Electroweak results from CMS experiment

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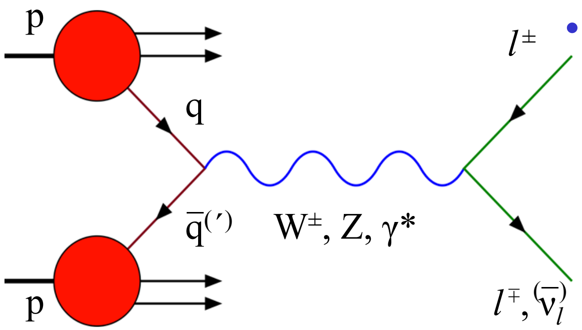
On behalf of CMS collaboration

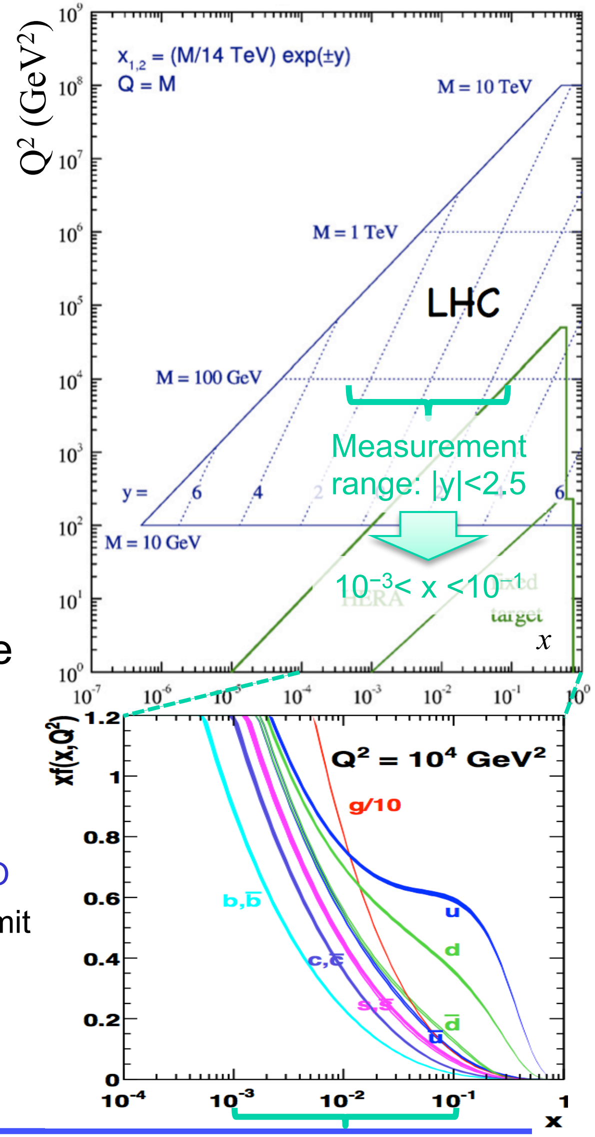
W and Z production at LHC

- W and Z production in pp collisions proceeds mainly form the scattering of a valence quark with a sea anti-quark
- The involved parton fractions are low ($10^{-3} < x < 10^{-1}$) and scattering of a sea quark with a sea anti-quark is also important
- W production is charge asymmetric: $\sigma(W^+)/\sigma(W^-)\sim 1.43$ (< 2, as from valence + sea only) in the Standard Model
- W and Z events produce very clean signals and allow to perform precision measurements
  - Large background control samples are available in data and reduce the need to rely on simulations



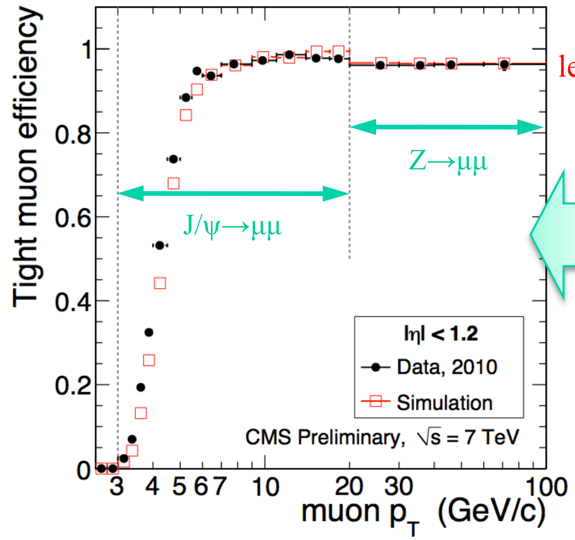
$$Q^2 = m^2_{W,Z} = x_1 x_2 s$$

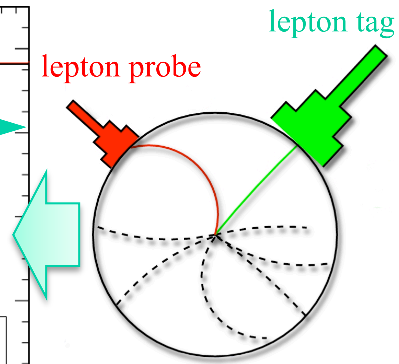
- Accurate theoretical predictions are available
  - NLO event generators: POWHEG and MC@NLO
  - NNLO cross section and differential distributions: FEWZ, RESBOS, DYNNLO
  - Uncertainties in valence and sea PDF limit the accuracy of theoretical predictions
- Differential distributions are sensitive to PDF

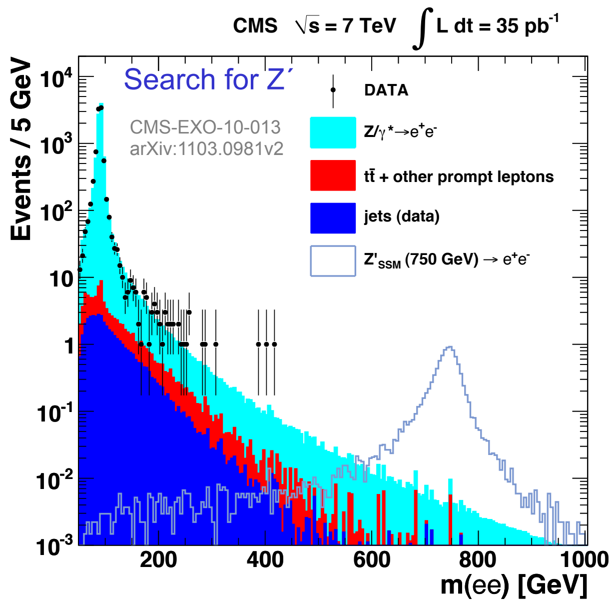


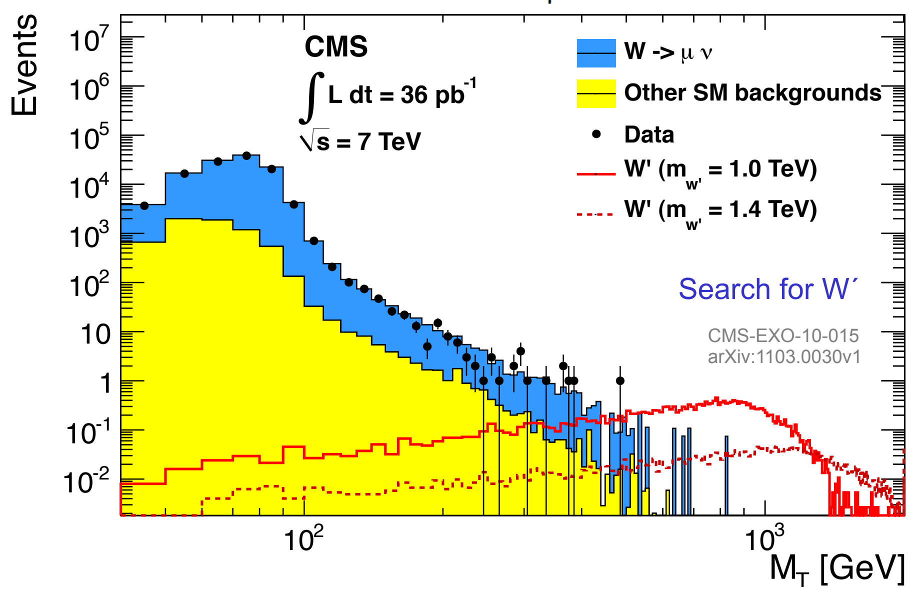
EWK as tool and background

- W and Z are also tools to understand and calibrate the detector
  - Tag and probe method for efficiency measurements
  - Lepton scale and resolution, …
- Many searches have EWK processes as main backgrounds
  - Studying EWK processes means keeping backgrounds under control



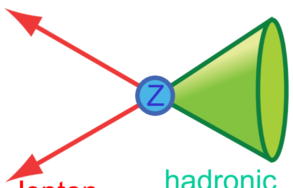


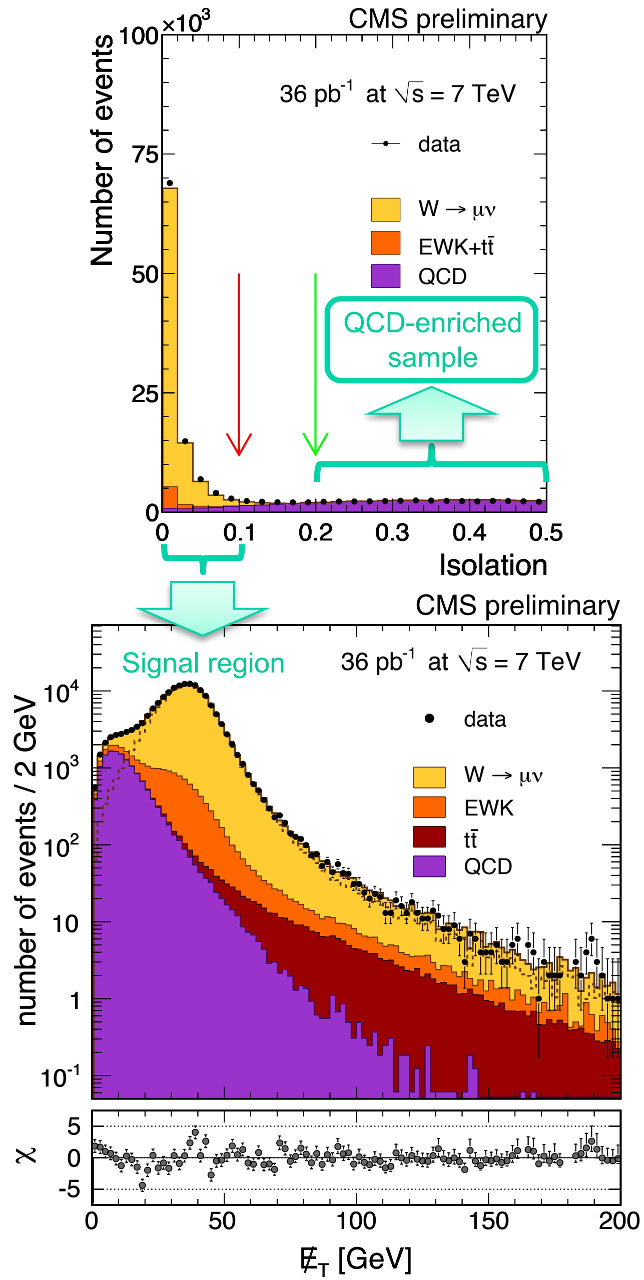




W→$l\nu$ analysis

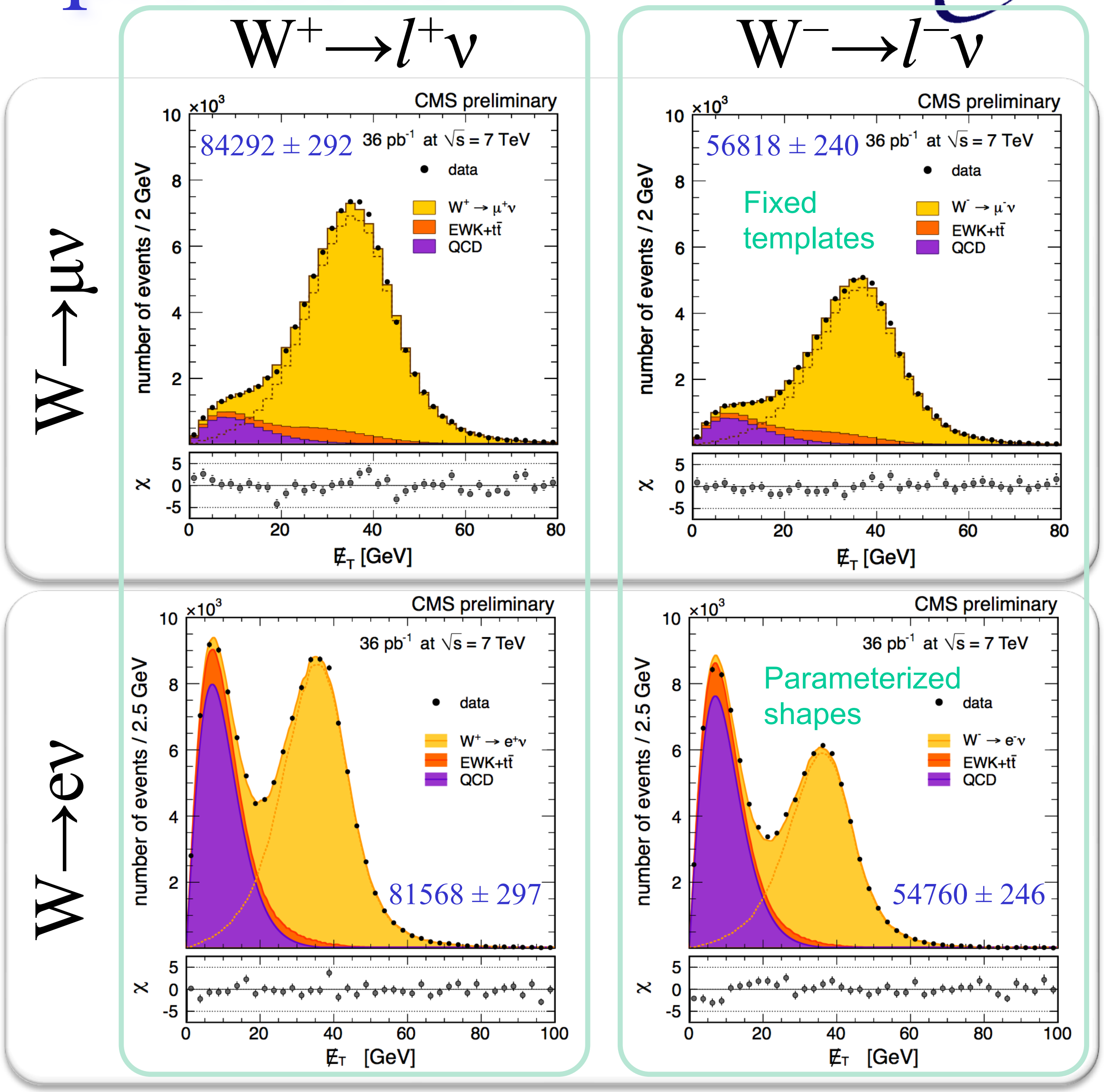
- W event selection is based on:
  - Loose single-lepton trigger
  - Lepton identification cuts, well understood
  - Lepton p_T>25 GeV, η within trigger fiducial volume
  - Isolation: tracker and calorimeter activity within $\Delta R=\sqrt{(\Delta\varphi^2+\Delta\eta^2)}<0.3$, normalized to the lepton p_T
  - Di-lepton veto (no Drell-Yan events)
- Signal extraction
  - W yield from fit to missing E_T distribution
    - Parameterized shapes or fixed binned templates
  - QCD shape determined from data inverting lepton id / isolation selections
  - Lepton efficiencies from Z tag and probe as a function of p_T and η
  - Missing E_T studied using Z recoil
  - Momentum scale and resolution studied from $Z\to l^+l^-$ data





W^+ and W^- production

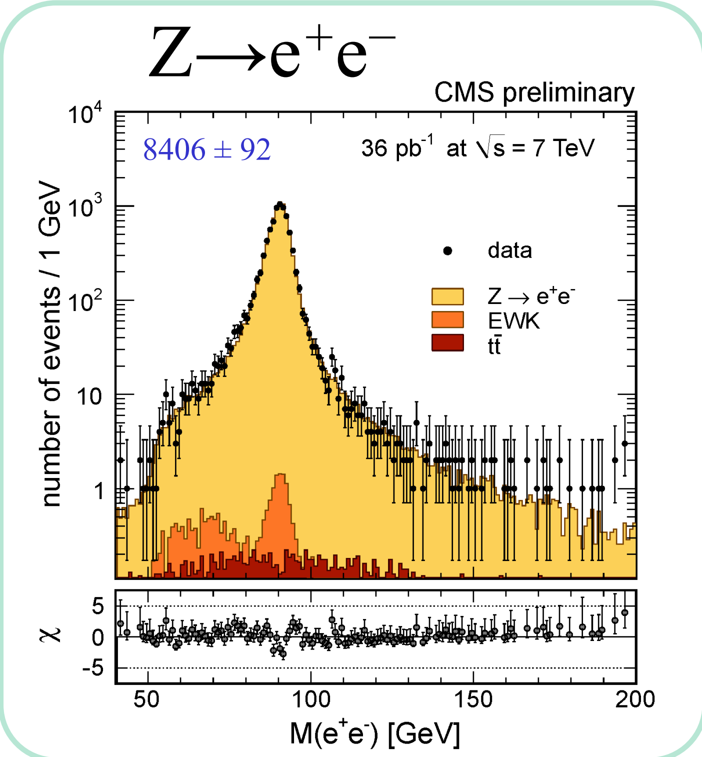
- Fit separately positive and negative lepton missing E_T spectra to extract $\sigma(W^+)$ and $\sigma(W^-)$
- Alternatively, fit simultaneously the total yield and ratio to extract $\sigma(W^\pm)$ and $\sigma(W^+)/\sigma(W^-)$
- In the ratio several uncertainties cancel

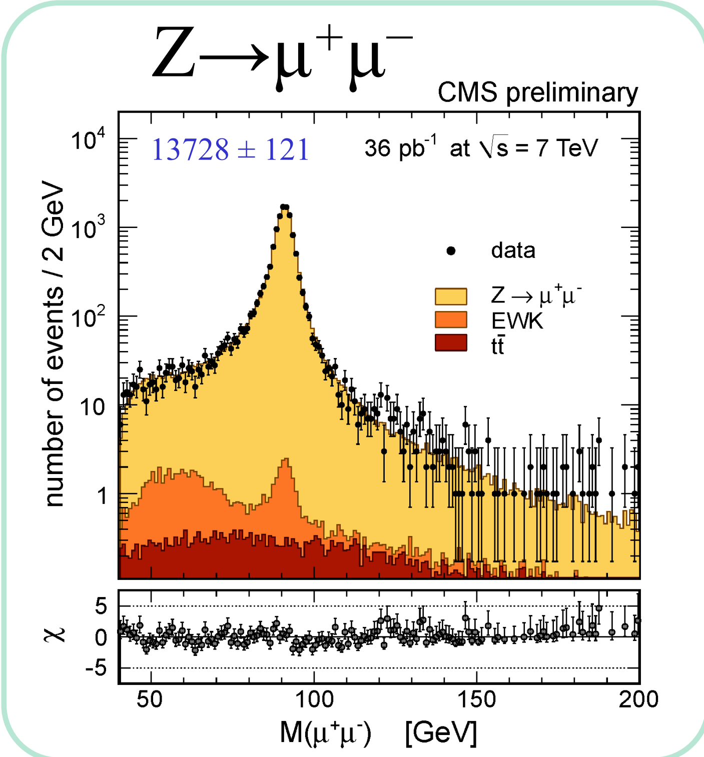


CMS-PAS-EWK-10-005

$Z \to ll$ analysis

- Isolated di-lepton pairs with p_T>20 (μ), 25 GeV (e) and η within trigger fiducial region. Mass range: 60 < m_{ll} < 120 GeV
- Fit simultaneously yield and efficiencies using different di-lepton categories (μμ)
- Cut and count analysis using tag & probe efficiencies (ee)





Systematic uncertainties

- Data-driven methods to determine efficiencies, background and signal shapes allow to reduce experimental uncertainties

$$\sigma \times \mathcal{B} = \frac{N}{A \times \varepsilon \times \mathcal{L}}$$

$$\rho = \frac{\varepsilon_{\rm data}}{\varepsilon_{\rm sim}}$$

Uncert. propagated from Z T&P to W p_T/η spectrum

Lumi. uncert.: 4%

CMS-DPS-11-002

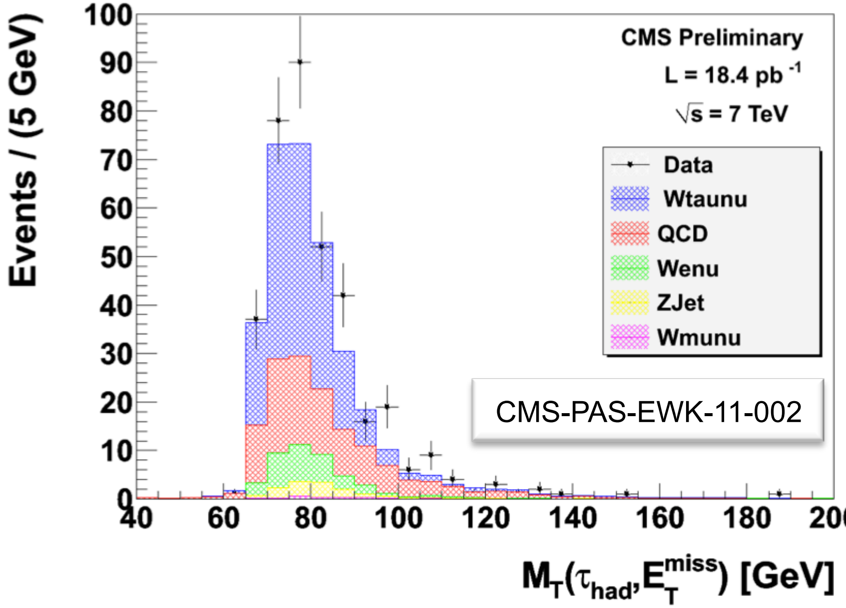
- Theory uncertainties affect acceptance determination:
  - PDF (PDF4LHC: CTEQ, MSTW, NNPDF), Initial-state radiation modeling, higher order effects (RESBOS), EWK corrections, Final-state radiation (HORACE), factorization and renormalization scale (FEWZ)

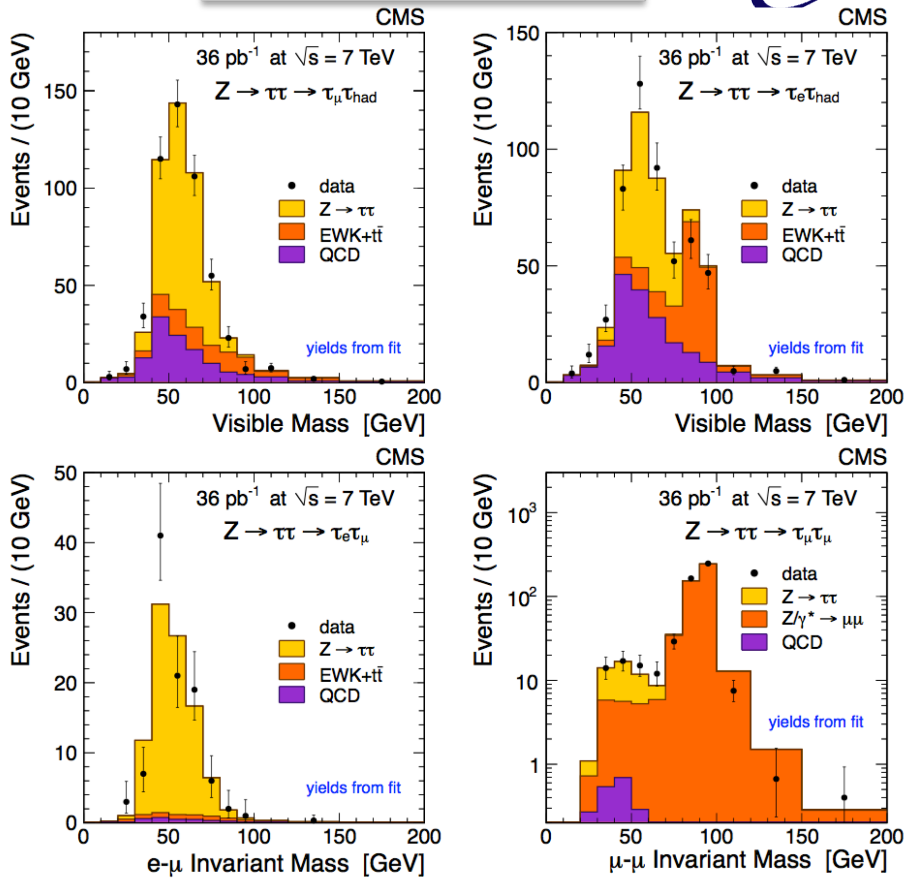
Source	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Lepton reconstruction & identification	1.3	0.9	1.8	n/a
Trigger pre-firing	n/a	0.5	n/a	0.5
Momentum scale & resolution	0.5	0.22	0.12	0.35
$\not\!\!E_T$ scale & resolution	0.3	0.2	n/a	n/a
Background subtraction / modeling	0.35	0.4	0.14	0.28
Total experimental	1.5	1.1	1.8	0.7
PDF uncertainty for acceptance	0.6	0.7	0.9	1.2
Other theoretical uncertainties	0.7	0.8	1.4	1.6
Total theoretical	0.9	1.1	1.7	2.0
Total	1.7	1.6	2.5	2.1

$Z \to \tau\tau$, $W \to \tau\nu$

CMS-PAS-EWK-10-013
arXiv:1104.1617

- Benchmark for searches using taus ($H^+ \to \tau\nu$, $H \to \tau\tau$, …)
- Particle Flow: combine tracker and calorimeter measurements to determine particle candidates
- Main systematic: tau id (23%) fit from data
- Challenging trigger on tau plus missing E_T for $W \to \tau\nu$
  - $p_T(\tau) > 20$ GeV, p_T(track)>15 GeV, missing E_T >25 GeV

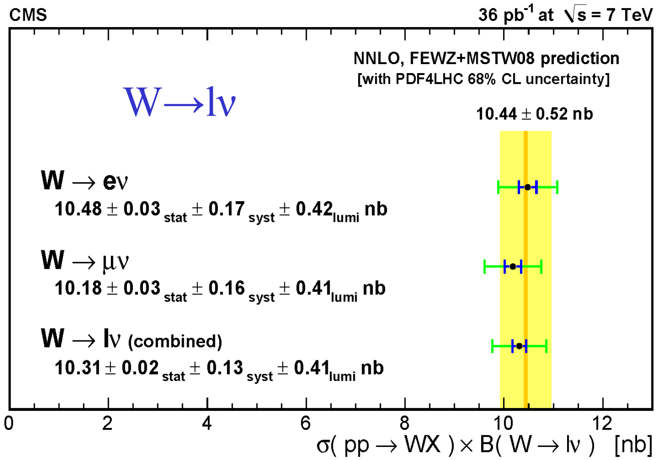


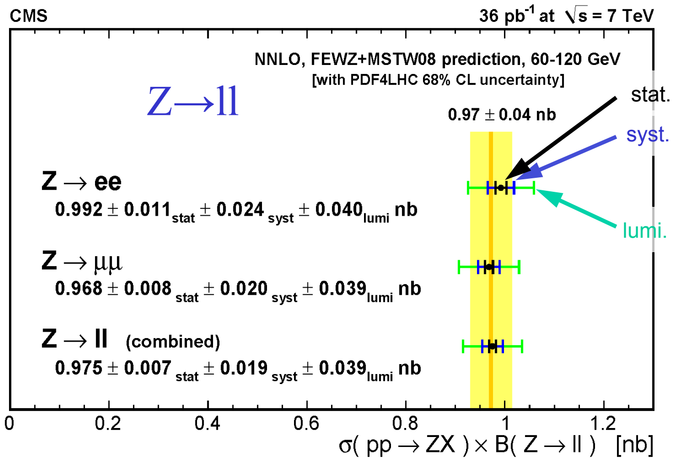


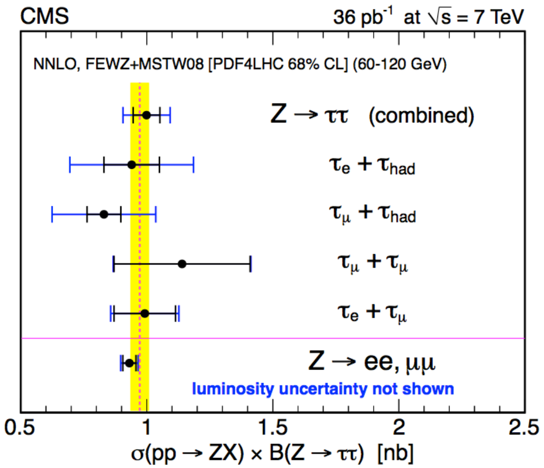
Process	Events
$W \to \tau\nu$ (sim.)	174 ± 3
EWK (sim.)	46 ± 2
QCD (sideband)	109 ± 6
Data	372

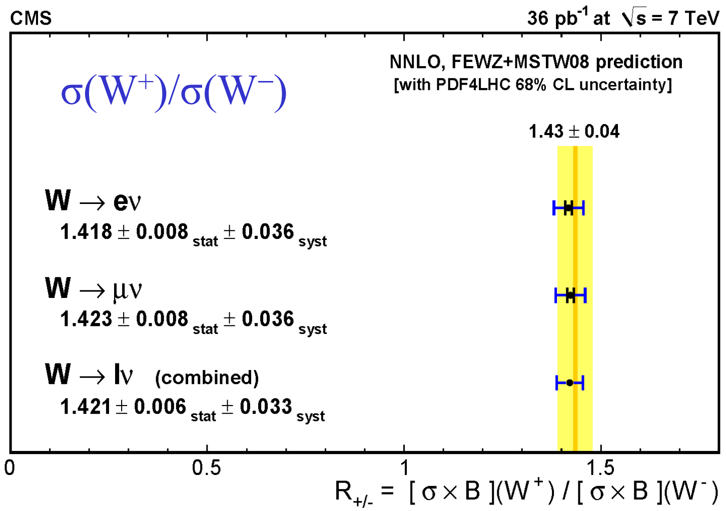
Cesare Calabria, poster on tau physics

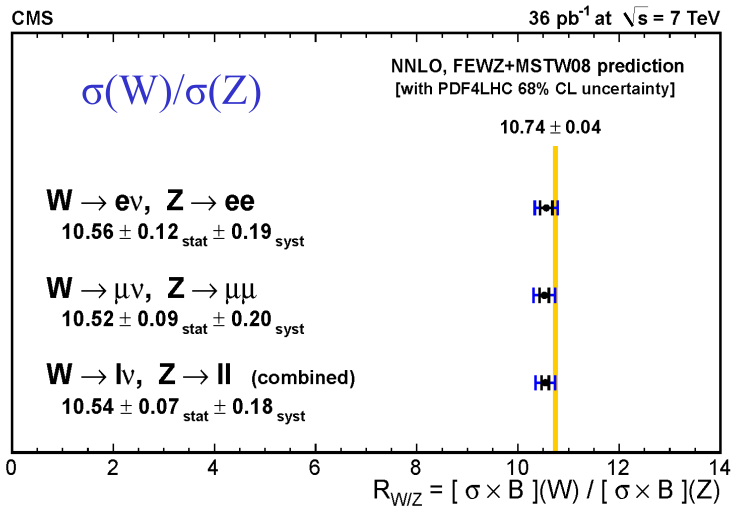
Comparison with theory





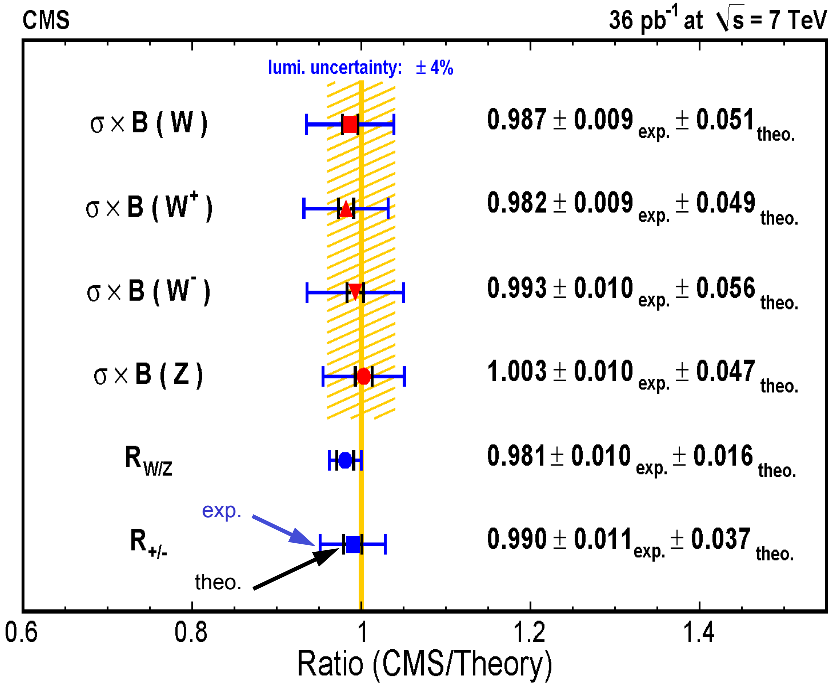


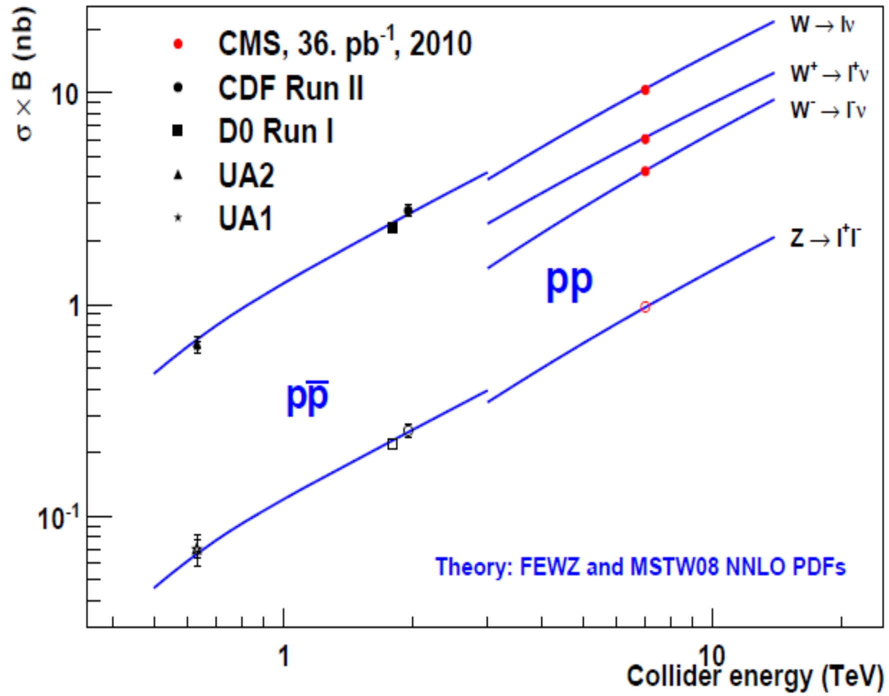




- Ratios are not affected by luminosity uncertainty
- W^+/W^- potentially sensitive to PDF, W/Z has precise prediction

More comparison with theory





- Good overall agreement with theory predictions at NNLO

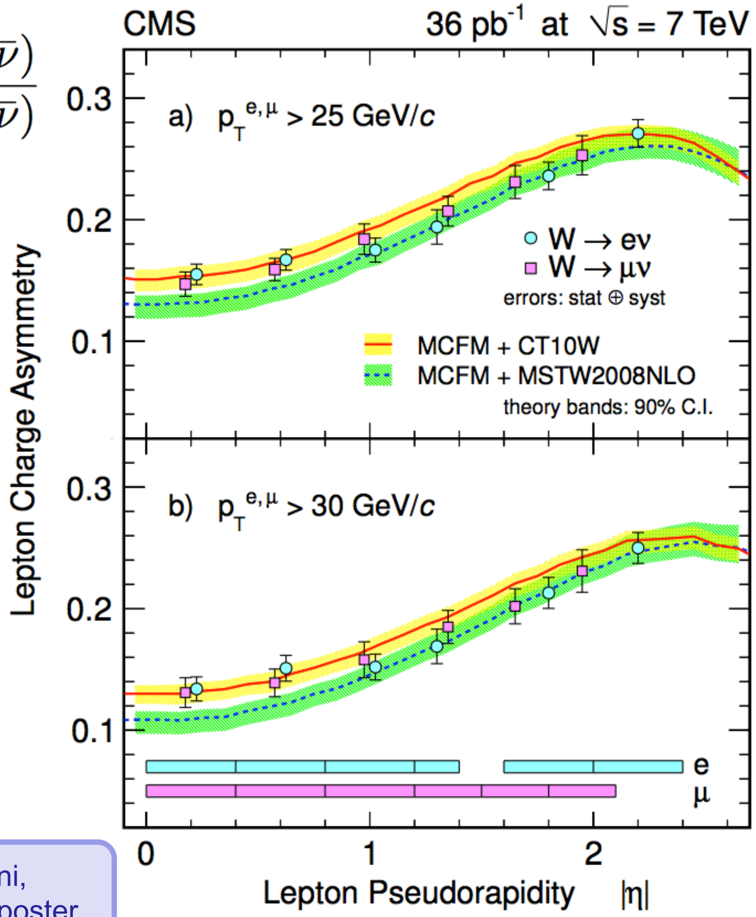
W charge asymmetry

JHEP04 (2011) 050

- W^+/W^- ratio measured as a function of the lepton pseudorapidity η
- Sensitive to PDF; several uncertainties cancel in the ratio

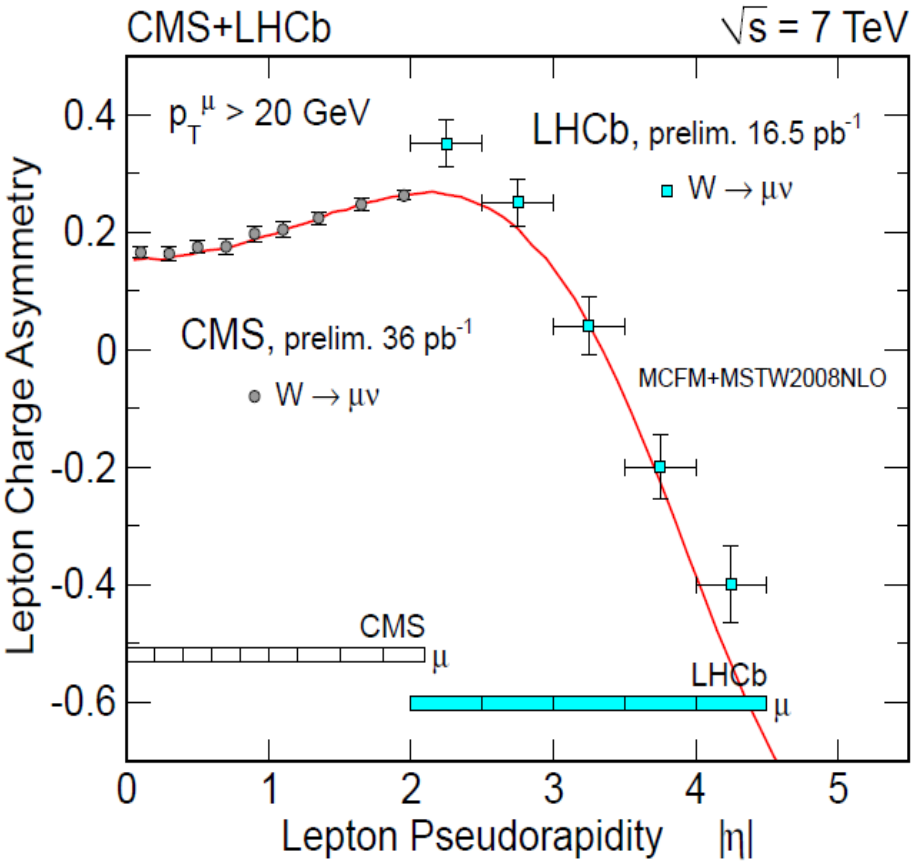
$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$

- Similar selection to inclusive cross section analysis
- Two p_T thresholds (25, 30 GeV) to probe different phase space regions
- Charge mis-id: 0.1(barrel)-0.4(endcap)% for electrons, $<10^{-4}$ for muons
- Systematic uncertainties (<1.6%) can be improved with increasing size of Drell-Yan data sample
  - Separate efficiency estimates for + and − leptons
  - p_T scale and resolution
  - Background and signal modeling

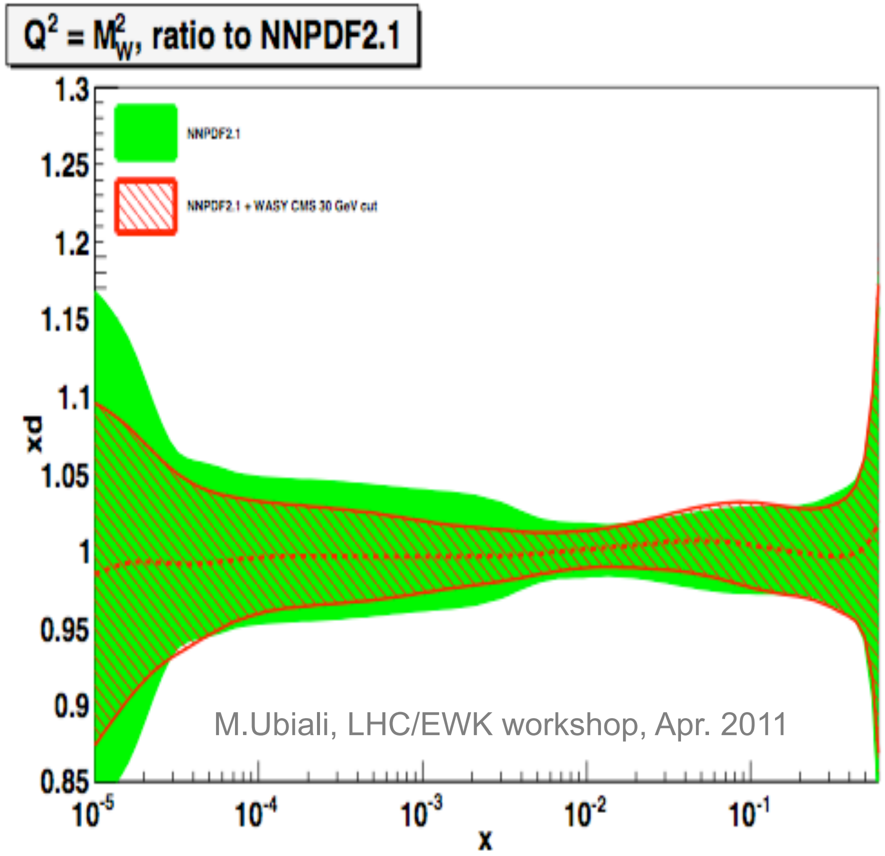


Silvia Taroni, dedicated poster

CMS ad LHCb measurements



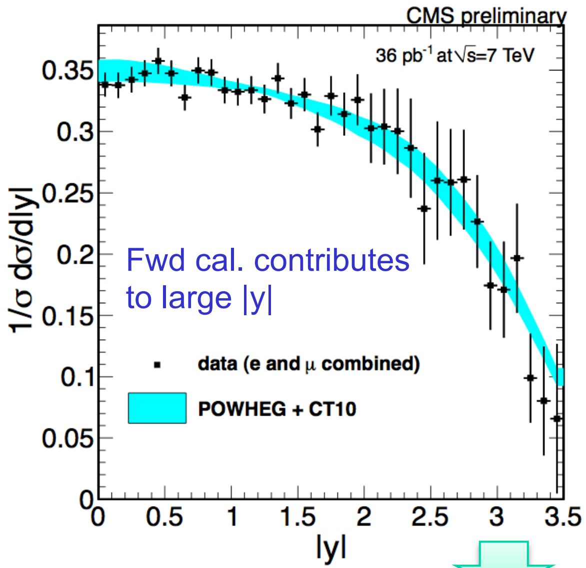
CMS complementary w.r.t. LHCb



CMS results already improve PDFs by >40% in the range $10^{-3} < x < 10^{-2}$

Z differential cross section

- Large statistics allows to study differential cross sections vs y and p_T
- compared to theory after an unfolding procedure correcting for resolution and final-state radiation

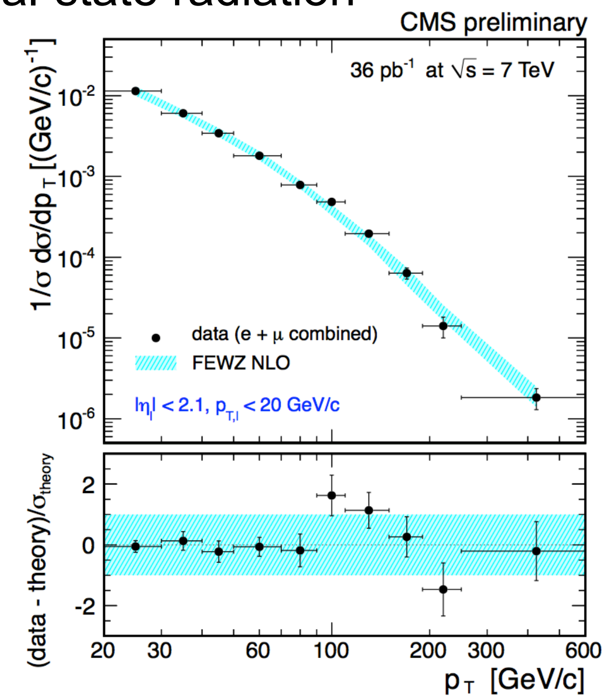


$$x = \frac{m_Z}{\sqrt{s}} e^{\pm y}$$

$x < 10^{-3}$

Sensitive to PDF at low x

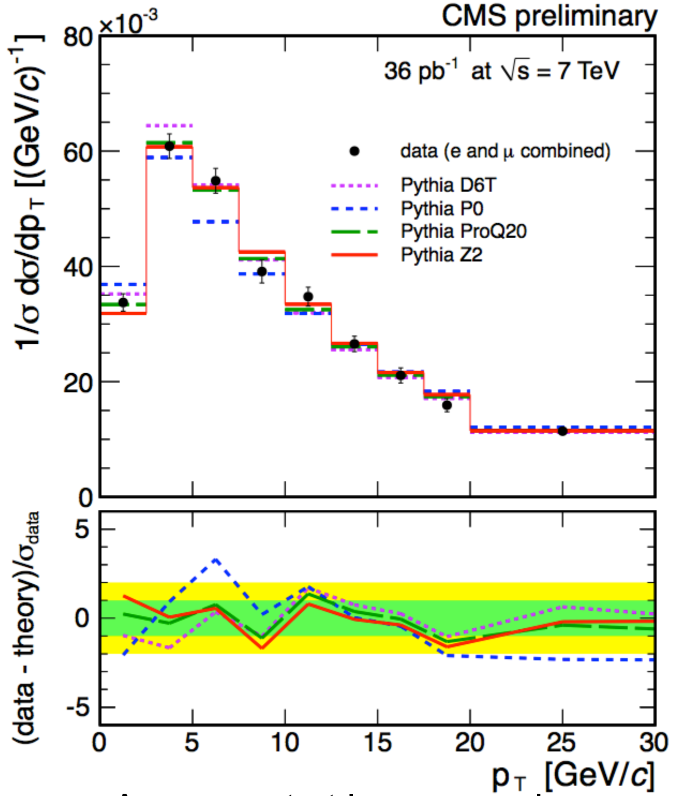
CMS-PAS-EWK-10-010



Good agreement with FEWZ prediction (NNLO) at high p_T

Perturbative contributions dominate

FSR unfolded, not included in FEWZ

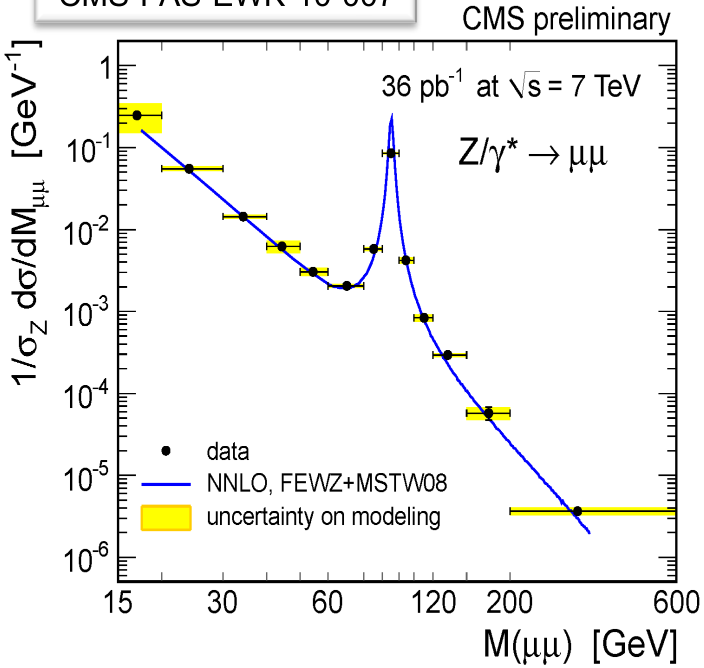


Agreement at low p_T requires PYTHIA tuning

Non-perturbative contributions

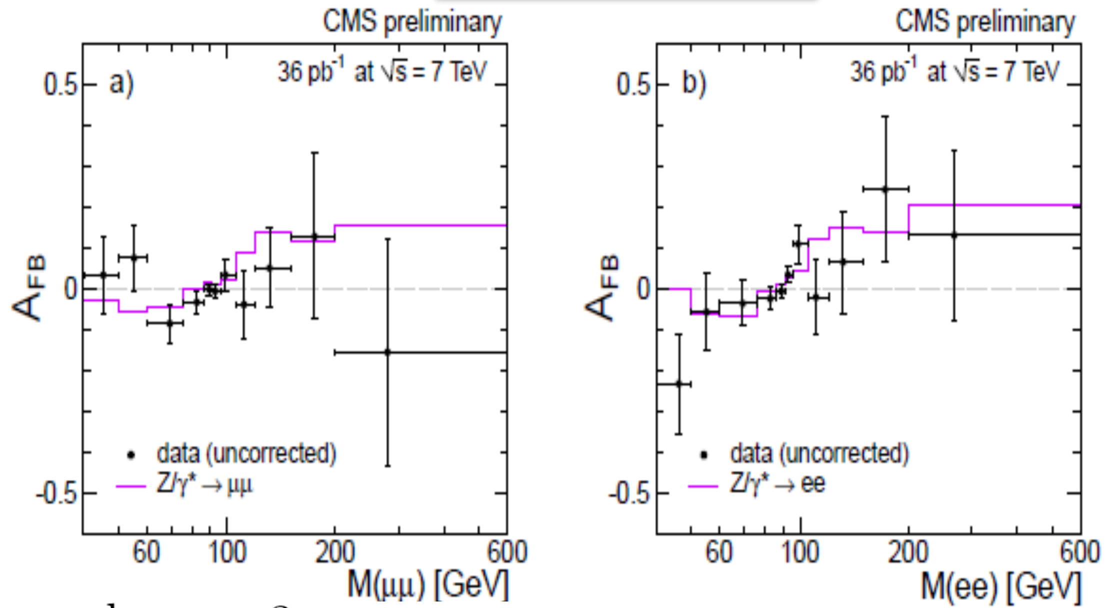
Drell-Yan, $\sin^2\theta_W$

CMS-PAS-EWK-10-007



Unfolded distribution, corrected for acceptance, efficiency and FSR effects (not included in FEWZ)

CMS-PAS-EWK-10-011

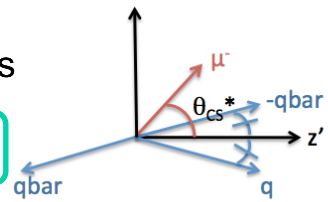


$$\frac{d\sigma}{d\cos\theta} = \frac{3}{8}(1+\cos^2\theta) + A_{FB}\cos\theta$$

Collins-Soper frame adopted[*]

$$\cos\theta^*_{CS} = \frac{2(P_1^+P_2^- - P_1^-P_2^+)}{\sqrt{Q^2(Q^2+Q_T^2)}}$$

More precise measurement also using y and m^2 of the di-muon pair distributions



Hwi Dong Yoo, Tuesday: talk on W, Z production, asymmetry and diff. cross sections

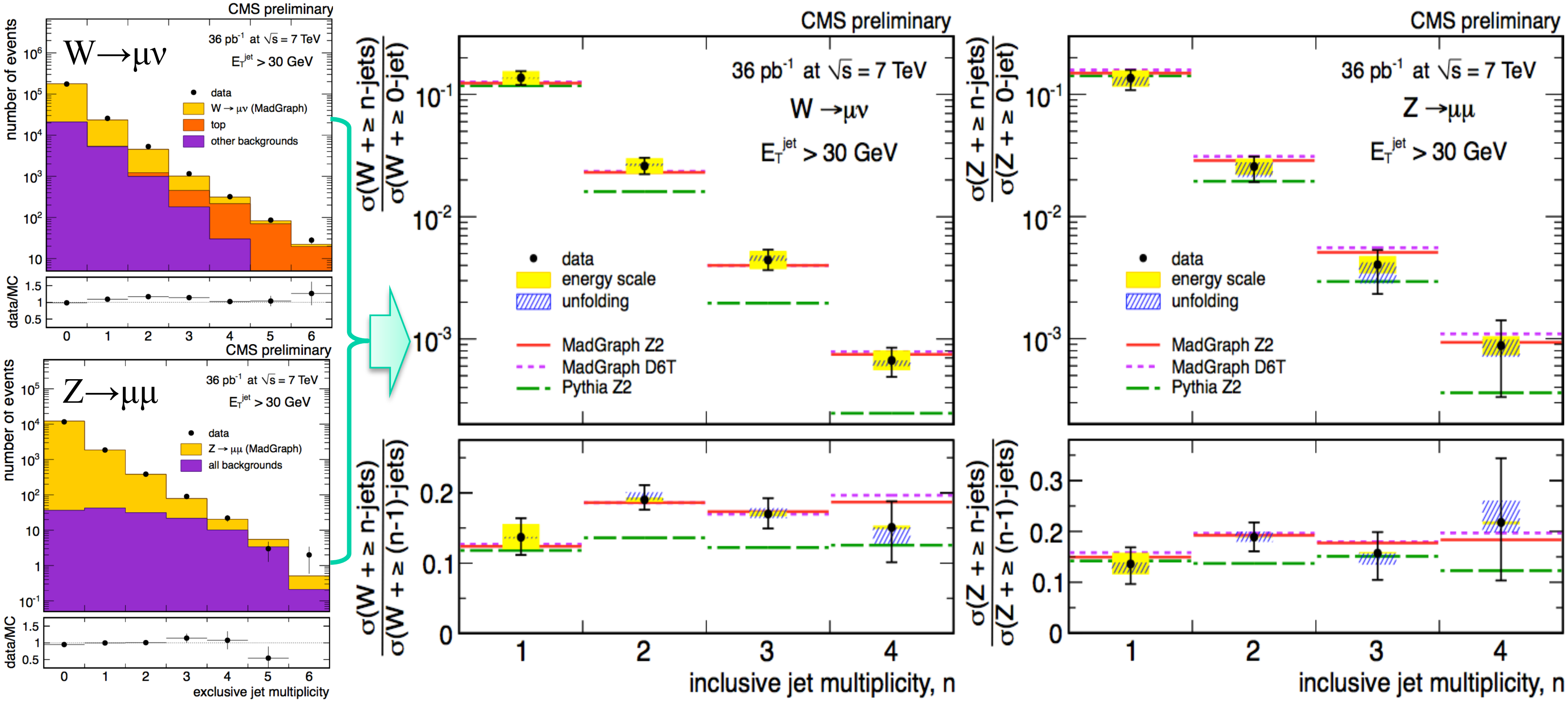
$$\sin^2\theta_{\text{eff}} = 0.2287 \pm 0.0077(\text{stat.}) \pm 0.0036(\text{syst.})$$

[*] CS frame: Z rest frame in which the z axis bisects p_1, $-p_2$, p_1 and p_2 being the incoming quark and anti-quark momenta

W, Z + *n* jets

CMS-PAS-EWK-10-012

- Important test of perturbative NLO predictions and background to Higgs and many searches
- Jets reconstructed from Particle Flow using anti-k_T algorithm (R=0.5), E_T > 30 GeV
- Systematics dominates, mainly due to energy scale and unfolding for large *n* (Singular Value Decomposition, assuming MadGraph jet migration from particle-level jets)
- Agreement with MadGraph, discrepancies with Pythia observed



W, Z + n jets scaling

- Berends-Giele scaling:

$$\frac{\sigma(V+\geq n-\text{jets})}{\sigma(V+\geq (n+1)-\text{jets})} = \alpha + \beta \times n$$

- Expected ~ constant with n

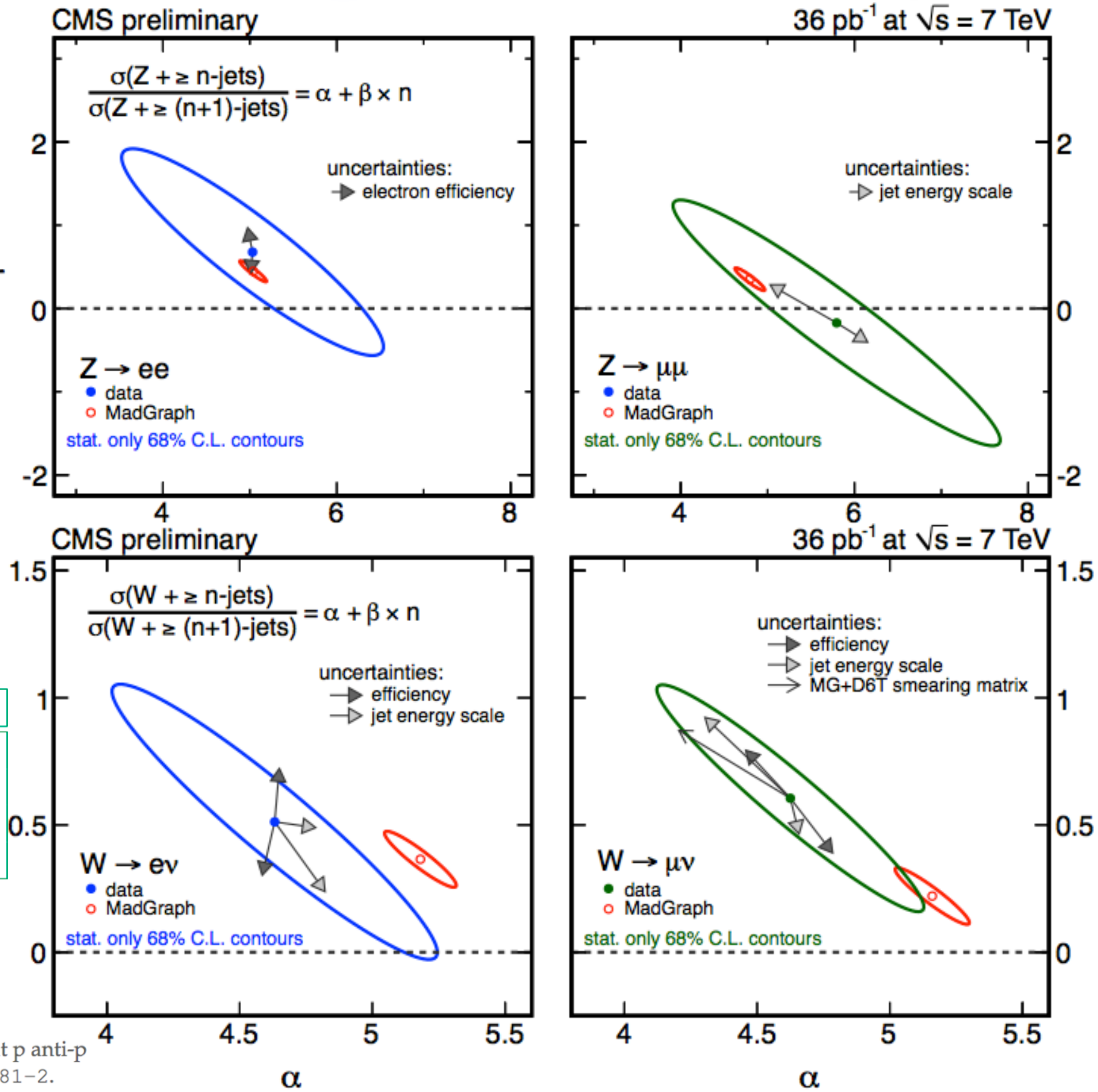
electrons

		data	stat	JES	$\epsilon(\ell)$	Theory
Z	α	5.0	± 1.0	$^{+0.1}_{-0.0}$	$^{+0.00}_{-0.06}$	5.04 ± 0.10
	β	0.7	± 0.8	$^{+0.08}_{-0.04}$	$^{+0.3}_{-0.6}$	0.45 ± 0.08
W	α	4.6	± 0.4	$^{+0.2}_{-0.0}$	$^{-0.05}_{+0.02}$	5.18 ± 0.09
	β	0.5	± 0.4	$^{+0.0}_{-0.3}$	± 0.2	0.36 ± 0.07

muons

		data	stat	JES MC	$\epsilon(\ell)$	D6T tune	Theory
Z	α	5.8	$\pm$ 1.2	$\pm$0.6	$\pm$0.1	+0.3	4.8 ± 0.1
	β	-0.2	$\pm$ 1.0	$\pm$0.3	$\pm$0.1	-0.0	0.35 ± 0.09
W	α	4.3	$\pm$0.3	$\pm$0.2	$\pm$0.2	-0.4	5.16 ± 0.09
	β	0.7	$\pm$0.3	$\pm$0.2	$\pm$0.3	+0.3	0.22 ± 0.06

Will Reece, dedicated talk on Thursday

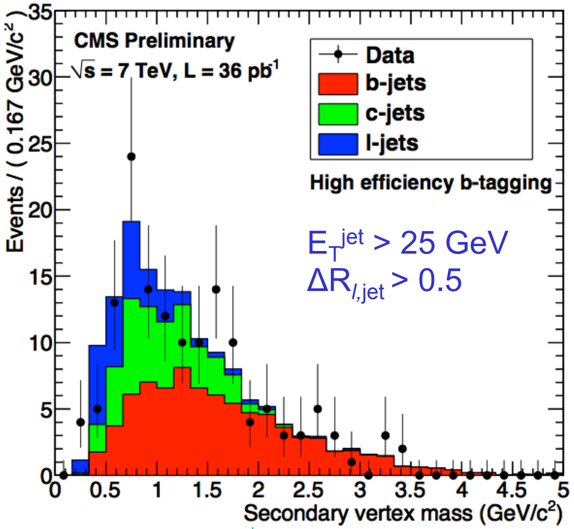


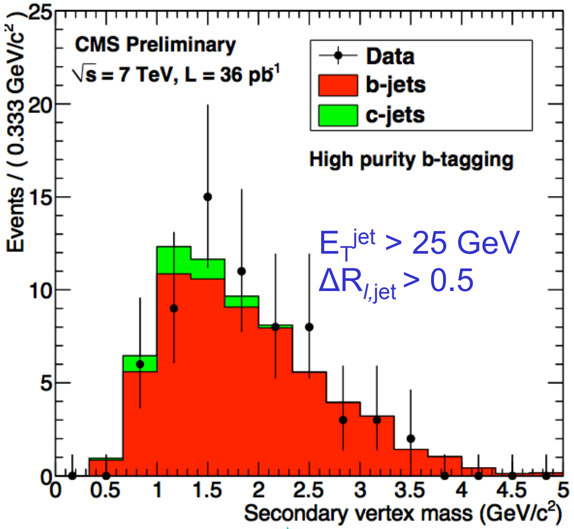
F. A. Berends, W. T. Giele, H. Kuijf et al., "Multi-jet production in W, Z events at p anti-p colliders", *Phys. Lett.* **B224** (1989) 237. doi:10.1016/0370-2693(89)91081-2.

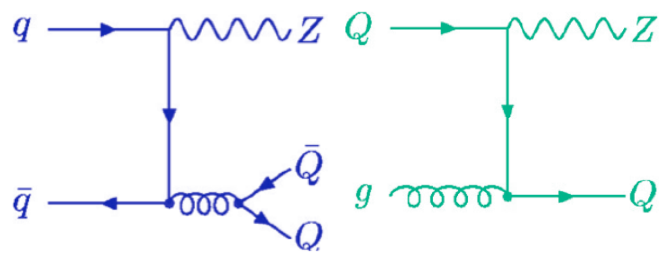
Z+b jets

CMS-PAS-EWK-10-015

- Two production mechanism: b pair produced from $q\bar{q}$, gg scattering ("fixed flavour"), or single b quark at partonic level ("variable flavour")
- Selection: two isolated leptons forming a Z, no missing E_T (top veto), b-tagging (lifetime)
- B-tagging purity determined from template fit to the distribution of the invariant mass of tracks associated to the secondary vertex







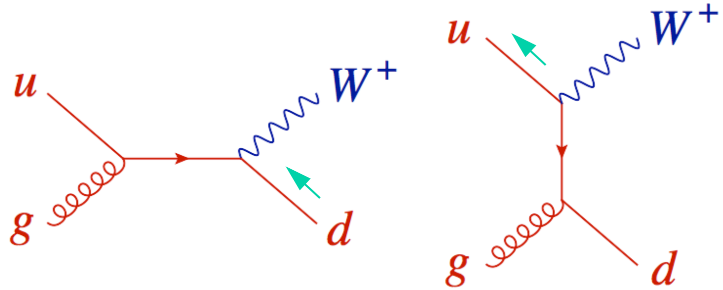
$$\mathcal{R} = \frac{\sigma(pp \to Z+b+X)}{\sigma(pp \to Z+j+X)}$$

Results are in agreement with theory within uncertainties (including theory)

Sample	$\mathcal{R}(Z \to ee)$ (%), $p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 2.5$	$\mathcal{R}(Z \to \mu\mu)$ (%), $p_T^\mu > 20$ GeV, $\lvert\eta^\mu\rvert < 2.1$
Data HE	$4.3 \pm 0.6(stat) \pm 1.1(syst)$	$5.1 \pm 0.6(stat) \pm 1.3(syst)$
Data HP	$5.4 \pm 1.0(stat) \pm 1.2(syst)$	$4.6 \pm 0.8(stat) \pm 1.1(syst)$
MADGRAPH	$5.1 \pm 0.2(stat) \pm 0.2(syst) \pm 0.6(theory)$	$5.3 \pm 0.1(stat) \pm 0.2(syst) \pm 0.6(theory)$
MCFM	$4.3 \pm 0.5(theory)$	$4.7 \pm 0.5(theory)$

W polarization in W+jets

- V-A W-quark coupling imposes L-polarized quarks ($m_q \approx 0$), high W p_T imply large W f_L, the exact value depending on amounts of different contributions
- Important for searches beyond SM with signals having different W polarization / lepton distributions
- Polarization should be measured in the W rest frame (experimentally inaccessible):

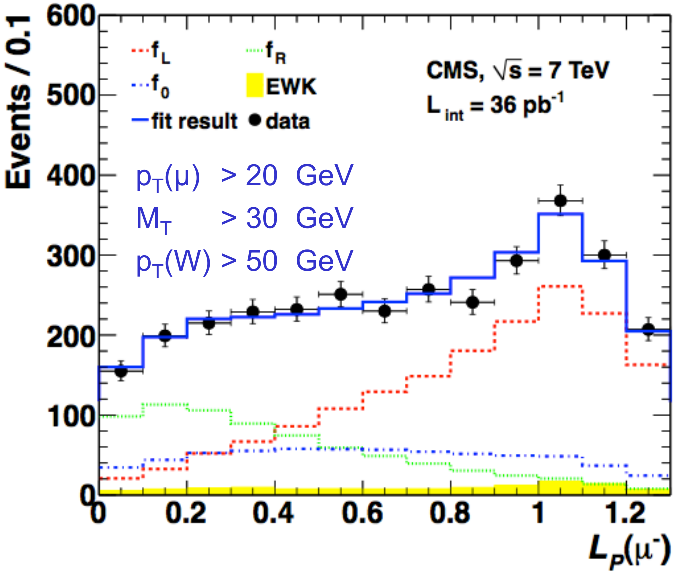


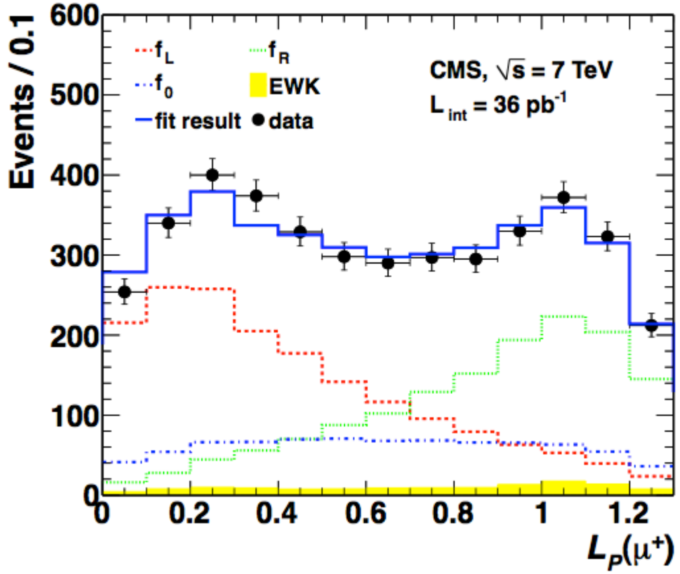
$$\frac{d\Gamma}{\Gamma d\cos\theta^*} = \frac{3}{8}\left[f_R(1+\cos\theta^*)^2 + f_L(1-\cos\theta^*)^2\right] + \frac{3}{4} f_0 \sin^2\theta^*$$

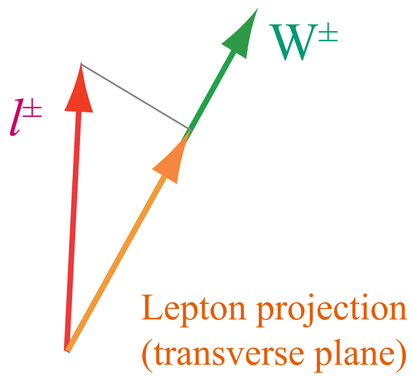
$$f_R + f_L + f_0 = 1$$

- Using lepton projection instead

$$L_P = \frac{\vec{p}_T(l)\cdot\vec{p}_T(W)}{|\vec{p}_T(W)|^2} \simeq \frac{1+\cos\theta^*}{2}$$





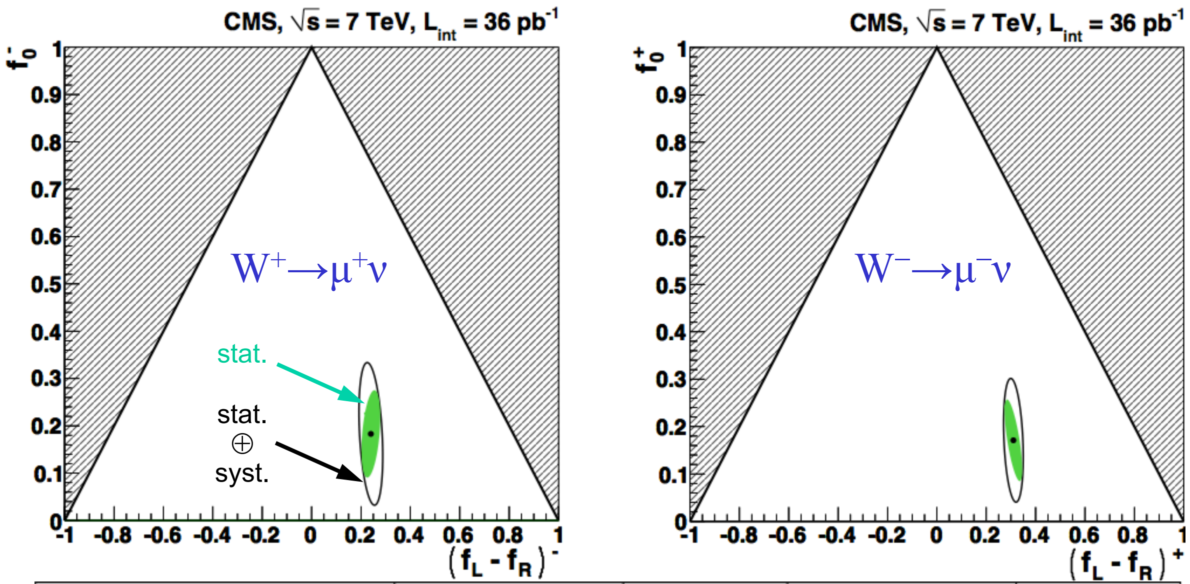


W p_T as lepton plus missing E_T

W polarization results

- More precise measurement with muons
  - smaller background: ~250 / 14000

CMS-PAS-EWK-10-014
arXiv:1104.3829 (→PRL)

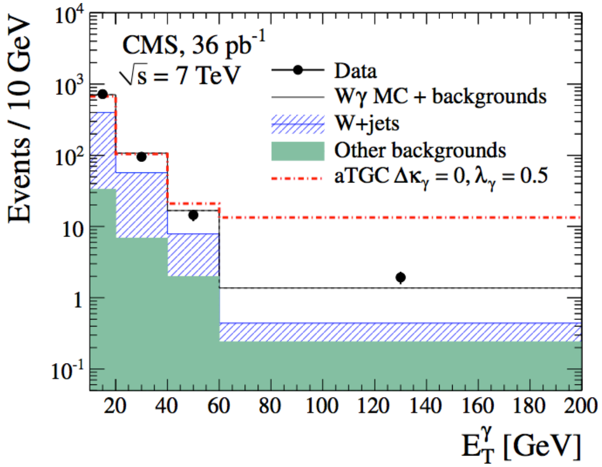


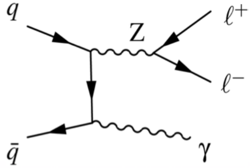
Uncertainty	$(f_L - f_R)^-$	f_0^-	$(f_L - f_R)^+$	f_0^+
	Muon channel			
Recoil energy scale	±0.029	±0.123	±0.011	±0.092
Recoil resolution	±0.012	±0.006	±0.012	±0.004
Muon scale	±0.002	±0.007	±0.004	±0.008
Total uncertainty	±0.031	±0.123	±0.017	±0.099

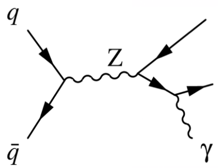
W, Z + γ

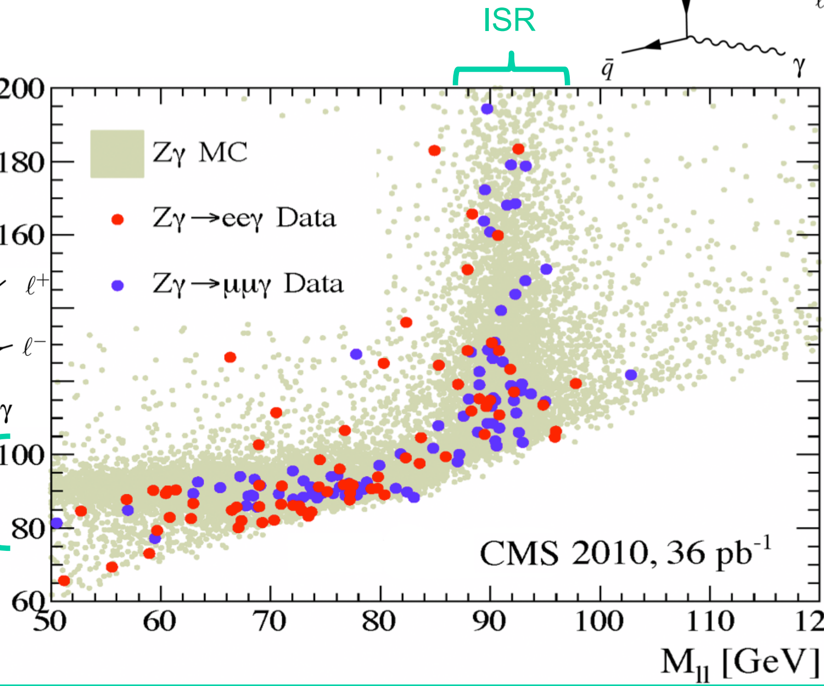
CMS-PAS-EWK-10-008
arXiv:1105.2758

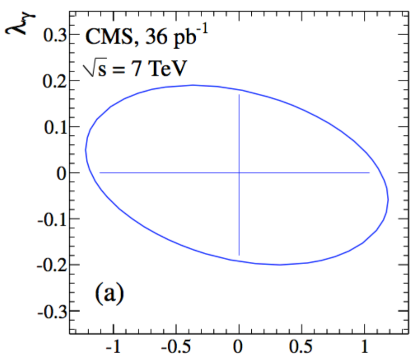
- Final state common to new physics searches, probes triple gauge coupling
- Fake photon estimate is a key task, performed with data-driven methods

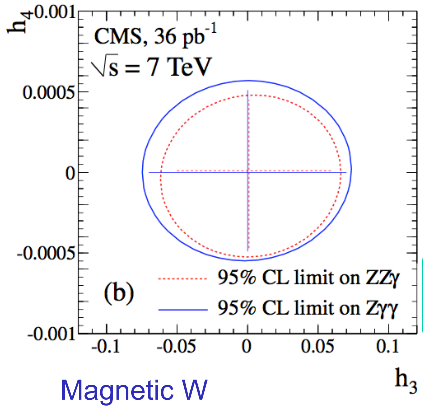












$$\sigma(\text{pp} \to \text{W}\gamma + \text{X}) \times \mathcal{B}(\text{W} \to \ell\nu) = 56.3 \pm 5.0(\text{stat.}) \pm 5.0(\text{syst.}) \pm 2.3(\text{lumi.})\ \text{pb}$$

$$\sigma(\text{pp} \to \text{Z}\gamma + \text{X}) \times \mathcal{B}(\text{Z} \to \ell\ell) = 9.4 \pm 1.0(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.4(\text{lumi.})\ \text{pb}$$

$E_T^\gamma > 10$ GeV, $\Delta R(\gamma, \ell) > 0.7$

$$\mu_W = \frac{e}{2M_W}(2 + \Delta\kappa_\gamma + \lambda_\gamma)$$

Magnetic W dipole mom.

$$Q_W = -\frac{e}{M_W^2}(1 + \Delta\kappa_\gamma - \lambda_\gamma)$$

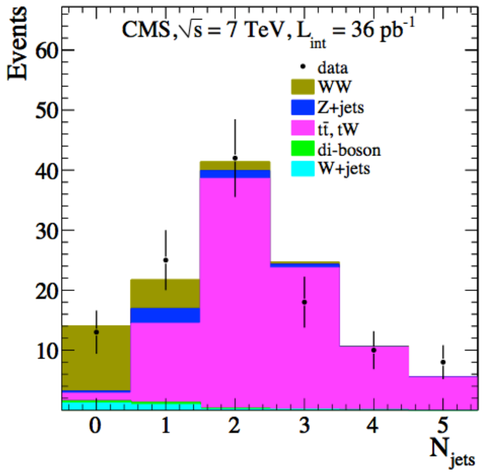
Electric W quadrupole mom.

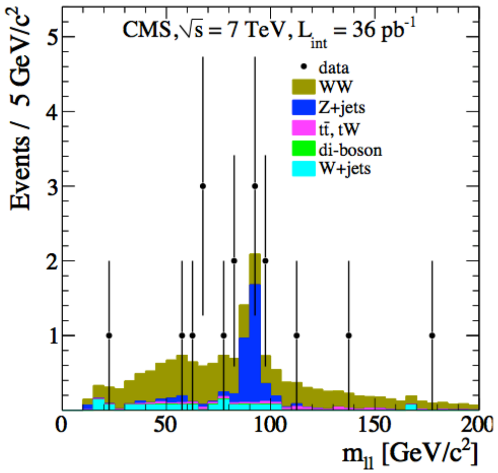
Armando Lanaro, talk on di-bosons (Vγ, WW) Thursday

WW production

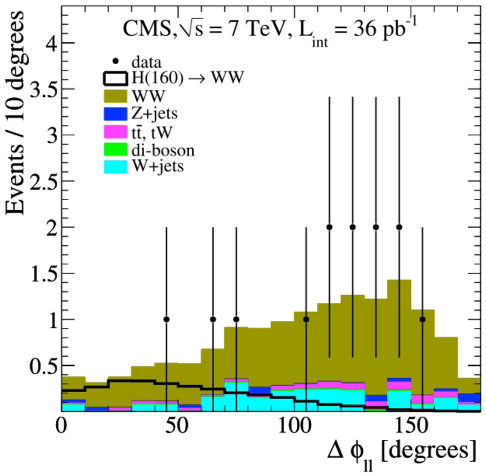
Phys. Lett. B 699 (2011) 25

- Challenging analysis, benchmark for H→WW search
- Limits to anomalous WWγ and WWZ couplings set





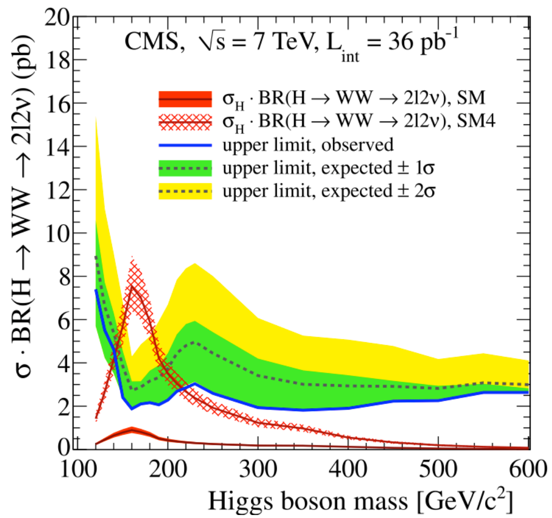
- Using W decays to electrons and muons (W→τν signal also included)
- Drell-Yan vetoed (missing E_T required, di-leptons mass far from Z peak)
- Z→ττ suppressed: missing E_T projection transverse to closest leptons > 35 GeV
- Top quark veto using number of jets, also using soft muon and b-tagging veto



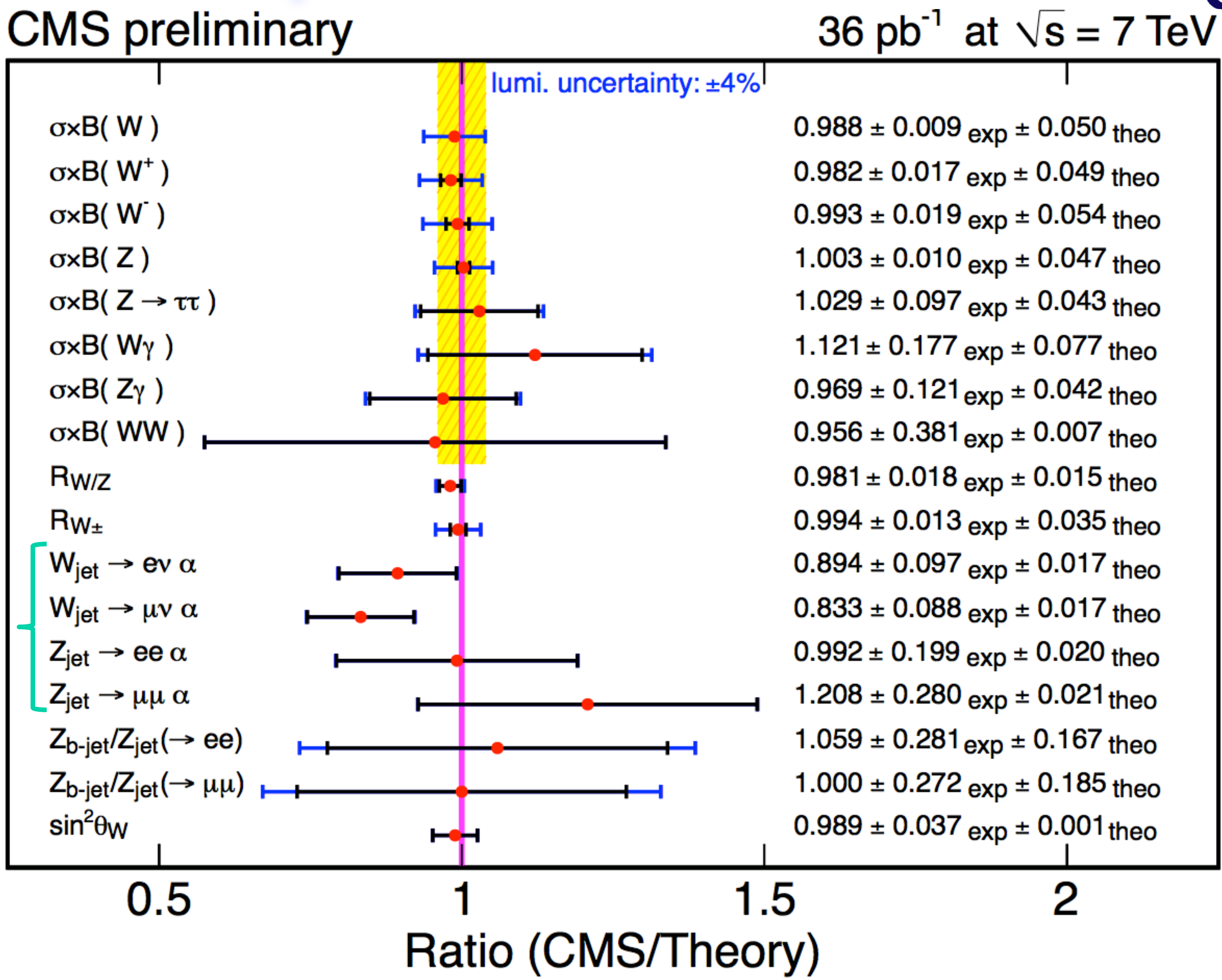
- 13 events selected against a background estimate of 3.3 ± 1.2

$$\sigma(WW) = 41.1 \pm 15.3(\text{stat}) \pm 5.8(\text{syst}) \pm 4.5\ (\text{lumi})$$

- Spin correlation used for a Higgs analysis
- Search for H→WW and limits to Higgs production with a fourth generation
  - Enhanced cross section



Summary of CMS EW results



$$\frac{\sigma(V + \geq n - \text{jets})}{\sigma(V + \geq (n+1) - \text{jets})} = \alpha + \beta \times n$$

Conclusions

- CMS produced many EWK measurements with the first 36 pb^{-1} of LHC data at 7 TeV
- Precision measurements of inclusive W and Z production cross section with large statistics
- Detailed studies of differential cross sections and many observables, like asymmetry
- W and Z production associated to jets, including Z plus b-jets, studied W polarization in W+jets
- Di-boson production: Wγ, Zγ, WW
- All measurements are so far in agreement with theoretical predictions from the standard model

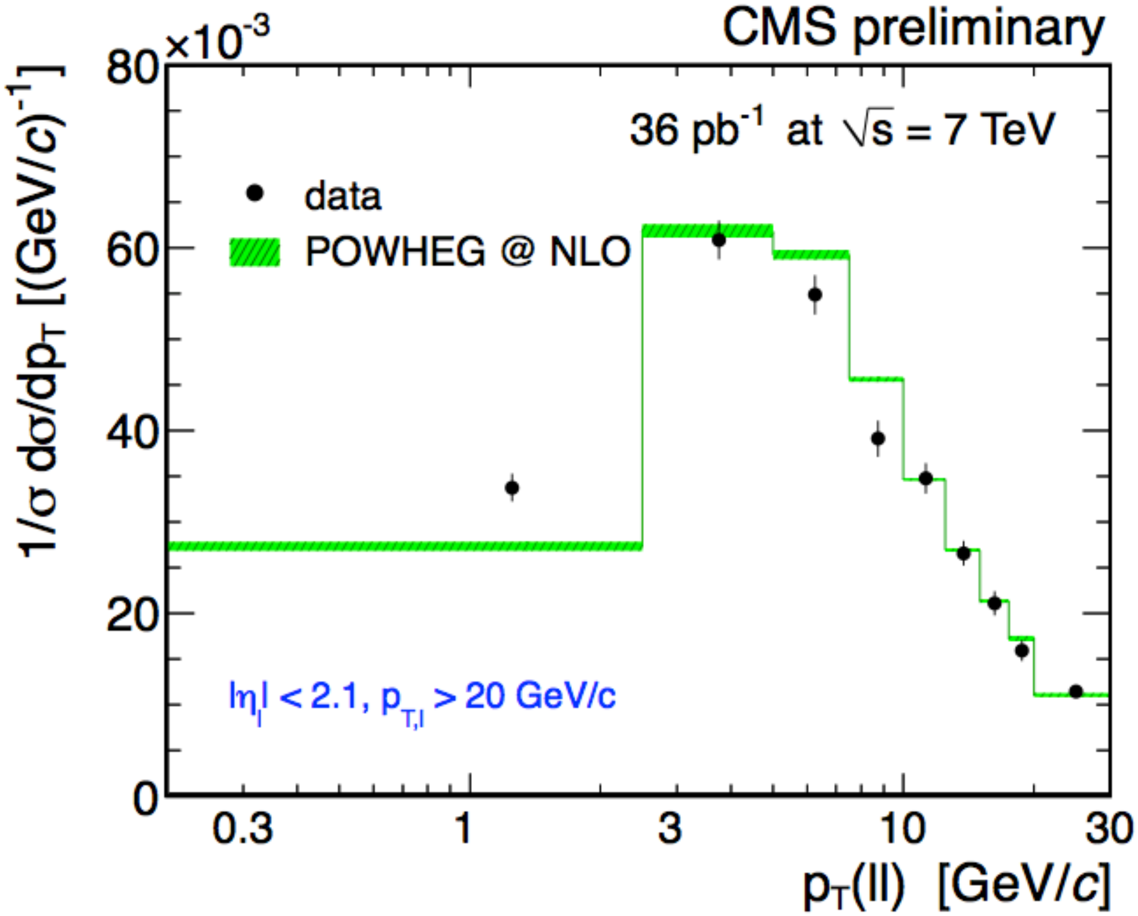
Backup

W charge asymmetry systematics

$p_T^\ell > 25\,\mathrm{GeV}/c$												
	Electron Channel						Muon Channel					
$\lvert\eta\rvert$ bin	[0.0, 0.4]	[0.4, 0.8]	[0.8, 1.2]	[1.2, 1.4]	[1.6, 2.0]	[2.0, 2.4]	[0.0, 0.4]	[0.4, 0.8]	[0.8, 1.2]	[1.2, 1.5]	[1.5, 1.8]	[1.8, 2.1]
Charge Misident.	0.02	0.03	0.03	0.08	0.09	0.10	0	0	0	0	0	0
Eff. Ratio	0.70	0.70	0.70	0.70	0.70	0.70	0.59	0.39	0.92	0.72	0.81	1.17
e/μ Scale	0.11	0.09	0.19	0.47	0.40	0.45	0.50	0.48	0.50	0.48	0.50	0.42
Sig. & Bkg. Estim.	0.16	0.19	0.26	0.33	0.25	0.25	0.23	0.29	0.34	0.40	0.53	0.58
Total	0.73	0.73	0.77	0.90	0.85	0.87	0.80	0.68	1.10	0.95	1.08	1.37
$p_T^\ell > 30\,\mathrm{GeV}/c$												
	Electron Channel						Muon Channel					
$\lvert\eta\rvert$ bin	[0.0, 0.4]	[0.4, 0.8]	[0.8, 1.2]	[1.2, 1.4]	[1.6, 2.0]	[2.0, 2.4]	[0.0, 0.4]	[0.4, 0.8]	[0.8, 1.2]	[1.2, 1.5]	[1.5, 1.8]	[1.8, 2.1]
Charge Misident.	0.02	0.02	0.03	0.07	0.08	0.10	0	0	0	0	0	0
Eff. Ratio	0.70	0.70	0.70	0.70	0.70	0.70	0.59	0.39	0.93	0.72	0.82	1.18
e/μ Scale	0.07	0.17	0.26	0.46	0.53	0.55	0.80	0.78	0.83	0.81	0.73	0.77
Sig. & Bkg. Estim.	0.16	0.19	0.26	0.33	0.25	0.25	0.20	0.20	0.27	0.35	0.51	0.56
Total	0.72	0.75	0.79	0.91	0.92	0.93	1.01	0.90	1.27	1.14	1.21	1.52

Systematic uncertainties (%)

Z differential cross section



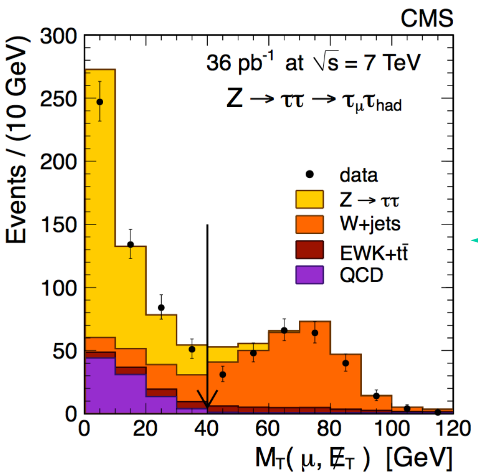
Disagreement w.r.t. POWHEG is significant in some bins

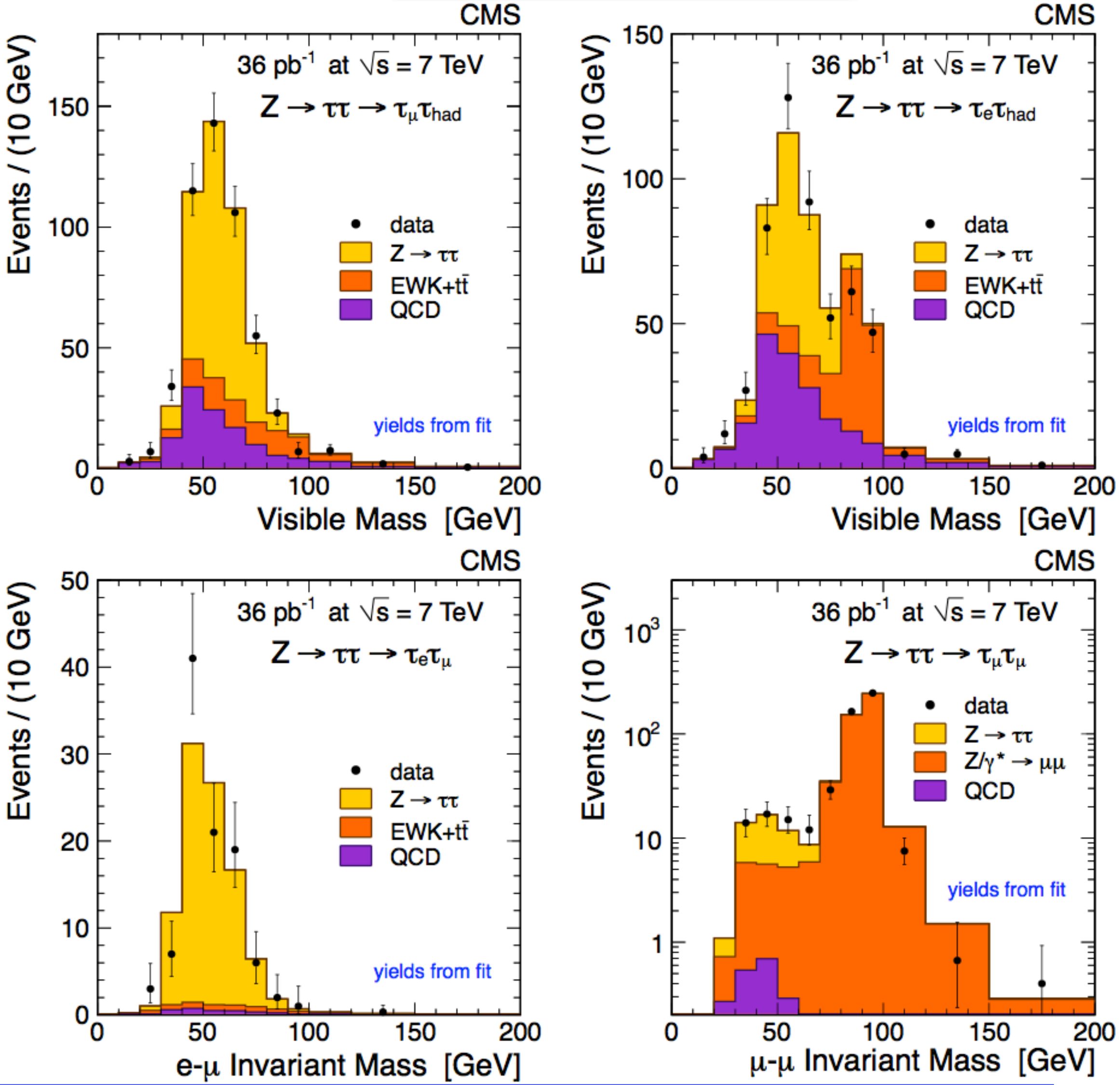
Non-perturbative effects dominate at low p_T, and are part of the 'tune' of the underlying model

$Z \rightarrow \tau\tau$

CMS-PAS-EWK-10-013
arXiv:1104.1617

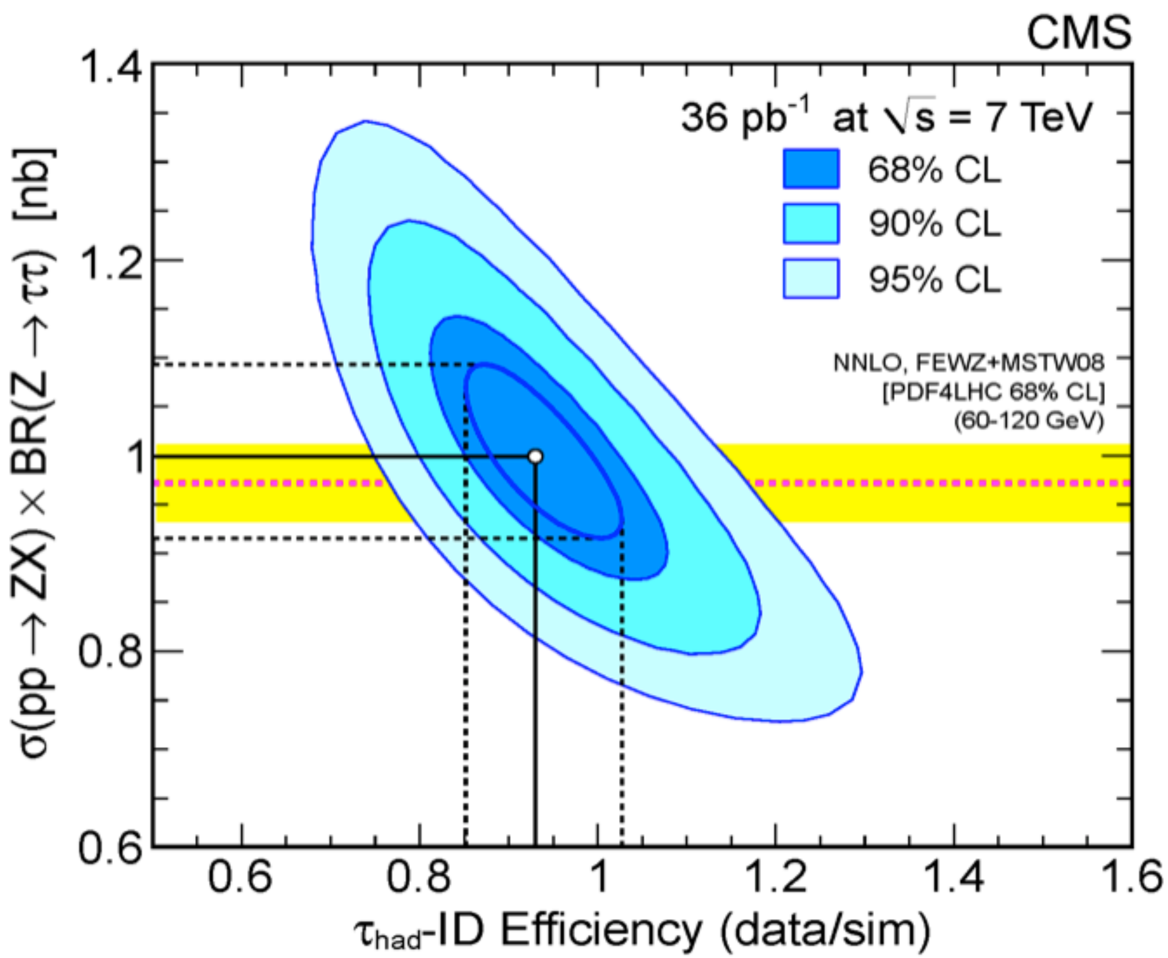
- Benchmark for searches using taus ($H^+ \rightarrow \tau\nu$, $H \rightarrow \tau\tau$, …)
- Particle Flow: combine tracker and calorimeter measurements to determine particle candidates
- $p_T(l)$>15 GeV, p_T(had)>20 GeV
- $M_T(l$, miss. $E_T)$<40 GeV (lep+had)
- Missing E_T < 50 GeV(lep+lep) to suppress W+jets
- Main systematic: tau id eff. in hadronic mode (23%), determined from data





$Z \rightarrow \tau\tau$

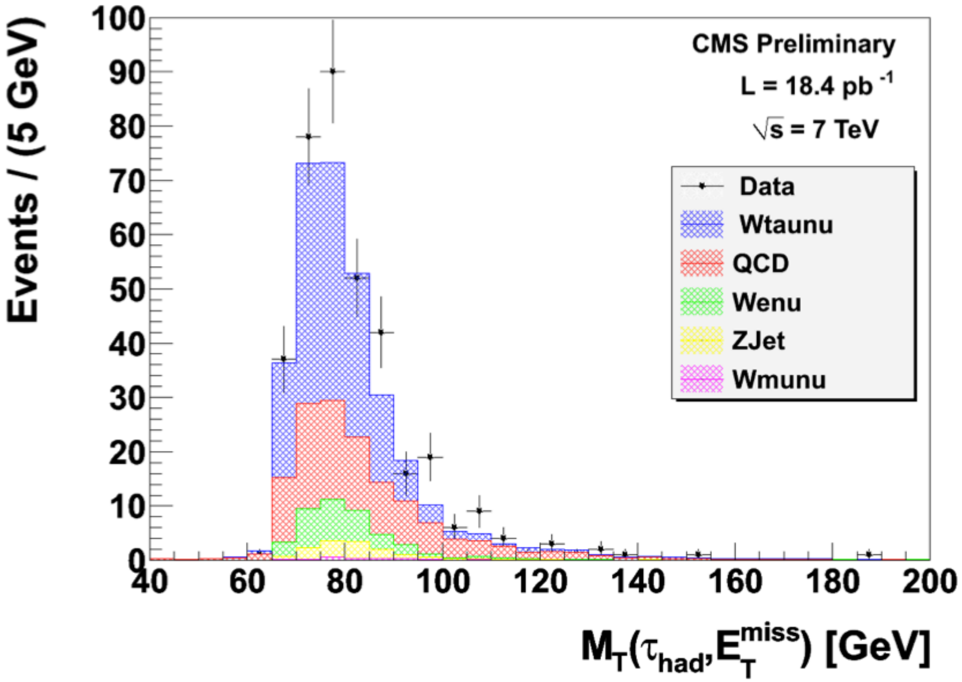
- Simultaneous fit of tau id and cross section



$W \rightarrow \tau\nu$

CMS-PAS-EWK-11-002

- Events triggered a single tau plus missing E_T
  - challenging, especially as luminosity increases
  - Trigger cuts: p_T (τ) > 20 GeV, p_T (track)>15 GeV, missing E_T >25 GeV
- QCD estimate from control regions
  - $p_T(\tau)$ / Σp_T(all jets) cut inversion



Selection:

- p_T (τ) > 30GeV, tightened as offline cut
- Tau isolated from other particle-flow particles
- $p_T(\tau)$ / Σp_T(all jets) > 0.65
- Missing E_T > 35 GeV

Process	Events
$W \rightarrow \tau\nu$ (sim.)	174 ± 3
EWK (sim.)	46 ± 2
QCD (sideband)	109 ± 6
Data	372