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Measurement of W and Z Boson production in proton-proton collisions at 7TeV

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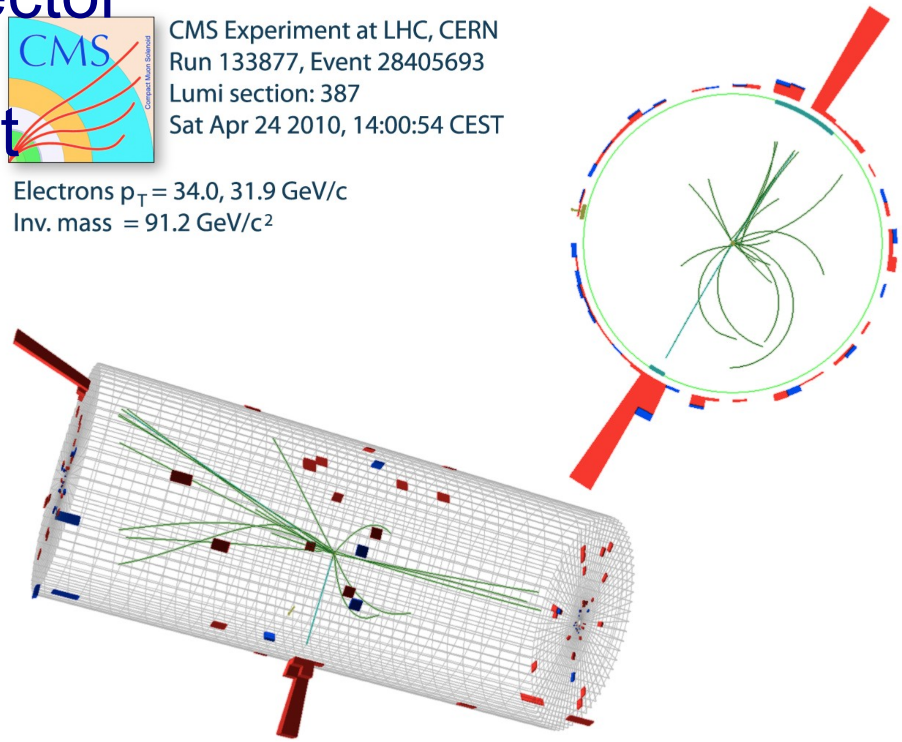
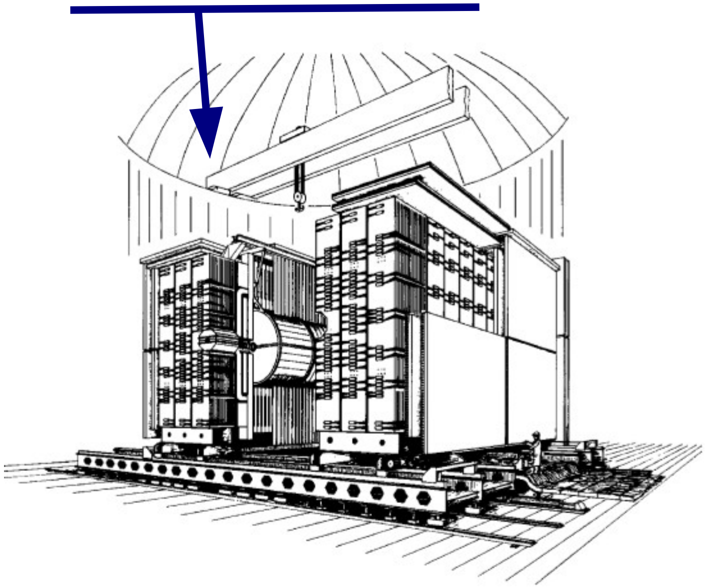
Seminar Overview

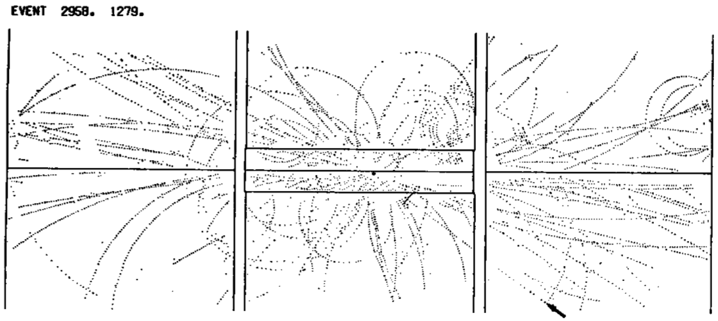
- W and Z Bosons
  - Discovery and Seminal results
  - Importance for Hadron Collider Experiments
- The LHC and the CMS Detector
  - Electrons and Muons in CMS
- Cross-Section Measurement
  - Overview
  - Acceptance
  - Luminosity
  - Event Selection
  - Selection Efficiency
  - Signal Extraction
  - Results
  - Prospects for the future
  - Conclusions



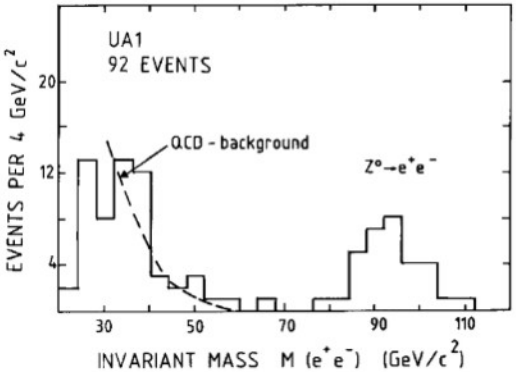
W and Z Bosons: Discovery

- W and Z bosons were discovered through their production in $p\bar{p}$ collisions in the $Sp\bar{p}S$ collider and the UA1 detector at CERN in 1983





W→eν candidate event in UA1 tracker



UA1 Collaboration. Phys. Lett. B 122 (1983) 103.
UA1 Collaboration. Phys. Lett. B 129 (1983) 273
UA1 Collaboration, CERN-EP/88-168, November 1988

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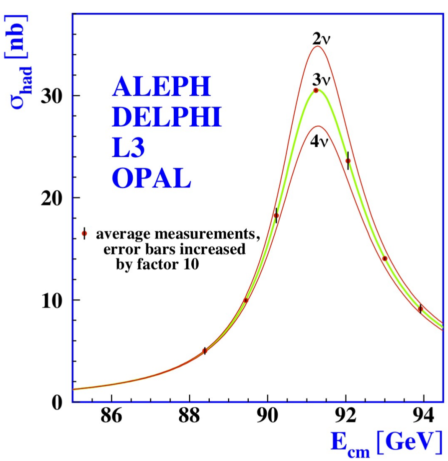
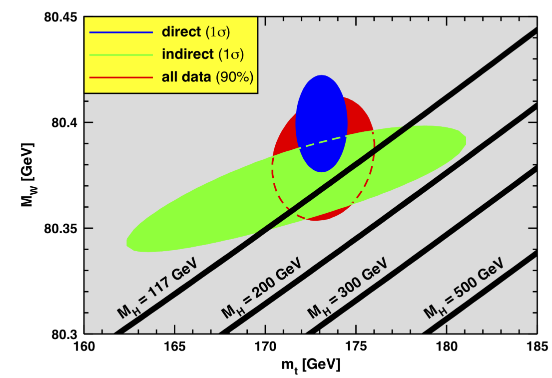
W and Z Bosons: Seminal Results

- After their discovery, detailed studies of their properties have significantly contributed to the establishment of the Standard Model



Number of light neutrino species
e.g. EPJ C28 (2003) 1



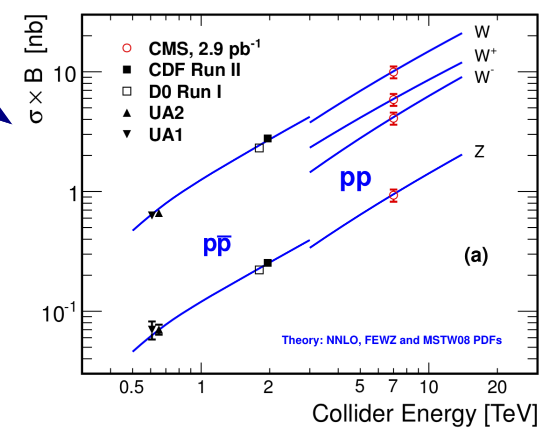
Constraints to the Higgs mass
e.g. PRL103:141801,2009

Electroweak precision tests
e.g. see
http://lepewwg.web.cern.ch/LEPEWWG

W and Z Bosons: Physics from Cross-Section Measurements

- W and Z production cross sections have been measured in pp or $p\bar{p}$ collisions at several centre of mass energies (0.5TeV, 0.63TeV, 1.96TeV, 7TeV)
  - Cross-section measurement provides a test of perturbative QCD and parton distribution functions (PDFs)
  - But also the possibility of a precise but indirect way to measure the W width through the measurement of the ratio of W and Z production

JHEP01(2011)080



$$\frac{\sigma_W \times Br(W \rightarrow l\nu)}{\sigma_Z \times Br(Z \rightarrow ll)} = \frac{\sigma_W}{\sigma_Z} \frac{\Gamma_Z}{\Gamma_{Z \rightarrow ll}} \frac{\Gamma_{W \rightarrow l\nu}}{\Gamma_W}$$

CDF W and Z measurements are sensitive to Γ_W at 2% level

c.f. Combination of all direct measurements gives similar result

J. Phys. G: Nucl. Part. Phys. 34, 2457 (2007), Particle Data Group

W and Z Bosons: Significance for Hadron Collider Experiments

- W and Z bosons are very important in hadron collider experiments:
  - their leptonic decays provide signatures that are easy to identify

$$W \rightarrow e\nu, \quad W \rightarrow \mu\nu, \quad Z \rightarrow ee, \quad Z \rightarrow \mu\mu$$

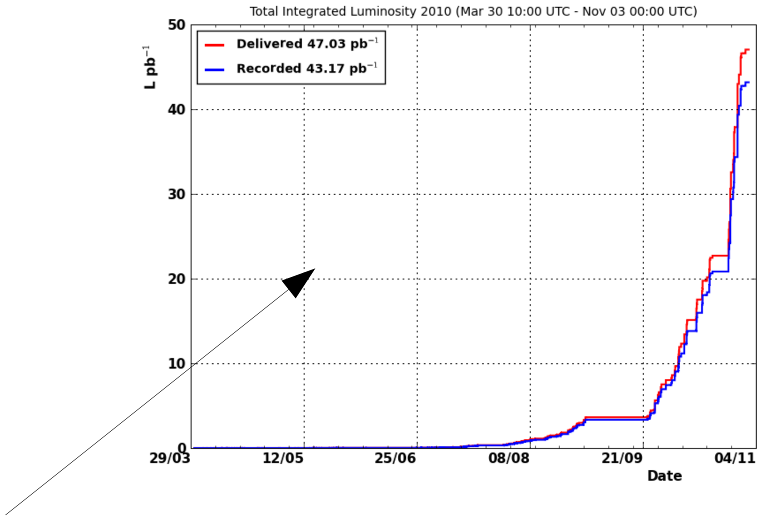
  - W decays is the most abundant source of prompt leptons and real missing transverse energy (MET)
    - » W give around 5000 "good" high-pT electrons or muons per pb^{-1} in CMS
  - Z decays are easy to identify with very high efficiency and low backgrounds: handle to access very pure lepton samples

W and Z Bosons: Significance for Hadron Collider Experiments

- Number of important tasks in hadron collider experiments are based on W and Z understanding
  - Lepton and MET commissioning
  - Energy scale determination (Z pole)
  - ECAL/Muon system Inter-calibration (Z pole)
  - Candle for precise luminosity measurement
  - ...
- Moreover, the understanding of their production and decay is essential in other SM or beyond SM studies
  - W+jets, Z+jets: very important background for top-quark measurements and SUSY searches
  - Top-quark studies ($t \rightarrow Wb$)
  - Higgs ($H \rightarrow WW$, $H \rightarrow ZZ$)
  - ...

The Large Hadron Collider (LHC)

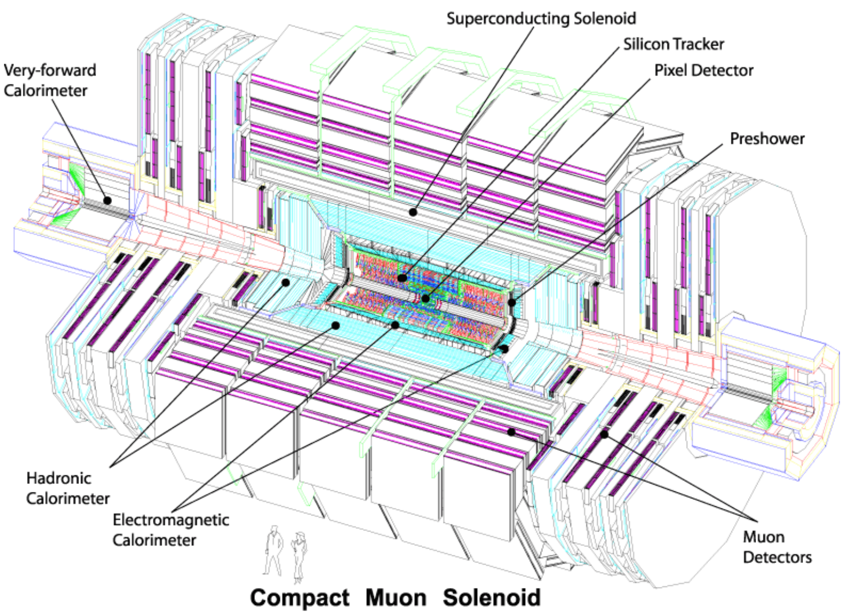
- The measurement presented here uses proton-proton collision data at 7TeV centre-of-mass energy delivered by the Large Hadron Collider (LHC) and recorded by the Compact Muon Solenoid (CMS) detector



Luminosity delivered by the LHC with proton-proton collisions at 7TeV and recorded by CMS in 2010 – this measurement uses the first 3 pb^{-1}

The CMS Detector

- CMS is a general-purpose detector designed to measure particles from LHC collisions



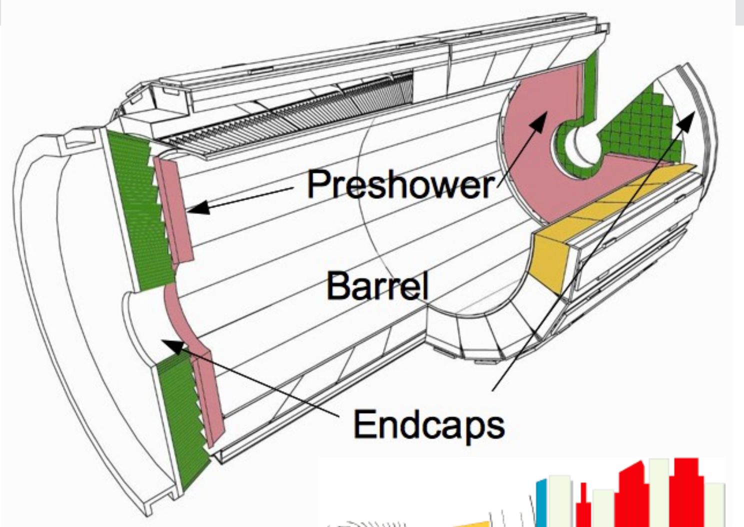
Basic features:

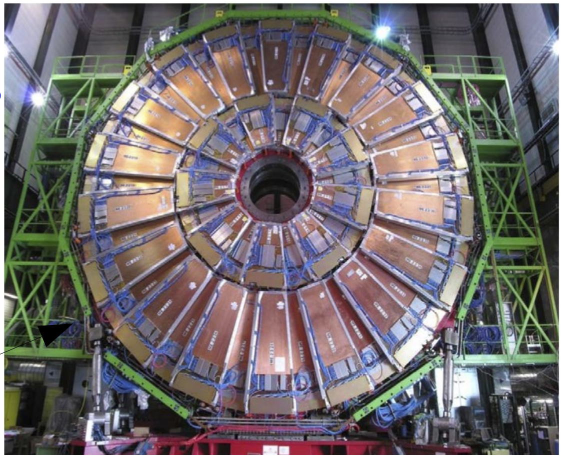
- Large solenoid magnet that encloses inner tracking and calorimetry systems
- All-silicon tracker $|\eta|<2.5$
- Homogeneous crystal electromagnetic calorimeter (ECAL) $|\eta|<3.0$
- Drift chambers for muons $|\eta|<2.4$
- Hermetic calorimetric coverage (up to $|\eta|<6.5$ including the very forward calorimeters)

$$\eta = -\ln \tan(\theta/2)$$

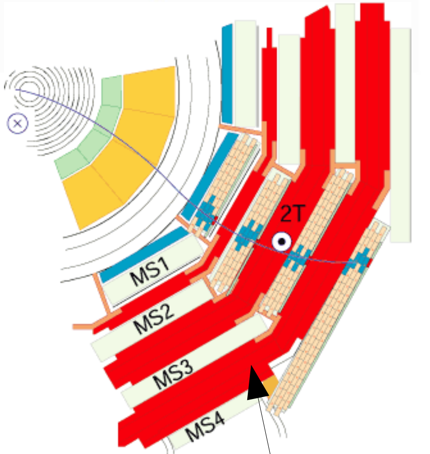
The CMS Detector

- CMS ECAL is a homogeneous lead tungstate crystal calorimeter
  - Designed to fit in the very compact CMS design
  - Good energy resolution (stochastic term ~3%/√E)
  - Coverage: |η|<3.0 but tracking coverage only till |η|<2.5
- Muon system:
  - 3 types of drift chambers stationed in the magnet yoke
  - Coverage: |η|<2.4 but trigger coverage till |η|<2.1





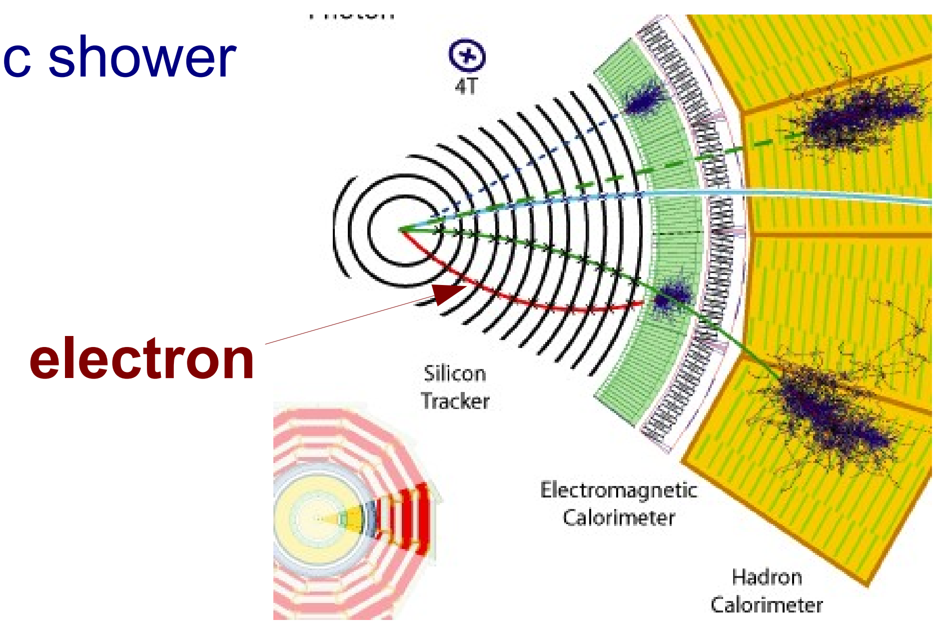
Endcap muon stations



Barrel drift tube stations

- Electrons: not as simple as you may think!

Electron Candidate Object:
track matched to an electromagnetic shower



Sources of Electron Background

Charged hadron - π^0 overlap:
matched in space with a photon shower from π^0

Charged Hadrons showering early in ECAL, Charge exchange
($\pi^+ n \rightarrow \gamma p$)

Electrons from **conversions**
or from **heavy flavor quark decays**
(real electrons)

Electrons in CMS

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Electrons from **conversions** or from **heavy flavor quark decays** (real electrons)

Electron Identification Handles:

Isolation (in tracker, ECAL, HCAL)
Shower shape: width and length
Track-ECAL cluster matching in η-φ space

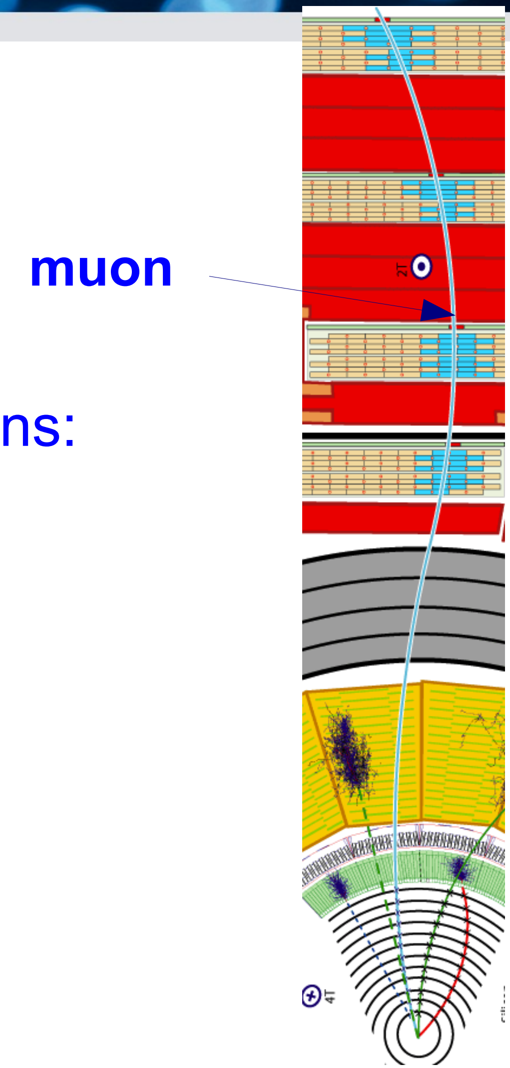
Conversion rejection:
Hits in the innermost tracker layers
Search for a conversion partner track

Muons in CMS

- Muons are easier :)

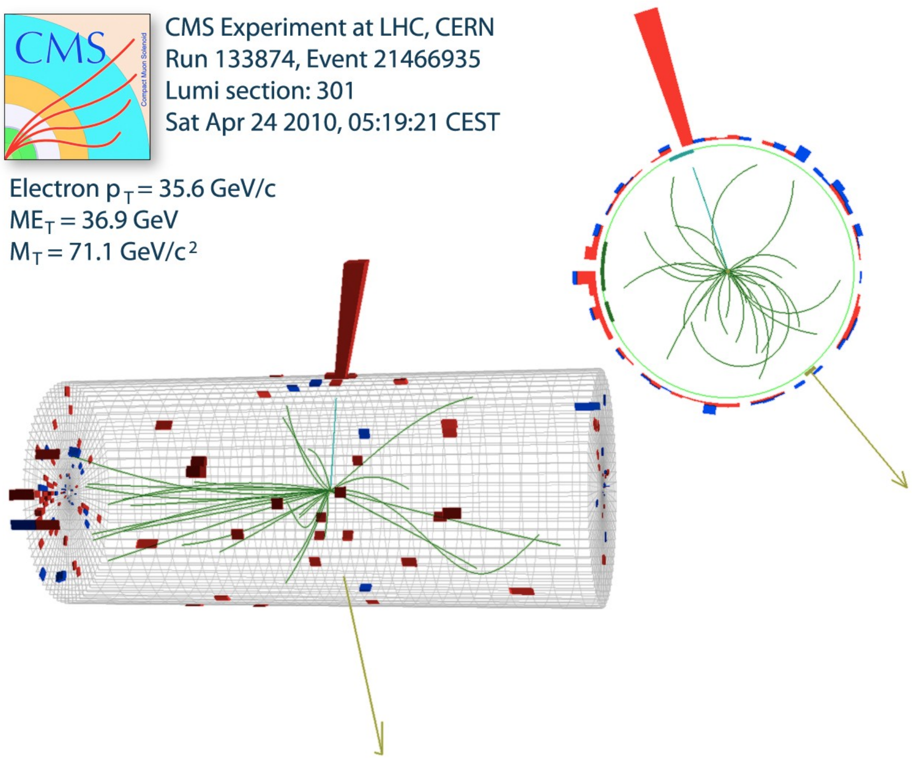
  Muon Candidate Object:
  matched tracks in the inner tracker
  and the muon system
  - There are some backgrounds for high-pT muons:
    - » Semi-leptonic quark decays
    - » Light meson decays in flight
    - » Long hadronic showers (punch-through)
    - » Cosmic muons

  Easy to suppress by demanding low activity in the calorimeters, good track quality and a small impact parameter

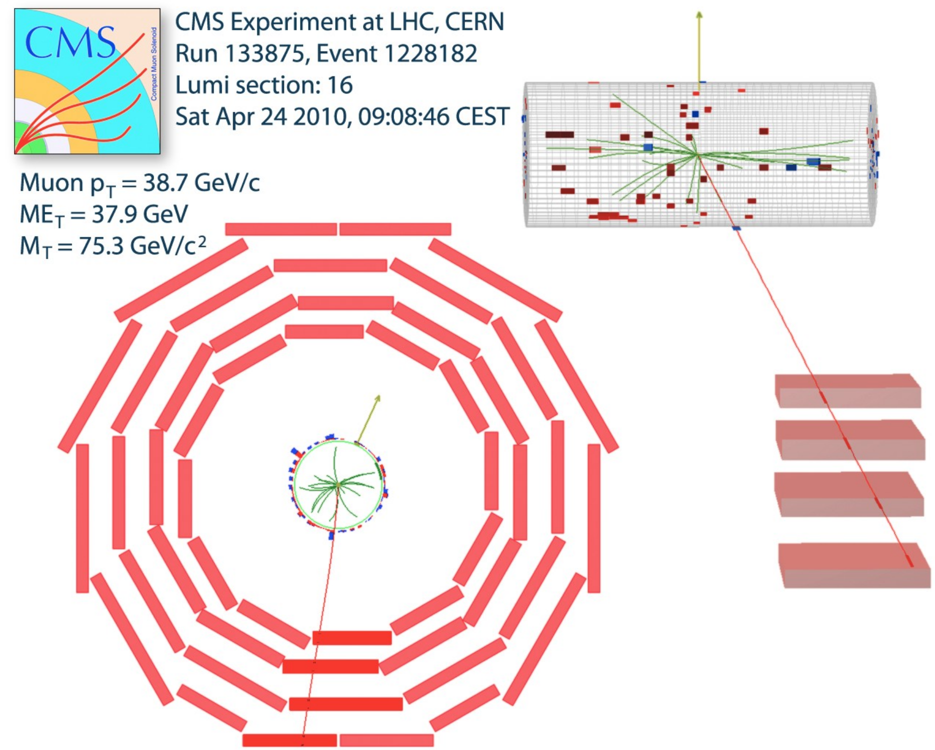


Examples of ElectroWeak Events in CMS

W→eν Candidate



W→μν Candidate



How to measure a cross section

- Recipe to measure cross sections:

$$\sigma = \frac{N_{candidates} - N_{bkg}}{A \epsilon \int L\,dt}$$

Signal extraction/ bkg removal

Integrated luminosity

Acceptance of kinematic cuts

Efficiency of selection criteria

In this seminar I will try to give a comprehensive overview of the measurement in the electron channels and discuss a little bit about the muon measurement too

Dataset in use corresponds to $3pb^{-1}$

Measurement also described in JHEP01(2011)080

Integrated Luminosity

- Luminosity is proportional to the mean number of interactions per LHC bunch crossing
  - This is proportional to the occupancy of the individual towers in the Hadronic Forward calorimeter
  - Absolute normalization of the luminosity for this measurement is given via direct beam parameter measurements: Van der Meer (VdM) Scans

The uncertainty in the beam current measurement in the VdM scans (10%) dominates the luminosity measurement uncertainty (11% in total)

Integrated Luminosity Result for this dataset:

$$\int L\,dt = 2.88 \pm 0.32\ pb^{-1}$$

See S. Van der Meer, ISR-PO/68-31, June 18th, 1968

Acceptance

- Estimated using simulation
- Definition:

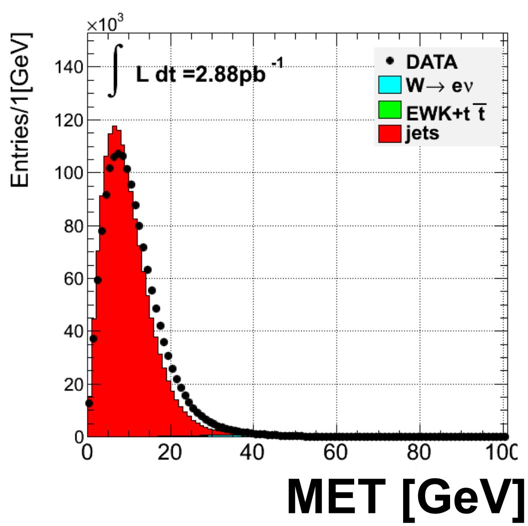
$$A = \frac{simulated\ events\ with\ lepton(s)\ reconstructed\ with\ E_T > 20\ GeV\ in\ detector\ acceptance}{all\ simulated\ events}$$

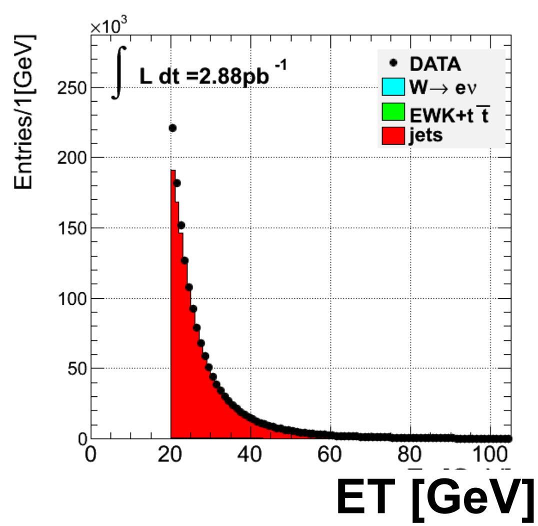
- Baseline generator is POWHEG and PDF choice is CTEQ6.6
- Uncertainties:
  - » PDF choice: < 1.2%, other effects: ~1.5%
  - » Energy scale effects are treated using signal extraction

JHEP 11(2010)074

Event Selection

- W→eν events are characterized by a high-pT electron (>20GeV/c) and high MET (>20GeV)
- But using only these properties are not enough to select a W sample





Strategy:

Apply tight selection criteria in the electron candidate of the event to obtain a purer sample

Single reconstructed electron sample with electron ET>20GeV

Electron Selection

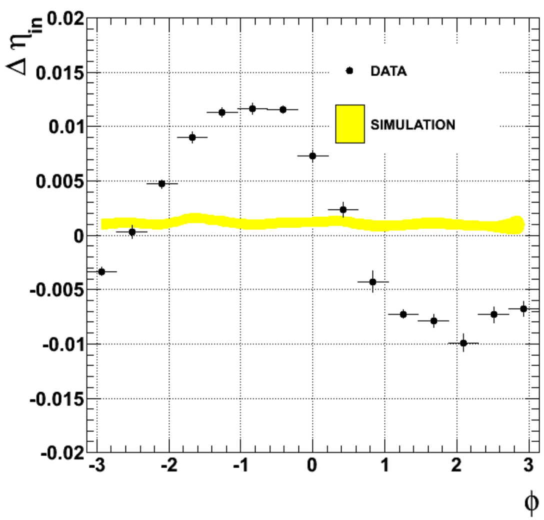
- The electron selection will be based on cuts on a set of variables based on properties that were previously discussed
  - Selection tuning is done with an **Iterative Technique** that has been proved to maximize the bkg rejection for a given signal efficiency and simultaneously has a number of advantages over traditional methods
    - » More details in back-up, full documentation in this link:

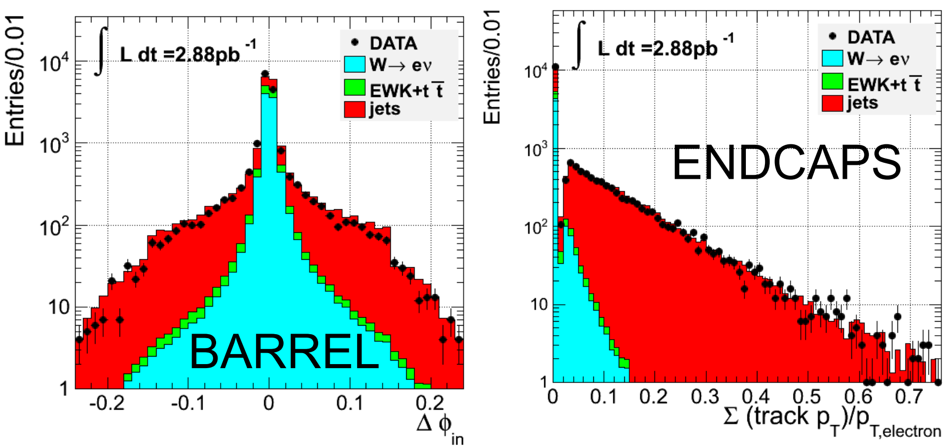
http://cdsweb.cern.ch/record/1327625

- The method has been used to derive electron selections with simulated samples
  - Data-driven selections are also possible

Event Selection: Electron Selection Tuning

- When data became available the simulation was found to describe adequately the detector response to electrons and their backgrounds
  - Apart from a misalignment between the tracker and the ECAL endcaps





Example of distributions of electron identification variables in data and simulation

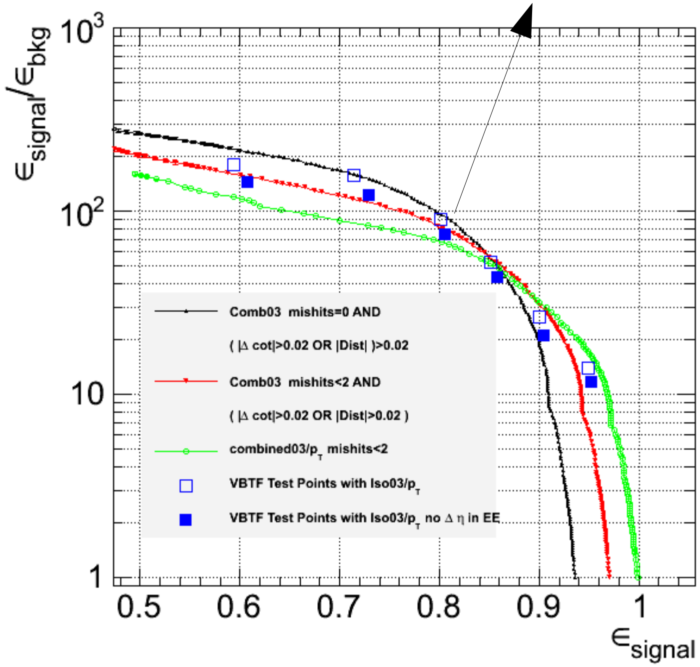
Electron Selections for the Cross-Section Measurement

- Due to the observed agreement the simulation-driven selections were used*

W→eν:
one electron with pT>20 GeV/c passing WP80 selection

Z →ee:
2 electrons with pT>20 GeV/c passing WP80 selection
60 <M_{ee}< 120 GeV

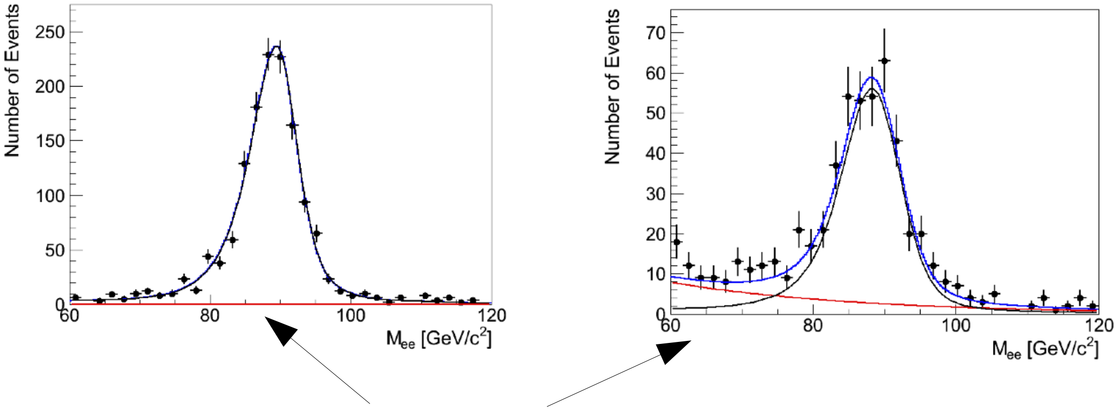
WP80 selection



* although data-driven selections with the same method were also available

Electron Selection Efficiency Measurement

- Electron selection efficiency is measured from data using a pure electron sample from Z decays (Tag-and-Probe)
  - One well identified electron tags the event and a second electron (probe) is used to estimate the efficiency
  - Efficiency is estimated by a template fit of the tag-probe invariant mass spectrum for the tag+(probe passing selection) and the tag+(probe failing selection)



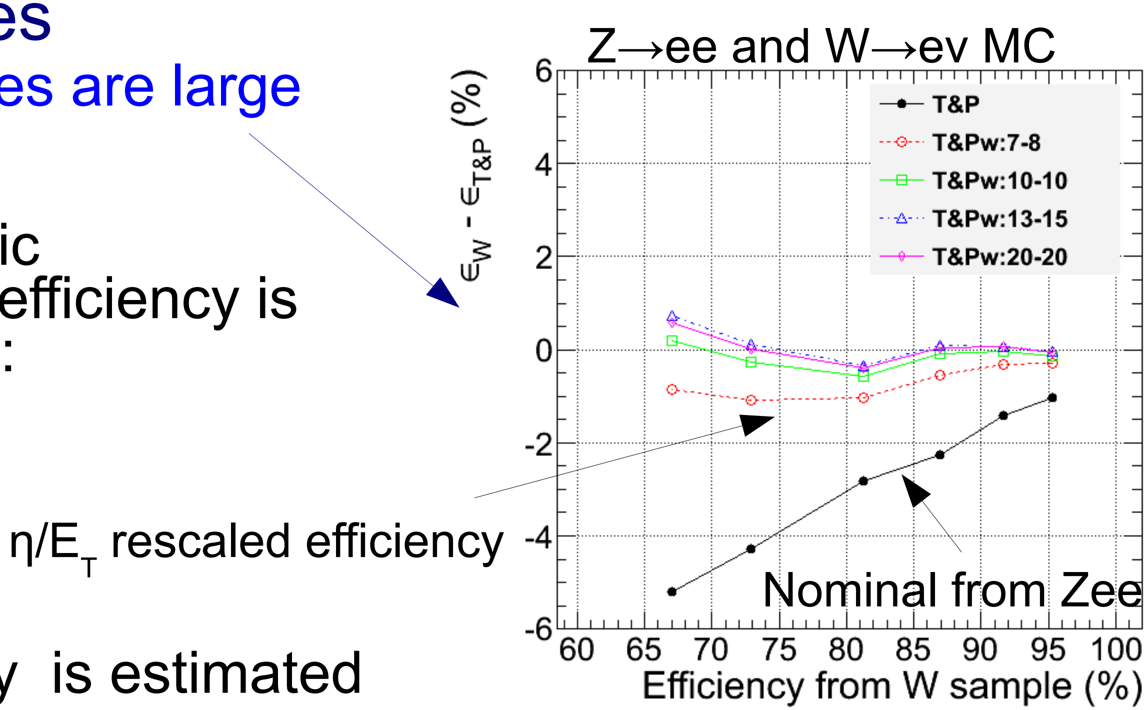
Example Fits:
probes are reconstructed electrons that **pass** or **fail** WP80 selection

Electron Selection Efficiency Measurement

- The tag-and-probe efficiencies are biased due to kinematic differences
  - For Ws the differences are large

To allow for these kinematic differences the measured efficiency is corrected using simulation:

$$\epsilon_{sele} = \frac{\epsilon_{MC}}{\epsilon_{TP,MC}} \epsilon_{TP,DATA}$$



Electron selection efficiency is estimated

$$\epsilon_{W,sele} = 72.0 \pm 2.8 \% \qquad \epsilon_{Z,sele} = 56.2 \pm 3.3 \%$$

(including electron reconstruction + trigger efficiencies)

Signal Extraction

- The electron selection eliminates the bkg in Z studies, however, in the W case the bkg is considerable

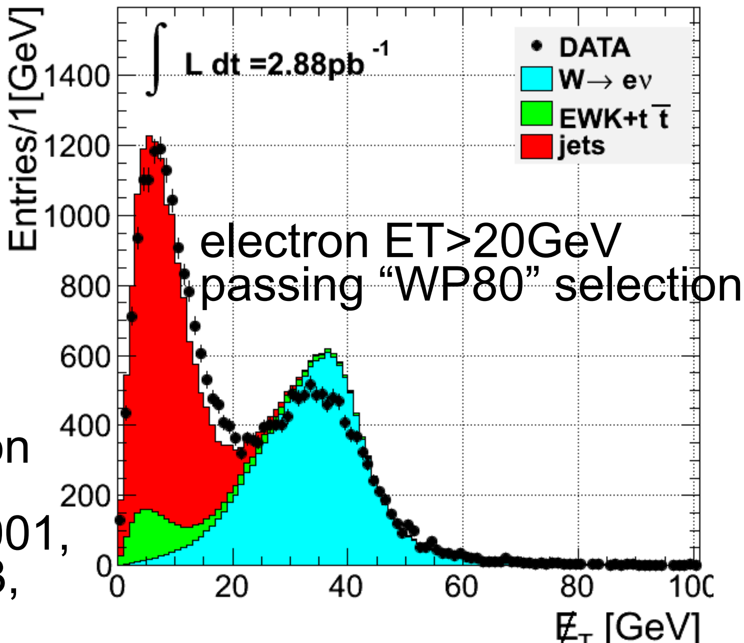
- Different methods to extract the signal

"Template"-based:
Estimate signal and bkg shapes and extract the signal from a fit

e.g. this study

"Extrapolation"-based:
Extrapolate bkg to signal region from a bkg-rich region

e.g. (D0)PRD61(2000)072001, (CDF) PRL94(2005)091803, CMS-PAS-EWK-09-004, this study (as a cross-check)



MET distribution of W candidate events

"Template" Driven Signal Extraction

- What it is all about:
  - Estimate somehow the MET shape of the components of the W candidate sample
  - Perform a fit to the data to extract the number of signal events

$$Nf_{DATA}(MET) = N_{jet} f_{jet}(MET) + N_W f_W(MET)$$

Many options on how to construct templates

Data-driven:
using a selection that rejects signal

Ansatz-based:
assuming a priori a functional form

Data-driven:
using Zee events

Simulation-based:
needs corrections for possible differences in MET resolution between data-MC

"Template" Driven Signal Extraction

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Data-driven: using a selection that rejects signal

Ansatz-based: assuming a priori a functional form

Data-driven: using Zee events

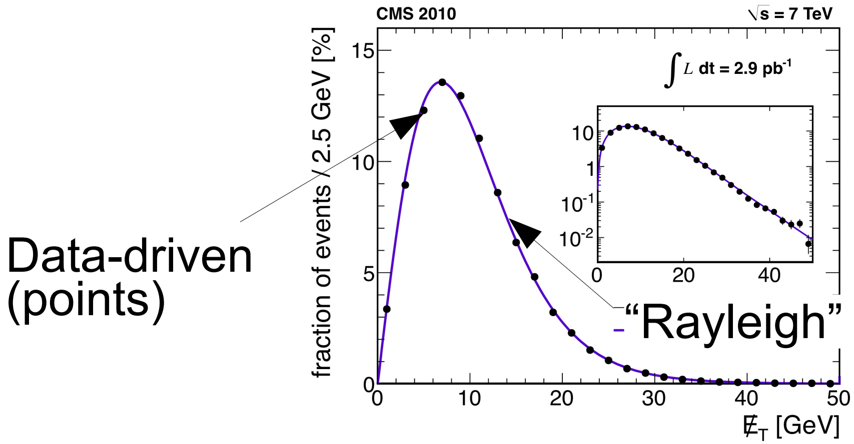
Simulation-based: needs corrections for possible differences in MET resolution between data-MC

Selected templates for the final result
(the other methods used as a cross-check when lumi allows)

Ansatz-based Jet "Template"

- Jet "template":
  physics-motivated Rayleigh function ansatz
  - Fake MET will appear like a Rayleigh distribution
  - Here we have used a slightly modified Rayleigh function to allow for non-gaussian tails

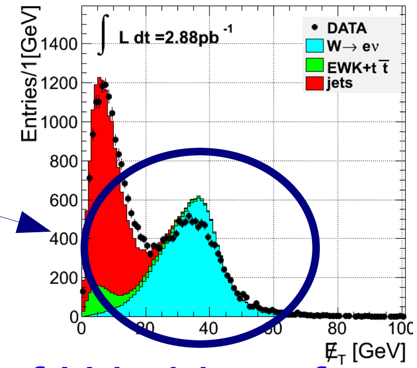
$$P_{jet}(x;\sigma_0,\sigma_1) = x\exp\left(-\frac{x^2}{2(\sigma_0+\sigma_1 x)^2}\right),$$

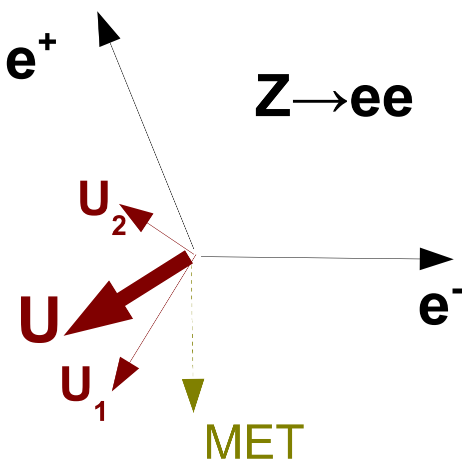


Most important systematic due to the high-MET tail contributes at about 1.3%

Simulation-Driven W "Template"

- W "Template" from simulation is a challenge
  - MET resolution is not described correctly in simulation
  - It is possible to derive a correction from data that is parameterized in terms of boson pT

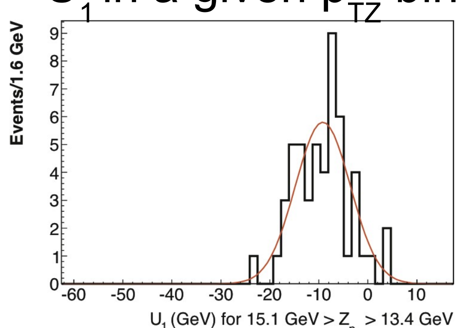


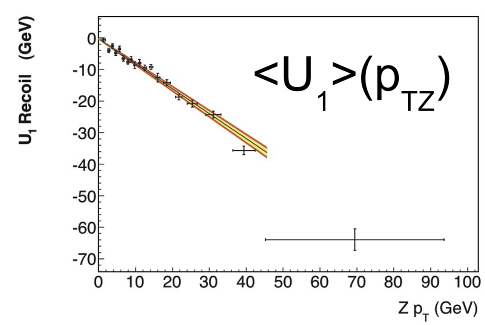


- model from data the components of U in bins of boson pT assuming gaussian behavior
- correct the Wev simulation

Systematic uncertainty from this method: 1.8%

$$\vec{U} = -(\vec{E}_{T,e1} + \vec{E}_{T,e2}) - \vec{MET}$$





Example recoil fits on Z data

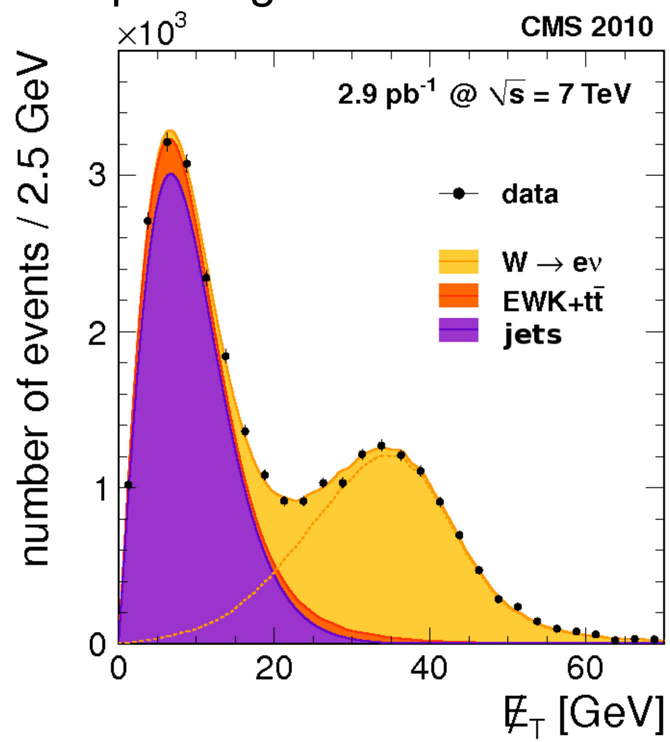
The “Template” Fit

- Excellent agreement of the templates with the data

Number of signal events from the fit:

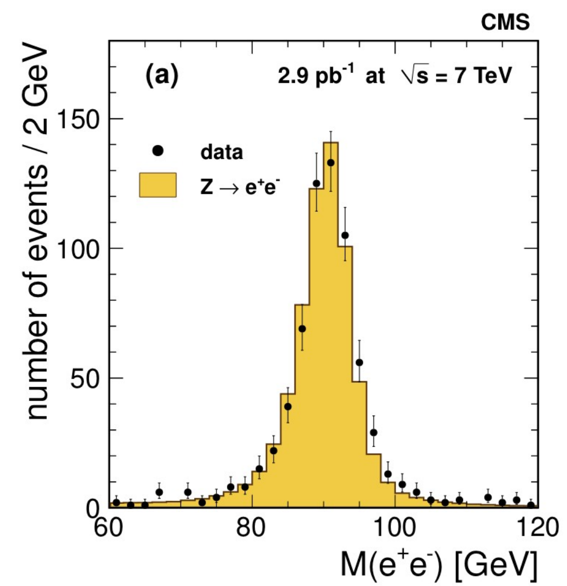
N = 11 895 ± 115
(statistical uncertainty only)

electron ET>20GeV
passing “WP80” selection

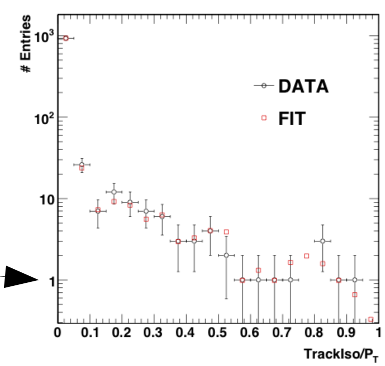


Extracting the Z→ee Signal

- Using a very tight selection in the 2 electrons eliminates the already small backgrounds
  - Signal is estimated by simple counting of the events that are in the invariant mass range 60-120 GeV
  - Correction for the (tiny) backgrounds from data-driven methods, e.g.
    - » Opposite sign/same sign events
    - » Template method
  - Total bkg 2.8±0.4 events
  - Signal events: 677 events

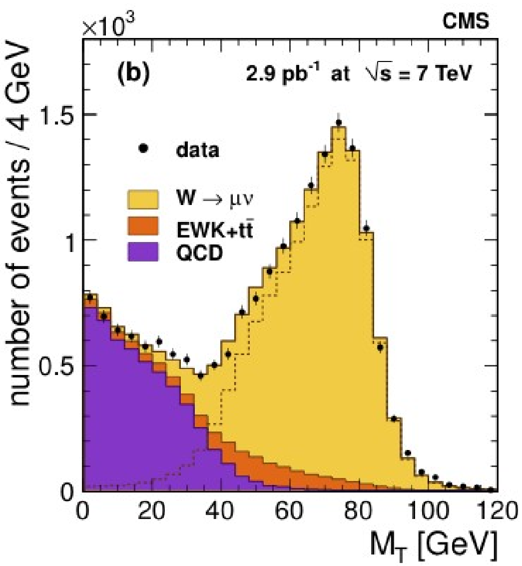


Demonstration of the concept of the template method



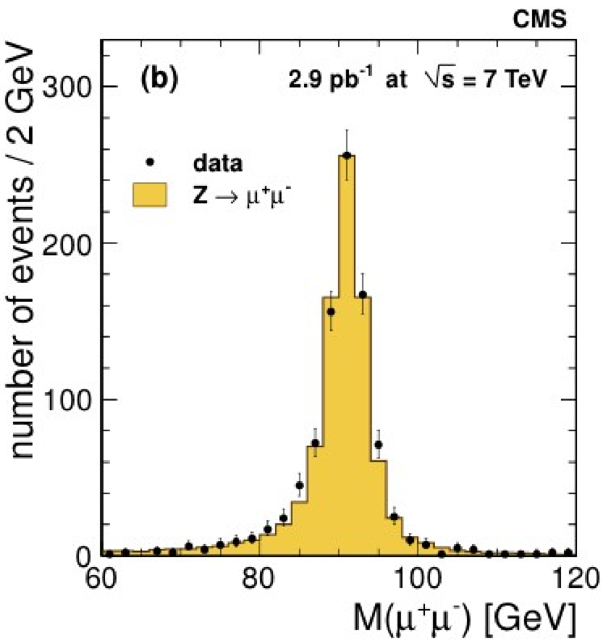
The Muon Channels: $W \to \mu\nu$

- Muon channels: almost same methodology as the electron channels
- $W \to \mu\nu$
  - Lower bkgs allow the use of a **much looser selection** (w.r.t. the electron channel)
    - » signal efficiency (tag-and-probe) 82.8±1.0%
  - Signal extraction with a template fit at the W transverse mass
    - » Data-driven jet template
    - » Simulation-driven W template



The Muon Channels: Z→μμ

- Z→μμ
  - Loose selection improves the statistics (w.r.t Z→ee)
  - Signal and efficiencies are extracted with a simultaneous template fit
  - Very small bkgs (<1%)



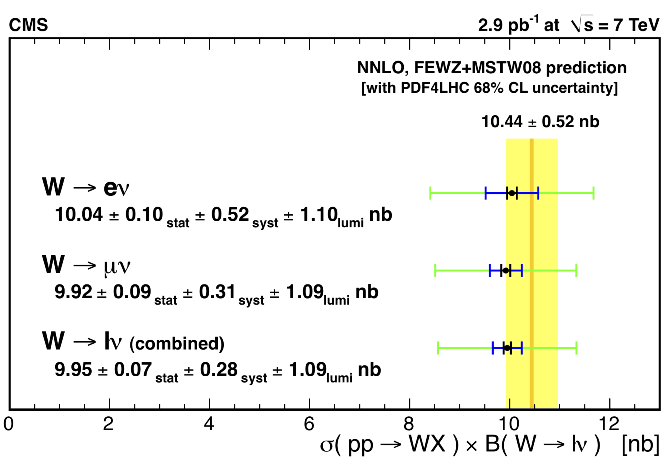
Summary of Systematic Uncertainties

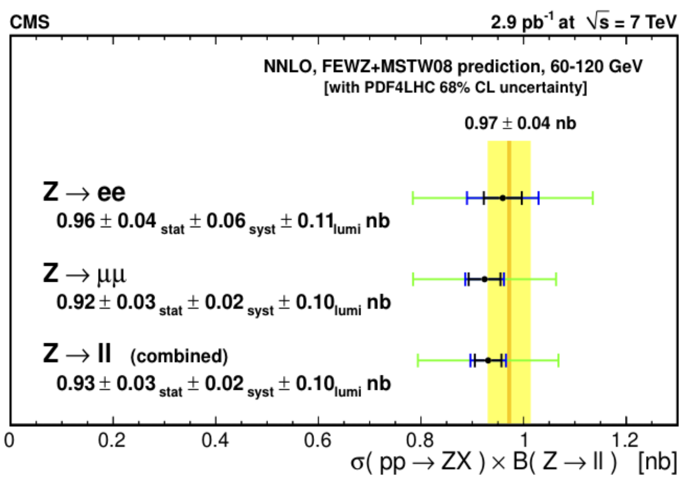
- Total systematic uncertainty (excluding luminosity)
  - W channels:~5-6% (c.f. stat:~1%)
  - Z channels:~2-6% (c.f. stat:~4%)
- The dominant uncertainty is from the efficiency measurement
  - Most of this error is statistical in nature. The same holds for many of the other errors
    - » Expect significant improvement if the measurement is repeated with a larger dataset

Source	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Lepton reconstruction & identification	3.9	1.5	5.9	0.5
Momentum scale & resolution	2.0	0.3	0.6	0.2
$\not{E}_T$ scale & resolution	1.8	0.4	n/a	n/a
Background subtraction/modeling	1.3	2.0	0.1	$0.2 \oplus 1.0$
PDF uncertainty for acceptance	0.8	1.1	1.1	1.2
Other theoretical uncertainties	1.3	1.4	1.3	1.6
Total	5.1	3.1	6.2	2.3

Results

- Excellent agreement with theoretical expectations





- Combined electron+muon result for the ratio

$$\frac{\sigma_W Br(W \rightarrow l\nu)}{\sigma_Z Br(Z \rightarrow l l)} = 10.64 \pm 0.40$$

Sensitive to Γ_W at about 4% level!

(c.f. **2%** all direct measurements combined)

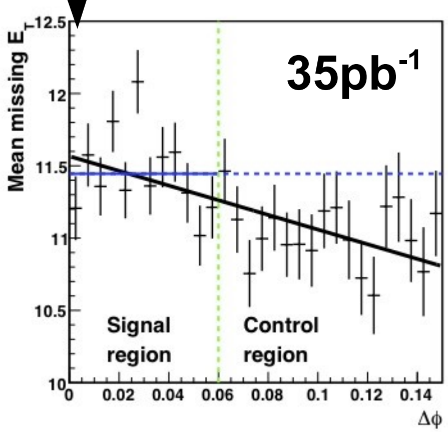
Prospects

- It is expected that the systematic uncertainty will be reduced significantly with larger samples
  - Efficiency uncertainty is of statistical nature
    - » Limited number of Z events affects both systematic and statistical uncertainty in efficiency
  - Larger samples
    - » will enable the test of different methods for signal extraction, e.g.
      - Data-driven jet template for electrons
      - Extrapolation methods
    - » give more insight into the systematics of the methods that were previously described

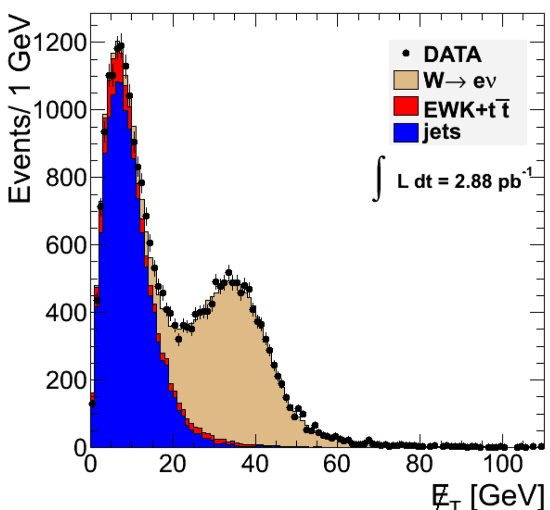
A measurement of the cross sections with the full 2010 proton-proton dataset (~35pb-1) is ongoing

With More Lumi: Data-driven Jet-"template" for W→eν

- Data-driven jet "templates" have been used as a cross-check of the 3pb-1 result-fully studied with $35pb^{-1}$
  - Defined by a selection that rejects signal: invert track-ECAL cluster matching cuts (Δη and Δφ)
  - Assumption: the inverted cuts are uncorrelated with MET
    - » And this is not quite true: possible to derive a correction with more data.
    - » This is the major source of systematic uncertainty of this method



With $3pb^{-1}$ the result using this jet template is in agreement with the Rayleigh "template" within 1.2%

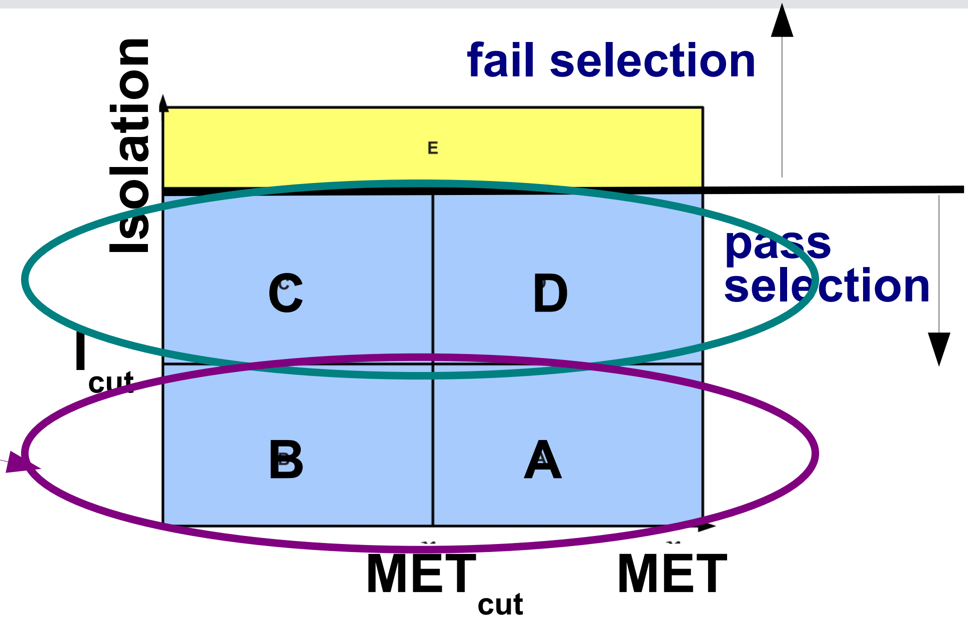


With $35pb^{-1}$ the uncertainty with this method is 0.6% (c.f. current value 1.3%)

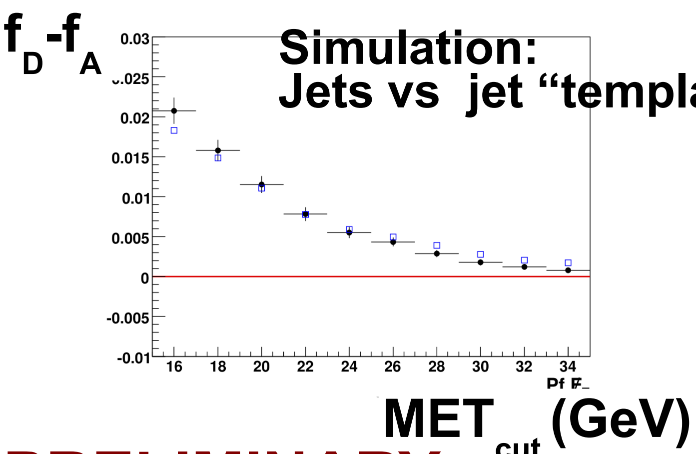
PRELIMINARY

With More Lumi: Extrapolation-based Signal Extraction

- Based on 2 uncorrelated variables w.r.t. the jets



Extrapolate the jet shape Assuming (Q=number of jet events):
$f_D \equiv Q_D/Q_C = f_A \equiv Q_A/Q_B$



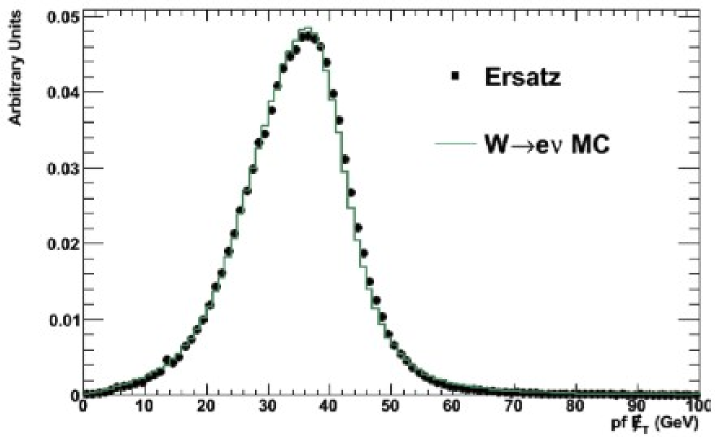
PRELIMINARY

This assumption is approximate: possible to derive a correction from data

This method with ~35pb can give a combined uncertainty in the signal extraction of **less than 1.5%**

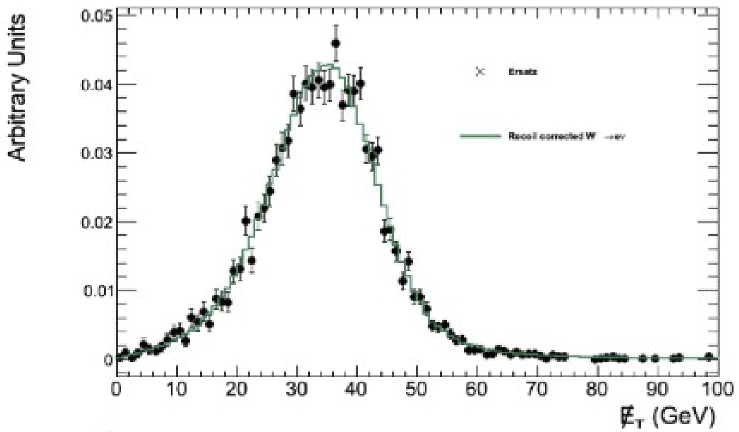
With More Lumi: Data-Driven Signal Template

- A W template can be derived using Z events and removing the one lepton to emulate the neutrino
  - But not that simple: corrections are needed
    - » Different W/Z kinematics
    - » Different neutrino acceptance, calorimeter readout, ...



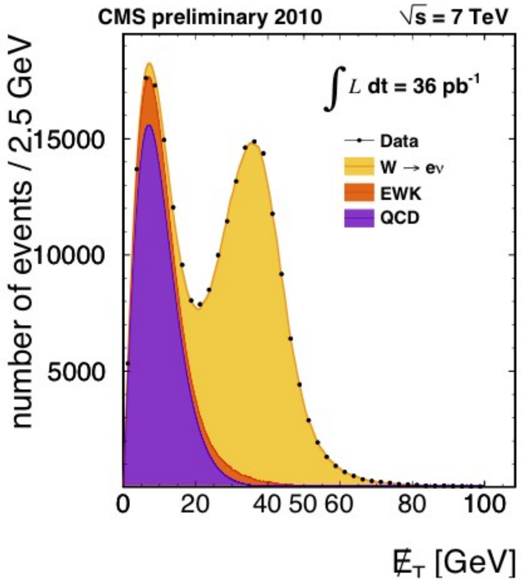
Demonstration in Simulation

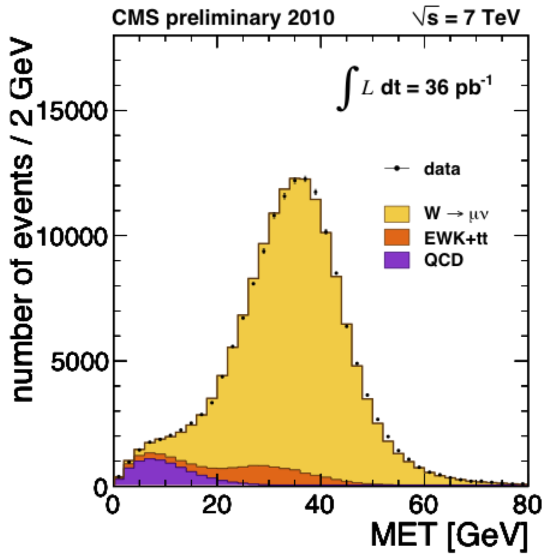
PRELIMINARY

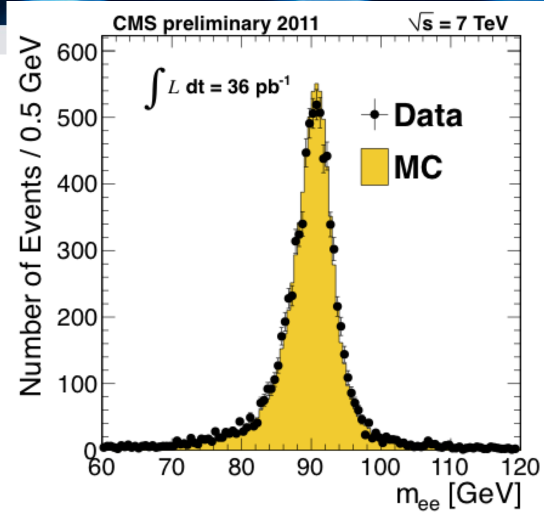


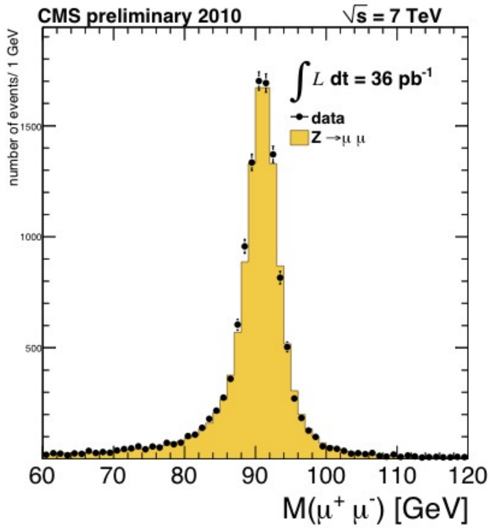
Example with $30pb^{-1}$ – comparison with the simulation driven template

Flavor of the 35pb^{-1} Results (PRELIMINARY)









Target for precision:
- † for the ratio: 2%
- † for the individual cross sections: error dominated by the theoretical uncertainties

PRELIMINARY

Conclusions

- W and Z production studies
  have shown the excellent status in CMS of
  - ECAL, inner tracker and muon system performance
  - Electron/Muon trigger, reconstruction and identification
  - MET performance
  - Simulation accuracy and detector understanding

  have lead to the establishment/validation of techniques useful to other studies
  - Lepton selections/efficiencies have been used in many other CMS measurements and searches for new physics

  In short they prepare the way towards discoveries!

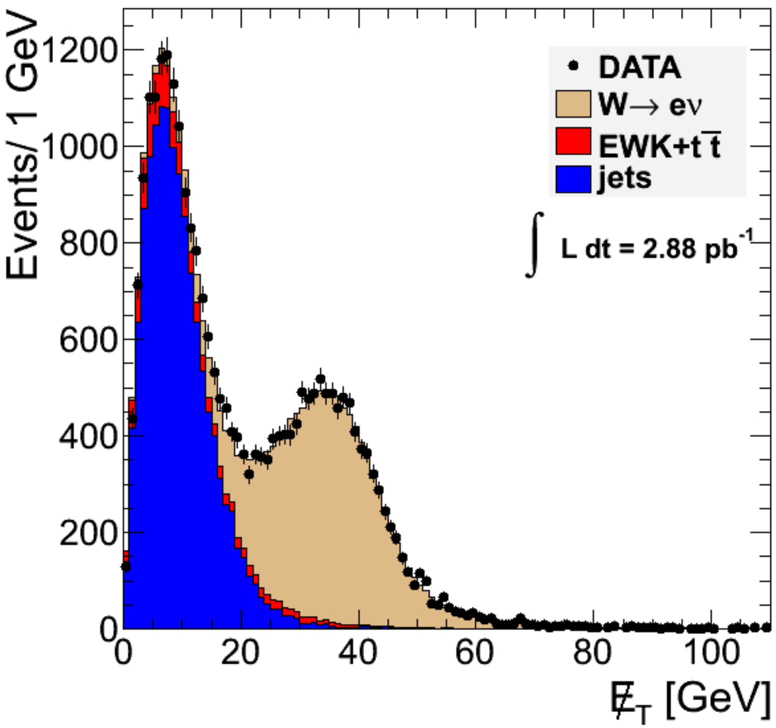
Acknowledgements

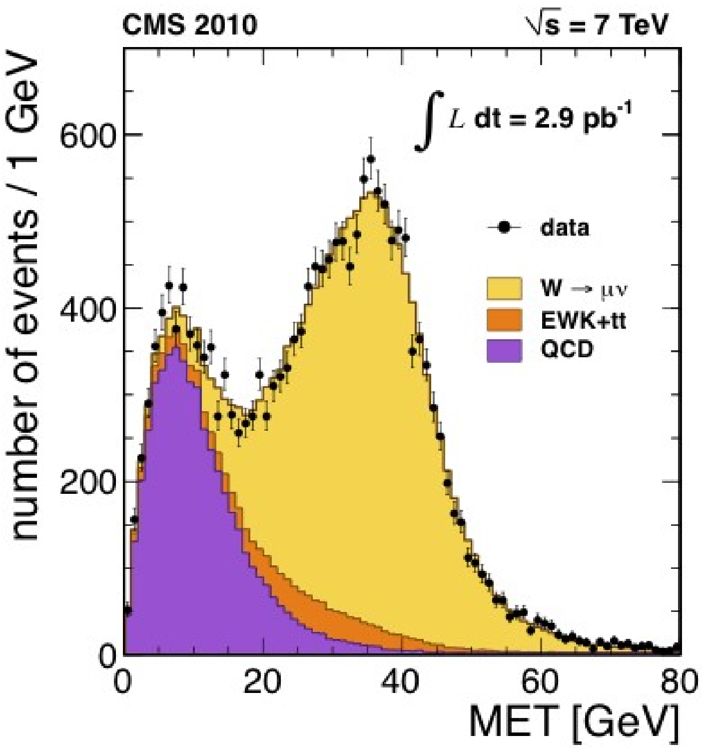
- Many thanks to all the members of the CMS "Vector Boson Task Force" and especially to Georgios Daskalakis, Chris Seez, Jim Virdee, David Futyan, David Wardrope,....

and to you for your attention!!!

Back-up slides

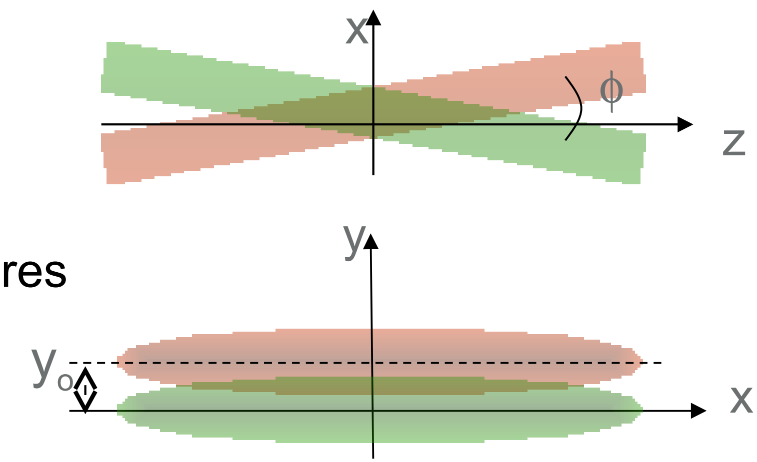
W channels: Muons vs Electrons in MET



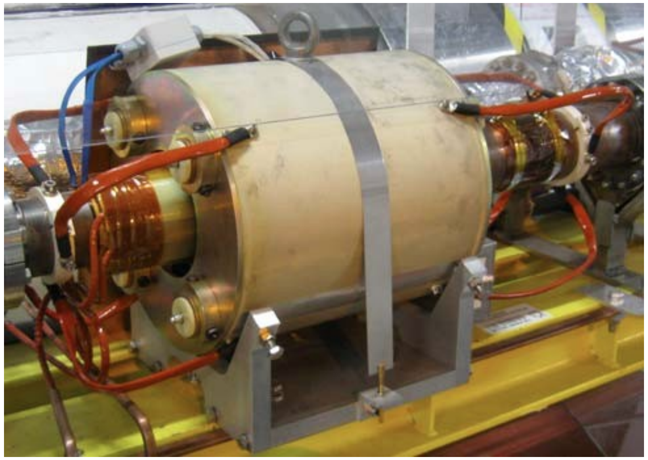


Luminosity absolute normalization

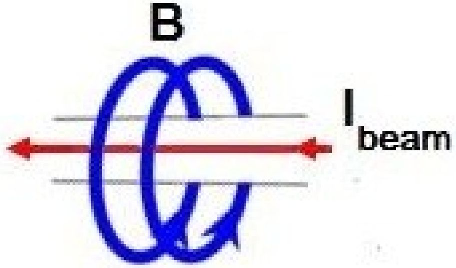
VdM scans: based on a trick invented by Van der Meer:
Record relative interaction rate as a function of transverse beam separation



We have to assume shapes for the beam proton density shape and measure the beam current intensity
This is done with a current transformer which measures the field that the beam produces



See S. Van der Meer, ISR-PO/68-31, June 18th, 1968

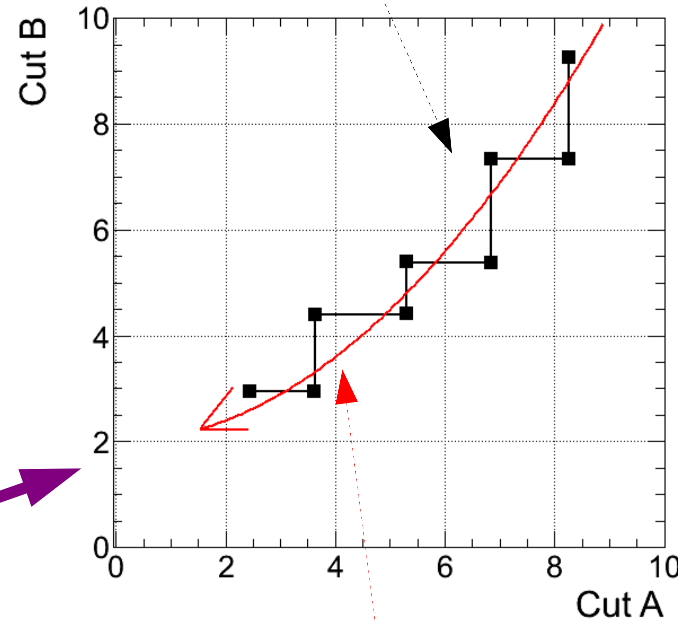


Electron Selection

- The electron selection will be based on cuts on a set of variables based on properties that were previously discussed
  - Selection tuning is done with an **Iterative Technique** that has been proved to maximize the bkg rejection for a given signal efficiency starting from a signal and a bkg sample

1. define a target in bkg rejection that is slightly higher than the current one
2. find which **single** cut can achieve this bkg rejection target with the highest signal efficiency
3. change this single cut only to obtain a new selection
4. iterate

path followed by the iterative technique



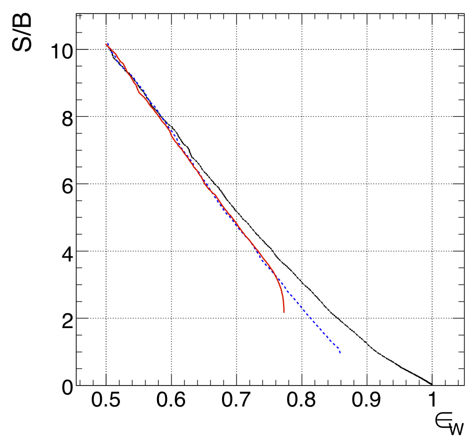
optimal curve that the algorithm tries to approximate

iterative algorithm concept illustration for a 2 cut case

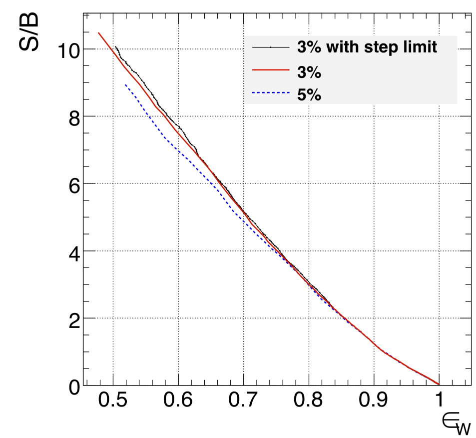
http://cdsweb.cern.ch/record/1327625

Validation of the Iterative Technique (I)

- The algorithm internal parameters have to be chosen appropriately in order to achieve the optimal performance



Initial Conditions



Step convergence

Validation of the Iterative Technique (II)

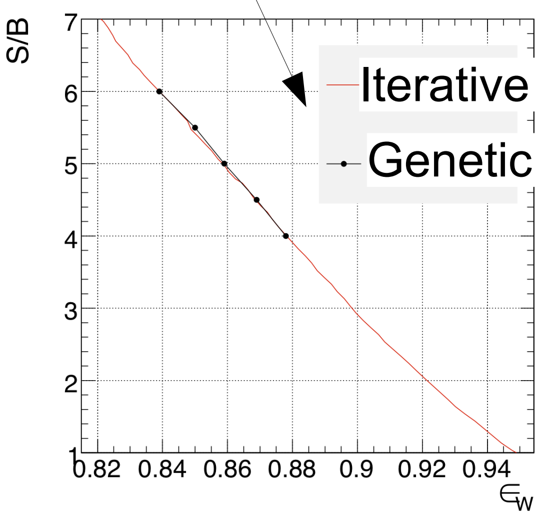
- Validation of the algorithm using simulation
  - Signal from W→ev; Bkg from jets+EWK bkgs to W→ev

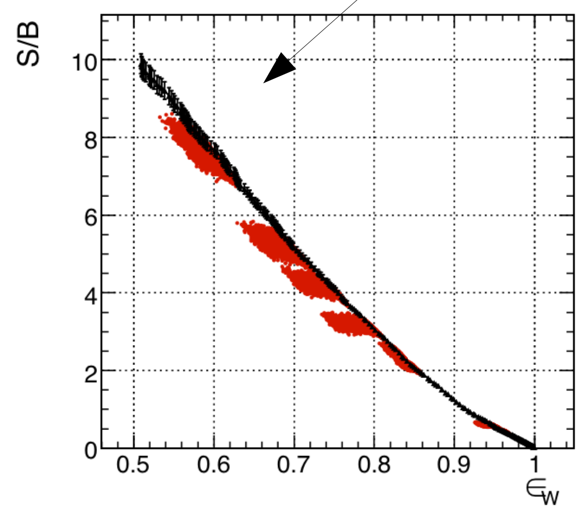
using electrons with ET>30GeV

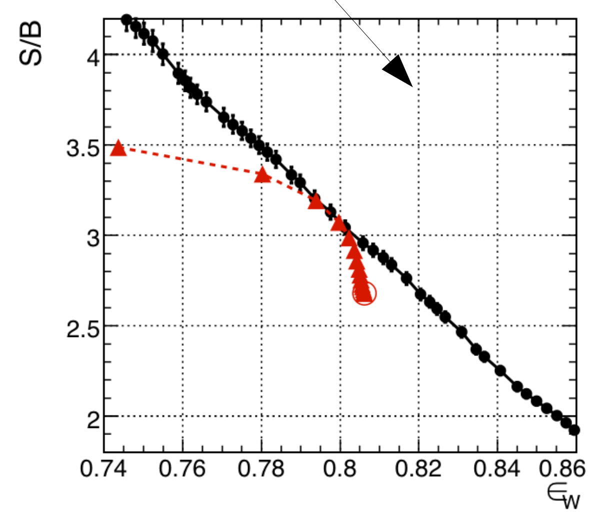
Moving the cut on a single variable (here ECAL isolation in EB)

Comparison with the Genetic Algorithm Tuning

Randomnly generated points, seeded by working points that the iterative produces

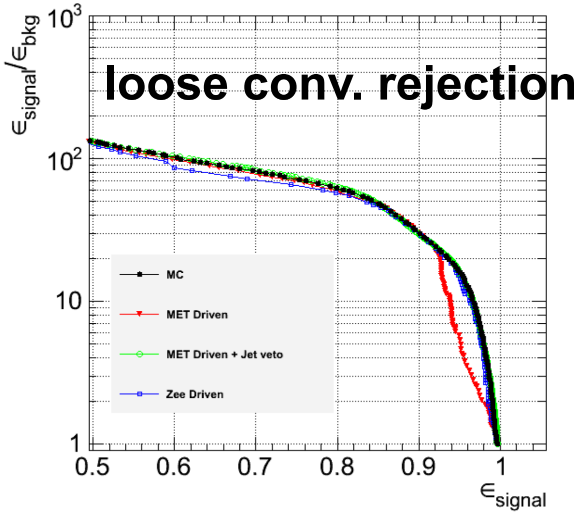






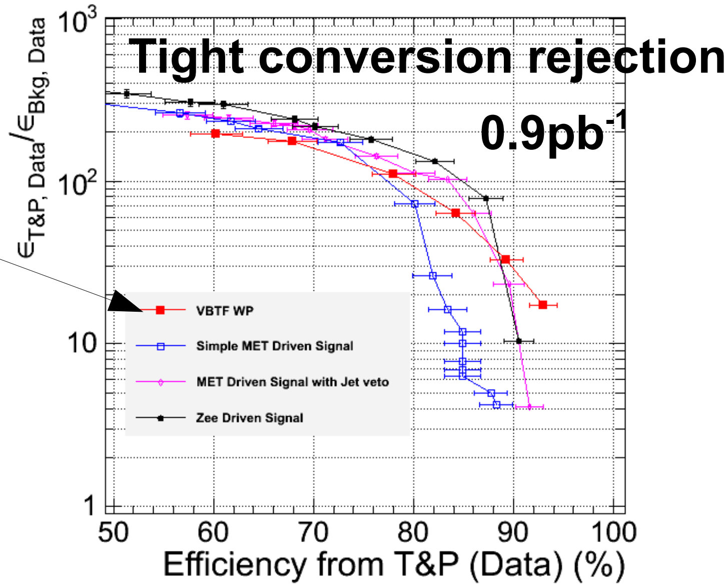
Demonstration of Data-Driven Selection Tuning

- Data-driven definitions of signal/bkg samples are also possible from a single electron (ET>20GeV) sample:
  - Bkg: MET < 20GeV
  - Signal: 3 different ways
    - » MET > 30GeV
    - » MET > 30GeV plus jet veto
    - » electrons from Zee



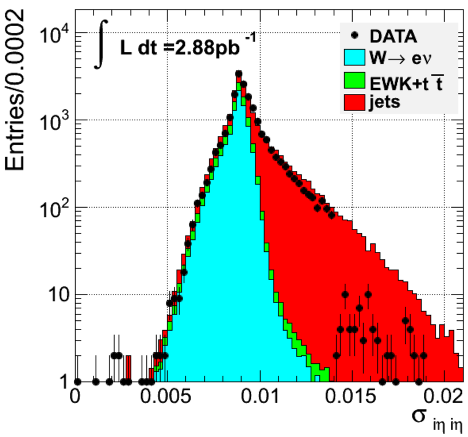
Example of MC test of the data-driven sample definitions

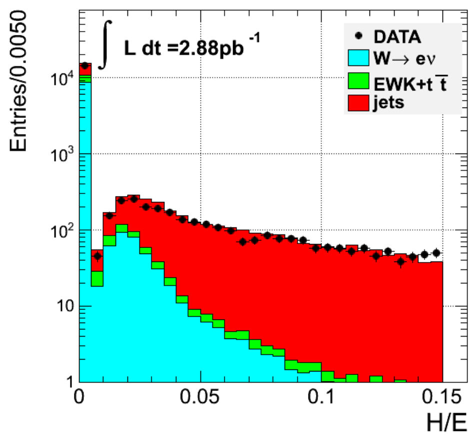
Tuning example with real data!

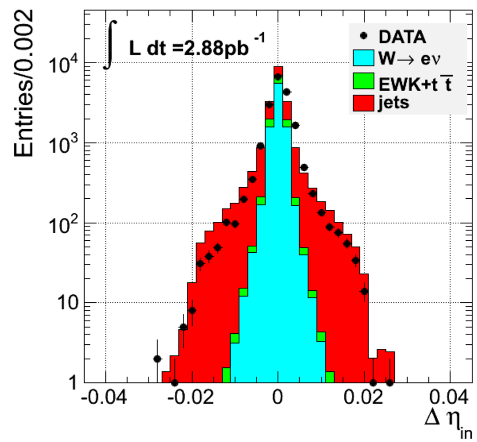


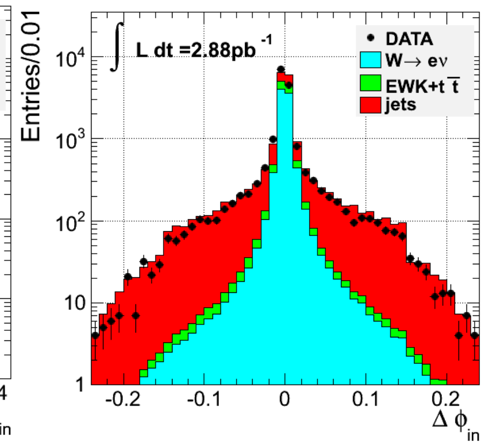
Imperial College London

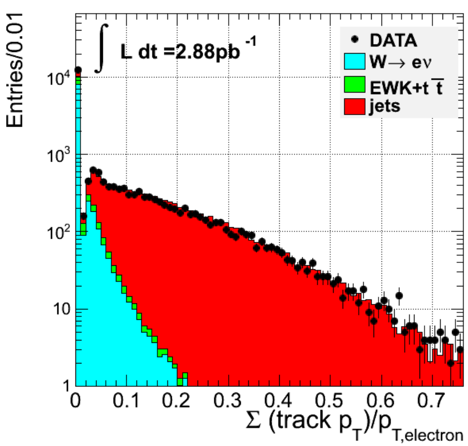
Electron ID Variables after* WP80: ECAL Barrel

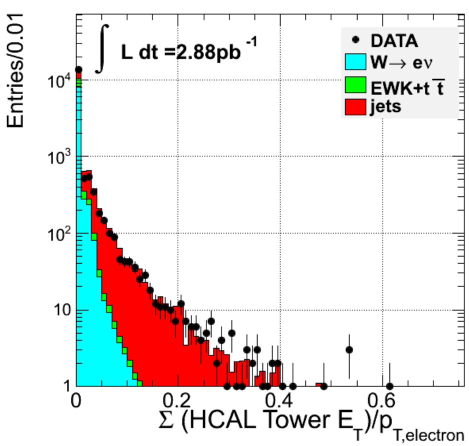


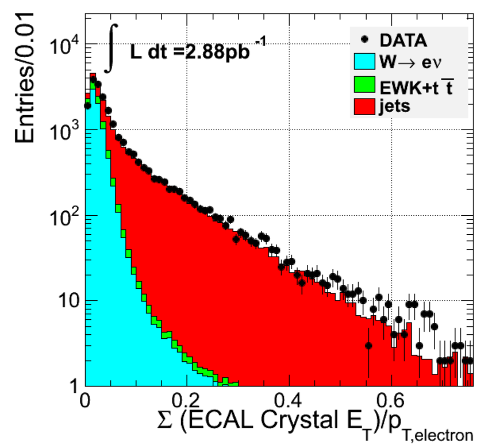




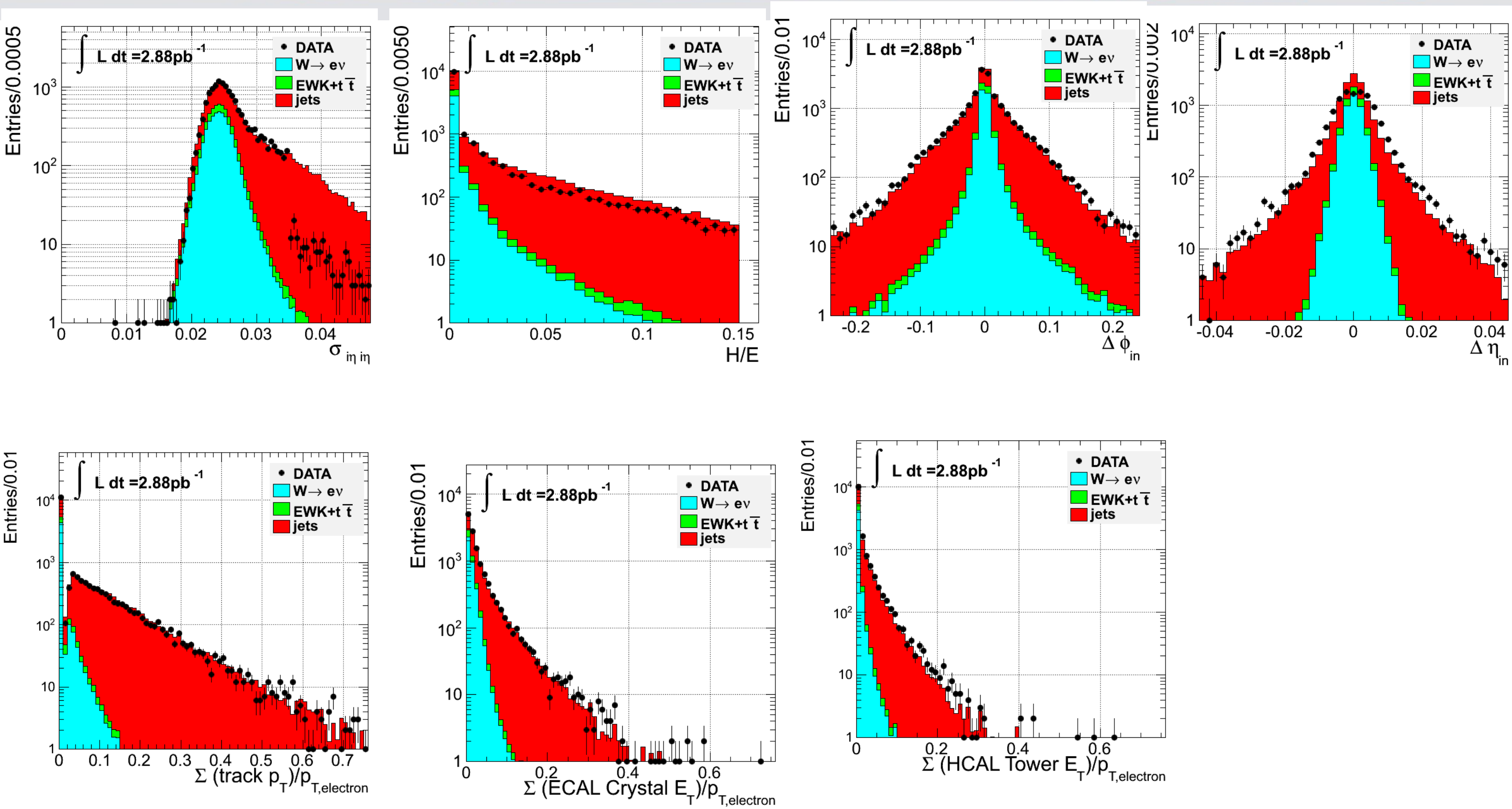








Electron ID Variables after* WP80: ECAL Barrel



Theoretical uncertainties for the W and Z Acceptance

Source	$W^+ \rightarrow e\nu$	$W^- \rightarrow e\nu$	$W^+ \rightarrow \mu\nu$	$W^- \rightarrow \mu\nu$
QCD-HO and ISR	-1.30%±0.09	-0.78%±0.10	-1.39%±0.09	-1.17%±0.14
QCD-α_s scaling	0.23%±0.22	0.37%±0.32	0.23%±0.22	0.37%±0.32
FSR	0.08%±0.17	0.07%±0.19	0.11%±0.12	0.01%±0.17
EWK	0.07%±0.13	0.21%±0.19	-0.02%±0.12	0.26%±0.17
Total	1.33%	0.90%	1.42%	1.26%

Source	$Z \rightarrow e^+e^-$	$Z \rightarrow \mu^+\mu^-$
QCD-HO and ISR	±0.6%	±0.6%
QCD-α_s scaling	±1.1%	±1.1%
FSR	-0.03%±0.21	0.38%±0.24
EWK	-0.51%±0.22	-1.02%±0.24
Total	1.34%	1.58%

Differences between W+ and W- due to the difference pseudorapidity distributions of the decay leptons: different x distributions between quark and antiquarks/valence-sea quarks difference