Testing the Standard Model of Elementary Particle Physics II

2nd lecture

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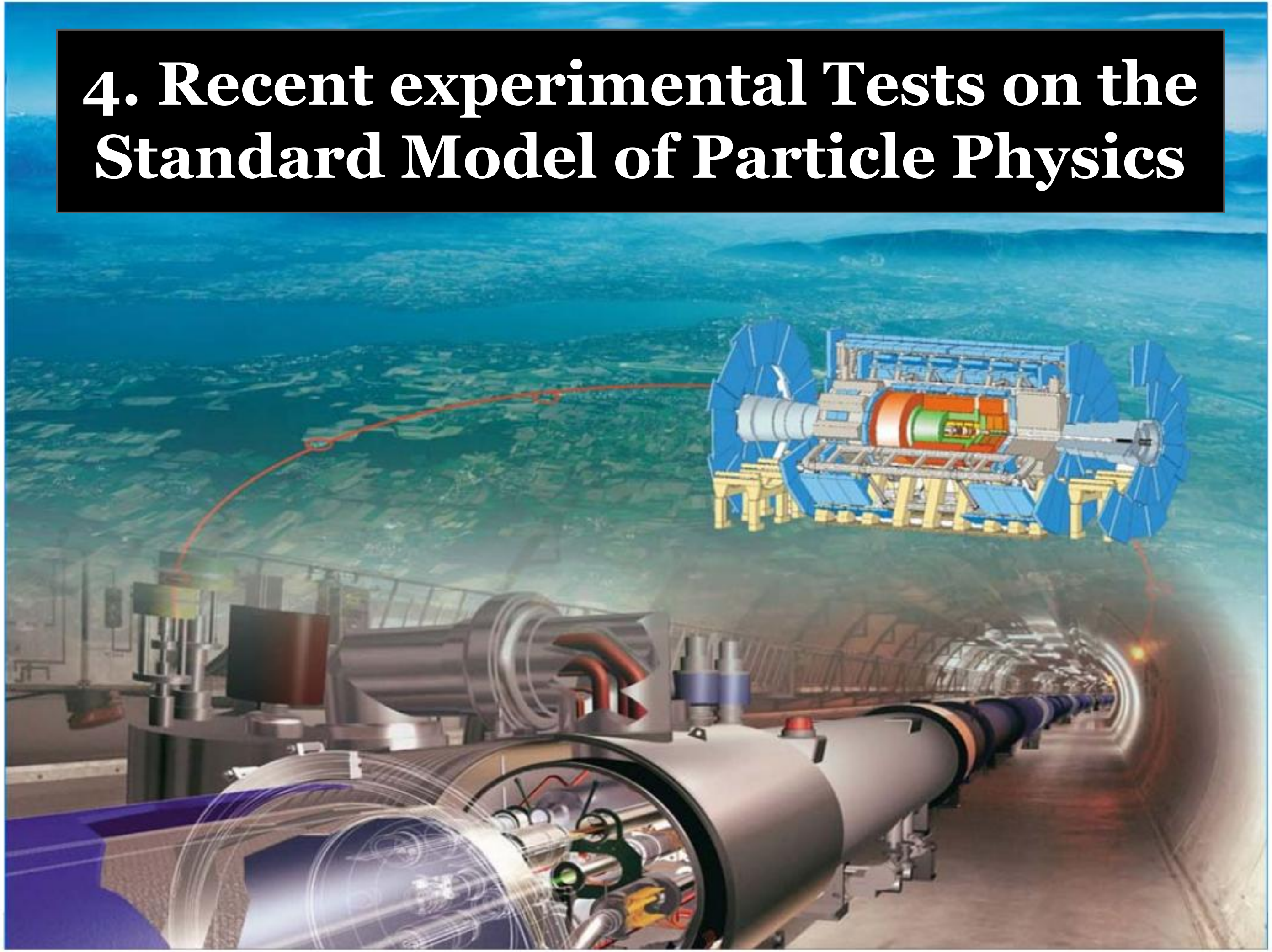
22th April 2021

4. Recent experimental Tests on the Standard Model of Particle Physics



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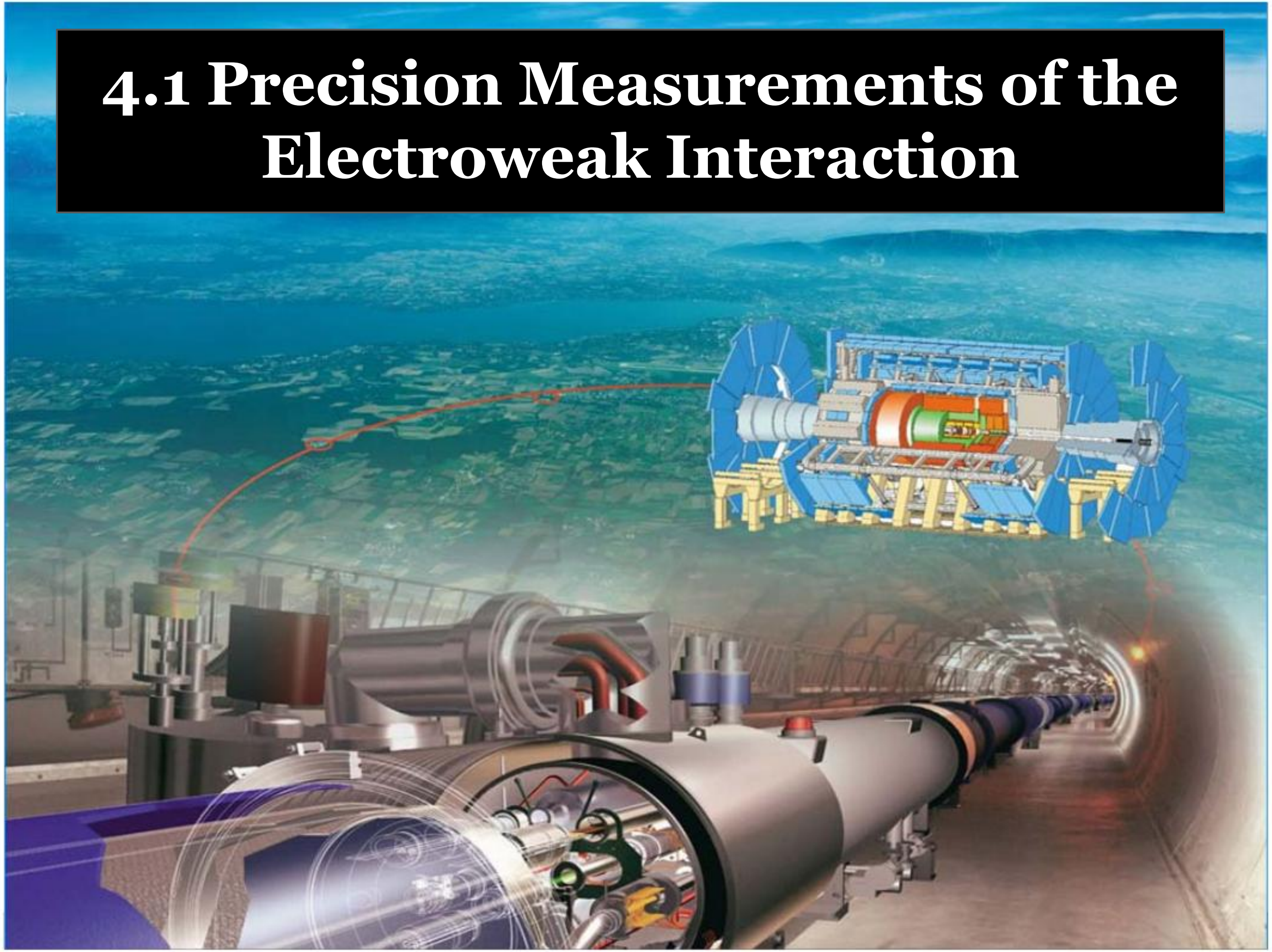
- **Precision measurements of the electroweak interaction:**
  - Measurements on the Z boson resonance
  - Measurement of the W boson production process
  - Precision tests of the Standard Model
  - W & Z bosons at the LHC

A detailed overview about "Precision Electroweak Measurements on the Z Resonance" can be found via e.g.: https://arxiv.org/pdf/hep-ex/0509008.pdf

4.1 Precision Measurements of the Electroweak Interaction



The W boson

- Predicted in the 1968 by Sheldon Glashow, Abdus Salam und Steven Weinberg
- Discovered in 1983 by the UA1 and UA2 collaborations at the **SppS** (CERN)
- **Properties:**
  - m_W = 80.385 ± 0.015 GeV
  - Γ_W = 2.085 ± 0.042 GeV
  - $\tau_W \approx 3 \cdot 10^{-25}$ s

Decay Mode	BR
$W \to e\nu$	$(10.71 \pm 0.16)\%$
$W \to \mu\nu$	$(10.63 \pm 0.15)\%$
$W \to \tau\nu$	$(11.38 \pm 0.21)\%$
$W \to$ hadrons	$(67.41 \pm 0.27)\%$

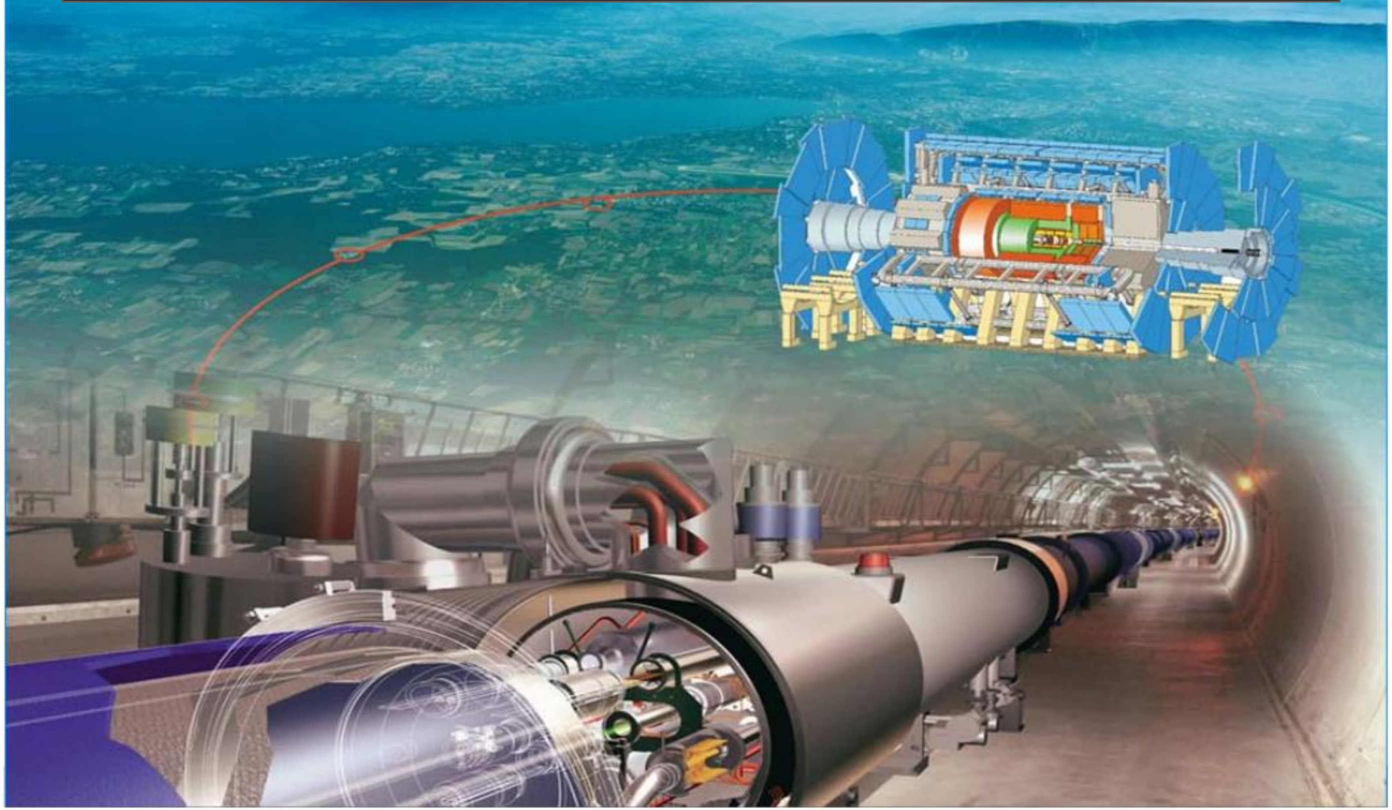
- W boson decay **(Lepton universality):**
  - All three types of charged lepton particles interact in the same way with other particles.
  - The three lepton types are created equally often in particle transformations, or decays (once differences in their mass are accounted for)

The Z boson

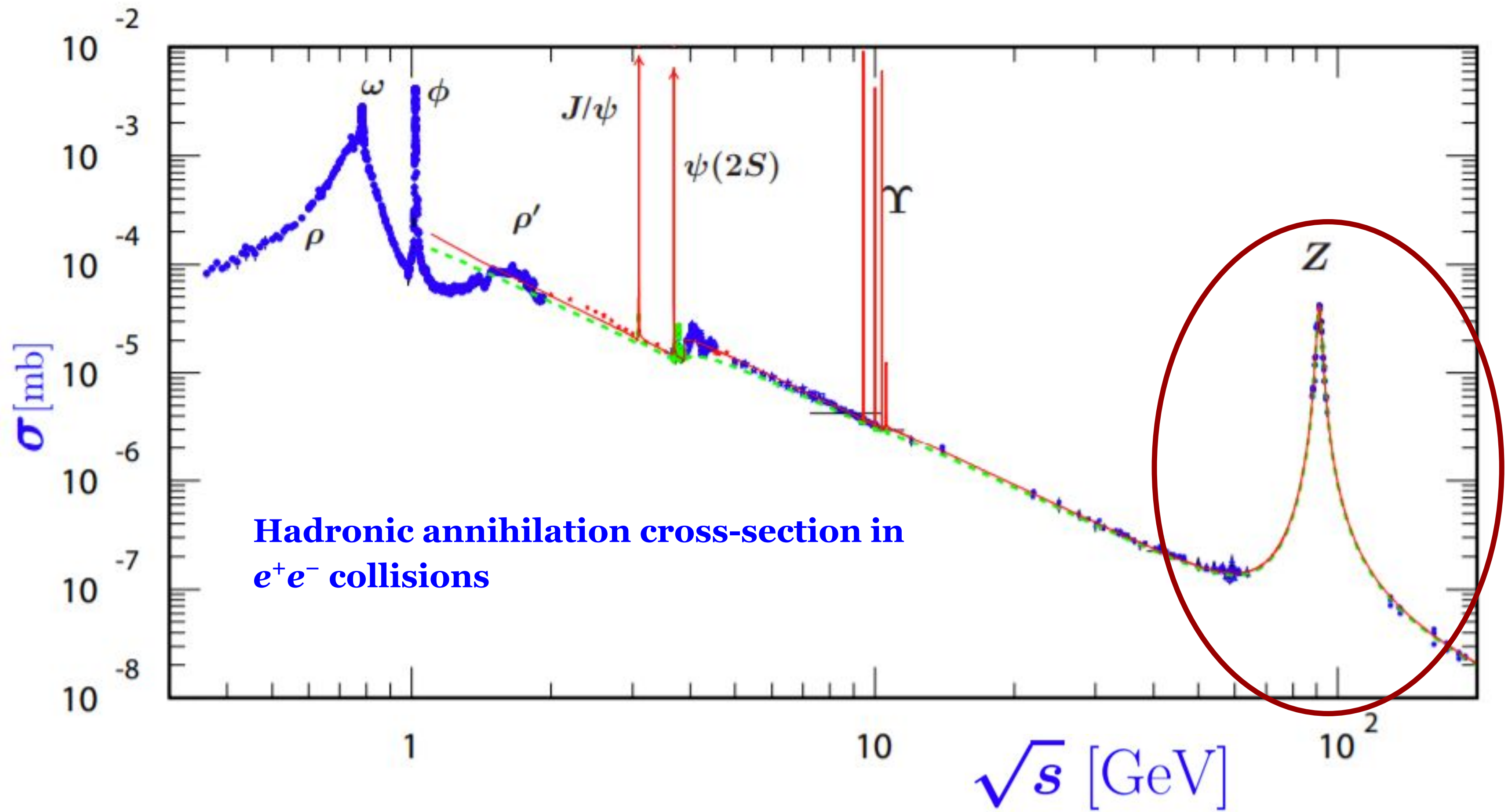
- Predicted in the 1960s by Sheldon Glashow, Abdus Salam und Steven Weinberg
- Discovered in 1983 by the UA1 and UA2 collaborations at the **SppS** (CERN)
- **Properties:**
    - $m_Z = 91.1875 \pm 0.0021$ GeV
    - $\Gamma_Z = 2.4952 \pm 0.0023$ GeV
    - $\tau_Z \approx 2.5 \cdot 10^{-25}$ s

Decay Mode	BR
$Z \to e^+e^-$	$(3.3632 \pm 0.0042)\%$
$Z \to \mu^+\mu^-$	$(3.3662 \pm 0.0066)\%$
$Z \to \tau^+\tau^-$	$(3.3696 \pm 0.0083)\%$
$Z \to$ invisible	$(20.000 \pm 0.055)\%$
$Z \to$ hadrons	$(69.911 \pm 0.056)\%$

4.1.1 Measurements on the Z⁰ boson resonance



Measurements on the Z boson resonance



Hadronic annihilation cross-section in
e^+e^- collisions

Measurements on the Z boson resonance

- Between 1989 and 1995 (LEP phase I), the LEP experiments measured the production of fermion-antifermion pairs in the e^+e^- annihilation at the Z^0 peak (i.e. at a center-of-mass energy of $\sqrt{s} = m_Z$)

- At this energy, electrons and positrons create almost exclusively real (i.e. on-shell) Z^0 bosons
  - Basically at rest
  - With subsequent decay into fermion-antifermion pairs ($2m_f \leq m_Z$)

- In general, significant contributions of interference effects between photon- and Z^0 exchange (electroweak interference between these two NC-processes):

Measurements on the Z boson resonance

- The fermion-antifermion pair production cross section (via e^+e^- annihilation) is a function of the center-of-mass energy $\sqrt{s} = 2E_e$ and the scattering angle θ and is given (in lowest order) via:

$$\begin{aligned}
\frac{d\sigma}{d\Omega}(e^+e^- \to f\bar{f}) &= const. \cdot s \cdot |\mathcal{M}_{QED} + \mathcal{M}_{\mathrm{weak}}|^2 \\
&= const. \cdot s \cdot \left[|\mathcal{M}_{QED}|^2 + 2\mathcal{R}e\left(\mathcal{M}_{QED}\mathcal{M}_{\mathrm{weak}}\right) + |\mathcal{M}_{\mathrm{weak}}|^2\right] \\
&= N_C^f \frac{\alpha^2}{4s}\left[C_1^f(1+\cos^2\theta) + C_2^f \cos\theta\right] \\
&= \frac{1}{2\pi}\sigma_{f\bar{f}}\left[\frac{3}{8}\left(1+\cos^2\theta\right) + A_{FB}^f \cos\theta\right]
\end{aligned}$$

Measurements on the Z boson resonance

with:

$$C_1^f(s) = Q_e^2 Q_f^2 + 8 Q_e Q_f v_e v_f \mathcal{R}e\left(\chi(s)\right) + 16(v_e^2 + a_e^2)(v_f^2 + a_f^2)|\chi(s)|^2$$

$$C_2^f(s) = 16 Q_e Q_f a_e a_f \mathcal{R}e\left(\chi(s)\right) + 32 v_e a_e v_f a_f |\chi(s)|^2$$

$$\sigma_{f\bar{f}}(s) \;=\; \int_0^{2\pi} \int_{-1}^{+1} \frac{d\sigma}{d\Omega} d\cos\theta \, d\Phi = N_C^f \frac{4\pi\alpha^2}{3s} \cdot C_1^f(s)$$

$$\boxed{\begin{aligned} A_{FB}^f(s) \;&=\; \frac{\int_0^{+1} \frac{d\sigma}{d\Omega} d\cos\theta - \int_{-1}^{0} \frac{d\sigma}{d\Omega} d\cos\theta}{\int_{-1}^{+1} \frac{d\sigma}{d\Omega} d\cos\theta} \\ &=\; \frac{N_F - N_B}{N_F + N_B} = \frac{3}{8} \cdot \frac{C_2^f(s)}{C_1^f(s)} \end{aligned}}$$

Coupling constants of the weak vector- and axial-currents v_i & a_i

Z^0 boson propagator $\chi(s)$

Forward-Backward asymmetry A_{FB}

Measurements on the Z boson resonance

Coupling constants of the weak vector- and axial-currents:

$$v_f = I_f^0 - 2Q_f \sin^2\theta_W \equiv \frac{1}{2} - 2Q_f \sin^2\theta_W$$

$$a_f = I_f^0 \equiv \frac{1}{2}$$

In the center-of-mass system:
$q^2 = (p_1+p_2)^2 =: s$ and $\sqrt{s} = 2E_e$

$G_F = 1.166\,3787 \times 10^{-5}\ \mathrm{GeV}^{-2}$ (Fermi coupling constant)

Z^0 boson propagator:

$$\chi(s) = \frac{1}{16\sin^2\theta_W\cos^2\theta_W} \cdot \frac{s}{s - M_Z^2 + iM_Z\Gamma_Z}$$

$$= \frac{G_F M_Z^2}{8\pi\alpha\sqrt{2}} \cdot \frac{s}{s - M_Z^2 + iM_Z\Gamma_Z}$$

Measurements on the Z boson resonance

- The QED contribution (only photon exchange) is described via:

$$\frac{d\sigma}{d\Omega}(e^+e^- \to f\bar{f}) = N_C^f \frac{\alpha^2 Q_f^2}{4s}(1+\cos^2\theta)$$

$$\sigma_{f\bar{f}} = \int \frac{d\sigma}{d\Omega} d\Omega = \frac{4\pi\alpha^2}{3s} = \frac{87\ \mathrm{n}b}{s[\mathrm{Ge}V^2]} \cdot Q_f^2 \cdot N_C^f$$

For leptons N_C is 1, while for quarks it is equal to 3.

- Thus:

$$\begin{aligned} R &= \frac{\sigma\left(e^+e^- \to \sum_{q(E_{CMS}>2m_q)} q\bar{q}\right)}{\sigma(e^+e^- \to \mu^+\mu^-)} \\ &= 3 \cdot \sum_{q(E_{CMS}>2m_q)} Q_q^2 \end{aligned}$$

Measurements on the Z boson resonance

- Since the Z^0 boson has a finite lifetime τ_Z and width Γ_Z, the curve of the Z^0 resonance is described by the **Breit-Wigner function**
- At the **pole mass** of the Z^0 boson, the cross section is given via:

$$\boxed{\begin{aligned}\sigma^0_{f\bar{f}}(s = M_Z^2) &= N_C^f \frac{G_F^2 M_Z^4}{6\pi\Gamma_Z^2} \cdot (v_e^2 + a_e^2)(v_f^2 + a_f^2) \\ &= \frac{12\pi\Gamma_Z^e\Gamma_Z^f}{M_Z^2\Gamma_Z^2}\end{aligned}}$$

Measurements on the Z boson resonance

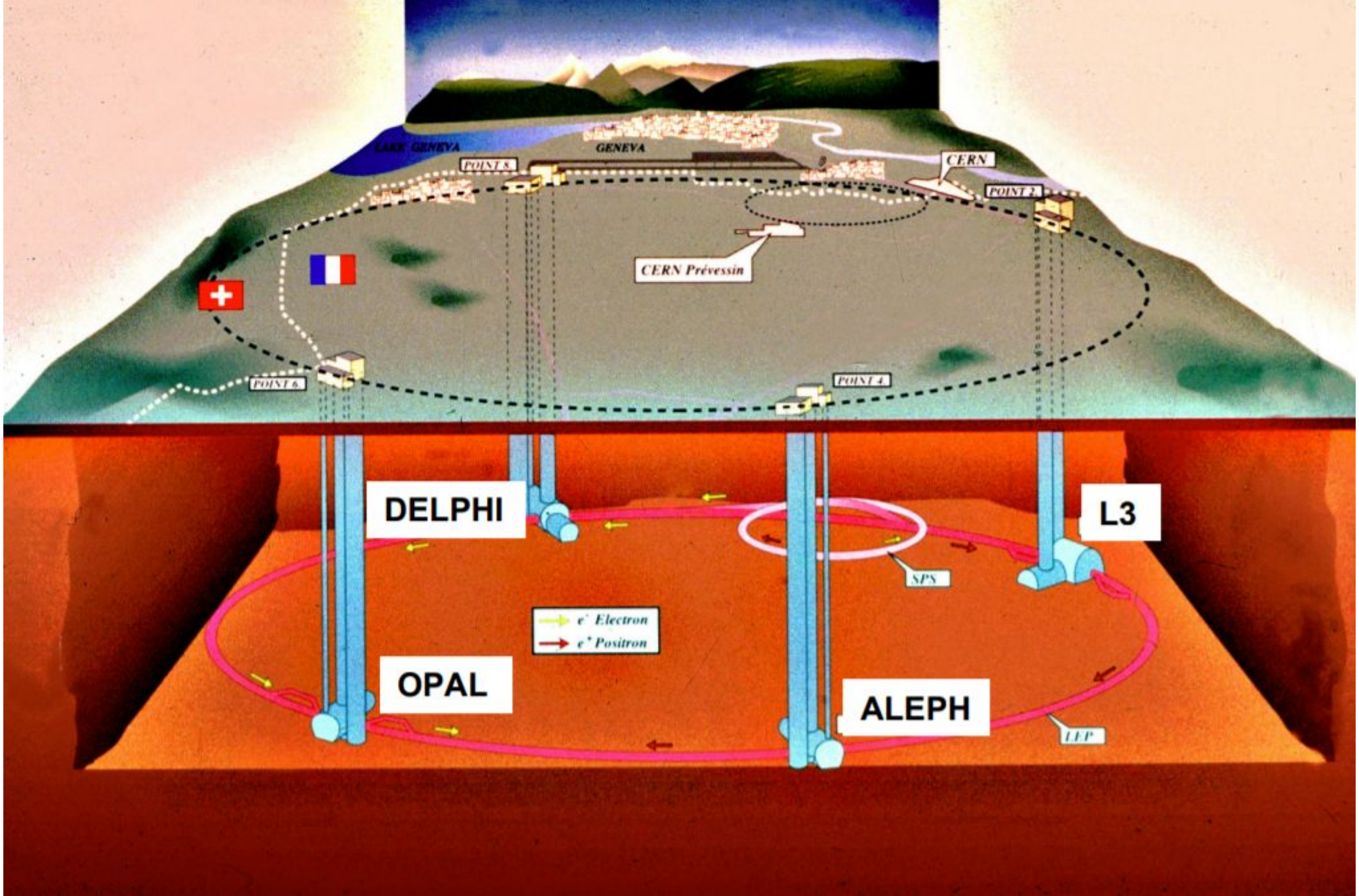
- Decay width of the Z^0 boson are given via:

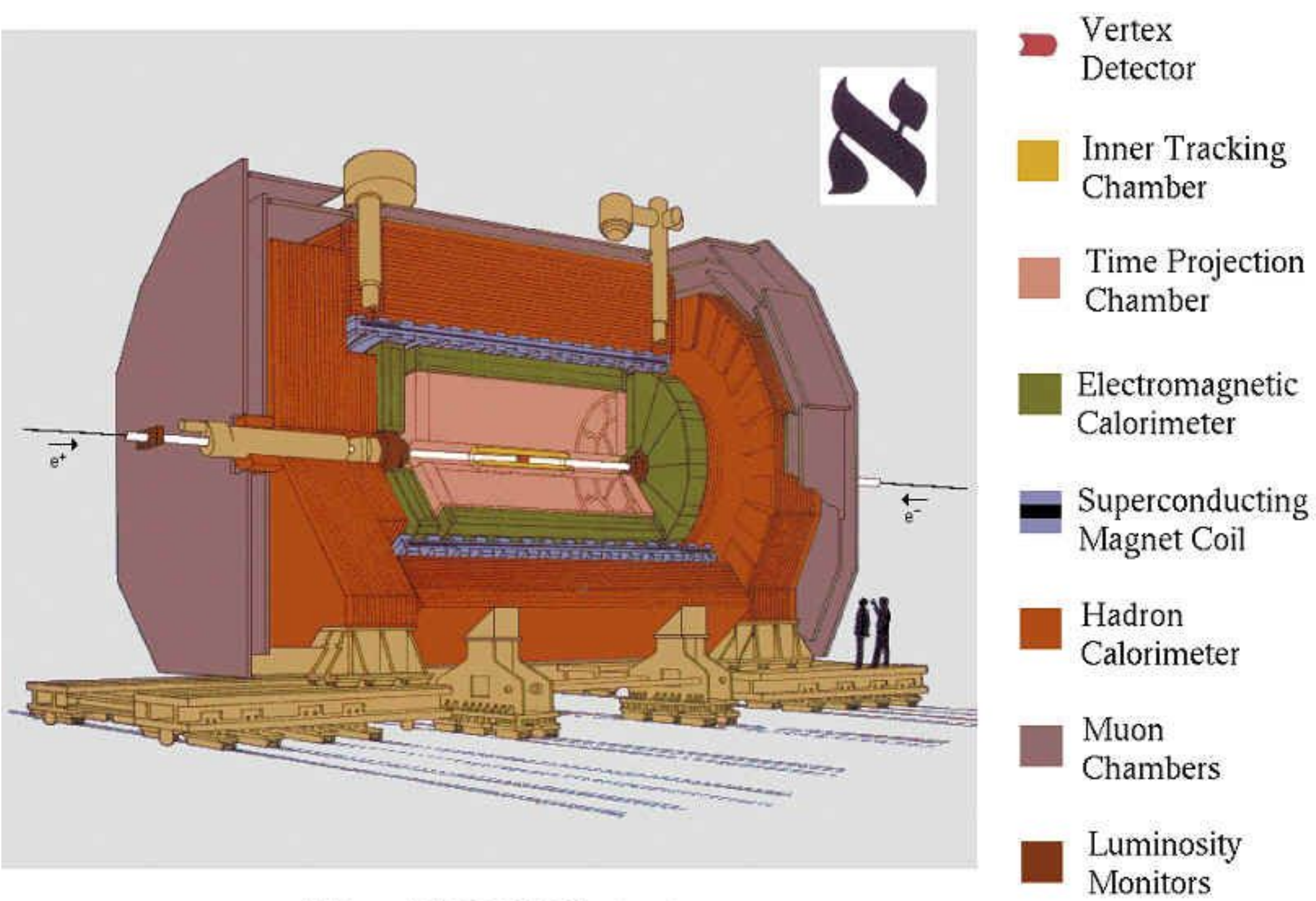
$$
\begin{aligned}
\Gamma(Z^0 \to f\bar{f}) &\equiv \Gamma_Z^f = \frac{G_F M_Z^3}{6\pi\sqrt{2}}(v_f^2 + a_f^2) \cdot N_C^f \\
\Gamma(Z^0 \to e^+e^-) &\equiv \Gamma_Z^e = \frac{G_F M_Z^3}{6\pi\sqrt{2}}(v_e^2 + a_e^2) \\
\Gamma_Z &\equiv \sum_f \Gamma_Z^f \\
\Gamma_Z^{\mathrm{h}ad} &\equiv \sum_q \Gamma_Z^q
\end{aligned}
$$

$$
A_{FB}^f = \frac{3}{4} A_e A_f \quad with \quad A_f = \frac{2 v_f a_f}{v_f^2 + a_f^2}
$$

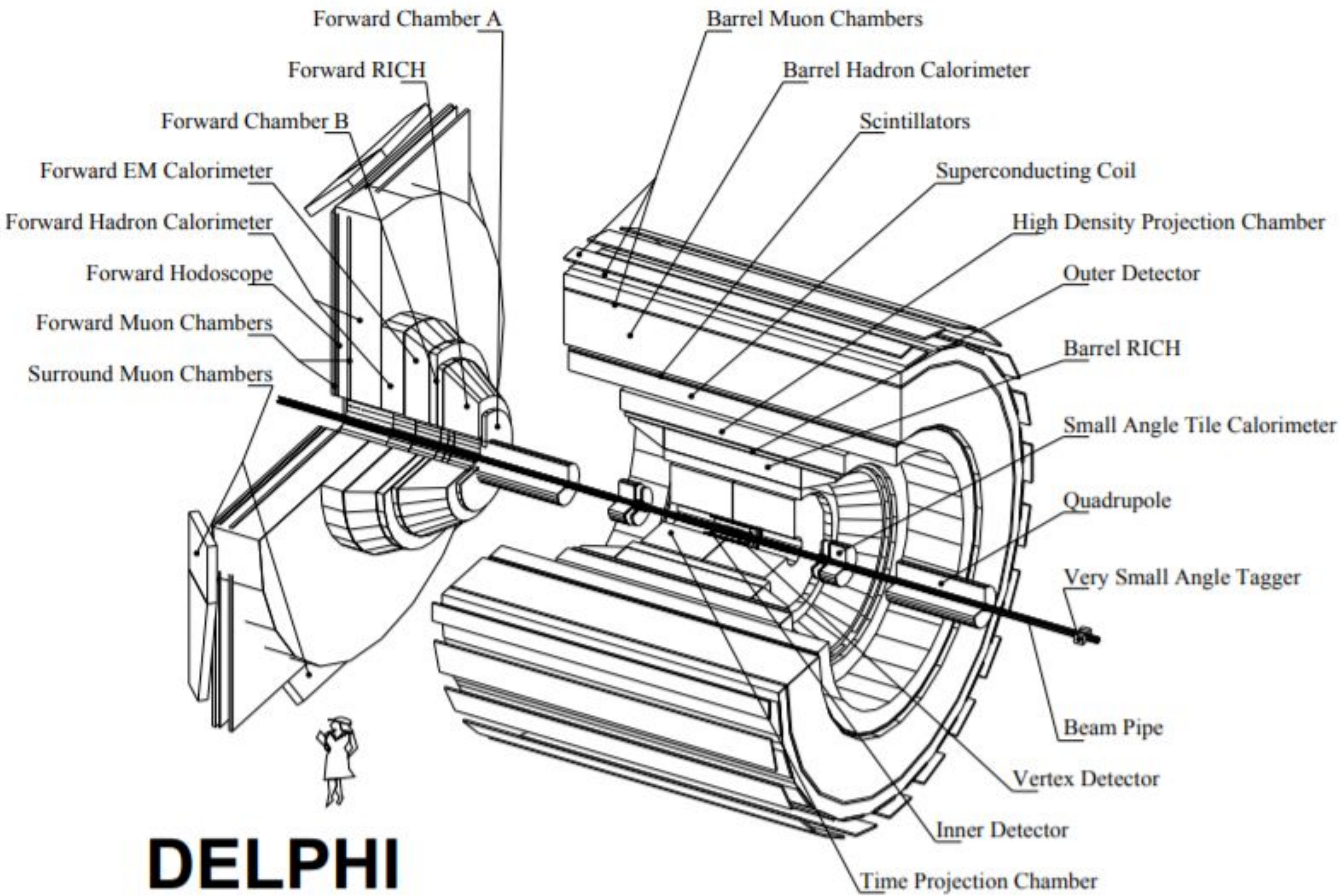
Define:

$$
R_f \equiv \Gamma_Z^{\mathrm{h}ad} / \Gamma_Z^f
$$

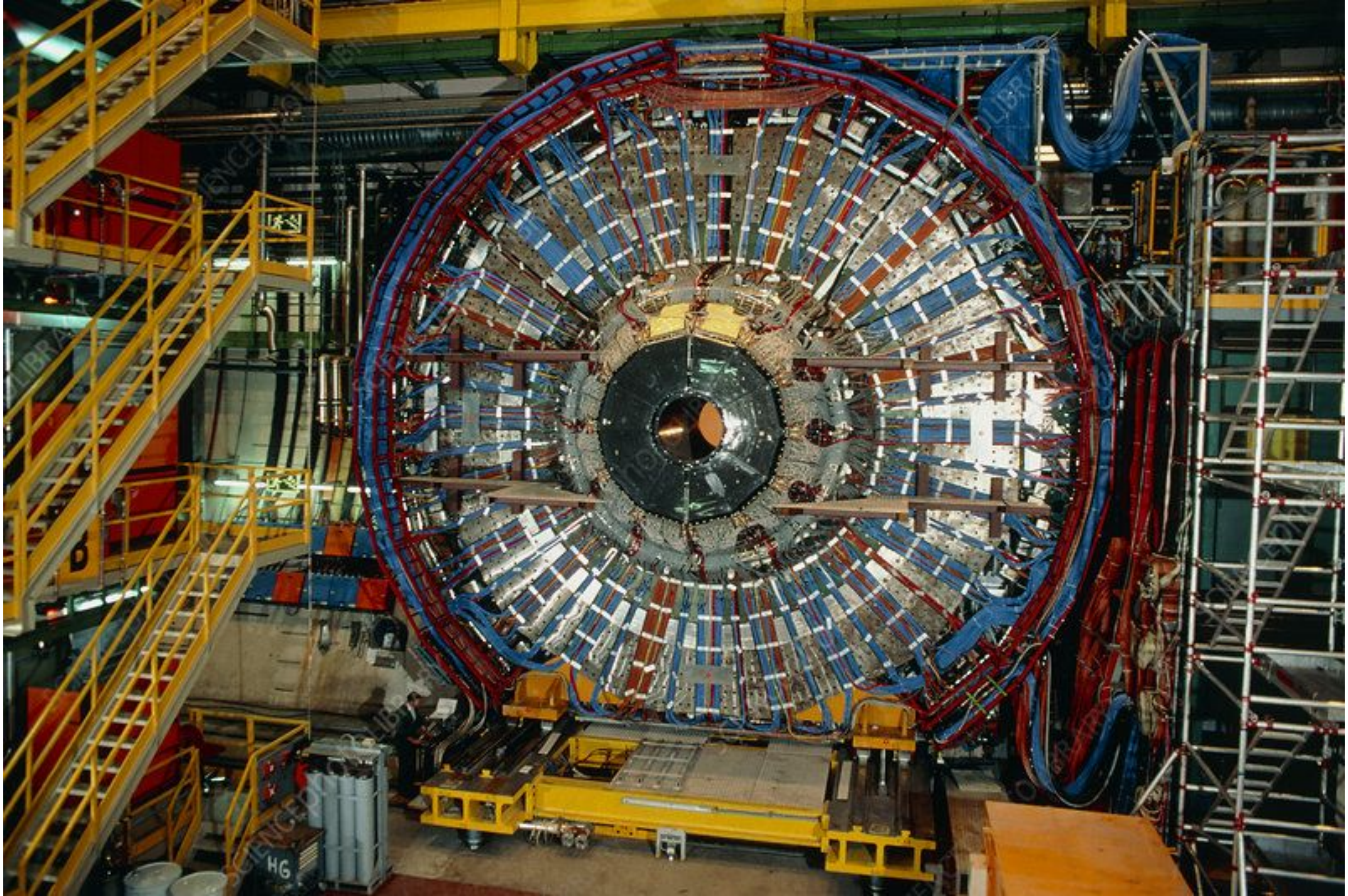

LAKE GENEVA
GENEVA
CERN
POINT 8.
POINT 2.
CERN Prévessin
POINT 6.
POINT 4.
DELPHI
L3
SPS
e^- Electron
e^+ Positron
OPAL
ALEPH
LEP



The ALEPH Detector

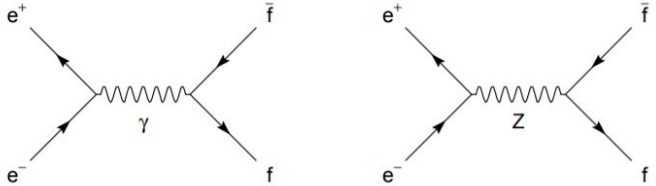


From: https://cds.cern.ch/record/295267/files/ppe-95-194.pdf

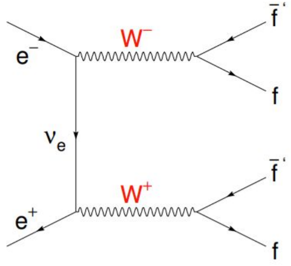


Cross-sections of electroweak SM processes at LEP

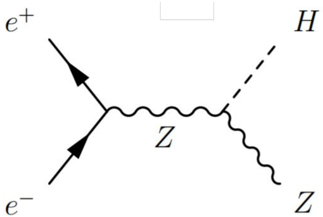
$$\boxed{e^+e^- \to f\bar{f}}$$

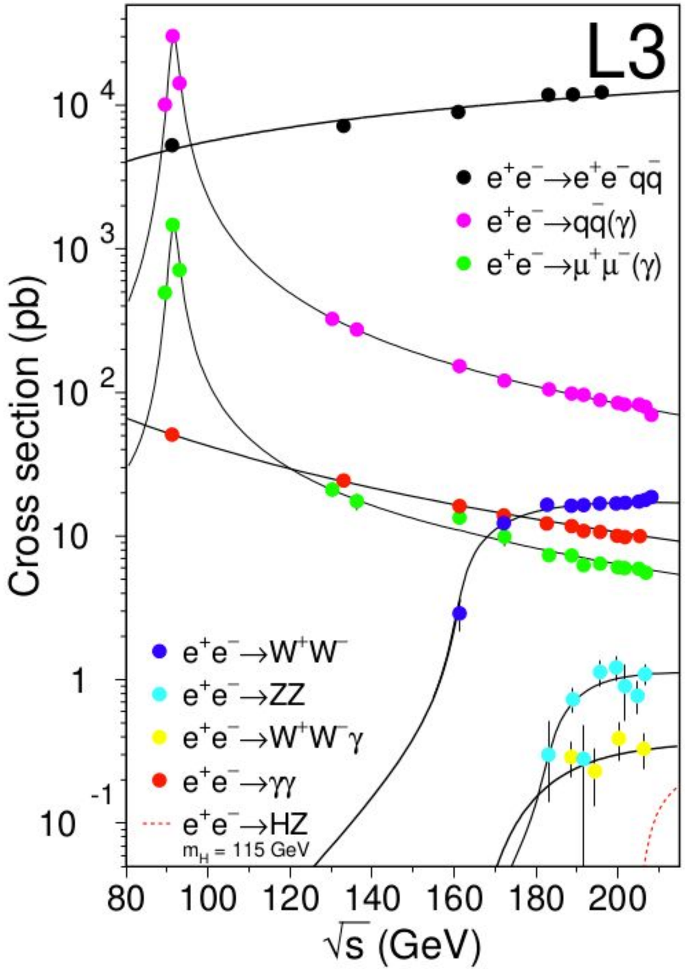


$$\boxed{e^+e^- \to W^+W^-}$$



$$\boxed{e^+e^- \to Zh}$$



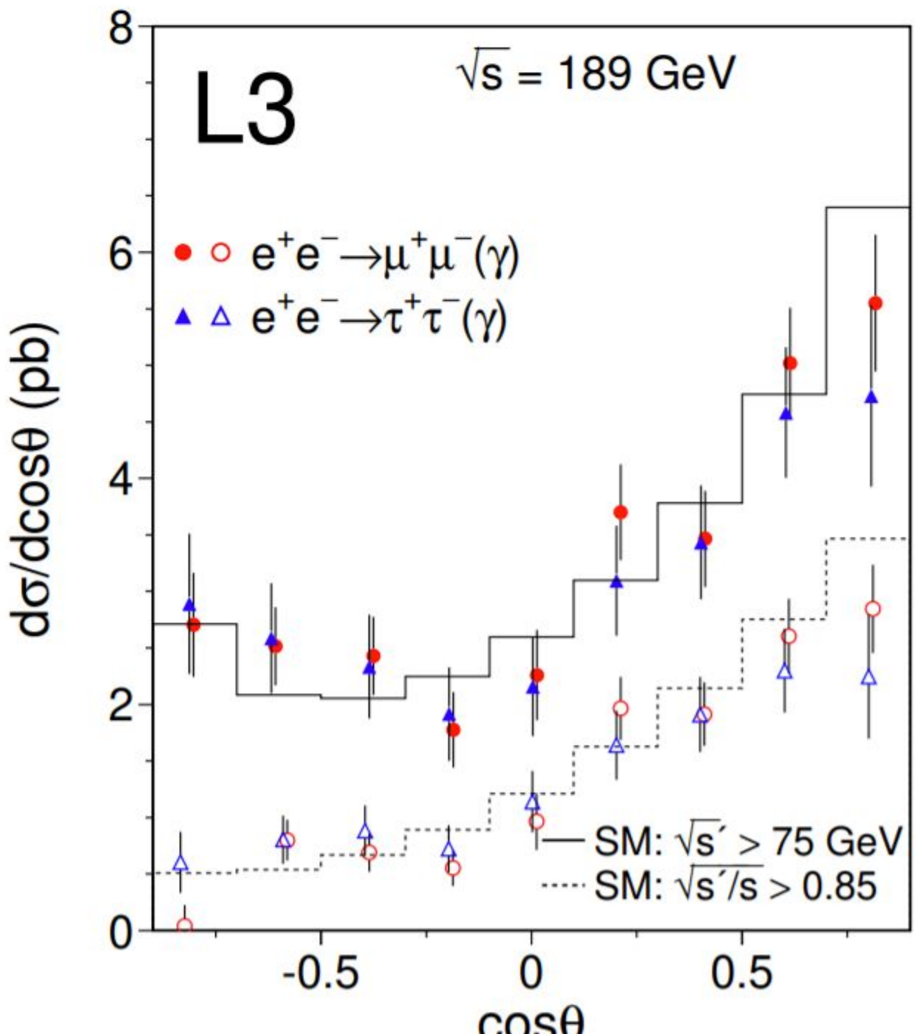


Measurements on the Z boson resonance

Number of Events										
	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

The qq and $\ell^+\ell^-$ event statistics, in units of 10^3 , used for Z analyses by the experiments ALEPH (A), DELPHI (D), L3 (L) and OPAL (O).

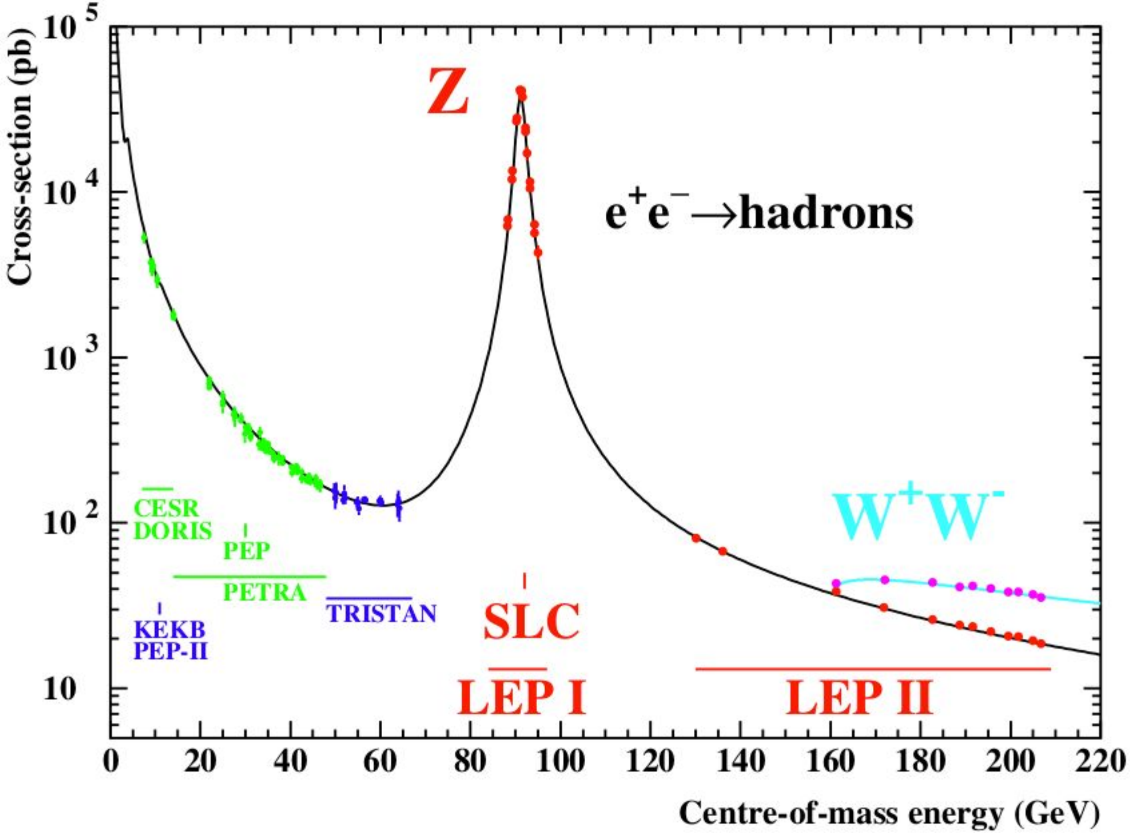
- Angular distribution observed in the lepton pair production at LEP
    - Characteristic forward background asymmetry A_{FB}



$\sqrt{s}$: centre-of-mass energy

$\sqrt{s'}$: effective centre-of-mass energy after initial-state photon radiation

Hadronic cross section

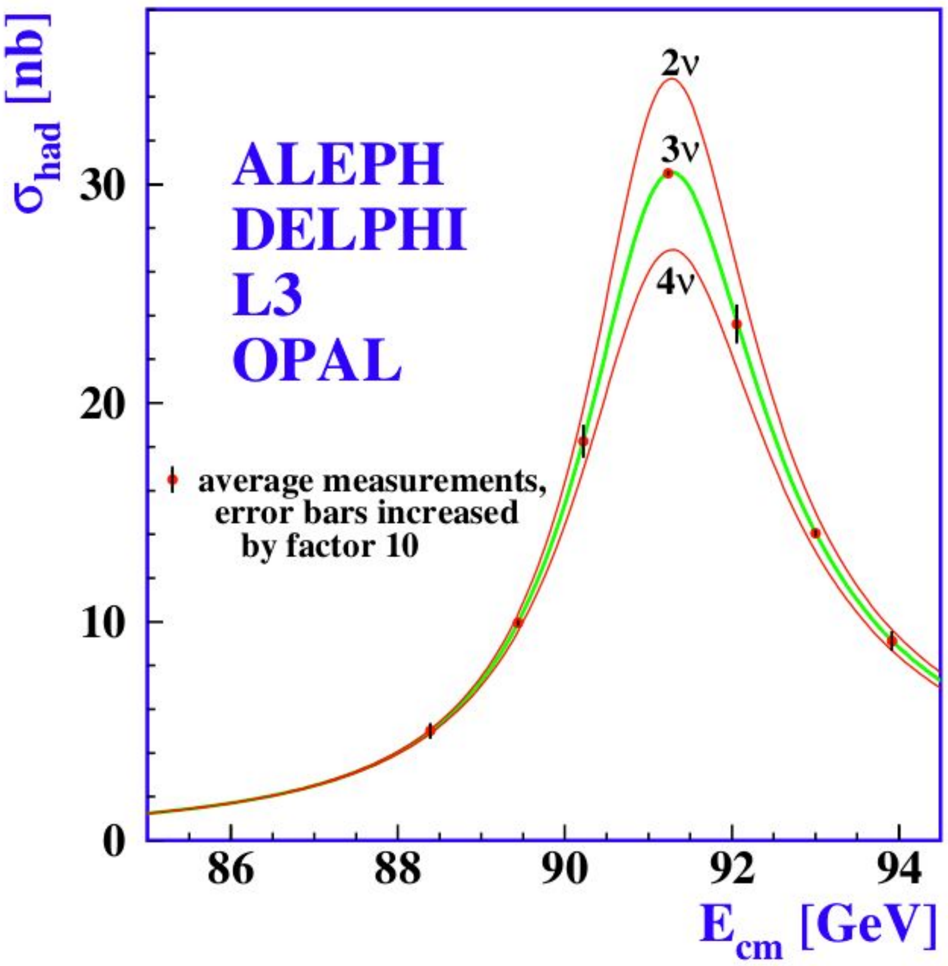


Hadronic cross section

- Measurement of number of light neutrinos ($2m_\nu < m_Z$):

$$\boxed{N_\nu = 2.9841 \pm 0.0083}$$

  - Equivalent to a measurement of quark-lepton generations
  - Measured in 1989 by the LEP experiments (but also by MARK-II at SLC)



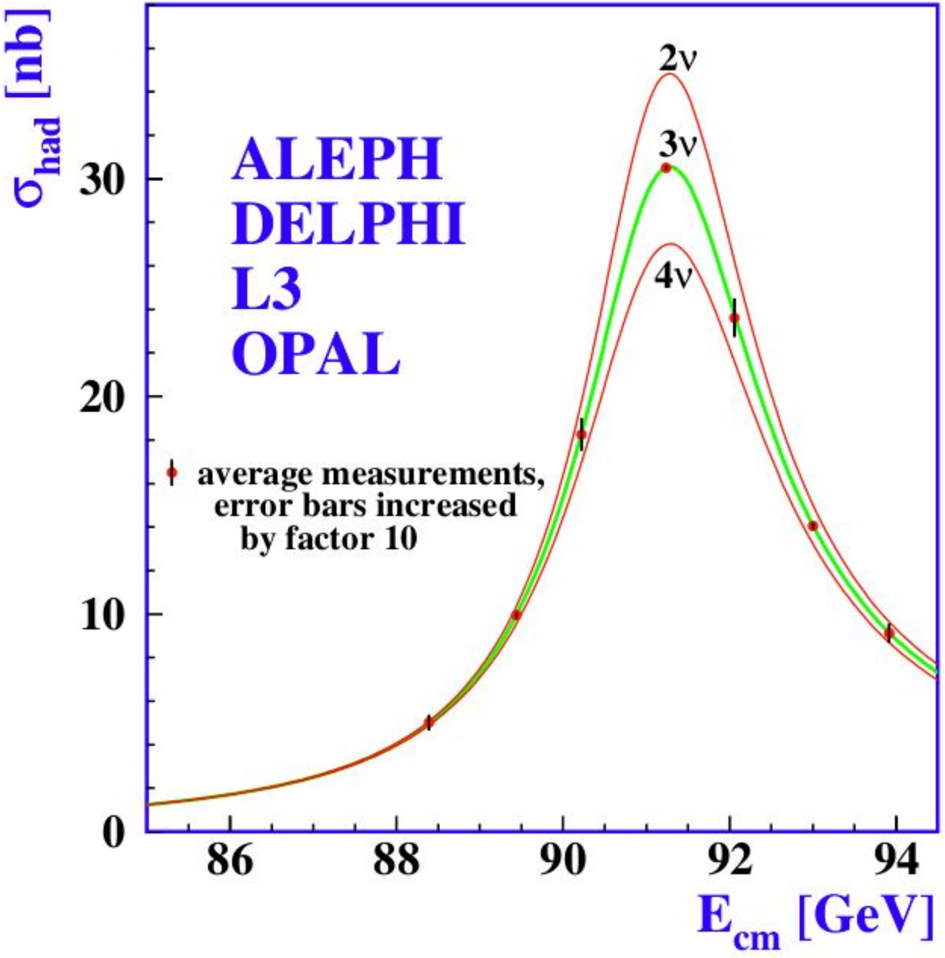
Hadronic cross section

- The total decay width of the Z^0 boson Γ_Z depends on the number of neutrino generations
  - while Γ^{had} does not

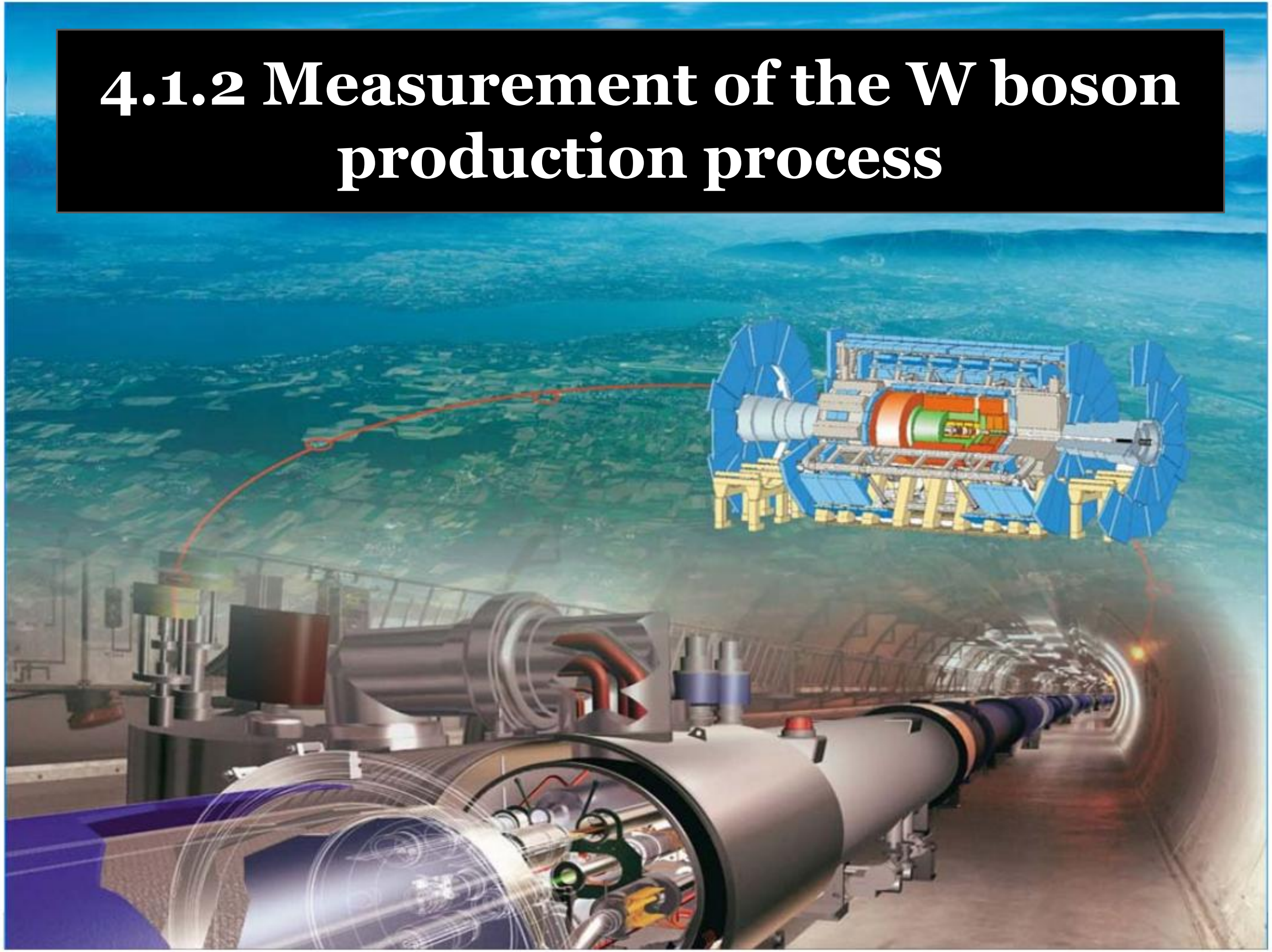
→ The hadronic cross section

$$\boxed{\sigma^0_{\mathrm{had}} = \frac{12\pi\Gamma_Z^e\Gamma_Z^{\mathrm{had}}}{M_Z^2\Gamma_Z^2}}$$

varies as a function of the neutrino numbers



4.1.2 Measurement of the W boson production process



W boson production at LEP

- Between 1996 and 2000, the center-of-mass energy of the LEP collider was increased (step-by-step) to:
  - 130, 161, 172 GeV (1996)
  - 183 GeV (1997)
  - 189 GeV (1998)
  - 192, 196, 200, 202 GeV (1999)
  - 208 GeV (2000)
- With these scans, the W^+W^- production threshold (and thus the W boson mass) was measured precisely

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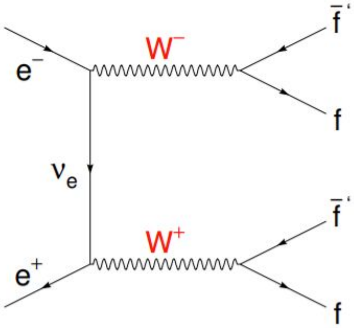
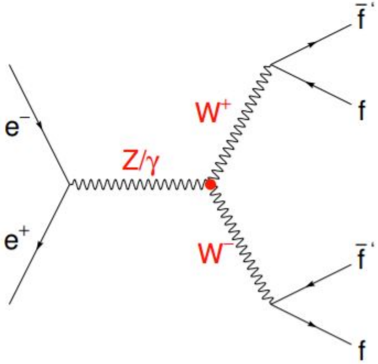
W boson production (and decay) at LEP

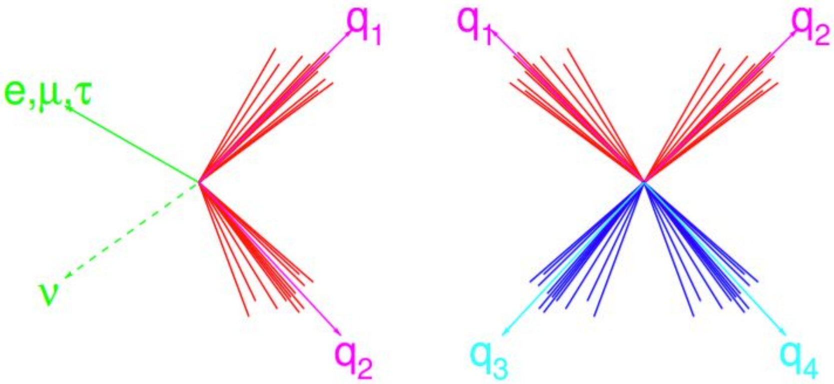
- Lowest order diagrams:





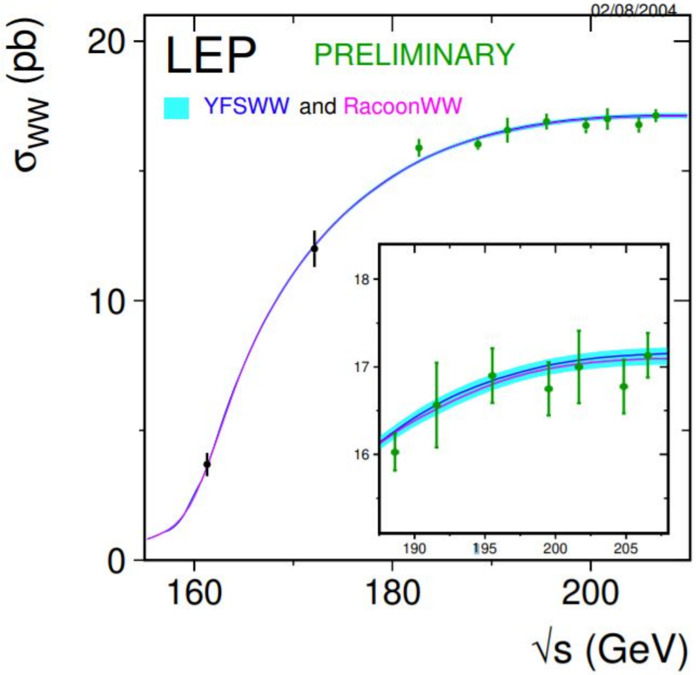
- WW decays:

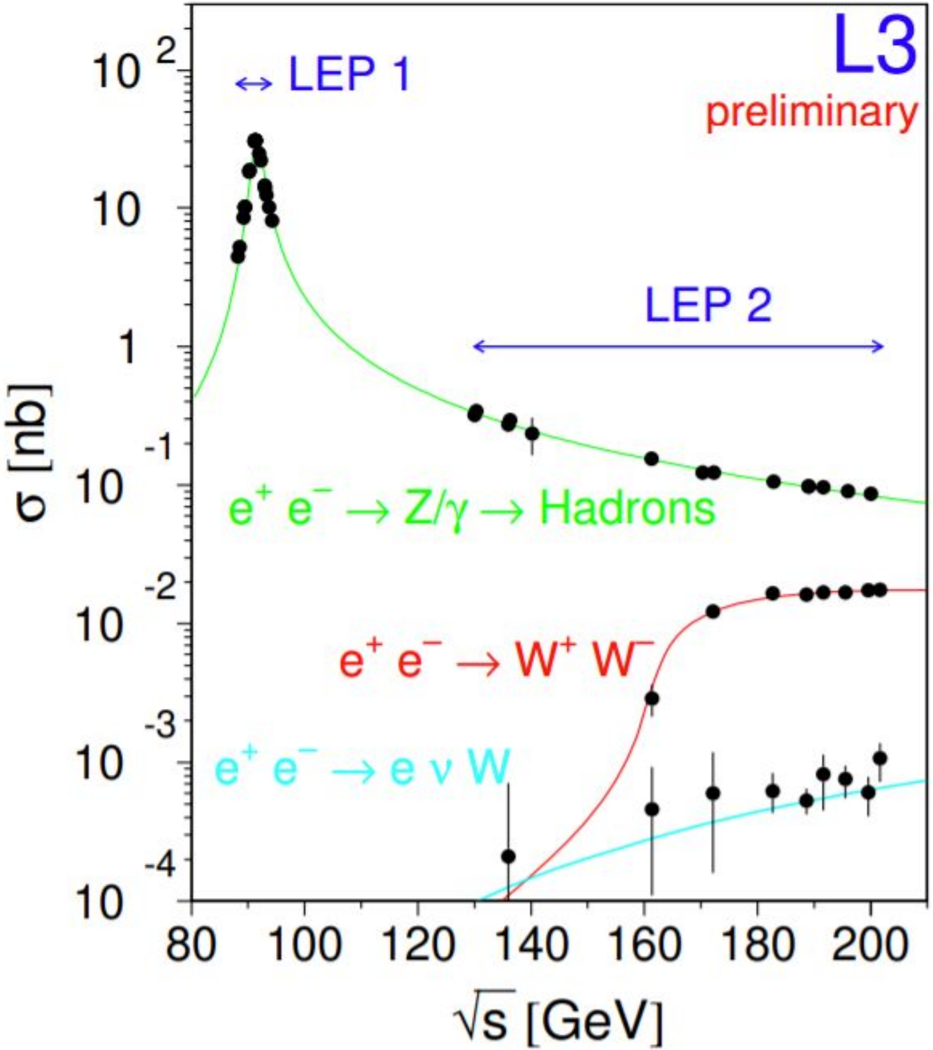
$WW \to qqqq$		45.6 %
$WW \to qq\ell\nu$	$\left\{\begin{array}{c} qqe\nu \\ qq\mu\nu \\ qq\tau\nu \end{array}\right\}$	43.8 %
$WW \to \ell\nu\ell\nu$		10.6 %



semileptonic **hadronic**

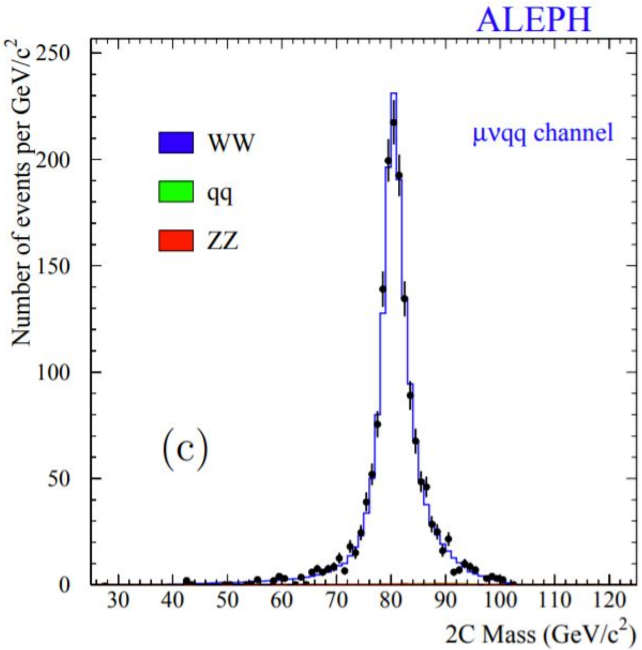
$W^+ W^-$ production cross section at LEP

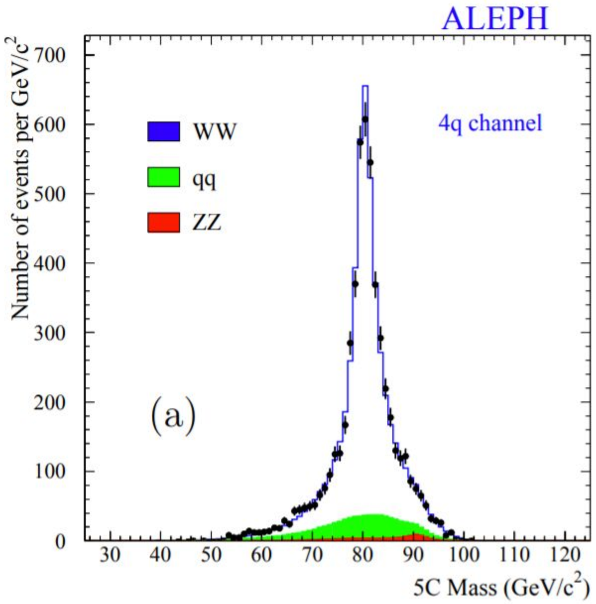




W boson mass measurements (at ALEPH)

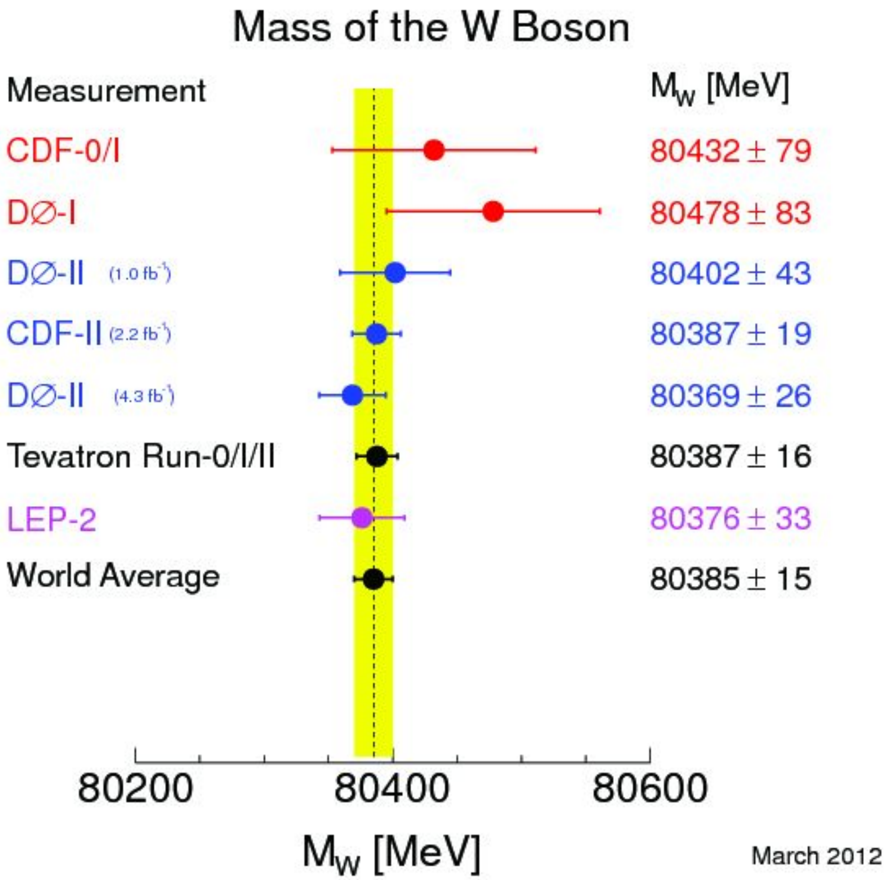
- The W boson mass and width are extracted by fitting simulated invariant mass spectra to the observed distributions.
    - Use an unbinned maximum likelihood procedure



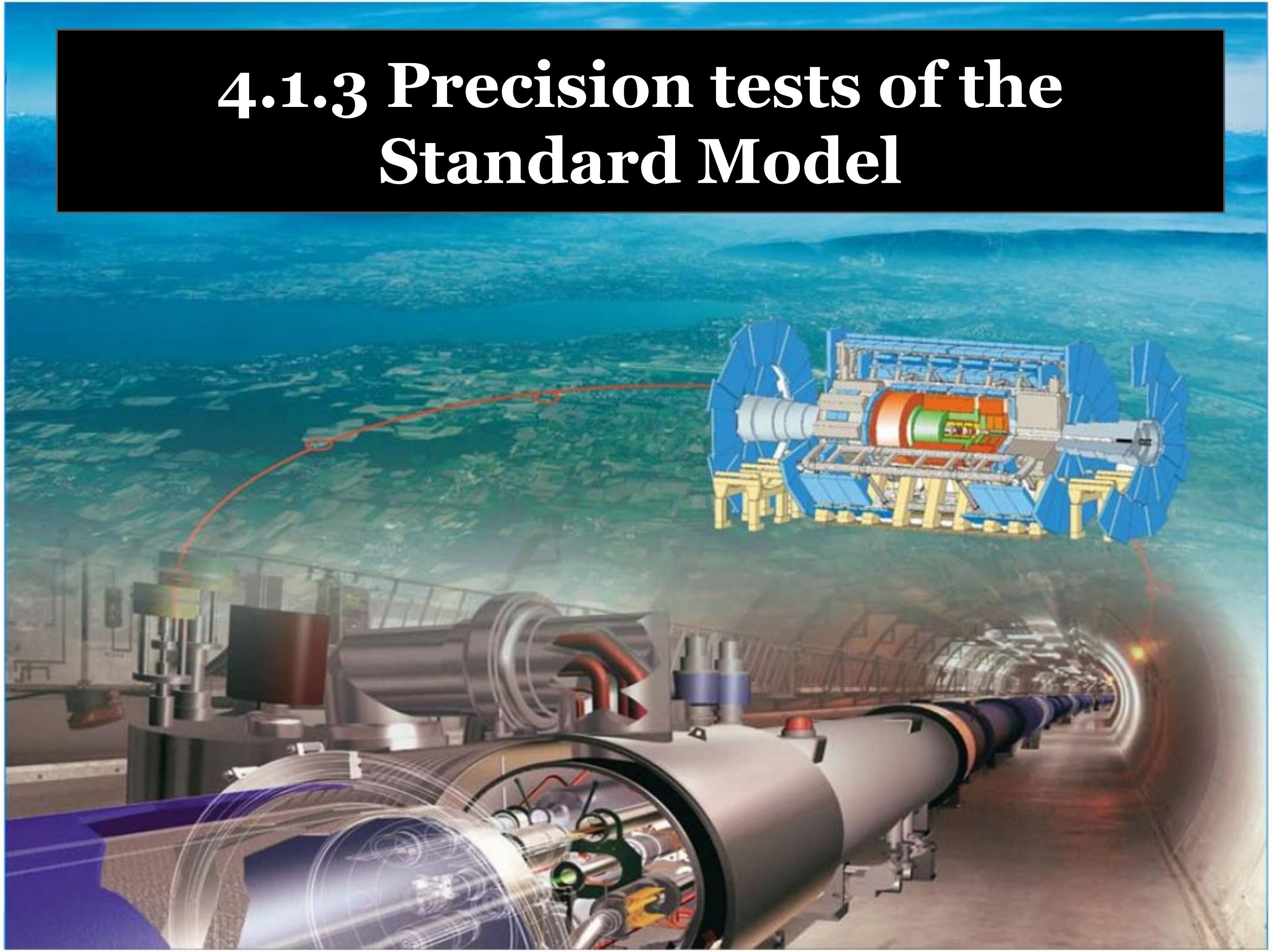


Taken from: https://arxiv.org/pdf/hep-ex/0605011.pdf

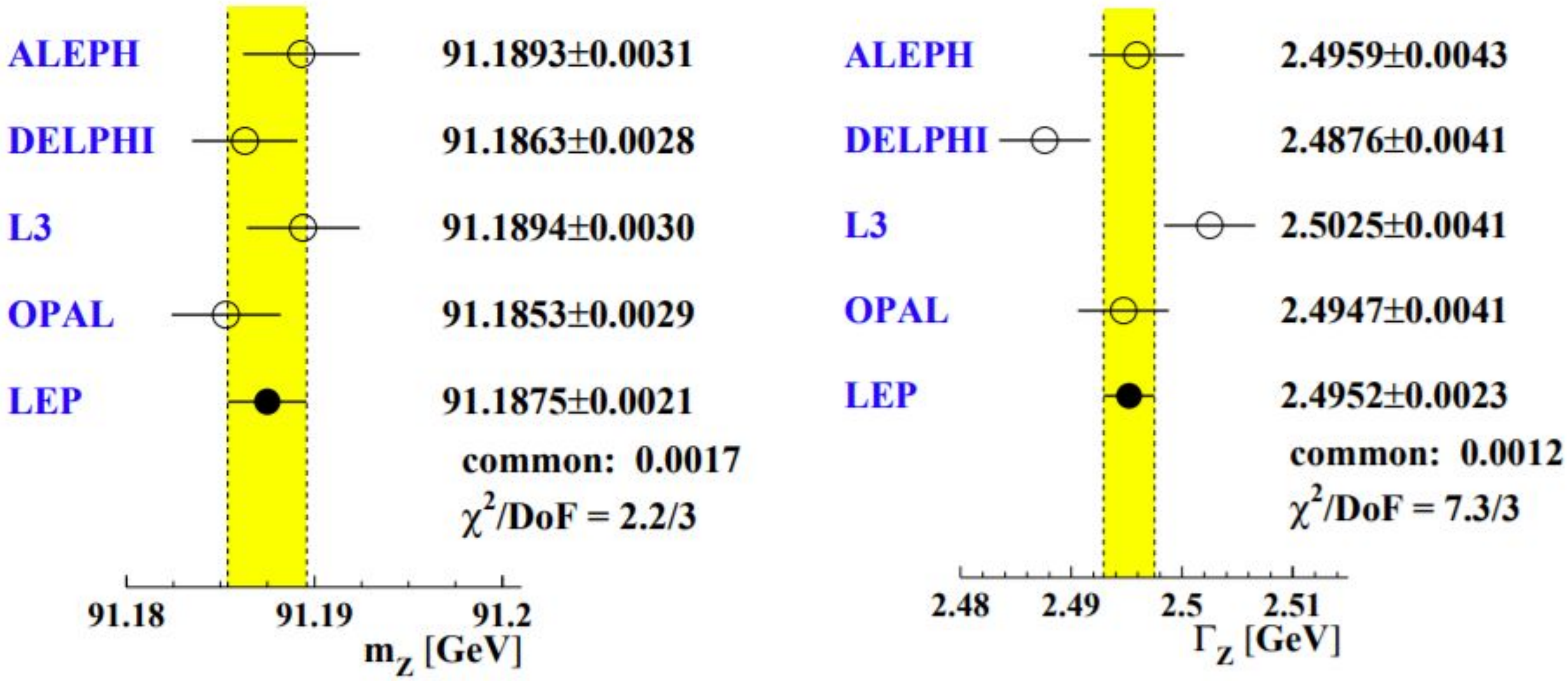
W boson mass measurements (at LEP & Tevatron)



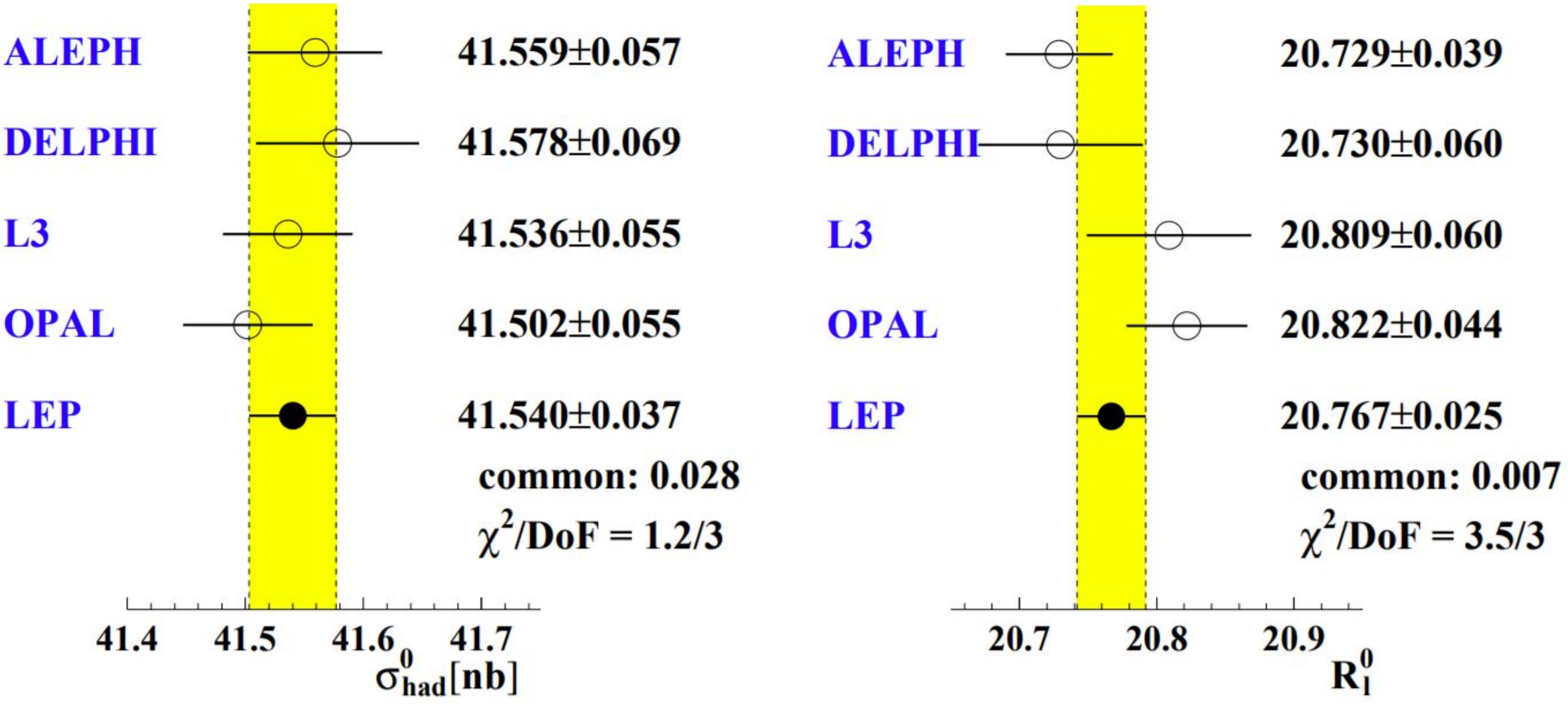
4.1.3 Precision tests of the Standard Model



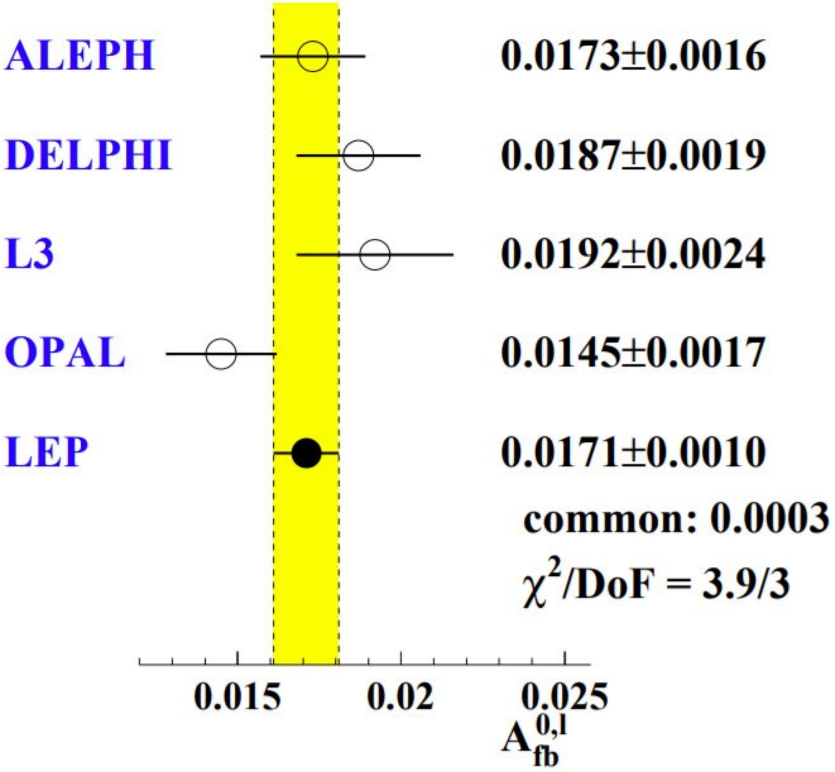
Precision tests of the Standard Model

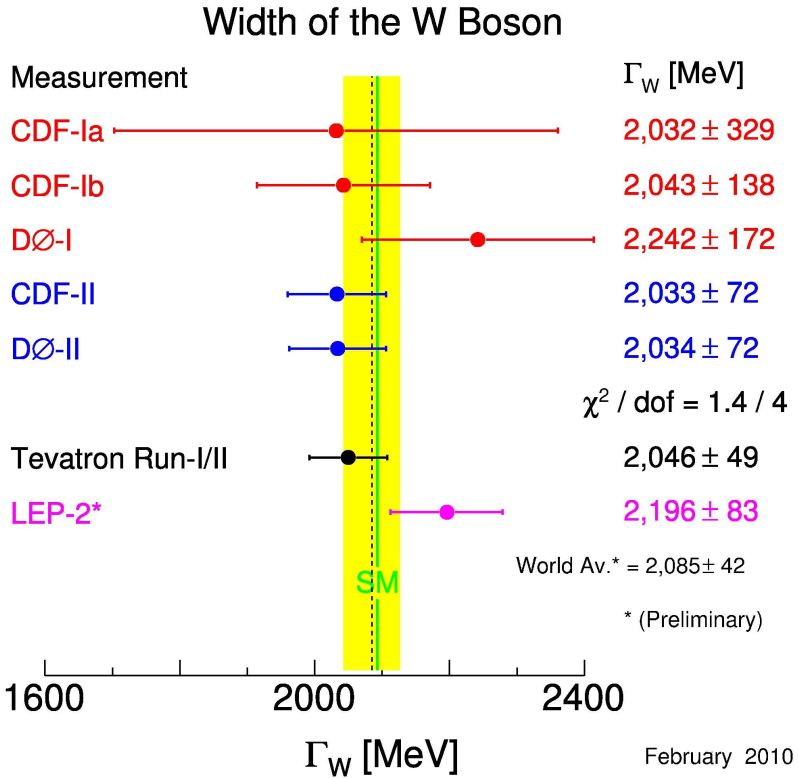


Precision tests of the Standard Model



Precision tests of the Standard Model





Precision tests of the Standard Model

- Electroweak radiative corrections modify the calculation of Z-pole observables.
  - Virtual W and Higgs bosons as well as top quarks contribute via loops
- The contributions from radiative corrections depend on the masses of these particles:
  - m_W and m_{top} (quadratic)
  - m_H (logarithmic)

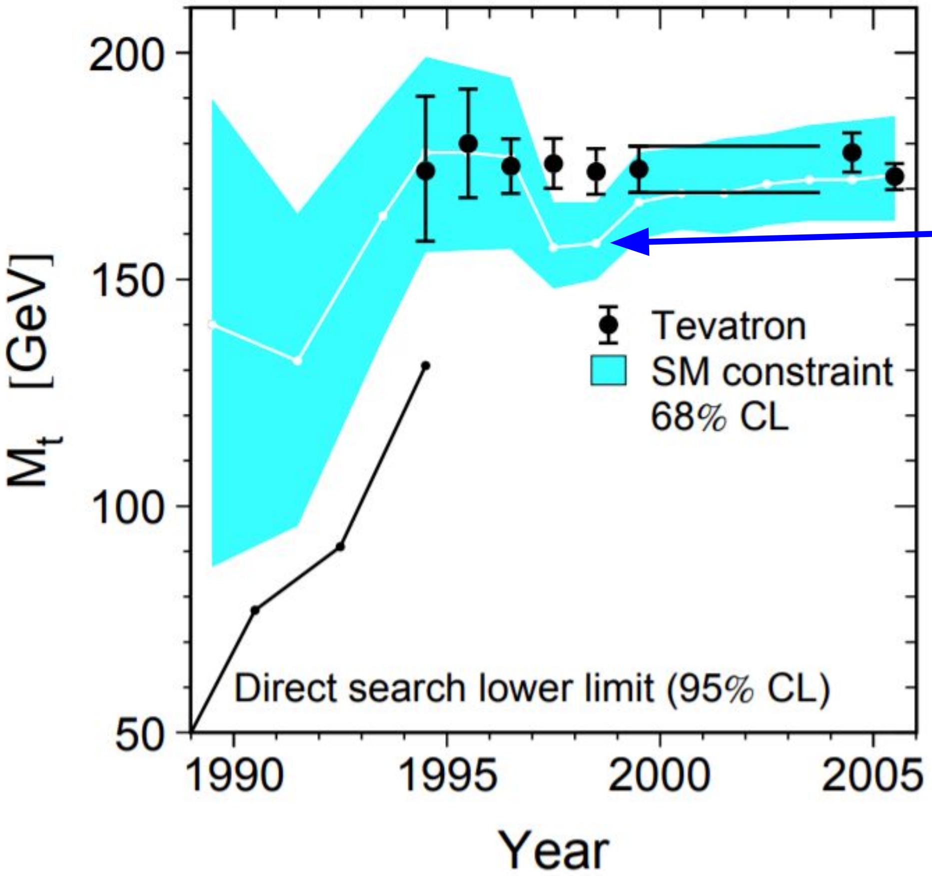
Taken from: https://arxiv.org/pdf/hep-ex/0509008.pdf

Higher-order corrections to the gauge boson propagators due to boson loops

Precision tests of the Standard Model

- Comparisons with the high precision measurements allow for an indirect determination of m_W, m_{top} and m_H
  - **Prediction:**
    - **m_W = 80.364 ± 0.021 GeV**
    - **m_{top} = 172.3 ± 10 GeV**
    - **m_H = 91 ± 45 GeV**
  - **Direct measurement:**
    - **m_W = 80.399 ± 0.025 GeV**
    - **m_{top} = 173.2 ± 0.8 GeV** (early: TEVATRON + LHC combination)
    - **m_H = 125.09 ± 0.21(stat) ± 0.11 (syst) GeV**

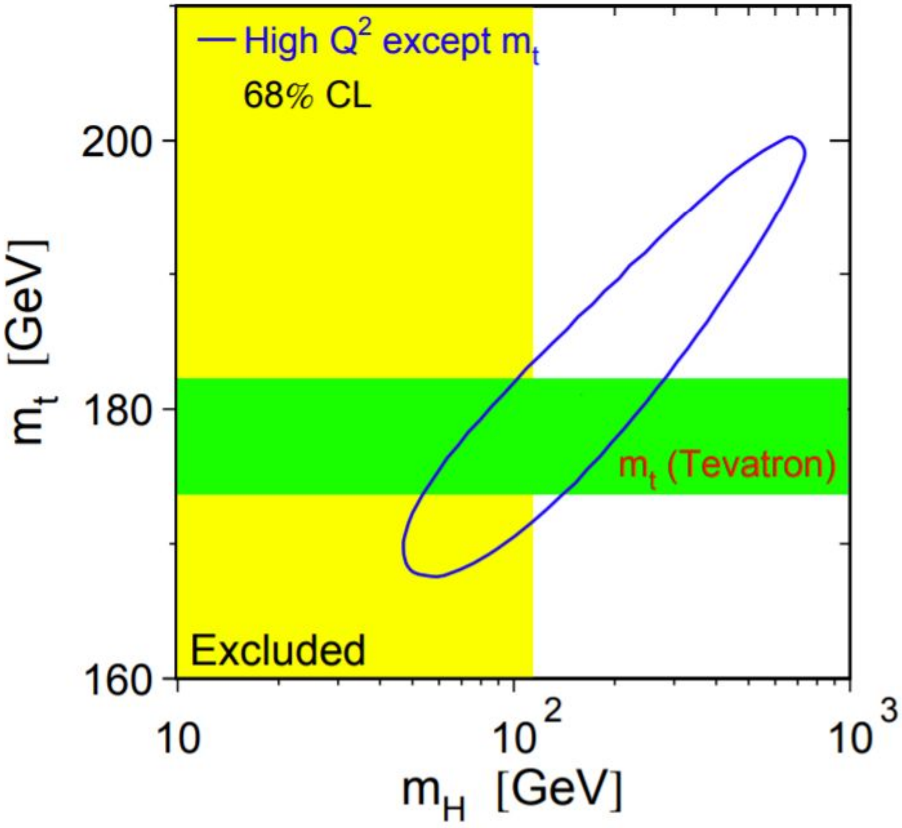
Precision tests of the Standard Model

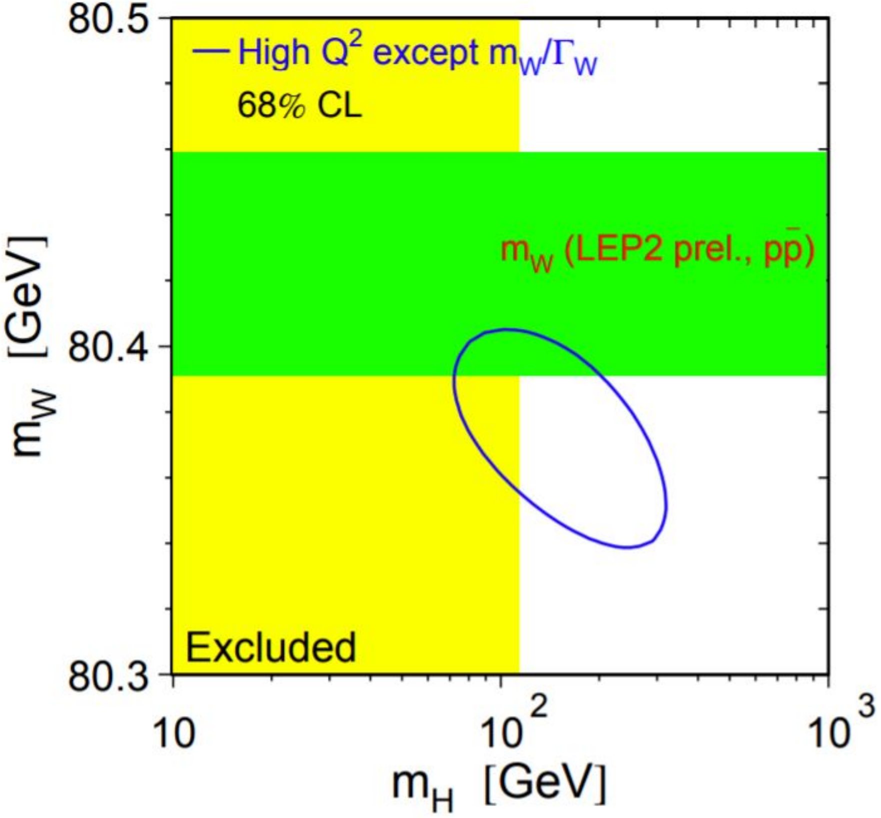


The shaded area denotes the **indirect determination of the top quark mass at the 68% Confidence Level (C.L.)** derived from the analysis of radiative corrections within the framework of the SM using precision electroweak measurements.

Taken from https://arxiv.org/pdf/hep-ex/0509008.pdf

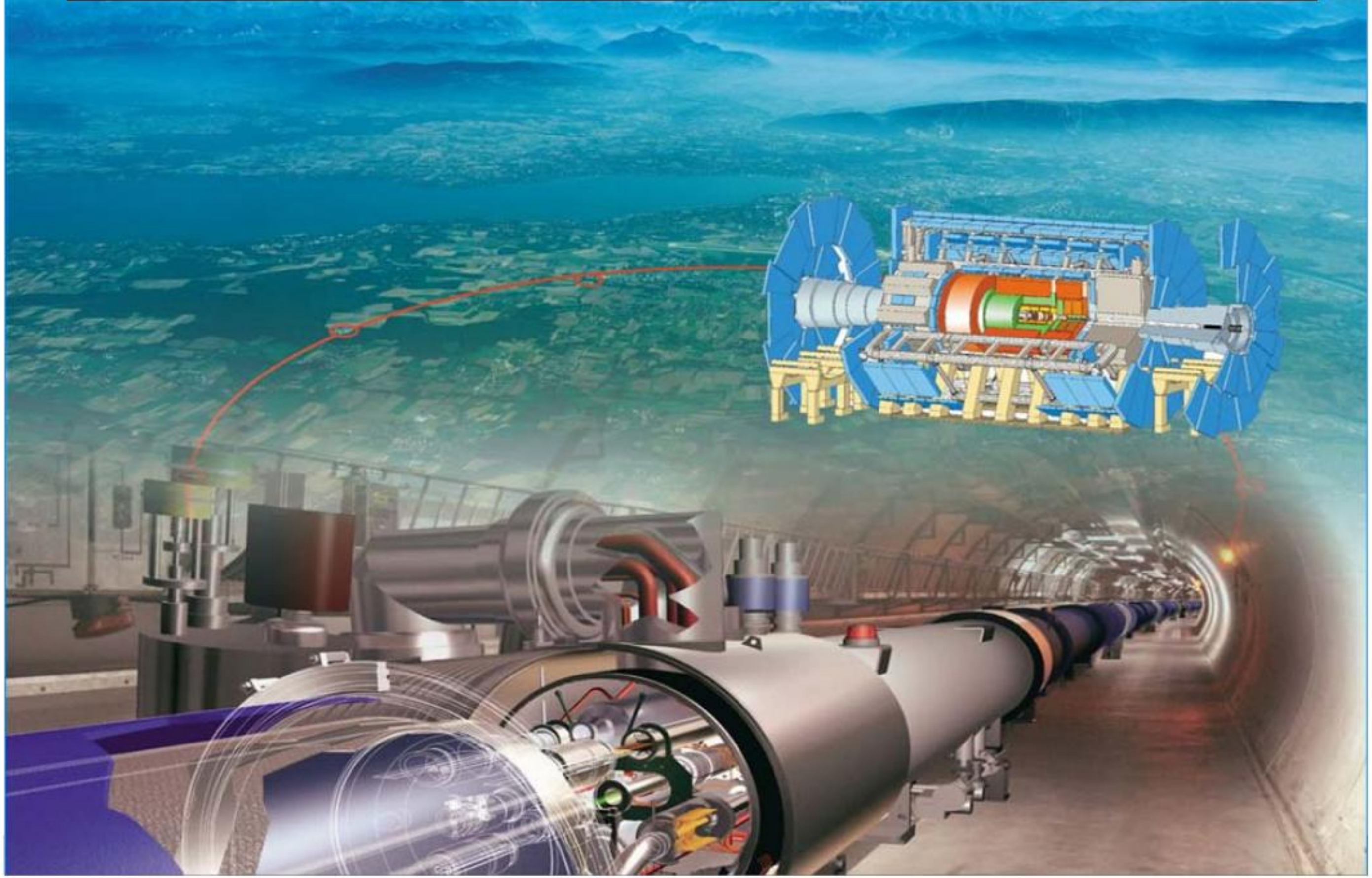
Precision tests of the Standard Model





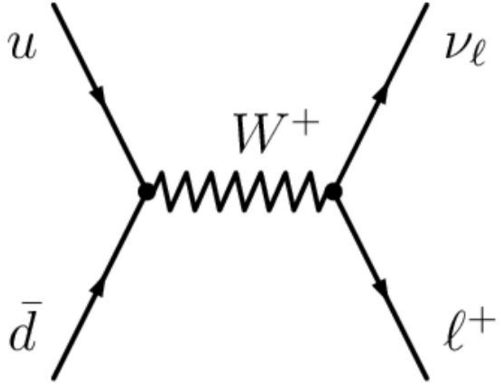
Taken from https://arxiv.org/pdf/hep-ex/0509008.pdf

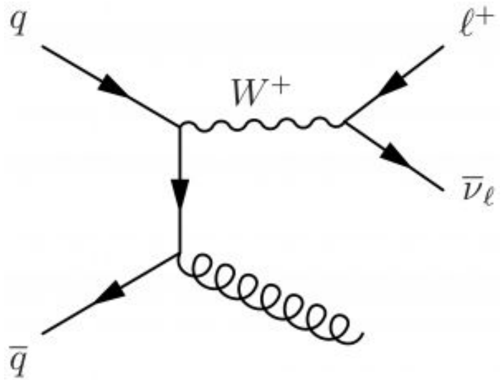
4.1.4 W & Z bosons at the LHC



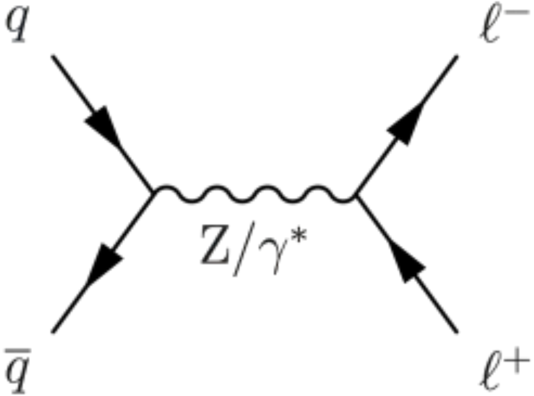
W/Z + jets production

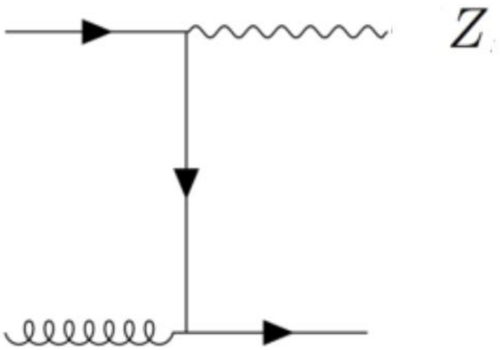
W + jets





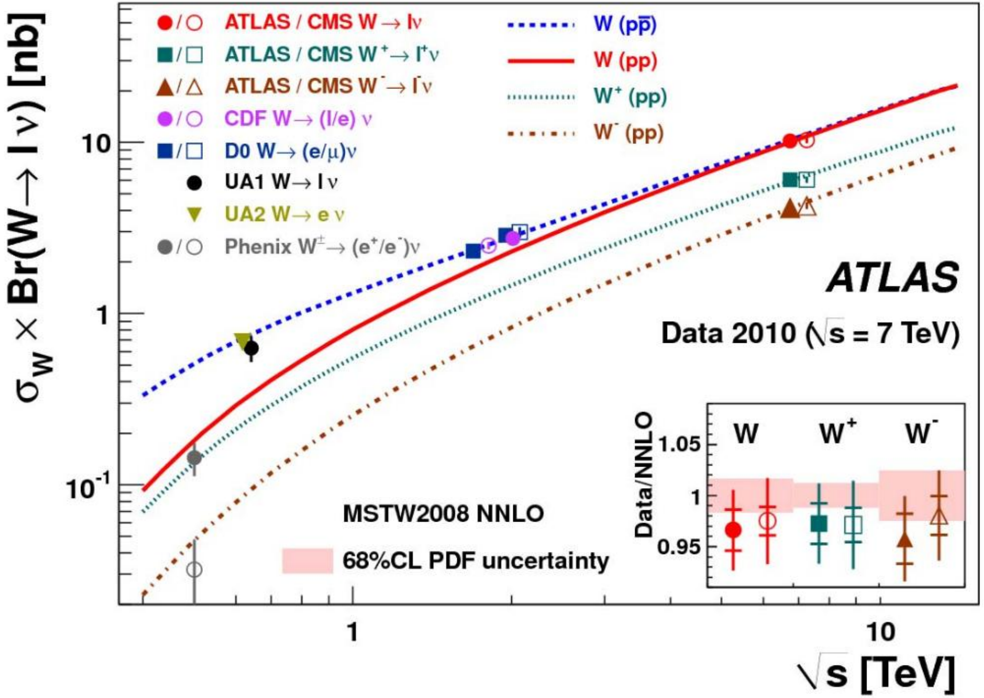
Z + jets

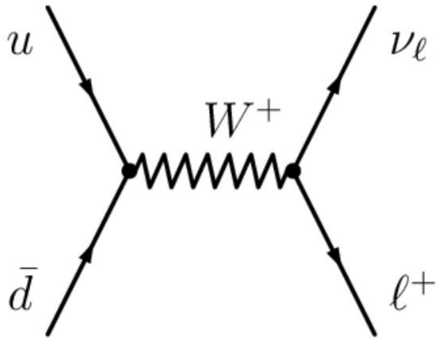


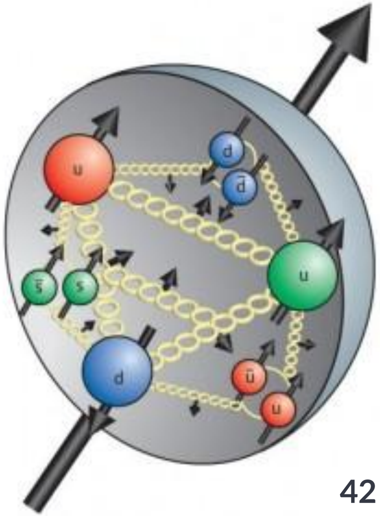


Charge asymmetry in W boson production

- **Parton distribution functions (PDFs) of u and d quarks in the proton differ** (mainly due to the fact that protons contain two valence u quarks and one valence d quark)

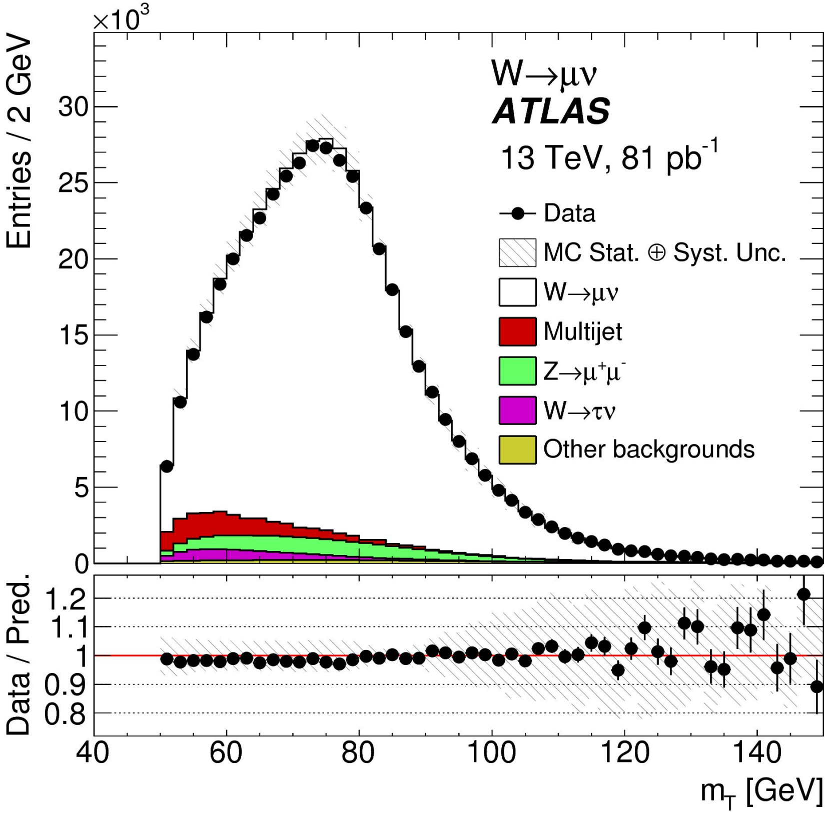




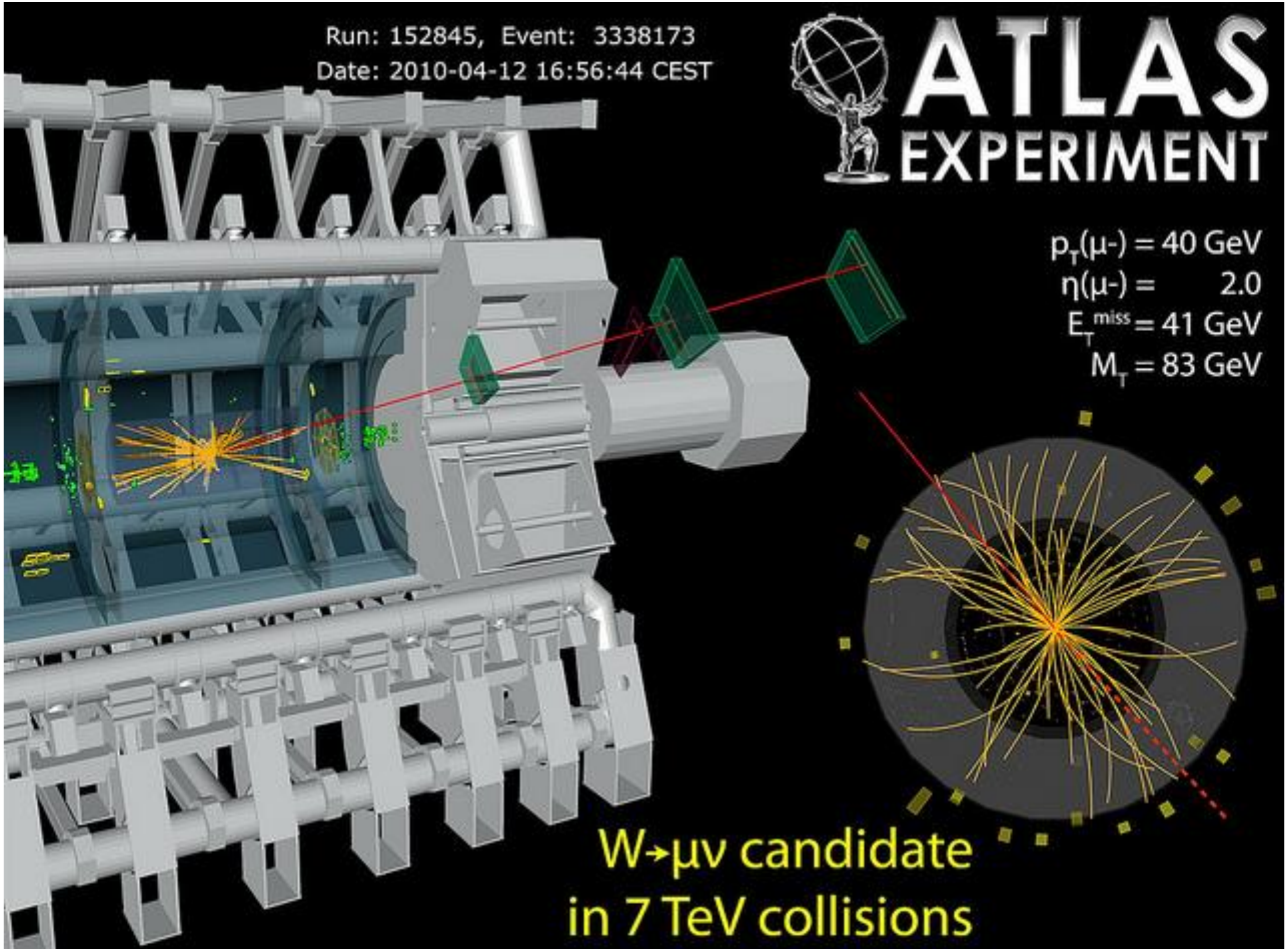


W boson production

- W boson candidate events are selected by requiring:
  - Exactly one identified electron or muon
  - MET > 25 GeV
  - m_T > 50 GeV
- Roughly 20% of all selected events stemm from background processes:
  - Most dominant contributions:
    - Multijets (10%)
    - $Z \rightarrow \ell\ell$ (5%)



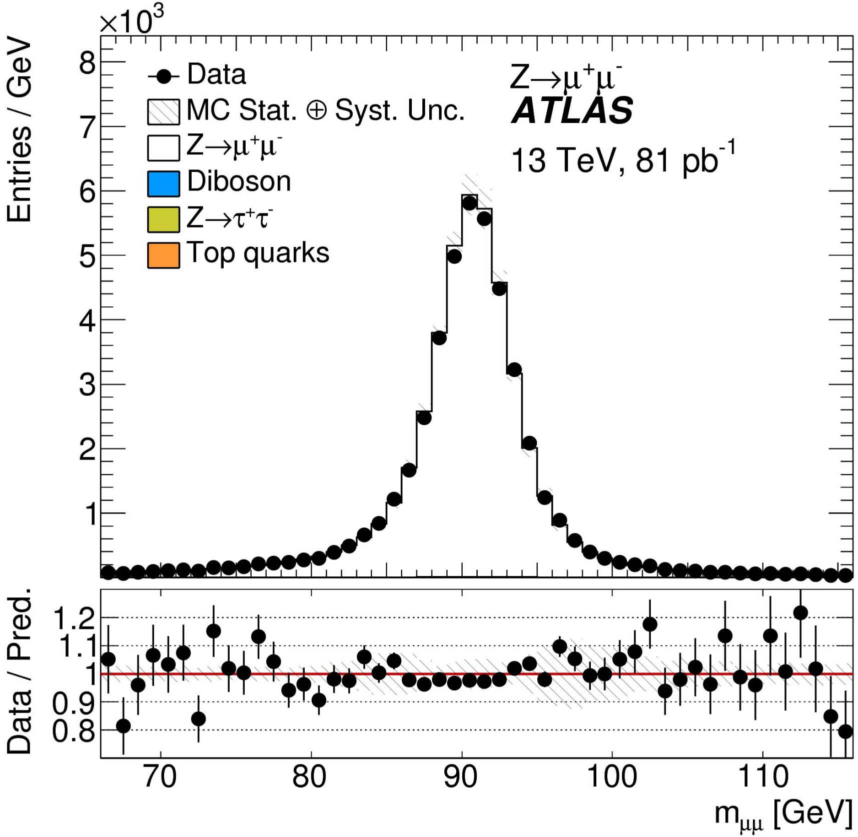
From: https://arxiv.org/abs/1603.09222


Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST
ATLAS
EXPERIMENT
$p_T(\mu-) = 40$ GeV
$\eta(\mu-) = 2.0$
$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV
W→μν candidate
in 7 TeV collisions

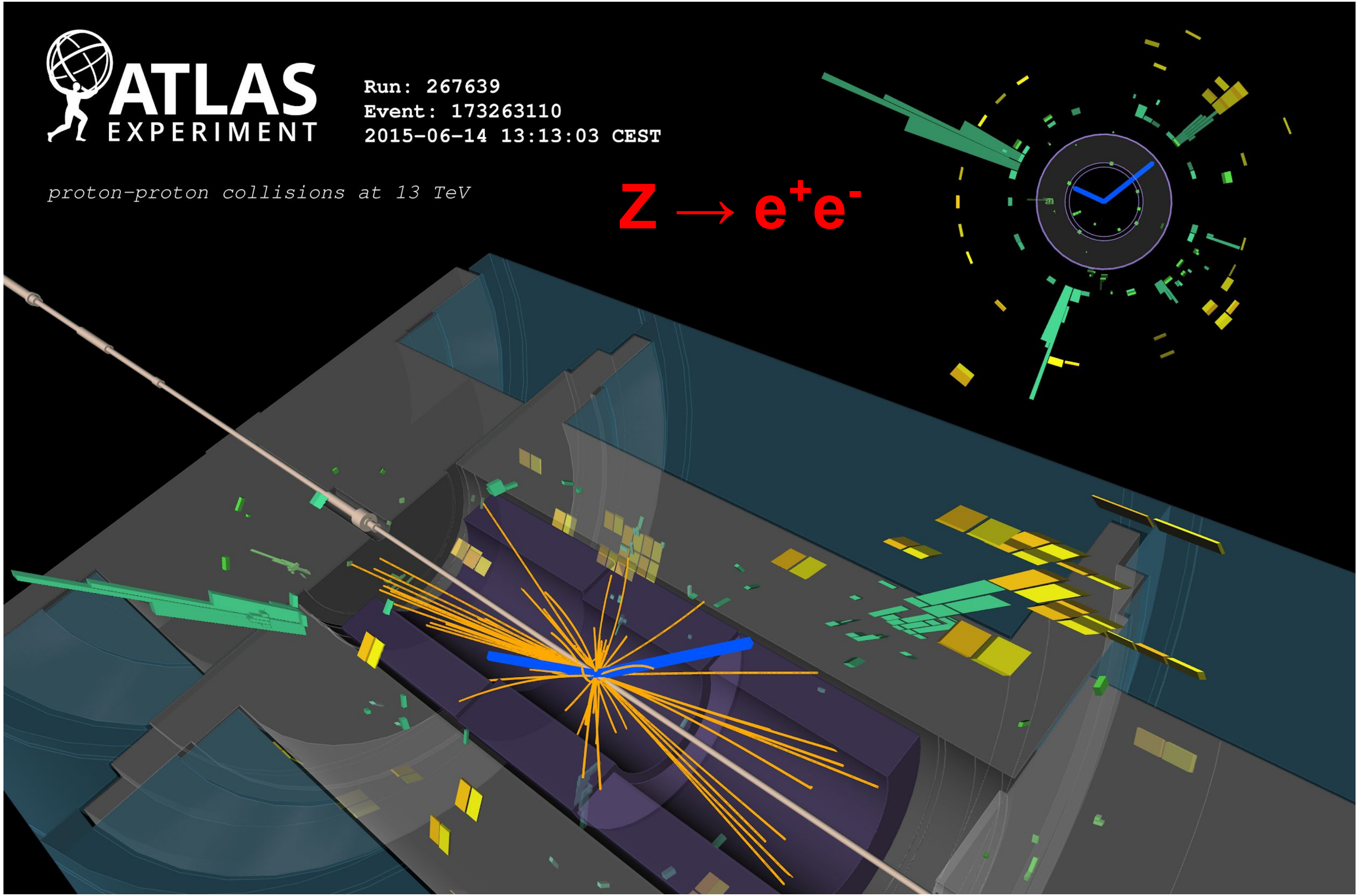
Z boson production

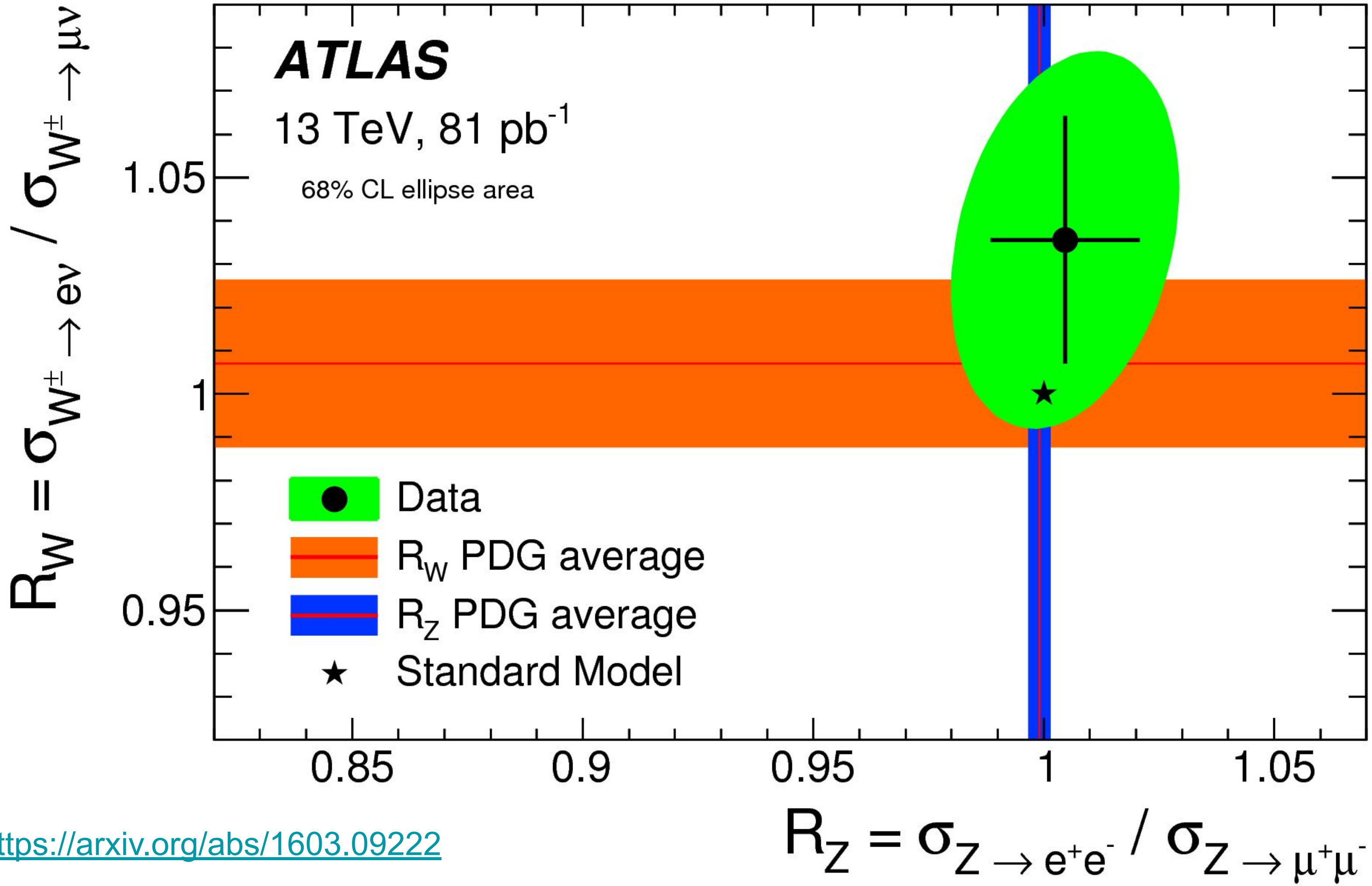
- Z boson candidate events are selected by requiring:
  - Exactly two leptons:
    - Same flavour & opposite charge
    - $66 < m_{\ell\ell} < 116$ GeV

- Roughly 0.5% of all selected events stemm from background processes:



From: https://arxiv.org/abs/1603.09222

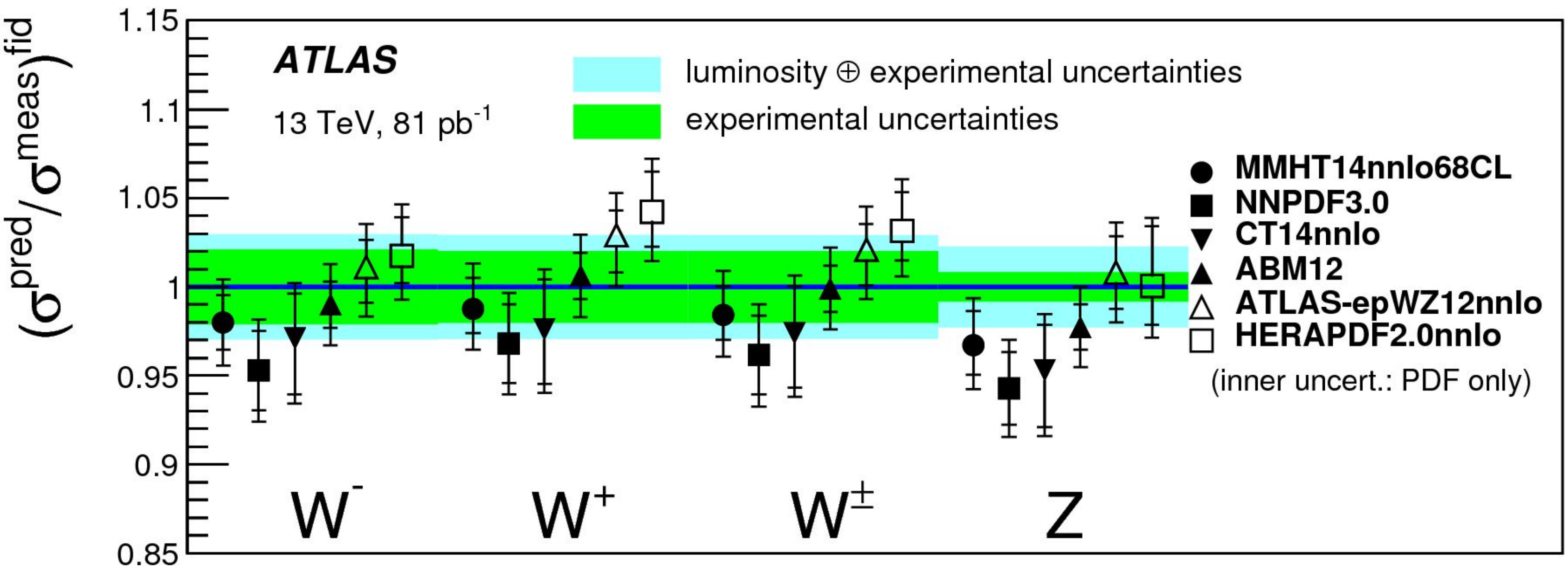

ATLAS EXPERIMENT
Run: 267639
Event: 173263110
2015-06-14 13:13:03 CEST
proton-proton collisions at 13 TeV
$Z \rightarrow e^+e^-$



From: https://arxiv.org/abs/1603.09222

W/Z production cross sections

From: https://arxiv.org/abs/1603.09222

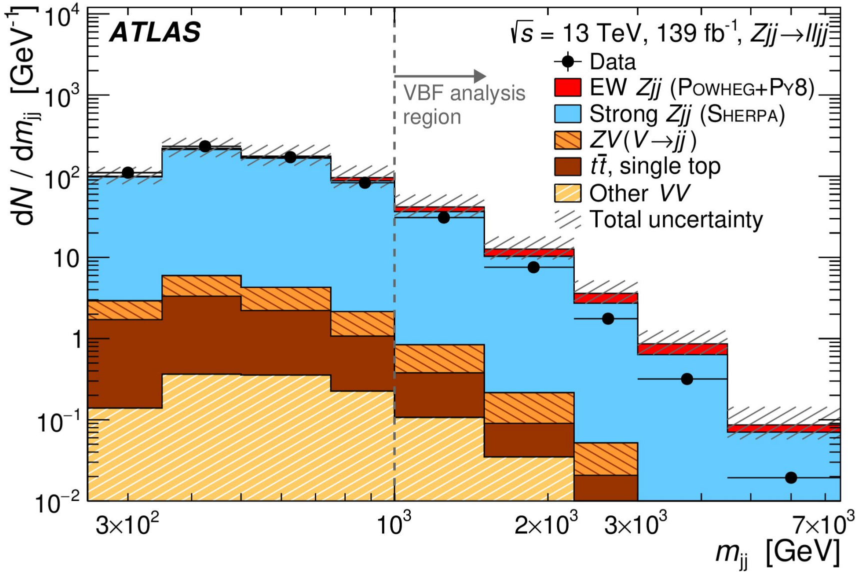


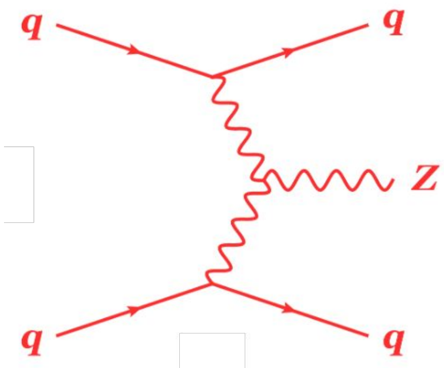
W & Z boson production cross section measurements are sensitive to the PDF sets

→ Can constrain them

EW Z boson production cross section

- Insights into the mechanism of electroweak (EW) symmetry breaking can be achieved via (VBS) processes
  - Via studies of vector boson self interaction
- Sensitive to BSM contributions:
  - Heavy-vector triplets
  - Extra dimensions



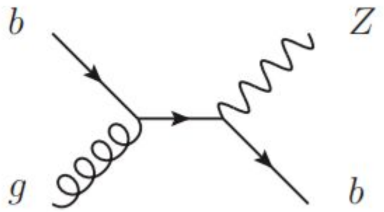


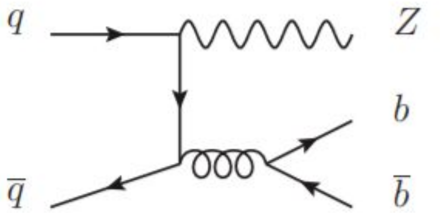
σ_{EW} = 37.4 ± 3.5 (stat) ± 5.5 (syst) fb

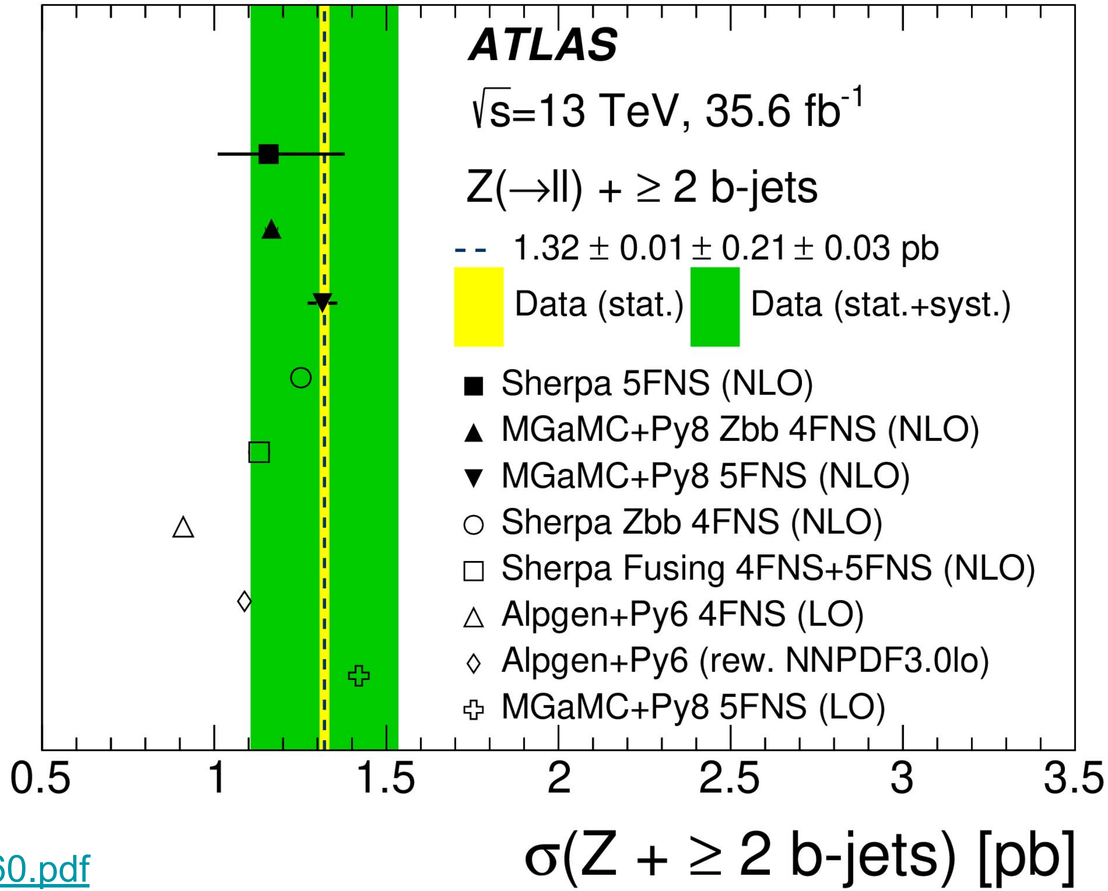
Taken from: https://arxiv.org/pdf/2006.15458.pdf

Cross section for a *Z* boson produced in association with *b*-jets

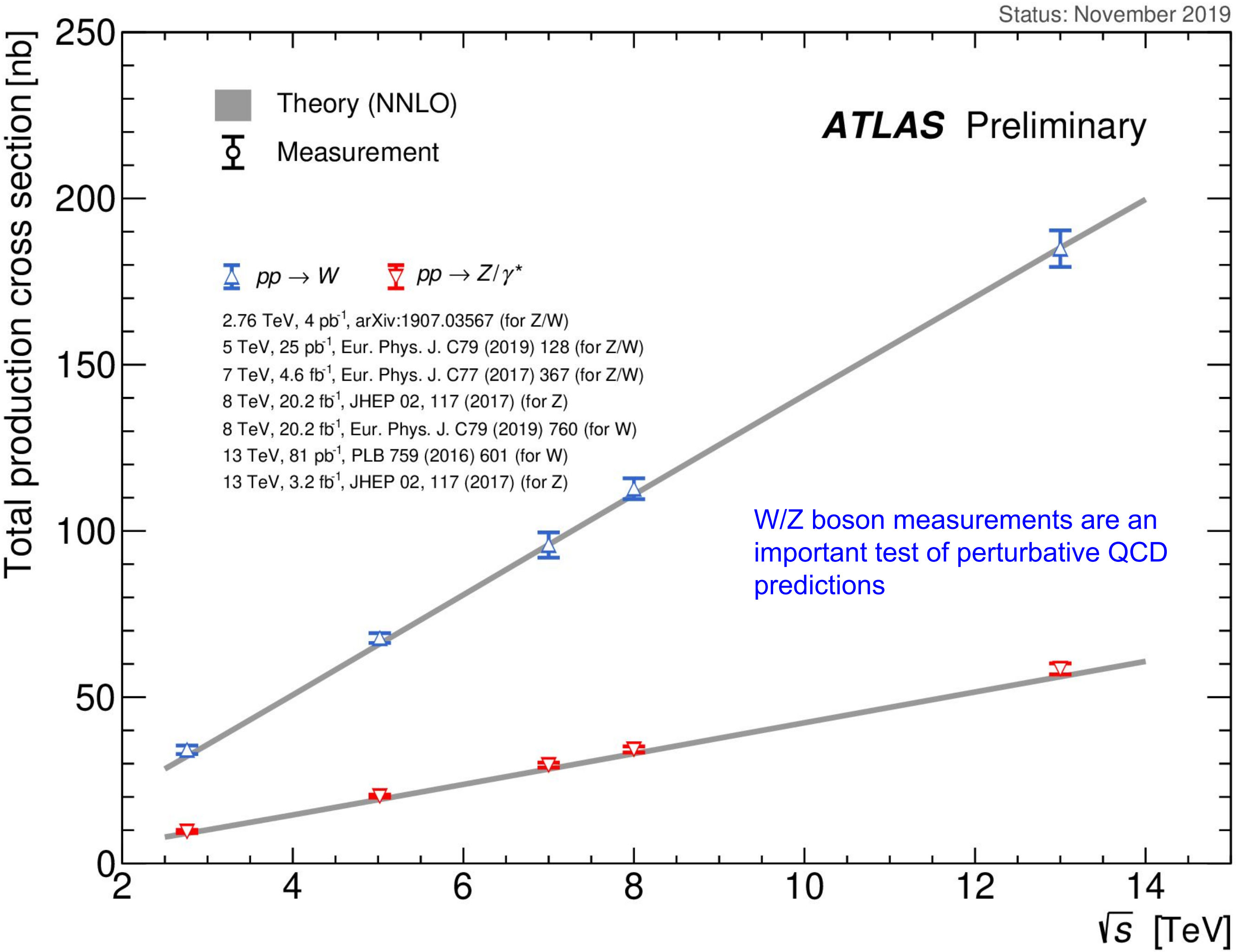
- **Test of:**
  - Perturbative QCD
  - b-quark PDF





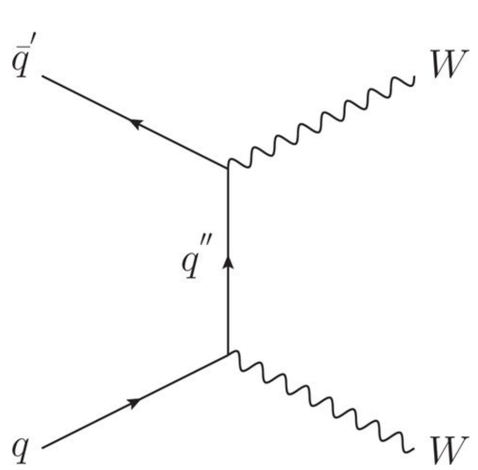


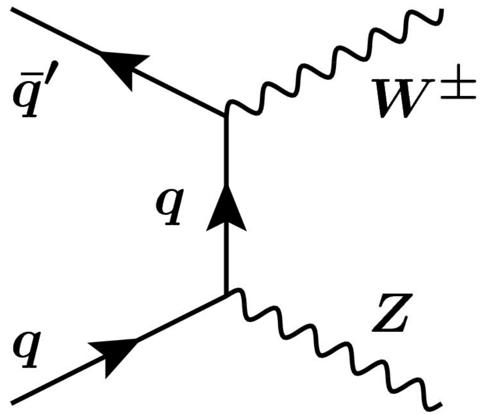
From https://arxiv.org/pdf/2003.11960.pdf

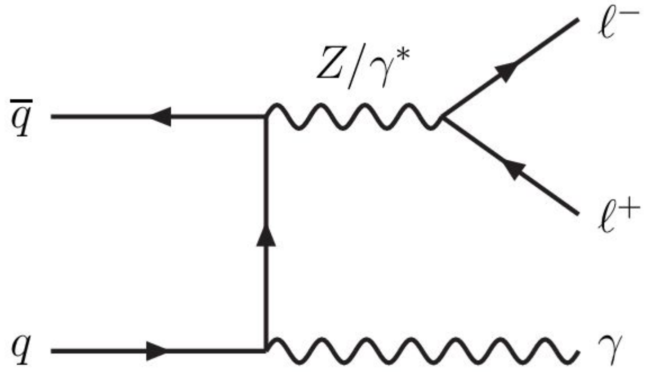


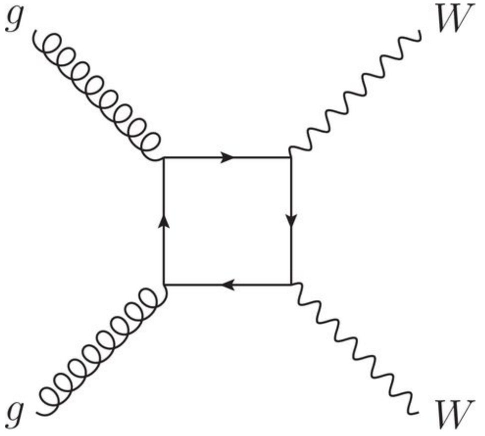
W/Z boson measurements are an important test of perturbative QCD predictions

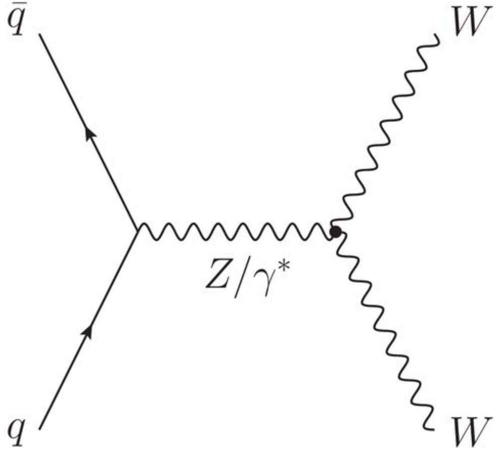
Diboson production (WW, WZ, ZZ)

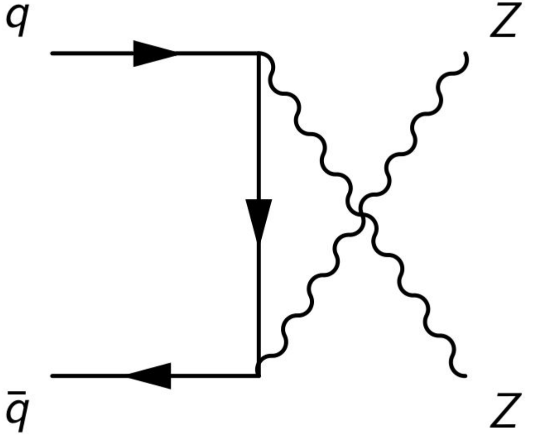


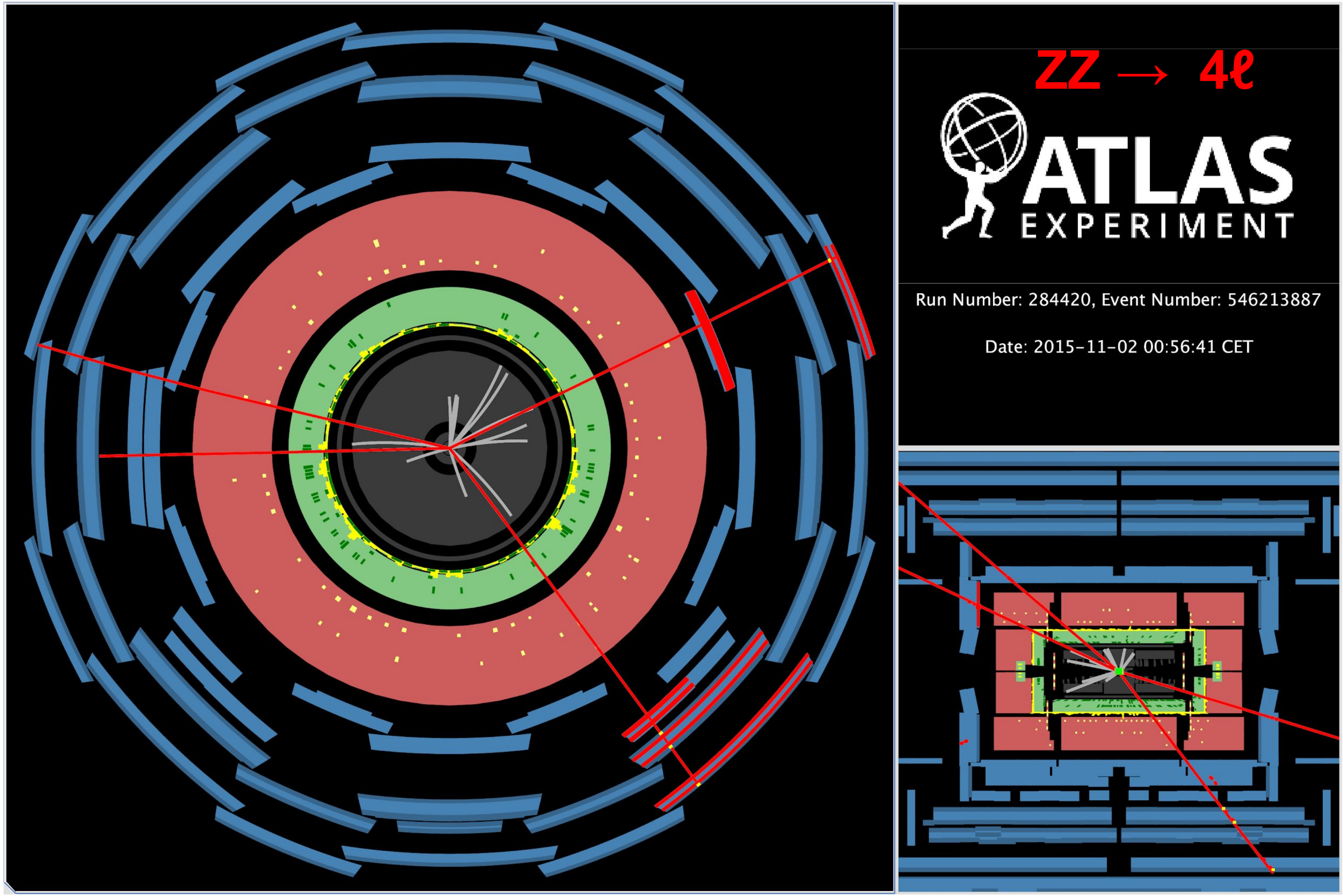




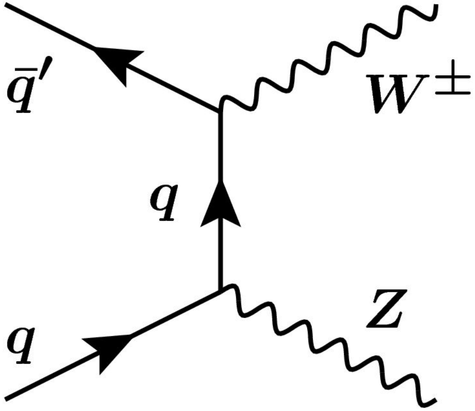


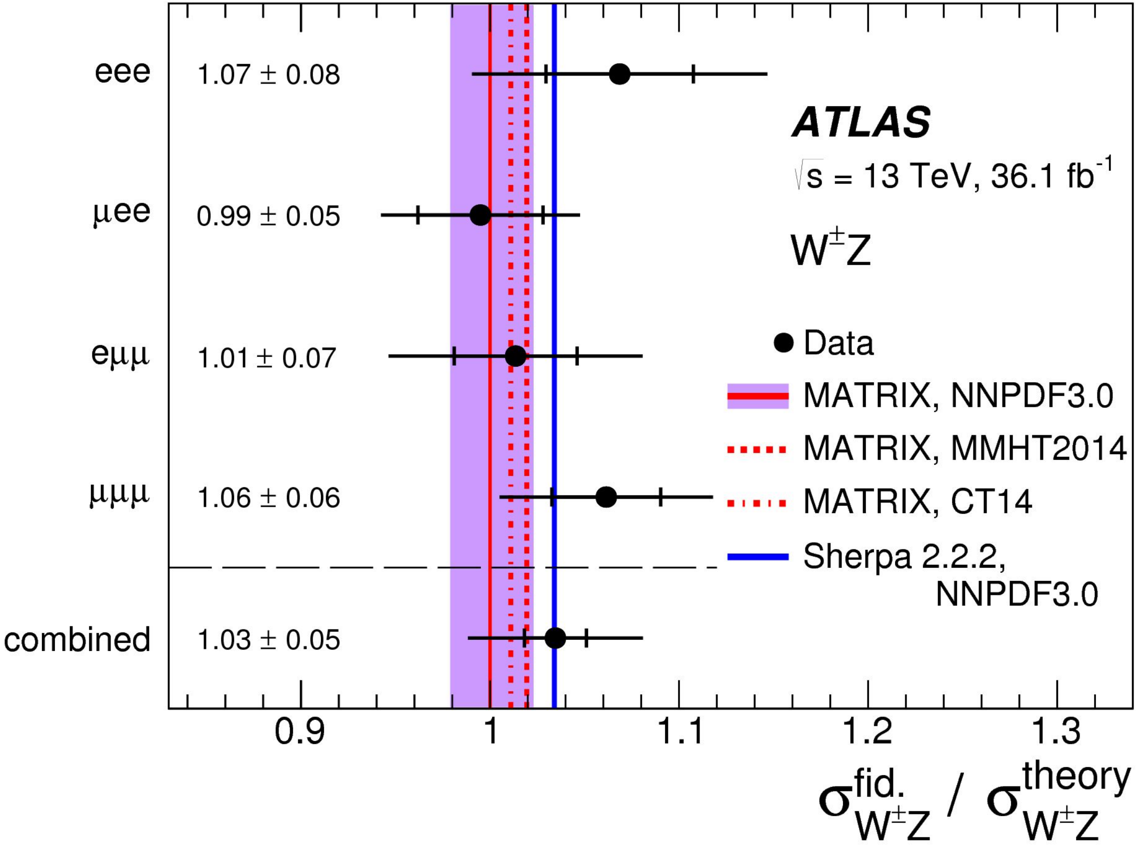





ZZ → 4ℓ
ATLAS
EXPERIMENT
Run Number: 284420, Event Number: 546213887
Date: 2015-11-02 00:56:41 CET

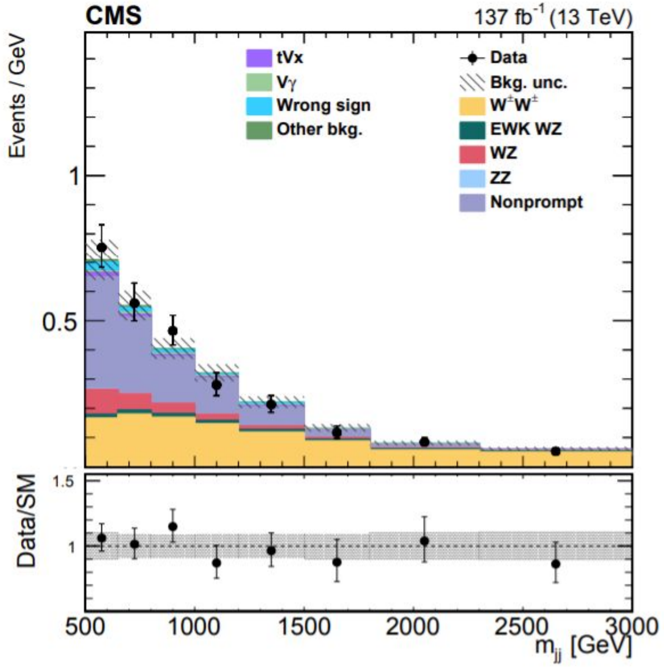
WZ production cross section measurements

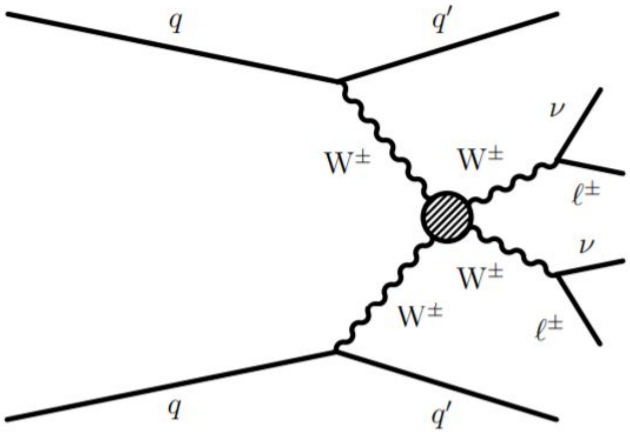




Same-sign WW boson pair production

- Insights into the mechanism of electroweak (EW) symmetry breaking can be achieved via vector boson scattering (VBS) processes
  - Via studies of vector boson self interaction
- Sensitive to anomalous quartic gauge couplings (aQGC)
- Same-sign $W^{\pm}W^{\pm}$ channel is promising due to small background yields from SM processes





σ BR($W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\ell^{\pm}$) = 3.98 ± 0.37 (stat) ± 0.25 (syst) fb

From https://arxiv.org/pdf/2005.01173.pdf

Triboson production

- Rare processes with cross sections in the order of 1pb
- Important background to Di-Higgs searches
- Test of the non-Abelian gauge structure of the SM
    - Any deviations from the SM prediction would provide hints of new physics at higher energy scales