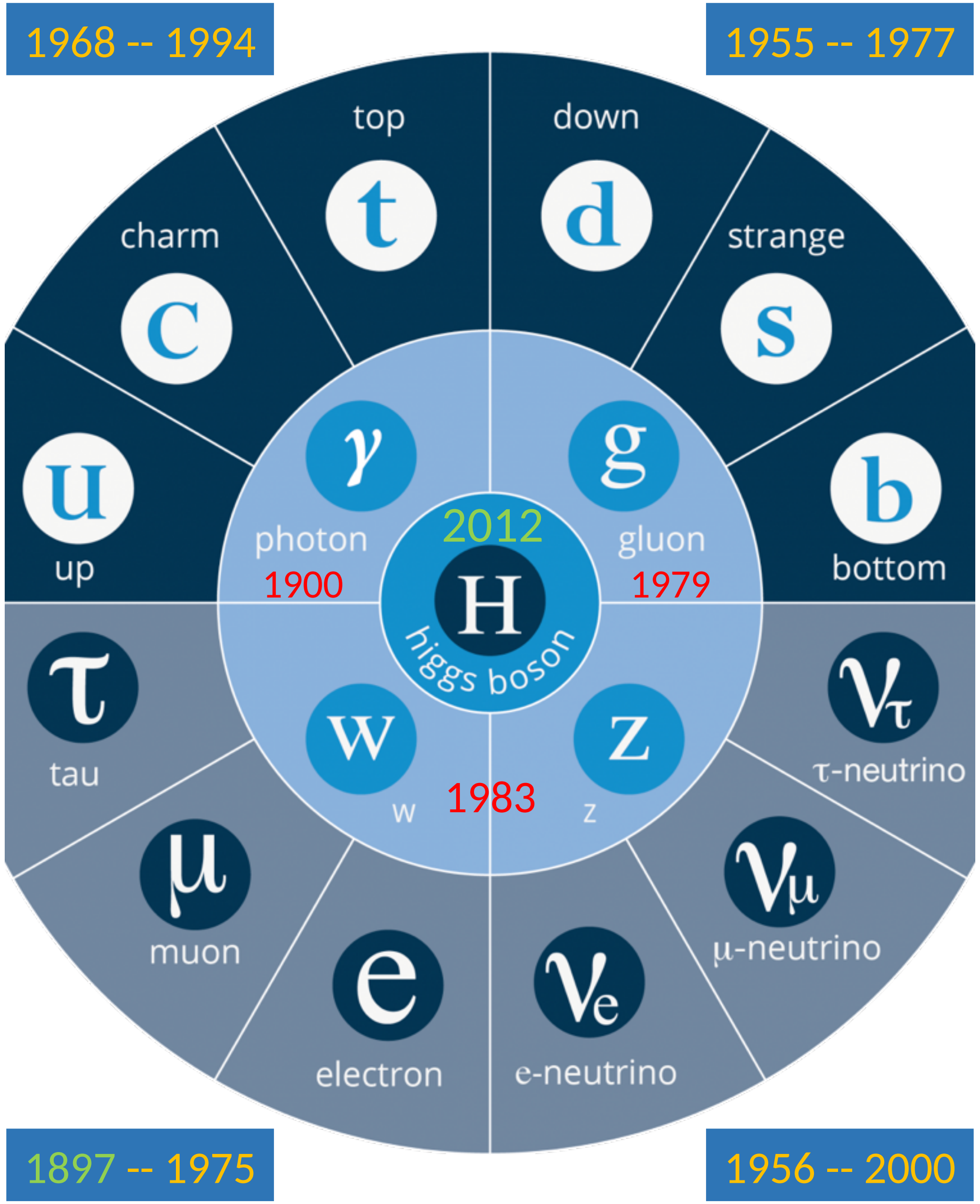
Lecture #1: XVII Mexican School of Particle Physics
2018 UNISON School of High Energy Physics

Top, ElectroWeak and QCD at the LHC

MAYDA M. VELASCO

NORTHWESTERN UNIVERSITY & COFI INSTITUTE

COLEGIO DE FISICA FUNDAMENTAL E INTERDISCIPLINARIA DE LAS AMERICAS



50 year anniversary of the Standard Model [1]

50 year anniversary of the Standard Model [1]

- Today: focus on Electroweak Interactions: γ^*, W, Z^0

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

- Tomorrow: on top-quark

➔ Tomorrow: on top-quark

Strong interactions: g will be included in both lectures

Strong interactions: g will be included in both lectures

Higgs Boson cover in other lectures

[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

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

Strong interactions

Colour

Weak Isospin

Weak Hypercharge

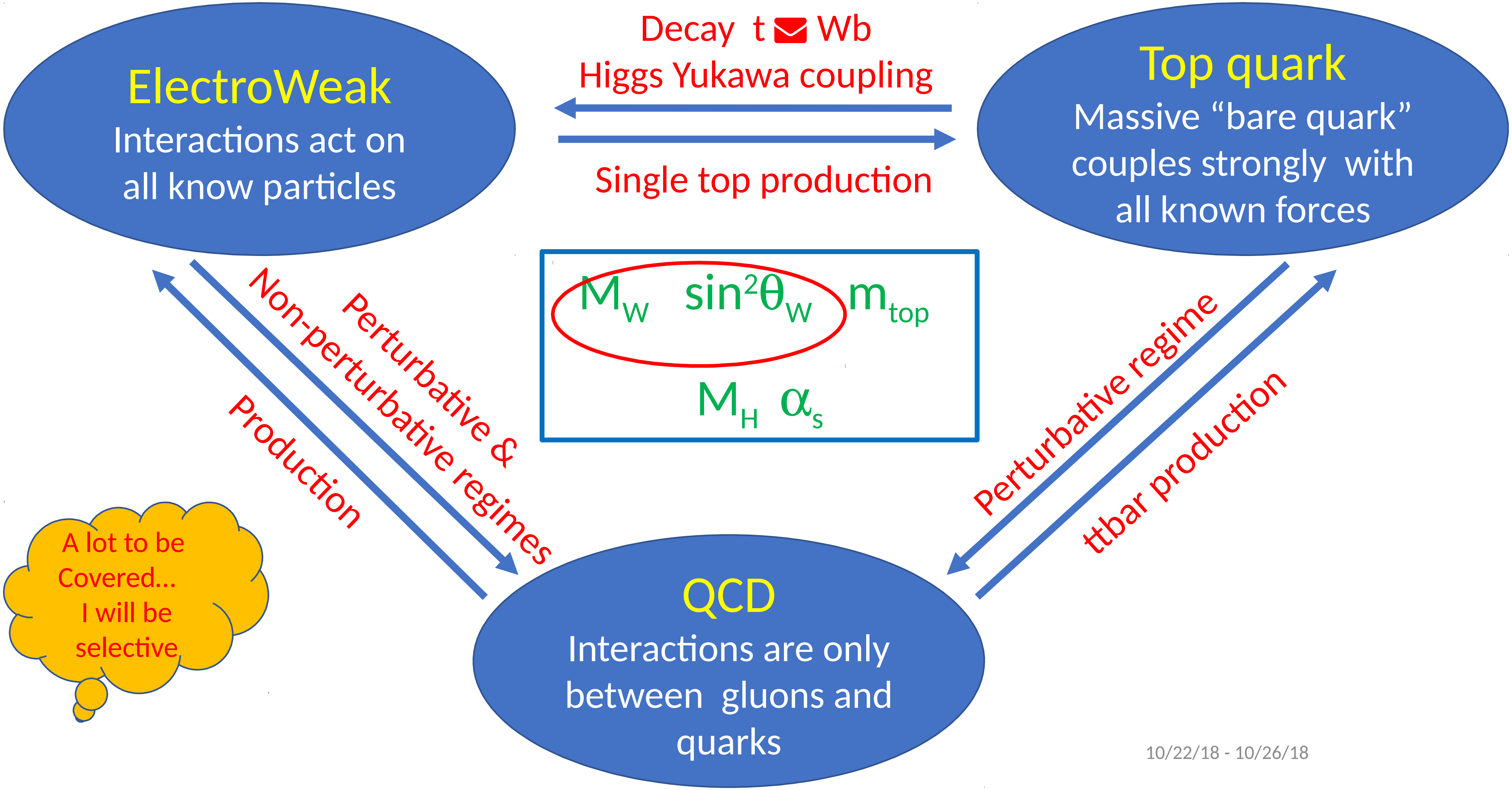
Electroweak interactions

LHC able to give us precision measurements of the relevant parameters and possible violation of current assumptions

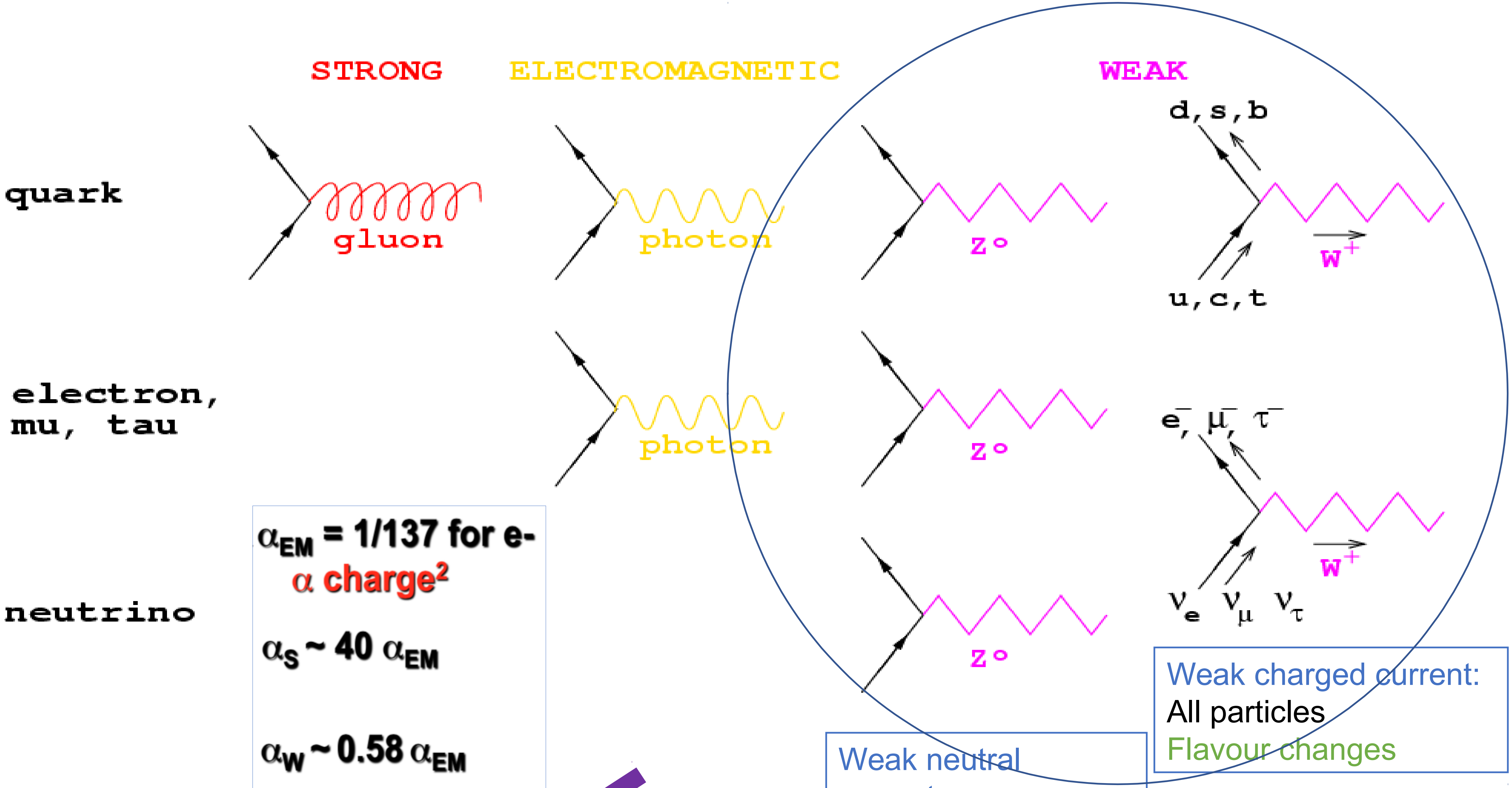
3 symmetry groups

⇒ Interactions described by 3 coupling constants: g_s, g, g'

⇒ Universal fermion-boson couplings



ElectroWeak
Interactions act on all know particles
Decay $t \to Wb$
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 α_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



α_{EM} = 1/137 for e-

α charge^2

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

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

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

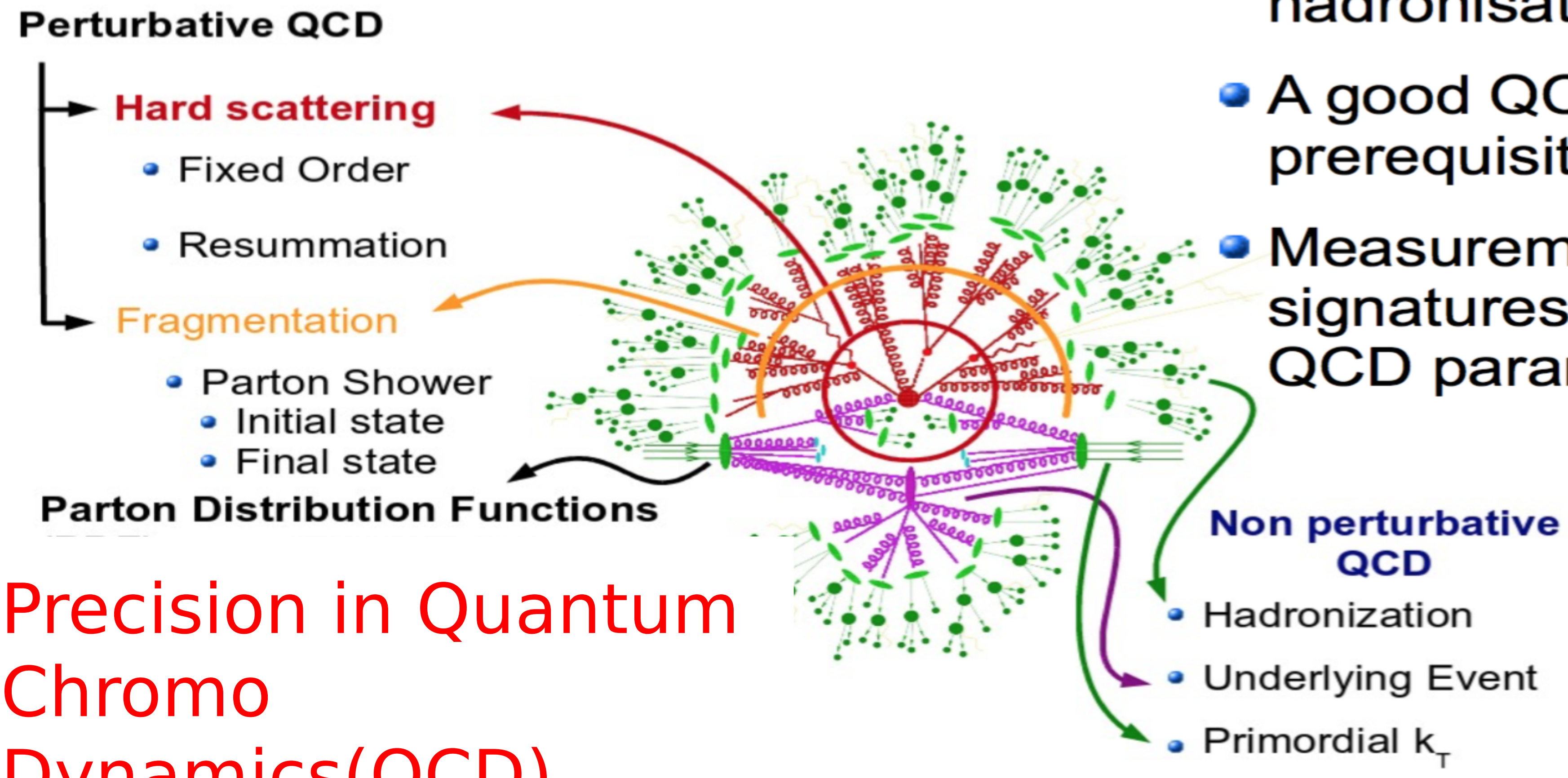
Weak charged current:
All particles
Flavour changes

Weak neutral current:
All particles
NO change of flavour

Precision in Quantum Chromo Dynamics(QCD)

Collinear factorization

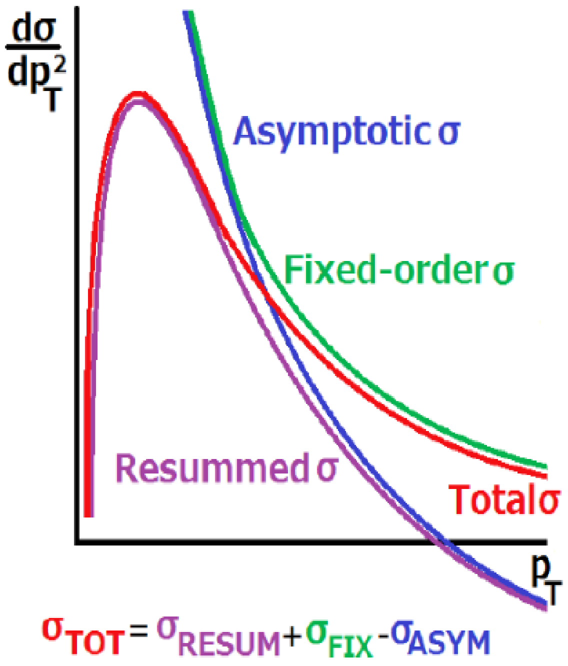
$$\sigma_{pp\to X} = \Sigma_{i,j} \int dx_1 dx_2 f_i^p(x_1,\mu) f_j^p(x_2,\mu) \times \sigma_{ij\to X}$$

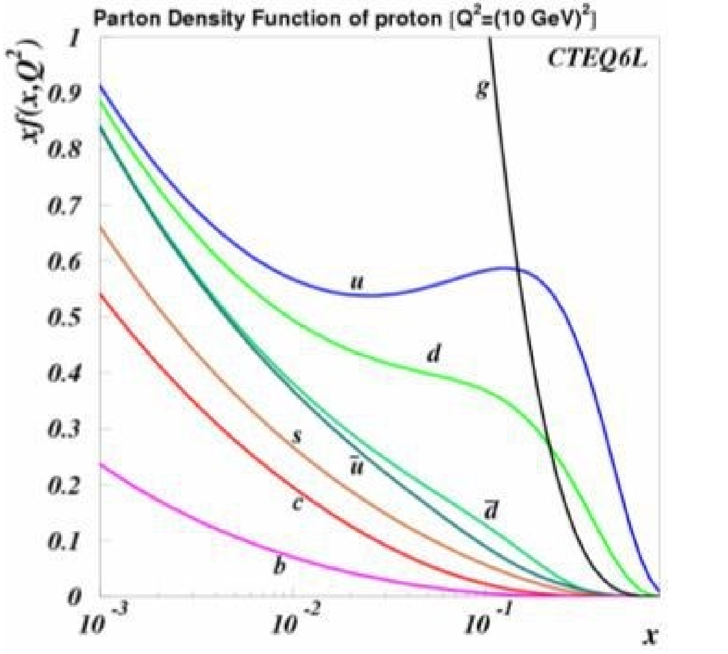


- EW physics at hadron colliders cannot forget about QCD: almost every EW observable is influenced by PDF, Underlying event, hadronisation
- A good QCD model is a prerequisite for EW physics
- Measurements of clean EW signatures help to constrain QCD parameters and models

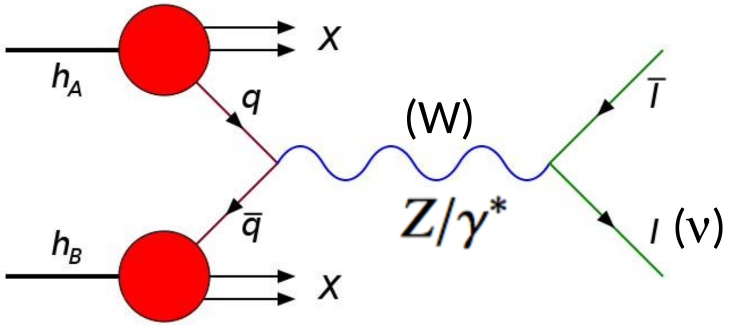
Example, Drell-Yan Process: pp ➔ Z or W

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





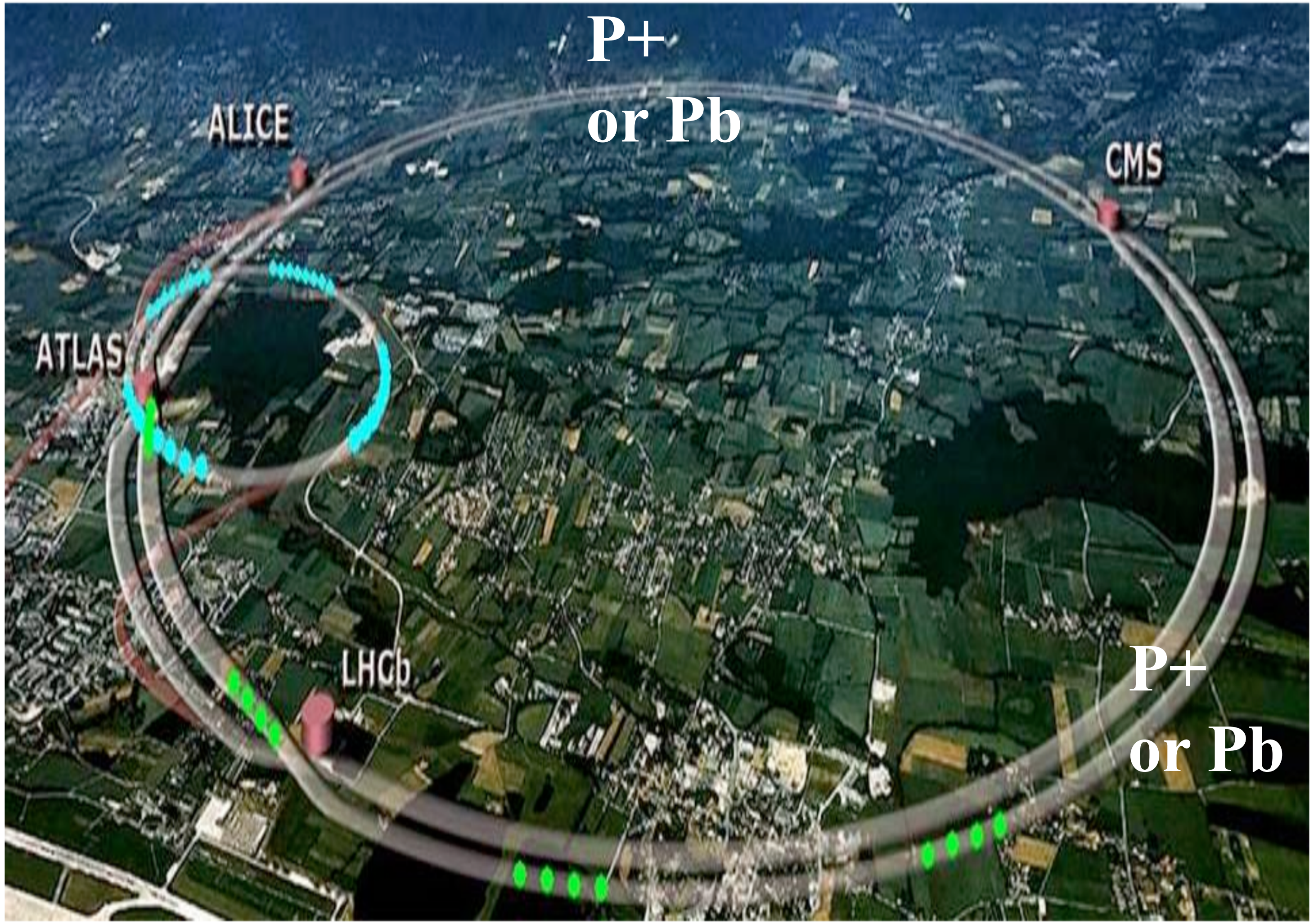
Main uncertainty in important EWK precision measurements



High p_T: described at fixed-order of α_s by perturbative QCD predictions

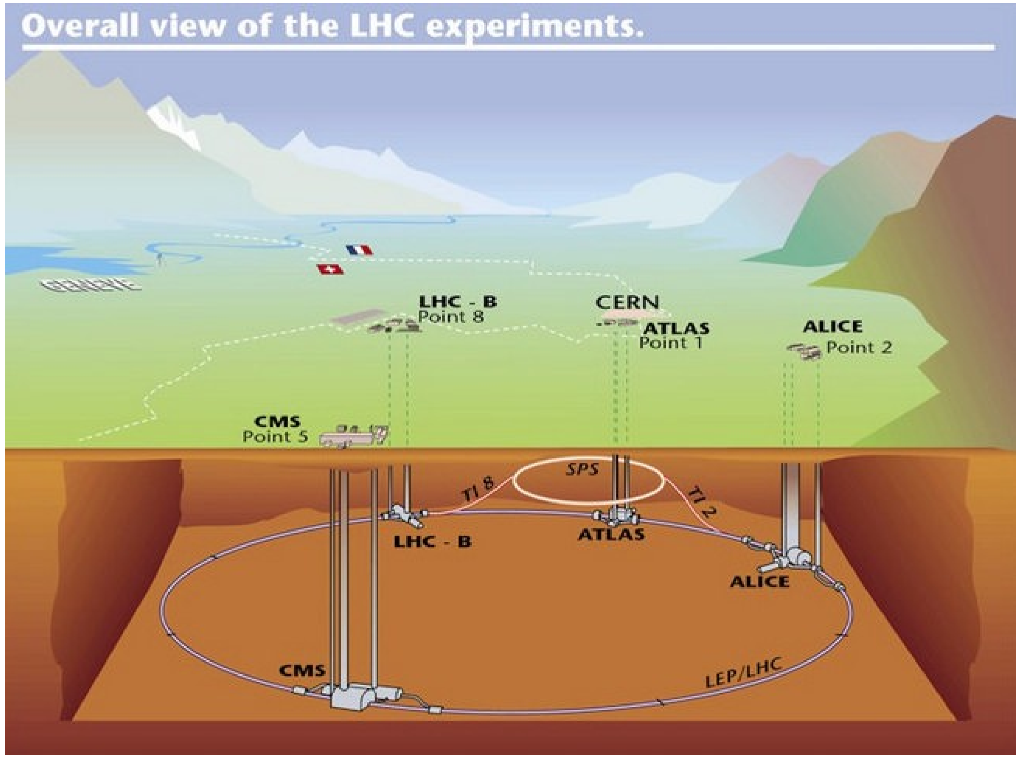
Small p_T: described using resummation of multiple soft-gluon emissions. Non-perturbative part that has to be parametrised and extracted from the data.

This is of great importance when calculating the W-mass

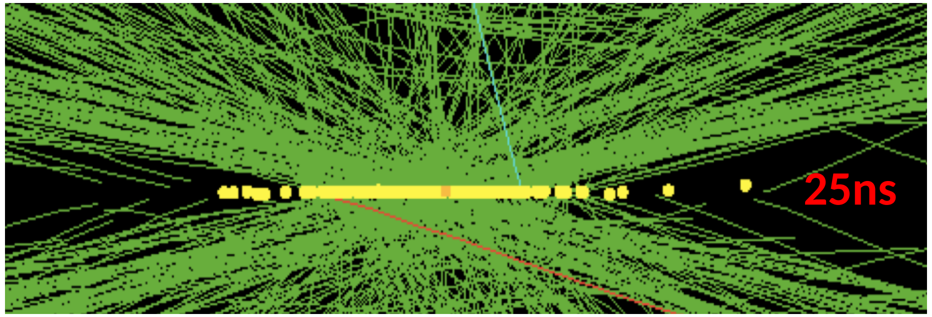


Large Hadron Collider @ CERN

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

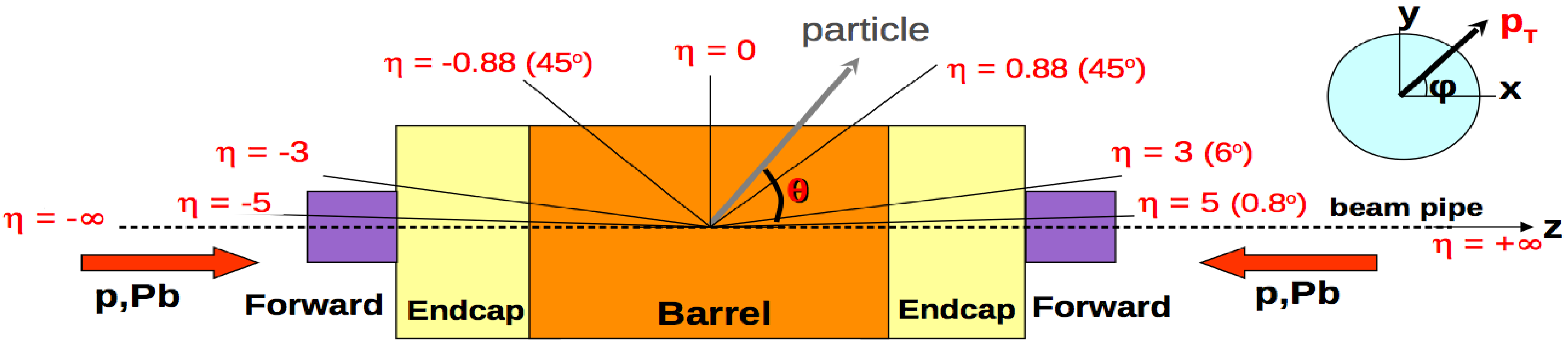


High Luminosity achieved with beams with
>10^{11} protons/bunch &
> 2800 bunches
in the ring



LHC collisions: kinematics

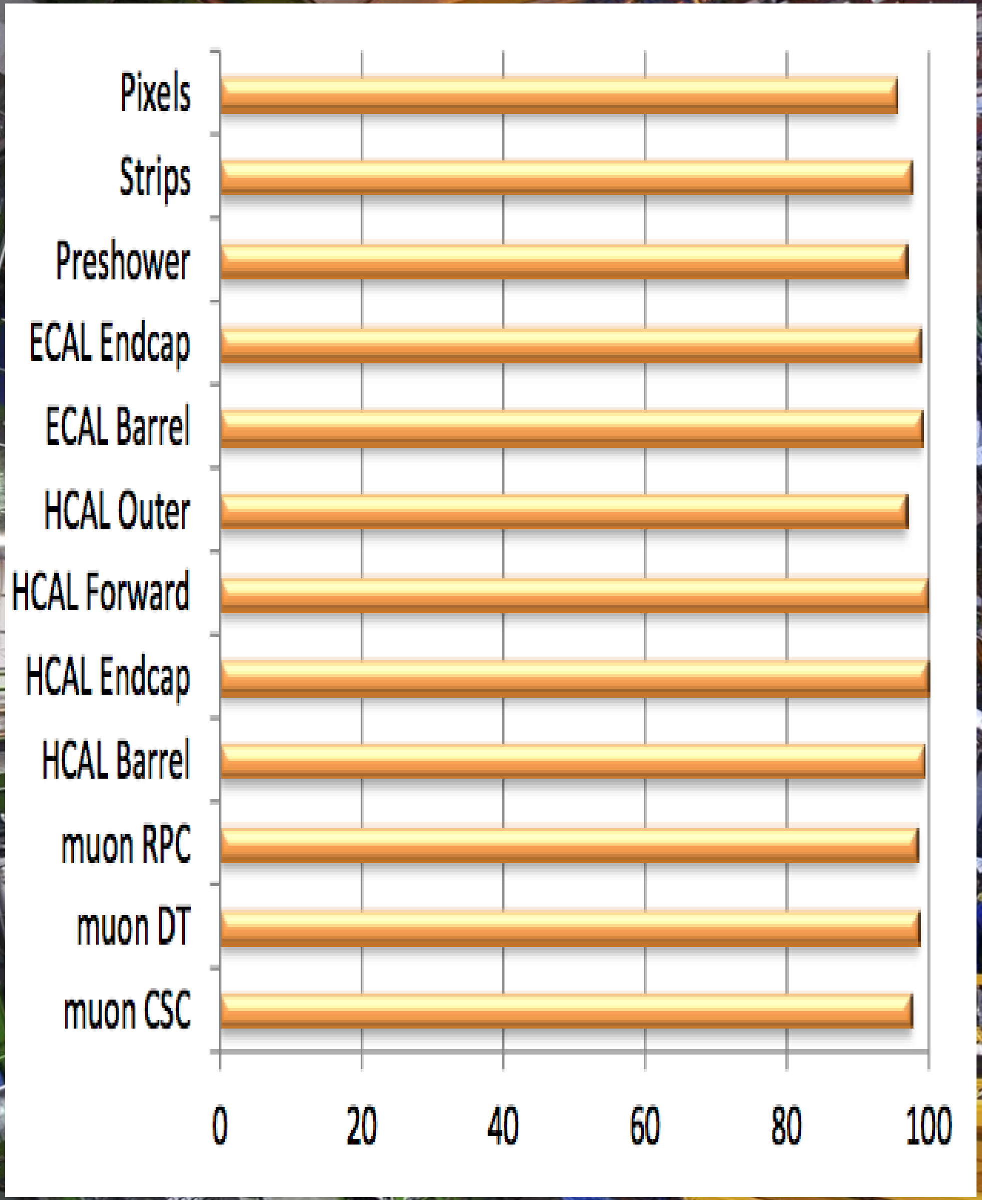
- Hadron = "beam" of partons with initial p_T~0 but unknown p_L fractions.
- Hadron-hadron collisions variables: p_T (transverse), y or η (longitudinal).

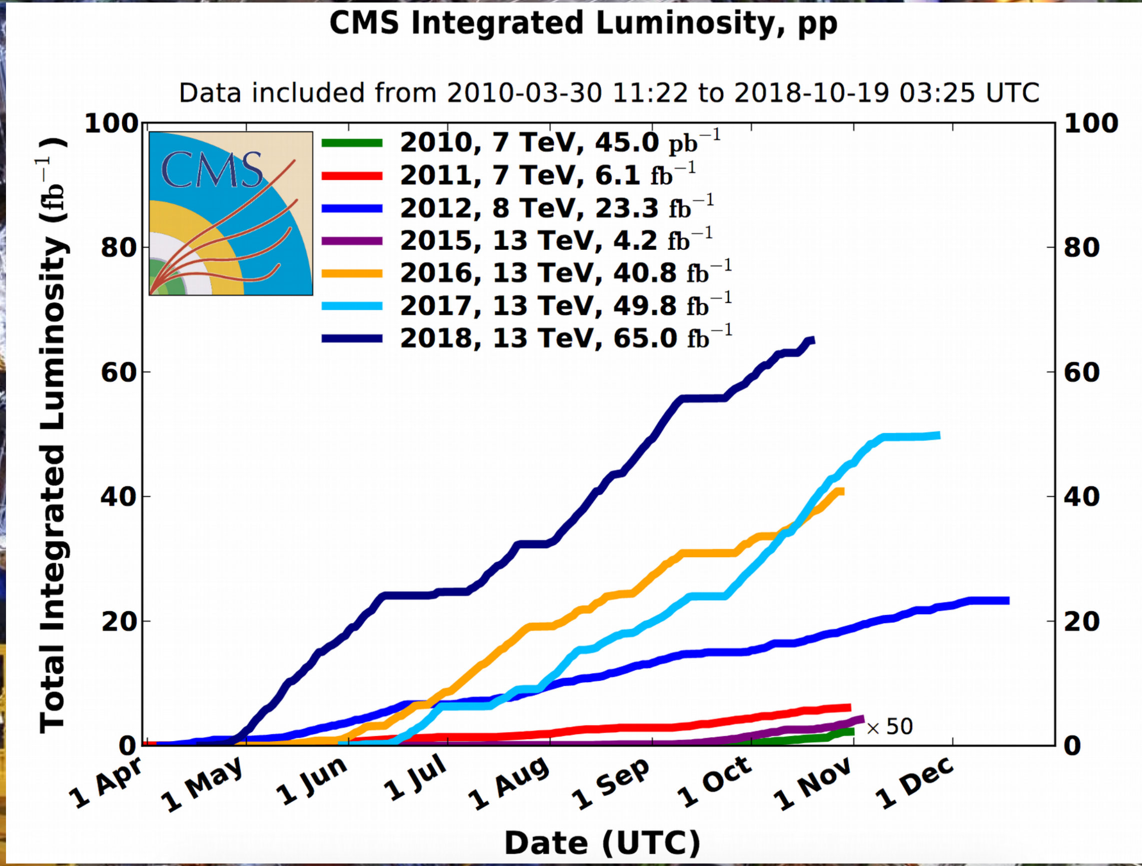


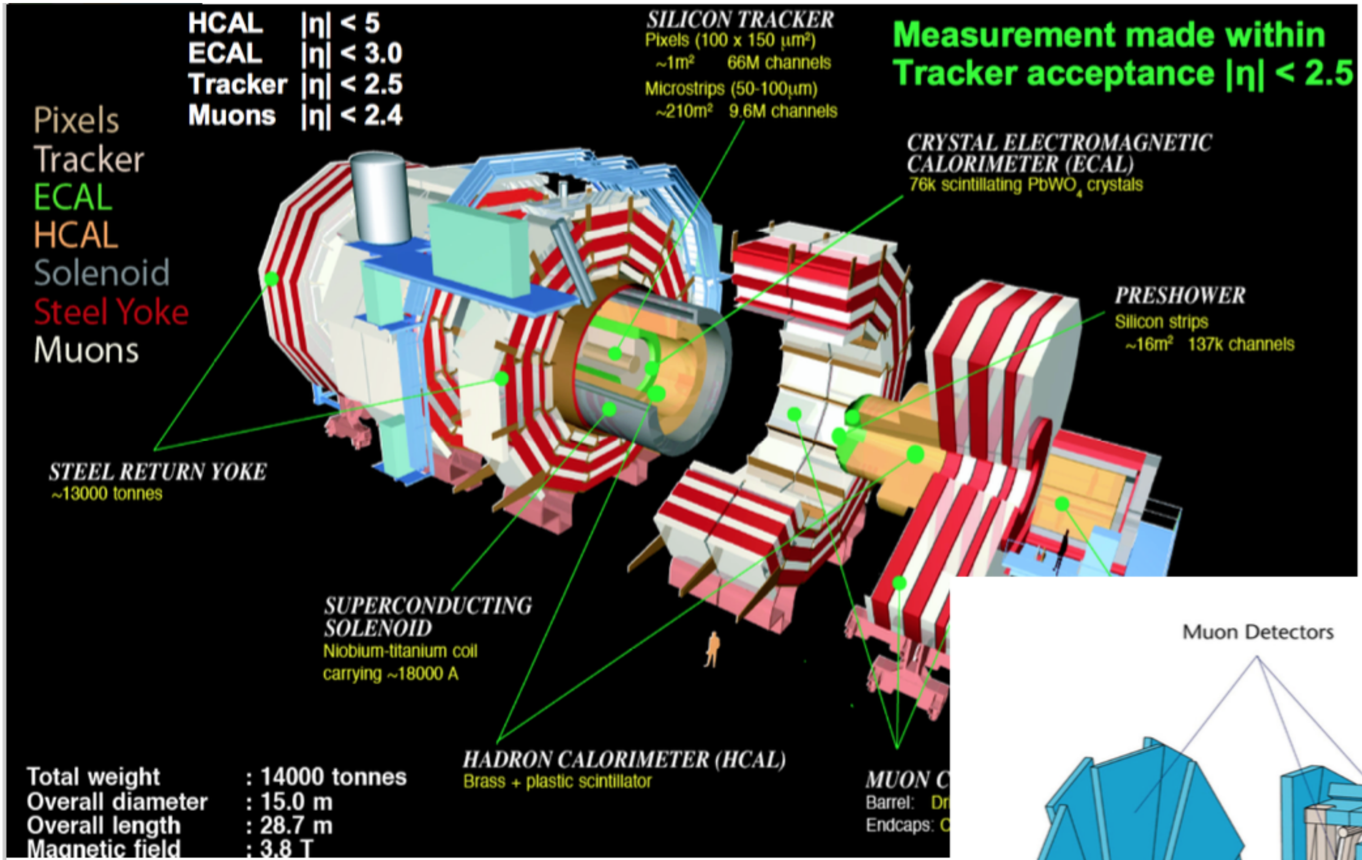
- Transverse momentum: $|\mathbf{p}_T| = p \sin(\theta)$ conserved in hadron-hadron colls.
- Rapidity: $y = -\log \frac{E + p_z}{E - p_z}$ (Differences in rapidity are conserved under Lorentz boosts in the z-direction)

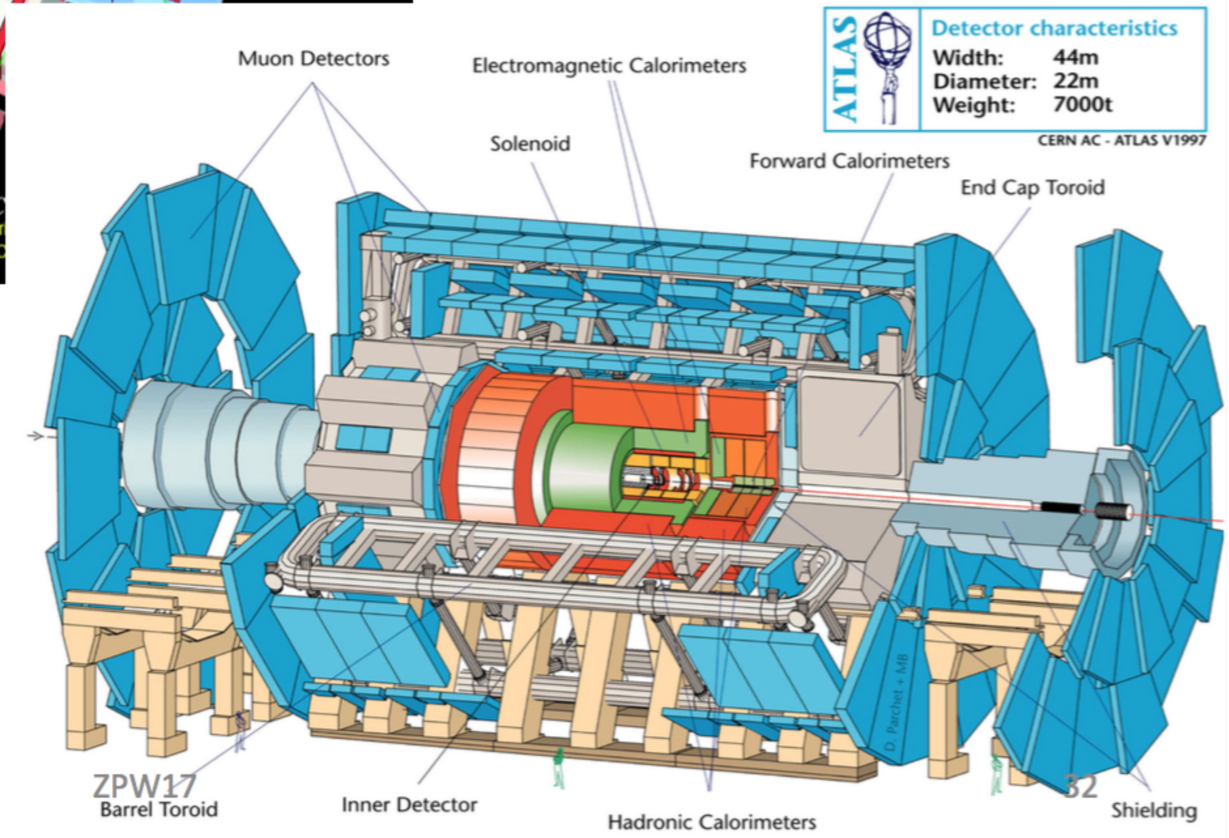
Pseudorapidity: $\eta = -\ln[\tan(\theta/_2)]$ (η~y if E≫m, and θ not too small)

CMS Transverse view

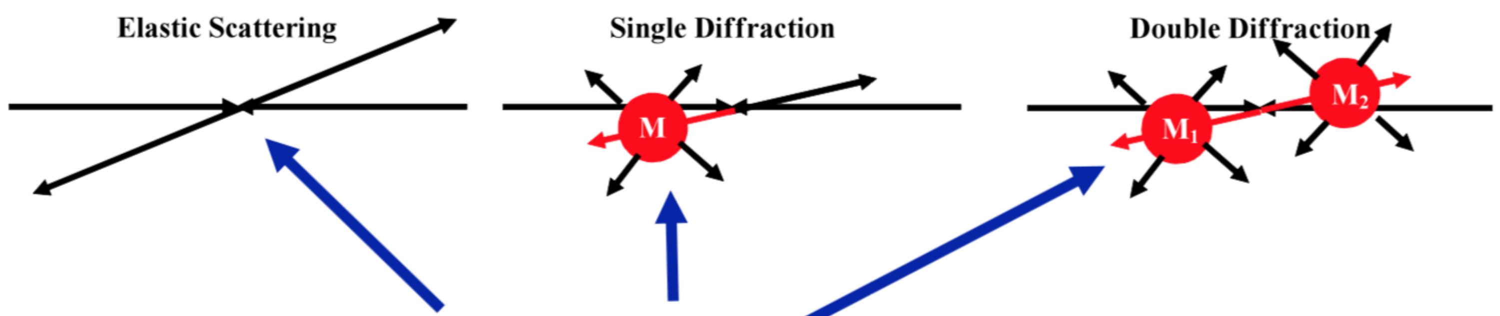




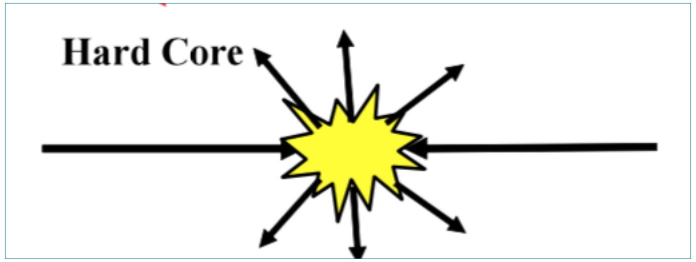

HCAL |η| < 5
ECAL |η| < 3.0
Tracker |η| < 2.5
Muons |η| < 2.4
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
Measurement made within
Tracker acceptance |η| < 2.5
CRYSTAL ELECTROMAGNETIC CALORIMETER (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


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

Proton – Proton Collisions

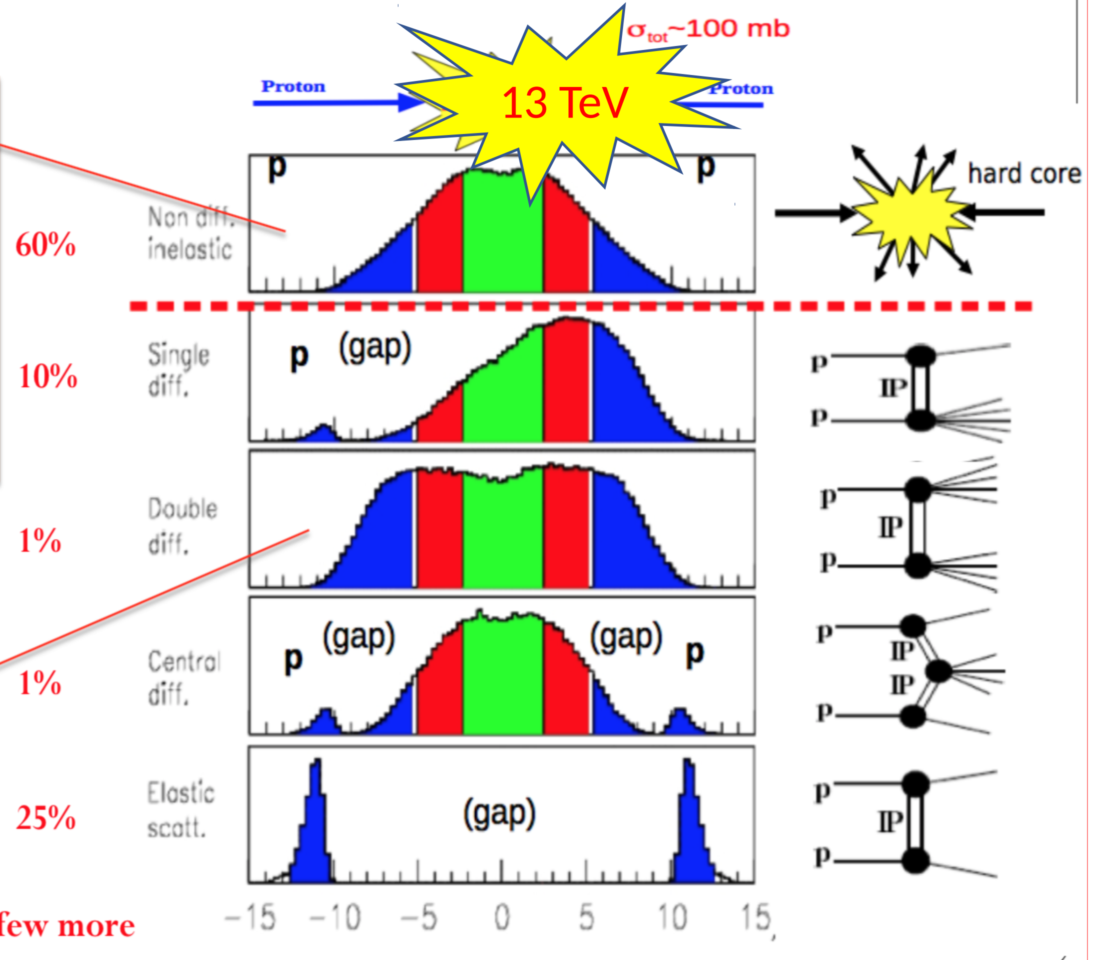


$$\sigma_{tot} = \sigma_{EL} + \sigma_{IN}$$



Non Diffractive

This includes Double-Parton Scattering (DPS)
➔Two hard Scatters by partons from the same pp collision
≠ to pileup

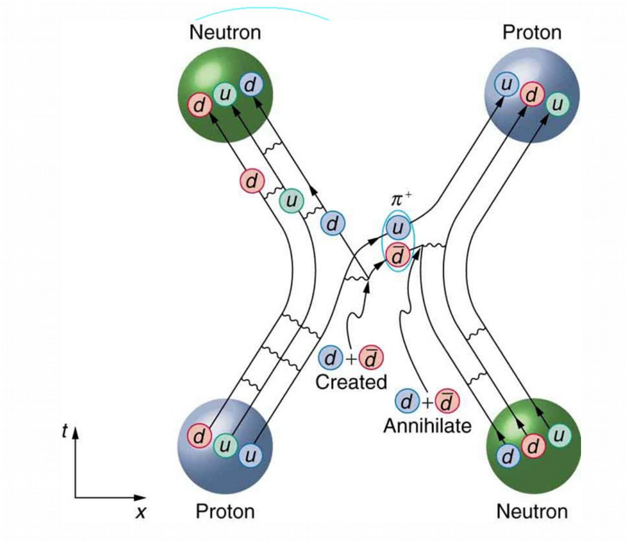


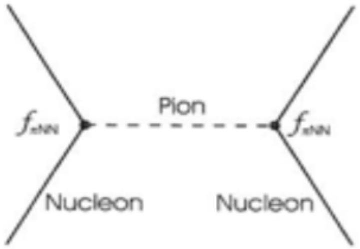
Important regime for Searches

Like VBF Topology

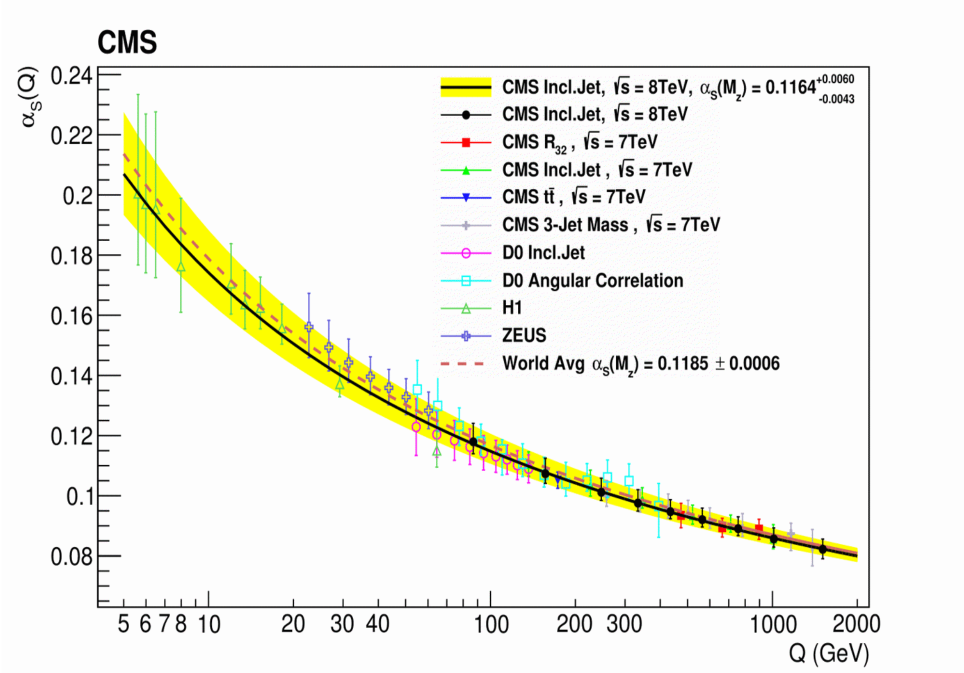
Low energy NUCLEON-NUCLEON INTERACTIONS

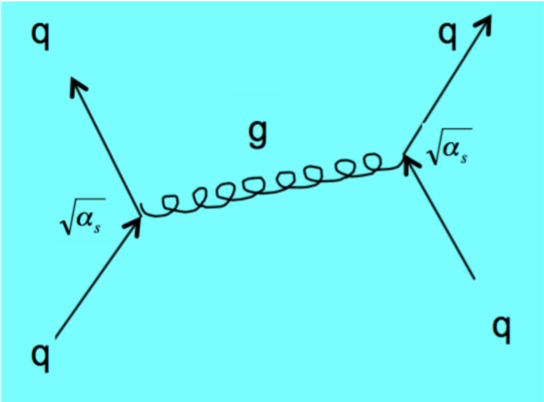
3 valence quarks





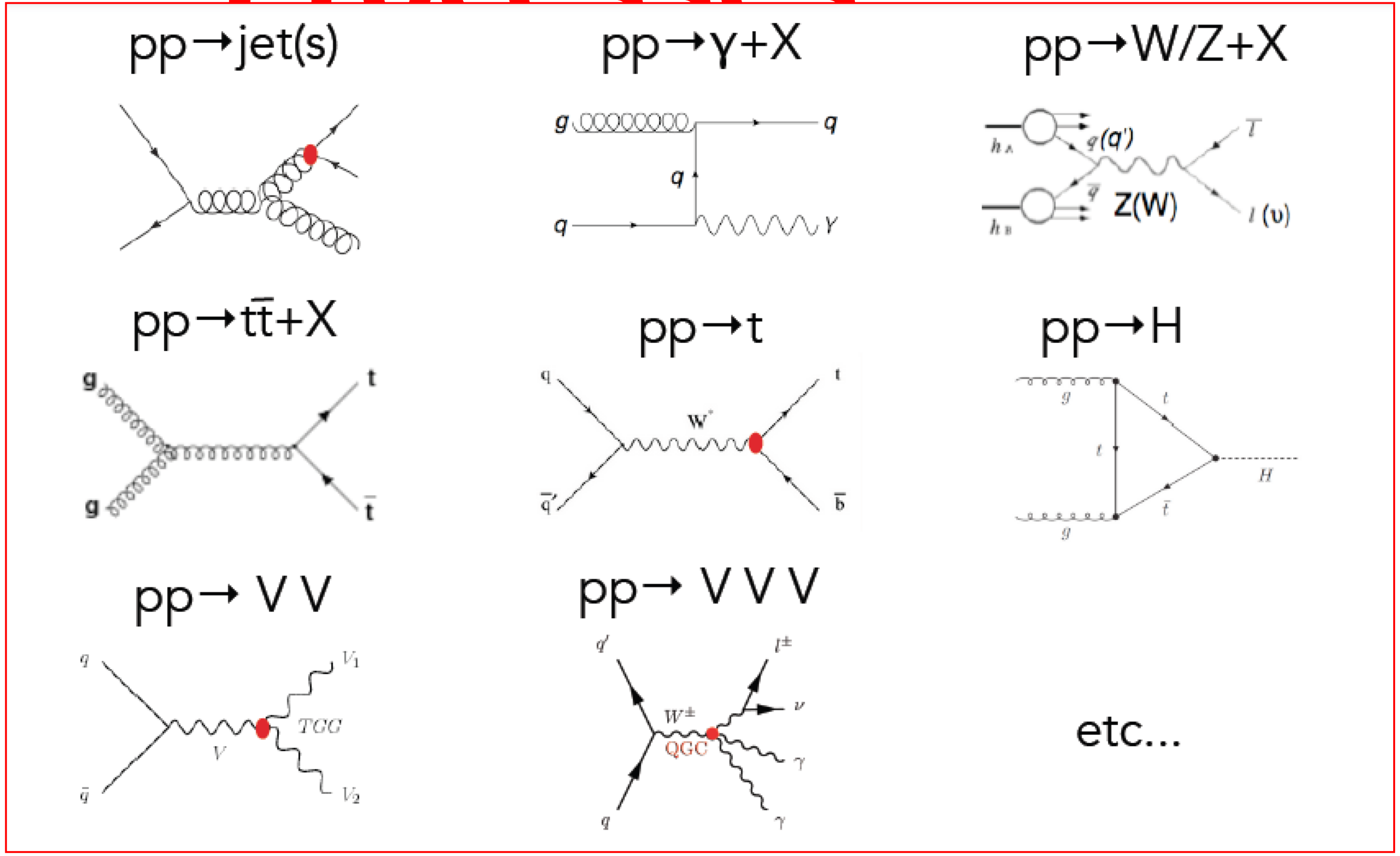
LHC: For "hard" processes strong Interactions is directly between quarks





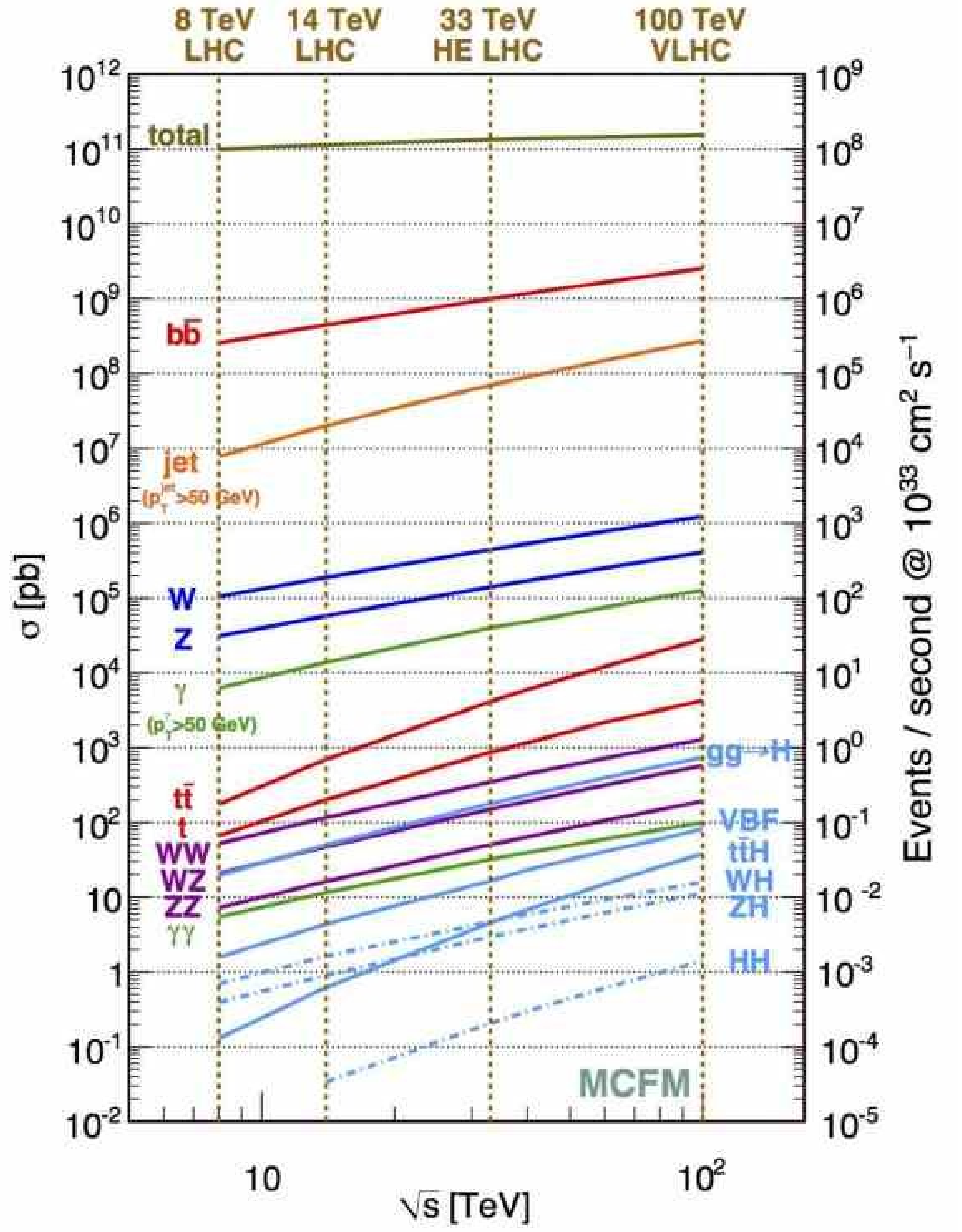
- Effective strength ~ #gluons exch.
  - low Q^2: more *g's*: large eff. coupling
  - high Q^2: few *g's*: small eff. coupling

Many Hard Processes



$N = L\,\sigma \times$ (acceptance) $\times$ (efficiency)

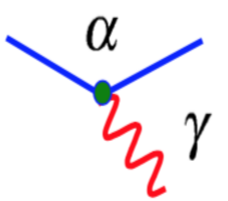
= number of events observed



Few comments on QCD relevant when discussion hard scattering processes

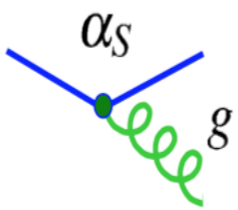
In QED:

- 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

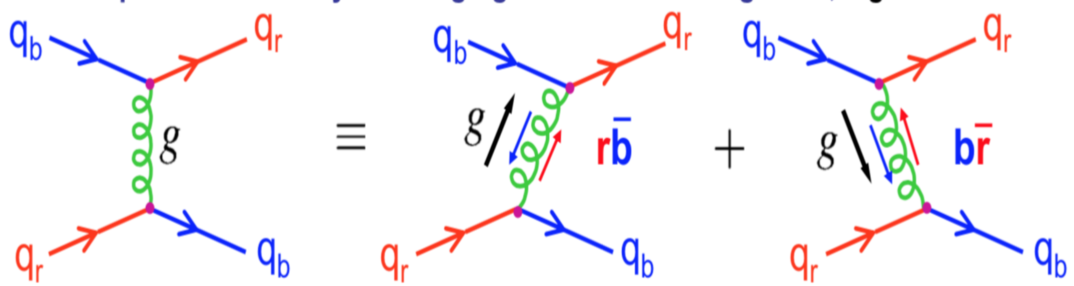


In QCD:

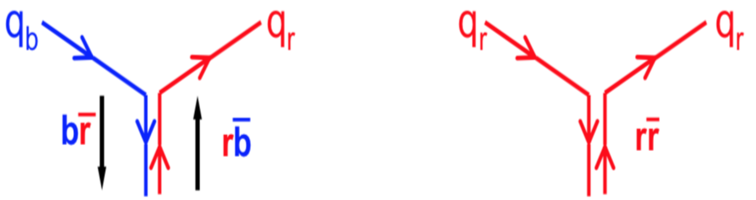
- quarks carry colour charge: r, g, b
- anti-quarks carry anti-charge: $\bar{r}, \bar{g}, \bar{b}$
- The force is mediated by massless gluons



★ In QCD quarks interact by exchanging virtual massless gluons, e.g.



★ Gluons carry colour and anti-colour, e.g.

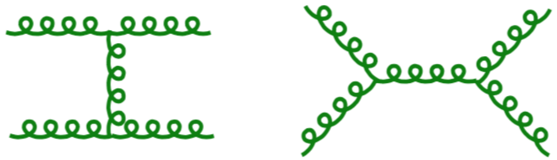


★ Two new vertices (no QED analogues)

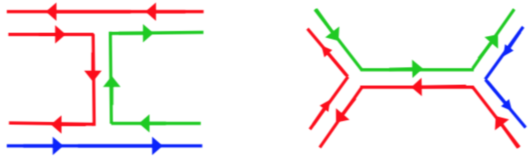
triple-gluon vertex

quartic-gluon vertex

★ In addition to quark-quark scattering, therefore can have gluon-gluon scattering

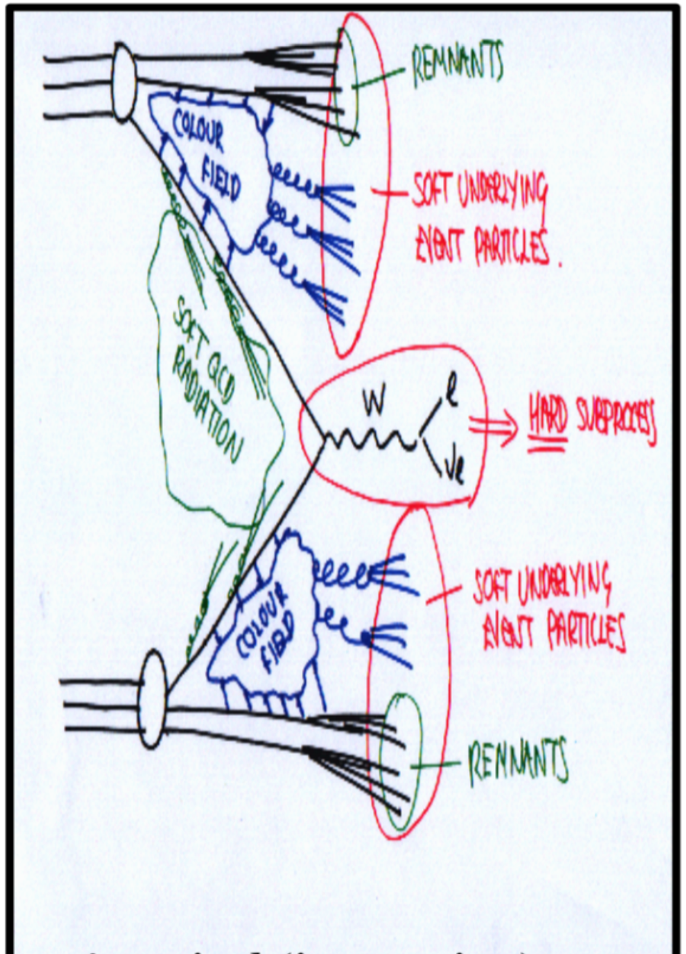


e.g. possible way of arranging the colour flow



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

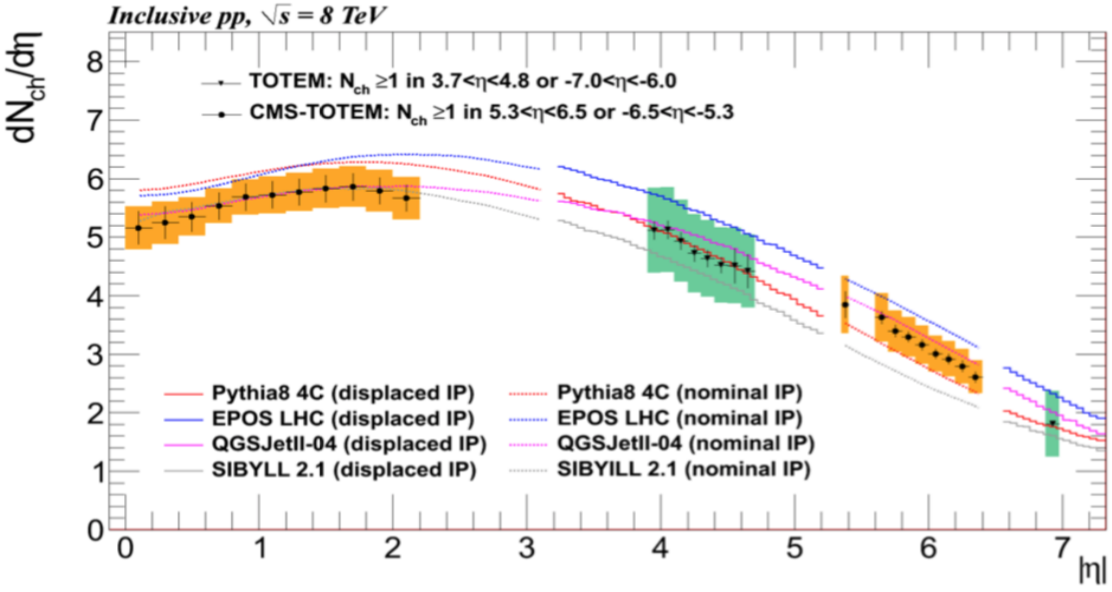
Will talk more about underlying event when we discuss top-quark



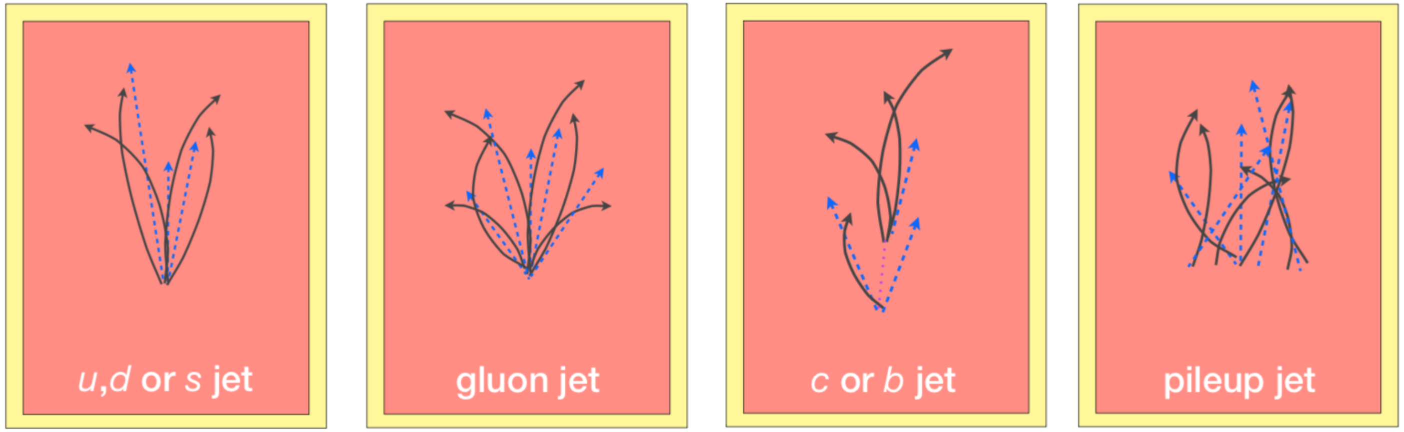
A typical (interesting) event

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

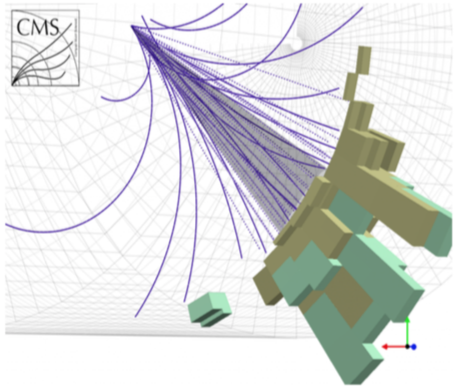
Eur. Phys. J. C (2015) 75:126; arXiv:1411.4963

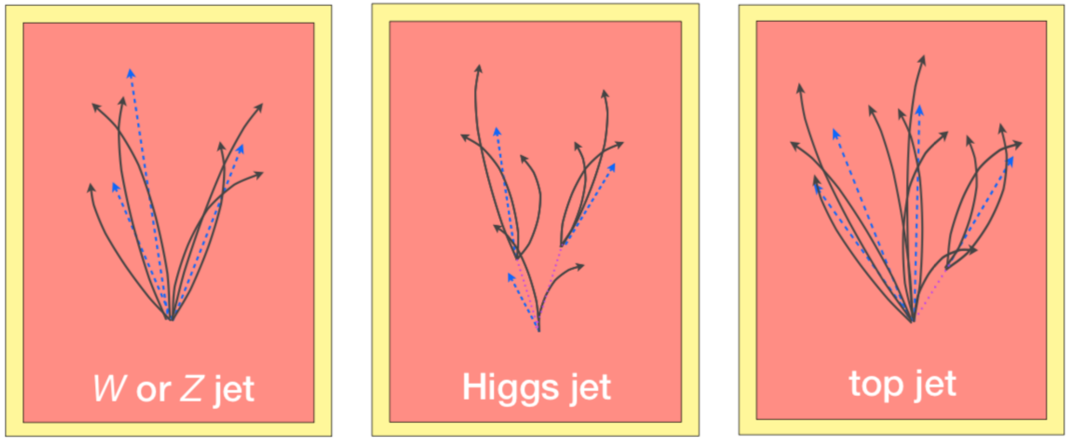


hard processes very often produces jets. We are continuously improving our jet reconstruction



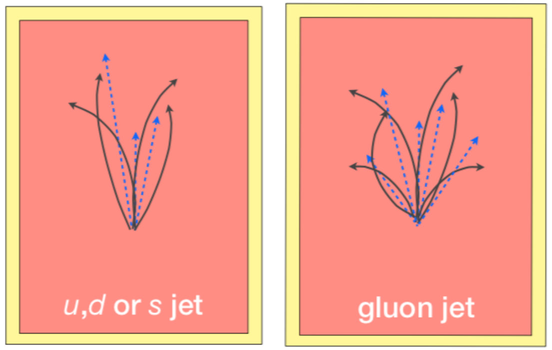
- Jets are ubiquitous at hadron colliders.
  - Collimated spray of hadrons resulting from an initial state quark or gluon)
- LHC jet tagging revolution
  - Enabled by new reconstruction techniques (ex. particle flow, sequential recombination jet algorithms)
  - Quark/gluon discrimination, Pileup jet 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



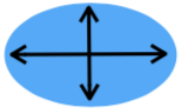


Identifying quark and gluon jets

- 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

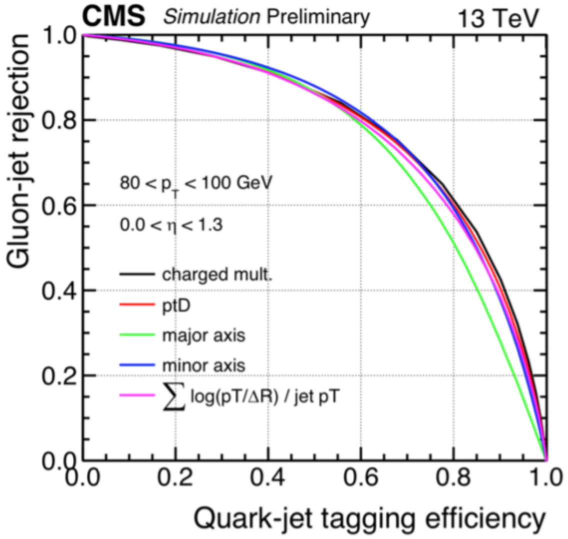


- Three tools:
  - Likelihood discriminator (3 variable)
  - BDT discriminator (5 variable)
  - Deep neural net (jet constituents)
- Quark/gluon discriminator variables:
  - Jet particle multiplicity
    - Total or charged
  - Jet shape
    - major axis width
    - minor axis width
    - ΔR weighted p_T $\sum_i \frac{\log(\frac{p_{T,i}}{\Delta R})}{\text{jet } p_T}$
  - Energy sharing ($p_T D$)



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

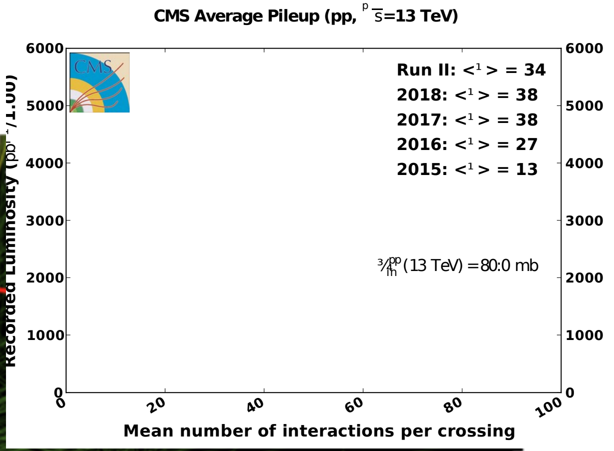
→ 1 if all momentum carried by one particle
→ 0 if jet has infinite number of particles

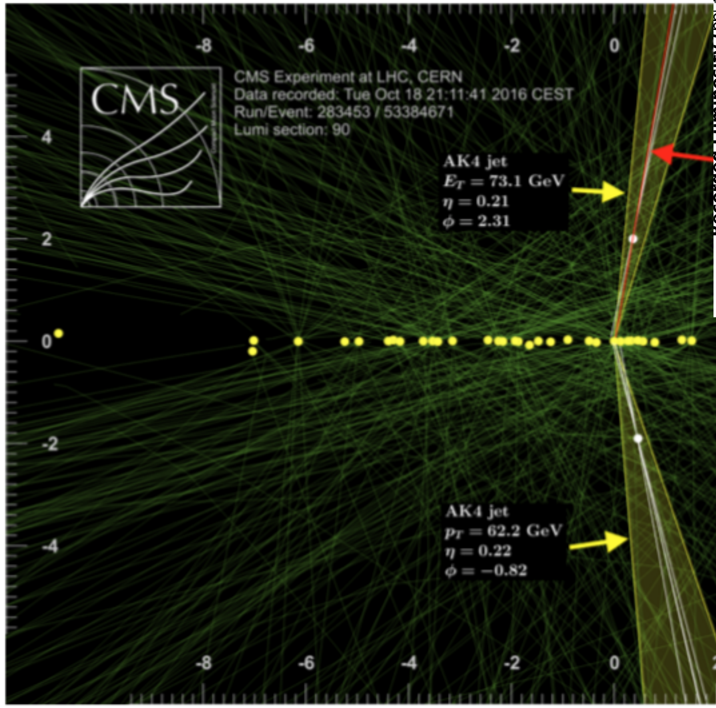


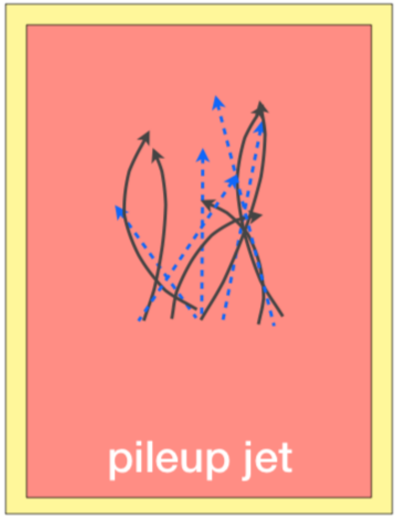
CMS DP Note 2017/027

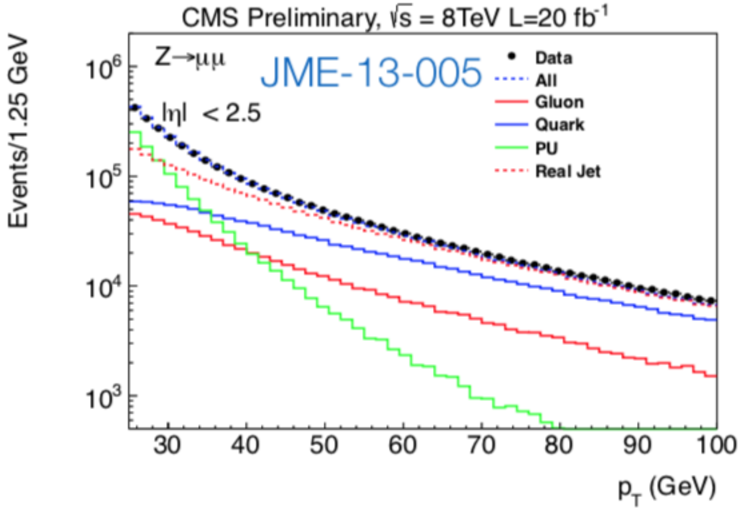
LHC Hostile environment

- 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

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

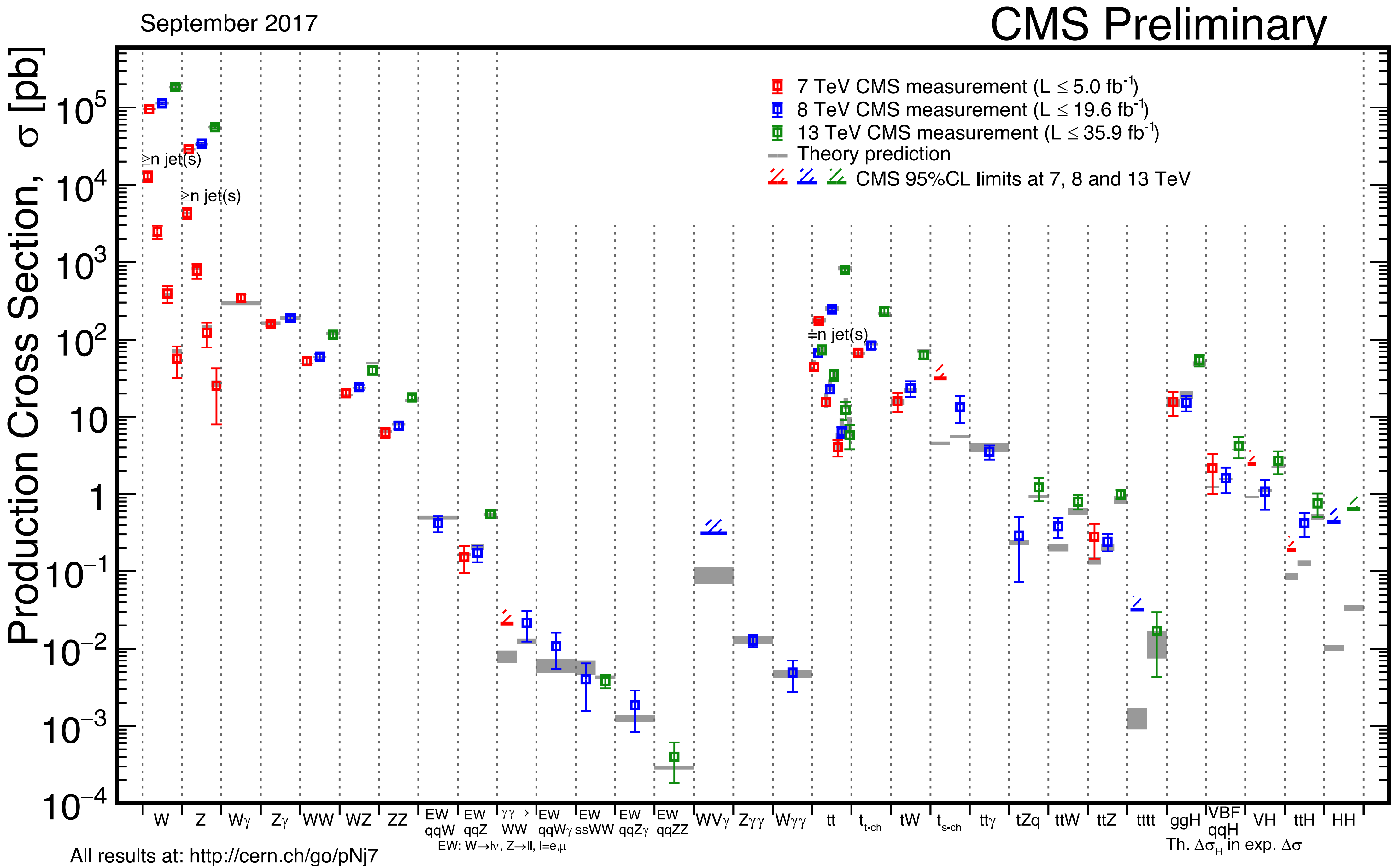
N_{obs}: observed number of events
N_{bkg}: estimated background
A: detector acceptance ($N_{gen,fiducial}$ / $N_{gen,total}$)
ε: experimental efficiency ($N_{reco}/N_{gen,fiducial} * \varepsilon_{data}/\varepsilon_{MC}$)
L: integrated luminosity

Fiducial cross-section

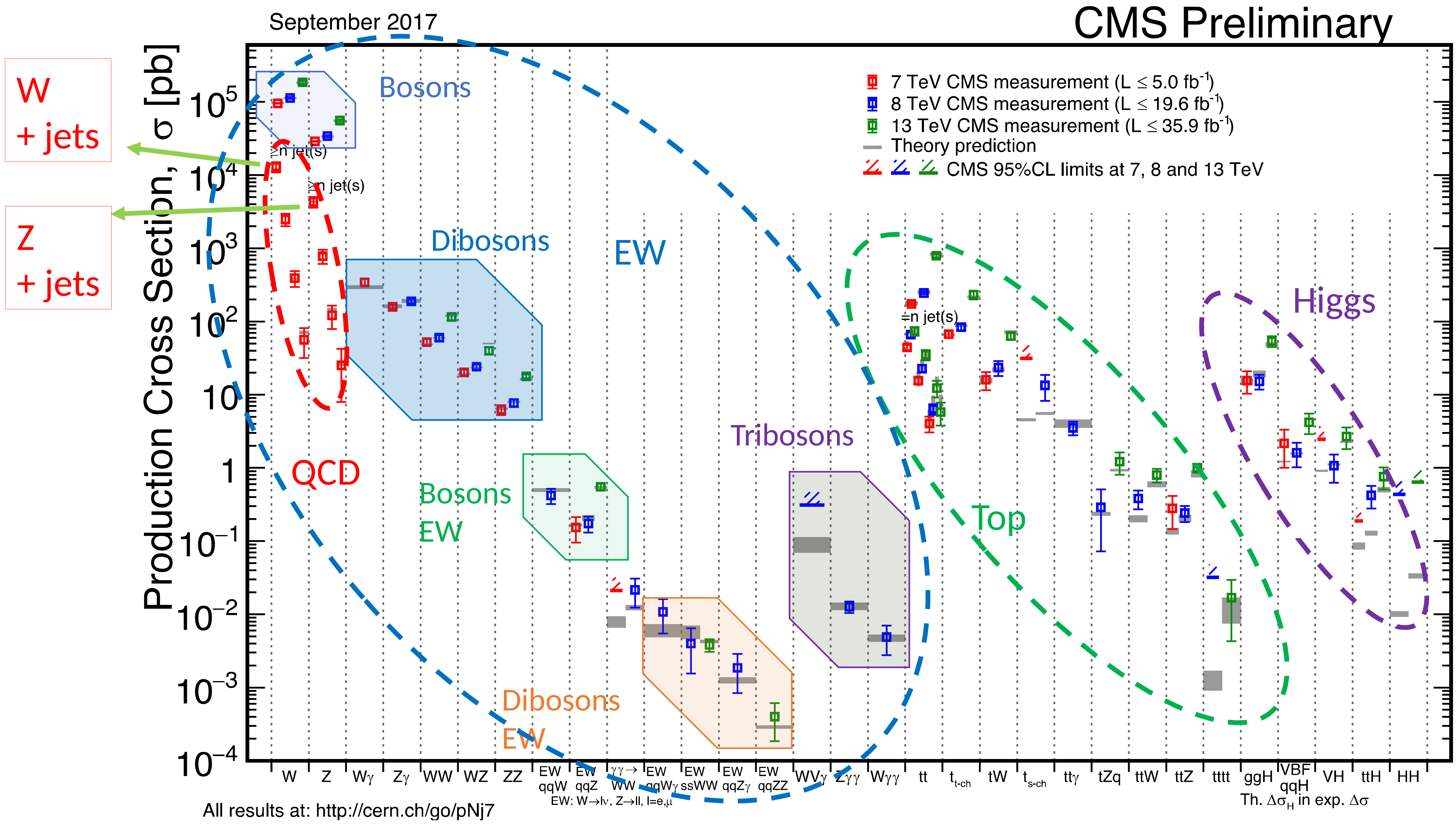
- no correction for detector acceptance to avoid theoretical uncertainty on extrapolation to the full phase space

Differential cross-section

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

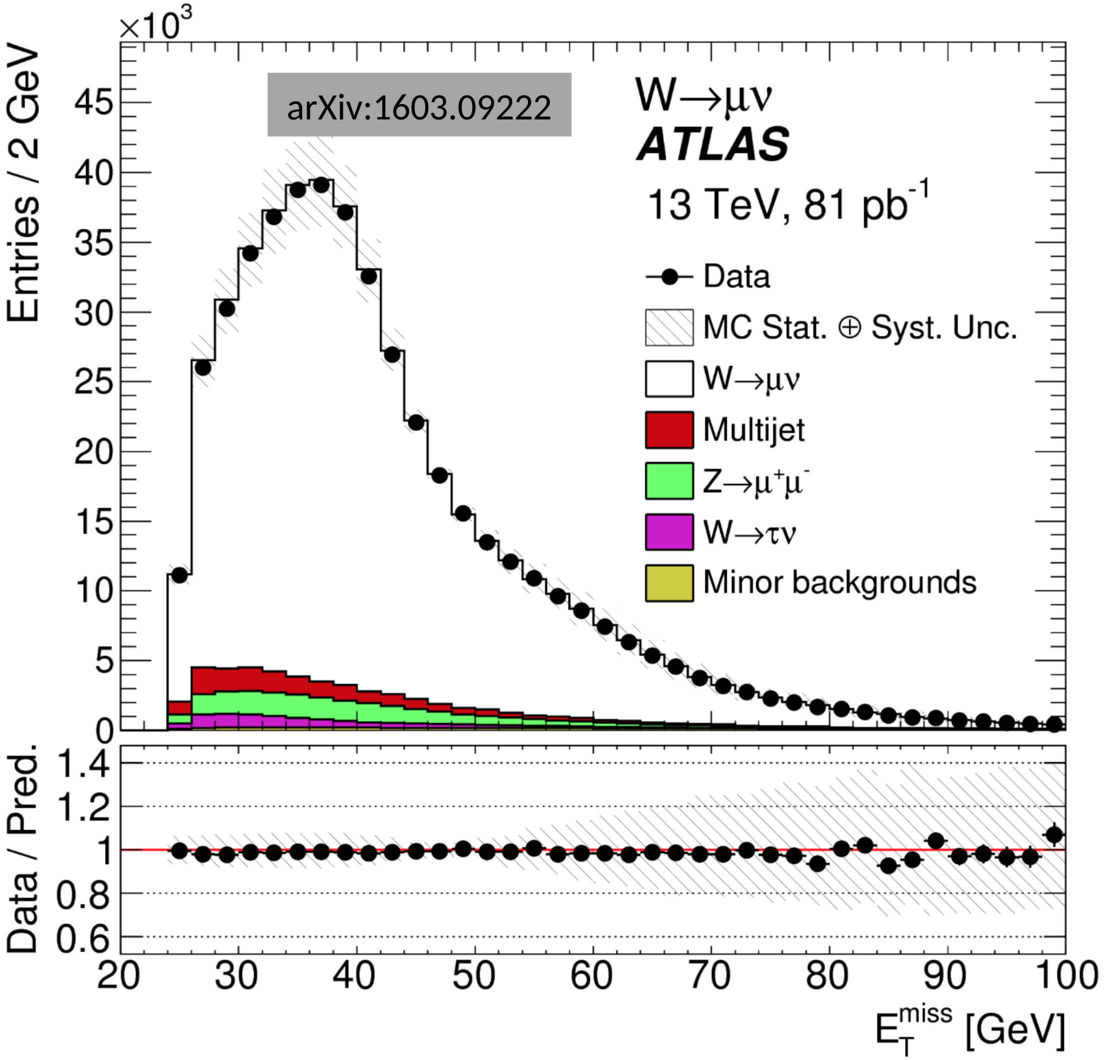


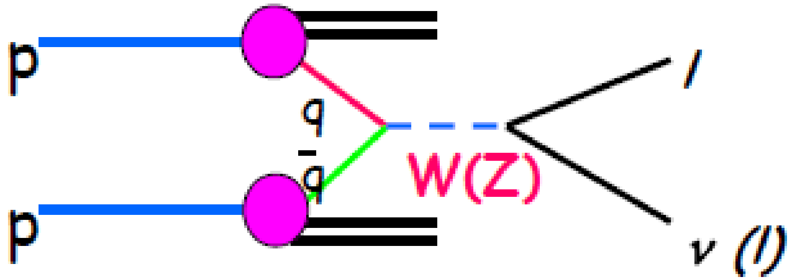
September 2017
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 35.9 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ
EW qqW
EW qqZ
γγ→WW
EW qqWγ
EW ssWW
EW qqZγ
EW qqZZ
WVγ Zγγ Wγγ tt
t t-ch
tW
t s-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

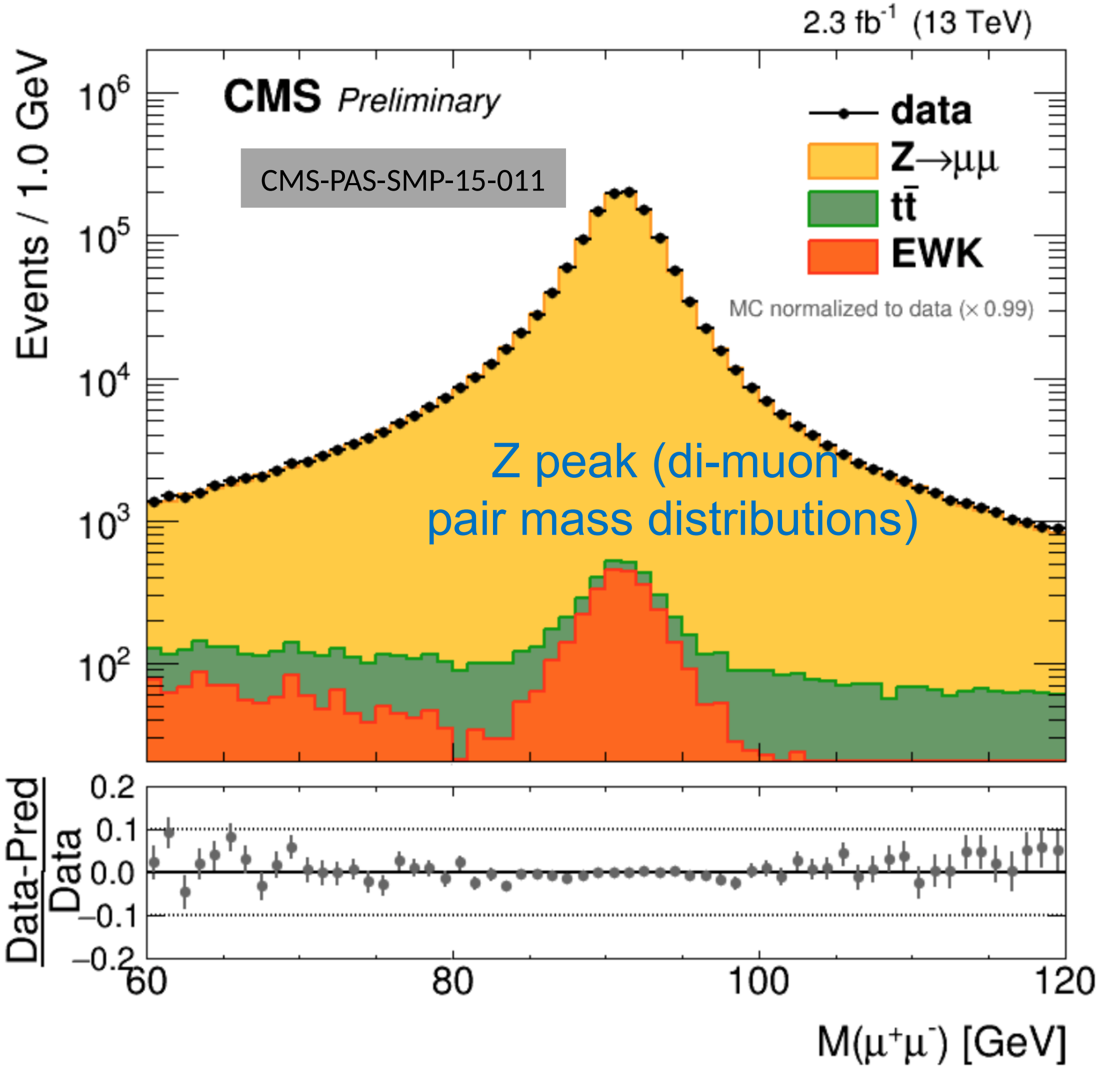


W
+ jets
Z
+ jets
September 2017
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb^{-1})
8 TeV CMS measurement (L ≤ 19.6 fb^{-1})
13 TeV CMS measurement (L ≤ 35.9 fb^{-1})
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
Bosons
Dibosons
EW
QCD
Bosons EW
Dibosons EW
Tribosons
Top
Higgs
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqZZ WVγ Zγγ Wγγ tt $t_{t\text{-}ch}$ tW $t_{s\text{-}ch}$ ttγ tZq ttW ttZ tttt ggH VBF qqH VH ttH HH
EW: W→lν, Z→ll, l=e,μ
Th. $\Delta\sigma_H$ in exp. Δσ
All results at: http://cern.ch/go/pNj7

"QCD" W and Z Boson Production







Z peak (di-muon pair mass distributions)

Missing transverse energy from the W ✉ μ+ν decays

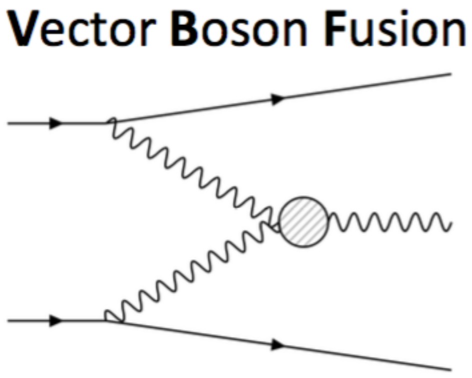
“Electroweak” W and Z Boson production

We know how to reconstruct jets…

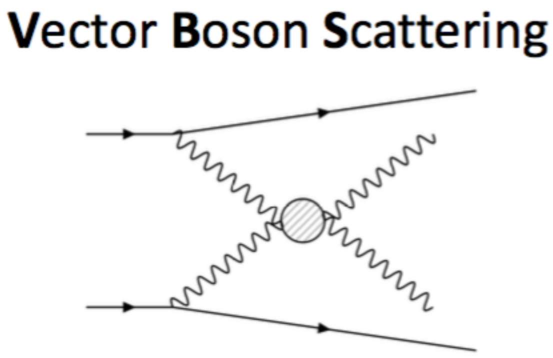
therefore we can identify:

pp✉ qqV or qqVV

V=W,Z or γ



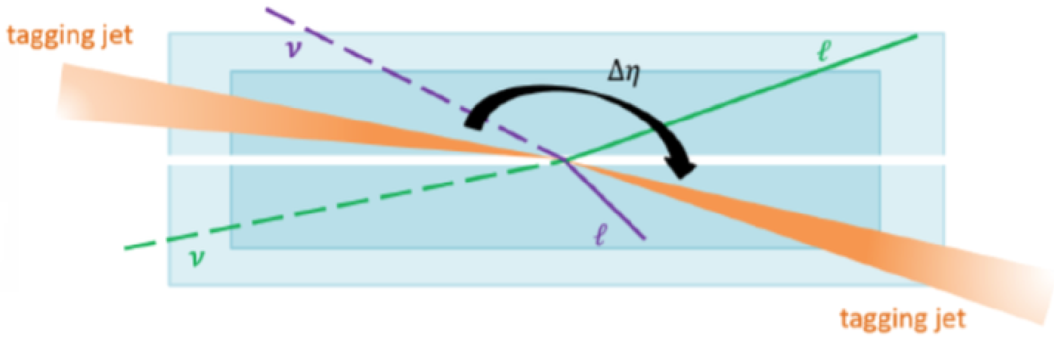
pp✉ jj V



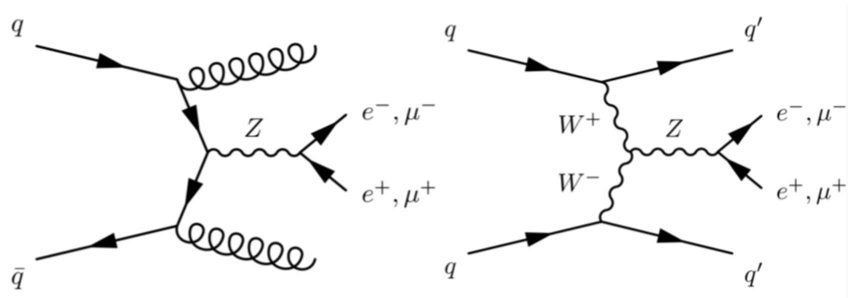
pp✉ jj VV

Process characteristics:

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



VBF: Vector Boson Fusion

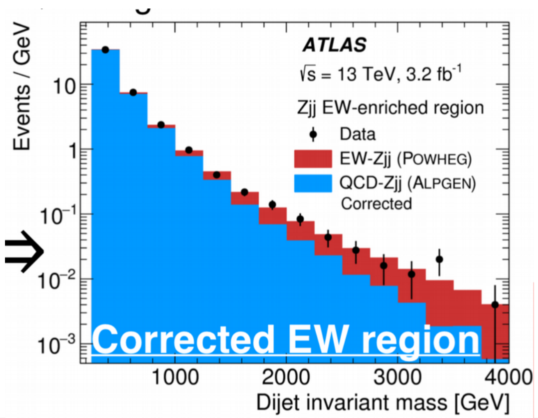


QCD Background

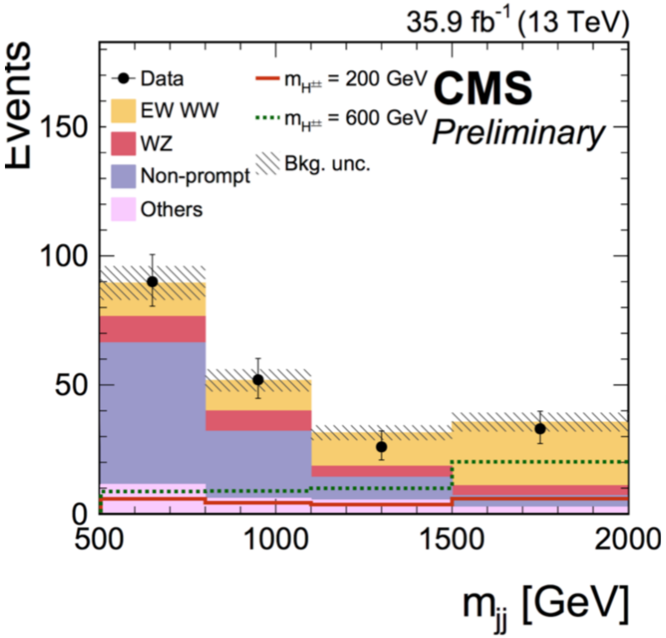
EWK: VBF Signal

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

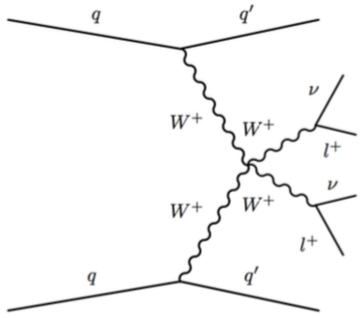
⇒



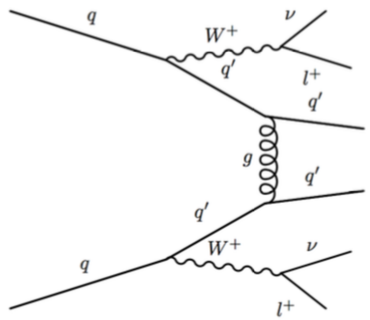
VBS: Vector Boson Scattering



VBS production



QCD production



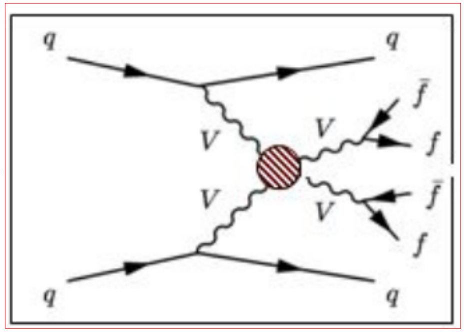
What do I mean by saying QCD or EW boson production ?

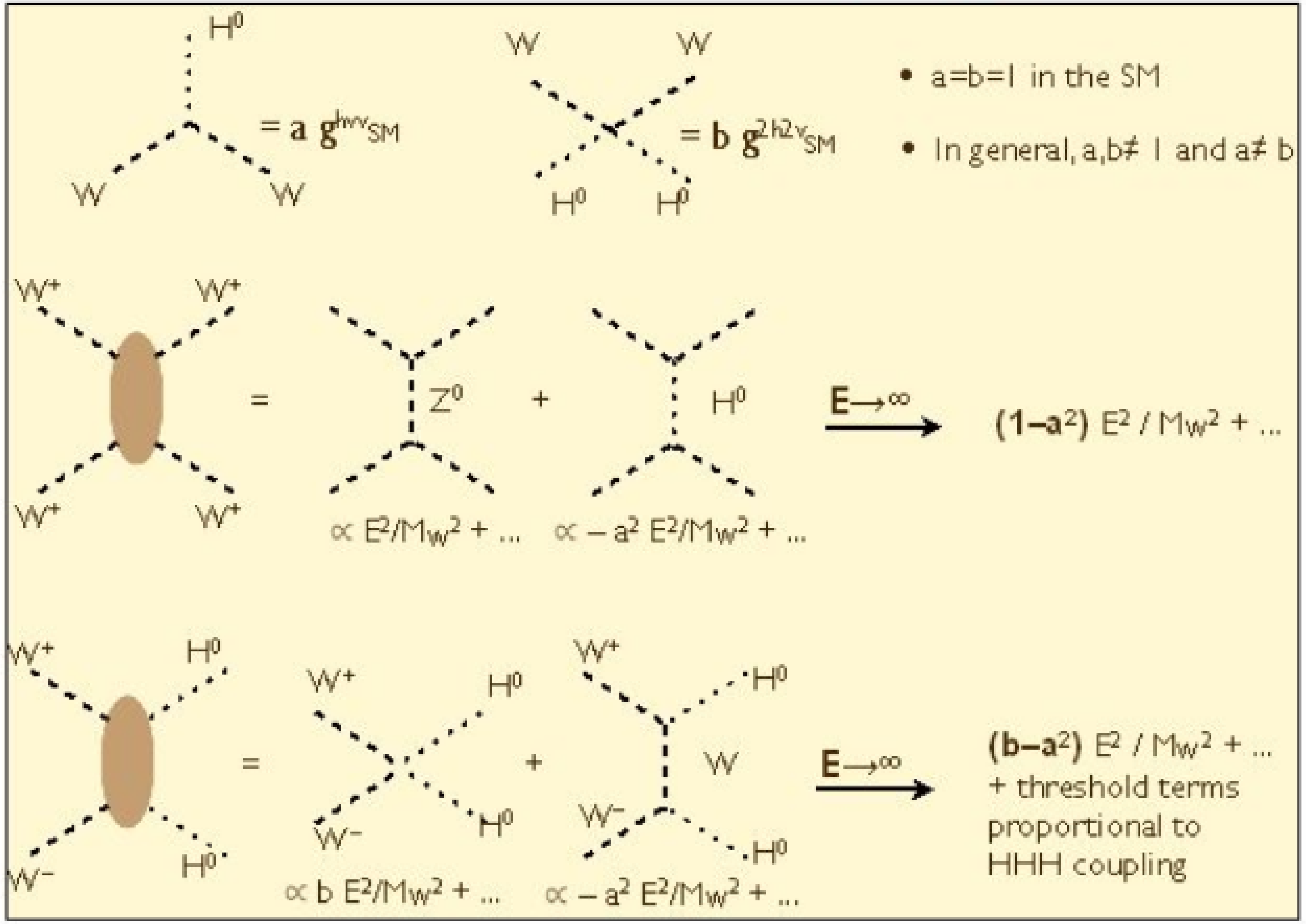
Many future analyses will have this topology

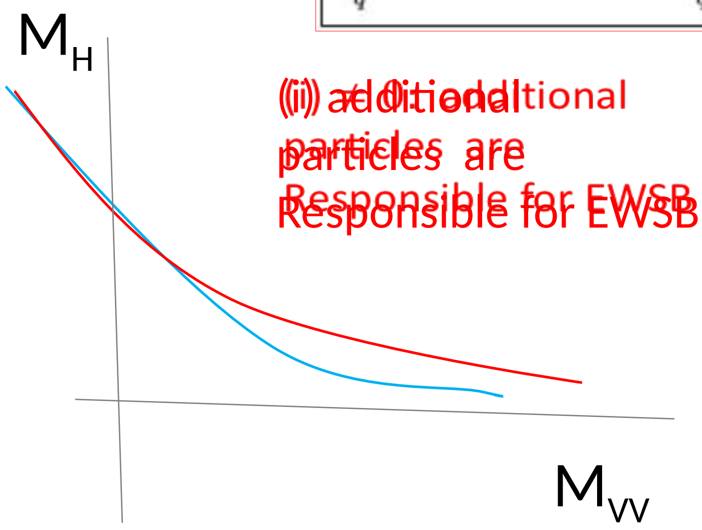
Notice that they all involve jets…

$W_L W_L$

vanishes, only (ii) $W_T W_T$ ✉ $W_T W_T$ is pre





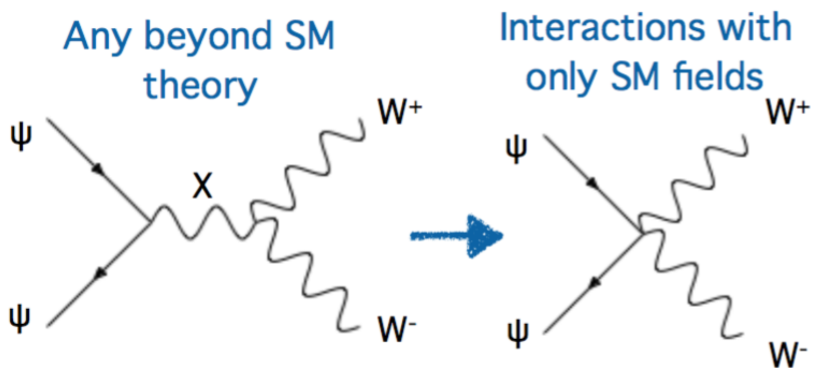


- $V_L\, V_L$ scattering linked to the mechanism responsible for the EWSB:

(massless vector) W^a_μ, B_μ (Higgs doublet) σ, χ^a → (massive vector) W^+_μ, W^-_μ, Z_μ (Higgs field) H

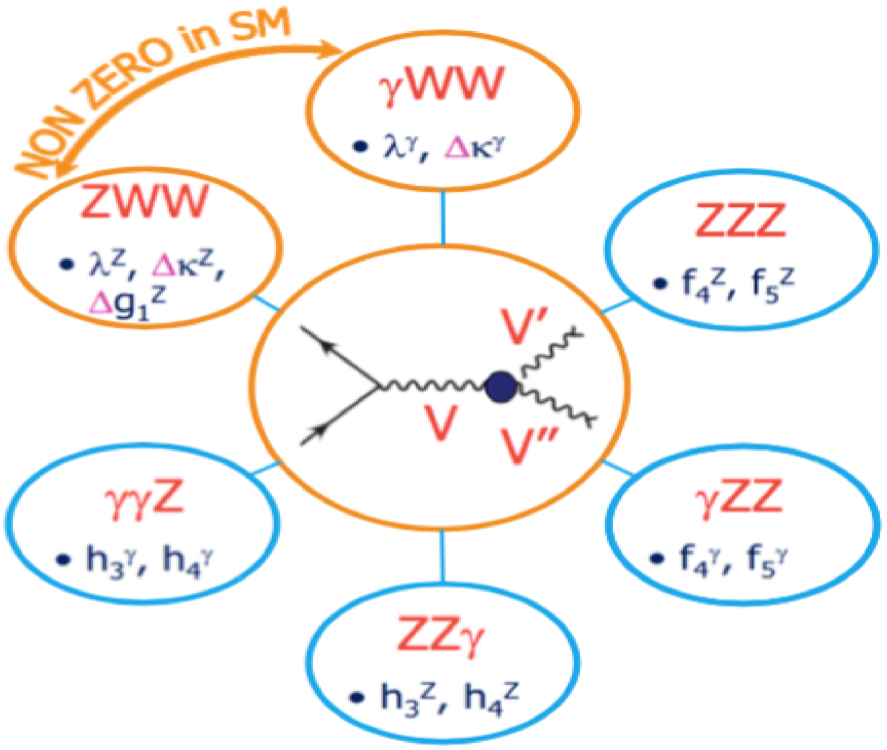
More on Higgs Lectures

Multi-bosons used to search for new physics: anomalous couplings



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

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



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

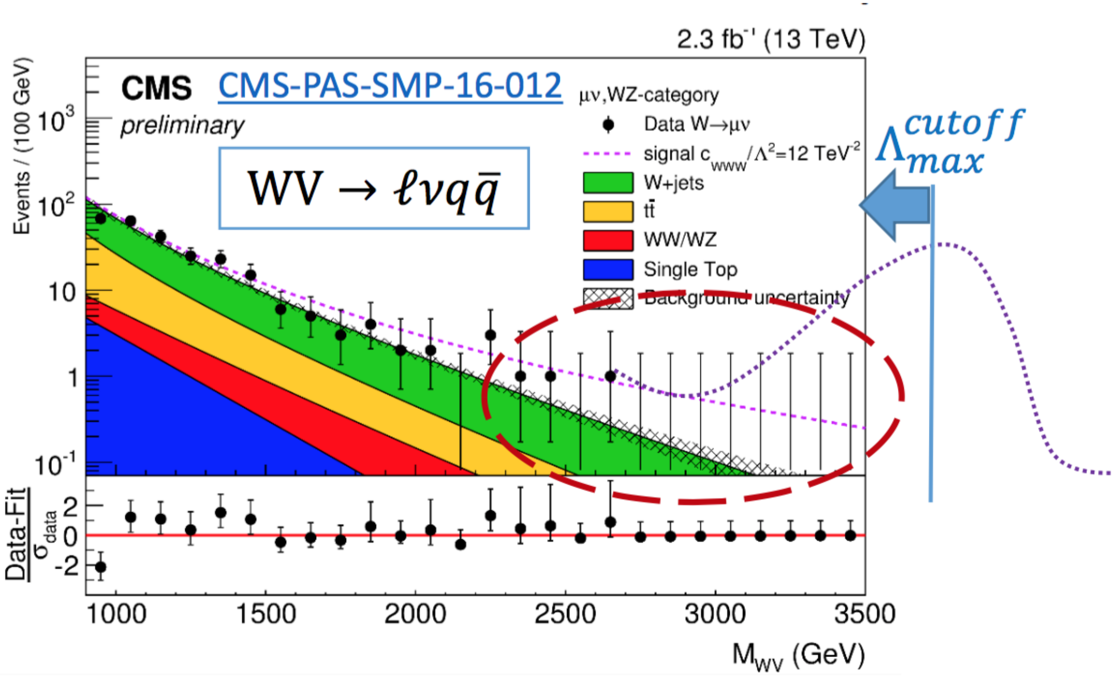
- 14 operators, 18 parameters
- 1 operator, 7 parameters
- 59 operators, 2499 parameters [arXiv:1312.2014]
- 4 operators, 408 parameters (all violate B number) [arXiv:1405.0486]
- 30 operators (all violate L number, 7 violate B number) [arXiv:1410.4193]
- 993 operators [arXiv:1510.00372]

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

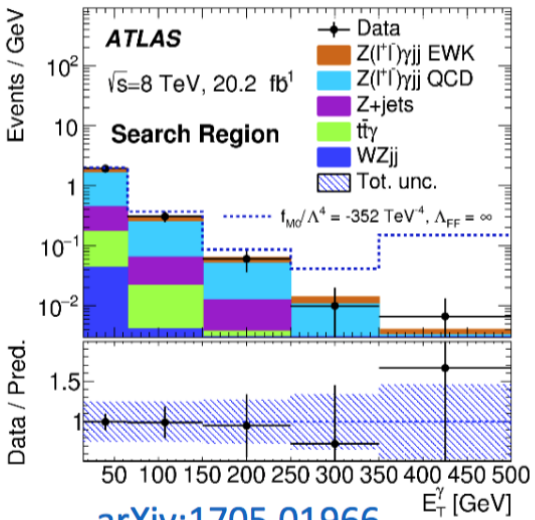
Existing measurements are limited to 2 operators. We can do better!

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

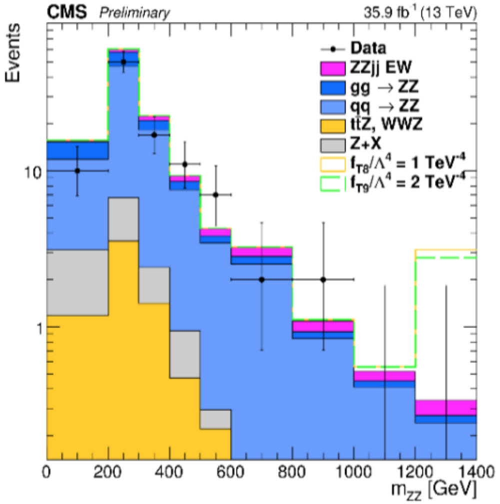


Zγjj→2ℓγjj (8 TeV)



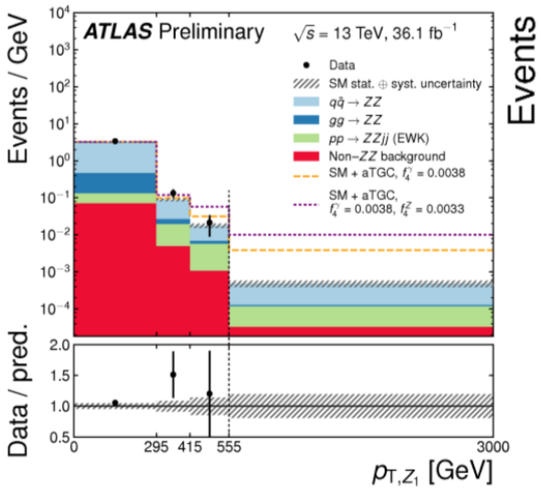
arXiv:1705.01966

ZZjj→4ℓjj (13 TeV)



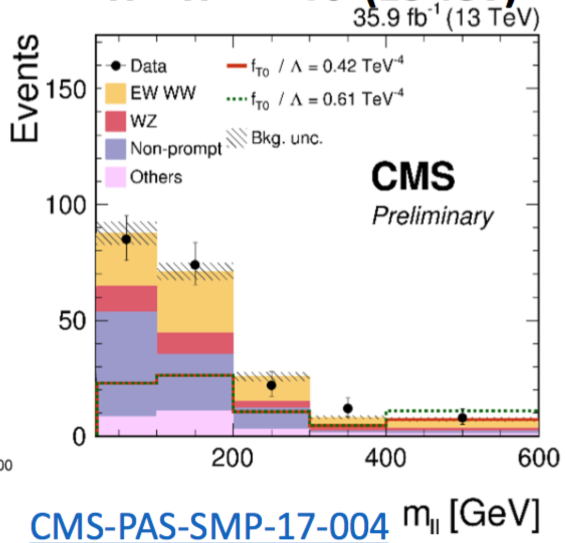
CMS-PAS-SMP-16-019

ZZ→4ℓ (13 TeV)



ATLAS-CONF-2017-031

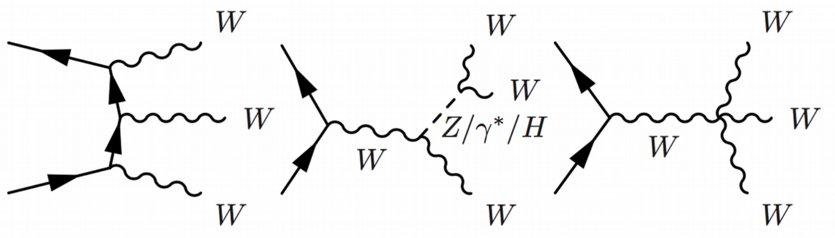
W±W±→4ℓ (13 TeV)



CMS-PAS-SMP-17-004

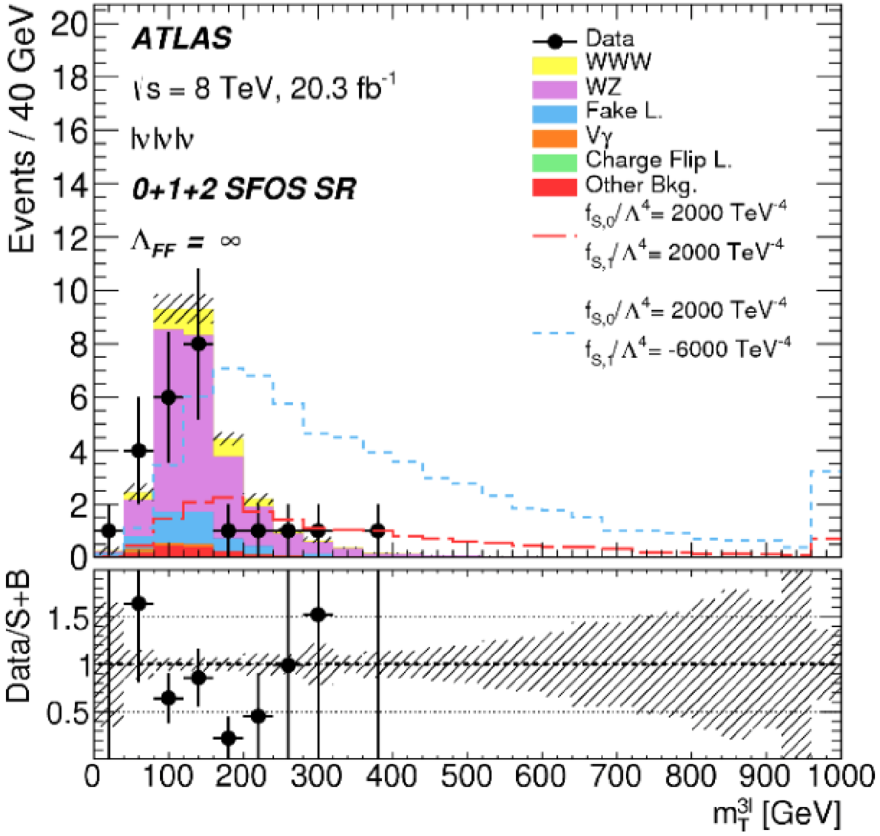
Tribosons

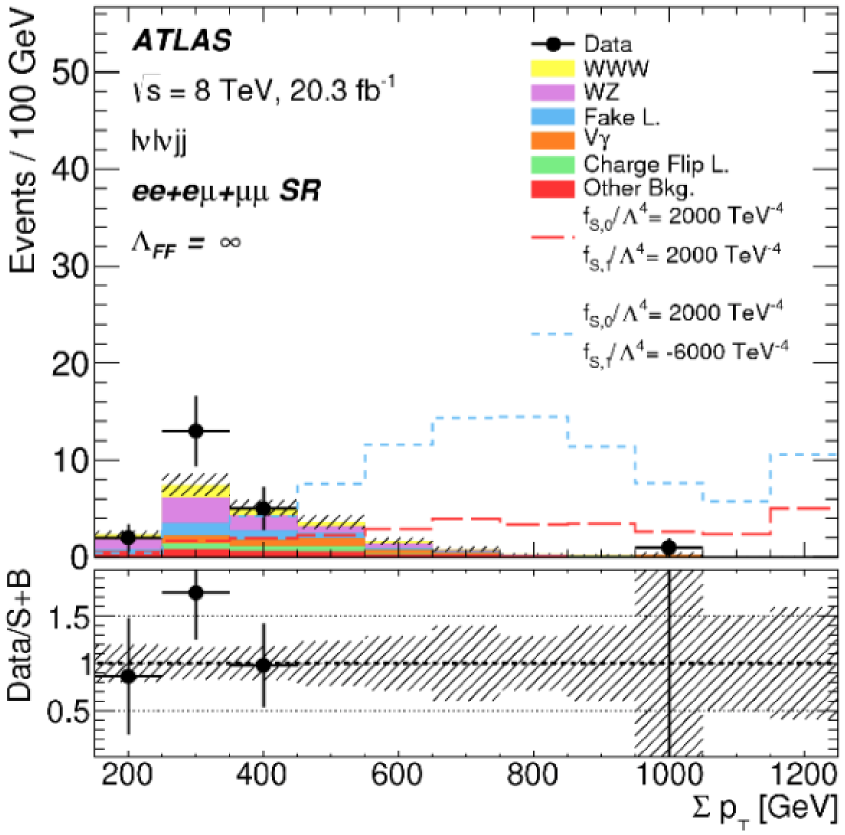
First study by ATLAS of $W^{\pm}W^{\pm}W^{\mp}$ to $l^{\pm}\nu + l^{\pm}\nu + l^{\pm}\nu$ and $l^{\pm}\nu + l^{\pm}\nu\, jj$



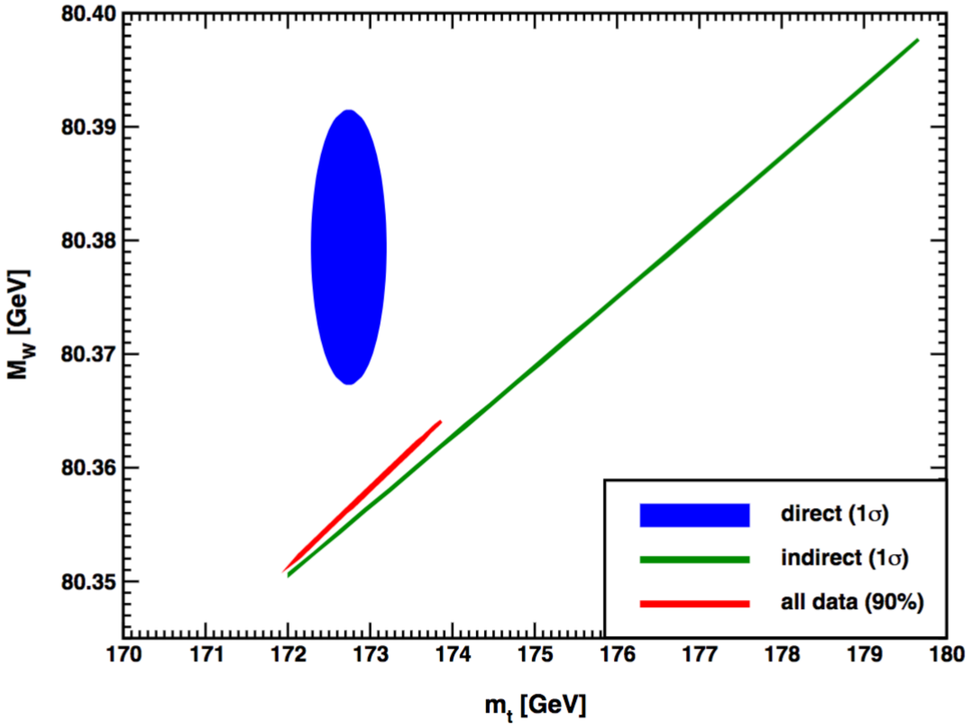
More statistics will come @13 TeV

EPJC (2017) 77: 141





Role of precision EWK measurements @ Hadron Colliders



Freitas & JE (PDG 2018)

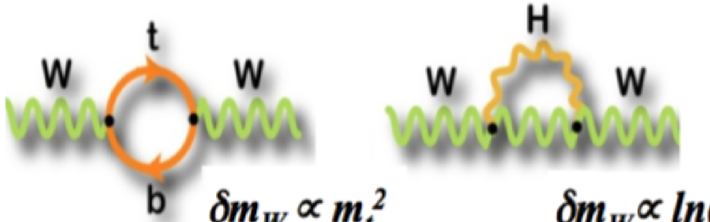
To provide precise measurements of fundamental parameters to tests the theory:

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

α_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

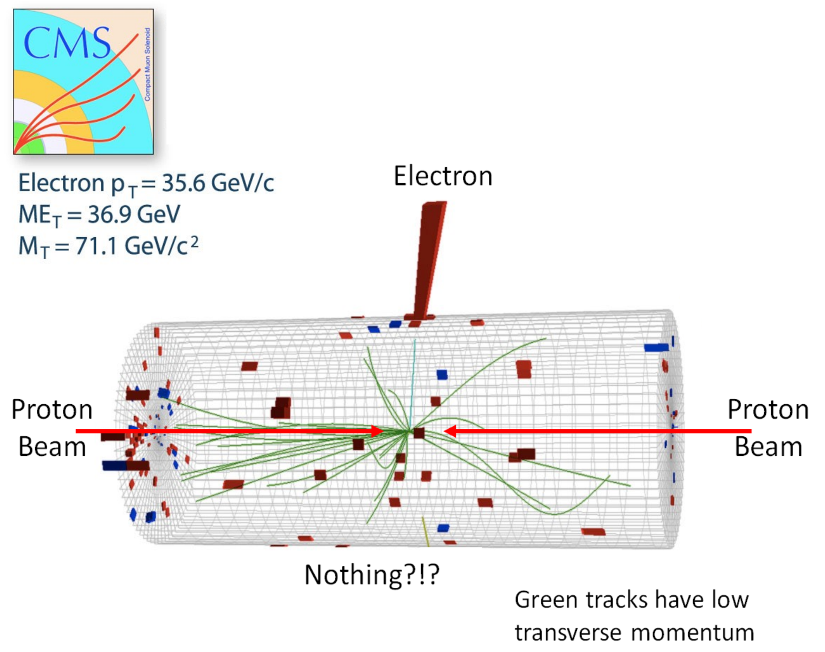
$$m_W = \frac{\pi\alpha}{\sqrt{2}G_F} \frac{1}{\sin^2\theta_W(1+\delta m_W)}$$

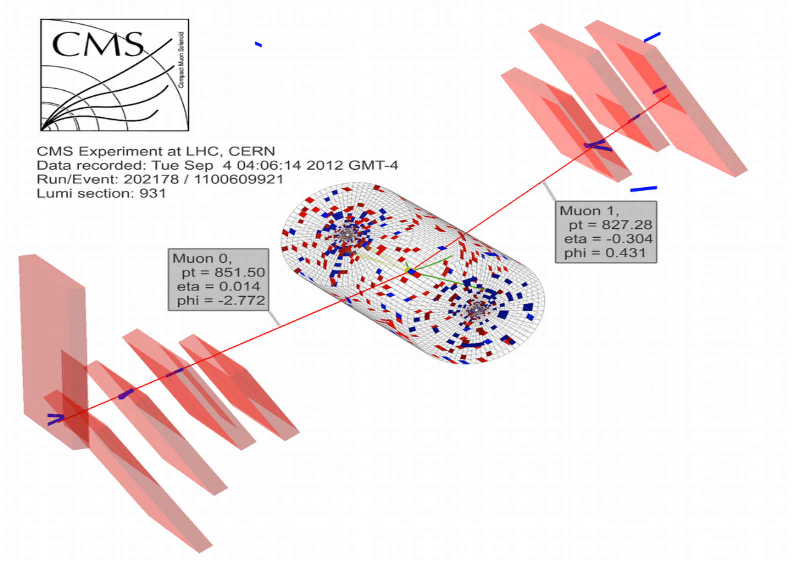


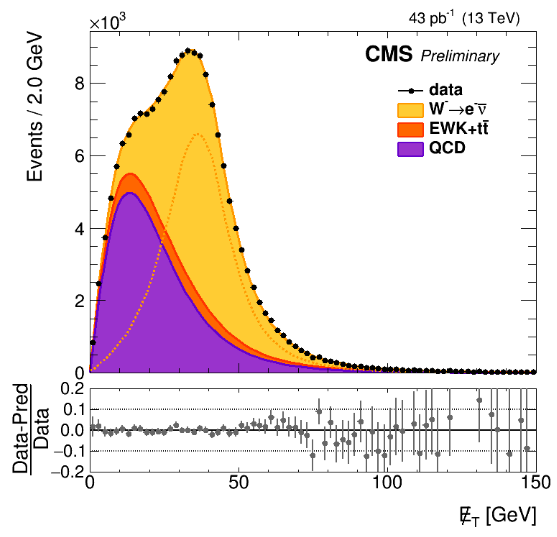
$\delta m_W \propto m_t^2$

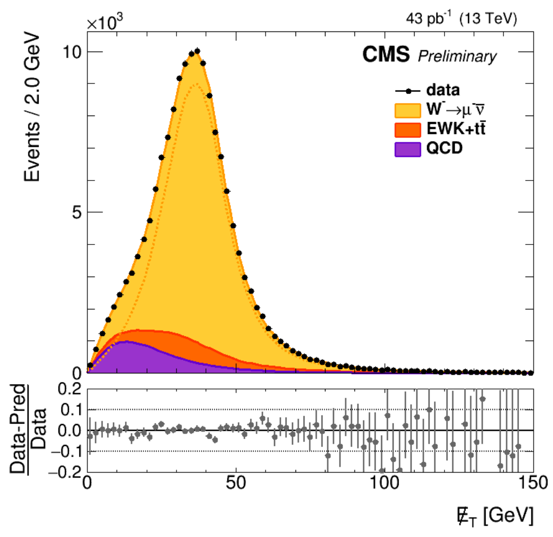
$\delta m_W \propto \ln(m_H)$

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



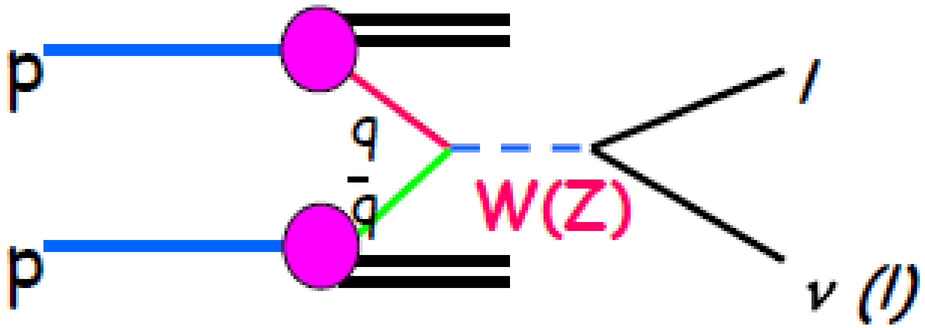


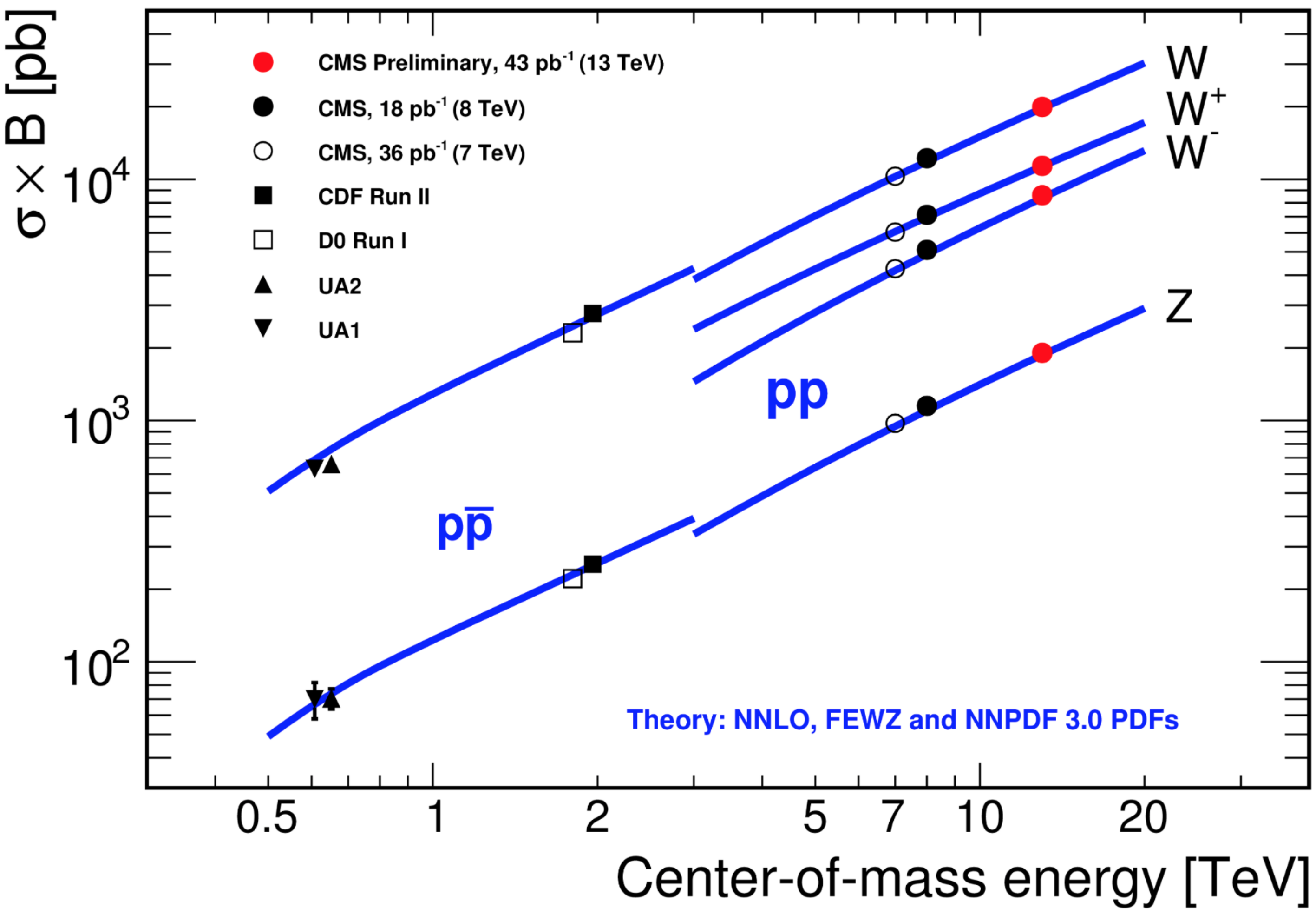




Precision measurements with W's and Z bosons

W and Z Boson Production





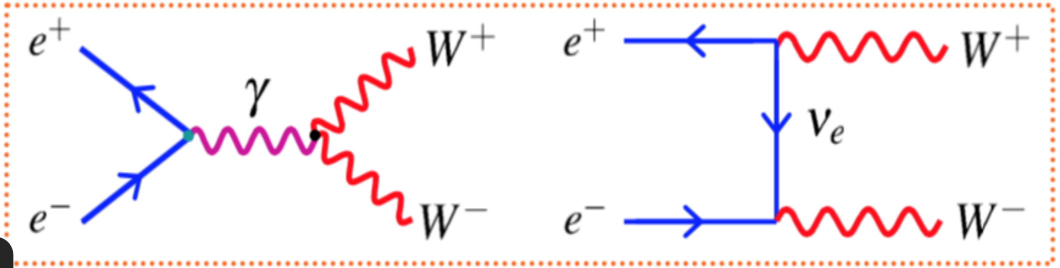
- Many detailed EWK studies possible – and done -- with the large Z, W samples

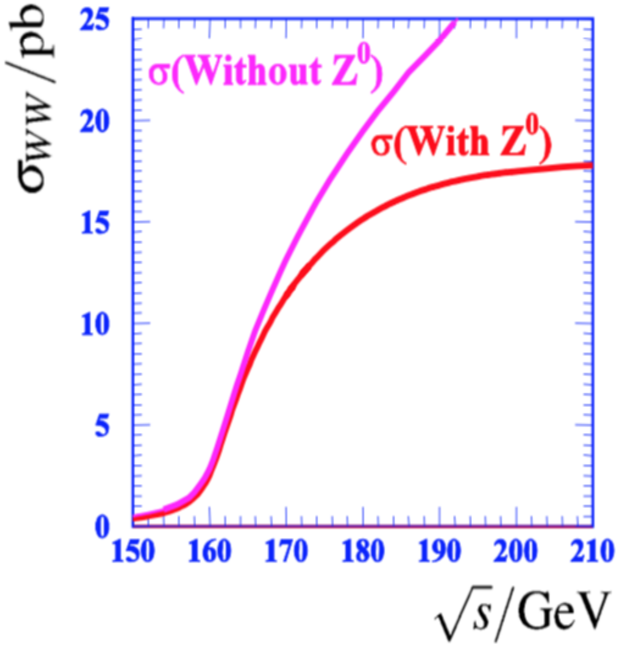
- Here we will focus on
  - $\sin^2\theta_W$
  - W-Mass
  - Lepton Universality

Historical & theoretical background of the Electro Weak model

From:
M.A. Thomson

- ★ The $W^{\pm}$ bosons carry the EM charge - suggestive Weak are EM forces are related.
- ★ W bosons can be produced in e^+e^- annihilation

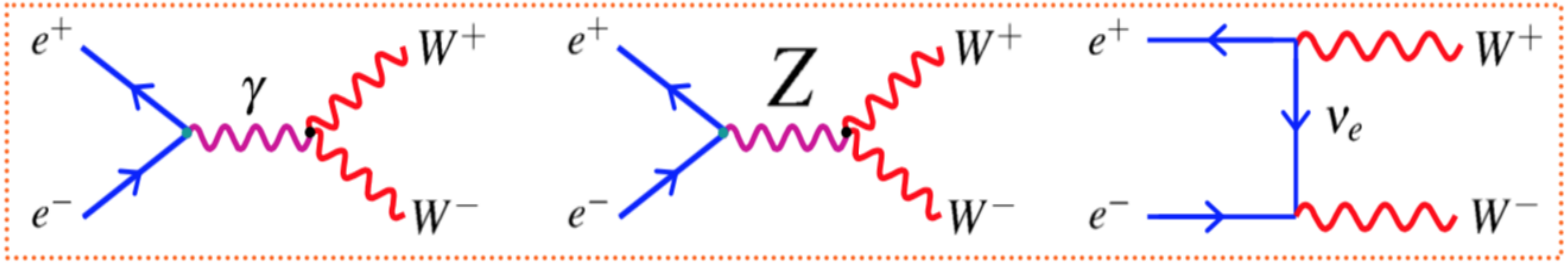




With just these two diagrams there is a problem: the cross section increases with C.o.M energy and at some point violates **QM unitarity**

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**

Standard Model: Nature described by the Symmetry Groups

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

Colour

Weak Isospin

Weak Hypercharge

Strong interactions

Electroweak interactions

3 symmetry groups

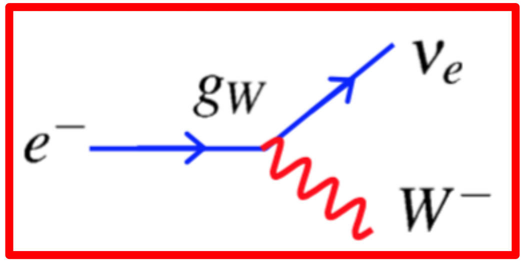
⇒ Interactions described by (only!) 3 coupling constants:

g_s, g, g'

$\boxed{g_W}$

⇒ Universal fermion-boson couplings

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

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

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

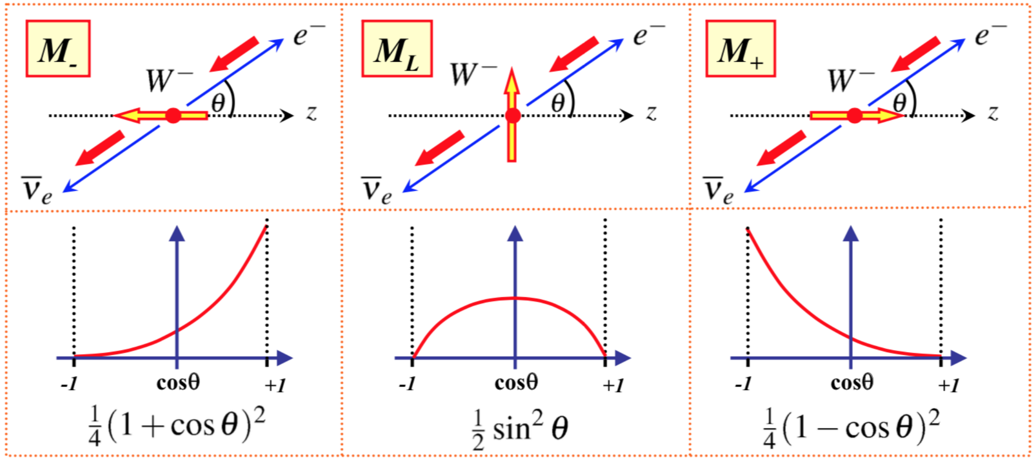
Note: RH/LH refer to chiral states

★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's Spin-1 therefore 3 possible polarizations: W-helicity affects the kinematics of the outgoing leptons

W's Spin-1 therefore 3 possible polarizations: W-helicity affects the kinematics of the outgoing leptons



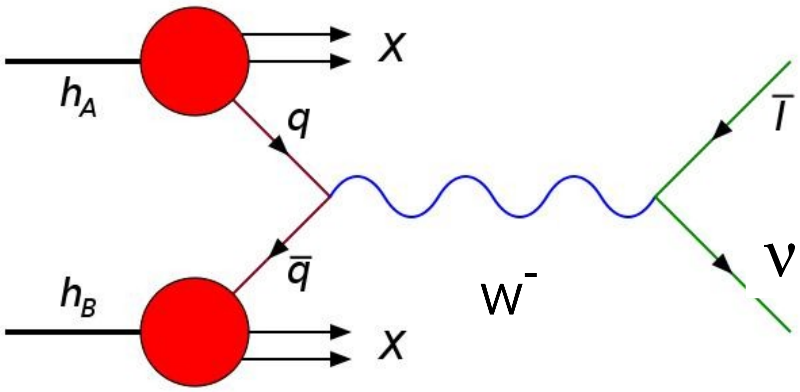
Both W^+ and W^- bosons produced with high p_T at the LHC have a dominant left-handed polarization along their direction-of-flight

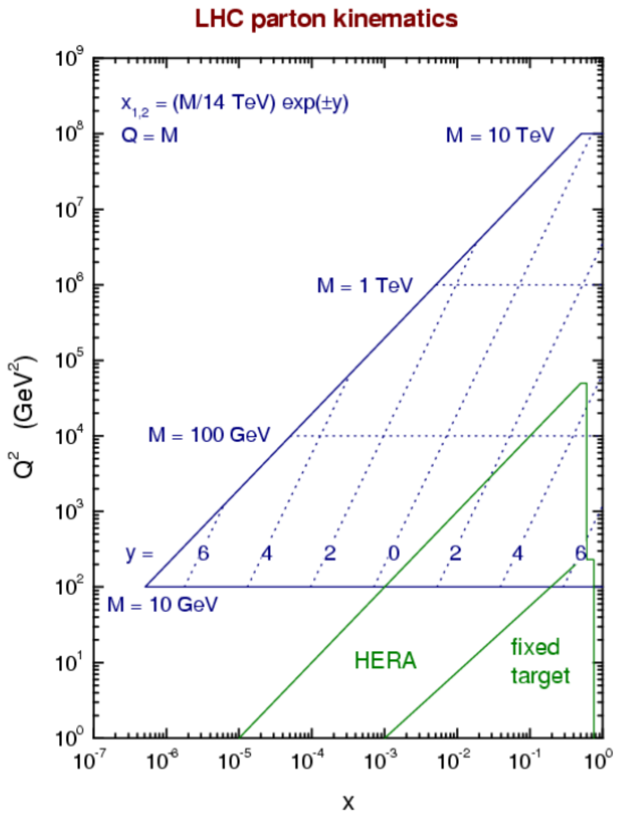
$$\frac{d\sigma_{l^+}}{d\cos\theta^* d\phi^*} = f_L \frac{(1-\cos\theta^*)^2}{4} + f_0 \frac{\sin^2\theta^*}{2} + f_R \frac{(1+\cos\theta^*)^2}{4}$$

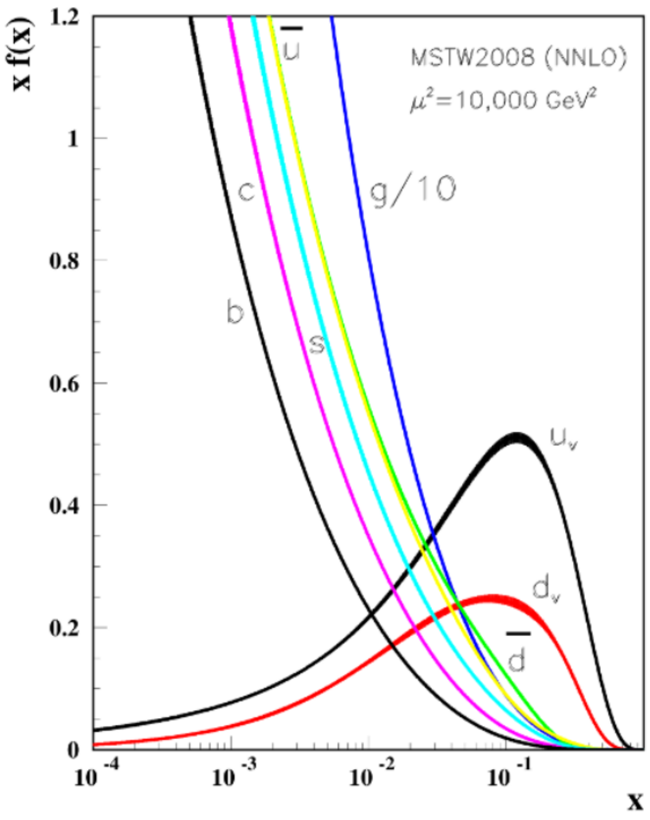
When left-handed W^+ is produced in the transverse plane, its decay left- handed neutrino will be preferentially emitted along the flight direction

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.

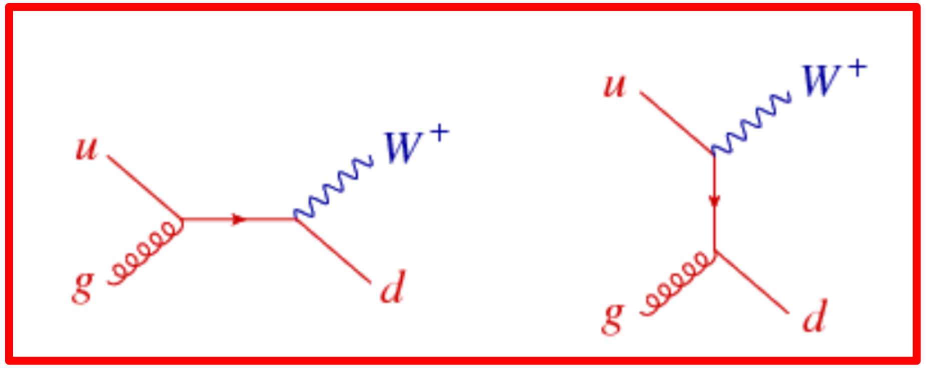
W-helicity and best production mechanism of W's with high momentum transfer



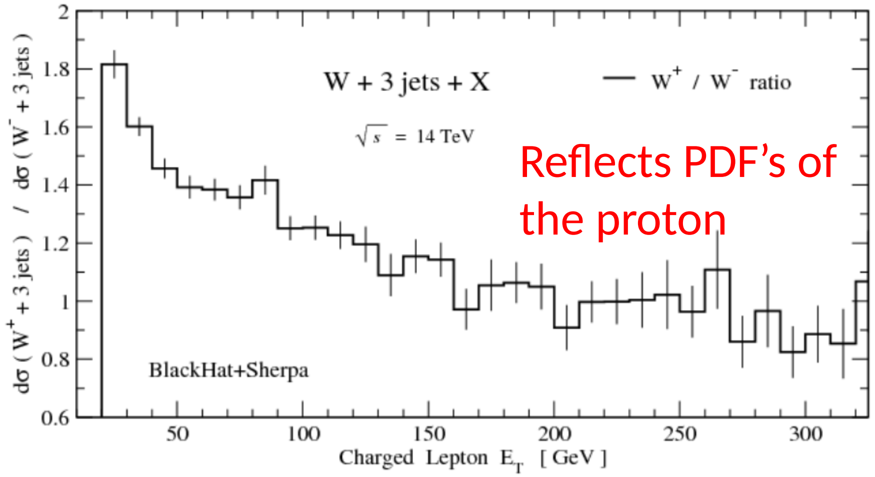




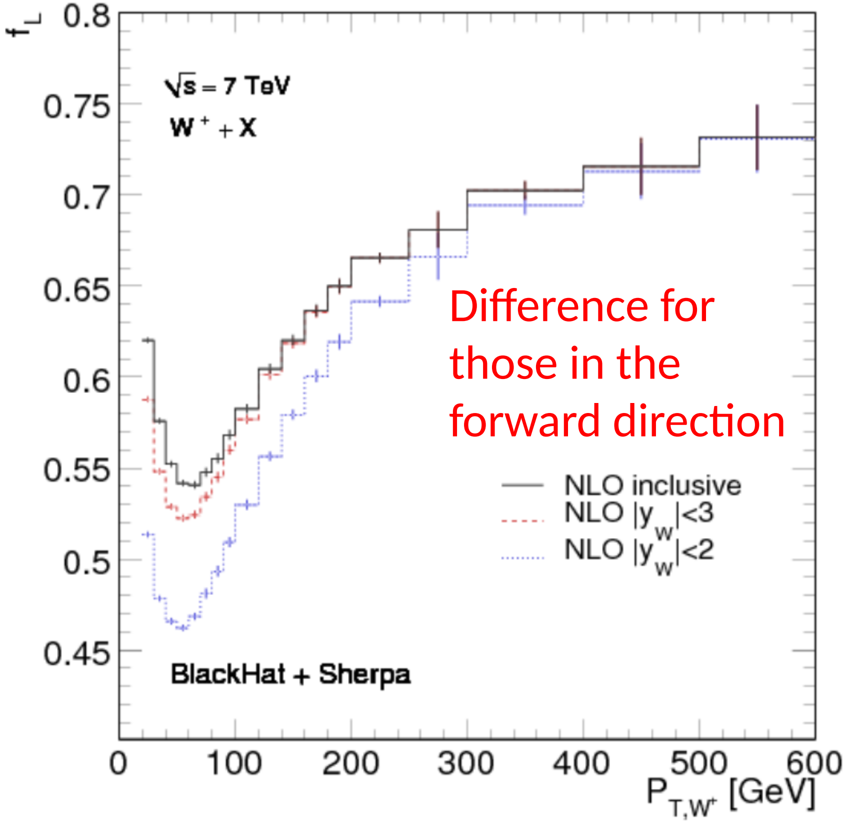
Dominates when starting from valence quarks



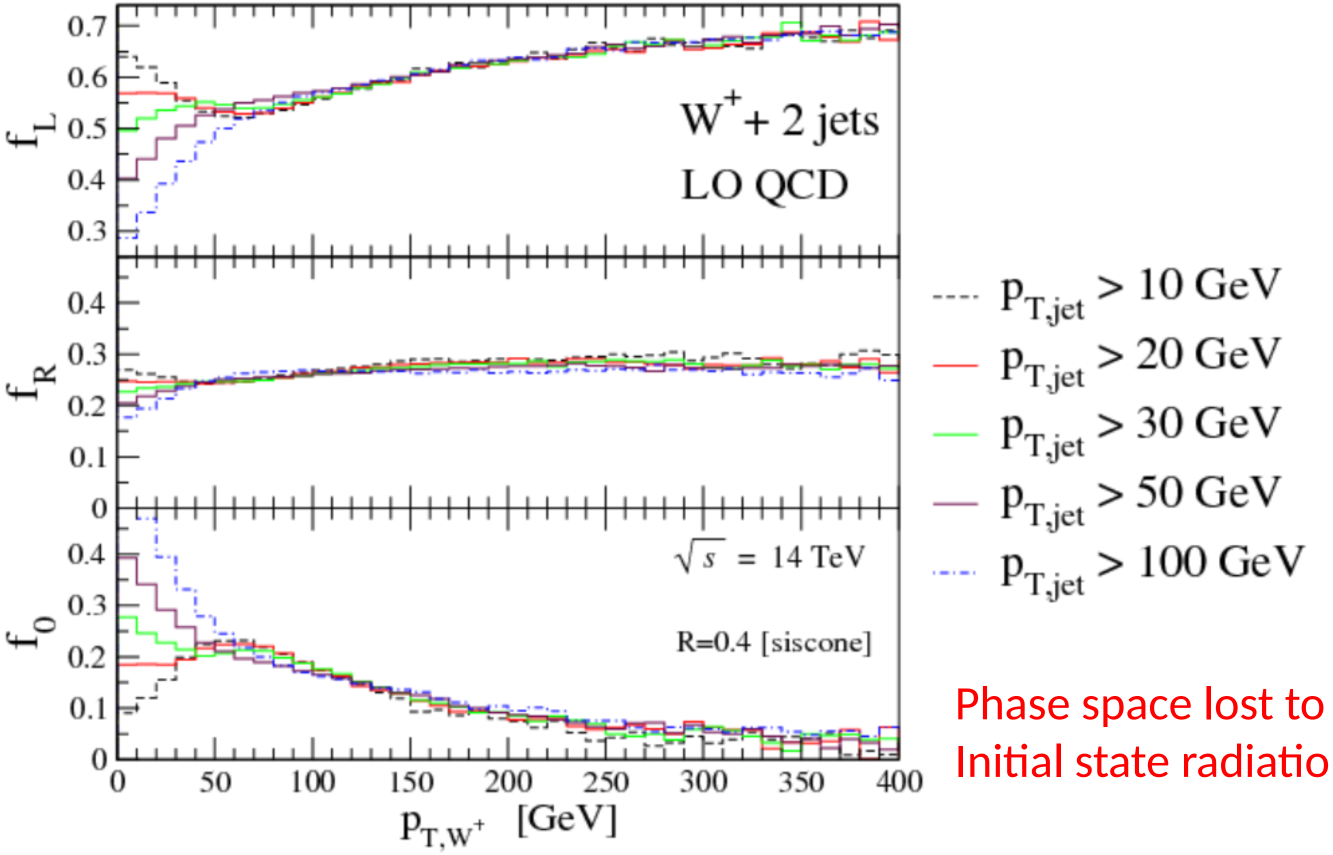
Polarization fraction depend not only on θ, ϕ, but also P_T and pseudorapitity y



Reflects PDF's of the proton



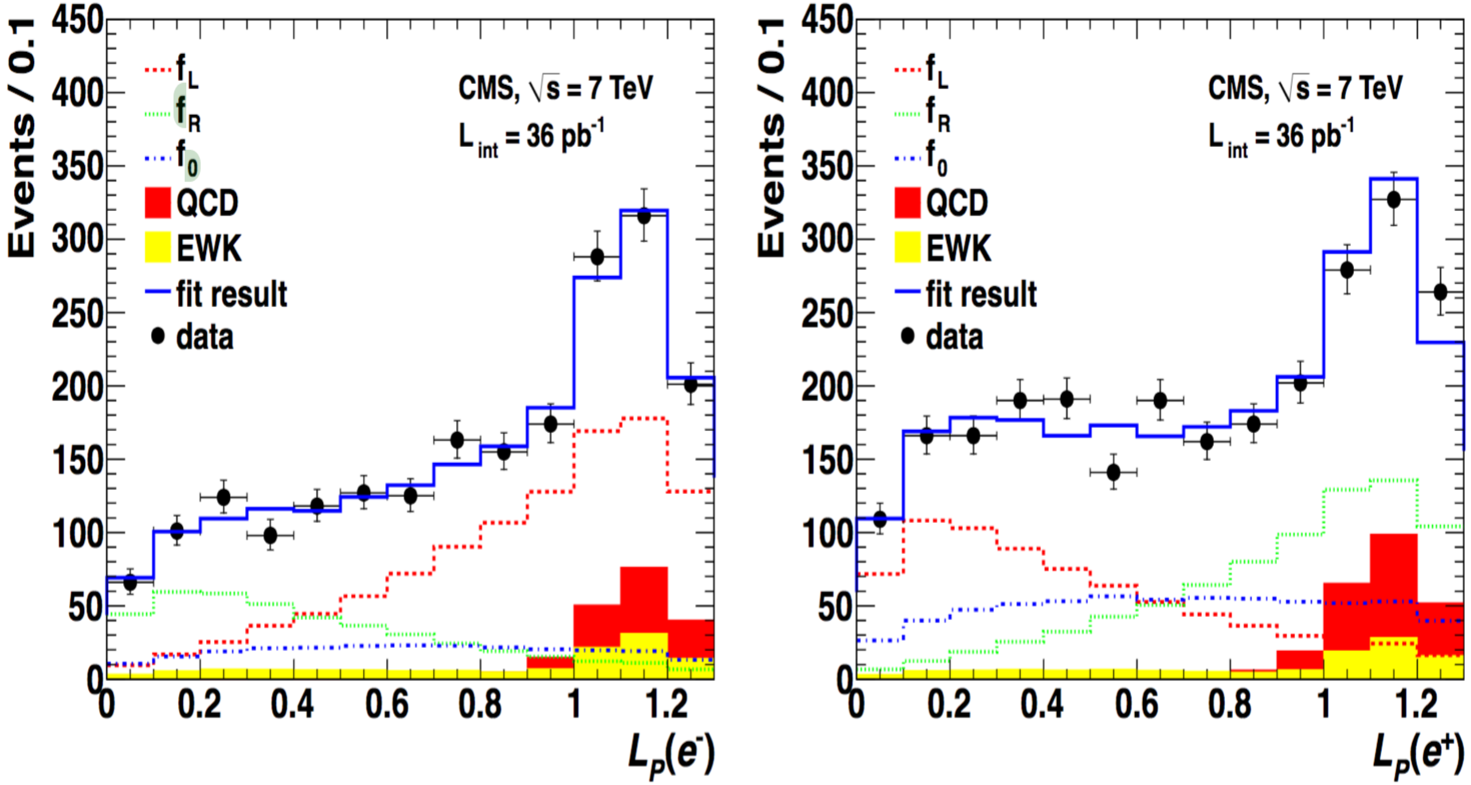
Difference for those in the forward direction

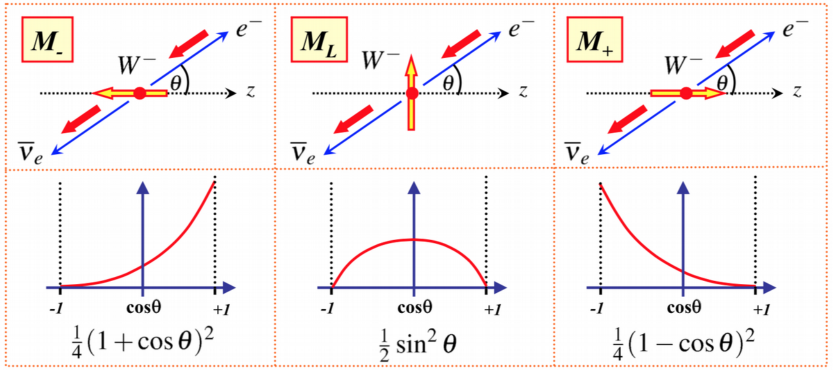


Phase space lost to Initial state radiation

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

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

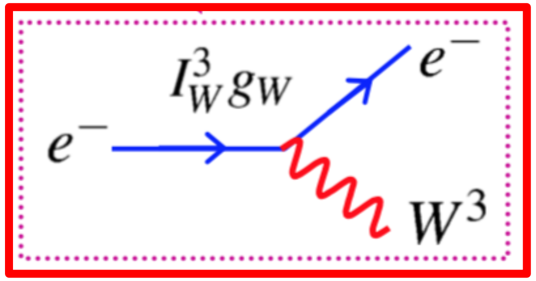




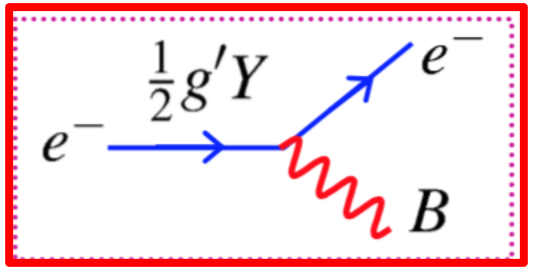
$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}.$$

Asymmetry is created

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



+



WEAK HYPERCHARGE

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

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:

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

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

θ_W is the weak mixing angle

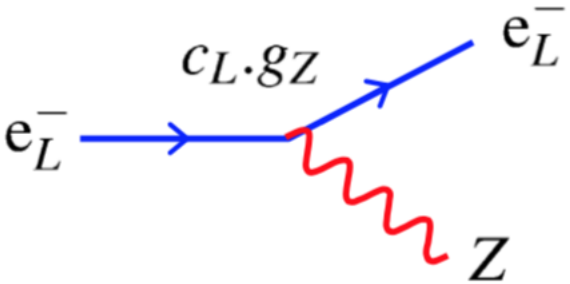
$$e = g_W \sin\theta_W = g' \cos\theta_W$$

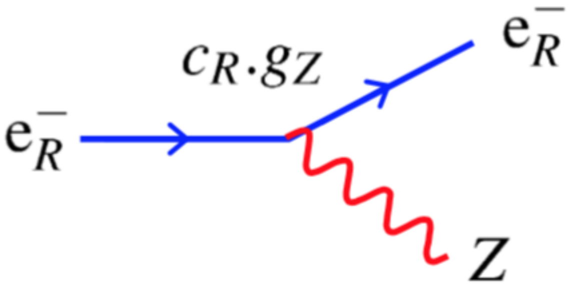
(i.e. equate coefficients of L and R terms)

$$e = g_Z \cos\theta_W \sin\theta_W$$

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

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





$$\boxed{c_L = I_W^3 - Q\sin^2\theta_W} \qquad \boxed{c_R = -Q\sin^2\theta_W}$$

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

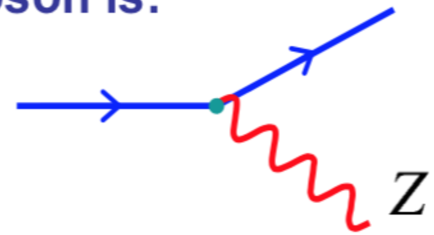
B_μ part of Z couples equally to LH and RH components

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

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

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

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



NEUTRAL WEAK INTERACTIONS

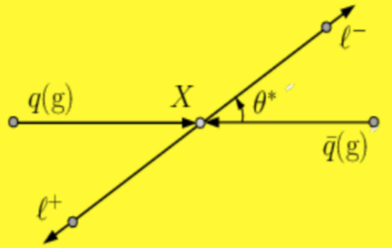
Neutral vector and axial vector coupling in GWS model :

f	c_V	c_A
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	$-\frac{1}{2} + 2\sin\theta_w$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$	$-\frac{1}{2}$

DY to measure $\sin^2\theta_W$

$$\frac{d\sigma}{d\cos\theta^*} = C\left[\frac{3}{8}\left(1+\cos^2\theta^*\right) + A_{FB}\cos\theta^*\right]$$

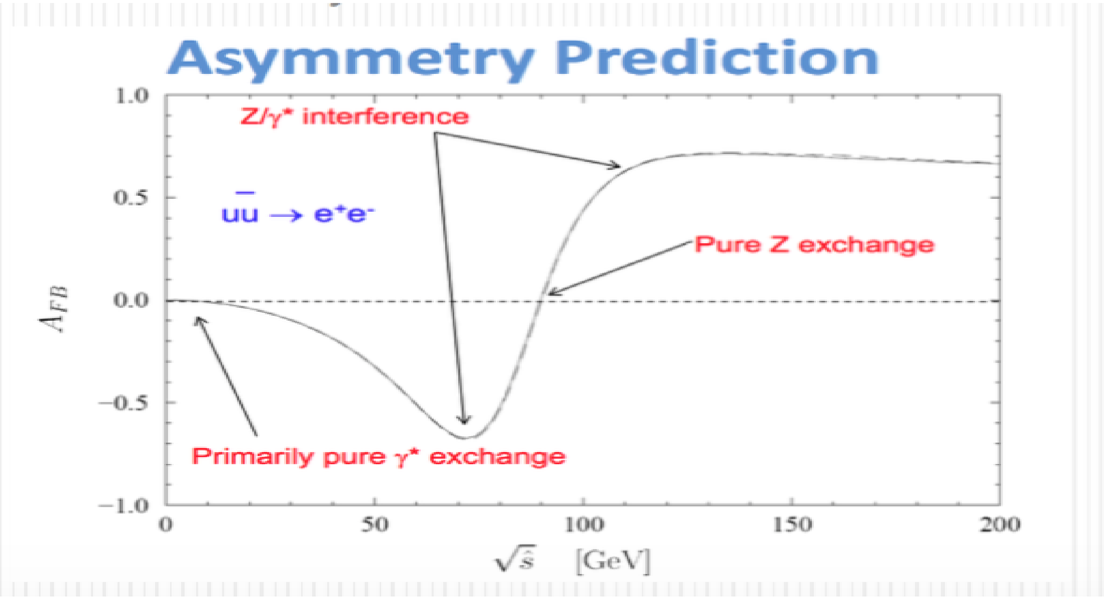
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

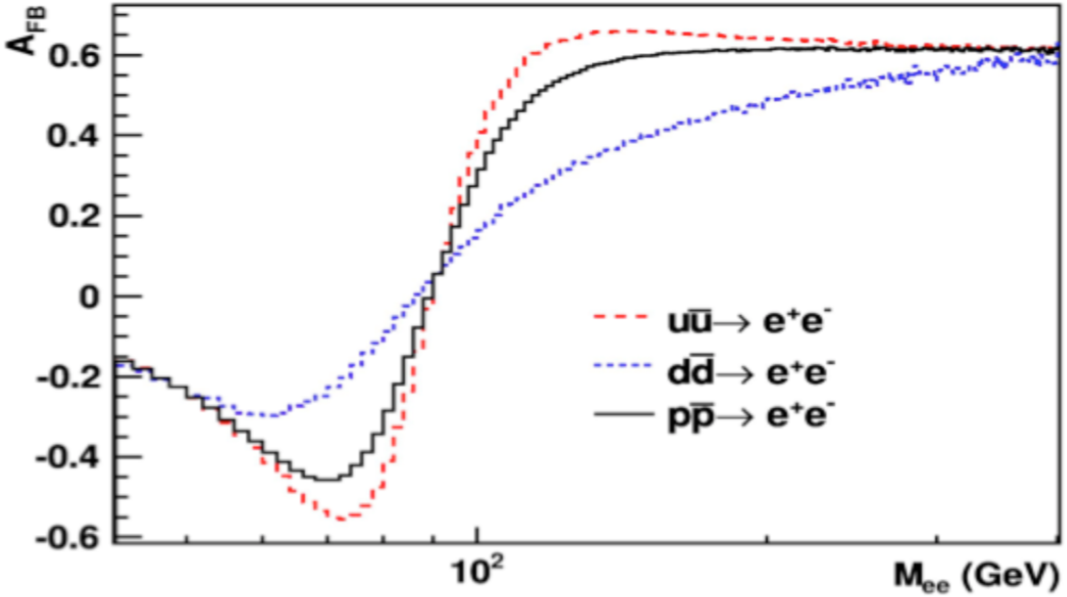


Presence of vector and axial-vector couplings (and weak mixing angle) introduces a forward-backward asymmetry. This is a **parton-level phenomenon** that we measure at **proton-level**.

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

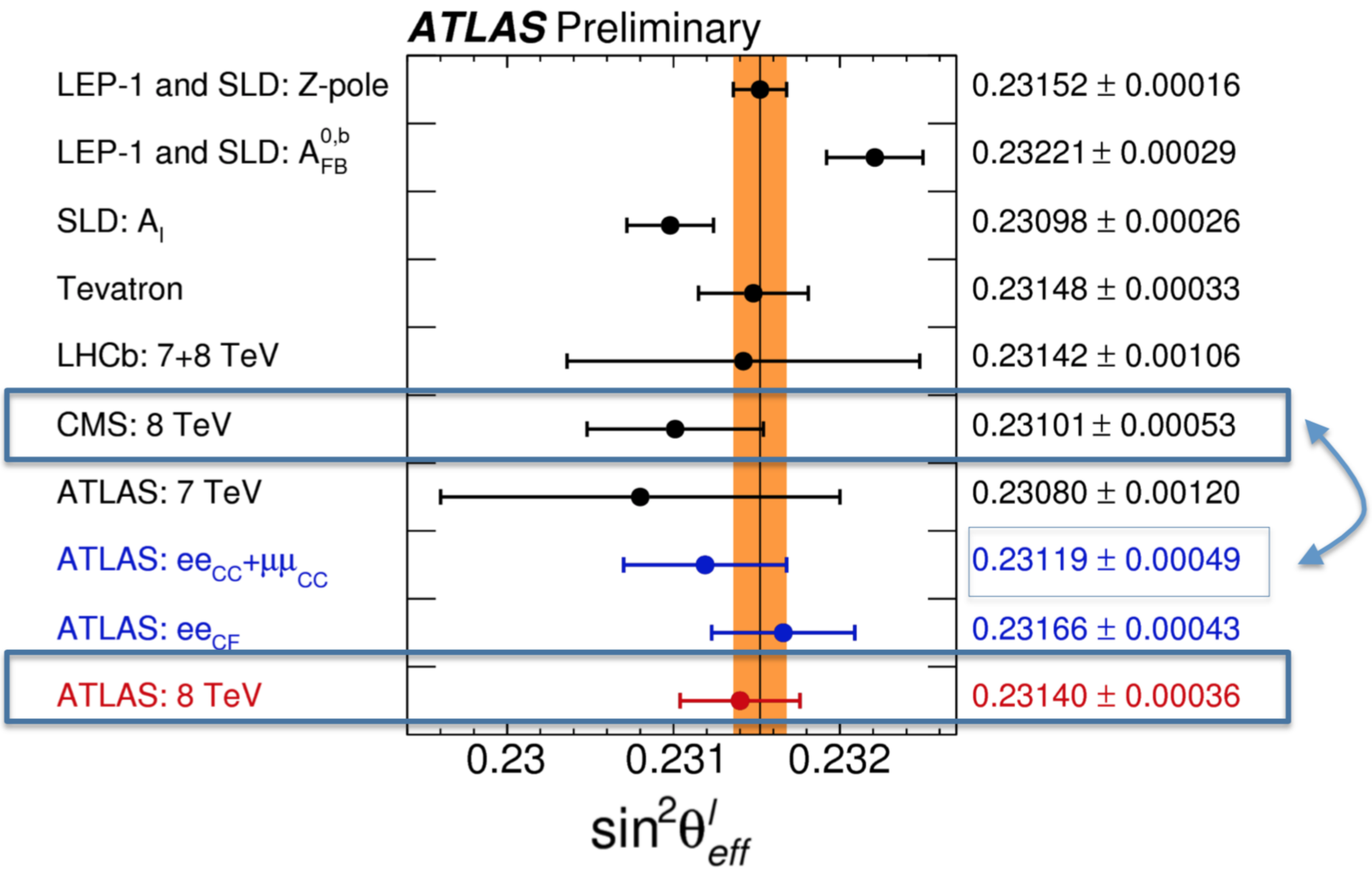
Asymmetry uncorrected for mass resolution or dilution effects

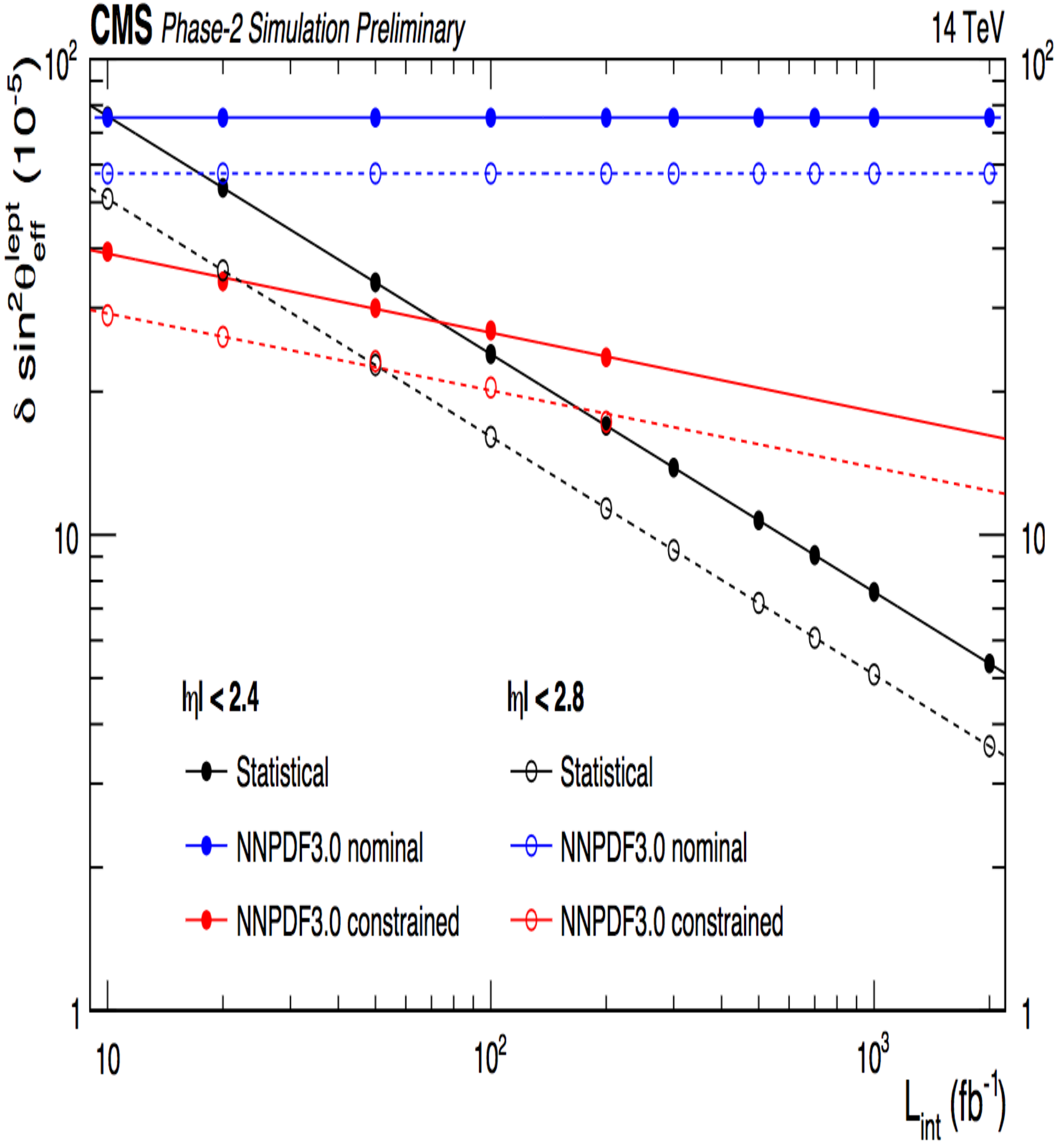




- ATLAS: $\sin^2\theta_W = 0.23140 \pm 0.00021$ (stat) ± 0.00024 (PDF) ± 0.00016 (sys)
- CMS: $\sin^2\theta_W = 0.23101 \pm 0.00036$ (stat) ± 0.00031 (PDF) ± 0.00018 (sys) ± 0.00016(theo)

- Matched Tevatron precision, now targeting precision of e+e- experiments

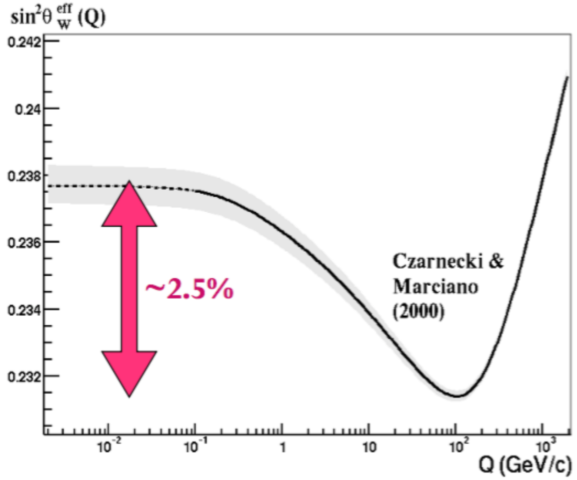


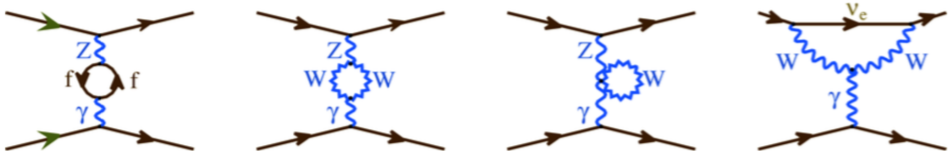


Future…

Running of $\sin^2\theta_W$

- Effective value of $\sin^2\theta_{eff}$ depends on loop effects
- Q^2 dependent, largest when $Q^2 \approx M_Z, M_W$
- Want to measure $\sin^2\theta_{eff}$ at different Q^2





Motivation for precise measurement of the W-mass

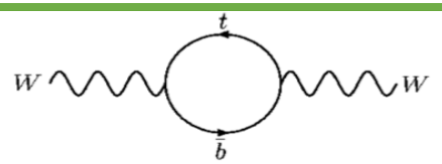
- SM at LO the W boson mass depends on parameters known with high precision:

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

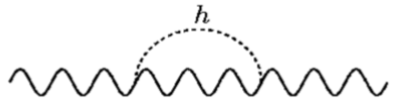
- Beyond LO : corrections depending on m_H and m_{top}

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

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



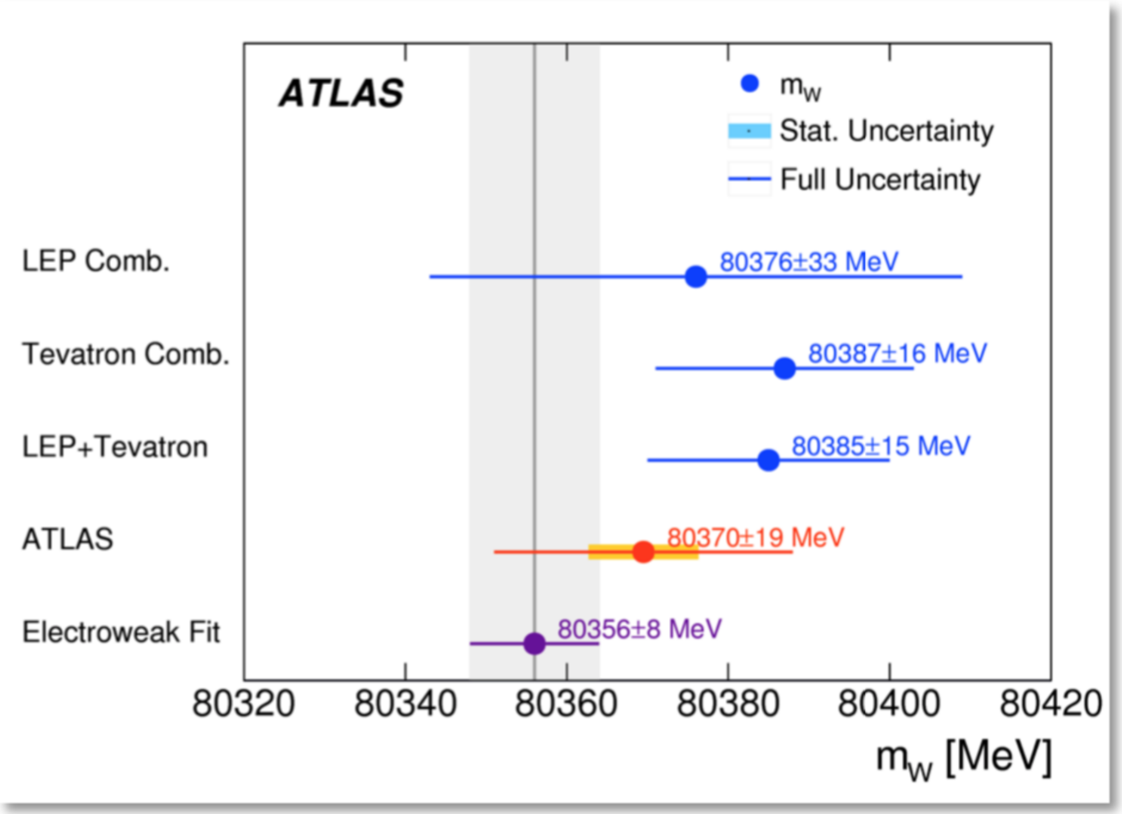
$$\Delta r_{Higgs} \approx \frac{11G_F M_Z^2\cos^2\theta_W}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2} \propto \ln(m_h)$$

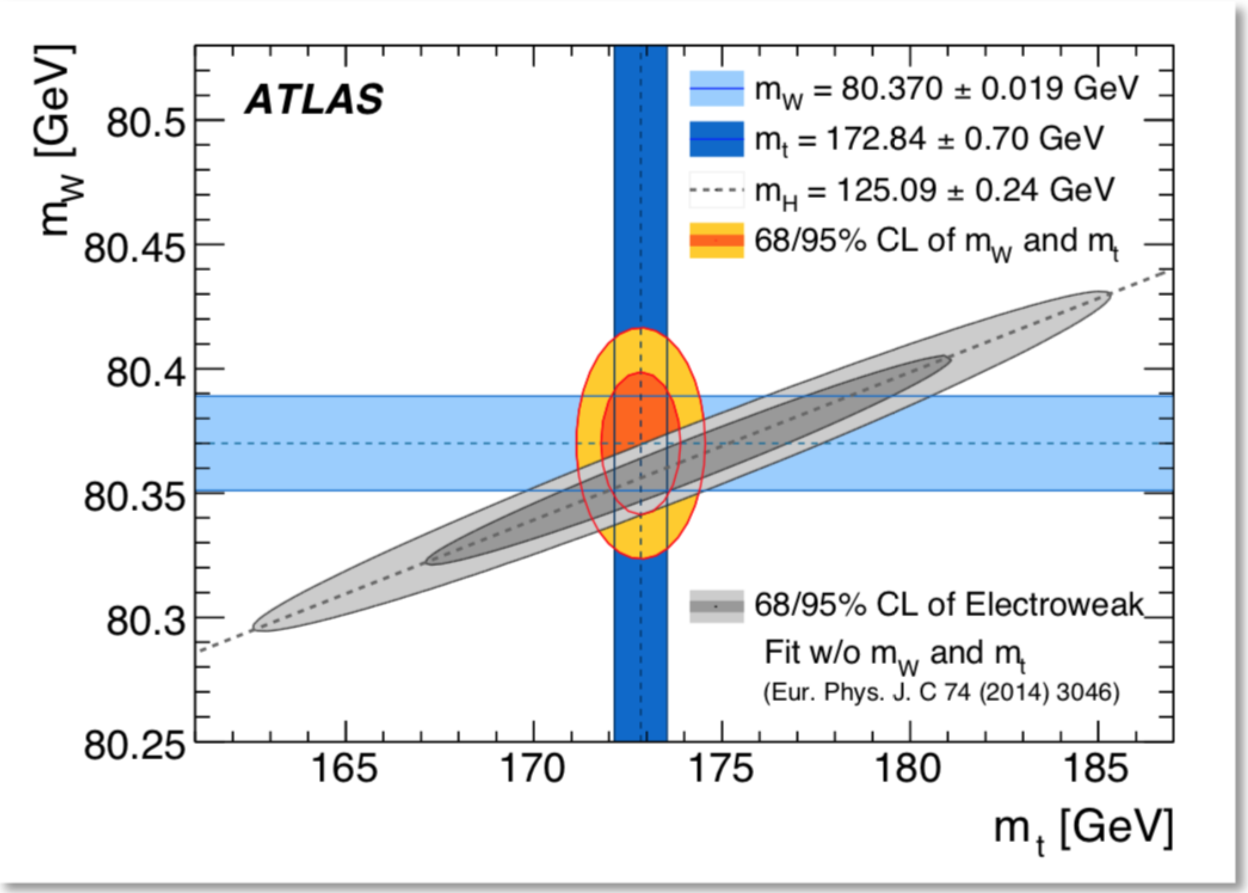


- Test of SM: compare measured m_W to prediction from SM EWK fit
- SM fit without m_W: m_W = 80354 +/- 7 MeV (arXiv:1803.01853)
- Previous combined measurements :

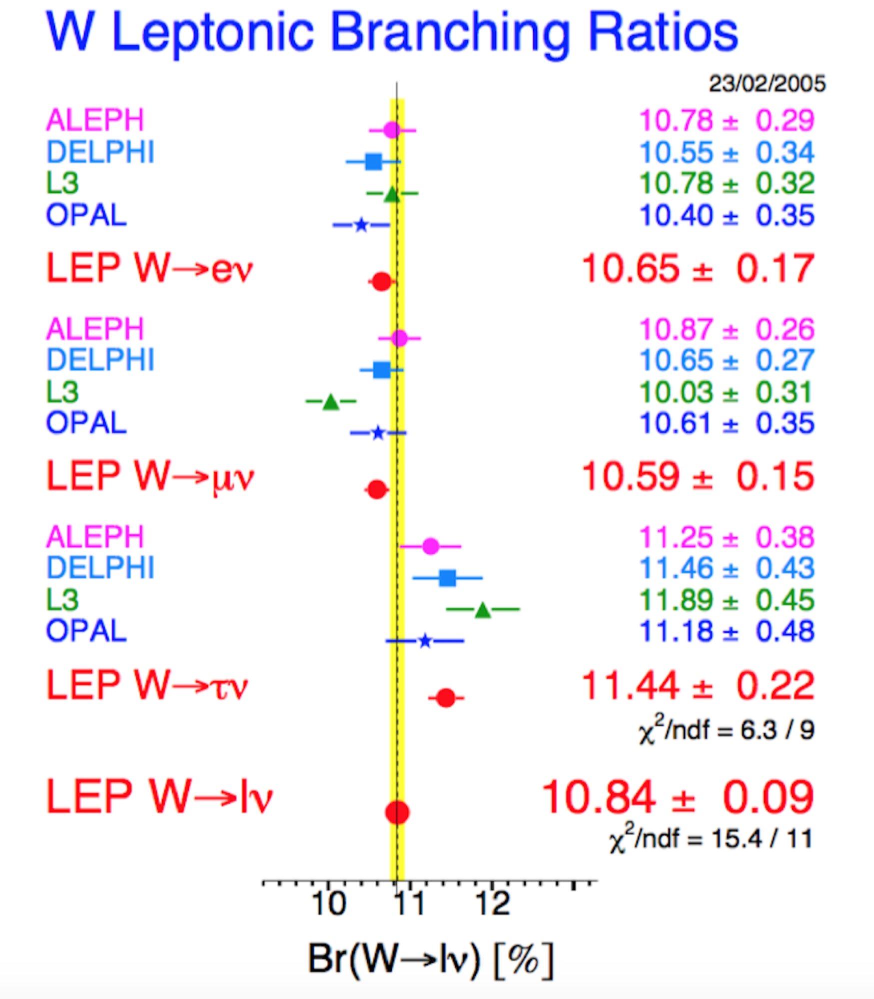
LEP m_W = 80376 +/- 33 MeV   Tevatron m_W = 80387 +/- 16 MeV

$m_W = 80370 \pm 19$ MeV (0.2 permille)



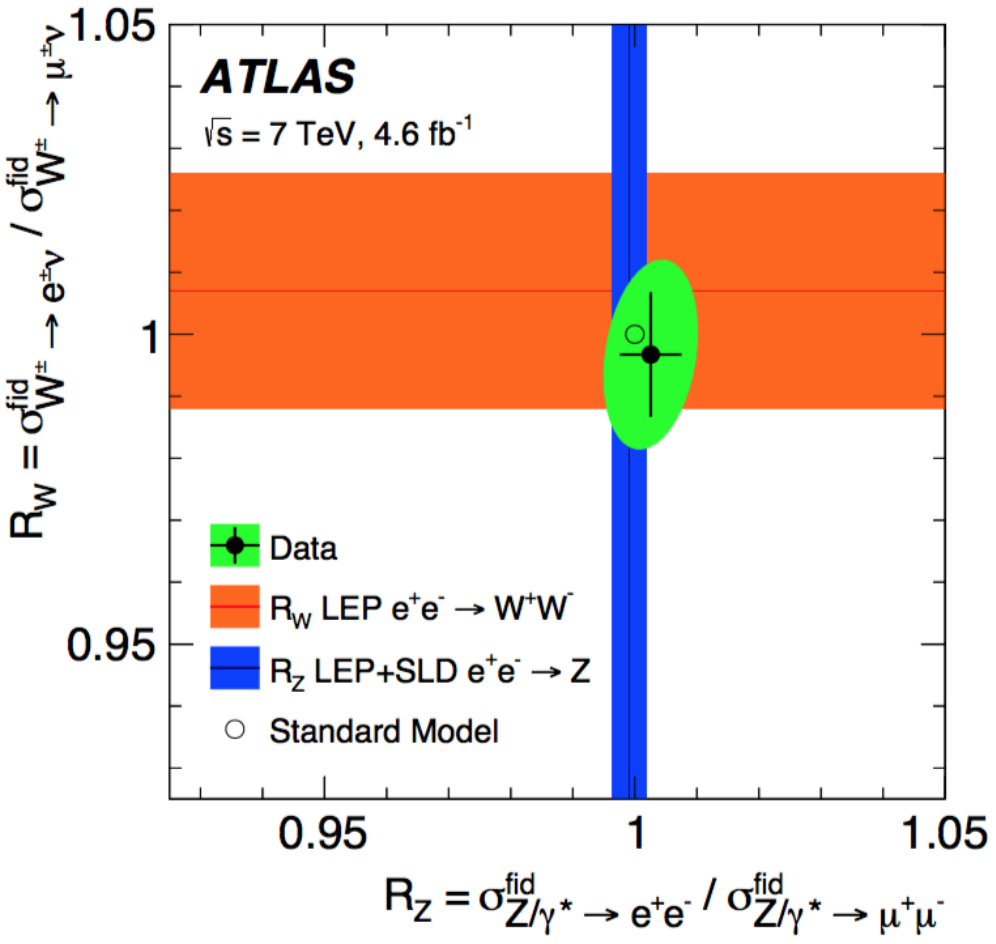


W Mass Measurement



No change
Since
2005…

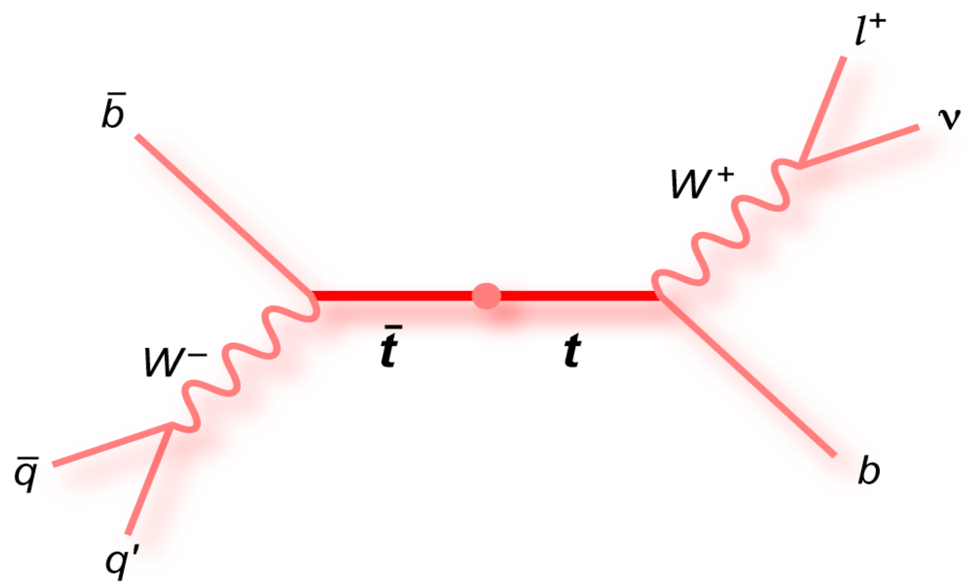
τ BR ~2.7 σ
larger than e/μ



Lepton Universality in W-decays

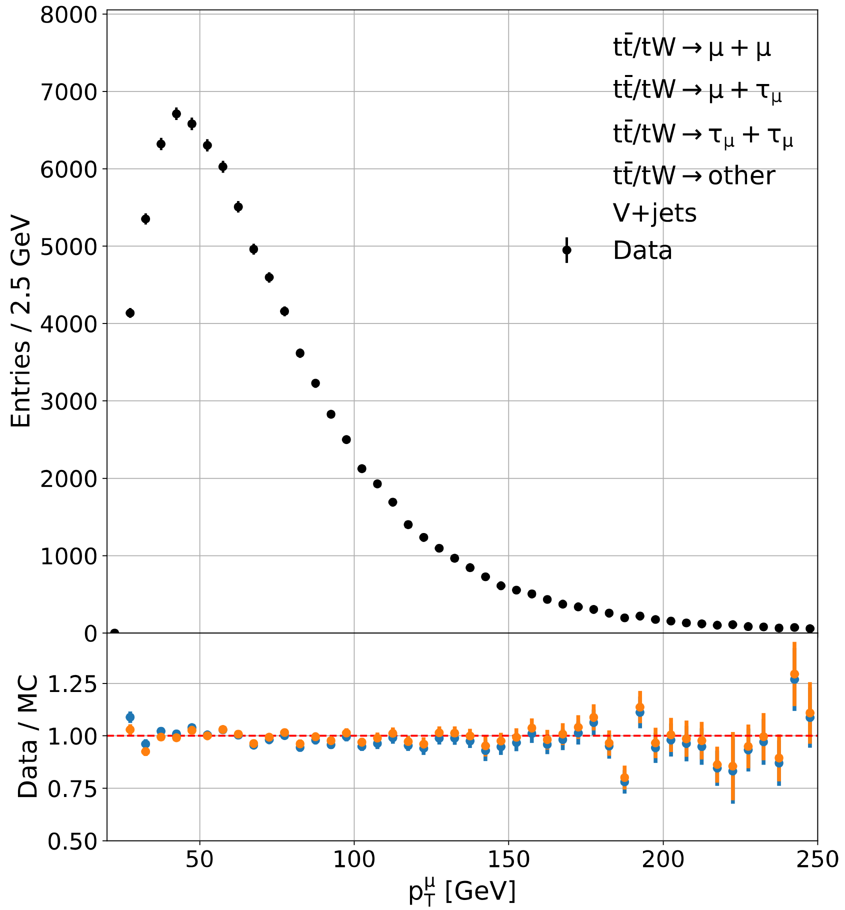
If anomalies in b-meson decays into τ's (D*τν) persists, it becomes more important to revise our assumptions on Lepton Universality

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

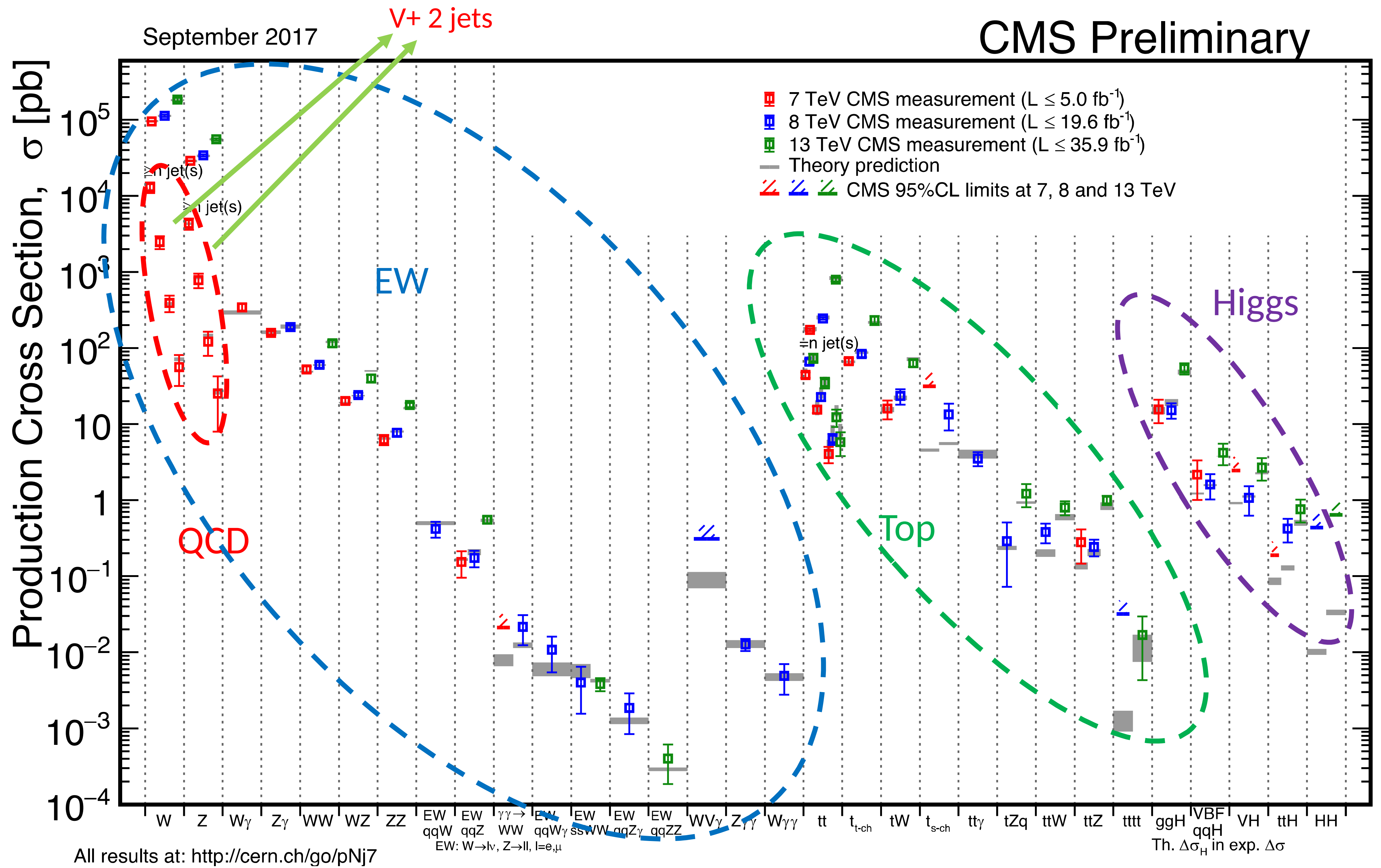


Becoming harder to mantain low energy thresholds for single lepton triggers level @ the LHC

- Future requires new trigger schemes



More tomorrow…
TODAY ⏪

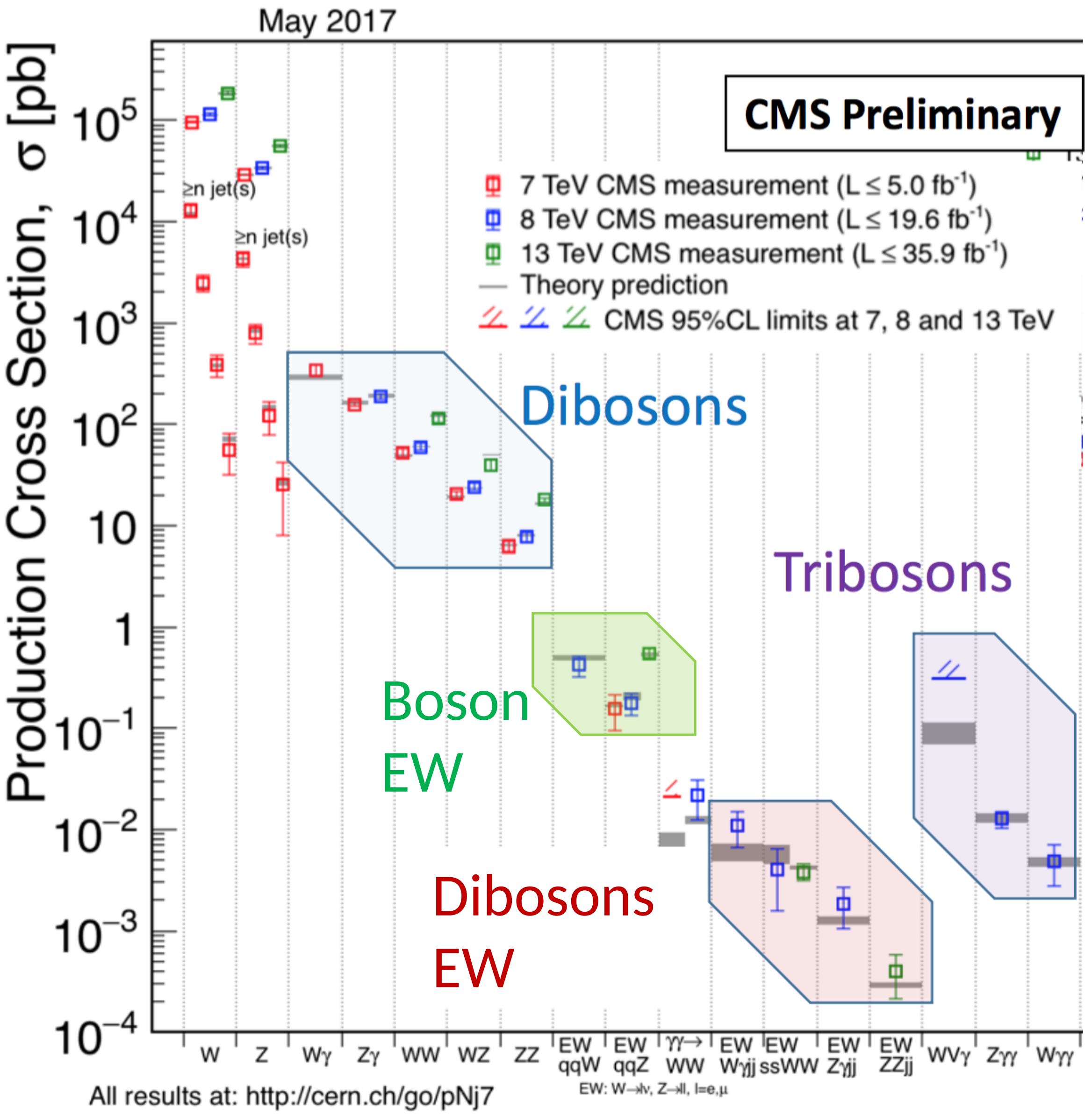


10/22/18 - 10/26/18

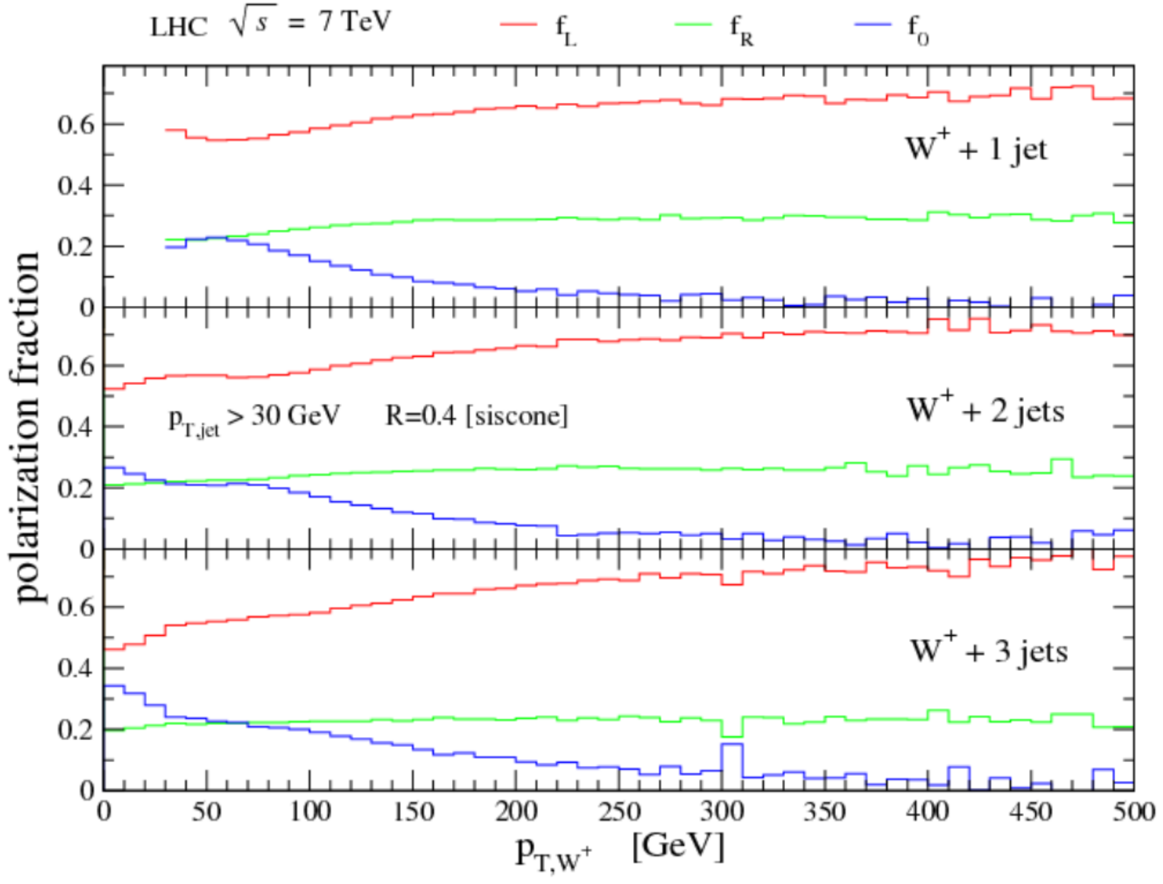
Focus 1st on EW production of single bosons and Multiboson

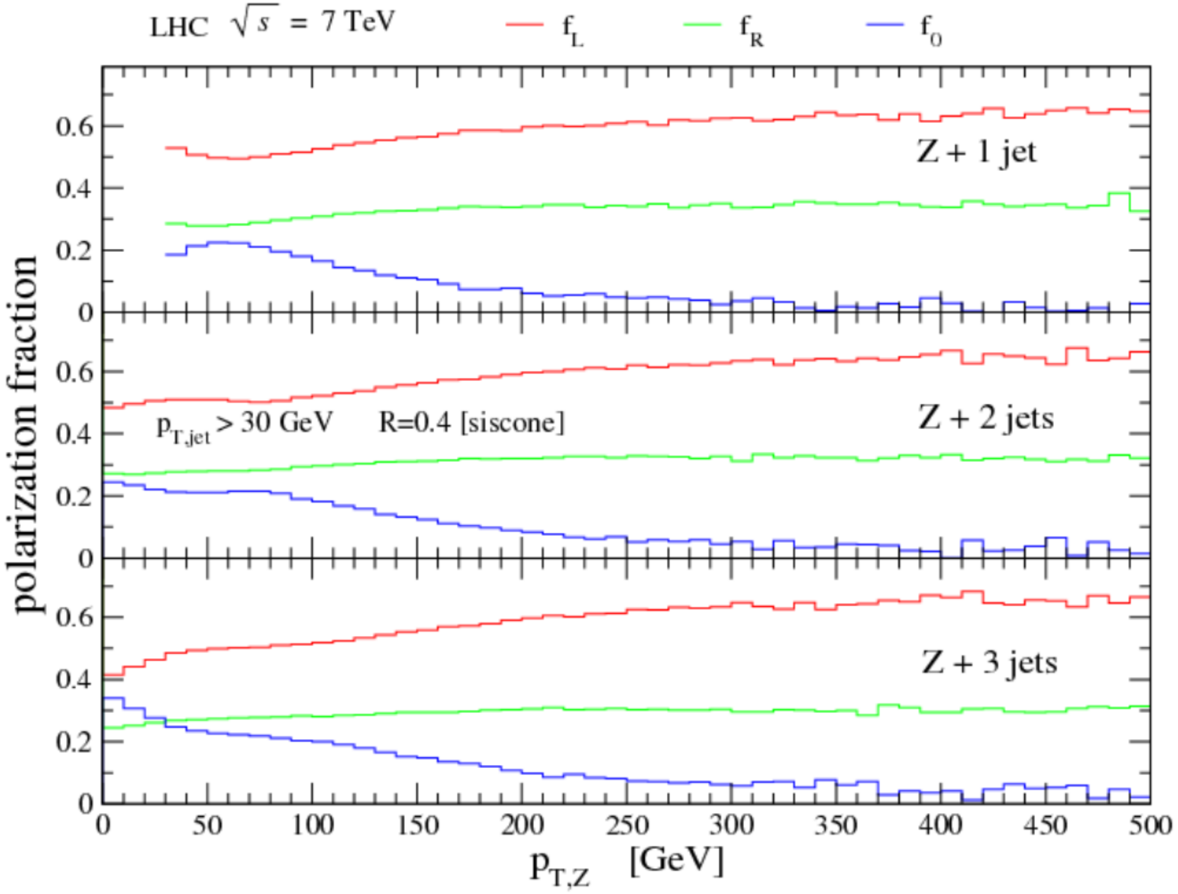
Huge range of production Cross Sections

- 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)



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

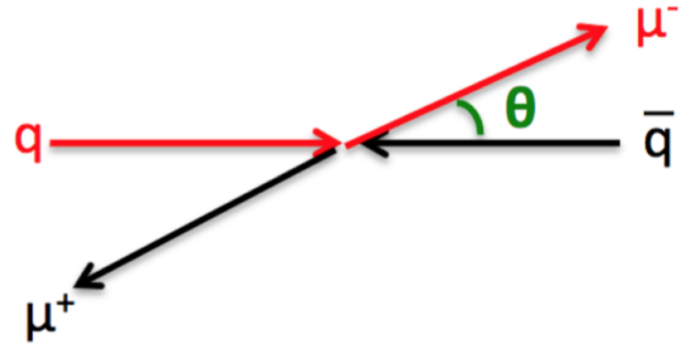




Presence of vector and axial-vector couplings (and weak mixing angle) introduces a forward-backward asymmetry. This is a **parton-level phenomenon** that we measure at **proton-level**.

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

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

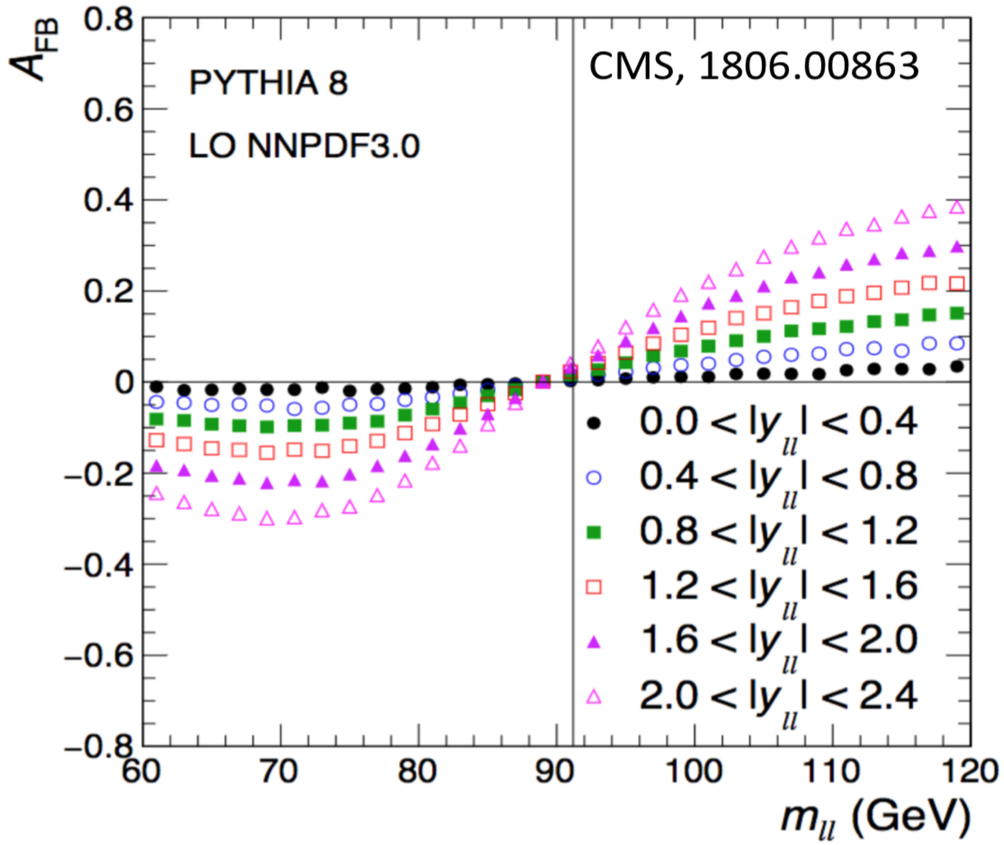


$$\cos\theta^* = \frac{2(P_1^+P_2^- - P_1^-P_2^+)}{\sqrt{m_{\ell\ell}^2(m_{\ell\ell}^2+p_{\mathrm{T},\ell\ell}^2)}} \times \frac{p_{z,\ell\ell}}{|p_{z,\ell\ell}|}$$

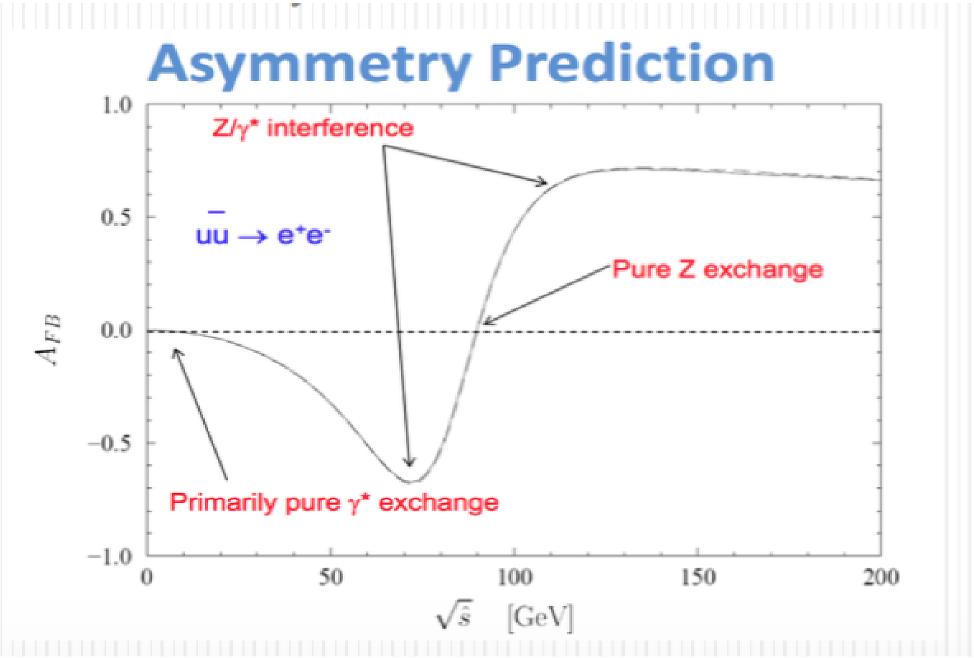
$$P_i^{\pm} = \frac{1}{\sqrt{2}}(E_i \pm p_{z,i})$$

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

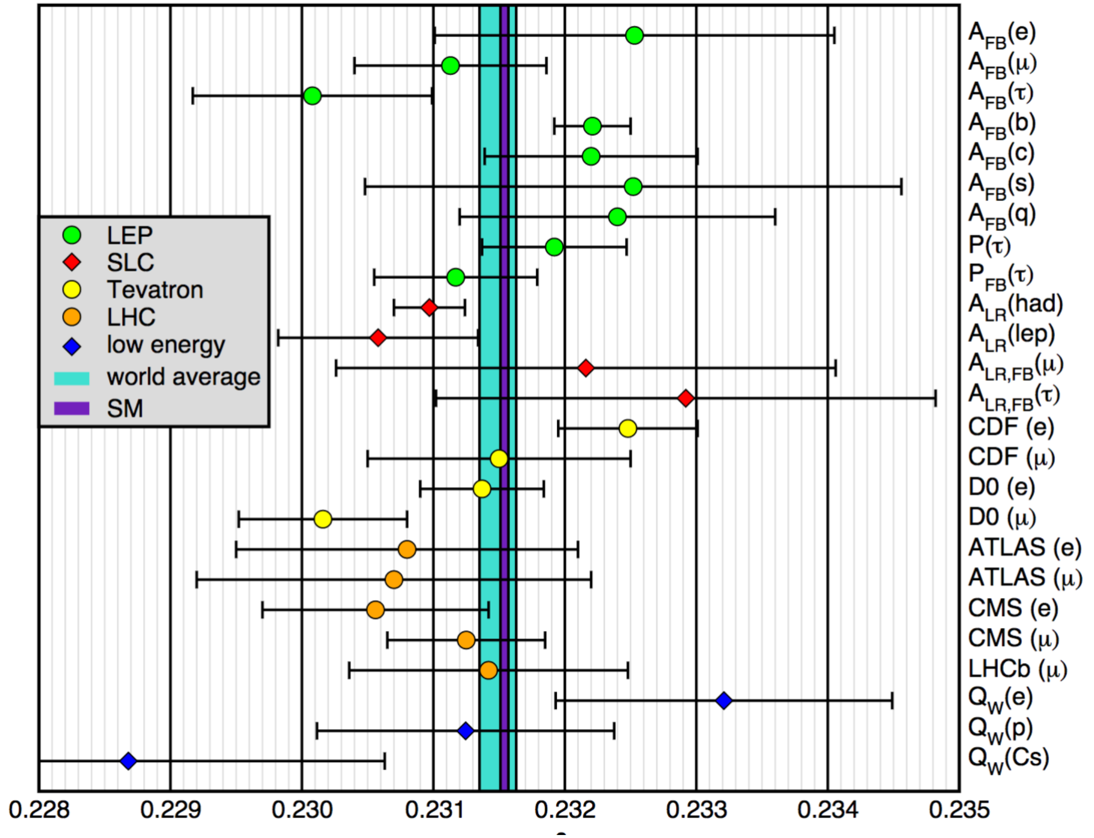
$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00036({\rm stat}) \pm 0.00018({\rm syst}) \pm 0.00016({\rm theory}) \pm 0.00030({\rm pdf})$$

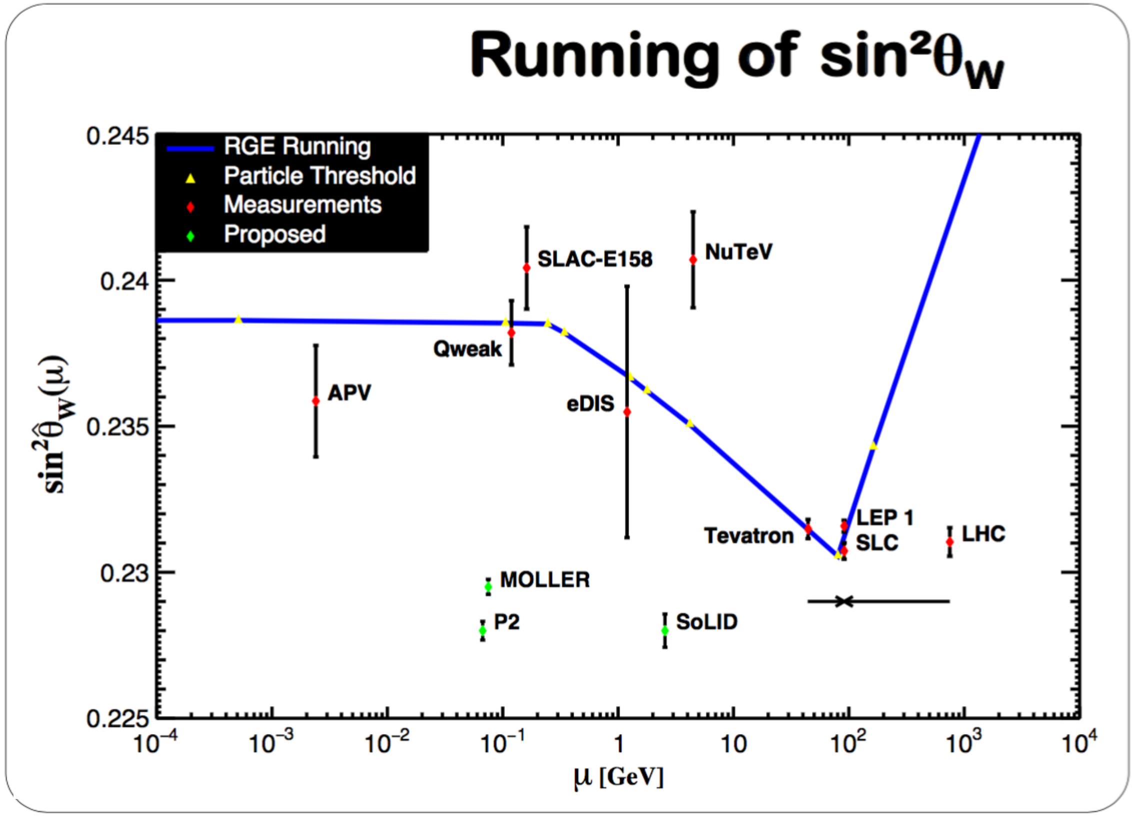


Quantum Mechanical Effects



Interplay between γ & Z^0 and the Vector and Axial-Vector nature of the Z^0



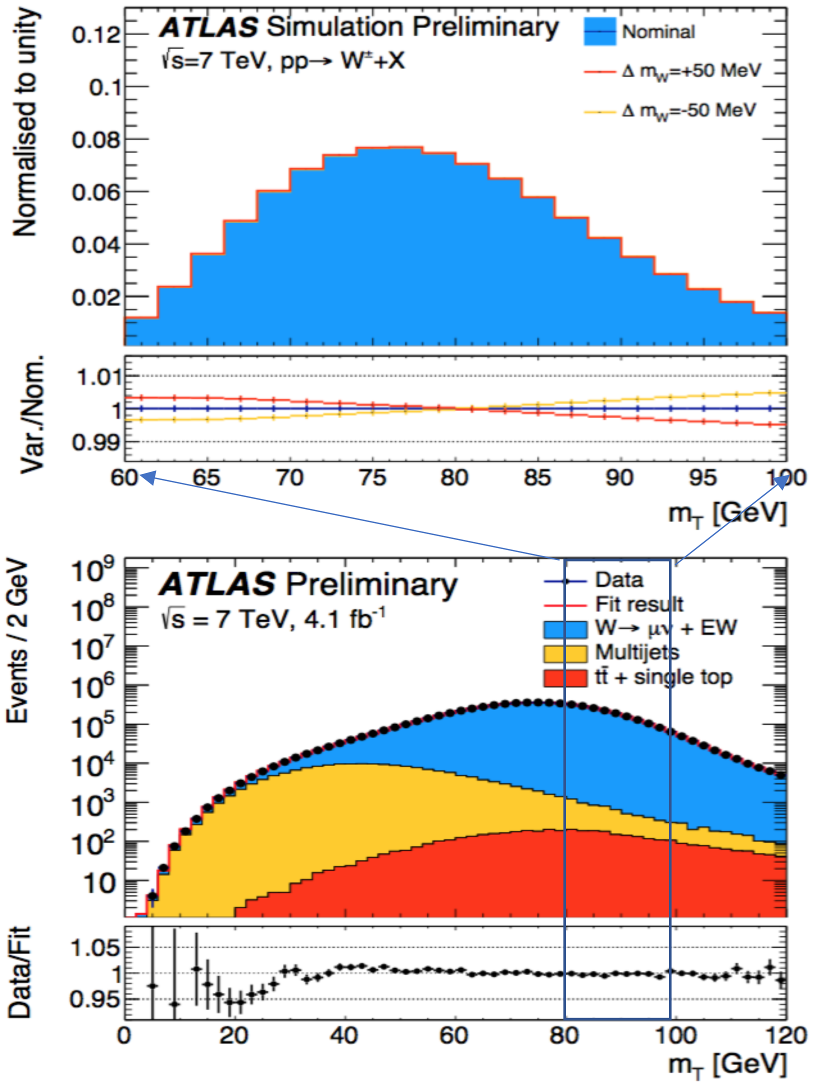


Reduction on the uncertainty by a factor of 2 expected with 13 TeV data and by 4 at the HL-LHC

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