Production of W and Z Bosons and of W/Z+Jets at CMS

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On behalf of the CMS Collaboration

Standard Model Benchmarks at High-Energy Hadron Colliders
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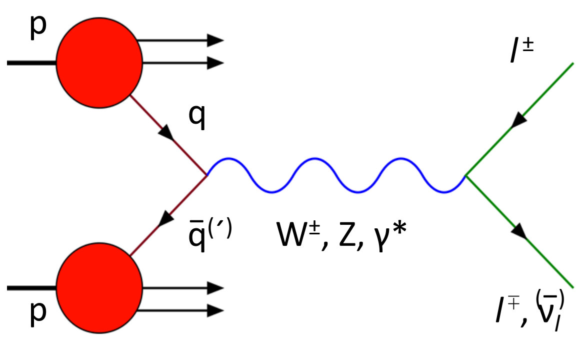
DESY (Zeuthen)

Electroweak Physics at the LHC

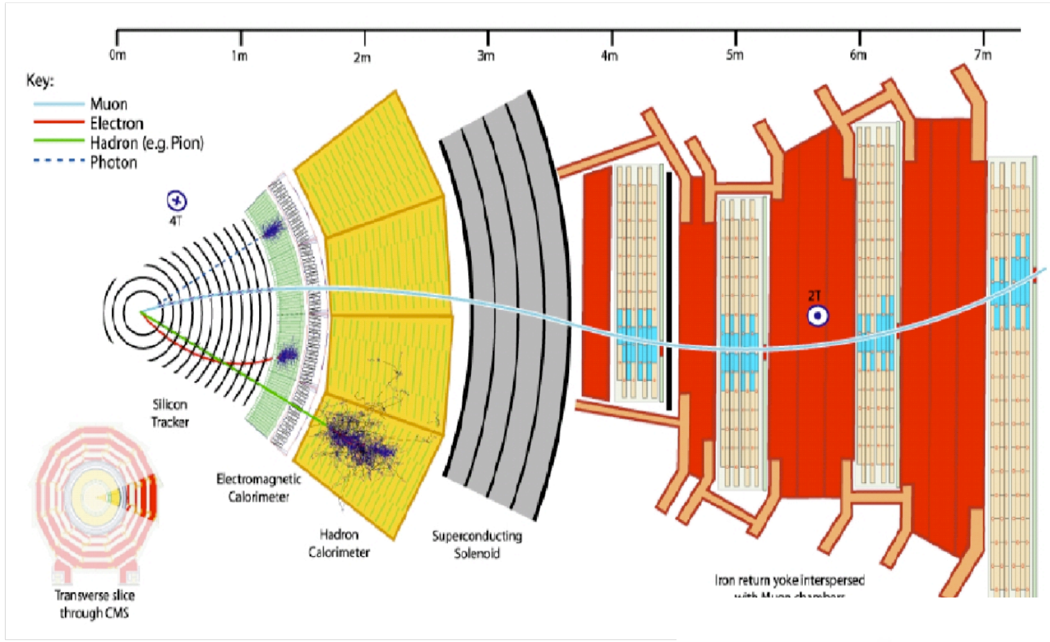


Selected EWK Results from CMS

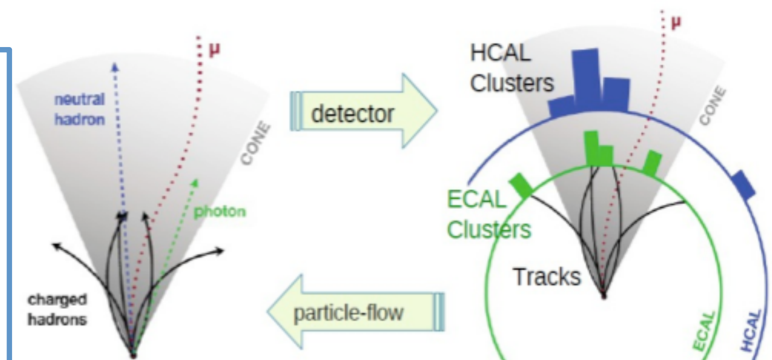
- W/Z Inclusive Cross Sections
- W Charge Asymmetry
- Z Differential Cross Sections
- Drell-Yan process, AFB and Weinberg Angle
- V+Jets
- Z+b jets
- W Polarization
- V+γ Production
- WW Production

- Understanding EWK production is essential before any discovery claims.
  - The production of W and Z bosons decaying into leptons is one of the best understood processes at the colliders.
  - Standard Candles and Backgrounds in searches for new particles
- EWK measurements are used to constrain PDFs.
- High p_T leptons from W's and Z's are used to understand efficiency, resolution, energy scale, and in general understanding the detector.

Particles Reconstruction, ID and Event Selection



- *Isolated high p_T leptons.*
- Unprescaled electron and muon triggers;
- trigger on τ + MET for $W \rightarrow \tau\nu$.
- Efficiencies determined using tag-and-probe using $Z \rightarrow l^+l^-$.
- Major backgrounds estimated using data-driven methods.
- Tau reconstruction using particle flow algorithm.

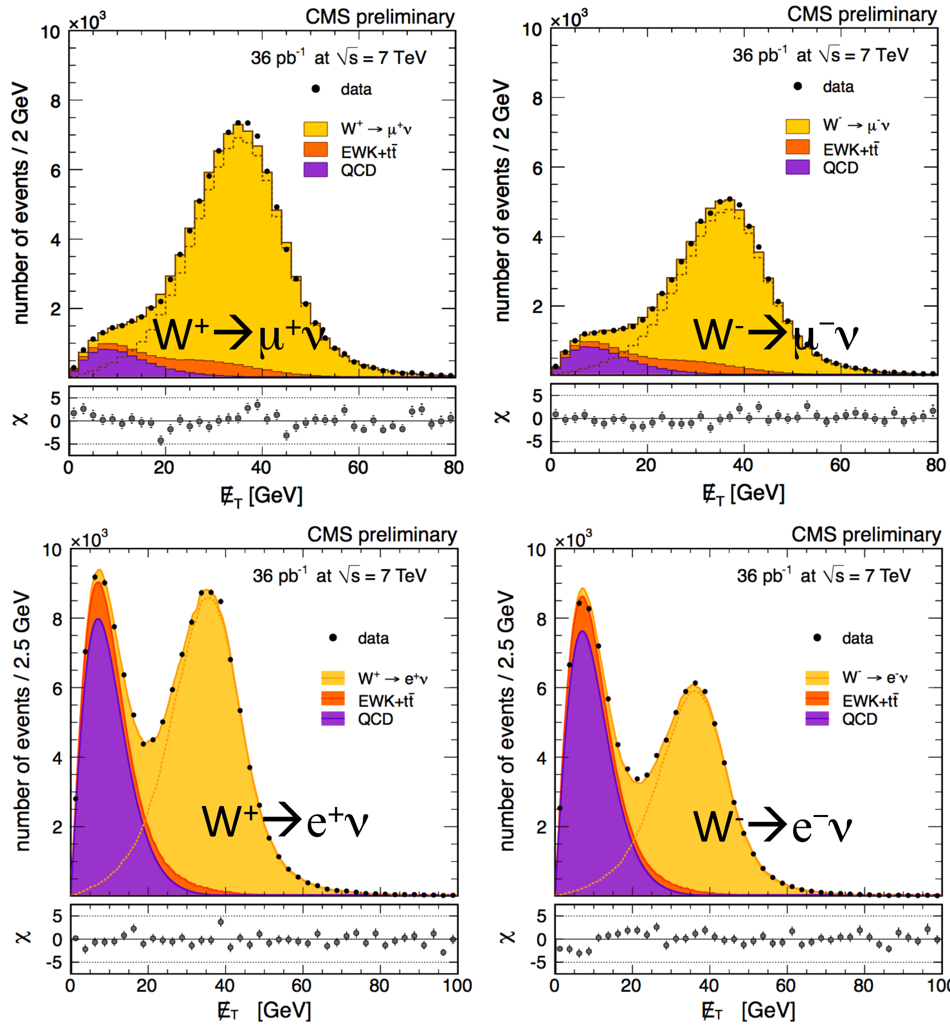


Particle-Flow Algorithm combines data from all sub-detectors to identify and reconstruct all particles from the collision; charged/neutral hadrons, photons, muons, electrons. Resulting list of particles are then used to construct jets, MET, taus, ..

CMS-PAS-EWK-10-005

$W \rightarrow e\nu, \mu\nu$

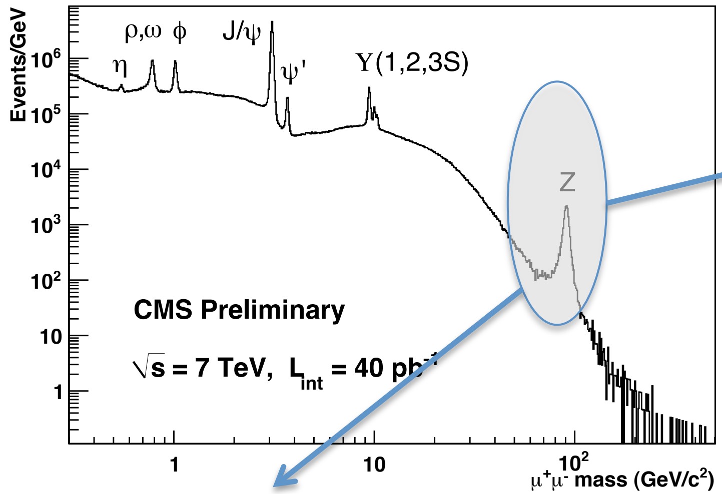
- W signal extracted from fits to the MET distributions.
- QCD background shape modeled from data inverting lepton ID and isolation cuts.
- Signal MET shapes from simulation for W^+ and W^- corrected event-by-event vs p_T^W determined from hadronic recoil response and resolution distributions of $Z \rightarrow l^+l^-$ from data.

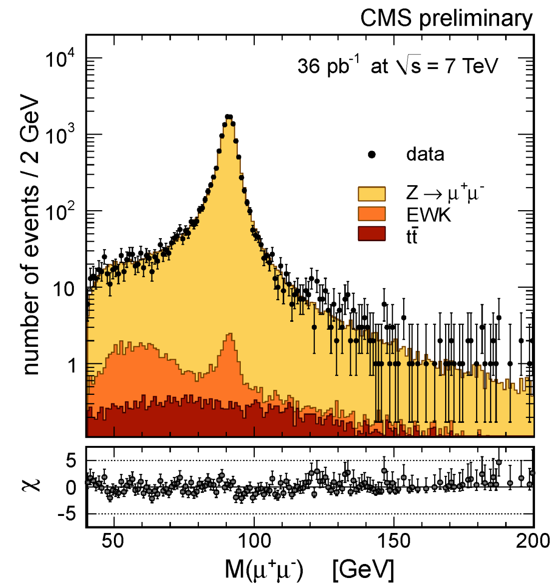


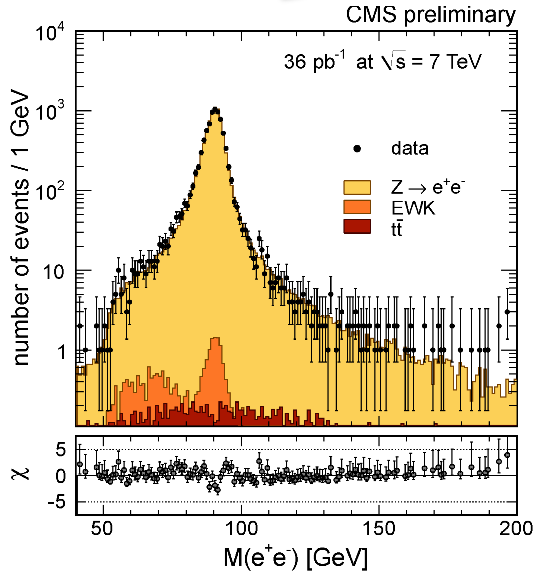
σxBR=10.31±0.02(stat) ±0.13(sys) ±0.41(lumi) nb

$Z \rightarrow e^+e^-, \mu^+\mu^-$

CMS-PAS-EWK-10-005





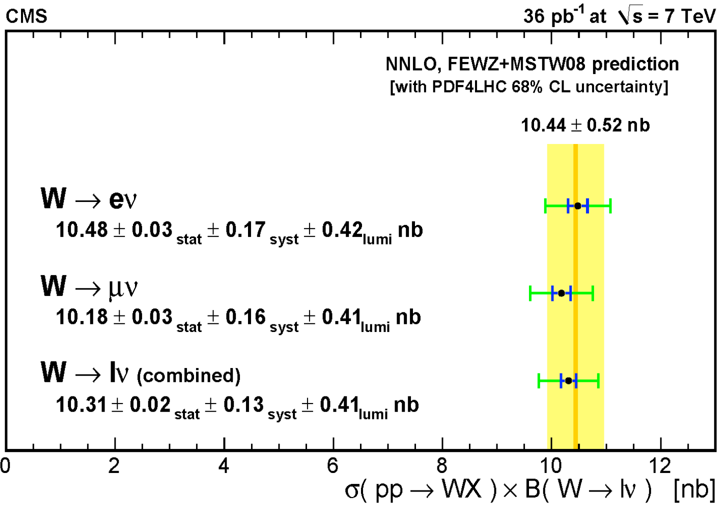


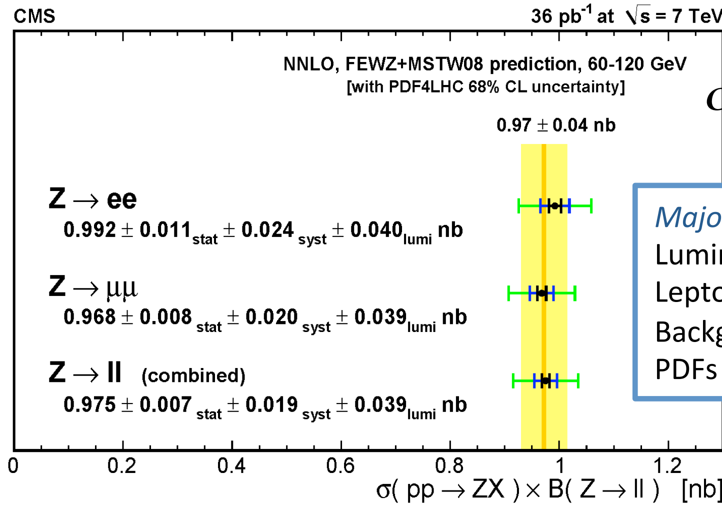
- Z signal: Two isolated opposite sign high p_T leptons.
- Fit to mass spectrum
  - μμ: Simultaneous likelihood ratio fit of the yield and efficiencies
  - ee: Cut and count using tag-and-probe efficiencies.
- 60 < $M(l^+l^-)$ < 120 GeV.

Small shift of the peak of MC w.r.t. data → ECAL cluster energy scale corrections (for EB and EE).

σxBR=0.975±0.007(stat)±0.019(sys) ±0.039(lumi) nb

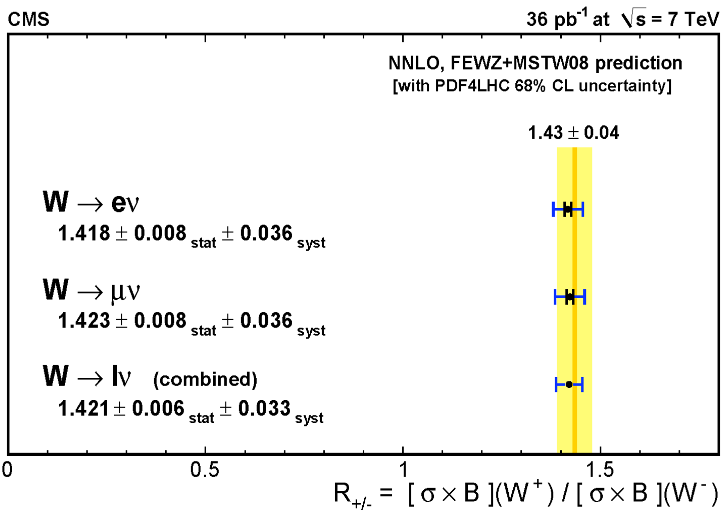
Comparison with Theory

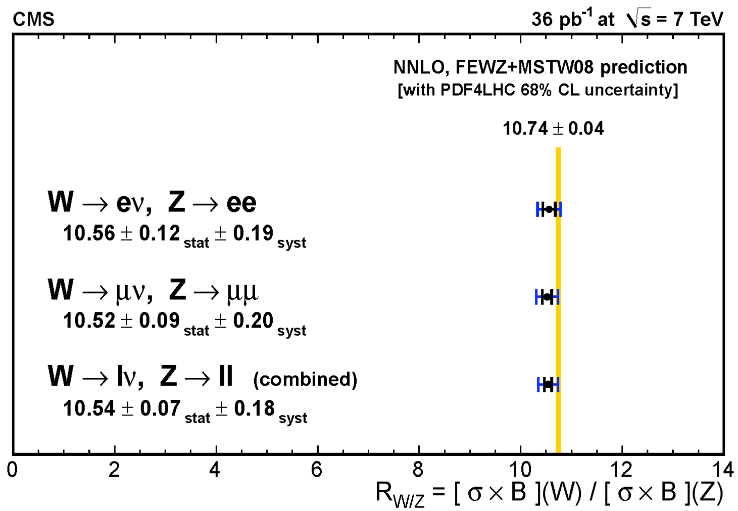




$$\sigma \times BR = \frac{N_s}{A \times \varepsilon \times \int Ldt}$$

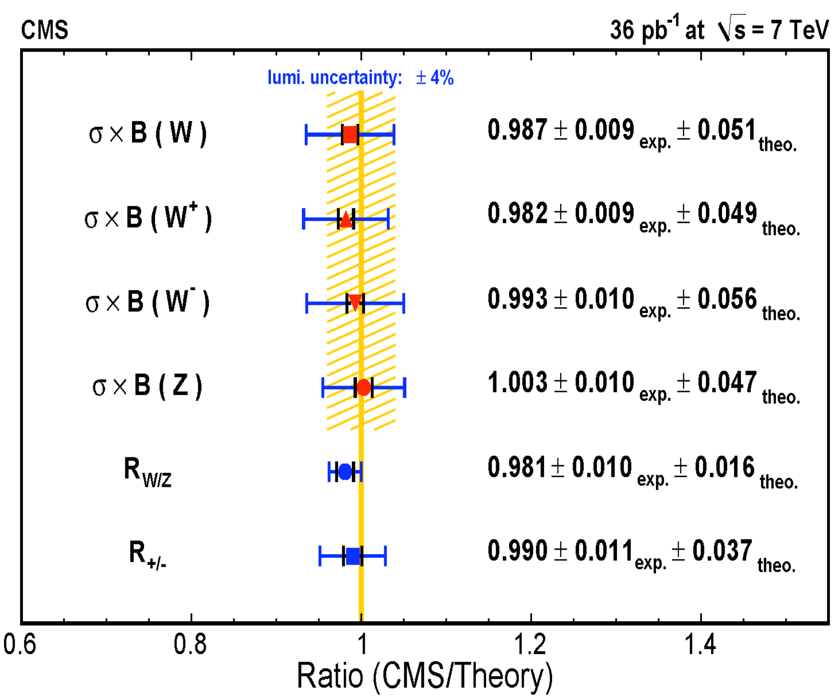
Major Systematics:
Luminosity normalization: 4%
Lepton reconstruction (ε): 0.9-1.3%
Backgrounds (N): 0.14-0.35%
PDFs (A): 0.6-1.2%

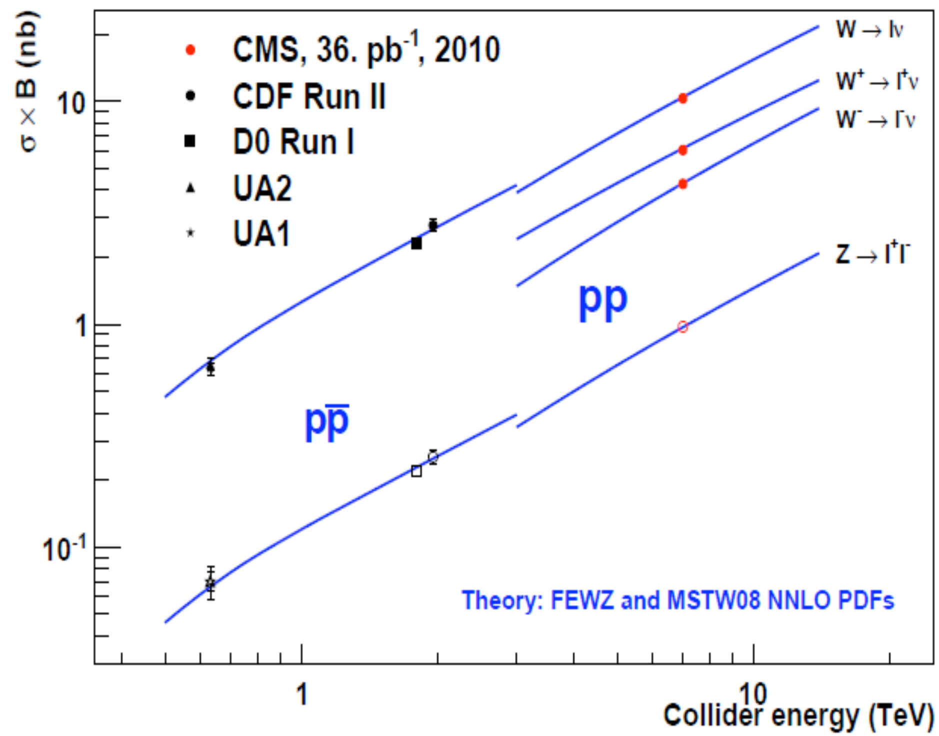




Individual cross sections, and their ratios agree well with theory predictions at NNLO.

Comparison with Theory





- **Individual cross sections, and their ratios agree well with theory predictions at NNLO.**
- **The increase of the Z and W cross sections with energy is confirmed.**

$W \to \tau\nu$

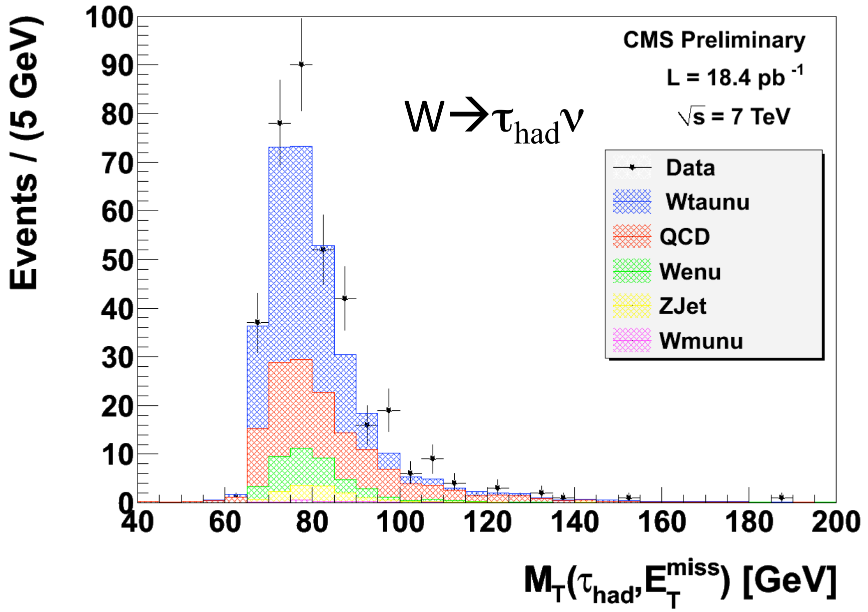
CMS-PAS-EWK-11-002

Important for searches of a light Higgs boson, SUSY or extra dimensions, ..

→ τ_{had}: highly-collimated jet with 1 or 3 charged mesons and 0,1 or 2 neutral pions.
→ **Single τ_{had} and MET trigger.**

QCD multi-jet background is controlled by dividing the phase space defined by MET and $p_T(\tau)/\Sigma p_T$(PF jets) into four regions.

Signal events from simulation: 174±3
EWK backgrounds from simulation: 46±2
QCD events from sideband: 109±6
 # Selected events in data: 372



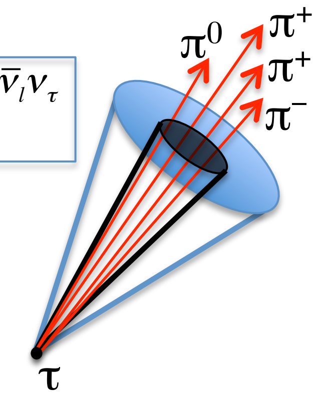
Preliminary analysis provide a statistically significant signal on top of QCD multi-jet and electroweak backgrounds.

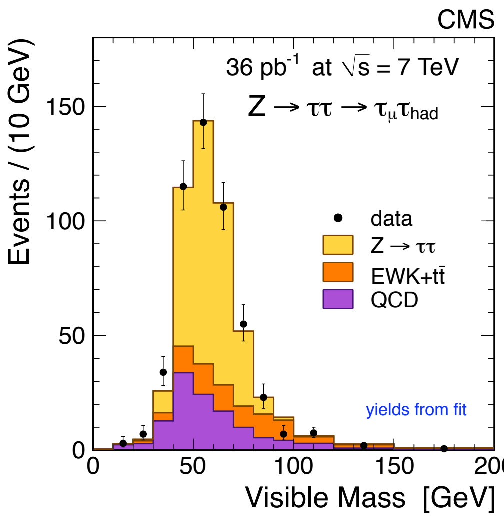
$Z \rightarrow \tau\tau$

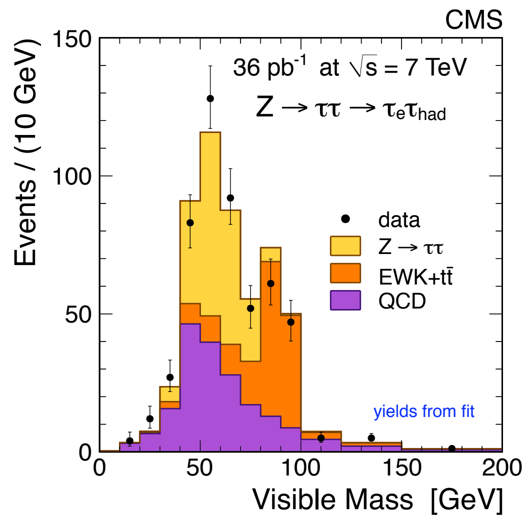
arXiv:1104.1617
CMS-PAS-EWK-10-013

Important for searches of a light Higgs boson, SUSY or extra dimensions, ..

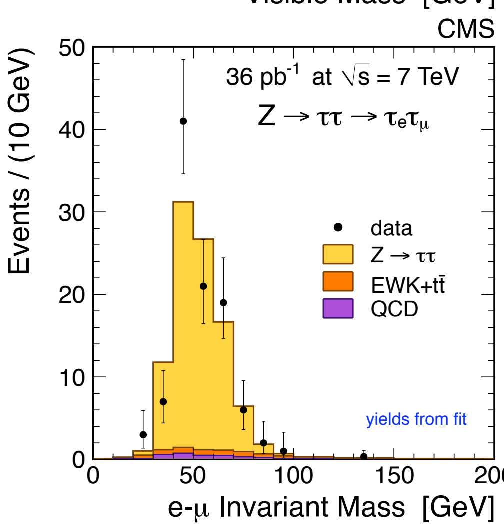
Leptonic final states: $\tau_l \equiv \tau \rightarrow l\bar{\nu}_l\nu_\tau$
Hadronic final states: τ_{had}

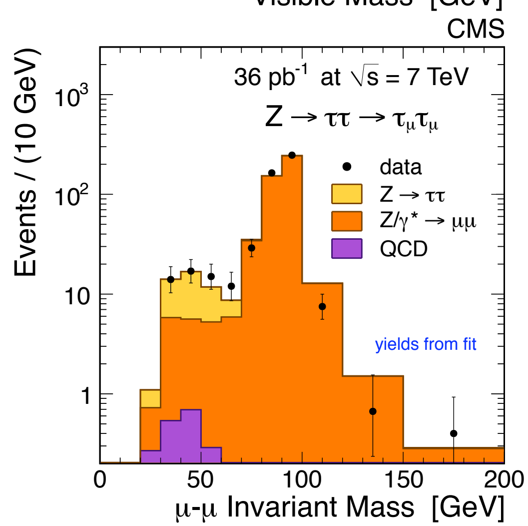






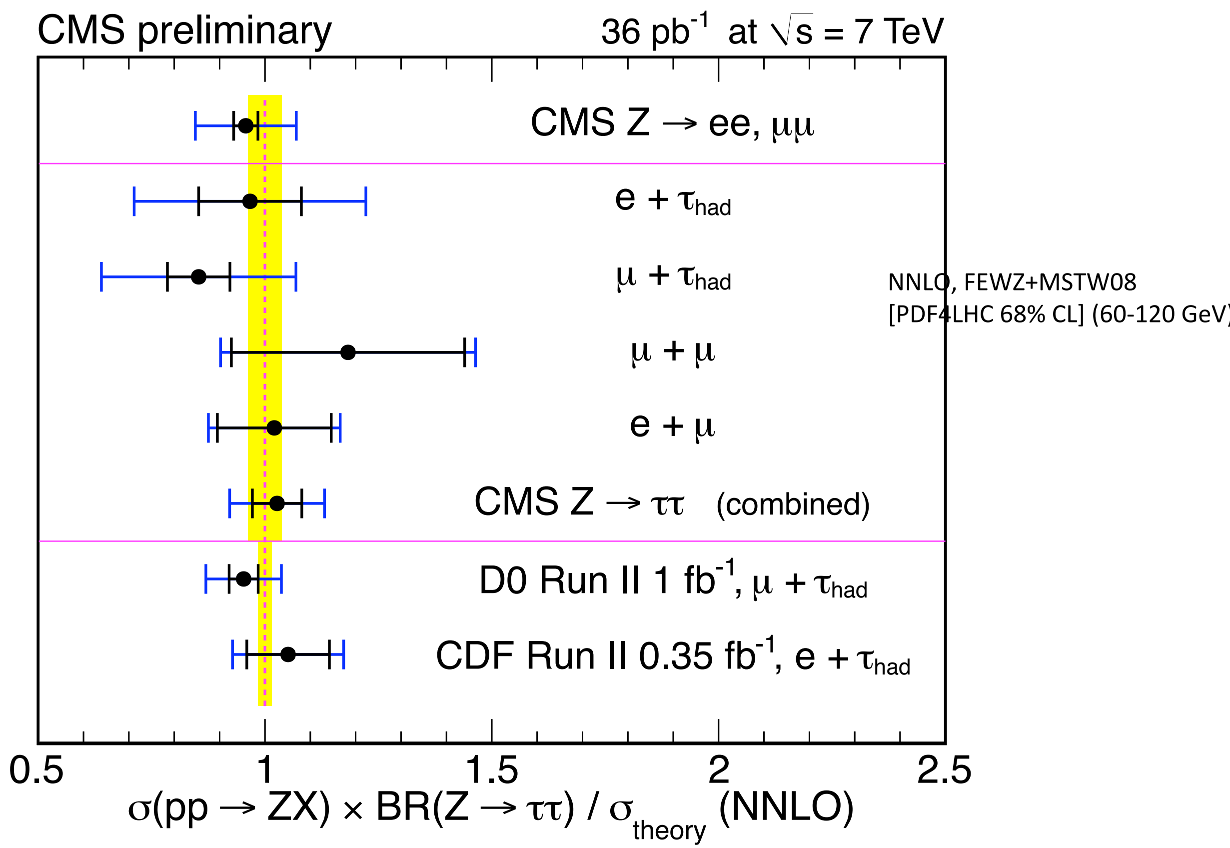
Signal yields from a maximum likelihood fit of the shapes from MC except for QCD, and $Z \rightarrow ll$ backgrounds.





Clear signal in all channels.
A global fit of the lepton+τ_{jet} channels provides a check on the reconstruction efficiency for semi-hadronic τ decays with a precision of ~7%.

Comparison to Theory and Previous Measurements

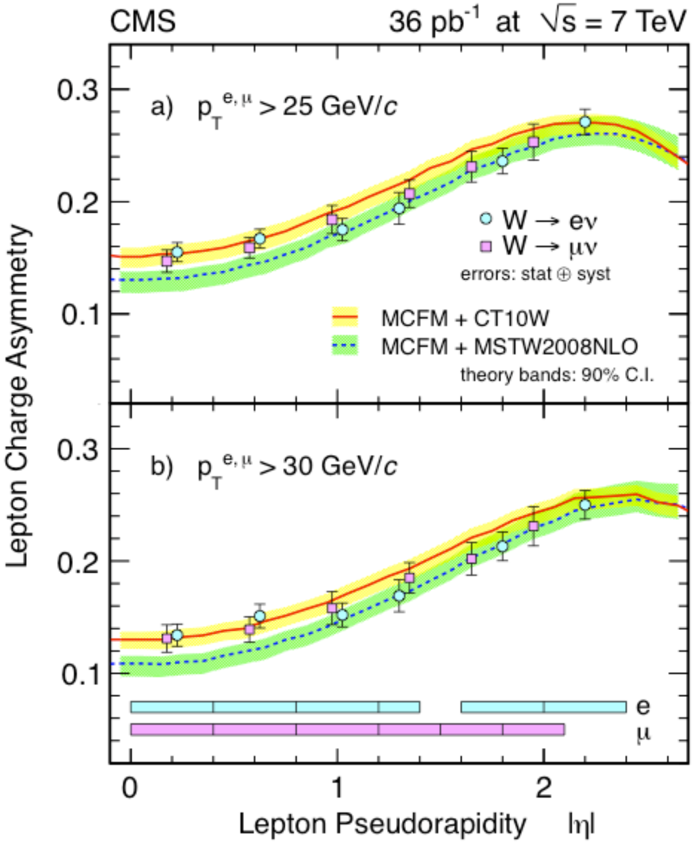


Statistical uncertainties smaller than the systematic uncertainties.
σxBR measurements are compatible with each other, with NNLO predictions, Tevatron measurements, and CMS measurements with Z→e^+e^-, $\mu^+\mu^-$ events.

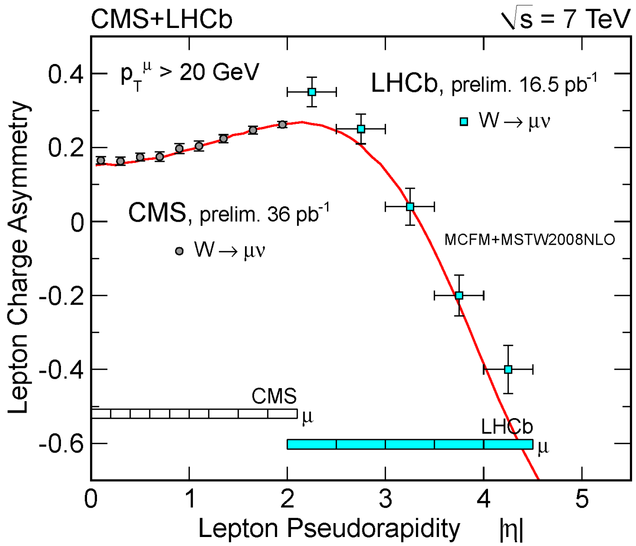
W Lepton Charge Asymmetry

JHEP04 (2011) 050

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



Highly sensitive to PDFs due to the cancellation of systematic uncertainties.
A vs η can provide better understanding of u/d ratio and the sea antiquark densities at √s=7 TeV.

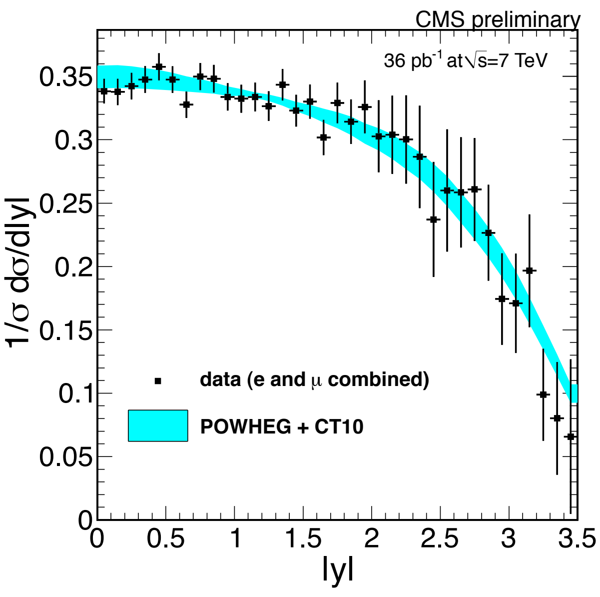


Flatter η-dependence than the PDF predictions.
In each η-bin, precision < 1.6%. Already sufficiently small to improve global PDF fits.

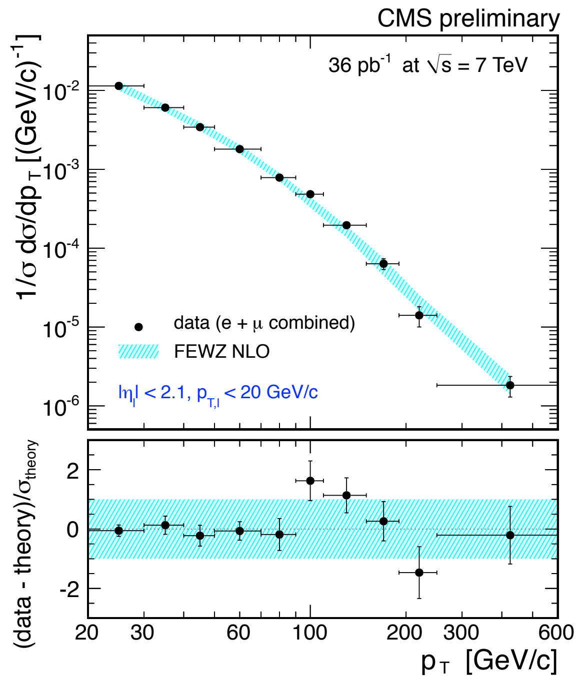
Z Differential Cross Sections

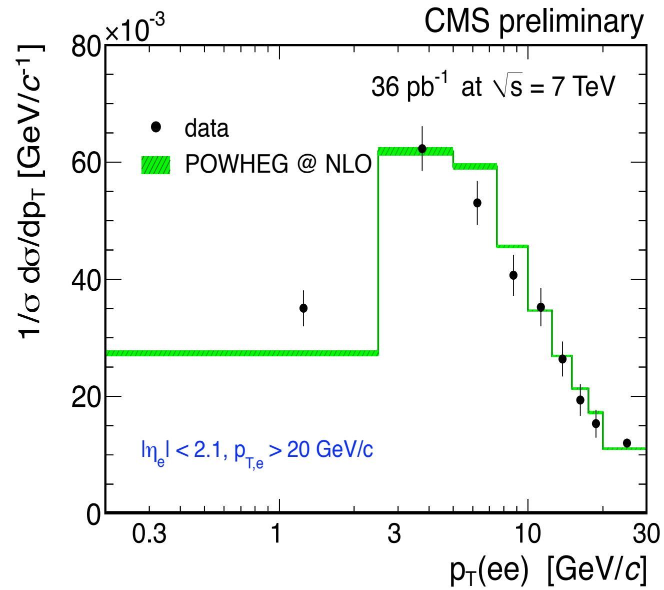
CMS-PAS-EWK-10-010

- An accurate description of the low and high p_T regions is essential for predicting the production rates and the kinematics. (Low p_T → multiple soft gluon emission. High p_T (pQCD)→ Sensitive to gluon PDFs.)
- *Double differential measurements will provide the most strict constraints on the PDFs.*



Large y (PDFs at low x)



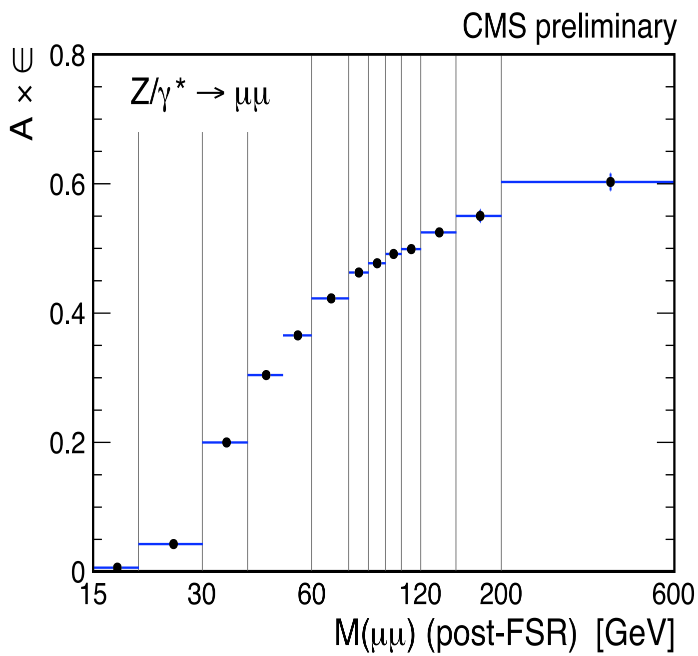


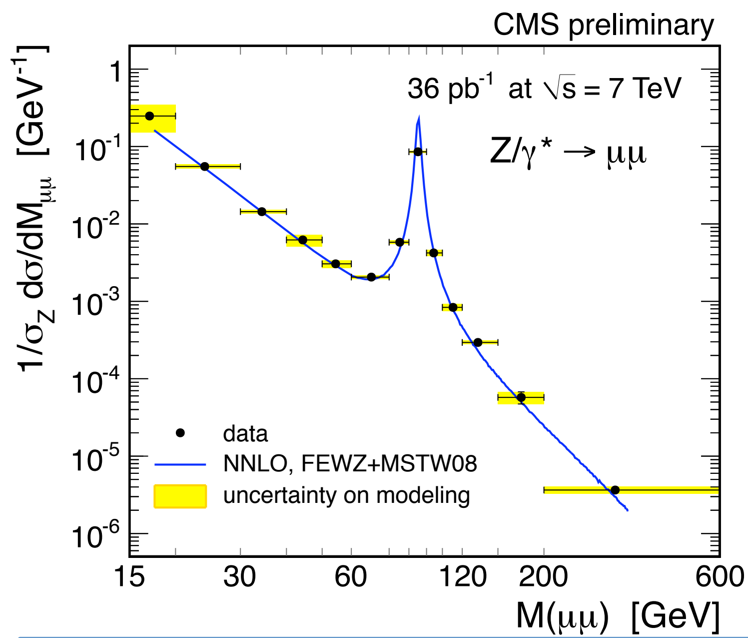
- **Good agreement with FEWZ(NNLO) for p_T>20 GeV**
- **Disagreement for p_T<20 GeV compared to POWHEG and different PYTHIA tunes.**

Drell-Yan Mass Spectrum

CMS-PAS-EWK-10-007

DY process is an irreducible background to searches for new particles such as a Z'.
Background to tt and di-boson processes.
Also allows test of perturbative QCD and precise measurements will constrain PDFs.





Uncertainty on modeling: difference of acceptance corrections derived from POWHEG and FEWZ.

Spectrum in good agreement with NNLO prediction.
NNLO essential for describing M <~30 GeV.

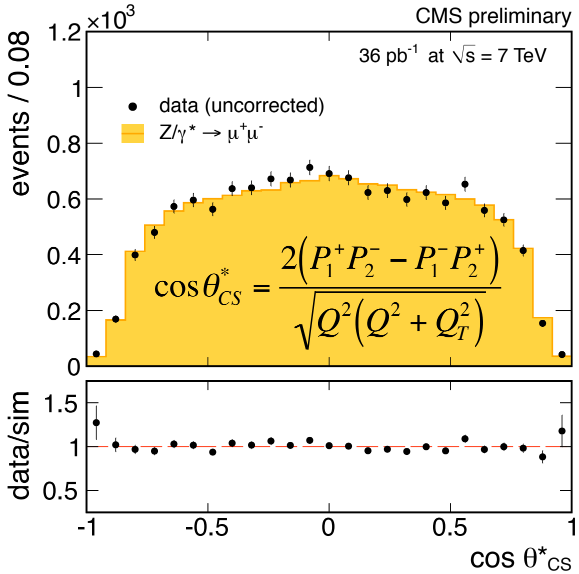
Z Forward-Backward Asymmetry

CMS-PAS-EWK-10-011

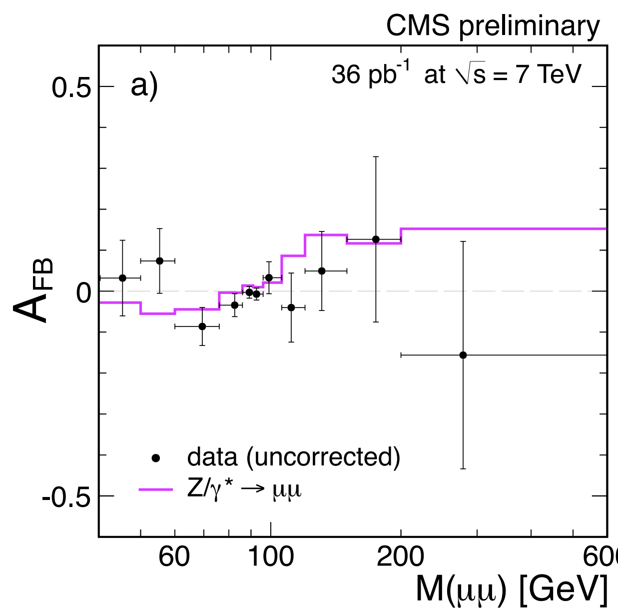
Z/γ* couples to fermions both with vector and axial-vector components.

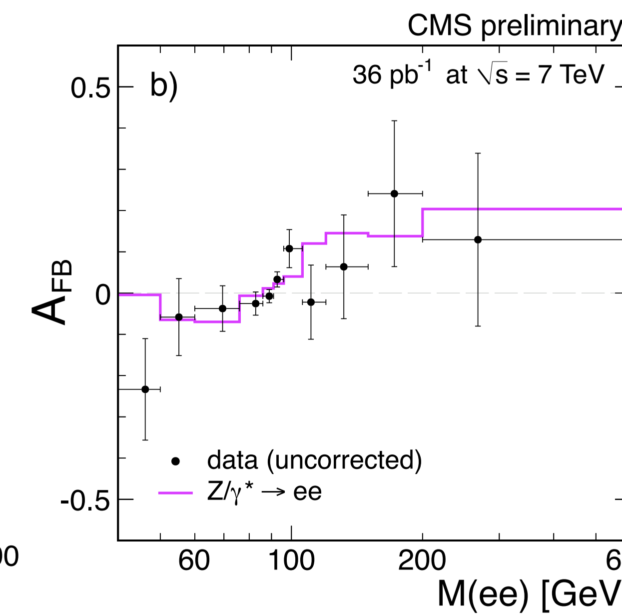
$$\frac{d\sigma}{d\cos\theta} = A(1+\cos^2\theta) + B\cos\theta \qquad A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N_F - N_B}{N_F + N_B} = \frac{3B}{8A}$$

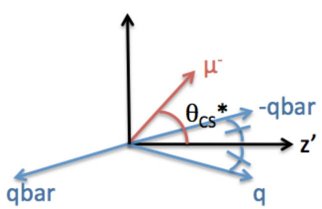
$$A_{FB} = A_{FB}(M, Y, \sin^2\theta_W, q-flavor)$$



Deviations from the SM prediction of AFB at high mass may indicate the existence of a new neutral gauge boson, quark-lepton compositeness, SUSY particles, …
AFB measurement can provide a precise measurement of $\sin^2\theta_W$.
Precise AFB measurement can also constrain PDFs.







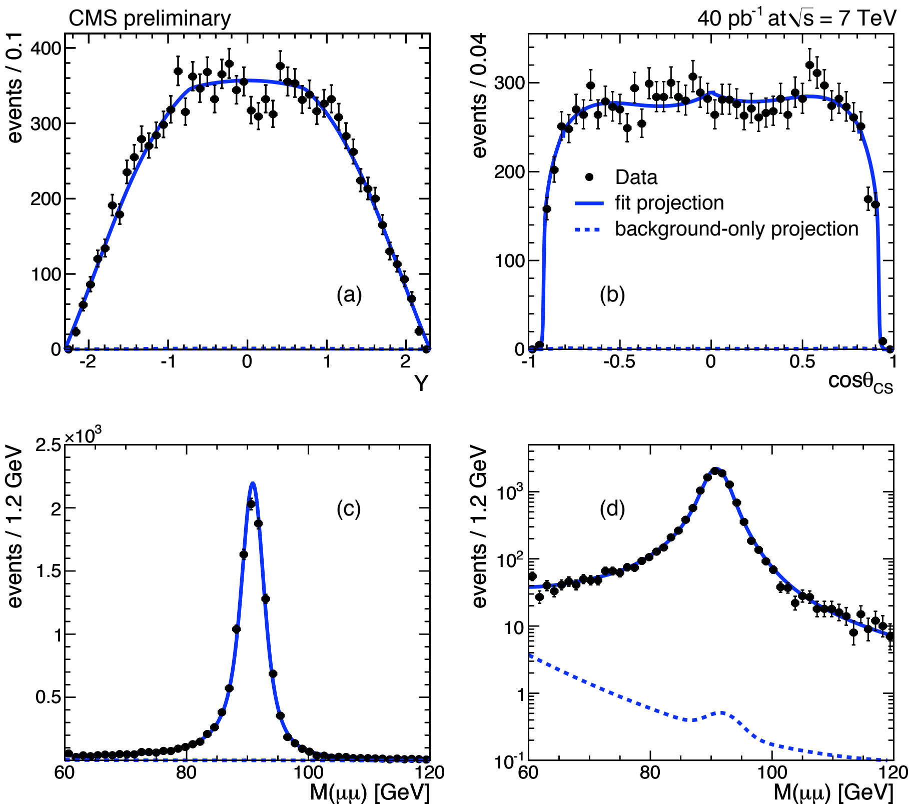
Collins-Soper frame

F: cos(θ*) > 0
B: cos(θ*) < 0

Good agreement between data and POWHEG+CMS Simulation.

Weinberg Angle

CMS-PAS-EWK-10-011



Build LO EWK (analytical) +PDF(CTEQ6) Model
Correct the fits for NLO

Allow only θ_W to be unconstrained.

G: Acceptance and efficiency description.

R: Resolution and QED FSR

P_{ideal}: Model from elementary qqbar cross sections and PDF including a dilution factor due to unknown quark direction.

$$\mathcal{P}_{\rm sig}(Y,s,\cos\theta^*_{CS};\sin^2\theta_W) = \mathcal{G}(Y,s,\cos\theta^*_{CS}) \times \int_{-\infty}^{+\infty} dx\,\mathcal{R}(x)\,\mathcal{P}_{\rm ideal}(Y,s-x,\cos\theta^*_{CS};\sin^2\theta_W)$$

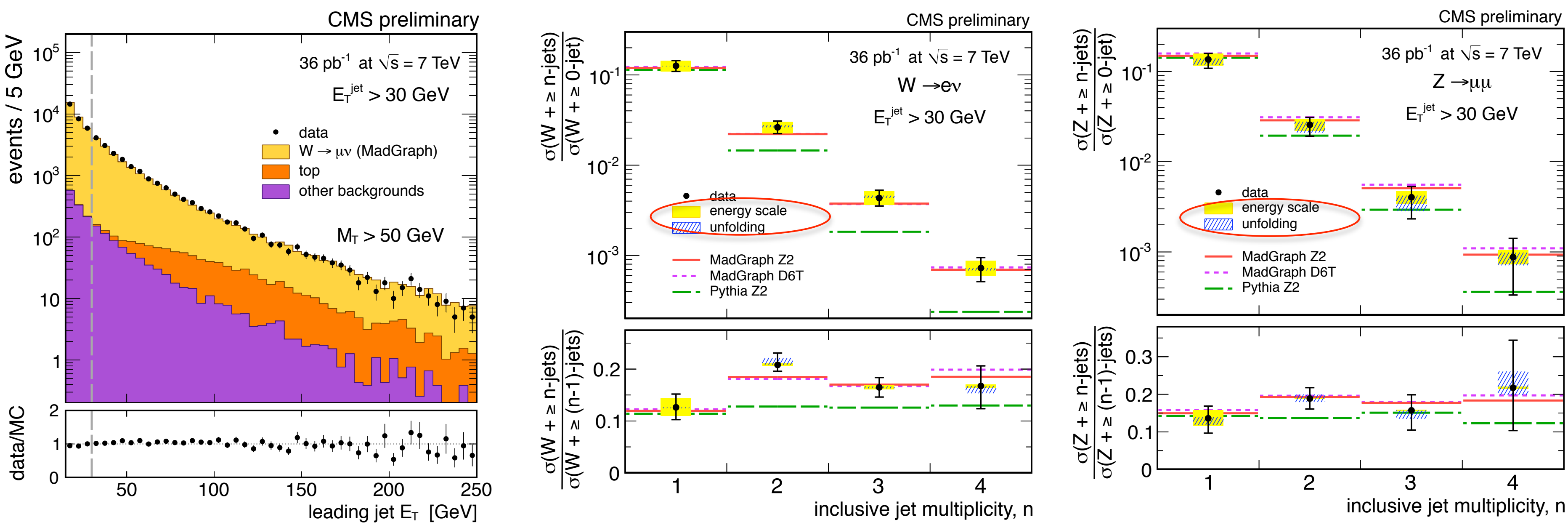
Major systematic uncertainties due to resolution/alignment and QED FSR.

Fit result: $\sin^2\theta_W$=0.2287 +/- 0.0077 (stat.) +/- 0.0036 (sys.) consistent with SM predictions.
Better precision than one can obtain from raw A_{FB} measurement.

V+Jets

CMS-PAS-EWK-10-012

→ Provide fundamental tests of perturbative QCD.
→ Important backgrounds for
  - any new physics
  - single top and tt (W+jets)
→ Used to verify and tune ME+PS MC & NLO simulations.



Particle flow jets with anti-k_T algorithm (cone size=0.5) with E_T>30 GeV in the tracker acceptance.
Unfolding to correct for the effects of jet-resolution.

Good agreement with ME calculation (MadGraph) and discrepancies with Pythia (as expected) for n > 1.

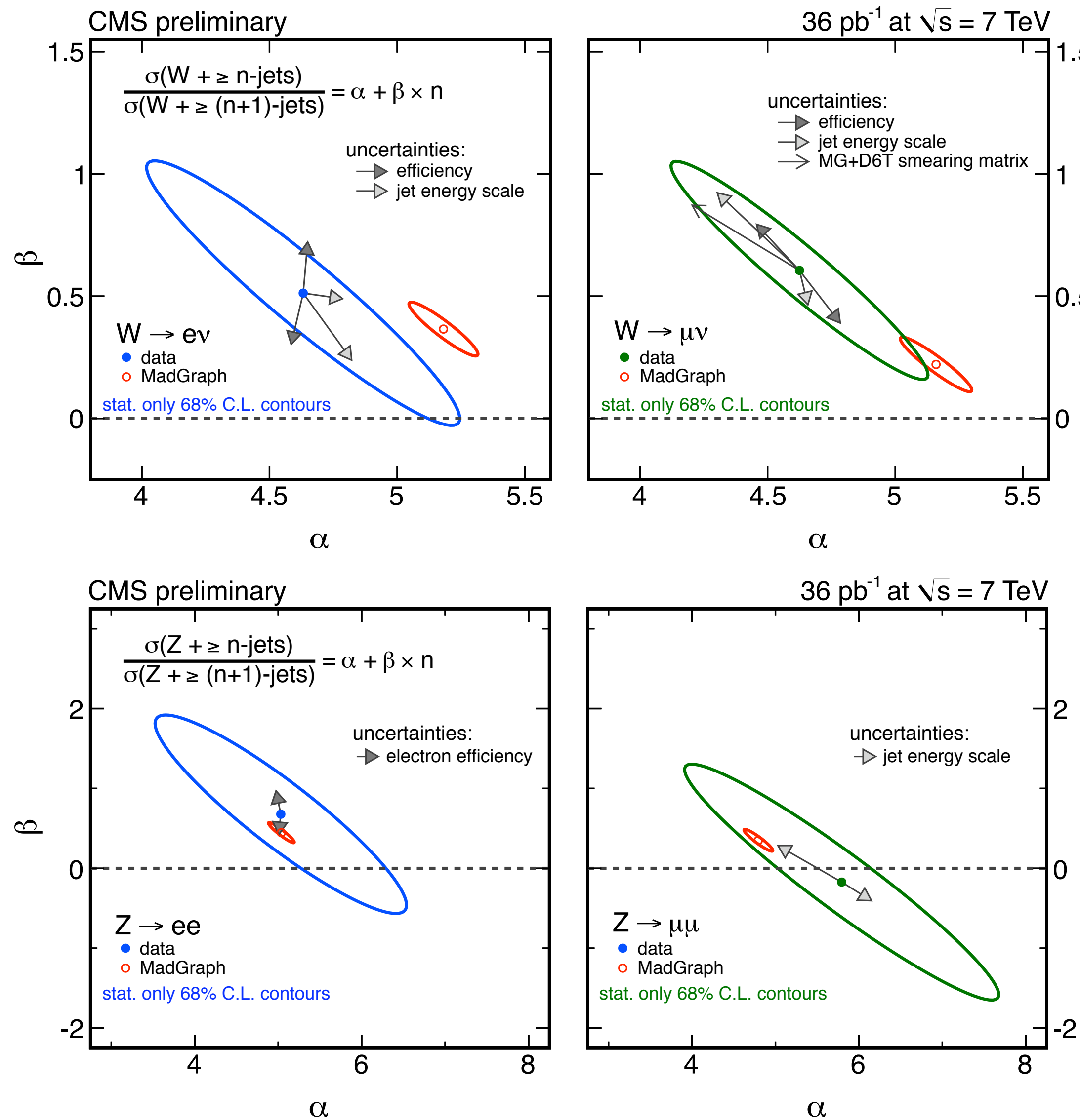
V+Jets: Berends-Giele "Scaling"

CMS-PAS-EWK-10-012

$$C_n = \frac{\sigma(V + \geq njets)}{\sigma(V + \geq (n+1)\, jets)},\ n>0$$

Leading-order prediction
C_n =constant α α_s^{-1}.

NLO + phase space effects
(for high n) → $C_n = \alpha + \beta n$.

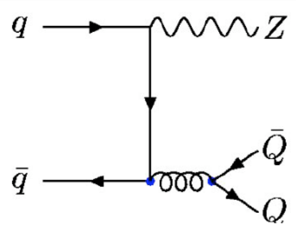


Fit to the data with c(n)=α+βn:
Good agreement between W+jets and Z+jets and fair agreement with the simulations.

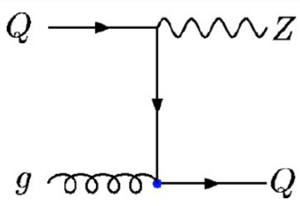
Z+b jets

CMS-PAS-EWK-10-015

Benchmark for associated production of Higgs boson with b-quarks and as a background to Higgs and new physics searches.
Precise measurement of Z+b can choose between fixed- and variable-flavour calculations.

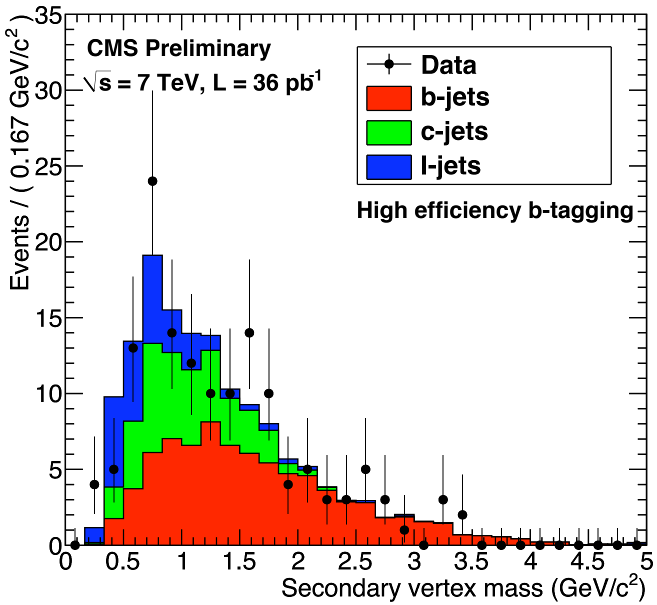


qq,gg→ZQQ
Fixed flavor
(no b-quark at the parton level)



gQ→ZQ
Variable flavor
(b-quark at the parton level)

b-quark in the hard scattering by integrating the gluon splitting process into the PDF.



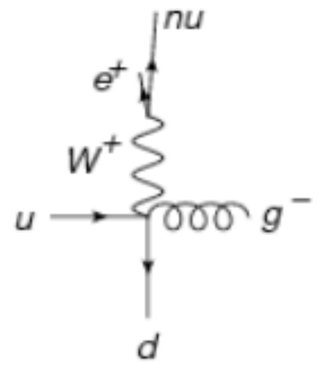
b-tag discriminant chosen such that mis-tagging rate is
High purity (ε~20%): <0.1%.
High efficiency (ε~40%): <1%.

Yields from Z(→*ll*)+b-jet are in good agreement with MadGraph+Pythia predictions.
Ratio σ(Z+b)/σ(Z+j) is found to be in good agreement with NLO expectations.
Both calculation schemes describe the data well – more events are needed to distinguish between them.

W Polarization

CMS-PAS-EWK-10-014
arXiv:1104.3829

- At high p_T the dominant production mechanism at the LHC is the quark-gluon initial state (only sea anti-quarks & more gluons than anti-quarks for x>0.1).
- V-A coupling → left handed polarizations to quarks (relativistic limit).
  - W bosons are expected to be produced predominantly in a left-handed state at the LHC.
  - significant asymmetry in p_T^{ν} and charged lepton from W decays.



u+g → W⁺+q
d+g → W⁻+q

$$\frac{dN}{d\cos\theta^*} \propto (1+\cos^2\theta^*) + \frac{1}{2}A_0(1-3\cos^2\theta^*) + A_4\cos\theta^*$$

Helicity frame: polarization axis is defined to be along the W boson flight direction.
θ* = The angle between the polarization axis and the charged lepton decay direction in the W boson rest frame.

$$A_0 \propto f_0 \qquad A_4 \propto \pm(f_L - f_R) \qquad f = f(p_T^W, \eta^W)$$

Parameters f_L, f_R, f_0 determine the fractions of left, right, and longitudinal helicity states.

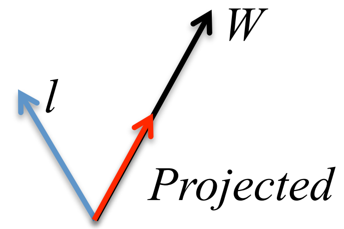
W Polarization

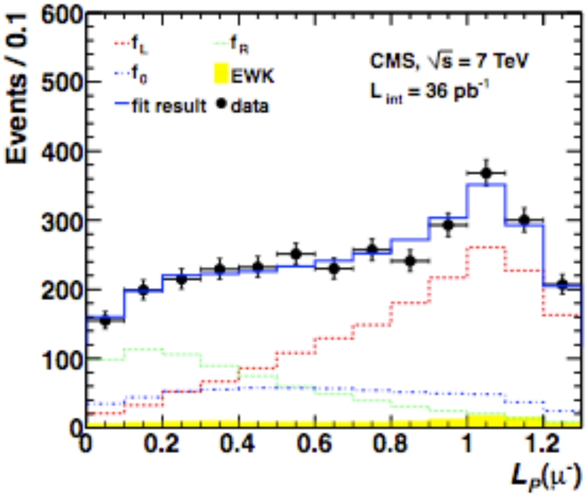
CMS-PAS-EWK-10-014
arXiv:1104.3829

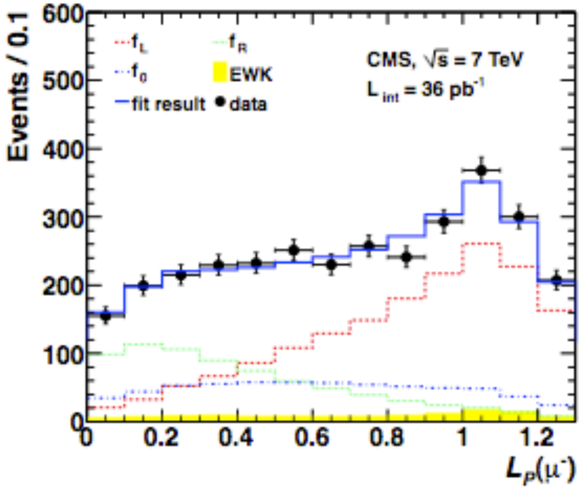
Not possible to precisely determine the W rest frame, but
→ "lepton projection variable" correlated to cosθ* can be used.

- → Reject QCD: $M_T^{e\text{-}chan}$>50 GeV, $M_T^{\mu\text{-}chan}$>30 GeV
- → Reject tt: ≤3 jets with p_T>30 GeV
- → Increase polarization: $p_T(W)$>50 GeV

$$L_p = \frac{\vec{p}_T(l) \bullet \vec{p}_T(W)}{\left|\vec{p}_T(W)\right|^2}$$







$$(f_L - f_R)^{W^-} = 0.240 \pm 0.036(stat) \pm 0.031(syst)$$

$$f_0^{W^-} = 0.138 \pm 0.087(stat) \pm 0.123(syst)$$

$$(f_L - f_R)^{W^+} = 0.310 \pm 0.036(stat) \pm 0.017(syst)$$

$$f_0^{W^+} = 0.171 \pm 0.085(stat) \pm 0.099(syst)$$

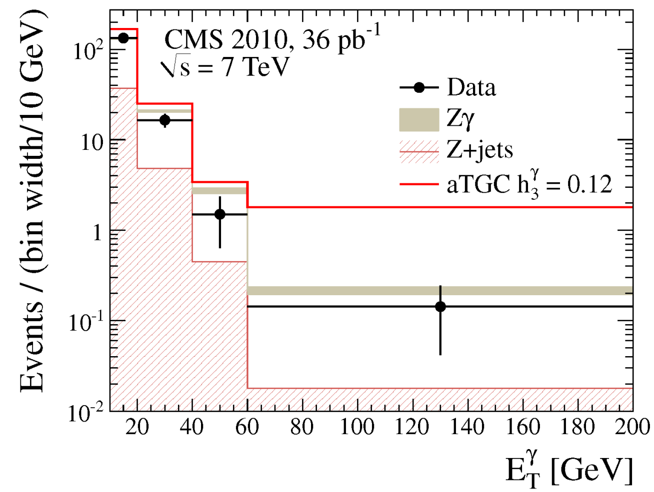
Main systematic uncertainties from recoil energy scale and resolution.

Difference between left- and right-handed polarization parameters 7.8σ for W^+ and 5.1σ for W^-.
First observation that W bosons produced in pp collisions with large p_T are predominantly left-handed (for both charges) as expected in the SM.

$V+\gamma$ *Production*

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

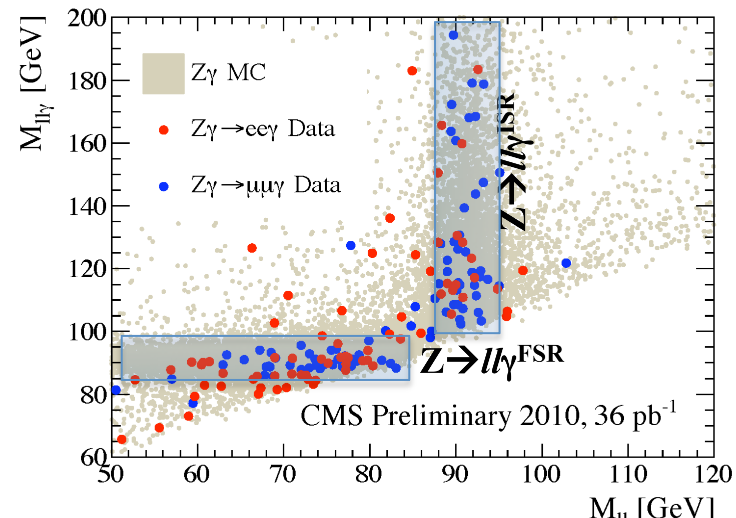
- Zγ,Wγ production important test of SM because of its sensitivity to the self-interaction between gauge bosons via TGC.
- Main backgrounds: *V+jets*, tt, QCD multijet



$\sigma(W\gamma+X) \times B(W \to l\nu) = 56.3 \pm 5.0(\text{stat.}) \pm 5.0(\text{syst.}) \pm 2.3(\text{lumi.})$ pb
$\sigma(Z\gamma+X) \times B(Z \to ll) = 9.4 \pm 1.0(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.4(\text{lumi.})$ pb
$E_T^\gamma > 10$ GeV and $\Delta R(l,\gamma) > 0.7$
$M_{ll} > 50$ GeV (Zγ)

Fake isolated photons estimated from V+jets.

Main systematic sources: photon and lepton energy scales, pile-up, PDFs, photon Id/iso., backgrounds.



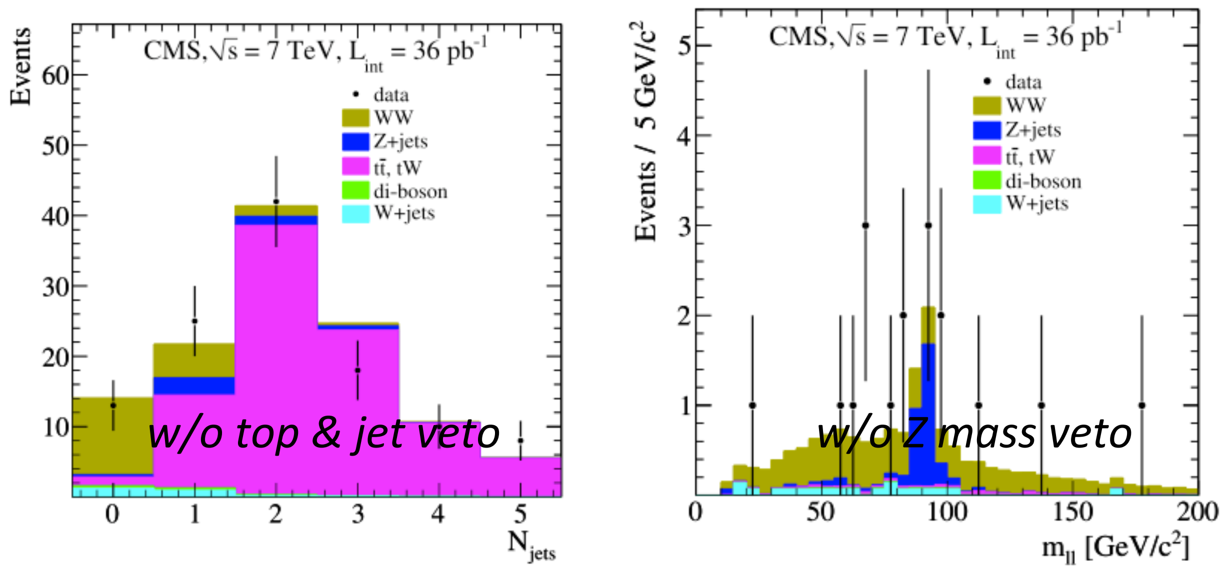
Wγ and Zγ cross sections are in good agreement with NLO predictions.
No evidence for anomalous WWγ, ZZγ, and Zγγ trilinear gauge couplings.

WW Production

Phys. Lett. B 699 (2011) 25

Benchmark for Higgs boson search in H→WW and limits on WWγ and WWZ anomalous couplings.

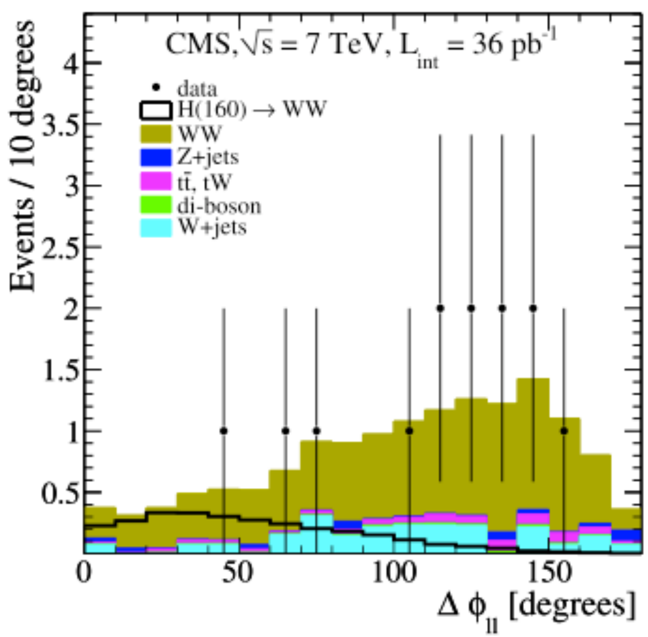
- DY→ee,μμ veto: require MET and reject events within 15 GeV around Z mass peak.
- DY→ττ veto: projected MET transverse to the closest lepton > 35 GeV
- Top quark veto: reject events with jets of p_T>25 GeV, |η|<5. + veto based on soft-muon and b-jet tagging
- Suppress WZ, ZZ, by rejecting events with >2 leptons.

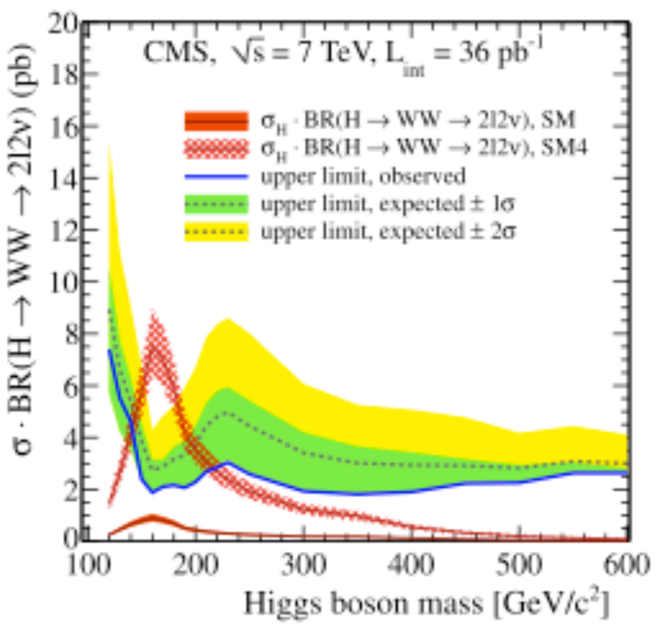


13 signal events in data with estimated background of 3.3±1.2 evts.
σ(WW)=41.1±15.3(stat)±5.8(syst)±4.5(lumi) consistent with the SM prediction.

WW Production: Higgs Boson Search

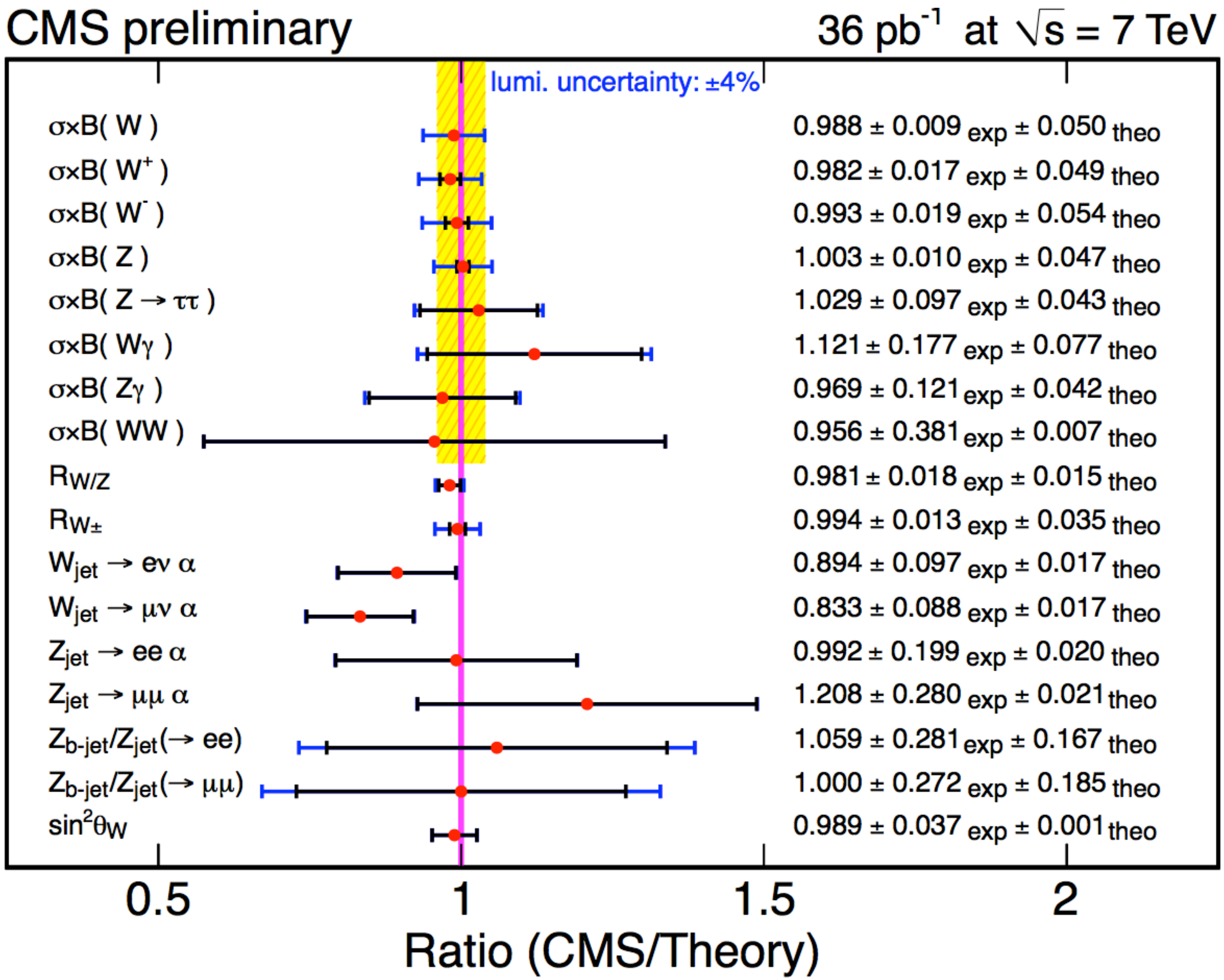
- $\Delta\phi_{ll}$ provides the best discriminating power.
- Cut based and Boosted Decision Tree (BDT) technique
- Additional backgrounds: WH,WZ, tt, VBF → by 0-jet and <=2 lepton requirements.
- Systematic uncertainty
  - signal yield ~14% → due to jet veto efficiency and luminosity uncertainty.
  - Background (in signal region) ~ 40% dominated by statistical uncertainties in the control regions.





No access above the SM expectations.
No Higgs boson in a 4-generation SM scenario in the range 144-207 GeV with 95% C.L.

Summary



CMS preliminary
36 pb^{-1} at $\sqrt{s}$ = 7 TeV
lumi. uncertainty: ±4%
σxB(W)
σxB(W$^+$)
σxB(W$^-$)
σxB(Z)
σxB(Z → ττ)
σxB(Wγ)
σxB(Zγ)
σxB(WW)
$R_{W/Z}$
$R_{W\pm}$
W_{jet} → eν α
W_{jet} → μν α
Z_{jet} → ee α
Z_{jet} → μμ α
$Z_{b\text{-}jet}/Z_{jet}$(→ ee)
$Z_{b\text{-}jet}/Z_{jet}$(→ μμ)
$\sin^2\theta_W$
0.988 ± 0.009 exp ± 0.050 theo
0.982 ± 0.017 exp ± 0.049 theo
0.993 ± 0.019 exp ± 0.054 theo
1.003 ± 0.010 exp ± 0.047 theo
1.029 ± 0.097 exp ± 0.043 theo
1.121 ± 0.177 exp ± 0.077 theo
0.969 ± 0.121 exp ± 0.042 theo
0.956 ± 0.381 exp ± 0.007 theo
0.981 ± 0.018 exp ± 0.015 theo
0.994 ± 0.013 exp ± 0.035 theo
0.894 ± 0.097 exp ± 0.017 theo
0.833 ± 0.088 exp ± 0.017 theo
0.992 ± 0.199 exp ± 0.020 theo
1.208 ± 0.280 exp ± 0.021 theo
1.059 ± 0.281 exp ± 0.167 theo
1.000 ± 0.272 exp ± 0.185 theo
0.989 ± 0.037 exp ± 0.001 theo
0.5
1
1.5
2
Ratio (CMS/Theory)

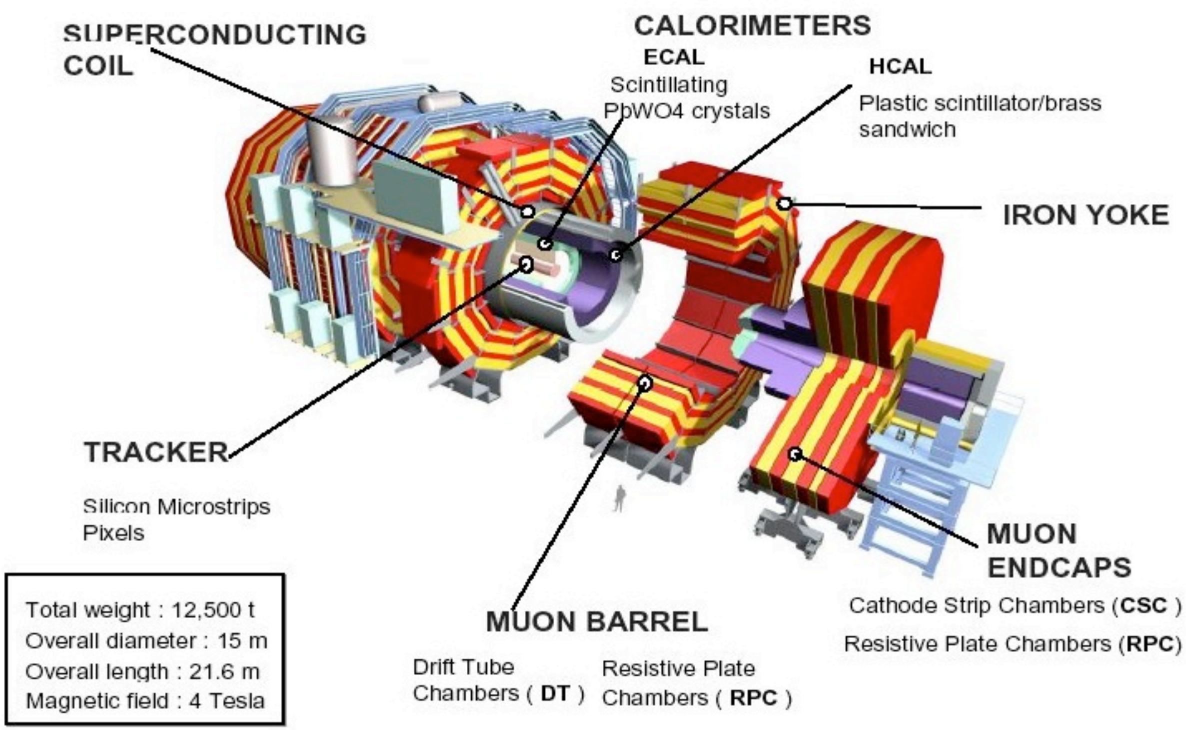
Conclusions

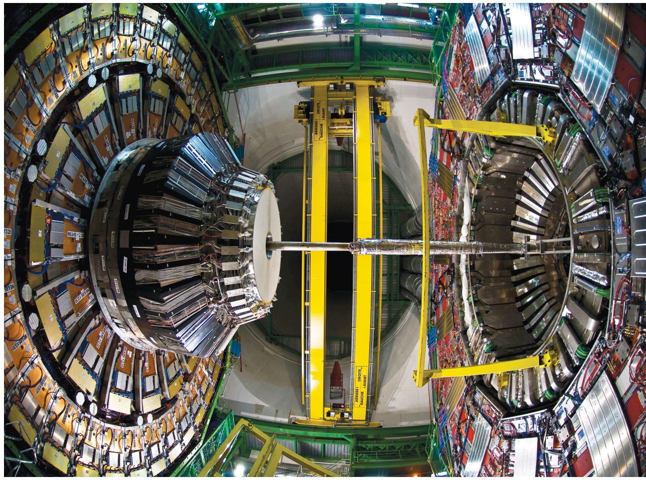
- With 36 pb^{-1} of data at 7 TeV, CMS has made fundamental measurements of the benchmark SM processes of W and Z production
  - Differential cross sections, Drell-Yan production
  - Asymmetries: W charge asymmetry and polarization, Z forward/backward asymmetry and Weinberg angle measurement.
  - V+jets including Z+b-jet measurement.
  - WW,Wγ,Zγ and measurements of anomalous triple gauge boson couplings.
- All results are in good agreement with SM predictions.

Standard Model benchmarks established.
Many new measurements to come from the already collected > 700 pb^{-1}.

Back-up

Compact Muon Solenoid(CMS)





Within the solenoid field volume:

ECAL: $PbWO_4$, High resolution, ~70 k crystals

HCAL: Brass and scintillator,

Tracker: 66 M Si pixels and 10 M Si strips

Superconducting Solenoid magnet: 6 m x 13 m, B=3.8 T, E = 1.6 GJ

Embedded within the iron yoke:

Muon System: Drift tubes (DT), Cathode Strip Chambers (CSC), Resistive plate chambers (RPC).

+ Forward Calorimeter: steel absorber, fibers

W/Z Systematic Uncertainties in Electron and Muon Final States

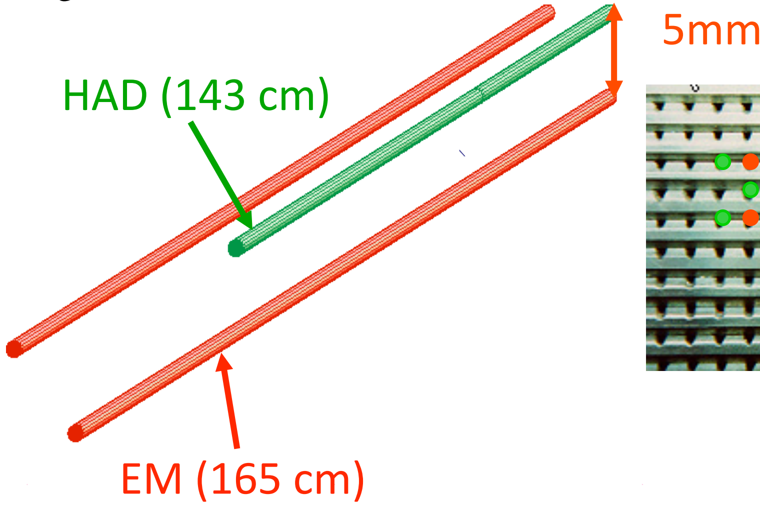
Source	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Lepton reconstruction & identification	1.3	0.9	1.8	n/a
Trigger pre-firing	n/a	0.5	n/a	0.5
Momentum scale & resolution	0.5	0.22	0.12	0.35
$\not{E}_T$ scale & resolution	0.3	0.2	n/a	n/a
Background subtraction / modeling	0.35	0.4	0.14	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

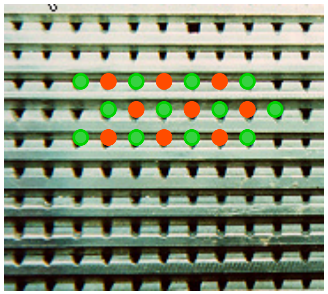
Electron Identification in HF

- **HF is located about 11 m from the interaction point, covers $3 < |\eta| < 5$ with depth of $10\ \lambda_{int}$**

  No tracker in front of HF.

- **Consists of iron absorber embedded with quartz fibers parallel to the beam direction in a 5x5 mm matrix**

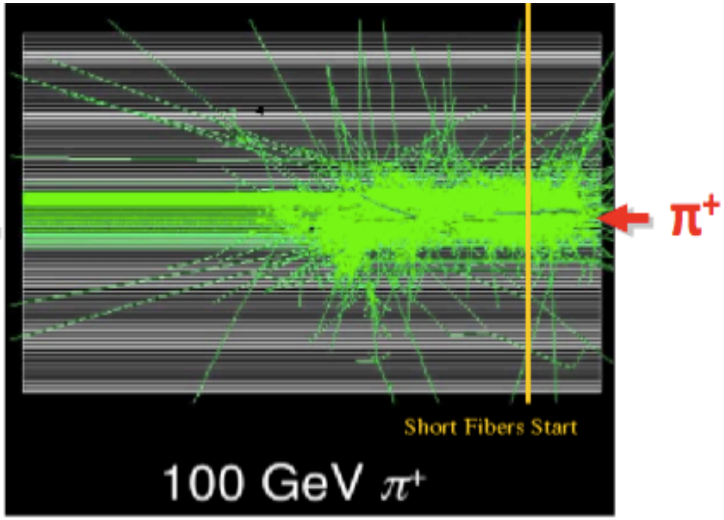


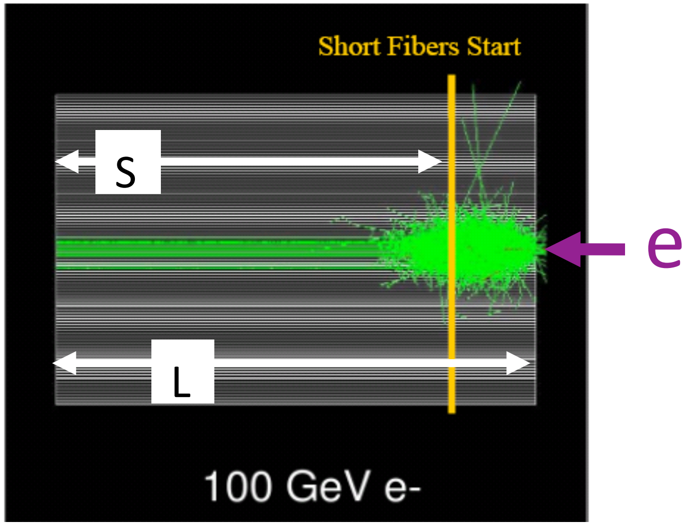


Electrons in HF can be identified using longitudinal and transverse shower shape variables:

Isolation: $E(L+S)_{3x3}/E(L+S)_{5x5} > XX$,

Compactness: $E(L_{core})/E(L_{3x3}) - cE_S/E_L$ = (shower shape) − c(shower depth) > XX

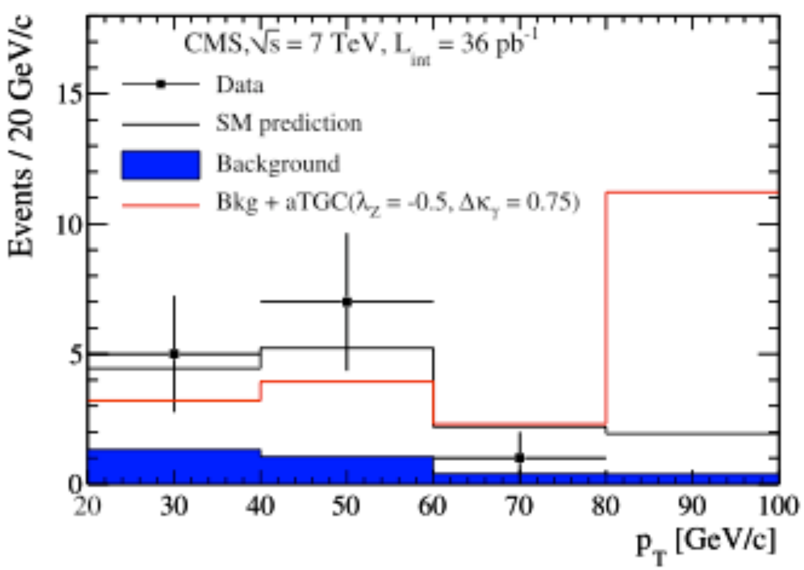


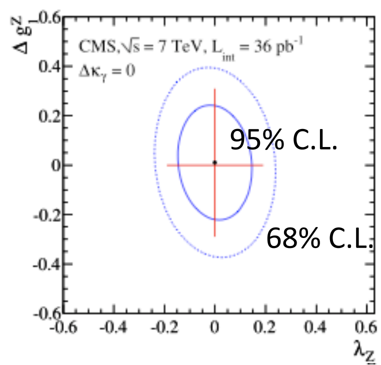


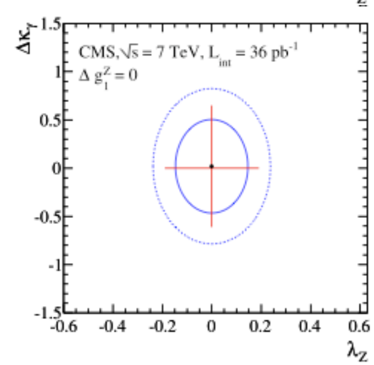
WW Production: Limits on WWγ and WWZ Anomalous Couplings

- Effective Lagrangian with HISZ parametrization without form factors.
  - λ_Z, κ_γ, and g_1^Z describe all the operators.
  - In SM, $\lambda_Z = 0$, $\kappa_\gamma = g_1^Z = 1$. ➔ $\Delta\kappa_\gamma$ and Δg_1^Z: deviation from SM.

Two different measurements both using the leading p_T^{lep} distribution.

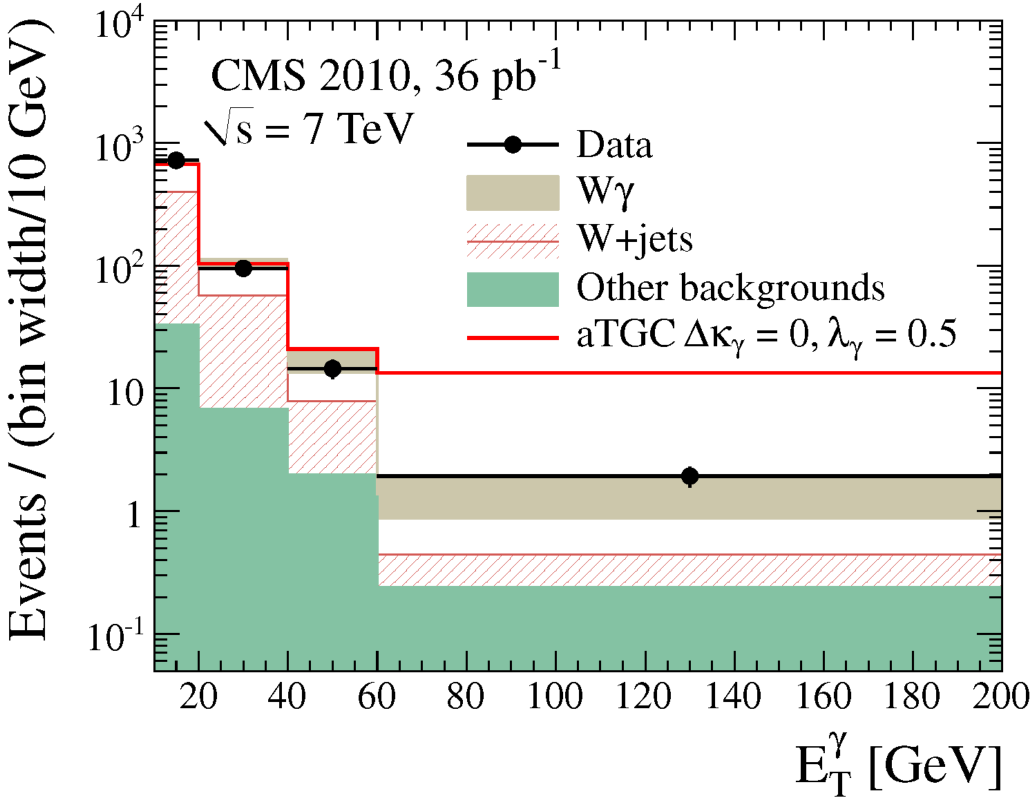






Results are in agreement with SM predictions and are consistent with the LEP precision measurements and comparable with Tevatron results.

$W\gamma$



CMS 2010, 36 pb^{-1}
$\sqrt{s}$ = 7 TeV
Data
Wγ
W+jets
Other backgrounds
aTGC $\Delta\kappa_\gamma = 0, \lambda_\gamma = 0.5$
Events / (bin width/10 GeV)
E_T^γ [GeV]
10^4
10^3
10^2
10
1
10^{-1}
20
40
60
80
100
120
140
160
180
200