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LHC results: Standard Model (EW, top, jets)

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Standard Model Physics

INTRODUCTION WITH A BIT OF HISTORY

Introduction

- At LHC **W & Z boson** 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

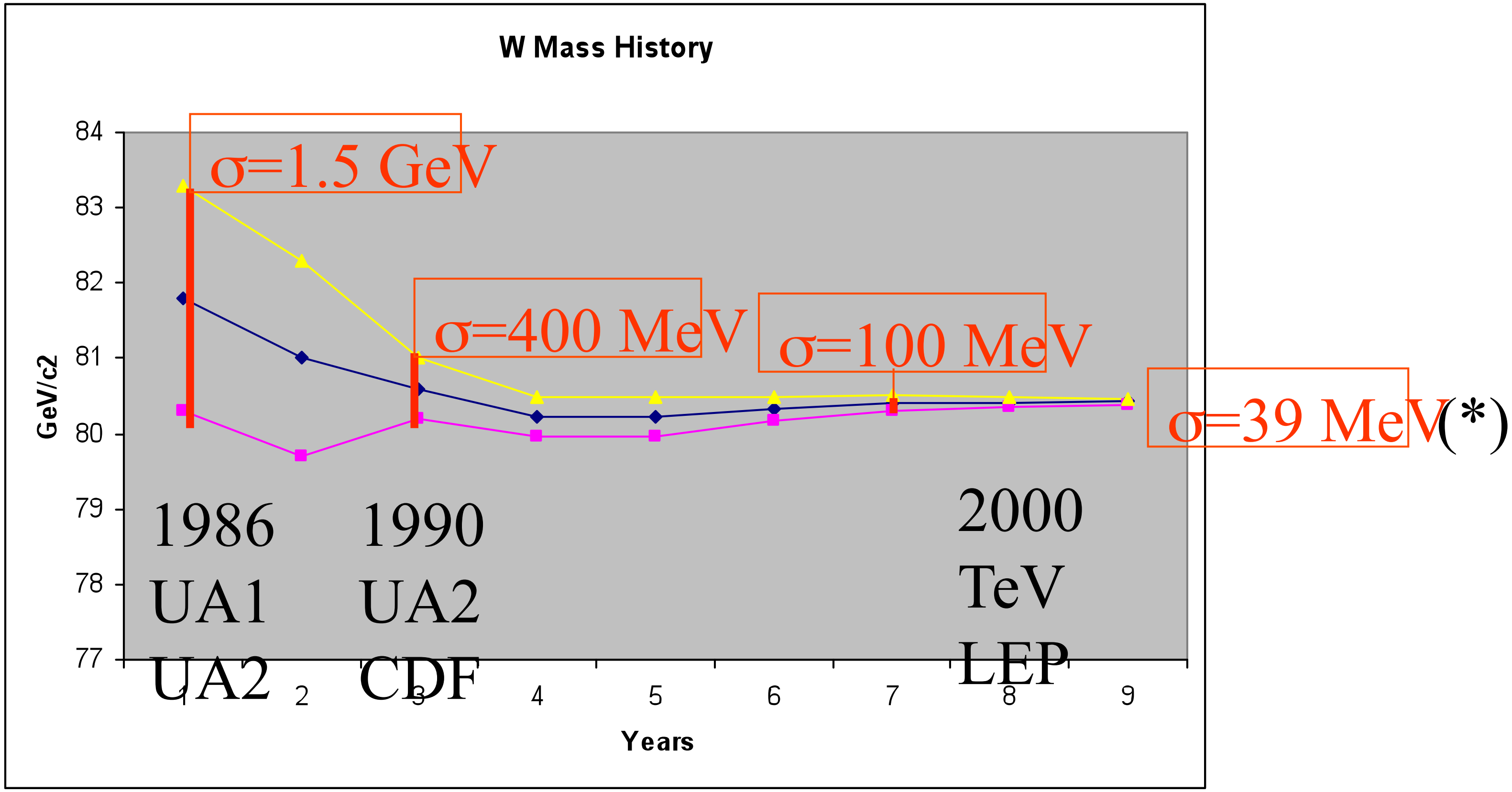
Jupiter was supposed to be a standard planet !

Standard Model and new phenomena

More specifically for our subject:

- 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

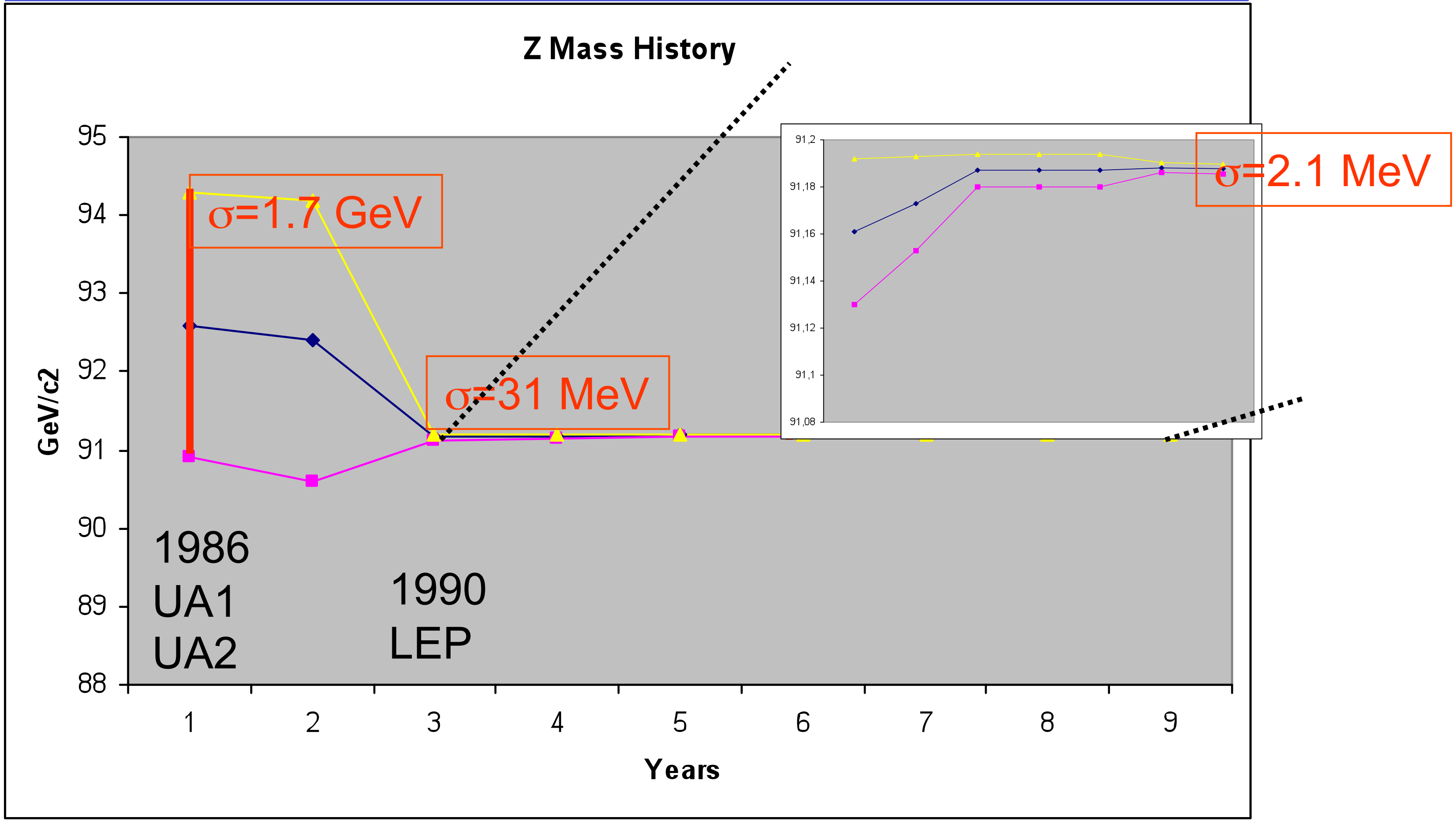


Only Published Results

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

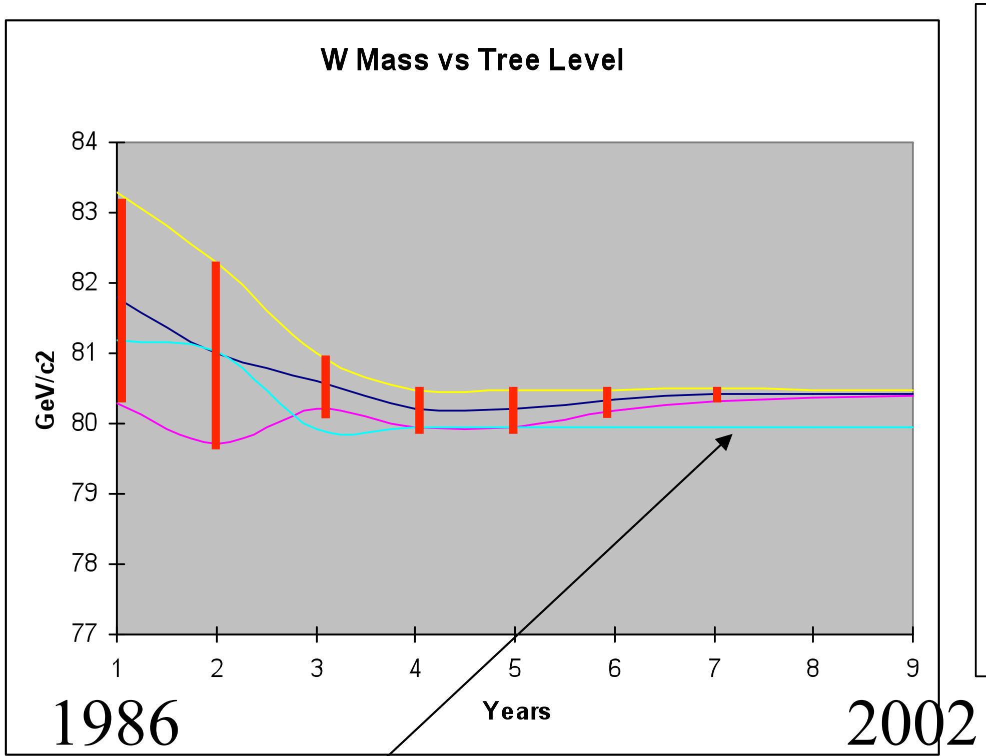
Z mass precision from 1986 to the end of LEP

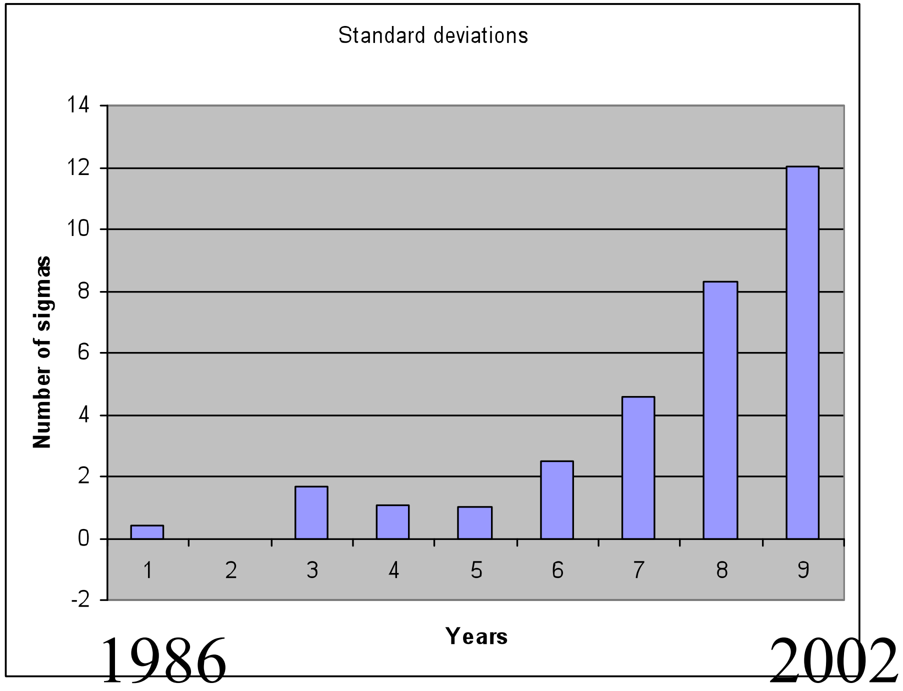
The Z mass: one of the most precise physical constants !



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)

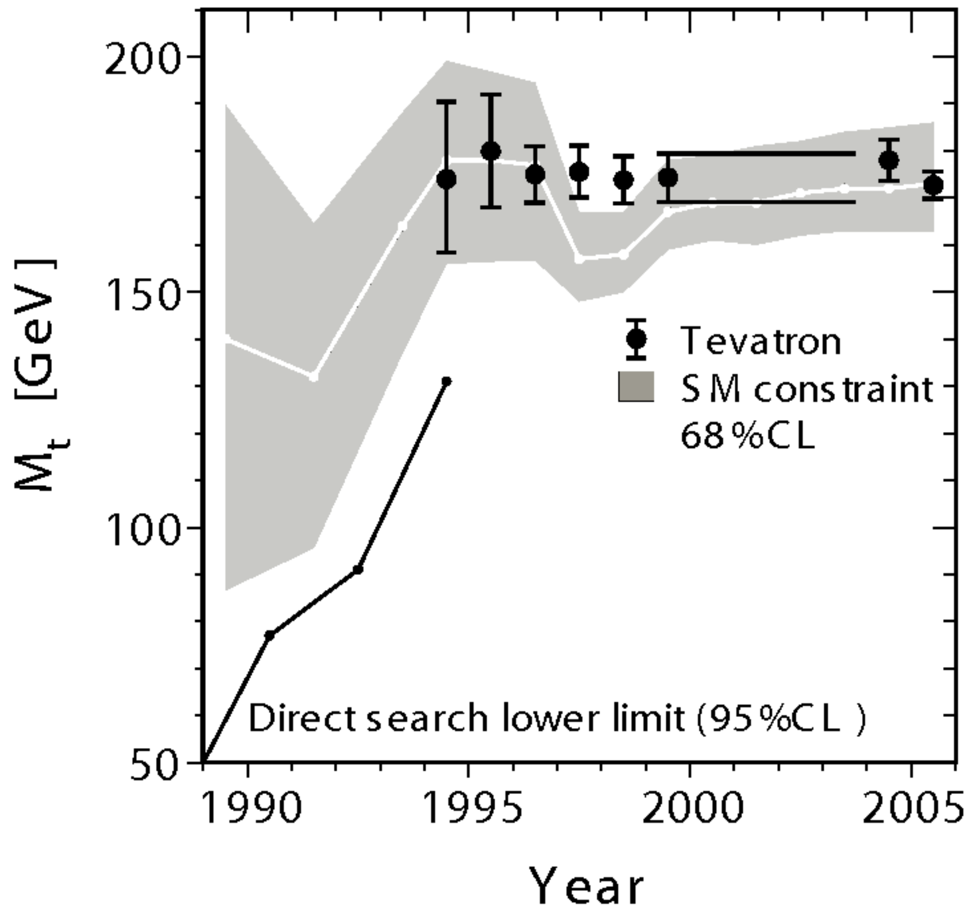
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha(M_Z)}{\sqrt{2}}\frac{1}{G_F}$$

$$\alpha(\sqrt{s}=\mathrm{M_Z})=\frac{1}{128.936\pm 0.046}$$

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 !

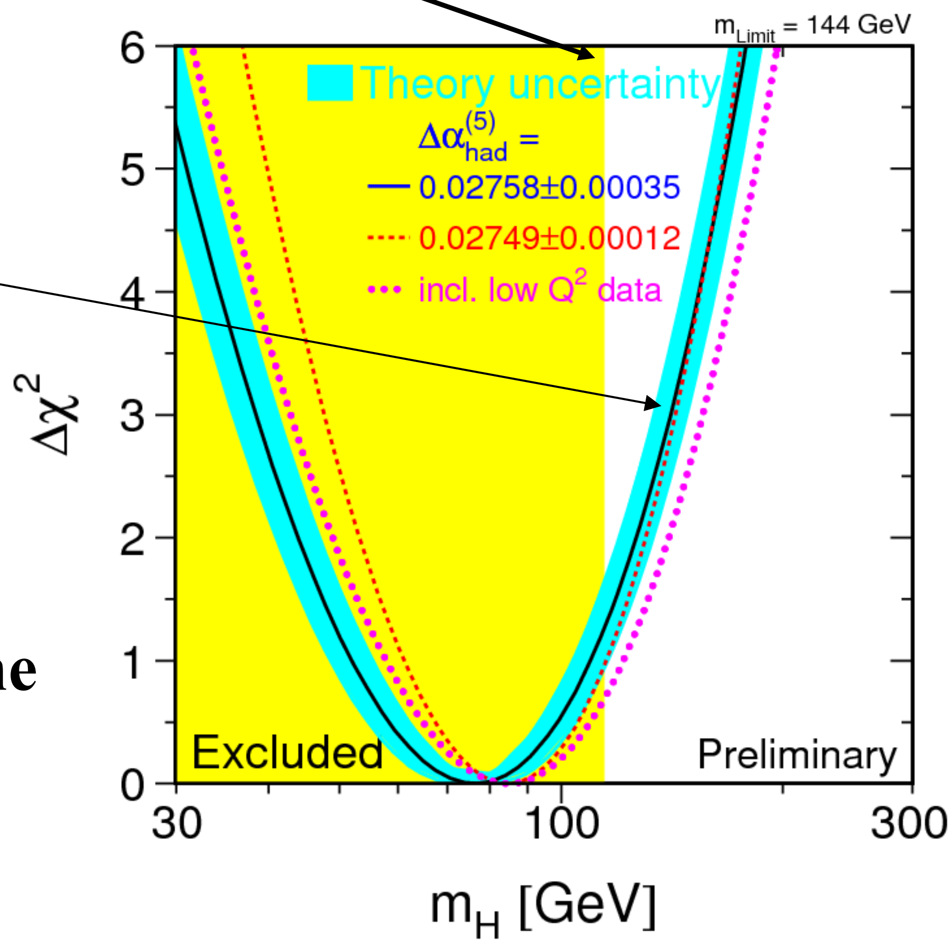


This is a slide from 2008

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

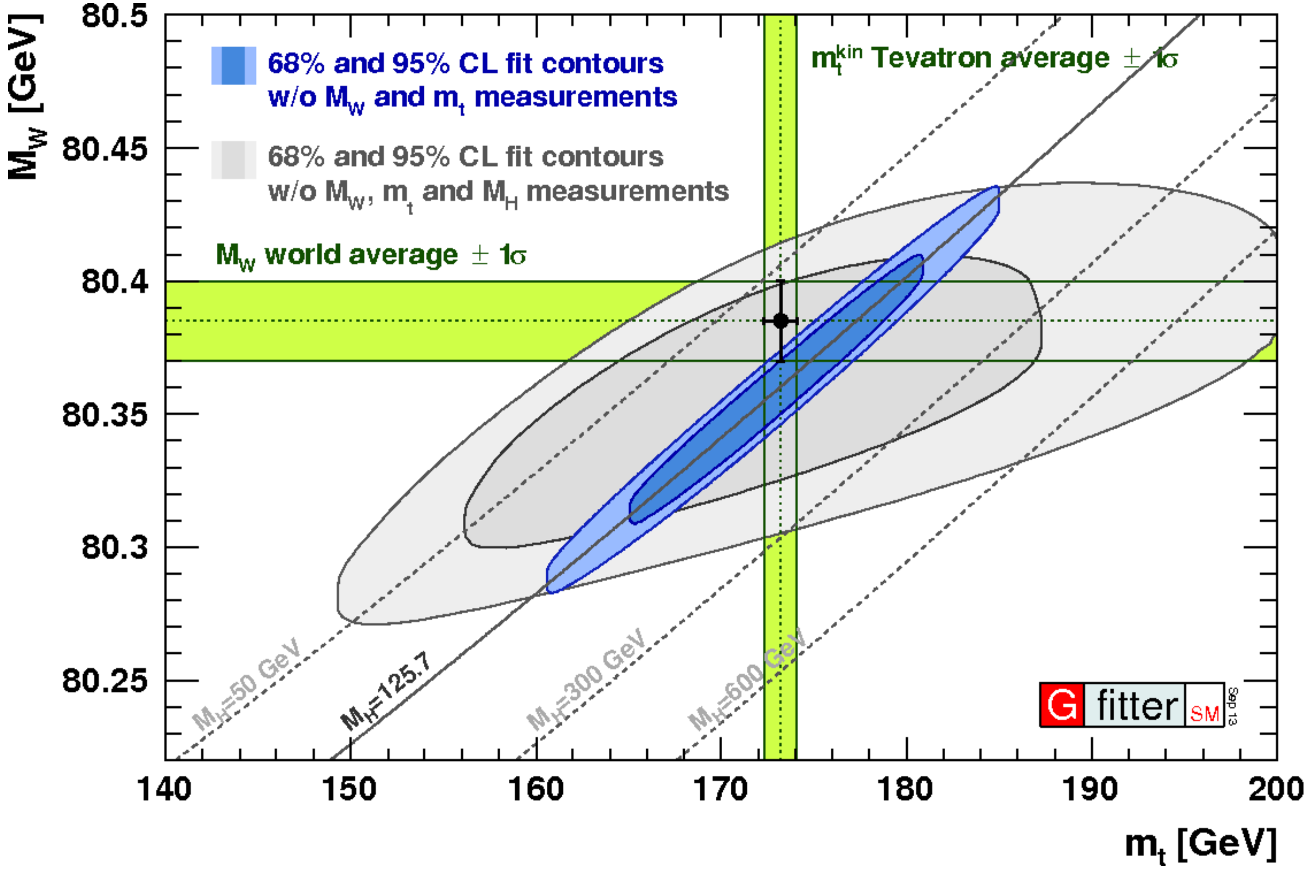
LEP direct searches:

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/c²): →0.1 Hz

t t production: →10 Hz

$W \rightarrow \ell \nu$: →10^2 Hz

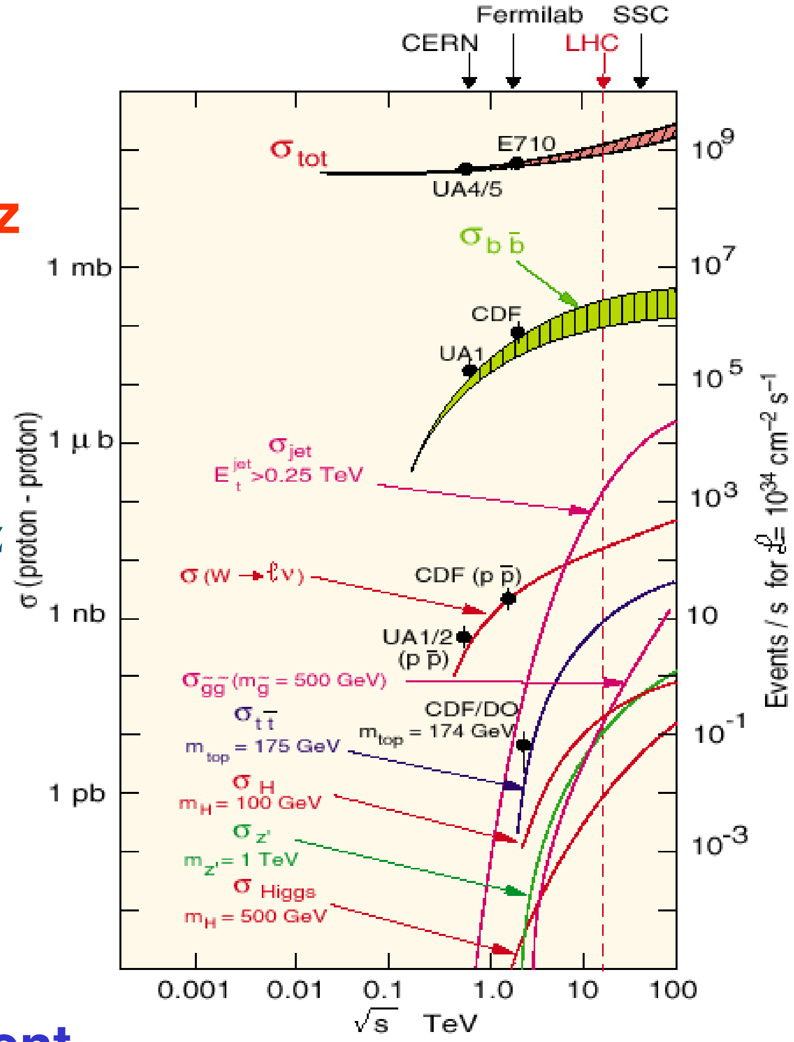
$Z \rightarrow \ell \ell$: →10 Hz

bb production: → 10^6 Hz

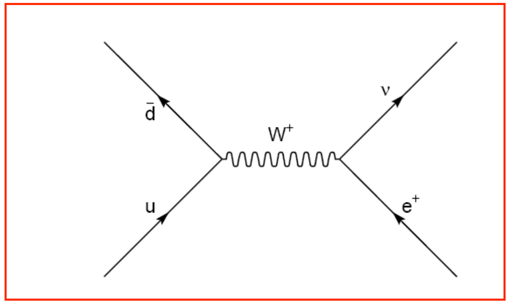
Inelastic: →10^9 Hz

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

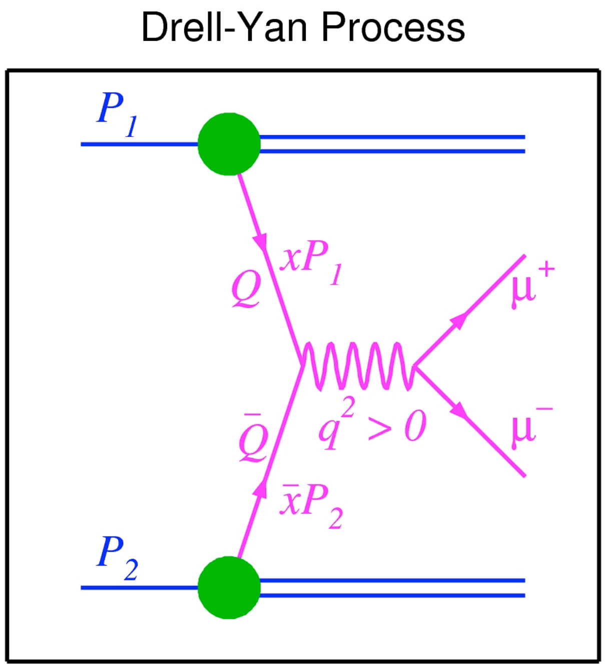
Experiments: need stringent and efficient online selection criteria (trigger)



W / Z / Drell Yan production



- Inclusive W and Z cross section
  - with muons
  - with electrons
  - with taus
- Measuring W/Z+n-jets, Zbb, 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 cross section predictions
  - Sensitive to Parton Distribution Functions (PDF)
  - Experiment: important test of luminosity

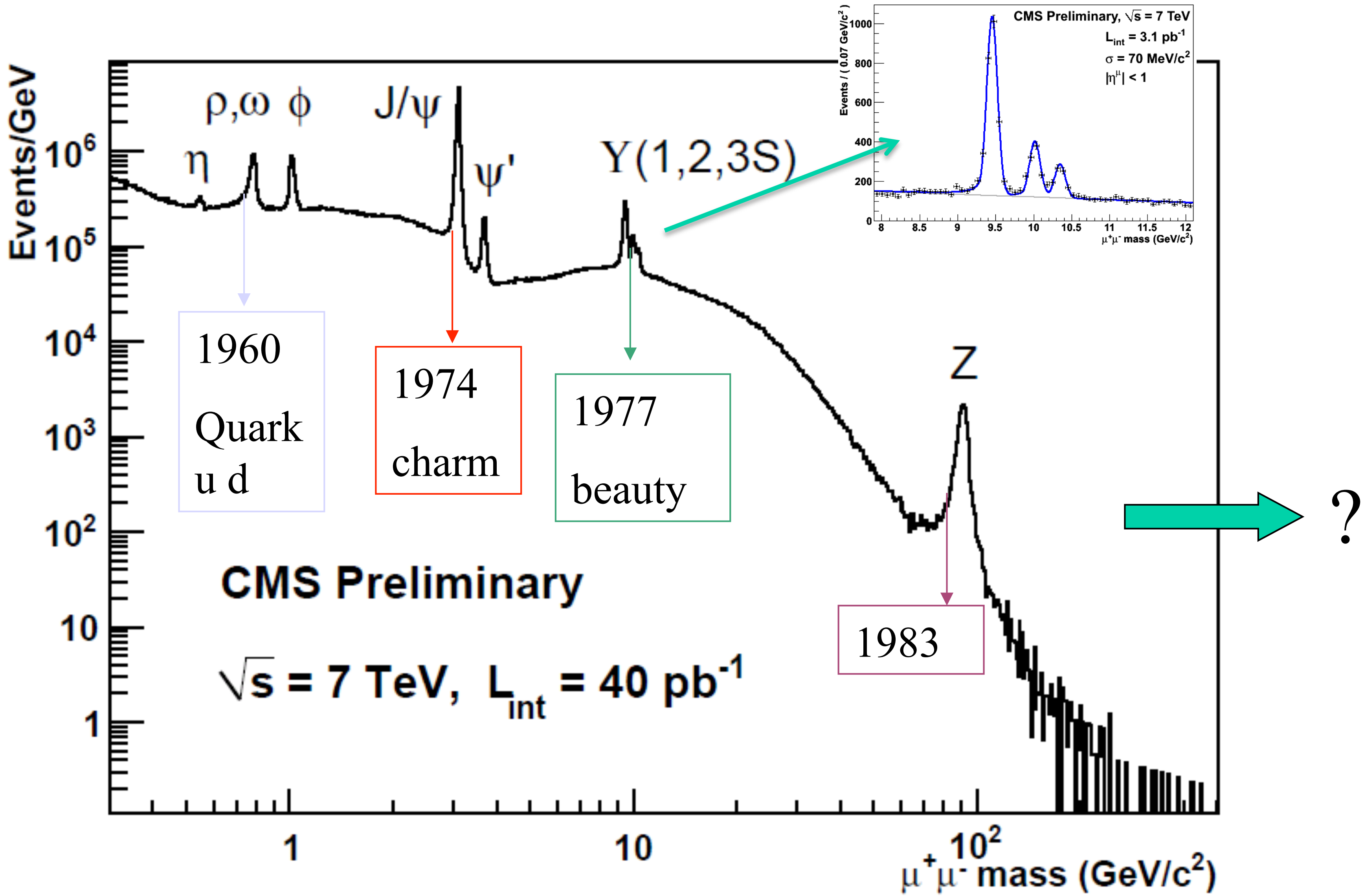
$$\sigma_{W(Z)} \times BR(W(Z) \rightarrow leptons) = \frac{N^{obs}_{W(Z)} - N^{bkg}_{W(Z)}}{\epsilon_{W(Z)} A_{W(Z)} \int \mathcal{L}\, dt}$$

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

Basic ingredients of cross section measurements with leptons

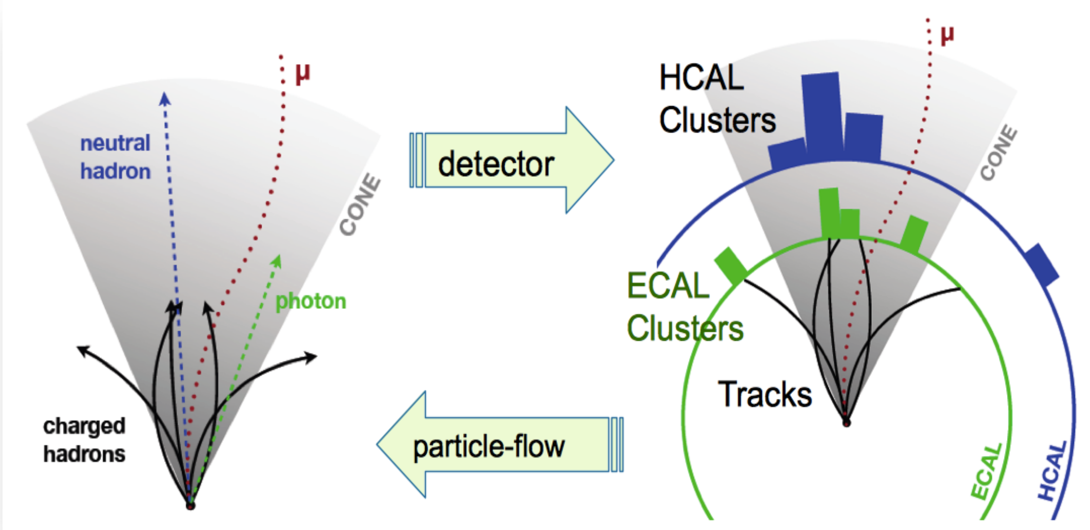
- Trigger on leptons **(e,μ,τ)→p_t**, **isolation cuts**
- Offline lepton selection → cuts with improved reconstruction, define acceptance in fiducial region
  - **need to measure efficiencies from data !**
- Suppress background (e.g. suppress jet production with transverse mass cut)
  - **need to measure 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 !)

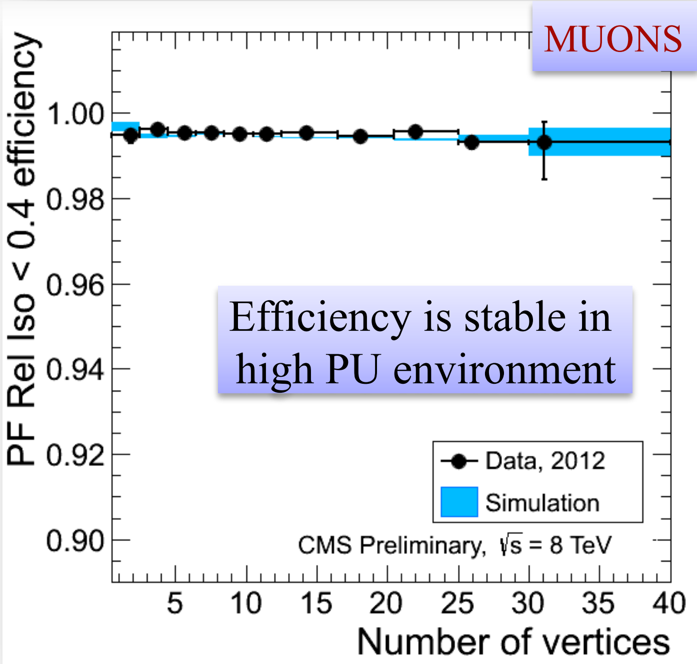


Example: Particle-based isolation

- 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



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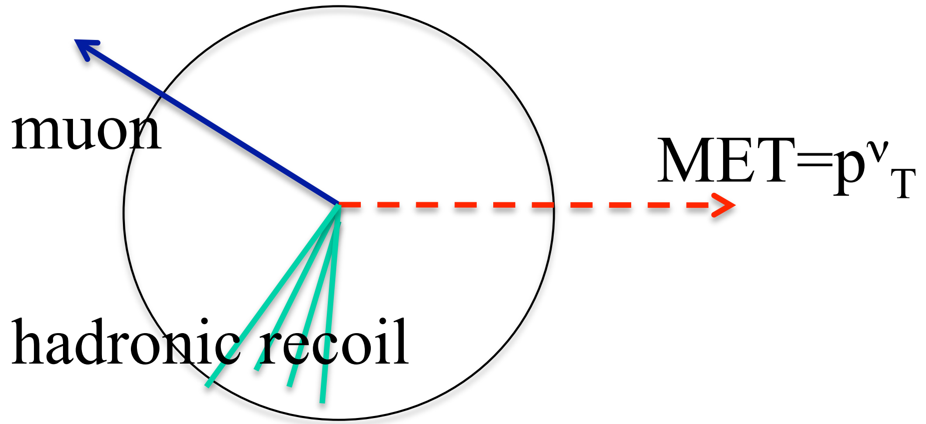
Example from a W→muon selection

- Selection of 'high pt' muon @ $\mathcal{L}=10^{32}$ cm^{-2}s^{-1}
  - No isolation criteria for muon at trigger level
  - $P_t > 16$ GeV (cut increases with luminosity)
  - $|\eta| < 2.0$ (trigger redundancy)
- Isolation (offline selection level):
  - (P_t sum all tracks in cone 0.3 around muon)/(P_t muon) < 0.09
- Measure Transverse Missing Energy (MET)
  - use for M_T definition and cut $M_T > 50$ GeV
  - (can also cut directly on MET)

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

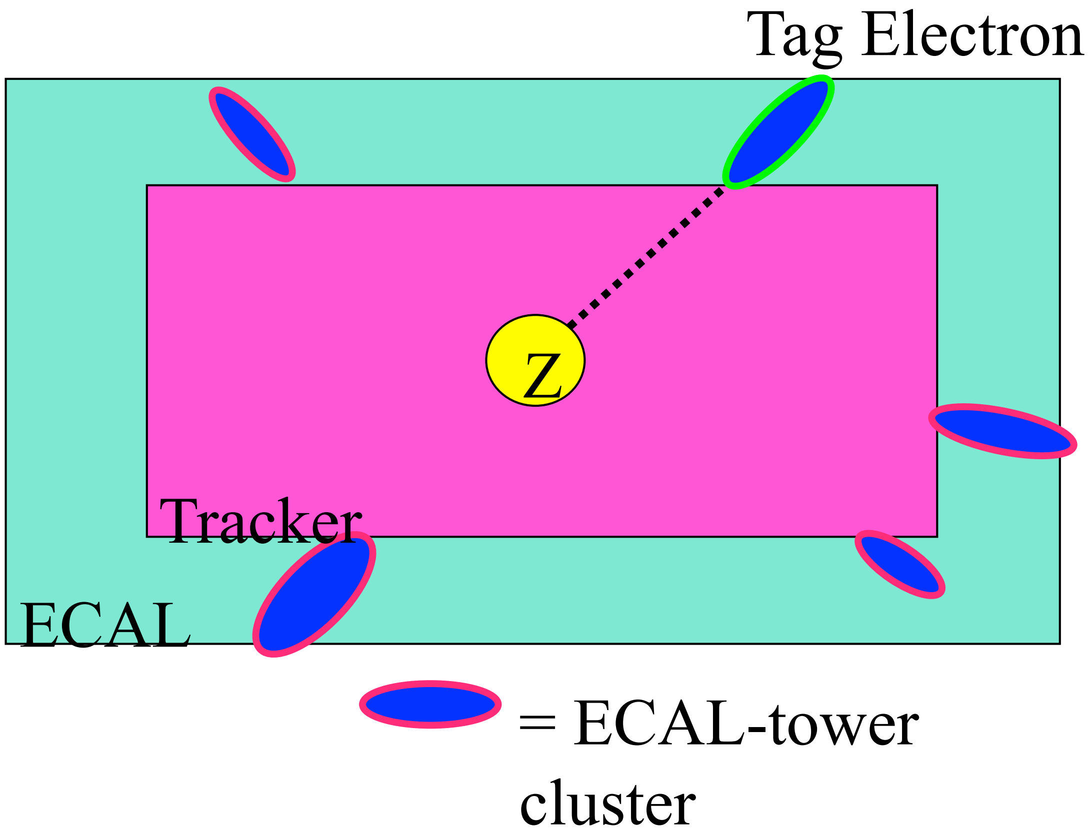
$$M_T = \sqrt{2 p_T^{lepton} p_T^{\nu} (1 - \cos\varphi)}$$



example of data driven methods: Tag & Probe

- Tag and Probe (TP) is a method used with real data to identify a physics object in an unbiased way in order to study efficiencies.
- One object, the tag, has strict criteria imposed on it to identify it. The probe is another object with looser criteria to meet, with an additional property that links it to the Tag object to ensure a pure sample.
- $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$ events are appropriate for TP because one lepton, meeting tight criteria, can be used as the tag, and the other can be a probe, providing the invariant mass of the pair is $\approx m_Z$
- Important to keep the method unbiased: the identification of the tag and the probe should be uncorrelated

Tag and Probe (Example)



Compute ECAL-tracker matching efficiency

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

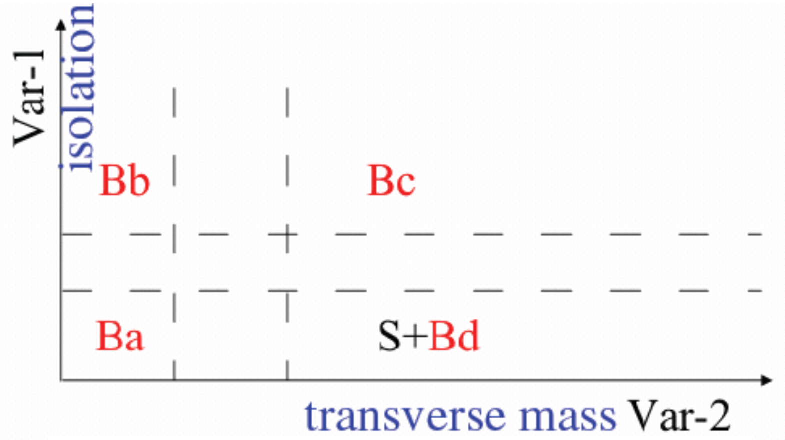
1. Find a good electron in a Z→ee event that meets Tag criteria
2. Loop over ECAL-tower clusters in the event with transverse energy above, e.g., 15 GeV and calculate the cluster-Tag invariant mass (M)
3. The cluster satisfying, e.g. : 82<M<100 GeV is a Probe

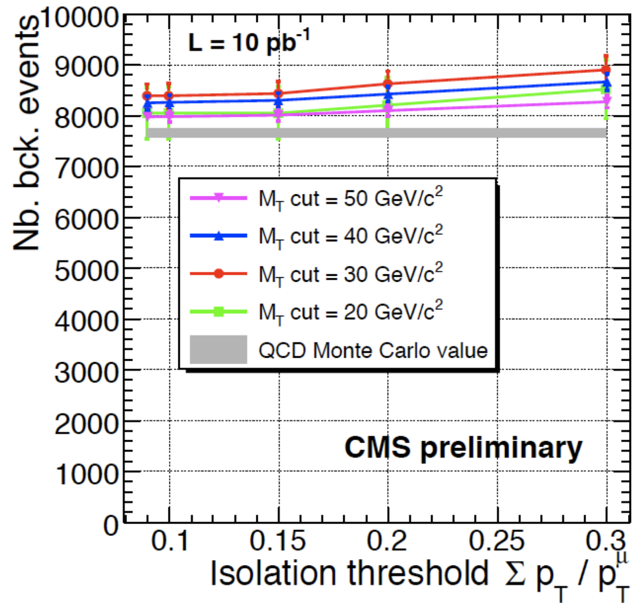
Data-driven background studies - Example -

- 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)



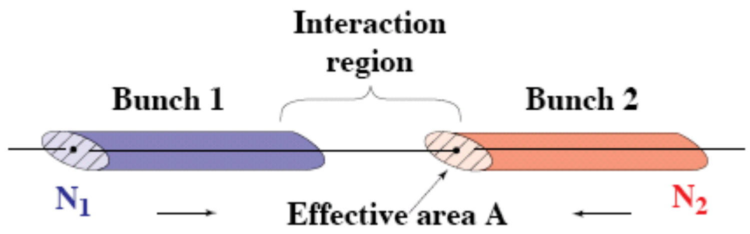


Luminosity determination

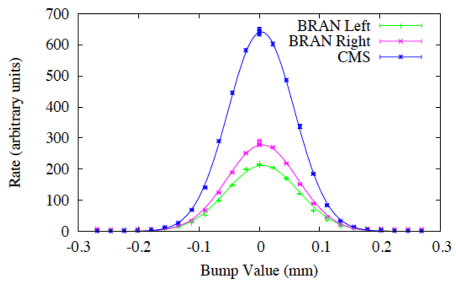
$$\text{Rate} = \frac{\sigma}{L}$$

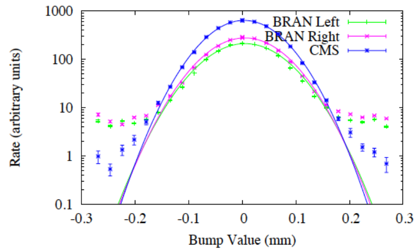
- The method is known as “Van Der Meer scan”

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



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



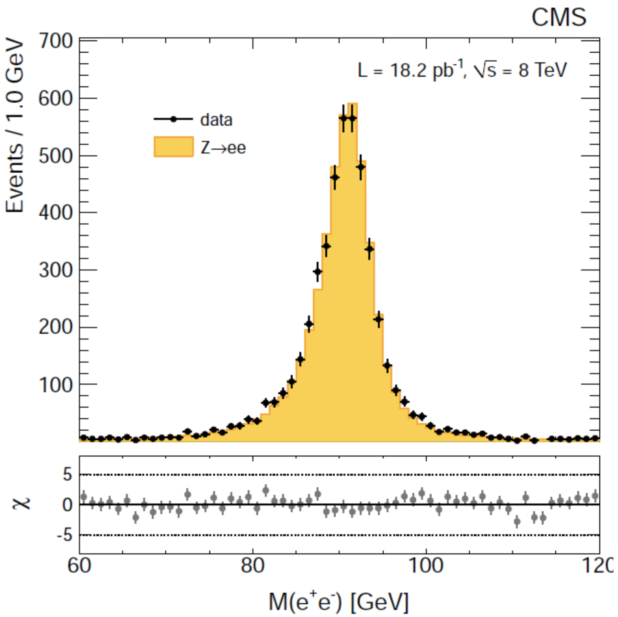


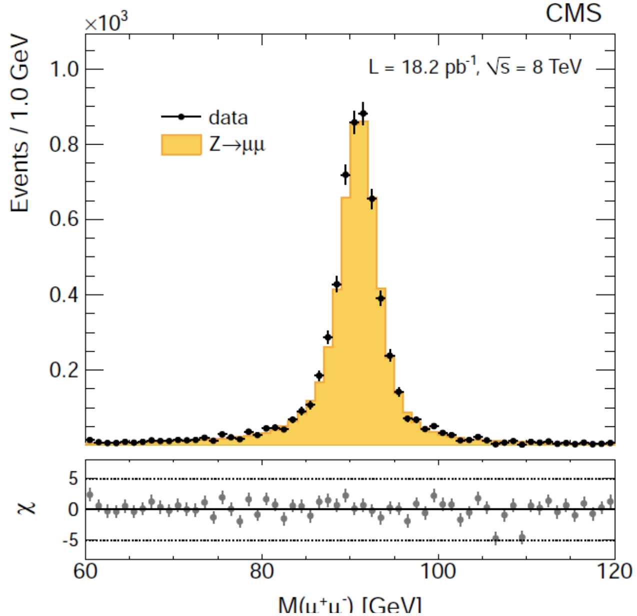
Details : LHC Report 1019 by Grafstrøm Burkhardt http://cdsweb.cern.ch/record/1056691

PRL 112 (2014) 191802

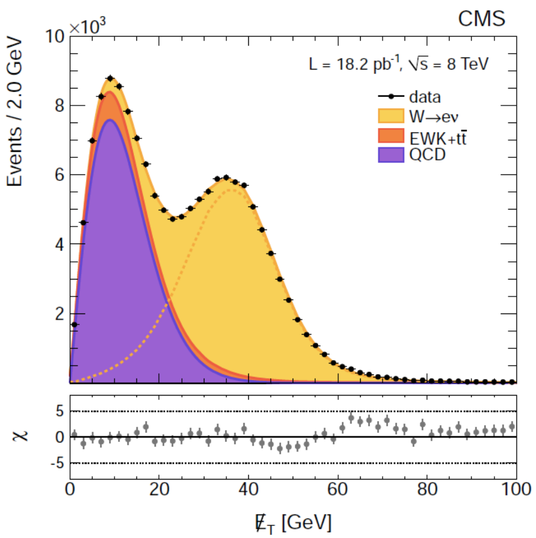
Z and W production at 8 TeV

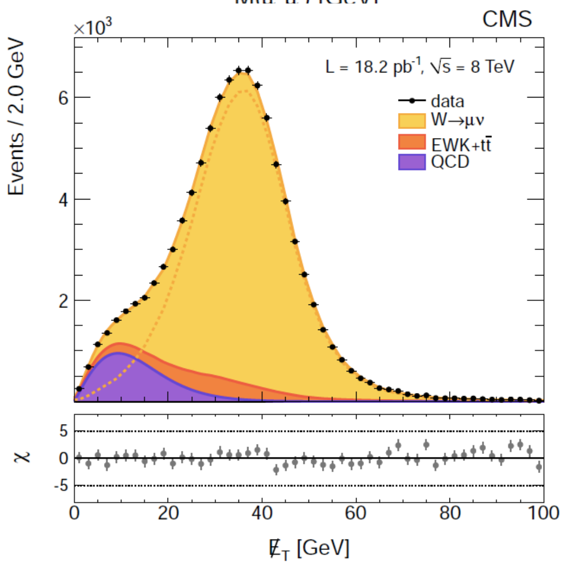
Z Boson





W Boson

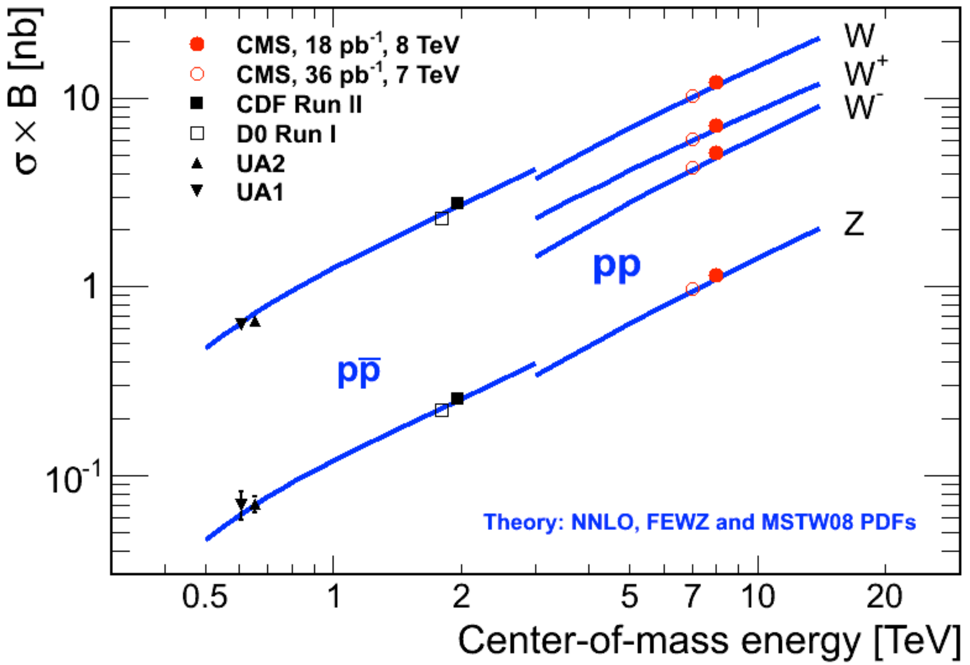


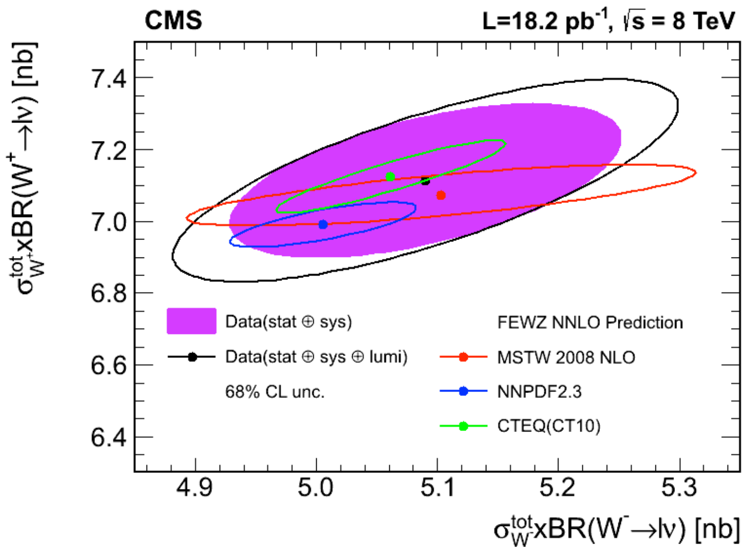


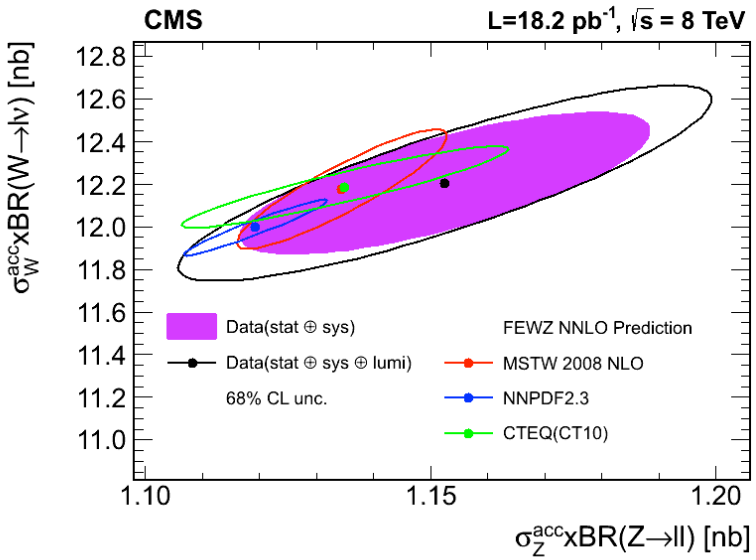
Electron(s) **Muon(s)**

PRL 112 (2014) 191802

Z and W production at 8 TeV



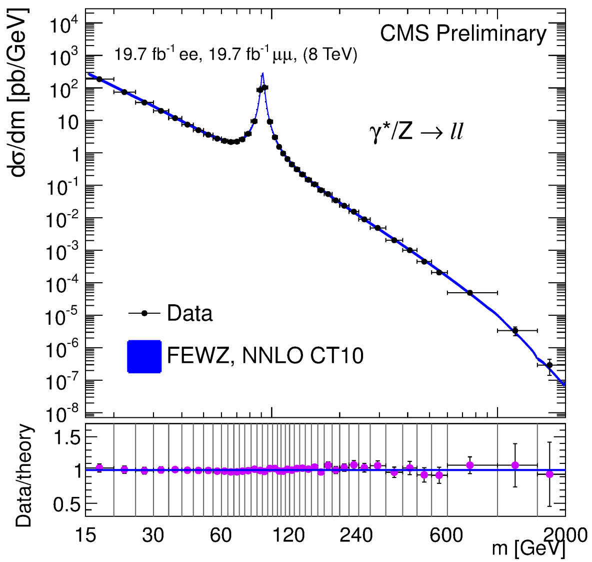


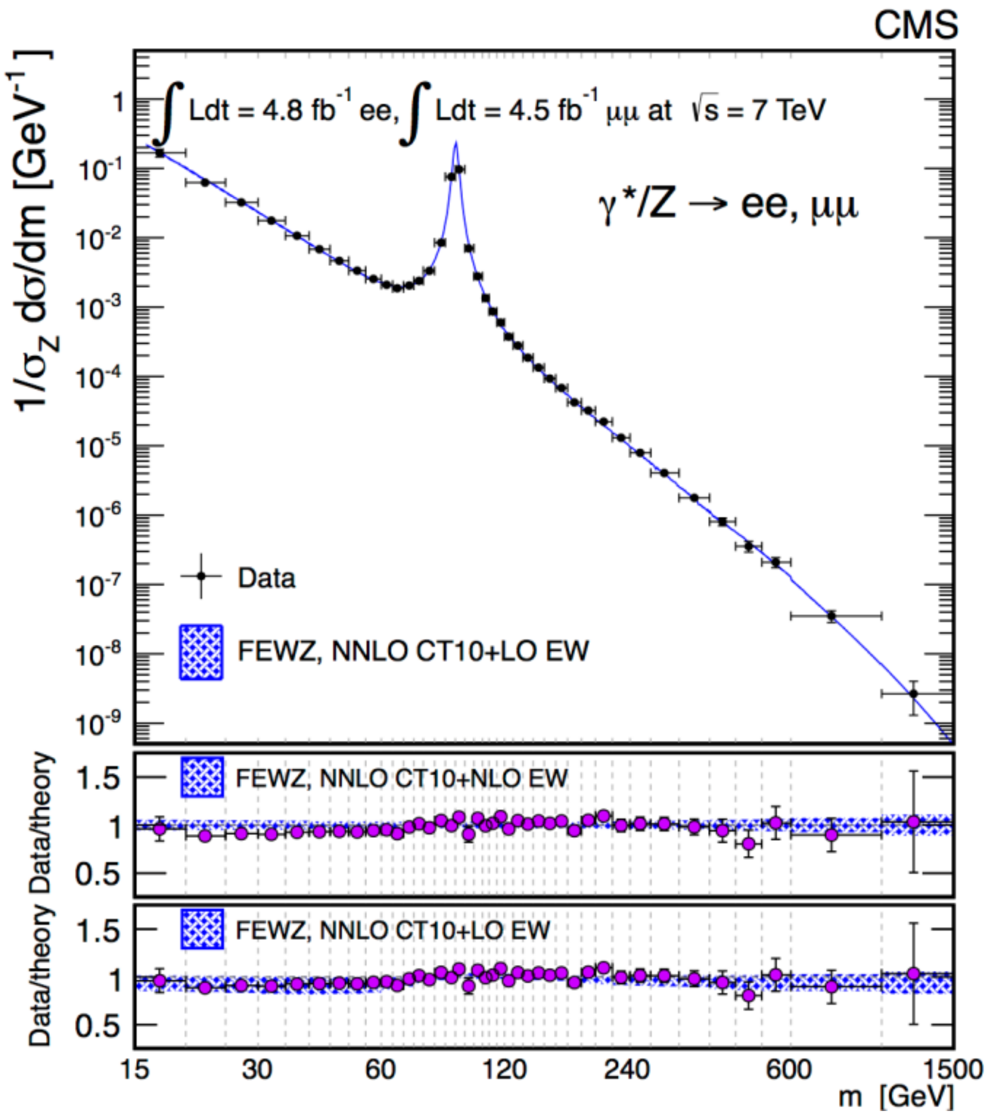


JHEP 12 (2013) 030

Dilepton Drell Yan cross section

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





CMS-PAS-SMP-1403

At this point we have to discuss a bit more the

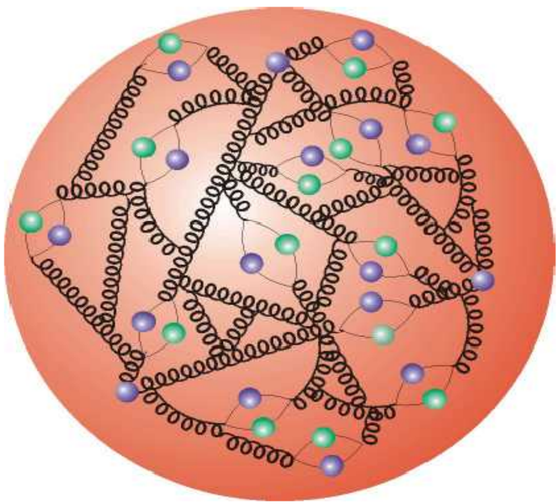
PARTON DISTRIBUTION FUNCTIONS (PDF)

LHC: the initial state

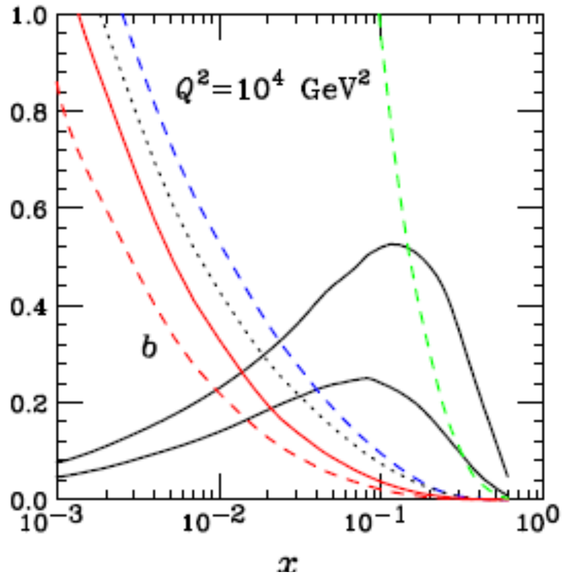
Parton Distribution Functions (PDFs)

a complex target: uud valence+sea

Current picture of the proton



Proton content:
u,d,s,c,b,gluons



LHC parton kinematics - definitions -

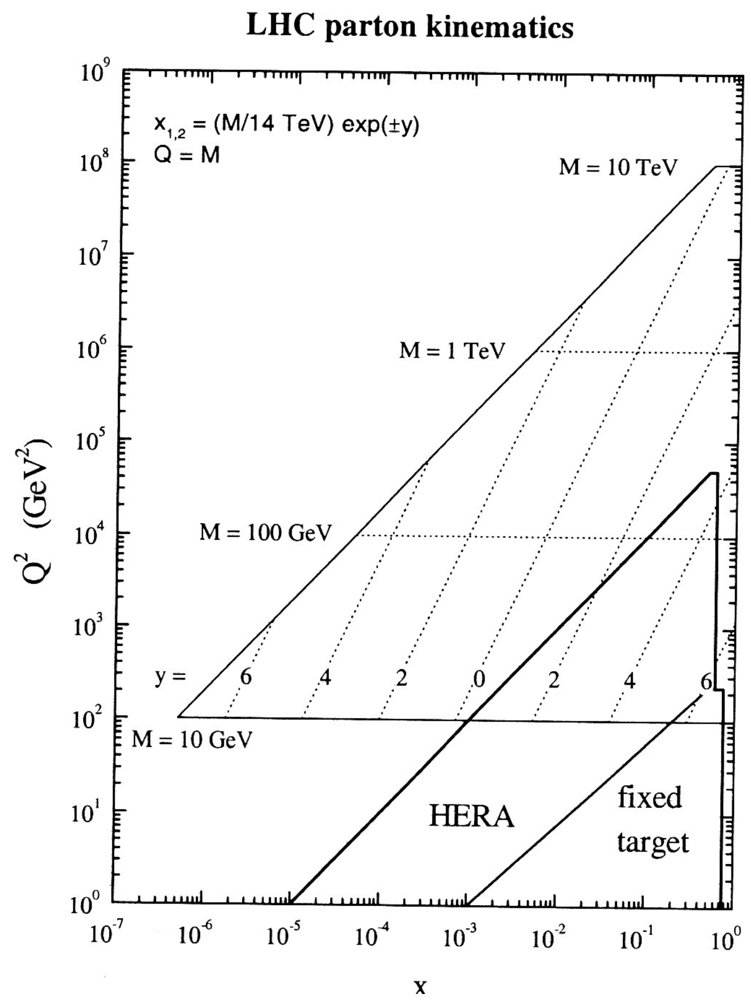
A particle of mass M and rapidity y produced by a pair of partons (1,2) carrying a fraction

$$x_{1,2} = \frac{P^L{}_{1,2}}{P_{\mathrm{BEAM}}(=7\ \mathrm{TeV})} = \frac{P^L{}_{1,2}}{\sqrt{s}/2}$$

of the proton momentum.

Can show that

$$x_{1,2} \approx \frac{\mathrm{M}e^{\pm y}}{\sqrt{s}}$$



Demonstration (left as exercize)

$$y = \frac{1}{2}\ln\left(\frac{E + P_L}{E - P_L}\right) \; ; \; M = \sqrt{x_1 x_2 s} = \sqrt{\tau s}$$

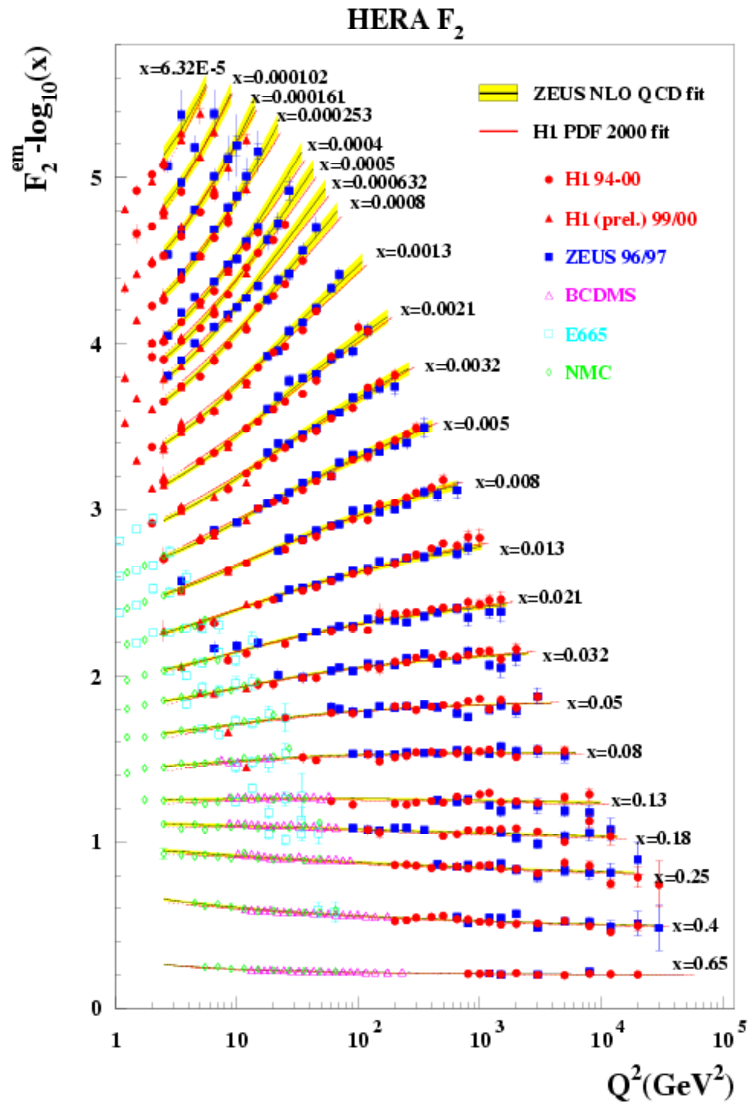
$$e^y = \sqrt{\frac{E + P_L}{E - P_L}} = \sqrt{\frac{(E + P_L)^2}{E^2 - P_L{}^2}} = \frac{E + P_L}{\sqrt{\tau s}}$$

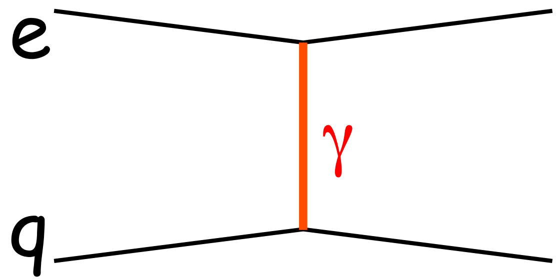
$$P_L = P_{1L} - P_{2L} \; ; \; E \approx P_{1L} + P_{2L} \; ; \; (\text{if } E >> M)$$

$$\sqrt{\tau} e^y = \frac{E + P_L}{\sqrt{s}} \approx x_1 \; ; \; \sqrt{\tau} e^{-y} = \frac{E - P_L}{\sqrt{s}} \approx x_2$$

$$x_{1,2} \approx \frac{M e^{\pm y}}{\sqrt{s}}$$

Measurements of PDFs from Deep Inelastic Scattering (e.g. HERA)





The measurement is in a limited region in Q^2 and **x**, extrapolation at a different Q^2 and higher **x** is done with the DGLAP evolution equation.

PDF fits from lower energy experiments

- Parameterize a set of pdfs at a "starting scale" Q_0^2

e.g. $xg(x) = A\, x^{\alpha}\, (1-x)^{\beta}\, P(x)$ to ensure rise at low x and $xg(x) \rightarrow 0$ as $x \rightarrow 1$
and a set of quark pdfs, e.g. u_{val}, d_{val}, TotalSea = $\Sigma\, \bar{q}$, $\bar{d} - \bar{u}$

- Usually impose sum and counting rules : $\int (xq + xg) = 1$, $\int u-\bar{u} = 2$, $\int d-\bar{d}$ - 1

- Starting scale : not too high, to keep as much data as possible (mainly DIS)
  not too low, to be in the perturbative domain.
  Typical value $Q_0^2 \sim 4$ GeV^2.

  - DGLAP equations give $f(x,Q^2)$ at any Q^2, once $f(x, Q_0^2)$ is known.
    Allows to calculate σ_{theo} (DIS, DY, jet data,…) and fit theory to data.

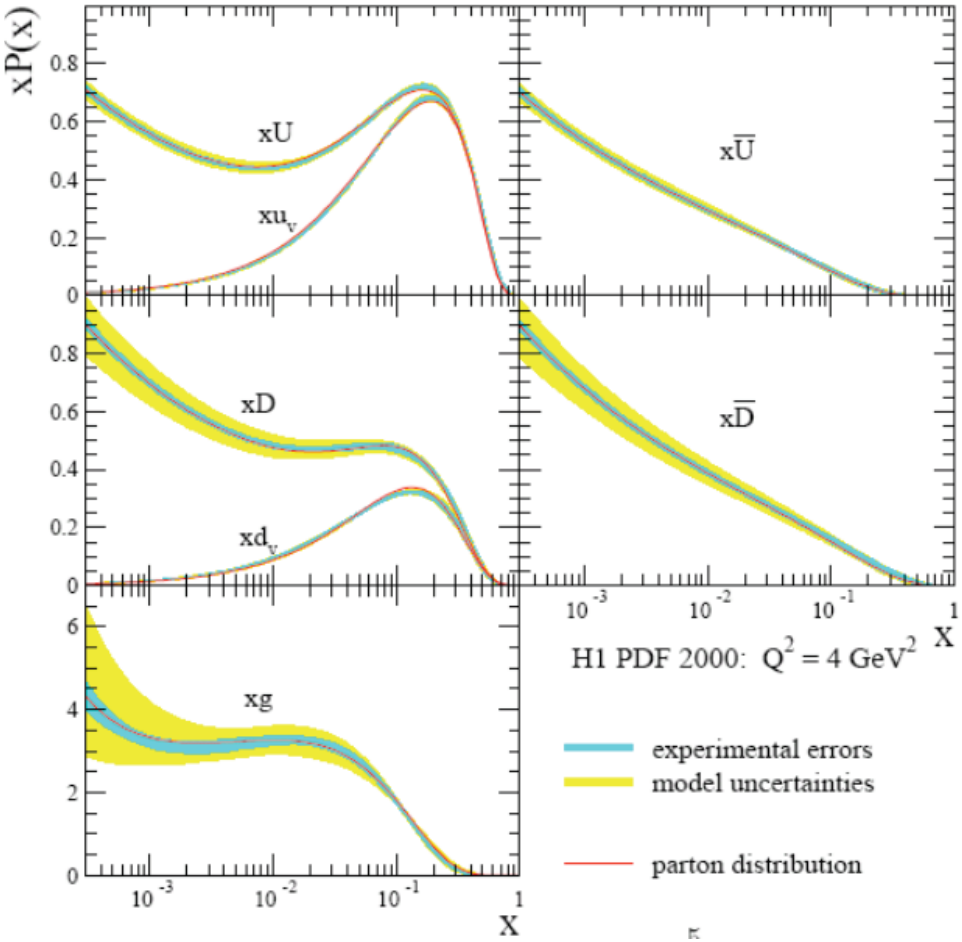
$\bar{u} = \bar{d}$ had been a "natural" assumption for a long time over the whole x range, until NA51, E866 (DY) found difference at x ~ 0.1.

→ All fits assume, directly or not, that $\bar{u} = \bar{d}$ at low x.

Results from HERA

H1 Collab, Eur Phys J C30 (2003) 1.

$Q^2 = 4$ GeV^2



"H1PDF2000" fit :

below bottom threshold

$$
\begin{aligned}
xU &= x(u+c)\\
x\overline{U} &= x(\overline{u}+\overline{c})\\
xD &= x(d+s)\\
x\overline{D} &= x(\overline{d}+\overline{s})
\end{aligned}
$$

i.e. parameterize what is measured.

Blue band = fit uncert.
Yellow band = model undert., i.e. vary $\alpha_S(M_Z)$, Q_0^2, m_c, m_b + others.

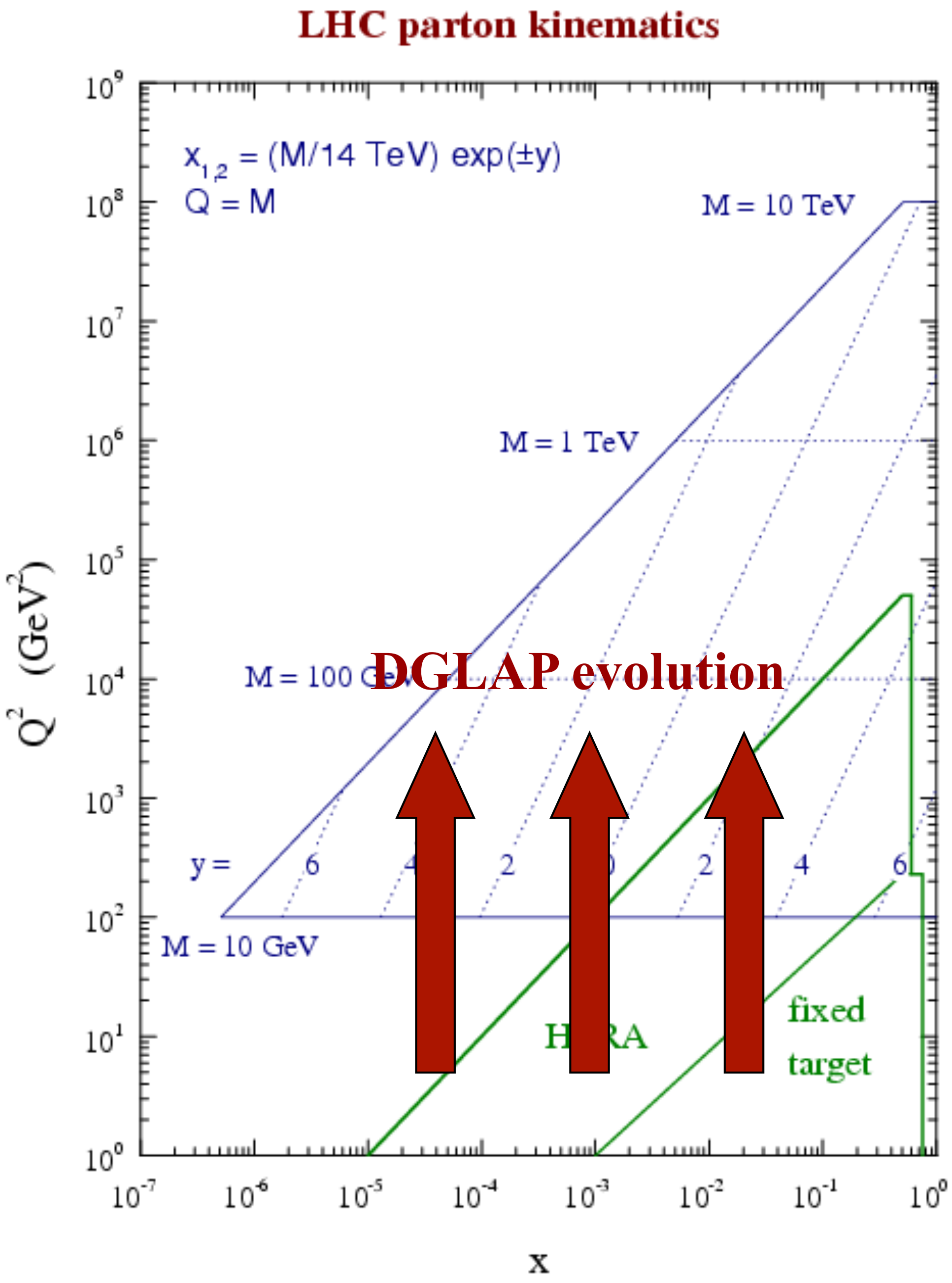
At $x \sim 10^{-3}$, central production of W, Z at LHC, uncertainties are not too large.

QCD Evolution of PDFs

At the LHC: momentum fractions x_1 and x_2 determined by mass and rapidity of X

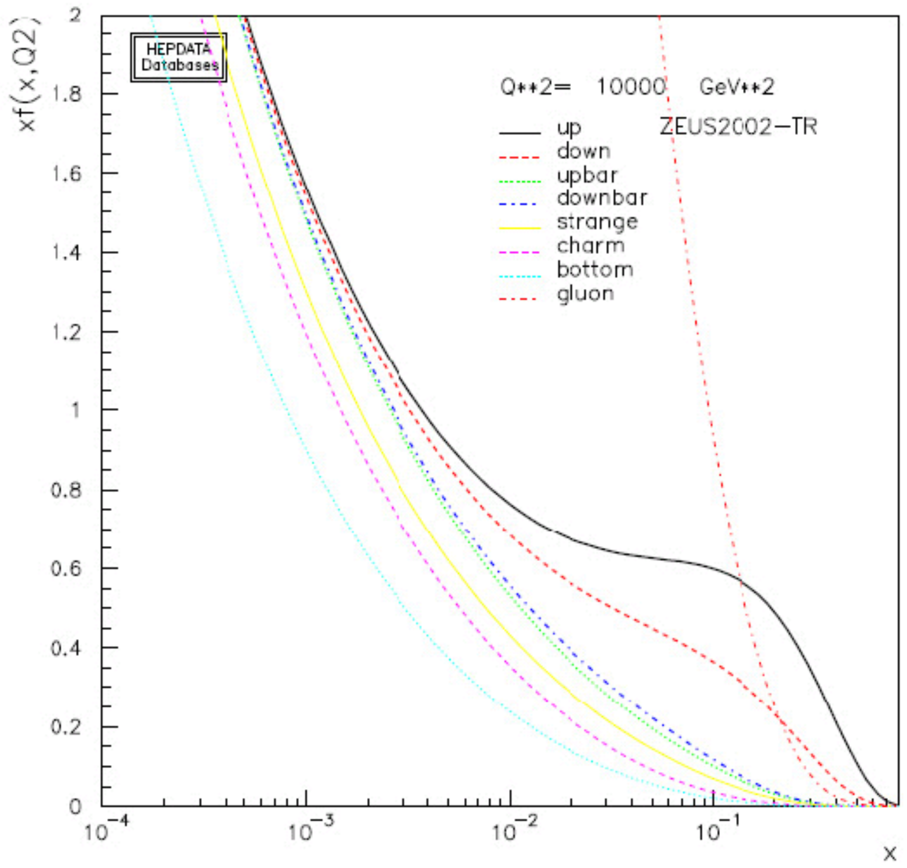
HERA measurements do not cover the LHC region, eg. for central Higgs production
⇒PDFs evolved via DGLAP equations from (x,Q^2_0) to (x,Q^2)

Note: W,Z, Higgs production needs PDFs from the x range 10^{-4} - 10^{-1}



LHC is a gluon collider

- The PDF phase space region explored by LHC was largely unknown and analysis of LHC data is of paramount importance in order to gain understanding.
- At the **electroweak scale** the **gluons** are the dominant partons at LHC.



Computing the cross sections

$$\sigma(p_1, p_2; Q, \{...\}) = \sum_{a,b} \int dx_1 dx_2 f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) \hat{\sigma}_{a,b}(x_1 p_1, x_2 p_2, Q, \{...\}; \alpha_s(Q))$$

Need a specific PDF set, example from MRST(2000)

$\sqrt{s} = 14$ TeV

$\sigma_{\mathrm{tot}} = 99.$ mb

$\sigma_{\mathrm{b}} = 63.\ \mu$b

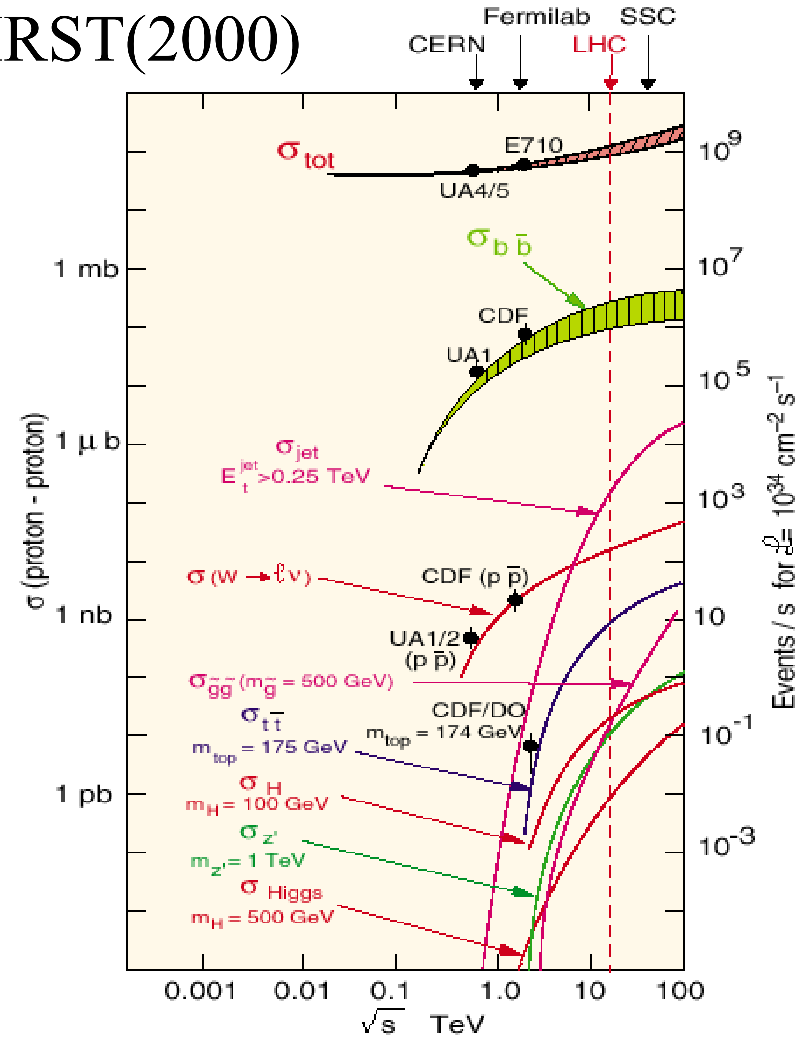
$\sigma_{\mathrm{t}} = 890$ pb

$\sigma_{\mathrm{W}} = 190$ nb

$\sigma_{\mathrm{Z}} = 56$ nb

$\sigma_{\mathrm{Higgs,(m_{Higgs}=150\,GeV)}} = 24$ pb

$\sigma_{\mathrm{Higgs,(m_{Higgs}=500\,GeV)}} = 3.8$ pb

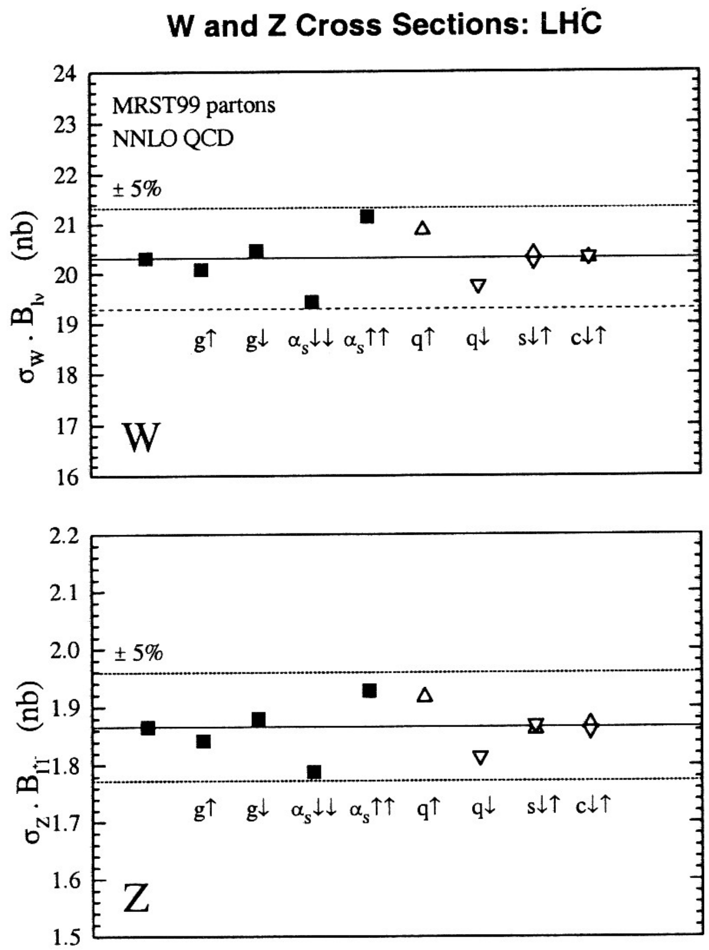


PDF uncertainties on the expected cross sections

- Uncertainties on the DGLAP evolution, mainly on the gluon component and on α_s
- Measurement errors on the original structure function
- Uncertainties on the strange and charm content

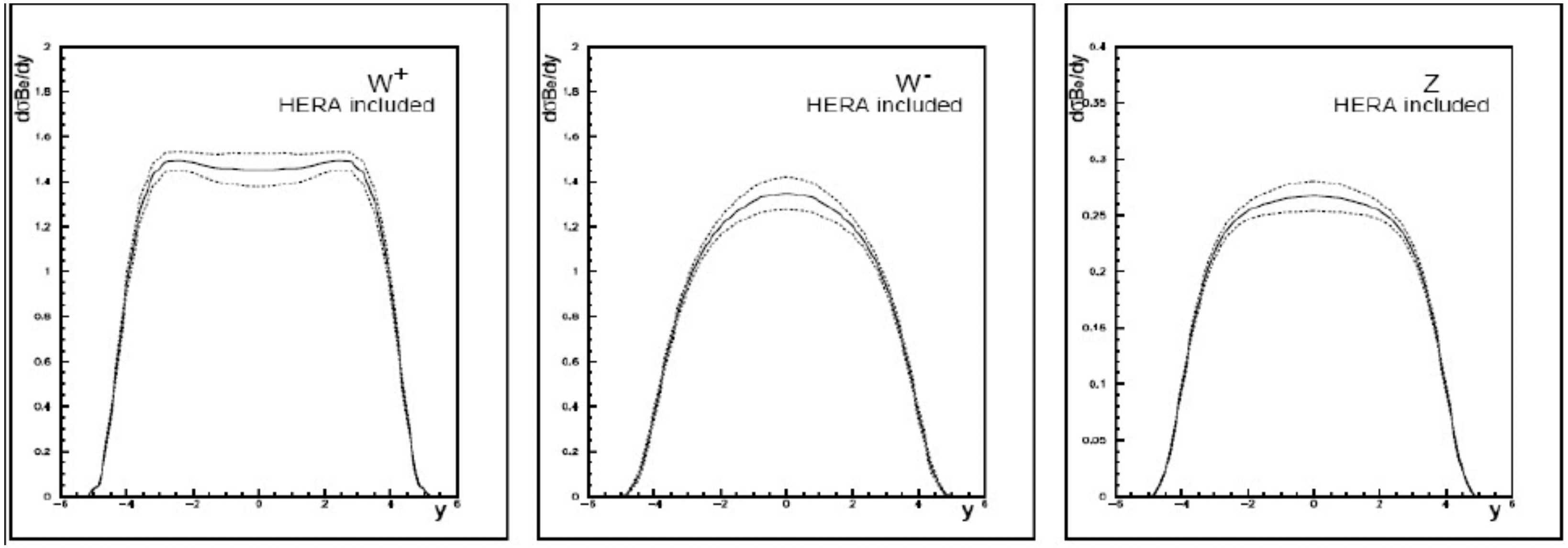
(Example: only 75% of the Ws are coming from u-dbar)

[not only PDFs but also higher orders on $\hat{\sigma}$ yield uncertainty]



Measure PDF with LHC data

- Production cross sections (W, Z, γ, jets)
  - e.g. γ+Jet for gluons (qg→qγ) **QCD Compton**
  - HF tagged qg→qγ, qZ, qW for c,b PDF
- Differential cross sections increase sensitivity
  - W, Z rapidity
  - W charge asymmetry → $\sigma(W^+) \sim 1.35\ \sigma(W^-)$

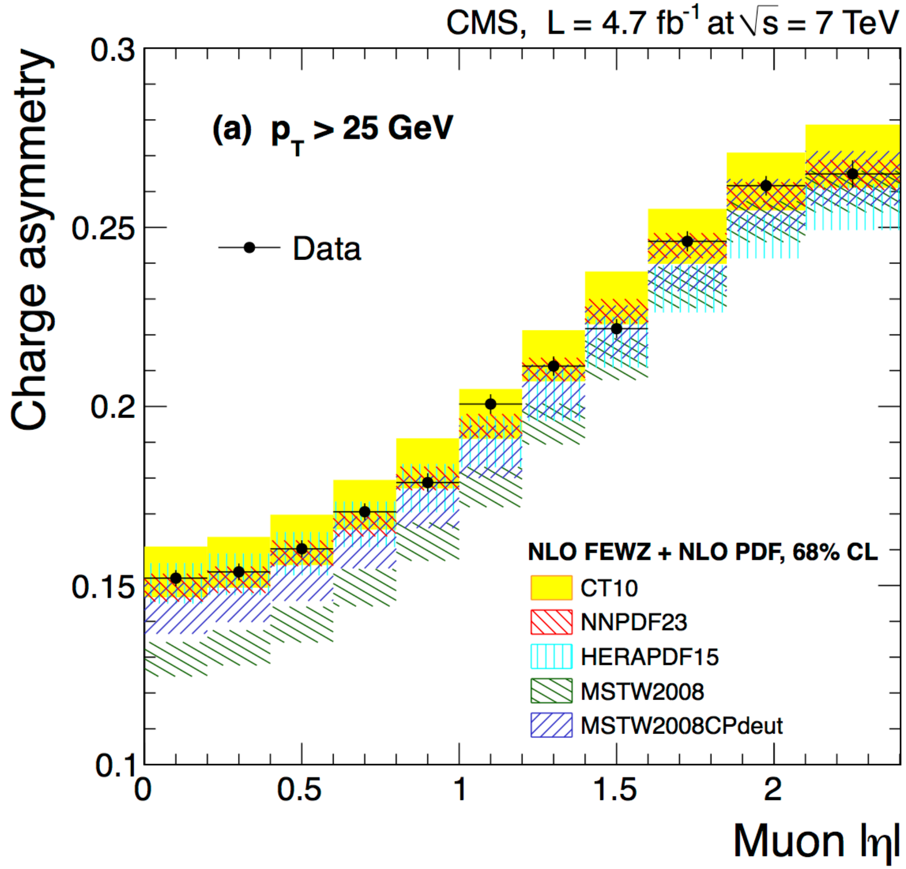


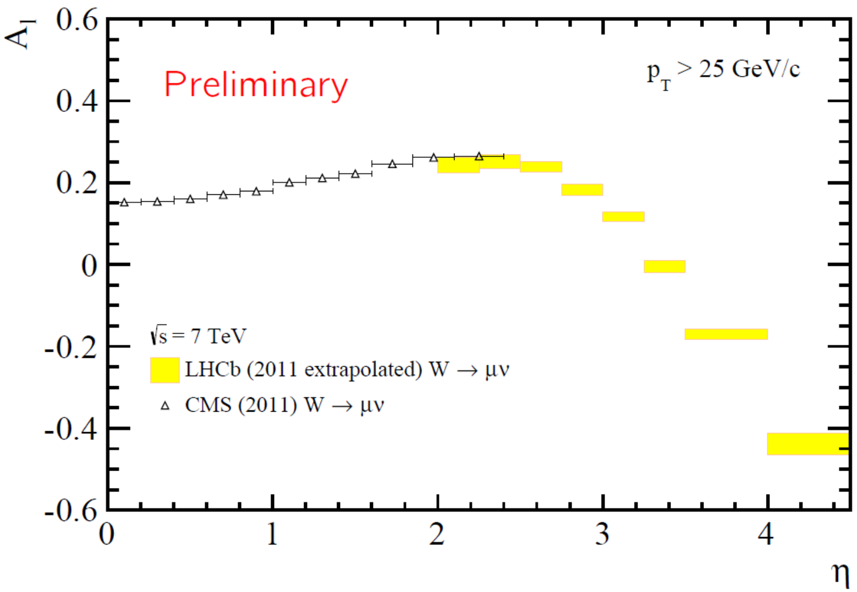
PRD 90 (2014) 032004

W charge asymmetry

- The differential charge asymmetry: sensitive to u/d ratio as a function of rapidity
- Asymmetry measured at permil level per bin
- Forward measurement from LHCb, sensitivity to low x !

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



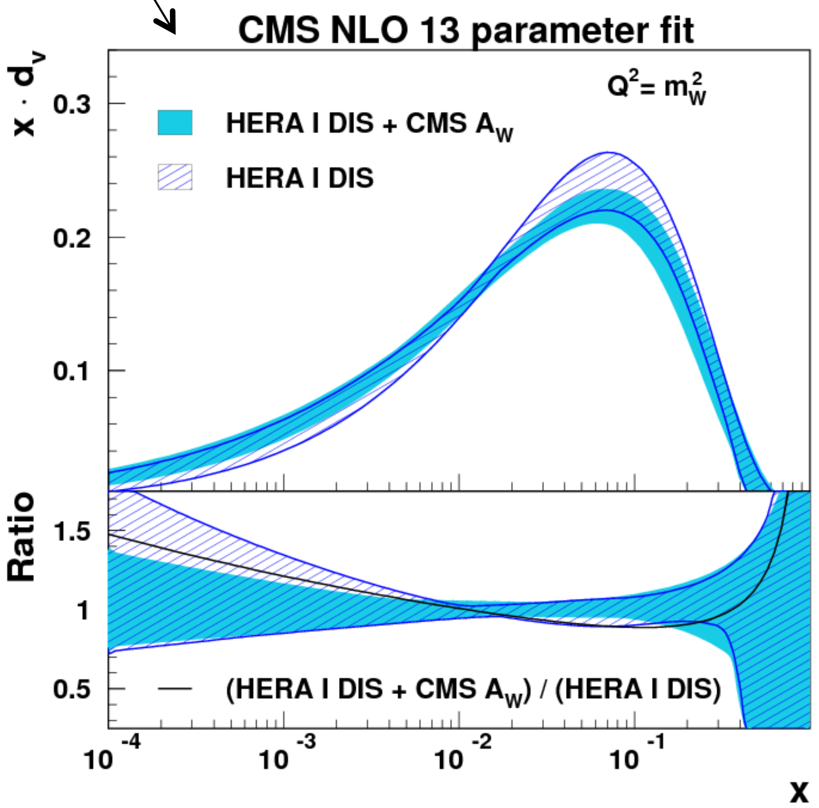


The dependence from $|\eta|$ follows from $x_{1,2} \approx \frac{Me^{\pm y}}{\sqrt{s}}$

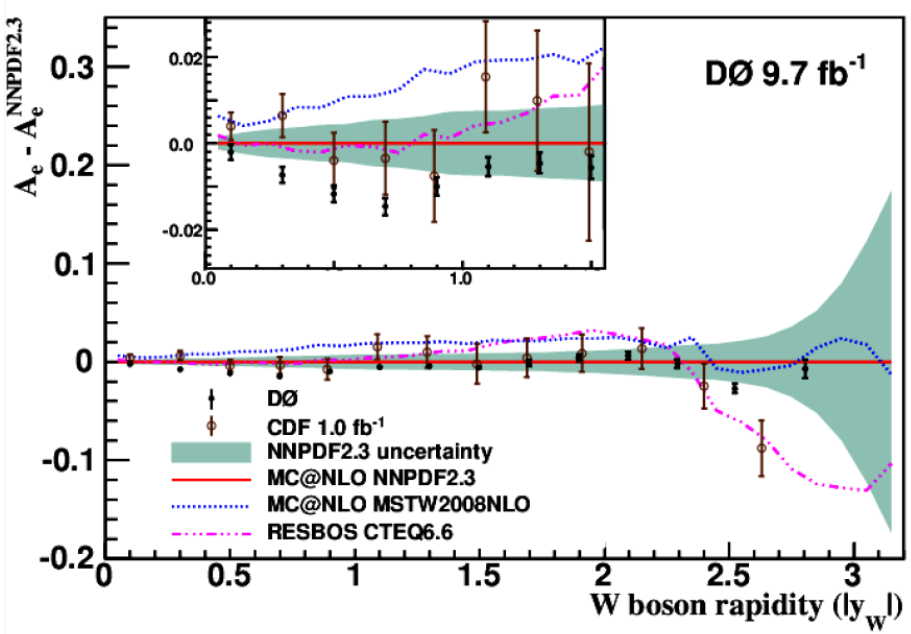
at high rapidity need one parton at very high x

W charge asymmetry and PDF fits

LHC data combined with HERA DIS to improve d-valence PDF



Input from W charge asymmetry at Tevatron



Z rapidity and p_T

Enough statistics to measure double differential cross section
Sensitivity to PDF and higher order QCD calculations (NNLO)