November 20th, 2014

ICTP-NCP School on LHC Physics

LHC results: Standard Model (W, Z, γ, jets)

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Standard Model Physics

INTRODUCTION WITH A BIT OF HISTORY

Introduction

- At LHC **W, Z, γ** physics, **jet** physics, ***top quark*** physics is called **Standard Model**
- "Standard" sounds like "boring", but it is not: historically new phenomena or new states were found by studying standard objects

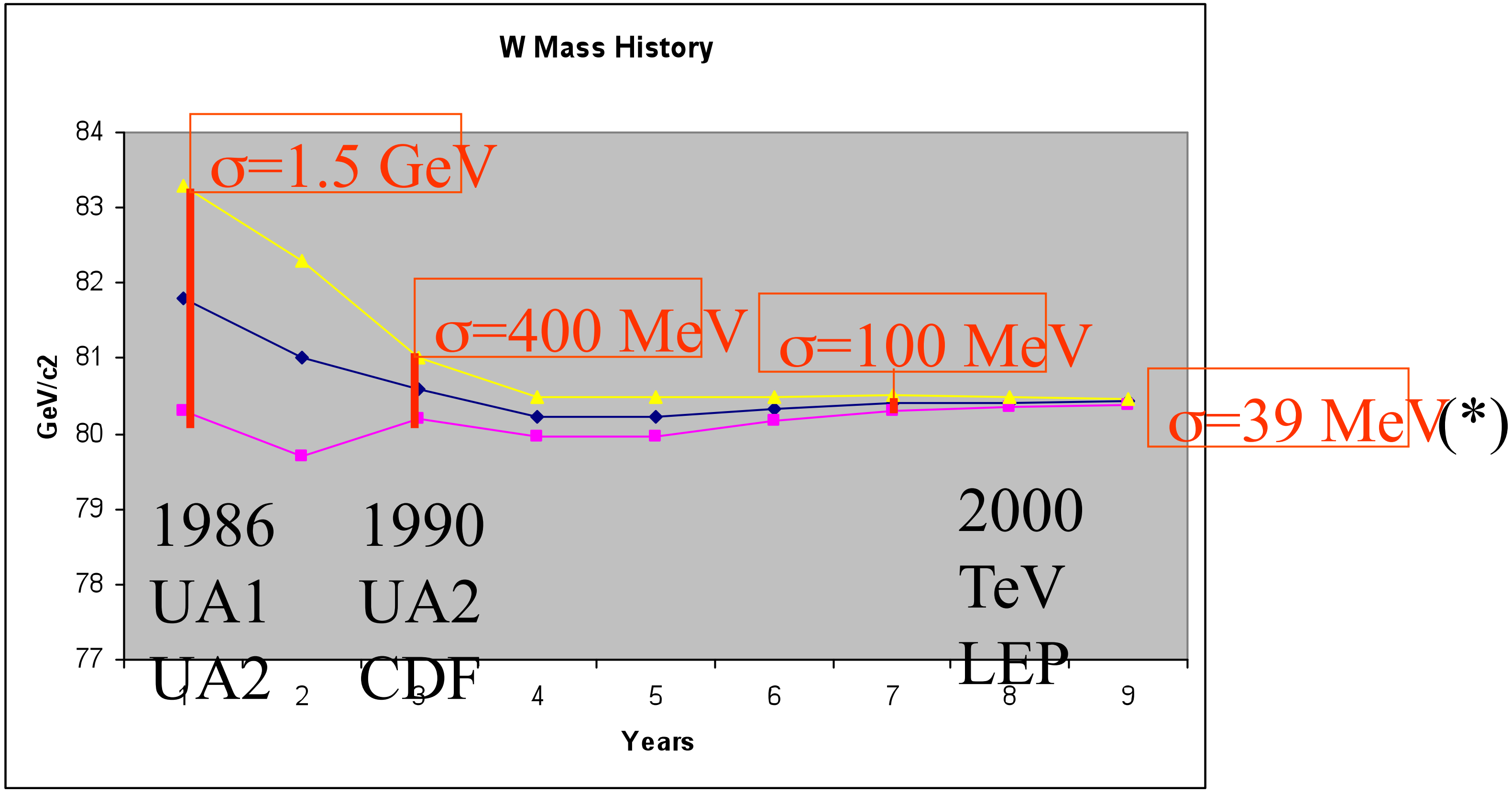
Jupiter was supposed to be a standard planet !

Standard Model and **new phenomena**

Two important examples:

- Electroweak theory has shown that **new heavy states can affect precision measurements** (non-decoupling property, Veltman, 1977)
- **Measurements of basic properties** (e.g. Parton Distribution Functions, di-boson cross sections, etc.) **is a pre-requisite for discoveries**

W mass precision from 1986 to 2004

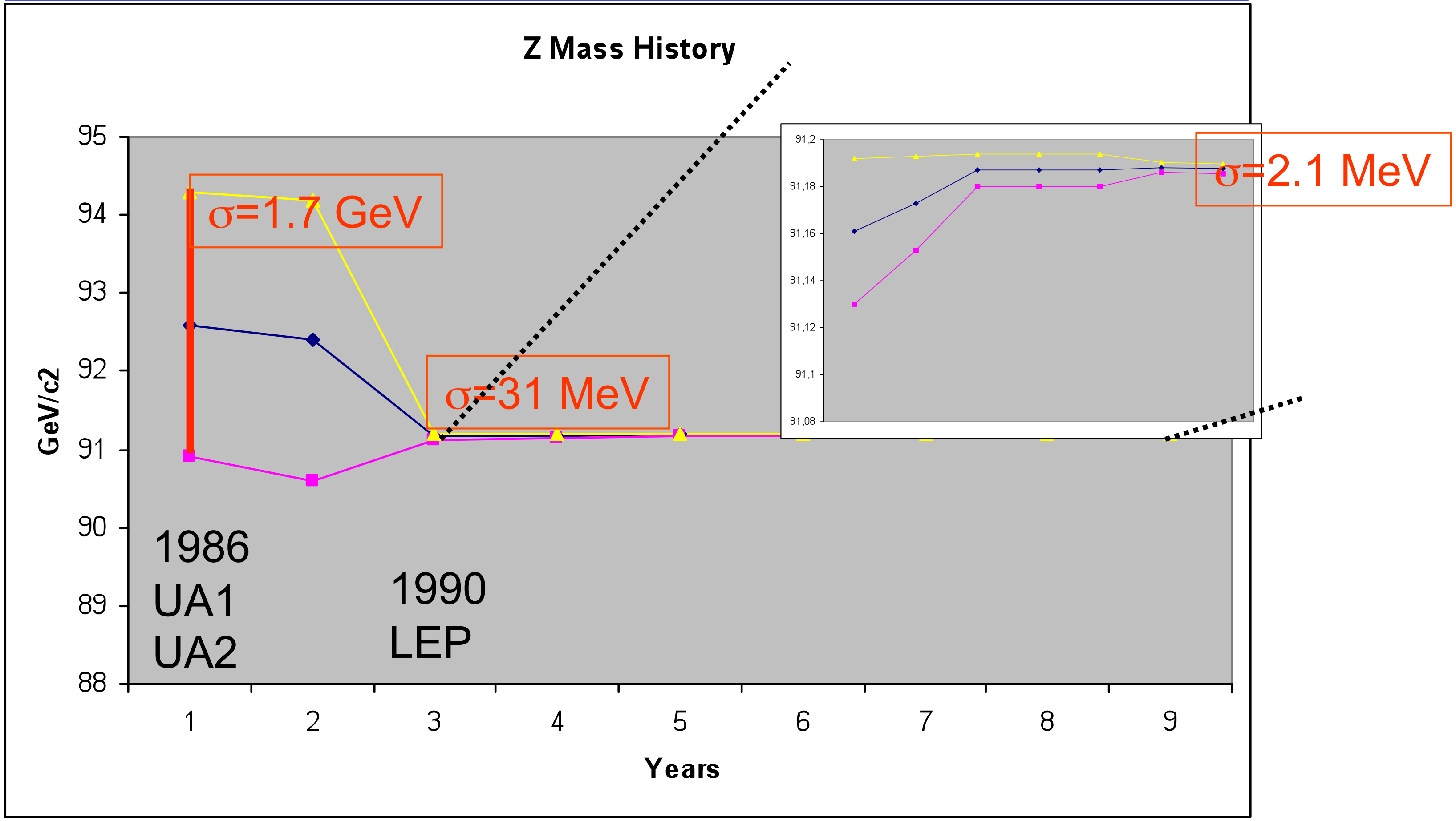


Only Published Results

(*) Preliminary w.a. 2004 : σ=34 MeV, weight of LEP 2/3, Tevatron 1/3

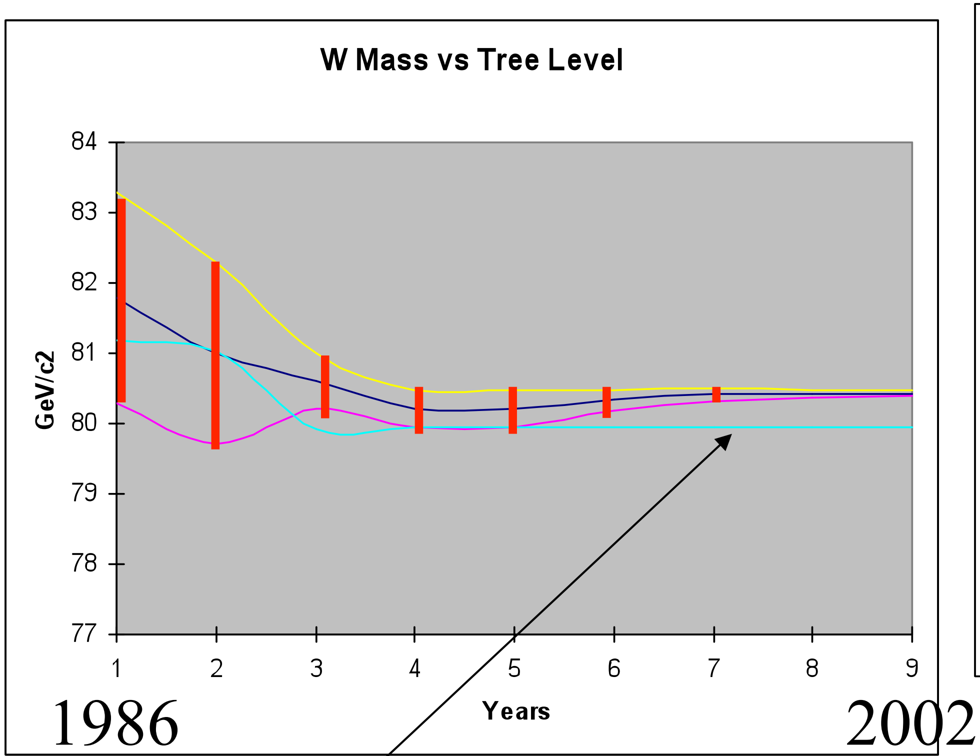
Z mass precision from 1986 to the end of LEP

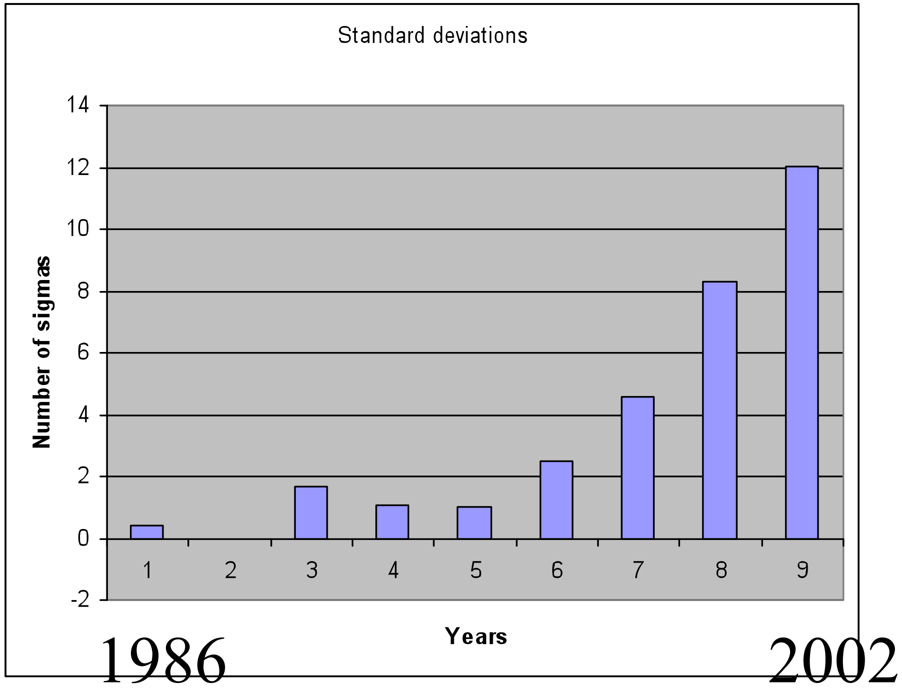
The Z mass: one of the most precise physical constants !



Only Published Results

Strong Evidence of electroweak radiative corrections from Z and W mass





Strong Evidence of pure E.W. Higher Order Corrections

E.W. Tree level SM relation

(with running α QED)

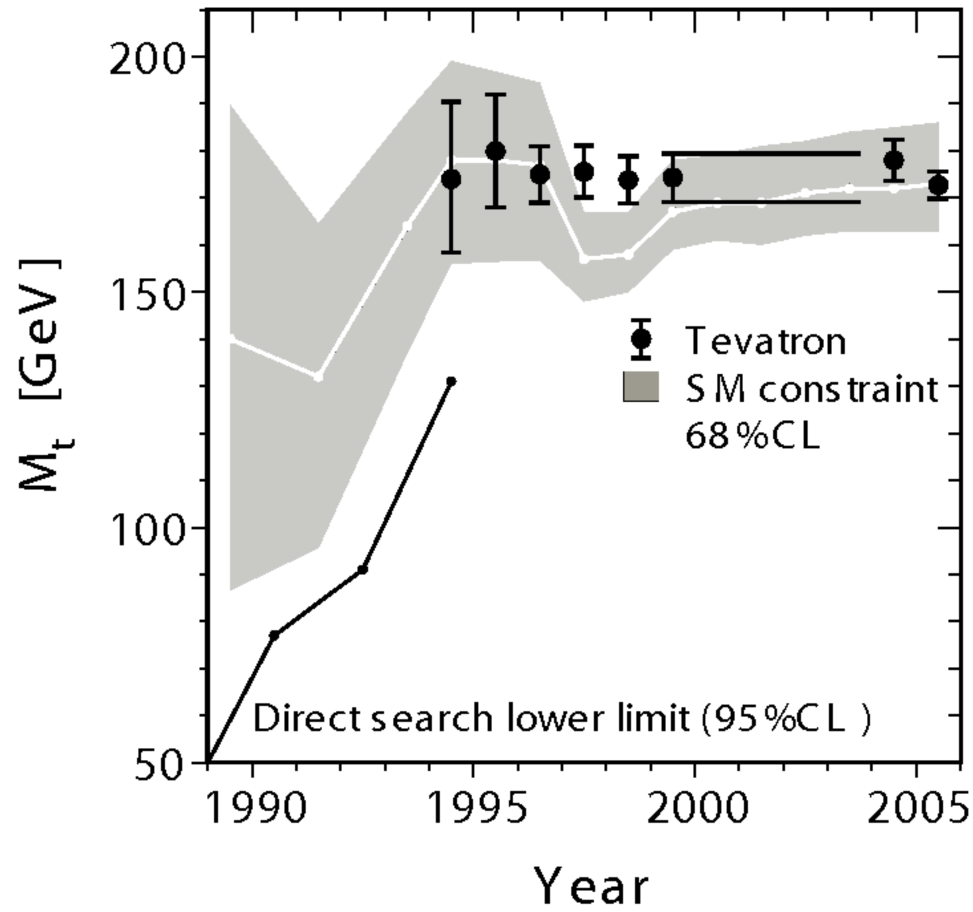
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha(M_Z)}{\sqrt{2}}\frac{1}{G_F}$$

$$\alpha(\sqrt{s}=\mathrm{M}_Z)=\frac{1}{128.936\pm0.046}$$

Top quark discovery and electroweak radiative corrections

The **precision measurements** of the W and Z mass, together with other electroweak observables (e.g. initial and final state asymmetries) **test the Standard Model at the level of radiative corrections**

The **top quark mass** from the **direct** measurement **matches** the **indirect** determination from radiative corrections !



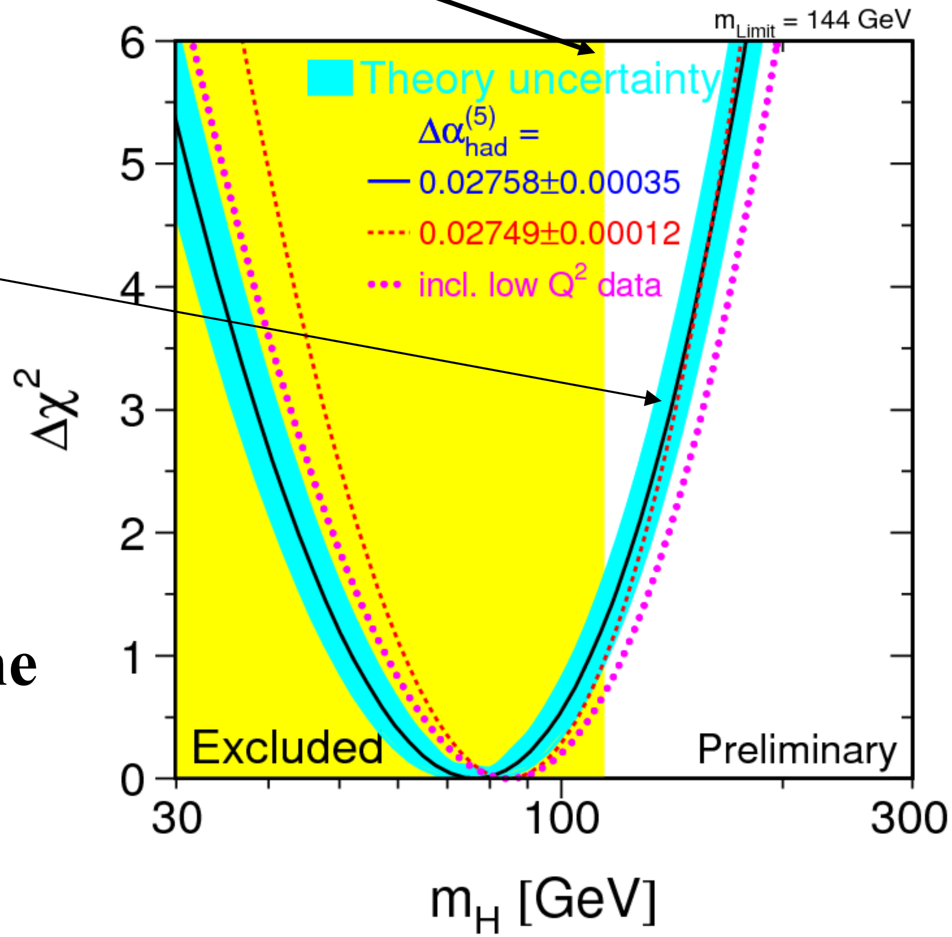
This is a slide from 2008

$M_{Higgs} \geq 114.4\ \mathrm{GeV}/c^2\ \ 95\%\ \mathrm{CL}$

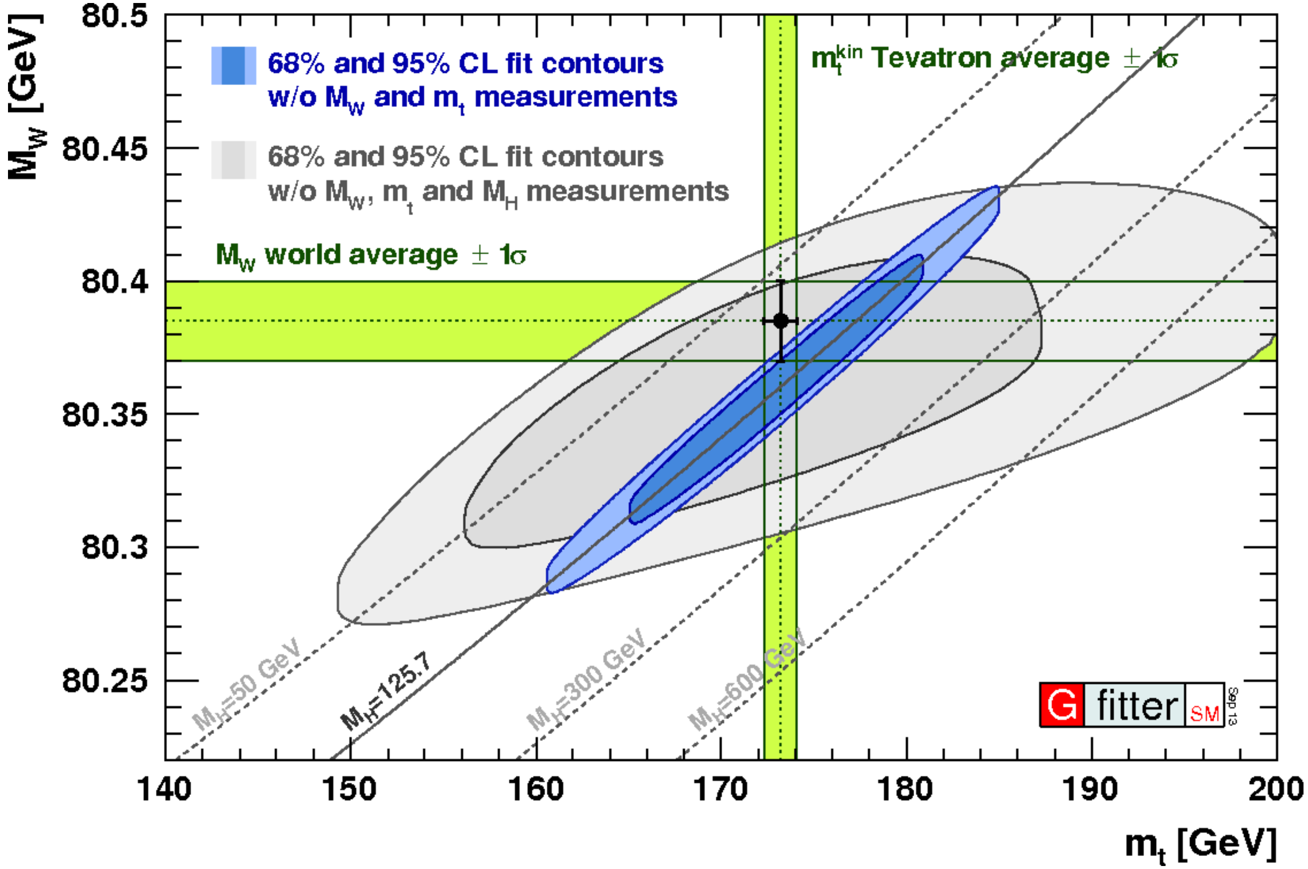
LEP direct searches:

From LEP, SLC, Tevatron and radiative corrections a light higgs (i.e. below 200 GeV) is expected

A narrow mass region is left for the Standard Model Higgs boson



This is a slide from 2014



W and Z Physics at LHC

Cross sections and rates at LHC

At High Luminosity (10^{34} cm^{-2} s^{-1})

SM Higgs (125 GeV/c^2): → 0.1 Hz

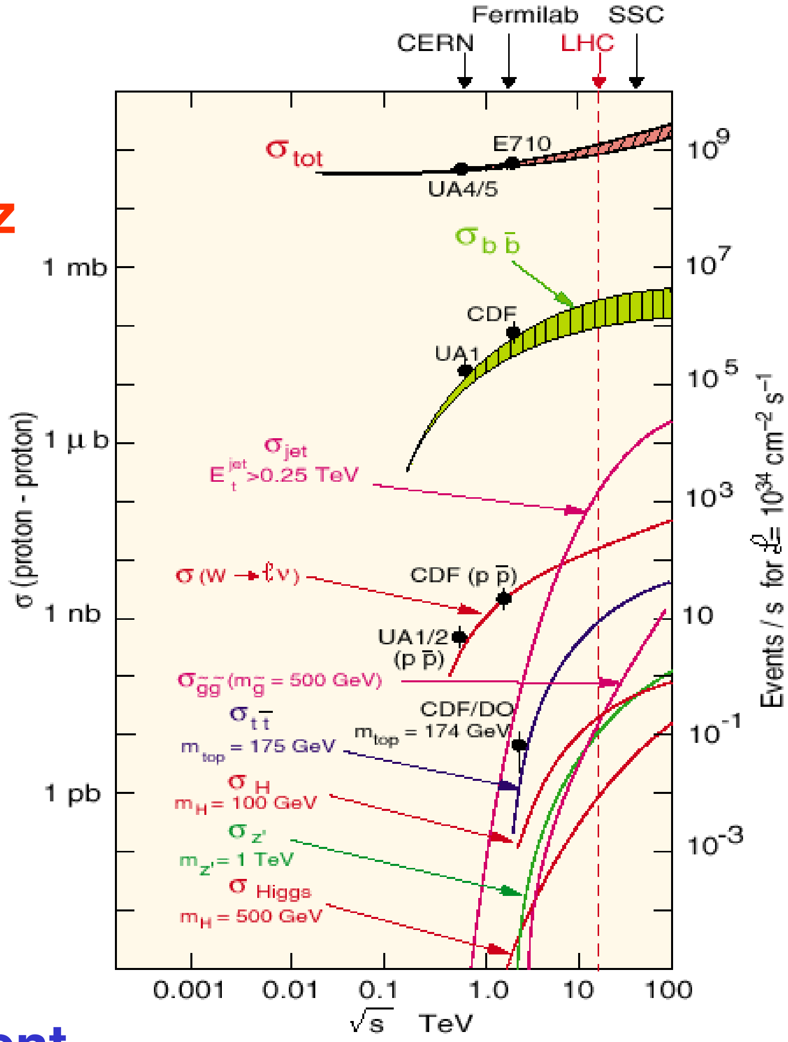
t t production: → 10 Hz

W → ℓ ν: → 10^2 Hz

Z → ℓ ℓ : → 10 Hz

bb production: → 10^6 Hz

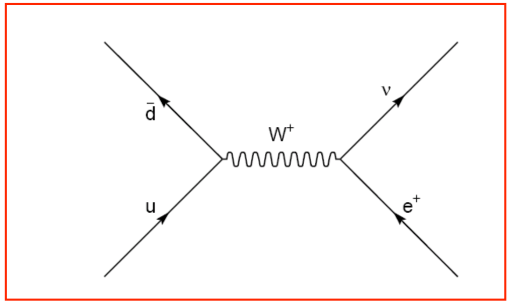
Inelastic: → 10^9 Hz



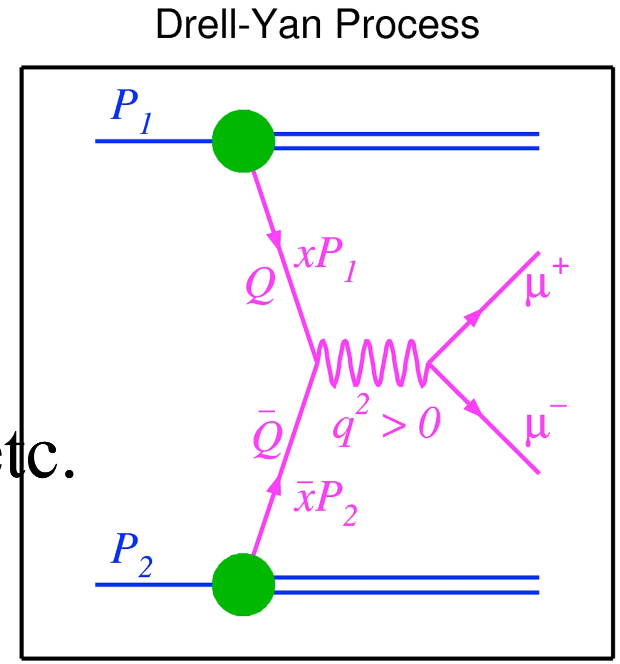
Beam crossing every 50 ns
at this luminosity →
50 pileup event / beam crossing

Experiments: need stringent and efficient online selection criteria (trigger)

W / Z (Drell Yan) production



- Inclusive W and Z cross section
  - with muons
  - with electrons
  - with taus
- Associate W/Z+n-jets, W+c, Z+bb, etc.
- Off-shell (generic DY)
- Differential cross sections, asymmetries
- W mass, $\sin^2\theta_W$



Inclusive production of W and Z

- Large W (Z) cross section(*): ~ 20 nb (2 nb) and clean leptonic signatures
  - Theory: important test of NNLO QCD and higher order EW predictions
  - Sensitive to Parton Distribution Functions (PDF)
  - Experiment: important test of luminosity

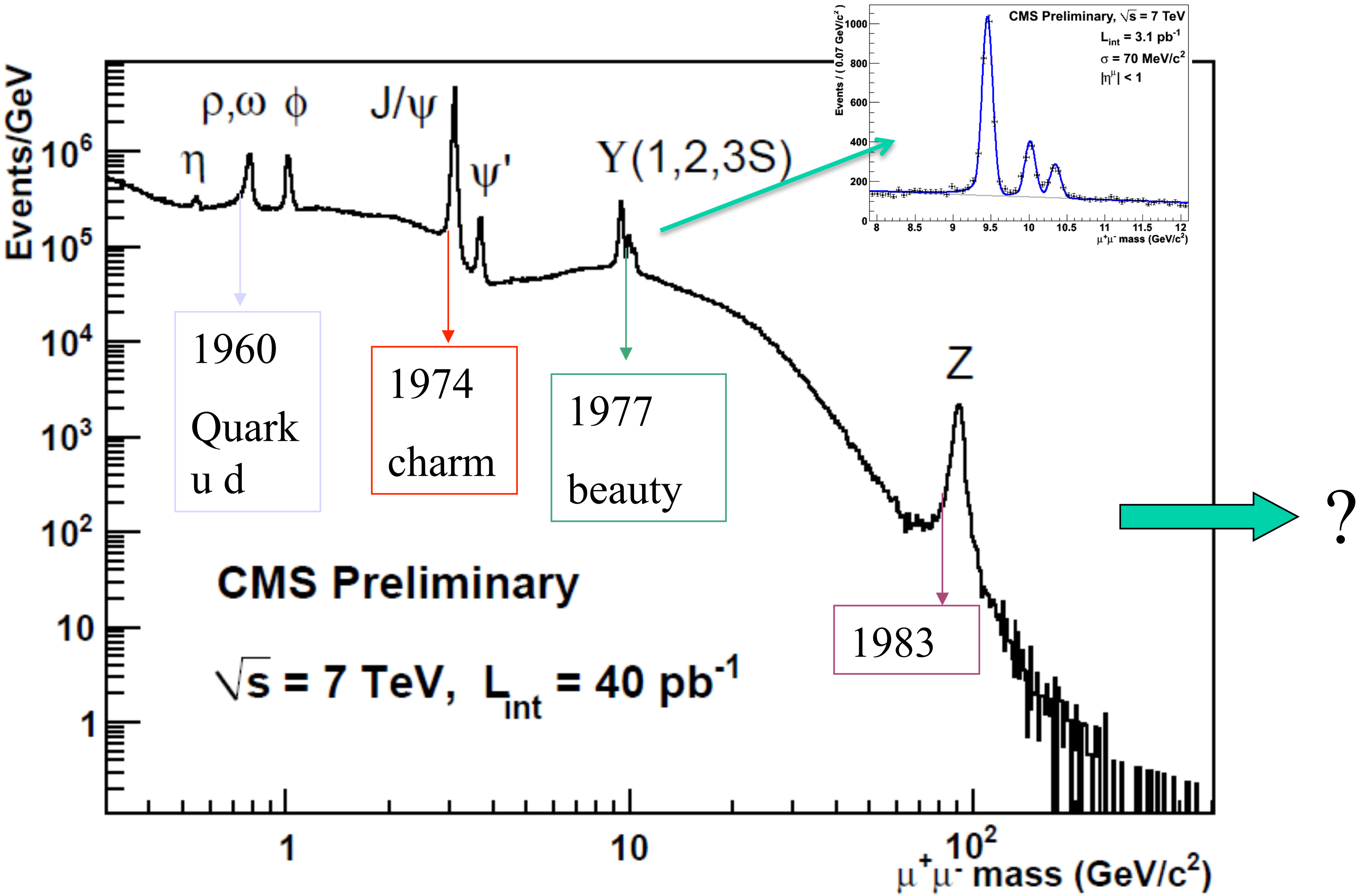
$$\sigma_{W(Z)} \times BR(W(Z) \rightarrow leptons) = \frac{N^{obs}_{W(Z)} - N^{bkg}_{W(Z)}}{\epsilon_{W(Z)} A_{W(Z)} \int \mathscr{L}\, dt}$$

(*) cross section to one lepton species at 14 TeV

Basic ingredients of cross section measurements with leptons

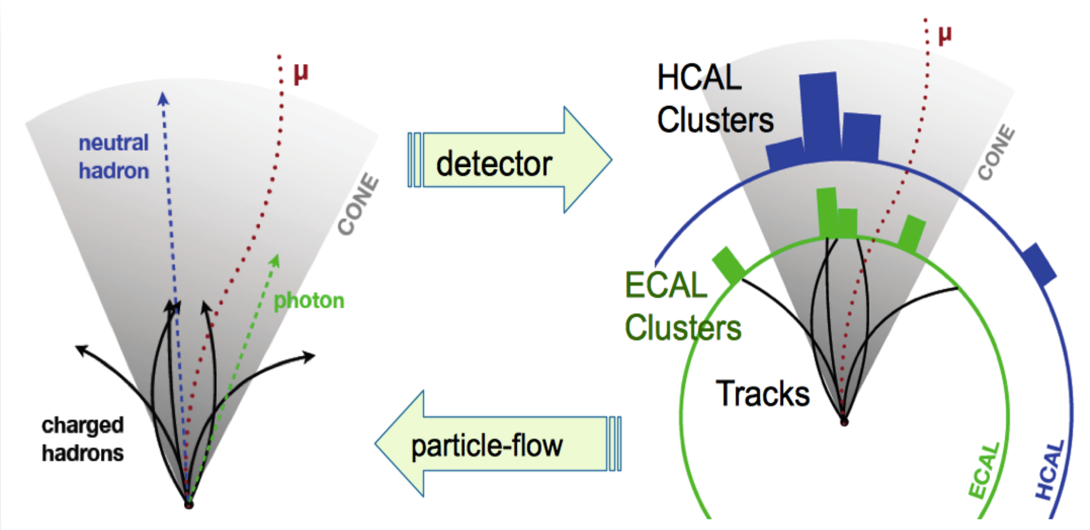
- Trigger on leptons **(e,μ,τ)→p_t, isolation cuts**
- Offline lepton selection → cuts with improved reconstruction, define acceptance in fiducial region
  - **need to measure efficiencies from data !**
- Suppress background (e.g. suppress jet production with transverse mass cut)
  - **need to measure background from data !**
  - (typical bkg: leptons from b,c decays, decay in flights of π, K, conversions $\gamma \rightarrow e^+e^-$,etc.)
- **Need information on accelerator luminosity**

example from 2010: μ+μ- inv mass spectrum, with trigger selection only (very low trigger thresholds !)

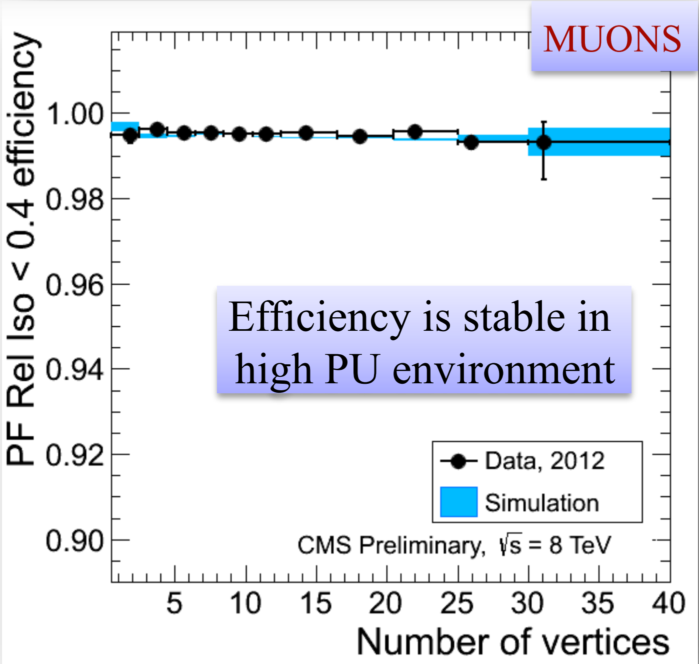


Example: Particle-based isolation

- Created by summing energy deposits from individual particles in ΔR=0.4 cone around the lepton
  - Avoids double counting of the energy deposit in the calorimeters from charged particles
  - Automatic footprint removal



- Pile-up contribution:
  - Negligible for charged hadrons from primary vertex
  - Neutral contribution corrected using the average energy density (ρ) from the pile-up and underlying event



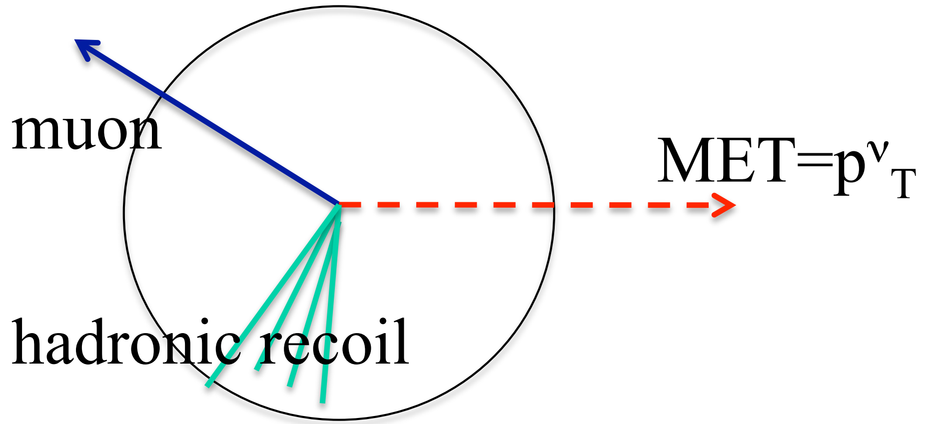
Example from a W→muon selection

- Selection of 'high pt' muon @ $\mathcal{L}$=5x10^{32} cm^{-2}s^{-1}
  - No isolation criteria for muon at trigger level
  - P_t > 15 GeV (P_t > 25 GeV offline)
  - $|\eta| < 2.1$ (trigger redundancy)

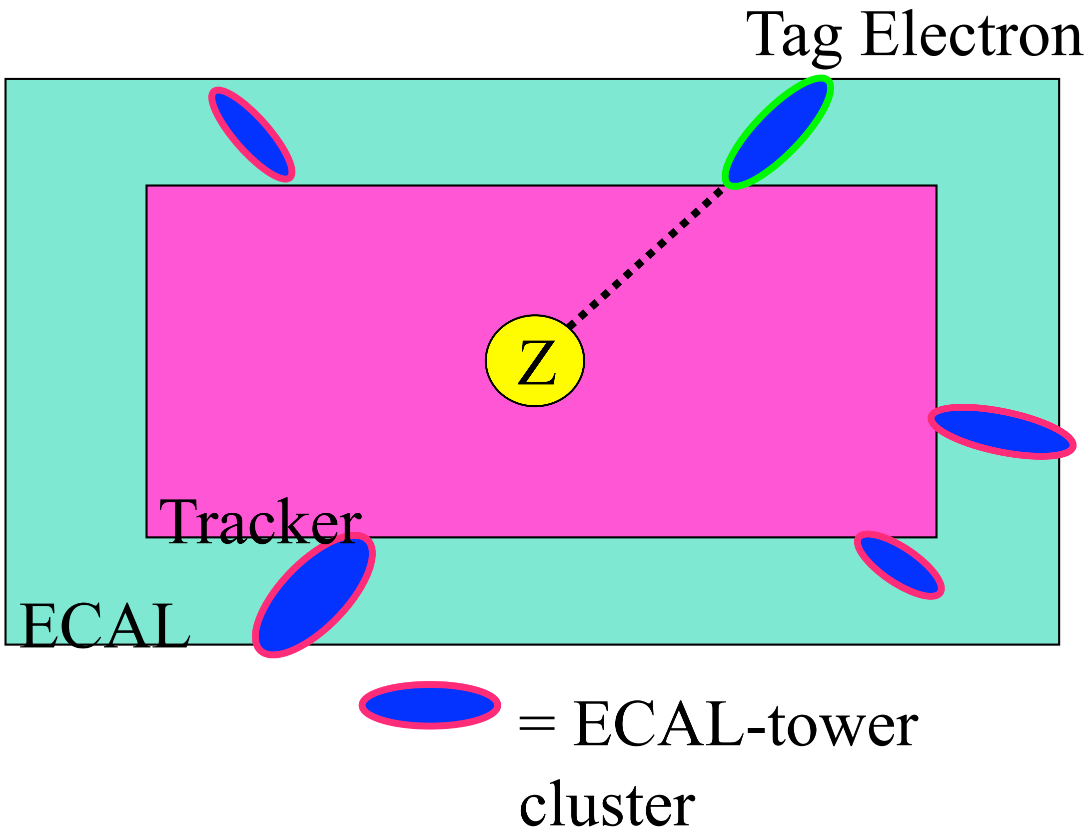
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- Isolation (offline selection level):
  - (P_t sum all tracks in cone 0.4 around muon)/(P_t muon) < 0.12
- Measure Transverse Missing Energy (MET)
  - use for M_T definition and cut M_T> 50 GeV
  - (can also cut directly on MET)

$$M_T = \sqrt{2 p_T^{lepton} p_T^{\upsilon} (1 - \cos\varphi)}$$



Measure efficiency from data



(Tag and Probe example)

Compute ECAL-tracker matching efficiency

$$eff = \frac{\text{number of matched probes}}{\text{number of probes}}$$

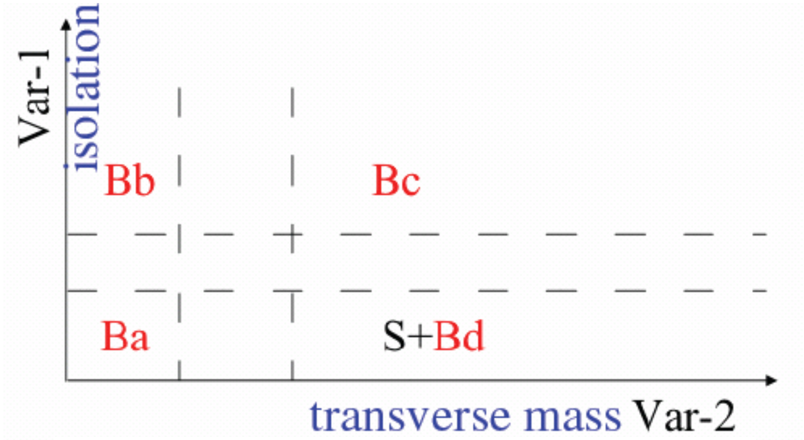
1. Find a good electron in a Z→ee event that meets Tag criteria
2. Loop over ECAL-tower clusters in the event with transverse energy above, e.g., 15 GeV and calculate the cluster-Tag invariant mass (M)
3. The cluster satisfying, e.g. : 82<M<100 GeV is a Probe

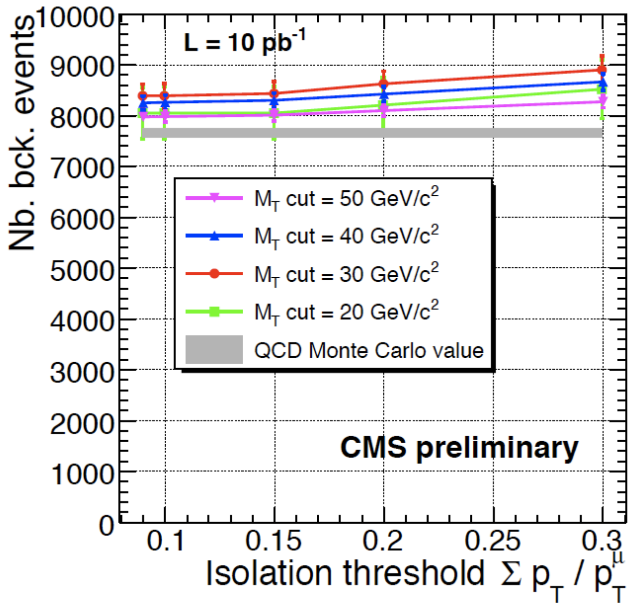
Data-driven background measurement
- Example -

- Take two variables with discriminating power (e.g. isolation and M_T)
- Assume that the two are uncorrelated
- Compute bkg from

$$N_{QCD} = N_d = N_a \times \frac{N_c}{N_b}$$

(Correct for small signal contamination in a,b,c)



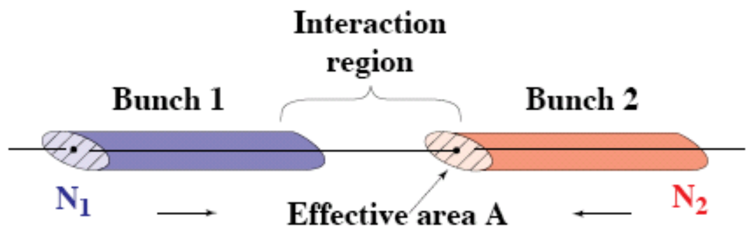


Luminosity determination

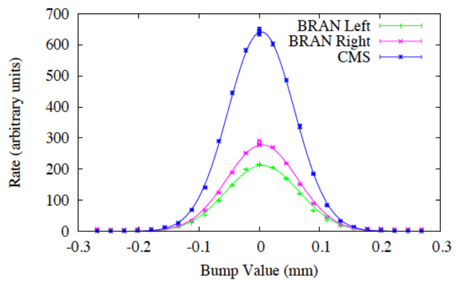
$$\text{Rate} = \frac{\sigma}{L}$$

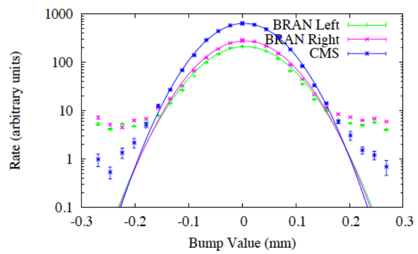
- The method is known as “Van Der Meer scan”

$$\mathcal{L} = \frac{N_1 N_2 f}{A_{\text{eff}}}$$



Beam intensities and crossing frequency are known with good accuracy
The effective overlap area A can be determined by scans in separation





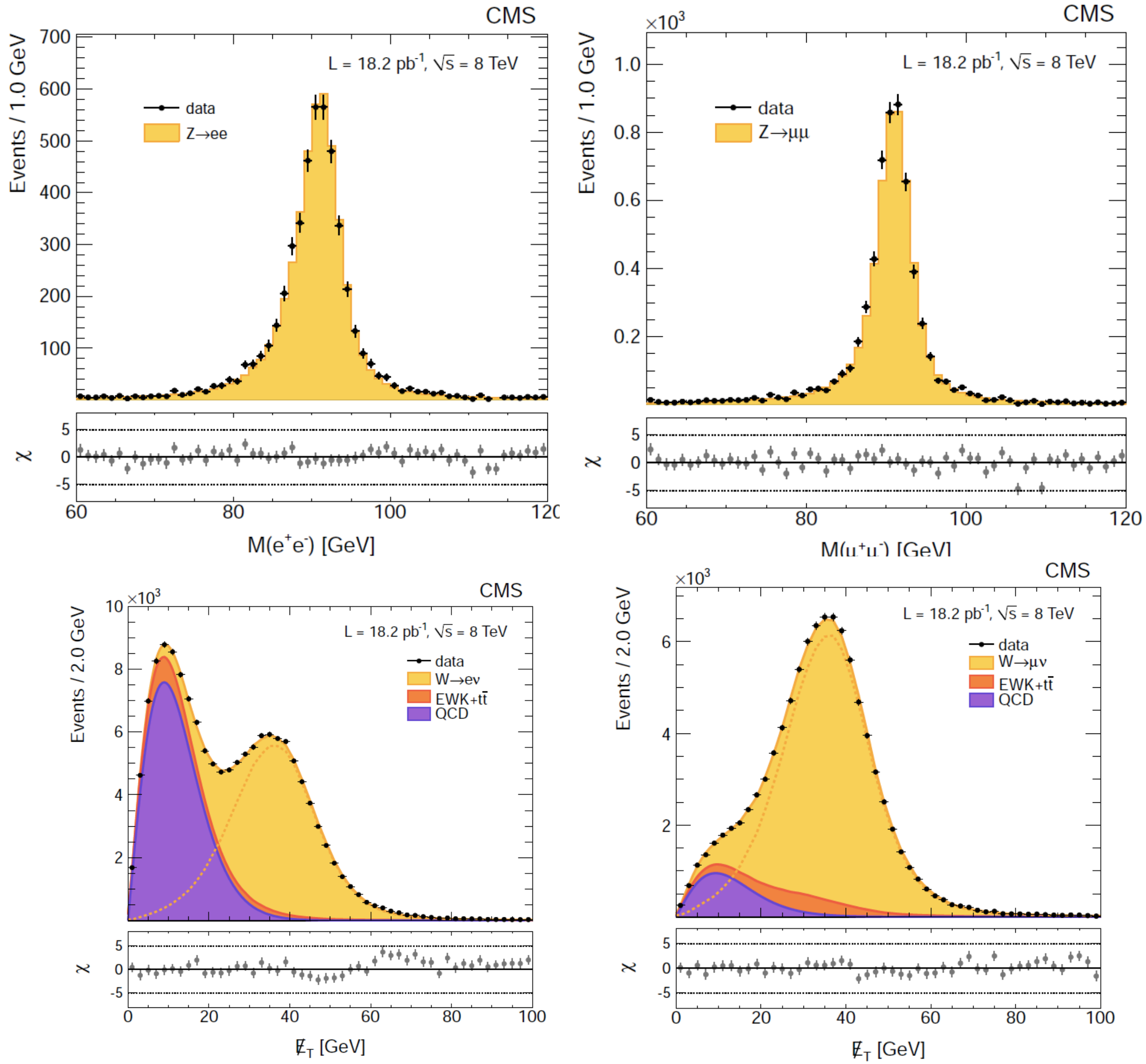
Details : LHC Report 1019 by Grafstrøm Burkhardt http://cdsweb.cern.ch/record/1056691

PRL 112 (2014) 191802

Z and W production at 8 TeV

Z Boson

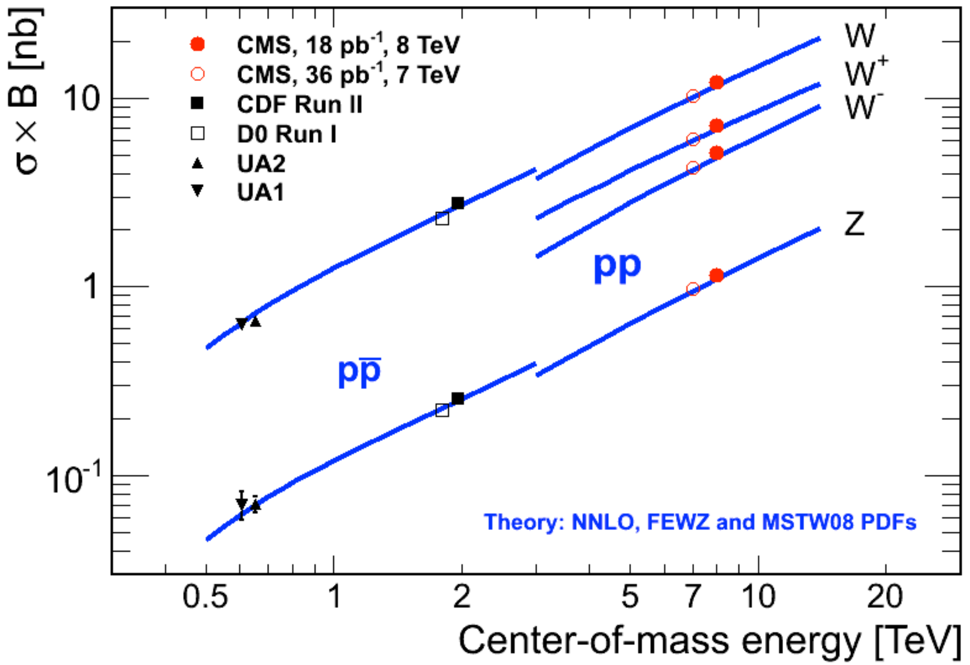
W Boson

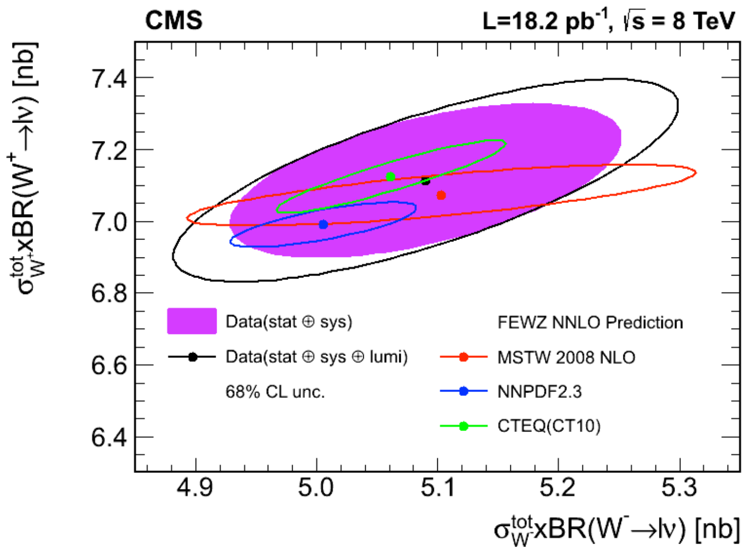


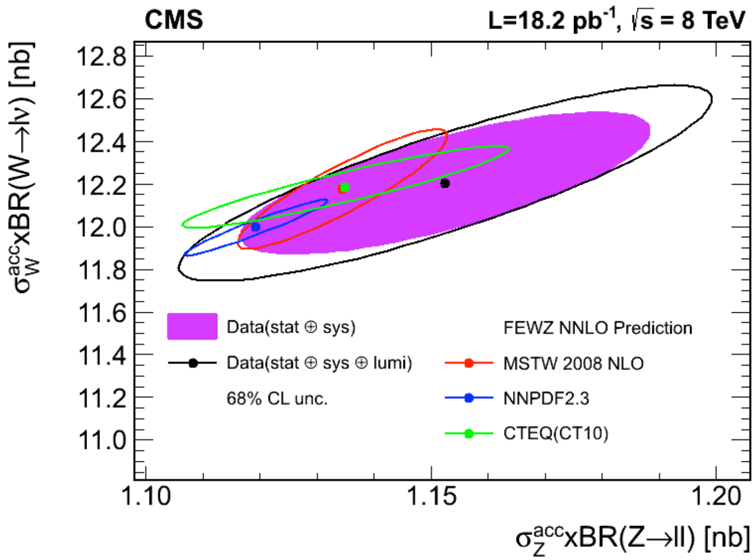
Electron(s) **Muon(s)**

PRL 112 (2014) 191802

Z and W production at 8 TeV







Dilepton Drell Yan cross section

Impressive test of the Standard Model from 15 GeV to 2000 GeV !