Lecture #1

# Top, ElectroWeak and QCD at the LHC

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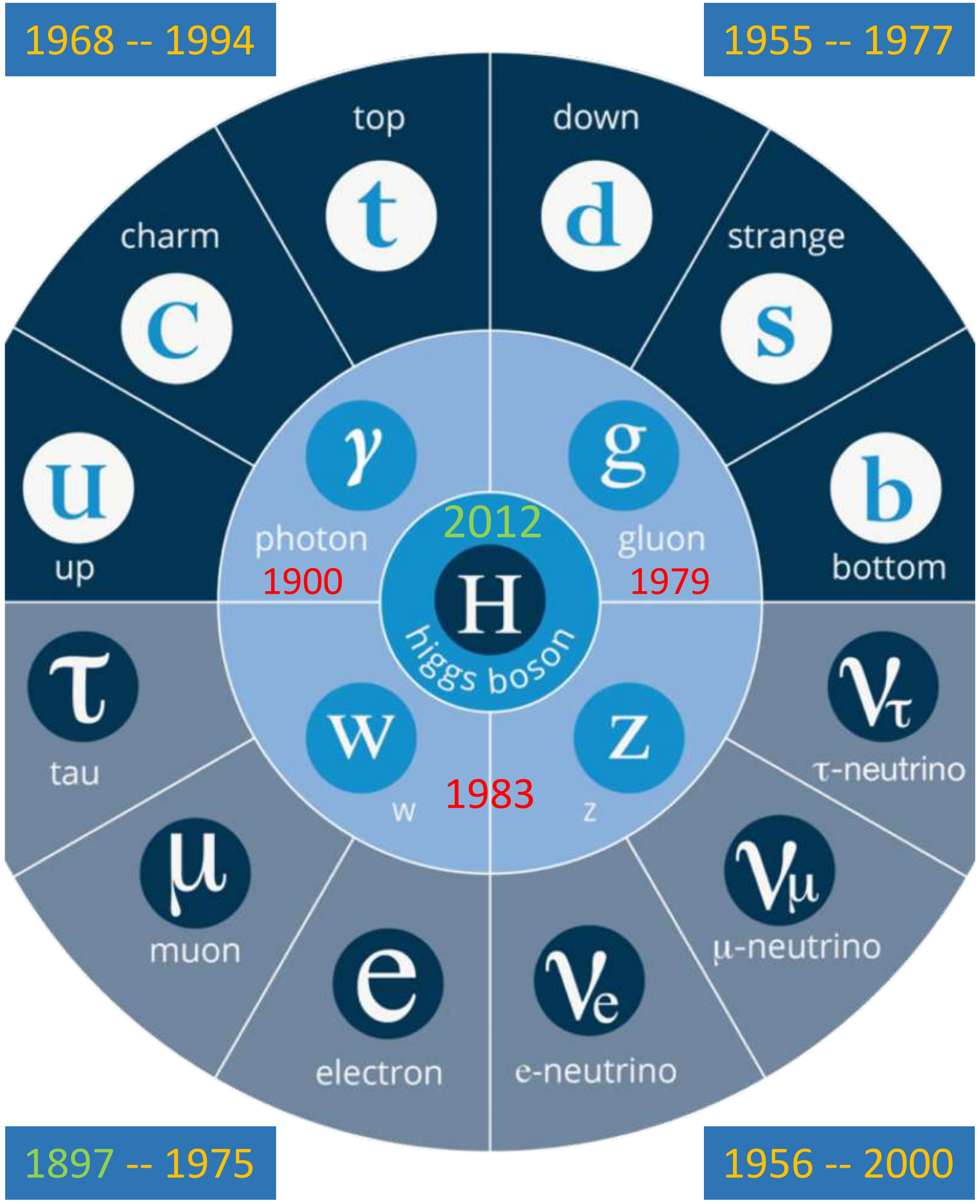



# 50 year anniversary of the Standard Model [1]

➔Today: focus on Electroweak Interactions: $\gamma^*$, $W^{\pm}$, $Z^0$

➔Tomorrow: on top-quark

Strong interactions: g will be included in both lectures

*Higgs Boson covered by Williams*



[1] S. Weinberg, A Model of Leptons, Phys. Rev. Lett. 19, 1264 (1967)

# Formal Description of elementary particles and forces given by the Standard Model of Particle physics

**Standard Model**: Nature described by the Symmetry Groups

LHC able to give us precision measurements of the relevant parameters

**SU(3) x SU(2) x U(1)**

*Colour*

Strong interactions

*Weak Isospin*

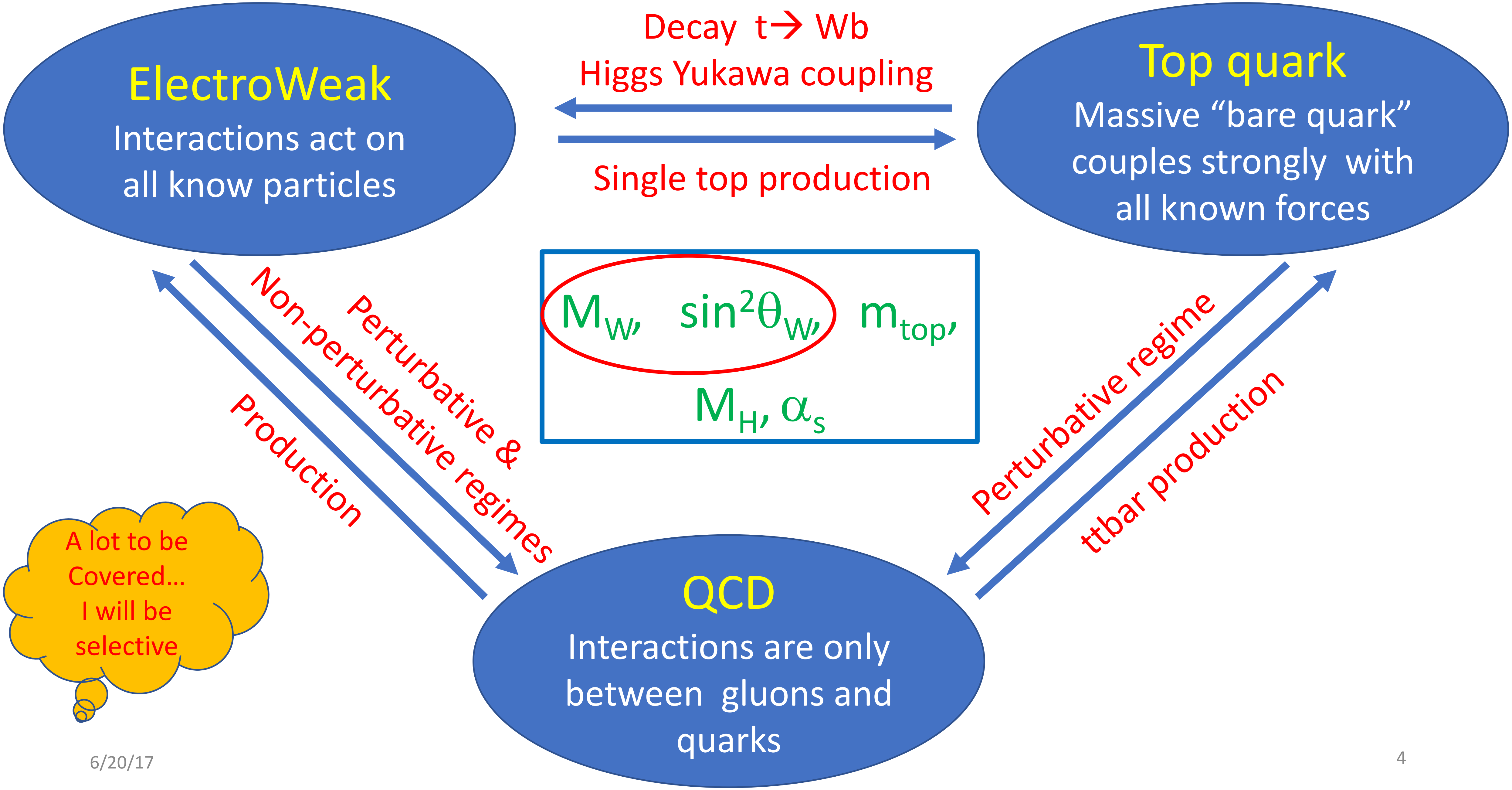
*Weak Hypercharge*

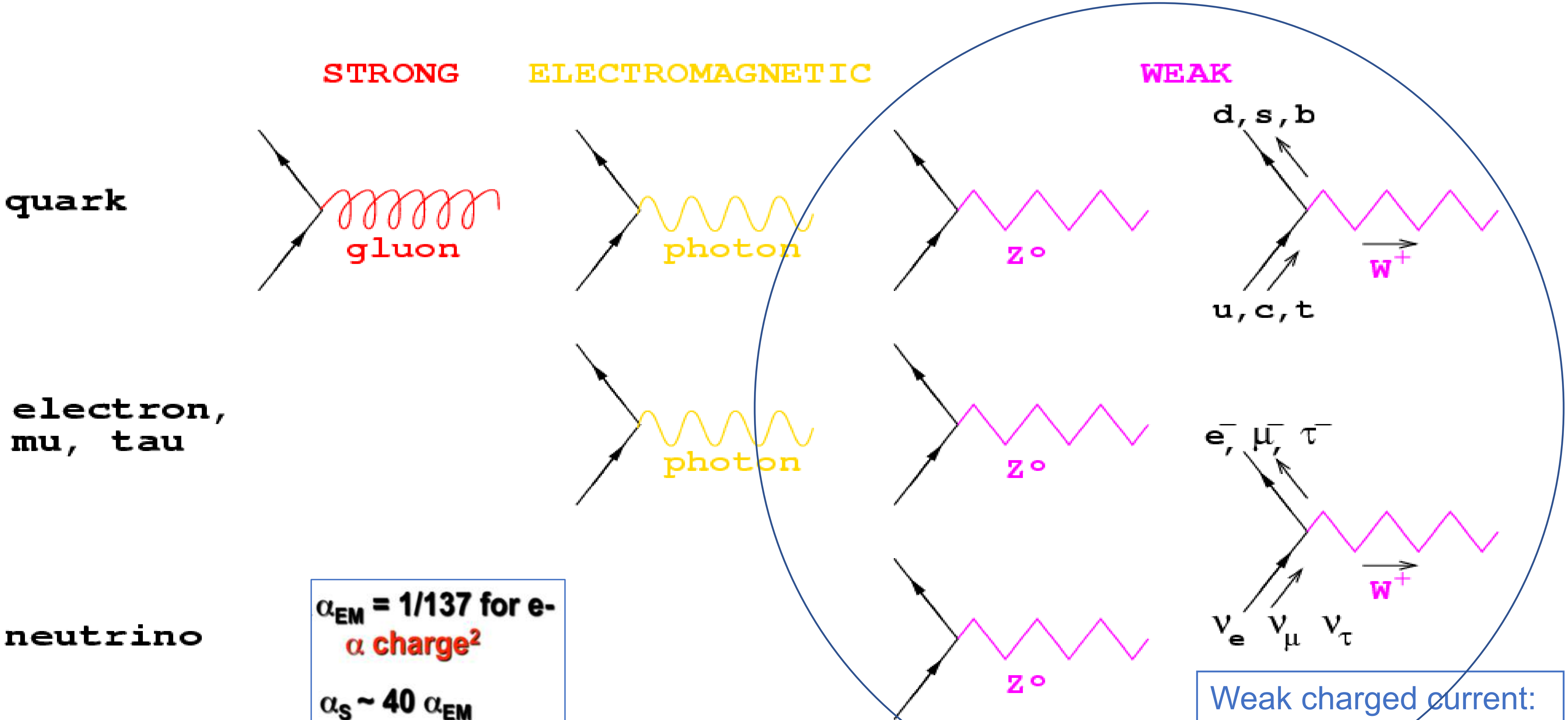
Electroweak interactions

3 symmetry groups

$\Rightarrow$ Interactions described by (only!) 3 coupling constants: $g_s$, $g$, $g'$

$\Rightarrow$ Universal fermion-boson couplings


ElectroWeak
Interactions act on all know particles
Decay t→ Wb
Higgs Yukawa coupling
Single top production
Top quark
Massive “bare quark” couples strongly with all known forces
$M_W$, $\sin^2\theta_W$, $m_{top}$,
$M_H$, $\alpha_s$
Production
Non-perturbative regimes
Perturbative &
Perturbative regime
ttbar production
QCD
Interactions are only between gluons and quarks
A lot to be Covered… I will be selective




$\alpha_{EM}$ = 1/137 for e-
$\alpha$ charge²

$\alpha_S \sim 40\ \alpha_{EM}$

$\alpha_W \sim 0.58\ \alpha_{EM}$

$\alpha_Z\ \alpha\ \alpha_W\ M_Z/M_W$

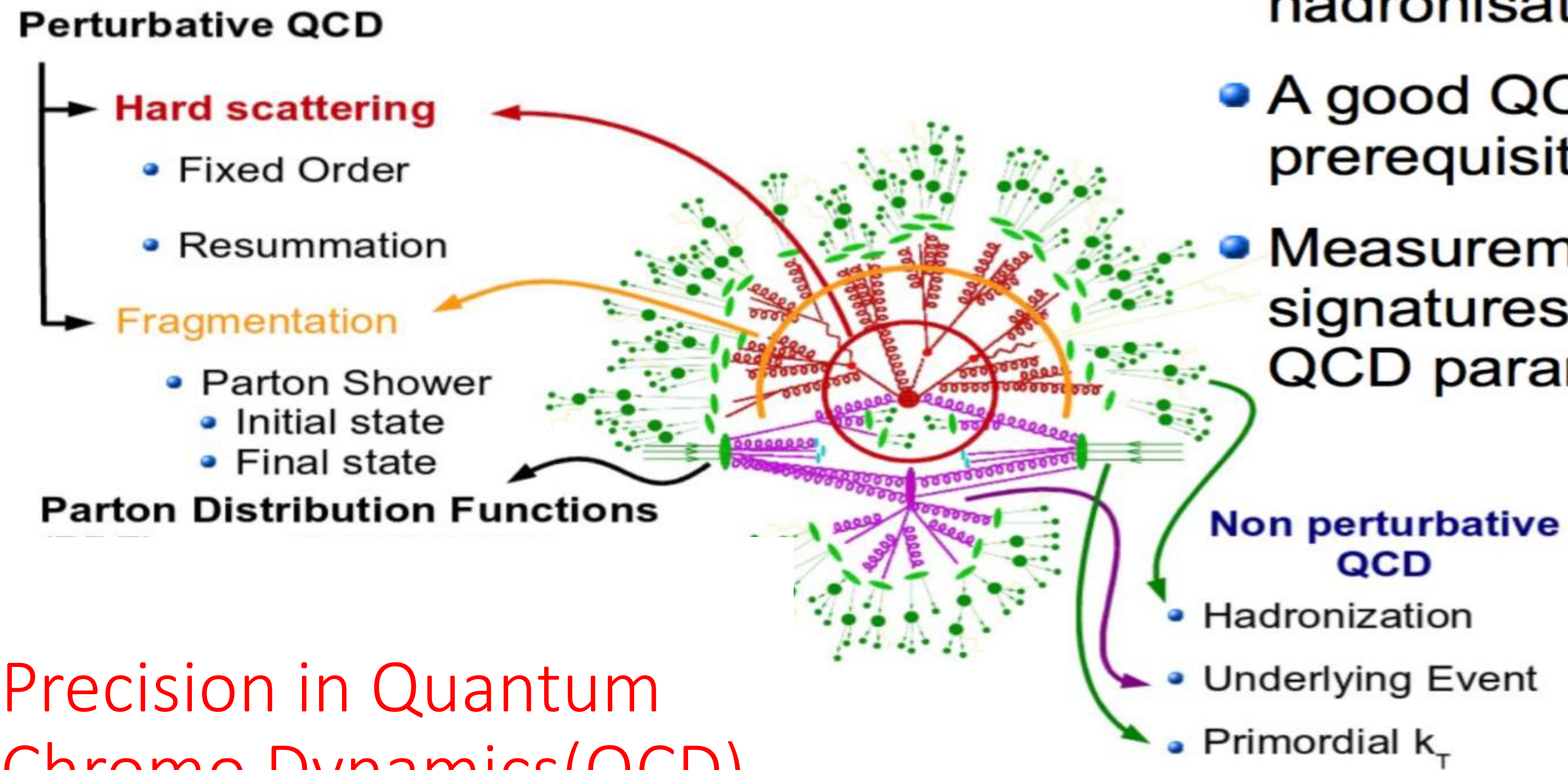
Weak neutral current:
All particles
No change of flavour

Weak charged current:
All particles
Flavour changes

# Precision in Quantum Chromo Dynamics(QCD)

Collinear factorization

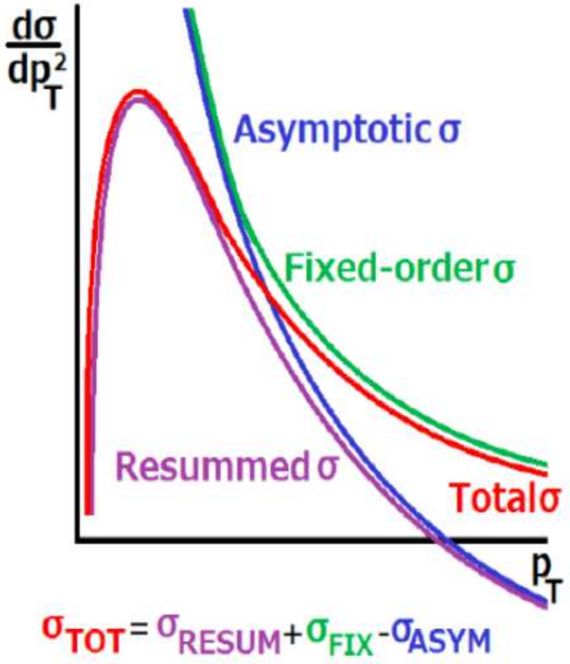
$$\sigma_{pp\to X} = \Sigma_{i,j} \int dx_1 dx_2 f_i^p(x_1,\mu) f_j^p(x_2,\mu) \times \sigma_{ij\to X}$$

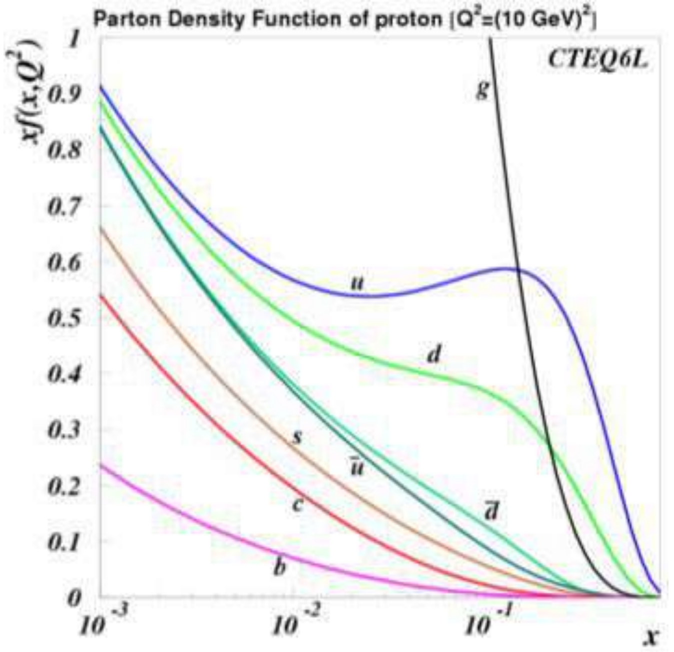



- EW physics at hadron colliders cannot forget about QCD: almost every EW observable is influenced by PDF, Underlying event, hadronisation
- A good QCD model is a prerequisite for EW physics
- Measurements of clean EW signatures help to constrain QCD parameters and models

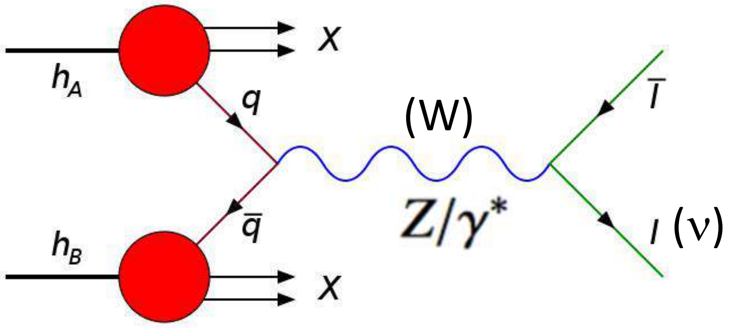
# *Example, Drell-Yan Process: pp→ Z or W*

→ Predictions needed as input
→ Serious test of QCD with EWK processes




Main uncertainty in important EWK precision measurements



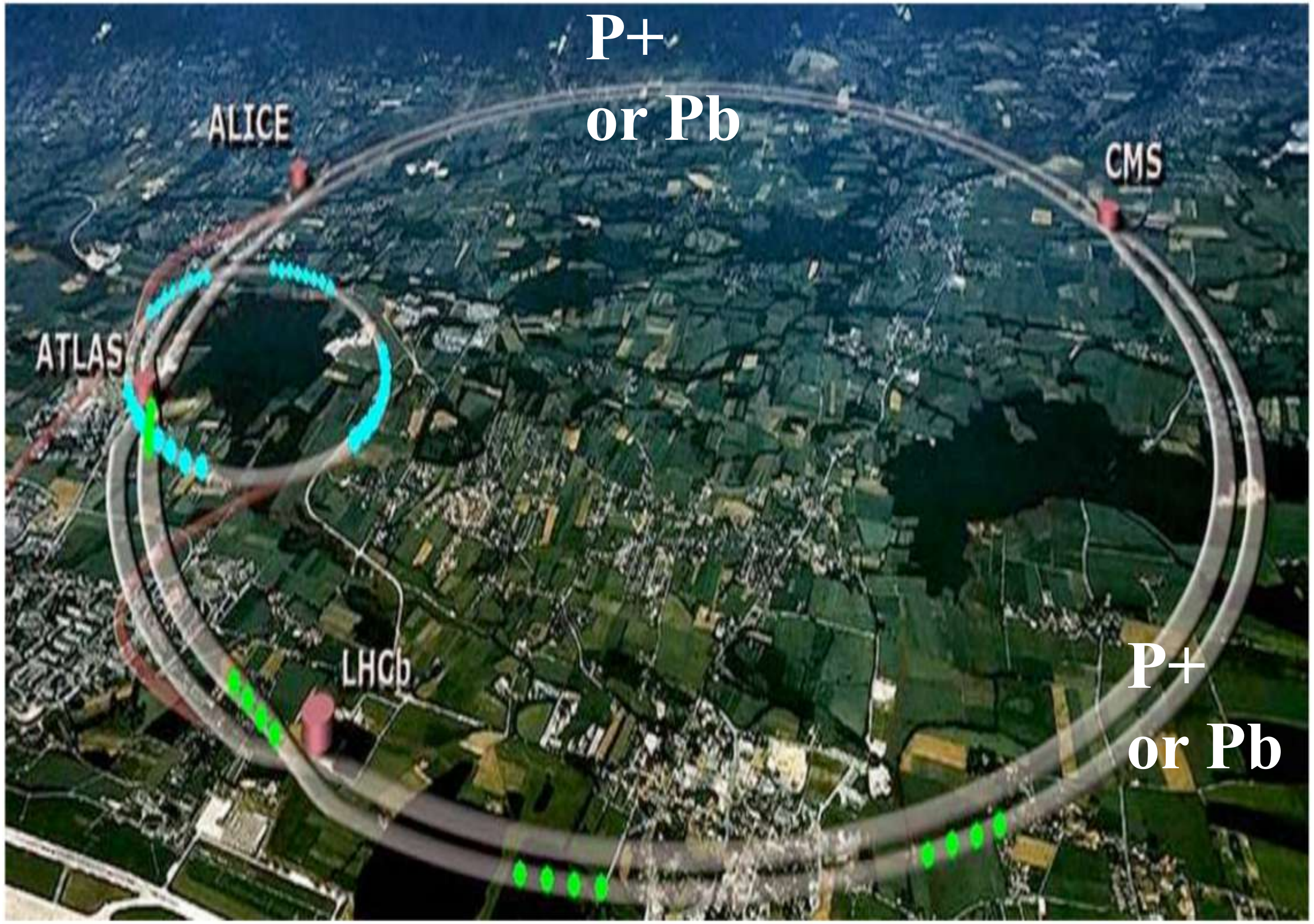

**High $p_T$:** described at fixed-order of $\alpha_s$ by perturbative QCD predictions

**Small $p_T$:** described using resummation of multiple soft-gluon emissions. Non-perturbative part that has to be parametrised and extracted from the data.

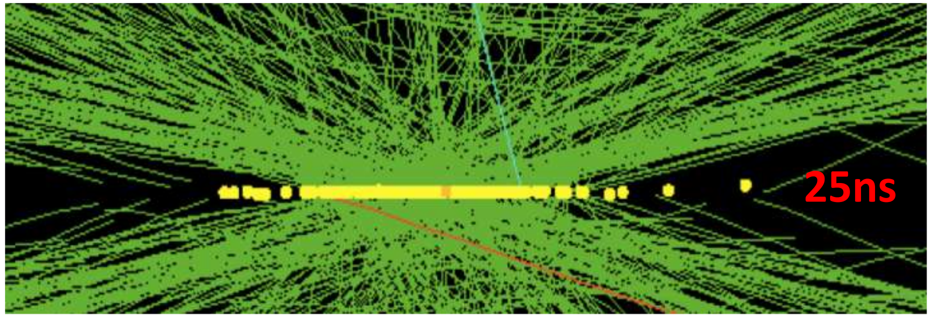
➔ This is of great importance when calculating the W-mass

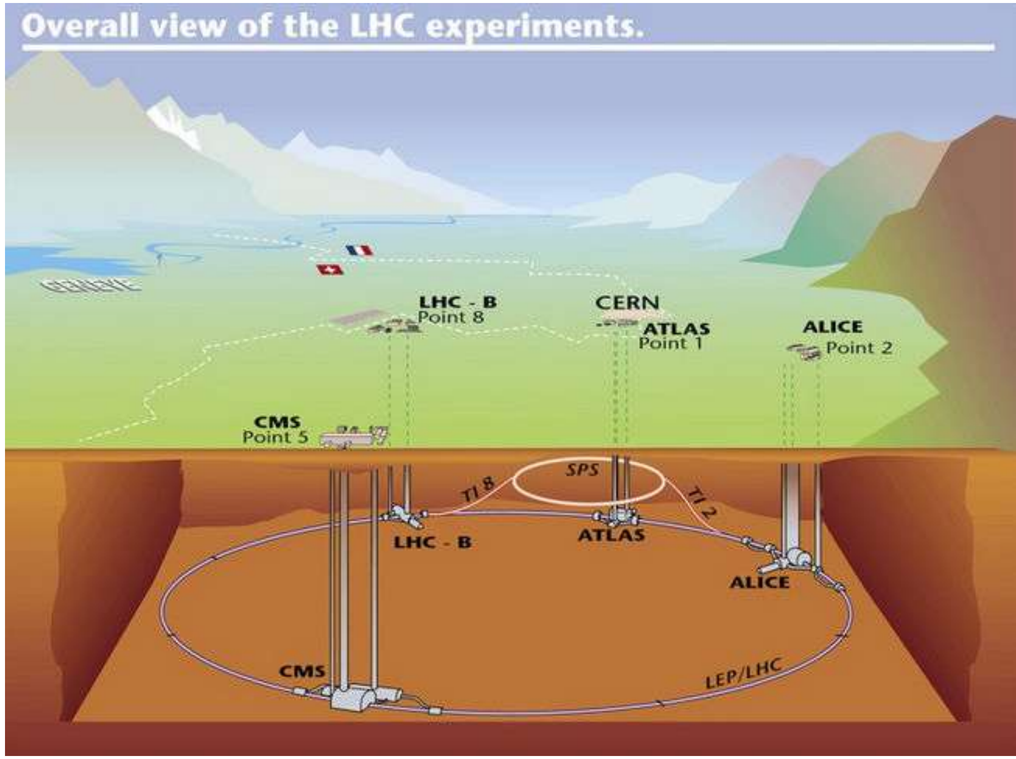
# Large Hadron Collider @ CERN

- **Energy Frontier**
- **20 Year program to accumulate > 3000 fb$^{-1}$**



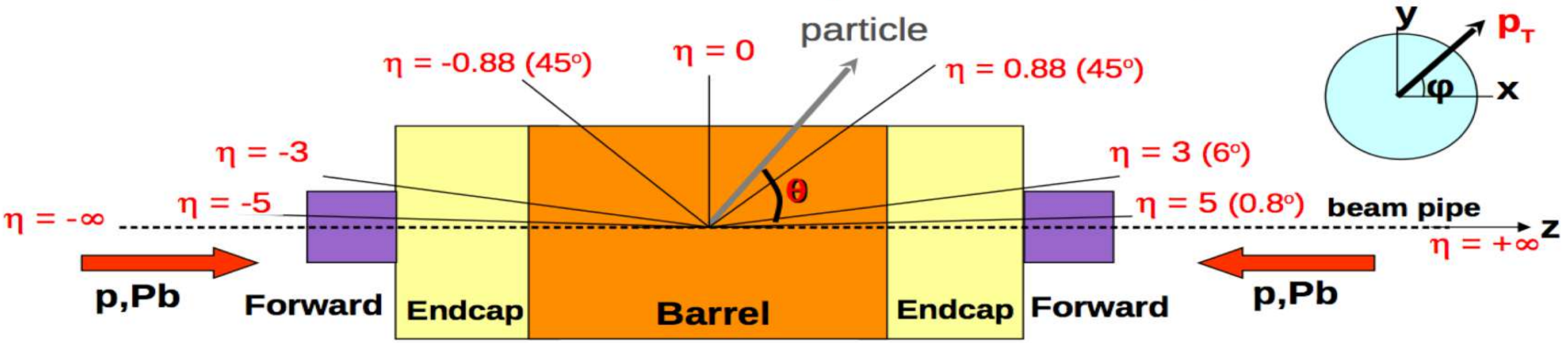

**High Luminosity achieved with beams with**
**>$10^{11}$ protons/bunch &**
**> 2800 bunches**
**in the ring**



# LHC collisions: kinematics

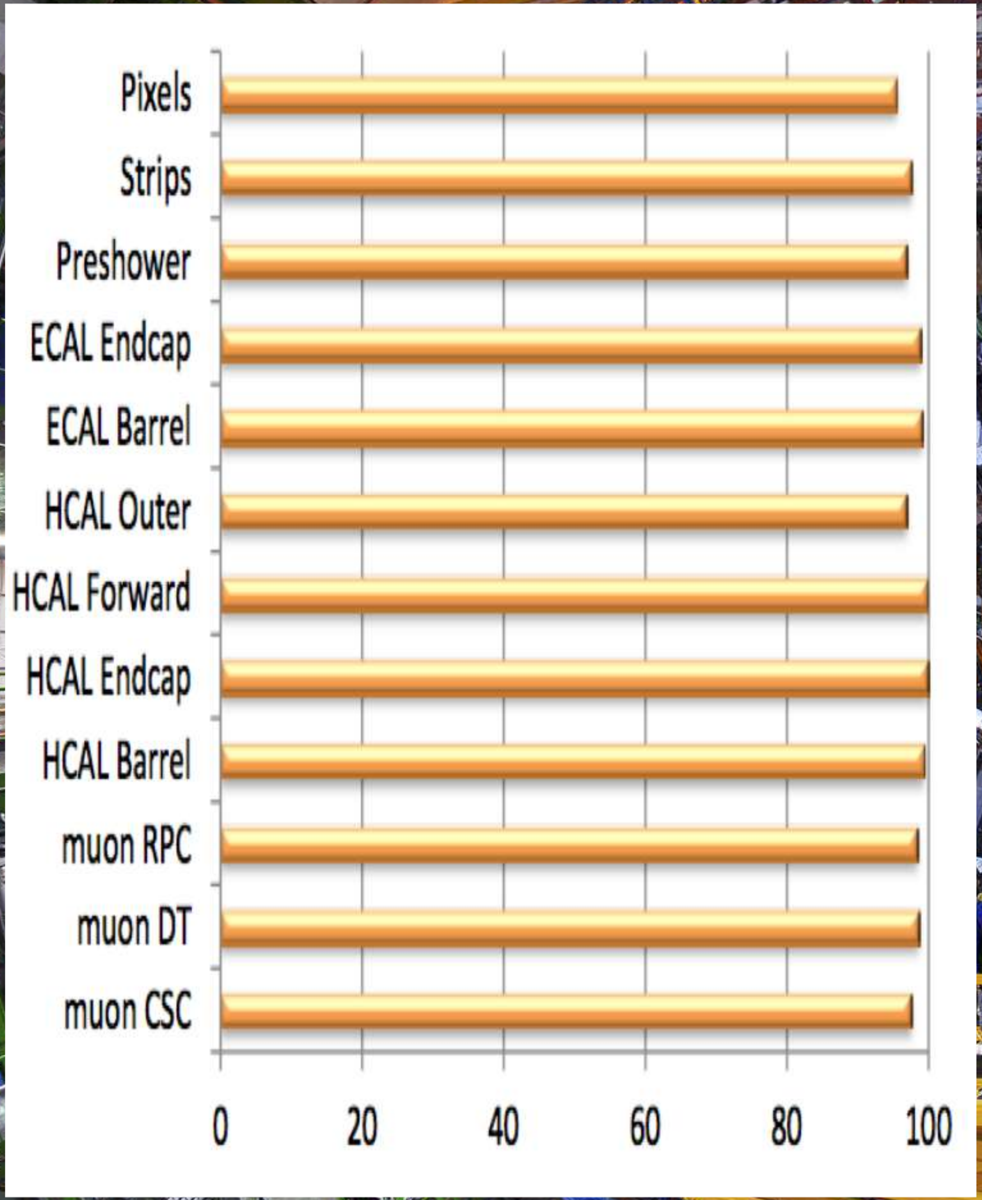
- Hadron = "beam" of partons with initial $p_T$~0 but unknown $p_L$ fractions.
- Hadron-hadron collisions variables: $p_T$ (transverse), y or η (longitudinal).

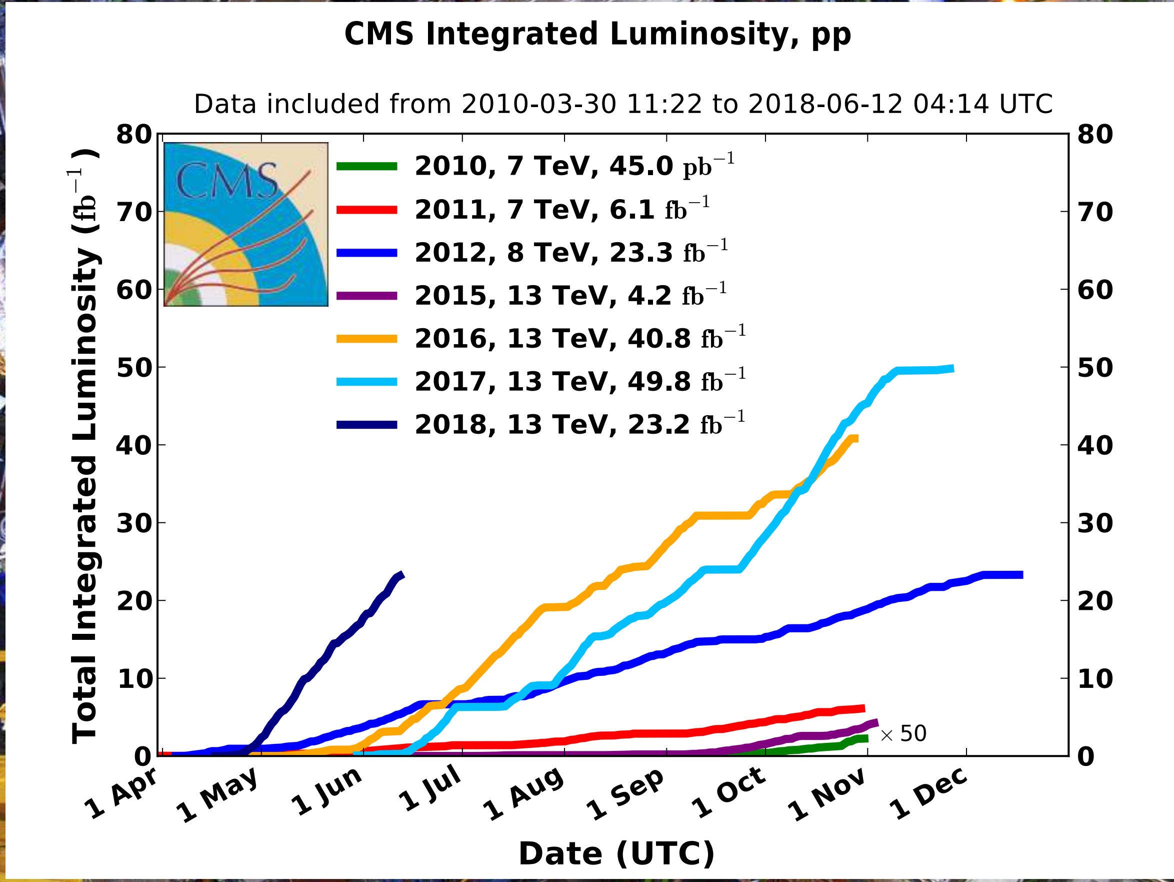


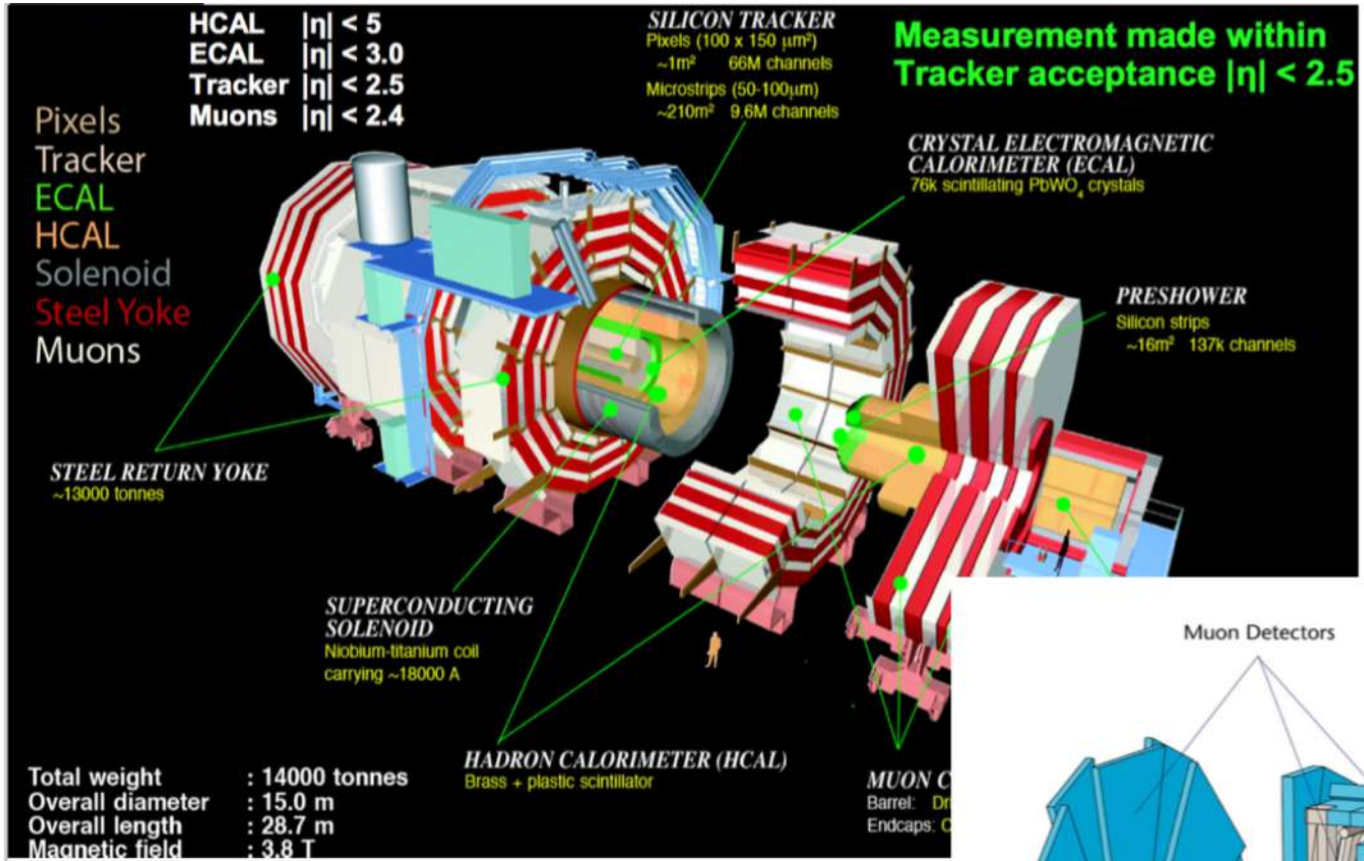

- Transverse momentum: $|\mathbf{p}_T| = p \sin(\theta)$ conserved in hadron-hadron colls.
- Rapidity: $y = -\log \frac{E + p_z}{E - p_z}$ (Differences in rapidity are conserved under Lorentz boosts in the z-direction)

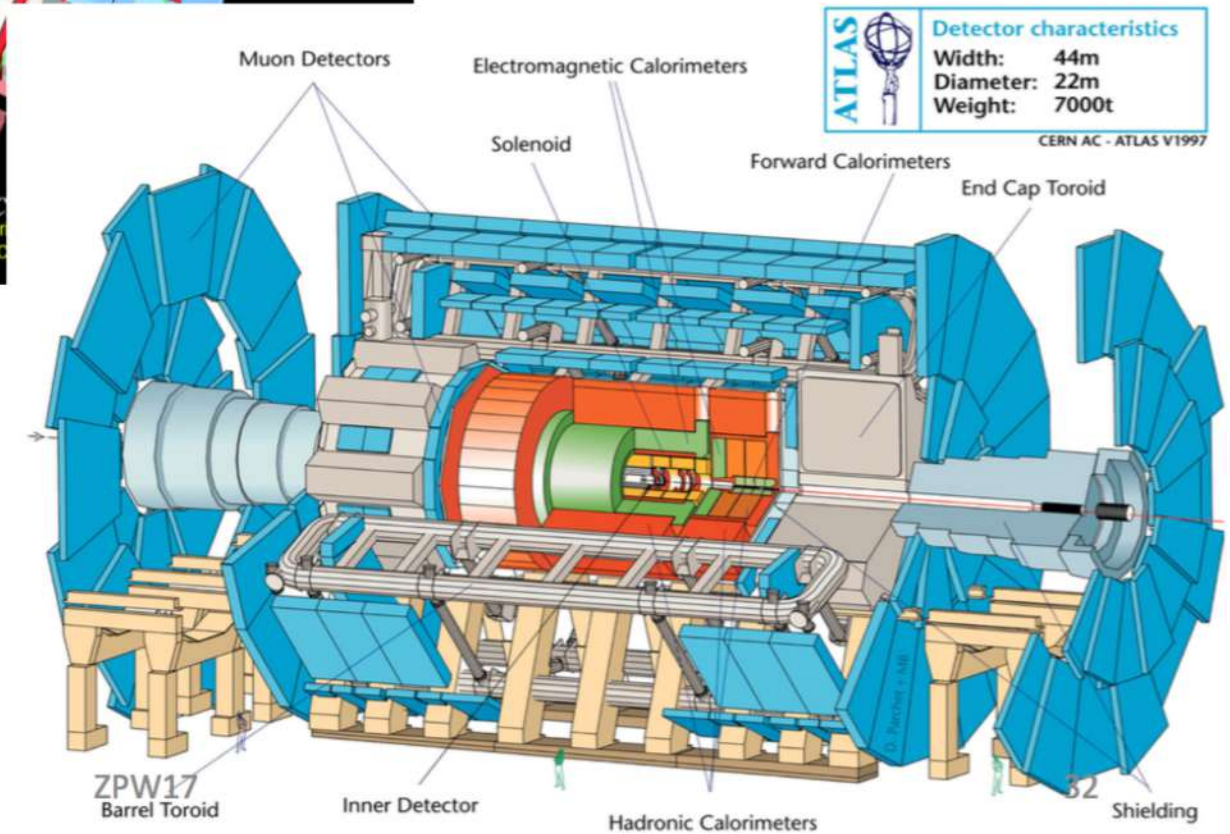
Pseudorapidity: $\eta = -\ln[\tan(\theta/2)]$ (η~y if E≫m, and θ not too small)

# CMS Transverse view

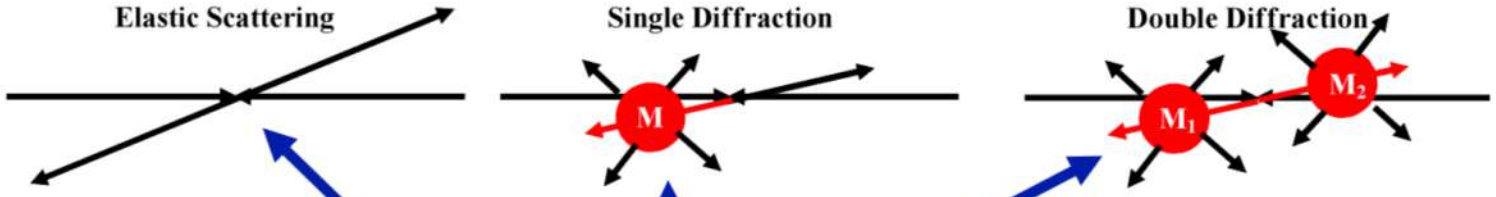


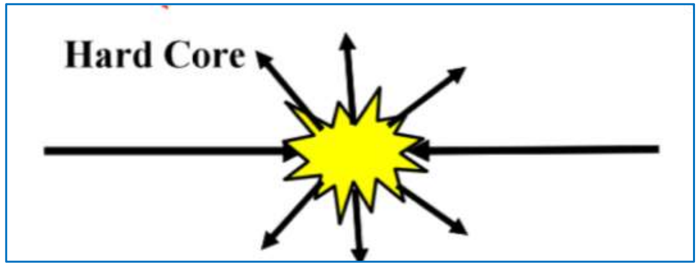

HCAL |η| < 5
ECAL |η| < 3.0
Tracker |η| < 2.5
Muons |η| < 2.4
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
Measurement made within
Tracker acceptance |η| < 2.5
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
CRYSTAL ELECTROMAGNETIC
CALORIMETER (ECAL)
76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² 137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING
SOLENOID
Niobium-titanium coil
carrying ~18000 A
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T


Muon Detectors
Electromagnetic Calorimeters
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

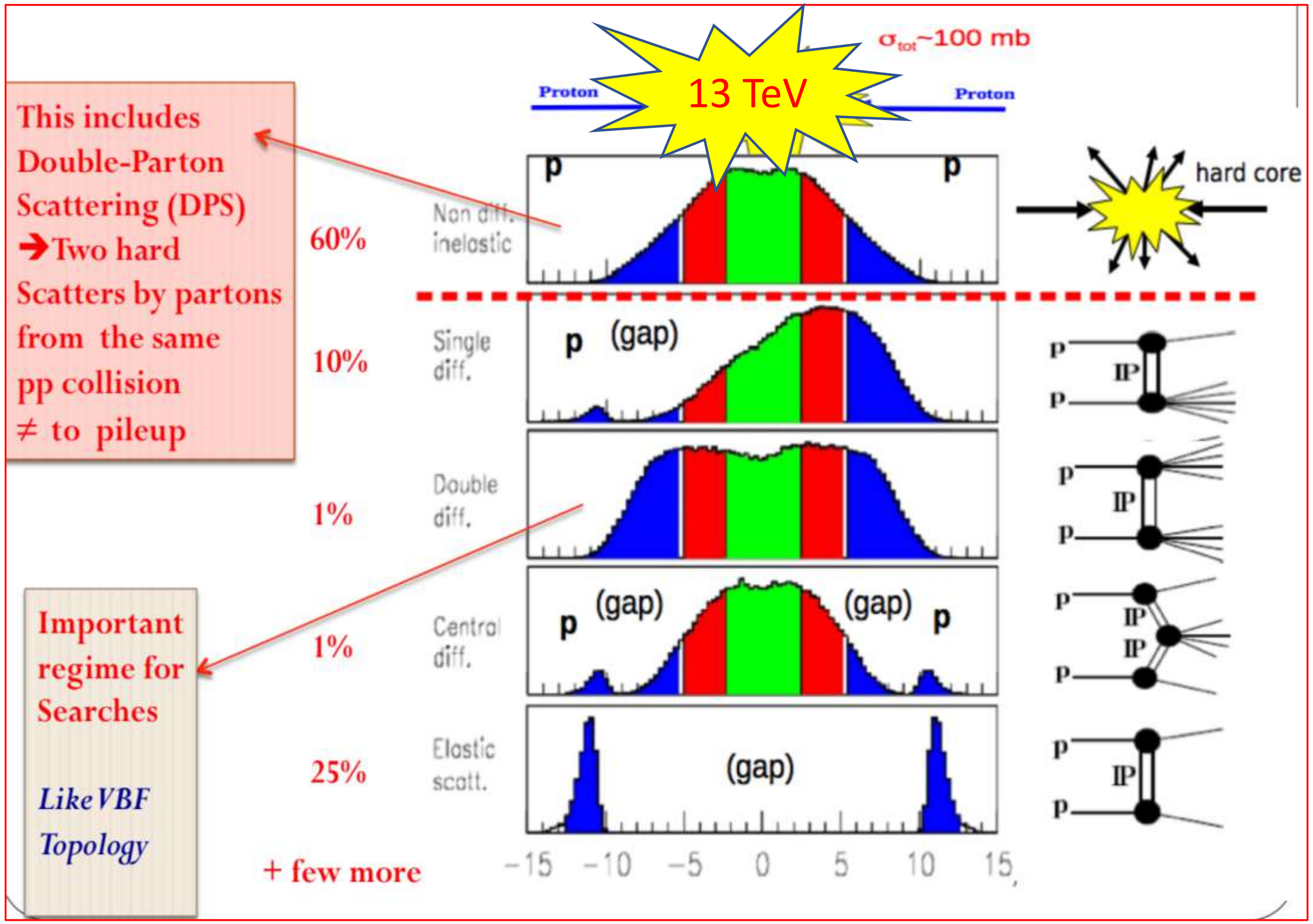
# Proton – Proton Collisions



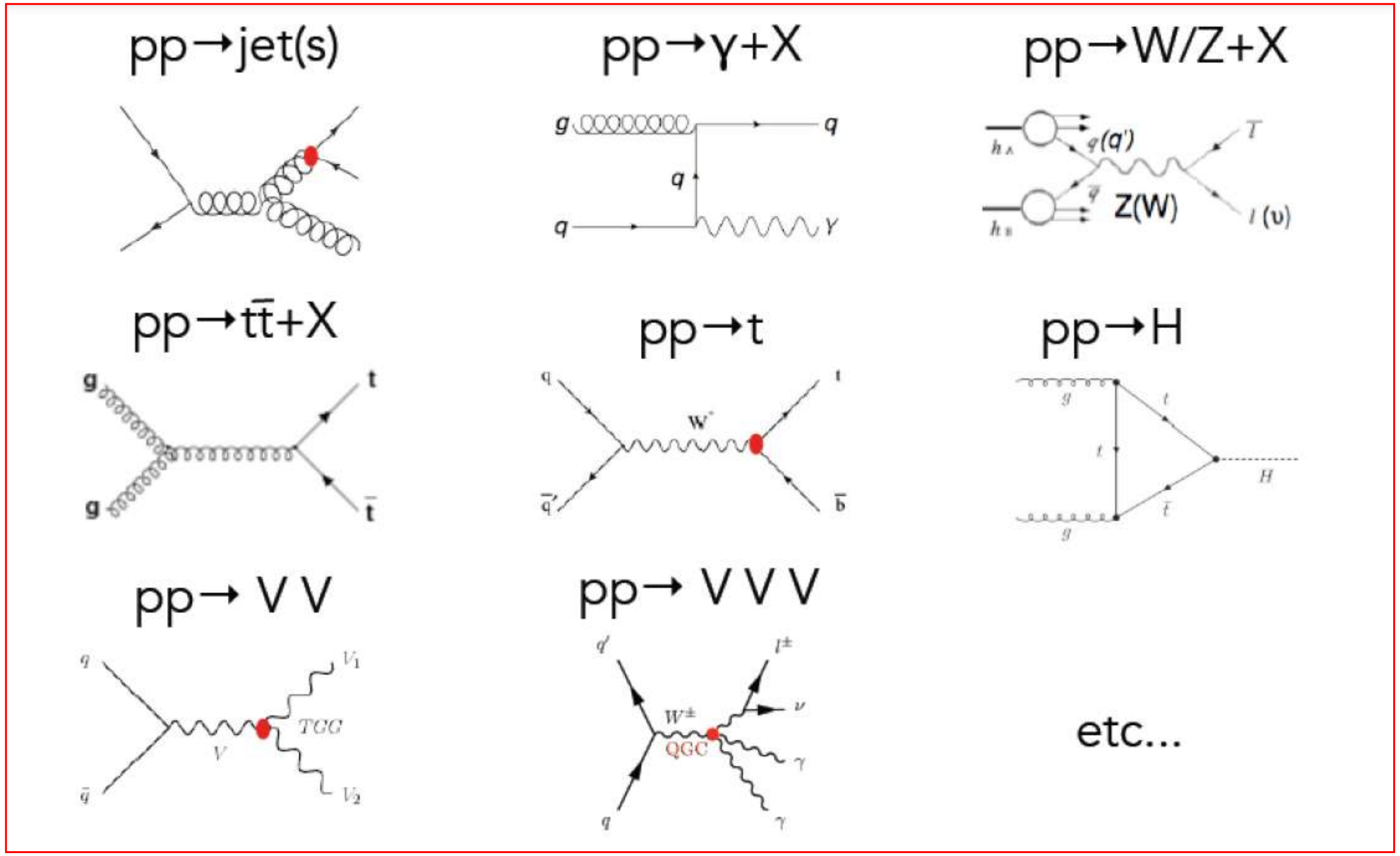

$$\sigma_{tot} = \sigma_{EL} + \sigma_{IN}$$



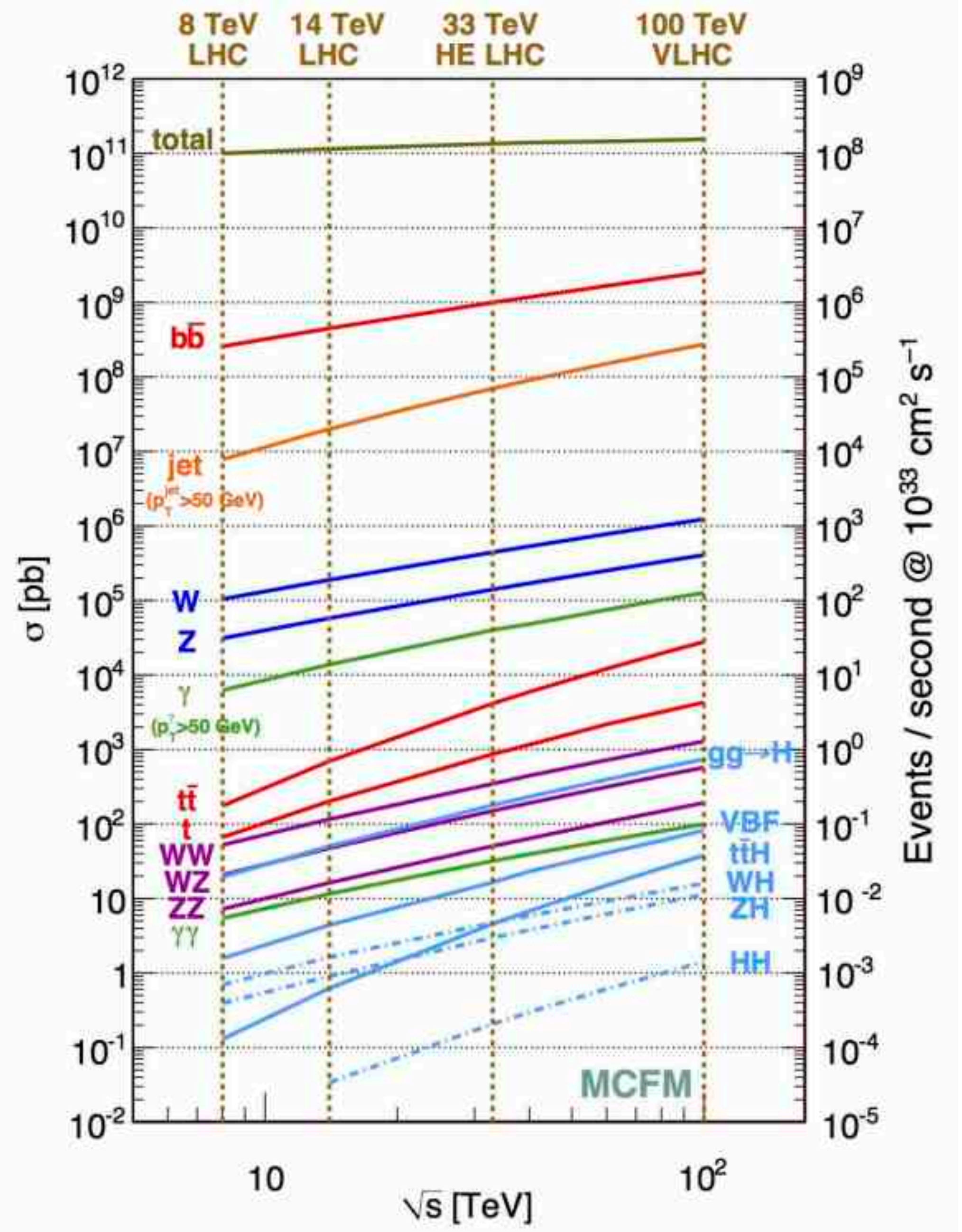

Non Diffractive



# Many Hard Processes

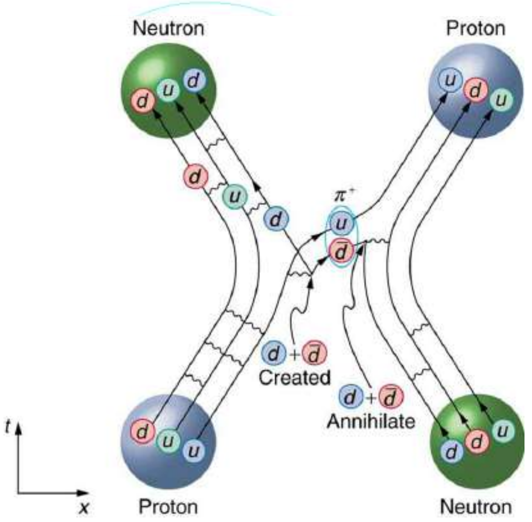


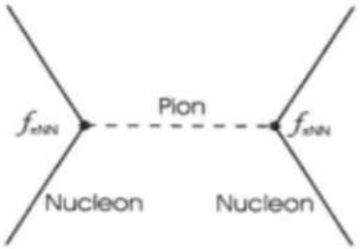

$N = \mathcal{L}\,\sigma$ (acceptance) x (efficiency)



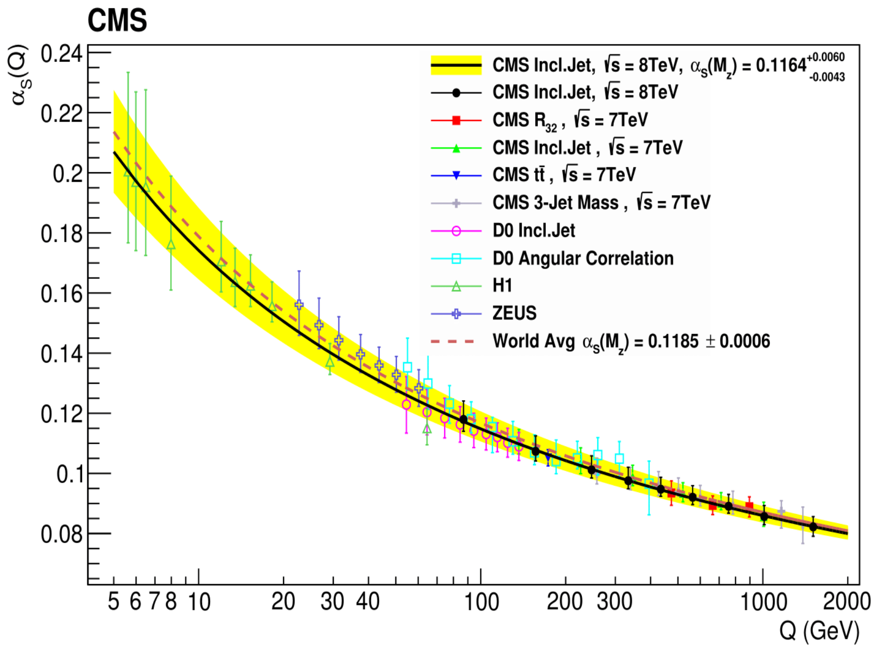
# Low energy NUCLEON-NUCLEON INTERACTIONS

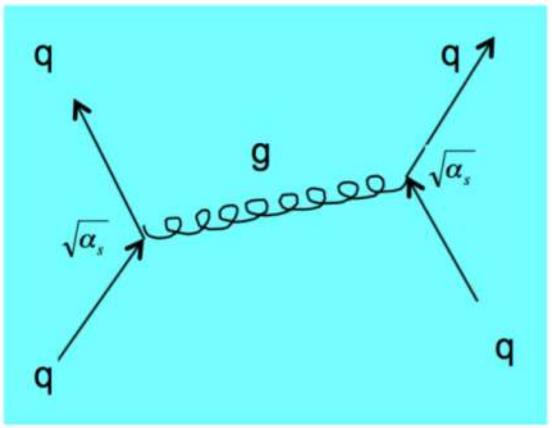
3 valence quarks




# LHC: For "hard" processes strong Interactions is directly between quarks



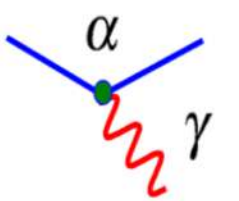




- Effective strength ~ #gluons exch.
  - low $Q^2$: more *g's*: large eff. coupling
  - high $Q^2$: few *g's*: small eff. coupling

# Few comments on QCD relevant when discussion hard scattering processes

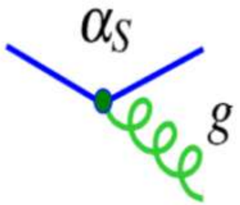
**In QED:**

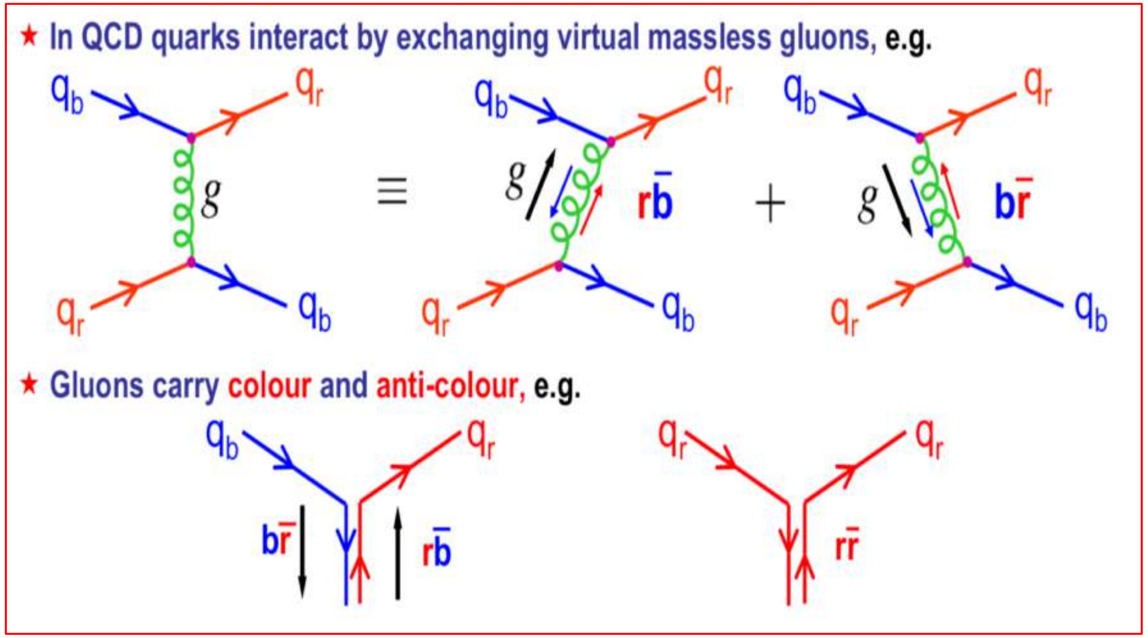
- the electron carries one unit of charge $-e$
- the anti-electron carries one unit of anti-charge $+e$
- the force is mediated by a massless "gauge boson" – the photon

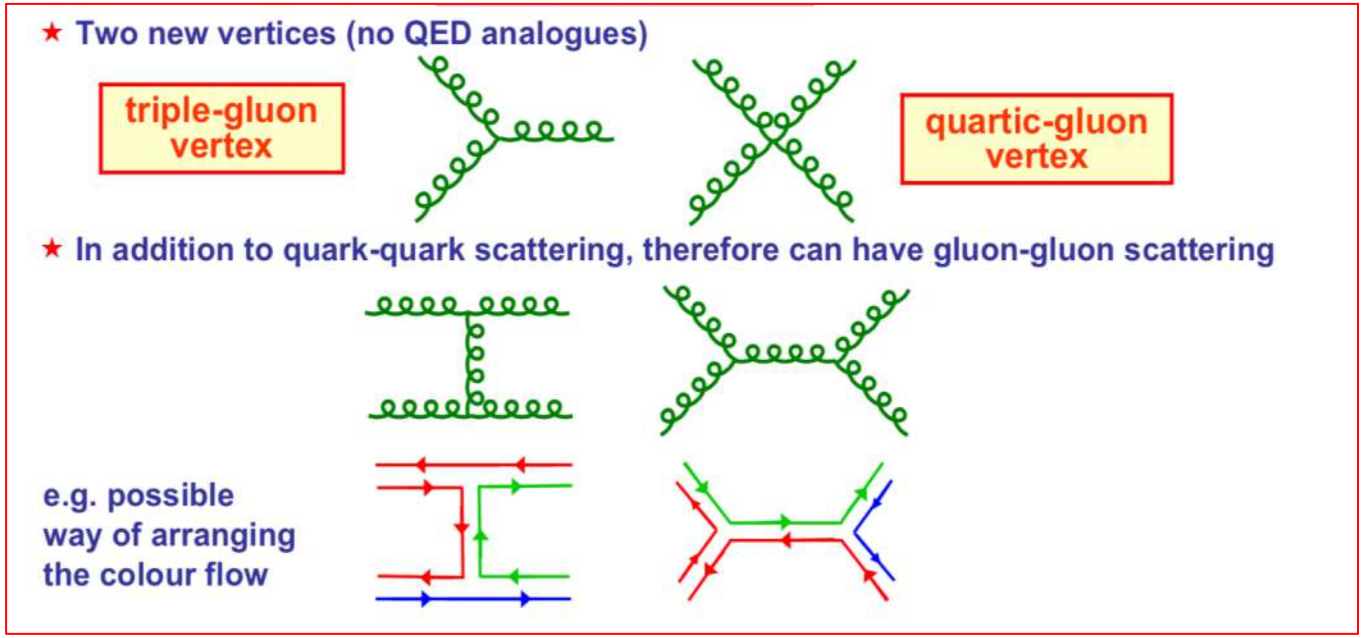



**In QCD:**

- quarks carry colour charge: $r, g, b$
- anti-quarks carry anti-charge: $\bar{r}, \bar{g}, \bar{b}$
- The force is mediated by massless gluons

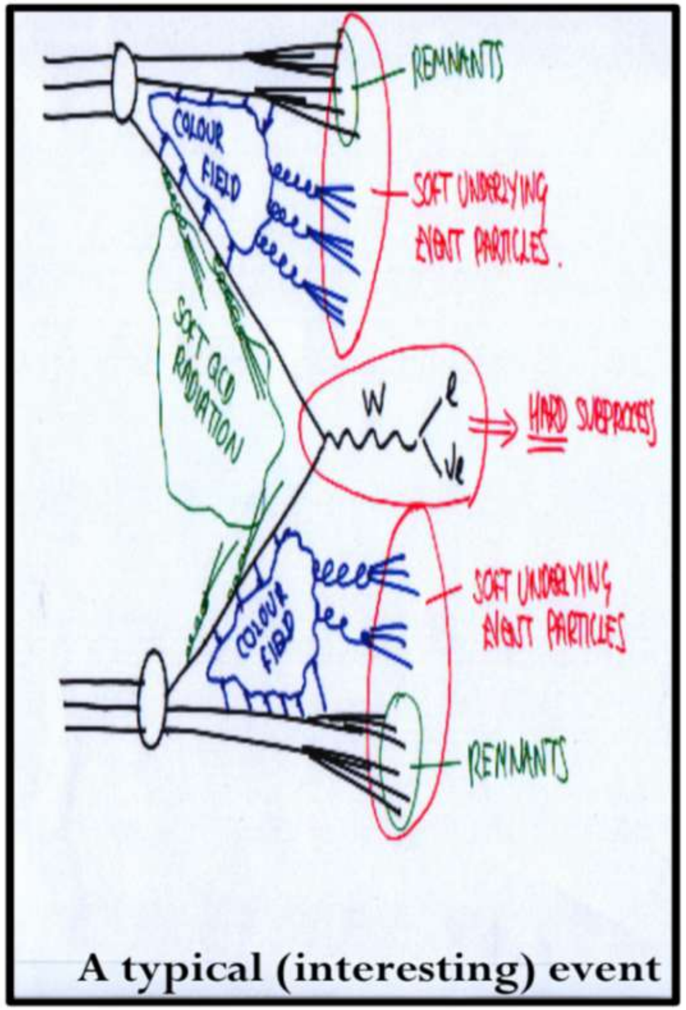


# At the LHC we need to have under control both the soft (underlying event) & hard QCD

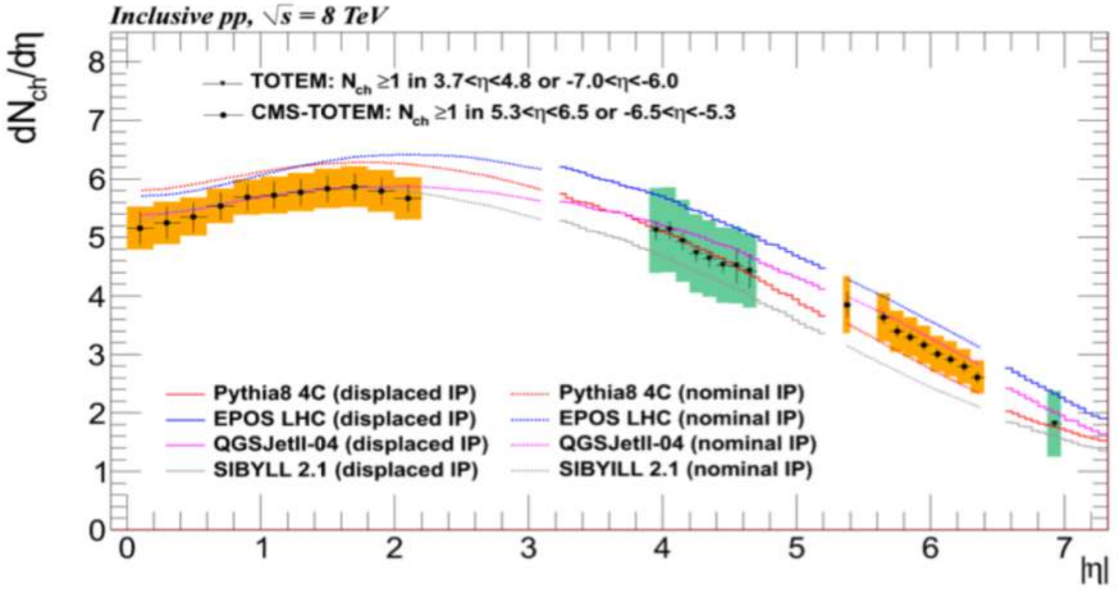
Will talk more about underlying event when we discuss top-quark



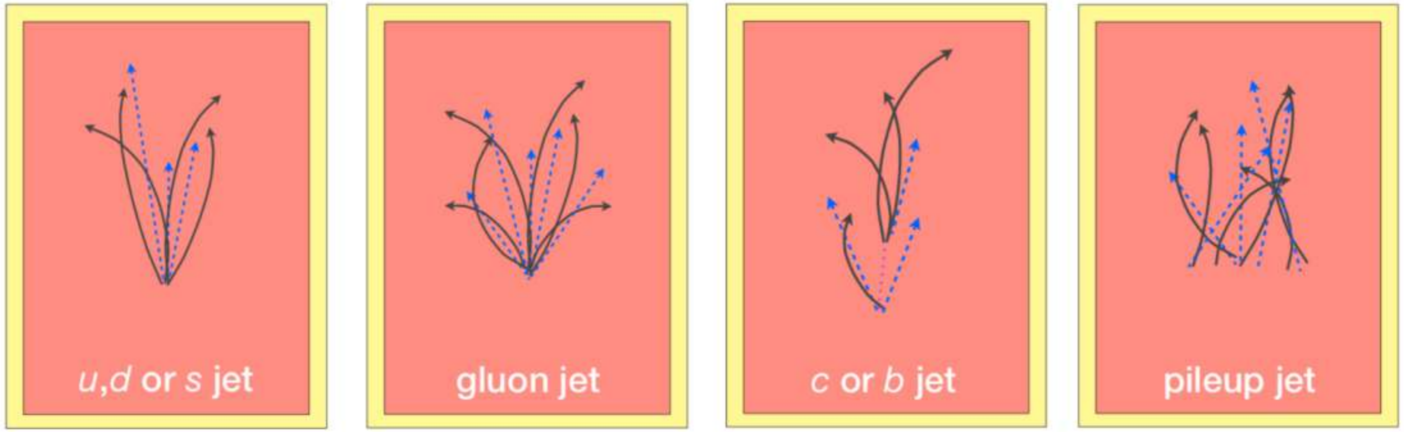
A typical (interesting) event

- Measurement of the forward charged particle pseudorapidity density in pp collisions at sqrt(s) = 8 TeV using a displaced interaction point

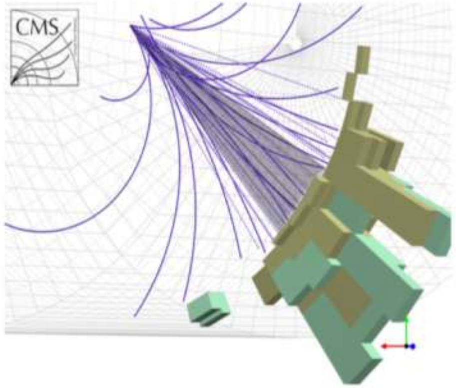
  Eur. Phys. J. C (2015) 75:126; arXiv:1411.4963

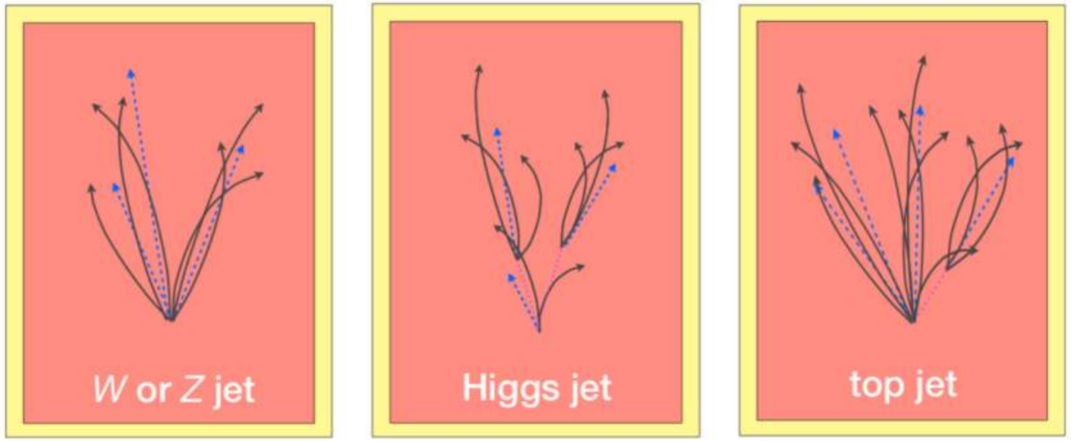


# Before we continue…The hard processes very often produce jets. We are continuously improving our jet reconstruction

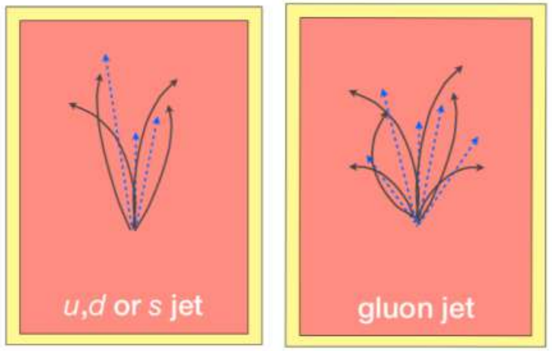



- Jets are ubiquitous at hadron colliders.
  - Collimated spray of hadrons resulting from an initial state quark or gluon)
- LHC jet tagging revolution
  - Enabled by new reconstruction techniques (ex. particle flow, sequential recombination jet algorithms)
  - Quark/gluon discrimination, Pileup jet ID
  - Boosted heavy object jet tagging (ex. top, W, Z, Higgs)
    - all decay products of reconstructed within one jet
  - Advanced b-tagging methods
    - Subjet b-tagging, double b-tagging



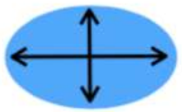



# *Identifying quark and gluon jets*




- Gluon more likely to radiate a gluon ($C_A = 3$ vs $C_F = 4/3$)
- Gluon fragmentation function softer
- Gluon jets
  - Wider than quark jets (η-Φ plane)
  - Larger multiplicities
  - Fewer hard particles
- Quark jets
  - Narrow
  - Smaller multiplicities
  - Asymmetrical energy shared between constituents

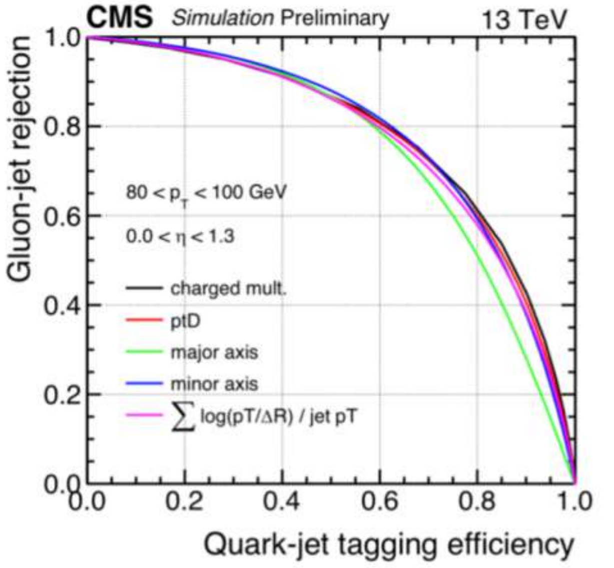
- Three tools:
  - Likelihood discriminator (3 variable)
  - BDT discriminator (5 variable)
  - Deep neural net (jet constituents)
- Quark/gluon discriminator variables:
  - Jet particle multiplicity
    - Total or charged
  - Jet shape
    - major axis width
    - minor axis width



    - ΔR weighted $p_T$ $\sum_i \frac{\log(\frac{p_{T,i}}{\Delta R})}{\text{jet } p_T}$
  - Energy sharing ($p_T D$)

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

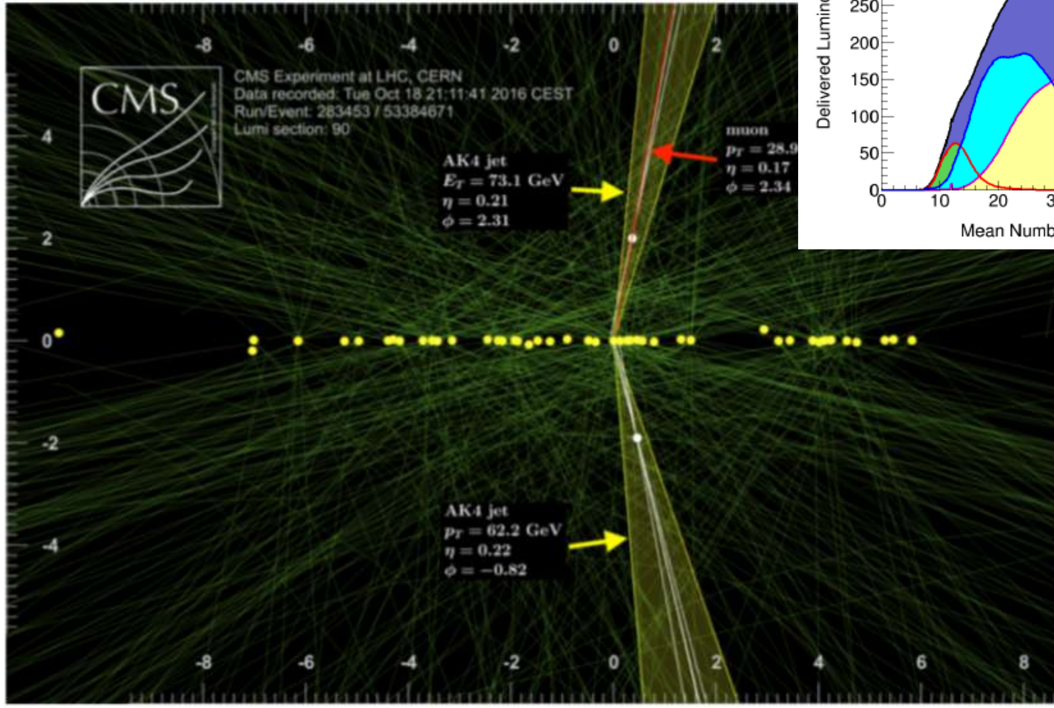
→ 1 if all momentum carried by one particle
→ 0 if jet has infinite number of particles

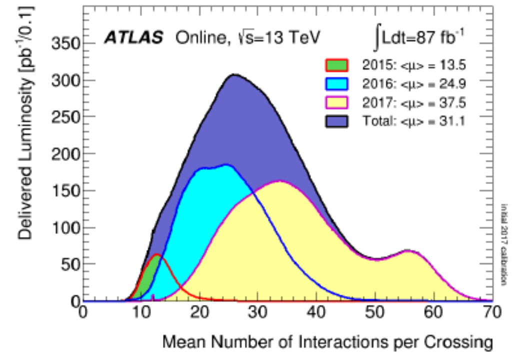


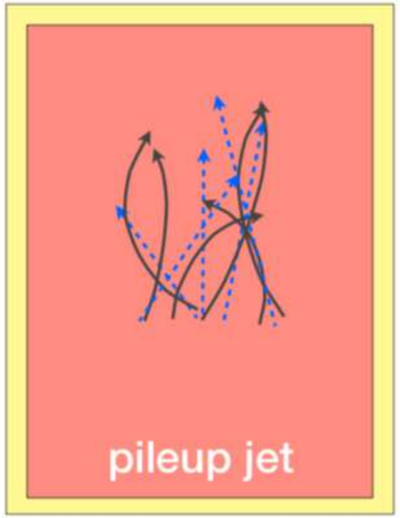

CMS DP Note 2017/027

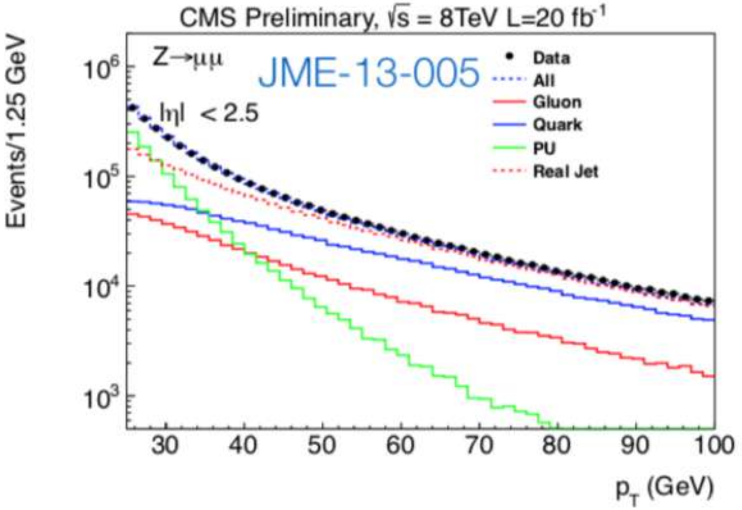
# LHC Hostile environment

- Pileup jets are formed from overlapping low pT pileup particles
  - Each pileup vertex contributes ~0.7 GeV of energy per unit area (η,Φ) of the detector
- Pileup jet tagging - tool used to identify and reject jets originating from pileup
  - Utilize vertex, track, and jet shape information
  - Charged particles inside pileup jets are not associated with the primary vertex
  - Pileup jets are more defuse (overlapping soft particles from multiple vertices)



# Aside… I am going to show several cross section measurements

$$\sigma = \frac{N_{obs} - N_{bkg}}{A \varepsilon L}$$

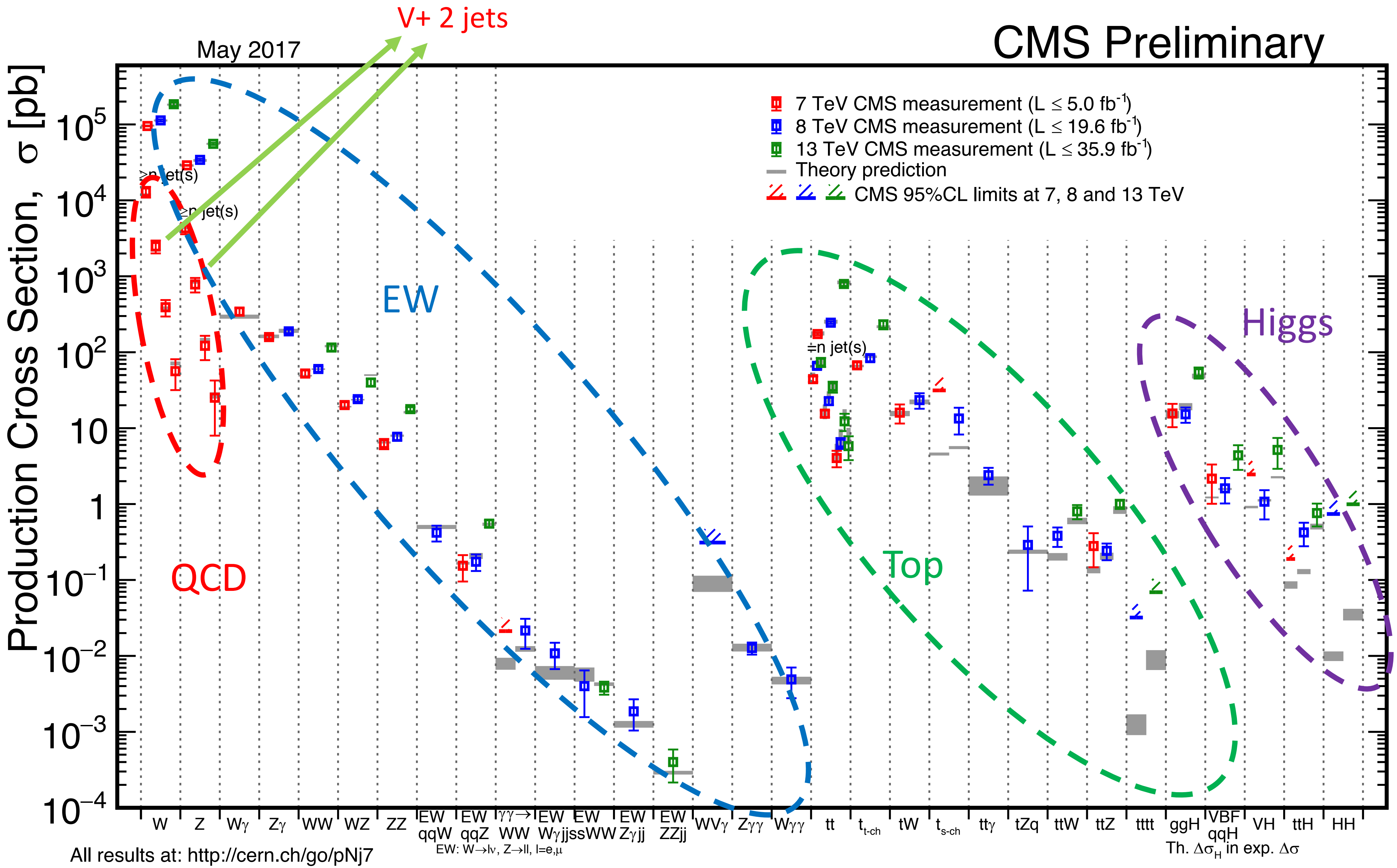
$N_{obs}$: observed number of events
$N_{bkg}$: estimated background
$A$: detector acceptance ($N_{gen,fiducial} / N_{gen,total}$)
$\varepsilon$: experimental efficiency ($N_{reco}/N_{gen,fiducial} * \varepsilon_{data}/\varepsilon_{MC}$)
$L$: integrated luminosity

Fiducial cross-section

- no correction for detector acceptance to avoid theoretical uncertainty on extrapolation to the full phase space

Differential cross-section

- Measure in bins of a variable (or of several variables)
- Use efficiency matrix that also describes migration between bins → unfolding

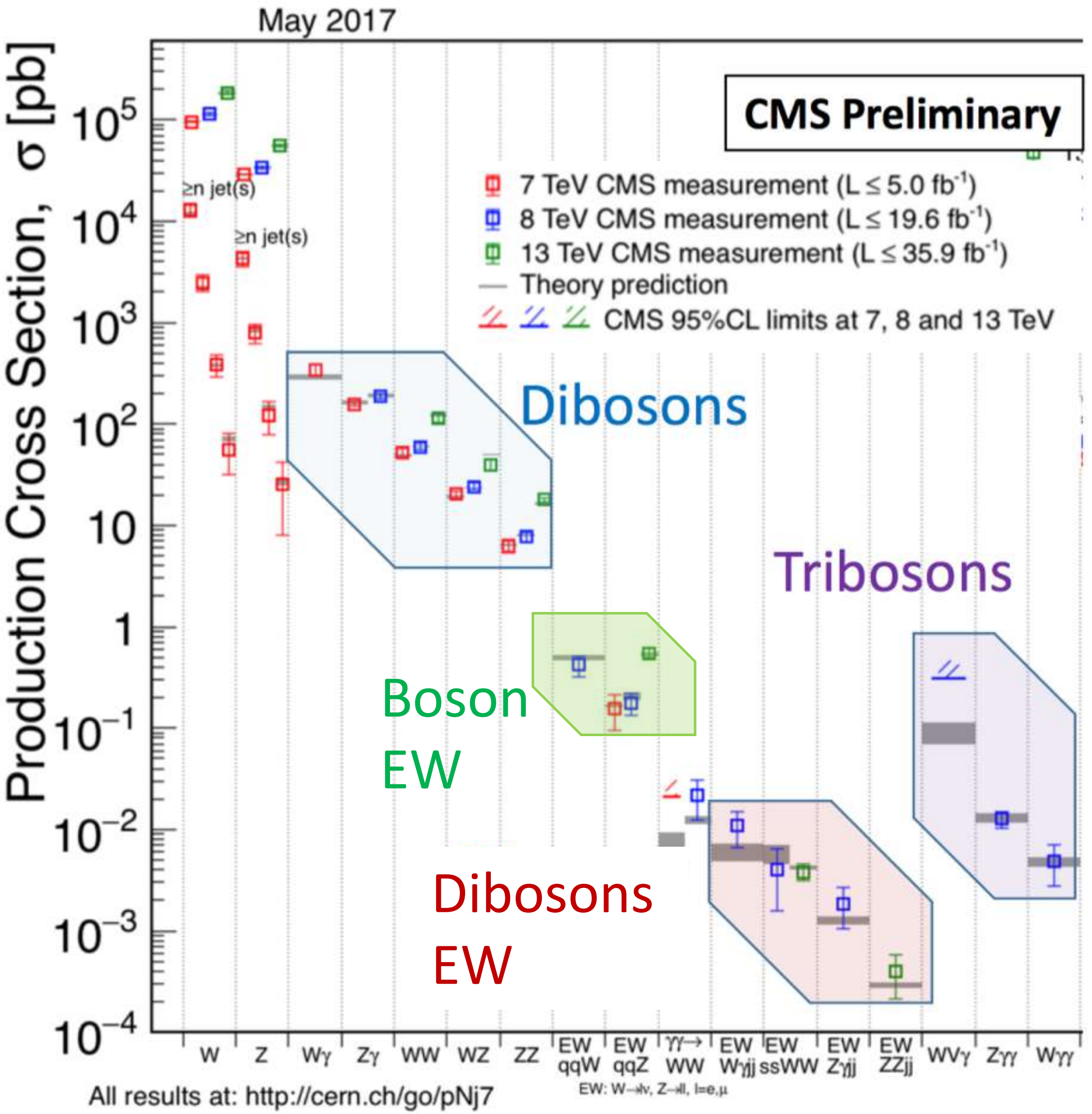


V+ 2 jets
May 2017
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 35.9 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
EW
QCD
Top
Higgs
≥n jet(s)
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW Wγjj ssWW EW Zγjj EW ZZjj WVγ Zγγ Wγγ tt t-ch tW ts-ch ttγ tZq ttW ttZ tttt ggH VBF qqH VH ttH HH
EW: W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7

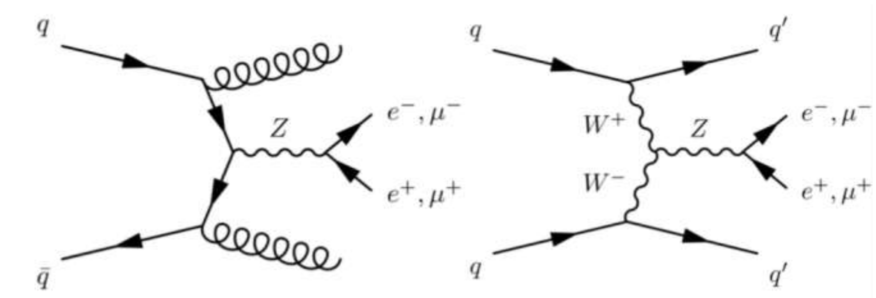
# Focus 1st on EW production of single bosons and Multiboson

## Huge range of production Cross Sections

- 5-300 pb: Inclusive (QCD) diboson production:
  - Sensitive to higher order QCD (and QED) perturbative corrections
  - SM gauge structure: Triple Gauge Couplings (TGC)
- <0.01 pb: VBS/VBF (QED) diboson production
  - Sensitive to higher order QED perturbative corrections
  - The nature of EWSB
  - SM gauge structure: Triple Gauge Couplings (TGC) and Quartic Gauge Couplings (QGC)
- $10^{-3}$-$10^{-1}$ pb: Inclusive (QCD) triboson production
  - Sensitive to higher order QCD (and QED) perturbative corrections
  - SM gauge structure: Quartic Gauge Couplings (QGC)



# VBF: Vector Boson Fusion

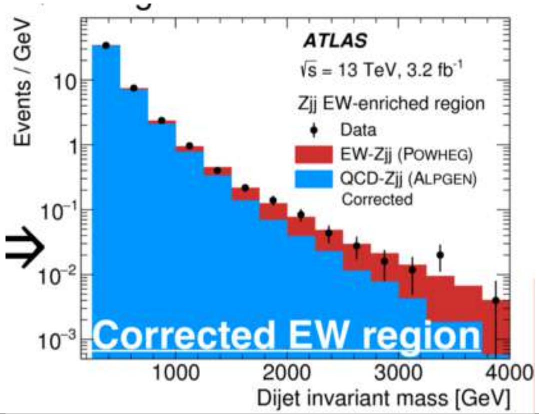



QCD Background

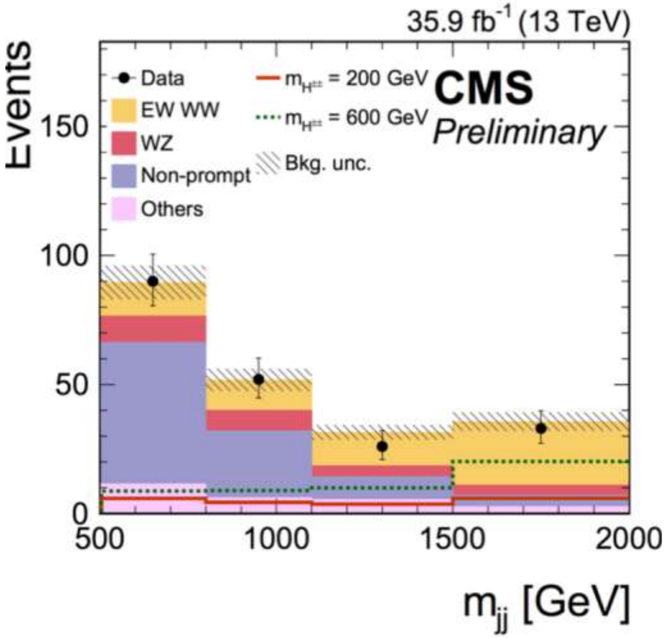
EWK: VBF Signal

Future of the LHC
Great topology to search for new high mass resonances

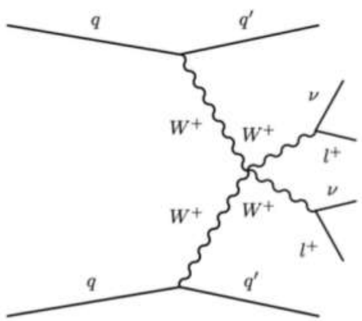
⇒



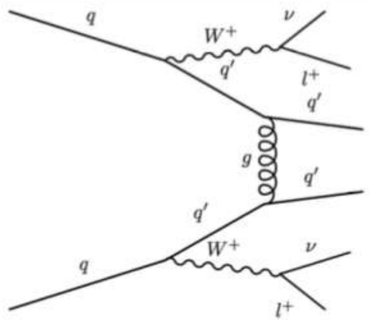

# VBS: Vector Boson Scattering




VBS production




QCD production

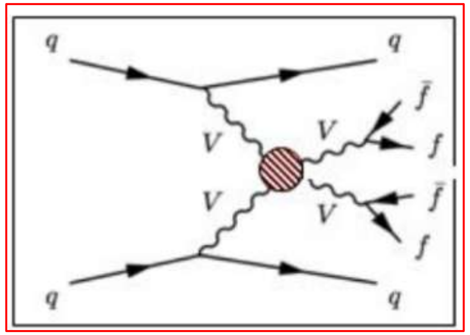


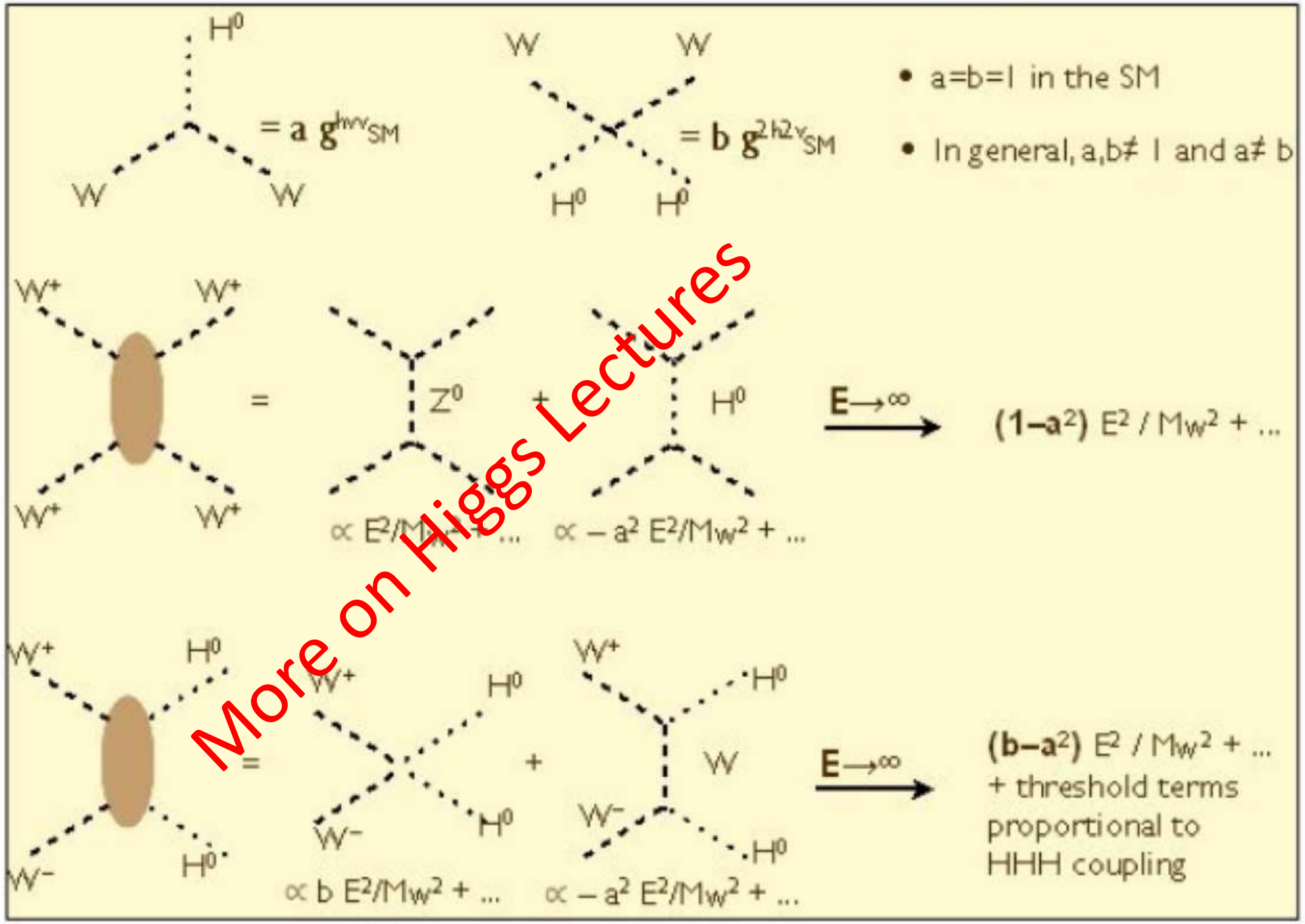

What do I mean by saying QCD or EW boson production ?

Many future analysis will have this topology

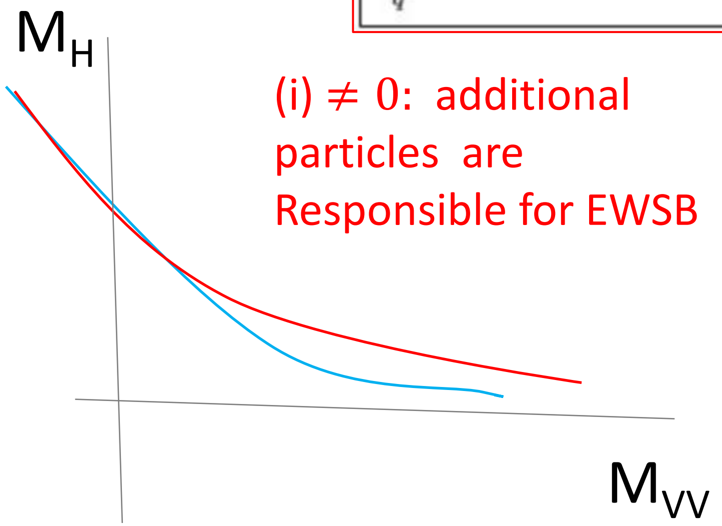
Notice that they all involve jets…

# In SM, VBS crucial because (i) $W_L W_L \rightarrow W_L W_L$ vanishes, only (ii) $W_T W_T \rightarrow W_T W_T$ is present




More on Higgs Lectures

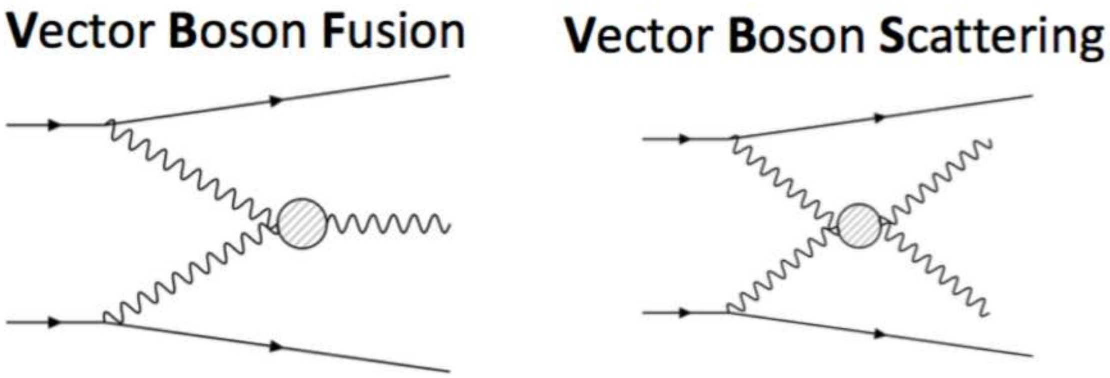



(i) $\neq 0$: additional particles are Responsible for EWSB

- $V_L\, V_L$ scattering linked to the mechanism responsible for the EWSB:

(massless vector) $W^a_\mu, B_\mu$ (Higgs doublet) $\sigma, \chi^a$ → (massive vector) $W^+_\mu, W^-_\mu, Z_\mu$ (Higgs field) $H$

# We know how to reconstruct jets… therefore we can identify:
pp→ qqV or qqVV

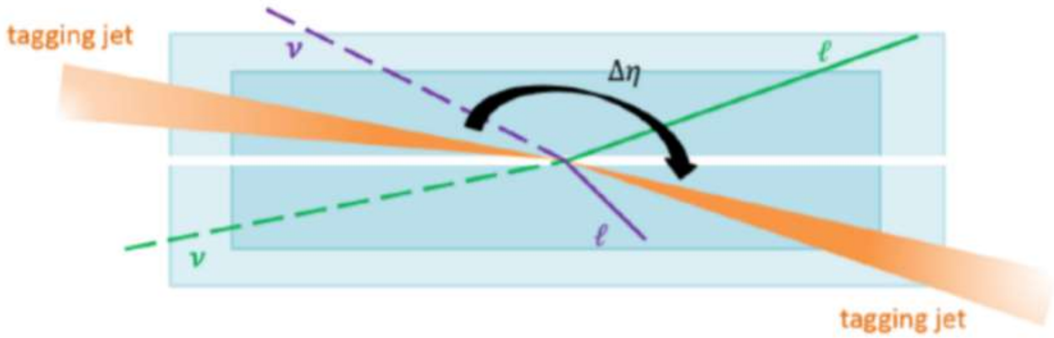



pp→ jj V

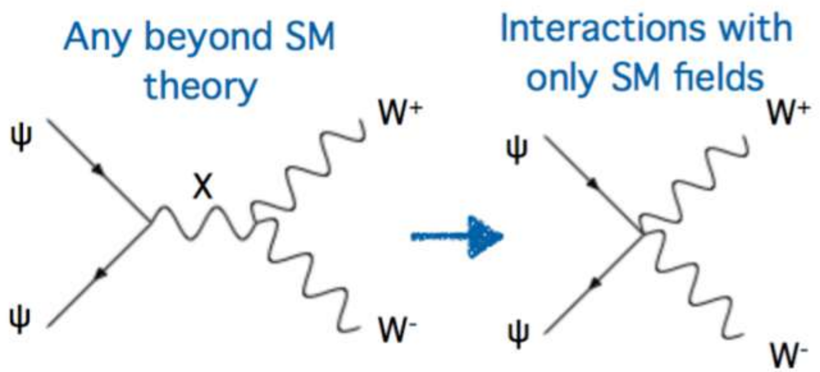
pp→ jj VV

Process characteristics:

- Tagging jets (large $|\Delta\eta_{jj}|$, $m_{jj,}$ quark tagging)
- Little central hadronic activity (jet veto)

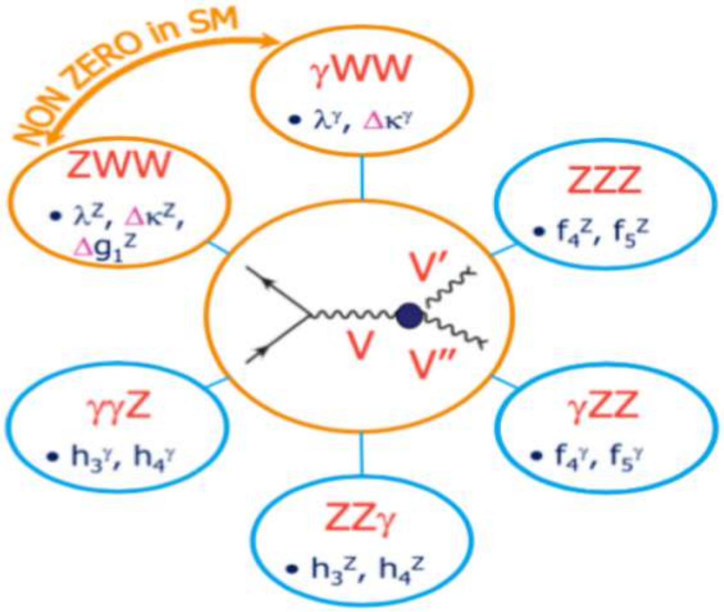


# Multibosons are also used to search for new physics via anomalous couplings




For large scales E/Λ « 1, only operators with lower mass dimension will matter...

$$\frac{1}{\Lambda^2}\mathcal{L}_6 \rightarrow \left(\frac{E}{\Lambda}\right)^2 \qquad \frac{1}{\Lambda^4}\mathcal{L}_8 \rightarrow \left(\frac{E}{\Lambda}\right)^4$$




$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}}\mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots$$

- 14 operators, 18 parameters
- 1 operator, 7 parameters
- 59 operators, 2499 parameters [arXiv:1312.2014]
- 4 operators, 408 parameters (all violate B number) [arXiv:1405.0486]
- 30 operators (all violate L number, 7 violate B number) [arXiv:1410.4193]
- 993 operators [arXiv:1510.00372]

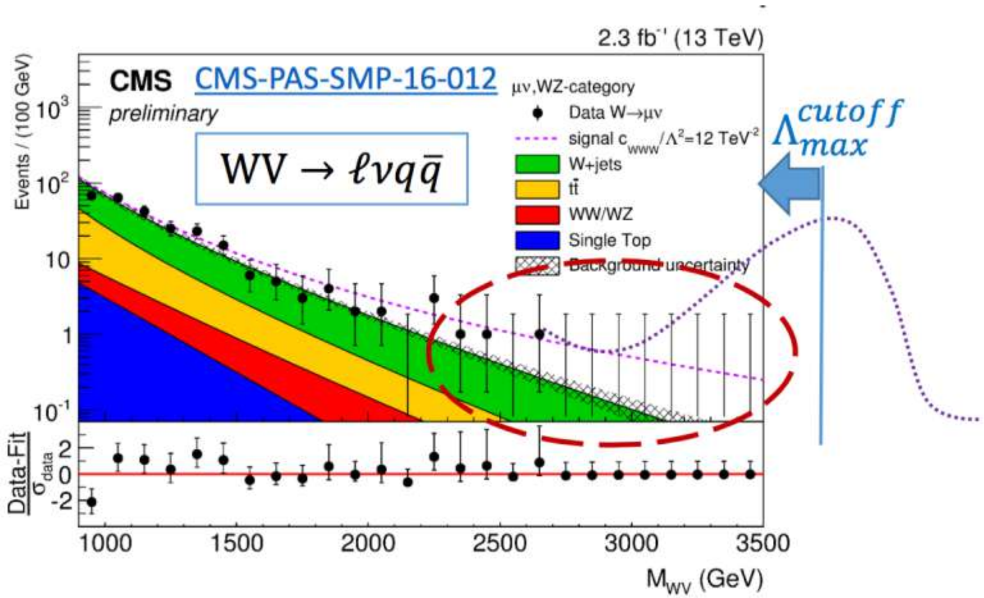
The 2499 parameters in D=6 can be reduced to a bit more than 50 assuming flavor symmetry and CP conservation



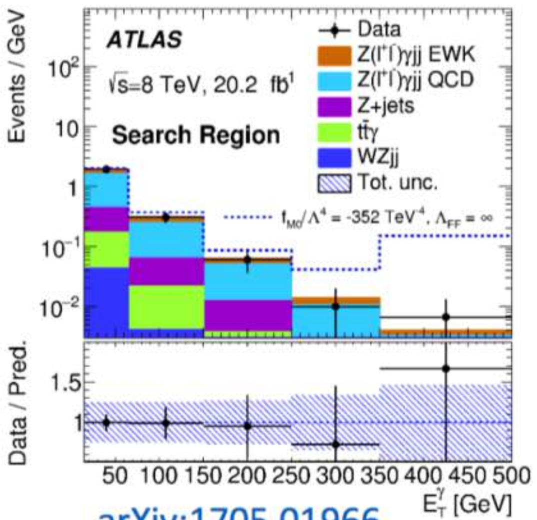
Existing measurements are limited to 2 operators. We can do better!

# Anomalous couplings

- Limiting factor: Observed statistics in the tail, systematics and statistical uncertainty on the S/B model ➔ Will improve as luminosity increases
- Anomalous couplings result in an increase of cross sections at high energies
  - Invariant mass of the diboson system and the boson $p_T$ are particularly sensitive

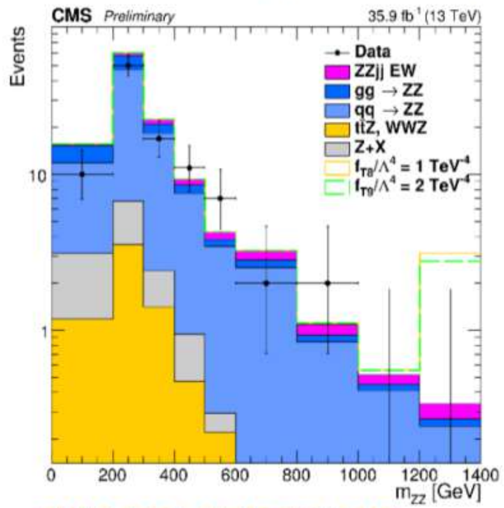



## Zγjj→2ℓγjj (8 TeV)



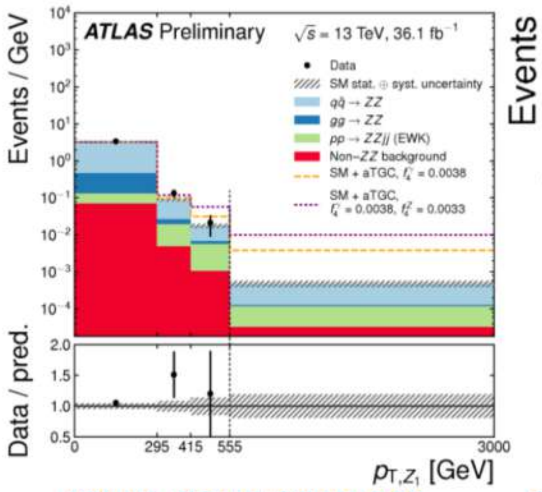

arXiv:1705.01966

## ZZjj→4ℓjj (13 TeV)



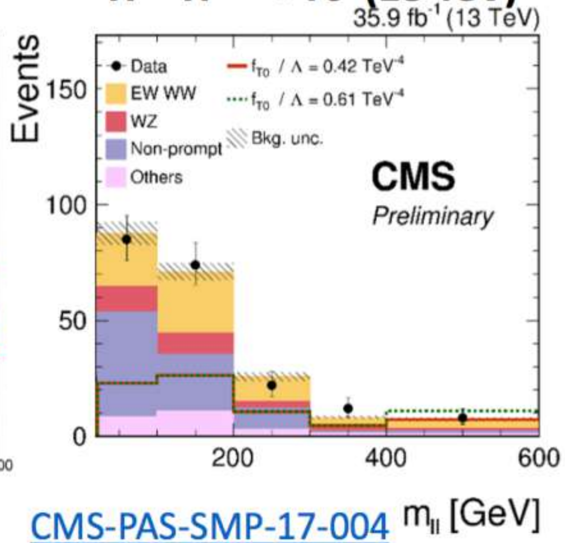

CMS-PAS-SMP-16-019

## ZZ→4ℓ (13 TeV)




ATLAS-CONF-2017-031

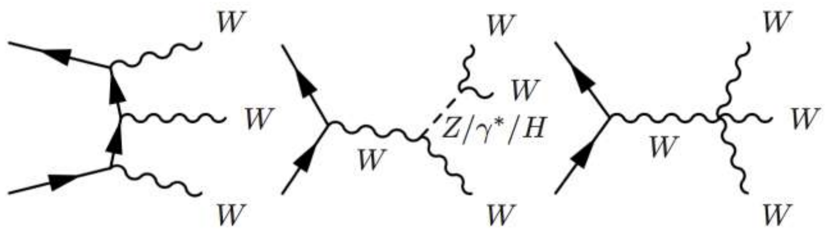
## W±W±→4ℓ (13 TeV)




CMS-PAS-SMP-17-004

# Tribosons

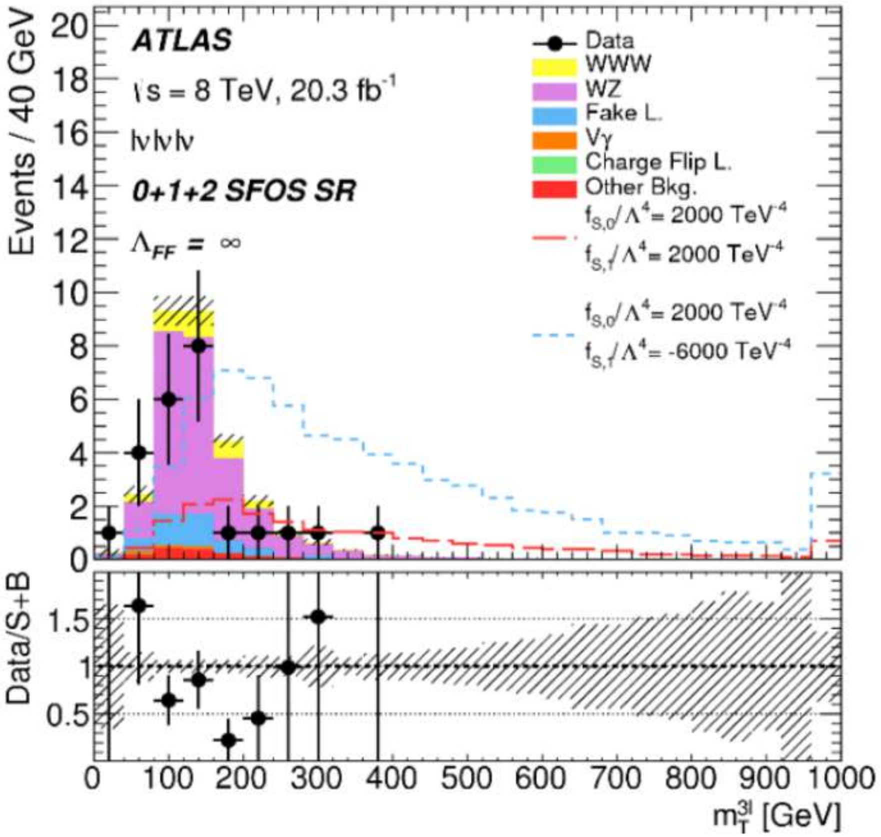
First study by ATLAS of $W^{\pm}W^{\pm}W^{\mp}$ to $l^{\pm}\nu + l^{\pm}\nu + l^{\pm}\nu$ and $l^{\pm}\nu + l^{\pm}\nu + jj$

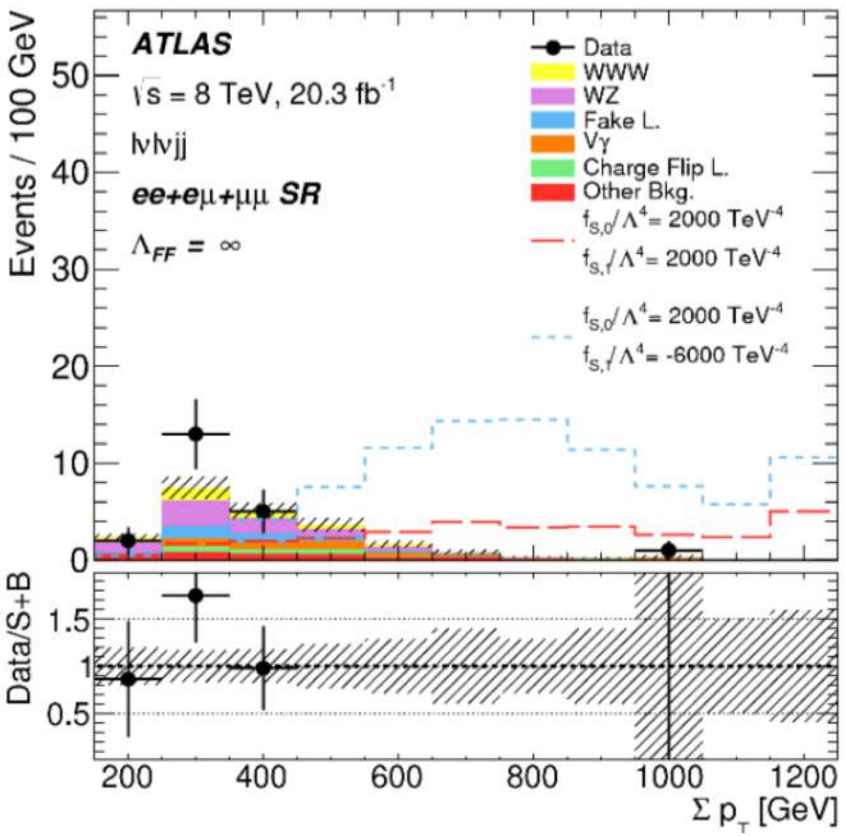



Access to quartic anomalous couplings

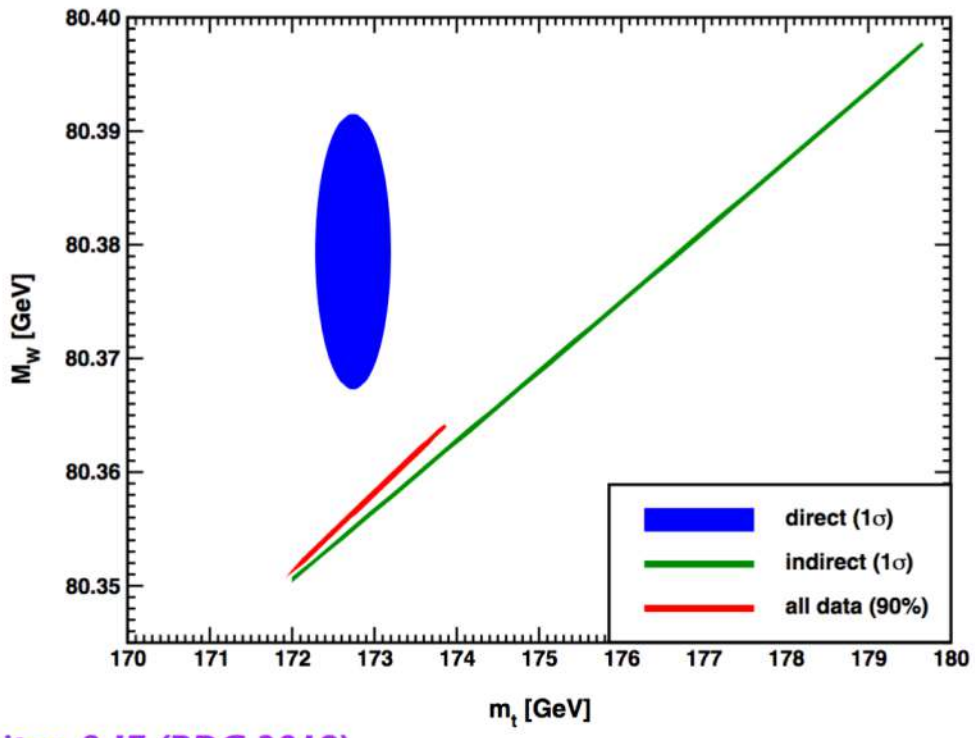
More statistics will come @13 TeV

EPJC (2017) 77: 141



# Role of precision EWK measurements @ Hadron Colliders



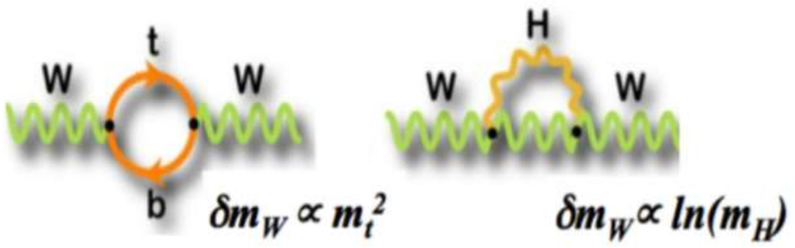

Freitas & JE (PDG 2018)

To provide precise measurements of fundamental parameters to tests the theory:

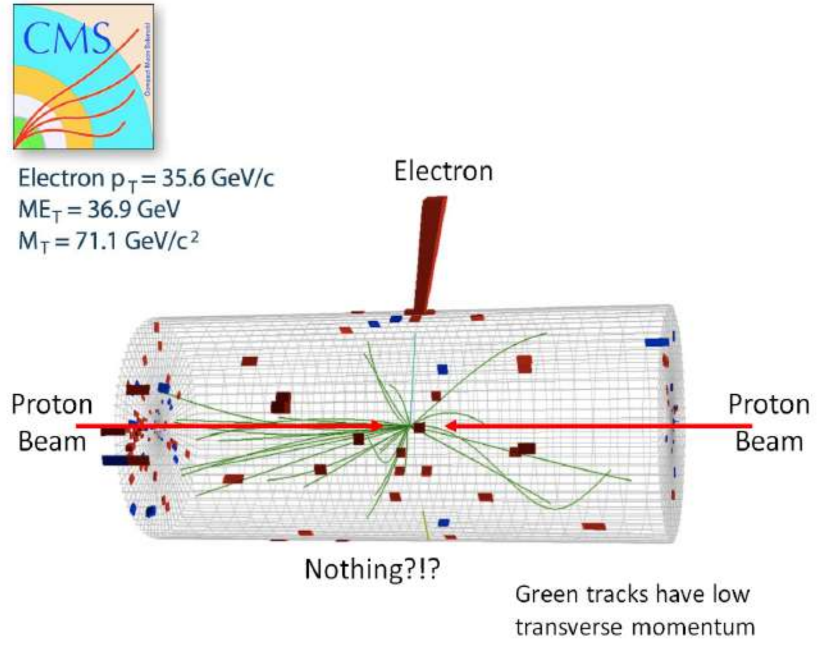
$\alpha_{em}$, $G_F$, $M_Z$, $M_W$, $\sin^2\theta_W$, $m_{top}$, $M_H$ $\alpha_s$

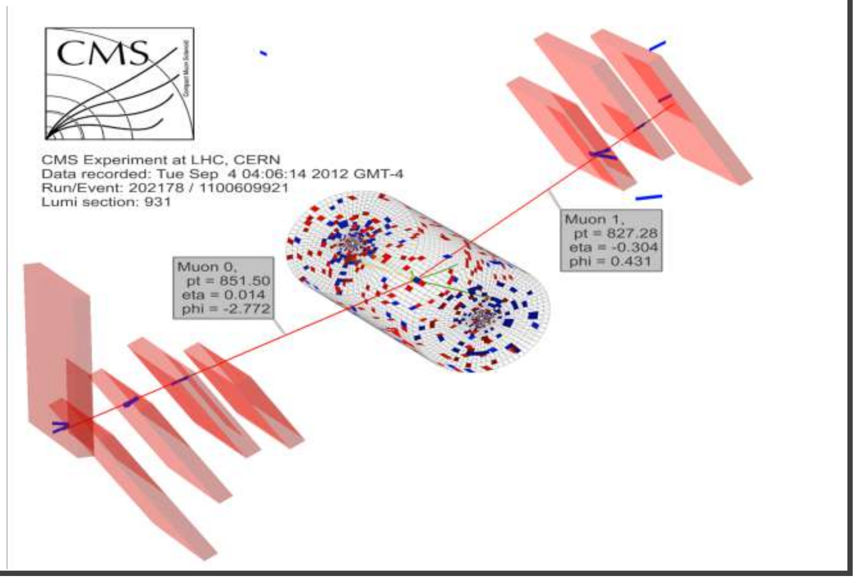
Why? To have access to potential *virtual new particles* that might not be directly accessible at the current center of mass energy… just as we did for the Higgs before the actual observation

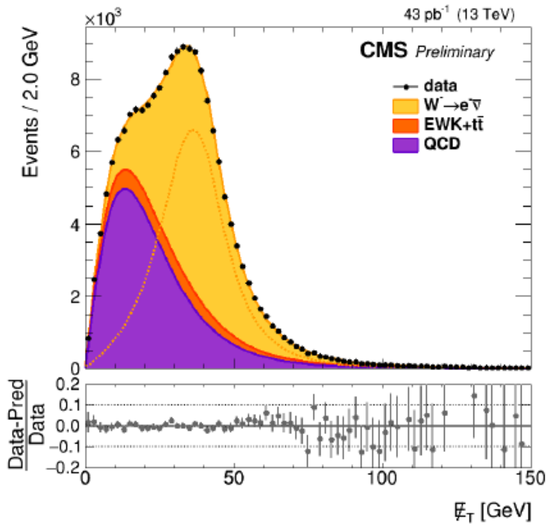
$$m_W = \frac{\pi\alpha}{\sqrt{2}G_F} \frac{1}{\sin^2\theta_W(1+\delta m_W)}$$

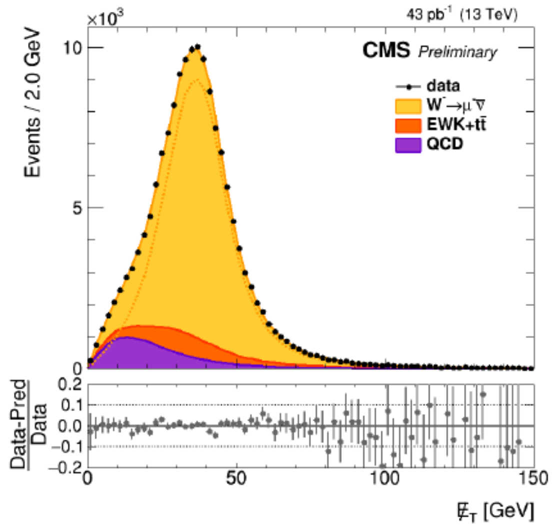



*Some tension already in data … Better precision before we can conclude if significant*



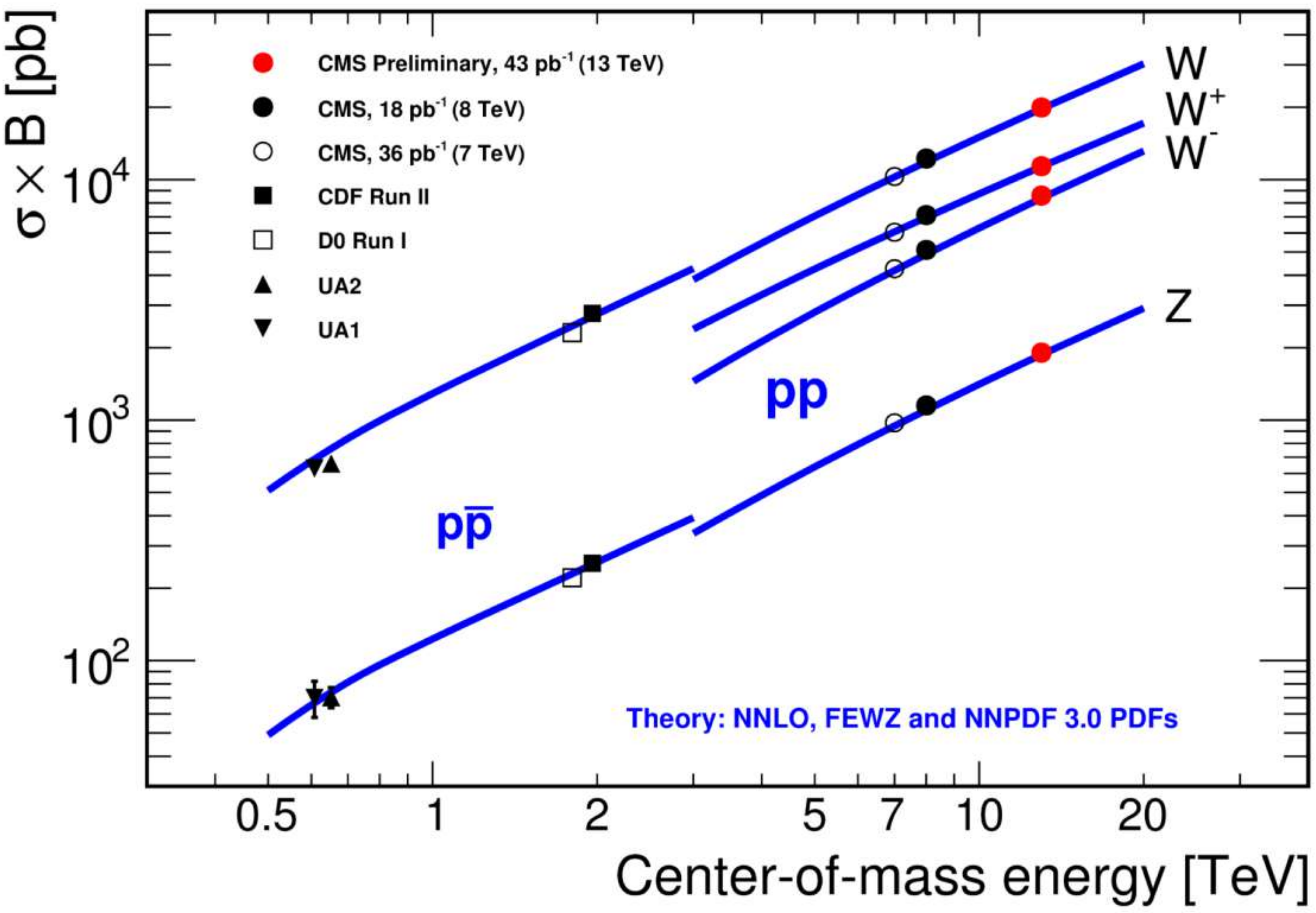




# Precision measurements with W's and Z bosons

# W and Z Boson Production

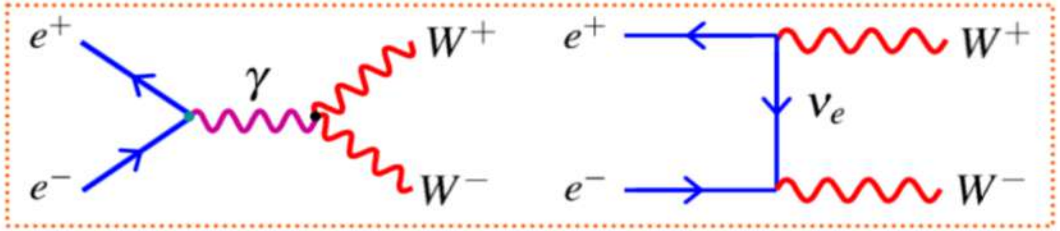


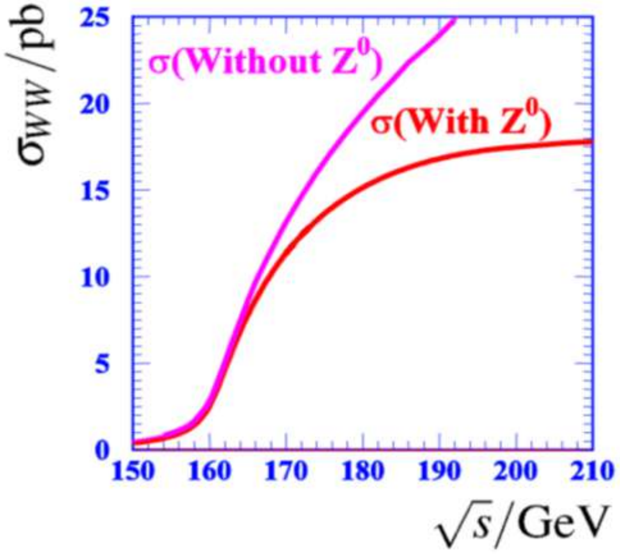

- Many detailed EWK studies possible – and done -- with the large Z,W samples

- Here we will focus on
  - $\sin^2\theta_W$
  - W-Mass
  - Lepton Universality

Before we proceed… Some historical & theoretical background of the ElectroWeak model

- ★ The W± bosons carry the EM charge - suggestive Weak are EM forces are related.
- ★ W bosons can be produced in e⁺e⁻ annihilation



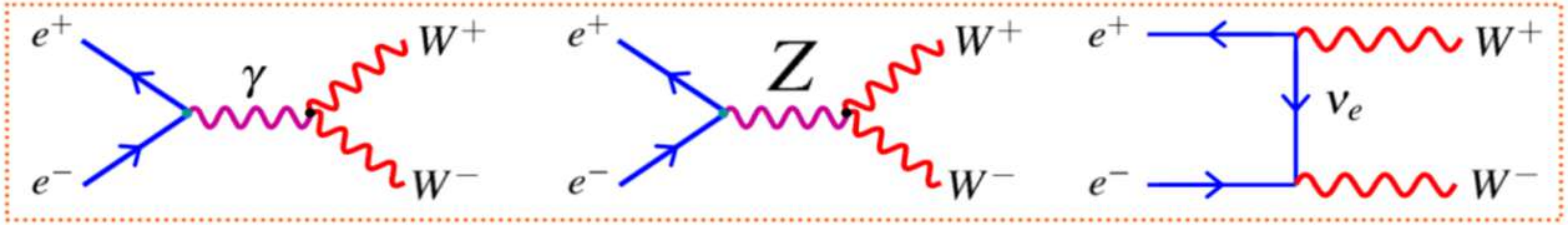




- ★ With just these two diagrams there is a problem: the cross section increases with C.o.M energy and at some point violates **QM unitarity**

**UNITARITY VIOLATION: when QM calculation gives larger flux of W bosons than incoming flux of electrons/positrons**

- ★ Problem can be “fixed” by introducing a new boson, the Z. The new diagram interferes negatively with the above two diagrams fixing the unitarity problem

⇨

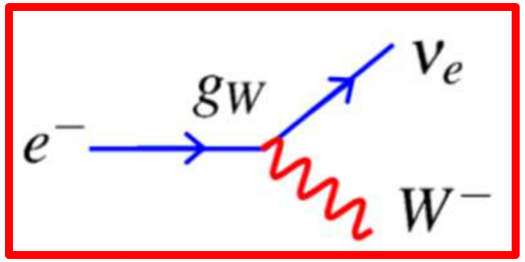



$$|M_{\gamma WW} + M_{ZWW} + M_{\nu WW}|^2 < |M_{\gamma WW} + M_{\nu WW}|^2$$

- ★ Only works if **Z, γ, W** couplings are related: need **ELECTROWEAK UNIFICATION**

From: M.A. Thomson

# $SU(2)_L$ : The Weak Interaction – W boson




**3 Gauge Bosons** $W_1^\mu,\ W_2^\mu,\ W_3^\mu$

★ Weak Interaction only couples to LH particles/RH anti-particles, hence only place LH particles/RH anti-particles in weak isospin doublets: $I_W = \frac{1}{2}$
RH particles/LH anti-particles placed in weak isospin singlets: $I_W = 0$

**Weak Isospin**

$I_W = \frac{1}{2}$ $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L$ ← $I_W^3 = +\frac{1}{2}$ (upper), $I_W^3 = -\frac{1}{2}$ (lower)

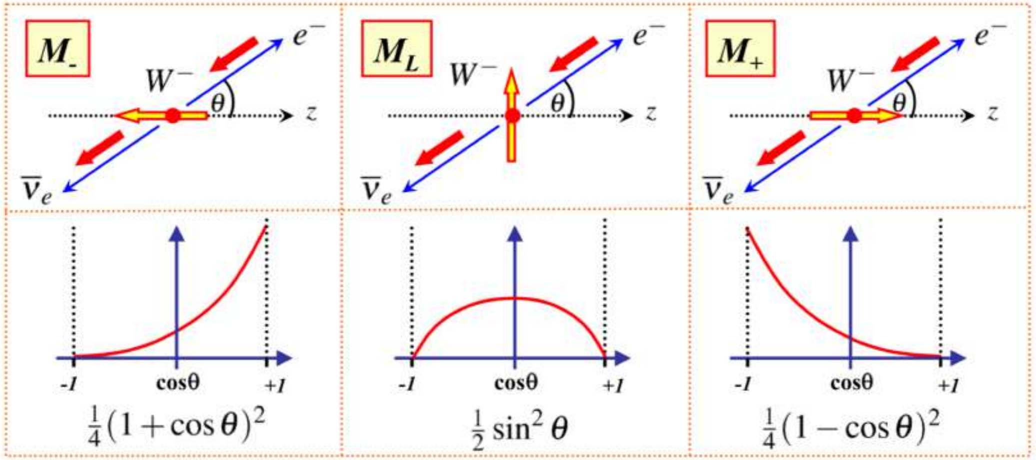
$I_W = 0$ $(\nu_e)_R,\ (e^-)_R, \ldots (u)_R,\ (d)_R, \ldots$

Note: RH/LH refer to chiral states

★The charged current $W^+/W^-$ interaction enters as a linear combinations of $W_1$, $W_2$

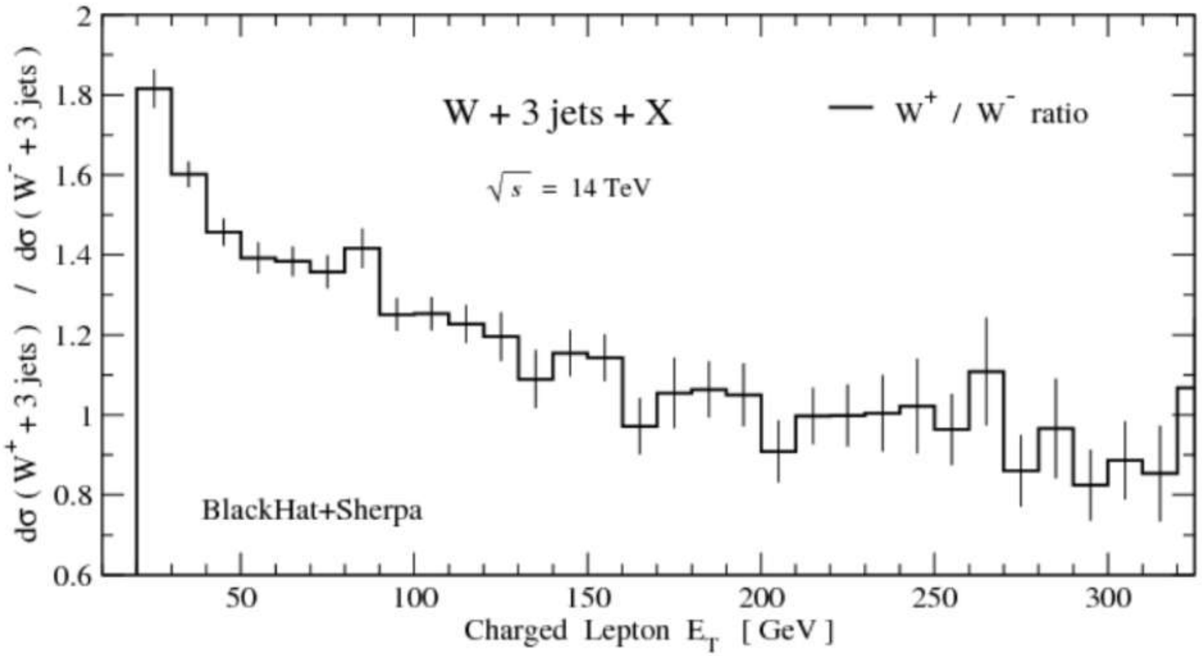
$$W^{\pm\mu} = \frac{1}{\sqrt{2}}(W_1^\mu \pm W_2^\mu)$$

# W Spin-1 – 3 possible polarizations: W helicity affects the kinematics of the outgoing leptons




**Both W+ and W− bosons produced with high pT at the LHC have a dominant left-handed polarization along their directionof flight**

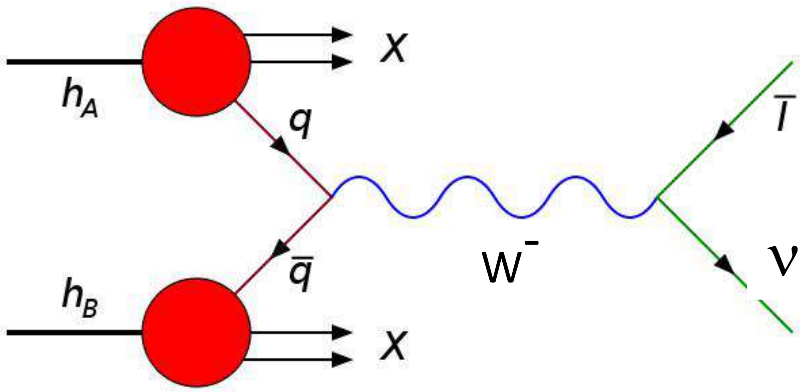
$$\frac{d\sigma_{l^+}}{d\cos\theta^* d\phi^*} = f_L\frac{(1-\cos\theta^*)^2}{4} + f_0\frac{\sin^2\theta^*}{2} + f_R\frac{(1+\cos\theta^*)^2}{4}$$

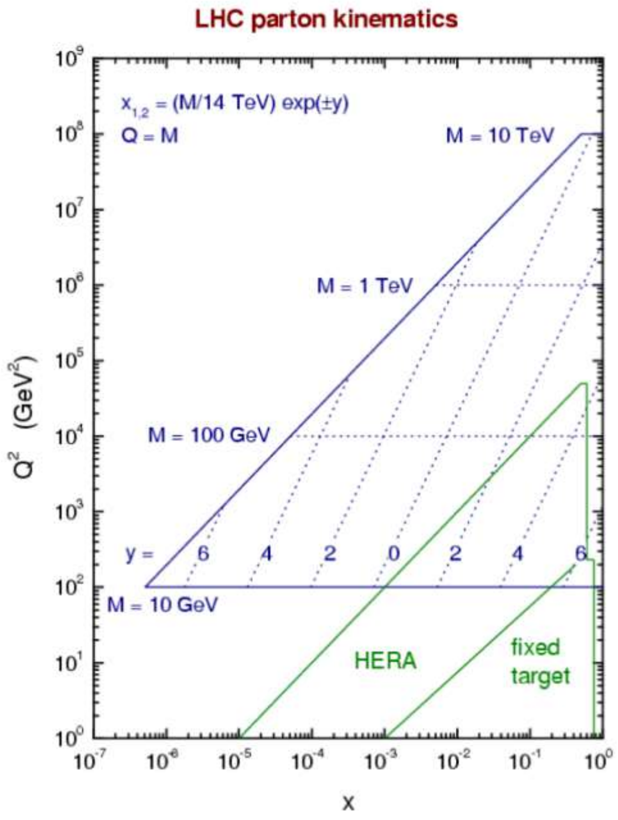


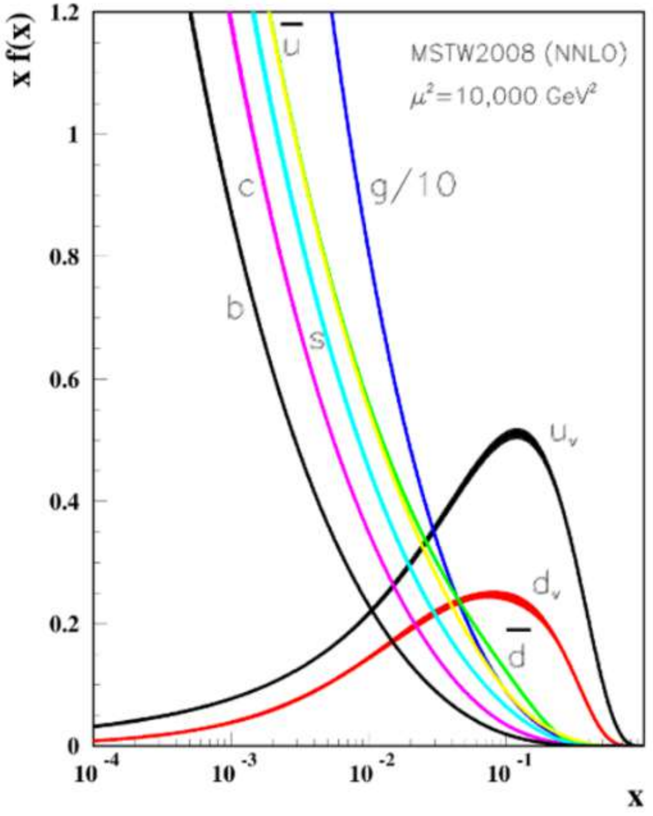

**When left-handed $W^+$ is produced in the transverse plane, its decay left- handed neutrino will be preferentially emitted along the flight direction**

**While for left-handed $W^-$ , the charged lepton will fly preferentially in the same direction of the W, and the right-handed anti-neutrino will choose the other direction.**

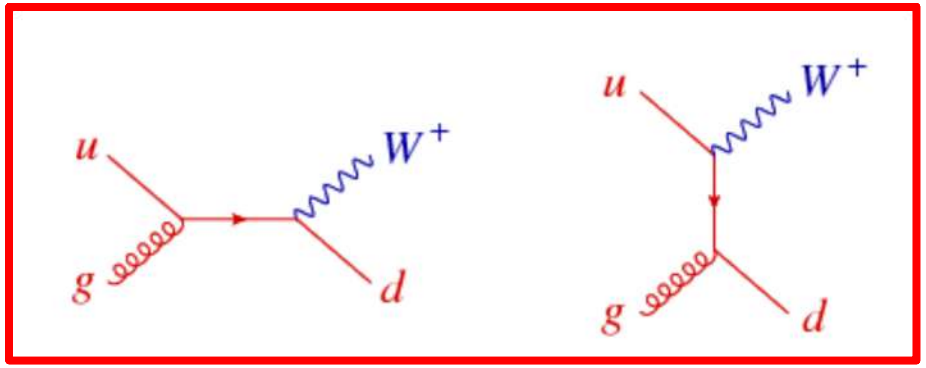
# W helicity and best production mechanism of W with high momentum transfer



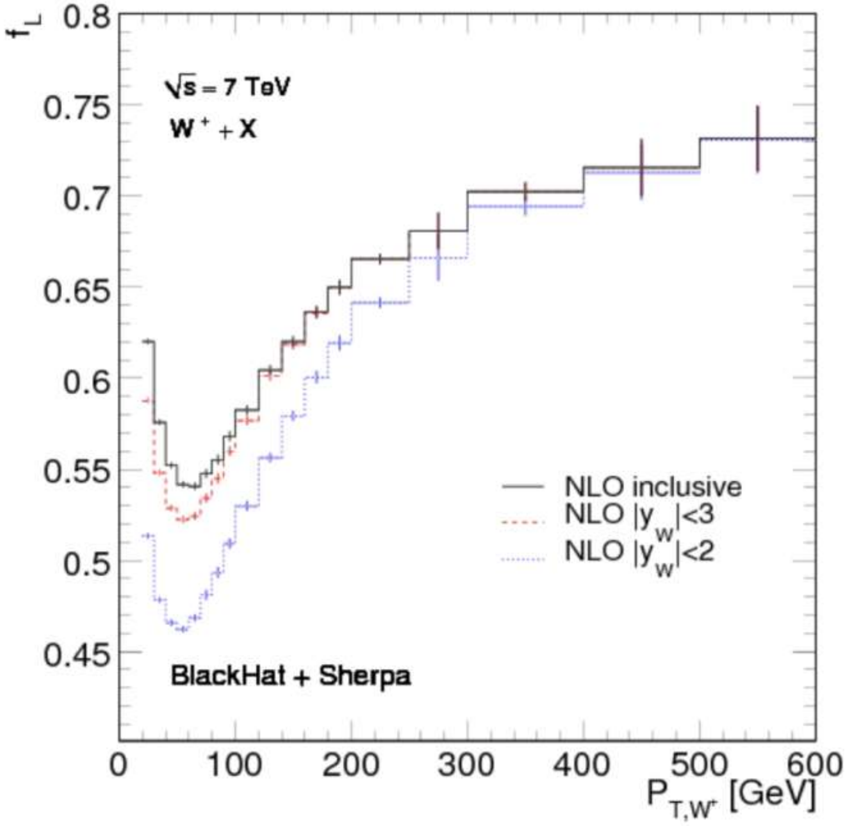



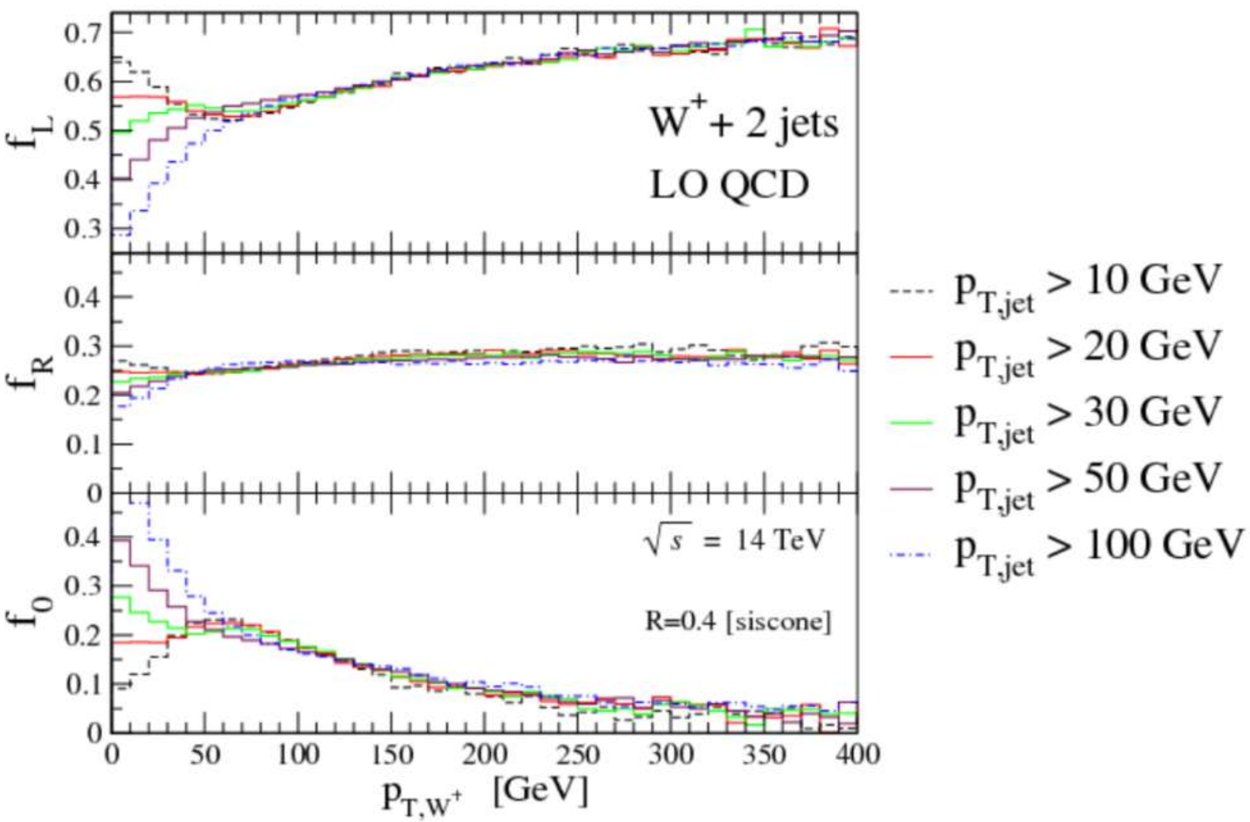




Dominates when starting from valence quarks

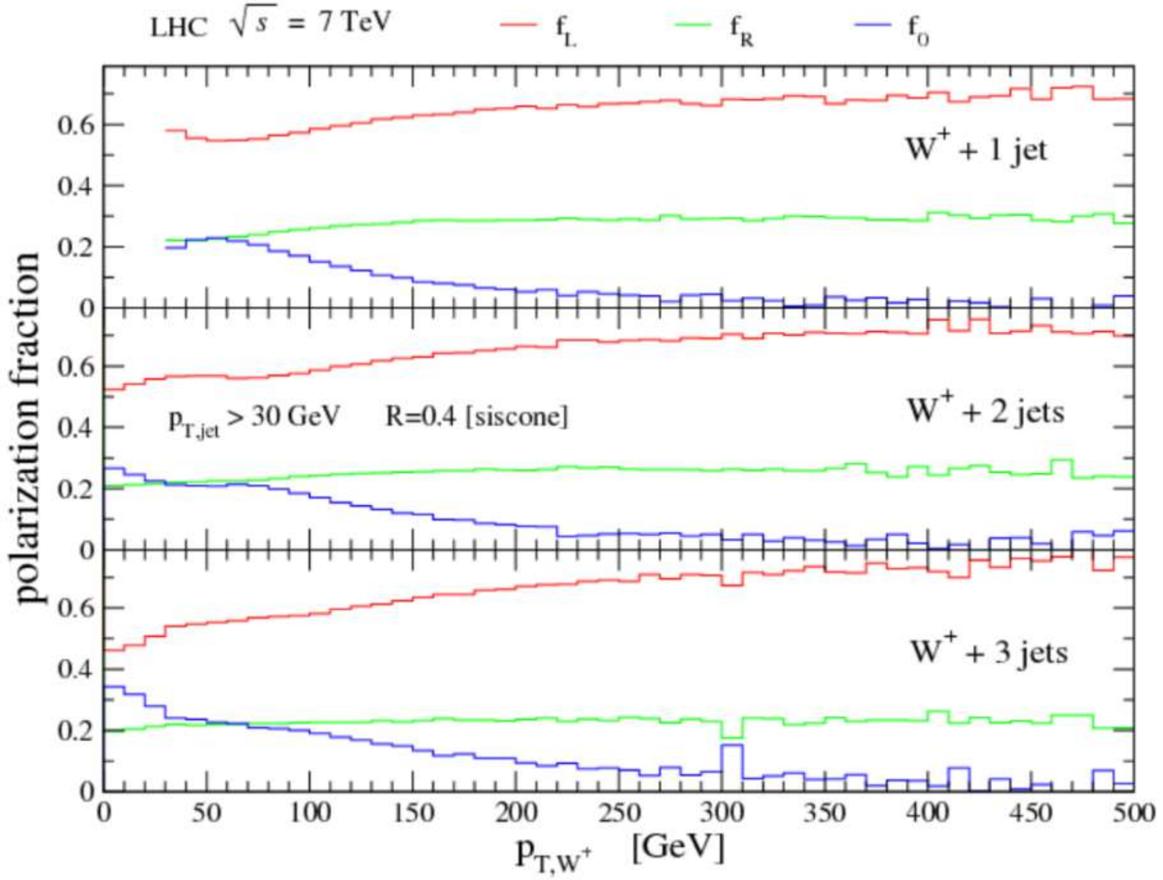


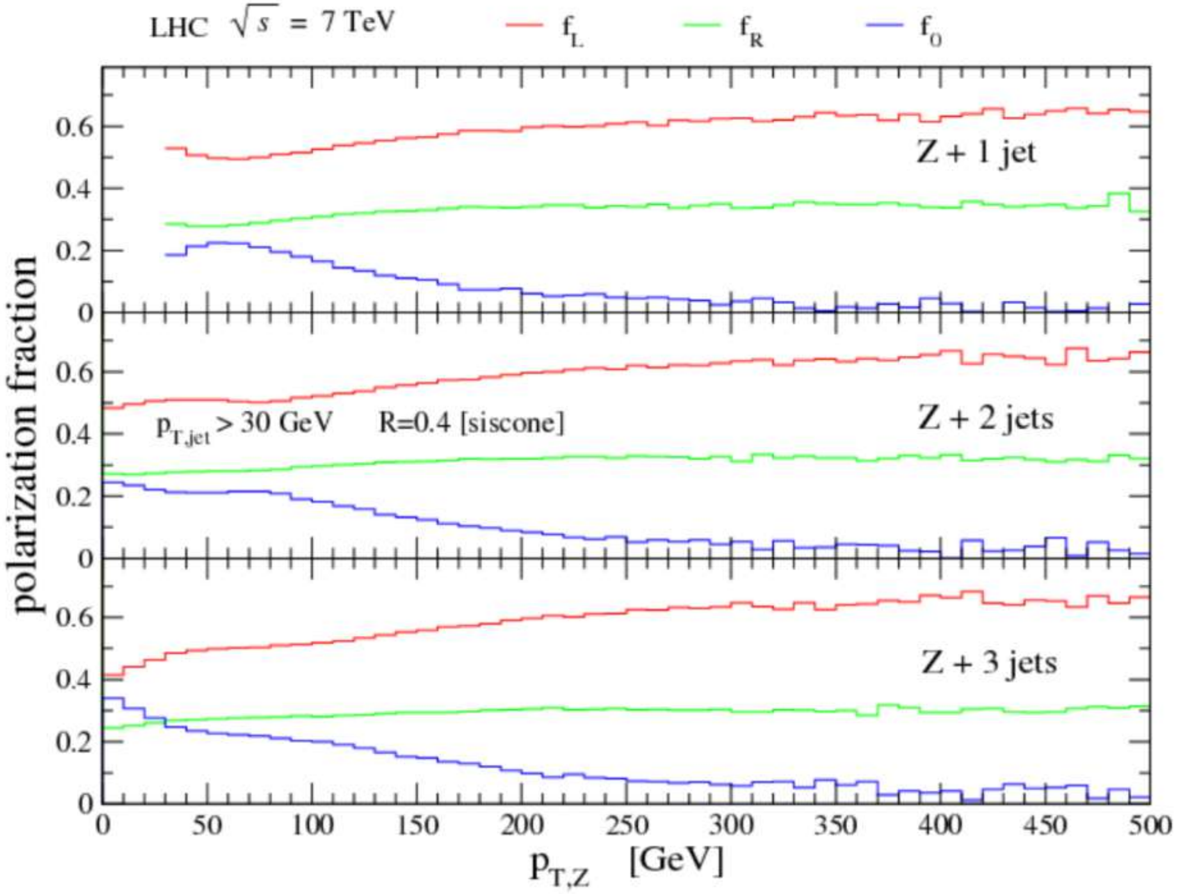
# Polarization fraction depend not only on θ, ϕ, but also PT and pseudorapitity y



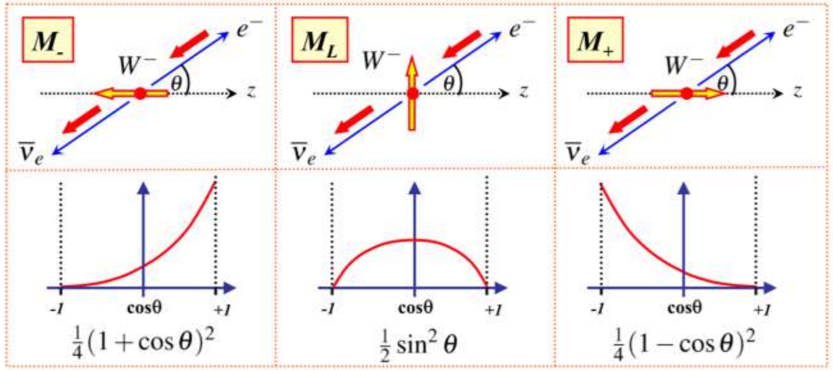
# But independent of the number of jets for W with high $p_T$

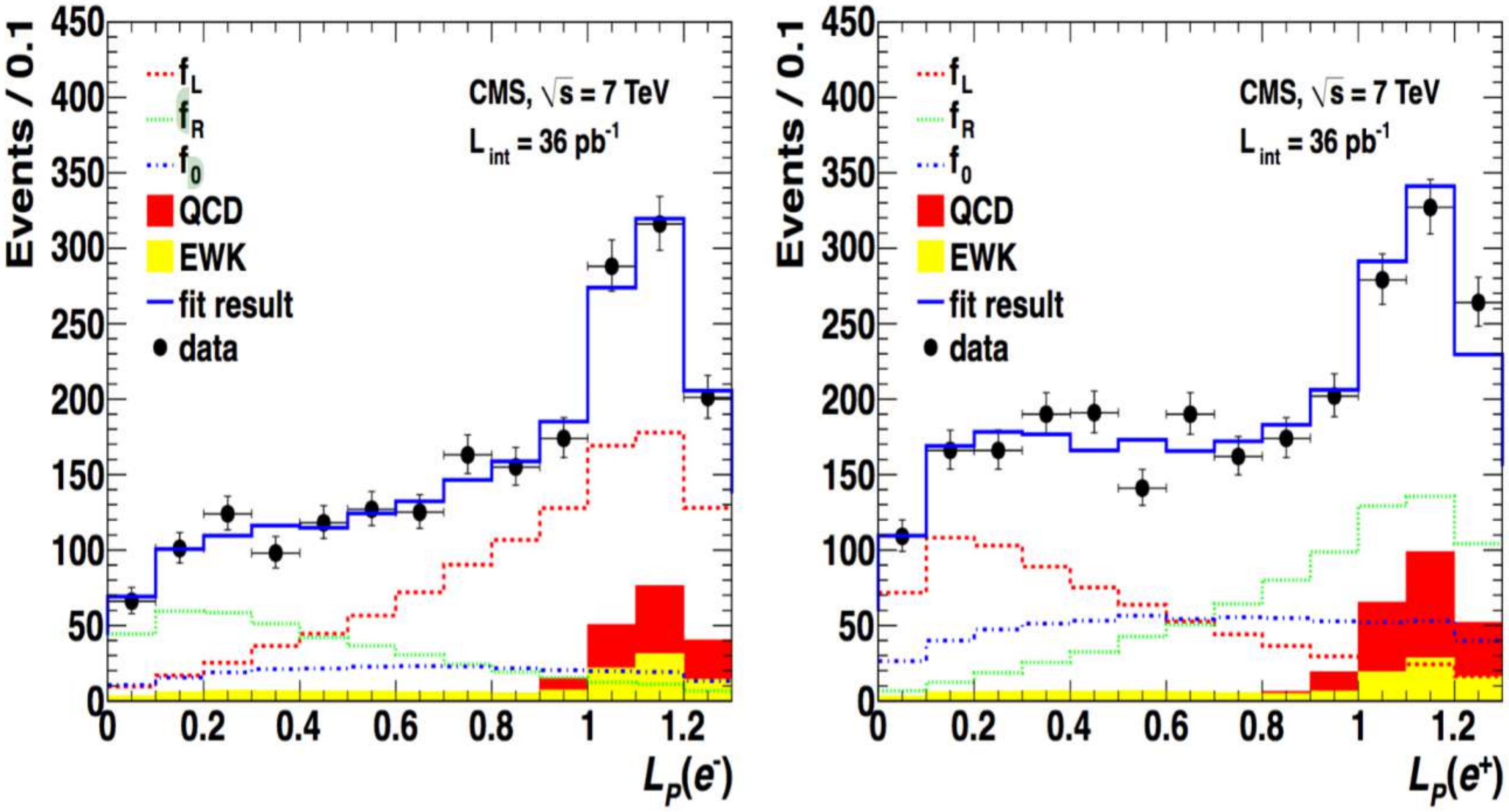


# Aside: W helicity sensitive to the u & d fraction on the proton

A priori, the values of the $f_i$ parameters are not expected to be the same for both charges, since for partons which carry a large fraction of the proton's momentum, the ratio of valence u quarks to sea quarks is higher than that for valence d quarks

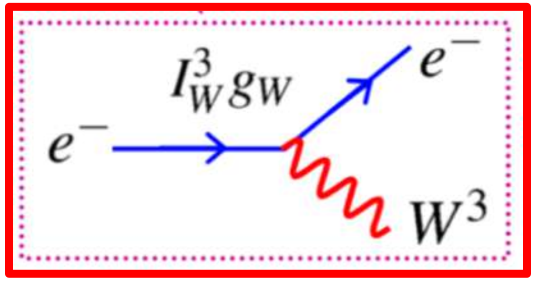



$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}.$$

Asymmetry is created

# SU(2)$_L$ : The Weak Interaction – Z boson

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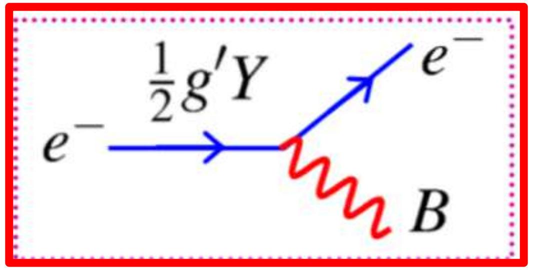



$$Y = 2Q - 2I_W^3$$

Q is the EM charge of a particle
$I_W^3$ is the third comp. of weak isospin

$$\sin^2\theta_W \approx 0.23$$

The physical bosons (the $Z$ and photon field, $A$) are:

$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$$
$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$$

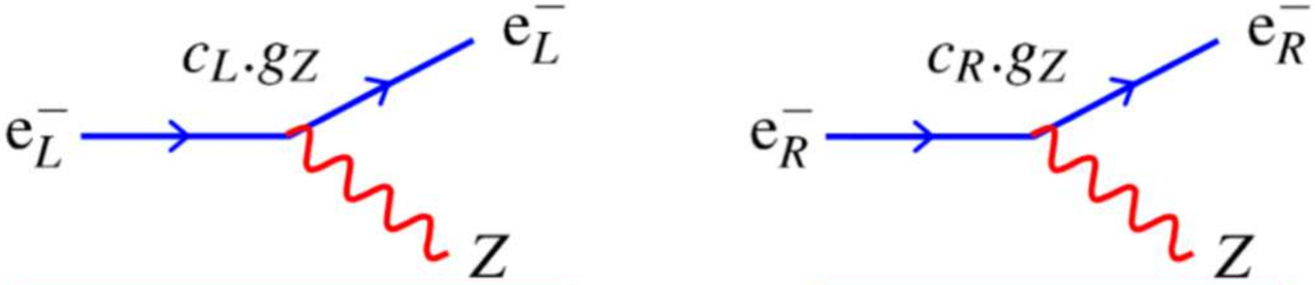
$\theta_W$ is the weak mixing angle

$$e = g_W \sin\theta_W = g' \cos\theta_W$$

(i.e. equate coefficients of L and R terms)

$$M_Z = \frac{M_W}{\cos\theta_W}$$

$$e = g_Z \cos\theta_W \sin\theta_W$$ i.e. $$g_Z = \frac{g_W}{\cos\theta_W}$$




$$c_L = I_W^3 - Q\sin^2\theta_W$$

$$c_R = -Q\sin^2\theta_W$$

**$W^3$ part of Z couples only to LH components (like $W^{\pm}$)**

**$B_\mu$ part of Z couples equally to LH and RH components**

★ **Which in terms of V and A components gives:**

with $$c_V = c_L + c_R = I_W^3 - 2Q\sin^2\theta_W$$ $$c_A = c_L - c_R = I_W^3$$

★ **Hence the vertex factor for the Z boson is:**

$$-ig_Z\frac{1}{2}\gamma_\mu\left[c_V - c_A\gamma_5\right]$$


**NEUTRAL WEAK INTERACTIONS**

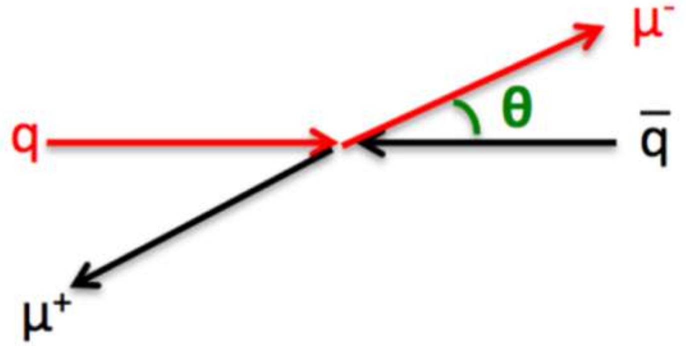
**Neutral vector and axial vector coupling in GWS model :**

| $f$ | $c_V$ | $c_A$ |
|---|---|---|
| $\nu_e, \nu_\mu, \nu_\tau$ | $\frac{1}{2}$ | $\frac{1}{2}$ |
| $e^-, \mu^-, \tau^-$ | $-\frac{1}{2} + 2\sin\theta_w$ | $-\frac{1}{2}$ |
| $u, c, t$ | $\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$ | $\frac{1}{2}$ |
| $d, s, b$ | $-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$ | $-\frac{1}{2}$ |

Presence of vector and axial-vector couplings (and weak mixing angle) introduces a forward-backward asymmetry. This is a **parton-level phenomenon** that we measure at **proton-level**.

$$A_{FB} = \frac{N(\cos\theta^*>0)-N(\cos\theta^*<0)}{N(\cos\theta^*>0)+N(\cos\theta^*<0)}$$

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{3}{8}A(1+\cos^2\theta^*) + \boldsymbol{B\cos\theta^*}$$

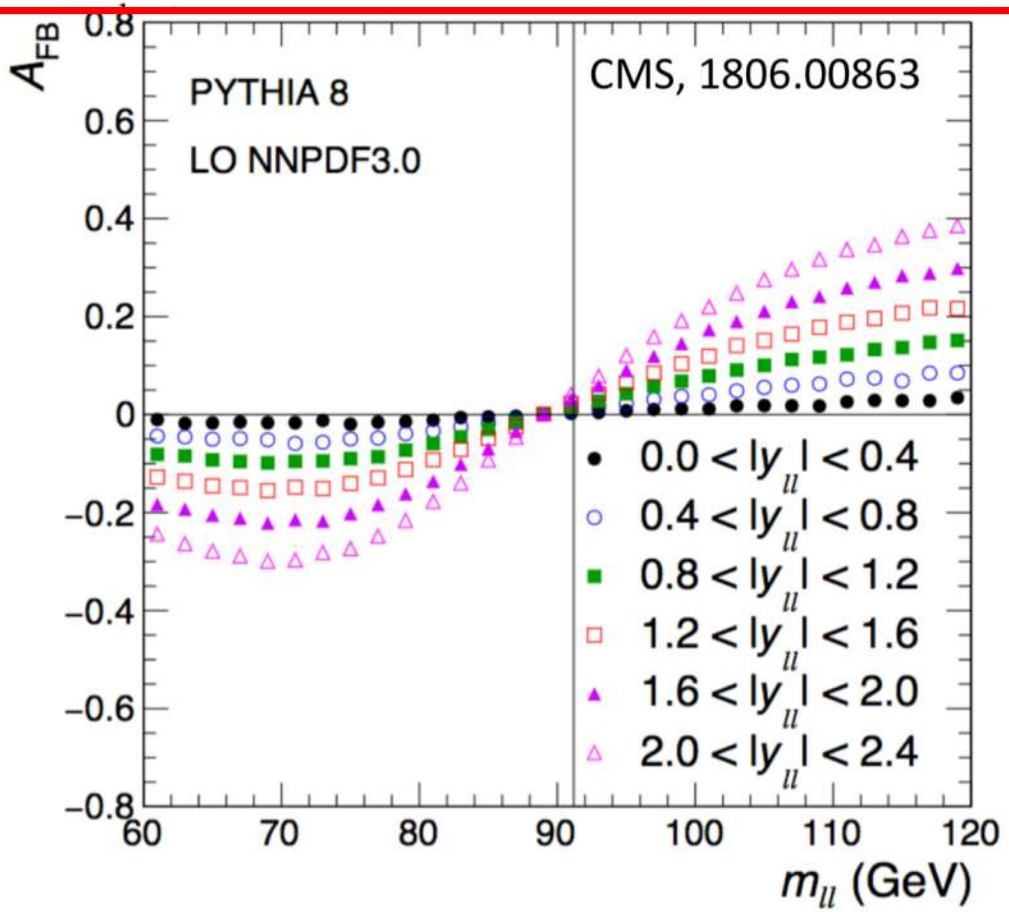



$$\cos\theta^* = \frac{2(P_1^+P_2^- - P_1^-P_2^+)}{\sqrt{m_{\ell\ell}^2(m_{\ell\ell}^2+p_{T,\ell\ell}^2)}} \times \frac{p_{z,\ell\ell}}{|p_{z,\ell\ell}|}$$

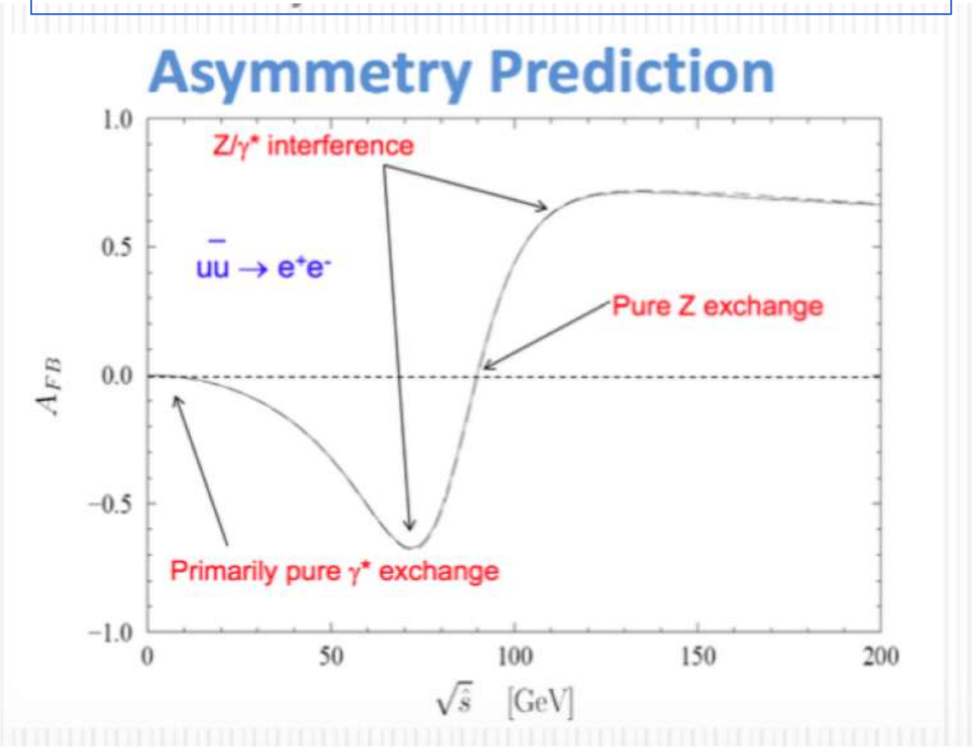
$$P_i^{\pm} = \frac{1}{\sqrt{2}}(E_i \pm p_{z,i})$$

# How to measure $\sin^2\theta_W$ at the LHC using pp→ Z ?

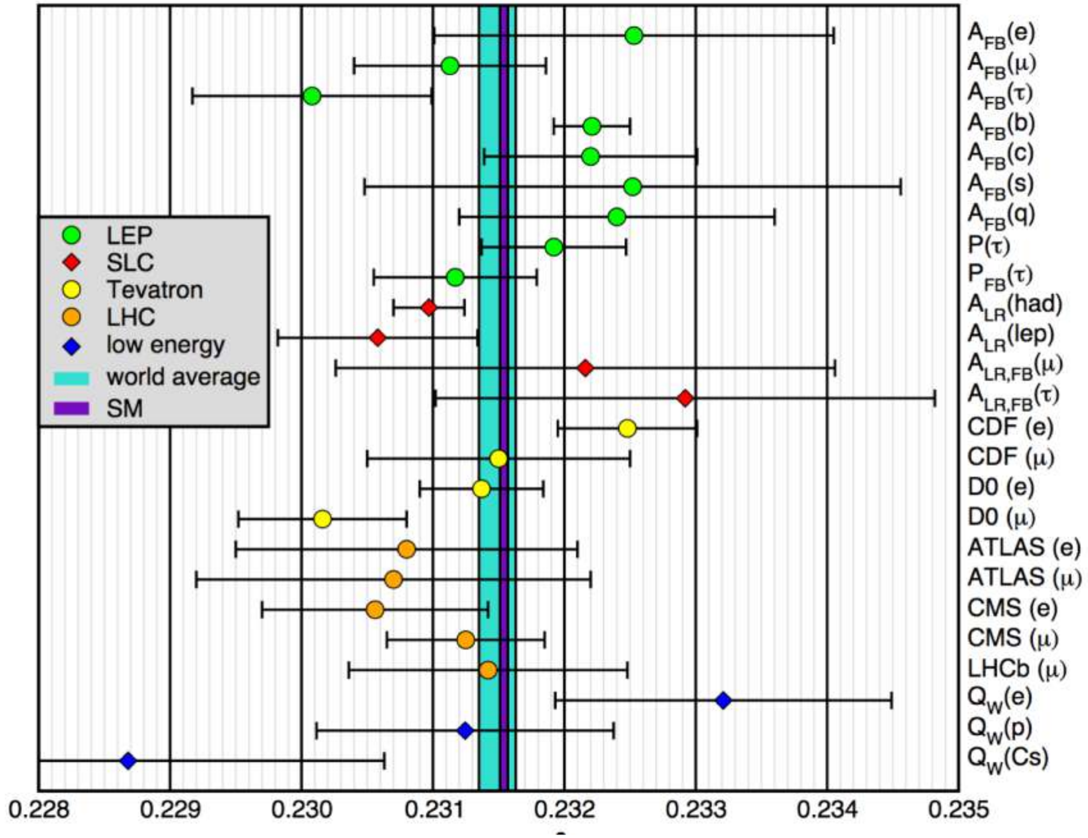
$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$

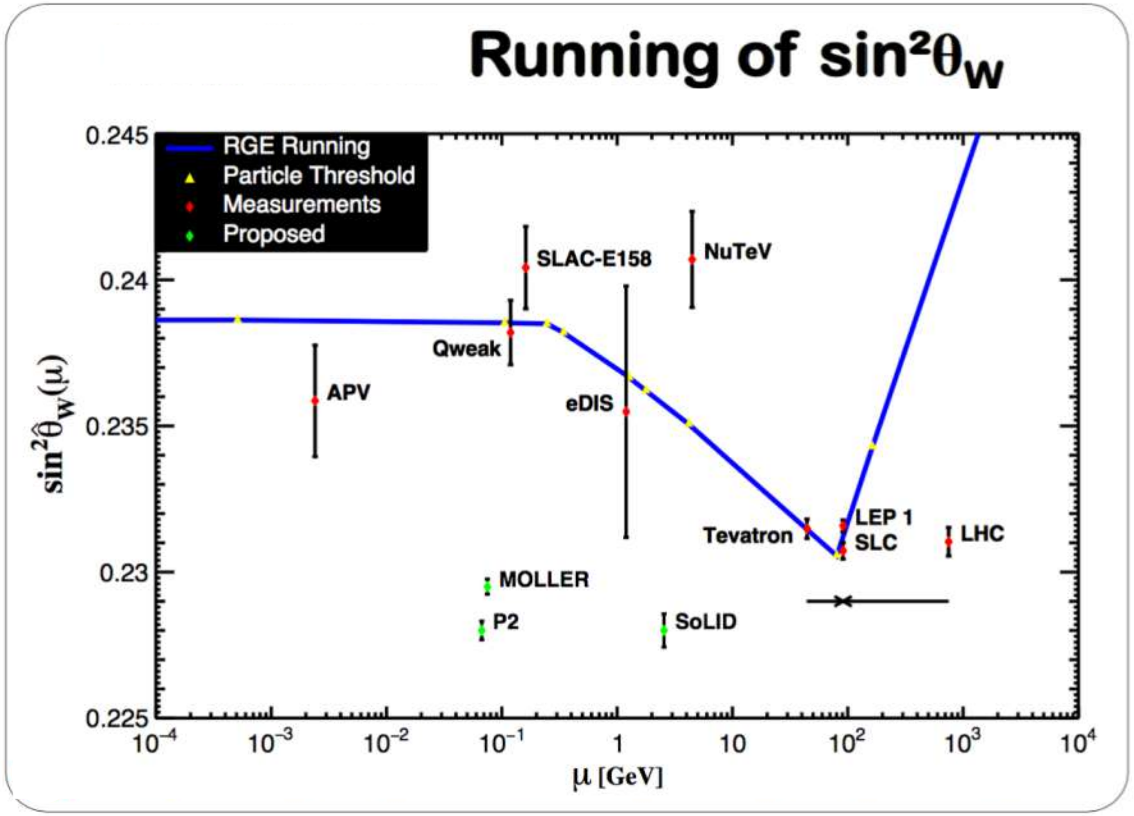



## Quantum Mechanical Effects




# Interplay between $\gamma$ & $Z^0$ and the Vector and Axial-Vector nature of the $Z^0$




# WORLD AVERAGE: Including LHC Results based on FB asymmetries in Z-decays



Reduction by factor of 2 expected with 13 TeV data and by 4 at the HL-LHC

# Motivation for precise measurement of the W-mass

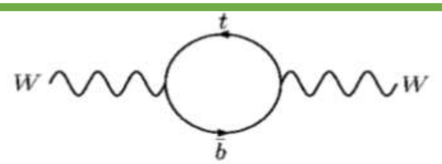
- SM at LO the W boson mass depends on parameters known with high precision:

$$\sin^2\theta_W = 1 - m_W^2 / m_Z^2$$

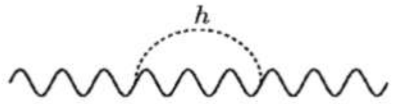
- Beyond LO : corrections depending on $m_H$ and $m_{top}$

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

$$\Delta r_{top} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2\tan^2\theta_W} \propto m_t^2$$




$$\Delta r_{Higgs} \approx \frac{11 G_F M_Z^2\cos^2\theta_W}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2} \propto \ln(m_h)$$



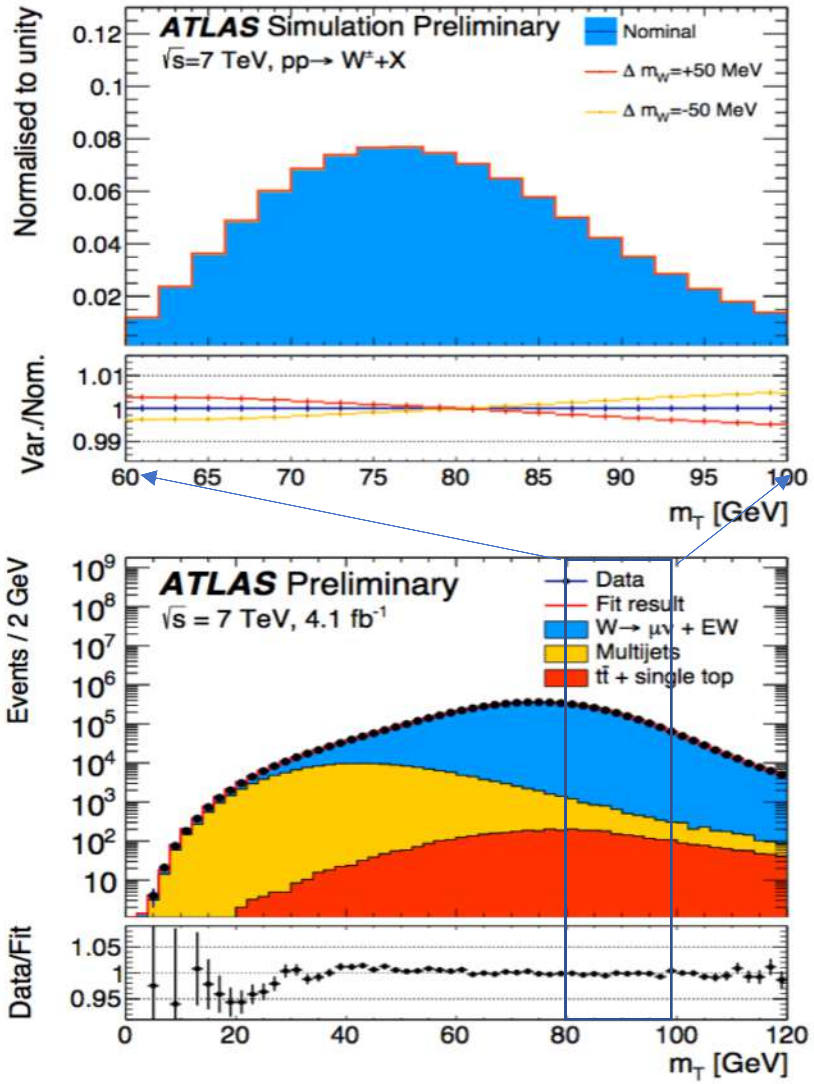

- Test of SM: compare measured $m_W$ to prediction from SM EWK fit
- SM fit without $m_W$: $m_W$ = 80354 +/- 7 MeV (arXiv:1803.01853)
- Previous combined measurements :

LEP $m_W$ = 80376 +/- 33 MeV Tevatron $m_W$ = 80387 +/- 16 MeV

# W-Mass Determination

$$m_W = 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

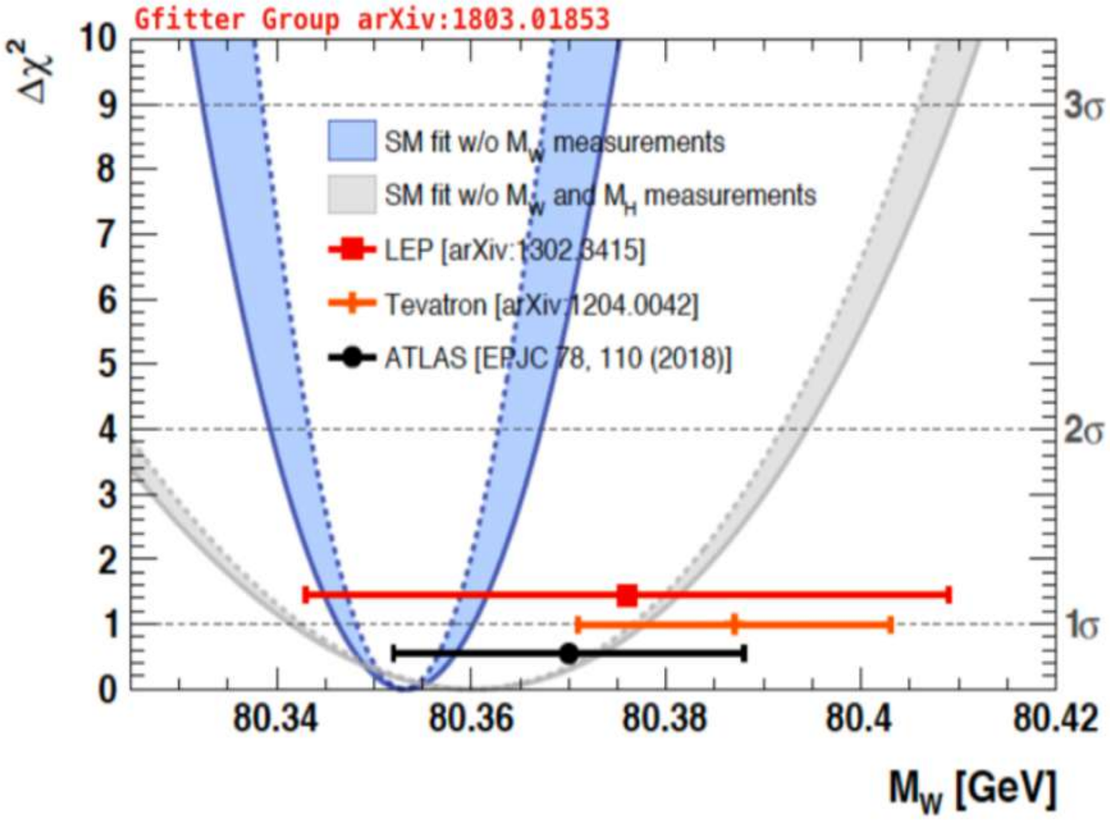
- Measurement based on 7 TeV data (4.6 $fb^{-1}$). It takes time to get the systematic uncertainties under control for precision!!
- Included ~$14.10^6$ W leptonically decaying W candidates
- Technique uses template fits to the W- $p_T$ and $m_T$ predictions

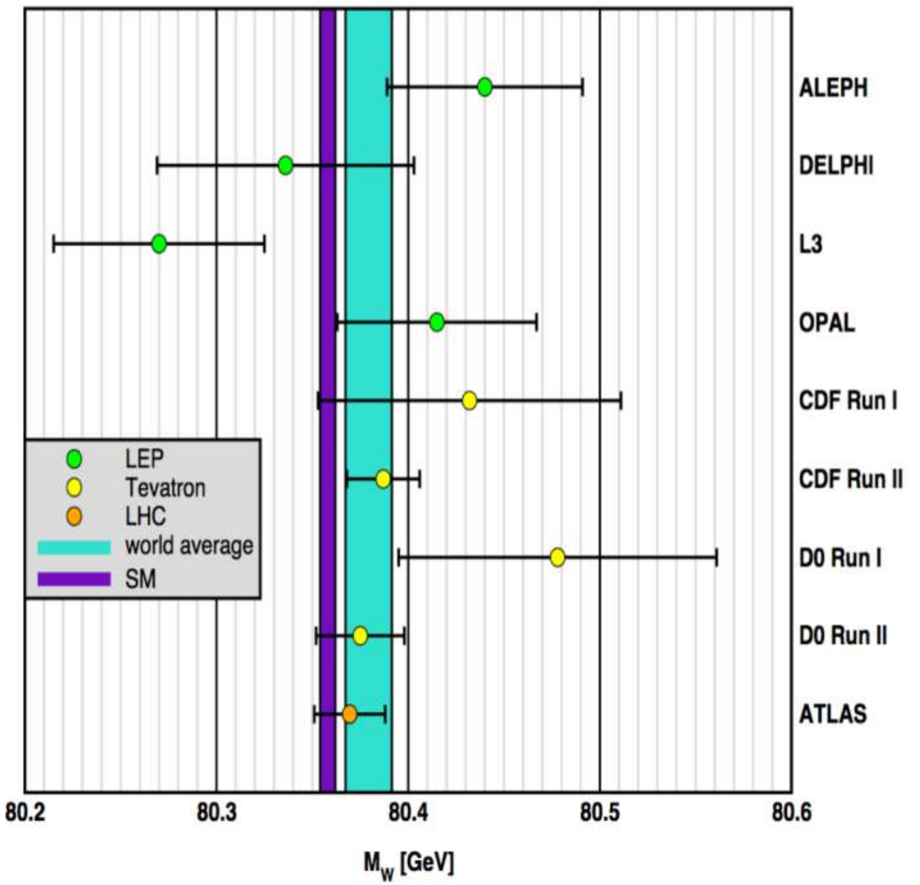



Calibration of energy scale, recoil response and efficiency studies using the large Z sample. Modelling of helicity effects constrained by W and Z data.

arXiv:1701.07240

- Good agreement with predicted $m_W$ from SM EWK fit.

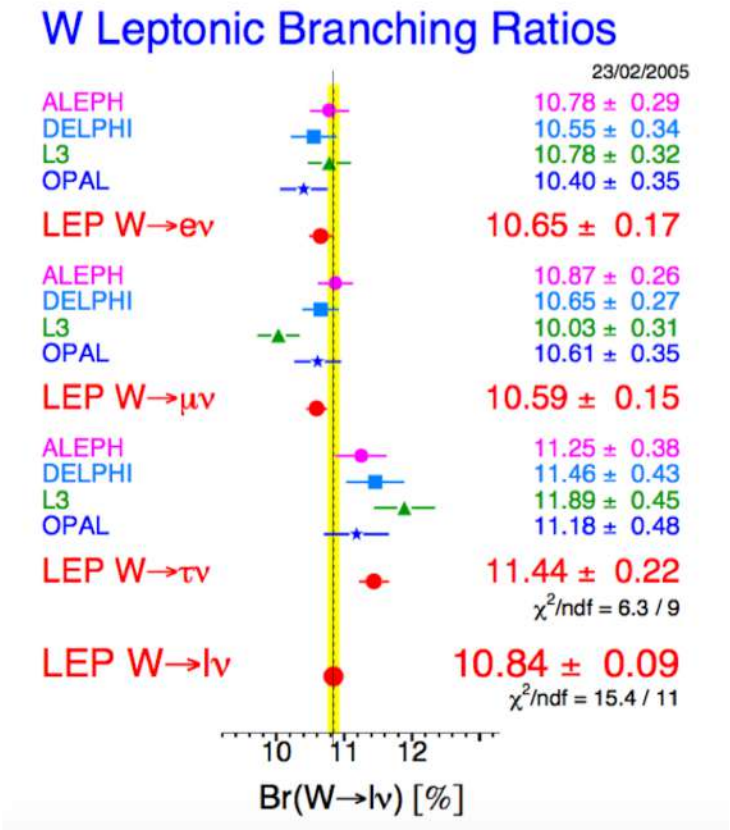



80.358 ± 0.004

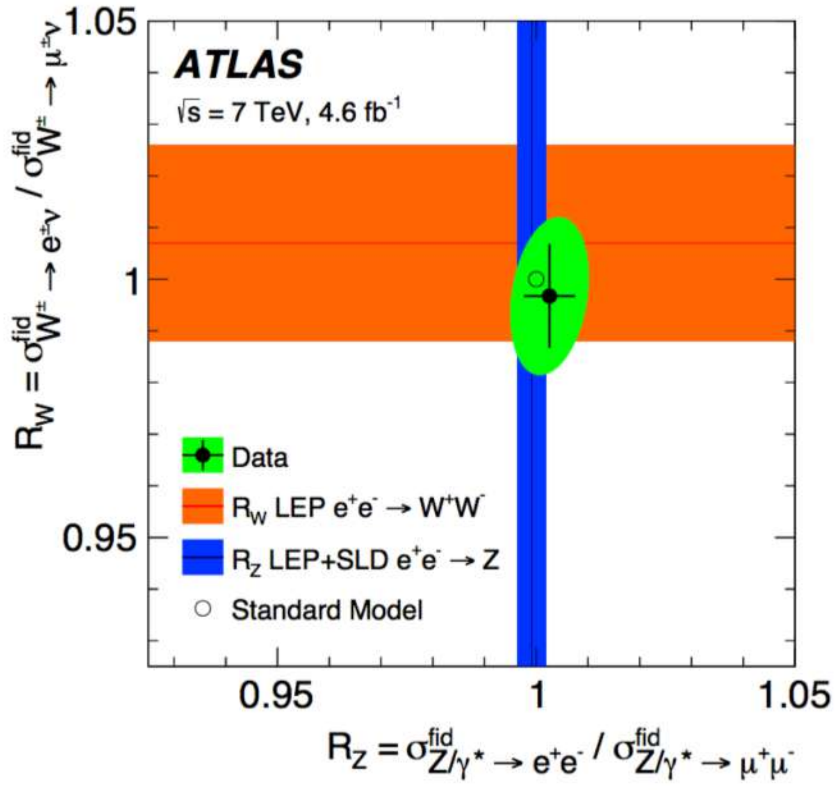
80.379 ± 0.012

# W Mass Measurement




No change
Since 2005...

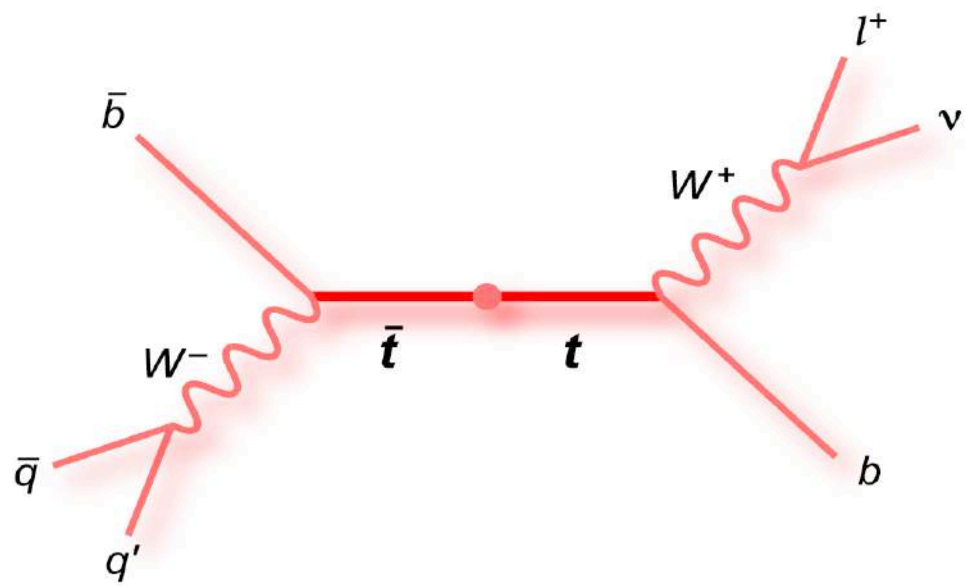
*τ BR ~2.7 σ larger than e/μ*




# Lepton Universality in W-decays

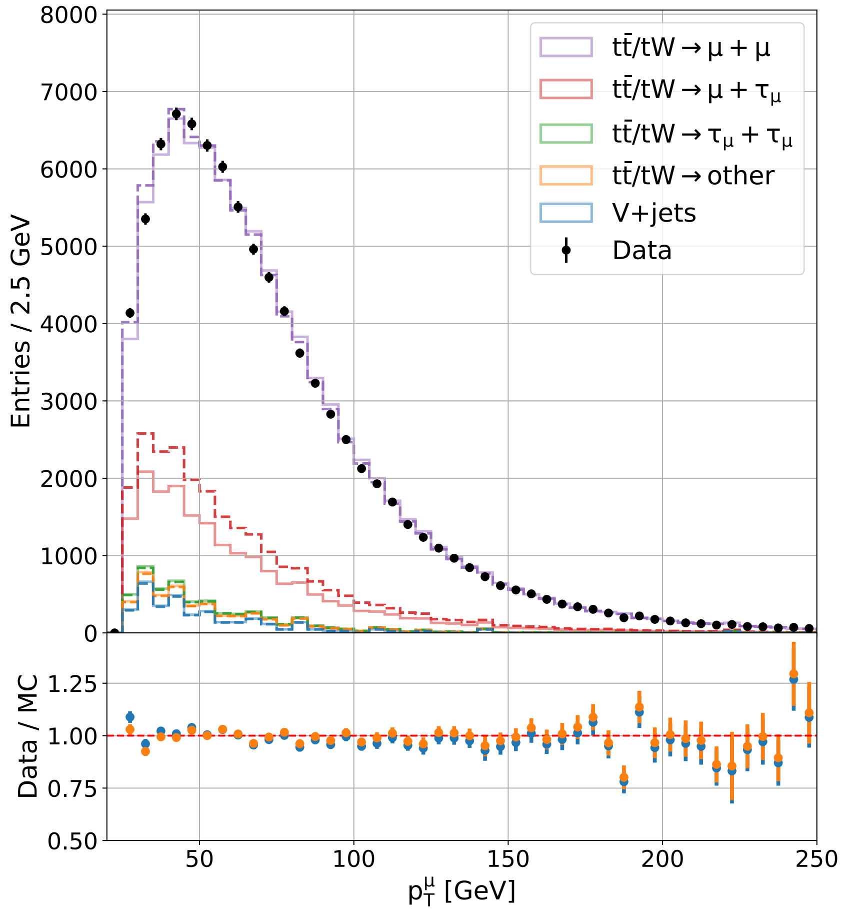
If anomalies in b-meson decays into τ's (D*τν) persists, it becomes more important to revise our assumptions on Lepton Universality

Possible because ttbar and tW are a great source of $W^{\pm}$



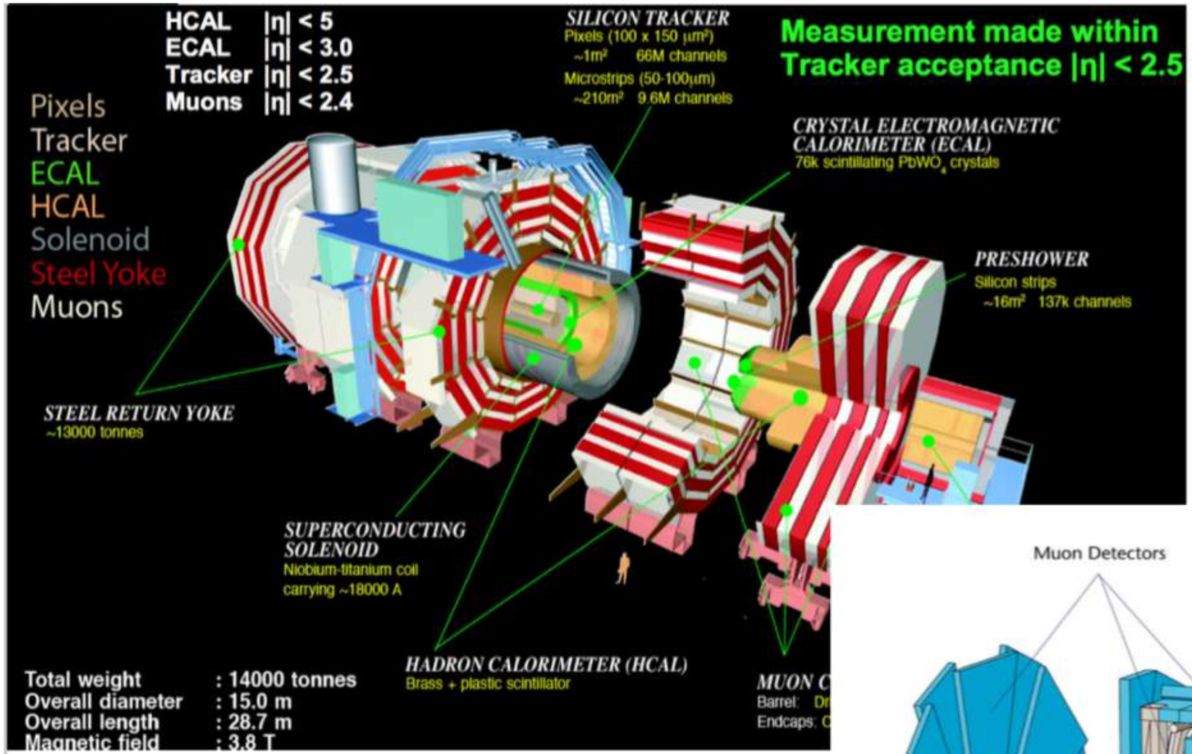

Becoming harder to mantain low energy thresholds for single lepton triggers level @ the LHC

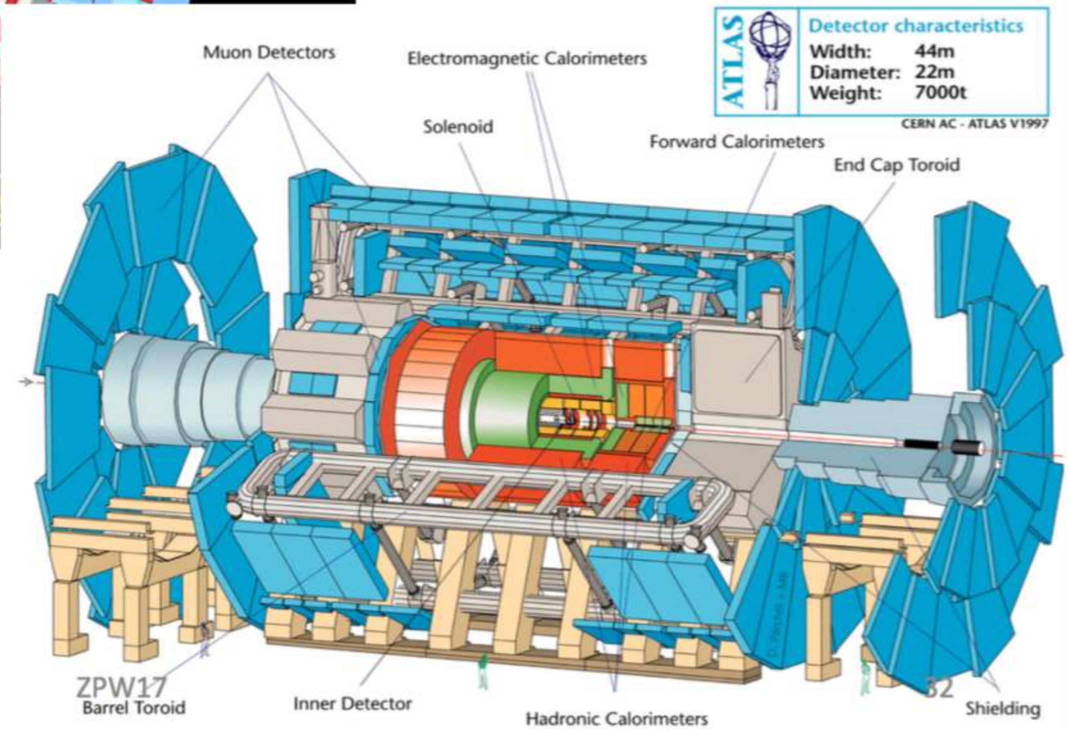
➔ Future requires new trigger schemes



# More tomorrow…

# Backup


HCAL |η| < 5
ECAL |η| < 3.0
Tracker |η| < 2.5
Muons |η| < 2.4
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
Measurement made within
Tracker acceptance |η| < 2.5
CRYSTAL ELECTROMAGNETIC
CALORIMETER (ECAL)
76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² 137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING
SOLENOID
Niobium-titanium coil
carrying ~18000 A
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T


Muon Detectors
Electromagnetic Calorimeters
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Solenoid
Forward Calorimeters
End Cap Toroid
ZPW17
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding