Discoveries

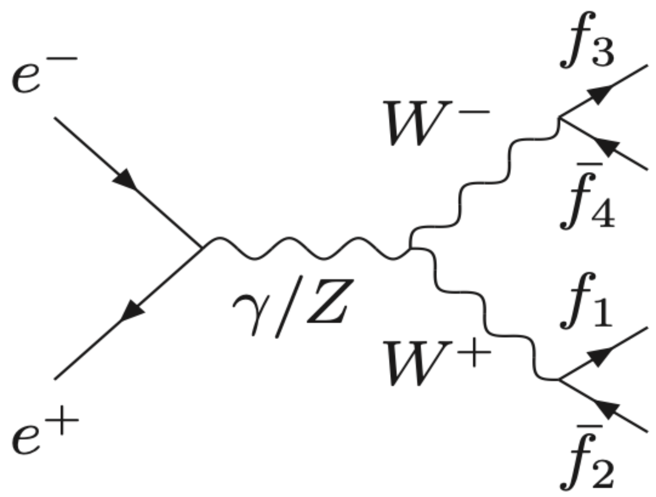
Particle Physics
Toni Baroncelli
Haiping Peng
USTC

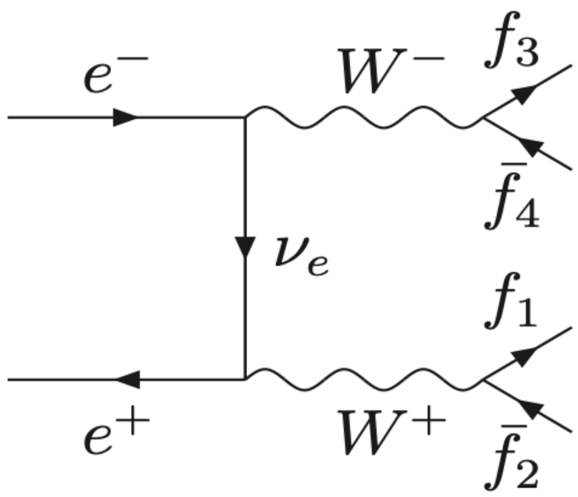
Year 2023

W Mass Measurements

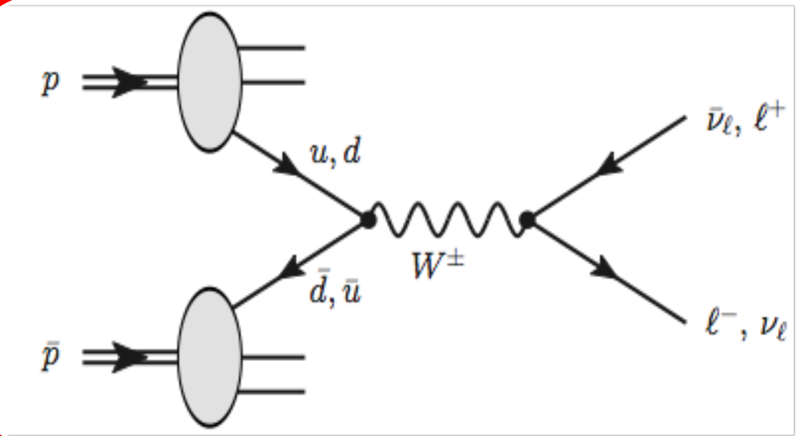
$$W^{+/-} \to q\bar{q}'$$
$$W^{+/-} \to l\nu_l$$

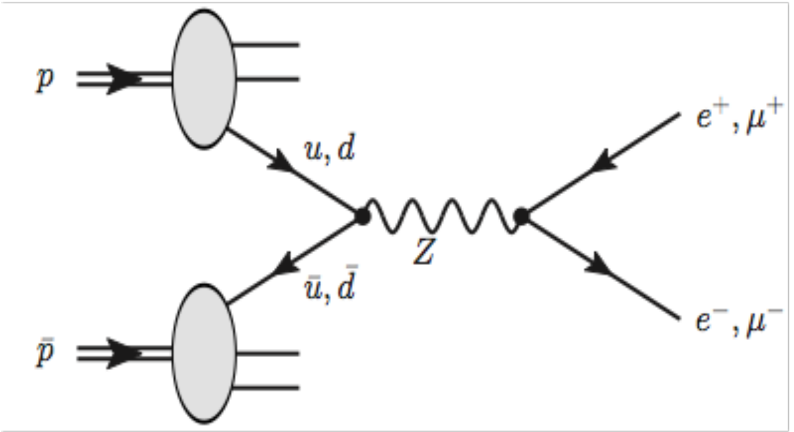
LEP



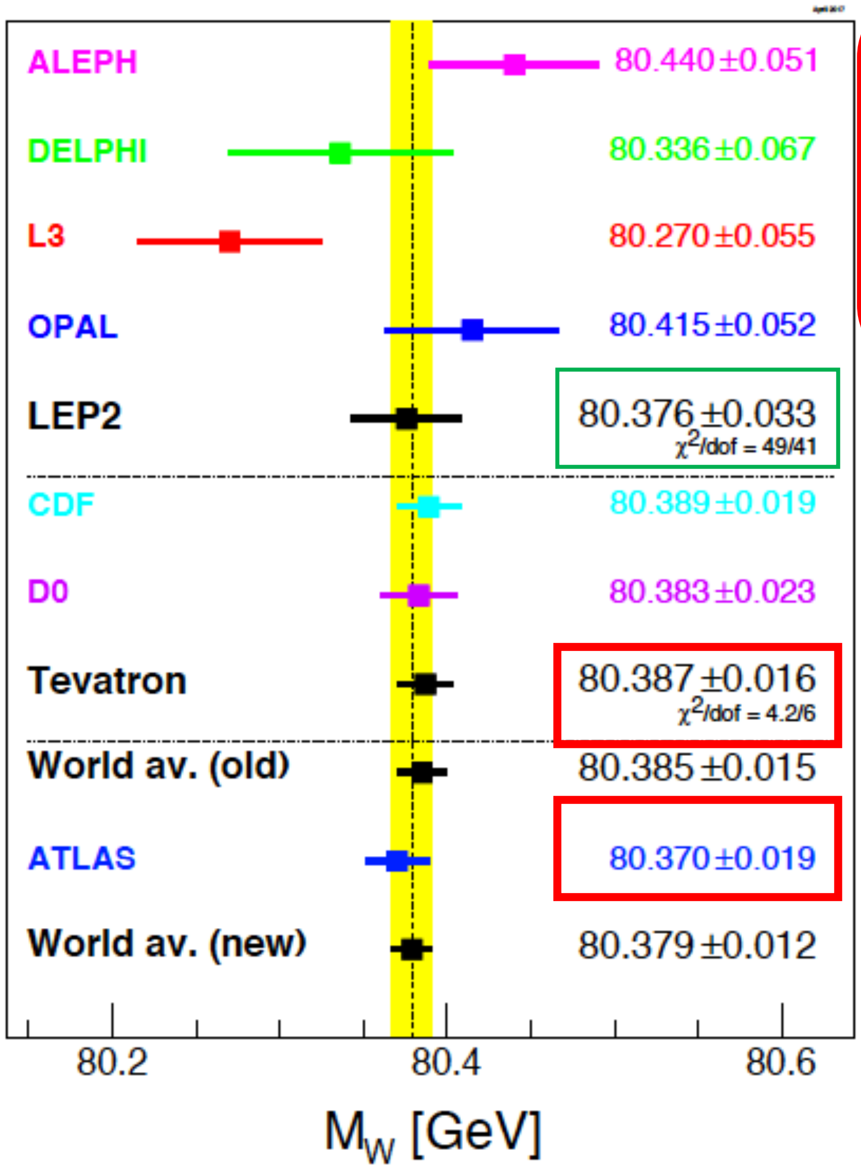


Hadronic Colliders



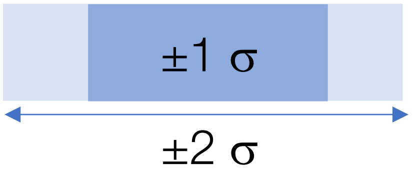


W Mass at Colliders & Other Observables



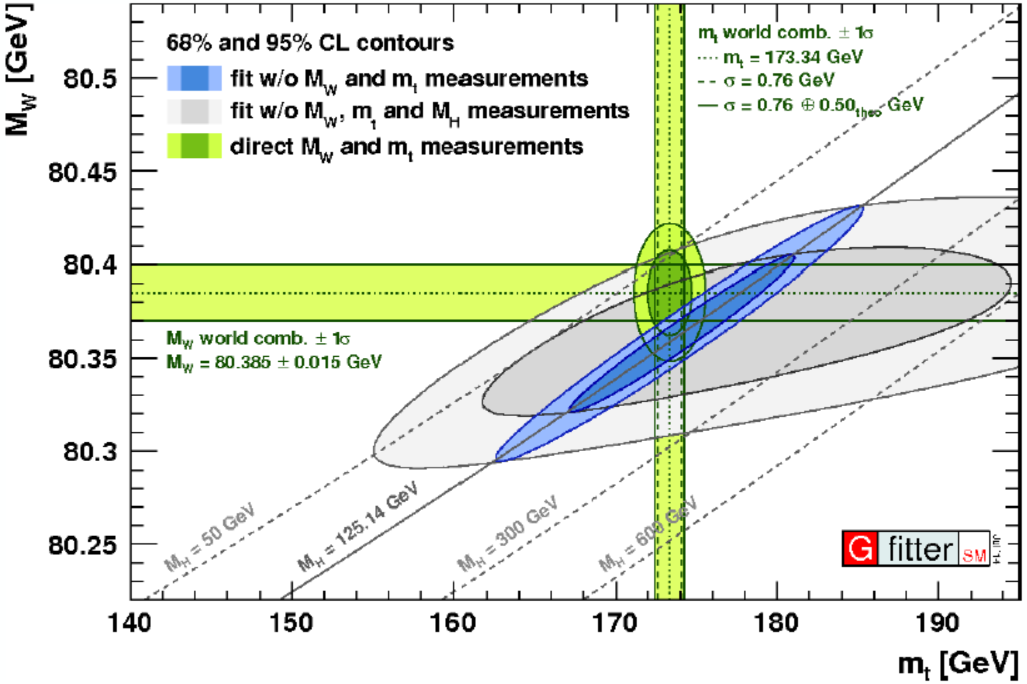
Standard Model: precise relations among many observables, → well defined ratios and/or relations.

- The mass of the W, of the Higgs, of the top quark are some of these observables.
- m_W is important because it is the best measured observable → check the consistency of the SM predictions with data.

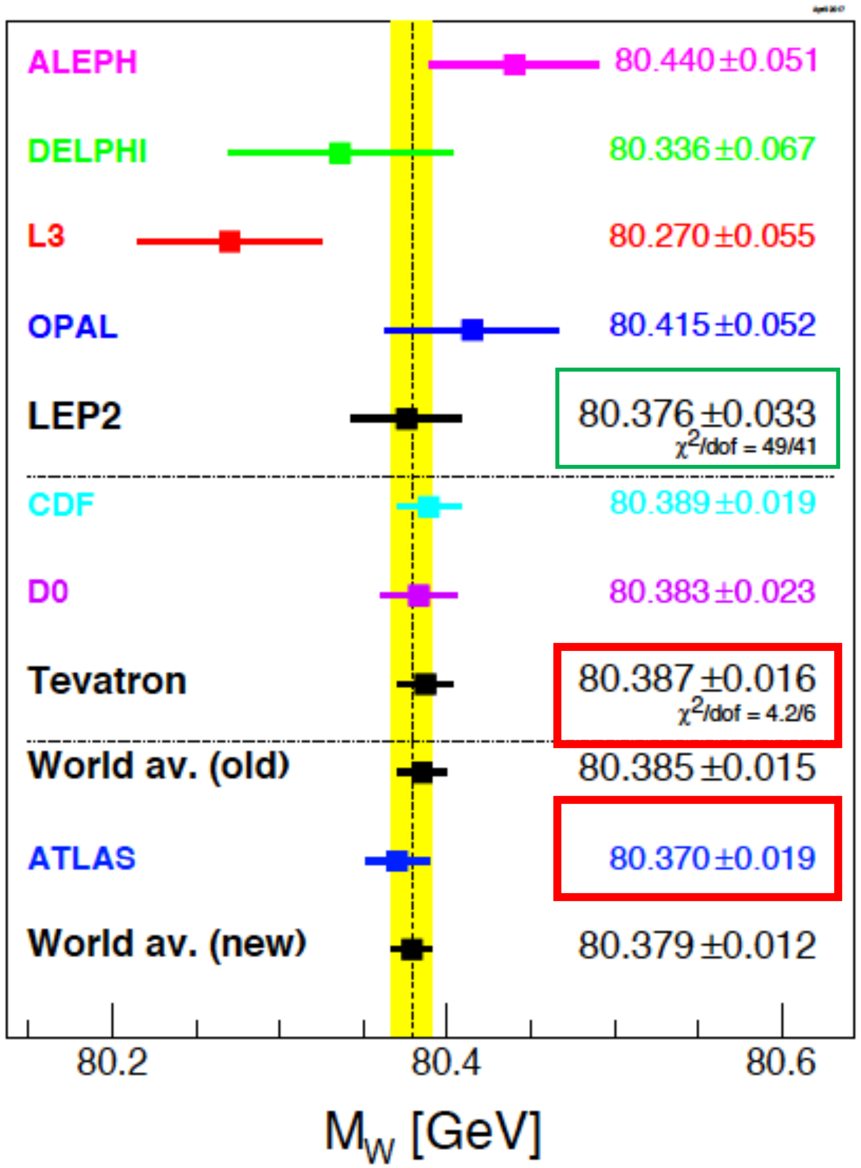


All these measurements must have an area of superposition

Inconsistencies could give possible indications of new physics



Methods to Measure the W Mass

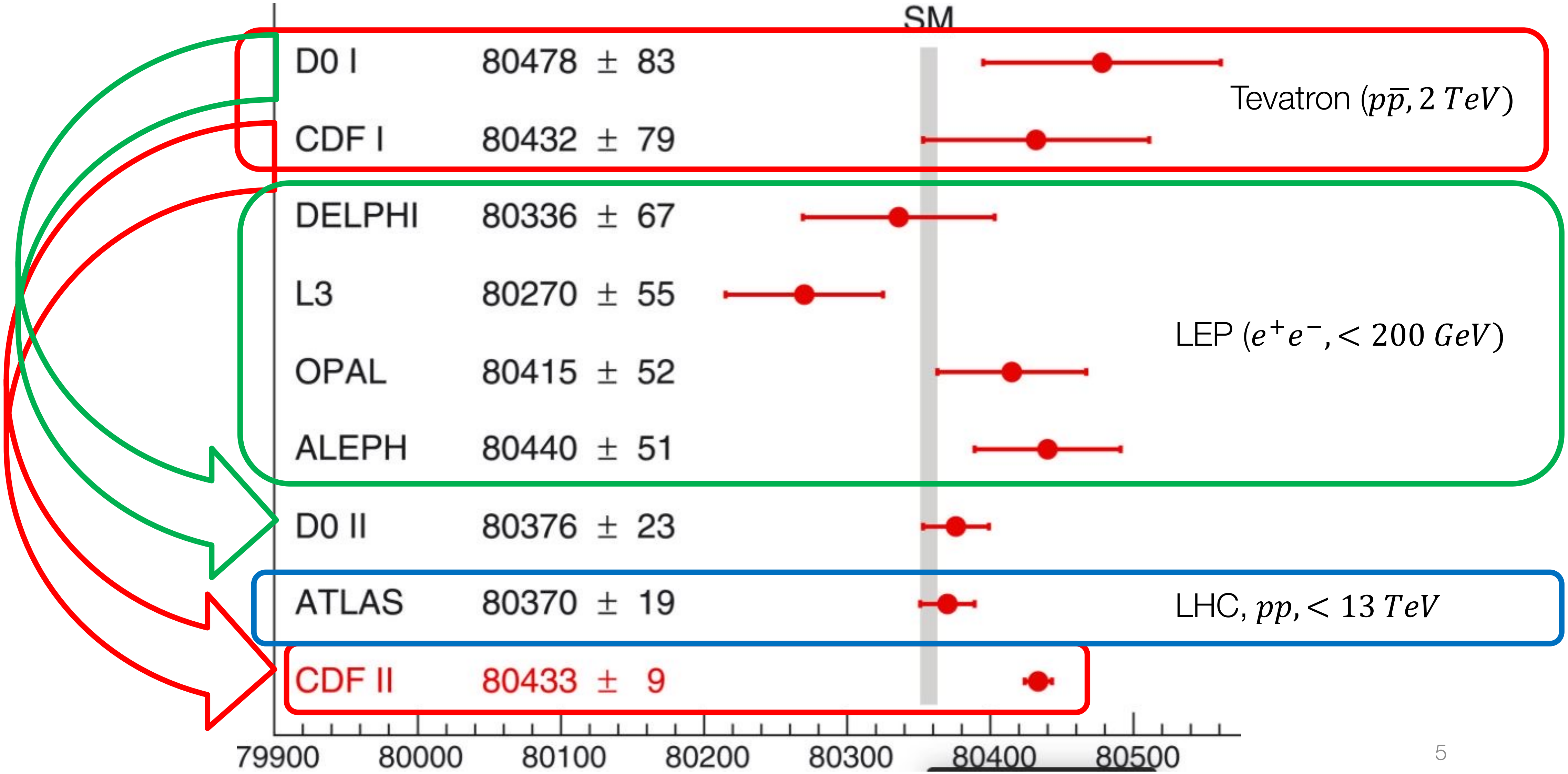


W mass and its width Γ_W is are the parameters that appear in a Breit-Wigner expression for the cross-section vs centre-of-mass-energy

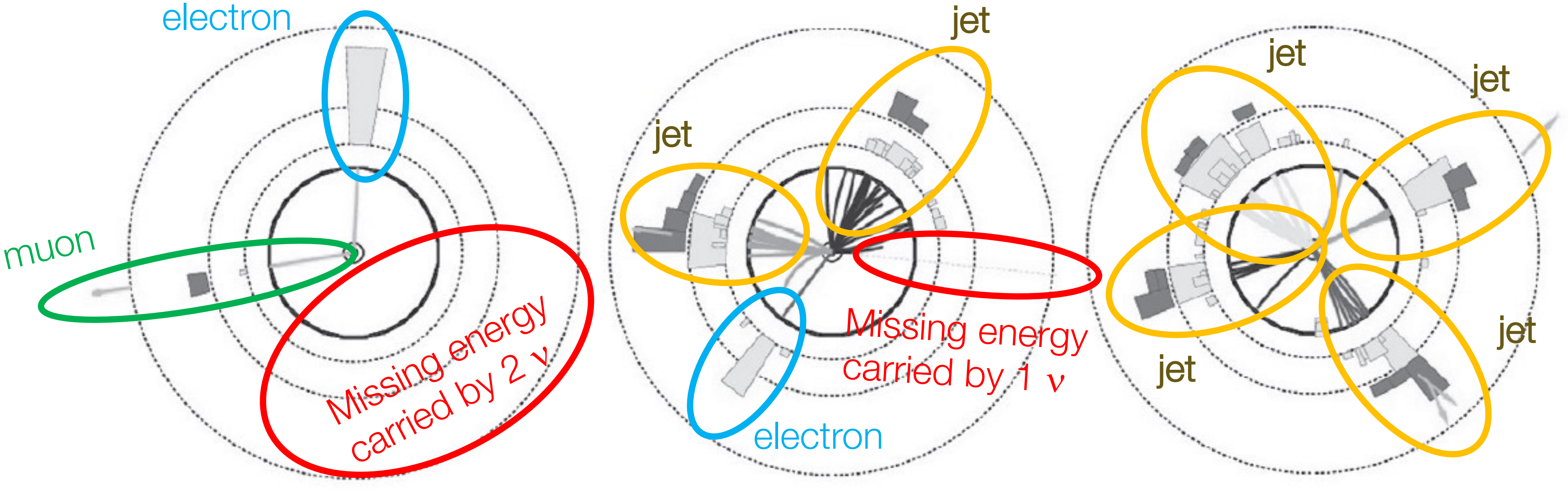
Decay	$W^+W^- \to q\bar{q}'q''\overline{q'''}$	$W^+W^- \to q\bar{q}' l\nu_l$	$W^+W^- \to l\nu_l l\nu_l$
Fraction	46%	44%	10%
Topology	4 jets, no missing energy	2 jets + missing energy + lepton	No jet + missing energy

Machine	Method	Present precision
e^+e^-	1-cross-section at threshold, 2-direct reconstruction	±33 MeV
$p\bar{p}$	High p_T charged lepton from its decay. Due to the presence of νs the mass is determined by comparison of the transverse mass m_T with MC predictions	±16 MeV (CDF and D0) (±9 MeV?)
pp		±19 MeV (ATLAS only)

W mass measurement at Colliders



W^+W^- Decay Topologies



$W^+W^- \to e^-\bar{\nu}_e\mu^+\nu_\mu$ $W^+W^- \to e^-\bar{\nu}_e q_1\bar{q}_2$ $W^+W^- \to q_1\bar{q}_2 q_3\bar{q}_4$

At LEP two point-like objects collide and this allowed the use of constraints:

- Total energy = $\sqrt{s}$ (= 2 x beam energy); → ν energy known
- Total momentum in 3 directions = 0;

At LEP rate is ~ low, events are clean, no pile-up!

→ adjust directions and p_T and E of objects to satisfy these constraints (fit) → improvement of m_W resolution

- If both Ws are reconstructed than also impose $m_W^1 = m_W^2$ (however in full hadronic topology 4 jets and 3 combinations; use pairing that gives best masses)

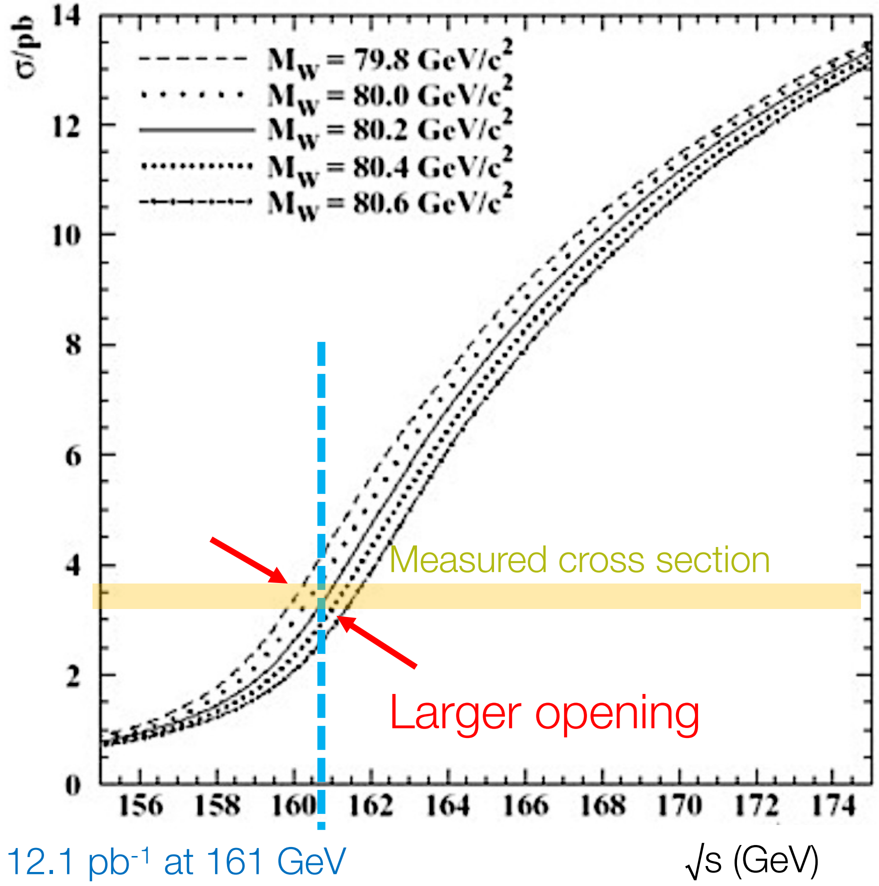
m_W Reconstruction at Threshold

Close to the W^+W^- threshold (161 GeV), the dependence of the W-pair production cross section rises as

$$\sigma_{WW} \propto \beta = \sqrt{1 - 4m_W^2/s}$$

→ The measurement of σ_{WW} at √s gives m_W (see plot on the right).
The most sensitive √s to m_W was determined to be √s = 161 GeV, but data at 172-183 GeV were also analysed to extract m_W.

The ***potential*** precision is similar to the direct reconstruction method, described below. However, LEP (mostly) operated at higher centre-of-mass energies (NP + precise EW) and only 3% of the full data set was taken at 161 GeV.



Threshold Analysis	
Experiment	m_W [GeV]
ALEPH	80.20 ± 0.34
DELPHI	$80.45^{+0.45}_{-0.41}$
L3	$80.78^{+0.48}_{-0.42}$
OPAL	$80.40^{+0.46}_{-0.43}$

The combination gives

$$m_W(\text{threshold}) = 80.42 \pm 0.20 \pm 0.03(E_{LEP})\ \text{GeV}$$

Δm_W~200 MeV, energy knowledge plays no role!

Direct Reconstruction of m_W

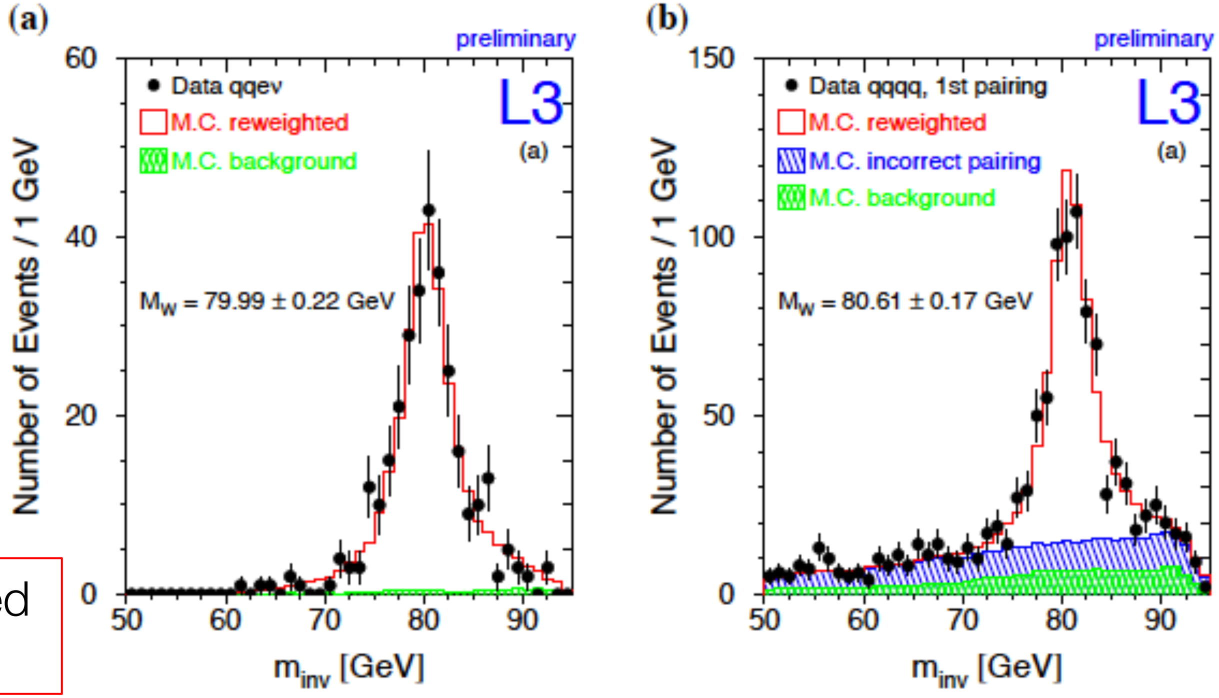
The direct mass reconstruction method was used at 172, 183 and 189 GeV centre-of-mass energies.

- W mass is reconstructed using the pairs of jets from each W decay.
- A constrained fit, mentioned before, is used
- fully hadronic and semileptonic channels are used
- In the fully hadronic channel ‘pairing problem’: (12+34, 13+24, 14+23) → combinatorial background.

Example: L3

qqeν: almost no background, no pairing problem

Full leptonic topology limited statistics (10% decays)



qqqq: some background, significant pairing contribution

→ similar precision to the semi-leptonic case even if statistics is larger

Getting the Mass and the Width

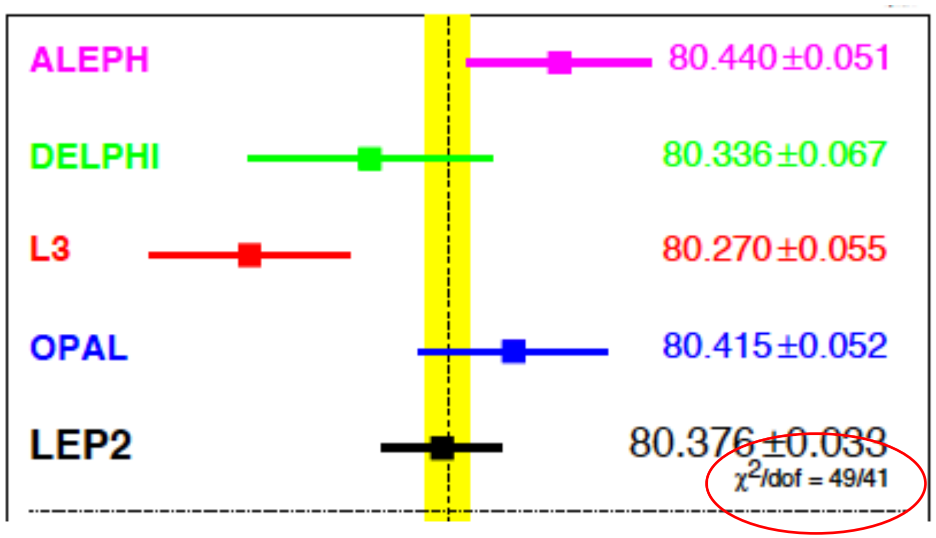
In the direct reconstruction method, the mass of the W boson is obtained by comparing data to simulated

$$e^+e^- \to W^+W^-$$

event samples generated with known values of m_W and Γ_W, in order to obtain those values which describe the data best.

These Monte-Carlo samples are of large statistics, typically 10^6 events. Since the generation of event samples for all possible parameter values is very computing time intensive, different methods are used to perform the m_W and Γ_W extraction in a more efficient, but still precise way (typically re-weight events).

The individual results of the four experiments are combined taking into account correlations



X^2/dof is ~good

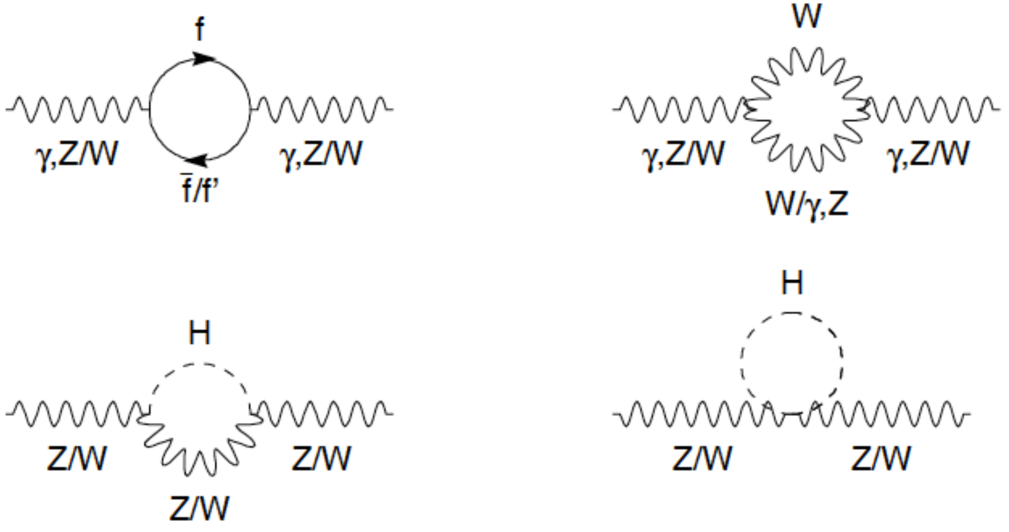
	Direct Reconstruction		
Experiment	$W^+W^- \to q\bar{q}\ell\nu_\ell$ m_W[GeV]	$W^+W^- \to q\bar{q}q\bar{q}$ m_W[GeV]	Combined m_W[GeV]
1 Published			
ALEPH	80.429 ± 0.060	80.475 ± 0.080	80.444 ± 0.051
DELPHI	80.339 ± 0.075	80.311 ± 0.137	80.336 ± 0.067
L3	80.212 ± 0.071	80.325 ± 0.080	80.270 ± 0.055
OPAL	80.449 ± 0.063	80.353 ± 0.083	80.416 ± 0.053
2 LEP combination			
ALEPH	80.429 ± 0.059	80.477 ± 0.082	80.444 ± 0.051
DELPHI	80.339 ± 0.076	80.310 ± 0.101	80.330 ± 0.064
L3	80.217 ± 0.071	80.324 ± 0.090	80.254 ± 0.058
OPAL	80.449 ± 0.062	80.353 ± 0.081	80.415 ± 0.052

How Precisely one has to Measure m_W?

One could ask: down to which level do we need to know m_W?

the effect of higher order diagrams:

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



Δr:

- Dependence is quadratic on m_t → more visible
- Logarithmic on m_H → weak

In extended theories, Δr receives contributions from physics beyond the SM.

The current Particle Data Group gives the world average of m_W (dominated by the CDF and D0 measurements):

world average of m_W = 80385 ± 15 MeV

Given the precisely measured values of , G_F and m_Z , and using m_t and m_H we can use the above relation to derive

SM prediction of m_W = 80358 ± 8 MeV and m_W = 80362 ± 8 MeV (different calculations).

The SM prediction uncertainty of 8 MeV represents therefore a target for the precision of future measurements of m_W.

W Mass Reconstruction at Colliders

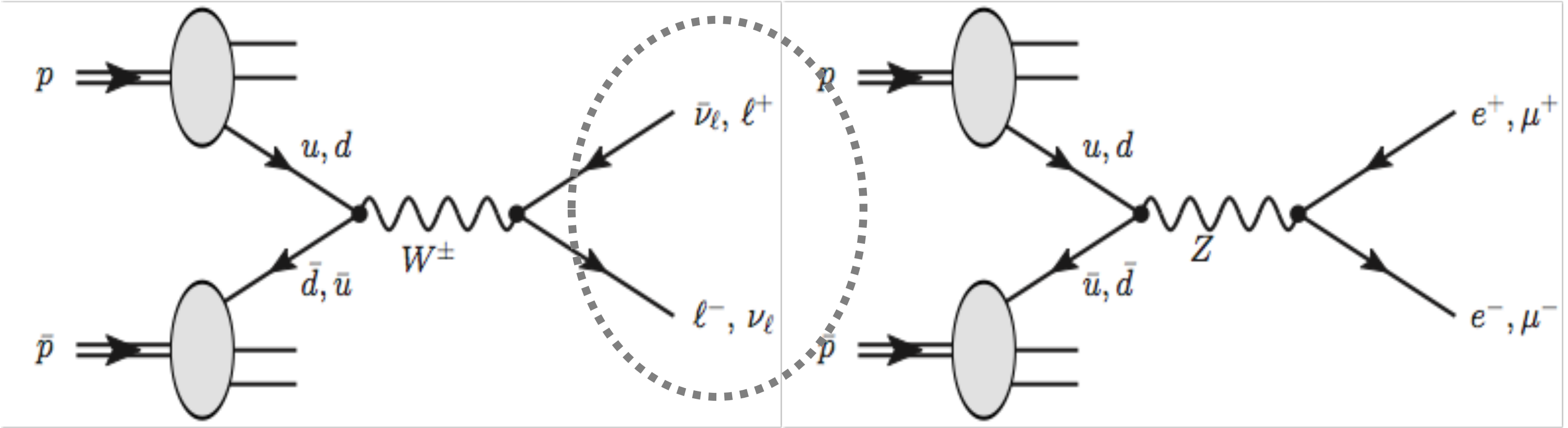
We have seen that at LEP m_W could be reconstructed using ALL decays of the W. This is possible because

- Electrons and positrons are point-like objects
- The centre-of-mass energy is defined
- The background: both hadronic and leptonic decays
- Conservation of energy and momentum allows to calculate the momentum and direction of one undetected particle (like neutrinos in the decay $W \rightarrow \nu l$)

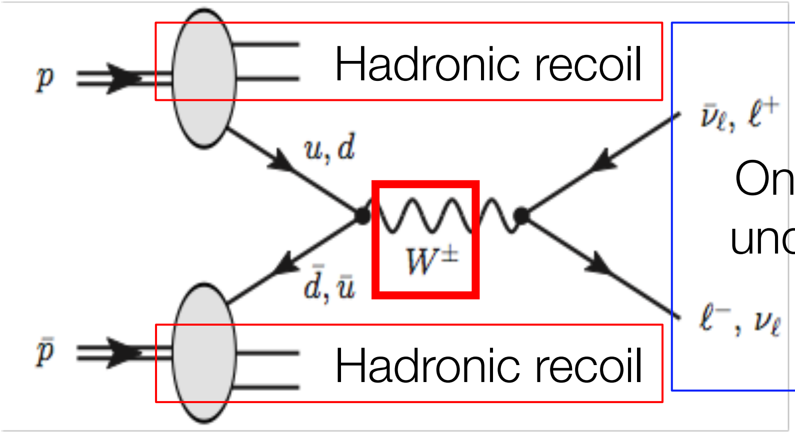
At hadronic collider machines there are difficulties in the use of hadronic decays:

- the QCD background is >>>>>>> the EW production of W's
- High energy W → the two jets $W \rightarrow qq'$ are ~merged. Sophisticated techniques look for internal structures in 'fat jets'.

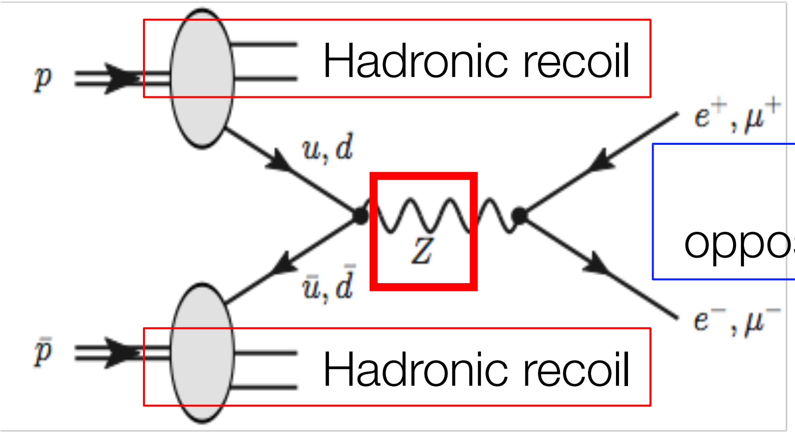
In practice all m_W measurements at hadron colliders are based on the study of W's leptonic decays



The Event Structure in W (and Z) Leptonic Decays



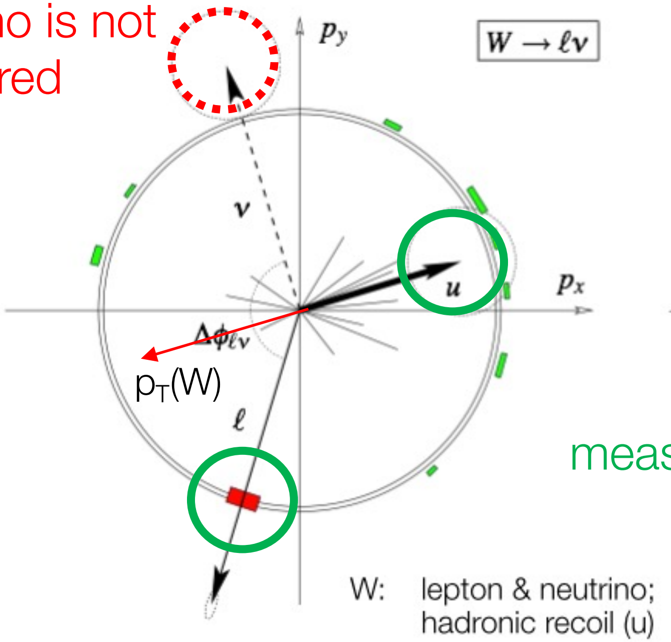
One lepton and one undetected neutrino

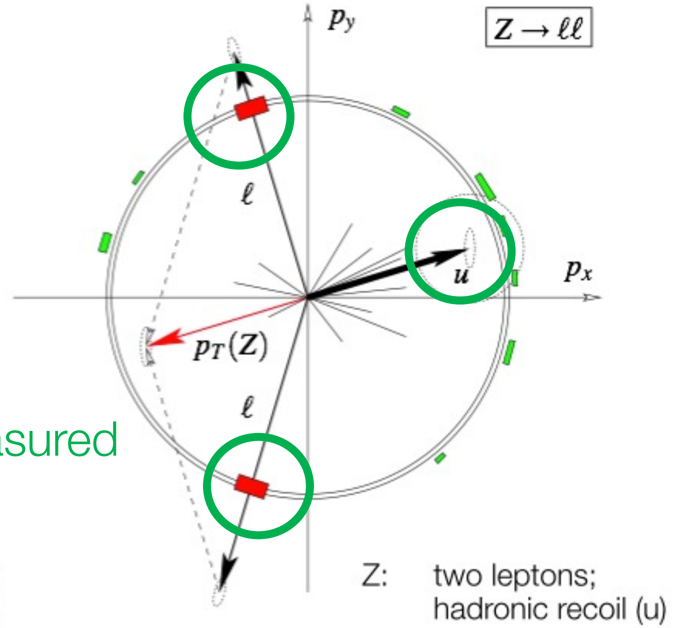


Two same flavour opposite charge leptons

Neutrino is not measured

$$\overrightarrow{p_T^{miss}} = -(\overrightarrow{p_T^{l}} + \overrightarrow{u_T})$$



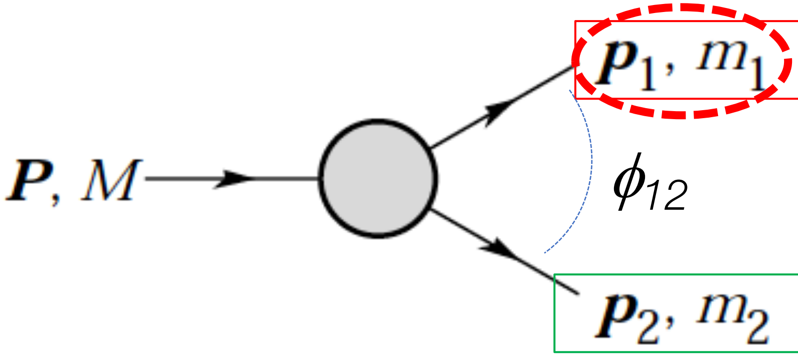


measured

Difficulty: p_T of the neutrino can be calculated only in the x-y plane.

→ how to compute the mass of the W using measurements in the transverse plane? → m_T

W Mass Measurements at Hadron Colliders



Invisible particle (like νs in W decays)

Visible particle (like leptons in W decays)

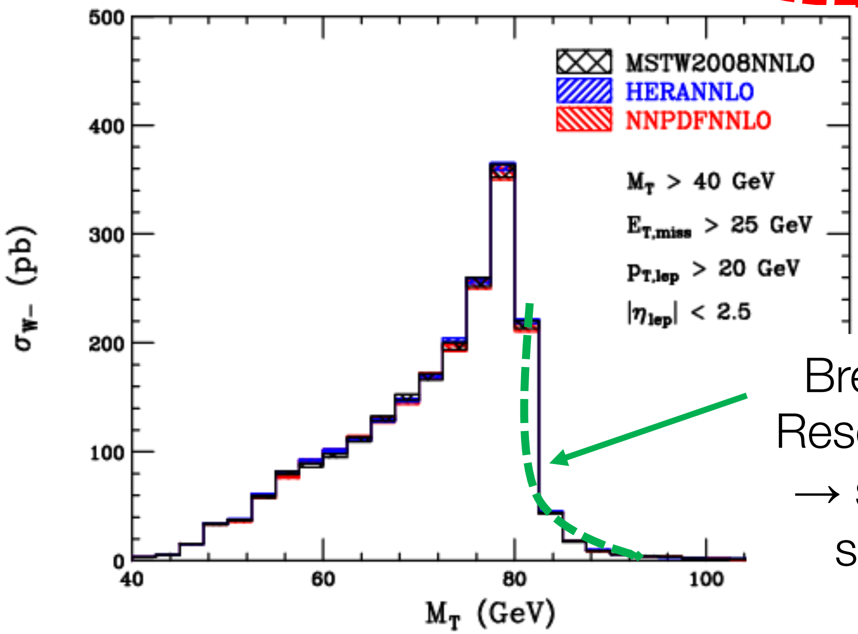
The mass of the parent particle can be constrained with the observable MT defined by

$$M_T^2 \equiv [E_T(1) + E_T(2)]^2 - [\mathbf{p}_T(1) + \mathbf{p}_T(2)]^2$$
$$= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \mathbf{p}_T(1) \cdot \mathbf{p}_T(2)]$$

where

$$p_T(1) = E_T^{miss}$$

For m1~m2~0→ $M_T^2 = 2|\mathbf{p}_T(1)||\mathbf{p}_T(2)|(1 - \cos\phi_{12})$



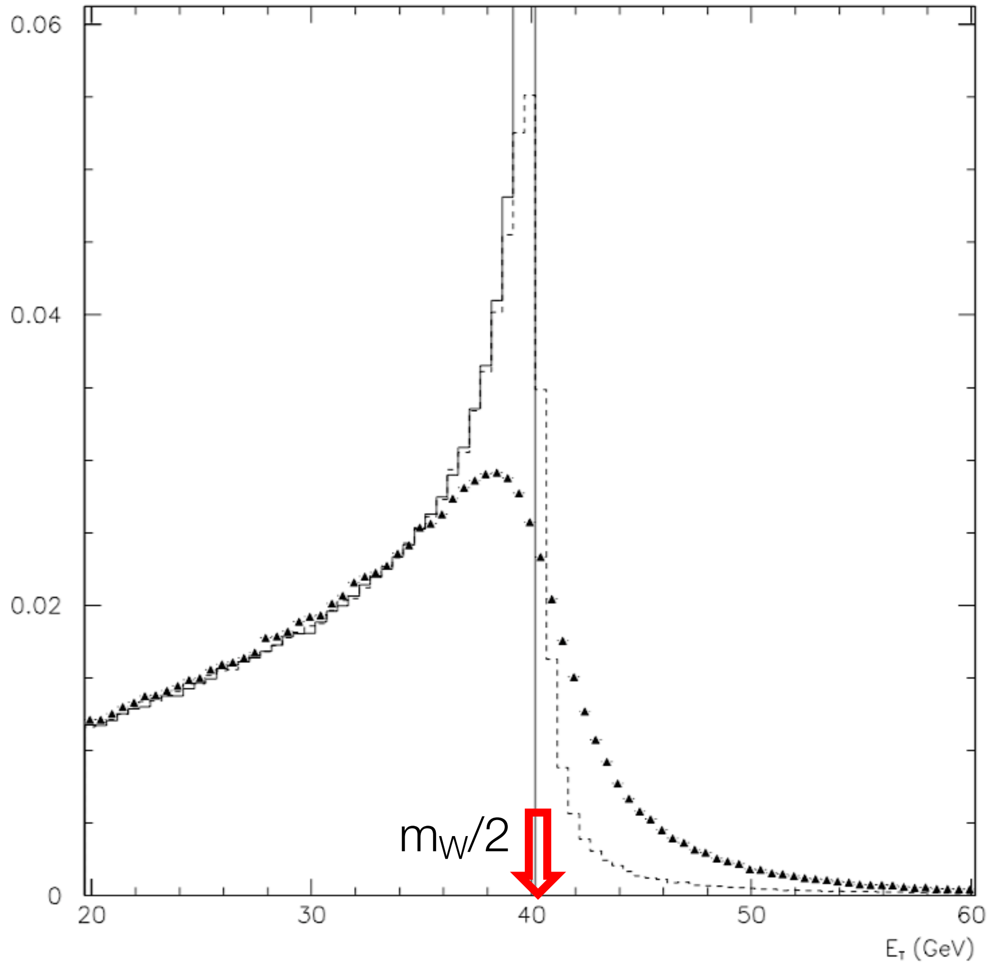
Breit-Wigner+ Resolution effect → sharp fall → smooth fall

Important characteristic: the end point of this distribution is $M_T^{max} = M$

Also the distribution of the p_T of the lepton has memory of m_W: the end-point is $m_W/2$

Effect on M_T of Resolution & Breit-Wigner Shape

Also the distribution of the p_T of the lepton has memory of m_W: the end-point is $m_W/2$



The figure ← shows the Jacobian peak of the p_T distribution when

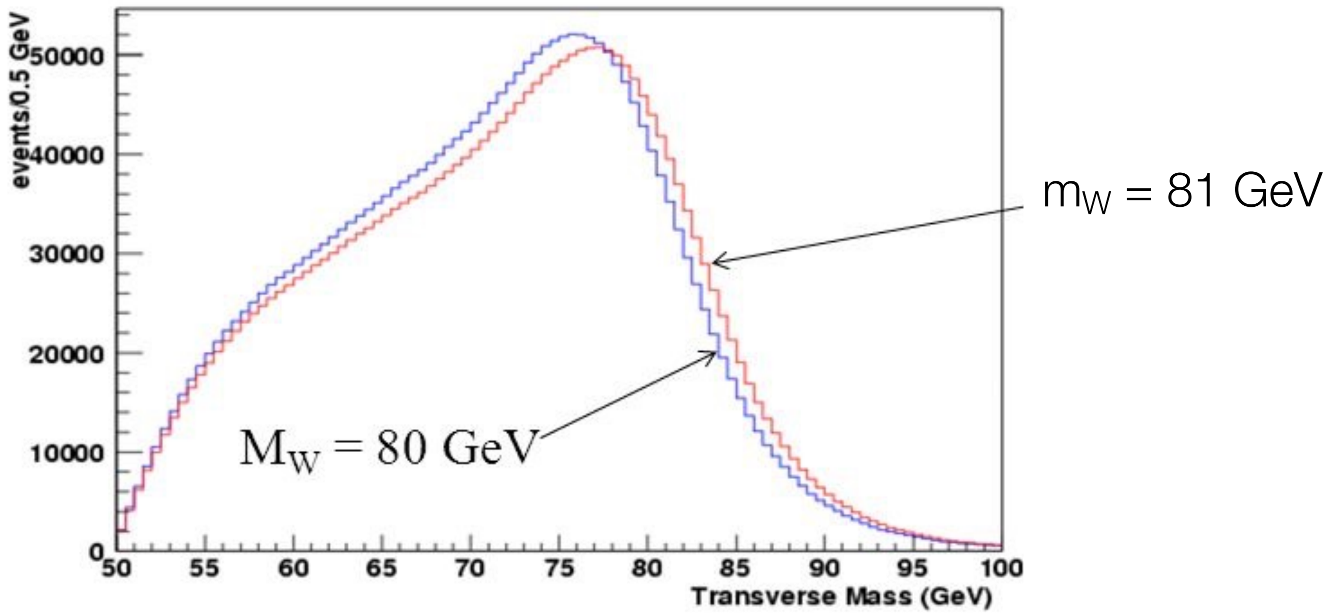
- no Breit-Wigner distribution, ideal detector with perfect acceptance and resolution (solid line)
- the W is produced according to a Breit-Wigner distribution, ideal detector with perfect acceptance and resolution (dotted line)
- Breit-Wigner distribution, detector with realistic acceptance and resolution (triangles)

→ the distribution becomes broader and broader

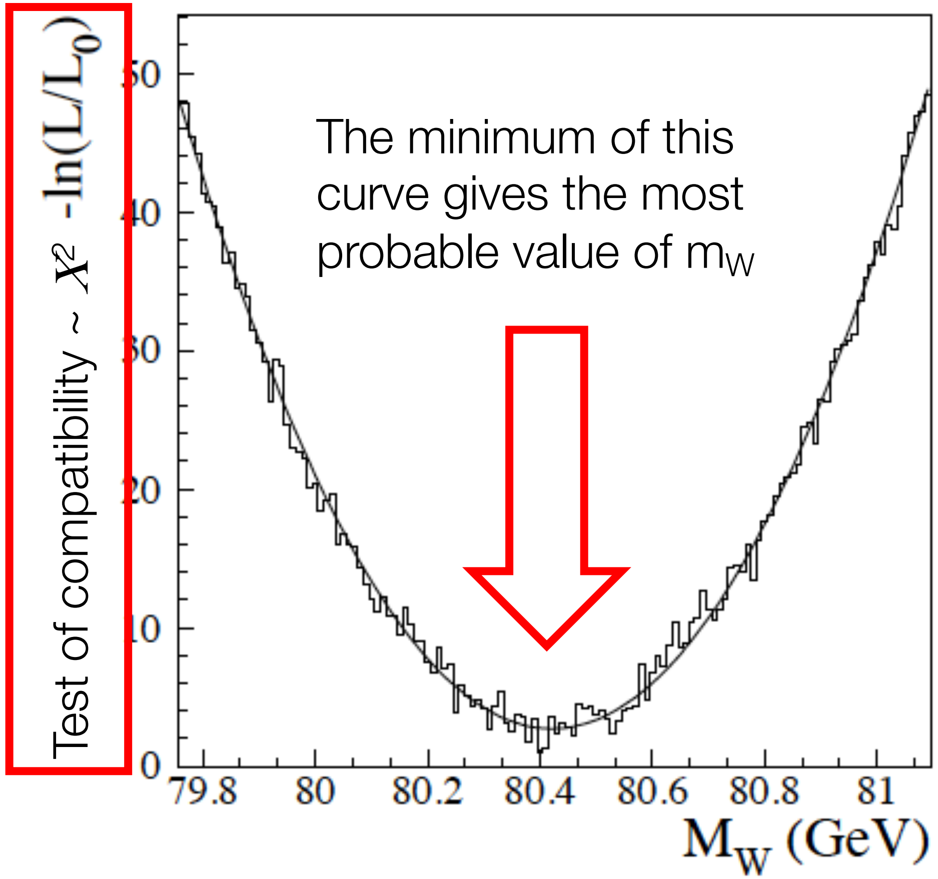
m_W and M_T (and p_T^l)

Strategy:

→ Generate MANY samples of simulated events including physics and detector effects with slightly different values of m_W and Γ_W and **find which one fits best the experimental M_T distribution.**



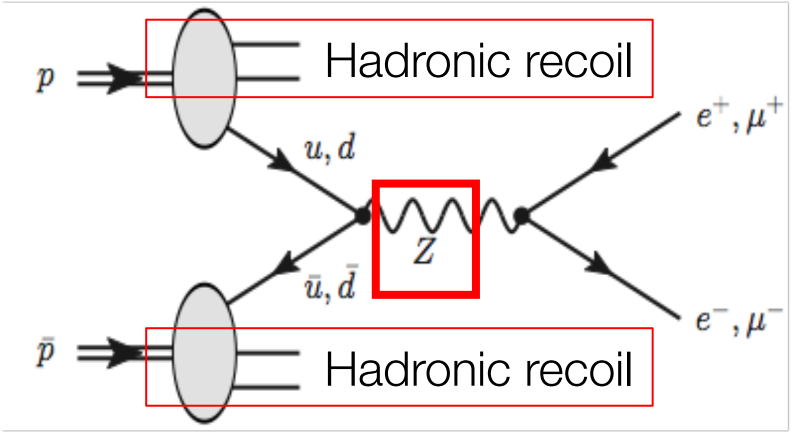
Also the distribution of the p_T of the lepton has memory of m_W: the end-point is $m_W/2$

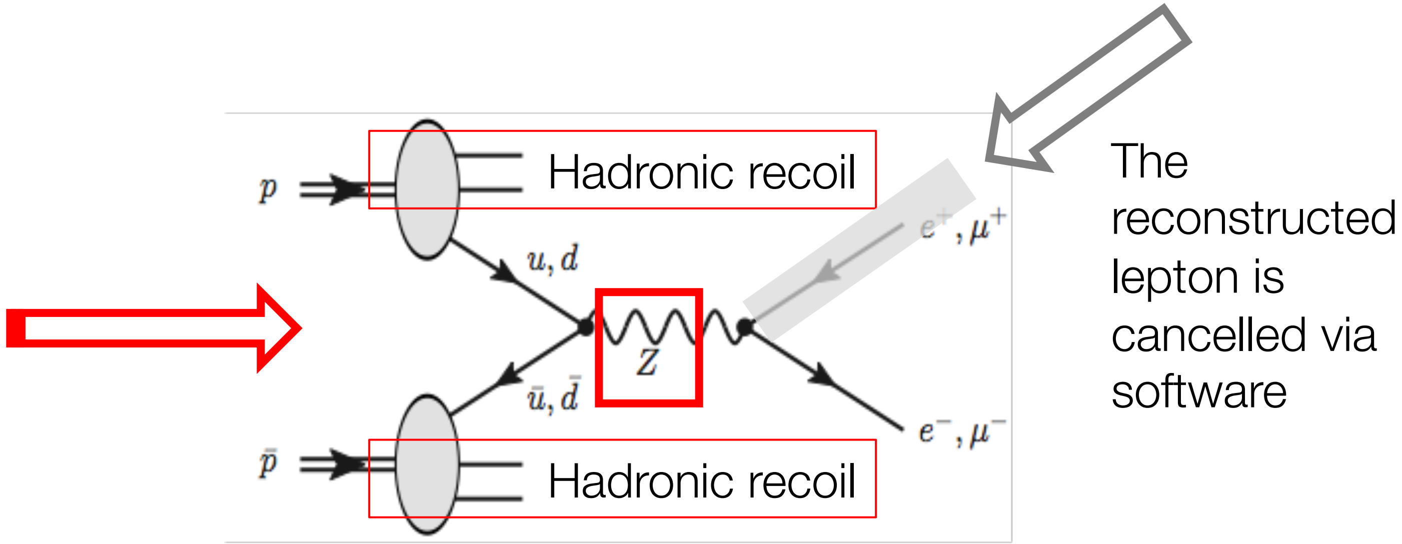


m_W Measurement Strategy: Use Z Boson

- ~10^7 (10^6) $W^\pm$ to $l\nu$ (Z to ll) → The sizes of these samples give a statistical error on m_W smaller than 10 MeV
- m_W is sensitive to the strange-quark and charm-quark distribution functions of the proton used in the of templates (less well known than u(x) and d(x)!)
- Use Z → *ll* events to calibrate the detector response: treat one of the reconstructed decay leptons as a neutrino.

The accuracy of this validation procedure is limited by Z-boson sample, ~ 10x smaller than the W sample.





Global EW fits – Input Parameters

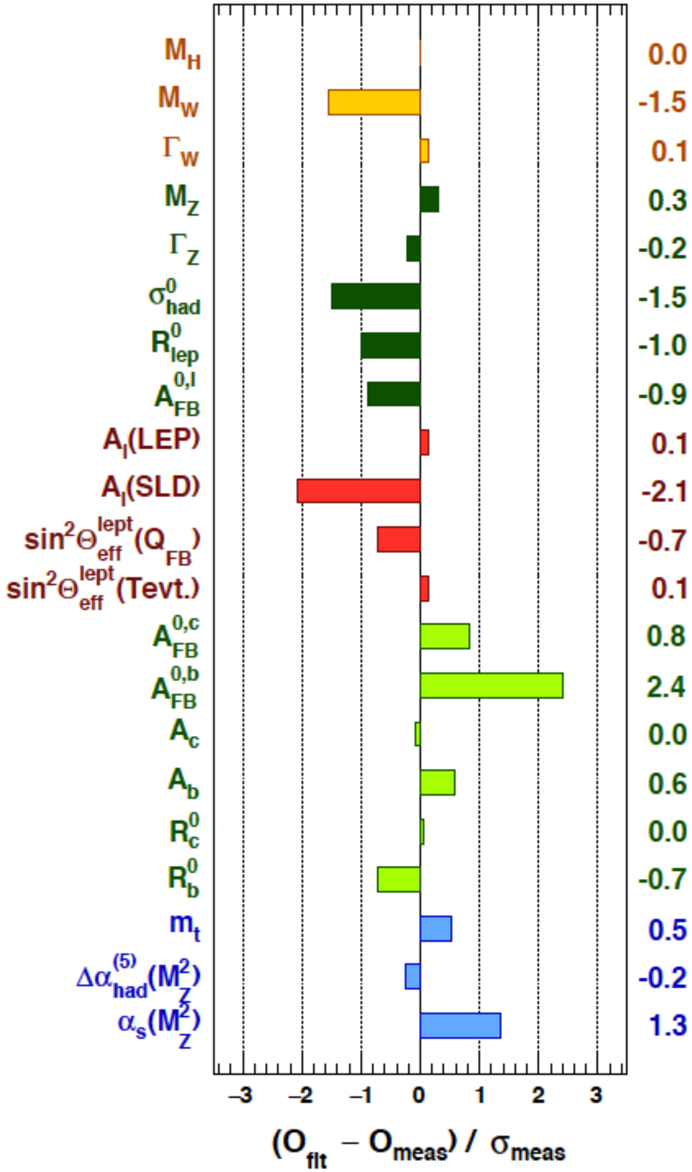
Parameter	Input value	Free in fit	Fit Result	Fit w/o exp. input in line	Fit w/o exp. input in line, no theo. unc.
M_H [GeV]	125.1 ± 0.2	yes	125.1 ± 0.2	90^{+21}_{-18}	89^{+20}_{-17}
M_W [GeV]	80.379 ± 0.013	–	80.359 ± 0.006	80.354 ± 0.007	80.354 ± 0.005
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1882 ± 0.0020	91.2013 ± 0.0095	91.2017 ± 0.0089
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4947 ± 0.0014	2.4941 ± 0.0016	2.4940 ± 0.0016
σ^0_{had} [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.475 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.742 ± 0.017	20.721 ± 0.026	20.719 ± 0.025
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	–	0.01620 ± 0.0001	0.01619 ± 0.0001	0.01619 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1470 ± 0.0005	0.1470 ± 0.0005	0.1469 ± 0.0003
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
$\sin^2\theta^\ell_{\text{eff}}(\text{Tevt.})$	0.23148 ± 0.00033	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
A_c	0.670 ± 0.027	–	0.6679 ± 0.00021	0.6679 ± 0.00021	0.6679 ± 0.00014
A_b	0.923 ± 0.020	–	0.93475 ± 0.00004	0.93475 ± 0.00004	0.93475 ± 0.00002
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	–	0.0736 ± 0.0003	0.0736 ± 0.0003	0.0736 ± 0.0002
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	–	0.1030 ± 0.0003	0.1032 ± 0.0003	0.1031 ± 0.0002
R^0_c	0.1721 ± 0.0030	–	0.17224 ± 0.00008	0.17224 ± 0.00008	0.17224 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21582 ± 0.00011	0.21581 ± 0.00011	0.21581 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]$^{(\triangledown)}$	172.47 ± 0.68	yes	172.83 ± 0.65	176.4 ± 2.1	176.4 ± 2.0
$\Delta\alpha^{(5)}_{\text{had}}(M^2_Z)$ $^{(\dagger\triangle)}$	2760 ± 9	yes	2758 ± 9	2716 ± 39	2715 ± 37
$\alpha_s(M^2_Z)$	–	yes	0.1194 ± 0.0029	0.1194 ± 0.0029	0.1194 ± 0.0028

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. The fit without the LEP (SLD) measurement gives $A_\ell = 0.1470 \pm 0.0005$ ($A_\ell = 0.1467 \pm 0.0005$). $^{(\triangledown)}$Combination of experimental (0.46 GeV) and theory uncertainty (0.5 GeV). $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

Input values and fit results for the observables used in the global electroweak fit.

1. the observables/parameters used in the fit
2. their experimental values or estimates
3. indicates whether a parameter is floating in the fit.
4. the results of the fit including all experimental data.
5. fit results are given without using the corresponding experimental or phenomenological estimate in the given row (indirect determination).
6. result using the same setup as in the fifth column, but ignoring all theoretical uncertainties.

Global EW fits - 1



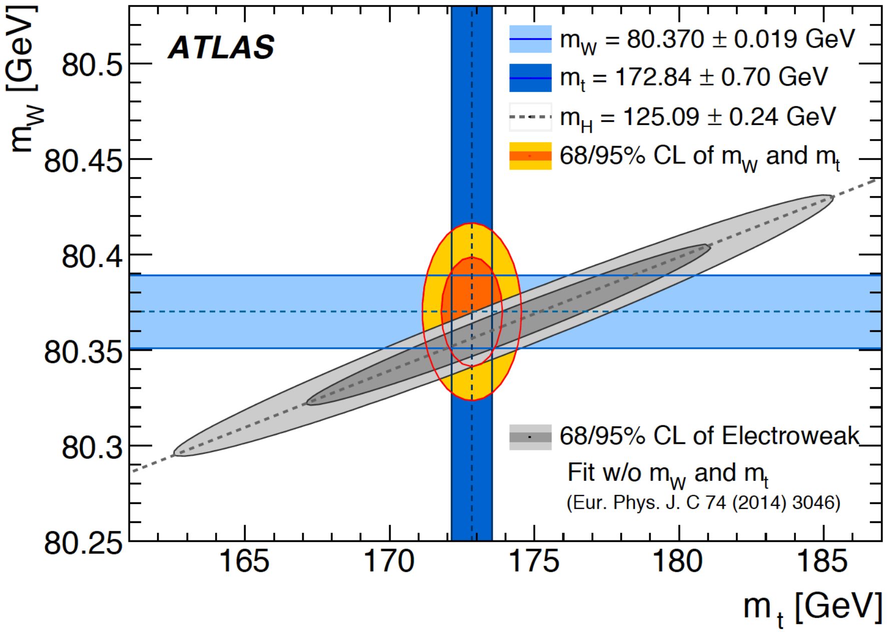
Comparison of the results with the indirect determination in units of the total uncertainty, defined as the uncertainty of the direct measurement and that of the indirect determination added in quadrature.

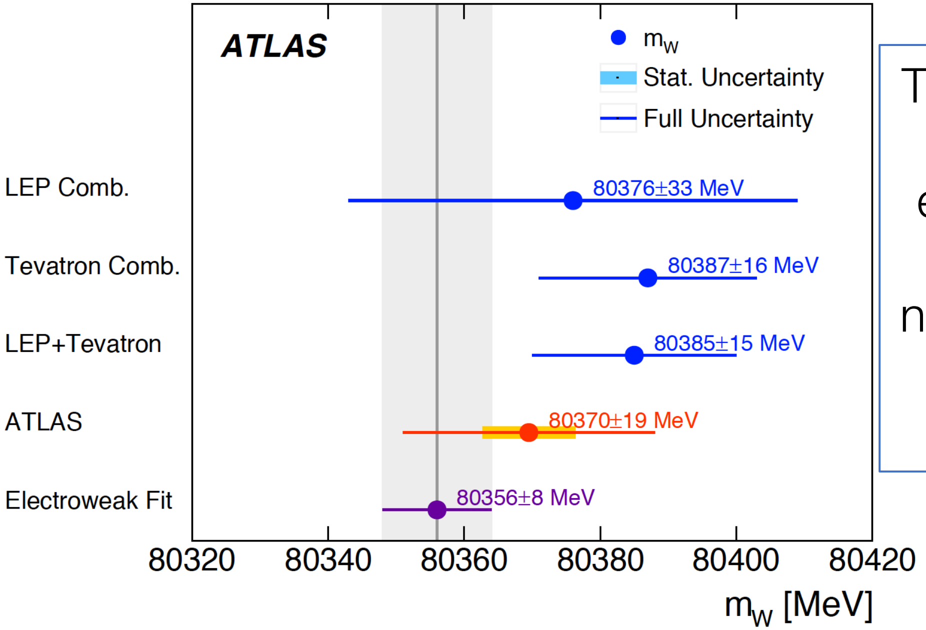
The indirect determination of an observable corresponds to a fit without using the corresponding direct constraint from the measurement.

$$\frac{Result - Indirect\ Determination}{\sqrt{\sigma^2_{Result} + \sigma^2_{Ind.Det.}}}$$

In the context of global fits to the SM parameters, constraints on physics beyond the SM are currently limited by the measurement of the W-boson mass. Therefore improving the precision of the measurements of m_W is of high importance for testing the overall consistency of the SM.

ATLAS paper





The determination of m_W from the global fit of the electroweak parameters has an uncertainty of 8 MeV → natural target for the precision of the experimental measurement of m_W.

Need to improve:

- The modelling uncertainties, which currently dominate the overall uncertainty of the m_W
- Better knowledge of the PDFs, as achievable with the inclusion in PDF fits of recent precise measurements of W- and Z-boson rapidity cross sections
- Improved QCD and electroweak predictions for Drell–Yan production

All these uncertainties are crucial for future measurements of the W-boson mass at the LHC.

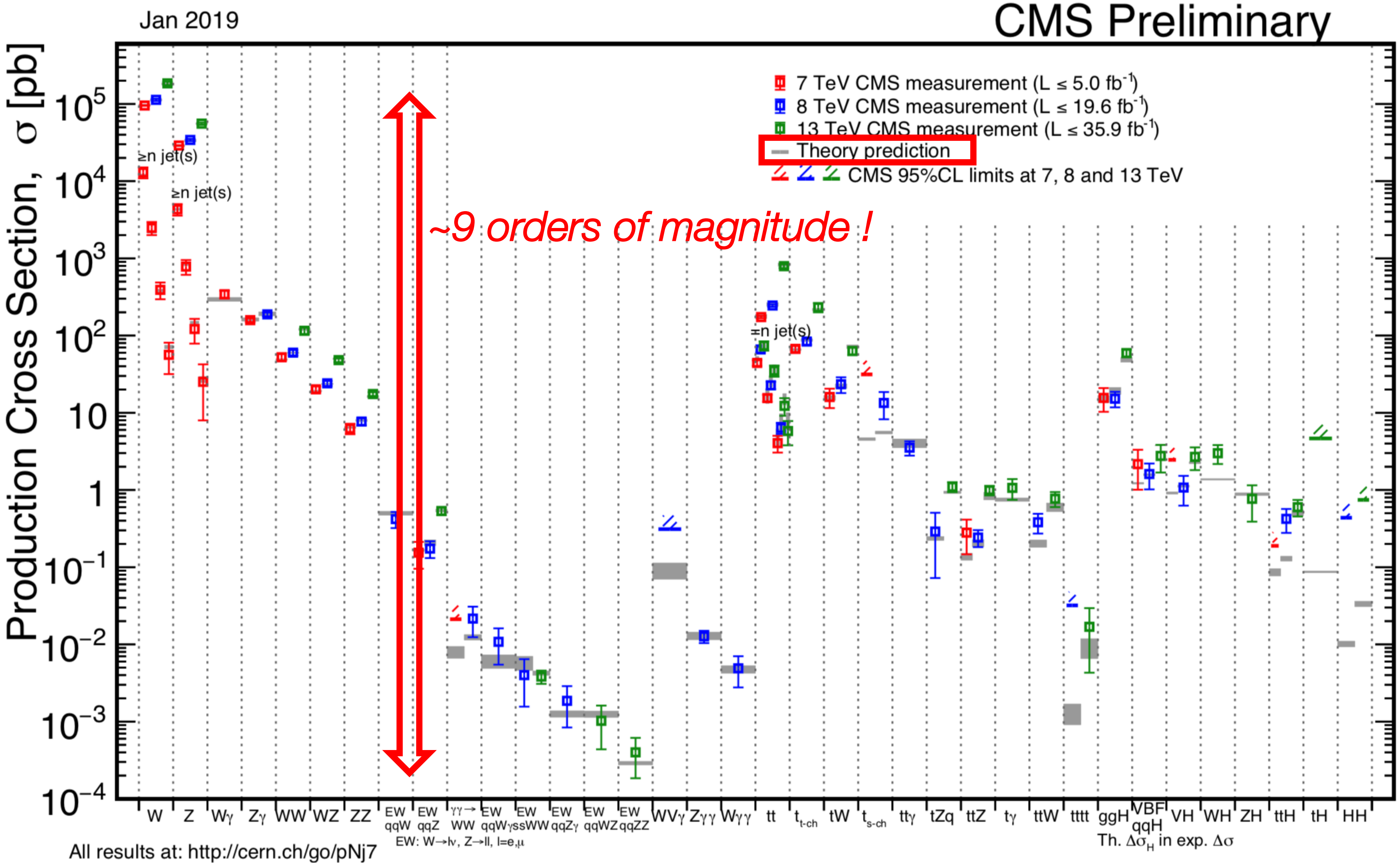
Not only m_W: EW Measurements at LHC: CMS

Measurements of many different EW processes have been performed:

Many different cross sections have been measured at different centre-of-mass energies, spanning over ~9 orders of magnitude.

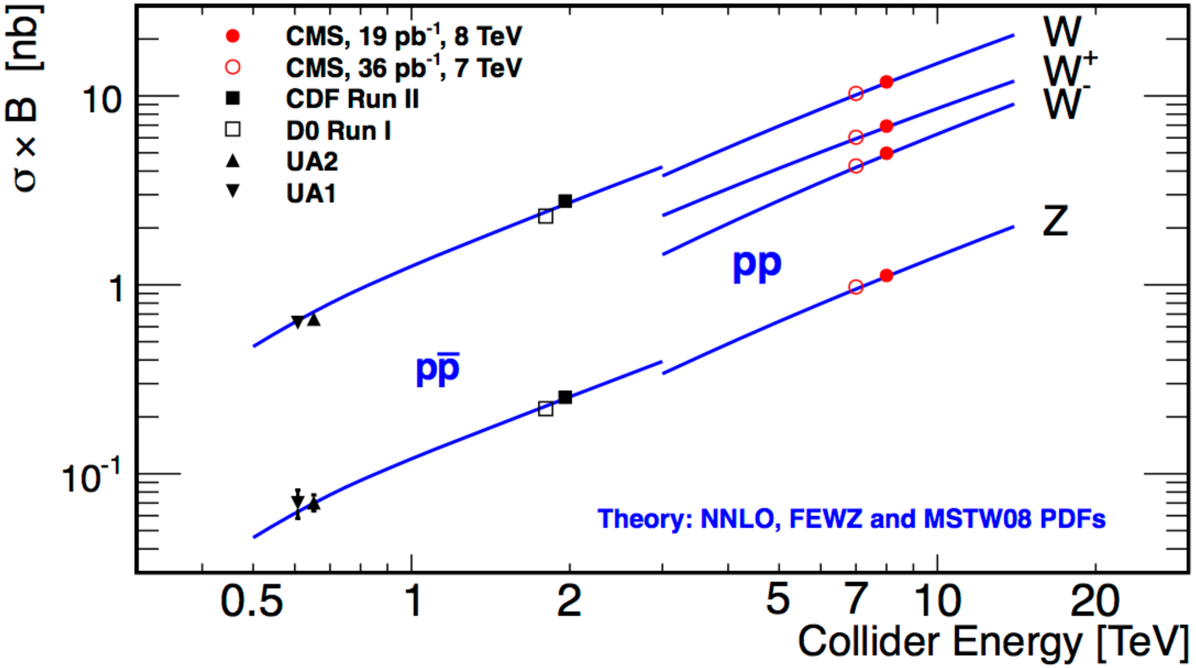
The comparison with SM predictions is also shown.

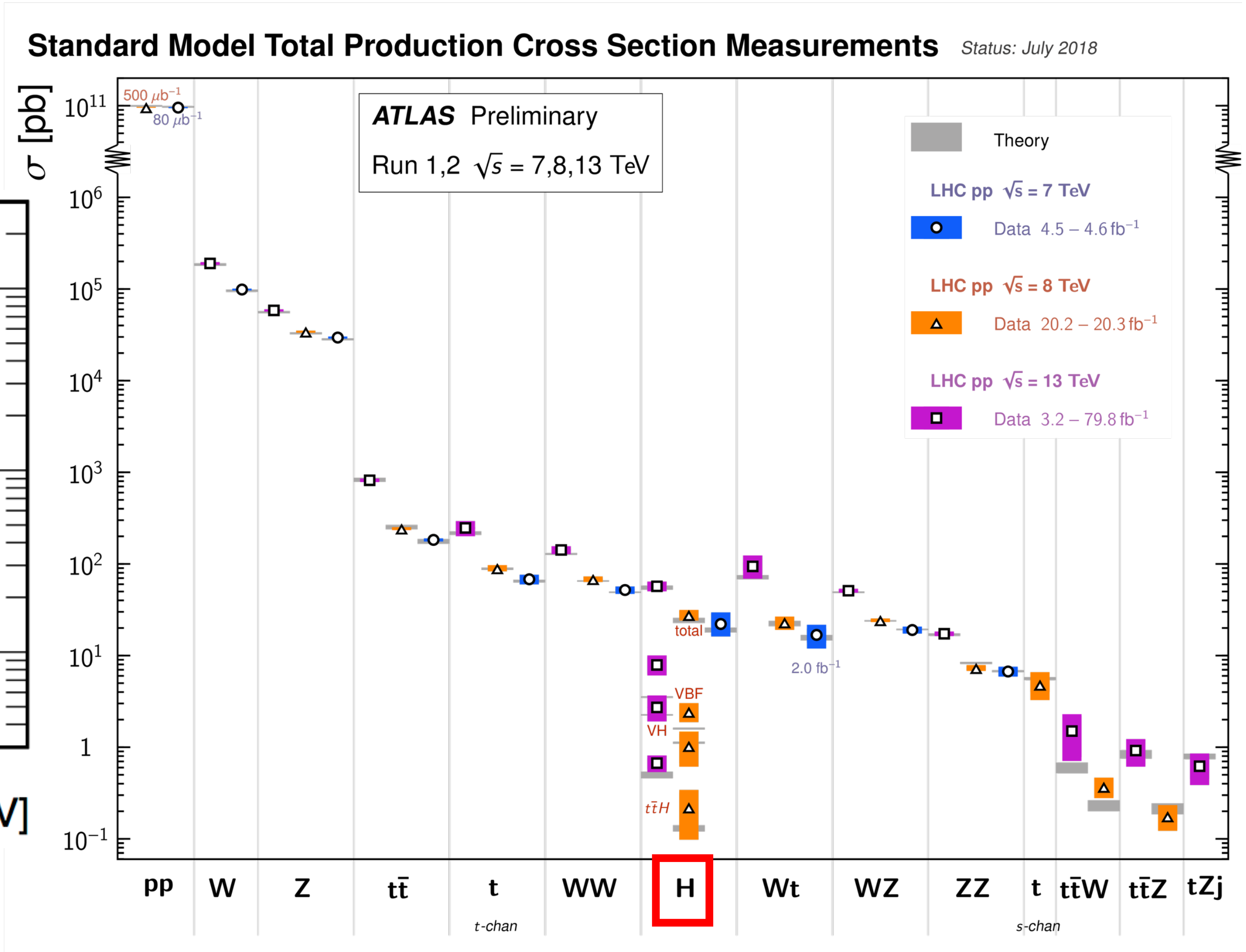
Agreement is generally good.



Not only m_W: EW Measurements at LHC: ATLAS

Very similar situation in ATLAS →

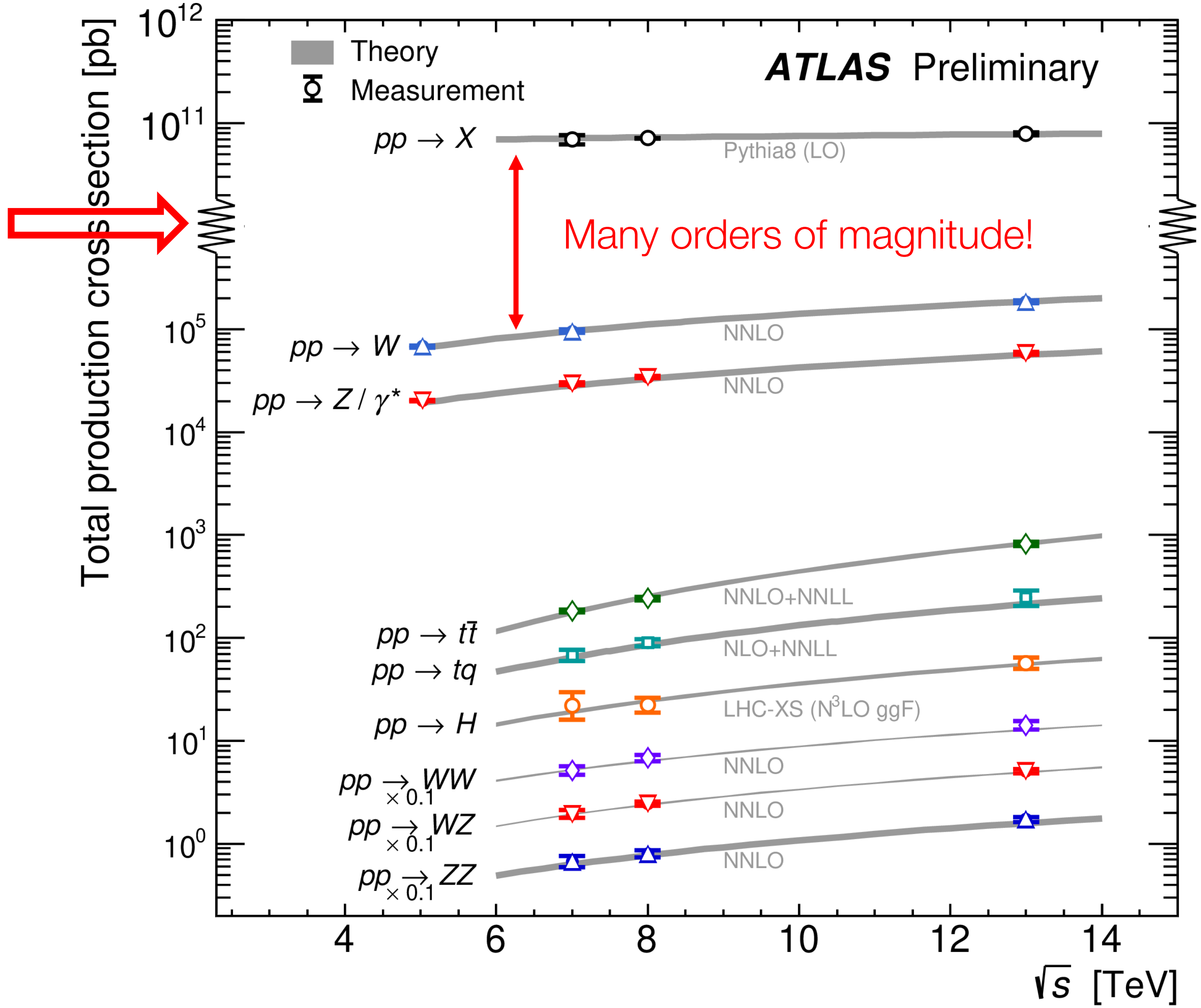




As an example the inclusive cross-section for the production of Ws and Zs is also shown compared to theory.

This is the end of the SM? Do we need to measure some observable to a better precision?

EW cross-sections as Measured by ATLAS



$pp \to X$
7 TeV, 20 μb^{-1}, Nat. Commun. 2, 463 (2011)
8 TeV, 500 μb^{-1}, Phys.Lett. B761 158 (2016)
13 TeV, 60 μb^{-1}, Phys. Rev. Lett. 117 182002 (2016)

$pp \to W$ $pp \to Z/\gamma^*$
5 TeV, 25 pb^{-1}, Eur. Phys. J. C79 (2019) 128 (for Z/W)
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C77 (2017) 367 (for Z/W)
8 TeV, 20.2 fb^{-1}, JHEP 02, 117 (2017) (for Z)
13 TeV, 81 pb^{-1}, PLB 759 (2016) 601 (for W)
13 TeV, 3.2 fb^{-1}, JHEP 02, 117 (2017) (for Z)

$pp \to t\bar{t}$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
13 TeV, 3.2 fb^{-1}, Phys. Lett. B 761 (2016)

$pp \to tq$
7 TeV, 4.6 fb^{-1}, PRD 90, 112006 (2014)
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C 77 (2017) 531
13 TeV, 3.2 fb^{-1}, JHEP 1704 (2017) 086

$pp \to H$
7 TeV, 4.5 fb^{-1}, Eur. Phys. J. C76 (2016) 6
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C76 (2016) 6
13 TeV, 36.1 fb^{-1}, Phys. Lett. B 786 (2018) 114

$pp \to WW$
7 TeV, 4.6 fb^{-1}, PRD 87, 112001 (2013)
8 TeV, 20.3 fb^{-1}, JHEP 09 029 (2016)
13 TeV, 3.2 fb^{-1}, Phys. Lett. B 773 (2017) 354

$pp \to WZ$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C (2012) 72:2173
8 TeV, 20.3 fb^{-1}, PRD 93, 092004 (2016)
13 TeV, 36.1 fb^{-1}, arXiv:1902.05759

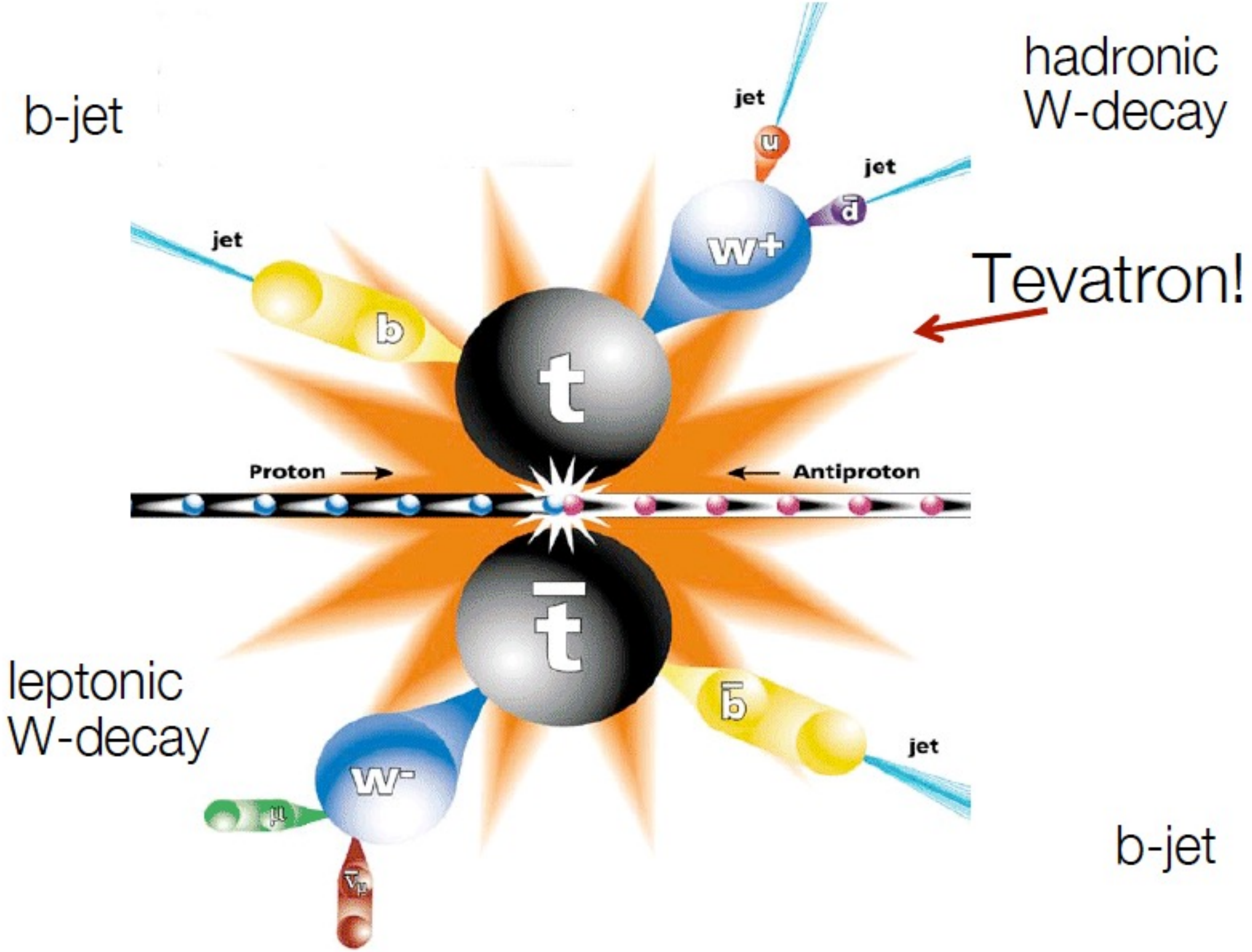
$pp \to ZZ$
7 TeV, 4.6 fb^{-1}, JHEP 03, 128 (2013)
8 TeV, 20.3 fb^{-1}, JHEP 01, 099 (2017)
13 TeV, 36.1 fb^{-1}, Phys. Rev. D 97 (2018) 032005

Precision Measurements

End of Precision Measurements

Particle Physics
Toni Baroncelli
Haiping Peng
USTC

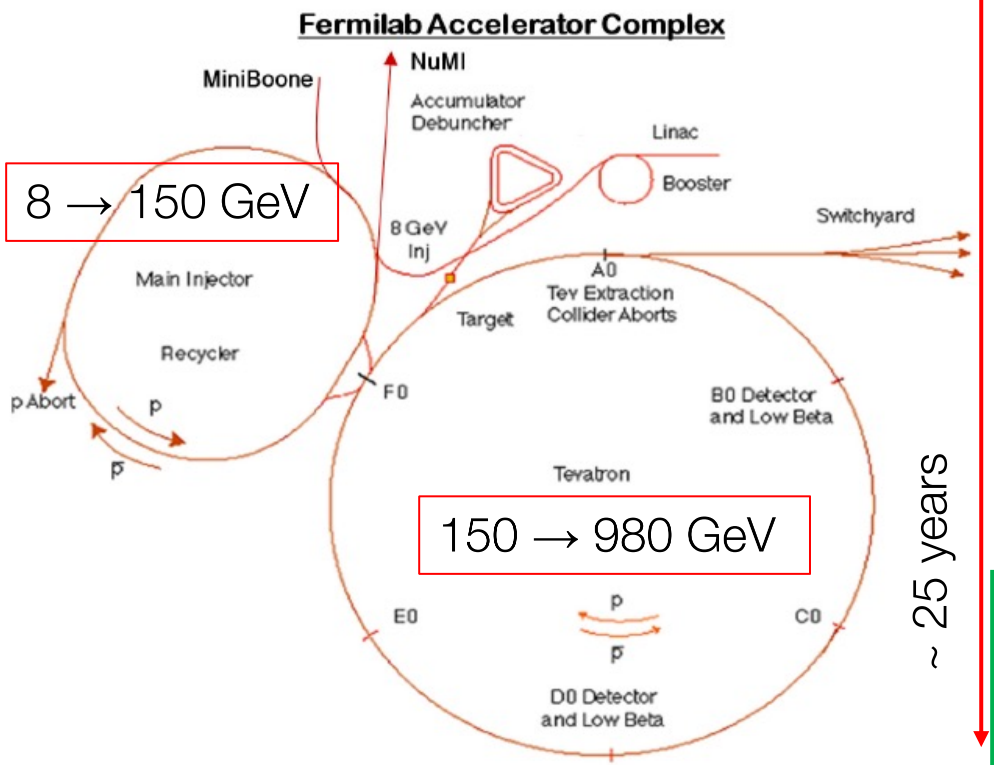
The Discovery of the Top



The Discovery of the top. The Tevatron

The *Tevatron:*

- proton-antiproton collider
- 1-km radius synchrotron, with superconducting magnets
- beam accelerated from 150 to 980 GeV two interaction points for the CDF and D0 detectors.



Timeline:

~ 25 years

- 1976 Initial proposal of a $p\bar{p}$ collider at *Fermilab* by transforming an existing accelerator into a storage ring → accumulation and cooling of antiprotons.
- 1978 *Fermilab* decided the construction of the accelerator. Design goals were: a luminosity of $11 \cdot 10^{30} cm^{-2} s^{-1}$ at $\sqrt{s}$=1.8 TeV.
- 1981 Tevatron starts as fixed target accelerator
- 1985 Tevatron operates as a $p\bar{p}$ collider, first collisions, experiments in construction
- 1987-1989 first ~test run of the Tevatron, 5 pb-1 of data collected
- 1992-96 Run Ia & Run Ib → upgrade of the collider to a luminosity of $5 \cdot 10^{31} cm^{-2} s^{-1}$, 180pb^{-1} collected
- 2001-2011 RunII top luminosity $5 \cdot 10^{32} cm^{-2} s^{-1}$

Introduction: the top Quark

The top quark is

- the heaviest known elementary particle
- Completes the third family of quarks
- its lifetime which is too short to build hadronic bound states.

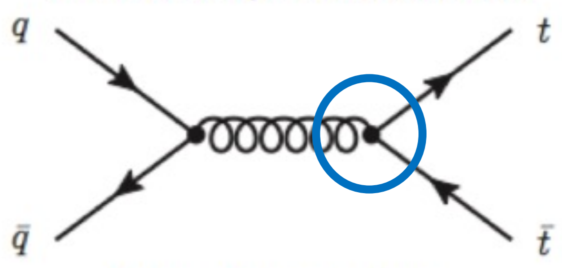
The large value of the top quark mass indicates a strong Yukawa coupling to the Higgs, → could provide special insights in our understanding of electroweak symmetry breaking.
Together with the W boson mass, it constrains the Higgs boson mass through global electroweak fits.

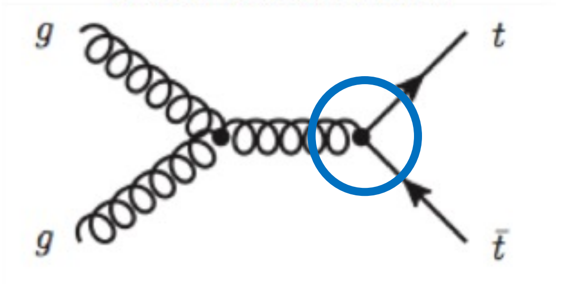
The top was discovered in 1995 at the Tevatron.

Different periods of data taking at the Tevatron

	Run Ia	Run Ib	Run II	
Energy (center-of-mass)	1800	1800	1960	GeV
Protons/bunch	1.2	2.3	2.9	$\times 10^{11}$
Antiprotons/bunch	3.1	5.5	8.1	$\times 10^{10}$
Bunches/beam	6	6	36	
Total Antiprotons	19	33	290	$\times 10^{10}$
Proton emittance (rms, normalized)	3.3	3.8	3.0	π mm-mrad
Antiproton emittance (rms, normalized)	2	2.1	1.5	π mm-mrad
β^*	35	35	28	cm
Luminosity (Typical Peak)	5.4	16	340	$\times 10^{30}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$
Luminosity (Design Goal)	5	10	200	$\times 10^{30}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

top Production and Decay





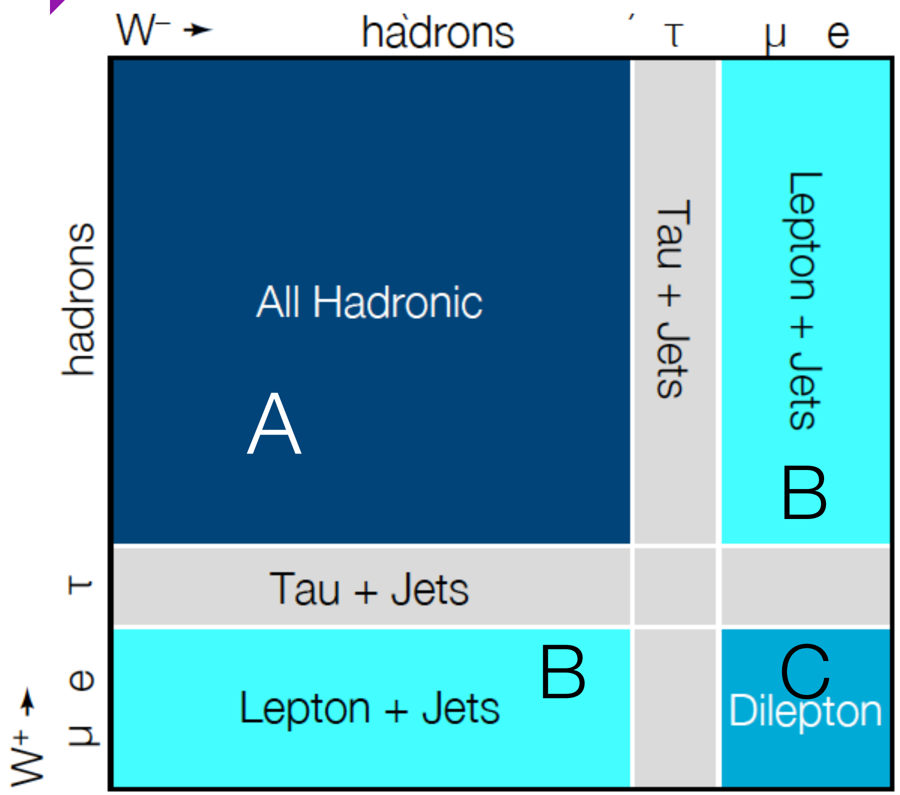
The primary mode, in which a $t\bar{t}$ pair is produced from a $gt\bar{t}$ vertex via the strong interaction, was used by the D0 and CDF collaborations to discover the top quark in 1995.

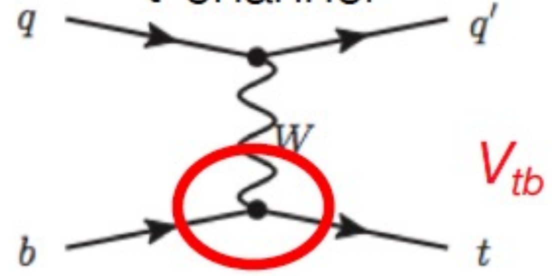
One pair of tops produced

A.	$t\bar{t} \to W^+ b\, W^- \bar{b} \to q\bar{q}'\, b\, q''\bar{q}'''\,\bar{b},$	(45.7%)
B.	$t\bar{t} \to W^+ b\, W^- \bar{b} \to q\bar{q}'\, b\,\ell^-\bar{\nu}_\ell\,\bar{b} + \ell^+\nu_\ell\, b\, q''\bar{q}'''\,\bar{b},$	(43.8%)
C.	$t\bar{t} \to W^+ b\, W^- \bar{b} \to \ell^+\nu_\ell\, b\,\ell'^-\bar{\nu}_{\ell'}\,\bar{b}.$	(10.5%)

Always 2 b-jets

SM: ~100% $t \to Wb$



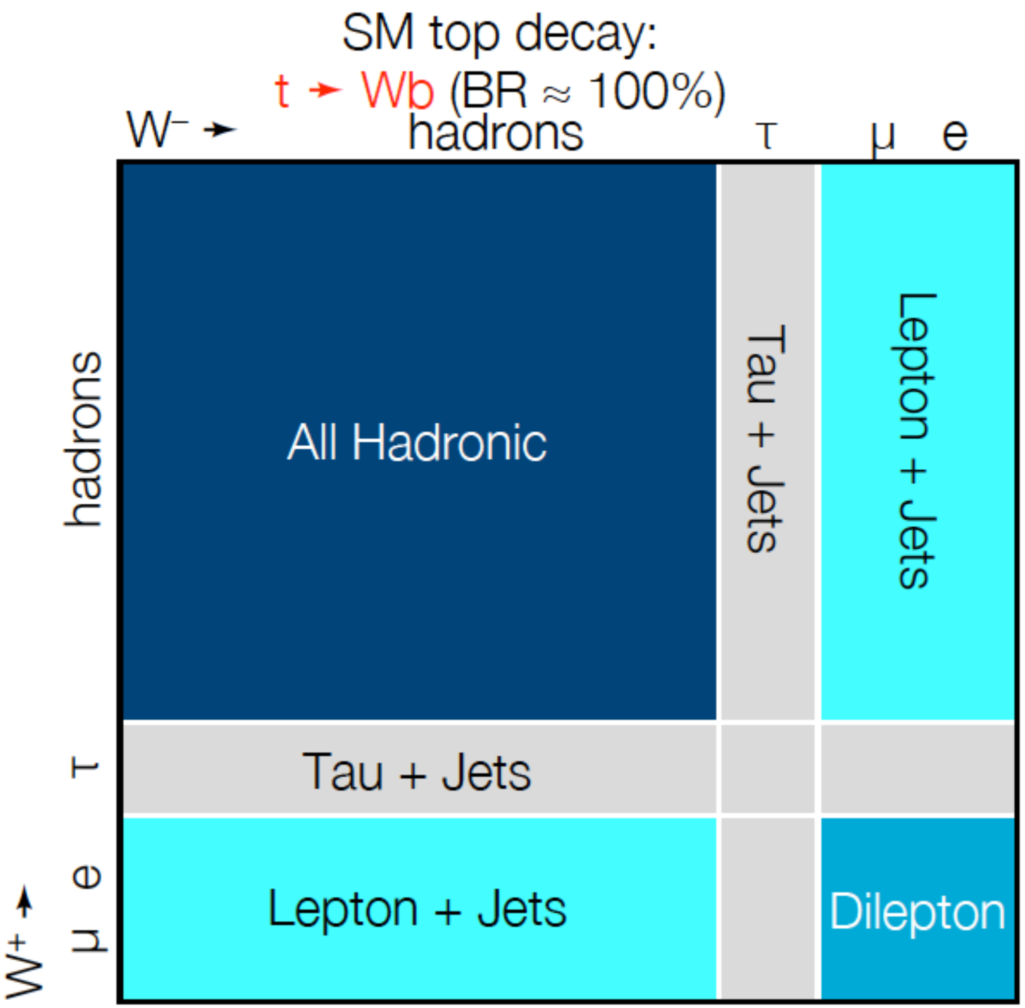


One top produced

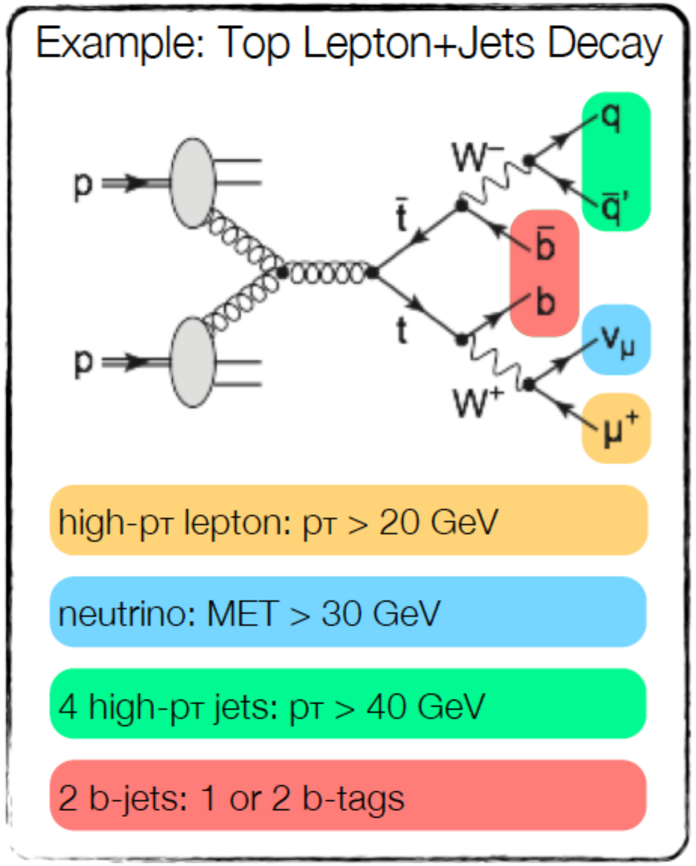
The second production mode of top quarks is the ew production of a single top quark from a Wtb vertex.

- Cross section ~ half that of $t\bar{t}$ pairs
- signal-to-background ratio is much worse

Topologies in $t\bar{t}$ Decays



- These events always contain two b quarks
- The W decays characterise the topology of the event:
  - **All hadronic** → 6 jets (2 b jets) with large QCD background. Problem is jet-pairing, many possible combinations (W mass as constraint…)
  - **Lepton + jets** → lepton, neutrino + 4 jets; lepton and missing energy suppress QCD background. 4 jets, pairing problem even if less than in the full hadronic case
  - **Di-lepton** → 2 leptons, 2 neutrinos 2 b jets; clean, little background but (10% BR) + ambiguities due to 2 neutrinos



How to Recognise a “b” Jet? → b-Tagging

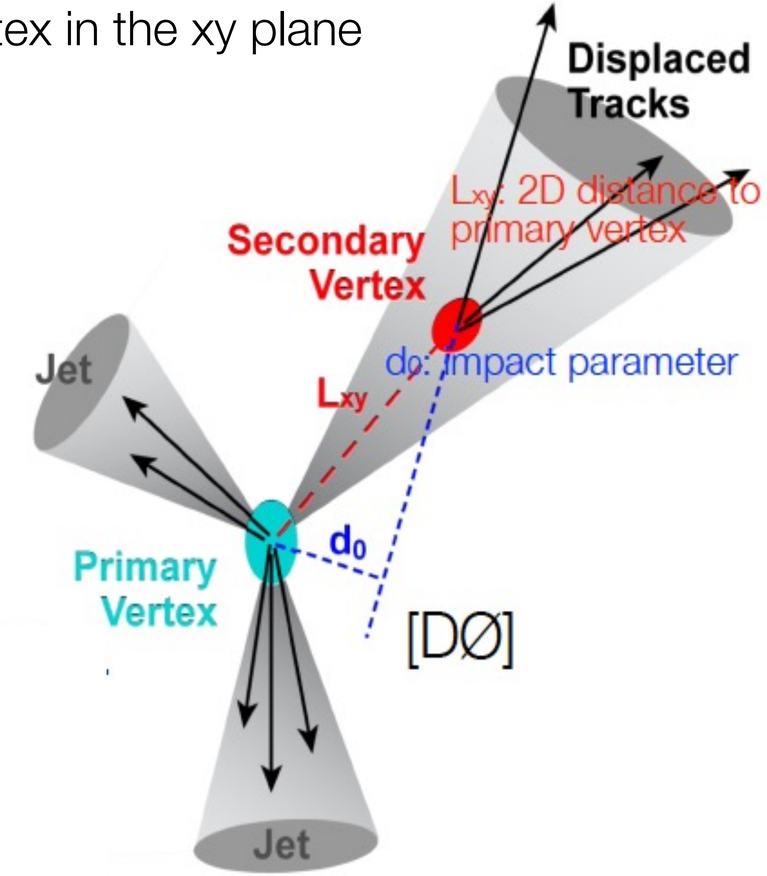
Heavy flavour hadrons (→”b hadrons”) are unstable (life-time ~ 1.5 x 10^{-12} s) and decay after a measurable path (mm’s).

First approach: hadronic decay of the b-hadron →

1. charged tracks do not extrapolate back to the primary vertex
2. A secondary vertex detached from the primary vertex is present in the event

The topology close to the primary vertex has to be studied → vertex detector

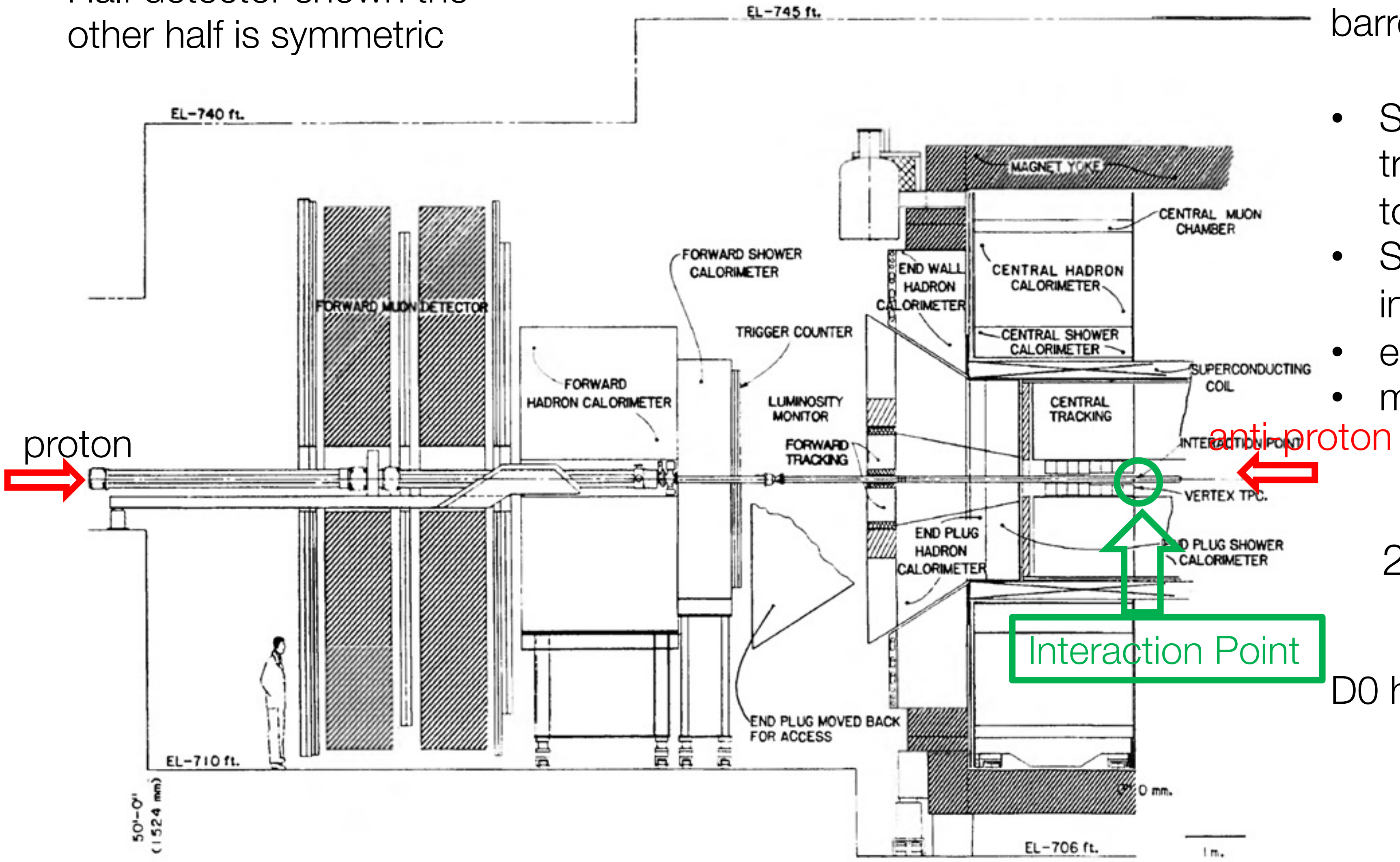
- d_0 track based indicator distance of minimum approach to the primary vertex
- Lxy distance between the secondary vertex and the primary vertex in the xy plane



Second approach: leptonic decay of the b-hadron →
b decay to lν+X → ~soft lepton close to a jet

The Experiments: CDF & D0

Half detector shown the other half is symmetric



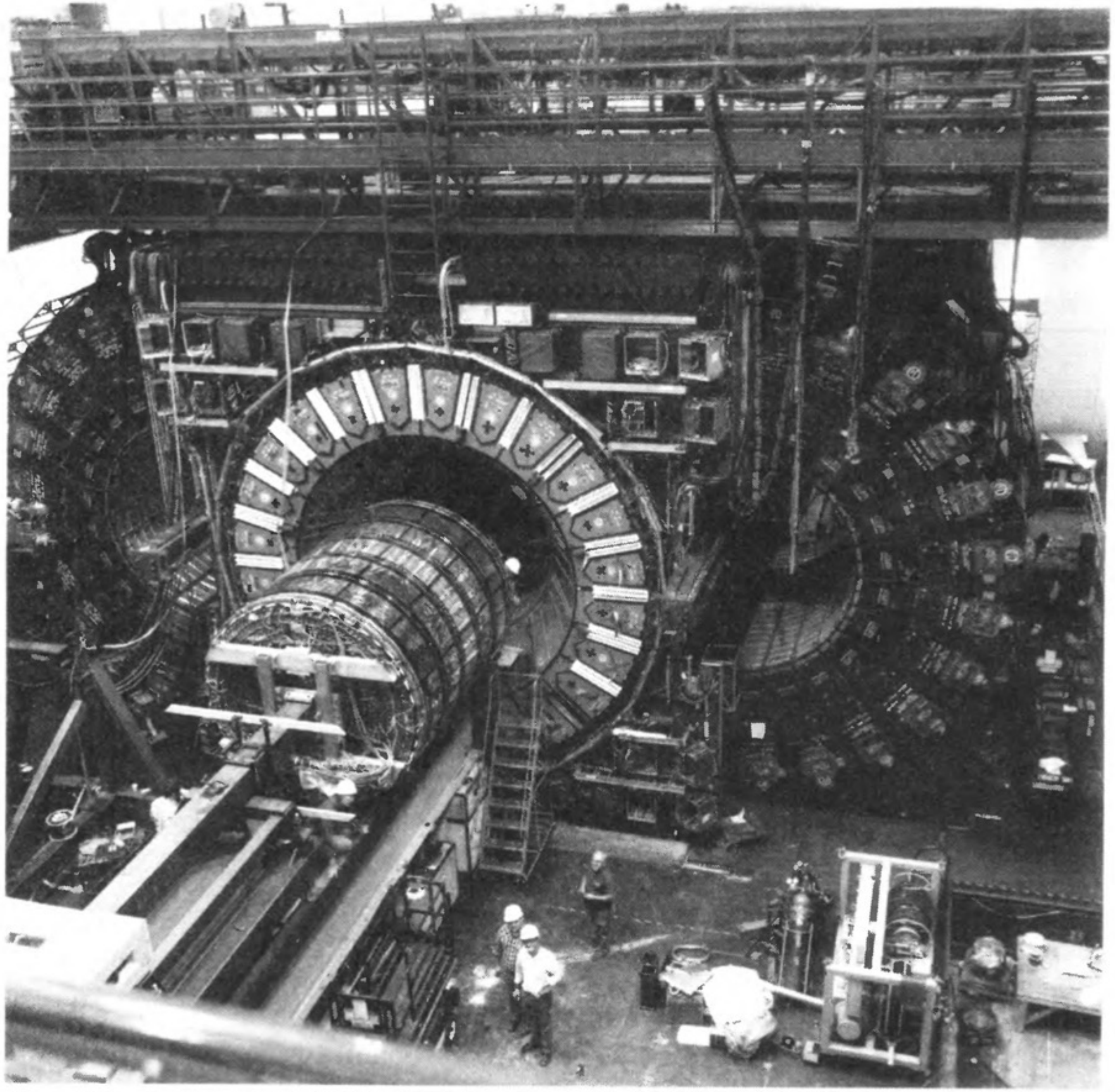
Already a ~ large modern detector: barrel part + forward/backward disks

- Silicon strip detector to measure tracks close to the interaction point to identify secondary vertices
- Superconducting solenoid + tracker inside
- em and had calorimeters
- muon chambers

26 m long and 10 m high

D0 had a similar structure

The Discovery of the top in CDF



CDF during installation

A. $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q \bar{q}' b q'' \bar{q}''' \bar{b},$ (45.7%)

B. $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q \bar{q}' b \ell^- \bar{\nu}_\ell \bar{b} + \ell^+ \nu_\ell b q'' \bar{q}''' \bar{b},$ (43.8%)

C. $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow \ell^+ \nu_\ell b \ell'^- \bar{\nu}_{\ell'} \bar{b}.$ (10.5%)

Always 2 b-jets

A: all hadronic, B: lepton + jets, C: leptons

Selections (optimise $S/\sqrt{S+B}$)

A: Lepton + jets	B: Di-lepton
$1{\times}W \rightarrow l\nu\ (l = e, \mu)$	$2{\times}W \rightarrow l\nu\ (l = e, \mu)$
$p_T^l > 20\ GeV$	$p_T^l > 20\ GeV$
$\geq 3\ jets\ (of\ which\ 2b)$	2 jets (from b-decay)
(1 secondary vertex) OR (1 soft lepton from b-decay p_T> 2 GeV	$E_T^{miss} > 25\ GeV$
	$75\ GeV < m_{ee,\mu\mu} < 105\ GeV$

Top Mass Reconstruction (2 methods)

1

Direct m_{top} reconstruction in the l+jet channel: take the hadronic side ('jet side') and compute

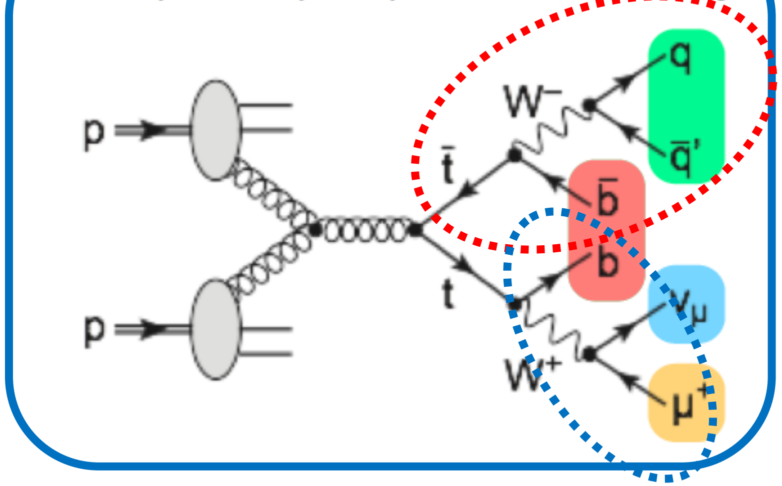
- m_W = invariant mass of jet_q and $jet_{\overline{q'}}$
- JES = Jet Energy Scale: scale factor which multiplies the jet energy. You look for the JES which gives the best reconstruction of m_W
- M_{top} = invariant mass of reconstructed hadronically decaying $W + jet_{\bar{b}}$

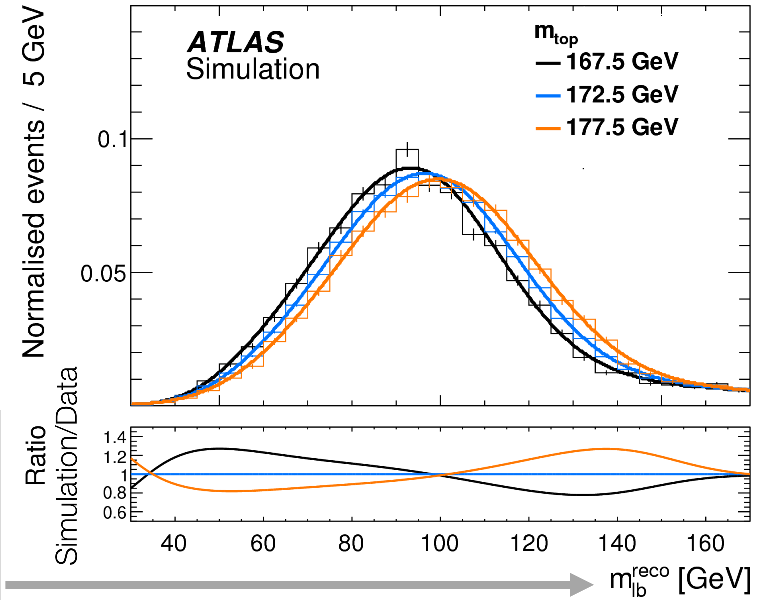
2

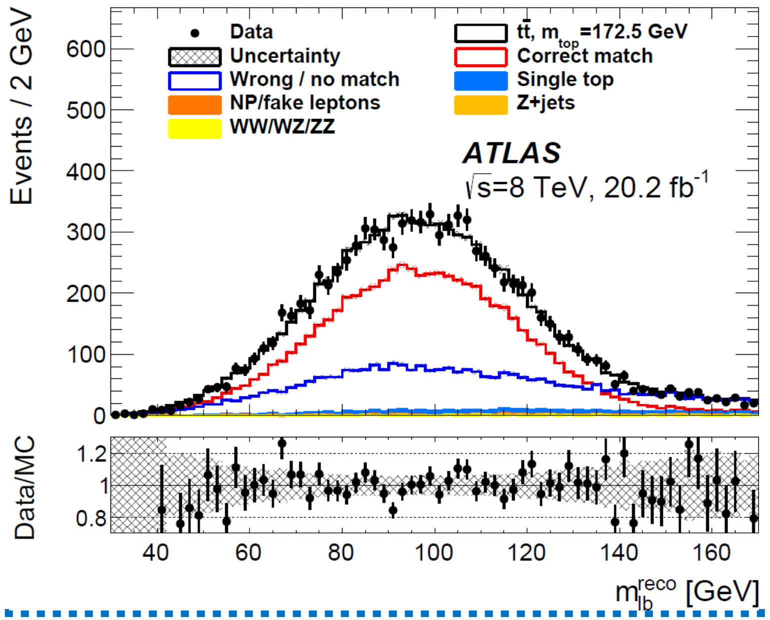
Template method: generate

- Many samples of tt events with m_{top} varying in small steps
- Take one observable with memory of m_{top} and compare with data
- Best agreement → m_{top}

Example: Top Lepton+Jets Decay







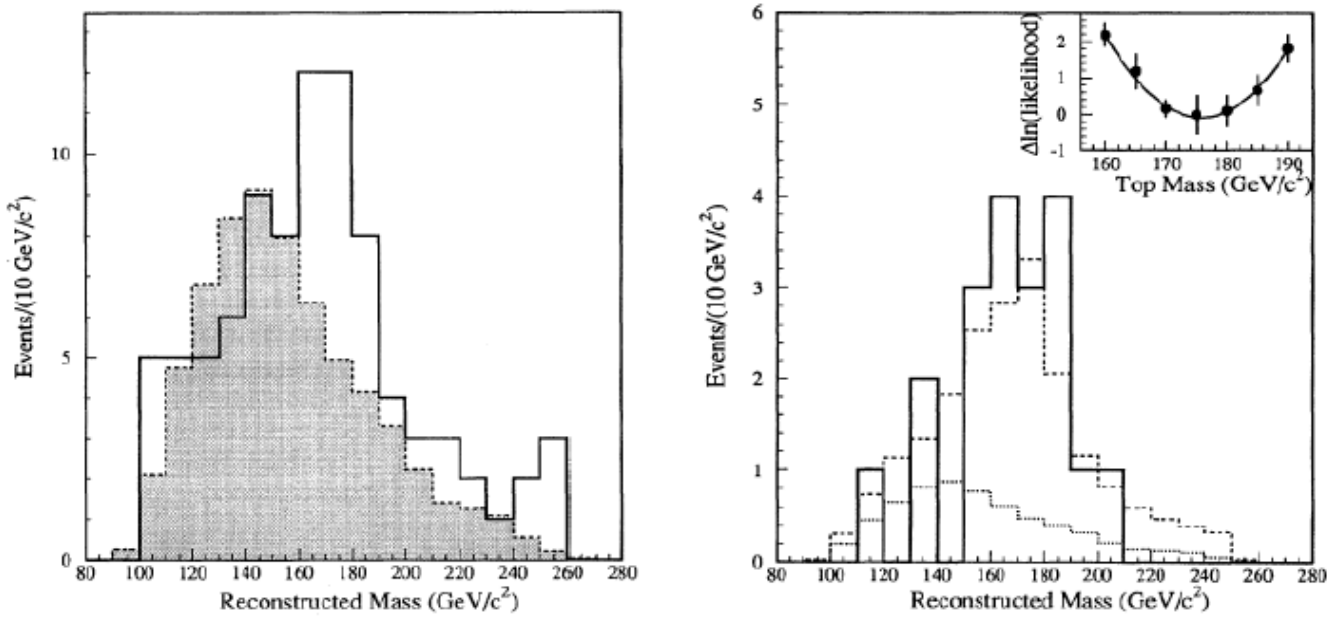
$m_{lb}^{reco} = invariant\ mass\ of\ lepton + jet_b$

$(\nu_l\ non\ included\ \rightarrow m_{lb}^{reco} < m_{top})$

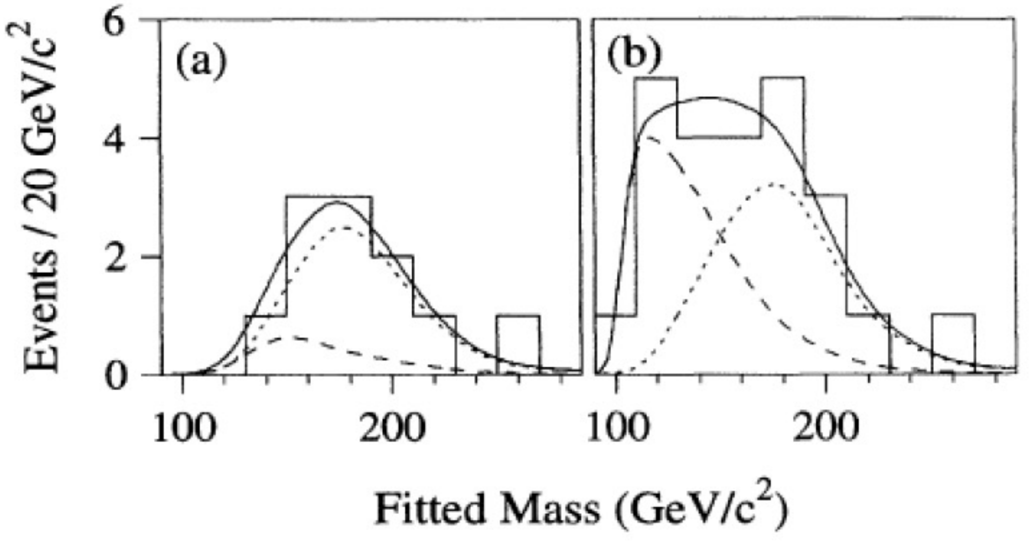
Discovery of the top at CDF & D0

Year	Number Selected Events (CDF+D0)		top mass (GeV)
	A: Lepton + jets	B: Di-lepton	$174 \pm 10^{+13}_{-12}$
1994 (evidence)	86 (background:37)	12 (background:2.5)	
1995 (discovery)	signal incompatible with background: CDF 4.9σ D0 4.6σ		CDF: $174 \pm 8 \pm 10$ D0: $199 \pm 22^{+19}_{-21}$

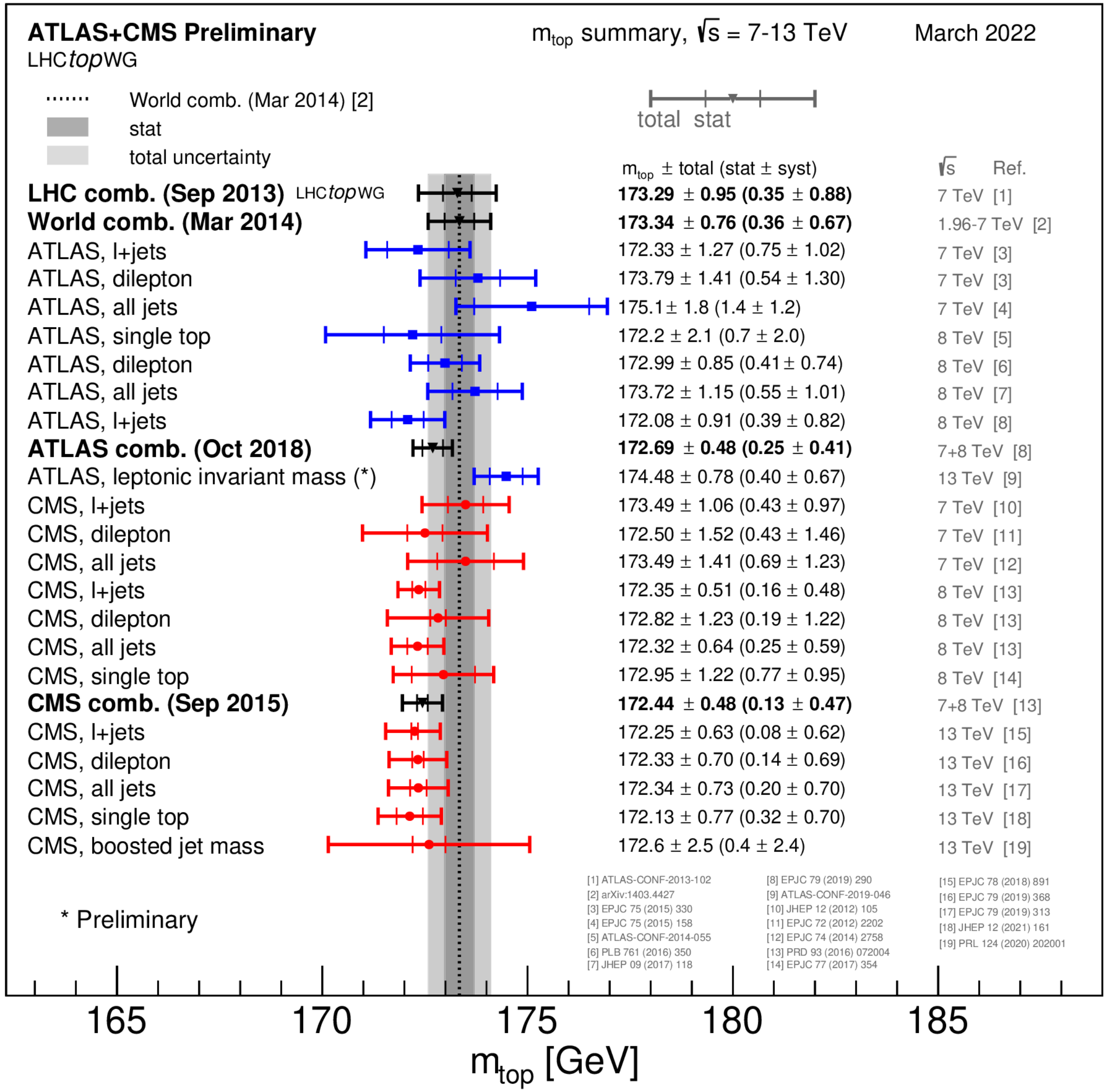
CDF



D0

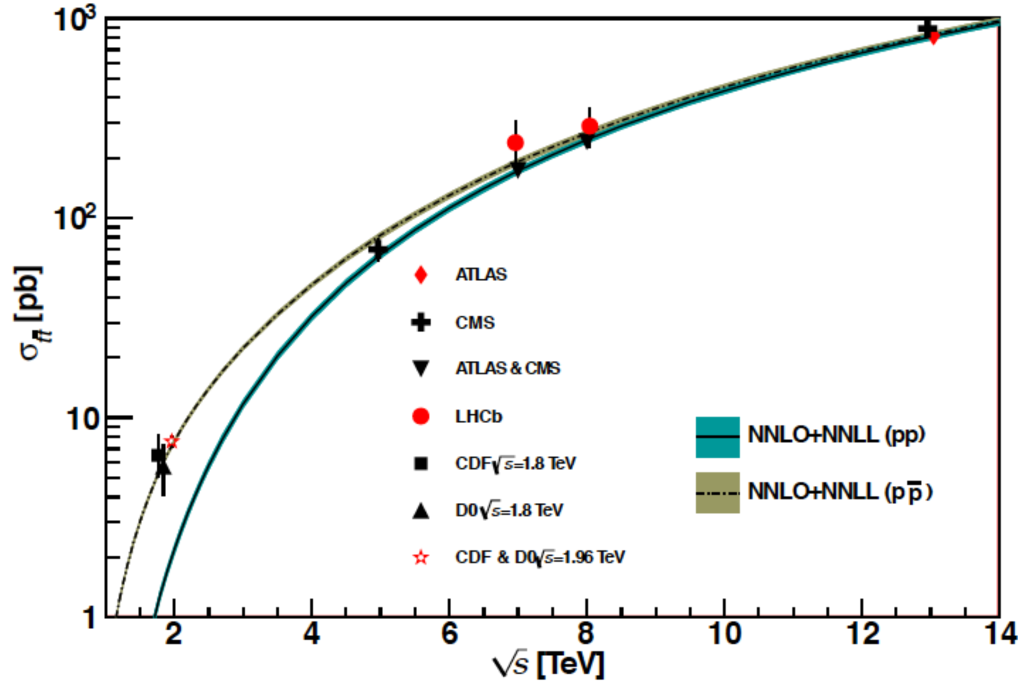


The Evolution of m_t from Tevatron to LHC



Important improvements with time (and going to LHC):

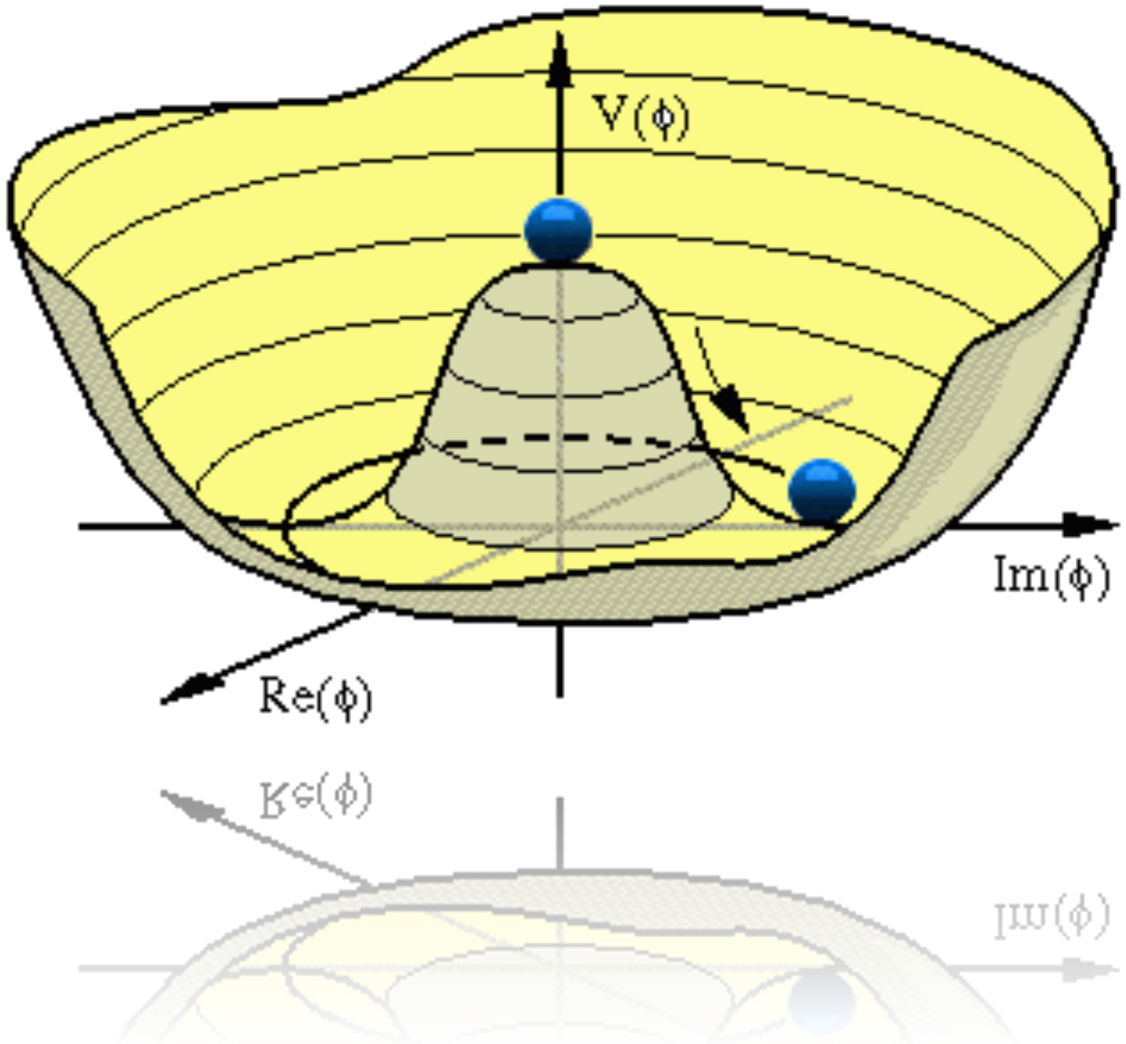
- $m_t = 174.30 \pm 0.35 \pm 0.54\ (CDF + D0)$
- $\rightarrow m_t = 173.34 \pm 0.36 \pm 0.67\ (CDF + D0 + LHC)$



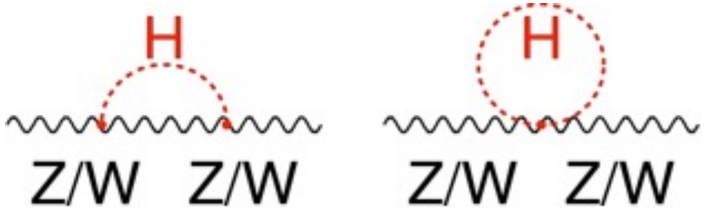
The σ_{tt} was measured from ~2 TeV to 13 TeV and found to be in agreement with SM predictions

Higgs Searches at LEP

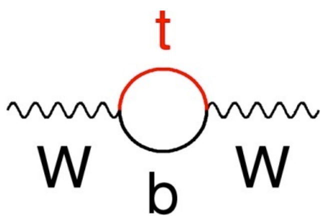
The Higgs, the (once!) missing piece of the Standard Model



Indications from EW measurements



$\sim\log(m_H)$

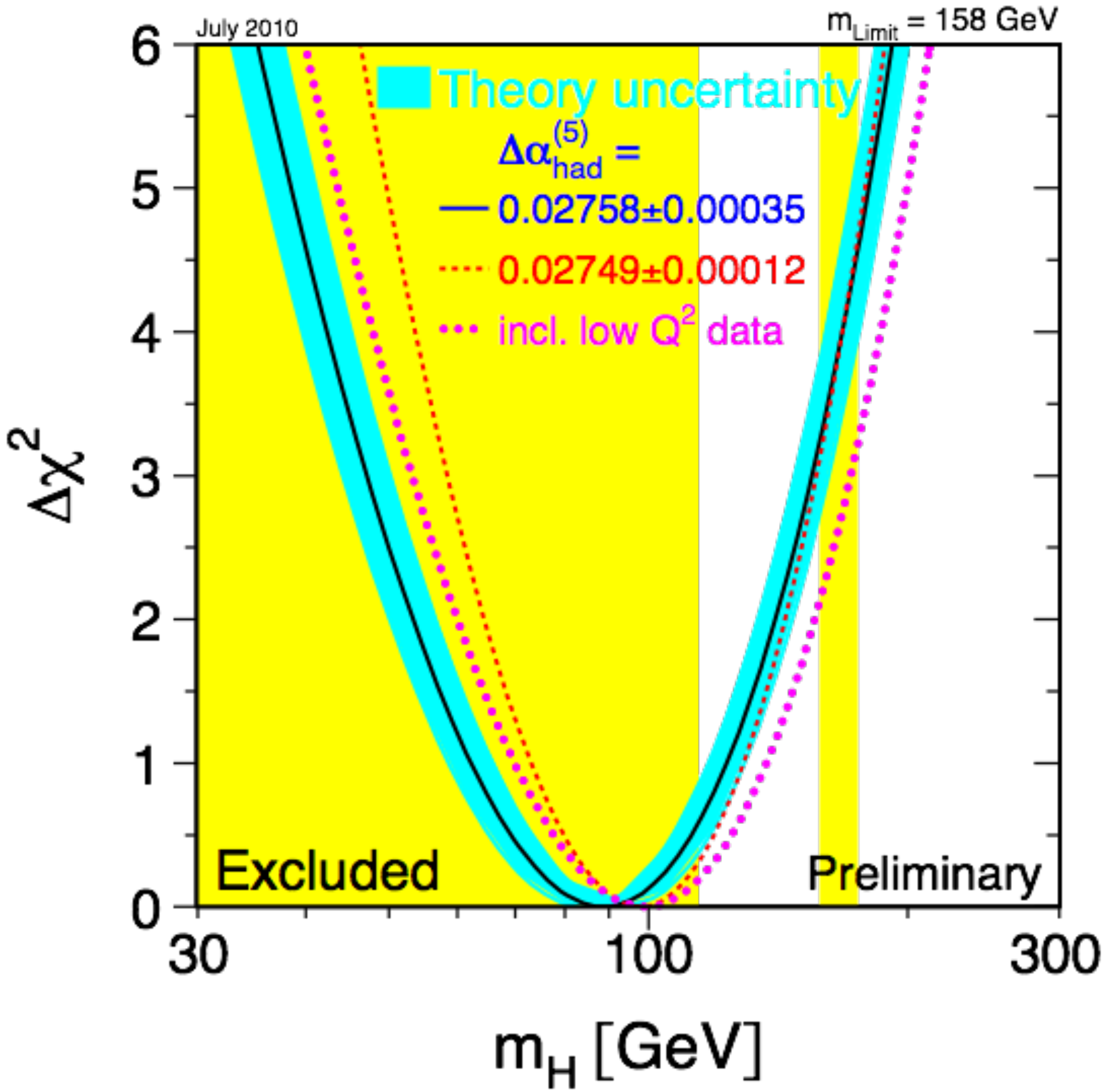


$\sim m_q^2$

EW-Fits:

M_H = 89 GeV

M_H < 158 GeV @ 95% CL



Where to Search for the Higgs Boson?

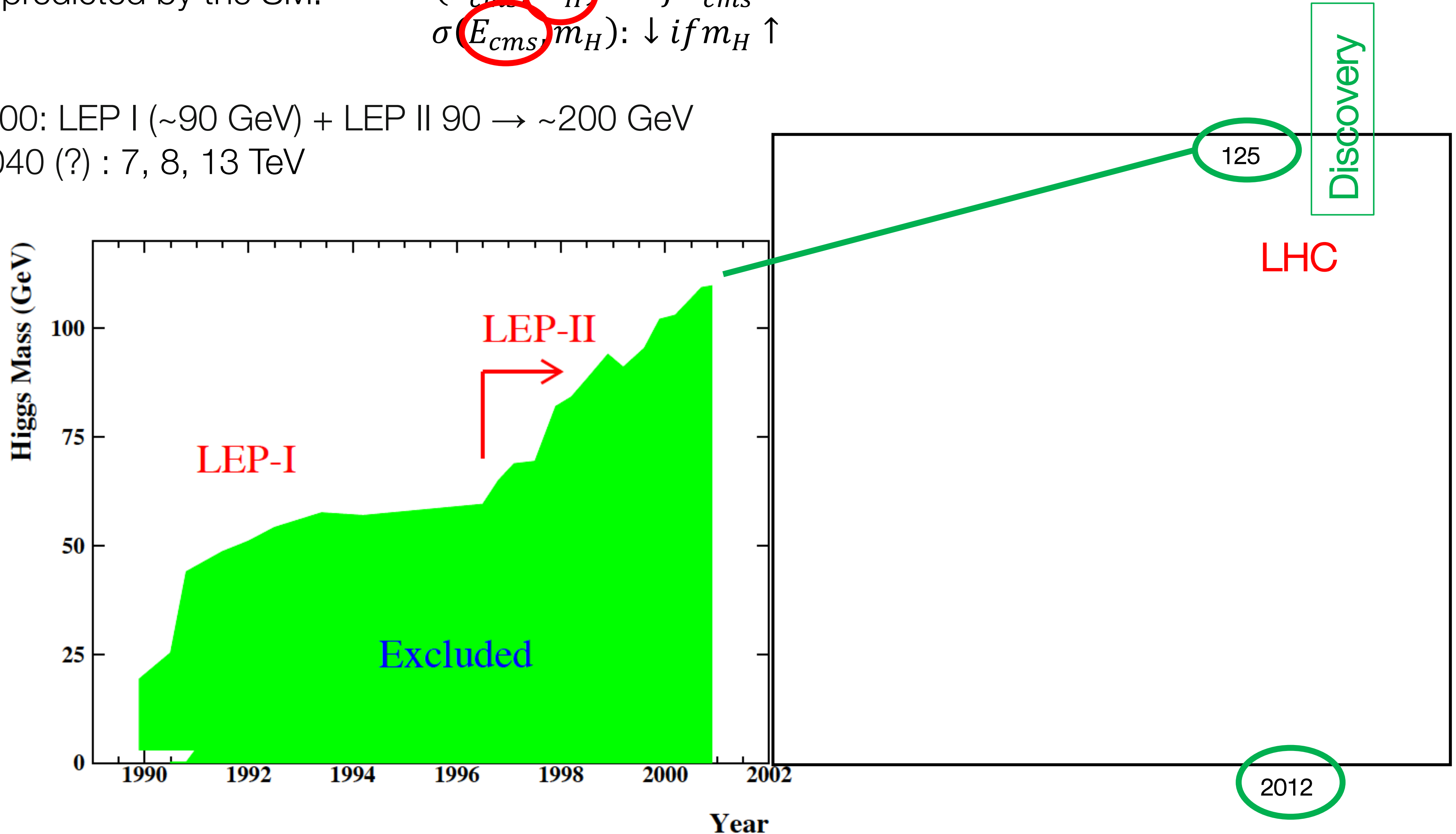
Higgs Mass not predicted by the SM.

$\sigma(E_{cms}, m_H): \uparrow if E_{cms} \uparrow$

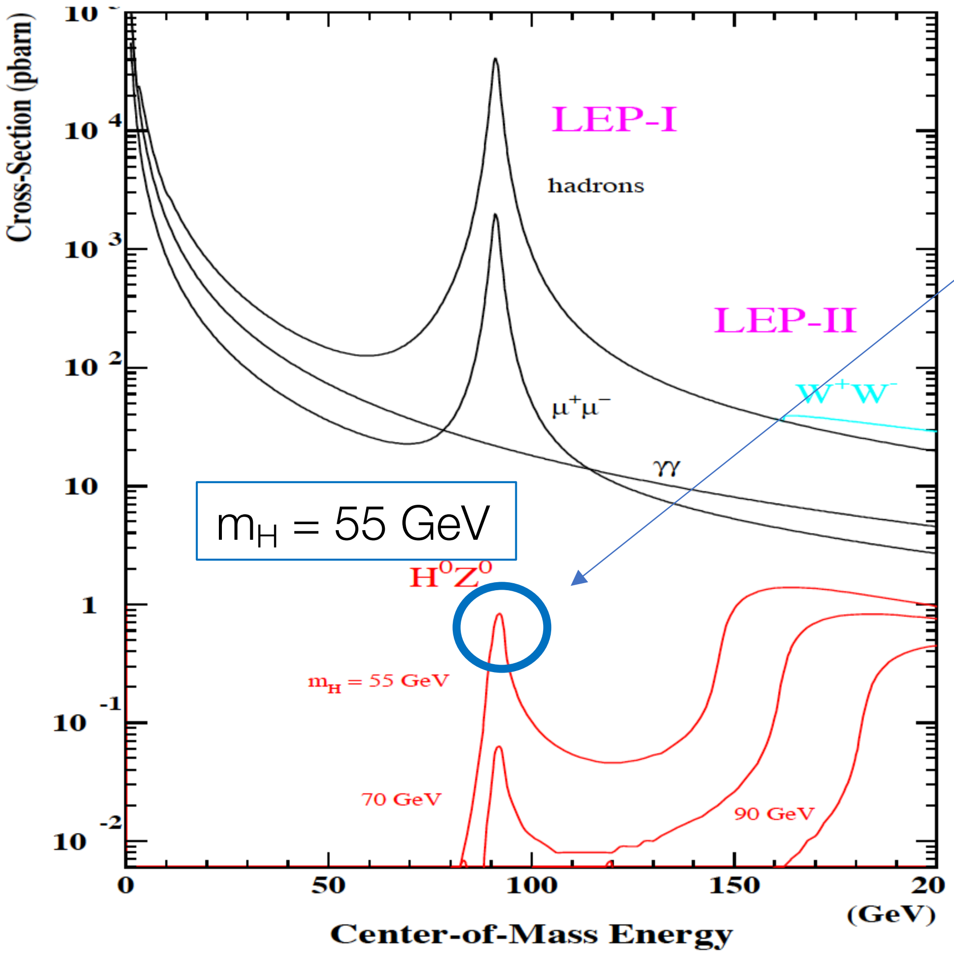
$\sigma(E_{cms}, m_H): \downarrow if m_H \uparrow$

LEP 1990 → 2000: LEP I (~90 GeV) + LEP II 90 → ~200 GeV

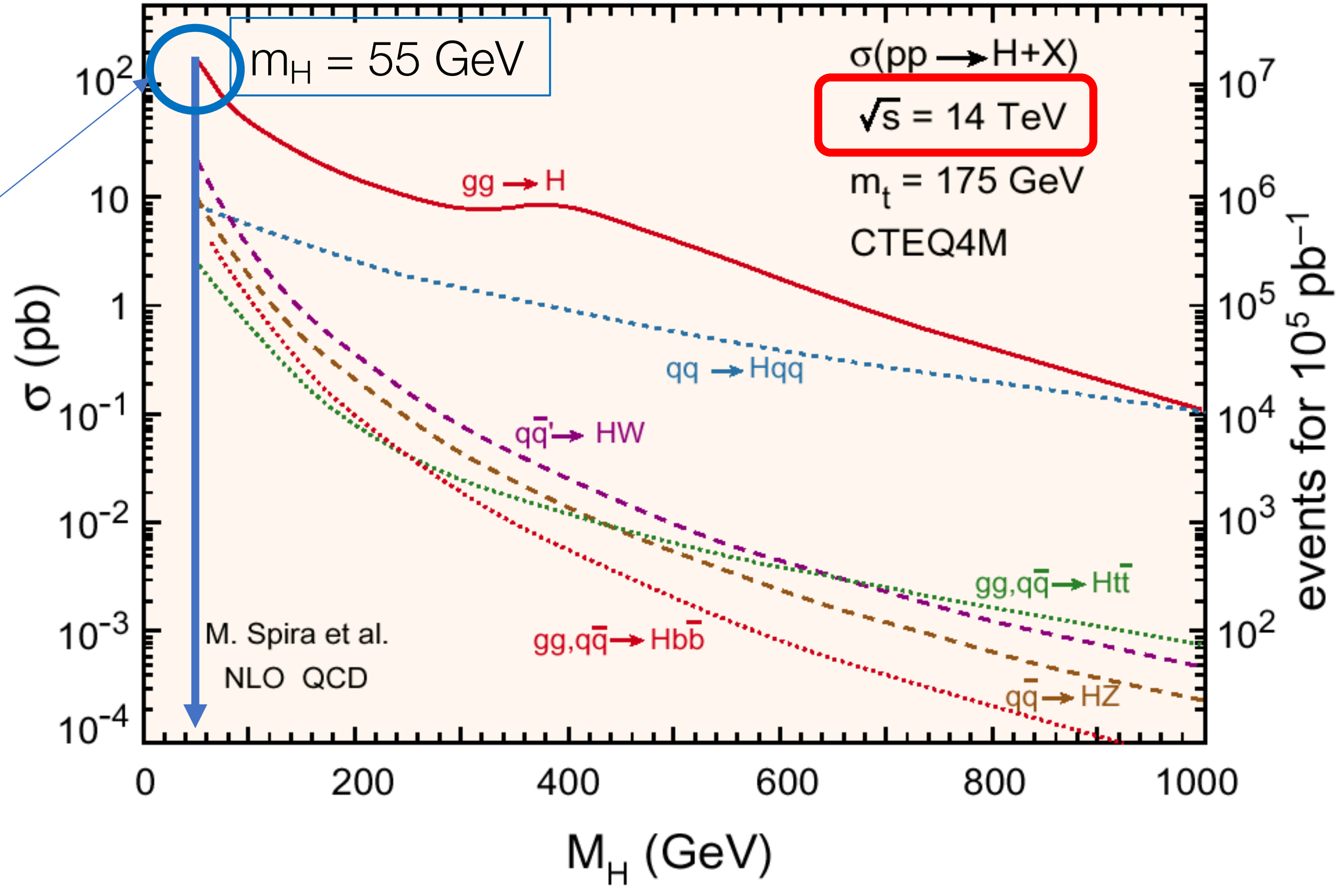
LHC 2010 → 2040 (?) : 7, 8, 13 TeV



Where to Search for the Higgs Boson?



LEP, "Large Electron Positron" collider



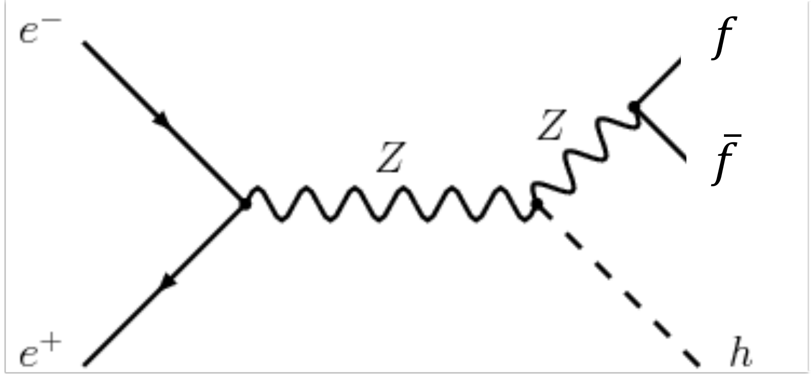
LHC, "Large Hadron Collider"

Variable cms energy: 90 → 200 GeV

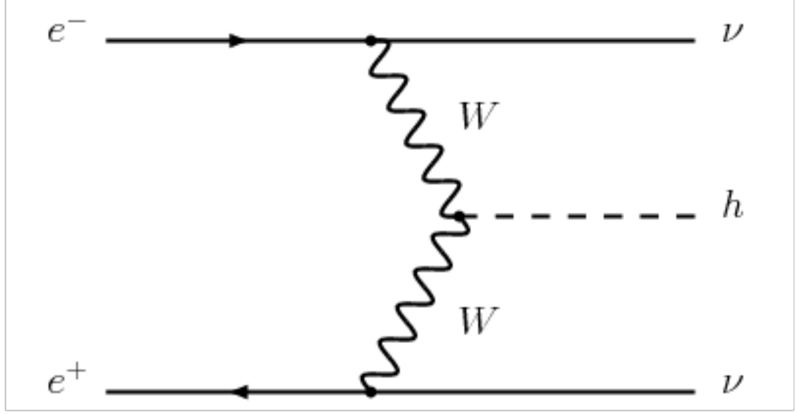
Higgs Production at LEP (e^+e^- Collider)

Production of Higgses at LEP:

- The *Higgsstrahlung* mechanism
- The *WW fusion* diagram (& ZZ fusion mechanism)



Higgsstrahlung



WW fusion

$\sigma_{Higgsstrahalung}$ $\gg\gg$ $\sigma_{WW\ fusion}$

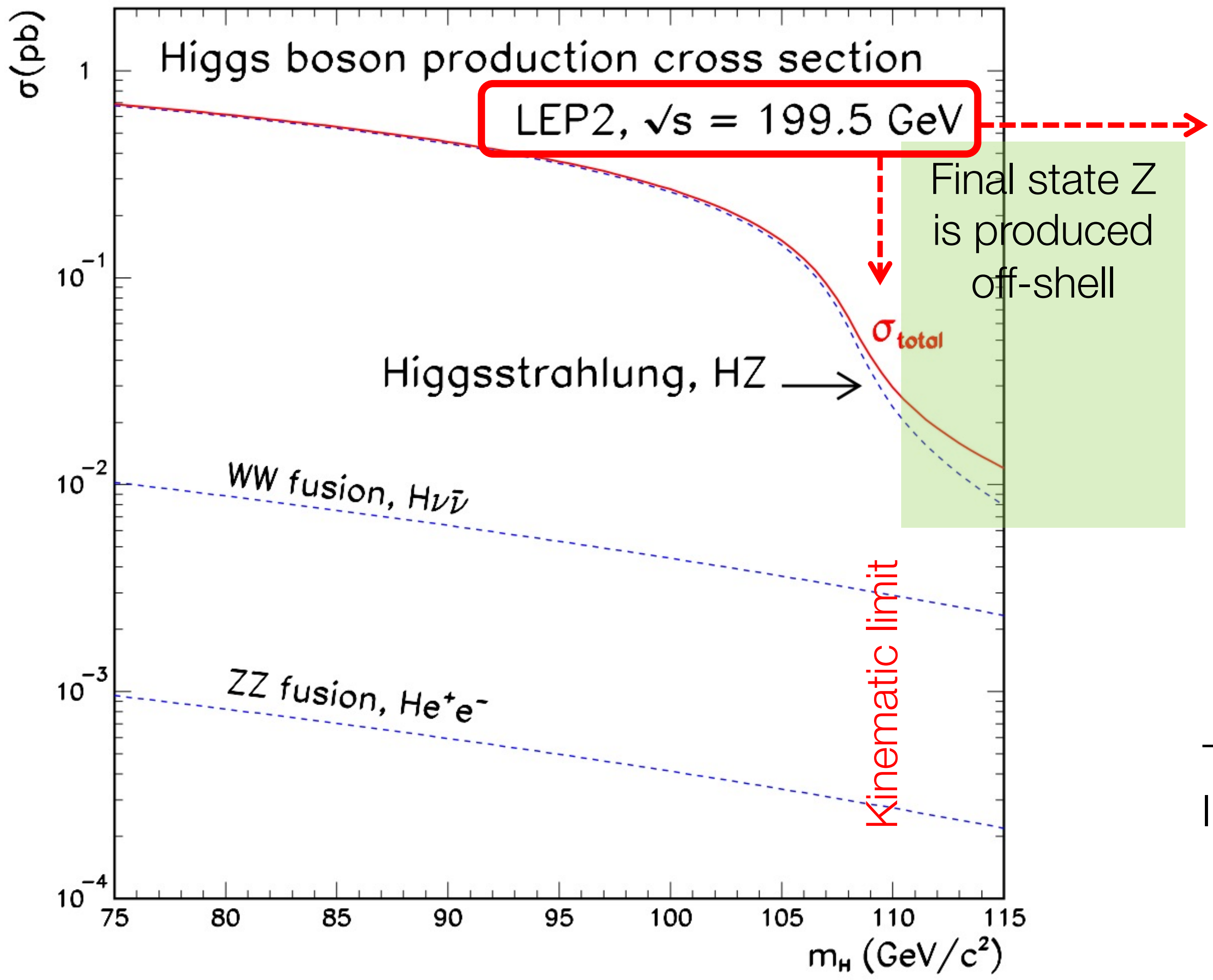
$\sigma_{Higgsstrahalung}$: kinematic limit: cms energy used to produce m_Z and $m_H \rightarrow m_H^{max} = \sqrt{s} - m_Z$ (…some margin by the tail of the Breit-Wigner distribution)

$\sigma_{WW\ fusion}$: can produce H up to $\sqrt{s}$ however small cross section limits drastically the statistics

Period	Energy (GeV)	Luminosity (pb^{-1})
1995	130/136	6.2
1996	161	12.1
1996	172	11.3
1997	183	63.8
1998	189	196.4
1999	192	30.

$m_H^{max} = 98\ GeV$

Higgs Production at LEP



Cross section

$$e^+e^- \rightarrow H + anything$$

@Cms energy of 199.5 GeV.

The *Higgsstrahlung* cross section drops rapidly when

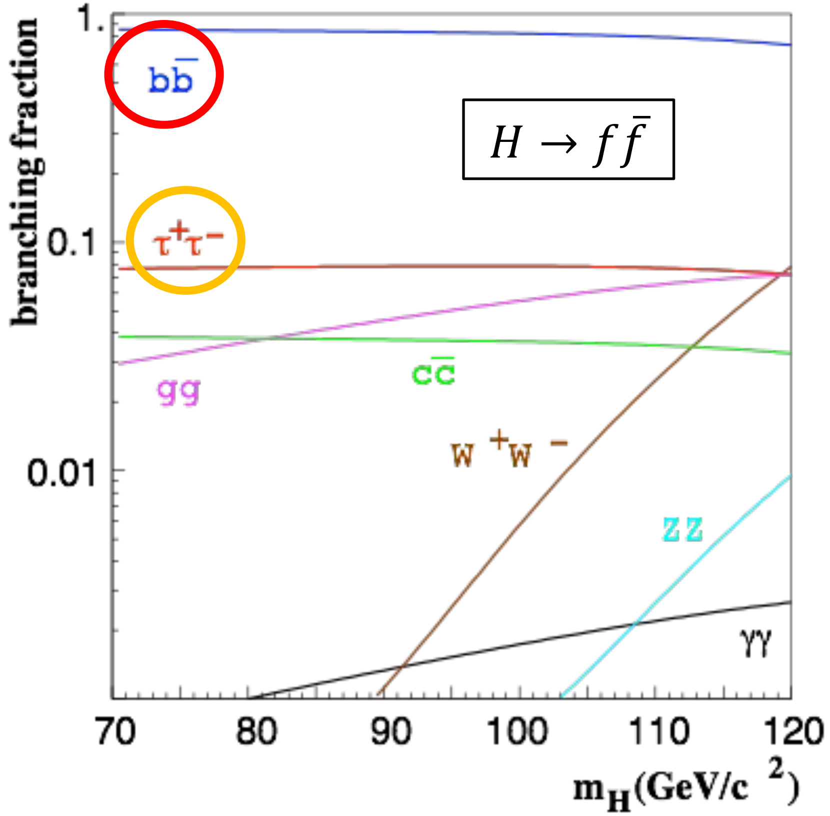
$$m_H = \sqrt{s} - m_Z$$

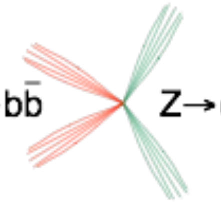
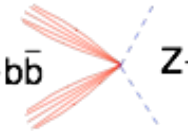
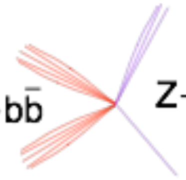
The two other mechanisms are not kinematically limited, but are statistically limited

Higgs Decay

The H couples to pairs of fermions with a strength proportional to the mass of the fermion itself

The H → decays to the heaviest kinematically accessible pair of $f\bar{f}$



Topologies			Rates	Backgrounds
$H \to b\bar{b}$ 	$Z \to q\bar{q}$	4-jets	51%	WW → qqqq ZZ → qqqq QCD 4-jets
$H \to b\bar{b}$ 	$Z \to \nu\bar{\nu}$	missing energy	15%	WW → qqlν ZZ → bbνν
$H \to b\bar{b}$ 	$Z \to \tau^+\tau^-$	τ-channel	2.4%	WW → qqτν ZZ → bbττ ZZ → qqττ QCD low mult. jets
$H \to \tau^+\tau^-$ 	$Z \to q\bar{q}$	τ-channel	5.1%	
$H \to b\bar{b}$ 	$Z \to e^+e^-$ $\mu^+\mu^-$	lepton channel	4.9%	ZZ → bbee ZZ → bbμμ

Analysis Strategy of the Higgs Search

The ~largest accessible Higgs mass at LEP was ~115 GeV @ LEP cms 200 GeV

Analysis strategy: compromise between

- of statistics and → (small) signal is hidden by a large background → almost invisible
- Need to reduce background → (even smaller) signal is ~insignificant over a ~reduced background

. The searches at LEP was driven by Z decay channels (since $H \rightarrow b\bar{b}$)

- the four-jet final state $(H \rightarrow b\bar{b})(Z \rightarrow q\bar{q})$ Including one very special case… $(H \rightarrow b\bar{b})(Z \rightarrow b\bar{b})$
- the missing energy final state $(H \rightarrow b\bar{b})(Z \rightarrow \nu\bar{\nu})$
- the leptonic final state $(H \rightarrow b\bar{b})(Z \rightarrow l^+l^-)$ where ℓ denotes an electron or a muon,
- and the tau lepton final states $(H \rightarrow b\bar{b})(Z \rightarrow \tau^+\tau^-)$ and $(H \rightarrow \tau^+\tau^-)(Z \rightarrow q\bar{q})$

Two approaches:

- Selection cuts based on kinematical variables and topologies
- MVA analysis → use global variables & neural networks → one indicator per each event to distinguish signal and background (more efficient)

Looking for an Higgs Boson: how?

Analysis Strategy for one final state topology:

Choose a mass & optimise selection as much signal (S) and as little background (B) as possible. *Use MC*

Count selected events in data → $N_{selected}$
Calculate background events (simulation) $N_{background}$

$$\frac{N_{selected}}{\sqrt{N_{background}}}$$

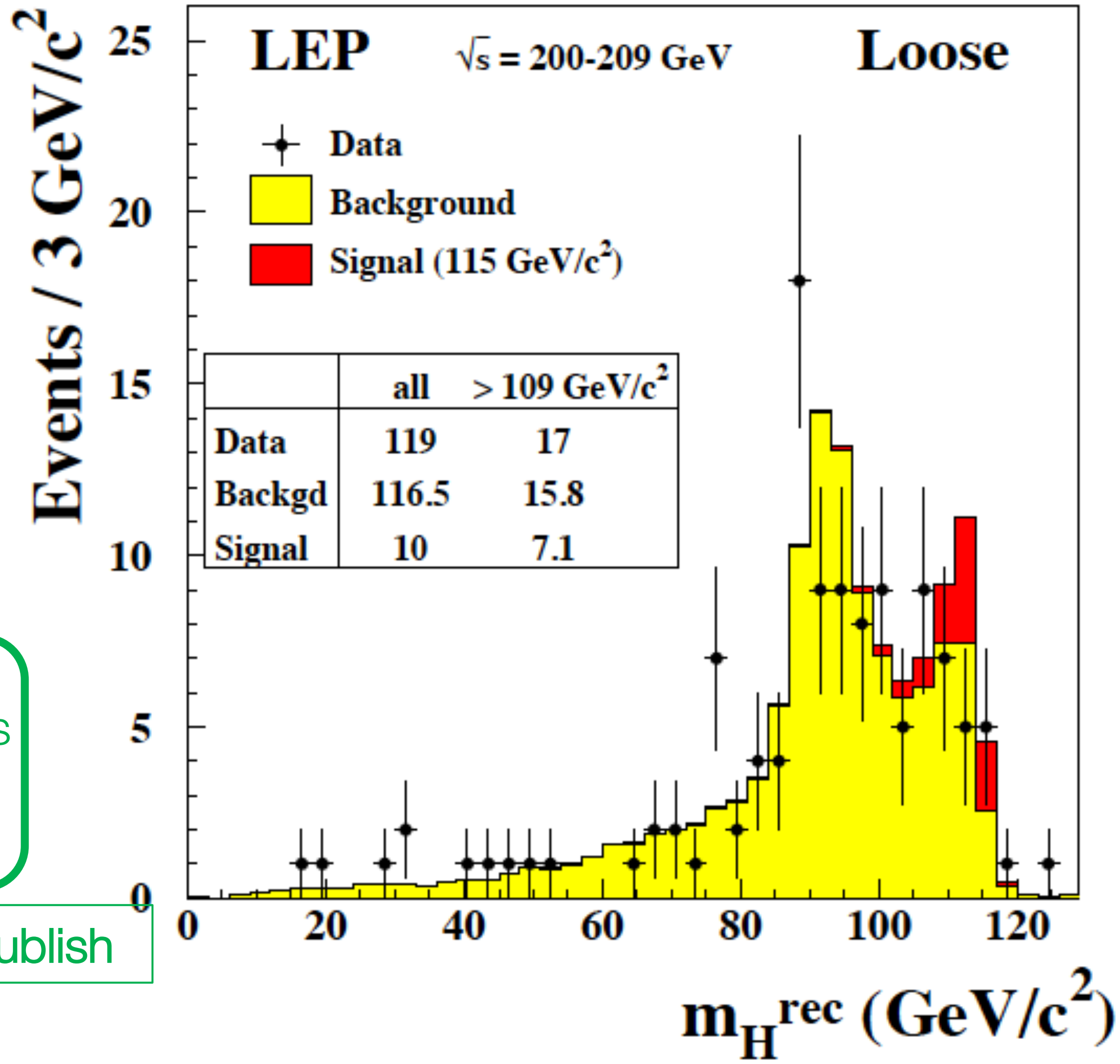
$< 3?$
Another mass

between 3 and 5?

Do more analysis and collect more statistics

≥ 5 ?
Significant excess
Discovery

Do a seminar & publish



Combining Different Channels

Higgs search at LEP = small signal + large background → two ways to increase statistics:

- Combine different experiments → 4 experiments → statistical significance of signal increases by $\sqrt{4} = 2$
- Combine different channels of the same experiment (= one final-state and one centre-of-mass energy)

  - m_h^{rec} the reconstructed Higgs boson mass, and a
  - *G*(many event variables): **how "Higgs-like" is the sample:**

    - G < 0 or G << 0 → likely it is Higgs (one choice, it could be the opposite, G>0)
    - G > 0 or G >> 0 → likely it is background (one choice, it could be the opposite, G<0)

The distribution of data in the plane (m_h^{rec},G) is interpreted

In two hypothetical scenarios:

- The distribution contains background only $\mathcal{L}_b$
- The distribution contains signal plus background $\mathcal{L}_{s+b}$

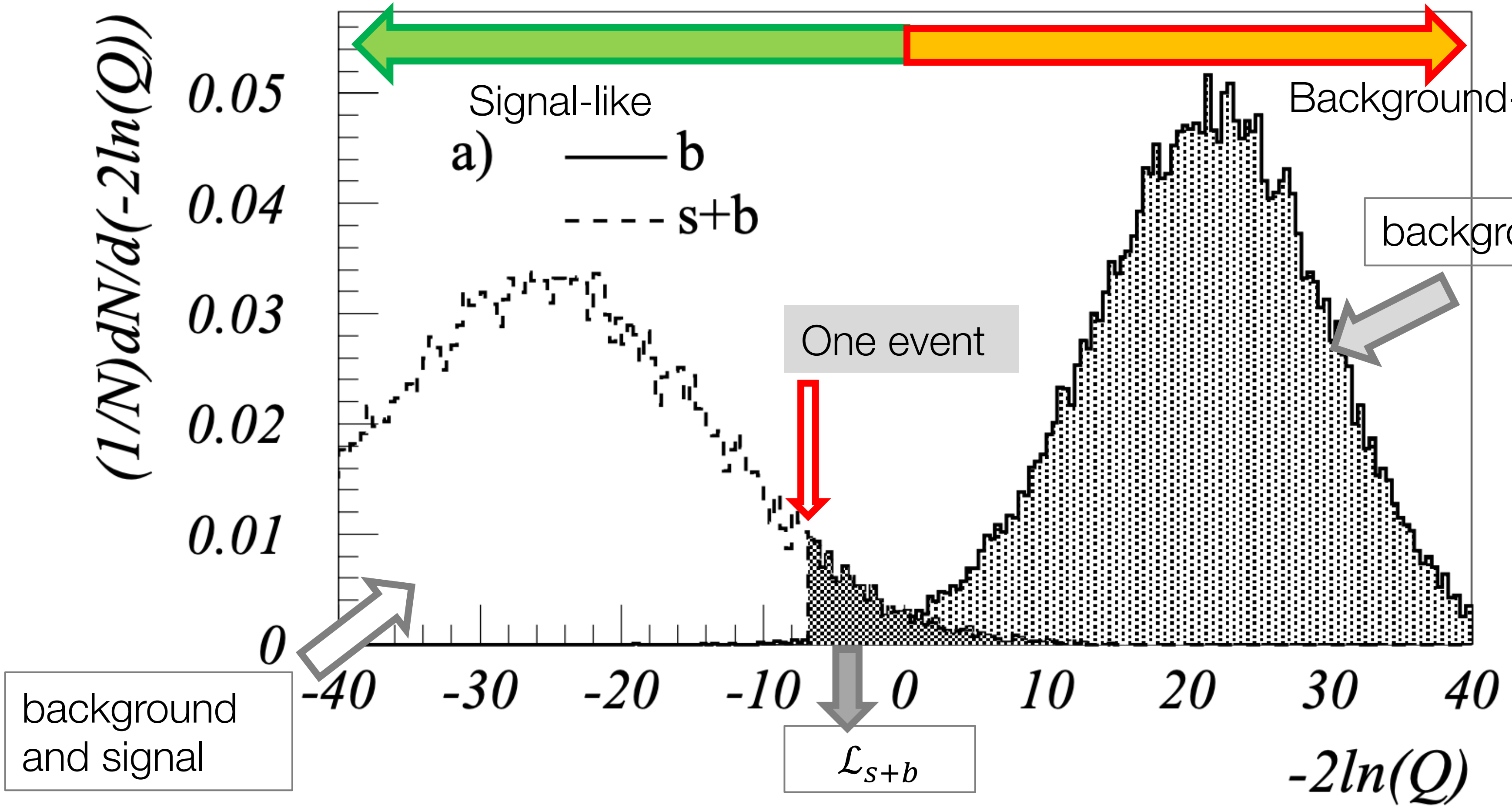
In a search experiment one very good indicator is the likelihood ratio

$$Q = \mathcal{L}_{s+b} / \mathcal{L}_b \quad (use \; -2\ln(Q))$$

Statistical Analysis

One cannot tell on an event-by-event basis whether one event is signal or background → statistical analysis.

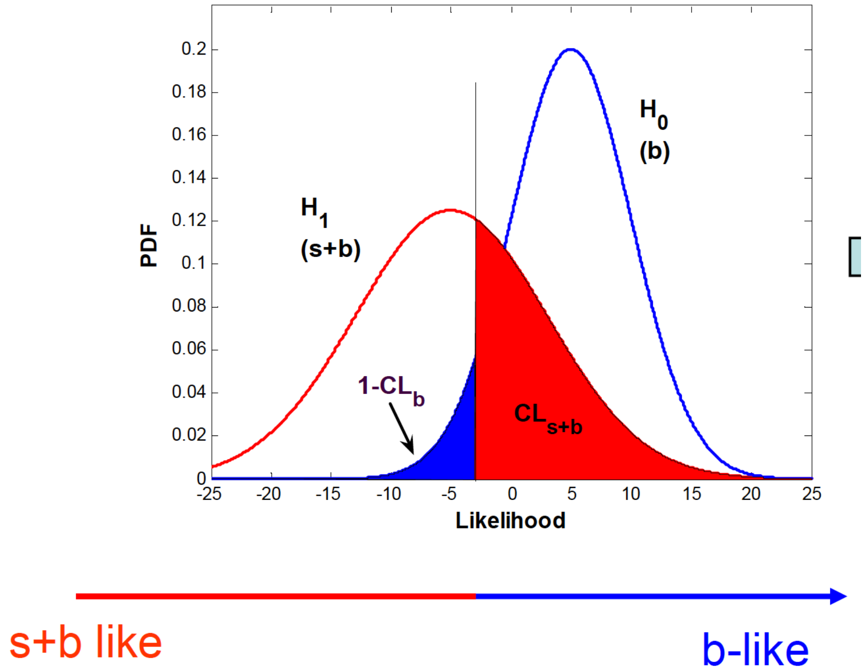
$Q = \mathcal{L}_{s+b} / \mathcal{L}_b$

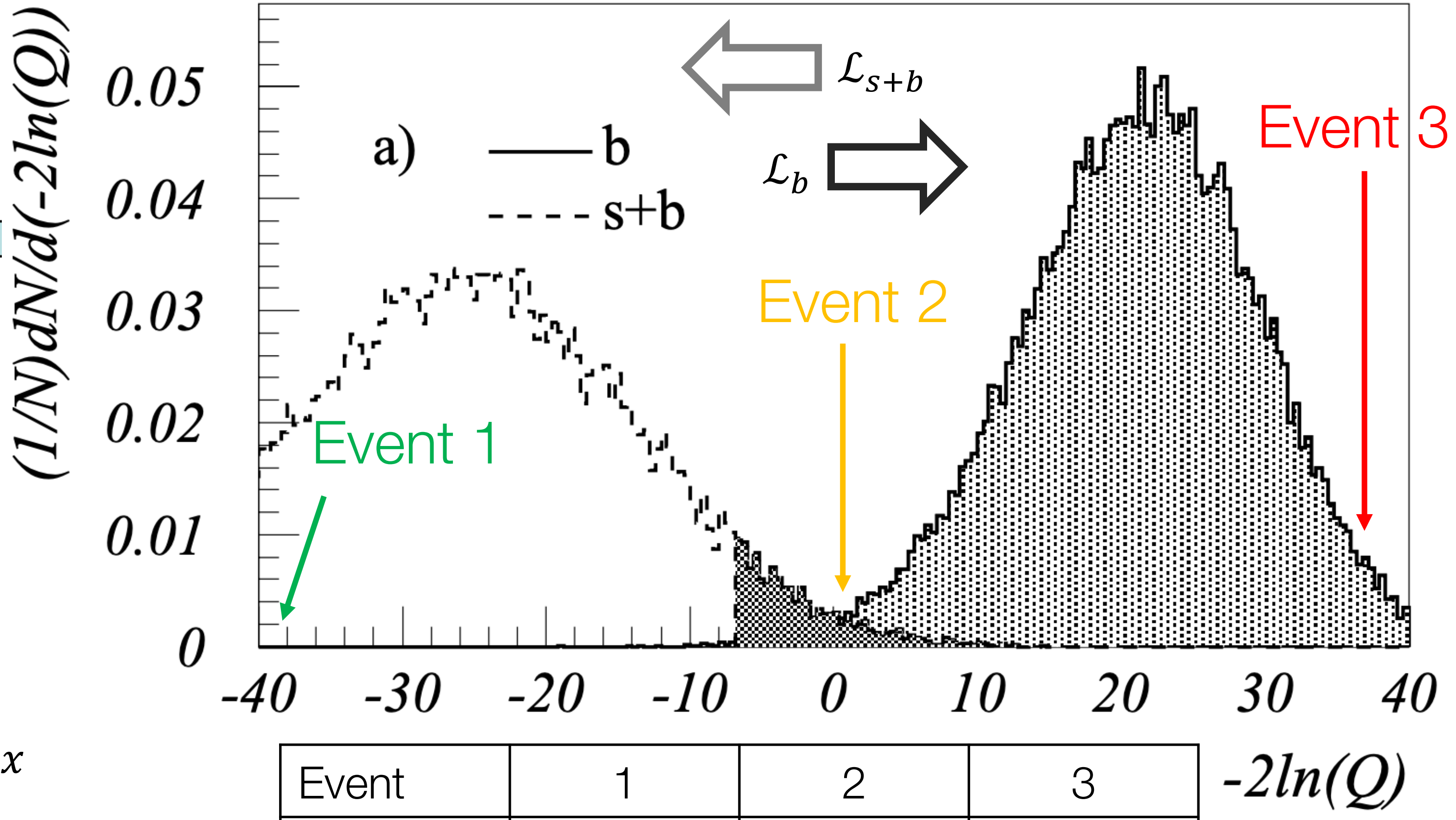


For each event compute

- $\mathcal{L}_b$ is the fraction of the *b* distribution “less background like” than *Q*
- $\mathcal{L}_{s+b}$ is the fraction of the *s+b* distribution “more signal + background like” than *Q*

Statistical Analysis



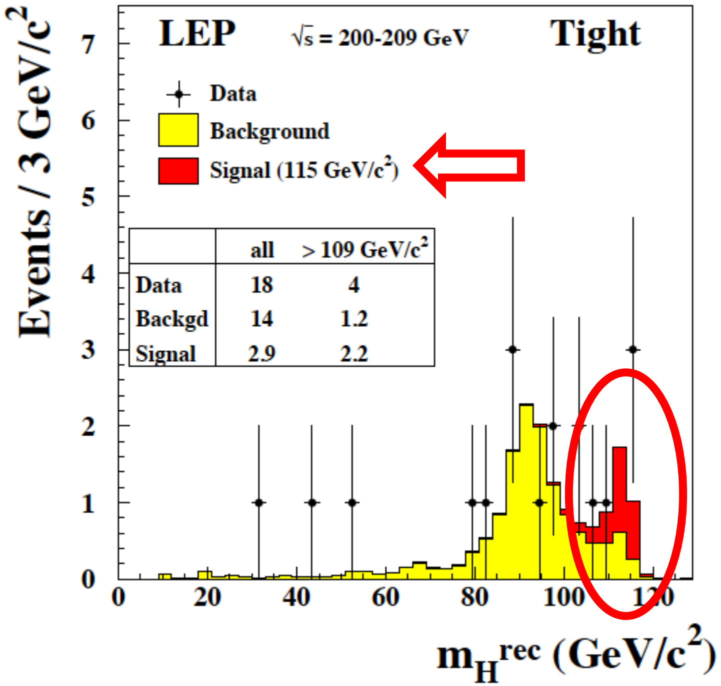


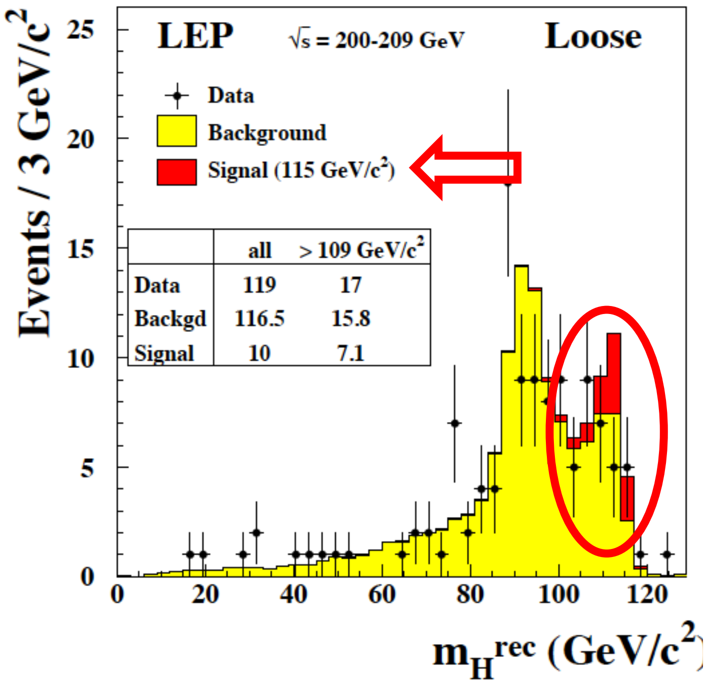
$$\mathcal{L}_b = \int_{-\infty}^{measurement} background(x)dx$$

$$\mathcal{L}_{s+b} = \int_{measurement}^{+\infty} background + signal(x)dx$$

Event	1	2	3
$\mathcal{L}_b$	Very small	Small	large
$\mathcal{L}_{s+b}$	Large	Small	Very small
$\mathcal{L}_{s+b}/\ \mathcal{L}_b$	Very large	~ 1	Very small

The Result: m_h^{rec} of Different Experiments





Loose

	Experiment	E_{cm}(GeV)	Final state topology	$m_{\mathrm{H}}^{\mathrm{rec}}$ (GeV/c^2)	$\ln(1+s/b)$ at 115 GeV/c^2
1	ALEPH	206.6	Four-jet	114.1	1.76
2	ALEPH	206.6	Four-jet	114.4	1.44
3	ALEPH	206.4	Four-jet	109.9	0.59
4	L3	206.4	Missing energy	115.0	0.53
5	ALEPH	205.1	Leptonic	117.3	0.49
6	ALEPH	208.0	Tau	115.2	0.45
7	OPAL	206.4	Four-jet	111.2	0.43
8	ALEPH	206.4	Four-jet	114.4	0.41
9	L3	206.4	Four-jet	108.3	0.30
10	DELPHI	206.6	Four-jet	110.7	0.28
11	ALEPH	207.4	Four-jet	102.8	0.27
12	DELPHI	206.6	Four-jet	97.4	0.23
13	OPAL	201.5	Missing energy	108.2	0.22
14	L3	206.4	Missing energy	110.1	0.21
15	ALEPH	206.5	Four-jet	114.2	0.19
16	DELPHI	206.6	Four-jet	108.2	0.19
17	L3	206.6	Four-jet	109.6	0.18

Distributions m_{H}^{rec} for two different signal purities.

Monte Carlo predictions:

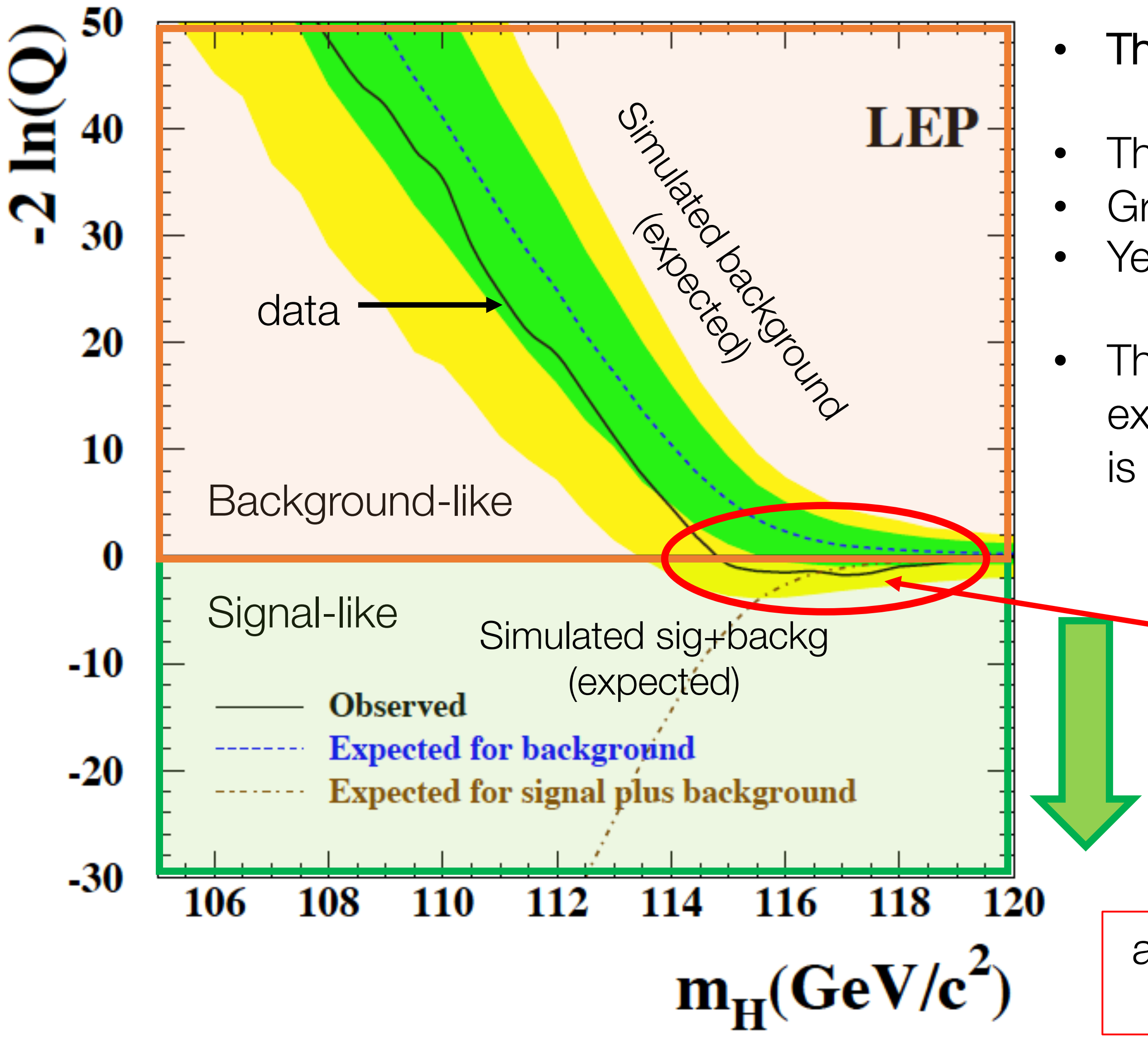
- yellow for the background
- red for an Higgs boson of mass 115 GeV.

The points with error bars show the data.

LEP final result:

- 17 candidate events
- 15.8 background events expected
- 7.1 expected signal events for m_h = 115 GeV

The Upper Limit of m_h^{rec}



- The solid curve represents the observation

- The dashed curve background expectation;
- Green band 68% probability around <background>
- Yellow band 95% probability around <background>

- The dash-dotted curve signal plus background expectation (when the signal mass given on the abscissa is tested).

Broad region of data just below 0 → no significant signal detected

Very negative values of -2ln(Q) would indicate the very likely presence of a signal

a lower bound of 114.4 GeV/c^2 is set on the mass of the SM Higgs boson at the 95% confidence level.

Discoveries

End of Discoveries

Particle Physics
Toni Baroncelli
Haiping Peng
USTC

The Combination Mechanism (ADLO)

For each given channel and bin in the (m_h^{rec},G) plane, the experiments give

- the number of selected data events,
- the number of expected background events, and
- the number of expected signal events for a set of hypothetical Higgs boson masses.

The expected signal and background estimates make use of detailed Monte Carlo simulations by the four experiments: all known experimental features, the centre-of-mass energies, integrated luminosities of the data samples, cross-sections and decay branching ratios for the signal and background processes, selection efficiencies and experimental resolutions with possible non-Gaussian contributions.