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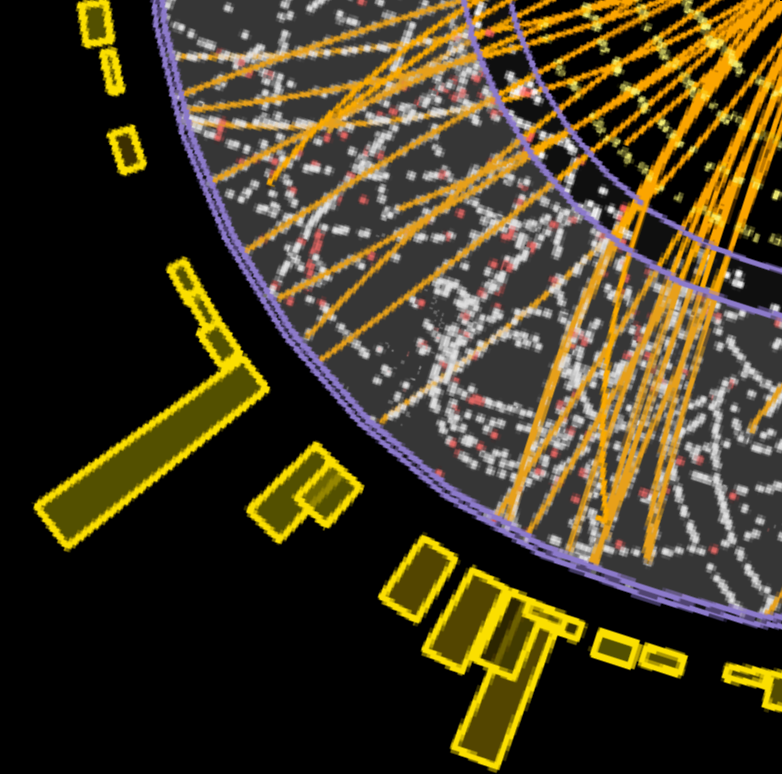

THE PRECISION FRONTIER AT THE LHC

status and perspective of SM precision physics

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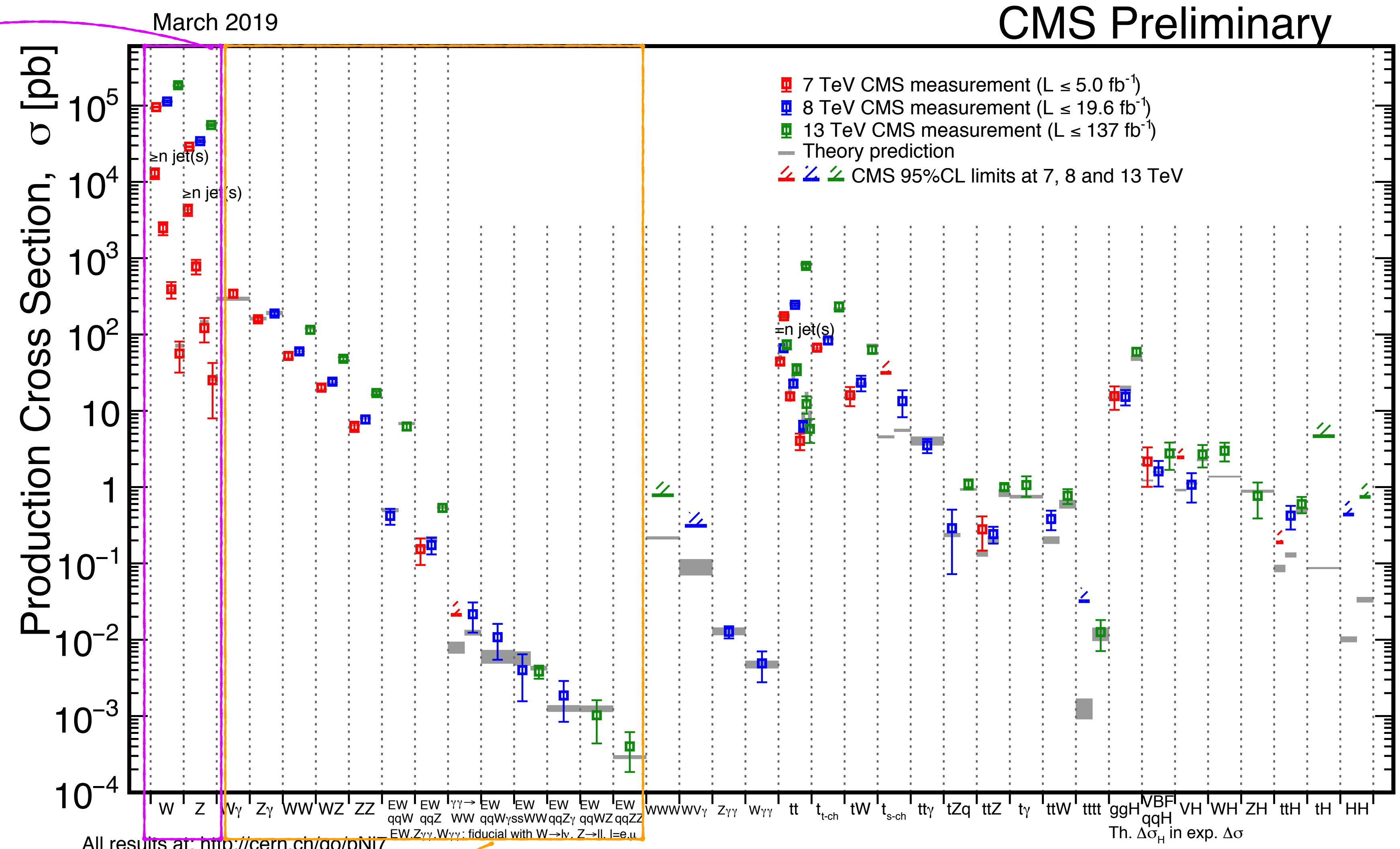
The Big Picture

- **ATLAS and CMS** precisely measure **SM processes involving gauge bosons**, top quarks and Higgs boson

Single Boson production
- High xsecs
- Measurements of SM *EWK parameters*

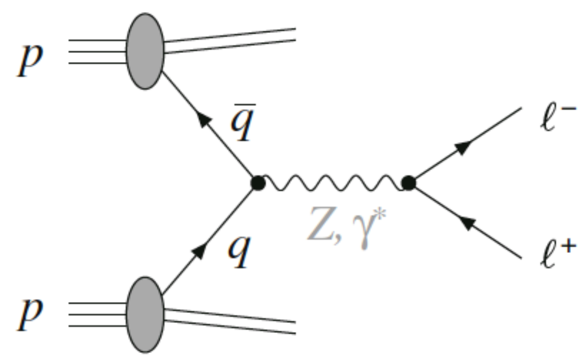
DiBoson/VBS/VBF
- *Era of precision measurements*
- First *Observation at 13 TeV*

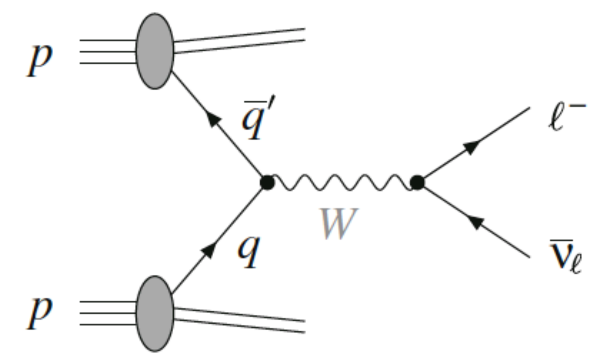


- Multiple **interdependent parameters** measured separately
- Very high cross-section processes used to **calibrate our objects/MC**
- Complementarity **Beyond-the-standard-model searches:** deviations from SM
- Many opportunities at **Run3 and HL LHC**

W/Z production via / DY processes

- Observables sensitive to both **QCD and EW sectors** of the Standard Model
- Theory cross sections computed up to **NNLO in QCD and NLO in EW**
- Total and differential cross-sections sensitive to the **proton structure(PDFs)**
- Purely **leptonic decays** are a very clean experimental signature





In the SM, 3 parameters (g, g', v) defines the EW sector connected to observables:

$$M_W = \frac{v|g|}{2}, \qquad M_Z = \frac{v\sqrt{g^2 + g'^2}}{2}, \qquad cos\theta_W = \frac{m_W}{m_Z}$$

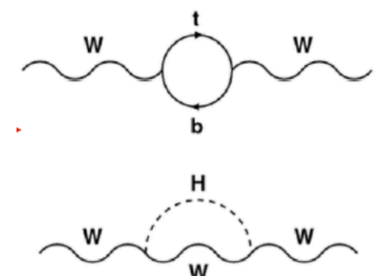
- **Mass of the W (Z**) measured at LHC and Tevatron (LEP) with millions of events

- Weak **mixing angle θ_W** from precision Z measurements

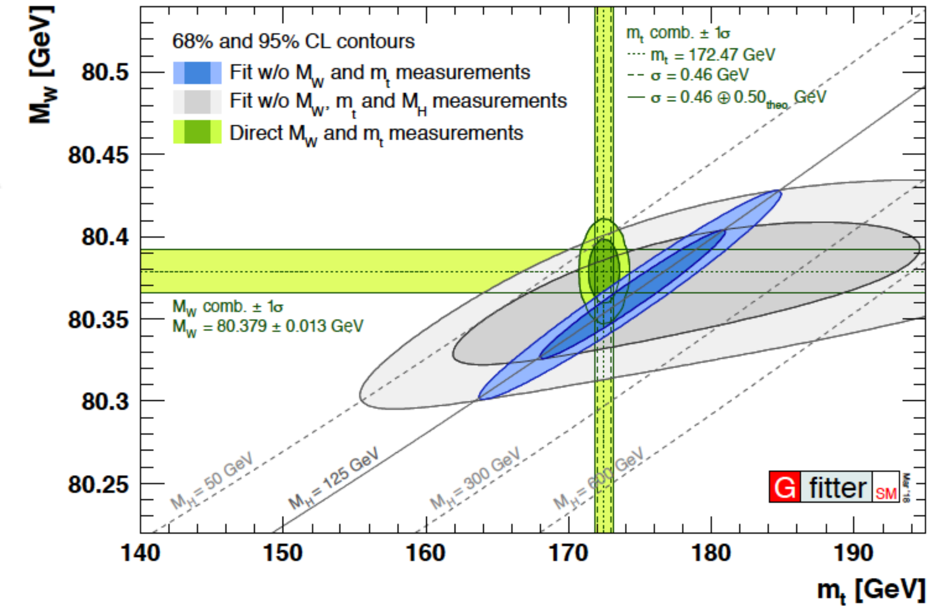
w/ contributions from E.Di Marco, N.Andari

- The relation M_W, m_t, and M_H provides stringent test of the SM and is sensitive to NP

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



$$\Delta m_W^{theory} = 8\ \text{MeV} < \Delta m_W^{exp} = 15\ \text{MeV}$$

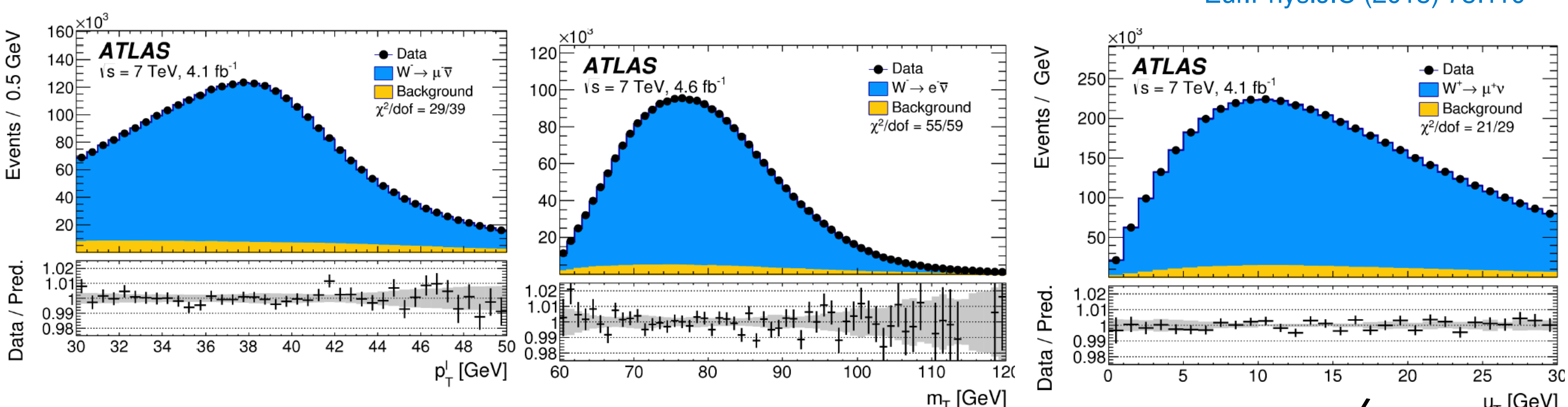


- Current **ATLAS measurement** *(4.7 fb^{-1} data @ 7 TeV)* of m_W performed using **1D p_{lT}, p_{Tmiss} and m_T distributions**

$$\vec{p}_T^{\,\text{miss}} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right), \quad m_T = \sqrt{2p_T^\ell p_T^{\text{miss}}(1-\cos\Delta\phi)}$$

- u_T being the recoil provides an estimate of the W boson p_T

Eur.Phys.J.C (2018) 78:110



M_W measurement at LHC II

$$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp.}) \pm 8.3(\text{QCD}) \pm 5.5(\text{EWK}) \pm 9.2(\text{PDF})\ \text{MeV}$$

- **PDFs** determine the W rapidity spectrum and lepton decay angles through W polarization
- **PDFs** large role at the LHC w.r.t Tevatron: pp need sea quarks (25% vs 5% second generation quark)

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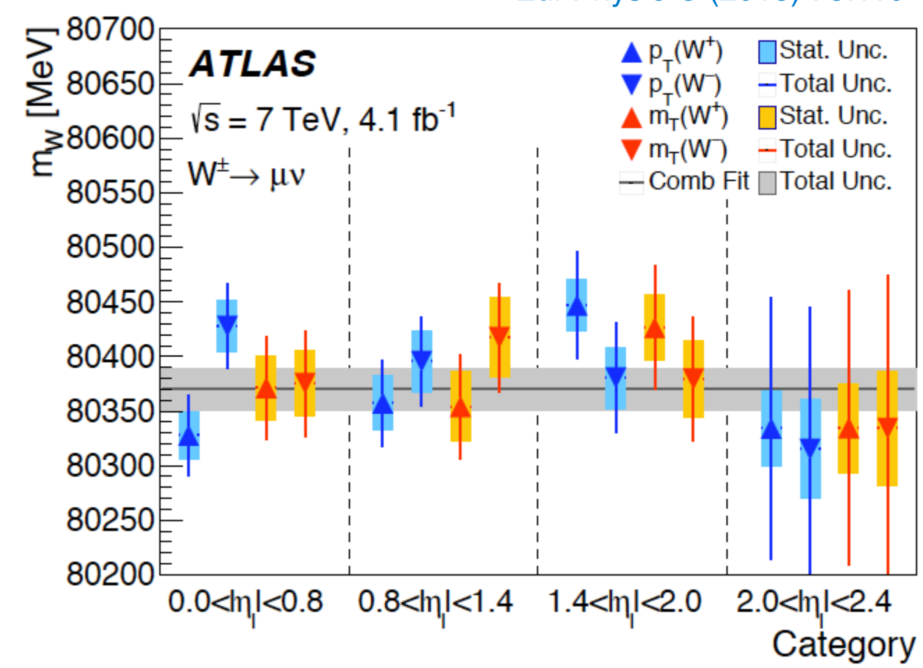

- W p_T in relevant region driven by large logarithms in **QCD calculation**
- Current measurement **using Z p_T to constrain W**,

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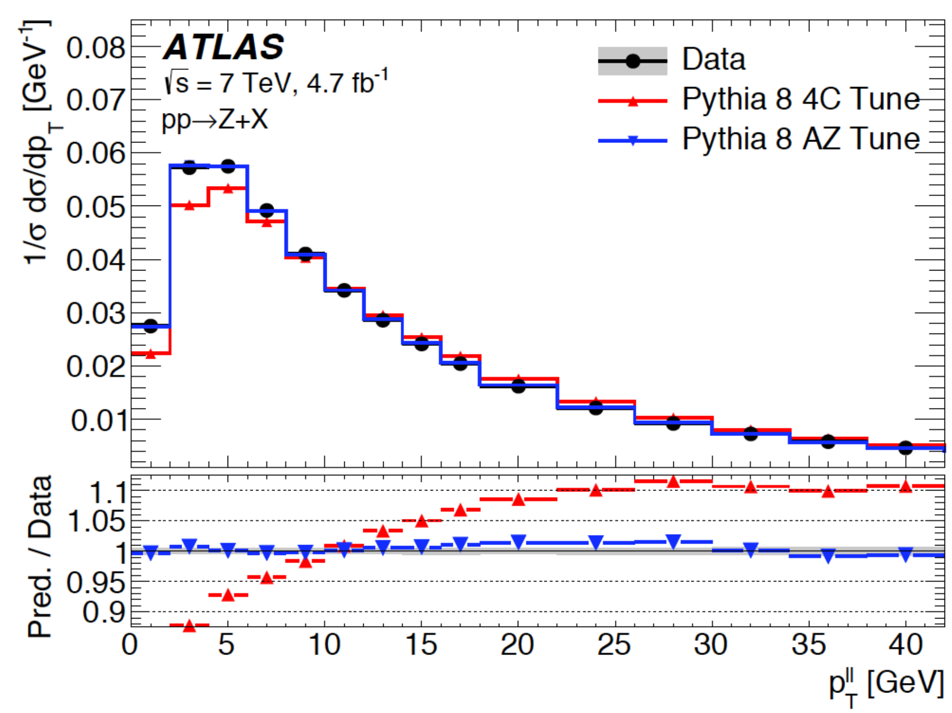
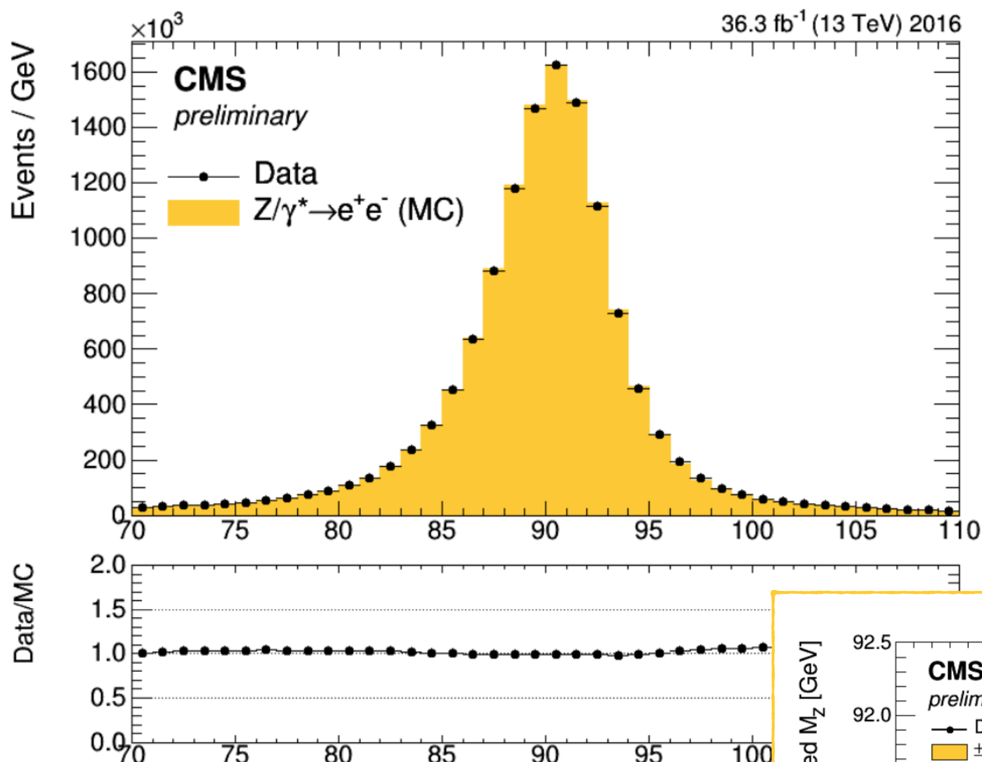


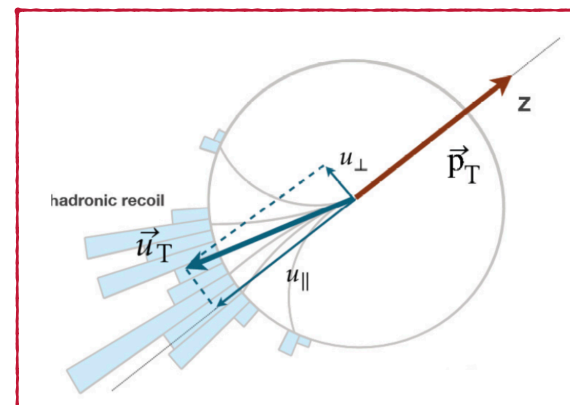
- *Better direct measurement w/ low pileup runs*
- *Better understanding of heavy-favour PDFs*

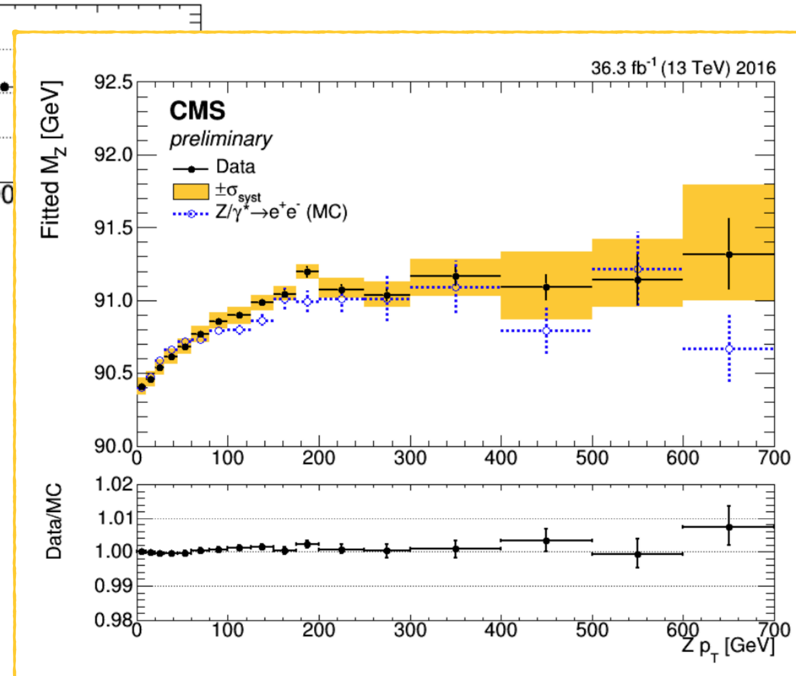
Z boson: the Standard Candle

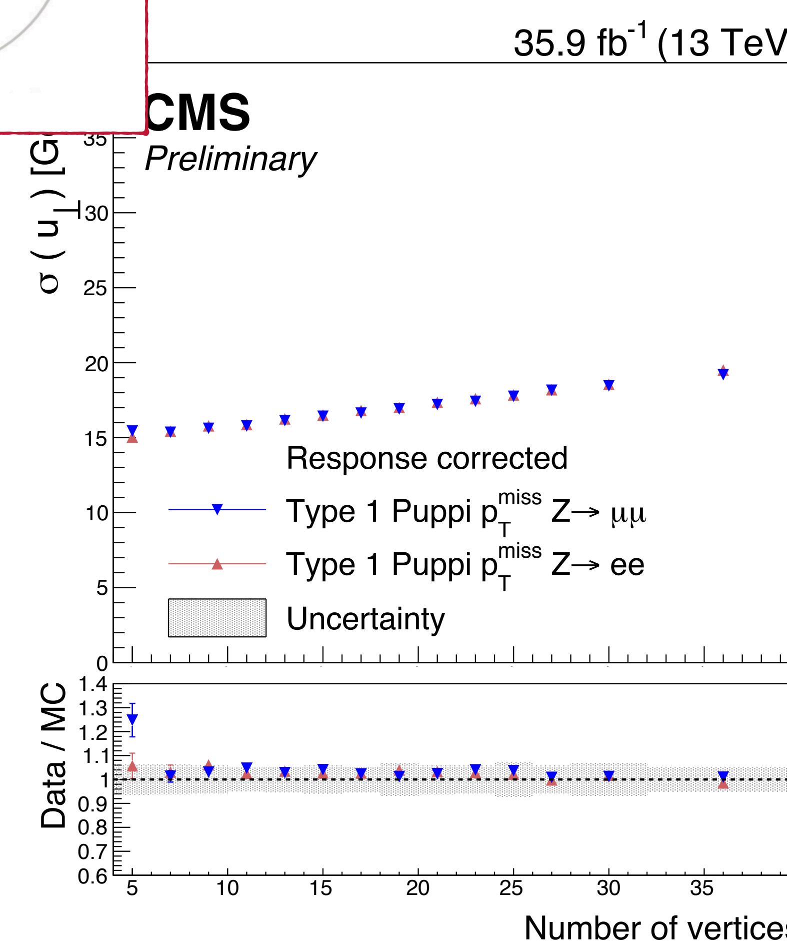
- **Energy calibrations** , **lepton-selection** efficiencies and **missing energy calibration** of detector response impacts both precision measurement and searches

- **Z(ll)+jets** event sample allows several validation and consistency tests of **detector performances**









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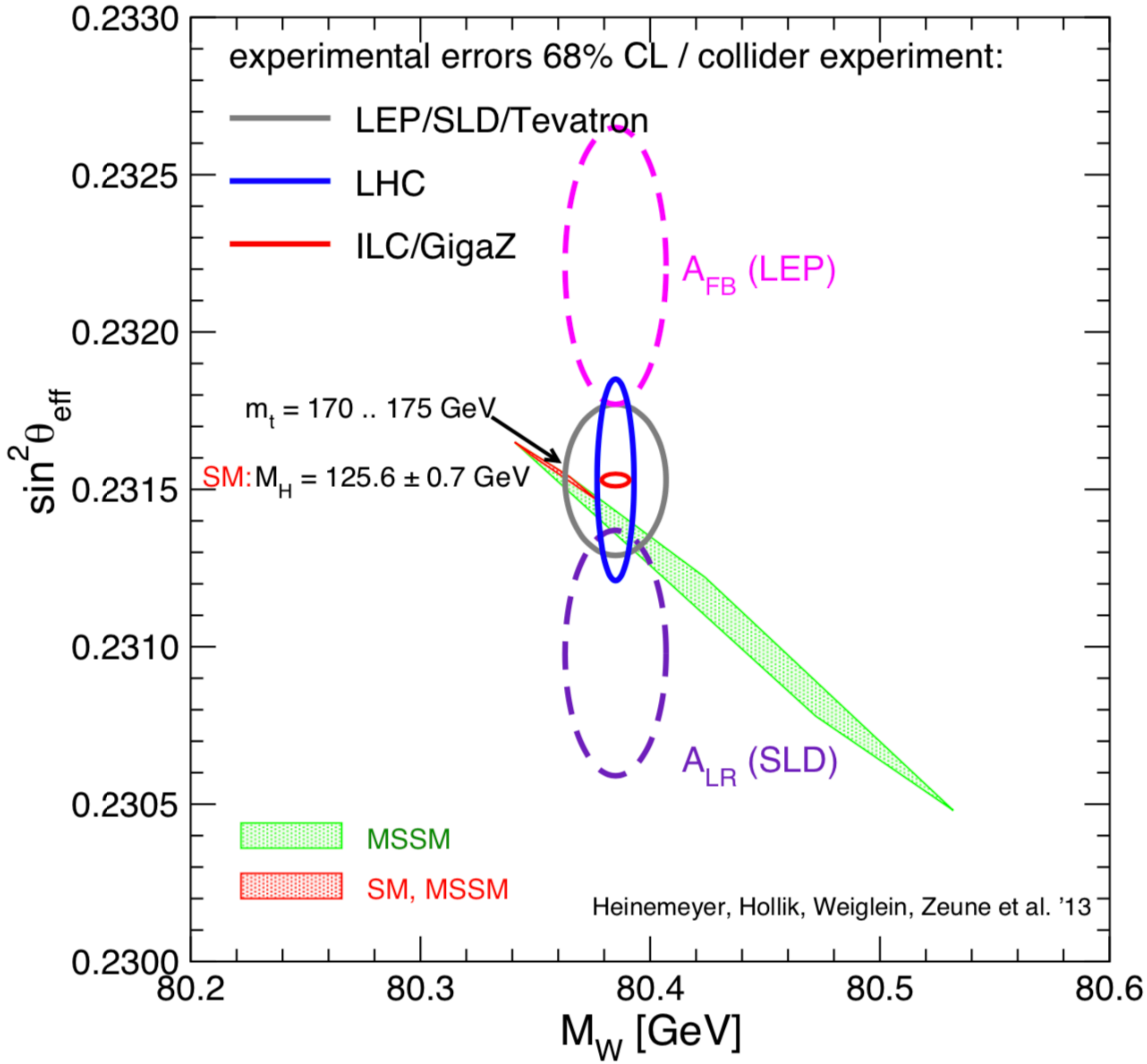
THE CASE OF $\sin^2\theta_{eff}$



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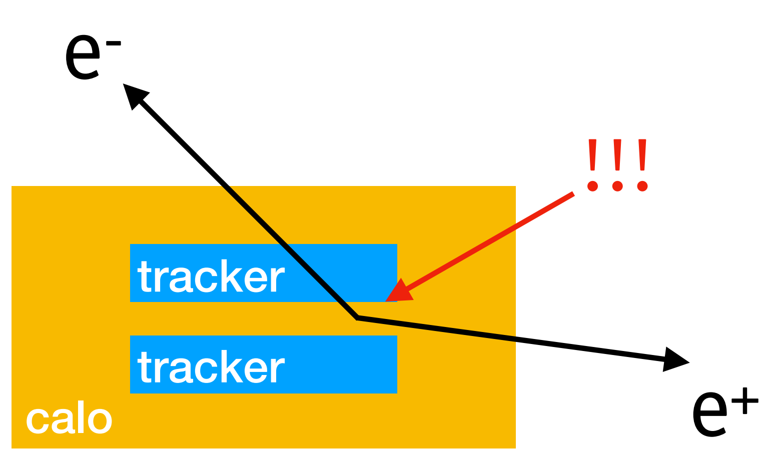
ATLAS, CMS OR LHCb?

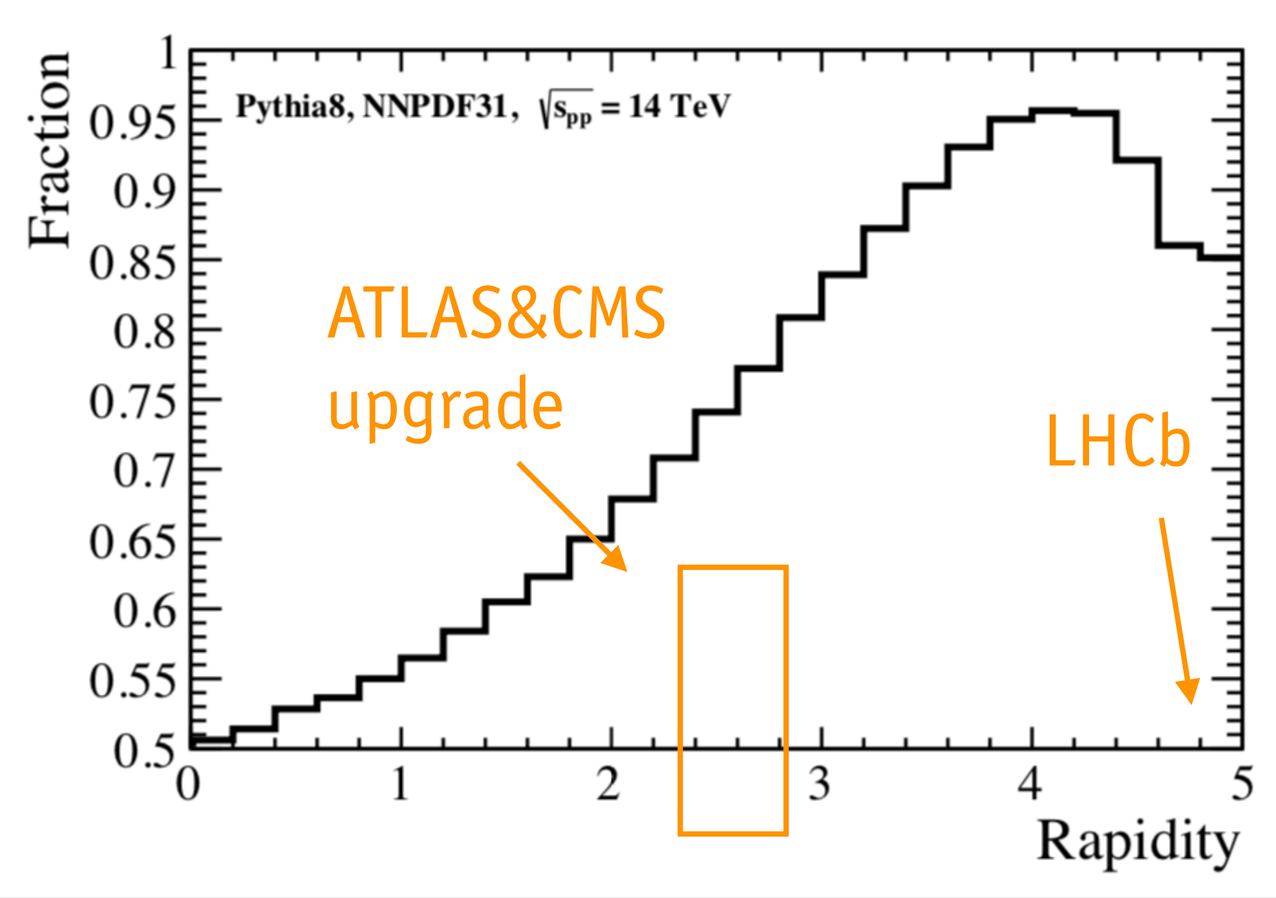
$$q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$$

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

what's the qbar direction?

- easy at LEP
- LHC: only if Z is boosted
  - → forward region
  - → challenge for lepton ID!





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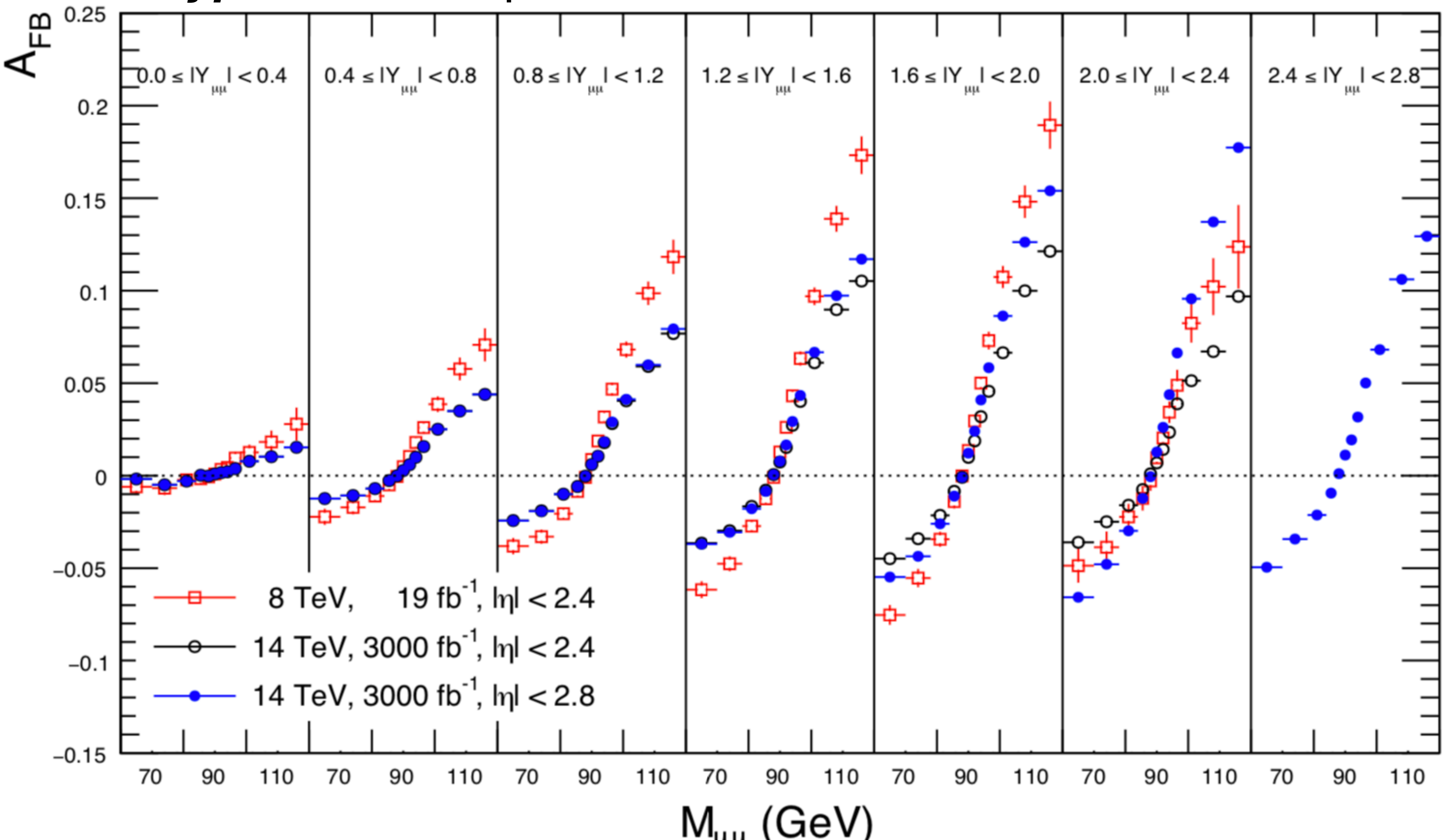
THE ASYMMETRY

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

- m_{ll} tails vs Z pole are complementary
- can simultaneously constrain PDFs and measure A_{FB}

A ***typical*** LHC experiment



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Future Prospects in Precision Physics at HL LHC

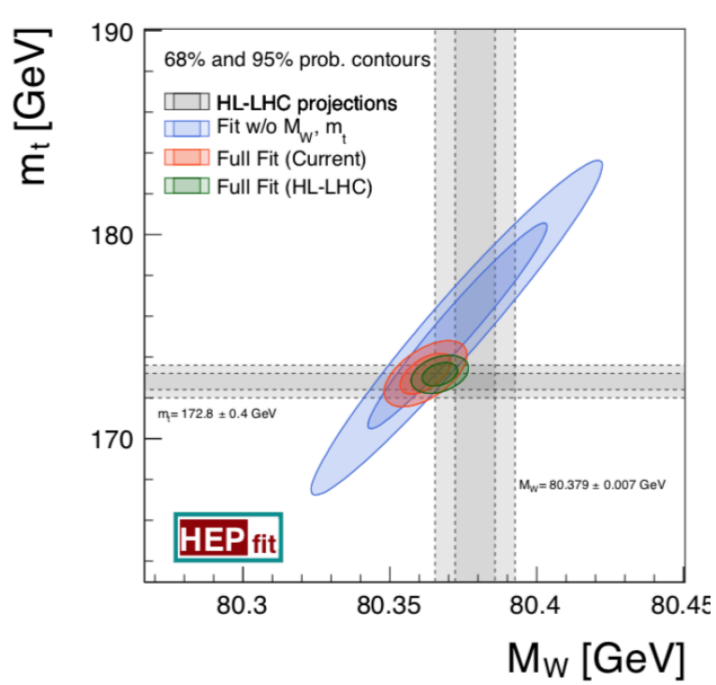
HL-LHC: @14 TeV w/ Inst. Lumi 7.2×10^{34} $cm^{-2}s^{-1}$, <mu> ~200

New detectors and methods ⟺ **Improved statistics and systematics**

- ML techniques, New **Triggers, Timing Detectors**
- Extended **acceptance** and forward topologies
- Experimental unc. at the level of statistical uncertainties
- Reduced **theory and PDF** uncertainties

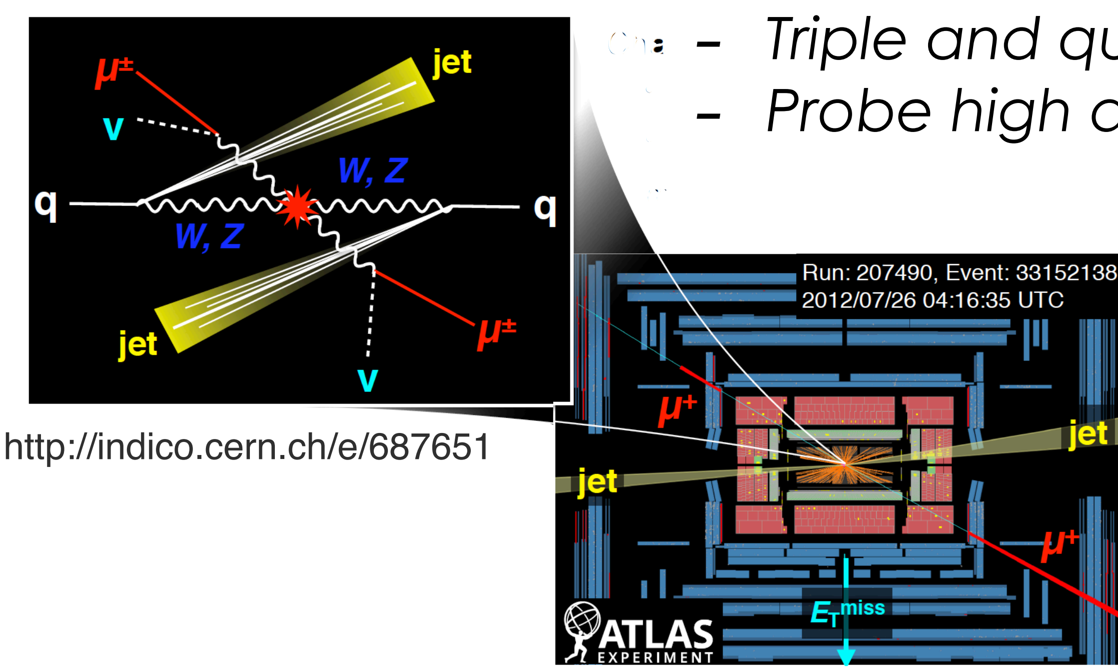
Global EW fit

- *M_W, m_t, and M_H*
- *θ_W*



Multiboson processes

- *VBF*
- *VBS*
- *Triple and quartic couplings*
- *Probe high dim operators and NP*



http://indico.cern.ch/e/687651

CERN-LPCC-2018-03, CERN-LPCC-2018-06

THE FUTURE OF $\sin^2\theta_{eff}$

- **planned ATLAS/CMS eta extension improves**

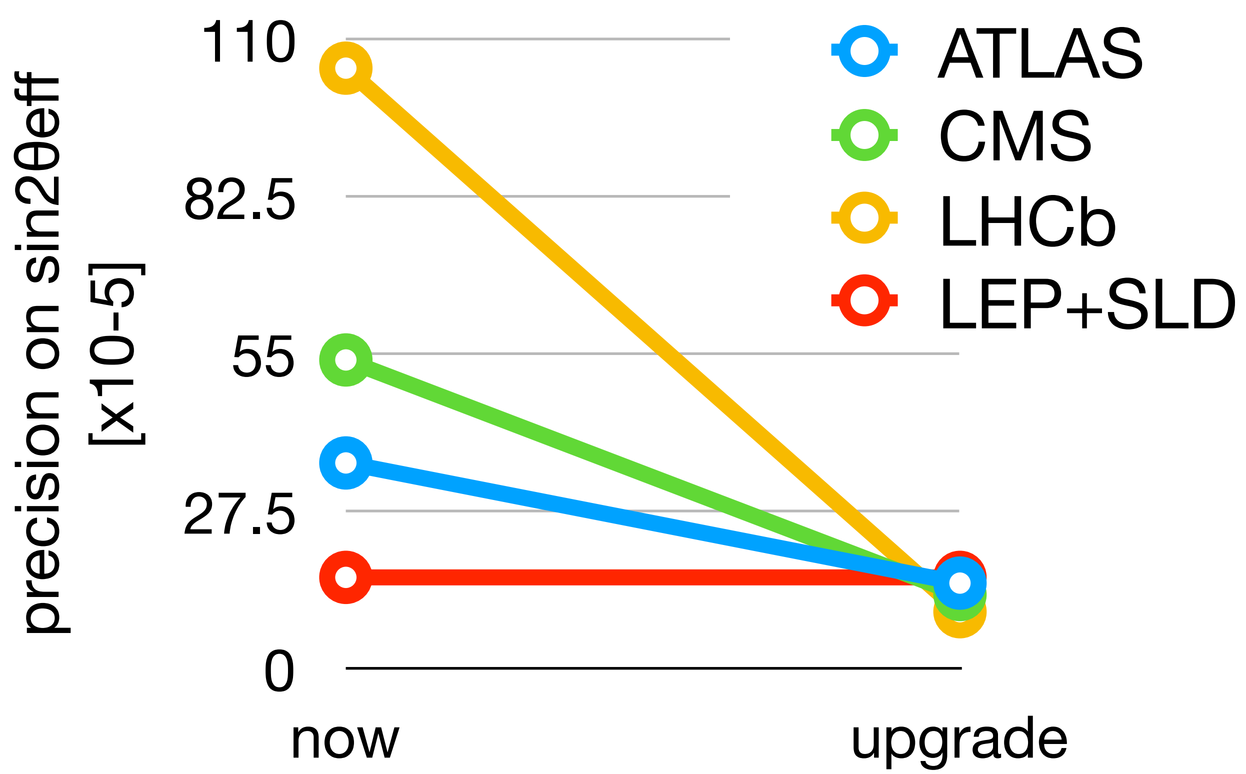
  stats gets 30% better, PDFs 20% better

- **LHCb Upgrade II can beat the LEP+SLD combo**

  300 fb-1 and fully-software trigger (lepton $(p_{T1}, p_{T2}) > (20, 5)$ GeV)

- **constrain PDF uncertainties with N-differential DY?**

  m_{ll}, p_T…



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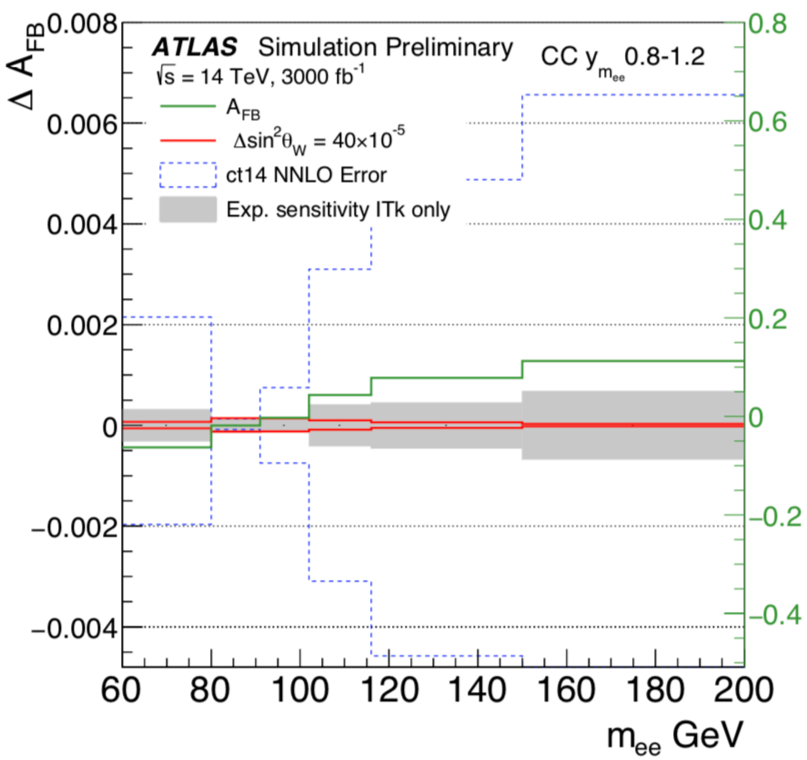
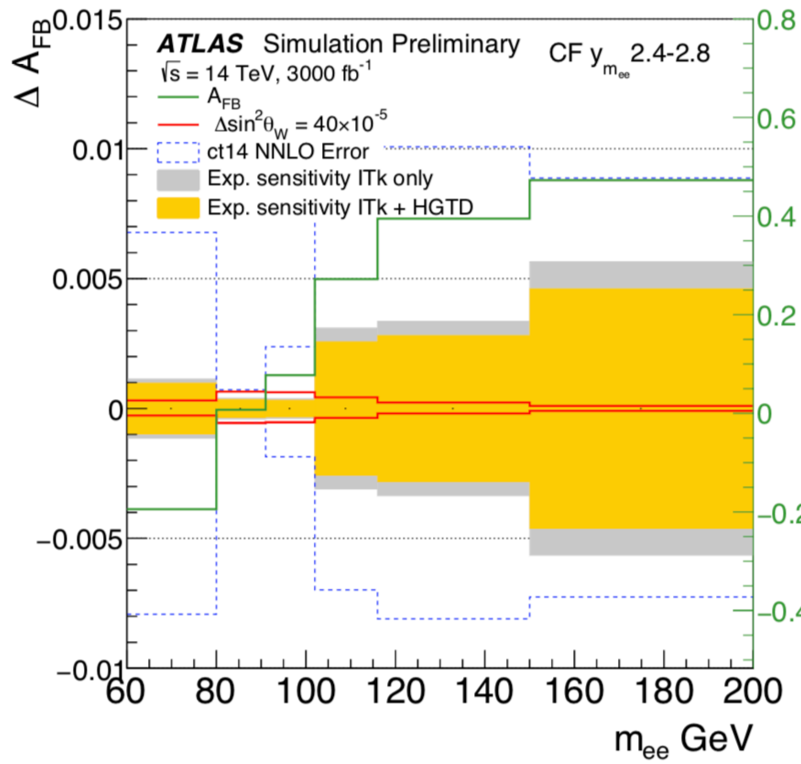
WHAT IF WE ADD A TIMING DETECTOR?

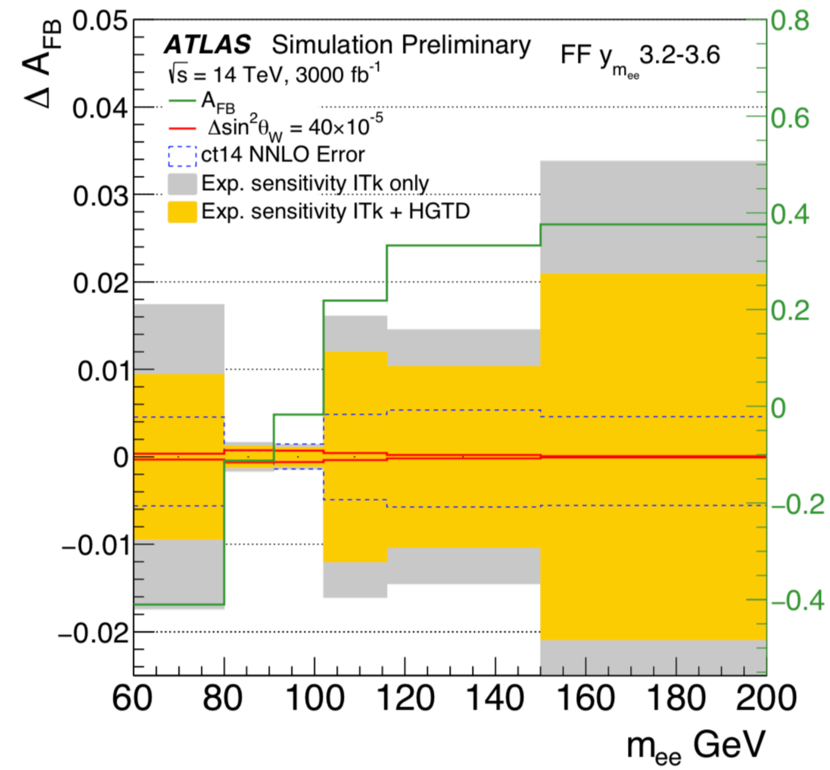
two central electrons



one central, one forward



two forward electrons



- to suppress pile-up, measure when (aka where) jets are produced
  - reject forward jets which look like electrons: 20% better sensitivity
- combined precision on $\sin^2(\theta_{eff})$: $(18\pm16_{[PDF]}\pm9_{[exp]})\times10^{-5}$
  - more precise than all single-experiment result so far

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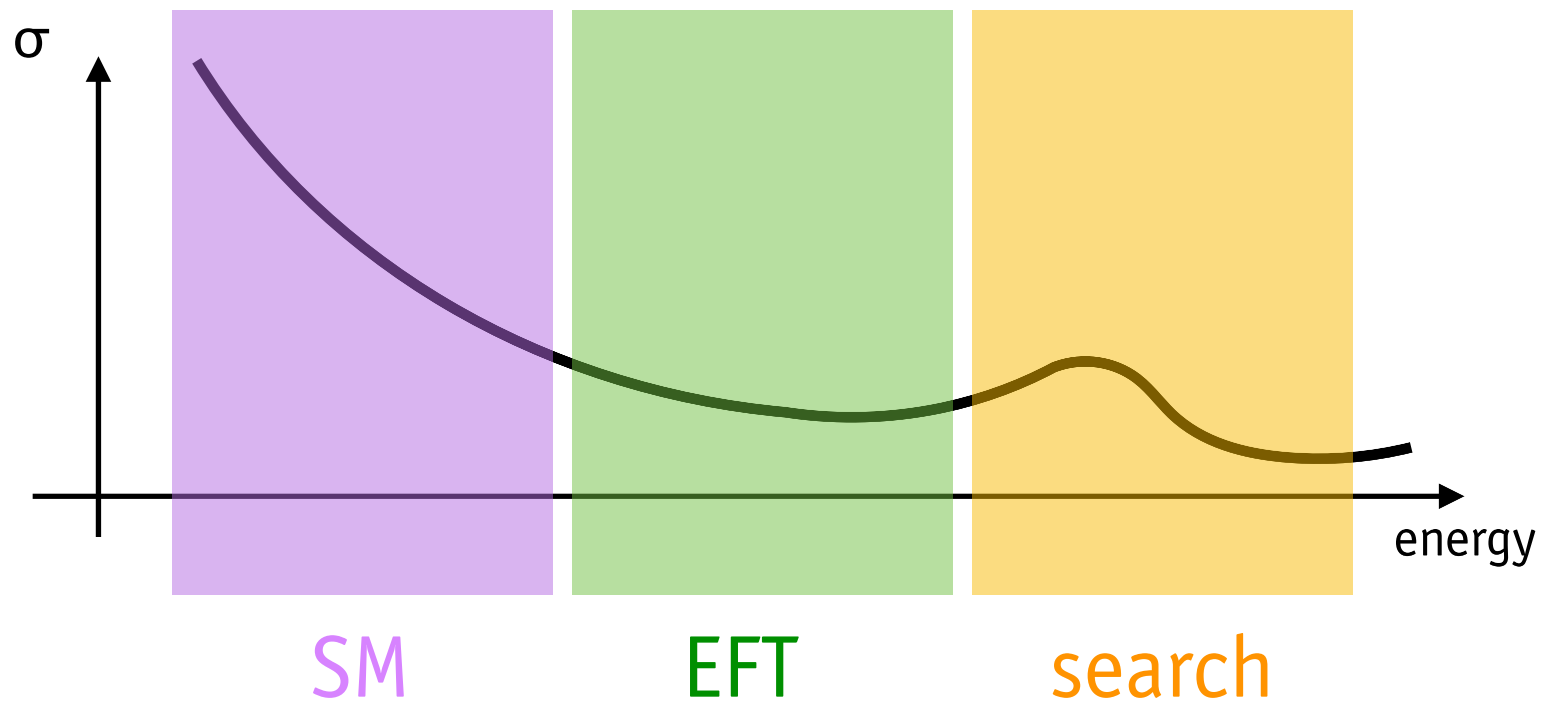
LHC VS LEP



experiment	energy	what	how precisely
LEP-I	mZ	Z properties	‰
LEP-II	from diboson threshold to 208 GeV	off-shell Z properties, trilinear gauge interactions	%
LHC	13 TeV COM	H couplings	10% ?

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HOW? OBLIQUE PARAMETERS

- Z-pole observables $-\frac{\hat{S}}{4m_W^2}\left(H^\dagger\tau^a H\right)W^a_{\mu\nu}B^{\mu\nu}$
  - LEP: ~100 GeV, %-‰ accuracy
  - LHC: ~1000 GeV, 10% accuracy
  - new physics not enhanced by energy

- off-Z-pole observable $-\frac{Y}{4m_W^2}\left(\partial_\rho B_{\mu\nu}\right)^2$
  - LEP: ~100 GeV, %-‰ accuracy
  - LHC: ~1000 GeV, 10% accuracy
  - new physics enhanced by $(E_{LHC}/E_{LEP})^2 \sim 100$

can then re-interpret within simplified models of new physics

→HepData / Rivet routines for differential measurements are important...

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WHY DRELL-YAN?

$$-\frac{W}{4m_W^2}\left(D_\rho W^a_{\mu\nu}\right)^2$$

$$-\frac{Y}{4m_W^2}\left(\partial_\rho B_{\mu\nu}\right)^2$$

strategy: extend the SM lagrangian with dimension-6 operators and measure Drell-Yan processes

$t = s/c = \sin(\theta_W)/\cos(\theta_W)$

neutral and charged Drell-Yan propagators

Z boson $$P_N = \frac{1}{q^2} - \frac{t^2W+Y}{m_Z^2} + \frac{t\left(\left(Y+\hat{T}\right)c^2 + s^2W - \hat{S}\right)}{(c^2-s^2)(q^2-m_Z^2)} + \frac{t(Y-W)}{m_Z^2}\,\frac{1+T-W-t^2Y}{q^2-m_Z^2} - \frac{t^2Y+W}{m_Z^2}$$

on-pole: LEP wins

off-pole: LHC can surpass LEP

W boson $$P_C = \frac{1+\frac{\left(\left(\hat{T}-W-t^2Y\right)-2t^2\left(\hat{S}-W-Y\right)\right)}{1-t^2}}{q^2-m_W^2} - \frac{W}{m_W^2}$$

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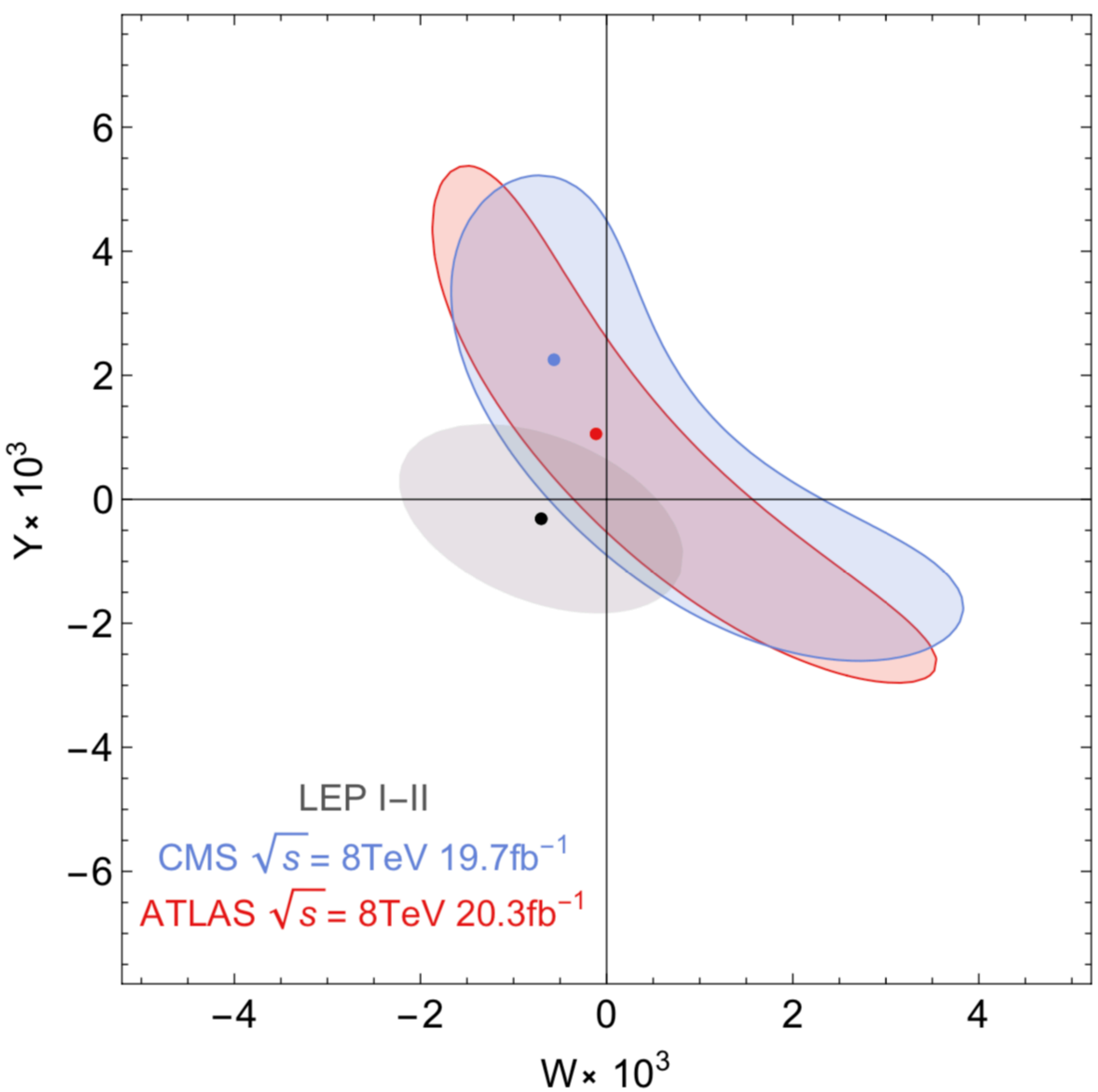
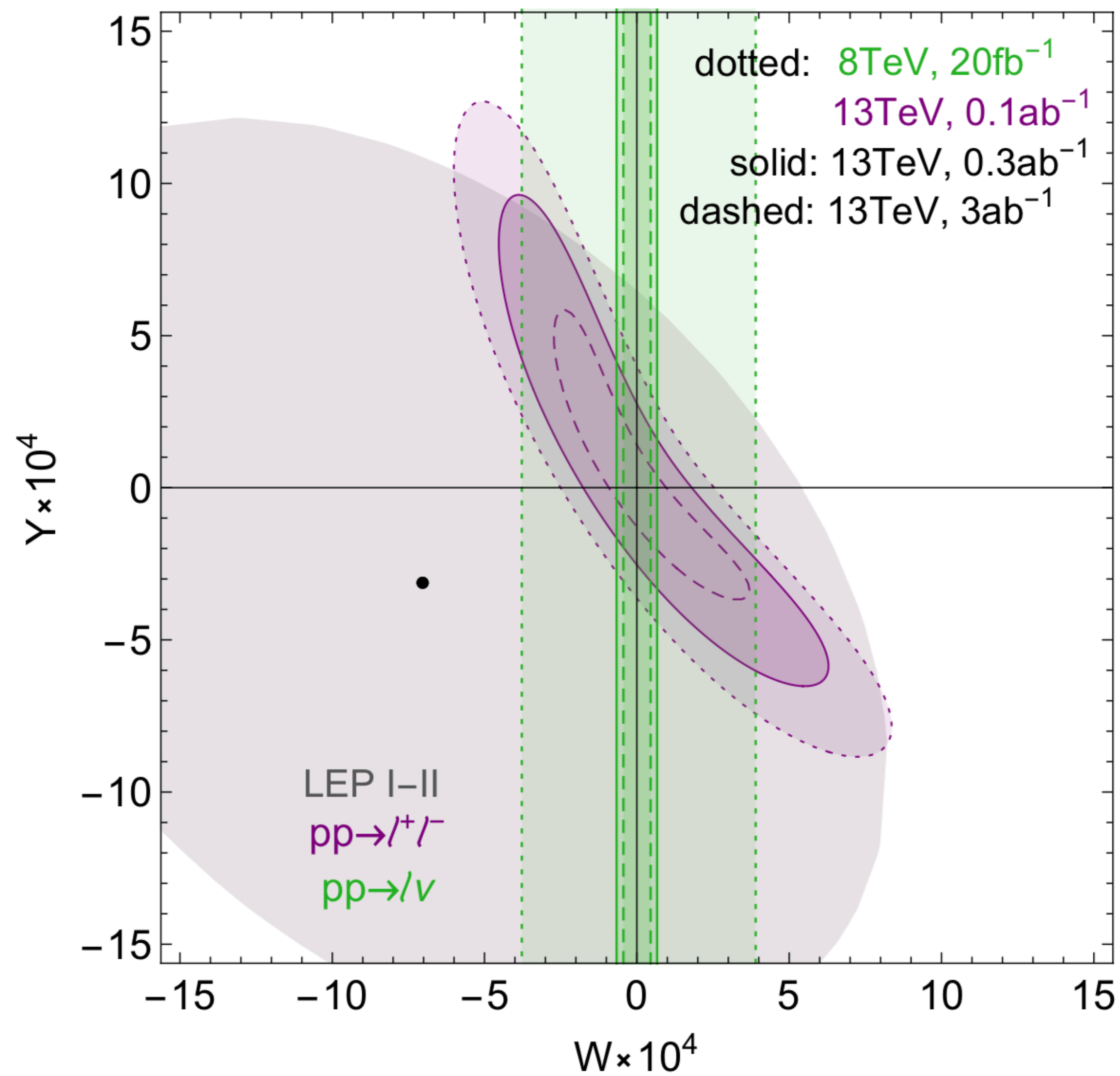
WHY DRELL-YAN?

today



LHC ~ LEP

tomorrow (zoomed in)



LHC > LEP!

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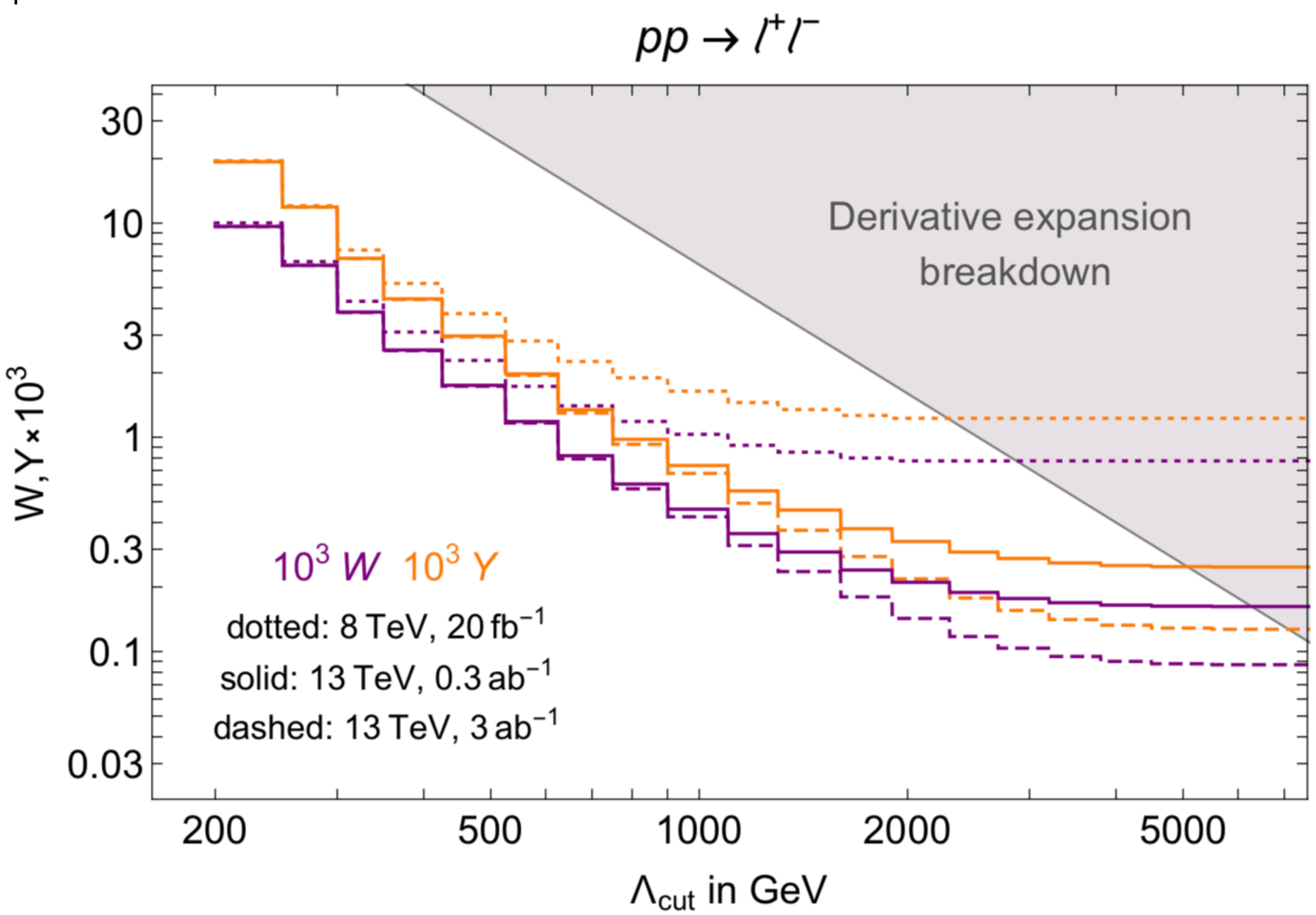
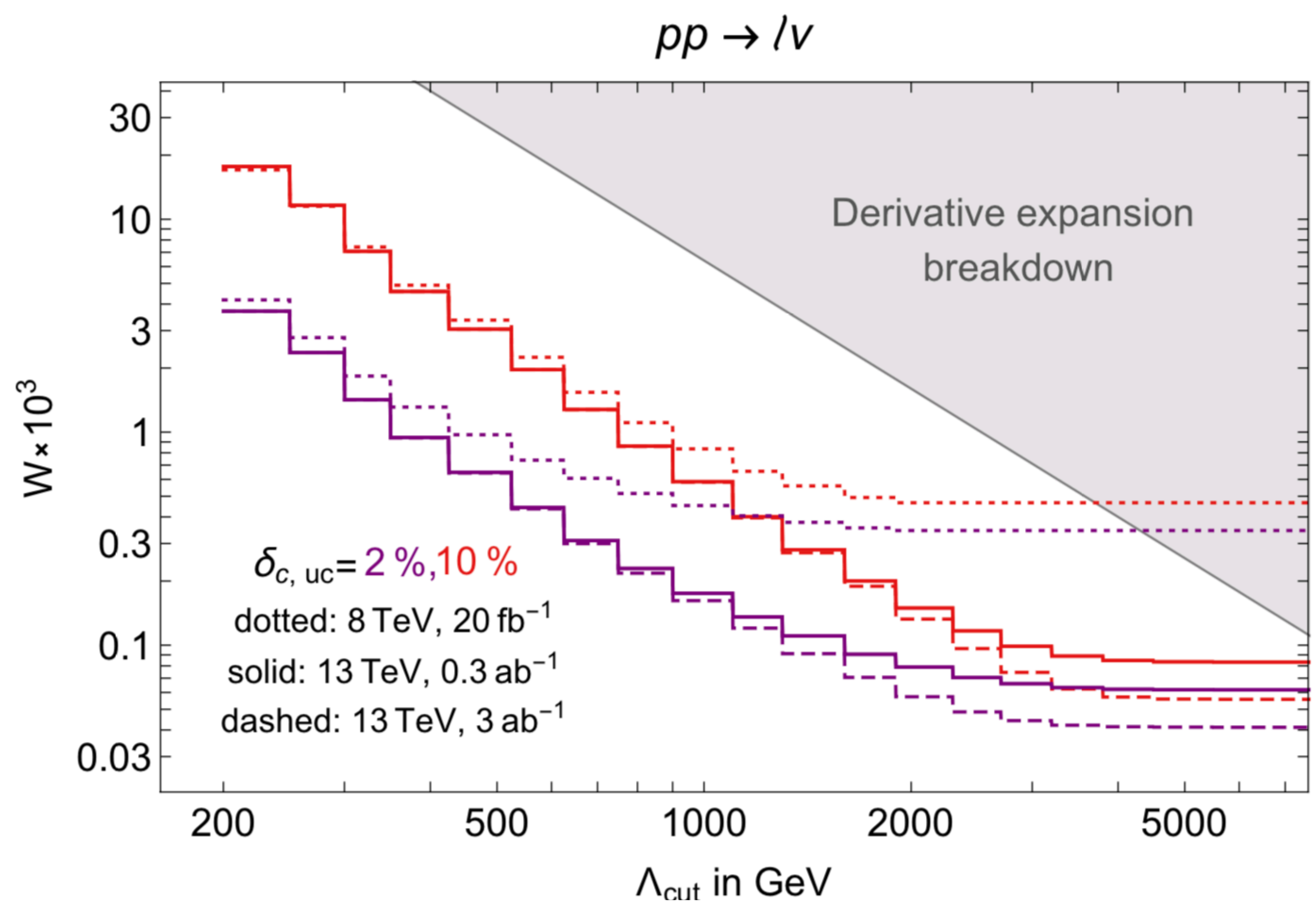
WHAT REALLY MATTERS: TAILS AND LUMINOSITY

neutral DY



charged DY

varying uncertainties from the assumed 5%



- tails matter!
  - 13 TeV: region up to mass ~ 2 TeV
- statistically dominated (next: lepton energy scale and EW uncertainties)
- can do the same with dijet

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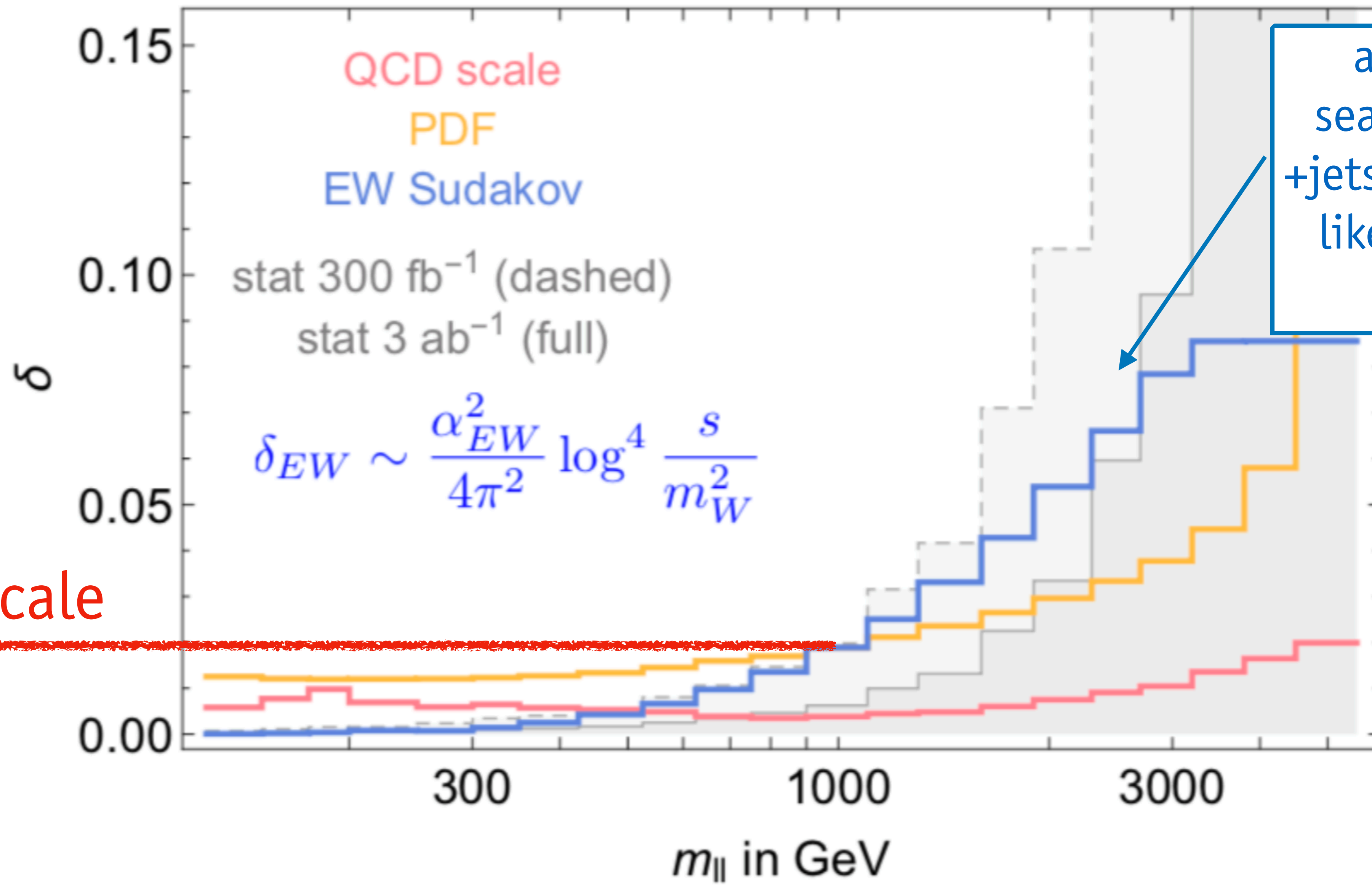
WHAT REALLY MATTERS: UNCERTAINTIES



~ energy scale

a nightmare for searches with Z(vv) +jets as a background, like WIMP searches with MET!

- tails matter!
  - 13 TeV: region up to mass ~ 2 TeV
- statistically dominated (next: lepton energy scale and EW uncertainties)
- can do the same with dijet

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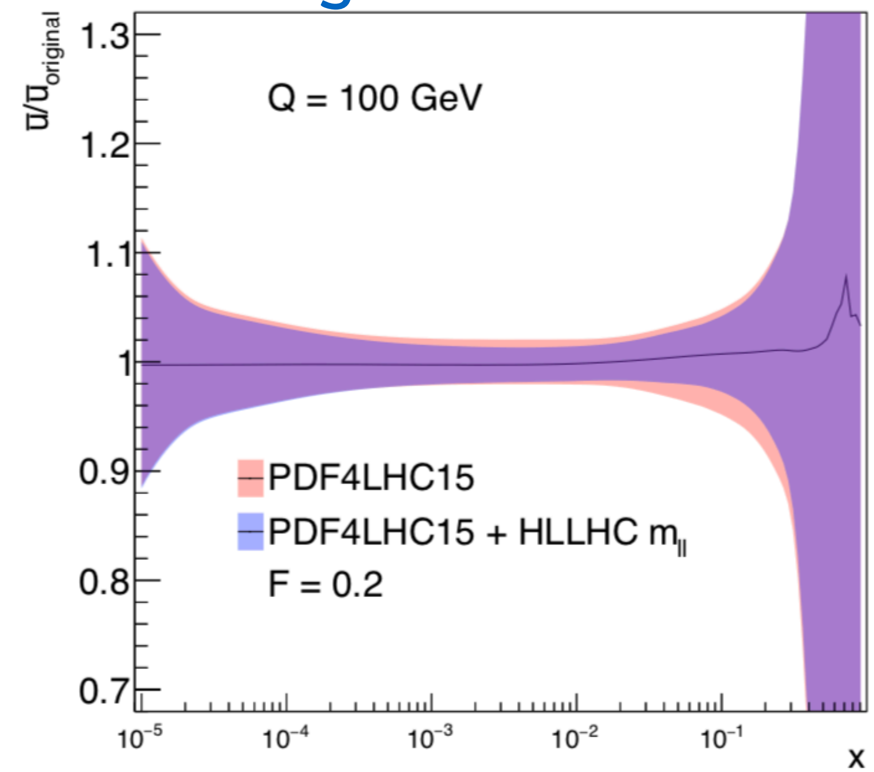
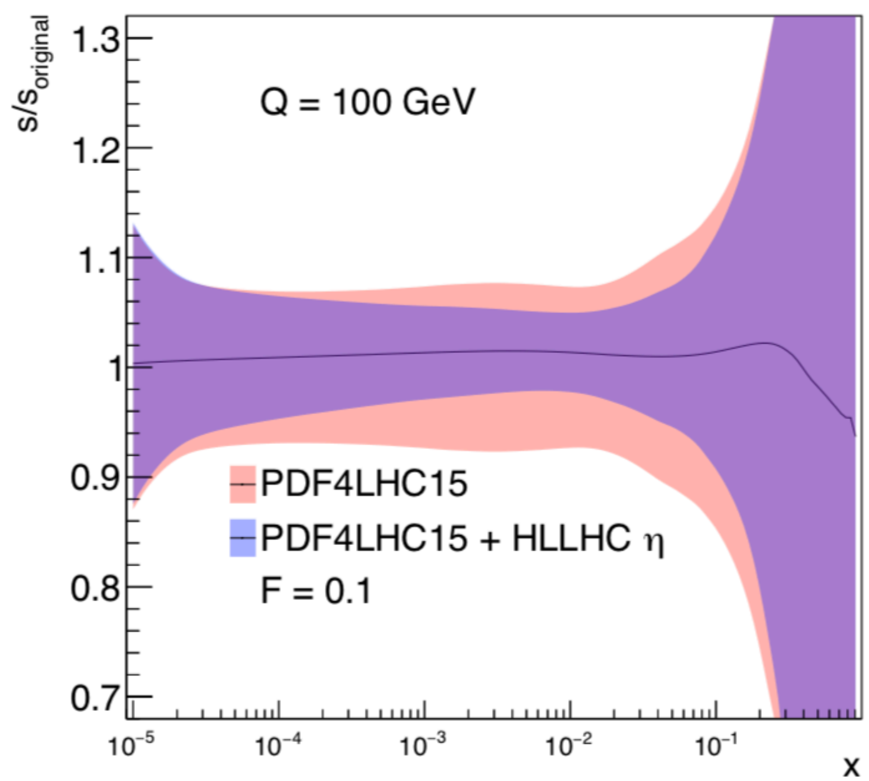
PDF UNCERTAINTIES

- significant reduction in PDF uncertainties due to large HL-LHC statistics foreseen
  - crucial for all EW observables!

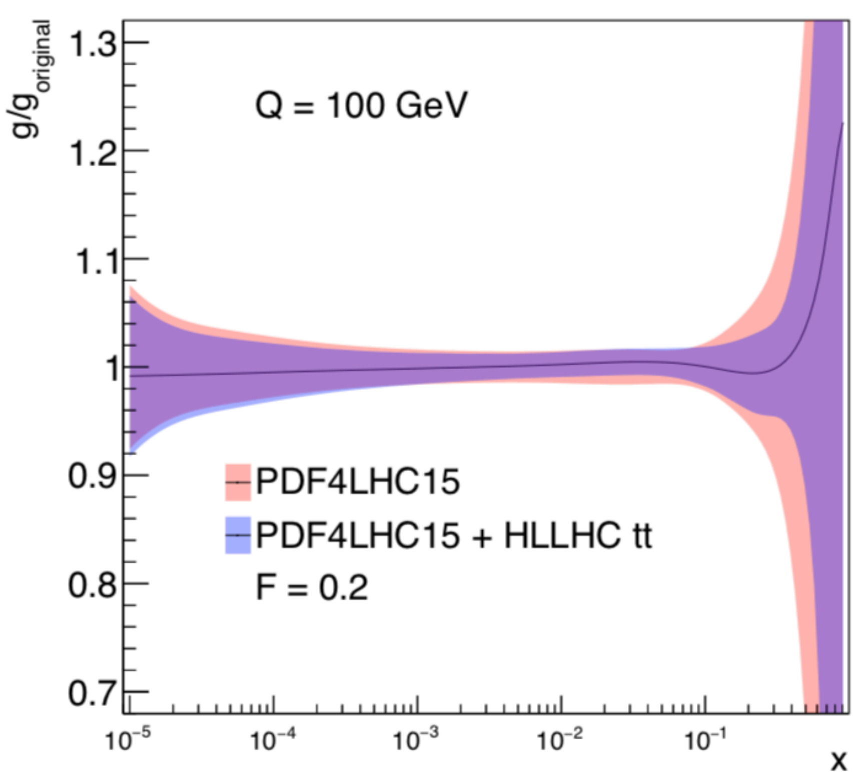
high-mass DY



W+c



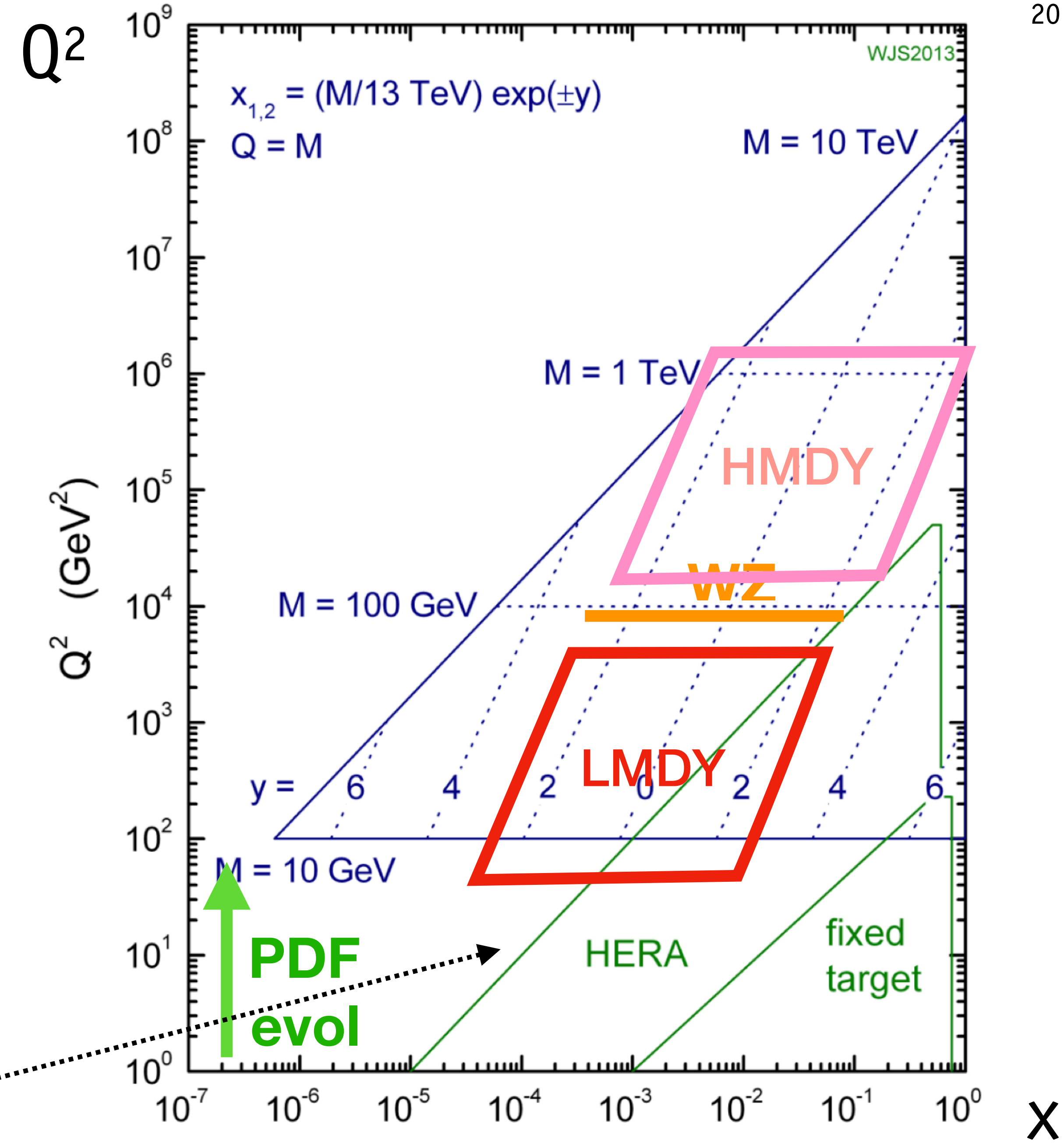
ttbar



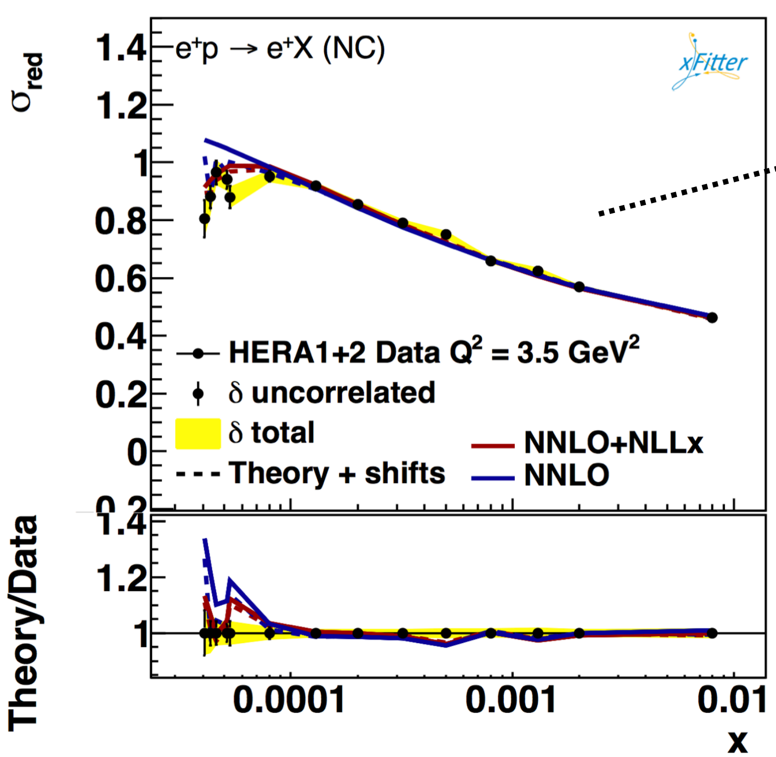
what	where
mid-x gluon	isolated photons
large-x gluon	ttbar differential
large-x gluon valence quarks	inclusive jets
s	W+c
large-x sea quarks (flavour separation)	high-mass DY

PDFs: EXPERIMENTAL CHALLENGES

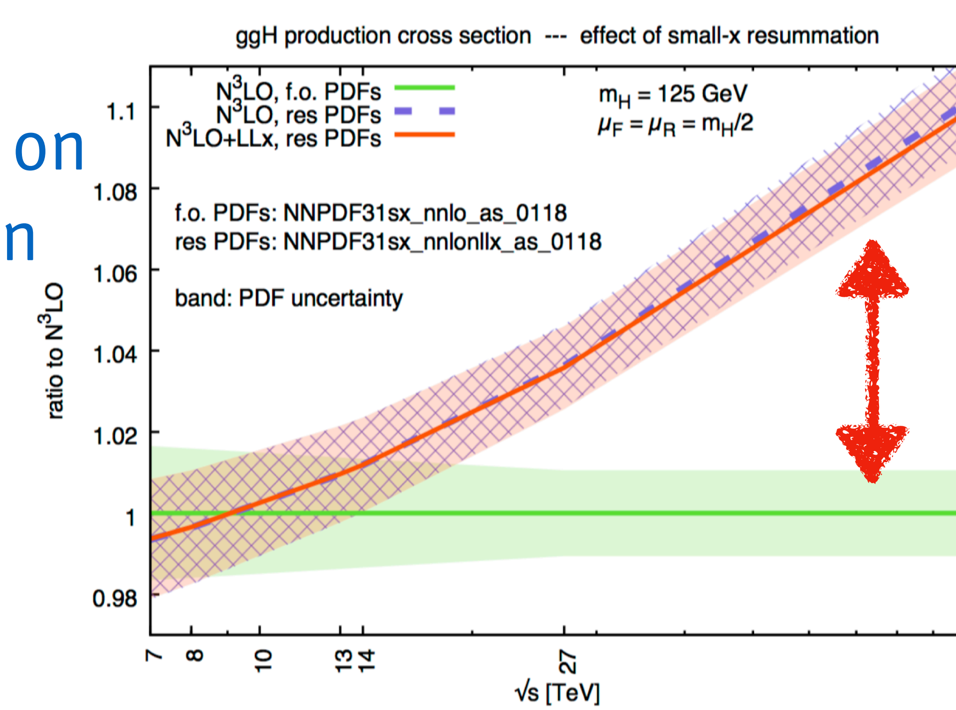
- PDFs don't reproduce low-x data from HERA
  - affects Higgs at FCC!
- due to low-x resummation?
  - answer with low-mass DY (at higher Q^2)
  - lepton trigger is a challenge!



HERA vs prediction



effect of resummation on H production (vs √s)



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W mass at HL LHC

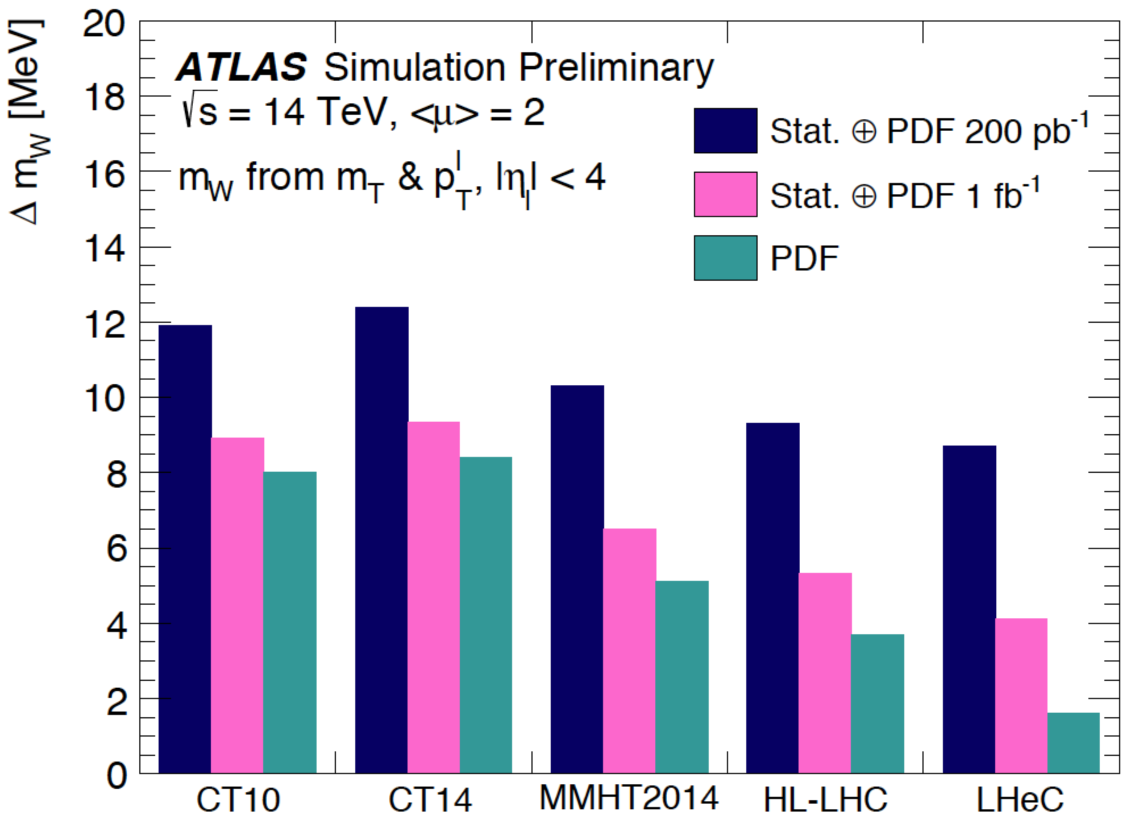
- Special **low pile-up collision data** at the HL-LHC (and HE-LHC) of large interest for W boson physics.

@14 TeV	$L = 5 \times 10^{32}\ cm^{-2}\ s^{-1}$	<mu> = 2	$2x\ 10^{6}$ events/week	10 MeV stat. unc.

- First **quantitative study** of the potential improvement in the W-boson mass considering **only statistical and PDF uncertainties.**

- Experimental uncertainties maintained at a level similar to the statistical uncertainty

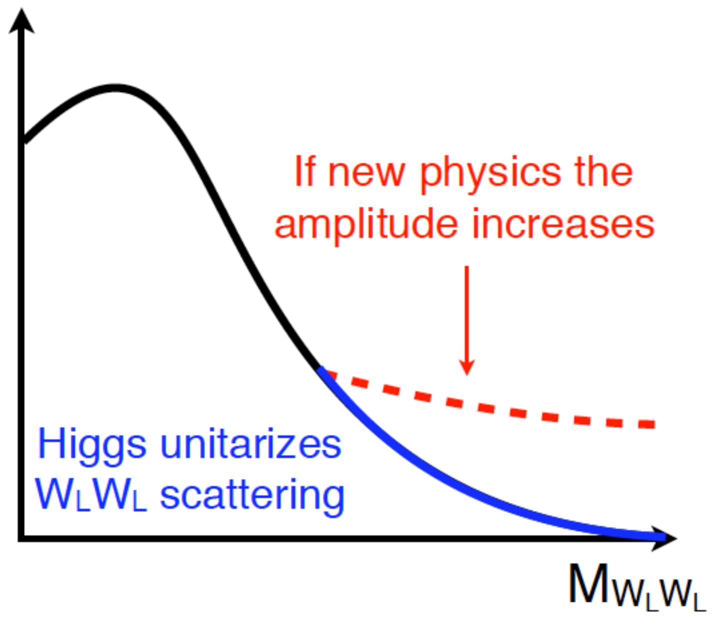
- Events are selected by applying Run2 cuts to the object kinematics

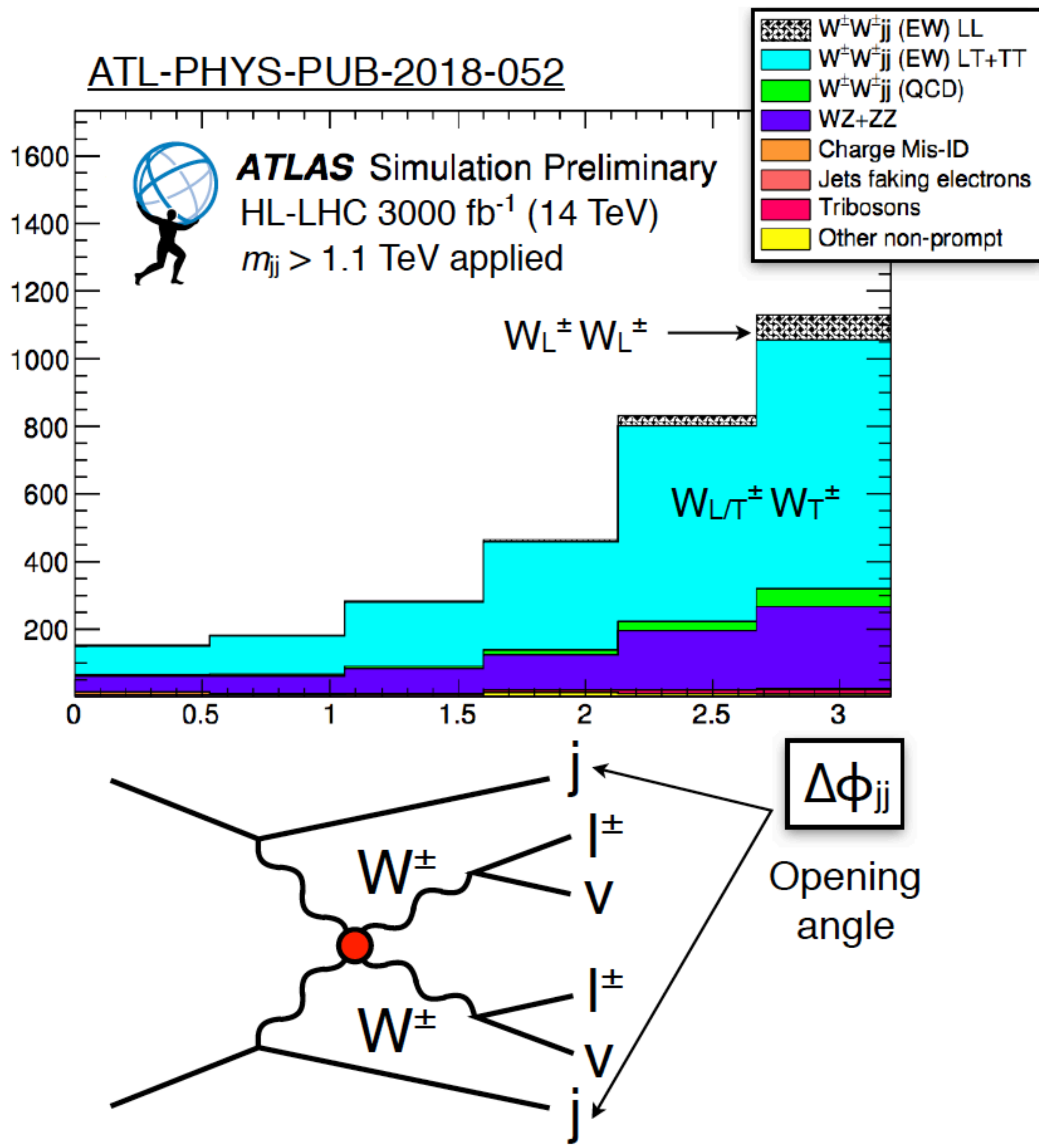


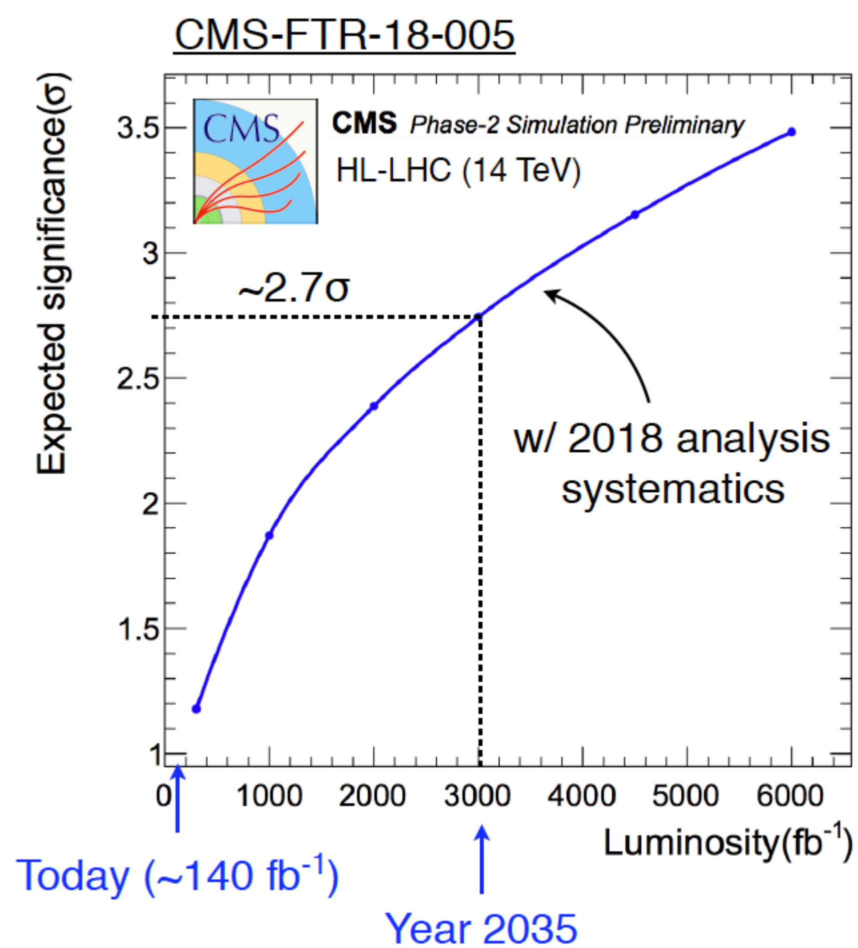
HL LHC Longitudinal VBS

- **LL component** indirect probe of the unitarization mechanism of the VBS amplitude through **Higgs and NP**

- Exploit **kinematic information to disentangle polarization**







- Polarized **WZ and ZZ** can be measured in similar way w/ 2D fit to mjj and opening angle

Conclusions

- **Both theory and LHC experiments are moving into an high precision era**

  LHC can improve precision observables and global SM fit

- **PDF uncertainties are often a limitation**

  overcome with differential cross-section measurements (e.g. $\sin^2(\theta_{eff})$)

- **SM-EFT highlights complementarity with LEP**

  examples in Drell-Yan and di-jet production

- **Detector acceptance upgrade and advanced experimental techniques for HL-LHC is crucial**

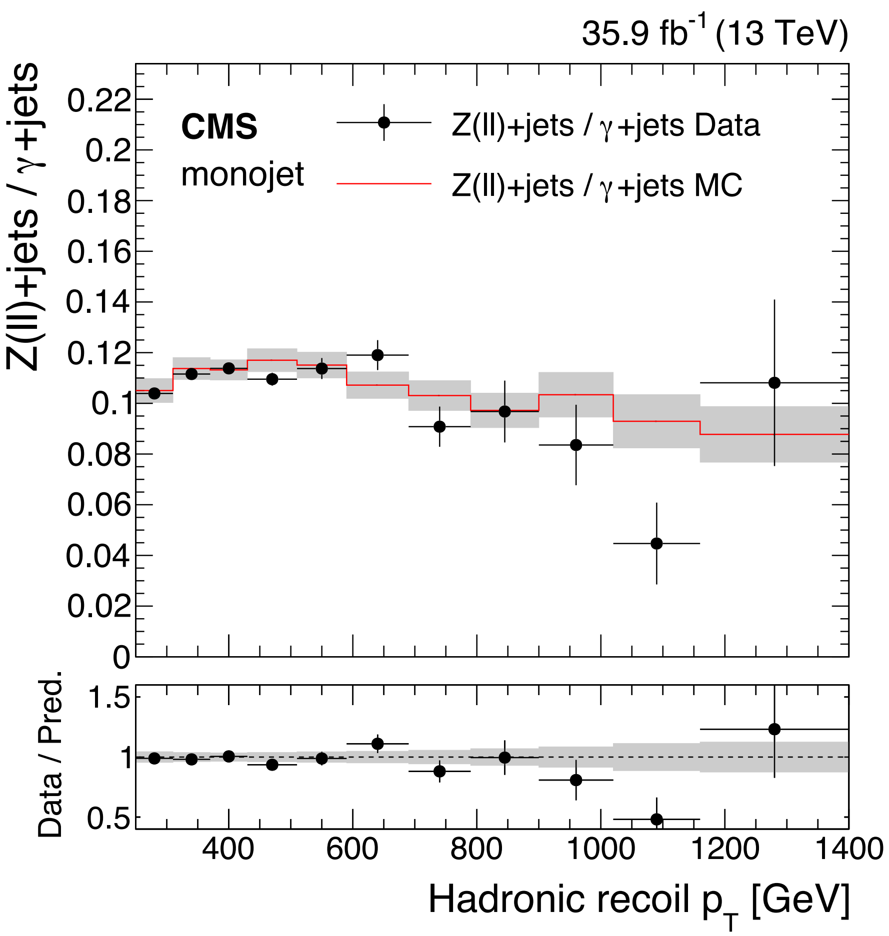
  forward region is the only hope for a pp collider

- **Improved measurements may further confirm the validity of the SM or indicate deviations which could point to new physics**

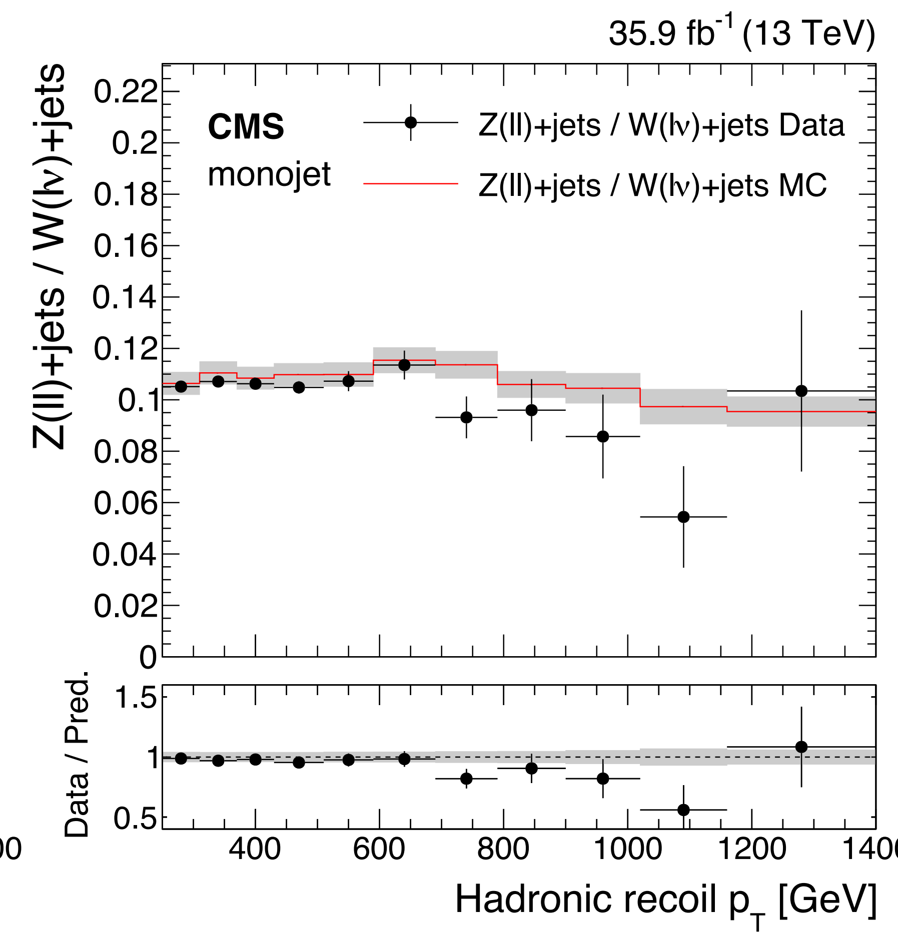
Backup

THE ELECTROWEAK CORRECTION NIGHTMARE

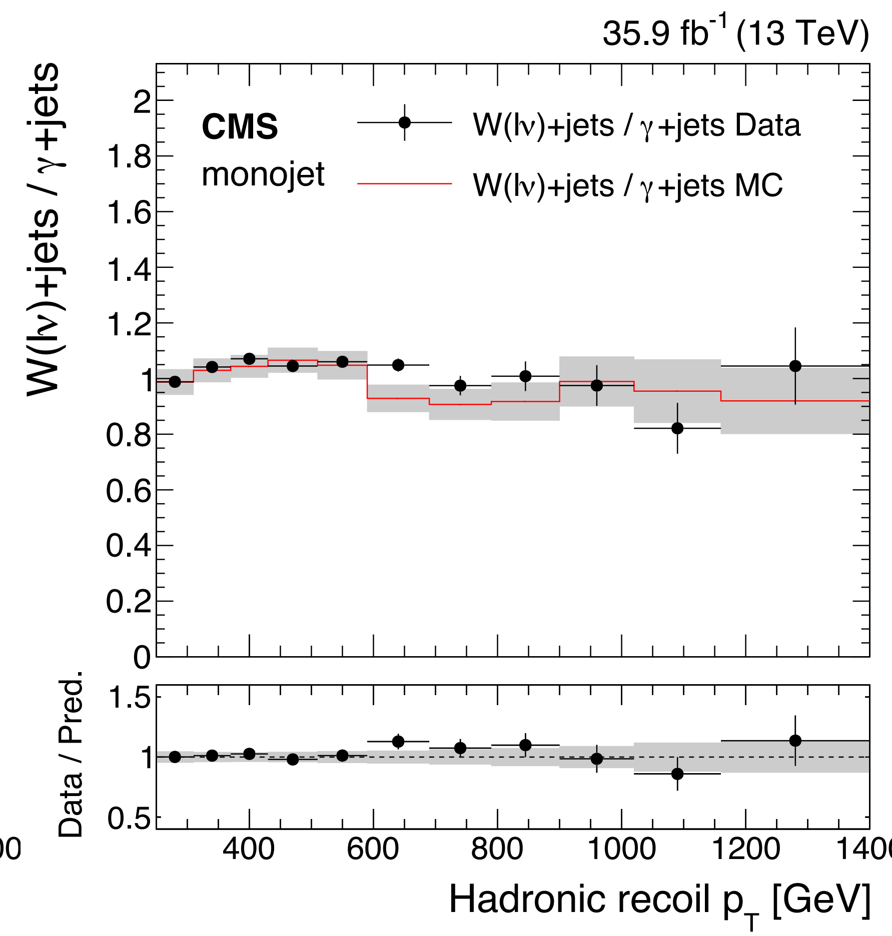
Z(ll) / gamma+jets



Z(ll) / W(lv)+jets



W(lv) / gamma+jets



- new physics searches often in invisible final states
  - e.g.: WIMP pair in association with jets ("mono-jet")
- obvious background: Z(vv)+jets
  - estimated from leptonic Z, W decays and gamma+jets (high stats!)
- <u>search</u> sensitivity limited by EW (and QCD) uncertainties!

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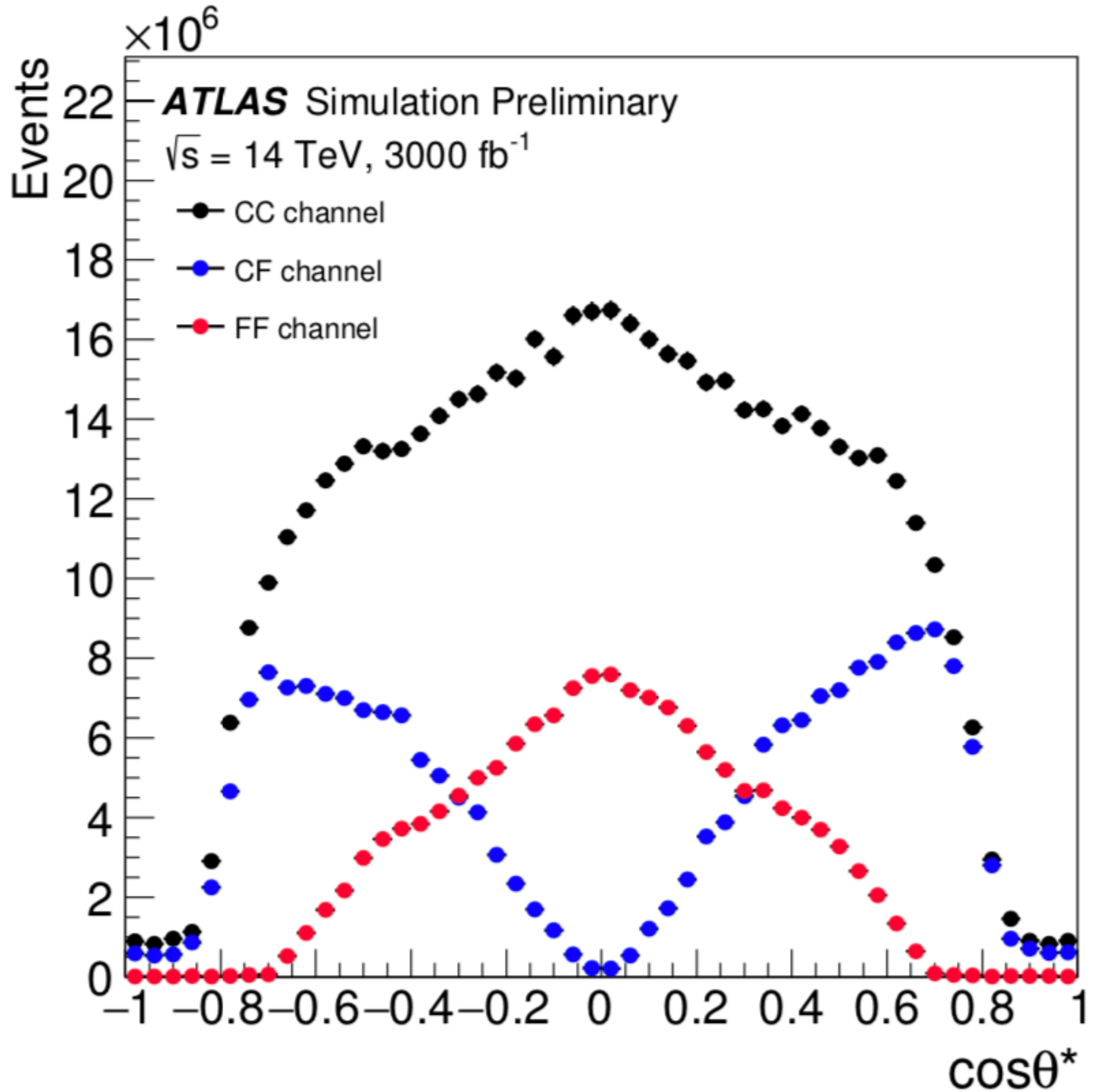
THE IMPORTANCE OF BEING FORWARD



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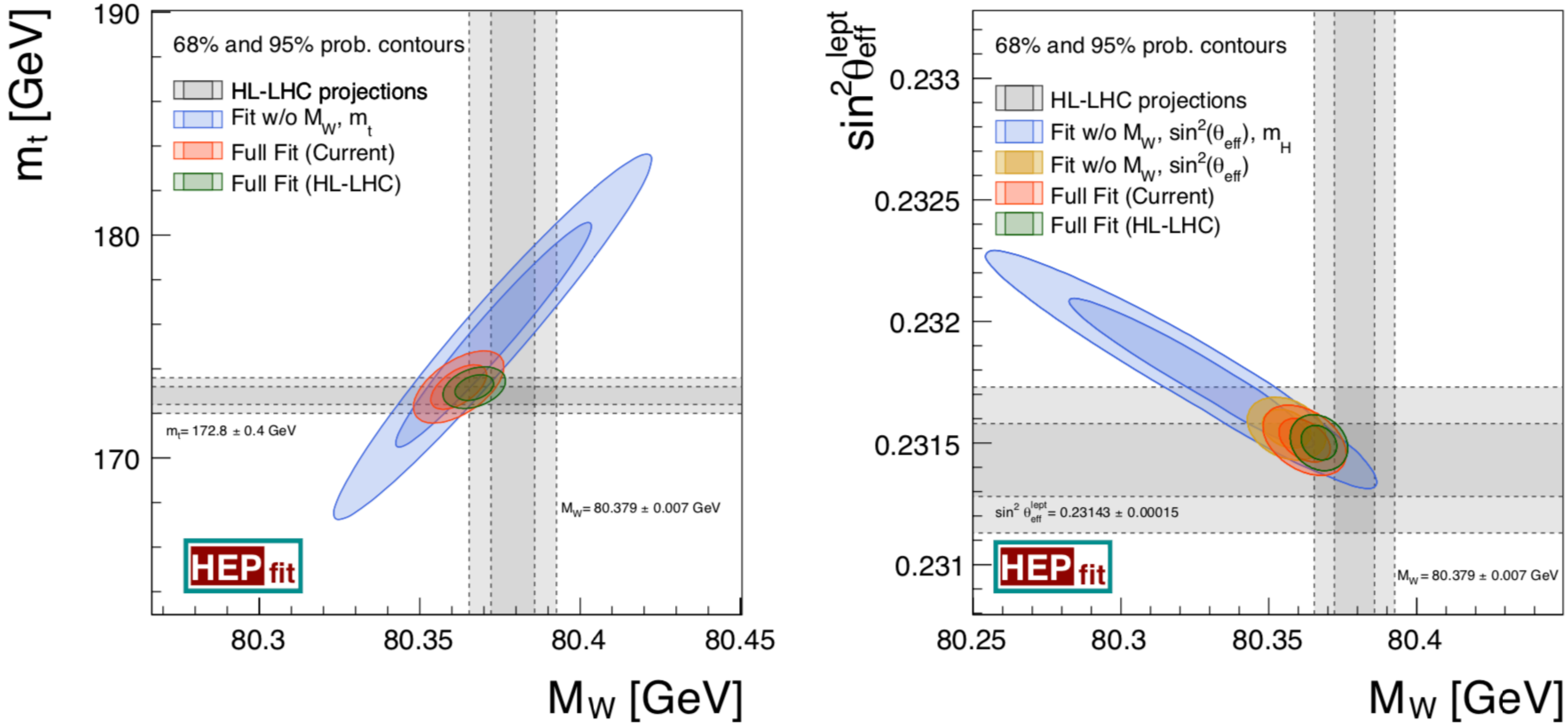
ELECTROWEAK FIT



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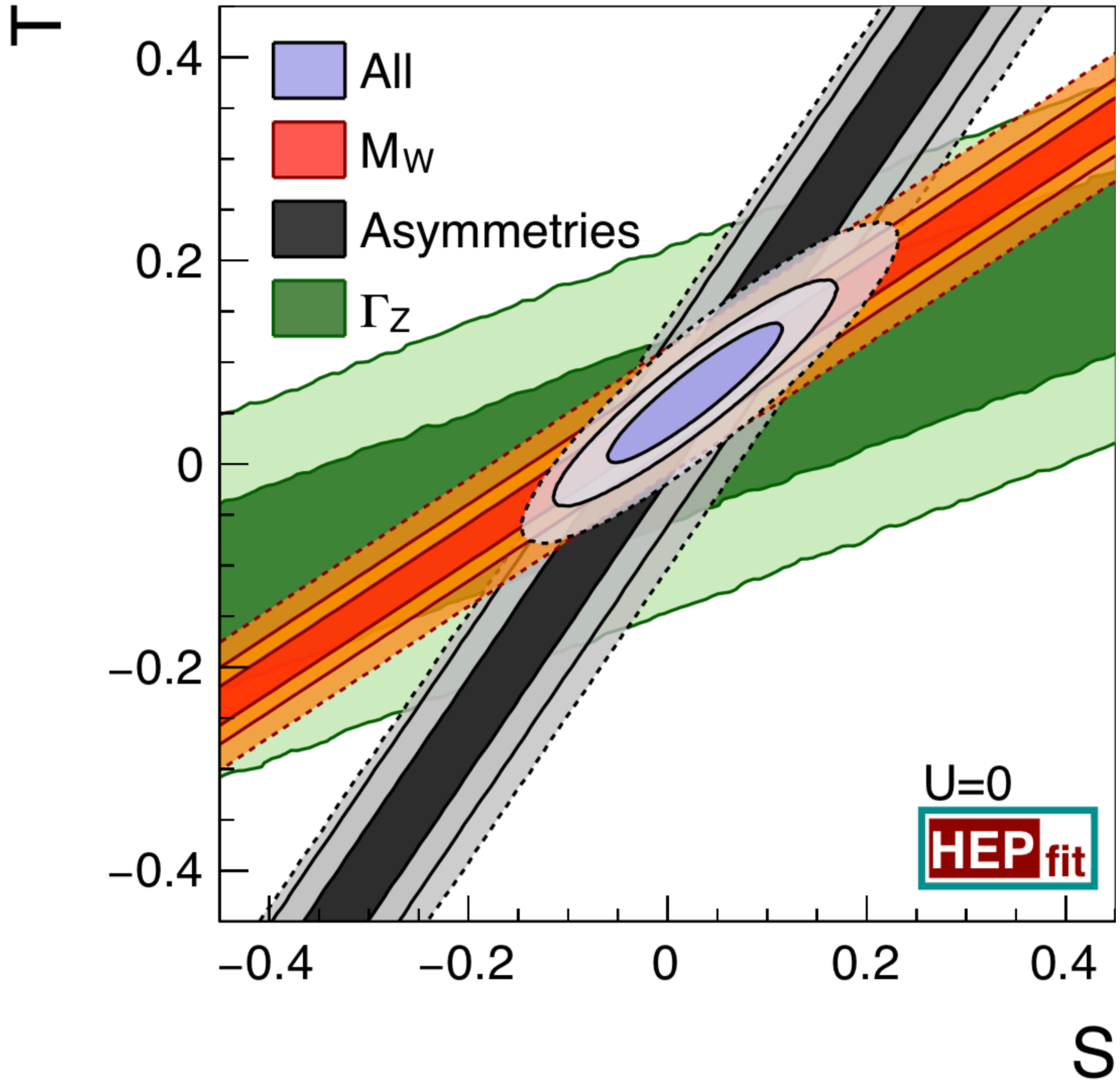
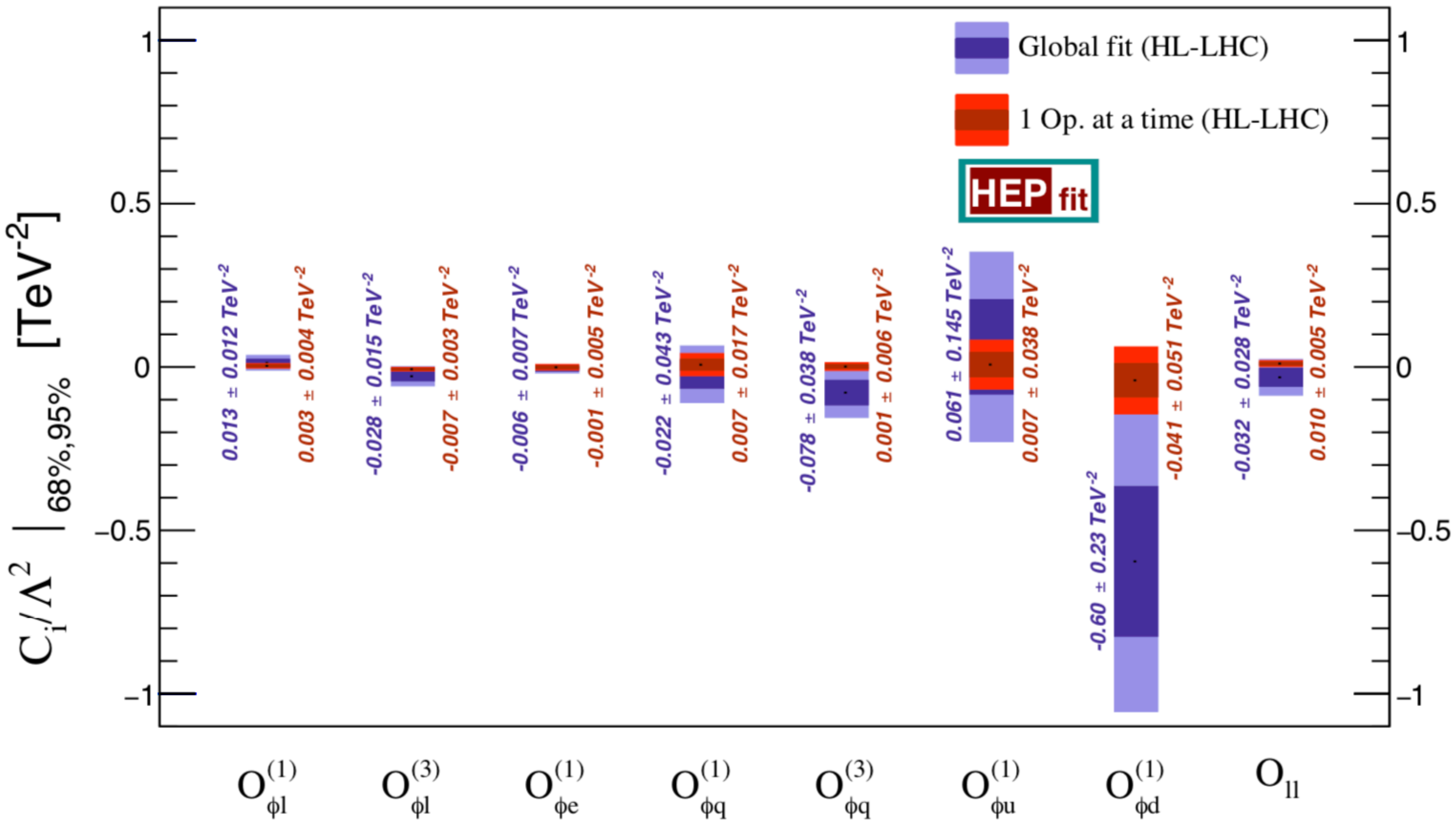
OBLIQUE PARAMETERS



ELECTROWEAK FIT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d, \quad \text{with} \quad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$



Operator Coefficient	Current uncertainty [TeV^{-2}] 1 op. at a time	Current uncertainty [TeV^{-2}] Global fit	Precision at HL-LHC [TeV^{-2}] 1 op. at a time	Precision at HL-LHC [TeV^{-2}] Global fit
$\overline{C}_{\phi l}^{(1)}$	0.004	0.012	0.004	0.012
$\overline{C}_{\phi q}^{(1)}$	0.018	0.044	0.017	0.043
$\overline{C}_{\phi e}$	0.005	0.009	0.005	0.007
$\overline{C}_{\phi u}$	0.040	0.146	0.038	0.145
$\overline{C}_{\phi d}$	0.054	0.237	0.051	0.230
$\overline{C}_{\phi l}^{(3)}$	0.004	0.017	0.003	0.015
$\overline{C}_{\phi q}^{(3)}$	0.007	0.040	0.006	0.038
$\overline{C}_{ll}$	0.007	0.028	0.005	0.028
$\overline{C}_{\phi WB}$	0.003	–	0.002	–
$\overline{C}_{\phi D}$	0.007	–	0.005	–

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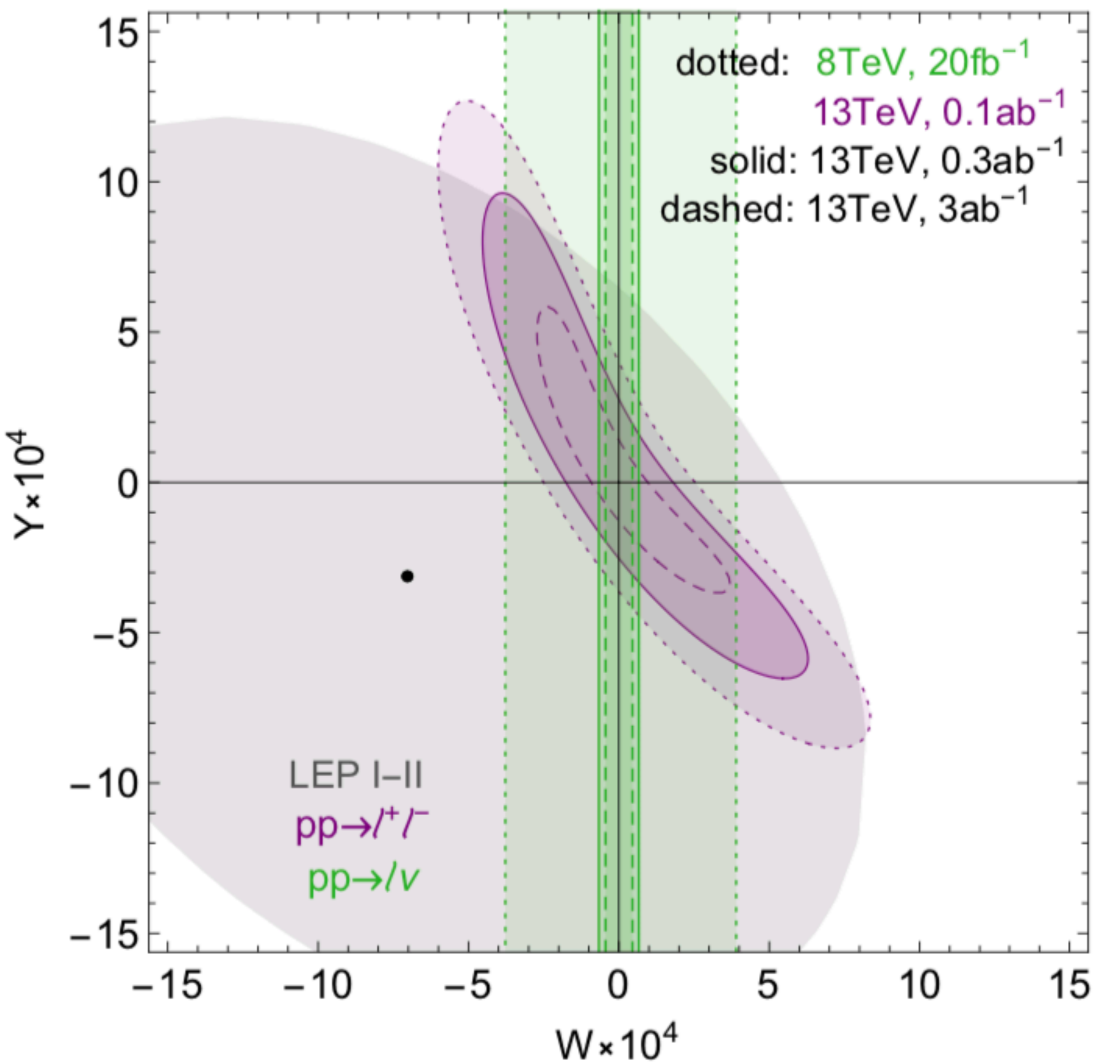
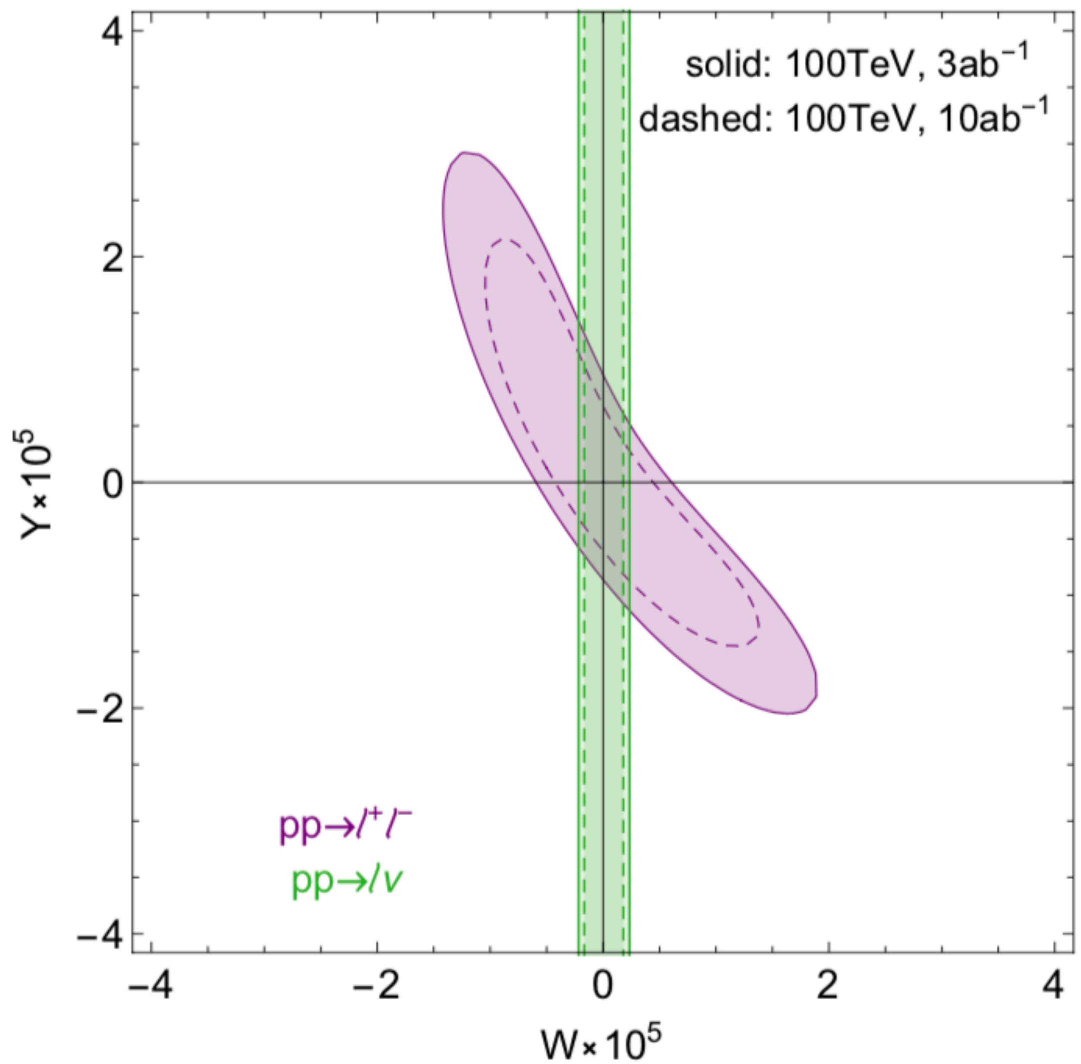
100 TeV, OR HOW TO APPROACH RETIREMENT

"quota 1"



"quota 100"zoomed in



< 2 TeV region important

< 10 TeV region important

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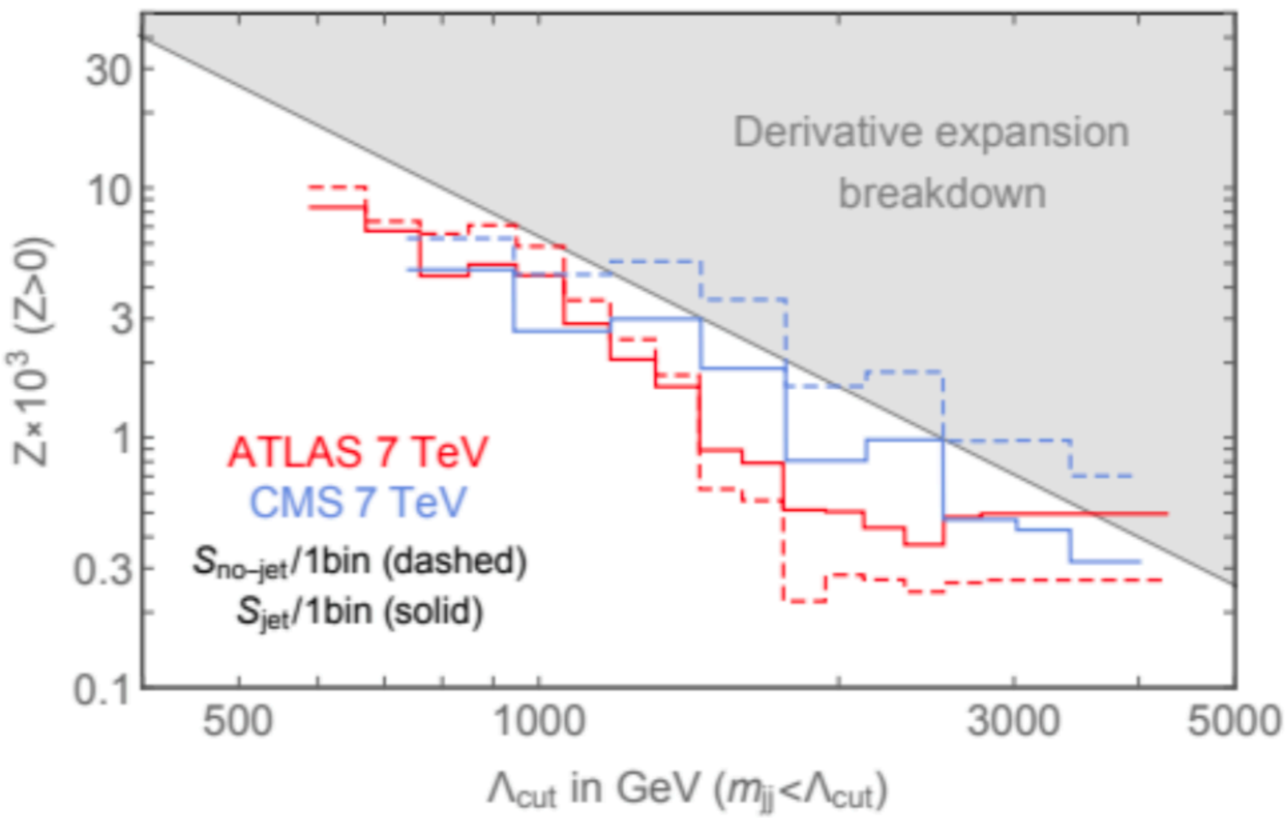
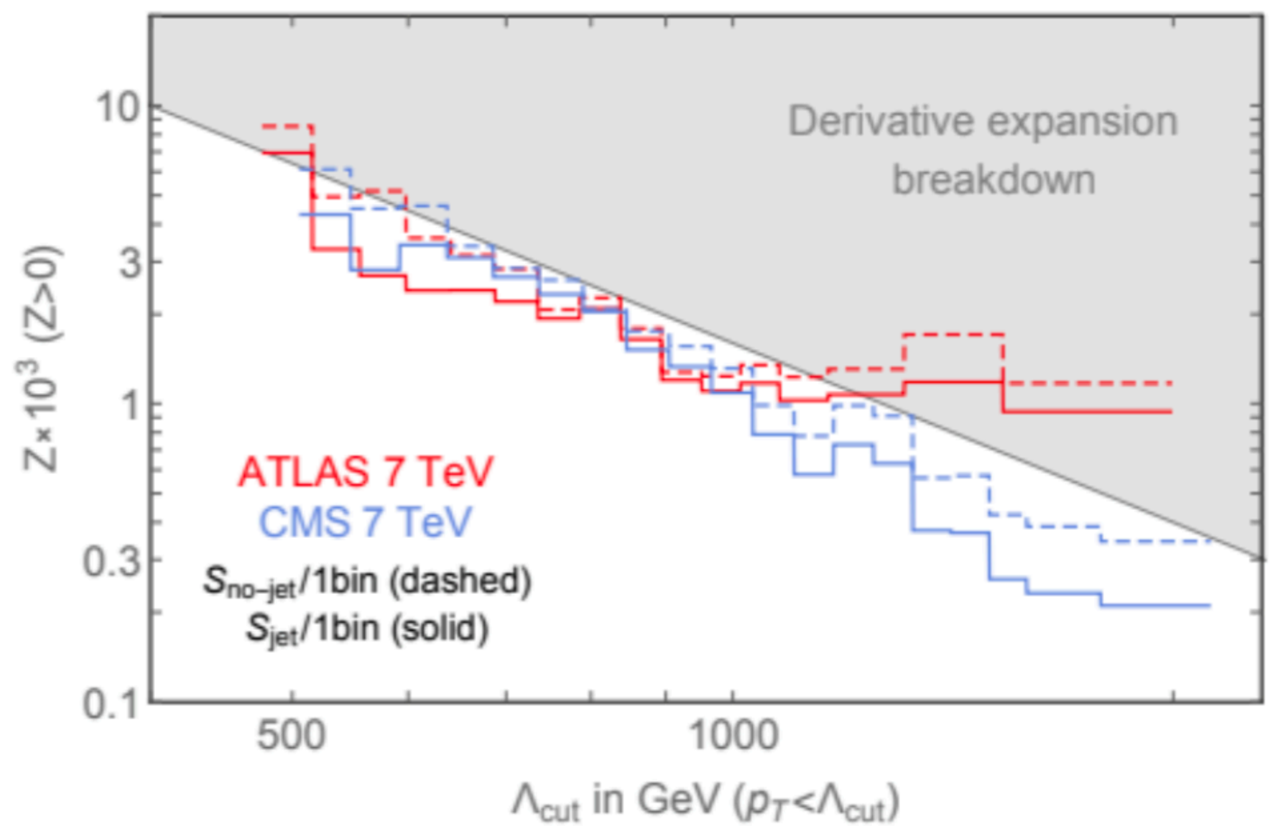
THE IMPORTANCE OF BEING DIJET

dijet mass



inclusive jet p_T



- sensitive to gluon propagator modifications: $-\frac{Z}{4m_W^2}\left(D_\rho G^A_{\mu\nu}\right)^2$
- obvious caveat: use LHC data for PDFs?
- O(1) new physics effects
- PDF uncertainties limit sensitivity...

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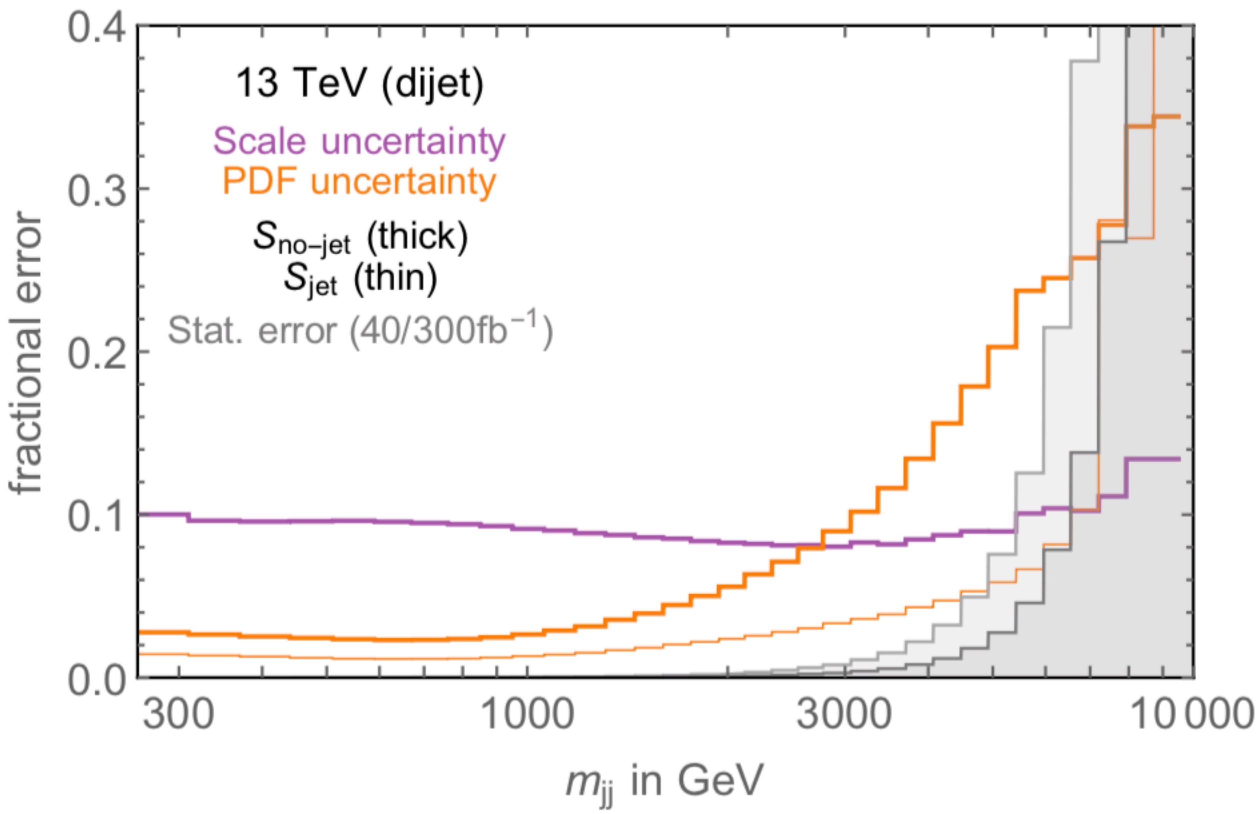
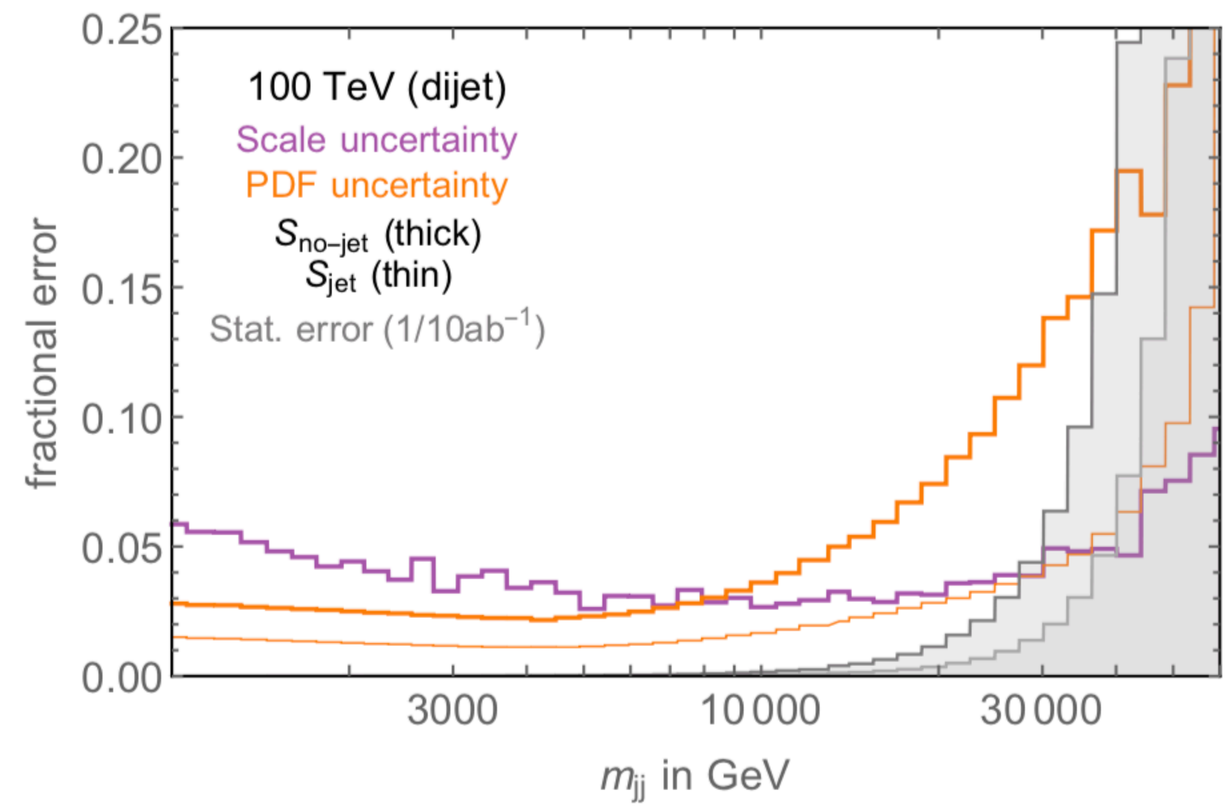
THE IMPORTANCE OF BEING DIJET: UNCERTAINTIES

13 TeV



100 TeV



- sensitive to gluon propagator modifications: $-\frac{Z}{4m_W^2}\left(D_\rho G^A_{\mu\nu}\right)^2$
- obvious caveat: use LHC data for PDFs?
- O(1) new physics effects
- PDF uncertanties limit sensitivity...

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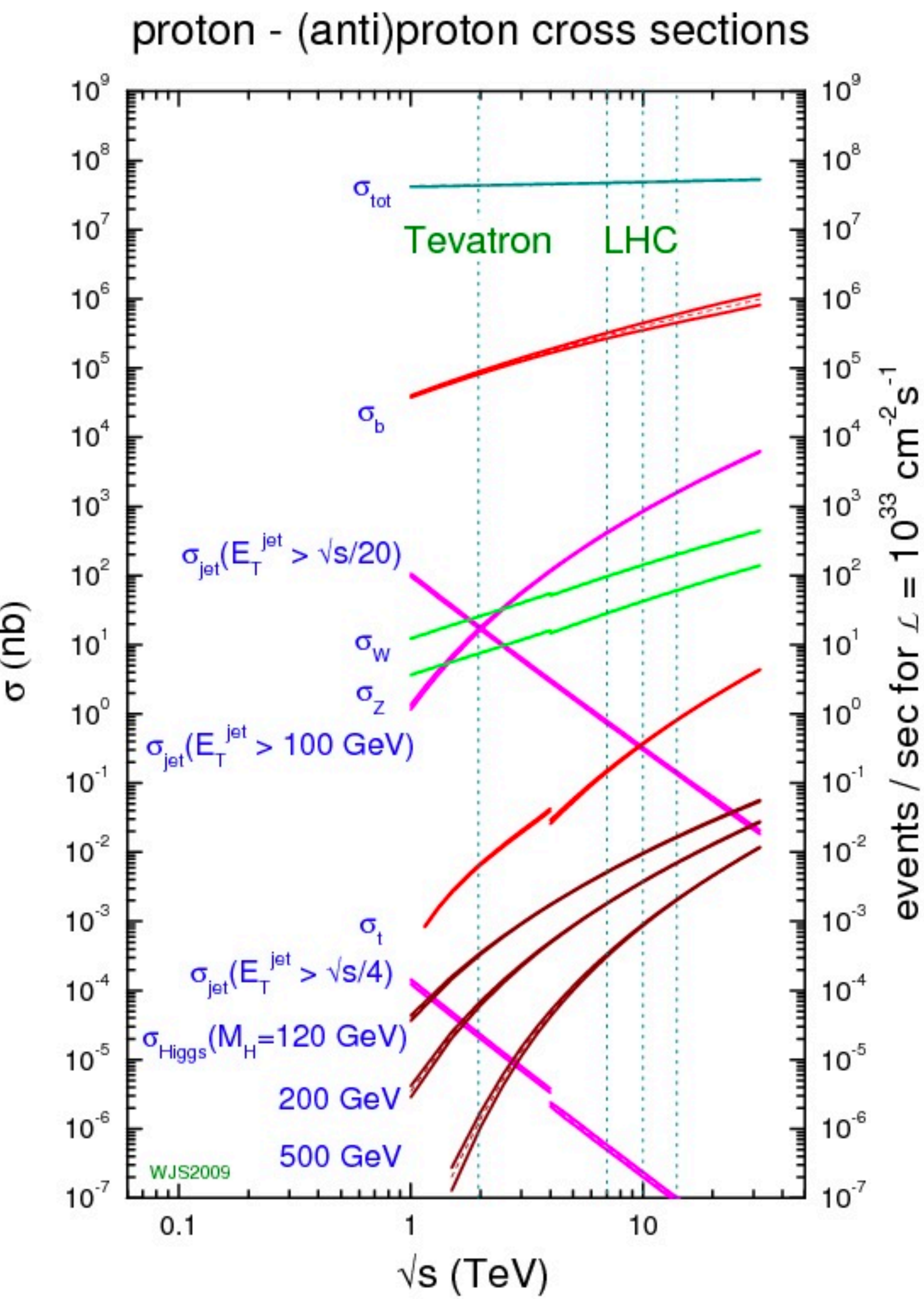
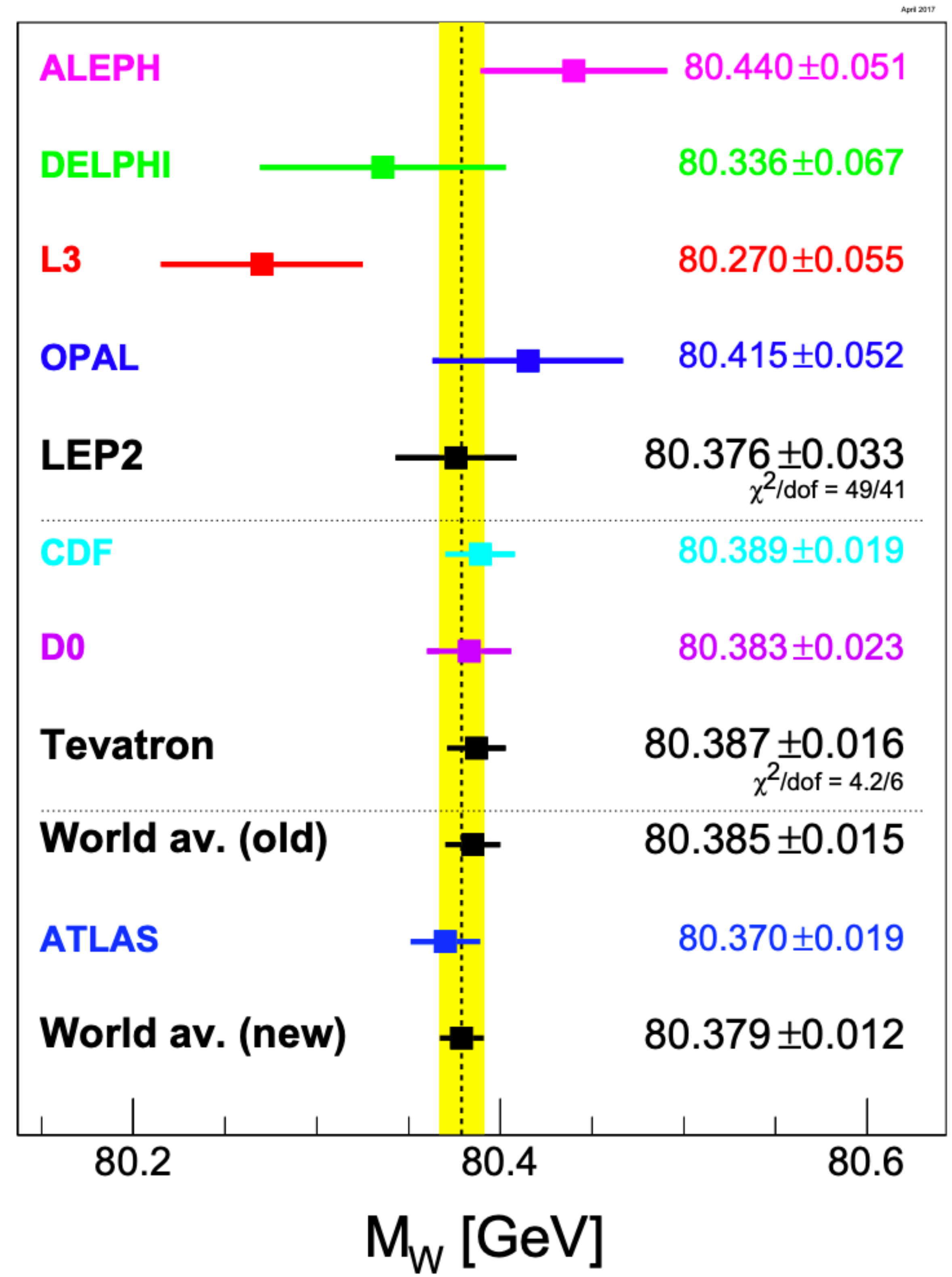
LHC vs Tevatron





Tevatron results

CDF experiment:

Phys. Rev. Lett.108 (2012) 151803

electron/muon channels
2.2 fb^{-1} integrated luminosity

m_W= 80387±12(stat)±15(syst) MeV

Source	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

D0 experiment:

Phys. Rev. Lett. 108 (2012) 151804

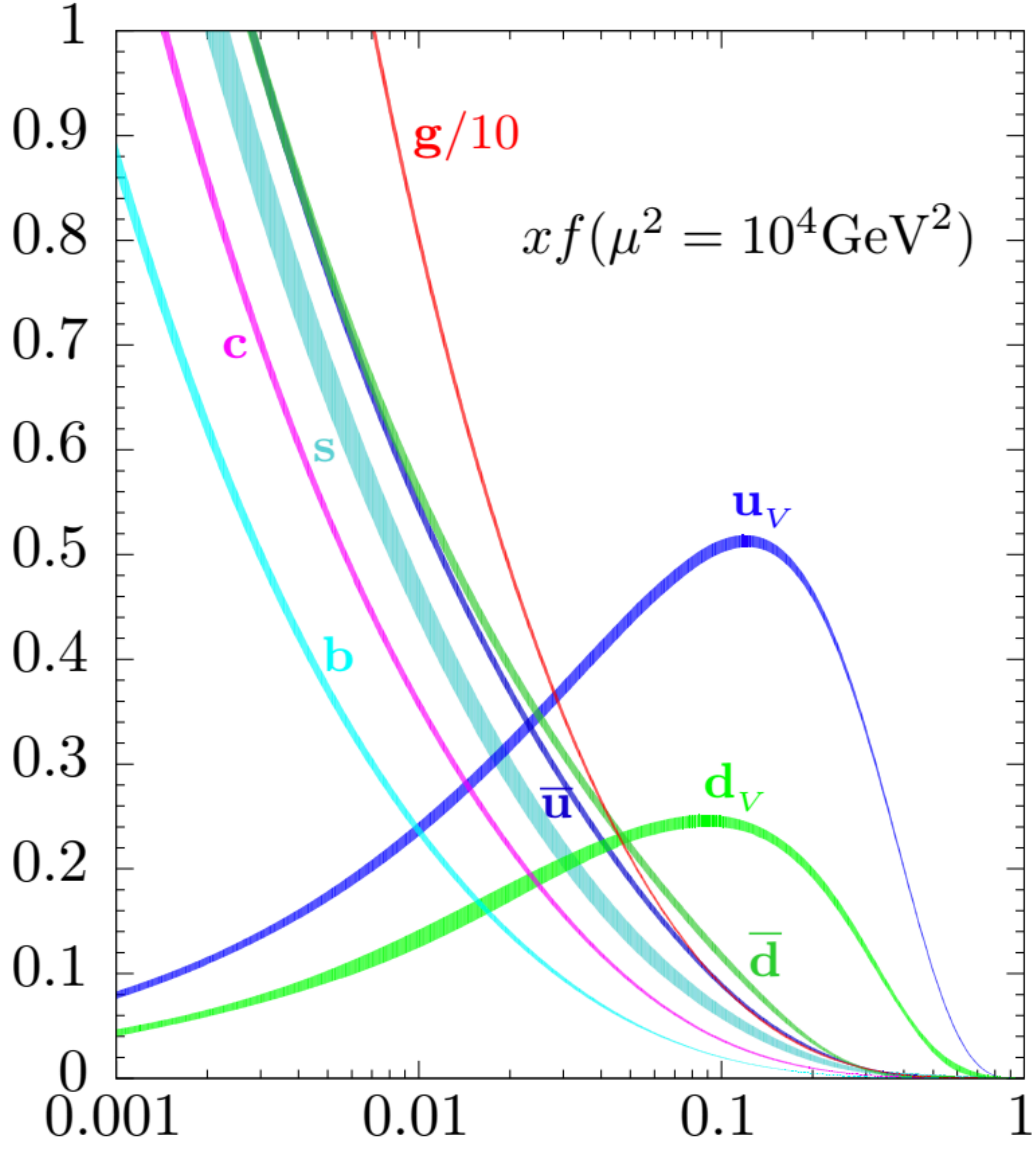
electron channel
~5.3 fb^{-1} integrated luminosity

m_W= 80375±11(stat)±20(syst) MeV

	ΔM_W (MeV)		
Source	m_T	p_T^e	$\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

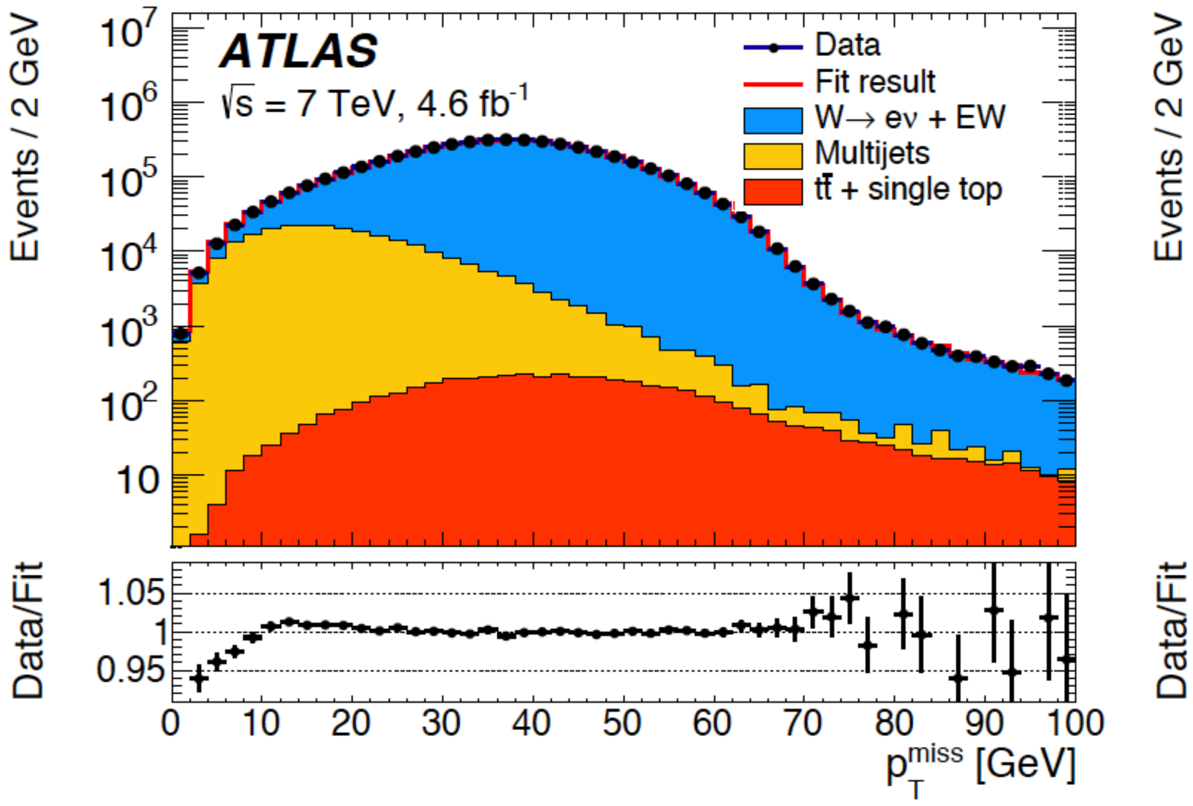
$$M_W = 80\,387 \pm 16 \text{ MeV}$$

LHC PDFs

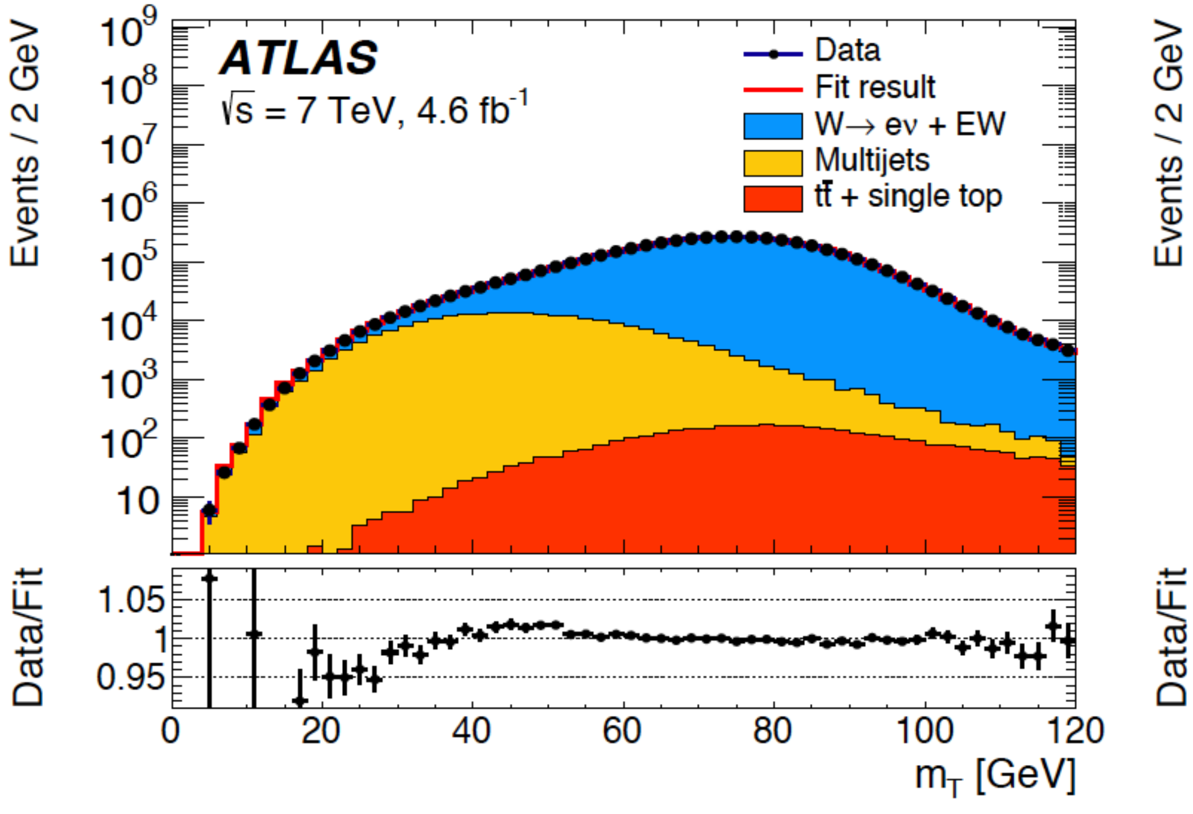


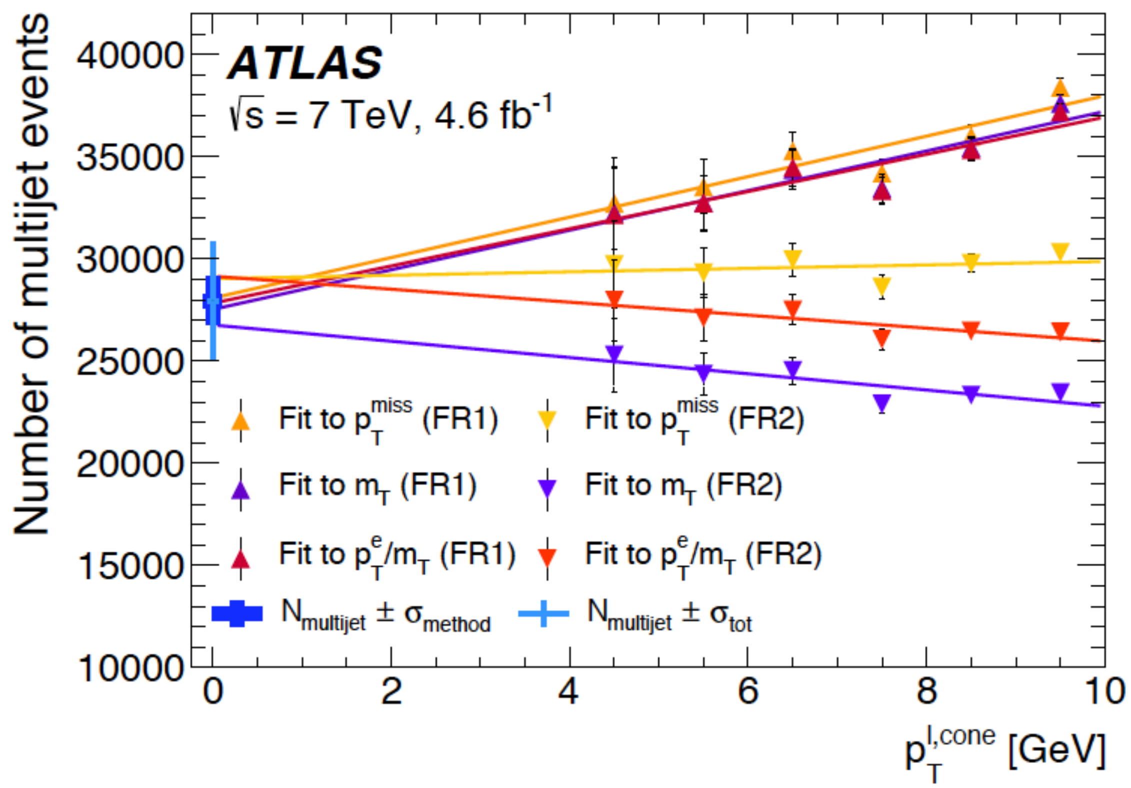
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.001
0.01
0.1
1
g/10
$xf(\mu^2 = 10^4\text{GeV}^2)$
c
s
b
u_V
d_V
$\bar{u}$
$\bar{d}$

W mass ATLAS - Background Summary



(a)





W mass ATLAS - Uncertainties Summary

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	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

$\|\eta_\ell\|$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	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

W mass ATLAS - Uncertainties Summary

$\lvert\eta_\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	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	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
ΣE_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

THEORY ERRORS: WHAT CAN WE ASSUME?

Quantity	Current theory error	Leading missing terms	Est. future theory error
$\sin^2\theta^{\ell}_{\mathrm{eff}}$	4.5×10^{-5}	$\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	$1...1.5\times10^{-5}$
R_b	$\sim 2\times10^{-4}$	$\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	$\sim 1\times10^{-4}$
Γ_Z	few MeV	$\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	< 1 MeV
M_W	4 MeV	$\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	$\lesssim 1$ MeV

Table 1-1. *Some of the most important precision observables for Z-boson production and decay and the W mass (first column), their present-day estimated theory error (second column), the dominant missing higher-order corrections (third column), and the estimated improvement when these corrections are available (fourth column). In many cases, the leading parts in a large-mass expansion are already known, in which case the third column refers to the remaining pieces at the given order. The numbers in the last column are rough order-of-magnitude guesses.*

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EXPERIMENTAL ERRORS: WHAT CAN WE ASSUME?

$\Delta \sin^2 \theta^l_{\text{eff}}\ [10^{-5}]$	ATLAS	CMS	LHC/per experiment		
$\sqrt{s}$ [TeV]	7	7	8	14	14
$\mathcal{L}[\text{fb}^{-1}]$	4.8	1.1	20	300	3000
PDF	70	130	35	25	10
higher order corr.	20	110	20	15	10
other systematics	70	181	60 (35)	20	15
statistical	40	200	20	5	2
Total	108	319	75 (57)	36	21

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