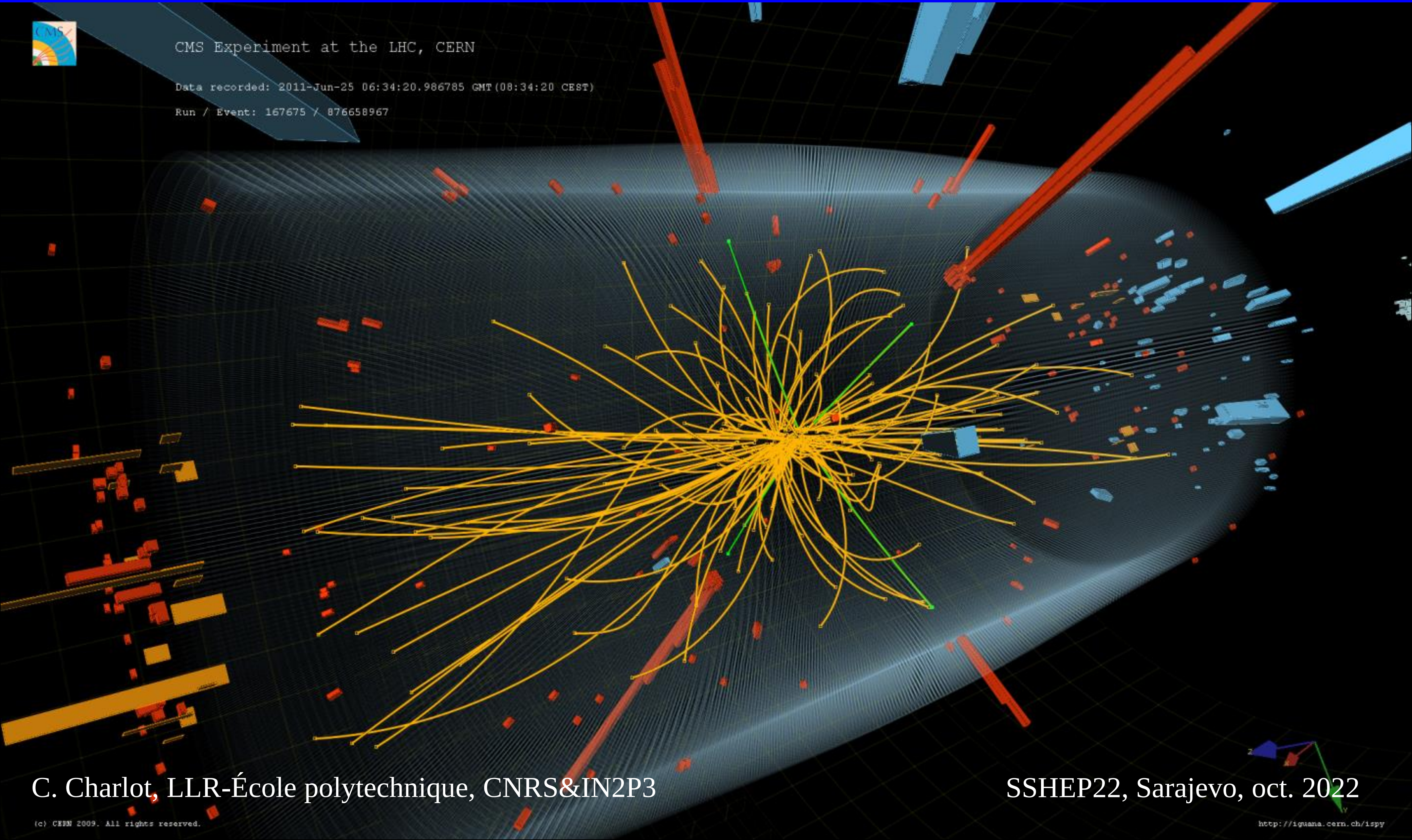
EW Physics at the LHC



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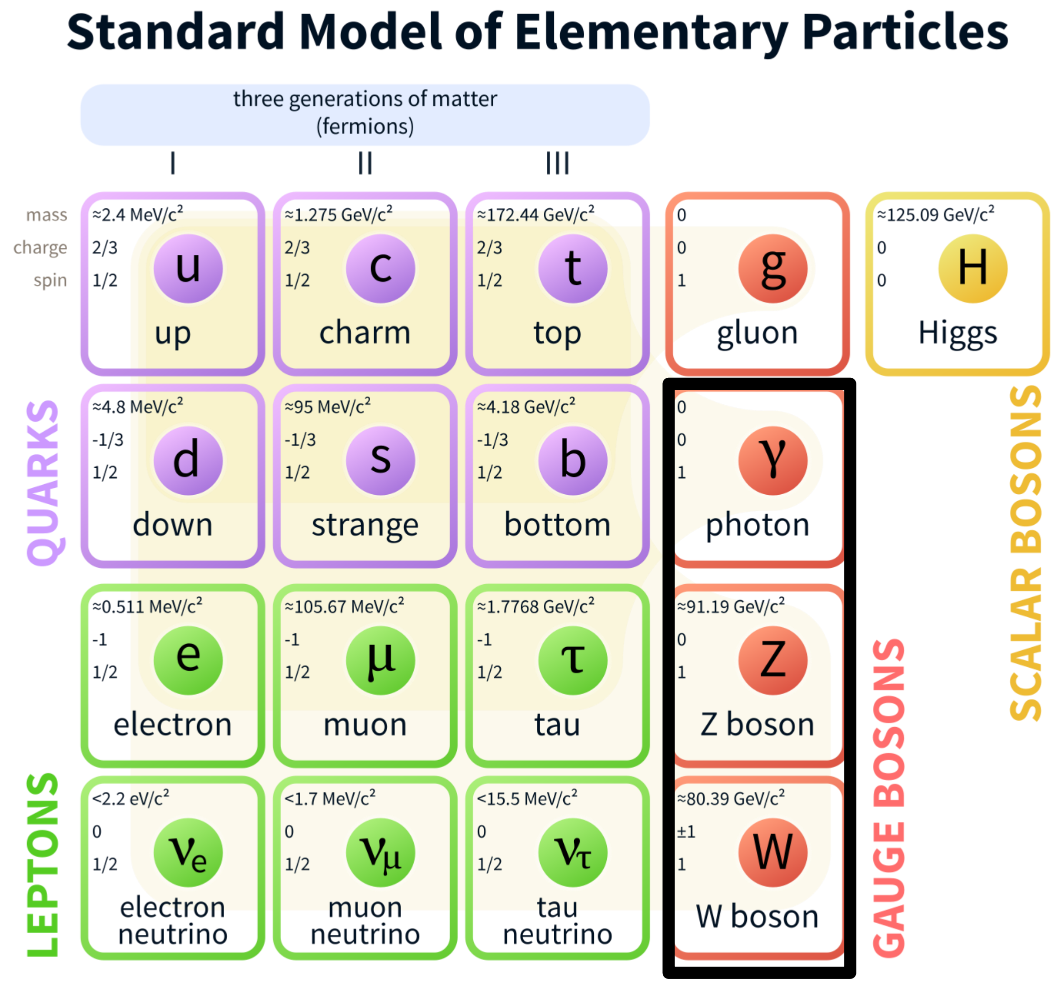
SSHEP22, Sarajevo, oct. 2022

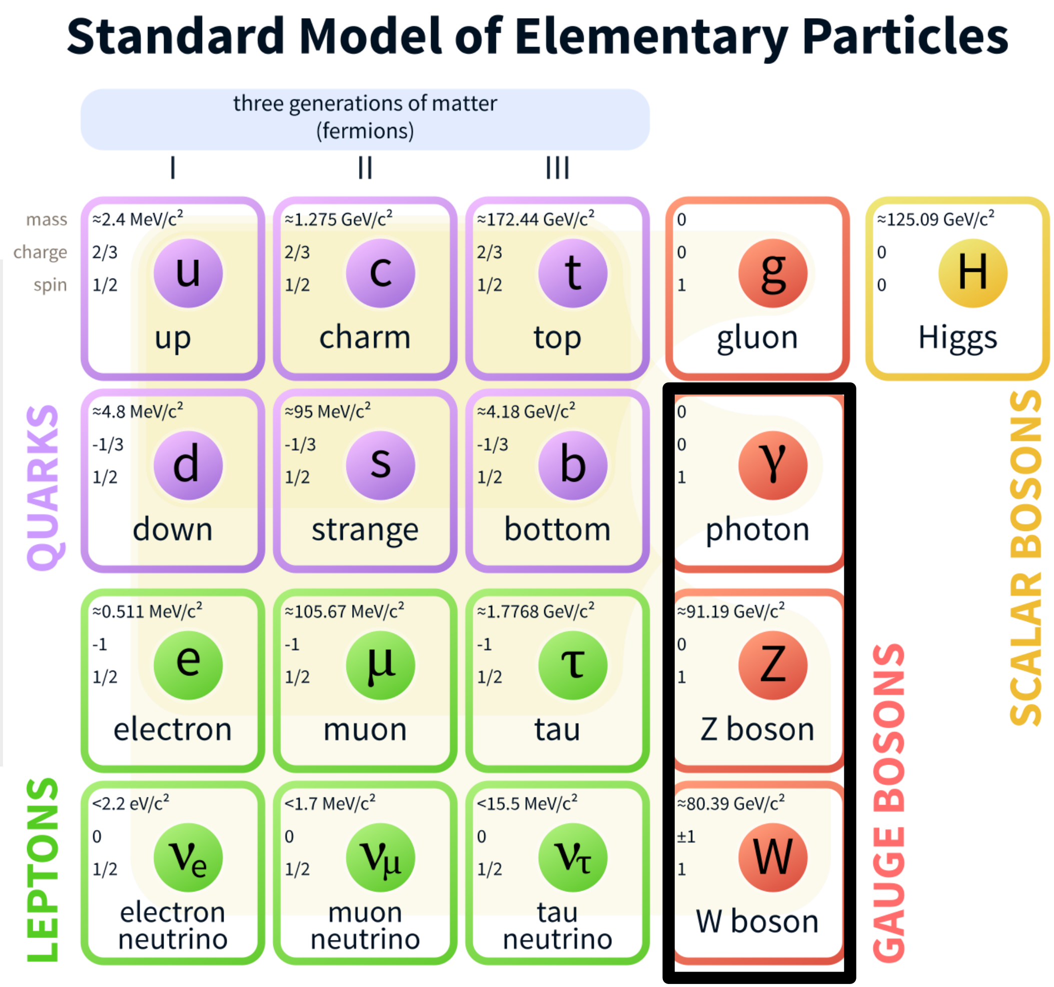
Fundamental particles & interactions

- ❑ <u>Why EW physics?</u>
- ❑ Understand/test *coherent* description of electromagnetic and weak interactions, unified through EW interaction
- ❑ Despite important differences
- ❑ Massive W,Z → **short range** weak interaction
- ❑ Contrary to **long range** electromagnetic interactions



Fundamental particles & interactions

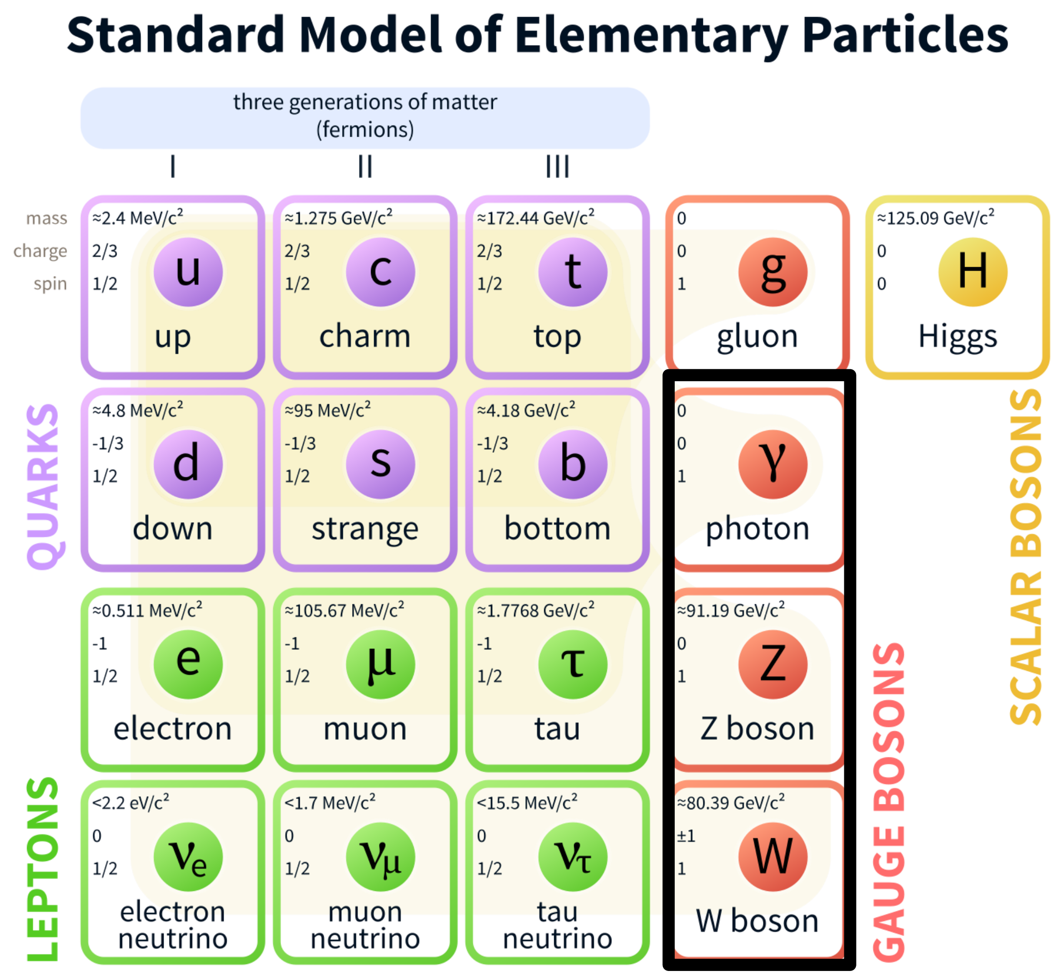
- Experimentally:
- W, Z: unstable particles, detected from their decay into lν/ll or qq’/qq
- Photon: stable, directly detected by e.m. calorimeters (only)



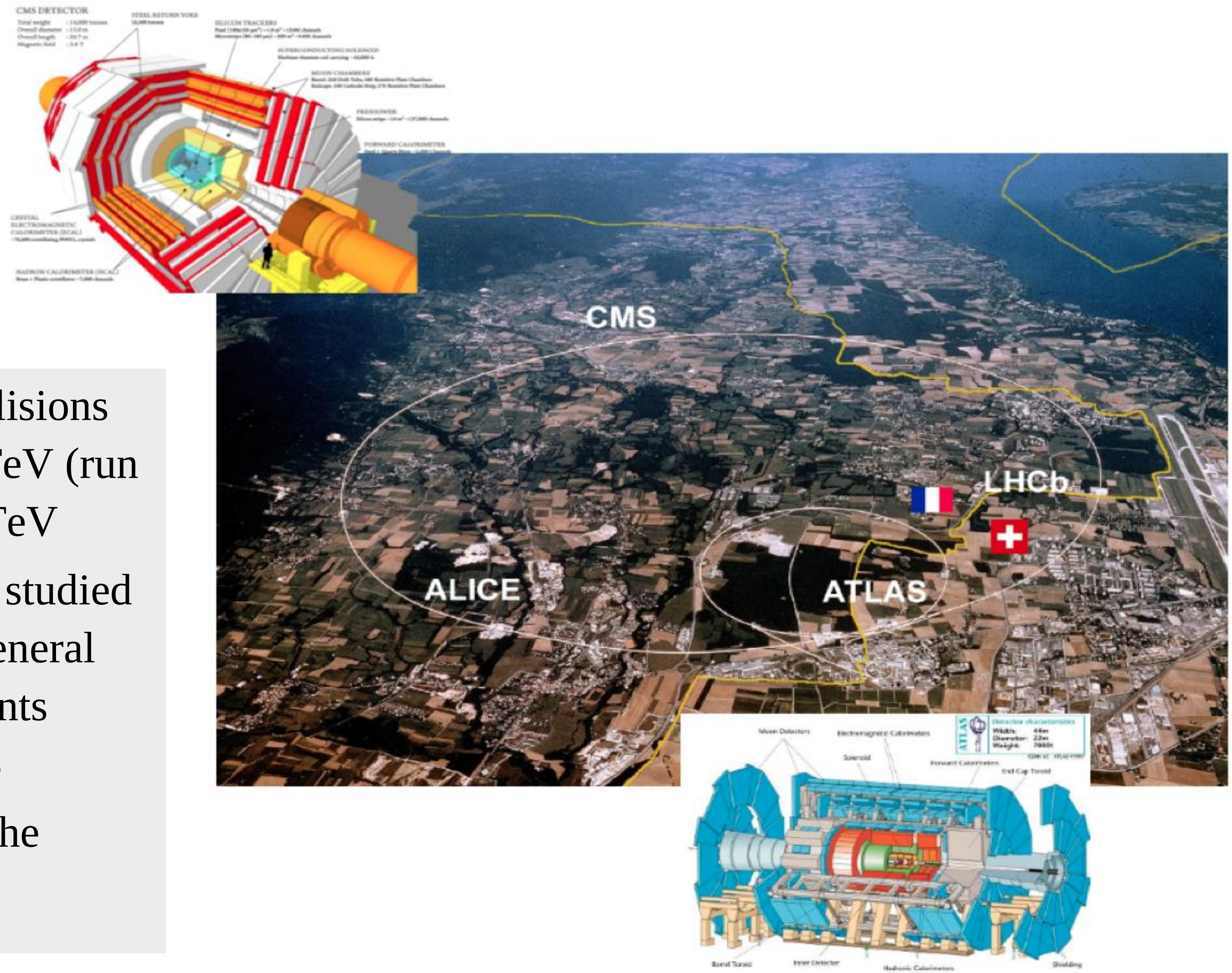
Fundamental particles & interactions

- In this lecture
  - Do EWK particles interact at the expected rates? W,Z production at LHC
  - F/B asymmetry and $\sin\theta_W$
  - m_W measurement, consistency check of the standard model
  - Vector boson scattering and unitarity

- Not in this lecture
  - Higgs physics
  - Although intimately connected



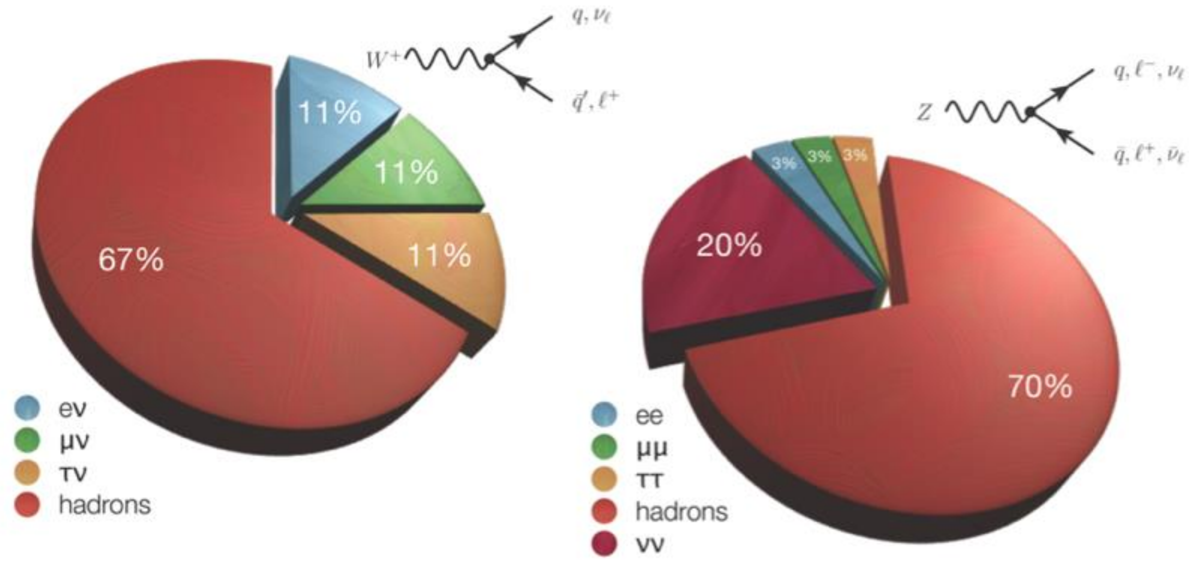
EWK measurements at LHC



- ❑ Proton-proton collisions at 7/8 (run 1, 13 TeV (run 2) and now 13.6 TeV
- ❑ SM-EWK mainly studied at the two large general purpose experiments ATLAS and CMS
- ❑ Also at LHCb in the forward direction

W and Z decays

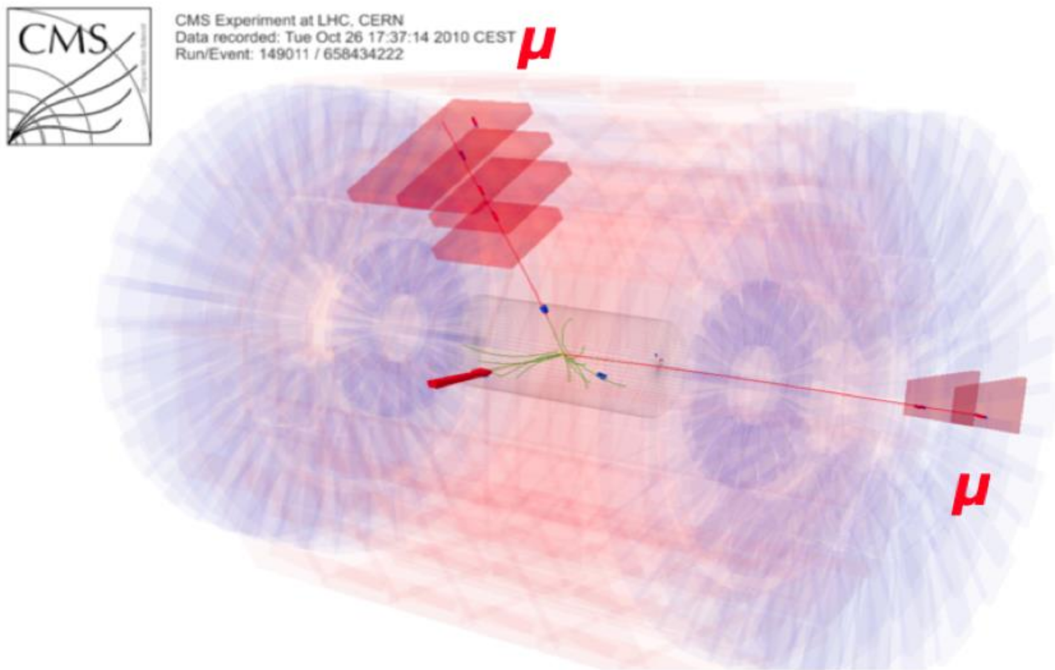
- Most of the time (~67-70%), W and Z bosons decay into quarks/jets
- Followed by decay in ν for the Z
- Highest rates but also large backgrounds, experimental resolution

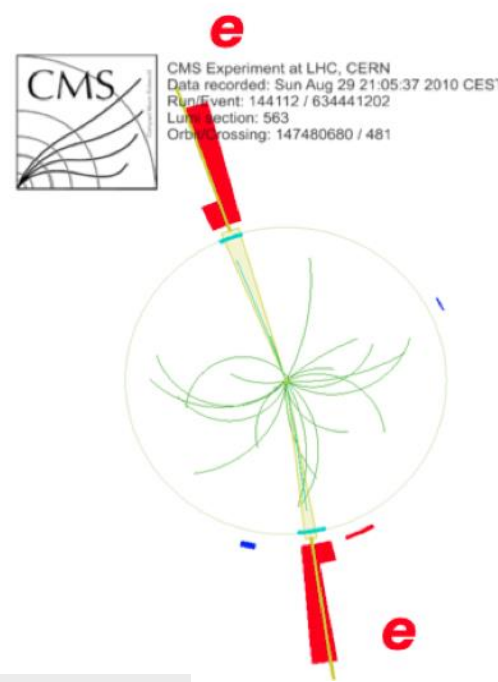


- Decays to e/μ have lower rates but have <u>lower backgrounds</u> and are <u>more precisely measured</u> => **cleanest signals at LHC**

- τ can also be reconstructed via their decay to e/μ or to hadrons

Leptonic Z reconstruction



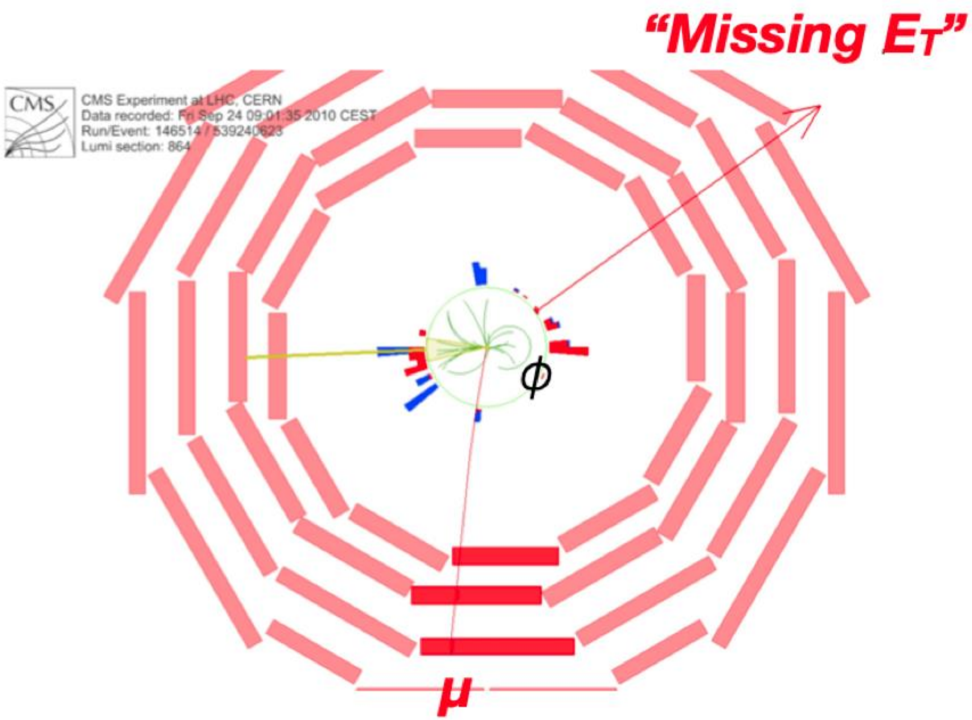


Z→ll: one of the cleanest signature at a hadron collider

- ❑ Opposite charge same flavor electron or muon pair with invariant mass near the Z mass (~91 GeV)
  - ❑ Lepton identification + isolation suppress fake background from jets and light mesons decay. Also suppress non-prompt leptons from heavy flavor (b/c) decays (eventually supplemented by IP cuts)

Leptonic W reconstruction

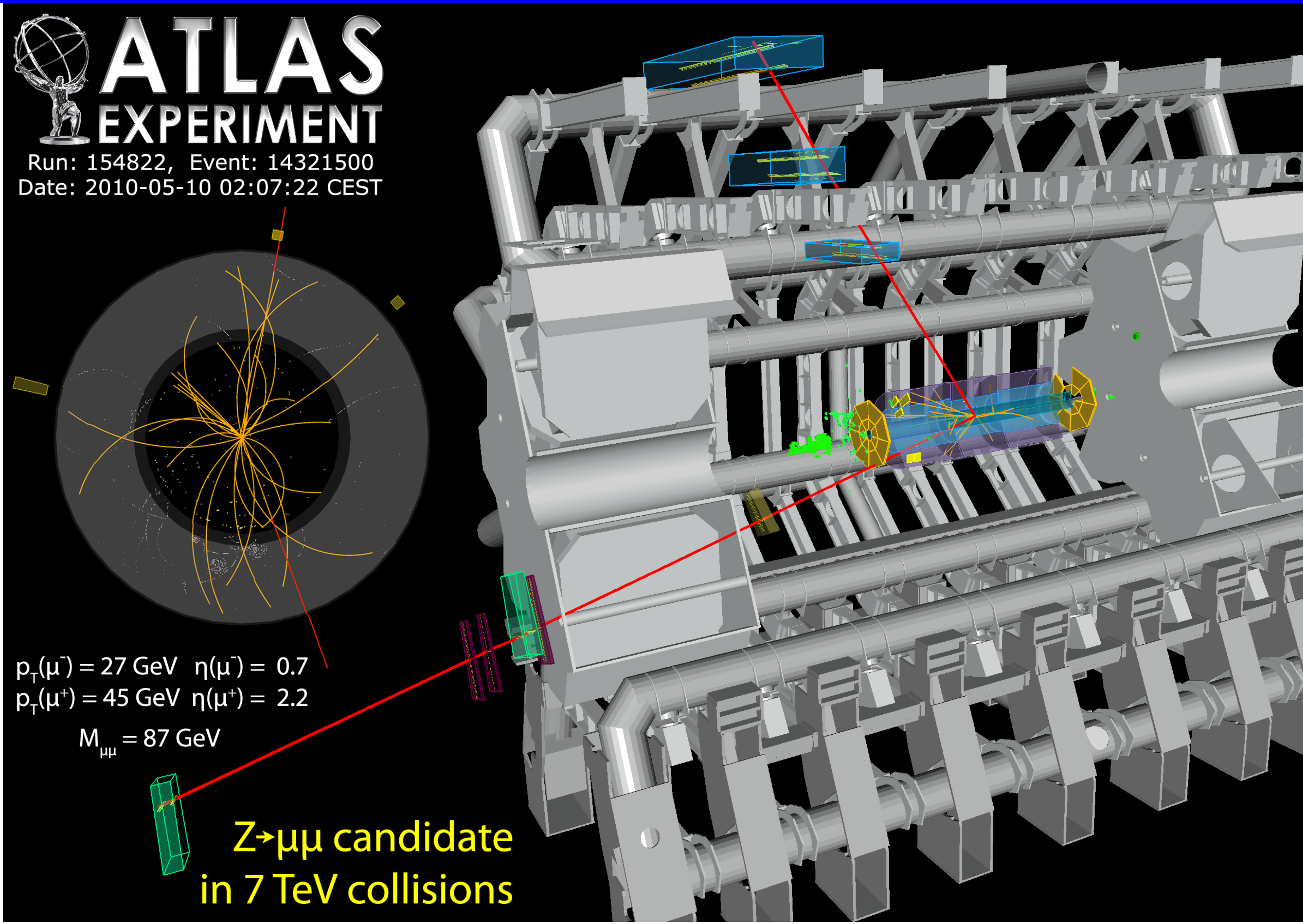
- $W \rightarrow l\nu$: high p_T isolated electron or muon, with missing transverse energy inferred from the sum of the p_T of all particles originating from the primary vertex



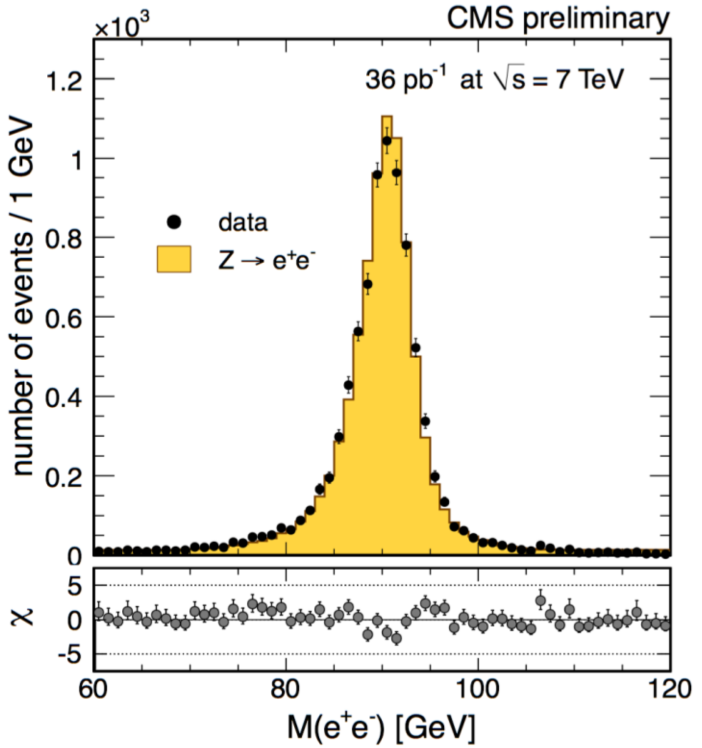
- Undetected neutrino: no clear mass peak, so rely on other observables
- Lepton p_T
- Missing transverse energy
- Transverse mass

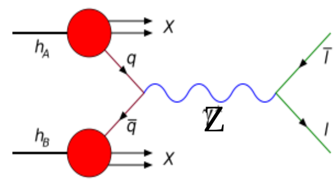
$$m_T = \sqrt{2 p_T^l p_T^{miss}(1-\cos\Delta\phi)}$$

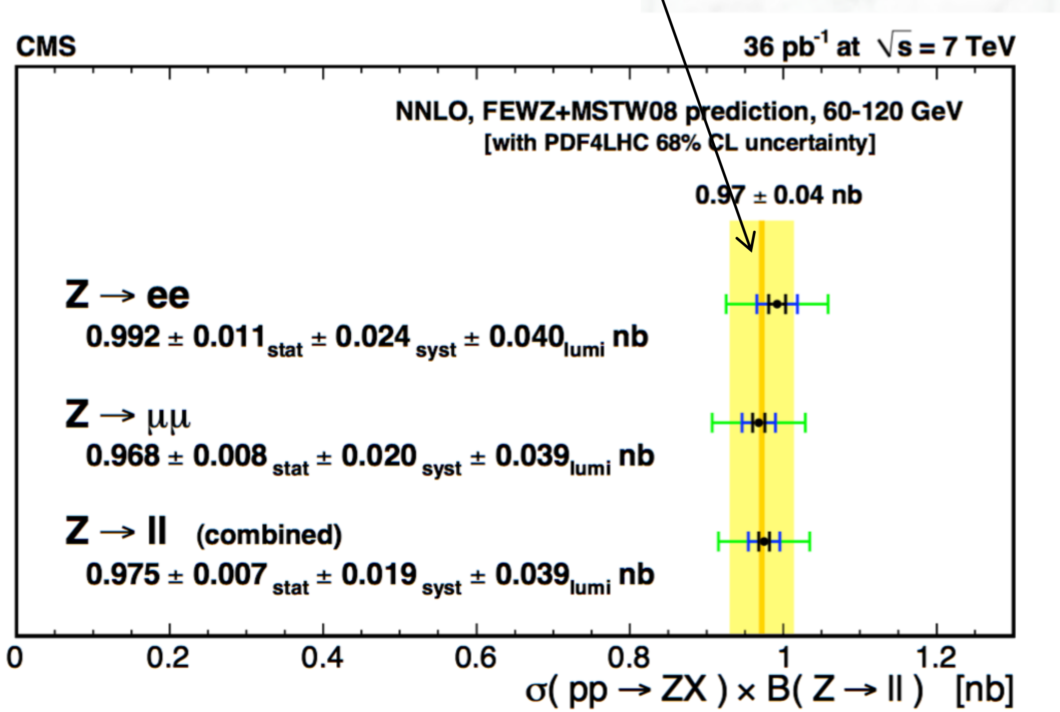
Z→μμ event


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

$pp \rightarrow Z^0 \rightarrow l^+l^-$ cross section at LHC



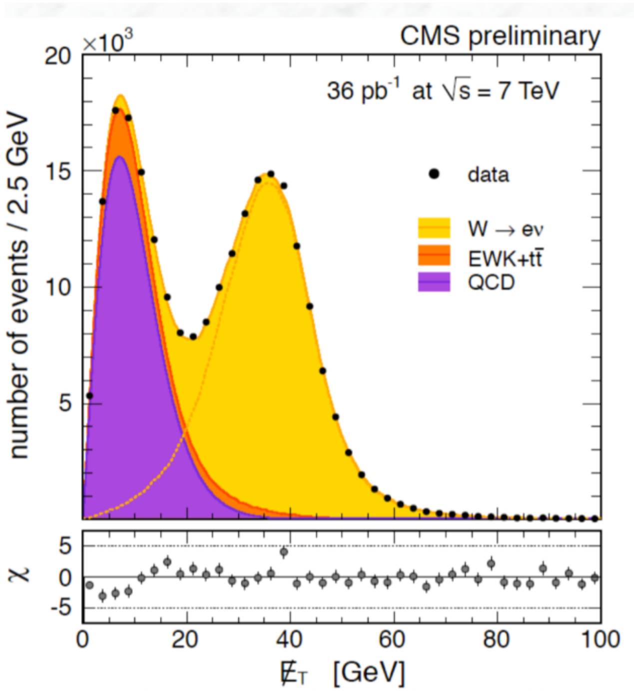




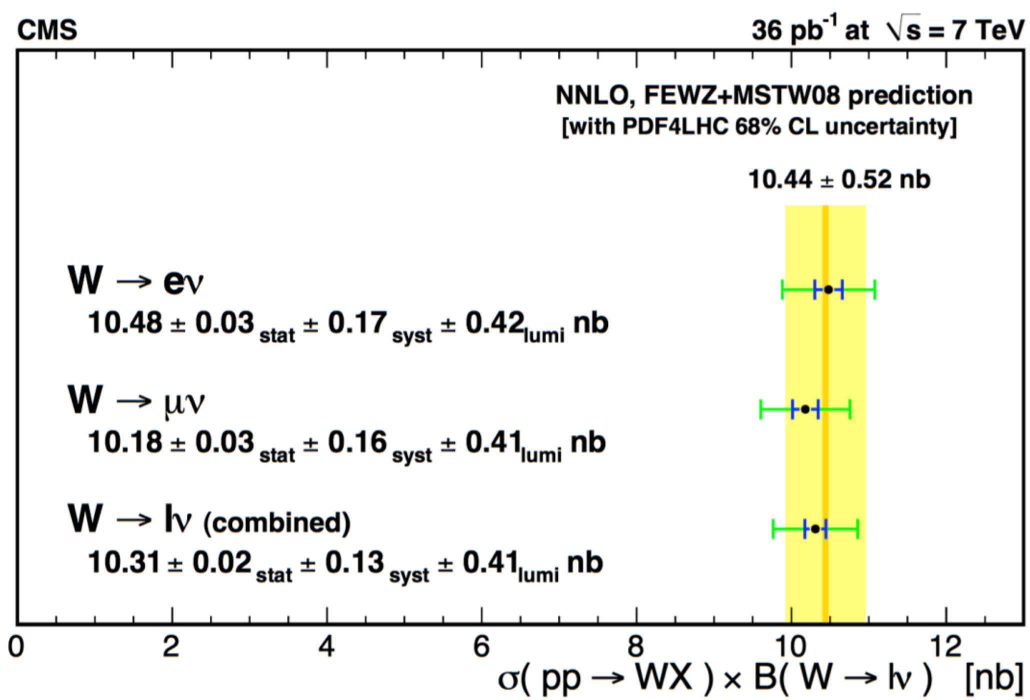
$M^2 = 2p_1p_2(1-\cos\theta)$

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

pp→W$^\pm$→l$^\pm$ν cross section

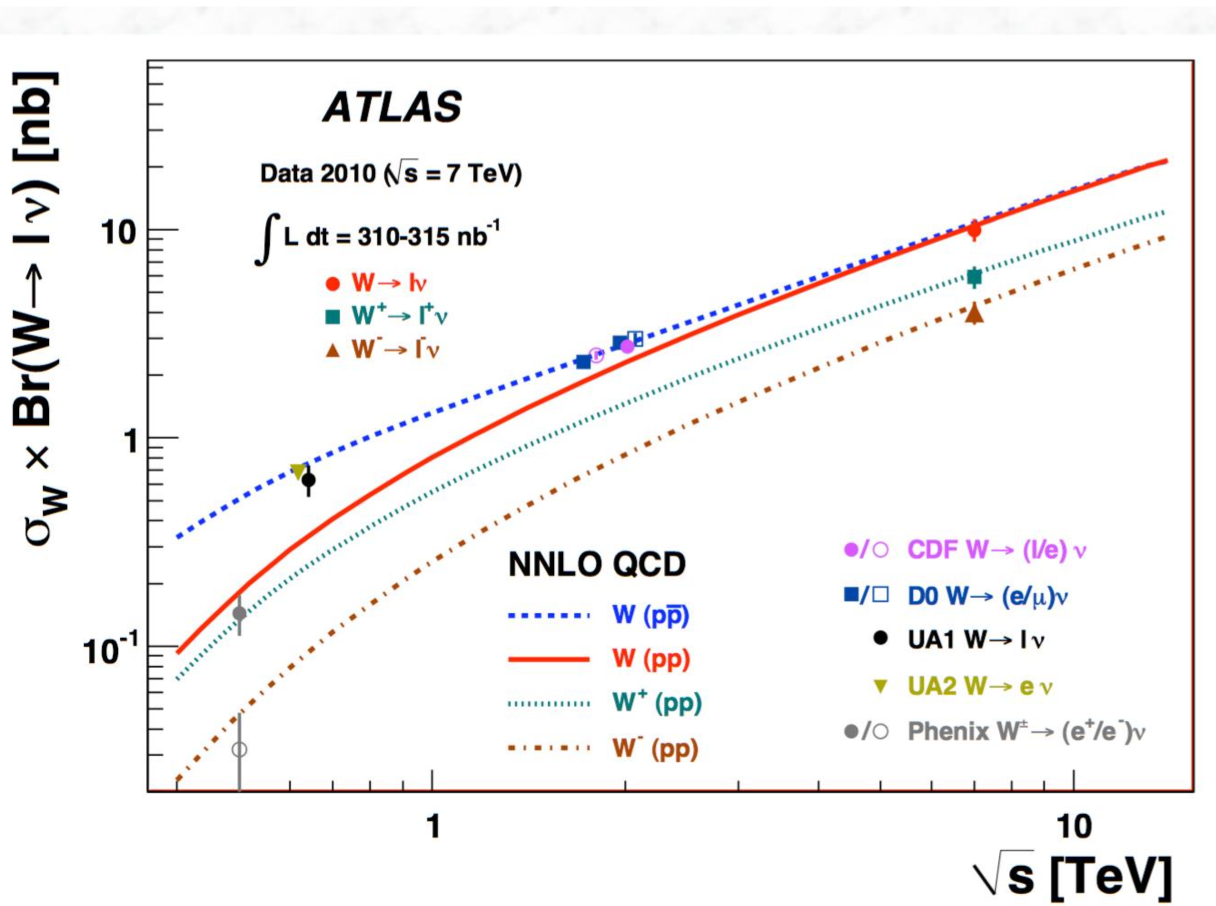


Neutrino transverse momentum from the transverse energy balance



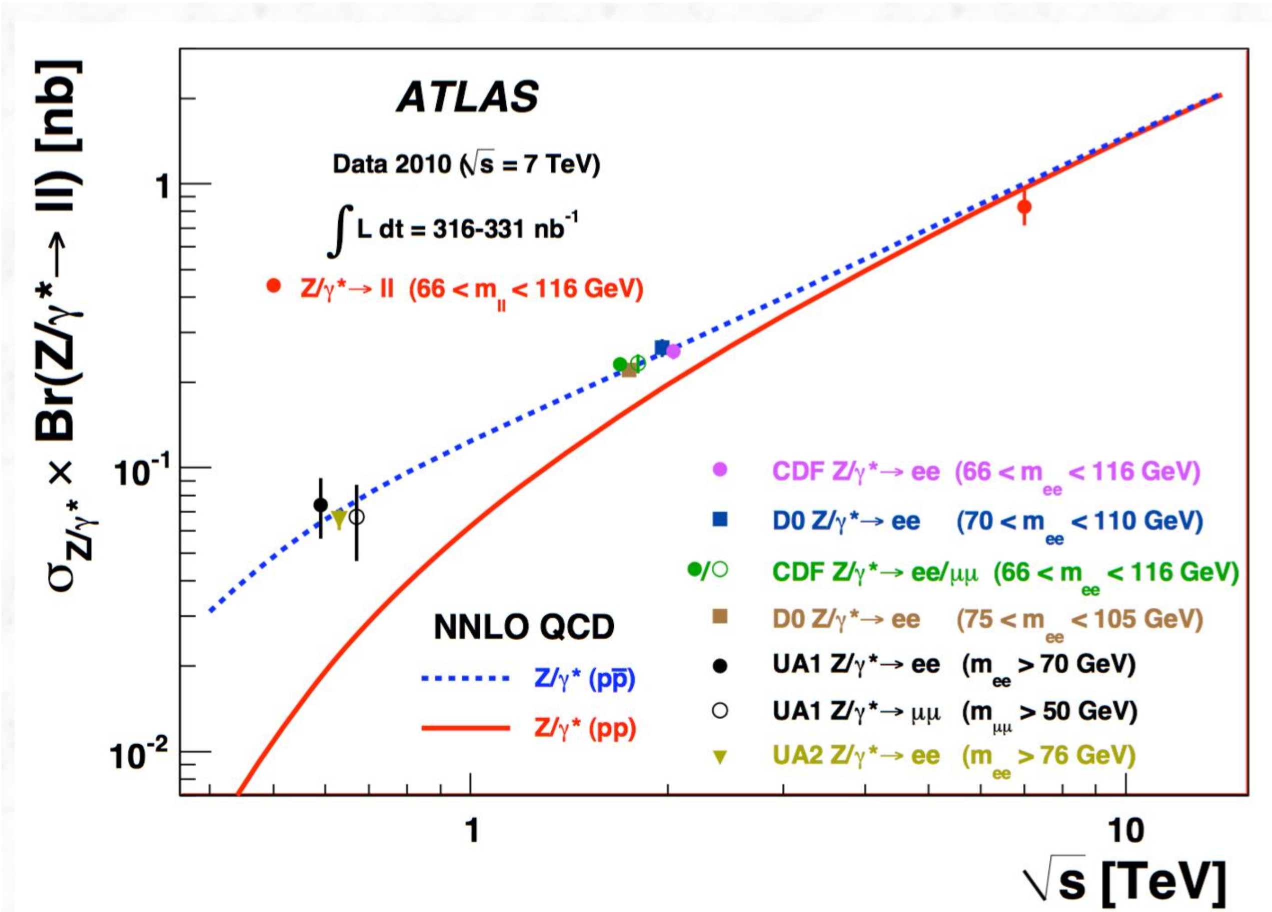
→ ~5% precision, EW theory predictions at NNLO in agreement with data

$W^{\pm}$ production cross section



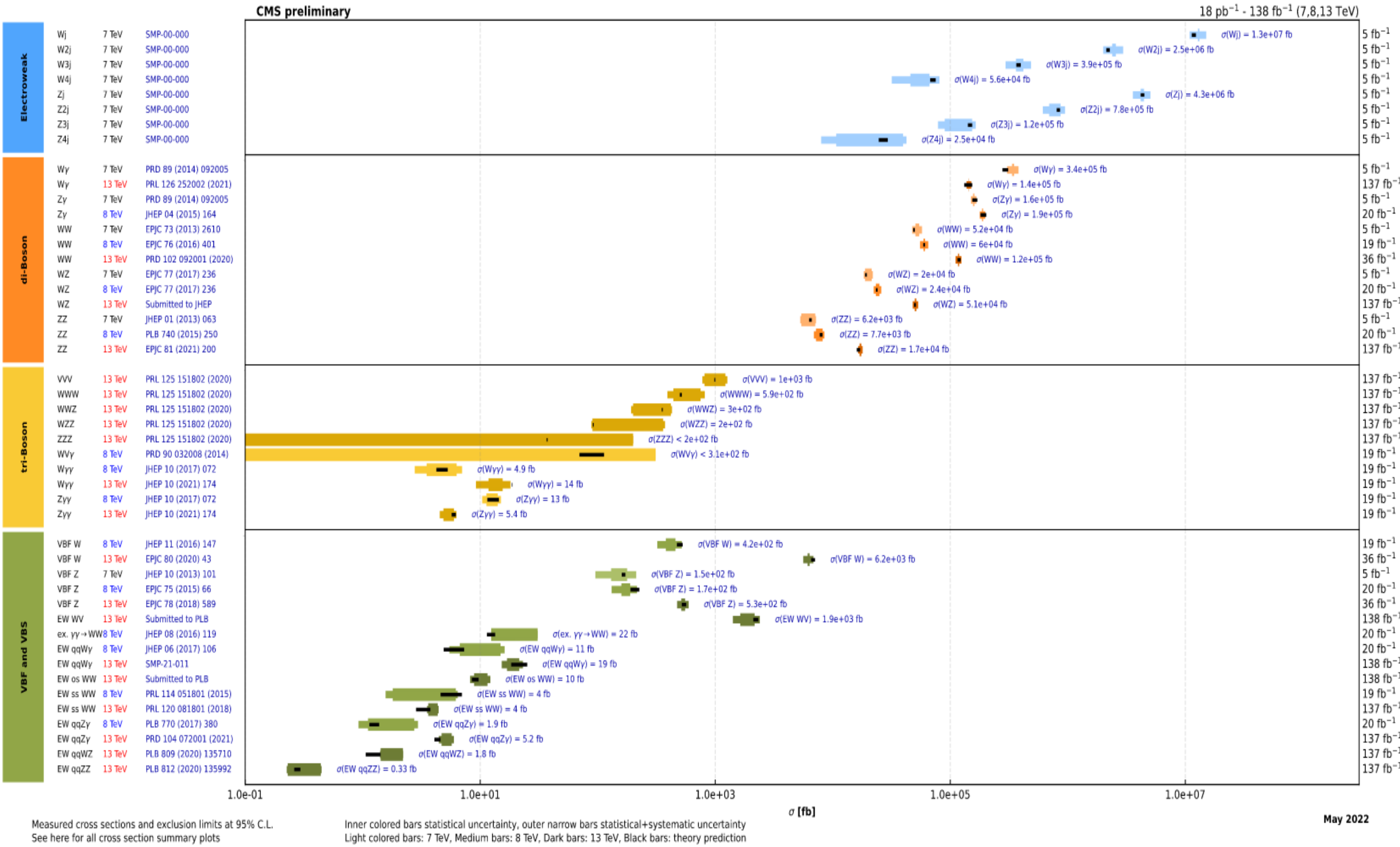
- Smaller cross section at pp than ppbar collider due to proton content
- Difference vanishes at high energy
- EW theory predictions in agreement with measurements

Z^0 production cross section

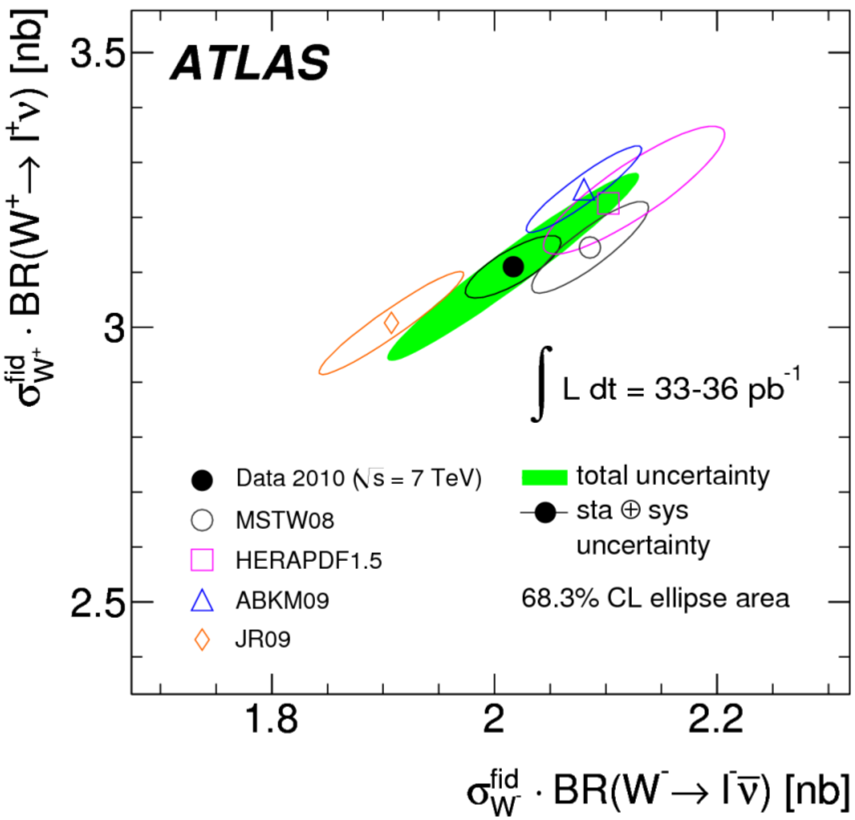


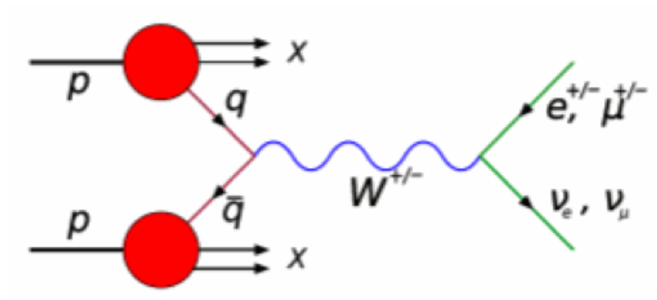
- ❑ Smaller cross section at pp than ppbar collider due to proton content
- ❑ Difference vanishes at high energy
- ❑ Prediction in agreement with data

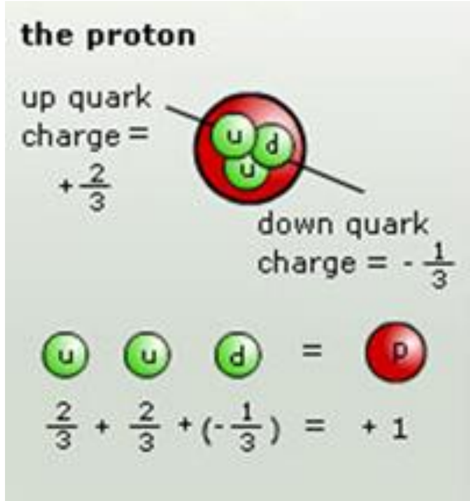
Summary of EW cross section measurements



W charge asymmetry





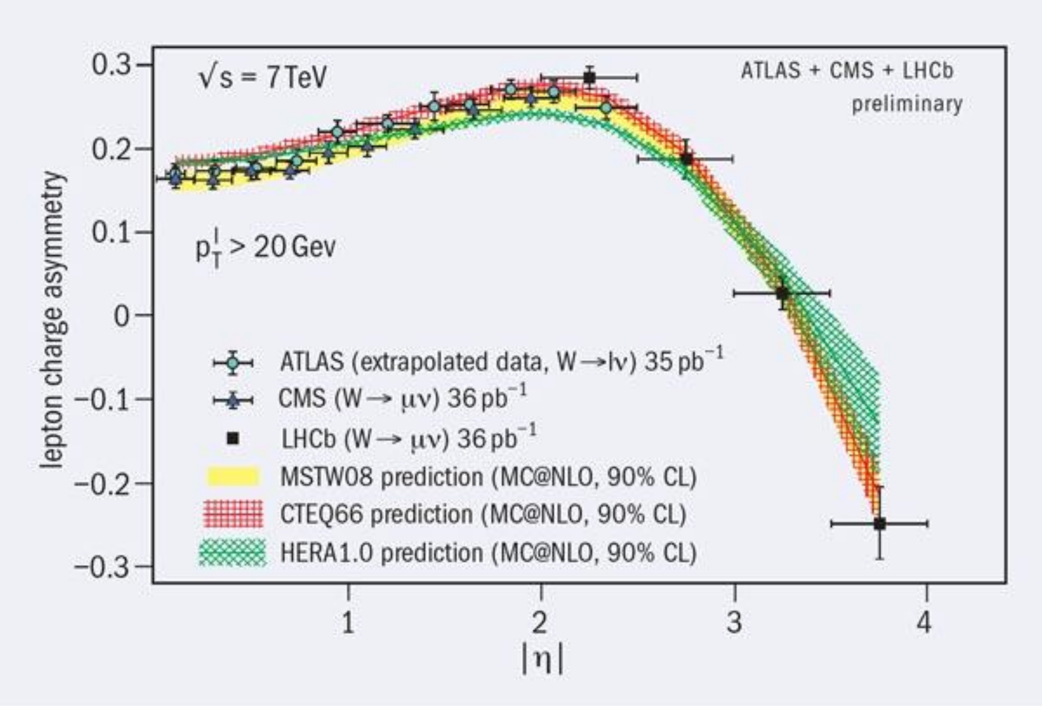


- ❑ LHC produces more W^+ than W^-

→ 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

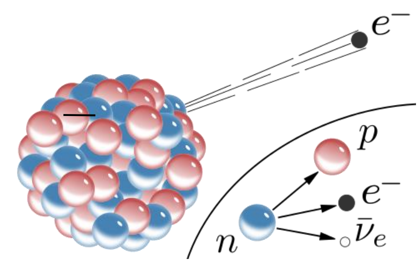
Parity violation in weak interactions

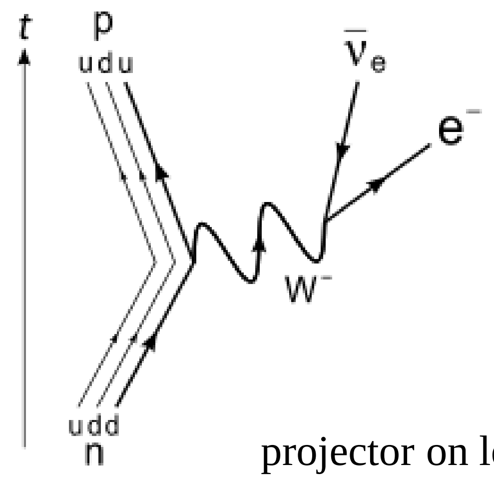
- **β decay**: within nuclei $n \longrightarrow p + e^- + \bar{\nu}_e$
- Weak interaction between quarks:

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

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





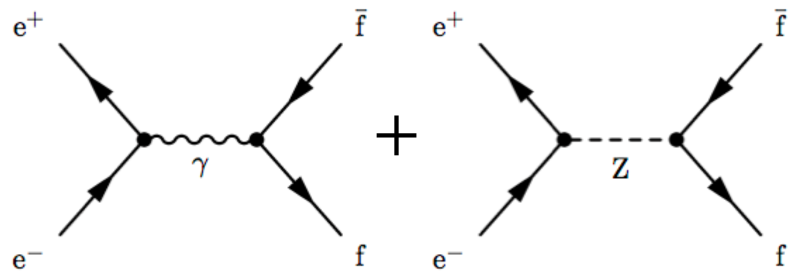
projector on left-handed states

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

→ Parity is conserved by electromagnetic (QED) and strong (QCD) interactions, but not in weak interactions

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 $e^+e^- \rightarrow f\bar{f}$, similarly $qq \rightarrow f\bar{f}$ at LHC



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

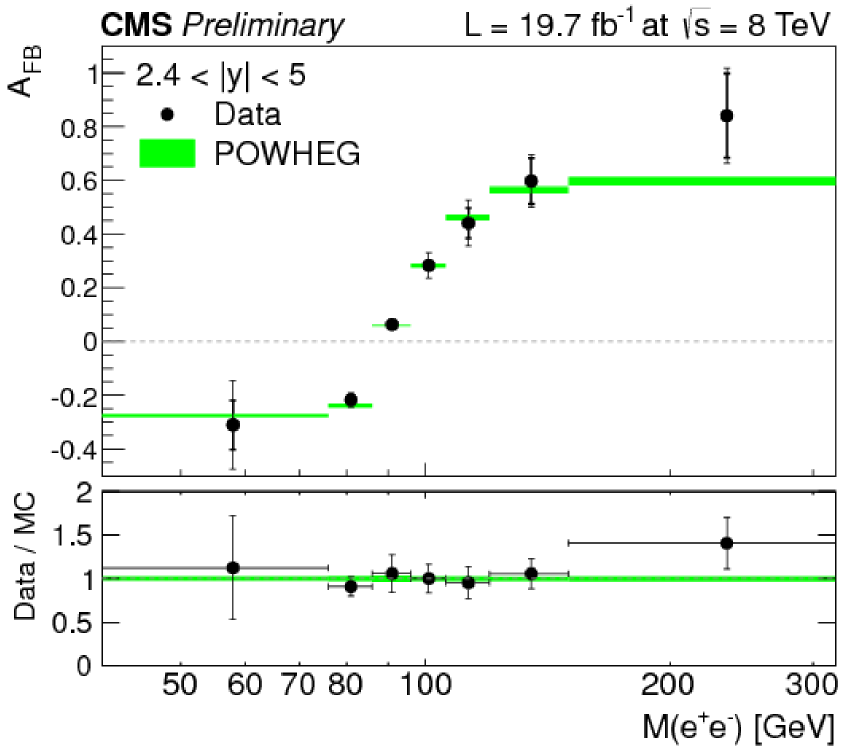
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta) + F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} + F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

γ — γ/Z interference — Z

x N_c^f: number of colours for fermion f

Forward-backward 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 $f\bar{f} \rightarrow Z^0 \rightarrow f\bar{f}$



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

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

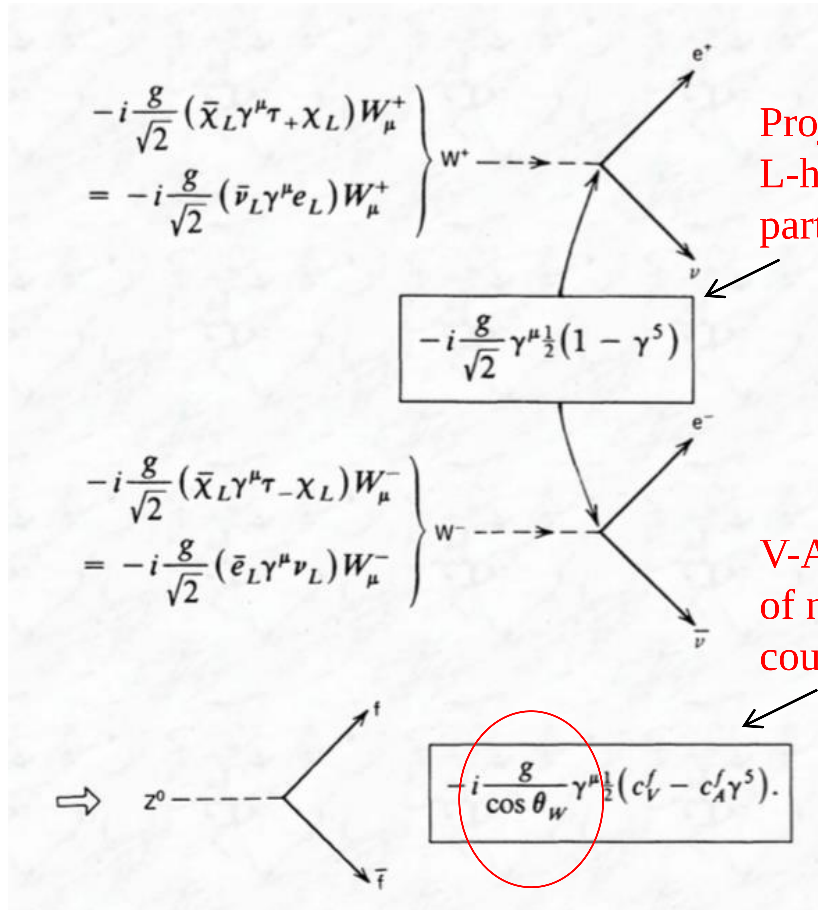
→ At the Z pole, Z term dominates. Moving away from the resonance pole the interference term dominates and gives larger contribution to A_{FB}

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

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

e.m. coupling weak coupling

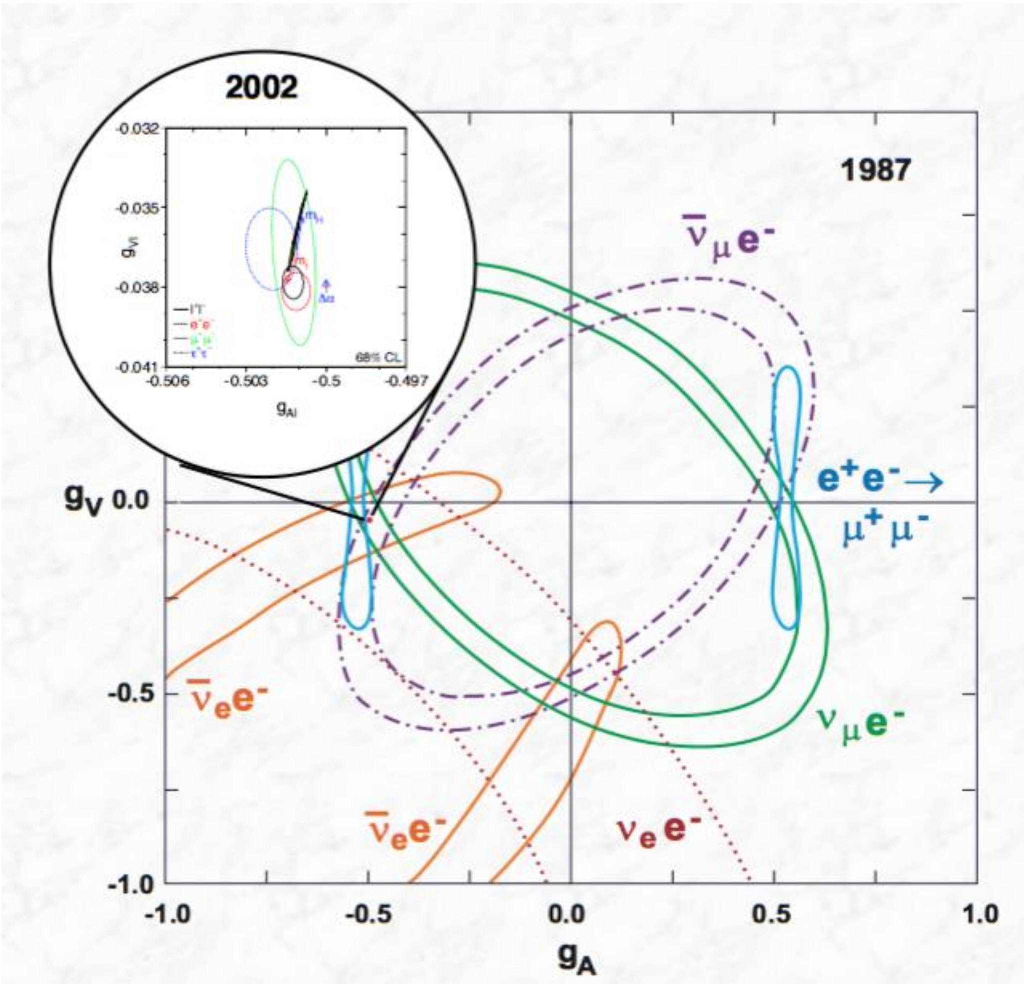


Projector onto L-handed particles

V-A structure of neutral coupling

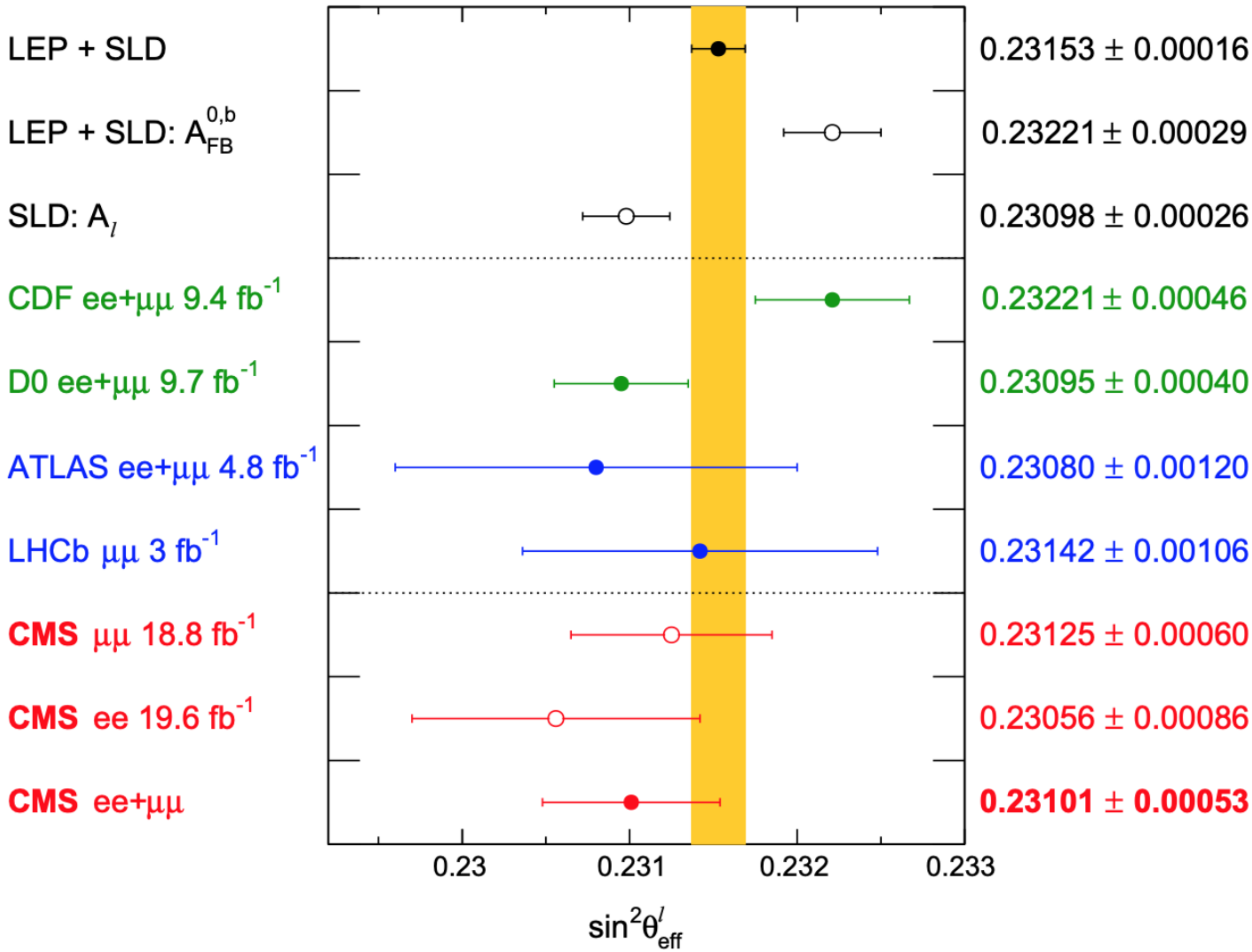
→ $\sin\theta_W$ is a parameter of the theory, has to be experimentally measured

$\sin\theta_W$: 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: $Z^0 \rightarrow l^+l^-$

$\sin\theta_W$: from LEP to LHC



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:

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

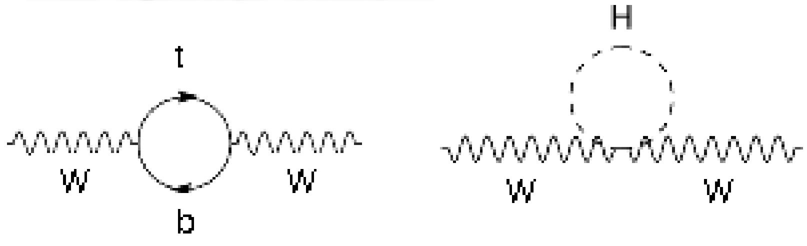
$$\sin^2\theta_{eff} = (1 + \Delta\kappa)\sin^2\theta_W$$

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

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

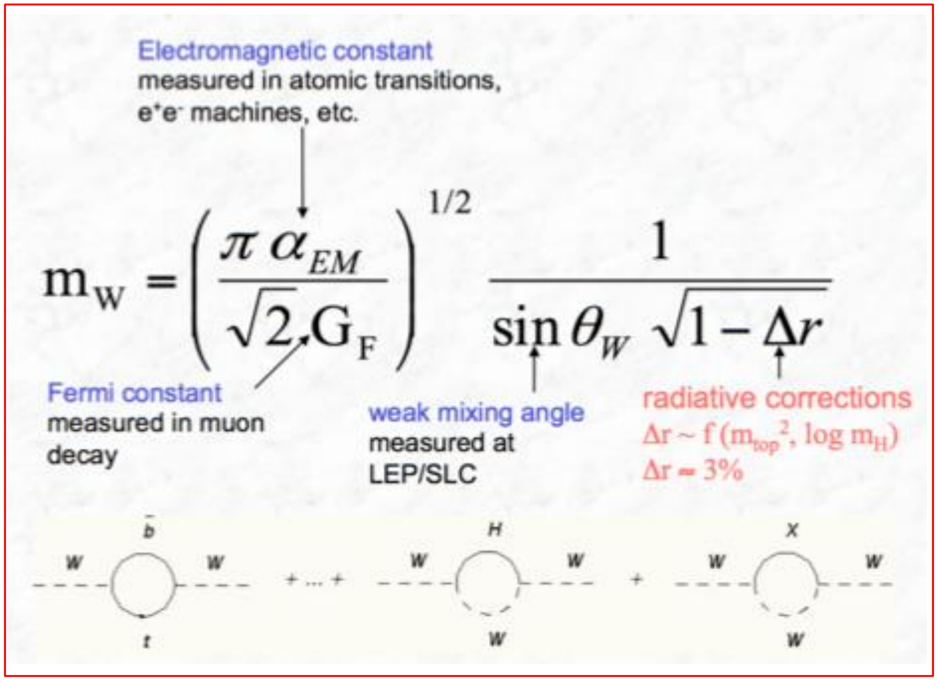
$$\Delta\alpha = \Delta\alpha_{lepl} + \Delta\alpha_{top} + \Delta\alpha_{had}^{(5)}$$

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



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



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

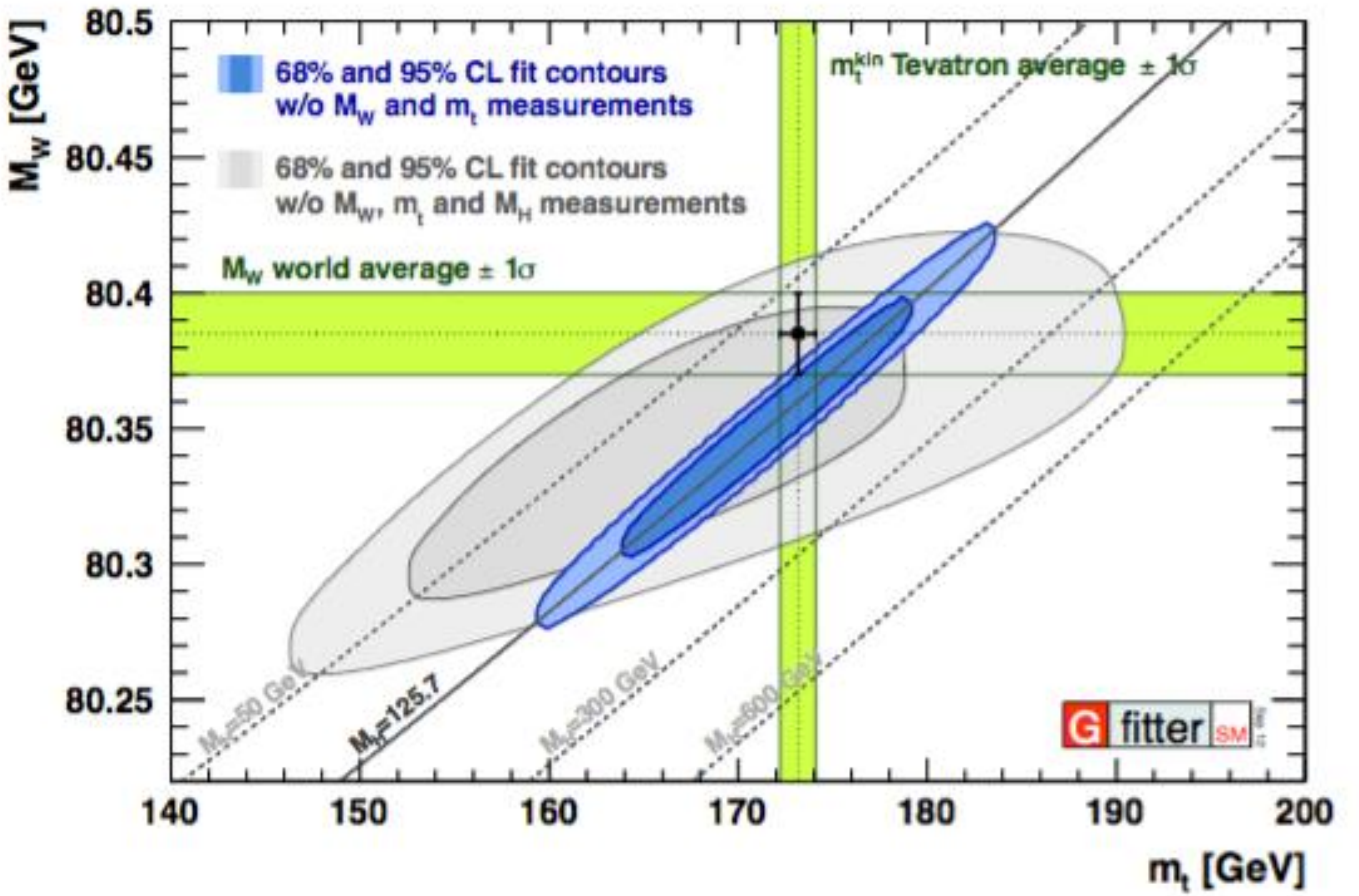
- G_F, α_{em} and $\sin\theta_W$ are known with high precision
  - α_{em}=1/137035999679..
  - G_F=1.16637(1)x10^{-5} GeV^{-2}
  - $\sin^2\theta_W$=0.23153(16)
- All 3 mass measurements provide **consistency check of the standard model** through **radiative corrections**

→ Very important test for new physics

Standard model consistency

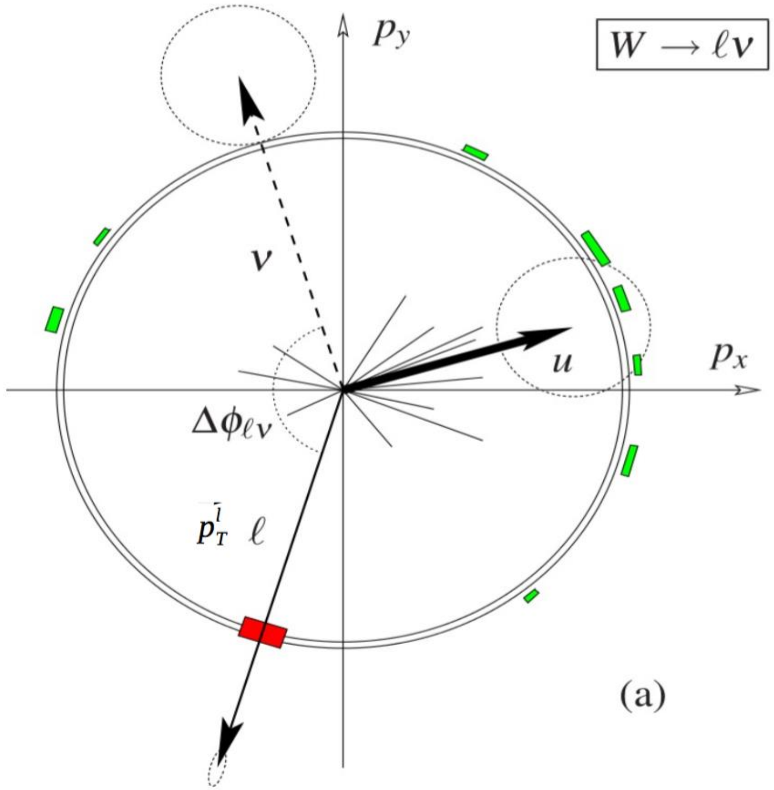
arXiv:1407.3792

2014: m_W from LEP and Tevatron, m_H and m_t from LHC



Measurement strategy

W→lν



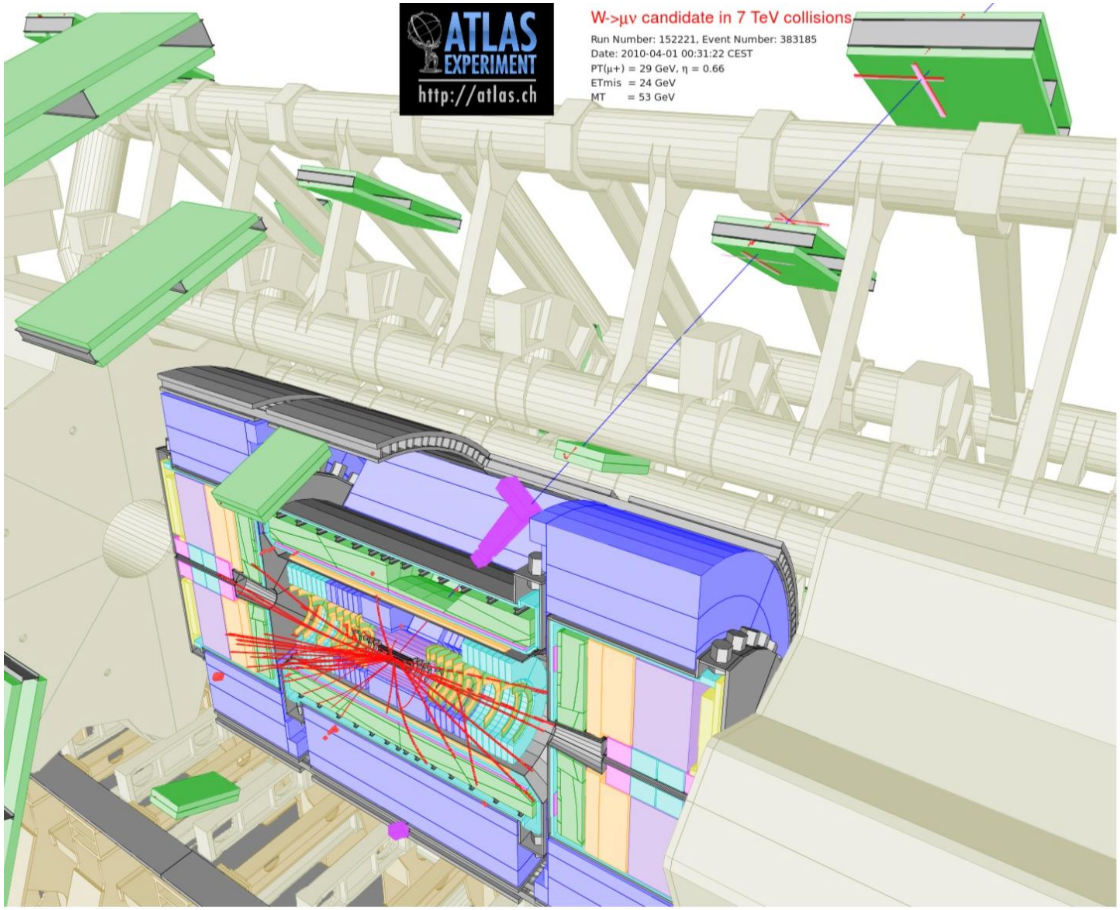
- **Main signature: high p_T lepton** (electron or muon): p_T^l
- The neutrino is undetected, and measured using the momentum conservation in the transverse direction

- 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 $m_T = \sqrt{2 p_T^l p_T^{miss}(1-\cos\Delta\phi)}$

→ challenging measurement for experiments, any mis-measured energy produces fake 'E_T^{miss}'

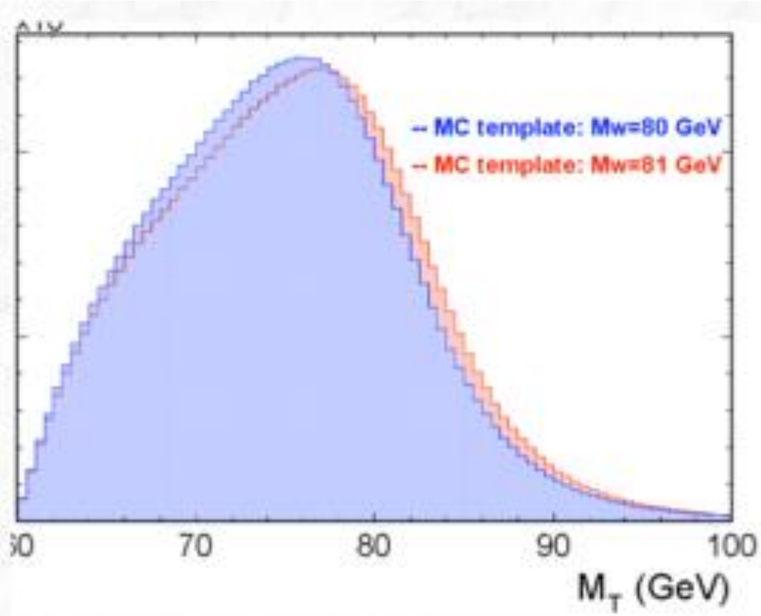
W mass measurement

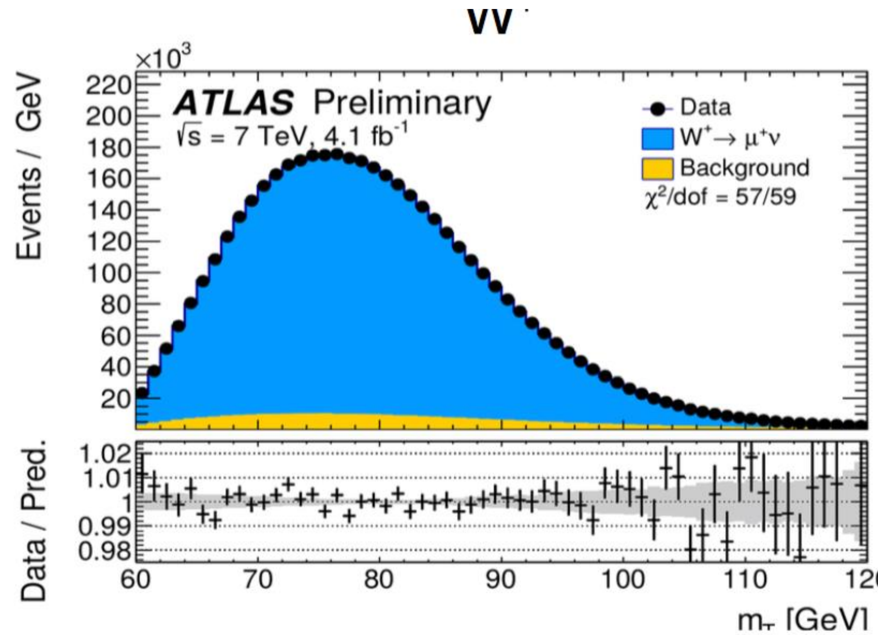
- $W \rightarrow \mu\nu$ candidate (2010)
- Muon measured from matching **muon spectrometer** and inner tracker tracks
- **Missing transverse energy** from the absence of additional high-p_T particles



Measurement strategy & result

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





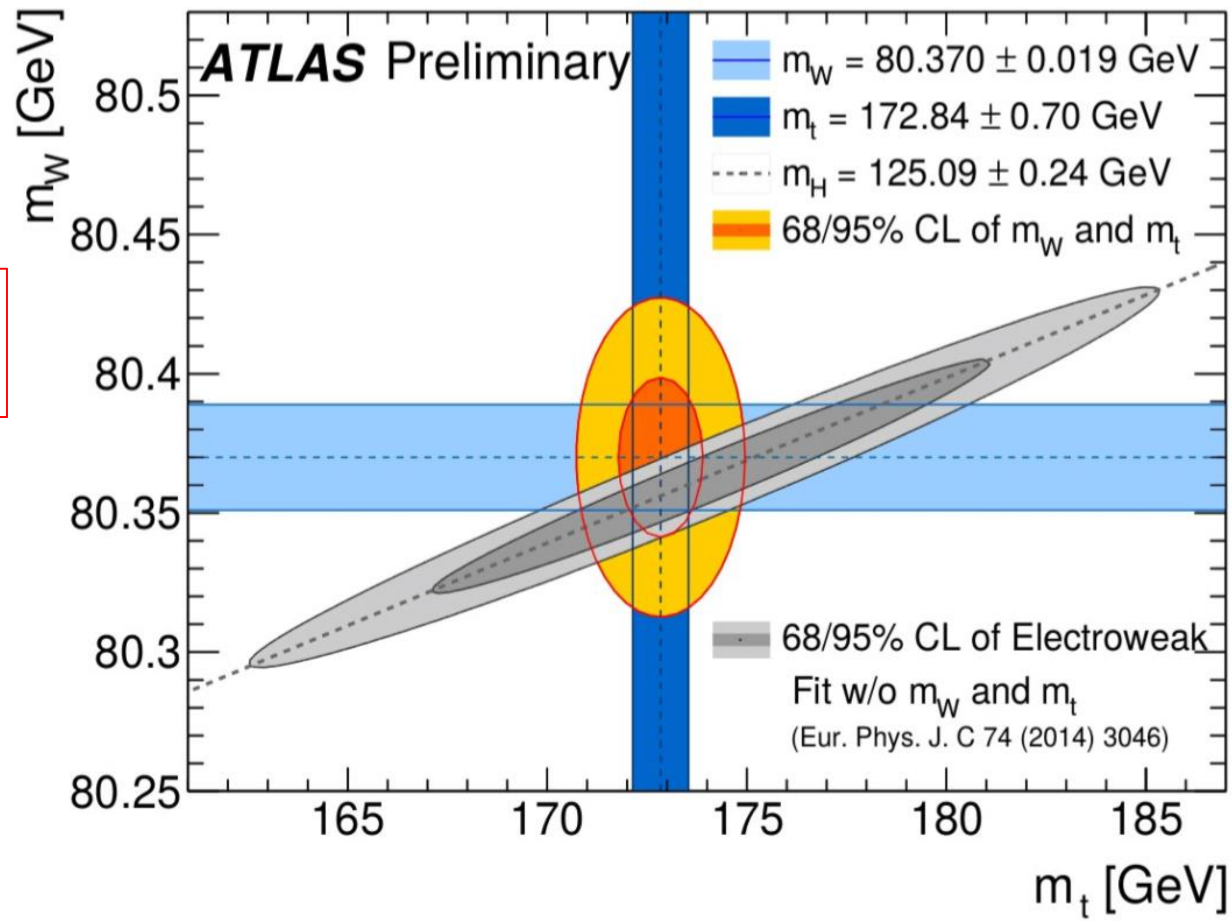
$$m_W = 80.370 \pm 0.007\,(\text{stat.}) \pm 0.011\,(\text{exp.syst.}) \pm 0.014\,(\text{mod.syst.})\ \text{GeV}$$
$$= \underline{80.370 \pm 0.019\ \text{GeV}}$$

→ one of the challenge is to very accurately model the expected m_T distribution

Standard model consistency

2016: m_W from LHC

$m_W = 80.370 \pm 0.019$ GeV

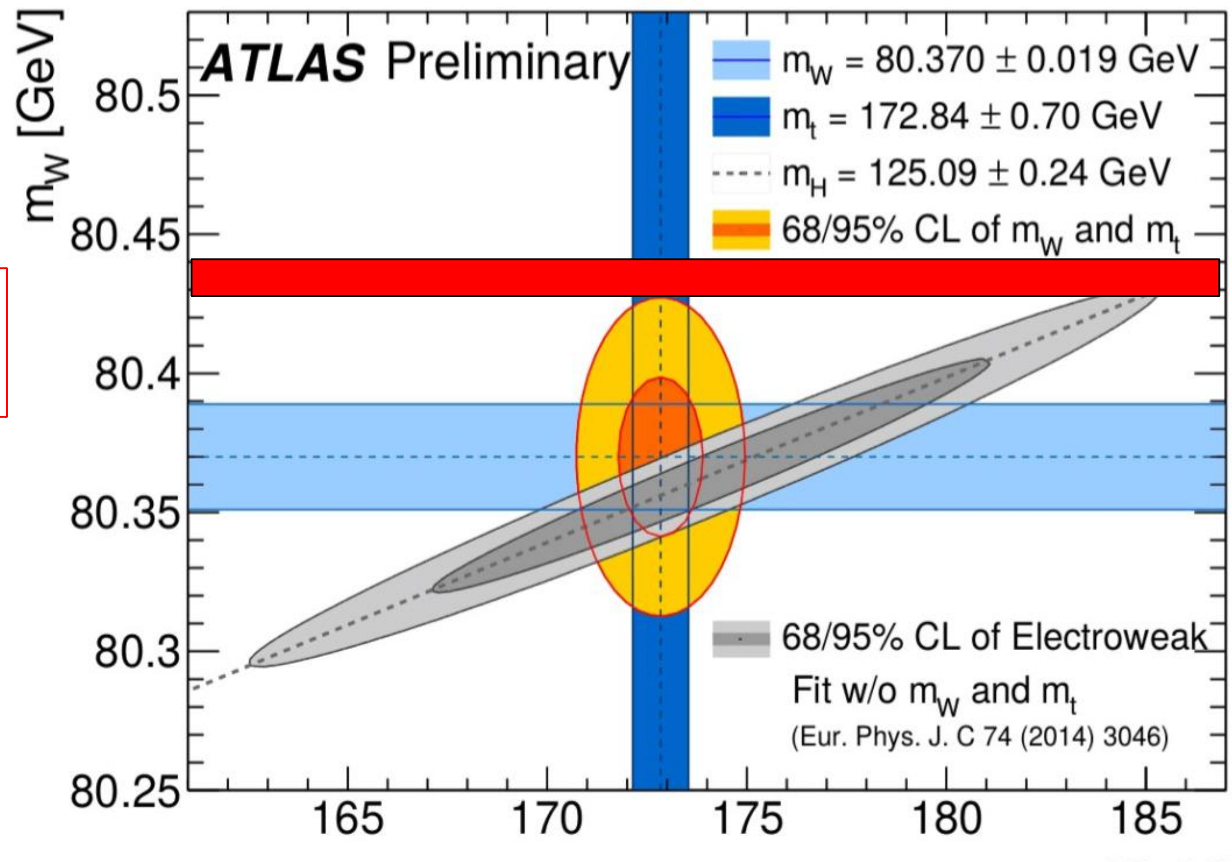


→ Agreement improved from refined measurement of m_W at LHC

Standard model consistency

2022: new m_W from CDF

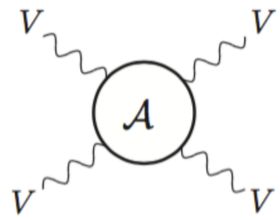
m_W = 80.434 ± 0.009 GeV



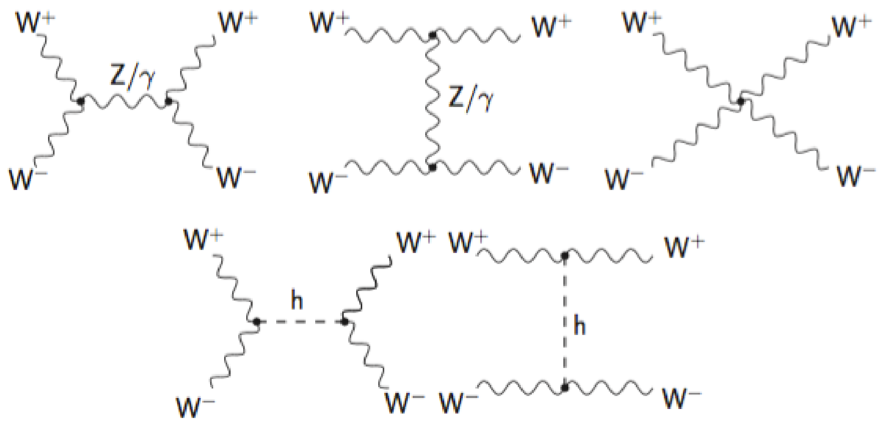
→ The >5σ shift of the W mass reported recently by CDF makes the global EW fit inconsistent!

Vector boson scattering (VBS)

- Scattering of on-shell (massive) bosons



- In the Standard Model (SM), at tree level = $O(\alpha_{EW}^2)$, for the $W^+W^- \rightarrow W^+W^-$ amplitude



pure gauge diagrams

Higgs-mediated diagrams

- Possible channels: $W^+W^- \rightarrow W^+W^-$, $W^\pm W^\pm \rightarrow W^\pm W^\pm$, $W^\pm Z \rightarrow W^\pm Z$, $ZZ \rightarrow ZZ$ (but also $W^+W^- \rightarrow ZZ$, $ZZ \rightarrow W^+W^-$)

Polarization of massless gauge bosons (γ)

- The photon field A_μ can be described by plane waves with constant polarization vectors

$$A^\mu(x) = \varepsilon^\mu \exp(-\mathrm{i}k \cdot x)$$

- Maxwell equations impose a first orthogonality condition (on-shell case):

$$k_\mu A^\mu(k) = 0 \quad => \quad k \cdot \varepsilon = 0$$

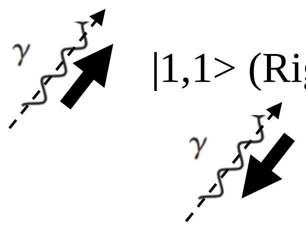
- U(1) gauge (phase) invariance => second orthogonality condition by gauge choice

$$k_i A^i(k) = 0 \quad => \quad \mathbf{k} \cdot \boldsymbol{\varepsilon} = 0 \qquad \text{(Coulomb gauge)}$$

- Therefore 2 degrees of freedom and for a photon propagating in the z direction, a commonly used basis for the polarization vectors are the helicity eigenstates

$$\varepsilon_+^\mu = \frac{1}{\sqrt{2}}(0, 1, \mathrm{i}, 0)^\mu$$

$$\varepsilon_-^\mu = \frac{1}{\sqrt{2}}(0, 1, -\mathrm{i}, 0)^\mu$$



|1,1> (Right)

|1,-1> (Left)

- These are the transverse polarization states, orthogonal to **k**

> ☞ The photon is only transversely polarized, this is directly related to the gauge invariance

Polarization of massive gauge bosons ($W^{\pm}$, Z)

- For a massive boson the same ortogonality condition arises from the equations of motion:

$$k_\mu A^\mu(k) = 0$$

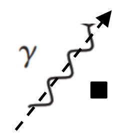
- But the mass term breaks U(1) symmetry, therefore there is not anymore the gauge choice freedom and therefore not the second condition

- For a boson propagating in the z direction

$$k_\mu = (E, 0, 0, k_3)^\mu \quad \text{with} \quad k^2 = m^2$$

- The polarization vector consists of the two transverse modes, and an additional longitudinal mode

$$\varepsilon_L^\mu = \frac{1}{m}(k_3, 0, 0, E)^\mu$$



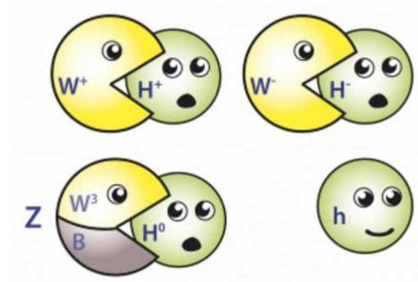
|1,0> (longitudinal)

☞ Fundamental difference in the massive case: additional longitudinal component

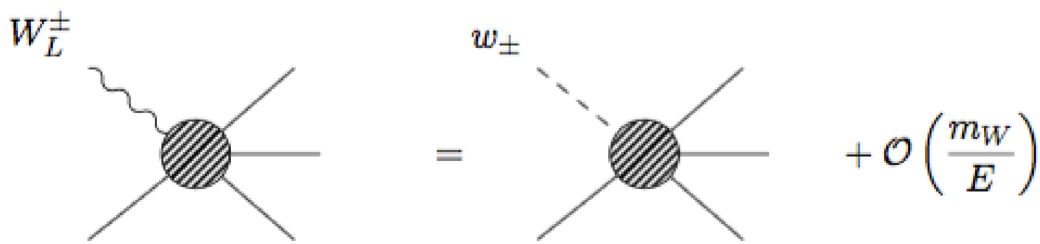
☞ At high energies E>>m the longitudinal mode dominates and grows with E

Electroweak symmetry breaking

- EWSB leads to 4 additional scalar (Goldstone) bosons: 3 are absorbed as longitudinal degrees of freedom for the $W^{\pm}$ and Z bosons, 1 remains as the Higgs boson



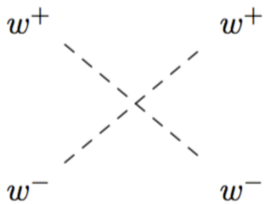
- In the high energy limit E>>m, amplitudes obtained by replacing all external weak bosons with the corresponding Goldstone bosons and use Feynman rules for their scattering derived from SM before EWSB (Goldstone theorem)



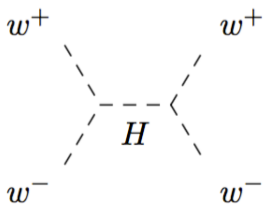
☞Fundamental difference between the transverse and longitudinal modes: at high energies the longitudinal states of the $W^{\pm}$ and Z are the Goldstone bosons of EWSB, while the transverse modes correspond to the original EW gauge bosons

- Consider $W_L^+W_L^- \rightarrow W_L^+W_L^-$
  - 7 diagrams in the SM: 4-W interaction, s-channel diagrams with a gamma, Z or H, and t-channel with a gamma, Z or H
  - Similar for other initial/final states

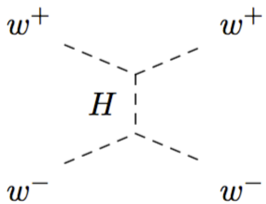
- Exact amplitude rather involved, but at high energy → use the Goldstone theorem
  - For the diagrams involving only Goldstone and H bosons (the gamma and Z diagrams are negligible):



$$= \quad -4\mathrm{i}\lambda\,,$$



$$= \quad \frac{-4\mathrm{i}\lambda^2 v^2}{s - m_H^2}\,,$$



$$= \quad \frac{-4\mathrm{i}\lambda^2 v^2}{t - m_H^2}\,.$$

$$\begin{aligned}
\mathcal{M}_{\mathrm{SM}}(W_L^+W_L^- \rightarrow W_L^+W_L^-) &\approx \mathcal{M}_{\mathrm{SM}}(w^+w^- \rightarrow w^+w^-) \\
&\approx -4\mathrm{i}\lambda - \frac{4\mathrm{i}\lambda^2 v^2}{s - m_H^2} - \frac{4\mathrm{i}\lambda^2 v^2}{t - m_H^2} \\
&\approx -\mathrm{i}\frac{m_H^2}{v^2}\left[2 + \frac{m_H^2}{s - m_H^2} + \frac{m_H^2}{t - m_H^2}\right]\,.
\end{aligned}$$

High energy behaviour

- In the high-energy limit: s, $|t|>>m_H^2$

$$\sigma_{\rm SM} \sim \frac{1}{s}$$

- In contrast in a scenario without the Higgs:

$$\mathcal{M}_{\rm Higgsless}(W_L^+ W_L^- \to W_L^+ W_L^-) \approx -\mathrm{i}\frac{m_H^2}{v^2}\left[2 - \frac{1}{1-\frac{s}{m_H^2}} - \frac{1}{1-\frac{t}{m_H^2}}\right]$$
$$\approx \mathrm{i}\frac{s+t}{v^2}\,.$$

- And in the high energy limit, the cross section is proportional to

$$\sigma_{\rm Higgsless} \sim s$$

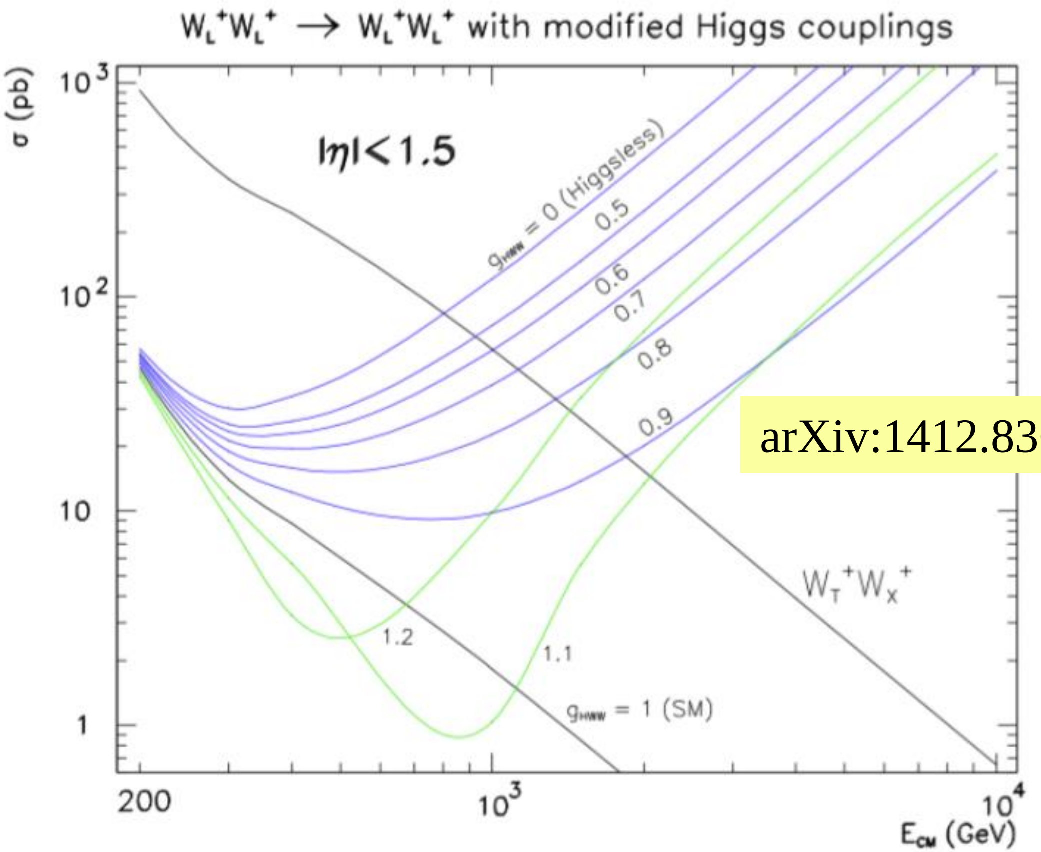
- This leads to unitarity violation at high energy, the energy at which unitarity is violated can be estimated as

$$\sqrt{s} \lesssim 1.2\ \mathrm{TeV}$$

and new physics is required to cure unitarity violation at this scale

☞ Goal is to see if indeed the H125 does restore unitarity or if something else is at work

Unitarity violation



arXiv:1412.8367

Beyond VBS

☞ This is not all: many other divergences in the SM are regularized by the Higgs boson!

☞ Full program of verification of the role of the Higgs boson in processes involving VV

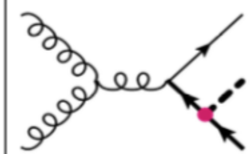
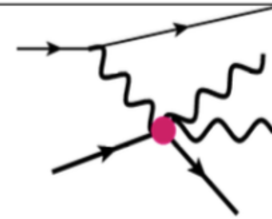
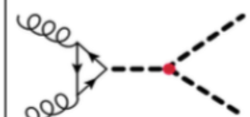
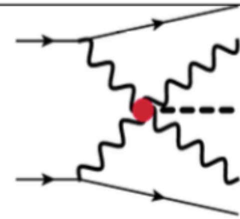
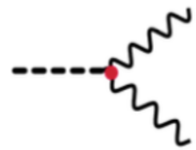
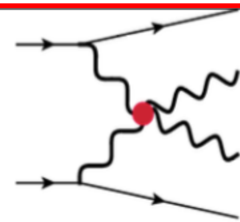
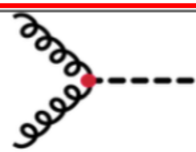
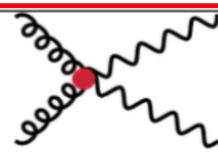
		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

TABLE I. *Each effect (left column) can be measured as an on-shell Higgs Coupling (diagram in the HC column) or in a high-energy process (diagram in the HwH column), where it grows with energy as indicated in the last column.*

tVV and tH

HVV and HH

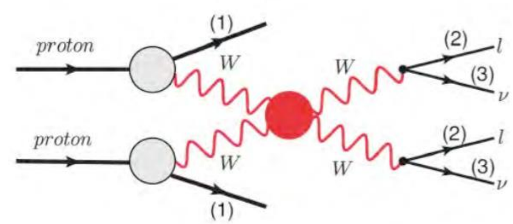
VV and H (VBS)

VV and H (gluon induced)

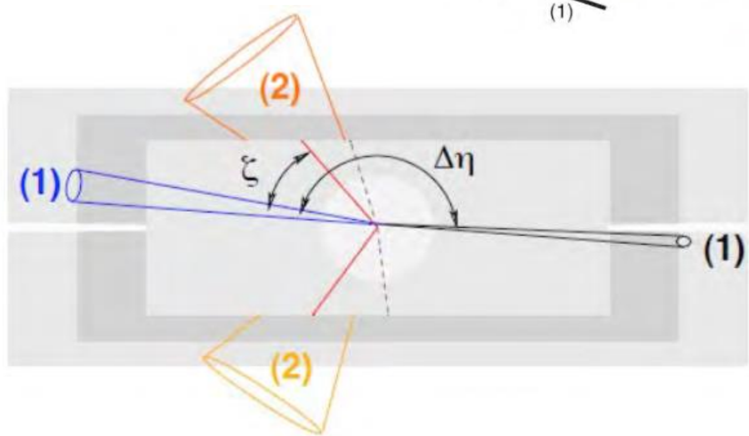
PRL 123, 181801 (2019)

VBS at LHC

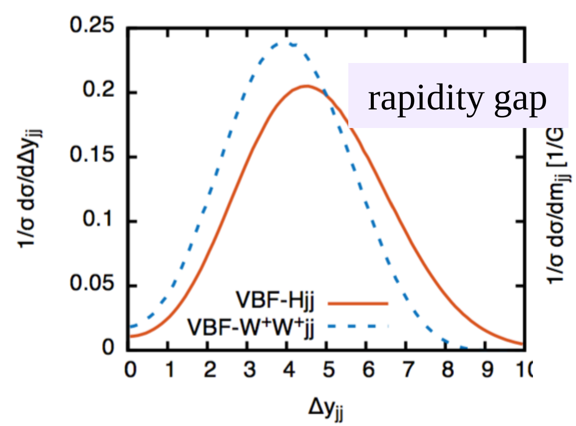
- VBS processes through emission of gauge bosons from colliding quarks

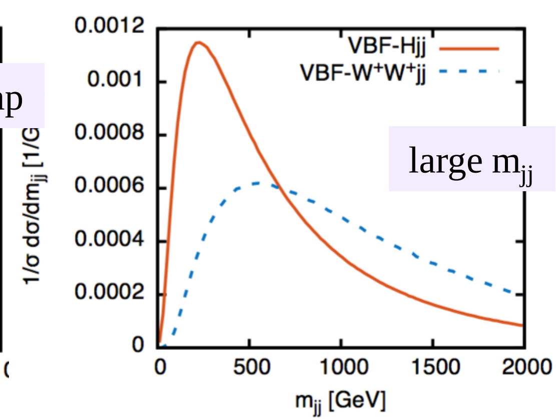


- Two hadronic jets in the forward and backward regions with very high energy (tagging jets)
- Hadronic activity suppressed between the two jets (rapidity gap) due to pure EW process
- Two bosons ~back-to-back

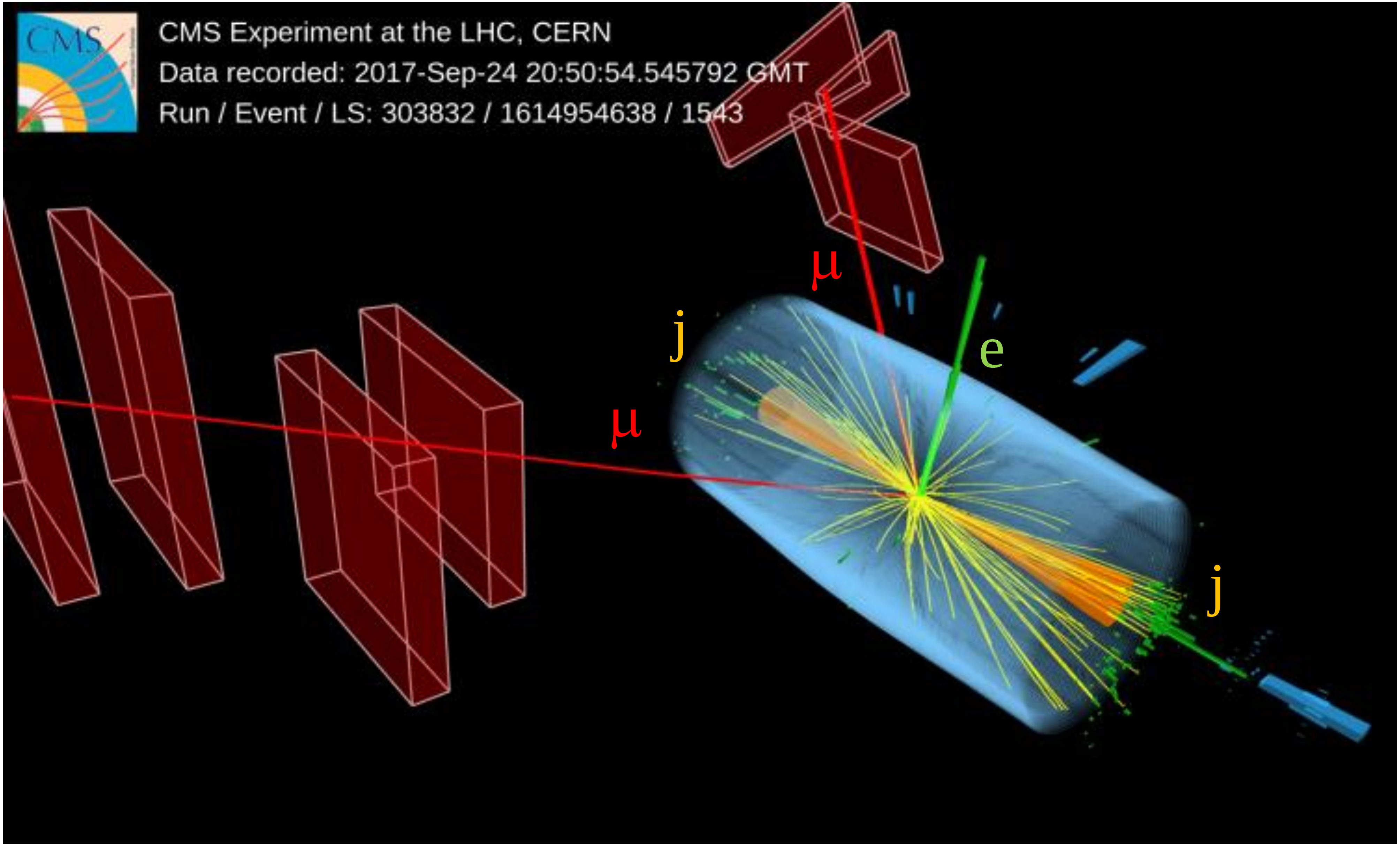


- Contributions to the final state
  - EW (signal) = $O(\alpha_{EW}^6)$
  - QCD (backgd) = $O(\alpha_{EW}^4 \alpha_S^2)$
  - Interference: $O(\alpha_{EW}^5 \alpha_S)$

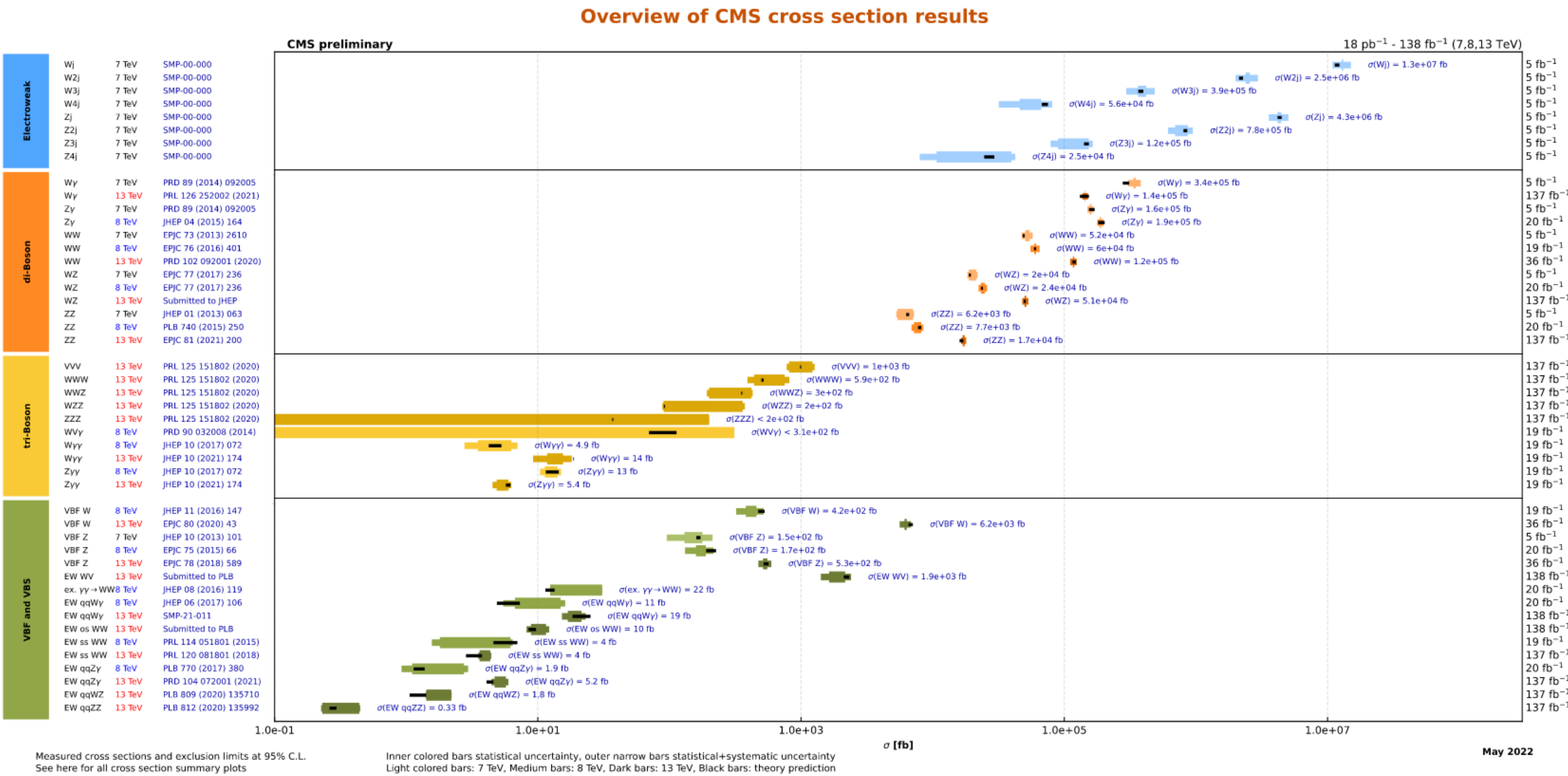




pp → WZjj → $e^+ \nu \mu^+ \mu^- jj$



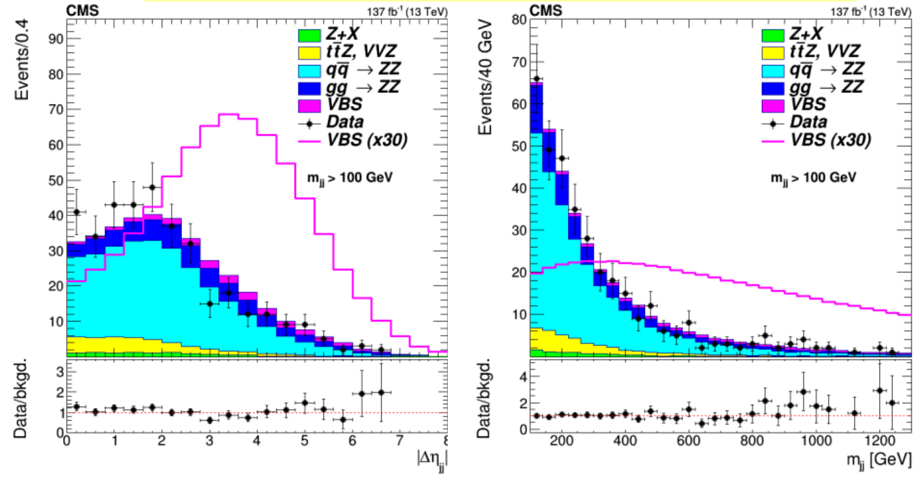
Where do we stand?



Smallest cross section measurements, up to now in agreement with SM predictions

VBS ZZ analysis

PLB 812 (2020) 135992, PhD D. Giljanovic

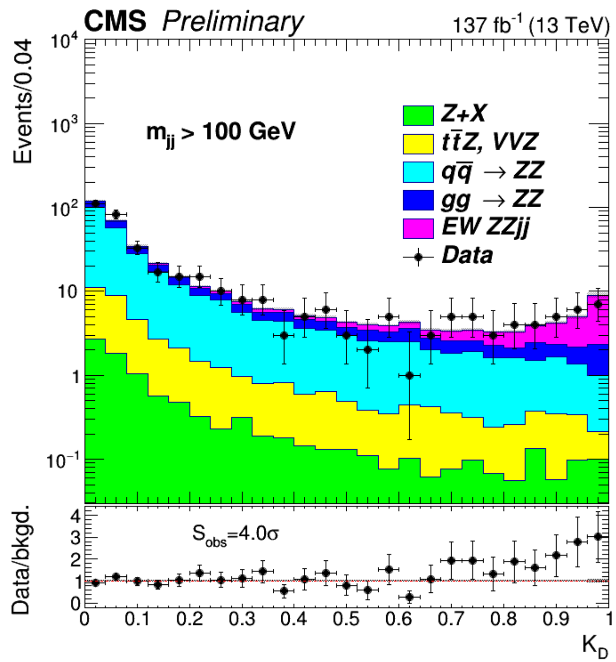


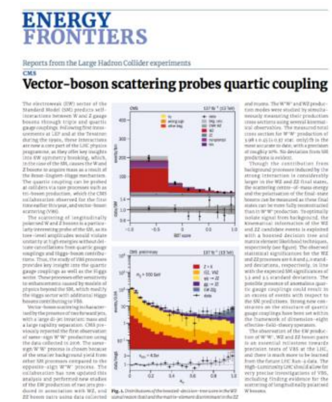
- Main bkgd from QCD-induced ZZjj
  - Special effort to accurately simulate the loop-induced contribution (part of N^{4}LO pp → ZZ)

PRD 102, 116003 (2020)

- K_D discriminant combines all observables to separate QCD-induced background
- 4.0 (3.5)σ observed (expected)

	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
EW	LO	0.275 ± 0.021	$0.33^{+0.11}_{-0.10}$ (stat)$^{+0.04}_{-0.03}$ (syst)
	NLO QCD	0.278 ± 0.017	
	NLO EW	$0.242^{+0.015}_{-0.013}$	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}$ (stat) ± 0.47 (syst)
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	$0.180^{+0.070}_{-0.060}$ (stat)$^{+0.021}_{-0.012}$ (syst)
	NLO QCD	0.197 ± 0.013	
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}$ (stat) ± 0.07 (syst)
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03}$ (stat) ± 0.02 (syst)
	NLO QCD	0.108 ± 0.007	
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04}$ (stat) ± 0.02 (syst)

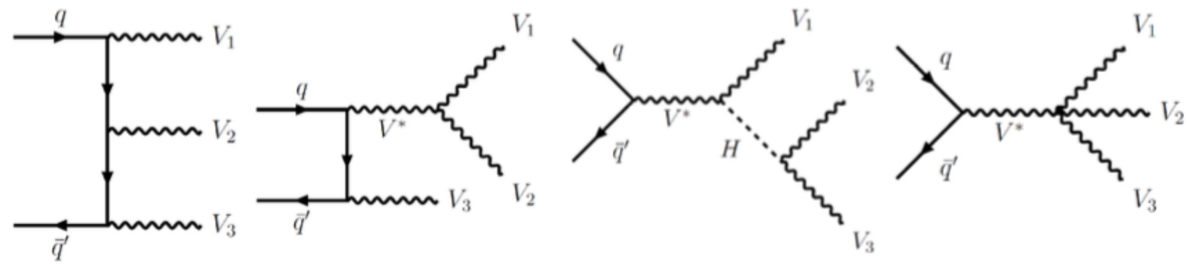




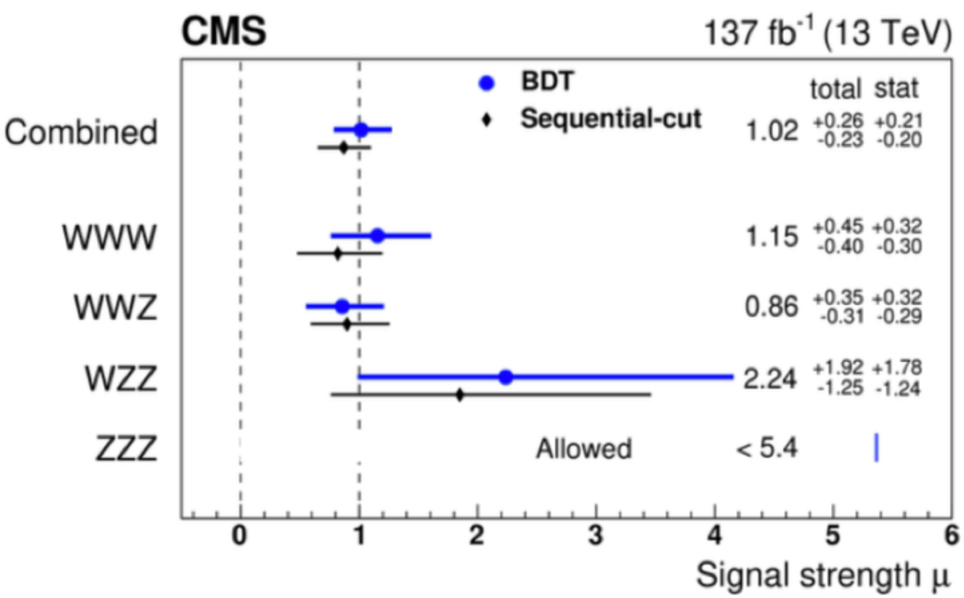
https://cerncourier.com

Triboson production

- Anomalous HVV, TGC or QGC couplings would break the delicate cancellation in the SM and produce divergent cross section at high energy



Process	VH as signal	
	cut-based	BDT-based
WWW	2.54 (2.94)	3.33 (3.09)
WWZ	3.53 (3.62)	3.35 (4.09)
WZZ	1.55 (0.70)	1.71 (0.69)
ZZZ	0.00 (0.90)	0.00 (0.89)
combined	5.02 (5.37)	5.67 (5.88)



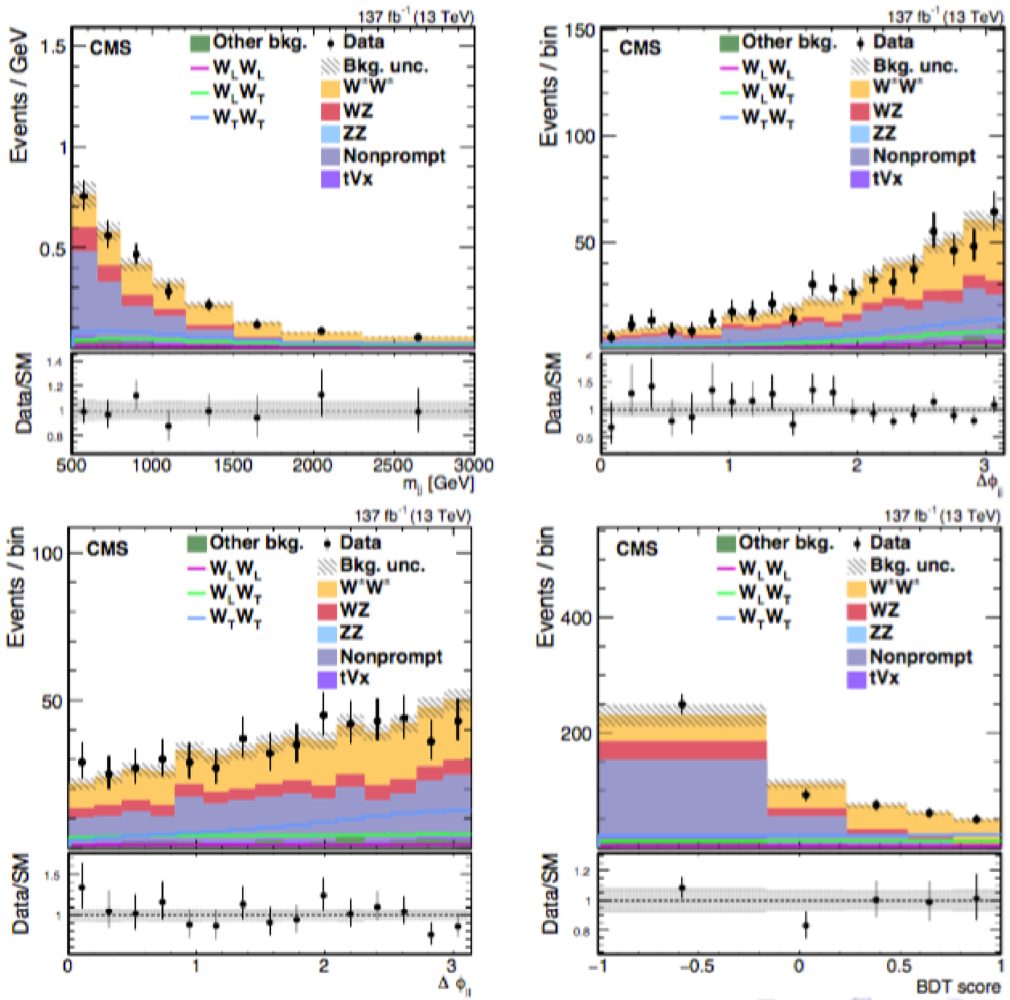
Process	Cross section (fb)
Treating Higgs boson contributions as signal	
VVV	$1010^{+210}_{-200}\,^{+150}_{-120}$
WWW	$590^{+160}_{-150}\,^{+160}_{-130}$
WWZ	$300^{+120}_{-100}\,^{+50}_{-40}$
WZZ	$200^{+160}_{-110}\,^{+70}_{-20}$
ZZZ	<200
Treating Higgs boson contributions as background	
VVV	$370^{+140}_{-130}\,^{+80}_{-60}$
WWW	$190^{+110}_{-100}\,^{+80}_{-70}$
WWZ	$100\,^{+80}_{-70}\,^{+30}_{-30}$
[illegible]	$110^{+100}_{-70}\,^{+30}_{-10}$
[illegible]	<80

PRL 125, 151802 (2020), PhD J. Rembser

First polarized measurement in $W^{\pm}W^{\pm}$ final sate

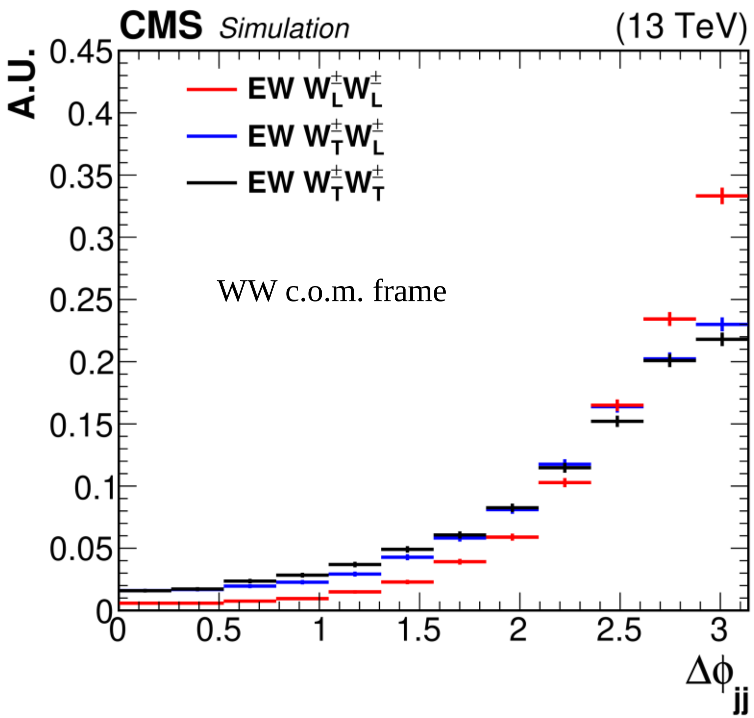
PLB 812 (2020) 136018

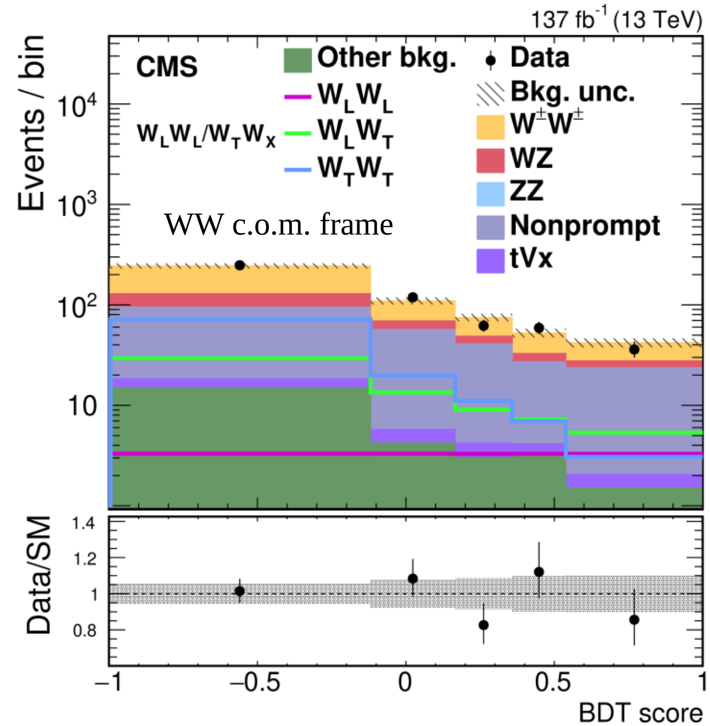
- ❑ Longitudinal scattering contributes to ~10% of total EW production
- ❑ Multivariate technique to enhance signal extraction
- ❑ inclusive BDT to separate VBS from other processes
  - ◻ then LL against LT+TT
  - ◻ and LL+LT against TT
- ❑ Non-prompt background estimation from data
- ❑ Simultaneous fit of WW and WZ signal regions plus control regions



Input variables to the inclusive BDT and BDT output

First polarized measurement in $W^\pm W^\pm$ final sate





WW c.o.m. frame

Observed (expected) limit of 1.17 (0.88) fb for $W^\pm_L W^\pm_L$

Observed (expected) significance of 2.3 (3.1) σ for $W^\pm_L W^\pm_X$

aGCs and EFT

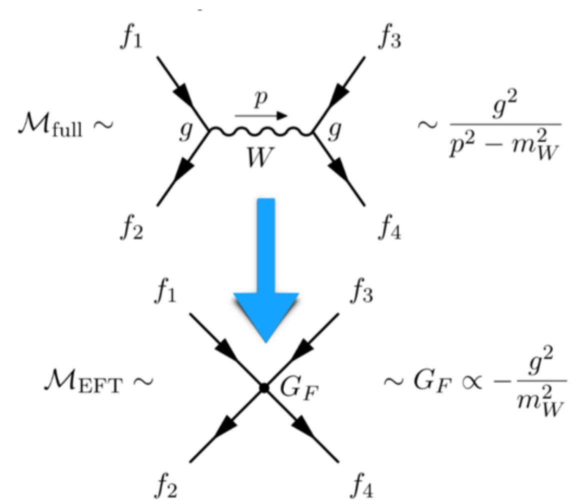
- New physics at high energy can be parameterized in the EFT framework

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} + \frac{c_i}{\Lambda^4} O_i^{(8)} + \ldots$$

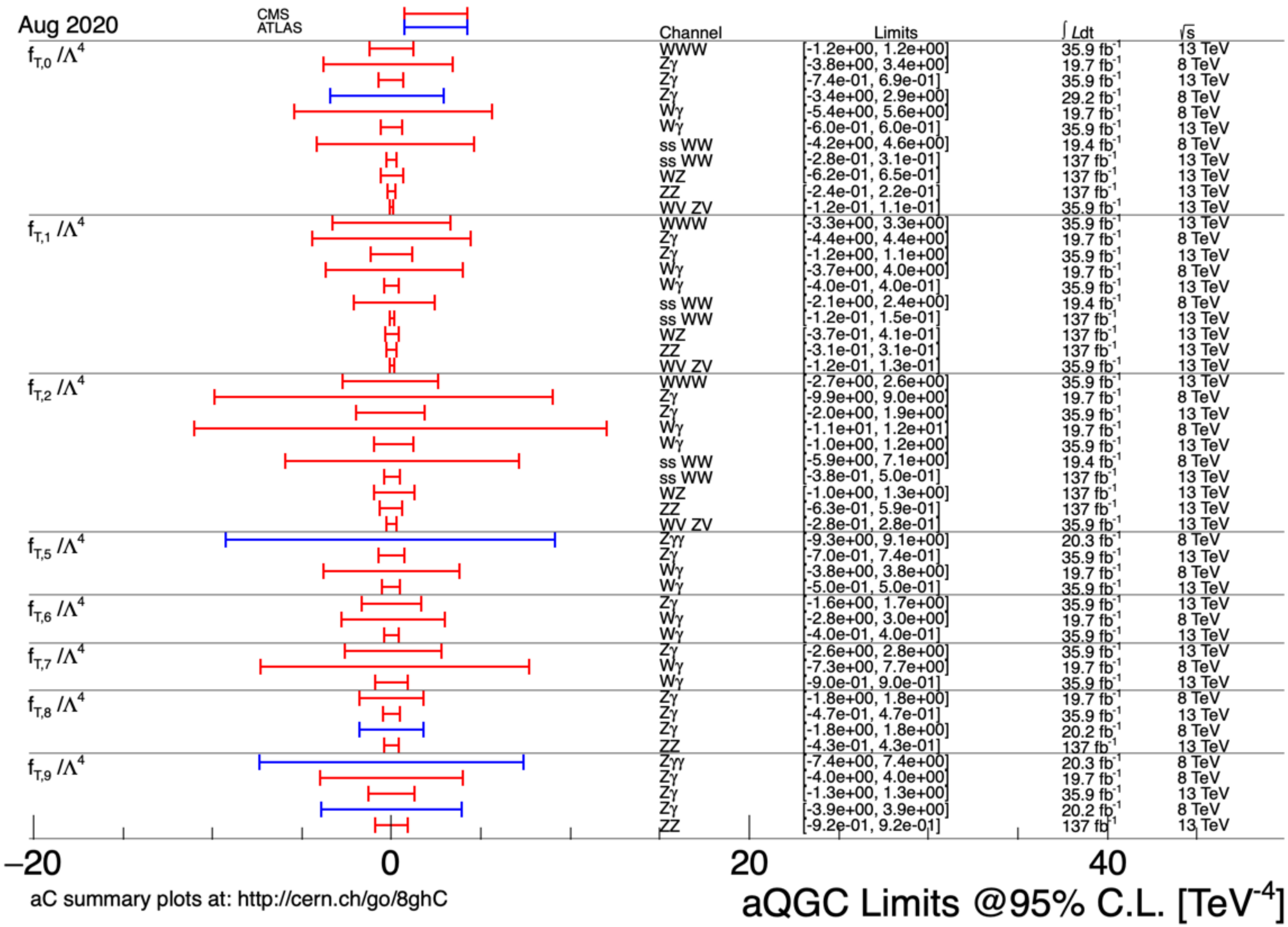
C_i = Wilson coefficients

where Λ is the (unknown) scale of new physics

- Analog to to Fermi theory of weak interaction before higher energy allows to resolve the W propagator
- Built upon SM fields and symmetries (neglecting B/L violating dim-odd operators, linear realization of EWSB)
- Useful tool to consistently interpret measurements/constraints on NP/anomalous couplings
  - with above limitations



aQGC limits



☞ Results shown here for the tensor operators

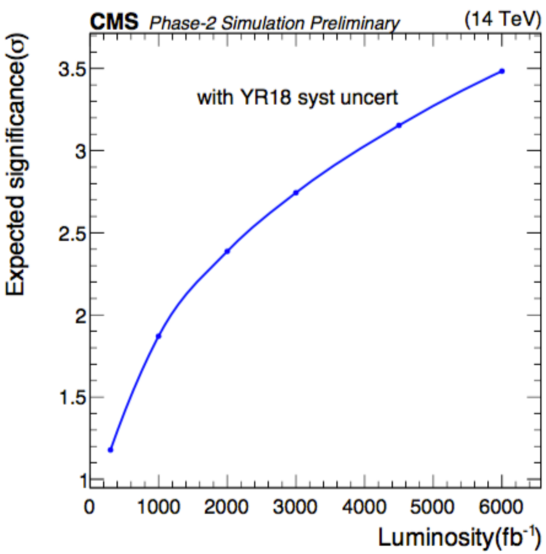
☞ Competitive or complementary results among final states, most stringent limits from semi-leptonic final states

Prospects for HL-LHC

CERN-LPCC-2018-03

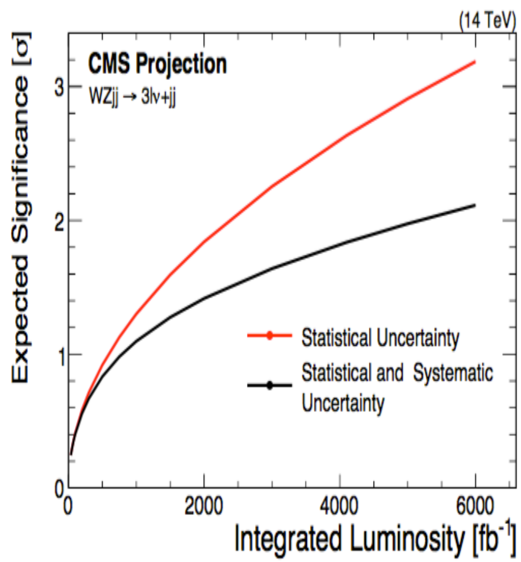
- Many projections in the context of the yellow report for HL-LHC (2018)
  - Various levels of analyses: Delphes simulation with 200PU, simulations on top of run 2 results, simple projection of run 2 results
- While the cross section for inclusive VBS in the different channels will be measured with a precision of o(5%), $V_L V_L$ will remain statistically limited

$pp \rightarrow W^{\pm}_L W^{\pm}_L jj \rightarrow l\nu l\nu jj$



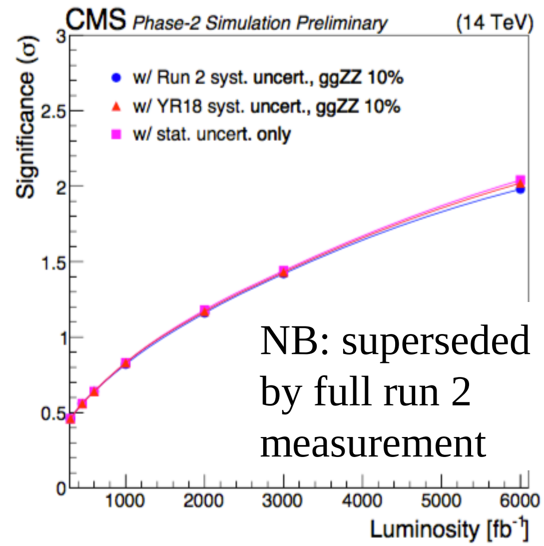
$2.7\sigma@3ab^{-1}$

$pp \rightarrow W^{\pm}_L Z_L jj \rightarrow 3l\nu jj$



$1.6\sigma@3ab^{-1}$

$pp \rightarrow Z_L Z_L jj \rightarrow 4ljj$



NB: superseded by full run 2 measurement

$1.4\sigma@3ab^{-1}$

Prospects for HL-LHC

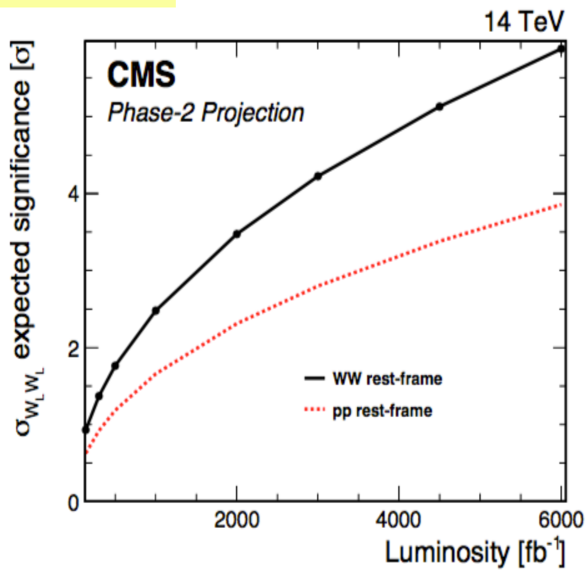
- New projection for $W^{\pm}_L W^{\pm}_L$ CMS-PAS-FTR-21-001
  - Simple projection of the current analysis: no attempt at fake bkgd nor PU simulation
  - Importance of choice of ref. frame for the definition of the polarization

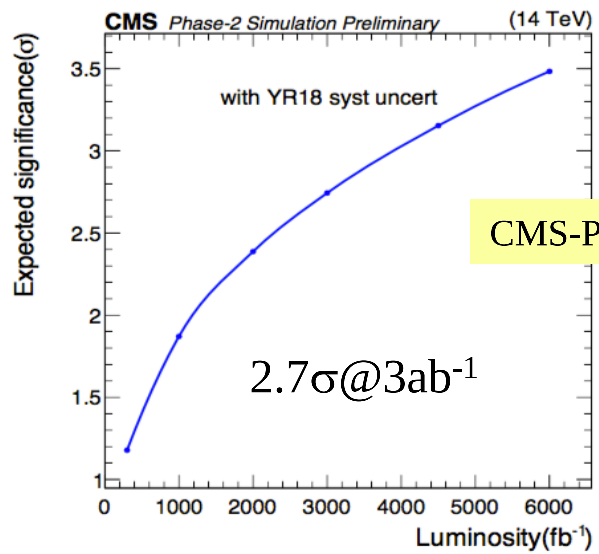
CMS-PAS-FTR-21-001

$pp \rightarrow W^{\pm}_L W^{\pm}_L jj \rightarrow l\nu l\nu jj$

4.2σ@3ab[-1]

2.7σ@3ab[-1]





CMS-PAS-FTR-18-005

2.7σ@3ab[-1]

Similar result if same chosen frame, significantly higher sensitivity for WW frame
Cross sections measured with ~5% precision for inclusive VBS

Prospect for higher energies

$pp \rightarrow W^+W^+jj \rightarrow l^+\nu l^+\nu jj$

CERN-LPCC-2018-03

$\sqrt{s}$	σ^{LO} [fb]	σ^{NLO}_{EW} [fb]	δ_{EW} [%]
14 TeV	1.4282(2)	1.213(5)	−15.1
27 TeV	4.7848(5)	3.881(7)	−18.9
100 TeV	25.485(9)	19.07(6)	−25.2

Factor ~15 increase from 14 to 100 TeV!

CMS-PAS-FTR-18-014

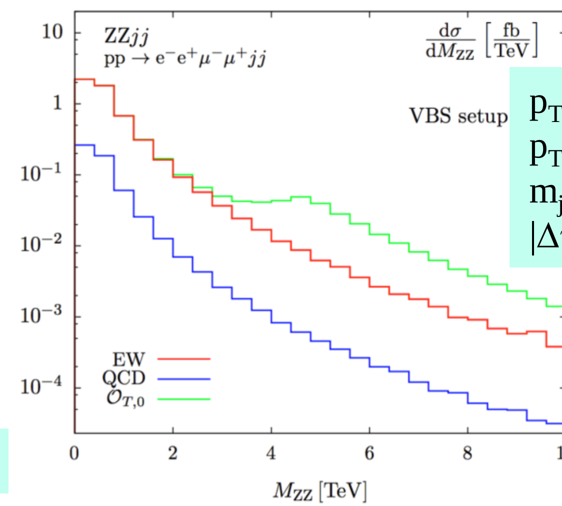
$pp \rightarrow Z_L Z_L jj \rightarrow 4ljj$

	significance		VBS $Z_L Z_L$ fraction uncertainty (%)	
	w/ syst. uncert.	w/o syst. uncert.	w/ syst. uncert.	w/o syst. uncert.)
HL-LHC	1.4σ	1.4σ	75%	75%
HE-LHC	5.2σ	5.7σ	20%	19%

Simple scaling of cross section but preliminary results indicate that the change in kinematical distributions from 14 TeV->27 TeV does not affect much the result

FCC-hh @30ab-1 with VBS cuts (m_{jj} and $|\Delta\eta_{jj}|$)

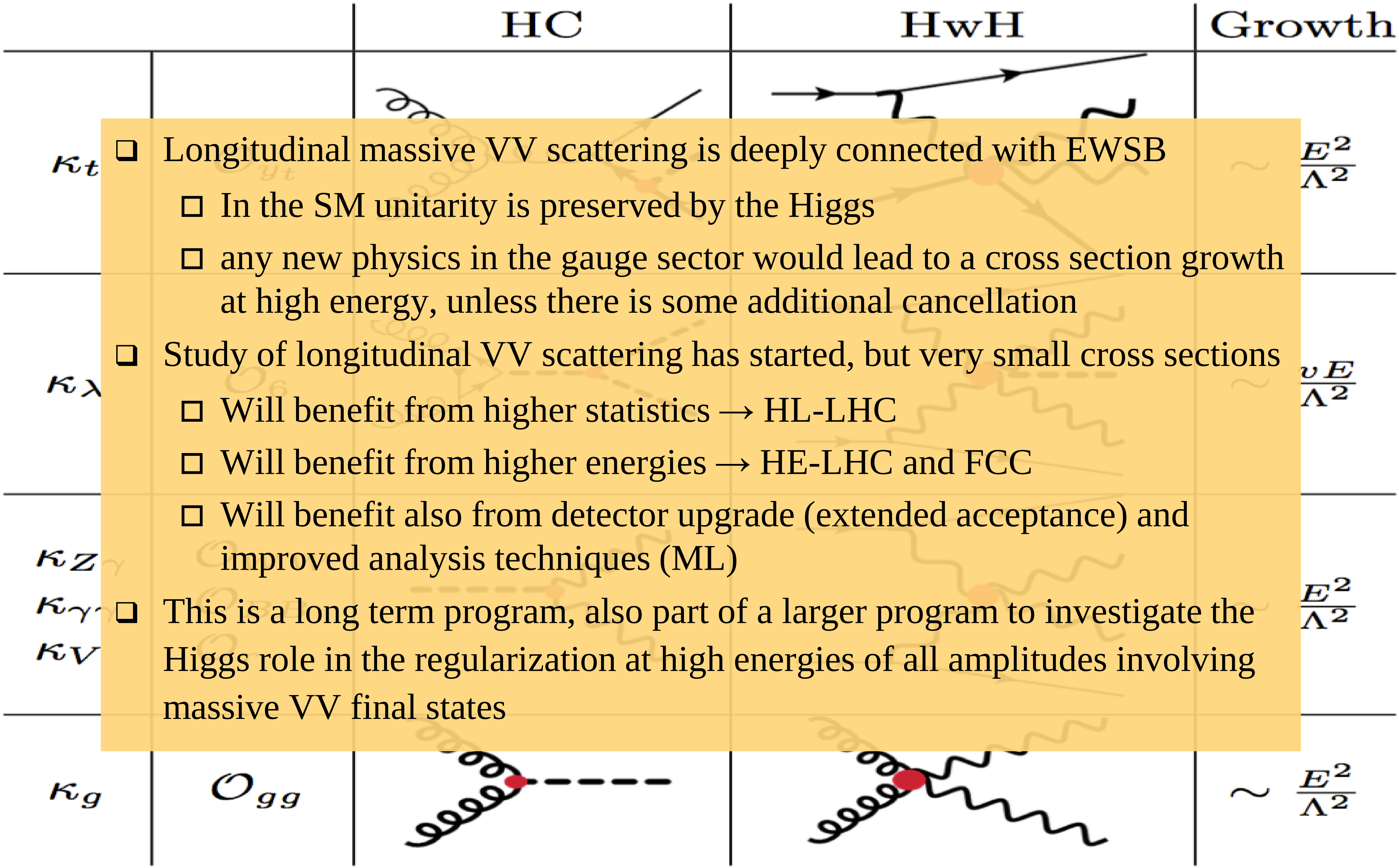
VBS channel	σ_S [fb]	σ_B [fb]	S/B	$S/\sqrt{B}$	$S/\sqrt{S+B}$
W^+W^+jj	0.48	0.04	12	416	115
W^+Zjj	0.047	0.008	5.9	91	35
$ZZjj$	0.11	0.008	13.7	213	56
W^+W^-jj	3.59	4.62	0.78	289	217



$p_{T,j}$>50 GeV
$p_{T,l}$>20 GeV
m_{jj}>2TeV
$|\Delta\eta_{jj}|$>3

~500 events $Z_L Z_L jj$ @ 30ab^{-1}, m_{4l}>2 TeV

The take away messages



- Longitudinal massive VV scattering is deeply connected with EWSB
  - In the SM unitarity is preserved by the Higgs
  - any new physics in the gauge sector would lead to a cross section growth at high energy, unless there is some additional cancellation
- Study of longitudinal VV scattering has started, but very small cross sections
  - Will benefit from higher statistics → HL-LHC
  - Will benefit from higher energies → HE-LHC and FCC
  - Will benefit also from detector upgrade (extended acceptance) and improved analysis techniques (ML)
- This is a long term program, also part of a larger program to investigate the Higgs role in the regularization at high energies of all amplitudes involving massive VV final states