The Abdus Salam
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2263-8

Beyond the Standard Model: Results with the 7 TeV LHC Collision Data

19 - 23 September 2011

CMS Standard Model Results

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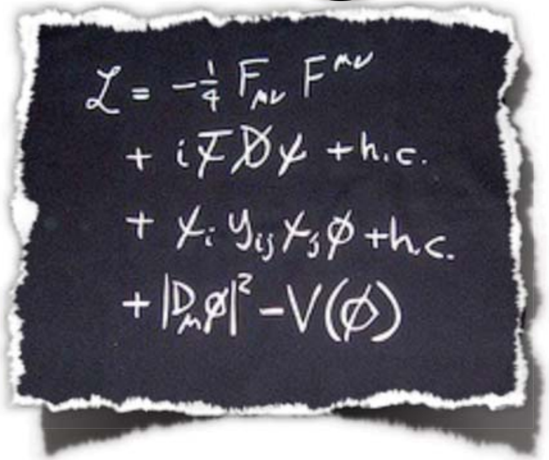
Exploring the Standard Model @7 TeV with CMS

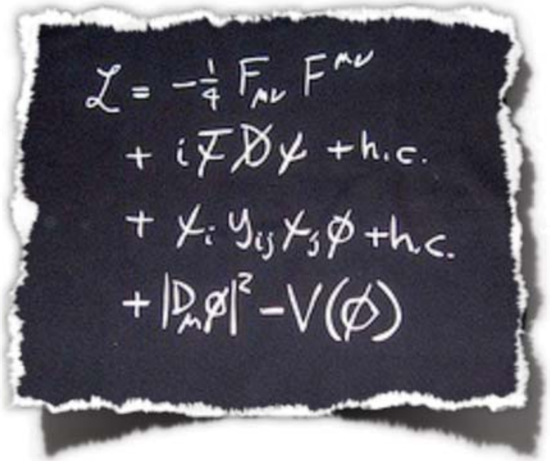


Vuko Brigljevic
Rudjer Boskovic Institute, Zagreb

On behalf of the CMS Collaboration

Beyond the Standard Model: Results with the 7 TeV Collision Data
Trieste, September 19-23 2011

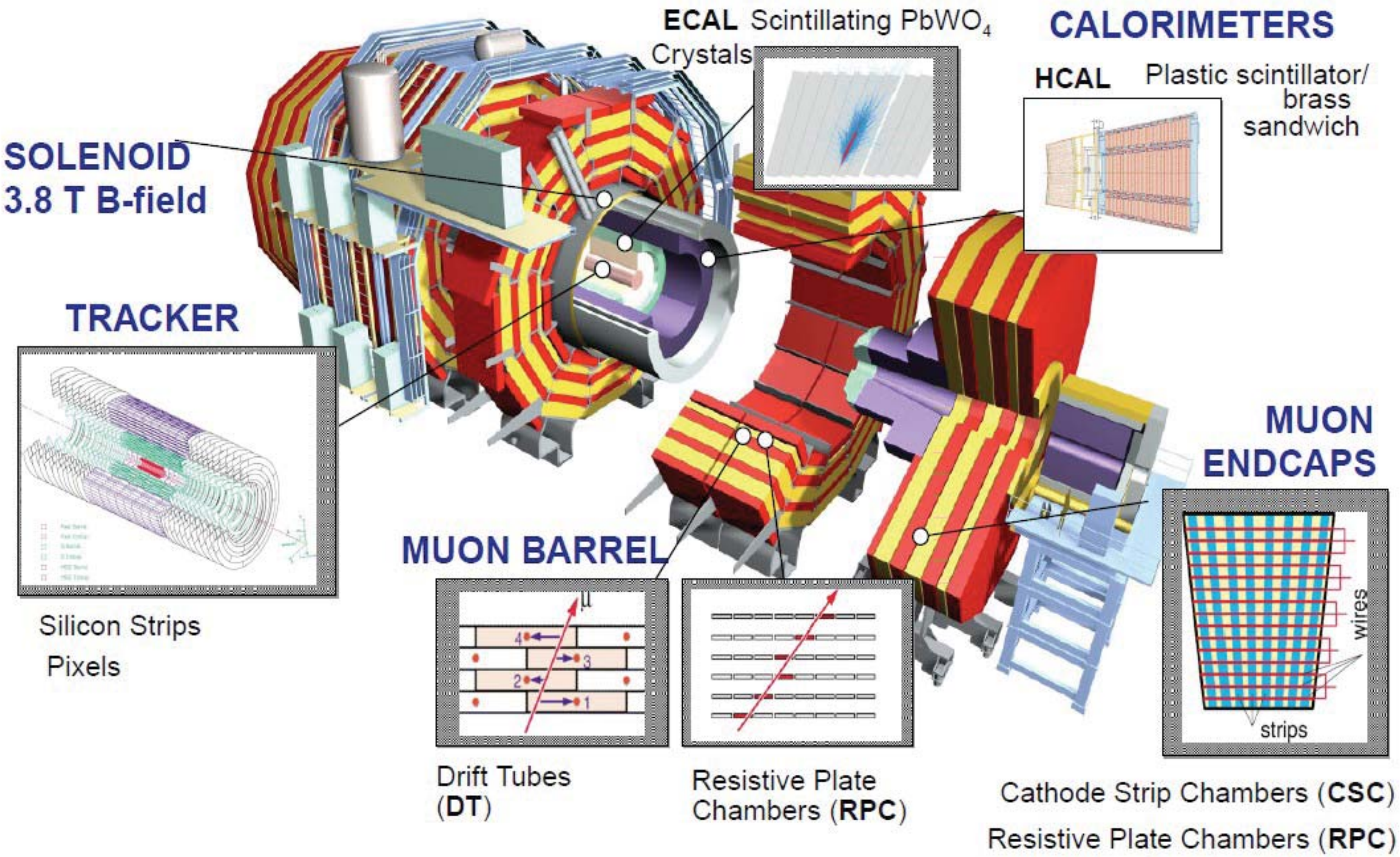
Motivation and Outline



describes { Electroweak interactions, QCD, Flavour, SSB (?), ...

- In this talk, as a benchmark of the SM, I have chosen to focus on **Electroweak Physics**
- It gives access to:
  - Electroweak interactions (of course!)
  - QCD (soft and hard)
  - Many entry points to new physics

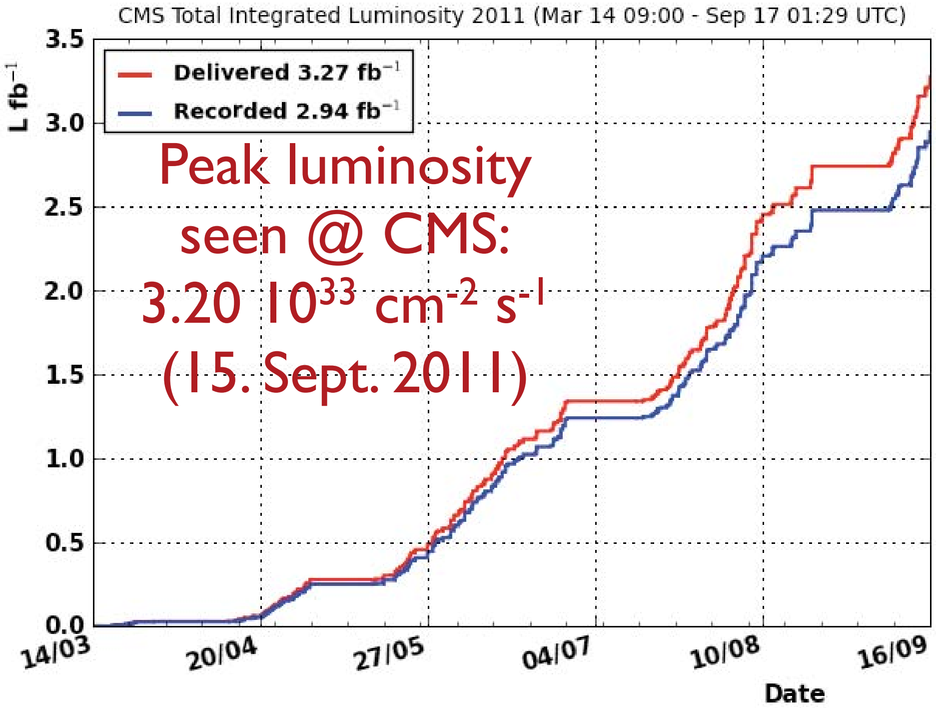
CMS @ 7 TeV


ECAL Scintillating $PbWO_4$ Crystals
CALORIMETERS
HCAL Plastic scintillator/ brass sandwich
SOLENOID
3.8 T B-field
TRACKER
Silicon Strips
Pixels
MUON BARREL
Drift Tubes (DT)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
wires
strips
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

LHC / CMS Operations @ 7TeV

Overall Data taking efficiency: ~90%

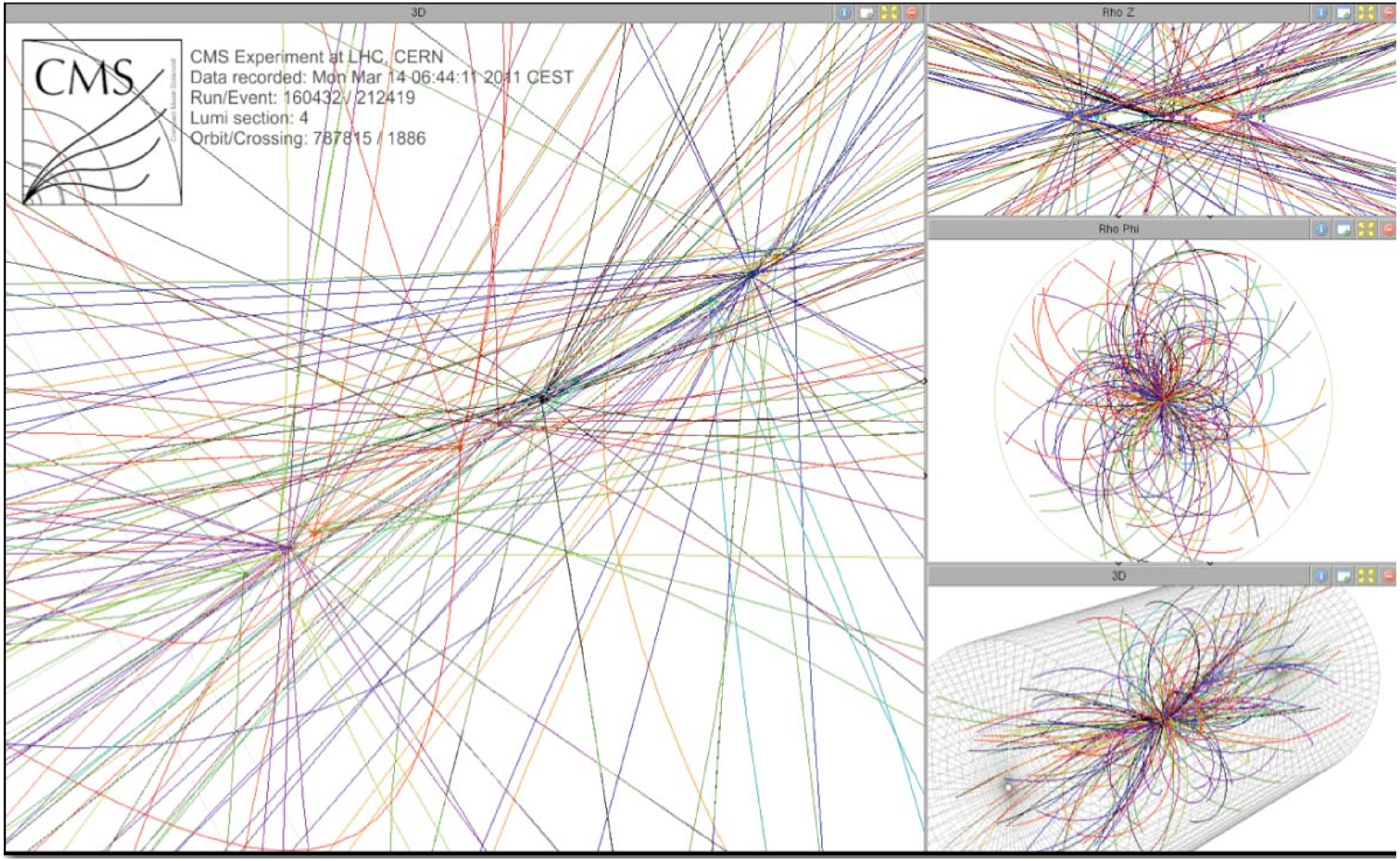
Average fraction of operational channels / subsystem >98.5%



RPC	98.5
CSC	98.3
DT	99.4
HF	99.9
HE	100.0
HB	99.9
ES	95.9
EE	98.6
EB	99.1
STRIP	97.8
PIXEL	96.9

- Results presented are based on up to ~ 1.1 fb^{-1}
- Still many results based on 2010 data: 36 pb^{-1} and some of them already systematic limited

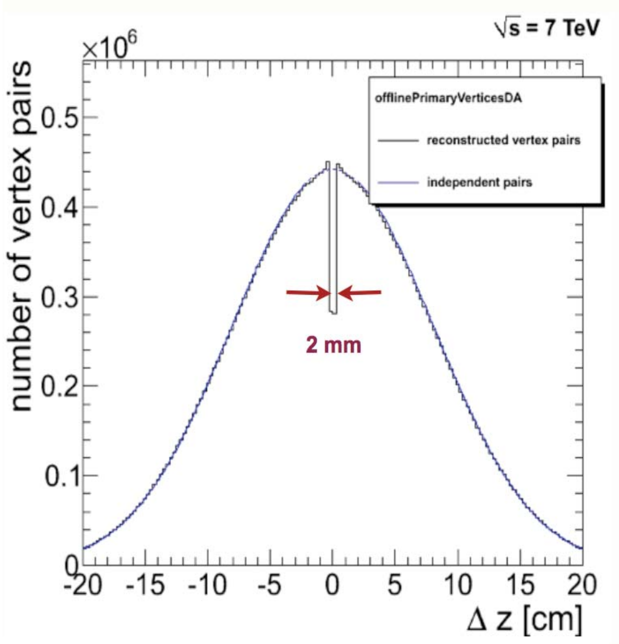
The price of the LHC success: The Pileup challenge in 2011

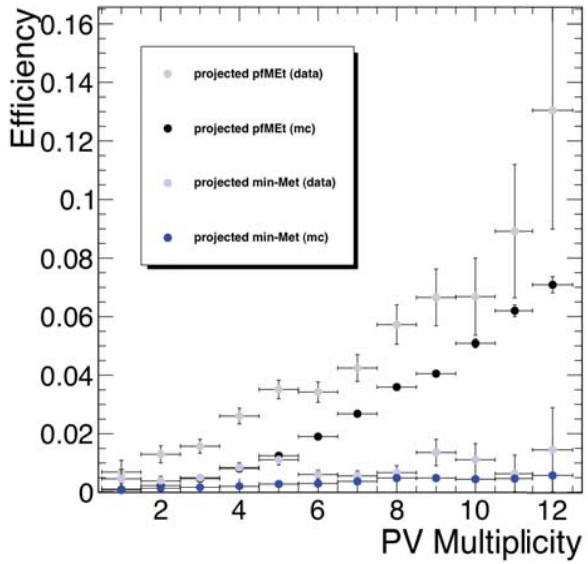


Learning how to deal with Pileup

- Developed new vertex algorithm capable to disentangle primary interactions separated less than 1mm in z
- Correct event by event for the tracks/energies contaminating the isolation or clustering cones coming from additional interactions
- Protect MET and jet veto selections from PU effects

All these tools heavily used in most analyses on 2011 data



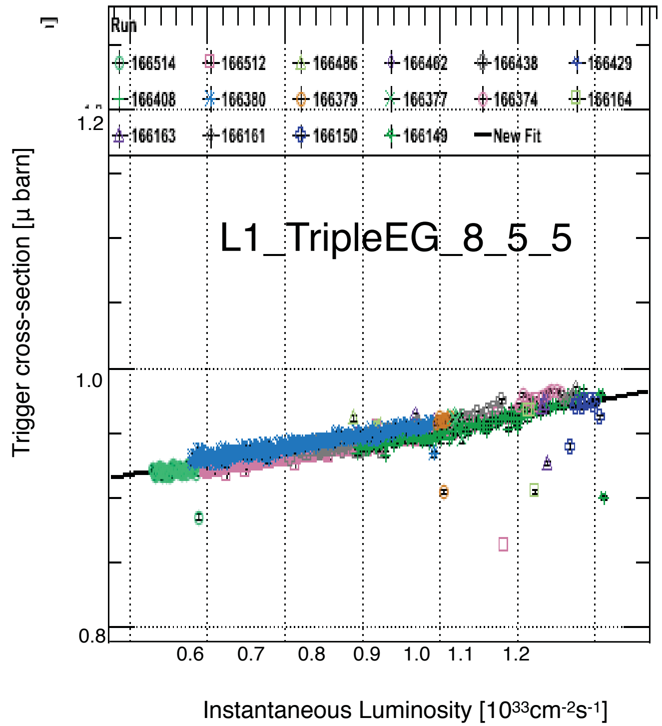


The price of the LHC success: the trigger challenge

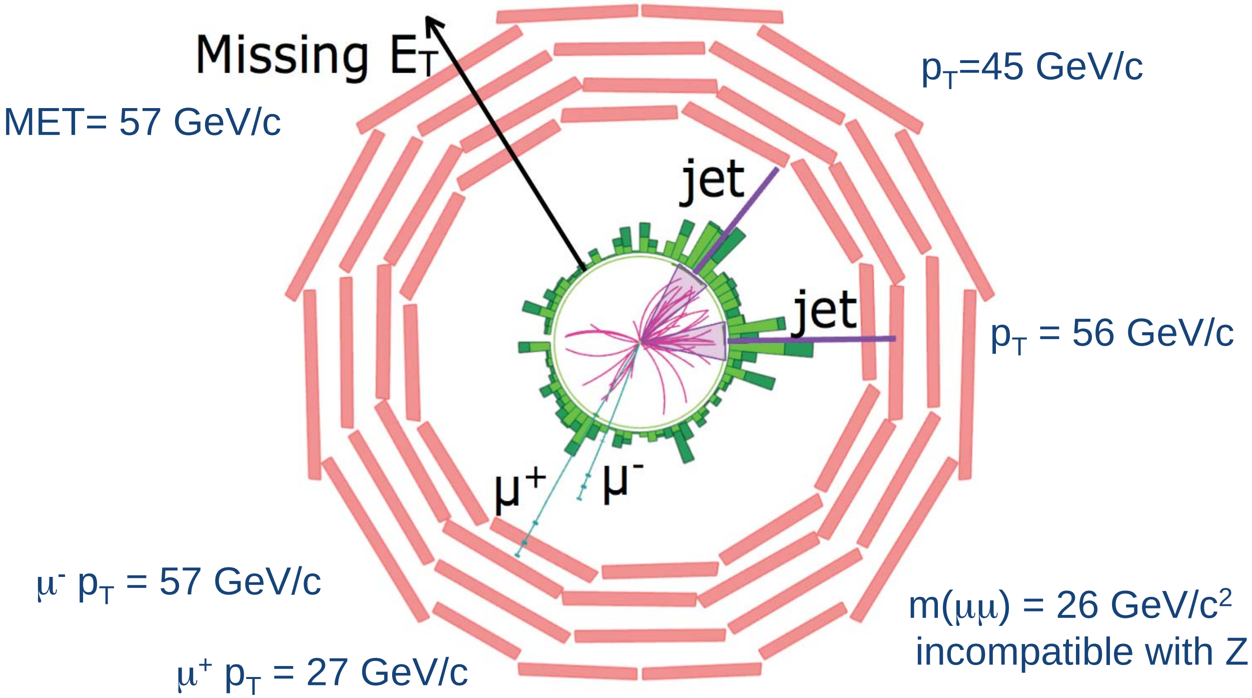
Lowest thresholds of unprescaled triggers

	1E33 (GeV)	*5E33(GeV)*
Single e/gamma	12	20
Di-electron/photon	8	12-5
Single muon	7	14 (η<2.1)
Dimuon		0, 3.5 (general)

- Increased importance of multi-object triggers, both at L1 and HLT
  - Many analyses cannot rely any more on single object triggers (nearly all 2010 analyses did)
  - Implemented over 200 multi-object triggers, including b-jets and τ triggers
- Mild dependence on PU: for 25 pile-up interactions, expect a rate increase of ~20%
- Overall good news: DAQ/L1/HLT running smoothly at > 10^{33} $cm^{-2}s^{-1}$



Physics Objects in CMS

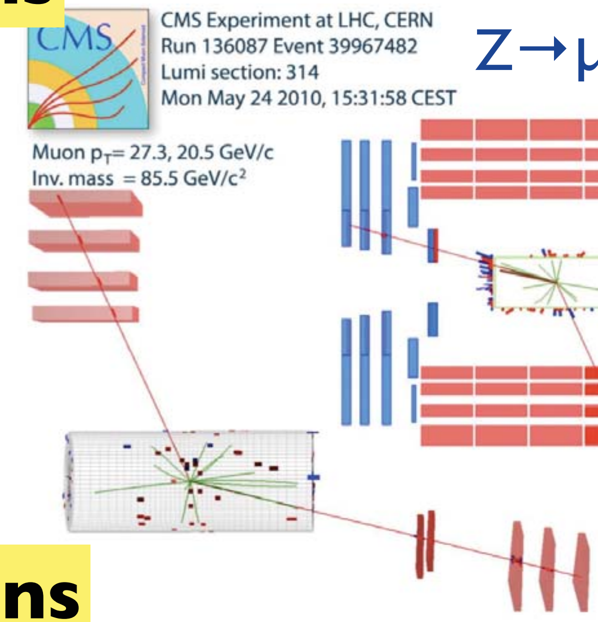


Top Di-Muon Candidate Event

Muons and Electrons

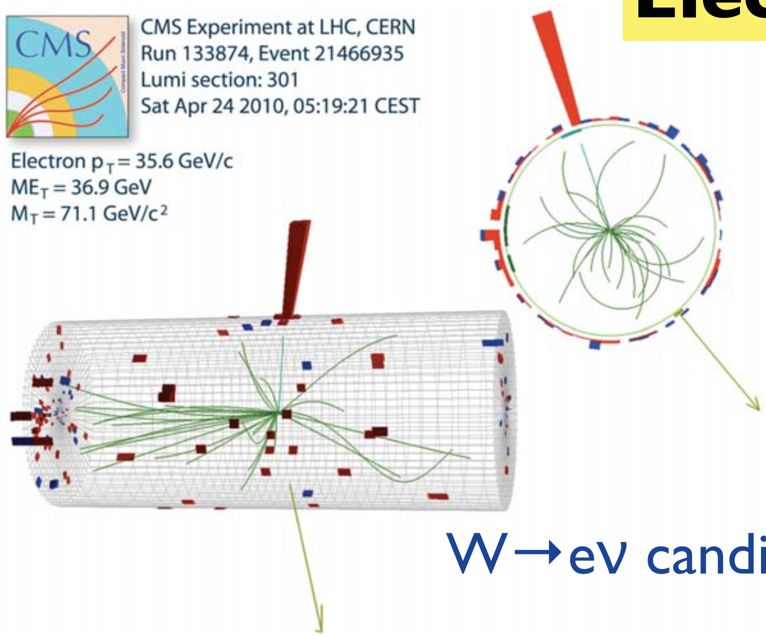
Muons

- Muon resolution dominated by inner tracking for P_t<200 GeV
- Typical P_t resolution for EWK Studies: 1-2%
- Muon chambers offer redundant trigger and coverage
- Muons can be reconstructed both in inner tracker and muon chambers



Z→μμ candidate

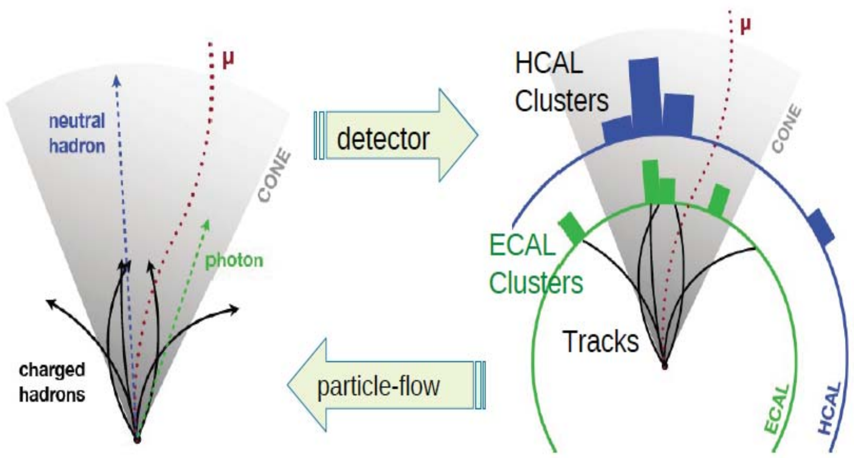
Electrons



W→eν candidate

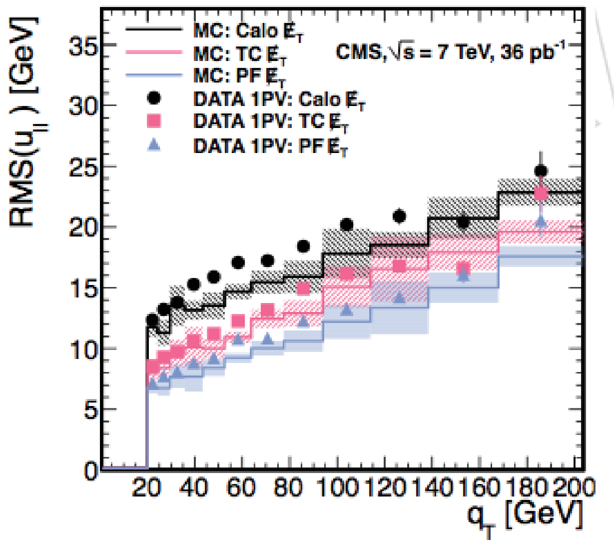
- Excellent resolution provided by the $PbWO_4$ crystal calorimeter
- Typical E_t resolution for EWK Studies: 1%
- Electron ID based on shower shape variables, ECAL-Tracker matching and HCAL/ECAL energy ratio

The wonders of Particle Flow



- Build particle candidates from tracks and energy deposits
- Exploits the good separation of charged particles due to the large tracker volume and high magnetic field and the good ECAL granularity

e.g. MET resolution measured from hadronic recoil in photon+jets events:



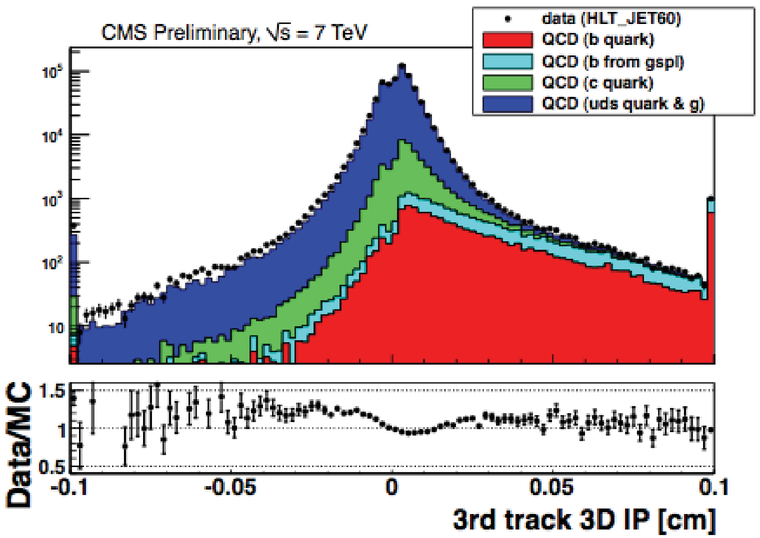
Large improvement in energy resolution and τ ID using particle flow techniques

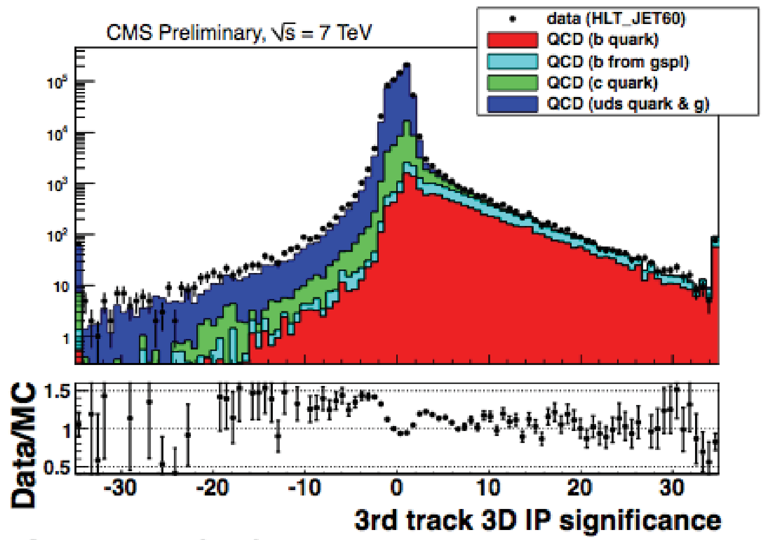
Jets and b-tagging

- Most EWK analyses using jets use particle flow to define jet constituents and an anti-kT jet algorithm with ΔR<0.5
- Typical scale uncertainty for EWK measurement is < 3%, typical jet resolution is 10-15%
- Good tracker performance allows good b-tagging capabilities
- SM Studies use:

(I) track counting (above some impact parameter threshold)

(II) Secondary vertex tagging



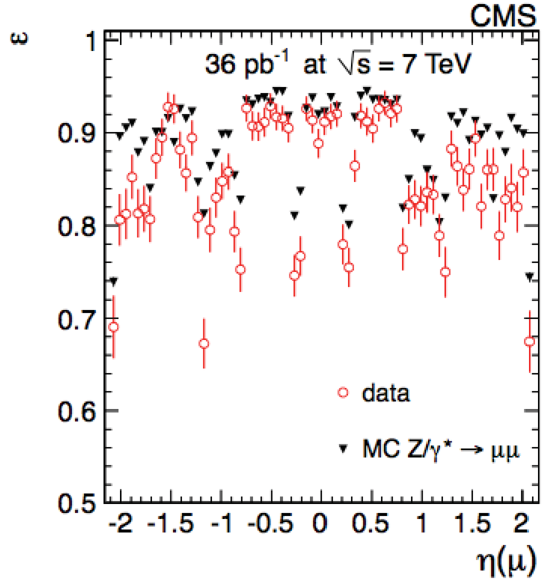


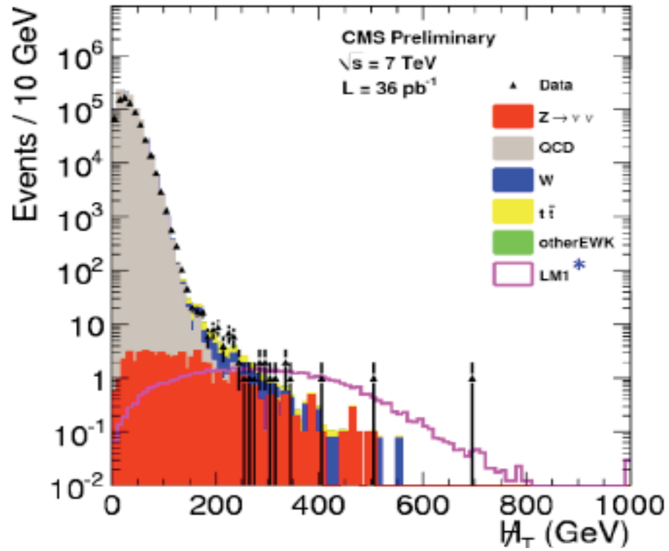
Electroweak measurements: Physics of W and Z bosons

Why study W and Z @ LHC?

- Standard Model Measurements:
  - Provide access to central parameters for global EWK fit (masses, couplings, asymmetries)
  - Provide powerful constraints for non-perturbative part (PDFs, tunes)
- Wonderful commissioning tool to understand and calibrate our detectors
- Dominant signal and/or background in many BSM searches

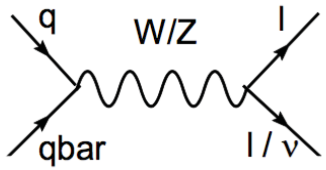
μ efficiency with "Tag-and-probe"



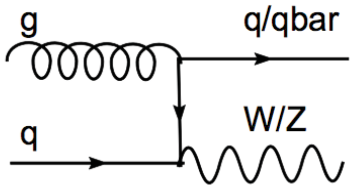


W/Z Production @ LHC

Production



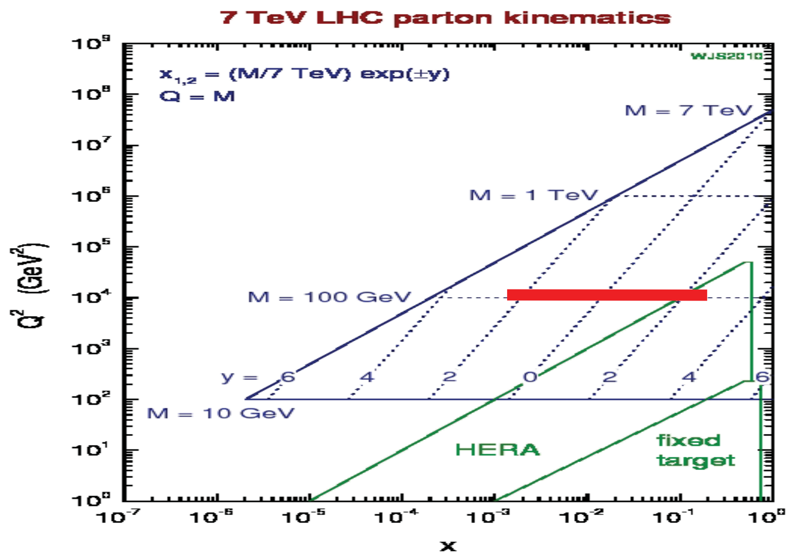
LO (Drell-Yan) +



NLO

gluons play a major role in associated jet production (W+jets)

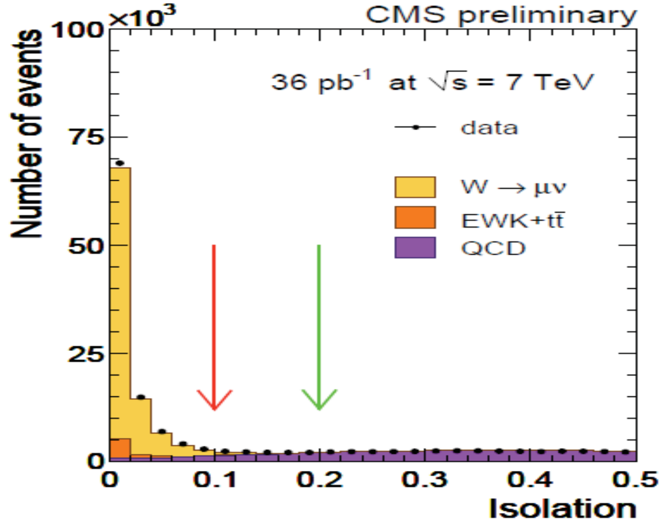
- At first order, W and Z production at the LHC proceeds through the collision of a valence quark to a sea anti-quark (Q~100 GeV)
- Since parton fractions are typically $10^{-3}<x<10^{-1}$, sea-sea contributions are also important

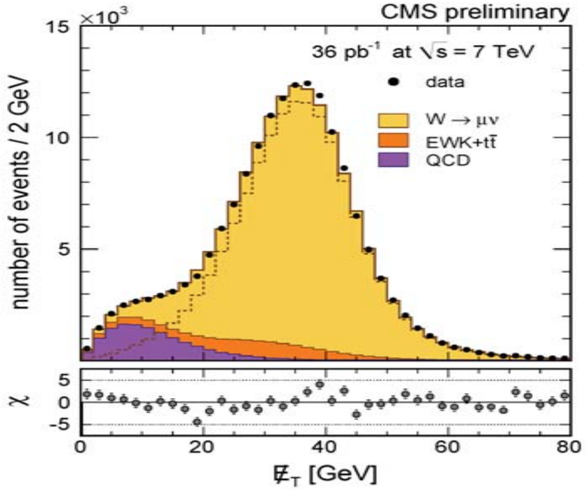


Electroweak processes are ideal for precise measurements and tests of PDFs at the LHC !

W Inclusive Production

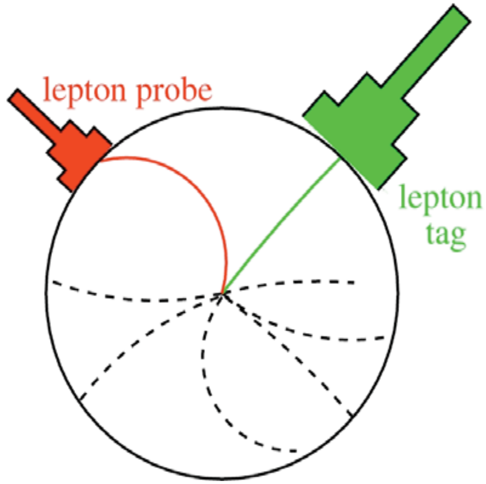
- W Selection
  - Loose single e/μ triggers
  - High P_t lepton (>25 GeV) in detector acceptance
  - Lepton isolated from hadronic activity
- Cross section Extraction:
  - Fit missing E_T distribution for signal and background for W^+ and W^-
  - Efficiencies, resolutions, signal and background shapes are extracted from data
  - W^+ and W^- cross sections are extracted separately, or equivalently the total W cross section and the W+/W- cross section ratio

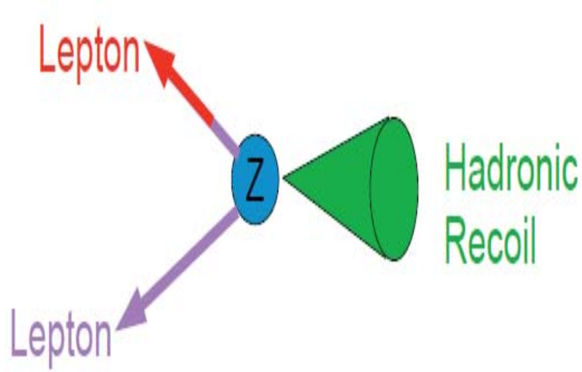




W Inclusive Production: the toolbox

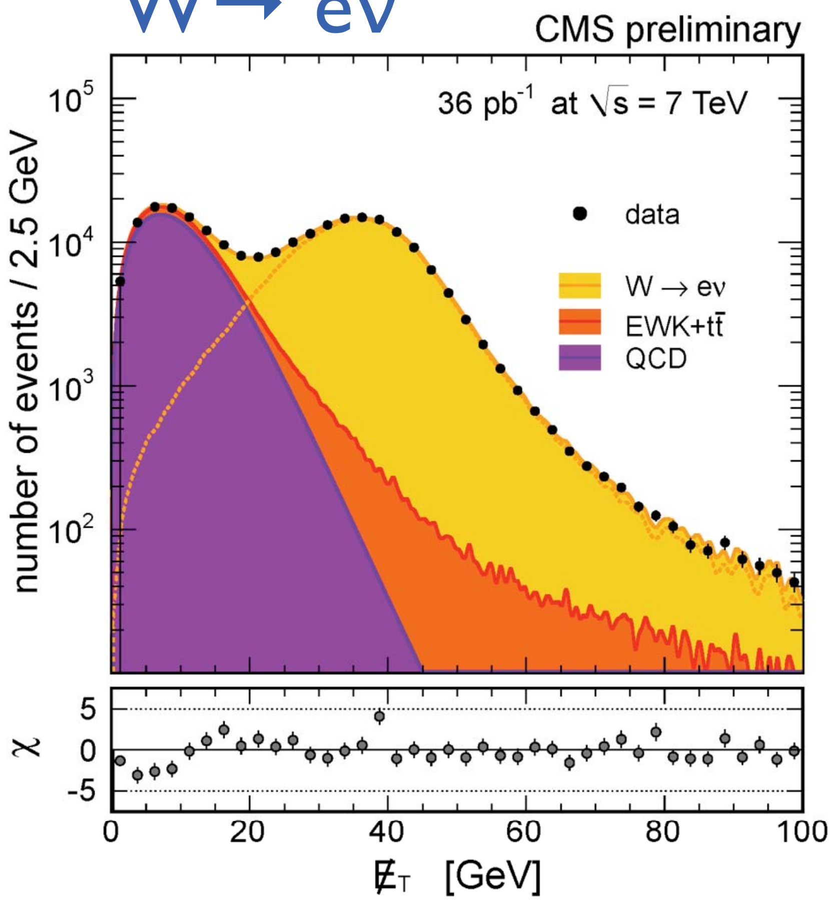
- e/μ trigger, reconstruction and ID efficiencies determined from data with Z events with the "Tag-And-Probe" method:
  - P_t and η dependent efficiencies
- Shape of the QCD background determined or parameterized from a sample of non-isolated leptons
- Z→ ee/μμ events also used to control momentum and energy resolution



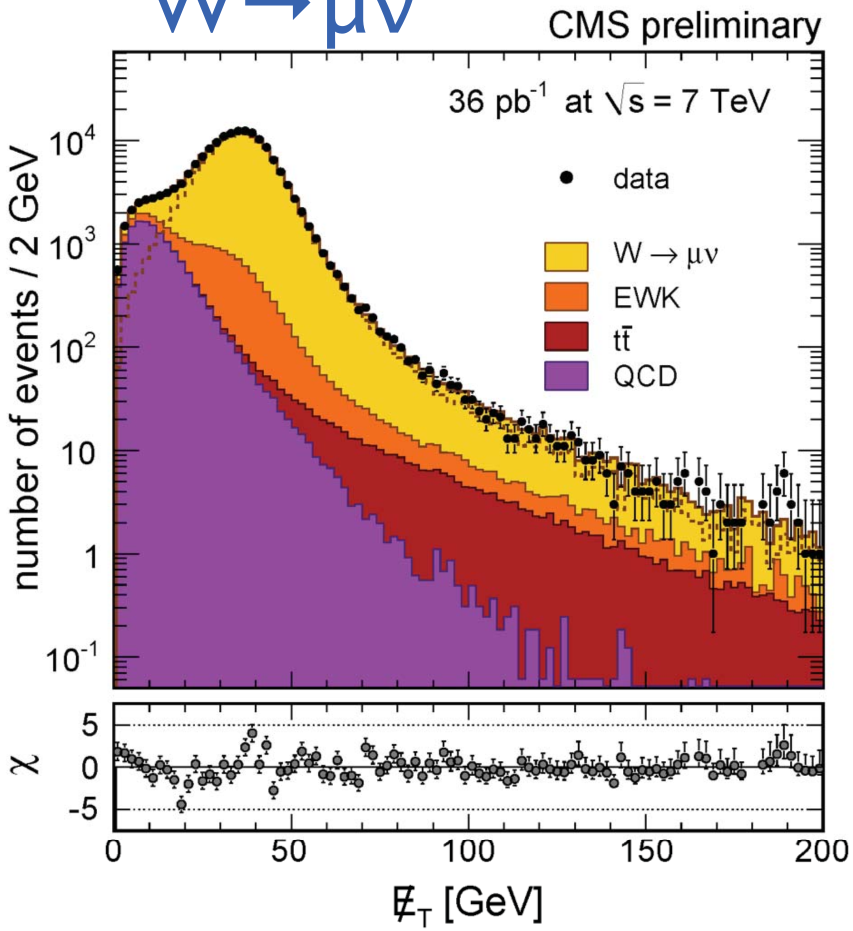


W Inclusive Production

W→ eν



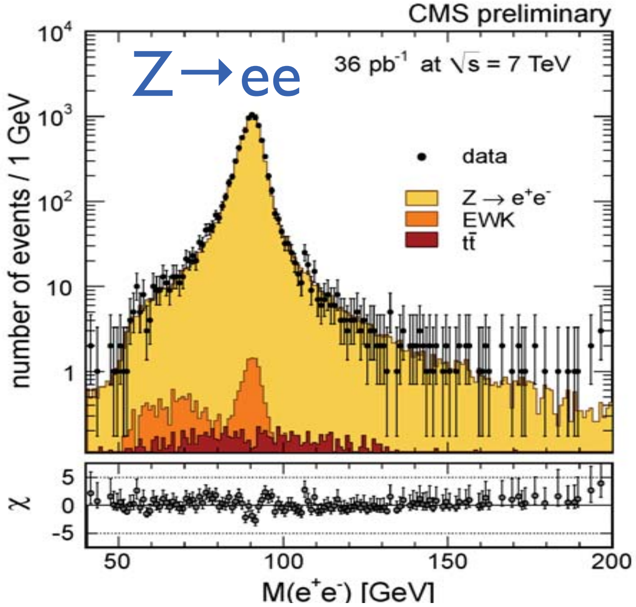
W→μν

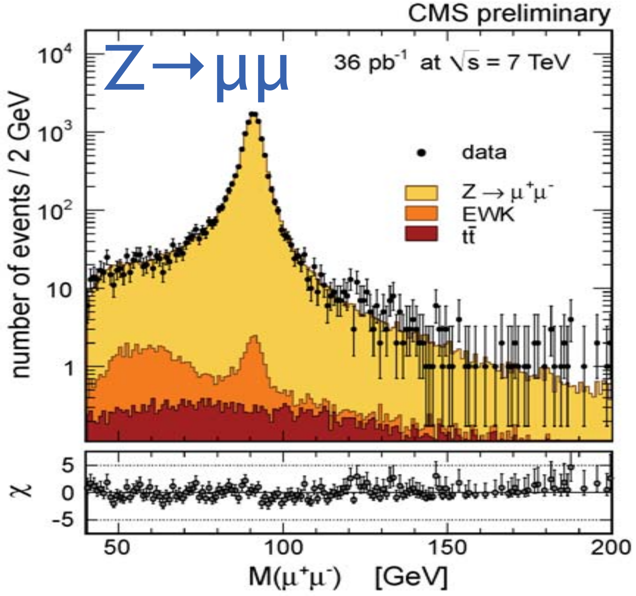


- W+ and W- cross sections are extracted separately, or equivalently the total W cross section and the W+/W- cross section ratio

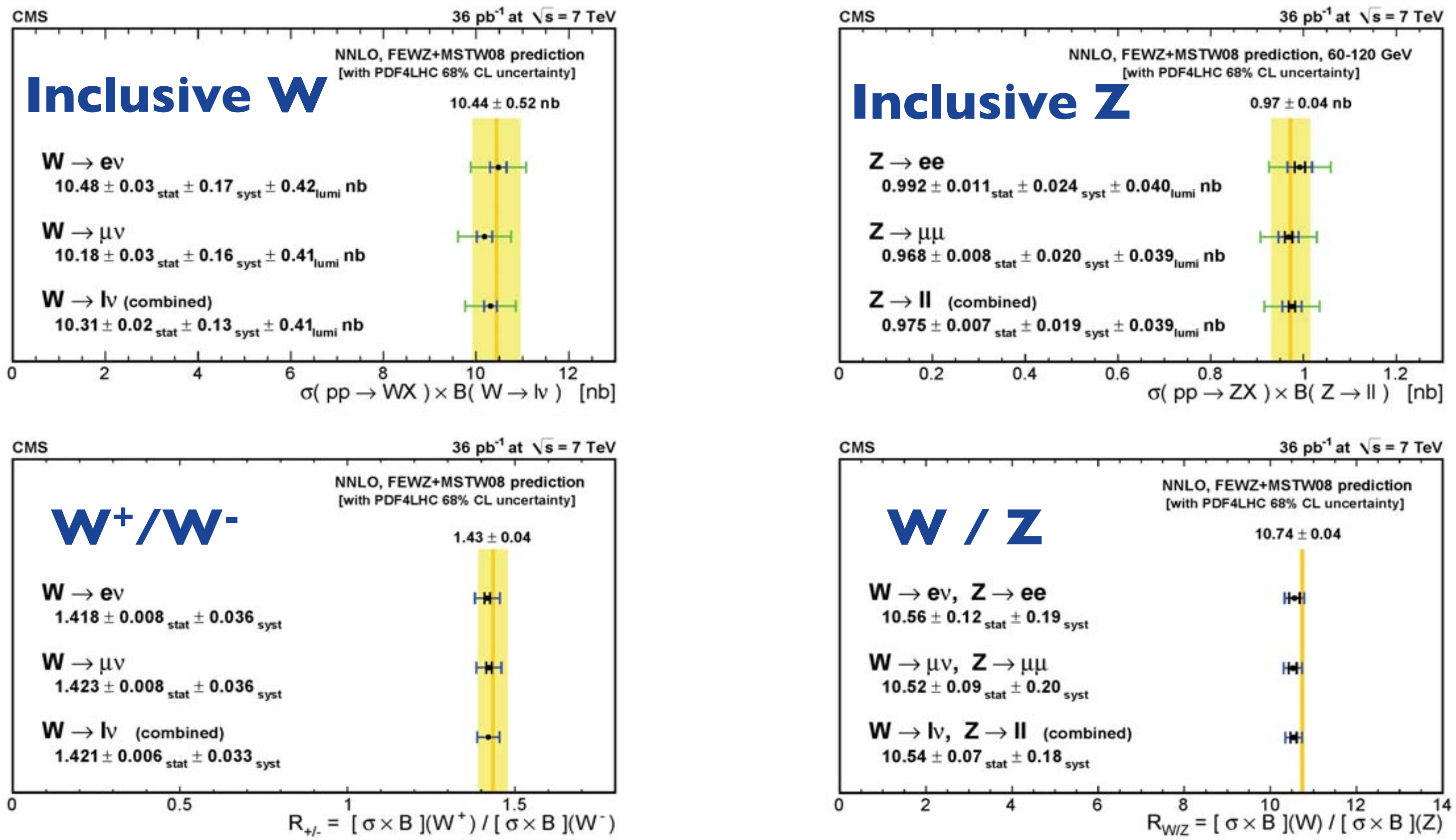
Z Inclusive Production

- Z→ ee / μμ Selection
  - Isolated pairs of high Pt electrons /muons (>25 GeV)
  - Cross sections are measured for M_{ll} in [60,120] GeV
  - Yields and lepton efficiencies determined simultaneously in fit
  - Nearly Background free analysis



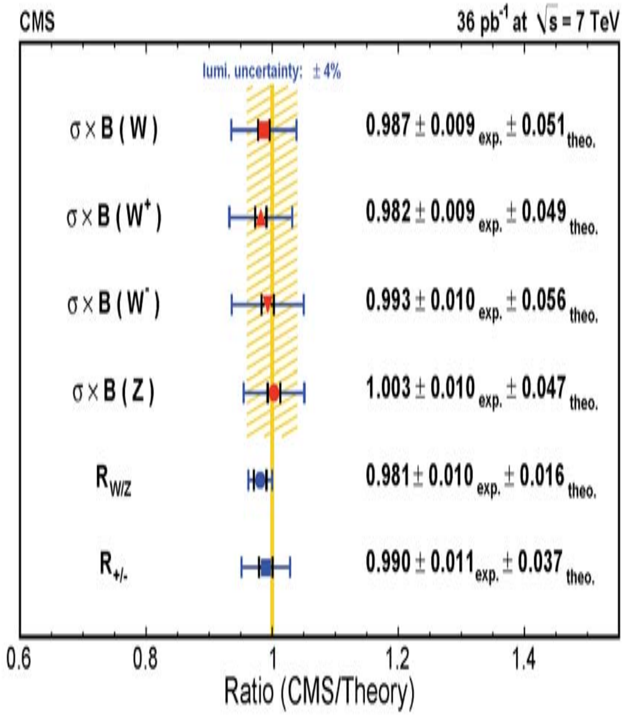


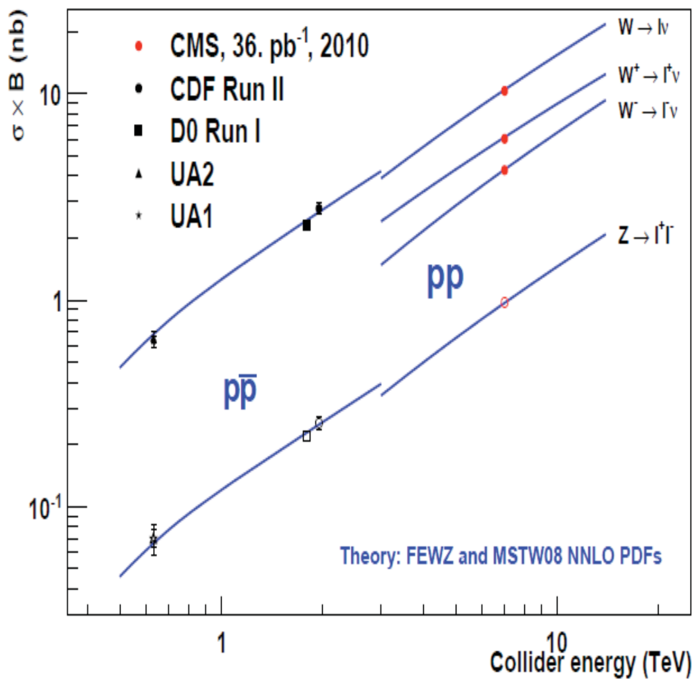
W/Z Inclusive Cross Sections



- Total cross sections are shown (i.e. extrapolated to full phase space). For Z/γ^* this means:
  - $60 < M_{ll} < 120$ GeV
- Experimental uncertainties dominated by luminosity uncertainty (~ 4%)

CMS W/Z Inclusive Results

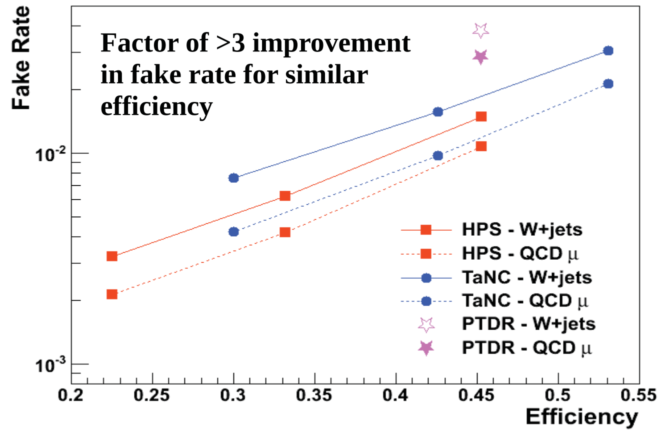


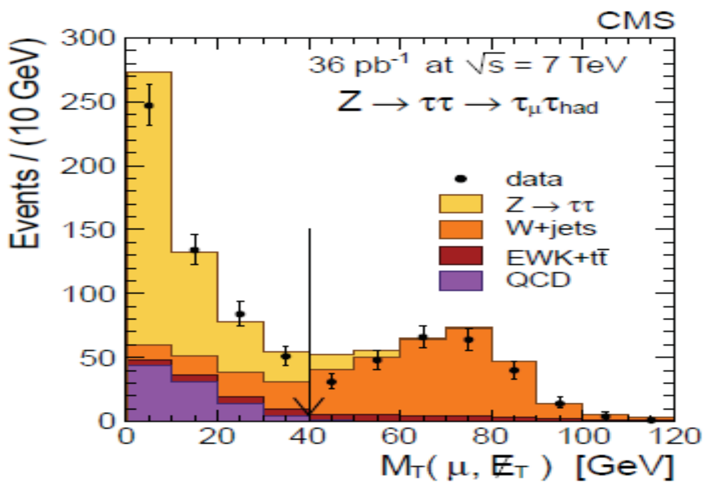


Good agreement with NNLO expectations

Measurement of Z→ττ

- Important benchmark for searches as τ decays are relevant in several BSM scenarios
  - e.g. MSSM Higgs, with H→ττ
- New methods in CMS to identify hadronic τ decays, large improvement since PTDR
- Typical Selection cuts:
  - P_t(isolated lepton) > 15 GeV
  - P_t(isolated hadr. τ) > 20 GeV
  - M_T(lepton,MET) < 40-50 GeV
- Special effort to determine most efficiencies and backgrounds directly from data

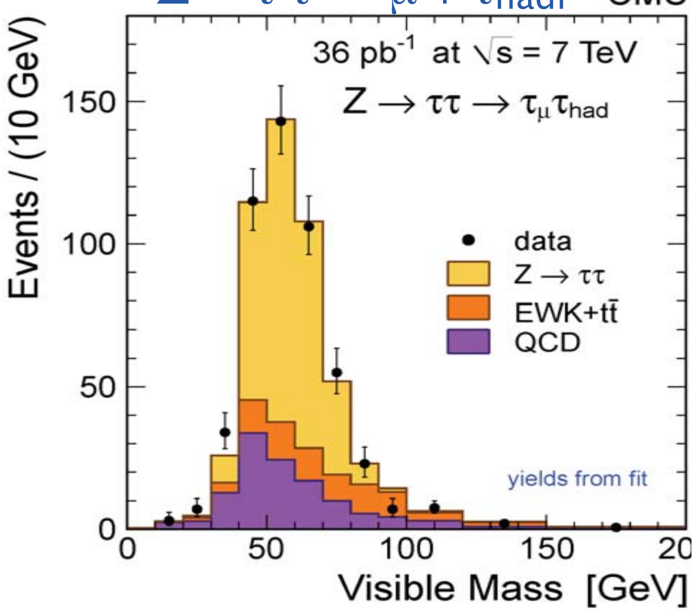




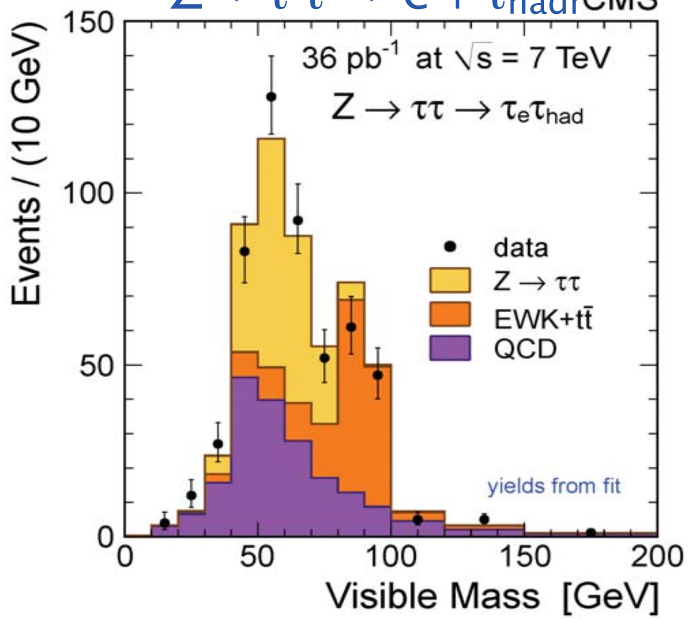
Z→ττ analysis

Channels with hadronic τ

Z→ τ τ → μ + τhadr

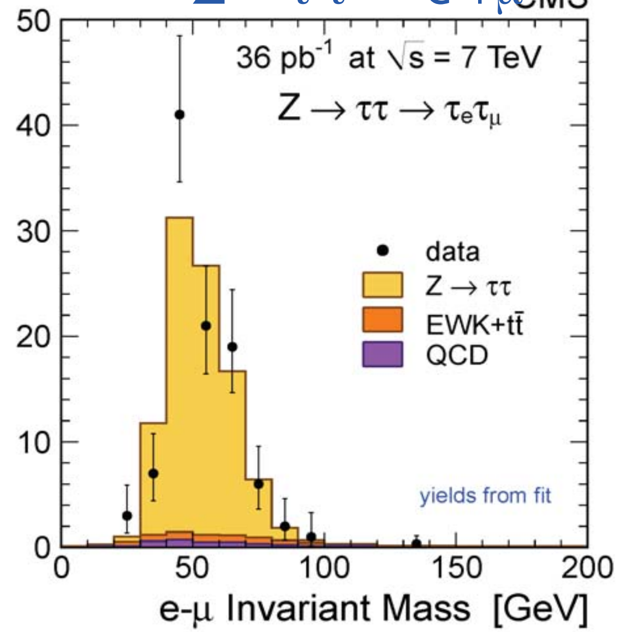


Z→ τ τ → e + τhadr

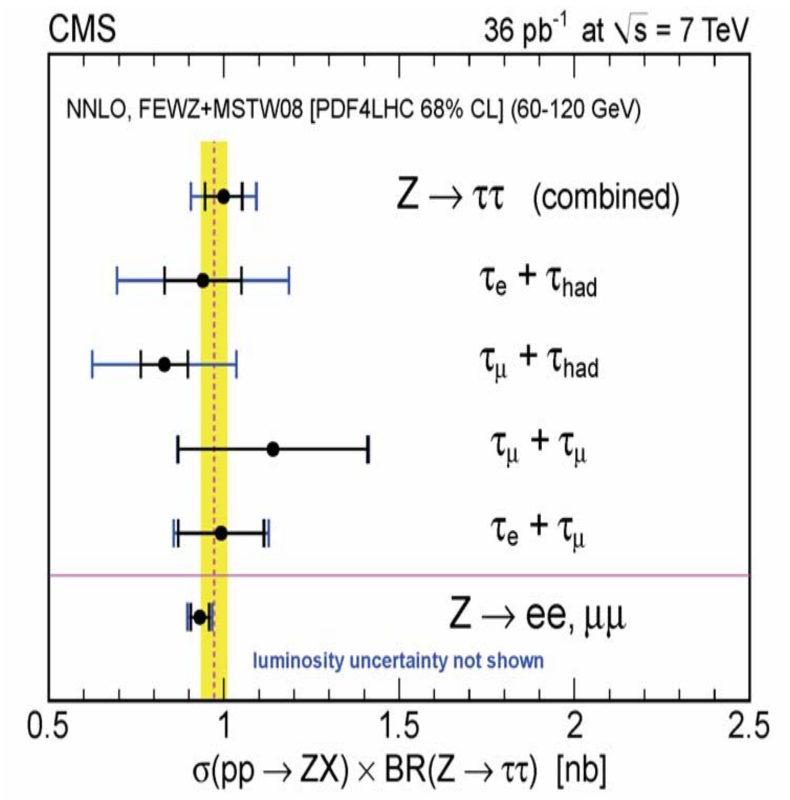


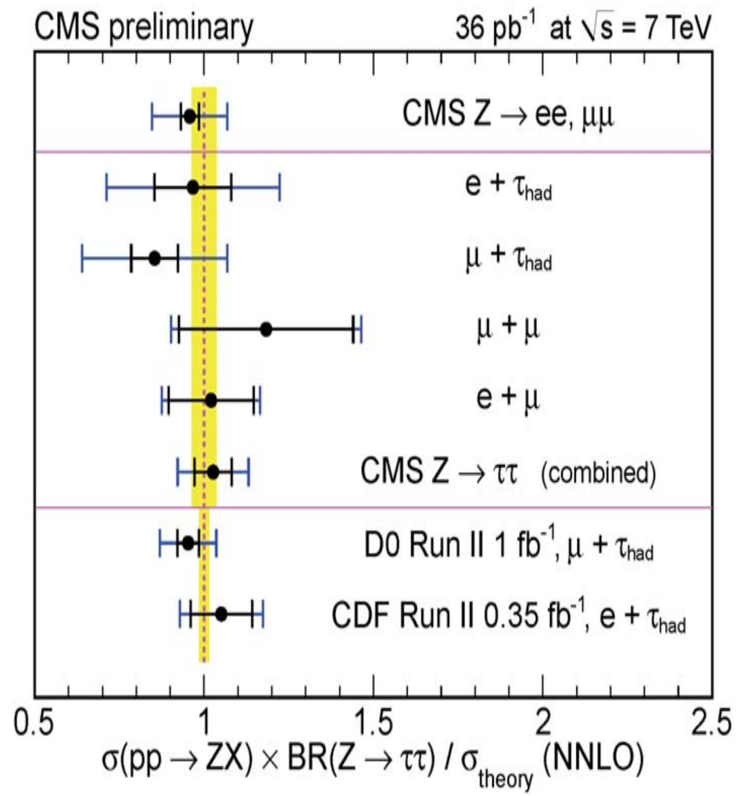
Purely Leptonic Channel

Z→ τ τ → e +μ



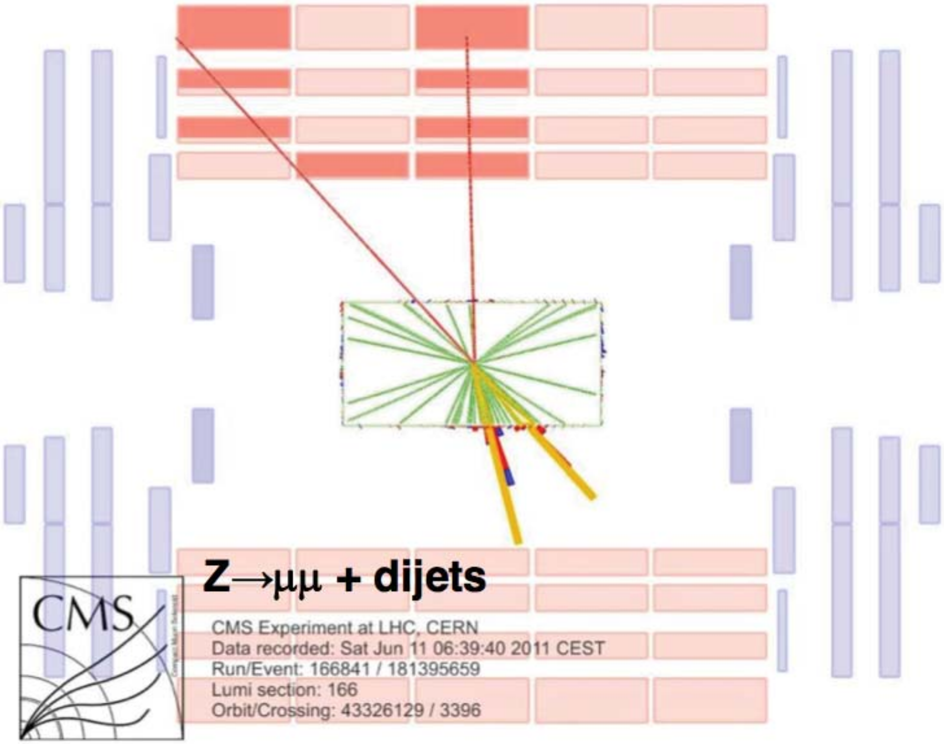
Z→ττ results





- Consistent with e/μ results
- Dominant systematic: hadronic τ identification efficiency
- Combined measurement already dominated by systematic uncertainties

Differential Z spectra



<u>Beyond Leading Order</u>

- Measuring additional recoiling jets is a direct probe of NLO and higher orders
- Z P_t is an indirect but cleaner probe

High P_t: Dominated by hard gluon emission, well described by perturbative QCD

Low P_t: Dominated by non-perturbative effects

Theoretical tools

★Fixed order:

➡Powheg, MC@NLO, MCFM: NLO

➡ResBos: NNLO + NNLL

➡Horace: EWK NLO

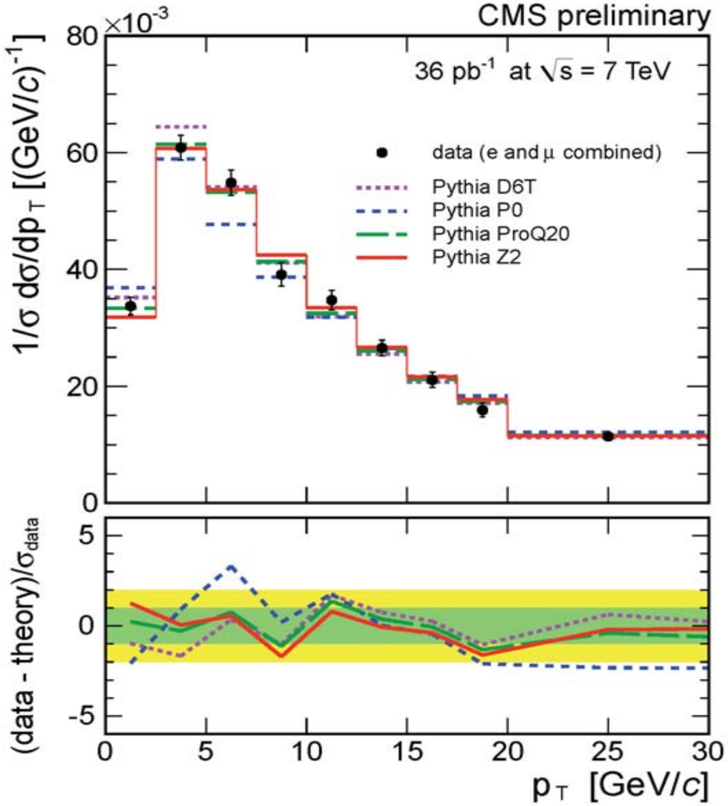
➡BlackHat: NLO up to 4 jets

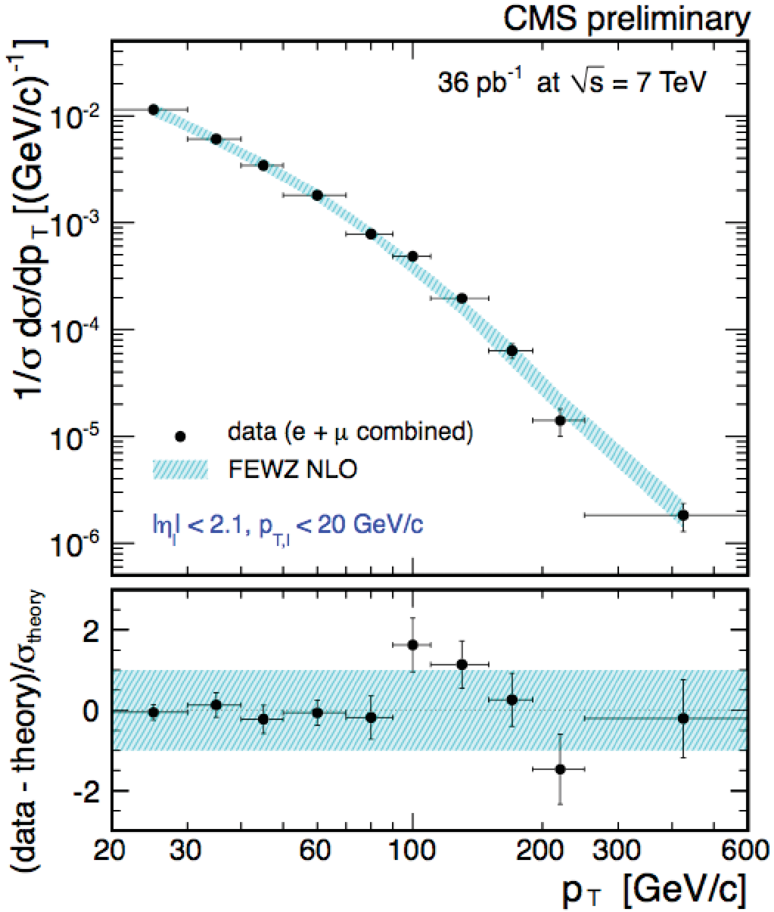
★ Matrix Element for hard/real emission up to high multiplicities:

Alpgen, Madgraph, Sherpa
+
Parton shower for non-perturbative part
(Pythia, Herwig)

Z Differential P_t Spectrum

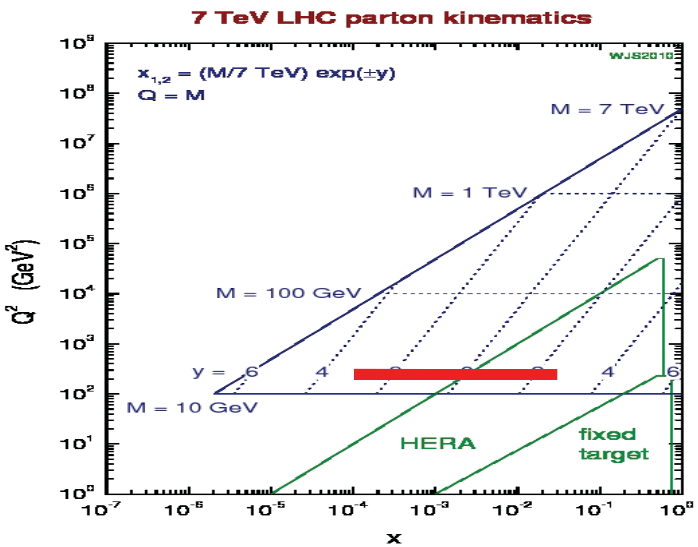
- Using Drell-Yan events selected in the same way as for the inclusive cross section, with $60<M_{ll}<120$ GeV: ~ 12'000 events per lepton channel

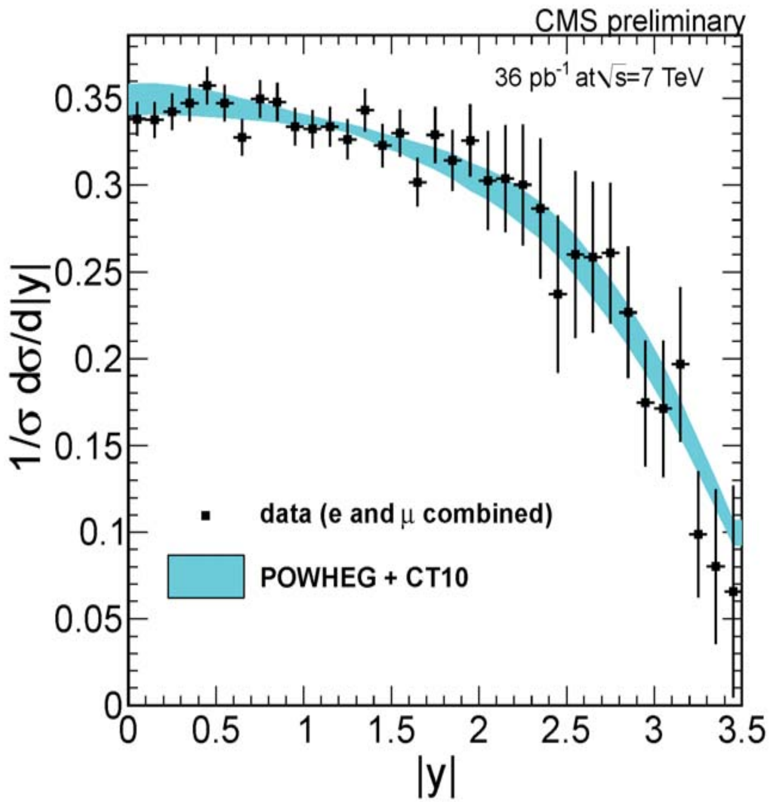




Z Rapidity Spectrum

- Rapidity distributions are sensitive to PDFs
- Large rapidities probe the smallest and largest x in the proton
- We study rapidities up to |y|<3.5, i.e. x below 10^{-3} and above 10^{-2}





Good agreement with current NLO Predictions (Powheg+CT10)

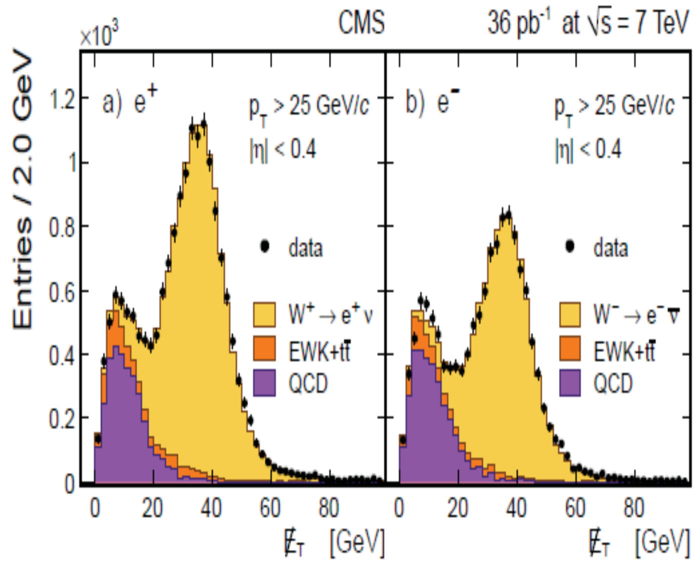
W Lepton charge asymmetry

- A natural extension of the inclusive measurement is the study of the W^+/W^- ratio R_W, as a function of different kinematic variables
- An experimentally clean way to do it is to study the charge asymmetry as a function of the lepton pseudorapidity
- This measurement is very sensitive to PDFs as most uncertainties cancel in the ratio
- Apply similar selection as for the inclusive measurement and divide the sample in different rapidity bins

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

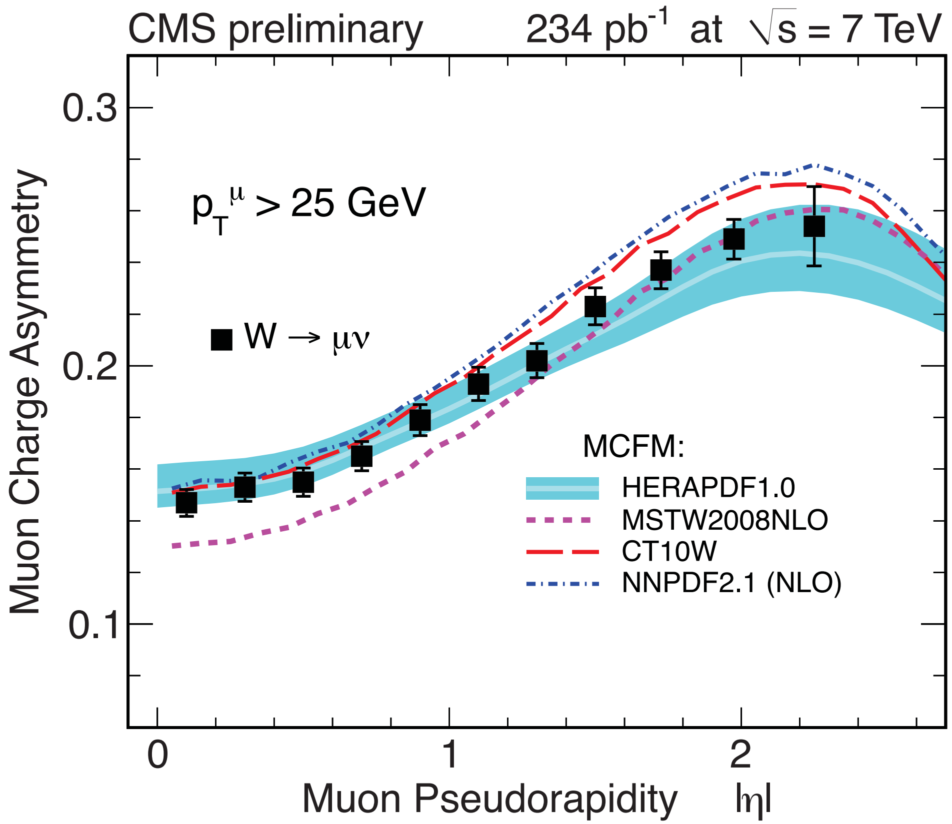
$$\left(A(\eta) \equiv \frac{R_W(\eta) - 1}{R_W(\eta) + 1} \right)$$

First η bin, electron channel



W lepton charge asymmetry

New result with 2011 data

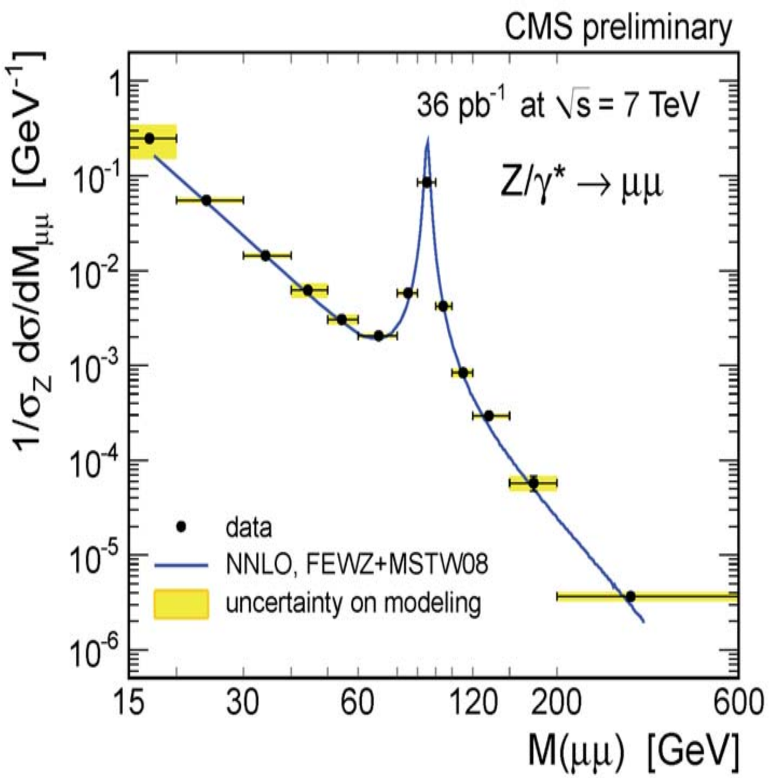


- New result with muon charge asymmetry significantly improves over 2010 result
- Provides significant constraint on PDF global fits
- Form χ^2 to measure agreement with different PDF models

PDF model	χ^2
MSTW2008NLO	5.3
CT10W	2.1
NNPDF2.1	4.1
HERAPDF1.0	0.9

Drell-Yan mass spectrum

- Provides important constraint to PDFs
- Source of large background for searches with isolated dileptons: needs to be understood accurately
- Distribution is unfolded for resolution, corrected for QED final-state radiation and normalized to Z yield



Excellent agreement with FEWZ+MSTW08 (NNLO QCD)

A_{FB} in Drell-Yan and $\sin^2\theta_W$

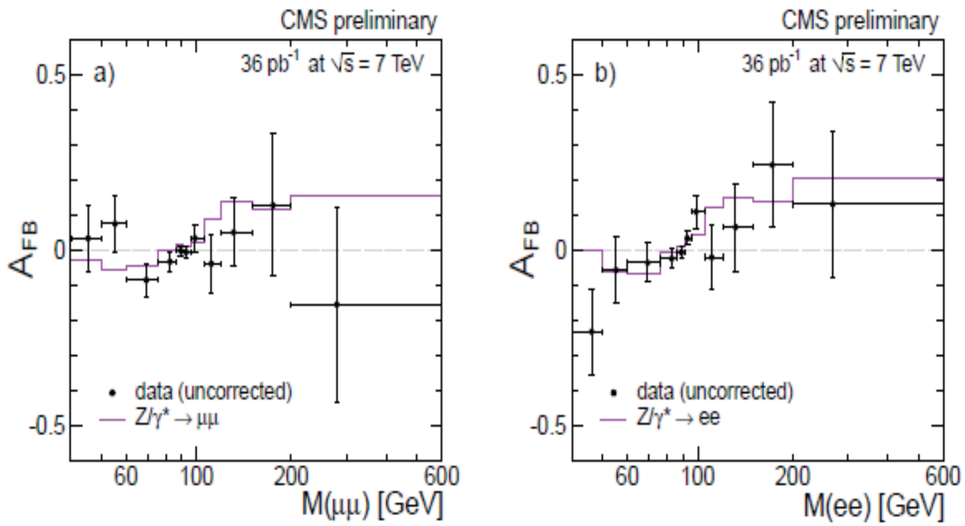
- Forward-Backward asymmetry in DY process sensitive to the effective $\sin^2\theta_W$ parameter in the SM
- cosθ* is approximated by the Collin-Soper angle wrt the beam direction closer to the dilepton direction (expected to be close to the quark direction in average
- Expect zero asymmetry at the Z pole, negative below and positive above (driven by axial couplings to Z)

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

θ^* is the quark-lepton angle in the CM frame

A_{FB} depends on the quark type (u,d) and on $\overline{\sin^2\theta_W}$

$$\cos\theta^*_{CS} = \frac{2(p_z^{l-}E^{l+} - p_z^{l+}E^{l-})}{Q^2(Q^2+Q_T^2)}$$

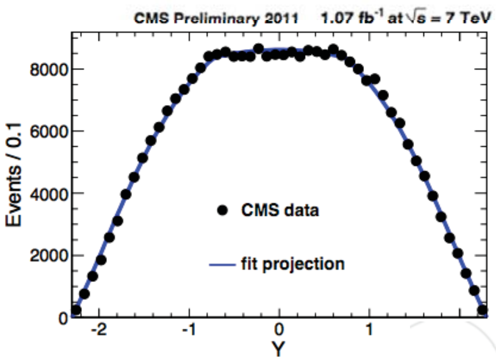


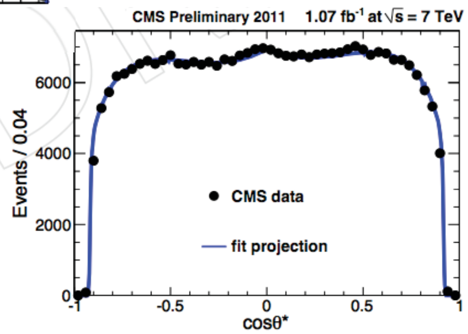
Asymmetry uncorrected for mass resolution or dilution effects.. In agreement with MC predictions (POWHEG+CT10)

A precise measurement of $\sin^2\theta_W$

- Build full likelihood of the experimental observables in the μμ channel: θ*, invariant mass and rapidity (Y) of the dimuon system, based on:
  - $\sin^2\theta_W$ dependence at generator level (P_{ideal})
  - Convolutions (R) and acceptances (G) to parameterize the experimental response

$$\mathcal{P}_{\rm sig}(Y,s,\cos\theta^*;\theta_W) = \mathcal{G}(Y,s,\cos\theta^*) \times \int_{-\infty}^{+\infty} dx\,\mathcal{R}(x)\,\mathcal{P}_{\rm ideal}(Y,s-x,\cos\theta^*;\theta_W)$$





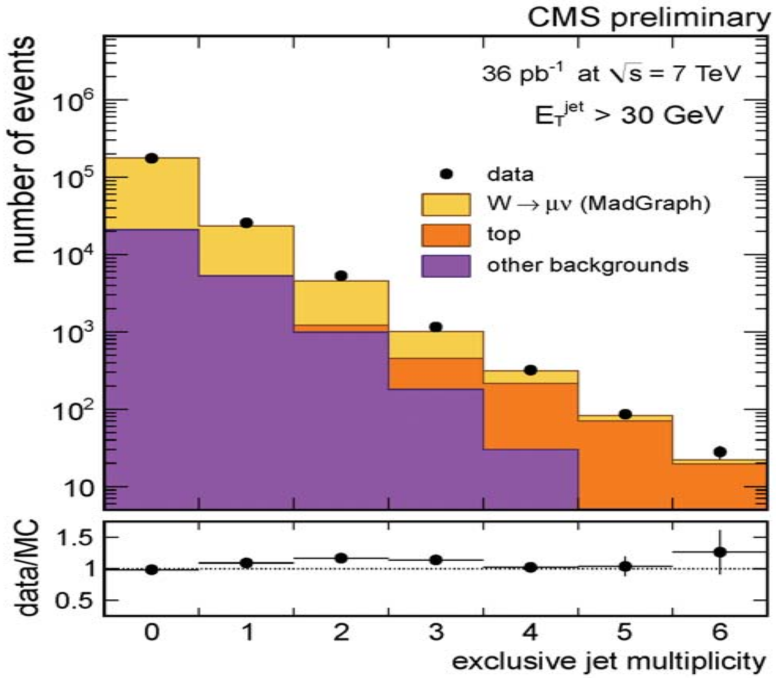
NEW Results based on 1 fb^{-1}

$\sin^2\theta_{eff}=0.2287\pm0.0020\pm0.0025$

Improved precision with respect to a measurement based on A_{FB} only !

W and Z produced in association with jets

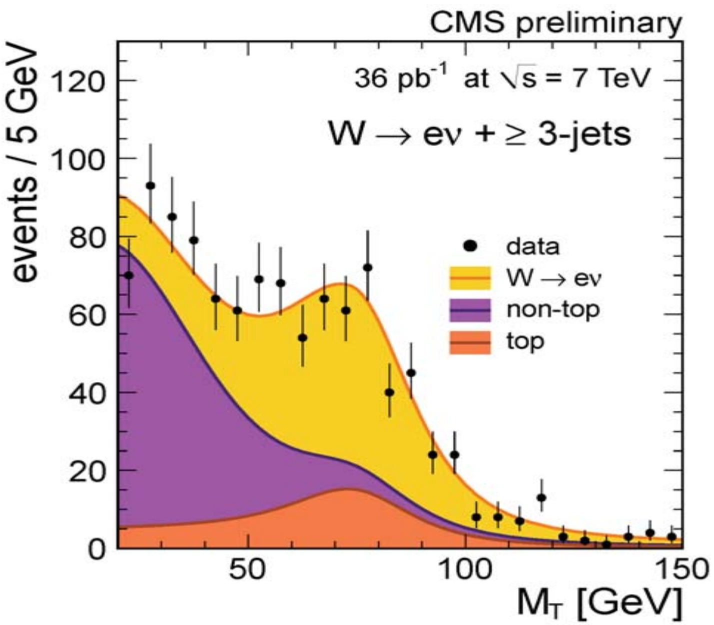
- Important background in many BSM searches
- W / Z Selection follows closely inclusive analysis
- Additional requirement for presence of jets:
  - Jet P_t> 30 GeV in $|\eta|$ <2.4
- Signal extraction more difficult because of large backgrounds (QCD, top)

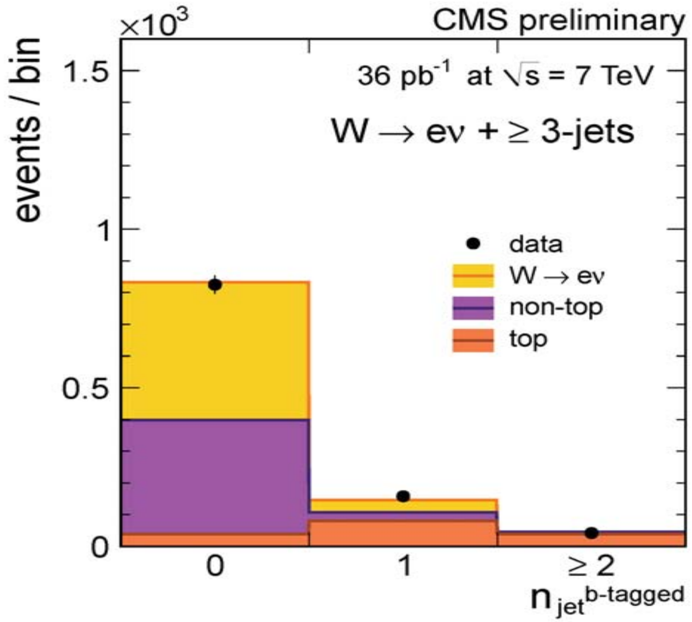


- Most CMS result presented in terms of ratios to allow for cancellation of systematic uncertainties

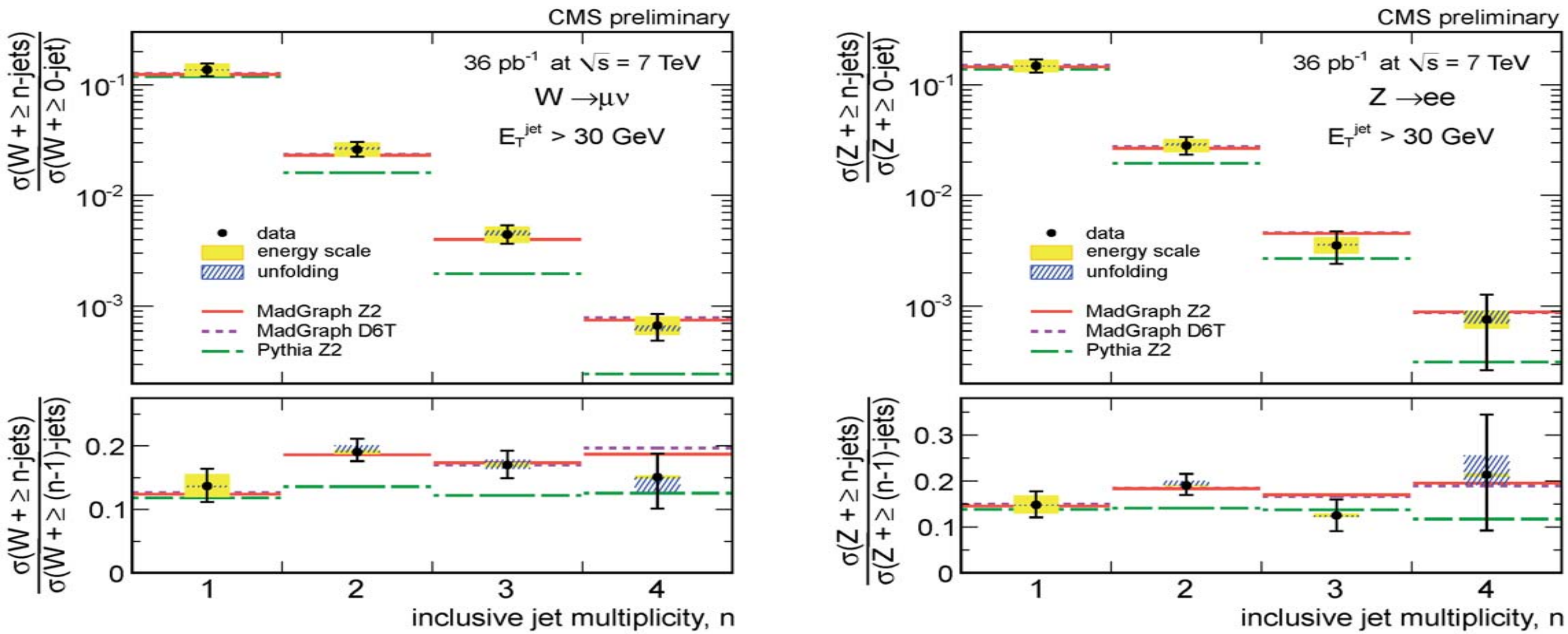
W+jets, Z+jets: signal extraction

- For each jet multiplicity:
  - Z+jets: fit the di-lepton invariant mass distribution
  - W+jets: fit the MT distribution and the number of b-tagged jets (to extract the top contribution in a data-driven way)





W+jets, Z+jets: Results



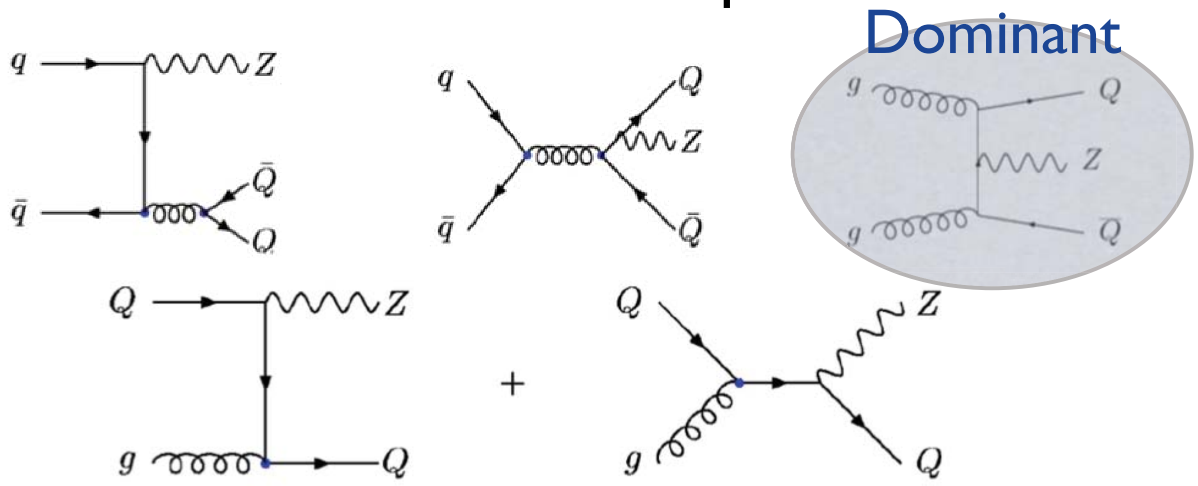
- Dominant systematics: Jet energy scale, unfolding at high jet multiplicities
- Data agree well with MadGraph, but not with Pythia

Z + b jets

- Important background for many searches, in particular for Higgs
- Two theory approaches used to model this process

Fixed-flavor scheme
(no b-quark at parton level)
Caclulations with massive b quark

Variable-flavor scheme
(b-quark at parton level,
gluon splitting integrated in PDF)

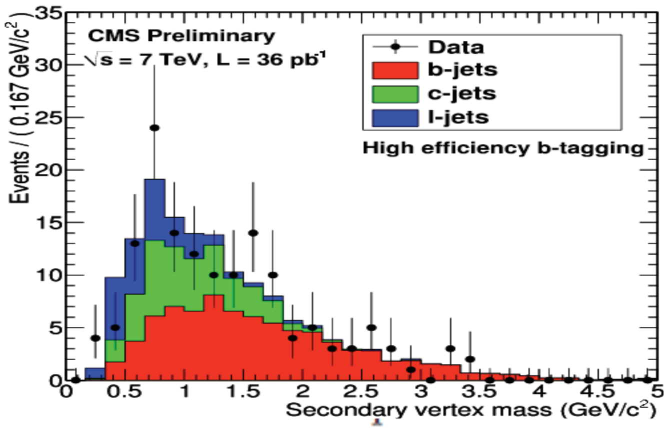


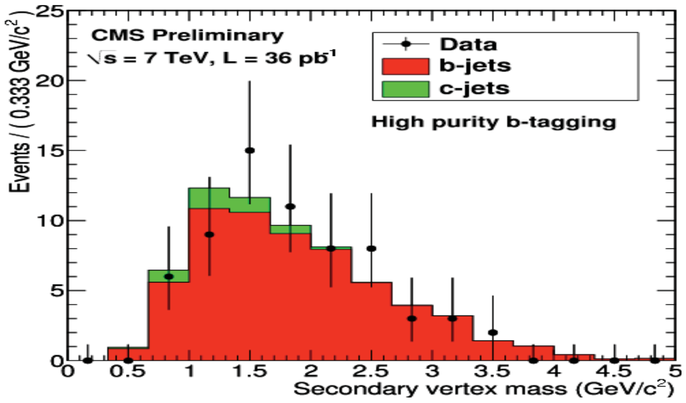
- Analysis strategy:

1) Select Z→ ee / μμ decays, MET<40 GeV (against top)
2) PF Jet with ET>25 GeV.
3) Apply b-tagging on jet: Seconday Vertex with high/low purity
4) Measure ratio σ(Z+b) / σ(Z+jet)

Z+b jets

- 65 selected events in 36 pb^{-1} of data
- B Purity determined from template fits to b and non b component of secondary vertex mass distribution





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	$4.3 \pm 0.5(theory)$	$4.7 \pm 0.5(theory)$

← Variable flavour (MADGRAPH)
← Fixed flavour (MCFM)

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

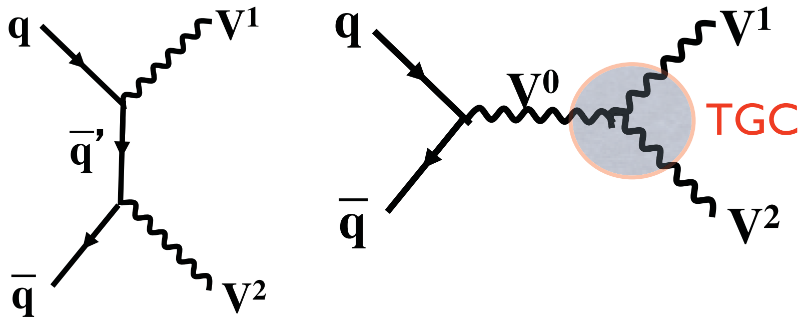
➡Results in agreement with predictions

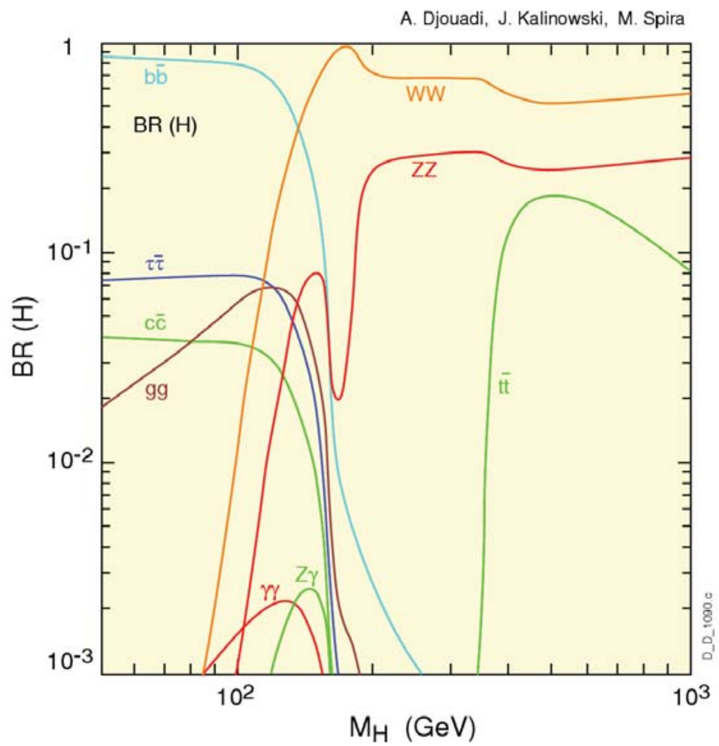
➡No statistical power to disentangle the 2 approaches yet

Update on 1 fb^{-1} coming soon

Diboson physics

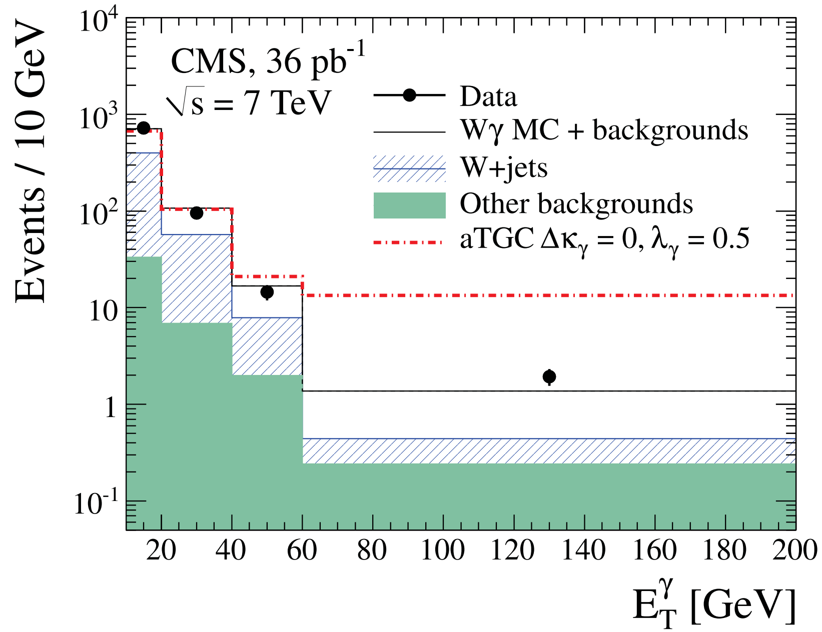
- Fundamental test of the Standard Model
  - Cross Section
  - Gauge boson self-interaction (TGCs) is of particular interest
- Probe for new Physics
  - Search for resonant production (Higgs, fermiophobic Higgs, Technicolor, …)
  - Search for anomalous couplings
- Important background in many searches
  - e.g. Higgs → WW, ZZ





Dibosons: $W\gamma(\rightarrow l\nu\gamma)$

- W Selection:
  - Pt(e/μ) > 20 GeV
  - Missing E_T > 25 GeV
- Photon Selection:
  - ET>10 GeV
  - ΔR(lepton,γ) > 0.7
- Dominant background: fake photon background from W+jets
  - Suppressed with tight γ isolation
  - Estimated from data



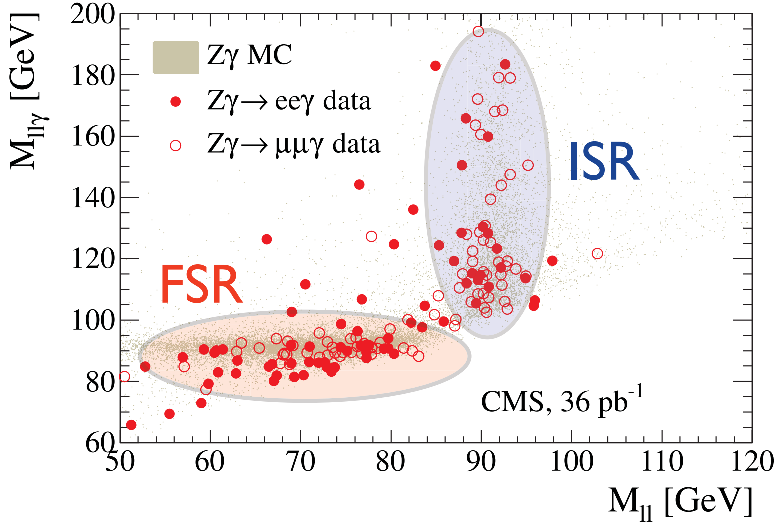
Measured cross section with 36 pb^{-1}:
(ET(γ)>10 GeV, ΔR(l,γ)>0.7)

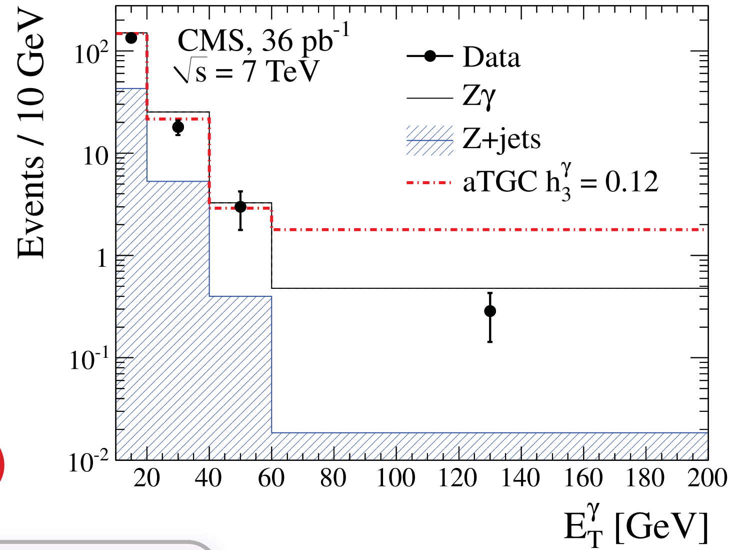
$$56.3 \pm 5.0\,(\text{stat.}) \pm 5.0\,(\text{syst.}) \pm 2.3\,(\text{lumi.})\ \text{pb}$$

NLO Prediction: 49.4±3.8 pb

Dibosons: Zγ(→ llγ)

- Z Selection follows inclusive selection:
  - 60<M_{ll}<120 GeV
- Photon Selection:
  - E_T>10 GeV
  - ΔR(lepton,γ) > 0.7
- Dominant (and nearly only) background: Z+jets





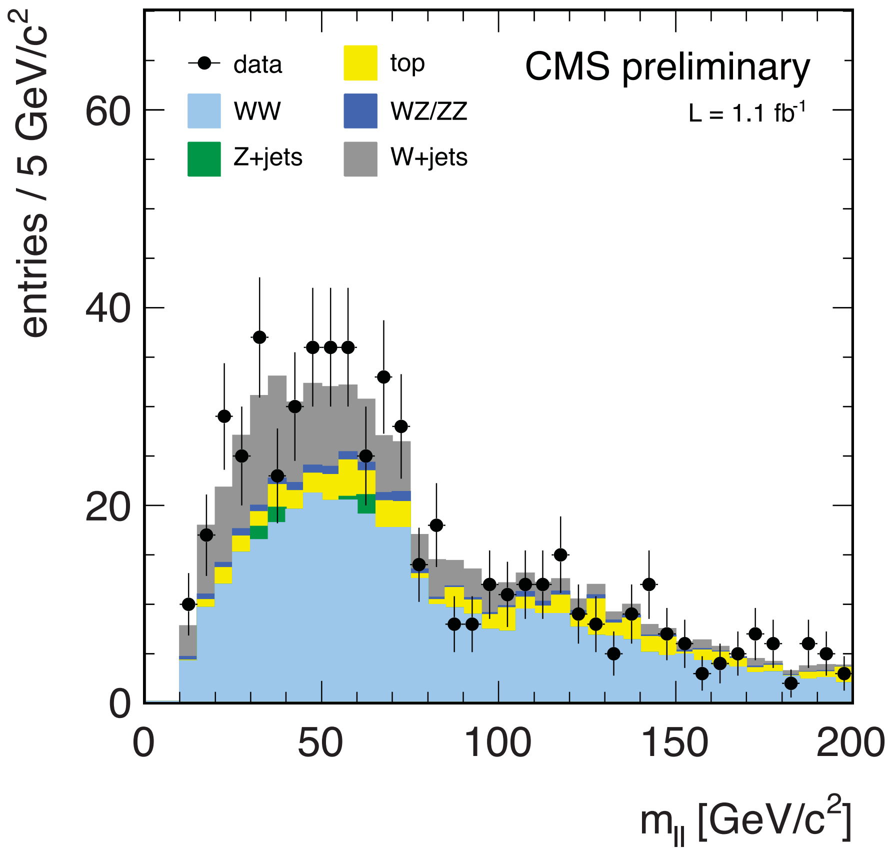
Measured cross section
with 36 pb^{-1}:
($E_T(\gamma)$>10 GeV, ΔR(l,γ)>0.7, 60<M_{ll}<120 GeV)

$$9.4 \pm 1.0\ (\text{stat.}) \pm 0.6\ (\text{syst.}) \pm 0.4\ (\text{lumi.})\ \text{pb}$$

NLO prediction:
9.6±0.4 pb

Dibosons: WW(→llνν)

- Signal Signature: 2 isolated leptons with significant missing ET from 2 ν's
  - Challenging due to many backgrounds



- Analysis strategy in 2011:
  - Leading (trailing) Lepton P_t>20 (10) GeV
  - Jet-veto (30 GeV): W+jets and top rejection
  - No missing E_T along lepton axes: ττ rejection
  - Missing E_T>40 (20) GeV for ee/eμ (eμ) final state
  - Third lepton veto: WZ/ZZ rejection
  - DY Rejection (for ee/μμ):
    - Mll>12 GeV
    - Veto Z window 76<Mll<106 GeV
    - ΔΦ(di-lepton,remaining jet p_T>15 GeV)<165°

Dibosons: WW(→ llνν) 2011 Result

- Background estimation
  - Dominant backgrounds estimated through data-driven methods:
    - QCD/W+jets
    - Top
    - DY/WZ/ZZ
  - MC Estimation for smaller backgrounds

Event yields

Sample	Yield
$qq \to W^+W^-$	349.7 ± 30.3
$gg \to W^+W^-$	17.2 ± 1.6
$W + \text{jets}$	106.9 ± 38.9
$t\bar{t} + tW$	63.8 ± 15.9
$Z/\gamma^* \to \ell\ell + WZ + ZZ$	12.2 ± 5.3
$Z/\gamma^* \to \tau\tau$	1.6 ± 0.4
WZ/ZZ not in $Z/\gamma^* \to \ell\ell$	8.5 ± 0.9
$W + \gamma$	8.7 ± 1.7
signal + background	568.6 ± 52.2
Data	626

Measured cross section for $\sigma(W^+W^-)$:

2011 data with 1.1 fb^{-1} 55.3±3.3(stat)±6.9(syst)±3.3(lumi) pb

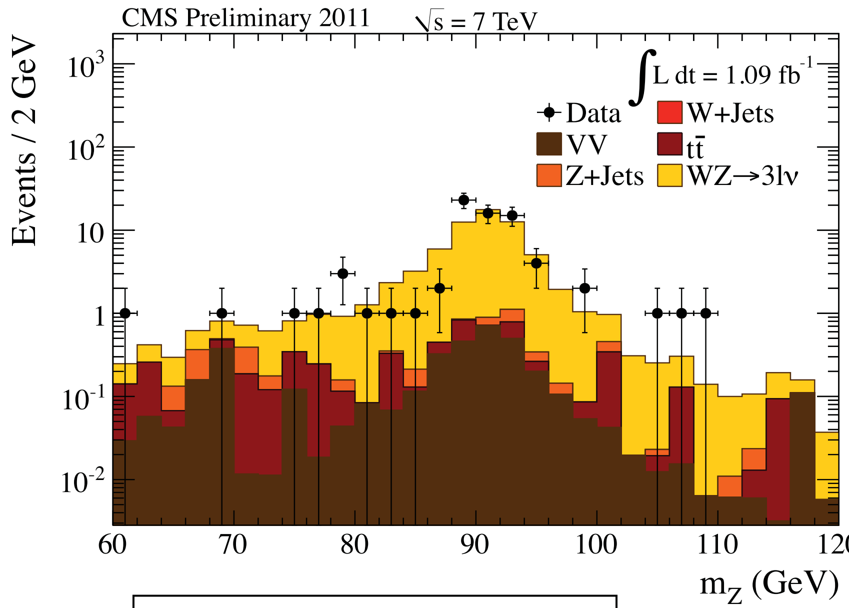
2010 data with 36 pb^{-1} 41.1±15.3(stat)±5.8(syst)±4.5(lumi) pb

NLO prediction: 43.0±2.1 pb (qq→WW) + 1.46 pb (gg→ WW)

Dibosons: WZ ($\rightarrow 3l\nu$)

Signal Signature: 3 leptons + significant missing E_T

- Analysis strategy:
  - Z Selection similar to inclusive analysis, $60<M_{ll}<120$ GeV
  - W Selection:
    - Pt(e/μ)>20 GeV
    - MET>30 GeV
- Main backgrounds estimated in data-driven way: Z+jets and Top



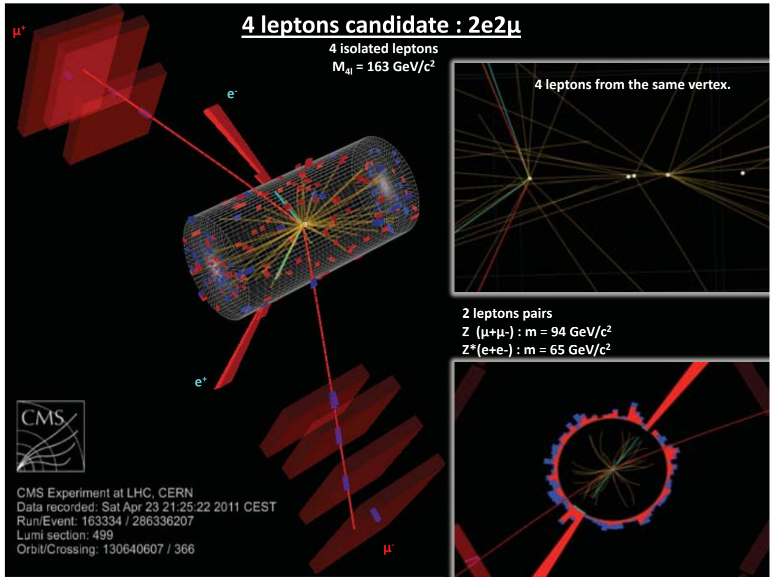
More details in S. Morović's talk

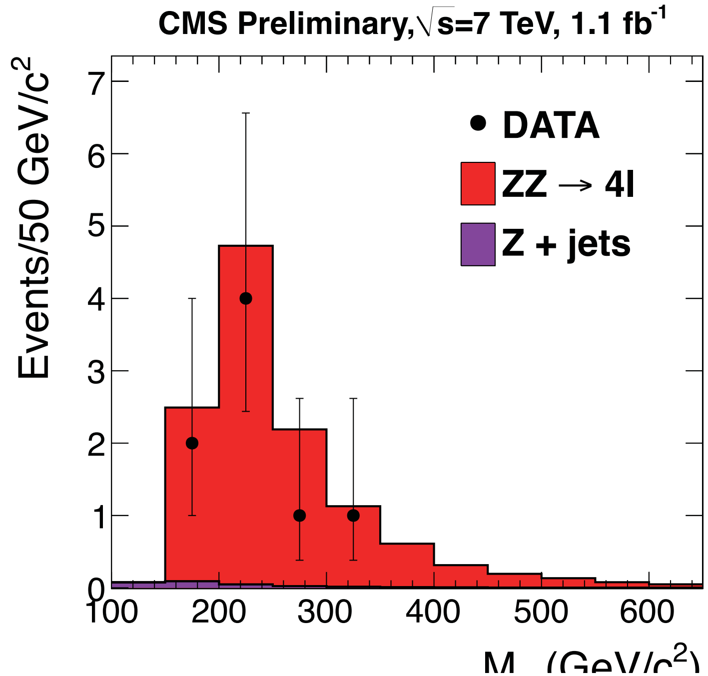
Measured cross section for σ(pp→ WZ): 17.0±2.4(stat)±1.0(syst)±1.0(lumi) pb

NLO prediction: 17.5±0.6 pb

Dibosons: ZZ ($\rightarrow$ 4l)

- Considered 4 leptons final states
  - 4e,4μ,2e2μ,2l2τ(l=e,μ)
- Z selection
  - $60 < M_{ll} < 120$ GeV for l=e,μ
  - 30 < visible ττ mass < 80 GeV
- Nearly background free
  - Remaining backgrounds determined from data: Zbb, top, Z+jets





Dibosons: ZZ(→4l) Results

Event yields

Final state	N_{obs}	$N^{backg.}_{estimated}$	$N^{ZZ}_{expected}$
4μ	2	0.004 ± 0.004	3.7 ± 0.4
$4e$	0	0.14 ± 0.06	2.5 ± 0.2
$2e2\mu$	6	0.15 ± 0.06	6.3 ± 0.6
$2l2\tau$	1	0.8 ± 0.1	1.4 ± 0.1

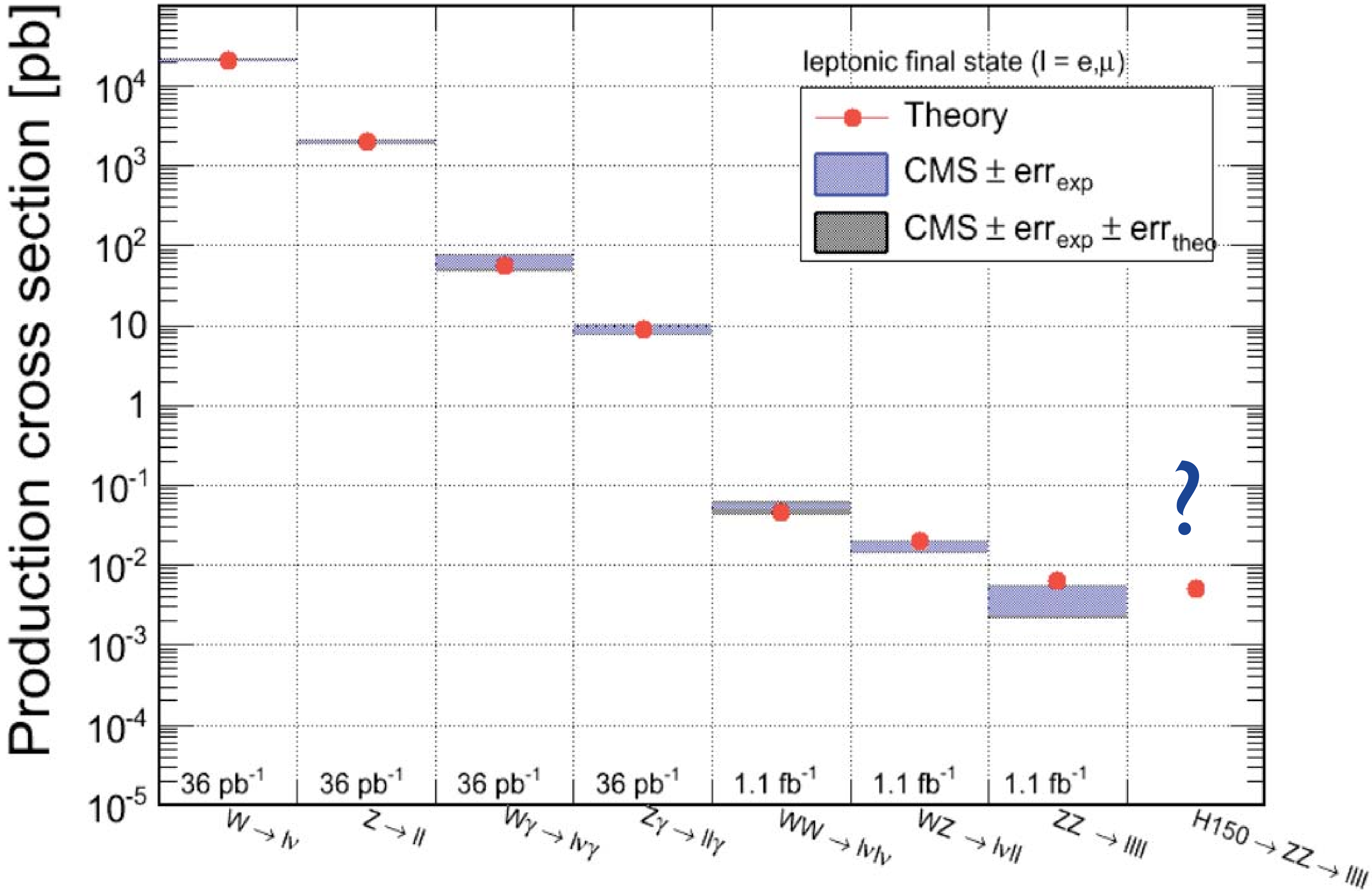
2010 and 2011 Data used: 1.1 fb^{-1}

Measured cross section (from a constrained fit using all channels):

$$\sigma(pp \to ZZ + X) = 3.8^{+1.5}_{-1.2}\,(\text{stat.}) \pm 0.2\,(\text{syst.}) \pm 0.2\,(\text{lumi.})\text{ pb}$$

NLO Prediction: 6.4±0.6 pb

EWK Bosons & Dibosons: the whole picture



Limits on anomalous couplings with Wγ and Zγ

Study the $E_t(\gamma)$ spectrum to search for anomalous couplings

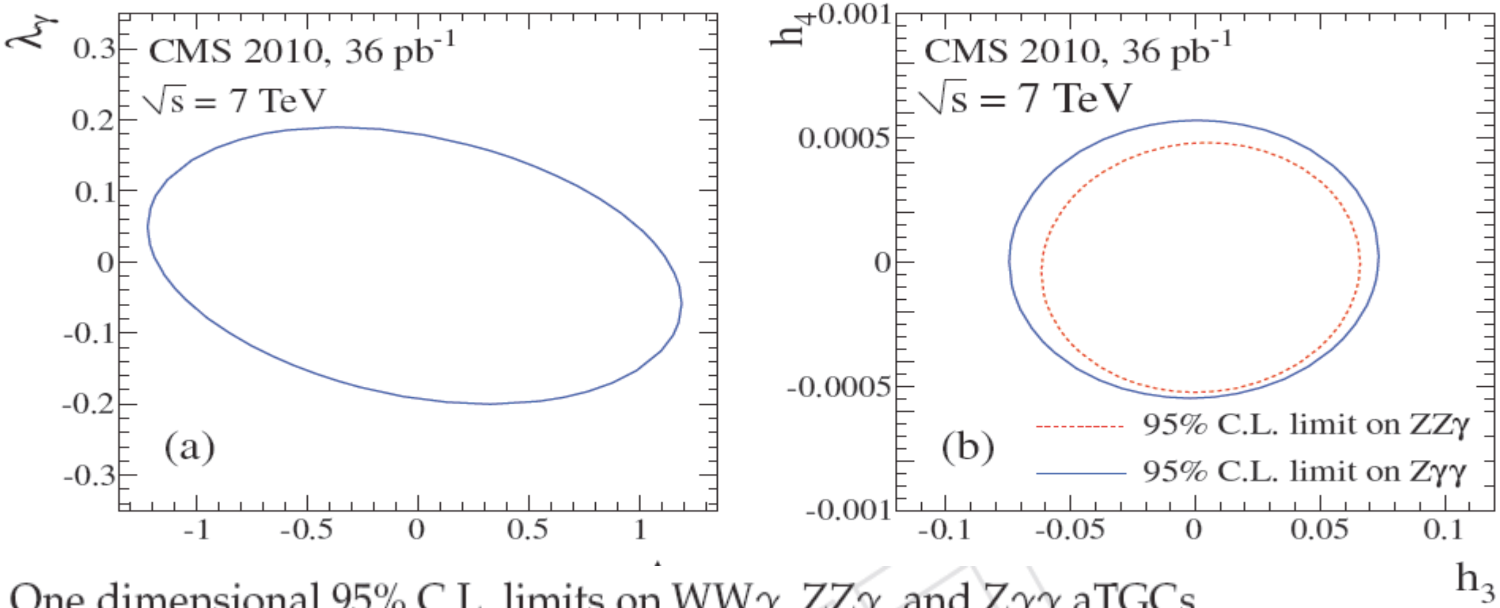


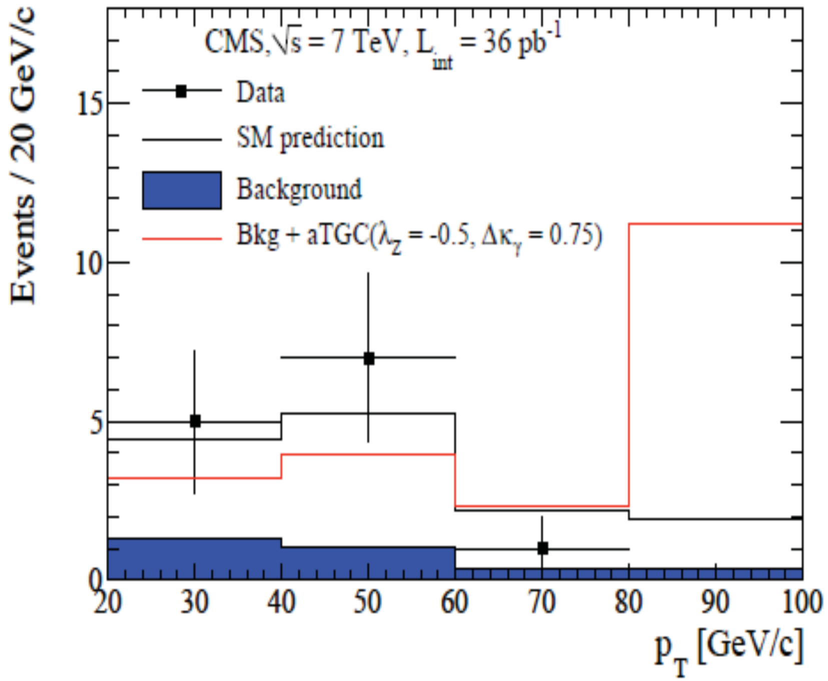
Table 3: One dimensional 95% C.L. limits on $WW\gamma$, $ZZ\gamma$, and $Z\gamma\gamma$ aTGCs.

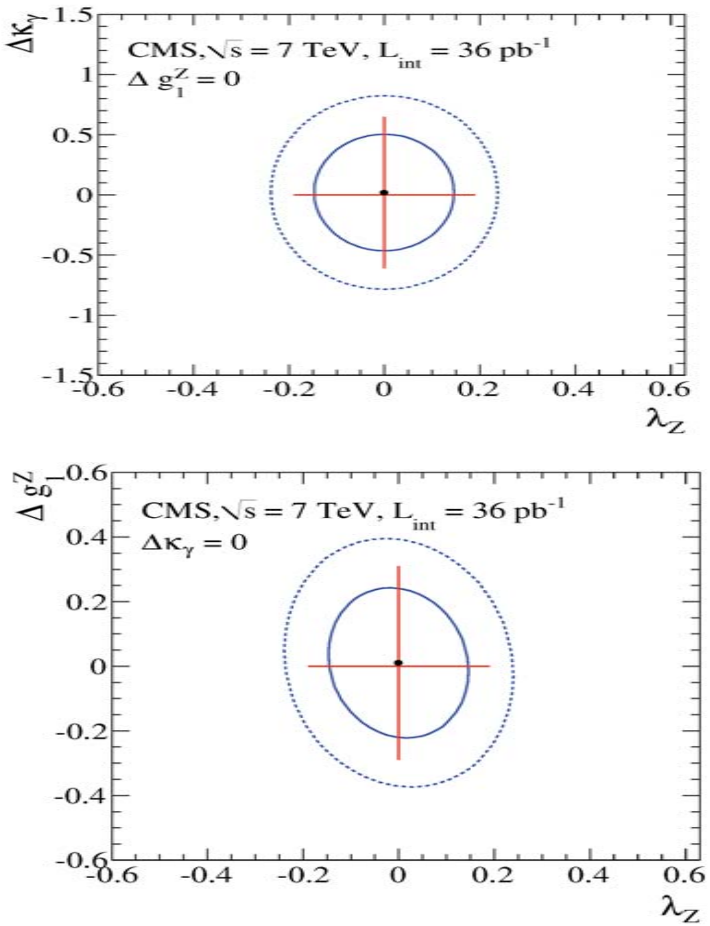
$WW\gamma$	$ZZ\gamma$	$Z\gamma\gamma$
$-1.09 < \Delta\kappa_\gamma < 1.03$	$-0.05 < h_3 < 0.06$	$-0.07 < h_3 < 0.07$
$-0.18 < \lambda_\gamma < 0.17$	$-0.0005 < h_4 < 0.0005$	$-0.0005 < h_4 < 0.0006$

- Limits on h_4 have similar sensitivity to Tevatron with just 36 pb^{-1}

Limits on anomalous couplings with WW

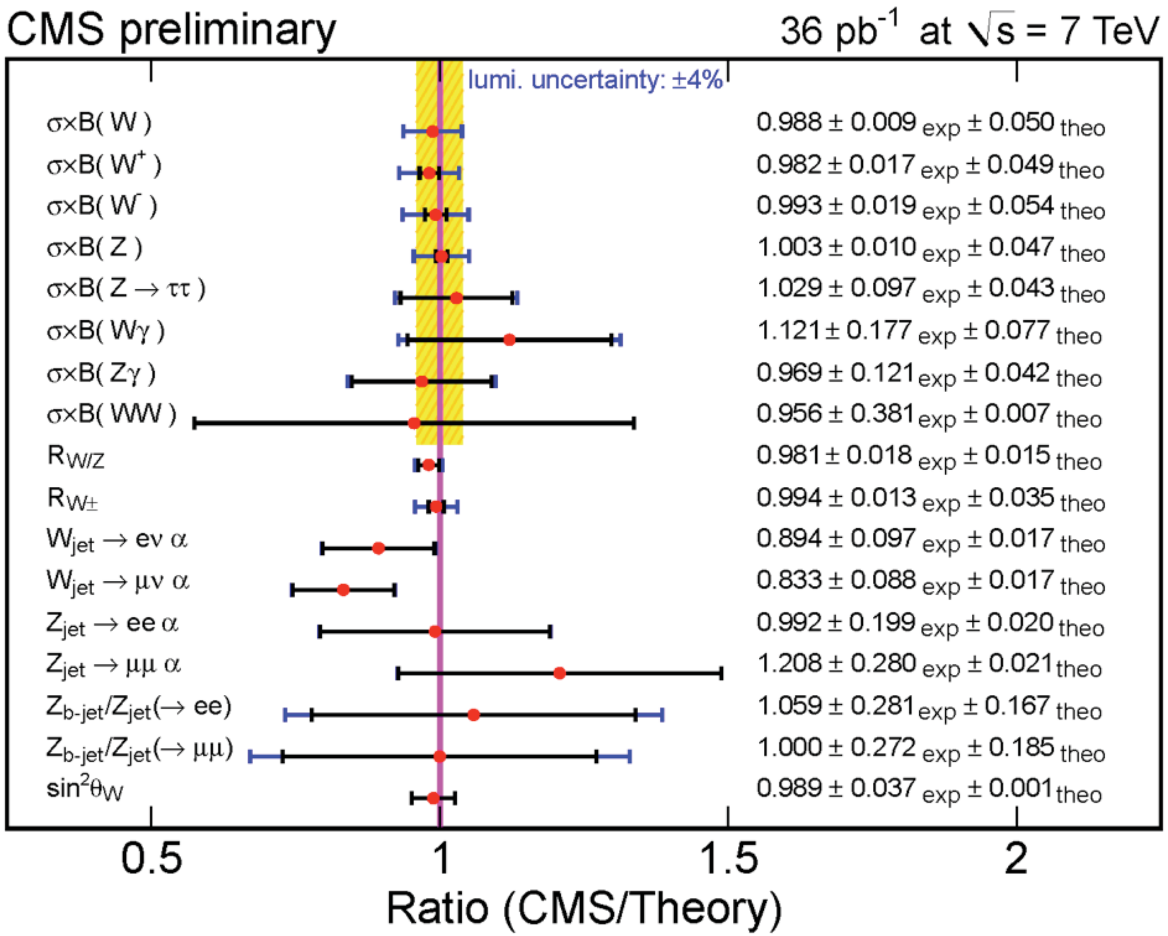
Use Leading Lepton P_T to set limits on anomalous WWγ and WWZ couplings





- Sensitivity similar to Tevatron also here with just 36 pb^{-1}

CMS EWK Measurements in 2010



- **The SM passes the 7 TeV test very well!**
- Needs to updated / extended with our 2011 measurements

Conclusions

- In 2010 and 2011, CMS has provided many electroweak measurements that test the SM @ 7 TeV
- So far, all electroweak measurements are in agreement with SM predictions
- But clear room for improvement:
  - Many measurements (V, V+jets, Vγ) are completed only with $36pb^{-1}$ and will profit greatly from more luminosity
  - VV measurements have only just begun
  - More new measurements to come soon (e.g. VV in hadronic final states)