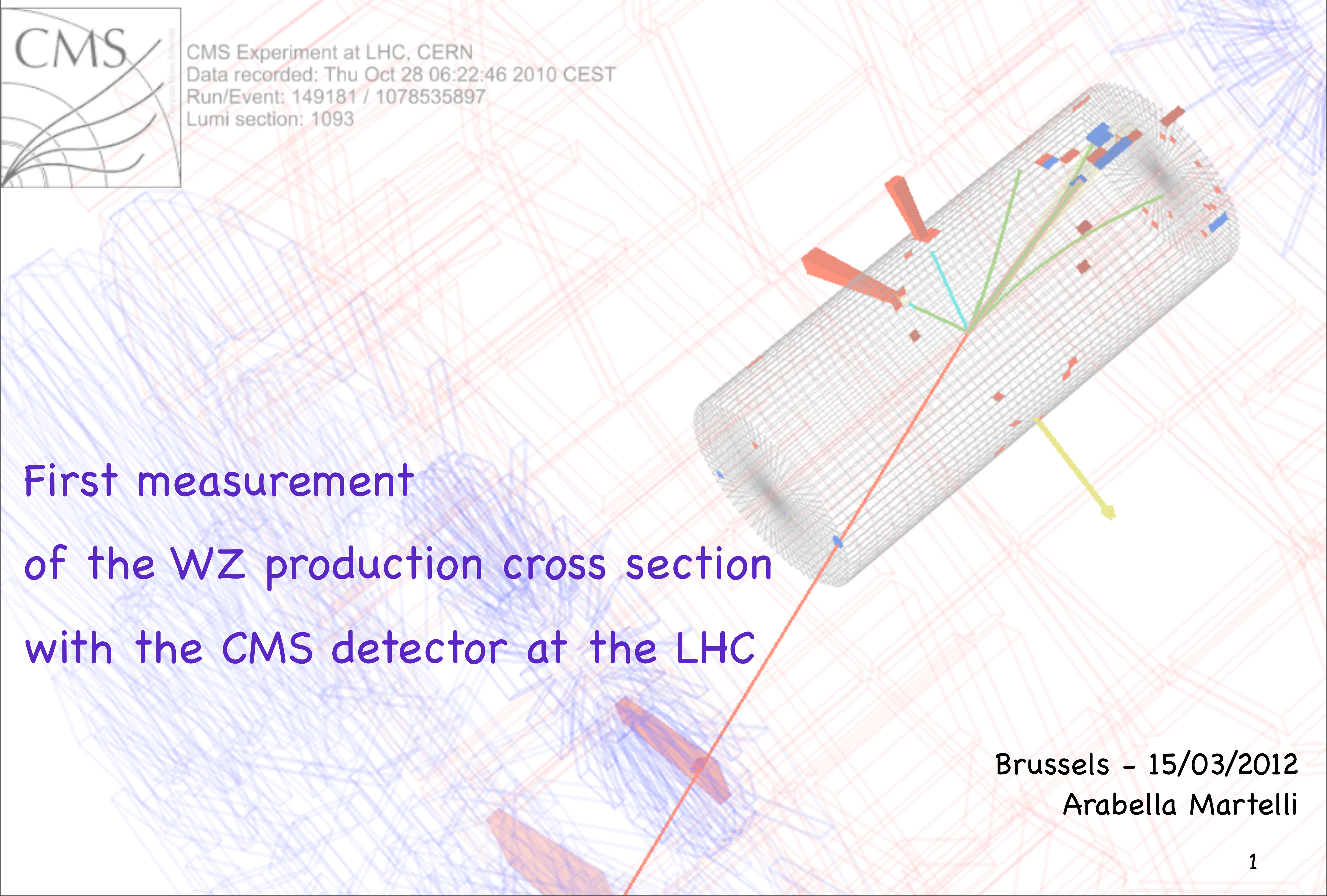


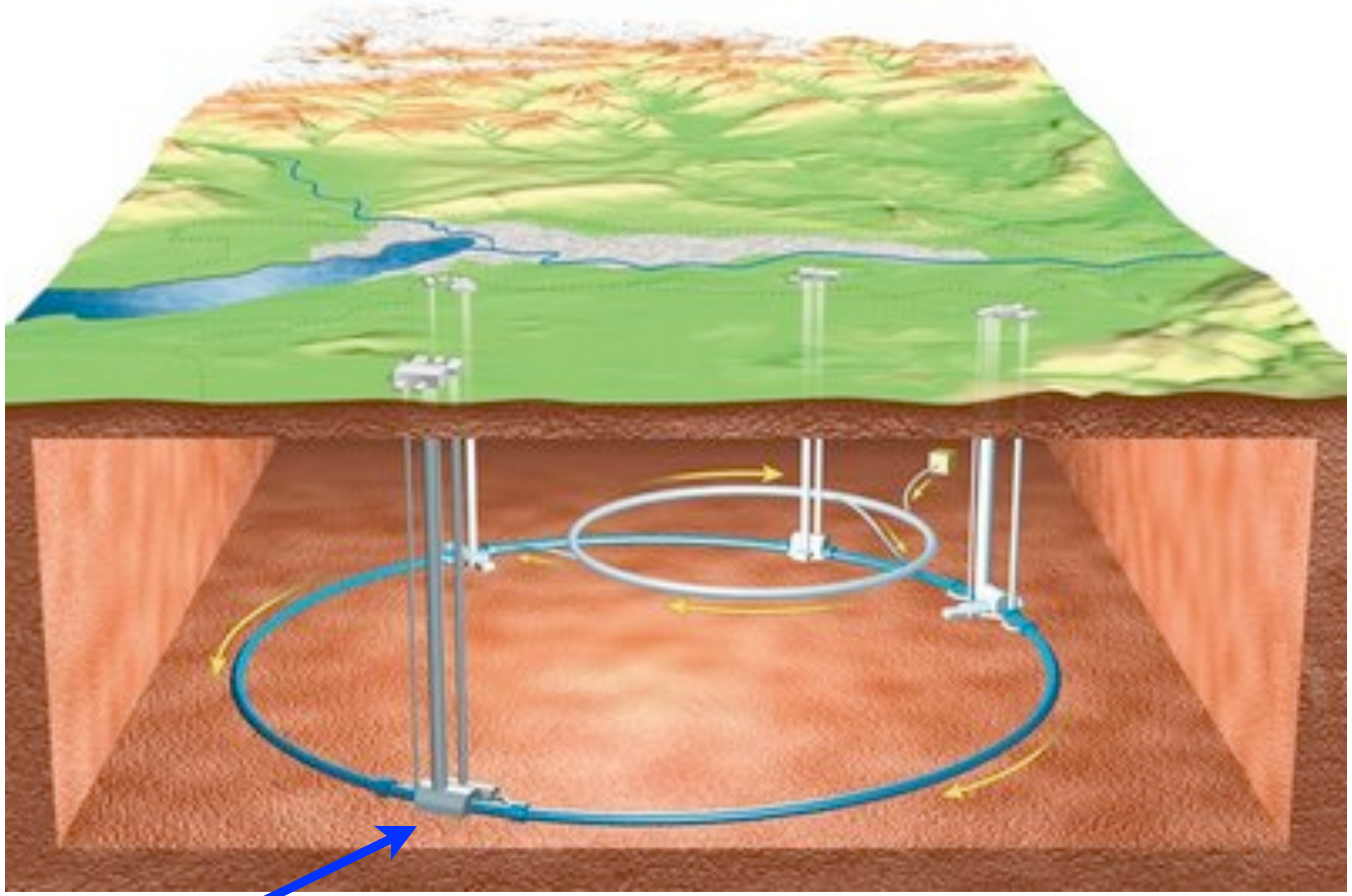
First measurement of the WZ production cross section with the CMS detector at the LHC

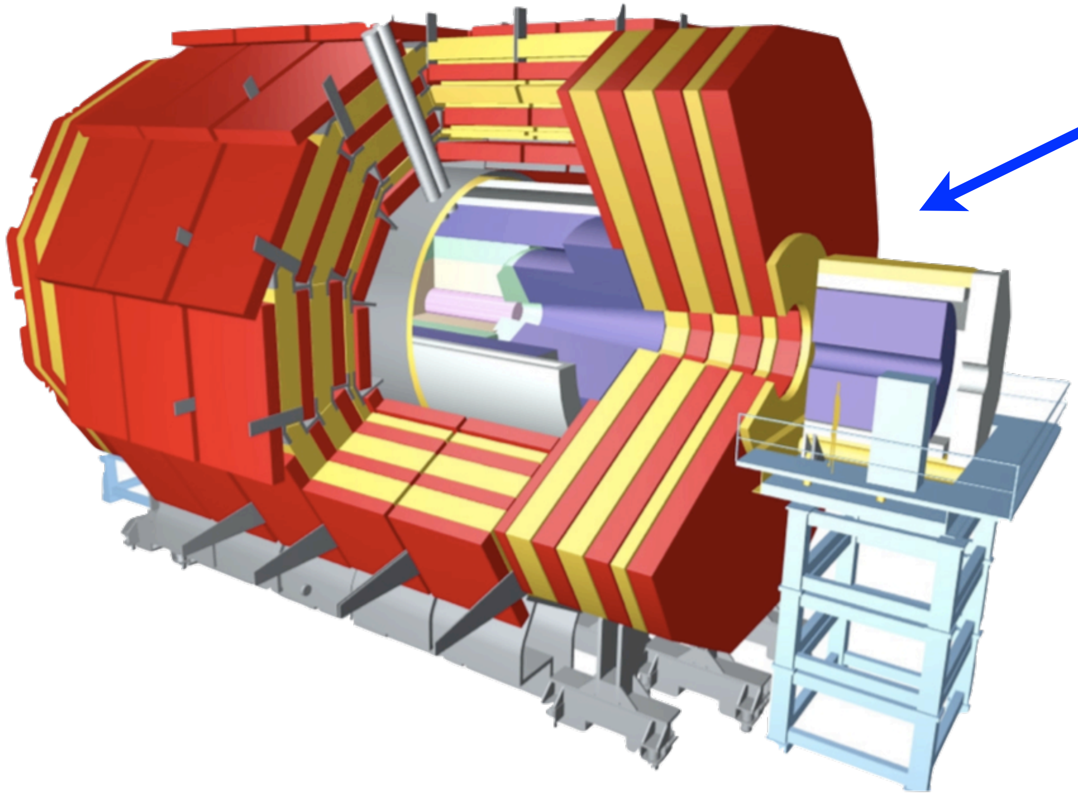
Brussels - 15/03/2012

Arabella Martelli

The Experimental context

Large Hadron Collider





Compact Muon Solenoid

Outline

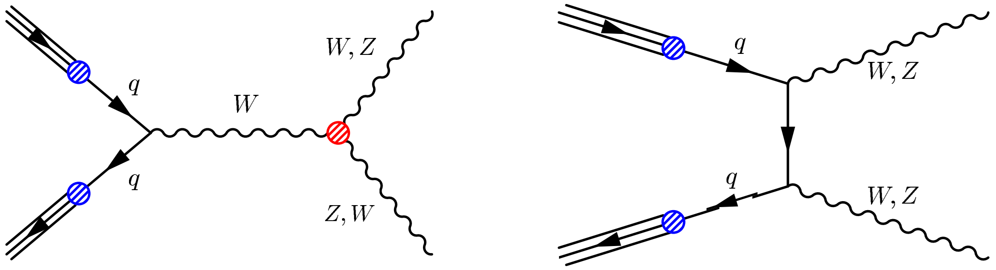
- Physics measurement: WZ -> $l\nu$ ($l = e, \mu$)
- Commissioning activity to understand detector and objects

CMS data taking

- ECAL energy scale validation with cosmic ray muons — 2008
  - context of the measurement
  - issues affecting the precision of the measurement
- Commissioning of the electron seeding with first data — 2009 – 2010
  - description of the procedure
  - evolution of the commissioning and final validation
- σ(pp -> WZ + X) measured with 1.09 fb^{-1} — 2011

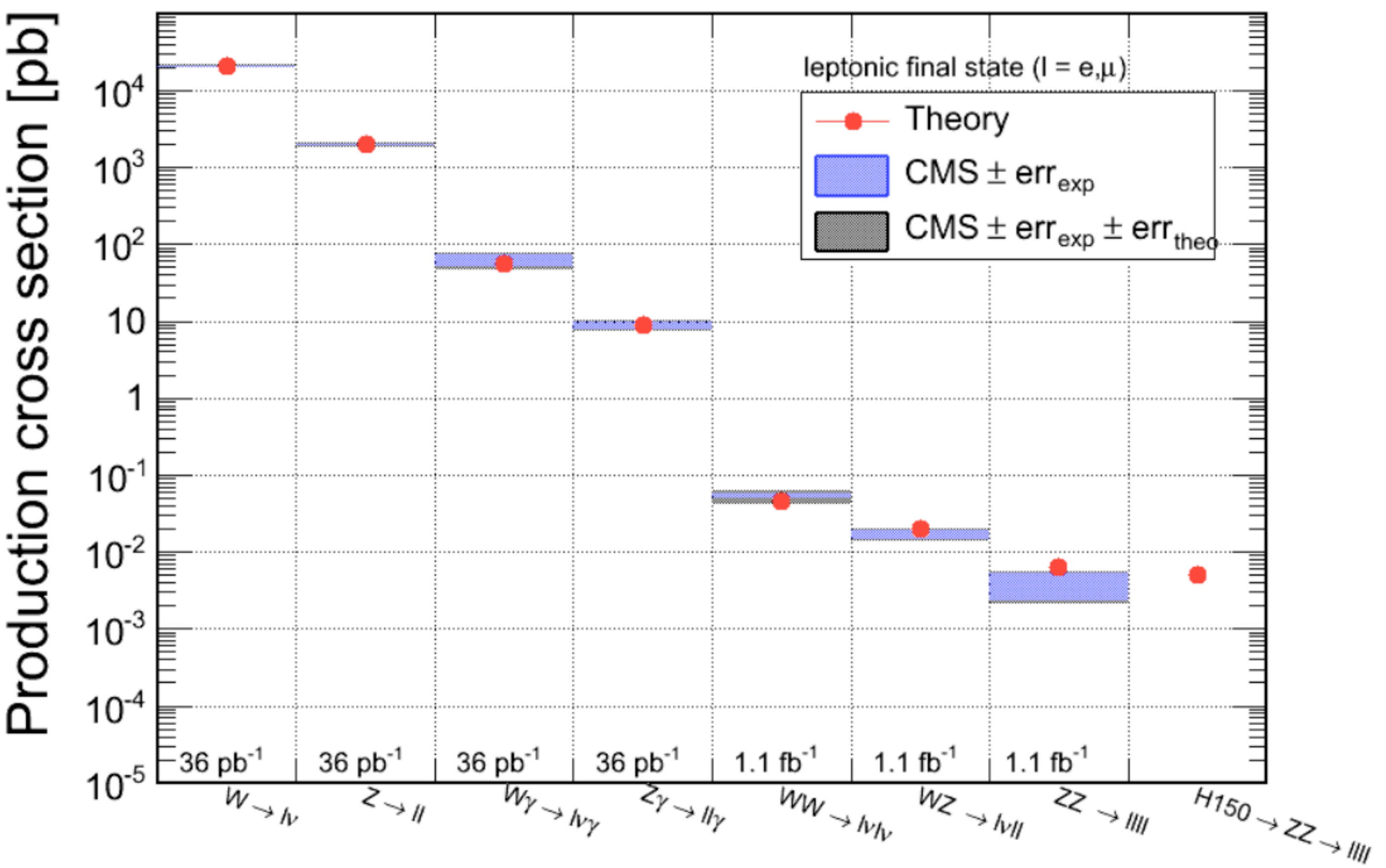
Physics Interests

- Diboson production study is an important test of the Standard Model
  - sensitivity to self-interactions between bosons, via the trilinear gauge couplings.
  - <u>**WZ is the only process which involves only amplitudes with the WWZ vertex**</u>



- Diboson production as indirect probe of New Physics
  - enhancement of production cross section
  - anomalous TGC (hint on new physics, if not high enough energy for direct production)

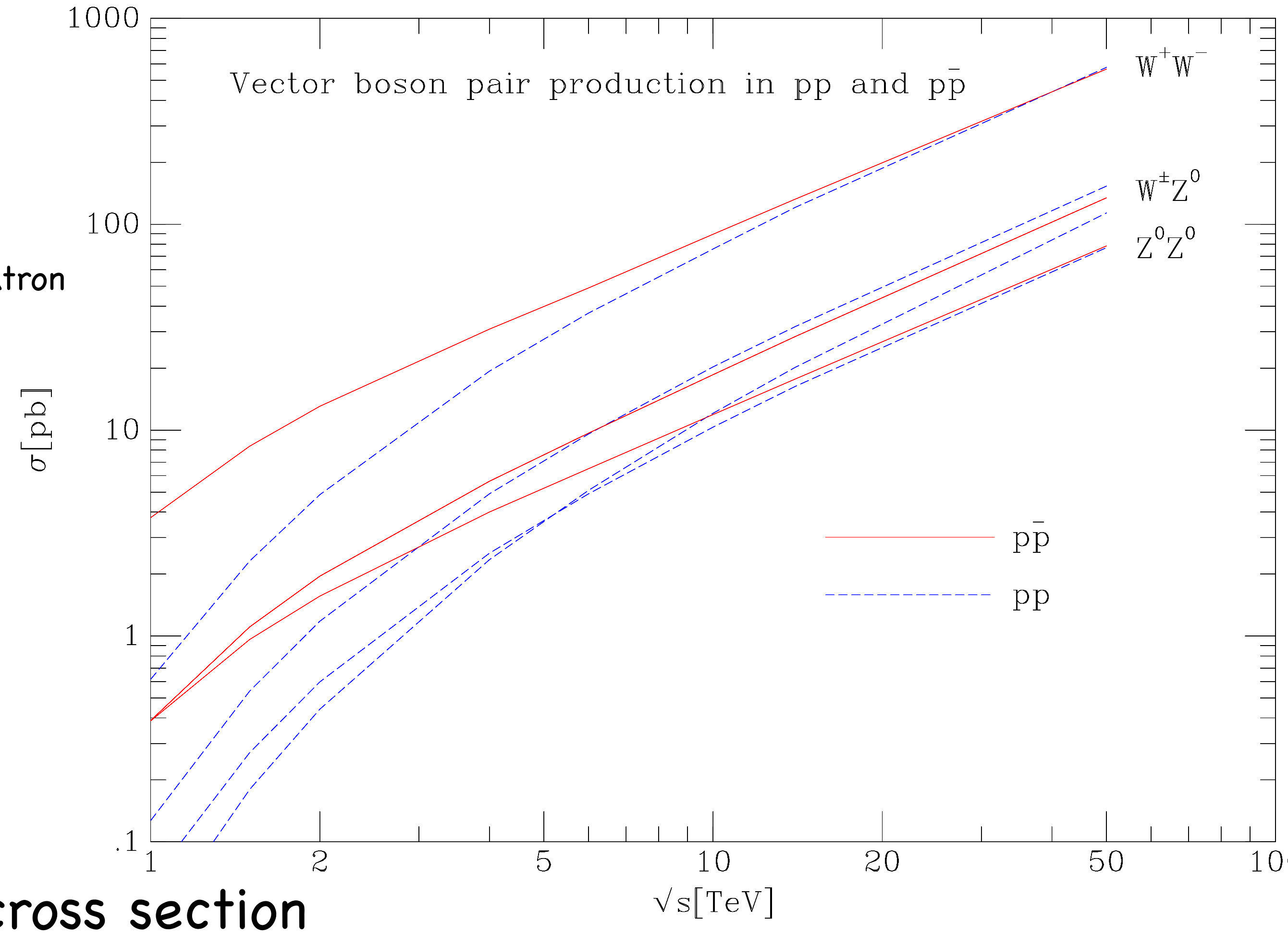
- Improve background modeling for multilepton final states



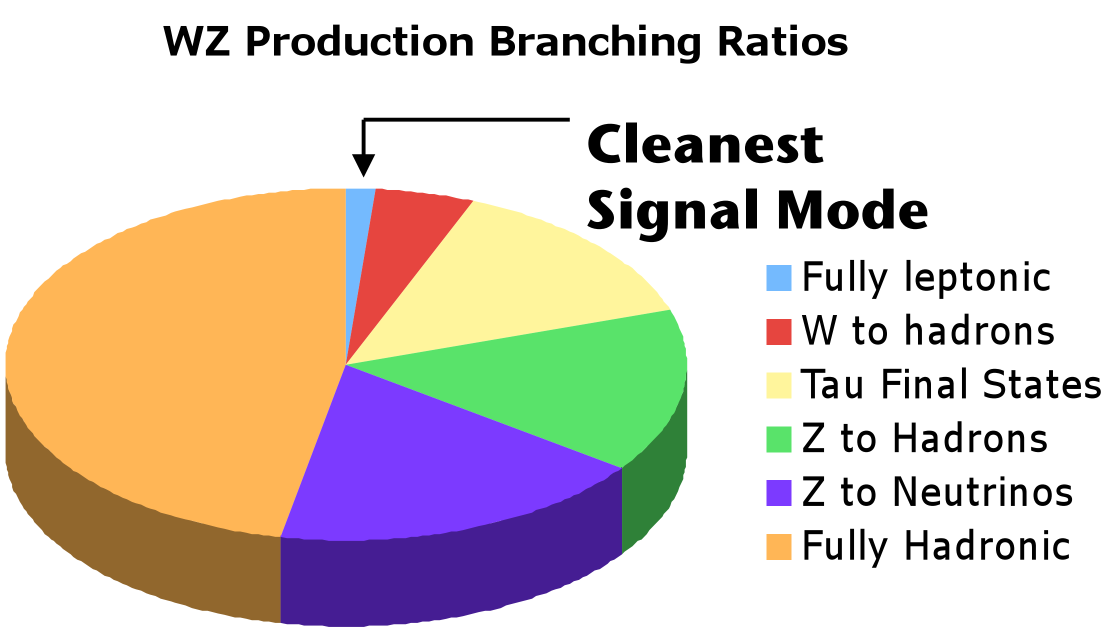
WZ at hadron colliders

- Inclusive NLO production cross-sections:
  - $\sigma(W^+Z) = \sigma(W^-Z)$ at Tevatron
  - higher center-of-mass energy $\sigma_{LHC} \approx 5\ \sigma_{Tevatron}$

$$\sigma(pp \to WZ)_{NLO} = 18.57^{+0.75}_{-0.58}\ \text{pb}$$

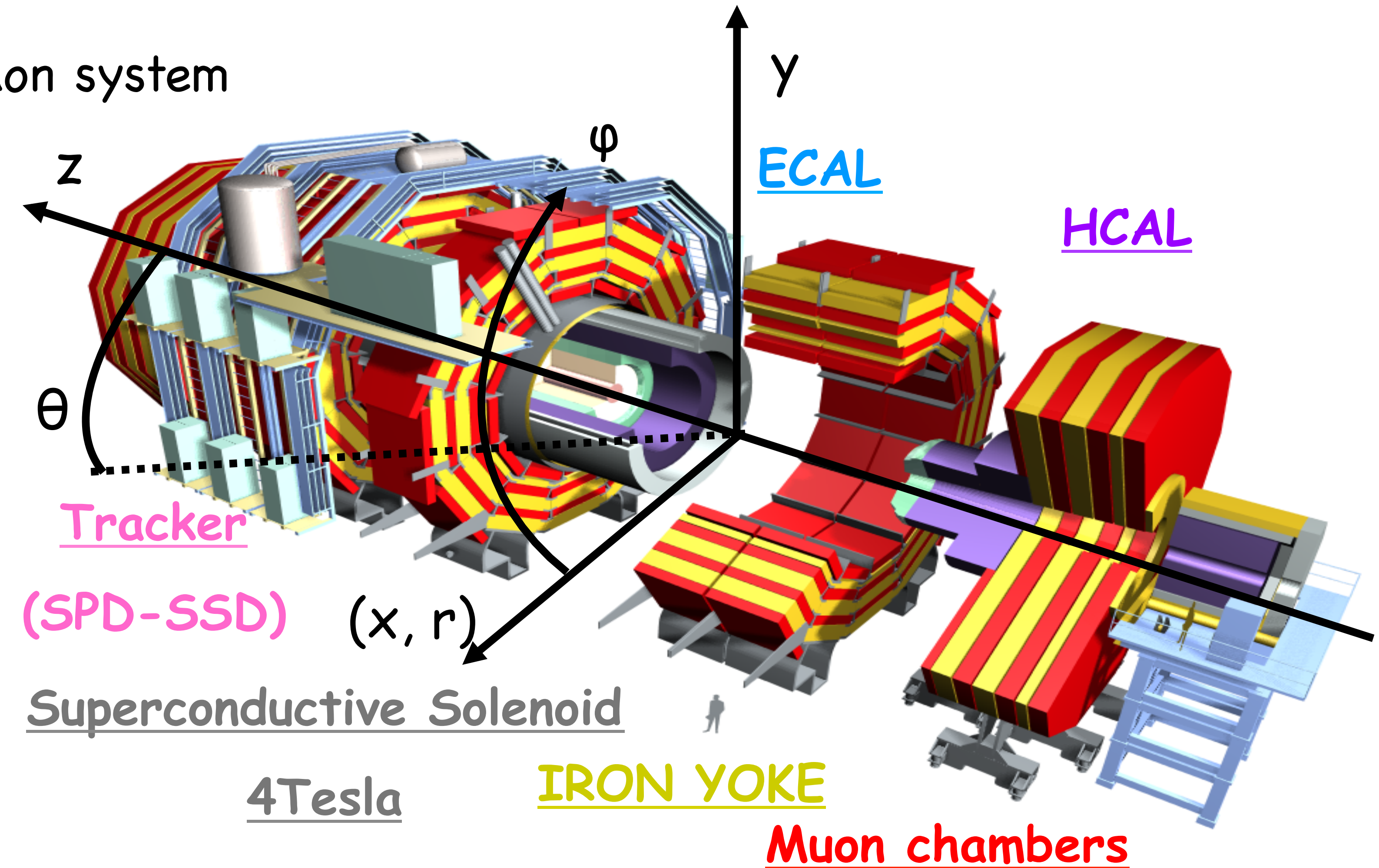


- **Interest here in measuring**: production cross section
- Fully leptonic final state: ($l = e, \mu$)
  - clear signature in hadronic environment
  - reduced BR (1.5% if lepton = e,μ)



The CMS detector

- High performances on leptons and photons reconstruction [as H->γγ, H->VV->4l]
    - clean signatures (low yield, low background)
- Strong solenoidal magnetic field 3.8 T
- Full silicon tracker and hermetic calorimeter
- Wide coverage and redundant muon system



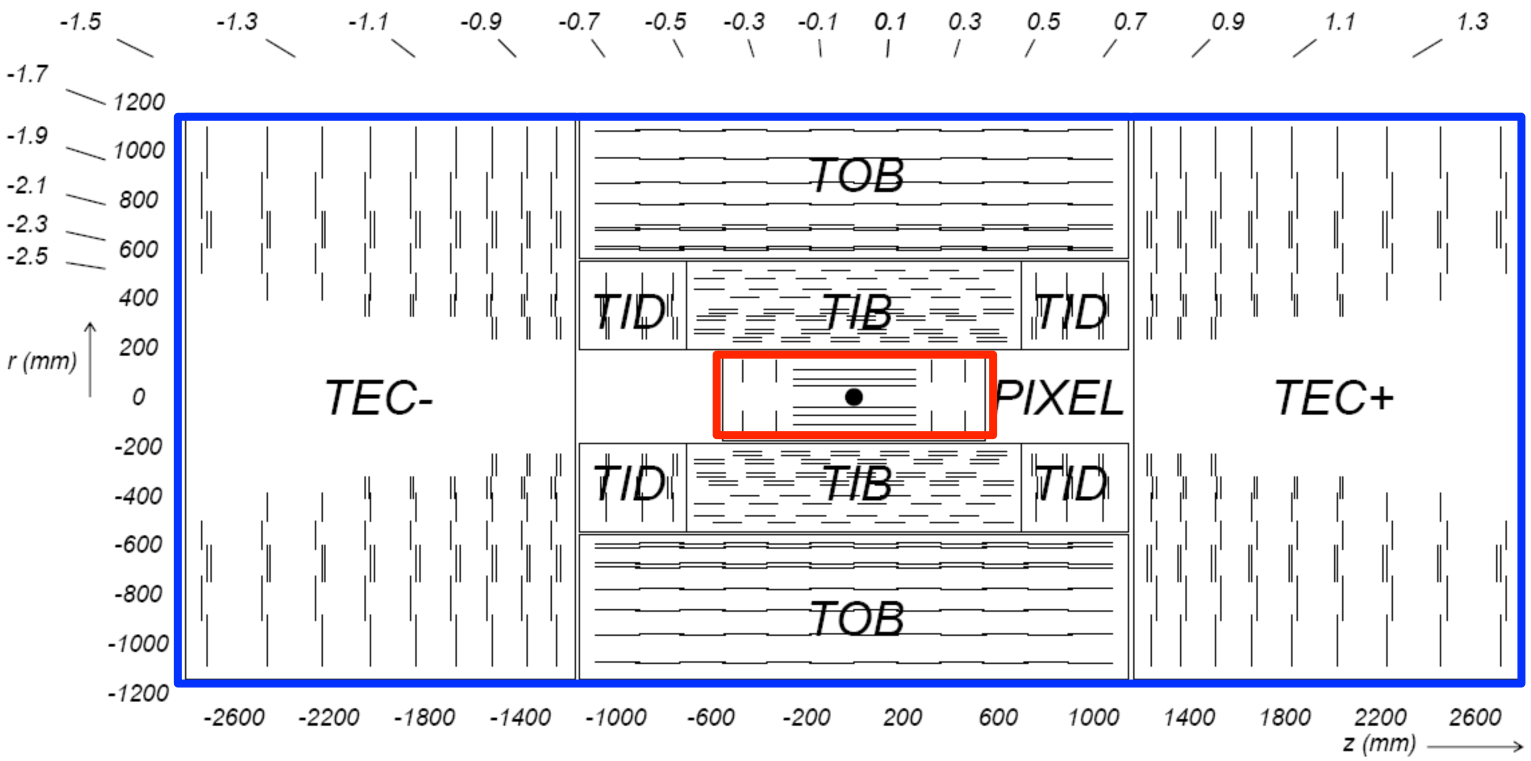
- CMS reference frame (r,η,φ)
    - pseudo-rapidity $\eta = -\ln[\tan(\theta/2)]$, with θ polar angle
    - (x,y) plane transverse to beam and B field (p_T, E_T)

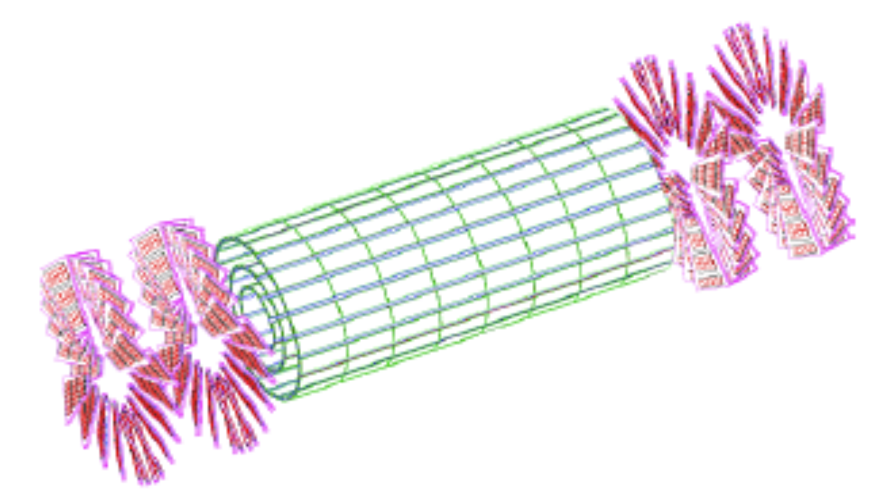
The tracker

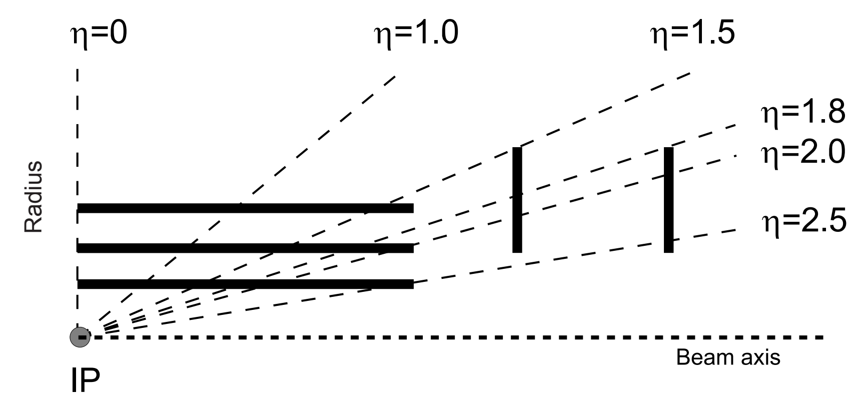
- Silicon tracker device around the beam line:

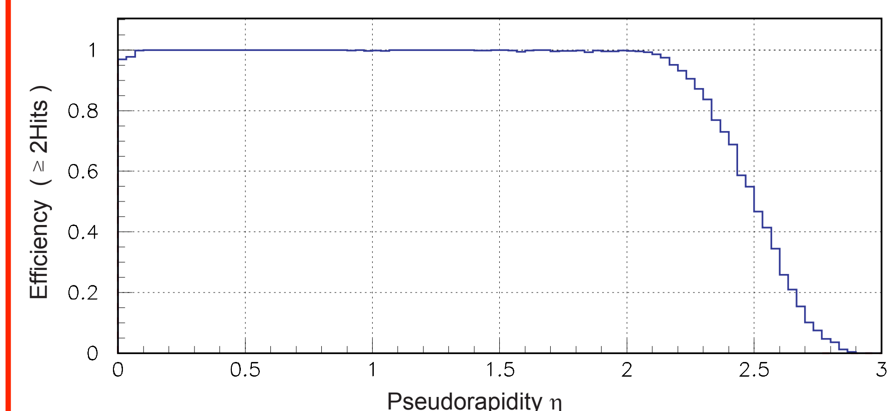
Pixel barrel layers and forward disks

Strips all around









Tracking efficiency:

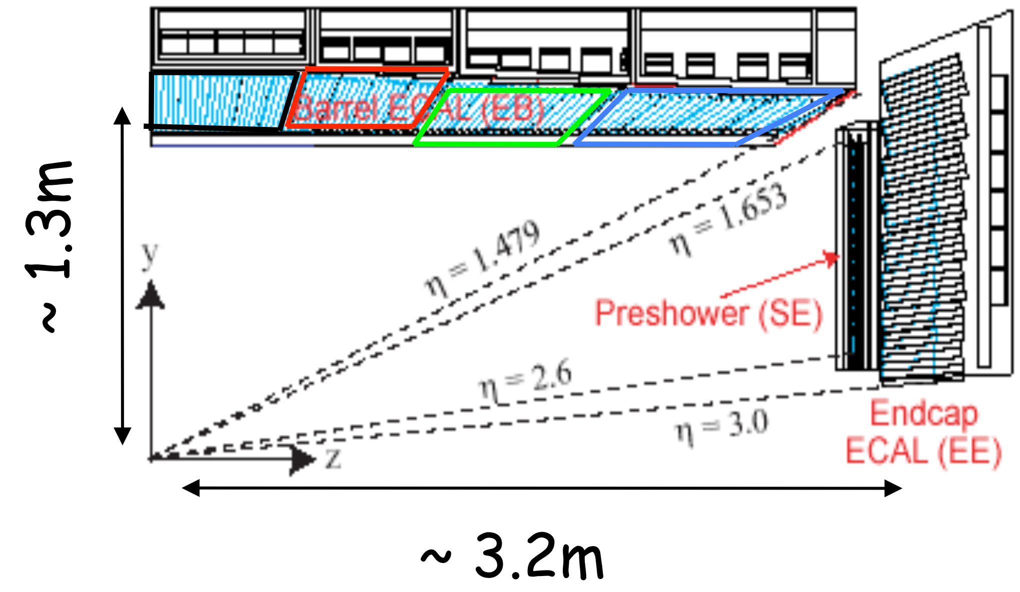
>99% (μ), ≈90% hadrons

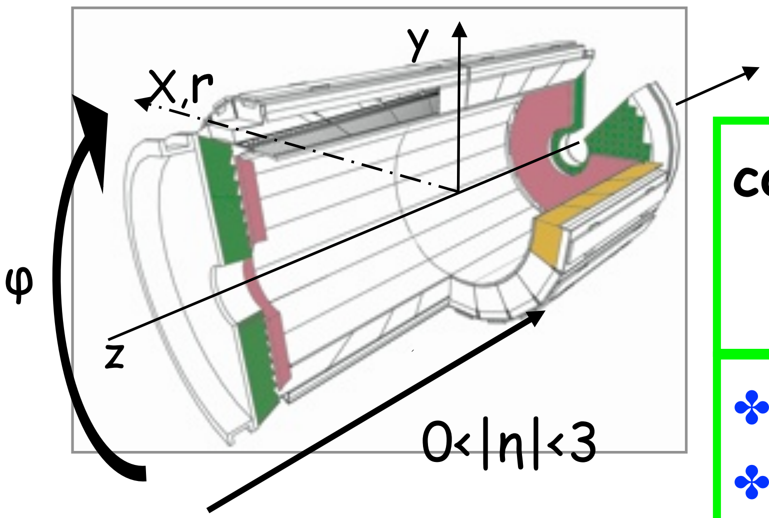
Resolution:

Δpt/pt ≈ 1-2% (@ 10 GeV/c) ≈10% (@ 1 TeV/c)

The ECAL (electromagnetic calorimeter)

- Homogeneous $PbWO_4$ crystal calorimeter
  - **BARREL** 61200 crystals in 36 super-modules
    APD photodetectors
  - **ENDCAP** 3662 crystals x 4 Dees
    VPT photodetectors

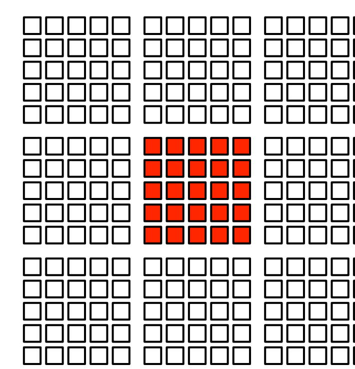




compact & **high granularity** for an **excellent energy containment**:
- Molière radius 22mm
- Radiation length X_0 8.9mm

- ECAL global energy scale fixed with a **120 GeV** electron beam (TB 2006)
- inter-calibration precision 1% (EB)
- time synchronizations better than 1ns
- excellent energy resolution (< 0.5% requirement)

- On-line data reduction: regional readout based on thresholds criteria
  - high E: 5x5 crystals (=TT) or 3x3 TT readout
  - low E: single channel readout (with Zero Suppression)



Energy scale validation with cosmic ray muons

- October-November 2008 **2009**
  - CMS installed in the underground cavern
  - 1 month long cosmic muons data taking (about 300 million events registered)
  - to calibrate and align the detector in preparation of LHC collisions

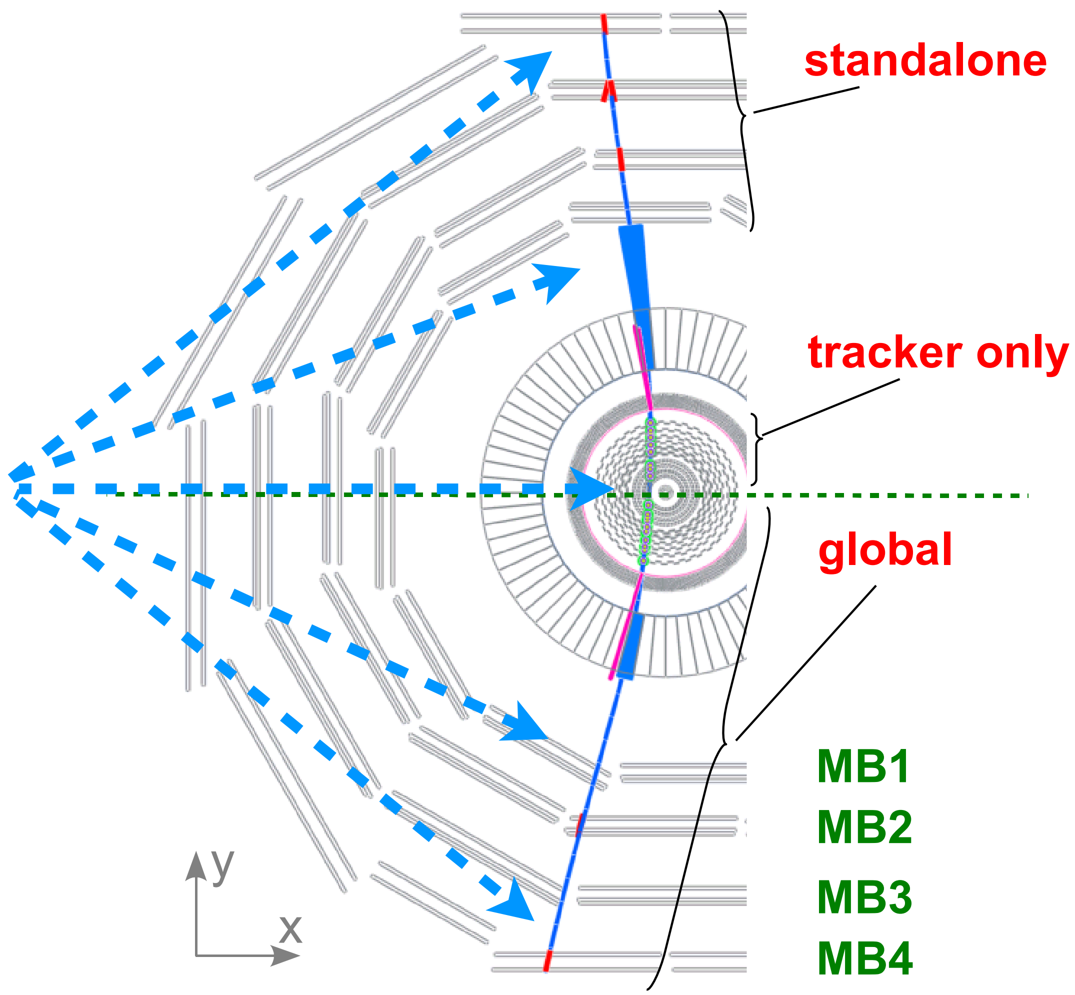
- First measurement of the Muon stopping power in lead tungstate (dE/dx in $PbWO_4$)
  - calibration purposes
  - muon critical energy measured in $PbWO_4$

- Analysis: $\approx 2.5\ 10^5$ events, in the momentum range 5 GeV/c - 1 TeV/c

The operation setup

- Dedicated setup for cosmic muons events

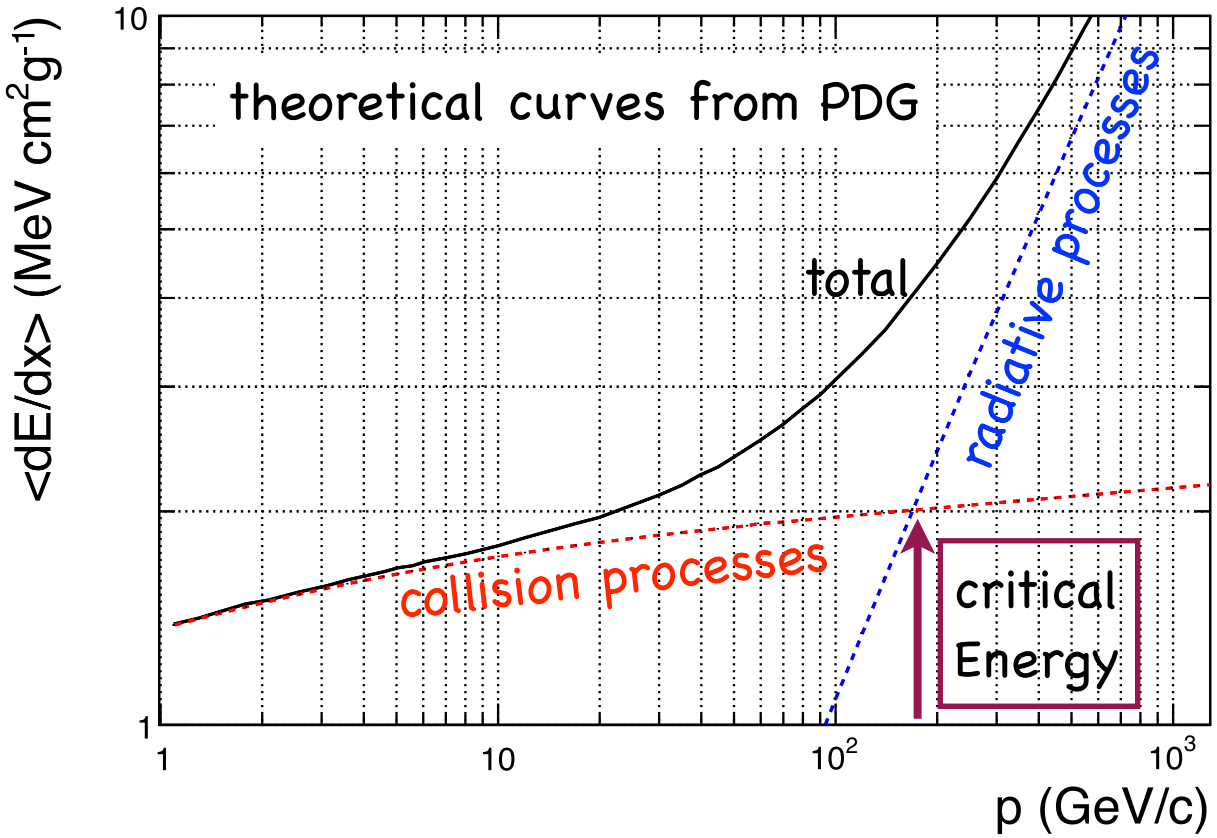
- <u>Muons reconstruction</u>
  - reconstruction for trajectory from top to bottom
  - not pointing to beam interaction region
  - **global fit through the whole CMS**



- <u>ECAL operation</u>:
  - good efficiency for low energies
    - ECAL optimized for high pT e/γ detection
    - A muon releases ~300MeV in a $PbWO_4$ crystal if traversed along its axis
  - **ad hoc thresholds** (electronic gain, online data reduction and clustering algorithm)
  - **energy containment corrections (muons ≠ electrons)**

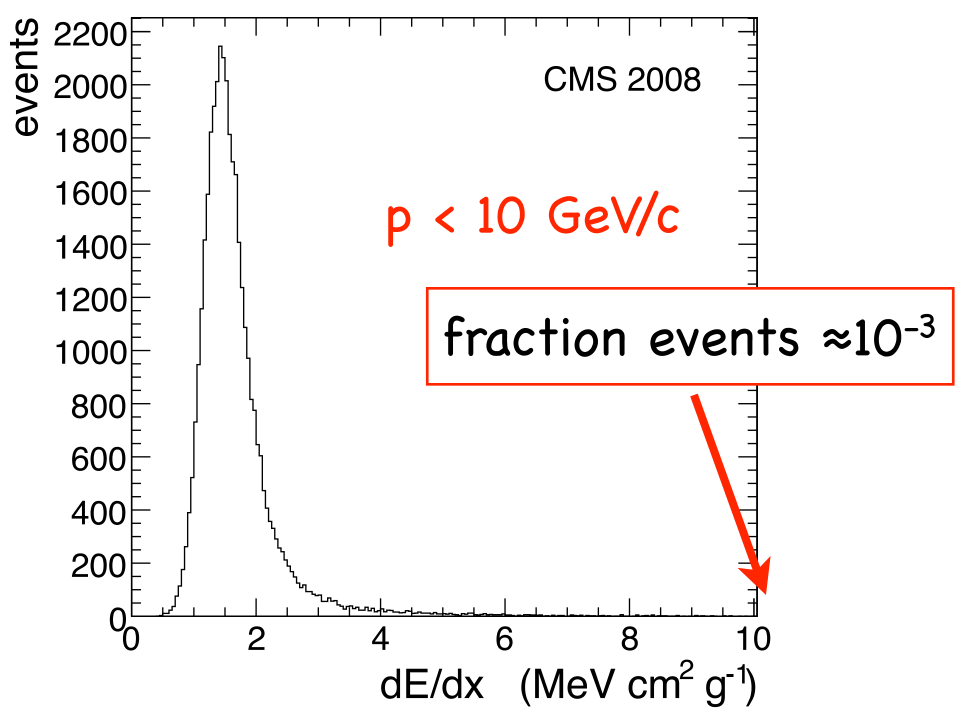
Event selection and measurement procedure

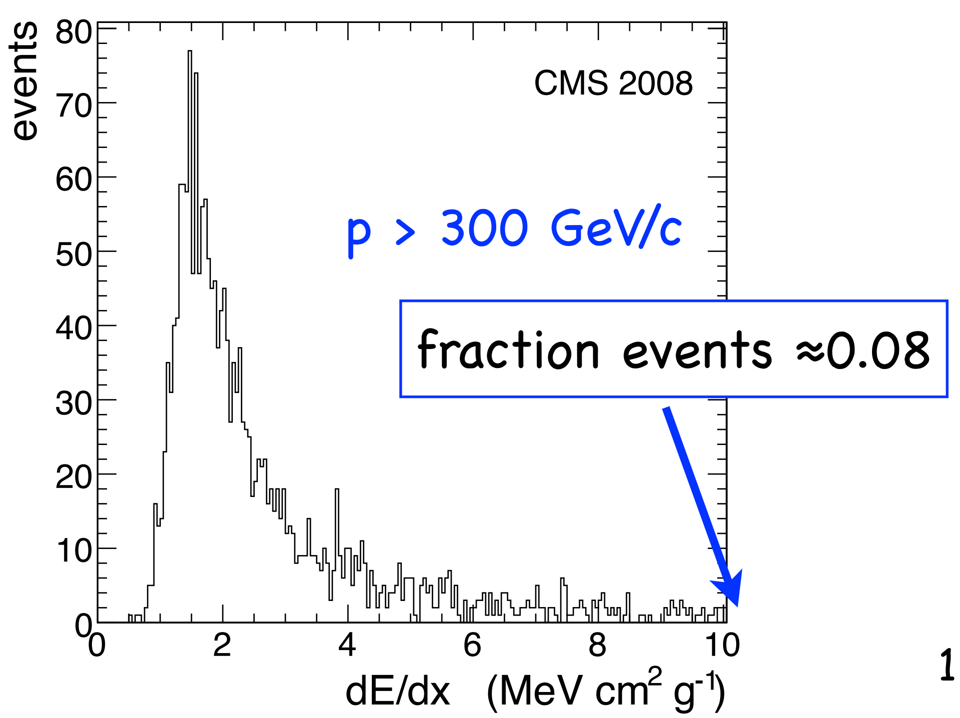
- To measure dE/dx vs p for muons:



  - momentum (p) from fit in the inner tracker
  - dx from track extrapolation through ECAL
  - dE of the ECAL cluster associated to the track

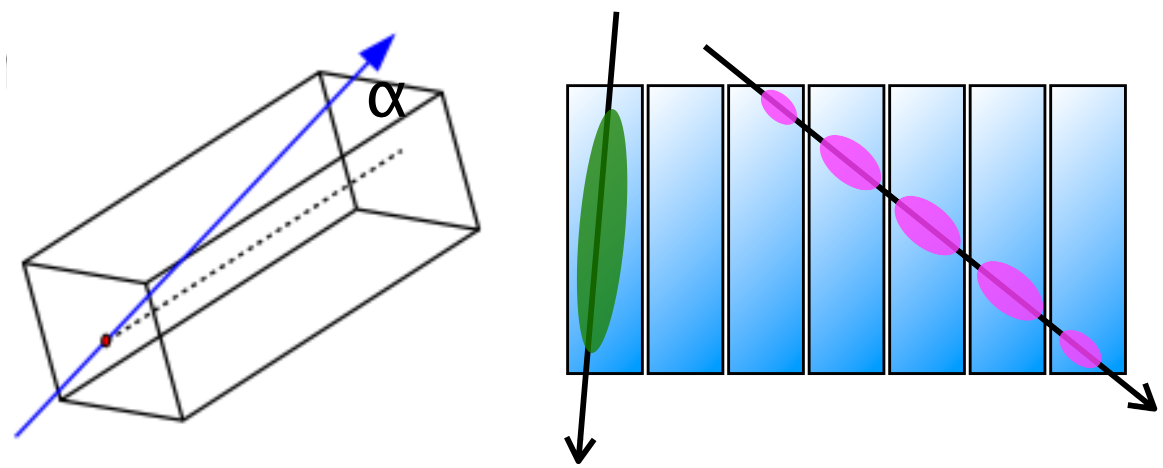
- A bias in the measured dE/dx has different impact on dE/dx rather than dE/dx

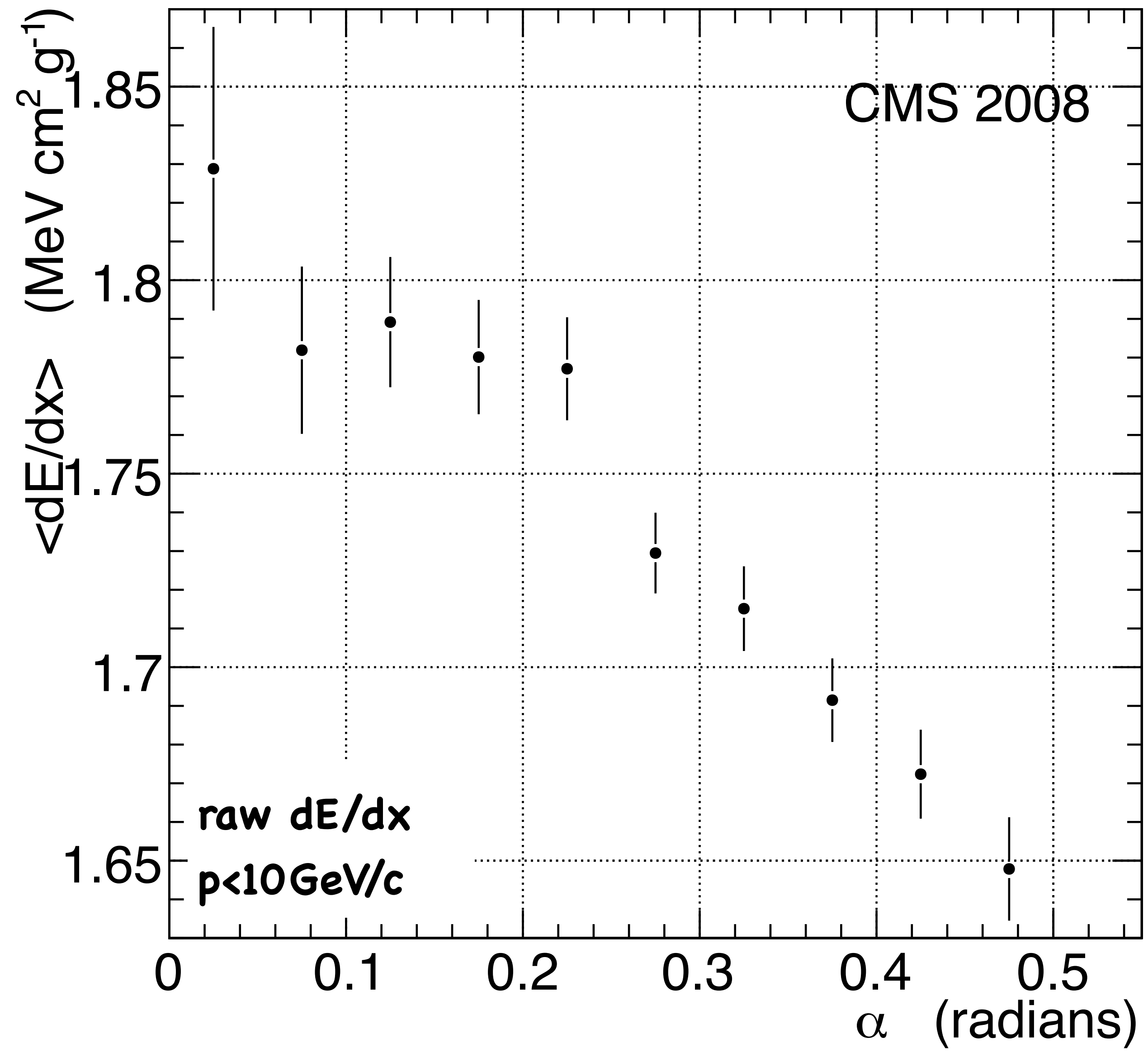




Instrumental effects

- **Relevant for collision processes**
- Noise fluctuations above clustering threshold (when no ZS is applied)
  - bias depends on muon direction wrt crystal (α)
  - α < 0.1 -> regional readout without ZS

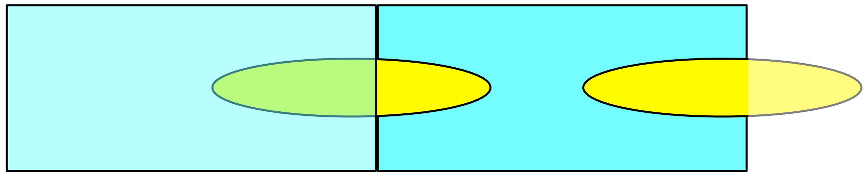


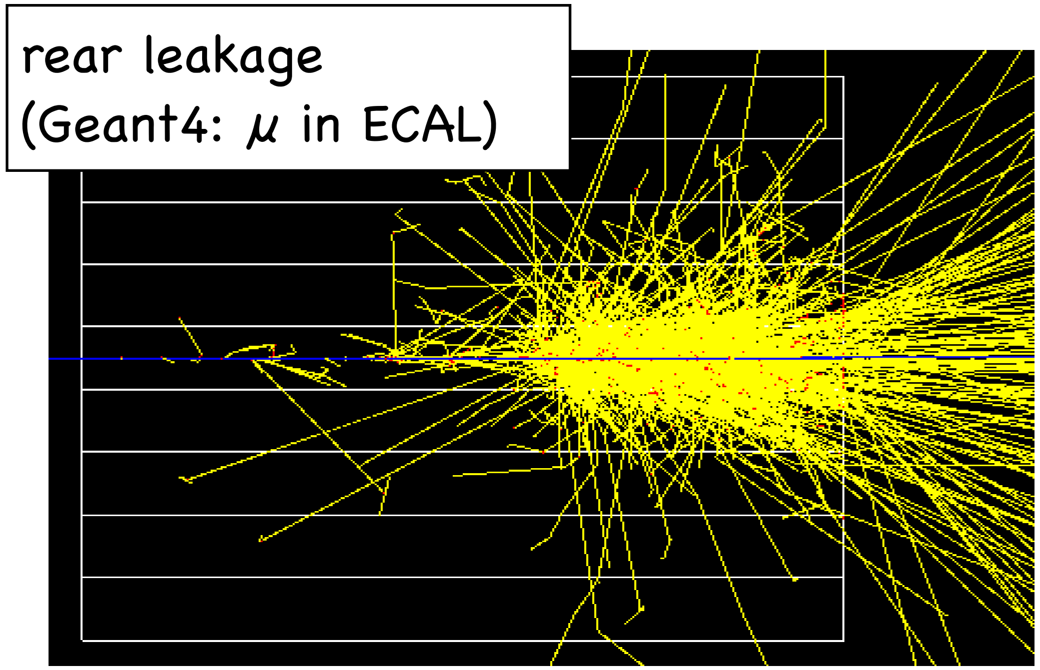


- Raw dE/dx measurement biased wrt α
  - offset measured for α<0.1 (≈14MeV)
  - negligible for radiative processes
  - systematic uncertainty ≈ 1.2%

Containment effects

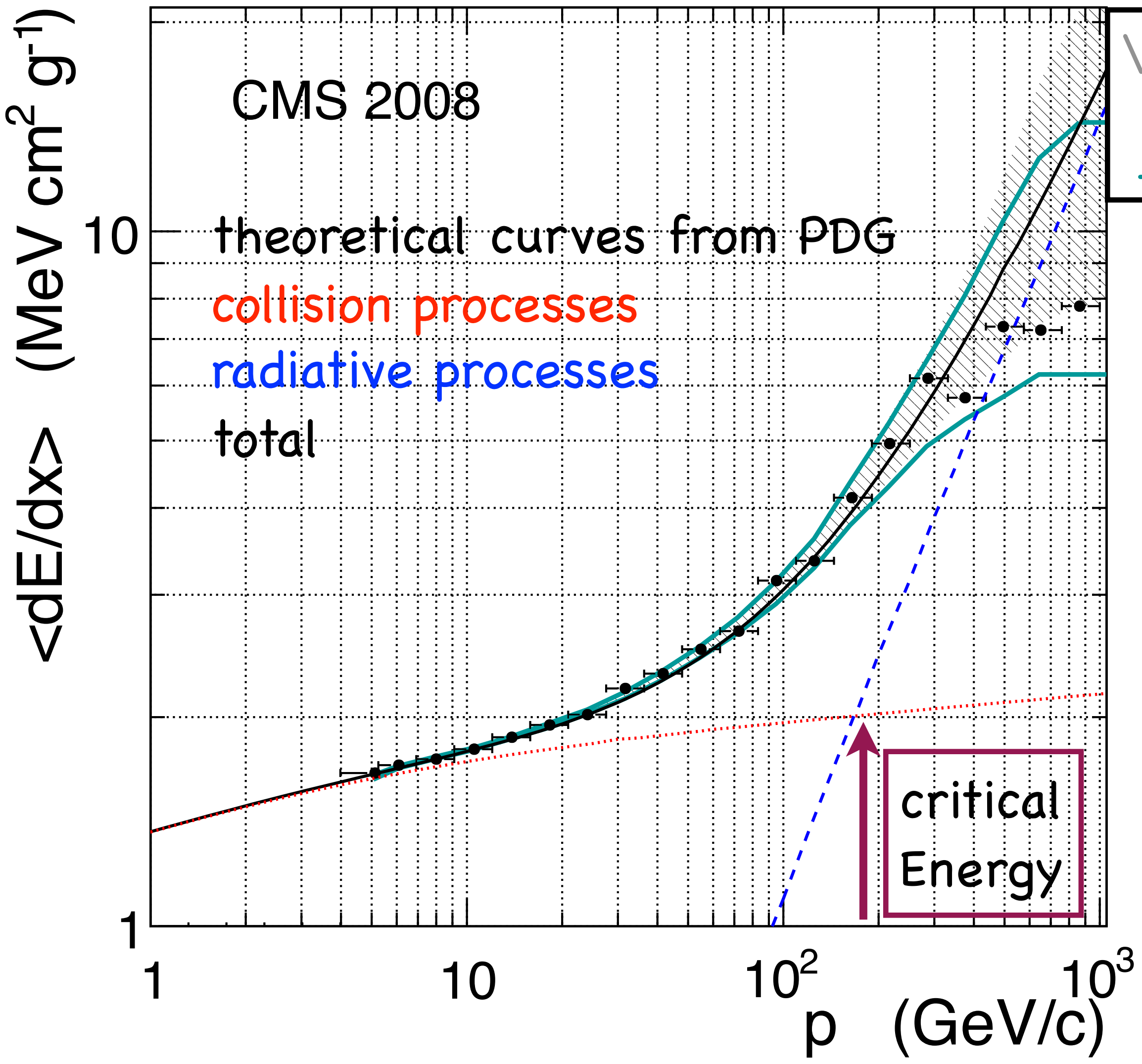
- **Relevant for radiative processes**
- Muon energy is lost all along muon trajectory
  - not all the energy lost in ECAL is collected in ECAL
  - at equilibrium, the rear energy loss is compensated by the energy flowing in through the front surface





- Energy containment corrections evaluated with proper Geant4 simulation for
  - collision processes: containment already at equilibrium within 1% (syst.)
  - radiative processes: containment correction order 15% at 170GeV/c and 30% at 1TeV/c

Results



\\\ 68% interval centered on the expected result

___ smallest interval containing 68% of the expected result

- Fit to theory with

$(dE/dx)_{meas}$ = α [$(dE/dx)_{coll}$ + β $(dE\backslash dx)_{rad}$]

$$\alpha \quad = \quad 1.004^{+0.002}_{-0.003}(stat.) \pm 0.019(syst.)$$

$$\beta \quad = \quad 1.07^{+0.05}_{-0.04}(stat.) \pm 0.06(syst.)$$

energy scale

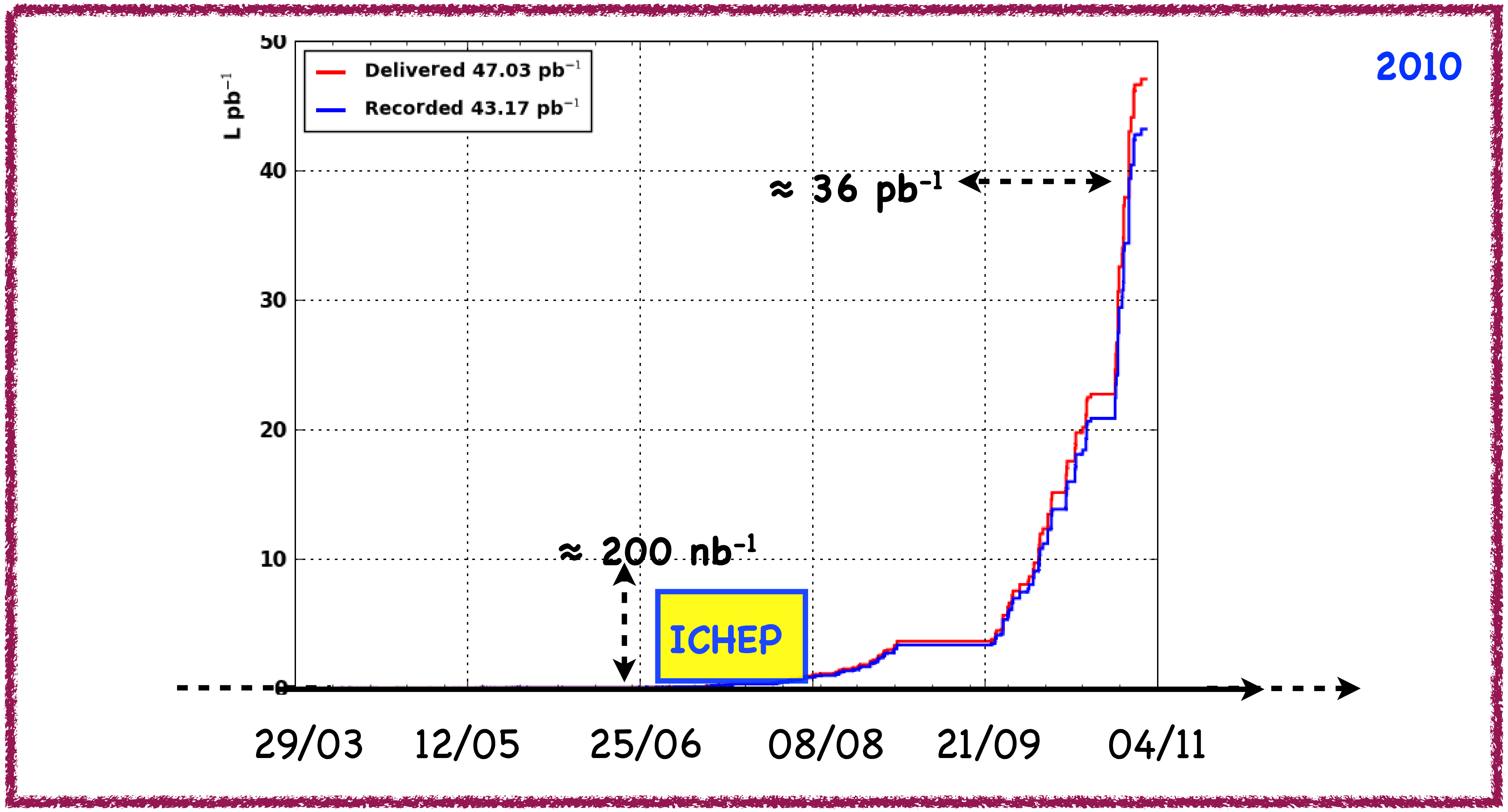
[expected 1] set with 120 GeV/c electrons

consistent within ≈2%

critical energy = 160^{+5}_{-6} (stat.) ± 8(syst.) GeV

[expected 165.9 GeV for PbWO4]

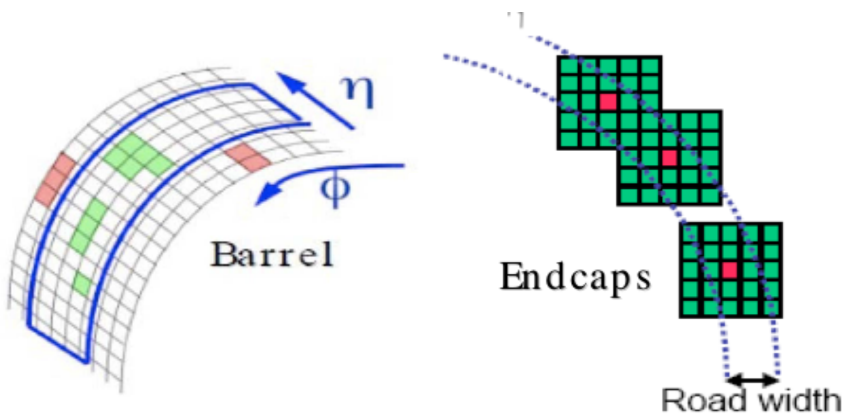
Commissioning of the electron seeding with the first data



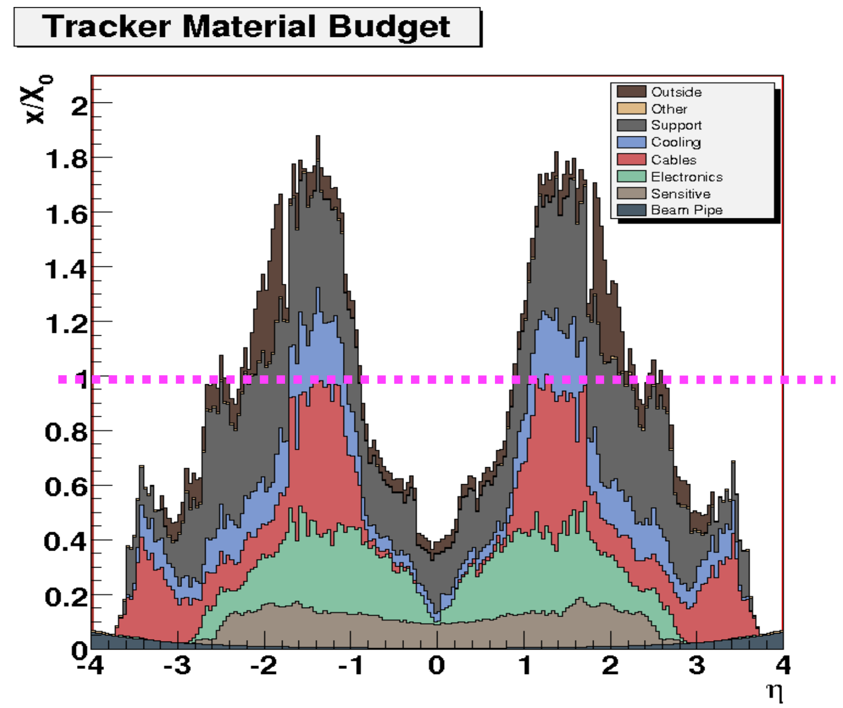
- Comparison data-MC
  - to validate the modeling of the detector with data
  - to validate the reconstruction algorithm
- Electrons
  - objects of primary importance for physics at the LHC

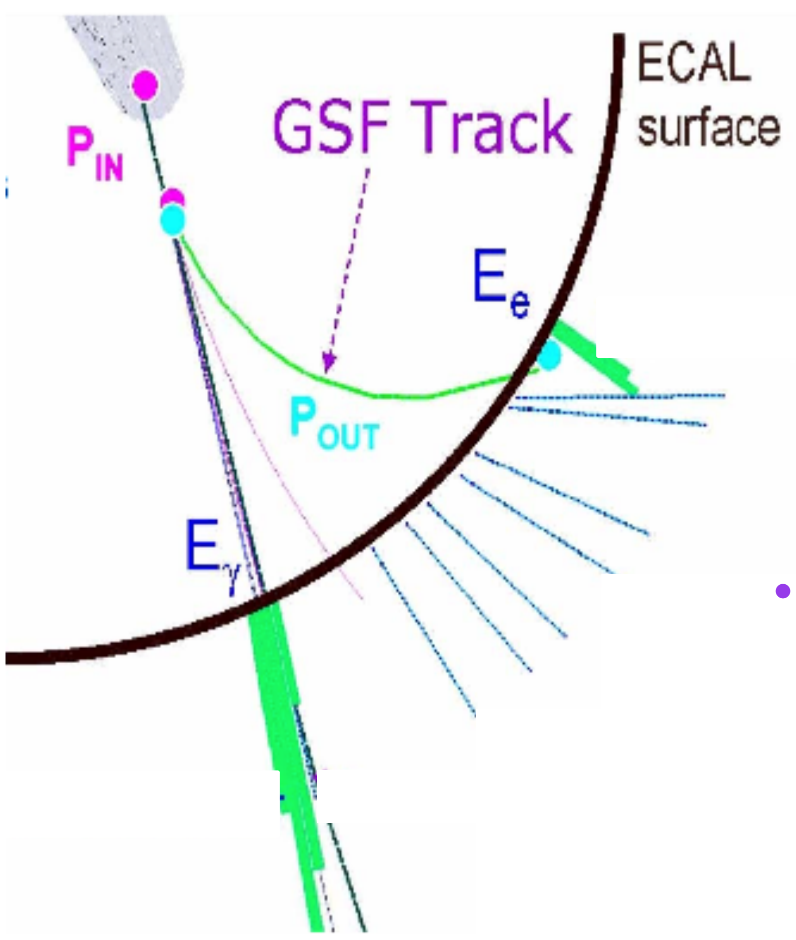
The "ecal-driven"electron reconstruction

- Track-seed = pair of measured hits in the inner tracker
- "ecal-driven"-> Seeding as filtering of track-seeds based on seed-cluster matching criteria



- Energy is clustered in a large φ window to account for
  - bremsstrahlung radiation in the tracker material and associated spread due to the strong B field

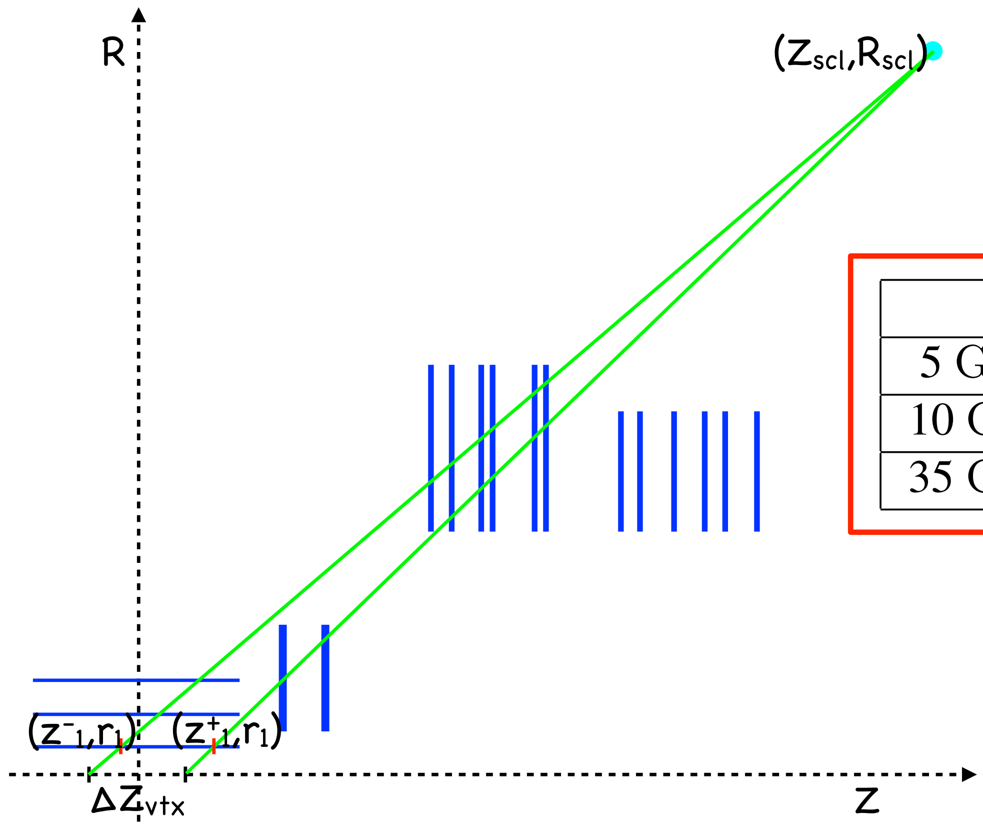




- Electron tracking based on Gaussian Sum Filter algorithm
  - high material budget in a high magnetic field contest
  - non gaussian energy loss due to bremsstrahlung
  - unbiased track estimate at each measured point

The ecal-driven seeding

- Hits from the track seeds are checked for compatibility with the ECAL super-cluster

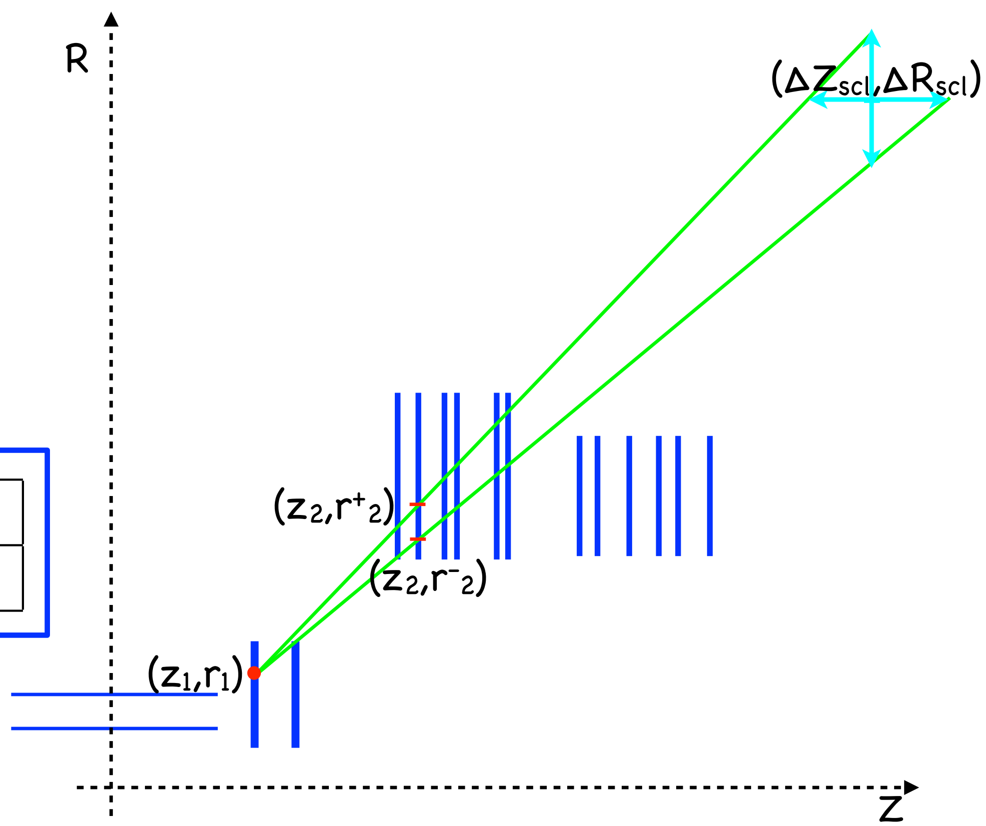


First hit: (Supercluster + vertex)

	δz (BPIX)	δr_T (FPIX or TEC)	$\delta\phi$ (pos. charge)	$\delta\phi$ (neg. charge)
5 GeV/c	$\pm 5\sigma_z$	$\pm 5\sigma_z$	[-0.075;0.155] rad	[-0.155;0.075] rad
10 GeV/c	$\pm 5\sigma_z$	$\pm 5\sigma_z$	[-0.046;0.096] rad	[-0.096;0.046] rad
35 GeV/c	$\pm 5\sigma_z$	$\pm 5\sigma_z$	[-0.026;0.054] rad	[-0.054;0.026] rad

Second hit: (Super-cluster + 1st hit)

δz (BPIX)	δr_T (FPIX)	δr_T (TEC)	$\delta\phi$ (BPIX)	$\delta\phi$ (FPIX or TEC)
± 0.9 mm	± 1.5 mm	± 2 mm	± 4 mrad	± 6 mrad



- **Interesting variable looked at:**

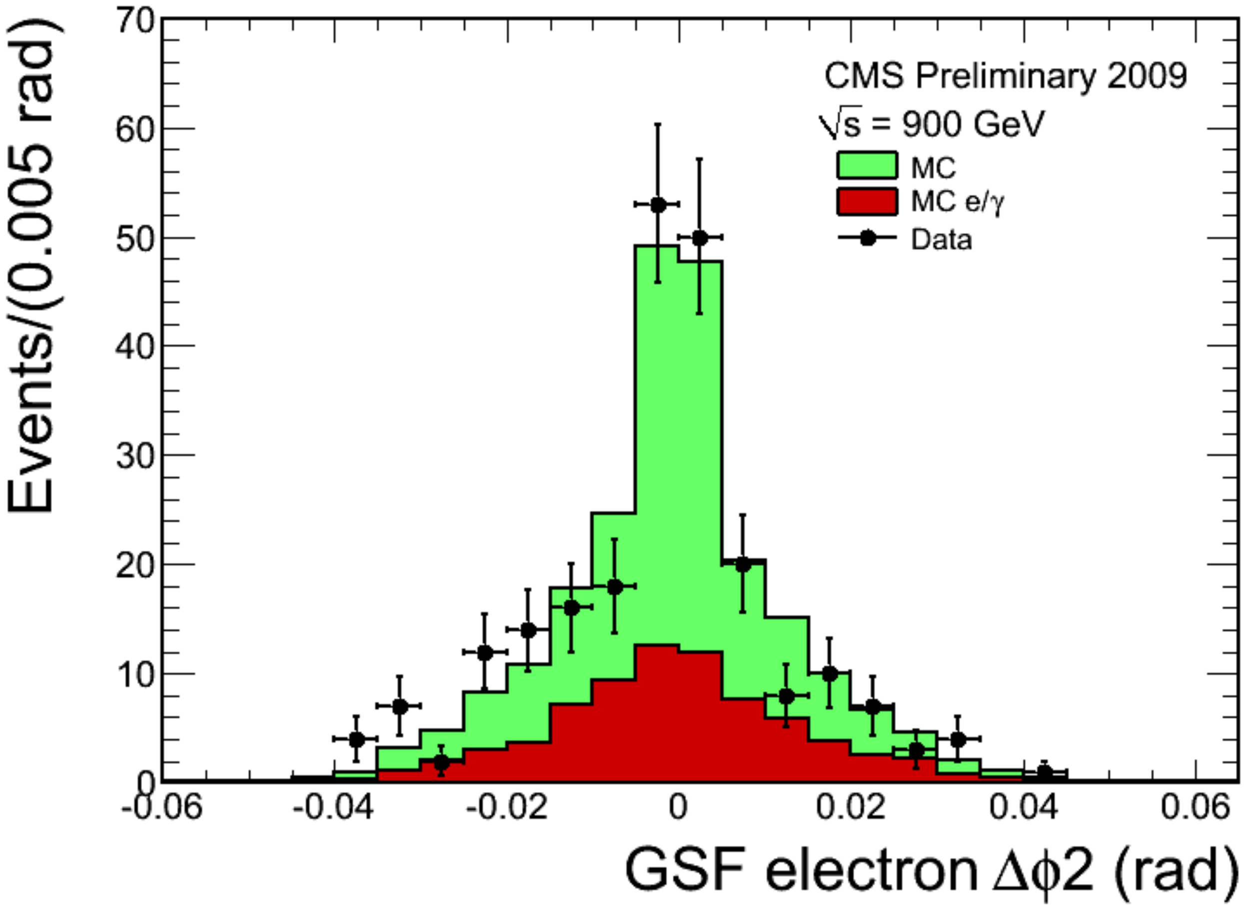
  Measured - Expected position on the layer wrt z, φ, r_T

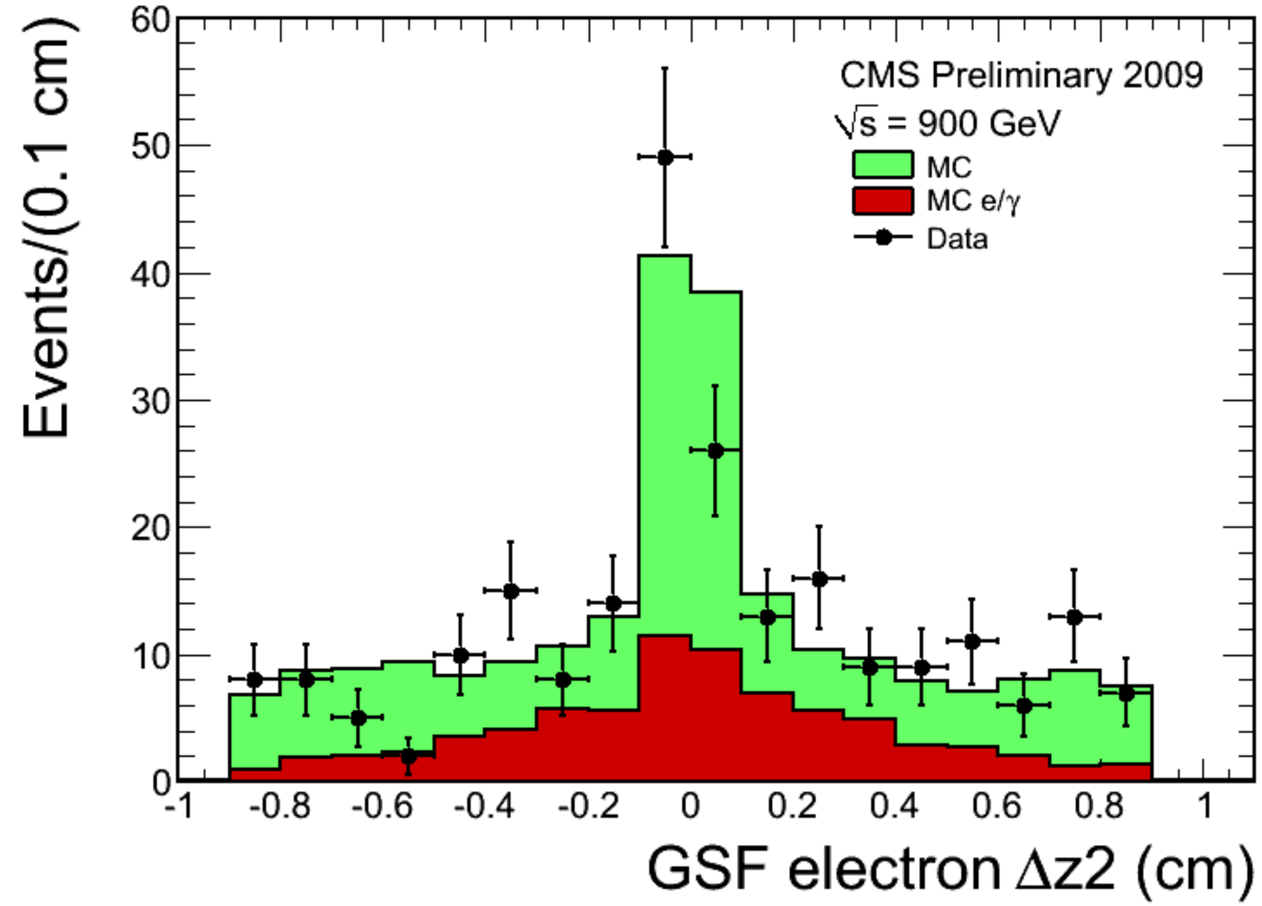
First studies at low energy

- From first minimum bias data at 900GeV
  - electrons are essentially fakes and electrons from conversions

$$\int \mathcal{L}dt = 10\mu b^{-1}$$

- Residuals for seeding windows for second hits in the EB





  - wider search windows no to bias tails with low statistic
  - large tails and peaks

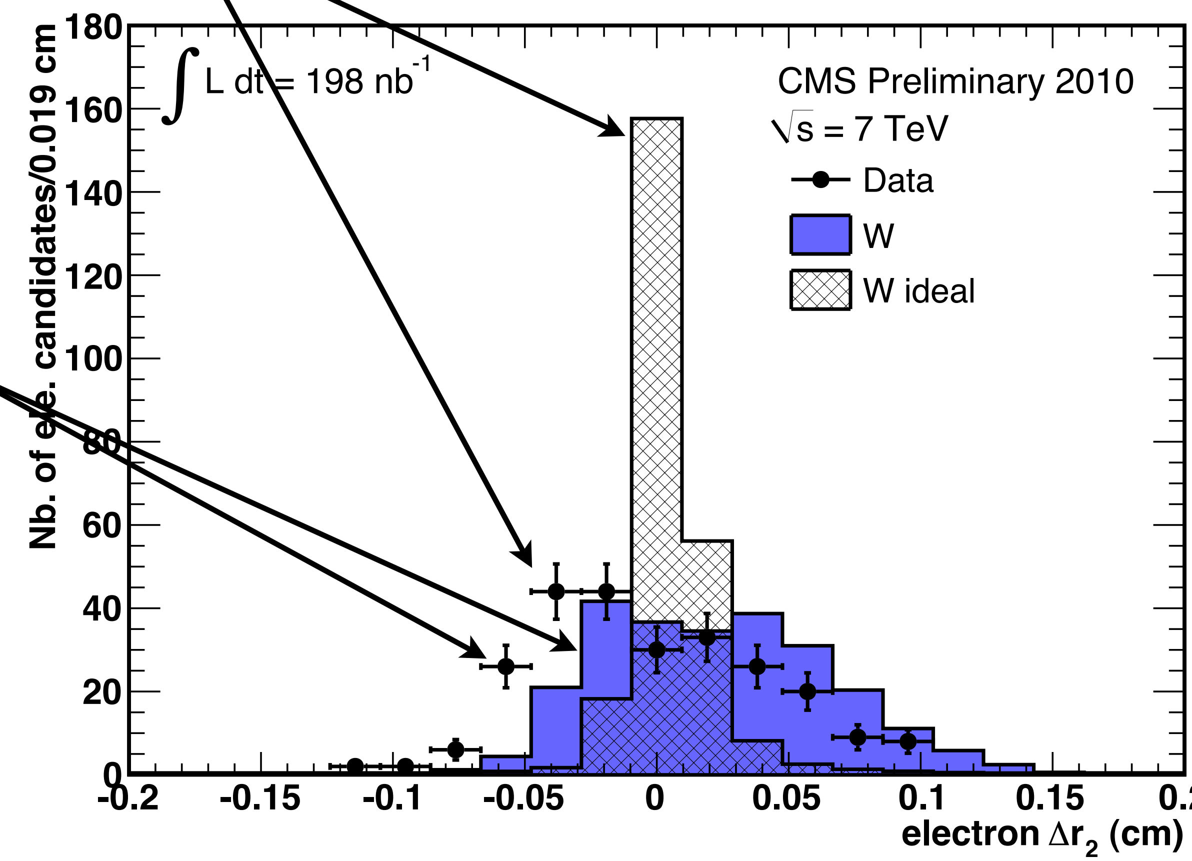
Sensitivity to initial alignment

- Electrons from W events in 7 TeV collisions
  - to validate the windows size for "good quality" high pT electrons

$$\int \mathcal{L} dt = 198 nb^{-1}$$

- Seeding distributions proved sensitive to misalignment

- Allowed for a prompt validation of the re-alignment corrections with first data

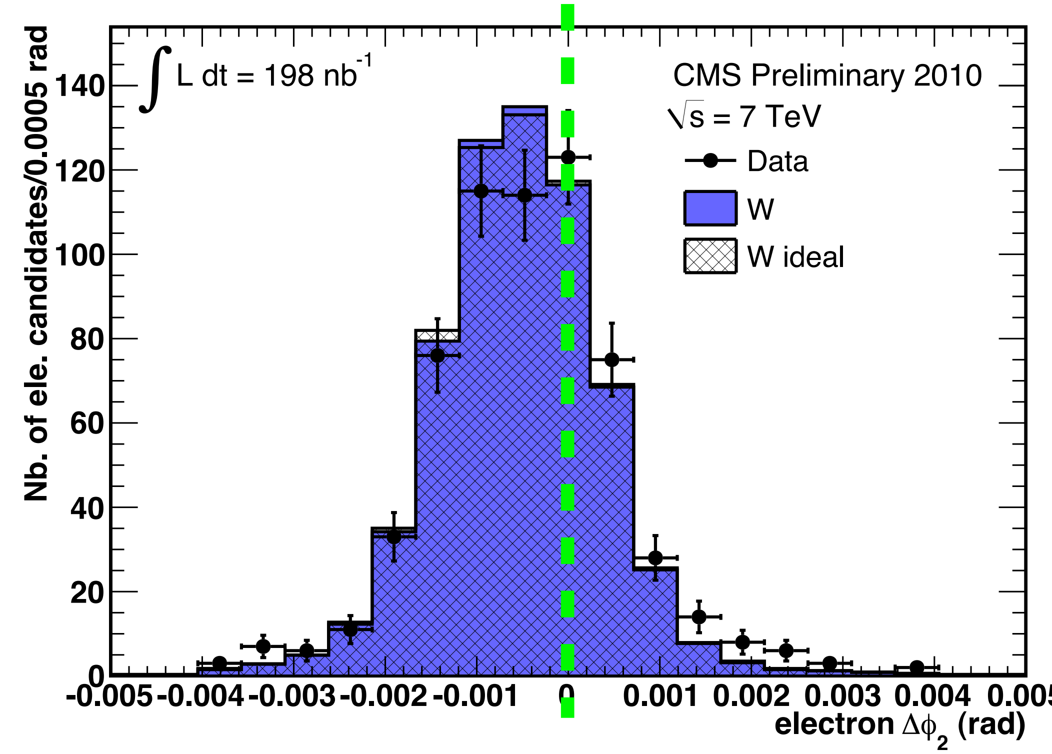


- W MC sample with ideal and real alignment
  - Misalignment was an issue mainly in the forward region

Sensitivity to systematic bias

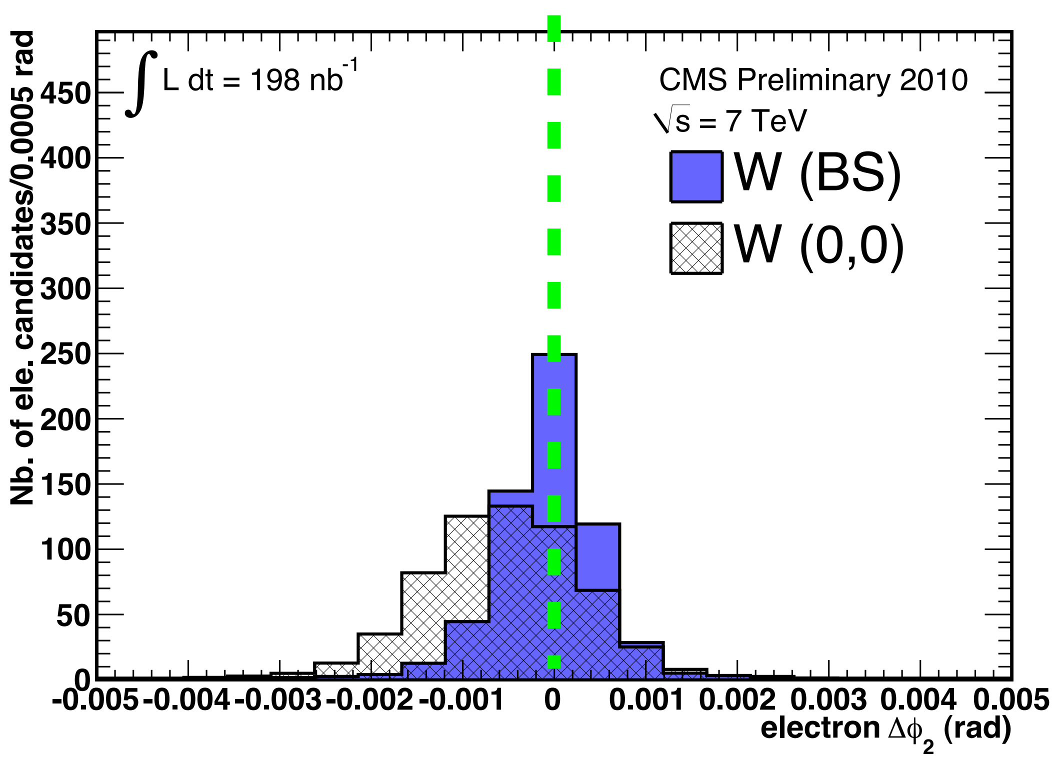
$$\int \mathcal{L}dt = 198nb^{-1}$$

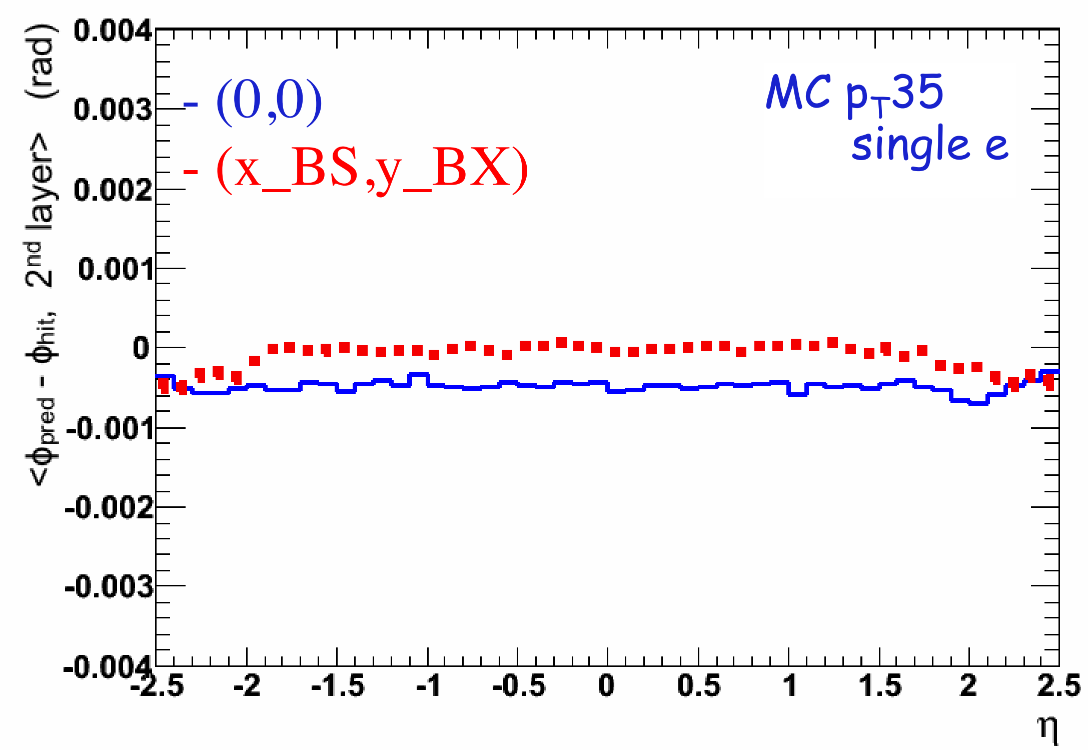
- Bias in Δφ distributions
- Systematic effect in the reco. algorithm (both data and MC)



- Pixel detector (0.1475,-0.3782,-0.4847cm) displaced from CMS center (0,0,0)

- Proper reference frame to compute residuals



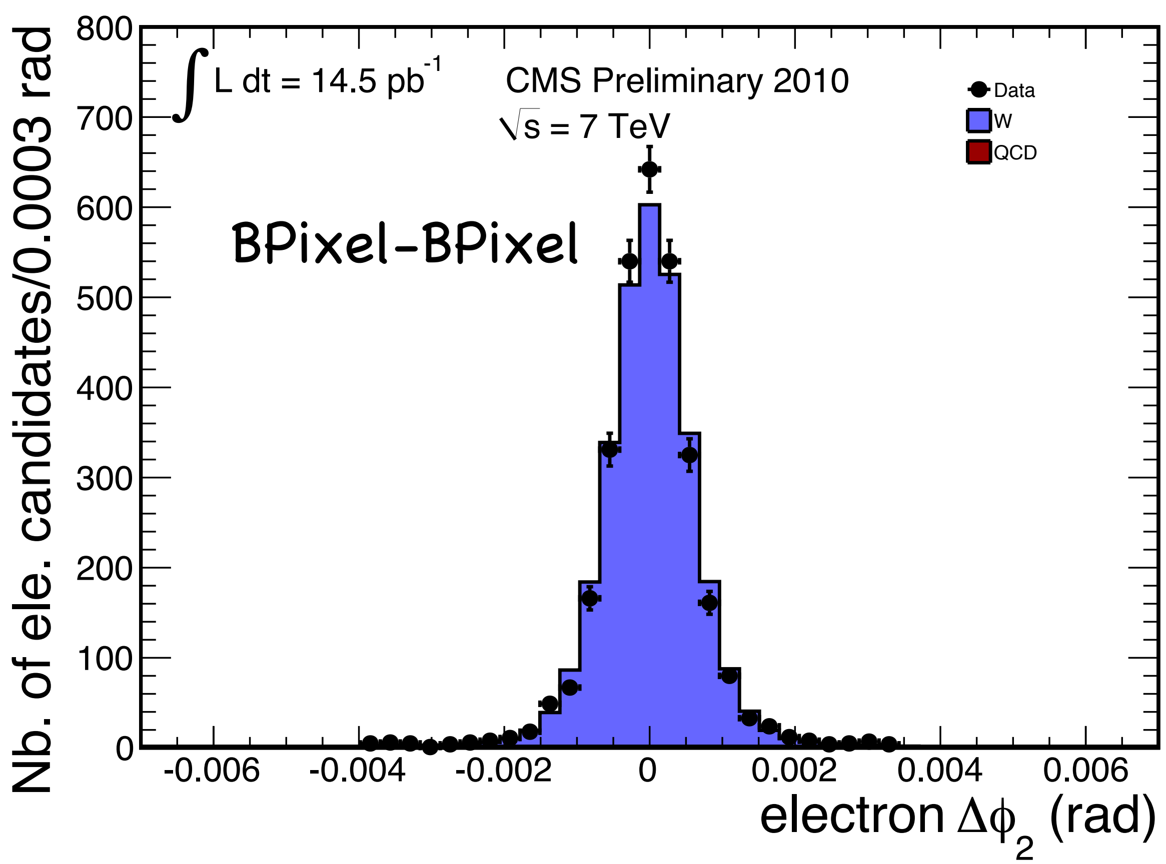


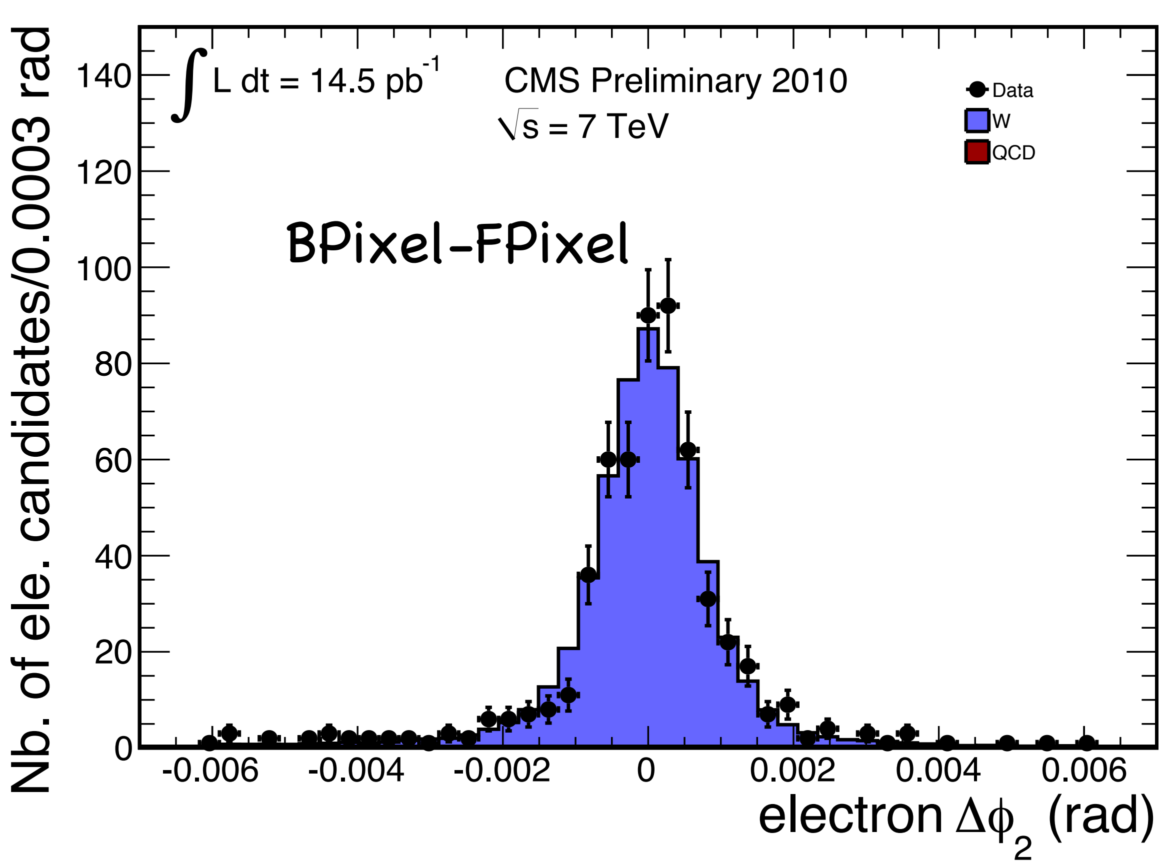
Final validation with $14.5pb^{-1}$

- W->eυ event selection
  - 1 electron, pT>25 GeV/c, tight selections

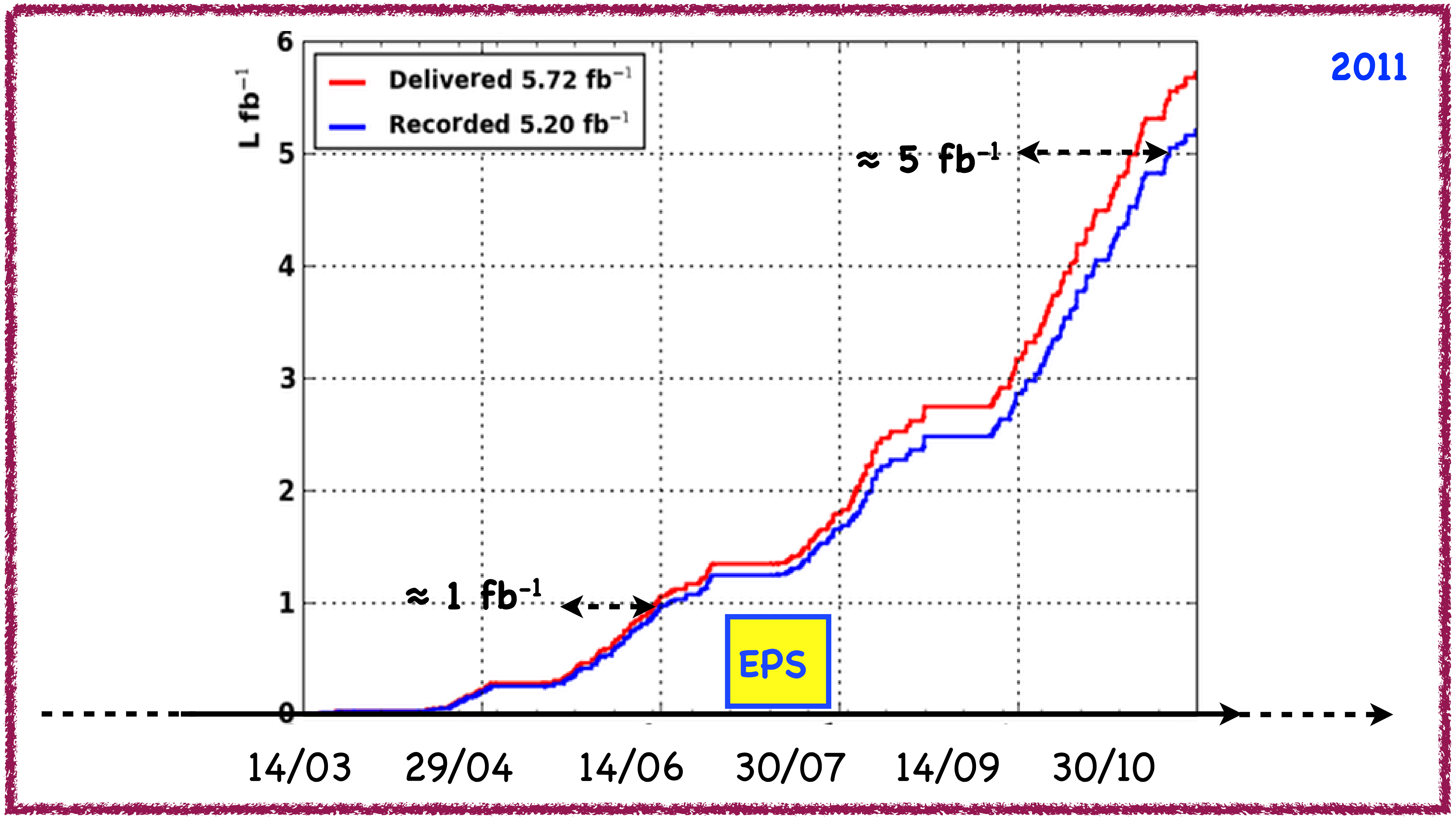
selections	events passing
Skim	65680
exactly one vertex	15970
MET > 25 GeV/c	12971
Jet Veto	11234
$40 < M_T < 100$ GeV/c^2	10116
electron ID WP 80%	9693
electron Iso WP 80%	9314
electron conversion rejection WP 80%	8625

- Distributions validated for electrons in EB





The measurement of the WZ production cross section



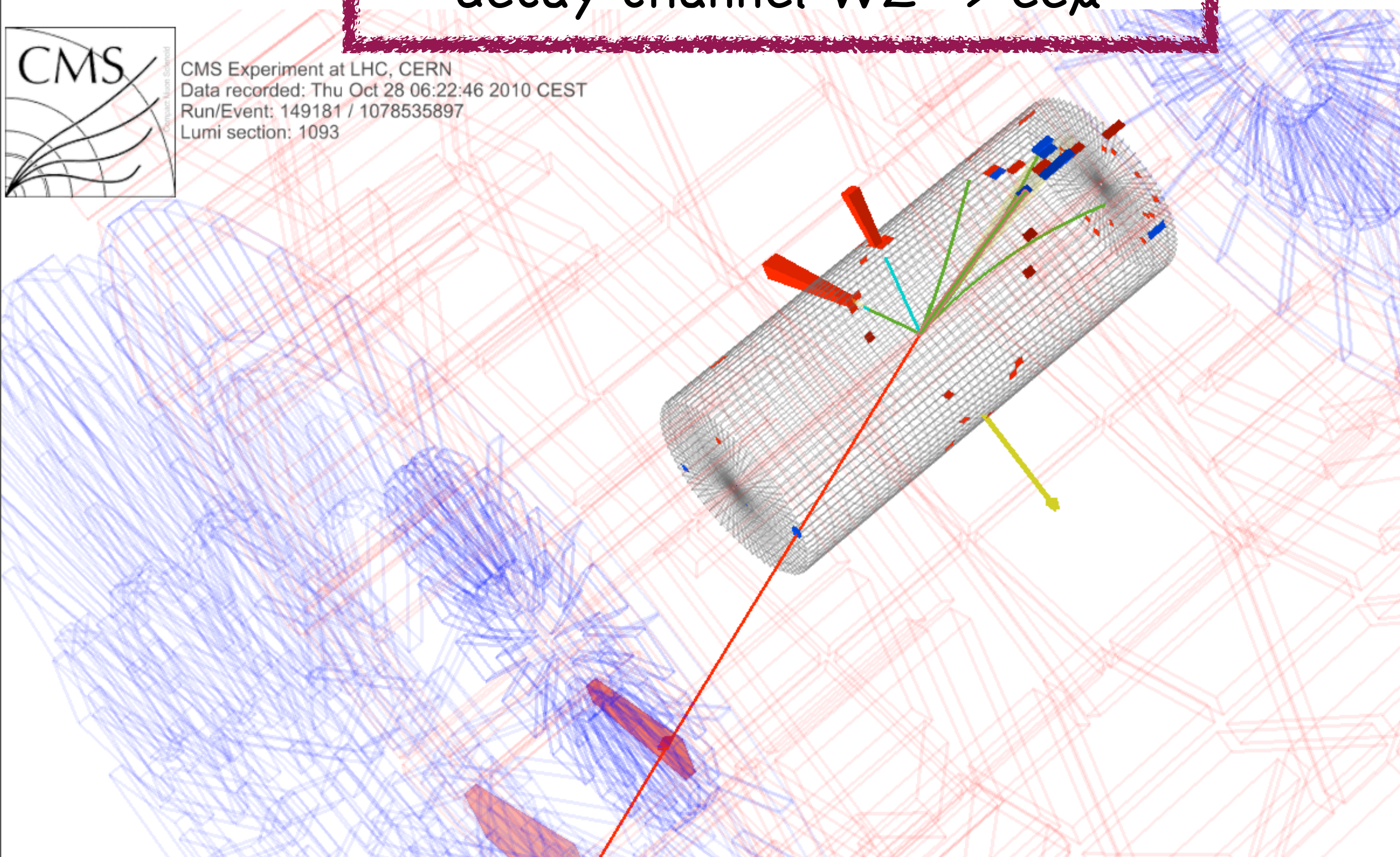
- Critical LHC operations: instantaneous luminosity ≈ 10^{33} $cm^{-2}s^{-1}$ in summer
  - important event pile-up (up to 16 reconstructed vertices per event)
  - increased detector occupancy and high energy depositions in the calorimeters

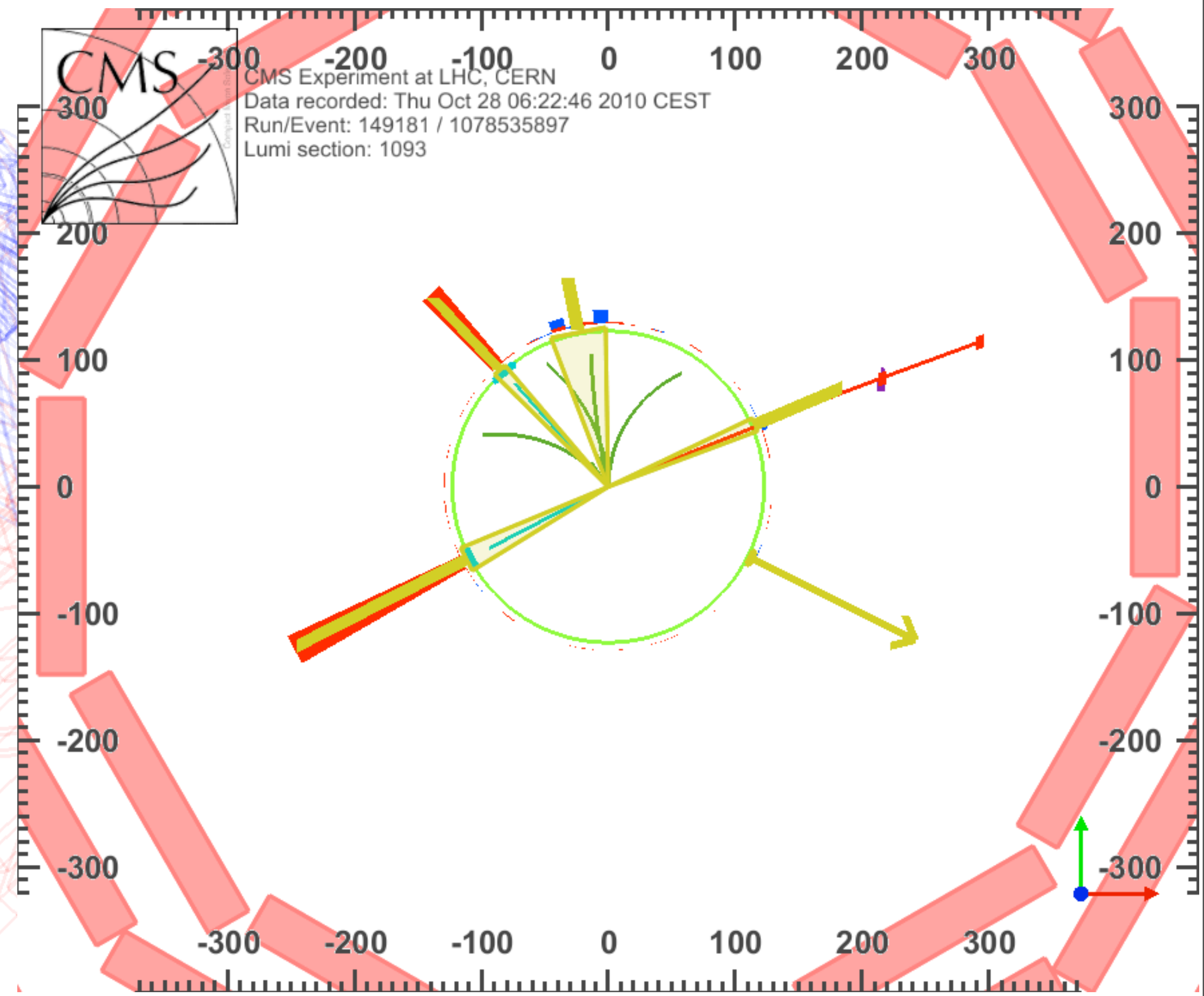
WZ topology

- Final state considered: WZ->3l + MET (4 channels -> eee, eeμ, $\mu\mu$e, $\mu\mu\mu$)
  - 3leptons pT> 20,10,10 GeV/c
  - 2leptons Same-Flavor Opposite-Sign in 60<Mll<120 GeV/c^2
  - MET for the escaping neutrino

First WZ event observed in CMS

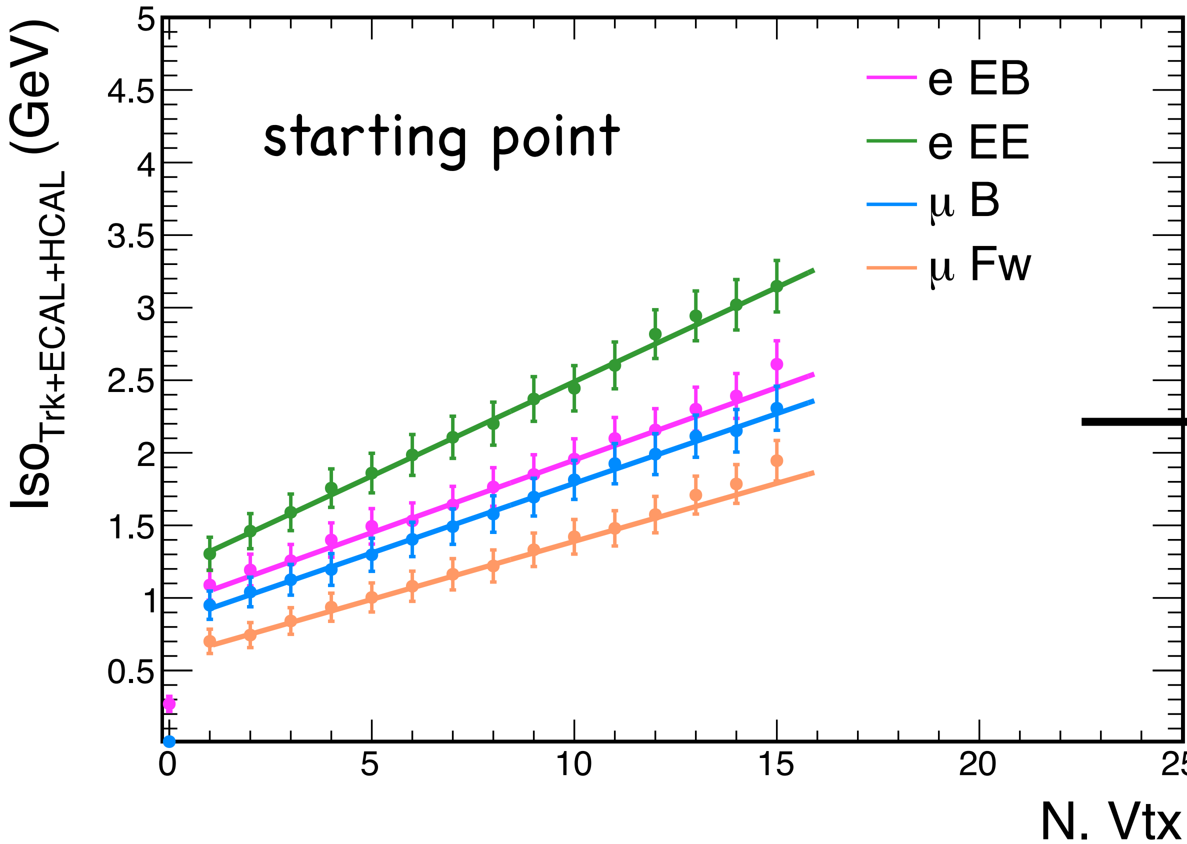
decay channel WZ -> eeμ

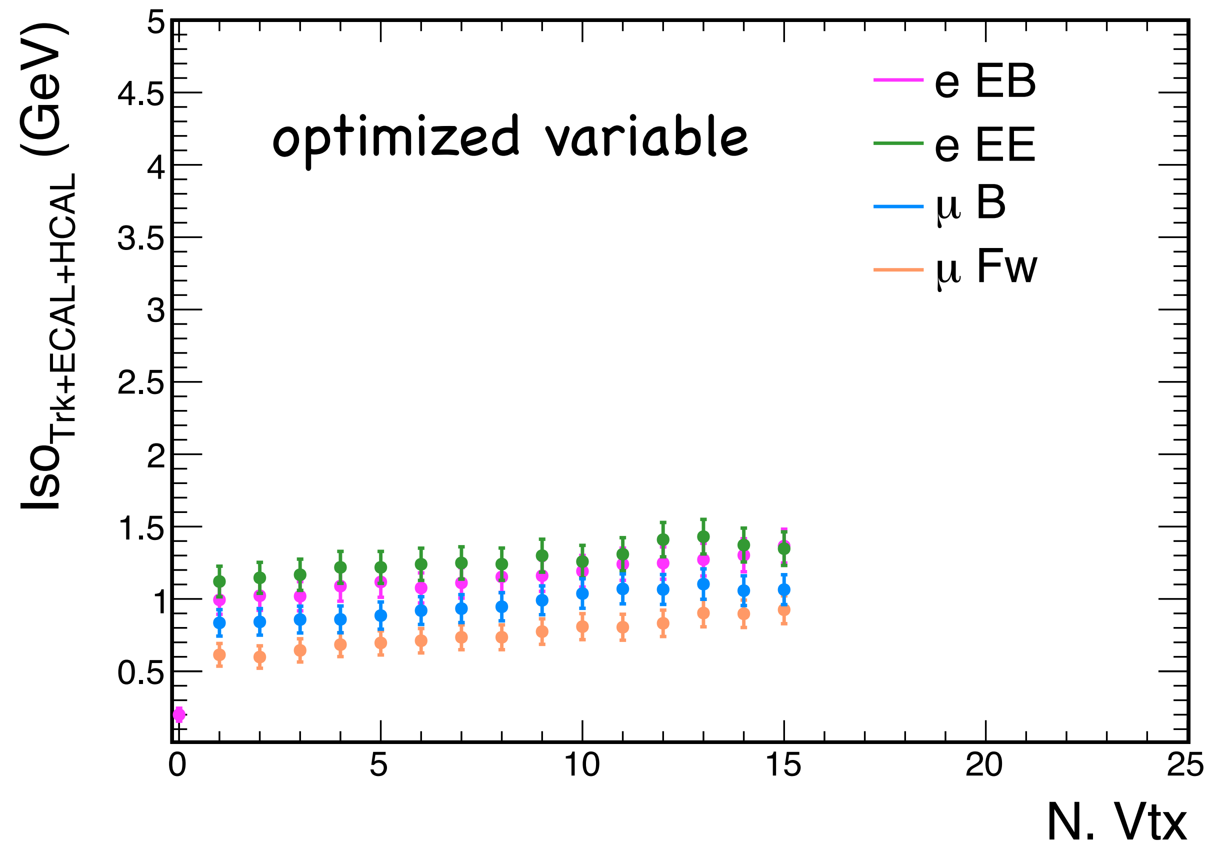




Lepton selections

- Crucial to define efficient and robust event selection
- 2 working points are optimized for Z leptons (loose) W lepton (tight)
  - Identification + Isolation criteria
- Isolation variable ≈ E deposited in a ΔR<0.3 cone (in Tracker+ECAL+HCAL)
  - sensitive to pile-up induced energy deposits in the detector

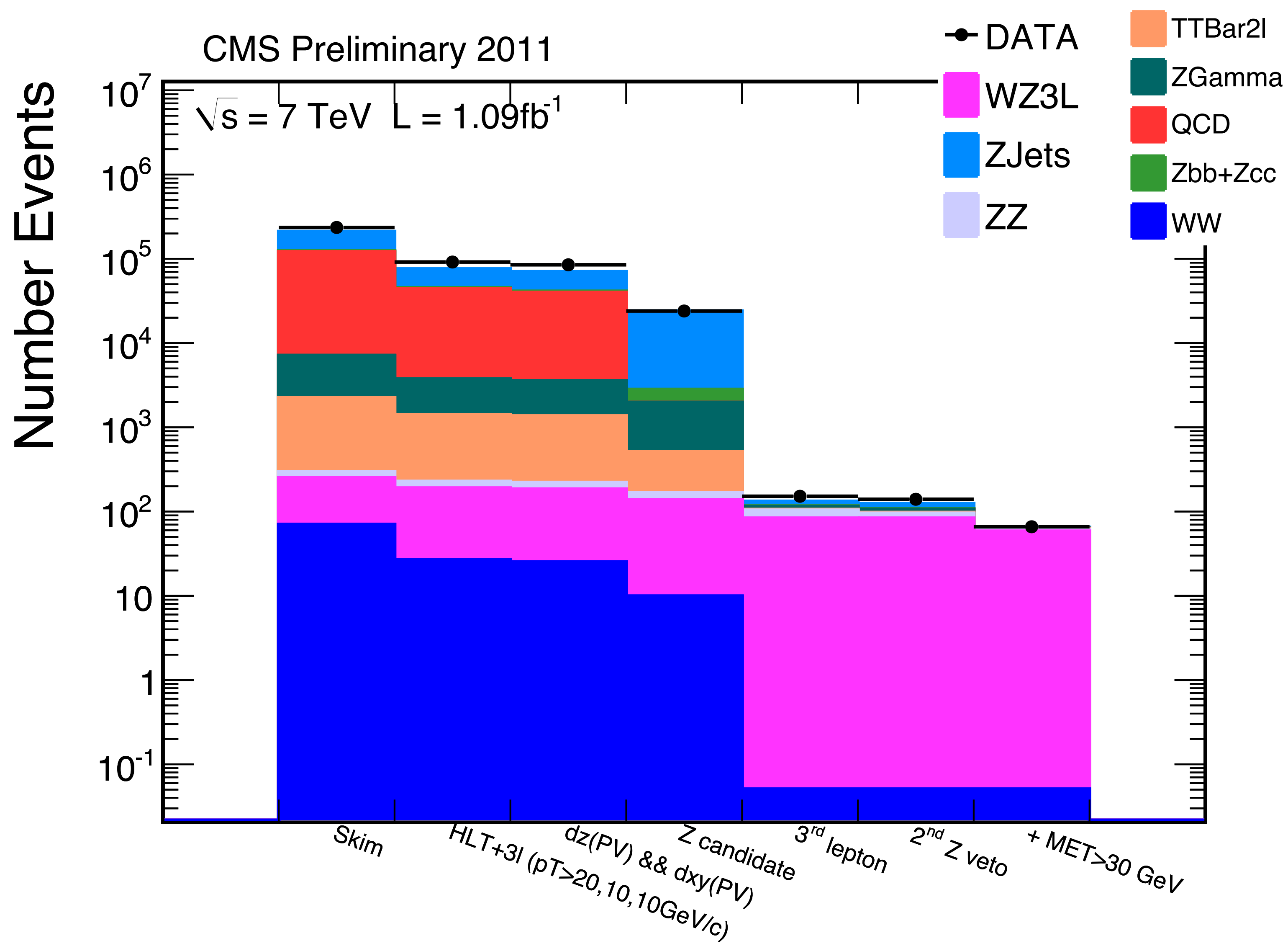




- Variable made stable wrt to increasing pile-up

WZ analysis

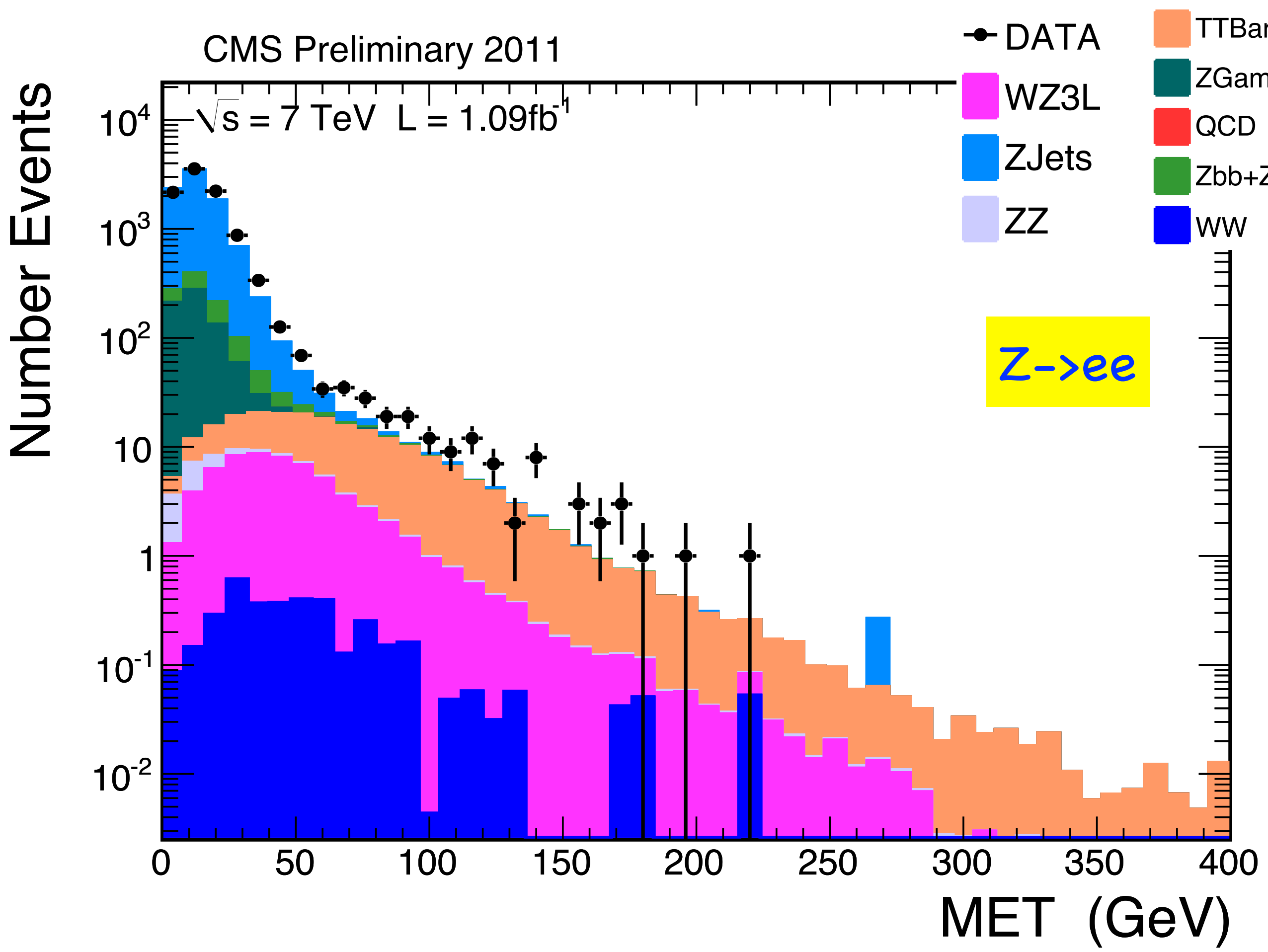
- Cut-based analysis strategy
  - signal phase space gradually defined
  - preserve unbiased control samples to estimate the backgrounds

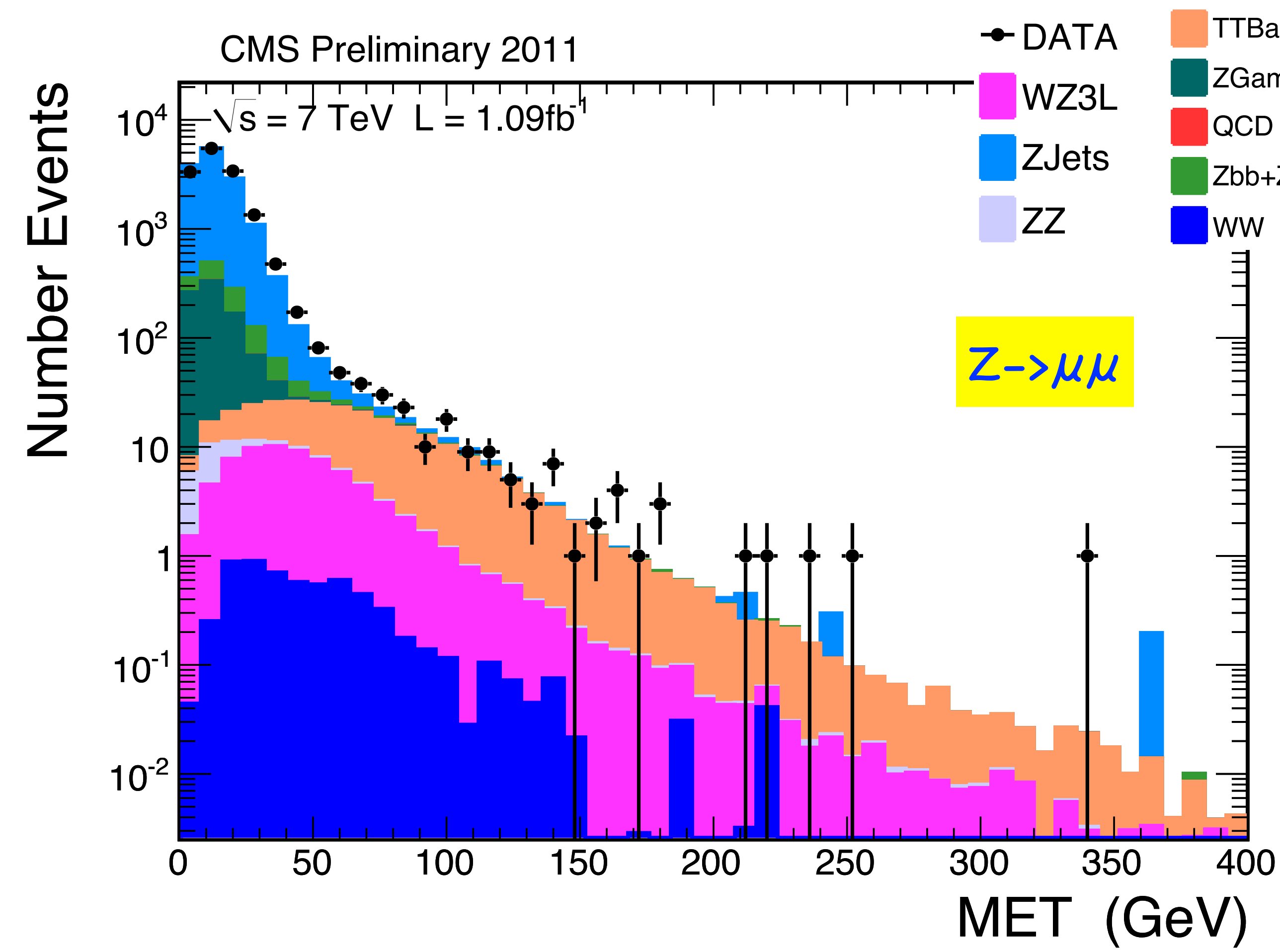


- Backgrounds:
  - Physical: ZZ
  - Instrumental: Z+jets, tt, Zγ
  - QCD looked at and found negligible
  - WZ -> taus taken as background and subtracted

Z selection

- **Z best candidate** in [60,120] GeV/c^2
  - Z->ee (pT>20,10 GeV/c) Z->$\mu\mu$ (pT > 15, 15 GeV/c)
  - attention to leptons selections (loose requirements)

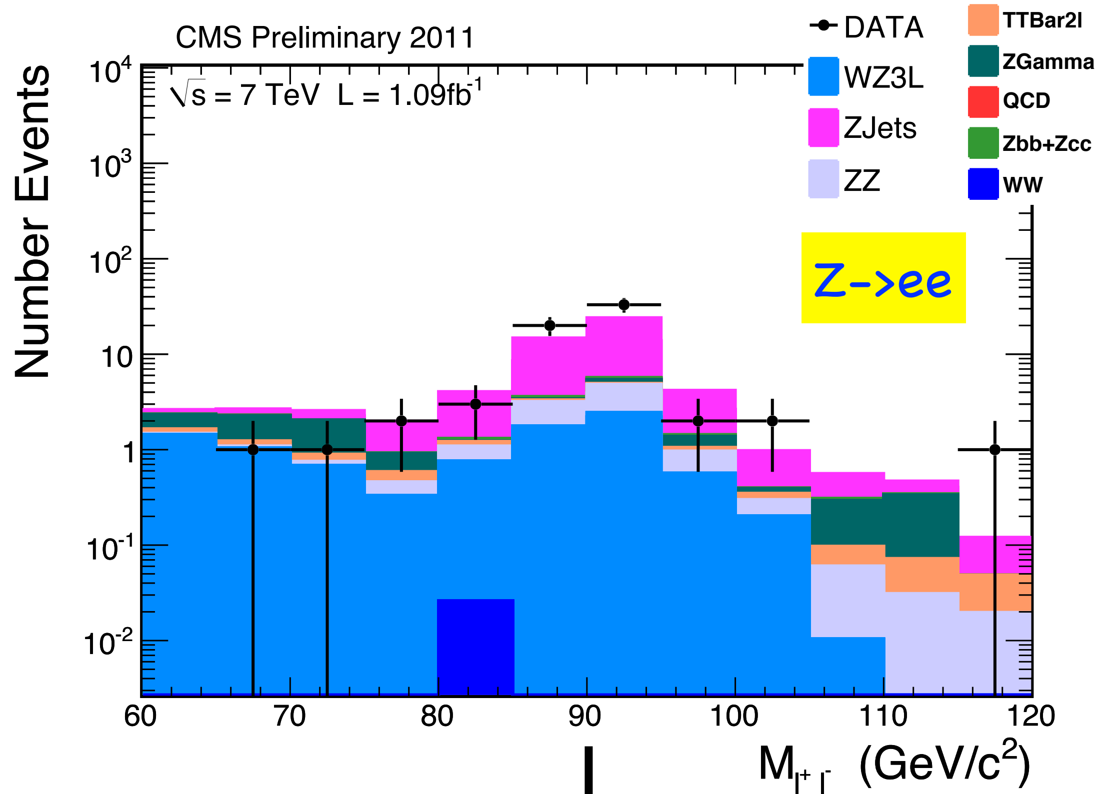


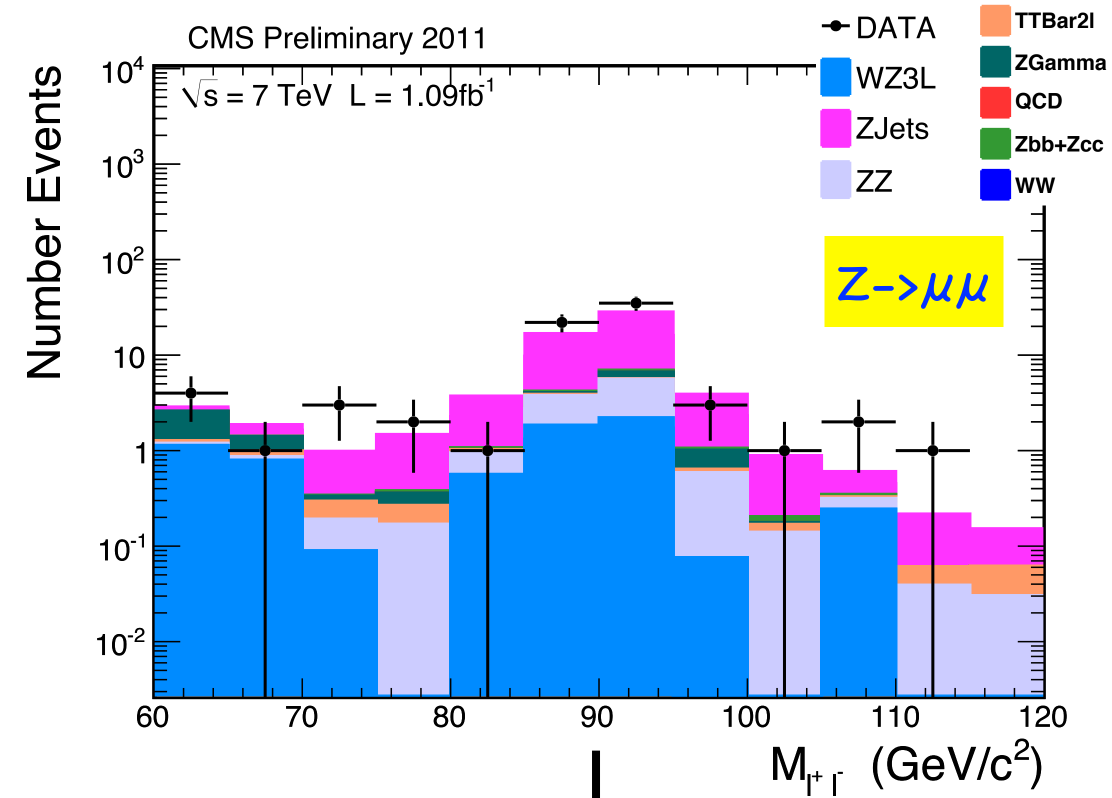


  - events rejected if second Z candidate found

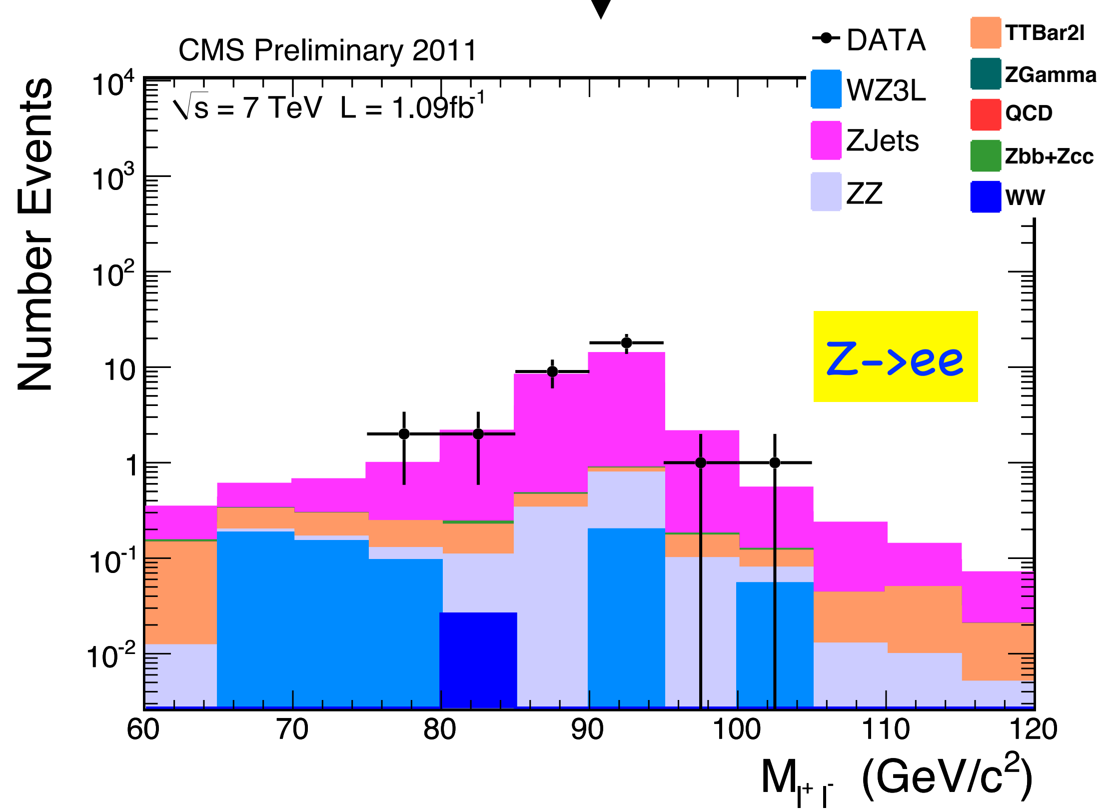
W selection

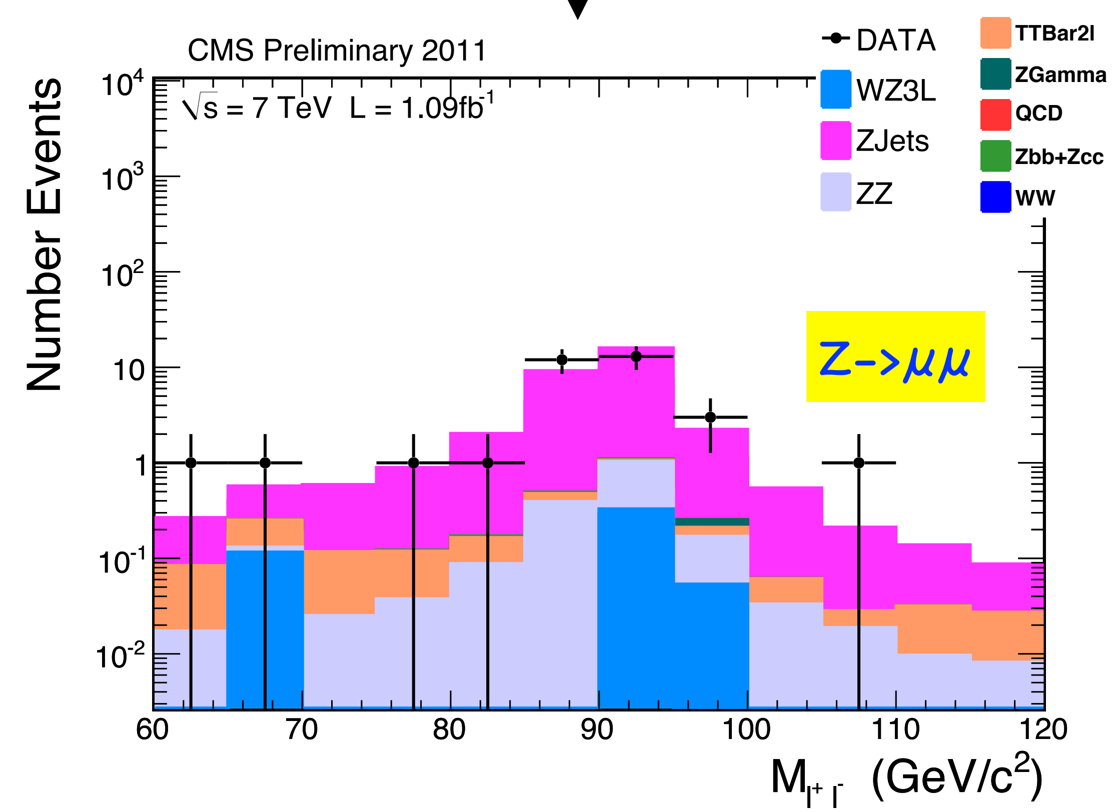
- **3rd lepton** pT>20GeV/c (tight selection)





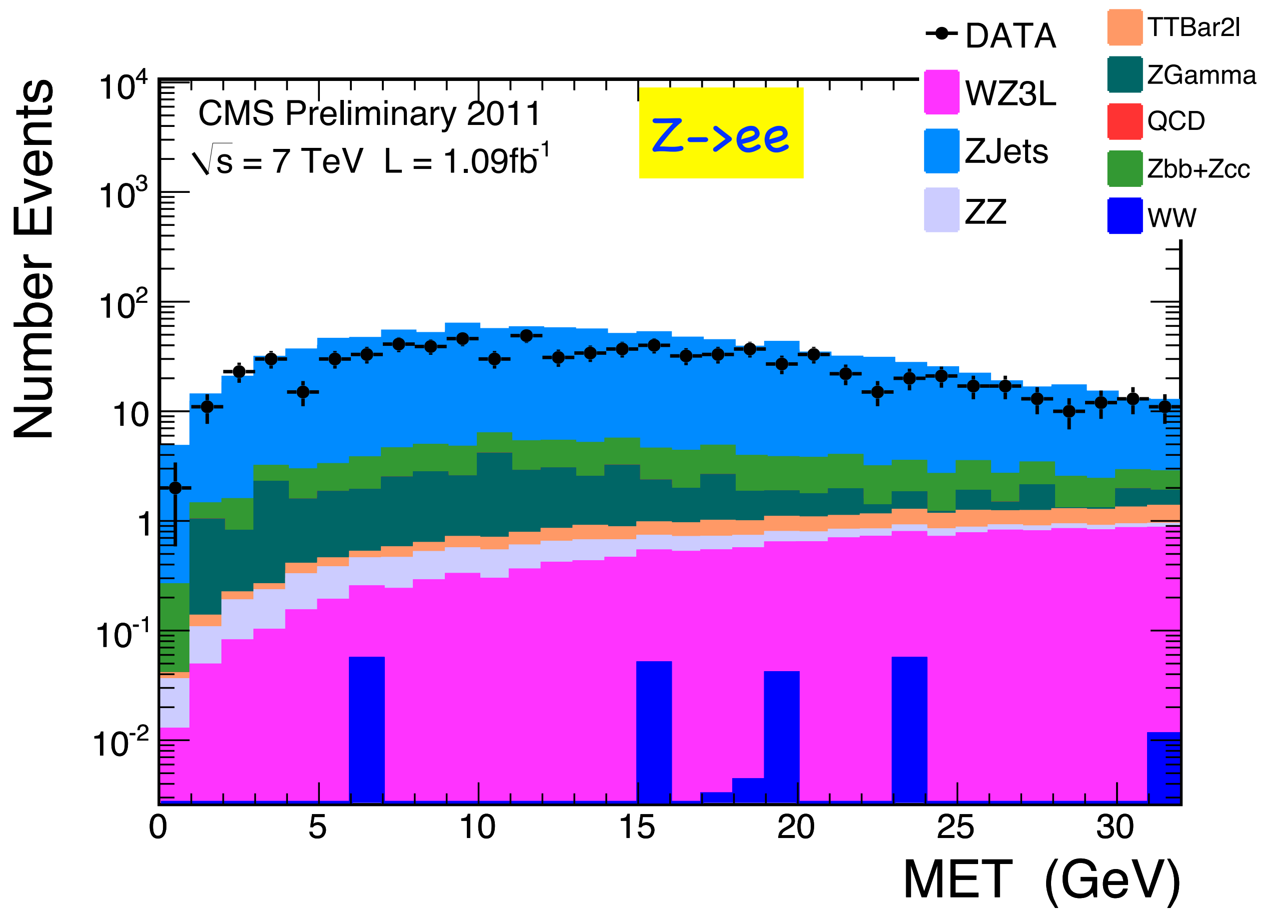
- **MET cut** (> 30 GeV)

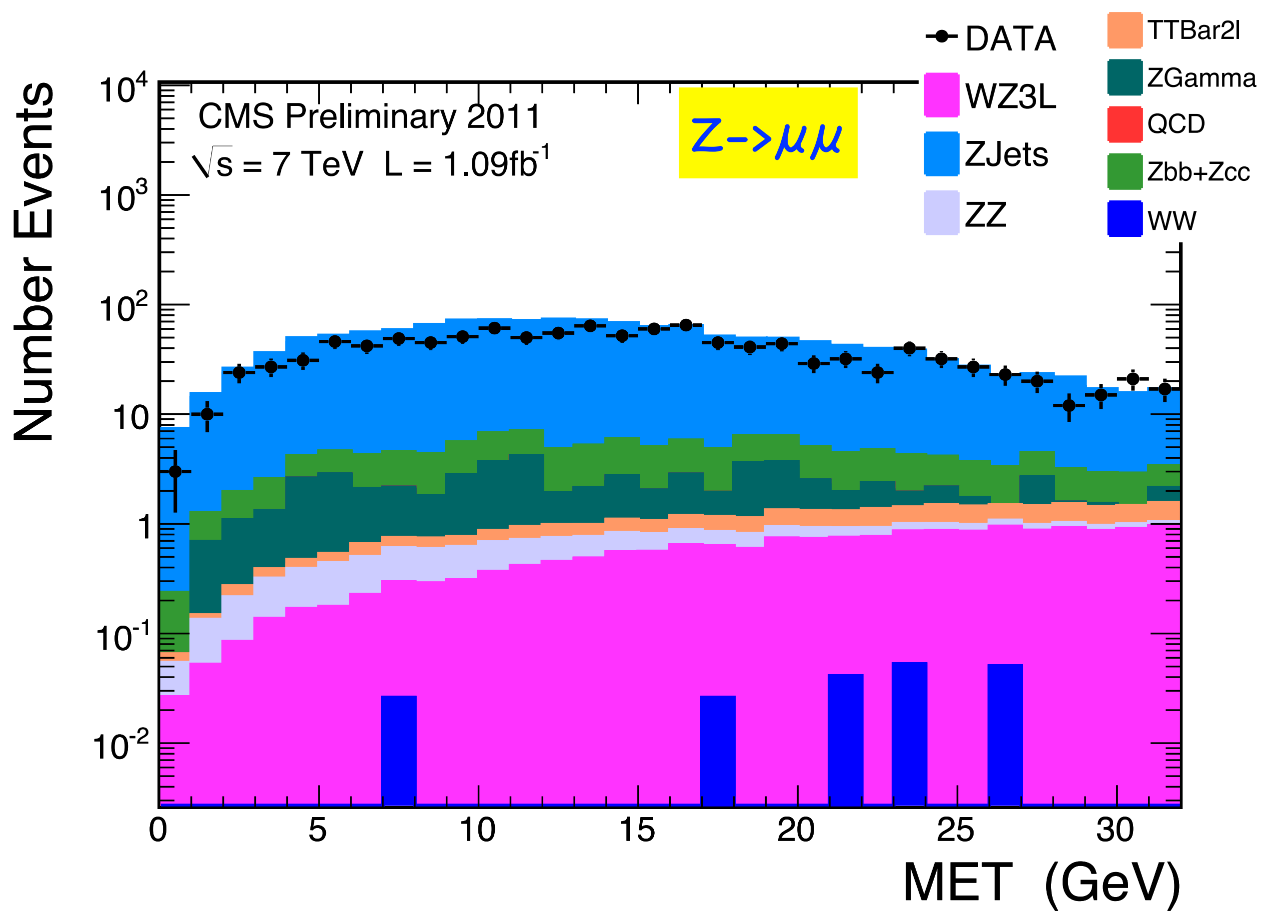




Z+jets from control region

- Estimate Z+jets from DATA/MC ratio in a control region dominated by Z+jets
  - Z selected and MET cut reverted (MET<30GeV) + 3rd lepton (pT>20GeV, no Iso, noID)
  - Purity => 0.92 (Z->ee) 0.93 (Z->$\mu\mu$)
  - Signal Contamination => 0.7% (Z->ee) 0.6% (Z->$\mu\mu$)





- Good data/MC agreement in this control region
- Conservative 20% systematic uncertainty assigned (for both Z->ee and Z->$\mu\mu$)

Systematic uncertainties

- **Backgrounds:** big uncertainty small impact on WZ yield

Source	Systematic uncertainty	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
Background estimation		Effect on WZ yield			
ZZ from simulation	7.5%	0.2%	0.5%	0.3%	0.5%
$Z\gamma$	13%	0.2%	0.%	0.2%	0.%
other	20%	0.1%	0.1%	0.07%	0.06%
$Z + jets$ from cross check	20%	1.0%	0.3%	0.7%	0.3%
$t\bar{t}$ with data	50%	1.4%	2.4%	1.5%	1.2%

- **Lepton efficiencies**:
  - ε = ε(RECO) * ε(ID/RECO) * ε(Iso/ID) * ε(HLT/ISO)
  - with Tag-and-Probe on data Z->ee, Z->μμ
    - HLT DoubleElectron take 100% efficiency + 1.5% sys. to be conservative

Source	Systematic uncertainty	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
		Effect on ρ_{WZ}			
Electron trigger	1.5%	1.5%	1.5%	n/a	n/a
Electron reconstruction	0.9%	2.7%	1.8%	0.9%	n/a
Electron ID and isolation	2.5%(WP95), 3.2%(WP80)	5.9%	5.0%	3.2%	n/a
Muon trigger	0.54%	n/a	n/a	1.08%	1.08%
Muon reconstruction	0.74%	n/a	0.74%	1.48%	2.22%
Muon ID and isolation	0.74%	n/a	0.74%	1.48%	1.94%
Total uncertainty on ρ_{eff}		6.7%	5.6%	4.2%	3.6%

Systematic uncertainties

- **Energy scale**:
  - ECAL energy scale known to 0.6%(EB) and 1.5%(EE) assume 2% to be conservative
  - Energy scale: from 2010 J/Psi and Z resonances error on absolute momentum scale < 1%

- **Acceptance**: to account for PDF (1%) and NLO re-weighting (2.5%)

Source	Systematic uncertainty	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
		Effect on $\mathcal{F} = A \cdot \epsilon_{sim}$			
Electron energy scale	2%	1.7%	0.25%	0.9%	n/a
Muon p_T scale	1%	n/a	0.5%	0.2%	0.9%
MET Resolution		0.5%	0.5%	0.5%	0.5%
MET Scale		0.3%	0.2%	0.1%	0.1%
Pileup		3.1%	0.8%	1.6%	1.6%
PDF	1.0%	1.0%	1.0%	1.0%	1.0%
NLO effect	2.5%	2.5%	2.5%	2.5%	2.5%
Total uncertainty on $\mathcal{F} = A \cdot \epsilon_{sim}$		4.5%	2.9%	3.3%	3.3%

- **Luminosity:** 6% uncertainty

Cross section measurements

- Cross section measured in 1.09 fb^{-1} and extrapolated to full acceptance
  - Considering l = e,μ only
  - f_τ = fraction of selected WZ decay channels containing a tau lepton (≈7%)

$$\sigma \times BR(W \to l\nu) \times BR(Z \to ll) = \frac{(1-f_\tau)\cdot(N_{obs}-N_{backg})}{F\cdot\rho\cdot L}$$

Channel	$A \cdot \epsilon_{sim}$	ρ
eee	$0.154 \pm 0.001(stat)$	0.97 ± 0.08
$ee\mu$	$0.200 \pm 0.001(stat)$	1.00 ± 0.06
$\mu\mu e$	$0.173 \pm 0.001(stat)$	0.94 ± 0.05
$\mu\mu\mu$	$0.224 \pm 0.001(stat)$	0.97 ± 0.05

  - Poisson 68% CL statistical error

channel	N_{obs}	N_{bkg}	$\sigma \times BR$ (pb)
$eee\nu$	16	2.69	$0.081^{+0.029}_{-0.022}(stat) \pm 0.007(syst) \pm 0.005(lumi)$
$ee\mu\nu$	17	2.85	$0.065^{+0.022}_{-0.017}(stat) \pm 0.004(syst) \pm 0.004(lumi)$
$\mu\mu e\nu$	13	2.12	$0.061^{+0.025}_{-0.018}(stat) \pm 0.003(syst) \pm 0.004(lumi)$
$\mu\mu\mu\nu$	20	3.04	$0.072^{+0.022}_{-0.017}(stat) \pm 0.004(syst) \pm 0.004(lumi)$

$\sigma(pp \to WZ \times BR)_{NLO} = 0.068^{+0.003}_{-0.002}$ pb

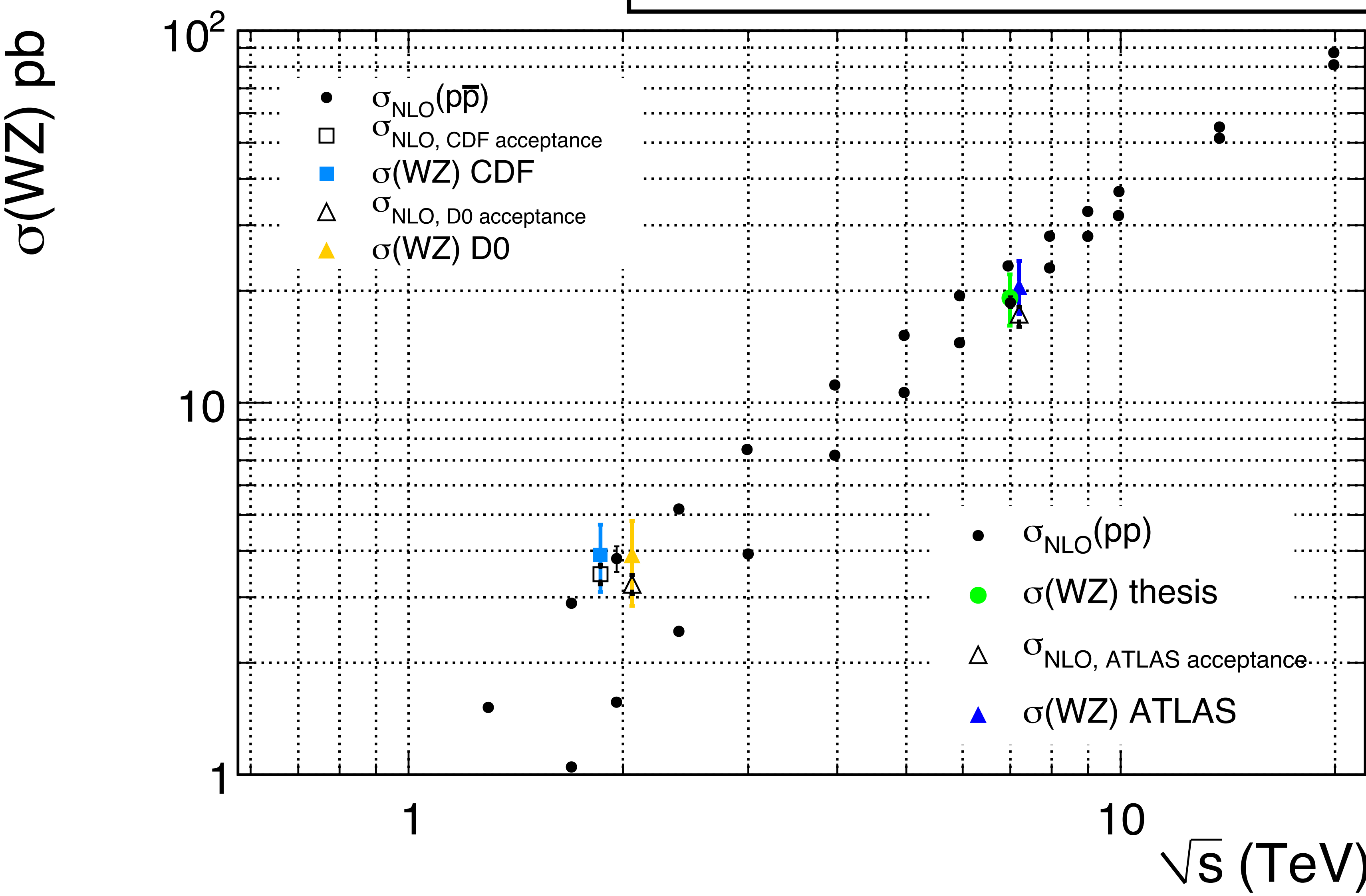
Inclusive cross section

- Maximum Likelihood with Nsig ≈ Poisson distribution
  - correlation between systematic uncertainties included

$$\sigma = \frac{\sum_i N_{sig_i}}{\mathcal{L} \cdot \sum_i (BR_i A_i \epsilon_i)}$$

$$\sigma(WZ) = 19.11^{+3.30}_{-2.53}(\text{stat.}) \pm 1.10(\text{syst.}) \pm 1.15(\text{lumi.})\text{pb}$$

$\sigma(pp \to WZ)_{NLO} = 18.57^{+0.75}_{-0.58}$ pb



Comparison with CMS public analysis

	chapter 6.5 results			CMS public analysis [25]		
channel	N_{obs}	N_{bkg}	WZ_{MC}	N_{obs}	N_{bkg}	WZ_{MC}
$eee\nu$	16	2.69	11.95	22	2.98	14.47
$ee\mu\nu$	17	2.85	15.50	20	3.63	17.40
$\mu\mu e\nu$	13	2.12	13.39	13	2.03	13.95
$\mu\mu\mu\nu$	20	3.04	17.34	20	3.15	18.56

- Different selection working points
- Inclusive cross section measured as

$$\sigma(WZ \to 3l) = w_1 \cdot \sigma_{WZ\to eee\nu} + w_2 \cdot \sigma_{WZ\to ee\mu\nu} + w_3 \cdot \sigma_{WZ\to \mu\mu e\nu} + w_4 \cdot \sigma_{WZ\to \mu\mu\mu\nu}$$

σ = 18.8 ± 2.6(stat.) ± 1.0(syst.) ± 1.1 pb

extrapolated to full acceptance

σ = 17.0 ± 2.4(stat.) ± 1.1(syst.) ± 1.1 pb

extrapolated to Mll in [60, 120]GeV/c^2

Conclusions and outlook

- Cosmic ray muons used to check the ECAL energy scale
  - CFT-09-005
- Electron track-seeds commissioning with first collision data
  - EGM-10-001
  - EGM-10-004
- WZ diboson production carefully studied $\sigma(pp \rightarrow WZ+X)$ measured with 1.09 fb^{-1}
  - EWK-11-010

- A first important result towards further multiboson measurement
- Higher statistic available:
  - already 5 fb^{-1} registered within 2011
  - target for 2012 15 fb^{-1} at 8TeV
    - more precise measurements
    - possibility to be competitive also in the measurement of TGC
    - exploit diboson precision measurements

BACKUP

dE/dx approximation

- Stopping power for muons parametrized as $f(E) = \langle -dE/dx \rangle = a(E) + b(E)\,E$
  - a(E) due to collisions with atomic electrons
  - b(E) due to radiative processes (bremsstrahlung, pair production, photo-nuclear interactions)

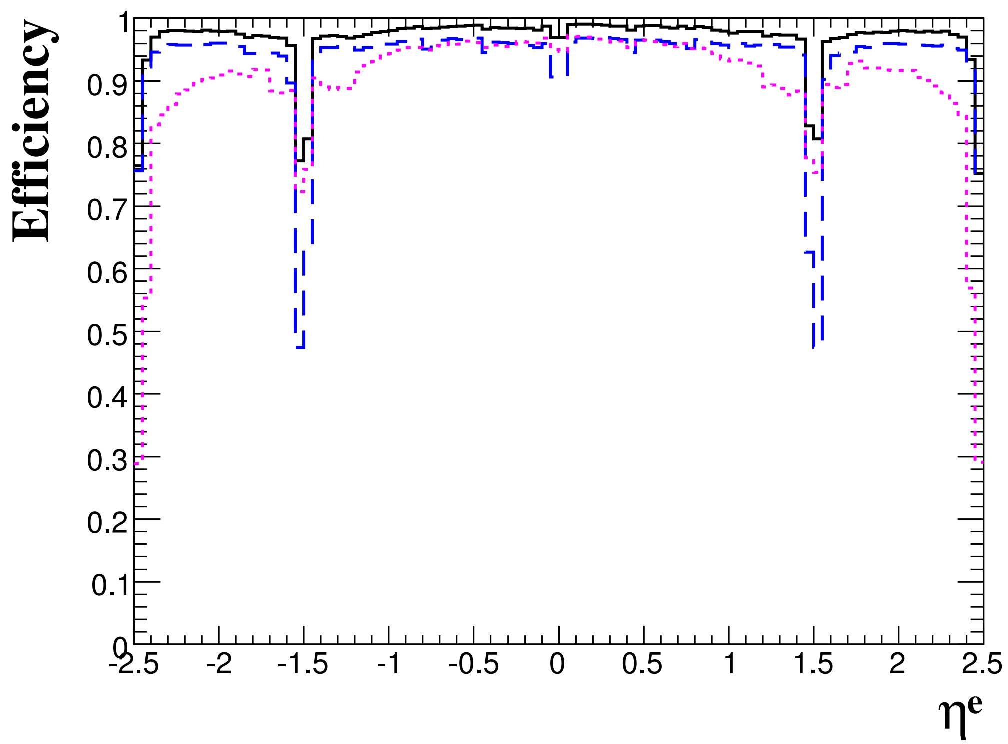
- $\Delta E/\Delta x \approx dE/dx$ if $\Delta f/f \leq$ desired relative precision on the measurement (order percent)
- $\Delta f/f = [\,(dE/dx)_{coll} + (dE/dx)_{rad}\,]\,\Delta x$
  - $(dE/dx)_{coll}$ maximum value expected at 5 GeV/c ($2.6\ 10^{-5}$ cm^2/g)
  - $(dE/dx)_{rad} \approx bE$, at 1 TeV/c ($1.6\ 10^{-5}$ cm^2/g)
  - $\Delta x \approx 180$ g/cm^2

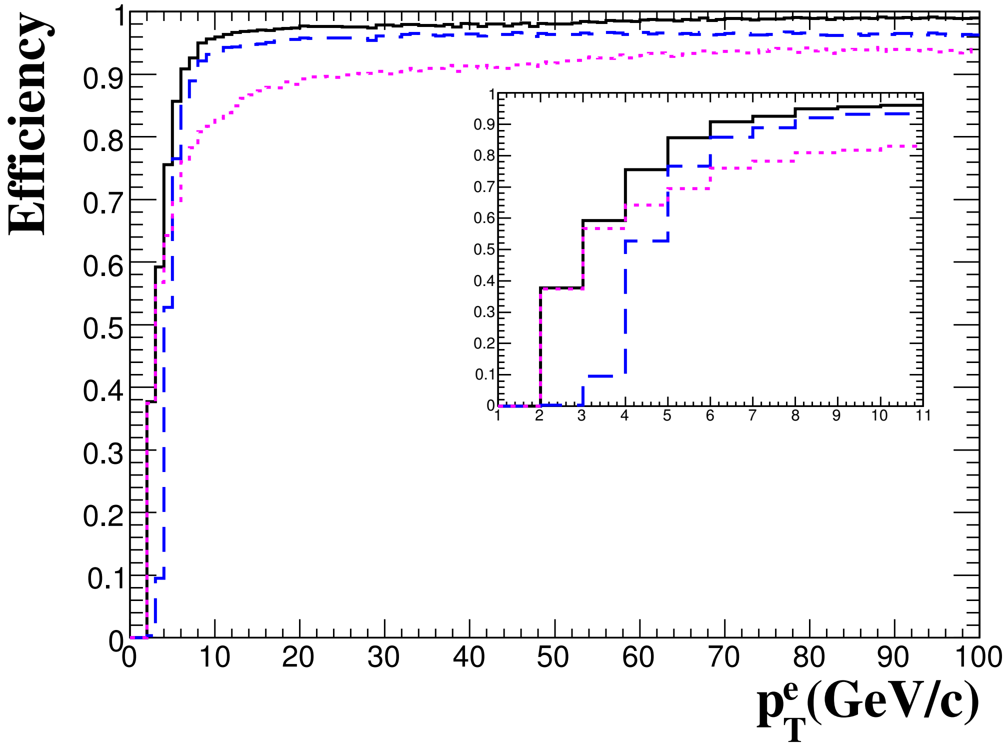
- Valid approximation also with large event by event fluctuations (on average $dE \ll E$)

- $\Delta f/f$ everywhere smaller than other systematic uncertainties

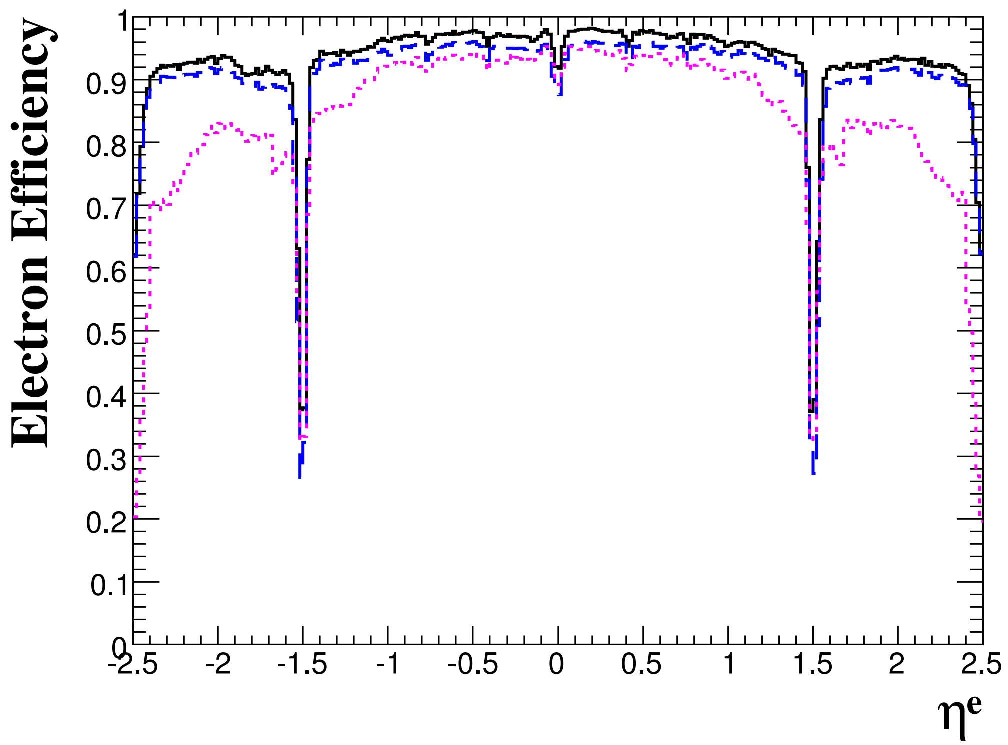
Electron efficiencies - simulation

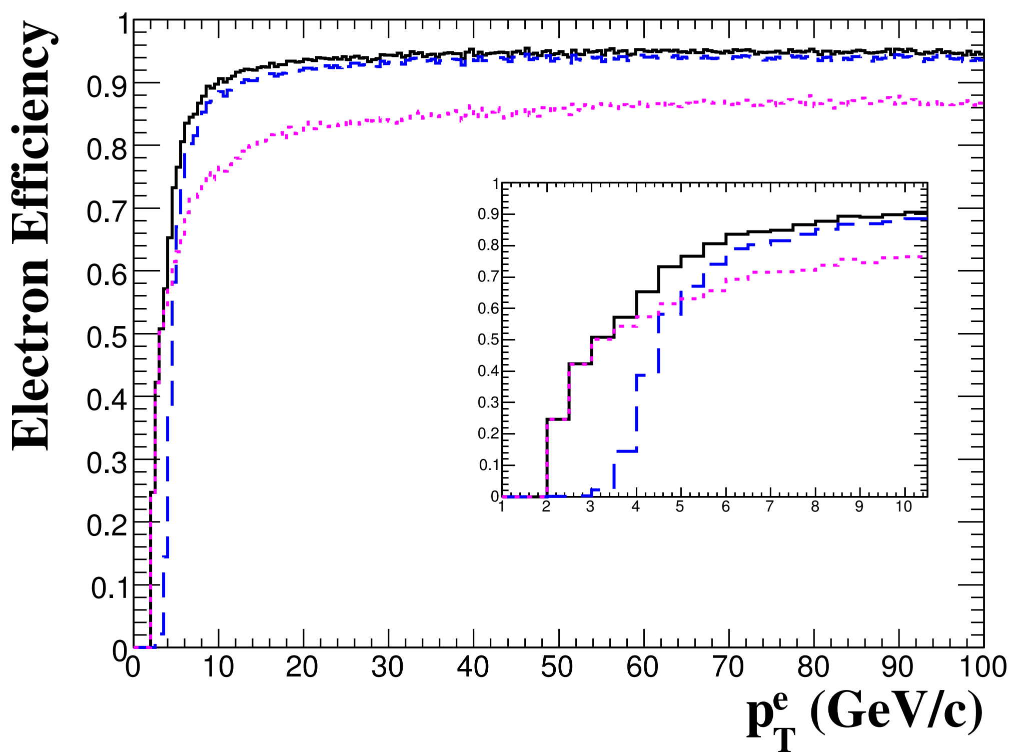
- Seeding (pT > 2 GeV/c)





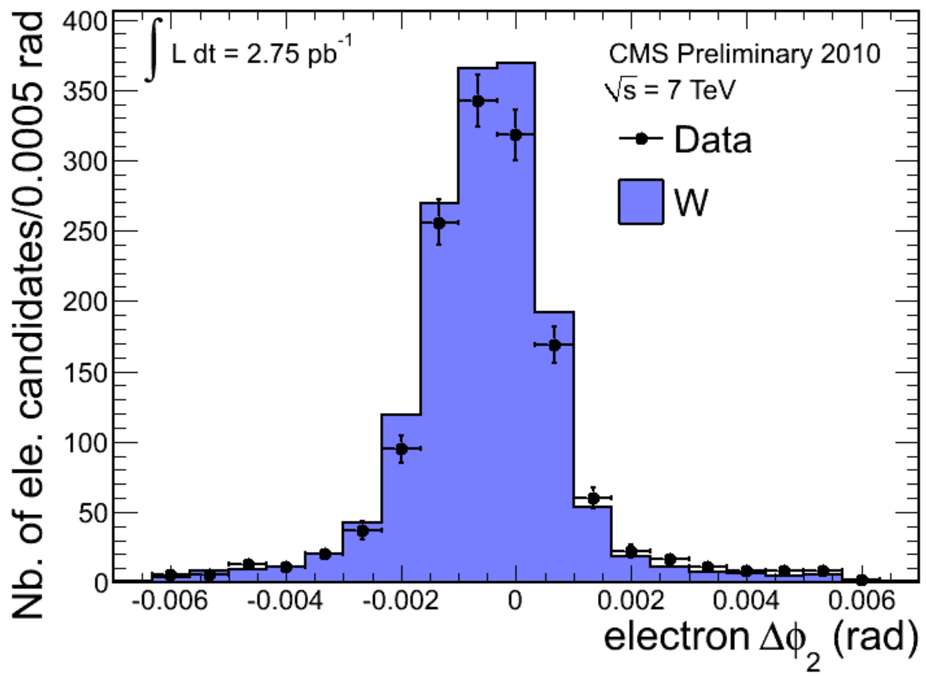
- Electron (pT > 2 GeV/c)

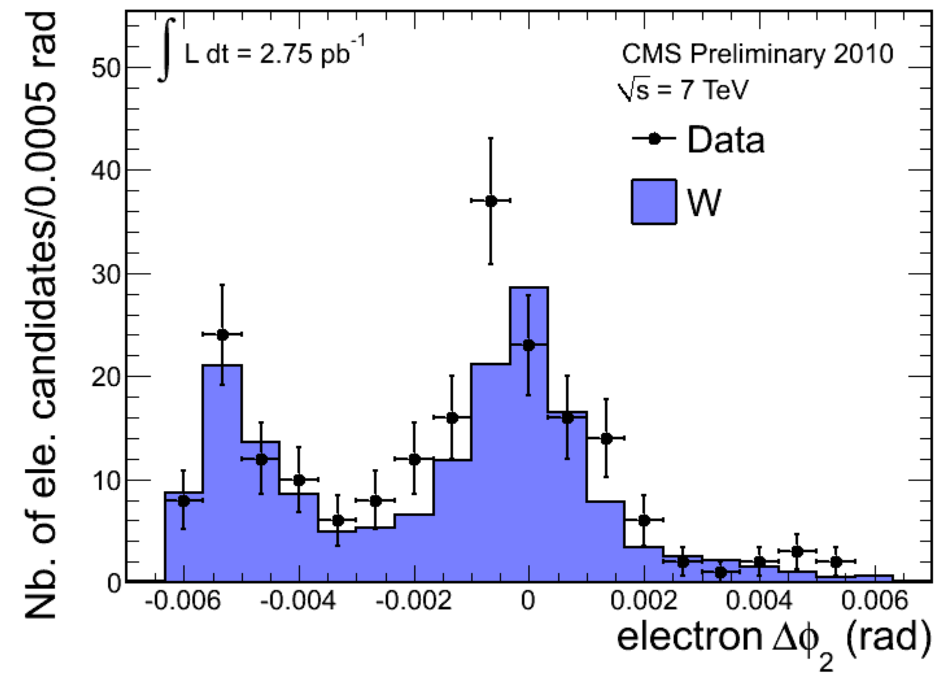




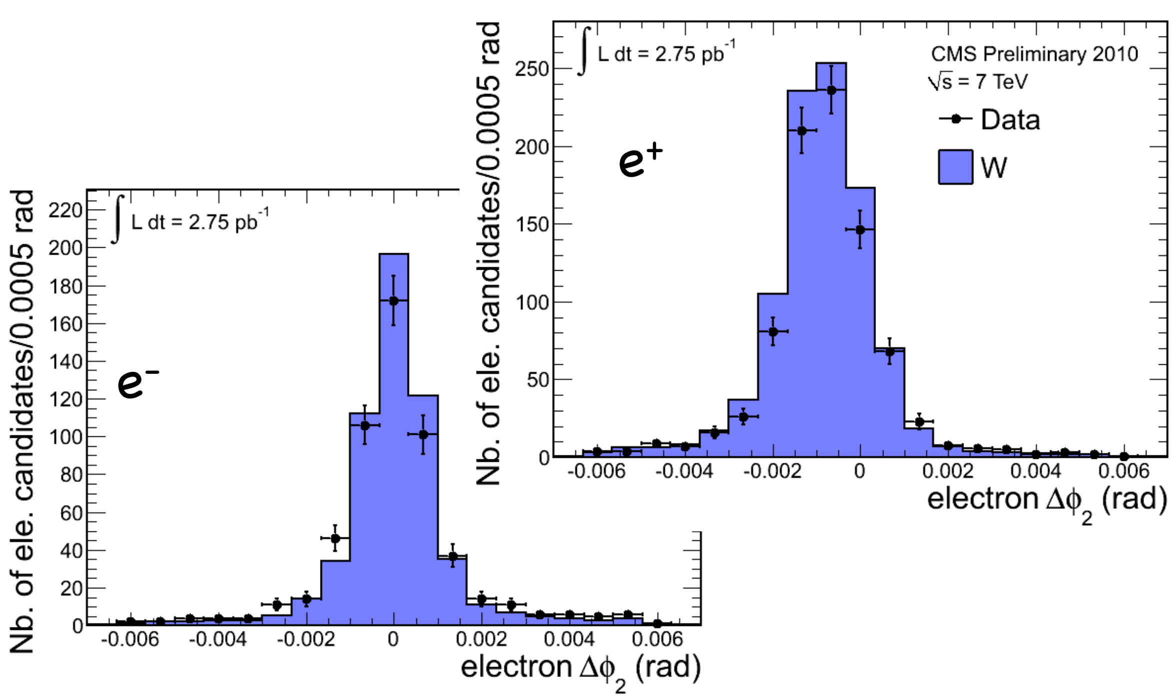
Residual bias in the forward region

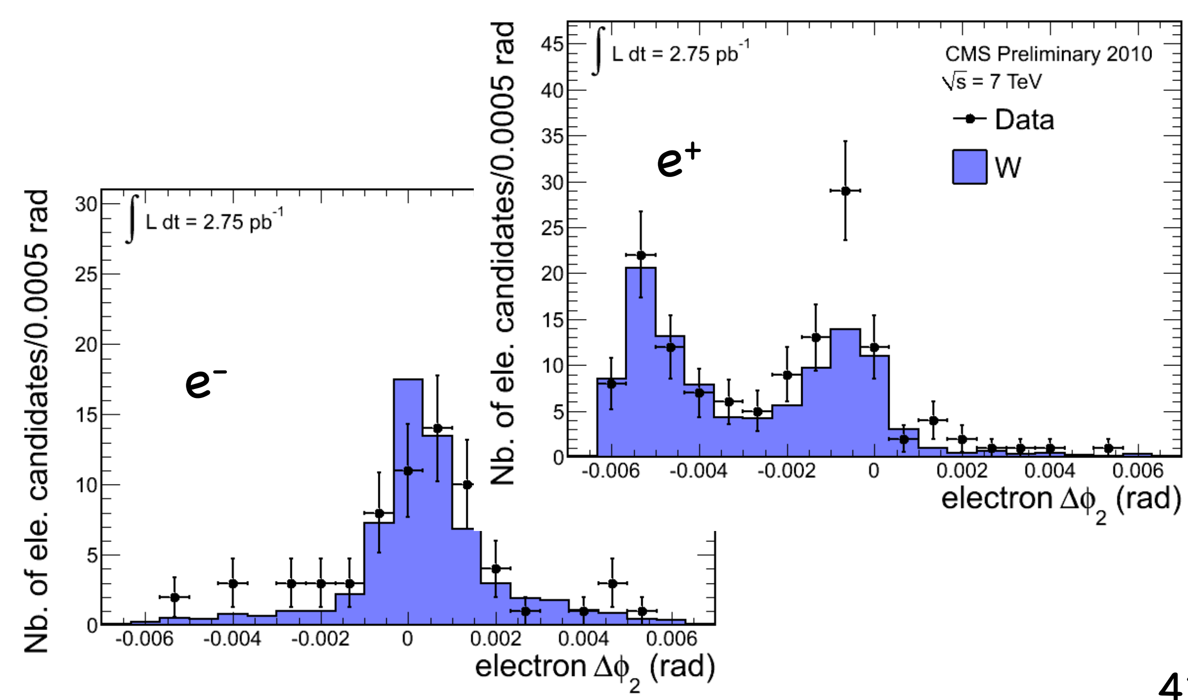
- FPixel: small offset (unresolved double peak) TEC: visible double peak





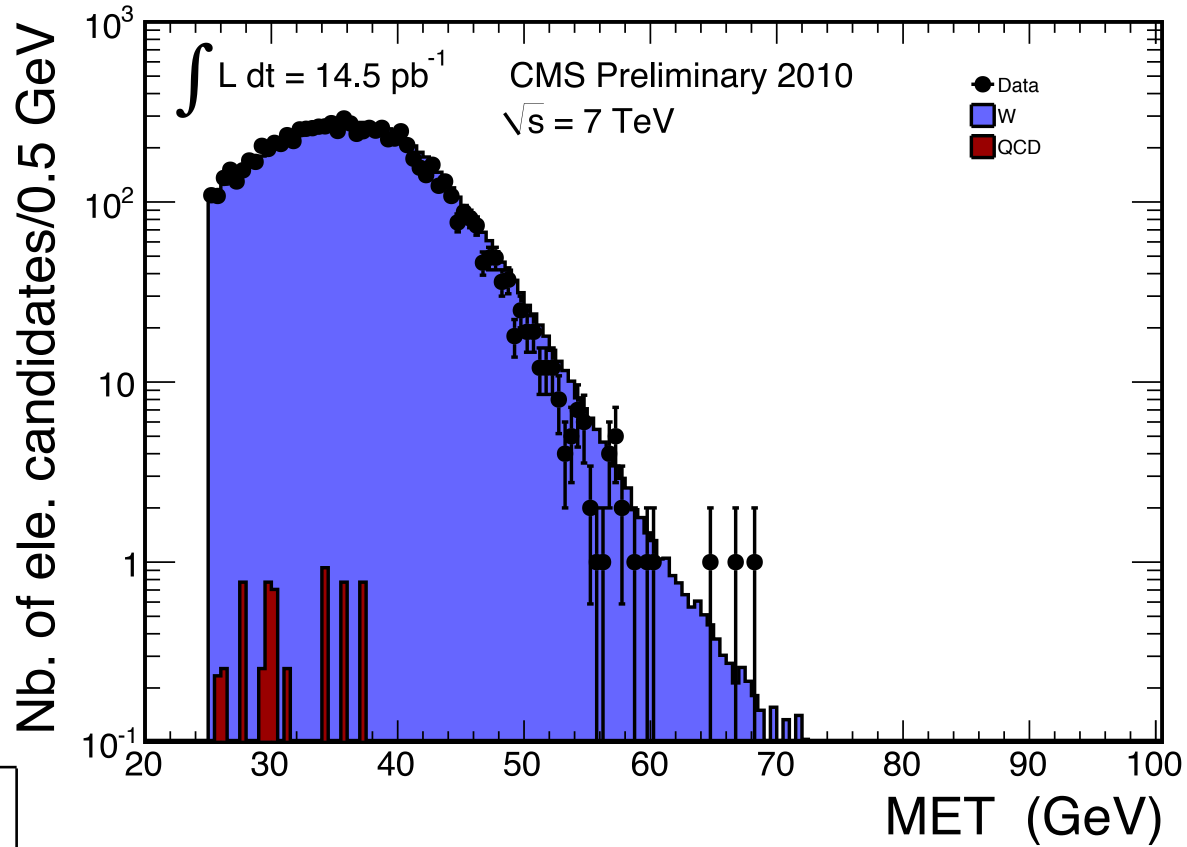
- $\Delta\varphi$ is correctly estimated for each charge hypothesis, but wrongly assigned same Measured hit but different Expected positions





Final validation with 14.5pb^{-1}

- Selected W -> e nu sample of high purity:
  - MET > 25 GeV
  - no Jet (pfJets, pT > 15 GeV/c)
  - 1 only reconstructed vertex (to get rid of pileUP effects)
  - electron pT > 25 GeV/c
  - electron-MET system:
    - DPhi > $\pi/2$
    - 40 < MT < 100 GeV/c^2
  - WP 80% electrons are considered:
    - NO $\Delta\varphi$, $\Delta\eta$ cuts applied



layers combination	number of electron candidates		
	EB + EE	EB	EE
BPIX-BPIX	7105	5765	1340
BPIX-FPIX	1478	9	1469
FPIX-FPIX	11	0	11
FPIX-TEC	31	0	31
TEC-TEC	0	0	0

Events yield

- Event yields in 1.09/fb

channel	DATA	WW	WZ	ZZ	$t\bar{t}$	$Z\gamma$	QCD	Zbb	$Z+jets$	S+B(MC)
Preselection: HLT requirement + 3 leptons $p_T >$ 20,10,10 GeV/c + Vtx compatibility										
combined	84978	25.12	159.36	36.89	1137.56	2207.03	36347.7	1131.61	29311.8	74216.71
eee	14086	5.96	38.55	9.57	209.27	925.49	3613.75	263.16	7663.85	12729.6
$ee\mu$	9423	3.54	36.63	4.60	214.95	74.08	4324.97	196.64	2724.96	7580.36
$\mu\mu e$	31209	12.53	44.57	14.13	503.82	1111.81	11914.	464.42	15278.7	29343.99
$\mu\mu\mu$	35415	3.56	43.26	10.02	340.40	119.55	19589.3	262.90	4193.76	24562.76
step 4: Z selection										
combined	24035	9.88	128.06	29.83	346.1	1458.72	0	838.31	21152.2	23963.16
$Z \rightarrow ee$	9547	3.82	59.69	11.23	149.43	646.01	0	346.61	7962.58	9179.38
$Z \rightarrow \mu\mu$	14493	6.07	68.36	18.60	196.66	646.01	0	491.69	13189.7	14783.78
step 5: 3^{rd} lepton selection										
combined	152	0.05	83.10	20.26	2.15	8.94	0.	1.47	16.41	132.38
eee	36	0.02	17.11	4.79	0.45	4.65	0.	0.4	8.89	36.32
$ee\mu$	34	0.03	21.99	2.21	0.84	0.16	0.	0.34	1.	26.57
$\mu\mu e$	41	0.	19.15	7.09	0.4	4.13	0.	0.27	4.67	35.71
$\mu\mu\mu$	41	0.	24.84	6.17	0.47	0.	0.	0.46	1.83	33.78
step 6: $2^{nd} Z$ veto										
combined	140	0.05	83.09	11.98	2.15	8.94	0.	1.47	16.41	124.09
eee	36	0.02	17.11	3.1	0.45	4.65	0.	0.4	8.89	34.62
$ee\mu$	29	0.03	21.99	2.0	0.83	0.16	0.	0.34	1.	26.36
$\mu\mu e$	35	0.	19.15	3.29	0.4	4.13	0.	0.27	4.67	31.92
$\mu\mu\mu$	40	0.	24.84	3.58	0.47	0.	0.	0.46	1.84	31.19
step 7: MET cut										
combined	66	0.05	58.18	2.84	1.81	0.32	0.	0.18	1.47	64.86
eee	16	0.02	11.95	0.44	0.38	0.16	0.	0.03	0.64	13.63
$ee\mu$	17	0.03	15.50	0.85	0.7	0.	0.	0.06	0.18	17.33
$\mu\mu e$	13	0.	13.39	0.45	0.33	0.16	0.	0.04	0.37	14.73
$\mu\mu\mu$	20	0.	17.34	1.10	0.4	0.	0.	0.05	0.27	19.17

Z+jets - matrix method

- 2 samples corresponding to different level of selections:
  - tight-cut sample: events passing all the signal extraction cuts
  - relaxed-cut sample: as tight-cut with Isolation on Wlepton removed

$$N_{\rm tight} = \epsilon_{\rm tight} N_{\rm lep} + P_{\rm fake} N_{\rm jet}, \qquad N_{\rm loose} = N_{\rm lep} + N_{\rm jet}$$

  - efficiency for TRUE (FAKE) lepton to pass the Isolation cut, both measured from data

- ε_{tight}: select a Z enriched sample: signal + Zjets and W+jets + tt as backgrounds
  - SF OS, pT>10GeV/c, satisfying the loose-cut selection, with Mll in [60,120]GeV/c^2
  - exactly one Z candidate required

$$\epsilon_{\rm tight} = \frac{2(N_{\rm TT} - B_{\rm TT})}{(N_{\rm TF} - B_{\rm TF}) + 2(N_{\rm TT} - B_{\rm TT})}$$

1 lepton Isolated, other not (TF) — both leptons Isolated (TT)

  - N = events in the Mwindow
  - B = background as linearly fitted in [70-80], [100-110]GeV/c^2

Z+jets - matrix method

- **P_{fake} measurement:** select W+jets sample from data and use Tag&Probe
  - (Tag) Wlepton: pT>20GeV/c, tight ID+ISO, matched to HLT lepton
  - Event requirements: MET>20GeV, W candidate MT > 20GeV
  - (Probe) the only remaining loose-cut lepton, with OF SS wrt Tag
    - to get rid of Z,WW still tt contamination

- Expected number of events in 1.09/fb

Type	$\epsilon_{\text{tight}} \cdot N_{\text{lep}}$	$P_{\text{fake}} \cdot N_{\text{jet}}$
eee	20.24 ± 4.76	1.76 ± 0.67
$ee\mu$	17.46 ± 4.56	2.54 ± 0.86
$\mu\mu e$	11.40 ± 3.67	1.60 ± 0.58
$\mu\mu\mu$	17.82 ± 4.54	2.18 ± 0.76

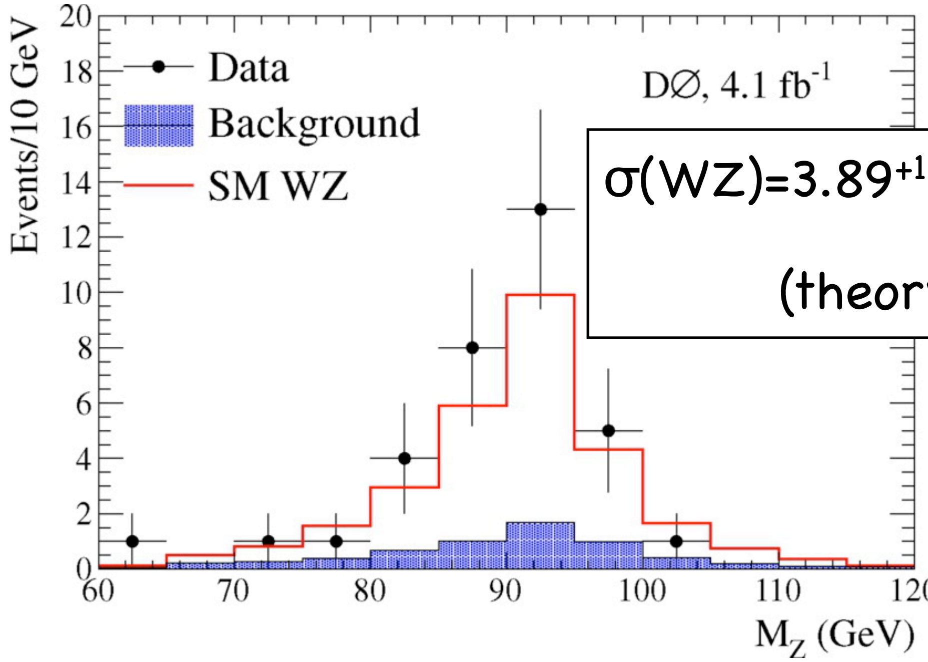
accounts for both Z+jets and tt

Systematic uncertainties

Source	Systematic uncertainty	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
		Effect on $\mathcal{F} = A \cdot \epsilon_{sim}$			
Electron energy scale	2%	1.7%	0.25%	0.9%	n/a
Muon p_T scale	1%	n/a	0.5%	0.2%	0.9%
MET Resolution		0.5%	0.5%	0.5%	0.5%
MET Scale		0.3%	0.2%	0.1%	0.1%
Pileup		3.1%	0.8%	1.6%	1.6%
PDF	1.0%	1.0%	1.0%	1.0%	1.0%
NLO effect	2.5%	2.5%	2.5%	2.5%	2.5%
Total uncertainty on $\mathcal{F} = A \cdot \epsilon_{sim}$		4.5%	2.9%	3.3%	3.3%
		Effect on ρ_{WZ}			
Electron trigger	1.5%	1.5%	1.5%	n/a	n/a
Electron reconstruction	0.9%	2.7%	1.8%	0.9%	n/a
Electron ID and isolation	2.5%(WP95), 3.2%(WP80)	5.9%	5.0%	3.2%	n/a
Muon trigger	0.54%	n/a	n/a	1.08%	1.08%
Muon reconstruction	0.74%	n/a	0.74%	1.48%	2.22%
Muon ID and isolation	0.74%	n/a	0.74%	1.48%	1.94%
Total uncertainty on ρ_{eff}		6.7%	5.6%	4.2%	3.6%
Background estimation		Effect on WZ yield			
ZZ	7.5%	0.2%	0.5%	0.3%	0.5%
$Z\gamma$	13%	0.2%	0.%	0.2%	0.%
other	20%	0.1%	0.1%	0.07%	0.06%
$Z + jets$	20%	1.0%	0.3%	0.7%	0.3%
$t\bar{t}$	50%	1.4%	2.4%	1.5%	1.2%
		Effect on $\mathcal{L}$			
Luminosity	6.0%	6.0%	6.0%	6.0%	6.0%

D0: WZ and TGC 2011

- At Tevatron ($\sqrt{s}$ = 1.96TeV, p-pbar) multiple diBoson topologies are exploited
- WZ for instance: first observation at CDF with 1.1fb^{-1} arXiv:hep-ex/0702027v1
- Current results (HCP 2011)

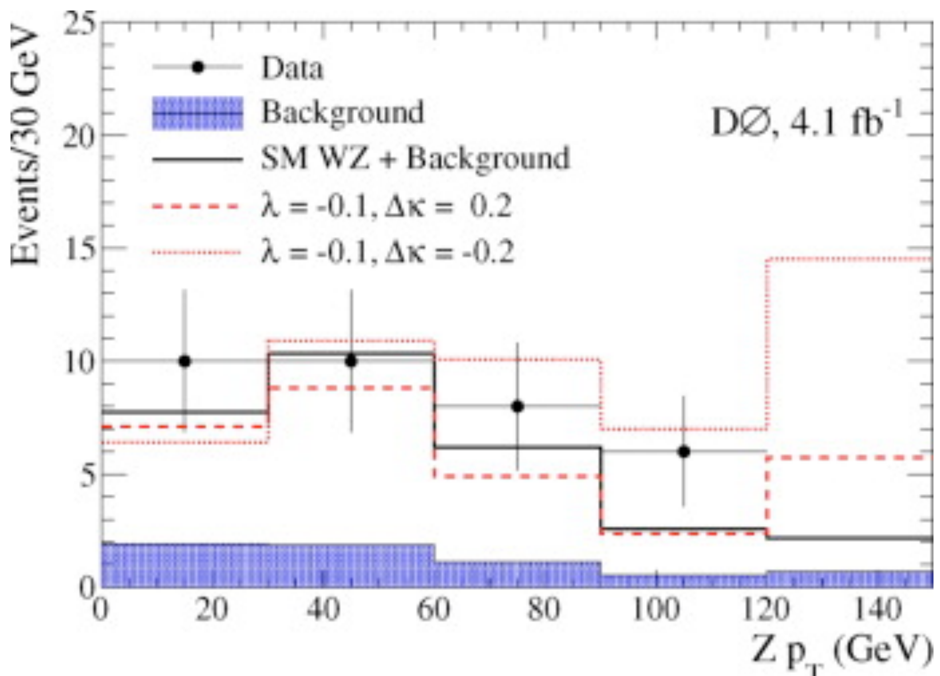


$\sigma(WZ)=3.89^{+1.02}_{-0.85}$(stat.)±0.31(lumi)pb

(theory) 3.25 ± 0.19 pb

- D0 TGC limits from WZ-> lnu ll:
  - 2D95% CL limits (2 varied, remaining fixed to SM value)
  - 1D95% CL limits (1 varied, remaining fixed to SM value)

Coupling relation	95% C.L. Limit
$\Delta g_1^Z = \Delta\kappa_Z = 0$	$-0.077 < \lambda_Z < 0.093$
$\lambda_Z = \Delta\kappa_Z = 0$	$-0.056 < \Delta g_1^Z < 0.154$
$\lambda_Z = \Delta g_1^Z = 0$	$-0.400 < \Delta\kappa_Z < 0.675$



Best limits from the direct measurement of WWZ vertex

TGC limits

Coupling	Δg_1^Z	Δk_Z	λ_Z	$\mathcal{L}$ [fb^{-1}]
CDF	[-0.08, 0.20]	[-0.39, 0.90]	[-0.09, 0.11]	7.1
D0	[-0.053, 0.156]	[-0.376, 0.686]	[-0.075, 0.093]	4.1
ATLAS	[-0.20, 0.30]	[-0.9, 1.1]	[-0.17, 0.17]	1.02

Table 1.7: One-dimensional 95% C.L. limits on TGC parameters obtained from varying one of the couplings while fixing the remaining couplings to the SM values. A form factor scale of Λ_{NP} =2 TeV is used.

Coupling	Δg_1^Z	Δk_γ	λ_Z
LEP2	[-0.051, 0.034]	[-0.105, 0.069]	[-0.040, 0.026]

Table 1.8: Best available one-dimensional 95% C.L. limits on TGC parameters, obtained from varying one of the couplings while fixing the remaining couplings to the SM values. From LEP2 combined results [26].

TGC measurements

- Considering CP conserving effective Lagrangian + SU(2)xU(1) gauge invariance
  - WWZ/WWγ
    - $$L_{eff}^{WWV} = -i\, g_{WWV} \left[g_1^V (W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V^\nu W^{\mu\nu}) + k_V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_{\rho\nu}^\dagger W_\nu^\mu V^{\rho\nu} \right]$$
      $$where\ \ V = \gamma, Z \ \ g_{WW\gamma} = e,\ g_{WWZ} = e\,cot\theta_W$$
  - ZZγ
    - $$\Gamma_{ZZ\gamma}^{\alpha\beta\mu} = \frac{P^2 - q_1^2}{m_Z^2} (h_1^Z (q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^Z}{m_Z^2} P^\alpha [(P \cdot q_2) g^{\mu\beta} - q_2^\mu P^\beta] + h_3^Z \epsilon^{\mu\alpha\beta\rho} q_{2\rho} + \frac{h_4^Z}{m_Z^2} P^\alpha \epsilon^{\mu\beta\rho\sigma} P_\rho q_{2\sigma})$$
  - Zγγ
    - by replacing $\frac{P^2 - q_1^2}{m_Z^2} \rightarrow \frac{P^2}{m_Z^2}$ and $h_i^Z \rightarrow h_i^\gamma,\ i = 1, \ldots, 4$
  - SM expectation: $g^V_1 = 1$, $k^V_1 = 1$, $\lambda_V = 0$ h^V_3, $h^V_4 = 0$ (tree level SM)
- Measure deviation from SM expectation: Δg_Z, Δk_γ, Δk_Z, λ_γ, λ_Z
  - $\Delta K_Z = \Delta g_Z - \Delta k_\gamma \tan^2(\vartheta_W)$