Early Z Boson Measurements at CMS in pp Collisions at 7 TeV

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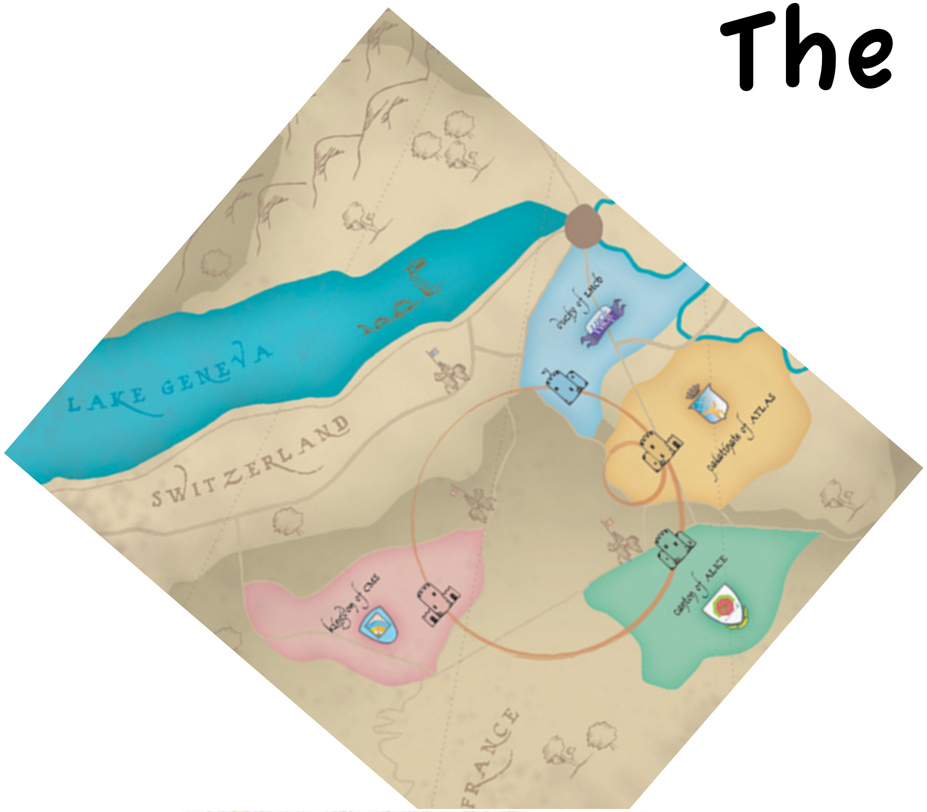
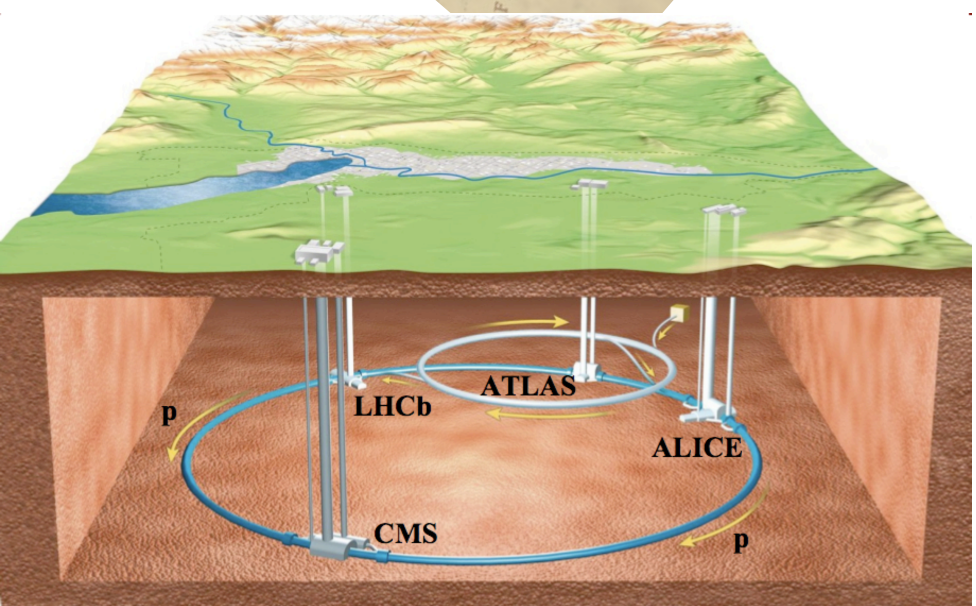
Selected Results and Planned Measurements:
Cross section
Differential measurements
Forward-backward asymmetry
Z+Jets, jet energy scale of tagging jets in qqH, and Double Parton Scattering

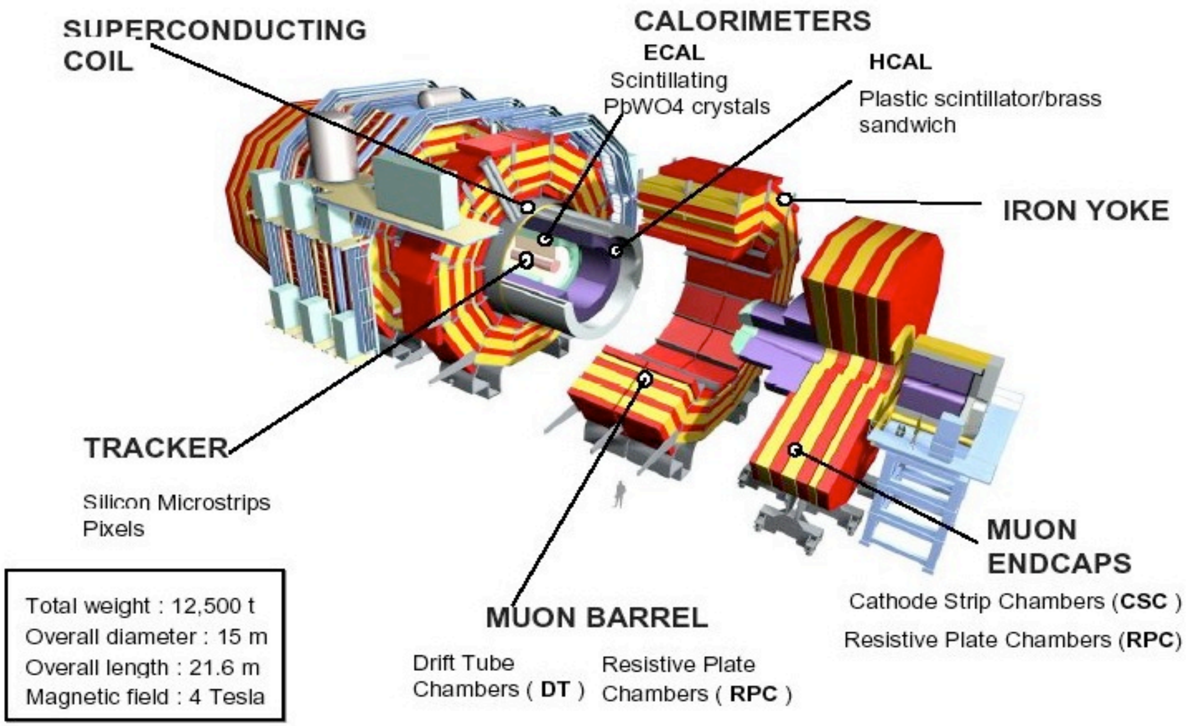
The LHC

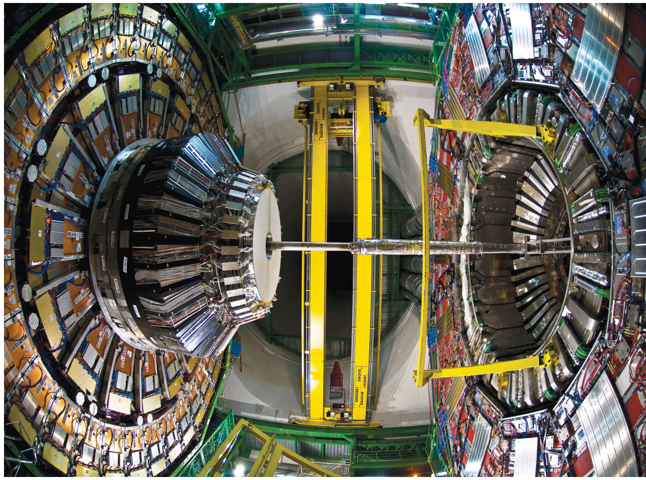




- Circumference: 27 km
- pp or ion-ion collider
- #quadrupoles: 858
- # magnets: 9300
- Dipole temperature: 1.9 K
- Peak magnetic dipole field: 8.33 T
- Design luminosity: $10^{34} cm^{-2} s^{-1}$

Compact Muon Solenoid(CMS)





Within the solenoid field volume

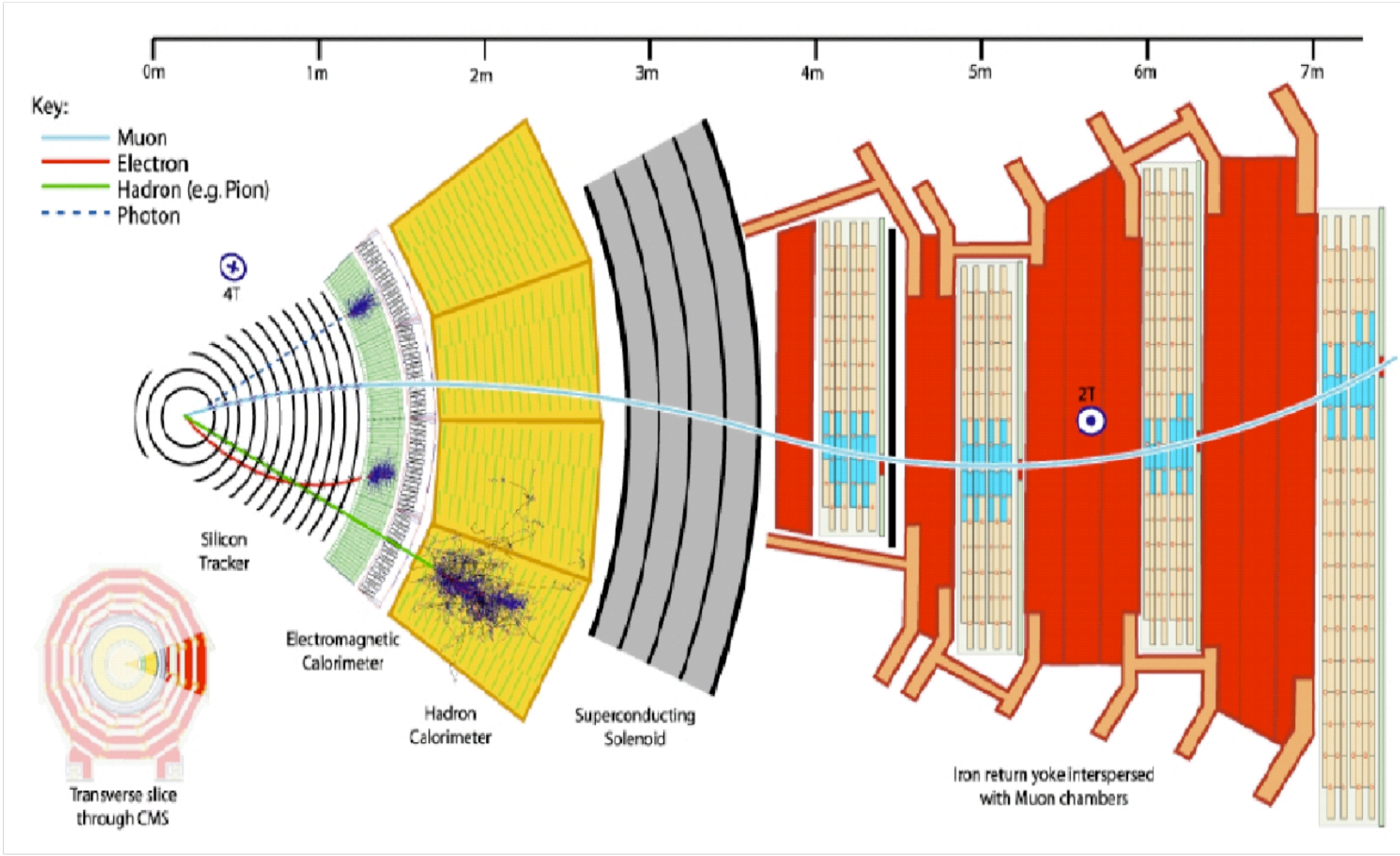
ECAL: $PbWO_4$, High resolution, ~70 k crystals
HCAL: Brass and scintillator,
Tracker: 66 M Si pixels and 10 M Si strips
Superconducting Solenoid magnet: 6 m x 13 m, B=3.8 T, E = 1.6 GJ

Embedded within the iron yoke

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

+ Forward Calorimeter: steel absorber, fibers

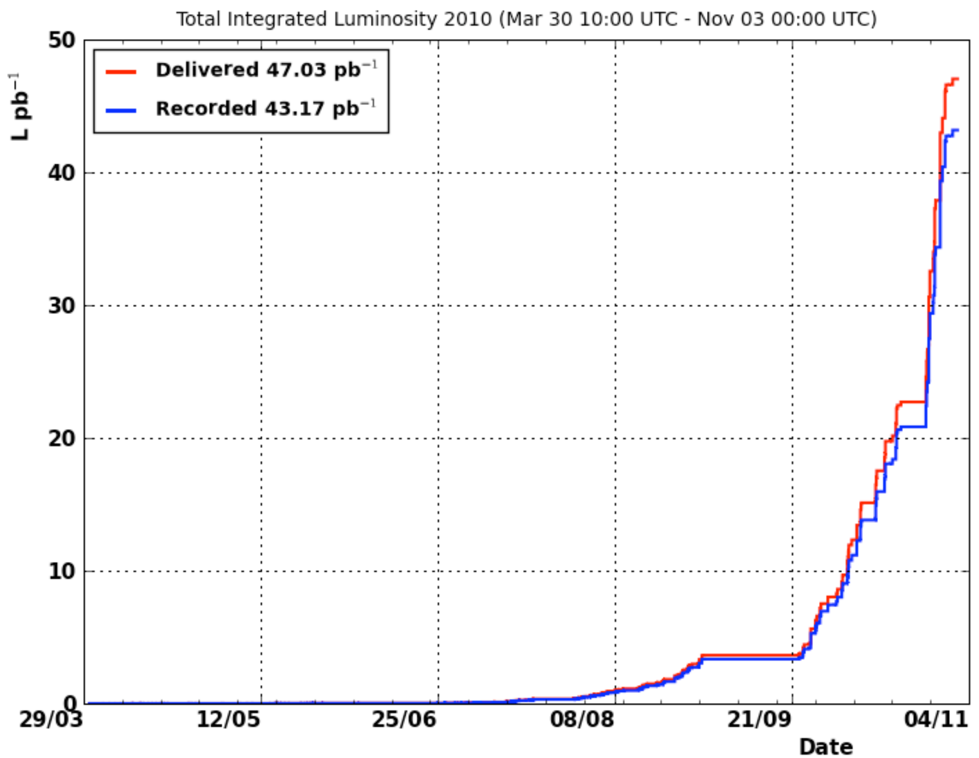
Particle Identification



CMS Operation (2010)

- *Integrated luminosity measurement is based on signals from the Forward Calorimeter (HF).*
- Van der Meer scans provide absolute normalization.
- Uncertainty on the integrated luminosity: 11%

→ Luminosity uncertainty will be reduced by improving experimental techniques & by using a well-known process (e.g. Z→ll).



- Global data taking efficiency ~92%
- Integrated luminosity excluding the problematic lumi-sections and runs for physics analysis ~36 pb^{-1}. → ~84% of recorded data.
- 40 pb^{-1} for analysis without calorimeters.

Electroweak Physics at the LHC

- Understanding EWK production is essential before any discovery claims.
  - The production of W and Z bosons decaying into electrons and muons are one of the best understood processes at the colliders
  - W and Z's are the only detected particles of the EWKSB mechanism.
- Deviations from Standard Model expectations may indicate existence of new physics.
- Backgrounds for Beyond Standard Model processes
- High p_T leptons from W's and Z's are used to understand efficiency, resolution, energy scale, and in general understanding our equipment.
- EWK measurements will be used to constrain PDFs
- Z production rate can be used to monitor and calibrate the luminosity.

Electrons

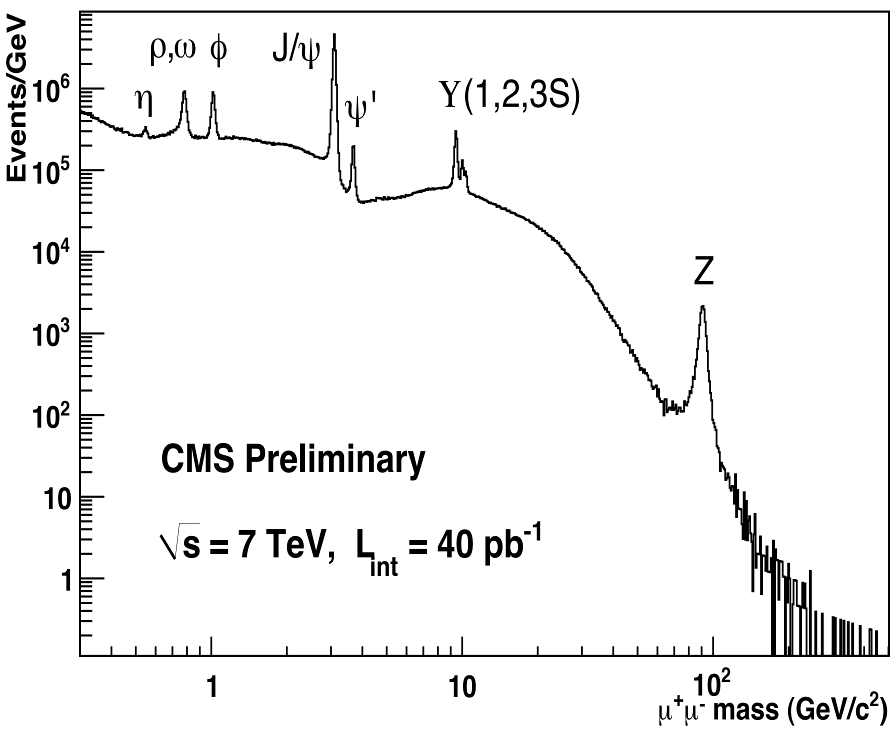
- ECAL clusters matched to tracks in the tracker accounting for possible energy loss in the tracker layers.
- Unprescaled HLT filter requiring an ECAL cluster with E_T > (10-17) GeV.
- p_T > 20 GeV, $|\eta|<1.4442$, $1.566<|\eta|<2.5$
- Electrons from photon conversions are reduced using tracker.
- Identification using shower shape variables

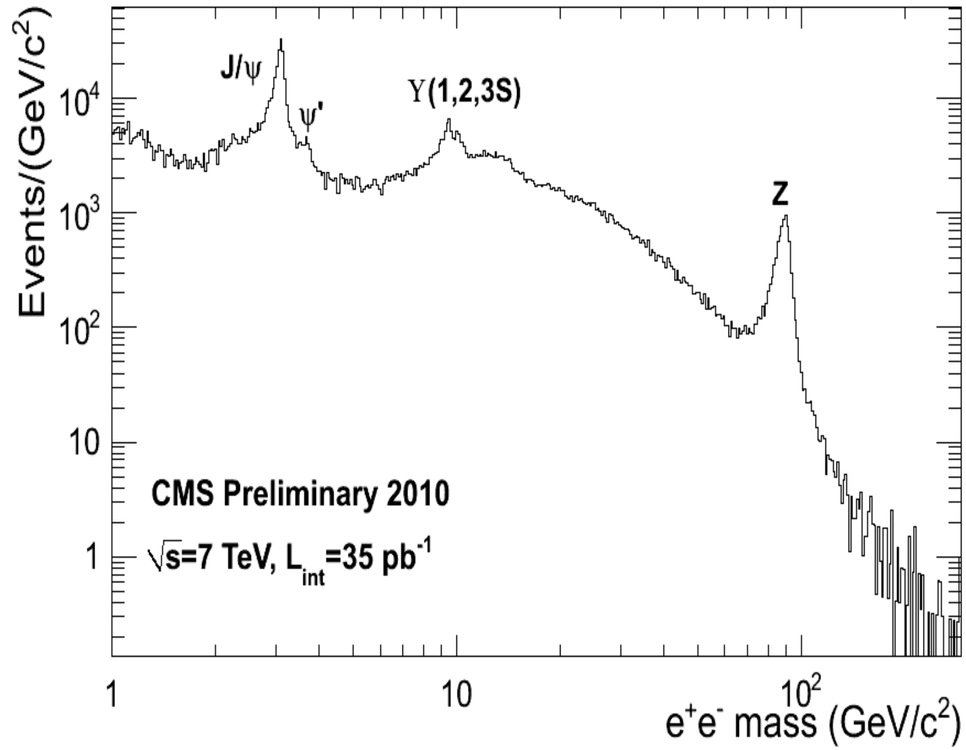
Muons

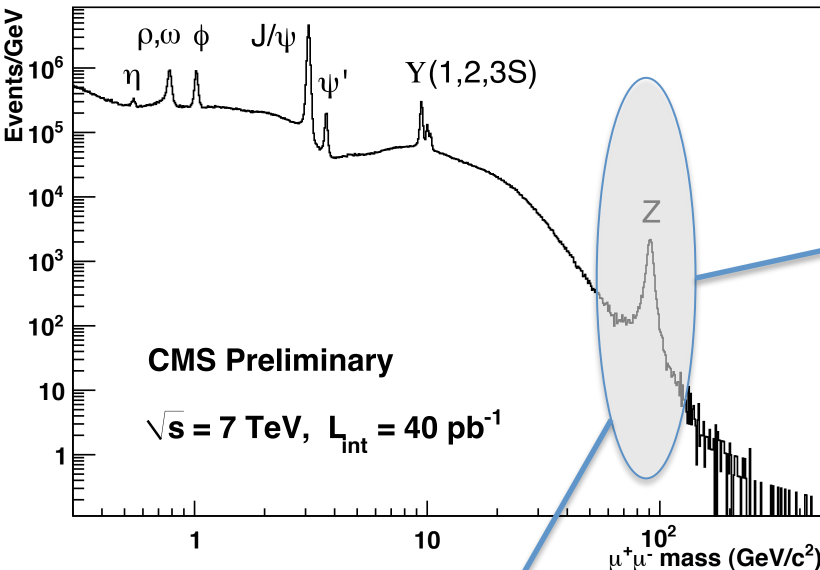
- Muons are required to be identified by tracker and global algorithms
- Unprescaled HLT filter with a threshold of P_T>(9-15) GeV in $|\eta|<2.1$.
- $P_T(\mu)>20$ GeV
- Quality cuts (#hits in pixels etc.)

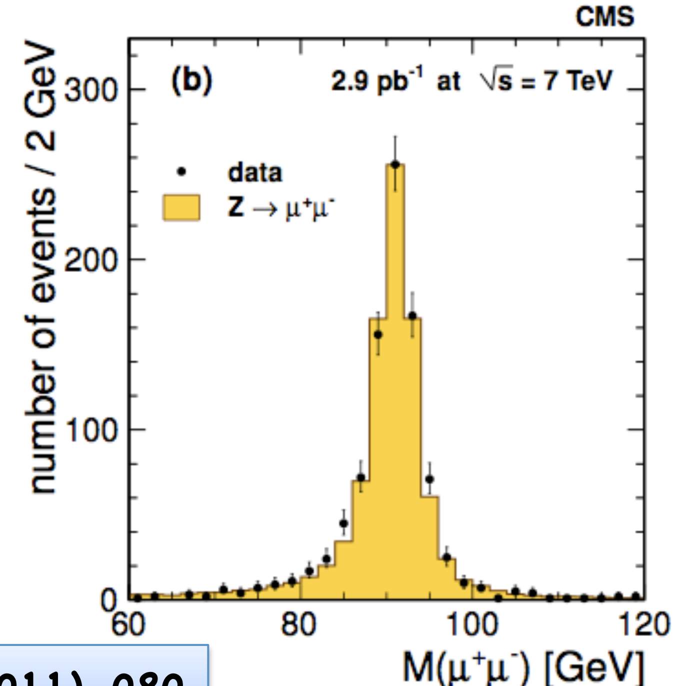
- Isolation using tracker and the calorimeters.

Dilepton Resonances









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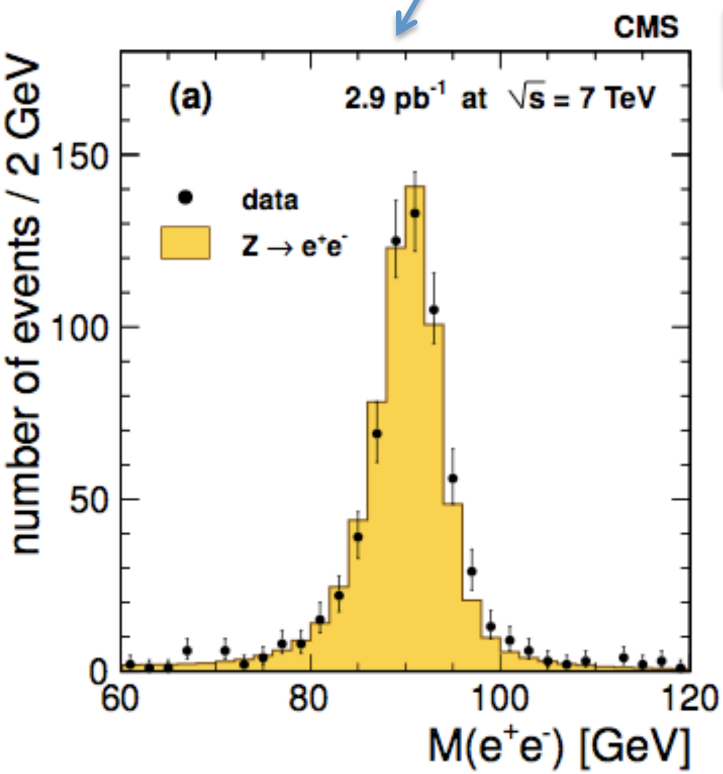
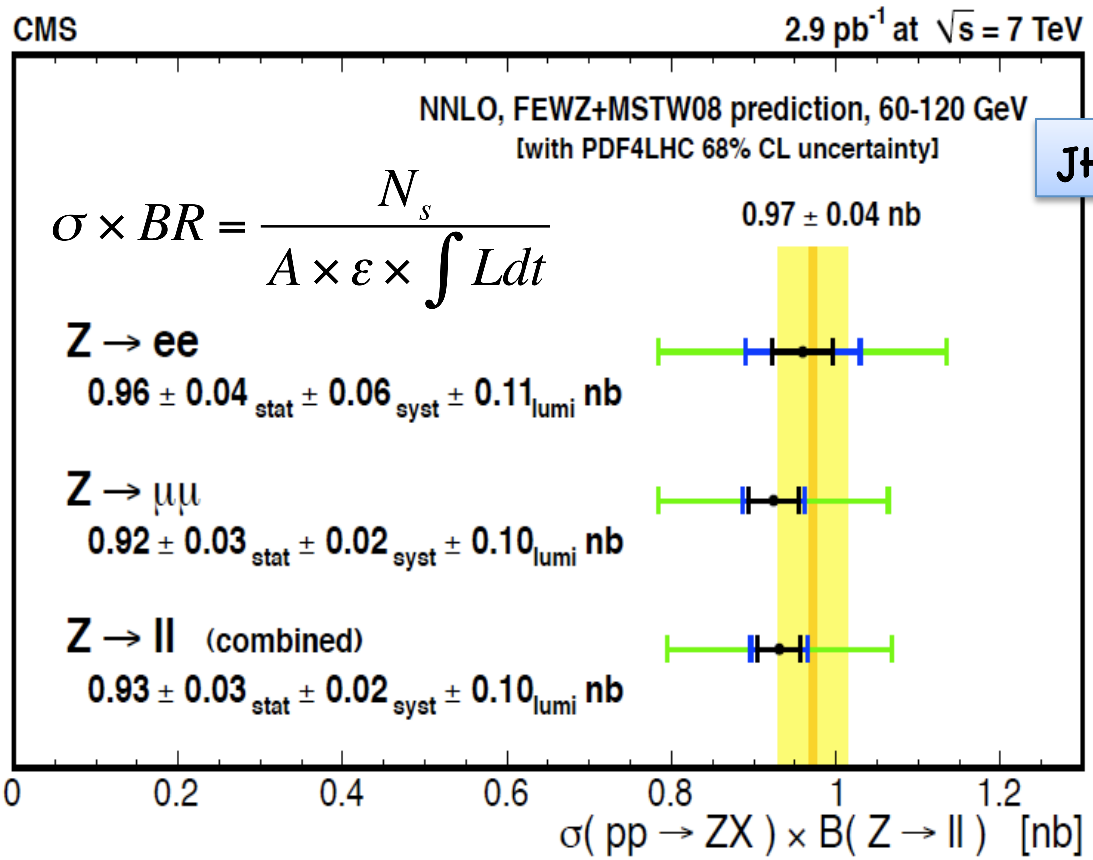


- Z signal: Two isolated opposite sign high p_T leptons.
- $p_T(l)>20$ GeV
- $|\eta_\mu|<2.1$
- $|\eta_e|<1.44$ & $1.57<|\eta_e|<2.5$
- Negligible background ($Z\rightarrow\tau\tau$, WW,WZ,ZZ,tt~)
- + small scale corrections



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Important systematics:

Luminosity normalization: 11%

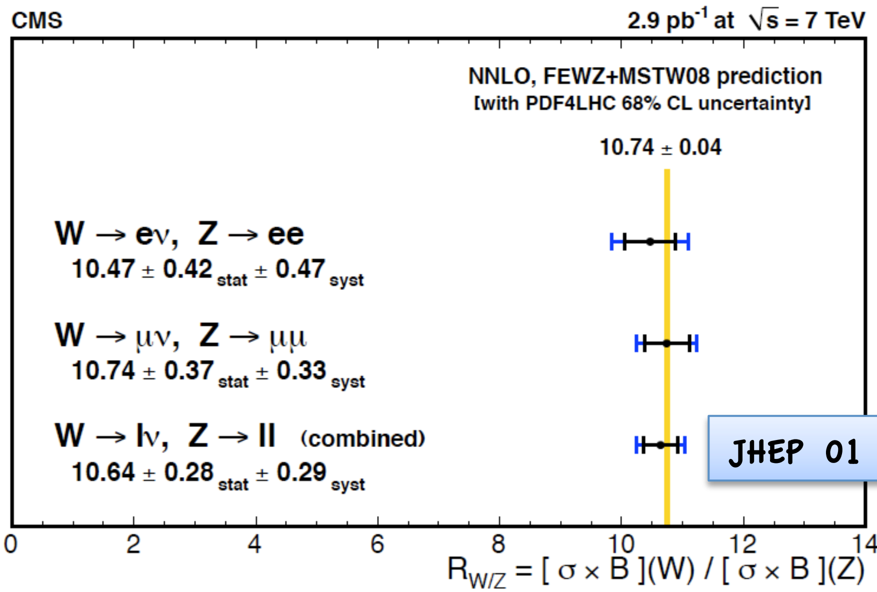
Lepton reconstruction (ε): ~3-4%

Backgrounds (N): ~1-2%

PDFs (A): 1-2%

(cross-sections measured within geometrical and kinematical acceptance are also reported eliminating the PDF uncertainties)

- Cross section x branching ratio measurements in the electron and muon channels are internally consistent.
- Both channels are combined by maximizing the likelihood that takes into account the individual statistical and systematic uncertainties and their correlations as well.



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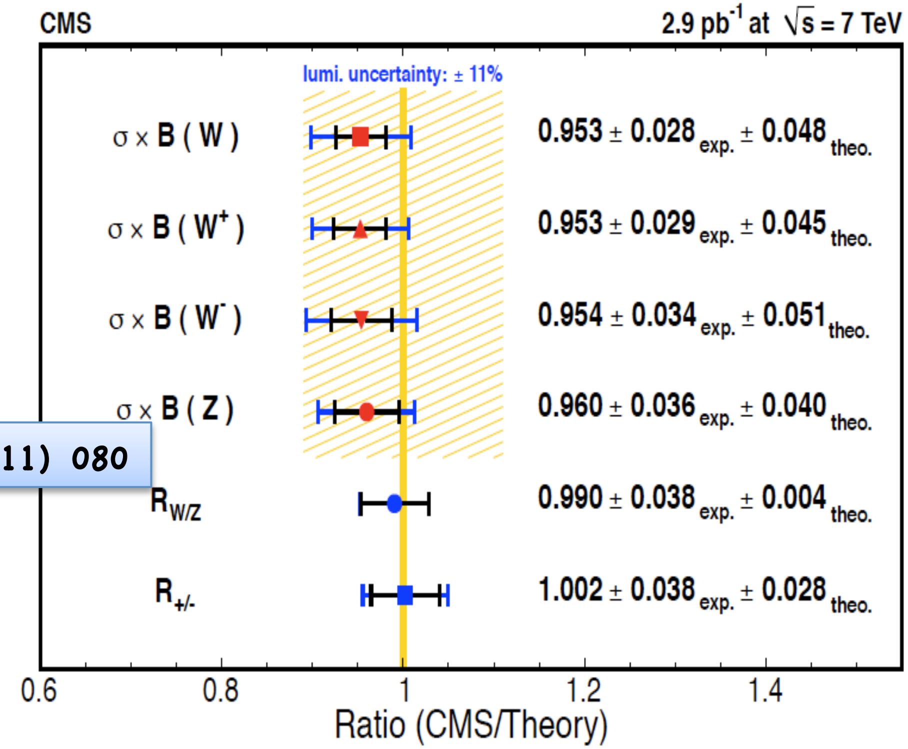
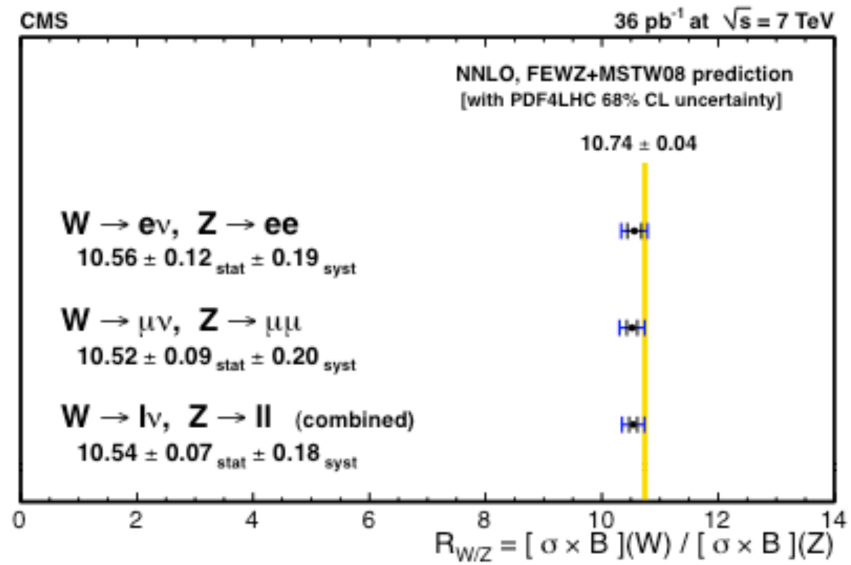


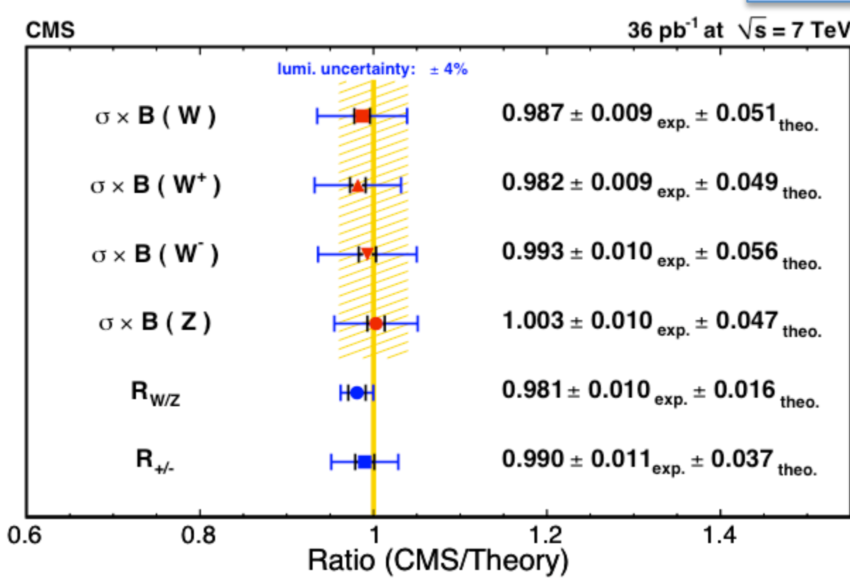
$$R_{W/Z} = \frac{[\sigma \times \mathcal{B}](W)}{[\sigma \times \mathcal{B}](Z)} = \frac{N_W}{N_Z}\frac{\rho_Z}{\rho_W}\frac{F_Z}{F_W} = \frac{N_W}{N_Z}\frac{\varepsilon_Z}{\varepsilon_W}\frac{A_Z}{A_W}$$

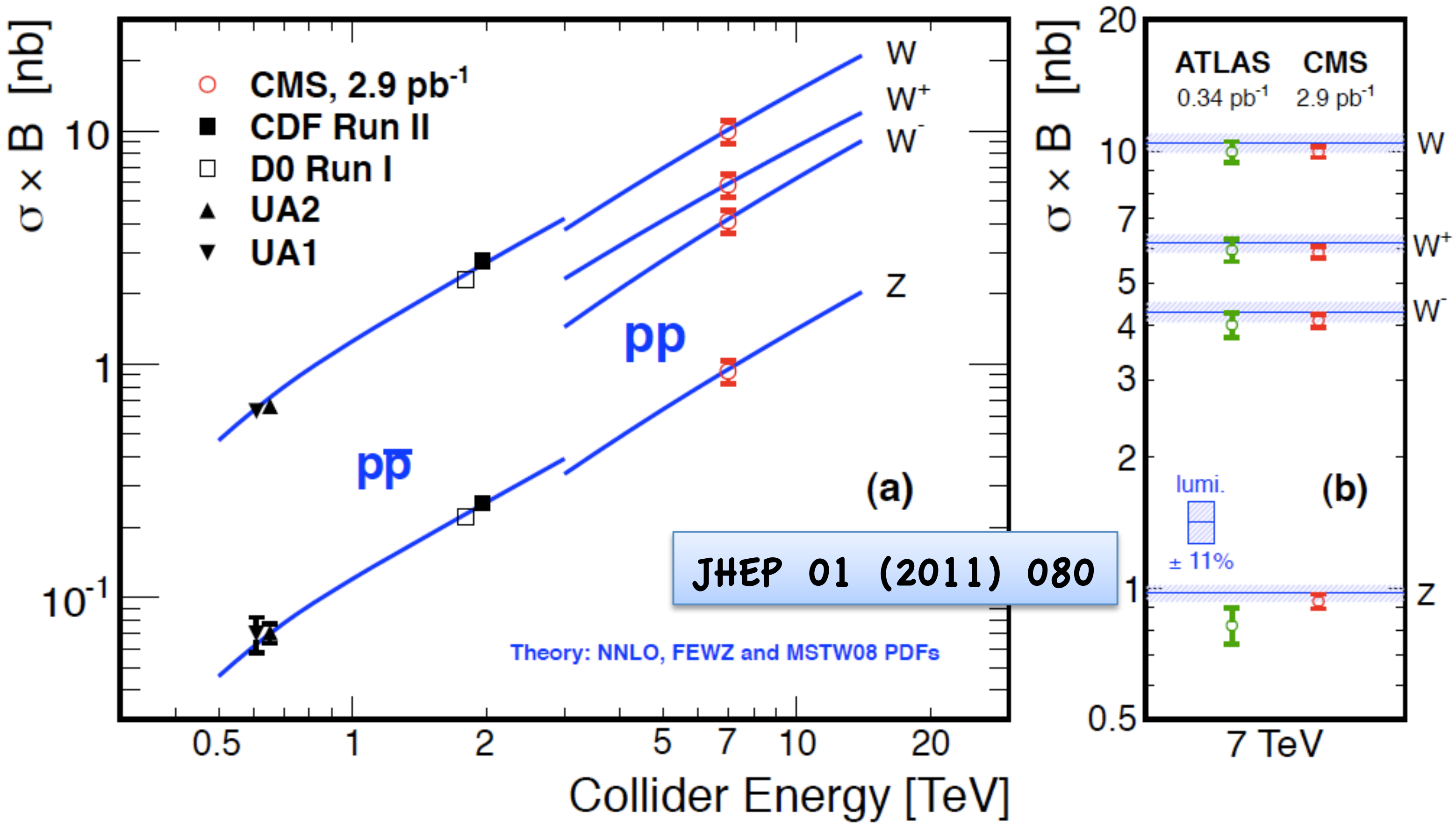
- Individual cross sections and ratios agree well with theory predictions.
- Systematical uncertainties ~ statistical uncertainties (w/o the luminosity uncertainty which cancel in the ratios).
- Central values of individual cross-sections are lower than the theory predictions by ~5%, but still within the luminosity uncertainty. ➔
- δ_{exp} < 4% → W and Z cross sections can be used to normalize the LHC luminosity with an uncertainty better than ~5%.

Updated results with 36 pb^{-1}.



CMS PAS EWK-10-005





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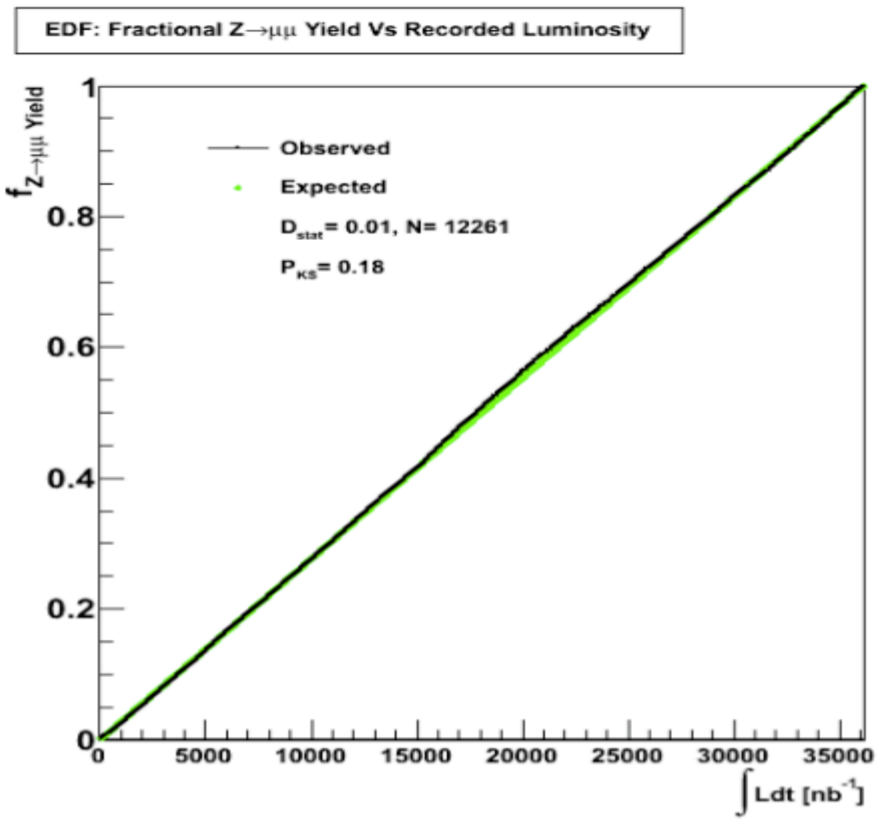
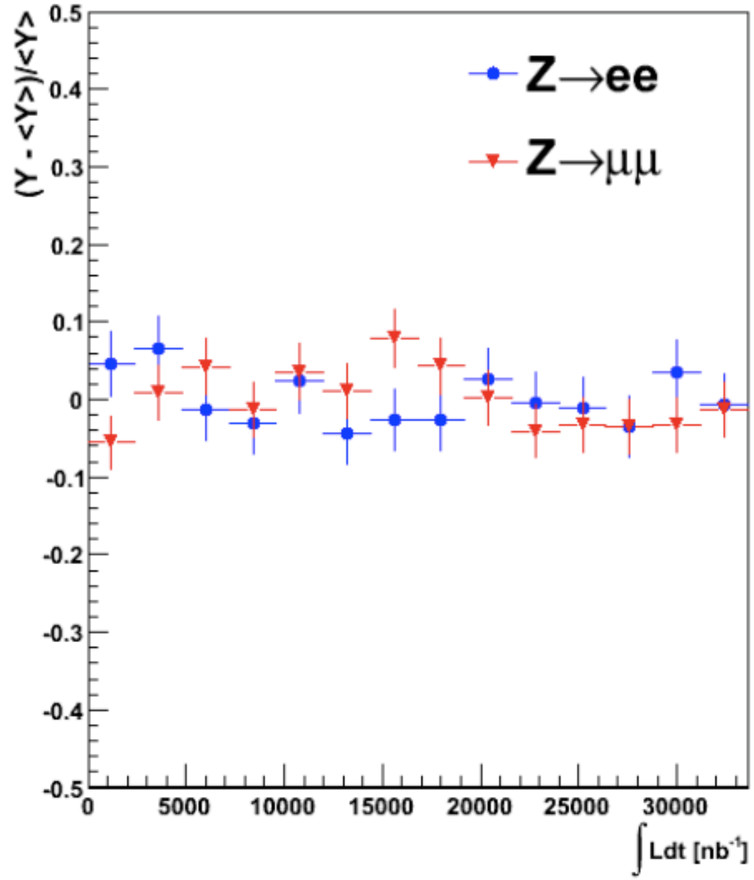
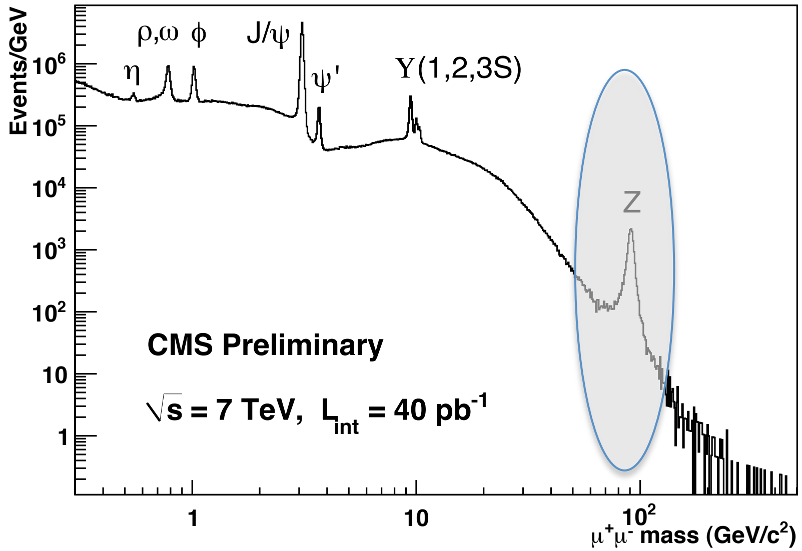
- The increase of the Z (and W) cross sections with energy is confirmed.
- Good agreement between CMS, ATLAS, and theory predictions.

Z yield vs. Time



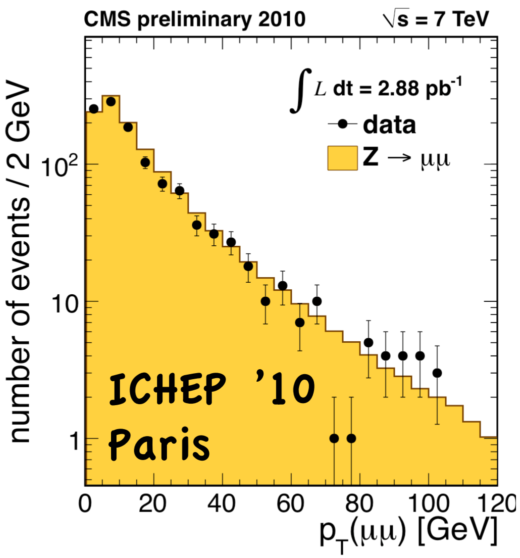
(Y - <Y>)/<Y> /2.4 pb^{-1}

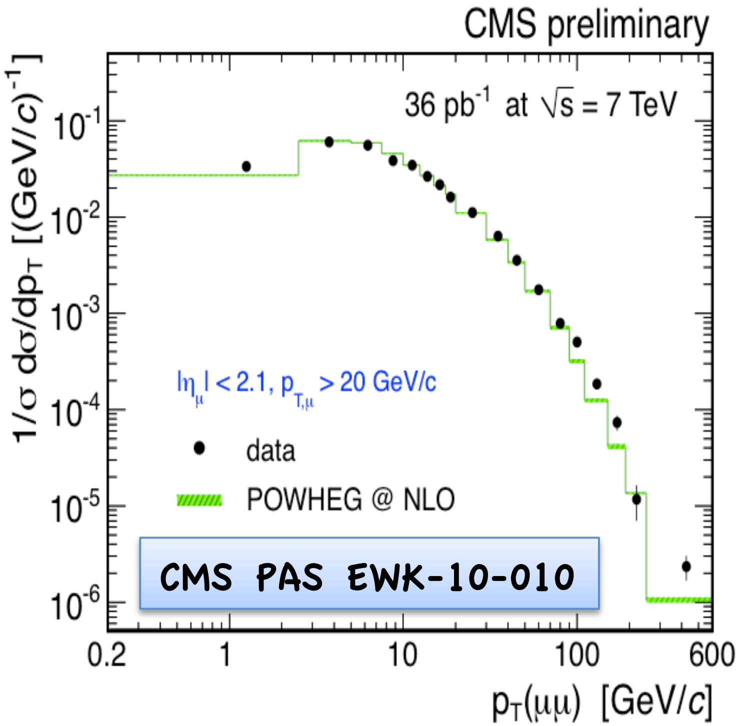




- Enough statistics to start slicing the Z's and study them as a function of rapidity, p_T, mass, and angular variables
- Double differential measurements will provide the most strict constraints on the PDFs → better understanding of sea quark and gluon contributions.
- Accuracy for low p_T region → Crucial for MC modelling.
- Access to higher p_T region with multi-jets

$d\sigma/dp_T$

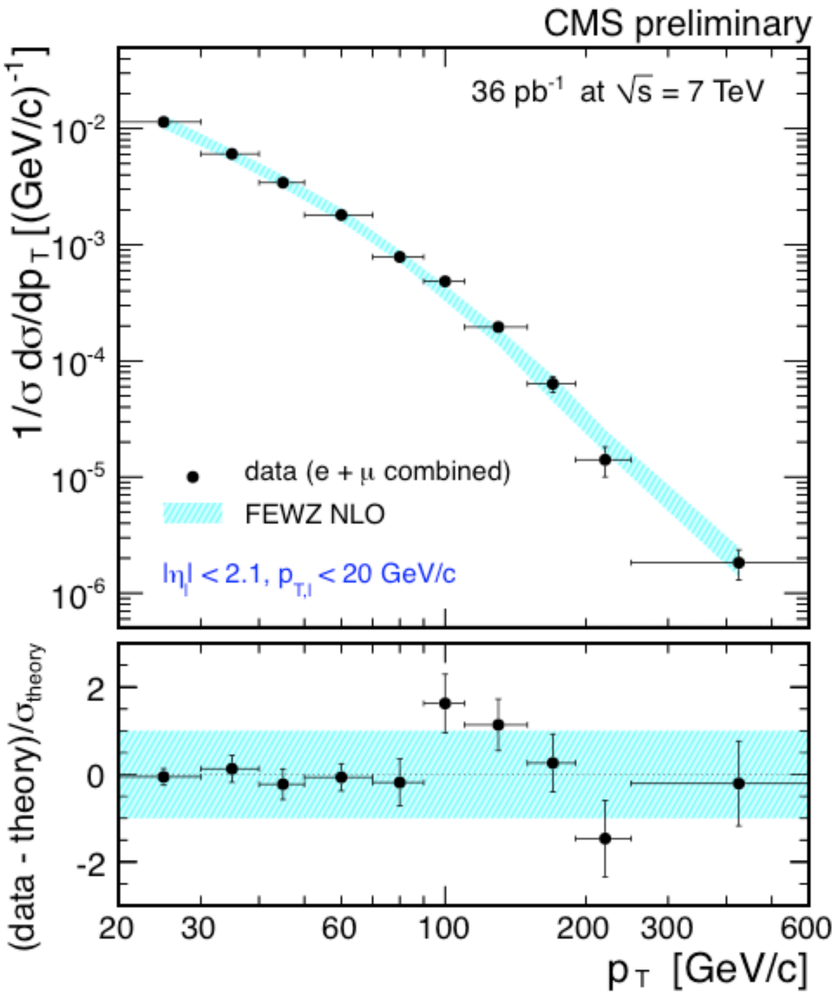


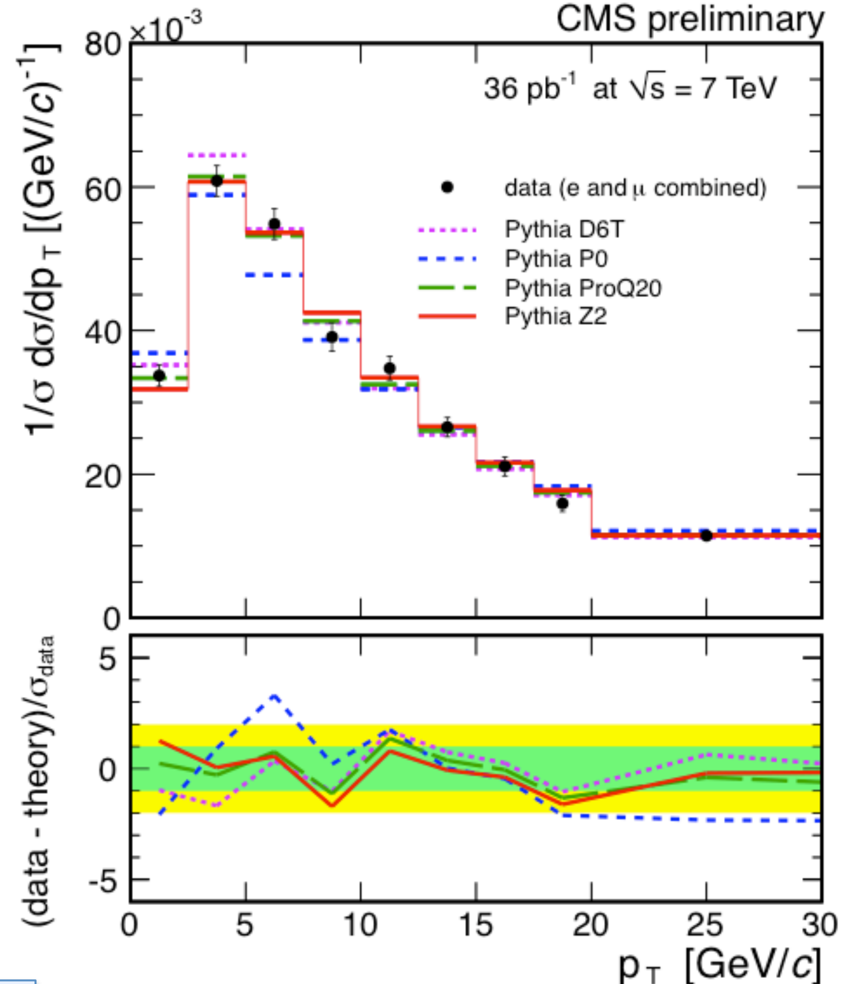


Probably the highest p_T Z events ever.

$$\frac{d\sigma}{dp_T} = \frac{N_s(p_T) - N_b(p_T)}{\delta p_T(p_T) \times (A \times \varepsilon)(p_T) \times \int L dt}$$

- **Backgrounds:**
  - Dominant background is ttbar for p_T>30 GeV.
  - Estimate it by counting the # events for which ttbar→WW→eμ which has identical kinematics and N(ttbar→eμ)=2N(ttbar→$\mu\mu$) reducing the uncertainty on the estimate.
- **P_T resolution is distorted due to bin migration caused mainly by tracker-muon system misalignment and QED FSR.**





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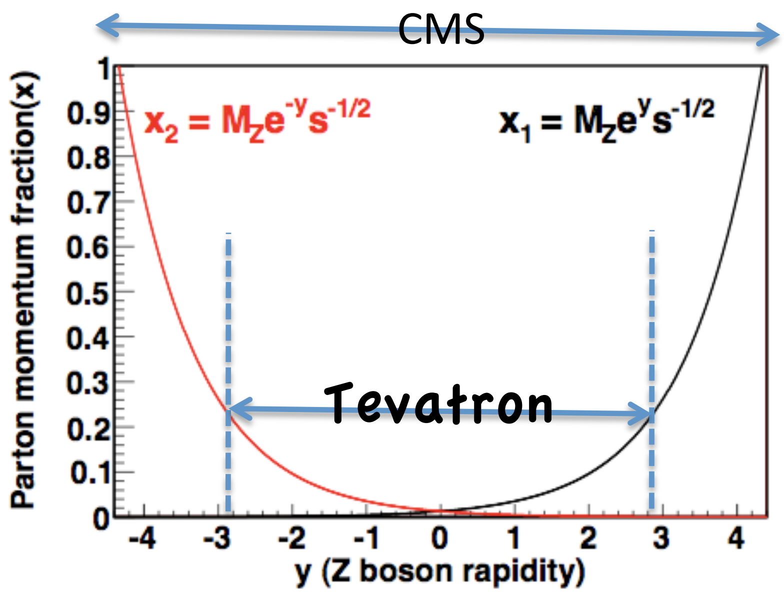
- Soft p_T spectrum → multiple soft gluon emission
- Hard p_T spectrum → pQCD
  - Sensitive to gluon PDFs
  - Deviations provide model independent BSM searches.
- Matching high and low p_T

dσ/dy

$$y = \frac{1}{2}\ln\frac{E + p_Z}{E - p_Z} = \frac{1}{2}\ln\frac{x_1}{x_2}$$

Parton momentum fractions (x_i), determine P(Z) and rapidity (y).



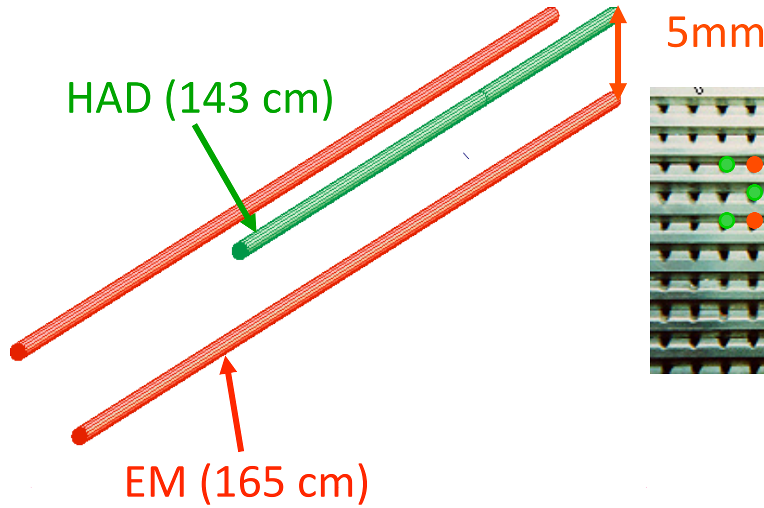
Large y (=high x) is not well known, but in the electron channel we are able to cover up to $|\eta|\sim 5$ thanks to HF.

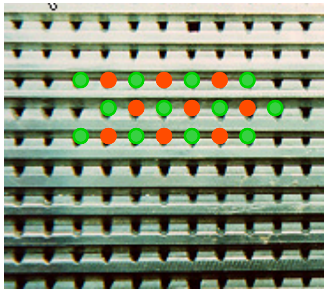
Electron Identification in HF

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

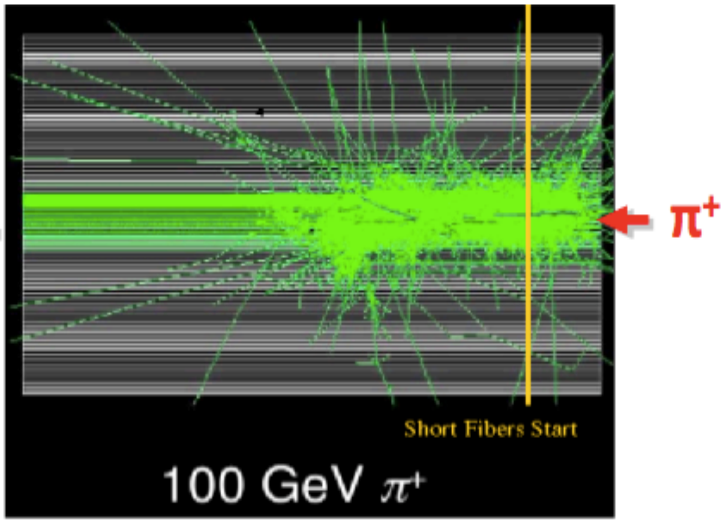


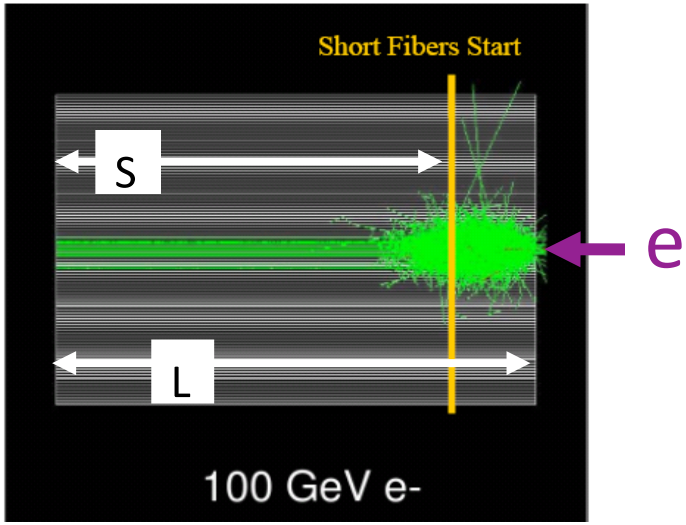


Electrons in HF can be identified using longitudinal and transverse shower shape variables:

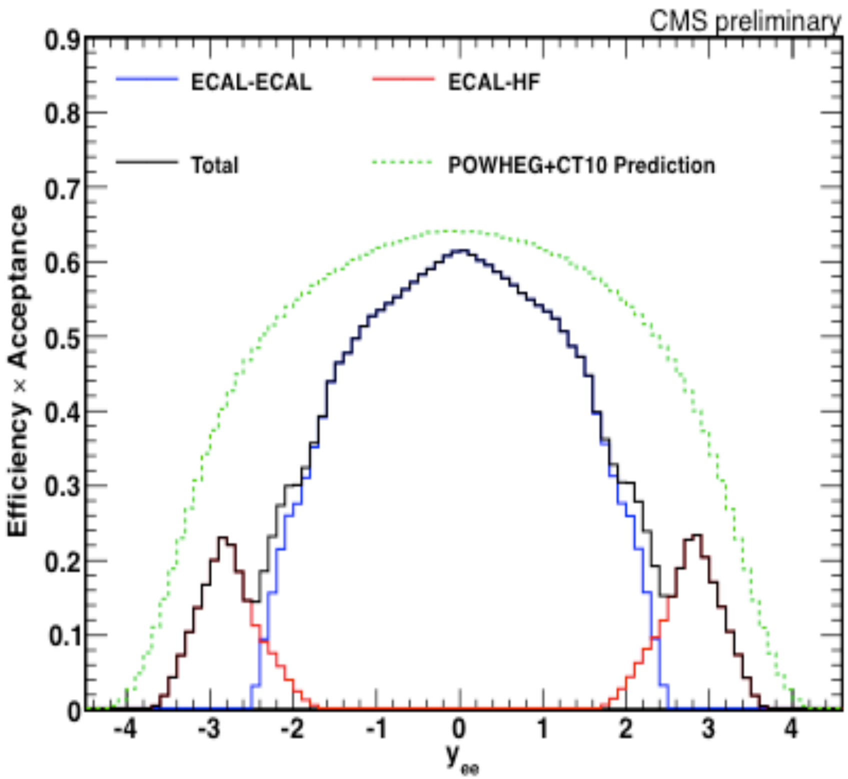
Isolation: $E(L+S)_{3x3}/E(L+S)_{5x5}$ > XX,

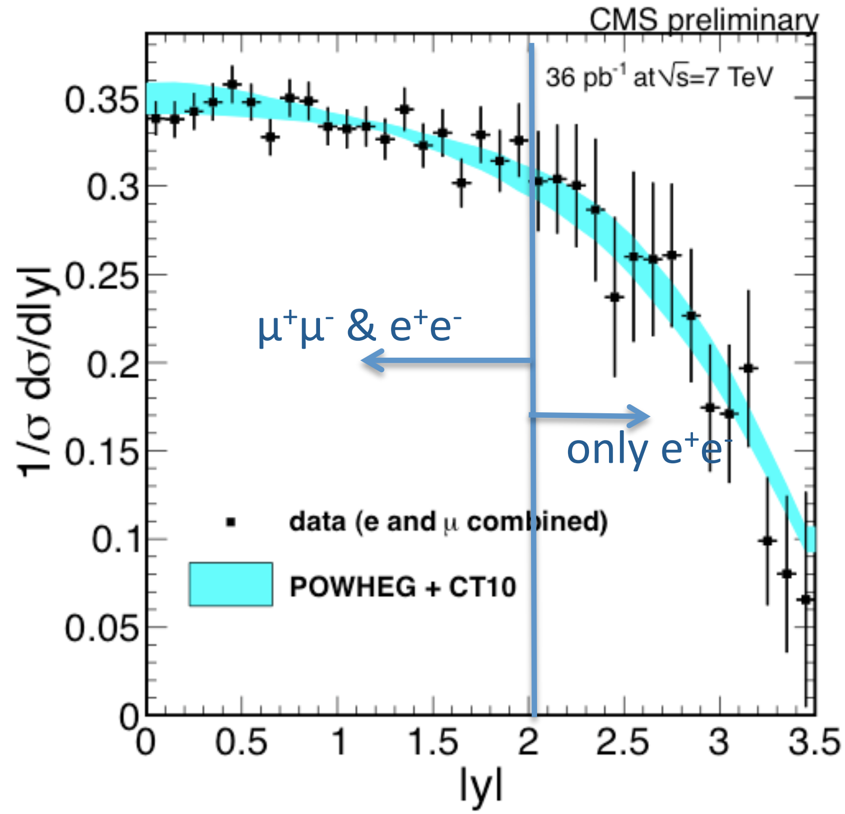
Compactness: $E(L_{core})/E(L_{3x3})-cE_S/E_L$ = (shower shape) − c(shower depth) > XX





dσ/dy





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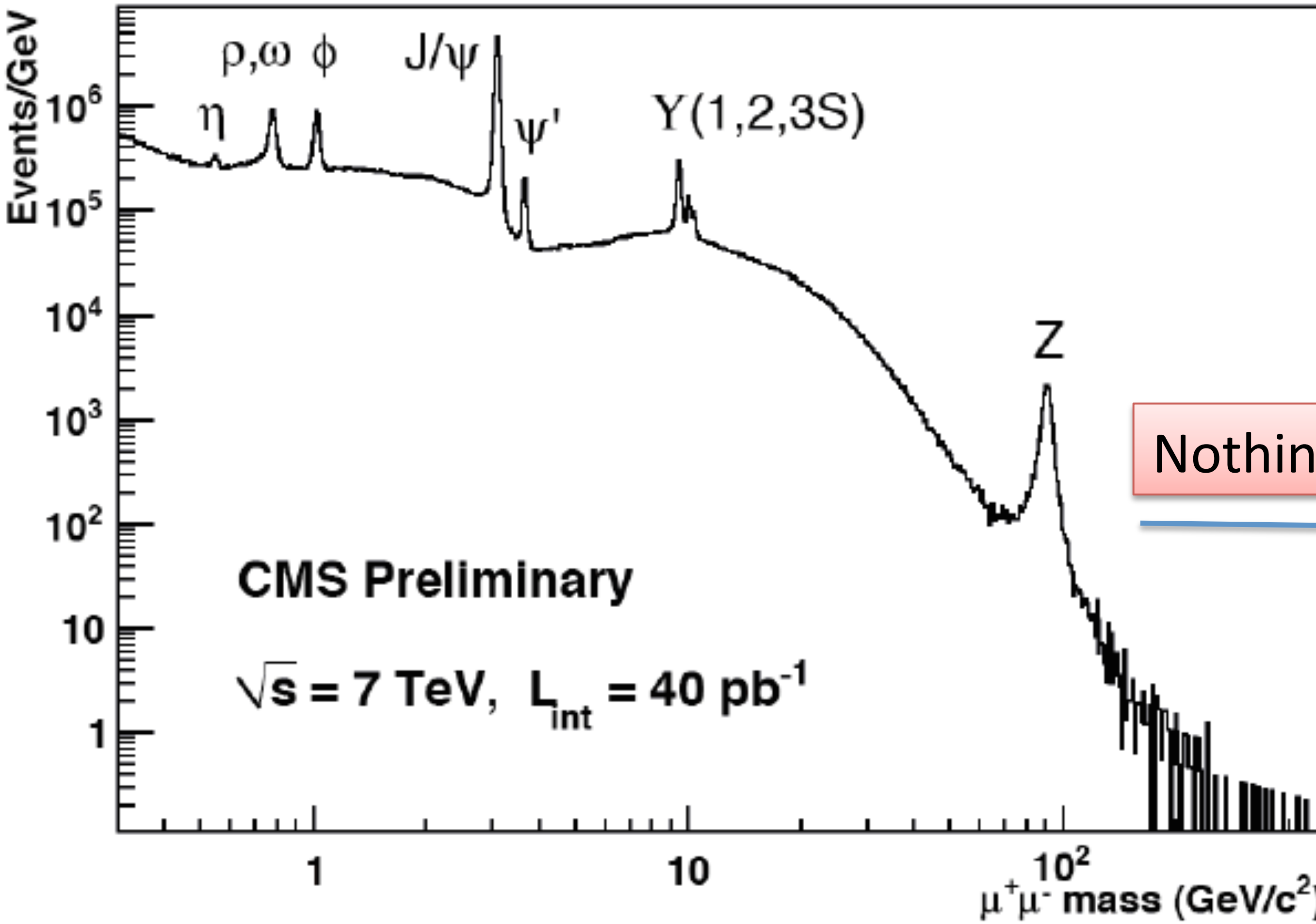
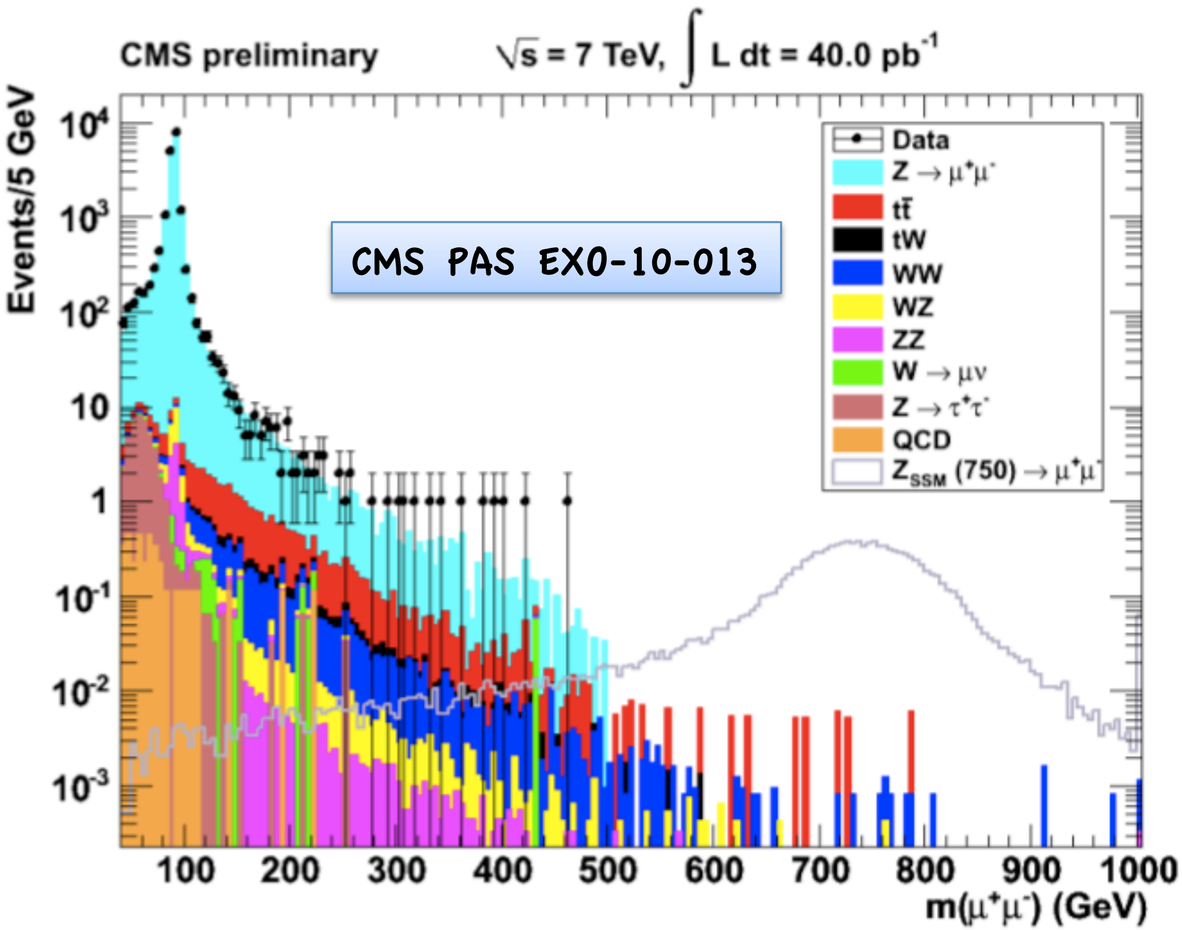
ee: For |η|>3, strict requirement on the ECAL electron and loose requirements on the HF to reconstruct the Z mass.



Nothing beyond?



- We do not know the width.
- But there are other ways to search for new resonances.

Forward-Backward Asymmetry in Di-Lepton events (A_{FB})

In the process $pp \rightarrow q\bar{q} \rightarrow Z/\gamma^{*} \rightarrow l^{+}l^{-}$ both vector and axial-vector couplings of electroweak bosons are present. This results in a forward-backward asymmetry in the Drell-Yan lepton pairs.

$$\frac{d\sigma}{d(\cos\theta^{*})} = A(1+\cos^{2}\theta^{*}) + B\cos\theta^{*}$$

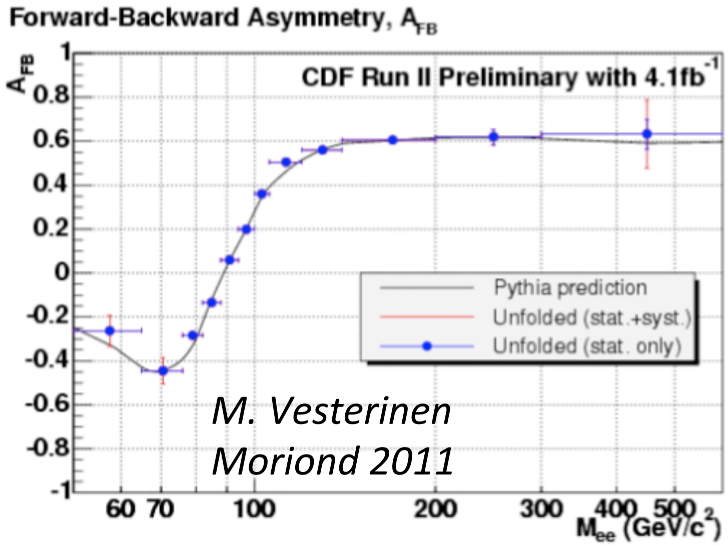
A,B are proportional to weak isospin and charge of the incoming fermions.

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N_F - N_B}{N_F + N_B} = \frac{3B}{8A}$$

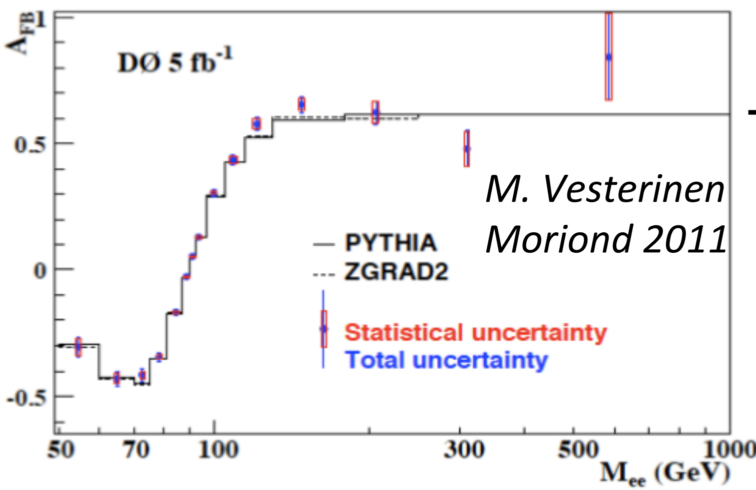
$$A_{FB} = A_{FB}(M, Y, \cos\theta^{*}, \sin^{2}\theta_W, q - flavor)$$

AFB for M>150 GeV→0.6 (at the generator level)

• With ~5 fb^{-1} Tevatron reaches ~0.5 TeV



→0.6



→0.6

$q\tilde{q} \rightarrow \gamma^* \rightarrow ll$ for $M<60$ GeV

$q\tilde{q} \rightarrow Z \rightarrow ll$ at $M=M_Z$ $\rightarrow \sin^2\theta_W$

$q\tilde{q} \rightarrow \gamma^*/Z \rightarrow ll$ for $M\sim>110$ GeV

We try to show that A_{FB} works at low mass and then look for deviations at high mass.

Defining forward/backward

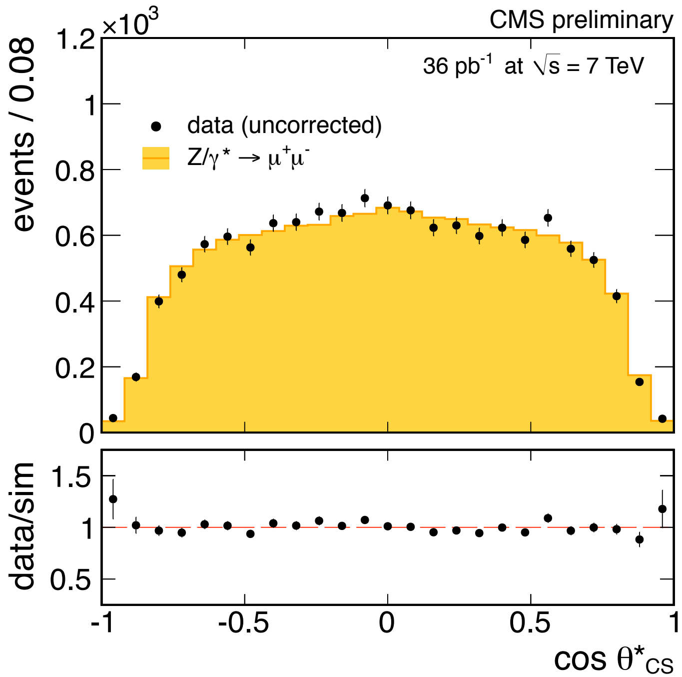
- At the LHC quark/anti-quark directions are not known (unlike Tevatron)
- But the anti-quark at the LHC is a sea-quark, → on average, we expect it to have a smaller momentum than the valence quark

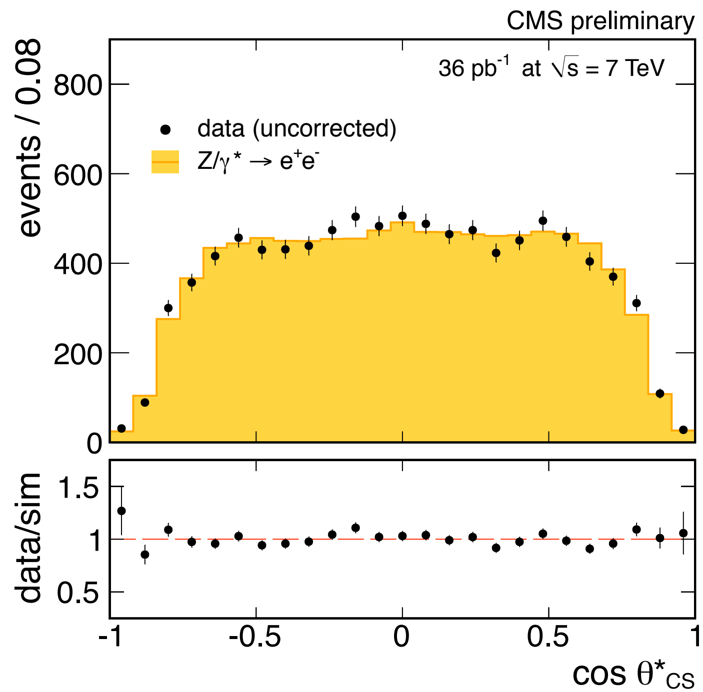
  →Di-lepton system is boosted along the quark direction.

→*We will correct for this effect by taking the `correct' quark direction known at the generator level.* (i.e. if Z direction is wrong $\cos\theta_{CS}^* \rightarrow -\cos\theta_{CS}^*$) → Something that must be valid for non-SMs as well.

  →PDF-dependent.

Defining forward/backward: $\cos\theta_{CS}{}^*$





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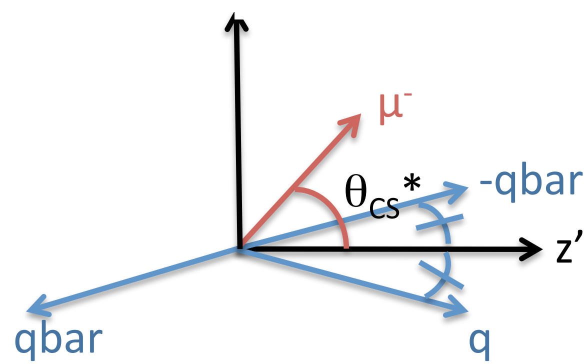
Collins-Soper frame



Sensitive to BSM and the spins of new particles.

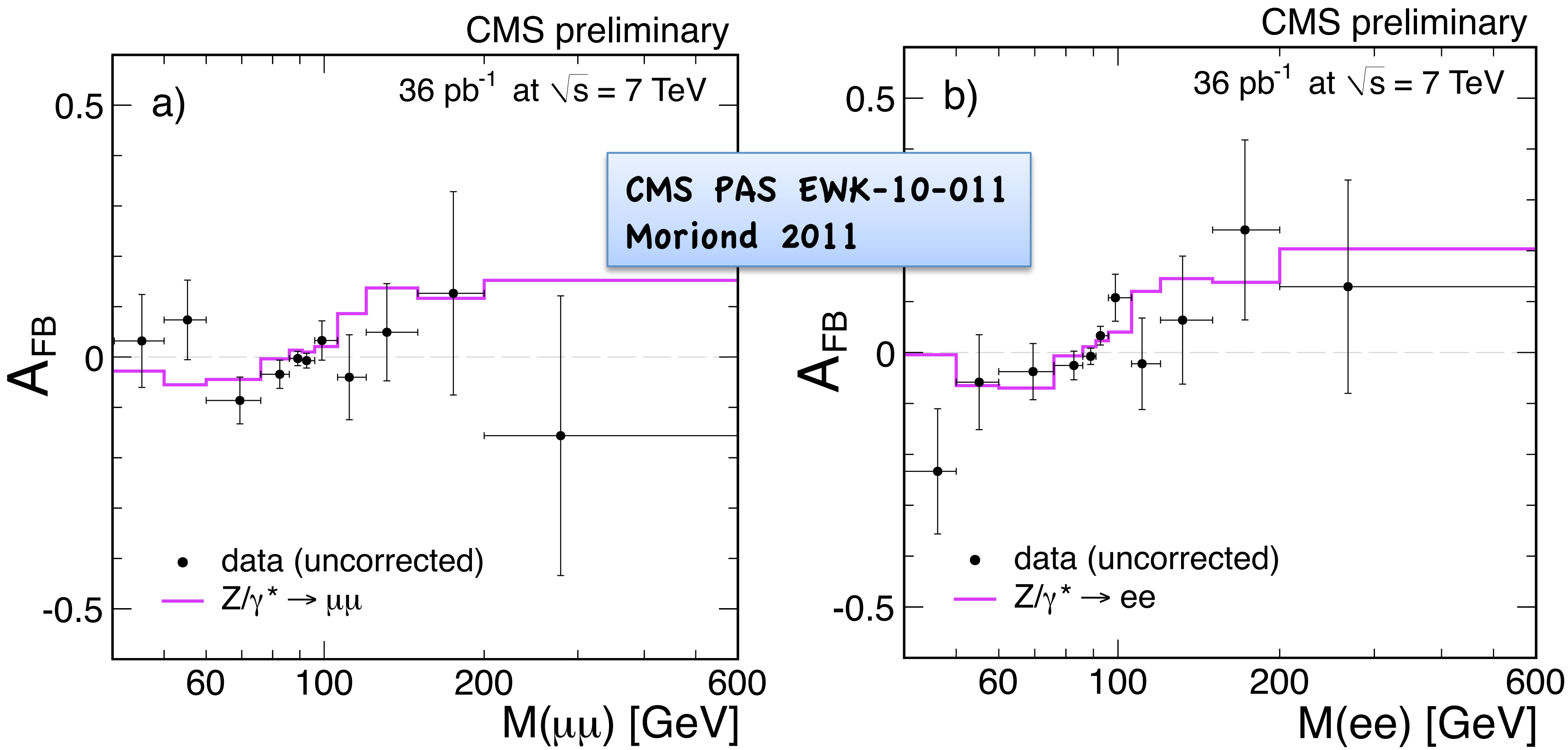
$$\cos\theta^*_{CS} = \frac{2\left(P_1^+P_2^- - P_1^-P_2^+\right)}{\sqrt{Q^2\left(Q^2+Q_T^2\right)}}$$

Q: four-momentum of the di-lepton system

$$P_i^{\pm} = 2^{-1/2}\left(P_i^0 \pm P_i^3\right)$$

- Asymmetry is *diluted* due to detector resolution, QED FSR (bremsstrahlung from the lepton), acceptance, and unknown quark/anti-quark directions.
  - Corrections can be applied
    - Unfolding for detector resolution and QED FSR
    - q/q~ direction corrections using MC
  - Compare to smeared theory
  - Extend the rapidity range as much as possible (smaller q/q~ direction ambiguity, smaller effect of acceptance).

Uncorrected Asymmetry



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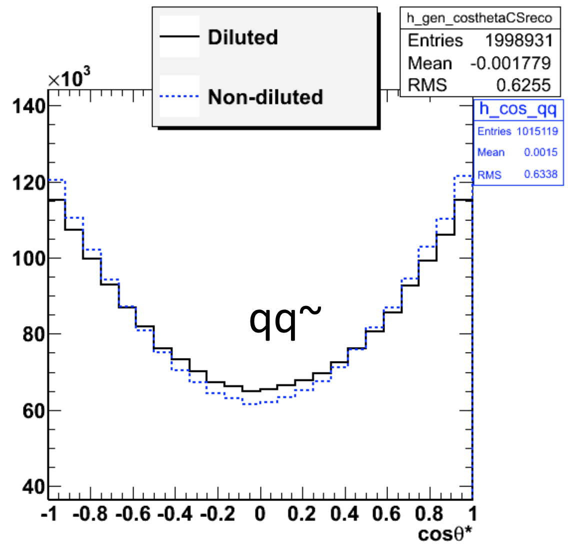
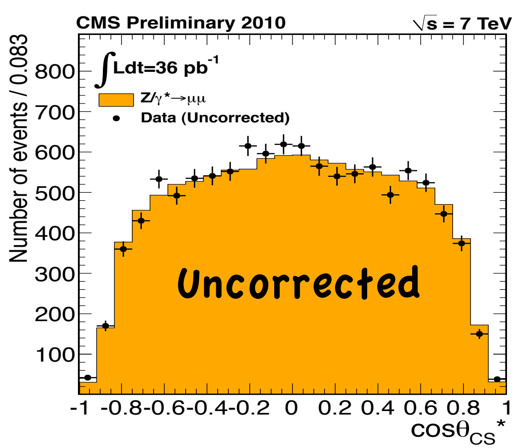
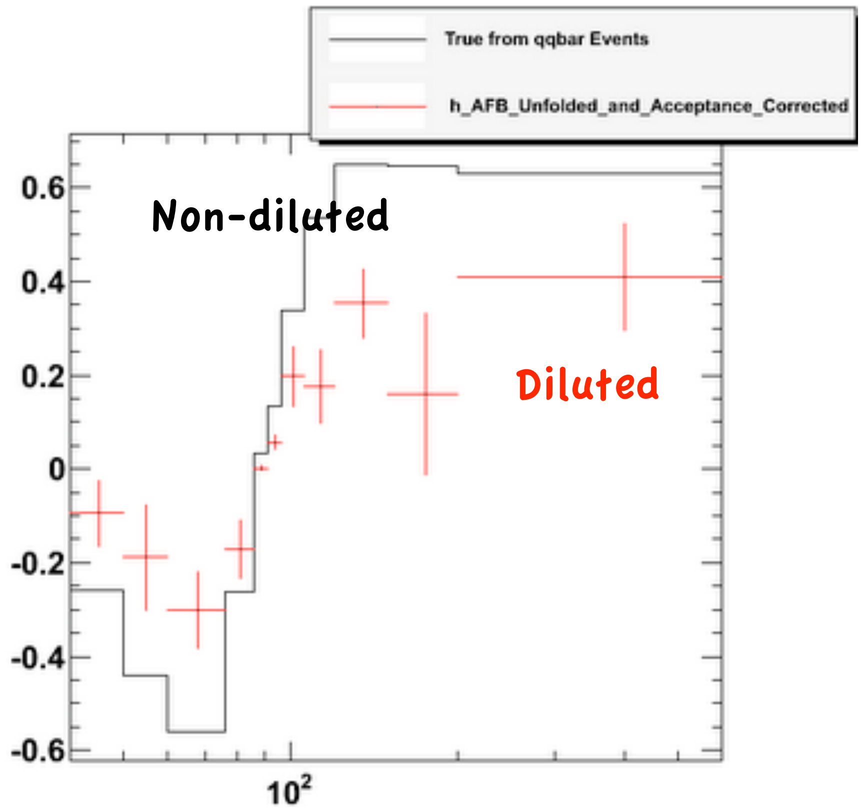
- Measured and simulated A_{FB} in 11 di-lepton mass bins.
- MC: POWHEG generated events passed through full CMS simulation with same selection cuts applied in data.

$$\Delta A_{FB} = \sqrt{\frac{1 - A_{FB}^{\;2}}{N_{obs}}}$$

Dilution (or quark-direction) Corrections





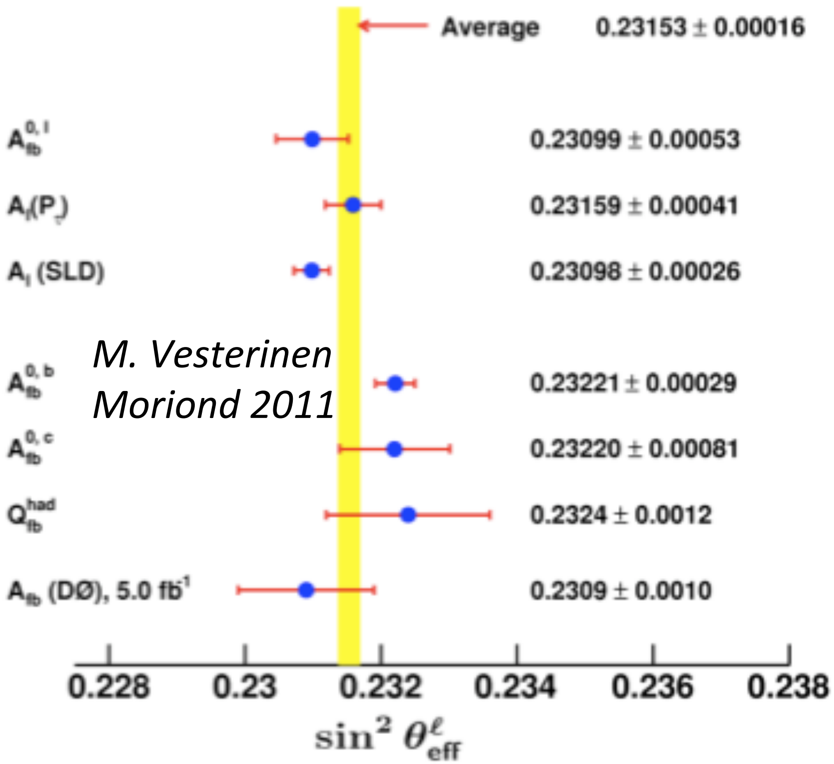


$$d_{FB}(M) = \frac{A_{FB}^{q}(M)}{A_{FB}^{Z-boost}(M)} = 1/D$$

- Unknown quark directions → Large effect on A_{FB} at the LHC
- Should be corrected for the cases in which the Z is not boosted in the quark direction
- Corrections through dilution factors which are functions of |Y|, M→ll, (and cosθ*).

$\sin^2\theta_W$

- A_{FB} ←→ Weinberg angle.
- Using the raw asymmetry measurement (or unfolded AFB) $\sin^2\theta_W$ can be extracted.
- But even a better way is to use a multivariate likelihood fit of the rapidity, dilepton invariant mass and angle distributions.
  - Initial CMS result: $\sin^2\theta_W^{eff}$=0.2287+/-0.0077(stat)+/-0.0036(syst). (CMS PAS EWK-10-011)



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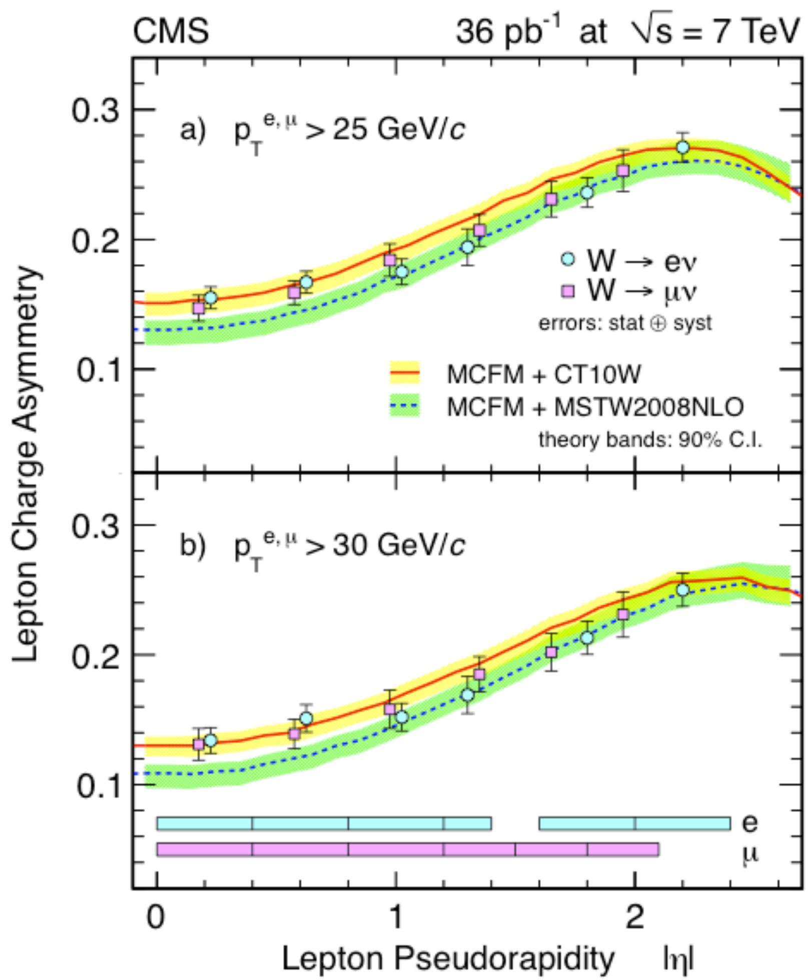
→ ***Measurement precision depends on how well we can control PDF systematics***

→ ***We need to use an independent measurement not using Z bosons***

Weinberg angle → M_H

PDF Constraints from W-Asymmetry



- Flatter η-dependence than PDF predictions.
- Statistical precision is already enough to provide new inputs to global PDF fits.

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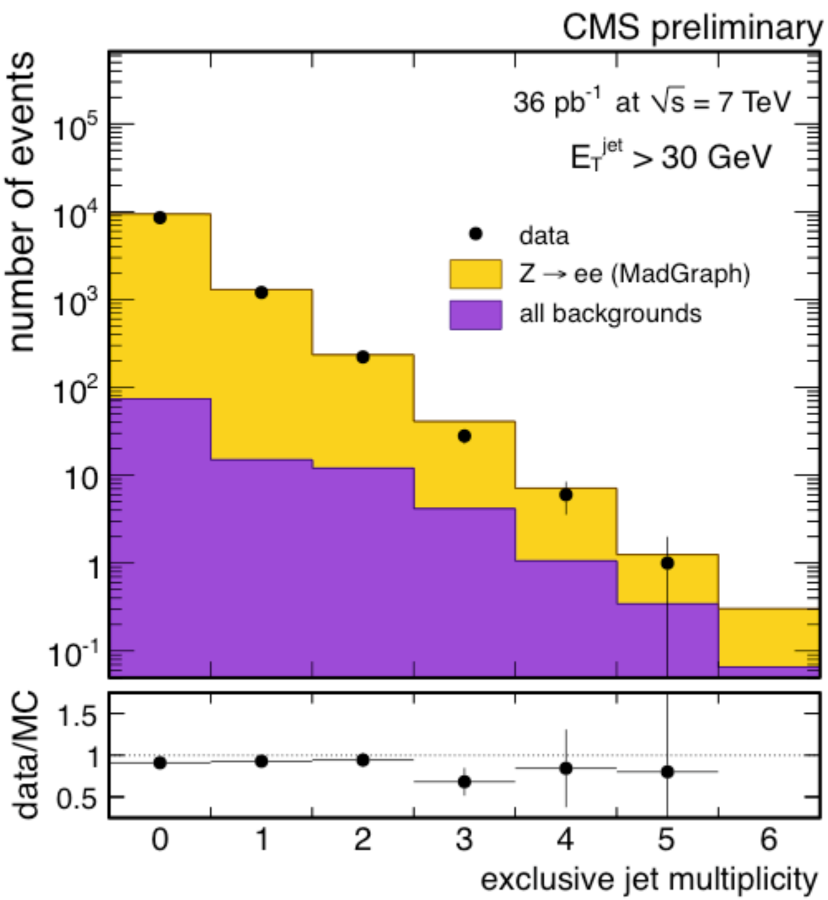
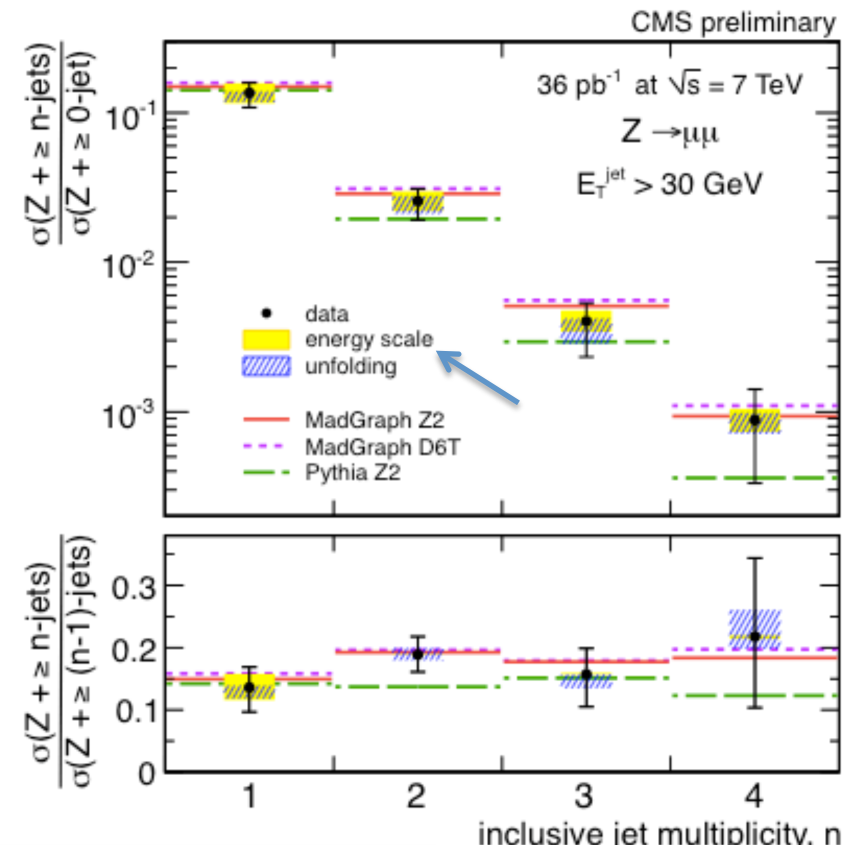
Z+Jets





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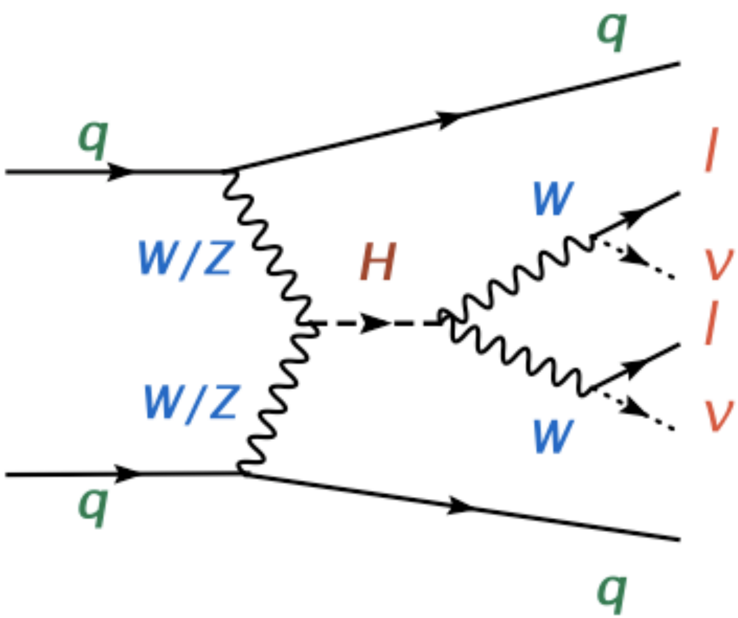
Moriond 2011

The Jet Energy Scale for qqH



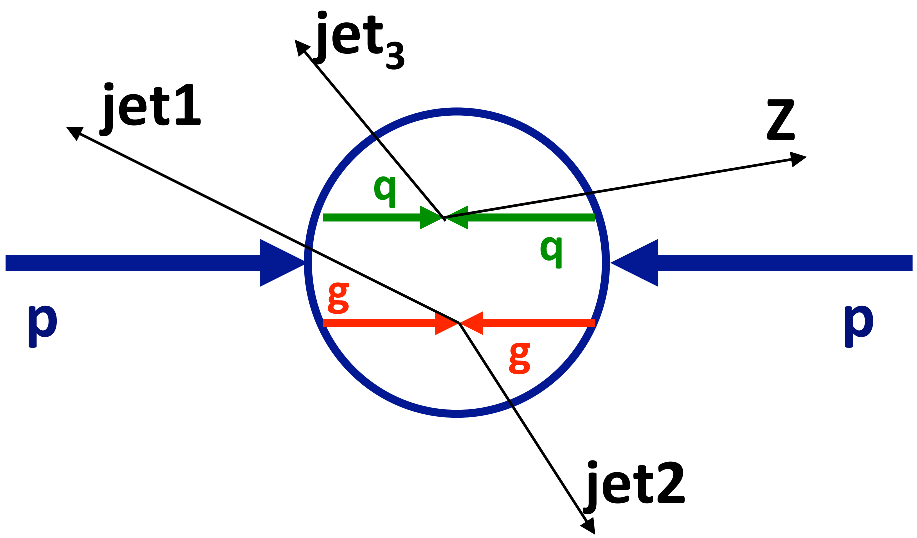
Large rapidity gap for tag jets $|\Delta\eta|>4$.

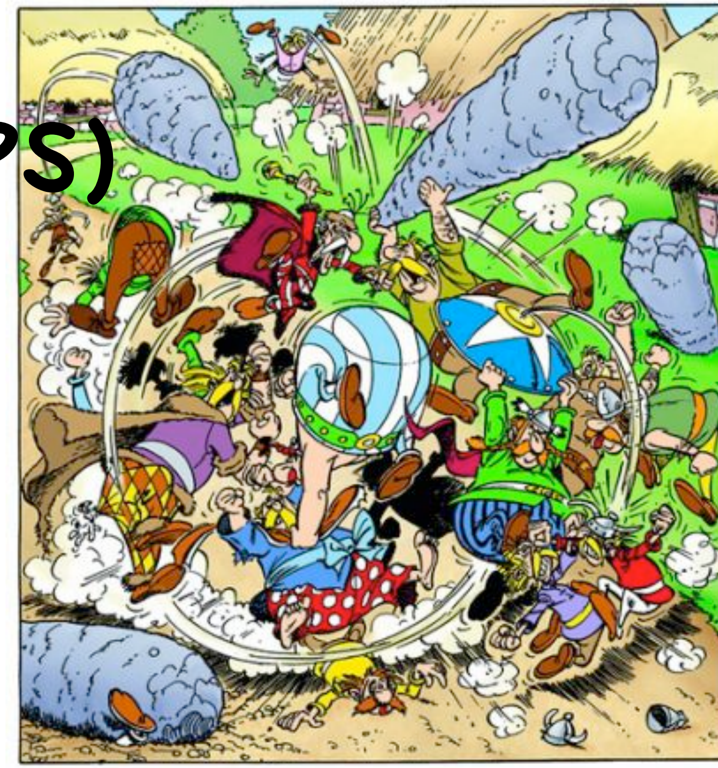
(VBF in CMS:
see e.g. Yazgan et al. EPJ-C 53, 329, 2008)

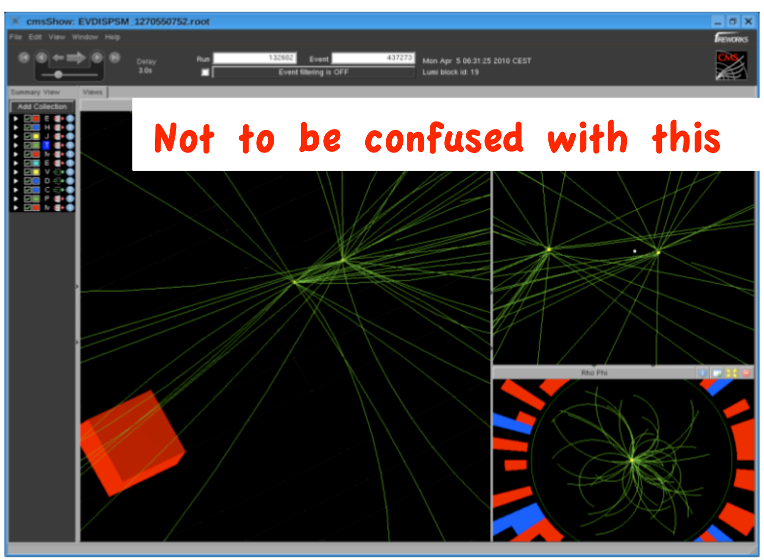
- The correct jes for tagging quarks is needed to correctly measure the Higgs boson mass in qqH, for example in $H\rightarrow\tau\tau\rightarrow l\nu\nu+\tau-jet$, events using properly corrected missing transverse energy.
- The correct jes for tagging quarks in qqH requires using a quark-rich sample.

Z+j events are almost background free and the ratio of quark and gluon jets is well known from the theoretical predictions.

Hard Double (or Multi) Parton Interactions (DPS)







- *Simultaneous interaction of two parton pairs in the same collision is a consequence of the parton model.*
- Proposed in 80's
- And it has been measured in AFS, UA2, CDF, and D0.

Higher energy at the LHC → sizable effect of DPS events compared to the previous experiments -- however the DPS cross section vs. $\sqrt{s}$ is not known

Background to Higgs, Z/W+Jets, …..

$$\sigma^{DPS}_{A,B} = \frac{m\sigma_A\sigma_B}{2\sigma_{eff}}$$

σ_{eff}: a measure of the effective interaction region of the hadron – in principle, process independent.

(m=2 for distinguishable prcesses; e.g. A=Z, B=di-jets)

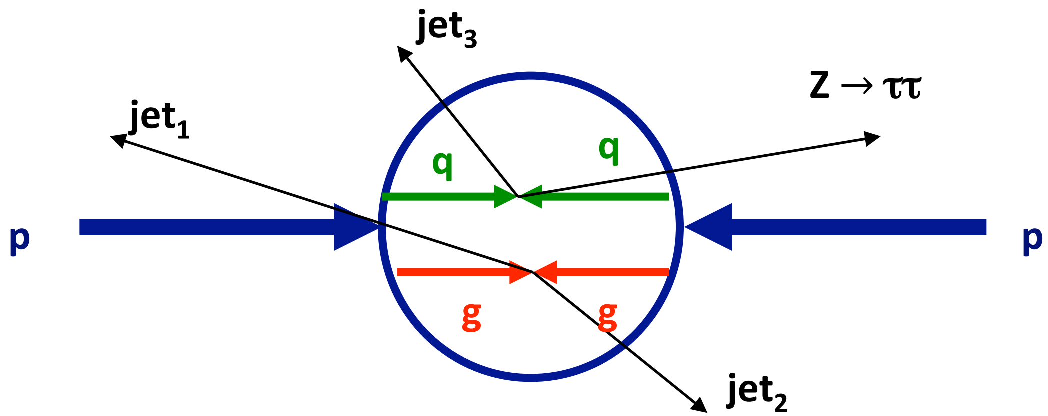
σ_{eff} = 16.4 mb (D0 γ+3j)

σ_{eff} = 14.5 mb (CDF 4j)

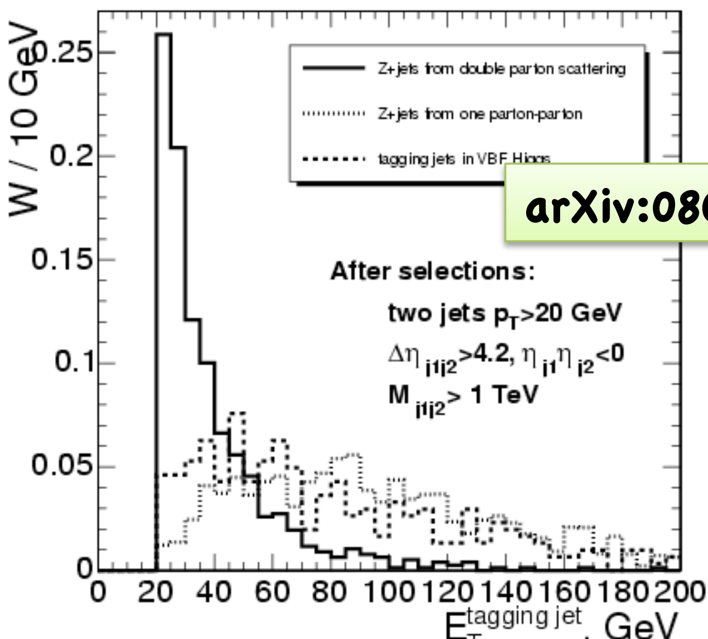
Transverse size ~ 0.5 fm << R(proton) → correlations.

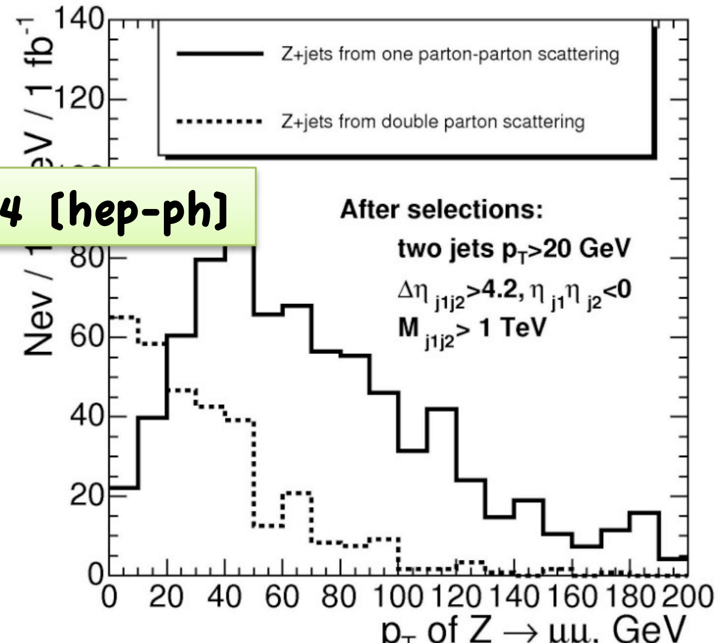
But also, longitudinal correlations in double-parton PDF (correlations in longitudinal Momentum fractions at large Q^2 and finite x) can have sizable effect (not accounted for in the formula above) [arXiv:1001.0104,0910.4347]

An example: $Z \to \tau\tau$ + jets bkgr. from DPS in qqH, $H \to \tau\tau$



One jet from DY, and the other from QCD di-jet production.





arXiv:0803.1154 [hep-ph]

DPS ~ 40 % of the "normal" Z+jets after cuts: E_T^j > 20 GeV, M_{j1j2}>1TeV, $\Delta\eta_{j1j2}$>4.2

DPS ~ 15 % of "normal" Z+jets after cuts: E_T^j > 40 GeV, M_{j1j2}>1TeV, $\Delta\eta_{j1j2}$>4.2

Conclusions and Outlook

- Re-discovery of the SM is "complete" through the measurement of standard objects including the Z boson.
- First Z differential di-lepton, Z-asymmetry, $\sin^2\theta_W$, and V+Jets measurements are/will be completed soon.
- Differential measurements will provide powerful constraints on PDFs (with ~250 pb^{-1}) that are independent of W-asymmetry.
- With 2011 LHC data, we will be able to start looking for new neutral bosons at high di-lepton mass using A_{FB}.
- $\sin^2\theta_W$: precise measurement with ~1 fb^{-1} possible.

- Studying Z+jets is not important only as a background to Higgs searches but also to improve tagging jet energy scale in VBF and to get the Higgs boson mass right.
- DPS is a new and significant background to several processes at the LHC (including the Higgs boson) and DPS measurements will help in better modeling of parton interactions. It seems to be measurable with Z+njets events with ~1 fb^{-1}.
- It is time to begin measurements on WW, ZZ which are important processes along the way to the Higgs boson.

If we can not find the Higgs boson at the LHC, W's and Z's can still be useful in providng clues about alternative symmetry breaking mechanisms.

We are exploring the surroundings of EWSB and trying to investigate EWK bosons in all aspects before we try to attack the problem of Higgs boson and its mass…