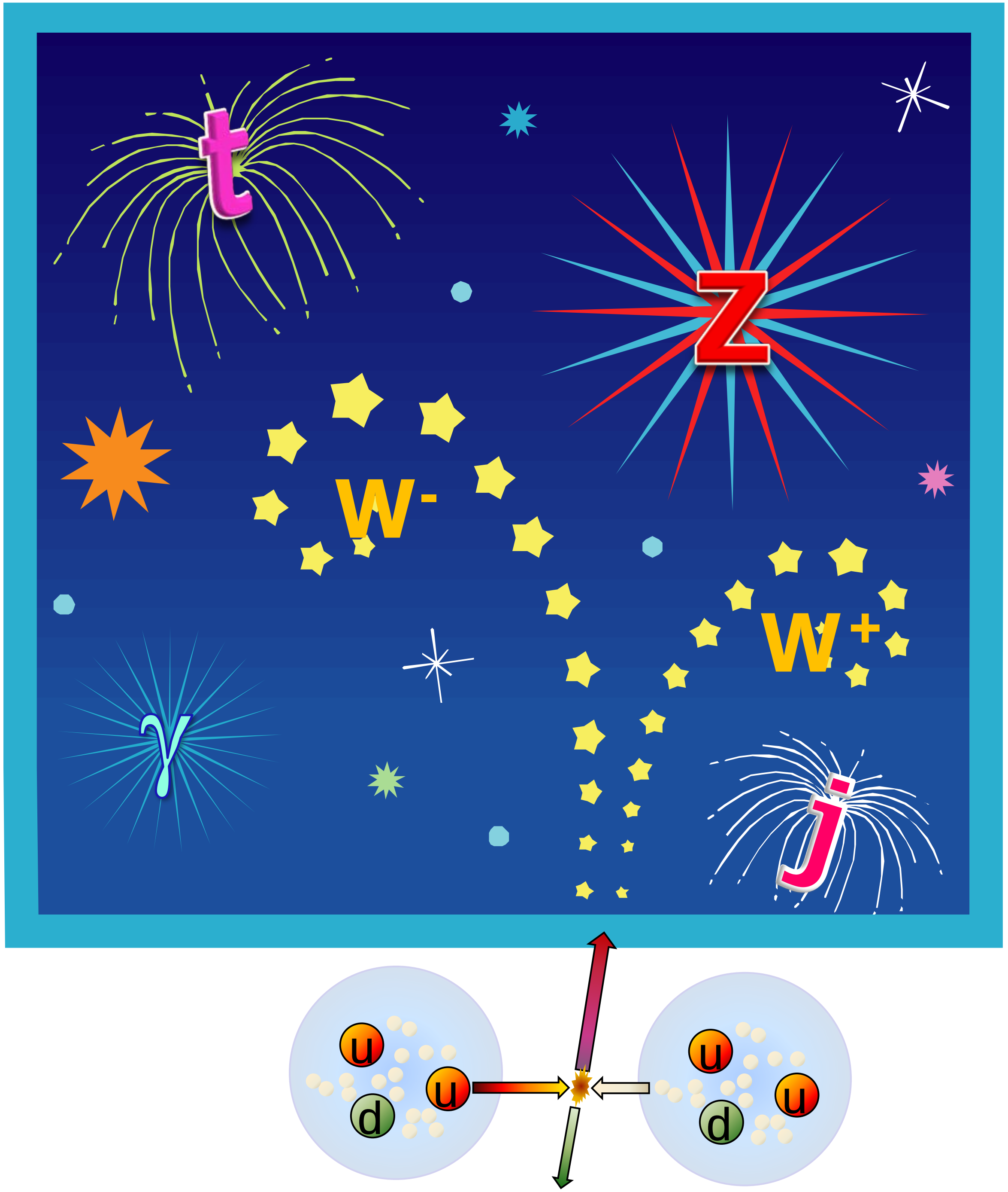


Strong and Electroweak Interactions

Top-quark Physics

Manuella G. Vincter
(Carleton University)
vincter@physics.carleton.ca

CTEQ summer school 2017

· BEVERAGES ·

pp collisions…

How to measure a cross section?

Single-boson production:

- Importance of various kinematic variables
- Orders and generators
- V+jets, γ+jets
- W,Z production vs η & impact on PDFs
- Z-production angular coefficients
- W mass

Multiboson production:

- diboson cross sections: WZ, ZZ
- aTGCs: WZ, WW, $Z\gamma$
- aQGCs: WWW, $Z\gamma\gamma$
- vector-boson scattering

· DESSERTS ·

Top-quark production and decay:

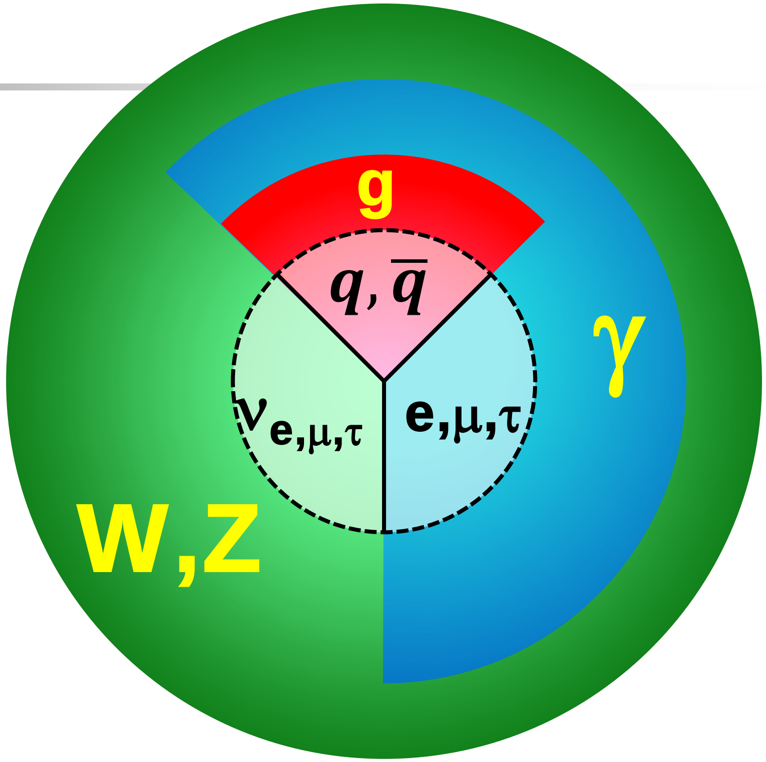
- Comparisons at different $\sqrt{s}$
- dilepton ttbar
- single top
- W polarisation in ttbar (Wtb vertex)
- top mass from dilepton

· FRUIT ·

Lots of pedagogical back-up slides…

- How to measure lumi, definitions, pileup, MB, UE…

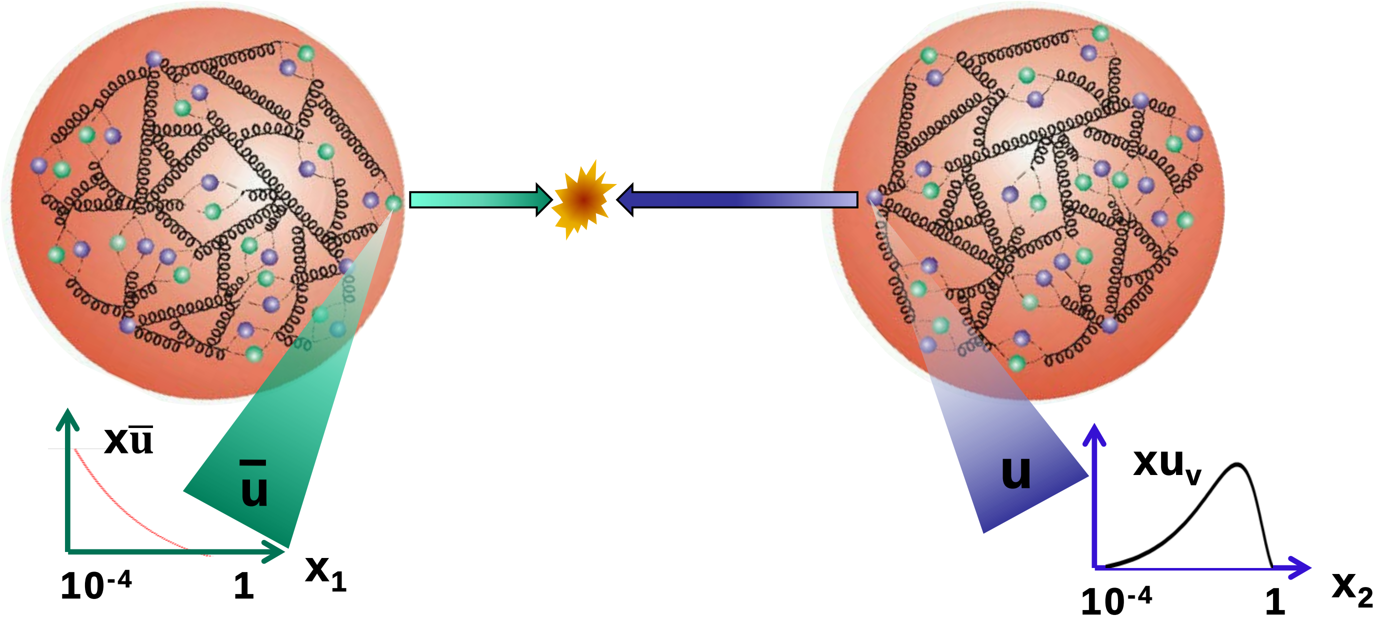

QCD
(mostly)



SINGLE W, Z, γ PRODUCTION

Parton distribution functions f of the proton (pdf)

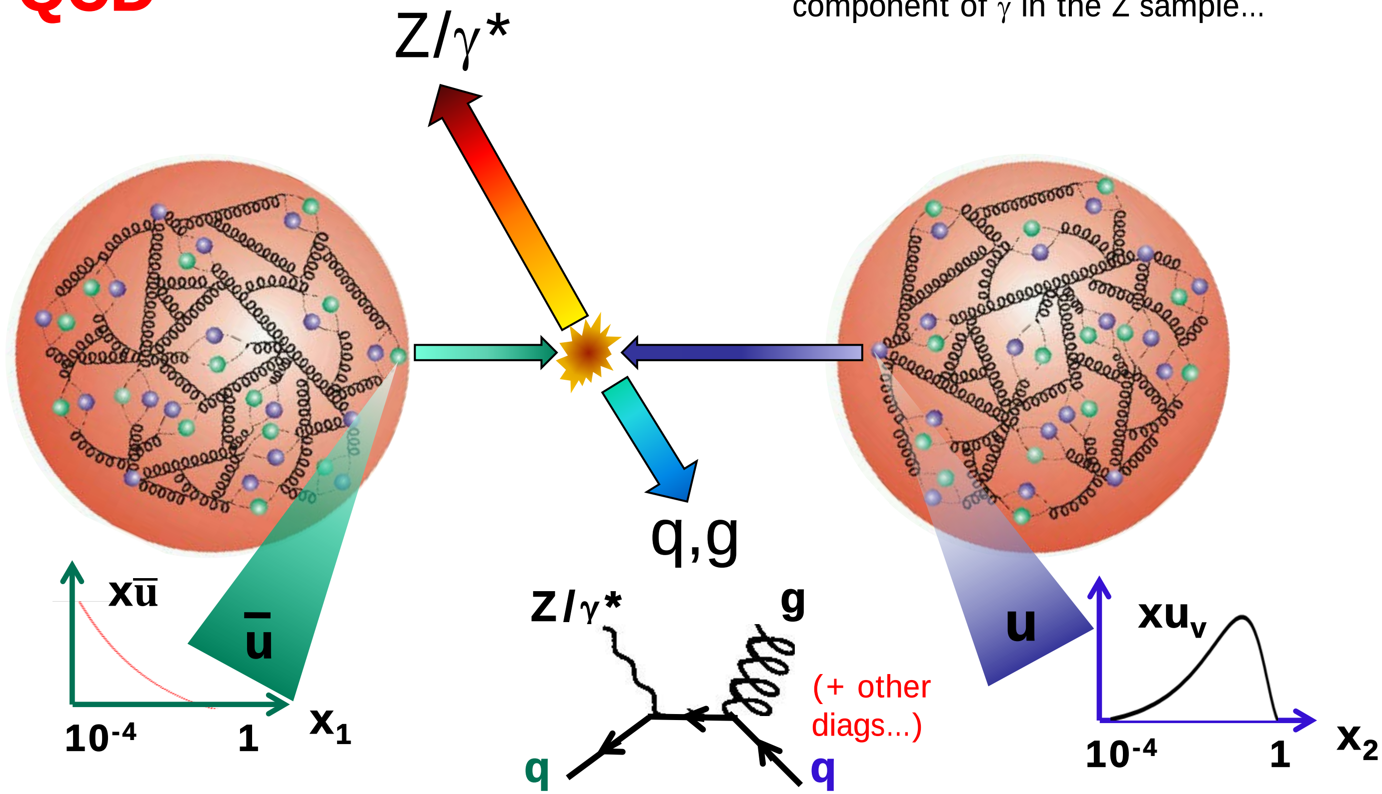
x_1, x_2 = momentum fraction of partons



Thanks to:
desy.de, hepdata.cedar.ac.uk

Perturbative QCD

Legal disclaimer: always some (small) component of γ in the Z sample...



Parton distribution functions f of the proton (pdf)

x_1, x_2 = momentum fraction of partons

Hard scattering $\hat{\sigma}$ for k[th] sub-process between partons of flavour a and b

$$\sigma = \sum_{a,b,k} \int dx_1 dx_2 \; f_a(x_1, Q^2) \quad \hat{\sigma}_{a,b,k}(x_a, x_b) \quad f_b(x_1, Q^2)$$

Via hard scatter, can test perturbative QCD (pQCD) between initial, final states

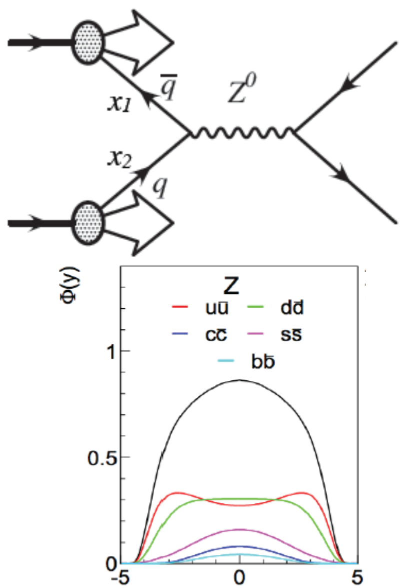
Z balances the hadronic system

e.g. gluon hadronises/showers to jet of particles

Thanks to:
desy.de, hepdata.cedar.ac.uk

Global fits to extract PDFs

- DY production at LHC probes PDFs in the region x ≈ 10^{-4}-10^{-1} and $Q^2 \approx 5\mathrm{x}10^2$-$10^6$ GeV^2
- Feed e.g. $W^{\pm}$, Z/γ^*, W+charm cross section information into global fits to extract PDFs
  - All data have differing sensitivity to different aspects of the proton's PDFs.
  - EW boson production sensitive to valence and sea quark distributions



Rapidity y

(related at LO to momentum fraction x)

$Z \sim 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$

Parameterise PDFs:

$xg(x) = A_g x^{B_g}(1-x)^{C_g} + \ldots$

$xu_v(x) = \ldots$

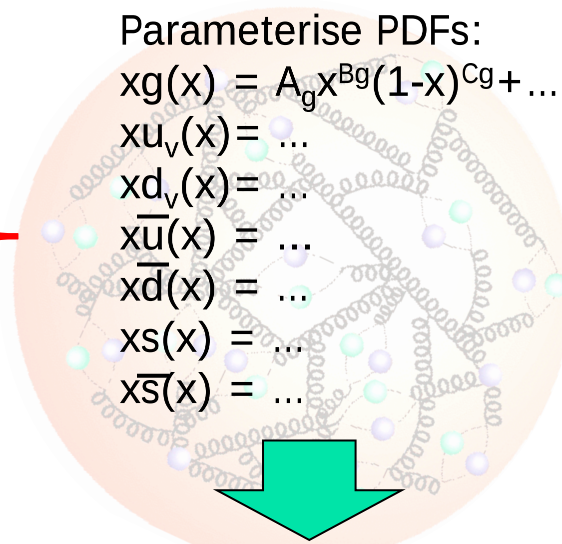
$xd_v(x) = \ldots$

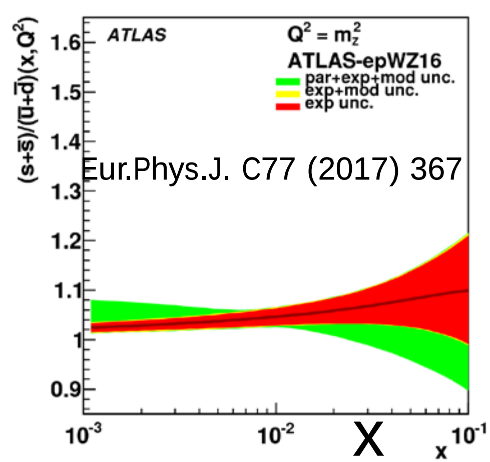
$x\bar{u}(x) = \ldots$

$x\bar{d}(x) = \ldots$

$xs(x) = \ldots$

$x\bar{s}(x) = \ldots$





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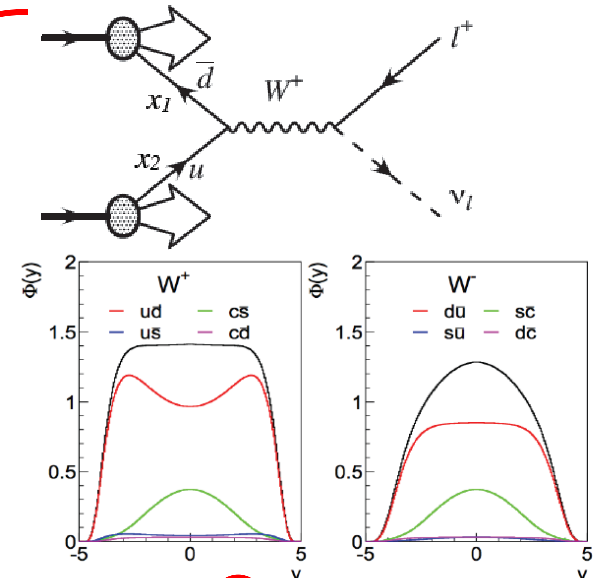
X



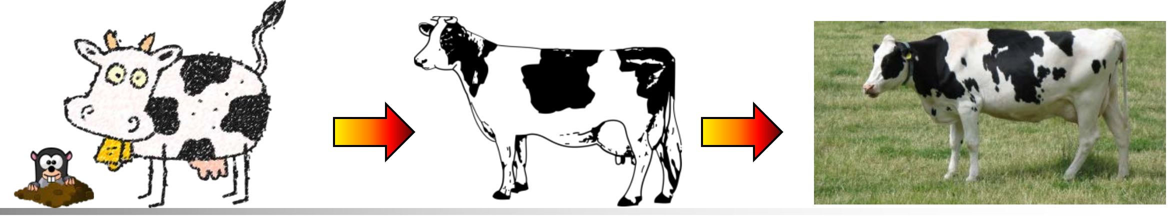
$W^+ \sim 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$

$W^- \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$

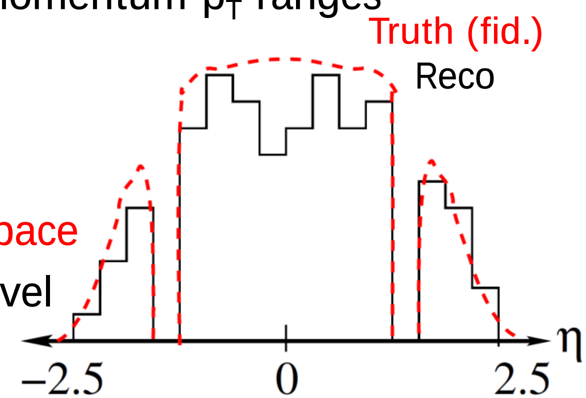
Result: e.g testing relationship between strange and down sea

$$x_1 = \frac{M_W}{\sqrt{s}} e^{y} \qquad x_2 = \frac{M_W}{\sqrt{s}} e^{-y}$$

Cross section methodology



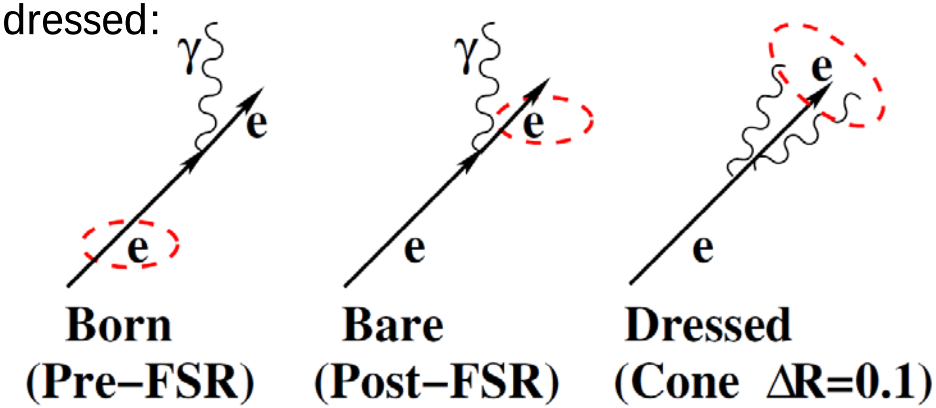
- Experiments select events that enhance the physics signal that they want to measure
  - W: 1 prompt, energetic, isolated charged ℓ + ν giving rise to E_T^{miss}: $W \rightarrow \ell\nu$
  - Z: 2 prompt, energetic , isolated charged ℓ, same flavour, opposite sign: $Z \rightarrow \ell^+\ell^-$
- Leptons reconstructed within pseudorapidity η and transverse momentum p_T ranges afforded by the detector
  - Fiducial phase space e.g. requirements on:
    - $p_{T,\ell}$, η_ℓ, $p_{T,\nu}$, m_T^W, $m_{\ell\ell}$

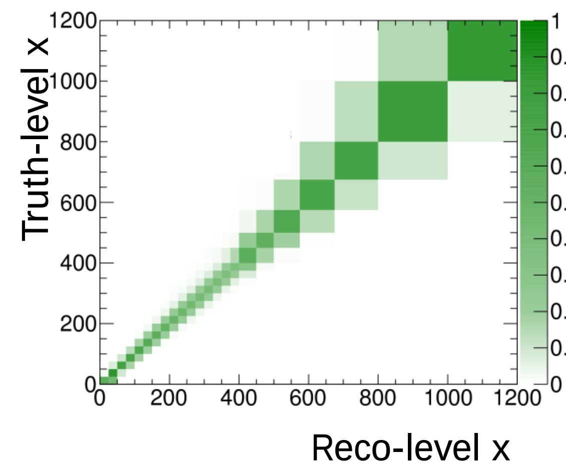


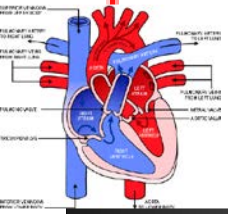
- Measurements reported (to the world) in fiducial or full phase-space
- Use simulation to unfold data from "reconstruction" to "truth" level
- Correction factor: reconstruction $\rightarrow$ truth level in fiducial region
- Acceptance: truth fiducial region $\rightarrow$ full truth phase-space

Cross-section measurement reported at one or more levels:

- Born, bare, dressed:







Anatomy of a cross section: simple sketch

σ

cand. evts

bkg evts

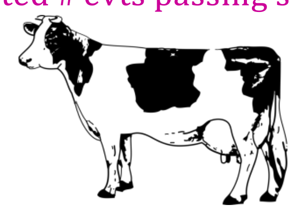
$$\sigma_{W,Z} \times BR(W,Z \to l\nu, ll) = \frac{N - B}{A_{W,Z} \cdot C_{W,Z} \cdot \mathcal{L}_{W,Z}}$$

Integrated lumi

A: acceptance factor from fiducial to full phase space (entirely from truth info and so can have considerable theory uncertainties)

C: correction factor from reco to fiducial

$$C = \frac{\text{Expected \# evts passing selection at reco}}{\text{Expected \# evts passing selection at truth}}$$



C includes MC-to-data correction factors (with uncertainties) for object reconstruction, identification, triggering, etc... as well as (usually small) theory uncertainties associated with going from reco to truth.

Going to differential cross sections in 1D, 2D etc... Important to think about the correlations in the uncertainties between the variables

$$\frac{d\sigma}{dx}, \quad \left(\frac{d^2\sigma}{dxdy}\right), \quad \ldots$$

Properties of the LHC

Luminosity L: ratio of the number of events detected N within a time t to the interaction cross-section σ:

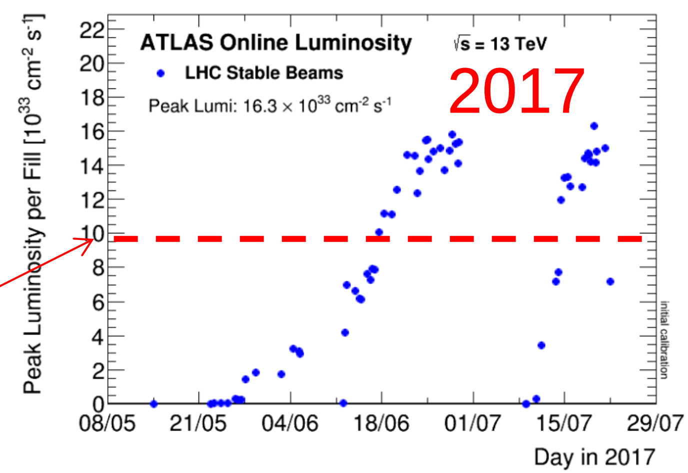
$$L = \frac{1}{\sigma}\frac{dN}{dt}. \qquad L \propto \frac{N_b{}^2\, n_b\, f_r}{beam\ pars}$$

L depends on the beam parameters

- N_b = number of particles per bunch ≈ 1.15 x 10^{11} protons
- n_b = number of bunches per beam ≈ 2800
  - 26659 m/7.5 m between bunches = 3550 bunches but need extra room to insert bunches etc… so effectively 2800
- f_r = revolution frequency of the accelerator ≈ [26659 m/3x10^8 m/s]$^{-1}$ ≅ 11245 Hz
- Parameters related to the size of the beam in the transverse plane

At full LHC design:

- Centre-of-mass energy of 14TeV
  - Run 1: 7TeV (2010/1), 8TeV (2012)
  - Run 2: 13TeV (2015-17)
- Collisions every 25 ns
  - 50 ns (2010-12), 25 ns (2015-17)
- Peak luminosity of L=10^{34} cm^{-2}s^{-1}

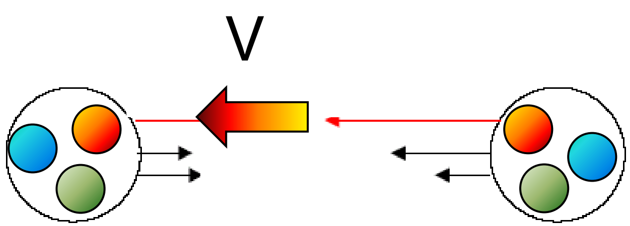


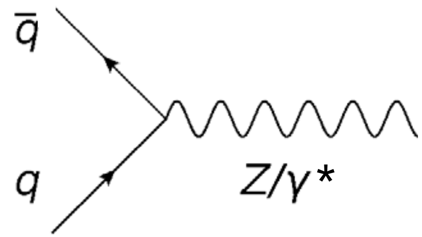
Integrated luminosity ∫Ldt so far:

- 0.04fb^{-1} (2010), 5fb^{-1} (2011), 20fb^{-1} (2012), 3fb^{-1} (2015) , 33fb^{-1} (2016), 2017 ongoing

V (=γ, W, or Z) production

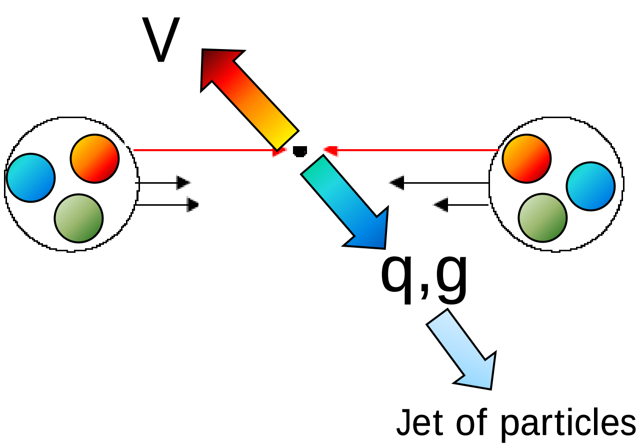
- At born level, V has nothing to recoil against in the transverse plane
  - V produced with no transverse momentum p_T

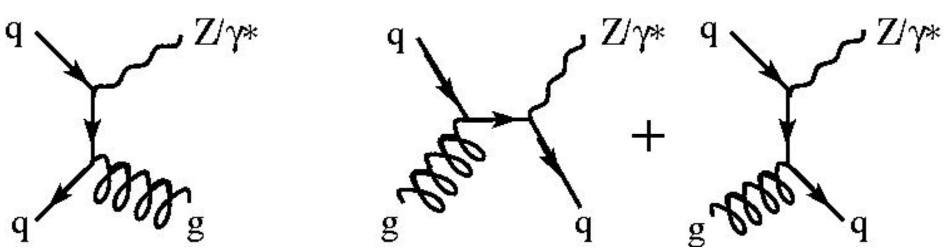




Born-level

- At one gluon emission (order α_s), V recoils against hadronic products
  - V produced with transverse momentum!





Annihilation Compton

(also other diagrammes...)

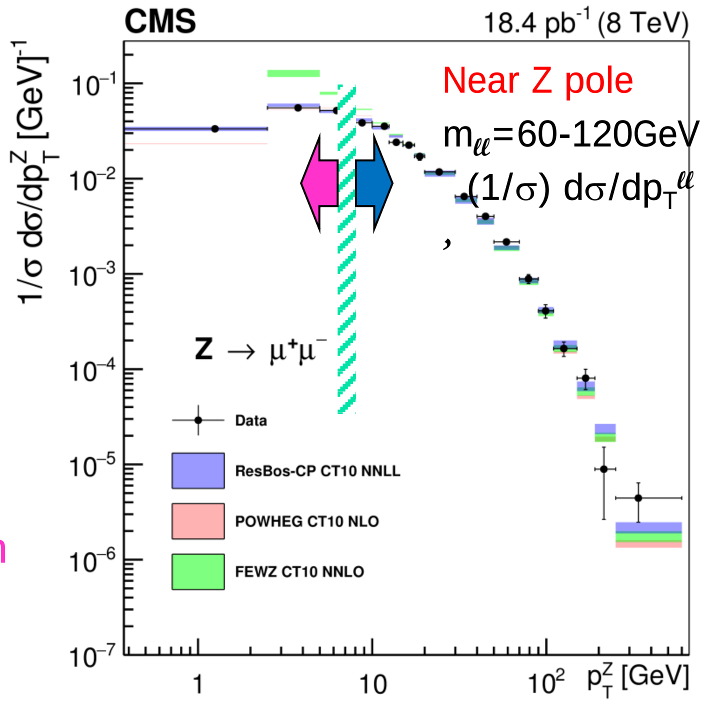
- V p_T tells us something about the hard interaction!

JHEP02(2017)096
EPJC75 (2015)147

$Z \to \ell^+\ell^-$

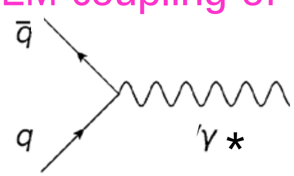
Z/γ^*: p_T, $m_{\ell\ell}$

- Low $p_T^{\ell\ell}$: region of ISR and intrinsic k_T of partons
- modeled through soft-gluon resummation (e.g. RESBOS NNLL) or parton showers (e.g. PYTHIA)

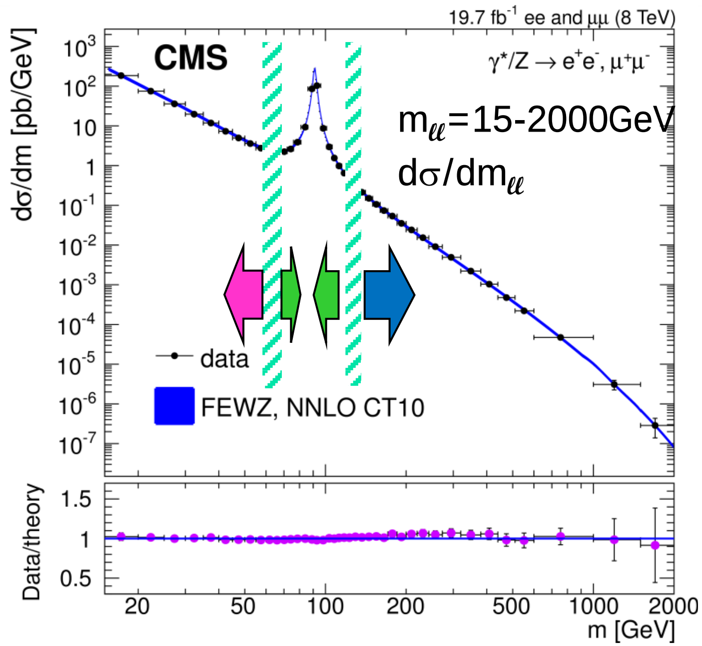


- High $p_T^{\ell\ell}$: region dominated by radiation of high p_T gluons
  - Sensitive to gluon PDF
- Modeled with fixed-order calculations like FEWZ@NNLO or generators like POWHEG

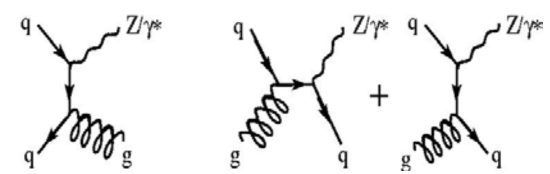
- Low-mass DY: dominated by EM coupling of γ^* to $q\bar{q}$



- Different sensitivity to u, d-type $q\bar{q}$ than on peak
  - Probe for PDFs

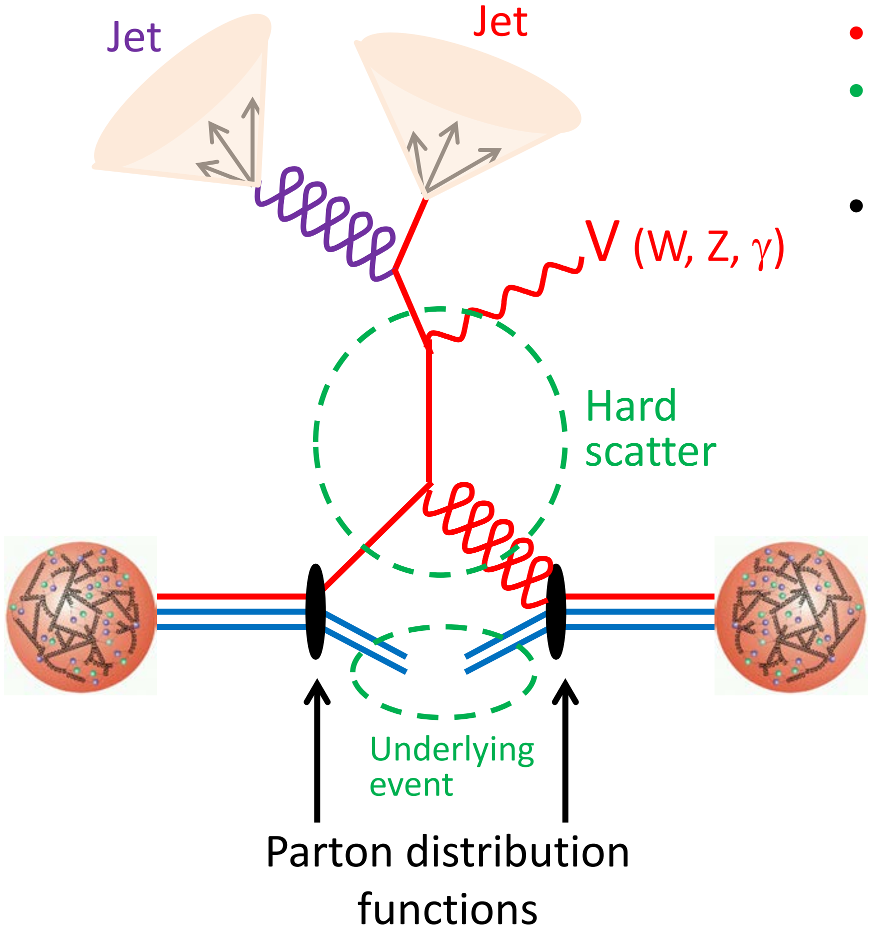


- Peak region and above dominated by Z, γ^* coupling to $q\bar{q}$
  - Probe for PDFs



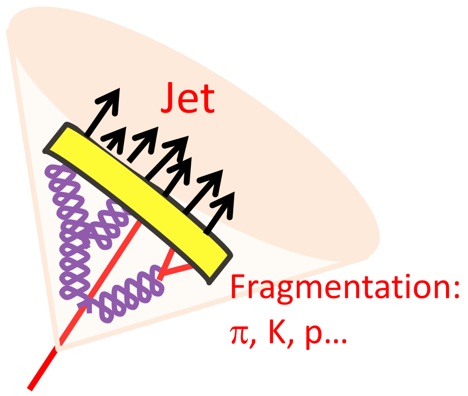
- High-mass DY shape can be modified by new physics

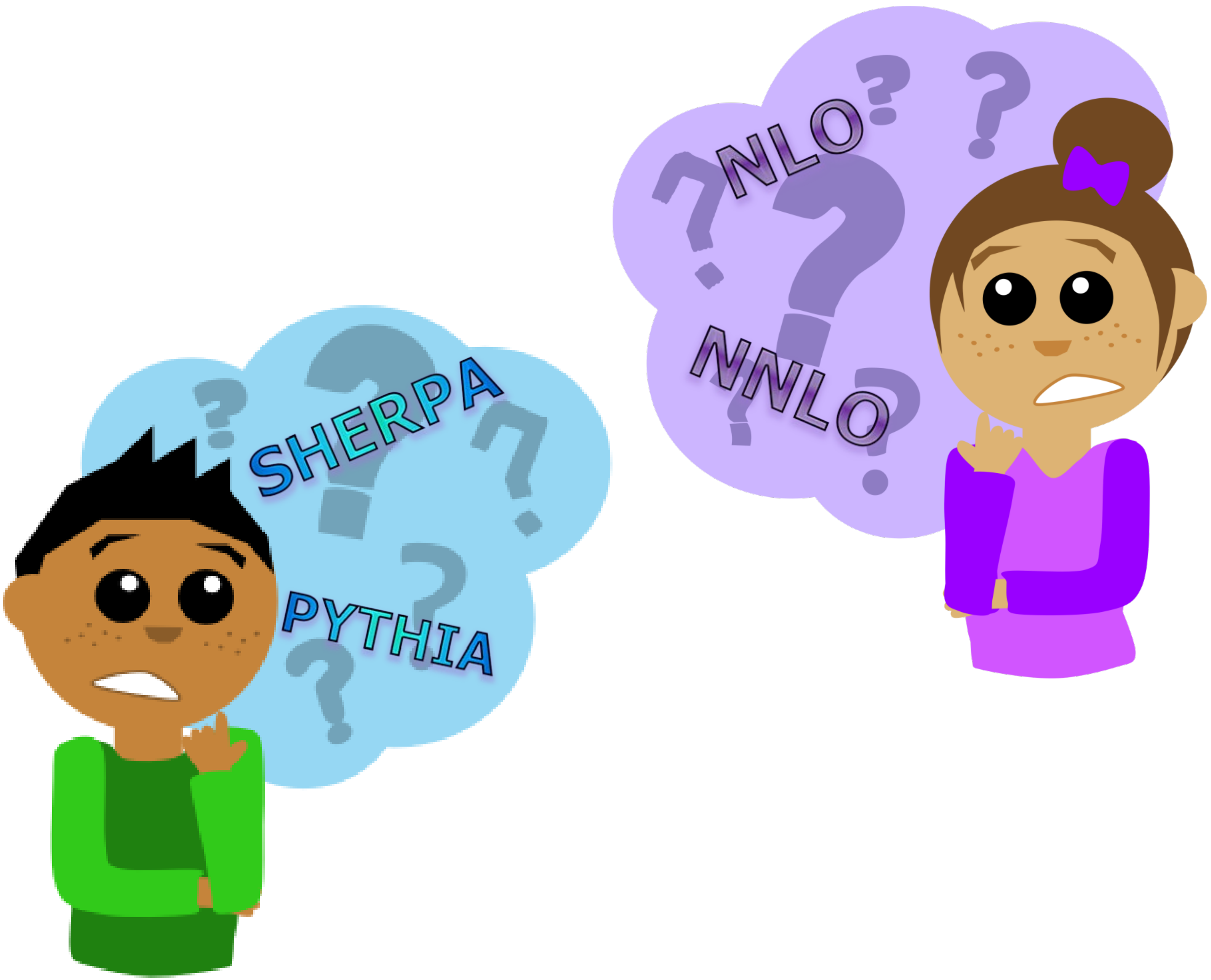
V+jet production



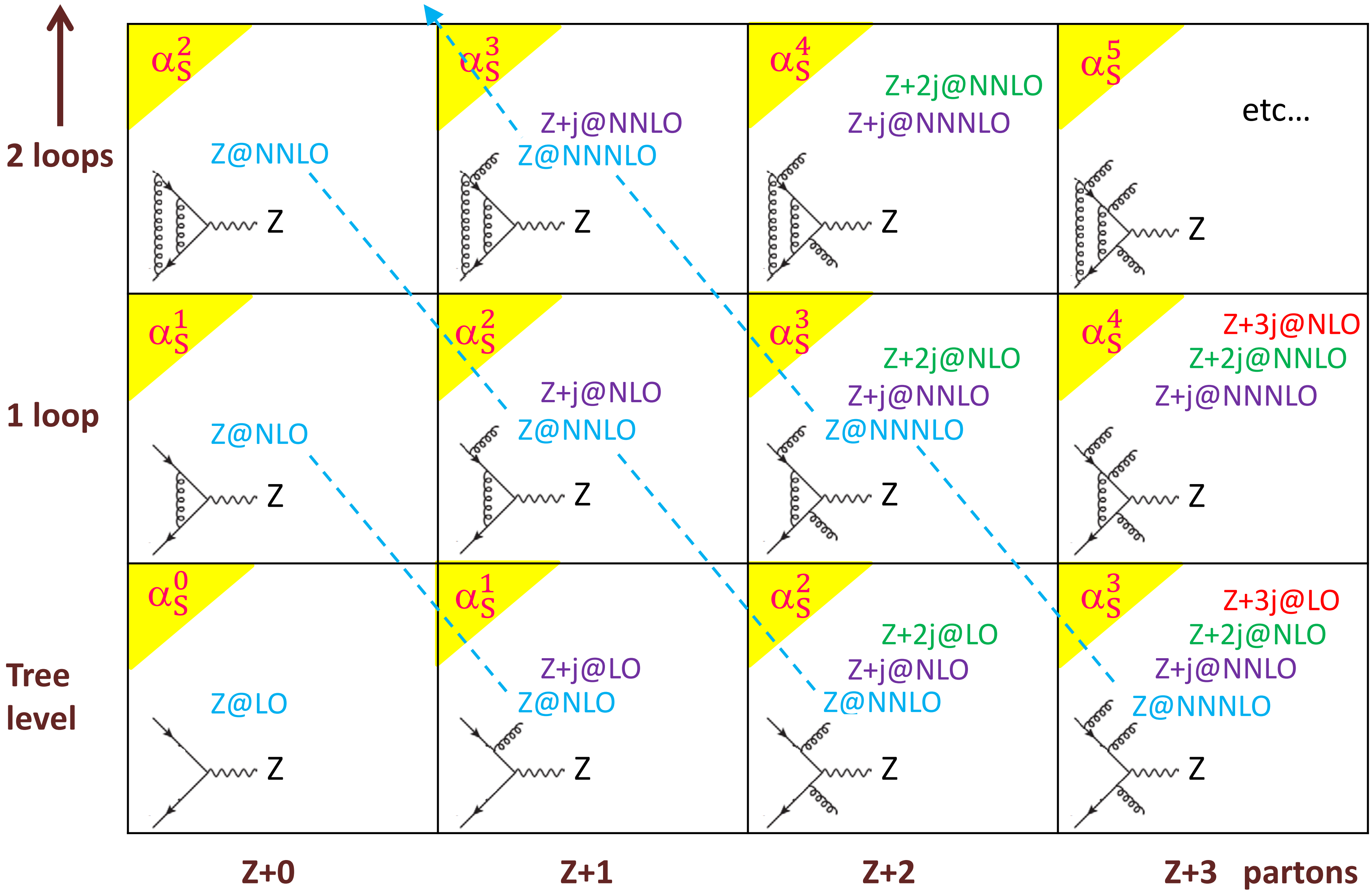
Probing QCD with V+jet production

- Hard scatter (matrix element, ME)
- Parton shower (PS), matching to ME
- Fragmentation to jets
- Jet composition/dynamics
- Multiparton interactions (MPI) from underlying event (UE)
- Parton distribution functions (PDF)



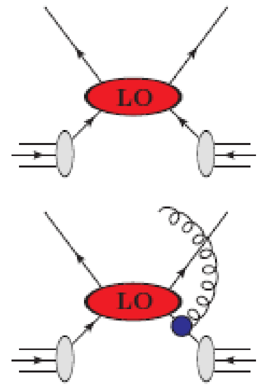
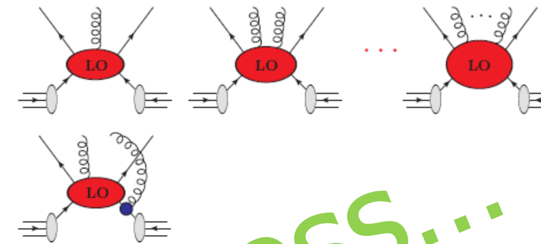
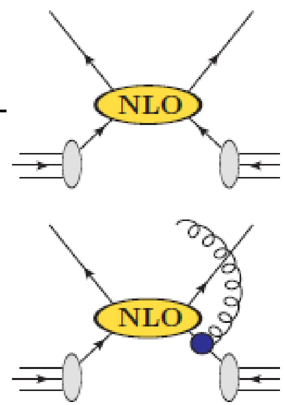
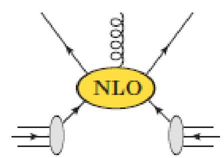
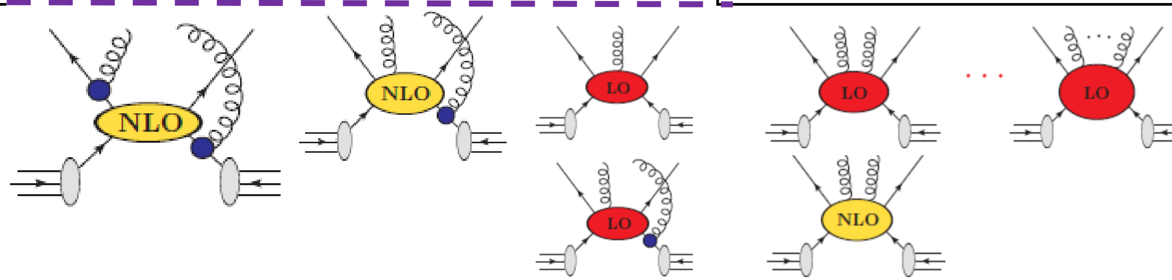

SHERPA
PYTHIA
NLO
NNLO

Iconic diagrammes contributing to each order



+ many other similar diagrammes…

Accuracy in the perturbative region: MC samples used in W,Z production

pQCD accur.	MC	Illustrative diagrammes
LO ME + PS	Pythia, Herwig	
Multiparton LO ME + PS	Alpgen, Sherpa 1.4, Madgraph	
NLO inclusive + PS	(a)MC@NLO, Powheg, Herwig++	
NLO at a given jet mult. + LO for other jet mult. + PS	Powheg MiNLO (e.g. W/Z+ 1 jet)	 Note: MiNLO formally NLO only for given a jet multiplicity. For lower and higher jet multiplicities in the ME, formally LO.
NLO for 0,1,2 parton ME + LO up to 3,4 (5 for Sherpa) partons + PS	Sherpa 2.X (MEPS@NLO), MG5_aMC@NLO	

My best guess...

Inspired from A. Tricoli!

V+jets

- Benchmark the validity range of our various generators!

Generator+PS:

- BLACKHAT+SHERPA: parton-level fixed-order predictions at NLO up to four partons
- SHERPA: matrix elements (ME) up to two additional partons at NLO and up to four partons at leading order (LO) interfaced to SHERPA showering
- ALPGEN+Py6: multiparton LO ME
- MG5_aMC+Py8 CKKWL: ME including up to four partons at LO, interfaced to Py8, using CKKWL merging scheme
- MG5_aMC+Py8 FxFx: ME up to two jets and with PS beyond, using FxFx merging scheme

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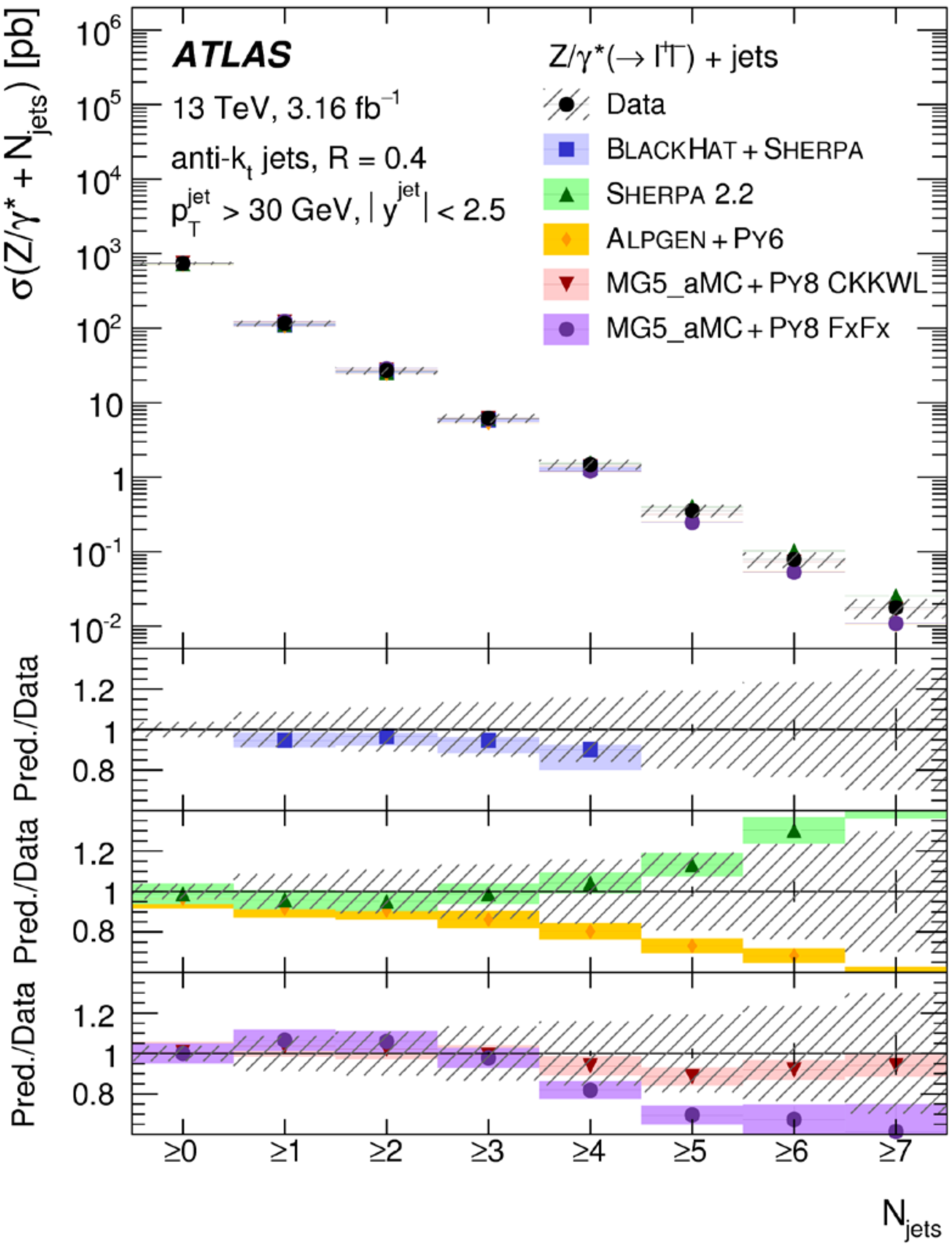
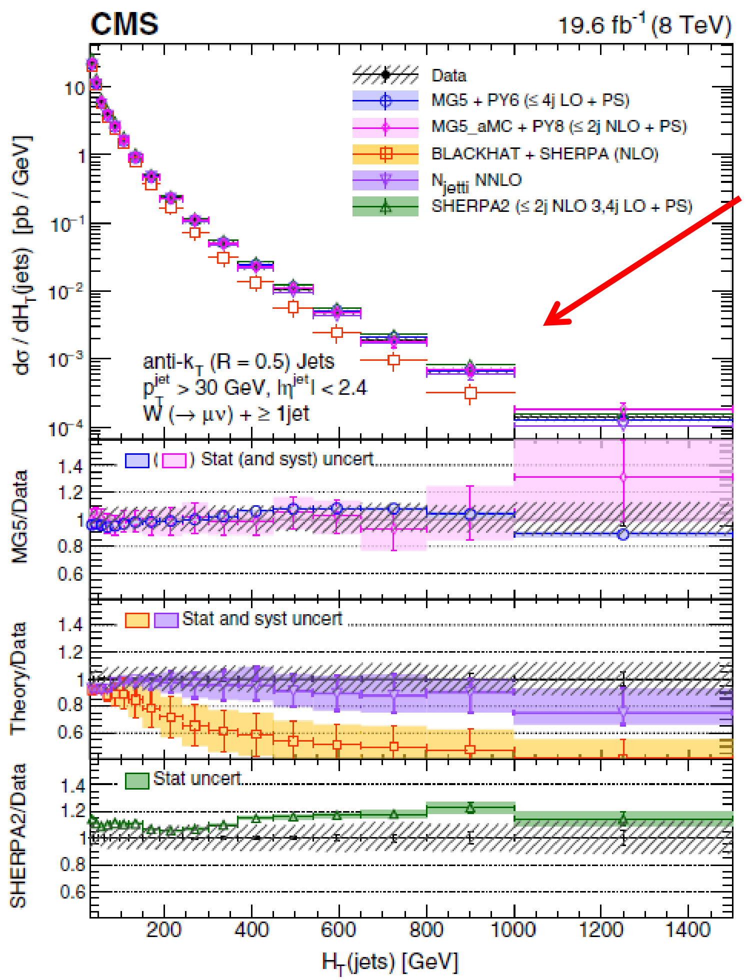


V+jets

- V+jets: non-negligible background for Higgs boson production and in BSM searches
  - kinematics of jets exploited to achieve separation of the signal of interest from SM bkg

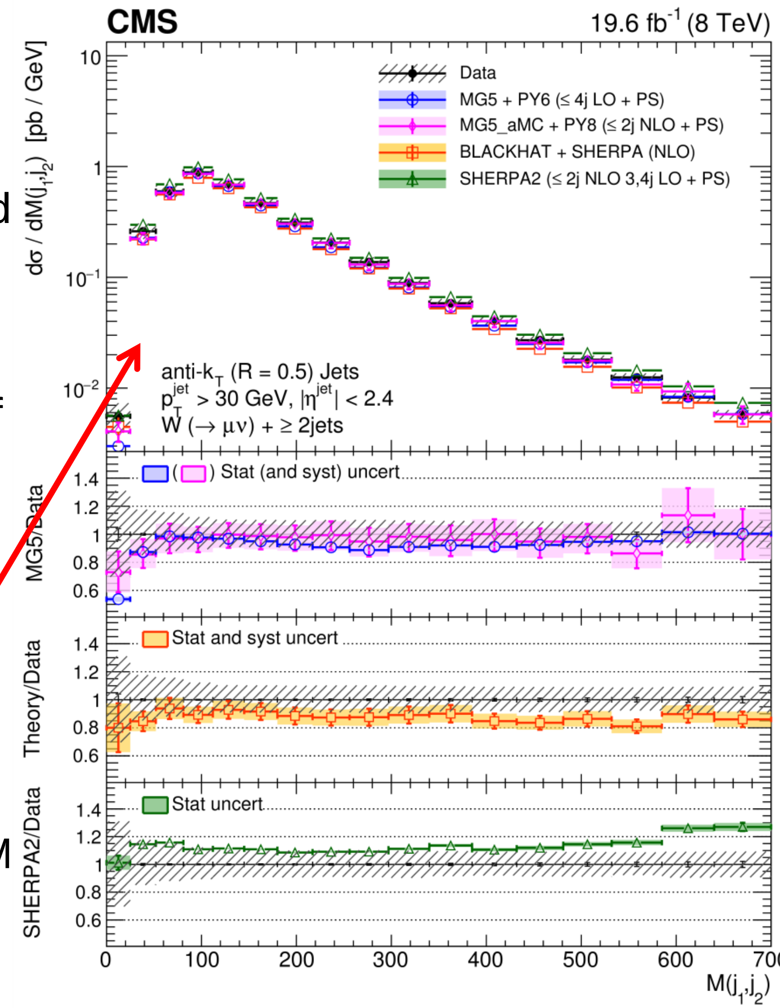


W+≥1jet:

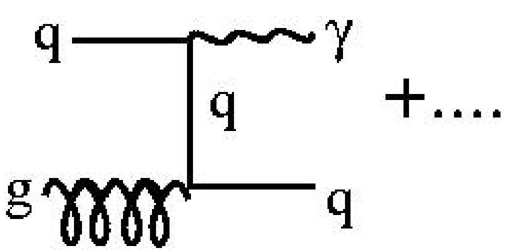
H_T, the scalar p_T sum of all visible objects, employed in BSM searches, to enrich final states resulting from the decay of heavy particles

W+≥2jets:

Di-jet invariant mass: modeling of correlations among jets important for BSM searched in dijet final states

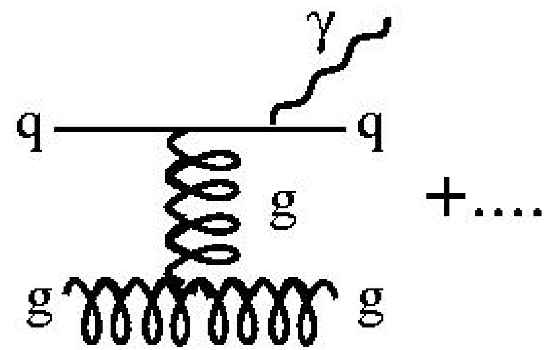


What can we learn from γ+jet production?



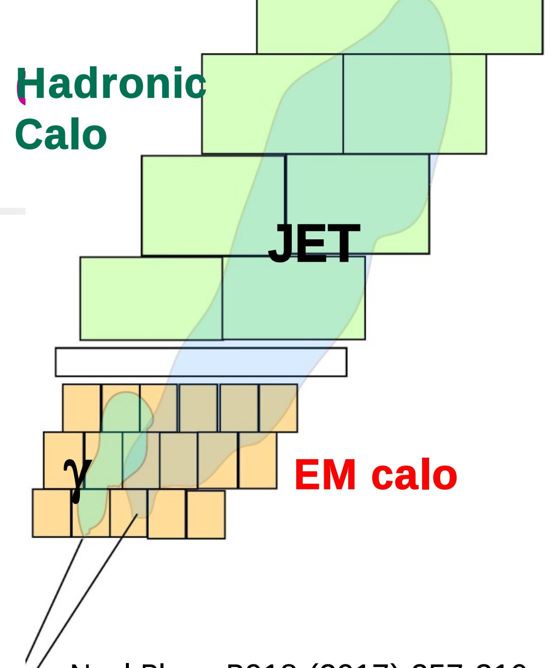
Direct photon

q exchange: $(1- |\cos \theta^{\gamma j}|)^{-1}$



Fragmentation photon

g exchange: $(1- |\cos \theta^{\gamma j}|)^{-2}$



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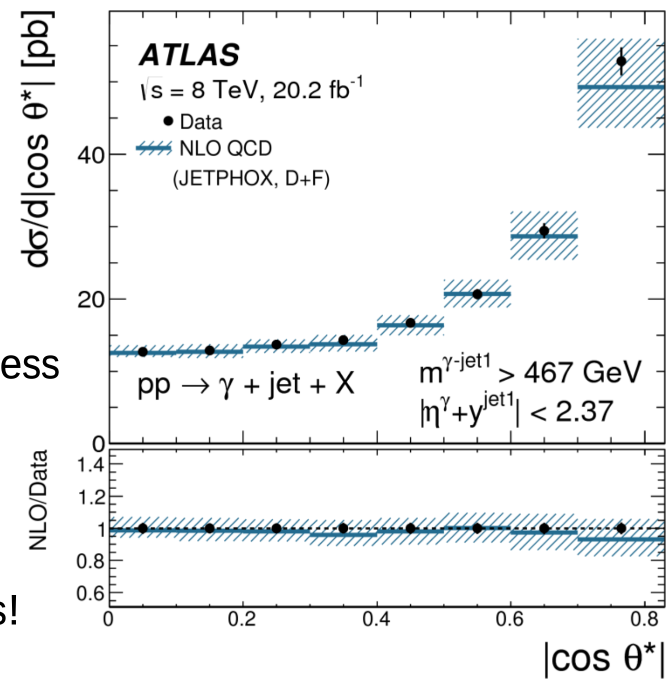


- Can test perturbative QCD (pQCD) in cleaner environment
  - Photon doesn't undergo hadronisation
- Understand diff betw (t-channel) quark & gluon exchange
  - Angular distrib. sensitive to spin of exchanged particle
    - $|\cos \theta^{\gamma j}|$ useful to study dynamics of underlying process
      - $d\sigma/d|\cos \theta^{\gamma j}|$ much closer to $(1- |\cos \theta^{\gamma j}|)^{-1}$
  - Dominance: process where (t-channel) quark exchanged
- A good source of high purity quark-originated jets!
    - Jets from quarks look different than jets from gluons!
- One of the main backgrounds to Higgs decay $H \rightarrow \gamma\gamma$

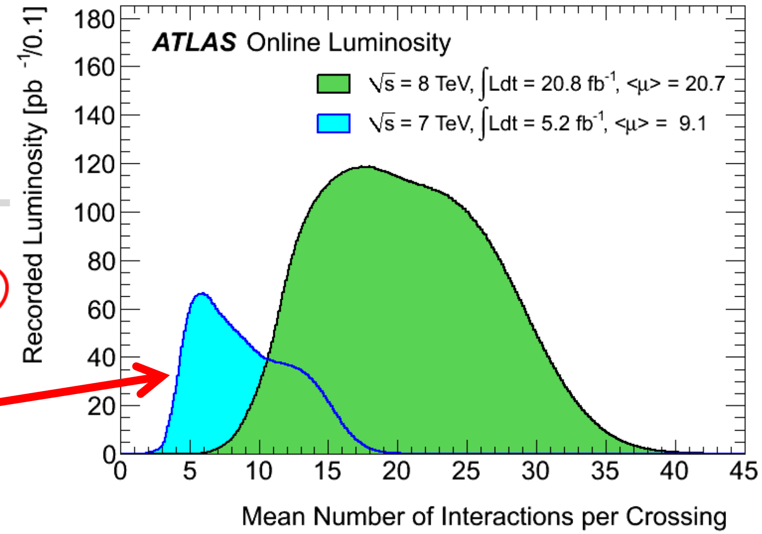
THREE MEASUREMENTS IN SOME DETAIL...

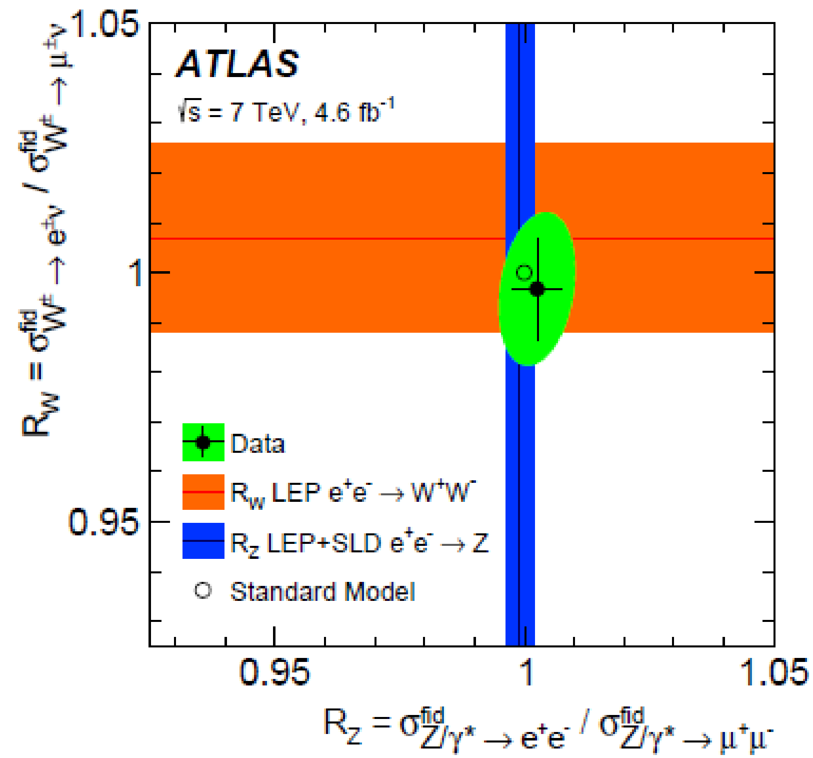
Precise measurements of W,Z production at 7TeV - I

- 2011 LHC dataset has a special place in our hearts
  - Relatively low pileup + well understood detector (in part from performing precise measurements like this one!)
- ATLAS 4.6fb^{-1}: lots of stats!
  - 30M $W\to\ell\nu$, ℓ=e,μ
  - 3M $Z\to\ell\ell$, ℓ=e,μ
- Measurement of inclusive fiducial and total cross sections as well as fiducial differential cross sections (extrapolated to a common phase space for e and μ)
- Compatibility of electron and muon channels a powerful test of lepton universality in weak vector-boson decay

$(R_{W^\pm} = \sigma^{\rm fid}_{W^\pm\to e\nu}/\sigma^{\rm fid}_{W^\pm\to\mu\nu})$ vs. $(R_Z = \sigma^{\rm fid}_{Z\to e^+e^-}/\sigma^{\rm fid}_{Z\to\mu^+\mu^-})$

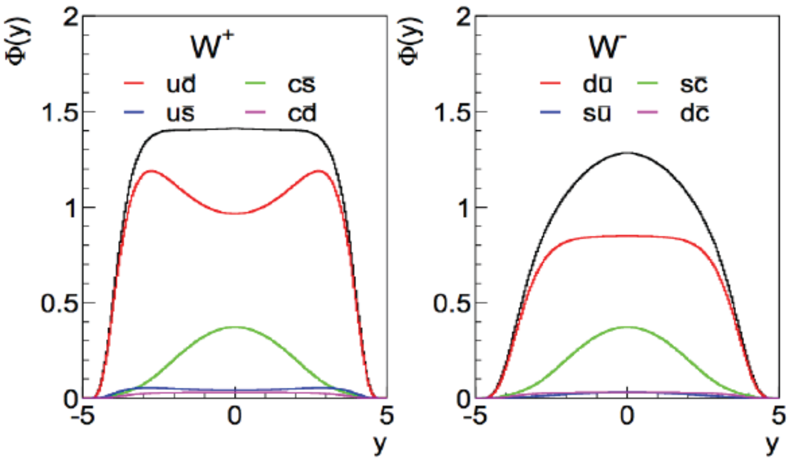
- Then combine lepton channels to ~ double your statistics...

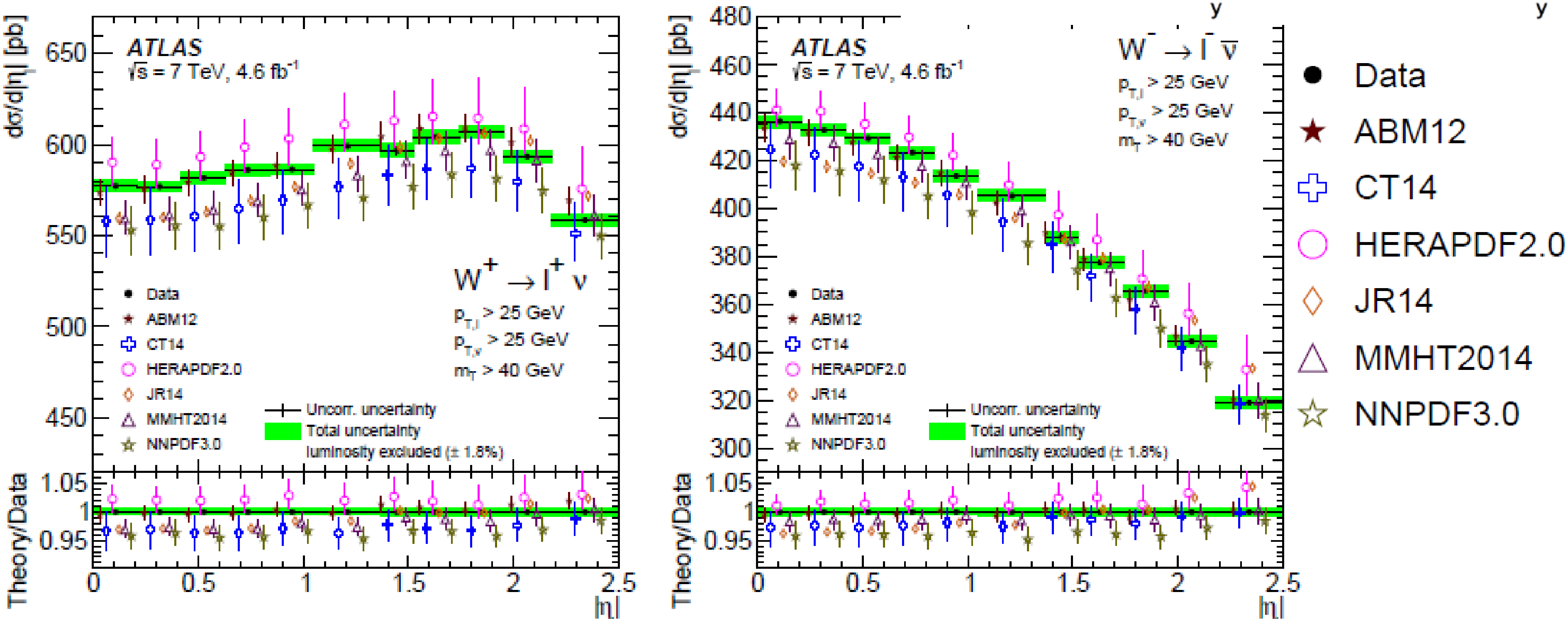




Precise measurements of W,Z production at 7TeV - II

- Measurement of fiducial cross sections vs. lepton (boson) rapidity for W (Z)
  - Recall that this is sensitive to PDFs!





- Some PDFs include other LHC data (some don't)
- ABM12 match quite well the data
- Most agree within 1.8% lumi uncertainty
- Don't forget that uncertainties can be correlated bin-to-bin!

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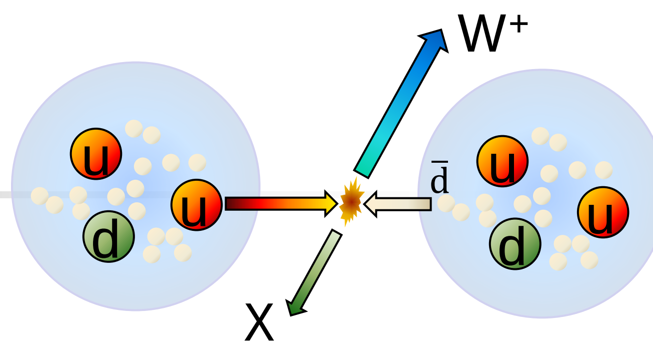
W-charge asymmetry



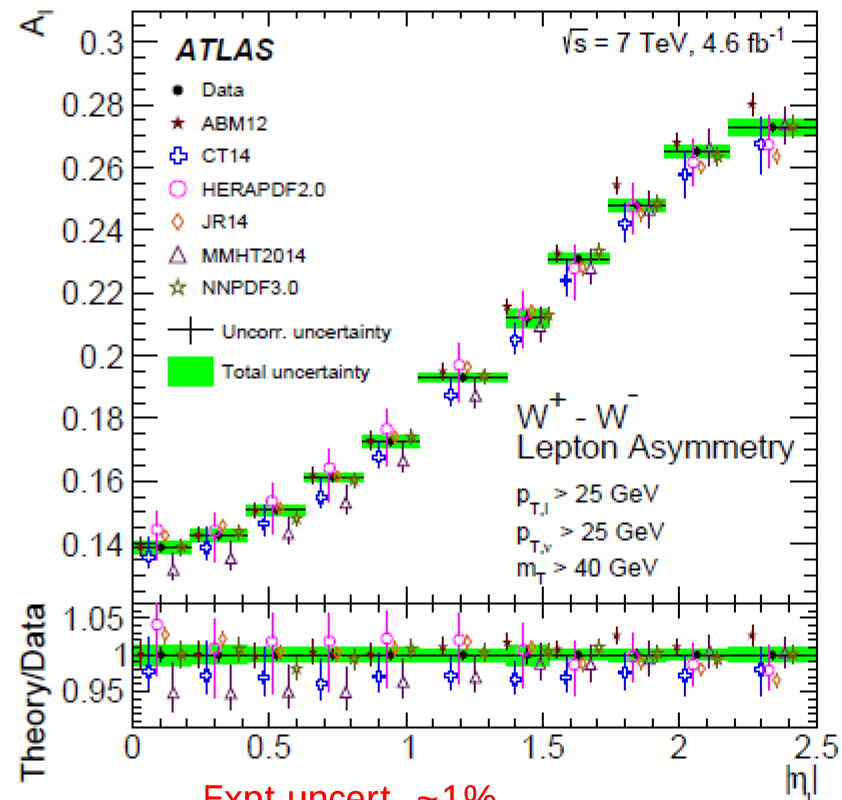
- Dominant W production mechanisms at LHC:
  - valence+sea antiquark: $d\bar{u} \rightarrow W^-$, $u\bar{d} \rightarrow W^+$
  - W^+,W^- asymmetry due to valence content

$R^{tot}_{W^+/W^-}$ $1.450 \pm 0.001\,(\mathrm{stat}) \pm 0.004\,(\mathrm{syst}) \pm 0.029\,(\mathrm{acc})$

- Lepton charge asymmetry vs. η provides information on PDFs

$$A_\ell = \frac{d\sigma_{W+}/d|\eta_\ell| - d\sigma_{W-}/d|\eta_\ell|}{d\sigma_{W+}/d|\eta_\ell| + d\sigma_{W-}/d|\eta_\ell|}$$

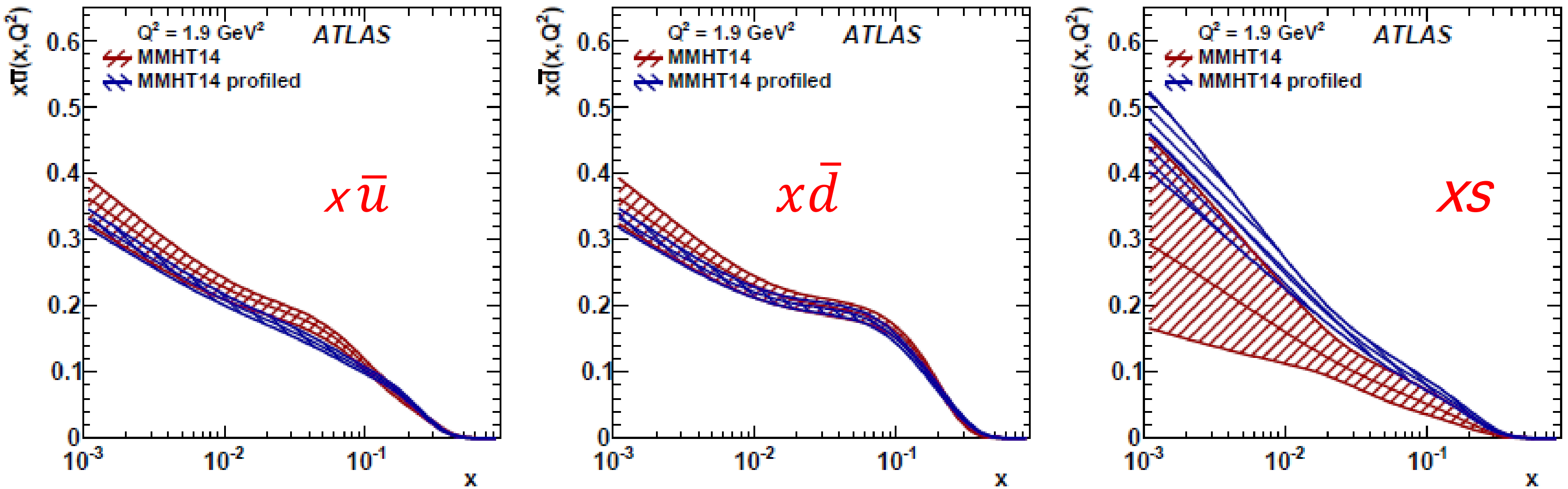
  - d/u ratio and sea antiquarks (including strangeness)
- significant cancellation of systematic uncertainties when taking ratios!
- Cross sections don't agree well with PDFs but ratios do!
  - Illustrates the importance of making absolute cross-section measurements!



Expt uncert. ~1%

Impact of precise W,Z results on PDFs

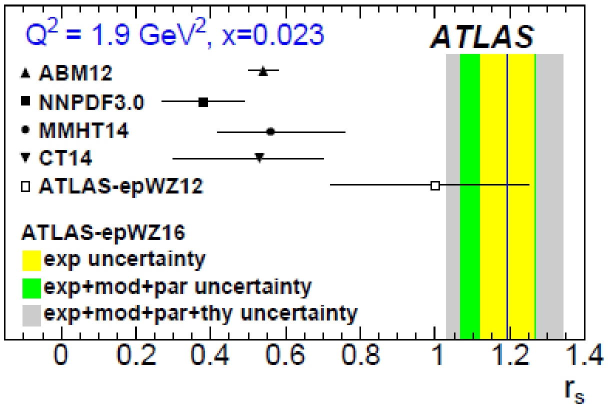
- Use profiling technique to see impact of data on knowledge of PDFs
  - Compare data to theo. predictions using χ^2, treating PDF uncert. as nuisance params
- Significant impact on strange sea central value (increased) and uncertainty (decreased)



- These data are combined with previous HERA data to extract a new set of PDFs
  - ATLAS-epWZ16

$$r_s = (s+\bar{s})/2\bar{d}$$

  - Close to unity



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Z production / decay: pp $\rightarrow Z(/\gamma^*) \rightarrow \ell\ell$ at 8TeV

Z@8TeV JHEP 08 (2016) 159

- Initial-state parton, final-state lepton spin correlations carry info about Z polarisation
- Five-dimensional differential cross section describing kinematics of the two Born-level leptons from Z decay can be decomposed as 9 harmonic polynomials (think Y_l^m !), dependent on the lepton polar θ, azimuthal φ (here in Collins-Soper frame) multiplied by helicity cross sections that depend on Z transverse momentum (p_T^Z), rapidity (y^Z), invariant mass (m^Z).
- Standard convention: factorise out unpolarised cross-section, σ^{U+L}. Differential cross section: expansion into 1+ 8 harmonic polynomials $P_i(\cos\theta, \varphi)$ and dimensionless angular coefficients $A_i(p_T^Z, y^Z, m^Z)$ (ratios of helicity cross-sections with respect to σ^{U+L})

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z} \left\{(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T^Z, y^Z, m^Z) \cdot P_i(\cos\theta, \varphi)\right\}.$$

- Dynamics from production described within structure of A_i, and factorised from Z decay kinematics.
- Angular coefficients A_i are a critical component to the measurement of m_W
- Current measurement: on Z peak $m_{\ell\ell}$ =80-100GeV

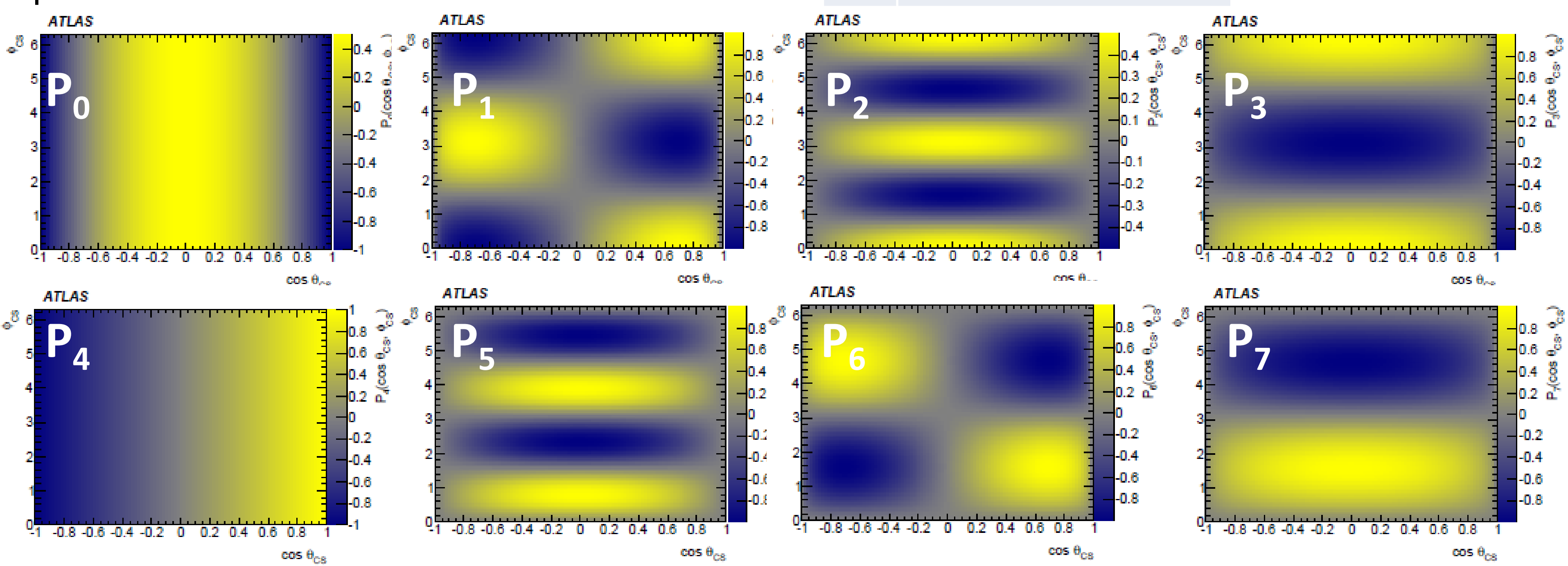
Differential cross section

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$

$$\text{x}\ \left\{(1+\cos^2\theta) + \sum_{i=0}^{7} A_i \cdot P_i\right\}.$$

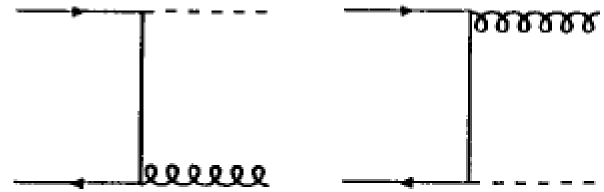
A_i	Polynomials P_i
A_0	$P_0 = \frac{1}{2}\,[1-3\cos^2\theta]$
A_1	$P_1 = \sin 2\theta \cos\varphi$
A_2	$P_2 = \frac{1}{2}\sin^2\theta \cos 2\varphi$
A_3	$P_3 = \sin\theta \cos\varphi$
A_4	$P_4 = \cos\theta$
A_5	$P_5 = \sin^2\theta \sin 2\varphi$
A_6	$P_6 = \sin 2\theta \sin\varphi$
A_7	$P_7 = \sin\theta \sin\varphi$

φ vs. cos θ

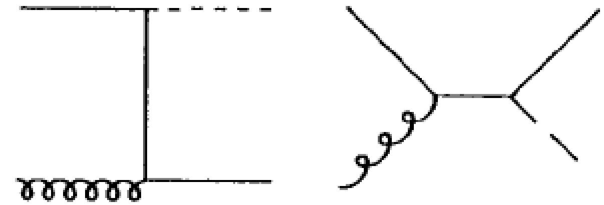


Order	A_i non-zero	Process	Comment
$\mathcal{O}(\alpha_S^0)$	A_4	$q\bar{q}\rightarrow Z$	
$\mathcal{O}(\alpha_S^1)$	A_0, A_1, A_2, A_3, A_4	$q\bar{q}\rightarrow Zg$	Annihilation
		$qg\rightarrow Zq$	Compton
$\mathcal{O}(\alpha_S^2)$	$A_0, A_1, A_2, A_3, A_4, A_5, A_6, A_7$	$q\bar{q}\rightarrow Zgg$	
		$q\bar{q}\rightarrow Zq\bar{q}$	
		$qg\rightarrow Zqg$	
		$qq\rightarrow Zqq$	
		$gg\rightarrow Zq\bar{q}$	
		$q\bar{q}\rightarrow Zg$	Loop
		$qg\rightarrow Zq$	Loop

$\mathcal{O}(\alpha_S^1)$: examples

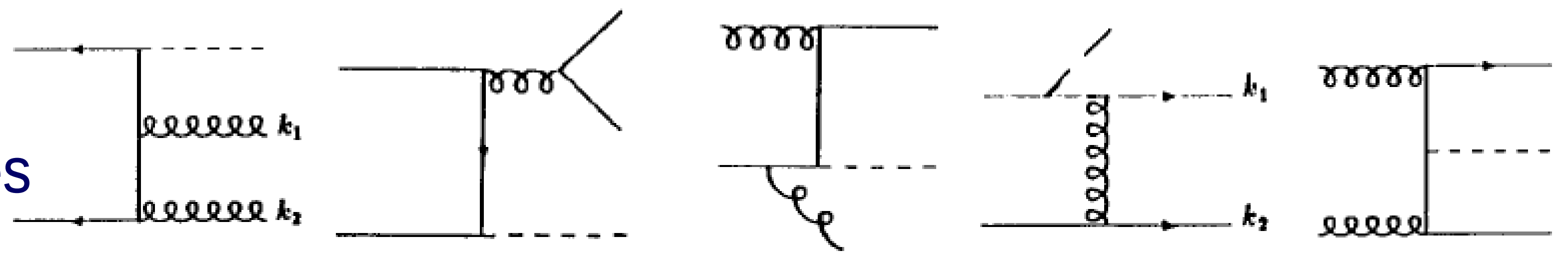


Annihilation

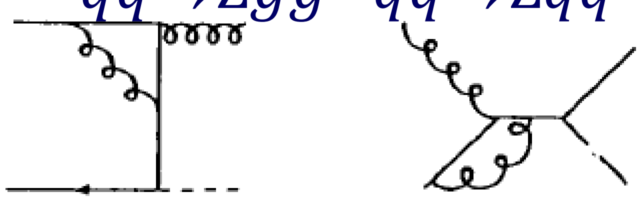


Compton

$\mathcal{O}(\alpha_S^2)$: examples



$q\bar{q}\rightarrow Zgg$ $q\bar{q}\rightarrow Zq\bar{q}$ $qg\rightarrow Zqg$ $qq\rightarrow Zqq$ $gg\rightarrow Zq\bar{q}$



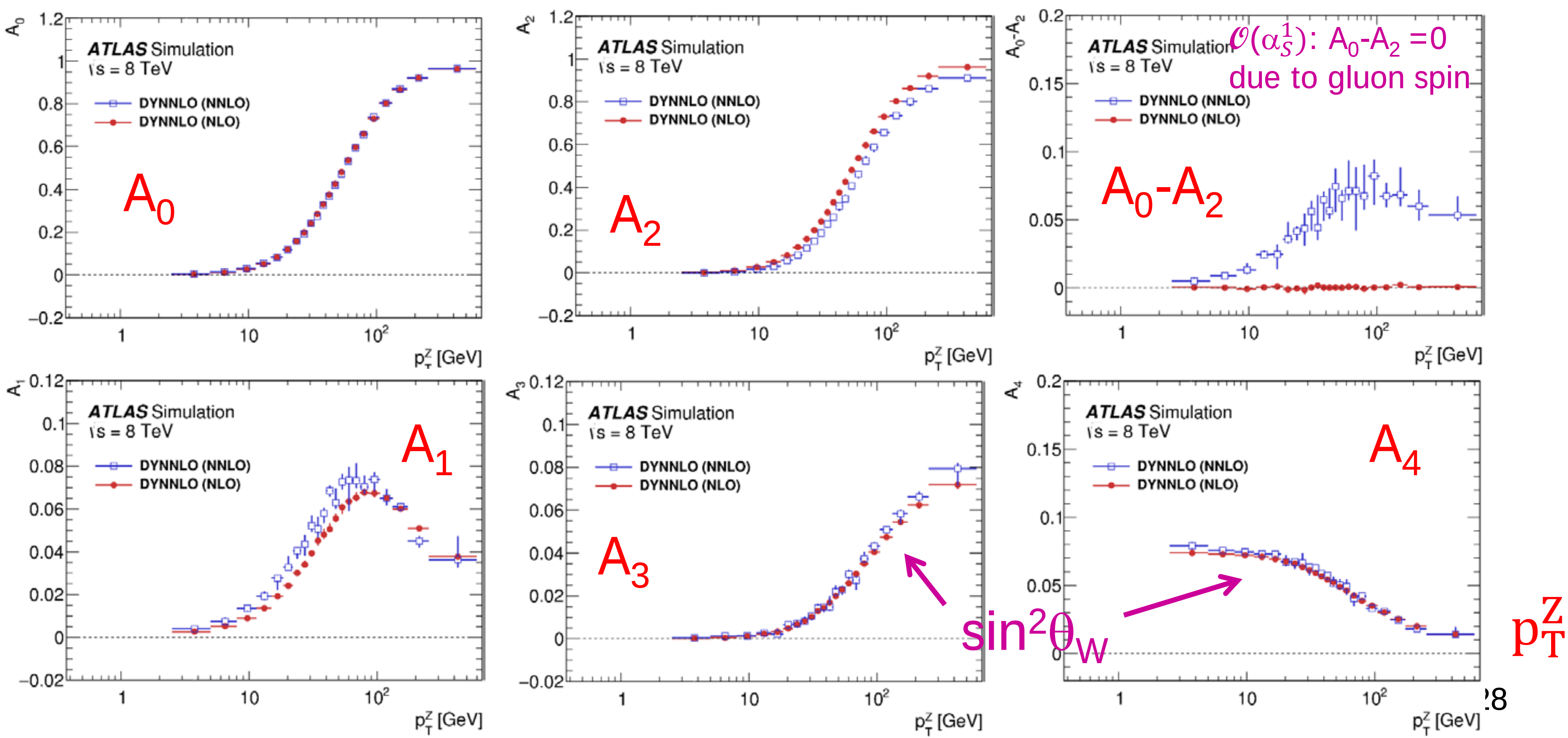
$q\bar{q}\rightarrow Zg$ $qg\rightarrow Zq$

Mirkes, NPB 387 (1992) 3-85

Some A_i values: DYNNLO at $\mathcal{O}(\alpha_S^1)$ (NLO), $\mathcal{O}(\alpha_S^2)$ (NNLO)

A_i	Polynomials P_i	Couplings	Non-zero
A_0	$P_0 = \frac{1}{2}\,[1-3\cos^2\theta]$	$(v_l^2+a_l^2)\cdot(v_q^2+a_q^2)$	$\mathcal{O}(\alpha_S^1)$
A_1	$P_1 = \sin 2\theta \cos\varphi$		$\mathcal{O}(\alpha_S^1)$
A_2	$P_2 = \frac{1}{2}\sin^2\theta \cos 2\varphi$		$\mathcal{O}(\alpha_S^1)$
A_3	$P_3 = \sin\theta \cos\varphi$	$(v_l a_l)\cdot(v_q a_q)$ ~ $\sin^2\theta_W$	$\mathcal{O}(\alpha_S^1)$
A_4	$P_4 = \cos\theta$		$\mathcal{O}(\alpha_S^0)$
A_5	$P_5 = \sin^2\theta \sin 2\varphi$	$(v_l^2+a_l^2)\cdot(v_q a_q)$	$\mathcal{O}(\alpha_S^2)$
A_6	$P_6 = \sin 2\theta \sin\varphi$		$\mathcal{O}(\alpha_S^2)$
A_7	$P_7 = \sin\theta \sin\varphi$	$(v_l a_l)\cdot(v_q^2+a_q^2)$	$\mathcal{O}(\alpha_S^2)$

$A_{5,6,7}$ ~0.005 at higher values of p_T^Z

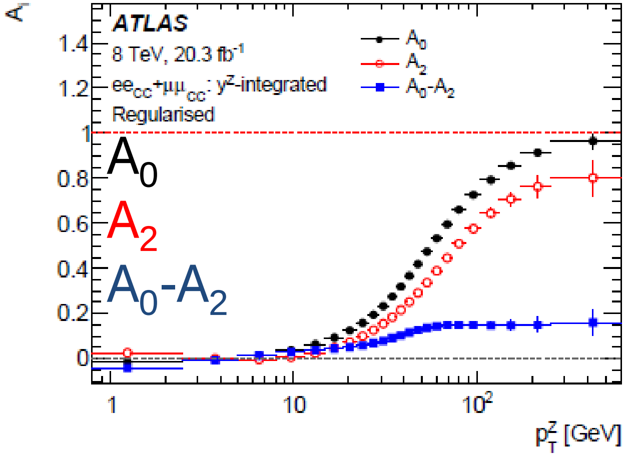


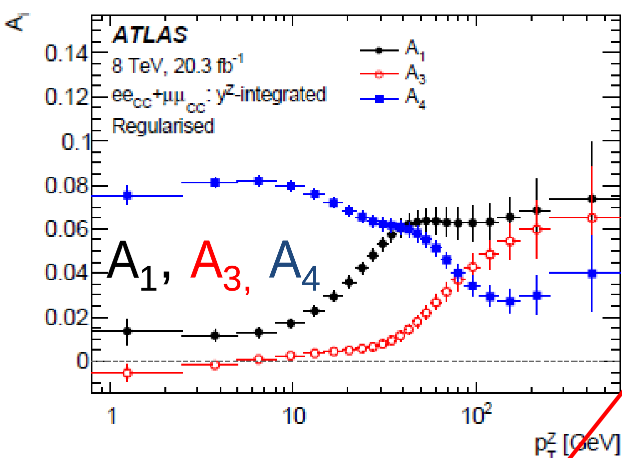
Some results…

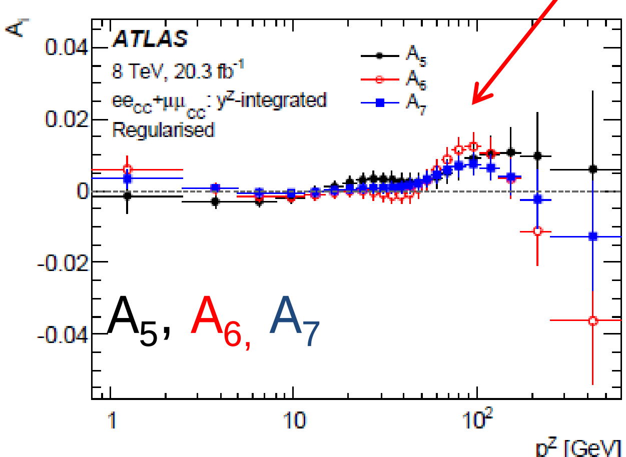
(also in 3 bins of $|y^Z|$)

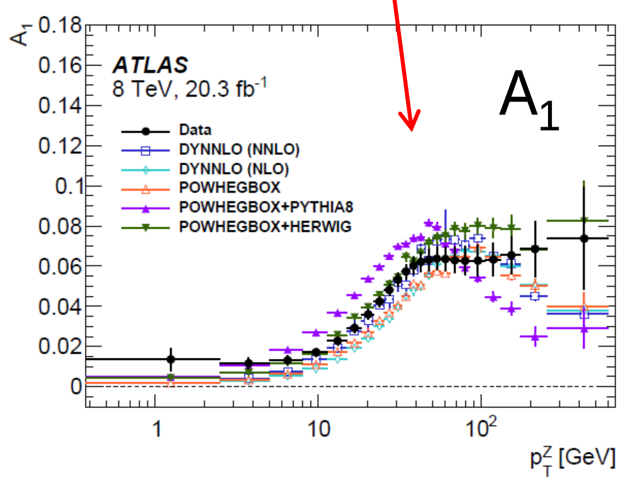
Observations

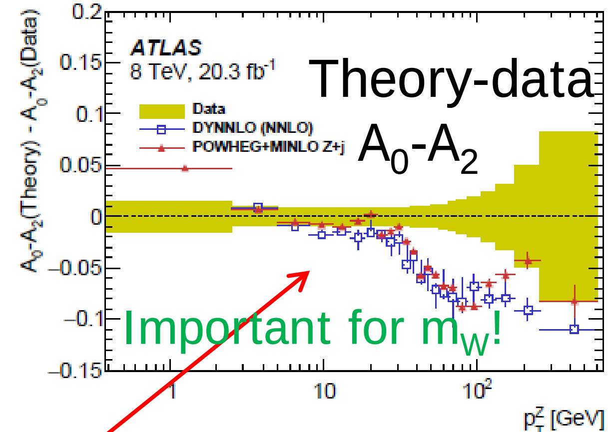
- Most cases: stats dominated even in most populated bins which contain 100,000s of events
- A_0-A_2 factor 2 larger than NNLO expectations, likely due to higher-order effects
- A_5,A_6,A_7 non-zero: 3σ level
- Some coefficients sensitive to parton-shower models

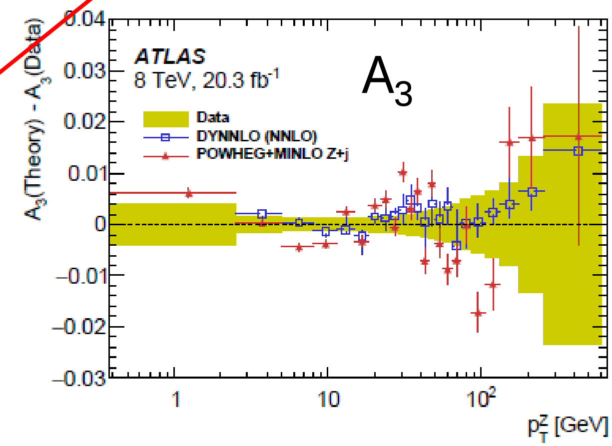


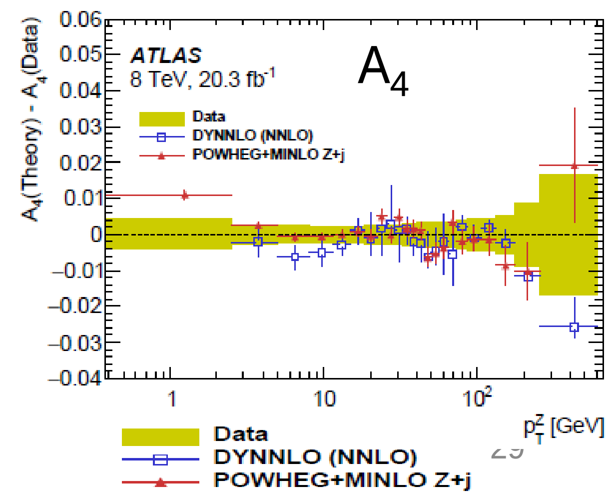


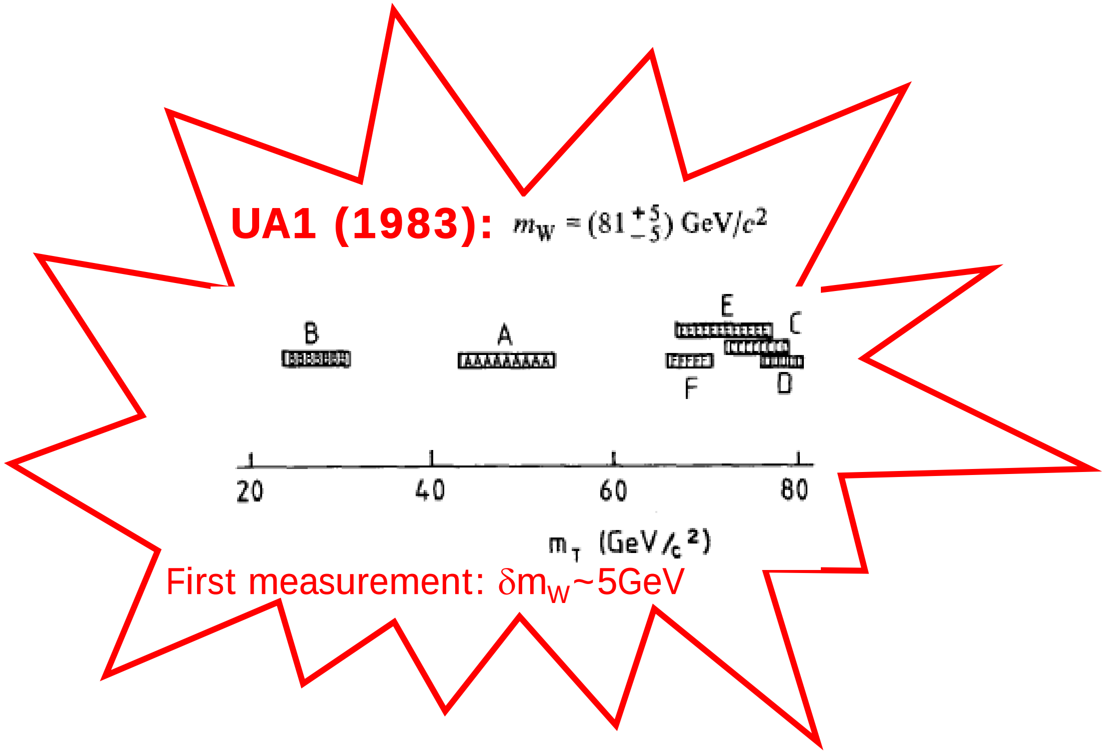


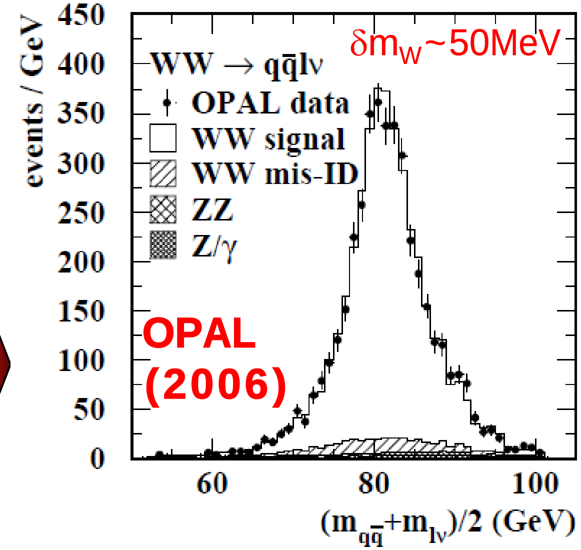


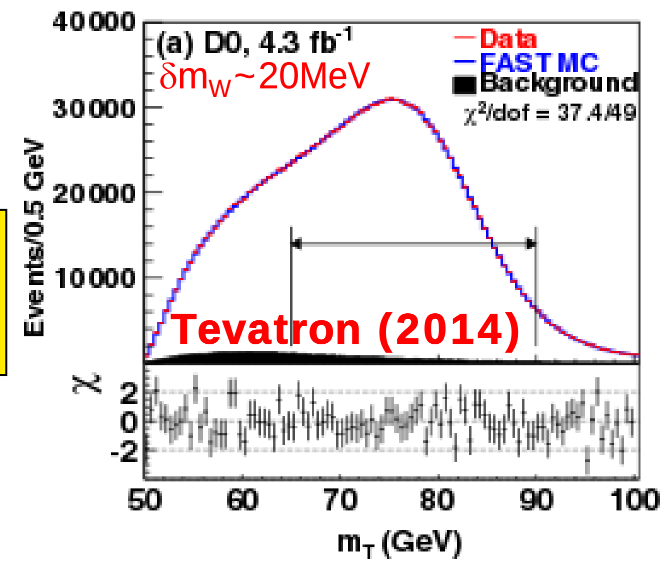




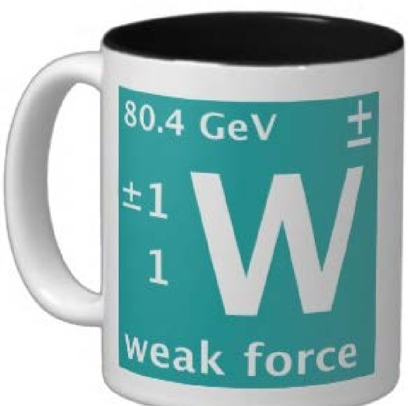



UA1 (1983): $m_W = (81^{+5}_{-5})$ GeV/c^2
B
A
E
C
F
D
20
40
60
80
m_T (GeV/c^2)
First measurement: δm_W~5GeV


δm_W~50MeV
WW → $q\bar{q}l\nu$
OPAL data
WW signal
WW mis-ID
ZZ
Z/γ
OPAL (2006)
events / GeV
450
400
350
300
250
200
150
100
50
0
60
80
100
$(m_{q\bar{q}}+m_{l\nu})/2$ (GeV)

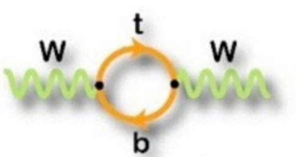

(a) D0, 4.3 fb^{-1}
δm_W~20MeV
Data
FAST MC
Background
χ^2/dof = 37.4/49
Tevatron (2014)
Events/0.5 GeV
40000
30000
20000
10000
χ
2
0
-2
50
60
70
80
90
100
m_T (GeV)

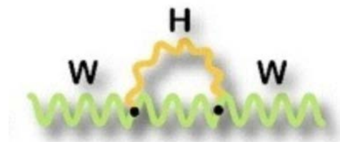
MASS OF THE


80.4 GeV
±
±1
1
W
weak force

The mass of the W boson: m_W

- EW sector of SM relates important parameters such as m_W, α_{EM}, G_F and $\sin^2\theta_W$
- Quantum corrections to m_W dominated by contributions depending quadratically on the top mass m_t and logarithmically on the Higgs mass m_H





$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r),$$

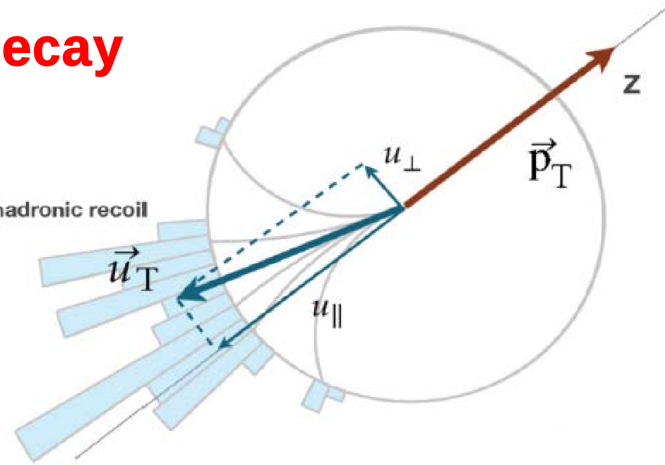
Higher orders, new physics?

- Precision measurements of m_W were first used to predict m_H before the Higgs was observed
- Now use comparisons of predicted m_H to measured m_H to look for new physics!
- Current SM prediction to 8MeV precision
- Extraction of m_W from hadron collisions
  - $u\bar{d}\rightarrow W^+(\rightarrow \ell^+\nu)+X$ → Can't fully reconstruct the final state!
  - Look at transverse plane balance
- Most recent measurements from
  - Tevatron: $p\bar{p}$ collider
  - ATLAS@LHC: pp collider
  - Different $\sqrt{s}$ and sensitivity to PDFs

Observables in W, Z decay

- Lepton ℓ: p_T^{ℓ}, η_{ℓ}, ϕ_{ℓ}
- Dilepton (Z): $m_{\ell\ell}$, $y_{\ell\ell}$, $p_T^{\ell\ell}$
- Recoil: $\vec{u}_T$, $u_{\perp}$, $u_{\parallel}$
- $\vec{u}_T$ a measure of $p_T^{W,Z}$
  - Excluding ℓ :

$$\vec{u}_T = \sum_i \vec{E}_{T,i},$$



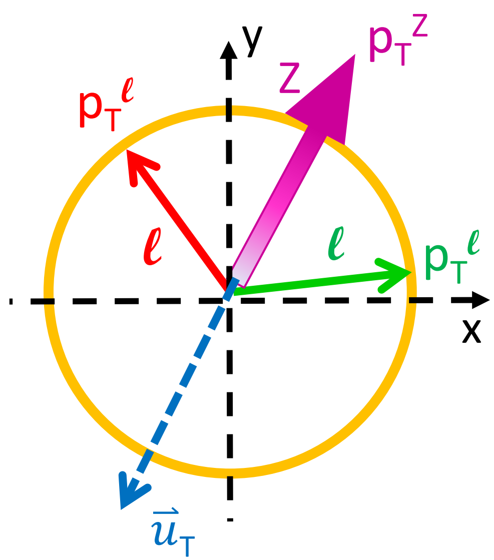
For W: $u_{\perp}$, $u_{\parallel}$
with respect to p_T^{ℓ}

- Transverse missing momentum:

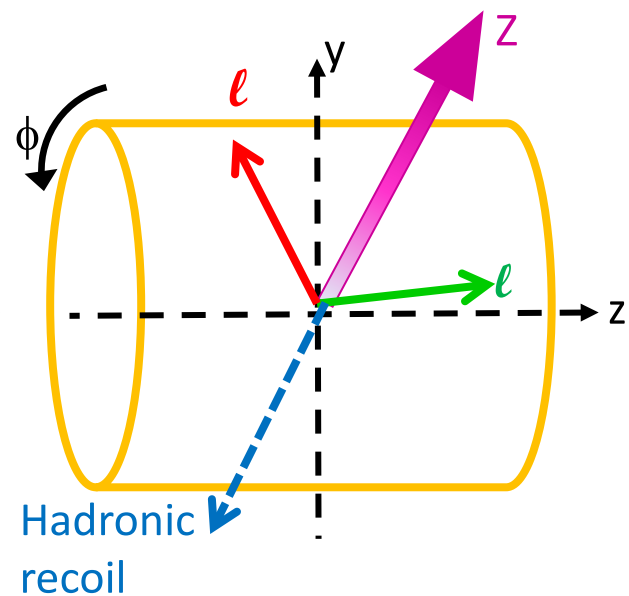
$$\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$$

- Transverse mass:

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



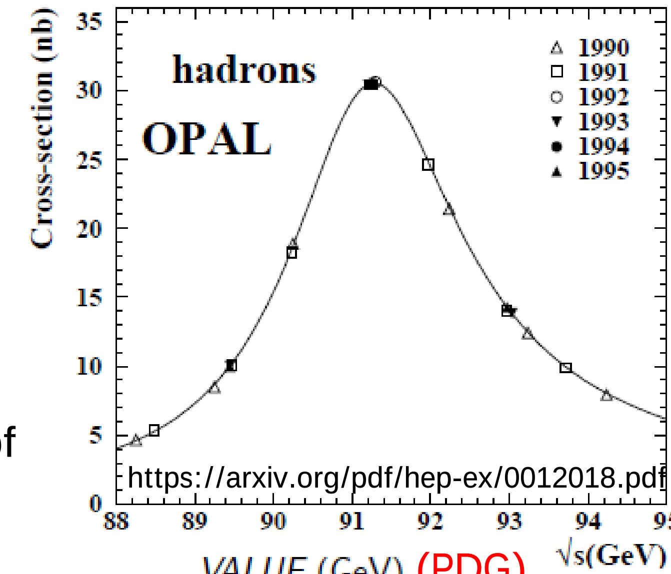
Transverse plane



The role of the Z

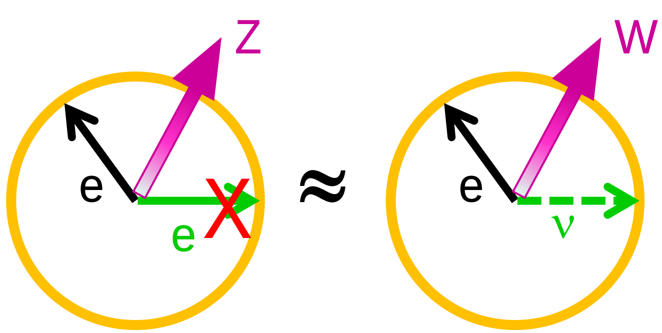
And the Oskkar for best supporting boson in a measurement goes to…

- Properties of the Z measured to exquisite precision at LEP
- Use this information at hadron colliders to nail down the experimental uncertainties e.g.
  - p_T^{ℓ}, p_T^{miss} : affected by lepton energy calibration
    - Use leptonic decay $Z \to \ell\ell$
  - Recoil calibration
    - $u_{\parallel}$ can be compared to - p_T^{ll} : probes the detector response to recoil RE: linearity, resolution
    - $u_{\perp}$ satisfies $\langle u_{\perp} \rangle = 0$: width provides an estimate of recoil resolution
  - Shape of kinematic distributions affected by lepton identification/reconstruction efficiency
    - From Z "Tag and probe" measurements
- Z used as an (approximate) avatar for the W of m_W
  - Use the Z to make "W-like" measurements
    - Measure m_Z using m_W techniques
      - Treat one ℓ as a ν
      - Extract m_Z from $m_{\ell\ell}$, p_T^{ℓ}, m_T



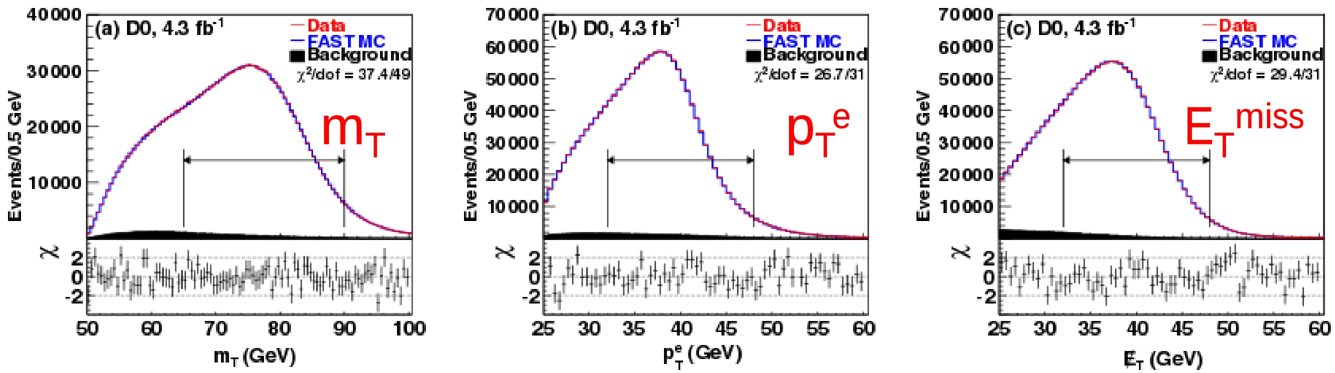
VALUE (GeV) (PDG)

$\mathbf{m_W = 91.1876 \pm 0.0021}$



Tevatron m_W

- Fermilab Tevatron measurements
  - D0: $W \to e\nu$, 4.3fb^{-1}, 1.68M evts (+earlier 1fb^{-1}) [PRD89 (2014) 012005, PRL108 (2012) 151804]
  - CDF: $W \to e,\mu\nu$, 2.2fb^{-1}, 1.10M evts [PRD89 (2014) 072003, PRL108 (2012) 151803]

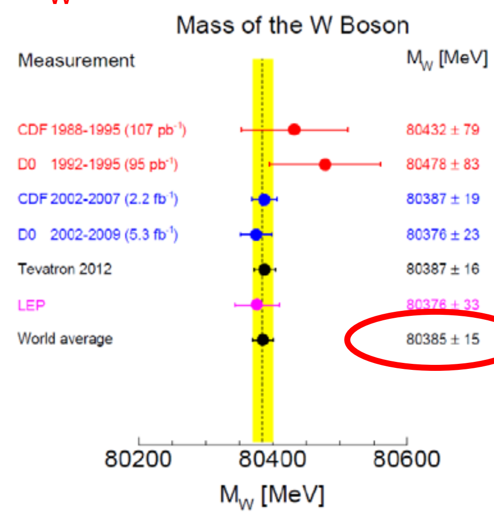


- Dominant expt sys: lepton E scale & hadronic recoil, dominant theo uncert: knowledge of PDF
  - ➡ δm_W^{D0} = 23MeV, δm_W^{CDF} = 19MeV
  - ➡ World avg: known to 15MeV!

$m_W^{Tevatron}$=80387±16MeV

TABLE II. Uncertainties for the final combined result on M_W.

Source CDF	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19



Updated from arXiv:1204.0042

arXiv:1701.07240

Measurement of m_W at ATLAS

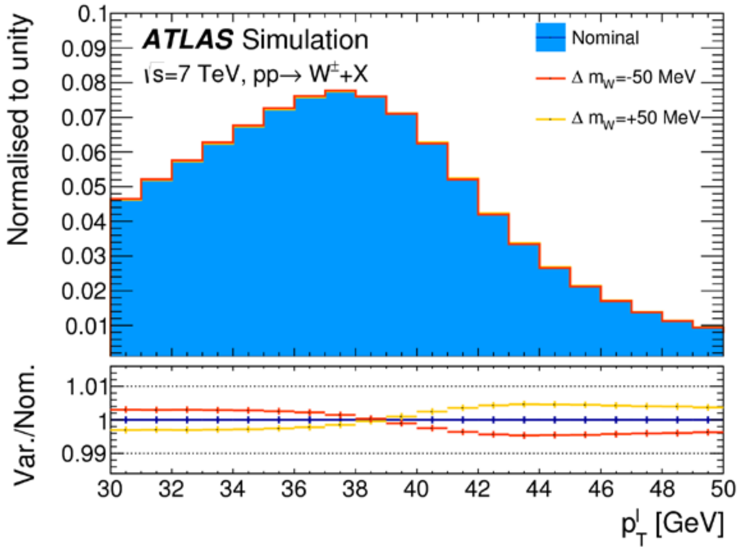
Compare expectations of p_T^ℓ, m_T for various values of m_W to measured distributions

- Build templates using a single reference sample (+background) for a given m_W, reweight to other m_W using a relativistic Breit-Wigner

$$\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2}$$

(width scaling as $\Gamma_W \propto m_W^3$)

- Signal expectations from Powheg+Pythia8, reweighted event-by-event for
  - Improvements in kinematics (better match data)
  - Missing higher-order terms e.g. EW
- Performed for several categories
- χ^2 compatibility test to judge best m_W value



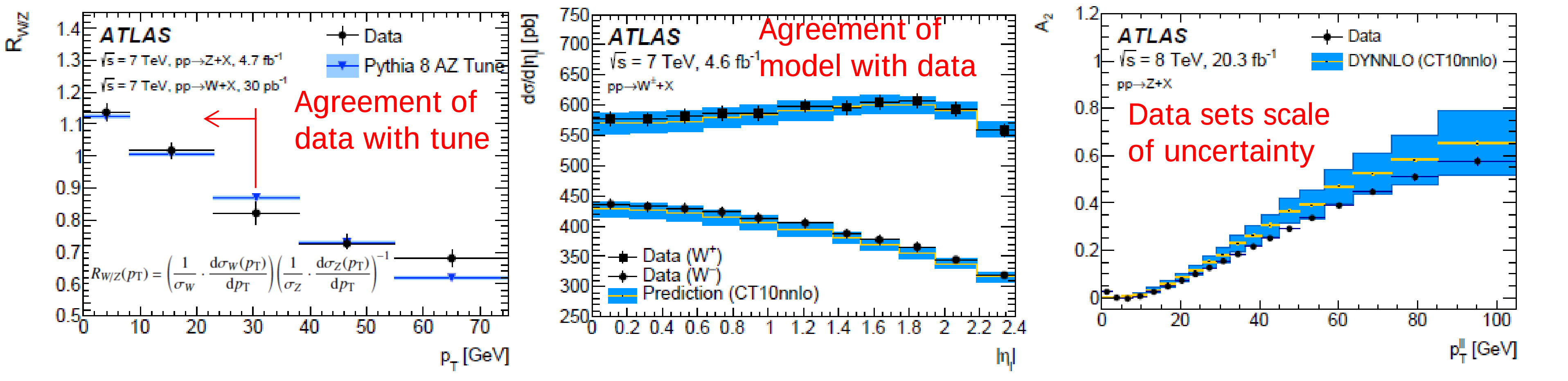
Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\lvert\eta_\ell\rvert$ categories	[0, 0.6], [0.6, 1.2], [1.8, 2.4]	[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]

The model, guided by data: Powheg+Pythia8 → best Drell-Yan cross section

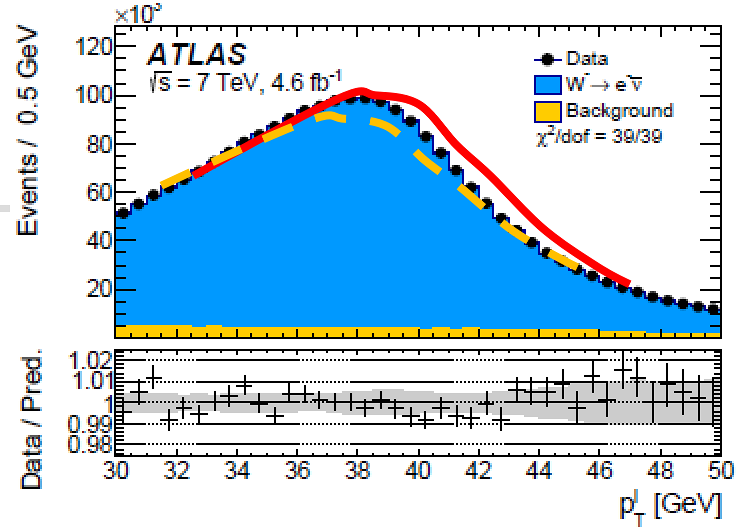
- Factorisation of fully differential leptonic Drell-Yan cross section:

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right],$$

- Modelling: $d\sigma/dm$ with a BW, $d\sigma/dy$ and A_i with fixed-order pQCD predictions (optimised DYNNLO), remaining component with Pythia8 MC
- Data-driven improvements in the modelling:
  - √s=7TeV Z data used to tune pQCD parameters in Pythia8 parton shower generator
- Validation of: $d\sigma/dy$ with √s=7TeV W,Z σ meas., A_i with √s=8TeV Z angular coefficients meas.
- Sources of uncertainties related to the above plus other important sources such as choice of PDF (CT10nnlo+variations and alternate PDFs: MMHT2014, CT14), effects of missing high orders on the NNLO predictions, contributions from heavy quarks (b,c)



Experimental considerations - I



Shape of p_T^ℓ, m_T sensitive to m_W: e.g. Jacobian edge at $m_W/2$ of p_T^ℓ $\rightarrow$ could be shifted or distorted by experimental effects?

$\rightarrow$ Correct and calibrate (mostly done to the MC)!

Select leptons

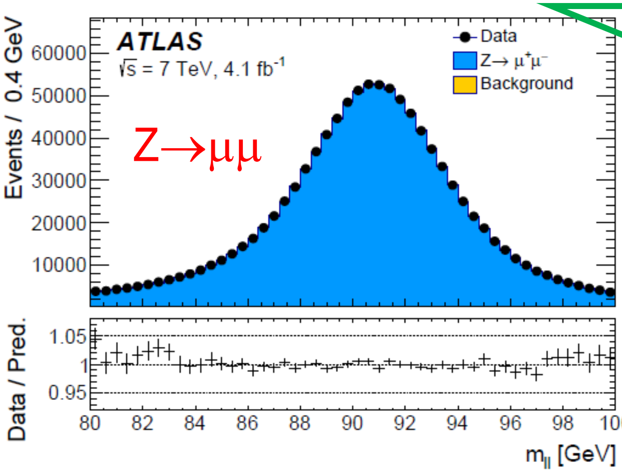
- Trigger
- Reconstruct
- Identify
- Isolate

Efficiencies(p_T^ℓ, η_ℓ, ϕ_ℓ, q, $u_\parallel$)

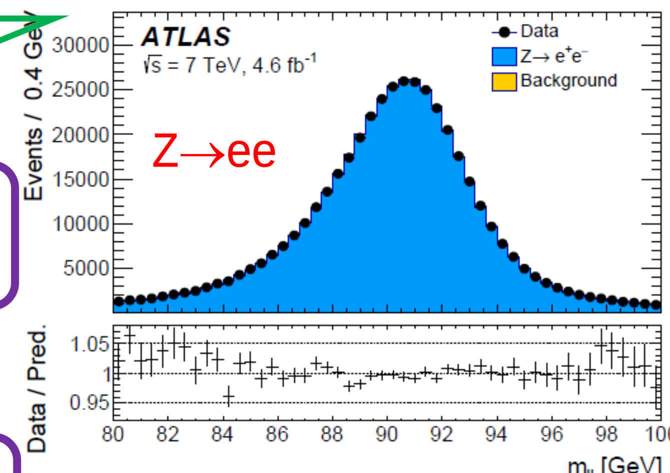
Calibrate leptons

- Energy/momentum Scale
- Resolution
- Biases

Use:
$Z\rightarrow\ell\ell$



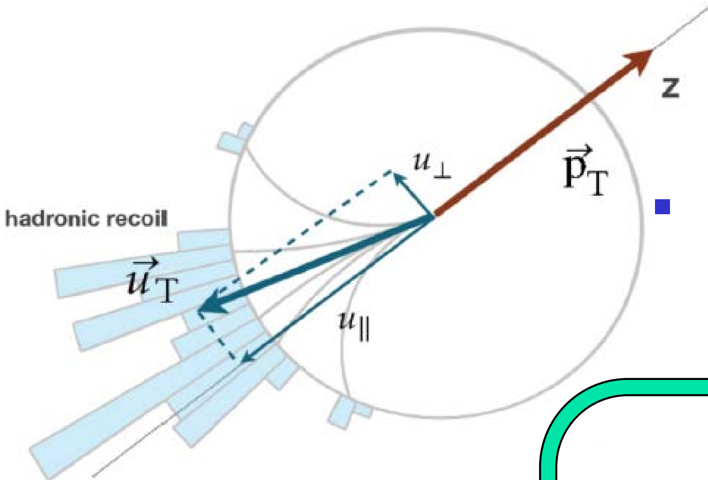
Data/MC agreement?
$\rightarrow$ Scale factors!



Transfer from Z to W

Experimental considerations - II

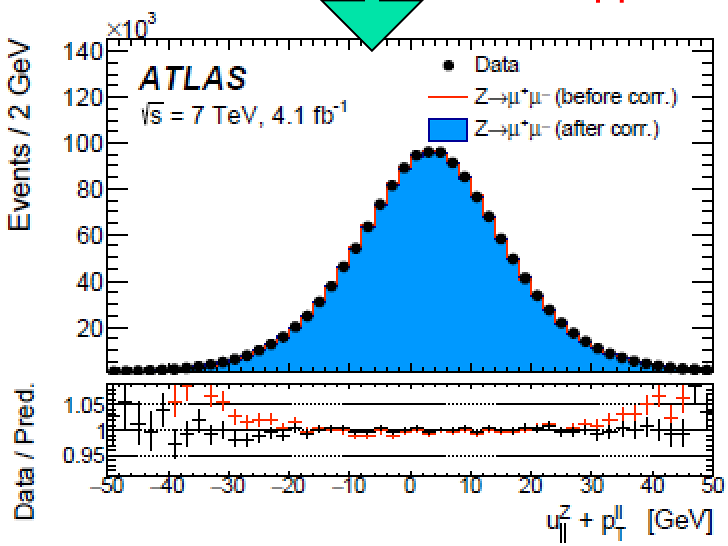
Recoil response

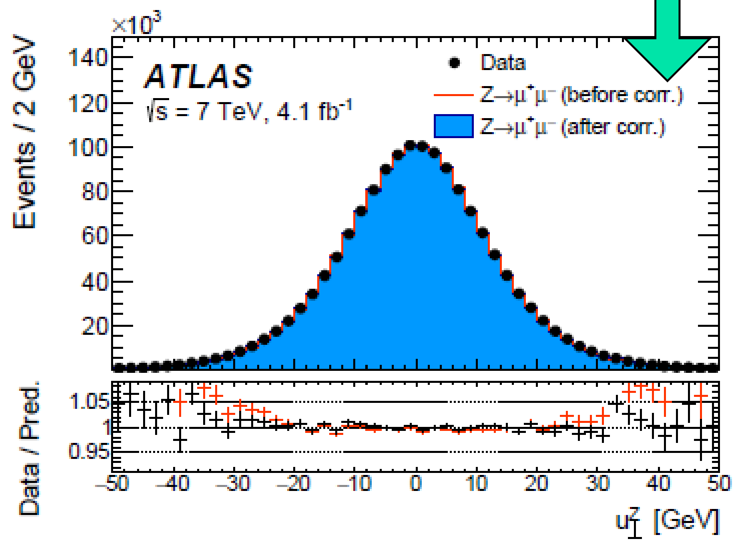


Correct for:

- Event activity
  - Pileup <μ>: match MC to what is observed in data
  - Sum E_T: $\Sigma\bar{E}_T$ residual data-MC differences responsible for remaining $u_\perp$ mismodeling
- Residual corrections:
  - Non-zero crossing angle of the beam
  - Energy scale and resolution
    - Z: $u_\parallel + p_T^{\ell\ell}$ → calibrates energy scale
    - Z: $u_\perp$ → resolution

Test applicability of Z-based corrections to the W



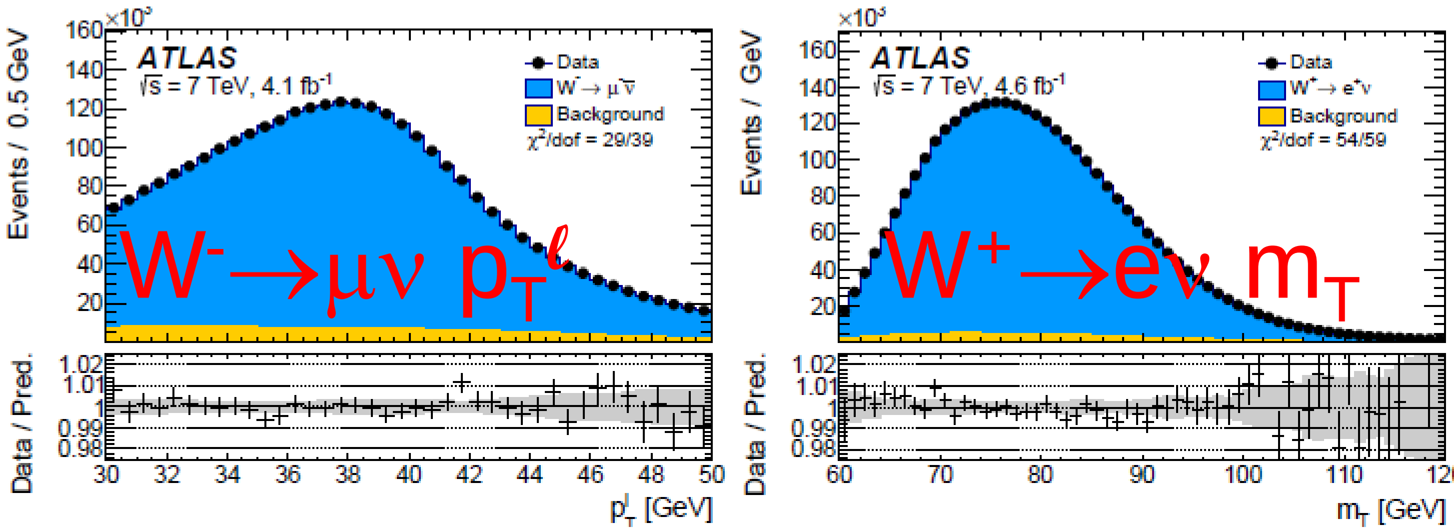


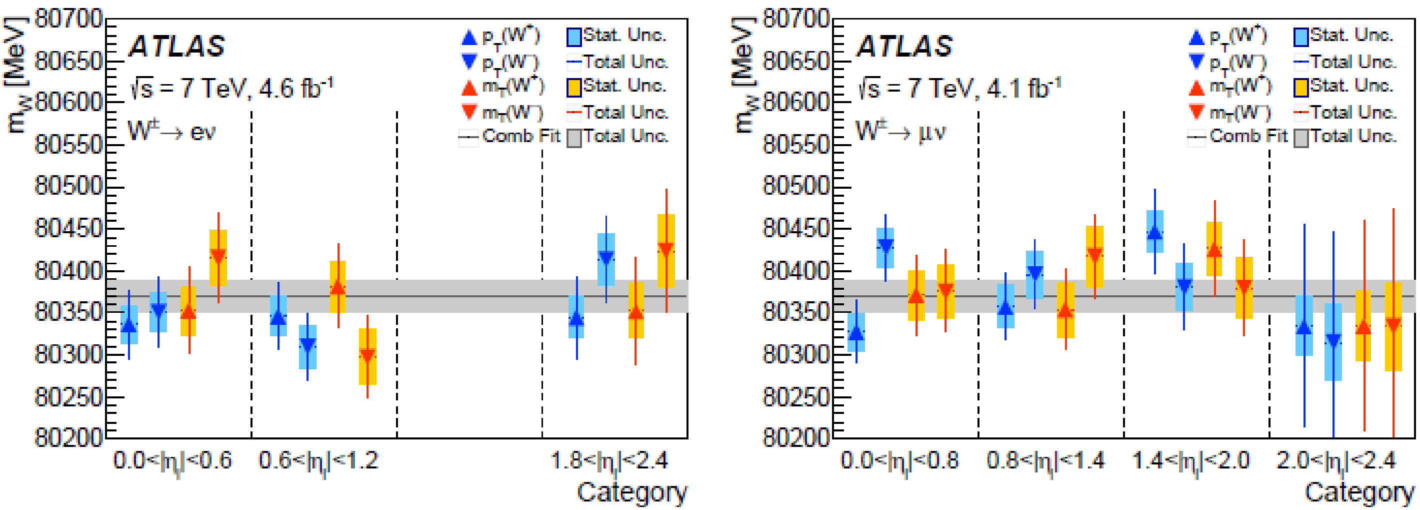
Measurement of m_W

7.8M $W \to \mu\nu$
5.9M $W \to e\nu$
4.6fb[-1]

$$\begin{pmatrix} W^+ \\ W^- \end{pmatrix} \times \begin{pmatrix} 3e \\ 4\mu \end{pmatrix} \eta \text{ bins} \times \begin{pmatrix} p_T \\ m_T \end{pmatrix}$$

- 28 measurements of m_W
- Optimise the fitting range of p_T (32-45GeV) and m_T (66-99GeV) (vary range as systematic)





Decay channel / Kinematic distribution	$W \to e\nu$ p_T^ℓ	$W \to e\nu$ m_T	$W \to \mu\nu$ p_T^ℓ	$W \to \mu\nu$ m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

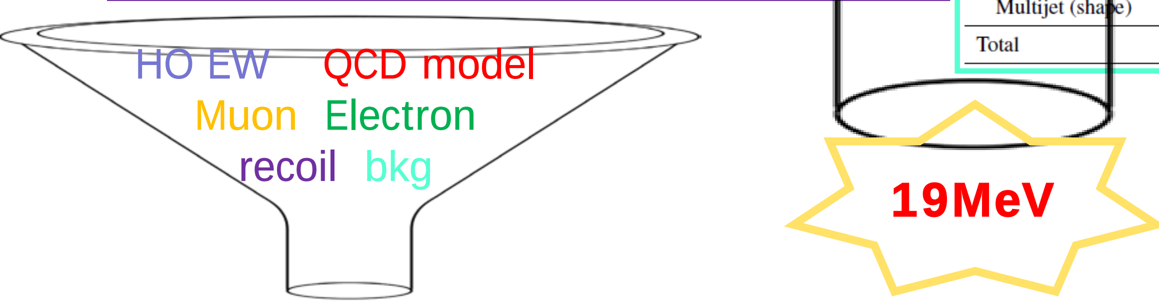
W-boson charge / Kinematic distribution	W^+ p_T^ℓ	W^+ m_T	W^- p_T^ℓ	W^- m_T	Combined p_T^ℓ	Combined m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

$\lvert\eta_\ell\rvert$ range / Kinematic distribution	[0.0, 0.8] p_T^ℓ	[0.0, 0.8] m_T	[0.8, 1.4] p_T^ℓ	[0.8, 1.4] m_T	[1.4, 2.0] p_T^ℓ	[1.4, 2.0] m_T	[2.0, 2.4] p_T^ℓ	[2.0, 2.4] m_T	Combined p_T^ℓ	Combined m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

$\lvert\eta_\ell\rvert$ range / Kinematic distribution	[0.0, 0.6] p_T^ℓ	[0.0, 0.6] m_T	[0.6, 1.2] p_T^ℓ	[0.6, 1.2] m_T	[1.82, 2.4] p_T^ℓ	[1.82, 2.4] m_T	Combined p_T^ℓ	Combined m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

W-boson charge / Kinematic distribution	W^+ p_T^ℓ	W^+ m_T	W^- p_T^ℓ	W^- m_T	Combined p_T^ℓ	Combined m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma \bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

Kinematic distribution / Decay channel / W-boson charge	p_T^ℓ $W \to e\nu$ W^+	p_T^ℓ $W \to e\nu$ W^-	p_T^ℓ $W \to \mu\nu$ W^+	p_T^ℓ $W \to \mu\nu$ W^-	m_T $W \to e\nu$ W^+	m_T $W \to e\nu$ W^-	m_T $W \to \mu\nu$ W^+	m_T $W \to \mu\nu$ W^-
δm_W [MeV]								
$W \to \tau\nu$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
$Z \to ee$ (fraction, shape)	3.3	4.8	–	–	4.3	6.4	–	–
$Z \to \mu\mu$ (fraction, shape)	–	–	3.5	4.5	–	–	4.3	5.2
$Z \to \tau\tau$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
WW, WZ, ZZ (fraction)	0.1	0.1	0.1	0.1	0.4	0.4	0.3	0.4
Top (fraction)	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3
Multijet (fraction)	3.2	3.6	1.8	2.4	8.1	8.6	3.7	4.6
Multijet (shape)	3.8	3.1	1.6	1.5	8.6	8.0	2.5	2.4
Total	6.0	6.8	4.3	5.3	12.6	13.4	6.2	7.4

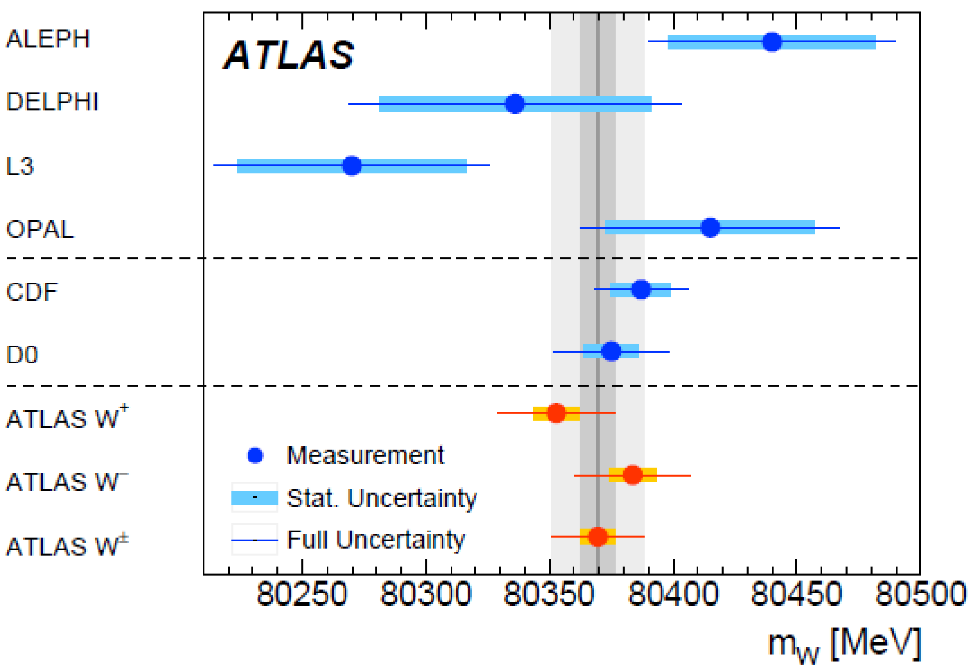


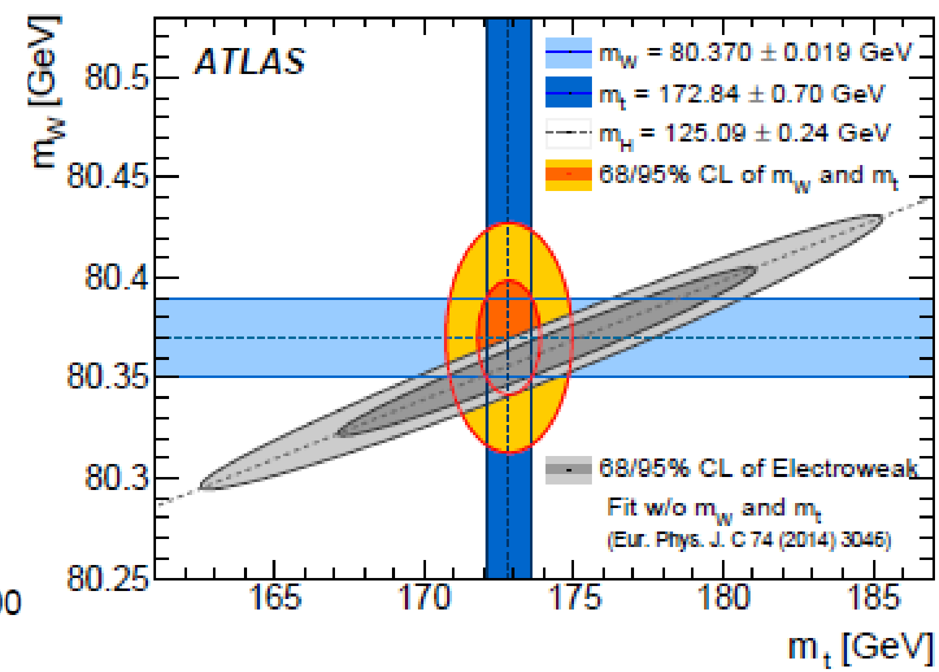
The final result

- Combine the measurements into one determination of m_W

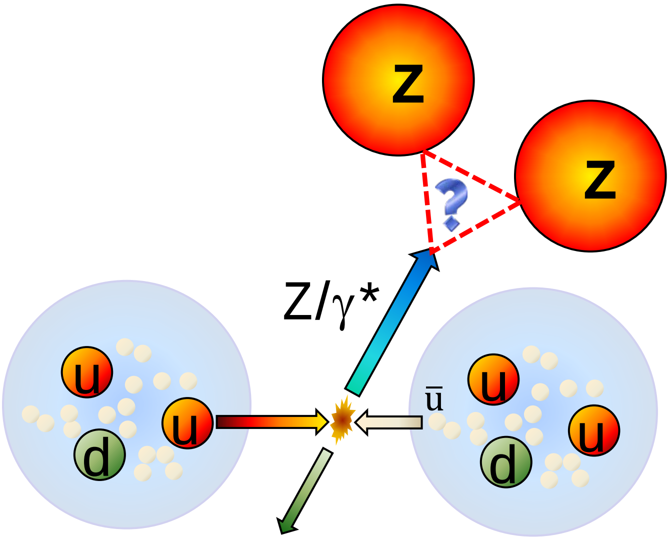
$$\begin{aligned} m_W &= 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} \\ &= 80370 \pm 19\ \text{MeV}, \end{aligned}$$

$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.$$






Weak
Weak
Weak
Weak

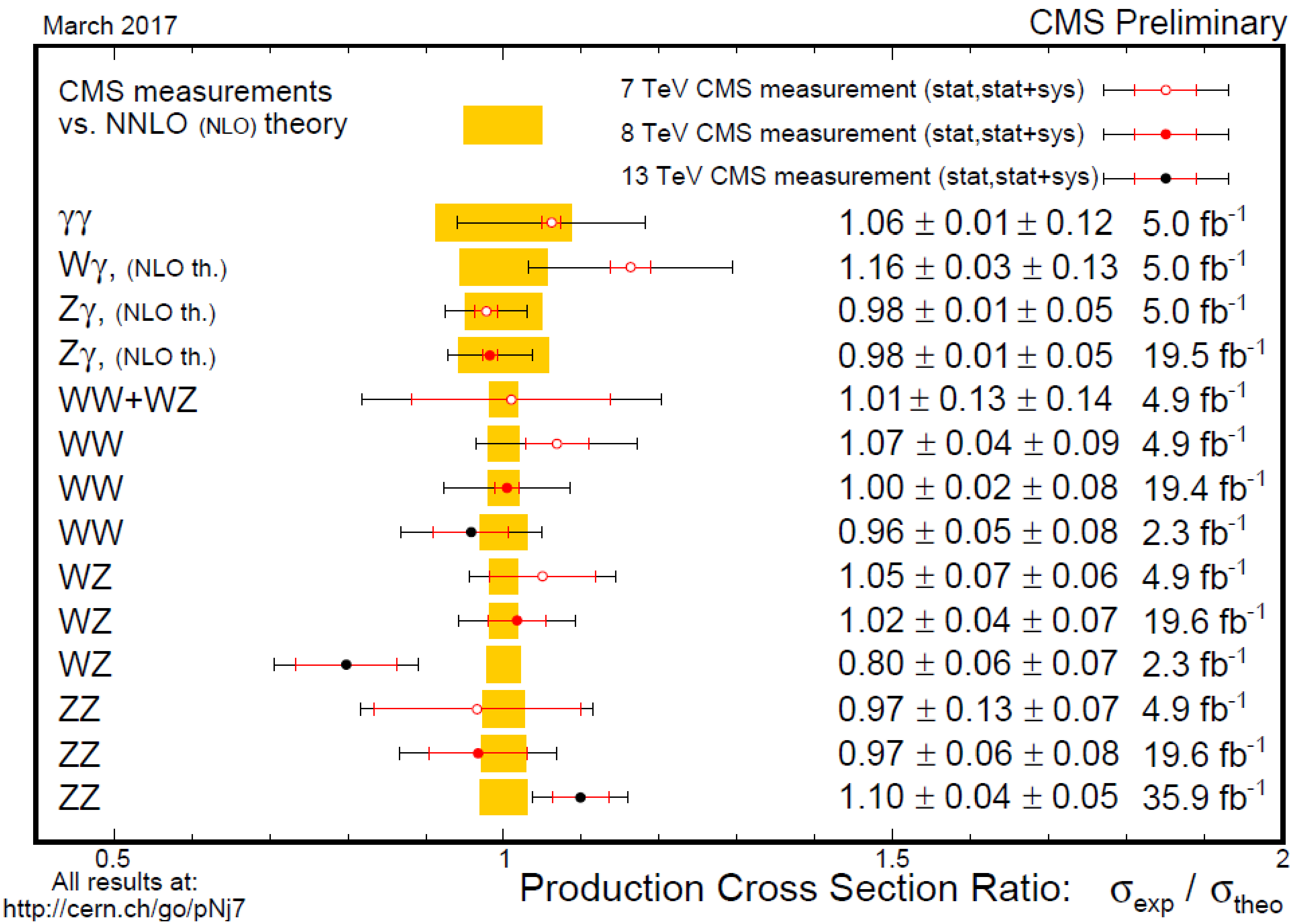


MULTIPLE W,Z,γ PRODUCTION:

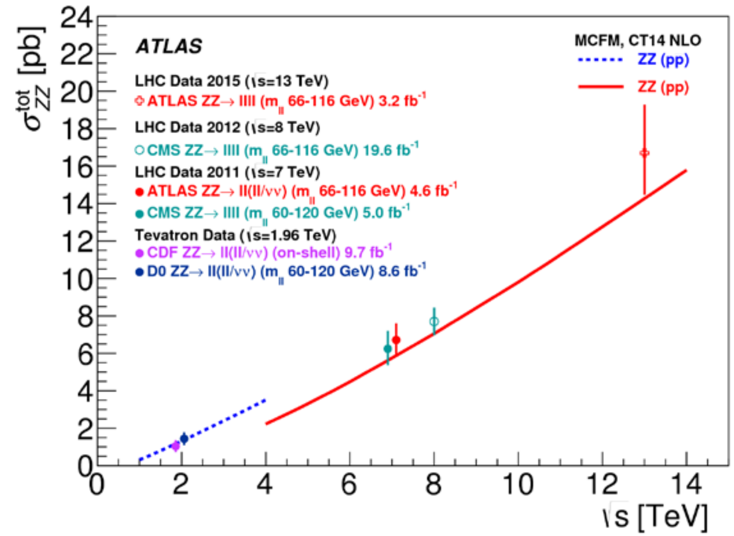
cross sections and aT/QGC

Diboson cross-section measurements

As with single-boson production, diboson cross-sections measurements are made and confronted to theory expectations → rather good agreement with the SM!

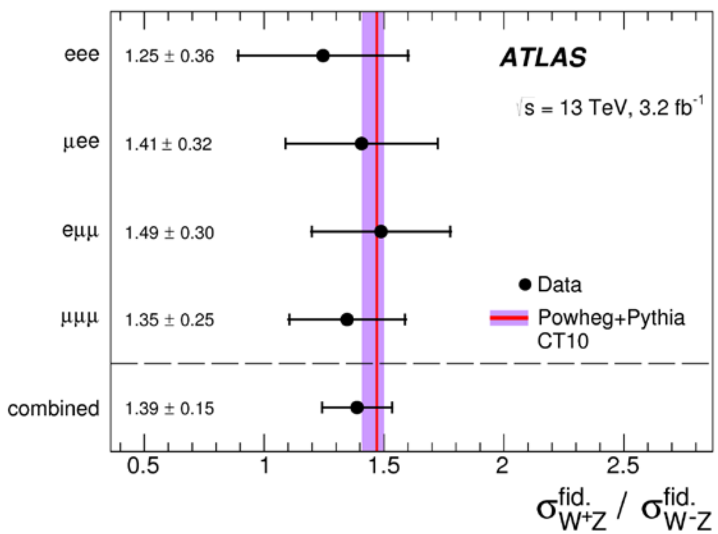


Examples of diboson cross section measurements



WZ@13TeV Phys. Lett. B 762 (2016) 1

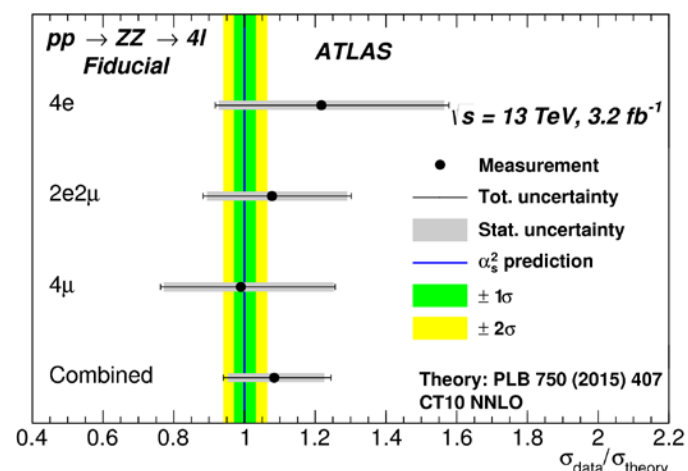
- Fiducial cross-section ratios W^+Z/W^-Z:
  - sensitive to PDFs
- Benefit from cancellation of sys uncertainties
- Syst+lumi: 5% → 2% (but stats dominated)



- Results also used to test pQCD in low bkg (unlike WW), high cross-section (unlike ZZ) environment

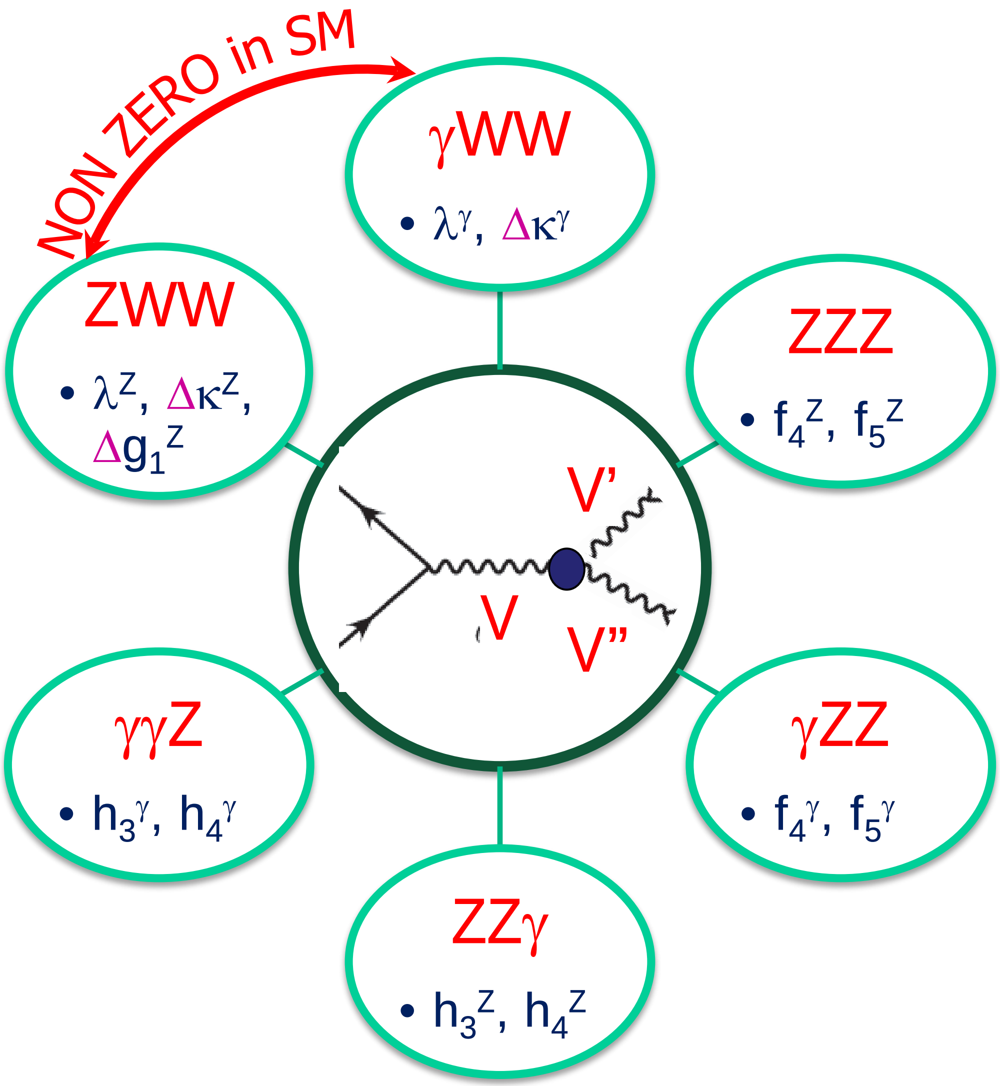
ZZ@13TeV Phys. Rev. Lett. 116 (2016) 101801

- Cross sections: fiducial and total
- Very much stats dominated
- ~ equal contributions from theory, experiment, luminosity



Data/Pred.

- Test EW sector of SM: gauge boson self-interactions
  - anomalous Triple Gauge Couplings (aTGC)
- SM multiboson production a source of bkg for:
  - Higgs production (e.g. $H \rightarrow WW$, ZZ)
  - New physics (e.g. new resonances→VV)



TGC

Effective Lagrangian formalism

- General V V' V" vertex
- Tree level some TGCs non-zero:
  - γWW, ZWW
- Other TGCs zero at tree level but non-zero contributions at higher order
- Couplings such that SM values = 0 or 1
  - For SM=1 → deviation Δ from 1
- Leptonic decays of V ($W \rightarrow \ell\nu$, $Z \rightarrow \ell\ell, \nu\nu$)
- Note: terms in Lagrangian would lead to unitarity violation vs. √s. New physics interactions at scale Λ needed
  - form factor parameterisation

$$f_i^V = f_{i0}^V / (1 + \hat{s}/\Lambda^2)^n$$

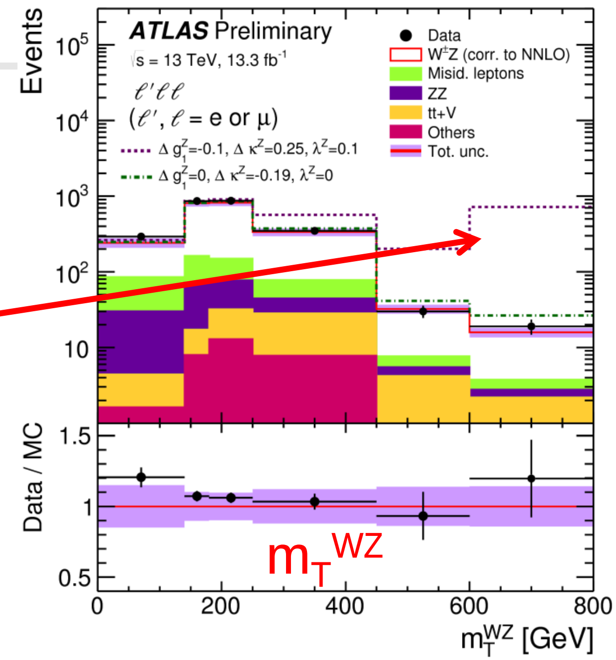
Effect Field Theory approach

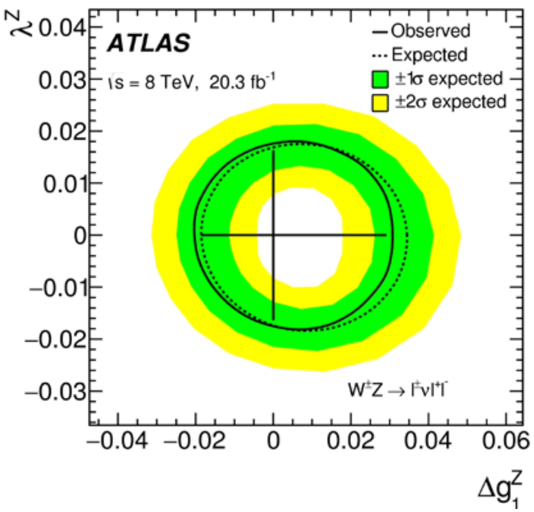
- Particle content of SM unchanged, add to Lagrangian linear combination of dimension–six operators: c_i/Λ^2
- Not considered here

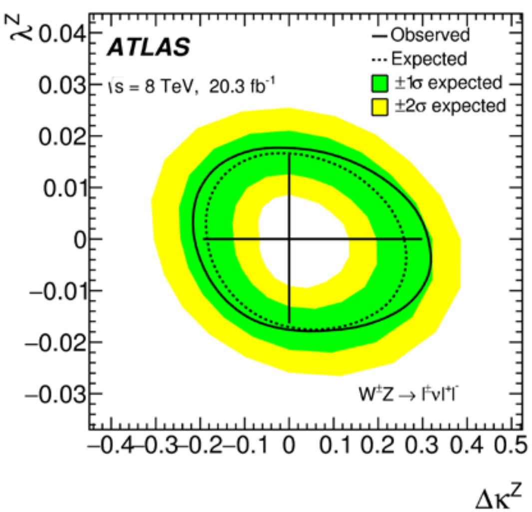
aTGC methodology.
An example: WZ@8 and 13TeV

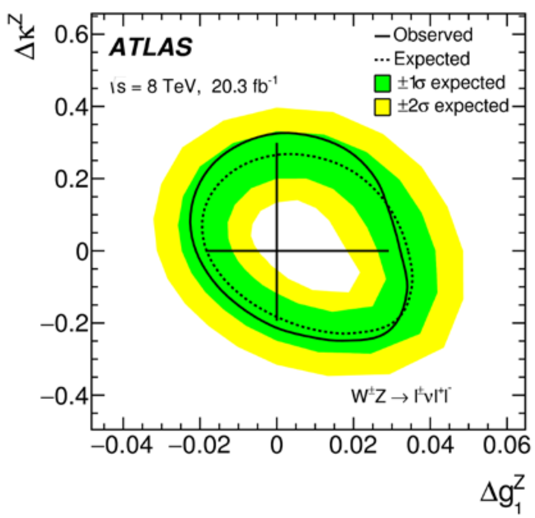
WZ@8TeV Phys. Rev. D 93 (2016) 092004
WZ@13TeV ATLAS-CONF-2016-043

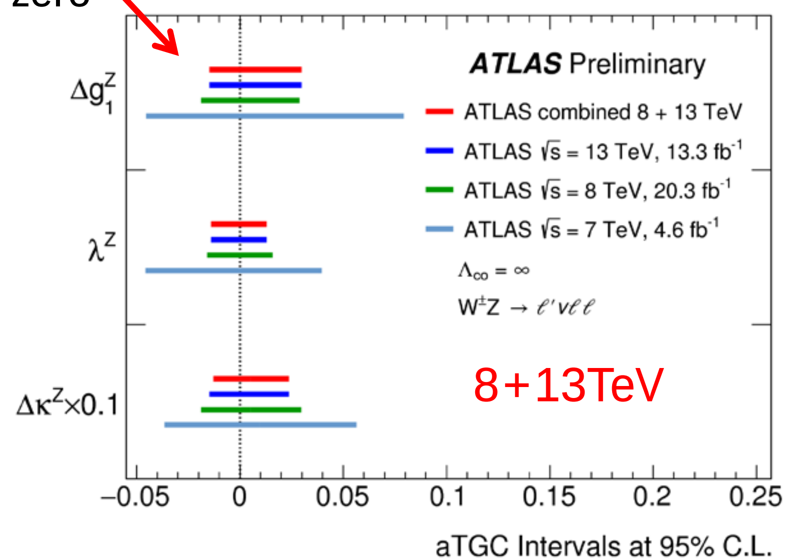
- Measure diboson kinematic distributions/cross section vs. variables sensitive to aTGCs
  - $WZ \to \ell\nu + \ell\ell$: m_T^{WZ}
- Presence of aTGC distorts shape
- Use MC@NLO MC to reweight to distributions with aTGCs
- Set limits on each coupling:
  - assuming others are zero or
  - pairs assuming others zero











Recent results: aTGCs

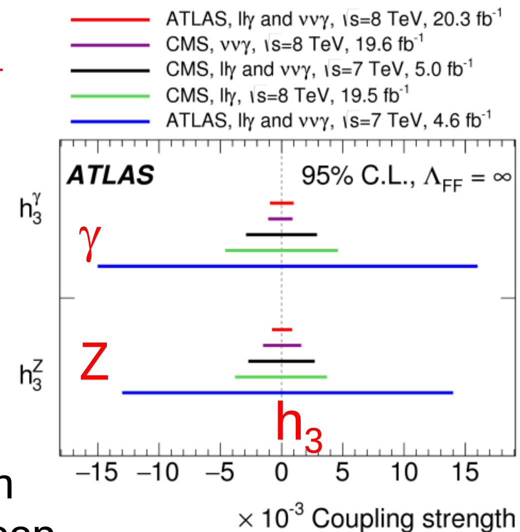
WW@8TeV JHEP 09 (2016) 029

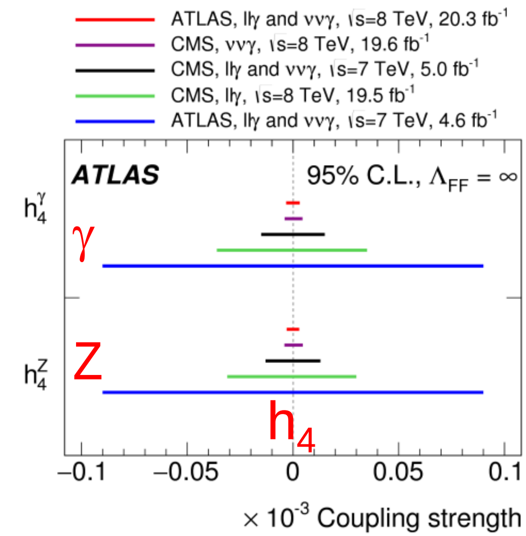
- aTGCs extracted from leading lepton p_T
- NLO EW corrections (signif. at high p_T)

Scenario	Parameter
No constraints scenario	Δg_1^Z, Δk^Z, λ^Z, Δk^γ, λ^γ
LEP	Δg_1^Z, Δk^Z, λ^Z
HISZ	Δk^Z, λ^Z
Equal Couplings	Δk^Z, λ^Z

Scenarios:

- No constraints
- LEP: SU(2)xU(1) gauge invariance
- HISZ: absence of cancellation between tree-level and one-loop
- Equal couplings: params same for WWZ, WWγ

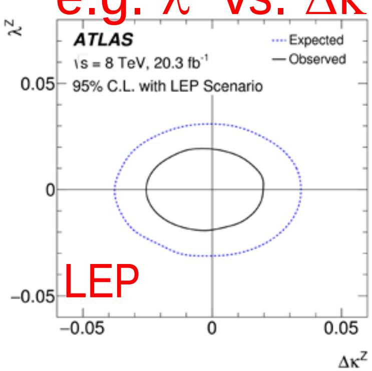


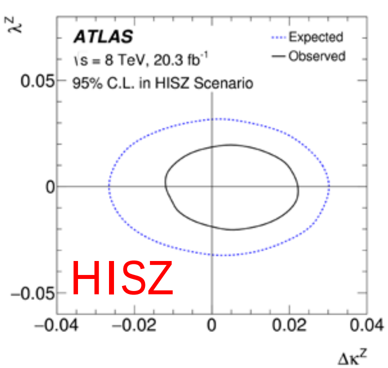


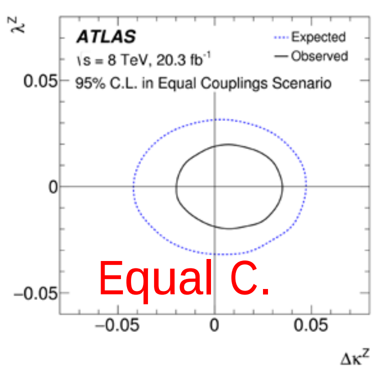
Zγ@8TeV Phys. Rev. D 93, 112002 (2016)

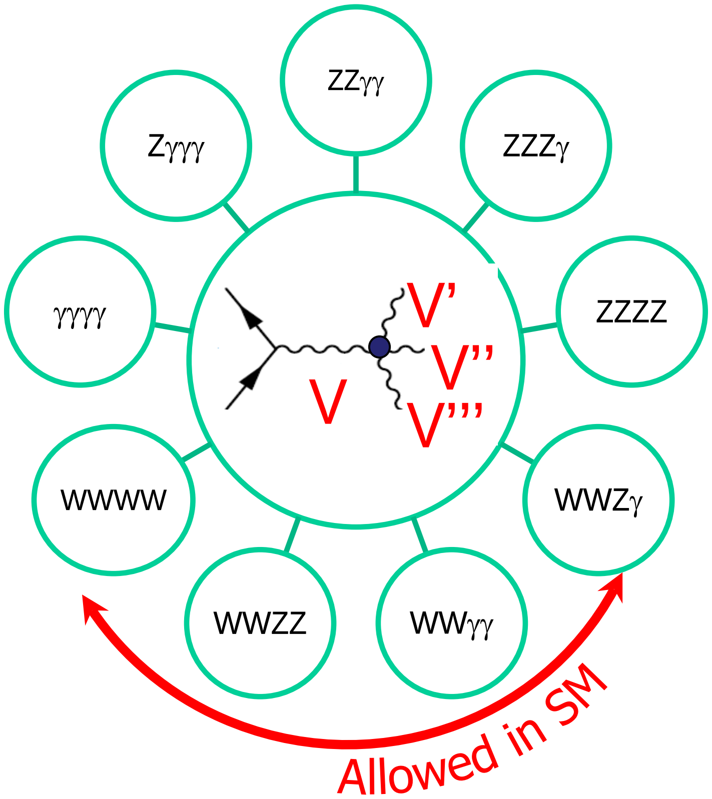
- Includes Z→νν!
  - Missing E_T requirements
- aTGCs extracted from Zγ fiducial cross section with high E_T^γ (>250GeV for $\ell\ell\gamma$, >400GeV $\nu\bar{\nu}\gamma$) with exclusive zero-jet
  - Stats dominated
- aTGC predictions from MCFM

e.g. λ^Z vs. $\Delta\kappa^Z$









- 18 dim-8 effective operators involving gauge bosons built from
  - Higgs field: f_{Si}/Λ^4, i=0,1
  - Field strengths $SU(2)_L$, $U(1)_\gamma$: f_{Ti}/Λ^4, i=0-2,5-9
  - Both: f_{Mi}/Λ^4, i=0-7

Dimension-8 operators and quartic vertices

M. Baak et al. arXiv:1310.6708

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

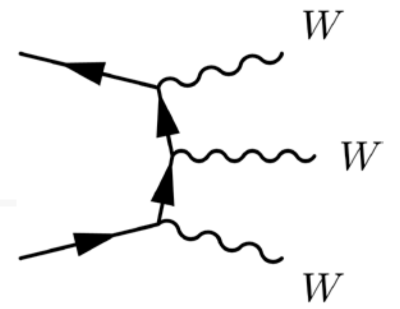
Table 1-16. *Quartic vertices modified by each dimension-8 operator are marked with X.*

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] ,$$
$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] ,$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] ,$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] ,$$
$$\mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} ,$$
$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} ,$$
$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu} W^{\beta\nu} D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu\Phi\right] ,$$

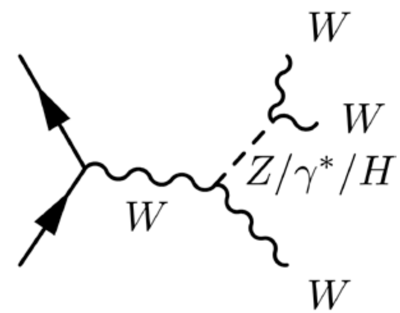
$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] ,$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] ,$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right] ,$$
$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} ,$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} ,$$
$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} ,$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} .$$

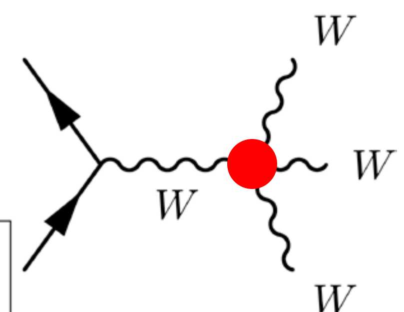
Recent results: aQGCs

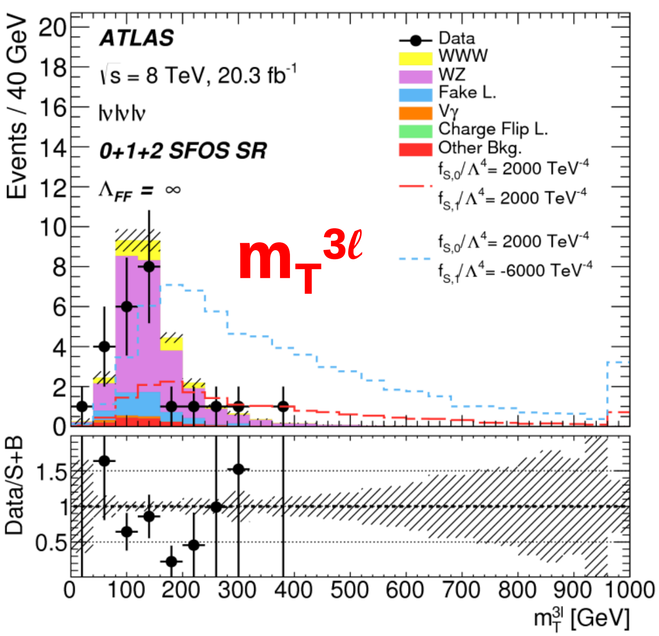


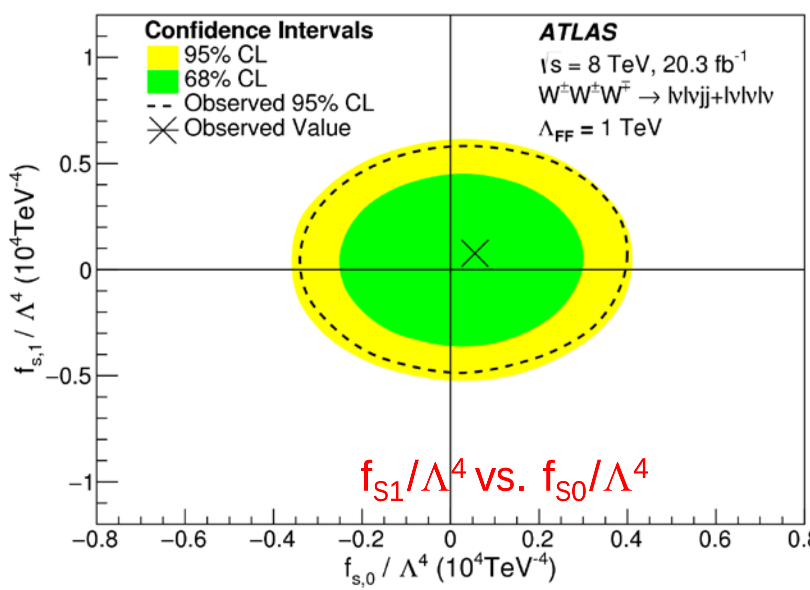
WWW@8TeV (Eur. Phys. J. C 77 (2017) 141)

- $\ell\nu\ell\nu\ell\nu$: categorised by number of same-flavour opposite-sign leptons SFOS=0, 1, 2
- $\ell\nu\ell\nu jj$: $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$ +2 jets consistent with m_W
  - Specific requirements on missing E_T and $m_{\ell\ell}$ to enhance signal, and veto Z background
- VBFNLO to produce events with aQGCs with coefficients f_{S0}/Λ^4, f_{S1}/Λ^4
- profile likelihood incorporates observed and expected numbers of events for different aQGCs





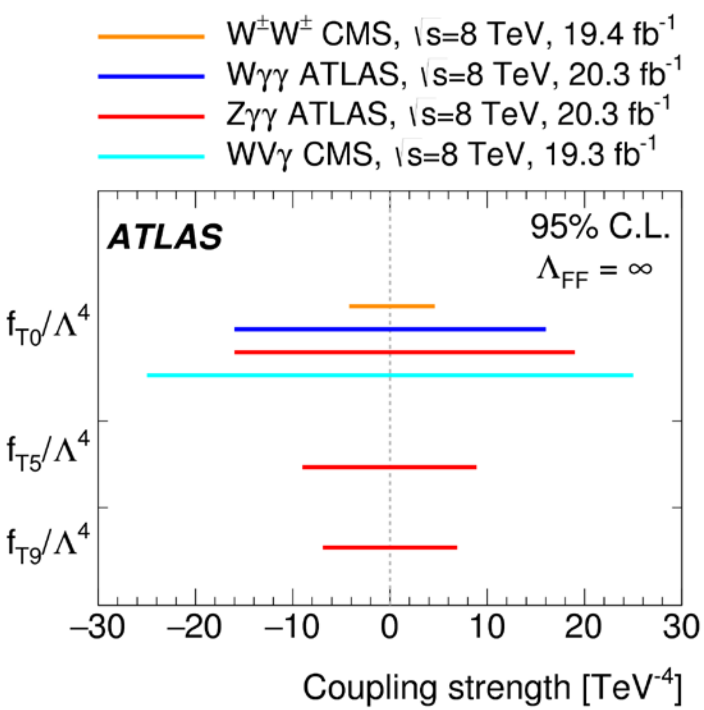


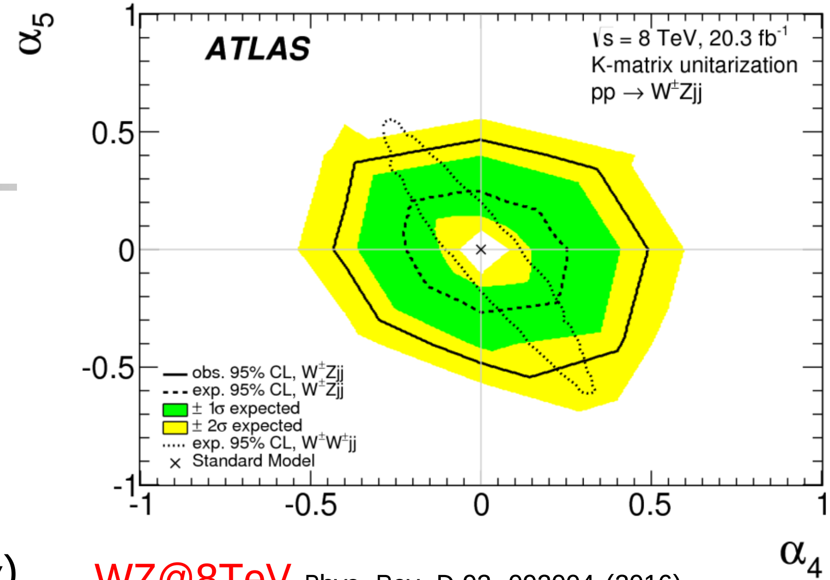


Recent results: aQGCs

Zγγ@8TeV Phys. Rev. D 93 (2016) 112002

- VBFNLO to produce events with aQGCs with coefficients:
  - f_{T0}/Λ^4, f_{T5}/Λ^4, f_{T9}/Λ^4, f_{M2}/Λ^4, f_{M3}/Λ^4
- aQGCs extracted from exclusive zero-jet fiducial cross section for $m_{\gamma\gamma}$>300 (200)GeV for $\nu\nu\gamma\gamma$ ($\ell\ell\gamma\gamma$)





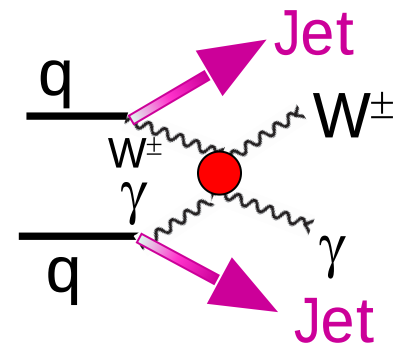
WZ@8TeV Phys. Rev. D 93, 092004 (2016)

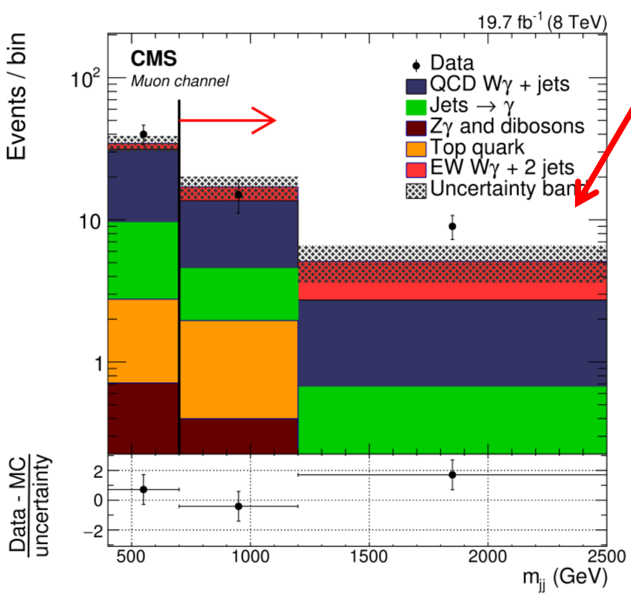
- WHIZARD to produce events with aQGCs with coefficients:
  - $\alpha_4 \rightarrow f_{S0}/\Lambda^4$, $\alpha_5 \rightarrow f_{S1}/\Lambda^4$
- aQGCs extracted from fiducial cross section of WZ production with at least 2 jets, in phase space:
  - $|\Delta\varphi(WZ)|>2$, $\Sigma|p_T^{\ell}|>250$GeV
  - ➔ Without these requirements, set limit on vector-boson scattering production WZjj-EW

95% CL upper limit on $\sigma^{\text{fid.}}_{W^\pm Zjj\text{-EW}\rightarrow \ell' \nu \ell\ell}$ [fb]	
Observed	0.63
Expected	0.45

Vector boson scattering (VBS): $W^{\pm}\gamma jj$

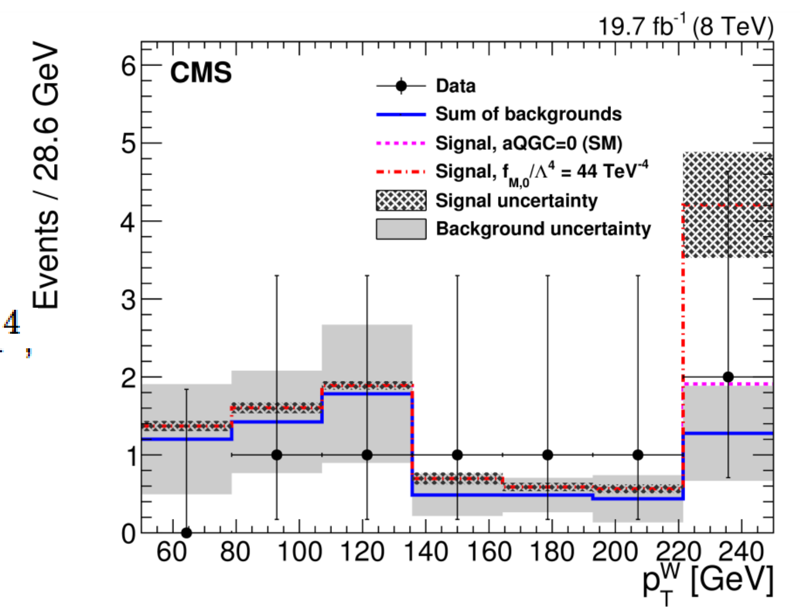
- VBS VV→VV where V=γ,W, Z: key process to probe nature of EW symmetry breaking
  - Without a SM Higgs, longitudinally polarised VBS amplitude violates unitarity at ~1TeV!
  - Newly discovered Higgs boson could unitarise process
- V+V+jet+jet in final state → both EW and QCD processes
- $W^{\pm}\gamma jj$ production at 8TeV
  - Enhanced EW-induced Wγ+2j region: exactly 1 e or μ + E_T^{miss} ≥2 well separated jets in y,η,φ, high invariant mass m_{jj}>700GeV
  - ~10 (20) EW (QCD)-induced events expected
- 2.7σ significance of EW signal



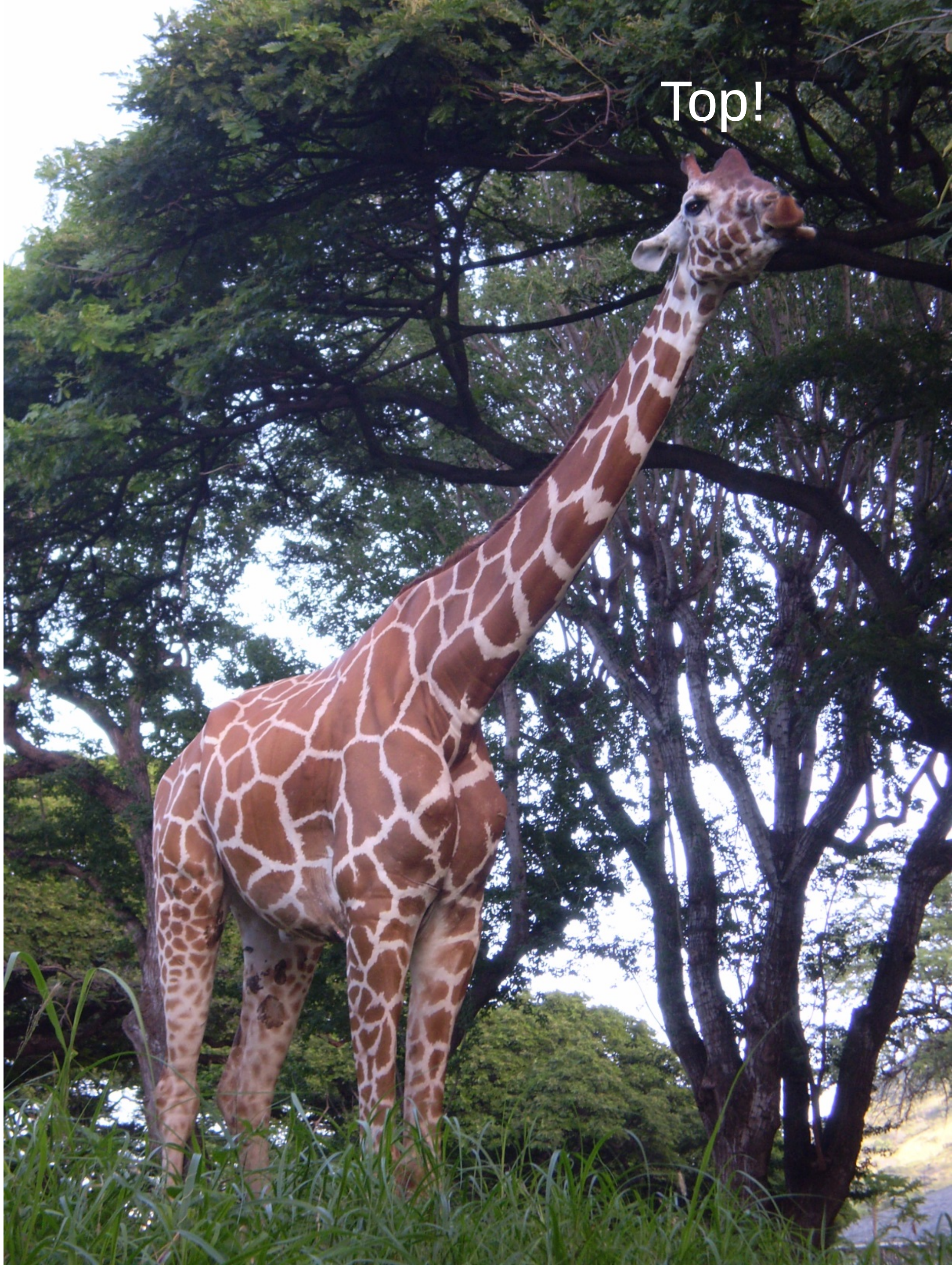


Shape of distribution at high p_T^W used to extract aQGC limits on:

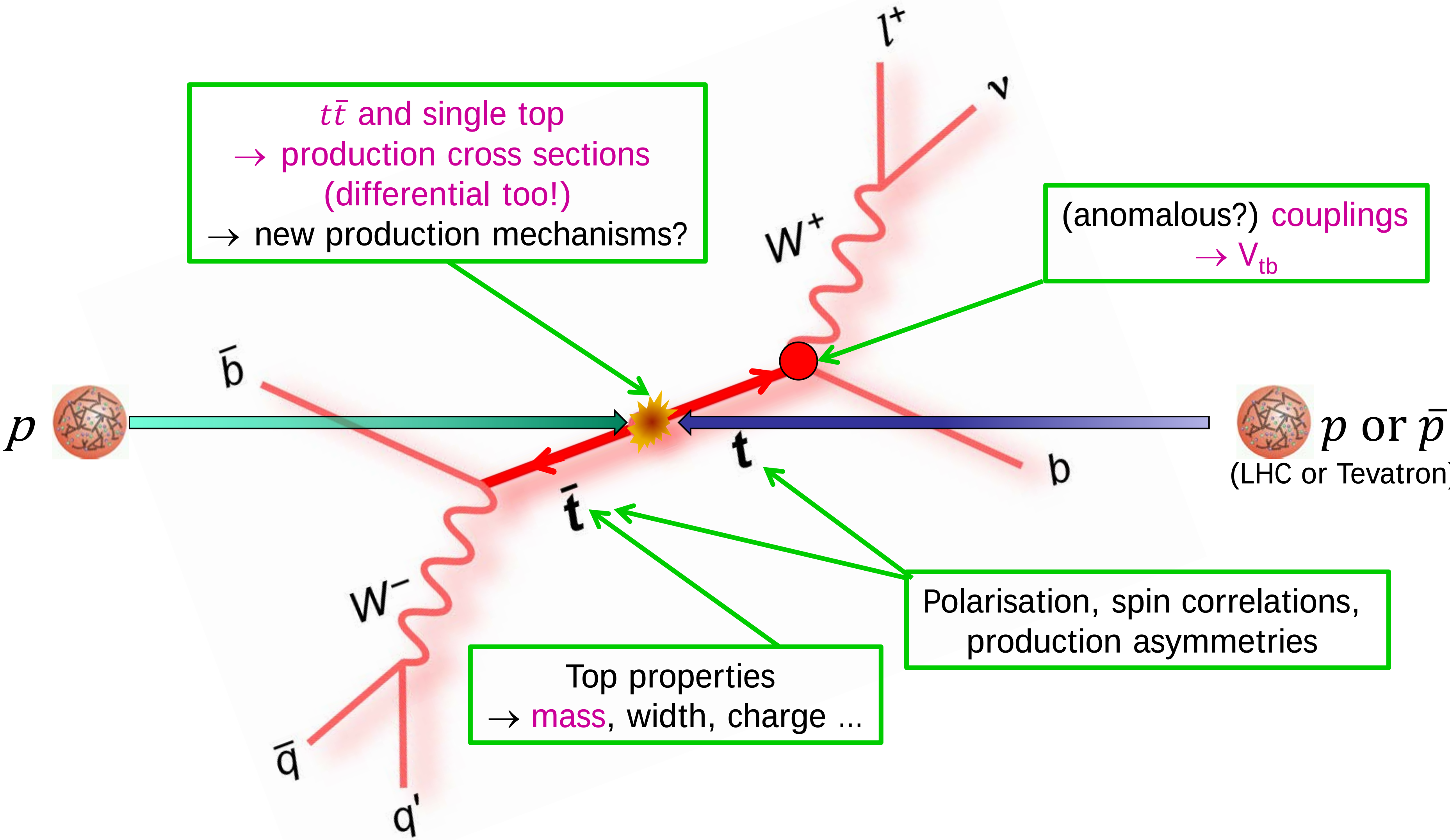
$$f_{M,0-7}/\Lambda^4,\ f_{T,0-2}/\Lambda^4,\ f_{T,5-7}/\Lambda^4$$



TOP-QUARK PHYSICS

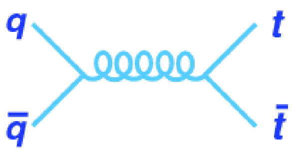


Top production and decay: the many properties



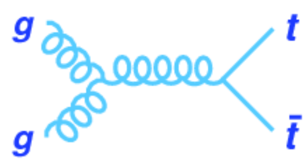
Top quark pair production and decay

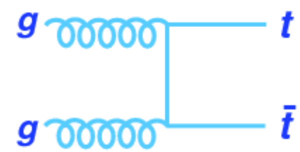
- Top quark pair ($t\bar{t}$) production is via the strong interaction



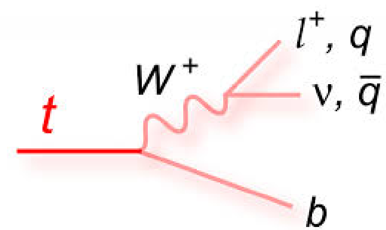
←85% Tevatron 15%→

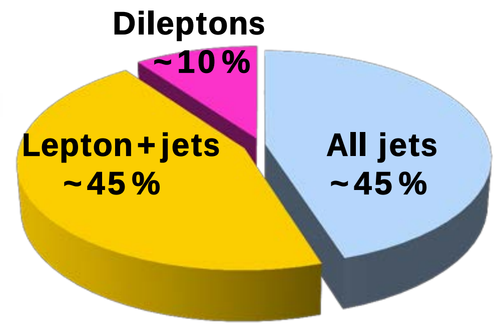
←15% LHC 85%→

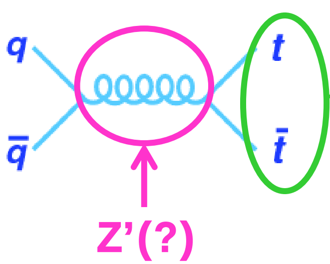




- Top quark subsequently decays ~100% to W + b: $t\bar{t} \rightarrow W^+W^- b\bar{b}$
  - W decays are hadronic or leptonic
- Dilepton channel: very clean but low rate
- Lepton+jets: clean and good rate
- Measure $t\bar{t}$ production cross section $\sigma(t\bar{t})$
  - Precise $\sigma(t\bar{t})$ → measurement of SM parameters: m_t and α_S
  - New physics could be hidden? New production modes or decays?





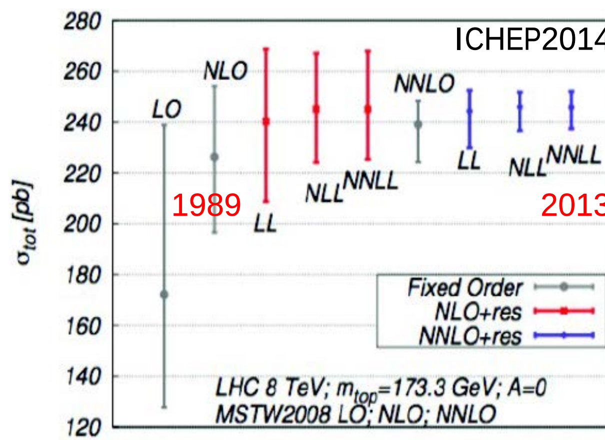


t' or $\tilde{t}$? New heavy quarks? SUSY decays?

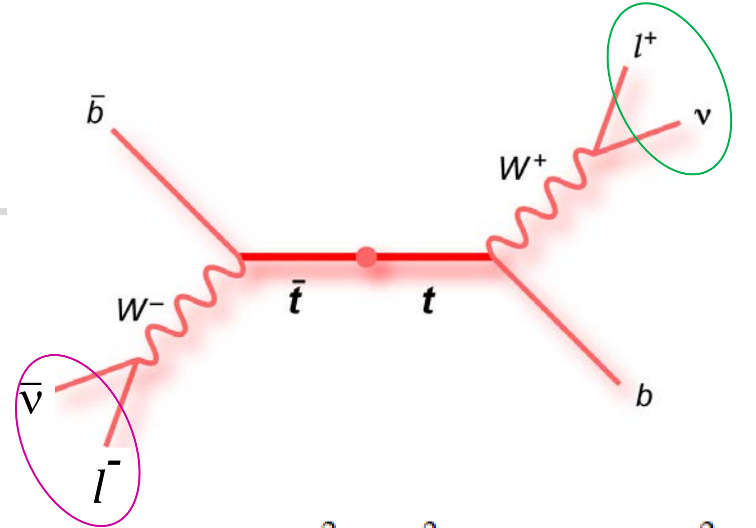
- SM predictions: →
- Will be a trade off:
  - stats vs. sys

√s [TeV]	$\sigma(t\bar{t})$ (NNLO+NNLL) [pb] (m_t=172.5GeV)	Uncert. [%]
2	7.35	~4-6%
7	177.3	
8	252.8	
13	824.2	

x100



$t\bar{t}$: dilepton – I



How to reconstruct t, tbar, ttbar system?

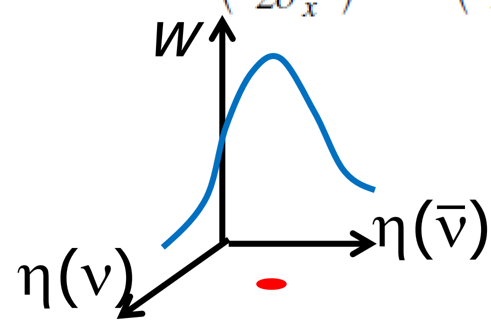
- 2 opposite-sign leptons
  - Usually take $e^{\pm}\mu^{\mp}$ to avoid $Z \rightarrow ee, \mu\mu$
- Several jets (two of them from b)
- Two unobserved ν, both contributing to $\vec{p}_T^{\,miss}$
- ➧ Ambiguity: mapping partons/leptons to reco objects
  - ➧ Under-constrained system!

$$(\ell_{1,2} + \nu_{1,2})^2 = m_W^2 = (80.2\ \text{GeV})^2,$$
$$(\ell_{1,2} + \nu_{1,2} + b_{1,2})^2 = m_t^2 = (172.5\ \text{GeV})^2,$$
$$\eta(\nu),\ \eta(\bar{\nu}) = \eta_1,\ \eta_2,$$

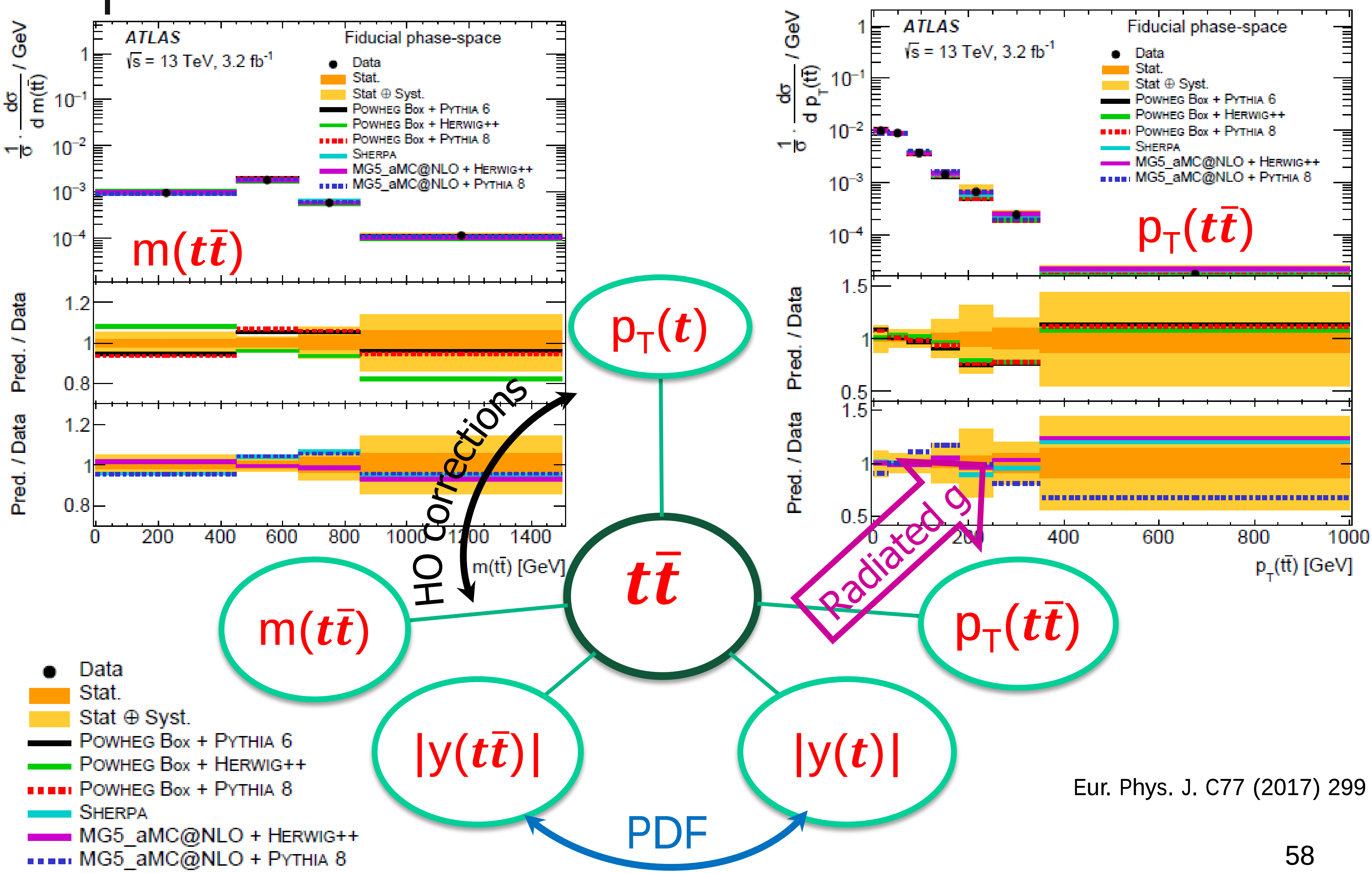
- e.g. apply additional constraints provided by event topology!
  - Scan $\eta(\nu)$, $\eta(\bar{\nu})$ for possible values e.g. between -5 to 5
- Equations can be solved with two possible solutions for each input $\eta(\nu)$, $\eta(\bar{\nu})$
  - Look at "E_T^{miss}" for each solution. See which $\nu+\bar{\nu}$ E_x, E_y best corresponds to reco E_T^{miss}
    - Which solution maximises the weight, w?
    - Used to assign ν, $\bar{\nu}$ to t, tbar

$$w = \exp\left(\frac{-\Delta E_x^2}{2\sigma_x^2}\right) \cdot \exp\left(\frac{-\Delta E_y^2}{2\sigma_y^2}\right),$$

- Not always successful…
  - Redo assuming mismeasurements of objects
    - ➧ Smearing
  - If all else fails
    - Count is as inefficiency in reconstruction
      - e.g. 20% for signal in Eur. Phys. J. C77 (2017) 299



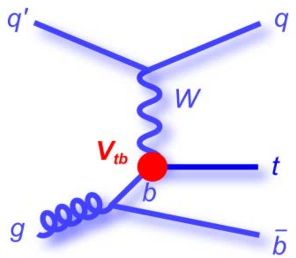
$t\bar{t}$: dilepton – II
cross section in a fiducial phase space at 13TeV



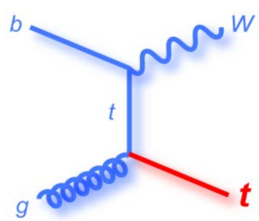
Eur. Phys. J. C77 (2017) 299

Single-top production

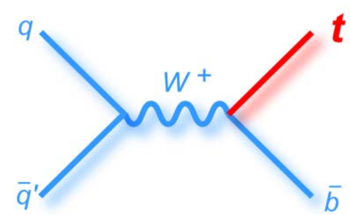
- Single-top production is via the EW interaction



t-channel

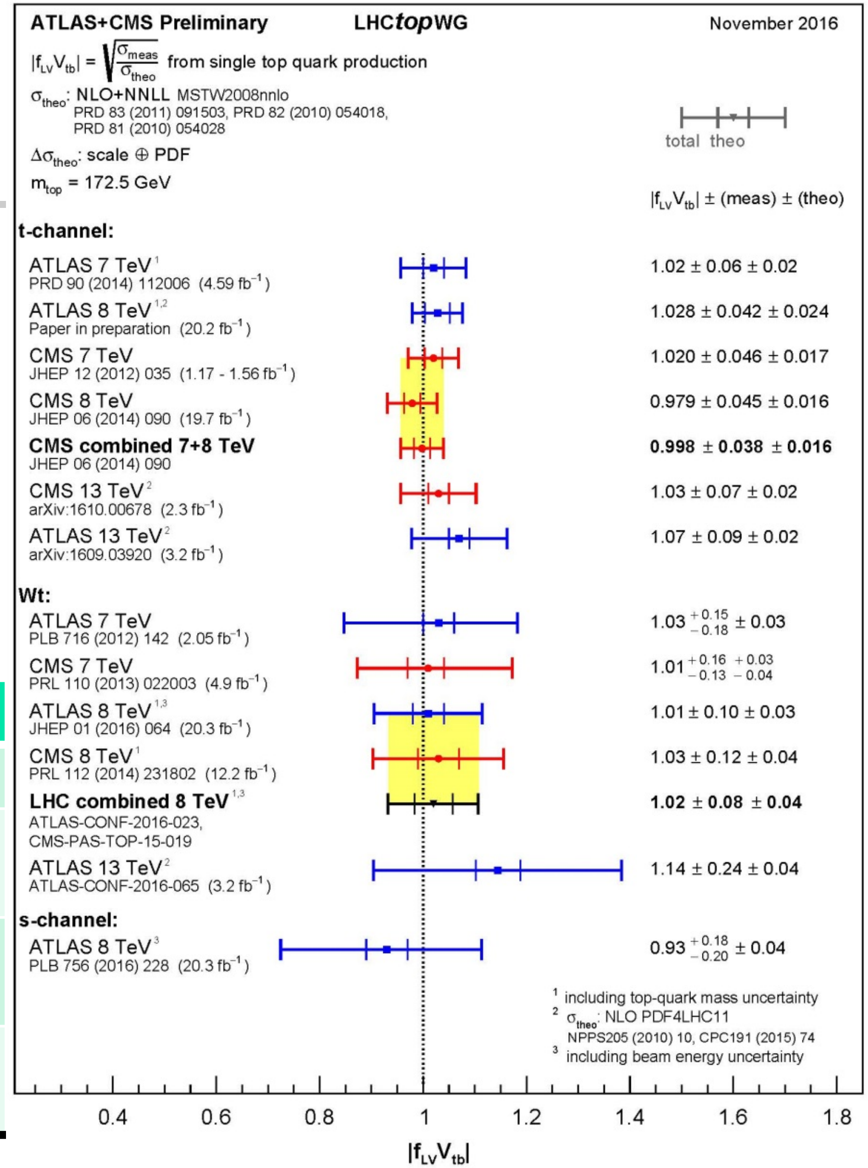


Wt-channel

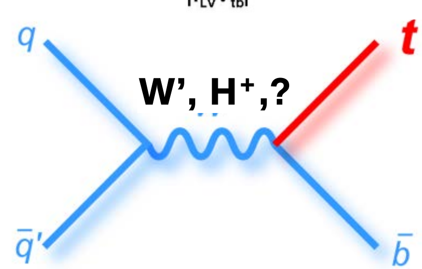


s-channel

	SM prediction [pb] arXiv:1311.0283			
√s [TeV]	t	Wt	s	Tot.
2	2.08 (62%)	0.25 (7%)	1.05 (31%)	~3
8	87.8 (76%)	22.2 (19%)	5.55 (5%)	~115
14	248 (72%)	83.6 (24%)	11.86 (4%)	~343

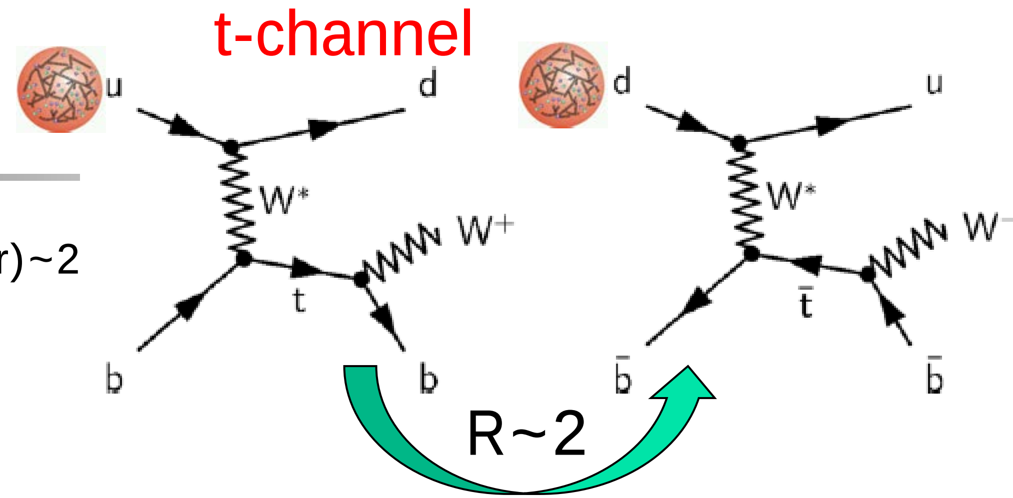


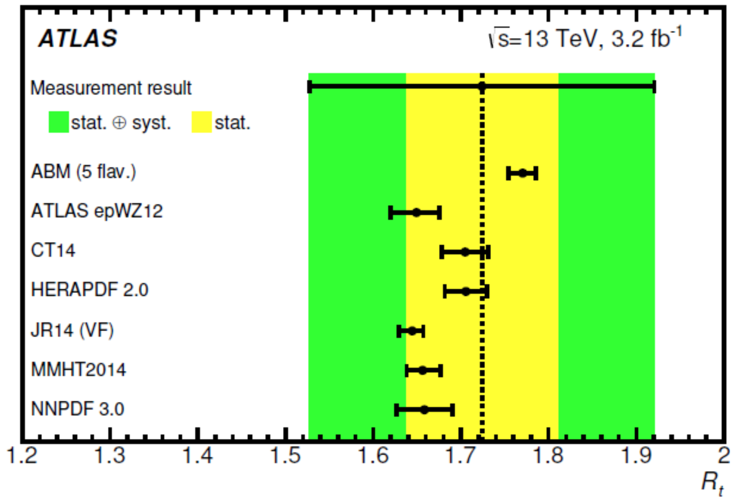
- Measure fundamental parameters of SM
  - $\sigma_{single\text{-}top} \sim |V_{tb}|^2 \to$ CKM and unitarity
    - ➧ V_{tb} measured at LHC, Tevatron: ~2-10%
- Bkg in Higgs and SUSY searches. Sensitive to new physics?

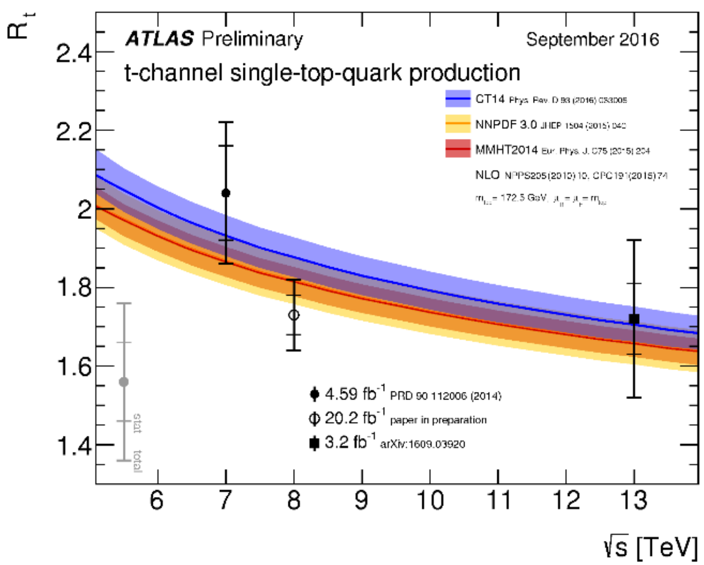


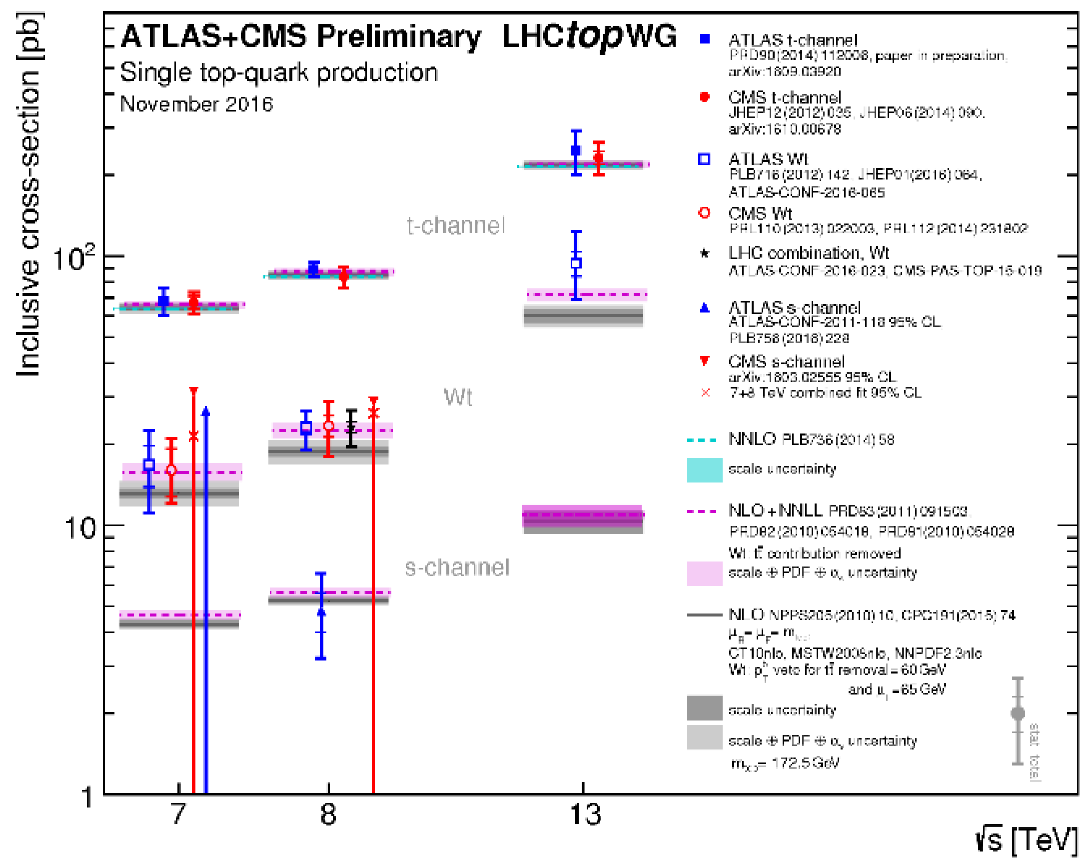
Single-top at 7,8,13TeV

- Sensitive: u,d PDFs, expect $R_t=\sigma(t)/\sigma(\bar{t})\sim 2$
  - Valence-quark arguments



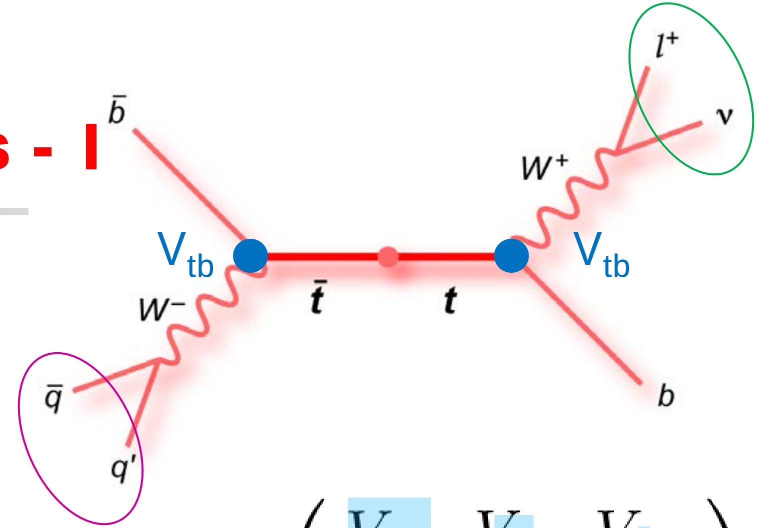






ONE MEASUREMENT IN SOME DETAIL...

Probing the Wtb vertex:
W polarisation in ttbar events - I



- Properties of Wtb vertex given by (V-A) structure of the weak interaction
- In the SM: $t \to bW$ ~100% of the time: $|V_{tb}| \sim 1$
- Real W from decay of top has 3 polarisation states
  - Left-handed: L, right-handed: R, longitudinal: O
- Predictions for helicity fractions:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

QCD order	F_L	F_R	F_0
LO	$\frac{2x^2}{1+2x^2}=0.3$	0	$\frac{1}{1+2x^2}=0.7$
NNLO*	0.311±0.005	0.0017±0.0001	0.687±0.005

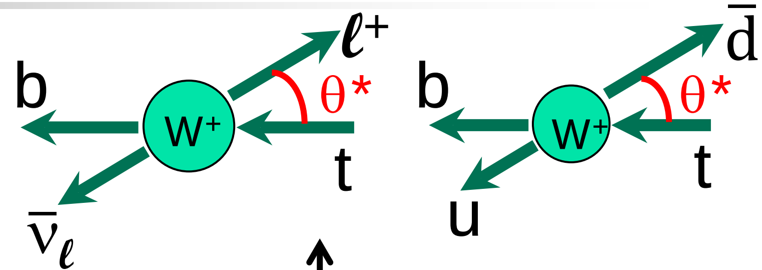
$$x = m_W / m_t$$

- LO: (V-A), massless b is L-H so W can only be L,O
- Two Wtb vertices in each ttbar event:
  - can be studied with leptonic or hadronic analysers

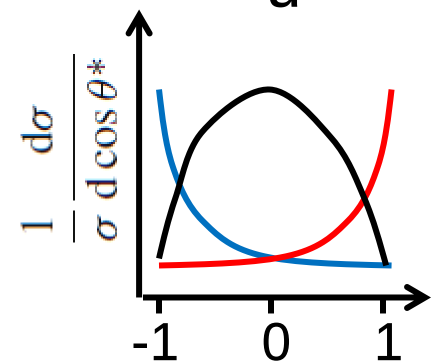
*arXiv:1005.2625

Probing the Wtb vertex:
W polarisation in ttbar events - II

- Differential cross section of analyser (ℓ or d-like):



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$



- New physics could modify the structure of the Wtb vertex
- Structure of Wtb vertex can be expressed in a more general form using left- and right-handed vector (V_L,V_R) and tensor couplings (g_L,g_R) giving the Lagrangian:

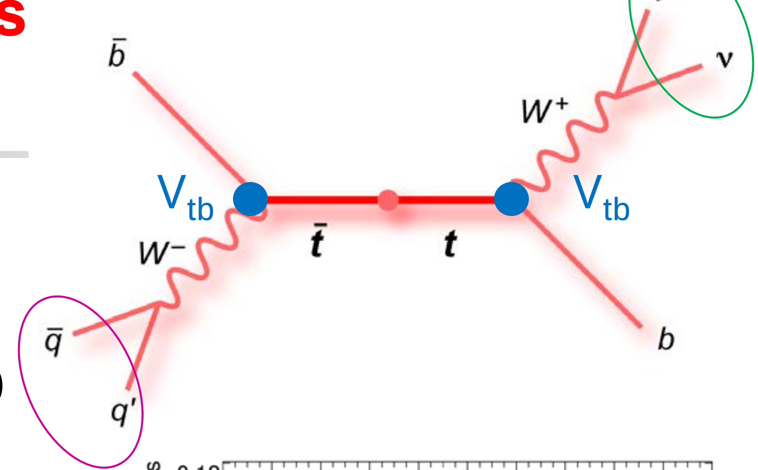
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\ ^{i}$$

- V_L (= V_{tb} ~1 in SM) and V_R,g_L,g_R anomalous couplings (=0 in SM)
- ➡ Dimension-six operators, introduced in effective field theories

can lead to non-zero values of V_R,g_L,g_R

W polarisation in ttbar events at $\sqrt{s}$=8TeV - I

EPJC77(2017)264



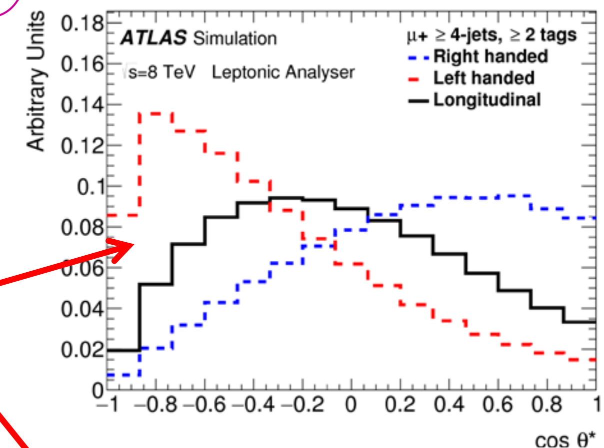
Desired final state: tt→(Wb)(Wb)→($\ell\nu$b)(qqb)

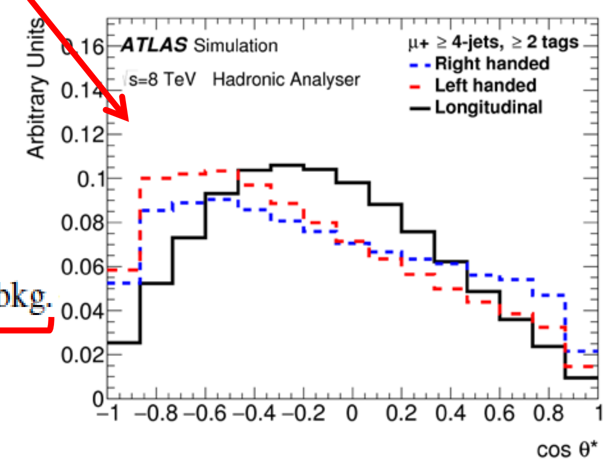
- 1 e or μ + ≥ 4 jets (≥1 b-tagged jet) + missing E_T
- Combinatorics methodology (kinematic likelihood fitter)
  - map 2b+qq to 4 jets
- Analysis has four categories of events:
  - e+1b, e+≥2b, μ+1b, μ+≥2b: ~35-45k evts in each
- Explore using both leptonic and hadronic analysers
  - i.e. θ^* from leptonic (e/μ) & hadronic decay (qq) of W
- Build templates of reconstructed θ^* for each F_i (MC for ttbar) and F_i-independent templates for various bkgs

$$F_i = \frac{N_i}{N_0 + N_L + N_R} \quad \text{for } i = 0, \text{L}, \text{R}. \qquad n_i = \epsilon_i^{\text{sel}} N_i$$

- Selection efficiency ε different for each polarisation state, determines the number of selected events n_i
- Likelihood of sum of templates to data: get n_{bkg} and N_i

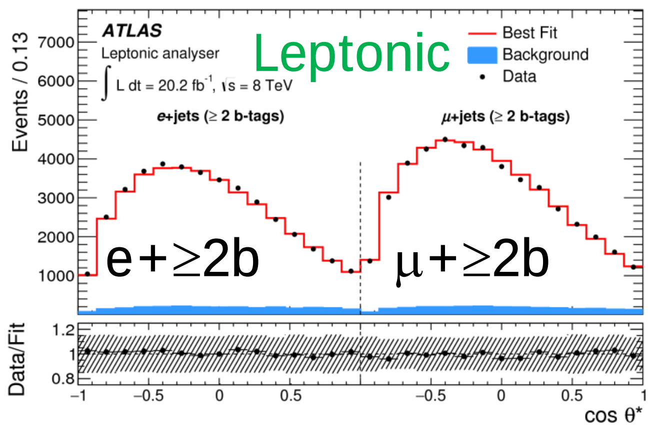
$$n_{\text{exp}} = \underbrace{n_0 + n_L + n_R}_{\text{Signal}} + \underbrace{n_{W+\text{light}} + n_{W+c} + n_{W+bb/cc} + n_{\text{fake}} + n_{\text{rem. bkg.}}}_{\text{backgrounds}}$$

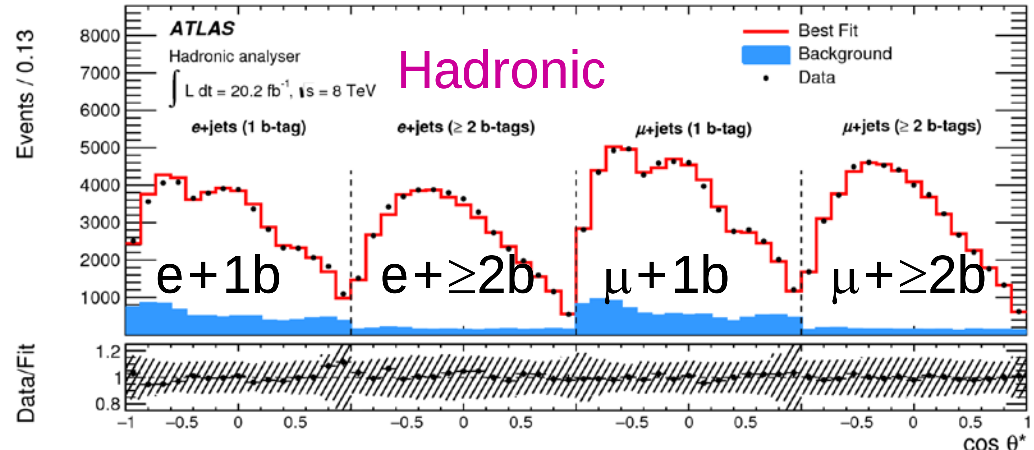




W polarisation in ttbar events at $\sqrt{s}$=8TeV - II

- Various combinations of simultaneous fits of 4 categories with two analysers: best results





Leptonic analyser (≥2 b-tags)

$F_0 = 0.709 \pm 0.012$ (stat.+bkg. norm.) $^{+0.015}_{-0.014}$ (syst.)

$F_L = 0.299 \pm 0.008$ (stat.+bkg. norm.) $^{+0.013}_{-0.012}$ (syst.)

$F_R = -0.008 \pm 0.006$ (stat.+bkg. norm.) ± 0.012 (syst.)

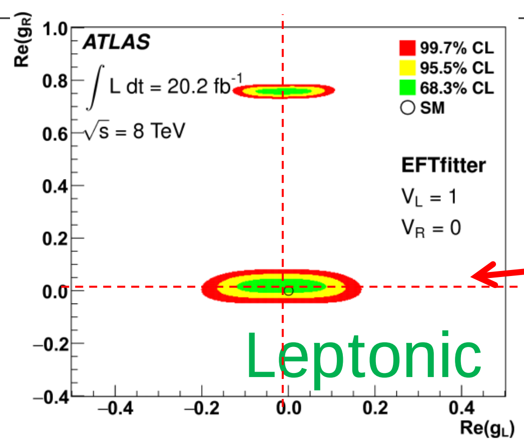
NNLO QCD
0.687±0.005
0.311±0.005
0.0017±0.0001

Hadronic analyser (1 b-tag + ≥2 b-tags)

$F_0 = 0.659 \pm 0.010$ (stat.+bkg. norm.) $^{+0.052}_{-0.054}$ (syst.)

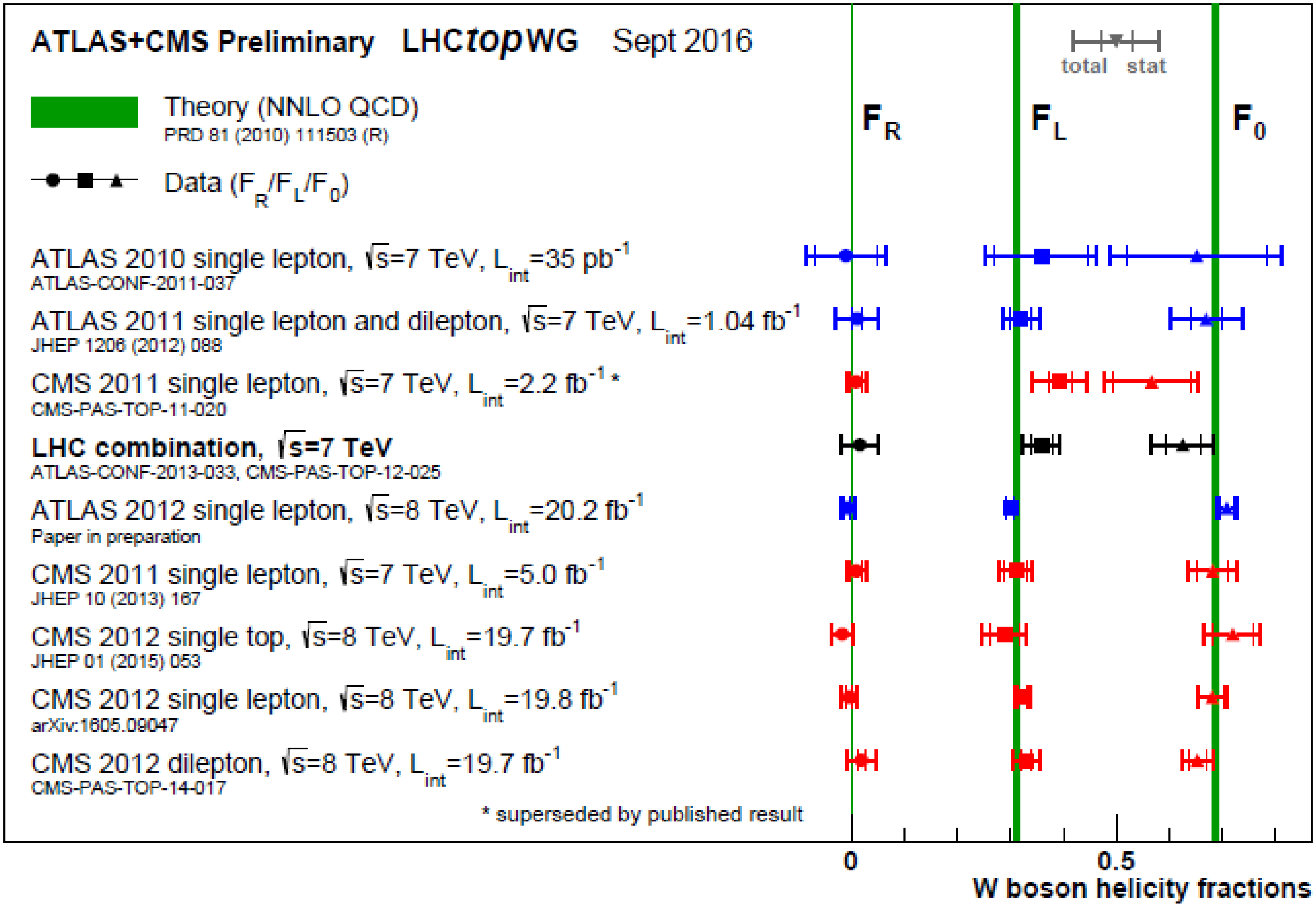
$F_L = 0.281 \pm 0.021$ (stat.+bkg. norm.) $^{+0.063}_{-0.067}$ (syst.)

$F_R = 0.061 \pm 0.022$ (stat.+bkg. norm.) $^{+0.101}_{-0.108}$ (syst.)



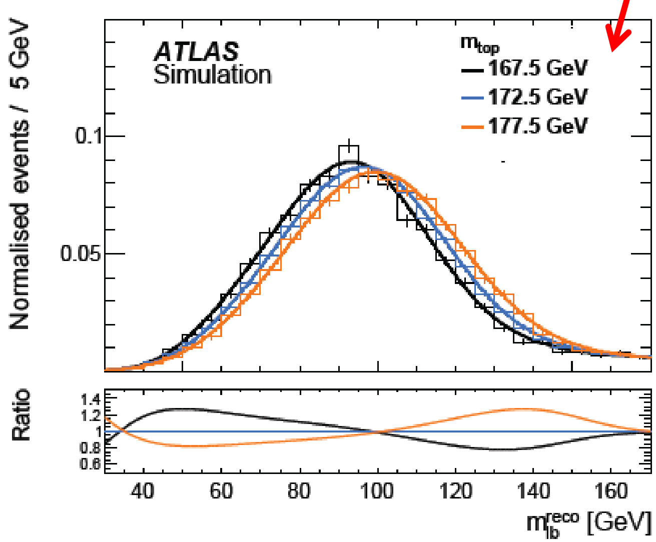
- No evidence for beyond-SM F_i
- 95% exclusion limits set on e.g. (g_L,g_R) assuming SM (V_L,V_R)

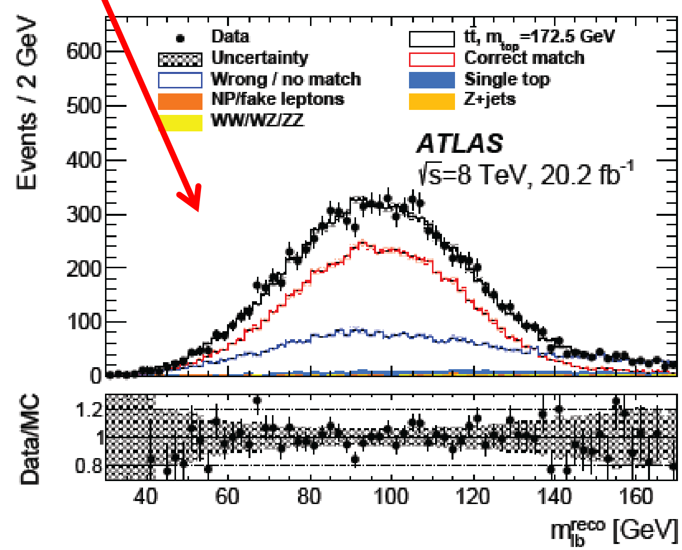
Summary of previous helicity-fraction measurements



Top mass: one example

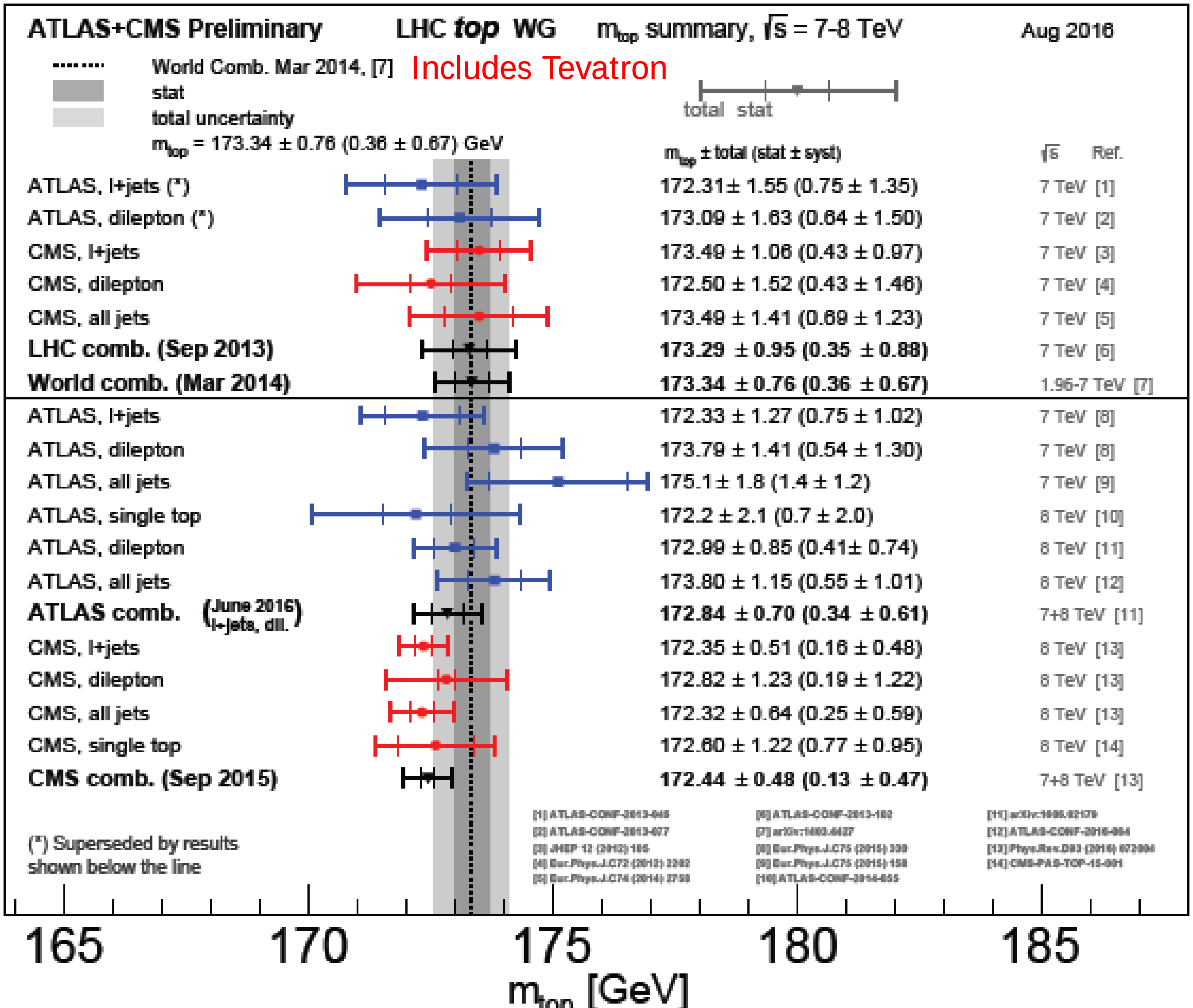
- m_t is a fundamental parameter: m_W, m_t, m_H together test the consistency of the SM
- Many techniques to extract m_t
  - Template method from dilepton events: $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell^+\ell^-\nu\bar{\nu}b\bar{b}$
- Exactly two opposite-sign leptons (ee, eμ, μμ) with at least two jets (one of them b-tagged)
- Templates: reconstructed $m_{\ell b}$ of MC signal events for different m_t values (interpolate between points) and for backgrounds
- Unbinned LH fit to data with only m_t as the free parameter





- m_t = 172.99±0.41(stat)±0.74(sys) [±0.84(tot)], dominated jet-energy-scale uncertainties
- Combined with 7TeV results (including correlations), which reduces uncertainty to 0.70GeV

Top-quark mass averages (Aug 2016)



Uncertainty ~0.5GeV

· BEVERAGES ·

pp collisions...

How to measure a cross section?

Single-boson production:

- Importance of various kinematic variables
- Orders and generators
- V+jets, γ+jets
- W,Z production vs η & impact on PDFs
- Z-production angular coefficients
- W mass

Multiboson production:

- diboson cross sections: WZ, ZZ
- aTGCs: WZ, WW, Zγ
- aQGCs: WWW, Z$\gamma\gamma$
- vector-boson scattering

· DESSERTS ·

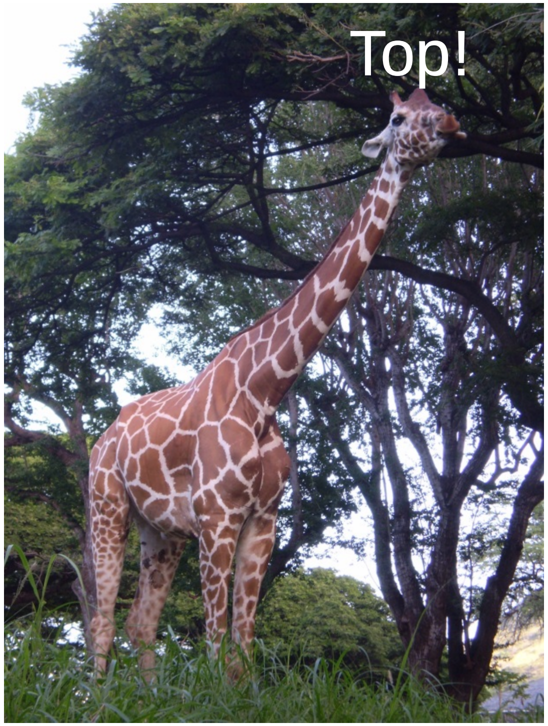
Top-quark production and decay:

- Comparisons at different $\sqrt{s}$
- dilepton ttbar
- single top
- W polarisation in ttbar (Wtb vertex)
- top mass from dilepton

· FRUIT ·

Lots of pedagogical back-up slides...

- How to measure lumi, definitions, pileup, MB, UE...

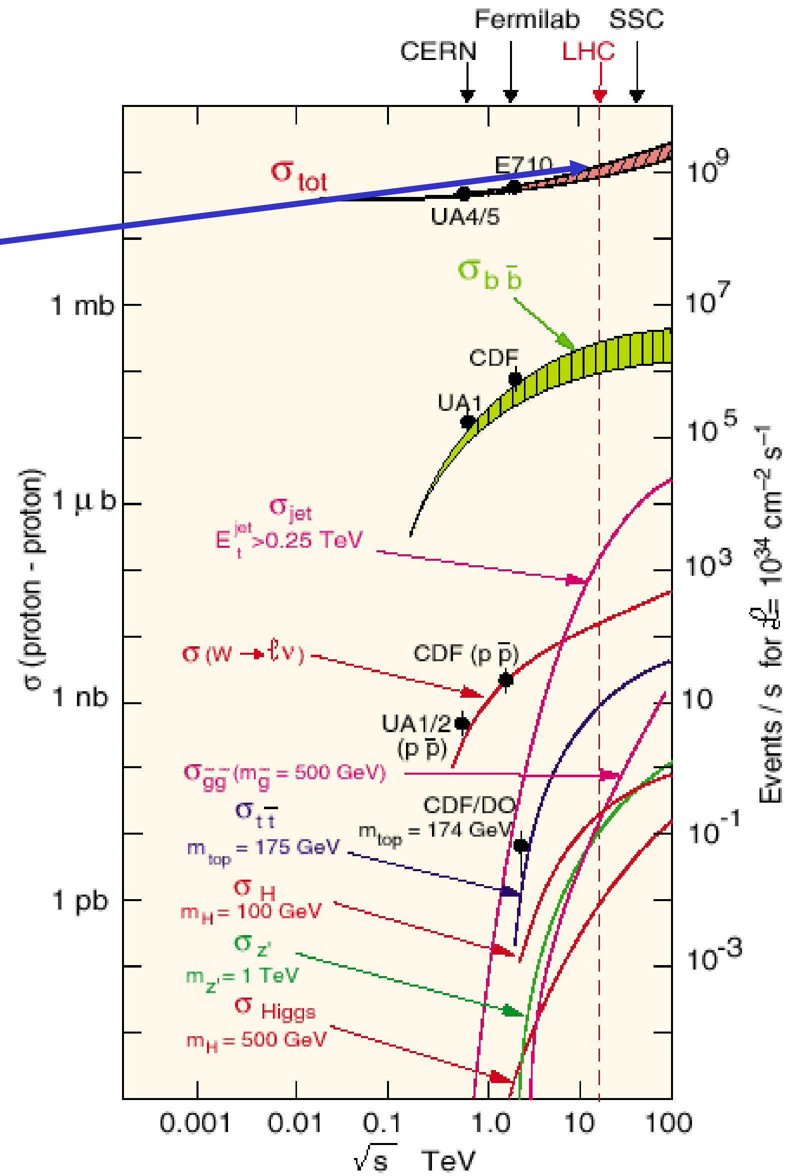


Back up...

Proton-proton collisions

Proton-proton cross section:

- $\sigma^{pp}_{tot}(s) = \sigma_{elastic}(s) + \sigma_{inelastic}(s)$
- At centre-of-mass energy $\sqrt{s}$ = 14TeV (LHC):
  - $\sigma^{pp}_{tot}(s) \approx$ 100mb
  - $\sigma_{elastic}(s) \approx$ 20mb
  - $\sigma_{inelastic}(s) \approx$ 80mb
  - Note: 1 millibarn (mb) = $10^{-31}m^2 = 10^{-27}cm^2$ (i.e. units of area)
- Orders of magnitude of event rates for various physics channels for $L=10^{34}$ $cm^{-2}s^{-1}$:
  - Inelastic: 10^9 Hz
  - $W \to l\nu$: 10^2 Hz
  - tt production : 10^1 Hz
  - Higgs 1 Hz



Inelastic collisions per bunch crossing

- Extract number of inelastic collisions per bunch crossing (BC)

μ σ Δ ε

- LHC: $<\mu>$ = ~70-80 mb x 10^{34} cm^{-2} s^{-1} x 25 ns / 0.8 = 20-25
  - On average, there are >20 simultaneous collisions per bunch crossing at high luminosity
- Big change compared to recent machines:
  - LEP: Δt = 22 ms and $<\mu> << 1$
  - SppS: Δt = 3.3 ms and $<\mu> \approx 3$
  - HERA: Δt = 96 ns and $<\mu> << 1$
  - Tevatron: Δt = 0.4 ms and $<\mu> \approx 2$

How do you measure the luminosity? – Part I

Inelastic interactions per BC

Bunch pairs colliding

LHC revolution frequency

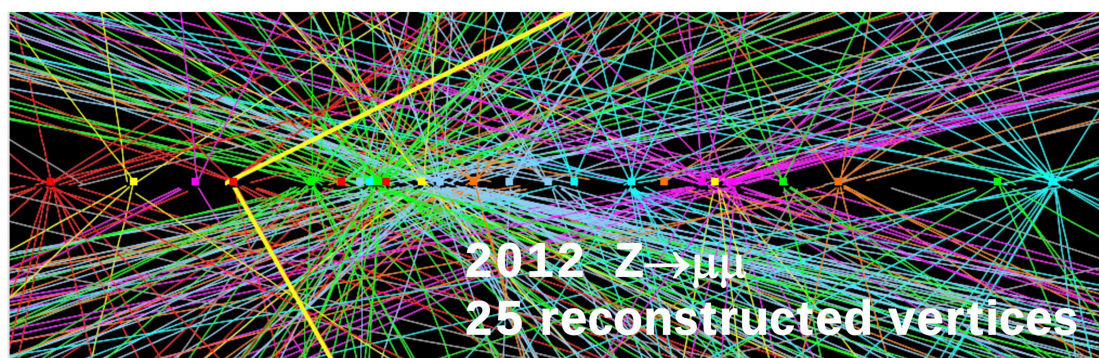
Measured quantity

- $L = \frac{\mu \, n_b \, f_r}{\sigma_{inel}} = \frac{\mu_{vis} \, n_b \, f_r}{\sigma_{vis}}$

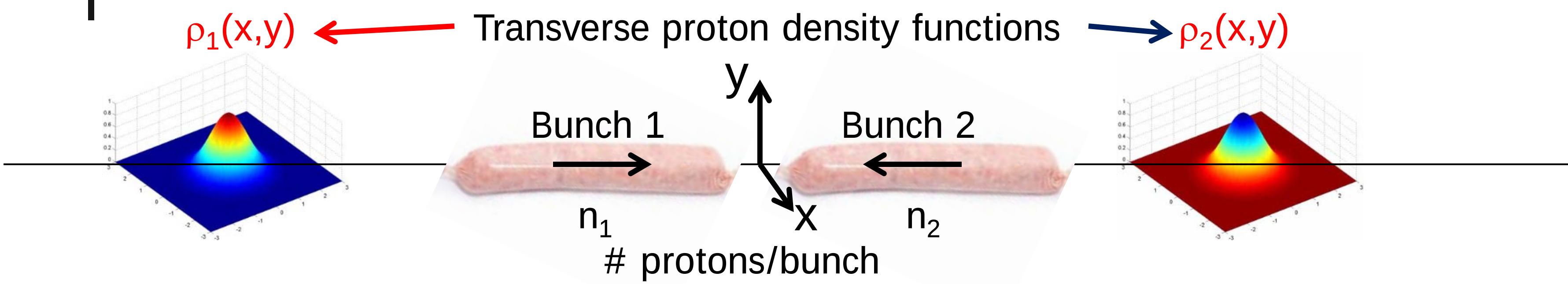
$= \varepsilon \times \sigma_{inel}$
Needs to be calibrated!
van der Meer scan

Luminosity detectors:

- Bunch-by-bunch luminosity
  - Dedicated lumi monitor (LUCID), beam conditions monitor (BCM), inner tracking detector to count the number of primary vertices
- Bunch blind:
  - Currents in the calorimeters
- Should all give consistent results!



How do you measure the luminosity? – Part II



- Beam-separation scan to get the absolute lumi calibration
- Peak luminosity is a convolution of the beam widths

$$\mathcal{L}_{peak} = f_r n_1 n_2 \iint \rho_1(x,y)\rho_2(x,y)\,dx\,dy$$

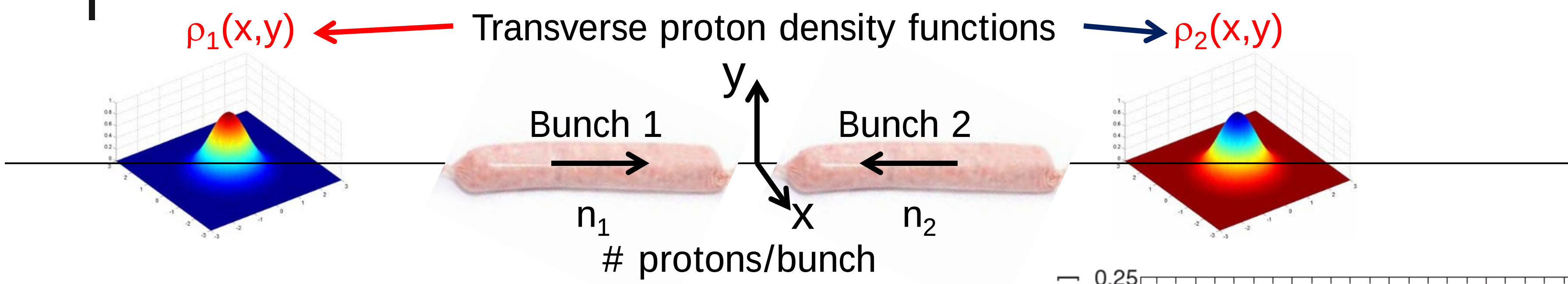
$$= f_r n_1 n_2 \frac{1}{2\pi \Sigma_x \Sigma_y}$$

Bunch population product ($n_1 n_2$)

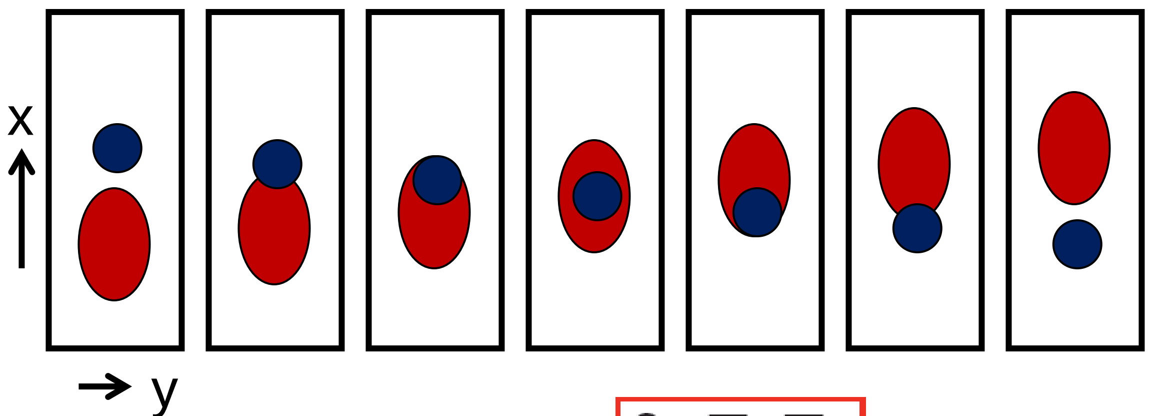
Convoluted beam widths ($\Sigma_x \Sigma_y$)

- Method assumed that you can factorise scan into x and y components
  - Not totally true

How do you measure the luminosity? – Part II



- Beam-separation scan to get the absolute lumi calibration
  - e.g. scan in x

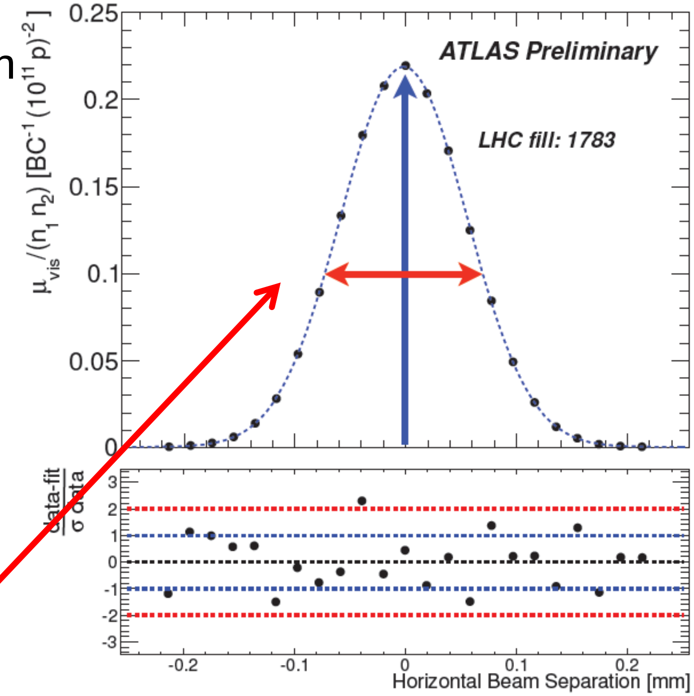


$$\sigma_{vis} = \mu_{vis}^{MAX} \frac{2\pi\Sigma_x\Sigma_y}{n_1 n_2}$$

Peak Rate

Scan Widths

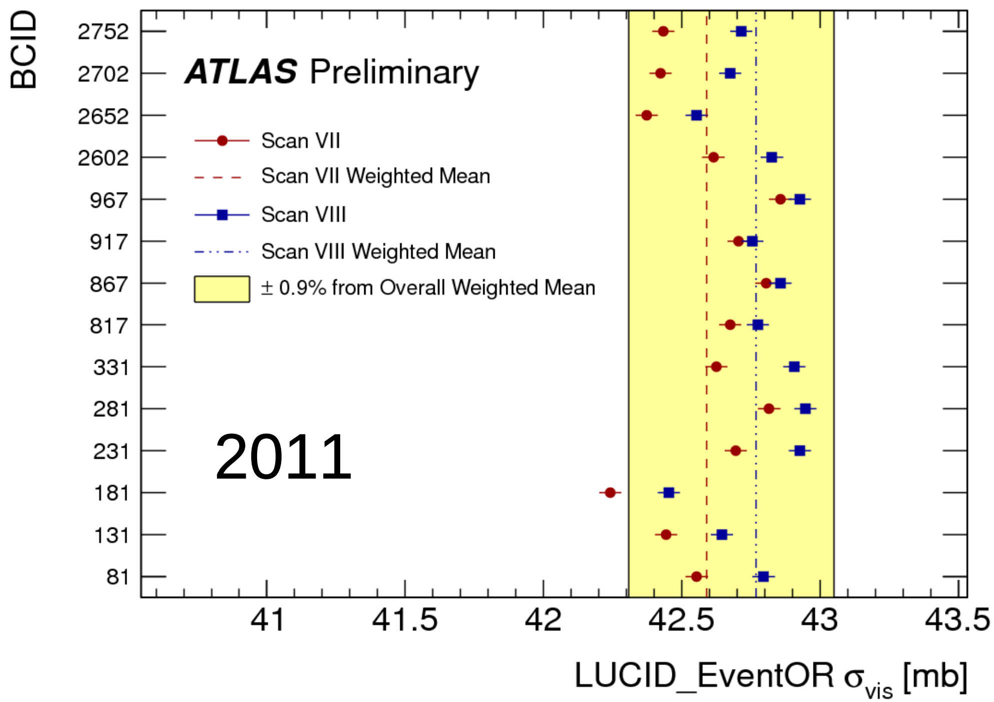
Bunch Population



x-scan width

How do you measure the luminosity? – Part II

- Example of σ_{vis} measured in 2011 using the LUCID detector
  - Two different scans (VII, VIII) as a function of which beam crossing (BCID) where you perform the scan



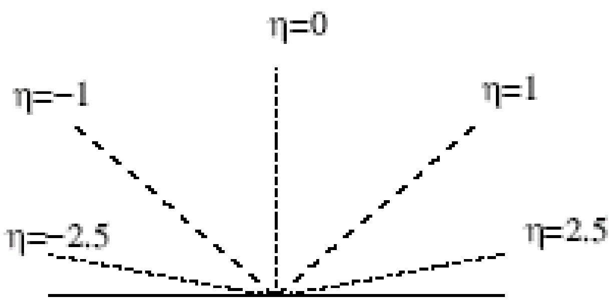
- Luminosity uncertainty: 2011 data: 1.8%, 2012: 1.9%, 2015: 2.1%

Jet kinematics: η

- Angular separations in θ are not invariant under longitudinal boosts: a given set of hadrons will appear more collimated depending on the boost. To treat equivalently partons with same p_T but different boost → use rapidity y

$$= - \ln \frac{+}{-}$$

- y is additive under Lorentz transformation, corresponding to a boost in the z direction: rapidity differences are boost invariant
- In practice, use pseudorapidity variable η, as this is what is measured in the detector. y and η coincide in the limit m→0



$$\eta \equiv - \ln (\tan \frac{\theta}{2})$$

$\eta = 0: \ \theta = 90 \qquad \eta = 1: \ \theta \sim 40$

$\eta = 2.5: \ \theta \sim 10 \qquad \eta = 5: \ \theta \sim 0.8$

$$\Delta = \sqrt{(\eta - \eta) + (\phi - \phi)}$$

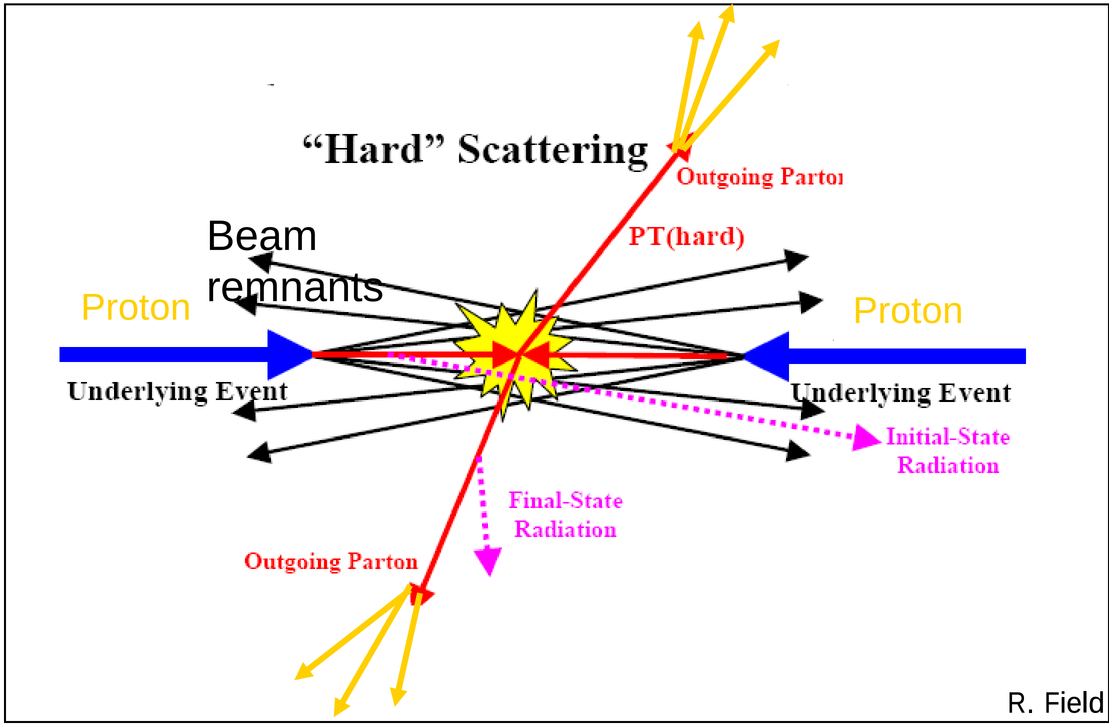
→

η

φ

The underlying event (UE)

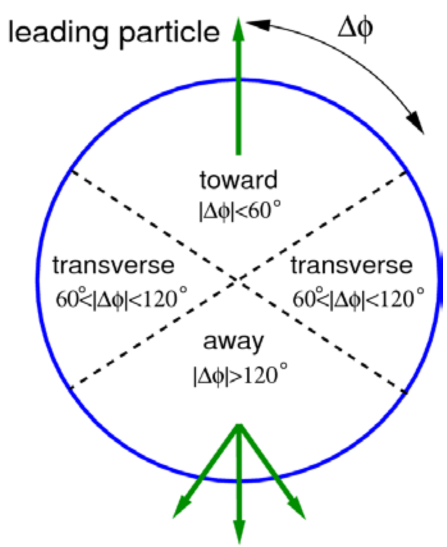
- Underlying event (UE): is the soft part associated with the hard scattering
  - Everything except the two outgoing hard scattered jets but has some correlations with the hard scatter
  - Contains hard components: e.g. initial/final state radiation, additional parton interactions (becomes significant at LHC)
  - Contains soft components: Beam-beam remnants



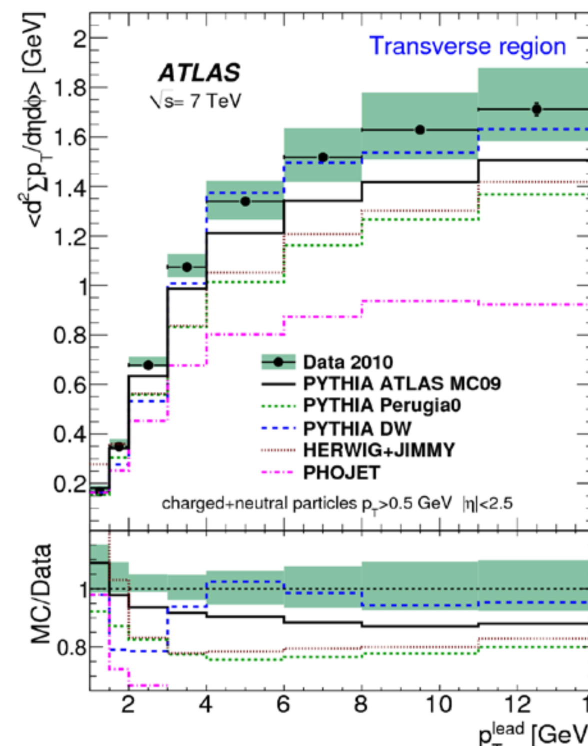
- UE: cannot be described by pQCD
  - Phenomenological models, tuned with LHC data

The underlying event (UE)

- Must understand the UE as it is an important “background” to jets and missing transverse energy E_T^{miss} (=negative of the vector sum of the calorimeter E_T)
  - generates E_T flow around the hard scatter (shifting up the signal)
  - generates fake jets not related to the hard scatter
  - distorts the E_T^{miss} resolution
- Can study UE by looking at region transverse to the hard scatter axis
  - Tune Monte Carlo event generators to data



Avg P_T^{sum} for stable particles per unit area in η-φ in transverse region as a function of p_T(lead)



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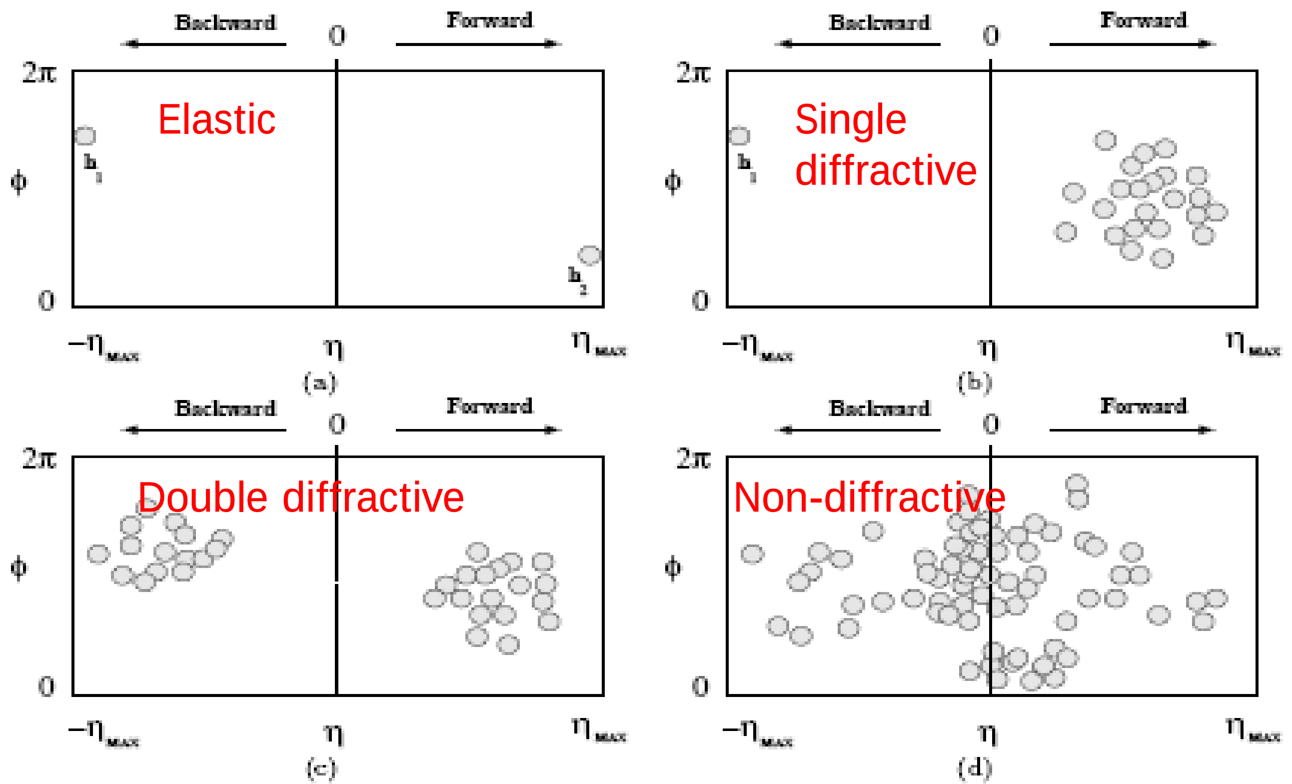
The inelastic term

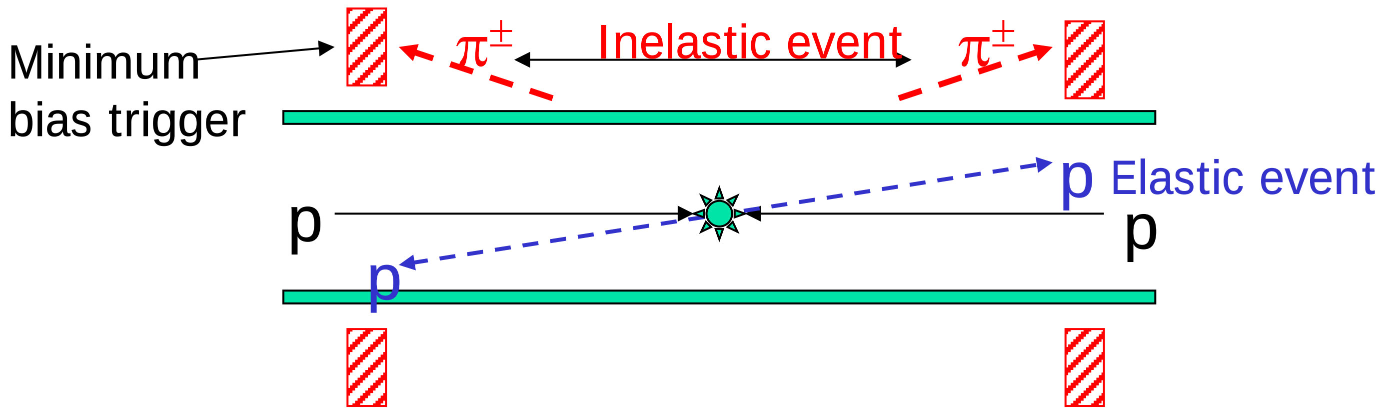
- Recall: $\sigma^{pp}_{tot} = \sigma_{elastic} + \sigma_{inelastic}$
- Can express inelastic term as:
  - $\sigma_{inelastic} = \sigma_{single\ diffractive,sd} + \sigma_{double\ diffractive,dd} + \sigma_{non\text{-}diffractive,nd}$

- Single (double) diffractive:
  - $pp \rightarrow pX \quad (XX)$
- Diffractive events: show clear gap
- Non-diffractive:
  - $pp \rightarrow X$
- Non-diffractive: gaps which naturally occur between 2 systems moving in opposite directions filled by particles moving in the central region



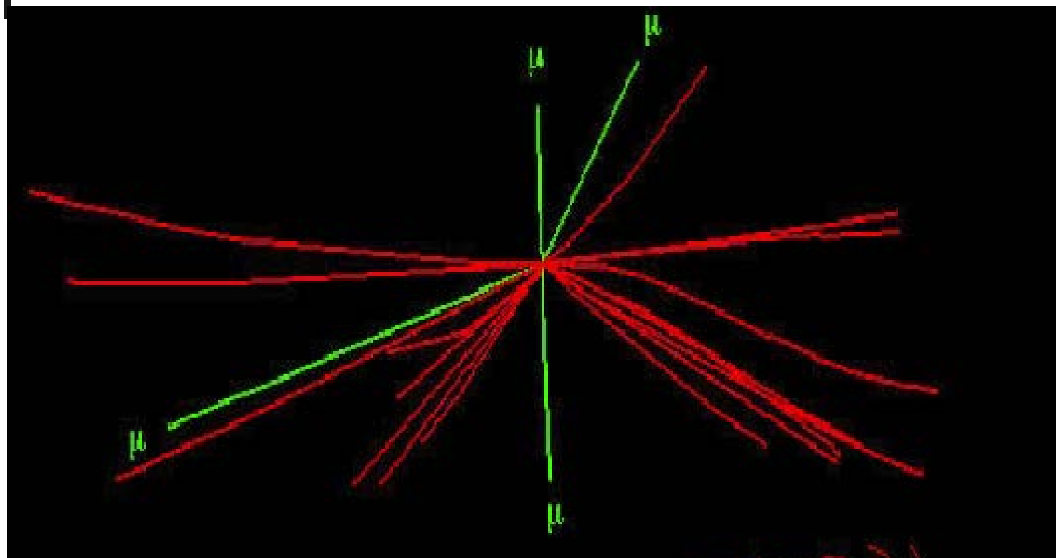
Minimum bias events (MB)

- What is a minimum bias event?
  - What a theorist might say: any non-diffractive inelastic event
  - What an experimentalist might say: anything that triggers my minimum bias trigger!

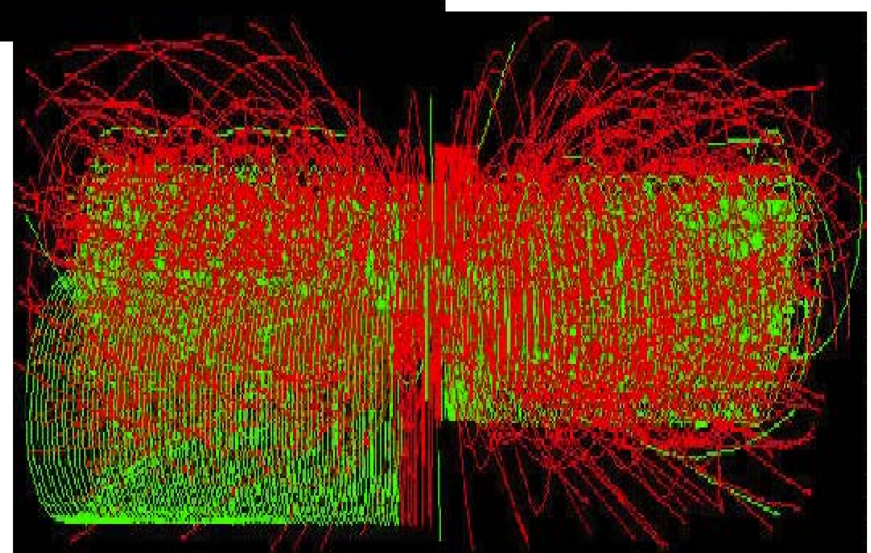


    - This effectively is any non-single diffractive (nsd) inelastic event
  - Minimum bias cross section not that different from total inelastic cross section: $\sigma_{inelastic}$~80-85mb, σ_{nsd}~65-70mb
  - Governed by the same non-perturbative QCD physics as the underlying event (but has no correlation to the hard scatter)
  - Depends on instantaneous luminosity
    - Number of MB per bunch crossing μ~25 at L=10^{34}, ~2.5 at L=10^{33}, ~0.025 at L=10^{31}

Impact of minimum bias events



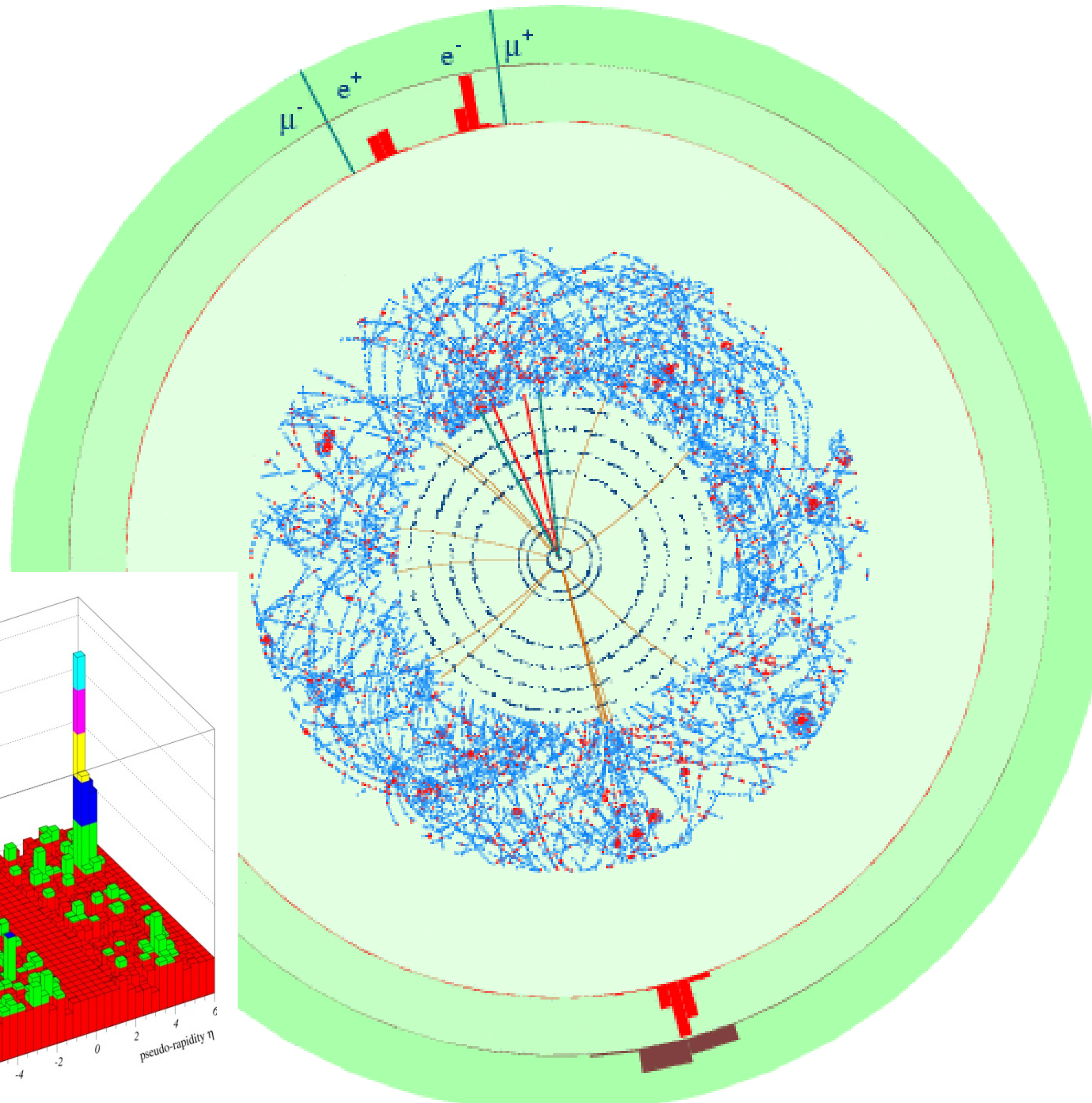
→ μ

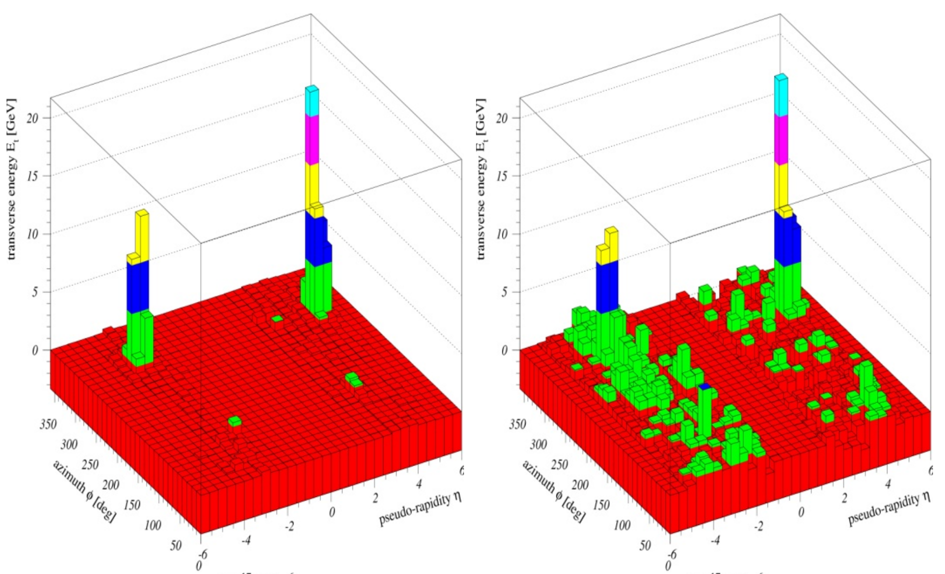


- Other examples of including MB
  - Impact of many MB events in physics collisions is called “pile up”

ATLAS Barrel

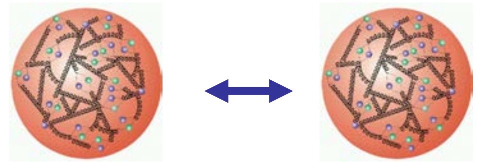
$H \rightarrow ZZ^* \rightarrow e^+e^-\mu^+\mu^-$ (m_H = 130 GeV)



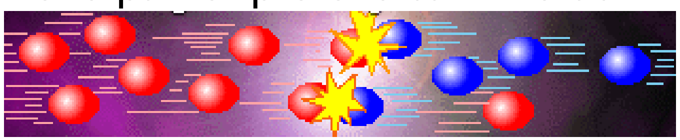


pile-up (in-time)

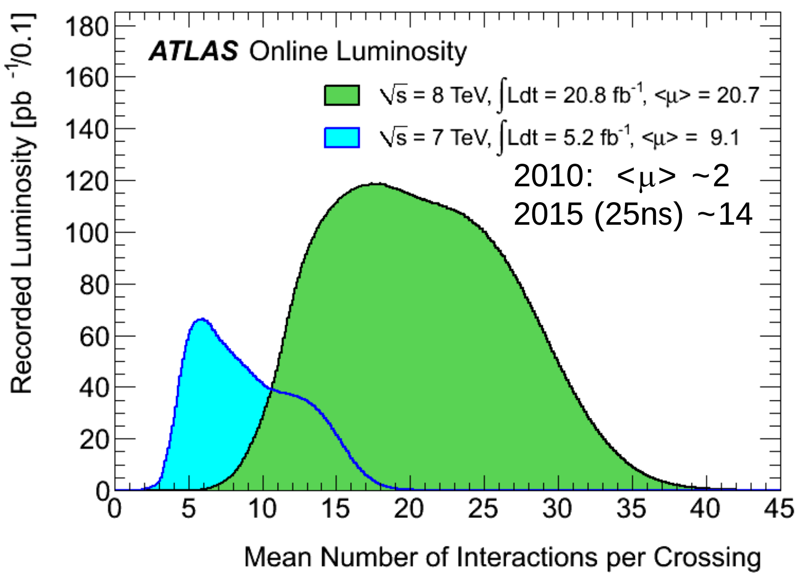
- Protons are not point-like objects!
- Protons are really small! 10^{-15} m

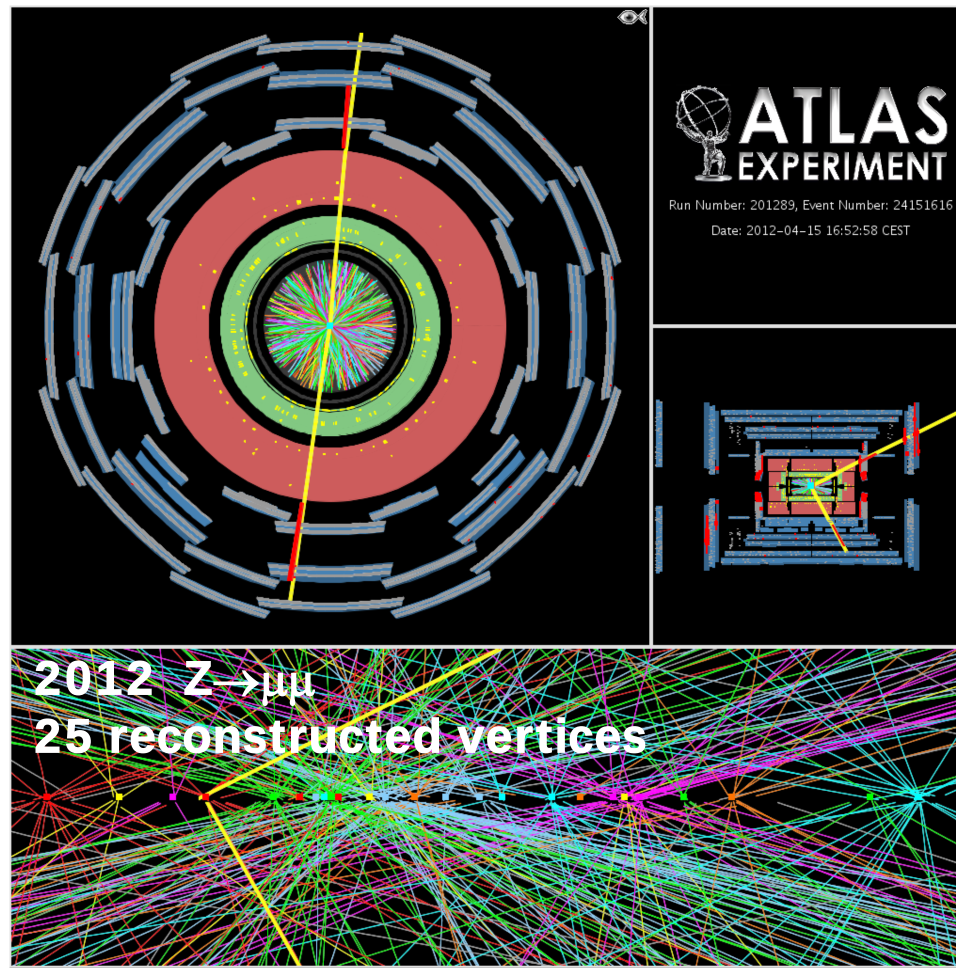


  - Collide many protons simultaneously in the hopes that one or more collide
- Every time the beams cross, more than just one pair of protons can interact!

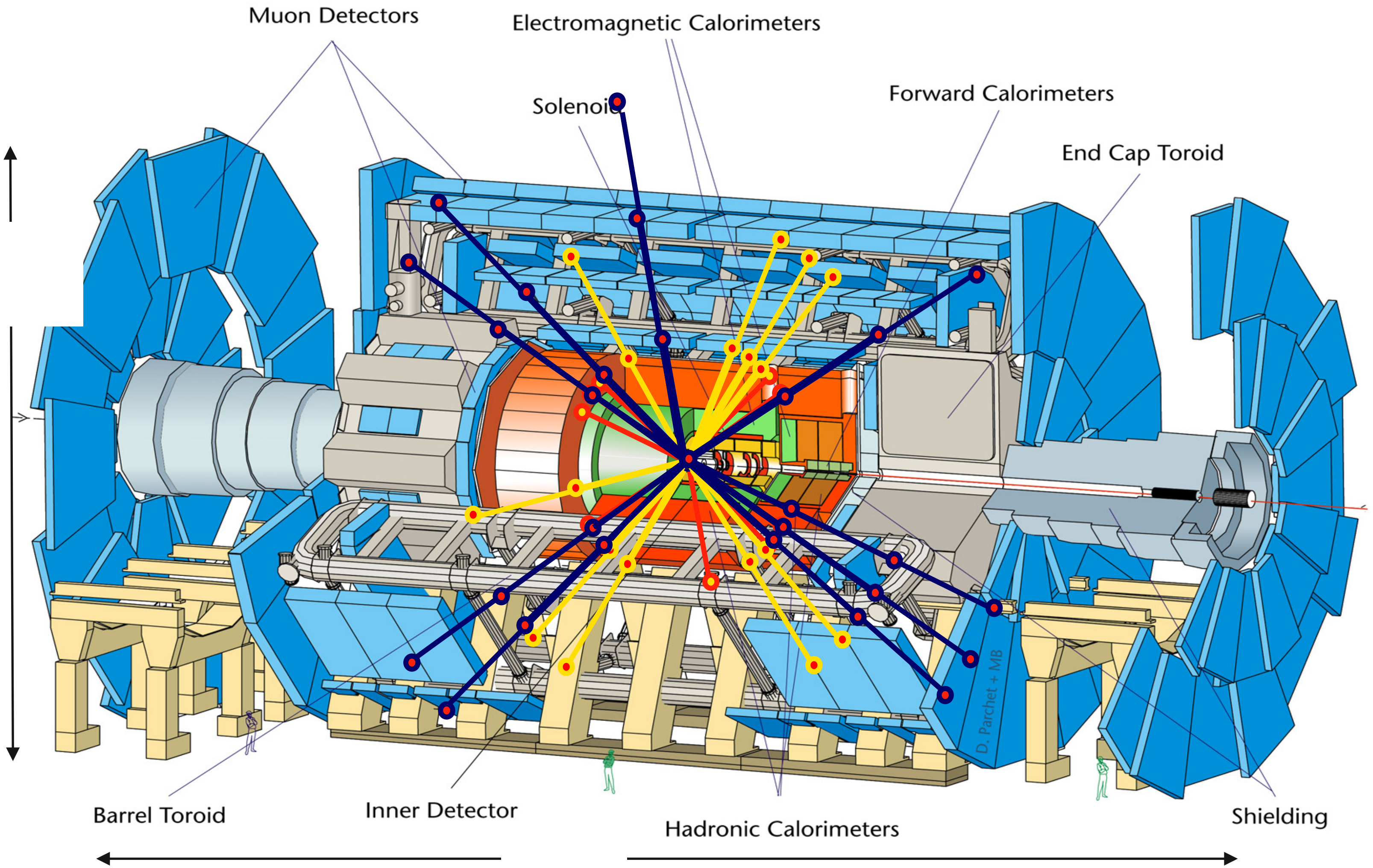


- Mean # of interactions per beam crossing





pile-up (out-of-time)



Time-of-flight

Collins-Soper frame (PRD16 (1977) 2219)

Definition of θ, φ measured in the experiment: CS frame

- z-axis: in Z rest frame, external bisector of angle between the two protons
  - +z: direction of positive longitudinally-polarised Z in lab frame
- y-axis: normal to plane spanned by the two incoming protons
- x-axis: right-handed cartesian system
- Polar θ_{CS} and azimuthal φ_{CS} angles: calculated with respect to negatively charged lepton