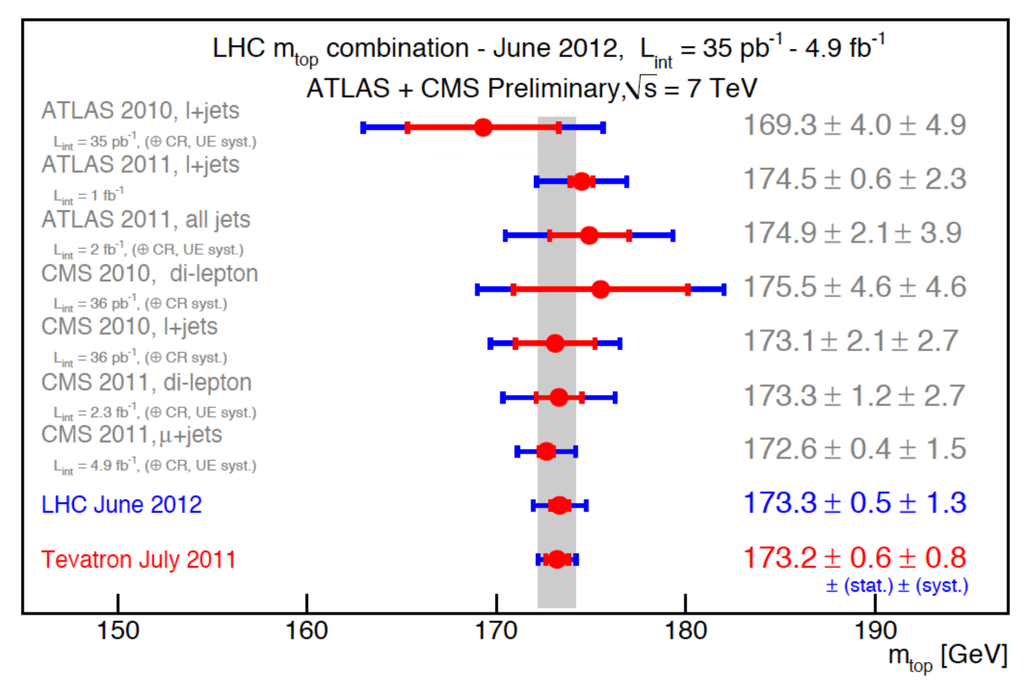


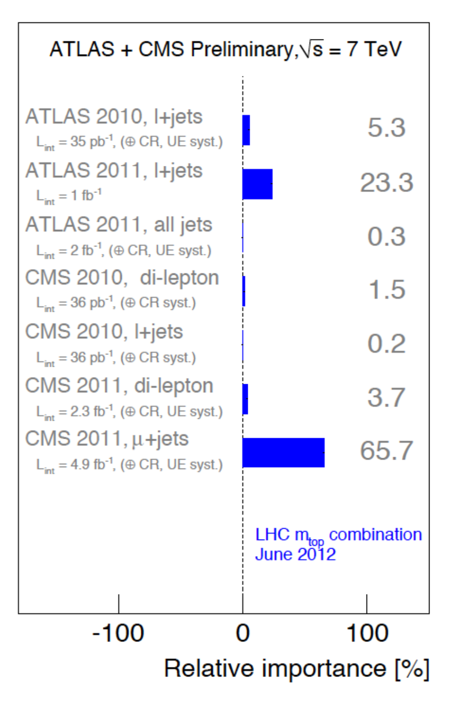
Two methods:
- templates
- angular asymmetries

V-A top coupling to W
is confirmed at LHC

Top Quark Mass

LHC Mass Combination





$$m_{\rm top}(\text{LHC-combined}) = 173.3 \pm 0.5 \ (\text{stat}) \pm 1.3 \ (\text{syst}) \ \ \text{GeV}$$ (0.8%)

$$m_{\rm top}(\text{Tevatron-combined}) = 173.2 \pm 0.6 \ (\text{stat}) \pm 0.8 \ (\text{syst}) \ \ \text{GeV}$$ (0.6%)

Methods to Measure the Mass

Template method

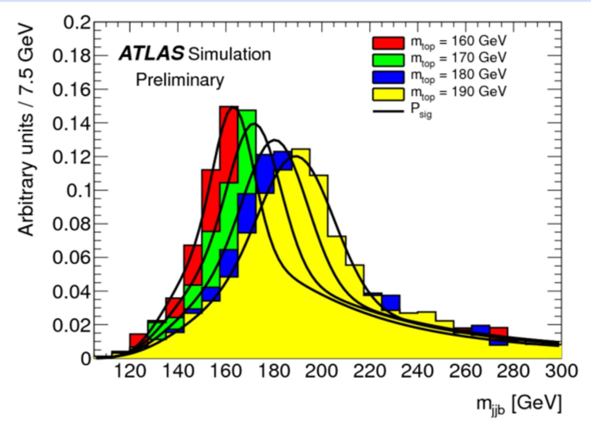
fit an observable with MC-generated distributions assuming different values of m_{top}

Ideogram method

event likelihood computed as the convolution of a resolution function with a distribution for the signal, plus wrong-pairing and backgrounds

Matrix Element method

build an event probability based on LO matrix element, using the full kinematics of the event



example of templates (ATLAS, all-hadronic)

JES crucial for top quark measurements!
In channels with ≥ 1 W decaying hadronically, use the invariant mass of light-quark jet pairs (constrained to the W mass) to calibrate the JES

Use **b-tagging** information to improve probability of choosing the correct jet combination in the reconstruction of the top-quark pair system

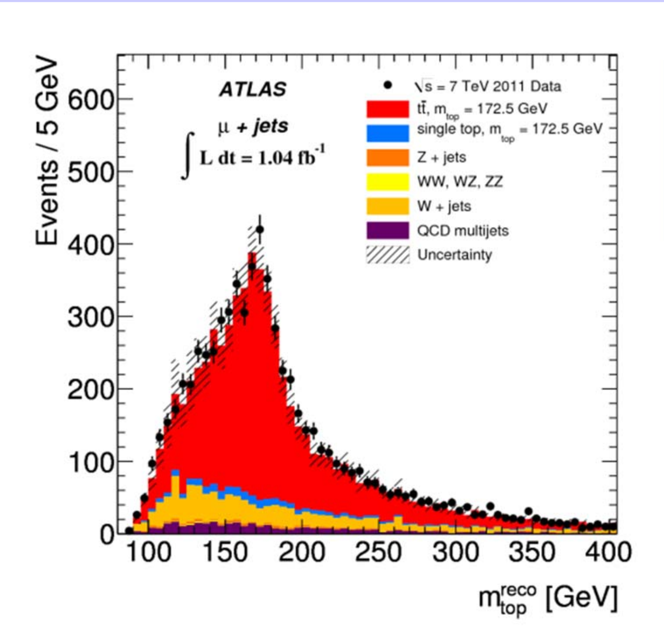
ATLAS: Lepton+Jets

ATLAS
LHC@√s=7 TeV (2011)
∫Ldt = 1.0 fb^{-1}

Eur. Phys. J. C (2012) 72:2046

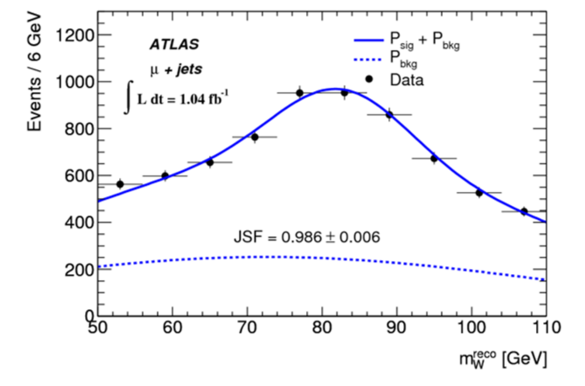
Strategy
- simultaneous fitting using a global jet scaling factor (JSF)
- "in-situ" calibration of JES: correct light-jet energy back to parton level to agree with m_W
- 2D-template fit as a function of JSF and m_{top}

Selection: similar to cross section measurement
- ~3,400 e+jets and ~5,100 μ+jets signal events



JSF sensitive not only to JES but also to MC modeling (fragmentation, radiation)

Fit of the j-j mass spectrum (before kinematic constraint)



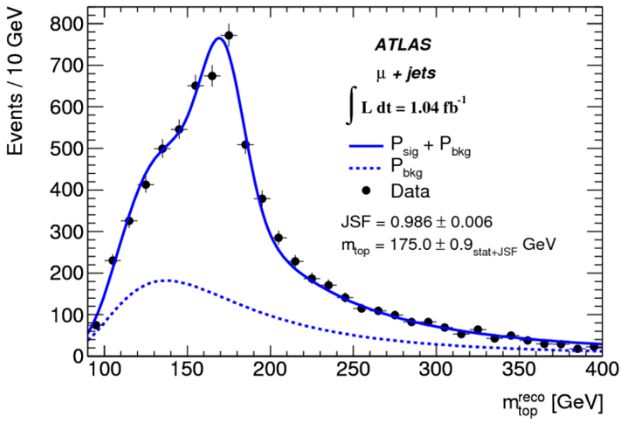
templates for the m_W^{reco} fit depend only on JSF

Kinematic χ^2 fit
- identify best light jet combination per event
- determine corresponding parton scales for jet energies
- keep j-j-b triplet with maximum p_T as top candidate
- rescale energies of jets used to compute m_{top}^{reco}

ATLAS: Lepton+Jets

ATLAS
LHC@√s=7 TeV (2011)
$\int Ldt = 1.0\ fb^{-1}$

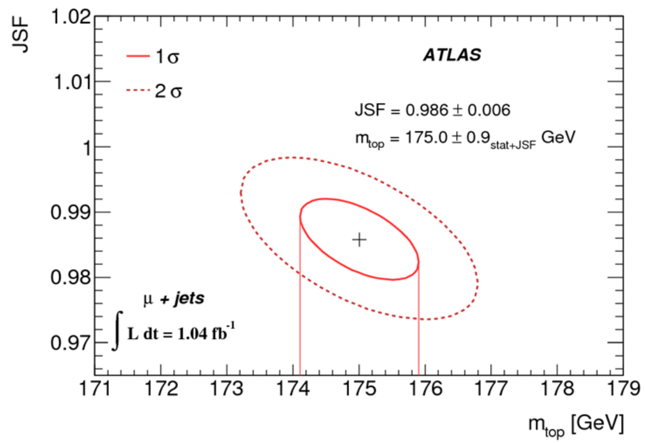
Fit of the j-j-b mass spectrum
(after kinematic constraint)



Signal: Gauss+Landau
Background: Landau

templates for the m_{top}^{reco} fit depend on m_{top} and JSF

Simultaneous determination of mass and JES with 2D-template method



Main sources of systematic uncertainties

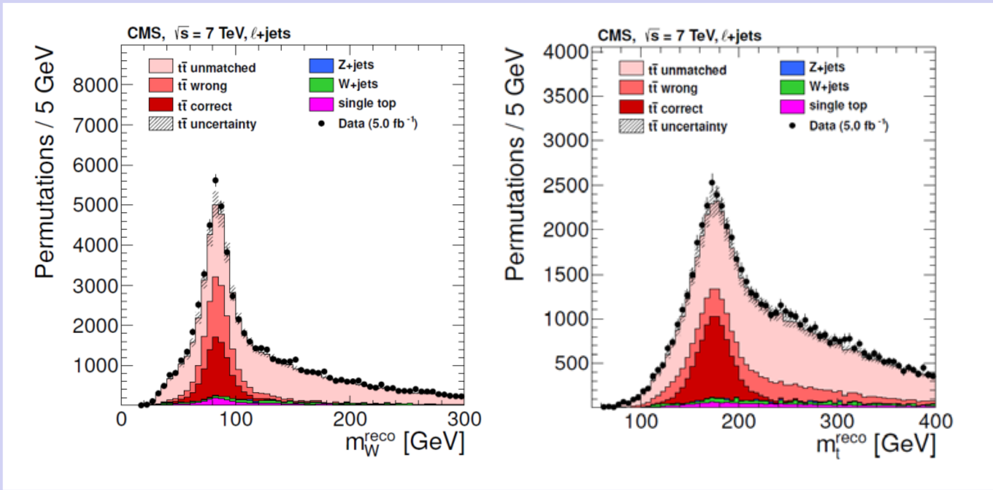
- JES and flavor-JES (for b-jets)
- signal modeling, ISR/FSR
- color reconnection
- b-jet tagging (efficiency and mis-tagging)

b-Jet Energy Scale
unconstrained by this method

$$m_{\rm top}(\text{ATLAS-lepton+jets}) = 174.5 \pm 0.6\ (\text{stat+JSF}) \pm 2.3\ (\text{syst})\ \ \text{GeV}$$ **(1.4%)**

and: JSF = 0.986 ± 0.006

CMS: Lepton+Jets



before constrained kinematic fit

CMS
LHC@√s=7 TeV (2011)
∫Ldt = 5.0 fb⁻¹

CMS-TOP-11-015
subm. to JHEP

Selection: similar to cross section measurement

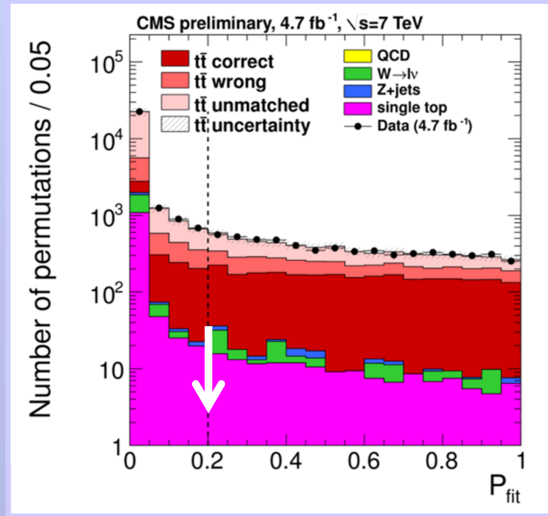
- 1 lepton + E_T^{miss} + ≥ 4 jets + ≥ 2 b-tagged jet
- ~5,174 events selected (purity>90%)

Constrained kinematic fit

to reduce wrong matching probability

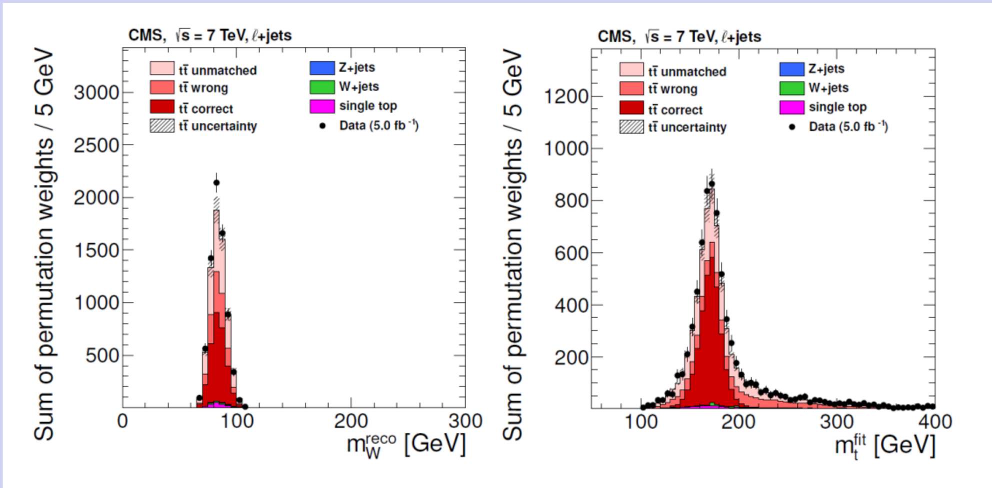
- two light-jets:
  constrain mass to m_W
- lepton and neutrino (MET)
  constrain mass to m_W
- two top candidates:
  constrained to equal masses

fraction of correct pairing:
13% → 44%



Fit probability > 20%
(used to weight permutations)

CMS: Lepton+Jets



CMS
LHC@√s=7 TeV (2011)
∫Ldt = 5.0 fb^{-1}

after constrained kinematic fit

CMS-TOP-11-015
subm. to JHEP

Selection: similar to cross section measurement

- 1 lepton + E_T^{miss} + ≥ 4 jets + ≥ 2 b-tagged jet
- ~5,174 events selected (purity>90%)

Constrained kinematic fit

to reduce wrong matching probability

- two light-jets:
  constrain mass to m_W
- lepton and neutrino (MET)
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- two top candidates:
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fraction of correct pairing:
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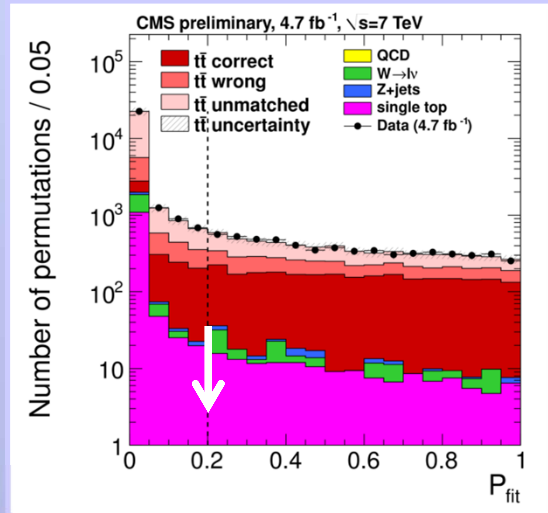
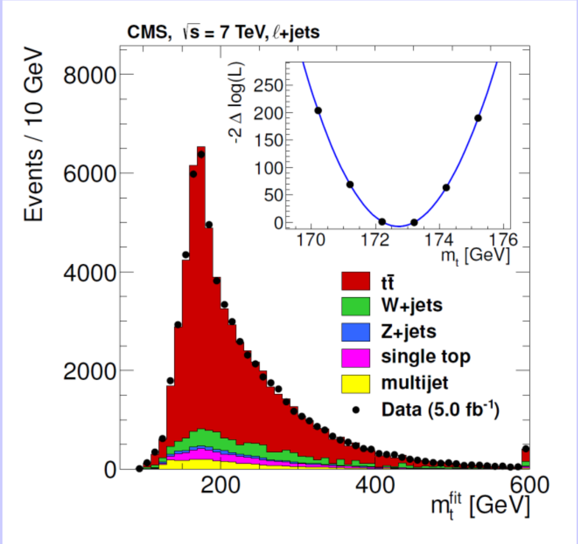


Fit probability > 20%
(used to weight permutations)

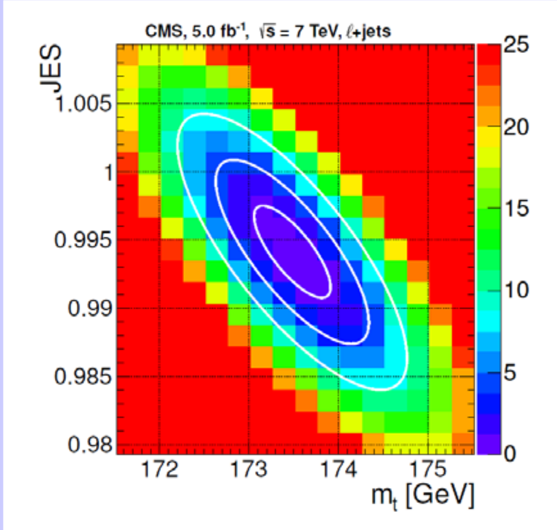
CMS: Lepton+Jets



Simultaneous determination of mass and JES with 2D-ideogram method

Per-event likelihood

- as a function of m_{top} and JES
- sum of probability densities:
  - signal with correct jet assignment
  - signal with wrong jet assignment
  - background
- parameterized analytically
  - (from simulation)



method calibrated with pseudo-experiments

Main sources of systematic uncertainties

- color reconnection effects
- b-jet JES
- p_T and η dependent JES
- underlying event tune

$$m_{\rm top}(\text{CMS-lepton+jets}) = 173.5 \pm 0.4\ (\text{stat+JES}) \pm 1.0\ (\text{syst})\ \ \text{GeV}$$

(0.8%)

and: JES parameter = 0.994 ± 0.003 (stat) ± 0.008 (syst)

Also, check of CPT symmetry:

$$\Delta m_{\rm top} = -0.44 \pm 0.46\ (\text{stat}) \pm 0.27\ (\text{syst})\ \ \text{GeV}$$

arXiv:1204.2807, subm. to JHEP

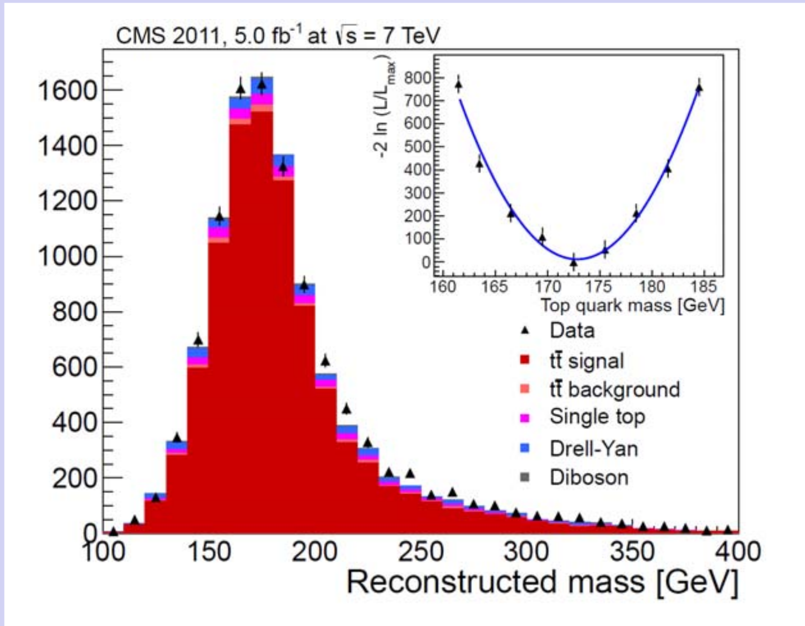
CMS: Dilepton

CMS
LHC@√s=7 TeV (2011)
∫Ldt = 5.0 fb^{-1}

CMS-TOP-11-016

Selection: similar to cross section measurement

- 2 leptons + Z veto + E_T^{miss} + ≥ 2 jets + 2 b-tagged jet
- 6,990 selected events (1,151 ee + 4,365 eμ + 1,474 μμ)



Analytical Matrix Weighting Technique (AMWT)

Underconstrained system:

24 (6x4) parameters, 14 measurements (4x3+2)

- constraints: masses of final states particles (6), W-boson mass (2), equal top-antitop masses (1)
  → one free parameter: the top quark mass
- For a given top mass (1 GeV steps from 100 to 400 geV) up to 8 solutions of the kinematic equations (analytical determination of the 2 neutrino E_T).
- A weight is assigned to each solution, which takes into account the PDFs and the probability of producing 2 leptons with the measured energy (LO Matrix Element)
- Vary all the experimental quantities within resolution
- Assign the mass with the maximum weight to the event
- Template fit of mass distribution (range 100-300 GeV)

- Main sources of systematic uncertainty: b-JES, scales, fit calibration (pseudo-exp.)

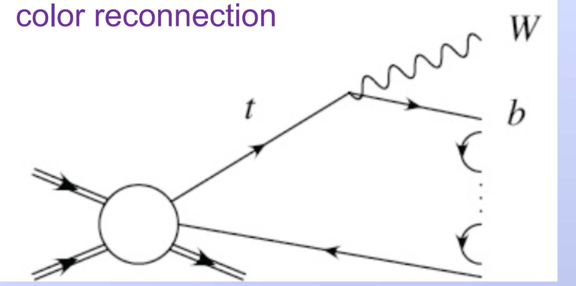
$$m_{\text{top}}(\text{CMS-dilepton}) = 172.5 \pm 0.4\ (\text{stat}) \pm 1.5\ (\text{syst})\ \text{GeV}$$ (0.9%)

most precise measurement in di-lepton mode to date

Top Mass from Cross Section

The definition of the top quark mass is ill-defined

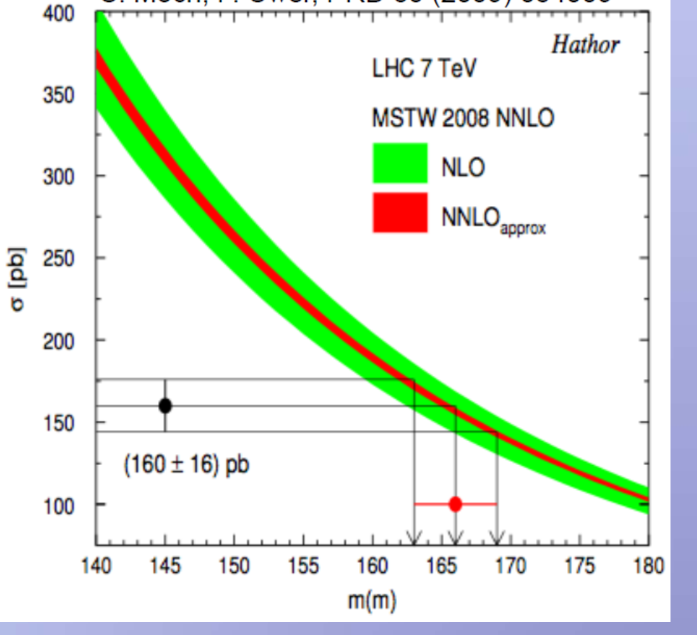
- The mass measured at colliders, from the invariant mass of the top decay products (bW) is assumed to be close to m_{pole}
- problem: for a quark, m_{pole} cannot be determined experimentally with accuracy better than $O(\Lambda_{QCD})$
  - in the case of the top quark (decay before hadronization) the limitation is traced to extra radiation and color reconnection



The renormalized mass

- is a fully-perturbative quantity unambiguously defined within a renormalization scheme
  - for instance, the MSbar scheme
- is a running quantity according to RGE
  - it varies as a function of the renormalization scale
- is used in perturbative calculations of the cross section
- can be linked to m_{pole}
  - up to an uncertainty of $O(\Lambda_{QCD})$ of course…

S. Moch, P. Uwer, PRD 80 (2009) 054009

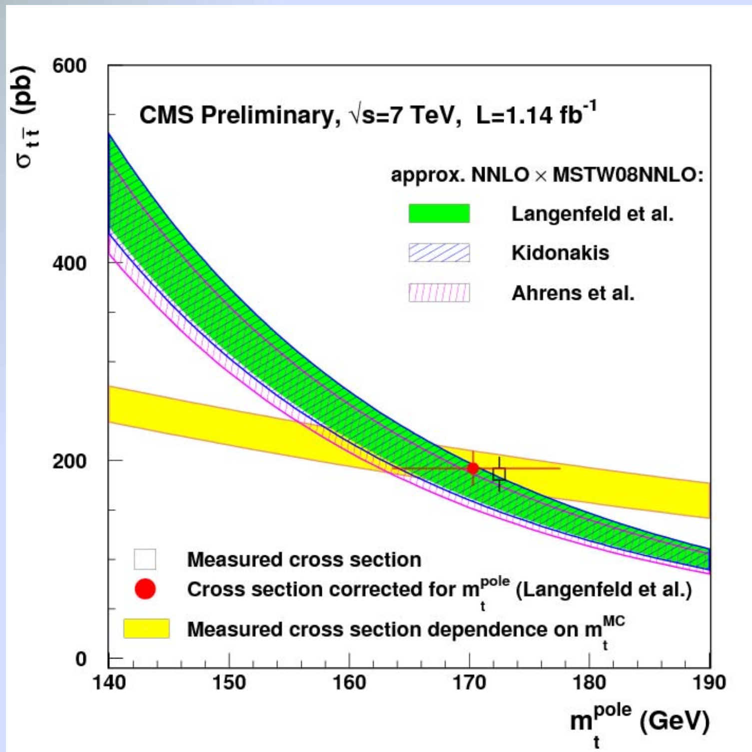


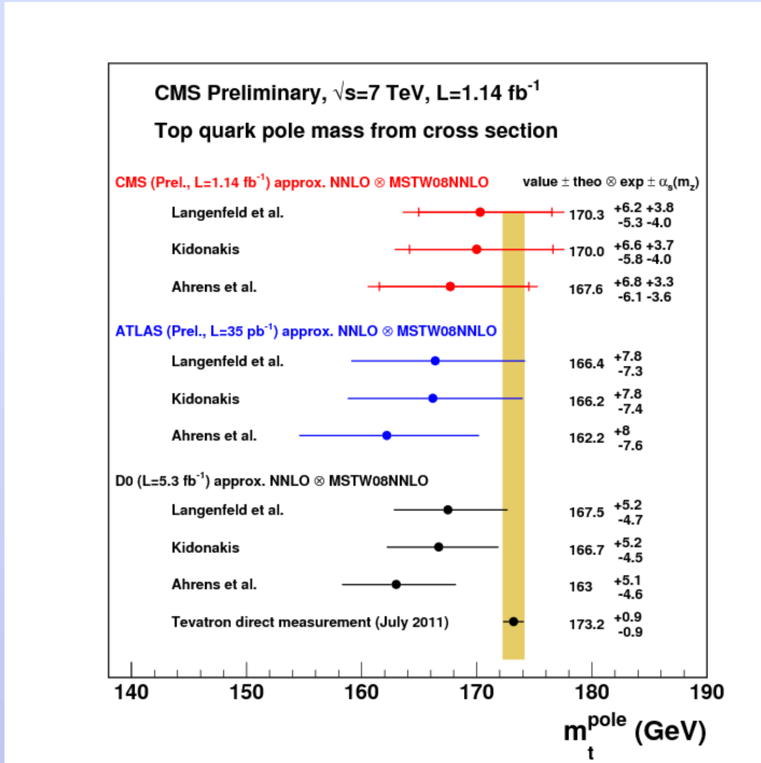
Extract the top mass from a measurement of the inclusive cross section

- Compare the measured cross section with (N)NLO QCD prediction
- Exploit the $\Delta\sigma/\sigma = -A \times \Delta m/m$ to extract m

A~4, so a typical 10% uncertainty at 160 pb corresponds to a 4 GeV uncertainty on the mass

Top Mass from Cross Section





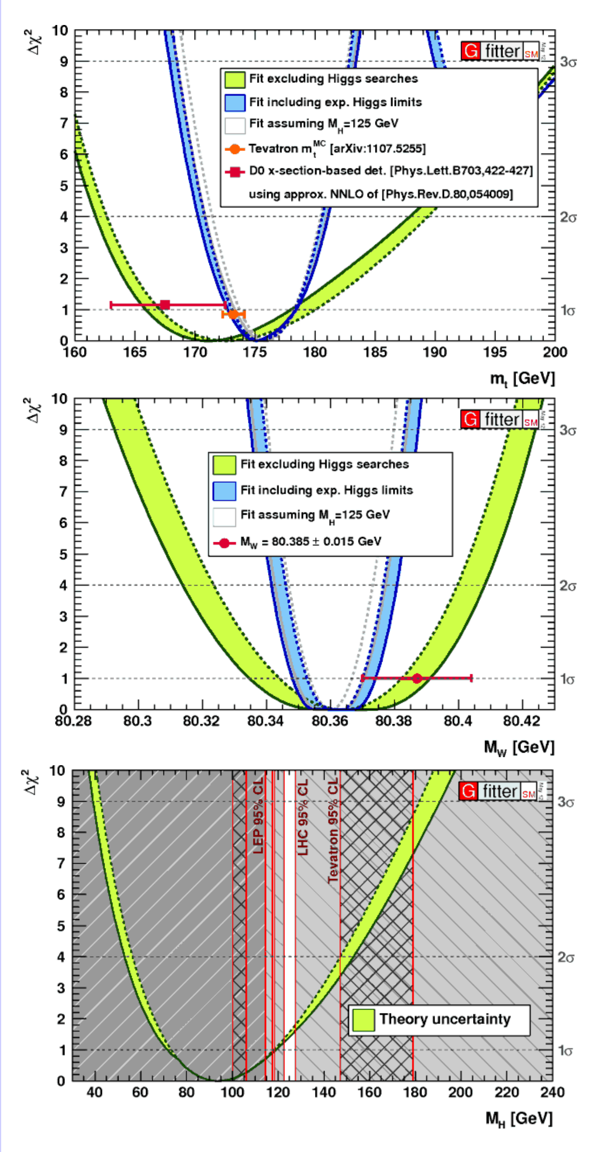
extract m_{top} using a joint likelihood:
- dependence of the measured cross section through acceptance
- dependence of the theory cross section

CMS measurements in the MSbar scheme:

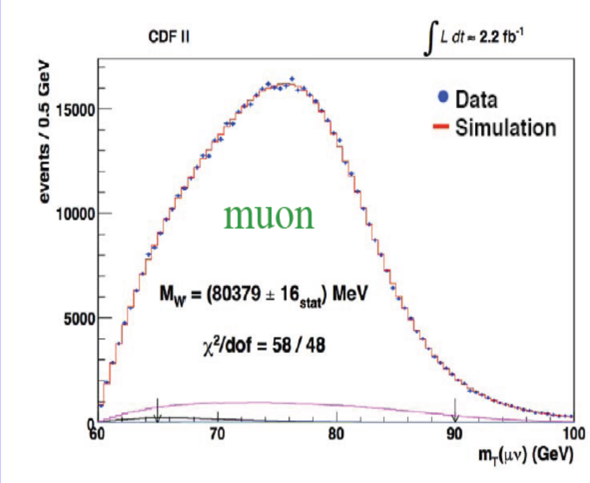
Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{MS}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

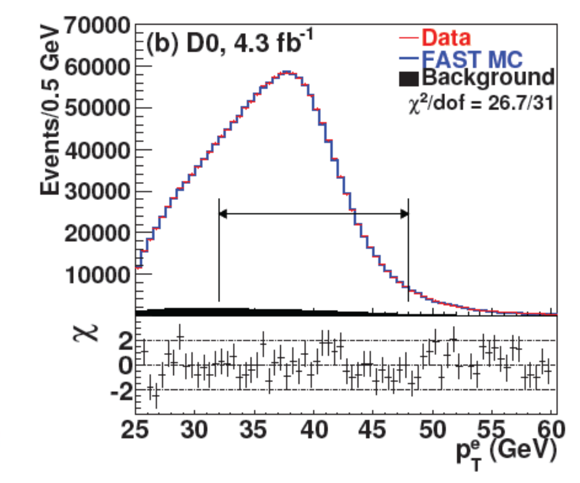
uncertainties are large, but
important cross check of direct mass measurements

Electroweak Fit & W Mass



W-Boson Mass Measurements at Tevatron





1.1M W events (e and μ)

1.7M W events (e only)

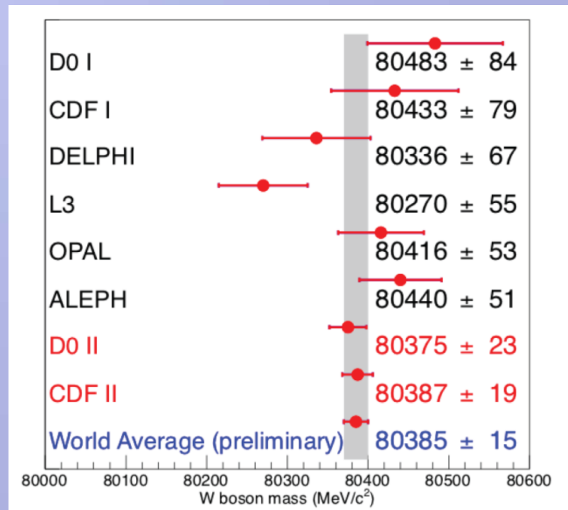
Current precision: 15 MeV
(ultimately ~10 MeV?)

Systematic uncertainties:

- PDFs: ~14 MeV
- lepton energy calibration
  16 MeV (D∅), 5 MeV (CDF)

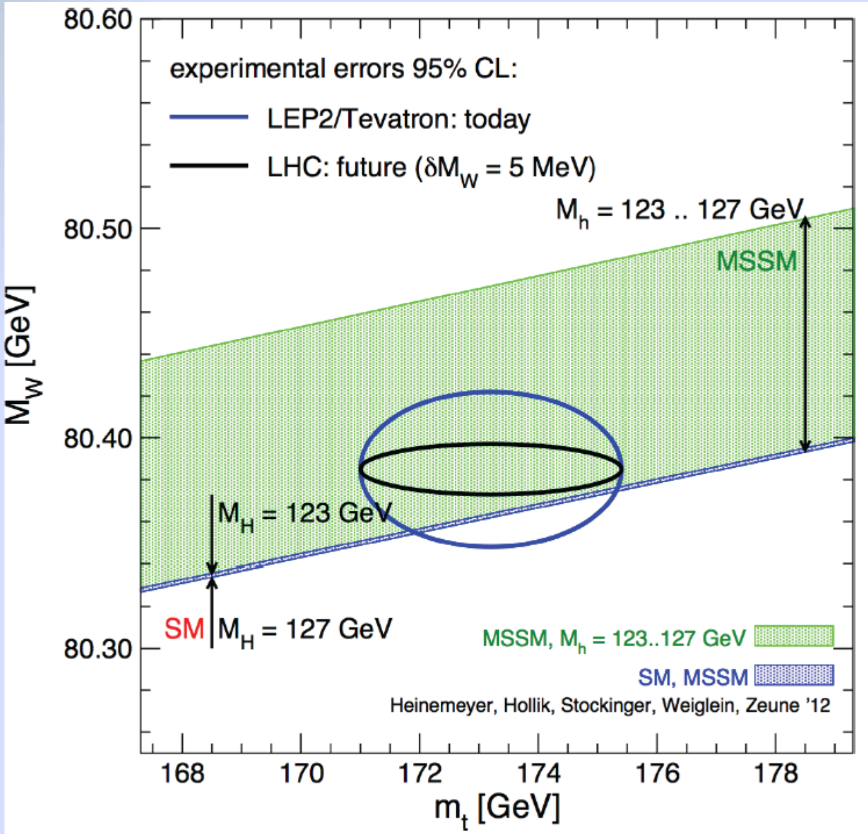
Goal at LHC? 5 MeV!

$$\Delta m_t = 0.9\ \text{GeV} \leftrightarrow \Delta m_W \approx 5\ \text{MeV}$$



5 MeV on the W Mass at LHC?

With 5 MeV W-mass accuracy
assuming present central values,
one could exclude the SM at the 95% CL!



A challenge for ATLAS and CMS!

- need to understand **p_T(W) distributions** in theory (and in the data)
  - for W^+ and W^-
- need improved **quark density functions** (and realistic uncertainties)
  experimental handles are:
  - lepton charge asymmetries
  - Z rapidity distributions
  - low mass Drell-Yan (sea anti-quarks)
  - W+charm (strangeness)

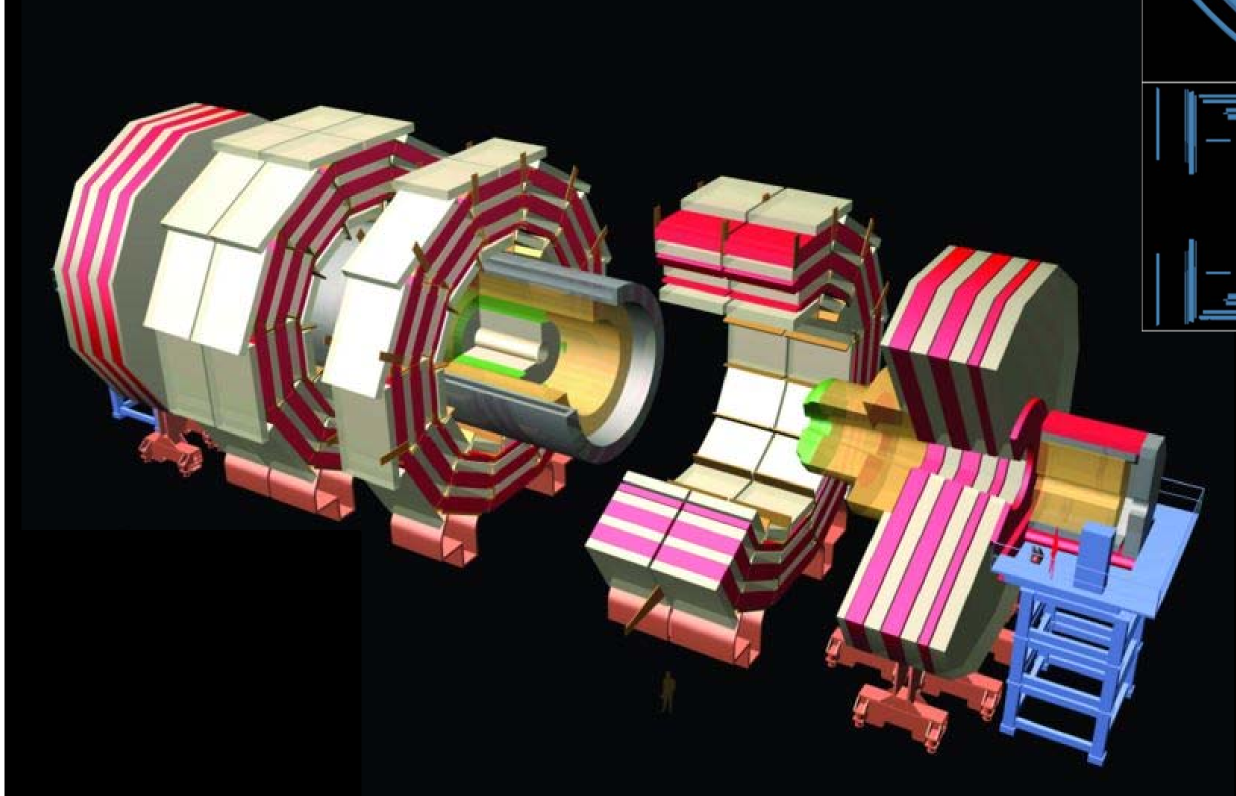
Critical: strange contribution to W production!

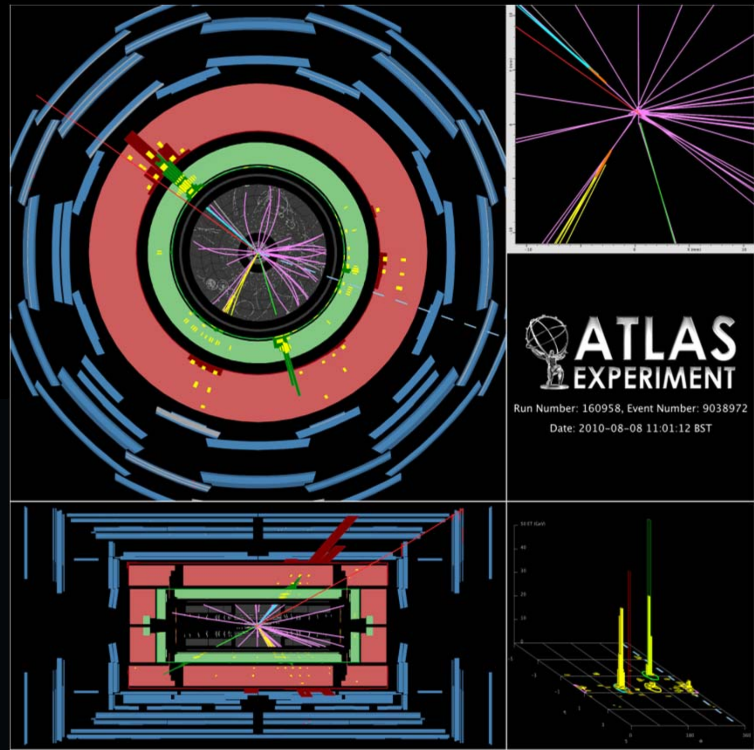
Experimental challenges

- control lepton energy scale at <0.1%
- energy resolution to ~1%
- p_T dependence of the efficiency to 1%

Critical: huge pile-up!

Electroweak and Top Quark Physics at the LHC





Part 3: Differential Cross Sections

Gautier Hamel de Monchenault
CEA-Saclay IRFU-SPP

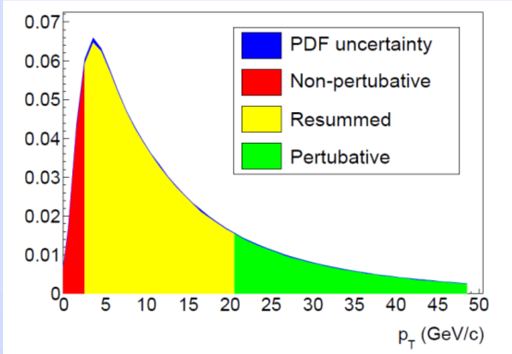
Ecole d'été de Gif
Septembre 2012

Differential Cross Sections

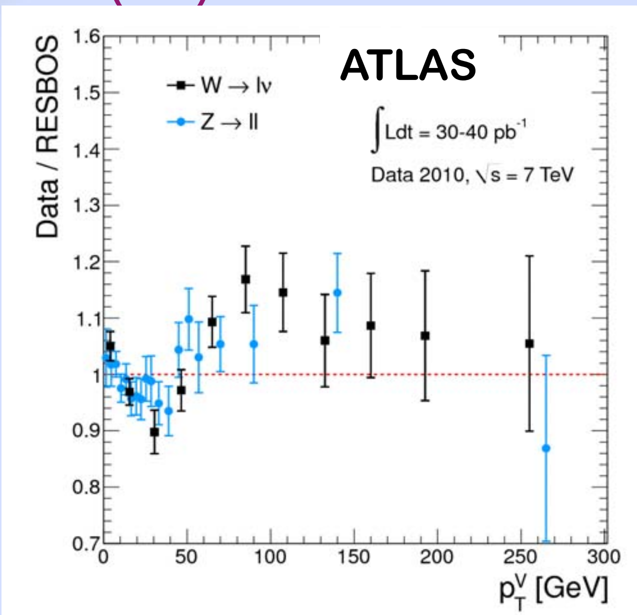
W Transverse Momentum

Important ancillary measurement for W mass

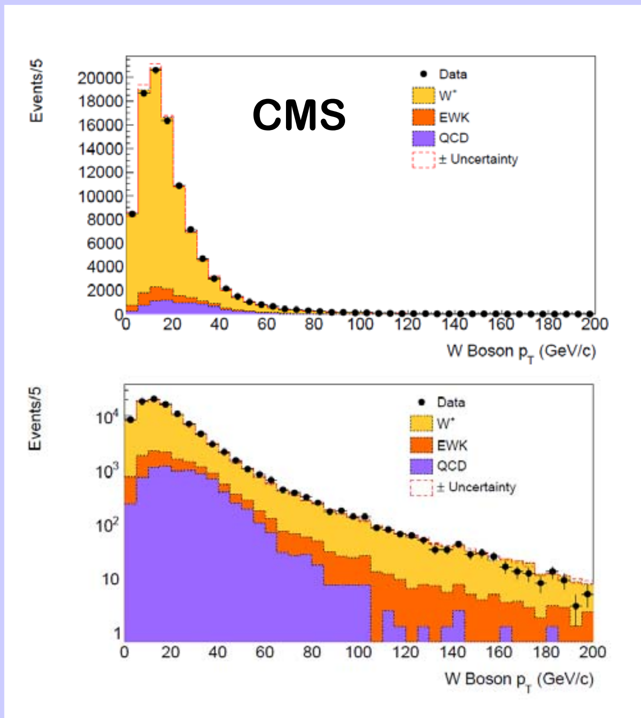
- the bulk of the W production is at low q_T
  QCD predictions are delicate
- the W production at high q_T
  test of perturbative QCD at *higher orders*



PRD85 (2012) 012005



unfolded fiducial distributions for W and Z, compared to RESBOS NNLO calculation (observe shape distortion at low energy)



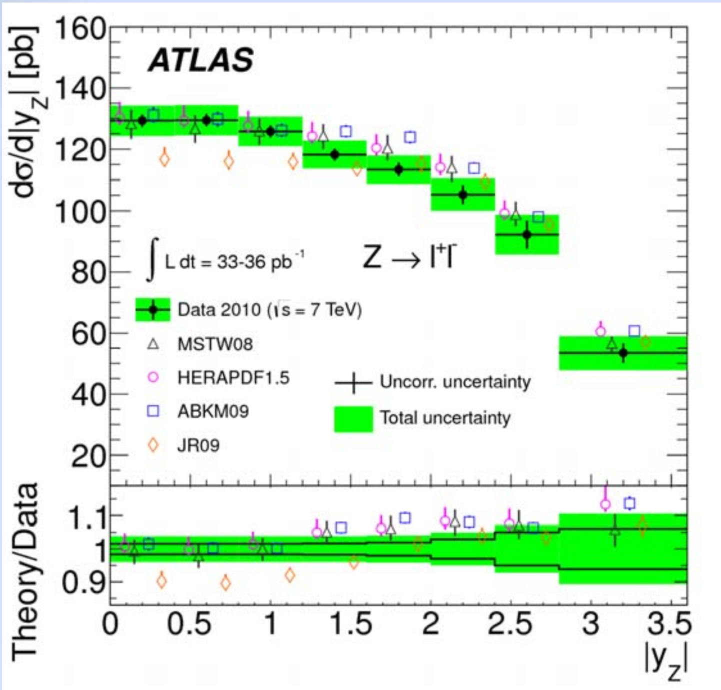
Signal MC corrected

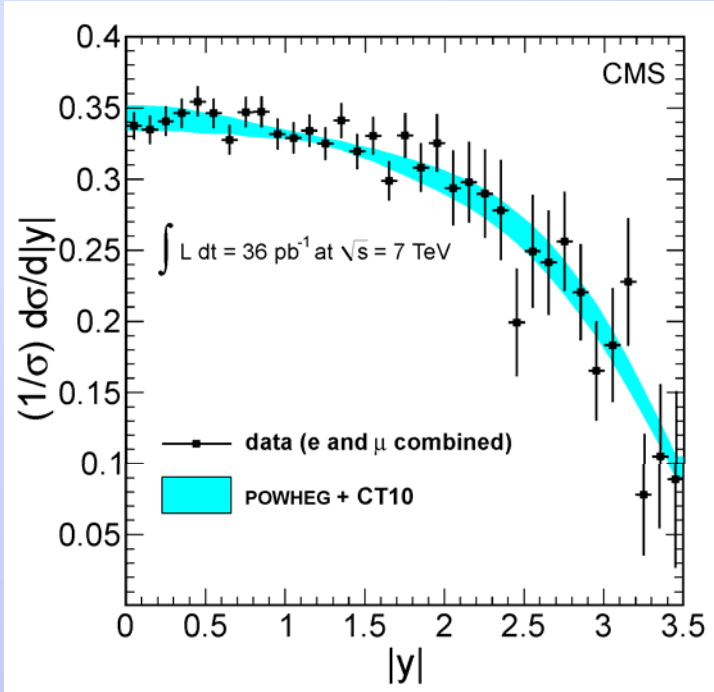
- for hadronic recoil from Z sample
- at NNLO level using **RESBOS**

NNLO corrections are needed to describe the perturbative region up to 200 GeV

Note: RESBOS tuned to Tevatron data

Z Rapidity





Fiducial cuts

- $p_T > 20$ GeV
- $66 < M(\mu\mu) < 116$ GeV

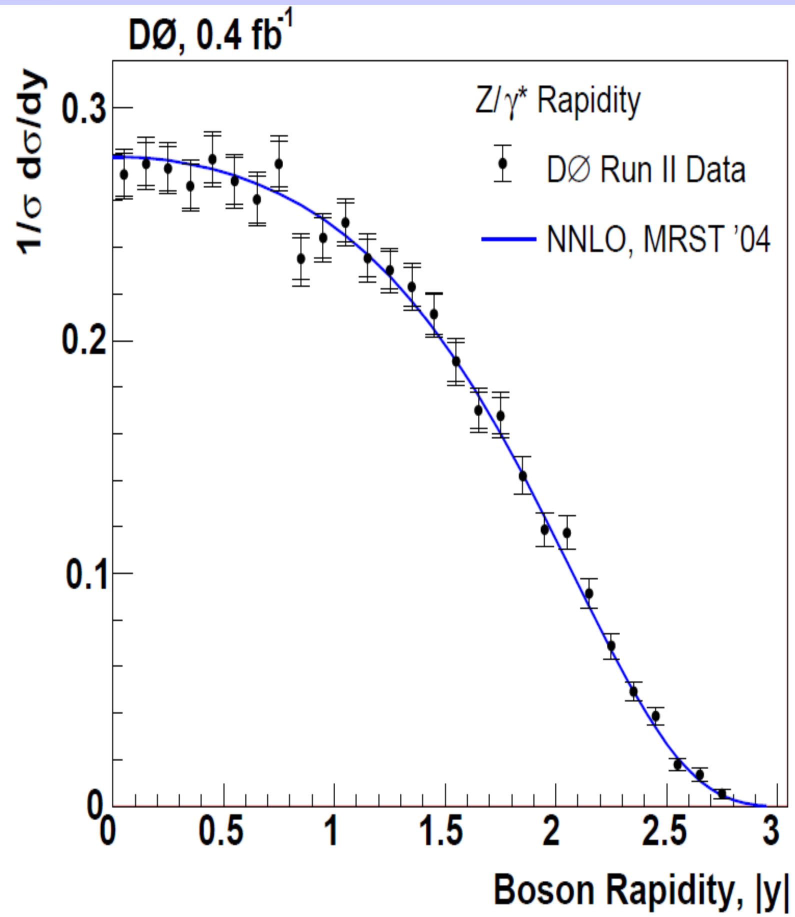
Fiducial cuts

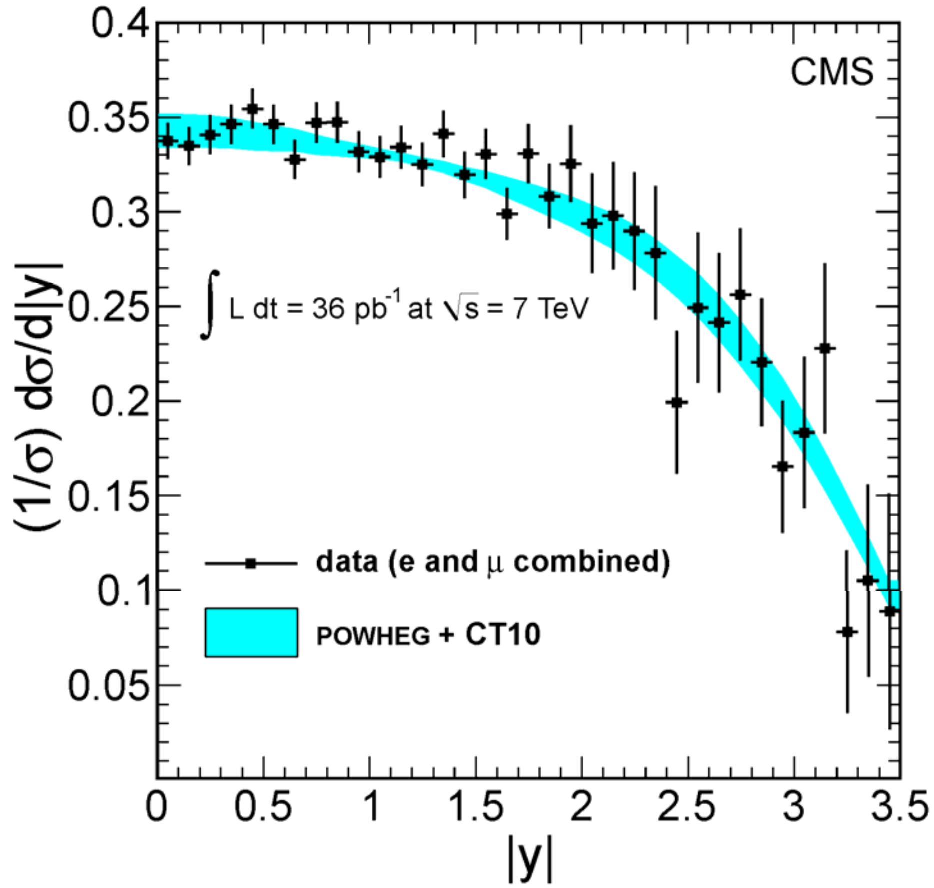
- $E_T > 20$ GeV
- $60 < M(ee) < 120$ GeV

Strong constraints on PDF sets

Tevatron versus LHC

Very different Drell-Yan rapidity distributions at the Tevatron and the LHC



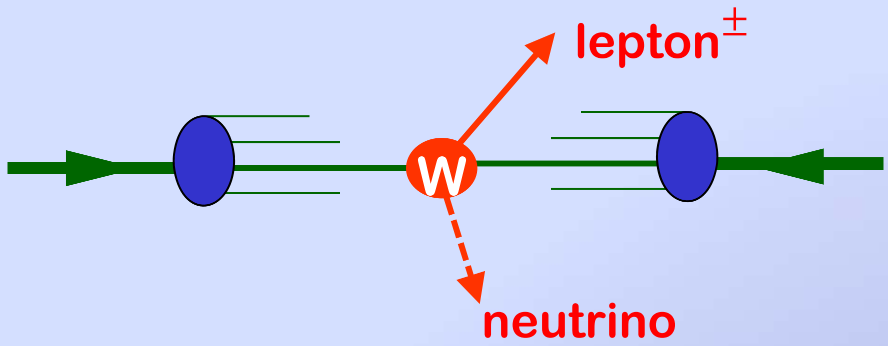


Explore much larger x-Bjorken range at the LHC!

W events: Lepton Pseudo-Rapidity

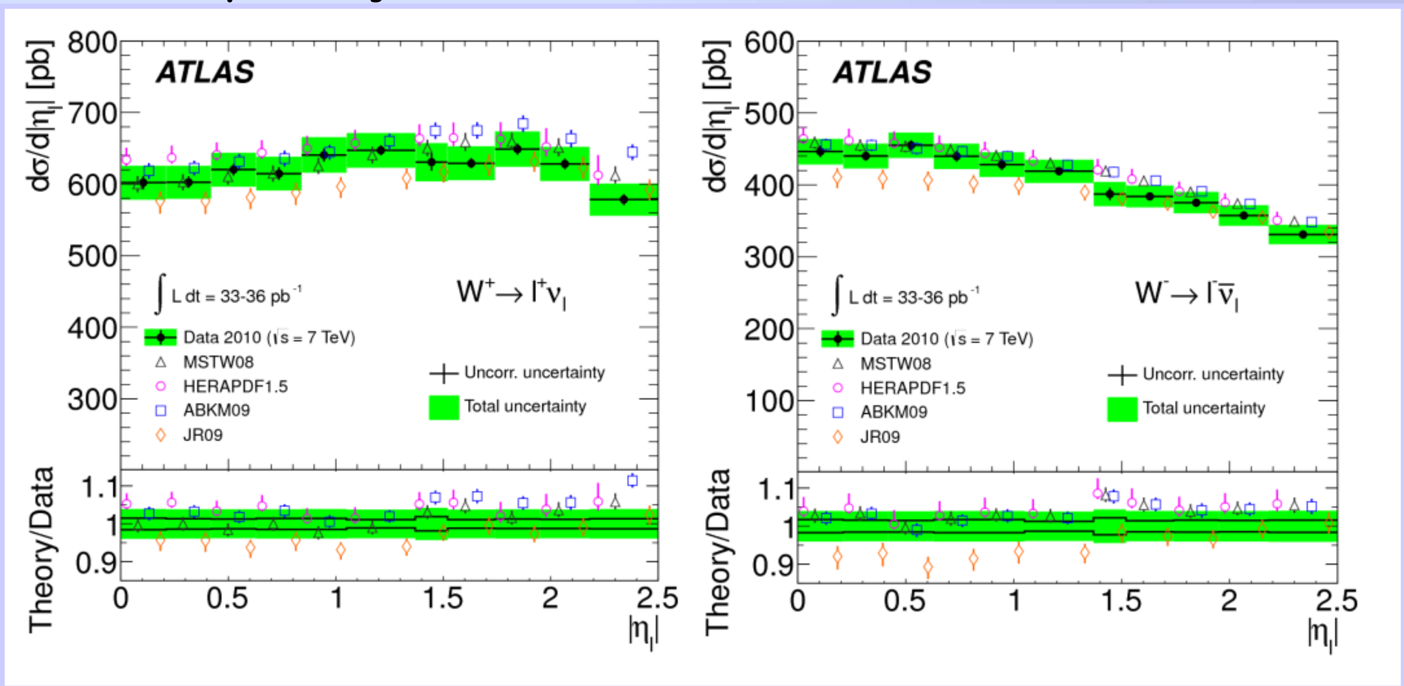
Fiducial cuts

- $p_T > 20$ GeV
- $E_T^{miss} > 25$ GeV
- $m_T > 40$ GeV



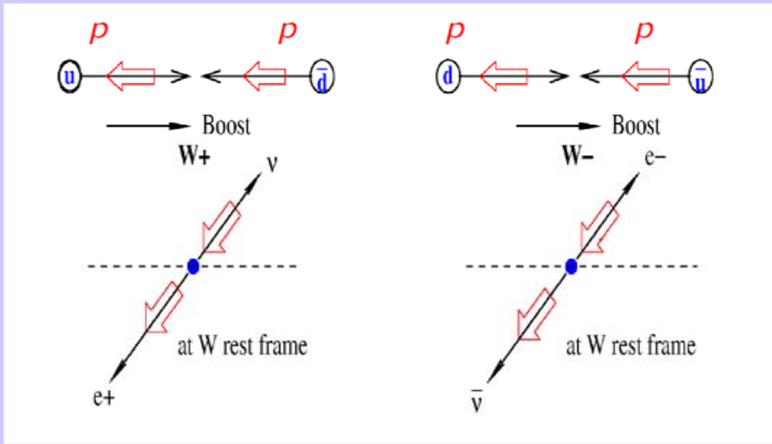
ATLAS: separately for W⁺ and W⁻

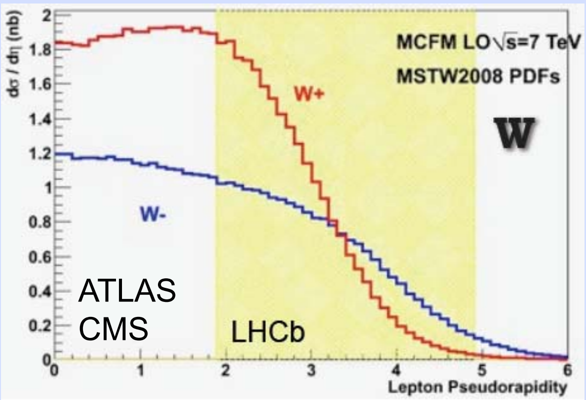
PRD85 (2012) 072004

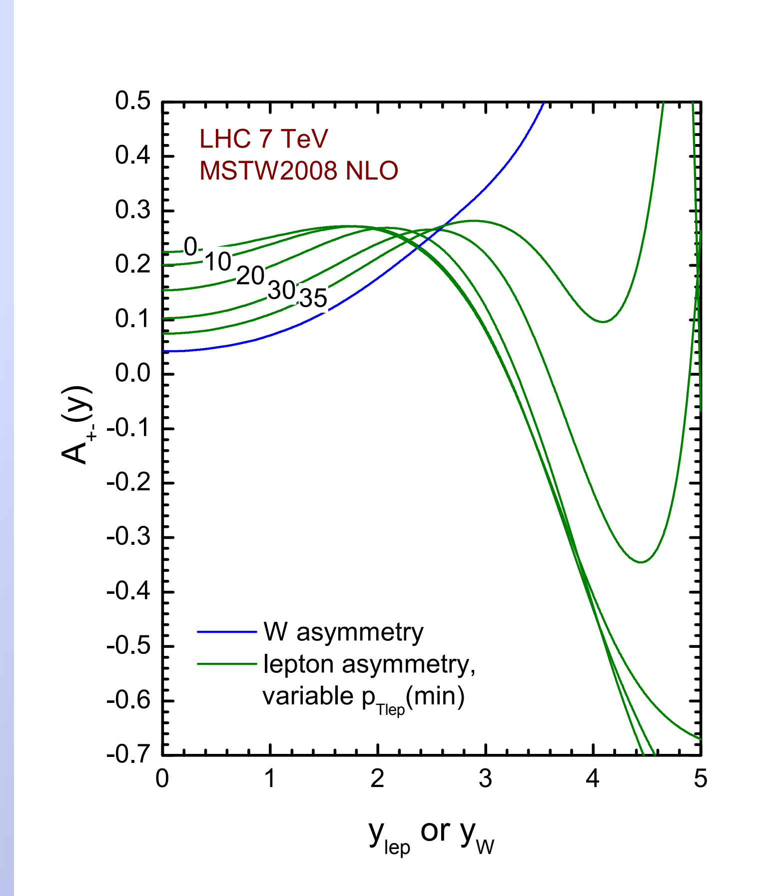


Lepton Charge Asymmetry

the lepton charge asymmetry is a complex interplay of u_V, d_V, sea quarks and the V±A structure of the W decays



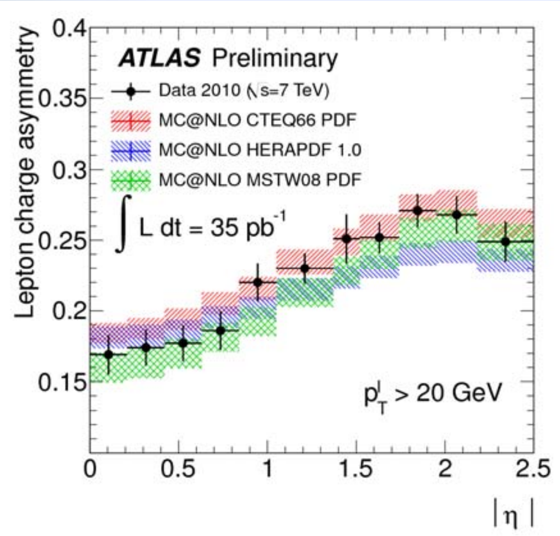




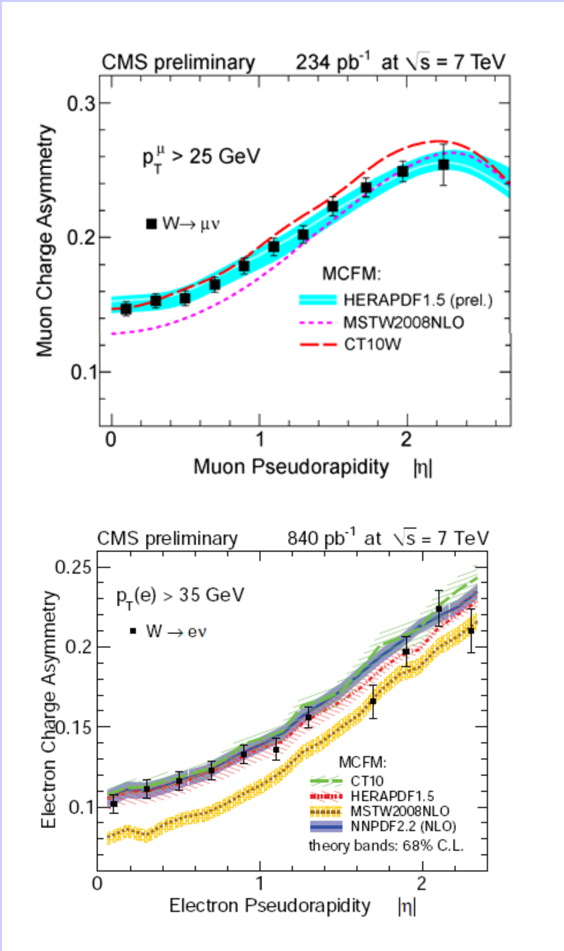
the asymmetry varies as a function of η of the lepton and changes sign: at large η the W^- cross-section is higher than the W^+ cross-section, as a consequence of the V-A structure of the W to lepton coupling

Lepton Charge Asymmetry

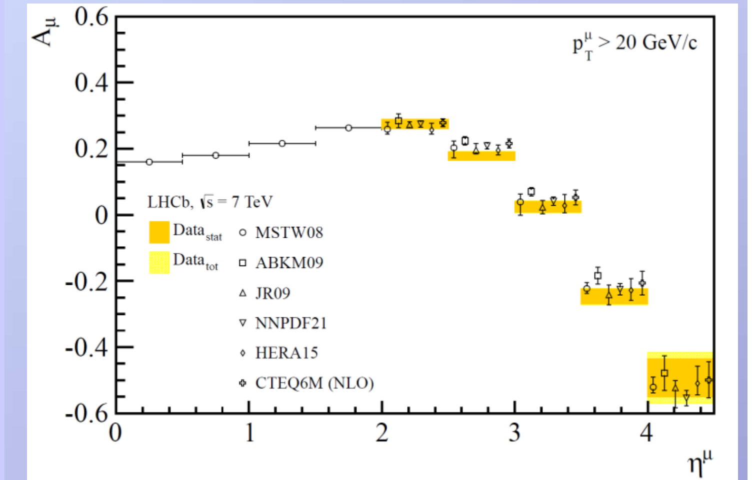
ATLAS



CMS

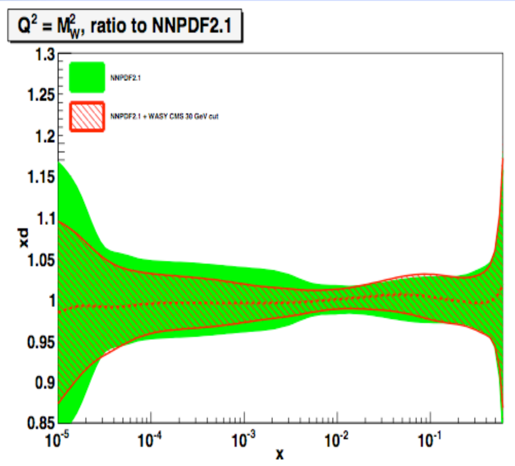


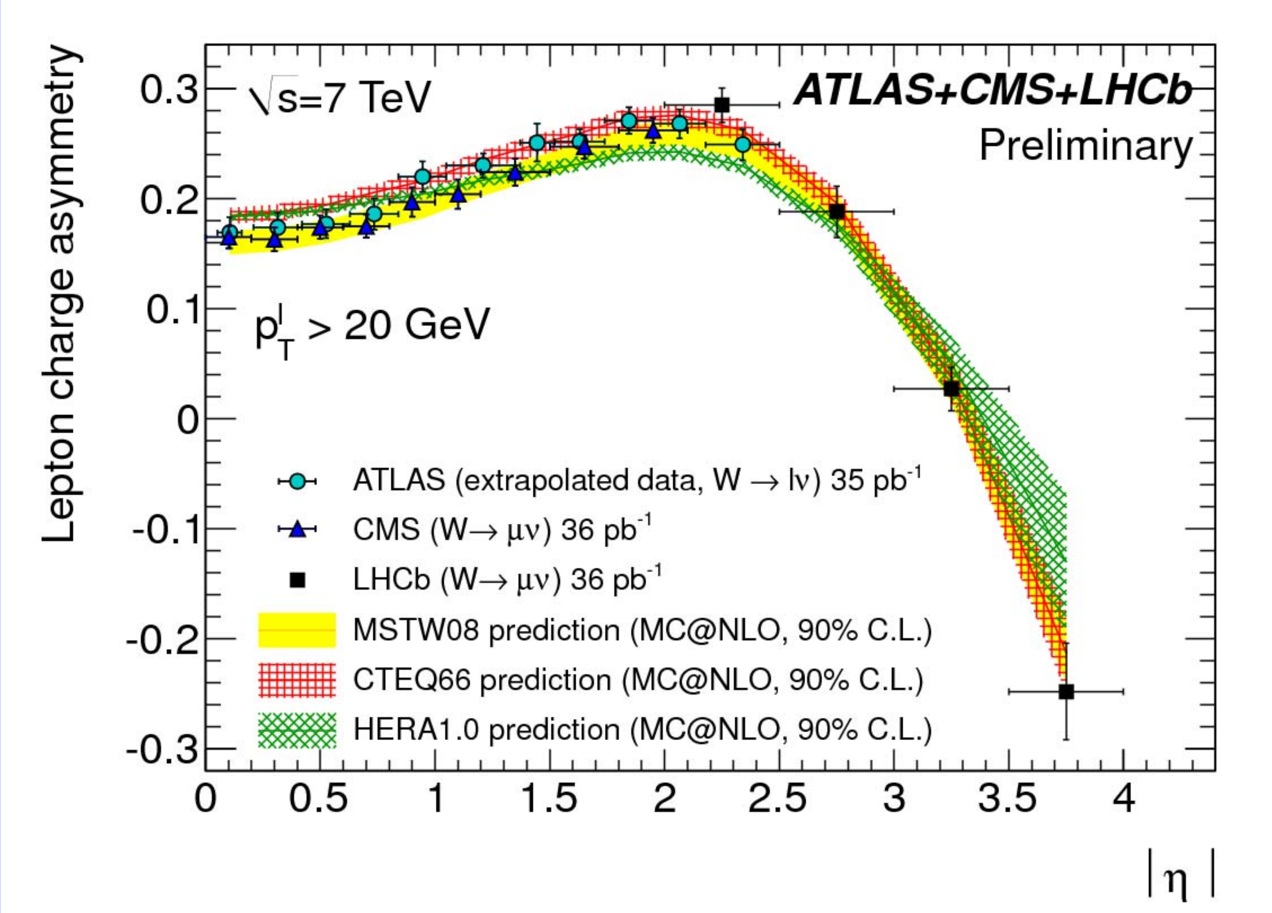
LHCb



Lepton Charge Asymmetry

ATLAS+CMS
charge asymmetry
results already improve
u, d, u/d quark PDFs
by up to 40%
in the range $10^{-3} < x < 10^{-2}$

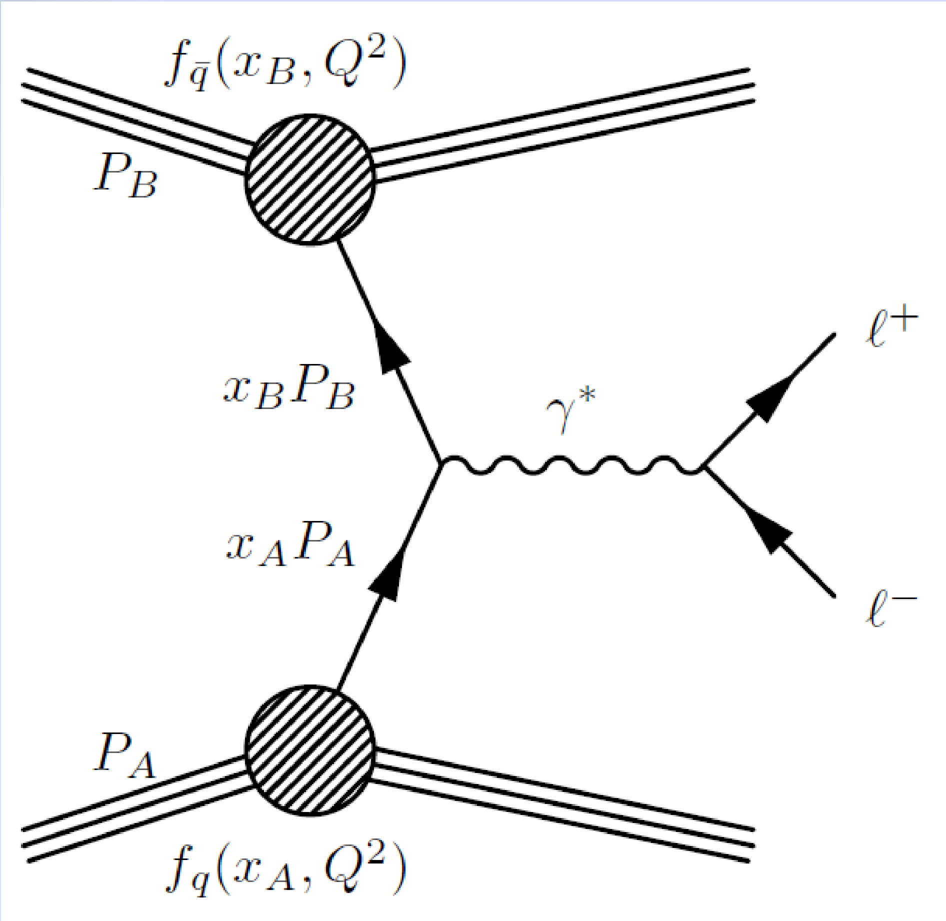




LHCb has coverage in rapidity
that goes beyond ATLAS+CMS acceptance
and extends sensitivity to much lower x values

Drell Yan

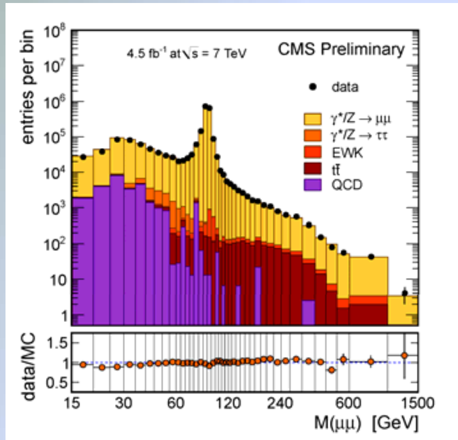
The Drell-Yan Process



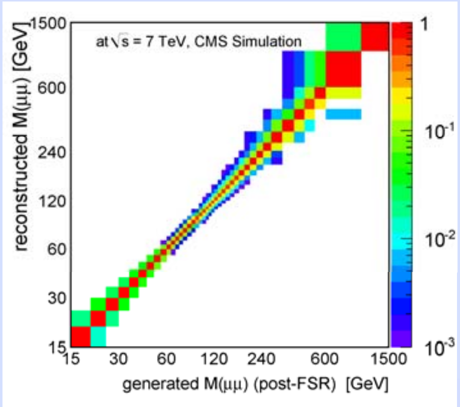
$$q + \overline{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^+\ell^-$$

A Differential Measurement

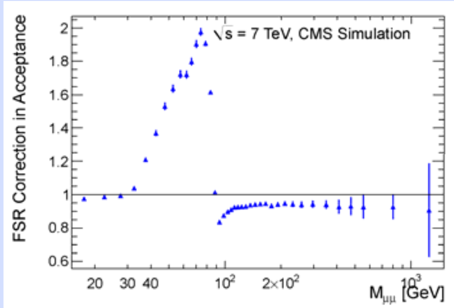
Raw spectrum



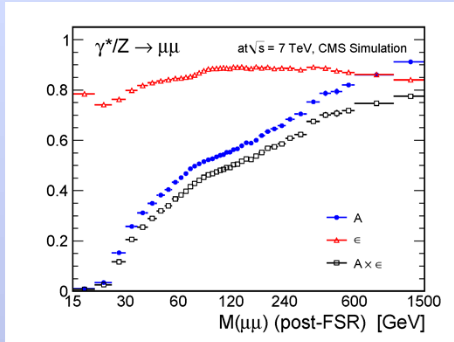
Unfolding



FSR correction



Acceptance & Efficiency



Backgrounds

- estimated from control samples in the data when possible (QCD, top) otherwise from simulation
- subtracted bin-by-bin

Unfolding

- correct for migrations from bin to bin due (*here*) to detector resolution effects
  - response matrix from simulation
  - several methods to invert the matrix

Final State QED Radiation

- correct back to the propagator level
  - bin-by-bin by comparing pre-FSR and post-FSR invariant mass spectra

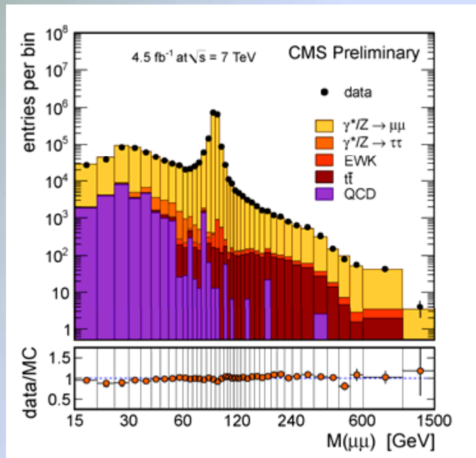
Acceptance and Efficiency

- using POWHEG MC
  - event-by-event corrections to NNLO with FEWZ

Additionnal Sources of Syst. Uncertainties

- lepton energy scale
- theory: PDFs, EWK corrections

CMS: Drell-Yan



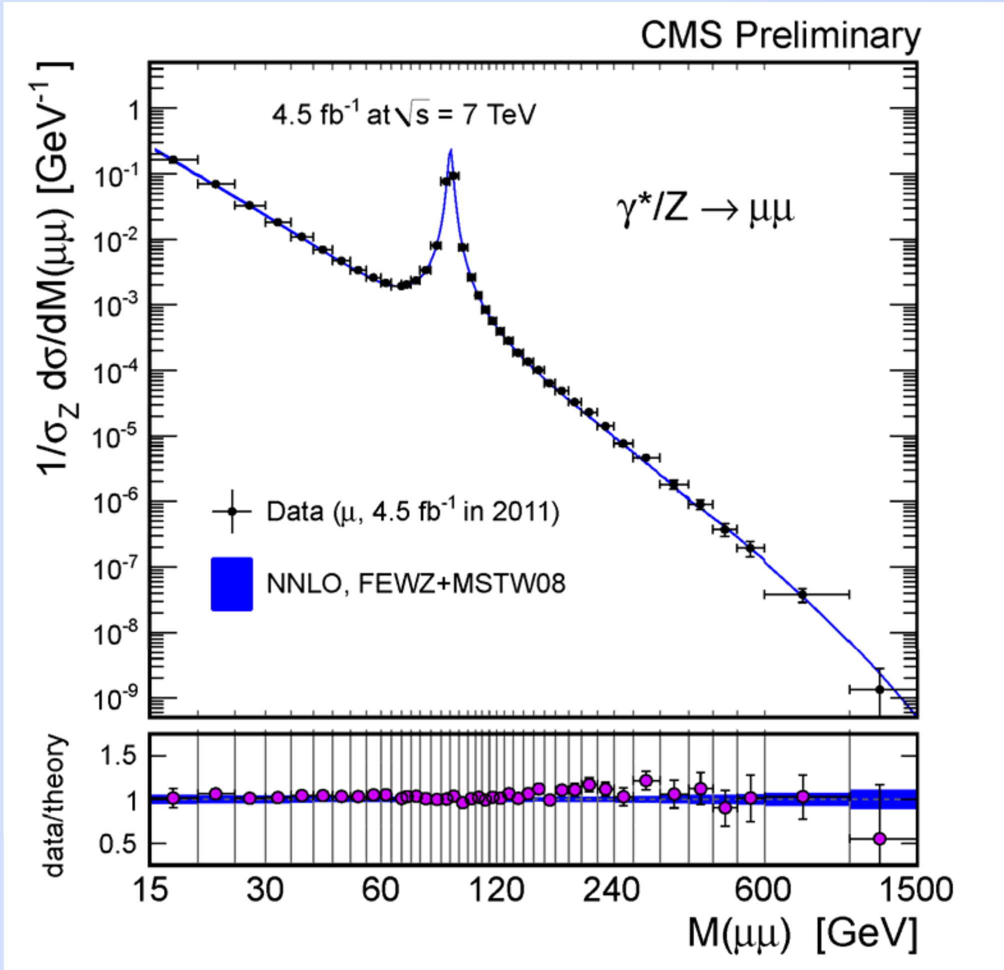
Raw Spectrum

CMS-EWK-11-007

CMS
LHC@√s=7TeV (2011)
∫Ldt = 4.5 fb^{-1}

Fully-Corrected Spectrum

normalized to
Z region
60-120 GeV



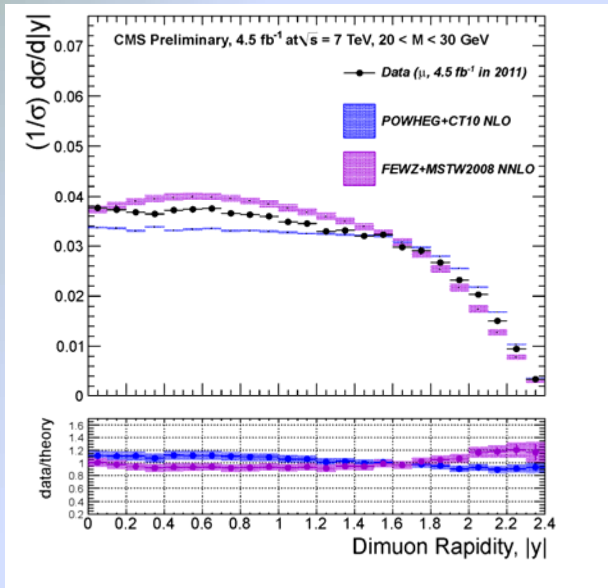
of the order of
1.4M events!

allows direct comparison with NNLO FEWZ calculations

CMS: Doubly-Differential DY

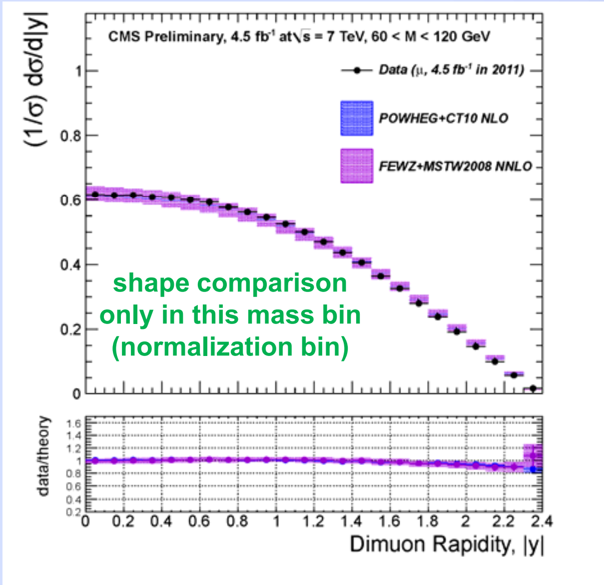
fully-corrected and unfolded rapidity distributions
in 6 bins of di-muon invariant mass

Low Mass Region
20 < M(μμ) < 30 GeV

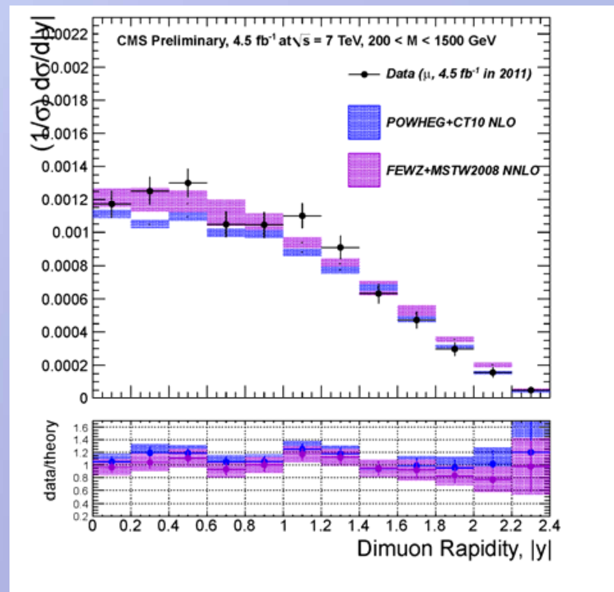


rapidity |y| of the DY pair

Z Mass Region
60 < M(μμ) < 120 GeV

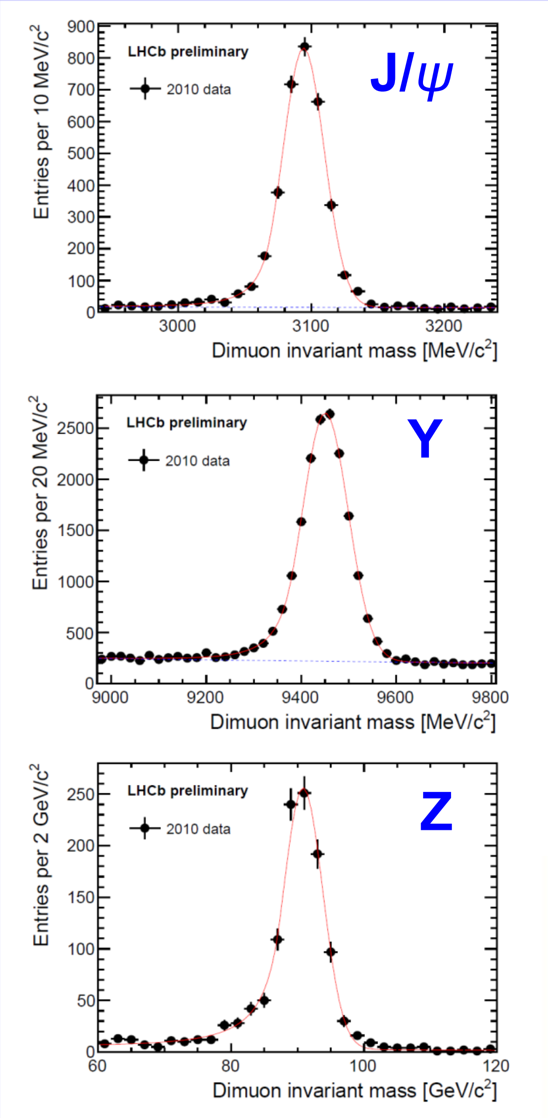


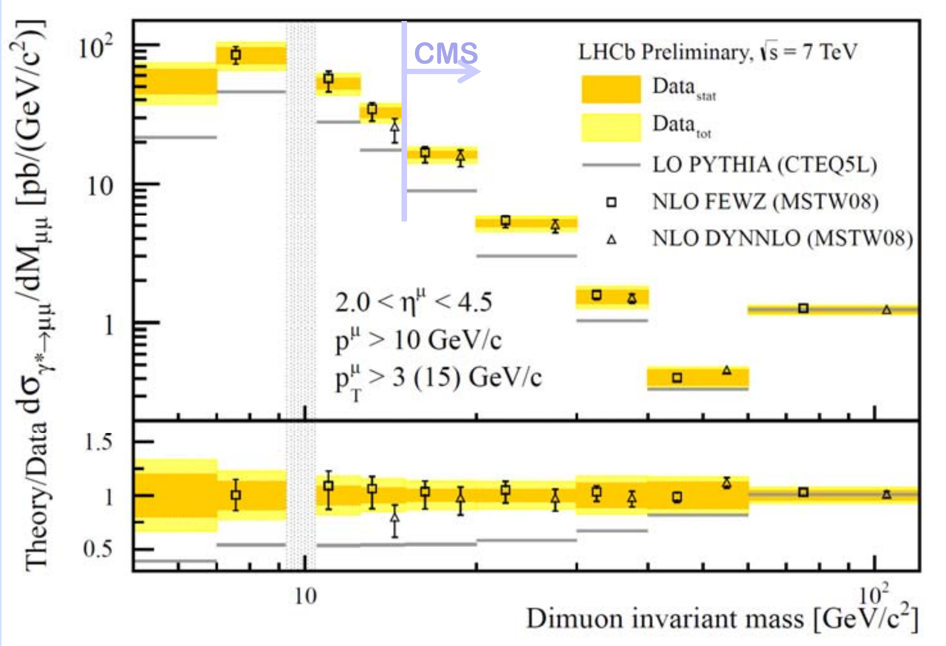
High Mass Region
200 < M(μμ) < 1600 GeV



- significant differences between data and calculations at **low mass** and **mid-rapidity**:
  - with FEWZ NNLO below 45 GeV
  - with POWHEG NLO below 30 GeV

LHCb: DY in Forward Region

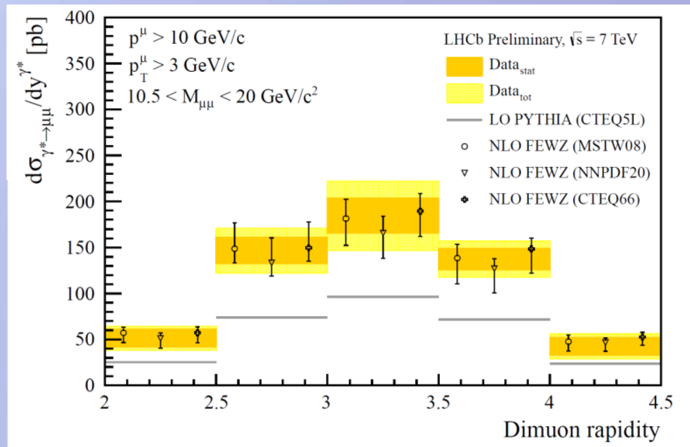




LHCb-CONF-2011-013

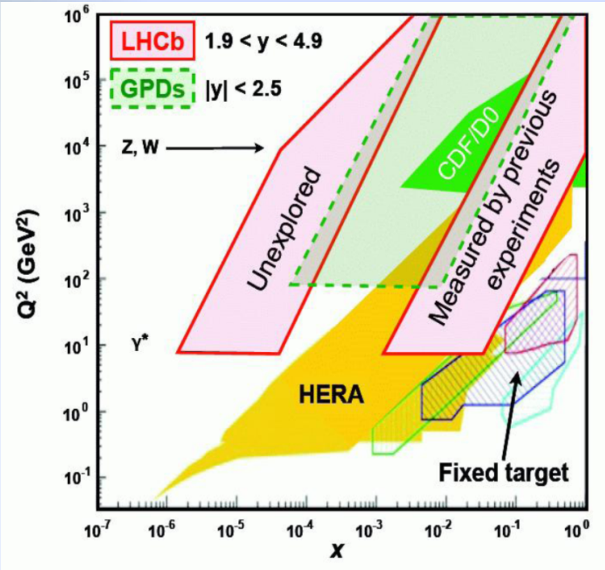
DY in dimuon channel

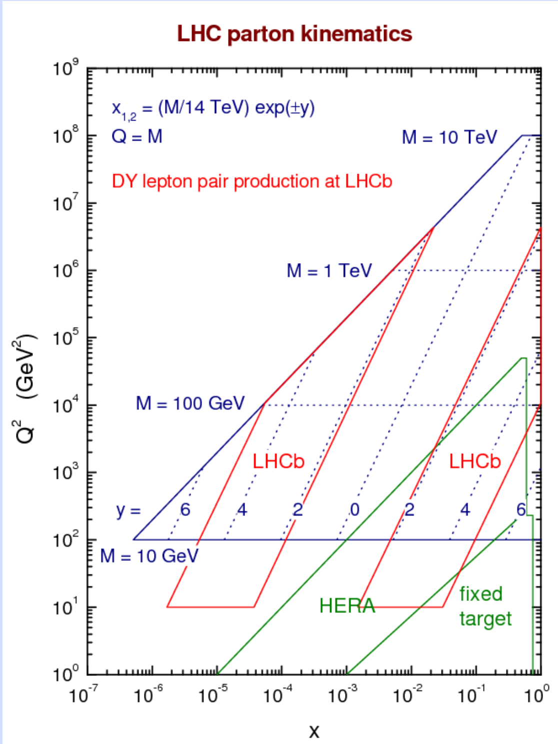
tests of NLO calculations and PDFs at low mass & large rapidity, probing different (x,Q^2) regions



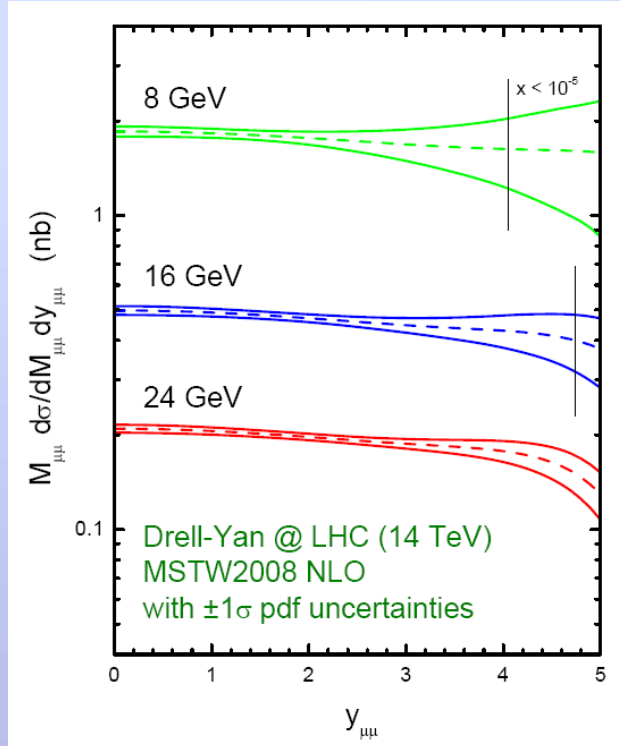
Probing Low x Values at LHCb

detect forward
low p_T muons
from Drell Yan





LHC@14 TeV



LHCb at 14 TeV can potentially explore the experimentally poorly-known region of very small values of x ($x<10^{-5}$) for relatively high Q^2 (test validity of DGLAP equations at low x)

Drell-Yan Angular Analysis

$$\frac{d\sigma_q}{d\cos\theta}(s) = \frac{3\pi\alpha_{\rm QED}^2}{2s} Q_q^2 \left(1+\cos^2\theta\right)$$ γ* exchange

Z/γ* interference

$$- \frac{3\alpha_{\rm QED} G_F M_Z^2}{2\sqrt{2}\Gamma_Z^2} \frac{s-M_Z^2}{s} {\rm BW}(s)\, Q_q g_{Vq} g_{V\ell} \left[\left(1+\cos^2\theta\right) + 2\frac{g_{Aq}g_{A\ell}}{g_{Vq}g_{V\ell}}\cos\theta\right]$$

$$+ \frac{3G_F^2 M_Z^4}{16\pi\Gamma_Z^2} {\rm BW}(s) \left({g_{Vq}}^2 + {g_{Aq}}^2\right)\left({g_{V\ell}}^2 + {g_{A\ell}}^2\right) \left[\left(1+\cos^2\theta\right) + \frac{8}{3}A_{\rm FB}^q \cos\theta\right]$$

Z exchange

with $\quad {\rm BW}(s) = \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} \quad$ and $\quad A_{\rm FB}^q \equiv \frac{3}{4}\mathcal{A}_q\mathcal{A}_\ell.$

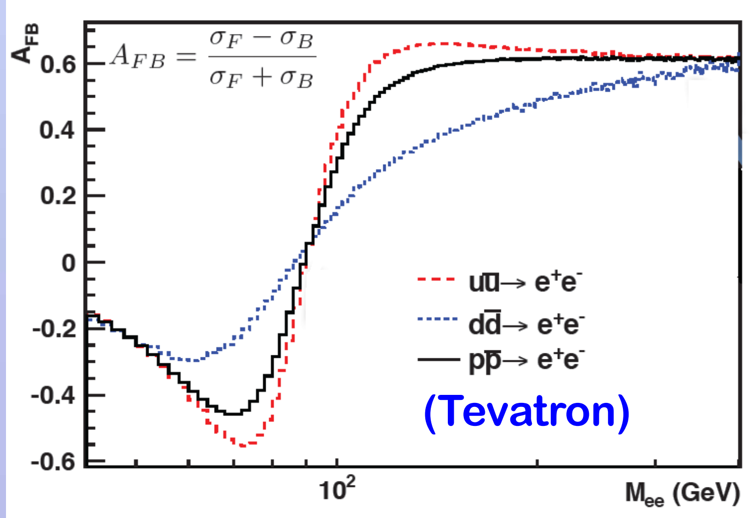
The forward-backward asymmetry $A_{\rm FB}$ results from an average over all flavor of quarks

$$\frac{d\sigma\left(Z^0/\gamma^* \to \ell^+\ell^-\right)}{d\cos\theta^*} = \frac{3}{8}\left(1+\cos^2\theta^*\right) + A_{\rm FB}\cos\theta^*$$

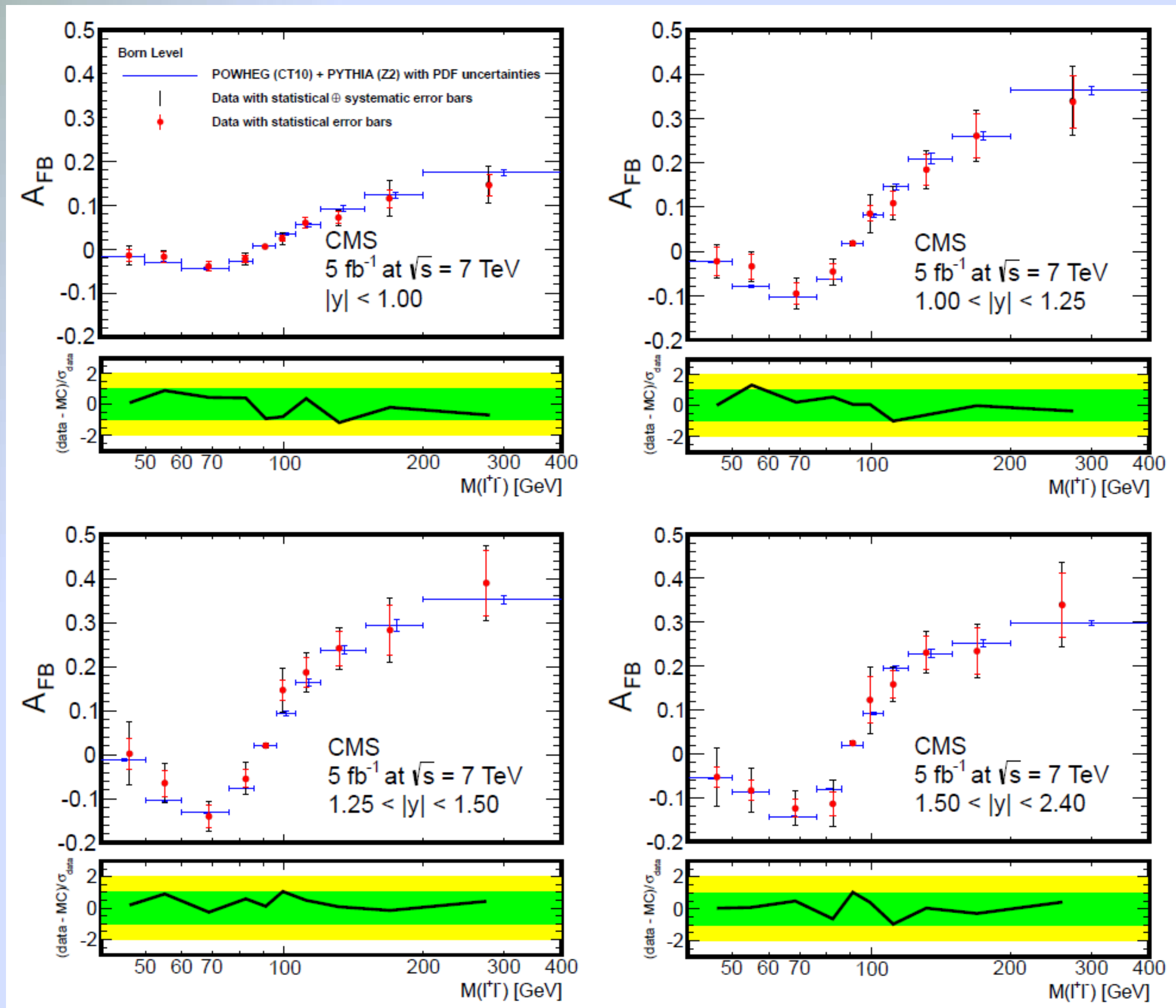
Difficulty at the LHC: the initial state is symmetric!

- at large rapidity, the longitudinal boost of the Z boson indicates more likely the direction of the parent (valence) quark

(use of Collins-Soper frame)



Forward-Backward Asymmetry



- good agreement with NLO predictions
- no sign of New Physics at high mass

Combined e+μ forward-backward asymmetries in Collins-Soper frame

(unfolded to Born level)

Full Angular Analysis

Triple-differential cross section for $s=M_{\mu\mu}^2$, y and cos θ^* (in **Collins-Soper** frame)

- at reconstruction level:

$$\frac{d\sigma}{ds\,dy\,d\cos\theta^\star} \propto \sum_{q=u,d,s,c,b} \mathcal{F}_{q\bar{q}}(s,y)\left[\sigma^{\text{even}}_{q\bar{q}}(s,\cos\theta^\star) + \mathcal{D}_{q\bar{q}}(s,y)\times\sigma^{\text{odd}}_{q\bar{q}}(s,\cos\theta^\star)\right]$$

with

$$\begin{cases} \sigma^{\text{even}}_{q\bar{q}}(s,\cos\theta^*) \propto \frac{3}{8}\left(1+\cos^2\theta^*\right) \\ \sigma^{\text{odd}}_{q\bar{q}}(s,\cos\theta^*) \propto A^{q\bar{q}}_{\text{FB}}(s,\theta_{\text{W}})\times\cos\theta^* \end{cases}$$

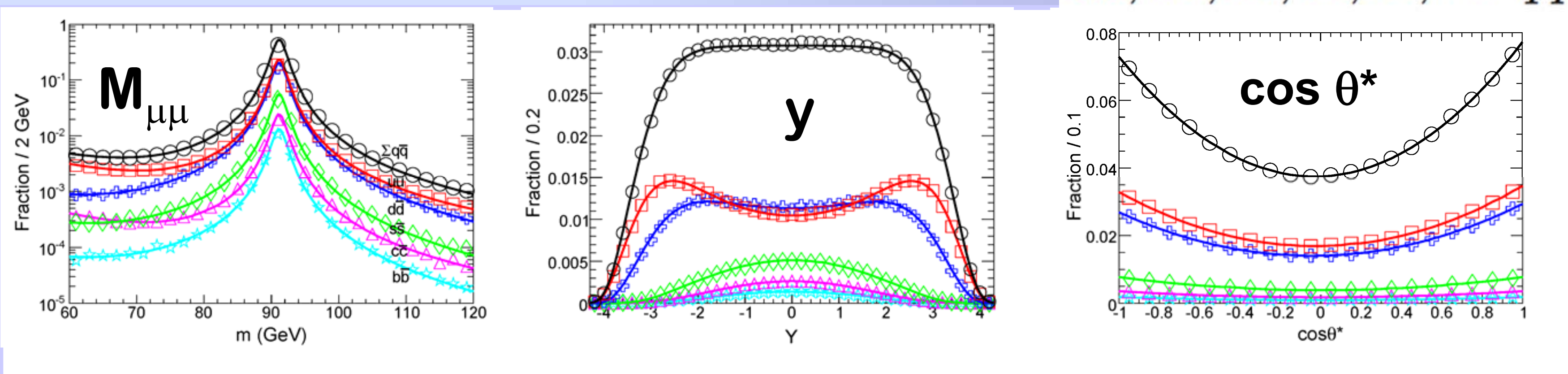
Fiducial cuts

- $|\eta^*| < 2.3$
- $p_T^* < 18$ GeV
- $q_T < 25$ GeV
- $80 < M < 110$ GeV

Quark "luminosity" *F*
using LO parton densities (CTEQ6) parameterized as a function of s and y

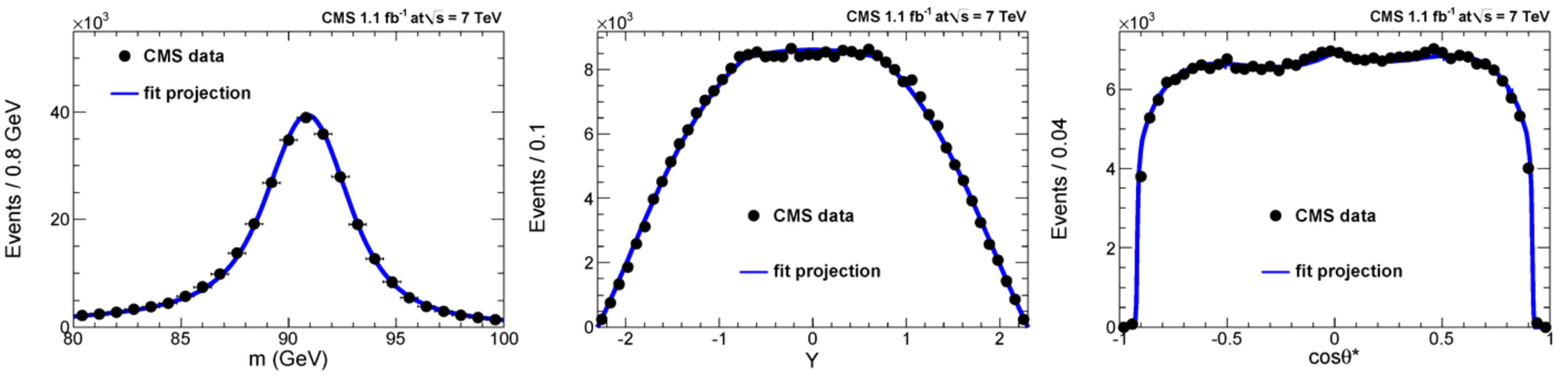
Acceptance function *D*
determined from Pythia at LO

$u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, $b\bar{b}$, all $q\bar{q}$



Mixing Angle

projections of the unbinned maximum likelihood fit



Analysis in the muon channel

- 1.1 fb^{-1} of 2011 data
  - about 300 000 events with 0.05% background
- efficiency, resolution and final-state radiation corrections

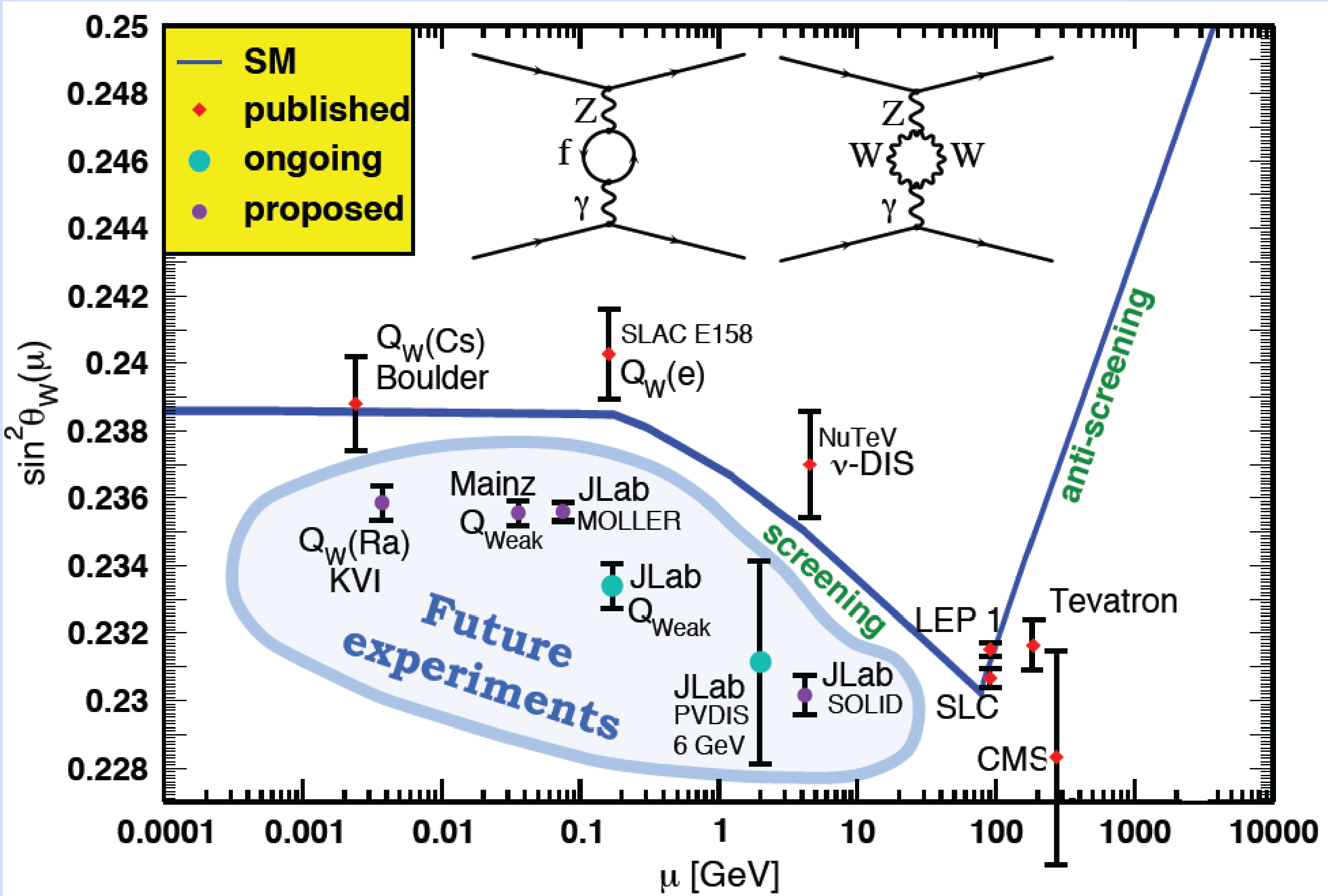
$$\sin^2\theta_{\text{eff}} = 0.2287 \pm 0.0020(\text{stat}) \pm 0.0025(\text{syst})$$

CMS-PAS-EWK-11-003

Main sources of systematic uncertainties

- LO modeling (POWHEG-NLO vs Pythia-LO)
- FSR corrections, PDF uncertainties
- resolution, tracker alignment

Running of $\sin^2\Theta_W$



from Joao Guimaraes, ICHEP2012

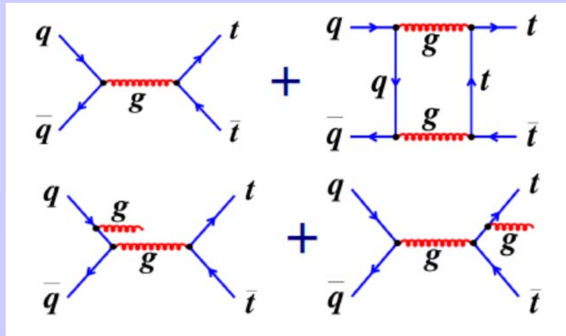
Charge Asymmetry in Top Quark Pair Production

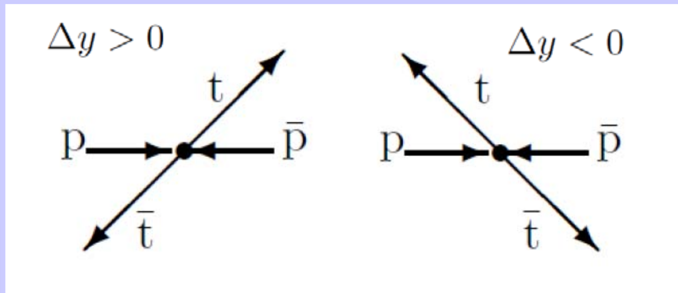
Charge Asymmetry in t-tbar

Charge asymmetry refers to differences in rapidity of top quarks and antiquarks

- **SM at LO QCD**: charge asymmetry is exactly zero
- **SM at NLO QCD**: a small asymmetry appears due to
  - interferences between Born and box diagrams in **qq → tt**
  - interferences between ISR and FSR in **qq → ttg**
  - amplitudes odd under the exchange of t-tbar in **qg → ttq**

small asymmetries at NLO
in quark annihilation and flavor excitation,
no asymmetry in gluon fusion





Tevatron: Forward-Backward Asymmetry

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \quad \text{where} \quad \Delta y = y_t - y_{\bar{t}}$$

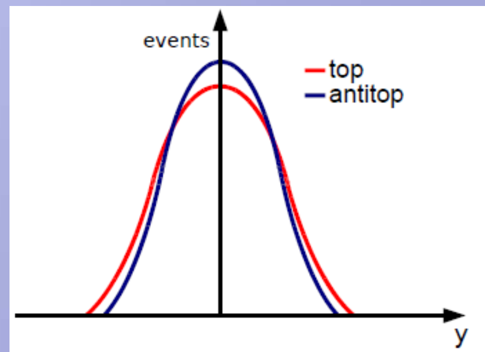
dominant production at Tevatron: qq annihilation

LHC: Charge Asymmetry

initial state is charge symmetric: no forward-backward asymmetry

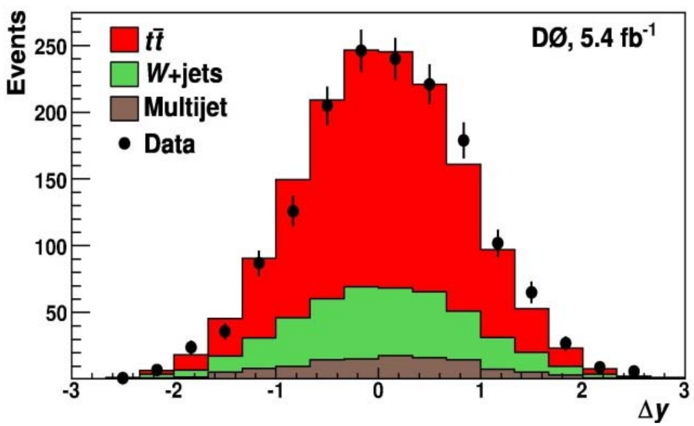
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \quad \text{where} \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

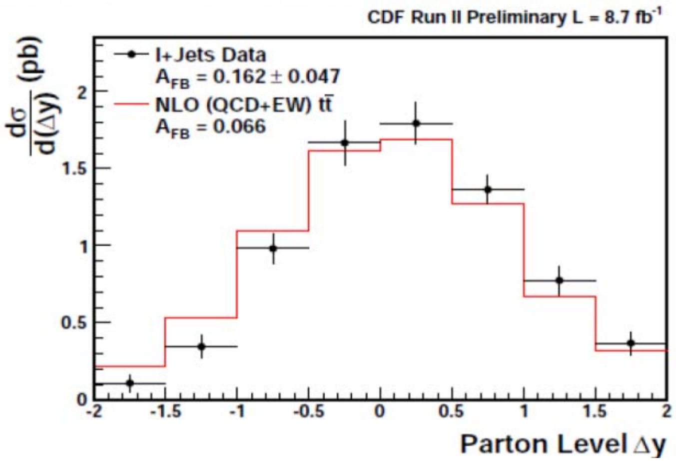
dominant production at LHC: gluon fusion



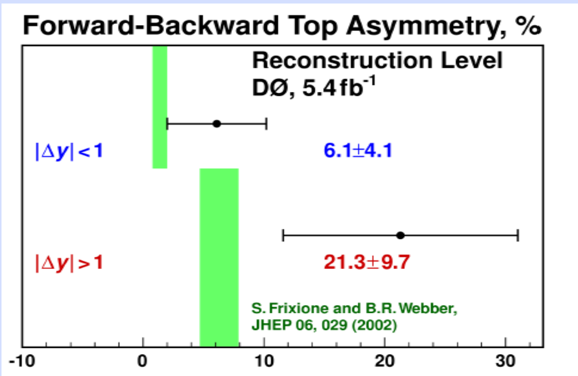
Tevatron: Charge Asymmetry

Experimentally, strong asymmetries are seen in D∅ and CDF:

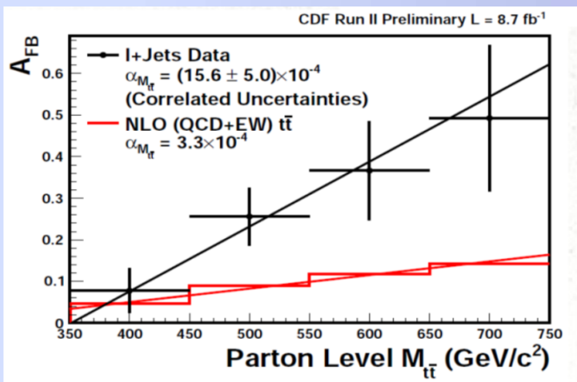




Δy in the lepton-jets channel



arXiv:1107.4995, arXiv:1207.0364



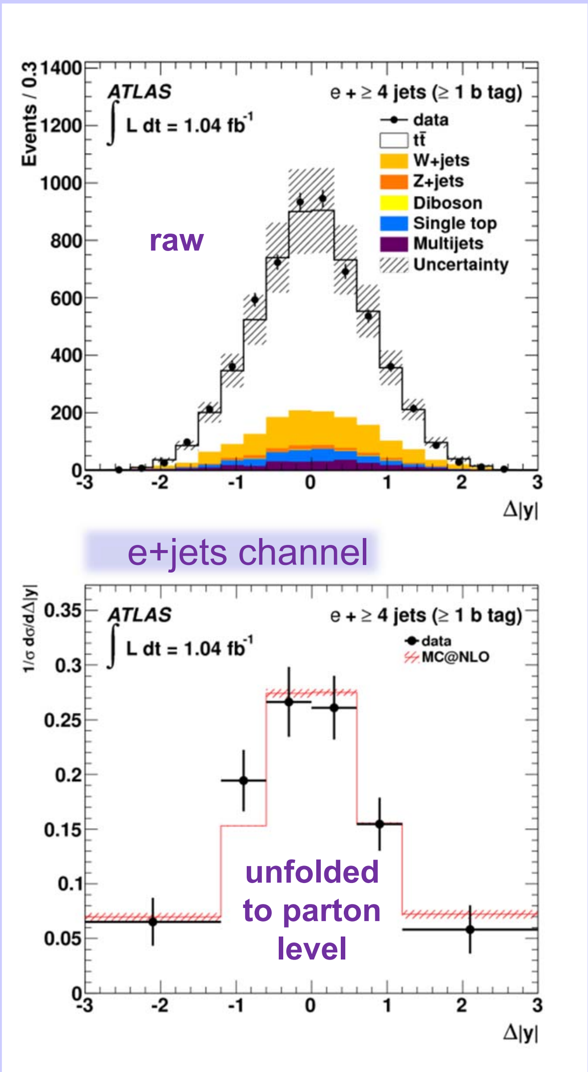
CDF-Note-1080

Significant asymmetries predominantly at

- high mass
- low pT
- large Δy

Hints of inconsistency with NLO QCD predictions up to 3σ at high mass

ATLAS: Charge Asymmetry



ATLAS
LHC@√s=7 TeV (2011)
∫Ldt = 1.04 fb^-1

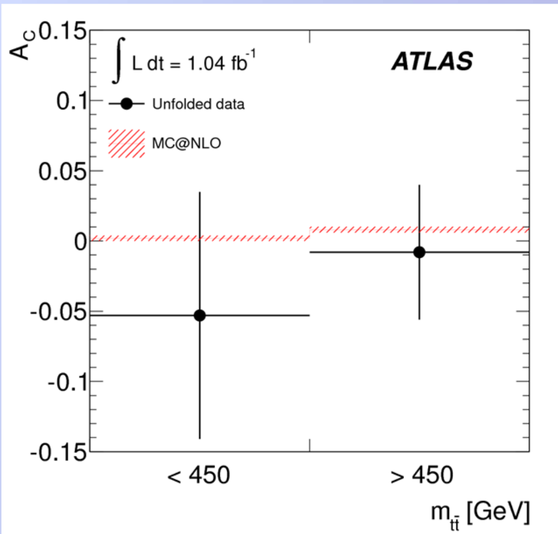
arXiv:1203.4211

Lepton+jets channel

- event selection and background estimation similar to that of cross-section measurement
- jet assignment with kinematic likelihood

Charge asymmetry

- inclusive and in two bins of the t-tbar mass
- (2D) iterative Bayesian unfolding method



agreeement with NLO QCD predictions

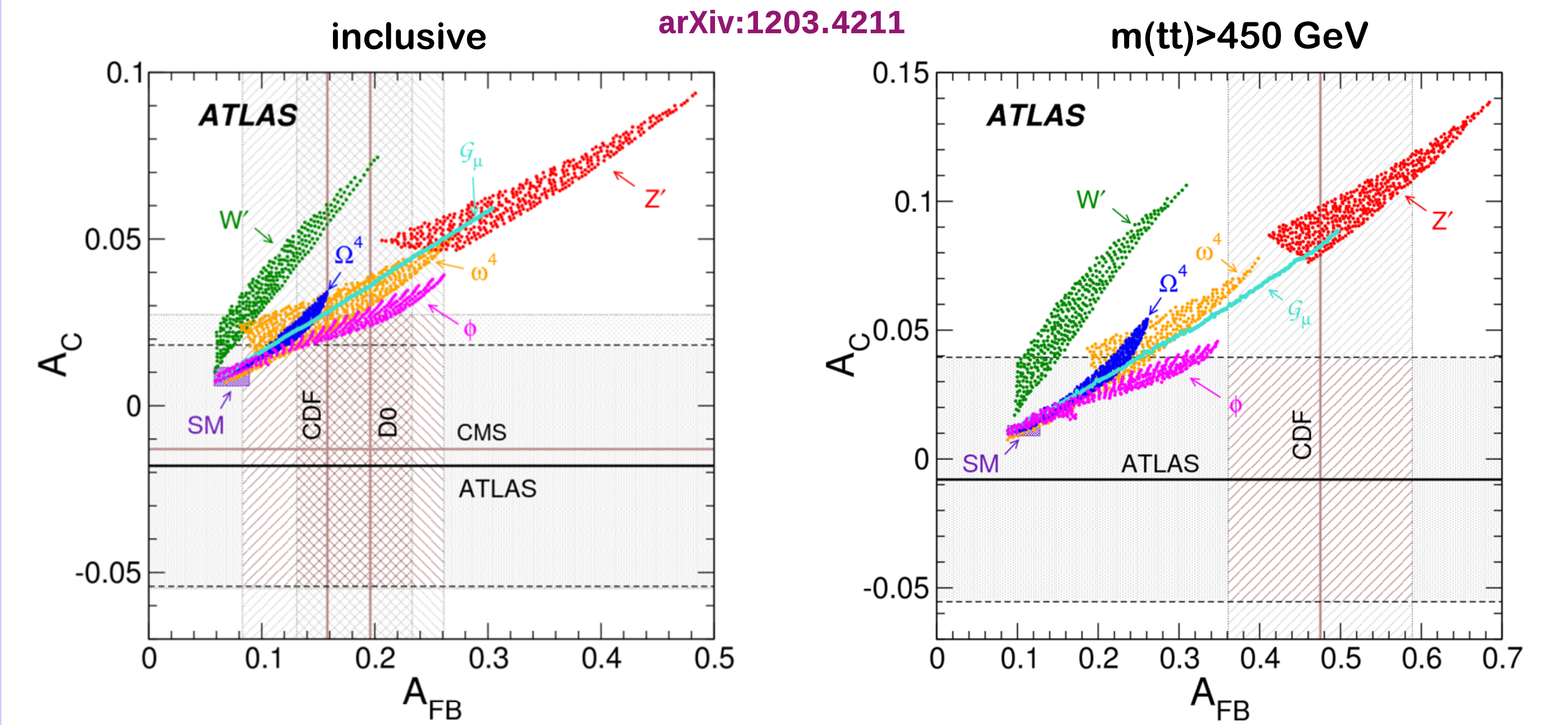
New Physics in Asymmetry ?

New Physics can result in a charge asymmetry
by exchange of new heavy particles, for instance:

- Z'-bosons
- W' bosons with right-handed couplings
- axigluons
- Kaluza-Klein excitations of gluons

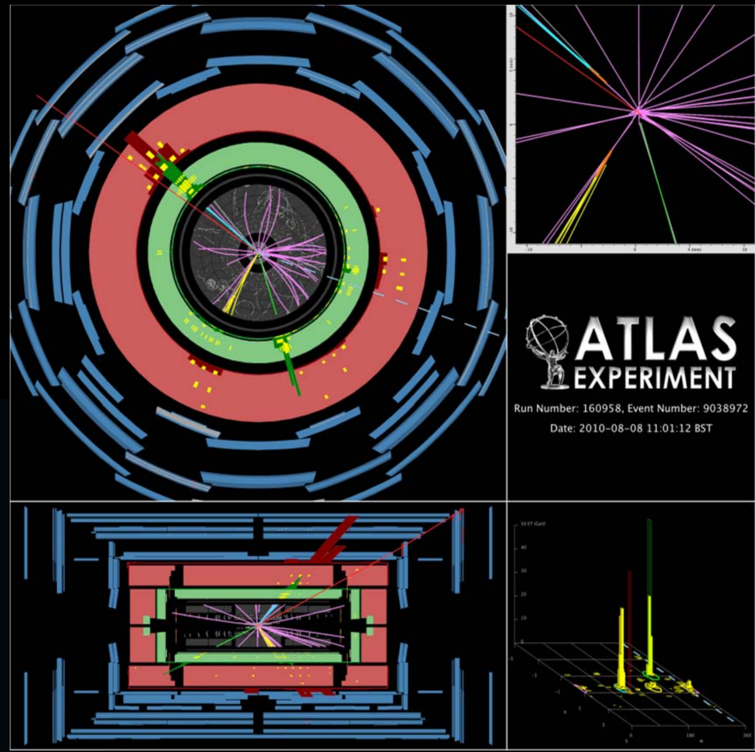
scans of model parameters taking into account available cross section measurements and constraints from searches for New Physics

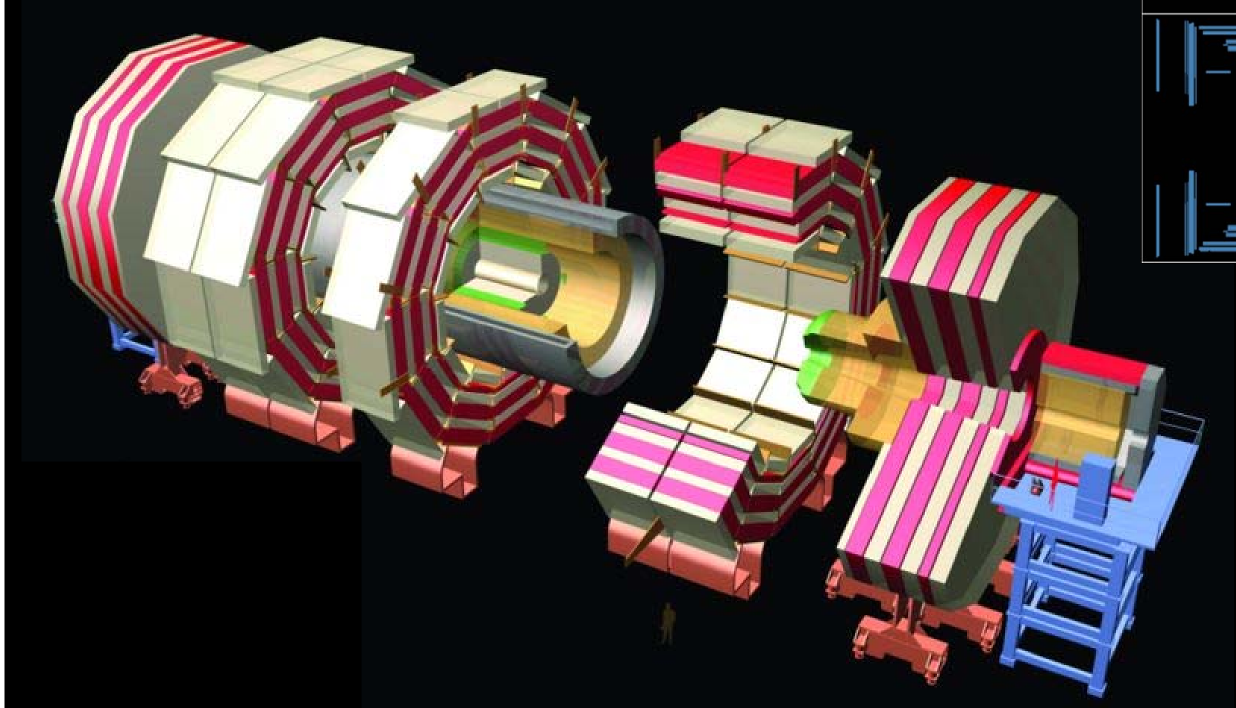
arXiv:1203.4211



LHC results tend to disfavor minimal Z' models

Electroweak and Top Quark Physics at the LHC



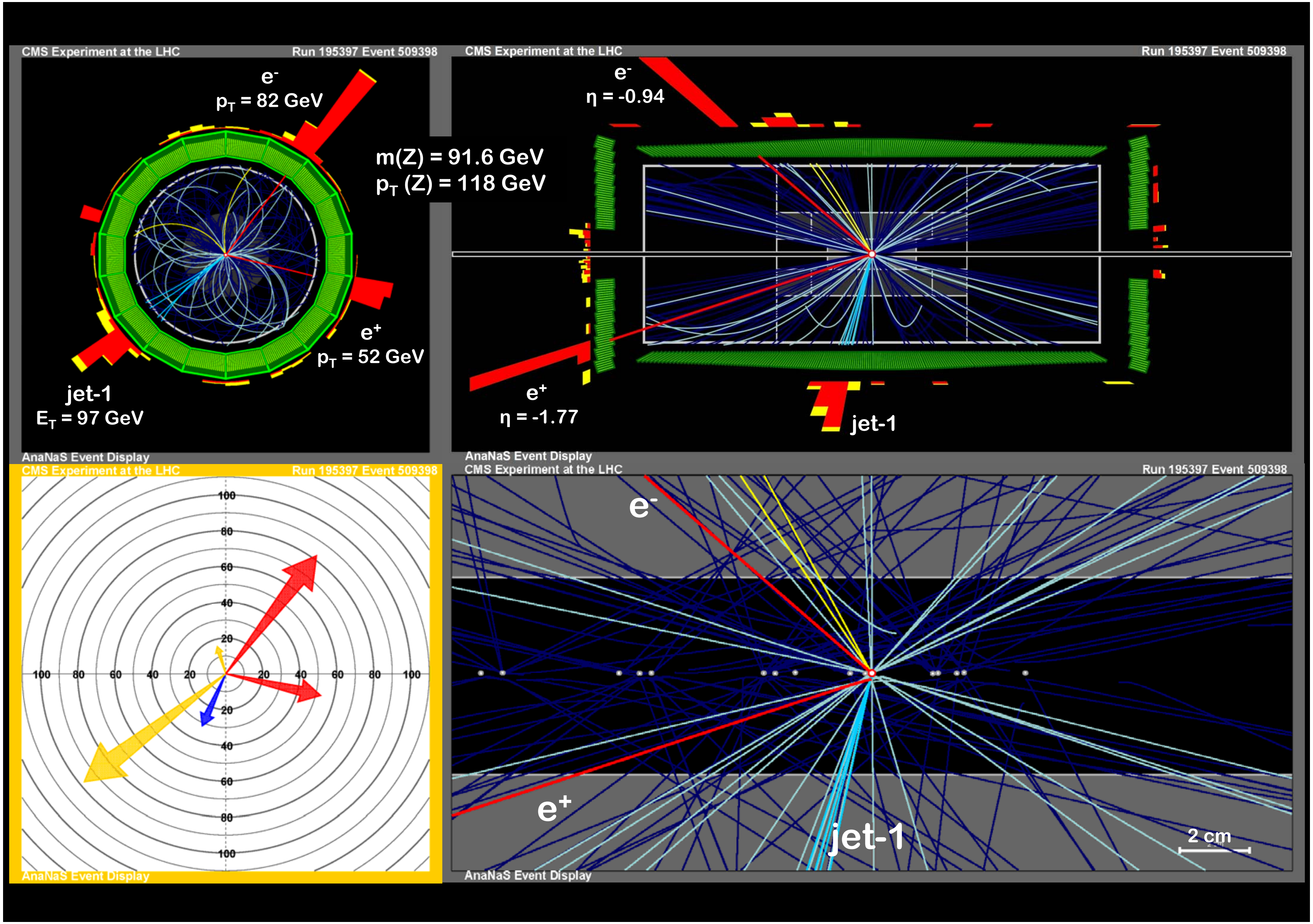


Part 5: Rare Processes

Gautier Hamel de Monchenault
CEA-Saclay IRFU-SPP

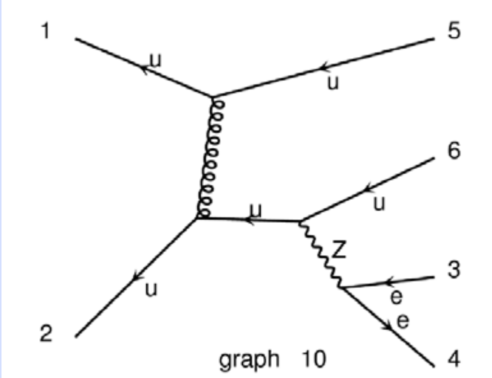
Ecole d'été de Gif
Septembre 2012

V+jets


CMS Experiment at the LHC
Run 195397 Event 509398
e-
pT = 82 GeV
m(Z) = 91.6 GeV
pT (Z) = 118 GeV
e+
pT = 52 GeV
jet-1
ET = 97 GeV
η = -0.94
η = -1.77
AnaNaS Event Display
2 cm

V+Jets

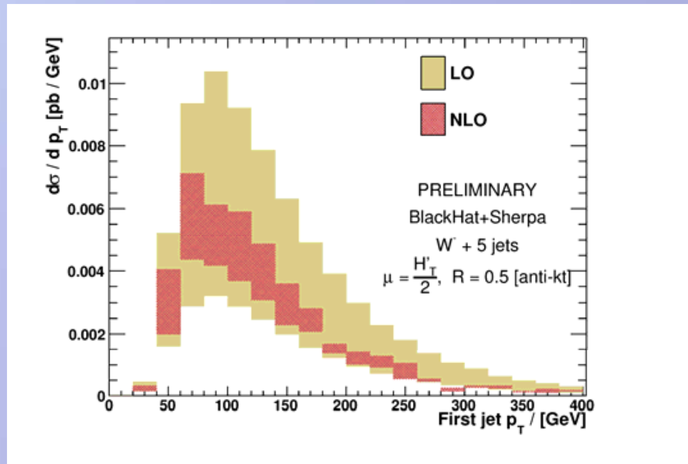
- One of the most important sources of backgrounds for many processes: top quark physics, dibosons, searches (Higgs, SUSY, exotica)



	3+ years ago	today
W/Z	NNLO	NNLO
V+1j	NLO	NLO+PS
V+2j	NLO	NLO
V+3j	LO	NLO
V+4j	LO	NLO
V+5j	LO	NLO soon

Accurate predictions for W/Z+jets production at the LHC are available

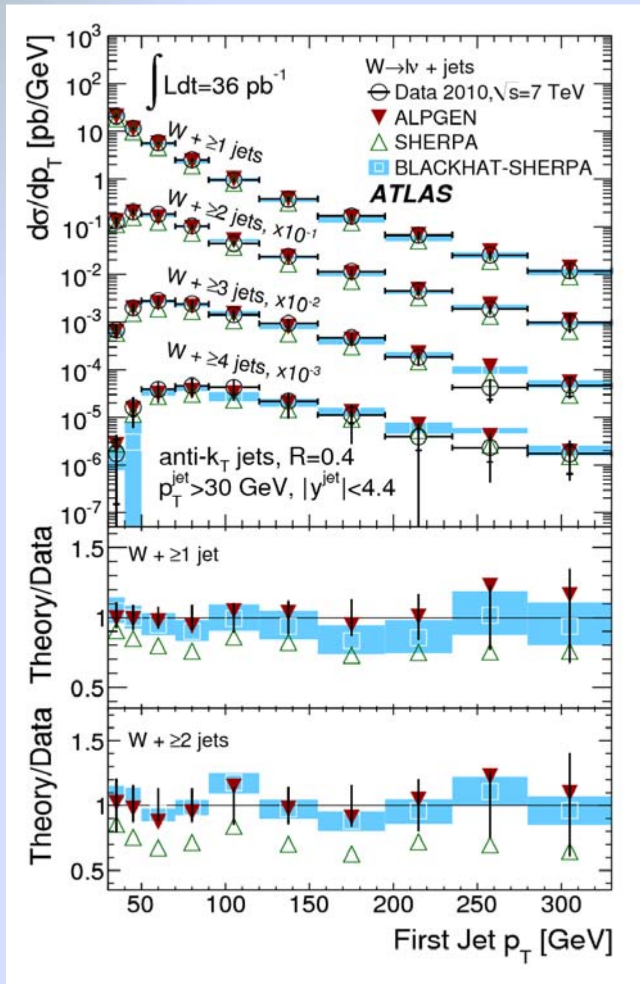
- Monte Carlo event generators
  - ♣ NLO + parton shower (MC@NLO, POWHEG...)
  - ♣ LO (many legs) + parton shower (Alpgen, MadGraph, Sherpa)
- Parton level codes for distributions at NLO
  - ♣ BlackHat, Rocket...



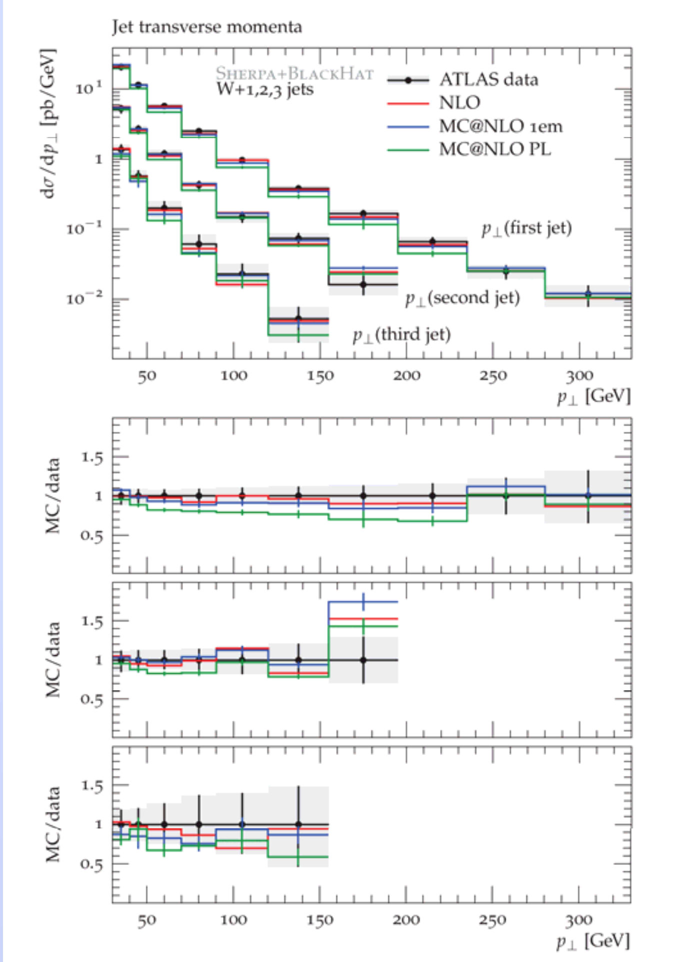
A tool to test most recent perturbative QCD predictions

Differential Distributions

W+jets: p_T 1st jet



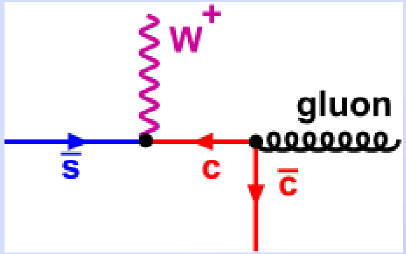
W+3-jets: p_T jet 1, 2 and 3

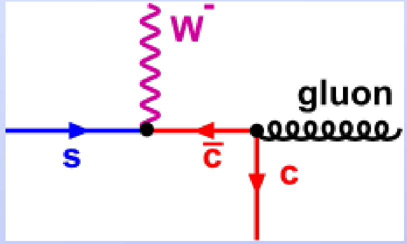


good agreement with fixed-order calculations (BlackHat+Sherpa) and NLO MC (MC@NLO

W+charm Production

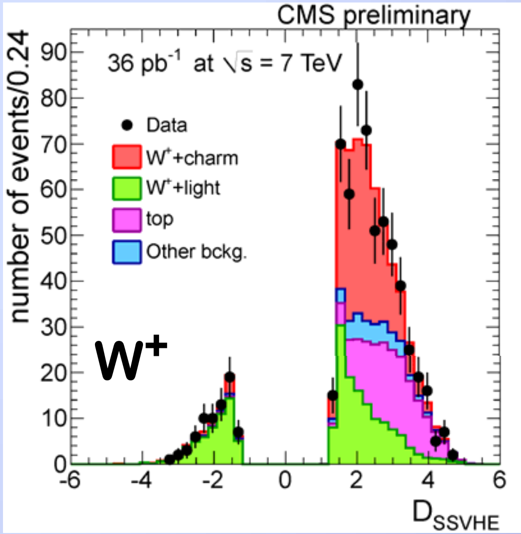
Sensitivity to the strangeness content of the proton ($\rightarrow$ input for W mass)

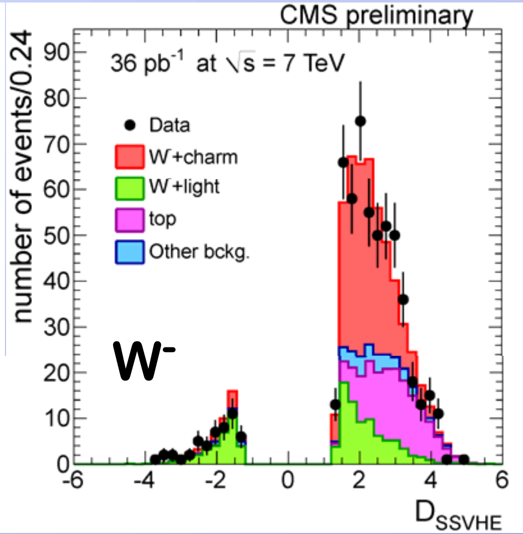




Muon channel

- p_T > 25 GeV and $|\eta|$ < 2.1
- m_T > 50 GeV
- no other muon
- at least 1 jet with
  p_T > 20 GeV and $|\eta|$ < 2.1
- not more than 2 jets with
  p_T > 40 GeV (against top)
- require secondary vertex with positive or negative projection onto the jet axis (tags)
- high efficiency B-tagger
  (secondary vertex significance)





$$R_c^{\pm} = \frac{\sigma\left(W^+ + c\right)}{\sigma\left(W^- + c\right)} = 0.92 \pm 0.19(\text{stat}) \pm 0.04(\text{syst})$$

$$R_c = \frac{\sigma\left(W^{\pm} + c\right)}{\sigma\left(W^{\pm} + \text{jets}\right)} = 0.143 \pm 0.015(\text{stat}) \pm 0.024(\text{syst})$$

MCFM + CT10

$$R_c^{\pm} = 0.915^{+0.006}_{-0.006}$$

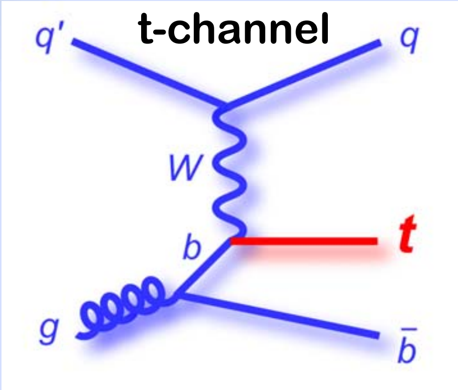
$$R_c = 0.125^{+0.013}_{-0.007}$$

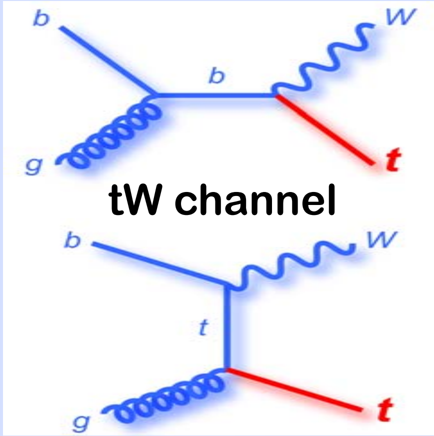
CMS-PAS-EWK-10-015

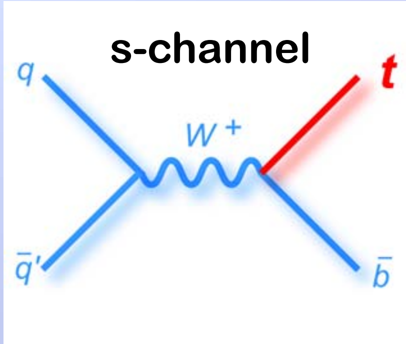
Electroweak Production of the Top Quark

Production of Single Top Quarks

Production of the top quark via electroweak interactions







<table>
<tr><th>m_{top} = 172.5 GeV</th><th colspan="2">t-channel</th><th>tW channel</th><th colspan="2">s-channel</th></tr>
<tr><td>Tevatron @ 1.96 TeV</td><td colspan="2">2.3 pb</td><td>0.3 pb</td><td colspan="2">1.0 pb</td></tr>
<tr><td rowspan="2">LHC @ 7 TeV</td><td colspan="2">64.2 pb</td><td rowspan="2">15.6 pb</td><td colspan="2">4.6 pb</td></tr>
<tr><td>41.7 pb</td><td>22.5 pb</td><td>3.2 pb</td><td>1.4 pb</td></tr>
</table>

Motivations

- test of the SM predictions: sensitivity to the Wtb vertex in many ways
- constraints on u/d, b-quark and gluon PDFs
- test unitarity of the CKM matrix; measurement of $|V_{tb}|$
- search for non-SM phenomena at the Wtb vertex

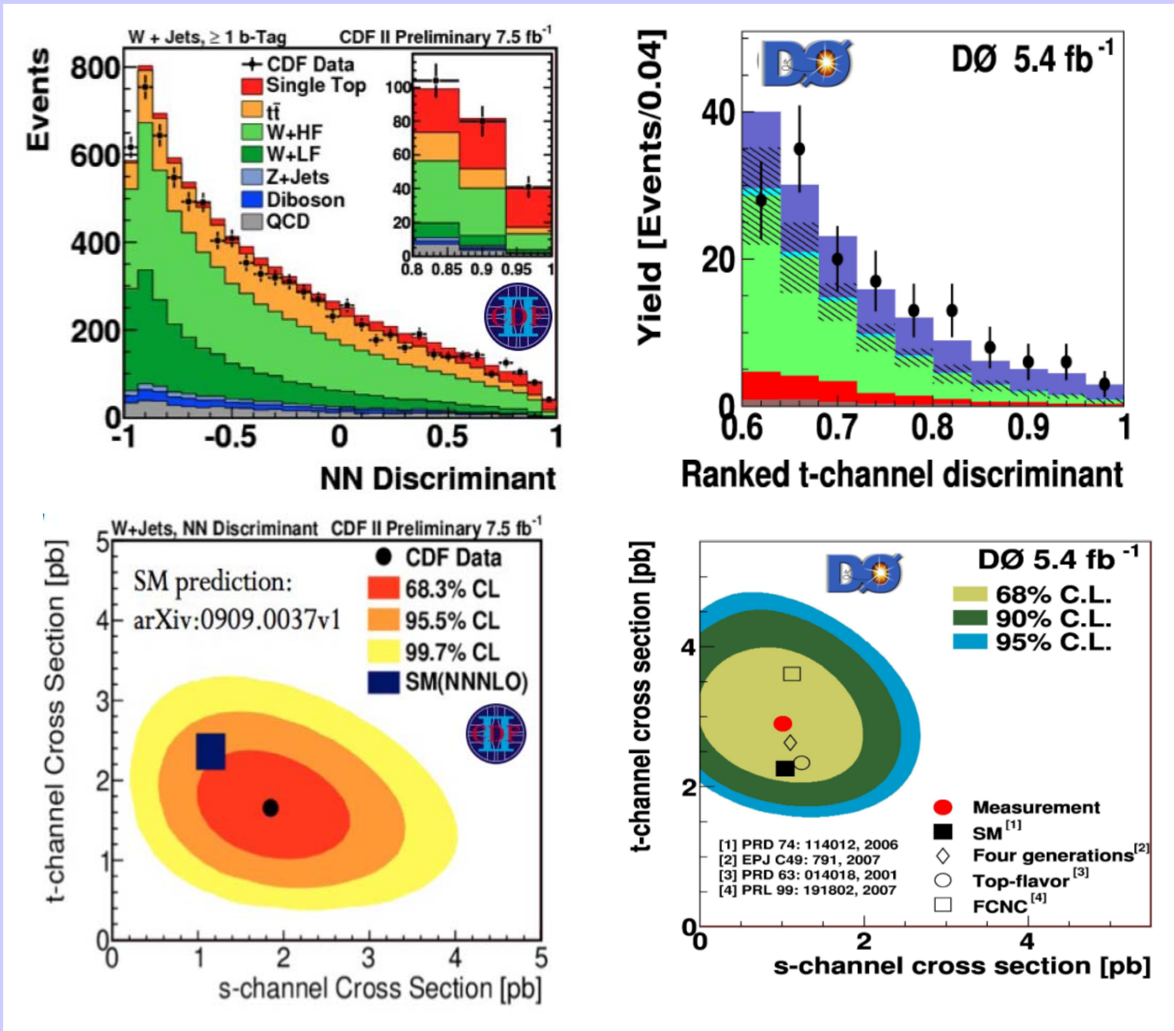
Single Top at the Tevatron

At the Tevatron

- very low cross sections
  - t- and s- channels comparable
  - tW channel even smaller
- similarities with WH(bb)
  - testing ground for advanced analysis techniques in Higgs boson searches (MVA: multivariate analyses)

Measure t- and s-channels simultaneously

- t-channel:
  - observation at 5.5σ
- s-channel:
  - no observation yet



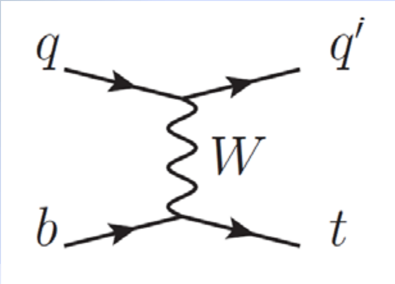
$$\sigma_{\text{s+t-ch}}(\text{CDF}) = 3.04 \pm 0.57\ (\text{stat+syst})\ \text{pb}$$

$$\sigma_{\text{s+t-ch}}(\text{DØ}) = 3.43 \pm 0.74\ (\text{stat+syst})\ \text{pb}$$

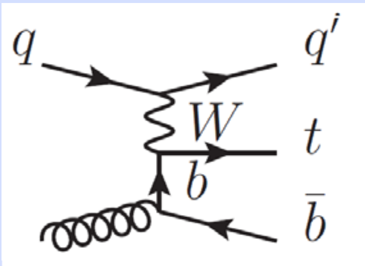
Single top, t-channel

Cross section @ LHC : 64 pb = 42 pb [t] + 22 pb [tbar]

t-channel cross section [t+tbar] about 40% of top quark pair production cross section



flavor excitation



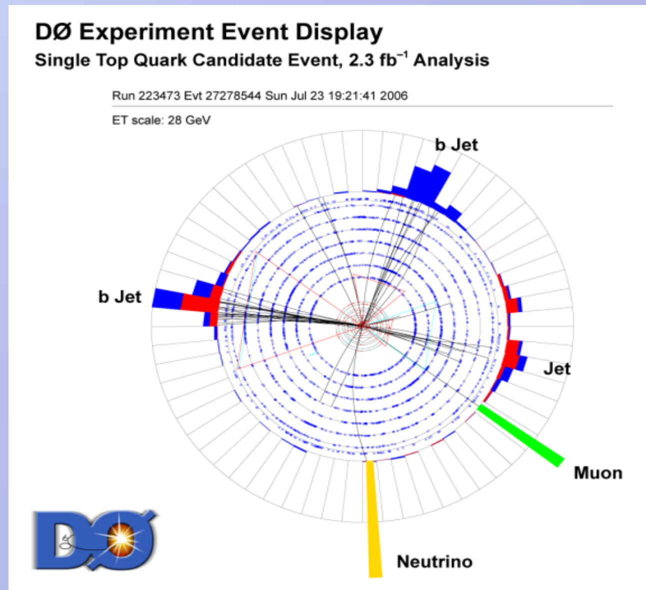
W-gluon fusion

Scattering of virtual W with a b-quark
considered either through:

- flavor excitation: from b-quark density from the proton
- W-gluon fusion: from gluon splitting, $g \rightarrow bb$

Event topology
Single top quark recoiling against a jet:

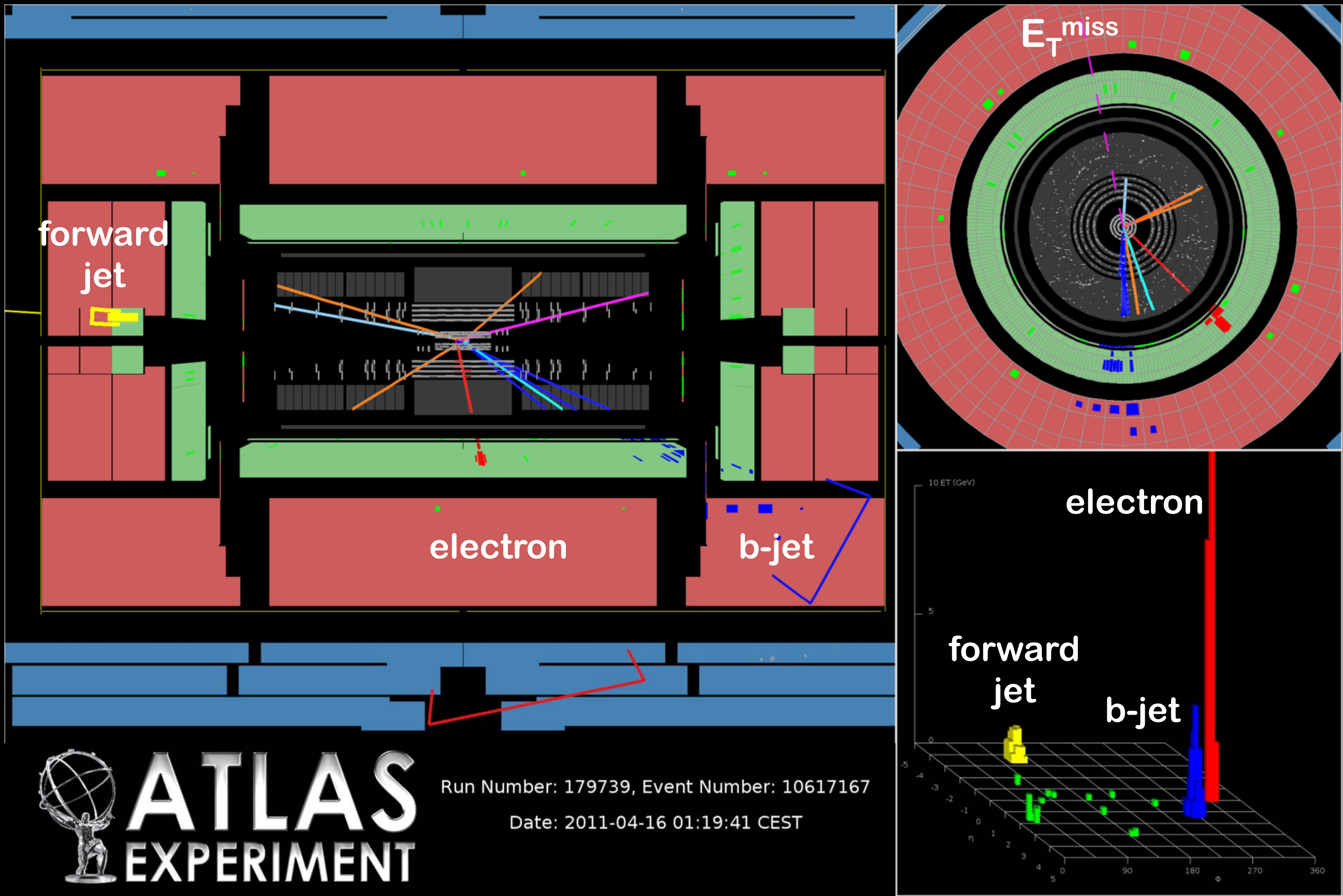
- W from top:
  1 isolated lepton (e or μ)
  E_T^{miss}
- b-quark from top:
  central high-p_T b-tagged jet
- one light-quark jet
  at high pseudo-rapidity
- possibly one low-p_T b-jet
  from gluon splitting



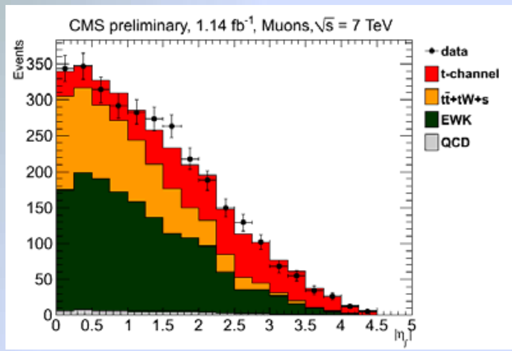
Main backgrounds

- W +jets, top quark pairs, QCD multijets

Single top, t-channel



CMS: t-channel



Selection

- exactly 1 isolated lepton
- exactly 2 jets, exactly 1 b-jet
- E_T^{miss} > 35 GeV (e); $m_T(W)$ > 40 GeV (μ)

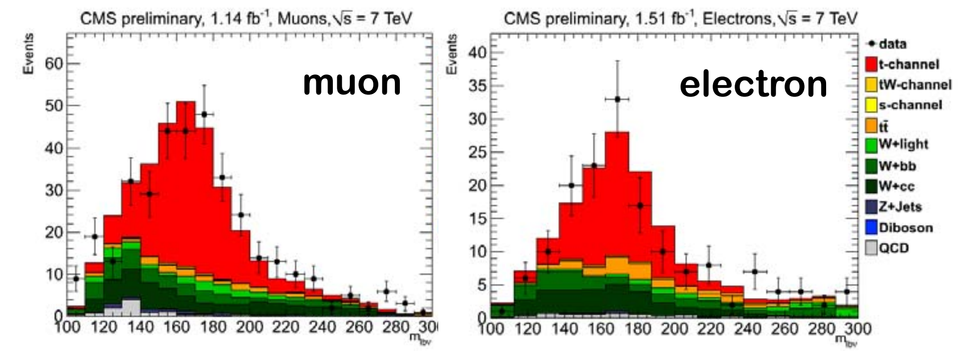
Signal extraction

- UML fit to pseudo-rapidity of light-quark jet $|\eta^{light\text{-}jet}|$

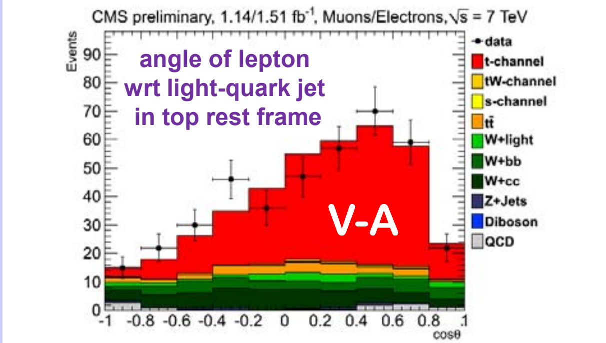
CMS
LHC@√s=7 TeV (2011)
$\int Ldt$ = 1.1-1.5 fb^{-1}

CMS-TOP-11-021

top-mass estimator m(lvb) in the $|\eta^{light\text{-}jet}|$ > 2.8 region



cos θ* in the $|\eta^{light\text{-}jet}|$ > 2.8 region



Systematic uncertainties

- JES, b-tagging, lumi.
- W+2-jets, from SB of [130 < m(lvb) < 220 GeV] and 2-jets/0-b-tag
- t-tbar, from 3-jets/1-b-tag

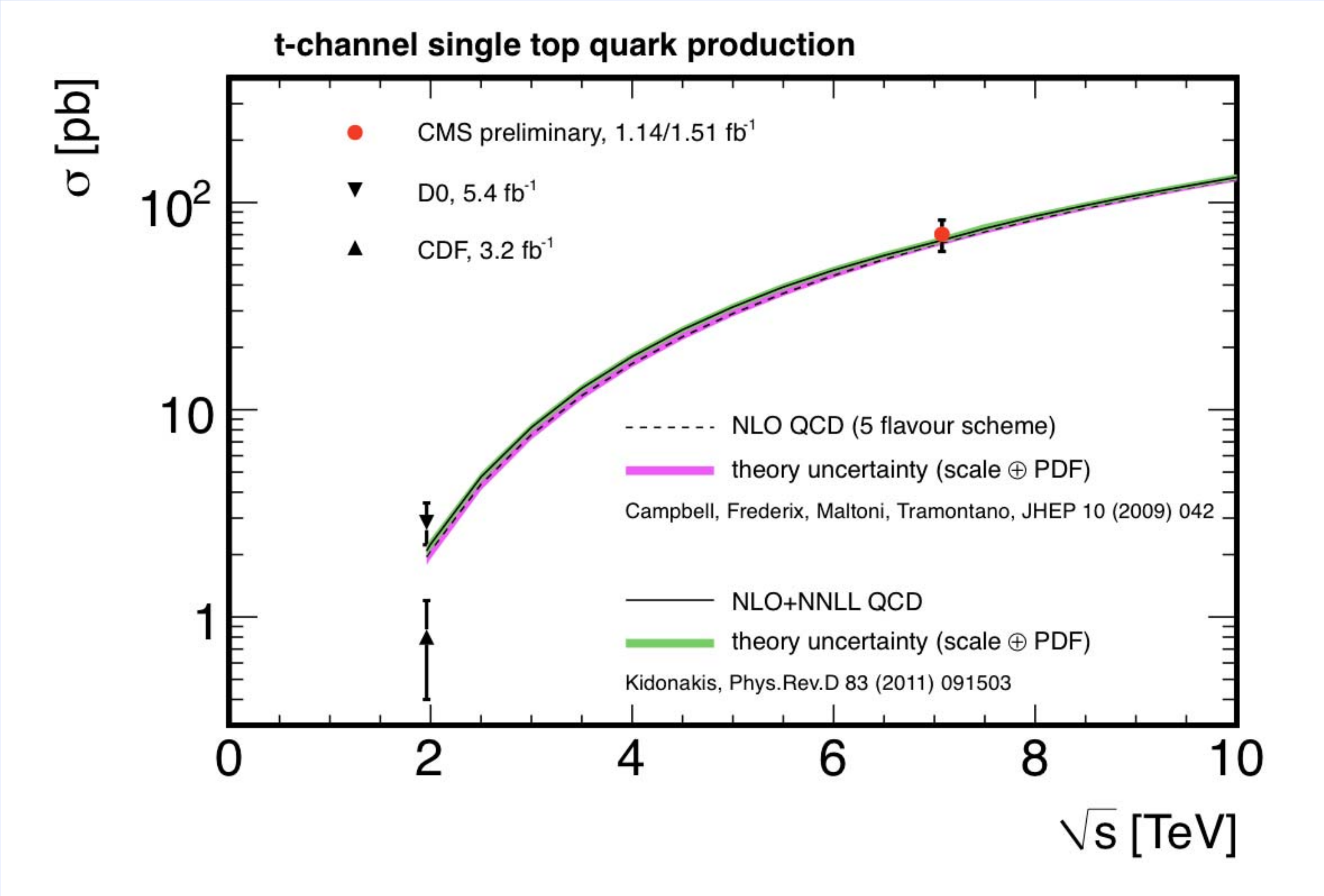
$$\sigma_{\text{t-ch}}(\text{CMS, 7 TeV}) = 70.2 \pm 5.2\ (\text{stat}) \pm 10.9\ (\text{lumi})\ \text{pb}$$

(16%)

$$|V_{tb}| = 1.04 \pm 0.09\ (\text{exp}) \pm 0.02\ (\text{theory})$$

(9%)

CMS: t-channel



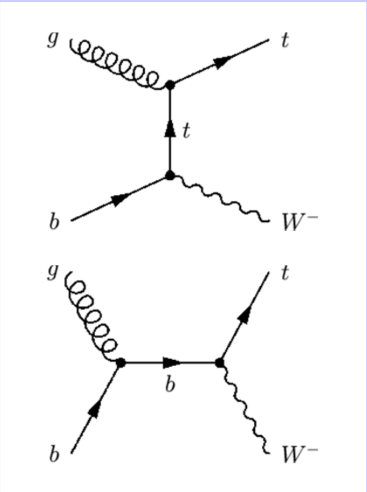
Single top, tW channel

Also known as Associated Production of Single Top

Cross section @ LHC : 16 pb [t+tbar] (charge symmetric)

tW channel not observed at the Tevatron

Top quark produced in association with a real W boson



Wt at LO

Event topology

Single top quark produced with a W

- 2 W bosons

  dilepton

  2 isolated leptons (e or μ)

  large E_T^{miss}

  lepton+jets

  1 isolated lepton (e or μ)

  2 light-quark jets

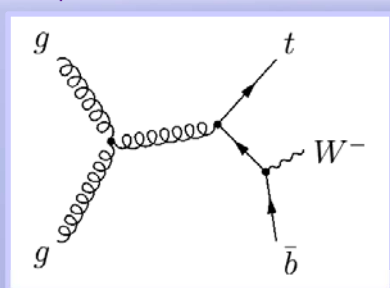
  E_T^{miss}
- 1 b-quark from top:

  1 central high-p_T b-tagged jet
- no additional jet

Interferences at NLO QCD
between tW channel and top pair production.
To define the tW signal, two schemes:

- DR (remove doubly-resonant diagrams)
- DS (locally cancel the contribution of top pair diagrams)

POWHEG implements DR and DS
MC@NLO implements DS



Wt at NLO (example)

Main backgrounds

- t-tbar (!)
- DY (in dilepton channels ee and μμ)

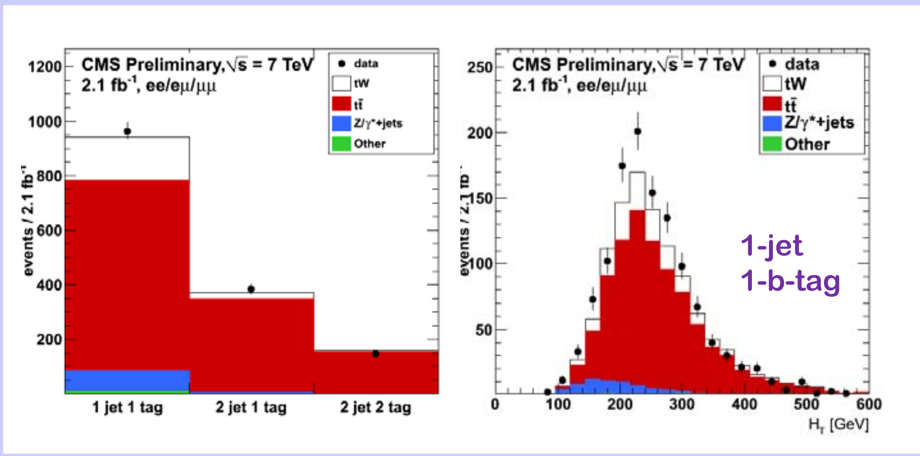
so far, tW only studied at the LHC in the **Dilepton** channel

ATLAS, CMS: tW channel

Event selection similar to t-tbar Dilepton channel
(except for jet requirements)

CMS
LHC@√s=7 TeV (2011)
$\int Ldt = 2.1\ fb^{-1}$

CMS-TOP-11-022



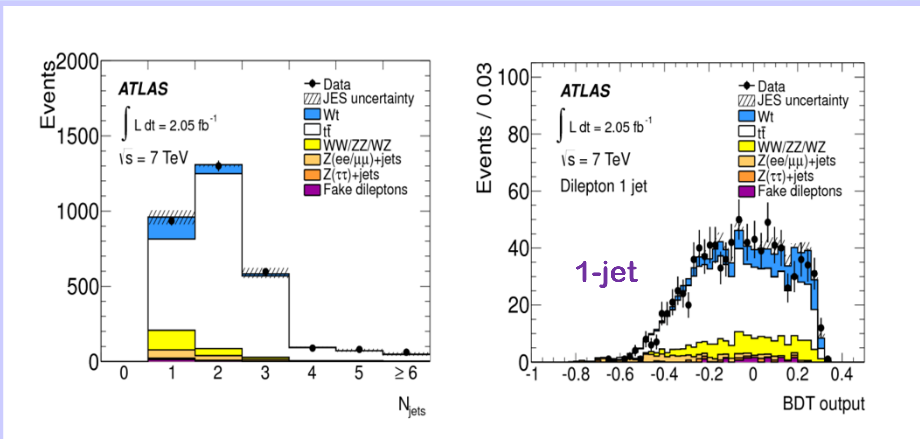
- exactly one b-tagged jet
- 964 events selected (exp. signal: 152)

  bkg-only hypothesis rejected at 2.7σ level

$$\sigma_{tW}(\mathrm{CMS,\ 7\ \ TeV}) = 22 \pm 9\ (\mathrm{stat{+}syst})\ \ \mathrm{pb}$$

ATLAS
LHC@√s=7 TeV (2011)
$\int Ldt = 2.05\ fb^{-1}$

arXiv:1205.5764, subm. to PLB



- ≥ 1 jet (no b-tagging requirement)
- BDT against t-tbar (22 kin. variables)
- 1-jet: 934 events selected (exp. signal: ~150)

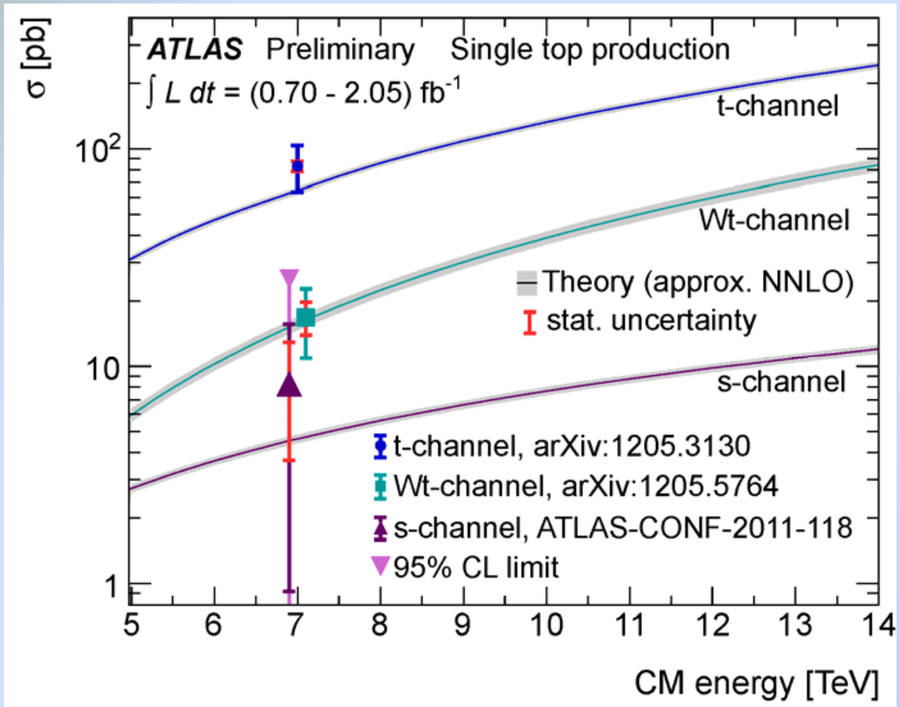
  bkg-only hypothesis rejected at 3.3σ level

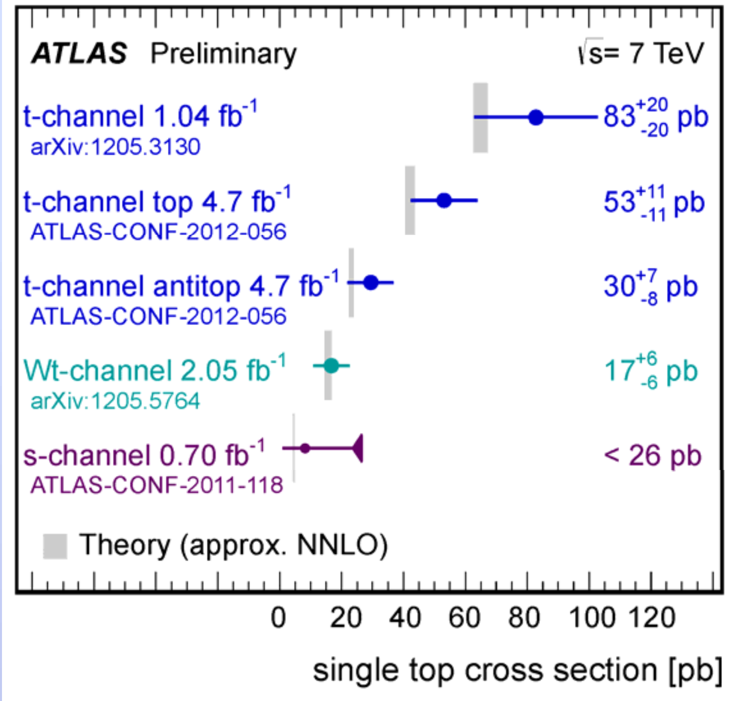
$$\sigma_{tW}(\mathrm{ATLAS,\ 7\ \ TeV}) = 17 \pm 6\ (\mathrm{stat{+}syst})\ \ \mathrm{pb}$$

ATLAS: first evidence of single-top in tW channel

…current results are consistent with predictions

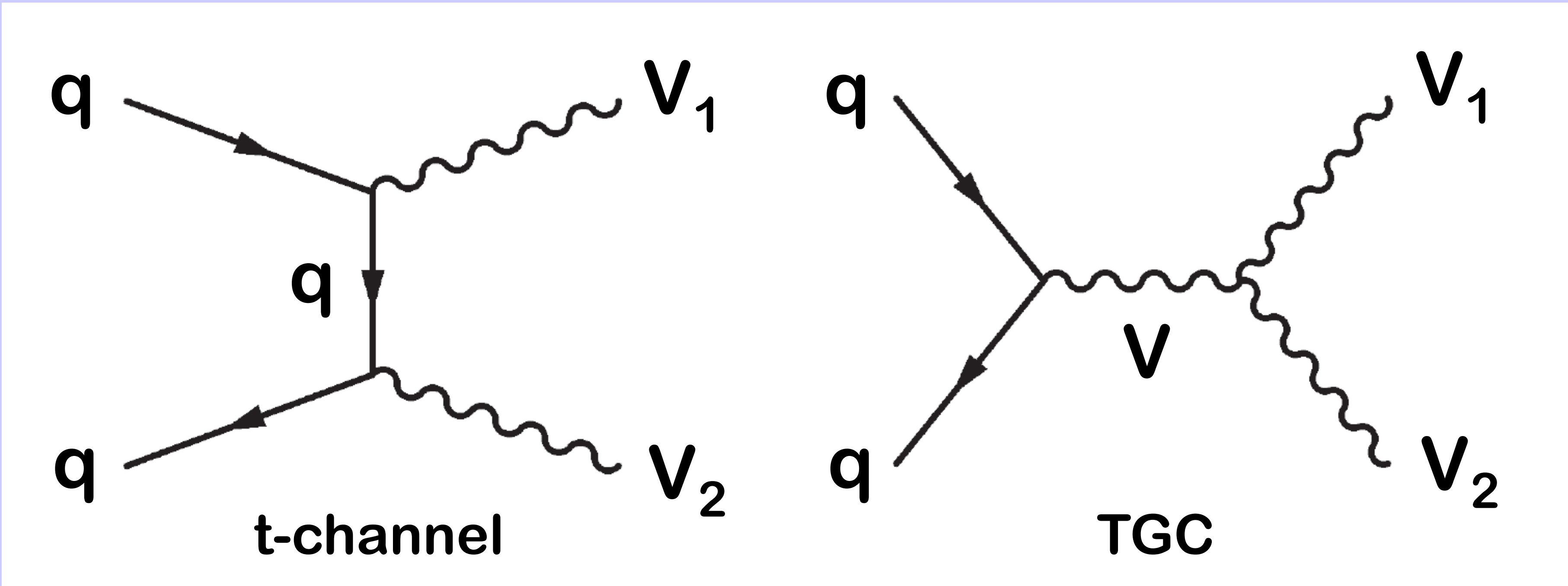
ATLAS: Single Top Summary





- slight excess in t-channel, both charges (not confirmed by CMS)
  - the R_t ratio provides original constraints on u and d-quark PDFs
- evidence for tW channel, in agreement with prediction
- s-channel still far from independent observation
  - larger cross section at 8 TeV will help

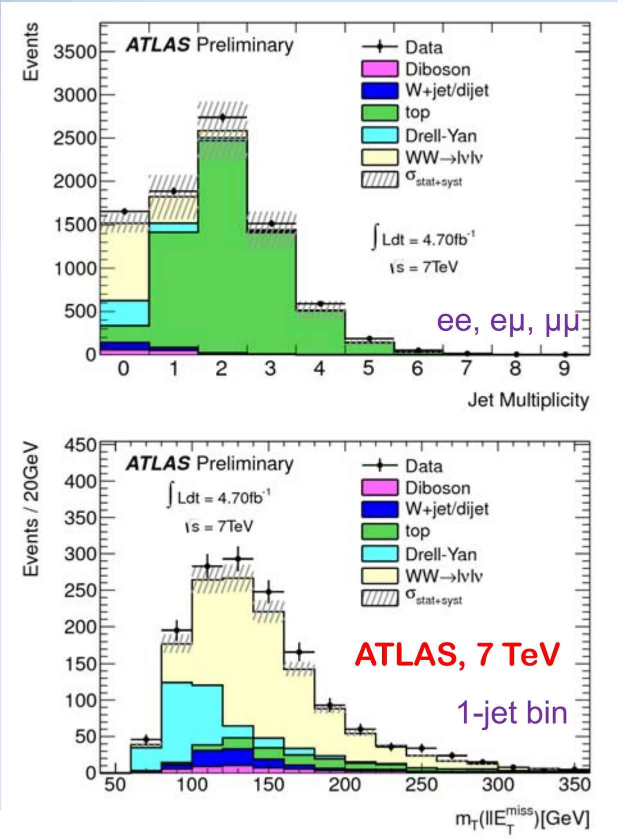
Pair Production of Gauge Bosons γ, W, Z

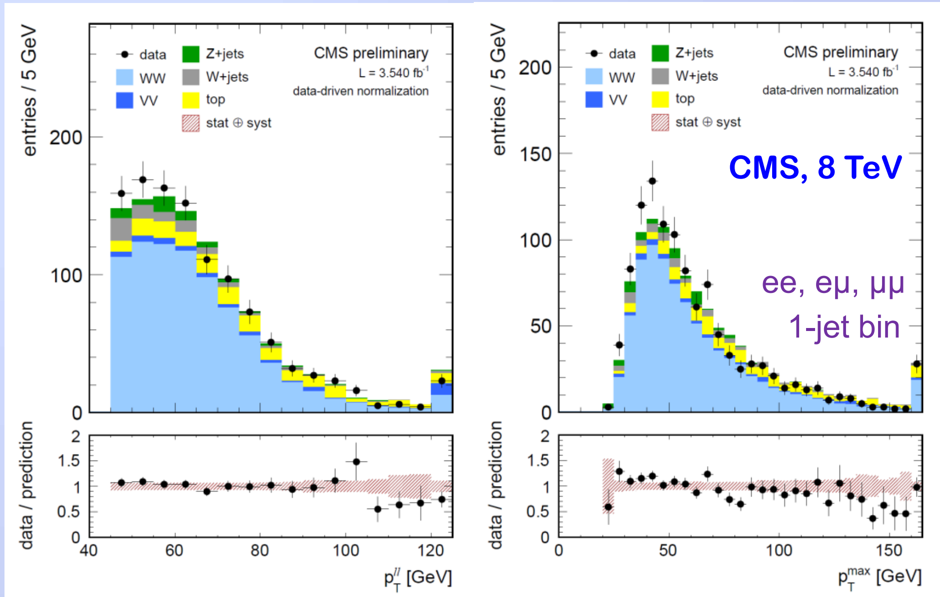


WW

Signature: two leptons plus missing ET

ATLAS	CMS
LHC@√s=7 TeV (2011)	LHC@√s=8 TeV (2011)
$\int Ldt = 4.7\ fb^{-1}$	$\int Ldt = 3.54\ fb^{-1}$
ATLAS-CONF-2012-025	CMS-SMP-12-013





7 TeV

ATLAS	$53.4 \pm 2.1\ (\mathrm{stat}) \pm 4.5\ (\mathrm{syst}) \pm 2.1\ (\mathrm{lumi})\ \ \mathrm{pb}$
CMS	$52.4 \pm 2.0\ (\mathrm{stat}) \pm 4.5\ (\mathrm{syst}) \pm 1.2\ (\mathrm{lumi})\ \ \mathrm{pb}$
theory	$45.1 \pm 2.8\ \ \mathrm{pb}$

8 TeV

CMS	$69.4 \pm 2.8\ (\mathrm{stat}) \pm 5.6\ (\mathrm{syst}) \pm 3.1\ (\mathrm{lumi})\ \ \mathrm{pb}$
theory	$57.3 \pm 2.4\ \ \mathrm{pb}$

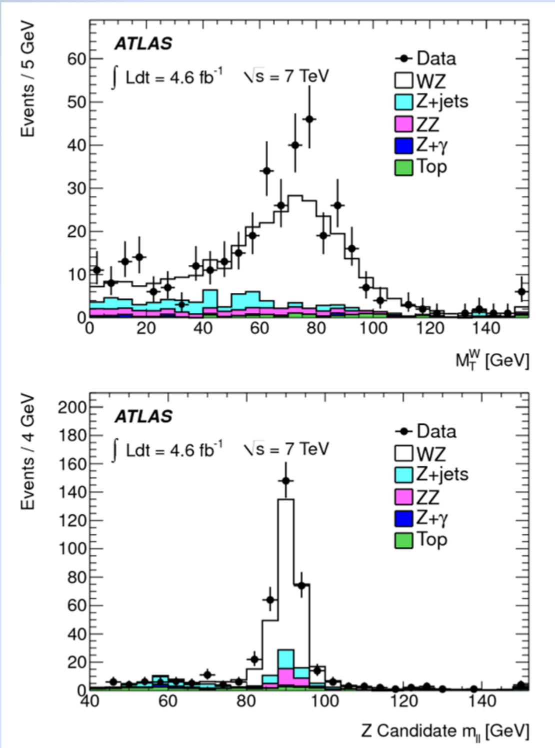
WZ

Signature: one Z bosons + one isolated lepton + missing ET

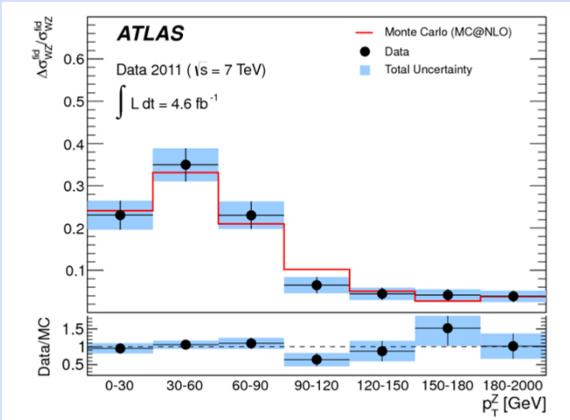
CMS	ATLAS
LHC@√s=7 TeV (2011)	LHC@√s=7 TeV (2011)
$\int Ldt = 1.1\ fb^{-1}$	$\int Ldt = 4.6\ fb^{-1}$

CMS-PAS-EWK-11-010

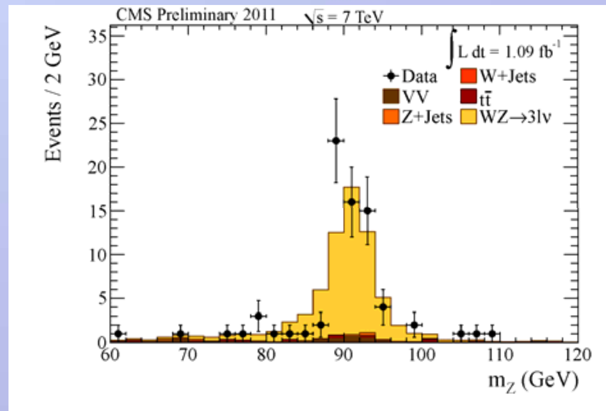
arXiv:1208.1390 subm. to EPJC



ATLAS, 7 TeV



CMS, 7 TeV



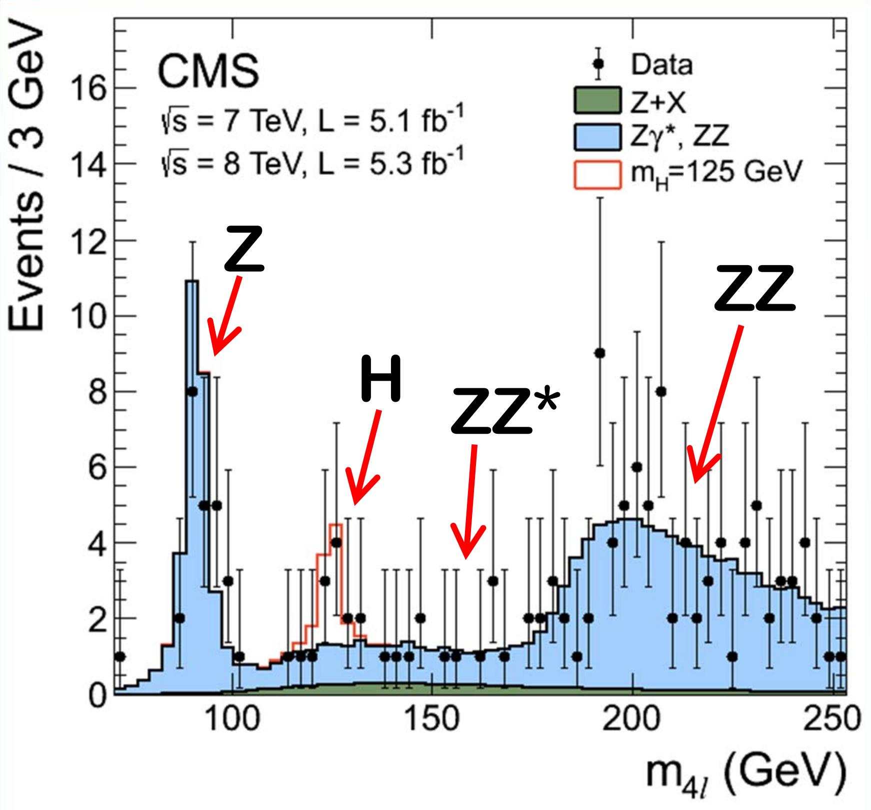
7 TeV

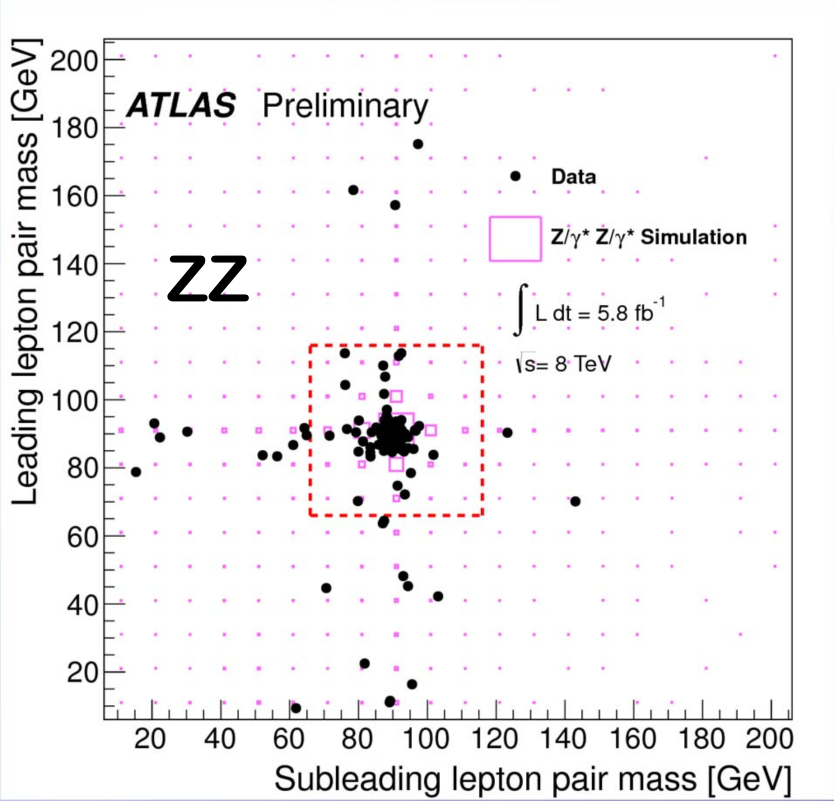
ATLAS	$19.0 \pm 1.4\ (\mathrm{stat}) \pm 0.8\ (\mathrm{syst}) \pm 0.4\ (\mathrm{lumi})$ pb
CMS	$17.0 \pm 2.4\ (\mathrm{stat}) \pm 1.1\ (\mathrm{syst}) \pm 1.0\ (\mathrm{lumi})$ pb
theory	17.6 ± 1.1 pb

ZZ

Signature: 4 leptons, no missing ET
eeee, μμμμ, eeμμ (1+1+2)

- Select both Z bosons on-shell
- **ATLAS**: [66-116] GeV
- **CMS**: [60-120] GeV

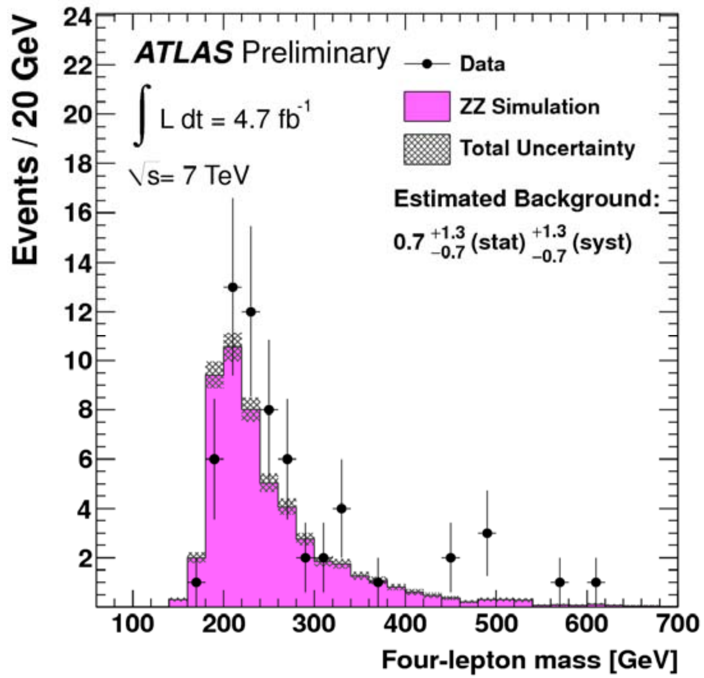


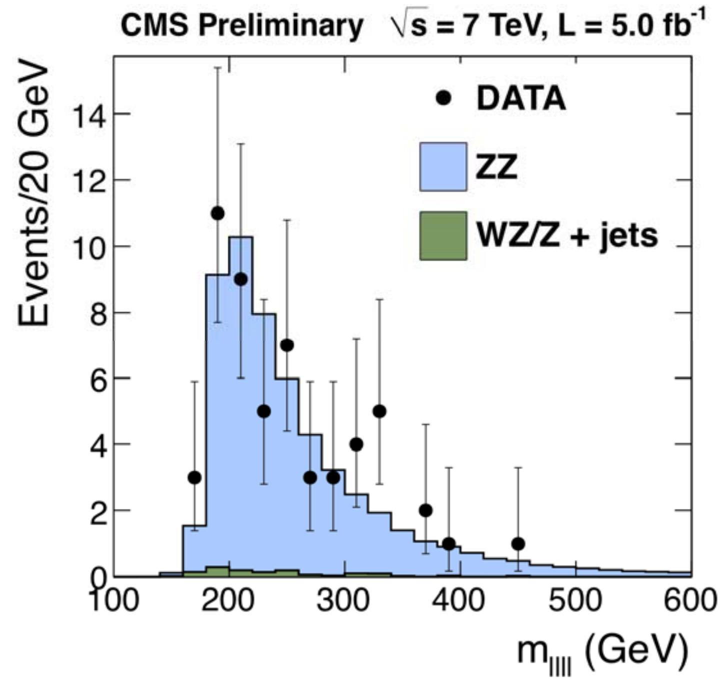


ZZ

CMS	ATLAS
LHC@√s=7 TeV (2011)	LHC@√s=7 TeV (2011)
∫Ldt = 5.0 fb^{-1}	∫Ldt = 4.7 fb^{-1}

ATLAS-CONF-2012-026





7 TeV

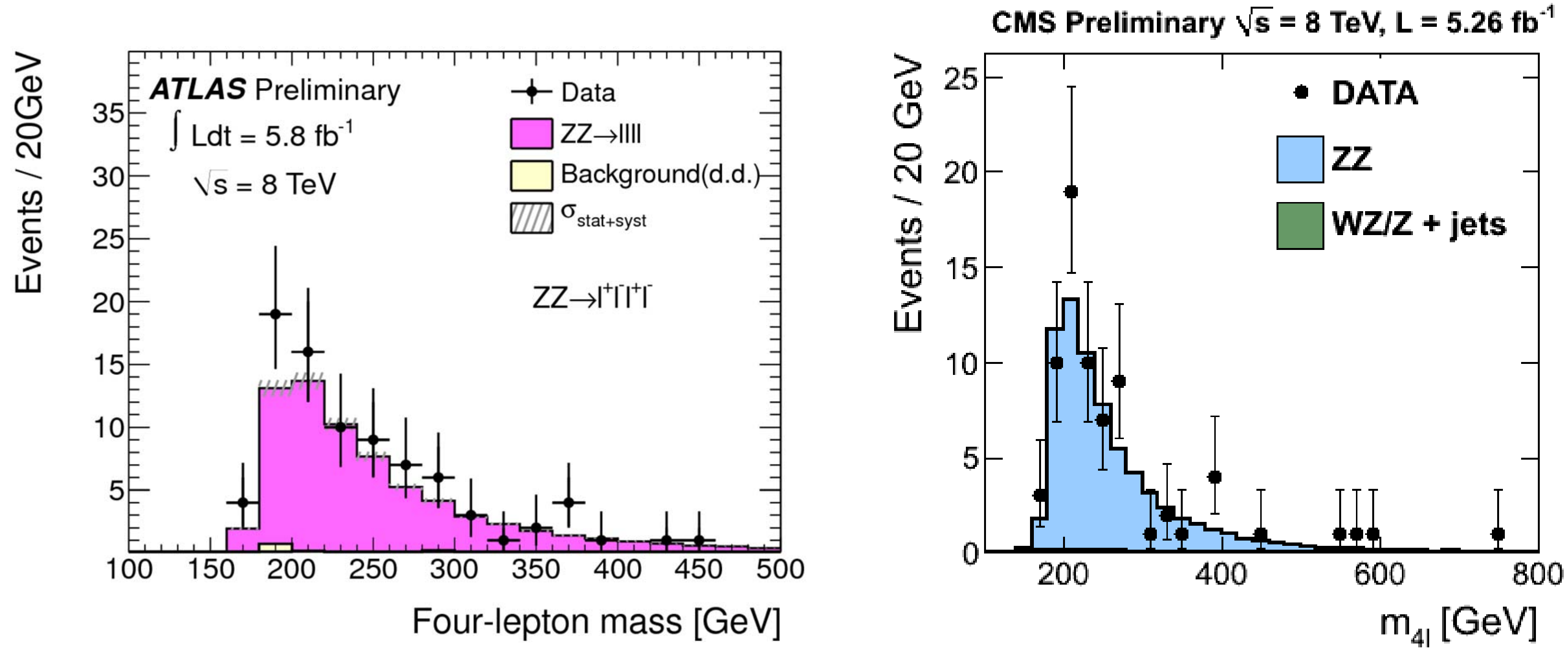
ATLAS	7.2 ± 1.1 (stat) ± 0.4 (syst) ± 0.3 (lumi) pb
CMS	6.2 ± 0.9 (stat) ± 0.4 (syst) ± 0.2 (lumi) pb
theory	6.5 ± 0.4 pb

ZZ

CMS	ATLAS
LHC@√s=8 TeV (2012)	LHC@√s=8 TeV (2012)
∫Ldt = 5.26 fb^{-1}	∫Ldt = 5.8 fb^{-1}

ATLAS-CONF-2012-090

CMS-SMP-12-014



8 TeV

ATLAS	9.3 ± 1.1 (stat) ± 0.4 (syst) ± 0.3 (lumi) pb
CMS	8.4 ± 1.0 (stat) ± 0.7 (syst) ± 0.4 (lumi) pb
theory	7.5 ± 0.4 pb

Anomalous Gauge Couplings

Effective Lagrangian WWV (V=γ,Z)

$$\begin{aligned}\mathcal{L}/g_{WWV} \; = \; & i g_1^V \left[W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right] + i\kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} \\ & + \frac{i\lambda^V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\ & + g_5^V \varepsilon^{\mu\nu\rho\sigma} (W^\dagger_\mu \partial_\rho W_\nu - (\partial_\rho W^\dagger_\mu) W^\nu) V_\sigma \\ & + i\tilde{\kappa}^V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + i \frac{\tilde{\lambda}^V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu \tilde{V}^{\nu\lambda}\end{aligned}$$

} anomalous

WWV: 10 anomalous couplings

assume QED, C and P invariance, and additional (LEP) relations

→ 3 anomalous couplings

$\Delta\kappa^\gamma$, Δg_1^Z, $\lambda = \lambda_\gamma = \lambda_Z$

SM: all zero

Effective Lagrangian ZVγ (V=γ,Z)

$$\begin{aligned}\mathcal{L}_{VV'V''} \frac{M_Z^2}{e} \; = \; & -[f_4^\gamma (\partial_\mu F^{\mu\beta}) + f_4^Z (\partial_\mu Z^{\mu\beta})] Z_\alpha (\partial^\alpha Z_\beta) \\ & + [f_5^\gamma (\partial^\sigma F_{\sigma\mu}) + f_5^Z (\partial^\sigma Z_{\sigma\mu})] \tilde{Z}^{\mu\beta} Z_\beta \\ & - [h_1^\gamma (\partial^\sigma F_{\sigma\mu}) + h_1^Z (\partial^\sigma Z_{\sigma\mu})] Z_\beta F^{\mu\beta} \\ & - [h_3^\gamma (\partial_\sigma F^{\sigma\rho}) + h_3^Z (\partial_\sigma Z^{\sigma\rho})] Z^\alpha \tilde{F}_{\rho\alpha} \quad + \text{dim } 8\end{aligned}$$

} anomalous

ZVγ: 12 anomalous couplings

assume CP invariance and dim<8

→ 4 anomalous couplings

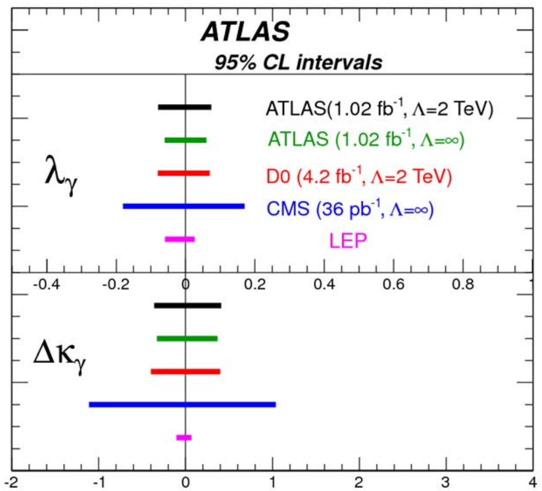
h_3^γ, h_1^Z, f_4^γ, f_5^Z

- anomalous couplings result in **violation of partial wave unitarity** at large energy

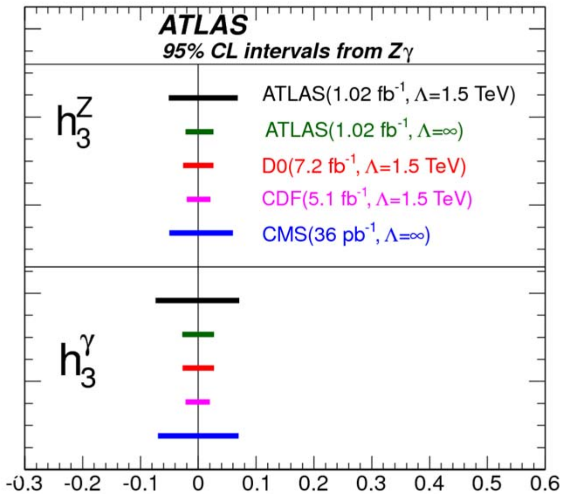
Tevatron/ATLAS: assume energy dependence (*form factors*) to preserve unitarity

Wγ, Zγ : Anomalous Couplings

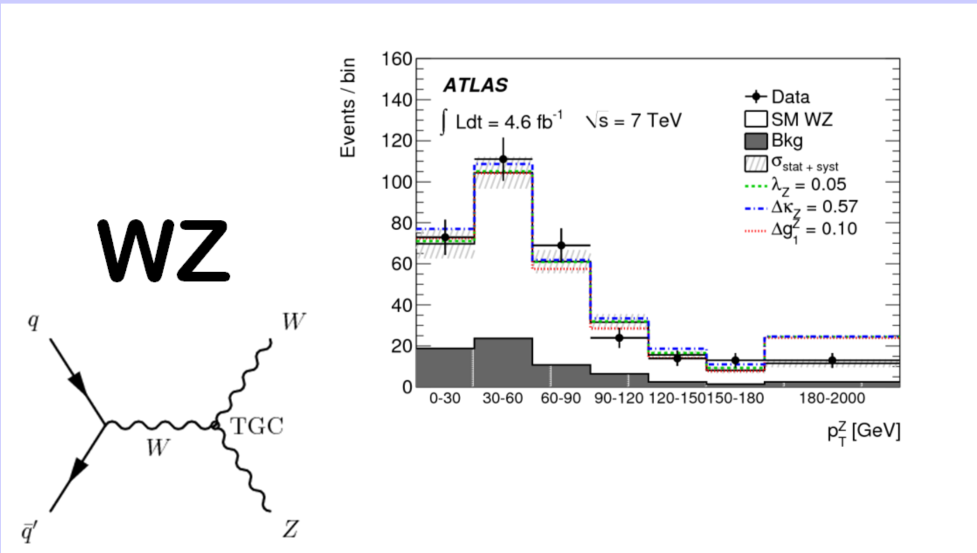
Wγ

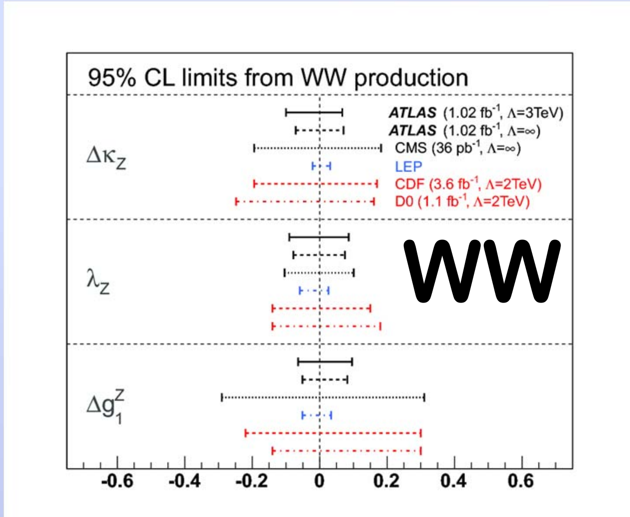


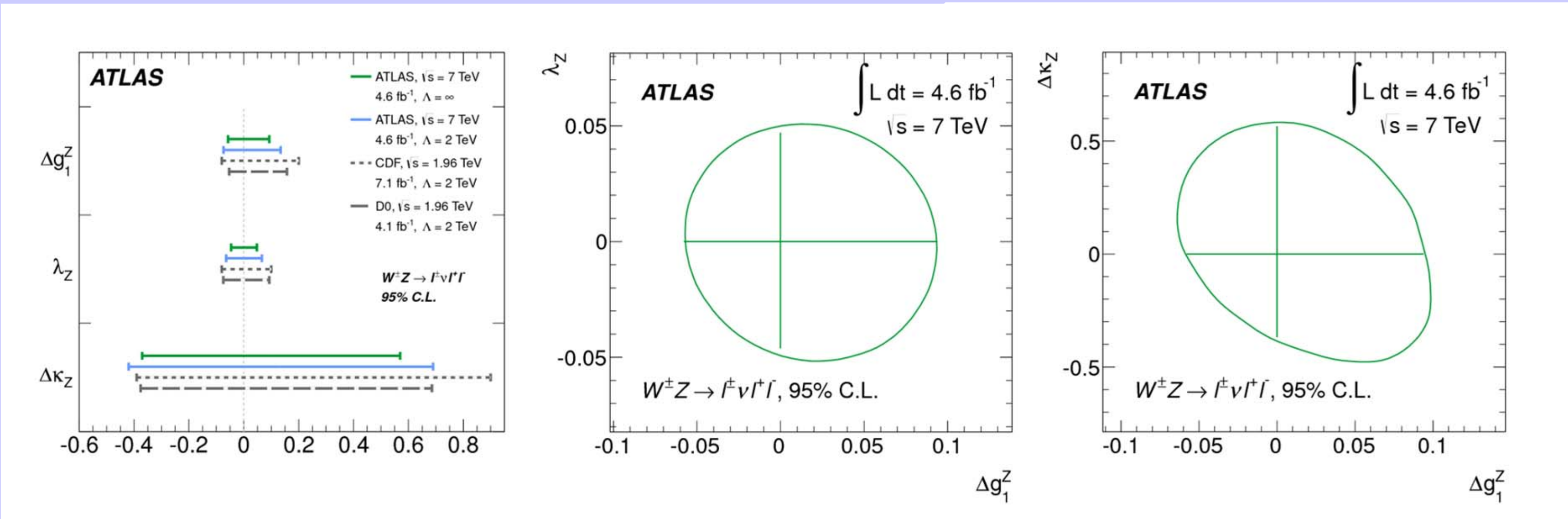
Zγ



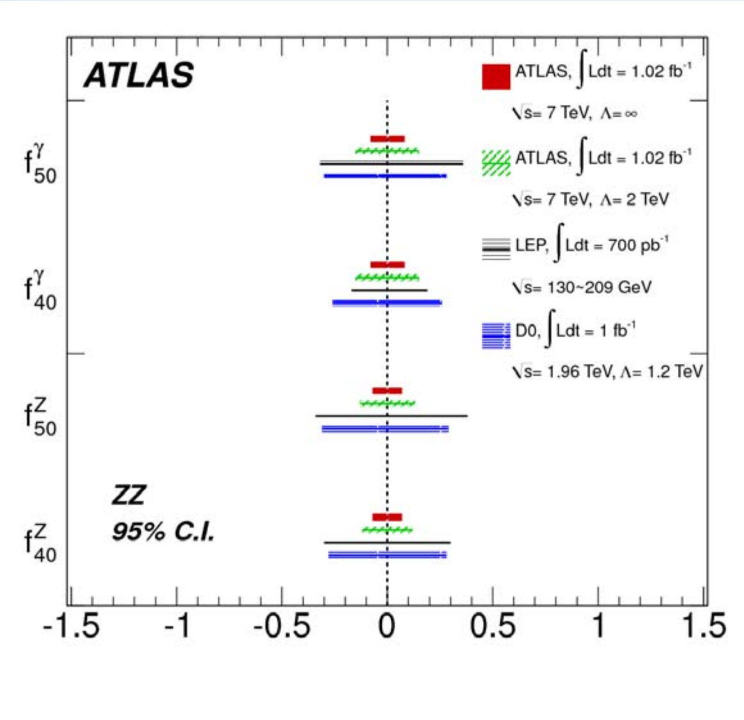
WZ/ZZ: Anomalous Couplings

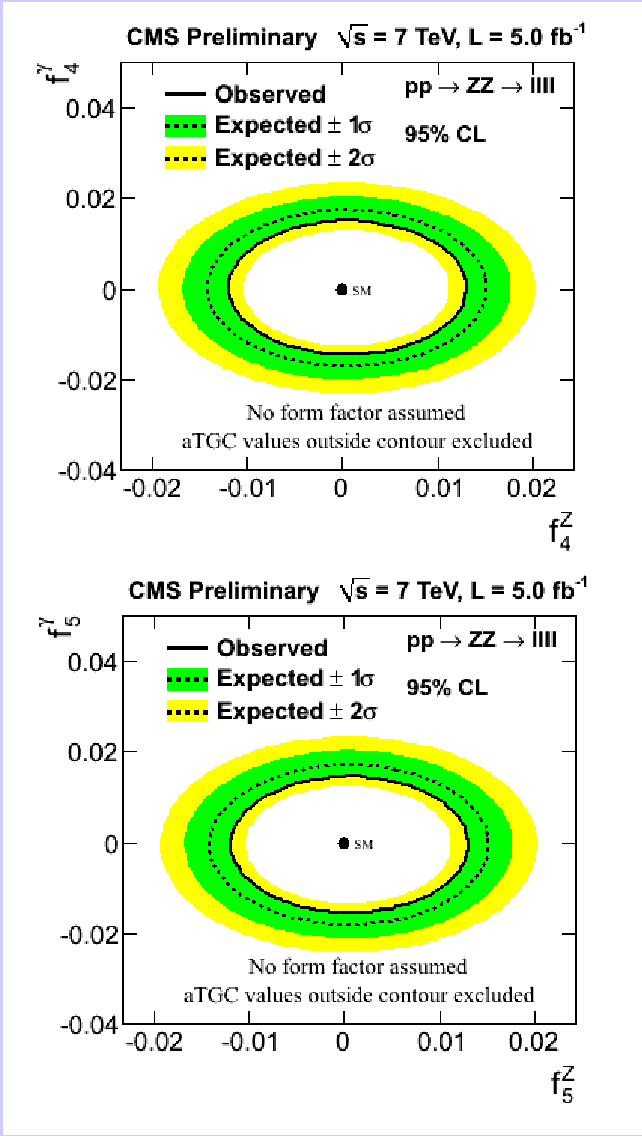




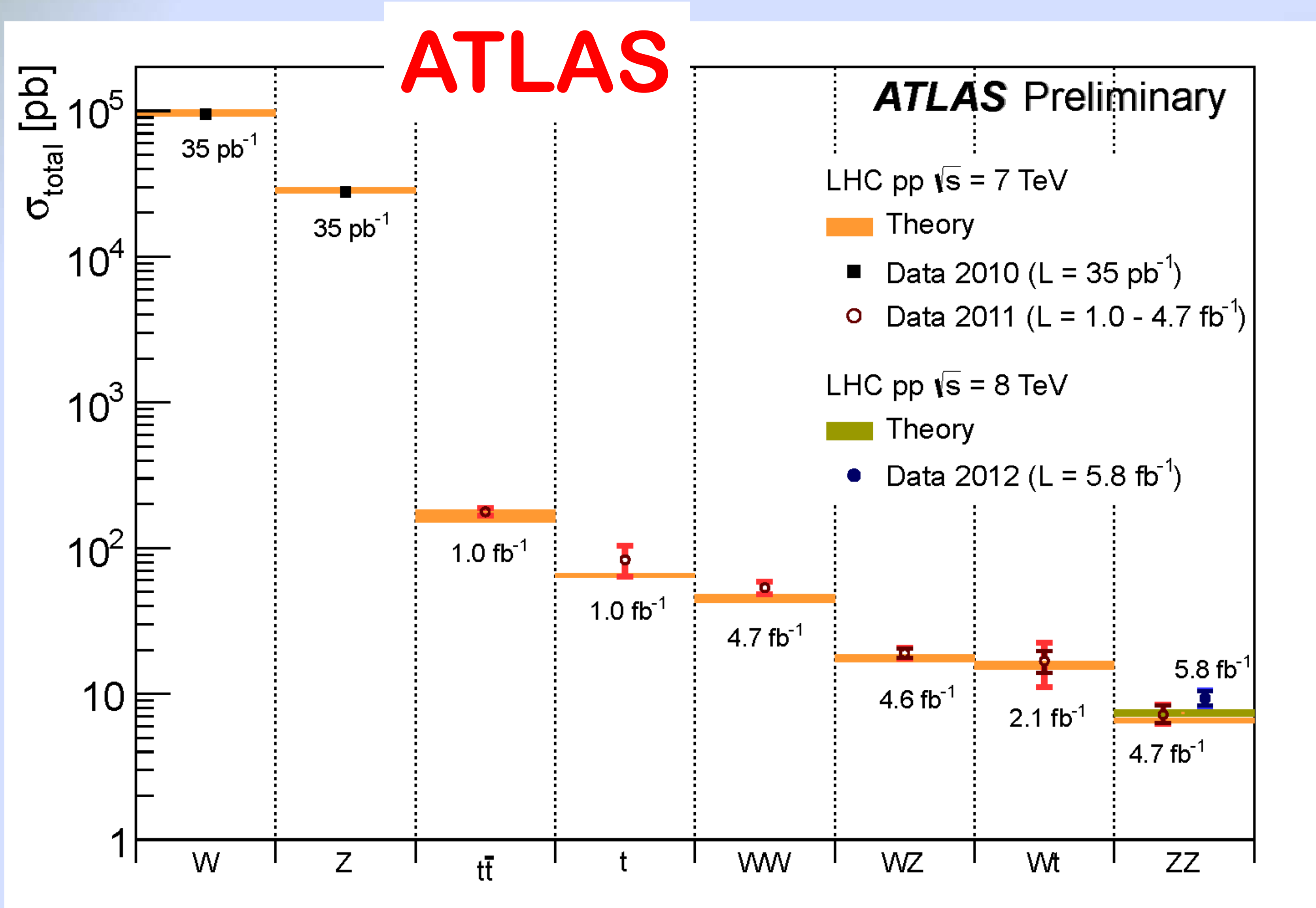


ZZ: Anomalous Couplings

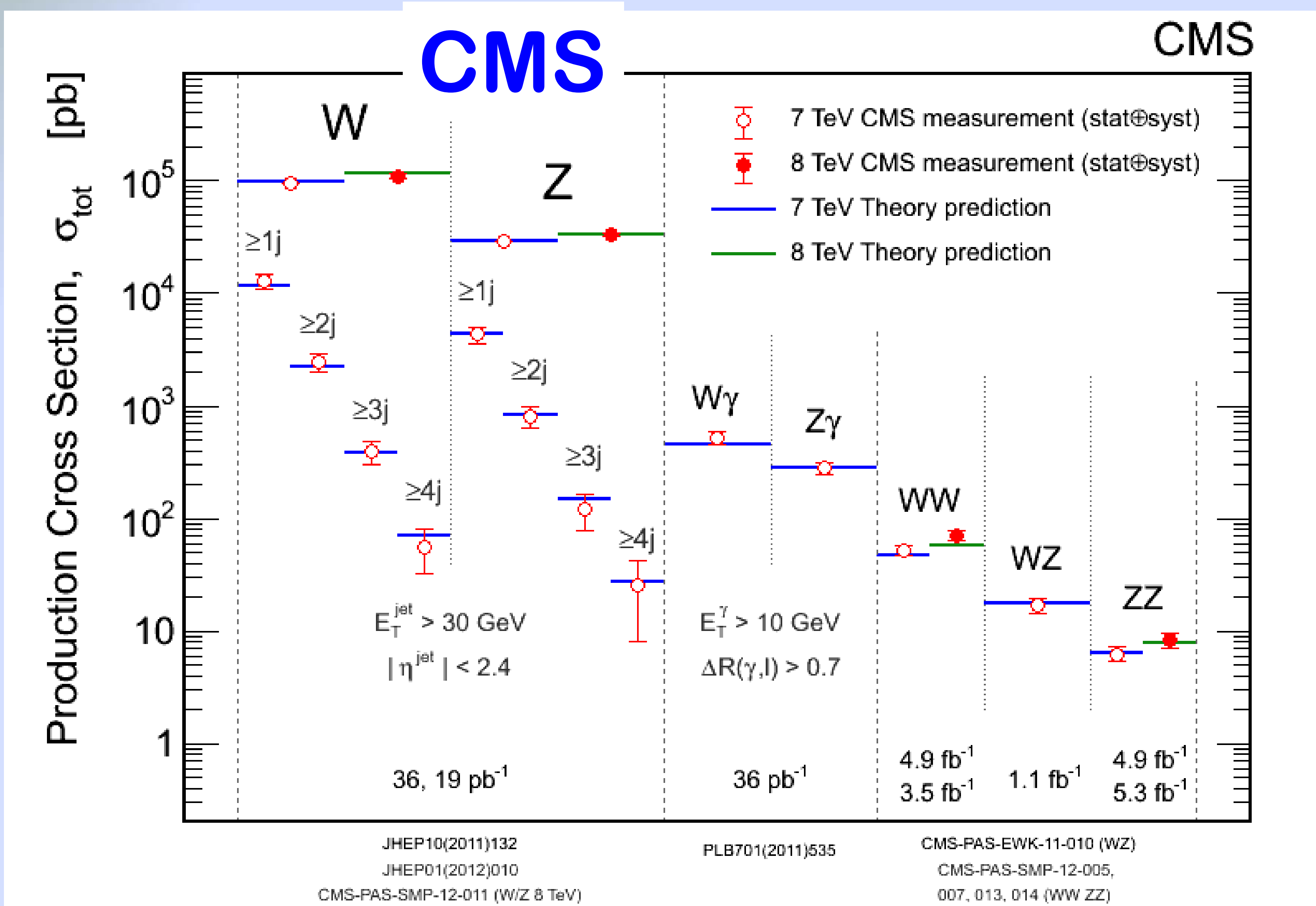




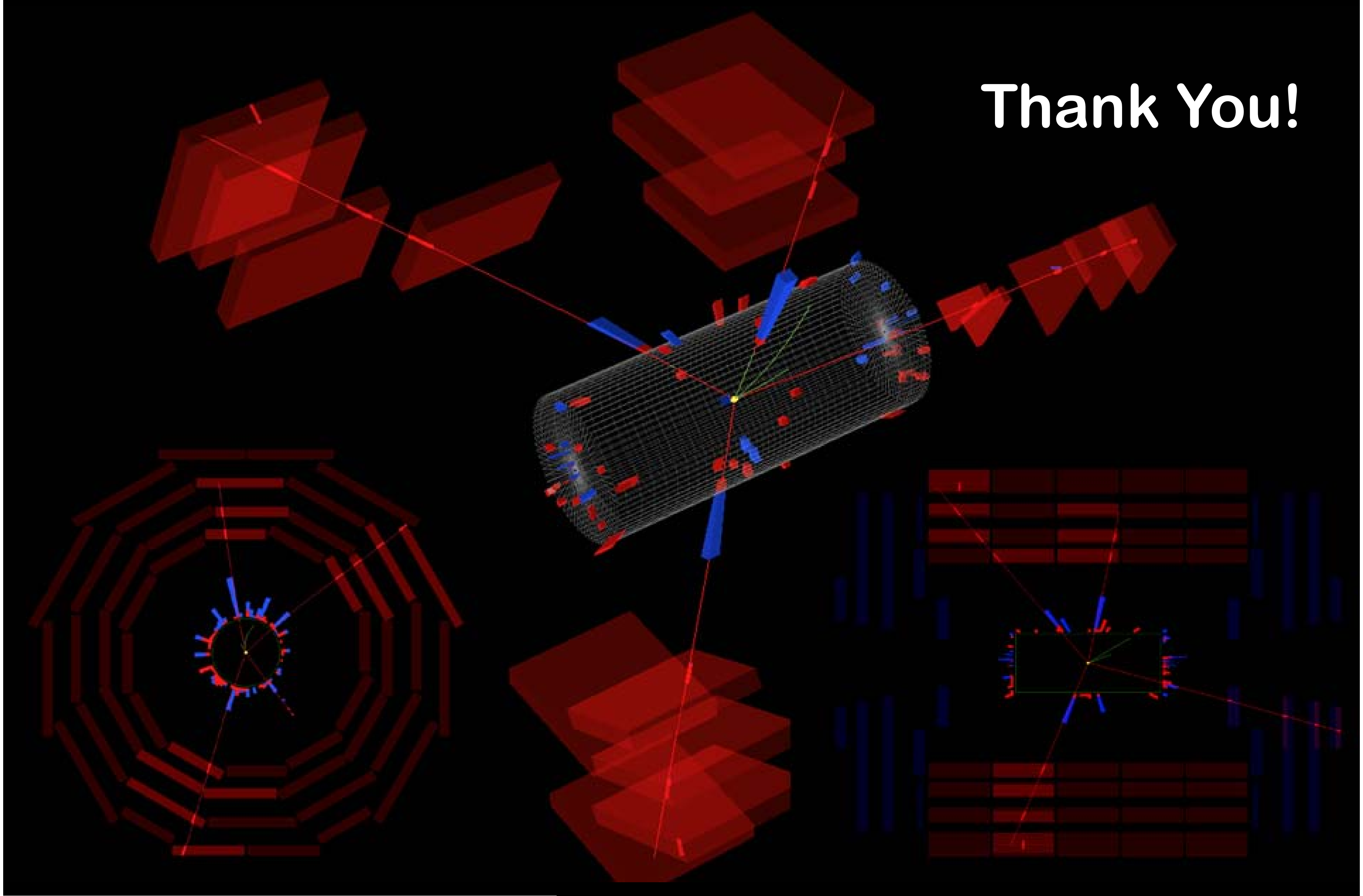
Summary of Cross Sections



Summary of W/Z Cross Sections



Thank You!



Gautier Hamel de Monchenault

2012