# KSETA-Course: Accelelerator-Based Particle Physics

## Electroweak Physics

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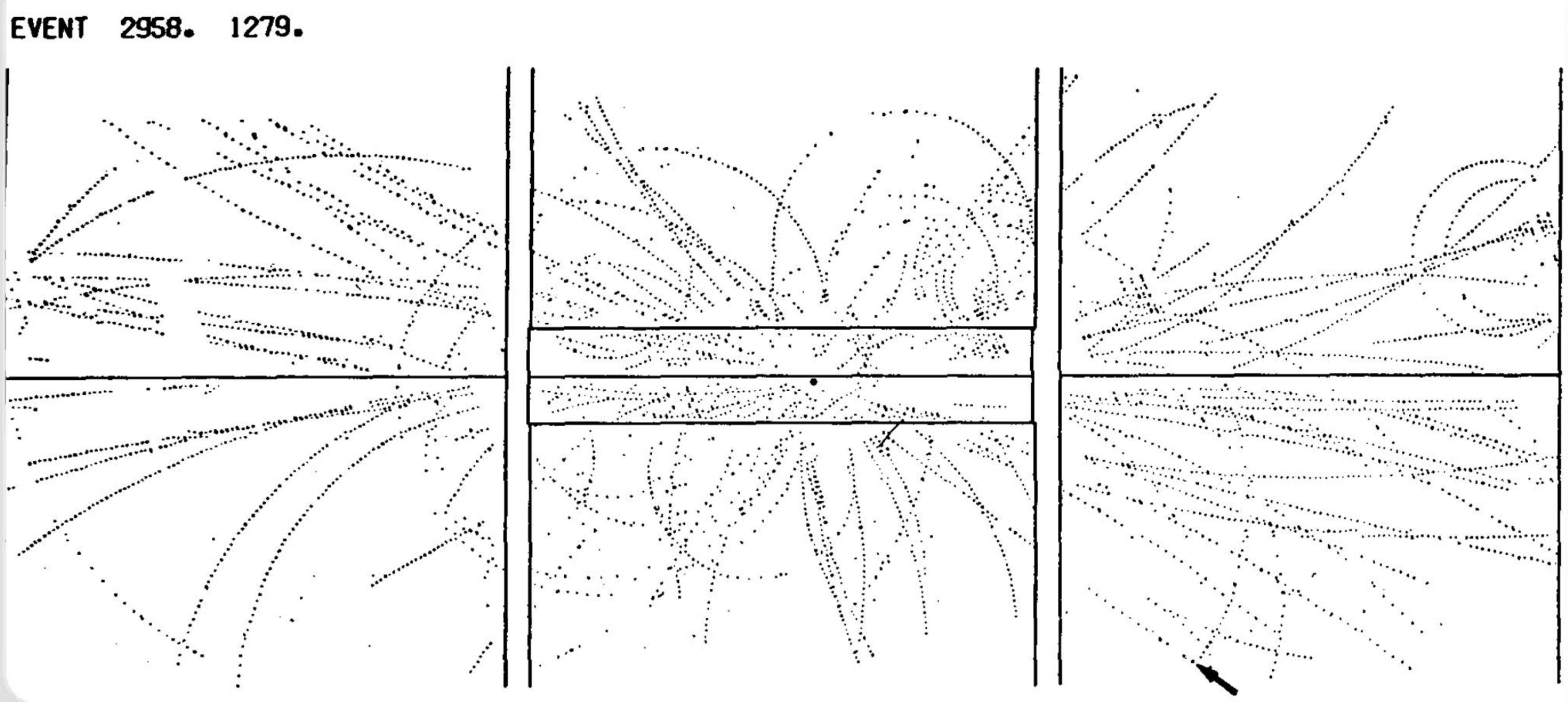
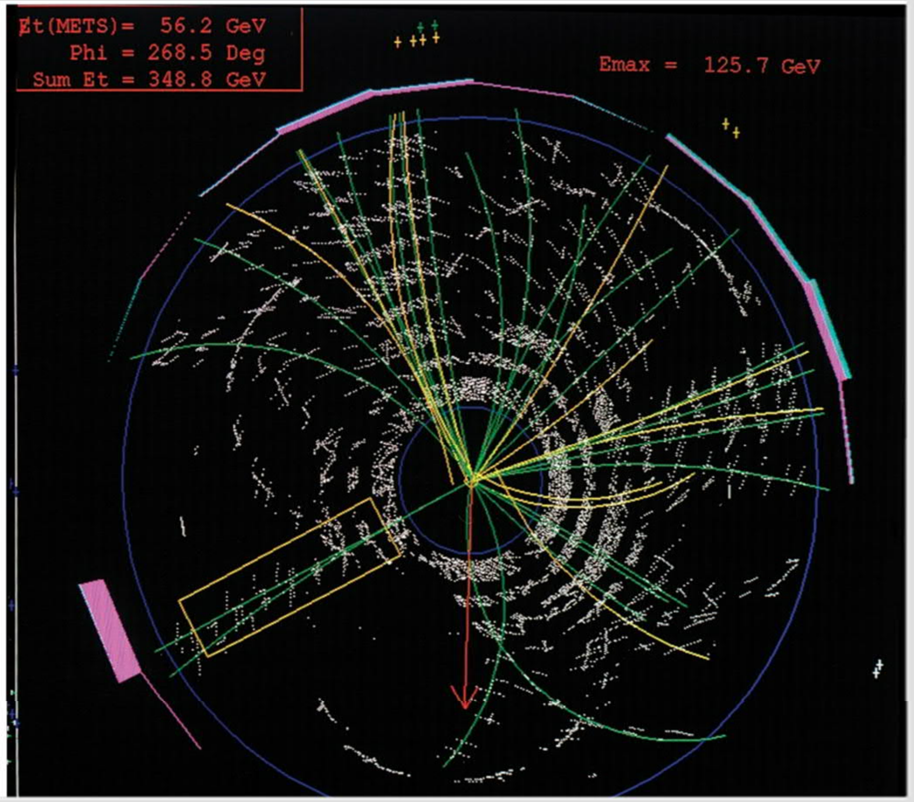
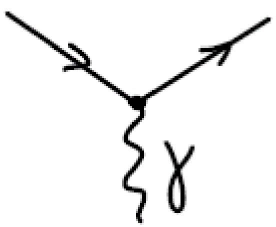


# Elektromagnetic Interaction & CC

- Electromagnetic Interaction (Fermion with charge e)

$$\mathcal{L}_{em} = e \cdot j_\mu^{em} \cdot A^\mu = \frac{g g'}{\sqrt{g^2 + g'^2}} \bar{f} \gamma_\mu f A^\mu$$




photon

elem. charge

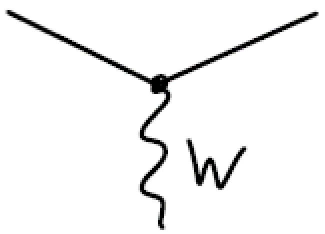
EM current

weak mixing angle

with $\quad e = g \sin\vartheta_W = g' \cos\vartheta_W$

- Charged Current: V-A structure

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left[ J_\mu^{+CC} W^{\mu-} + J_\mu^{-CC} W^{\mu+} \right]$$




quark mixing

CC for quarks

$$J_\mu^{+CC} = (\bar{u}, \bar{c}, \bar{t}) \gamma_\mu \frac{1}{2} (1 - \gamma_5) V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

V-A

# NC & Selfcoupling

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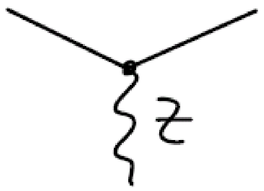
- Neutral Currents $\mathcal{L}_{NC} = -\frac{\sqrt{g^2 + g'^2}}{2} J_\mu^{NC} Z^\mu$




with:

$$J_\mu^{NC} = \bar{f}\gamma_\mu \frac{1}{2}\left(g_V^f - g_A^f \gamma_5\right) f$$

vector-coupling   axial-coupling

$$g_V^f = \left(I_3^f - 2q^f \sin^2\vartheta_W\right) \qquad g_A^f = I_3^f$$

( $I_3^f$ third component of isospin, $q^f$ fermion charge)

- Selfcouplings of gauge bosons: only WWγ, WWZ

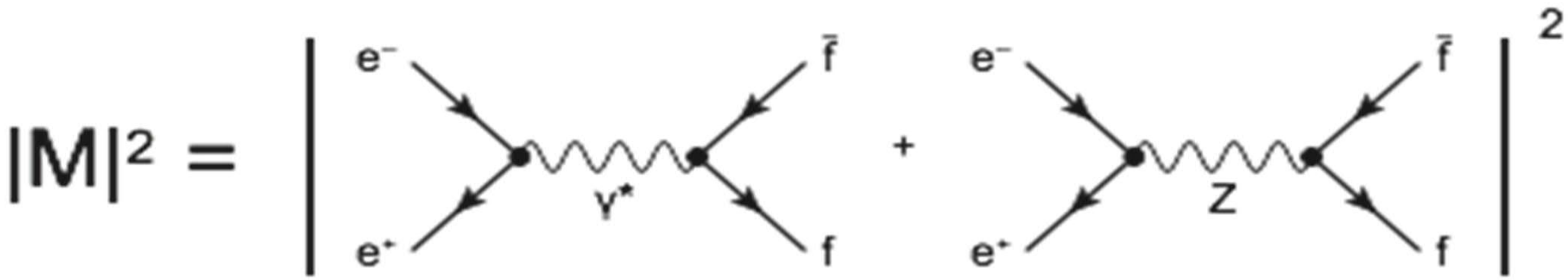
$$\mathcal{L}_{\mathrm{WW}\gamma} = -\mathrm{ie}\left[A_\mu\left(W^{-\mu\nu}W_\nu^+ - W^{+\mu\nu}W_\nu^-\right) + F_{\mu\nu}W^{+\mu}W^{-\nu}\right]$$

$$\mathcal{L}_{\mathrm{WWZ}} = -\mathrm{ie}\cot\vartheta_w\left[Z_\mu\left(W^{-\mu\nu}W_\nu^+ - W^{+\mu\nu}W_\nu^-\right) + Z_{\mu\nu}W^{+\mu}W^{-\nu}\right]$$

- +quartic couplings WWWW, WWZZ, WWZγ, WWγγ

# Cross Section

- Resonant (s-channel-) production von Z-bosons in $e^+e^-$-scattering
  - Photon and Z-boson: identical quantum numbers ($J^P = 1^-$) → interference
  - Matrix-element:



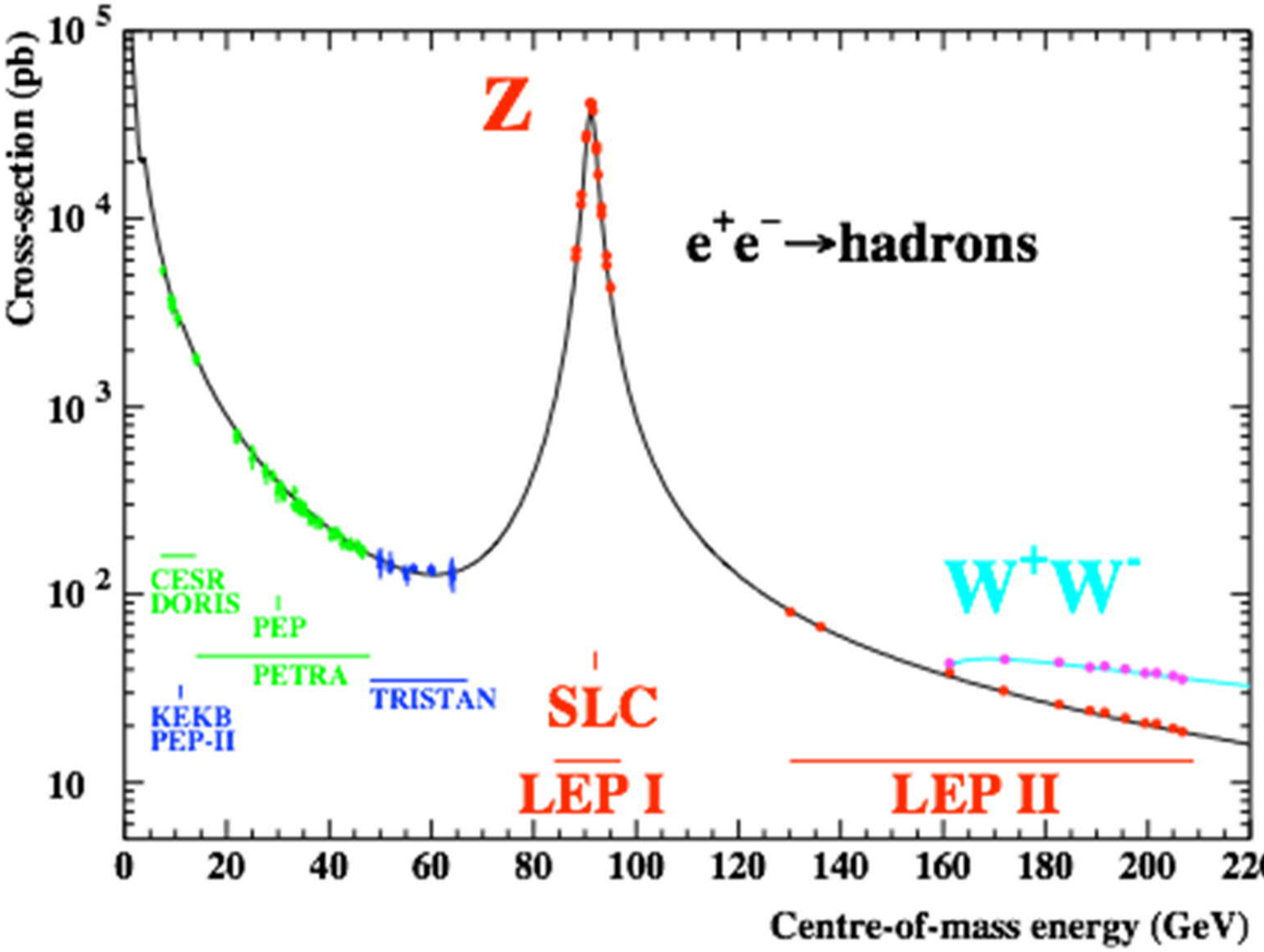

  - cross section: $$\sigma(e^+e^- \to f\bar{f}) = \sigma_{\gamma^*} + \sigma_{\gamma^*/Z} + \sigma_Z$$

- $\sqrt{s} \ll m_Z$: photon exchange dominant → simple QED

- $\sqrt{s} \simeq m_Z$: Z-boson-exchange dominant, photon- and interference-term negligible

# Widh of the Z-Resonance

- Z = unstable particle
  - finite lifetime $\tau_Z$
    $\rightarrow$ decaywidth $\Gamma_Z = 1/\tau_Z$
    („smeared" mass)
  - modified propagator




[Phys. Rep. 427 (2006) 257]

- Decay width
  - sum of partial decay widths („partial widths")
  - for $\sqrt{s} \simeq m_Z$:

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

  - in leading order:

$$\Gamma_f = N_C^f \frac{G_F m_Z^3}{6\sqrt{2}\pi} \left[(g_V^f)^2 + (g_A^f)^2\right]$$

# Number of light neutrinos

- Cross section for a fermion f:

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

Breit-Wigner
=> 1 for $s = m_Z^2$

- Compare different cross sections to find $\Gamma_{\text{inv}}$ from $\Gamma_Z$ and other f

$$\frac{\Gamma_{inv}}{\Gamma_e} \equiv R_{inv}^0 = \frac{\Gamma_Z}{\Gamma_e} - 3 - R_e^0 = \sqrt{\frac{12\pi}{m_Z^2} \cdot \frac{R_e^0}{\sigma_{had}^0}} - 3 - R_e^0$$

- Divide $\Gamma_{\text{inv}}$ by $\Gamma_\nu$ derived from theory

=> $N_\nu = 2.9840(82)$

# Number of neutrinos in pictures

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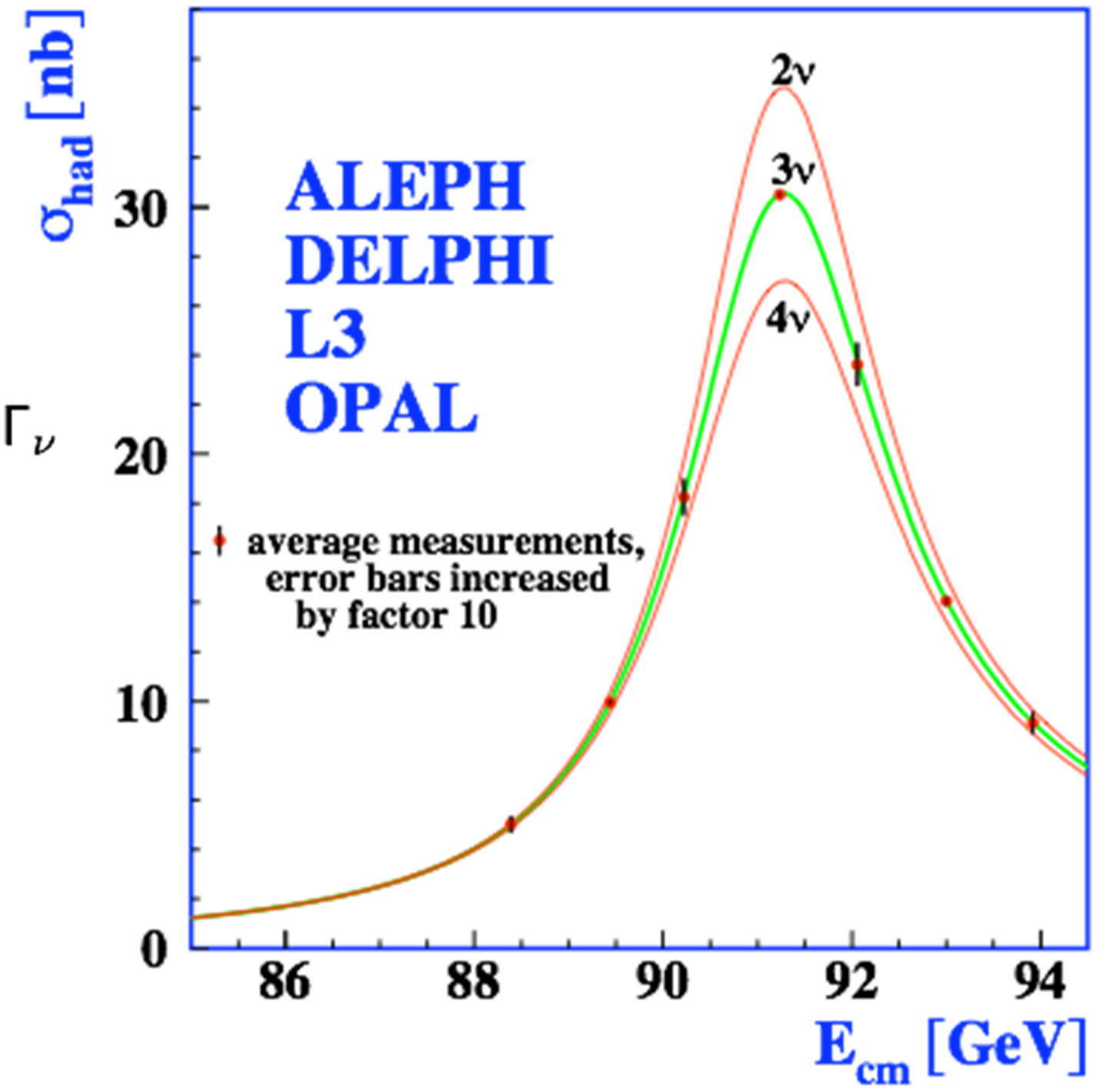
$$\sigma_f = \frac{12\pi}{m_Z^2} \cdot \frac{\Gamma_e \cdot \Gamma_f}{\Gamma_Z^2} \cdot \frac{s \cdot \Gamma_Z^2}{(s - m_Z^2)^2 + s^2 \frac{\Gamma_Z^2}{m_Z^2}}$$

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

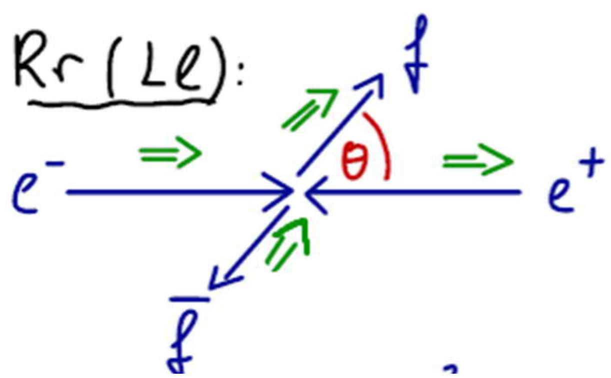



[Phys. Rep. 427 (2006) 257]

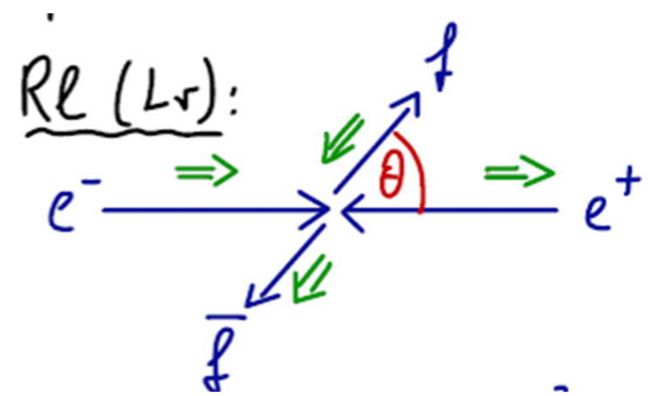
# $\sqrt{s} \ll m_Z$: differential Xsec

$\sqrt{s} << m_z$: photon exchange (pure QED)

helicities: photon $\Rightarrow$ spin 1




$\sigma \sim (1+\cos\vartheta)^2$




$\sigma \sim (1-\cos\vartheta)^2$

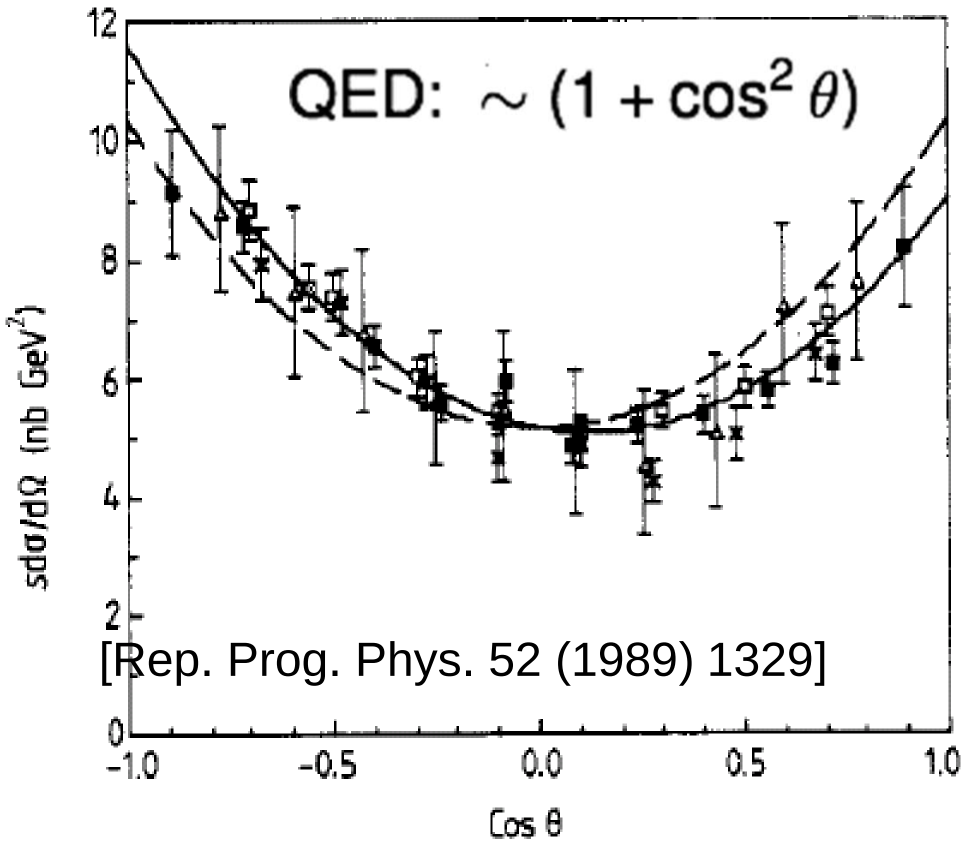
$$\Longrightarrow \frac{d\sigma_\gamma}{d\cos\vartheta} = N_c^f \cdot q_f^2 \cdot \frac{\pi\alpha^2}{2s}(1+\cos^2\vartheta)$$

# colors ($N_c^f$) — charge ($q_f^2$)

# √s ≪ $m_Z$: Angular Distribution

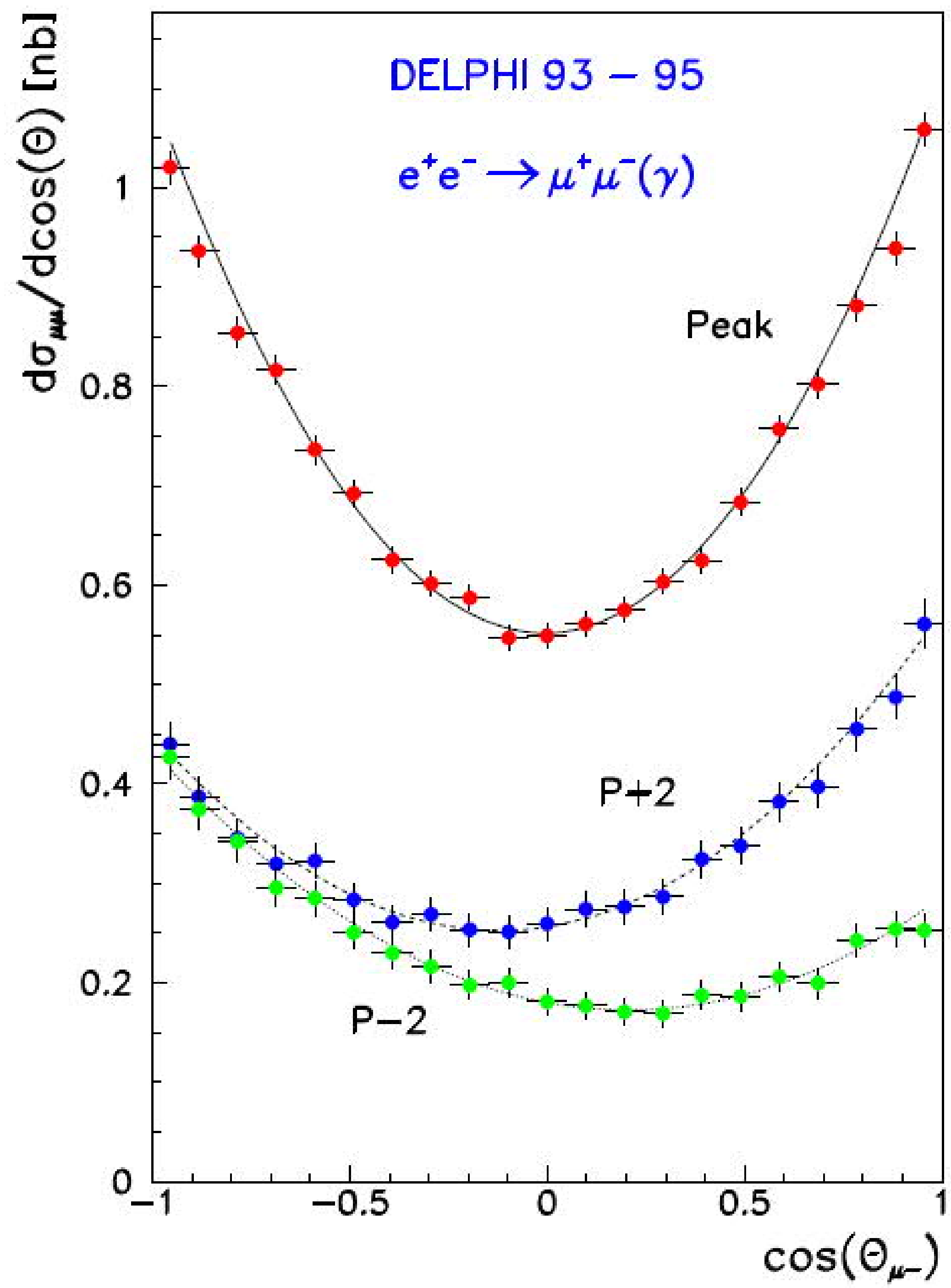
- Before LEP: measurements at PETRA (DESY) → first deviations from pure QED
- LEP: γ*/Z-interference und Z central physics topic

**PETRA: √s = 29-35.5 GeV**




[Rep. Prog. Phys. 52 (1989) 1329]

**LEP: √s = $m_Z$ ± 2 GeV**




[Phys. Rep. 427 (2006) 257]

# Asymmetries

- Generic definition of an asymmetry:
  Partition a dataset into two parts X,Y → $A = \frac{X - Y}{X + Y}$
- Why asymmetries?
  - Asymmetries = Ratios, not absolute rates
  - Backgrounds and systematic effects on numerator/denominator equal or similar
    → Reduction of uncertainties due to cancellations
  - Increased sensitivity to small differences

# Differential Cross Section

Angular distribution for Z exchange:

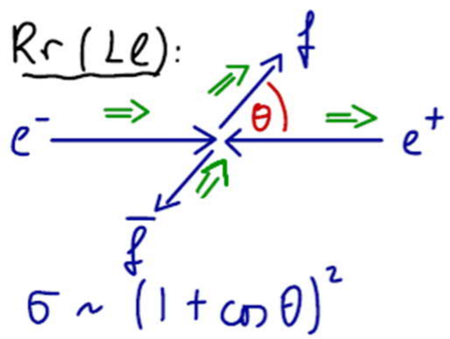
$\rightarrow$ 4 helicities (using $g_R = g_V + g_A, g_L = g_V - g_A$)

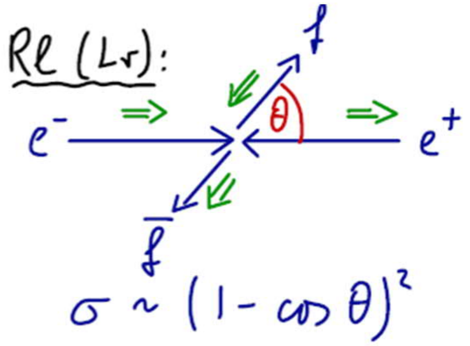
$$\frac{\mathrm{d}\sigma_f}{\mathrm{d}\cos\theta} \sim (g_L^e)^2 (g_L^f)(1 + \cos\vartheta)^2$$

$$\frac{\mathrm{d}\sigma_f}{\mathrm{d}\cos\theta} \sim (g_L^e)^2 (g_R^f)(1 - \cos\vartheta)^2$$

$$\frac{\mathrm{d}\sigma_f}{\mathrm{d}\cos\theta} \sim (g_R^e)^2 (g_R^f)(1 + \cos\vartheta)^2$$

$$\frac{\mathrm{d}\sigma_f}{\mathrm{d}\cos\theta} \sim (g_R^e)^2 (g_L^f)(1 - \cos\vartheta)^2$$




$$\rightarrow \frac{\mathrm{d}\sigma_f}{\mathrm{d}\cos\theta} = \frac{3}{8}\sigma_f\left[(1 + \cos^2\vartheta) + 2\, A_e A_f \cos\vartheta\right]$$

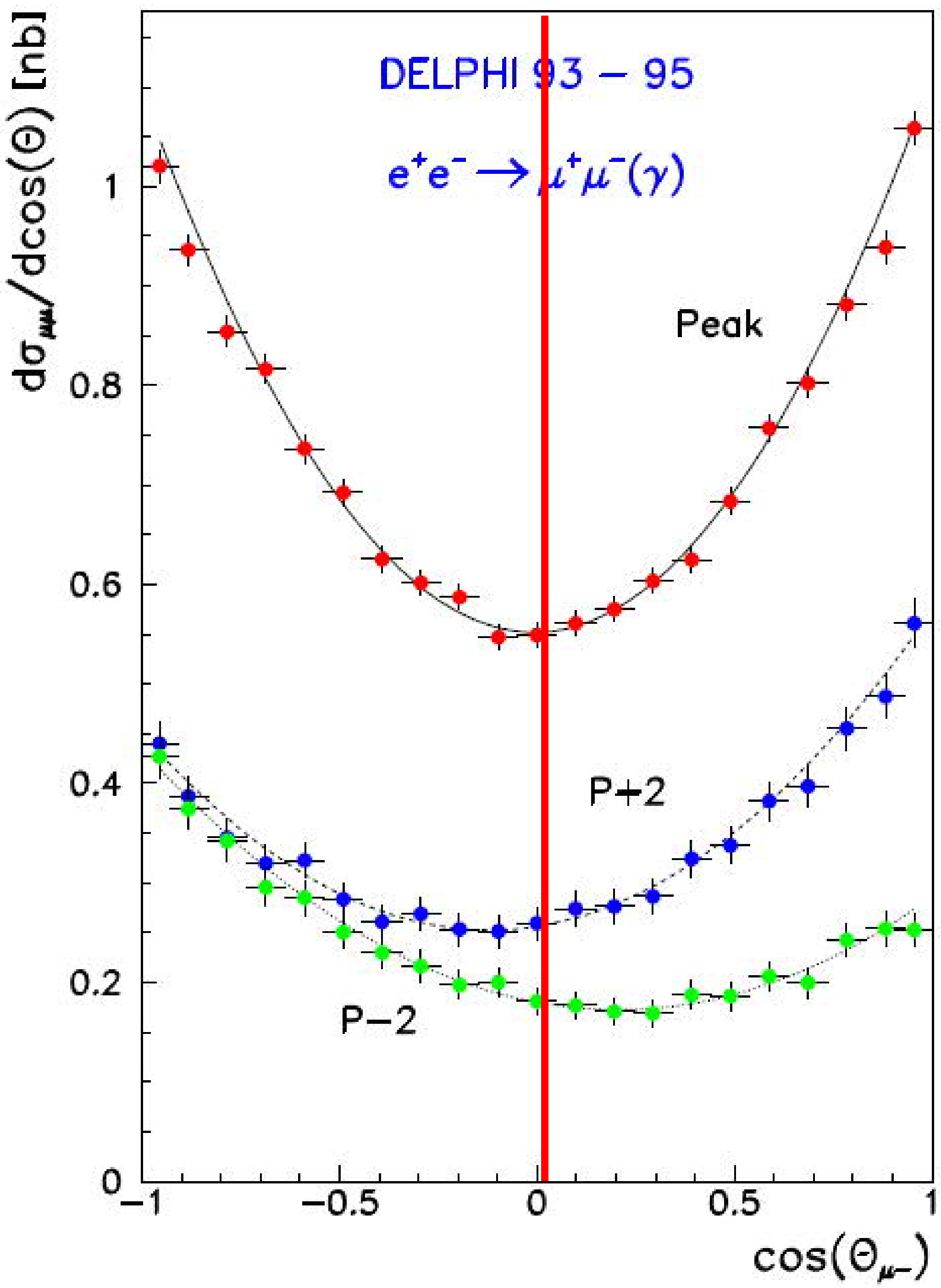
$$A_f = \frac{\left(g_L^f\right)^2 - \left(g_R^f\right)^2}{\left(g_L^f\right)^2 + \left(g_R^f\right)^2} = 2\,\frac{g_V^f / g_A^f}{1 + \left(\frac{g_V^f}{g_A^f}\right)^2}$$

access ratio $\left(\frac{g_V^f}{g_A^f}\right)$

# Forward-Backward-Asymmetry

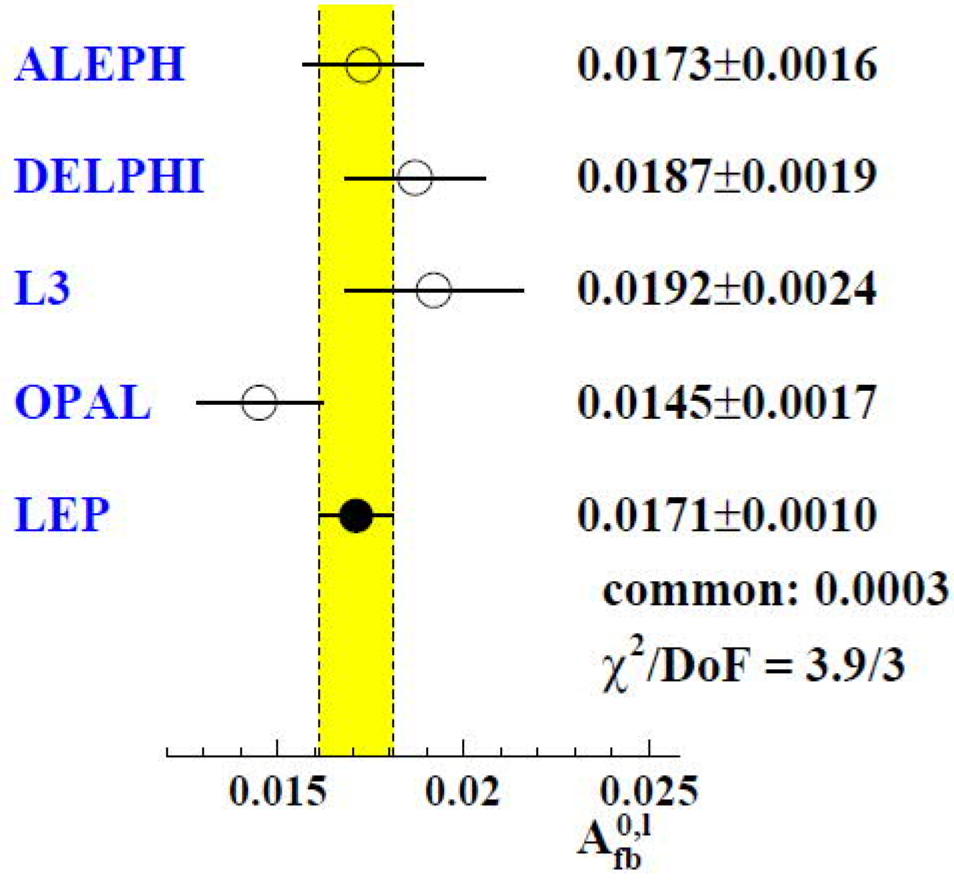
$$\sigma_F \equiv \int_0^{\pi/2} \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\vartheta}\,\mathrm{d}\vartheta \qquad \sigma_B \equiv \int_{\pi/2}^{\pi} \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\vartheta}\,\mathrm{d}\vartheta$$

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

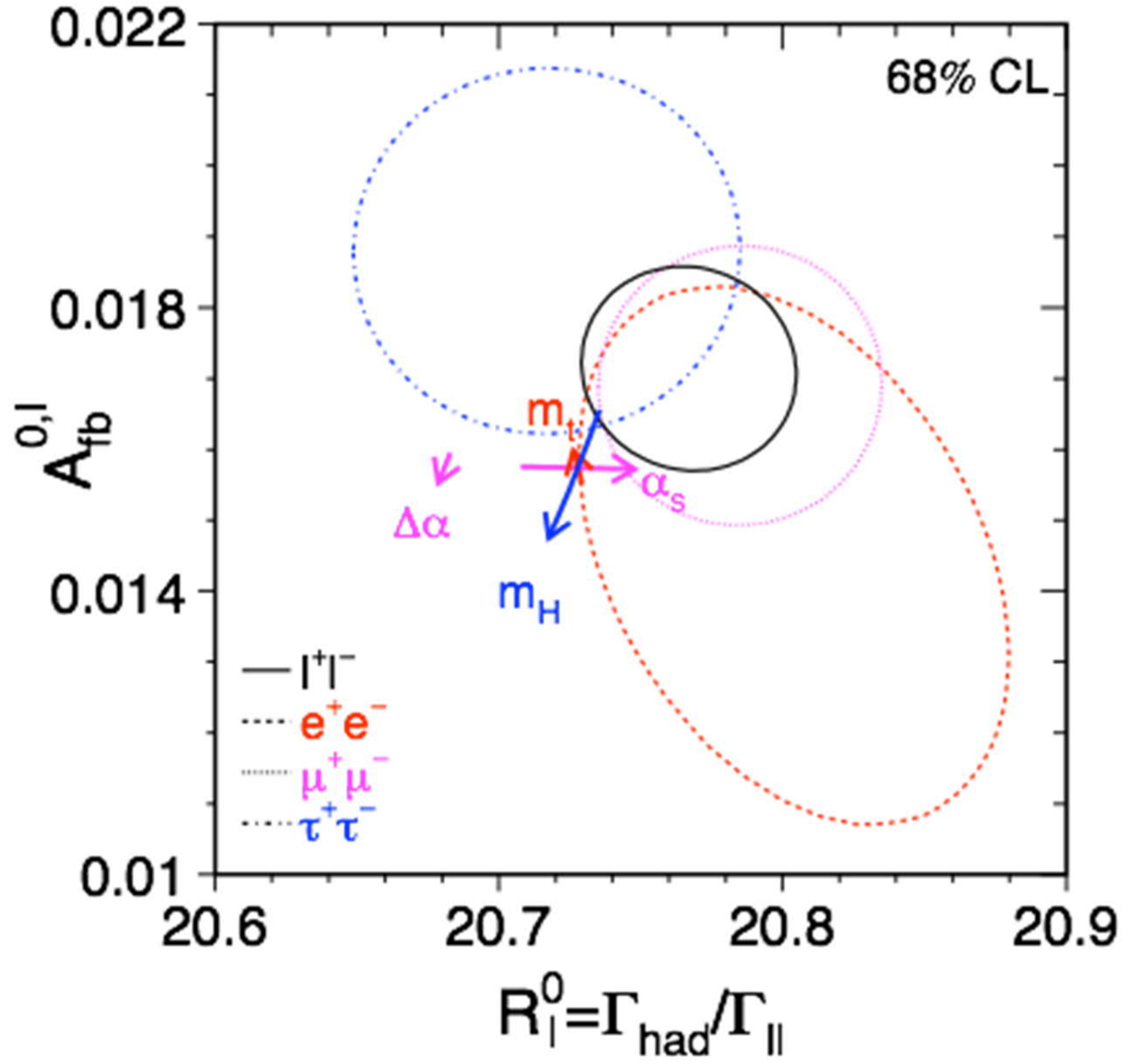


# $A_{FB}$: Results from LEP

**LEP-average: $A_{FB}$ for leptons**

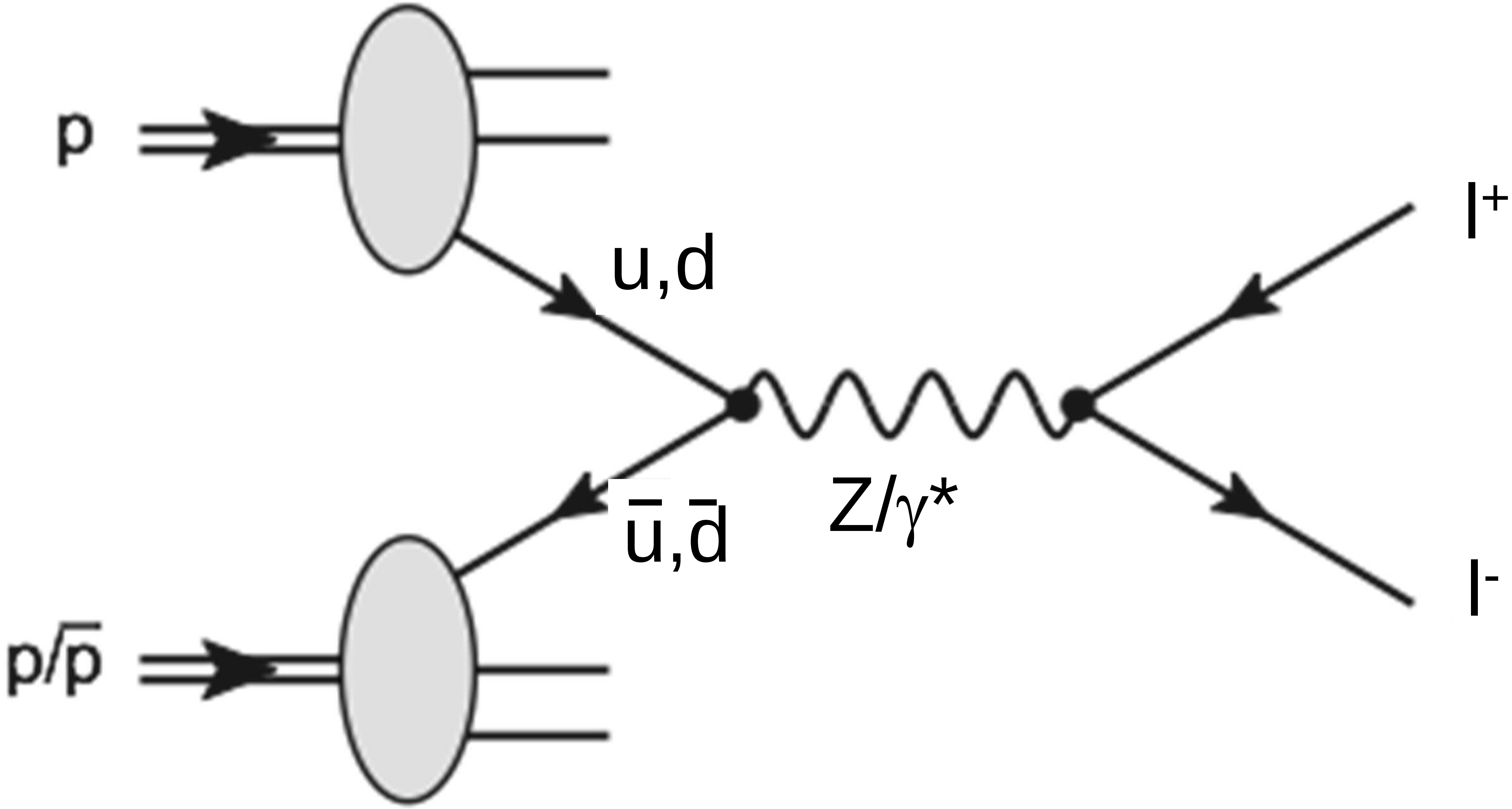



**$A_{FB}$ separatly for e, μ, τ vs. $R^0$**




[Phys. Rep. 427 (2006) 257]

# Z at hadron colliders



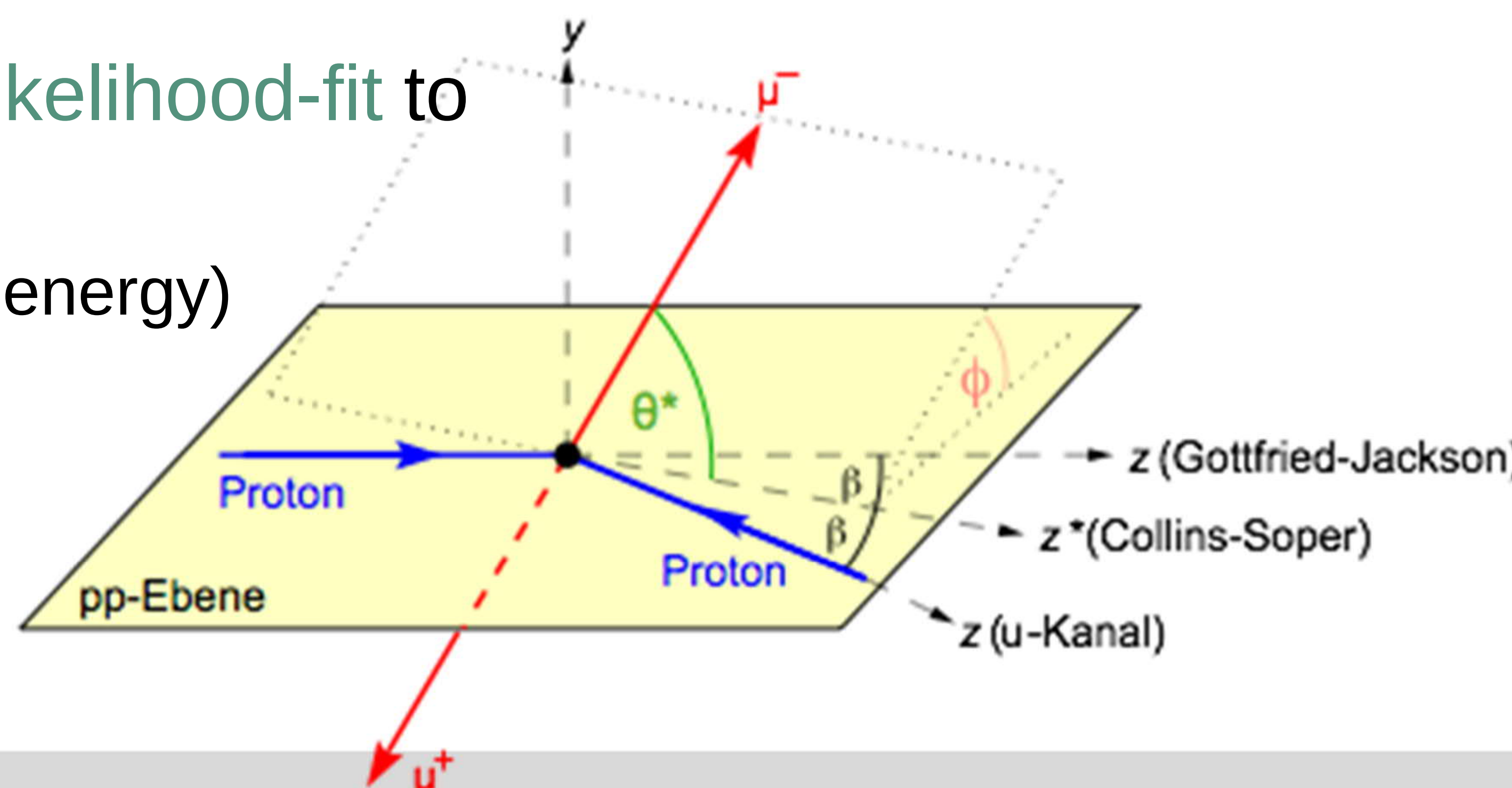

- Lepton final states preferred for low backgrounds, precise reco
- Learn about proton structure (See other lecture)
- Unknown initial state complicates studies of EWK physics

# Weak mixing angle

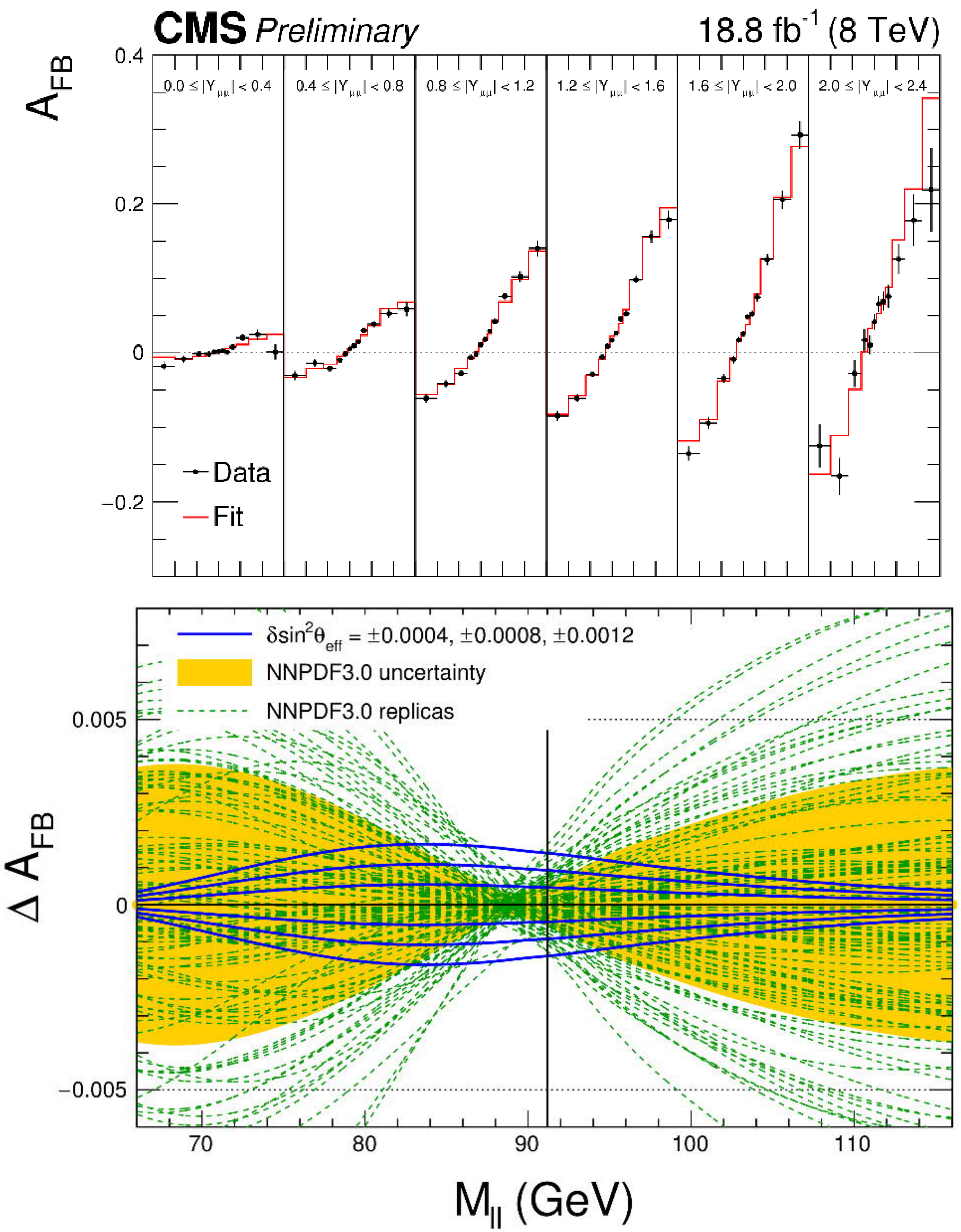
- Drell-Yan-Prozess: qq → γ*/Z → ff
  - Standard model: relative couplings of fermions to γ/Z given by $\sin^2 \theta^f_{W,eff}$

$$\sin^2 \theta^f_{W,\mathrm{eff}} = \frac{I_3^f}{2q^f}\left(1 - \frac{g_V^f}{g_A^f}\right)$$

  - Assumption: differential cross section and PDFs known
    → Extraktion von $\sin^2 \theta^f_{W,eff}$
  - Tricky: which direction did the quark/antiquark come from?
- Simulatenous maximum-likelihood-fit to
  - Lepton pair mass M(μμ)
    (= partonic center of mass energy)
  - $A_{FB}$(Collins-Soper-frame)



# Weak Mixing Angle




[CMS-SMP-16-007]

- CMS-results:

  $\sin^2 \theta^f_{W,eff} = 0.23101 \pm 0.00052$

  - consistent with LEP- resultat ($\sin^2 \theta^f_{W,eff} = 0.23153 \pm 0.00016$)
  - uncertainty: 0.2% ( LEP: 0.07%)

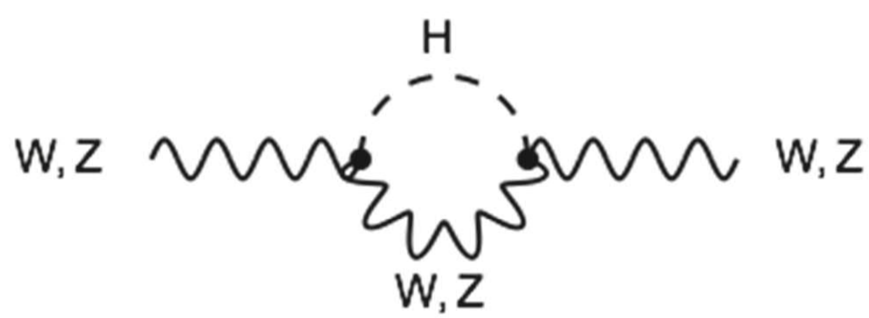
- Systematic uncertainties:
  => reduce effect of PDF uncertainty by simultaneous fit

# Measuring the W-mass

- electroweak theory predicts
  - Connection of W- and Z-mass by the weak mixing angle

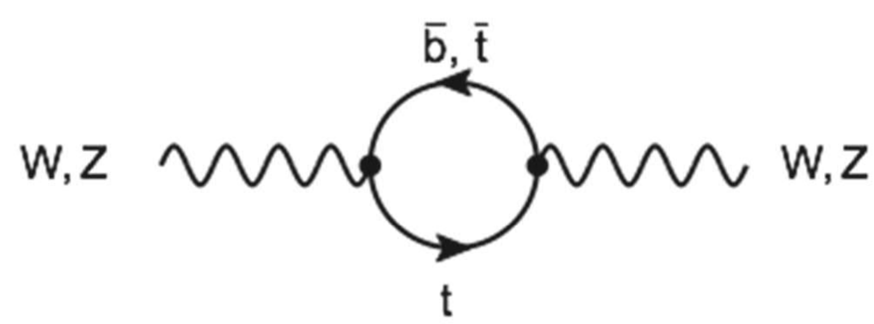
$$m_W^2 = \frac{g^2 v^2}{4}, \quad m_Z^2 = \frac{v^2}{4}(g^2 + g'^2) \quad \rightarrow \quad \rho_0 = \frac{m_W^2}{m_Z^2 \cos\theta_W} = 1$$

  - Connection with Top-quarks and Higgs-Boson masses through loop diagram , i.e. „self-energy" of W and Z




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

weak dependence
(logarithmic)



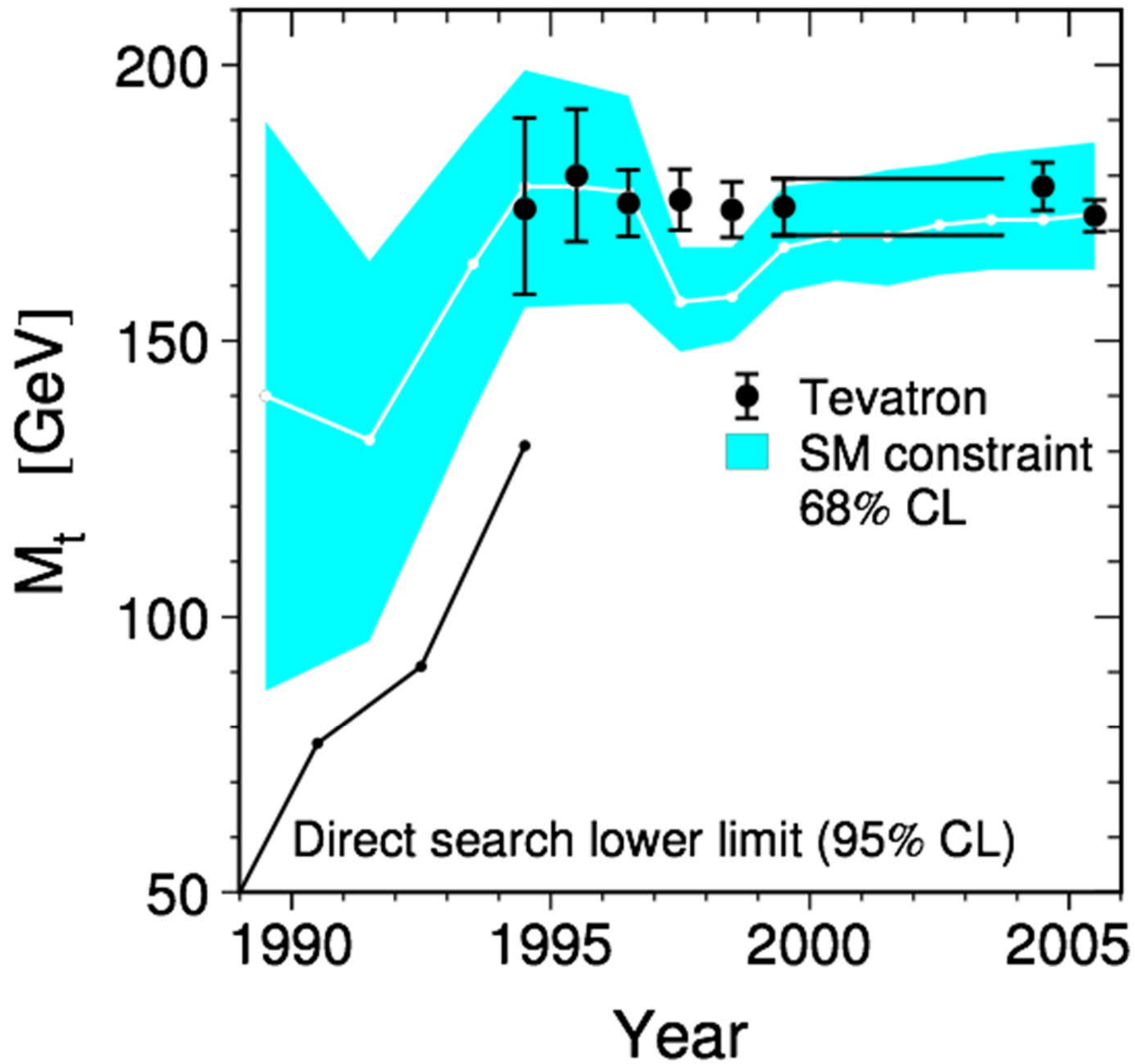

$\sim G_F\, m_t^2$

strong dependence
(quadratic)

# Measuring the W-mass

- Looking for indirect effect needs highest precision
  - Z-mass: extremely precise measurements at LEP (uncertainty: $2 \cdot 10^{-5}$)
    - W-mass: LEP + Tevatron
    - Prediction of Top-quark mass before discovery
    - bounds on allowed Higgs-boson masses before discovery

vgl. Tevatron (2012):
$m_t = 173.2 \pm 0.9$ GeV

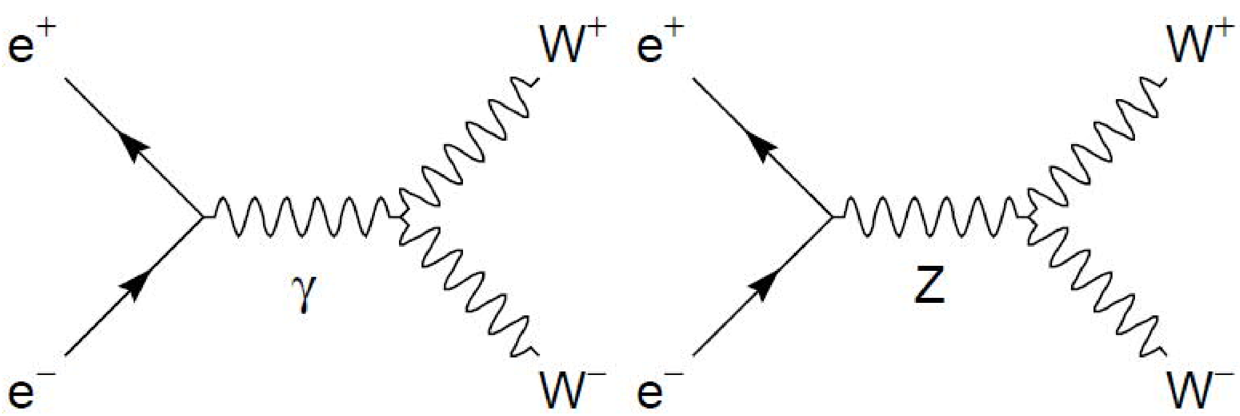



[Phys. Rept. 427 (2006) 257]

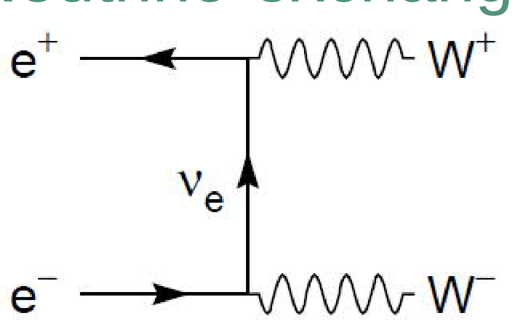
# W-pair creation at LEP-II

- LEP-II: passes kinematic Threshold for W-boson-pair creation

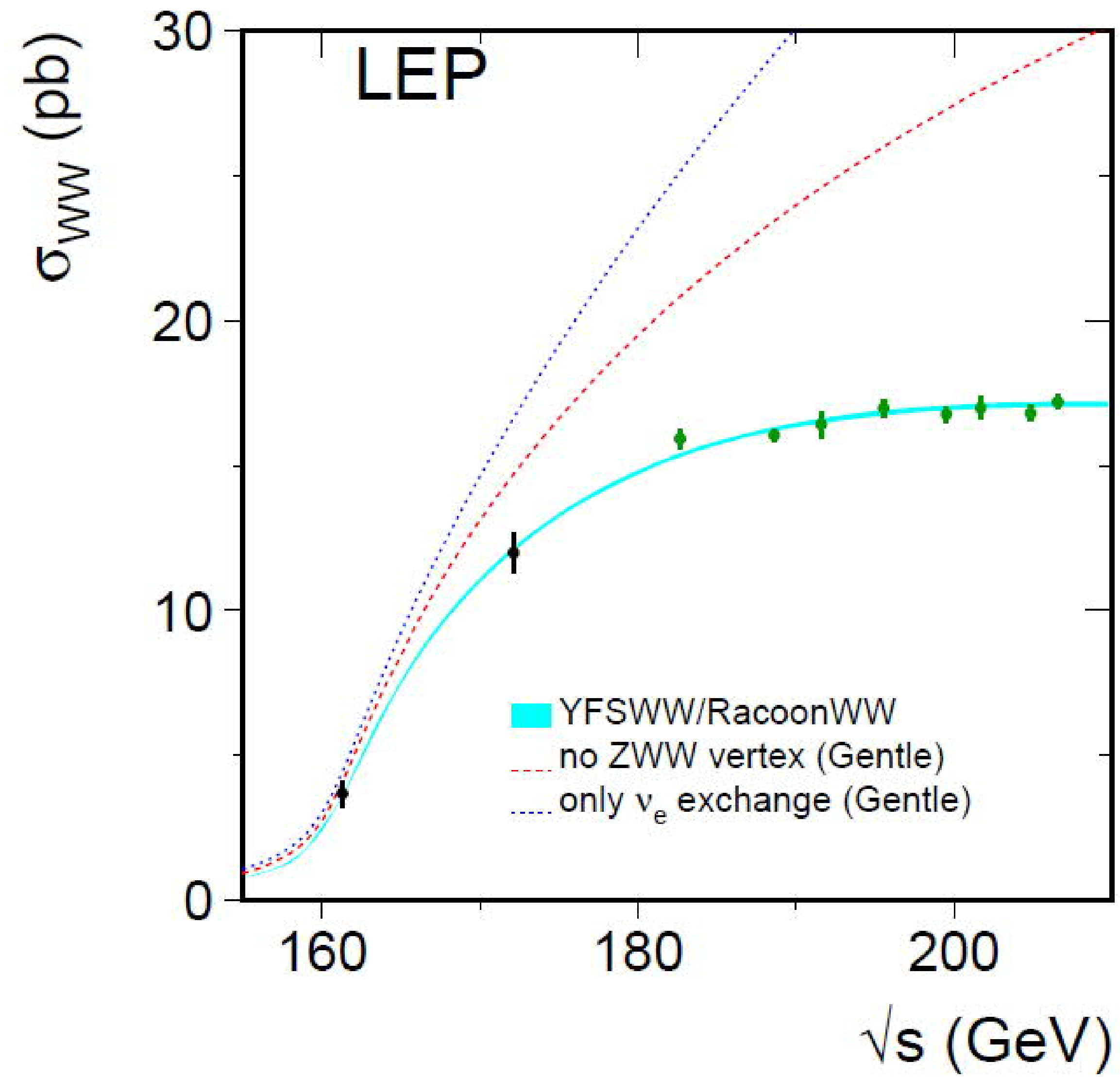
- Feynman-diagrams (Born)
  - TGC: γWW und ZWW




  - Neutrino-exchange




Cross section: $e^+e^- \rightarrow W^+W^-$




[arXiv:1302.3415]

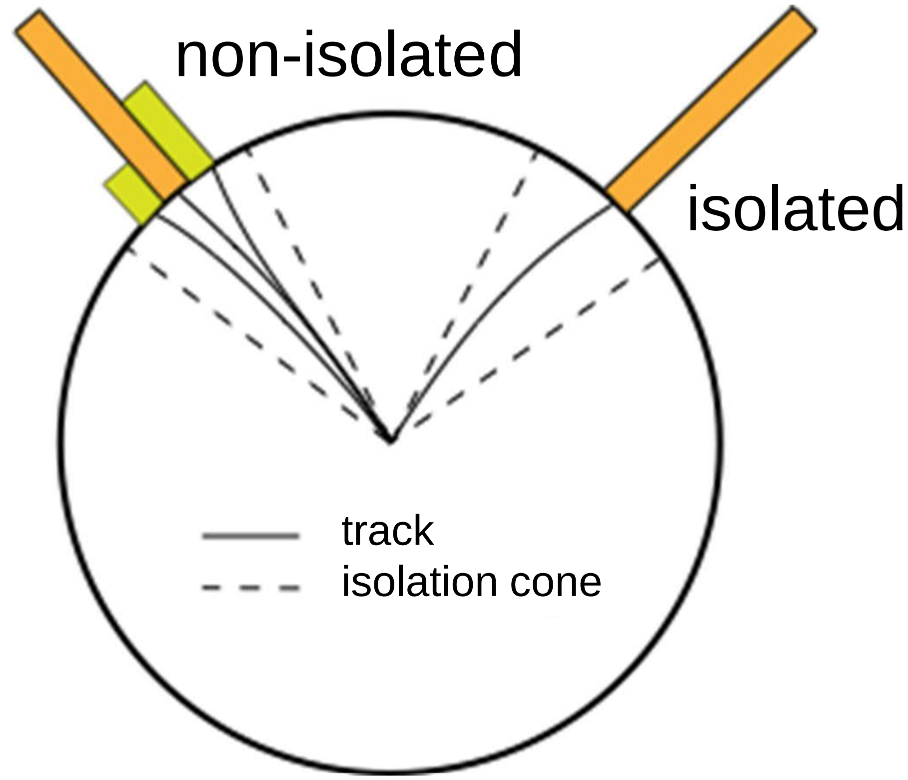
# W-Mass at Hadron-Colliders

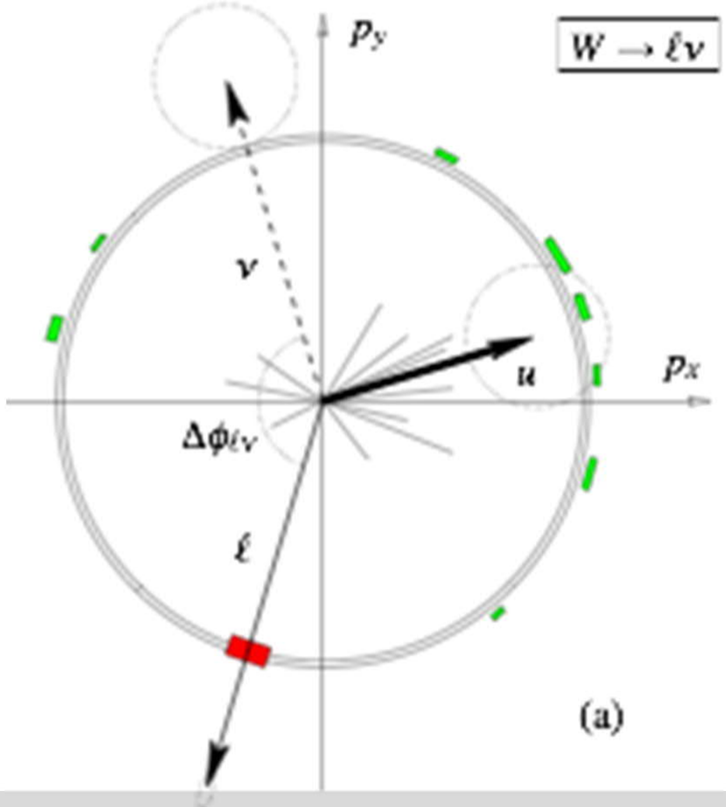
- Start the reconstruction with lepton
  - Isolated leptons with high transverse momentum → suppress multijet background
  - Prototype for many high-$p_T$-analyses at hadron-colliders
  - Additional hadronic activity → recoil against W

- Observable: transverse mass

$$m_T^2 = (E_T^\ell + E_T^\nu)^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2$$
$$\approx 2\,|\vec{p}_T^\ell|\,|\vec{p}_T^\nu|\,(1 - \cos\Delta\phi_{\ell\nu})$$

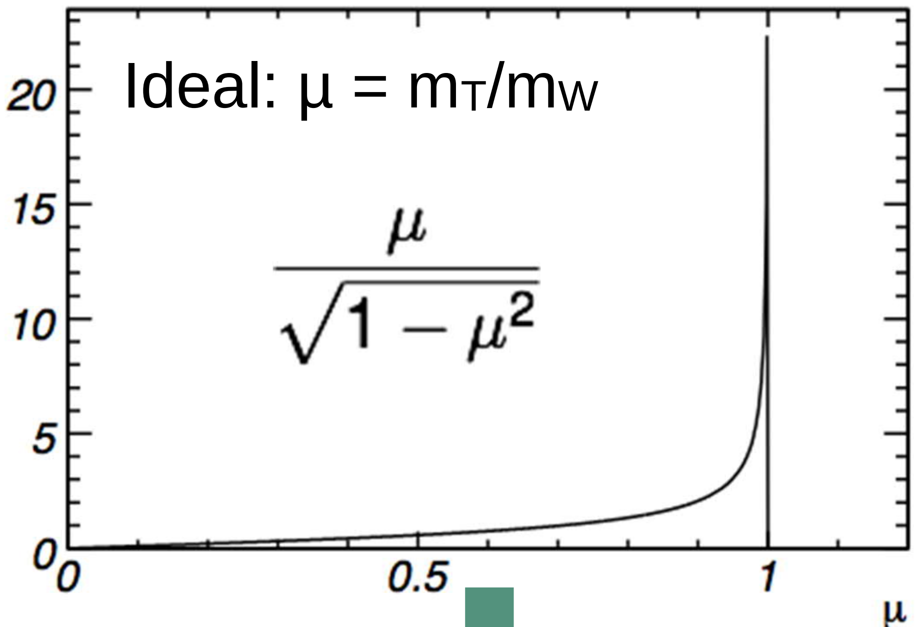
  - $p_T^\nu$ missing transverse energy in the event → assumed to represent neutrino



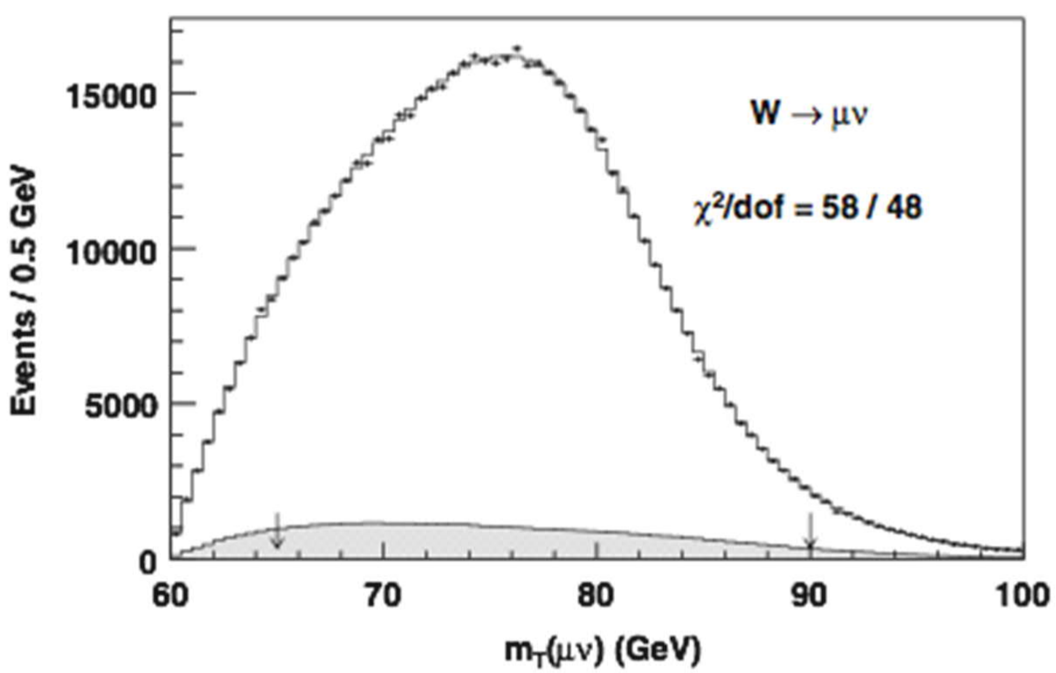



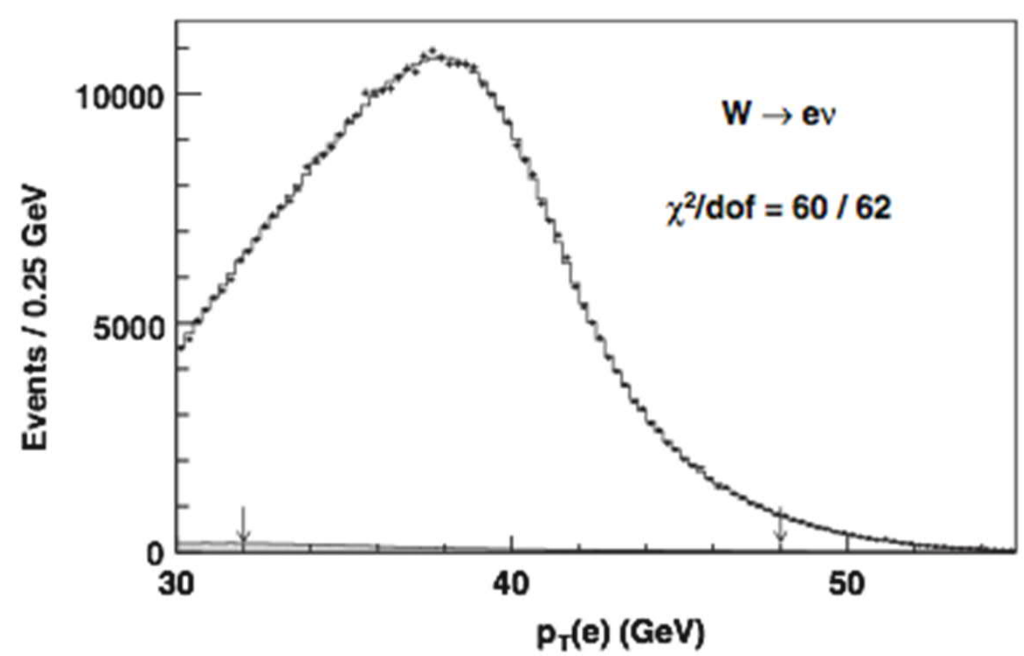

[CERN-OPEN-2008-020]

# W-Mass at Hadron-Colliders



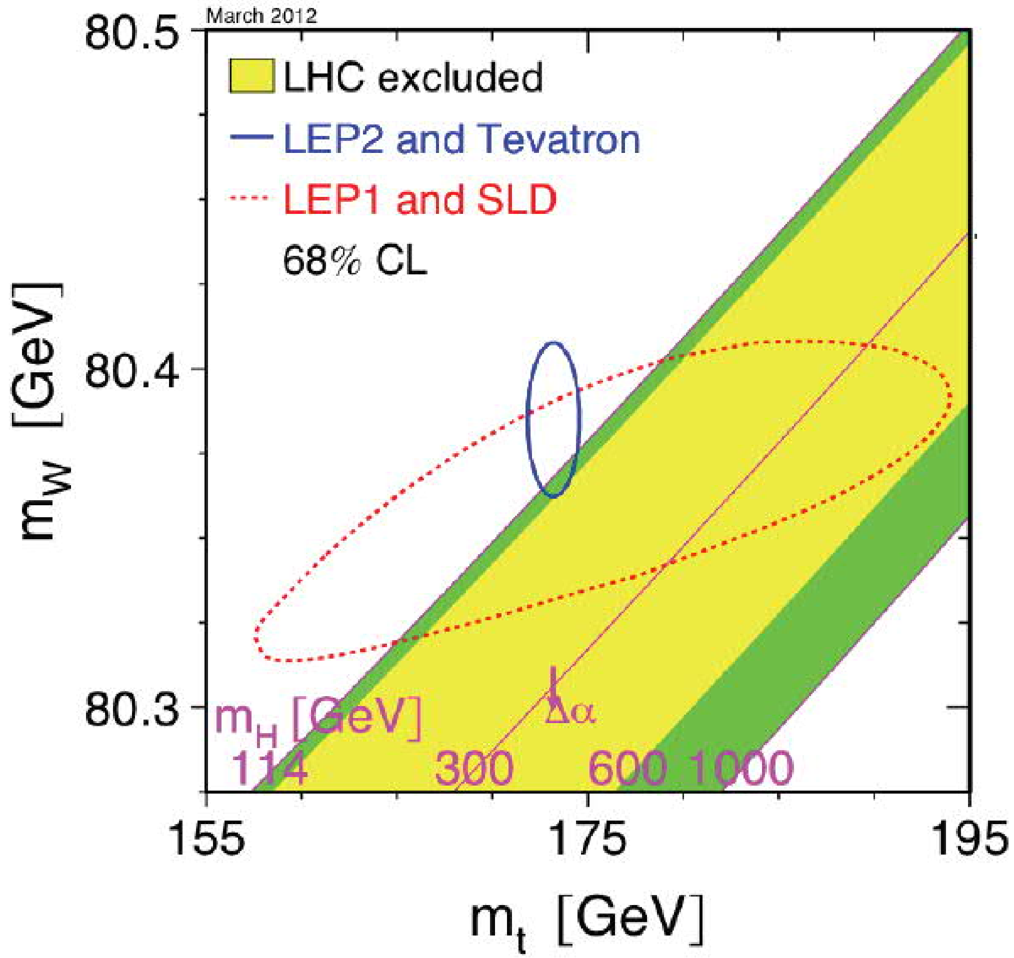

- Analysis: Likelihood-fit with templates from simulations with different W-masses
- Precision limited by systematic uncertainties: parton-densities, lepton energies, …

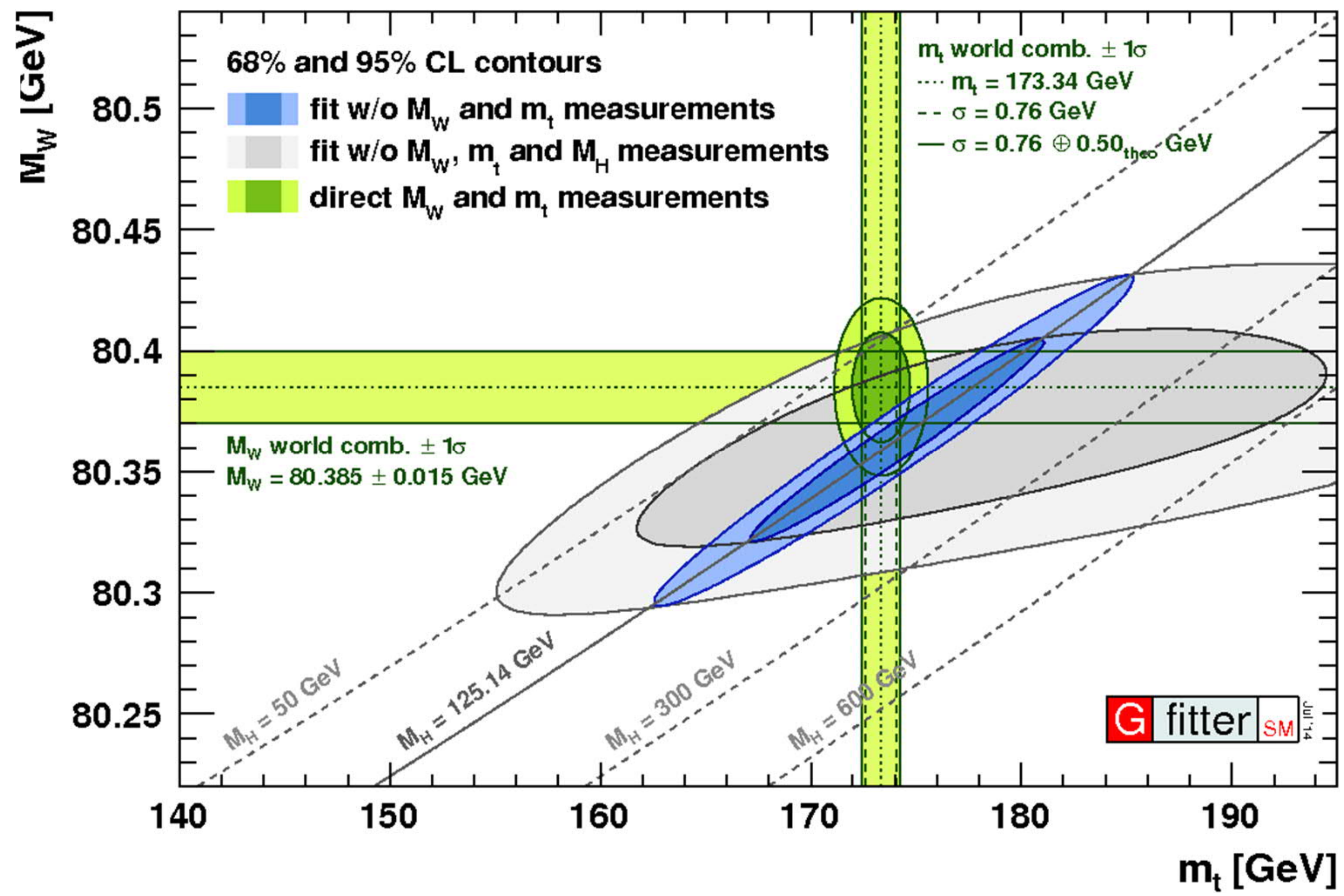



[Phys. Rev. Lett. 108 (2012) 151803]

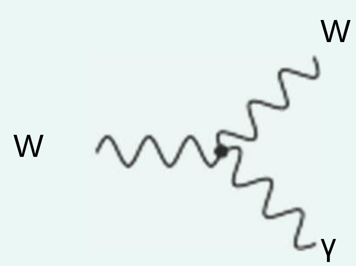
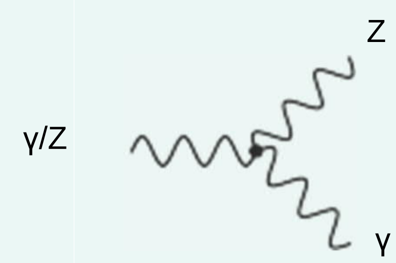
# Then and Now




- Pre-Higgs discovery: use $M_W$ + $M_{top}$ to constrain Higgs mass
- Post Hoggs discovery: use $M_W$ + $M_{top}$ + $M_H$ to constrain exotic theories that could add more particles to the loops
  → very strong limits on supersymmetry

# Anomalous TGC

| | WW | Wγ | WZ | ZZ | Zγ |
|---|---|---|---|---|---|
| **SM** |  |  |  | | |
| **aTGC** |  |  |  |  |  |

- Modified couplings caused by physics beyond the SM:
  higher cross sections, especially at high V-transverse-momentum

# Anomalous TGC: Lagrange density

- Remember: SM only allows WWγ and WWZ triple boson vertices

$$\mathcal{L}_{WW\gamma} = -\mathrm{ie}\left[A_\mu (W^{-\mu\nu} W_\nu^+ - W^{+\mu\nu} W_\nu^-) + F_{\mu\nu} W^{+\mu} W^{-\nu}\right]$$
$$\mathcal{L}_{WWZ} = -\mathrm{ie}\cot\vartheta_w \left[Z_\mu (W^{-\mu\nu} W_\nu^+ - W^{+\mu\nu} W_\nu^-) + Z_{\mu\nu} W^{+\mu} W^{-\nu}\right]$$

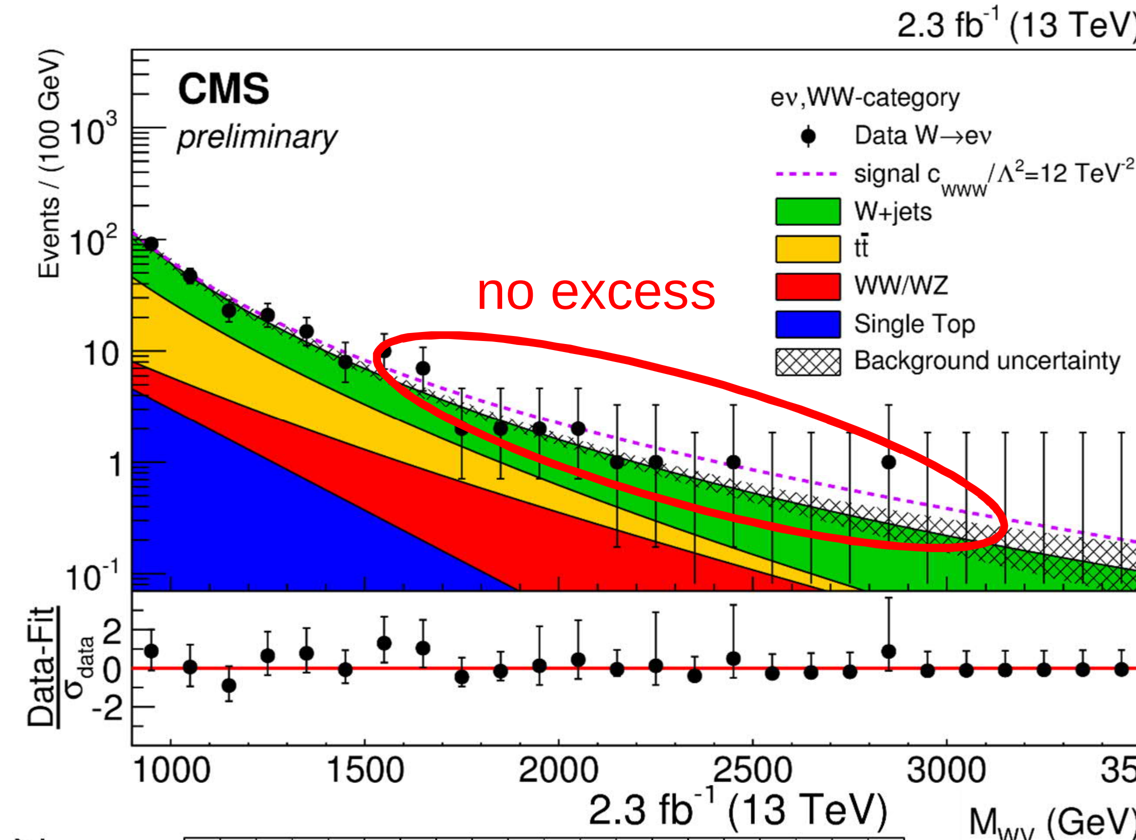
- Most general possibe effektive Lagrange density ($V$ = γ, Z)

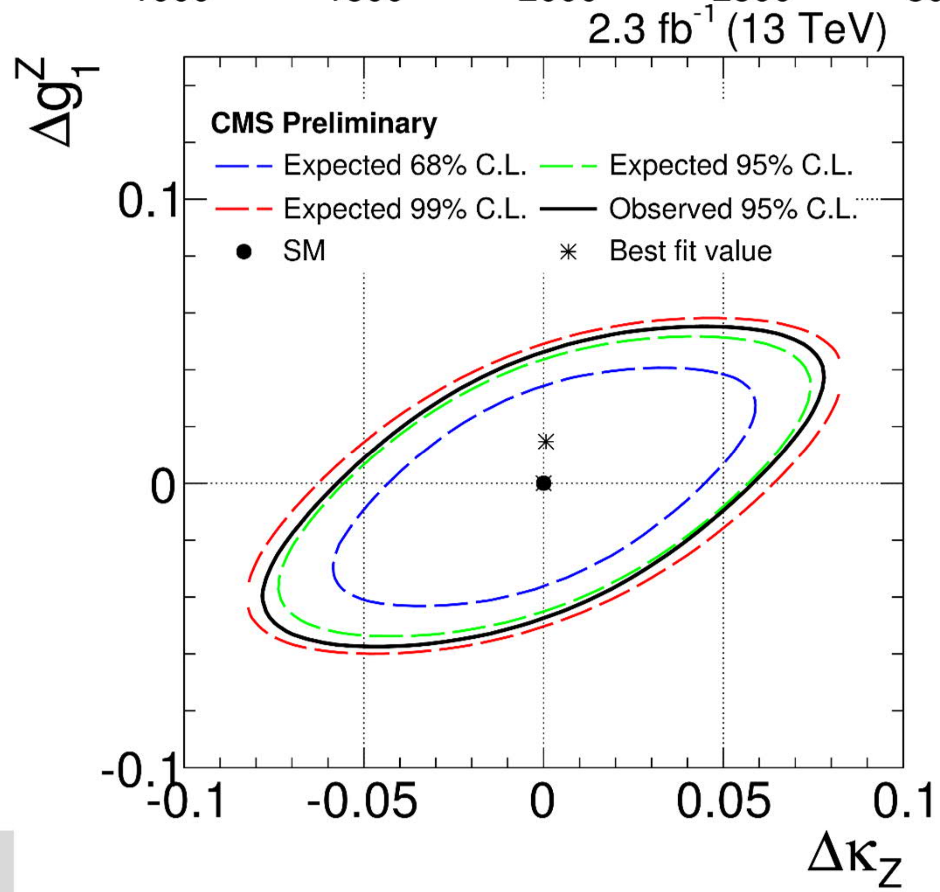
$$L_{WWV}^{\mathrm{eff}} = -ig_{WWV}\Big[g_1^V V_\mu (W^{-\mu\nu} W_\nu^+ - W_{\mu\nu}^+ W_\nu^-) + \kappa_V V_{\mu\nu} W^{+\mu} W^{-\nu}$$
$$+ \frac{\lambda_V}{m_W^2} V_{\mu\nu} W^{+\nu\rho} W_\rho^{-\mu} + ig_5^V \epsilon_{\mu\nu\rho\sigma} \left((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right) V^\sigma$$
$$+ ig_4^V W_\mu^- W_\nu^+ (\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m_W^2} W_{\rho\mu}^- W_\nu^{+\mu} \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}\Big]$$

  - SM: $g^V_1 = \kappa_V = 1$, all all other couplings vanish
  - C- und P-Erhaltung: $g^V_1$, $\kappa_V \neq 1$, $\lambda_V \neq 0$, $g_4^V = g_5^V = \tilde{\kappa}_V = \tilde{\lambda}_V = 0$

# Limits on aTGCs

- Example:
  CMS W + W/Z semi-leptonic
- Isolated lepton + MET
  → leptonic W candidate
- Fat jet with substructure
  → hadronic W candidate
- Search for excess at high diboson invariant masses
  → high aTGC contributions
- Extract limits from likelihood contours in signal+background fit

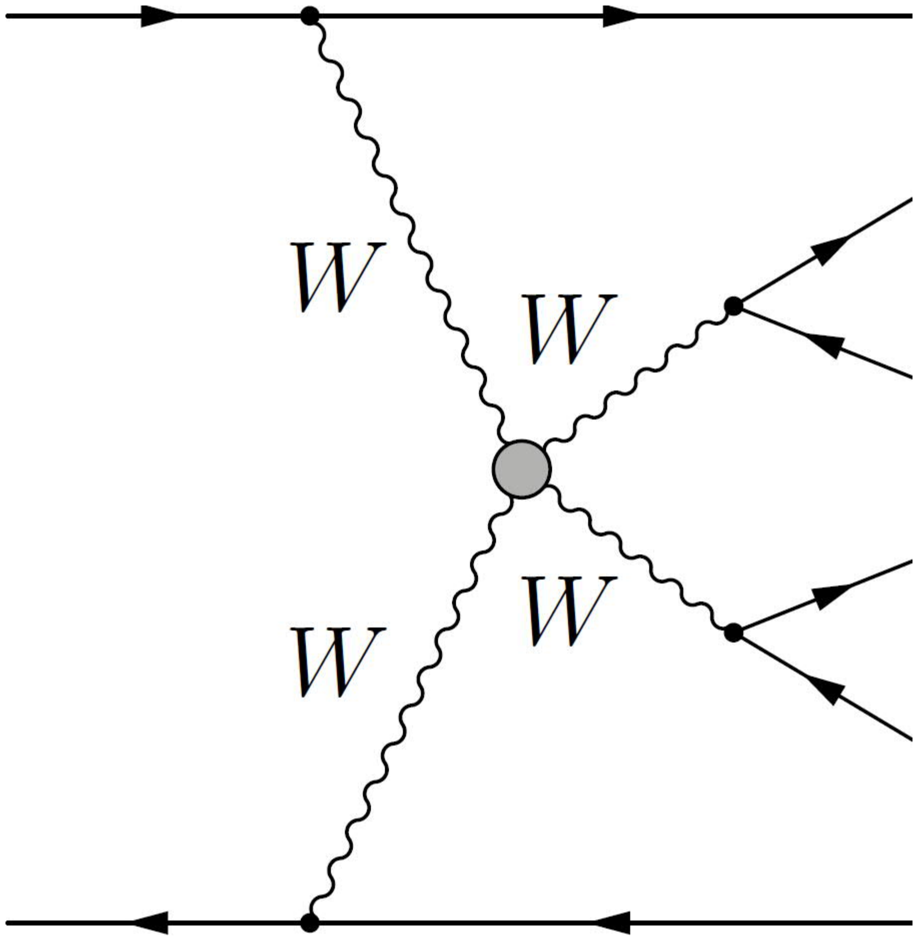


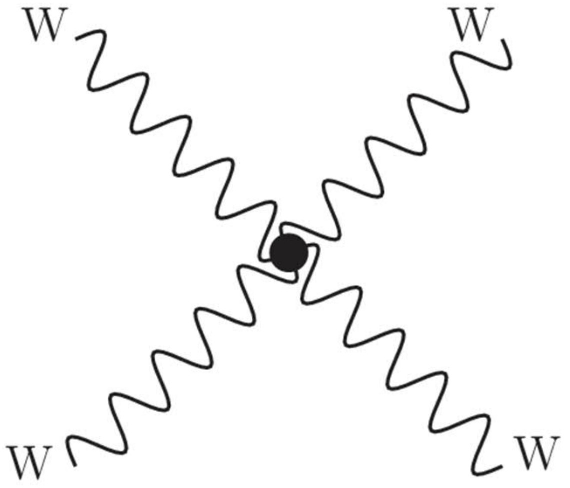



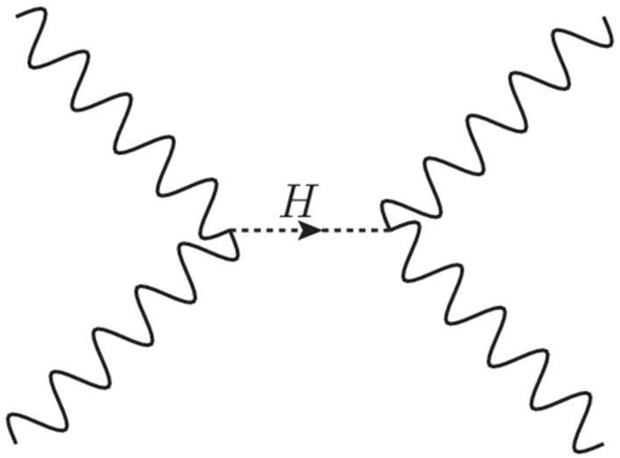

[CMS-PAS-SMP-16-012]

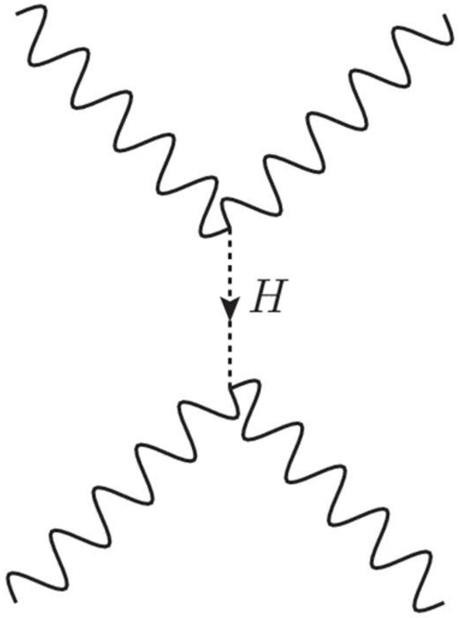
# Vector-Boson Scattering

- Study quartic vertex in vector boson scattering
- Similar to VBF process in Higgs boson physics
- Scattering cross section with longitudinally polarized bosons not unitary at high energies
- Regularised in SM by interference with Higgs boson graphs



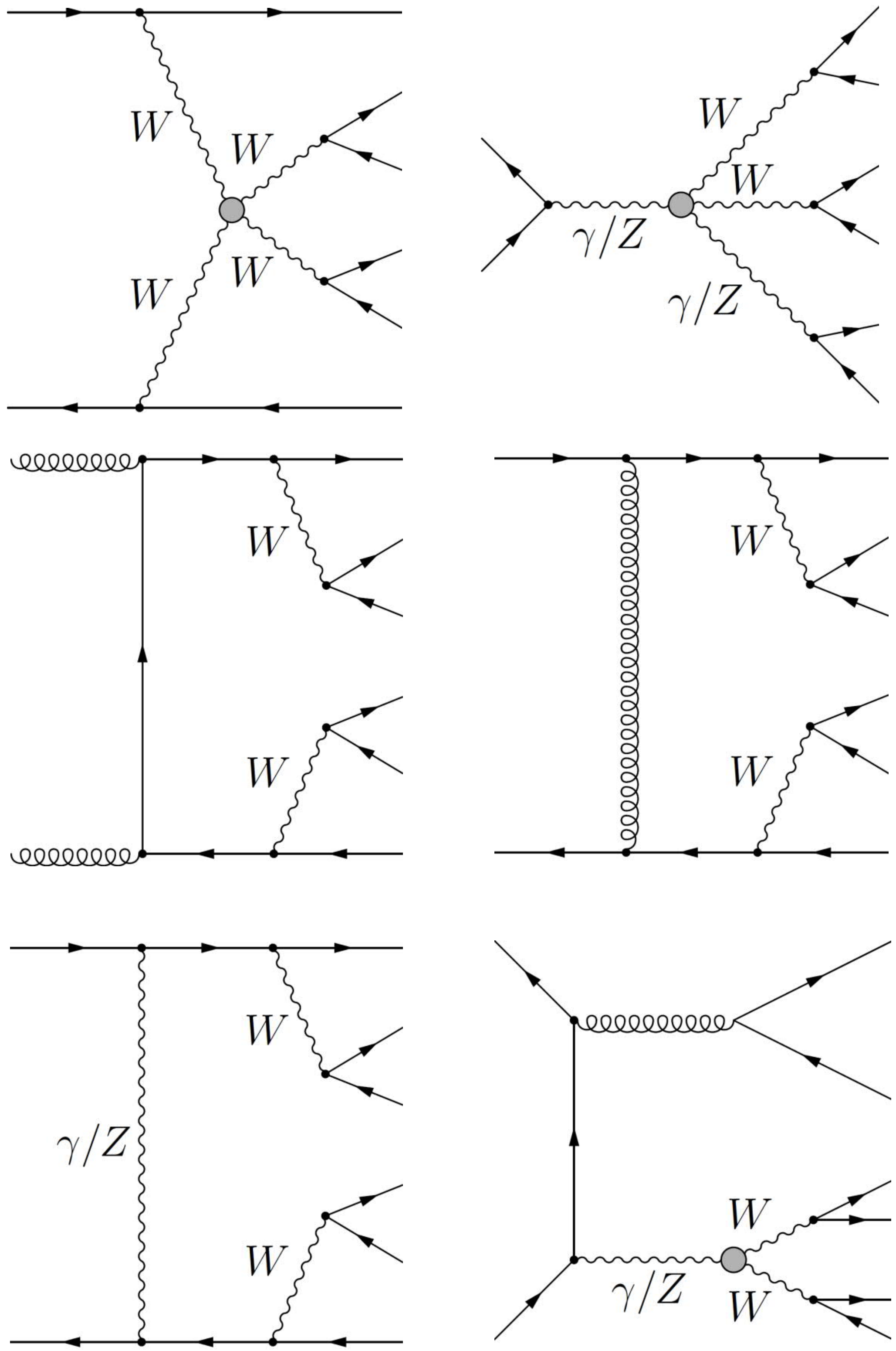



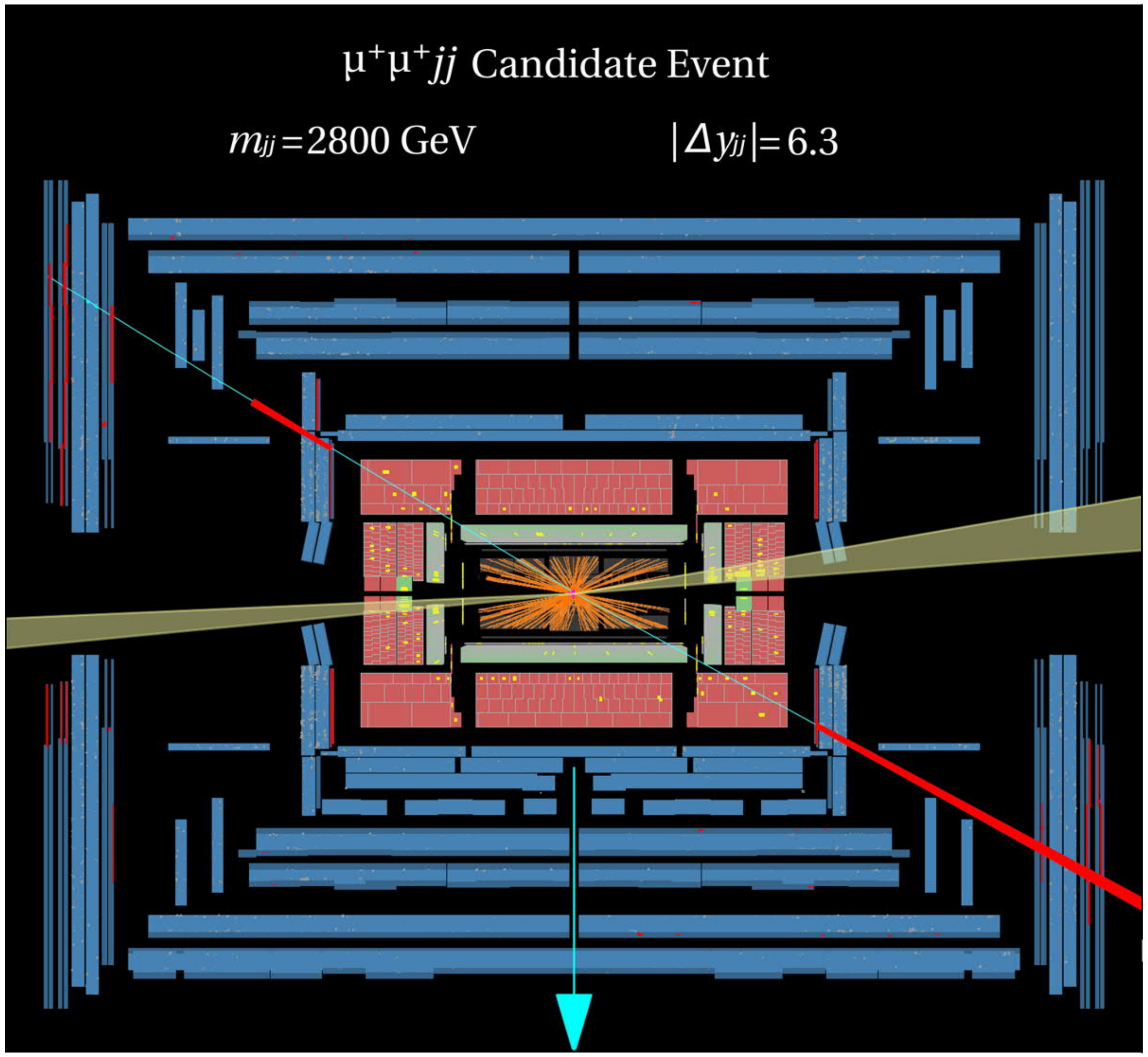
# Vector-Boson Scattering

- Detailed test of the Higgs mechanism
- 2W + 2jet processes „common“ even without quartic vertex
- Enhance VBS with suitable selections:
  - jets with high dijet-mass
  - large difference in rapidity
- Only look at $W^{+/-}W^{+/-}$
  => no gluons in the initial state

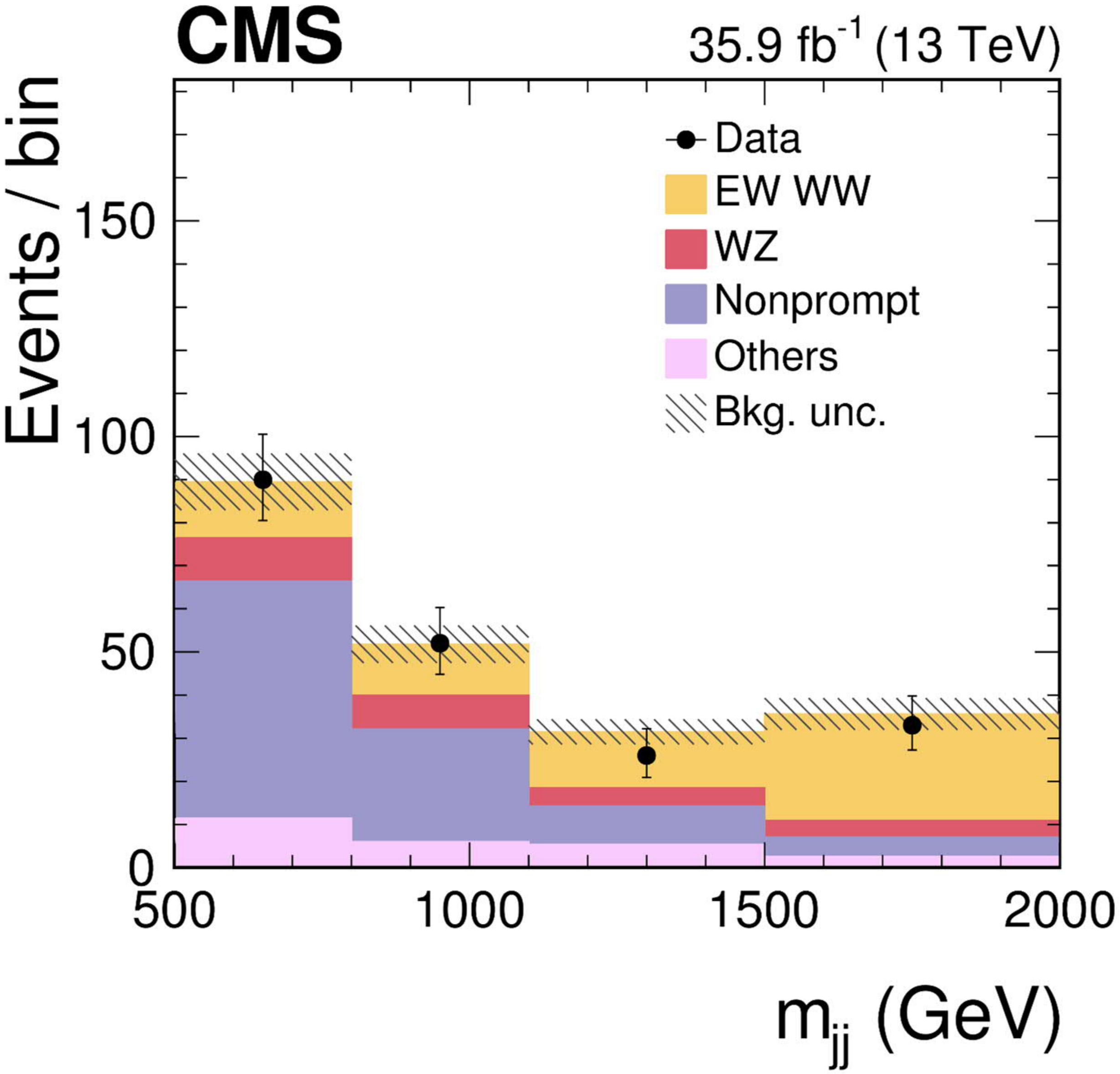


# Quartic Couplings

- Measurement in pp $\rightarrow$ $W^+W^+jj$
- Limits on anomalous couplings




[Atlas-CONF-2014-013]




[CMS-SMP-17-004]