V9 – Electroweak measurements at LEP & LHC

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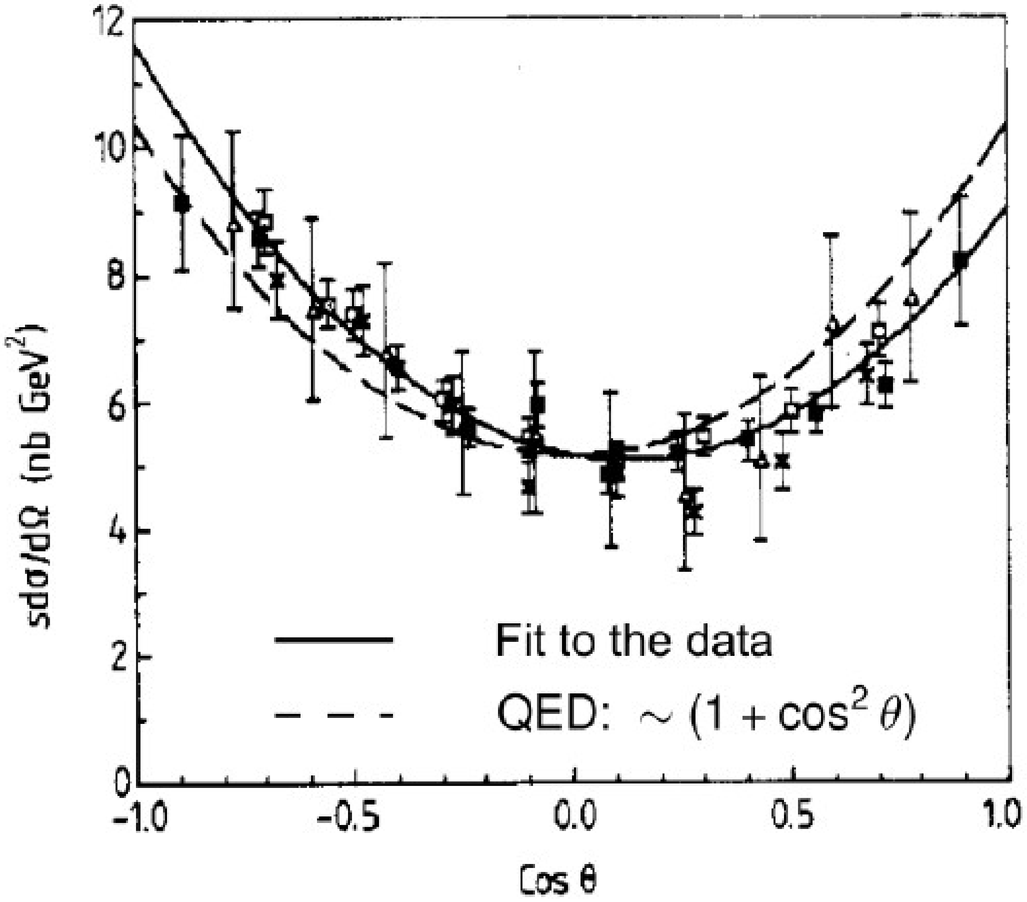
Asymmetry: First indications of Z

- **Interference** between γ^* and Z boson exchange already visible for $\sqrt{s} < m_Z$
- Example: **PETRA** (DESY)
  $\rightarrow$ first deviations from pure QED

PETRA: $\sqrt{s}$ = 29-35.5 GeV



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Asymmetries

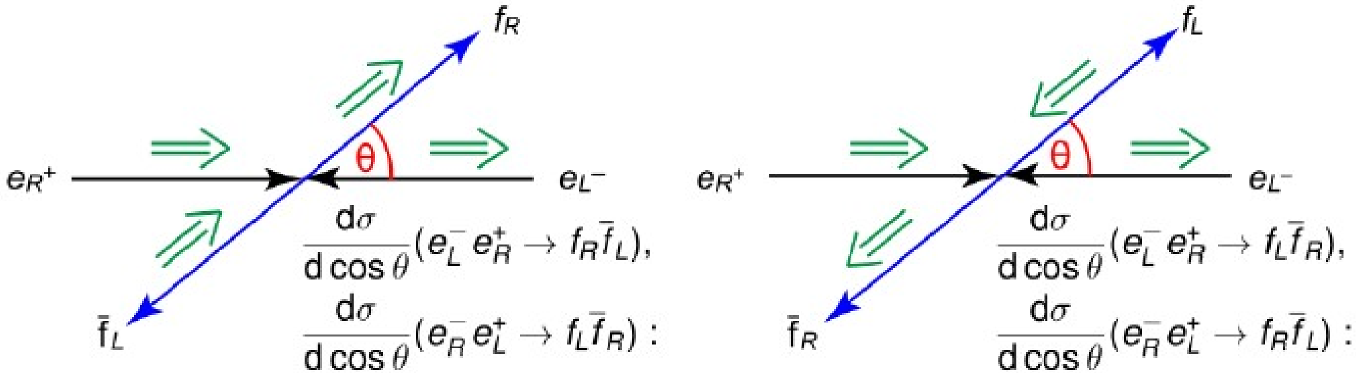
- **Generic definition:**
  - **Divide dataset into two parts X and Y**

$$A = \frac{X - Y}{X + Y}$$

- **Predict and measure asymmetry, which is a ratio!**
  - **Identical or similar backgrounds and systematic uncertainties cancel at least partially!**
  - **Improved sensitivity to small differences**

Again: Scattering angle θ

- Angular dependence from **particle spins**:



$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to f_R \bar{f}_L),\quad \frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \to f_L \bar{f}_R): \sim (1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to f_L \bar{f}_R),\quad \frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \to f_R \bar{f}_L): \sim (1+\cos\theta)^2$$

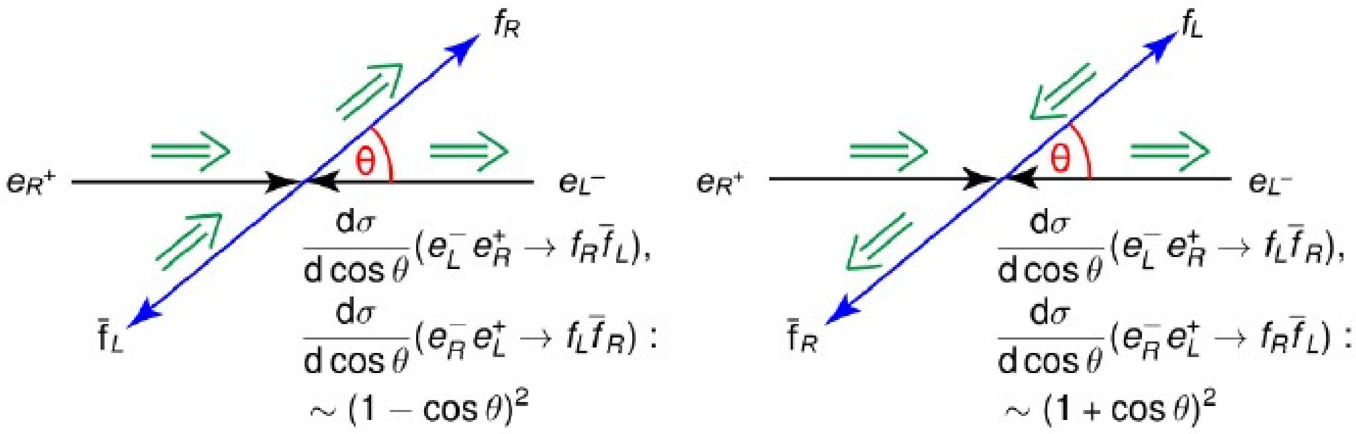
- For pure **QED process**

$$\frac{d\sigma}{d\cos\theta} = N_{C,f} Q_f^2 \frac{\pi\alpha^2}{2s}(1+\cos^2\theta)$$

$\rightarrow$ **symmetric in scattering angle**

Now with Z exchange

- Angular dependence from **particle spins**:



- For pure **Z exchange**

$$\frac{d\sigma_f}{d\cos\theta} = \frac{3}{8}\sigma_f \left[\boxed{(1 + \cos^2\theta)} + \boxed{(2A_l A_f \cos\theta)} \right]$$

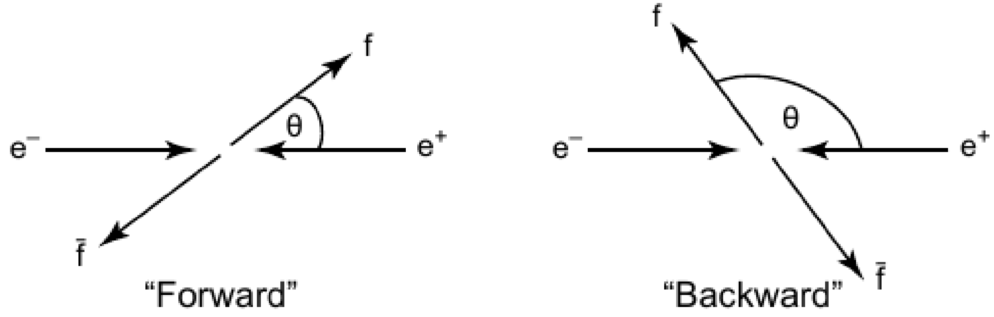
symmetric in $\cos\theta$ asymmetric in $\cos\theta$

with "**asymmetry parameter**"

$$A_f = \frac{2\, g_V^f / g_A^f}{1 + (g_V^f / g_A^f)^2} \equiv \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}, \qquad g_{L/R} = g_V \mp g_A$$

$\rightarrow$ **asymmetric in scattering angle?**

- Cross-sections depending on scattering angle of final-state fermion

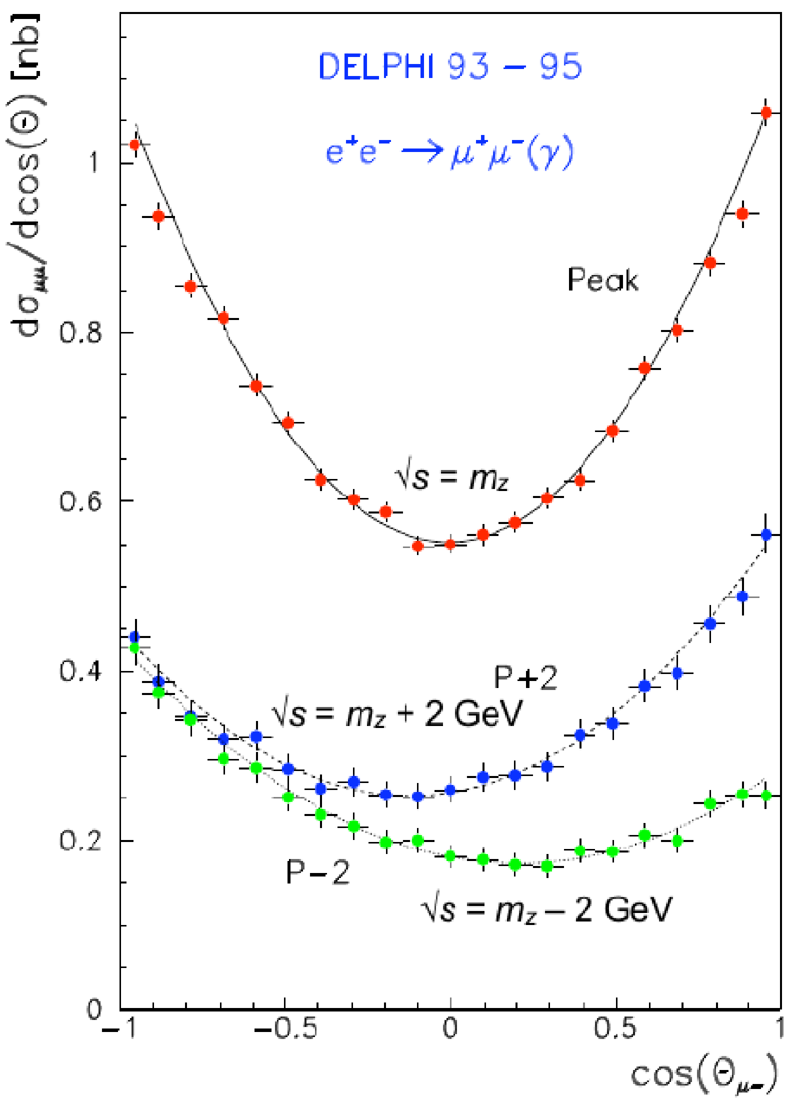


$$\sigma_F = \int_0^{\pi/2} \frac{d\sigma}{d\cos\theta} d\theta\,, \quad \sigma_B = \int_{\pi/2}^{\pi} \frac{d\sigma}{d\cos\theta} d\theta$$

- **Forward-backward asymmetry**

$$\boxed{A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \ldots = \frac{3}{4} A_e A_f}$$

LEP: √s = m_Z ± 2 GeV



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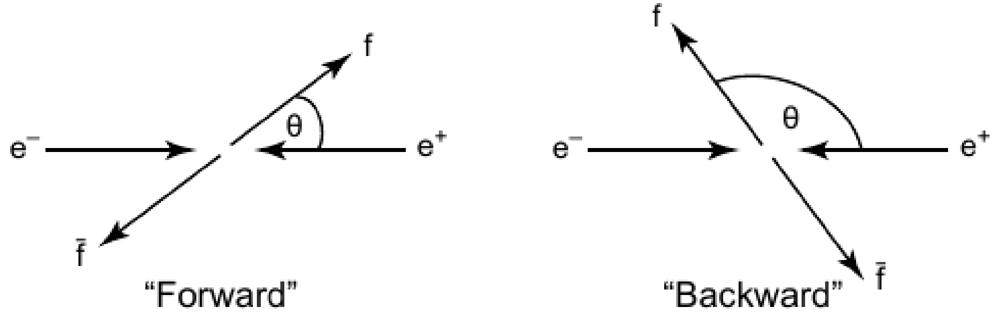

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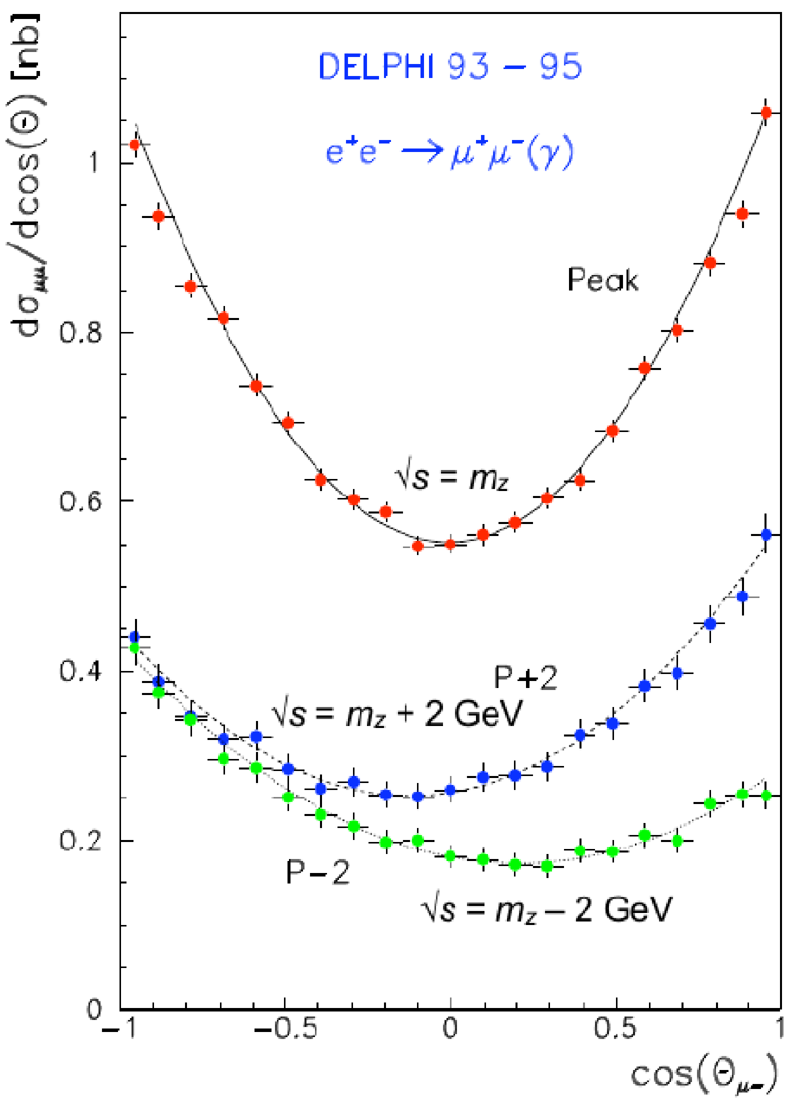
- **Forward-backward asymmetry**

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \ldots = \frac{3}{4} A_e A_f$$

We'll come back to that later for $\sin^2\theta_W$ ...

LEP: $\sqrt{s} = m_Z \pm 2$ GeV



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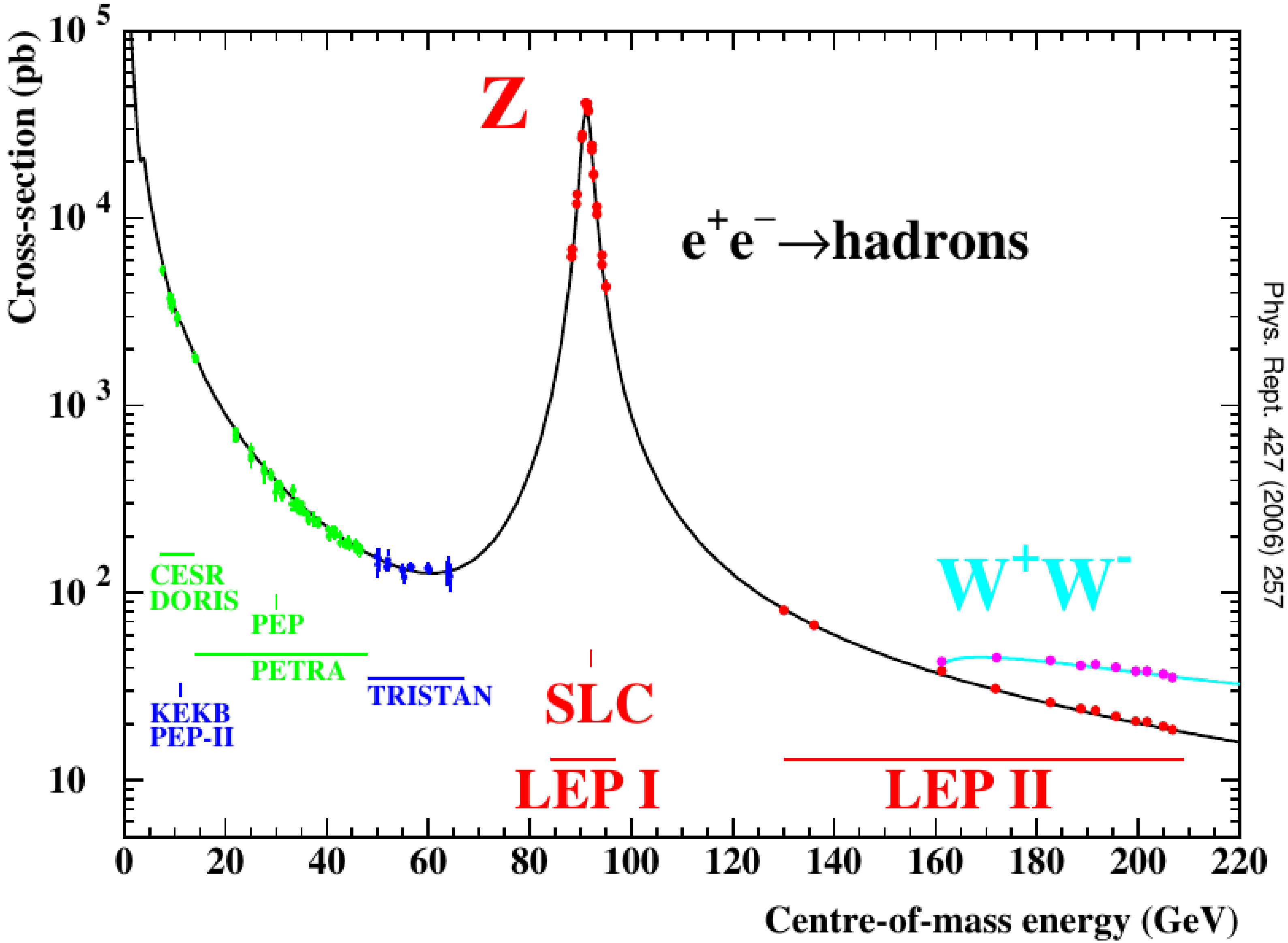
Z pole



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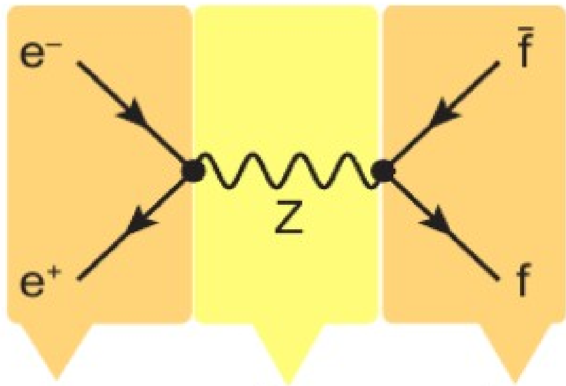
Pole ~ infinity !?

For $\sqrt{s} \approx m_Z$: Z boson exchange dominates



$$\mathcal{M} \sim \frac{g^2}{(2\cos\theta_W)^2} J^e_{NC,\mu} \frac{ig^{\mu\nu}}{s - m_Z^2 + is\frac{\Gamma_Z}{m_Z}} J^f_{NC,\nu}$$

Propagator: Z boson **unstable** → **resonance** in scattering amplitude

- Wave function for stable particle at rest: $\psi \sim \exp[-imt]$
- Unstable particle: $\psi^*\psi \sim \exp\left[-\frac{t}{\tau}\right] = \exp[-\Gamma t] \quad \rightarrow \quad \psi \sim \exp[-imt]\exp\left[-\frac{\Gamma t}{2}\right]$
- **Decay width** = inverse of lifetime: $\Gamma = 1/\tau$
- **Breit-Wigner** prescription: in the propagator, **replace *m* by *m* – iΓ/2** (quantum field theory: scattering amplitude contains **pole** in complex plane)

Decay width of Z boson

Total width Γ_Z of the Z resonance:

- Sum of **partial (decay) width**
- Consider all possible Z-boson decays in the standard model:
  5 quarks (top quark too heavy), 3 charged leptons, 3 neutrinos

$$\Gamma_Z = \sum_f \Gamma_f = \sum_{q=u,d,s,c,b} \Gamma_q + \sum_{\ell=e,\mu,\tau} \Gamma_\ell + \sum_{\nu=\nu_e,\nu_\mu,\nu_\tau} \Gamma_\nu$$

Partial widths Γ_f (standard model in leading order):

$$\Gamma_f = \Gamma(Z \to f\bar{f}) = N_{C,f} \frac{G_F m_Z^3}{6\sqrt{2}\pi} \left[(g_V^f)^2 + (g_A^f)^2 \right] \text{ with } g_V^f = I_{3,f} - 2Q_f \sin^2\theta_W,\ g_A^f = I_{3,f}$$

→ Measure **quadratic sum** of vector couplings and axial vector couplings

Lepton universality:

- Same decay width for all charged leptons: $\Gamma_e = \Gamma_\mu = \Gamma_\tau \equiv \Gamma_\ell$
- Same decay width for all neutrinos: $\Gamma_{\nu_e} = \Gamma_{\nu_\mu} = \Gamma_{\nu_\tau} \equiv \Gamma_\nu$

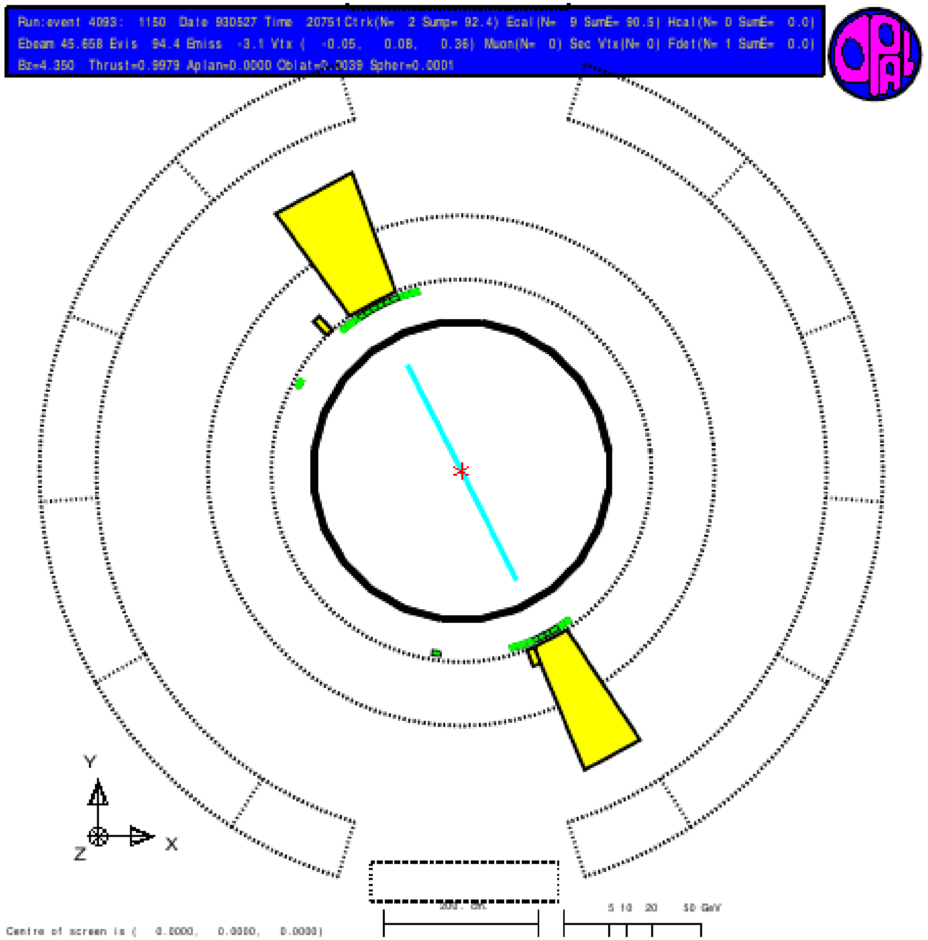
!!! Γ_τ recieves a mass correction !

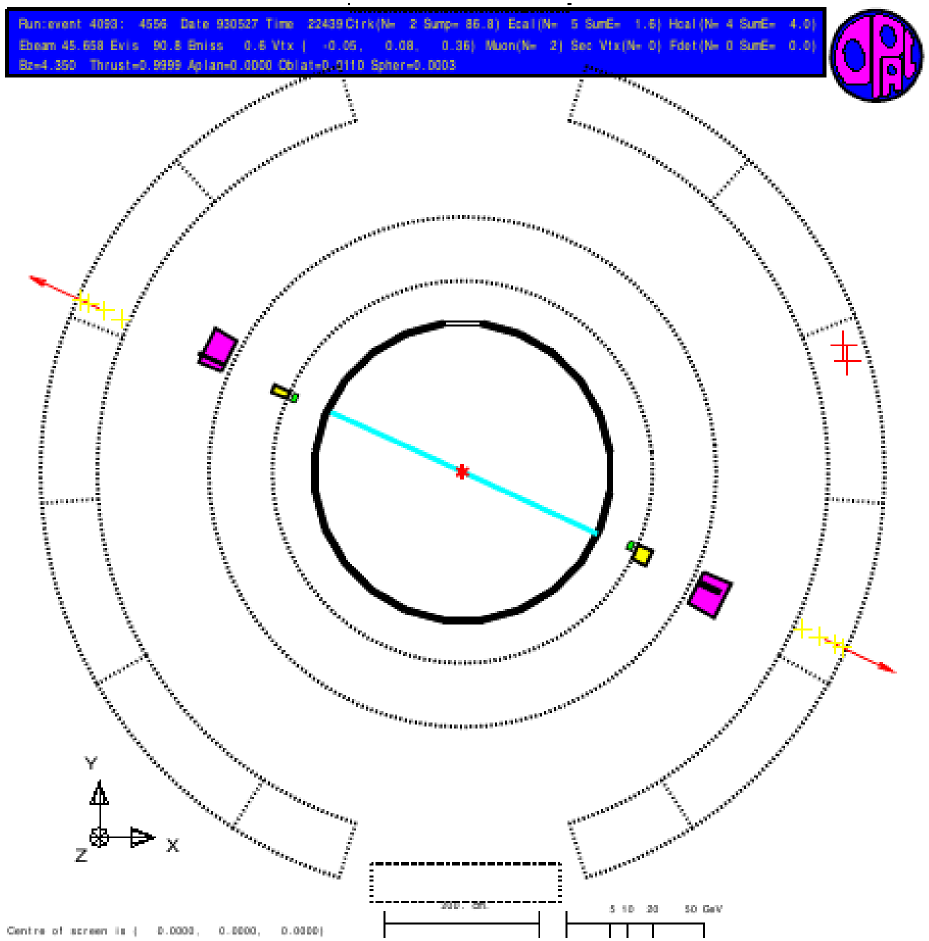
Z boson decay channels

Particle	Branching Fraction (PDG 2017)	Detection at Colliders
Left-handed neutrinos	20.00(06)% in total	No direct detection
Left-handed and right-handed charged leptons	3.3658(23)% each	e, μ "simple" τ: depends on decay
Left-handed and right-handed up-type quarks (u,c) in three colors	11.6(6)% each	Jets = collimated bundles of hadrons
Left-handed and right-handed down-type quarks (d,s,b) in three colors	15.6(4)% each	Jets = collimated bundles of hadrons

Example events from OPAL

Can you identify and explain what is produced?





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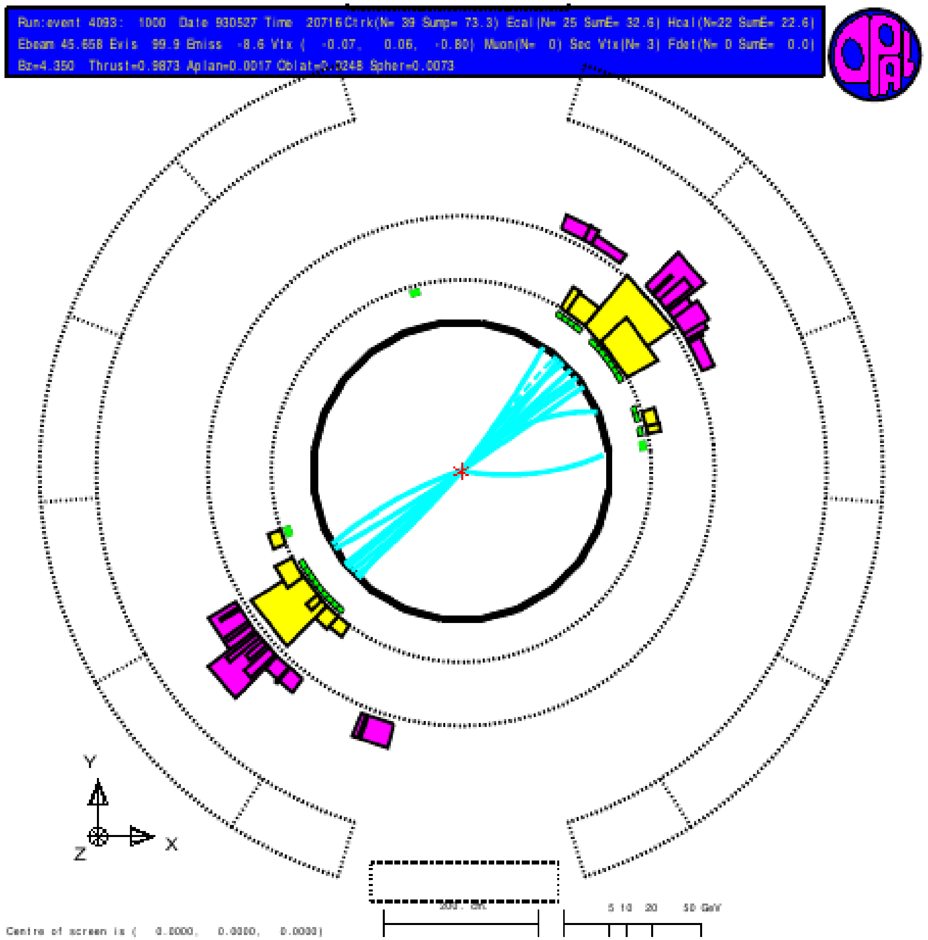
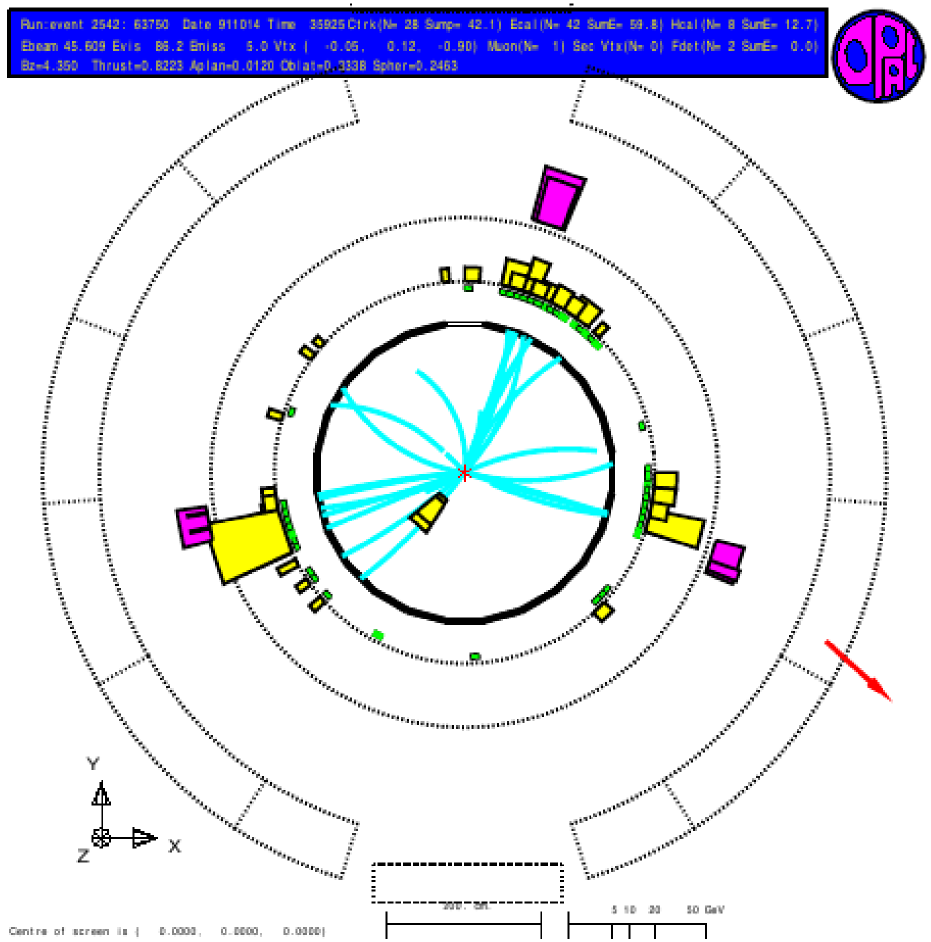




Z resonance

Parametrerization of the cross section around the Z-pole

(neglecting γ contributions)

$$\sigma_f = \underbrace{\frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}}_{\sigma_f^0} \cdot \underbrace{\frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\frac{\Gamma_Z^2}{m_Z^2}}}_{\text{Breit-Wigner}}$$

Note: s-dependent width is a special choice at LEP !

Resonance peak **height**: $\sigma_f^0 \sim \Gamma_e\Gamma_f$

- Measure of **product of partial decay widths**, e.g. $\sigma_{had}^0 \sim \Gamma_e\Gamma_{had}$
- Determine **single** partial widths: combine certain **ratios** of cross sections

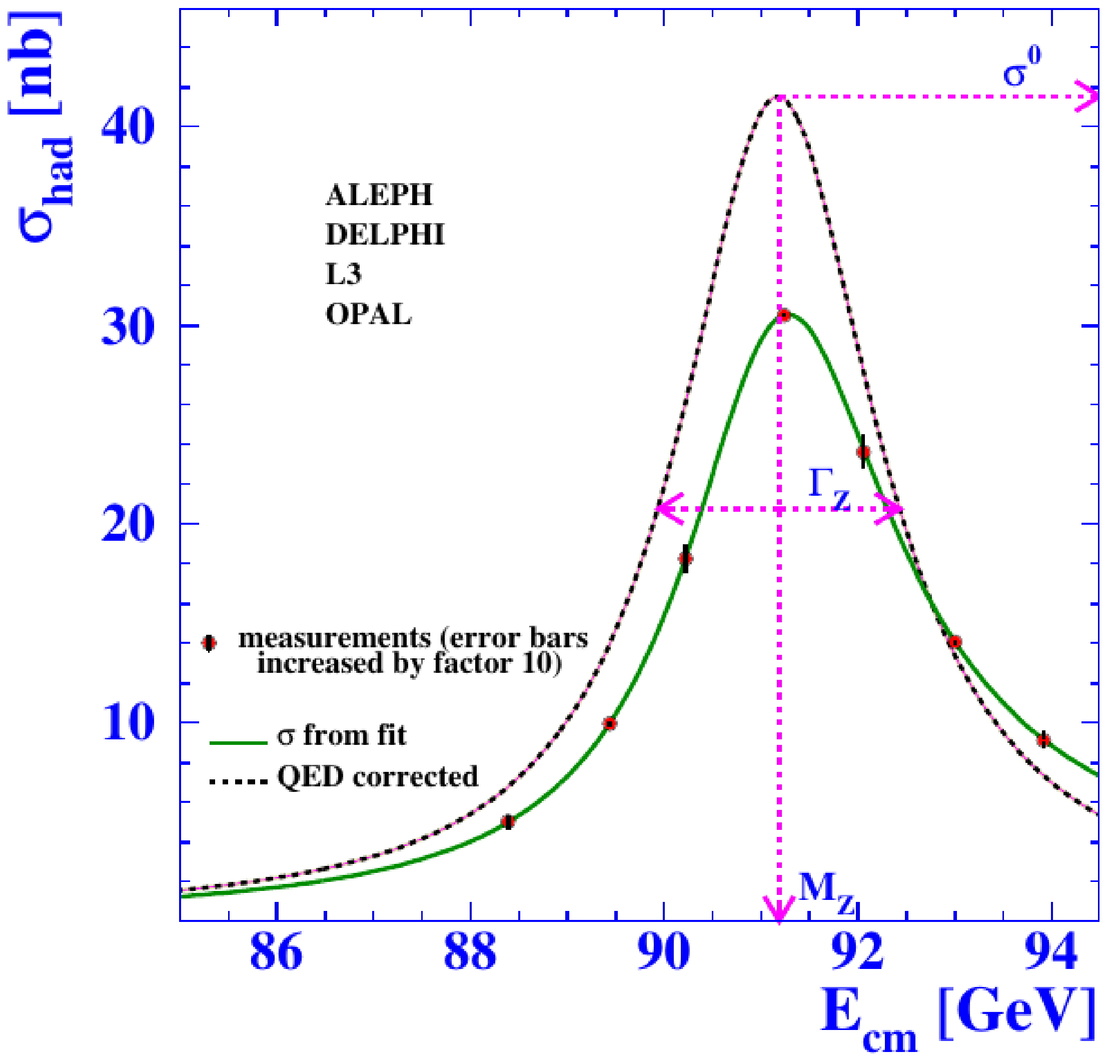
Resonance shape depends on number of neutrino generations:

- Partial decay with to neutrinos is invisible in the detector, but contribues to Γ_Z
- with three neutrino generations: $\Gamma_{inv} = \Gamma_{\nu_e} + \Gamma_{\nu_\mu} + \Gamma_{\nu_\tau} = 3\Gamma_\nu$
- assume there are more (or fewer) neutrino generations:
  - $\rightarrow$ height and width of the reconance would change

Hadronic coss section

- **Shape** of Z resonance
  - **Energy scan**: vary $\sqrt{s}$
  - Selection: $Z \to \bar{q}q$

  $\to$ **hadronic cross section** σ_{had}
- Correct generic fit to data for QED radiative corrections
- (Pseudo-)Observables
  - **Position** of resonance $\to m_Z$
  - **Height** of resonance $\to \sigma^0_{\text{had}}$
  - **Width** (FWHM) $\to \Gamma_Z$



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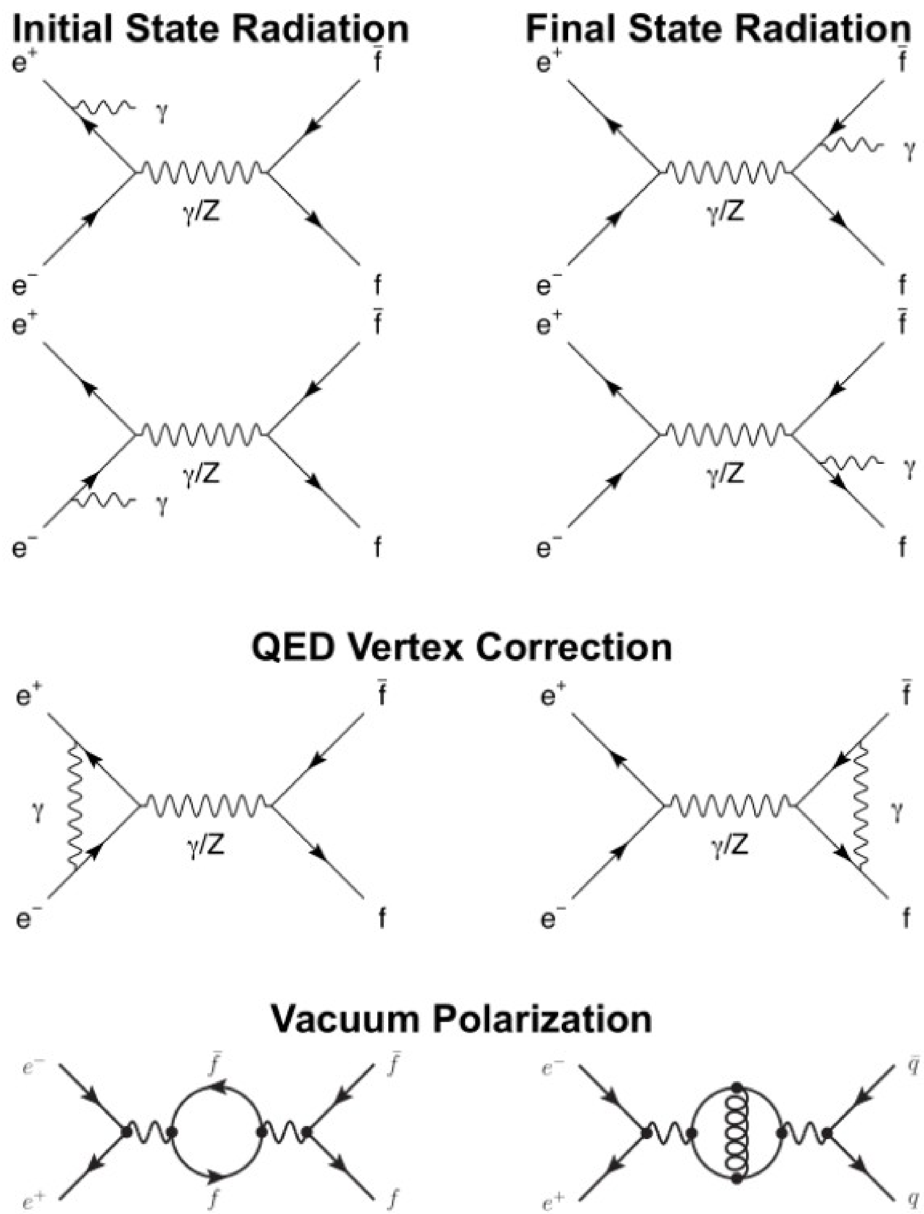
- Precision of LEP and SLC data: sensitive to **higher-order corrections**
  - **Real emission** of photons and **loop corrections**
- Consequence: running coupling constant

$$\alpha(m_Z^2) \approx \frac{1}{128} > \alpha \approx \frac{1}{137}$$



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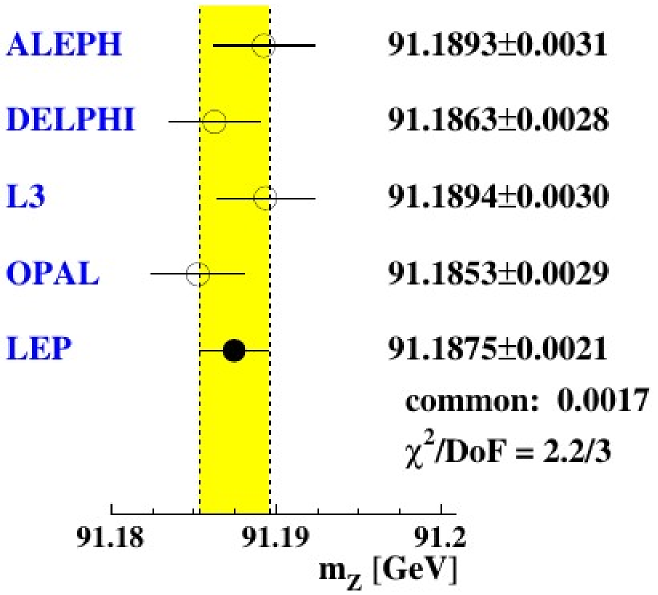
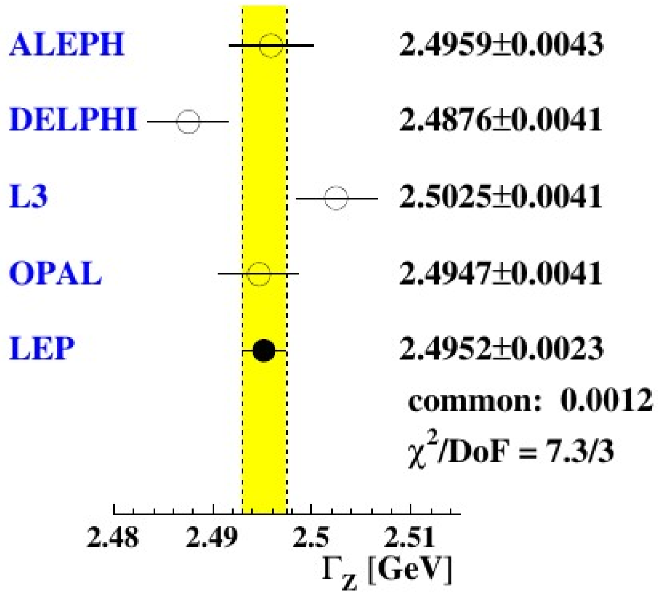
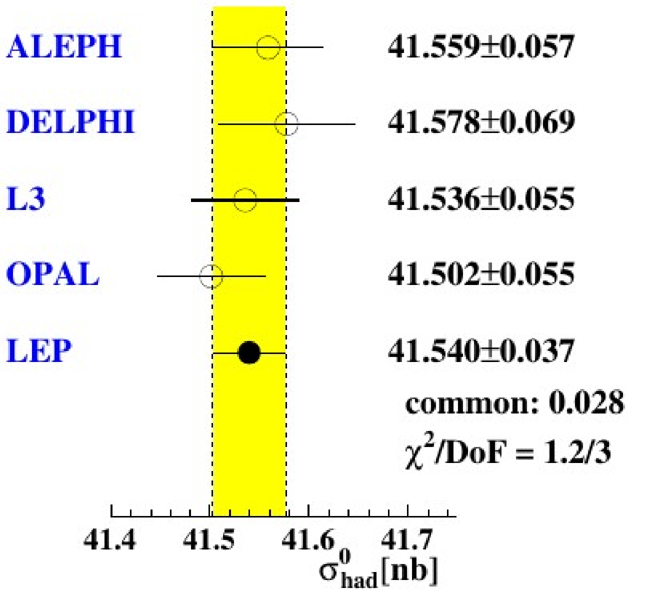






Combination of LEP results

relative uncertainty:

Z boson mass:	$2.3 \cdot 10^{-5}$
Z boson width:	$9.2 \cdot 10^{-4}$
Cross section:	$8.9 \cdot 10^{-4}$

Final measurements of the Z resonance shape at LEP

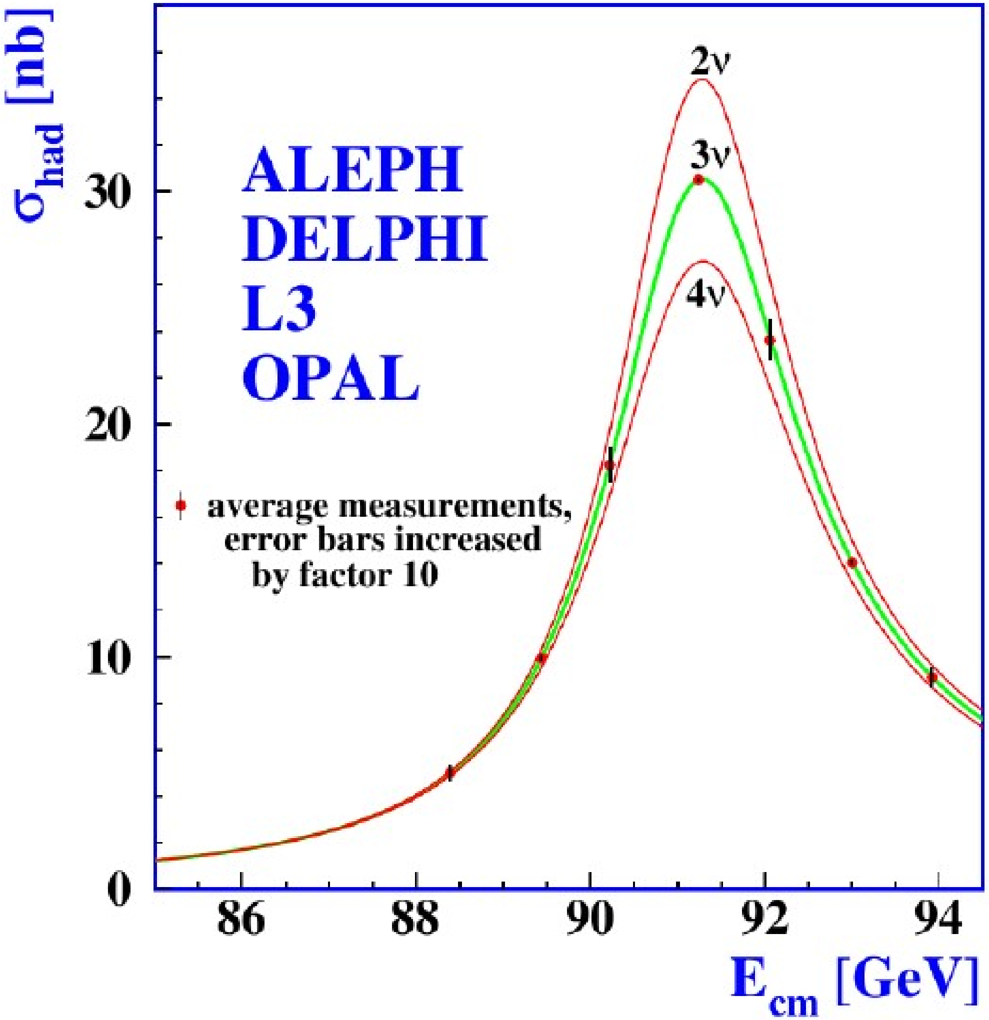
curves assuming 2, 3 or 4 neutrino flavours are also shown

clearly confirms that there are three light neutrino generations

Measurement of the number of light neutrino generations was the first exciting results from LEP and SLC.

very robust observable:

$$R^0_{\rm inv} \equiv \frac{\Gamma_{\rm inv}}{\Gamma_{ll}} = N_\nu \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{ll}}\right)_{\rm SM}$$



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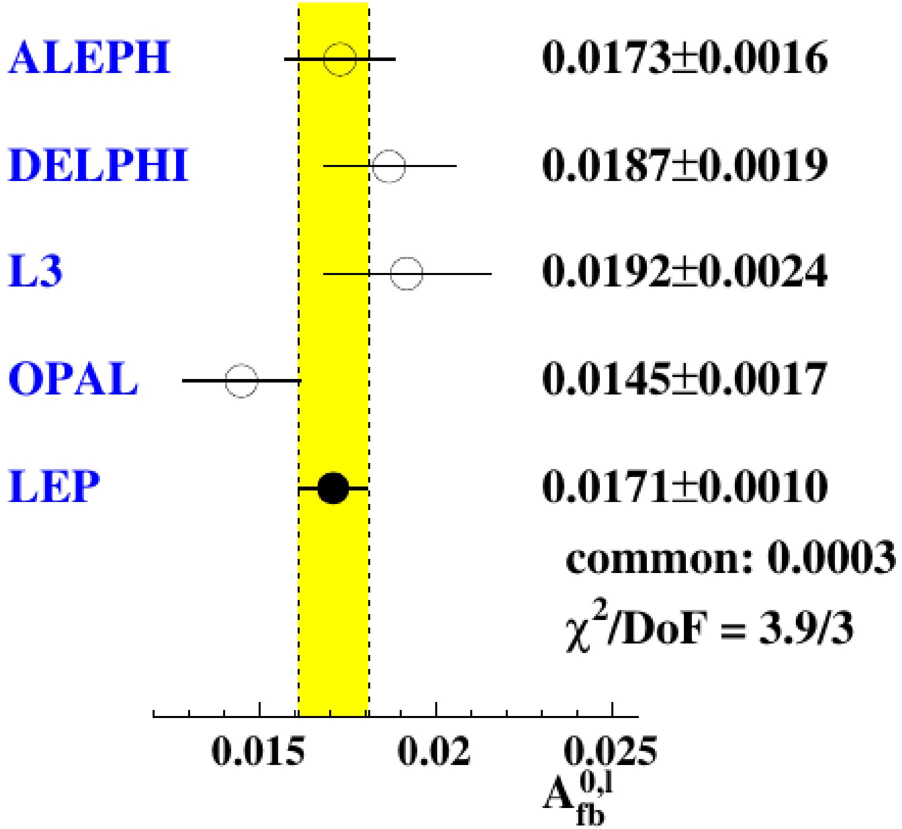
best value today:

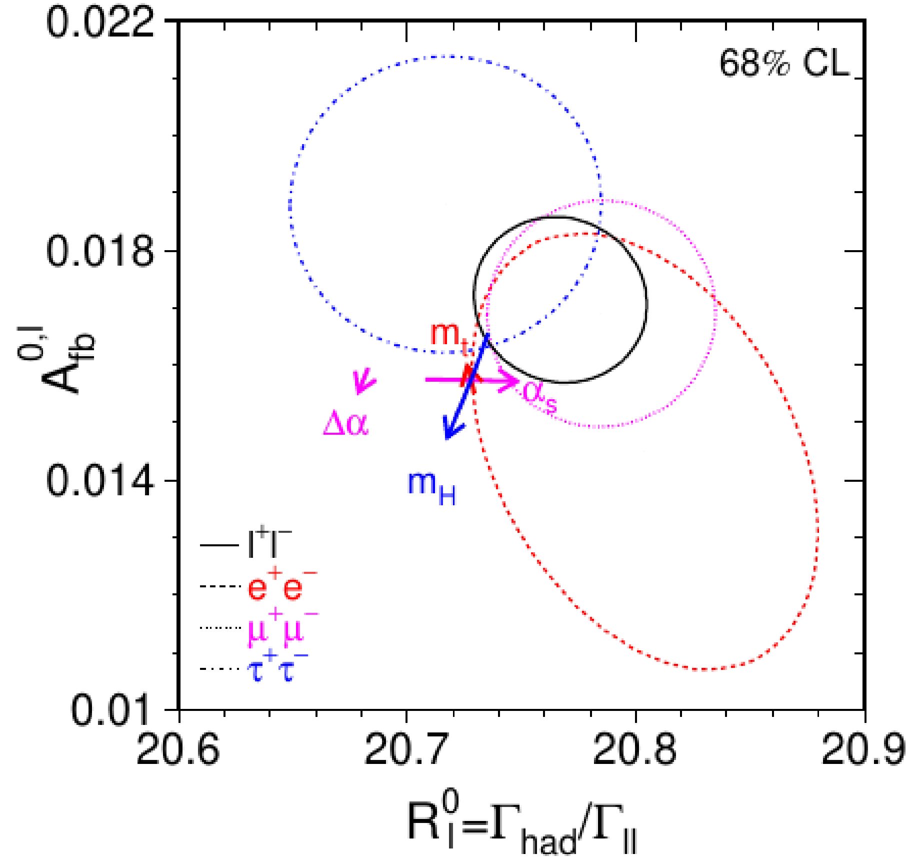
$$N_\nu = 2.9840 \pm 0.0082$$

Asymmetry: A_{FB} LEP results

LEP average: A_{FB} for leptons



A_{FB} separately for e, μ, τ vs. R^0



$\rightarrow$ test of lepton universality

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Weak mixing angle

- Electroweak theory: (effective) weak mixing angle

$$\sin^2 \theta^{\mathrm{f}}_{W,\mathrm{eff}} = \boxed{\frac{I_{3,\mathrm{f}}}{2Q_\mathrm{f}}\left(1 - \frac{g^\mathrm{f}_V}{g^\mathrm{f}_A}\right)} = \boxed{\left(1 - \frac{m^2_\mathrm{W}}{m^2_\mathrm{Z}}\right)}$$

LEP, SLC, ν LEP, SLC, TeV, LHC

  - Non-trivial **dependence on radiative corrections** absorbed in "effective" quantity

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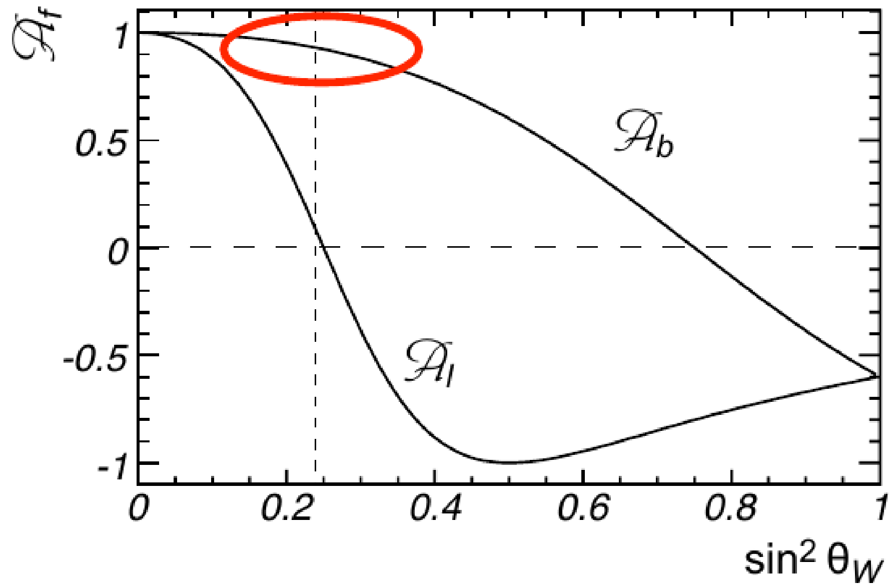
LEP, SLC, ν LEP, SLC, TeV, LHC

  - Non-trivial **dependence on radiative corrections** absorbed in "effective" quantity

- LEP and SLC: $\sin^2\theta_W$ from A_{FB}

$$A^f_{FB} = \frac{3}{4}A_e A_f \text{ with } A_f = \frac{2\,g^f_V/g^f_A}{1+(g^f_V/g^f_A)^2}$$

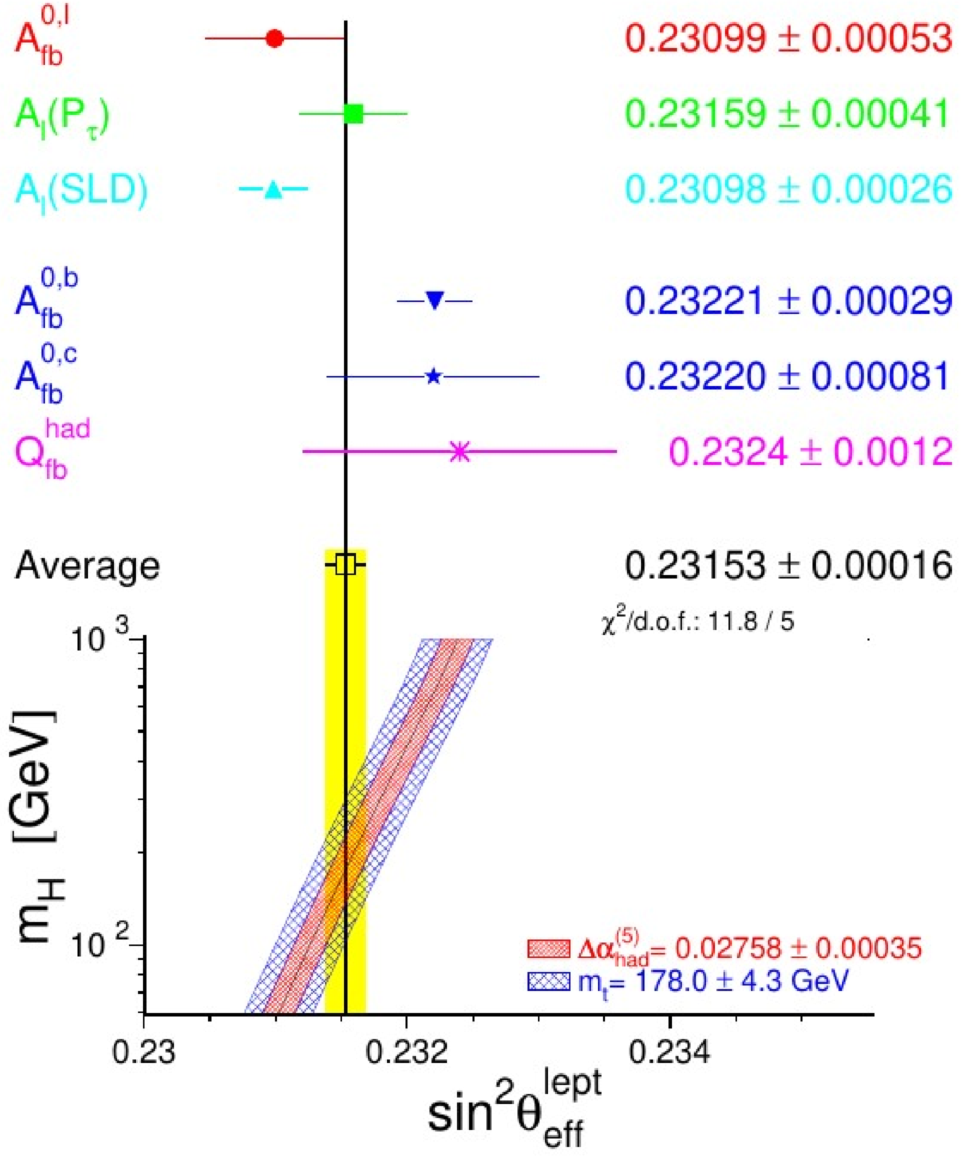
  - **Leptons**: A_l very sensitive to $\sin^2\theta_W$
  - **Down-type quarks**: only weak dependence of A_q on $\sin^2\theta_W$
  - Experimentally: only down-type quarks can be identified (**b tagging**)



Weak mixing angle: LEP/SLD

- Compare different channels
  - **Most precise: A_{FB}^{b}**
  - 3.2 σ discrepancy between leptonic and hadronic final states!
- Additional 3.2 σ deviation: neutrino-nucleon scattering (NuTeV)

Unresolved. . .



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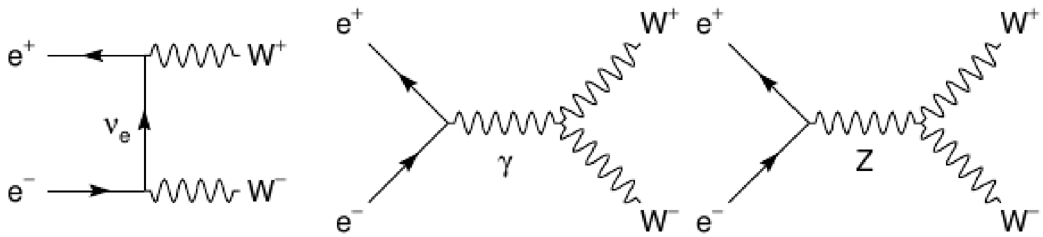
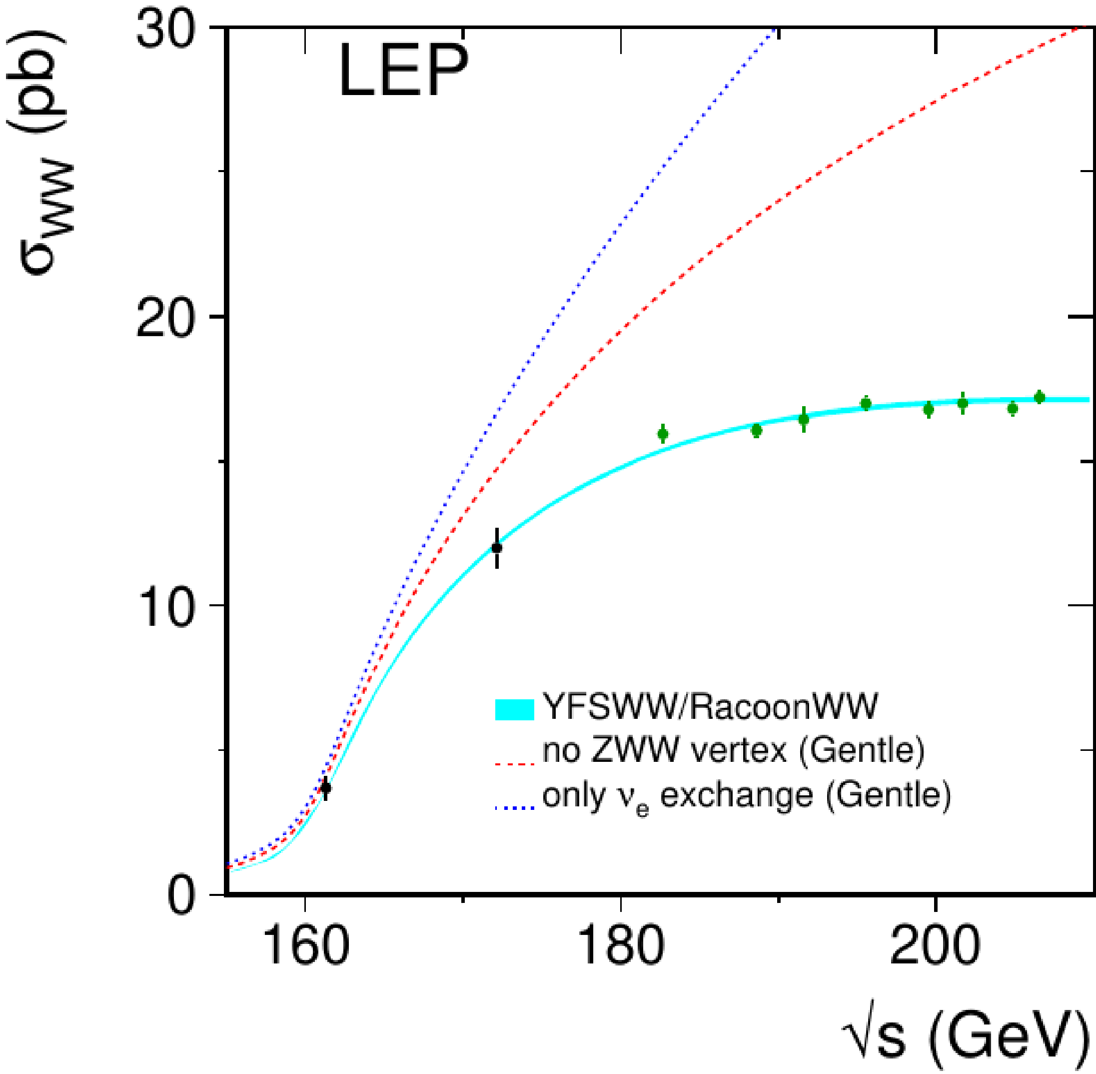
WW production at LEP 2

- W^+W^--pair production at e^+e^- colliders



  - Kinematic **production threshold**: $\sqrt{s} \geq 2m_W$
  - **Pair production**: cross section reaches **plateau** (no peak!)



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- Threshold scan: scattering matrix only unitary if both ν exchange and triple-gauge-boson vertex (ZWW) are considered

Global electroweak fits

- **Free parameters of Standard Model Lagrangian**
  - Gauge couplings: 3 ($\alpha_{\text{em}}, \alpha_{\text{weak}}, \alpha_{\text{s}}$)
  - Higgs potential: 2
  - Fermion masses/Yukawa couplings: 9 (neglect neutrino masses)
  - Quark-mixing matrix: 4
  - Neutrino-mixing matrix: 4

  $\rightarrow$ 14–22 free parameters

- But **many more independent properties measured**

  $\rightarrow$ constraints of SM parameters

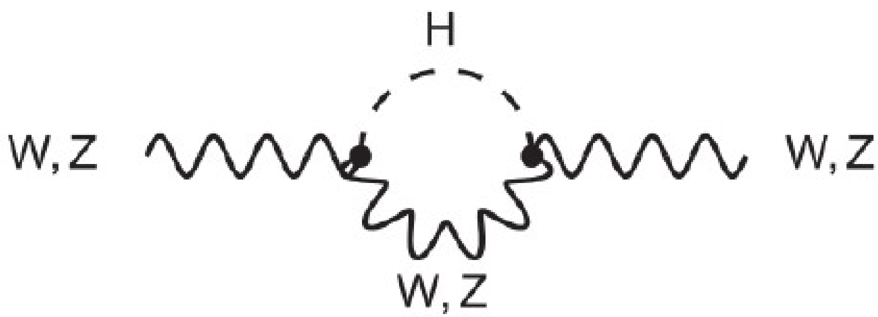
  (each property: different superposition of SM parameters)
  - Allows prediction of unmeasured quantities,
    e. g. top-quark mass before 1995, Higgs-boson mass before 2012

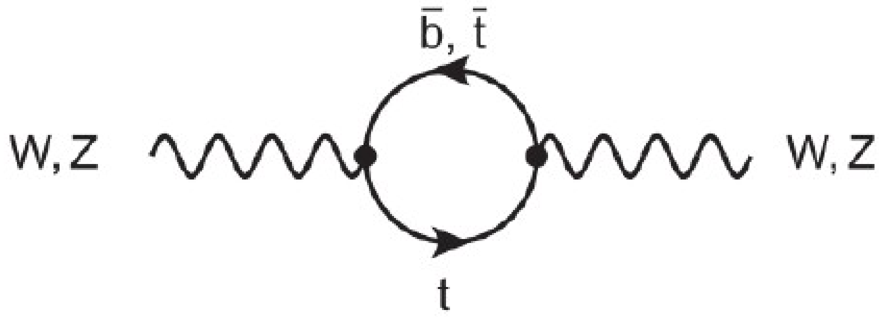
Interdependencies in fits

- Predictions of **electroweak theory**
  - Interdependence of W and Z masses via weak mixing angle

$$m_W \equiv \frac{1}{2} g v \,, \quad m_Z \equiv \frac{1}{2}\sqrt{g^2 + g'^2}\, v \quad \rightarrow \quad \rho = \frac{m_W}{m_Z \cos\theta_W} = 1$$

  - Interdependence with masses of Higgs boson and top quark via loop corrections





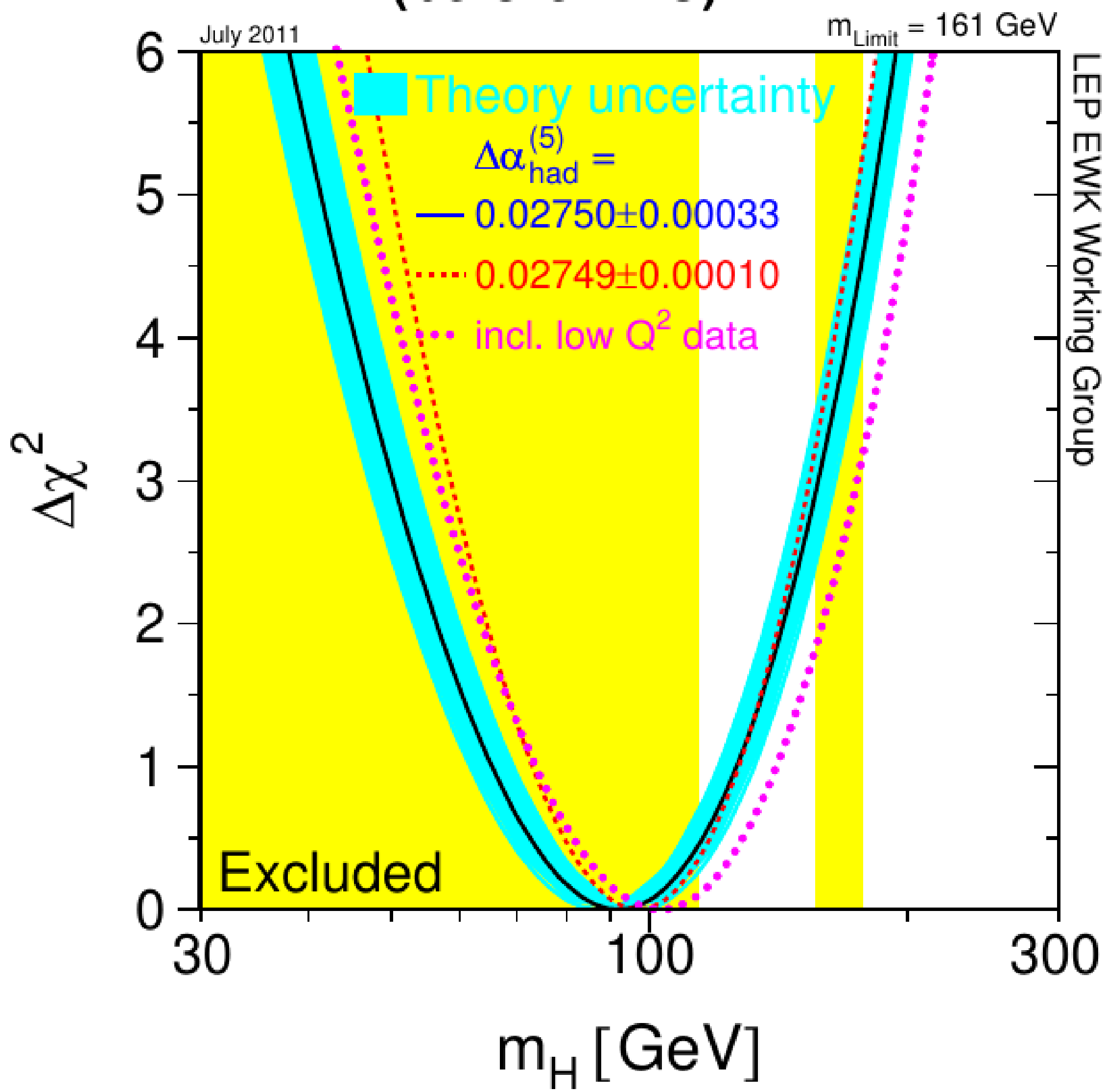
$\sim g' \ln(m_H / m_W)$

Weak dependence (logarithmic)

$\sim G_F\, m_t^2$

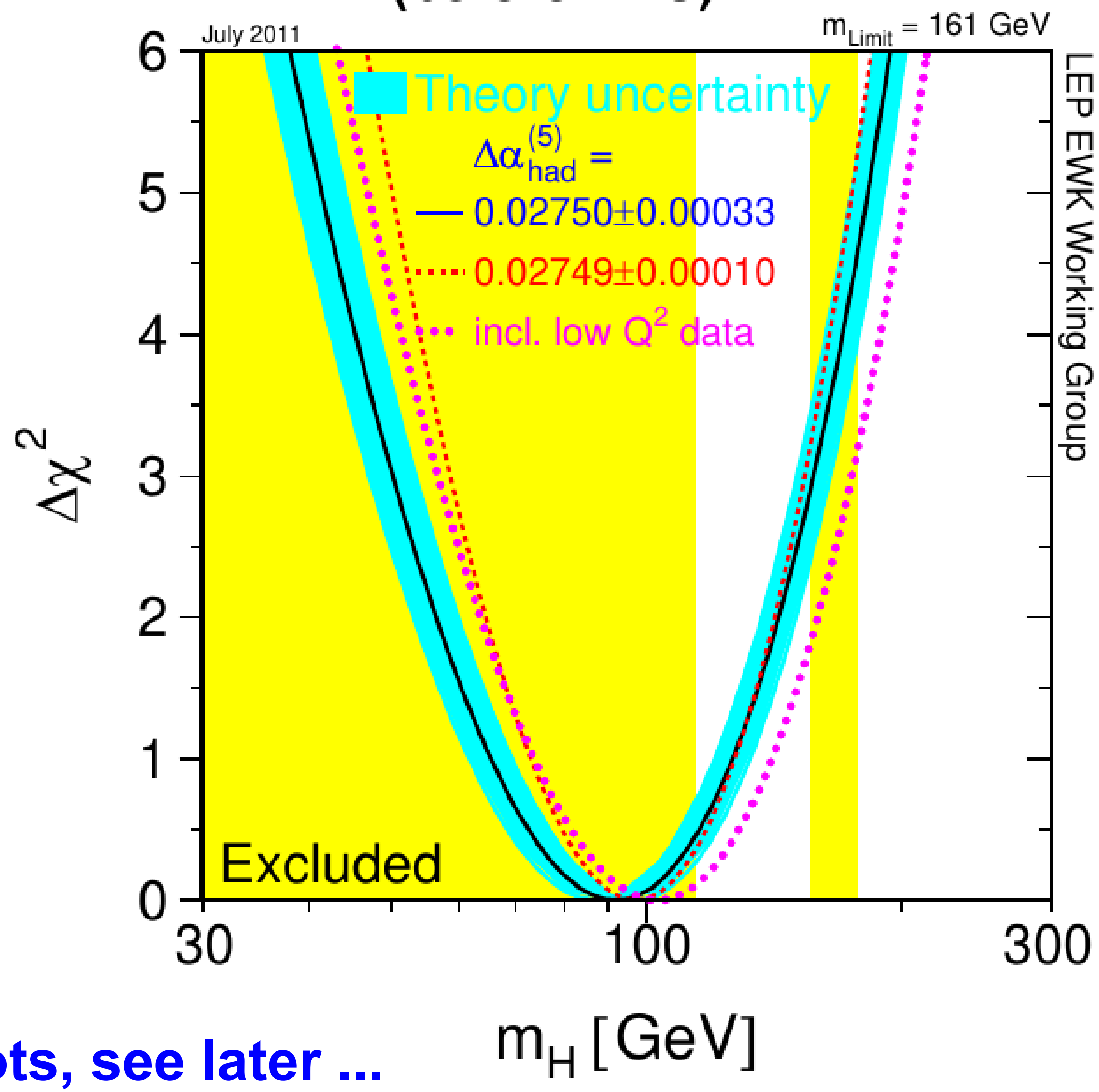
Strong dependence (quadratic)

"Blue Band Plot": Higgs mass limits (before LHC)



- Best-fit Higgs-boson mass: $\boldsymbol{m_H = 94^{+29}_{-25}}$ **GeV**
  - **Light** Higgs boson preferred
- **Logarithmic** dependence: m_H only weakly constrained

"Blue Band Plot": Higgs mass limits (before LHC)



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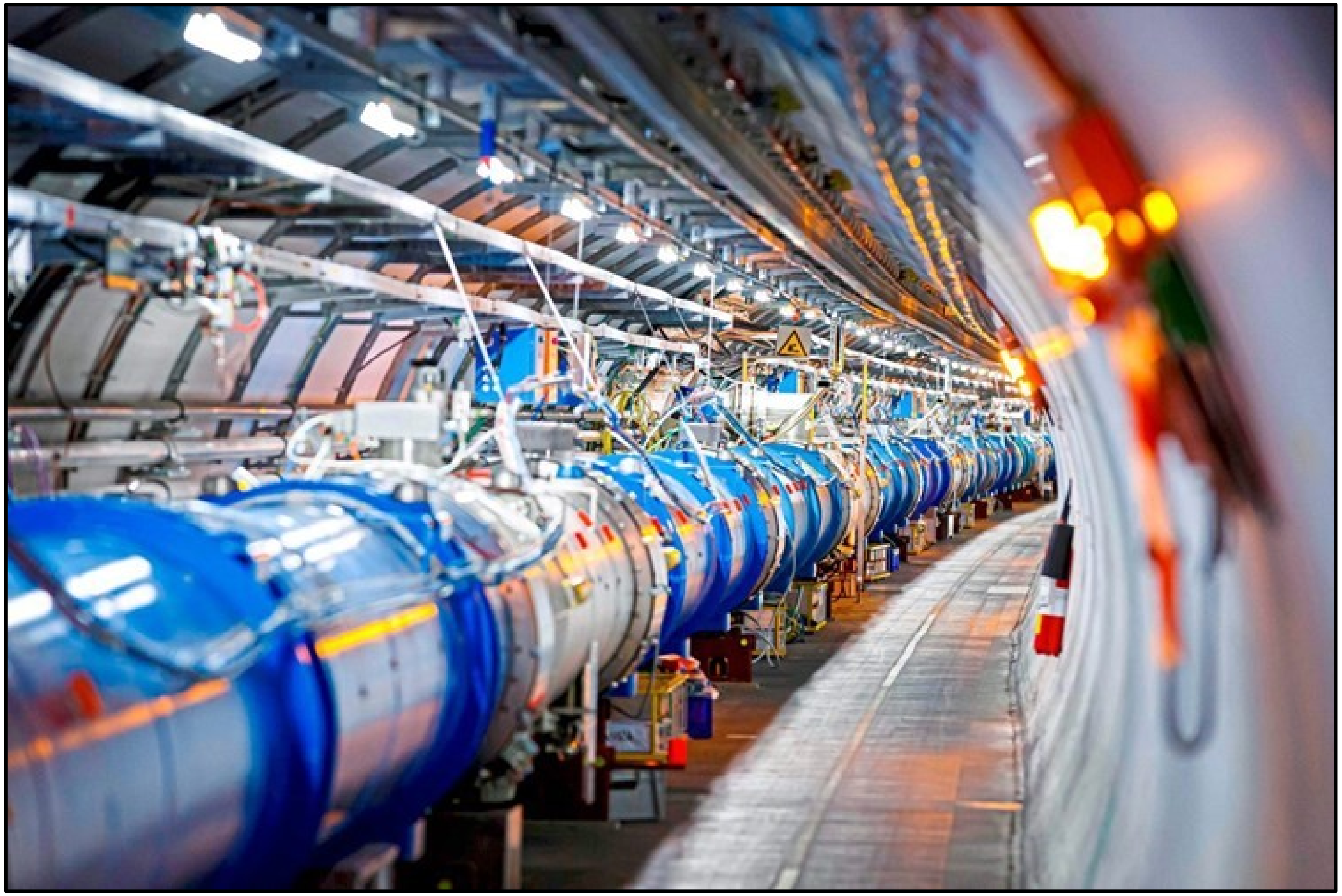
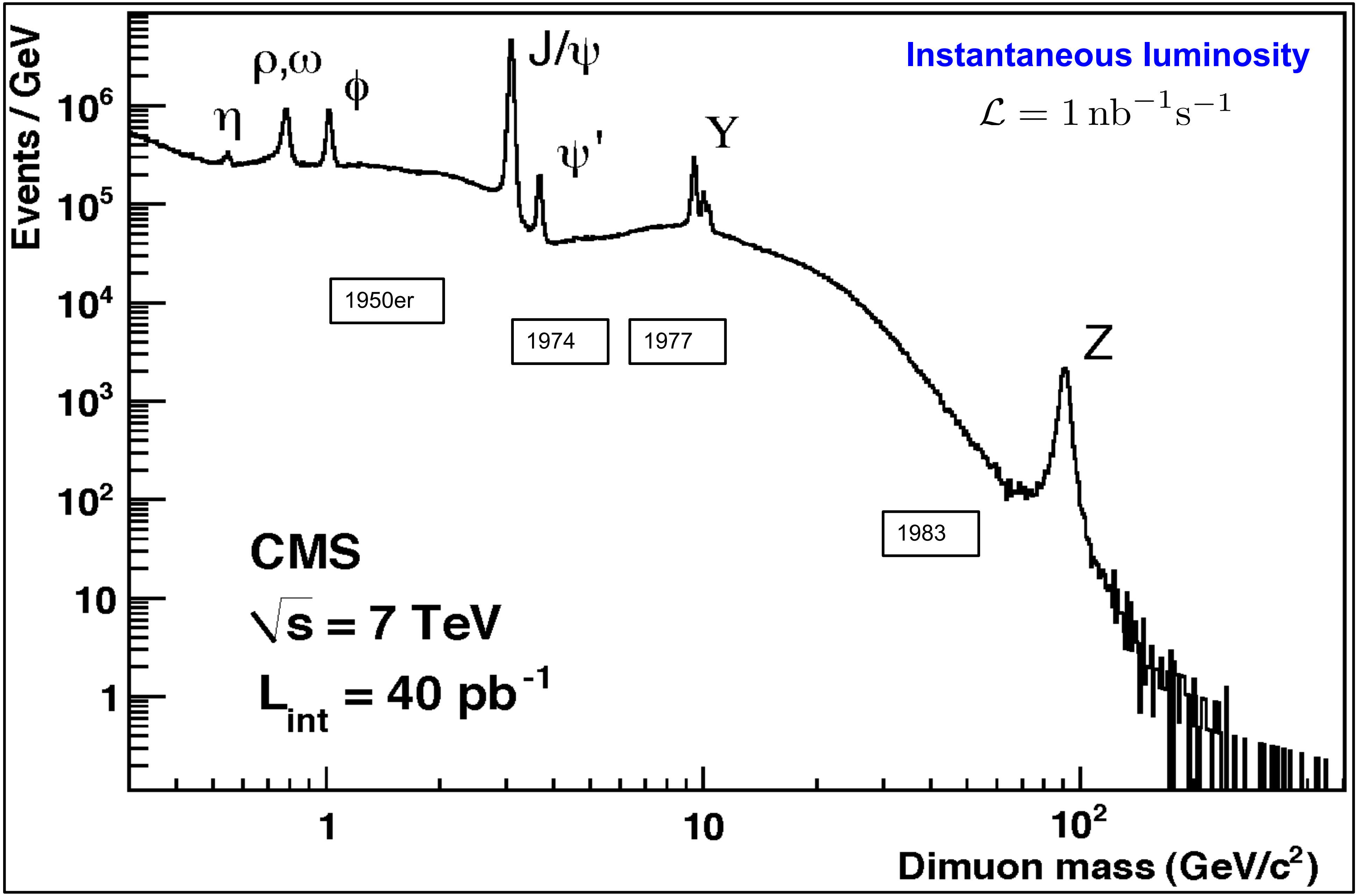
Since discovery of Higgs:
More popular the "brazilian flag" plots, see later ...

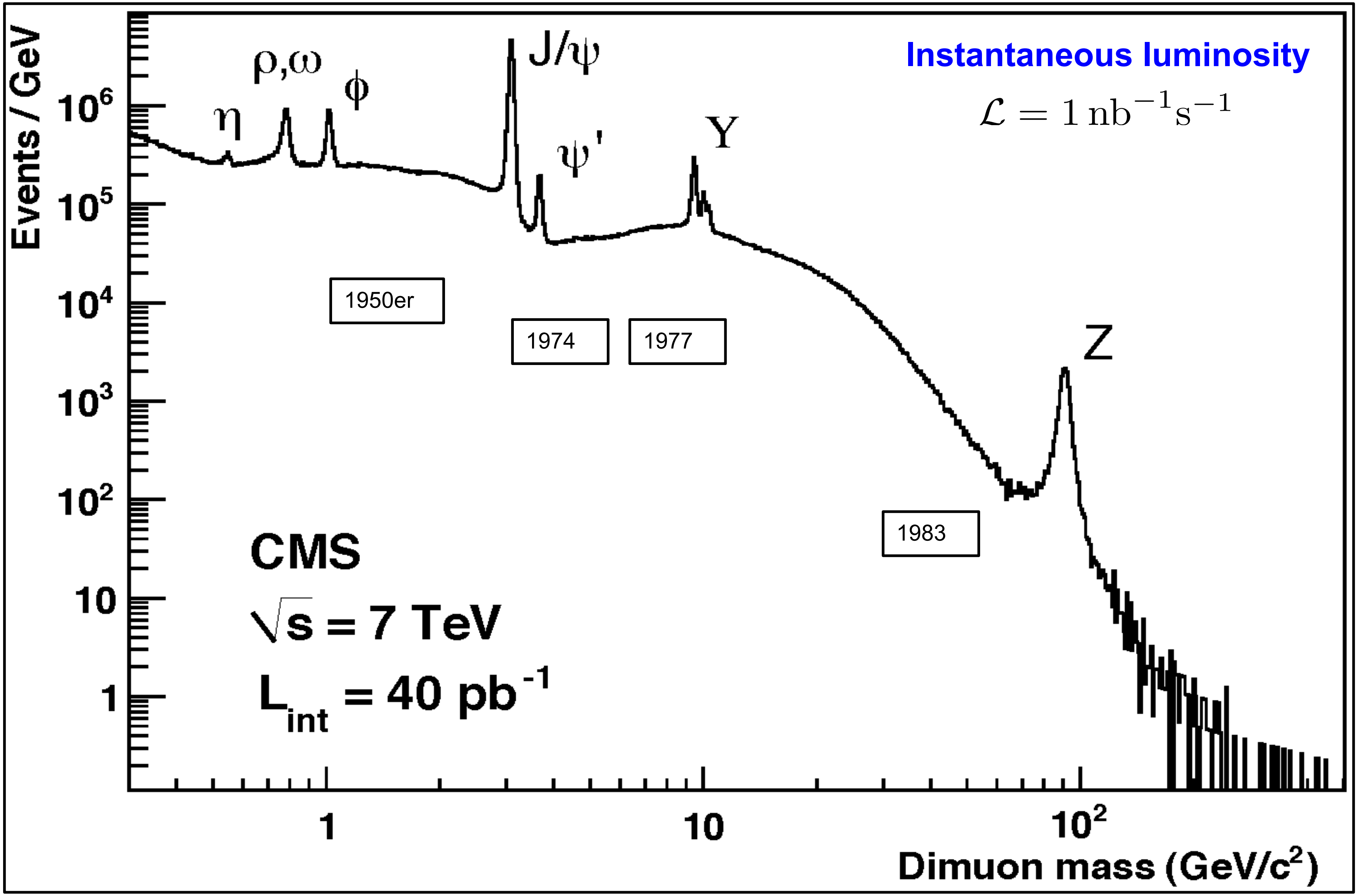
W/Z at the LHC



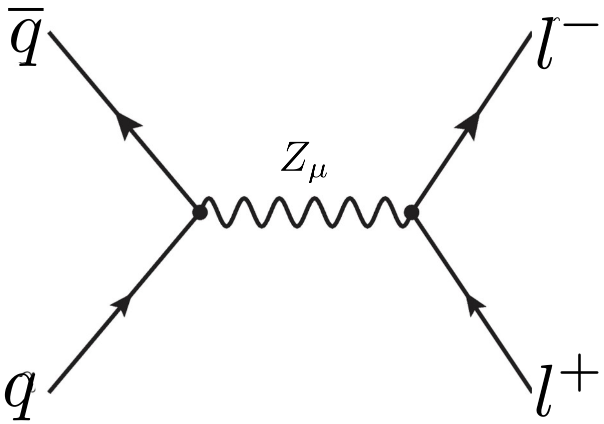
Rediscovery of the past ...



… in under 12 hours!



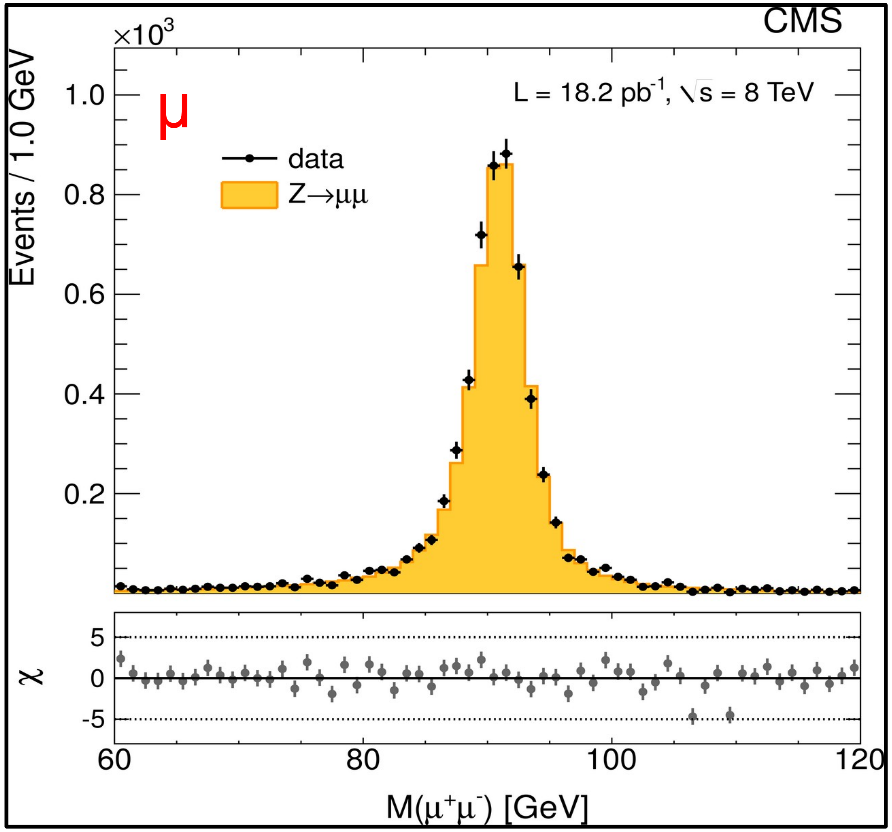
Inclusive Z boson production

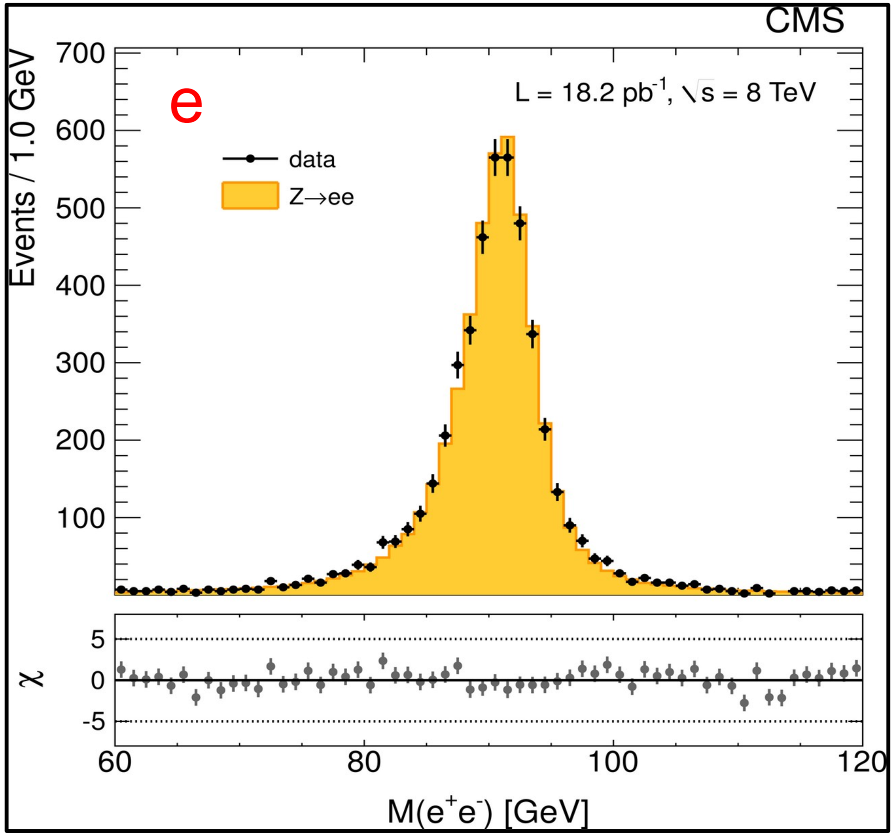


Signature:

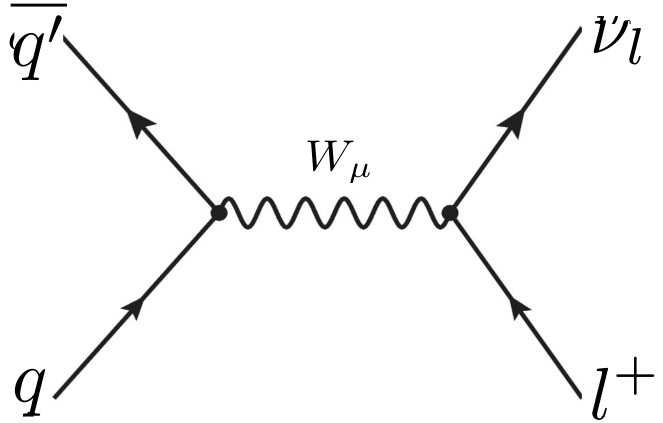
CMS-SMP-12-001

- **Two leptons (l = e, μ):**
  - **isolated, i.e. no hadronic activity in vicinity**
  - **large transverse momentum $p_{T,l}$**
  - **same flavour, opposite charge**



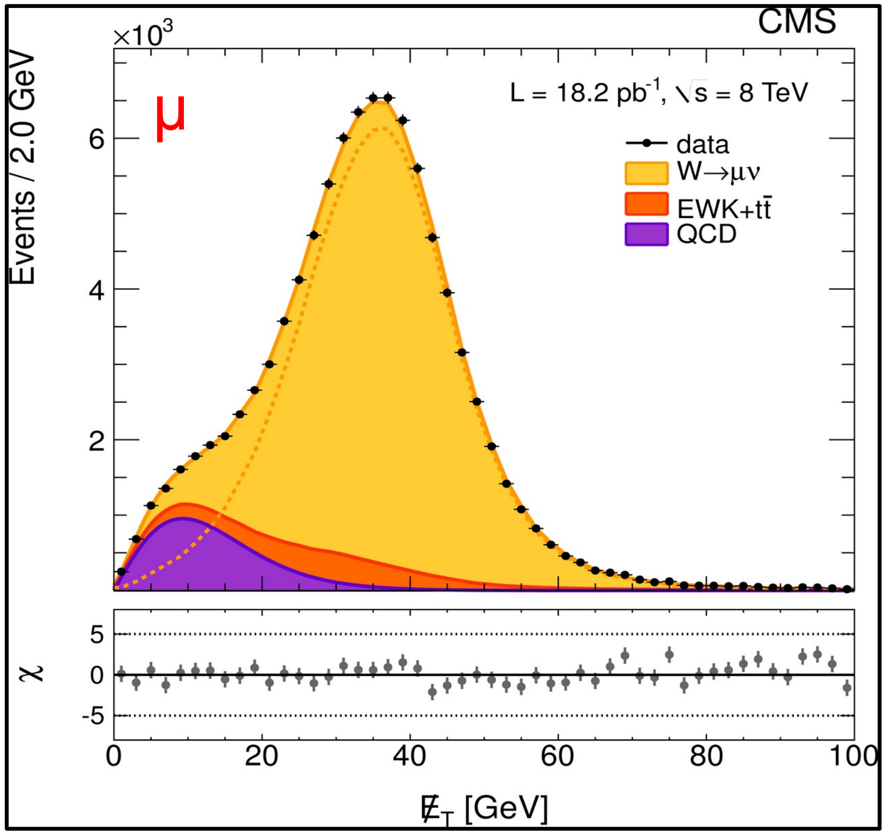


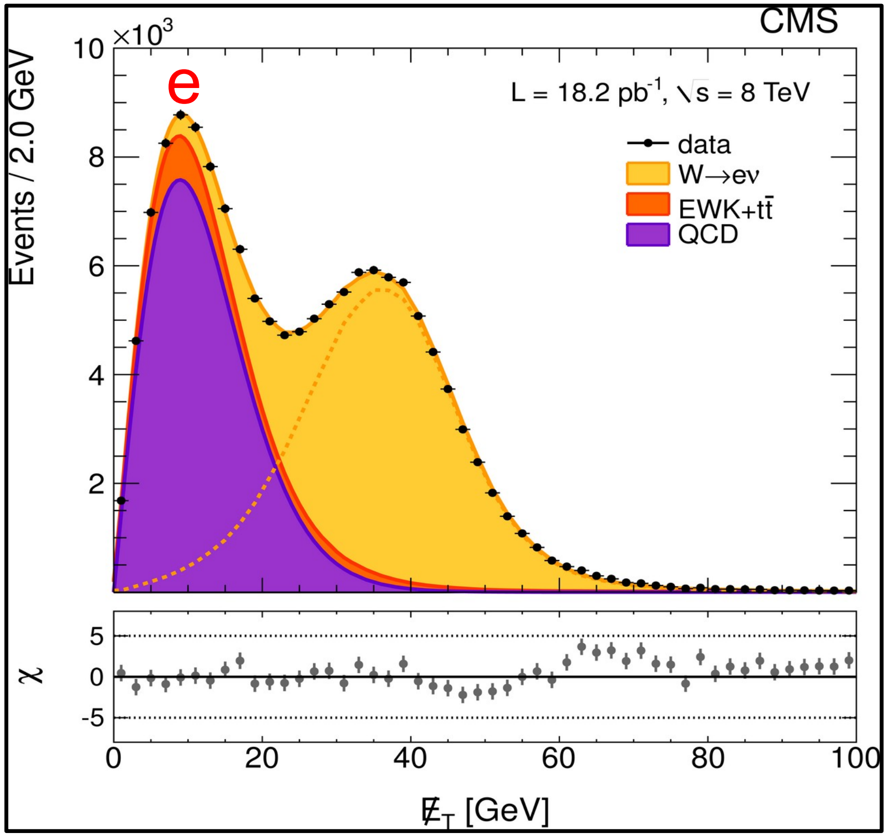
Inclusive W boson production



CMS-SMP-12-001

- **Signature:**
  - **One lepton (l = e, μ):**
    - **isolated, i.e. no hadronic activity in vicinity**
    - **large transverse momentum $p_{T,l}$**
    - **large missing transverse momentum**



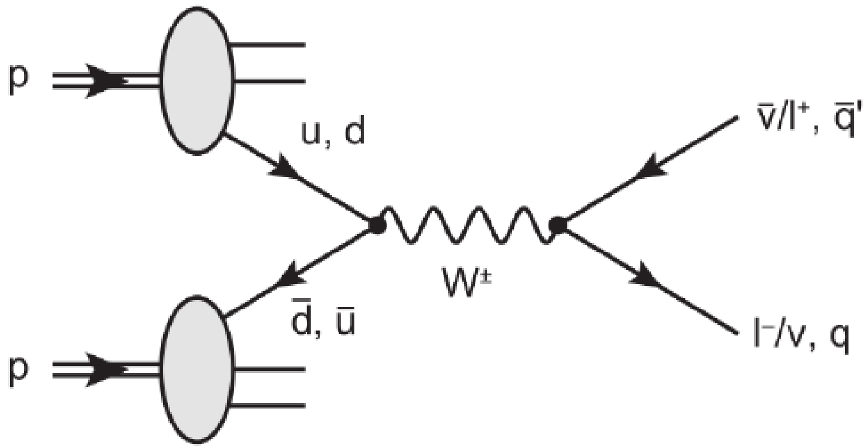


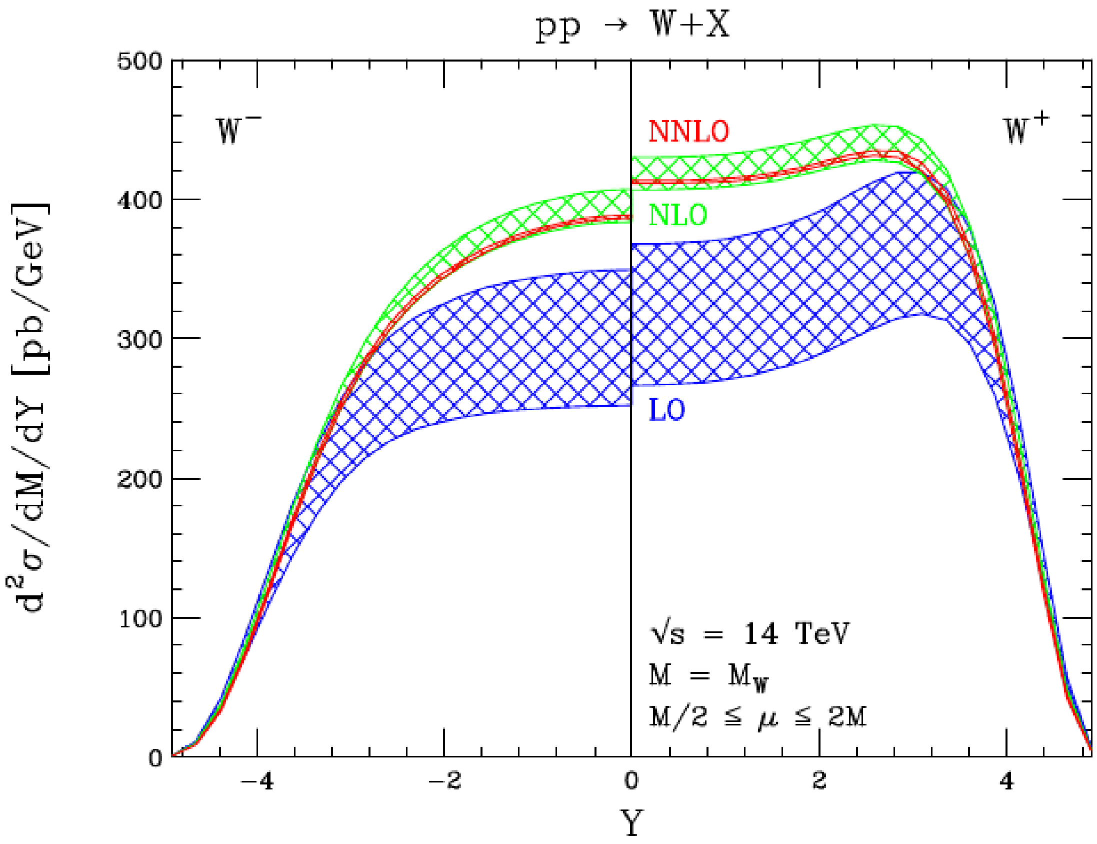
$W^{\pm}$ bosons at hadron colliders

What do you expect for W^+ versus W^- production at the LHC?

$W^{\pm}$ bosons at hadron colliders

- Single W boson production at hadron colliders





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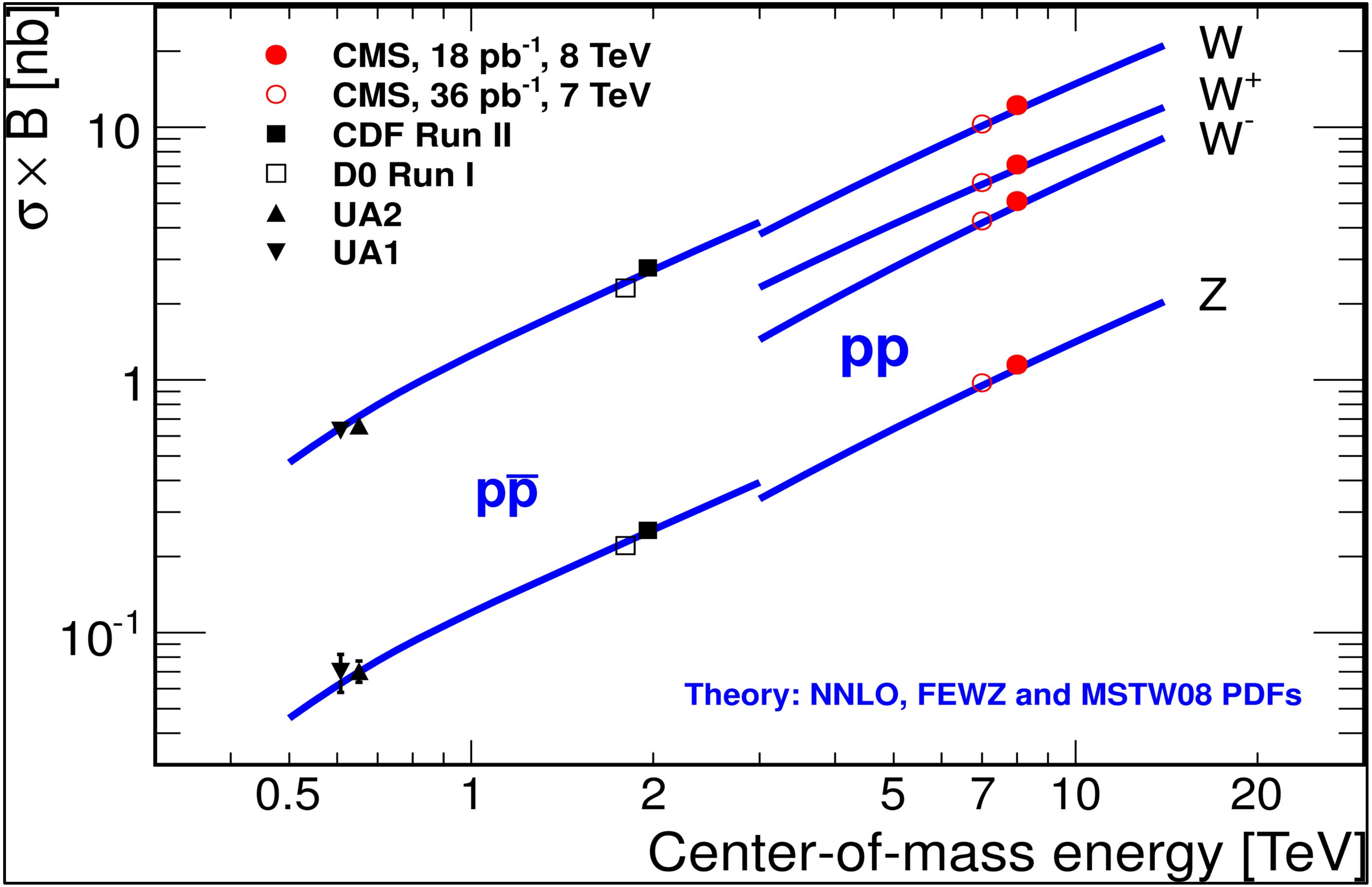
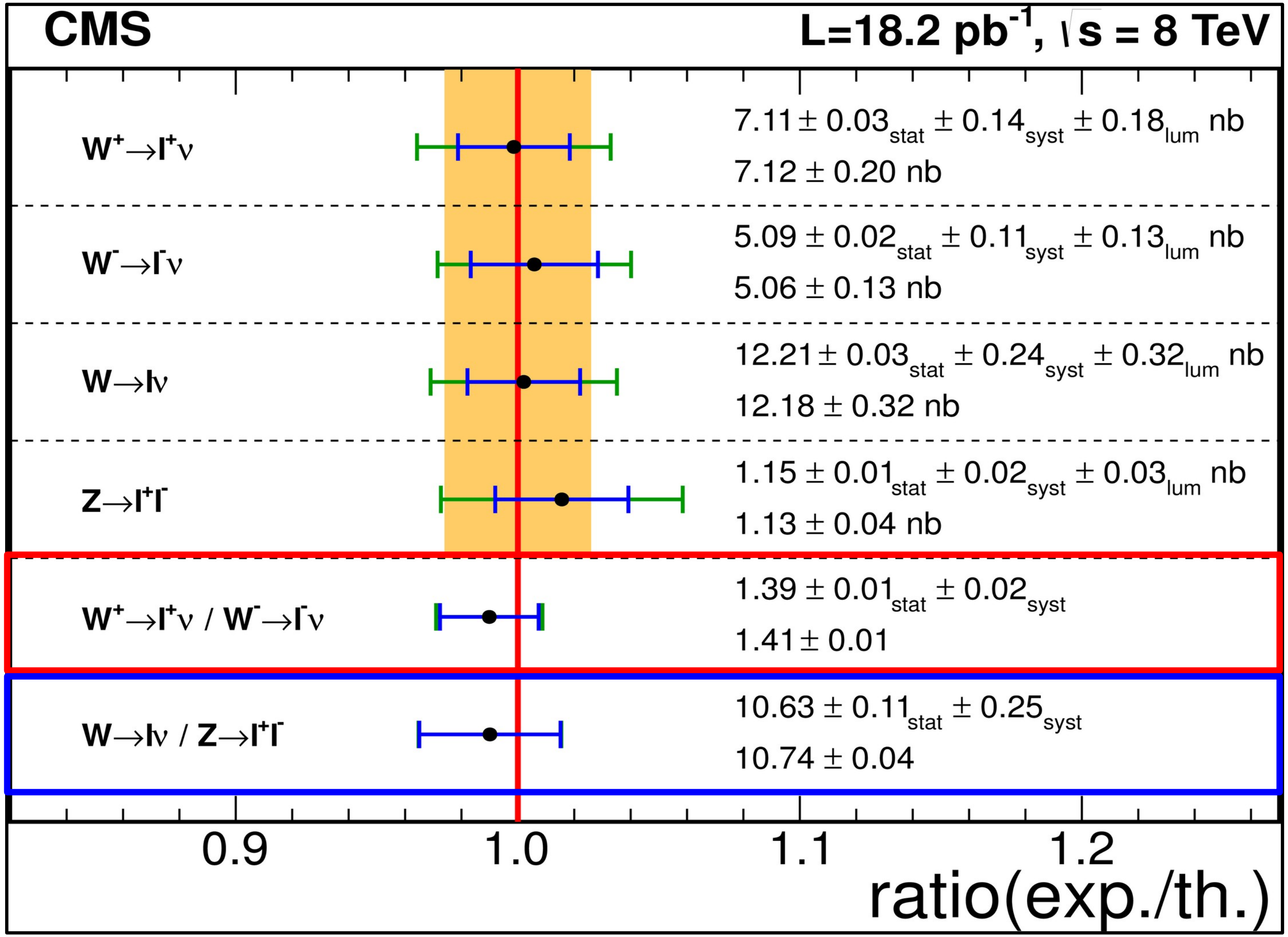
- LO: valence-quark annihilation
  - **$p\bar{p}$: equal $W^{\pm}$ cross section**
  - **pp: uud $\rightarrow W^{+}$ more probable**
- Differential cross-section known at NNLO QCD (partially also EWK)

Inclusive $W^{\pm}$ cross sections



Inclusive V cross section ratios



$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx 1.4$$

$$\frac{\sigma_W}{\sigma_Z} \approx 10$$