EW & QCD results and prospects

Strategic Workshop on Particle Physics in Switzerland

Kostas Theofilatos (**ETH Zurich**)

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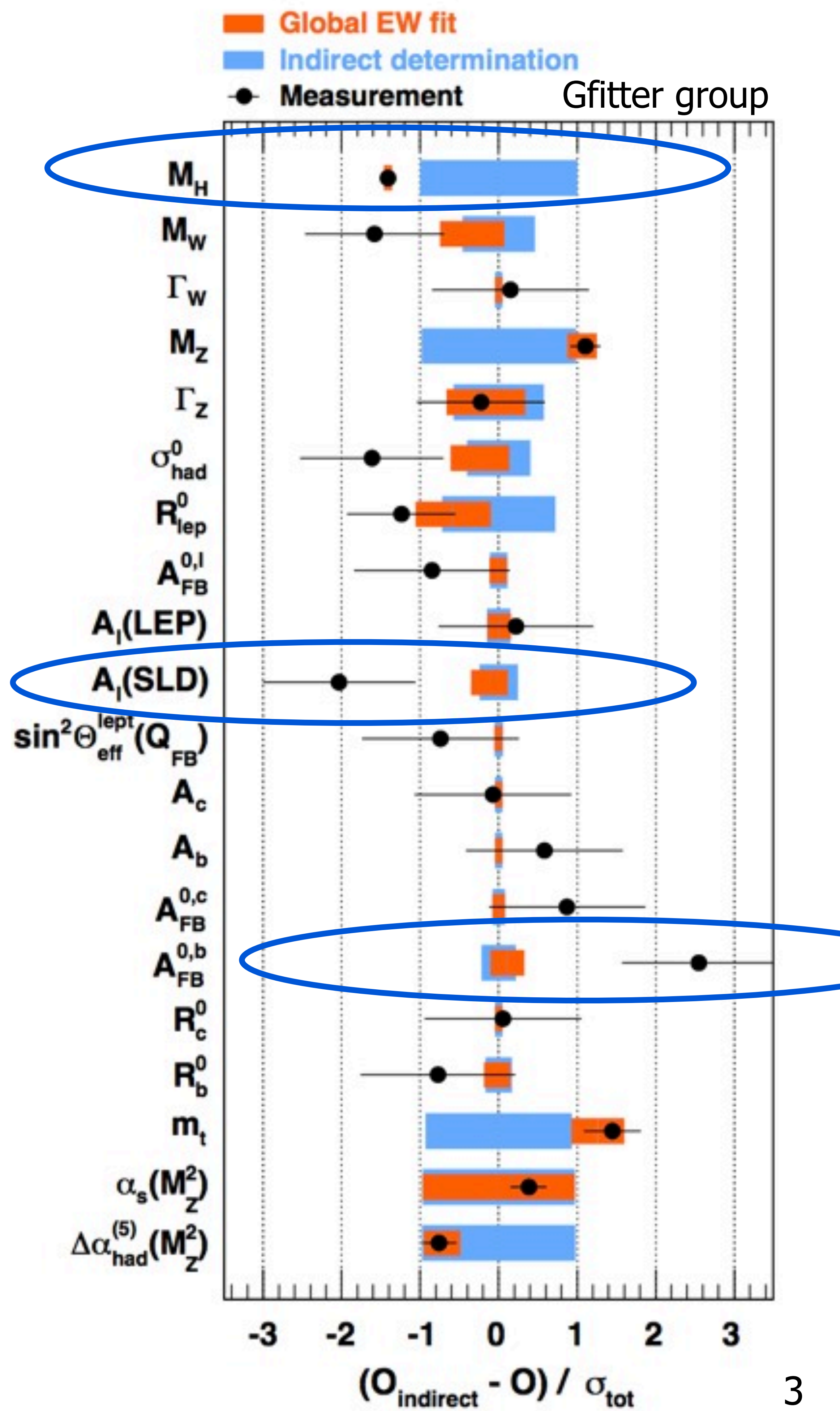
Introduction

This is not a review talk!

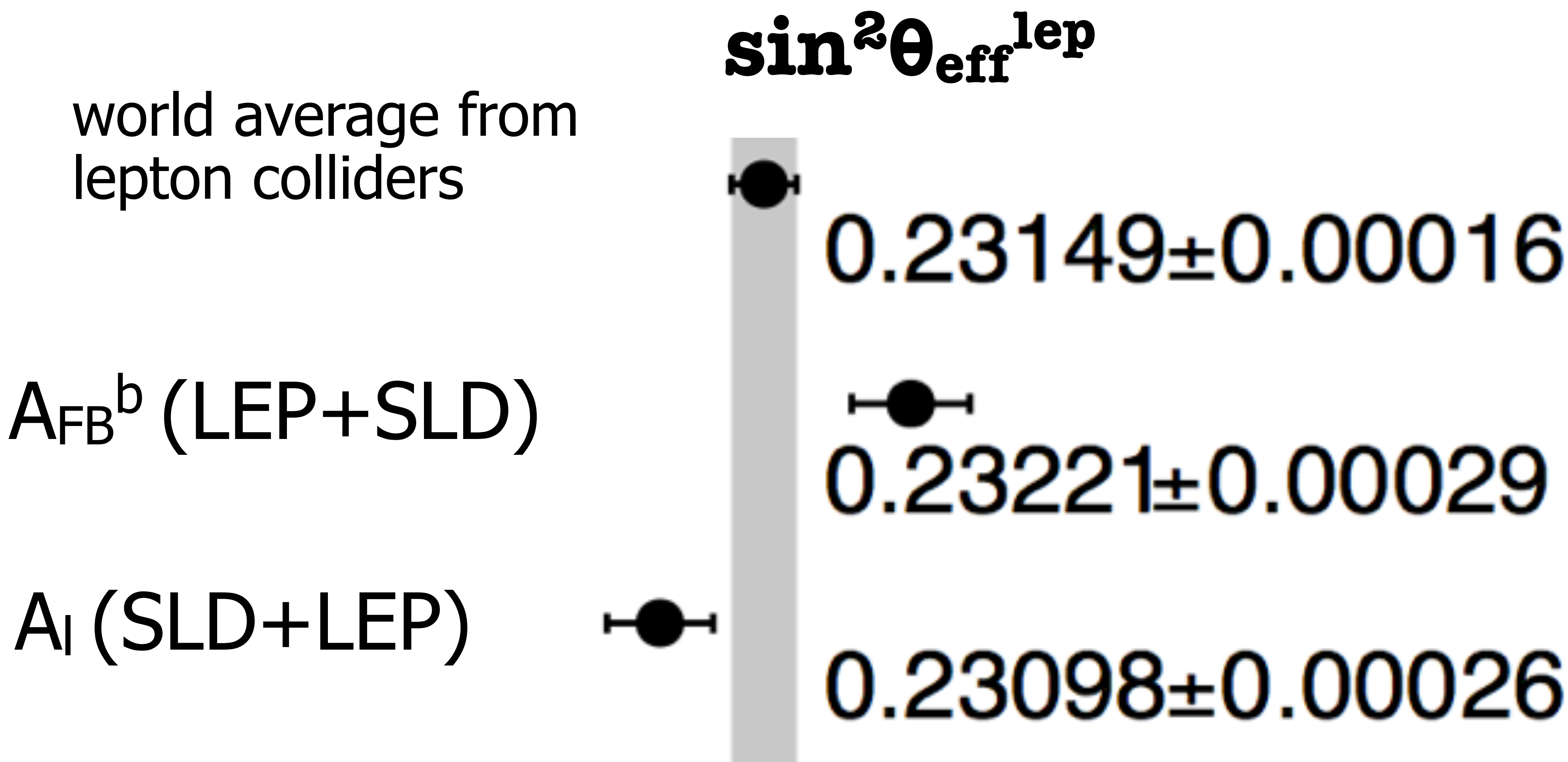
- A complete experimental summary on **EW**, **QCD** & **PDFs** can be found in Blois and Moriond 2016 conferences
- I've made a **preselection of specifics topics** that I thought might be good to mention in this workshop
- I also took ideas/slides from F. Cossutti, H. Jung, K. Rabbertz, J. Kunkle and S. Djuric

The EW global fit

- Assuming **M_H** @ **125 GeV** is the **SM Higgs**, fit becomes overconstraint & very predictive (indirect determinations)
- Overall SM fit is not bad but
  - The fit prefers a ~bit lighter SM Higgs predicting **M_H = 93 ± 25 GeV**
  - Tension between **A_l(SLD)** and **$A_{FB}^{0,b}$** , removing **$A_{FB}^{0,b}$** would make the fit worse predicting even lighter **M_H**

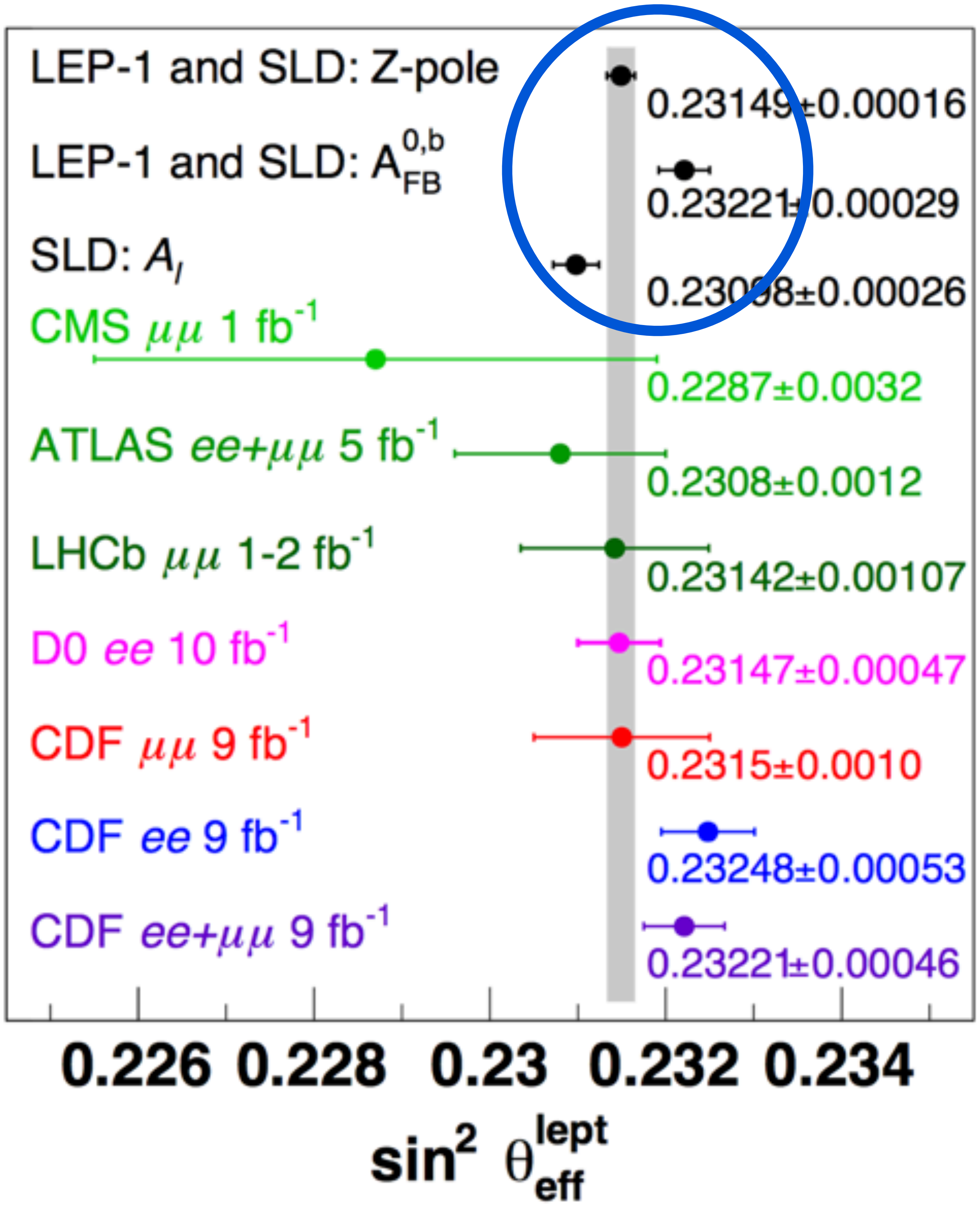


A closer look into the problem



- There is 3.2σ tension (p-value ~ 0.2%)
- We need new measurements to shed light into this

Hadron colliders weigh in



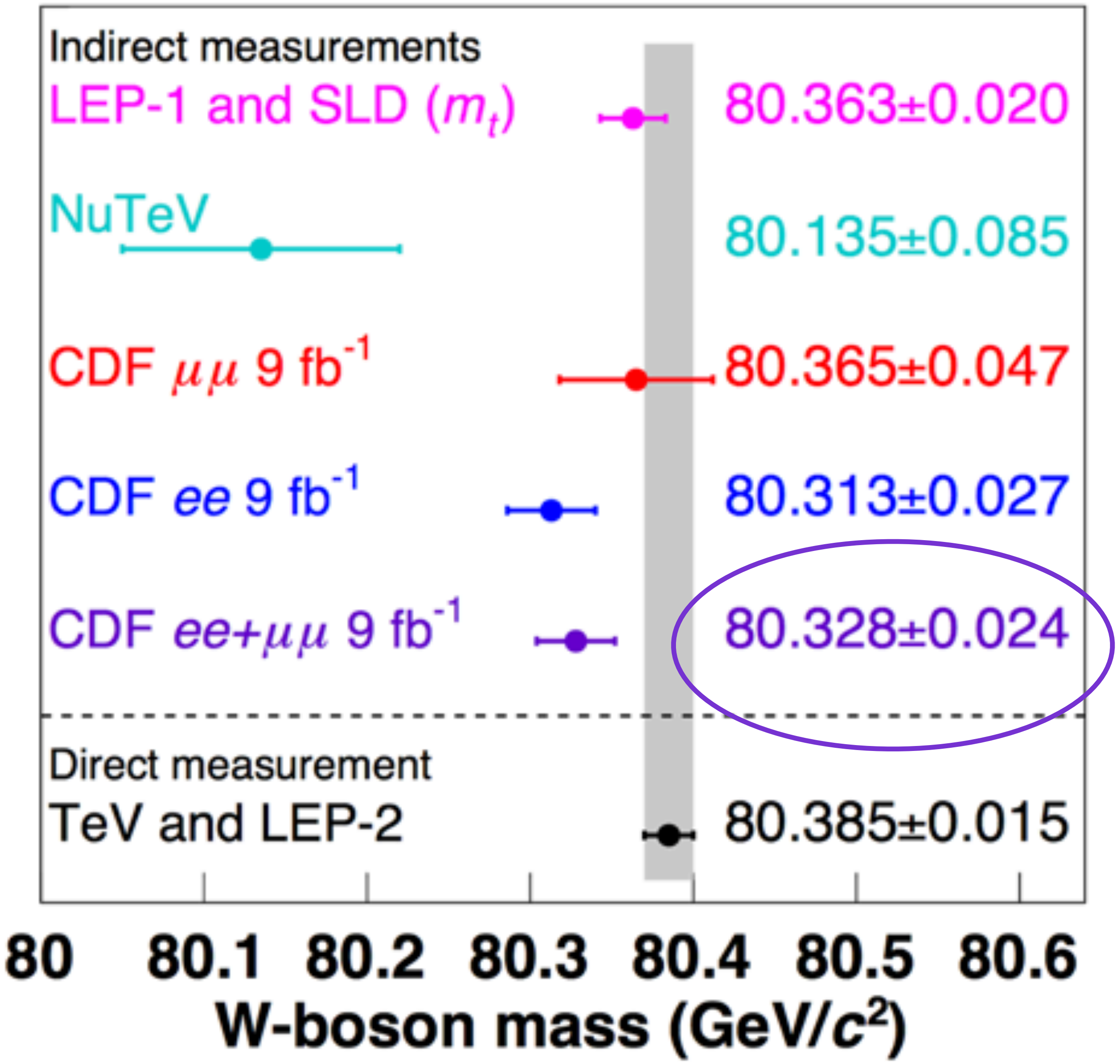
More measurements are useful if they come with similar precision wrt those we want to cross-check

precision	
0.1%	SLD
0.1%	LEP
0.5%	ATLAS/LHCb
0.2%	D0/CDF
COMING SOON	CMS

http://arxiv.org/abs/1605.02719

Hadrons colliders start to rival LEP/SLD in terms of precision

Indirect M_W (CDF)



LEP data

$$M_W \text{ (indirect)} = M_Z \cos\theta_W$$

*on shell renormalization scheme

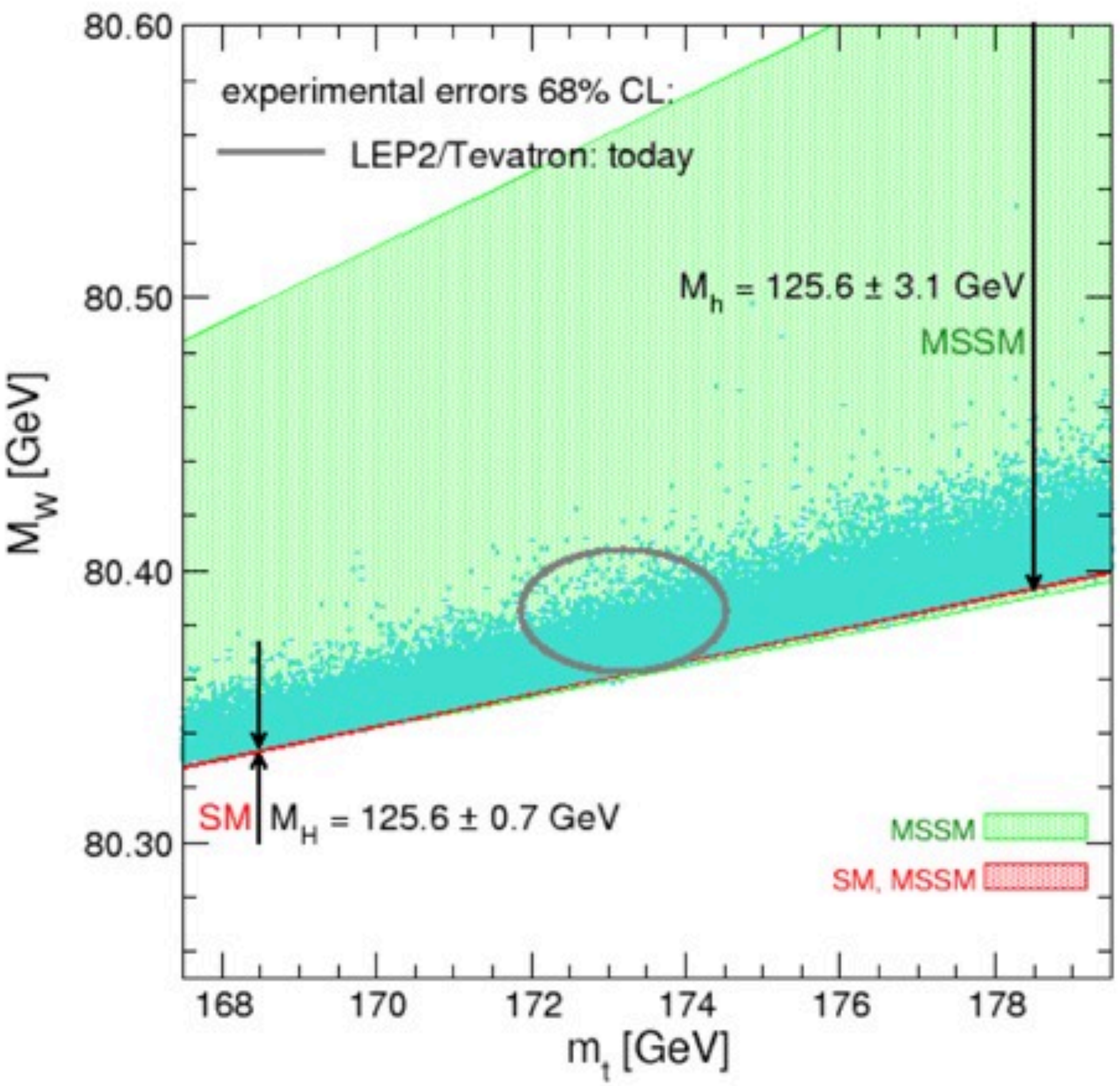
0.03% precision

CDF data

M_W in SM and MSSM

direct (world av.)	**80385 ± 15 MeV**	**(0.02%)**
indirect (fit)	**80358 ± 8 MeV**	**(0.01%)**

sets the bar for the LHC



http://arxiv.org/abs/1311.1663

SM (fit) prefers a bit lighter W-boson than current world average

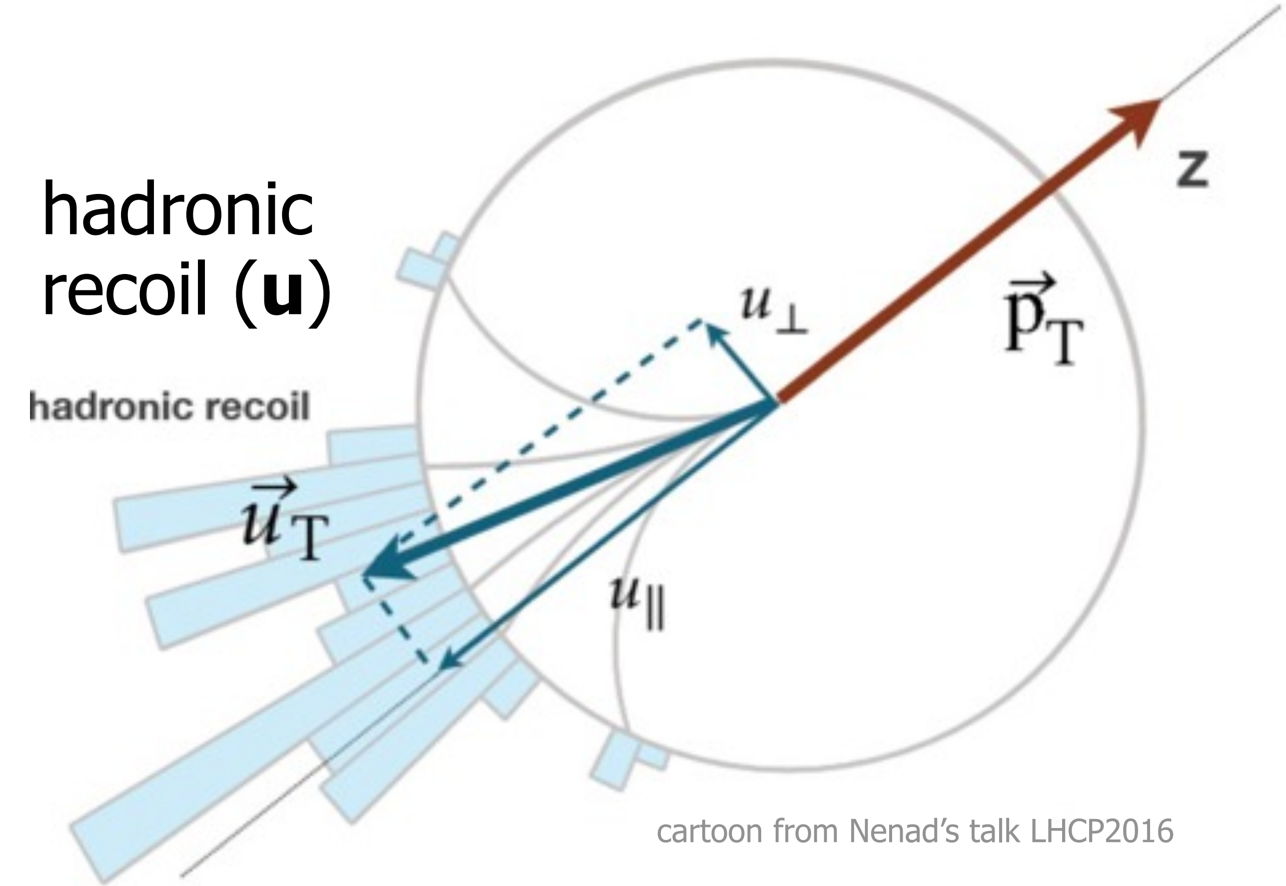
MSSM prefers heavier W-boson than what SM does

The challenge for measuring M_W

Experimental challenge for δM_W = 10 MeV

$\delta p_T/p_T$	0.01%
$\delta u_{||}/u_{ii}$	0.1%

hadronic recoil (**u**)

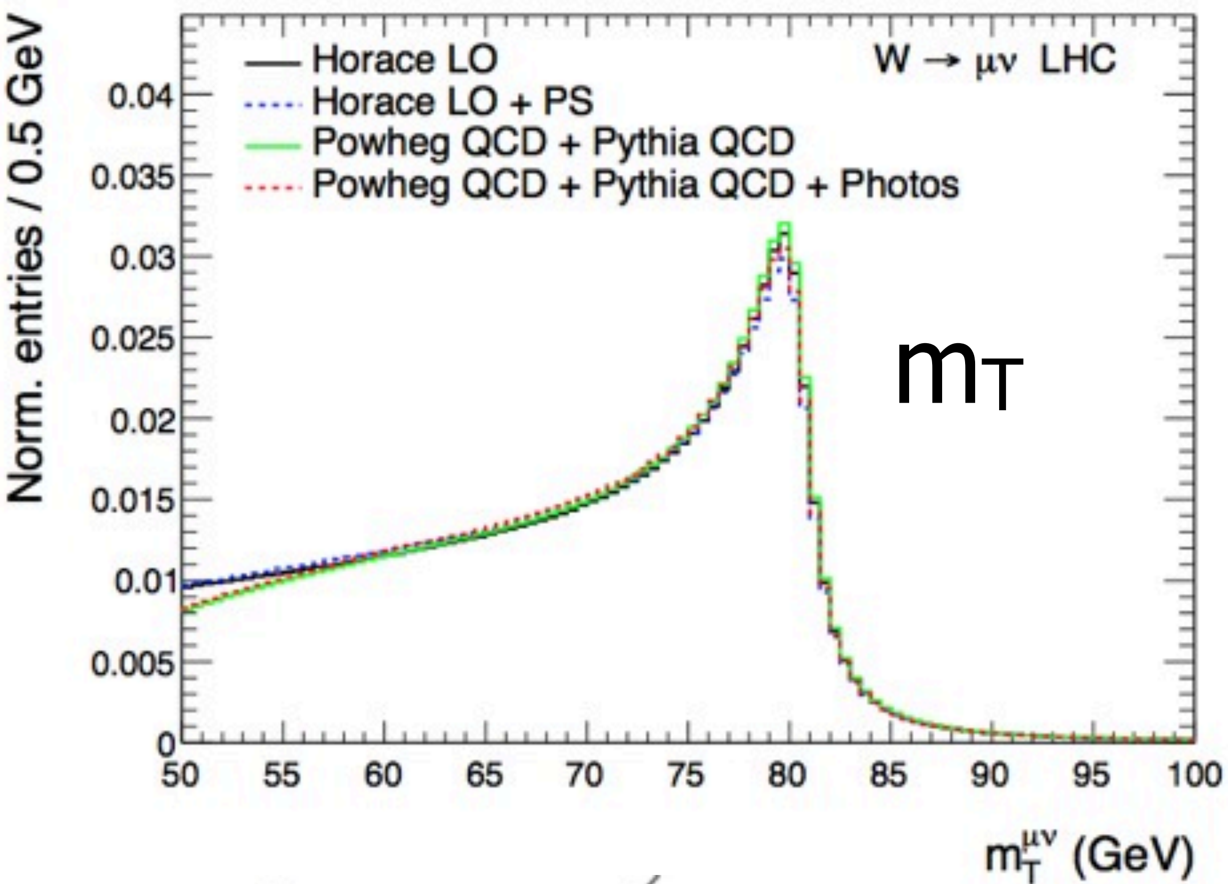


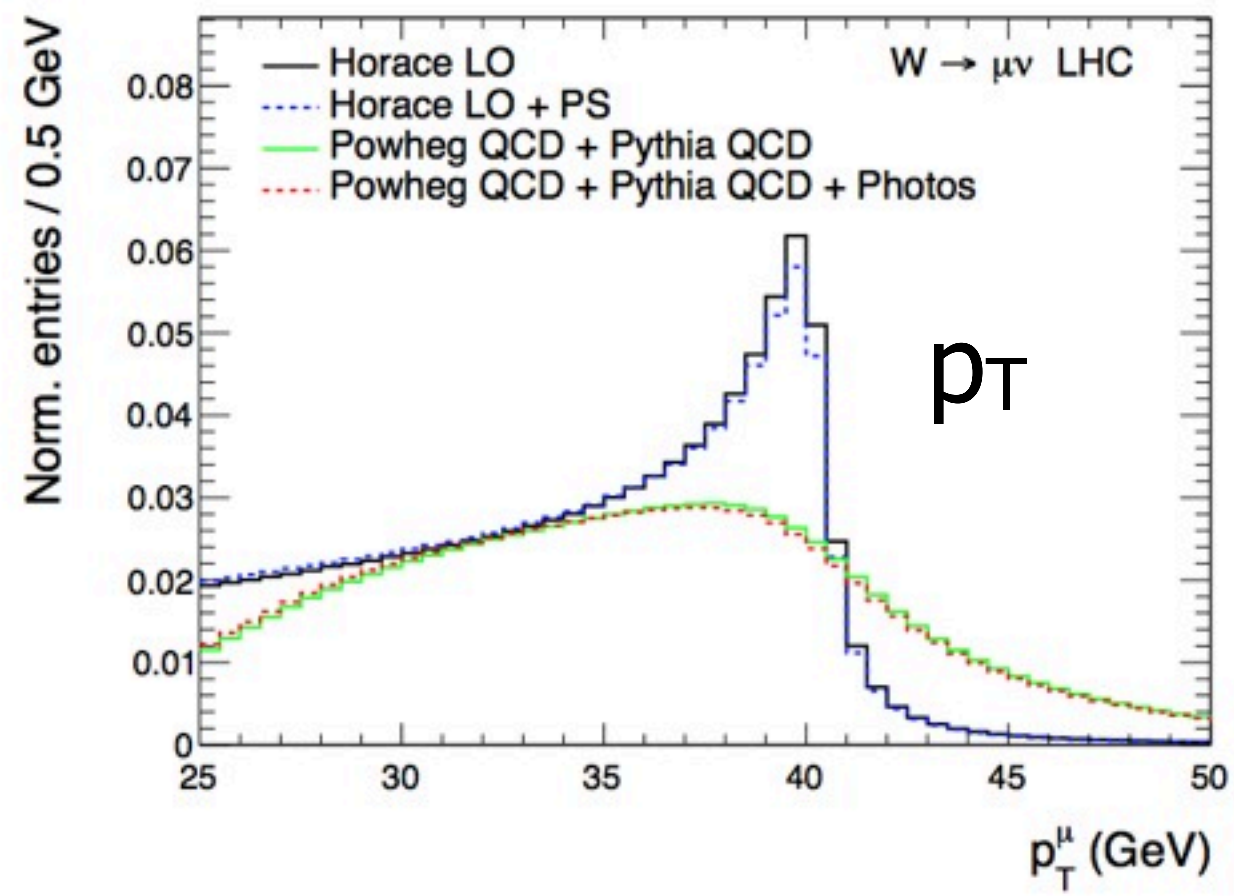
cartoon from Nenad's talk LHCP2016

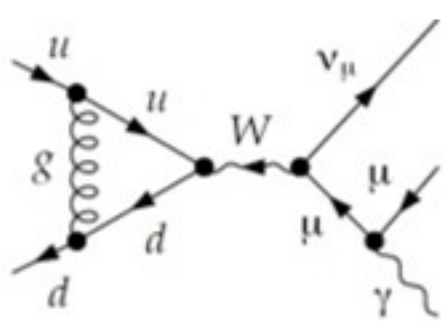
M_W can't be reconstructed per event. What to do ? Fit MC(M_W) templates to data. Observables of interest to fit :

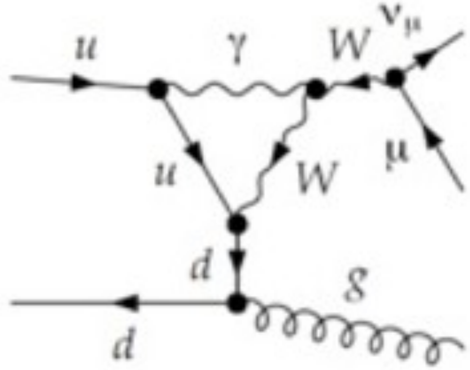
- P_T charged lepton small experimental & large theory uncert. on P_T(W)
- $M_T = 2p_T E_T^{miss}(1-\cos\Delta\varphi)$ has large experimental but smaller theory uncert.

Theory uncertainties on M_W







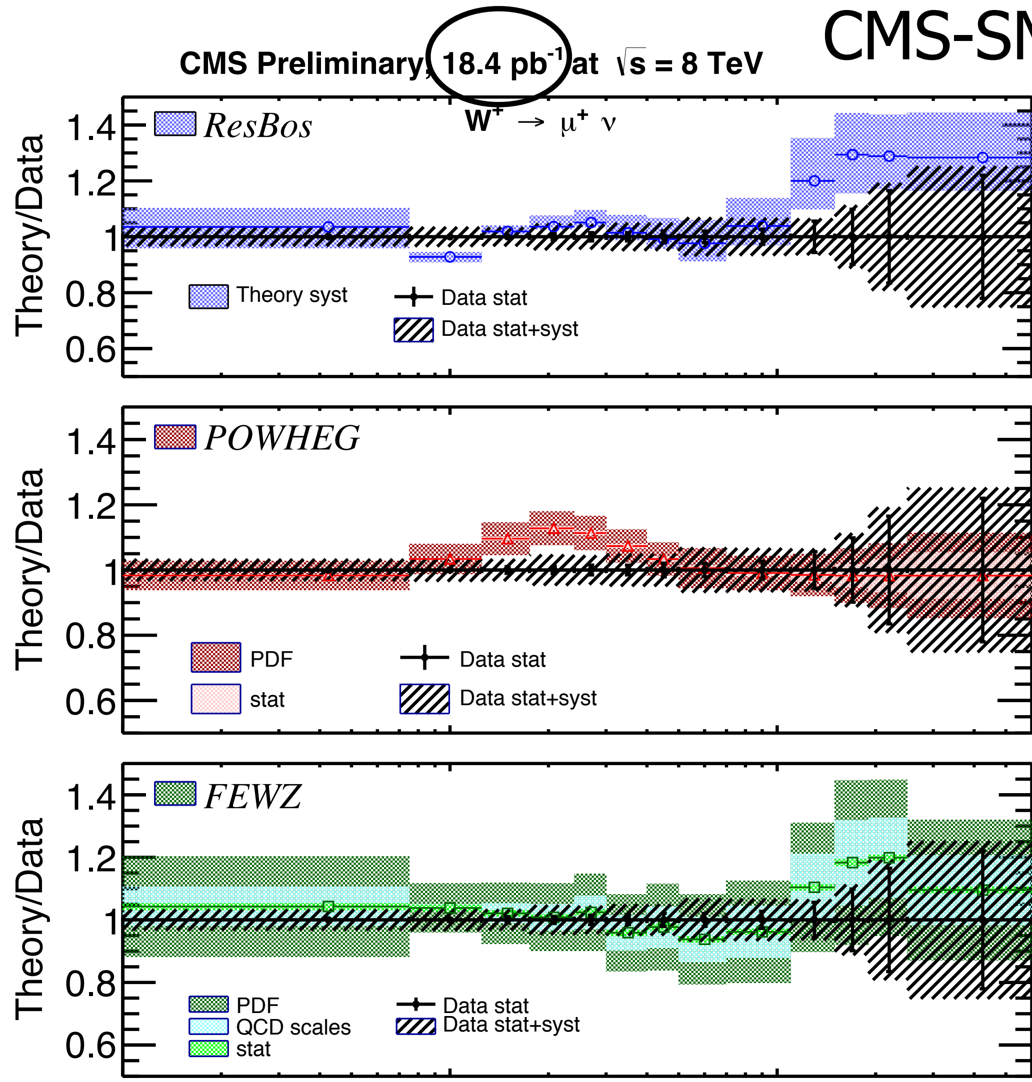


O(100 MeV) shifts on M_W due to theory uncertainties threaten the M_W measurement

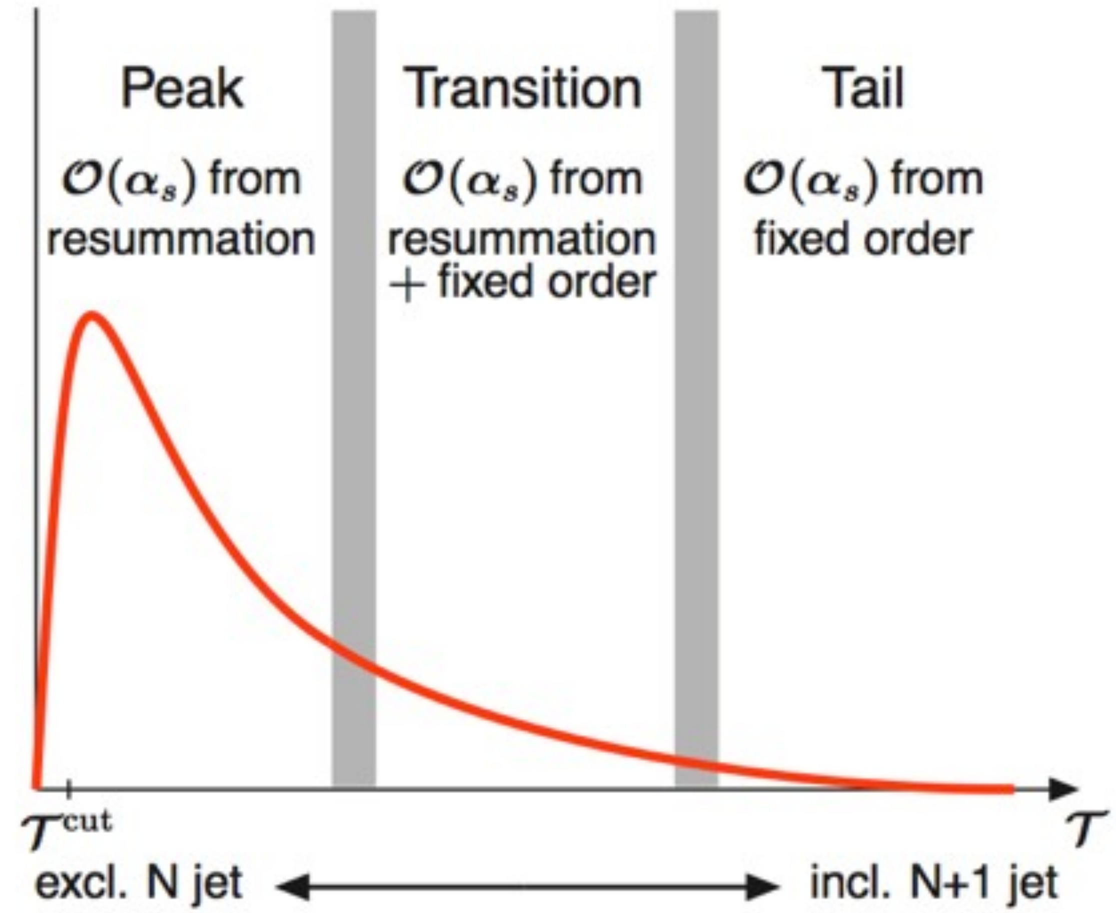
See Alessandro Vicini's talk for details on the theoretical challenges

The p_T recoil of W

CMS-SMP-13-006



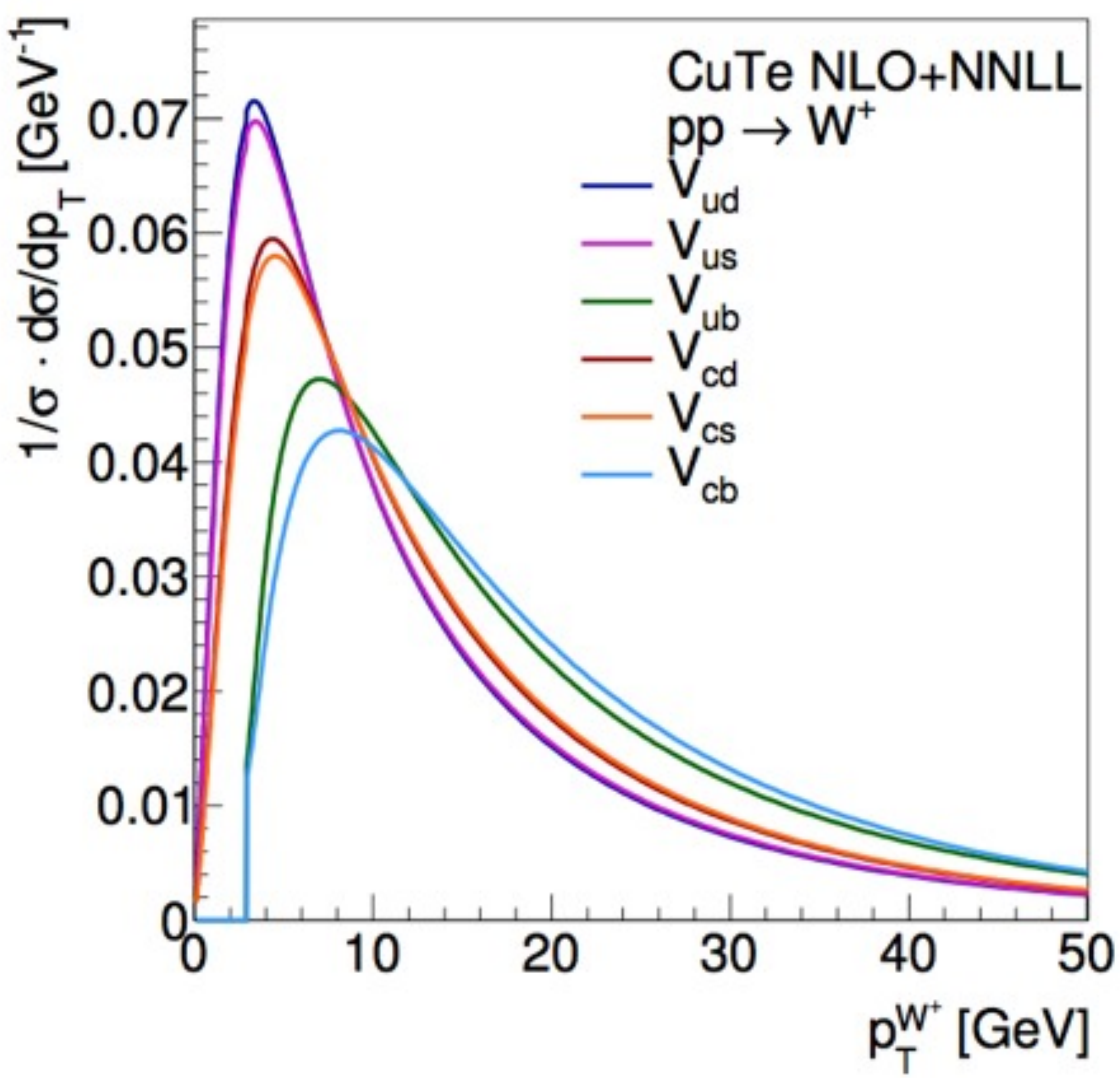
S. Alioli

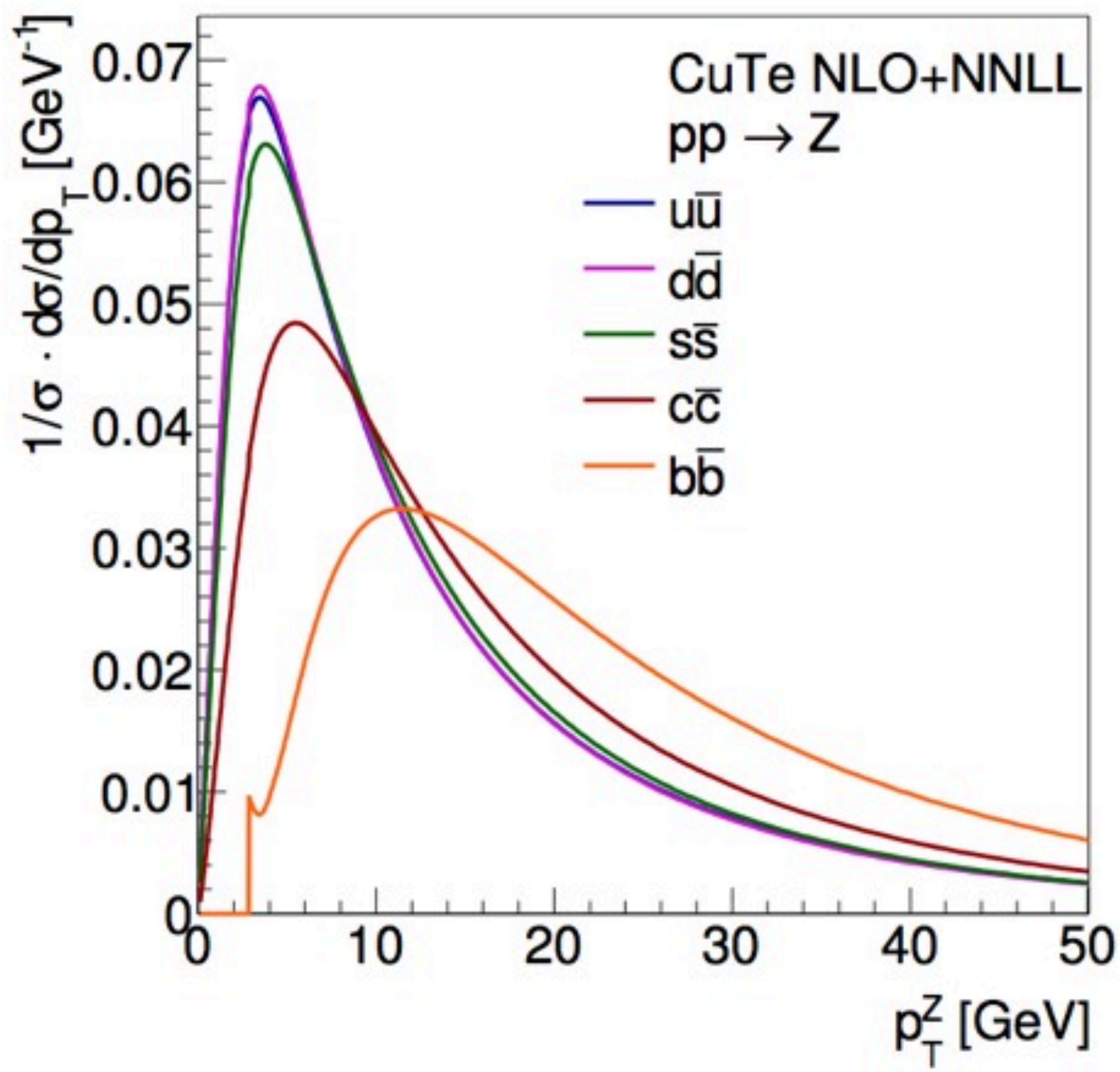


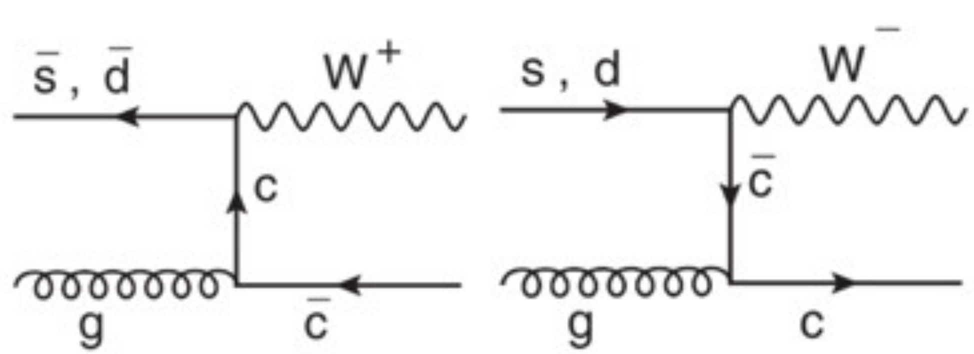
- In theory, we need to merge regimes that are described by different approximations
- CMS measured $P_T(W)$ in **special LHC runs** with very low pile-up, but that doesn't allow to collect much data. $P_T(W)$ is corrected for leptonic reco efficiencies, which are measured with Z^0 [has ~10 lower cross section, precision is driven by L x σ(Z)]
- We can always ask for more special runs to reduce uncertainties, alternatively one can use the $P_T(Z)$ and extrapolate using theoretical ratio $k = P_T(W)^{theory}/P_T(Z)^{theory}$

PDFs for M_W

ATL-PHYS-PUB-2014-015

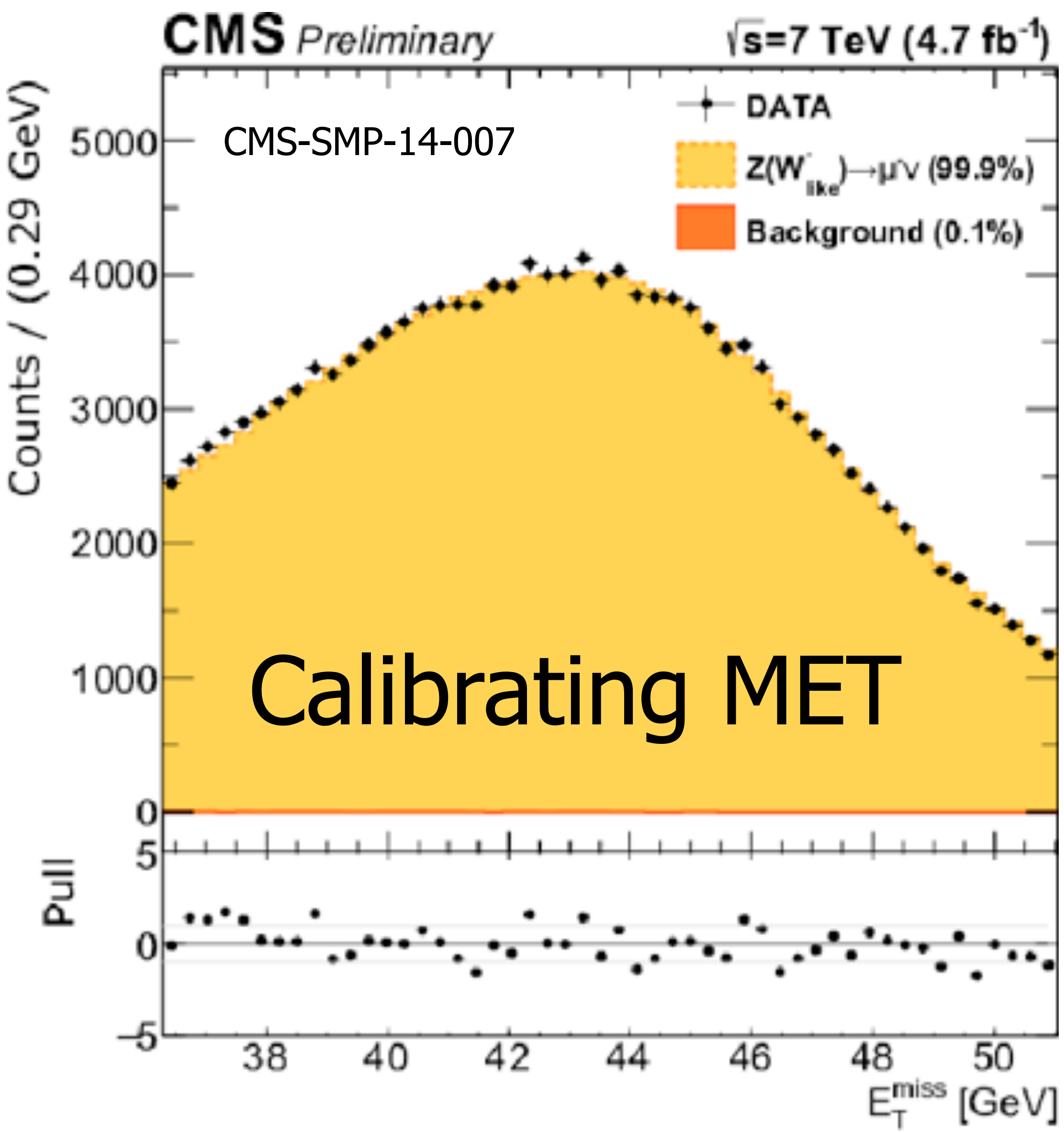


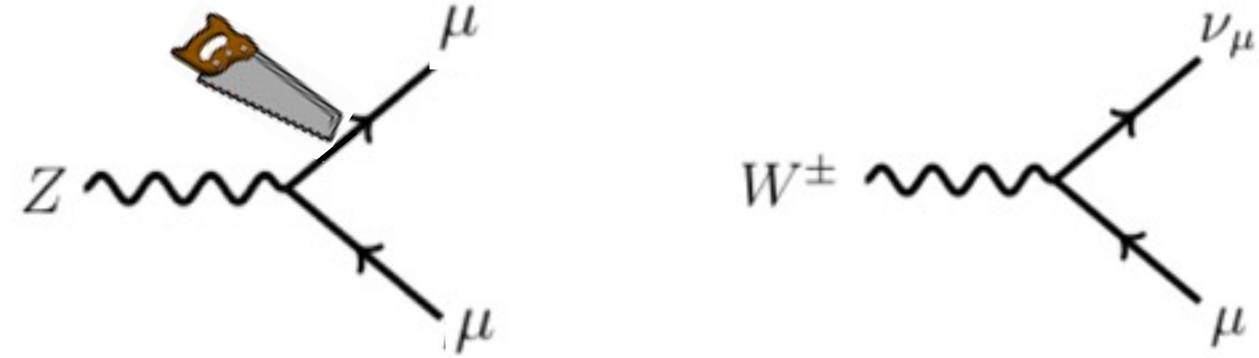




$P_T(W)$ and $P_T(Z)$ "see" different views of the proton! Large PDF uncertainty if extrapolate $P_T(Z) \rightarrow P_T(W)$

Calibrations for M_W (CMS)

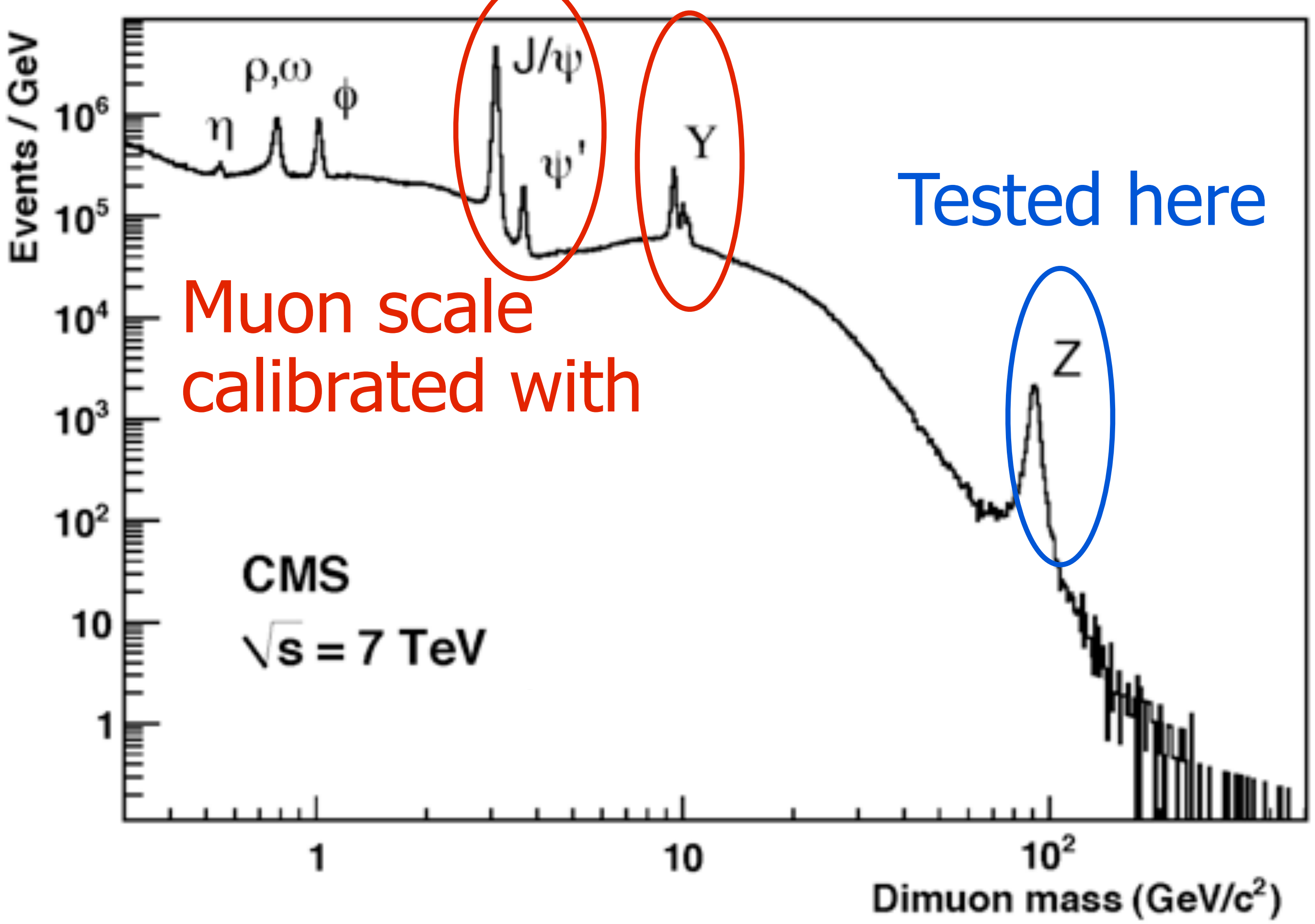


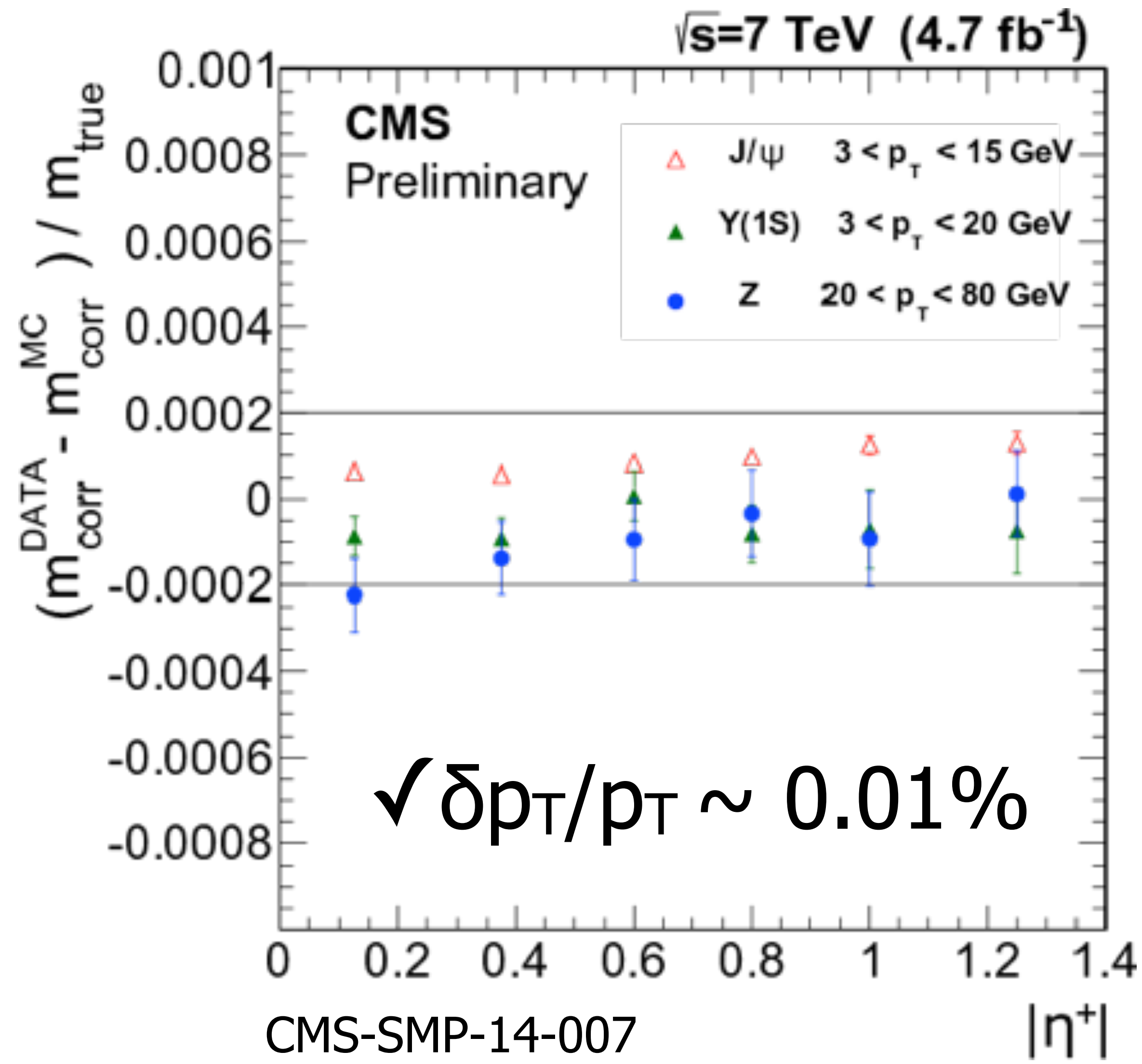


- Cut away one μ from the Z decay to mimic W, reconstruct $M_Z^{W\text{-like}}$
- Analysis features special "CMS tracker-only" MET reconstruction

Proof of principle that **MET (MT)** calibration can reach ~**14 (9) MeV** precision (from studies on $\mathbf{M_Z^{W\text{-like}}}$)

Calibrations for M_W (CMS)





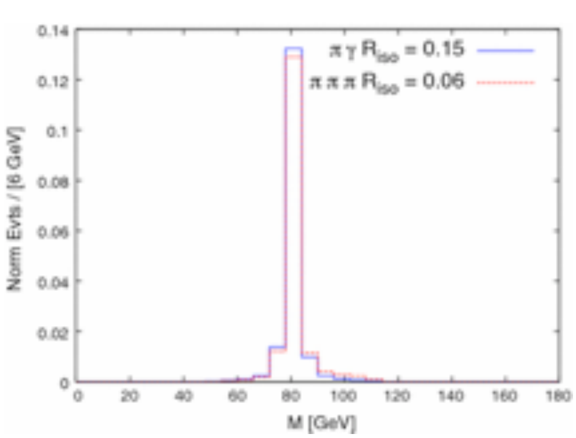
http://coffeeshopphysics.com/cmsresults/

Calibrating Muons: muon energy scale for measuring M_W has reached the prerequisite precision

Prospects for a direct M_W

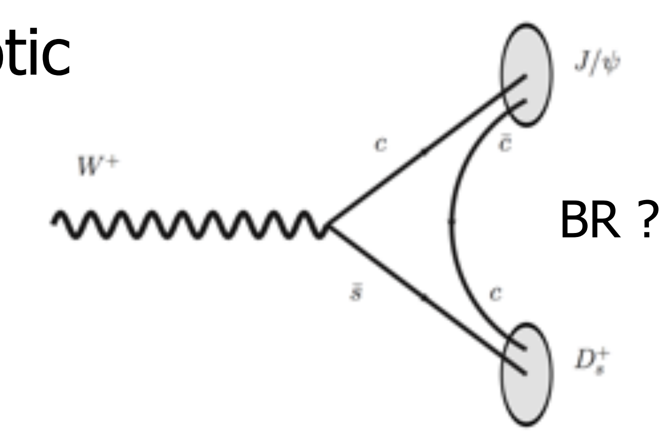
✓ Experiments are close-to-be-ready (sooner or later) ;-)

- $P_T(W)$? use $P_T(Z)$ to calibrate it or a direct $P_T(W)$ measurement in data ? :-|
- PDFs ? potential improvement by combining LHCb & CMS/ ATLAS data :-|
- Theory uncertainties :'-(
- **Other means for measuring M_W ?** :-X
  - Mangano & Melia used W-> hadrons to fully reconstruct m_W (concluded that is beyond reach of HL-LHC)



$$W^+ \to \pi^+\pi^+\pi^-,$$
$$W^+ \to \pi^+ p \bar{p},$$
$$W^+ \to \pi^+ K^+ K^-$$
$$W^+ \to \pi^+ n^0 \bar{n}^0,$$
$$W^+ \to \pi^+ \pi^0 \gamma,$$

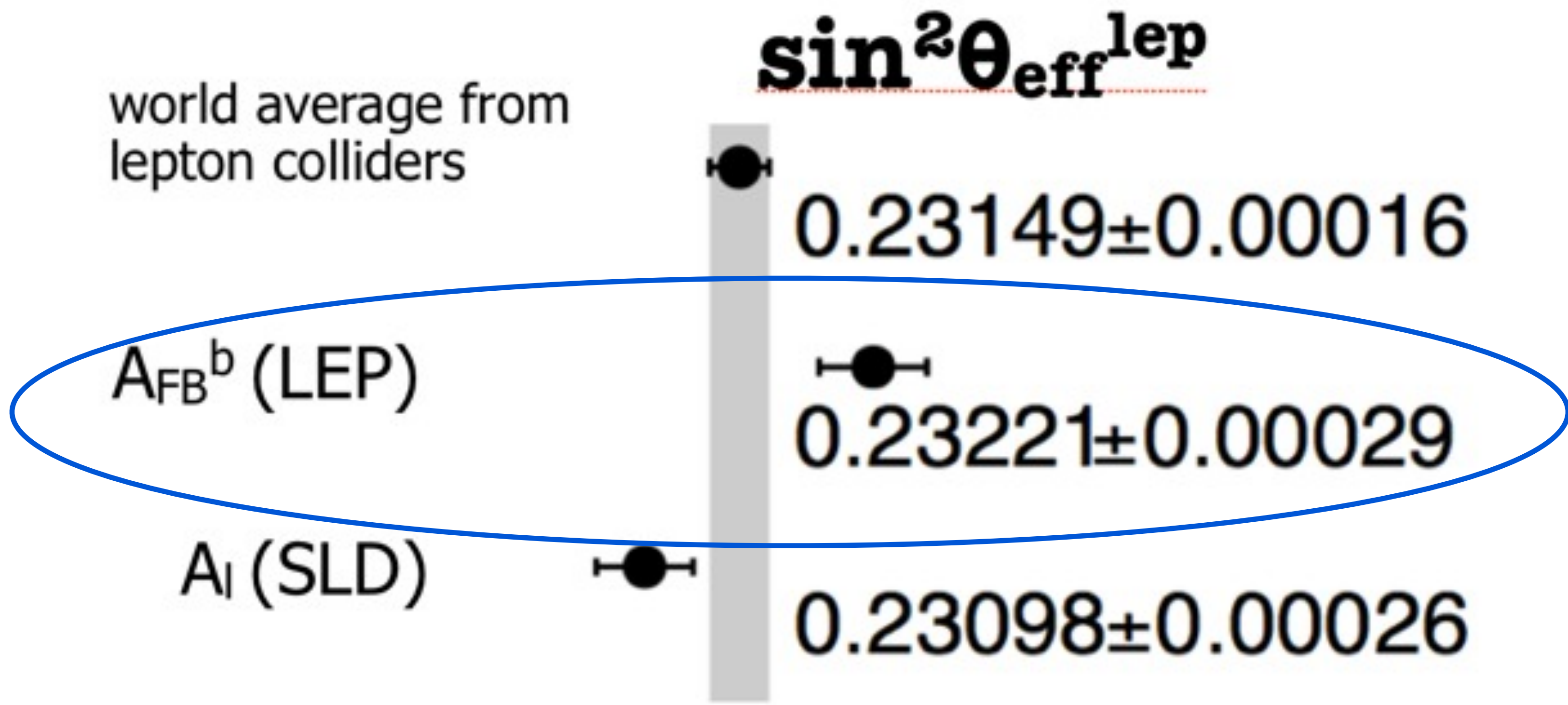
more exotic ideas?



http://link.springer.com/article/10.1140/epjc/s10052-015-3482-x

Open for challenge

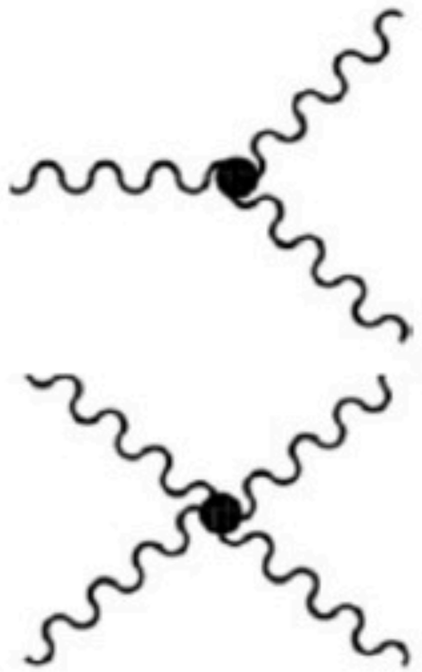
Can this be investigated at the LHC ? maybe, but this wouldn't be an easy measurement, a recent proposal [PLB 730 (2014) 149-154]



- Confirming the tension might have implications for the nature of BSM physics (e.g., MSSM would not be able to explain the data)

Physics with boson-boson interactions

EW is a non-abelian theory

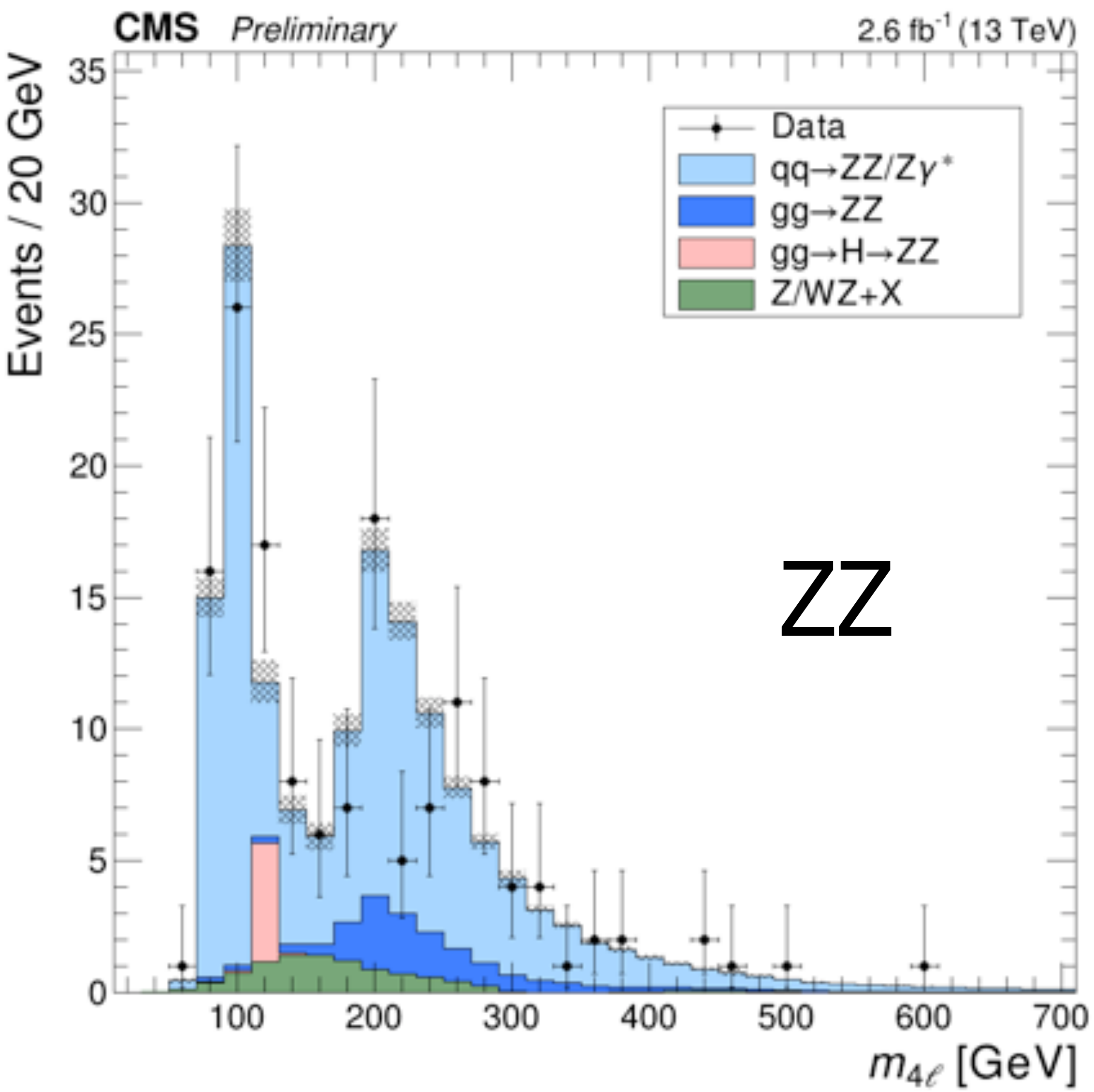


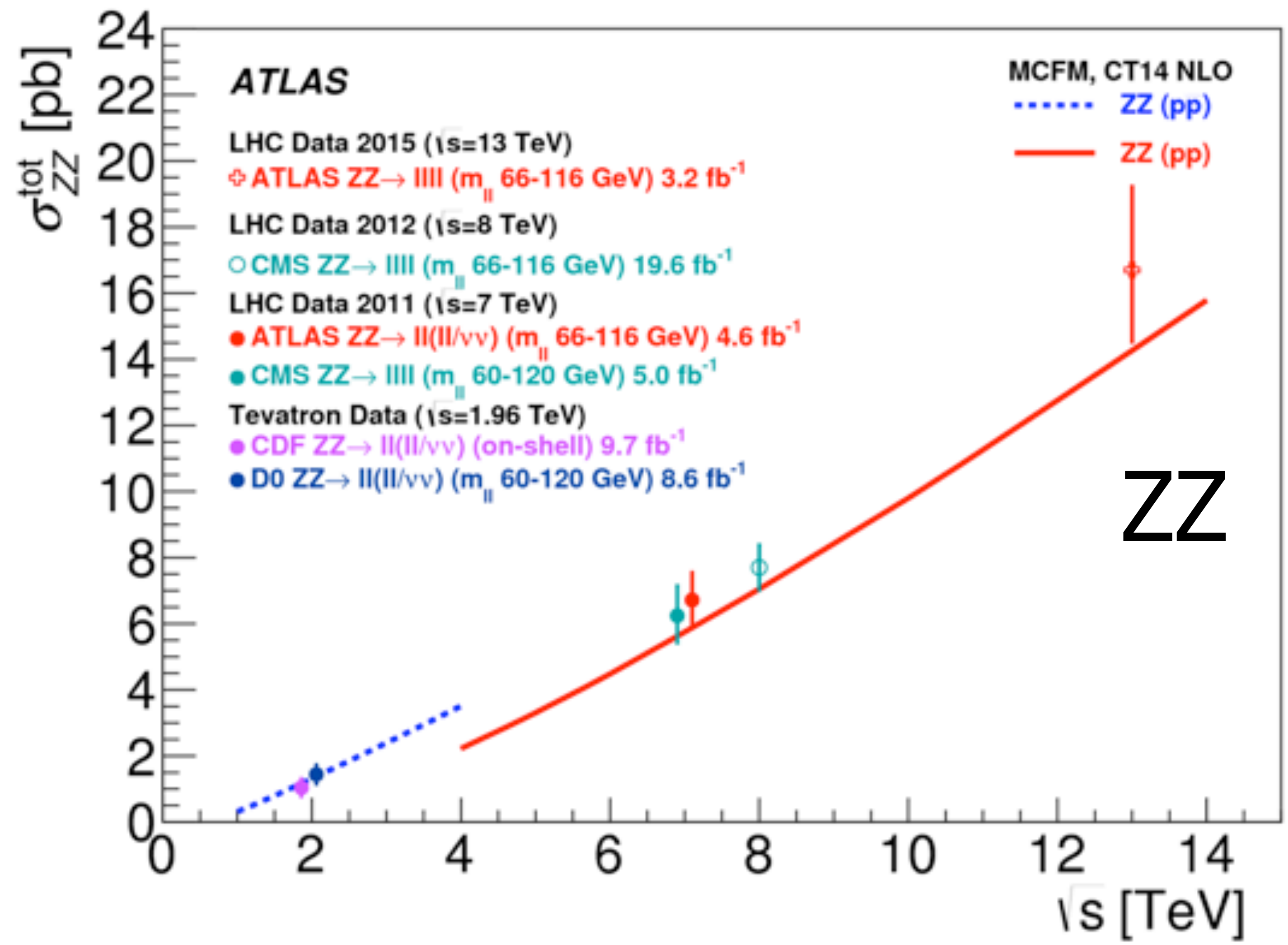
coupling	parameters	channel
$WW\gamma$	$\lambda_\gamma, \Delta k_\gamma$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta k_Z, \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	$f_{40}^\gamma, f_{50}^\gamma$	ZZ
ZZZ	f_{40}^Z, f_{50}^Z	ZZ

Anomalous couplings
parametrized with EFT

- Tests of the gauge structure of the SM inevitably mix Higgs with VV(V) see F. Riva's talk
- Some channels are yet-to-be observed, multibosons have not entered the precision frontier yet ...

Dibosons @ 13 TeV

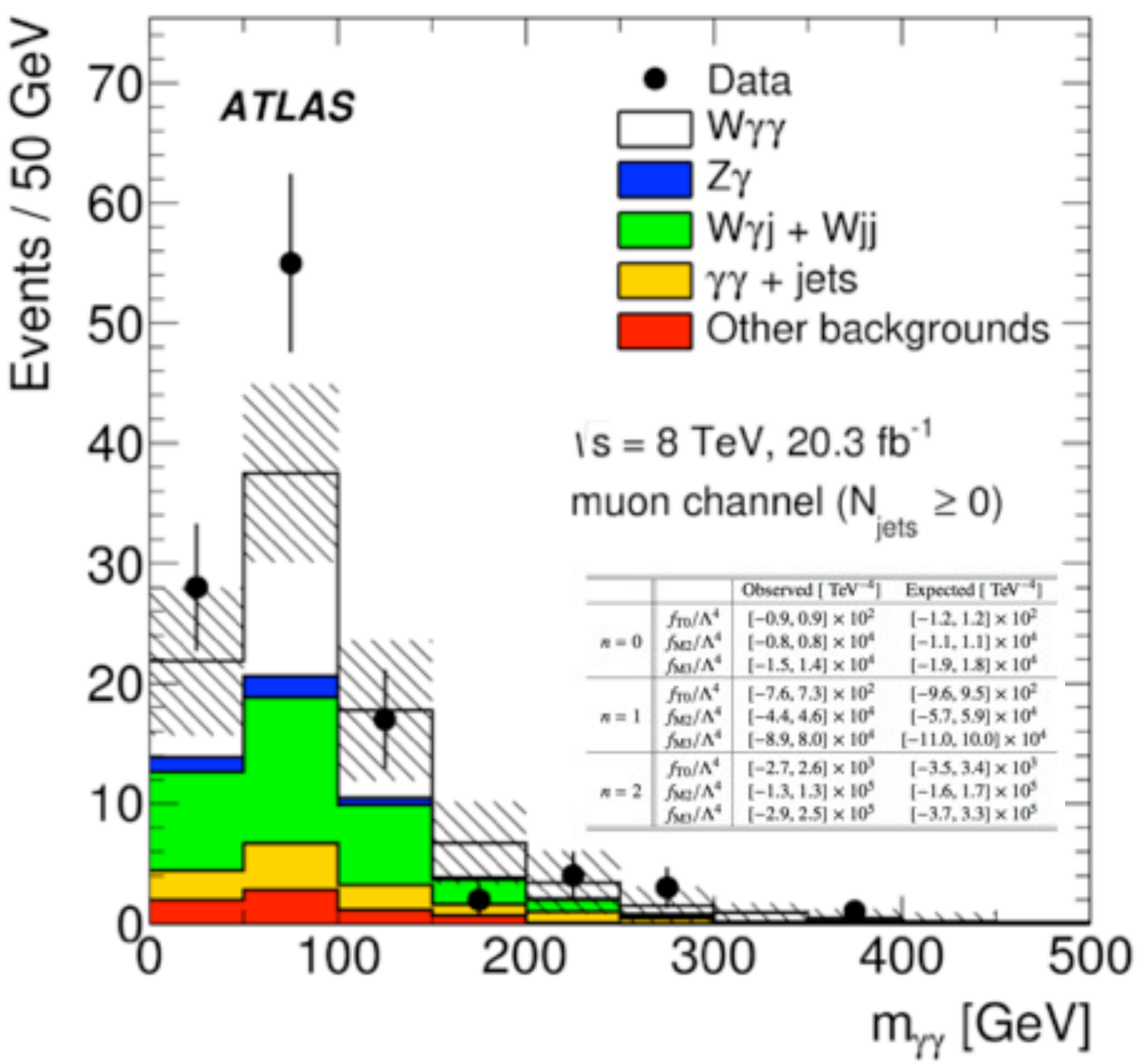




- ZZ (and WZ) were the first diboson results at 13 TeV, SM Higgs is a background in the VV cross section measurement

Wγγ - first evidence (>3σ)

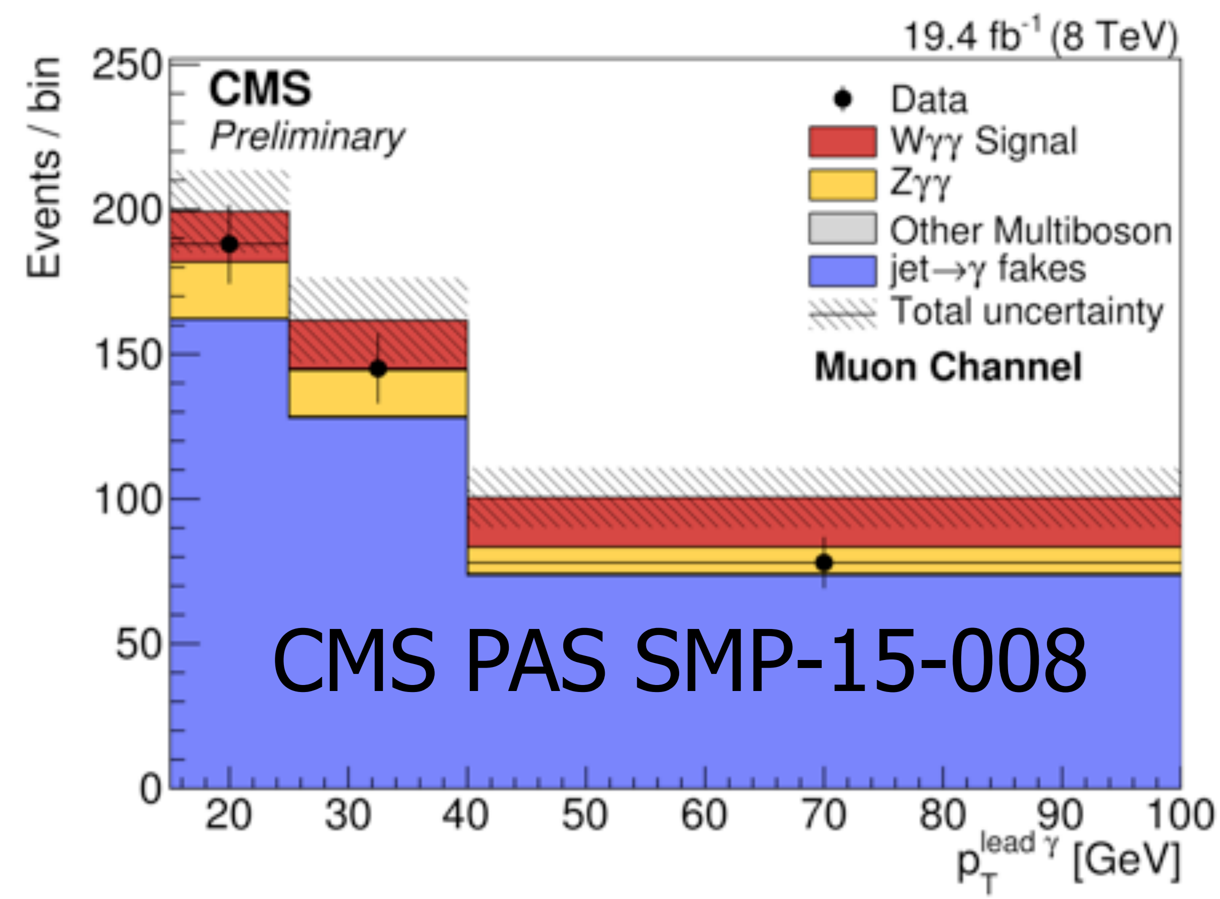
PRL 115 031802 (2015)



		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n = 0$	f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$
$n = 1$	f_{T0}/Λ^4	$[-7.6, 7.3] \times 10^2$	$[-9.6, 9.5] \times 10^2$
	f_{M2}/Λ^4	$[-4.4, 4.6] \times 10^4$	$[-5.7, 5.9] \times 10^4$
	f_{M3}/Λ^4	$[-8.9, 8.0] \times 10^4$	$[-11.0, 10.0] \times 10^4$
$n = 2$	f_{T0}/Λ^4	$[-2.7, 2.6] \times 10^3$	$[-3.5, 3.4] \times 10^3$
	f_{M2}/Λ^4	$[-1.3, 1.3] \times 10^5$	$[-1.6, 1.7] \times 10^5$
	f_{M3}/Λ^4	$[-2.9, 2.5] \times 10^5$	$[-3.7, 3.3] \times 10^5$

	$\sigma^{\rm fid}$ [fb]	$\sigma^{\rm MCFM}$ [fb]
Inclusive ($N_{\rm jet} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\rm jet} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

interesting excess in ATLAS analysis

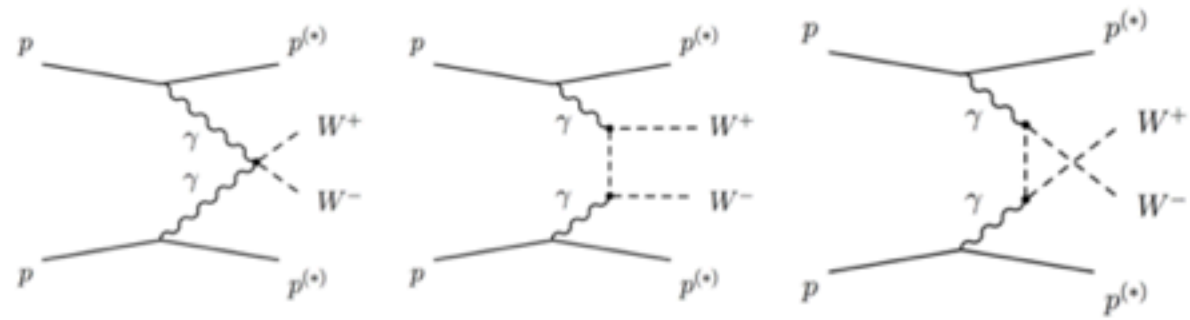


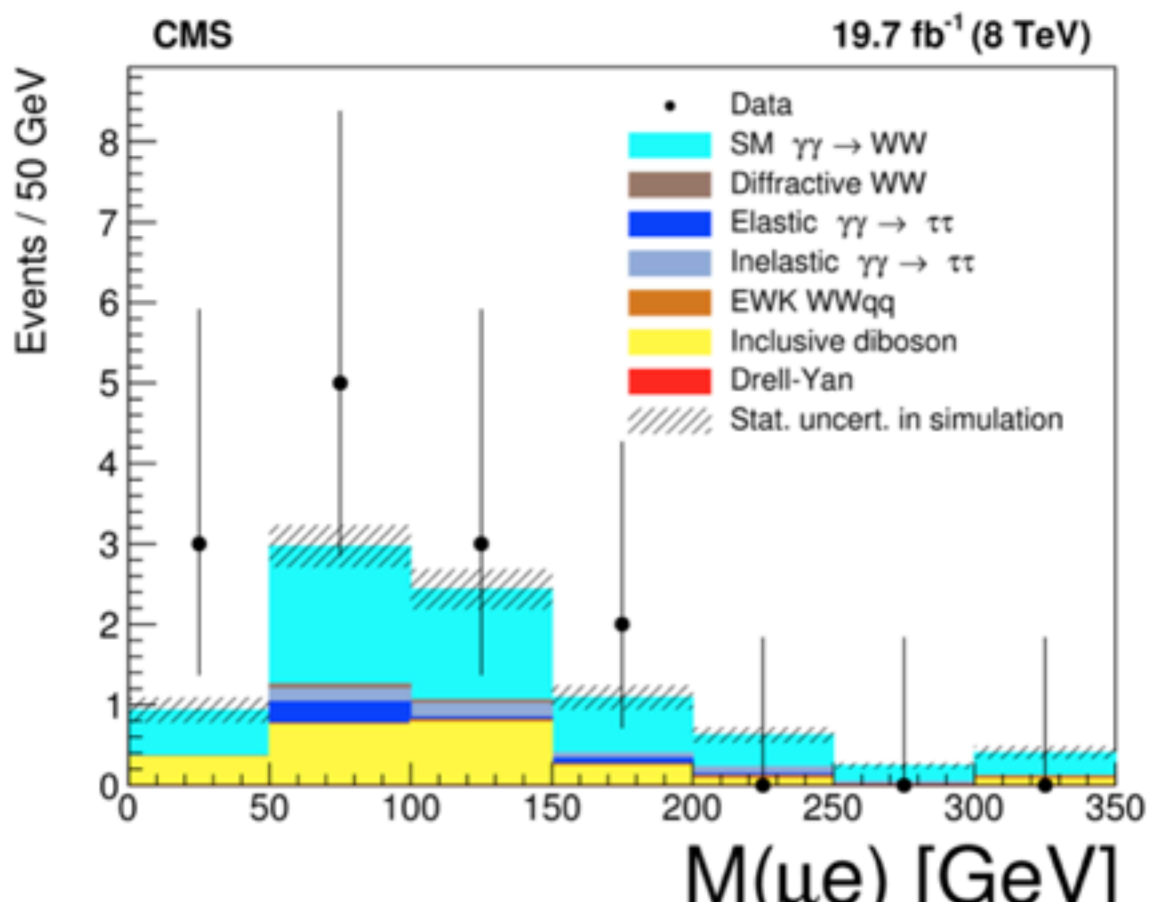
limits on aQGC

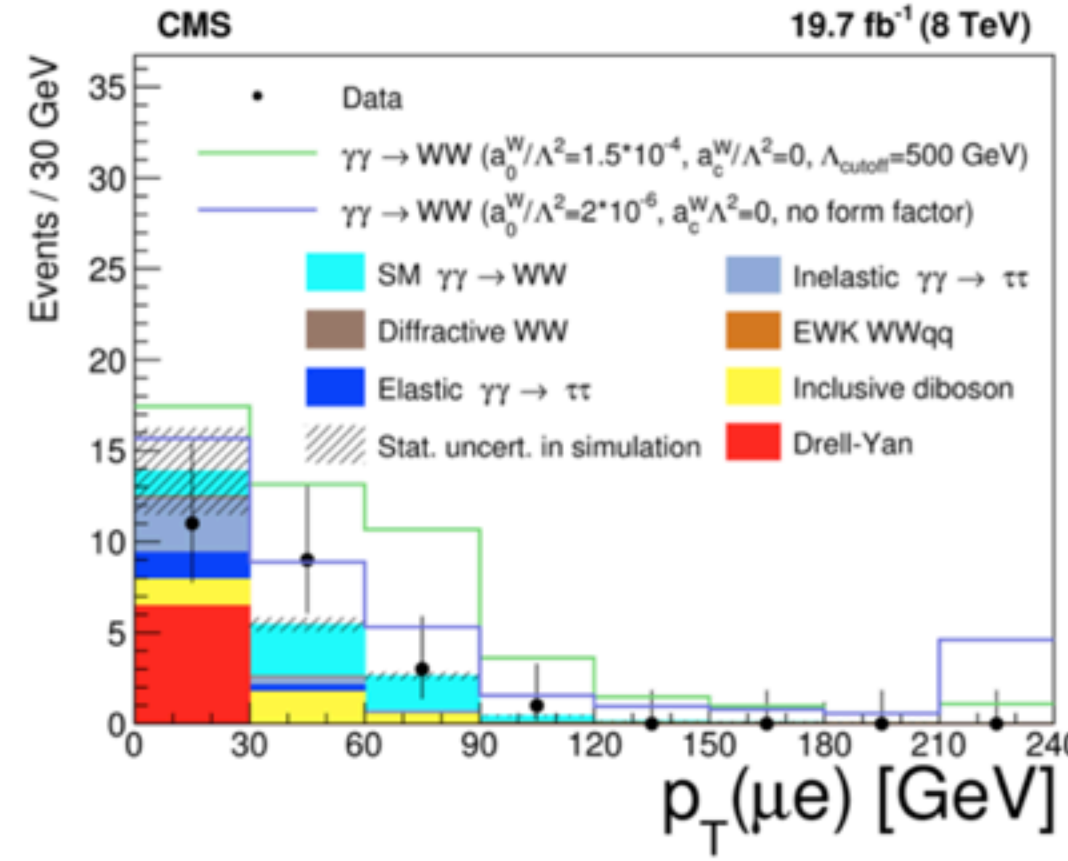
[contributing mainly to $m_{\gamma\gamma}$>300 GeV]

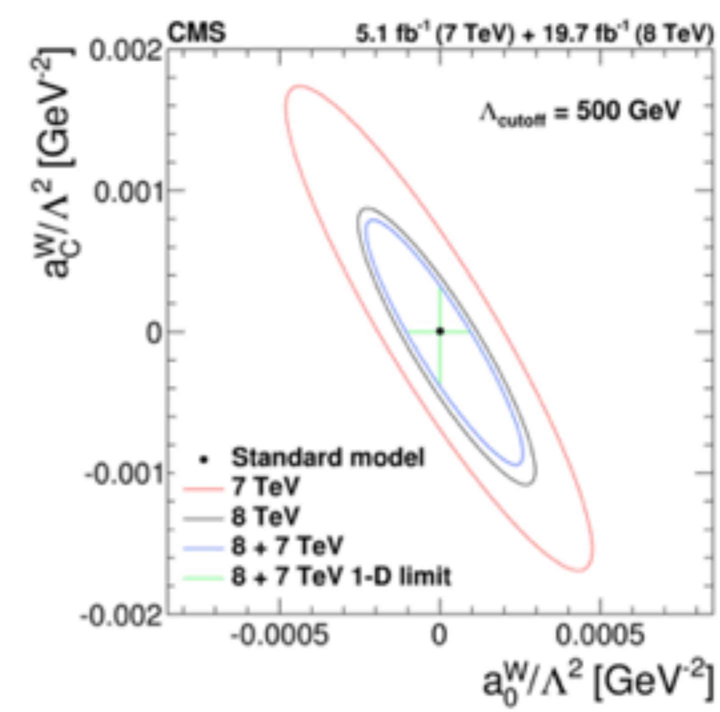
γγ->WW - first evidence

- $pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}$ @ 7,8 TeV
- Combined significance of 3.4σ
- Limits on aQGC





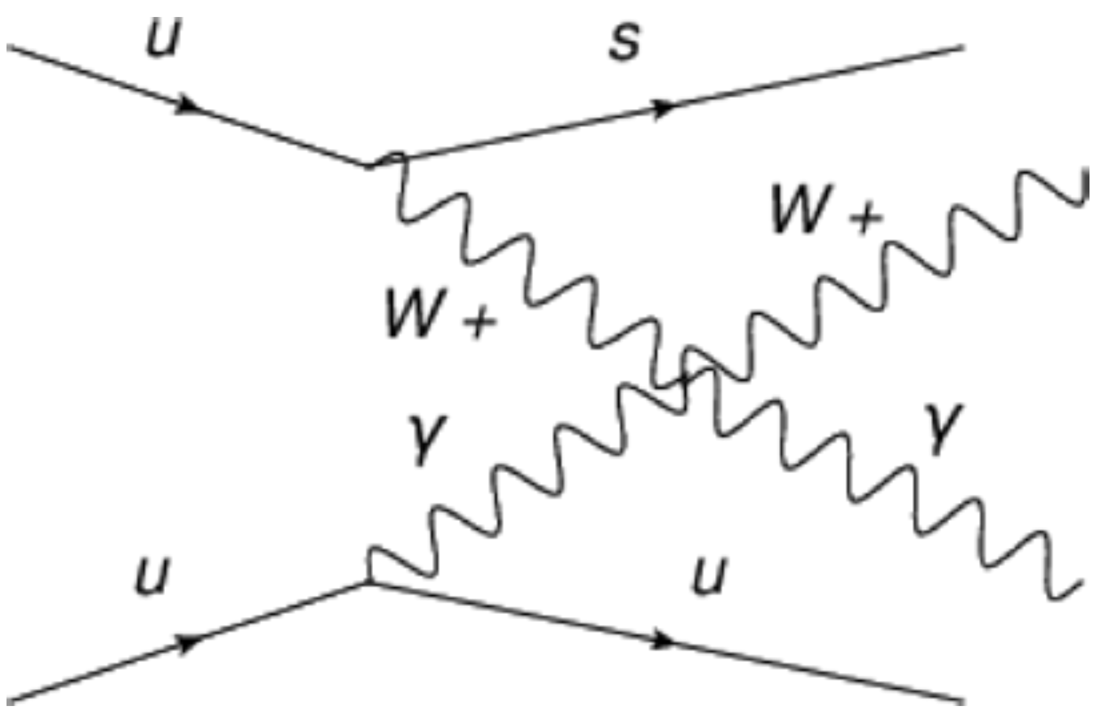




http://arxiv.org/abs/1604.04464

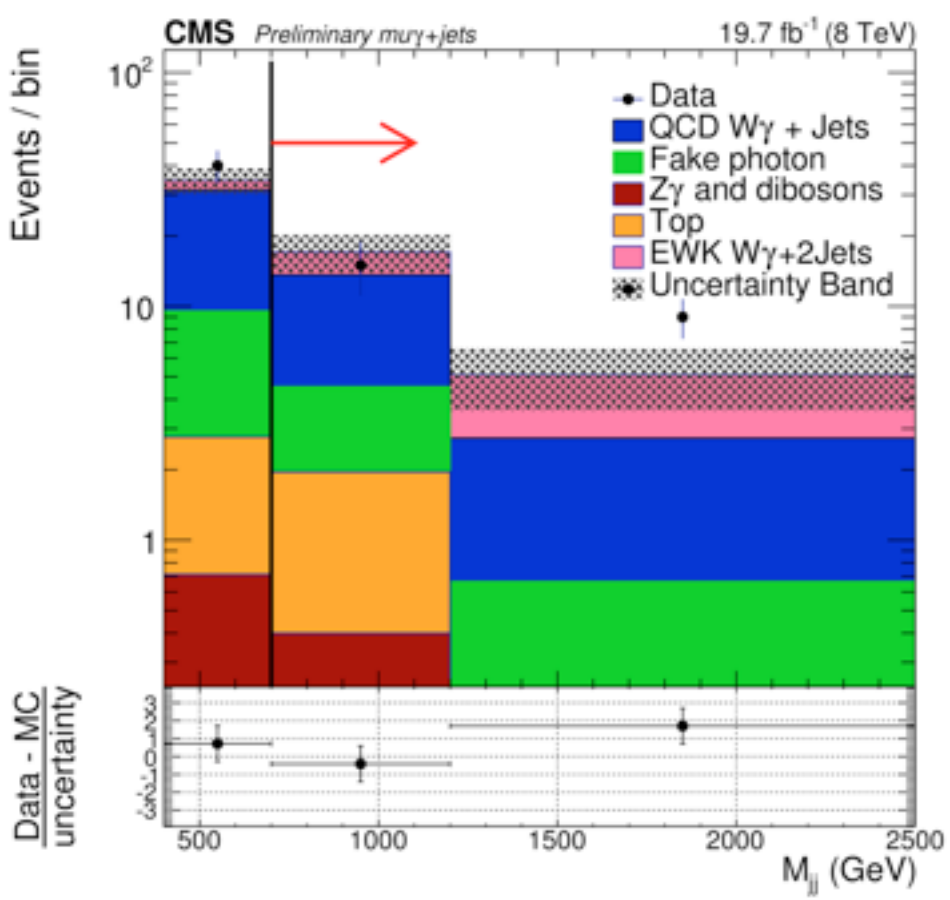
slide stolen from A. Khukhunaishvili Blois2016

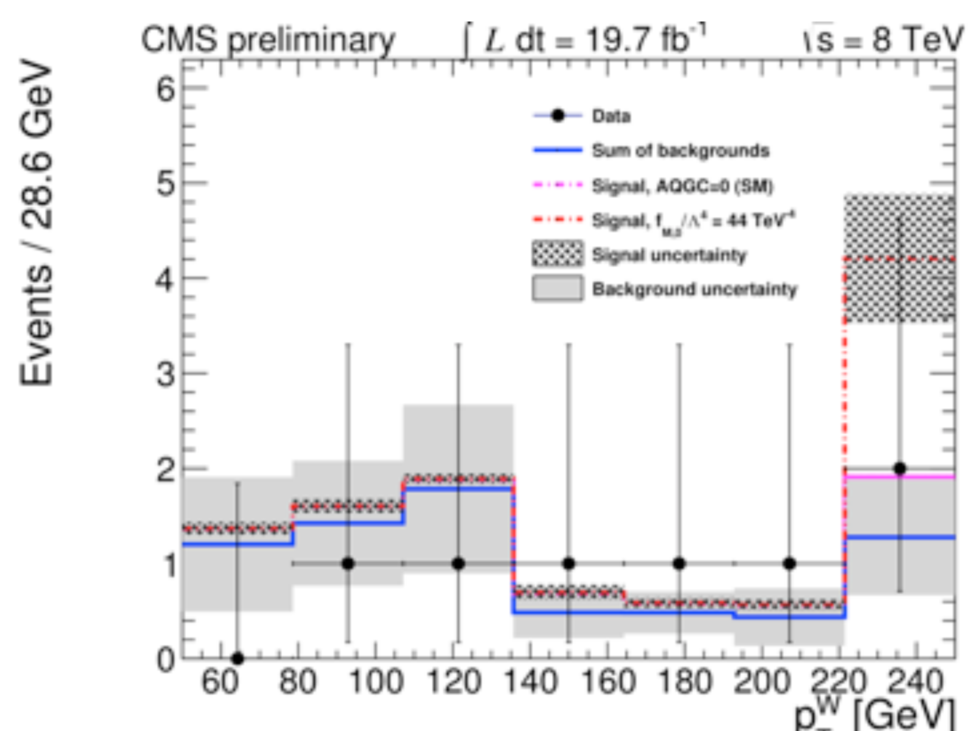
Hints of EW Wγ



This gauge boson vertex has been probed for first time using Wγ + 2j (VBS)

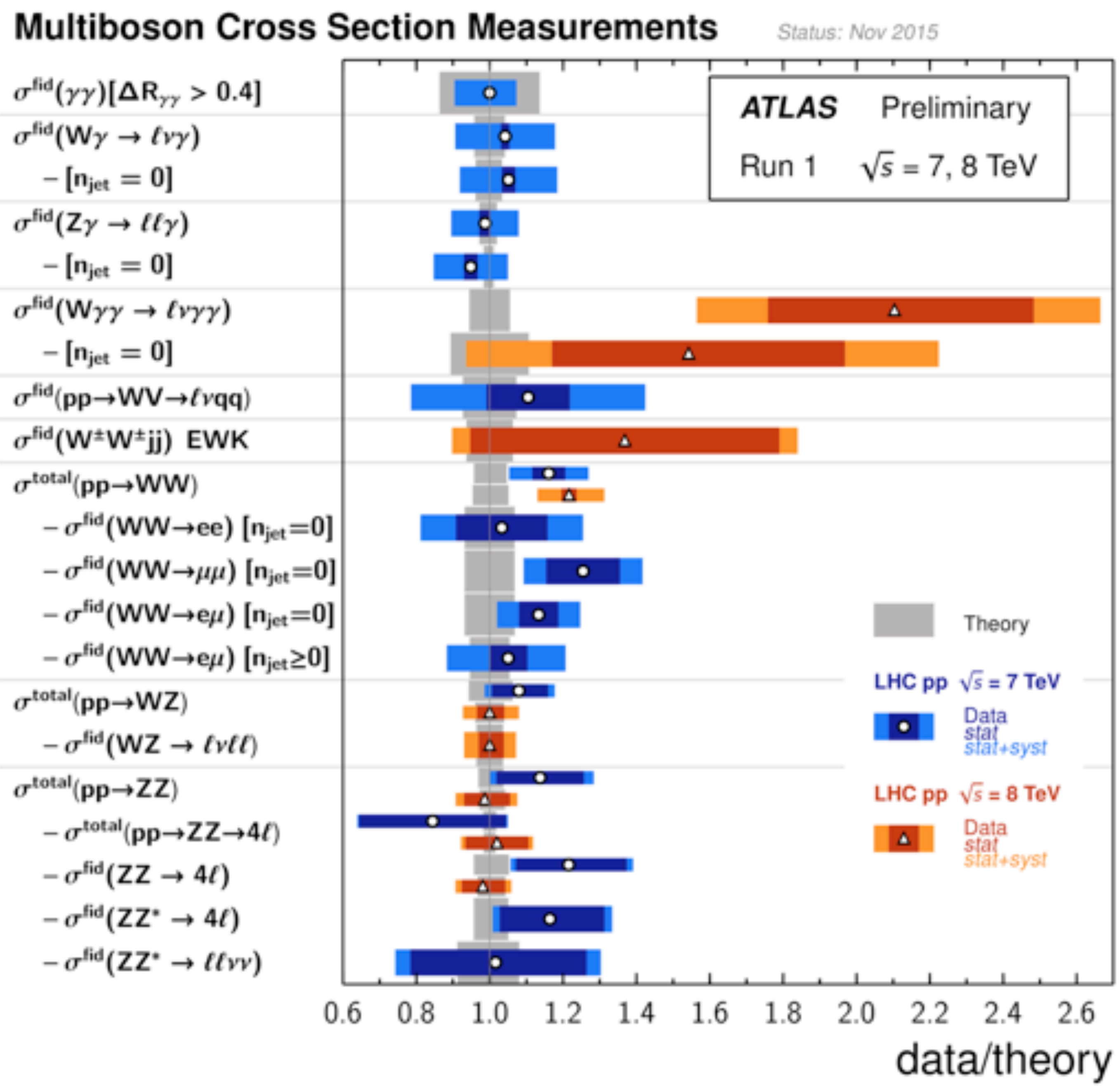
hints (2.6σ) for EW Wγ, more data needed for first observation

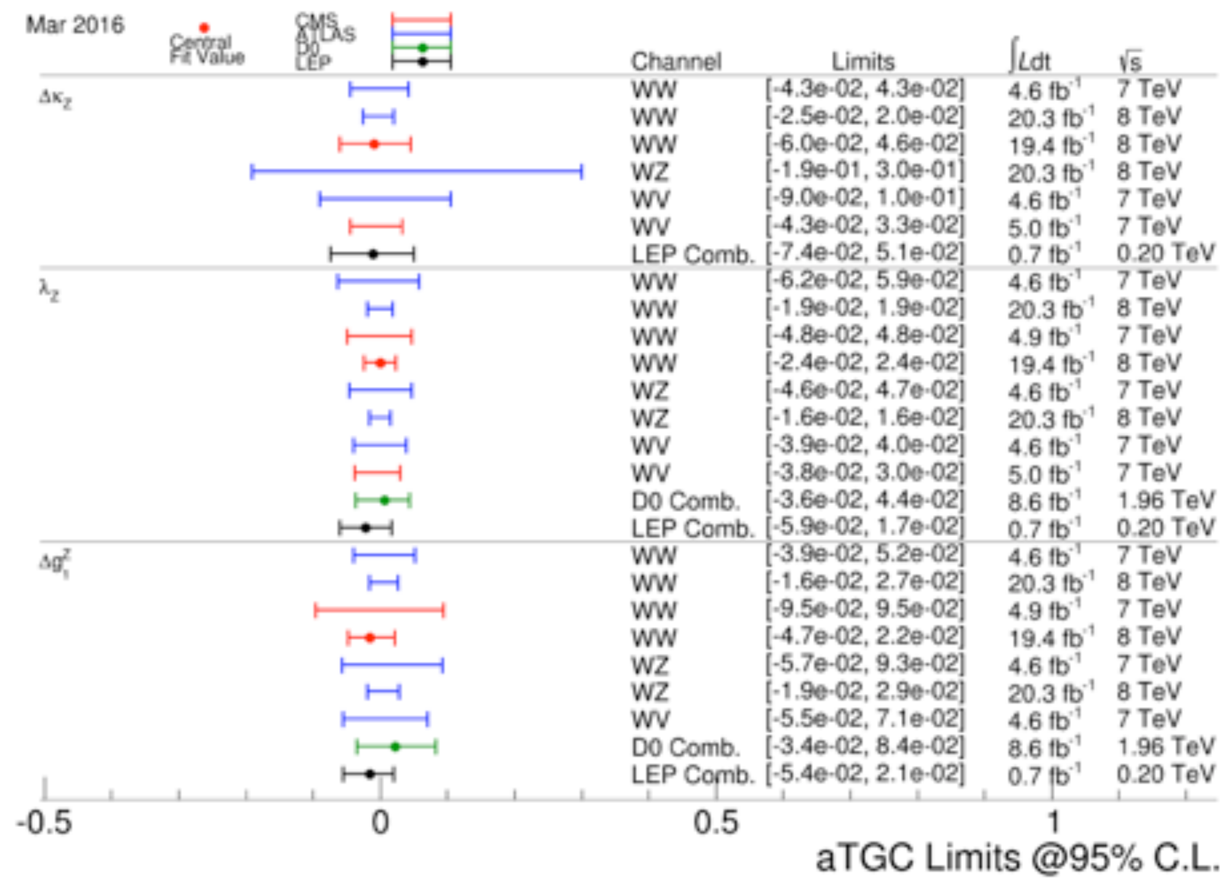




CMS-SMP-14-011

Limits on anomalous couplings

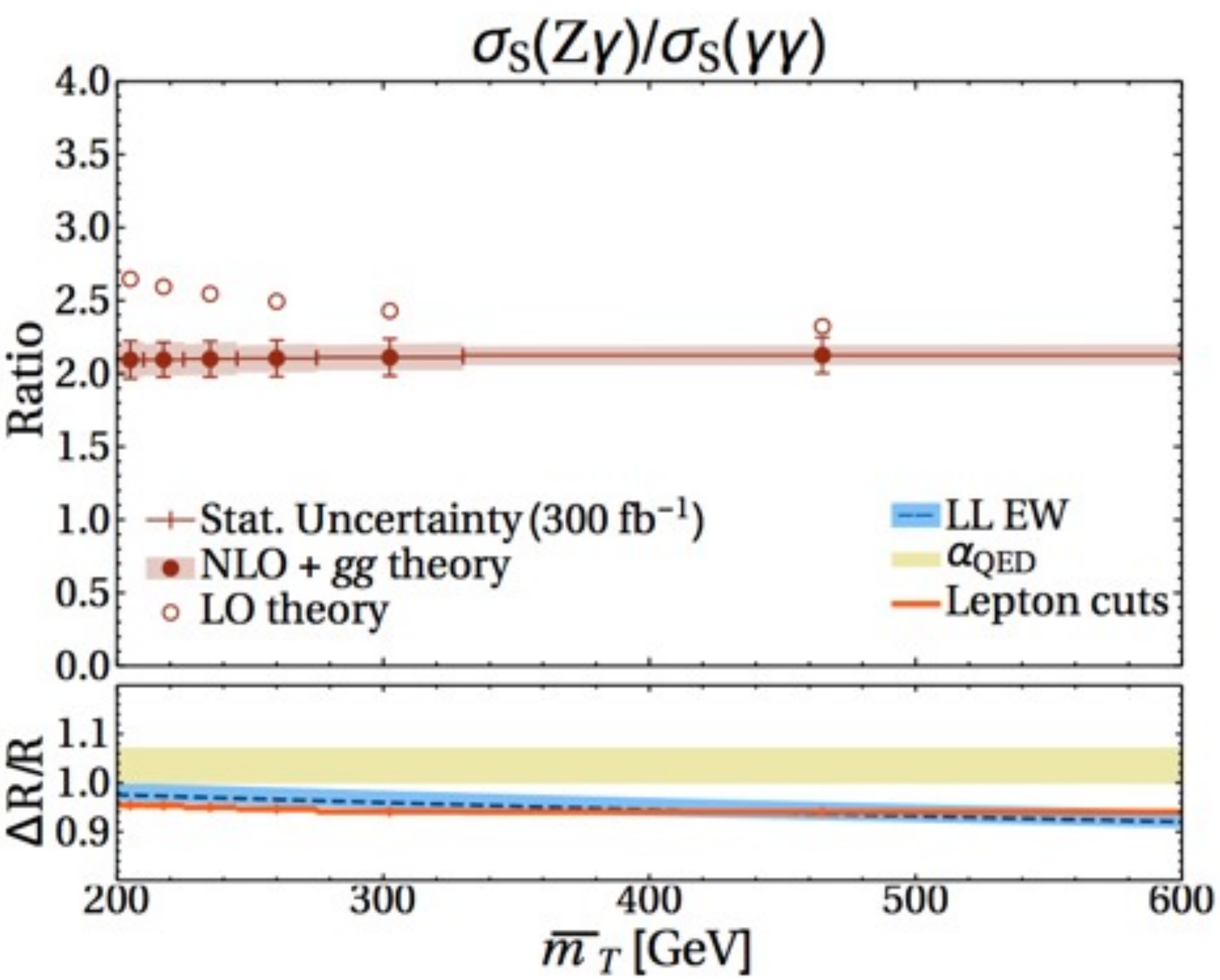




- Many channels still dominated by statistical uncertainty
- We can place limits however to large anomalous couplings
- 8 TeV data (20 fb-1) are still more constraining than the 13 TeV 2015 data

Prospects for multiboson studies

- More data are needed and they will come soon!
- Detector upgrades:
  - Forward jets needed in vector boson fusion
  - W/Z hadronic tagging for boosted/high p_T fat-jets
  - Machine learning to dig out some of the very rare processes

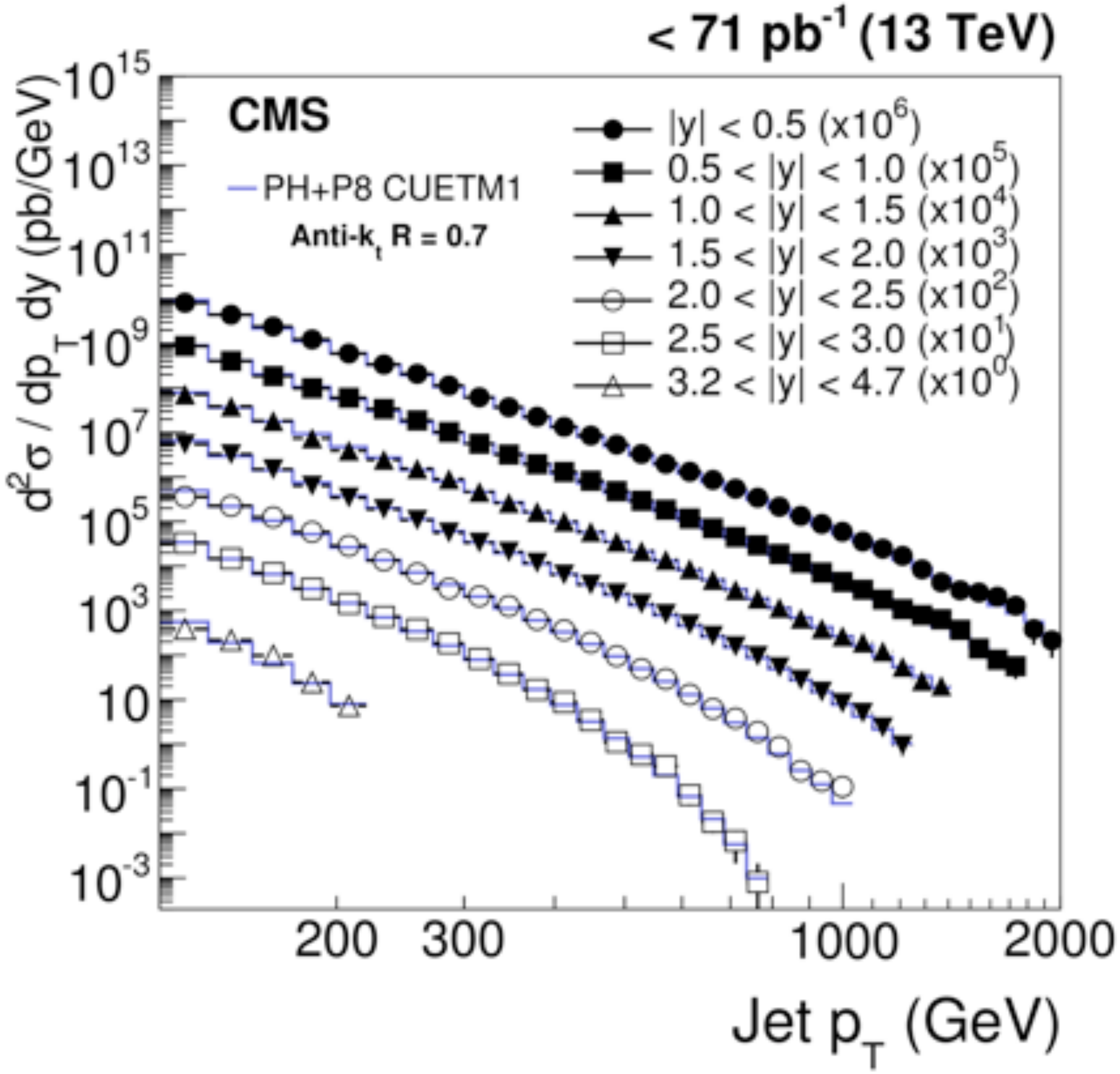


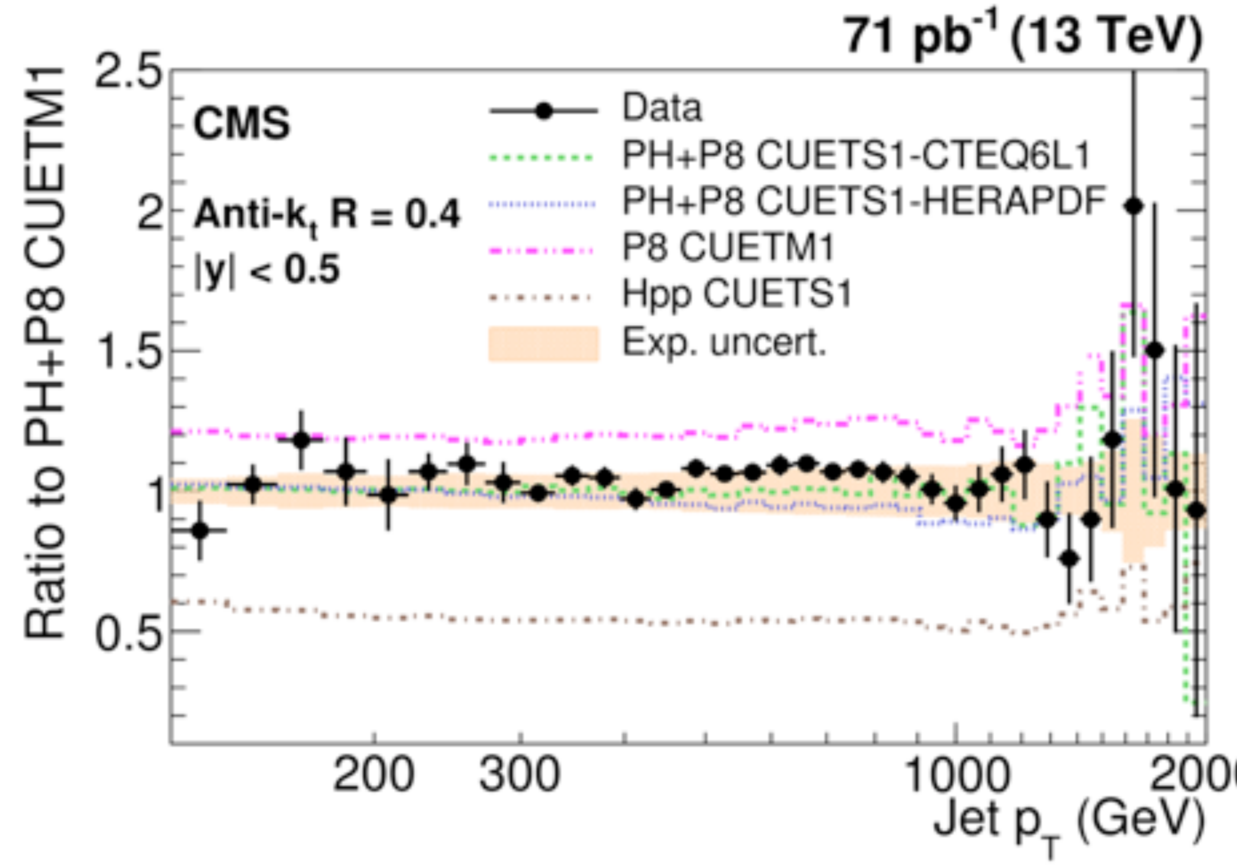
Ratios between VV process is expected to reach 5% theoretical accuracy, **enabling precision** in this field of studies Run II/HL-LHC, **photons** will play an important role and are difficult to deal experimentally

http://arxiv.org/abs/1510.08451

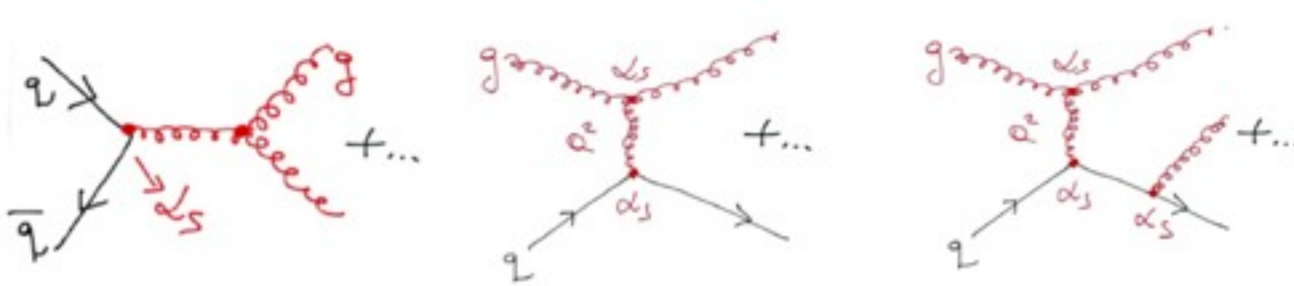
QCD in less than 6 slides (next-to-impossible)

Inclusive jet data (13 TeV)





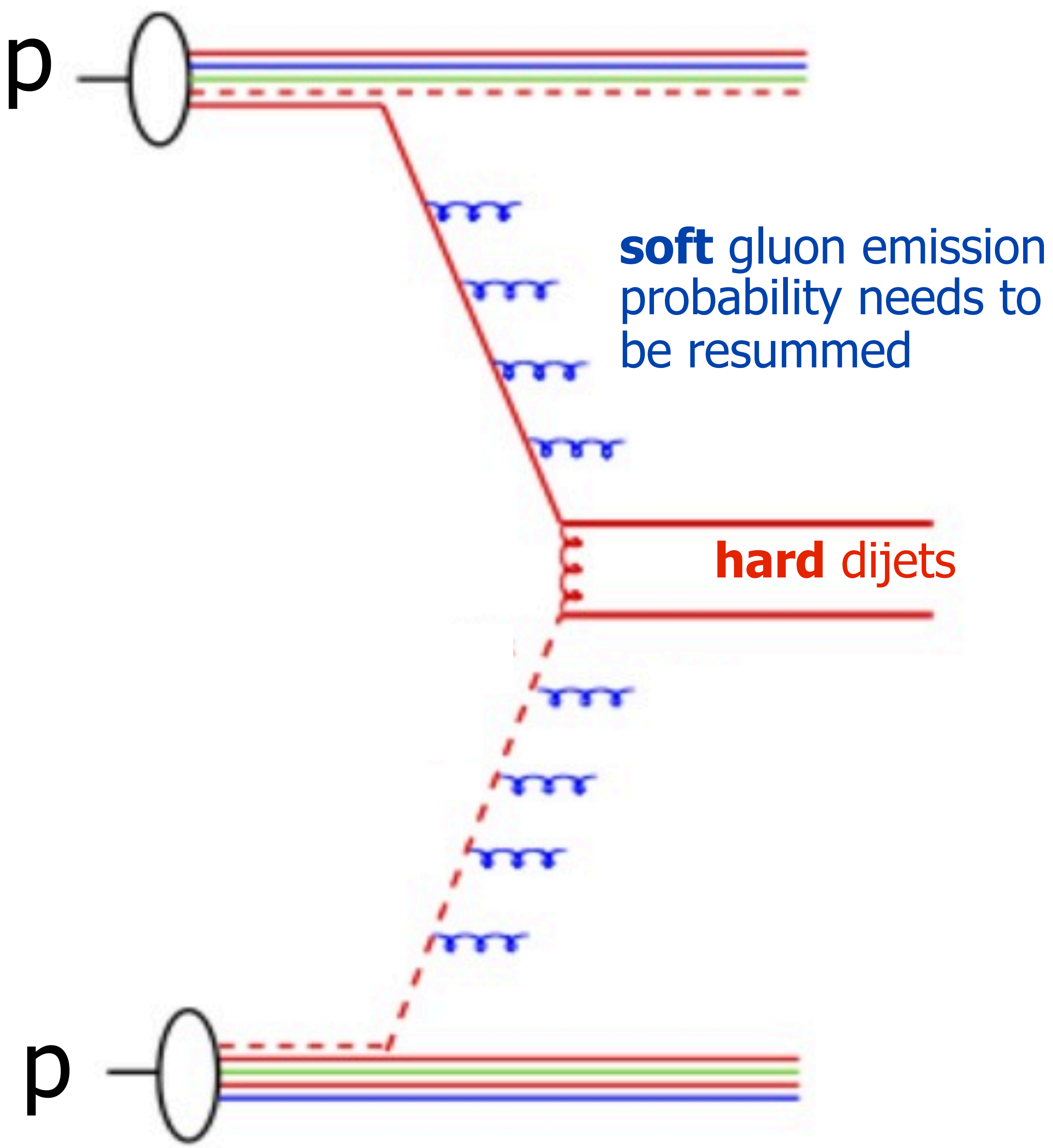
Soon we will have to face 3 TeV dijets!



G. Dissertori

Dominant exp uncertainty: Jet Energy Scale, gets larger at high P_T

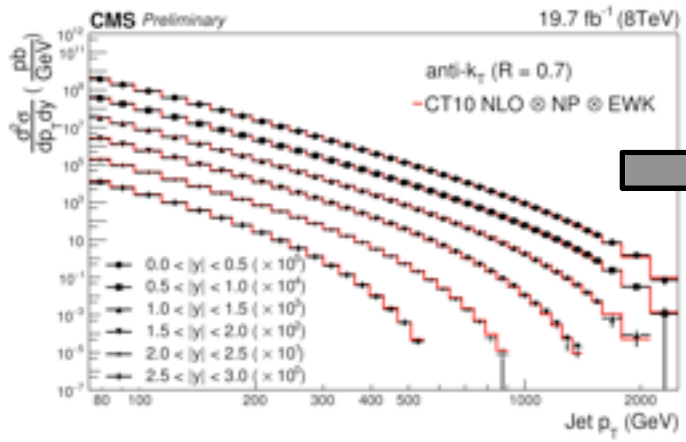
Studies with Di-jets @ 3 TeV



- For P_T^{hard} = 3 TeV -> P_T^{soft} ~= 30 GeV (will soon be measurable)
- Extreme di-jets will offer a testbed to study resummation

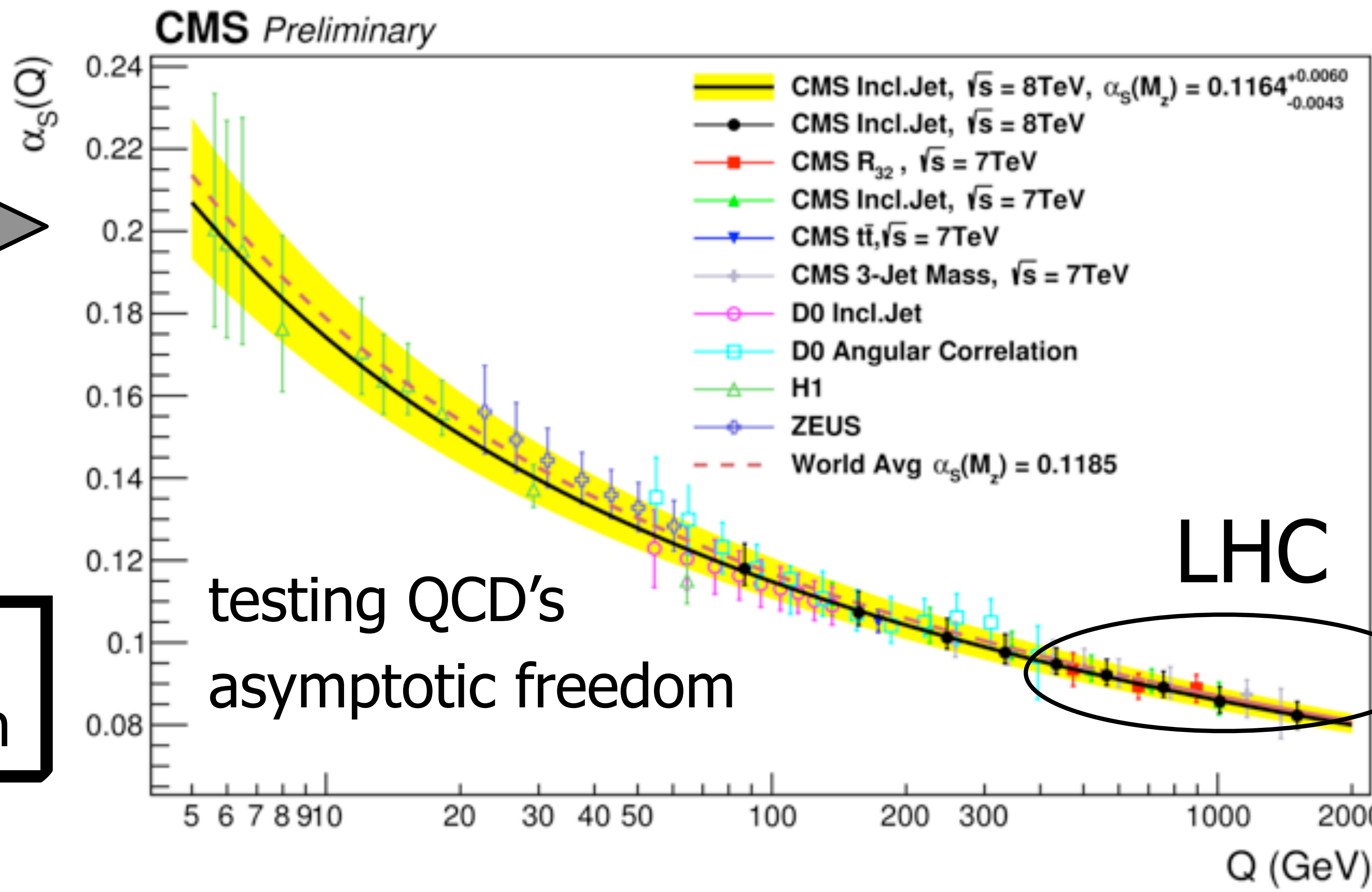
this topic has been highlighted to me by Hannes Jung

The QCD coupling constant

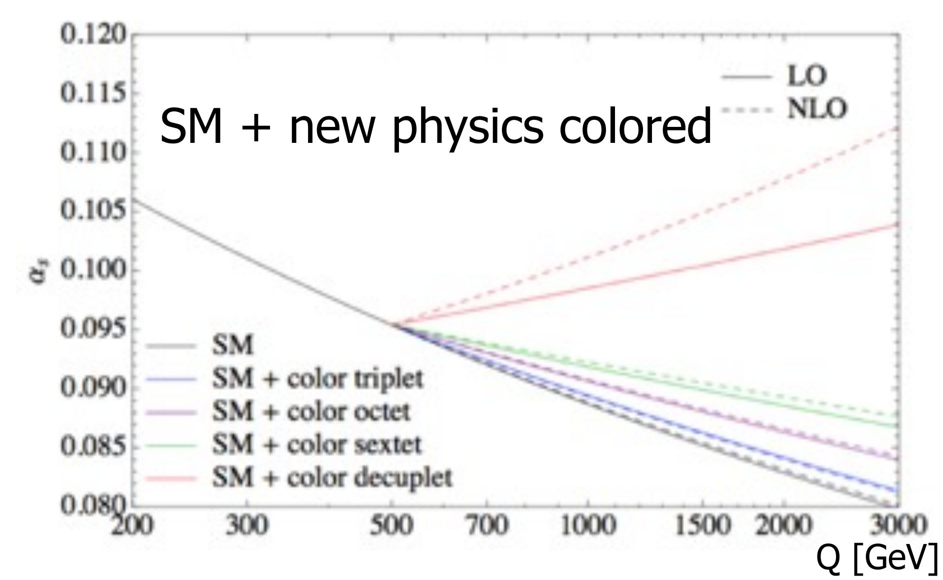


From jet cross-sections to a_S

a_S is the SM coupling known with least precision

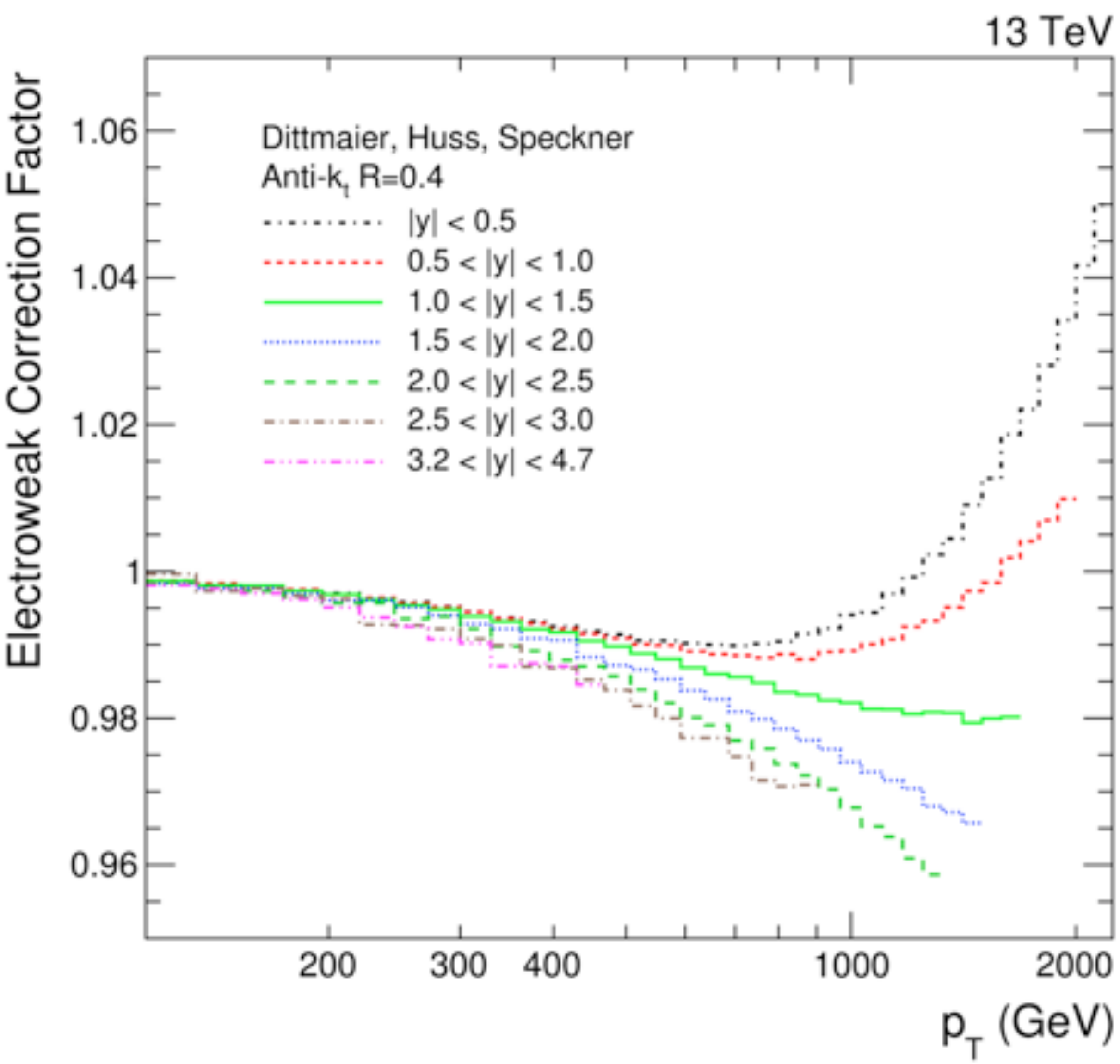


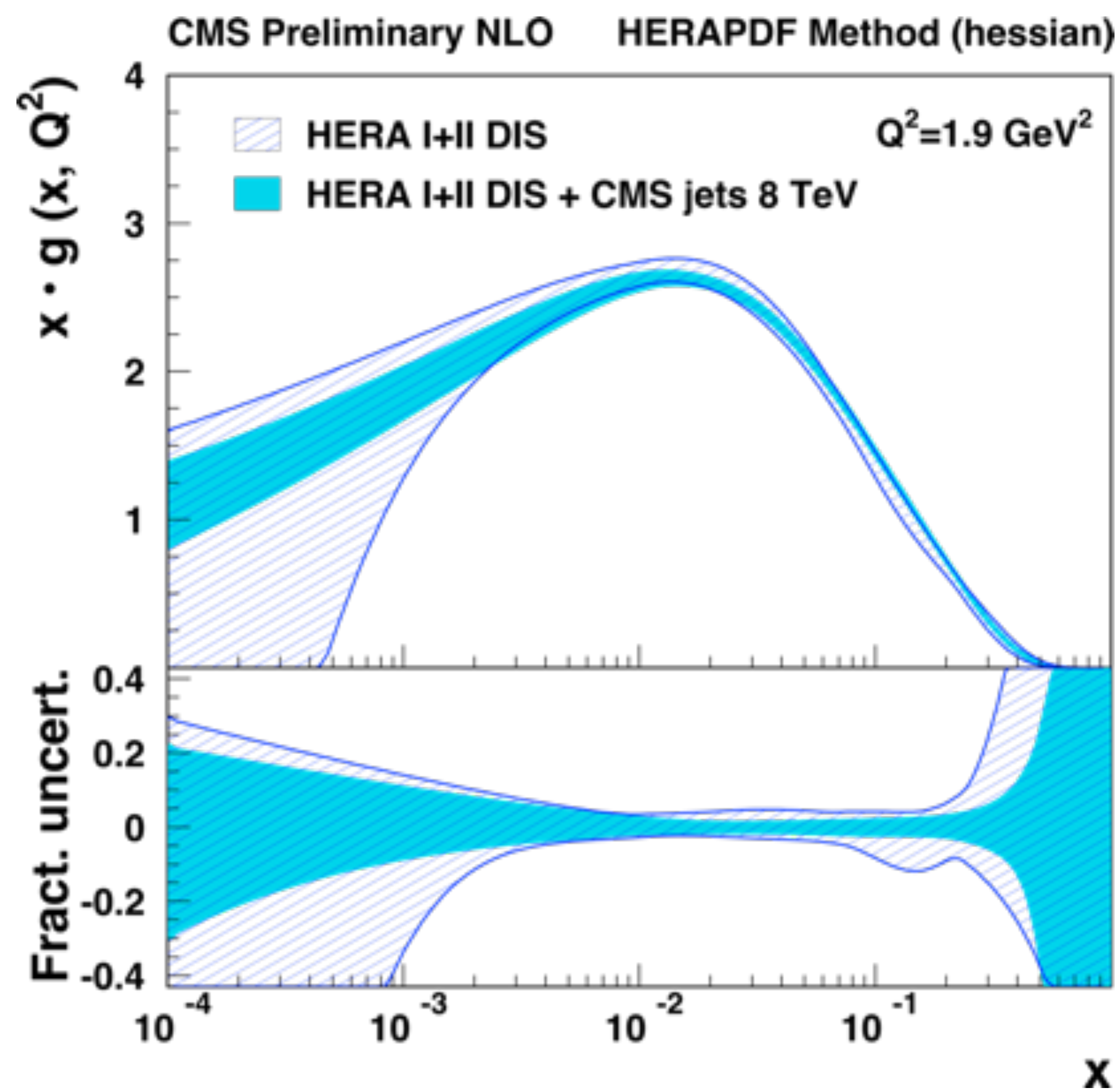
NNLO for pp->jets will enable better usage of the jet data (currently not used in PDG a_S world average).



Francesco Sannino et al

Jet data probe highest p_T/x



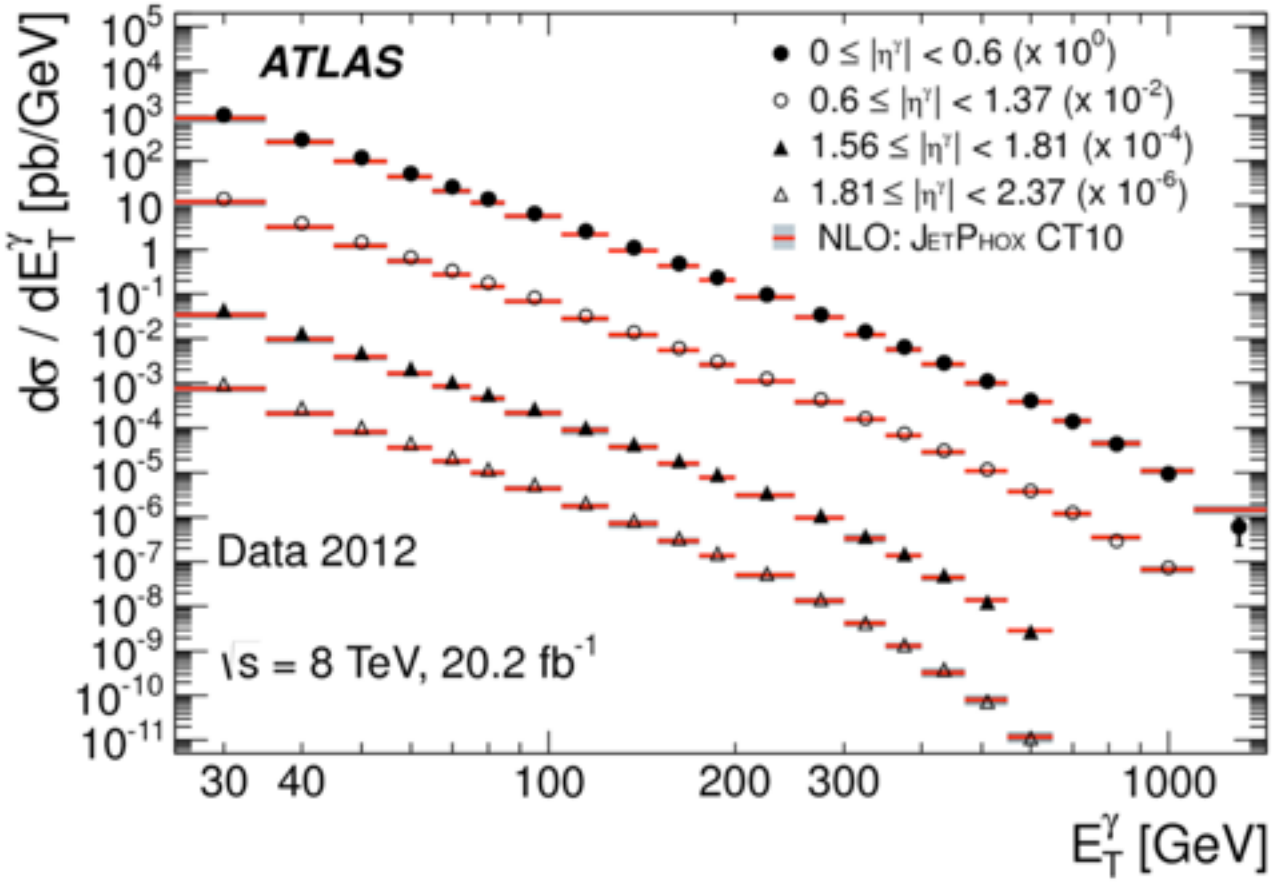


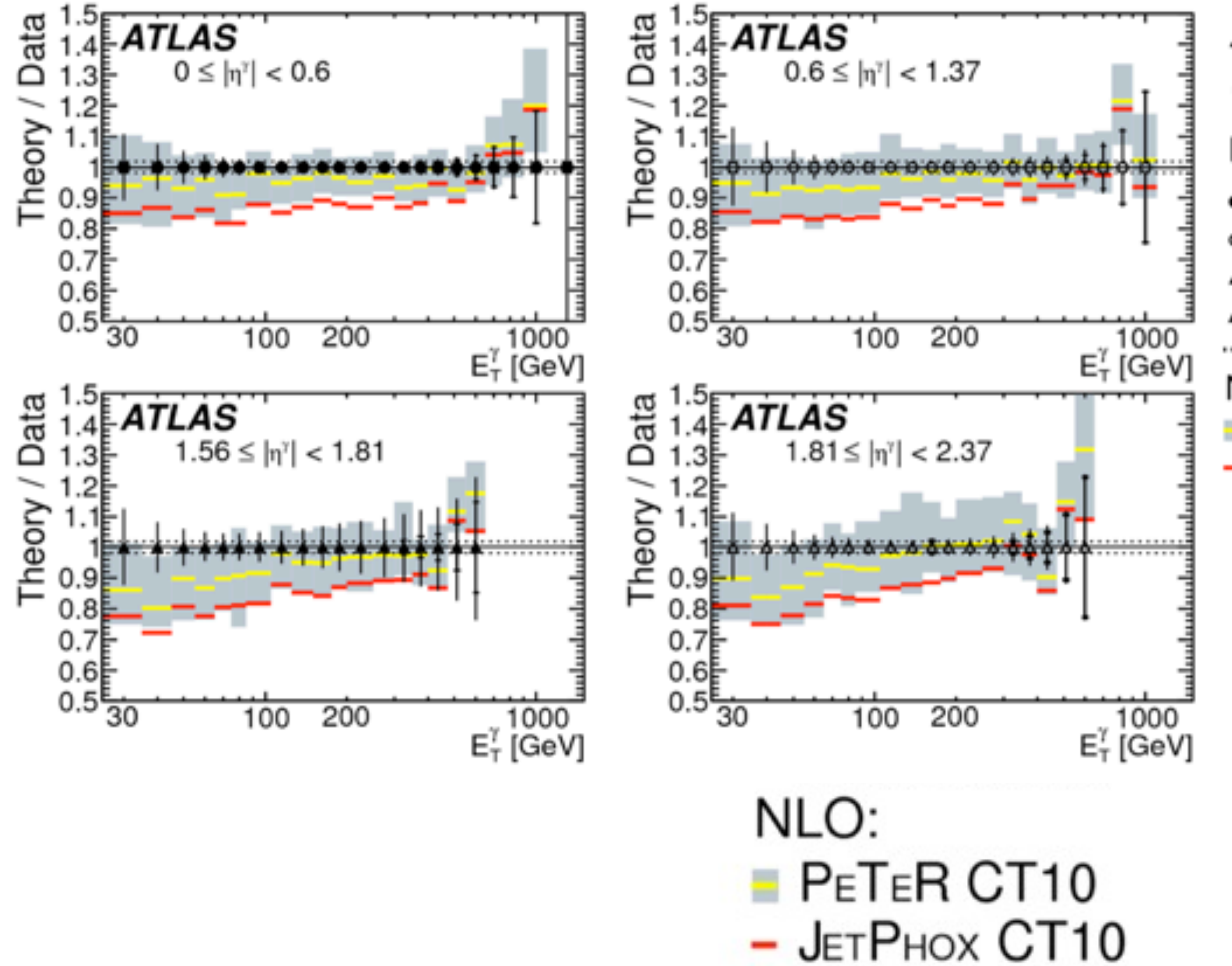
It's not only QCD, NLO EW effects become important at high jet P_T (factorized approach on showered / fixed-order ?)

Gluon PDF uncertainty is reduced* for low/high x using jet data

*NB other than jet data needed for g(x) in order to avoid circularity jets->g(x) & jets->a_S

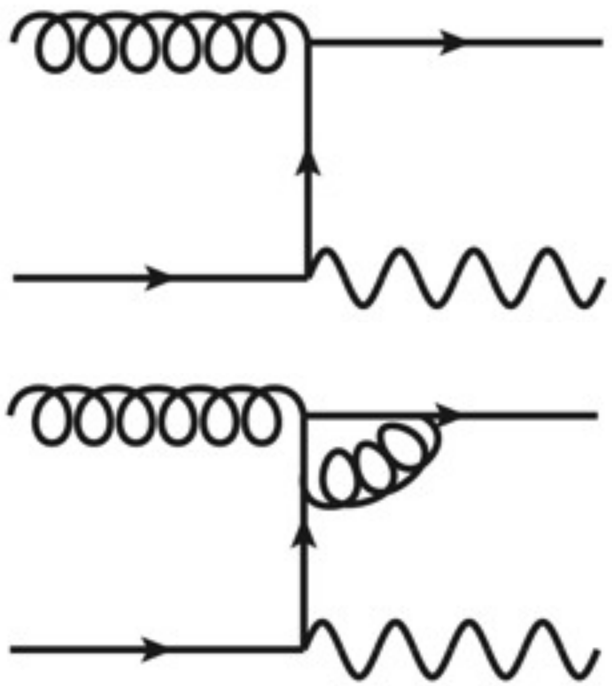
Photon (inclusive)

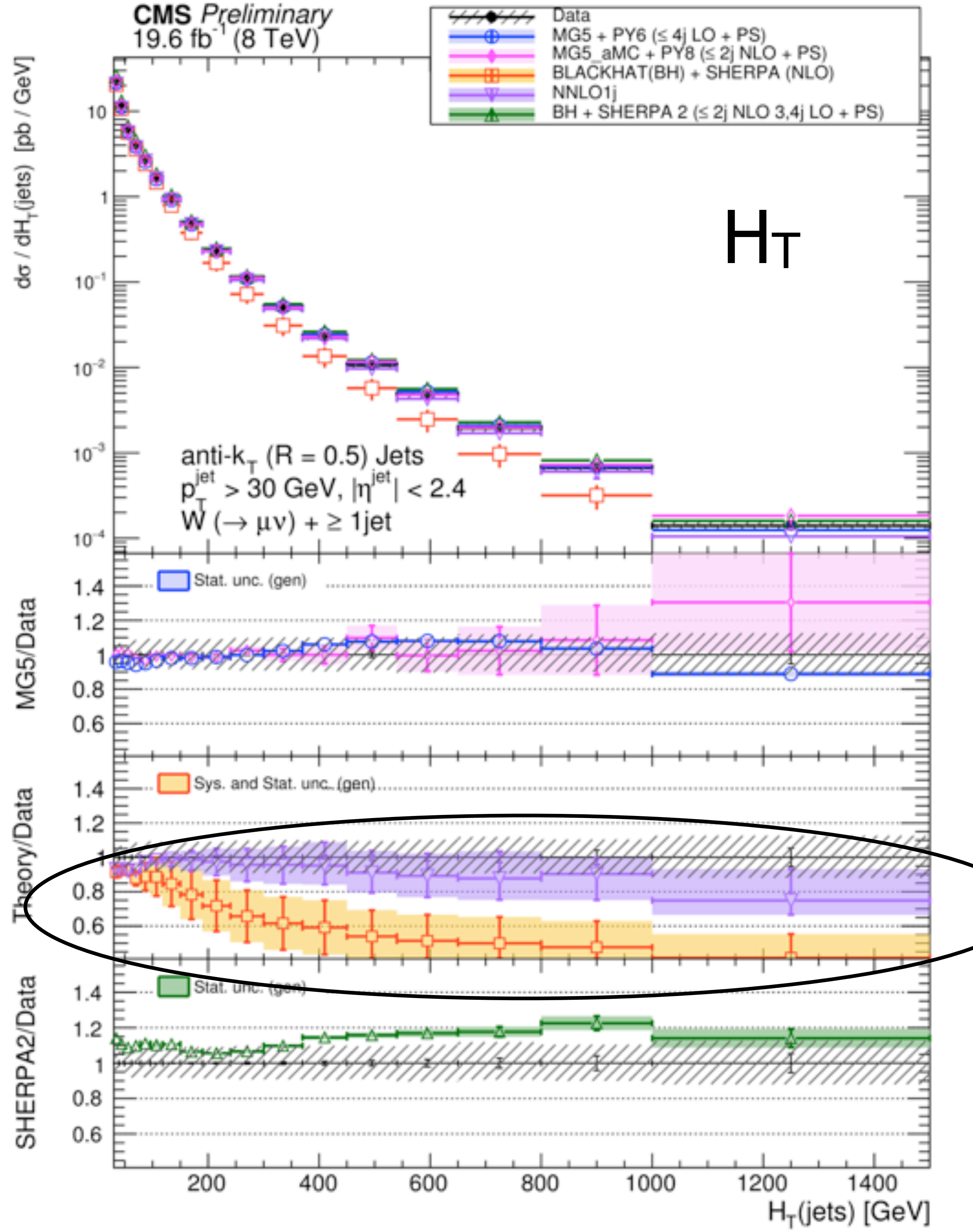




Photon data can be used for PDFs/a$_S$, but NNLO is also missing for this process

V+jets @ NNLO



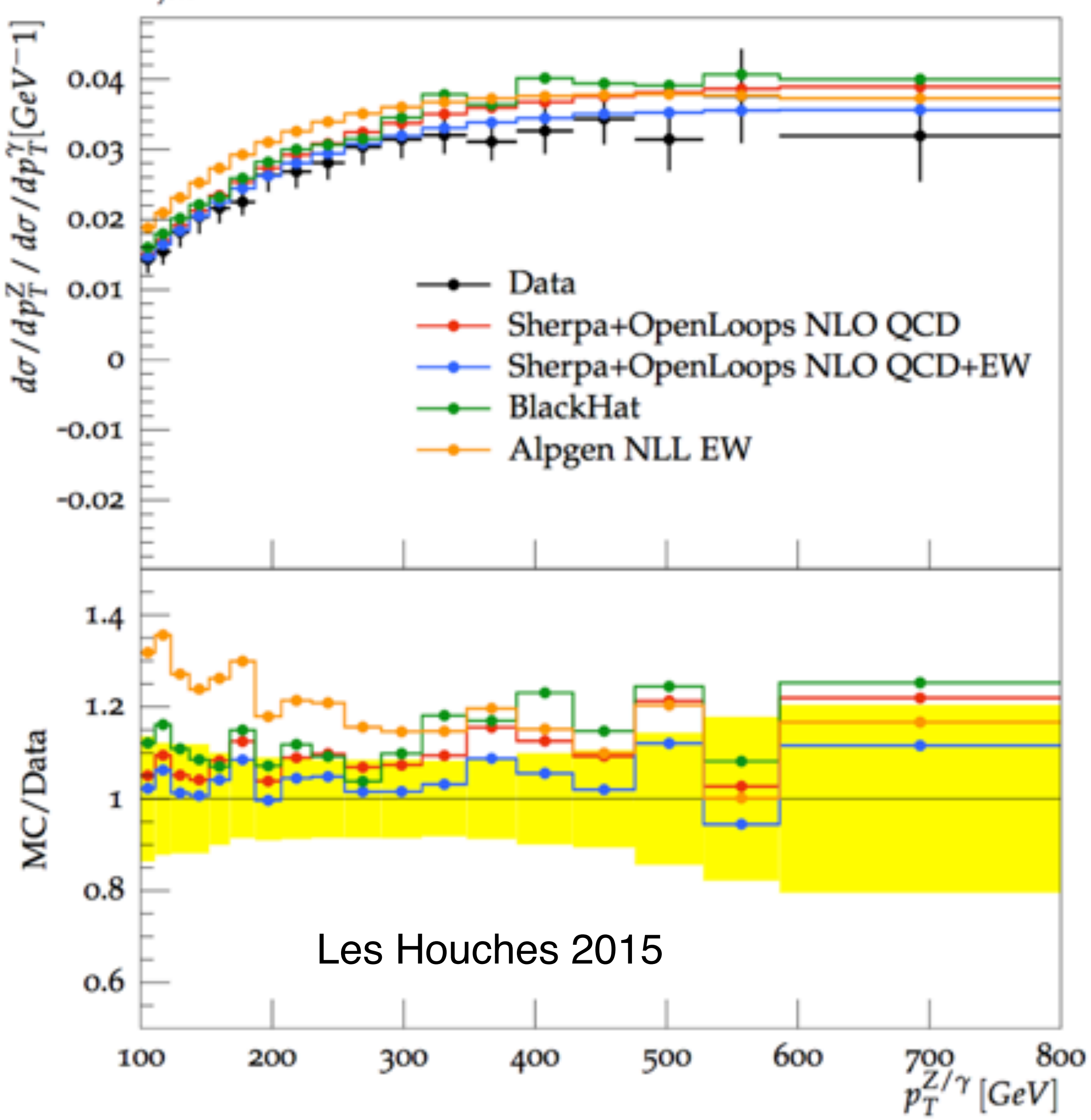


V+jets, V=W, Z are candles for studying P_T(jet), N_{jets}, PDFs and test new MC developments (τ event shapes, merging NLO +PS ...)

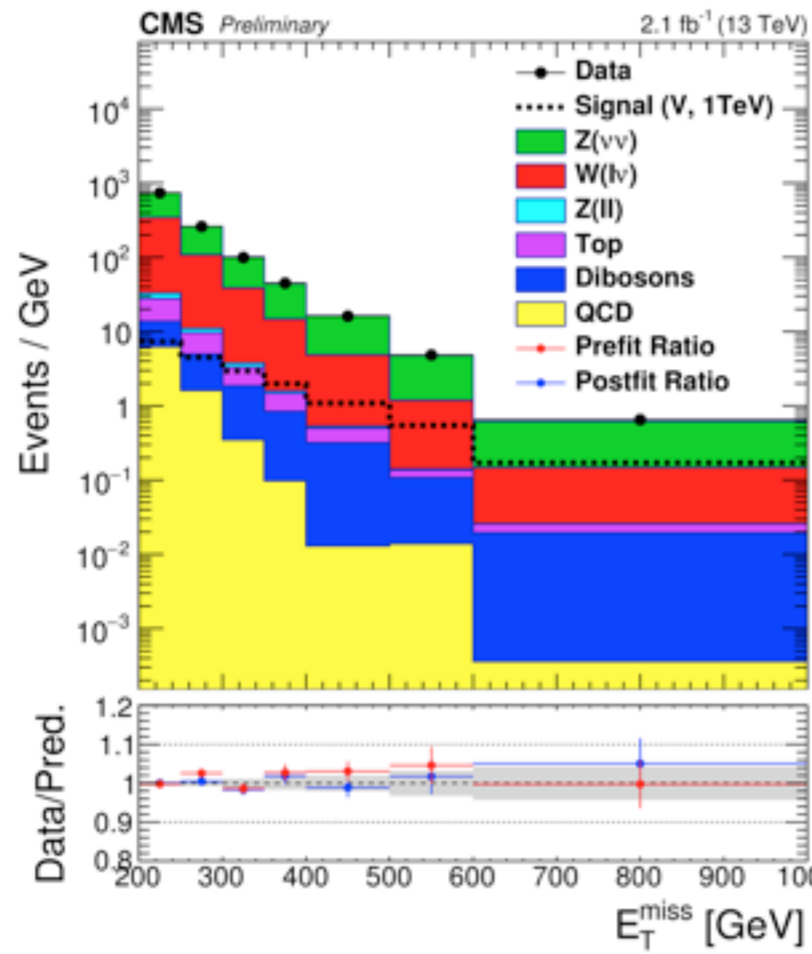
Newly available NNLO for V+1j enables precision in V+jets studies, paving the way for a_S extraction in V+jets ?

QCD x EW corrections in ME+PS

https://arxiv.org/abs/1605.04692



R(Z/γ) data at used to study different possible implementations of QCDxEW corrections in general purpose MCs



State-of-the-art EW corrections bring better data/theory agreement but still some discrepancy with the CMS data (CMS-SMP-14-005)

DM mono-jet searches used NLO electroweak correction as systematic uncertainty entering the fit as a constrained nuisance parameter

Summary & Outlook

Year	∫ L dt [fb^{-1}]
2015	3
2016	30
2018	100
2024	400
2035	3000

A new landscape **will open** for precision measurements

Measurements can probe BSM even if **BSM is not visible at tree-level**

EW precision at LHC implies good understanding of QCD, the two are perplexed!

QCD with jets and V+jets is a rich field for $a_S(Q)$, PDFs, ME+PS merging, QCD x EW MC

Multibosons are thirsty for more data and will benefit a lot from HL-LHC and detector upgrades

Bonus slides

QCD/EW studies : What-is-it

Cross section measurements

pp → jj(jjjjjjj)

pp → V(+jets)

pp → VV (+jets)

pp → VVV (+jets)

Inference of SM parameters

$\sin^2\theta_W^{eff}$ ($\sin^2\theta_W$), m_W

$a_S(Q)$

aTGCs, aQGCs

PDFs

MC modeling

ME+PS merging

UE, MPI, tuning

QCD/EW corrections

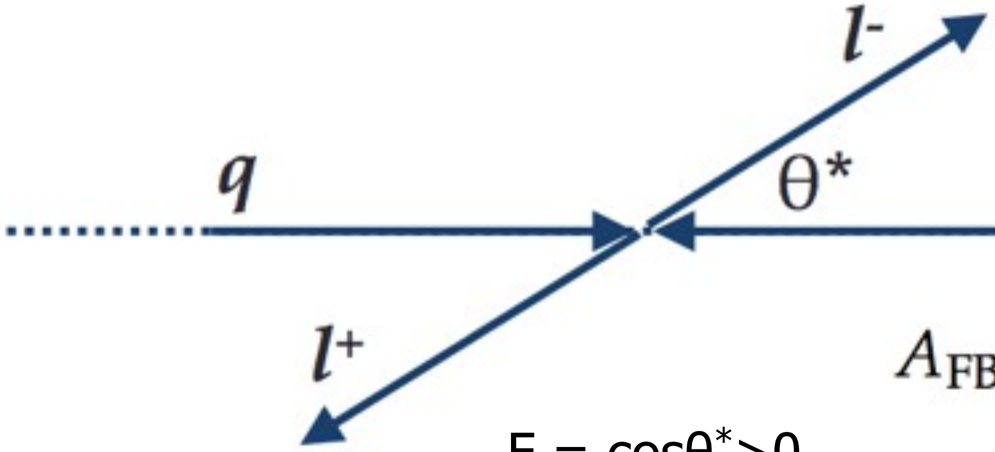
Beyond the SM

anomalous couplings

extreme QCD

precision frontier

Leptonic A_{FB} at LHC



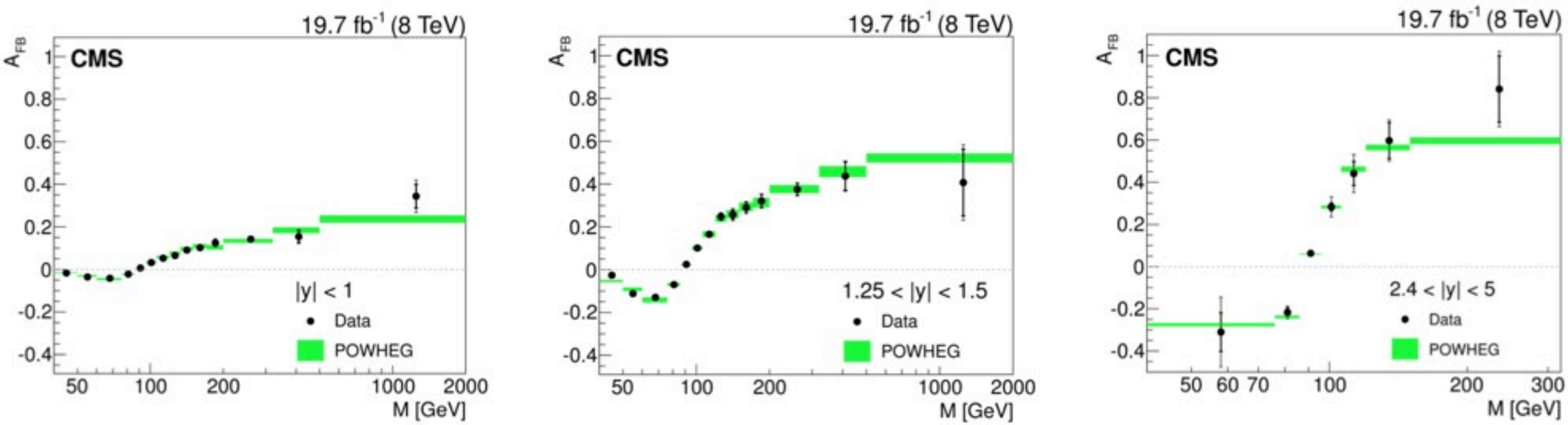
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

F = cosθ*>0

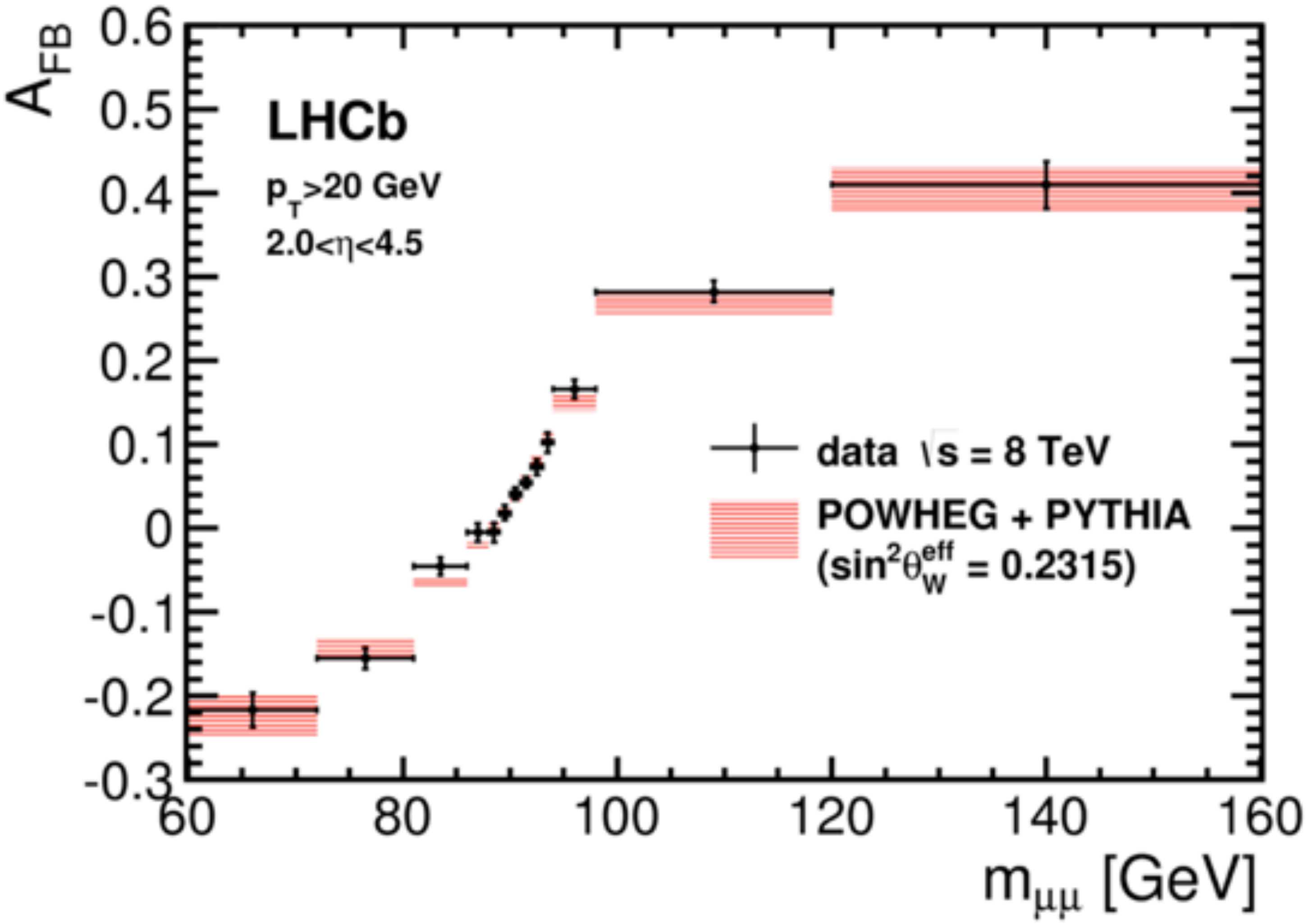
B = cosθ*<0

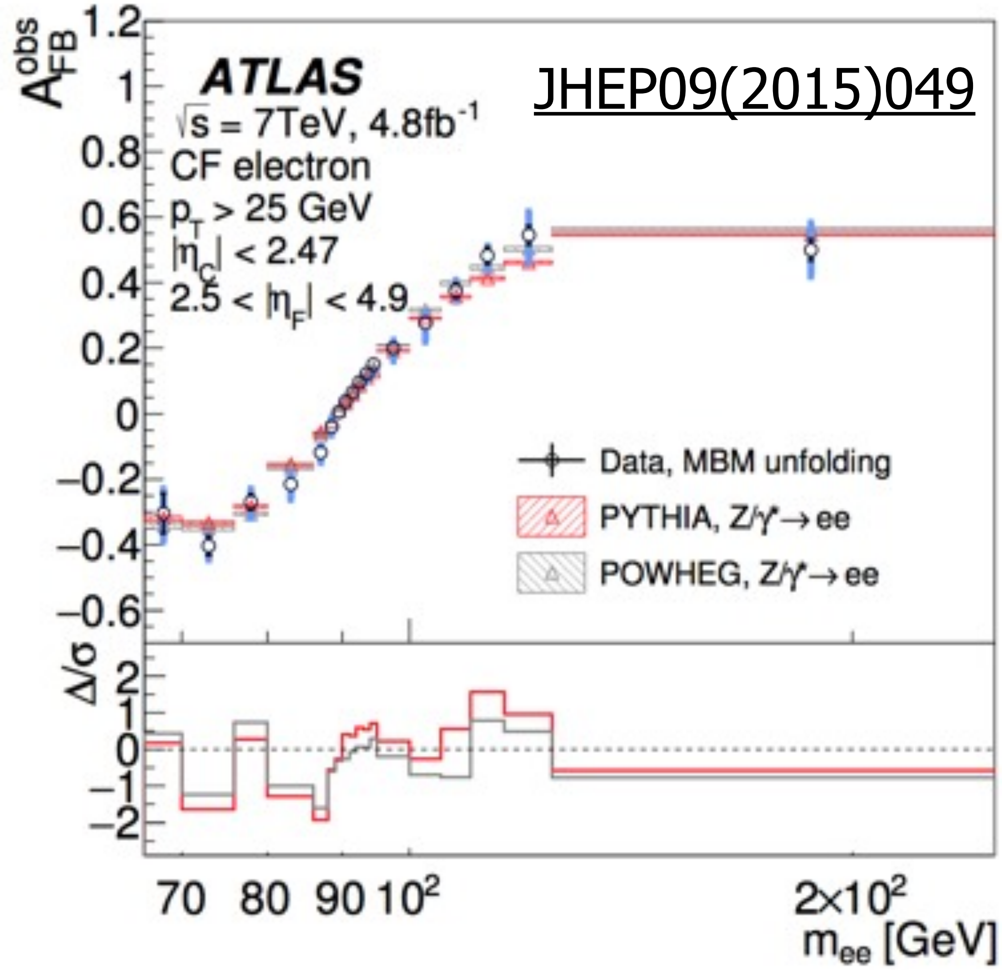
- A_{FB} is a key EW observable for inferring $\sin^2\Theta_W$ & indirect M_W
- A_{FB} is diluted at LHC, because quark direction is unknown!
- ... q-direction is strongly correlated with rapidity of l^+

A_{FB} becomes stronger at large $|y_{lep}|$, Phase II upgrades will empower ATLAS/CMS with more precision



Leptonic A_{FB} at LHC





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- A_{FB} measurements dominated by PDF uncertainties
- Double differential dσ/d(mll, Y) measurements will come with more data