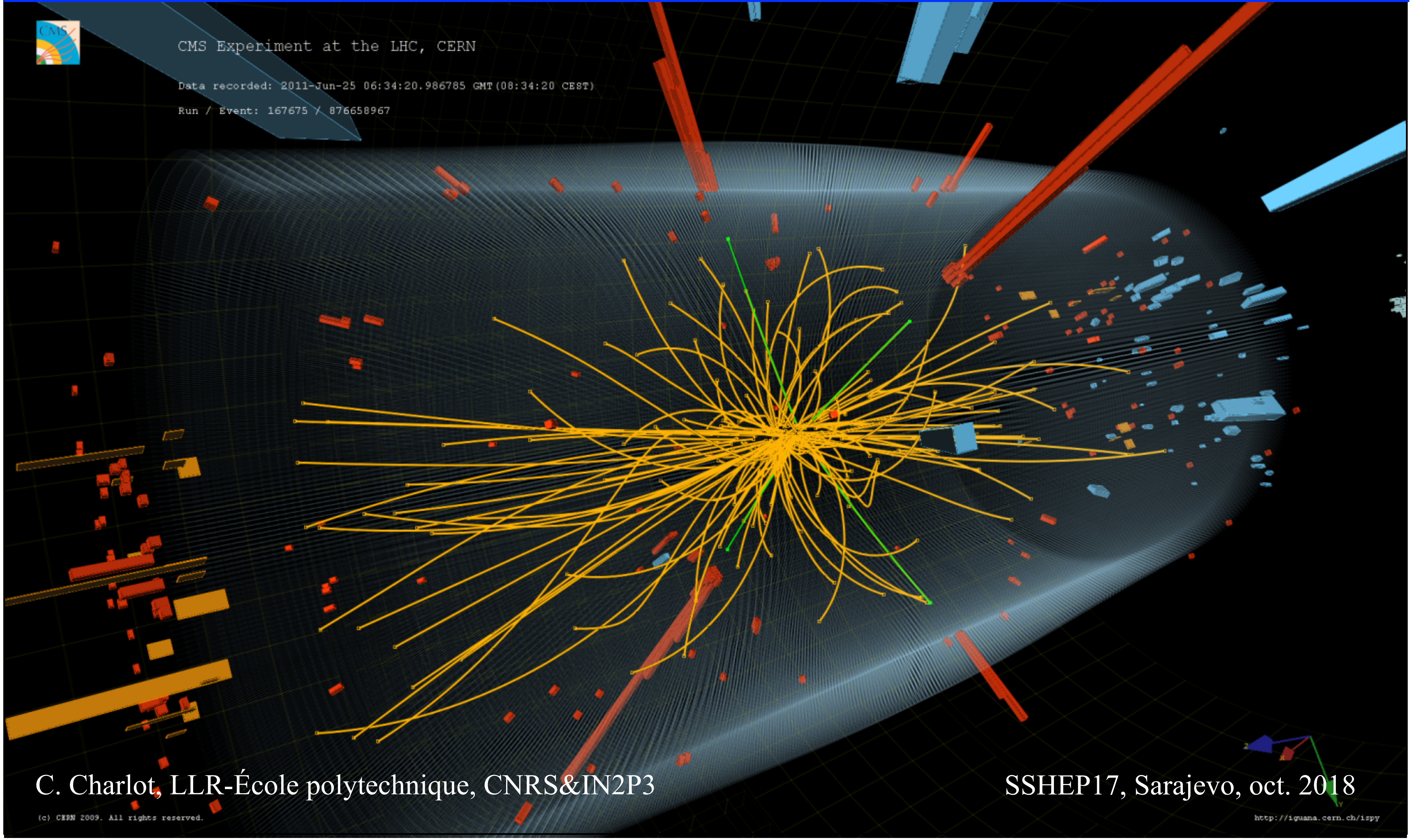
LHC Physics



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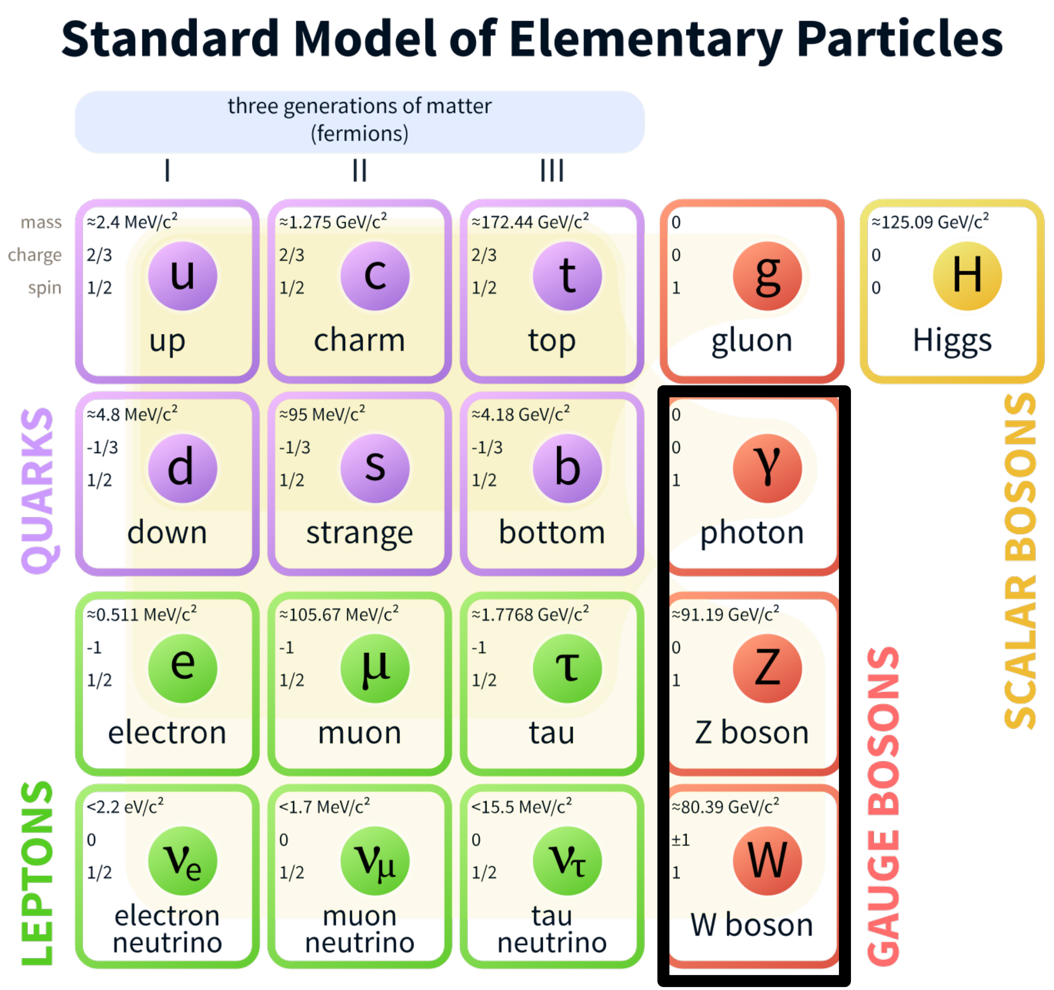
Part 3: Electroweak Physics

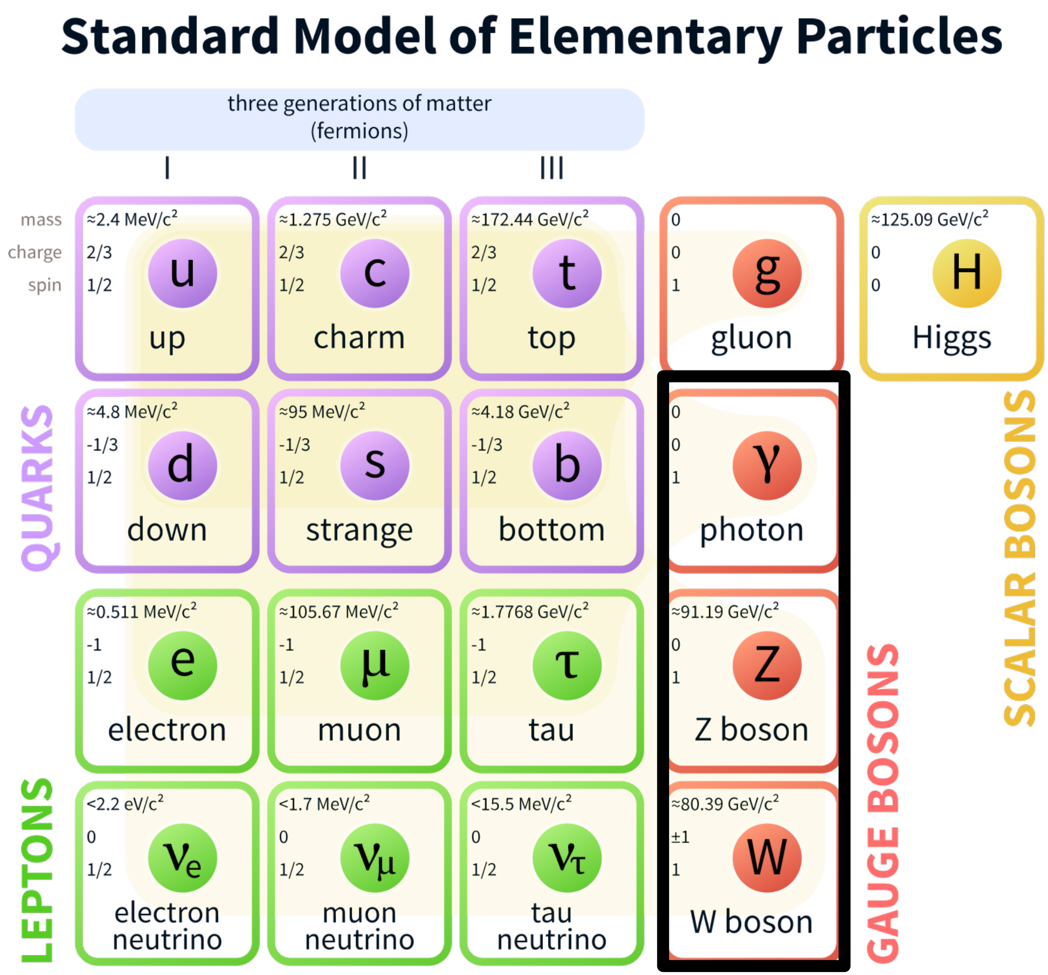
Fundamental particles & interactions

- <u>Why EW physics?</u>
- Understand and describe *coherently* electromagnetic and weak interactions
- Despite important differences
- Massive W,Z → **short range** weak interaction
- Contrary to **long range** electromagnetic interactions
- Parity violation, standard Model as a **chiral** theory



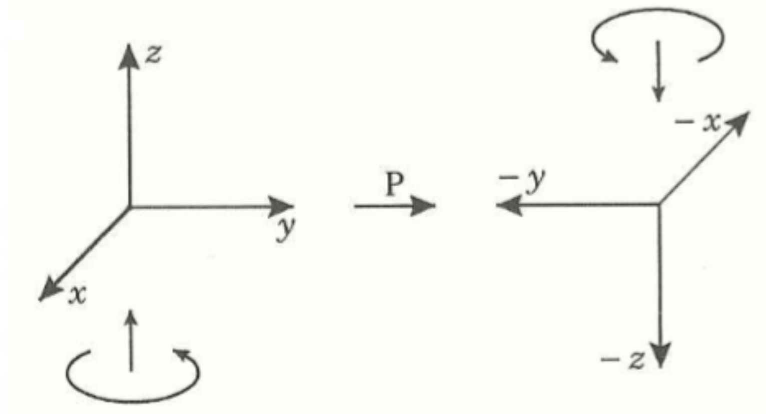
Fundamental particles & interactions

- ❑ <u>In this lecture</u>
  - ❑ V-A structure of the standard model
  - ❑ $\sin\theta_W$ and F/B asymmetry
  - ❑ W,Z production at LHC
  - ❑ m_W measurement, consistency check of standard model
  - ❑ Vector boson scattering and unitarity



Parity transformation

- ❑ Parity transformation P
- ❑ Transform all coordinates x → -x
- ❑ Left handed frame → right handed frame



- ❑ How do common mathematical objects transform under P?
  - ❑ Scalar (E): E → E
  - ❑ Pseudo-scalar (h): h → -h
  - ❑ Vector (p): p → -p
  - ❑ Pseudo-vector (J): J → J

→ Parity is conserved by electromagnetic (QED) and strong (QCD) interactions

Helicity and chirality

- Helicity: sign of projection of the spin onto the momentum direction
- A particle is right-handed (left-handed) if its helicity is >0 (<0)

- For massive particle it is possible to change reference frame such that helicity is inverted (helicity is not a Lorentz invariant)
- Chirality relates to the behaviour under parity transformation, intrinsic field property
- Dirac spinors can be decomposed into Ψ_R and Ψ_L, applying projectors

$$\Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \qquad \mathrm{P}_L = \frac{1}{2}(1 - \gamma^5)$$

Parity violation in weak interactions

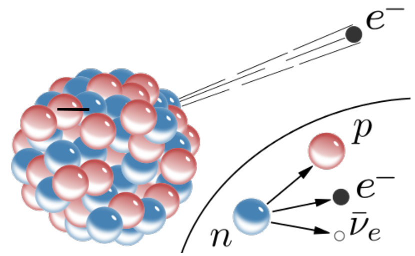
- **β decay**: within nuclei $n \rightarrow p + e^- + \bar{\nu}_e$
- Weak interaction between quarks:

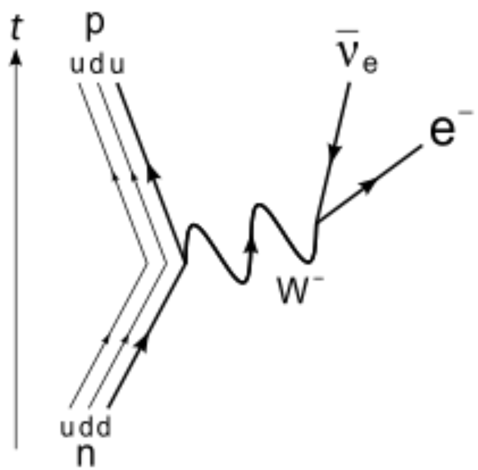
  $$d \rightarrow u + e^- + \bar{\nu}_e$$

- Experimental fact (1956: Lee, Yang, Wu):

  e^- is always left-handed
- This means P is (maximally) violated by weak interactions
- But CP is (approximately) conserved:

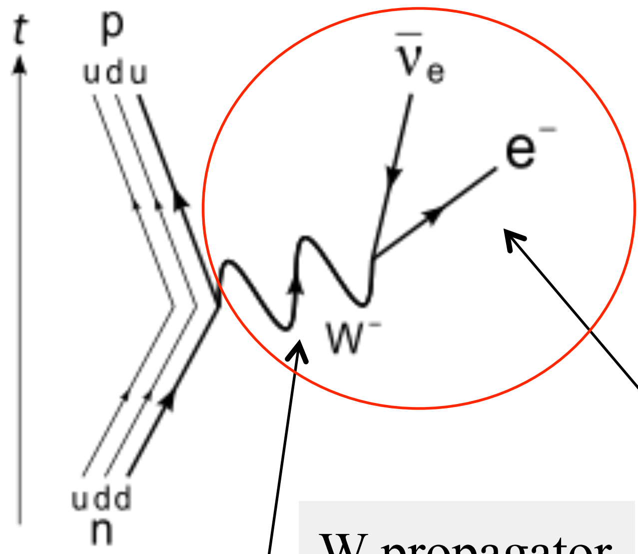
  $$u \rightarrow d + e^+ + \nu_e$$





$$i\mathcal{M} = \left(-i\frac{g_W}{\sqrt{2}}\right)^2 \left[\bar{\nu}_l\gamma^\mu\left(\frac{1-\gamma^5}{2}\right)l\right] \frac{-i}{q^2 - m_W^2}\left(\eta_{\mu\nu} - \frac{q_\mu q_\nu}{m_W^2}\right) \left[\bar{l}\gamma_\mu\left(\frac{1-\gamma^5}{2}\right)\nu_l\right]$$

Weak interactions



W propagator

fermion line

$$i\mathcal{M} = (-i\frac{g_W}{\sqrt{2}})^2 \left[\bar{\nu}_l \gamma^\mu (\frac{1-\gamma^5}{2}) l\right] \frac{-i}{q^2 - m_W^2}(\eta_{\mu\nu} - \frac{q_\mu q_\nu}{m_W^2}) \left[\bar{l}\gamma_\mu (\frac{1-\gamma^5}{2})\nu_l\right]$$

projector on left-handed states → **V-A structure of the electroweak interaction**

EW interactions in the SM

Weak Isospin and Hypercharge Quantum

Lepton	T	T^3	Q	Y
ν_e	$\frac{1}{2}$	$\frac{1}{2}$	0	-1
e^-_L	$\frac{1}{2}$	$-\frac{1}{2}$	-1	-1
e^-_R	0	0	-1	-2

Numbers of Leptons and Quarks

Quark	T	T^3	Q	Y
u_L	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$
d_L	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$
u_R	0	0	$\frac{2}{3}$	$\frac{4}{3}$
d_R	0	0	$-\frac{1}{3}$	$-\frac{2}{3}$

- **Weak interaction only affects left-handed particles** (weak isospin T not 0)
- T^3 conserved by weak interaction
- Q conserved by e.m. interaction
- **Y is conserved by EW interaction**
  - $Y = 2(Q-T^3)$
- This means only terms that are neutral to overal Y are allowed
- Left-handed doublets $SU(2)_L$

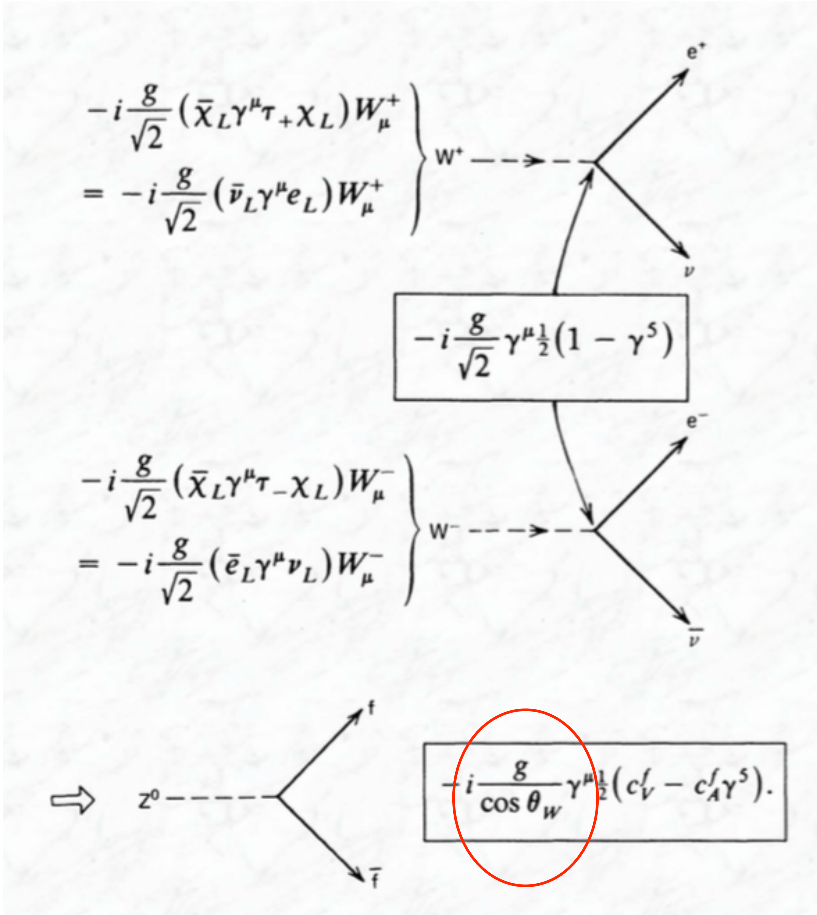
→ SM is a chiral theory

EW neutral interactions

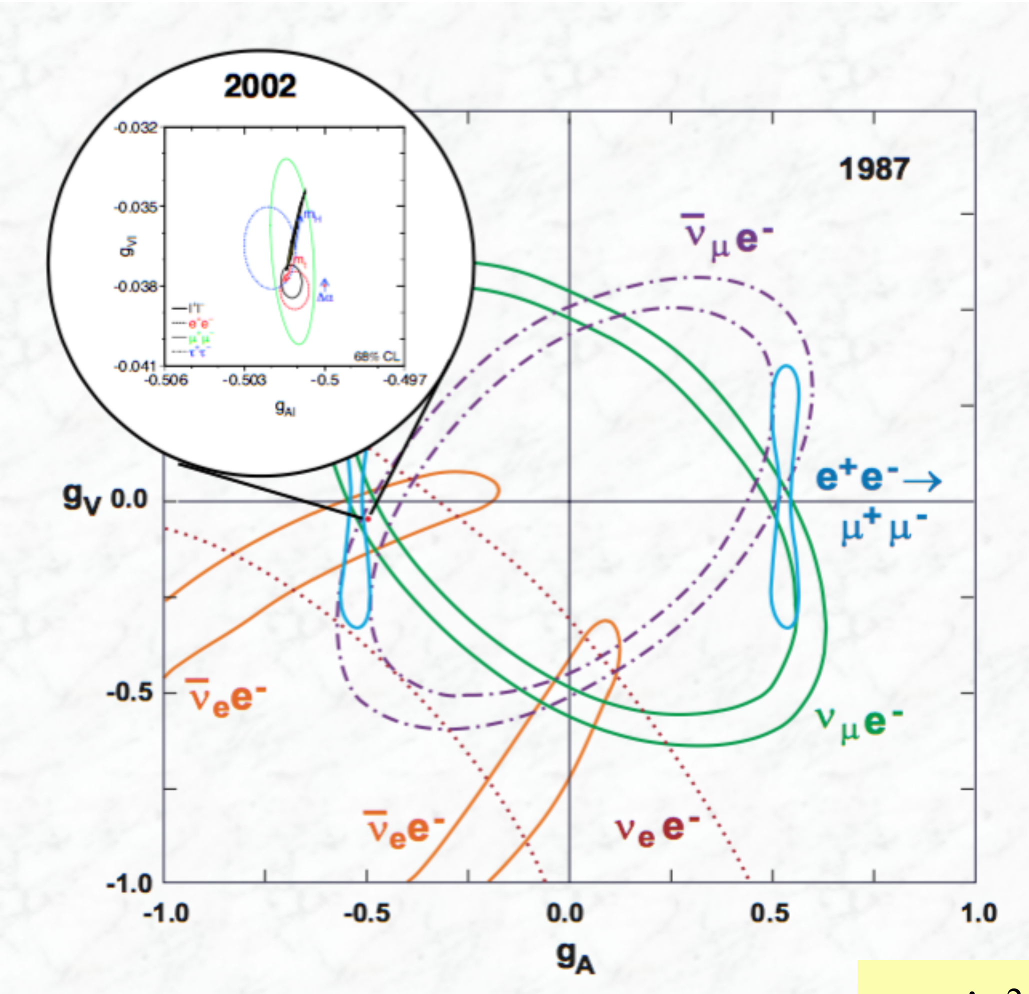
- ❑ In the electroweak theory, two carriers for **neutral interactions** (γ and Z)
- ❑ The resulting interaction is a **mixture** of the two
- ❑ The **Weinberg angle** θ_W quantifies this mixing

$$\boxed{\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}}$$

e.m. coupling   weak coupling



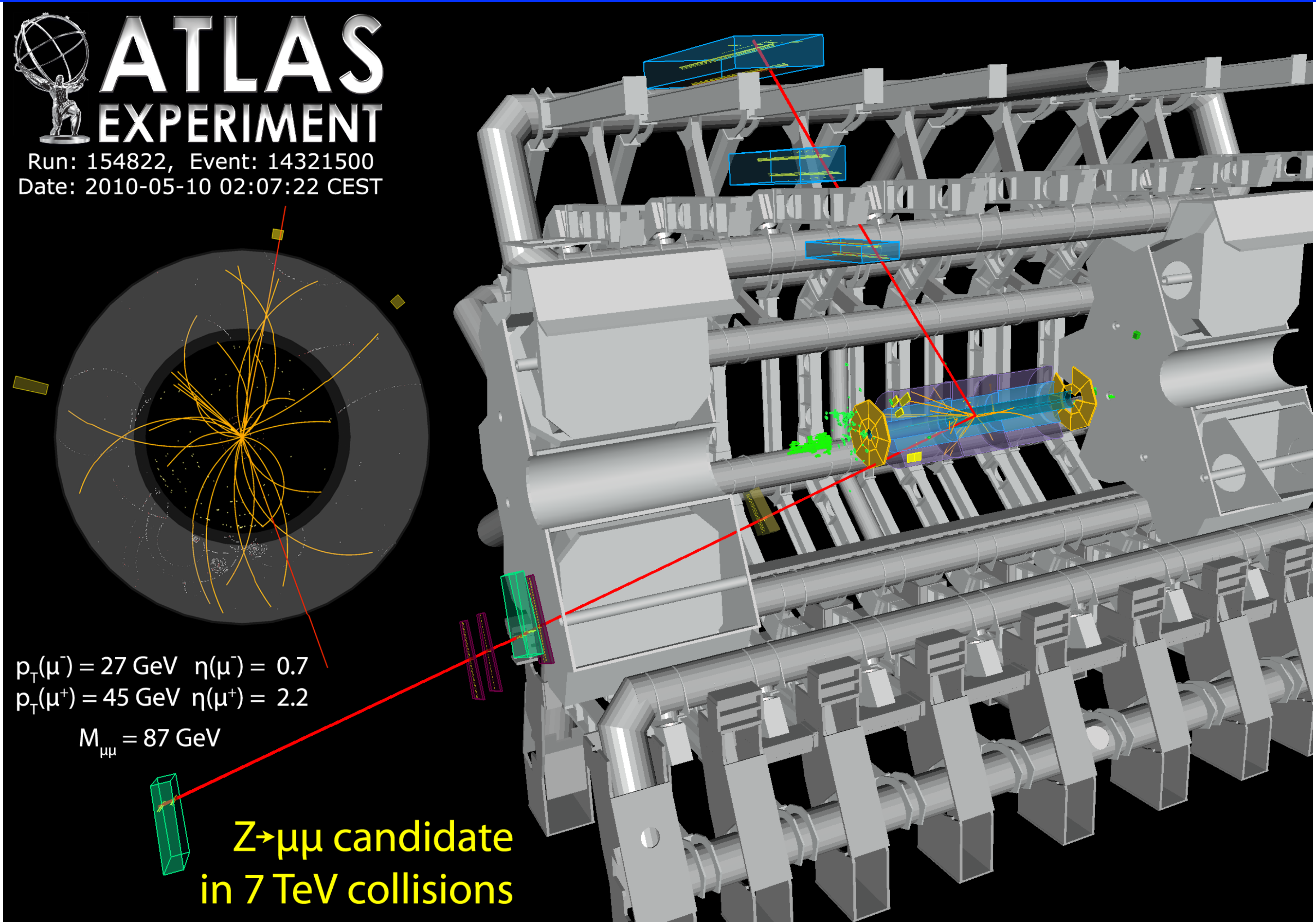
sinθ$_W$: from LEP to LHC



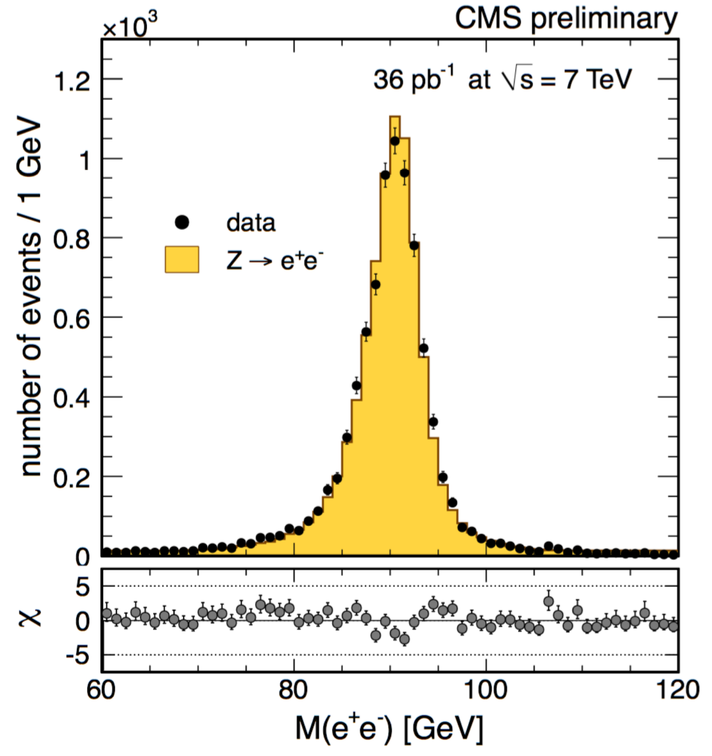
- **Many years of experimental and theoretical progress**
- EW theory tested at ~10^{-4} at LEP
- Further measurements at LHC
- **Far more Z than at LEP**
  - O(100M) recorded
  - In cleanest mode: $Z^0 \to l^+l^-$

$\to \sin^2\theta_W = 0.234$, experimentally measured

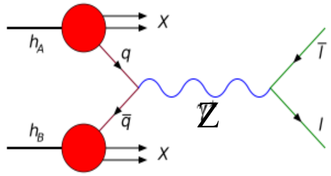
Z→μμ event


ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions

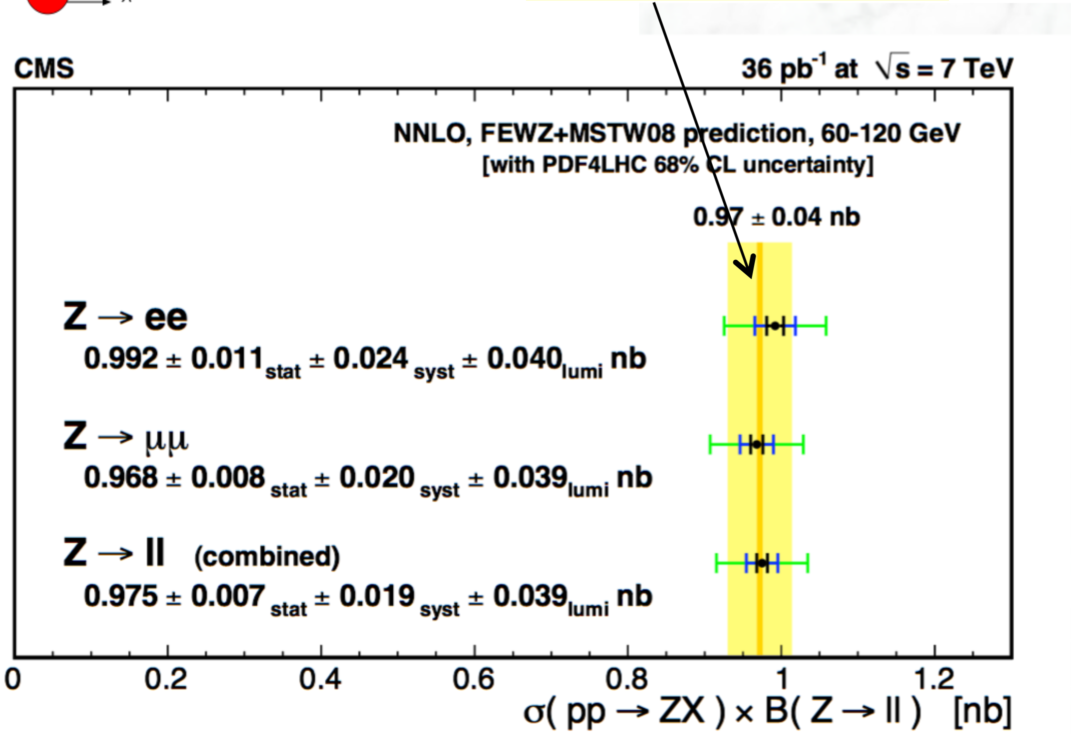
pp→Z⁰→l⁺l⁻ cross section at LHC



m^2=2p_1p_2(1-cosθ)

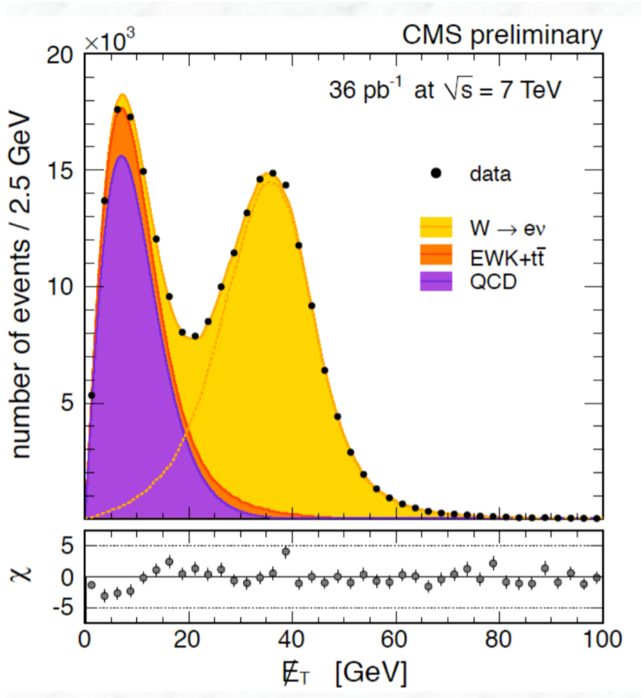


theory prediction

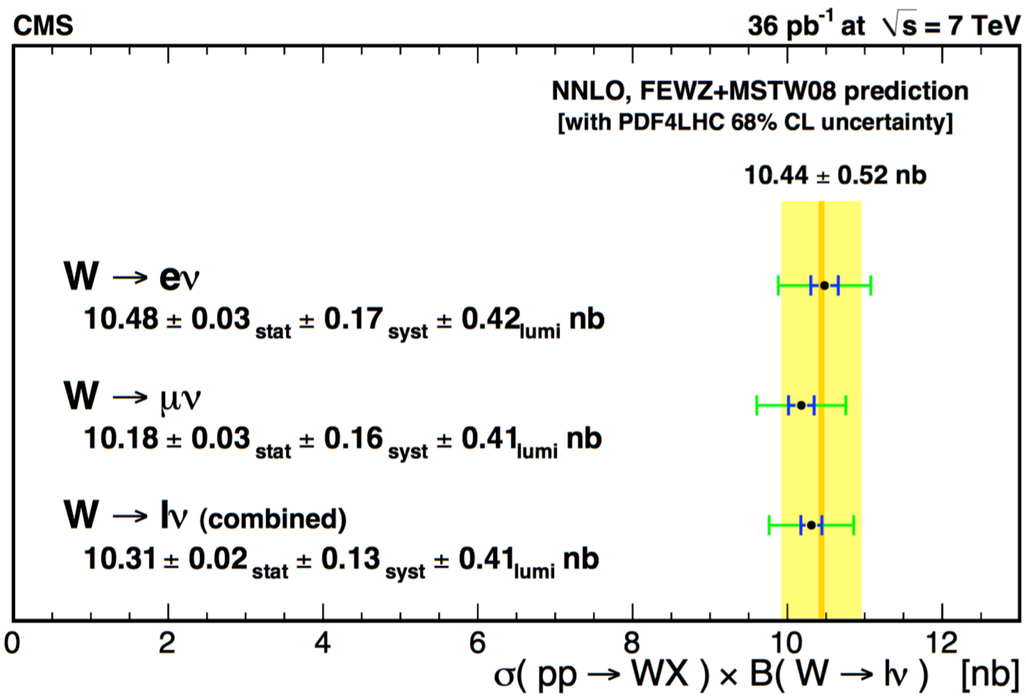


- ❑ O(5%) precision, limited by systematic and luminosity uncertainties
- ❑ Large corrections from quantum chromodynamics (QCD), test of QCD

pp→W±→l±ν cross section

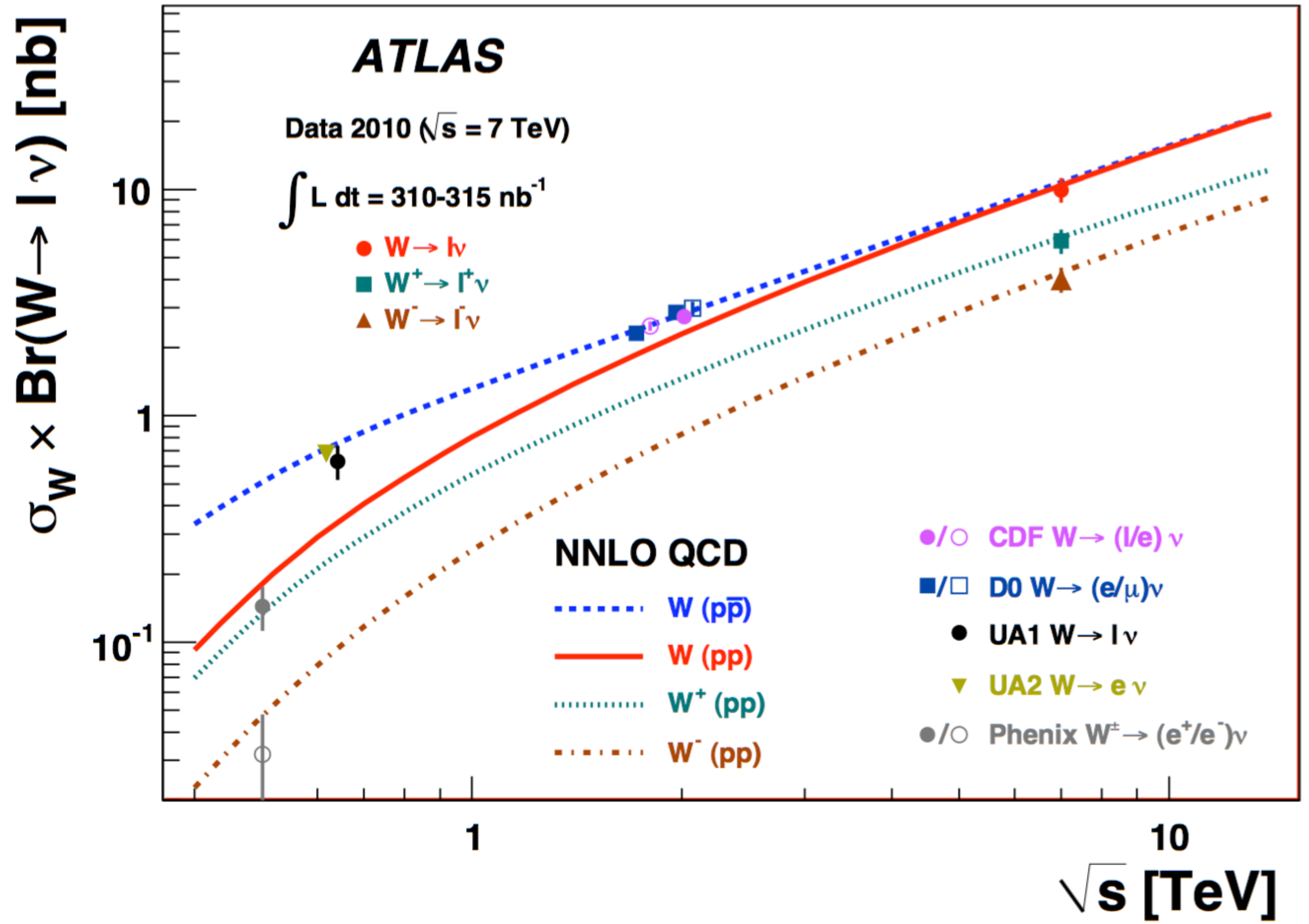


Neutrino transverse momentum from the transverse energy balance



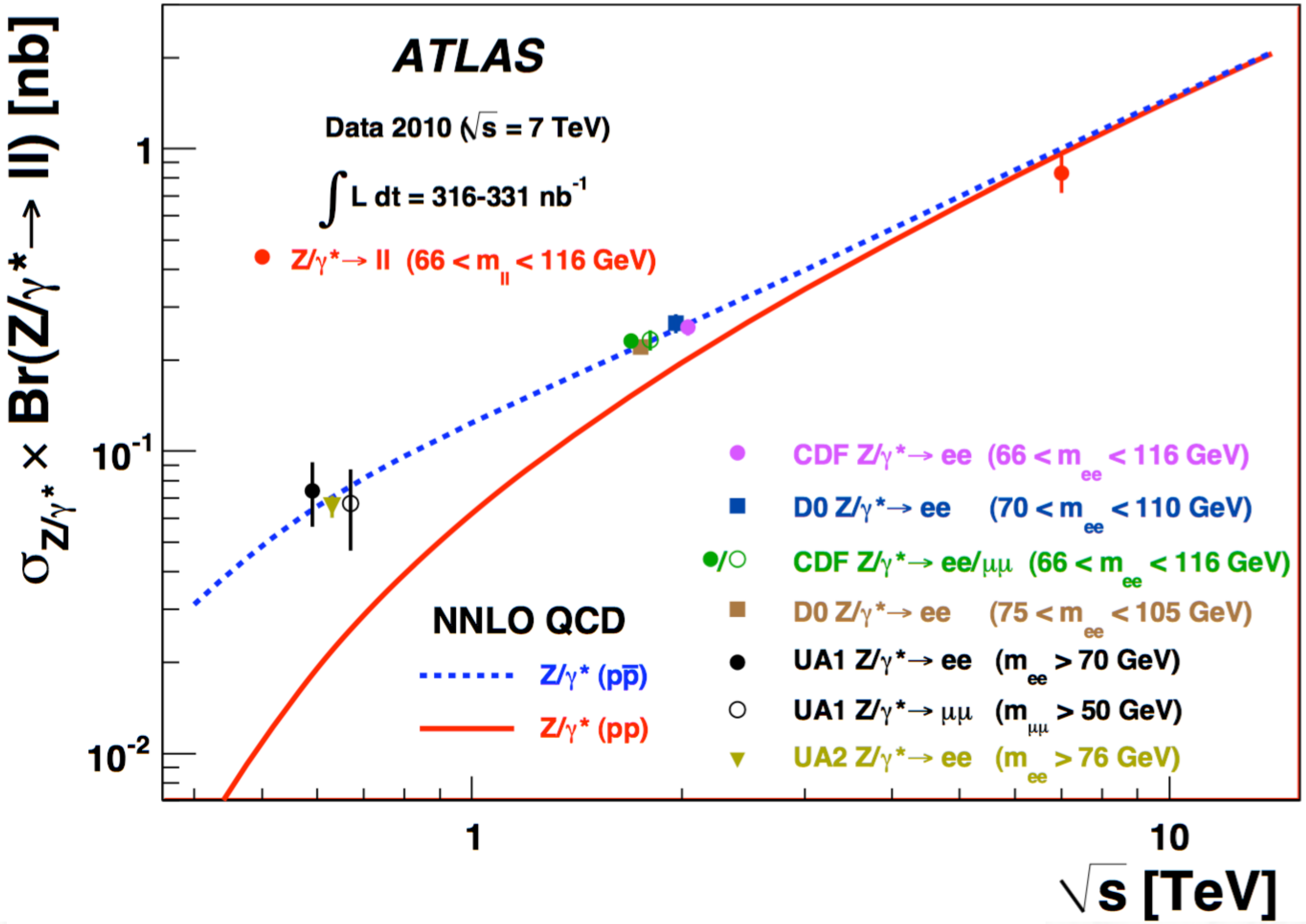
→ Excellent agreement with theory prediction, ~5% precision

W± production cross section



The measured values of σ_W x BR(W → l ν) for W+, W- and for their sum compared to the theoretical predictions based on NNLO QCD calculations. Results are shown for the combined electron-muon results. The predictions are shown for both proton-proton (W+,W- and their sum) and proton-antiproton colliders (W) as a function of root(s). In addition, previous measurements at proton-antiproton and proton-proton colliders are shown. The data points at the various energies are staggered to improve readability. The CDF and D0 measurements are shown for both Tevatron collider energies, √s = 1.8 TeV and √s = 1.96 TeV. All data points are displayed with their total uncertainty. The theoretical uncertainties are not shown.

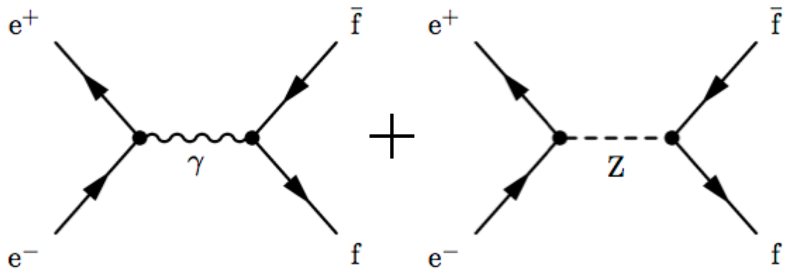
Z^0 production cross section



The measured values of σ_Z x BR(Z→ ll) where the electron and muon channels have been combined, compared to the theoretical predictions based on NNLO QCD calculations. The predictions are shown for both proton-proton and proton-antiproton colliders as a function of √s. In addition, previous measurements at proton-antiproton colliders are shown. The data points at the various energies are staggered to improve readability. The CDF and D0 measurements are shown for both Tevatron collider energies, √s= 1.8 TeV and √s = 1.96 TeV. All data points are displayed with their total uncertainty. The theoretical uncertainties are not shown.

Forward-backward asymmetry

- Because of parity violation in weak interaction, there are differences in interaction strength between left-handed and right-handed particles
- This reflects in an asymmetry in the direction of fermions produced in $f\bar{f}\rightarrow Z\rightarrow f\bar{f}$
- Here $e^+e\rightarrow\mu^+\mu^-$, at LHC similarly $qq\rightarrow\mu^+\mu^-$



f: fermion
$\bar{f}$: anti-fermion

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta)+F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}+F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

γ | γ/Z interference | Z

x N_c^f: number of colours for fermion f

Forward-backward asymetry

$$F_\gamma(\cos\theta) = Q_e^2 Q_f^2 (1+\cos^2\theta) = (1+\cos^2\theta)$$

$$F_{\gamma Z}(\cos\theta) = \frac{Q_e Q_f}{4\sin^2\theta_W \cos^2\theta_W}[2g_V^e g_V^\mu (1+\cos^2\theta) + 4g_A^e g_A^f \cos\theta]$$

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W \cos^4\theta_W}[(g_V^{e^2} + g_A^{e^2})(g_V^{f^2} + g_A^{f^2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^f g_A^f \cos\theta]$$

⇒ **terms in cosθ →= asymmetry in the angular distribution of the outgoing fermion**

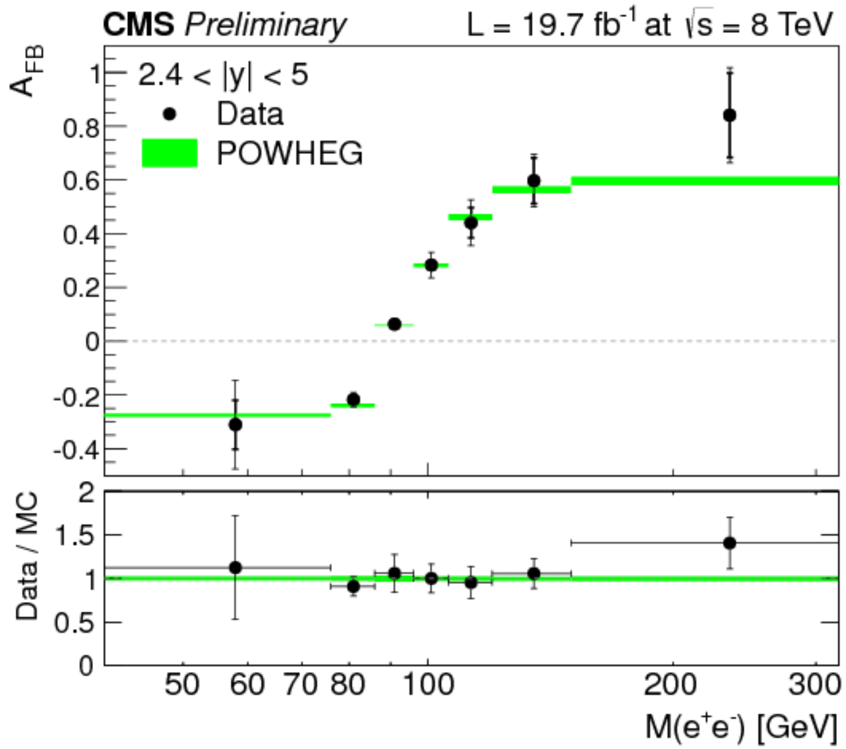
(Note that these terms vanish if there is no axial coupling)

$$\sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Forward-backward asymmetry

- Because of parity violation, there are differences in interaction strength between left-handed and right-handed particles
- This reflects in an asymmetry in the observed leptons direction in $f\bar{f} \rightarrow Z \rightarrow f\bar{f}$

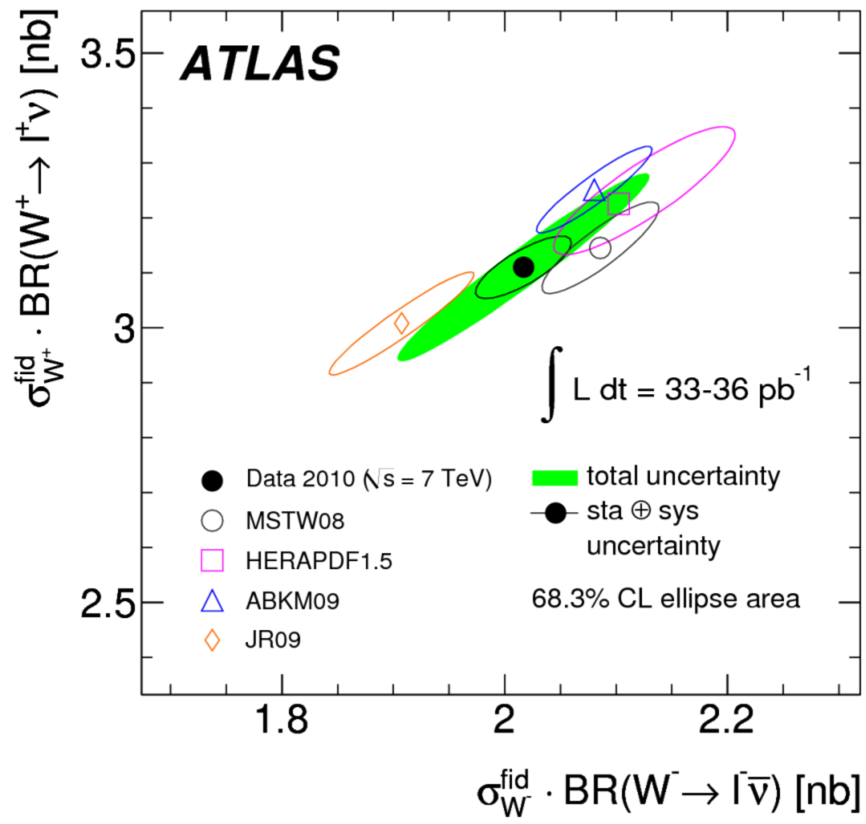


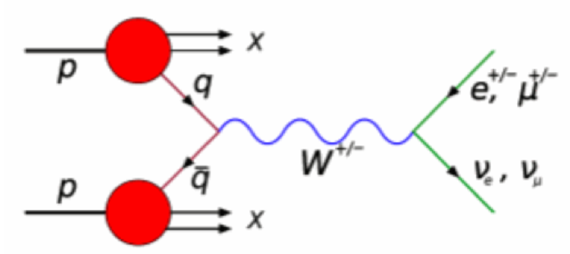
$$\sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

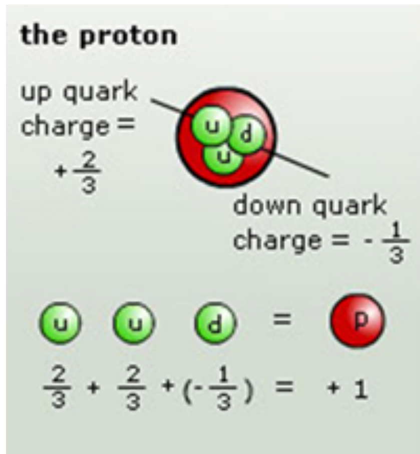
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$\rightarrow$ At the Z pole, Z term dominates. Moving away from the resonance peak the interference term dominates and gives larger contribution to A_{FB}

W charge asymmetry







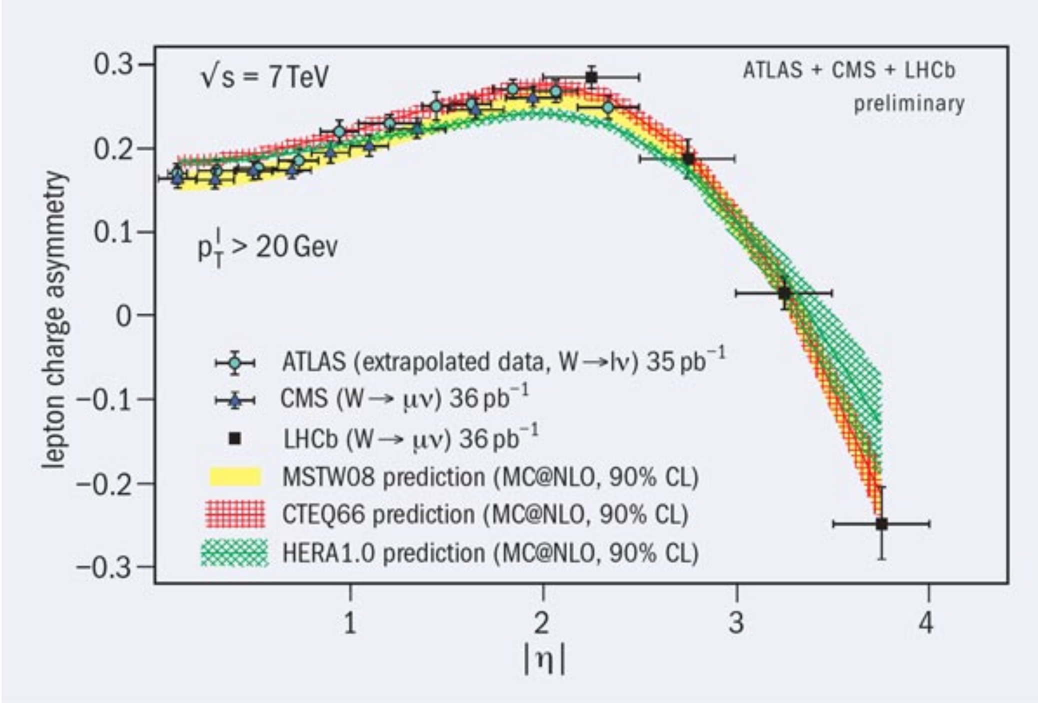
- ❑ LHC produces more W^+ than W^-

→ Dominance of u-quark vs d-quark inside the proton

Lepton charge asymmetry

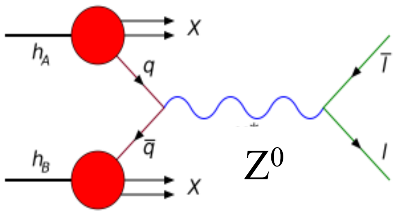
- Can go further and evaluate **charge asymmetry vs W rapidity**
- Cannot reconstruct p_Z of the ν => measure lepton charge asymmetry instead

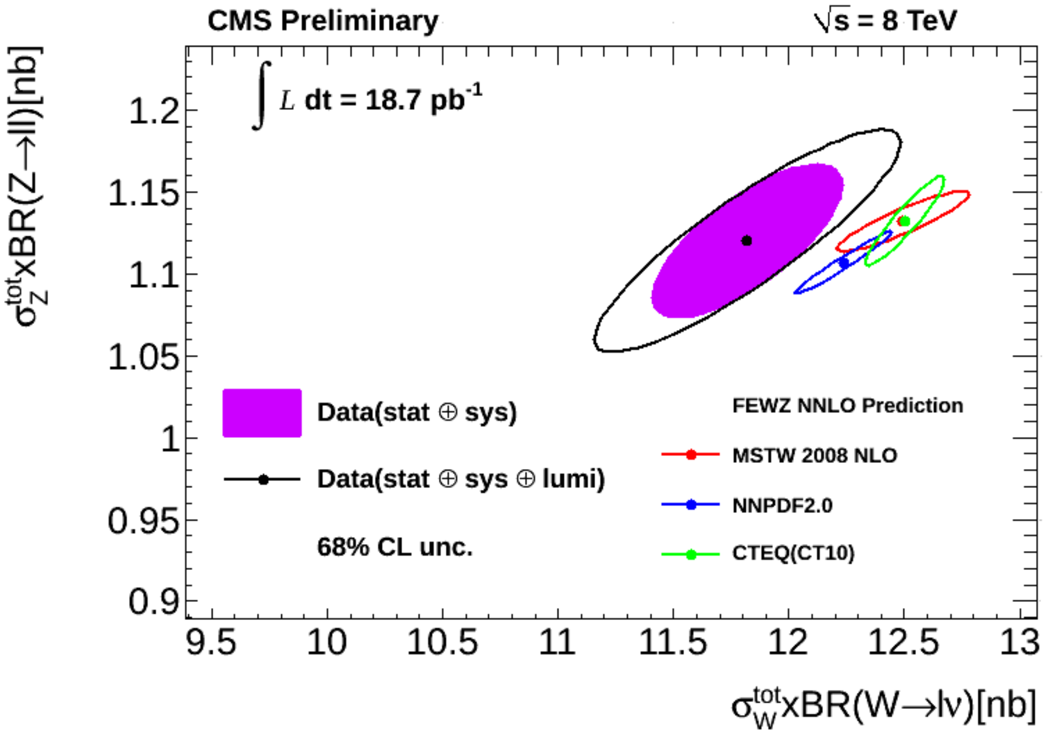
$$A = \frac{\frac{d\sigma}{d\eta}(W^+ \to l^+\nu) - \frac{d\sigma}{d\eta}(W^- \to l^-\nu)}{\frac{d\sigma}{d\eta}(W^+ \to l^+\nu) + \frac{d\sigma}{d\eta}(W^- \to l^-\nu)}$$

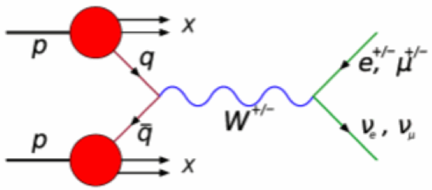


→ measurement of charge asymmetry allows to put constraints on the parton distribution functions for quarks inside the proton

W vs Z production







- ❑ About 10 times more pp→W→lν than pp→Z→l^+l^- at LHC

→ measurement of charge asymmetry allows to put constraints on the parton distribution functions for quarks inside the proton

Virtual corrections

- W mass and top quark mass are fundamental parameters of the Standard Model
- There are well defined relationships between m_W, m_{top} and m_H due to virtual corrections

At leading order:

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m^2 Z}$$

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}$$

$$\alpha(0)$$

Including virtual corrections:

$$\vec{\rho} = 1 + \Delta\rho$$

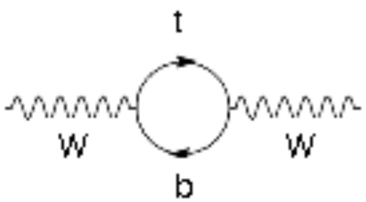
$$\sin^2\theta_{\rm eff} = (1+\Delta\kappa)\sin^2\theta_W$$

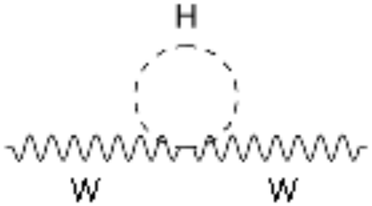
$$\boxed{m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}\cdot\frac{1}{(1-\Delta r)}}$$

$$\alpha(m_Z^2) = \frac{\alpha(0)}{1-\Delta\alpha}$$

$$\Delta\alpha = \Delta\alpha_{\rm lepl} + \Delta\alpha_{\rm top} + \Delta\alpha_{\rm had}^{(5)}$$

$$\boxed{\Delta\rho, \Delta\kappa, \Delta r = f(m_t^2, \log(m_H), \ldots)}$$





Standard model consistency

- W mass and top quark mass are fundamental parameters of the Standard Model
- There are well defined relationships between m_W, m_{top} and m_H due to virtual corrections

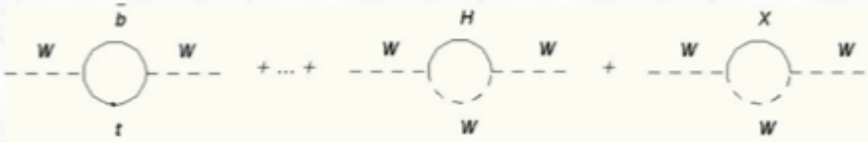
Electromagnetic constant
measured in atomic transitions, e^+e^- machines, etc.

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2} G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Fermi constant
measured in muon decay

weak mixing angle
measured at LEP/SLC

radiative corrections
$\Delta r \sim f(m_{top}^2, \log m_H)$
$\Delta r \approx 3\%$



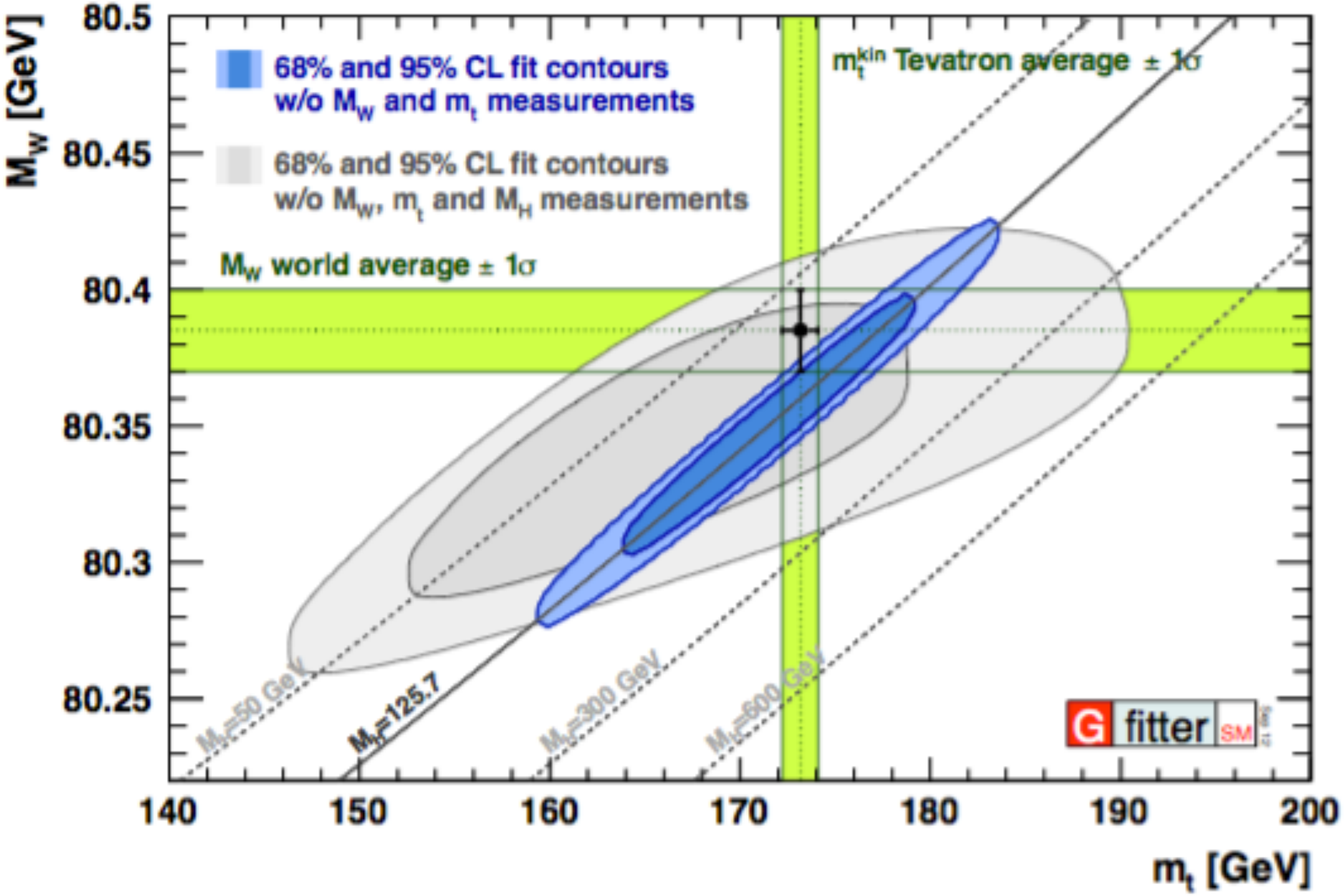
- G_F, α_{em} and $\sin\theta_W$ are known with high precision
  - α_{em}=1/137035999679..
  - G_F=1.16637(1)x10^{-5} GeV^{-2}
  - $\sin^2\theta_W$=0.2223(21)
- All 3 mass measurements provide **consistency check of the standard model** and its **radiative corrections**

→ Important test for new physics

Standard model consistency

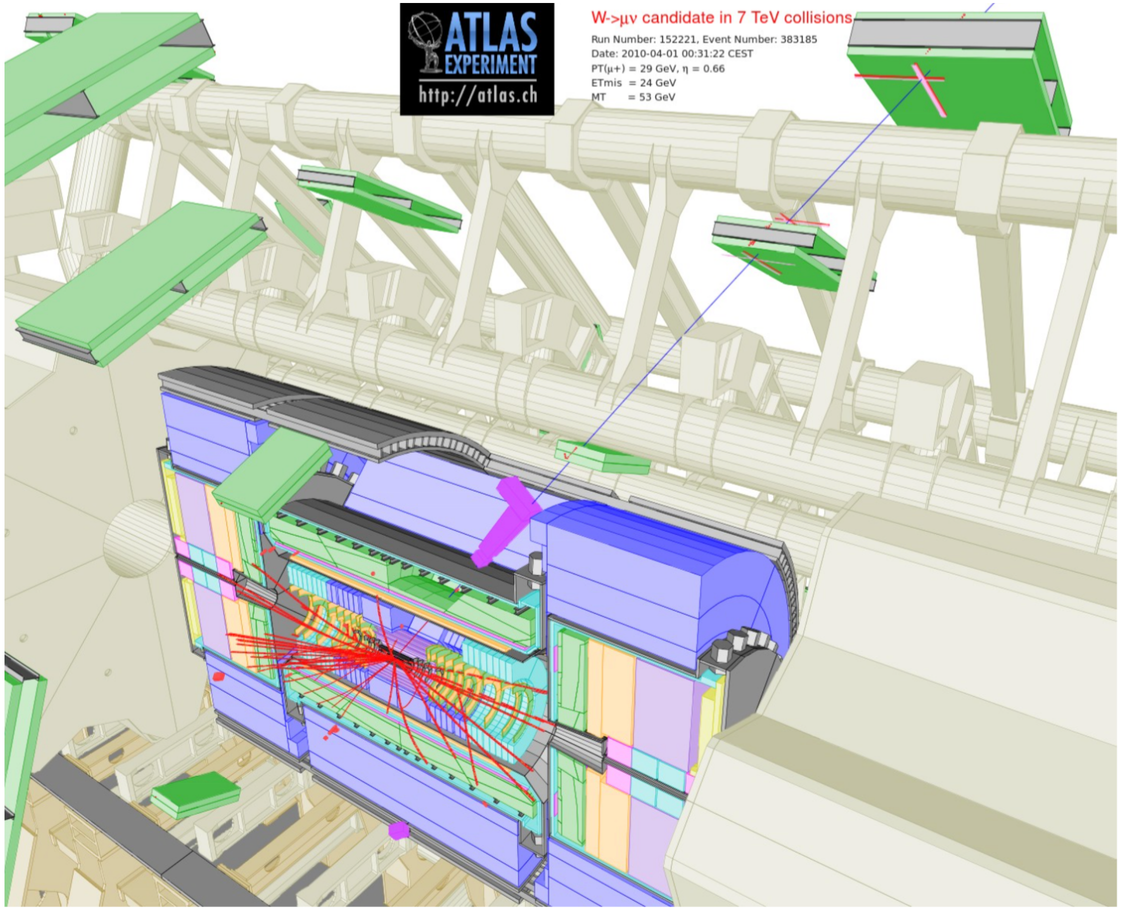
2014: m_W from LEP and Tevatron

arXiv:1407.3792



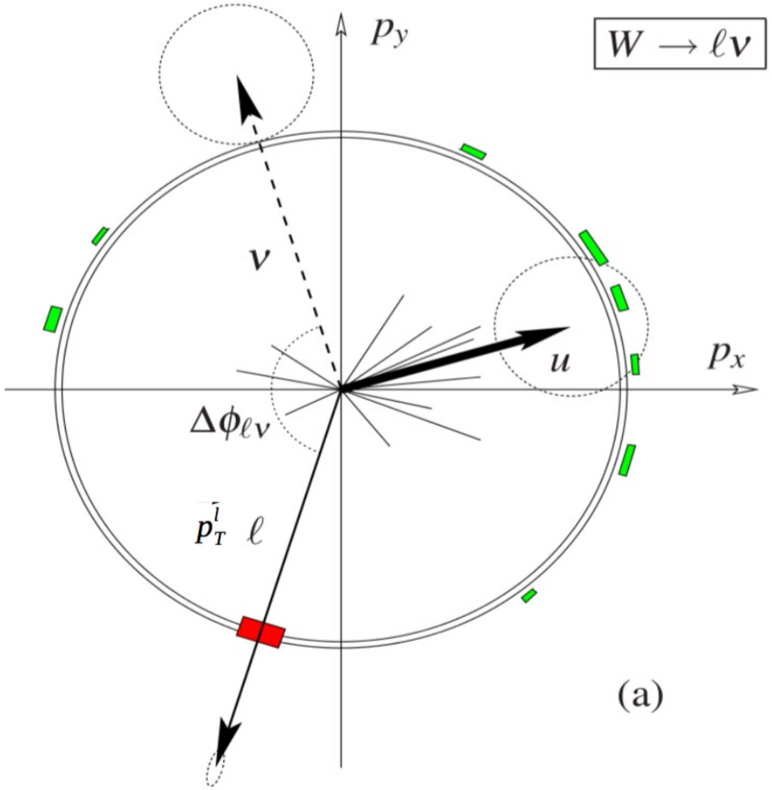
W mass measurement

- W→μν candidate (2010)
- Muon measured from matching **muon spectrometer** and inner tracker tracks
- **Missing transverse energy** from the absence of additional high-p_T particles



Measurement strategy

W→lν



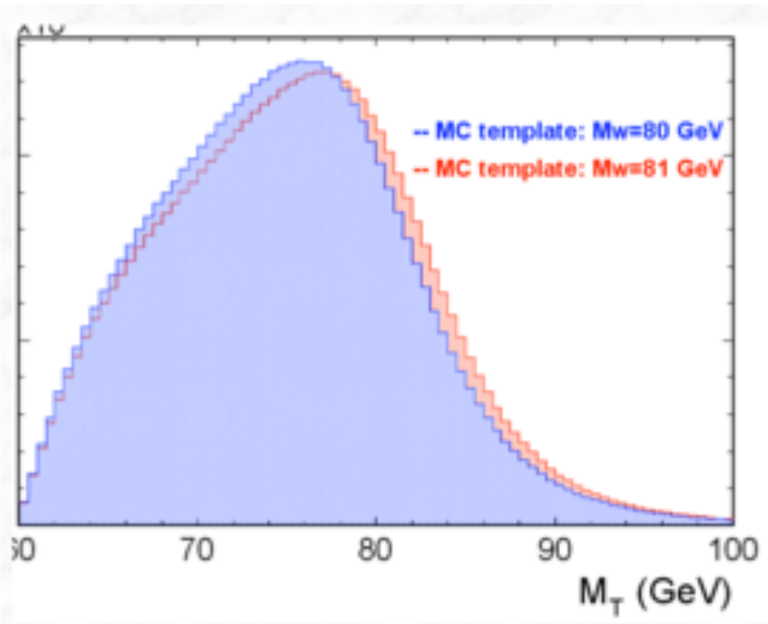
- **Main signature: high p_T lepton** (electron or muon): p_T^l
- The neutrino is undetected, and measured using the momentum conservation in the transverse direction

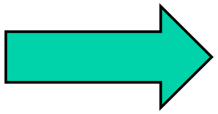
- Recoil = sum of everything else: $\vec{u}_T = \Sigma \vec{E}_{T,I}$
- $\vec{p}_T^{miss} = -(\vec{p}_T^{\,l}+\vec{u}_T)$ and $m_T = \sqrt{2p_T^l p_T^{miss}(1-\cos\Delta\phi)}$

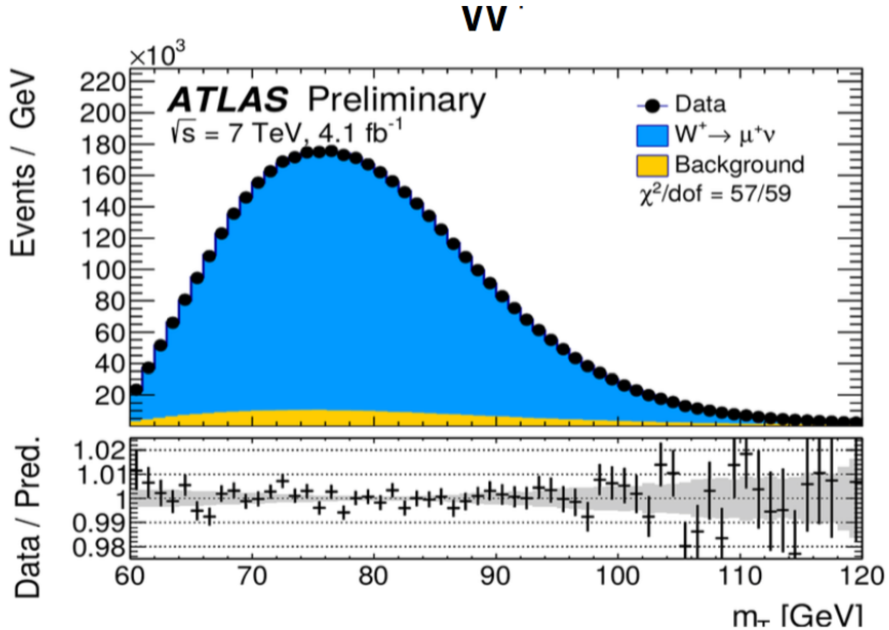
→ challenging measurement for experiments, any mismeasured energy produces 'E_T^{miss}'

Measurement strategy & result

- Shape of the transverse mass distribution is sensitive to m_W
- Measured distribution fitted with Monte Carlo predictions with varying parameter m_W





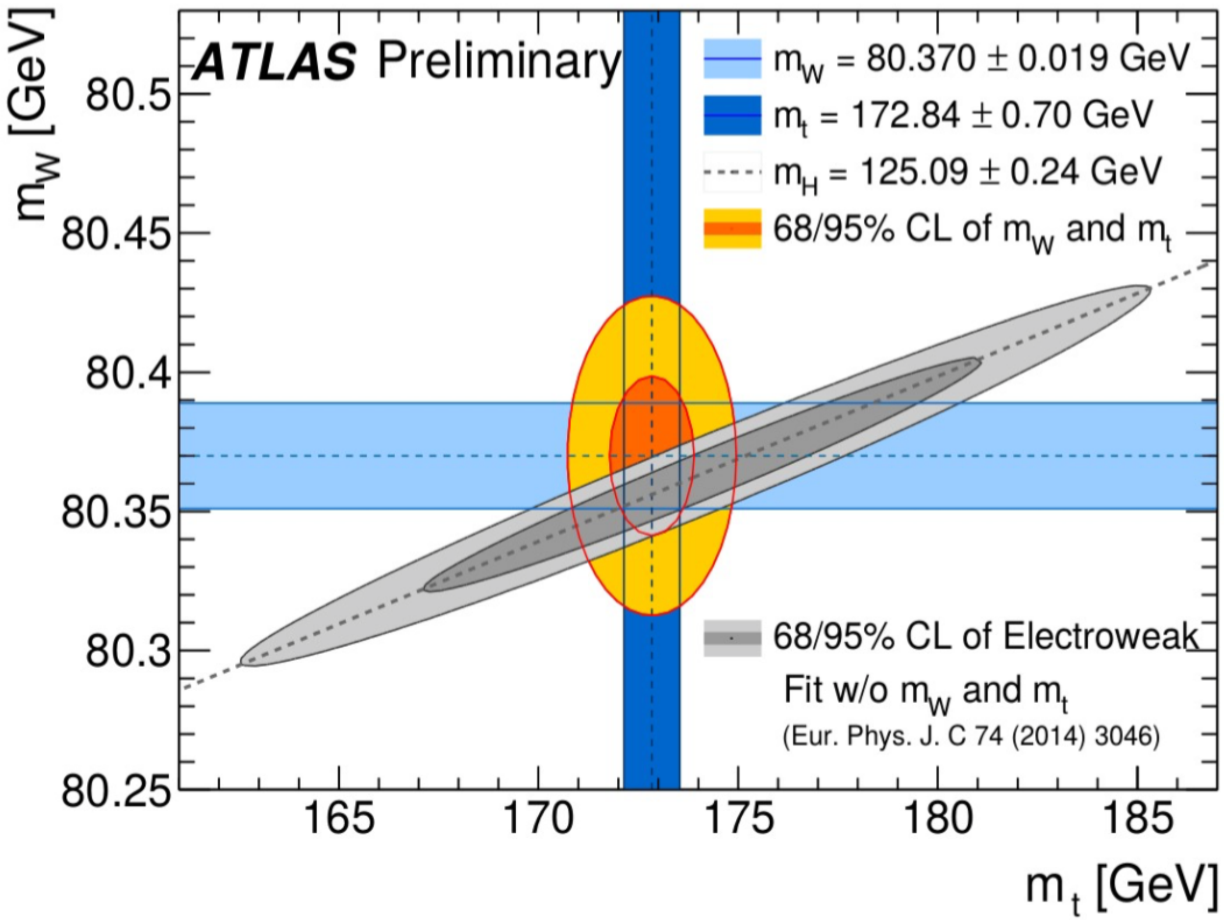


$$m_W = 80.370 \pm 0.007\,(\text{stat.}) \pm 0.011\,(\text{exp.syst.}) \pm 0.014\,(\text{mod.syst.})\ \text{GeV}$$
$$= \underline{80.370 \pm 0.019\ \text{GeV}}$$

Standard model consistency

2016: m_W from LHC

$m_W = 80.370 \pm 0.019$ GeV



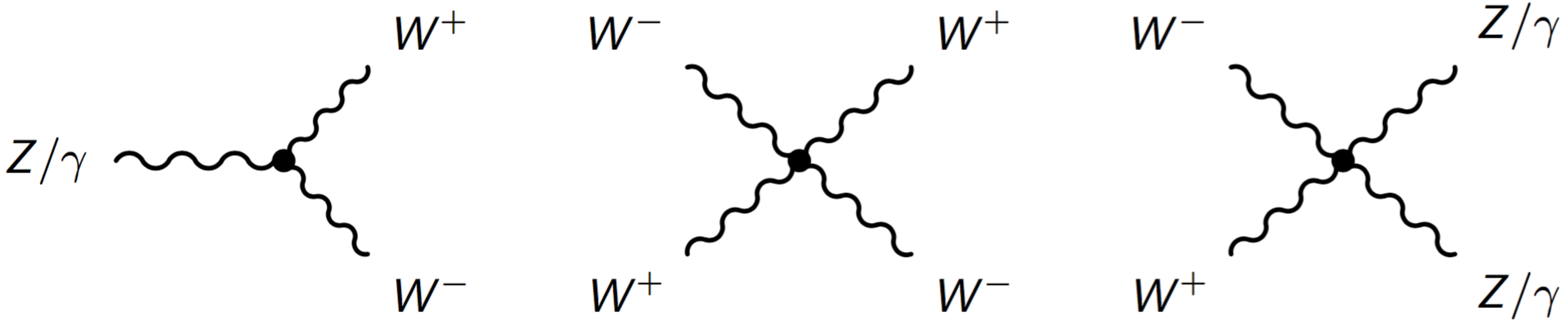
→ Agreement improved from refined measurement of m_W at LHC

Gauge boson self-couplings

Cubic and quartic interaction terms resulting from $\mathcal{L}_{kin}$:

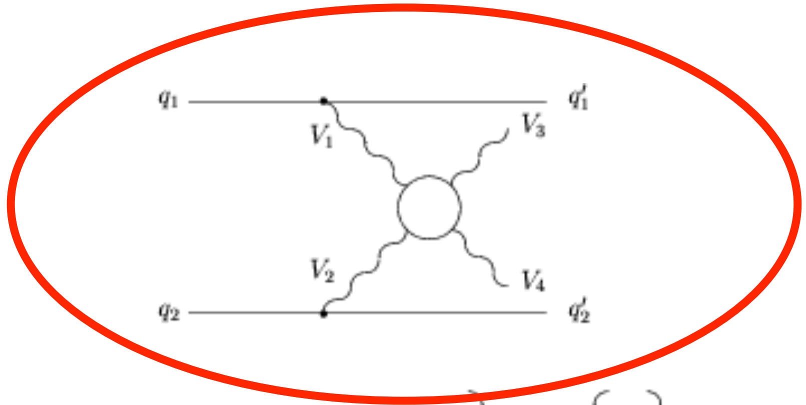
$$\mathcal{L}_3 = -\, ie\cot\theta_W \Big[\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right) W^\dagger_\mu Z_\nu - \left(\partial^\mu W^{\nu\,\dagger} - \partial^\nu W^{\mu\,\dagger}\right) W_\mu Z_\nu + W_\mu W^\dagger_\nu \left(\partial^\mu Z^\nu - \partial^\nu Z^\mu\right) \Big]$$
$$- ie\Big[\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right) W^\dagger_\mu A_\nu - \left(\partial^\mu W^{\nu\,\dagger} - \partial^\nu W^{\mu\,\dagger}\right) W_\mu A_\nu + W_\mu W^\dagger_\nu \left(\partial^\mu A^\nu - \partial^\nu A^\mu\right) \Big]$$

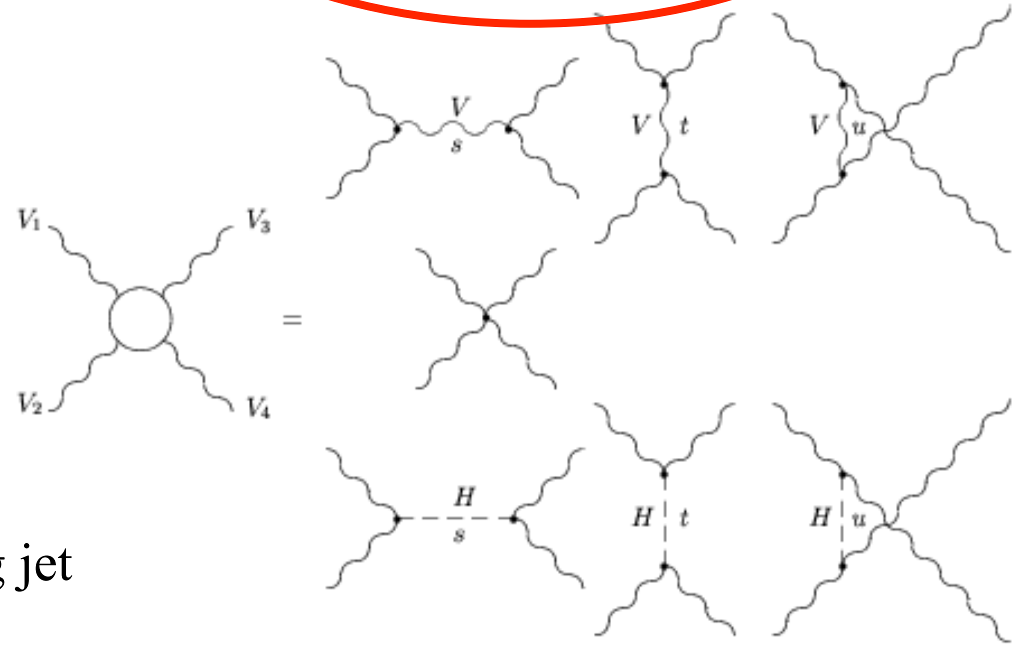
$$\mathcal{L}_4 = -\frac{e^2}{2\sin^2\theta_W}\left[(W^\dagger_\mu W^\mu)^2 - W_\mu{}^\dagger W^{\mu\,\dagger} W_\nu W^\nu\right] - e^2\cot^2\theta_W\left[W^\dagger_\mu W^\mu Z_\nu Z^\nu - W^\dagger_\mu Z^\mu W_\nu Z^\nu\right]$$
$$- e\cot\theta_W\left[2W^\dagger_\mu W^\mu Z_\nu A^\nu - W^\dagger_\mu Z^\mu W_\nu A^\nu - W^\dagger_\mu A^\mu W_n u Z^\nu\right]$$
$$- e^2\left[W^\dagger_\mu W^\mu A_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu A^\nu\right]$$

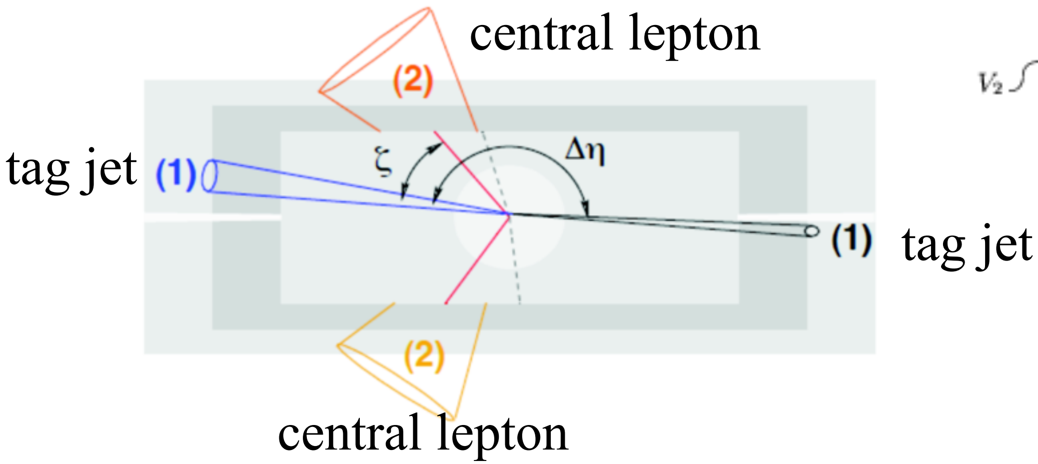


Vector boson scattering

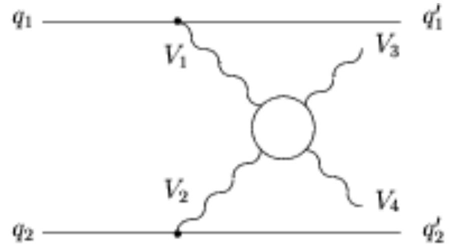
- What is VBS?
- Interaction between gauge bosons
  - W/Z beams out of the p beams
- Outgoing quarks **scattered at large E and large rapidity difference Δη**
- No colour exchange: little hadronic activity in the central region







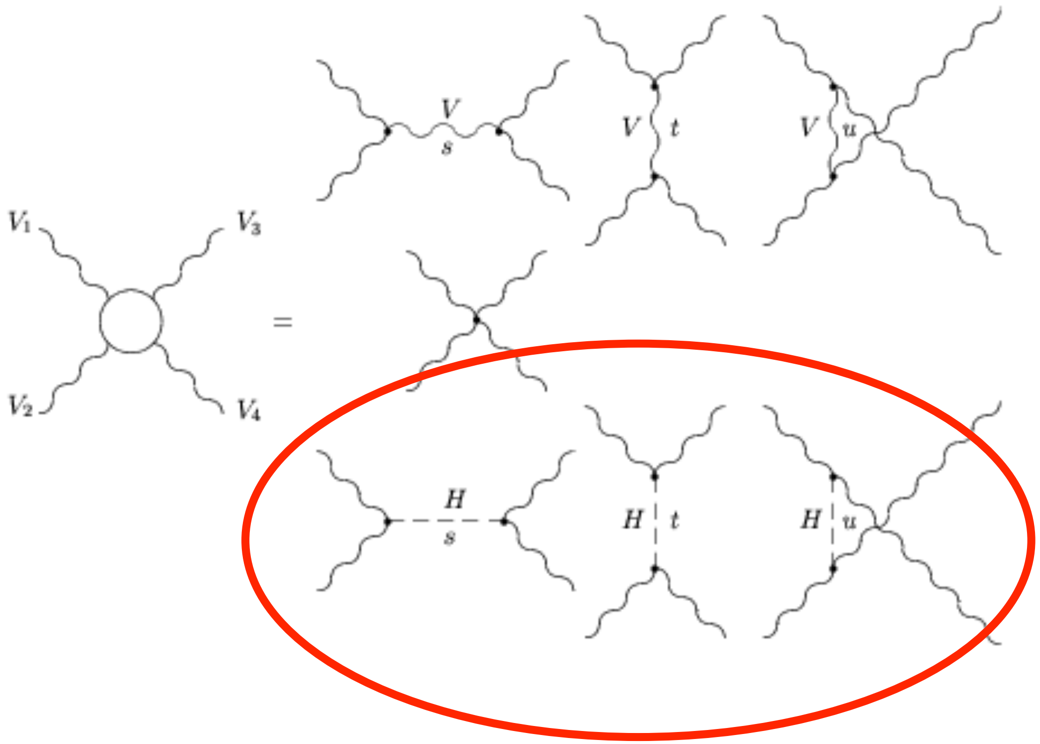
Vector boson scattering



- ❑ <u>Why is VBS interesting?</u>
- ❑ <u>Without the Higgs boson,</u> amplitude ~ $G_F E^2$, E = hard scattering energy

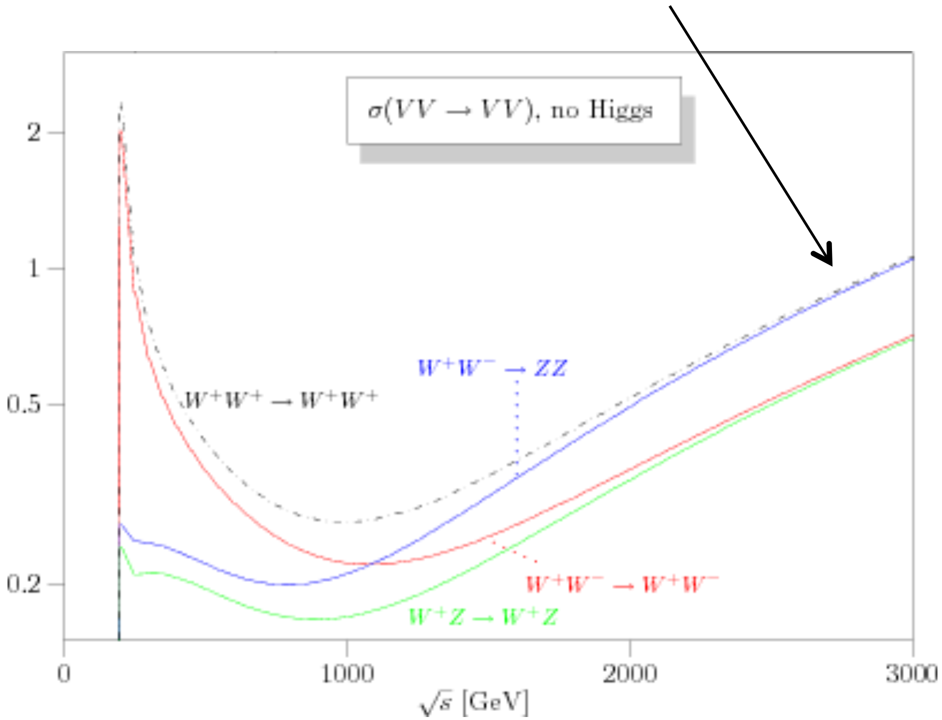
⇒ **Diverge with increasing E**

- ❑ Process would violate unitarity
- ❑ **Unitarity restored** by adding a spin 0 particle with couplings exactly as those of the **SM Higgs**

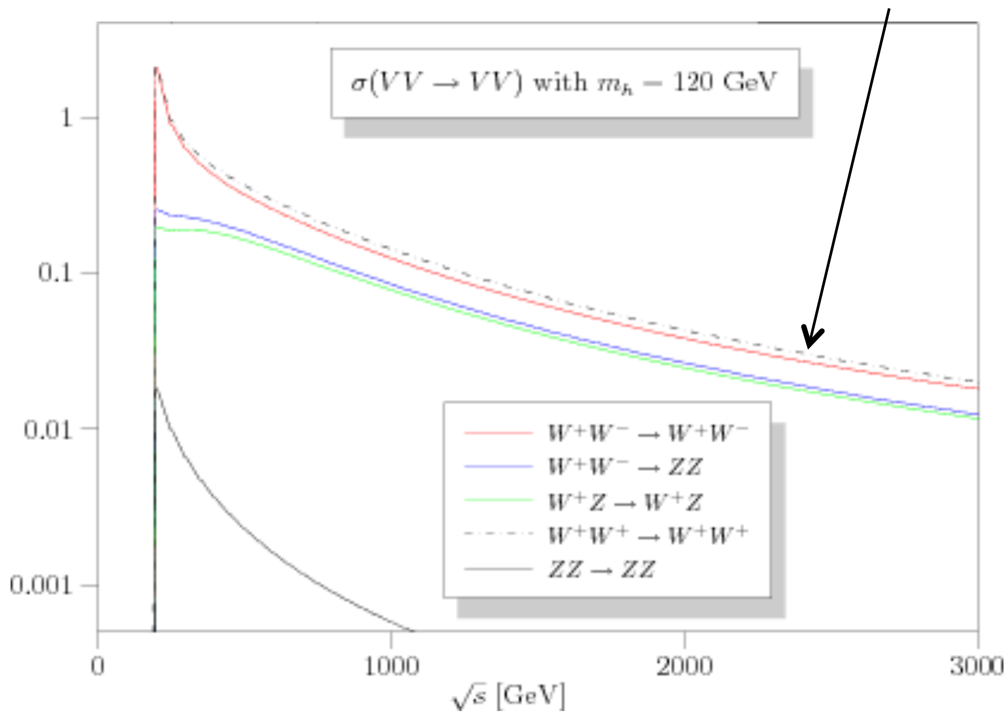


Vector boson scattering and unitarity

Unitarity violation

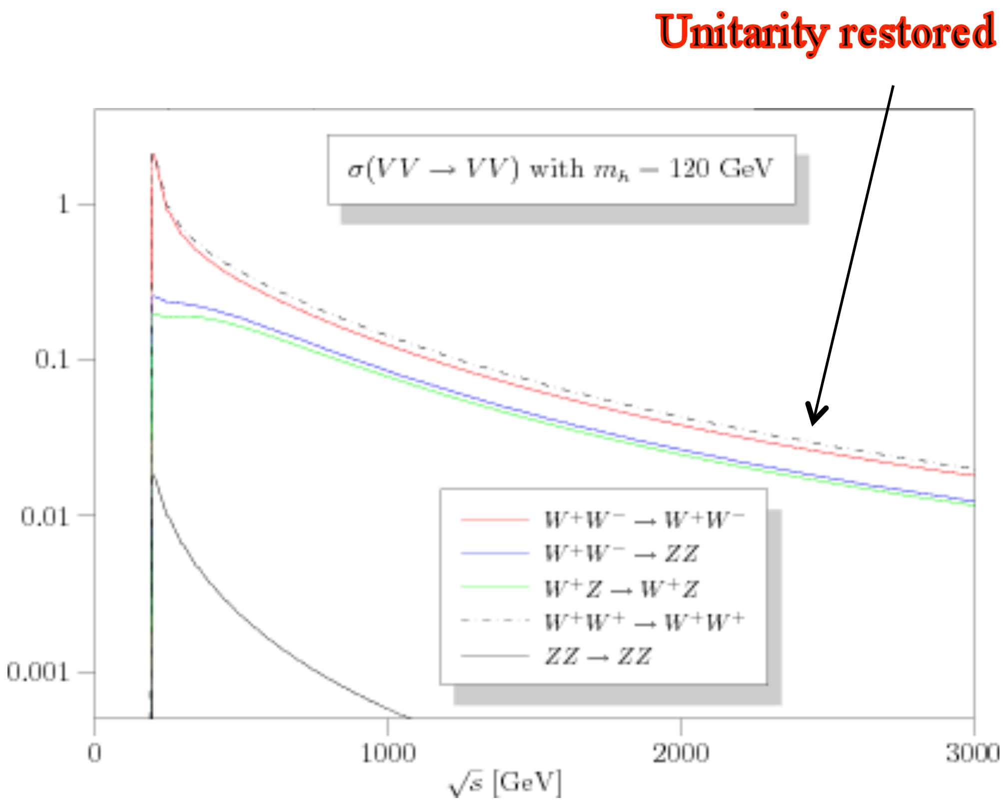


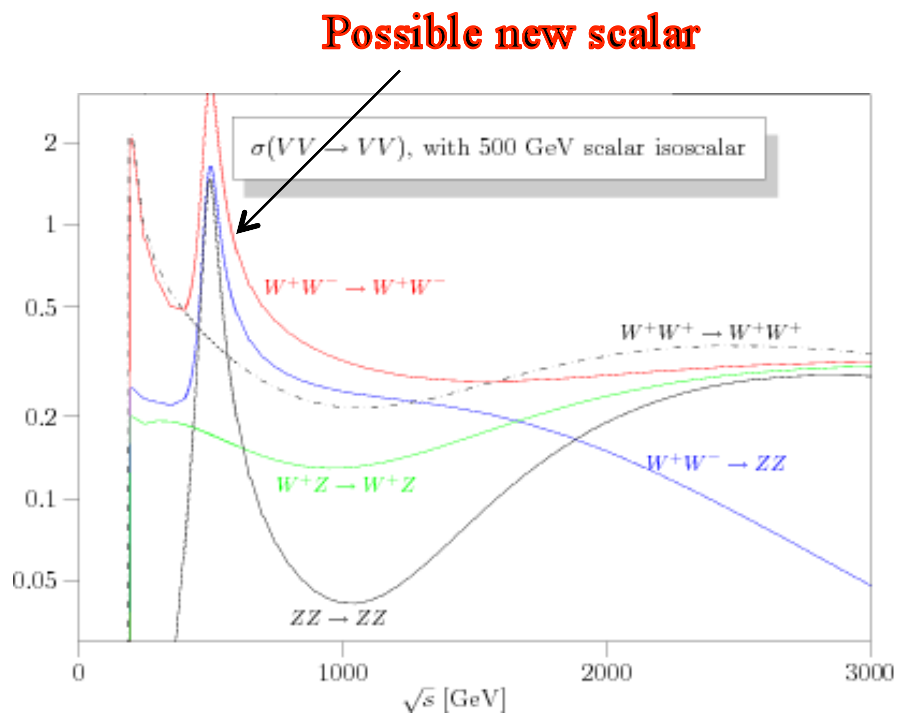
Unitarity restored



- Higgs boson has the fundamental role in the standard model to cancel the high energy divergencies in the longitudinal VV scattering

Vector boson scattering and new physics



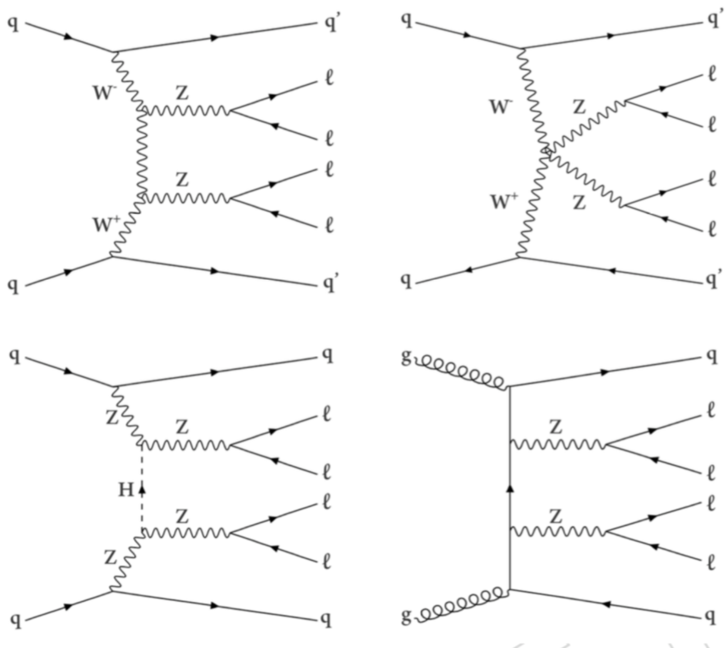


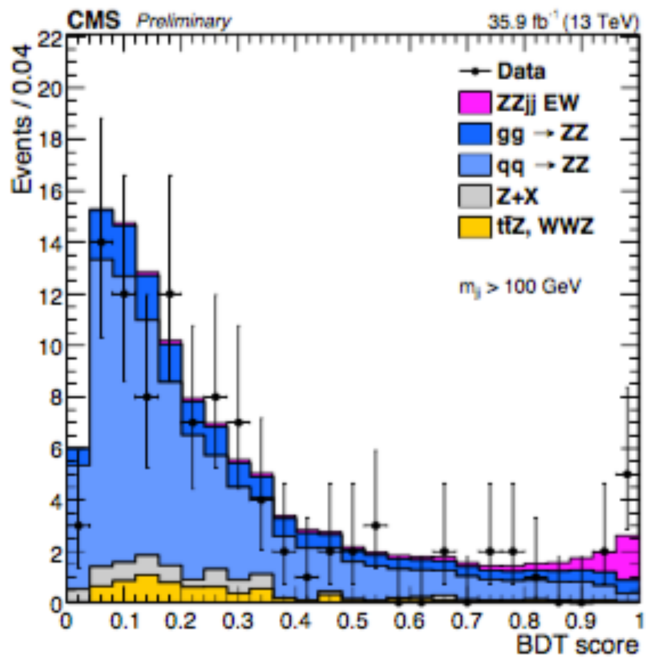
- ❑ longitudinal VV scattering may also reveal new resonances

→ Much interest in these rare processes at LHC in particular with High Luminosity LHC (HL-LHC) starting in 2025

Vector boson scattering measurements

- Weak vector boson scattering **measured at LHC in WW and ZZ**
- $W^{\pm}W^{\pm}jj$: same sign channel to avoid QCD background
- $Z^0Z^0jj \to 4ljj$: very rare, CMS measurement published last year





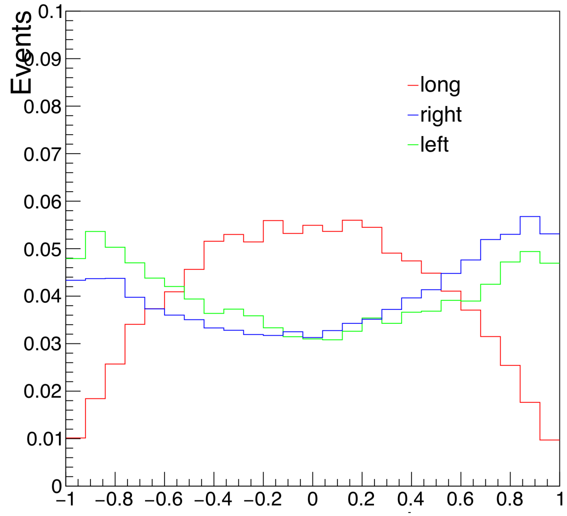
$$\sigma_{\text{fid.}}(\text{EW pp} \to \text{ZZ}jj \to \ell\ell\ell'\ell' jj) = 0.40^{+0.21}_{-0.16}(\text{stat})^{+0.13}_{-0.09}(\text{syst})\ \text{fb}$$

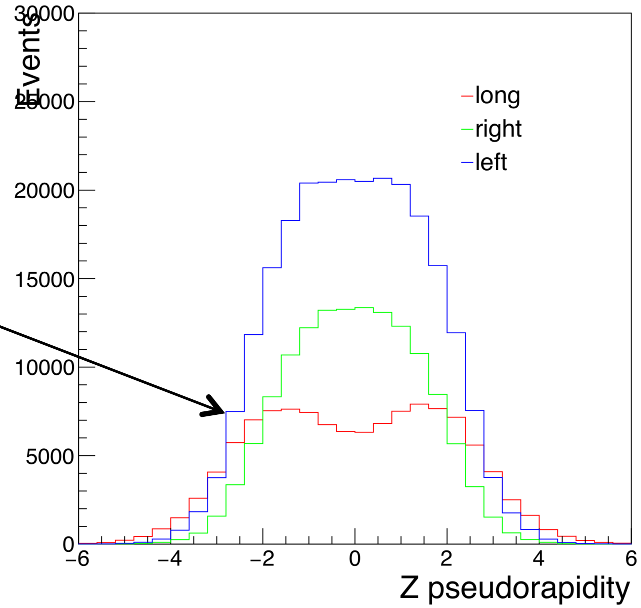
VBS $V_L V_L$ @ HL-LHC

- Main interest is longitudinal scattering: $V_L V_L \rightarrow V_L V_L$
- Higgs boson contribution (negative) interference stabilize the amplitude that would grow like s otherwise
- Main strengths of $ZZ \rightarrow 4ljj$ channel: fully reconstructed final state gives precise access to scattering energy (m_{4l}) and bosons polarizations via lepton angular distributions

- Recently emphasized that the V_L are dominantly produced in the forward region
- Important consequences for the detector upgrade being planned for HL-LHC

=> Forward acceptance is important for $V_L V_L$





EW Physics summary

- Electromagnetic and weak interaction are **mixed in a coherent theory** in the SM
- Parity violation from weak interaction lead to a V-A structure
  - Weak interaction only couples to **left-handed particles**
- This implies **asymmetries** in the angular distribution for $Z \rightarrow f\bar{f}$
- Enormous amount of Z and W produced at LHC allows for **precise measurements** at LHC despite the complex environment
  - W and Z production, $\sin^2\theta_W$, F/B asymmetry and lepton charge asymmetry
- **Interactions between gauge bosons** probed with vector boson scattering
  - Rare processes, delicate cancellations appear for scattering amplitudes
  - Higgs needed to restore **unitarity**
  - HL-LHC will allow to probe $\mathbf{V_L V_L}$ **scattering**

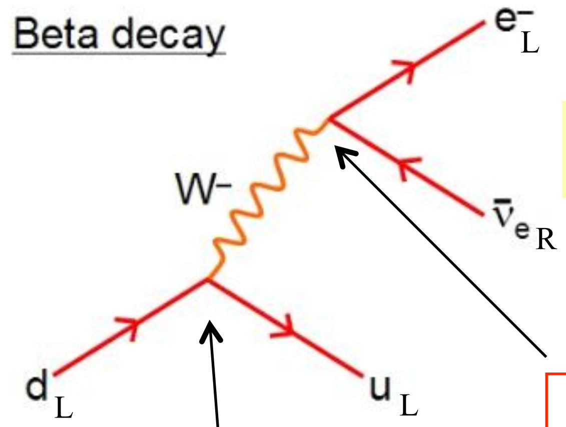
EW interactions in the SM

Weak Isospin and Hypercharge Quantum

Lepton	T	T^3	Q	Y
ν_e	$\frac{1}{2}$	$\frac{1}{2}$	0	-1
e_L^-	$\frac{1}{2}$	$-\frac{1}{2}$	-1	-1
e_R^-	0	0	-1	-2

Numbers of Leptons and Quarks

Quark	T	T^3	Q	Y
u_L	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$
d_L	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$
u_R	0	0	$\frac{2}{3}$	$\frac{4}{3}$
d_R	0	0	$-\frac{1}{3}$	$-\frac{2}{3}$



$$d \longrightarrow u + e^- + \bar{\nu}_e$$

Q: $-1 + 0 = -1$

T^3: $-1 + 1/2 = -1/2$

Y: $0 = -1 + 1$

Q: $-1/3 = -1 + 2/3$

T^3: $-1/2 = 1/2 - 1$

Y: $1/3 = 1/3 + 0$

d_L W^- u_L

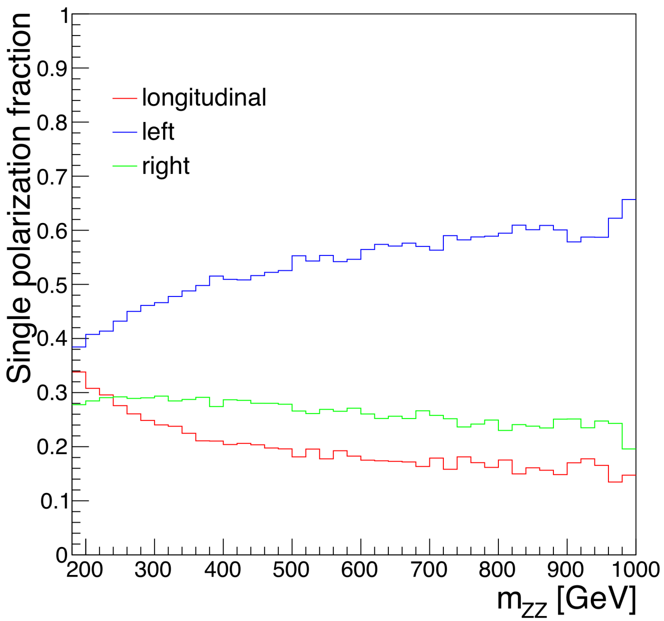
Axial and vector couplings

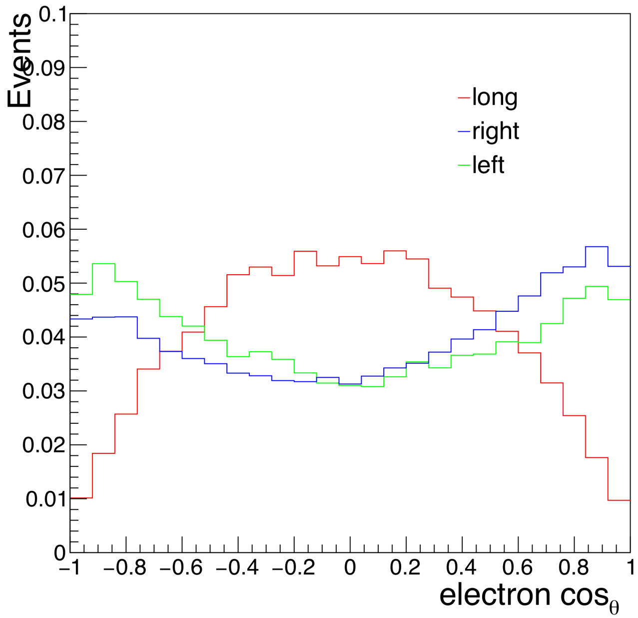
f	Q_f	c_A^f	c_V^f	
$\nu_e, \nu_\mu, \ldots$	0	$\frac{1}{2}$	$\frac{1}{2}$	
$e \quad , \mu \quad , \ldots$	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W$	0.03
$u, c, \ldots$	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$	0.19
$d, s, \ldots$	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$	0.34

$\rightarrow \sin^2\theta_W = 0.234$, experimentally measured

Sensitivity to $Z_L Z_L$

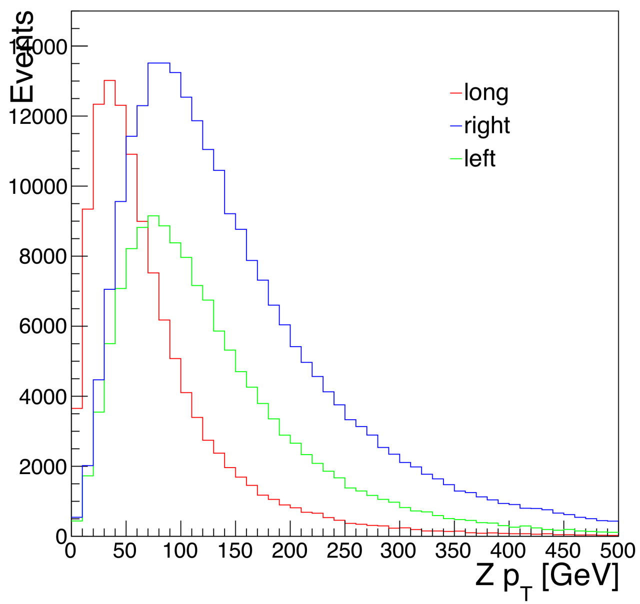
- Longitudinal fraction is ~35-15% for each Z depending on m_{ZZ}
- Double boson production largely dominated by transverse-transverse and mixed longitudinal-transverse combinations
- Separation from the lepton kinematics has been studied
  - Lepton angle from Z decay directly connected to polarization state

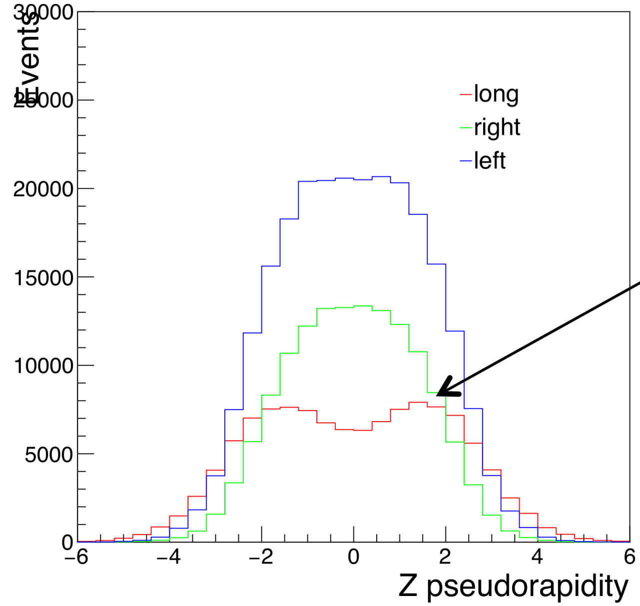




Sensitivity to $Z_L Z_L$

- Longitudinal fraction is ~35-15% for each Z depending on m_{ZZ}
- Double boson production largely dominated by transverse-transverse and mixed longitudinal-transverse combinations
- Polarization separation from the lepton decay kinematics has been looked at
  - But also Z η is particularly interesting and peaked in the forward region





Longitudinal
Z produced in
forward region!

- Forward extension expected to play a very important role here

more plots in AN