Elektroweak Physics
Higgs Physics
from the Tevatron to the LHC
DESY summer student lectures
Hamburg, Aug. 16, 2011

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GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Outline (Electroweak)

- Why electroweak physics at a hadron collider?
- W and Z production and detection
- Cross section measurements
- Drell-Yan forward-backward asymmetry and the weak mixing angle
- The W mass
- The W charge asymmetry
- Diboson physics/ TGCs
- Electroweak Summary

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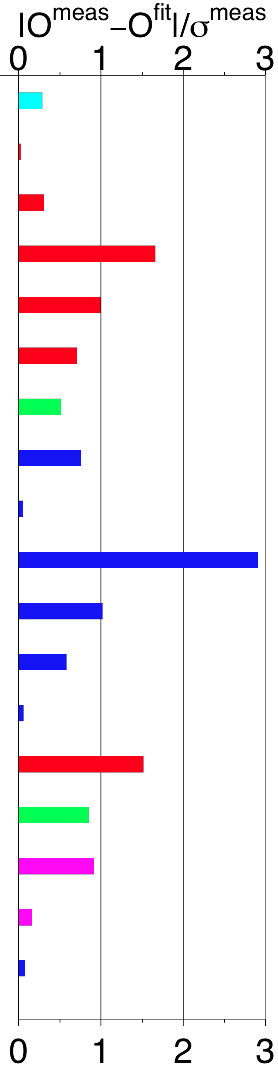
Why EW at a hadron collider?

- Electroweak physics is precision physics: Testing the SM at the loop level and beyond
- e+e-collider are predestined to achieve the highest precision due to their simple initial state: LEP. Many LEP measurements are still the most precise: Z mass...
- However: Abundant statistics and very clean samples make EW physics competitive at hadron colliders. Have surpassed LEP in many measurements: W mass!

- Many interesting measurements at the interface of EW and QCD. Specific measurements for hadron colliders...

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



July 2011

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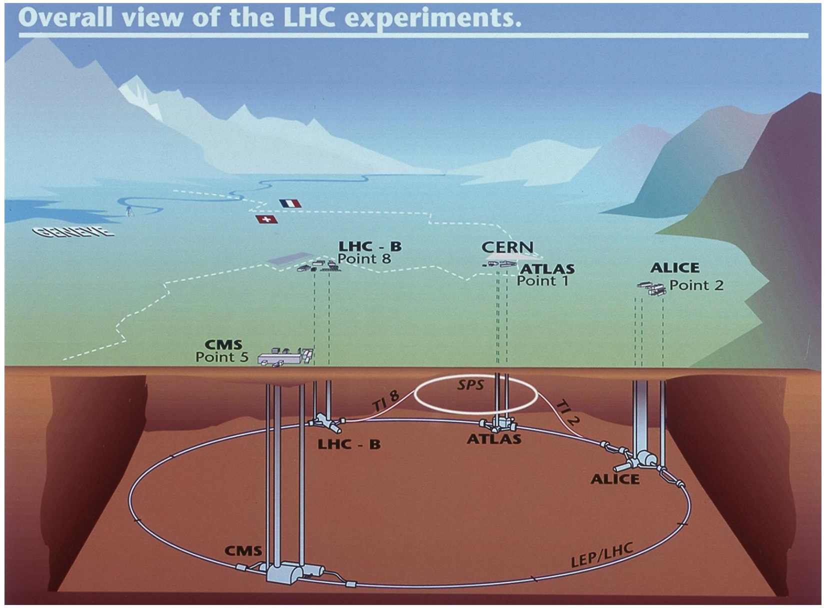
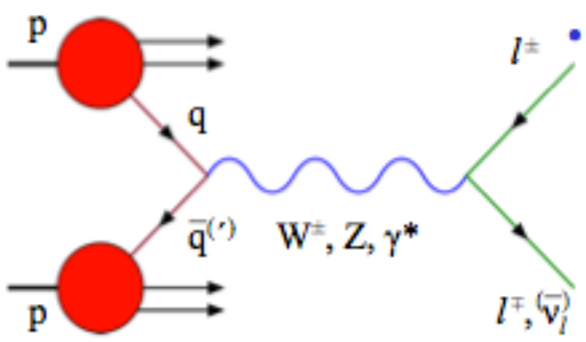
W/Z Factories: Tevatron →LHC



location	:	Fermilab, USA	CERN, Geneve, Switzerland
start	:	1987	2008 (restart 2010)
collider type	:	proton – anti-proton	proton – proton
experiments (top)	:	**CDF, D0**	**ATLAS, CMS**, ALICE, LHC-B
$\sqrt{s}$	:	1.8 GeV→ 1.96 GeV	14 TeV (7 TeV for 2010)
L (instantaneous)	:	$10^{30} \rightarrow 3\times10^{32}$ cm^{-2}s^{-1}	10^{34} (4×10^{32} for 2010) cm^{-2}s^{-1}
L (integrated)	:	≈ 10,000 pb^{-1}	≈ 300/3000 fb^{-1}
σ(pp→W+X→lν+X)	:	≈ 2.7 nb	≈ 10.5 nb at 7 TeV
W+X→lν+X events / 100 pb^{-1}	:	≈ 270000	≈ 1 M

W/Z production

W/Z production from quark/antiquark annihilation



$$Q^2 = m^2_{W,Z} = x_1 x_2 s$$

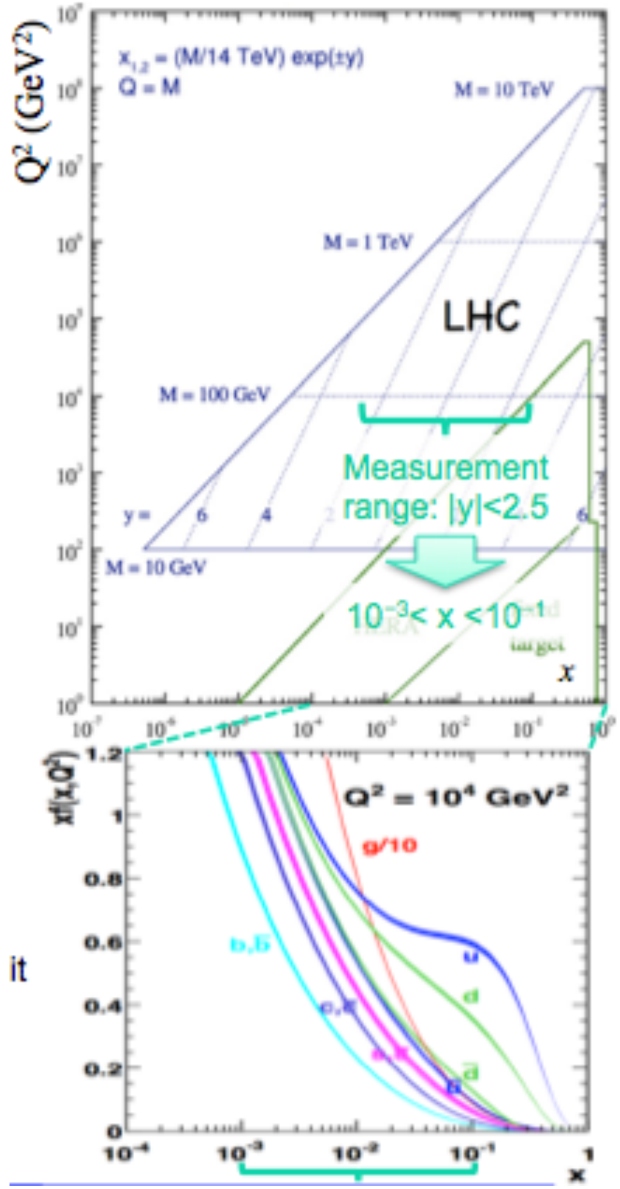
Tevatron (ppbar):

- Equal number of W^+ and W^-
- asymmetric production in rapidity for each W^+ and W^-

LHC (pp):

- $\sigma(W+)/\sigma(W-)=1.43$ (if purely valence-sea: 2)
- Symmetric production in rapidity for each W^+ and W^-

- Accurate theoretical calculations exist
- Differential distributions sensitive to PDFs



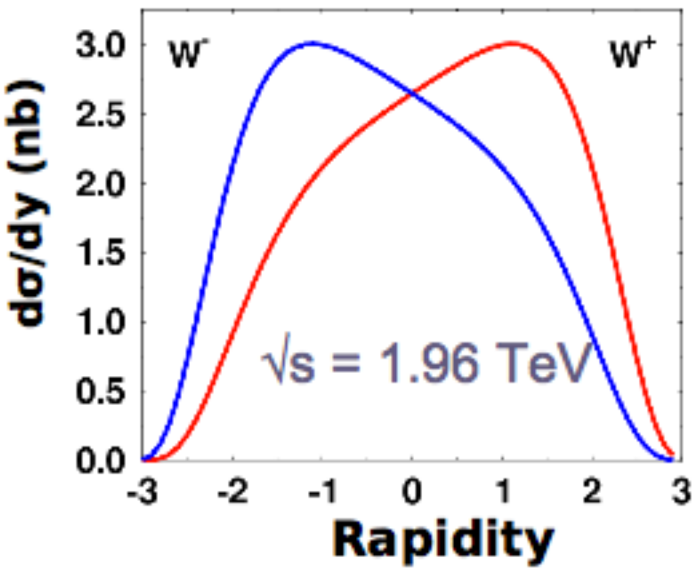
W production

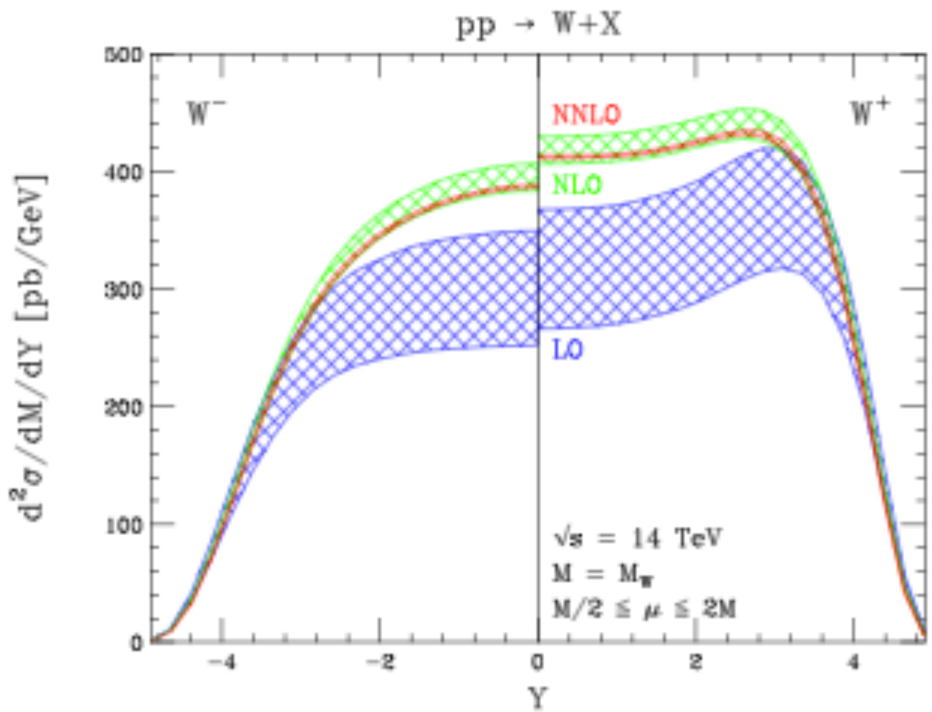
Tevatron: W^+ produced more abundantly in the direction of the proton and vice versa.

However: W^+ and W^- rapidity distributions are identical (but mirrored), absolute rates the same.

LHC: W^+ and W^- each symmetric in rapidity (symmetric initial state: pp).

However: W^+ and W^- rapidity distributions and absolute rates differ: Valence u quarks carry more momentum on average than d quarks.





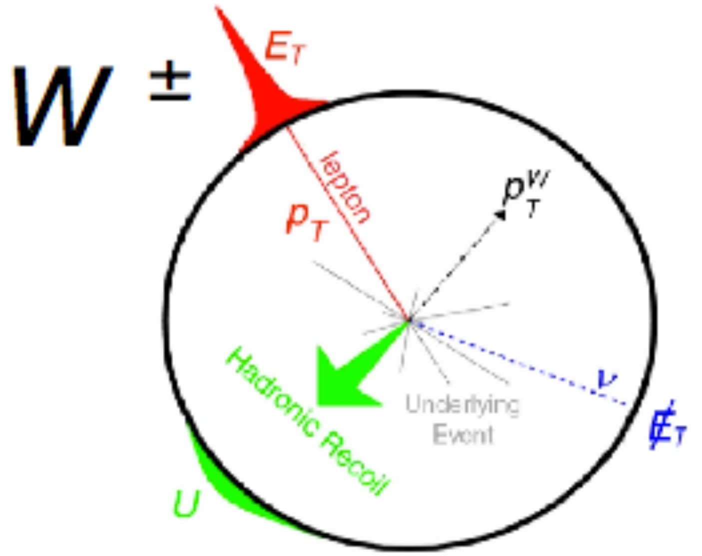
W and Z detection

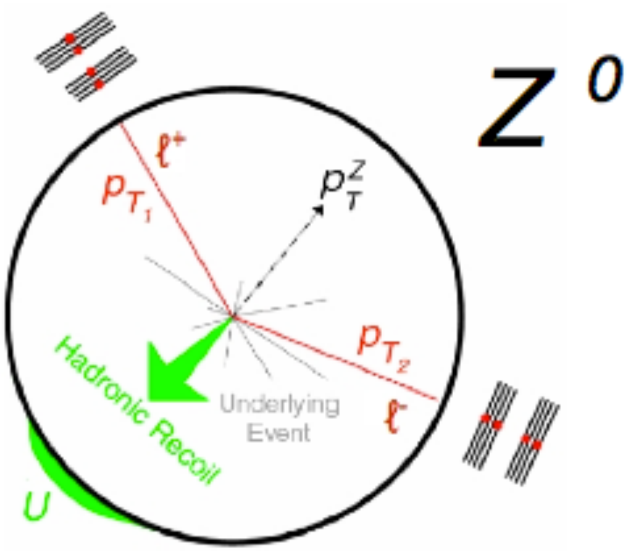
Decay channels:
W:
1/9=11% W→lν (lepton universality)
2/3=67% hadrons

Z:
Z→ll: 3.4%
Z→νν: 20.5% („invisible channel“)
Z→hadrons: 69.2%

Leptonic decay channels almost exclusively used at hadron colliders.
- One or two charged leptons
- Large missing transverse Energie (Neutrino from W decay)
- Possibly additional hard jets

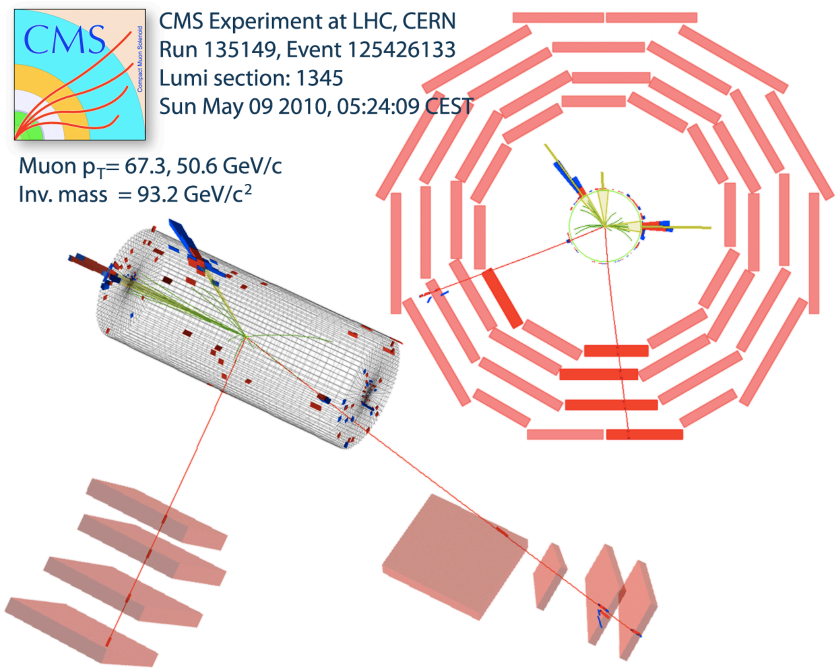
→Clean signatures→low background
→Large cross sections →W/Z produced in abundance →Precision measurements, differential
→Can be used as a tool to understand the detector



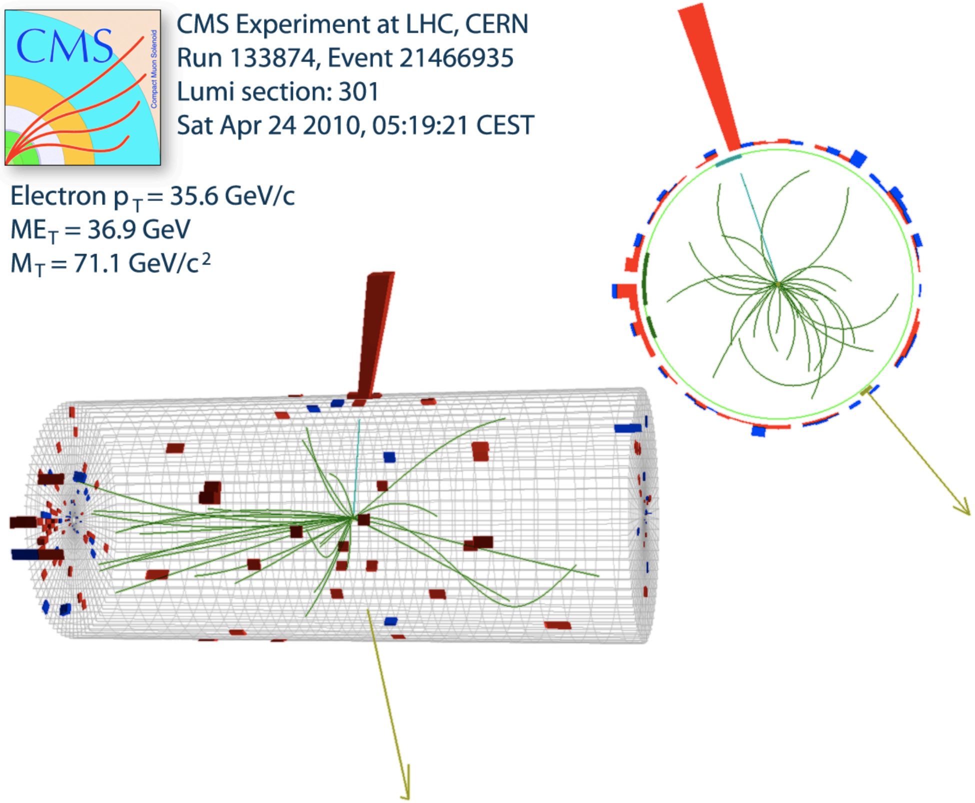


Event Displays

Z→μμ candidate event



W→eν candidate event



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Cross section measurements

Cross section measurements are conceptually simple*:

Data driven methods or from Monte Carlo

$$\sigma = \frac{N_{meas} - N_{bkg}}{L \cdot A \cdot \varepsilon}$$

Monte Carlo

Data/Monte Carlo

* The devil is in the details!

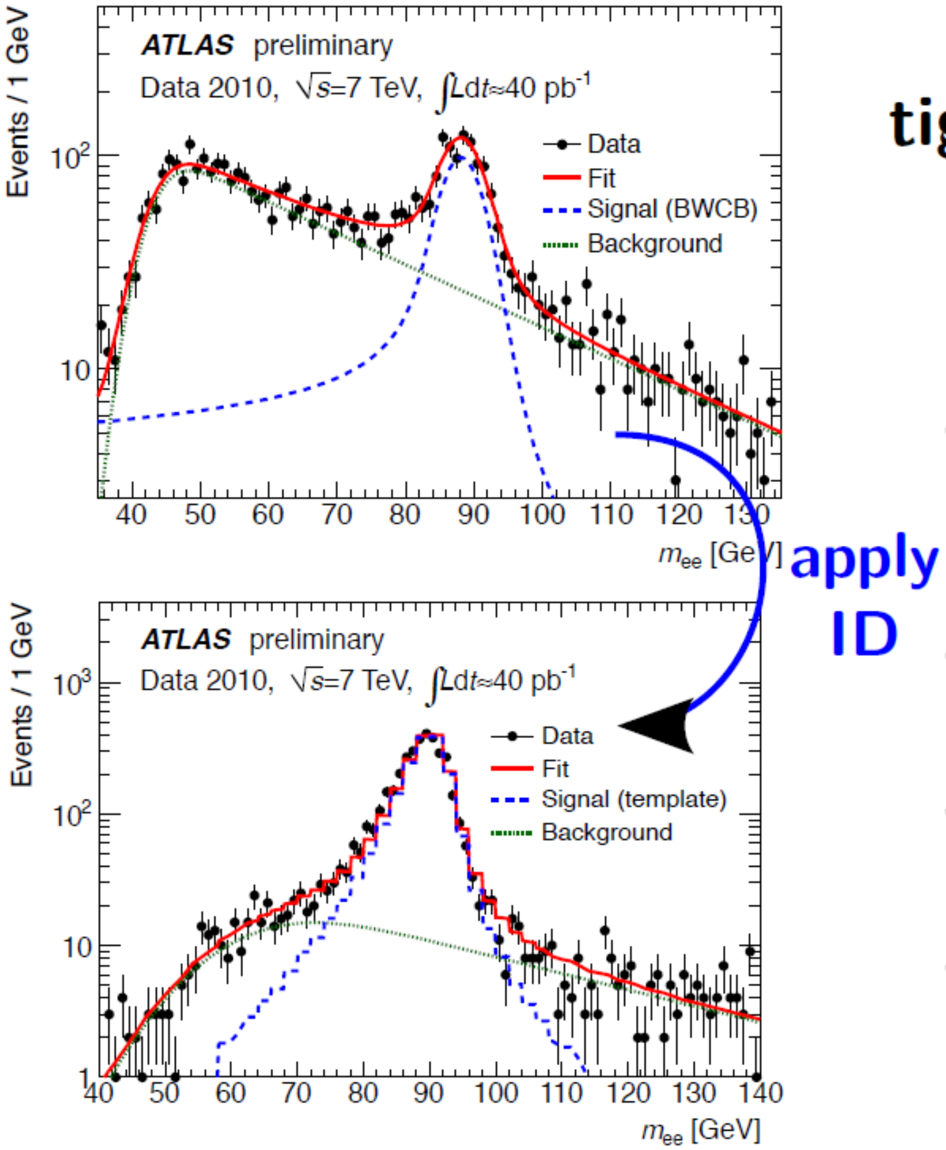
Backgrounds and efficiencies often have to be know as a function of kinematic variables:

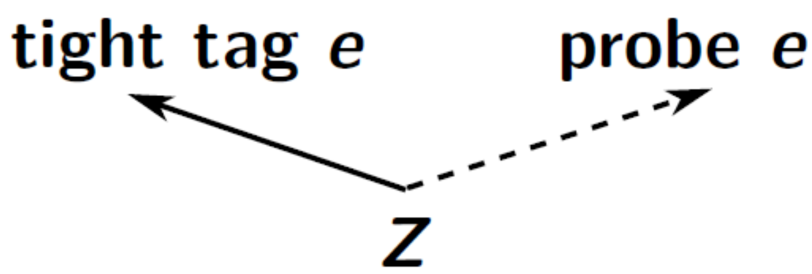
I.e.: Differential cross sections

Sometimes cross section ratios are measured:

(Partial) cancellation of uncertainties!

Measurement techniques: Tag and probe method





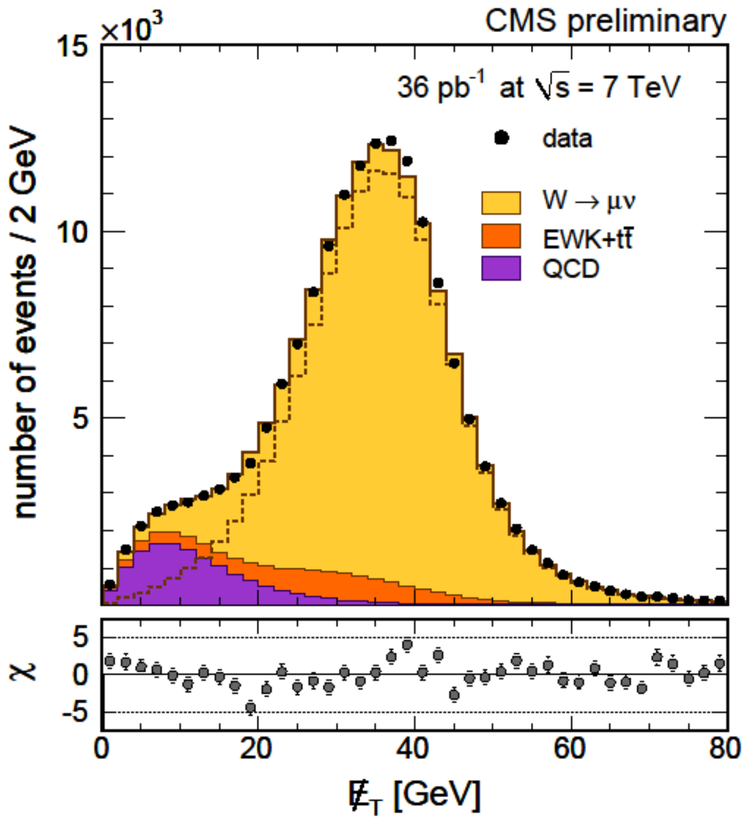
- **"Tag"** events with sufficient purity, leaving an unbiased **"probe"** object.
- Measure probe ID efficiency *in situ*.
- Constrains the performance of our object identification.
- Derive **scale factors** for correcting our simulation.

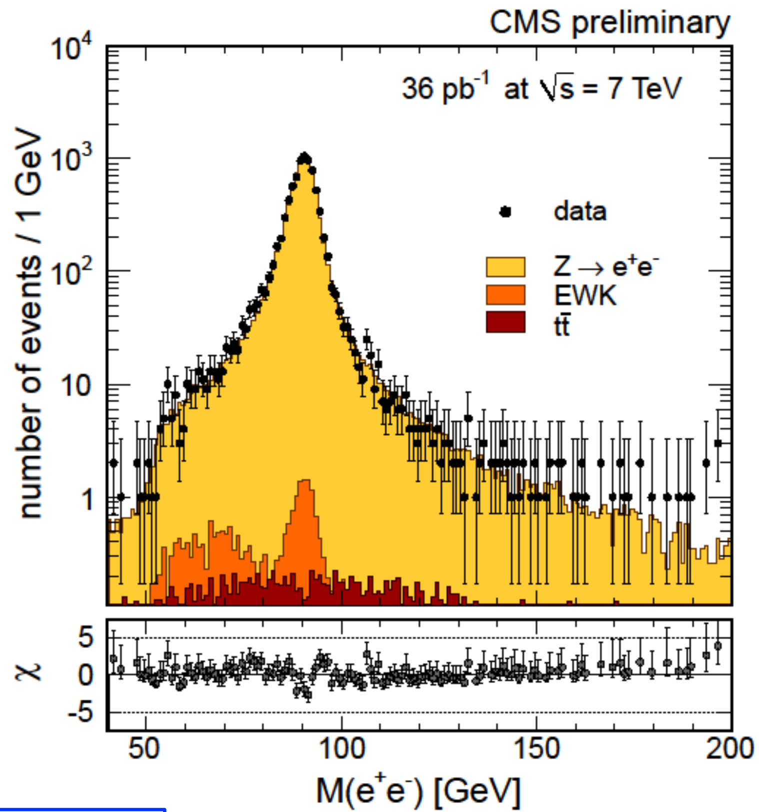
[4] ATLAS-PERF-2010-04-001

Some Key Distributions

Missing transverse Energy for W candidate events in the muon channel.

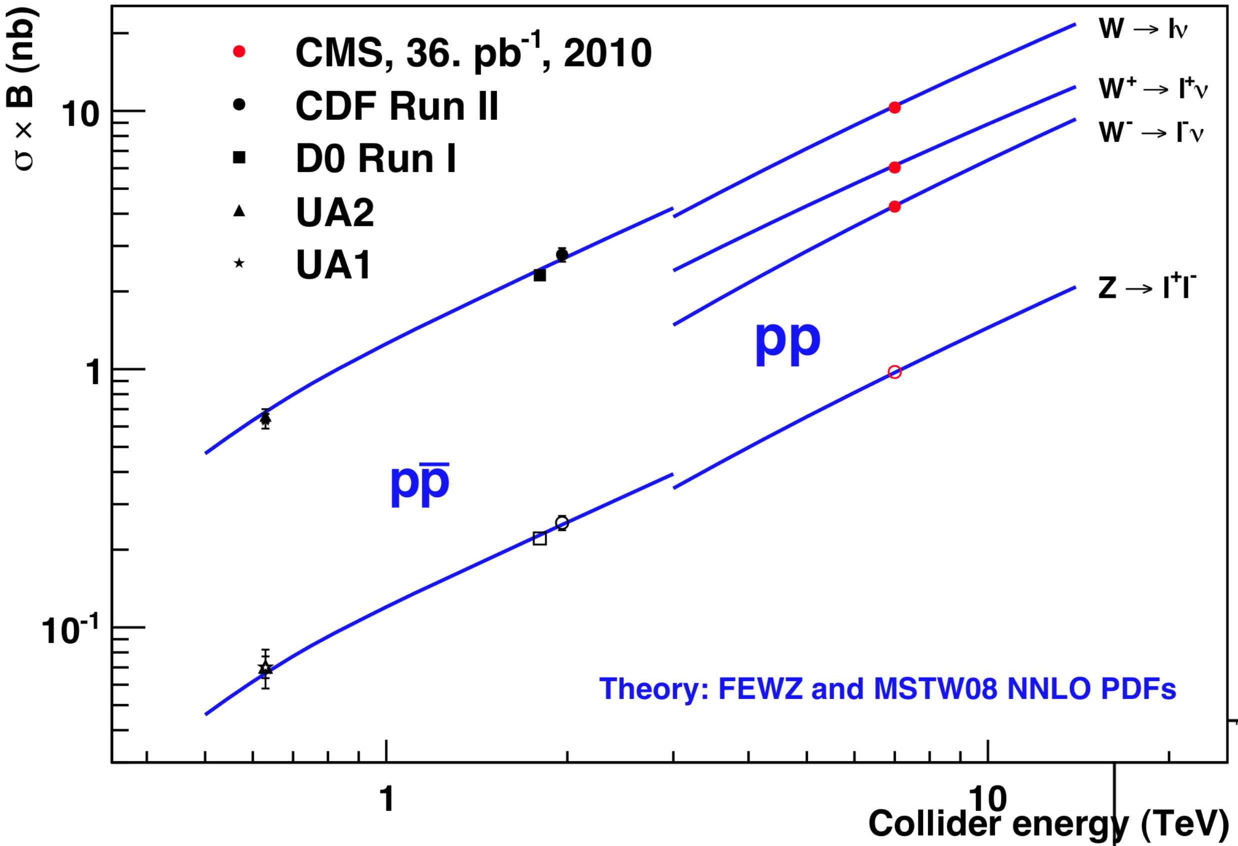
Dielectron invariant mass distribution in for Z candidate events.



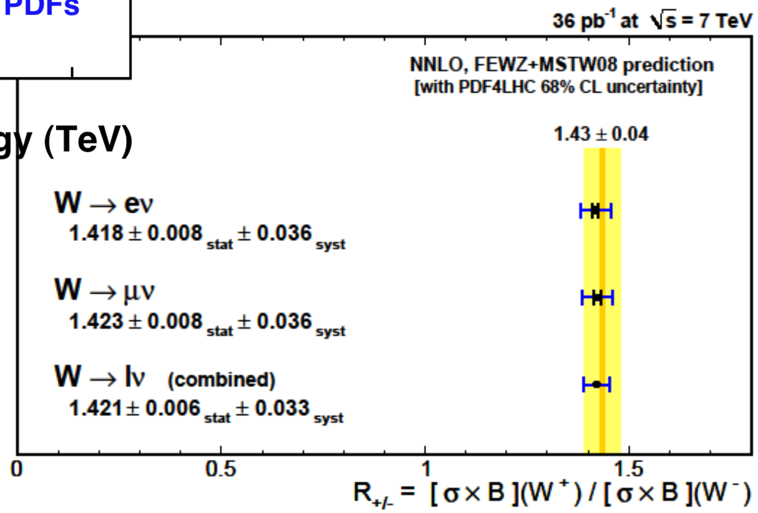


Very clean signals:
Backgrounds small and well understood!

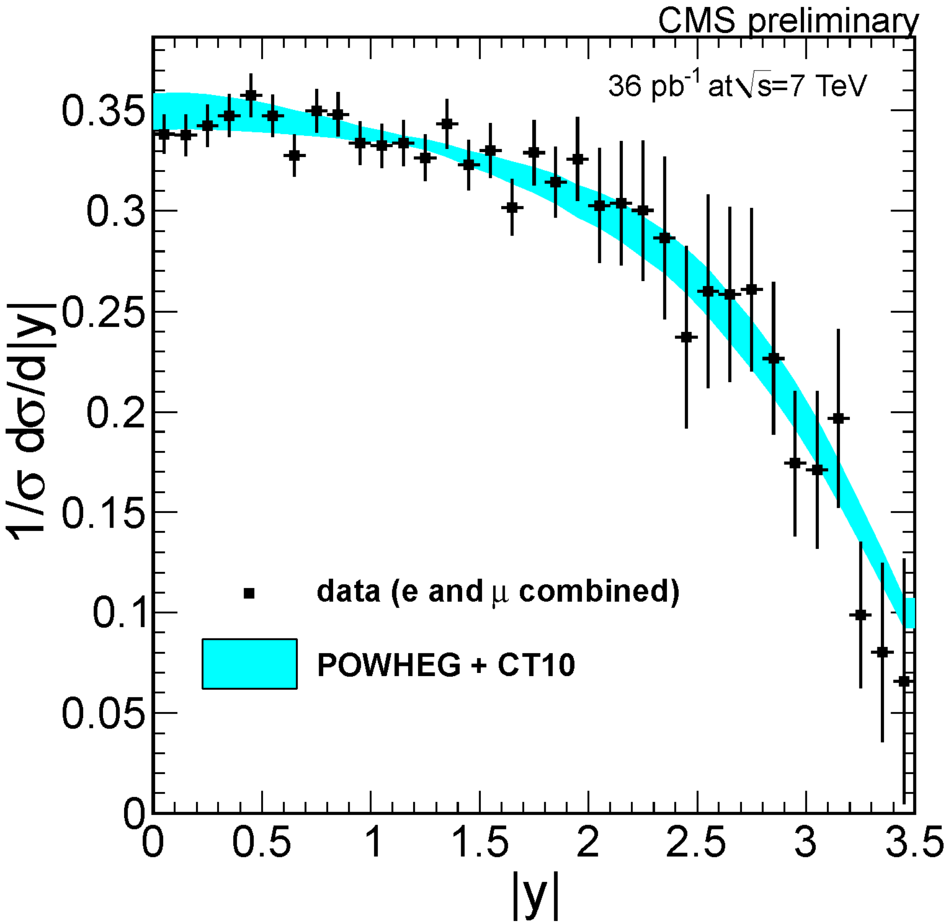
Cross section measurements: Results

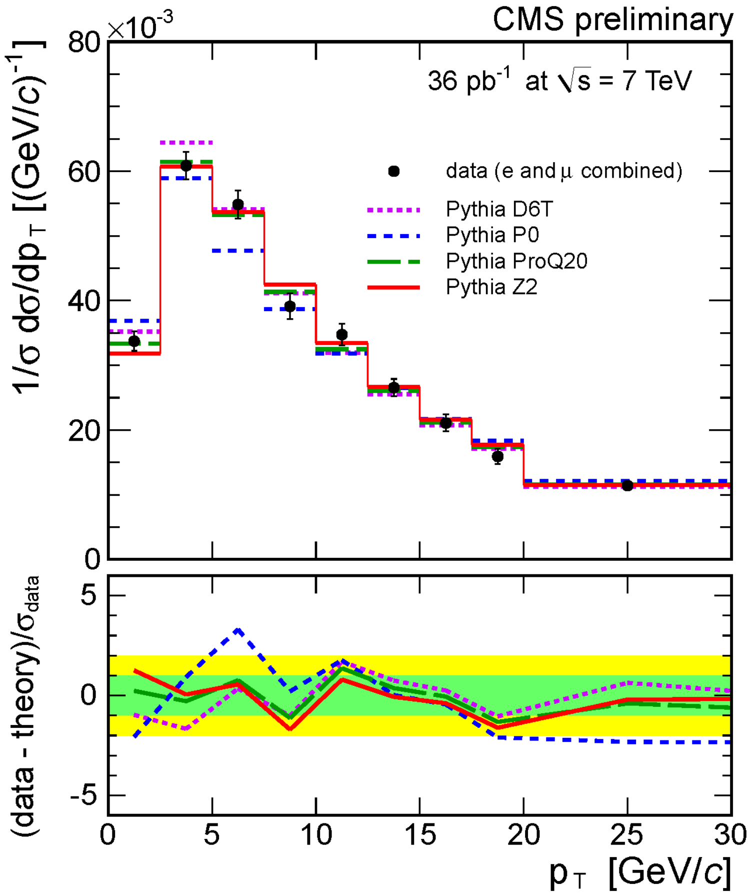


W+/W- ratio



Differential cross sections (Z)





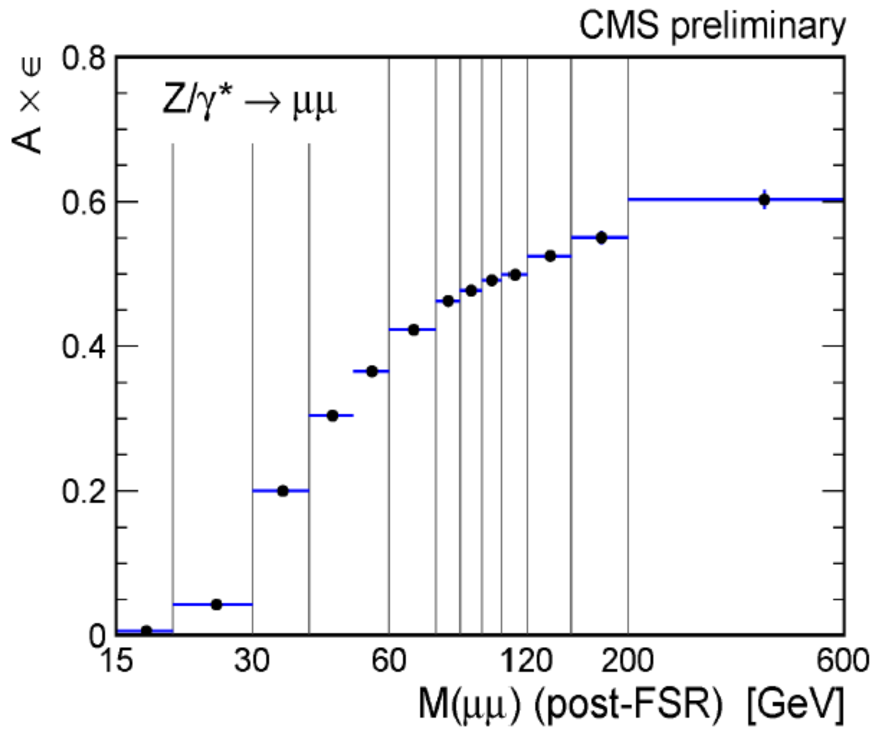
Data well described by Monte Carlo Programs.

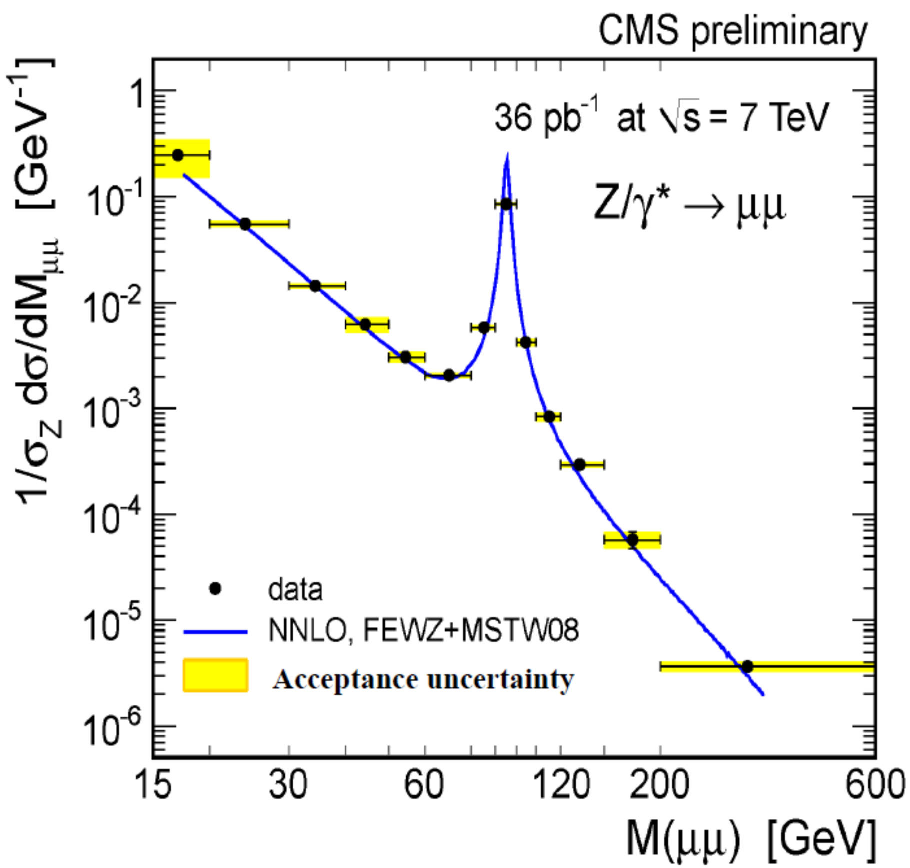
POWHEG: A Shower Monte Carlo at next-to-leading order

Pythia: A high energy physics event generator. Here with different „tunes“

Drell-Yan Mass Distribution

Important benchmark measurement:
- Sensitive to PDFs
- Background for searches with isolated di-leptons





Tighter cuts at low mass suppress QCD background →A×ε strongly mass-dependent→exact dependence needs to be understood!

Unfolded distribution, normalized to Z peak cross section, corrected for QED FSR
→Good agreement with NNLO prediction.

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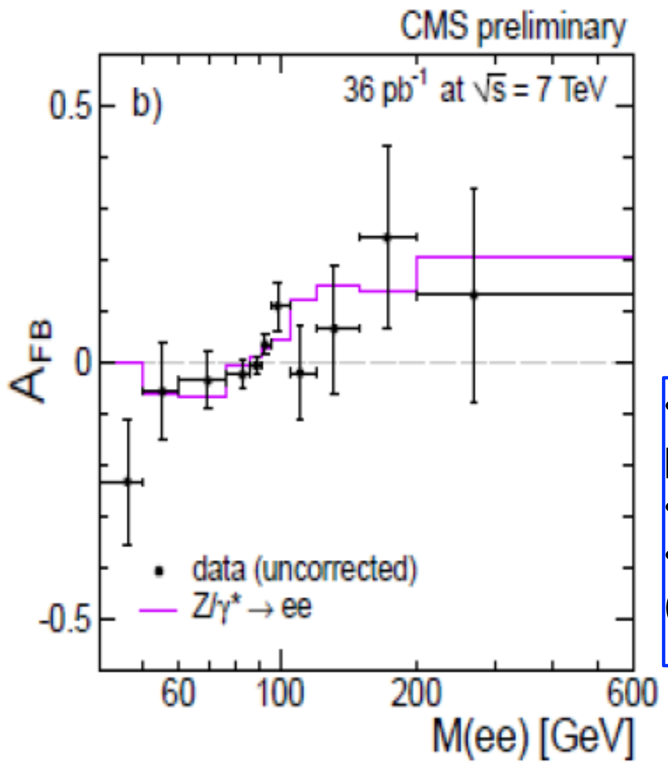
Drell-Yan Forward-Backward Asymmetry

$$\frac{d\rho}{d\cos\theta^*} = \frac{3}{8}\left(1+\cos^2\theta^*\right) + A_{FB}\cos\theta^*$$

- θ^* is the quark-lepton angle in the CM-frame
- Choose special frame where dilepton-direction is used to approximate quark direction
- A_{FB} depends on quark-type and effective weak mixing angle, $\sin^2\theta_{W,eff}$
- → Sensitive to $\sin^2\theta_{W,eff}$



$$\sin^2\theta_{eff} = \frac{1}{4}\left(1 - \mathrm{Re}\frac{g_V}{g_A}\right) = 1 - M_W^2 / M_Z^2$$

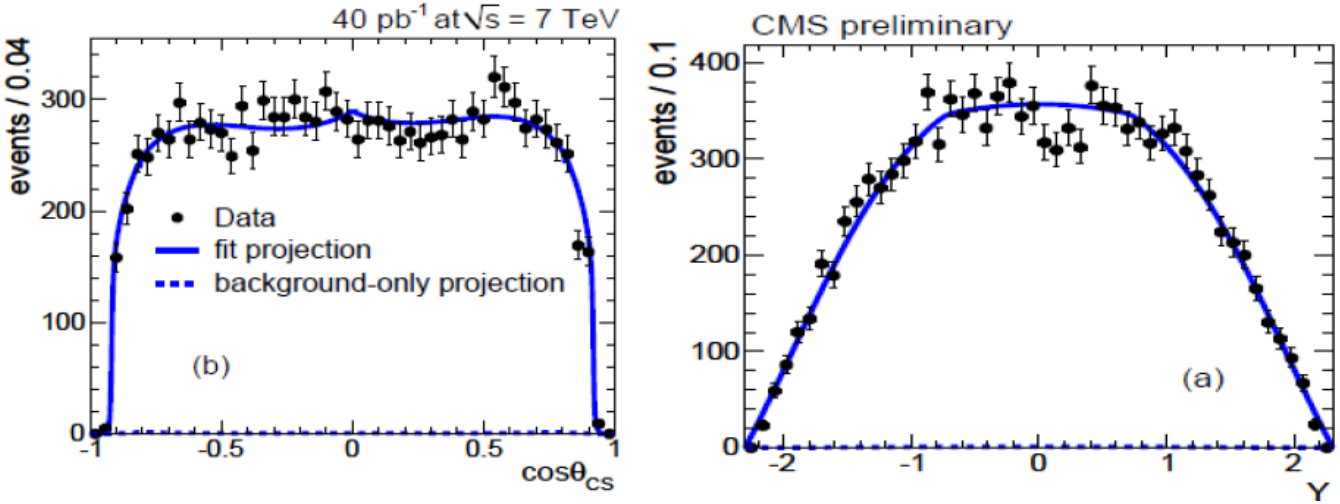
at tree level

Forward events: $\cos\theta^* > 0$
Backward events: $\cos\theta^* < 0$

- Low mass (<60 GeV): Reaction dominated by virtual photon exchange, asymmetry 0
- Asymmetry 0 at Z-pole ($v_l \sim 0$)
- Sizeable asymmetry below (negative) and above (positive) the Z-pole: Axial coupling to the Z

Direct measurement of $\sin^2\theta_{W,eff}$

- Model the dependence of experimental observables in the dimuon-channel on $\sin^2\theta_{W,eff}$ at generator level
- M(μμ), y(μμ), Collins-Soper angle (θ^*_{CS})
- Parametrize experimantal response
- → Extract $\sin^2\theta_{W,eff}$



LO model (ISR)	0.0011
PDFs	0.0015
FSR	0.0018
resolution/alignment	0.0022
fit model	0.0010
background	0.0007
total	0.0036

$$\sin^2\theta_{\text{eff}} = 0.2287 \pm 0.0077(\text{stat.}) \pm 0.0036(\text{syst.})$$

Better precision than using A_{FB} alone.
World average: 0.23153+/- 0.00016

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W Mass Measurement: D0

Using three different observables which are correlated with the W mass, with different systematics. Fit to templates generated in fast Monte Carlo.

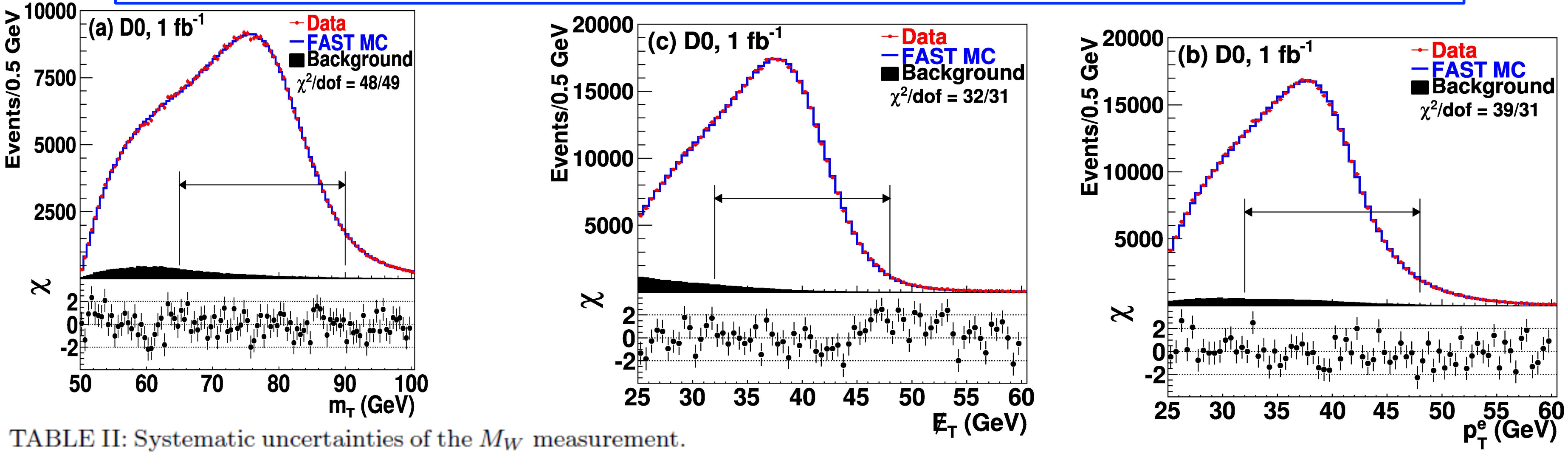


TABLE II: Systematic uncertainties of the M_W measurement.

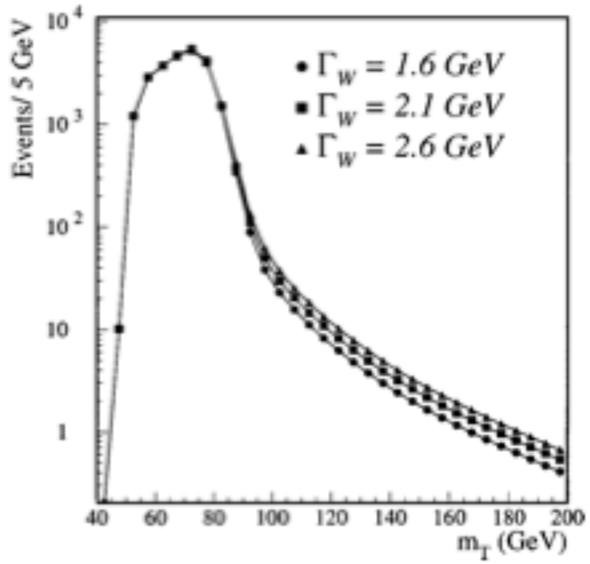
	ΔM_W (MeV)		
Source	m_T	p_T^e	$\not{E}_T$
Electron energy calibration	34	34	34
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	6	12	20
Electron efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	35	37	41
PDF	10	11	11
QED	7	7	9
Boson p_T	2	5	2
Production Subtotal	12	14	14
Total	37	40	43

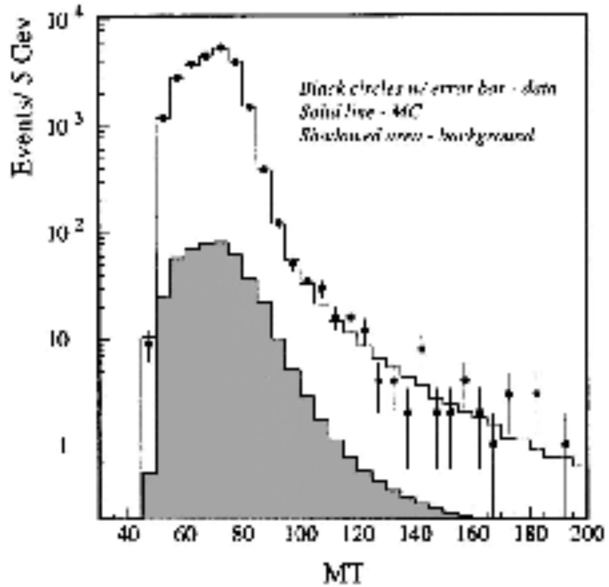
$$M_W = 80.401 \pm 0.021 \text{ (stat)} \pm 0.038 \text{ (syst) GeV}$$
$$= 80.401 \pm 0.043 \text{ GeV}.$$

Most precise single W mass measurement!

Direct W Width: D0

Squezing everything out of one distribution:
Tail of transverse W mass distribution sensitive to width of the W boson.





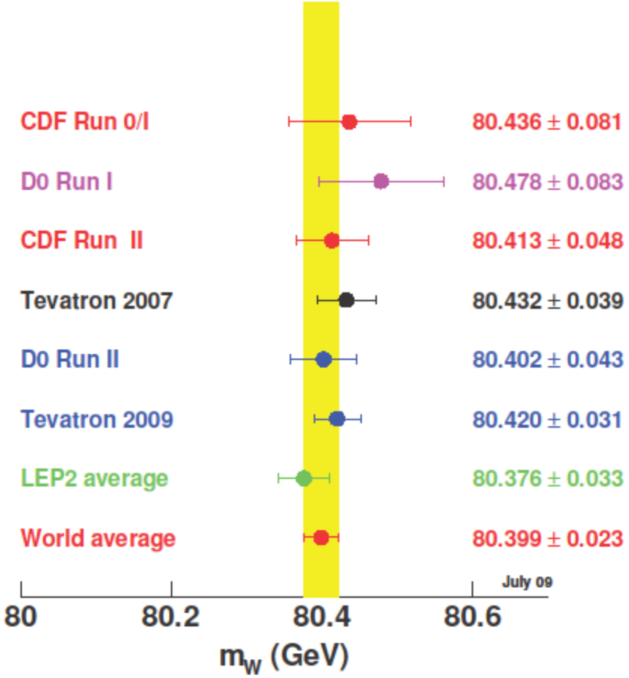
$$\Gamma_W = 2.23^{+0.15}_{-0.14}(\text{stat}) \pm 0.10(\text{syst}) \ \text{GeV}$$
$$= 2.23^{+0.18}_{-0.17} \ \text{GeV}.$$

Not as precise as indirect measurement from W/Z cross section ratio, but less model dependent.

W Mass Measurements in Perspective

The W mass is one of the fundamental parameters of the standard model. Together with the Top mass, it is connected to the Higgs mass via virtual loop corrections: See also lecture on top quark physics on Thursday.

Mass of the Z Boson: Measured to <u>extremely</u> High precision in LEP-1 (Remember: LEP-1 scanned the Z-resonance → Precision through precision on beam energy)
W mass at LEP-2: W only produced in pairs at LEP. W mass not as precise.
→ Tevatron has surpassed LEP on W mass.



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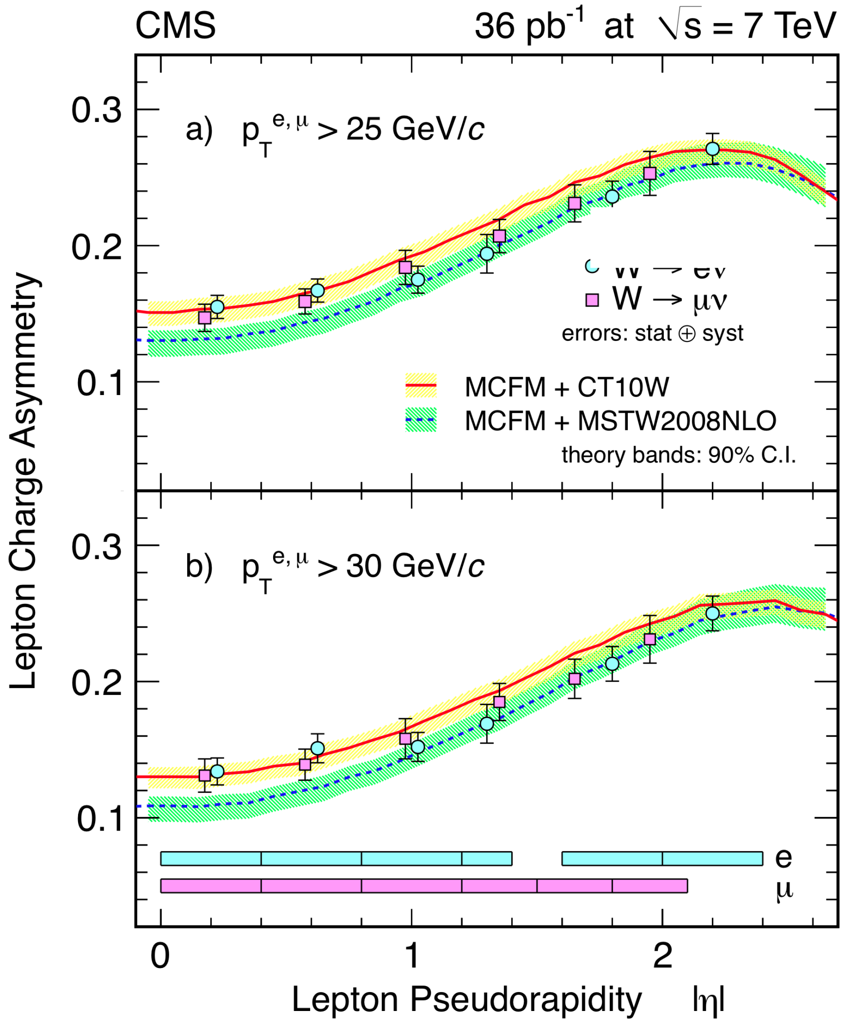
W charge asymmetry at the LHC

Measure W+/W- ratio as a function of pseudorapidity

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

Two pT cuts probe different regions of phase space.

Theory: NLO-QCD (MCFM-Program)
Sensitive to PDFs: Measurement compared to two different PDF-sets: CT10W and MSTW2008NLO

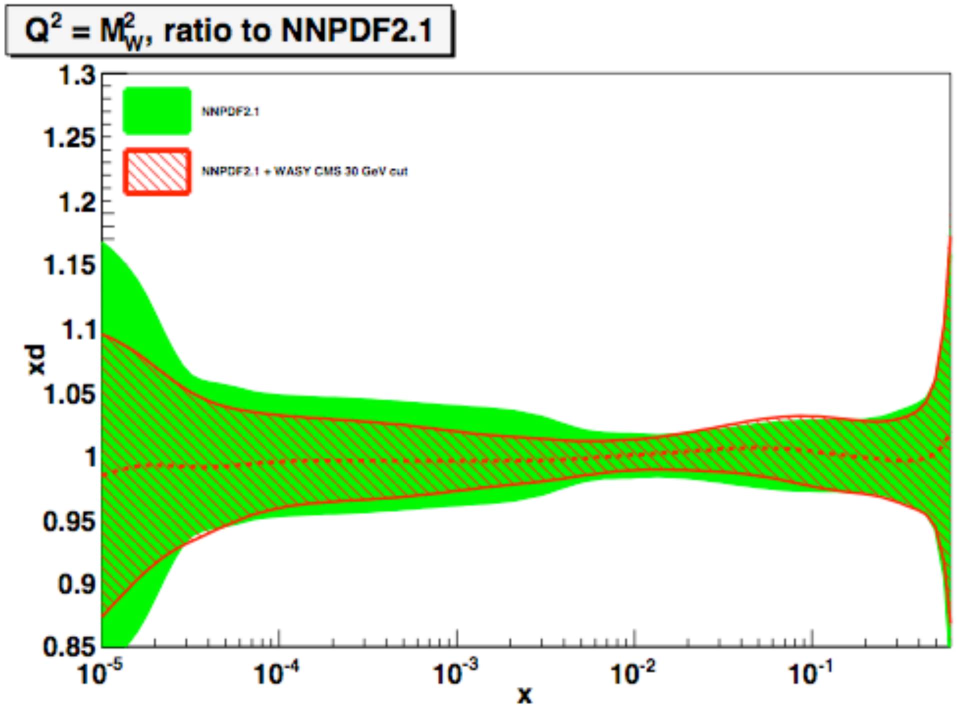


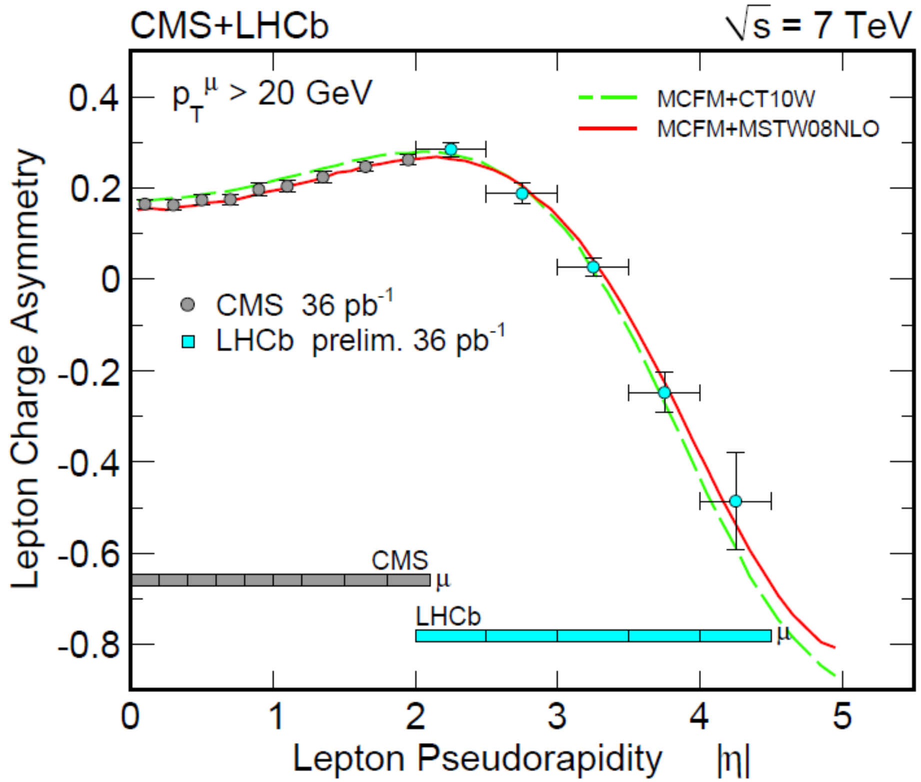
Steinbrück

W charge asymmetry at the LHC: Impact

Uncertainty of d,u,dbar,ubar,s pdf's already reduced by 40% in $10^{-3}<x<10^{-2}$ using CMS measurement.

LHCb significantly extends angular range of this measurement!





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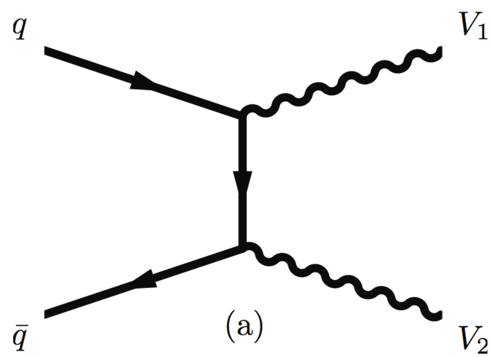
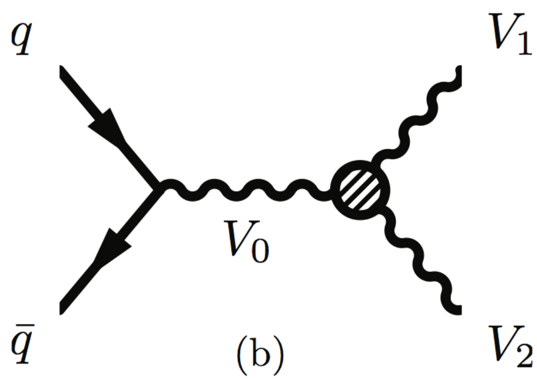
Diboson Physics

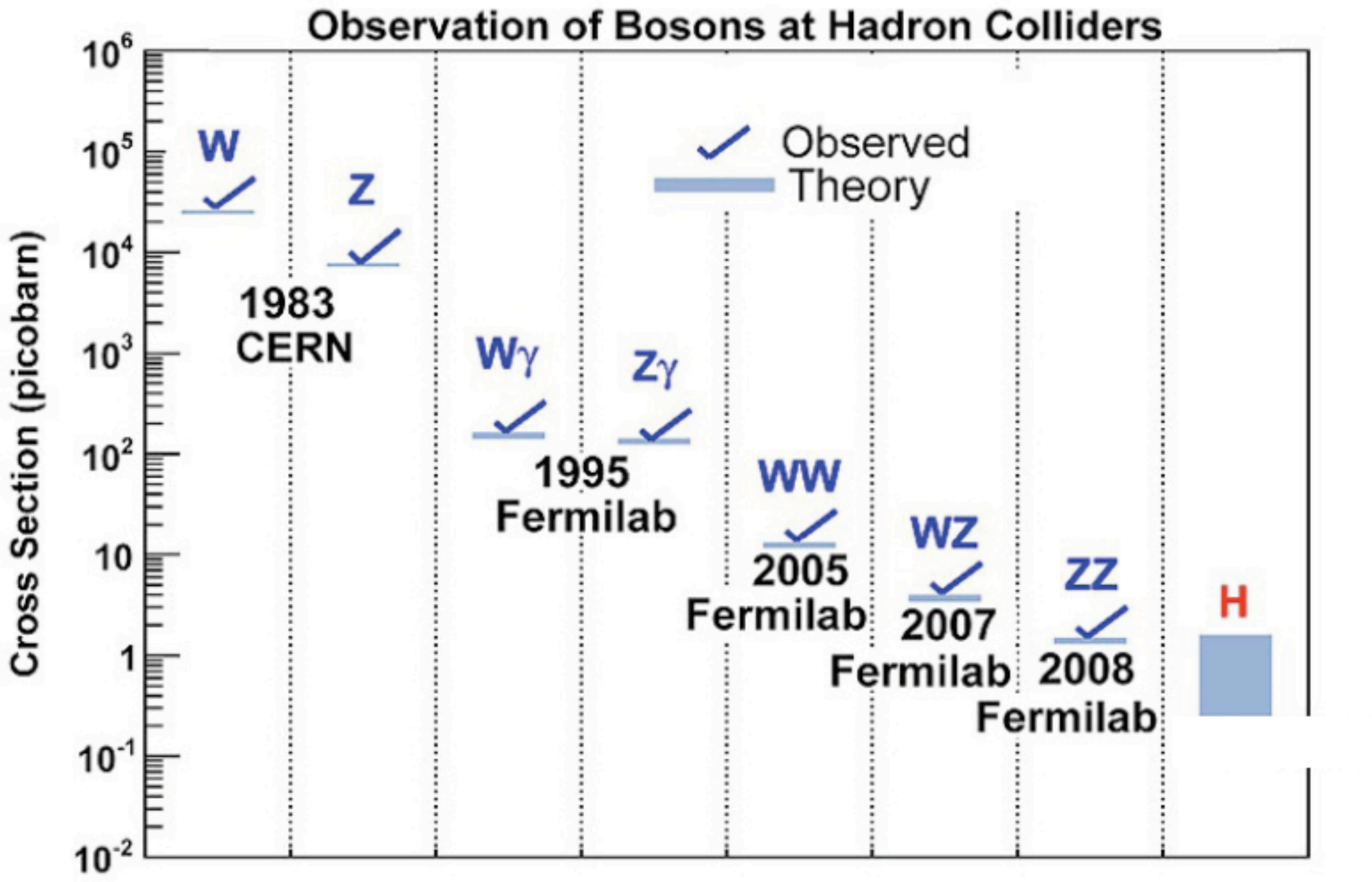
- SM processes
- Test the gauge structure of the SM
- Boson self-interactions via the non-abelian gauge structure
- Anomalous triple (and quartic) couplings would be a hint of physics beyond the standard model



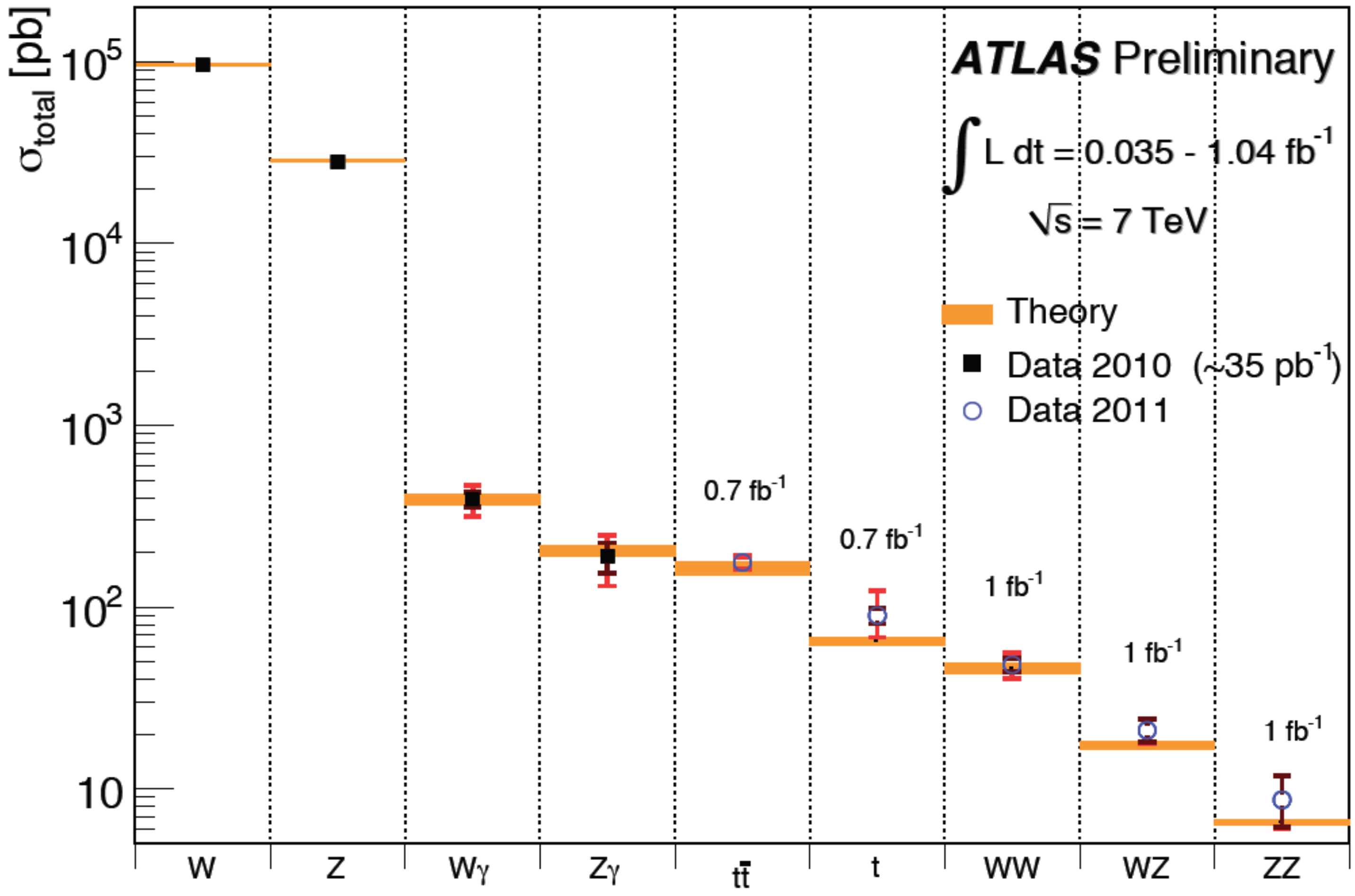


Triple boson vertex (only WWZ, WWγ in the SM, no ZZZ, ZZγ, Zγγ)

A little history…



Current results (cross sections): ATLAS



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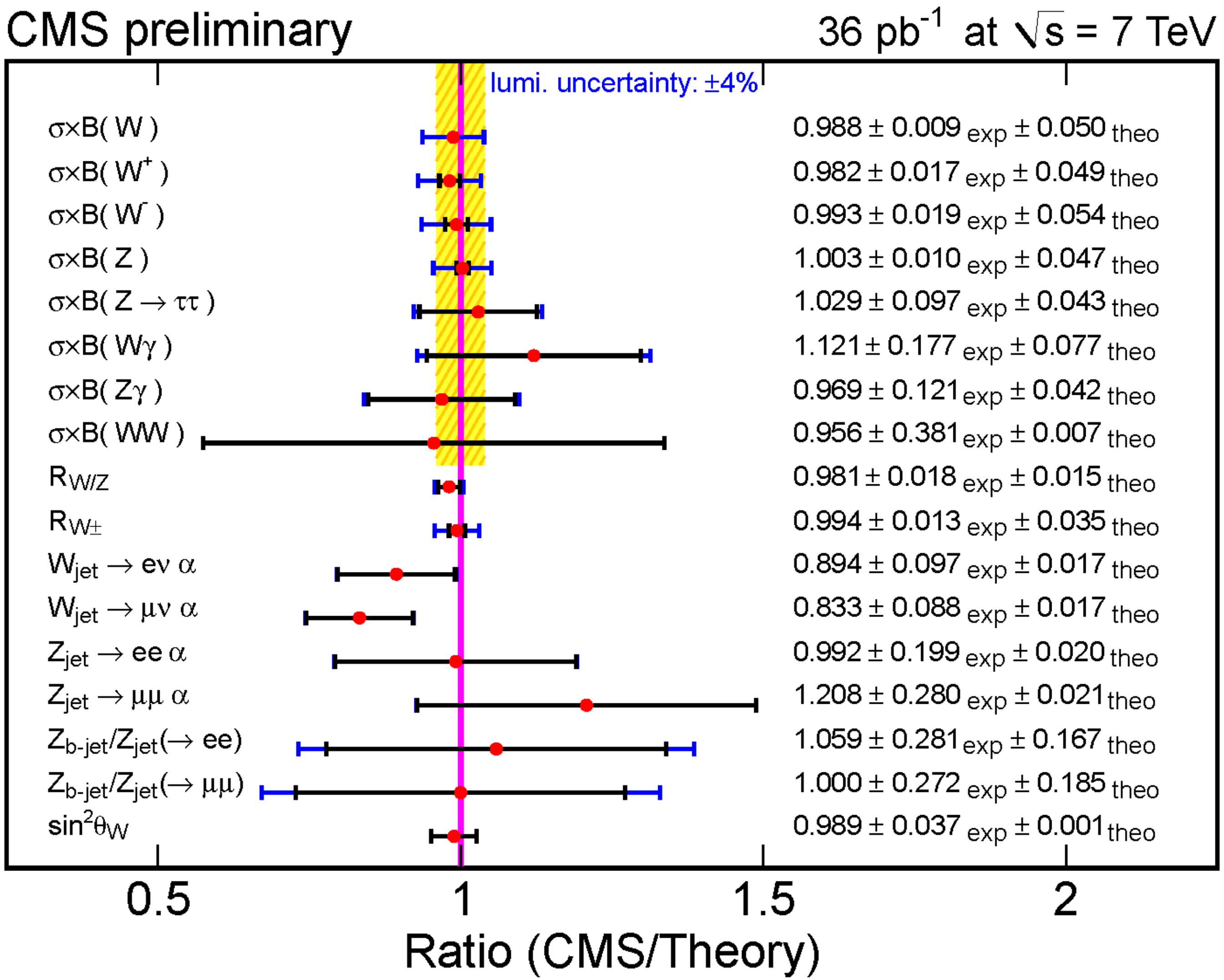
CMS EW Results: Summary



Higgs Physics

Outline (Higgs)

- Introduction
- Higgs searches at LEP
- Higgs searches at Hadron colliders
    - Higgs searches at the Tevatron
    - Higgs searches at the LHC

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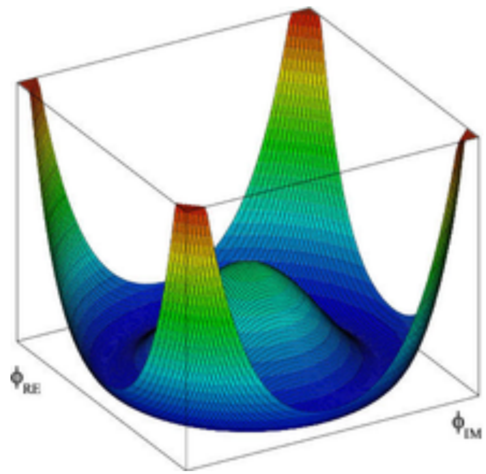
Three Words on the Higgs Mechanism

You probably already learned some basics of the Higgs mechanism in one of the previous lectures.

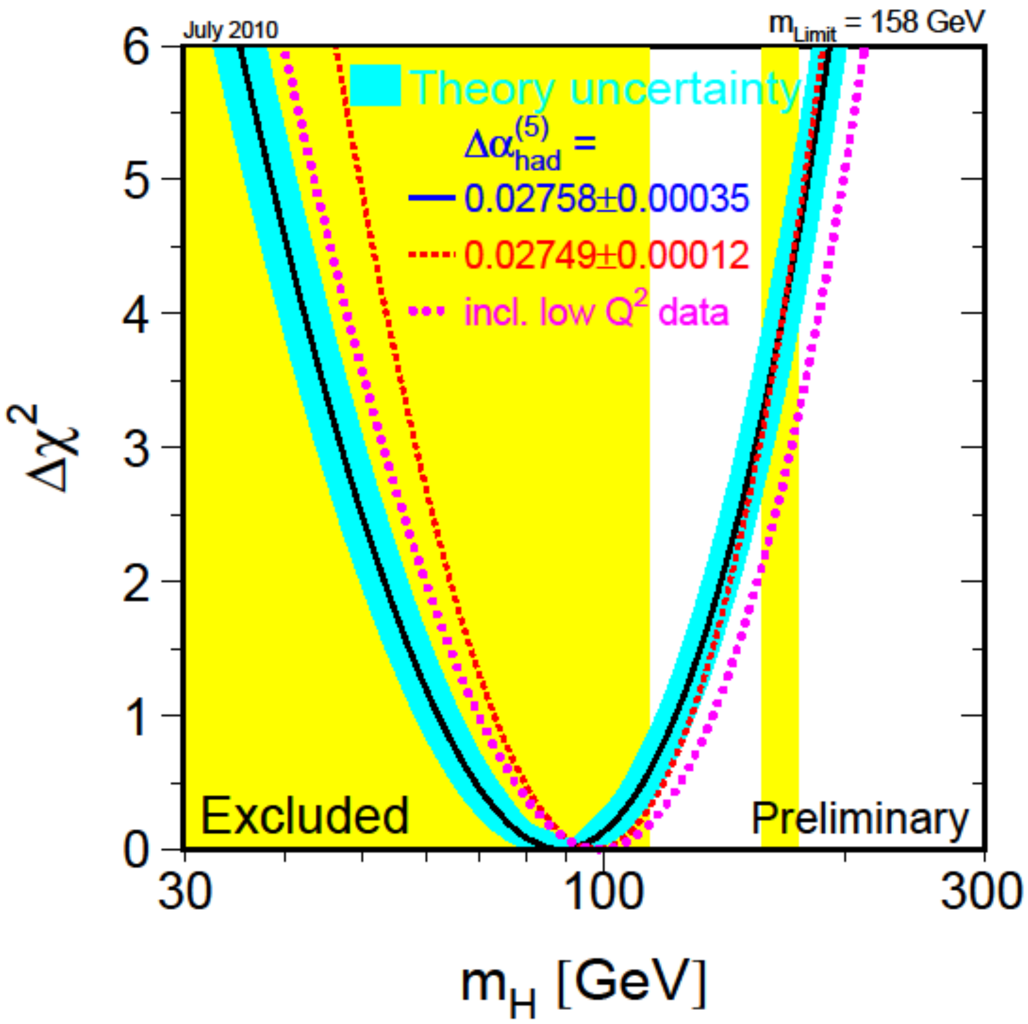
In a nutshell:
Standard model described by $SU(3)_{Color}xSU(2)_{L}xU(1)_{Y}$ symmetry.
Initially leads to massless particles, in clear contradiction to observation.
One solution: Electroweak symmetry breaking aka Higgs-Mechanism
Introduces new scalar Higgs field with non-zero vacuum expectation value v=246 GeV that breaks the SU(2)xU(1) electroweak symmetry.



Electroweak gauge interaction → Weak gauge bosons (W,Z) obtain their masses
Yukawa coupling Y → Lepton and quark masses proportional to Higgs VUV and $Y_{q,l}$

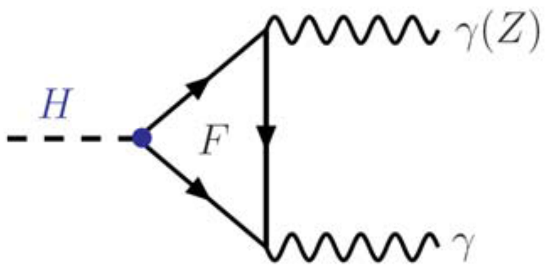
Higgs Boson Searches: Where to look…

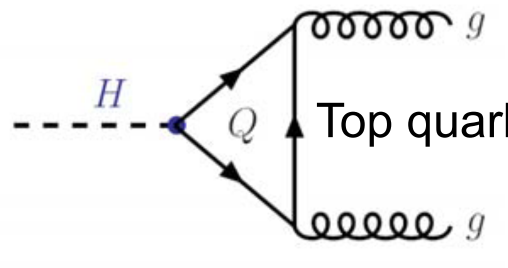
- Precision EW data prefer a light Higgs boson: m(Higgs) <158 GeV at 95%CL
- „Most likely“ Higgs masses (89+35-26 GeV) already excluded by direct searches at LEP: m(Higgs)>114 GeV
- Second exclusion band (158<m(Higgs)<175 GeV at 95%CL) from recent Tevatron measurements. →More later…



Higgs Boson Searches: Where to look…

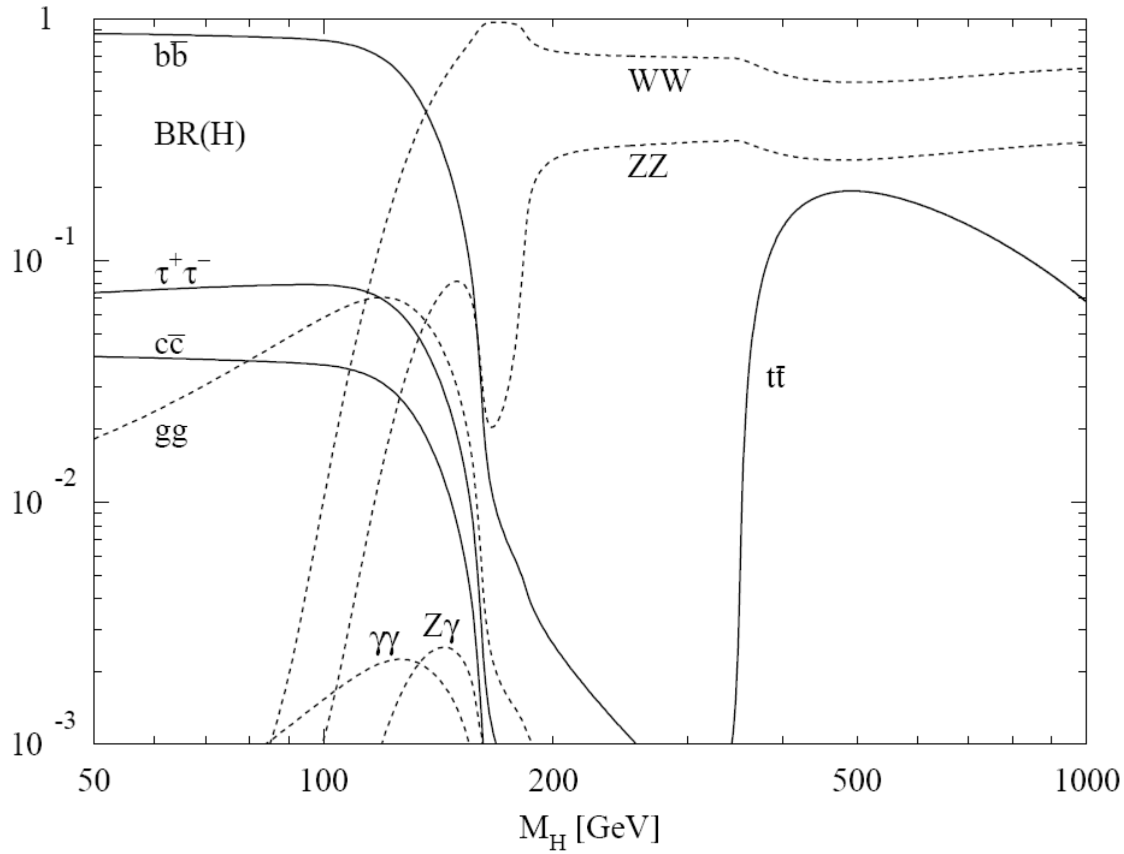
- Coupling of Higgs boson to SM particles proportional to their masses („Yukawa coupling“) →Decay favored in heaviest particle which is kinematically accessible
- Coupling to massless particles (photon, gluon) via fermion loops:





Top quark loop

Branching ratios for Higgs decay:



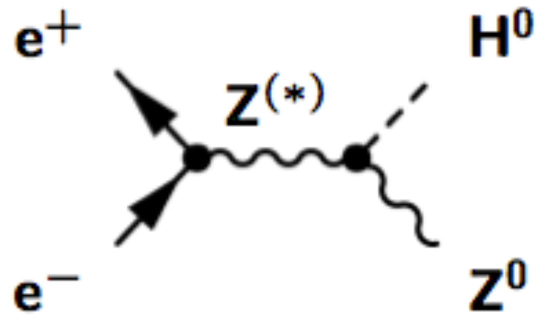
Higgs searches:
„No channel left behind“ strategy

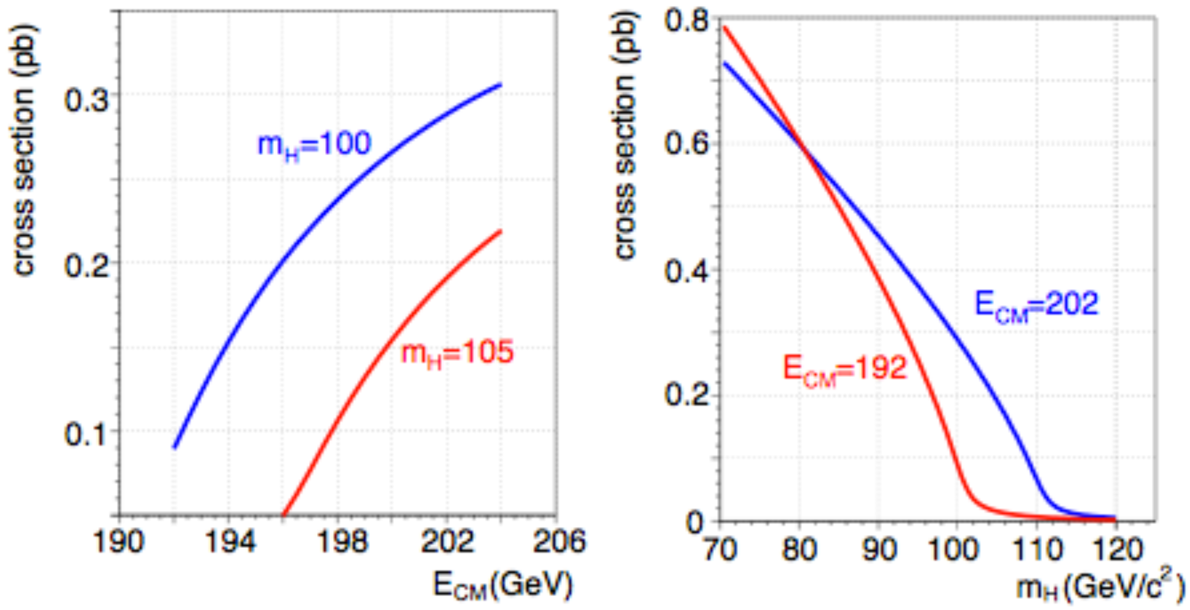
Outline (Higgs)

- Introduction
- Higgs searches at LEP
- Higgs searches at Hadron colliders
    - Higgs searches at the Tevatron
    - Higgs searches at the LHC

Higgs Searches at LEP

- Main production channel ee→Z→HZ (Higgs-Strahlung)
- Kinematic threshold at m(H) = √s − m(Z)
- Main search channels governed by decay of H and Z:
  - Mainly H→bb, also tau tau
  - Z→ll, qq, nunu





- No significant excess seen at LEP-2. →Higgs mass limit close to the kinematic threshold. (At LEP 2 the beam energy was increased to up to 207 GeV)

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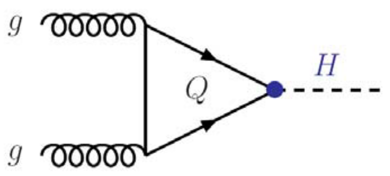
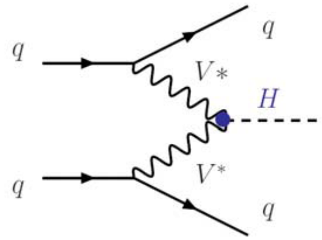
Higgs Searches at Hadron Colliders

A variety of different production processes:

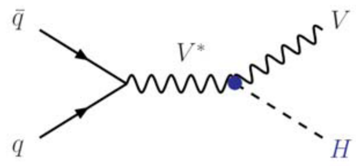
gluon-gluon fusion



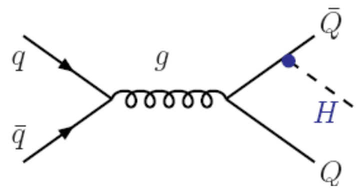
vector boson fusion

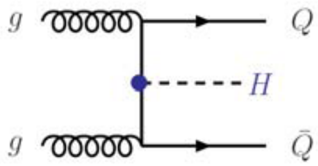


H-radiation
(associated production)



asscociated prod.
with heavy Quark

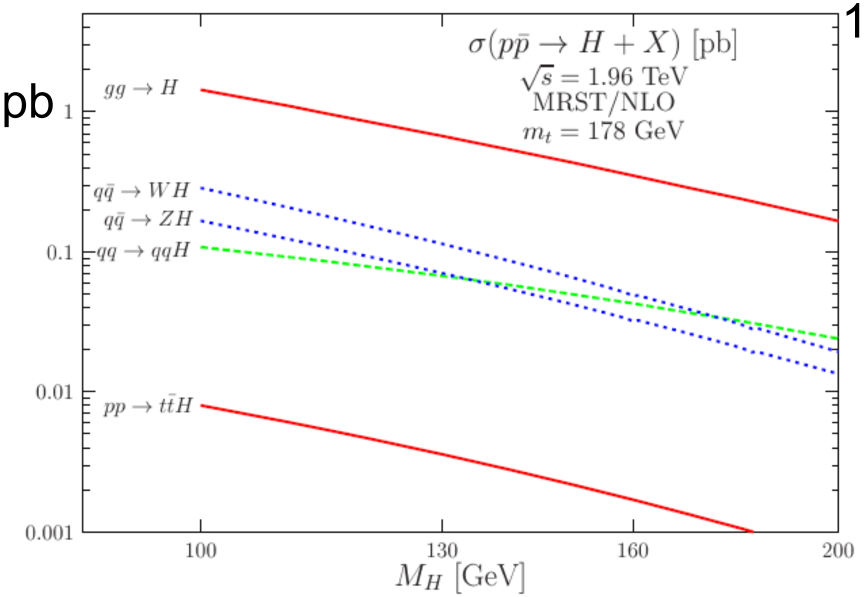




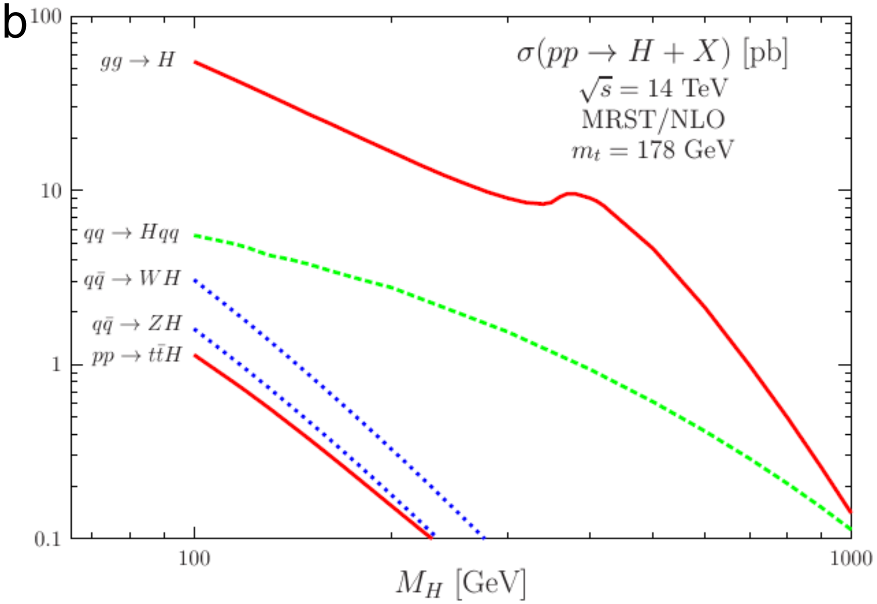
Tevatron

→LHC

1 pb



100 pb



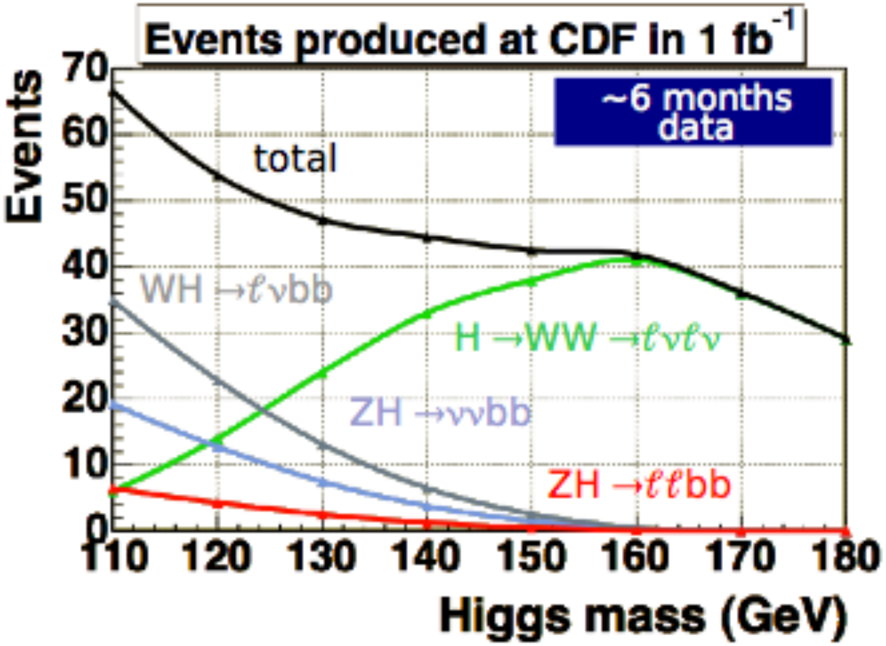
Higgs Searches at the Tevatron

Low mass: Overwhelming background from QCD multijet events → gg → H not viable

→ Associated Higgs production channels (H+W/Z) much cleaner, despite the lower branching ratios

High mass:

→ Direkt Higgs production (gg → H) can be used since the clean channels H → VV are open now.



channel	events @ 115	events @ 165
WH→ℓνbb	28	0.1
ZH→ννbb	16	0.07
ZH→ℓℓbb	5	0.02
H→WW→ℓνℓν	9	38
total	58	38

Higgs Searches at the Tevatron: High Mass

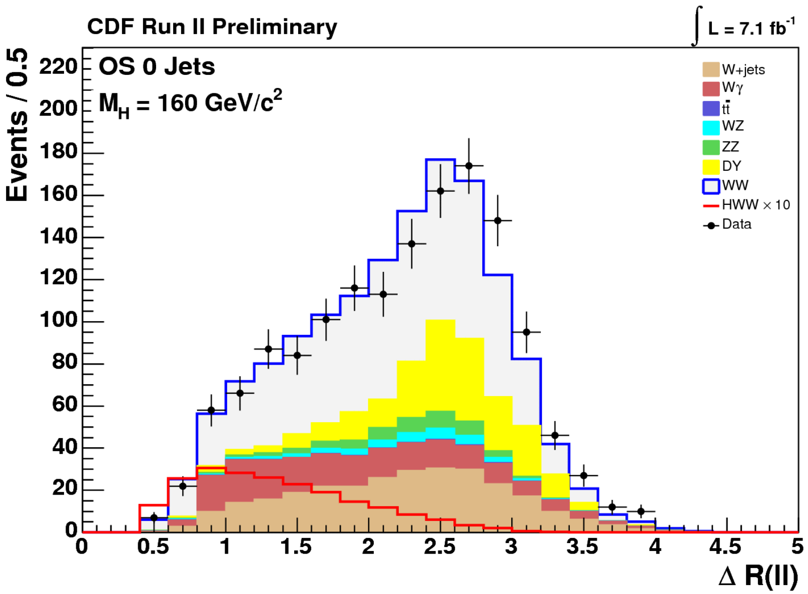
Example for Higgs search at the Tevatron: H→WW*

BR (WW→lνlν)=10%, but clean channel

Take all combinations of leptons and jet multiplicities (0,1,>1)

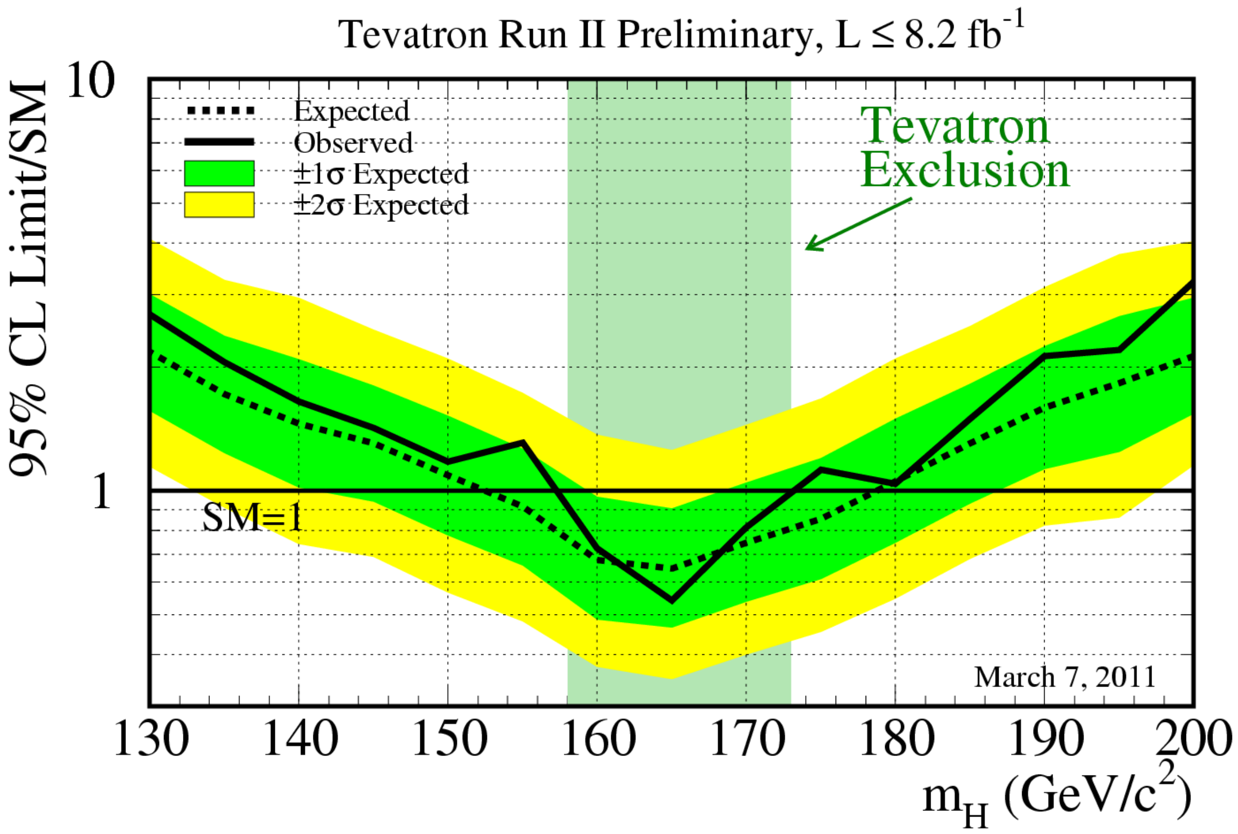
Use neural network or boosted decision trees to maximize sensitivity

→ Example variable from opposite sign dilepton analysis from CDF:



Higgs Searches at the Tevatron

Combination of many analyses by CDF and D0 yields cross section limit as a function of Higgs mass. Limit/SM expectation<1→exclusion!



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Higgs Searches at the LHC

Primary Higgs Search Channels vs M_H

Low Mass:

H -> γγ WW

VBF H -> ττ bb WW

V H -> V bb

Intermediate Mass:

H -> WW ZZ

VBF H -> WW ZZ

High Mass:

H -> ZZ WW

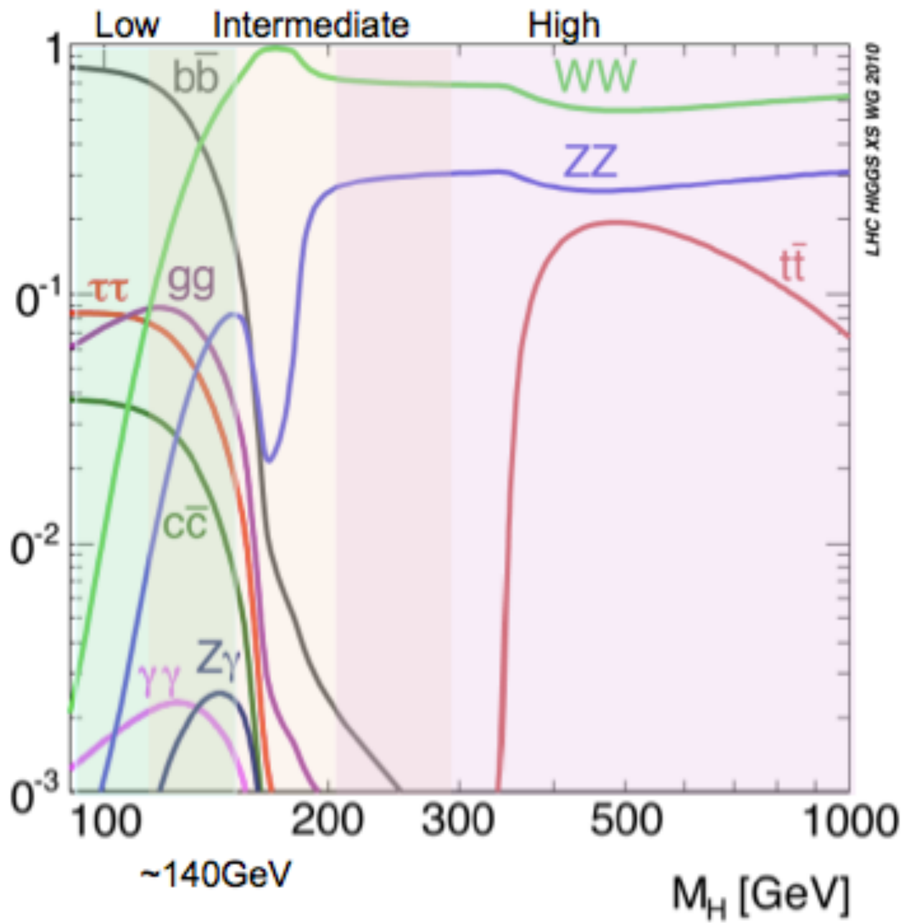
VBF H -> ZZ WW

MSSM Higgs:

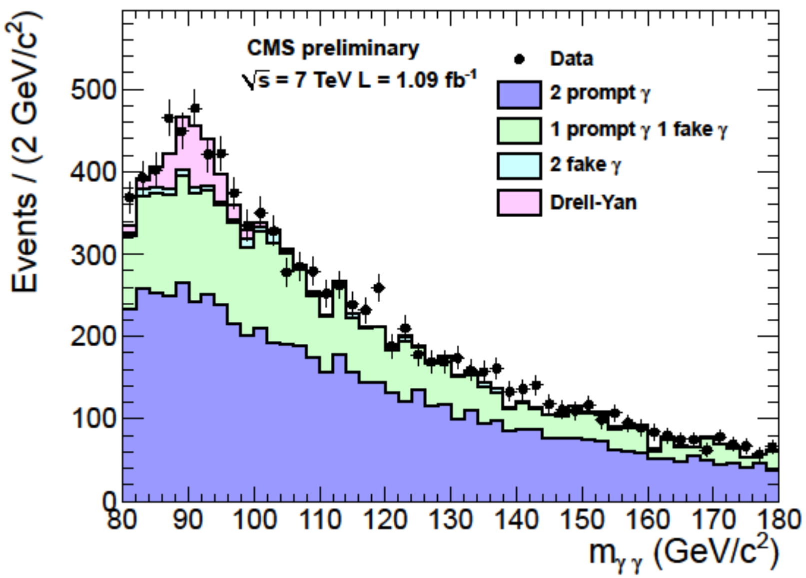
H -> ττ

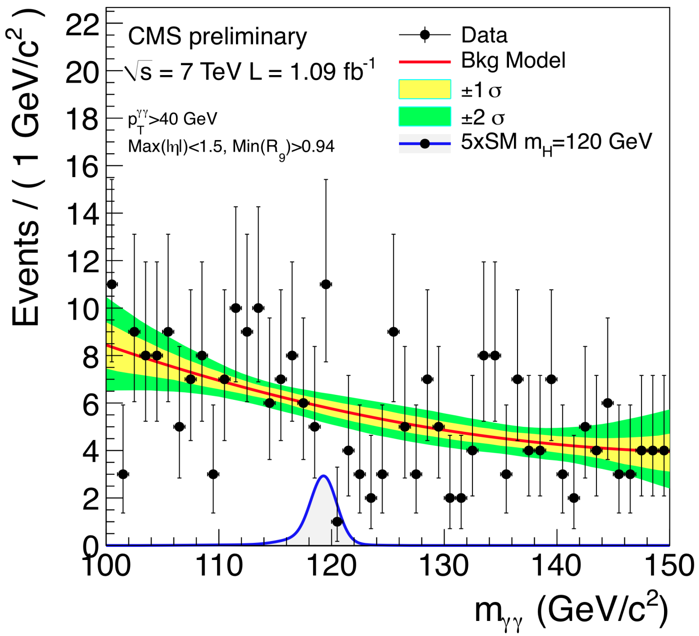
bb H -> ττ

Many channels/ analyses again!



Higgs Searches at the LHC: H→γγ



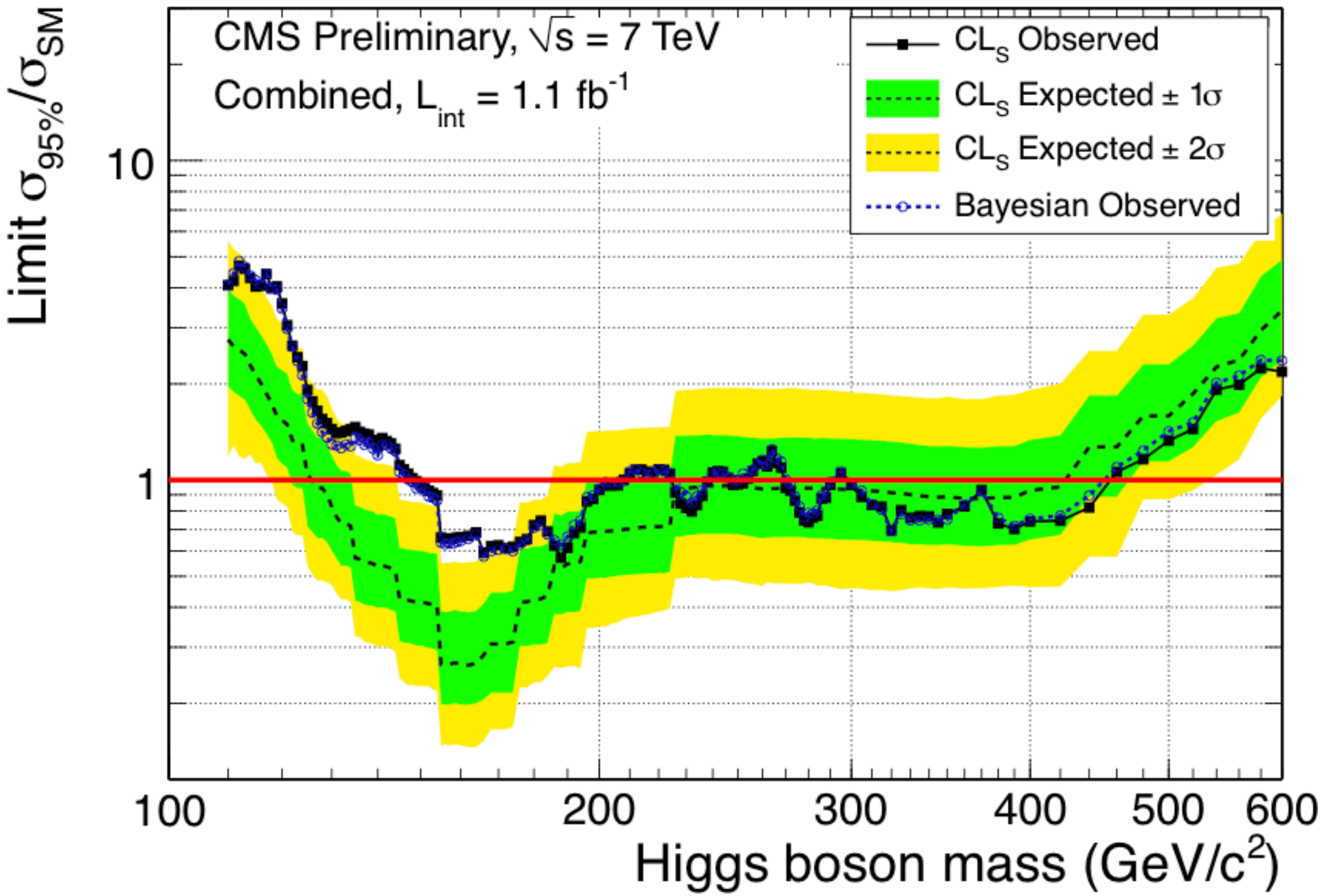


Understanding of background and of signal resolution very important.

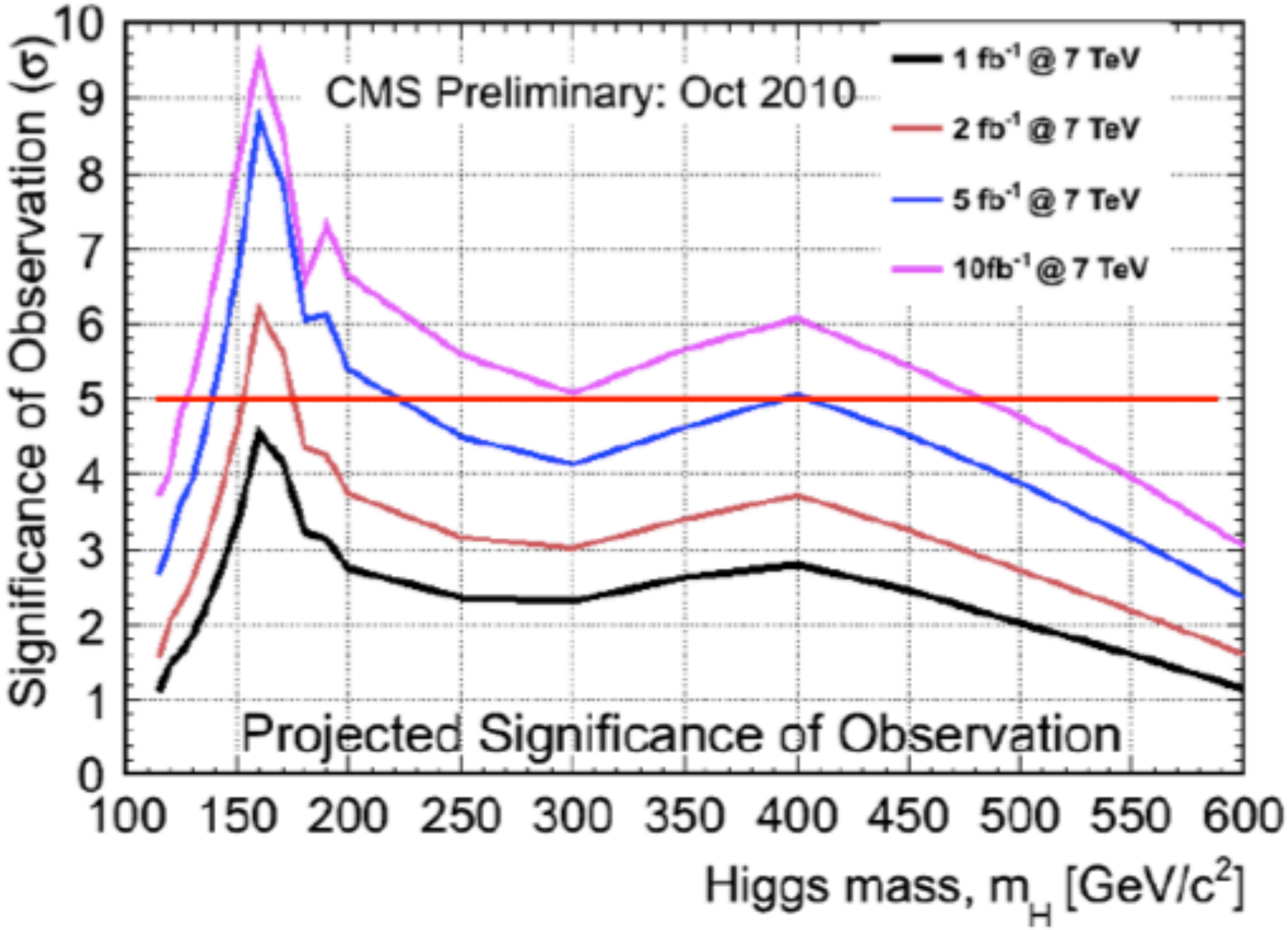
Analysis done in 8 event categories.

Higgs Searches at the LHC: CMS combined

$H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$, $H \rightarrow WW \rightarrow 2l2\nu$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow ZZ \rightarrow 2l2\nu$, and $H \rightarrow ZZ \rightarrow 2l2q$.



CMS Higgs discovery prospects



Conclusions

- Precision Electroweak Physics can be done at a hadron collider!
- Huge statistics and clean samples.
- Many measurements surpassed the ones from LEP: I.e. W mass
- Much more to come....

- Electroweak Symmetry Breaking plays a leading role in the standard model. Finding the Higgs boson is one of the main aims of the LHC.
- First exlusion beyond LEP at the Tevatron (around 165 GeV)
- LHC has taken over! Excellent prospects with several fb^{-1} coming this year.