W/Z Physics at hadron colliders

J. Alcaraz (CIEMAT – Madrid)

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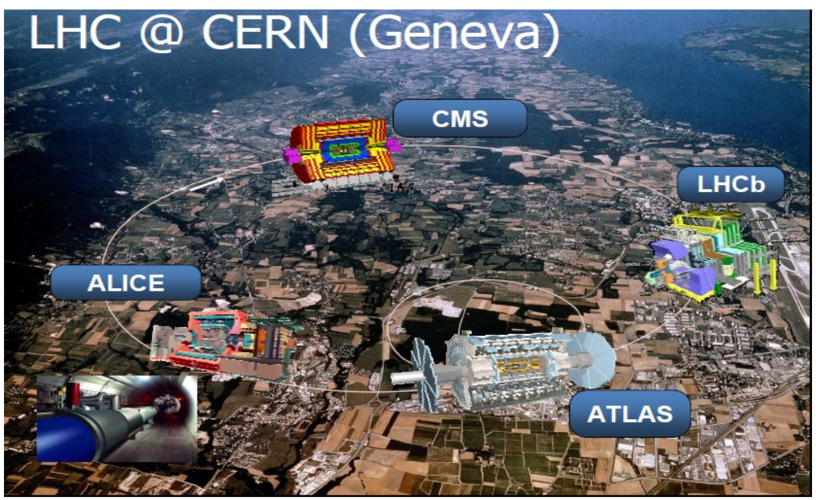
Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

CMS
Compact Muon Solenoid

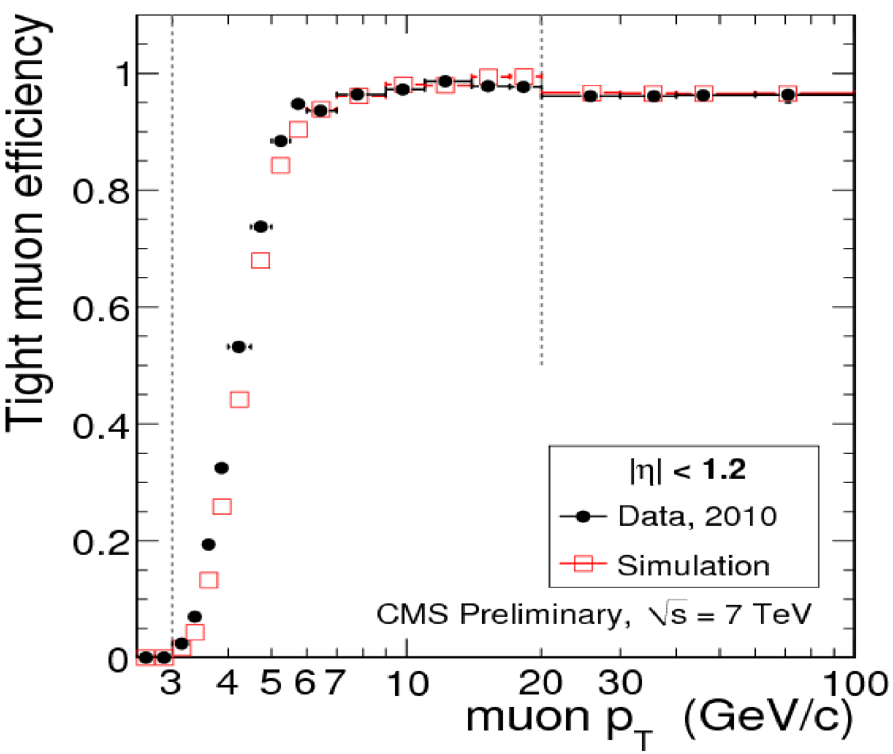
OUTLINE

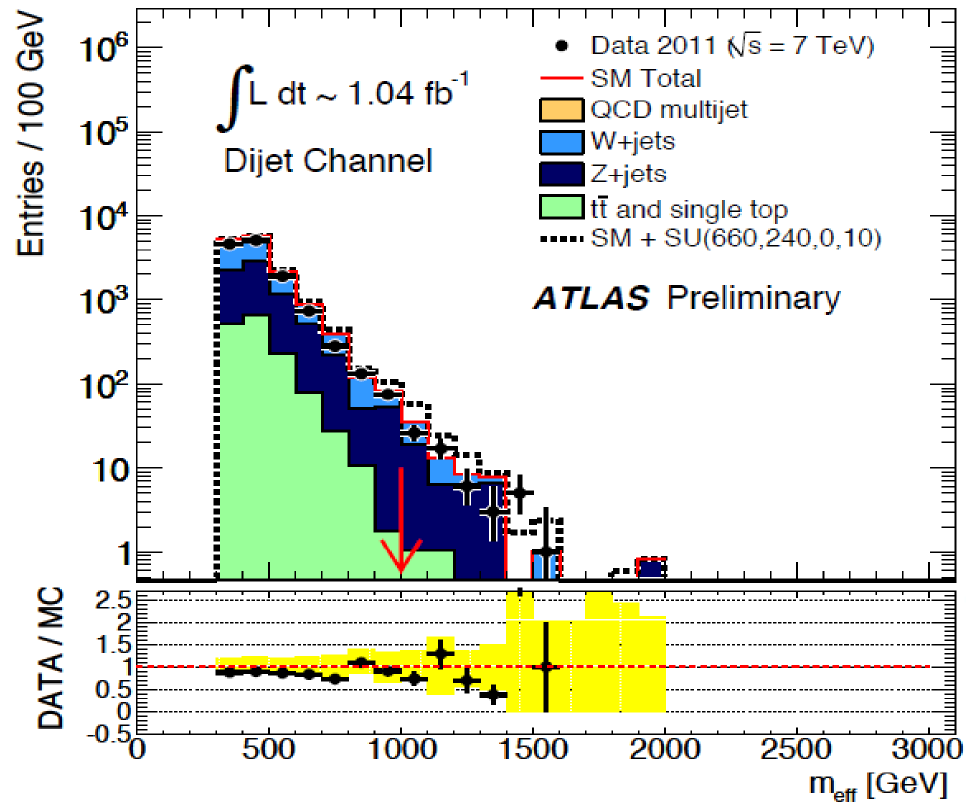
- Introduction
- The EWK path towards precision measurements and searches:
  - Inclusive W and Z cross sections at LHC
  - Ratios, differential distributions
  - W bosons plus heavy quark jets
  - Diboson cross sections, anomalous triple gauge couplings
- Summary



Why W/Z studies at colliders?

1) W and Z decays are special final states:
   a) They are used to understand and calibrate our detector response (trigger, identification, resolution, efficiencies)
   b) They are dominant signal and/or background in many other analyses and searches for new physics (top, Higgs, SUSY, ...)

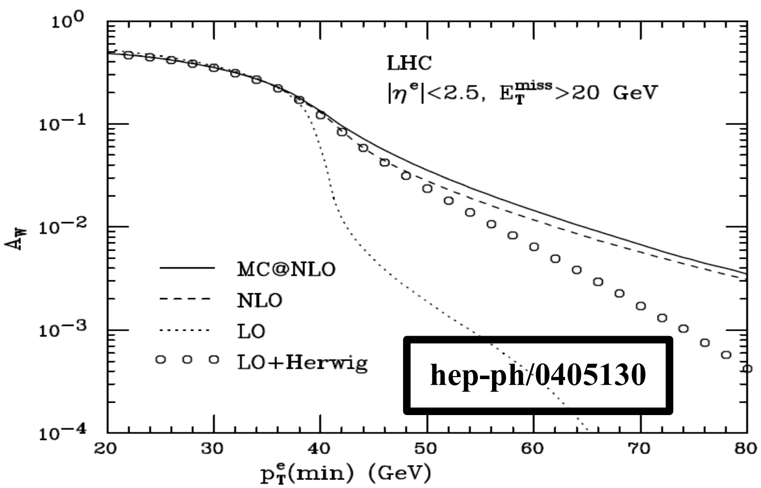




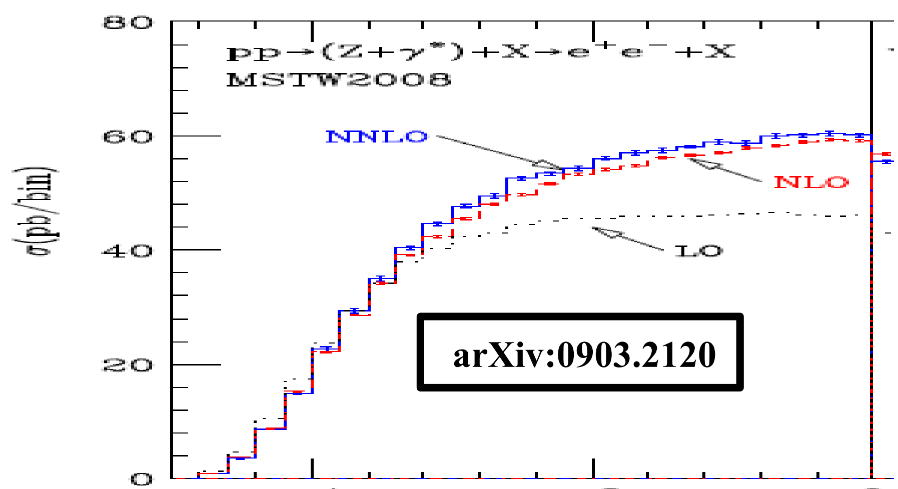
W and Z production at hadron colliders

2) We can really do precision physics studies on W and Z production:

- Experimentally the $W \rightarrow l\bar{\nu}$ and $Z \rightarrow l\bar{l}$ channels are among the cleanest final states that we can exploit at hadron colliders
- Higher order QCD corrections modify the cross sections by 30-40% and have a visible effect on kinematics. Many new tools at our disposal: NLO QCD MC generators (MC@NLO, POWHEG, …), LO-matched multi-jet generators (ALPGEN, MADGRAPH, SHERPA), which will become NLO-matched in the next future.
- NNLO QCD theoretical tools for cross section and kinematic studies are also available (FEWZ, DYNNLO, RESBOS). Effect: 3-4% on cross sections, smaller on acceptances
- There are other important pieces at this level of precision: EWK corrections (HORACE, ...)



NLO approach important for acceptance calculations

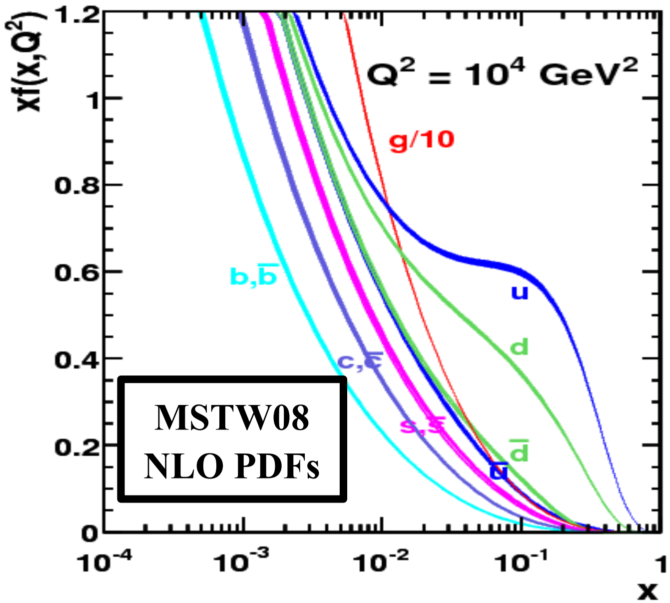


NLO → NNLO transition less critical for acceptances

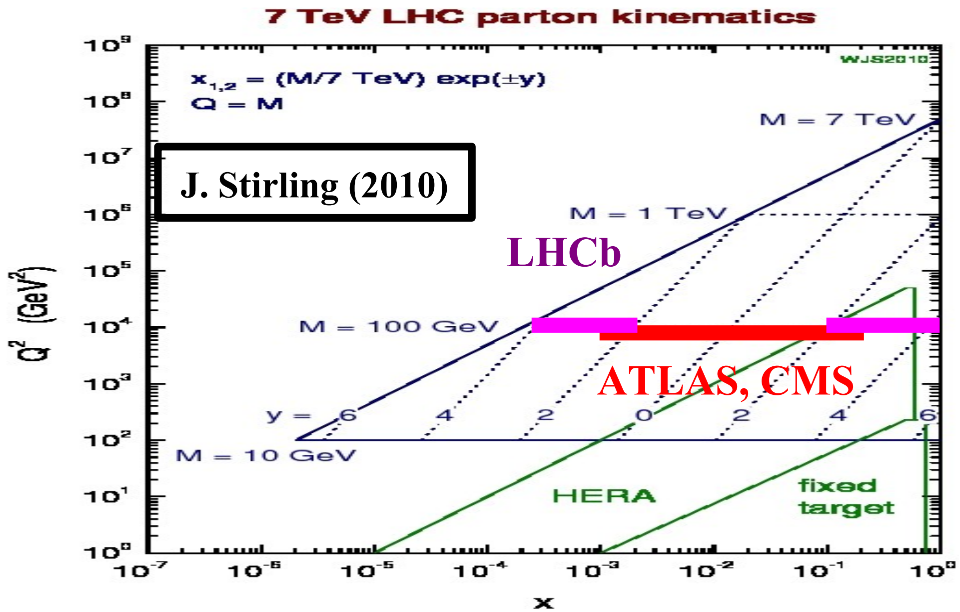
LHC versus Tevatron

- W and Z production at LHC proceeds at the hard scattering level and first order via collisions of a valence quark (u,d) and a sea antiquark (Q≈100 GeV):

$$u+\bar{d}\left(\bar{s}\right)\rightarrow W^{+} \qquad u+\bar{u}\rightarrow Z$$
$$d+\bar{u}\left(\bar{c}\right)\rightarrow W^{-} \qquad d+\bar{d}\rightarrow Z$$



- LHC parton density fractions in this process are typically $10^{-4} < x < 10^{-1}$, so sea-sea $q\bar{q}$ contributions are also important



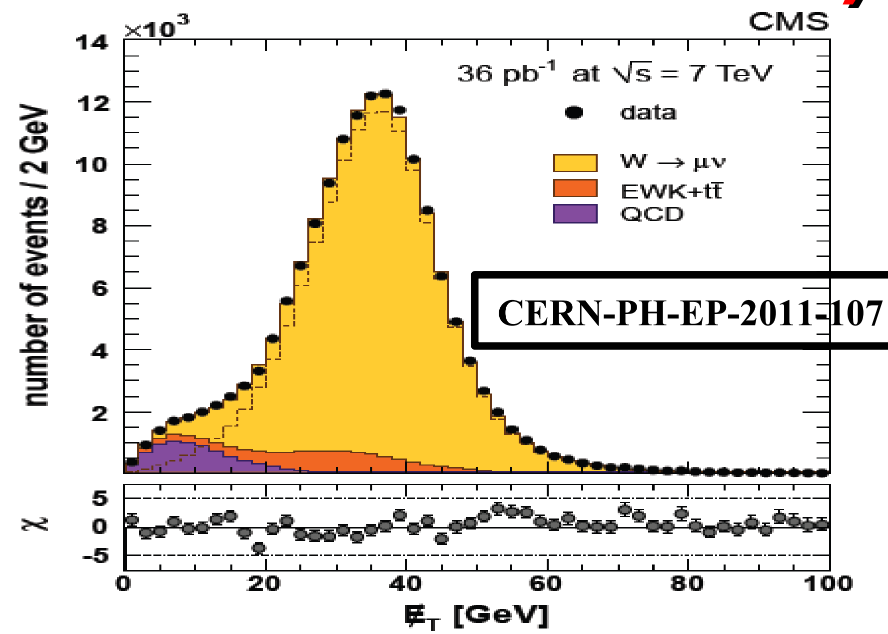
- Cross sections at LHC are a factor of 3 higher than at the Tevatron. We expect: $\sigma(W)*B(W\rightarrow l\nu) \approx 10$ nb, and $\sigma(Z)*B(Z\rightarrow l^+l^-) \approx 1$ nb

- **At LHC: > 10^6 $W\rightarrow l\nu$ events and ~ 10^6 $Z \rightarrow l^+l^-$ events per experiment and per lepton channel in 2011 data !!**

W and Z selection (muons/electrons)

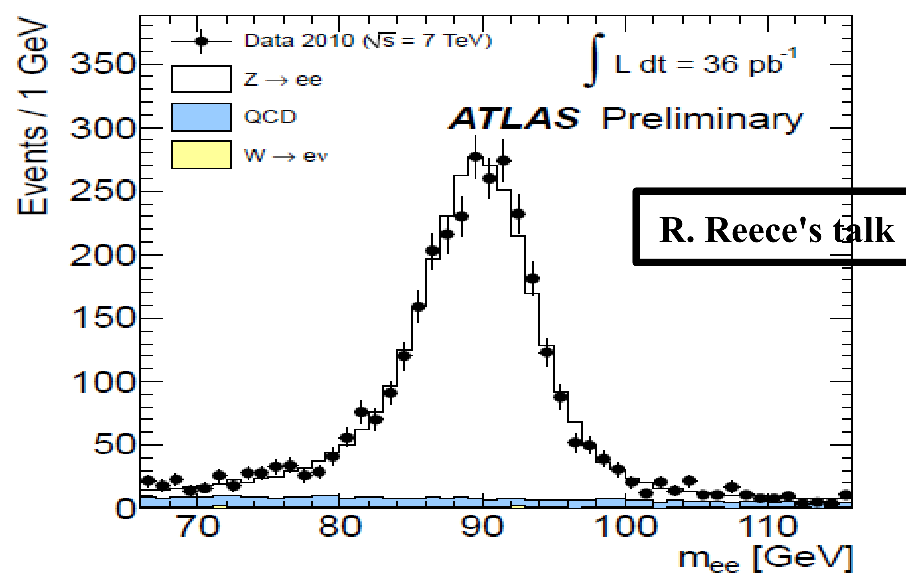
W selection:

- High-p_T lepton (p_T>20-25 GeV)
- Well Isolated from hadronic activity
- Loose cut on missing transverse energy (or not cut at all (CMS))
- Efficiencies, resolutions, signal and background shapes studied / extracted from data.



Z selection:

- Two high- p_T leptons (p_T>20-25 GeV), also isolated
- Dilepton mass consistent with a Z
- Efficiencies, resolutions studied / extracted from data.
- Almost background free



Systematic uncertainties (CMS)

Source (%)	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Lepton reconstruction & identification	1.4	0.9	1.8	n/a
Trigger prefiring	n/a	0.5	n/a	0.5
Energy/momentum scale & resolution	0.5	0.22	0.12	0.35
$\not{E}_T$ scale & resolution	0.3	0.2	n/a	n/a
Background subtraction / modeling	0.35	0.4	0.14	0.28
Trigger changes throughout 2010	n/a	n/a	n/a	0.1
Total experimental	1.6	1.1	1.8	0.7
PDF uncertainty for acceptance	0.6	0.8	0.9	1.1
Other theoretical uncertainties	0.7	0.8	1.4	1.6
Total theoretical	0.9	1.1	1.6	1.9
Total (excluding luminosity)	1.8	1.6	2.4	2.0

- These are the final 2010 results from CMS (already submitted for publication)
- Experimental uncertainties are significantly reduced thanks to the extensive use of data-driven methods to control efficiencies, backgrounds and signal shapes
- Theoretical and experimental uncertainties have similar sizes
- Measurements in fiducial volume are also provided (smaller theory uncertainty)

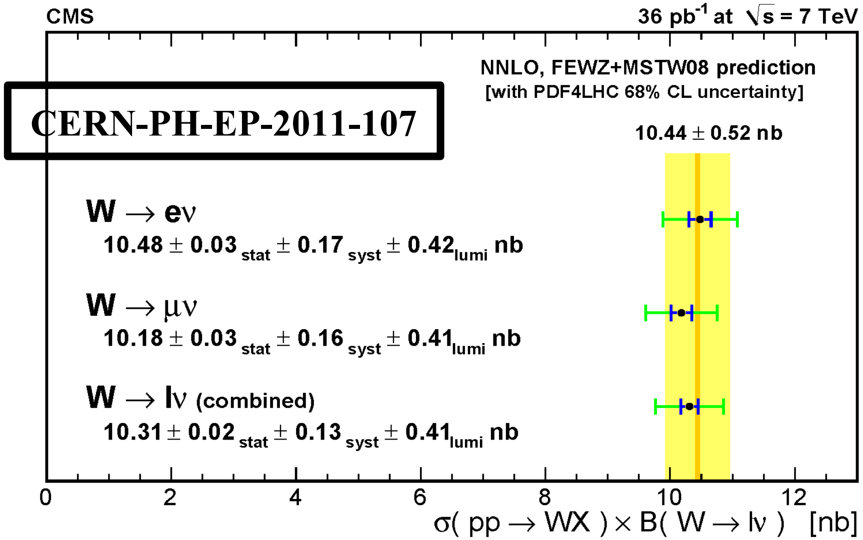
Systematic uncertainties (ATLAS)

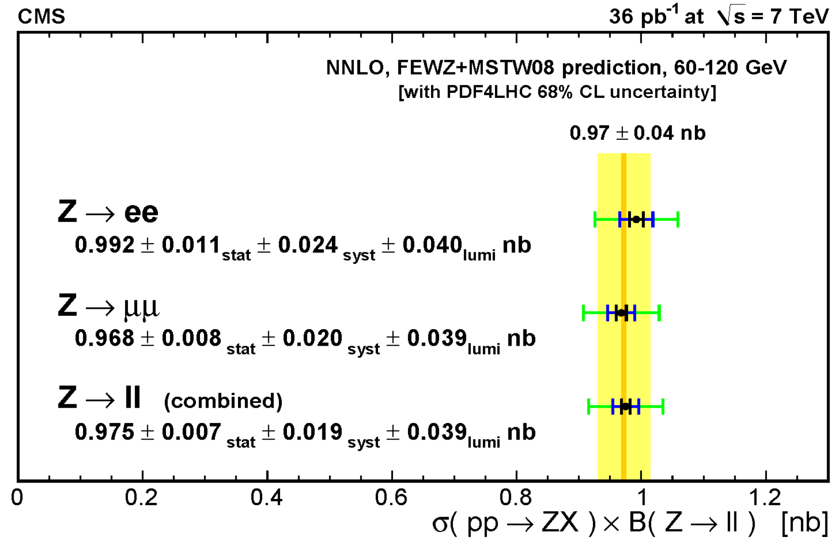
Electron channels (%)	$W^{\pm}$	W^{+}	W^{-}	Z
Trigger	0.4	0.4	0.4	<0.1
Reconstruction	0.8	0.8	0.8	1.6
Identification	0.9	0.8	1.1	1.8
Isolation	0.3	0.3	0.3	—
Energy scale and resolution	0.5	0.5	0.5	0.2
Defective LAr channels	0.4	0.4	0.4	0.8
Charge misidentification	<0.1	0.1	0.1	0.6
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.8	0.7	1.0	—
Pile-up	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
QCD Background	0.4	0.4	0.4	0.7
EWK+$t\bar{t}$ Background	0.2	0.2	0.2	<0.1
$C_{W/Z}$ Theor. uncertainty	0.6	0.6	0.6	0.3
Total Exp. uncertainty	1.8	1.8	2.0	2.7
$A_{W/Z}$ Theor. uncertainty	1.4	1.6	1.9	1.9
Total excluding Luminosity	2.3	2.4	2.8	3.3

Muon channels (%)	$W^{\pm}$	W^{+}	W^{-}	Z
Trigger	0.5	0.5	0.5	0.1
Reconstruction	0.4	0.3	0.3	0.6
Isolation	0.2	0.1	0.2	0.3
p_{T} Resolution	0.04	0.03	0.05	0.02
p_{T} Scale	0.4	0.6	0.6	0.2
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.5	0.4	0.6	-
Pile-up	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
QCD Background	0.6	0.5	0.8	0.3
EWK+$t\bar{t}$ Background	0.4	0.3	0.4	0.02
$C_{W/Z}$ Theor. uncertainty	0.8	0.8	0.7	0.3
Total Exp. uncertainty	1.6	1.7	1.7	0.9
$A_{W/Z}$ Theor. uncertainty	1.4	1.6	2.0	2.0
Total excluding Luminosity	2.1	2.3	2.6	2.2

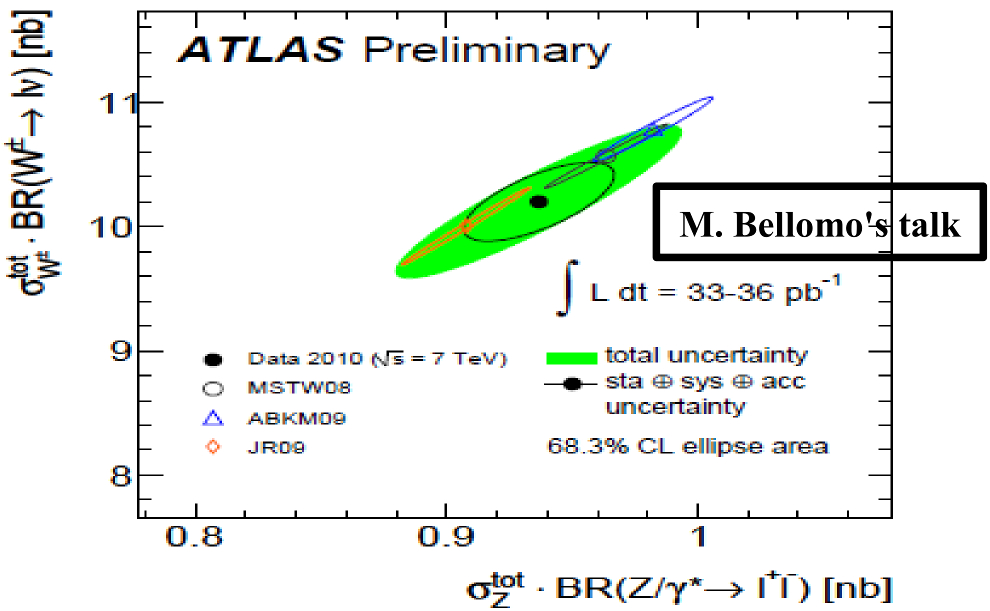
- These are almost final 2010 results from ATLAS, to be published very soon
- CMS comments are also applicable to ATLAS (significant reduction of uncertainties, similar theory/experimental uncertainties, ...)
- Measurements in fiducial volume are also provided (smaller theory uncertainty)

LHC W/Z inclusive cross sections





- Total cross sections are shown (i.e. extrapolated to full phase space). For Z/γ^*, full acceptance means:
  - $60 < M_{ll} < 120$ GeV (CMS)
  - $66 < M_{ll} < 116$ GeV (ATLAS)
- Experimental uncertainties dominated by luminosity uncertainty (≈4%)
- Good agreement with NNLO theory expectations



$Z \rightarrow \tau\tau$

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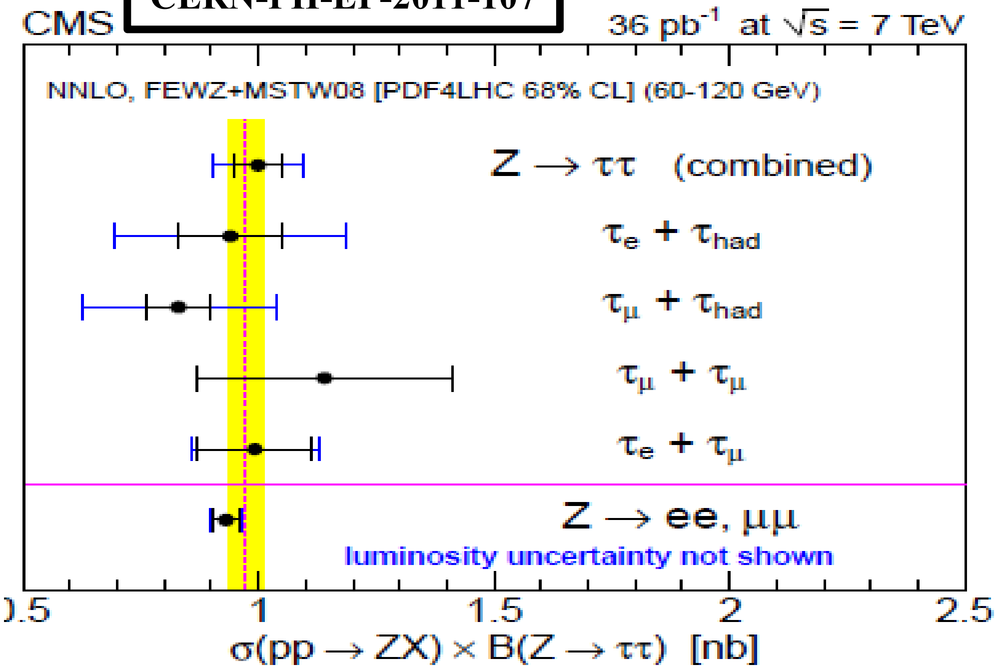
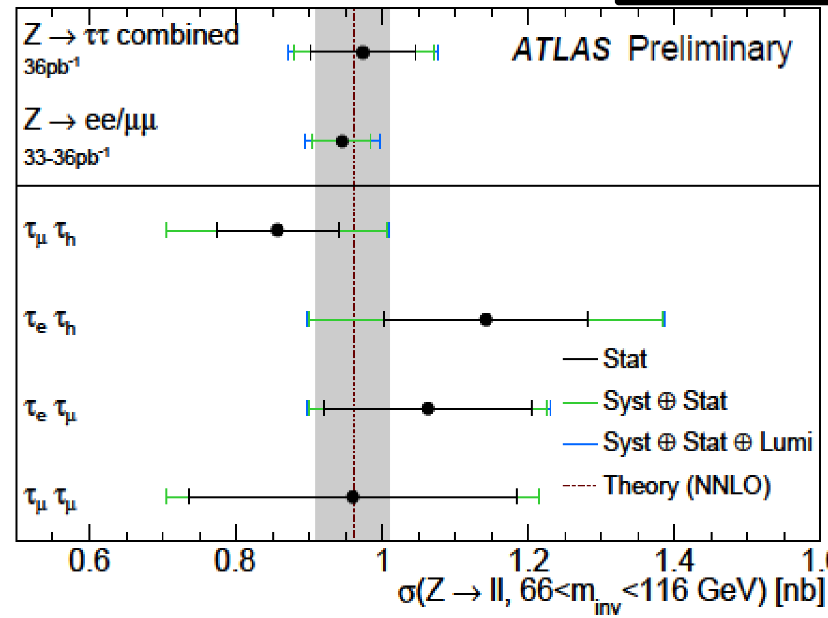
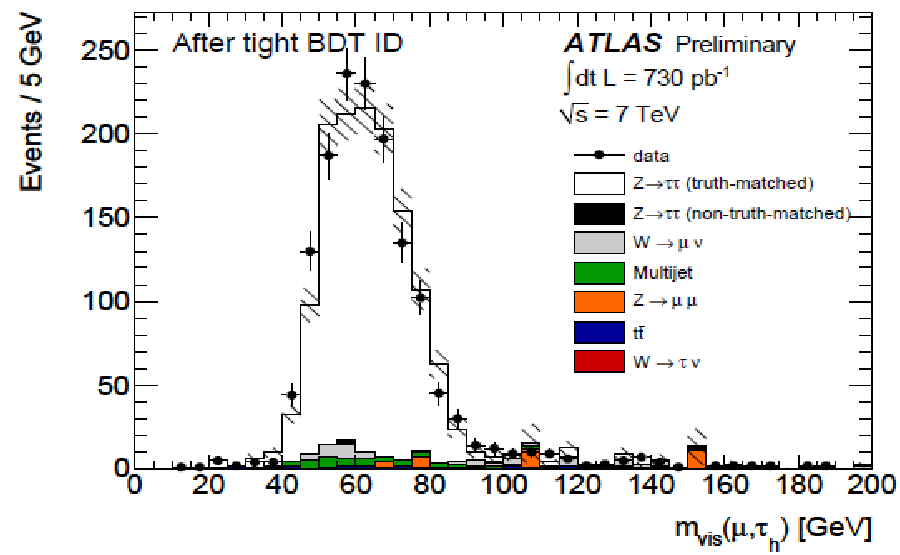


R. Reece's talk

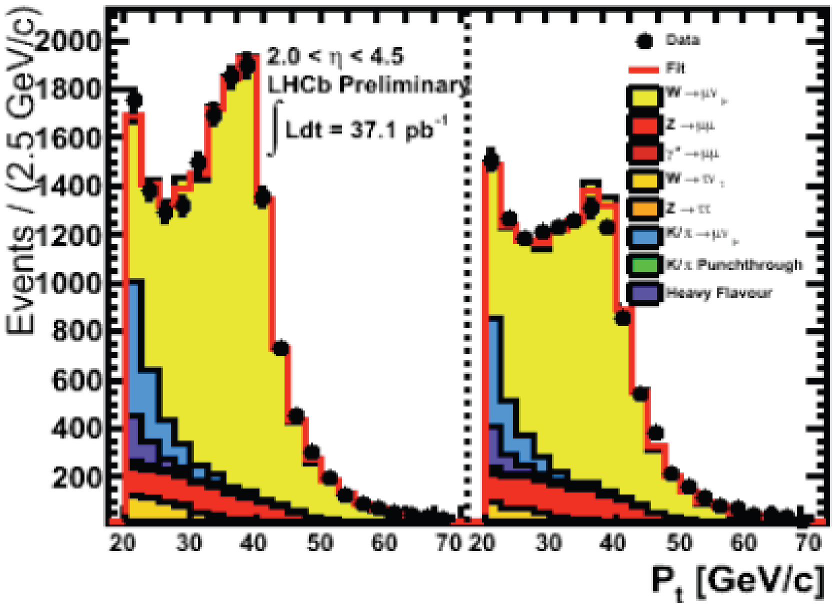


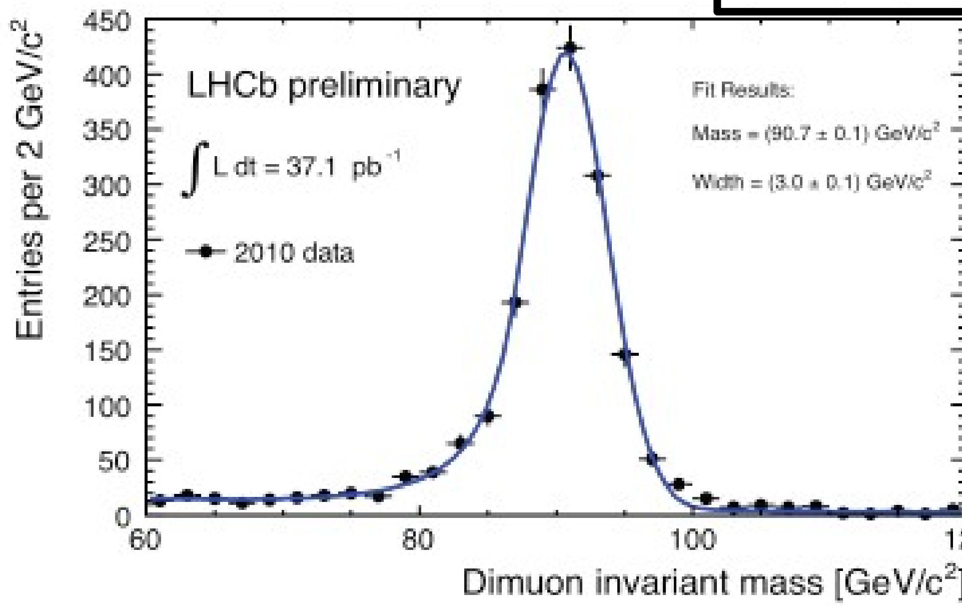
- CMS: published results, ATLAS: new results presented at this conference:
  - Extremely good tau identification capabilities: taus are reasonably clean at LHC
  - Four channels studied: $e\tau_{had}$, $\mu\tau_{had}$, $e\mu$, $\mu\mu$
  - Backgrounds estimated from data control samples
- Good news for new physics searches wih taus



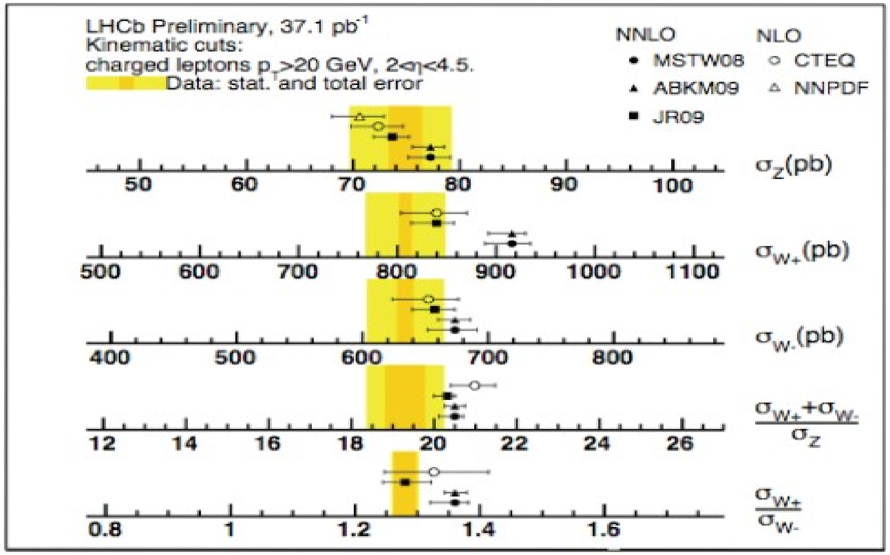
W and Z at LHCb

T. Shears's talk

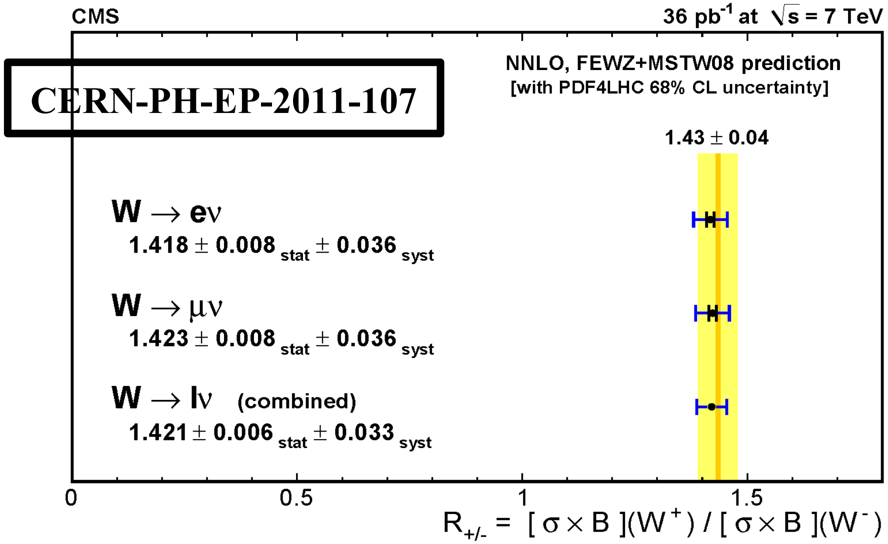


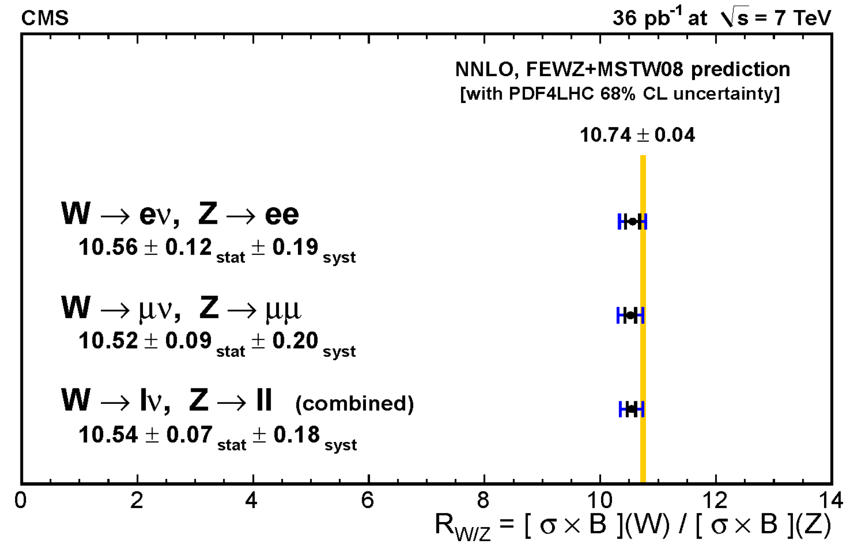


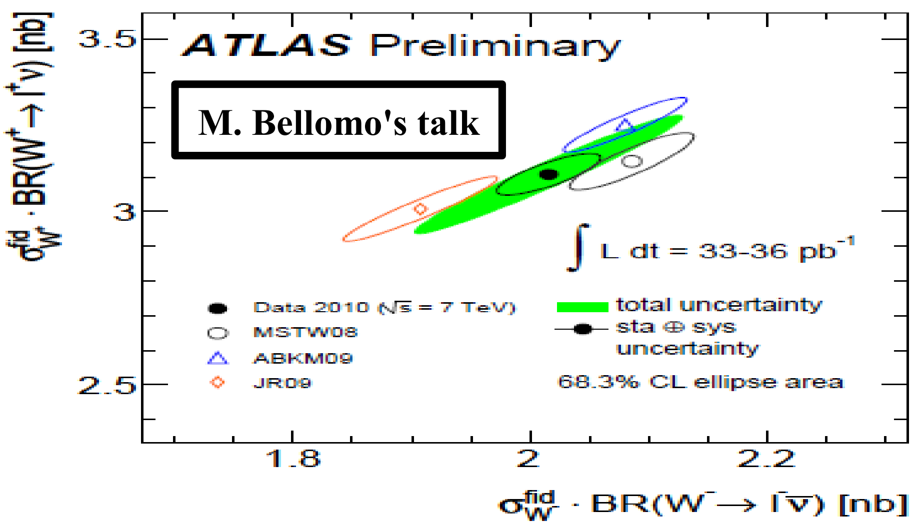
- Missing E_T measurement not necessary to select Ws:
  - p_T>20 GeV, isolated muon, consistent with primary vertex, 2<|η|<4.5
- Excellent resolution for $Z \rightarrow \mu\mu$
  - Backgrounds estimated from data control samples
- Also: $Z \rightarrow \tau\tau$ measurements in eμ and μμ final states

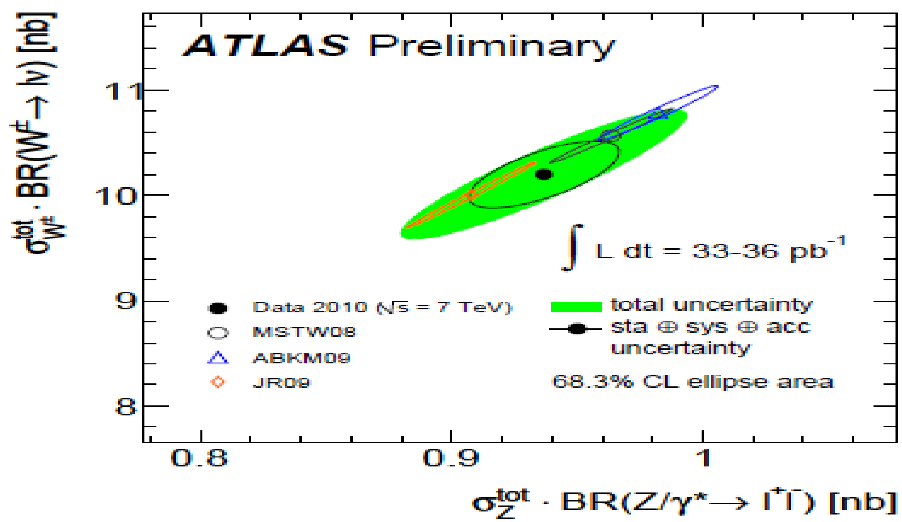


LHC W+/W- and W/Z ratios









W+/W-: potential to constrain PDF uncertainties

W/Z: stringent test of theoretical expectations

W lepton charge asymmetry

- A first natural extension of the W inclusive studies is the study of the W^+/W^- ratio, R_W, as a function of different kinematic variables.
- Experimentally, a clean way to do this study is to measure the charge asymmetry as a function of the lepton pseudo-rapidity

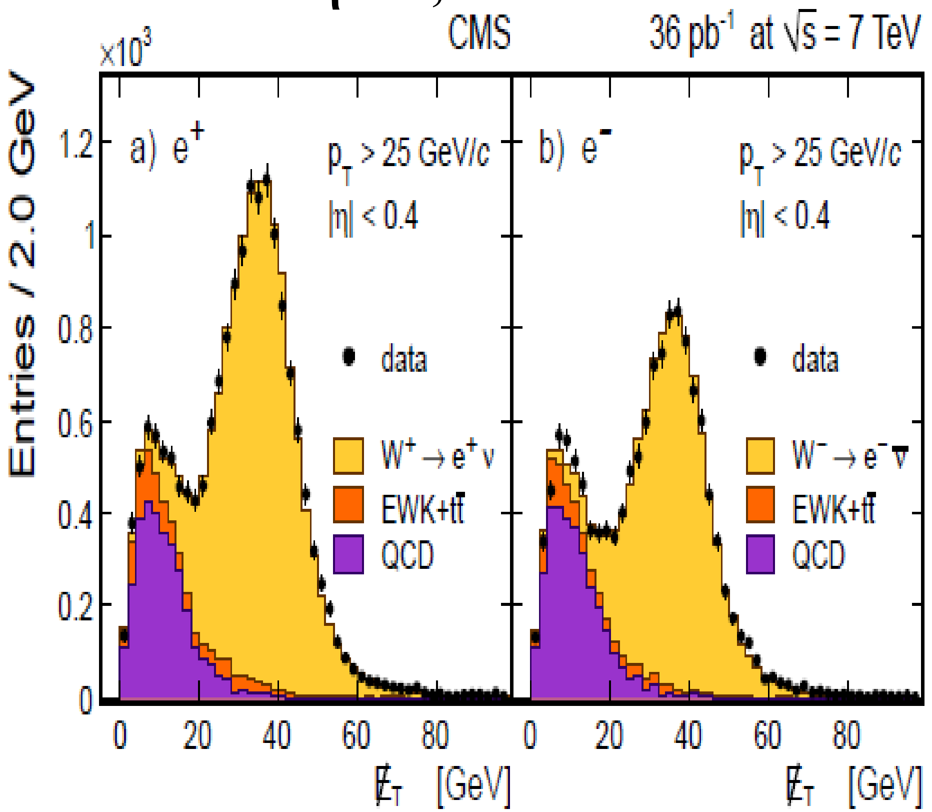
$$A(\eta)=\frac{\frac{d\sigma}{d\eta}(W^+\to l^+\nu)-\frac{d\sigma}{d\eta}(W^-\to l^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+\to l^+\nu)+\frac{d\sigma}{d\eta}(W^-\to l^-\bar{\nu})}$$

$$\left(A(\eta)\equiv\frac{R_W(\eta)-1}{R_W(\eta)+1}\right)$$

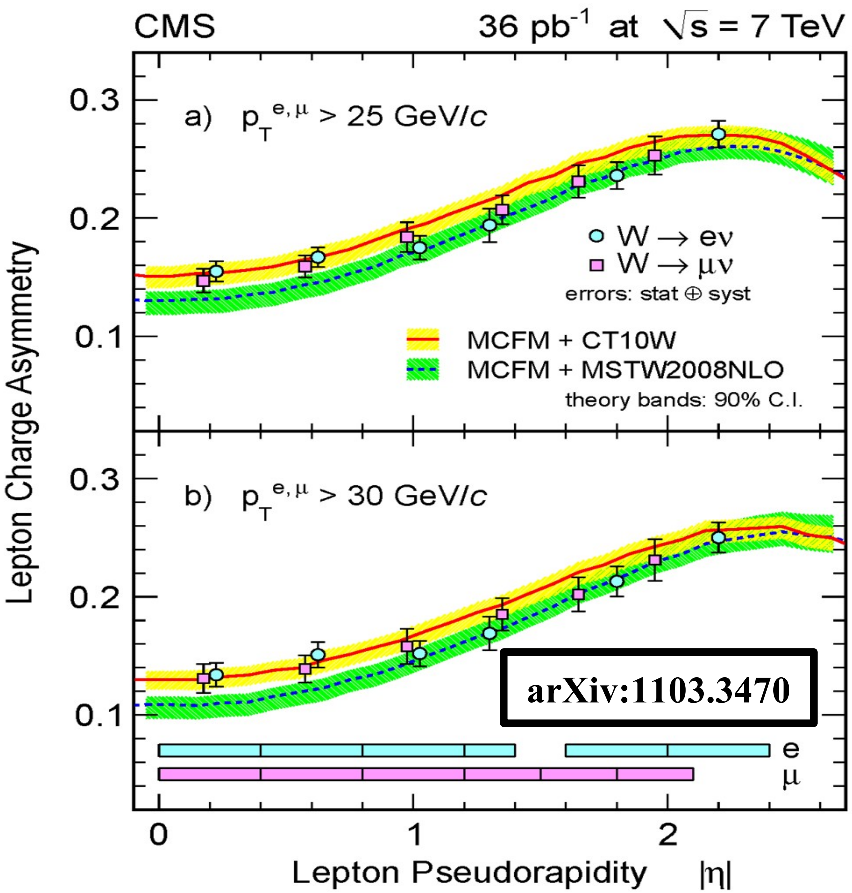
- This measurement is rather sensitive to PDFs because most systematic uncertainties cancel in the ratio
- Selections follow closely the criteria used in inclusive measurements.

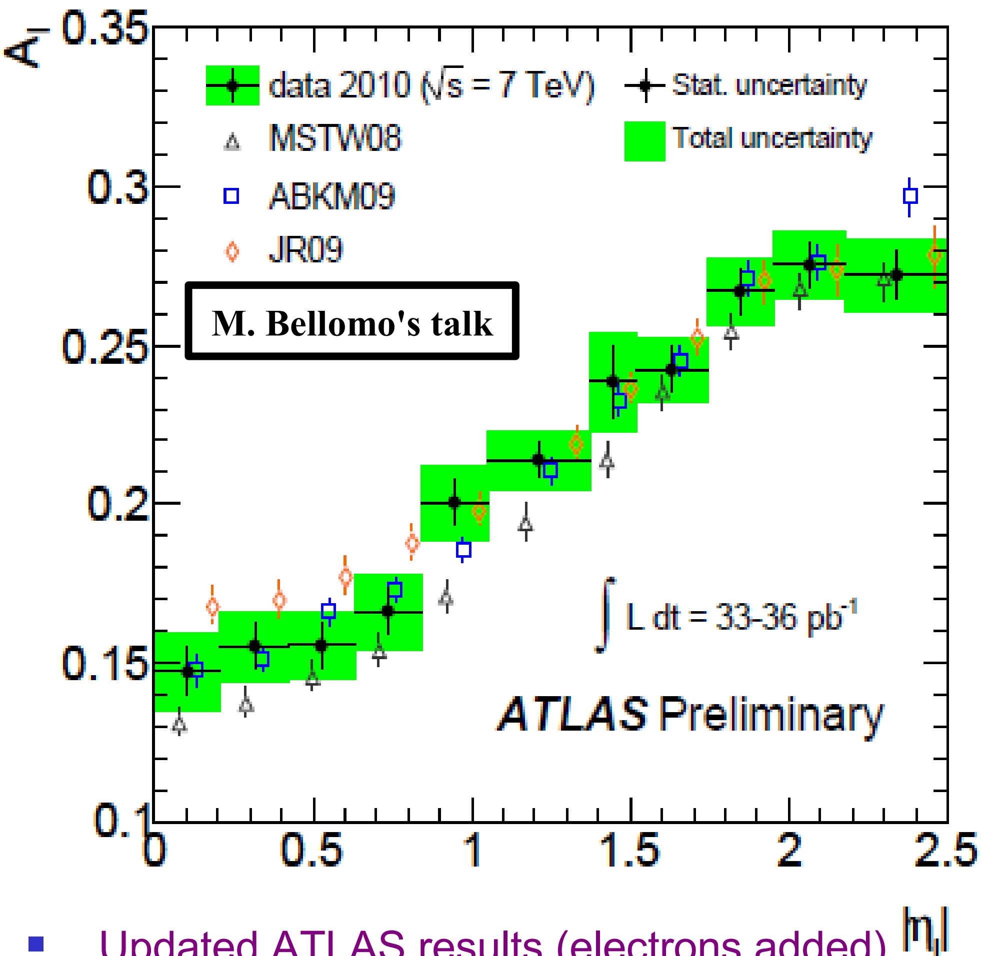
arXiv:1103.3470

First η bin, electron channel



W lepton charge asymmetry

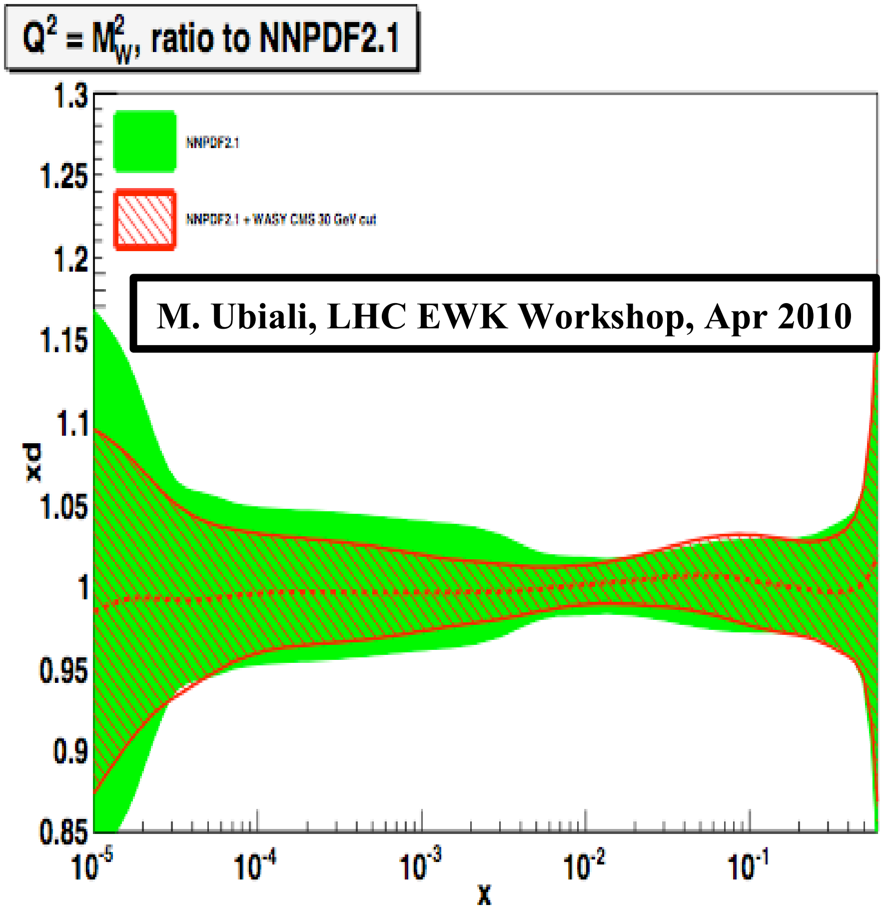


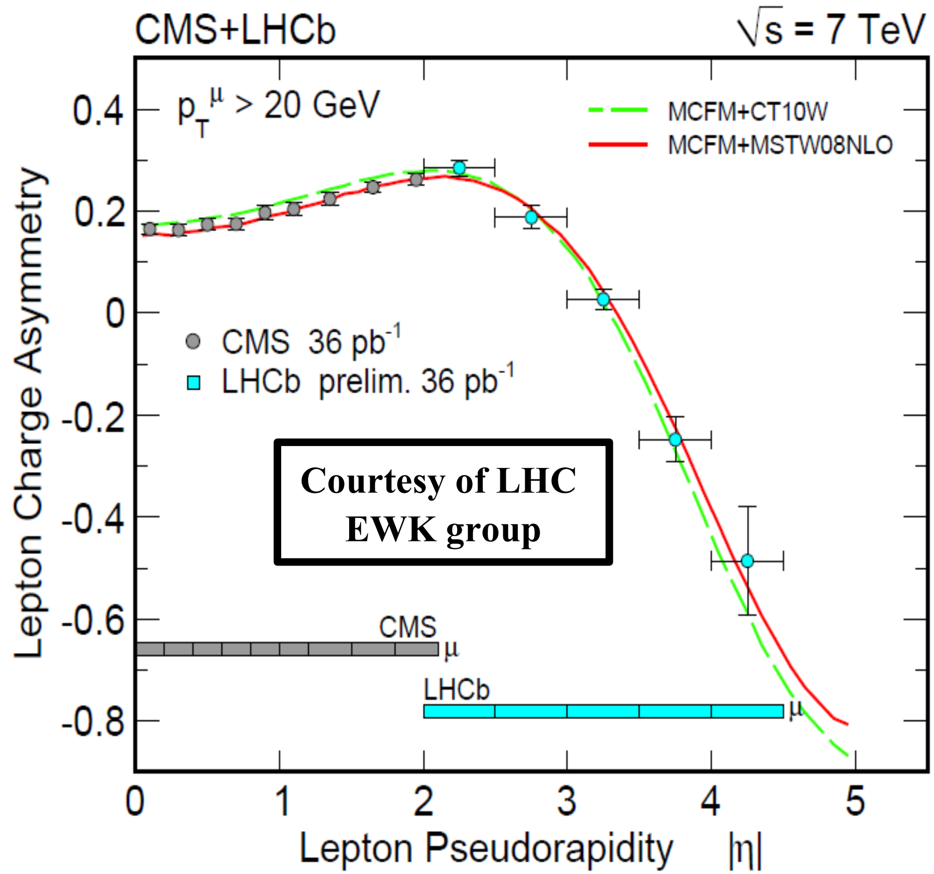


- CMS published results
- Updated ATLAS results (electrons added)

In reasonable agreement with different PDF predictions, but extremely sensitive to shape details

W lepton charge asymmetry



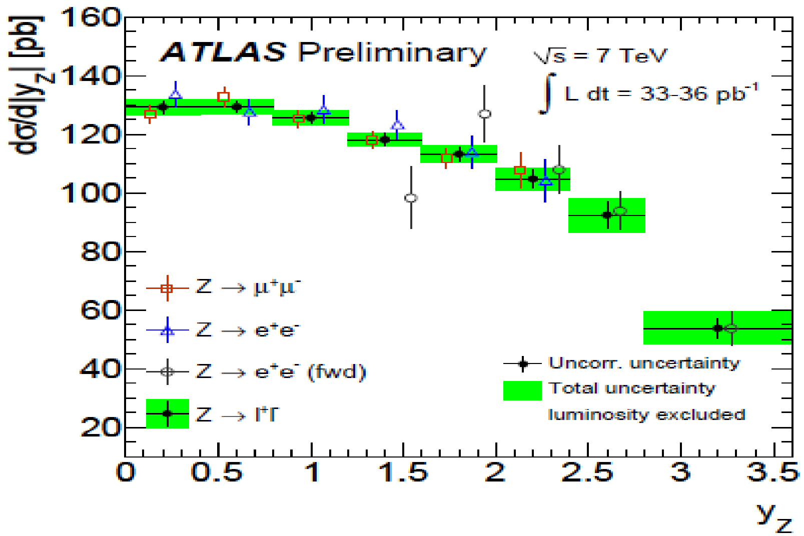


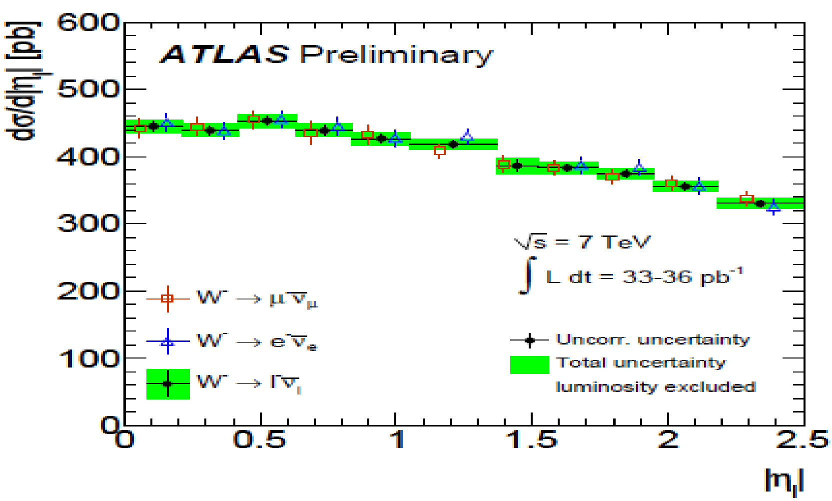
CMS results already improve $d,u,\bar{d},\bar{u},s$ quark PDFs by >40% in the range $10^{-3} < x < 10^{-2}$

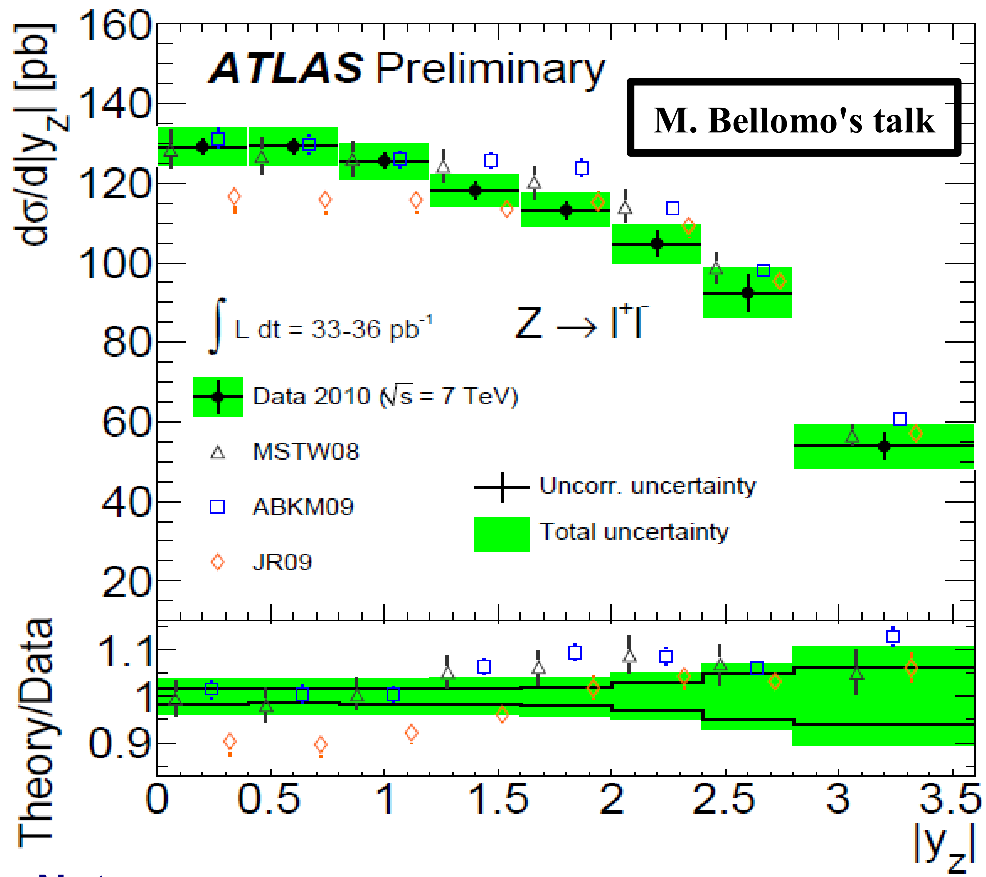
(similar sensitivities expected from updated ATLAS results)

Updated 2010 LHCb results: interesting constraints at high rapidities ($x < 10^{-3}$)

Many differential distributions compared to NNLO PDF sets (ATLAS)



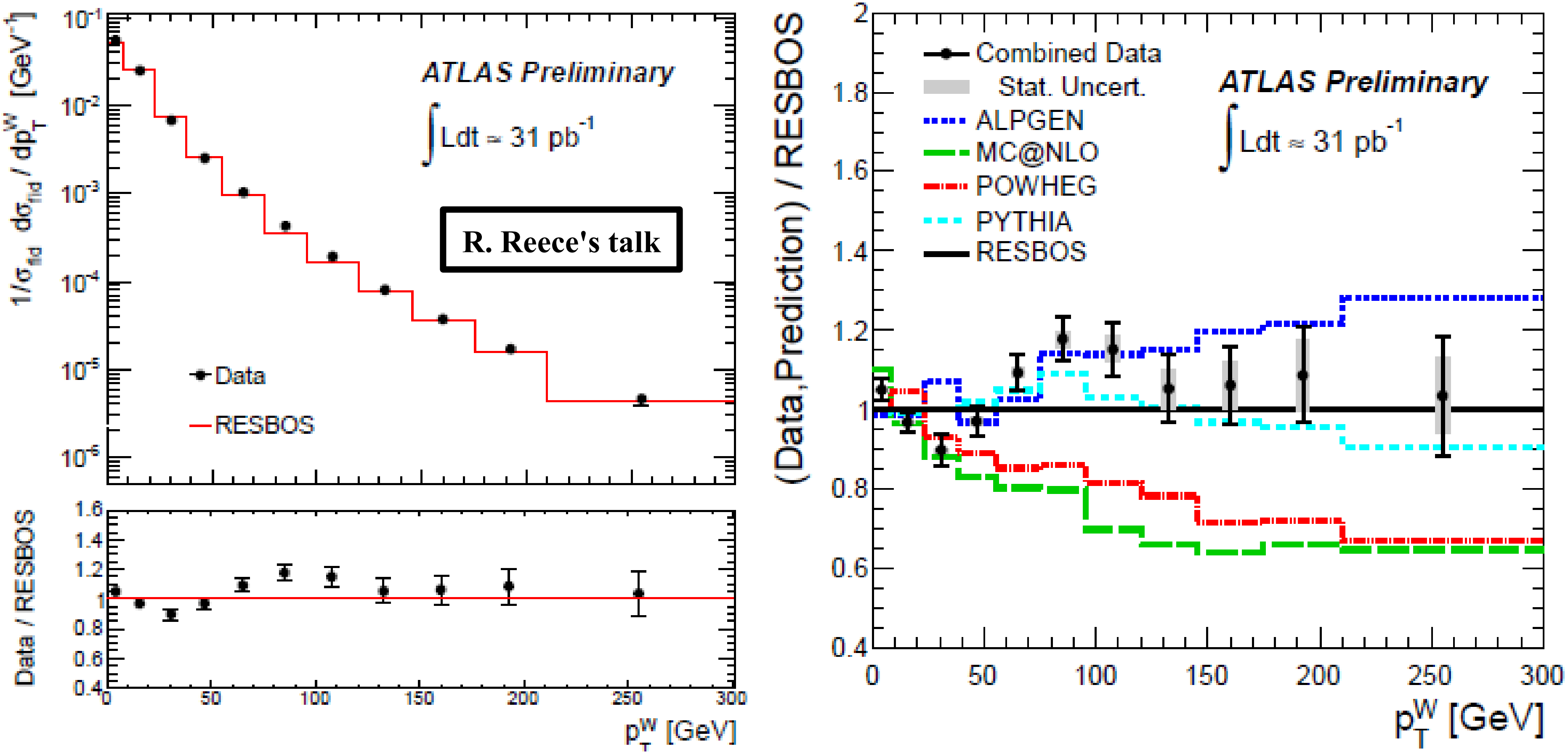




Notes:

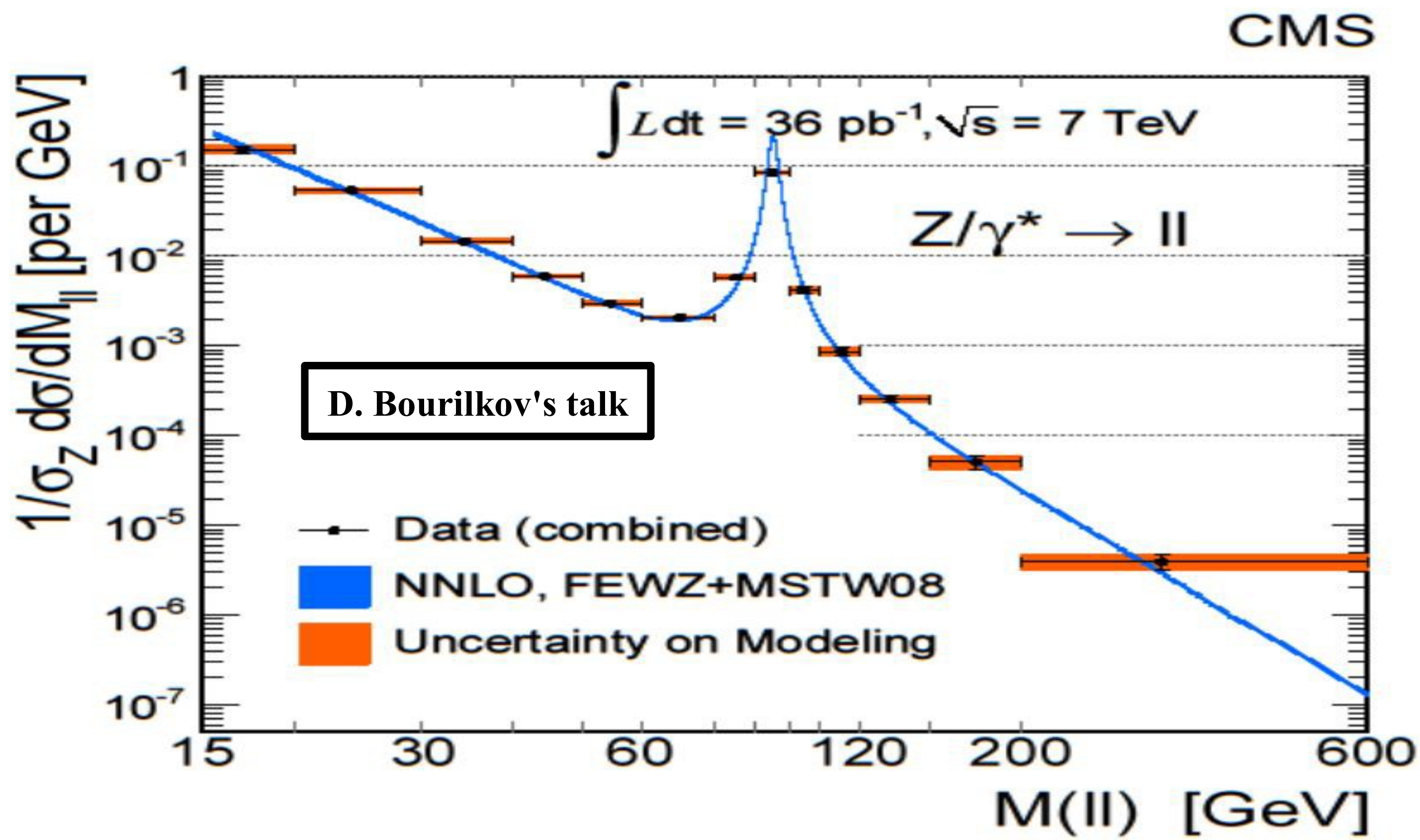
- **CMS DY differential distributions already released for Winter 2011 conferences**
- **Both CMS and ATLAS can identify electrons up to large rapidities ($|\eta|<3.5$)**

First W p_T results at LHC (ATLAS)



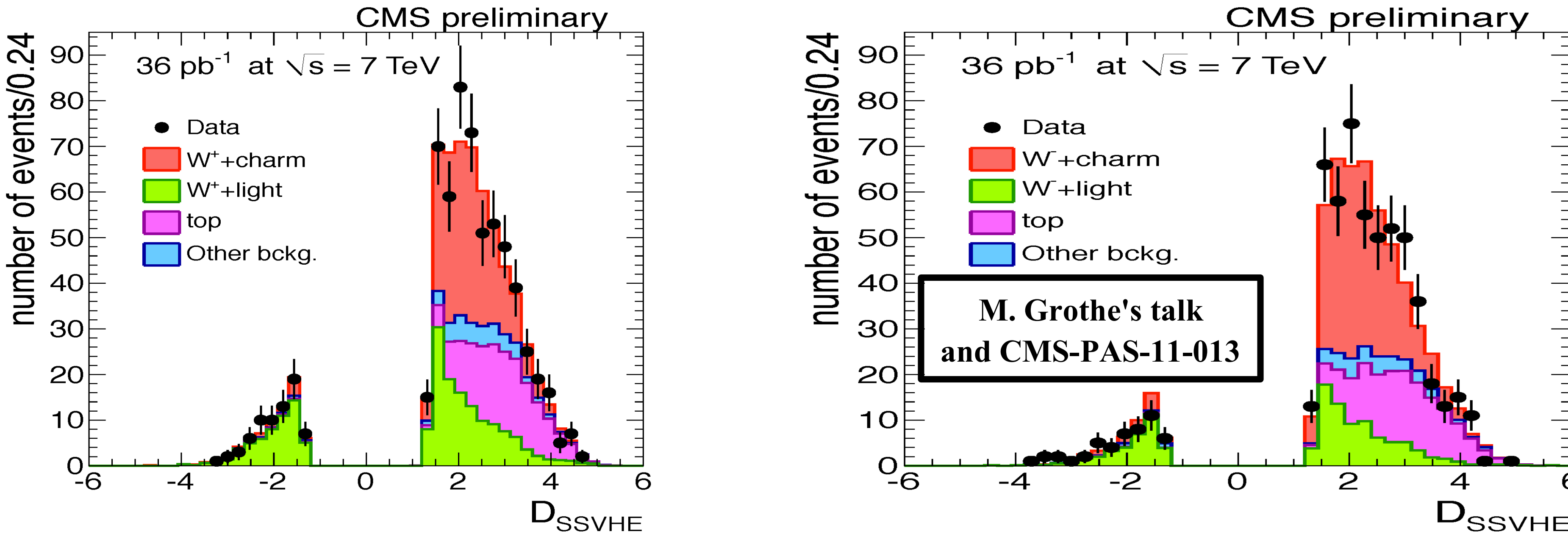
- Better agreement with PYTHIA than with RESBOS:
  - Missing NNLO corrections, tuning effects. … ?
  - It is important to have more dedicated studies on this. It may be critical for the future measurements of M_W. D0 and CMS favor RESBOS (+ Z recoil data) as reference

Drell-Yan mass spectrum (CMS)



- Remarkable agreement with FEWZ+MSTW08 predictions (NNLO QCD):
  - Distribution unfolded for resolution and final state radiation effects, normalized to Z yield
  - Using a NNLO description is necessary for low masses (most selected events in that region are of $l\bar{l}$ + hard jets type)
  - Sensitive to PDFs (different u/d composition outside the Z peak)

First LHC results on W+charm (CMS)



- Sensitive to strange quark PDFs (process dominated by s+g → W + charm):
  - PDF uncertainties from the second quark generation are a potential source of uncertainty for the W mass measurement at the LHC
  - Data-driven control of light-quark and top backgrounds
  - Enormous margin for improvement (only 2010 statistics used), new method (secondary vertex tagging), complementary to the one employed until now at Tevatron (semileptonic charm decay tagging):

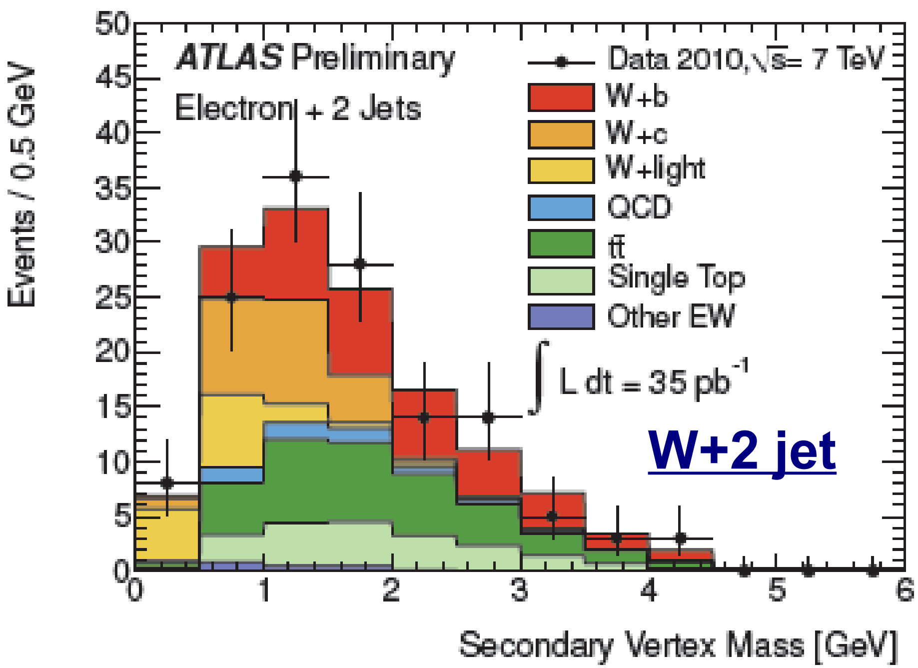
$$\underline{For\quad p_T^{jet}>20\quad GeV, |\eta^{jet}|<2.1}:$$

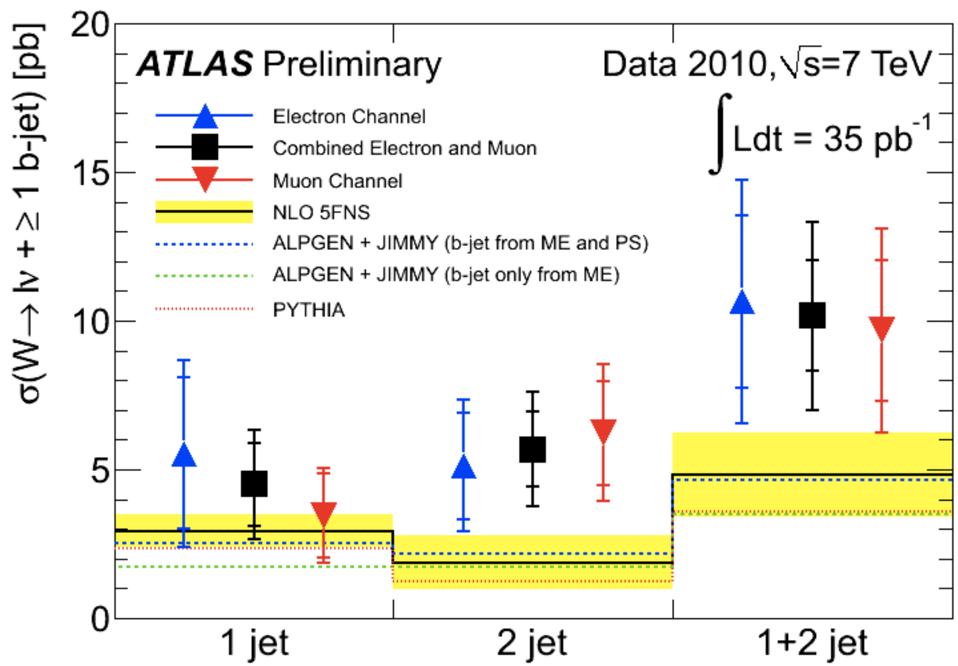
$$\frac{\sigma(W^+ + charm)}{\sigma(W^- + charm)} = 0.92 \pm 0.19(stat.) \pm 0.04(syst.)\,; \quad \frac{\sigma(W + charm)}{\sigma(W + jets)} = 0.142 \pm 0.015(stat.) \pm 0.024(syst.)$$

First LHC W+b results (ATLAS)

- Important background for Higgs searches: W+H ($H \to b\bar{b}$) at low Higgs masses. Also a background for $t\bar{t}$ and single-top measurements
- W+b excess over expectations published by CDF

A. Messina's talk





- Significant decay length (>5.85 σ), fit to the reconstructed mass at secondary vertex
- Challenging analysis: it requires significant reduction and control of top backgrounds and W+charm. Analysis performed independently for 1 and 2 b-tags in the event

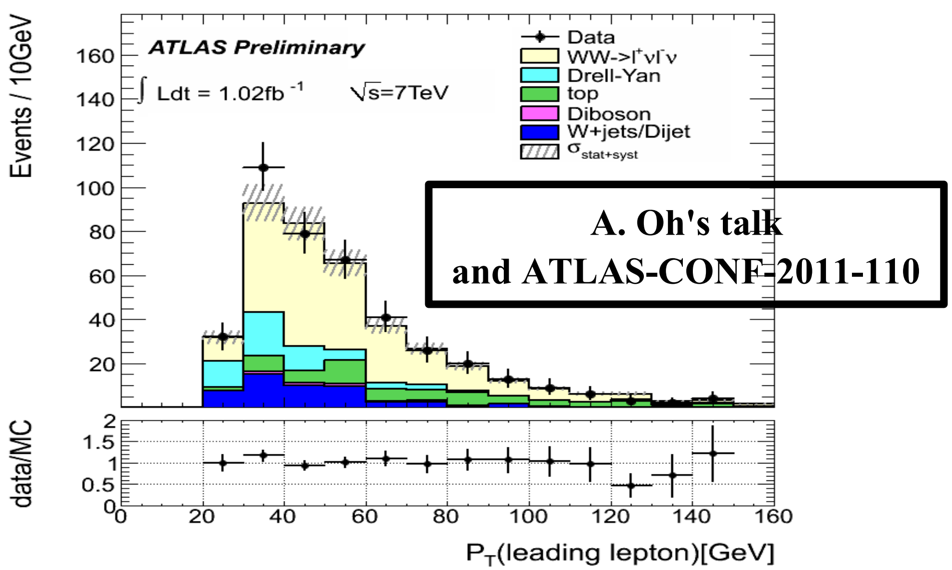
Agreement with theoretical predictions at the 1.5 σ level

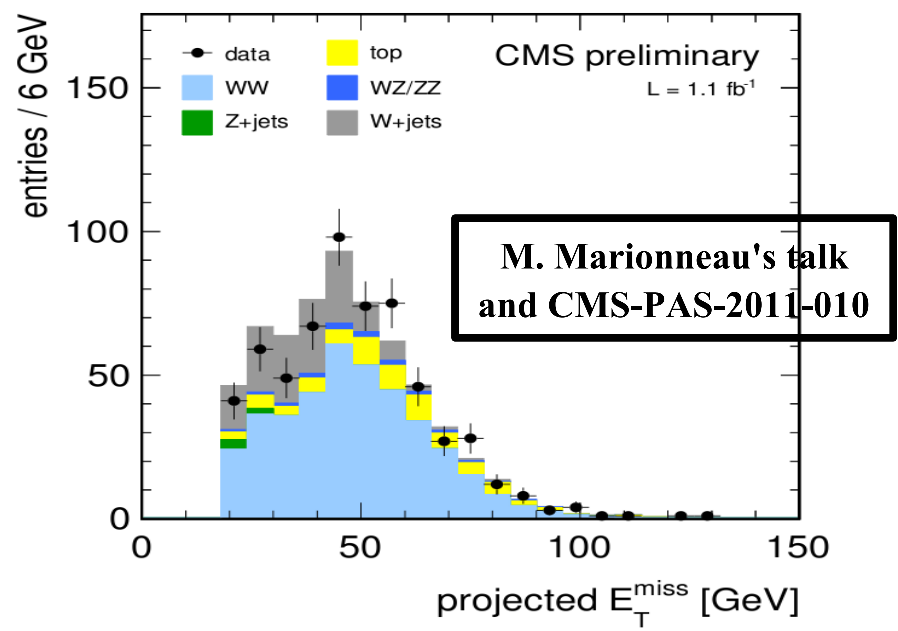
WW production at LHC, L=1 fb^{-1}

- Challenging analysis: ≈400 selected events with ≈40% background

Analysis strategies similar in ATLAS and CMS, 1 fb^{-1} ALREADY PROCESSED:

- Electron and muon identification similar to the one used in inclusive W analysis
- Veto Drell-Yan->ee,μμ (no Z peak, require missing E_T)
- Veto taus (no missing E_T along lepton axes)
- Veto tops, W+jets, multi-jets (no jets), WZ, ZZ (no extra leptons)
- Most backgrounds controlled via data-driven methods (W+jets, top, DY(CMS))



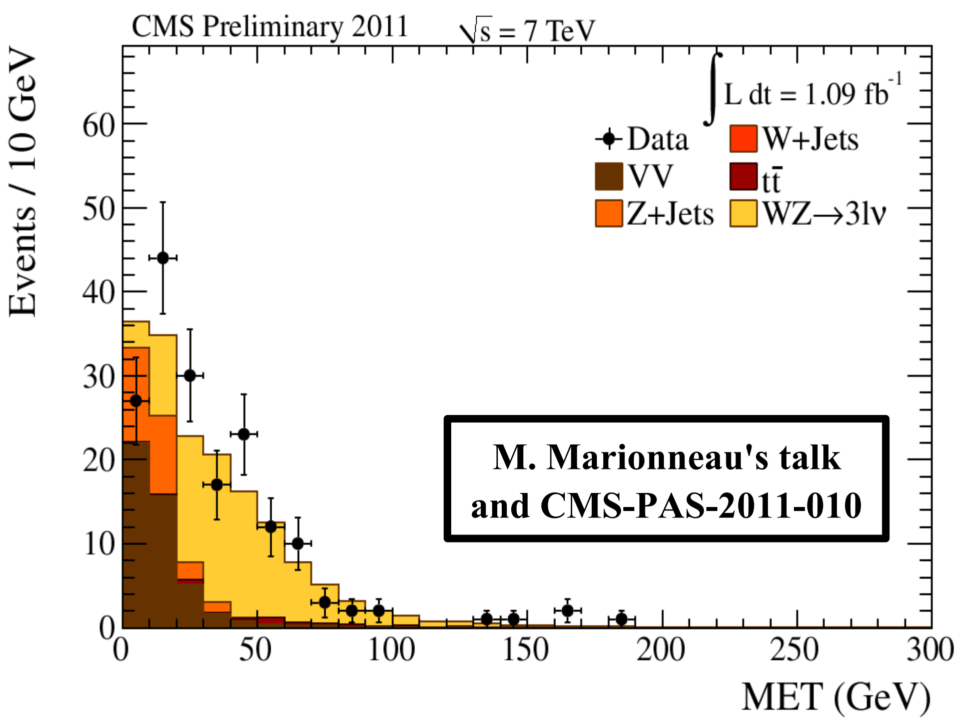


WZ production at LHC, L=1 fb^{-1}

- Cleaner than WW: ≈70-80 events with ≈10-15% background

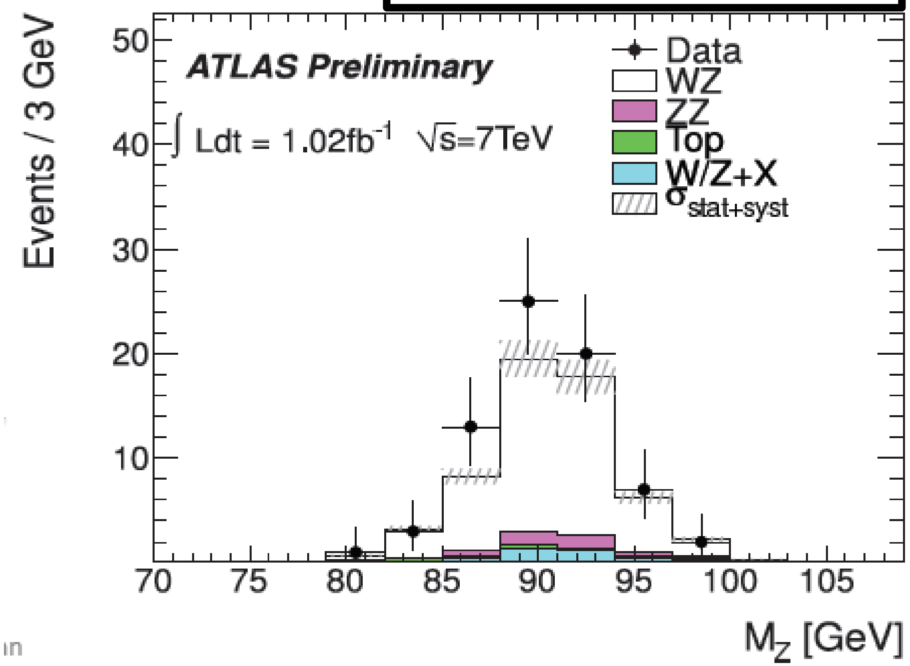
Analysis strategies similar in ATLAS and CMS, 1 fb^{-1} ALREADY PROCESSED:

- Electron and muon identification similar to the one used in inclusive W analysis
- Select e^+e^-,$\mu^+\mu^-$ events consistent with the Z resonance (like in inclusive studies)
- Add a third lepton, require missing E_T
- Backgrounds controlled via data-driven methods (Z+jets, top) or MC (ZZ, Zγ)



M. Marionneau's talk and CMS-PAS-2011-010

A. Oh's talk and ATLAS-CONF-2011-099

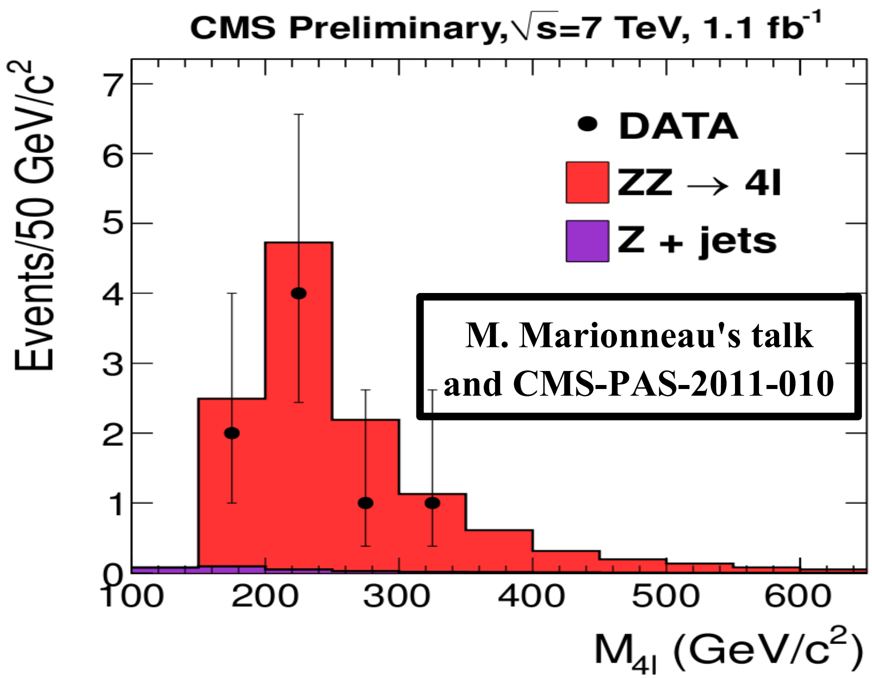


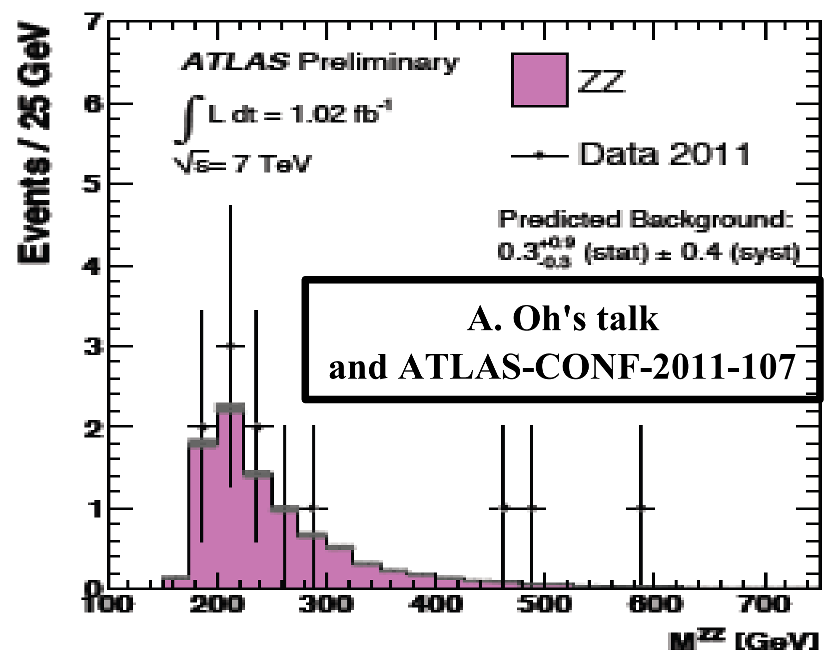
ZZ production at LHC, L=1 fb^{-1}

- Cleanest channel: ≈ 10 events in 1 fb^{-1} with almost negligible background

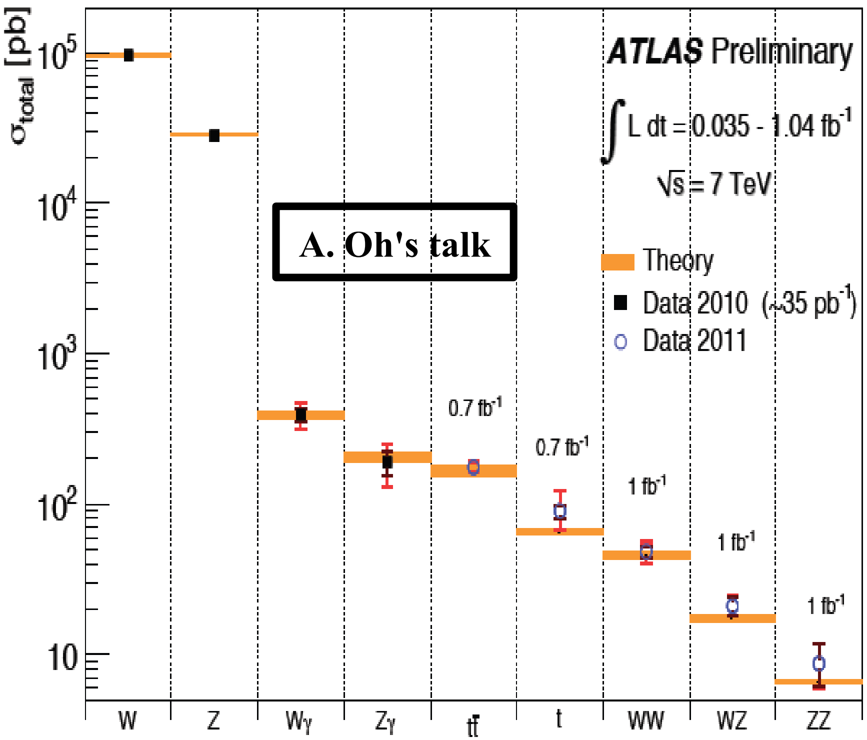
Analysis strategies similar in ATLAS and CMS:

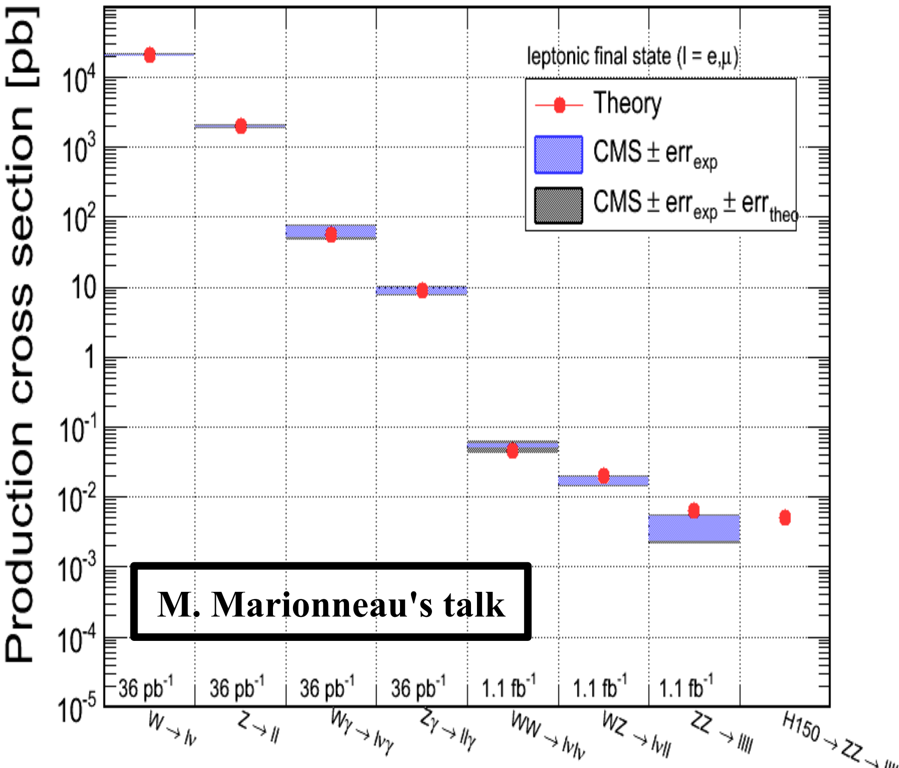
- Electron and muon identification relaxed with respect to the Z inclusive analysis (lower p_T cuts, looser isolation)
- Select four-lepton events with e^+e^- and/or $\mu^+\mu^-$ pairs consistent with the Z
- (Small) backgrounds tested via control samples (Z+jets, top, Z$b\bar{b}$)
- CMS also considers ZZ events with one of the Z decaying into $\tau^+\tau^-$





Diboson results consistent with SM expectations





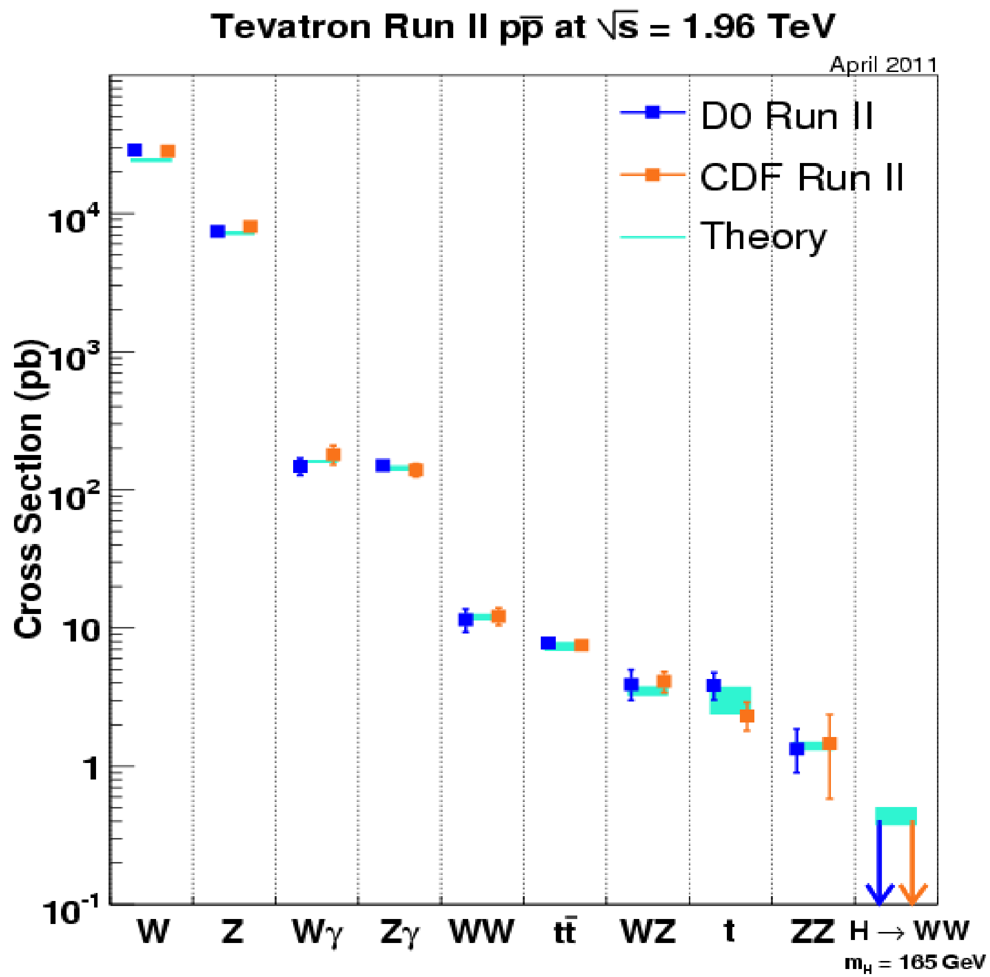
Cross Section [pb]	WW	WZ	ZZ
Expected total	46	17.2	6.5
Measured total	**48.2**	**21.1**	**8.4**
Stat err	4	2.95	2.5
Syst err	6.4	1.2	0.55
Lumi err	1.8	0.85	0.3

σ [pb]	WW	WZ	ZZ
Expected total	43 ± 3	20 ± 2	6.4 ± 0.6
Measured	**55.3**	**17.0**	**3.8**
Stat. unc.	3.3	2.4	+1.5/-1.2
Syst, unc.	6.9	1.0	0.2
Lumi unc.	3.3	1.0	0.2

Tevatron results

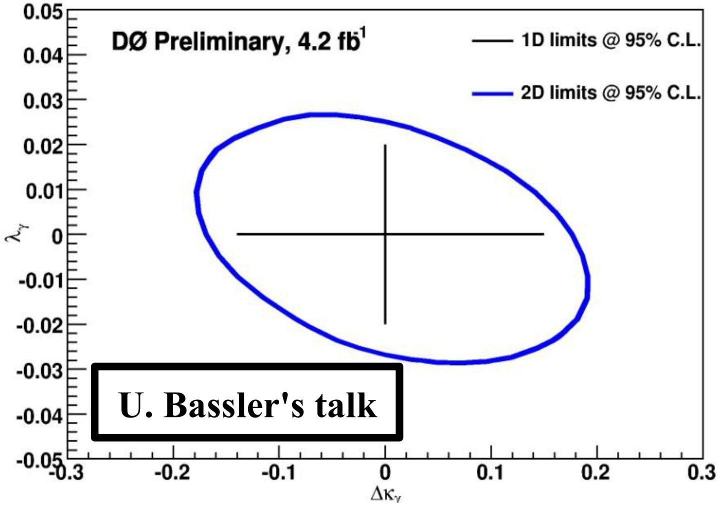
U. Bassler's talk

$W\gamma$	4.2 fb^{-1}	15.2 ± 1.6 pb
WW	1.1 fb^{-1}	11.5 ± 2.1 pb
WZ	4.1 fb^{-1}	$3.90^{+1.01}_{-0.85}$ pb
$Z\gamma$	3.6 fb^{-1}	4.96 ± 0.42 pb
$Z\gamma \rightarrow \nu\nu\gamma$	3.6 fb^{-1}	32 ± 9 fb
ZZ	6.4 fb^{-1}	$1.40^{+0.45}_{-0.40}$
hadronic channel:		
WW+WZ	1.1 fb^{-1}	20.2 ± 4.4 pb

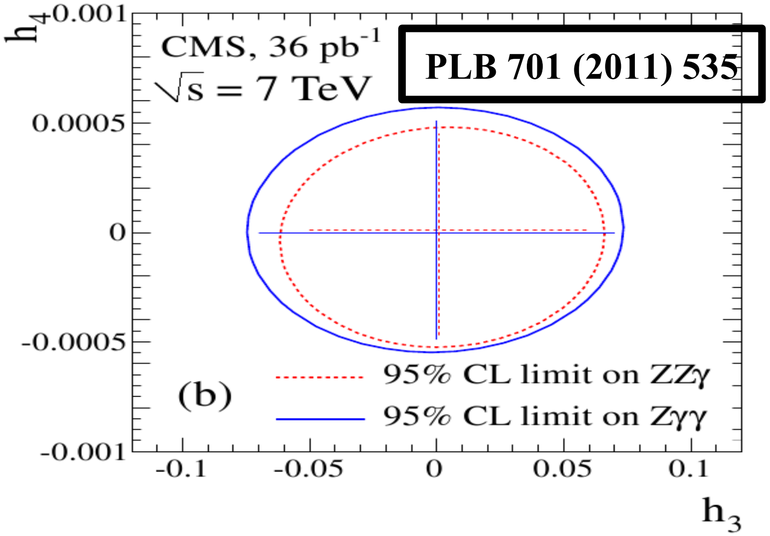


- New precise D0 results presented at EPS11 on Wg, WZ, ZZ with more than 4 fb^{-1} !!
- In practice, LHC (1 fb^{-1}) and Tevatron (6 fb^{-1}) have similar sensitivites for single boson and diboson production (factor >3 at production level, slightly larger acceptance)

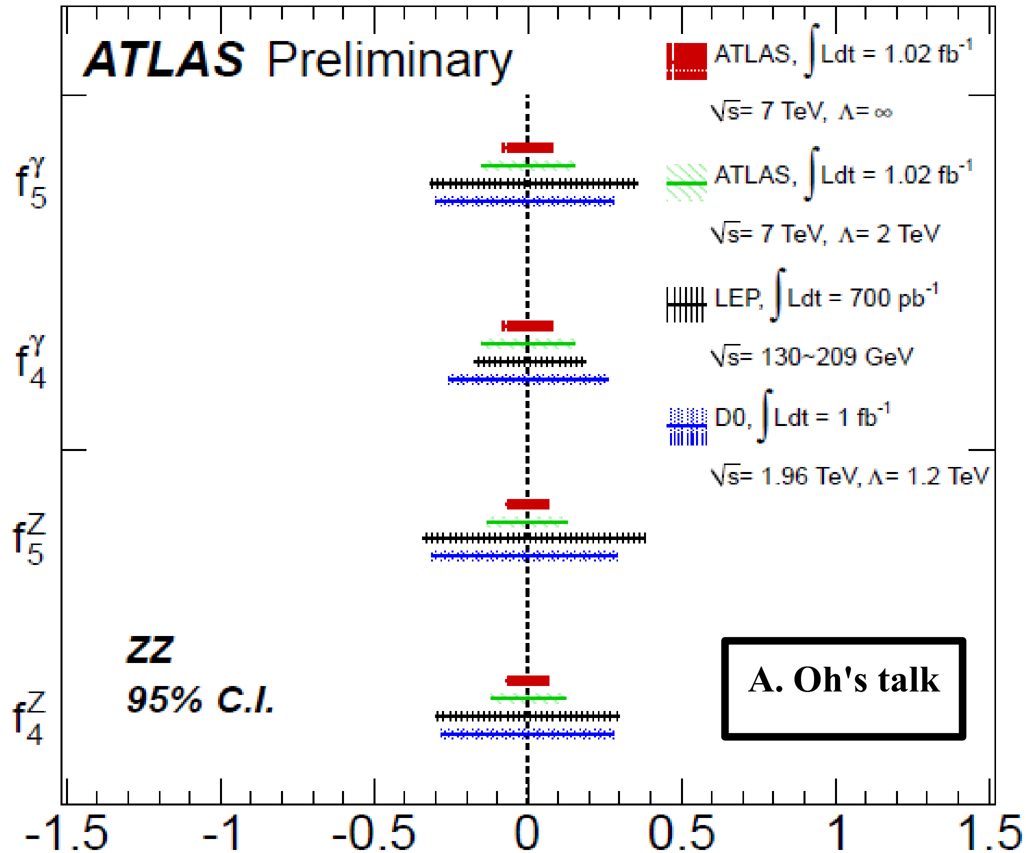
Wγ and Zγ results, anomalous TGC limits (LHC, D0)



Latest stringent TGC limits from Tevatron



Large center-of-mass at LHC pays off (stringent limits on h4 with low statistics)



LHC taking over Tevatron efforts with >1 fb^{-1}:

- Equivalent / larger SM yield
- More sensitivity to new physics scales (effects increasing with √s)

Many more results at EPS11 (uncovered in this talk)

- **W into taus (ATLAS (new))**
- **Comprehensive V+jets studies (LHC, Tevatron, partially covered in the QCD summary by N. Varelas)**
- **CDF Wjj anomaly (CDF, D0, ATLAS, discussed in the New Physics session)**
- **Z+b measurements (ATLAS(new), CDF(new))**
- **W polarization at the LHC (CMS)**
- **Drell-Yan differential distributions as a function of p_T (ATLAS(new))**
- **W mass, asymmetries, width (D0 (2009))**
- **Measurement of $\sin^2\theta_{eff}$ from forward-backward asymmetry (D0 (2011))**
- **W and Z lepton universality tests (ATLAS(new))**

- **Plus other recent LHC results (2011) not shown at EPS11 and many interesting details associated to the analyses shown in this talk**

Summary

- With the data from the first LHC run in 2010, and several fb^{-1} of Tevatron data, hadron collider experiments have provided many physics results from final states containing W and Z boson decays:
  - Precise measurements of inclusive cross sections with boson decays into leptons (electrons, muons and also taus)
  - Detailed studies of differential cross sections in Drell-Yan production (as a function of transverse, rapidity, invariant mass)
  - Precise measurements of different observables (asymmetries, ratios, polarization)
  - Precise measurements of the W mass (Tevatron) and interesting measurements of the effective electroweak mixing angle (Tevatron, CMS)
  - Detailed studies of associated jet production (V+jets) and first results of associated charm and bottom production
  - Measurement of diboson cross sections (WW, WZ, ZZ, Wγ, Zγ) and strong constraints on anomalous triple gauge boson couplings
- Results are in most cases in excellent agreement with theoretical predictions

A successful and necessary step before discoveries

More exciting results expected in a few months with >1 fb^{-1} at the LHC!!