KSETA-Course: Accelelerator-Based Particle Physics

Electroweak Physics

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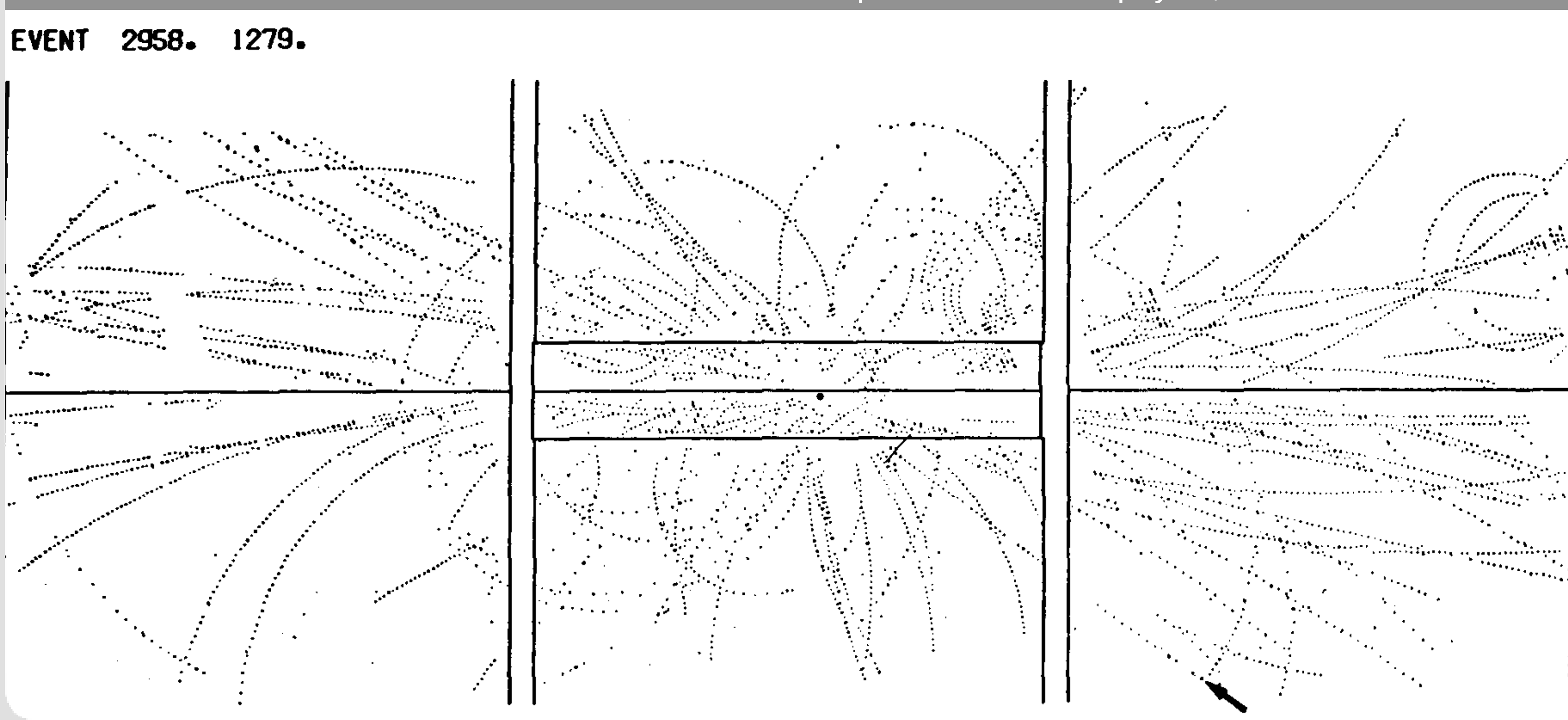
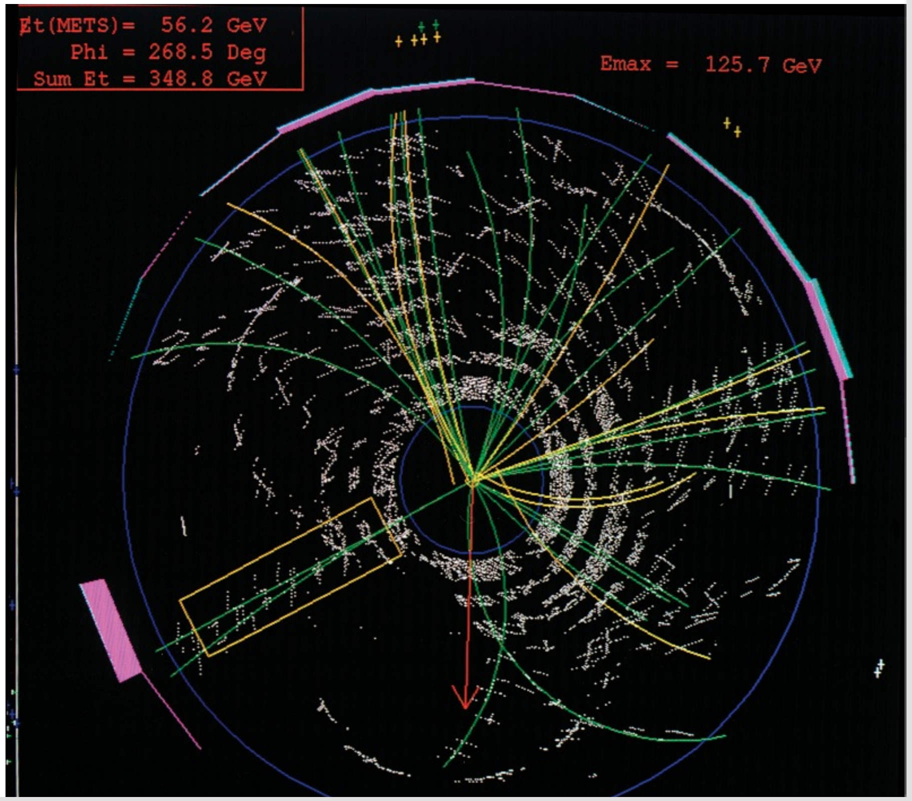
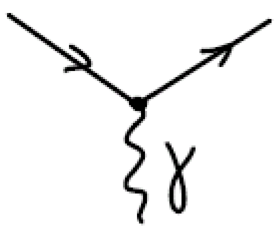




Elektromagnetic Interaction & CC

- Electromagnetic Interaction (Fermion with charge e)

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



elem. charge

EM current

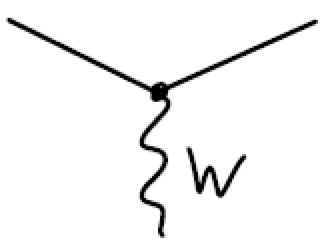
photon

weak mixing angle

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

- Charged Current: V-A structure

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



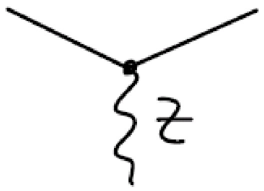
quark mixing

CC for quarks

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

NC & Selfcoupling

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



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

vector-coupling axial-coupling

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

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

- Selfcouplings of gauge bosons: only WWγ, WWZ

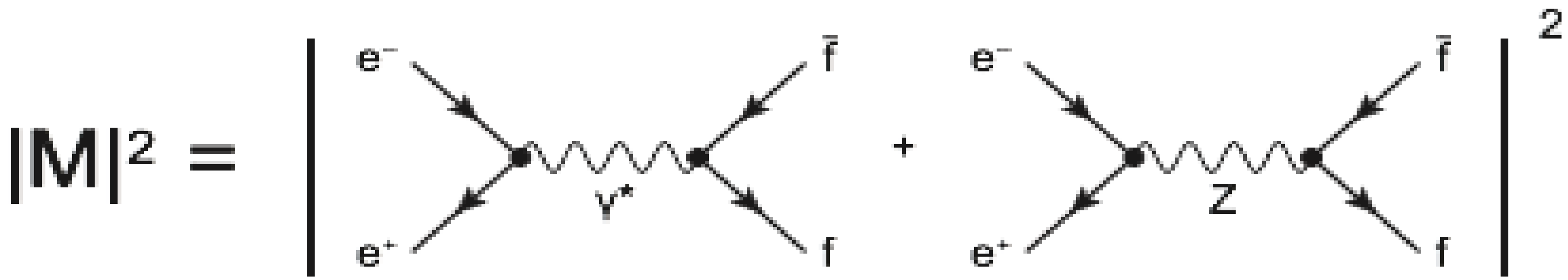
$$\mathcal{L}_{\mathrm{WW}\gamma} = -\mathrm{ie}\left[A_\mu (W^{-\mu\nu} W_\nu^+ - W^{+\mu\nu} W_\nu^-) + F_{\mu\nu} W^{+\mu} W^{-\nu}\right]$$

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

- +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:

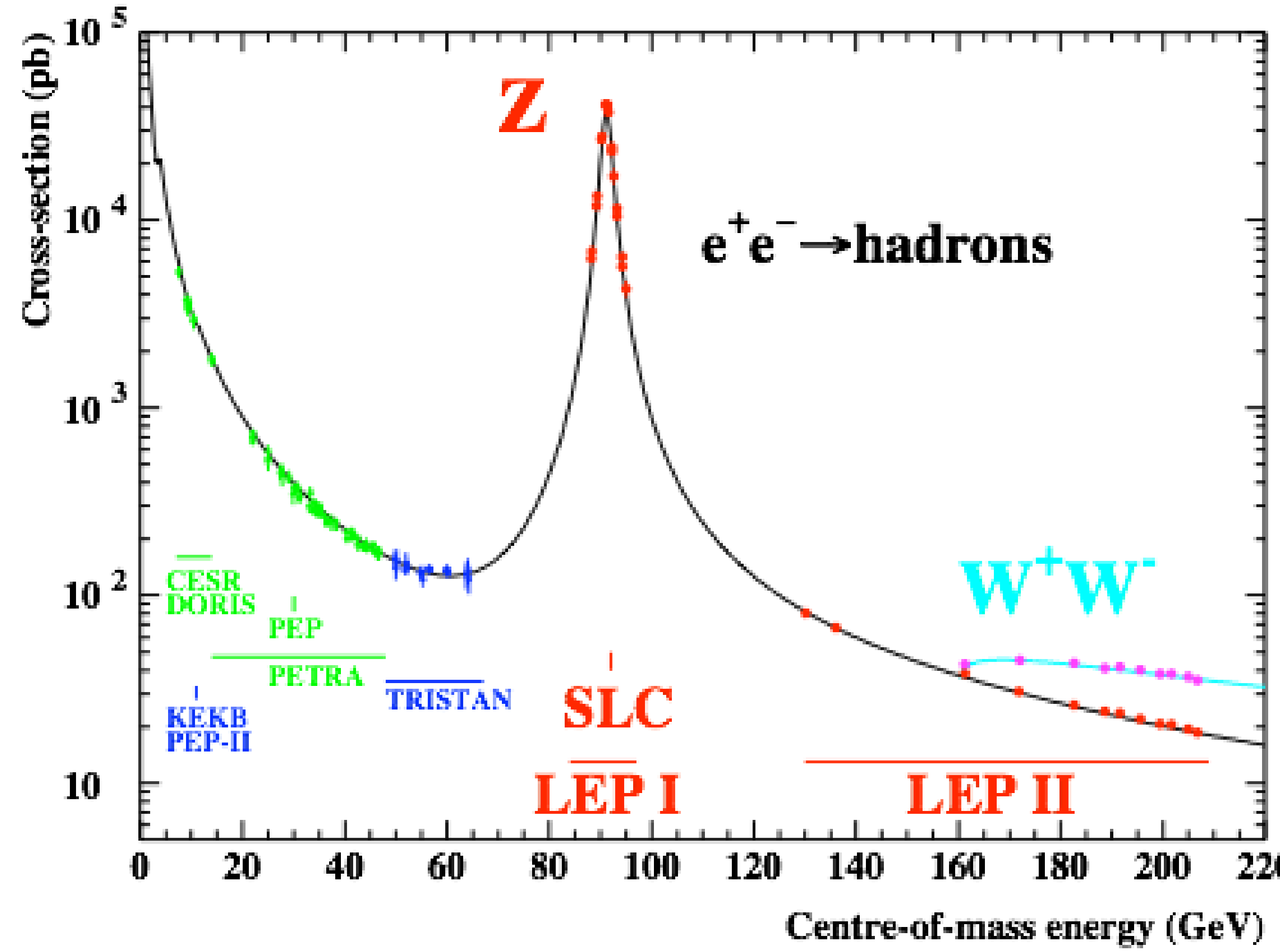


  - cross section: $$\sigma(e^+e^- \to f\bar{f}) = \sigma_{\gamma^*} + \sigma_{\gamma^*/Z} + \sigma_Z$$

- $\sqrt{s} \ll m_Z$: 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 τ_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

Karlsruher Institut für Technologie

- 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 Γ_{inv} from Γ_Z and other f

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

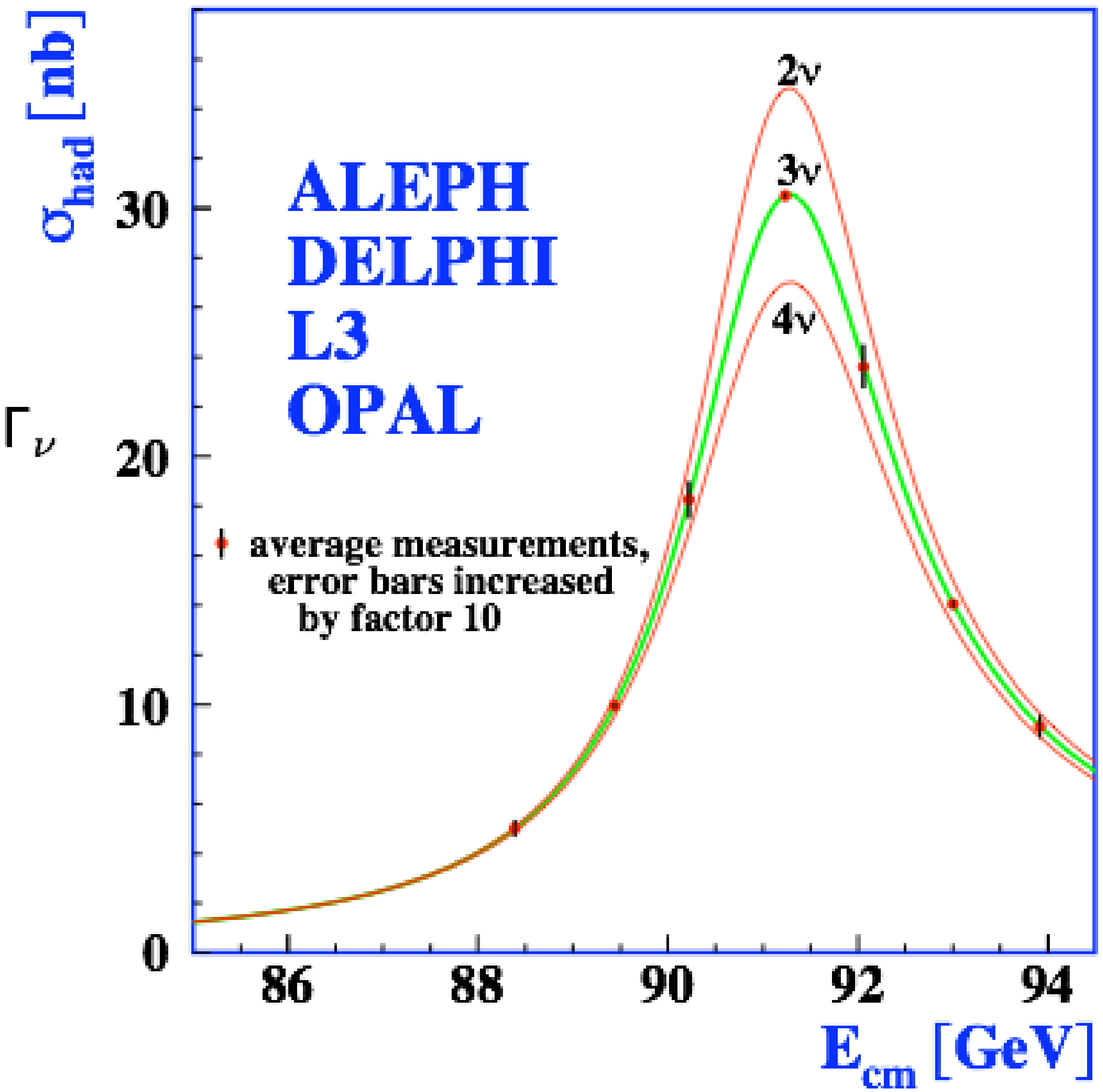
- Divide Γ_{inv} by Γ_ν derived from theory

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

Number of neutrinos in pictures

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

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

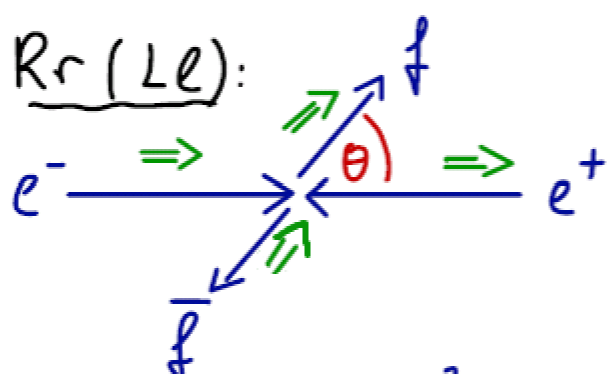


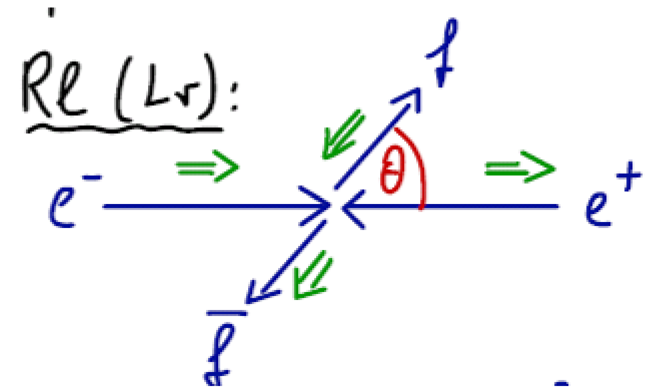
[Phys. Rep. 427 (2006) 257]

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

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

helicities: photon $\Rightarrow$ spin 1





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

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

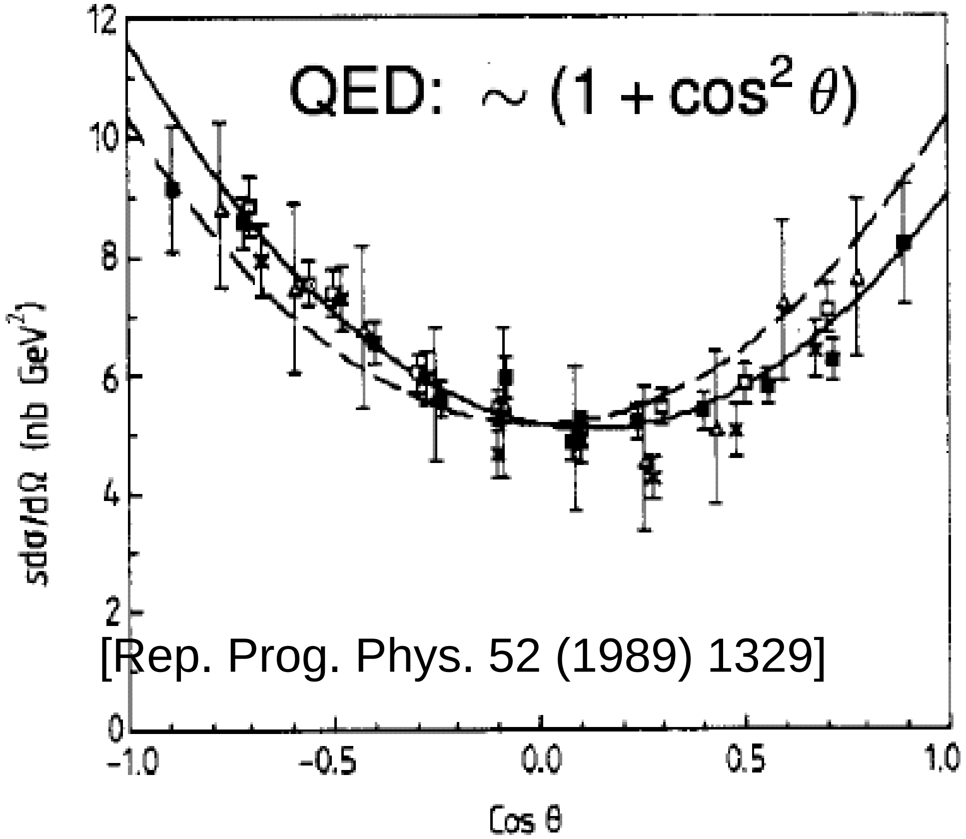
colors $\qquad$ charge

√s ≪ m_Z: Angular Distribution

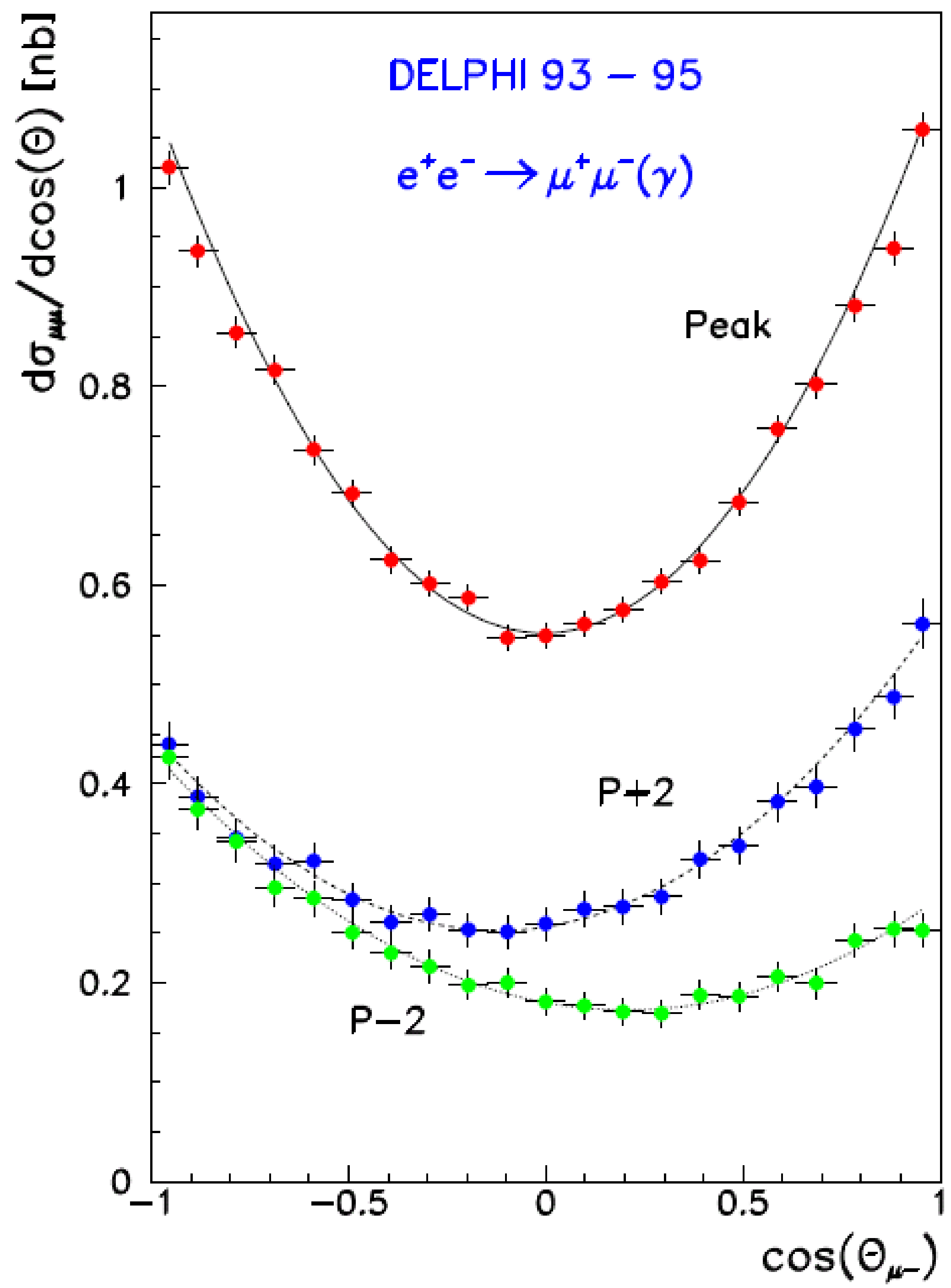
LEP: √s = m_Z ± 2 GeV

- 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]



[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:

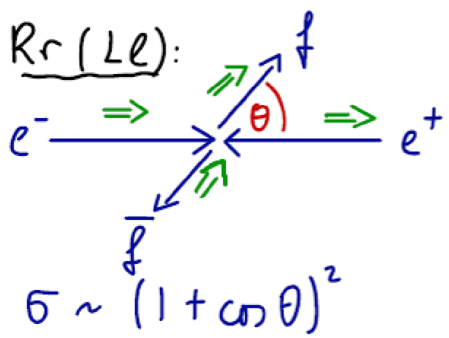
→ 4 helicities (using $g_R = g_V + g_A, g_L = g_V - g_A$)

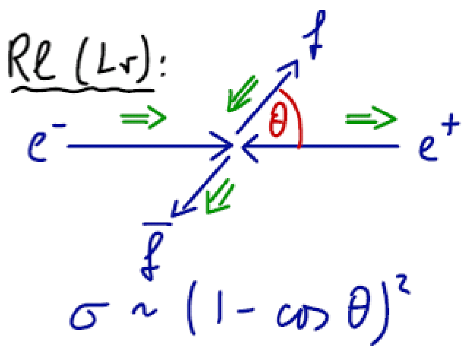
$$\frac{d\sigma_f}{d\cos\theta} \sim (g_L^e)^2 (g_L^f)(1 + \cos\vartheta)^2$$

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

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

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





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

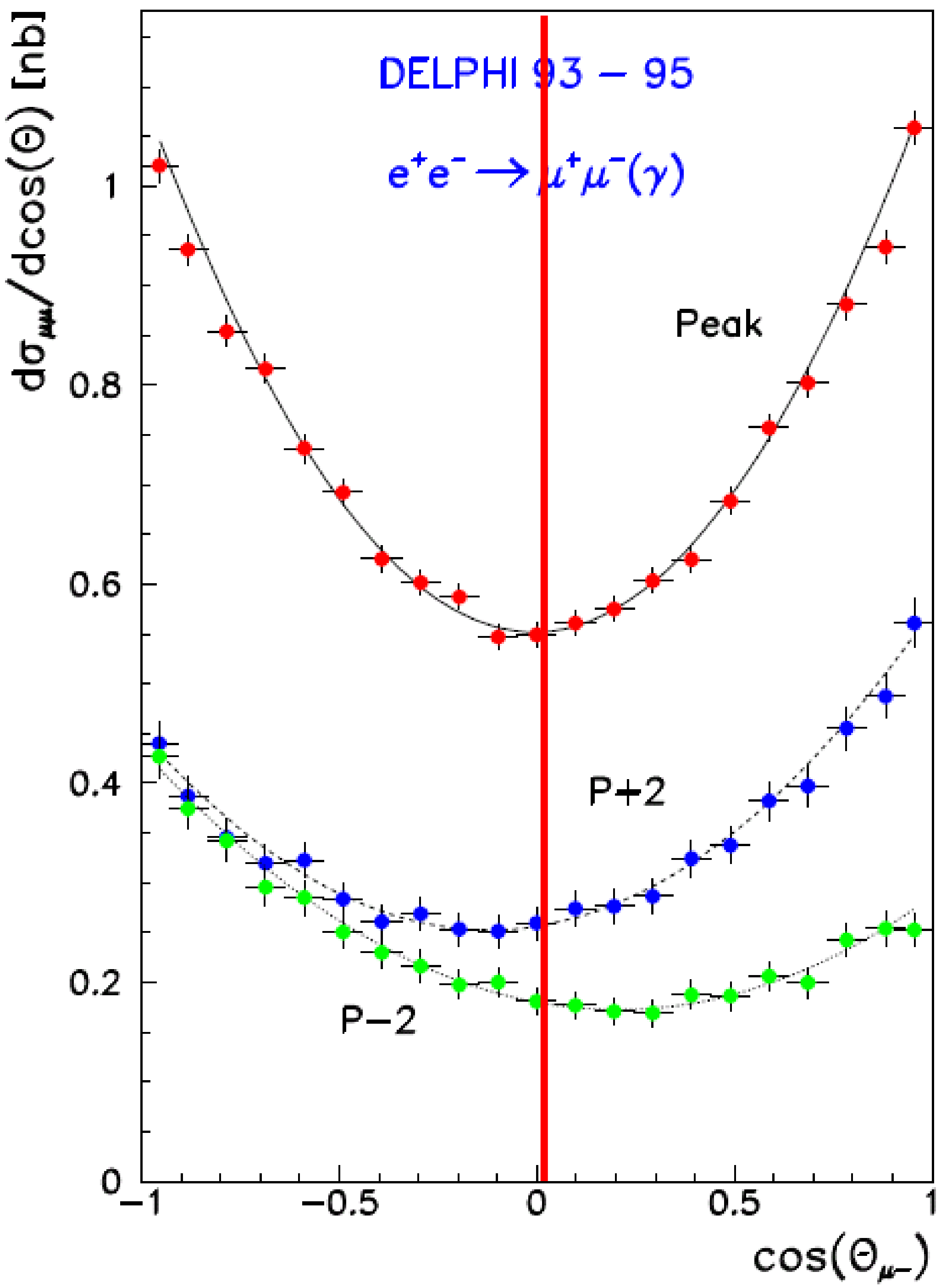
$$A_f = \frac{\left(g_L^f\right)^2 - \left(g_R^f\right)^2}{\left(g_L^f\right)^2 + \left(g_R^f\right)^2} = 2\,\frac{g_V^f / g_A^f}{1 + \left(\frac{g_V^f}{g_A^f}\right)^2}$$

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

Forward-Backward-Asymmetry

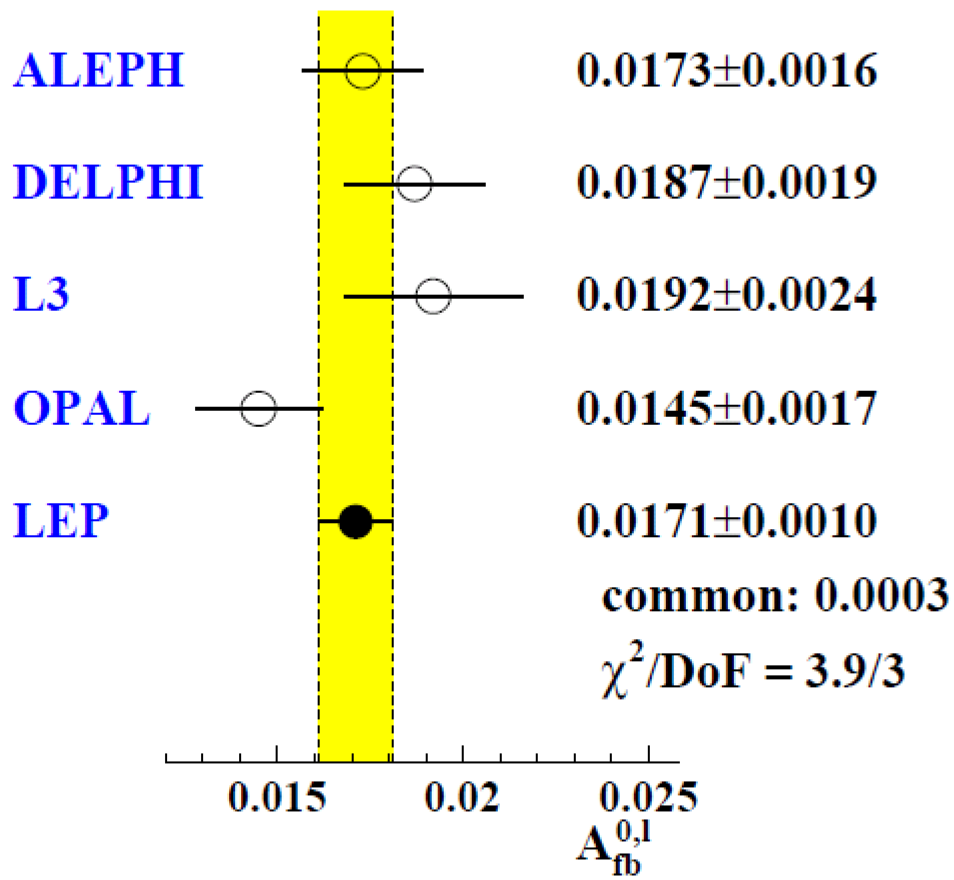
$$\sigma_F \equiv \int_0^{\pi/2} \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\vartheta}\,\mathrm{d}\vartheta \qquad \sigma_B \equiv \int_{\pi/2}^{\pi} \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\vartheta}\,\mathrm{d}\vartheta$$

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

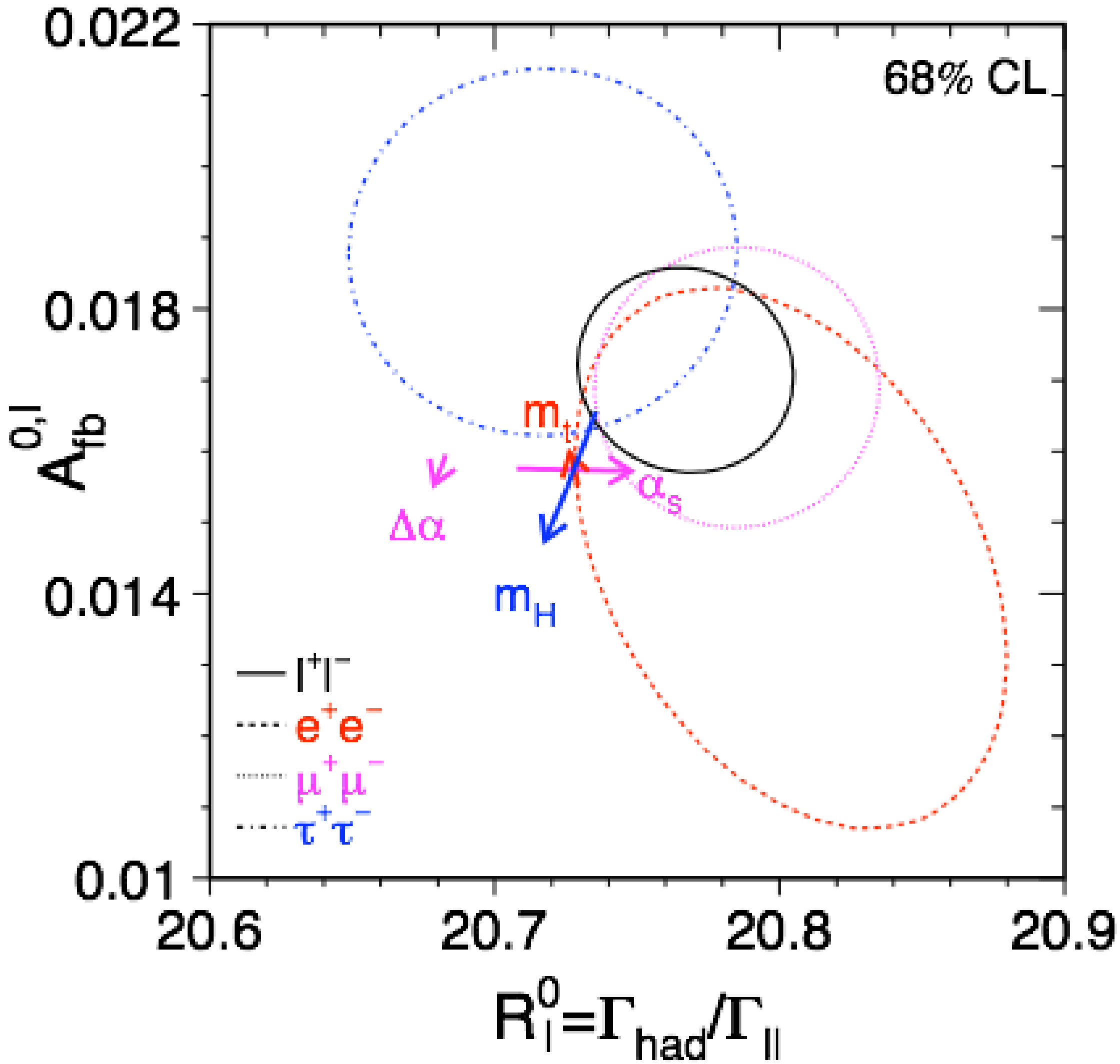


A_{FB}: Results from LEP

LEP-average: A_{FB} for leptons



A_{FB} separatly for e, μ, τ vs. R^0



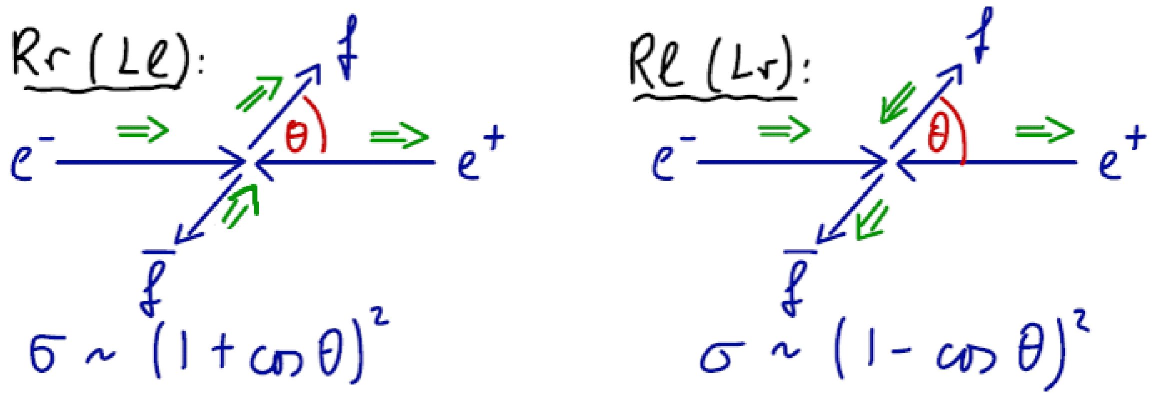
[Phys. Rep. 427 (2006) 257]

Final State Polarisation

- Measure the polarization P of the outgoing particles
- $P_f \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$
- No initial state polarization at LEP

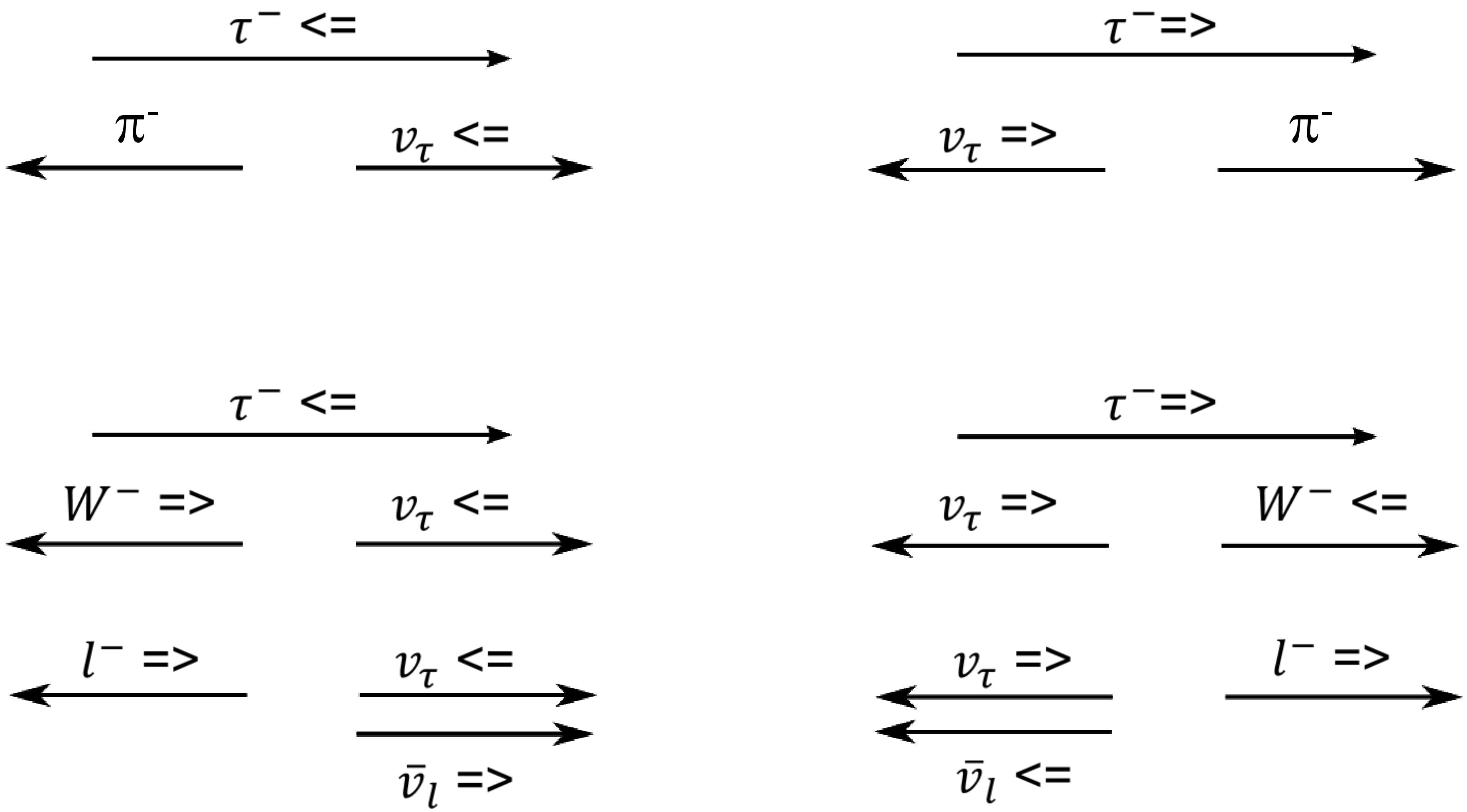
$$\Rightarrow P_f(\cos\vartheta) = \frac{A_f(1+\cos^2\vartheta)+2A_e\cos\vartheta}{(1+\cos^2\vartheta)+\frac{8}{3}A_{fFB}\cos\vartheta}$$

- Separate access to A_f and A_e



Polarisation Measurement

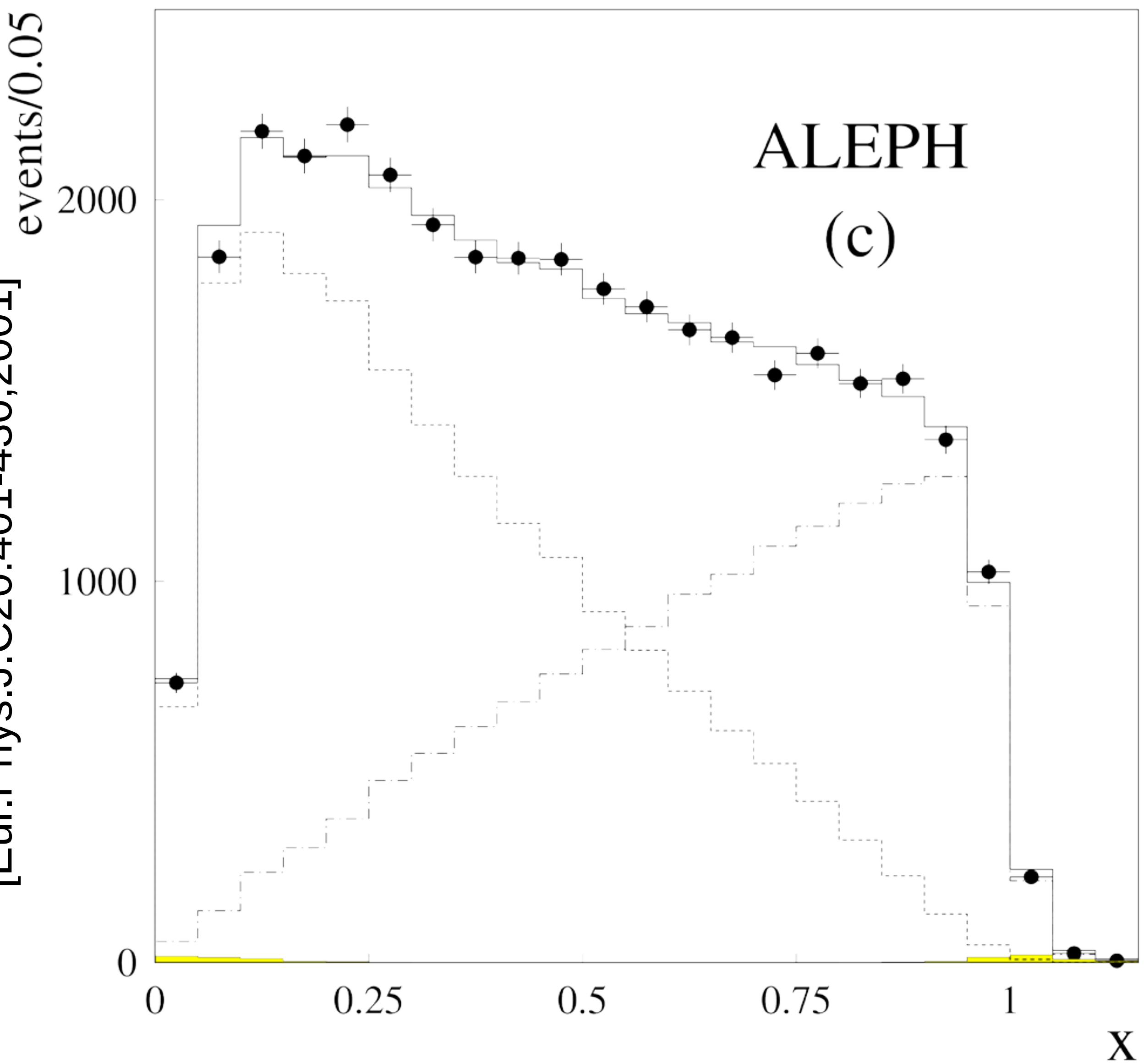
- τ-lepton has self-analyzing decay

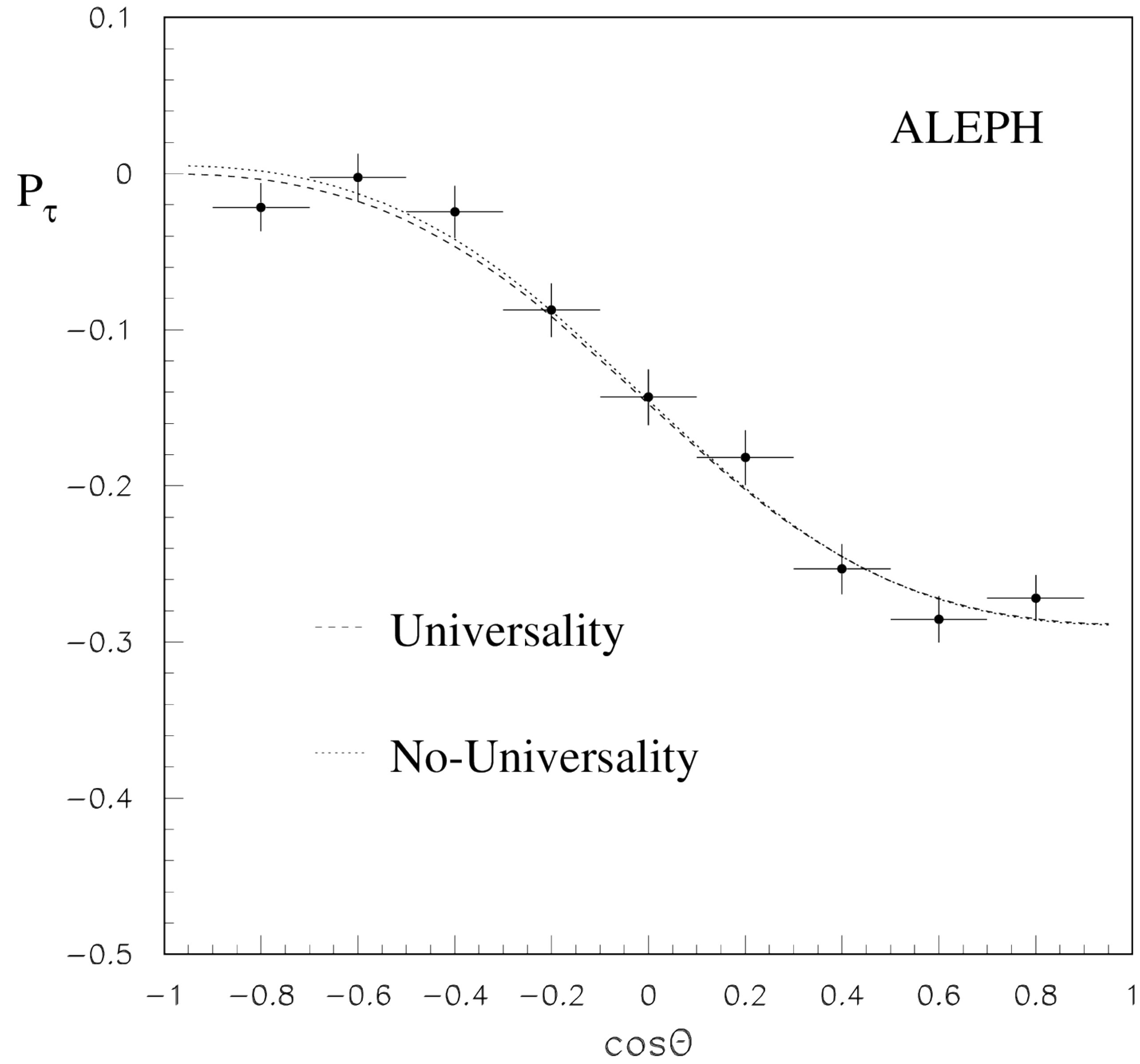


- Visible daughter(s) carry larger (smaller) momentum fraction for right- (left-) handed τ-leptons

Polarisation: Results

[Eur.Phys.J.C20:401-430,2001]

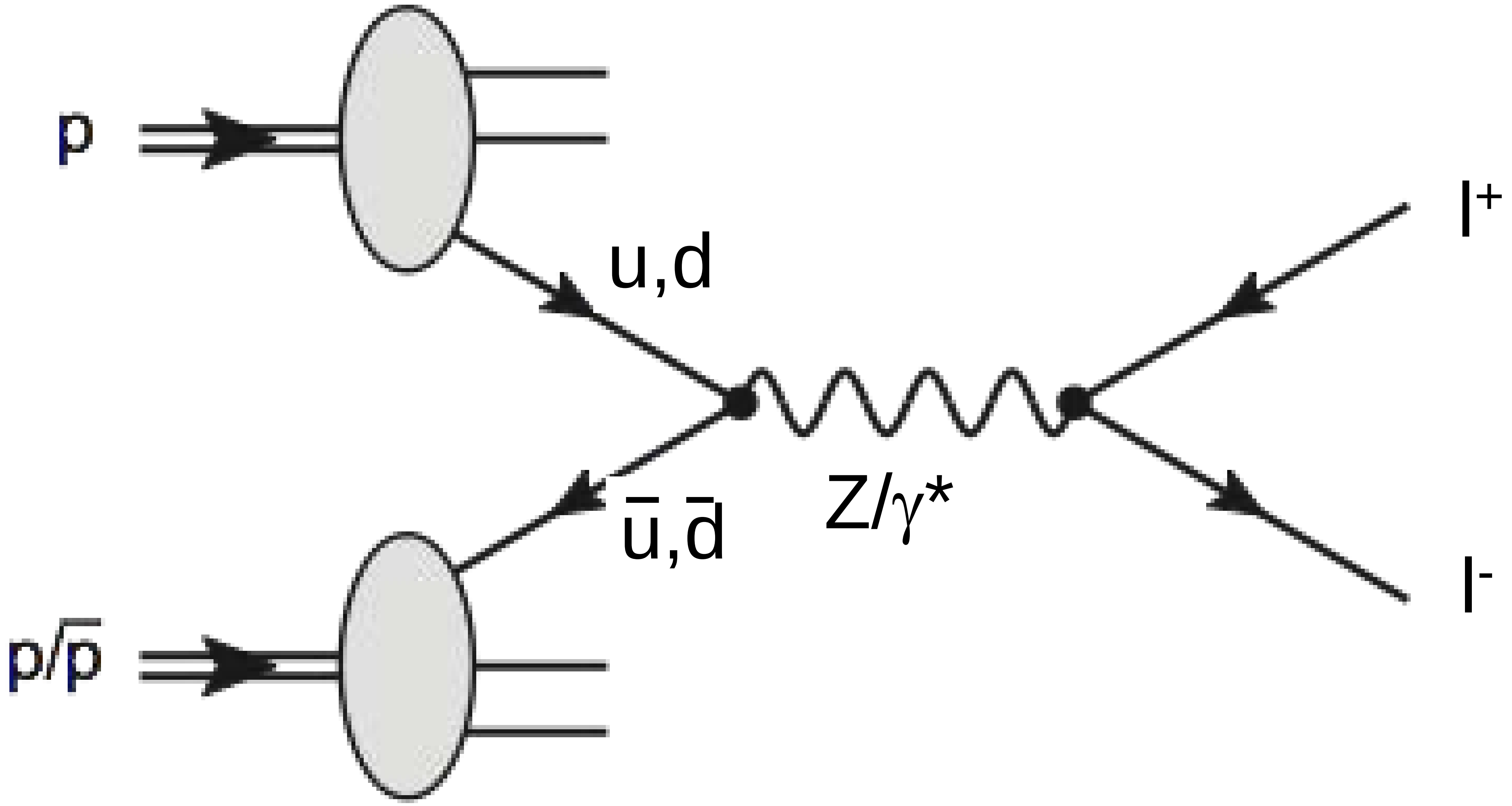




Fit for P with $A_e = A_\tau$ and $A_e \neq A_\tau$

$\Rightarrow$ test lepton universality

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

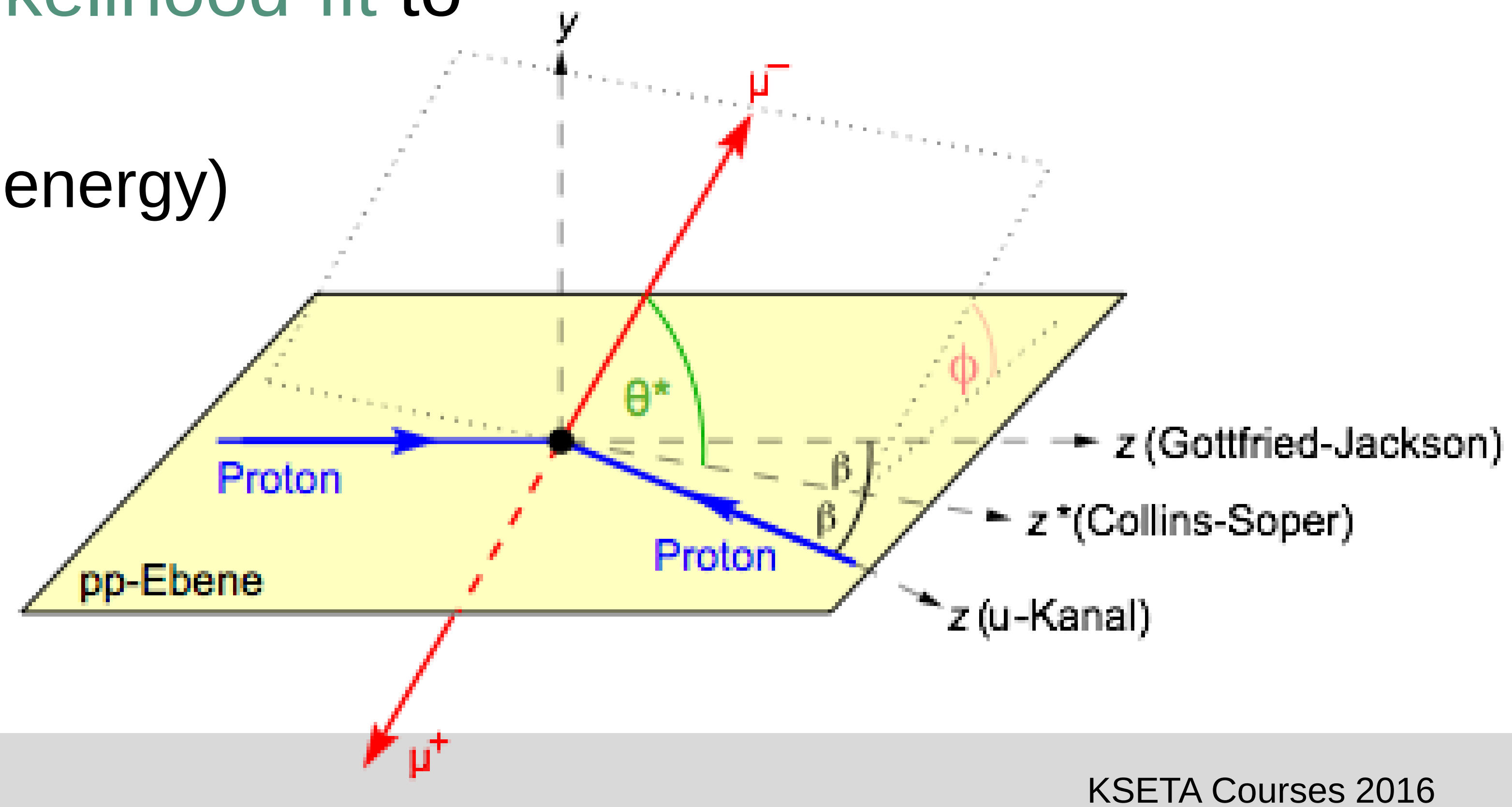
Weak mixing angle

- Drell-Yan-Prozess: $q\bar{q} \rightarrow \gamma^*/Z \rightarrow f\bar{f}$
  - Standard model: relative couplings of fermions to γ/Z given by $\sin^2 \theta^f_{W,eff}$

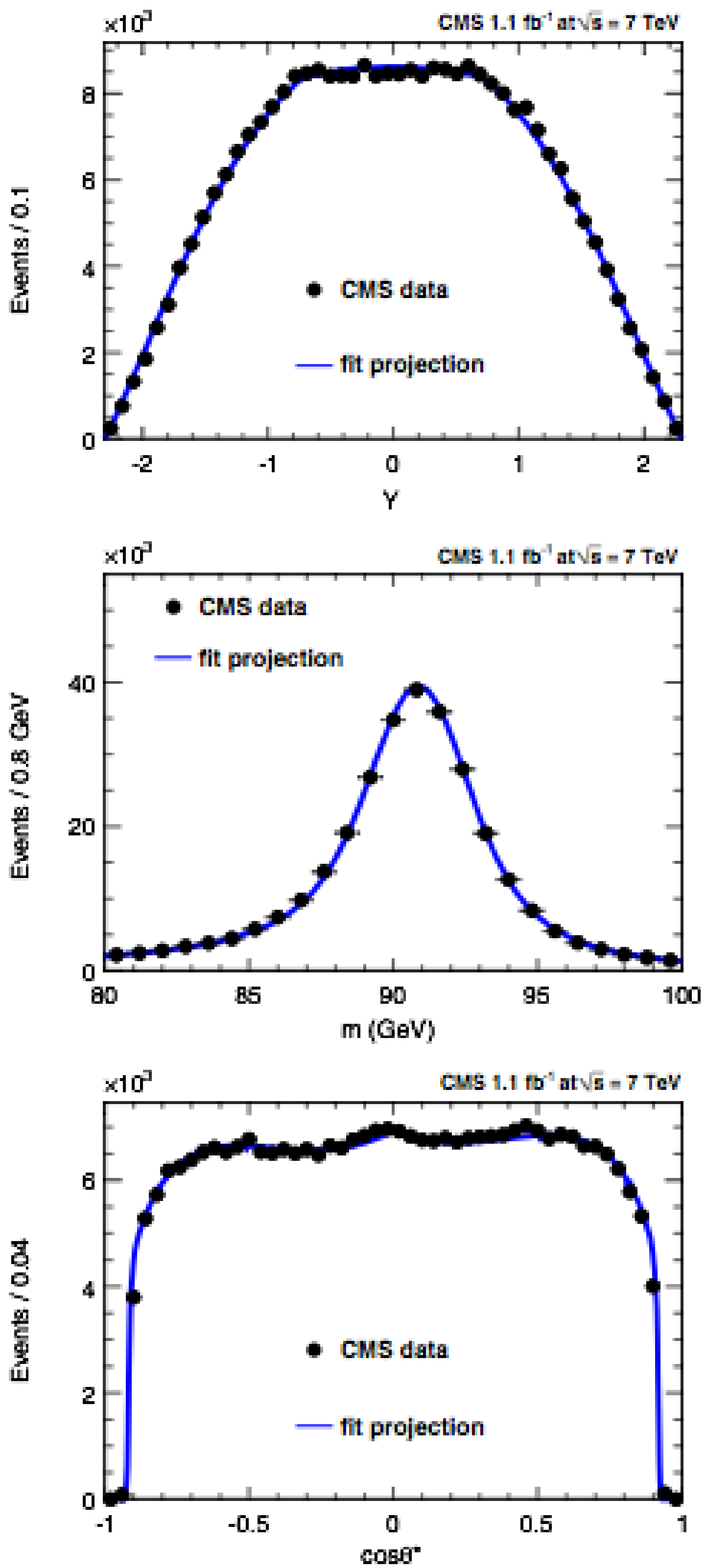
$$\sin^2 \theta^f_{W,\text{eff}} = \frac{I_3^f}{2q^f}\left(1 - \frac{g_V^f}{g_A^f}\right)$$

  - 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
  - Myon pair mass M(μμ)
    (= partonic center of mass energy)
  - Myon pair rapidity Y
  - Myon angle θ*
    (Collins-Soper-frame)



Weak Mixing Angle



[Phys. Rev. D84 (2011) 112002]

- CMS-results:

$\sin^2 \theta^f_{W,eff} = 0.2287 \pm 0.0020$ (stat.) ± 0.0025 (syst.)

  - consistent with LEP- resultat ($\sin^2 \theta^f_{W,eff} = 0.23153 \pm 0.00016$)
  - uncertainty: 1.4% (LEP: 0.07%)

- Systematic uncertainties:

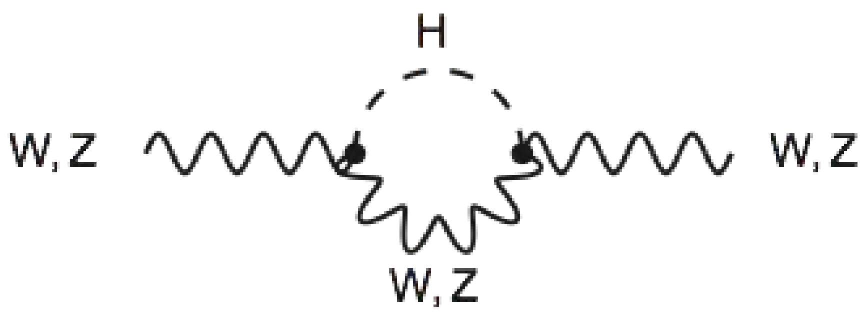
source	correction	uncertainty
PDF	–	± 0.0013
FSR	–	± 0.0011
LO model (EWK)	–	± 0.0002
LO model (QCD)	$+0.0012$	± 0.0012
resolution and alignment	$+0.0007$	± 0.0013
efficiency and acceptance	–	± 0.0003
background	–	± 0.0001
total	$+0.0019$	± 0.0025

Measuring the W-mass

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

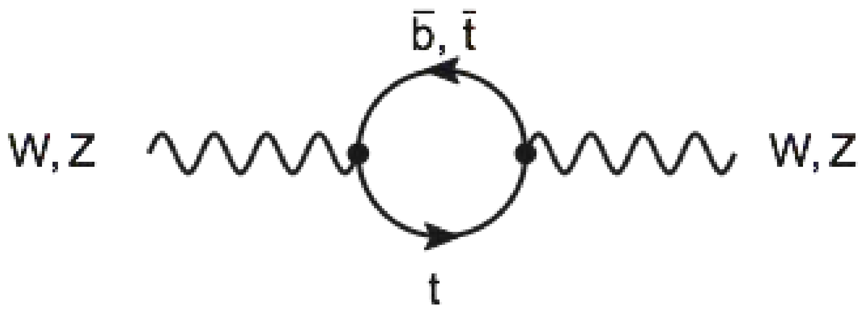
$$m_W^2 = \frac{g^2 v^2}{4}, \quad m_Z^2 = \frac{v^2}{4}(g^2 + g'^2) \quad \rightarrow \quad \rho_0 = \frac{m_W^2}{m_Z^2 \cos\theta_W} = 1$$

  - 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)



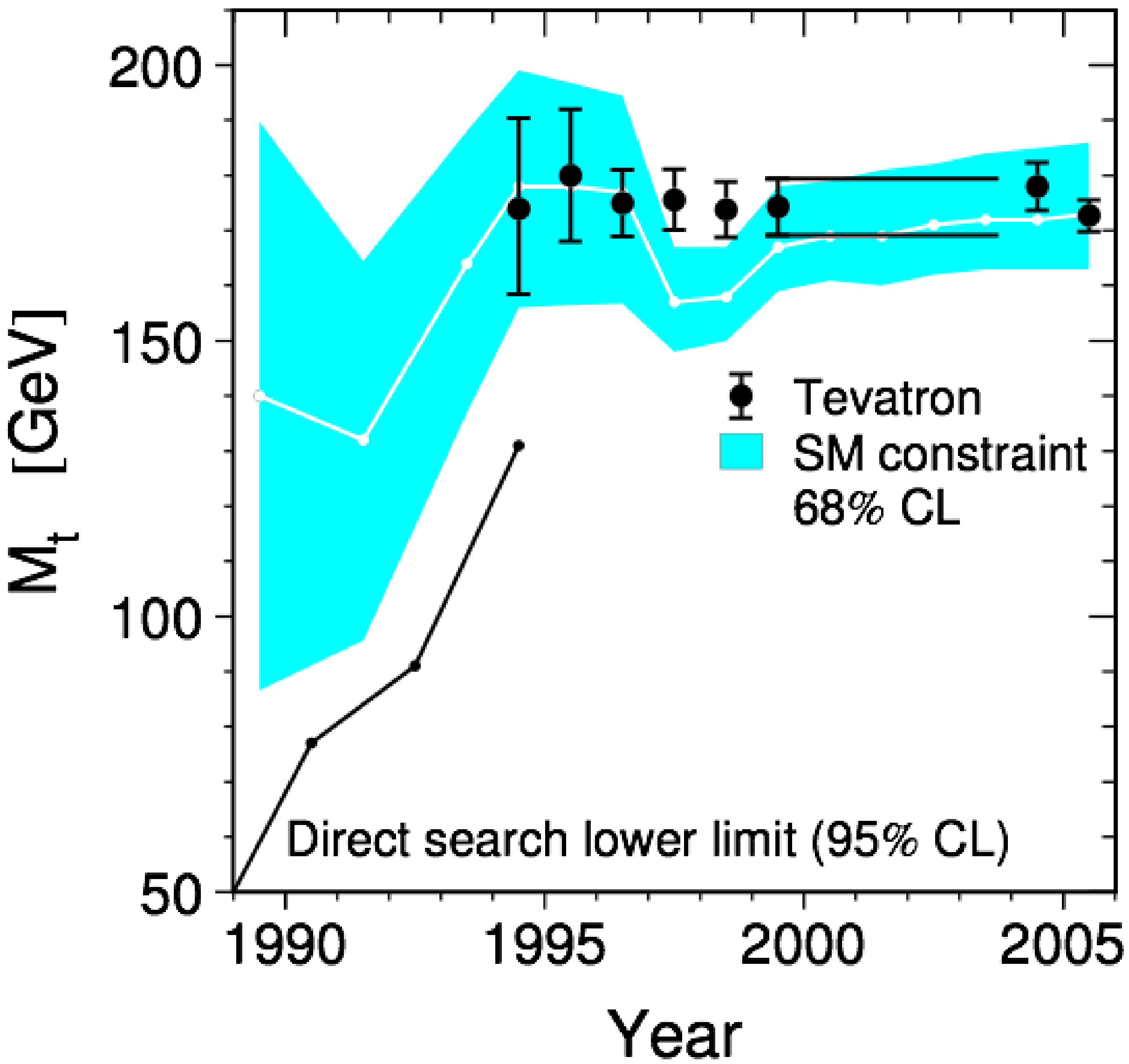
$\sim G_F\, m_t^2$

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

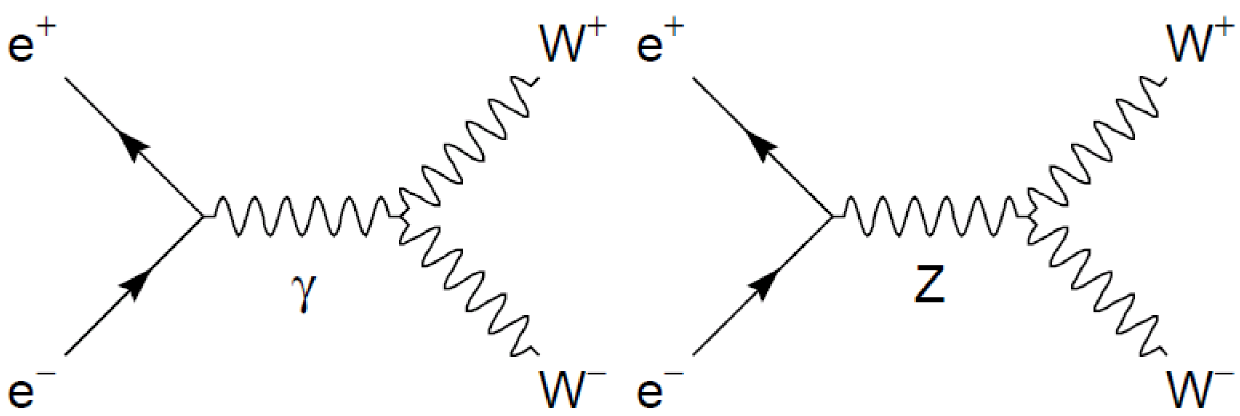
vgl. Tevatron (2012):
$m_t = 173.2 \pm 0.9$ GeV



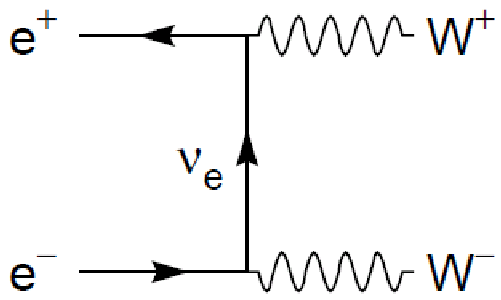
[Phys. Rept. 427 (2006) 257]

W-pair creation at LEP-II

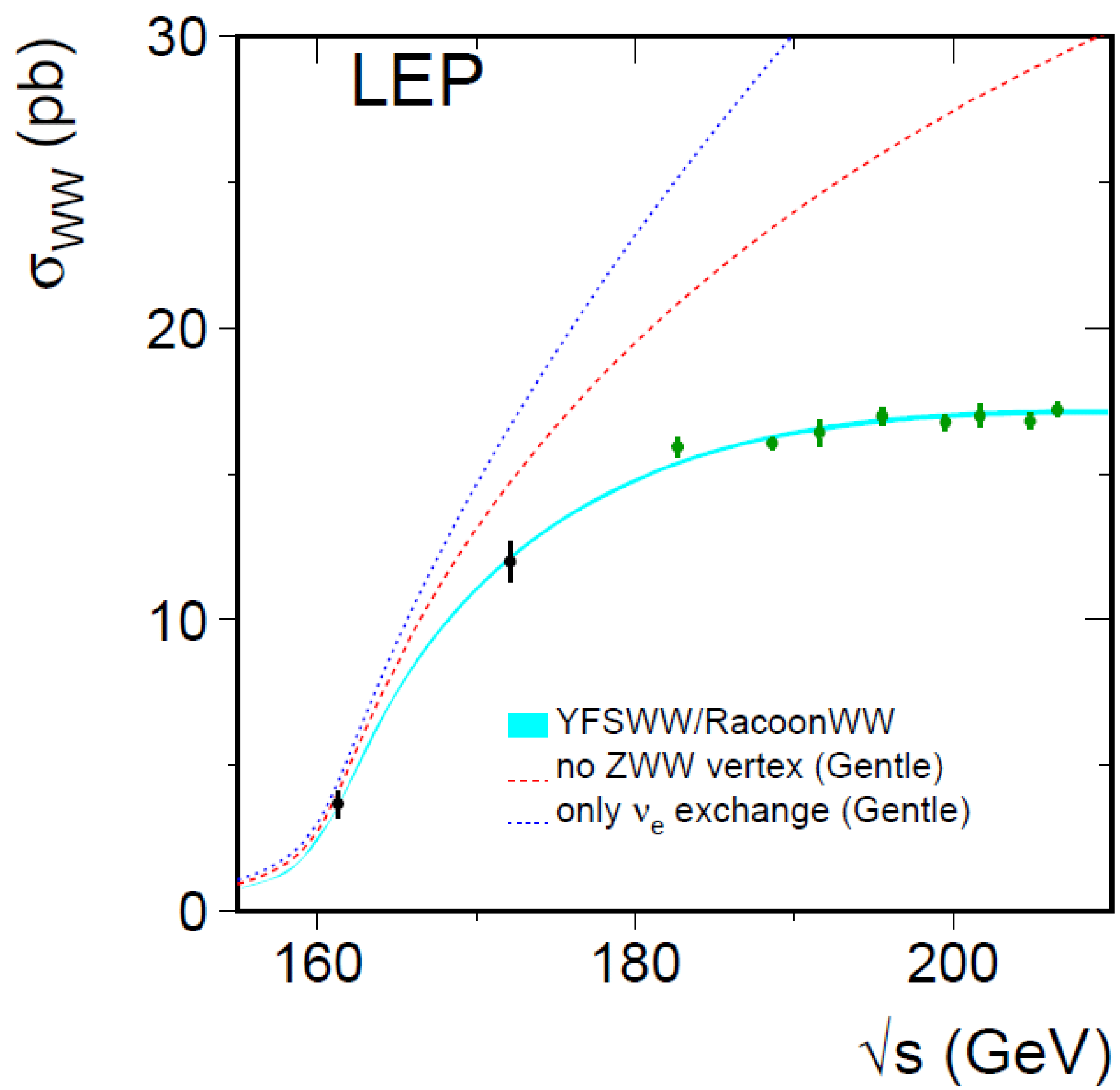
- LEP-II: passes kinematic Threshold for W-boson-pair creation
- Feynman-diagrams (Born)
  - TGC: γWW und ZWW



  - Neutrino-exchange



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



[arXiv:1302.3415]

W-Mass at Hadron-Colliders

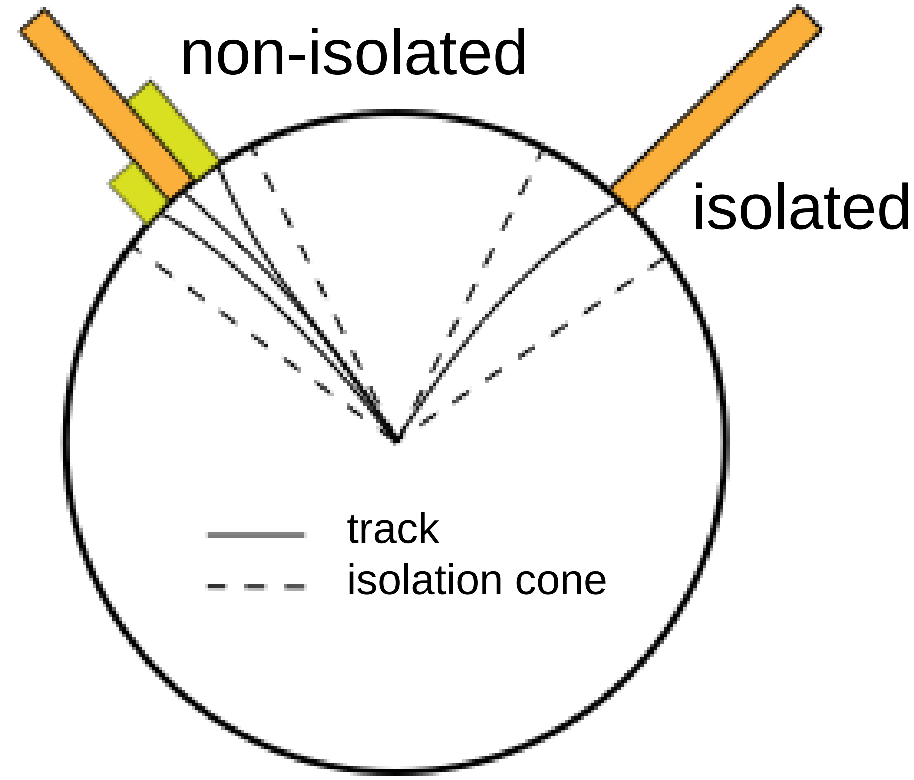
- Start the reconstruction with lepton
  - Isolated leptons with high transverse momentum → suppress multijet background
  - Prototype for many high-p_T-analyses at hadron-colliders
  - Additional hadronic activity → recoil against W

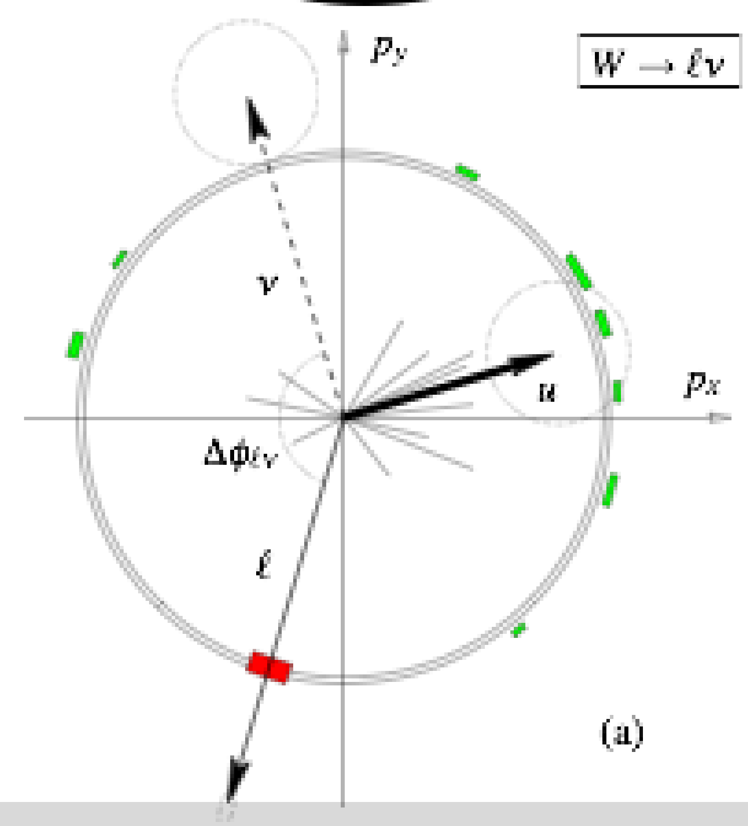
- Observable: transverse mass

$$m_T^2 = (E_T^\ell + E_T^\nu)^2 - (\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\nu})^2$$

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

  - p_T^ν missing transverse energy in the event → assumed to represent neutrino





[CERN-OPEN-2008-020]

W-Mass at Hadron-Colliders

- Extraction of the W-boson Mass: differential cross sections as function of $p_T{}^{\nu}$, $p_T{}^{l}$, m_T (different systematic uncertainties)

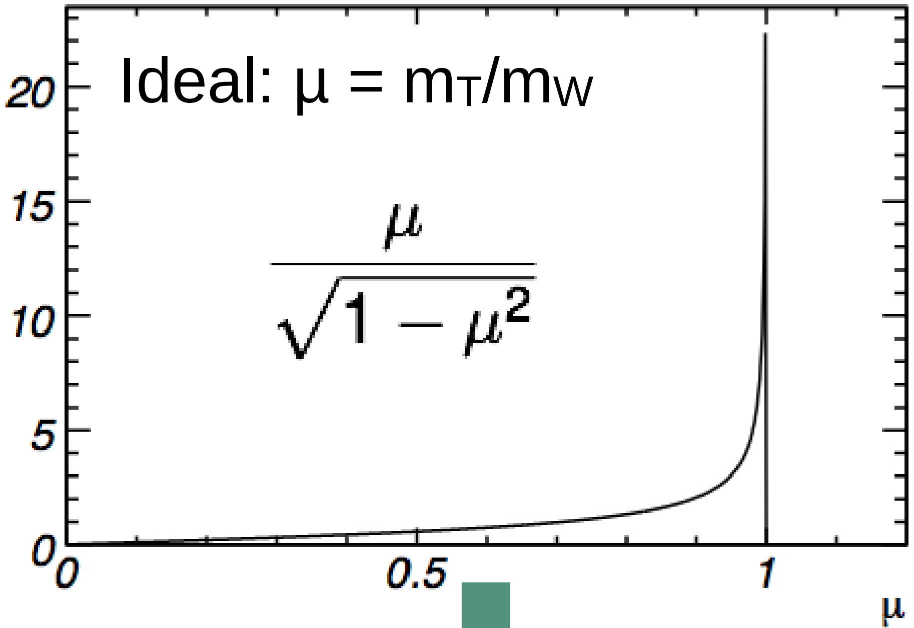
- Look for edge/flank in the cross section: Jacobian edge
  - W-boson: created approximately at rest → two-body decay

$$p_T^{\ell} = p_T^{\nu} = \frac{m_W}{2} \sin\theta, \quad \cos\Delta\phi_{\ell\nu} = -1 \quad \rightarrow m_T = m_W \sin\theta$$

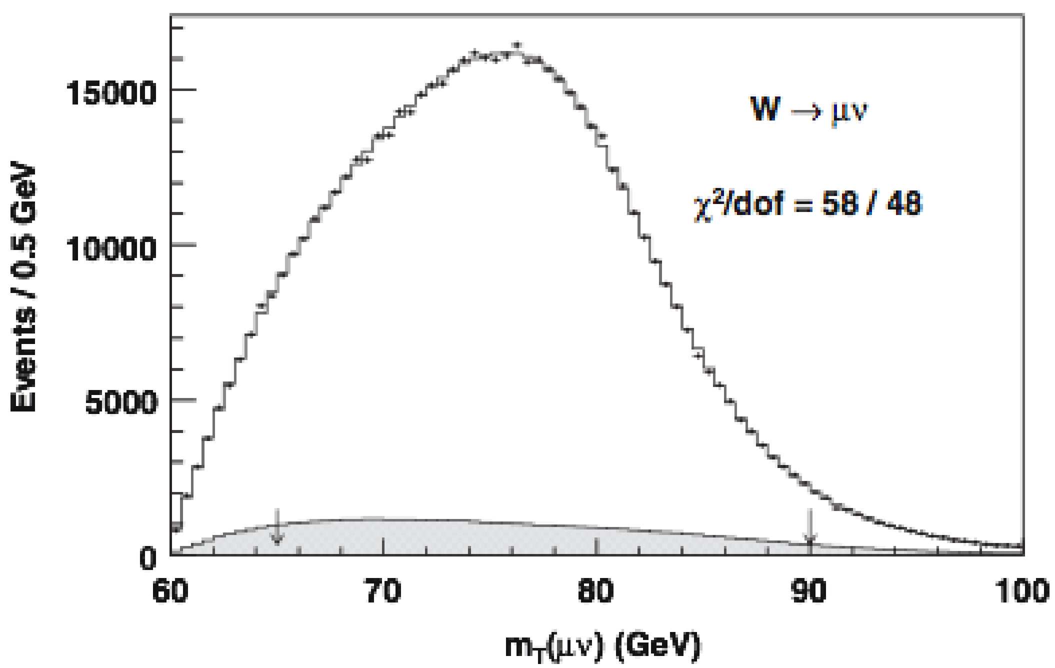
  - $\mu := \dfrac{m_T}{m_W}$: $\quad \dfrac{d\sigma}{d\mu} = \dfrac{d\sigma}{d\cos\theta} \cdot \left|\dfrac{d\cos\theta}{d\mu}\right| = \dfrac{d\sigma}{d\cos\theta} \cdot \left|\dfrac{d\sqrt{1-\mu^2}}{d\mu}\right| = \dfrac{d\sigma}{d\cos\theta} \cdot \left|\dfrac{-\mu}{\sqrt{1-\mu^2}}\right|$

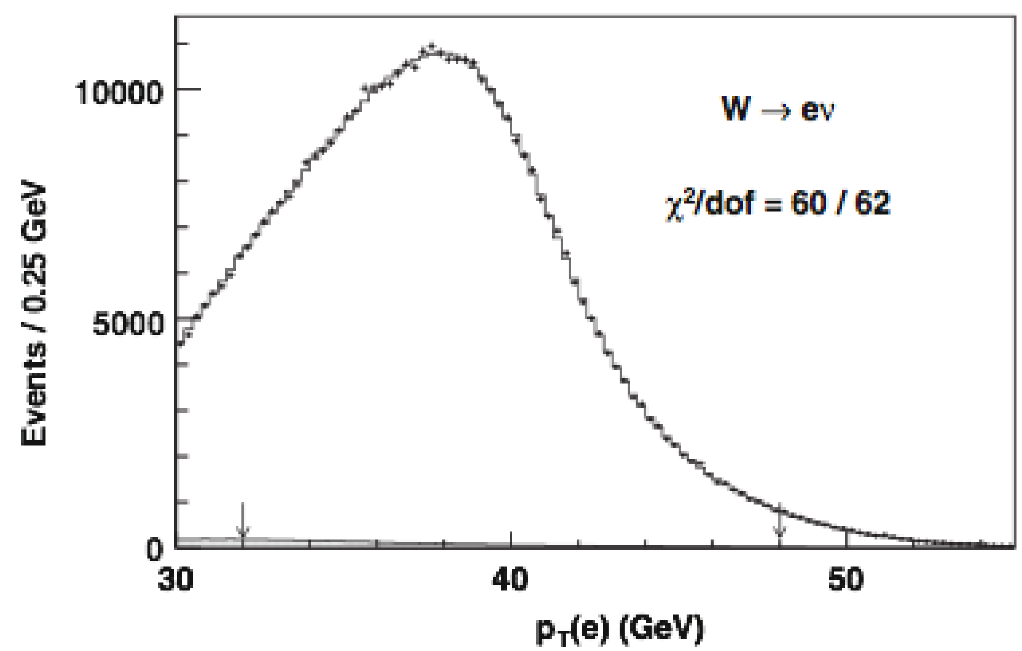
    → singular for μ = 1
  - Jacobi edge is smeared: finite W boson width ($\Gamma_W \approx 2$ GeV)
    W boson not exactly at rest
    detector resolution effects

W-Mass at Hadron-Colliders



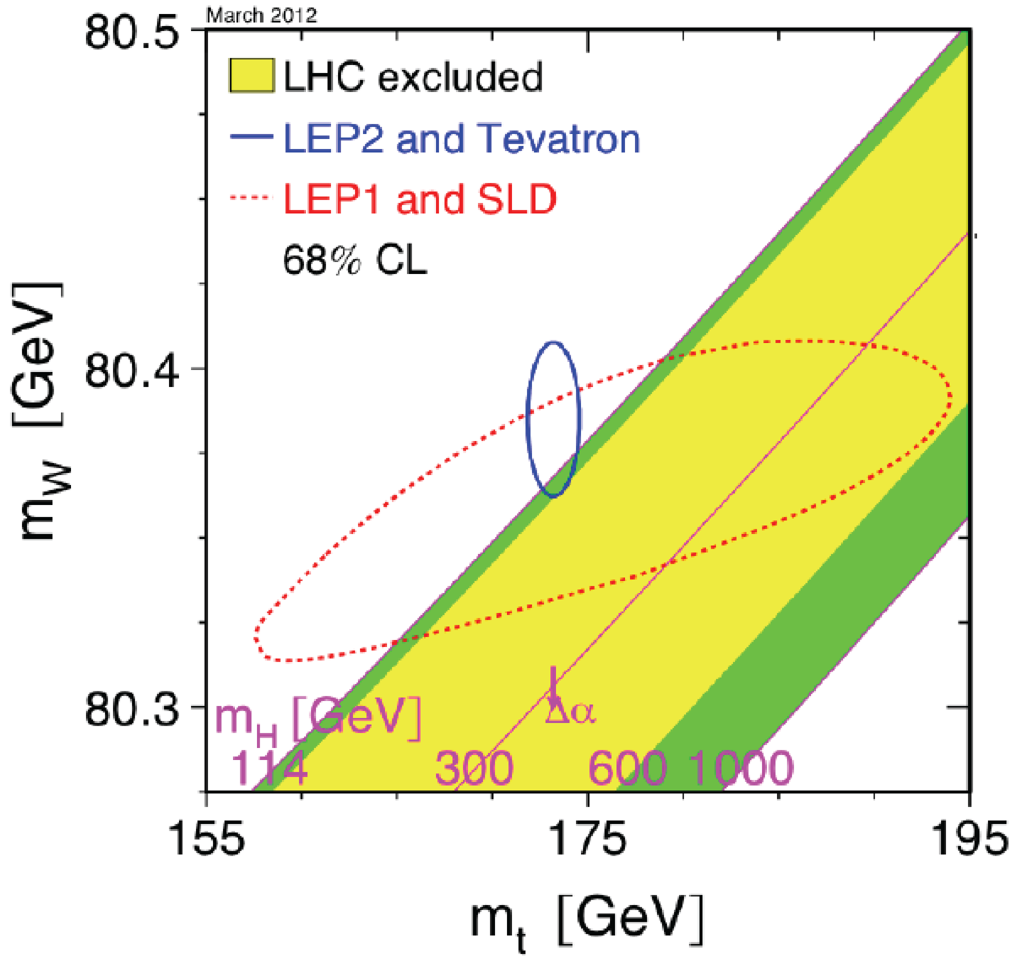
- Analysis: Likelihood-fit with templates from simulations with different W-masses
- Precision limited by systematic uncertainties: parton-densities, lepton energies, …

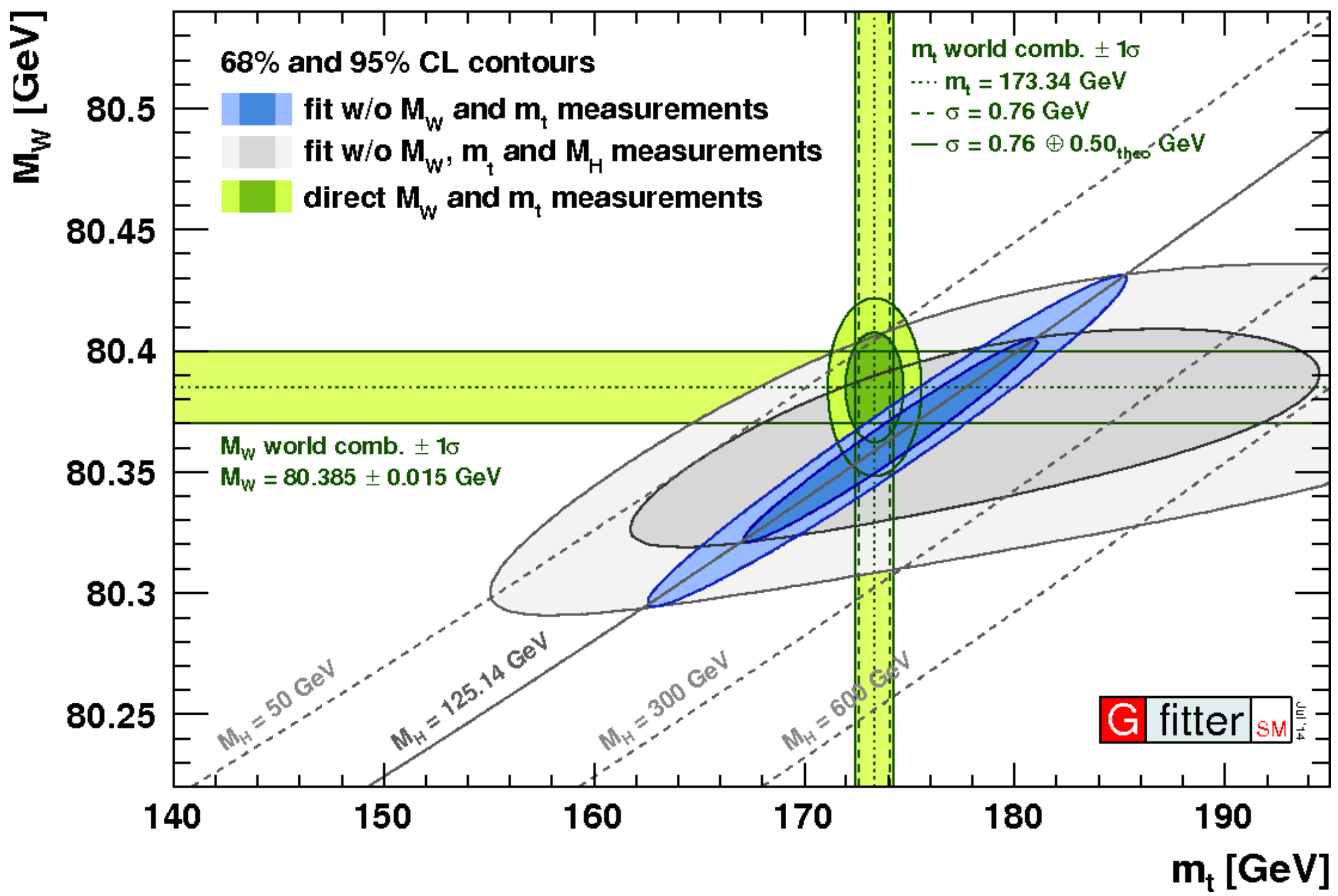




[Phys. Rev. Lett. 108 (2012) 151803]

Then and Now

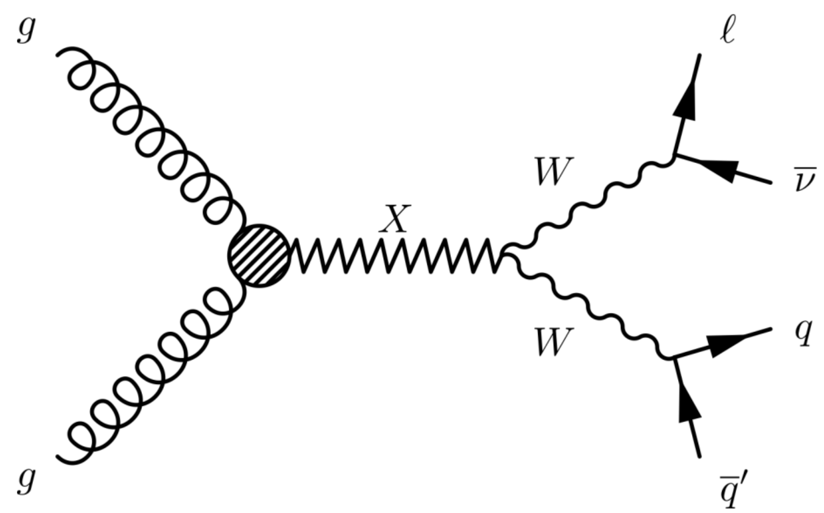


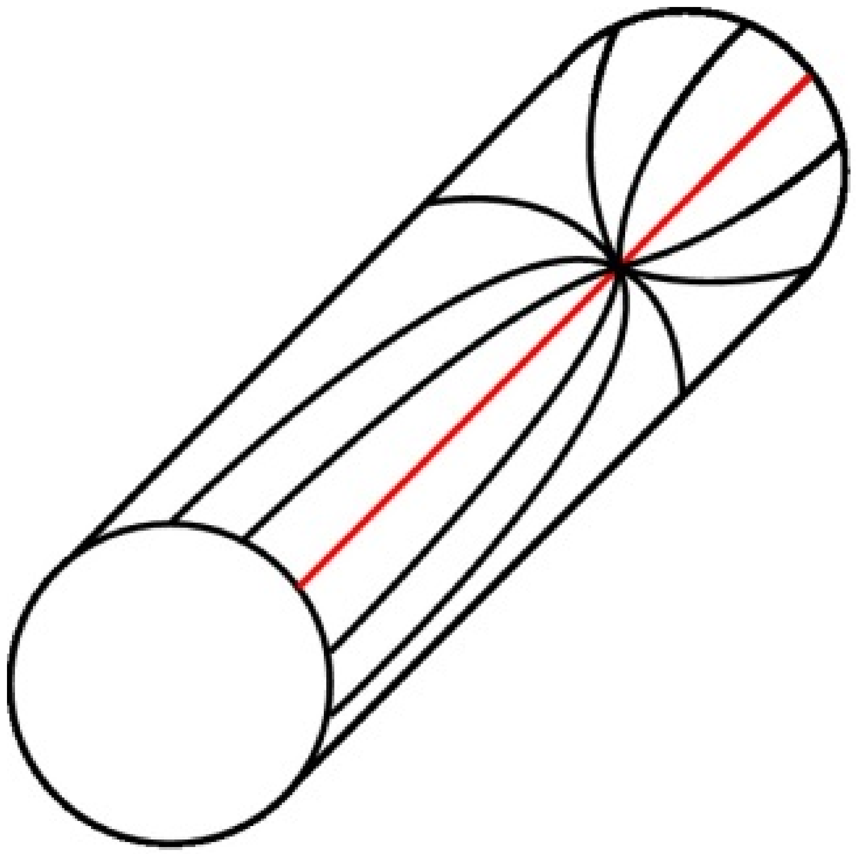


- Pre-Higgs discovery: use M_W + M_{top} to constrain Higgs mass
- Post Hoggs discovery: use M_W + M_{top} + M_H to constrain exotic theories that could add more particles to the loops
  → very strong limits on supersymmetry

Resonant Di-Boson Production

- Typical model: Graviton with extra-dimensionen
- would explain relatively weak gravitational force
- EWK + QCD confined to usual 3 dimensions
- Gravitation also progates in extra-dimension(s)
- „curled up“ extra-dimension prohibits macroscopic effects

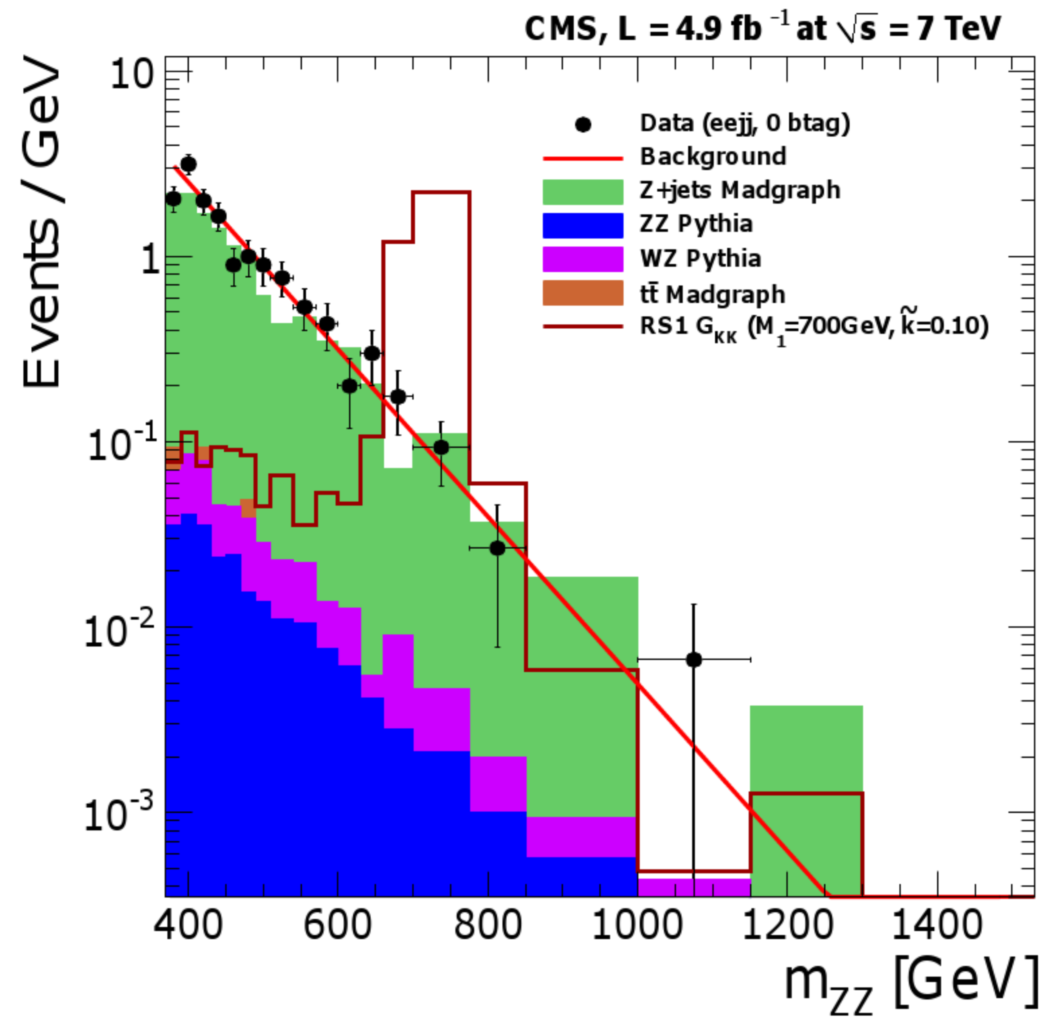




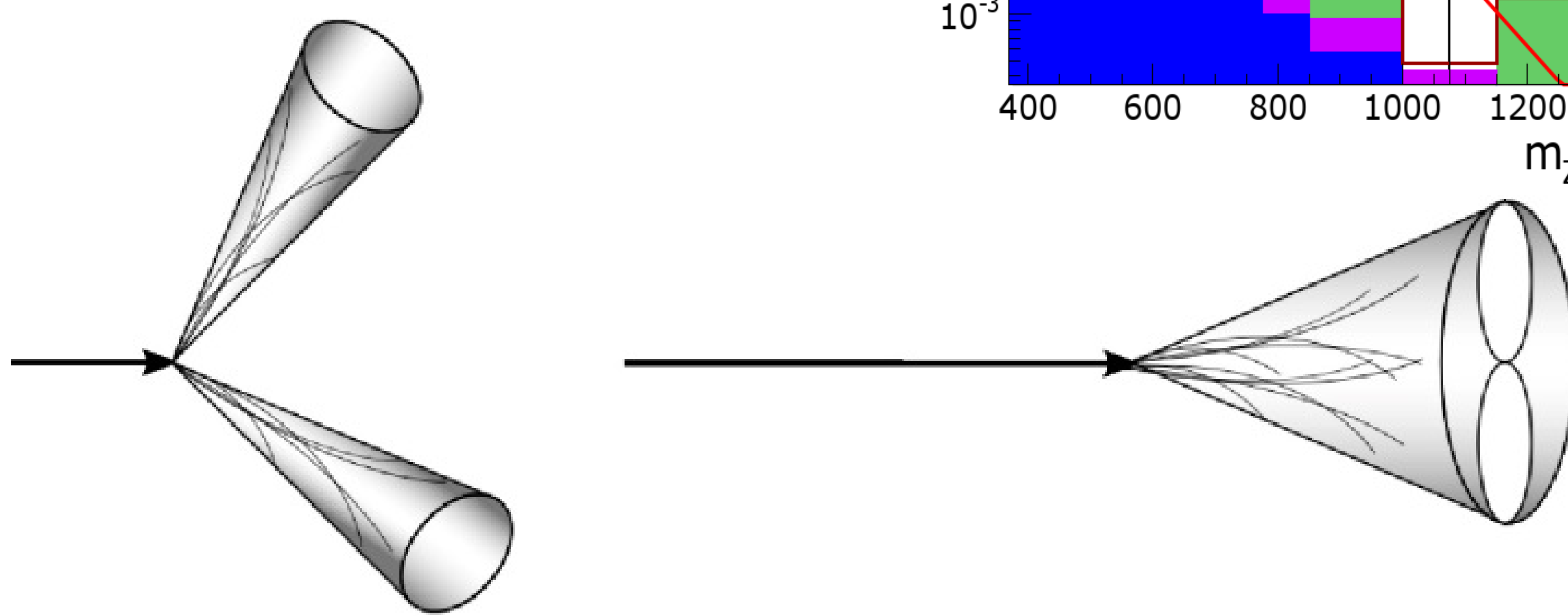
Graviton Search

- Semi-leptonic Decay
best compromise
of purity/backgrounds
and branching ratio

- „Merged Decays“ for high
gravtion masses



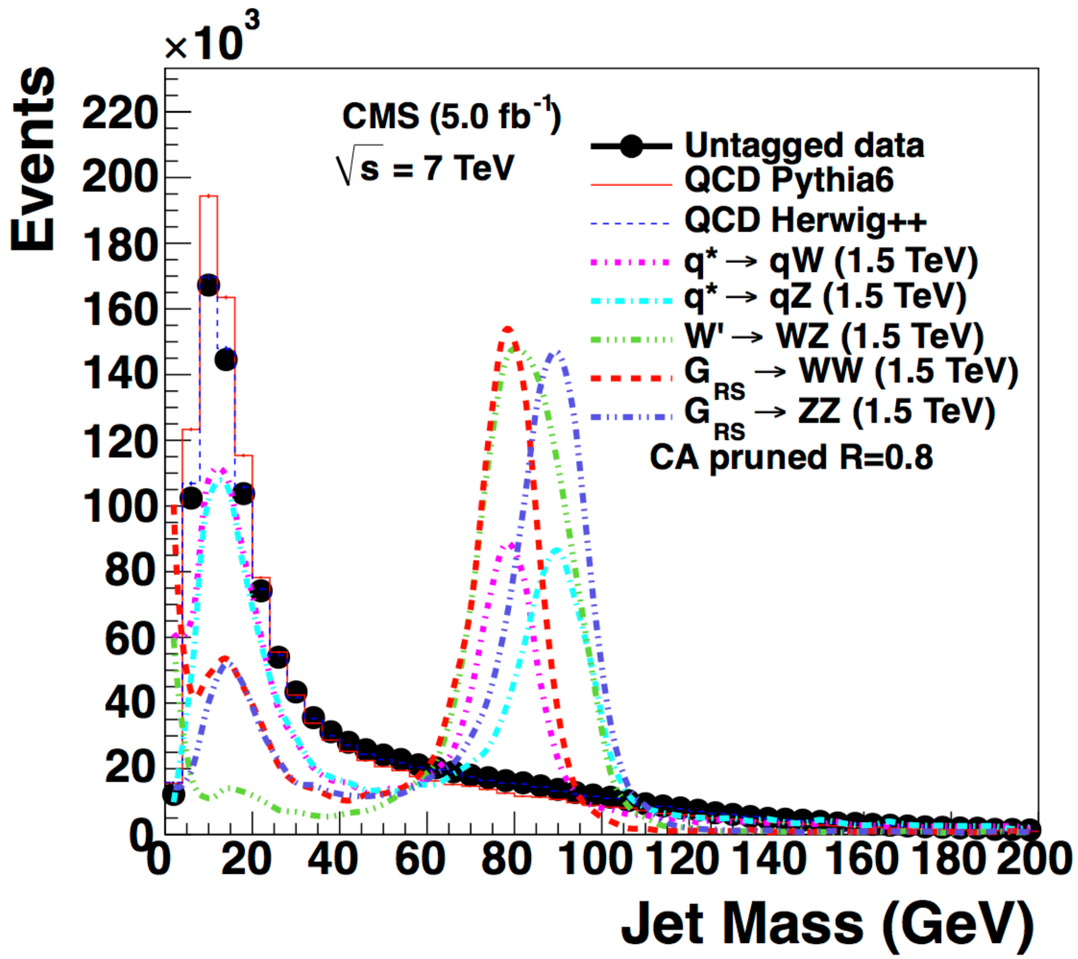
[10.1016/j.physletb.2012.11.063]



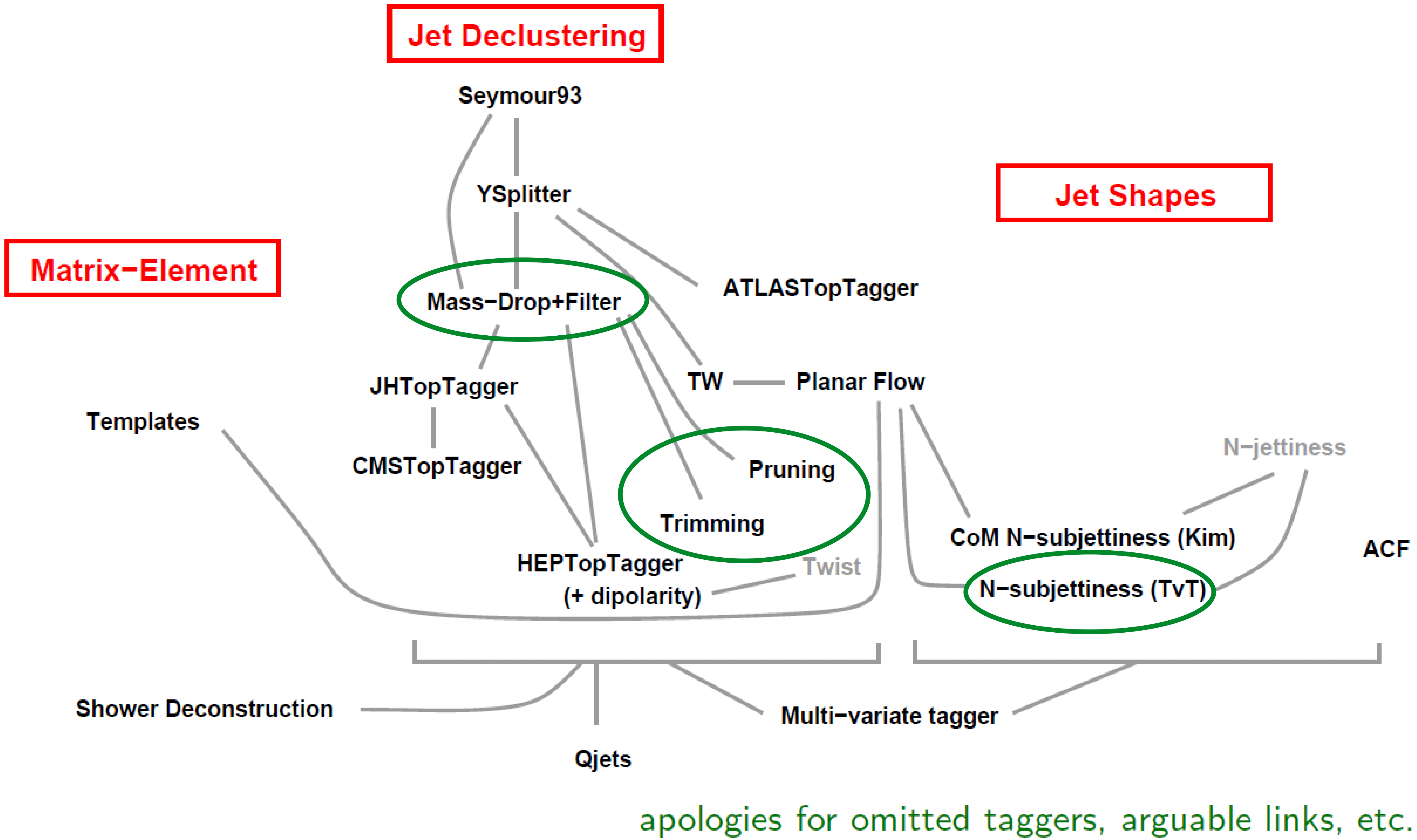
V-tag

- Finding „fat jets“ compatible with W/Z decay
  => jet mass
  => jet substructure

- Jet mass:
  - sum of constituent four-vectors
  - falling steeply for quark/gluon jets
    (~ virtuality of outgoing particles)
  - peak at 83/91 GeV for W/Z
  - W/Z hard to separate



Jet-Substruktur-Landscape



[G. Salam, BOOST 2012]

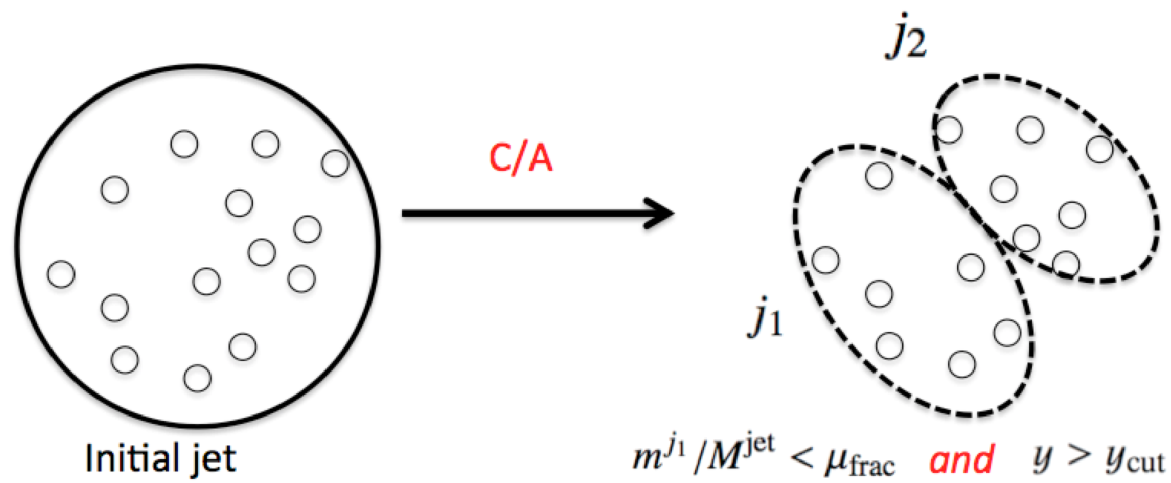
Example: Massdrop + Filter

Karlsruher Institut für Technologie

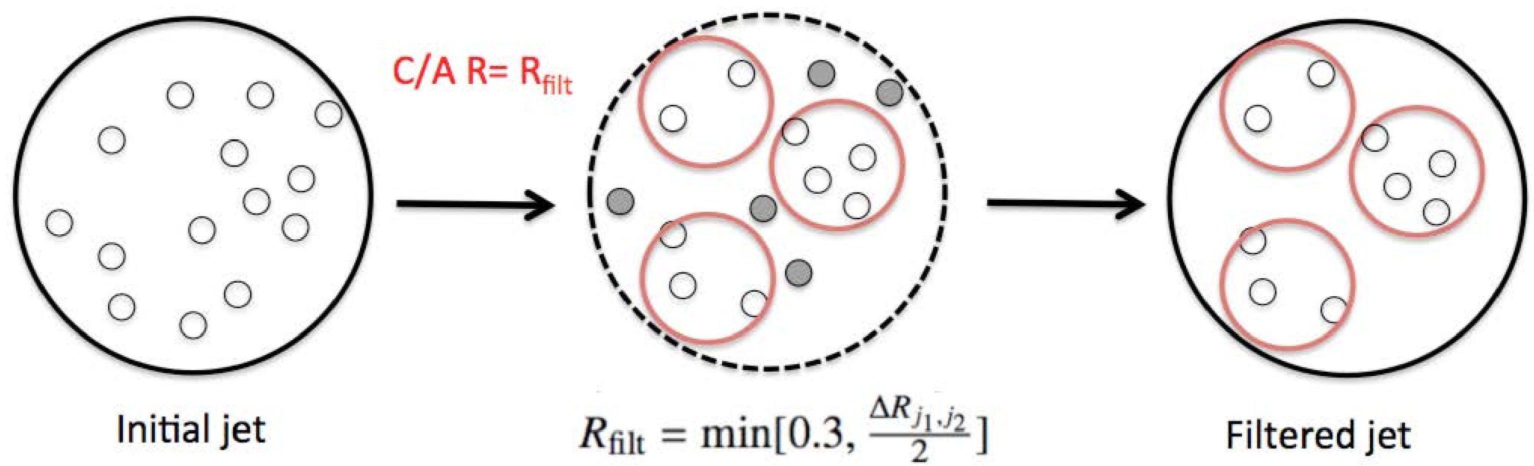
- Start: fat jet from Cambridge-Aachen-Algorithmus

$$d_{ij} = \frac{\Delta R_{ij}}{R}$$

- Uncluster jet into pair of subjets if significant mass drop occurs
→ candidate for jet with substructure



- Re-custering with smaller R, remove all particles not caught in hard subjets



[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-065]

Beispiel: N-Subjettiness

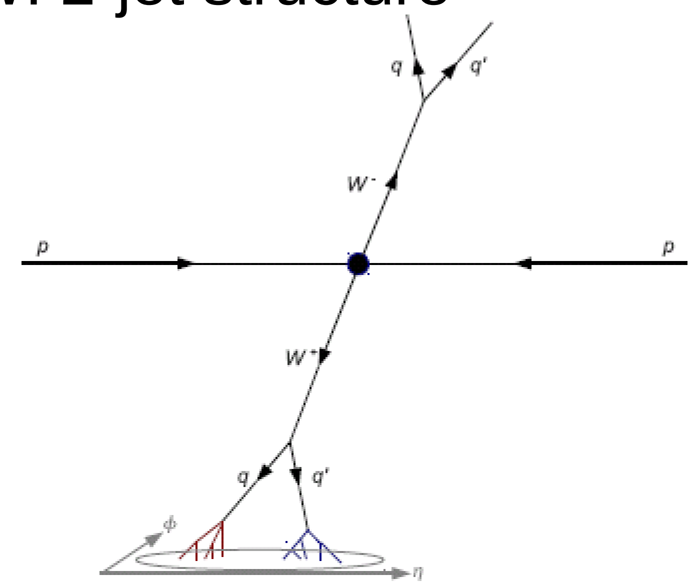
average distance to clostest of N subjet axis

$$\tau_N = \frac{\sum_{i=1}^{M} p_{T,i} \min\{\Delta R_{i1}, \ldots, \Delta R_{iN}\}}{\sum_{i=1}^{M} p_{T,i} R_0}$$

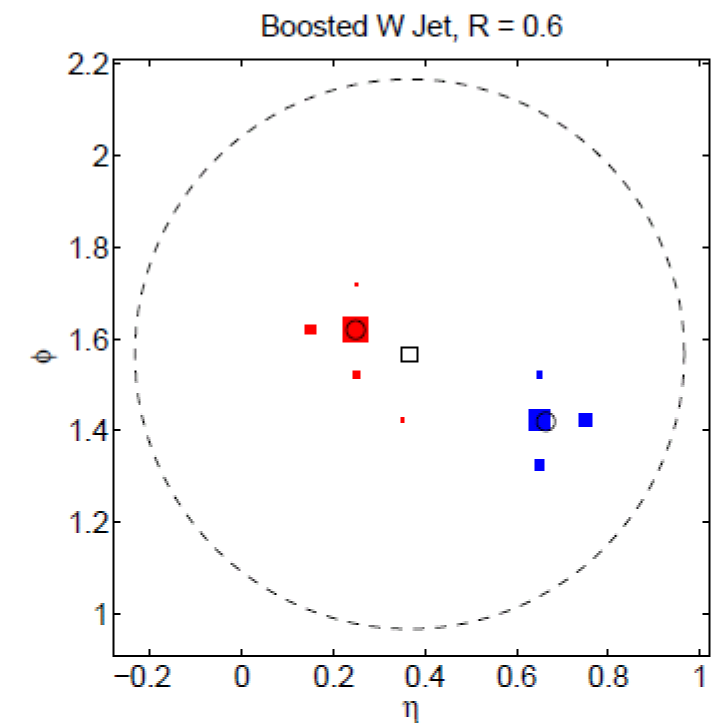
small if N real subjets exist
lare otherwise

=> use ratio τ_2/τ_1
small for W/Z
large for QCD

W: 2-jet structure

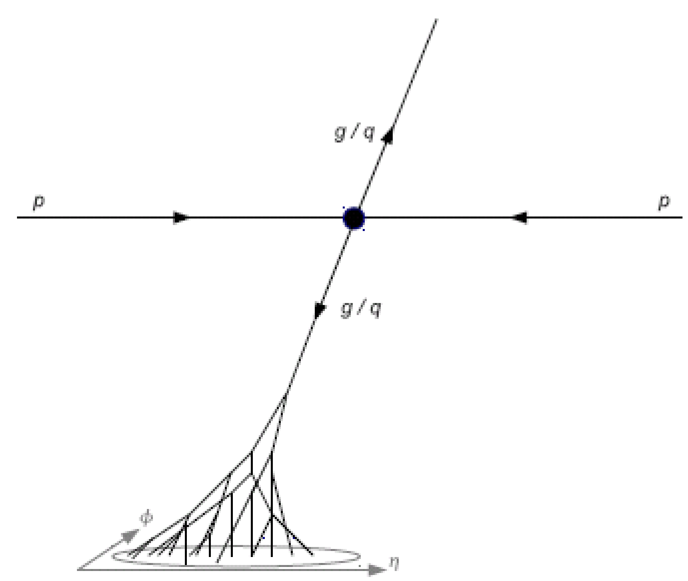


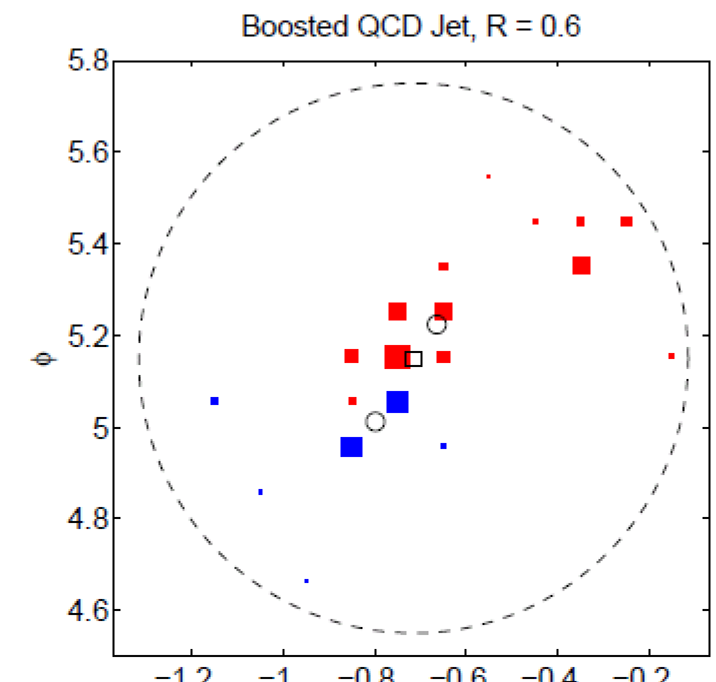
(a)



(b)

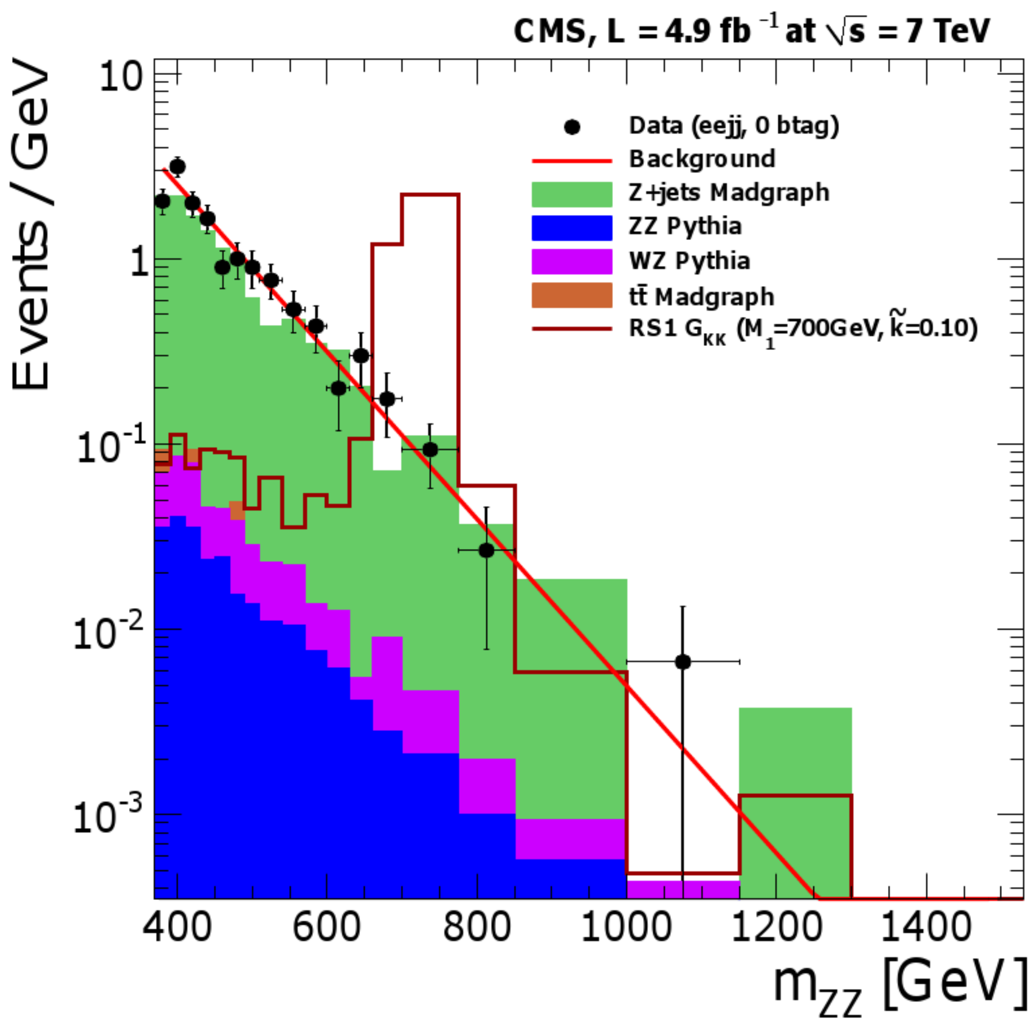
QCD: diffuse/round



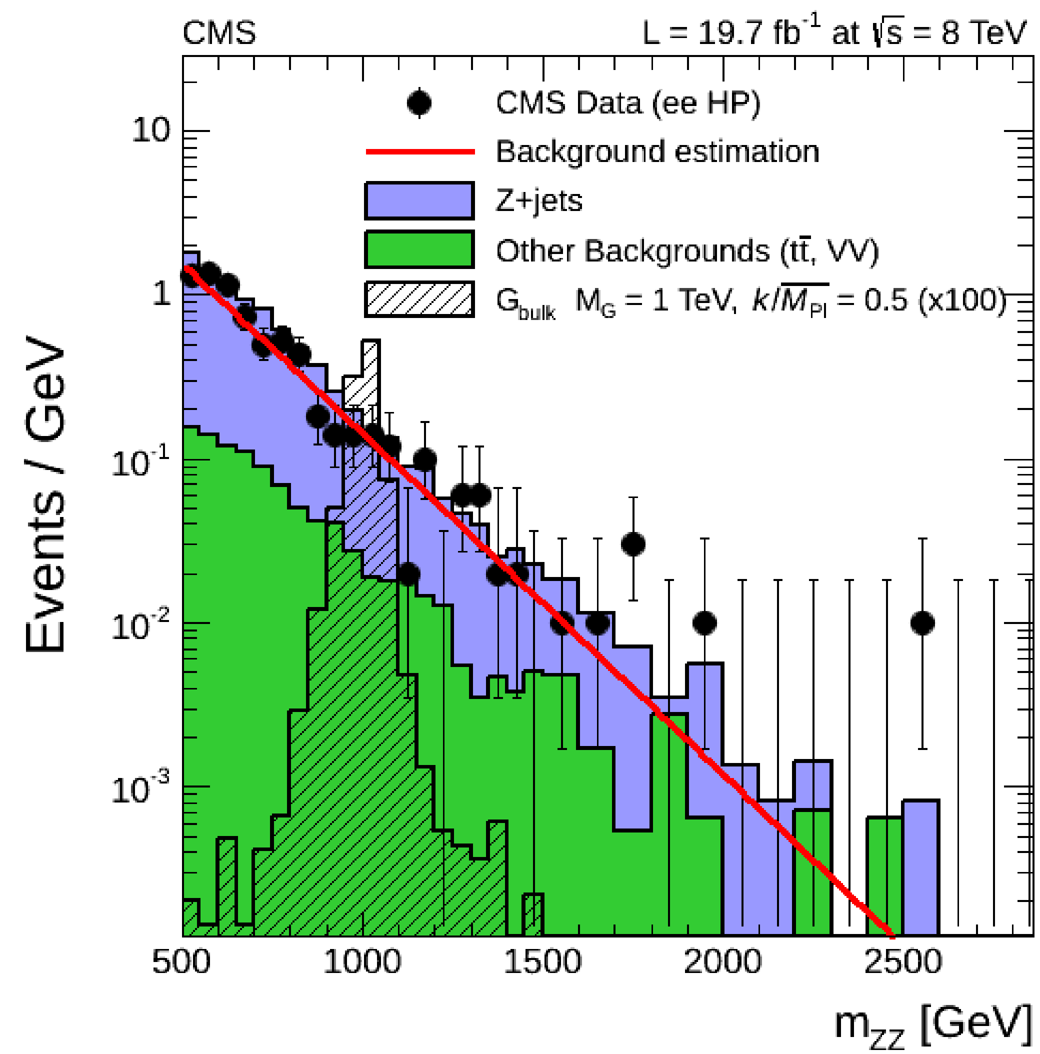


[JHEP03 (2011) 015]

Graviton with boosted W/Z



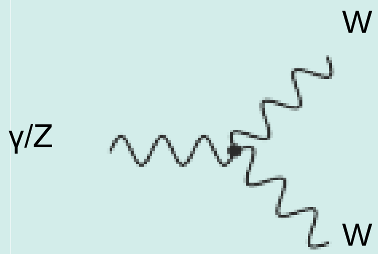
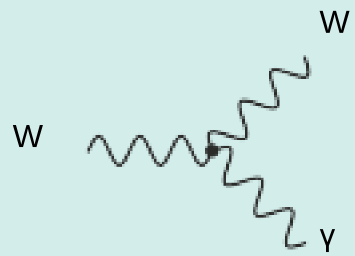
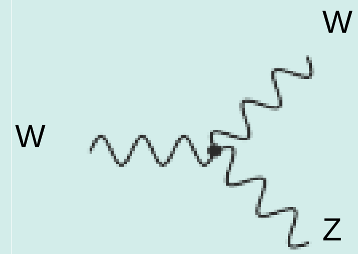
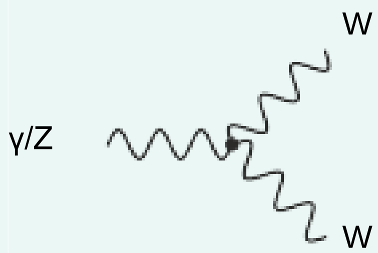
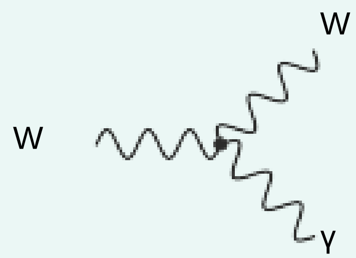
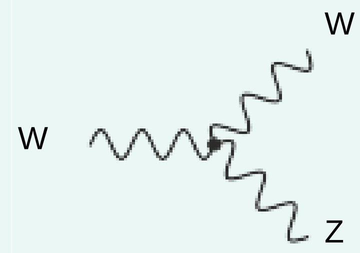
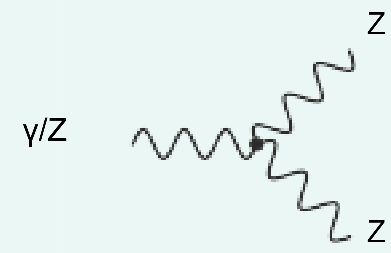
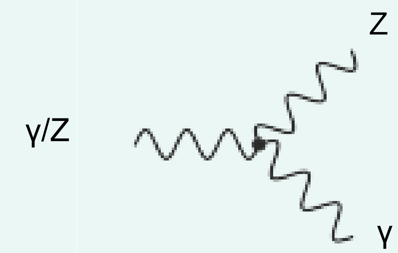
[10.1016/j.physletb.2012.11.063]



[10.1007/JHEP08(2014)174]

But: nothing found yet, looking again at 13TeV

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

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

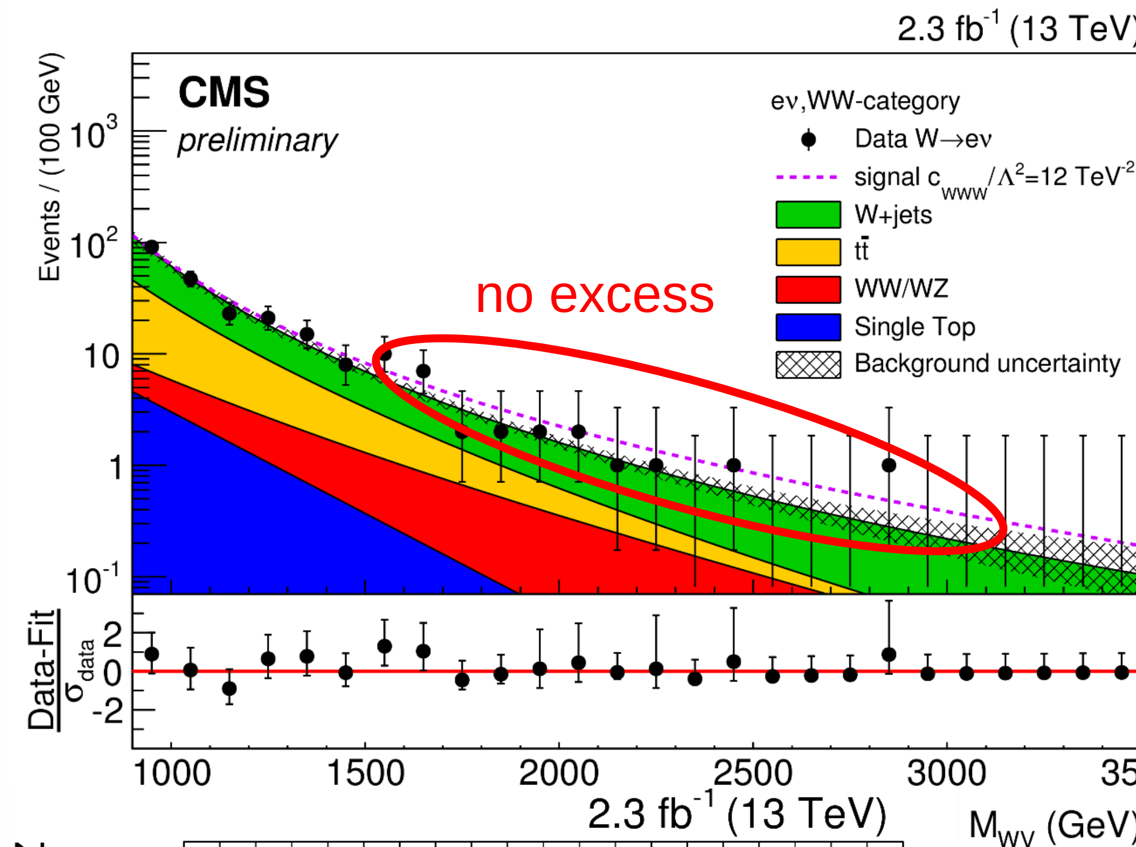
- Most general possibe effektive Lagrange density (V = γ, Z)

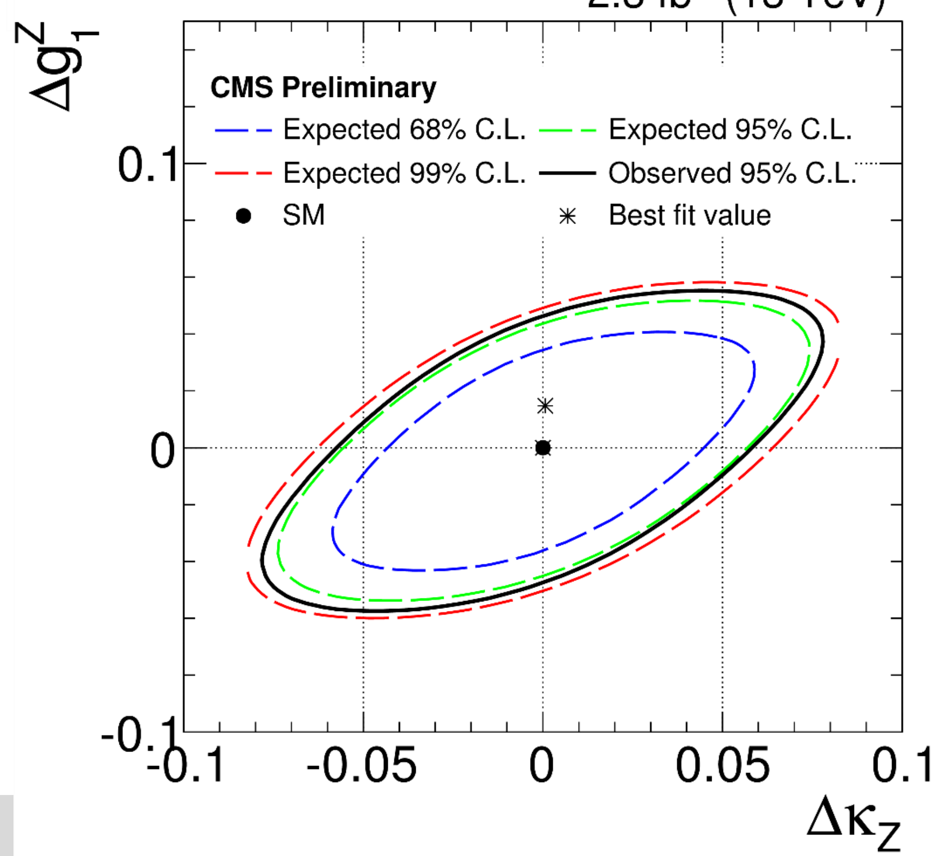
$$L^{\text{eff}}_{WWV} = -ig_{WWV}\Big[g_1^V V_\mu\left(W^{-\mu\nu}W^+_\nu - W^+_{\mu\nu}W^-_\nu\right) + \kappa_V V_{\mu\nu}W^{+\mu}W^{-\nu}$$
$$+ \frac{\lambda_V}{m_W^2}V_{\mu\nu}W^{+\nu\rho}W^{-\mu}_\rho + ig_5^V\epsilon_{\mu\nu\rho\sigma}\left((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho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

  - 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

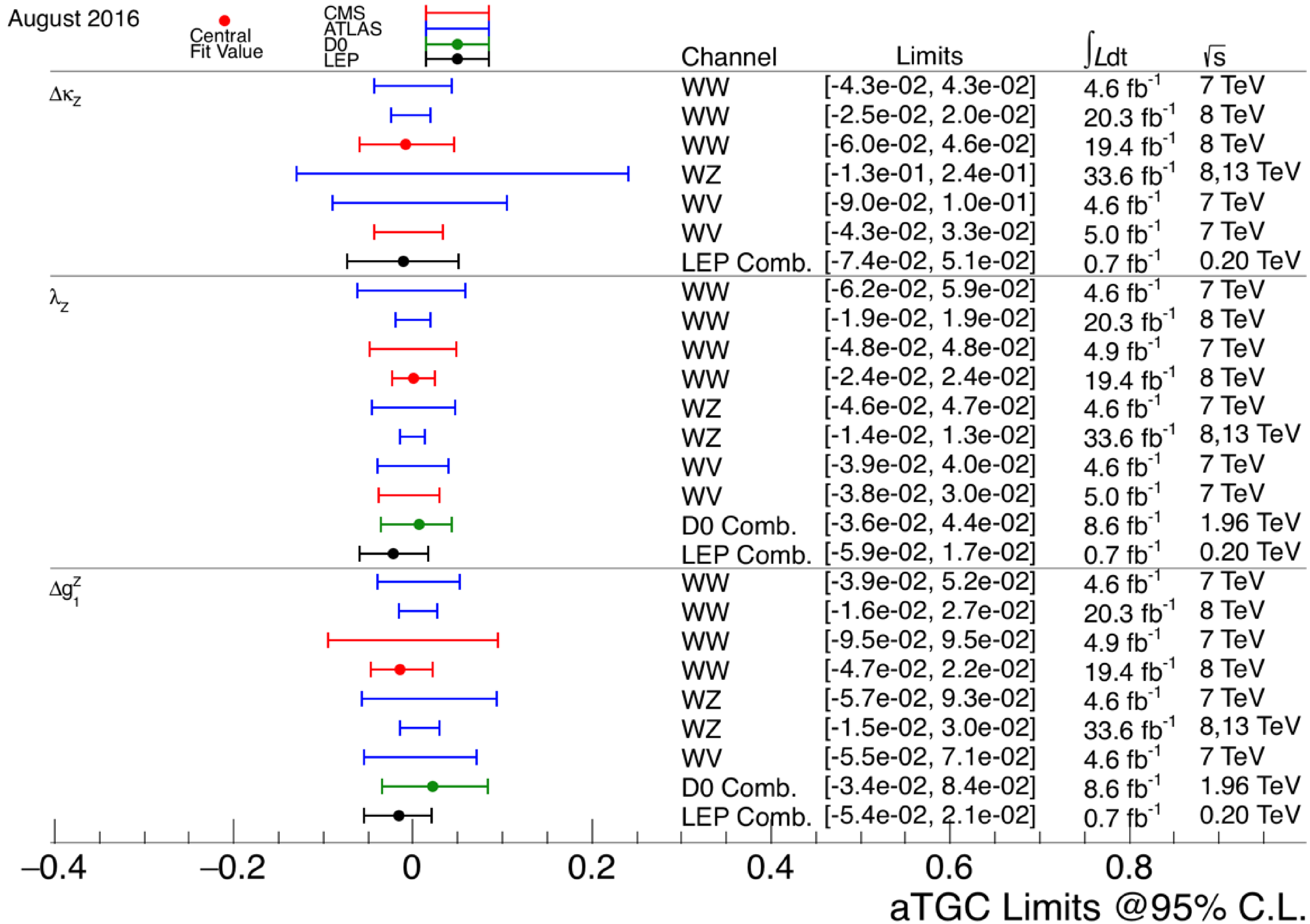
- Example:
  CMS W + W/Z semi-leptonic
- Isolated lepton + MET
  → leptonic W candidate
- Fat jet with substructure
  → hadronic W candidate
- Search for excess at high diboson invariant masses
  → high aTGC contributions
- Extract limits from likelihood contours in signal+background fit





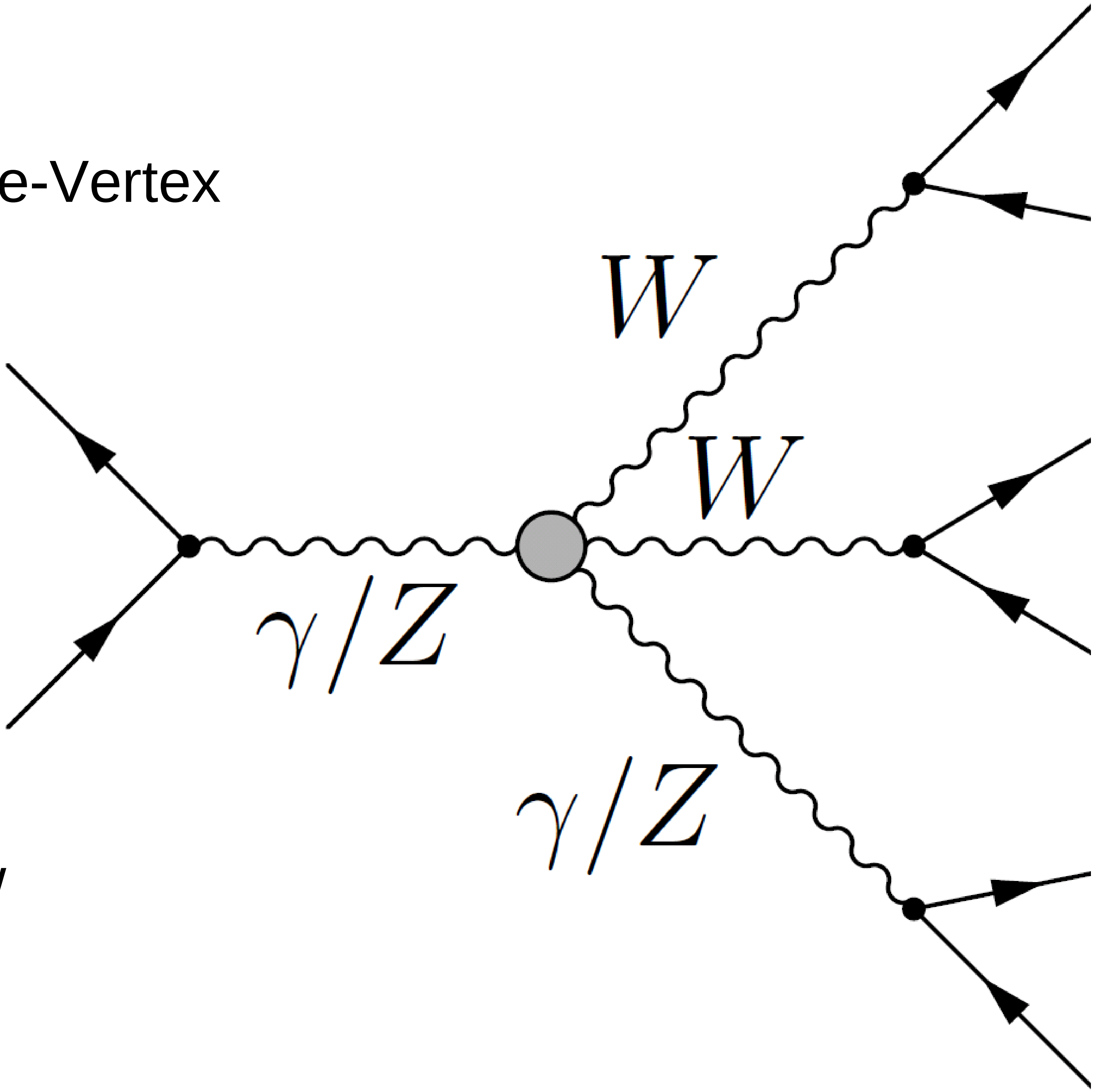
[CMS-PAS-SMP-16-012]

aTGC limits


August 2016
Central Fit Value
CMS
ATLAS
D0
LEP
Channel Limits ∫Ldt √s
Δκ_Z
WW [-4.3e-02, 4.3e-02] 4.6 fb-1 7 TeV
WW [-2.5e-02, 2.0e-02] 20.3 fb-1 8 TeV
WW [-6.0e-02, 4.6e-02] 19.4 fb-1 8 TeV
WZ [-1.3e-01, 2.4e-01] 33.6 fb-1 8,13 TeV
WV [-9.0e-02, 1.0e-01] 4.6 fb-1 7 TeV
WV [-4.3e-02, 3.3e-02] 5.0 fb-1 7 TeV
LEP Comb. [-7.4e-02, 5.1e-02] 0.7 fb-1 0.20 TeV
λ_Z
WW [-6.2e-02, 5.9e-02] 4.6 fb-1 7 TeV
WW [-1.9e-02, 1.9e-02] 20.3 fb-1 8 TeV
WW [-4.8e-02, 4.8e-02] 4.9 fb-1 7 TeV
WW [-2.4e-02, 2.4e-02] 19.4 fb-1 8 TeV
WZ [-4.6e-02, 4.7e-02] 4.6 fb-1 7 TeV
WZ [-1.4e-02, 1.3e-02] 33.6 fb-1 8,13 TeV
WV [-3.9e-02, 4.0e-02] 4.6 fb-1 7 TeV
WV [-3.8e-02, 3.0e-02] 5.0 fb-1 7 TeV
D0 Comb. [-3.6e-02, 4.4e-02] 8.6 fb-1 1.96 TeV
LEP Comb. [-5.9e-02, 1.7e-02] 0.7 fb-1 0.20 TeV
Δg^Z_1
WW [-3.9e-02, 5.2e-02] 4.6 fb-1 7 TeV
WW [-1.6e-02, 2.7e-02] 20.3 fb-1 8 TeV
WW [-9.5e-02, 9.5e-02] 4.9 fb-1 7 TeV
WW [-4.7e-02, 2.2e-02] 19.4 fb-1 8 TeV
WZ [-5.7e-02, 9.3e-02] 4.6 fb-1 7 TeV
WZ [-1.5e-02, 3.0e-02] 33.6 fb-1 8,13 TeV
WV [-5.5e-02, 7.1e-02] 4.6 fb-1 7 TeV
D0 Comb. [-3.4e-02, 8.4e-02] 8.6 fb-1 1.96 TeV
LEP Comb. [-5.4e-02, 2.1e-02] 0.7 fb-1 0.20 TeV
–0.4 –0.2 0 0.2 0.4 0.6 0.8
aTGC Limits @95% C.L.

Triple Boson Production

- Quartic Vertex similar to triple-Vertex
- SM:
  - WWWW
  - W^+W^-ZZ
  - $W^+W^-Z\gamma$
  - $W^+W^-\gamma\gamma$
  - 4x neutral forbidden
- Problem:
  cross sections extremely low



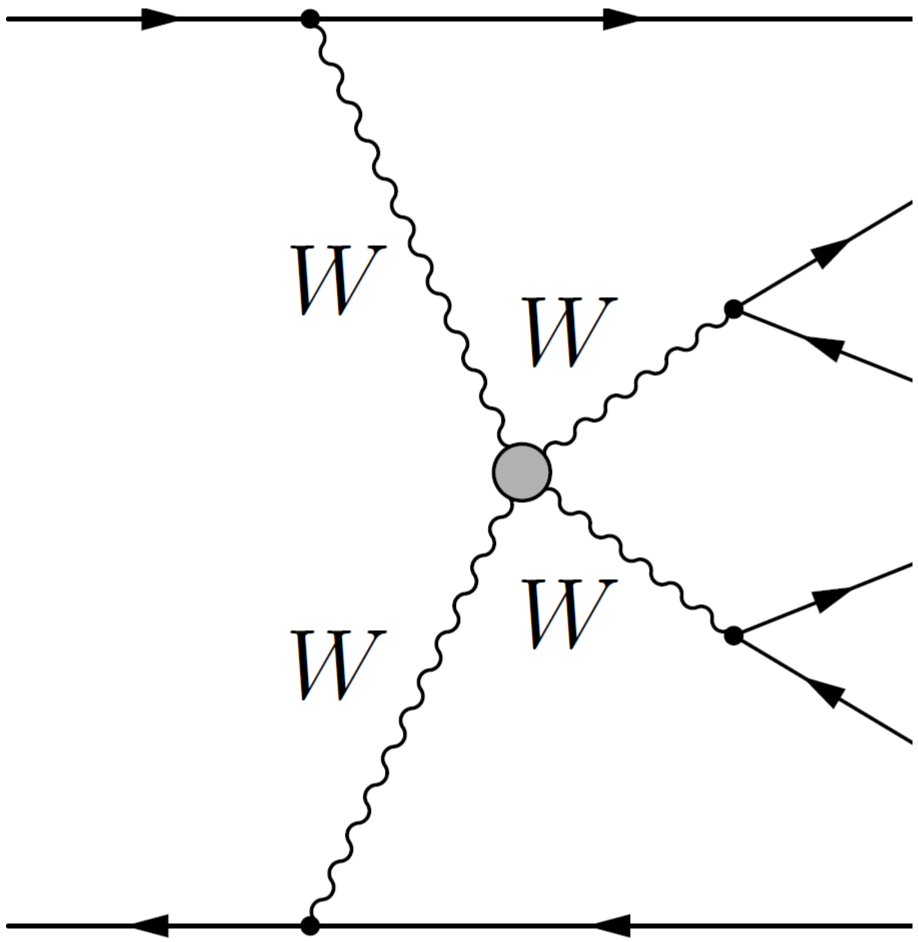
Vector-Boson Scattering

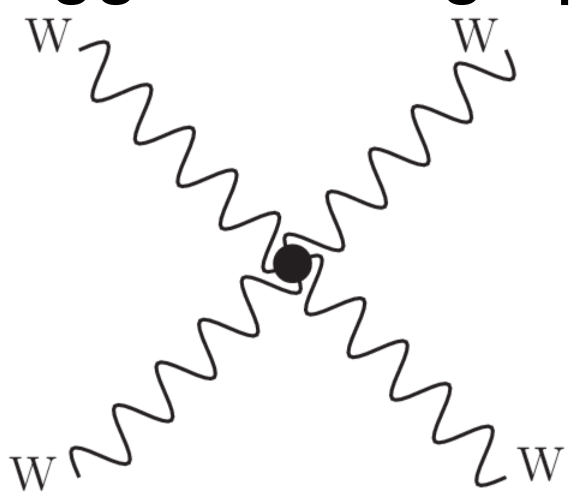
- Study quartic vertex in vector boson scattering

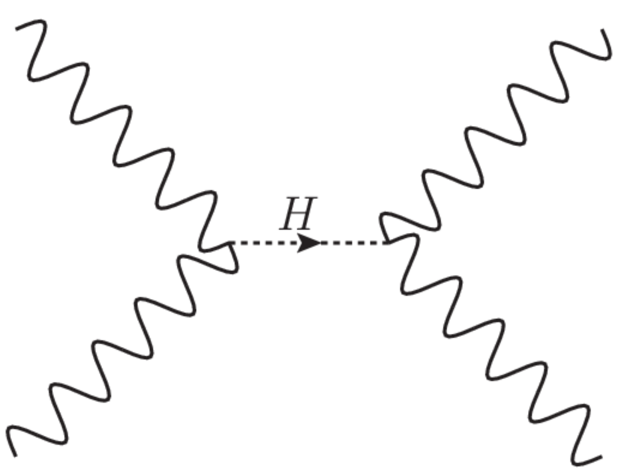
- Similar to VBF process in Higgs boson physics

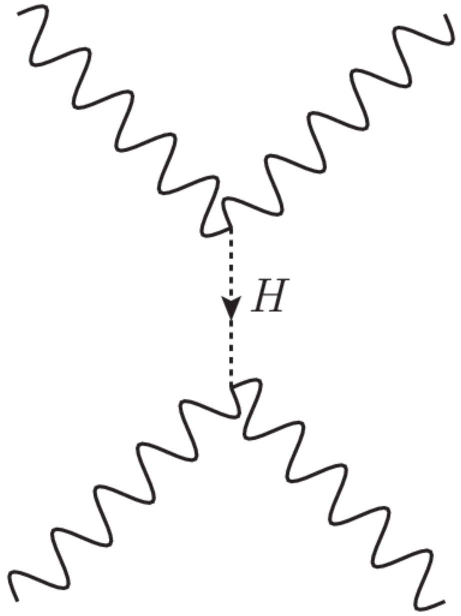
- Scattering cross section with longitudinally polarized bosons not unitary at high energies

- Regularised in SM by interference with Higgs boson graphs



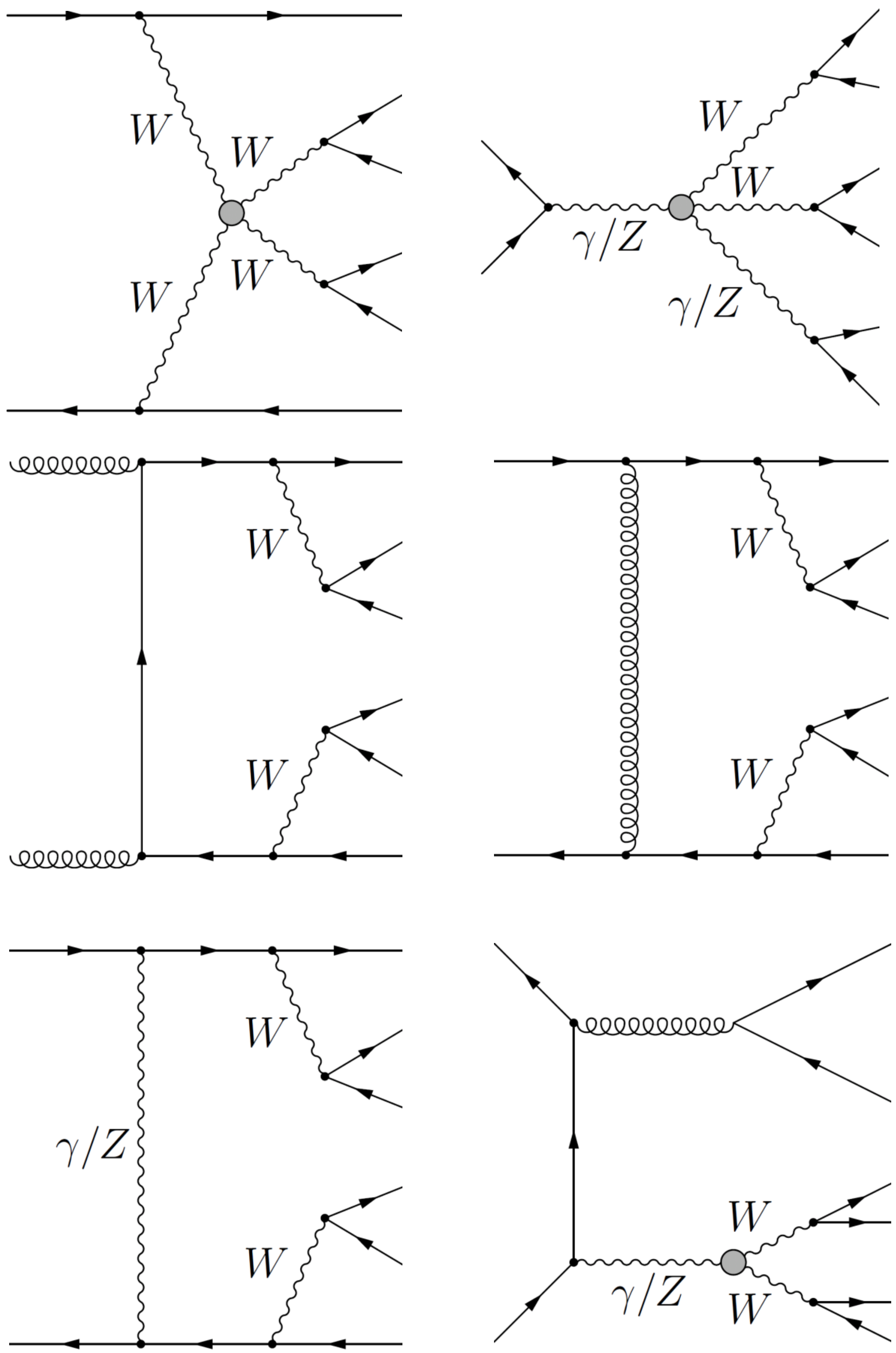






Vector-Boson Scattering

- 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 → W^+W^+jj
- Limits on anomalous couplings

[Atlas-CONF-2014-013]