Teilchenphysik 2 — W/Z/Higgs an Collidern

Sommersemester 2019

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Institut für Experimentelle Teilchenphysik (ETP)

4. Physics of the W and Z Bosons

4.1 Determination of SM parameters

- Precision measurements at the Z pole
- W production at colliders
- Global electroweak fits

4.2 W/Z physics at the LHC

- Single W/Z boson production
- $\mathrm{W}/\mathrm{Z}+$ jets production
- Vector boson pair-production
- Vector boson scattering
- Anomalous couplings
- Exotic resonances

4.1.1. Precision measurements at the Z pole

Asymmetries

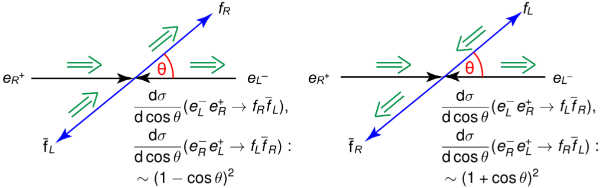
- Generic definition of **asymmetry**: split dataset into 2 parts X, Y:

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

- Measure/predict asymmetry = ratio, not absolute rate
  - If backgrounds or systematic uncertainties identical or similar in numerator/denominator $\rightarrow$ uncertainties reduced by cancellation
  - Improved sensitivity to small differences

Differential $e^+e^- \to \bar{f}f$ Cross-Section

- Angular dependence from **particle spins**:



- 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**

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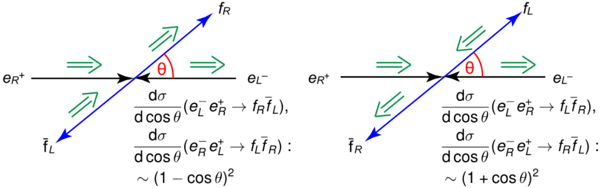


- For pure **Z exchange**

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

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

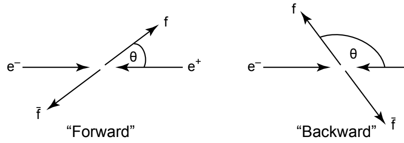
with "**asymmetry parameter**"

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

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

Forward-Backward Asymmetry

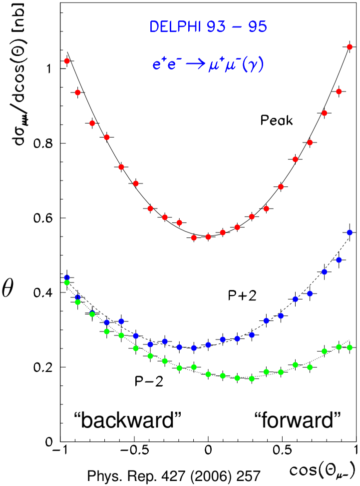
- Cross-sections depending on scattering angle of final-state fermion



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

- **Forward-backward asymmetry**

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



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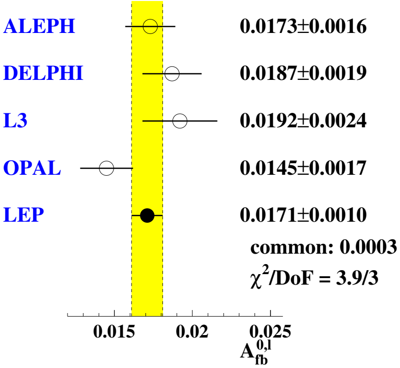
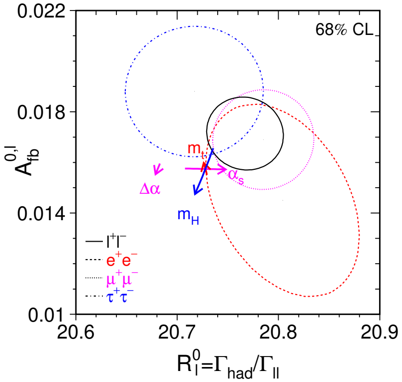
Forward-Backward Asymmetry: LEP Results

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

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

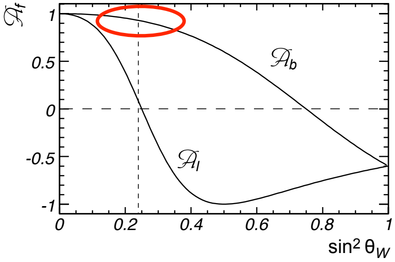
LEP, SLC, ν LEP, SLC, TeV, LHC

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

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

$$A^\mathrm{f}_{\mathrm{FB}} = \frac{3}{4}A_e A_\mathrm{f} \text{ with } A_\mathrm{f} = \frac{2\,g^\mathrm{f}_V/g^\mathrm{f}_A}{1+(g^\mathrm{f}_V/g^\mathrm{f}_A)^2}$$

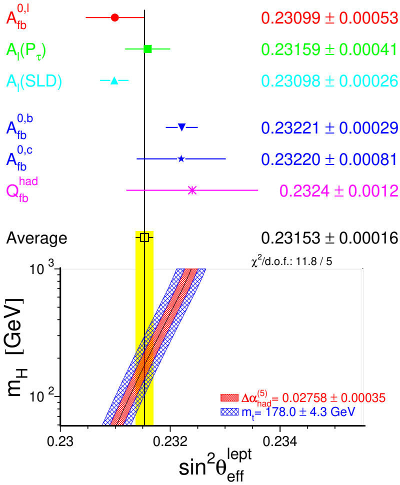
  - **Leptons**: A_l very sensitive to $\sin^2\theta_W$
  - **Down-type quarks**: only weak dependence of A_q on $\sin^2\theta_W$
  - Experimentally: only down-type quarks can be identified (**b tagging**)



Weak Mixing Angle: LEP/SLC Results

- Compare different channels
  - **Most precise: A^{b}_{FB}**
  - $3.2\,\sigma$ discrepancy between leptonic and hadronic final states!
- Additional $3.2\,\sigma$ deviation: neutrino-nucleon scattering (NuTeV)

Unresolved…



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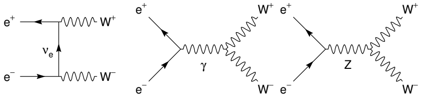
4.1.2. W production at colliders

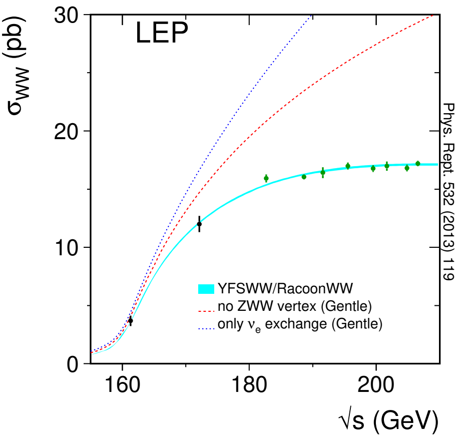
W Boson production at LEP

Karlsruher Institut für Technologie

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



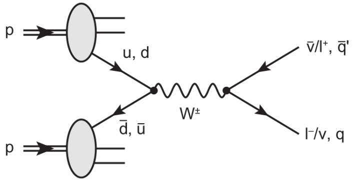
  - Kinematic **production threshold**: $\sqrt{s} \geq 2m_W$
  - **Pair production**: cross section reaches **plateau** (no peak!)

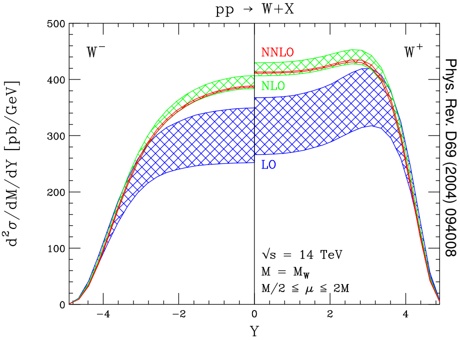


- Threshold scan: scattering matrix only unitary if both ν exchange and triple-gauge-boson vertex (ZWW) are considered

W Boson production at Hadron Colliders

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

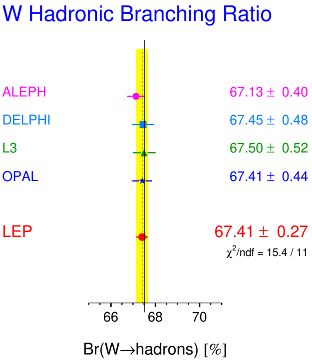


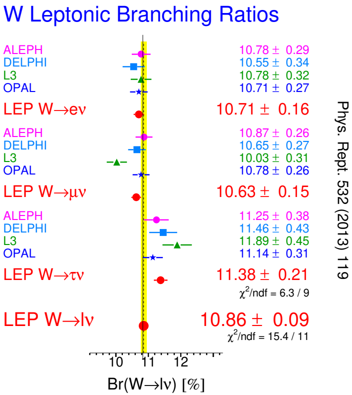


- LO: valence-quark annihilation
  - **$p\bar{p}$: equal $W^{\pm}$ cross section**
  - **pp: uud $\rightarrow W^+$ more probable**
- Differential cross-section known at NNLO QCD (partially also EWK)

W Boson Decays

- Expectation: "democratic" distribution of branching fractions into **9 final states**
  - W $\rightarrow l\nu$: 3 lepton flavours
  - W $\rightarrow$ qq$'$: q (=u,c) $\times$ 3 colours = 6 final states
- Results from LEP:





W Boson Mass

See Exercises No 5

4.1.3. Global electroweak fits

Global Electroweak Fits

- **Free parameters of Standard Model Lagrangian**
  - Gauge couplings: 3 (α_{em}, α_{weak}, α_{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

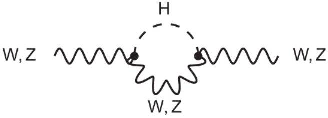
- But **many more independent properties measured**
  $\rightarrow$ constraints of SM parameters
  (each property: different superposition of SM parameters)
  - Allows prediction of unmeasured quantities,
    e. g. top-quark mass before 1995, Higgs-boson mass before 2012

Reminder of Interdependencies

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

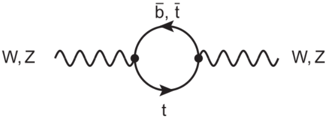
$$m_W \equiv \tfrac{1}{2} g v\,, \quad m_Z \equiv \tfrac{1}{2}\sqrt{g^2 + g'^2}\, v \quad \rightarrow \quad \rho = \frac{m_W}{m_Z \cos\theta_W} = 1$$

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



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

Weak dependence (logarithmic)

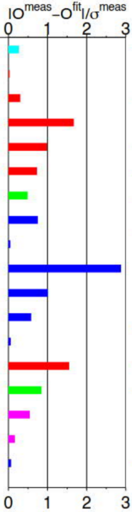


$\sim G_F\, m_t^2$

Strong dependence (quadratic)

Global Electroweak Fits: Typical Ingredients

	Measurement	Fit	
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759	Running of em coupling due to *udscb* quarks
m_Z [GeV]	91.1875 ± 0.0021	91.1874	Z-boson line shape
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	Ratio: hadronic/leptonic partial *Z* width
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645	Leptonic forward-backward asymmetry
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	Leptonic left-right asymmetry from tau polarization
R_b	0.21629 ± 0.00066	0.21579	Ratios: *b*/*c*-quark width/hadronic partial *Z* width
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	forward-backward asymmetry for *b*/*c* quarks
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	left-right asymmetry for *b*/*c* quarks
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	Leptonic left-right asymmetry from polarized beam
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	Leptonic effective electroweak mixing angle
m_W [GeV]	80.385 ± 0.015	80.377	W-boson mass and width
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.20 ± 0.90	173.26	Top-quark mass



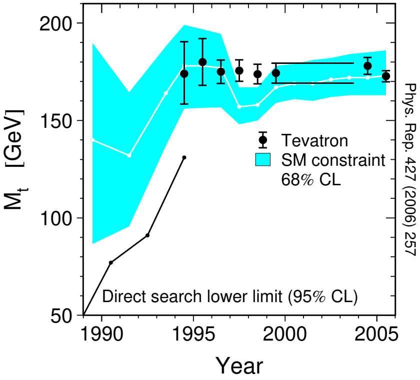
March 2012

Details: Phys. Rep. 427 (2006) 257

Fit of the Top-Quark Mass

- Existence of the top quark strongly assumed since discovery of the b quark (1977)
- Mass **well-constrained due to quadratic contribution to W/Z mass**
  - Still, direct t-quark mass measurement much more precise (≈ 500 MeV uncertainty)

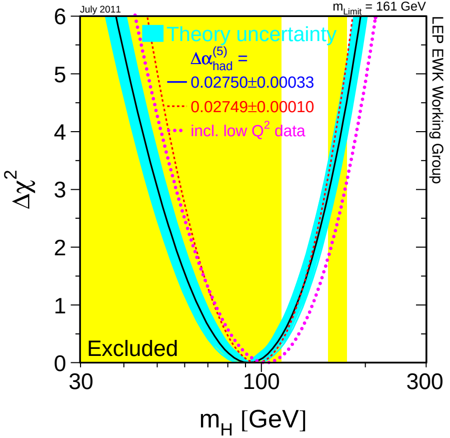
cf. CMS (2016):
$m_{\mathrm{t}} = 172.4 \pm 0.5\,\mathrm{GeV}$



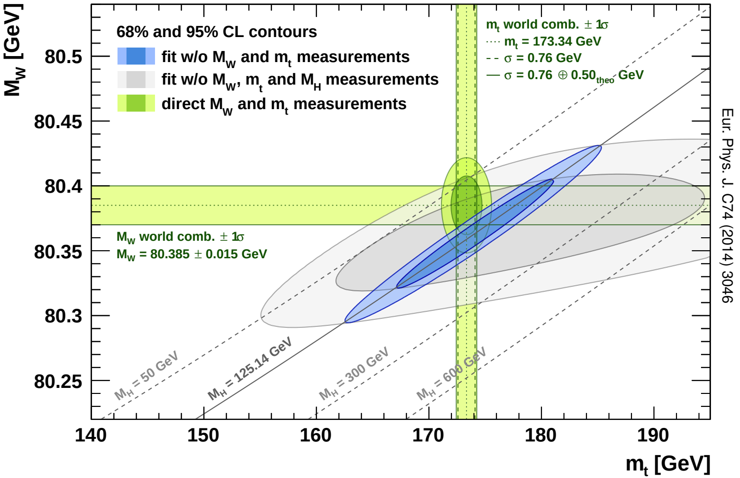
Fit of the Higgs-Boson Mass

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

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



Including the Higgs Boson



4. Physics of the W and Z Bosons

4.1 Determination of SM parameters

- Z factories
- Precision measurements at the Z pole
- W production at colliders
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4.2 W/Z physics at the LHC

- Single W/Z boson production
- $\mathrm{W}/\mathrm{Z} + $ jets production
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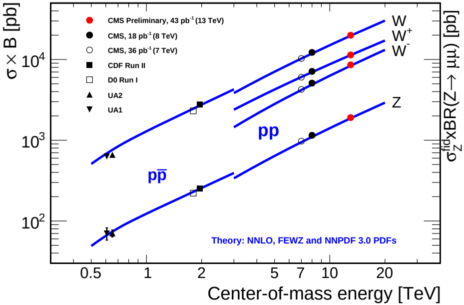
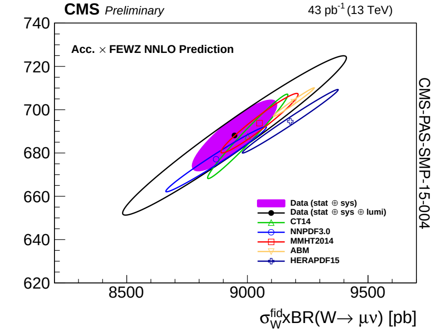
4.2 W/Z physics at the LHC

4.2.1. Single W/Z boson production

Inclusive W/Z Cross-Section



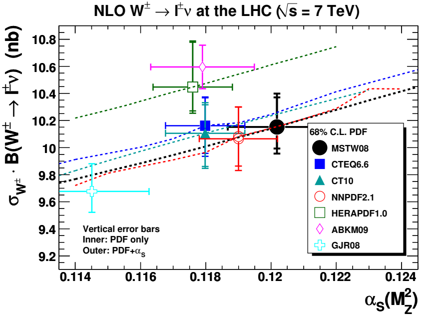


- Wide range of centre-of-mass energies probed from 0.6–13 TeV (SppS – Tevatron – LHC): very good agreement with NNLO prediction
- Correlation of W and Z cross-sections relatively well modelled

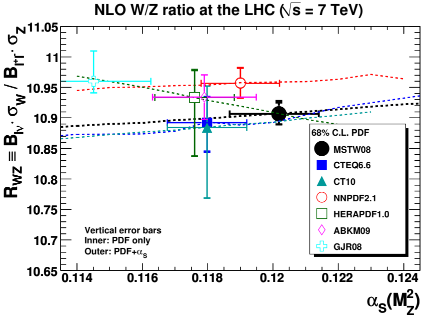
Comparing PDF Predictions

- Inclusive **W/Z cross-section sensitive to differences in PDF sets**
- For example:

W production

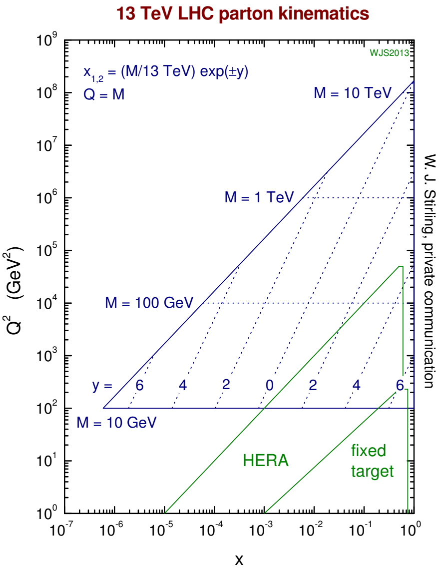


Ratio W/Z



JHEP 1109 (2011) 069

Kinematic (x, Q^2) Plane



W/Z as Probes to QCD

- Idea:
  - Same initial-state momenta: Z at rest
  - Deduce initial-state momenta from Z speed of flight

→ **probes directly parton density**

$$Y = \frac{1}{2}\ln\left(\frac{E(\mu\mu)+p_z(\mu\mu)}{E(\mu\mu)-p_z(\mu\mu)}\right) = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$$

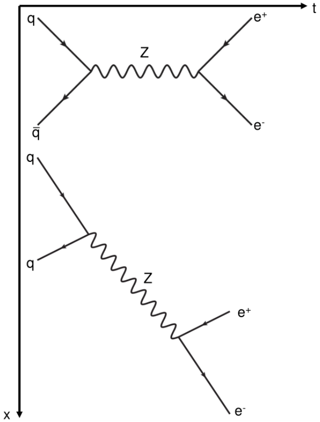
(see Exercises No 1)

- **Double-differential cross-section**

$$\boxed{\frac{d^2\sigma(pp\to\mu\mu)}{dm\,dY}}$$

  - Di-μ mass m
  - Di-μ rapidity Y

→ **Compare to different PDFs**



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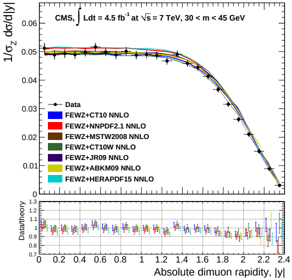
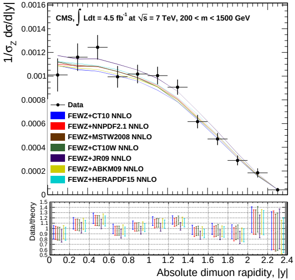




JHEP 1312 (2013) 030

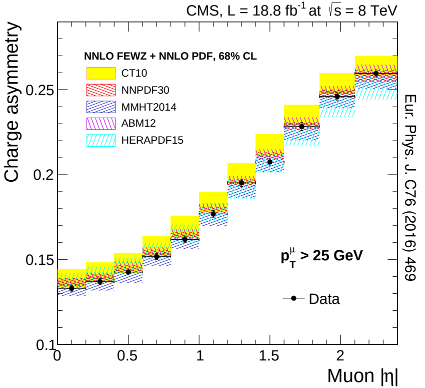
W-Charge Asymmetry

- Event selection targeting $W \to \mu\nu$
  - Muon with $p_T > 25\,\text{GeV}$
  - $\not{E}_T > 25\,\text{GeV}$
  - $m_T > 40\,\text{GeV}$
- **Measure charge asymmetry**

$$A_\mu = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$$

with

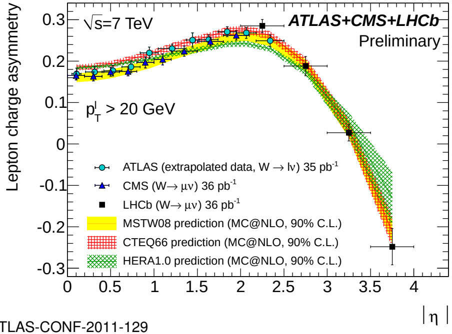
$$\sigma_\eta^\pm = \frac{d}{d\eta}\sigma(pp \to W^\pm \to \mu^\pm\nu)$$



- **Constrains ratio of u/d-quark PDFs** for $10^{-3} < x < 10^{-1}$

W-Charge Asymmetry and LHCb

- LHCb: forward spectrometer
- Extends measurement to $2.5 < |\eta| < 4.0$



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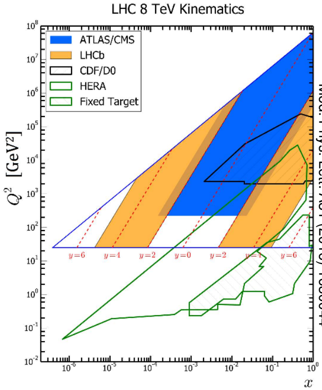


Mod. Phys. Lett. A31 (2016) 1630044

4.2.2. W/Z+jets production

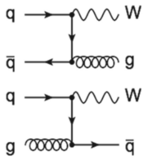
W/Z + Jets

- W/Z at the LHC: high probability for **radiation of additional partons**
  - Important background for many high-p_T analyses (Higgs, Top, Supersymmetry, ...)
  - Requires good theoretical understanding and precise simulation
- **Cross section** for W/Z + jets (V + jets)
  - Naive: factor α_s per additional parton
  - More precise: inclusive cross-section scales geometrically $\rightarrow$ ratio of $n/(n+1)$ jets constant ("Berends–Giele scaling")

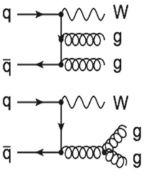
$$\frac{\sigma(\mathrm{pp} \rightarrow \mathrm{W} + (n+1)\ \mathrm{jets})}{\sigma(\mathrm{pp} \rightarrow \mathrm{W} + n\ \mathrm{jets})} = \frac{\sigma(\mathrm{pp} \rightarrow \mathrm{W} + 2\ \mathrm{jets})}{\sigma(\mathrm{pp} \rightarrow \mathrm{W} + 1\ \mathrm{jets})}$$

(except for $n = 0$ due to phase-space difference)

LO-diagrams: W+1 Jet

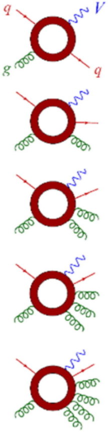


LO-diagrams: W+2 Jet



Radiative Corrections

- **W/Z + jets** prototype for processes with **many particles in the final state** ("2 → *n* process")
- LO: solved for 2 → 10 processes
  - Computation completely automated
- NLO: solved for 2 → 4 processes
  - Higher multiplicities (2 → 6) depending on process
  - Partially automated (NLO revolution)
- NNLO: up to now largely low multiplicity

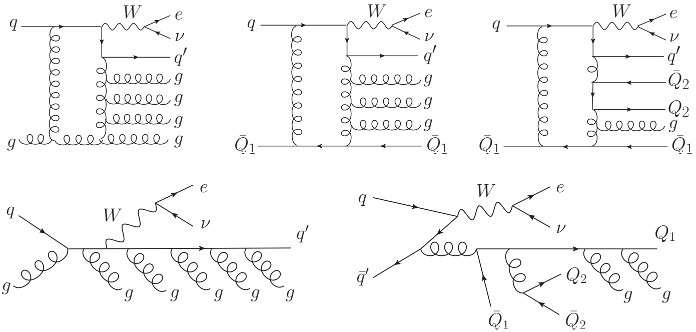


#Jets	# NLO-diagramms
1	11
2	110
3	1,253
4	16,648
5	256,265

[L. Dixon]

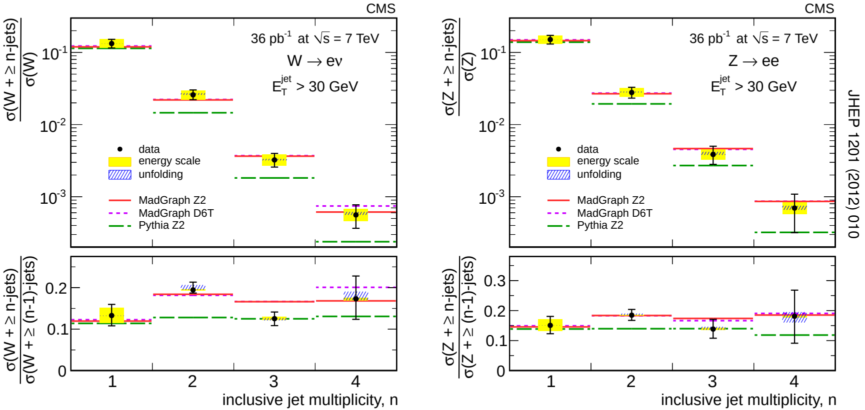
State-of-the-Art Example: W + 5 Jets @ NLO

- W + jets production at the LHC



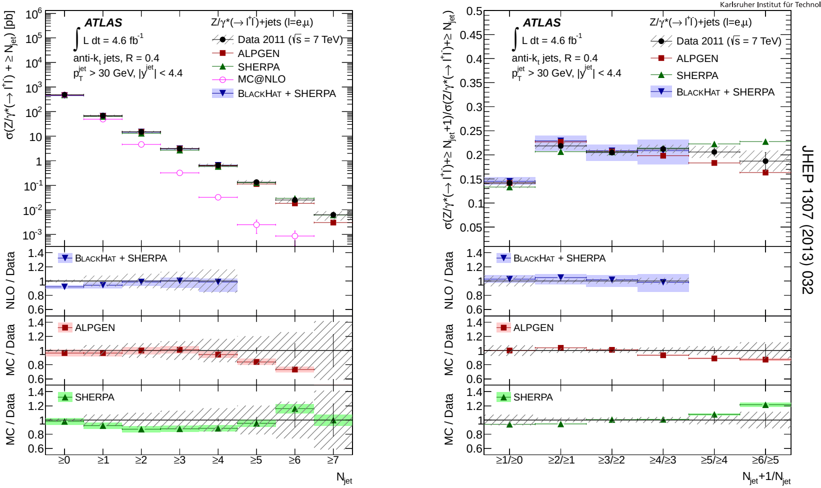
- Computed for **up to 5 additional jets at NLO** precision (using the programmes BlackHat and Sherpa) [Phys. Rev. D88 (2013) 014025]
  - Inclusive cross-section and per-jet p_T distributions
  - Ratios of inclusive cross-sections → extrapolation formula to larger number of jets

W/Z + Jets: Measurements



- Measured **cross-section well-described by (most) MC simulations** (ME+PS simulation)
- Berends–Giele scaling: decent description of data

W/Z + Jets: Measurements

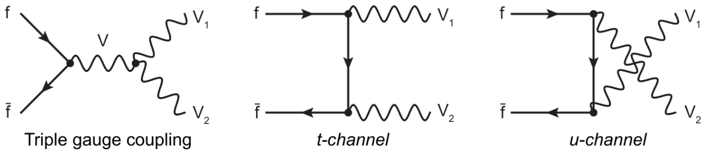


- **NLO calculation** (BlackHat+Sherpa): **very good description** of data
- MC **simulations (N)LO ME plus PS**
  - PS simulates additional jets beyond 5, **some significant deviations**

4.2.3. Vector boson pair-production

Vector Boson Pair-Production at the LHC

- LO Feynman diagrams for **diboson production**

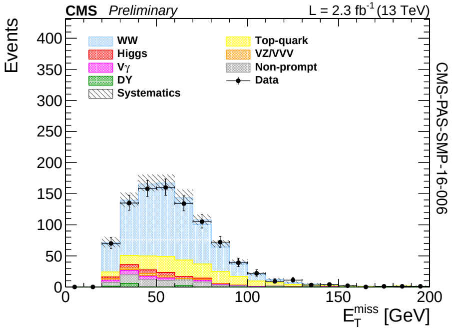


  - Standard Model: $V_1 V_2 = WW, WZ, ZZ, W\gamma, Z\gamma$

- **Diboson physics**
  - SM test and search for new physics, e. g. anomalous triple gauge couplings (aTGC)
  - Background for other high-p_T processes: Higgs boson, top quarks, ...

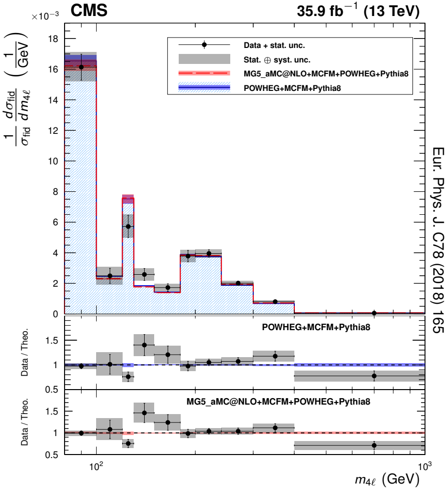
WW Production

- Cleanest channel: WW $\rightarrow ll\nu\nu$ ($e\mu$ better than ee, $\mu\mu$)
- Important background: $t\bar{t}$ production



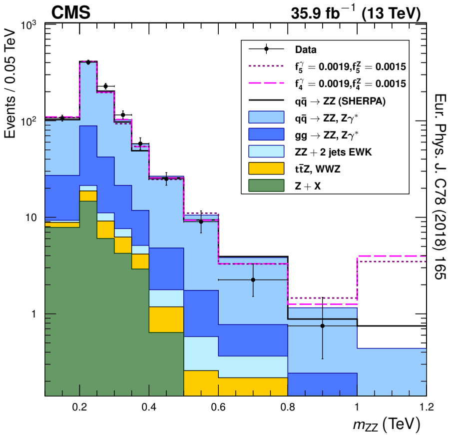
ZZ Production

- Cleanest channel: ZZ $\rightarrow 4l$
  - $\approx$ background free
  - Low statistics
- Background for Higgs measurements



ZZ Production

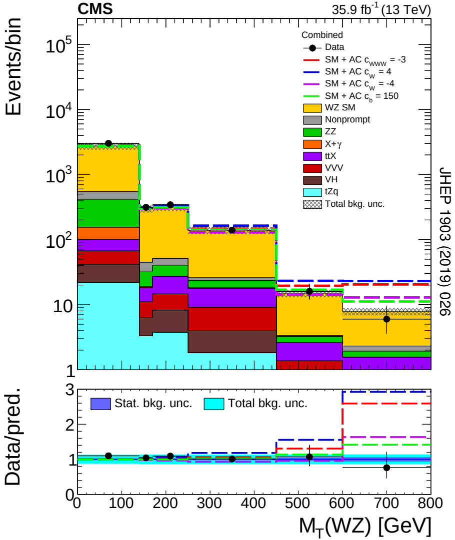
- Cleanest channel: ZZ $\to 4l$
  - $\approx$ background free
  - Low statistics
- Background for Higgs measurements
- Interpret also as aTGC



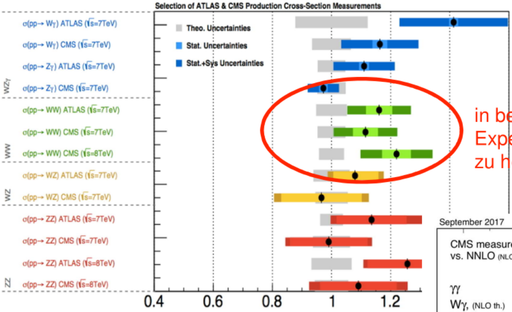
WZ Production

- WZ reconstruction
  - **Signature: 3 leptons**
    (W $\rightarrow l\nu$, Z $\rightarrow ll$)
  - Main backgrounds: Z + jets, ZZ
- Search for new physics
  - High-p_T Z boson
  - High invariant WZ mass

NEW 2019

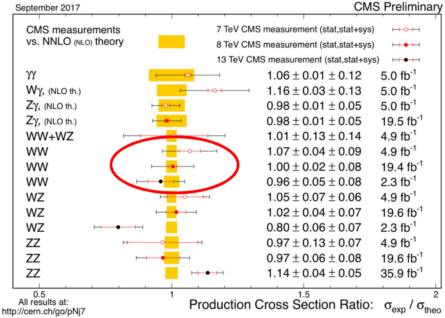


Diboson Cross-Section



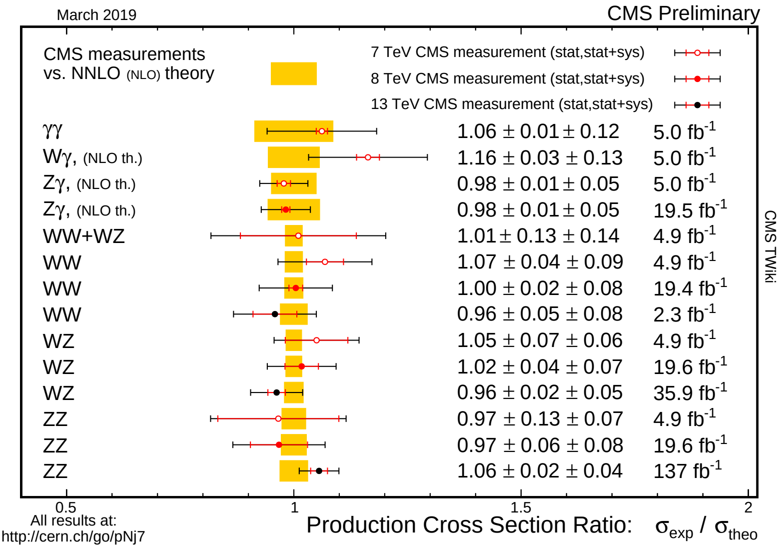
in beiden Experimenten zu hoch?

[M. Schott, DPG 2013]

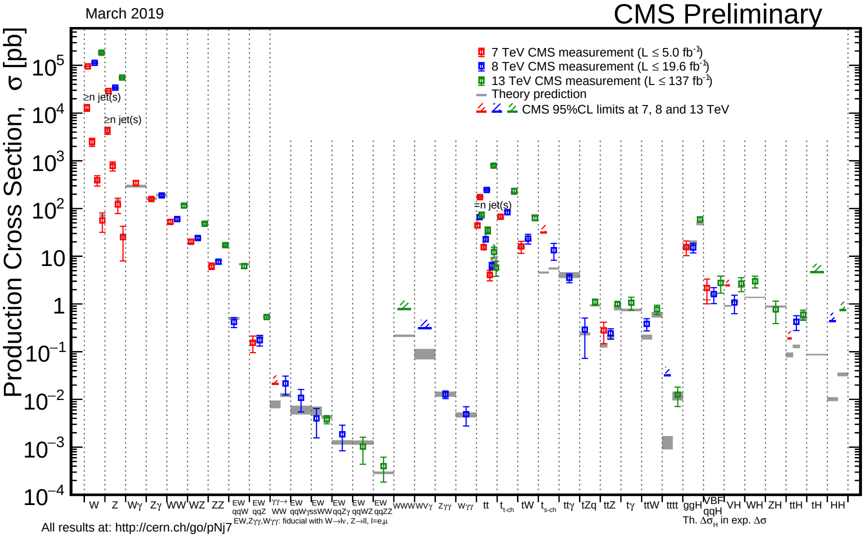


Deviation reduced by improved prediction
NLO => NNLO
Thoery – error-estimate non-trivial

Diboson Cross-Section (Status 2019)



“Stairway-to-Heaven” Plot



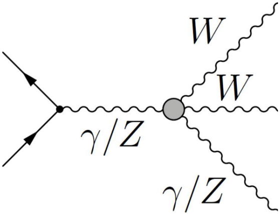
CMS TWiki

4.2.4. Vector boson scattering

Triple Boson Production

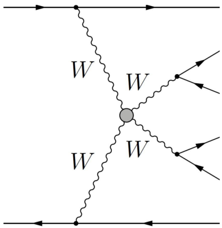
- Mediated by **4-point V boson interaction vertex** (“quartic vertec”)
- In the Standard Model
  - WWWW
  - WWZZ
  - WWZγ
  - WW$\gamma\gamma$

  (4 neutral bosons forbidden)
- Problem: cross-section extremely small

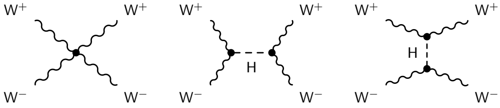


Vector Boson Scattering

- Study quartic vertex in V boson scattering (VBS)

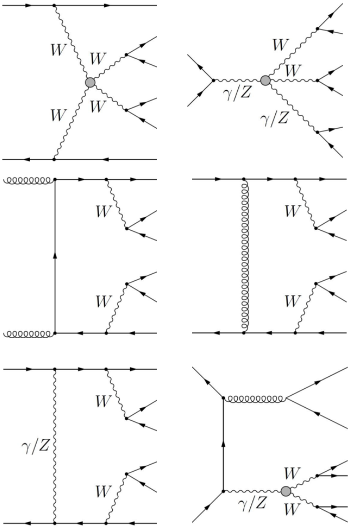


- Cross-section for longitudinally polarised states diverges at high energies: in SM cancelled by negative interference with Higgs diagrams



Vector Boson Scattering

- $2\,W + 2\,$jets processes common
  - **Jets typically forward**
- Event selection: 2 jets with
  - **high dijet mass**
  - **large rapidity difference**
- Study $W^{\pm}W^{\pm}$
  - No gluon-induced initial states
  - Largely reduced backgrounds



Vector Boson Scattering

Karlsruher Institut für Technologie

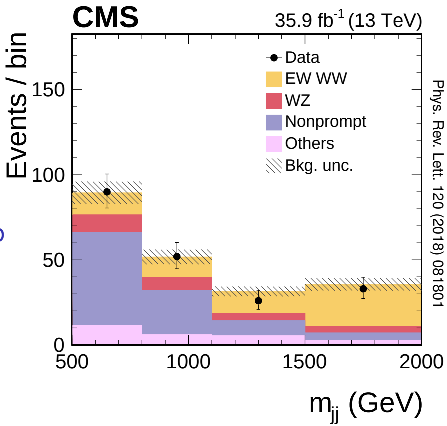
- First **observation in 2017**
  - EWK contribution detected at 5 σ significance

    $\sigma(\mathrm{pp} \to \mathrm{W}^{\pm}\mathrm{W}^{\pm}) = 3.83 \pm 0.66\,(\mathrm{stat}) \pm 0.35\,(\mathrm{syst})\ \mathrm{fb}$

    (SM prediction: 4.25 ± 0.2 fb)

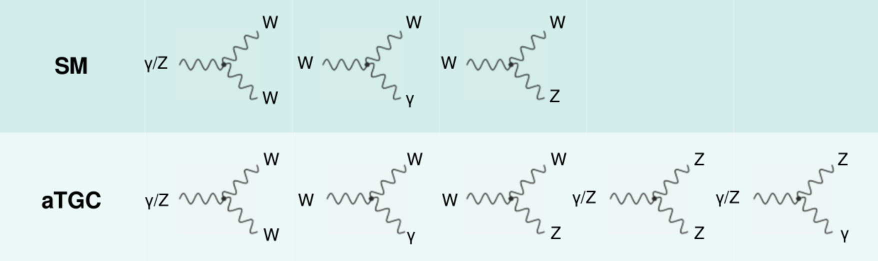
- New evidence also in ZZ channel

  [Phys. Lett. B774 (2017) 682]



4.2.5. Anomalous couplings

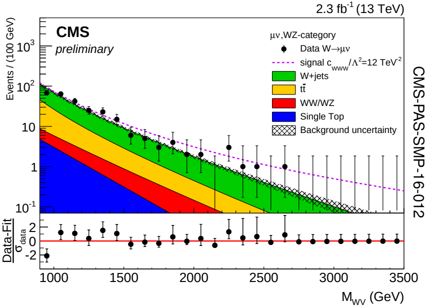
Anomalous Triple Gauge Couplings (aTGC)



New physics beyond the Standard Model can **modify couplings**
$\rightarrow$ expect **higher cross sections**, especially at **high p_T (V)**

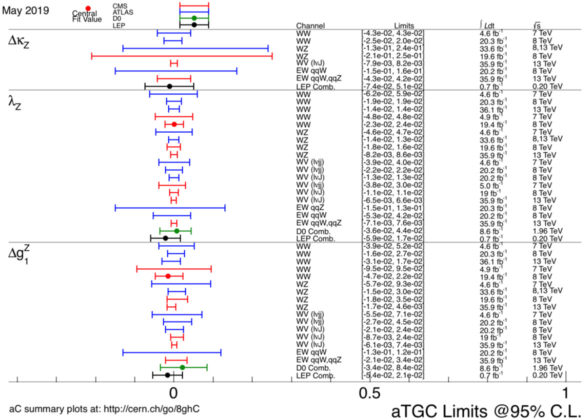
Searching for aTGC

- Interpret **diboson results as limits on aTGCs**
- Example: CMS WV analysis
  - Typical assumption: no C or P violation
  - Expect largest effect at high diboson mass
- Observable: **invariant WV mass**
  - $W \to e^- \nu$, $W/Z \to q\bar{q}$
  - Reconstruct $p_z(\nu)$ using W mass constraint



Summary WWZ aTGC

- **Many different results**
- **Common interpretation** e. g. in “LEP parametrisation”
  - All parameters defined such that they equal 0 in the SM

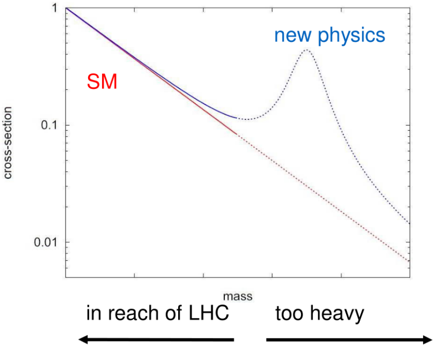


CMS TWiki

Effective Field Theory

- New physics might be out of direct LHC reach
- "Integrate out" high-mass particles (like in Fermi theory)

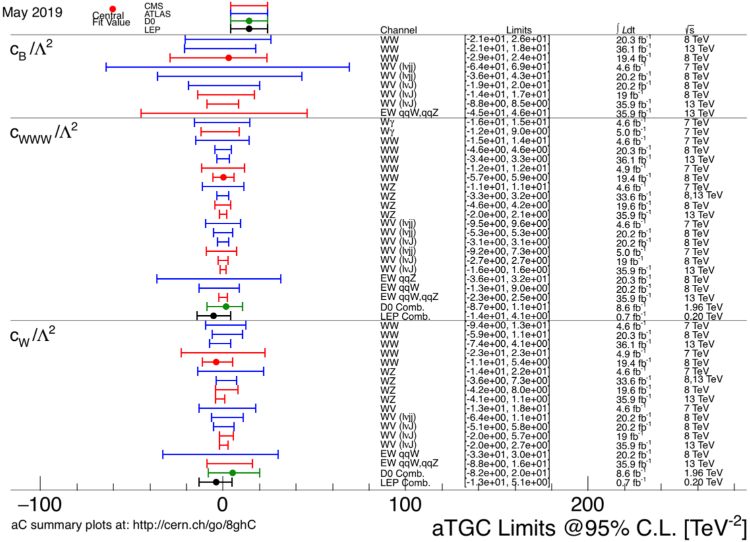
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$



→ **parametrise any theory without low-mass particles**

- Standard Model covers all dimension-4 operators
- Dimension 5, 7 violate lepton number
- Dimension 6: includes triple gauge couplings
- Dimension 8: includes quartic gauge couplings

Summary aTGC in EFT



Summary aQGC in EFT

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