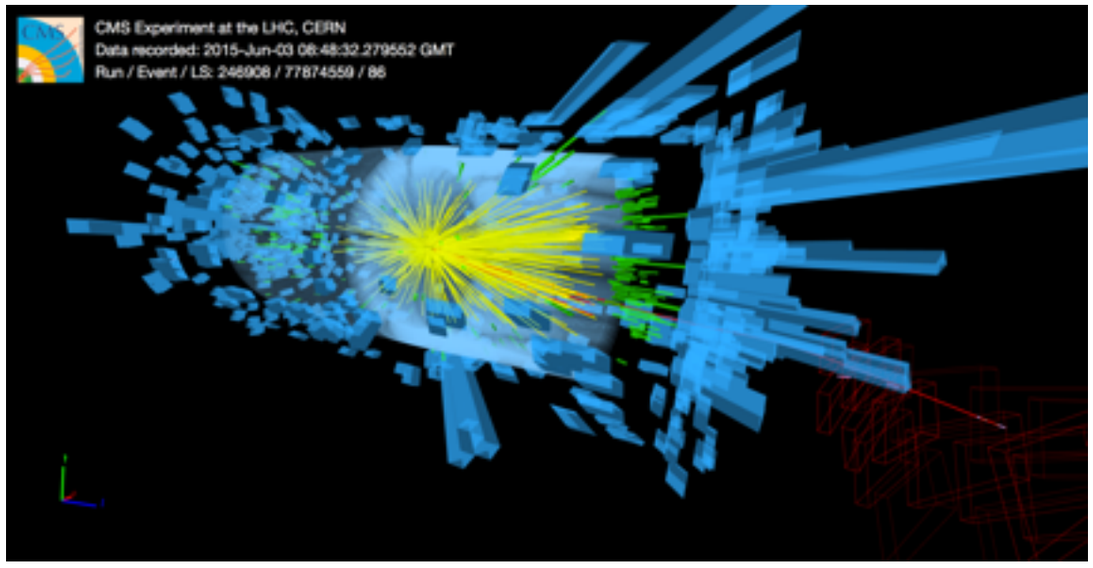


(A quite brief summary of) SM results from LHC

Simon de Visscher (F.N.R.S-UCL-CP3)

Belgian IUAP meeting, Antwerp, Dec 2015

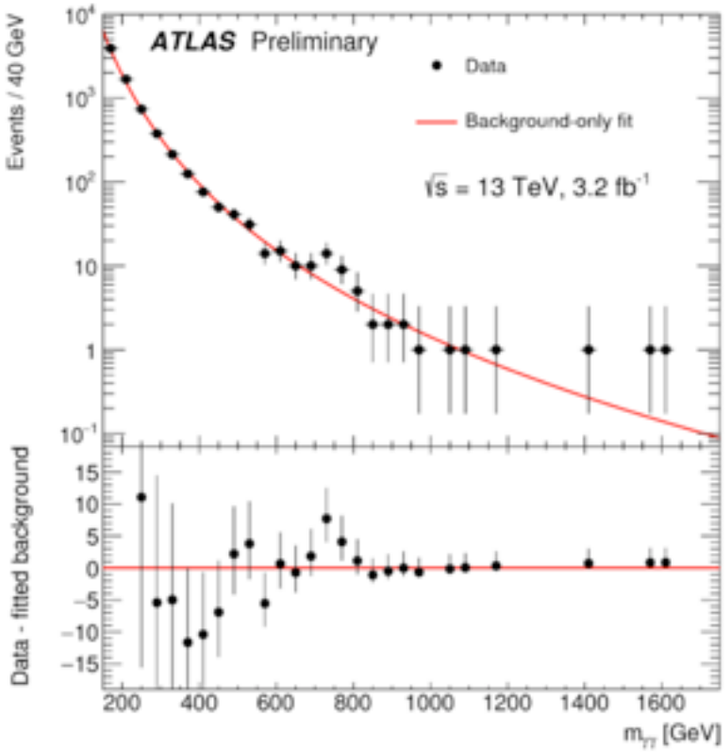
Disclaimer

- A **lot** of Run I SM measurements! In this talk:
  - multi-jets, Z/γ/W+jets, di-boson
    - No soft QCD and Higgs: discussed already today
    - No Top (no time...)
- For more details
  - CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  - LHCb: http://cds.cern.ch/collection/LHCb%20Papers?ln=en

Why doing SM measurements at the LHC?

- LHC is a discovery machine: Higgs and/or SUSY, other exotic scenarios.

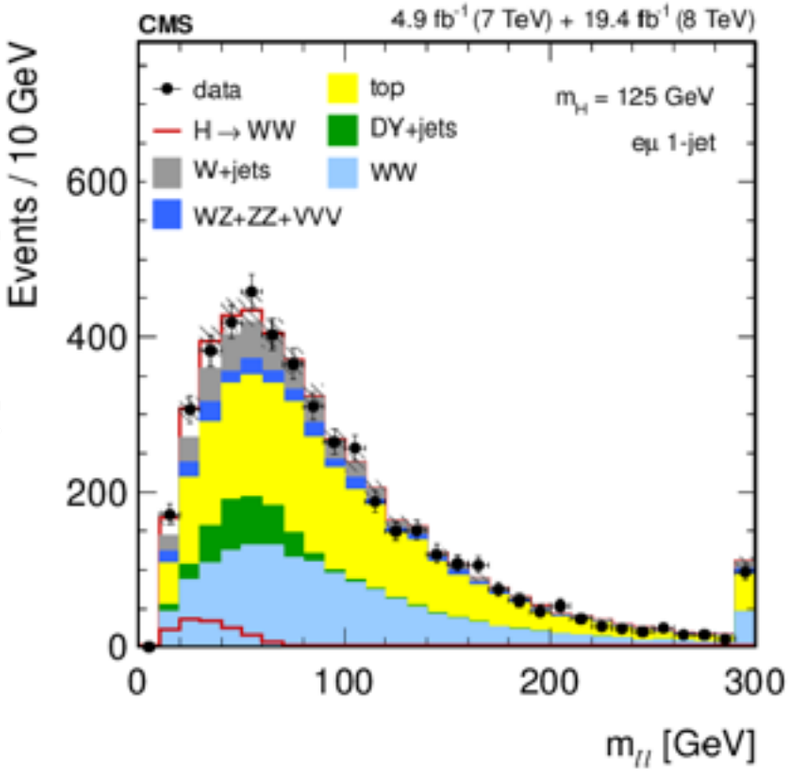
Peak scenario



«easy»

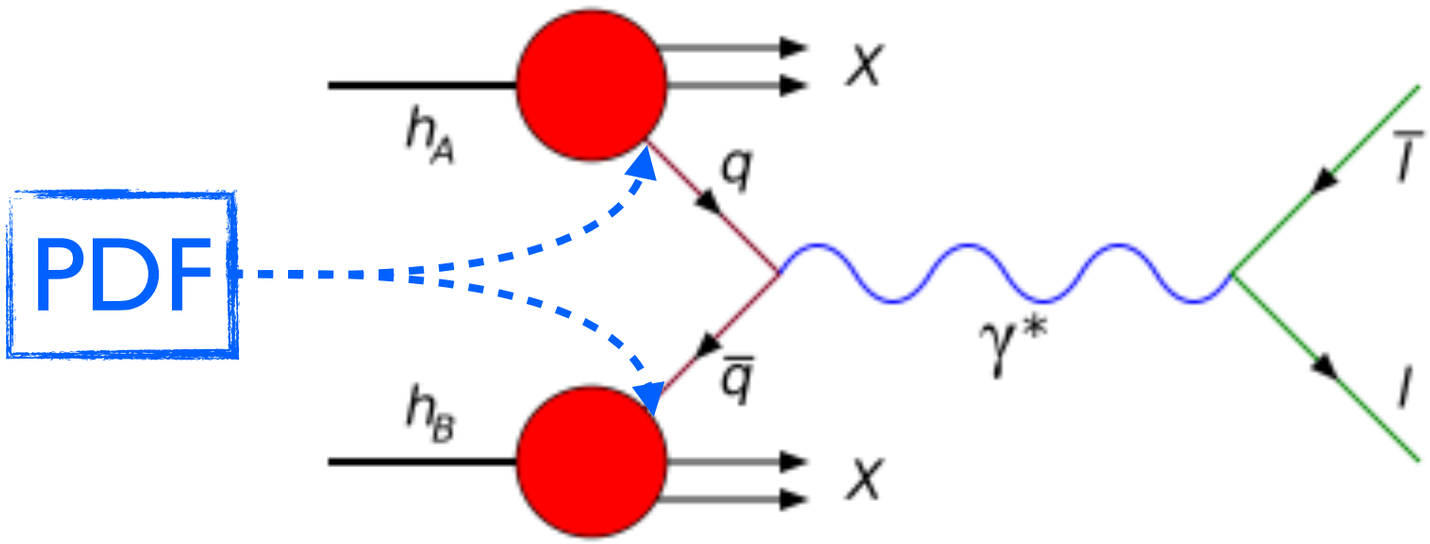
Rate scenario

hard!



LHC discovery potential may depend very strongly on our ability to model the background processes. And that relies very strongly to our ability to model QCD (and QED)!

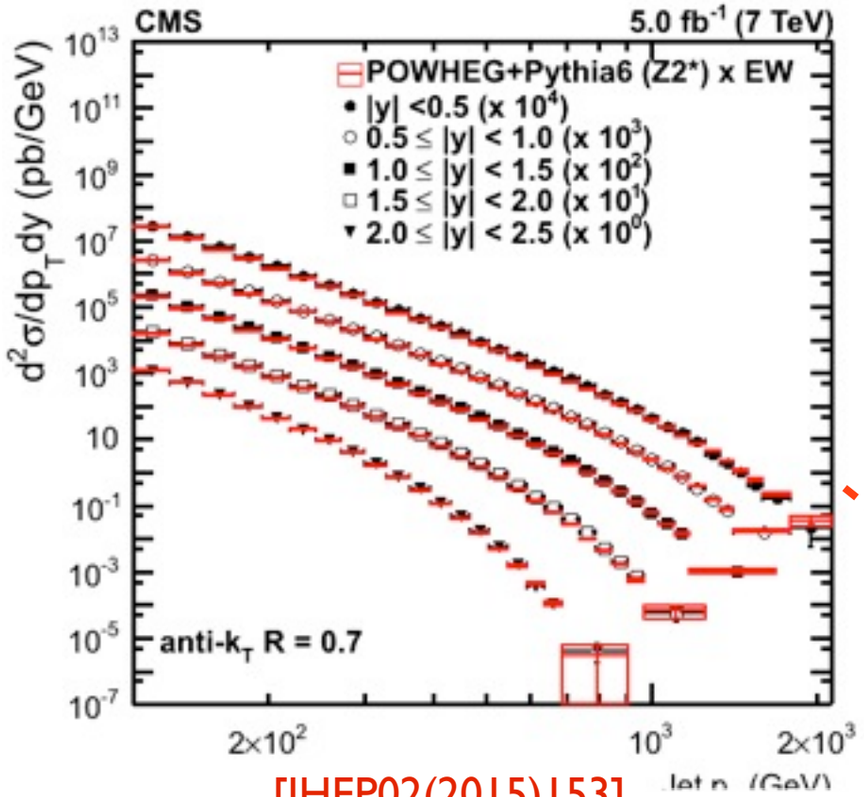
Parton Distribution Function (PDF)



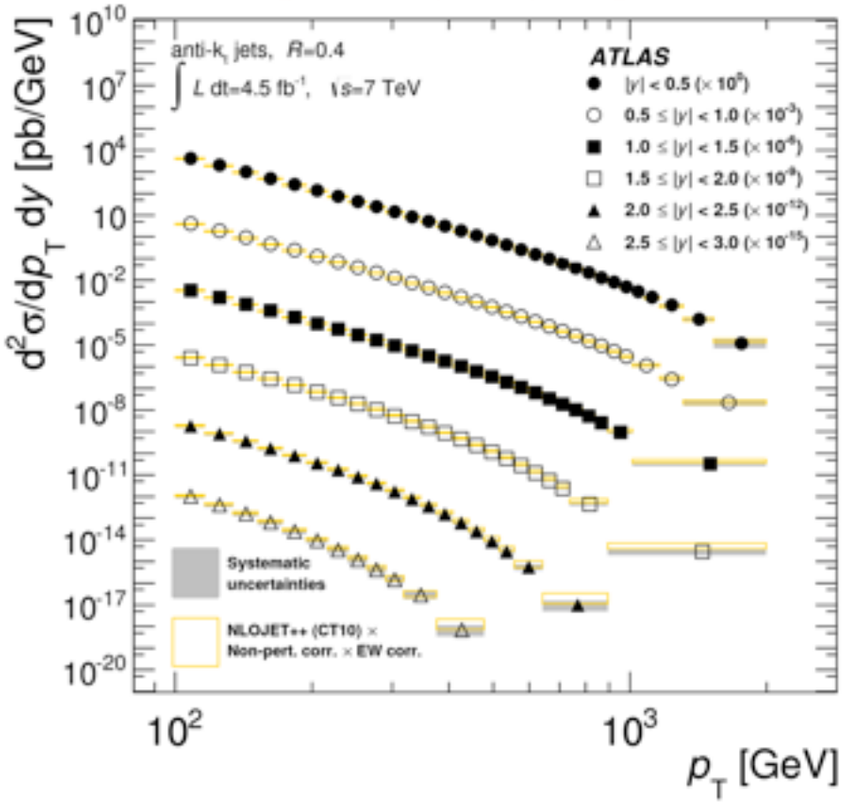
- How is this critical? For instance:
  - Higgs boson couplings measurement
  - W mass measurement
  - Prediction for heavy (> n TeV) new particle production (e.g. SUSY)
- General idea
  - 1) Use NLO or NNLO prediction to match data (jets, V+jets, top,...)
  - 1) Deduce what parametrization of the PDF does the best job!

g-PDF from >=2-jet cross-section @ 7 TeV

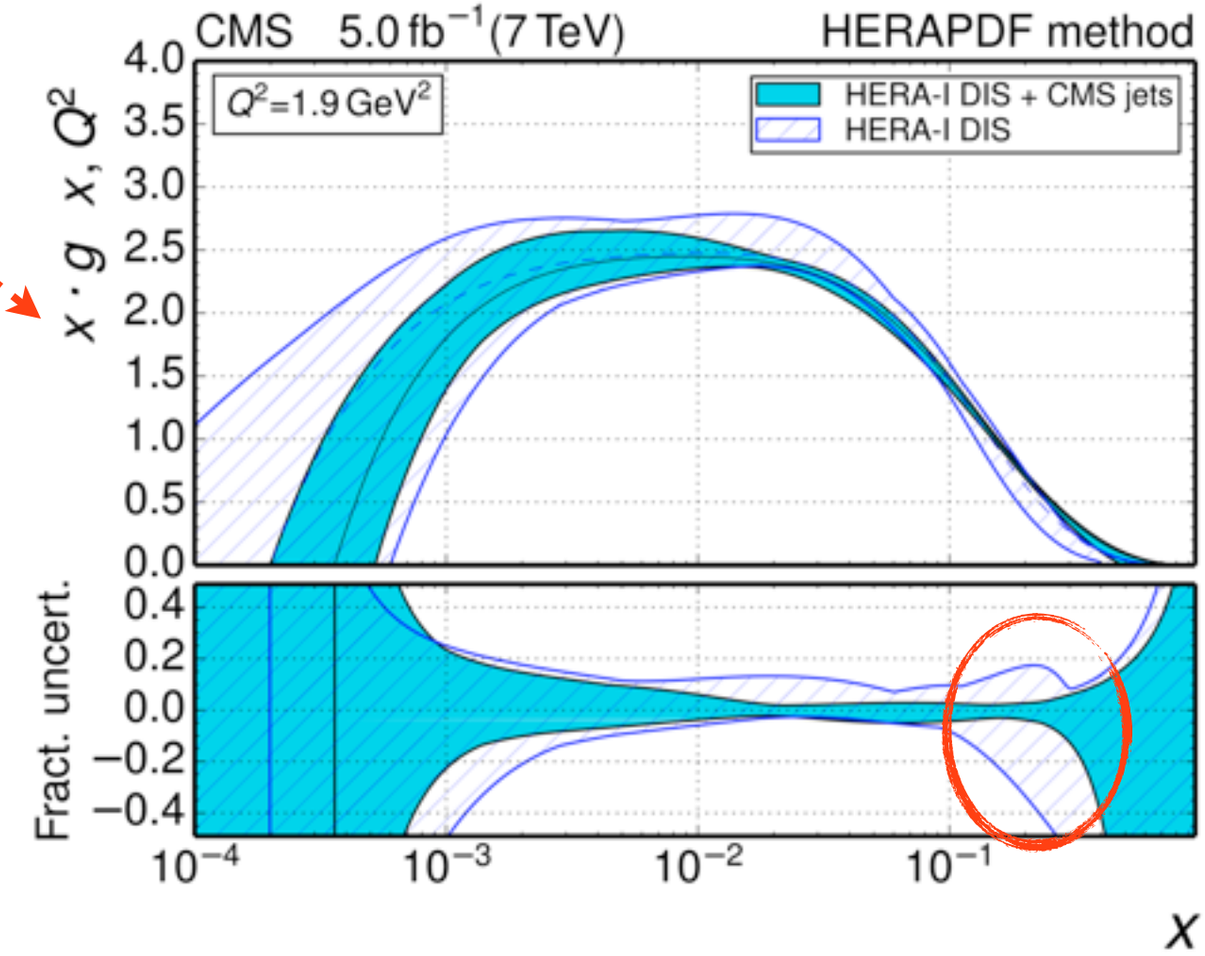
[Eur.Phys.J.C (2015) 75:288]



[JHEP02(2015)153]

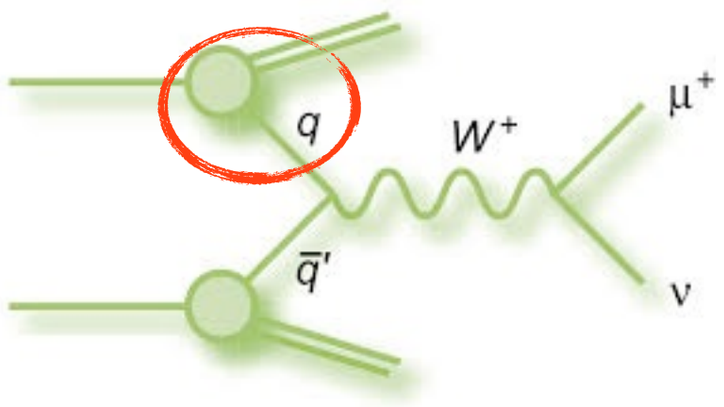


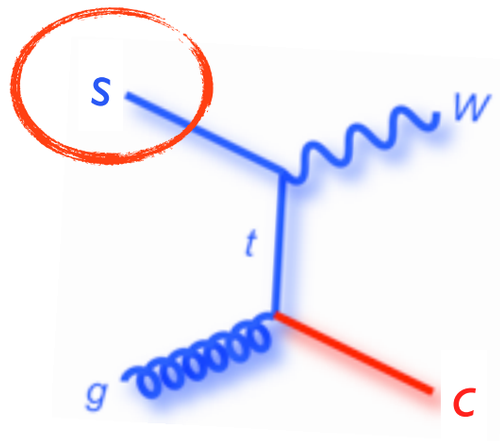
Significant reduction of uncertainties for g-PDF at high x



u/d/s quark PDF @ 7 TeV

- Use W+jets



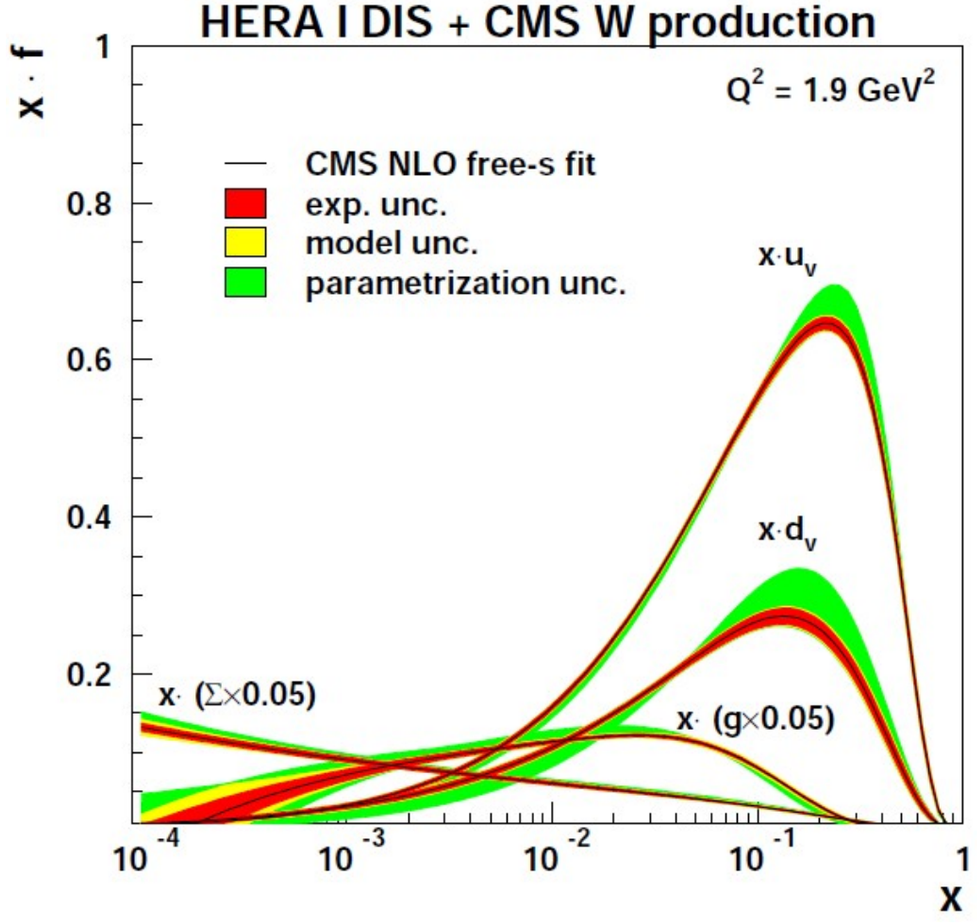


[PRD 90 (2014) 032004]

[JHEP 02 (2014) 013]

- W+c : sensitivity to s-PDF
- Inclusive W: sensitivity to u/d PDF

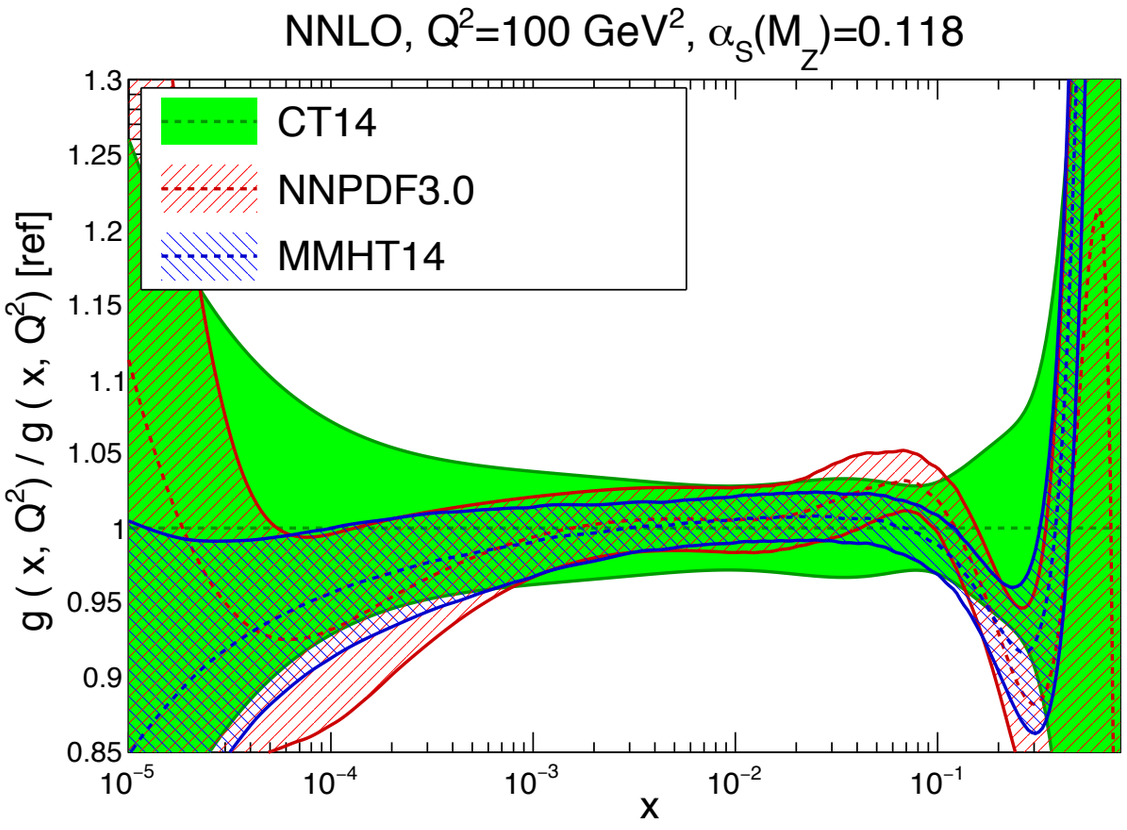
Exploit muon rapidity asymmetry

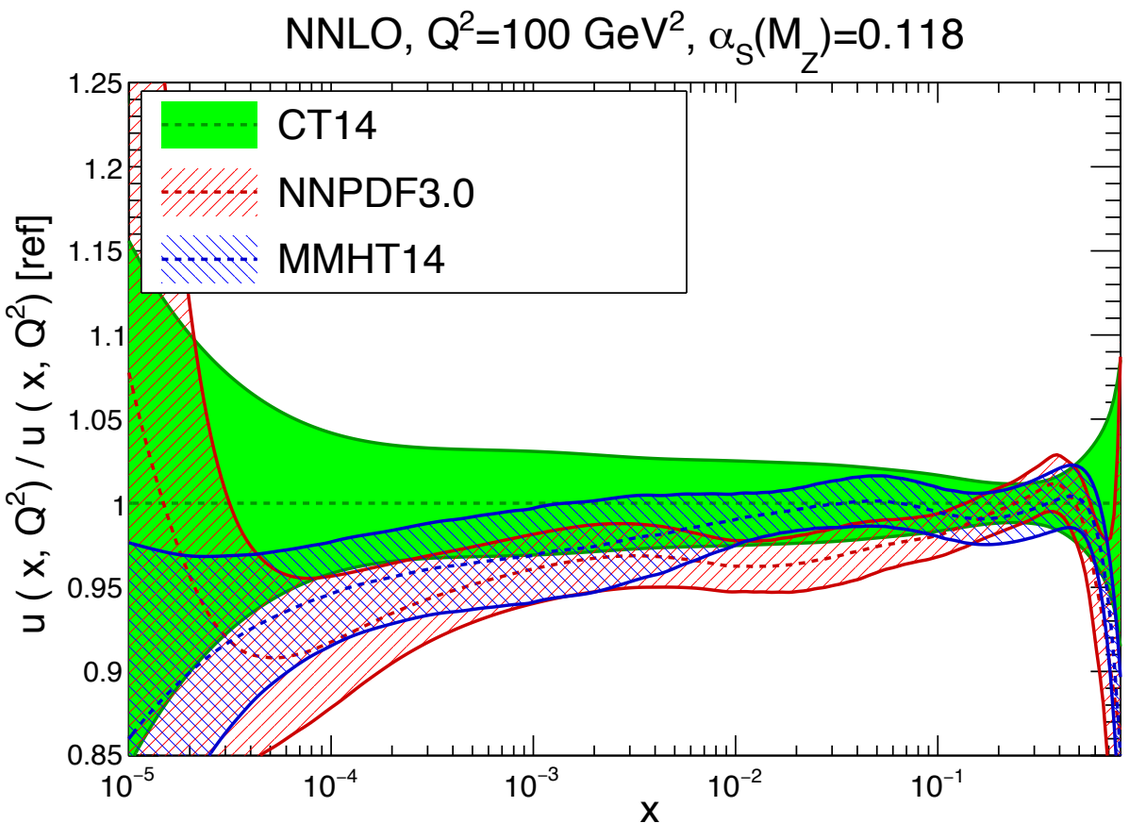


PDF from global fits

LHC data are now used by most PDF coll.
Generally quite good agreement!

[CERN-PH-TH-2015-249]



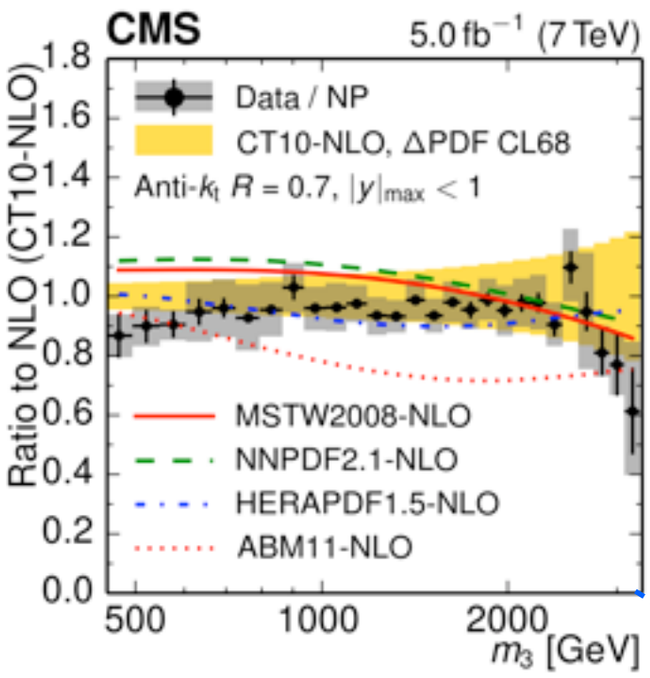


Prospects for Run II

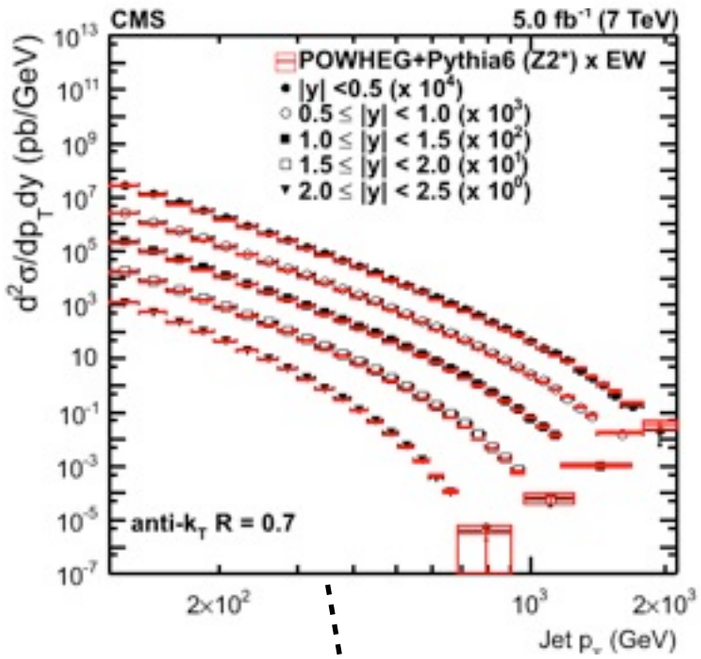
- g-PDF
  - Jets: profit of NNLO + and probe higher x
    - Exploit further pt spectra ratio (13/8/7/2.76 TeV)
  - photon: NNLO could be needed to go further.
    - Exploit pt spectra ratio (13 TeV/8 TeV): partial cancellation of systematic uncertainties. First tests are encouraging.

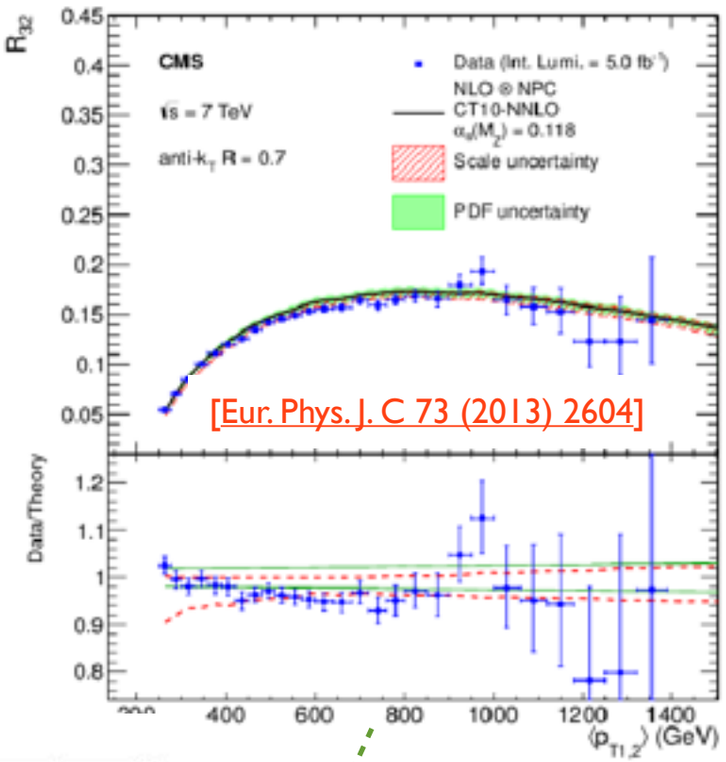
- q-PDF
  - W+c: make sure that ATLAS and CMS results are comparable. 'Fake' discrepancy from 7 TeV analyses should be avoided
  - DY: improvement expected at low x~0.0001 and high x ~0.2.
    - 2/3D measurements could be used.
  - Intrinsic charm PDF: through deviation of jet pt spectrum!

$\alpha_s(Q)$ @ 7 TeV

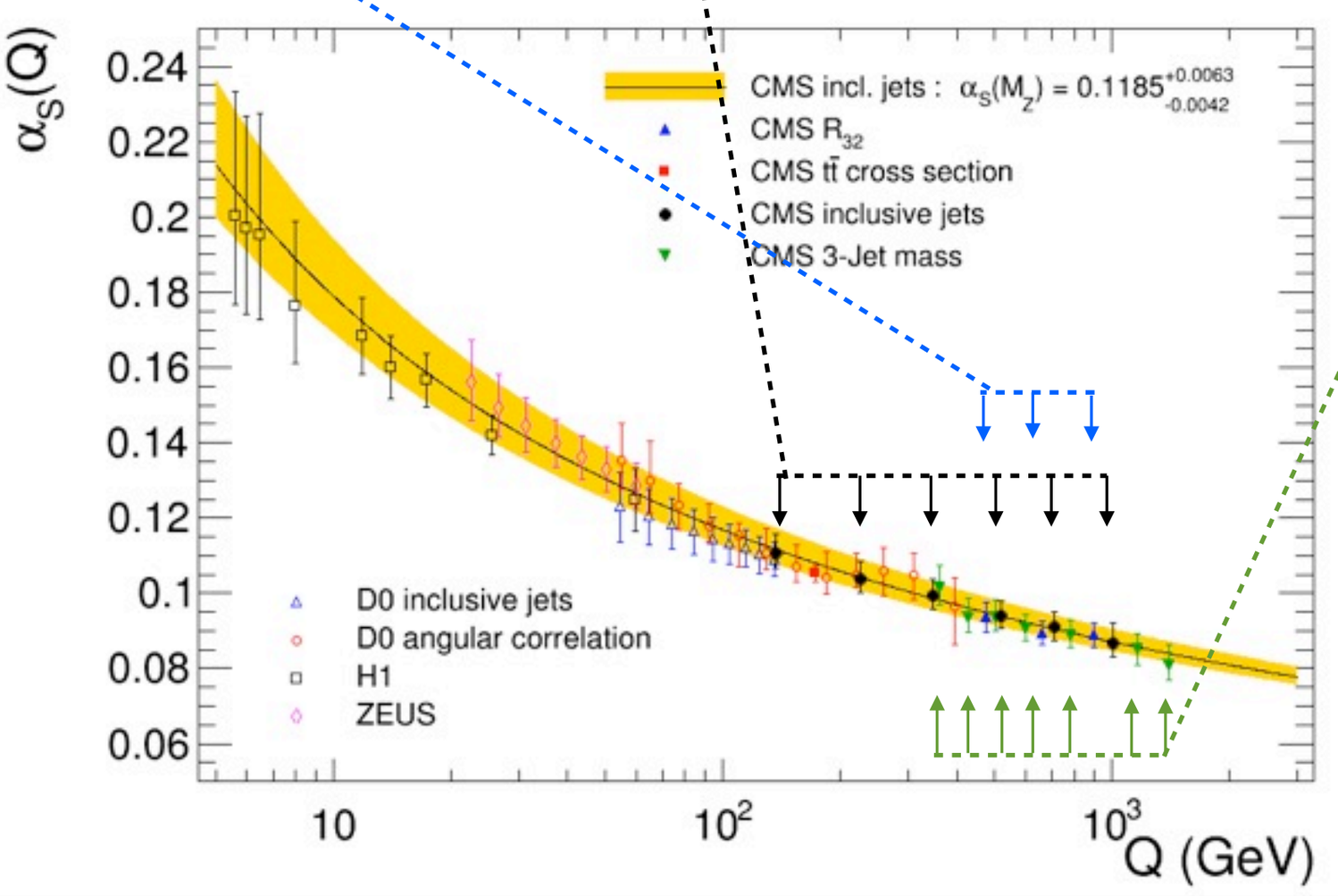


[Eur. Phys. J.C75(2015)288]

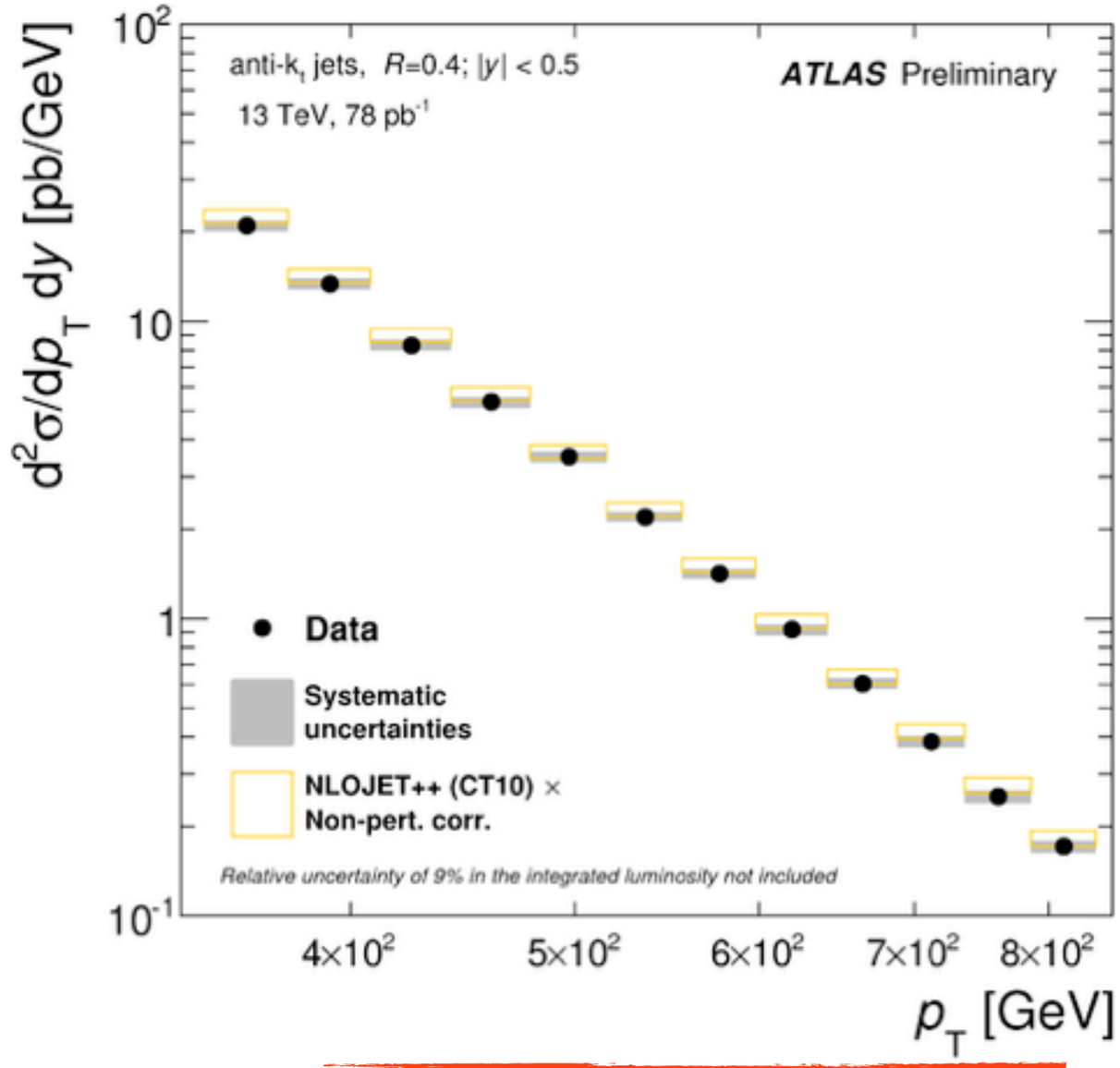




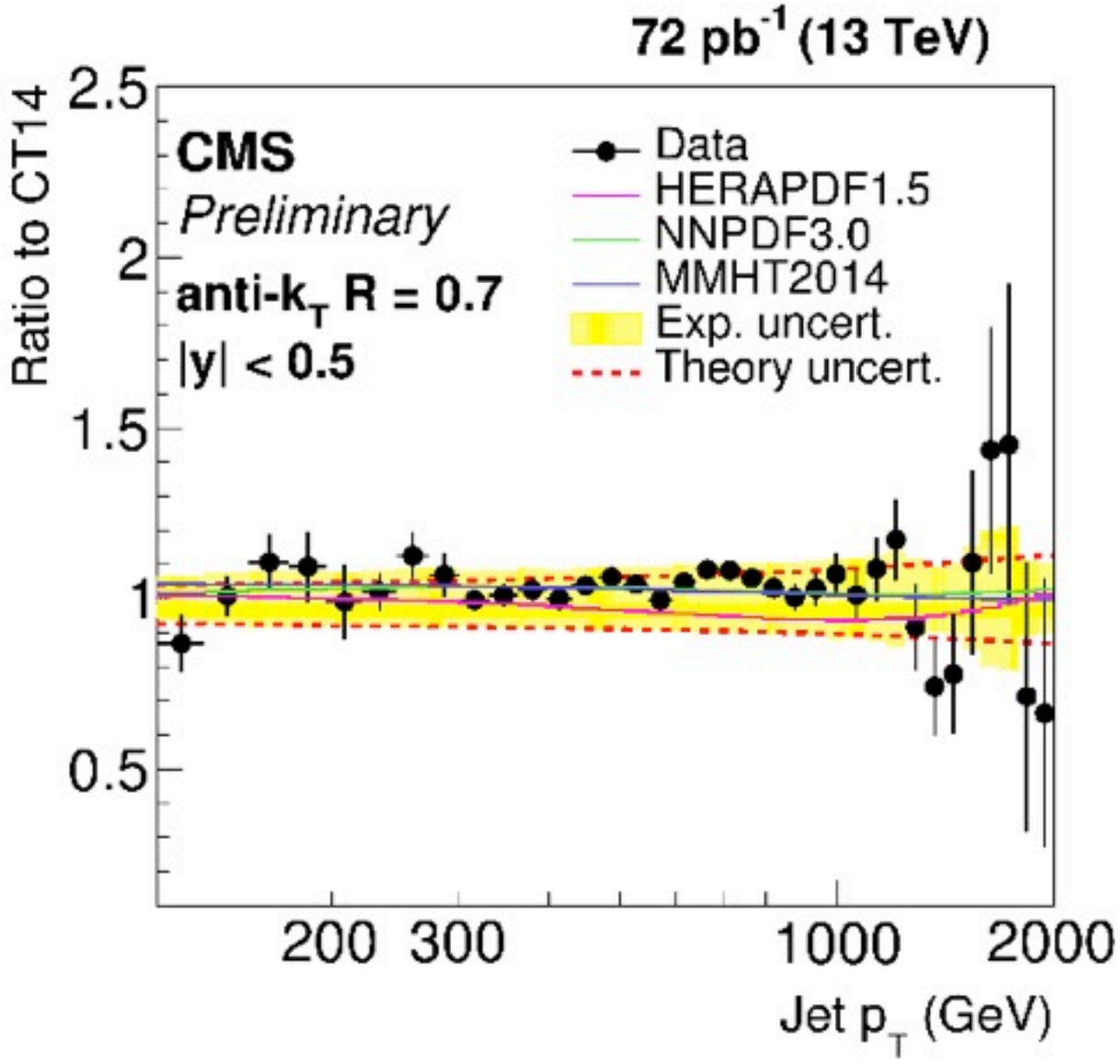
[Eur. Phys. J. C 73 (2013) 2604]



Jets @ 13 TeV



NLO agrees with 13 TeV data on orders of magnitude!

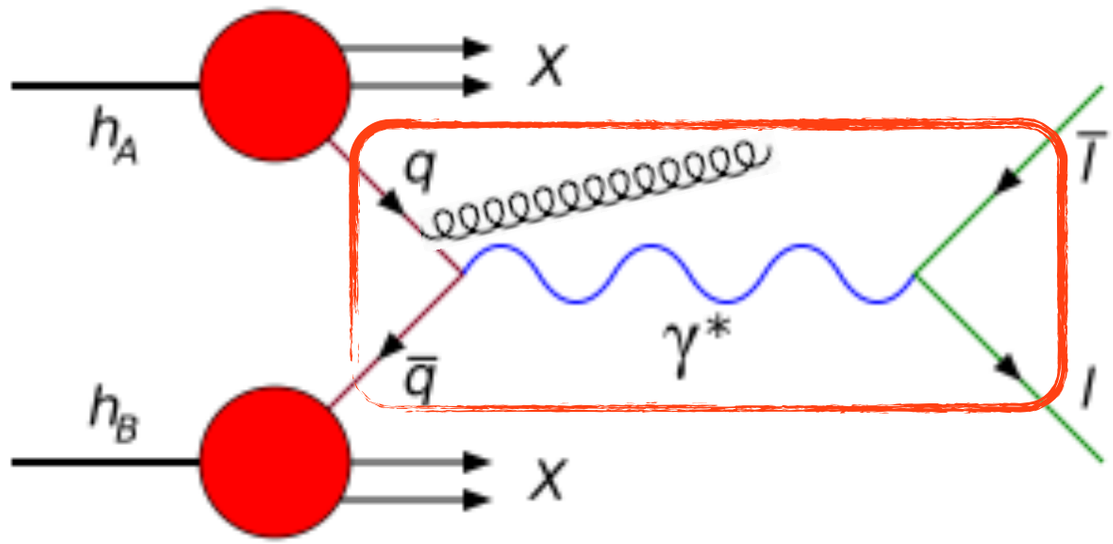


Data/MC ratio from CMS

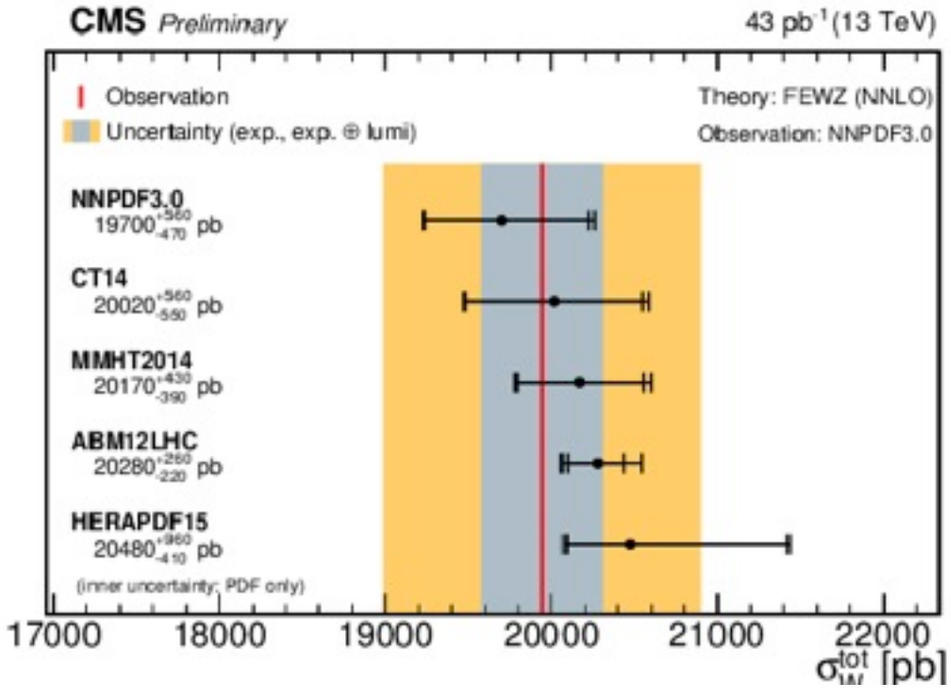
Data/MC comparisons for V, V+ light jets

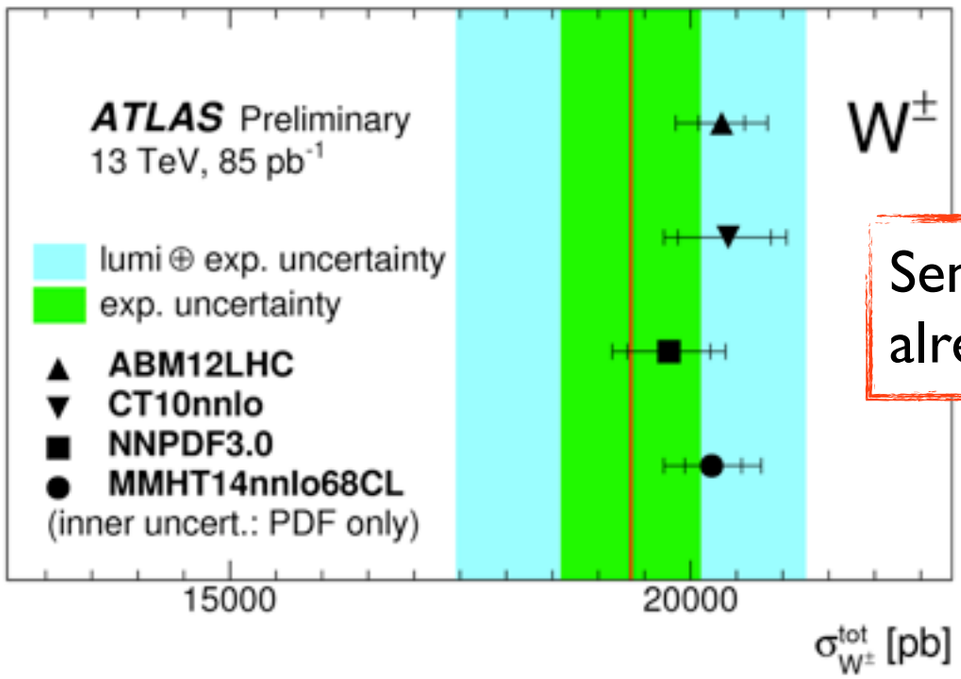
V, V+jets

- stress test of event generators/ calculations
  - tree-level,NLO,NNLO (ME), Parton Shower (PS)
    - Madgraph_aMC@NLO, Powheg, Sherpa, BlackHat, MEPS@NLO, ALPGEN,Pythia6,Pythia8,Herwig, ...
  - ME+PS: KtMLM , MLM, ShowerKt, CKKW-L FxFx, UMEPS, UNLOPS,...

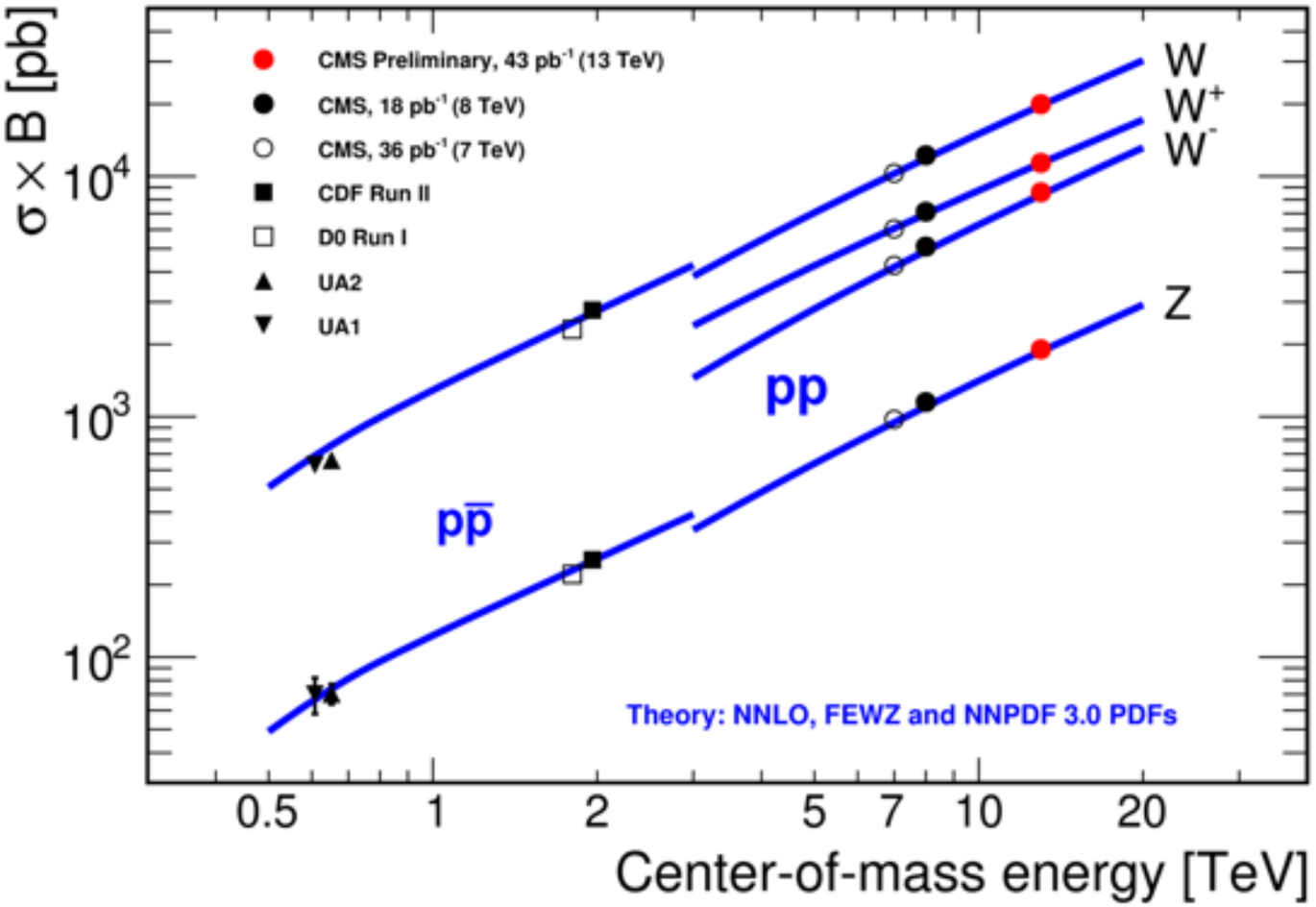


Inclusive V production @ 13 TeV





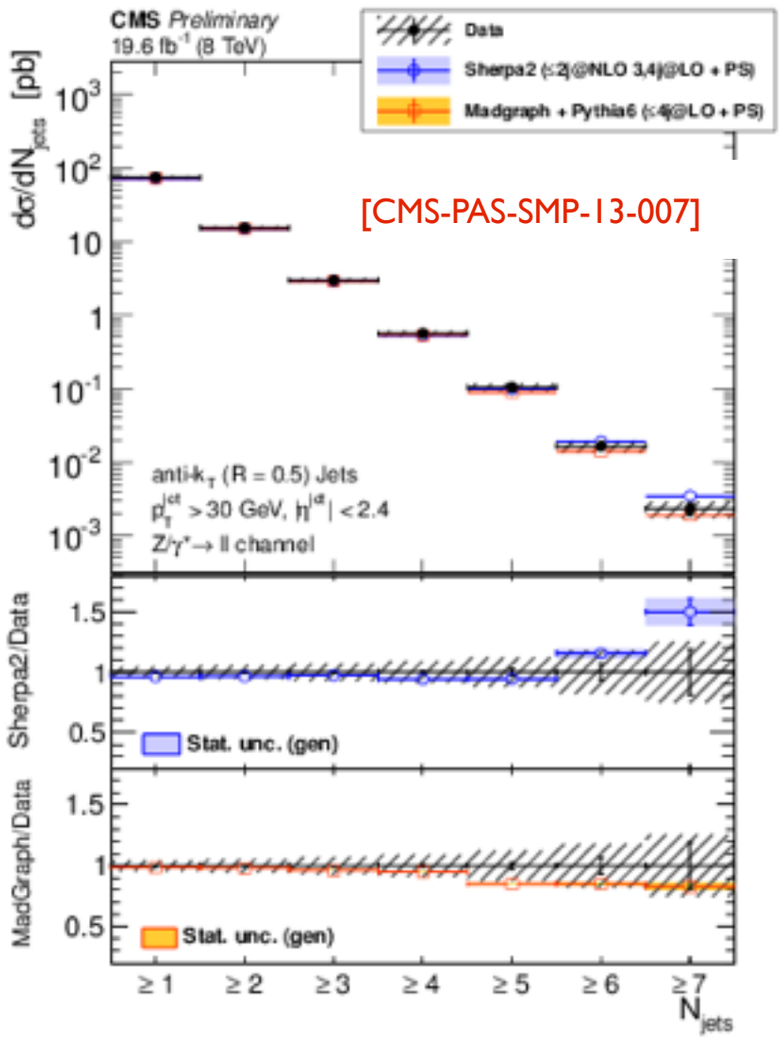
Sensitivity to PDF already present



NNLO prediction (FEWZ) matches very well the new data points!

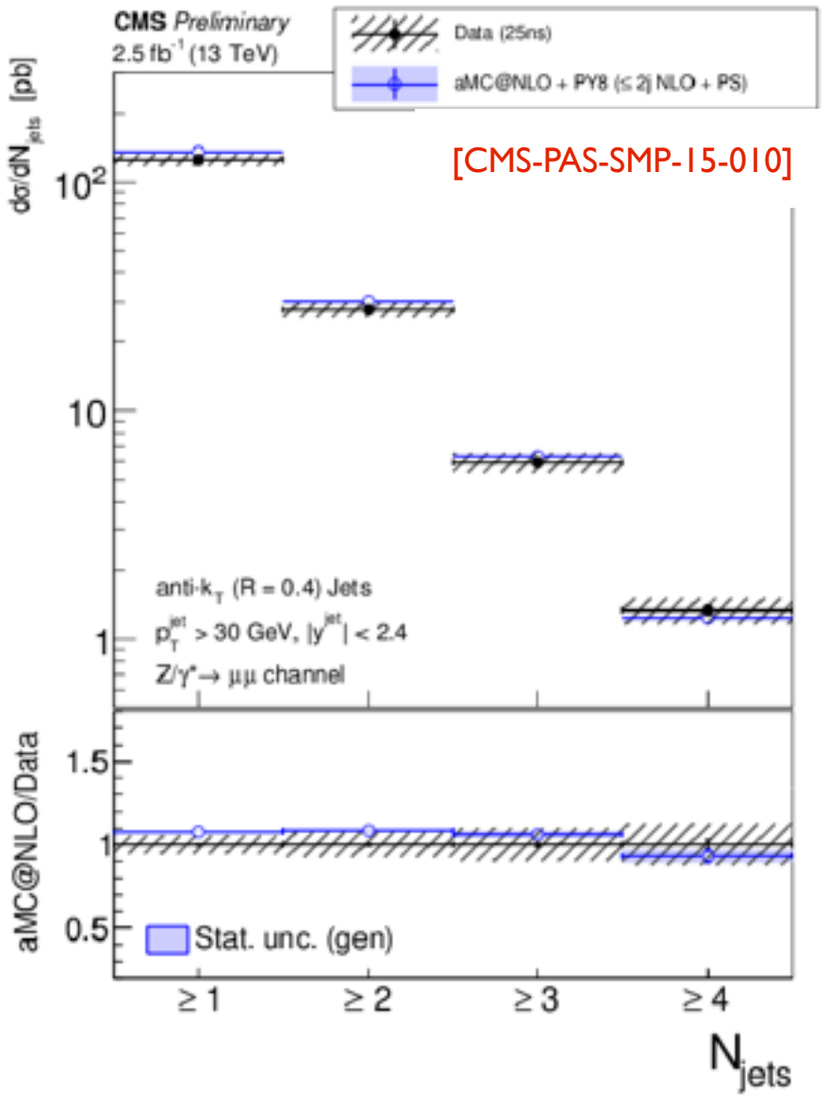
Z+jets

CMS@8 TeV



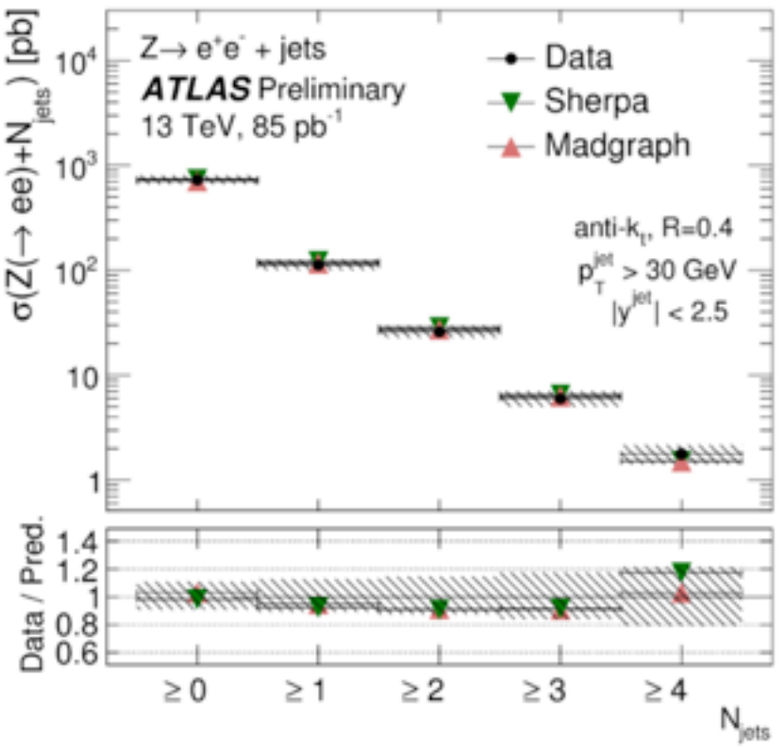
[CMS-PAS-SMP-13-007]

CMS@13 TeV



[CMS-PAS-SMP-15-010]

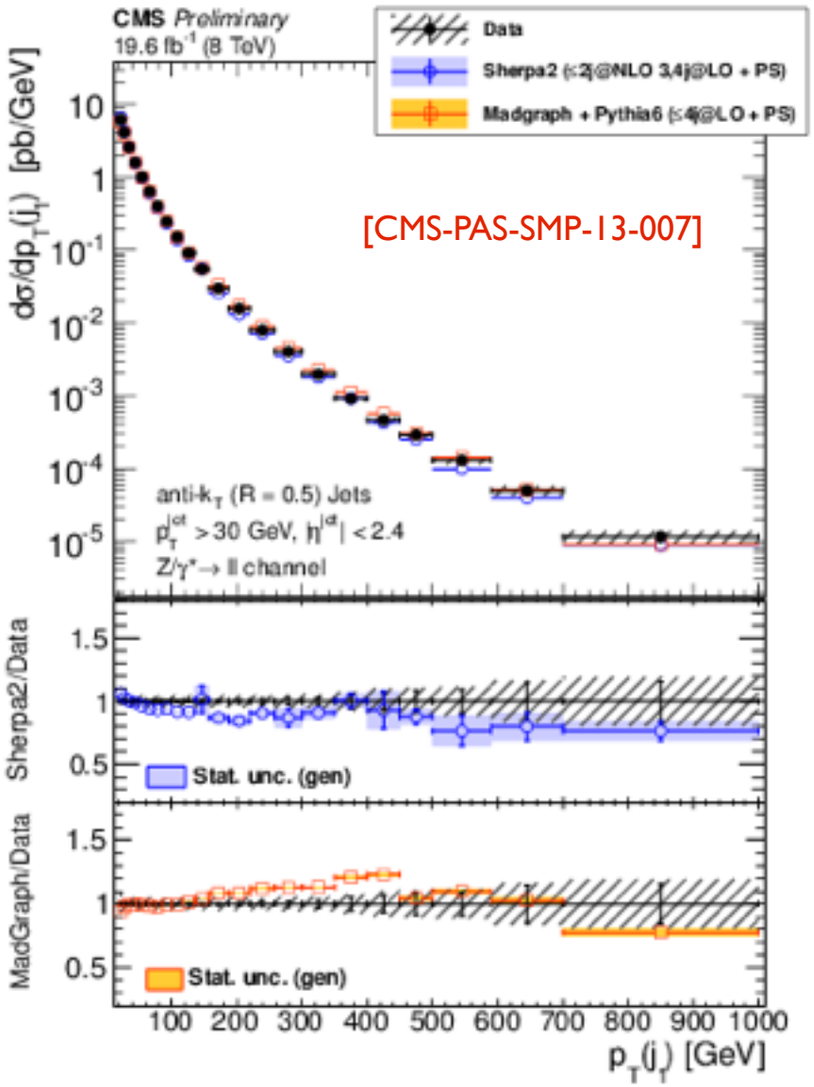
ATLAS@13 TeV



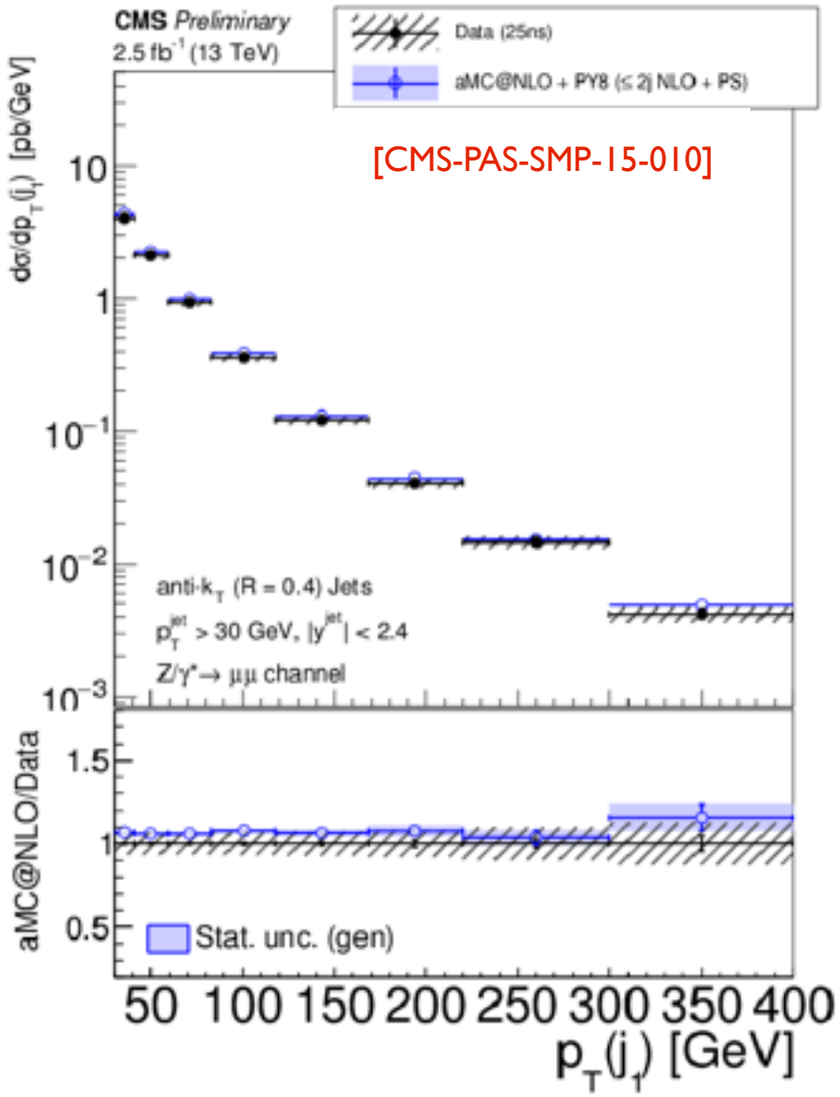
Different trends observed. Generally very reasonable agreement, even with tree-level predictions

Z+jets

CMS@8 TeV



CMS@13 TeV

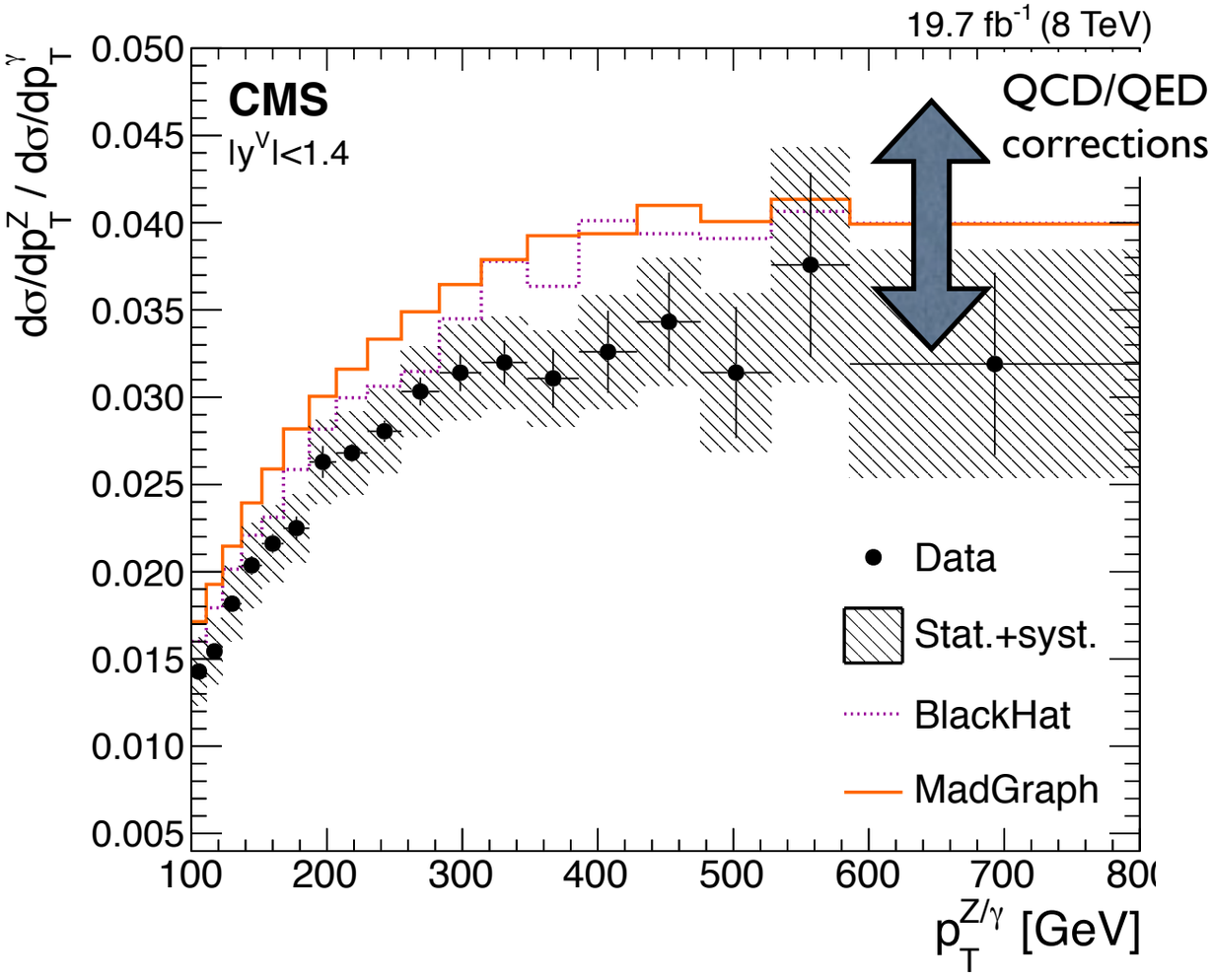


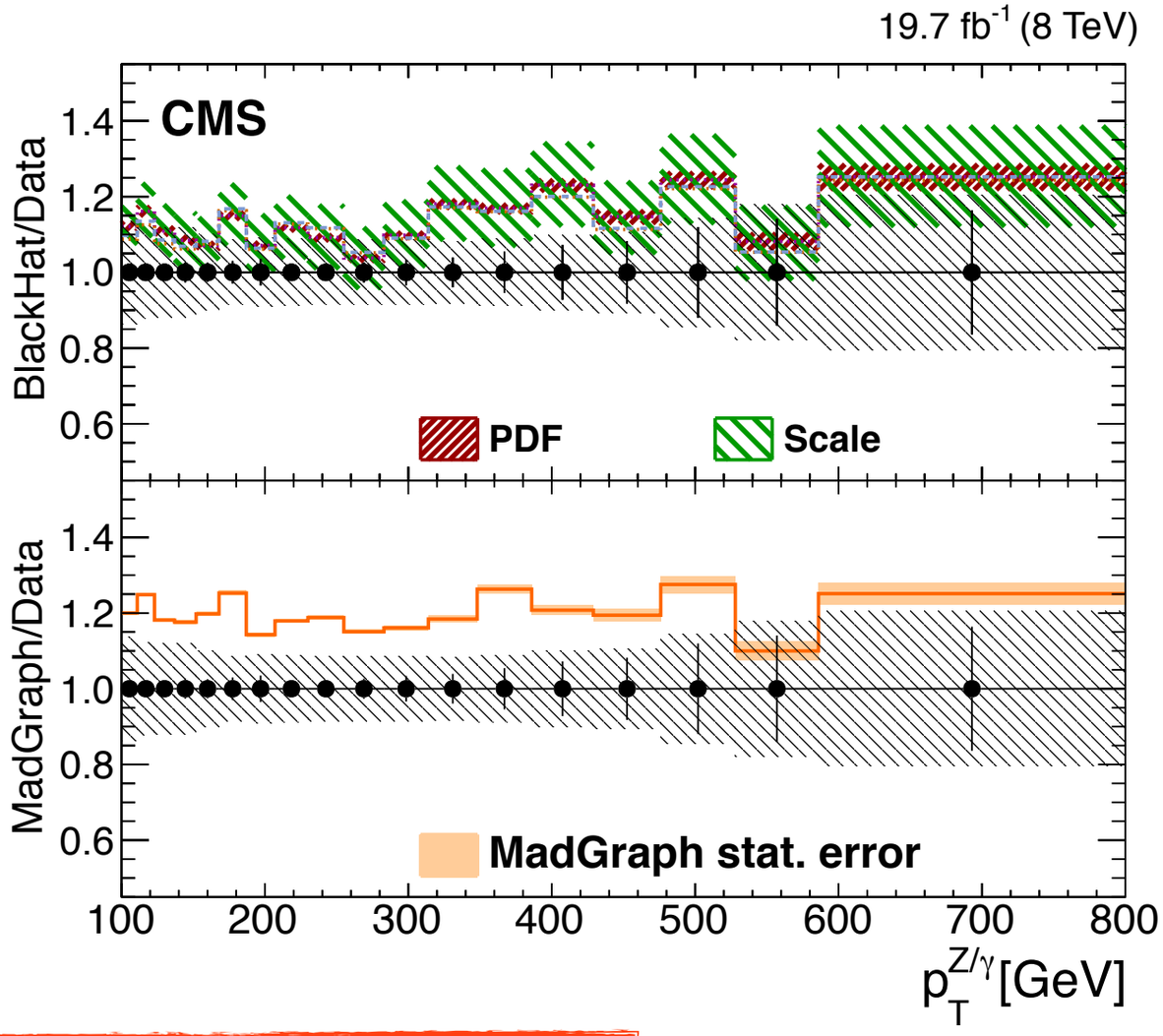
Different trends observed. Generally very reasonable agreement, even with tree-level predictions

V+jets ratio: Z+jets/γ+jets @ 8 TeV

1) Precision measurement (partial cancellation of systematics)
2) Data-driven prediction of Z+jets through γ+jets

[arxiv.1505.06250]





Data and MC agree within uncertainties.
tree-level and NLO behave similary

Run II prospects for V+jets

- V+jets measurement are high priority in Run II
  - background for Higgs, SUSY,... searches
    - Challenge: fast measurements coming sufficiently early!
  - Getting sensitivity to QED corrections
  - Testing new NNLO predictions
  - High statistics means also focus on detailed regions of the phase-space
    - radiative production of W, Z,...
    - better sensitivity to PDF

Data/MC comparisons for V+ heavy-flavoured jets*

*only LHC...but Tevatron has also new results

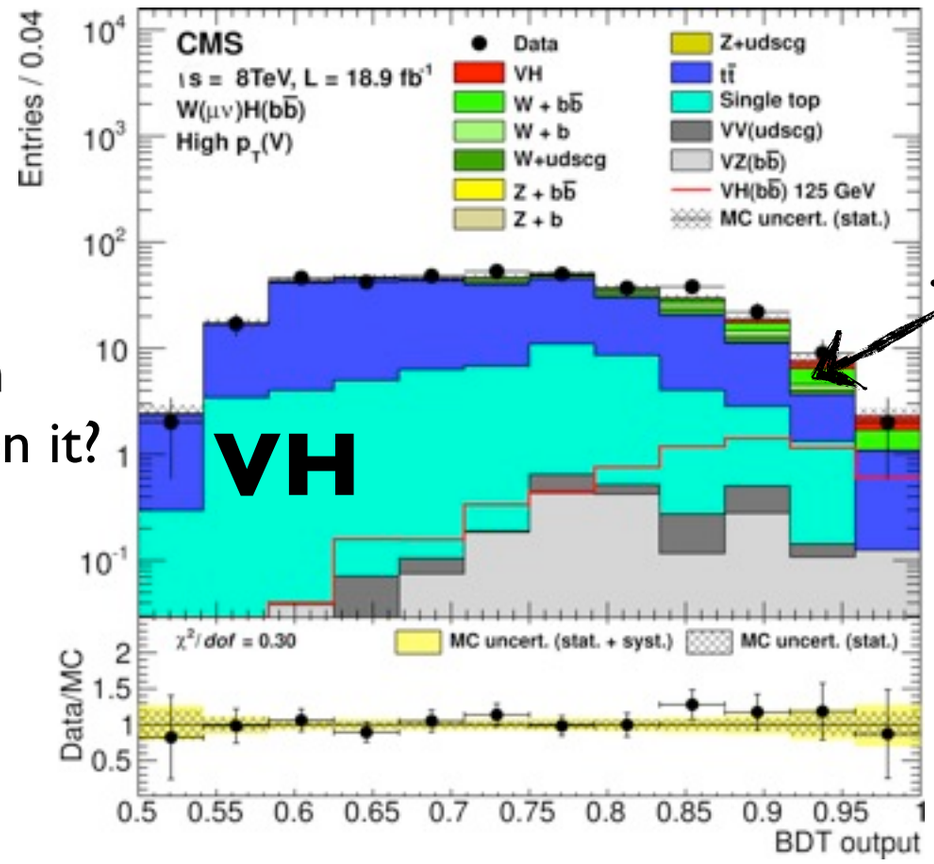
TH

Number of quark flavour in p (NQF)
ME-PS merging vs NQF
Scales
Q mass
fragmentation, decay
...

V+HF

Really worth spending time on it?

[Phys.Rev. D89 (2014) 012003]



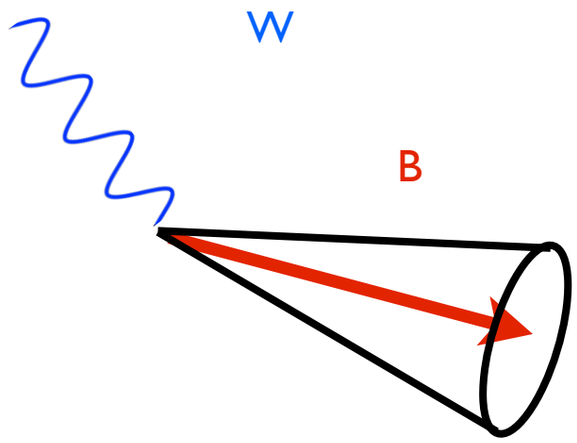
...yes

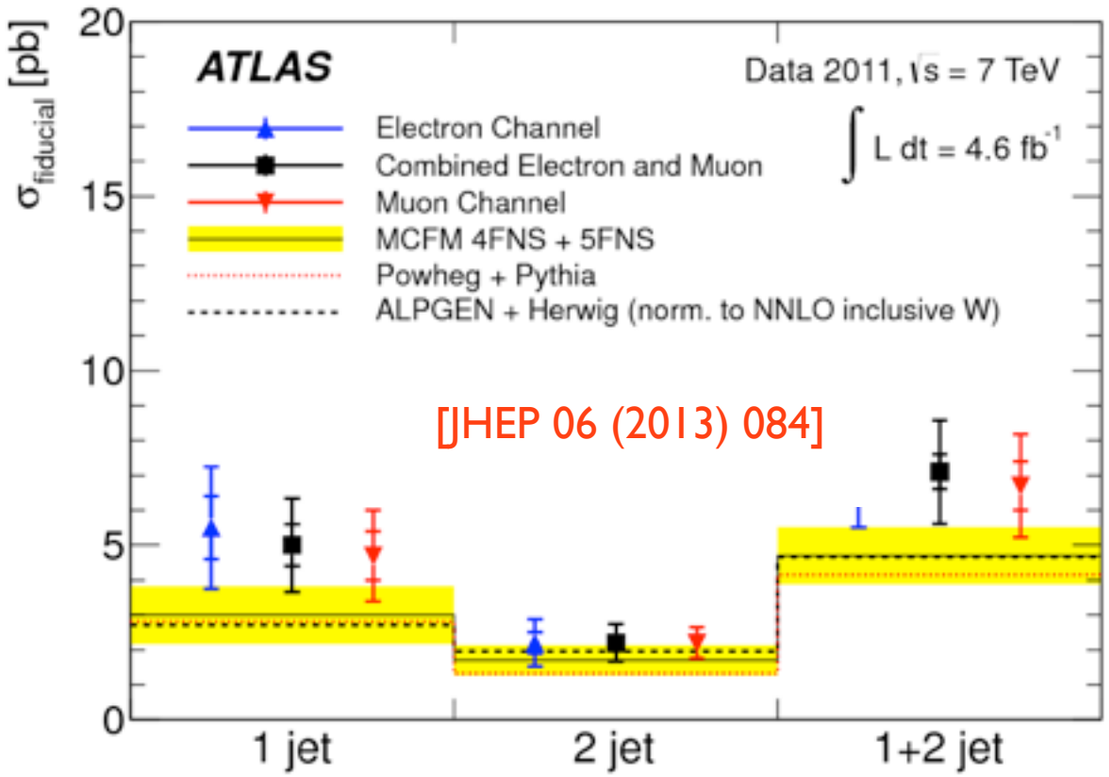
Exp.

heavy flavours tagging
much smaller statistics
potentially large background
removing DPS component
...

W+1 b/c @ 1.96,7 TeV

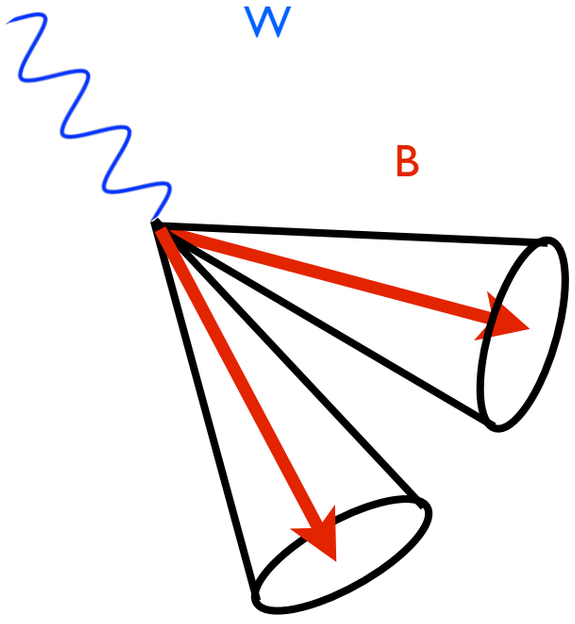
Large data/MC excess

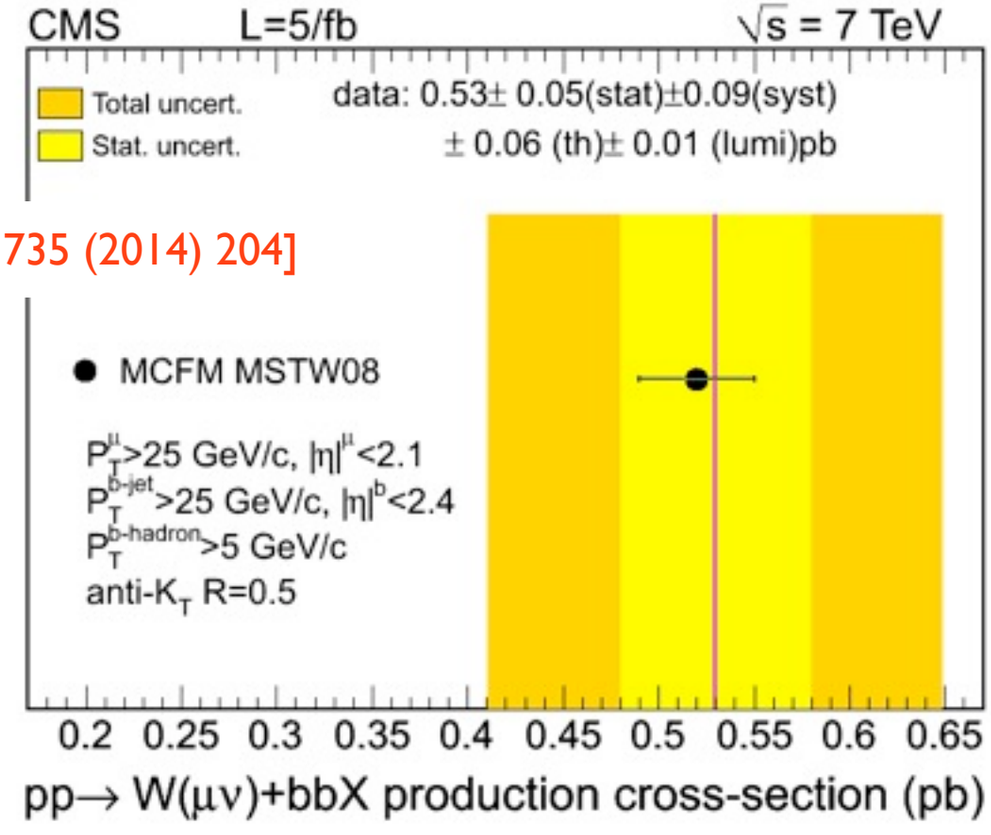




[JHEP 06 (2013) 084]

Good agreement with MCFM

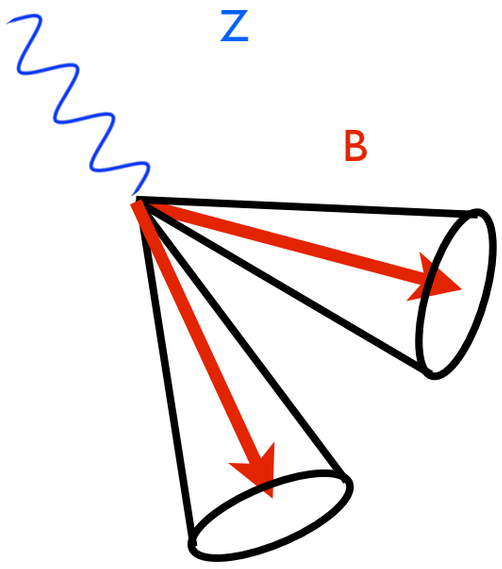


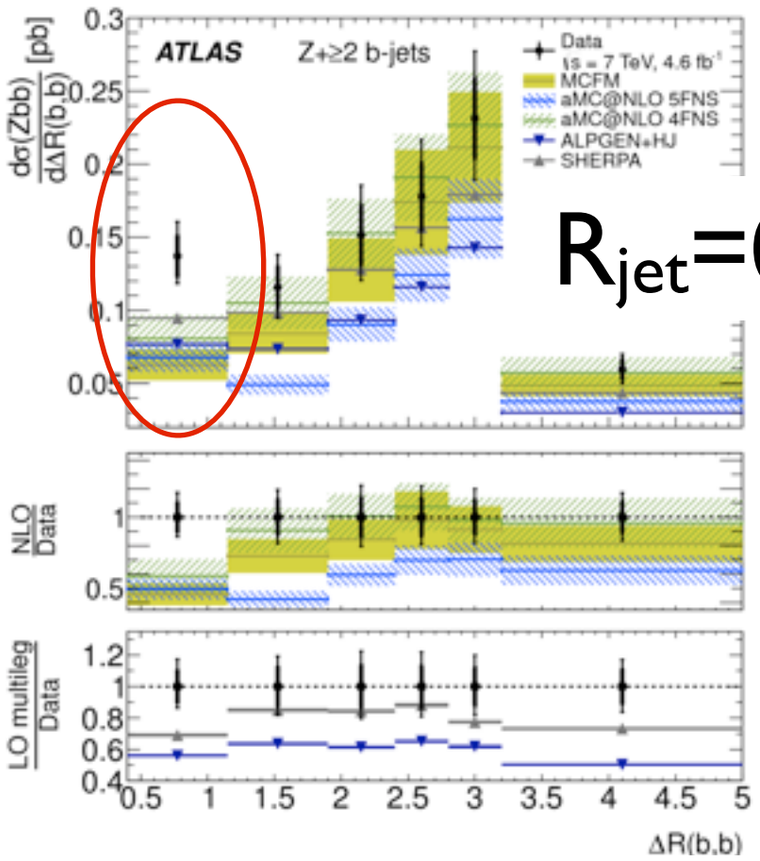


[PLB 735 (2014) 204]

Z+2b@7,8 TeV

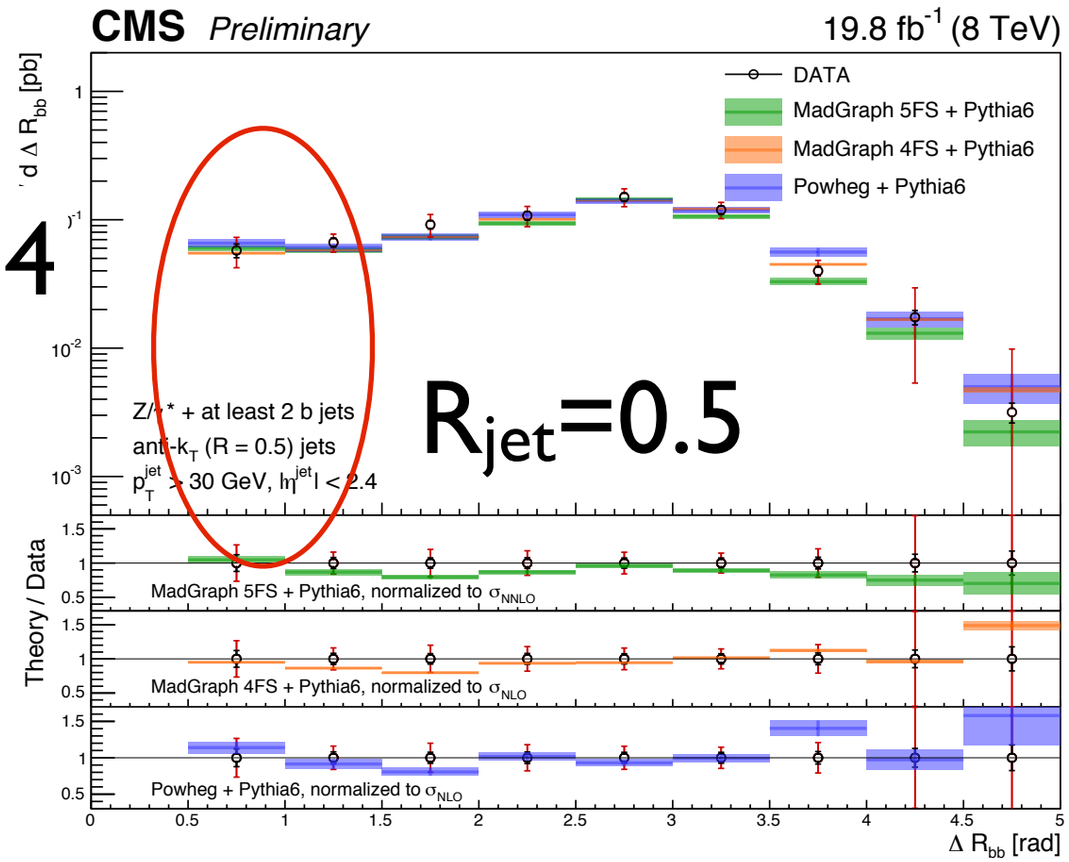
[JHEP 10 (2014) 141]





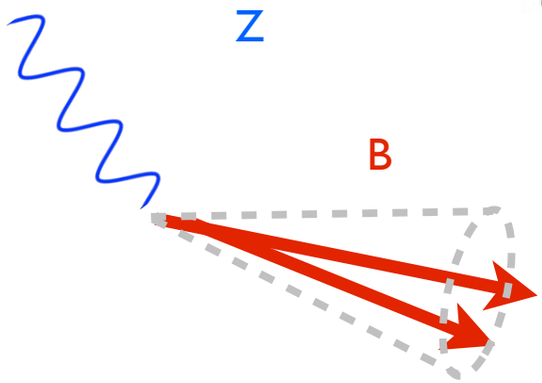
R_{jet}=0.4

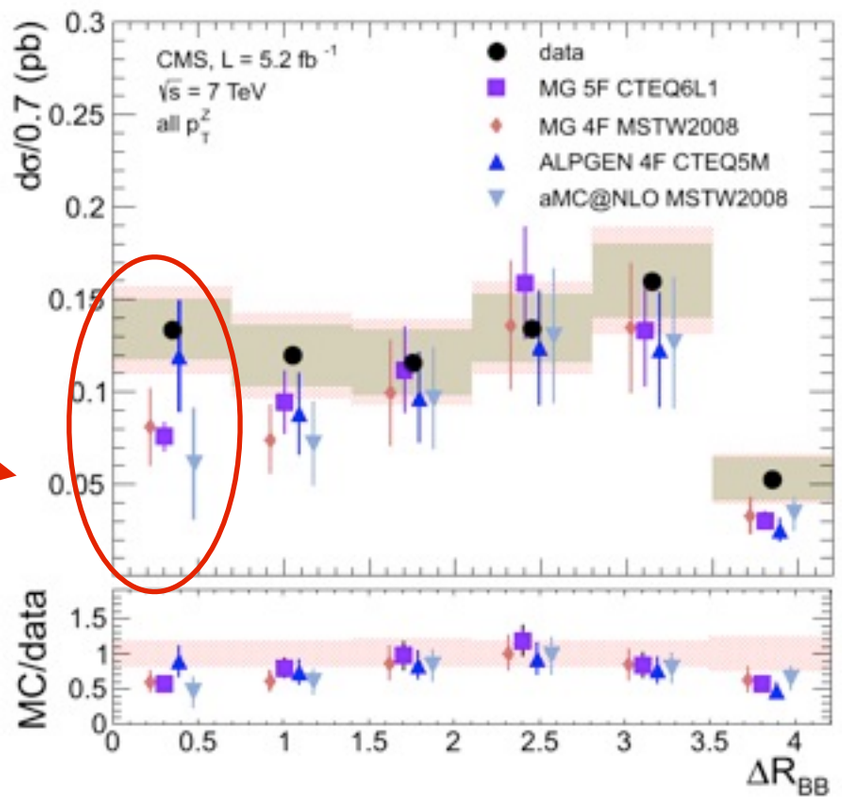
CMS-PAS-SMP-14-010



R_{jet}=0.5

[JHEP 12 (2013) 39]



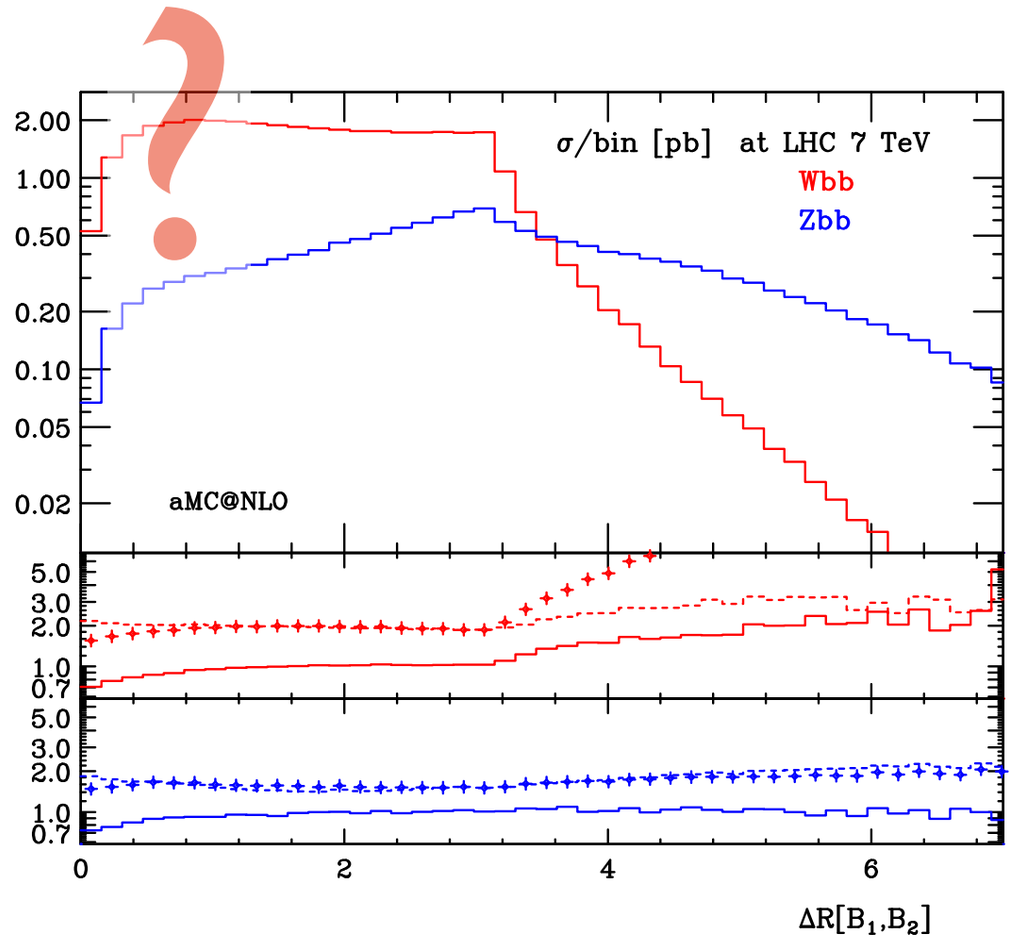


7 TeV: Both CMS and ATLAS see an excess of data around and below 0.5

8 TeV: CMS does not see anything wrong

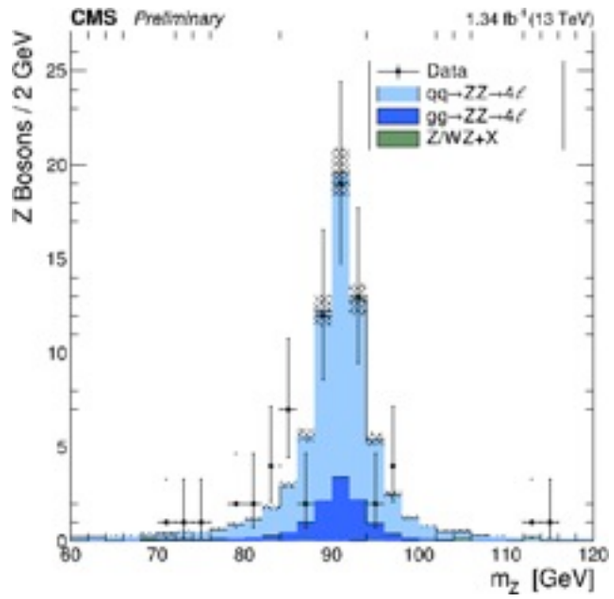
V+HF in Run II?

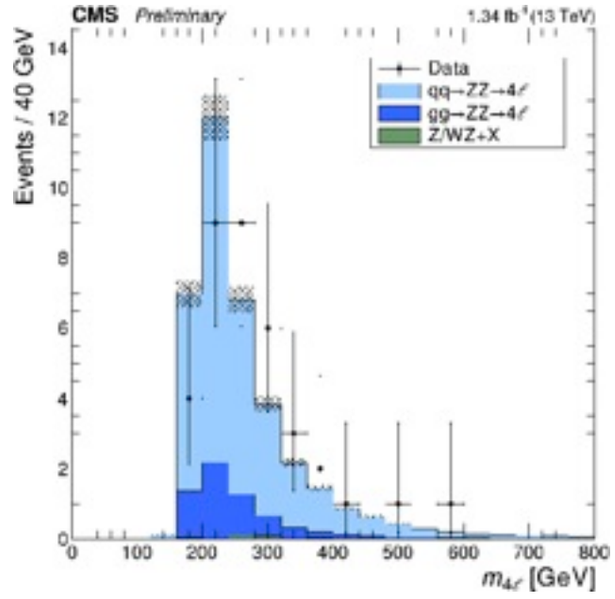
- Run II wish list
  - V+1b/c at very high Pt(V): test the n-partons numbering schemes
  - Angular correlation: collinear production of the heavy quarks
    - Use b's and c's. Key measurement: collinear production of bb/cc with a W. This possibly solves the W+1b-jet data excess.
  - Why c? Exclusive D-mesons decay provide a clean signature. e.g. $D^{\pm} \rightarrow K\pi\pi$, $D^{*} \rightarrow K\pi\pi\pi$,...but lot of statistic is needed.



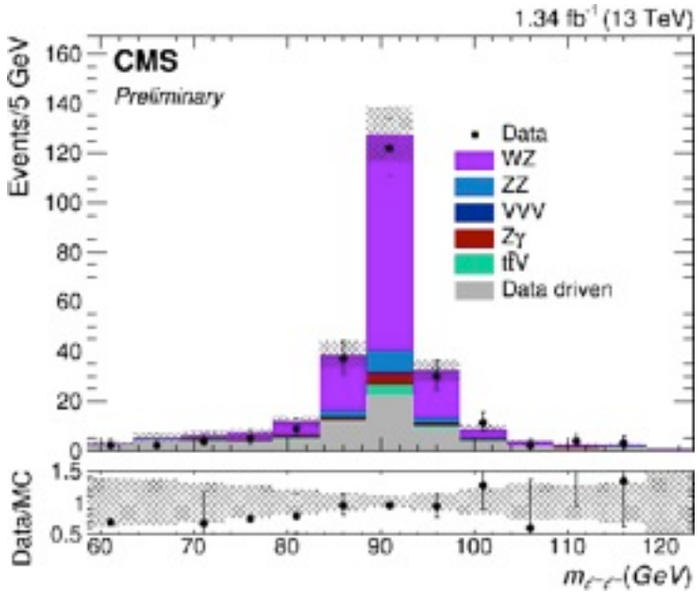
Diboson studies @ 13 TeV

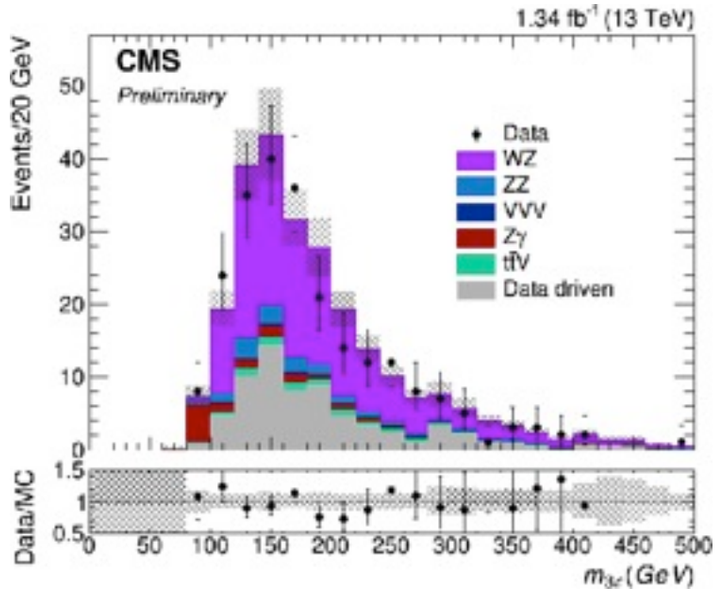
- ZZ





- WZ





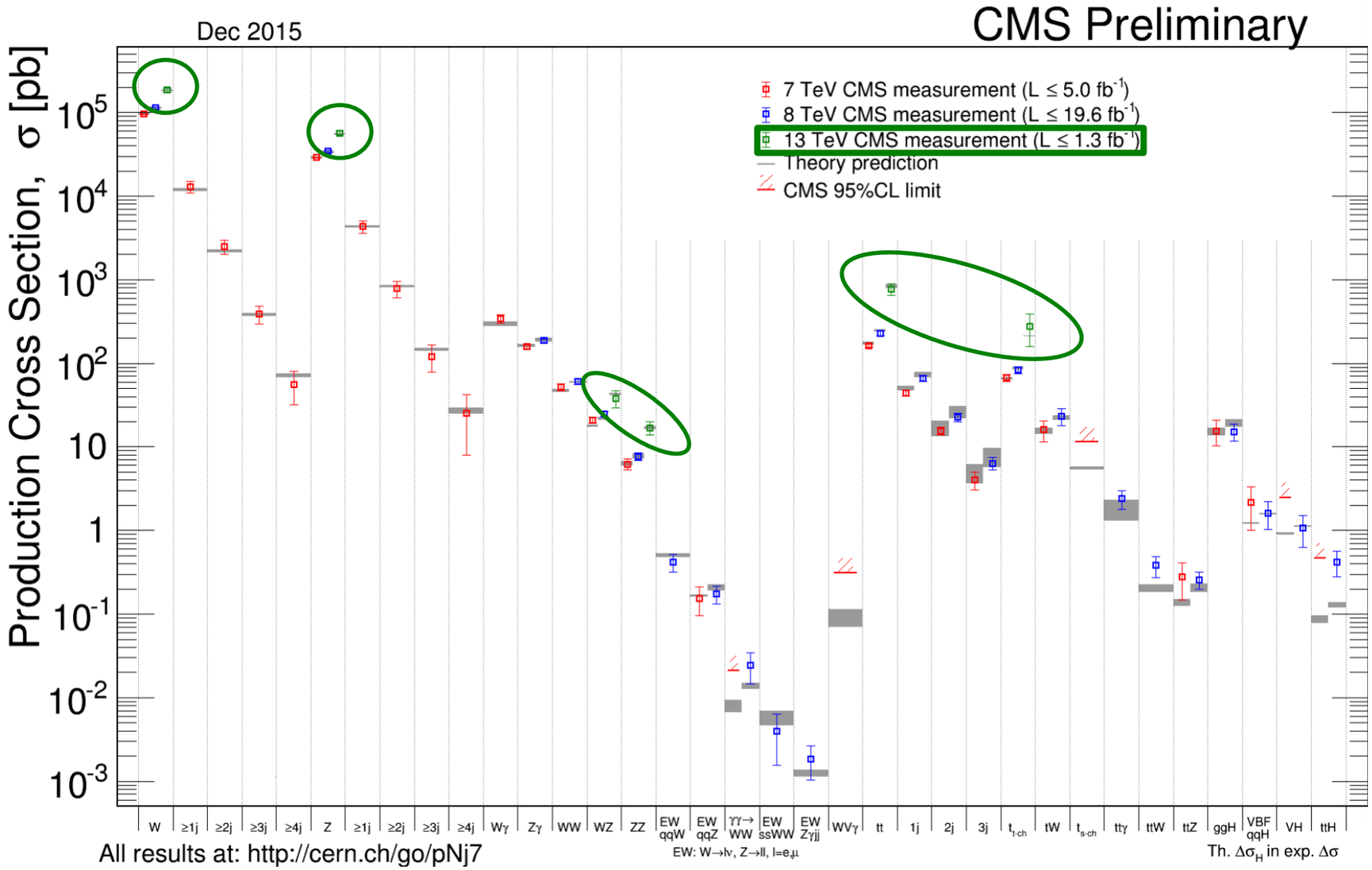
Excellent agreement of theory with data!

Diboson studies

- Why?
  - Background for searches
    - ZZ, WW, γγ
  - Gate to explore «extended» Standard Model
    - moving to dim 6 or 8: adds new couplings without involving new particles
    - Trilinear anomalous gauge couplings
      - ZZγ, Zγγ, WWγ, ...
    - Quartic gauge couplings
      - WWWW, WWZZ,..
  - diboson process xsec are well predicted by theory (NLO, NNLO)
    - Any significant deviation could be a sign of anomalous gauge coupling
- Run I: limited by statistics.
  - Run II will enhance strongly the discovery power power!
  - Prediction from theory has evolved a lot (NLO)

Conclusion

- Impressive effort in LHC experiments to improve our knowledge of Standard Model during Run I. Run II data analysis has started...

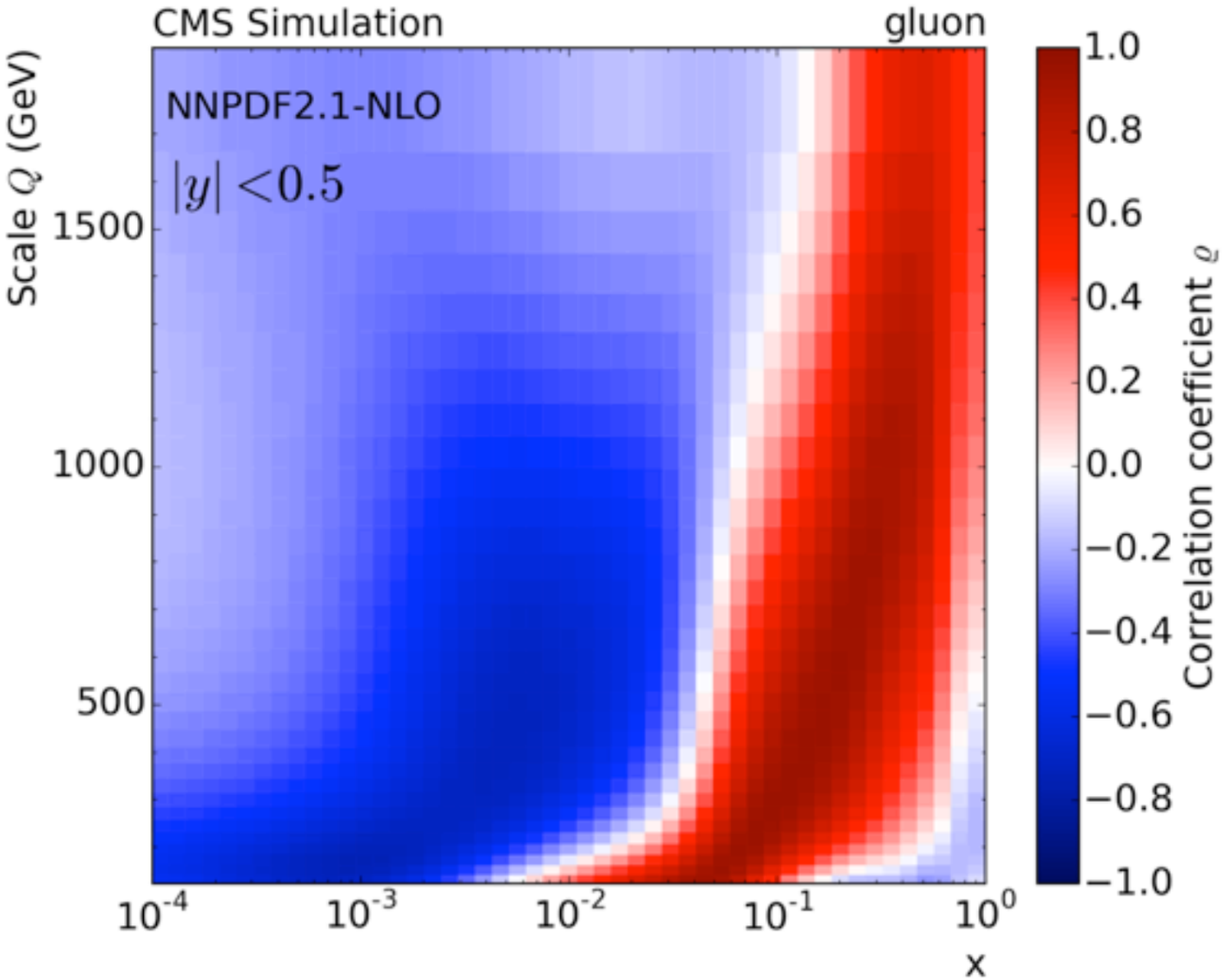


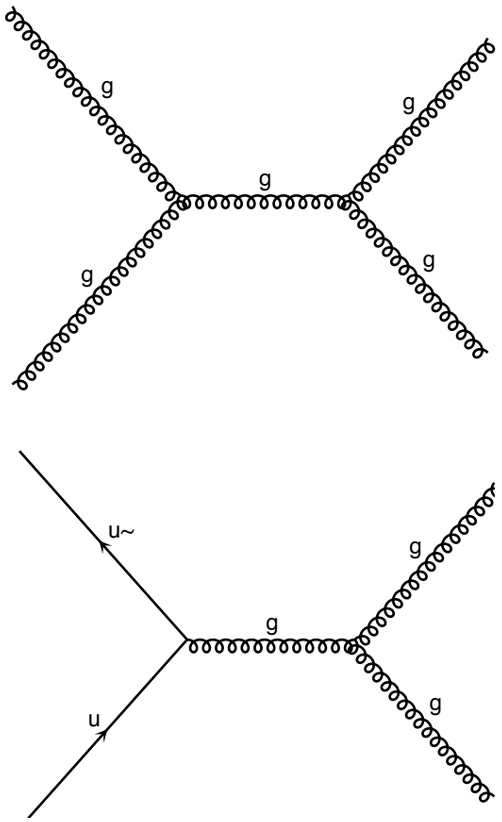
- Run II should bring further on almost all topic already studied, and will allow us to push new gates, thanks to the improved statistics, increased cross-sections, and lessons from Run I

Backup slides

Jets, PDF, alphaS

PDF from >=2-jet cross-section



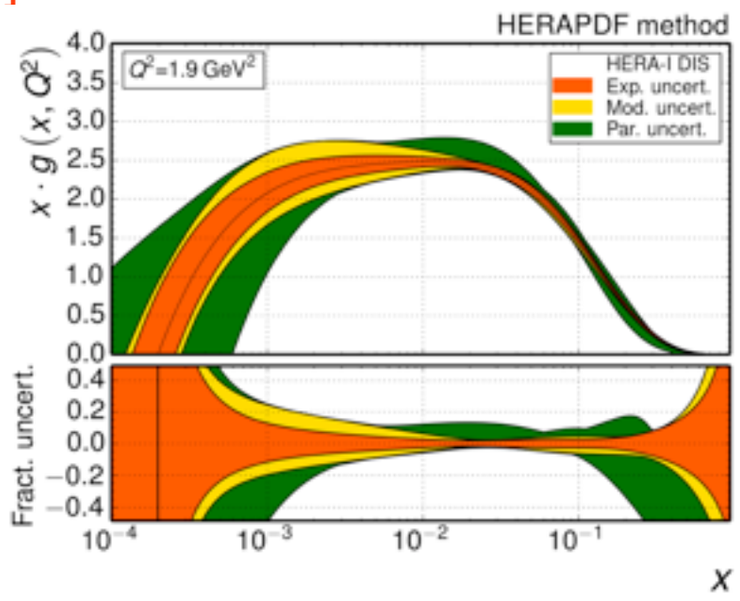


Strong correlation in (x,Q)
⇒good to constrain PDF

PDF from n-jet cross-section

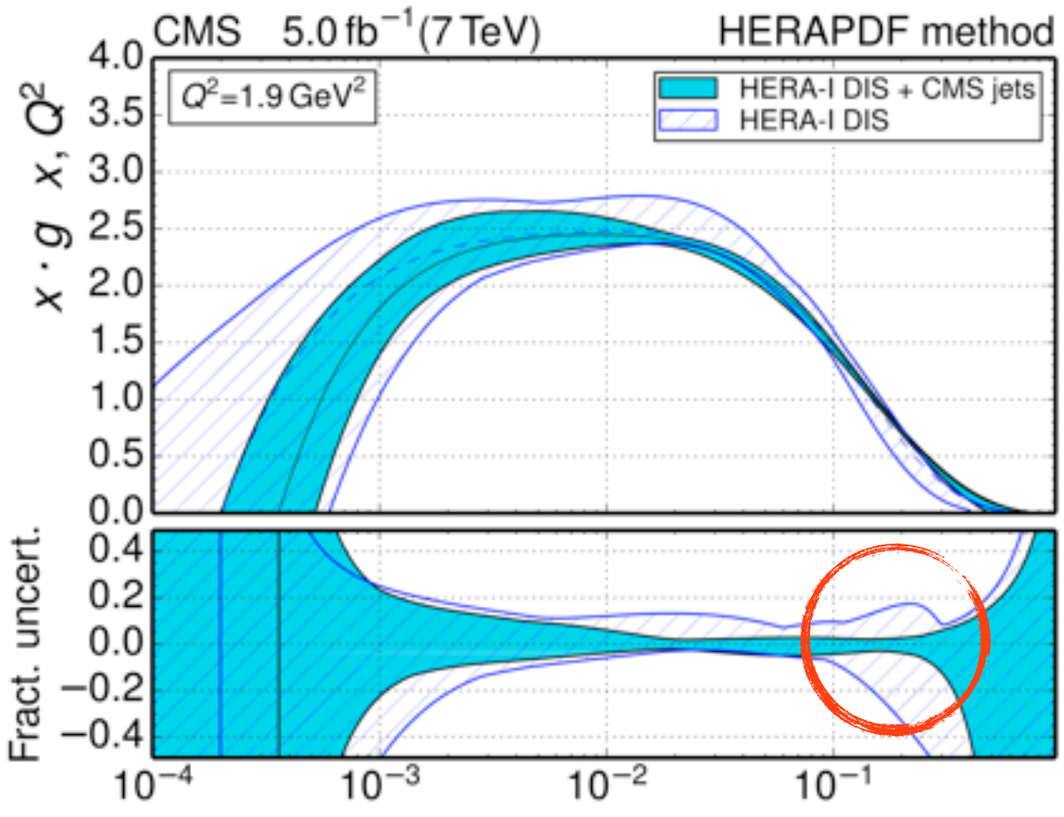
[Eur.Phys.J.C (2015) 75:288]

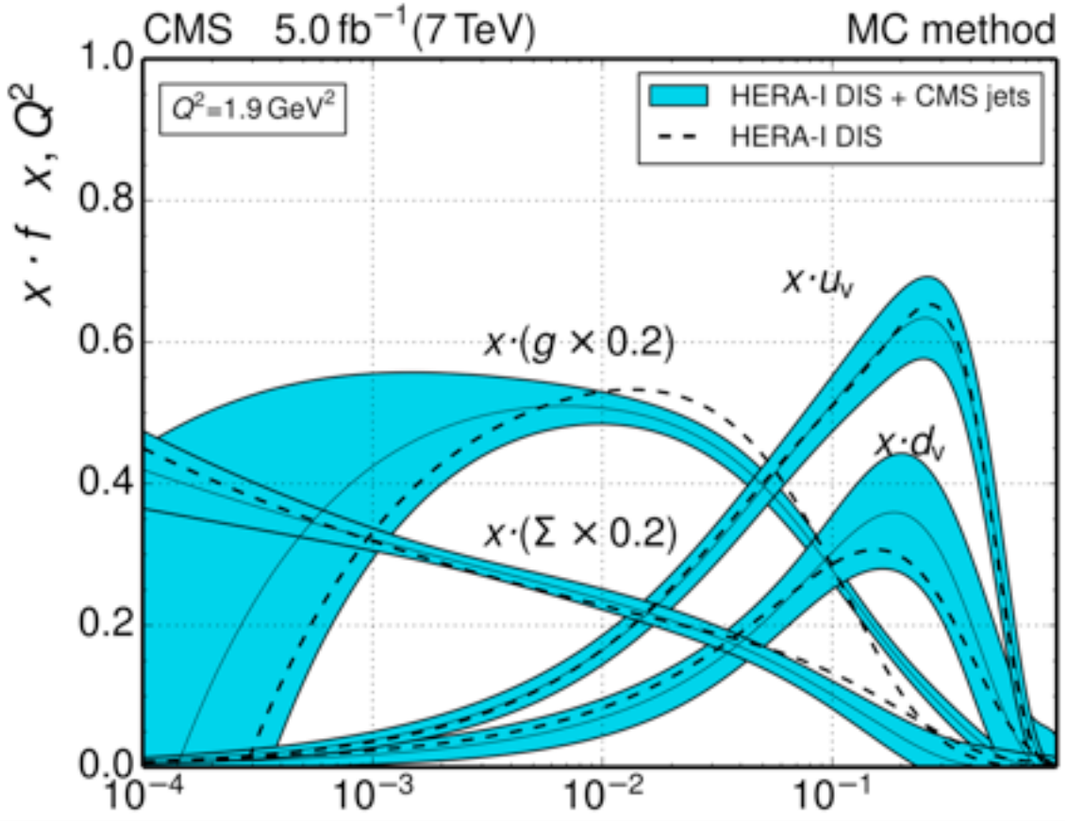
HeraFitter package used to constraint the PDFs
- CMS Jet Pt data: input
- input compared with prediction from theory (NLOJet)
- PDF parameters chosen to fit the theory to the data



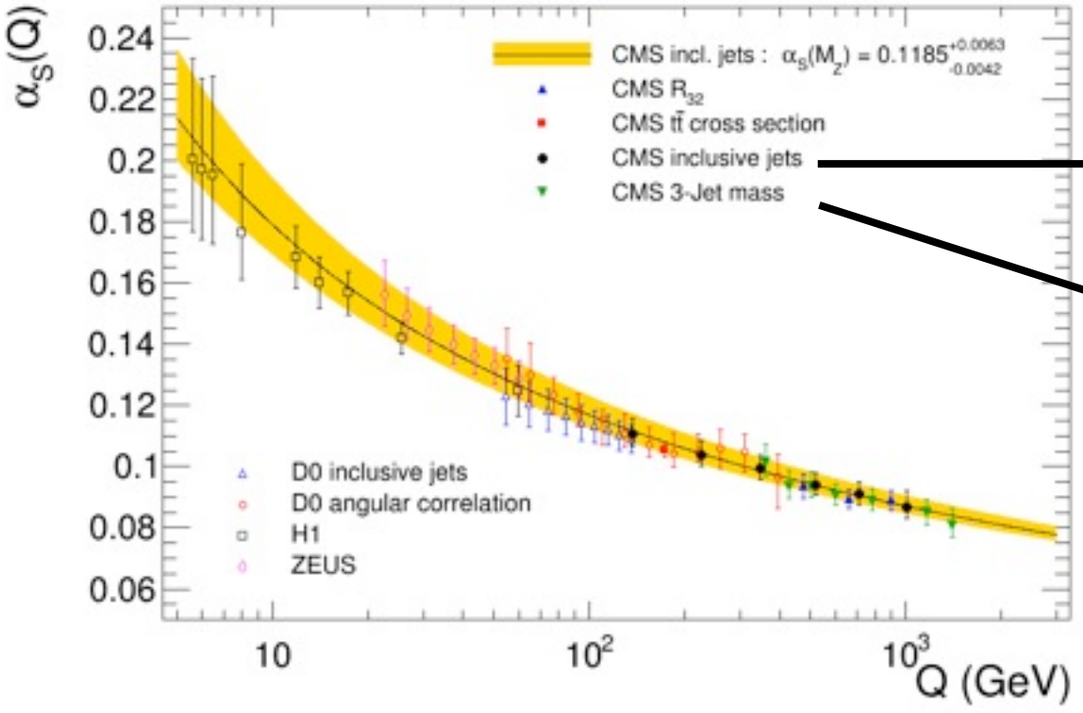
Reduction of uncertainties, especially for g-PDF

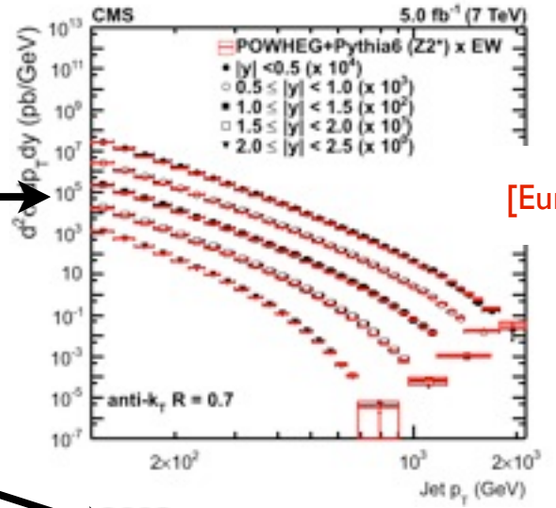
Impact on all PDF's is present, here at Q^2=1.9 GeV^2



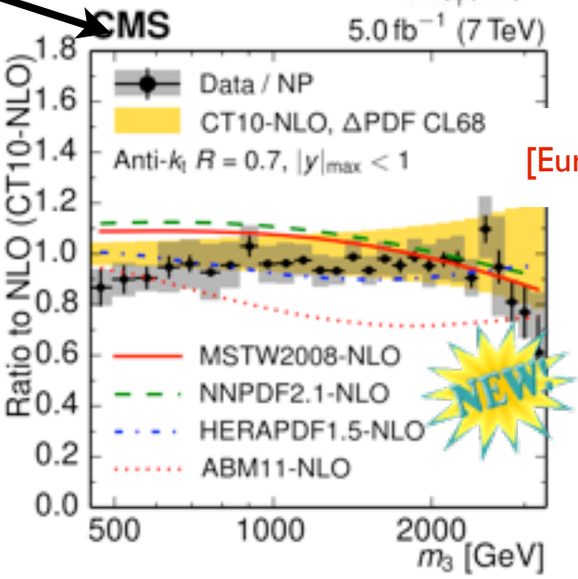


$\alpha_s(Q)$

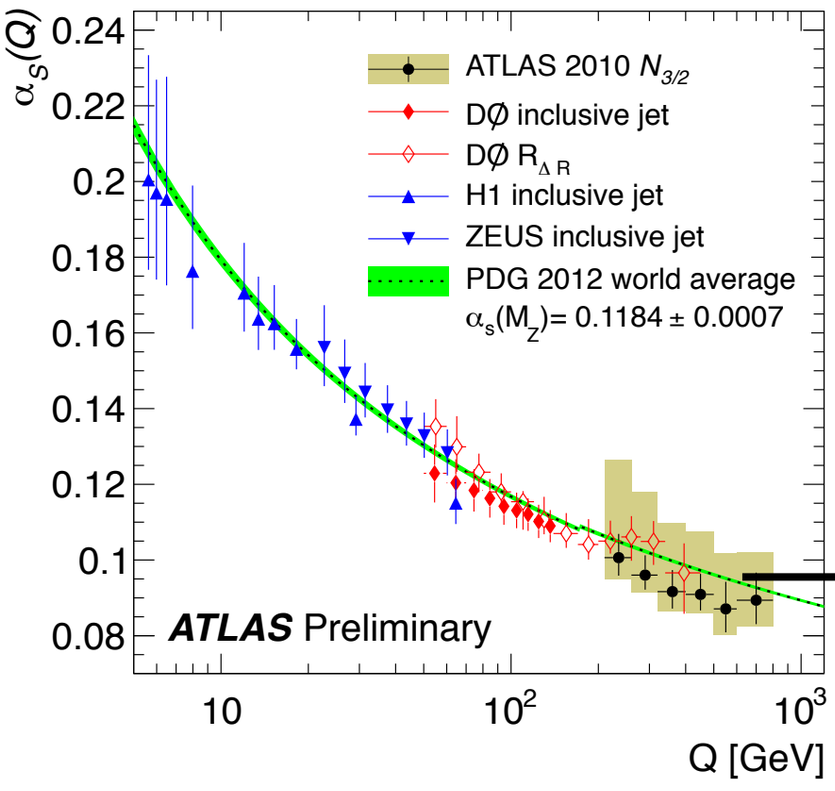


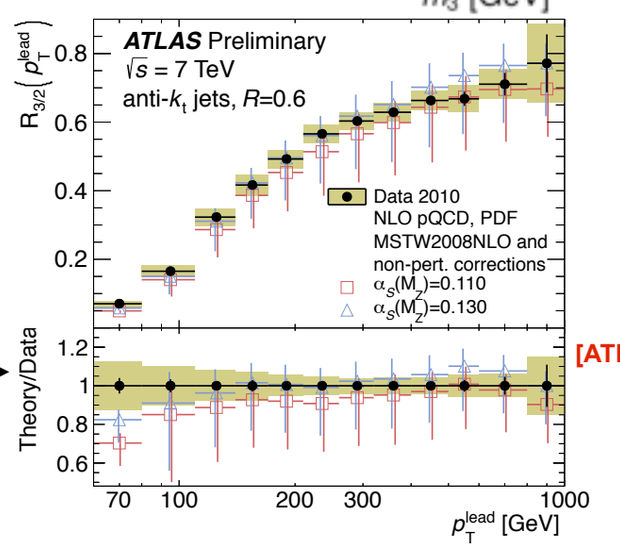


[Eur. Phys. J.C75(2015)288]



[Eur. Phys. J.C75(2015)186]



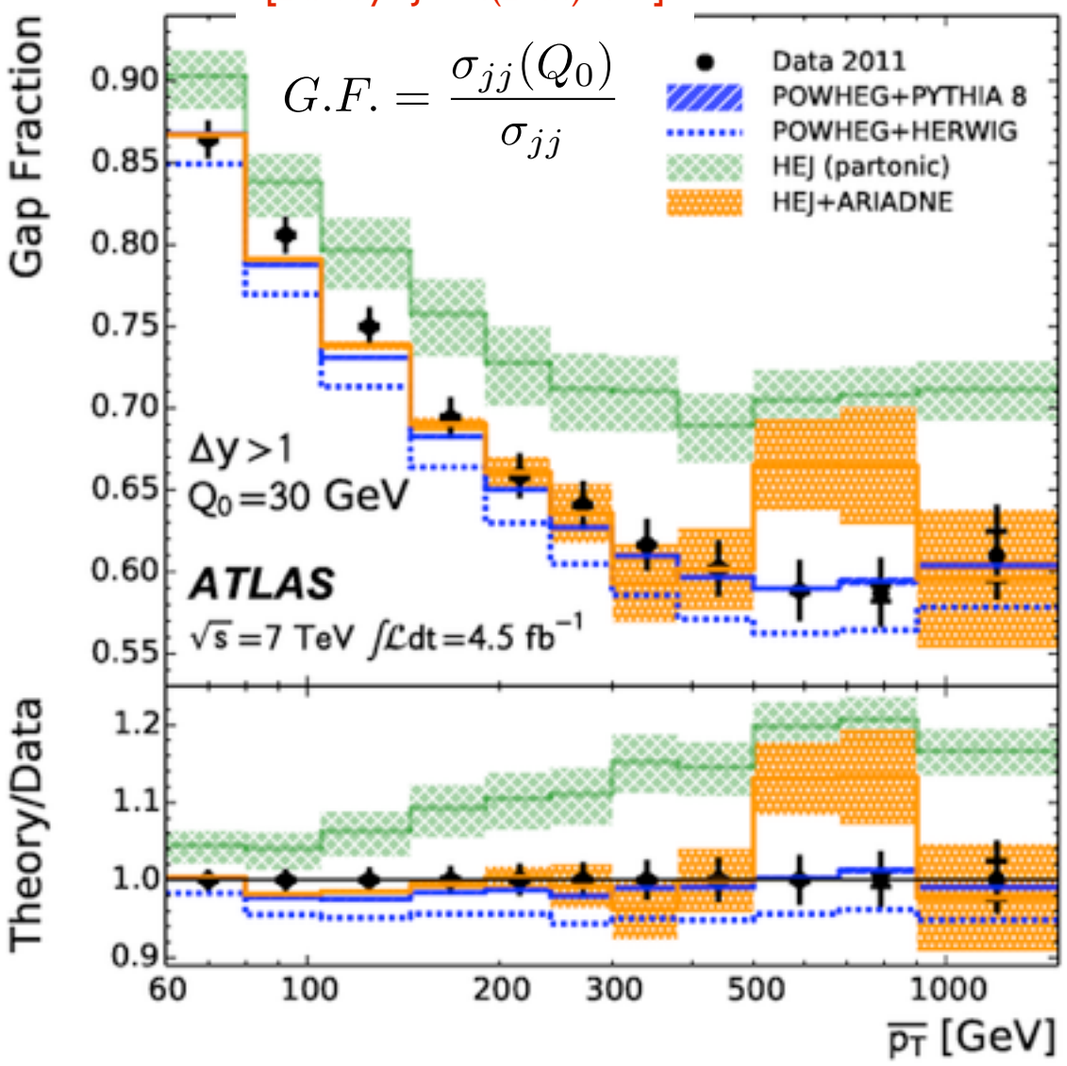


[ATLAS-CONF-2013-041]

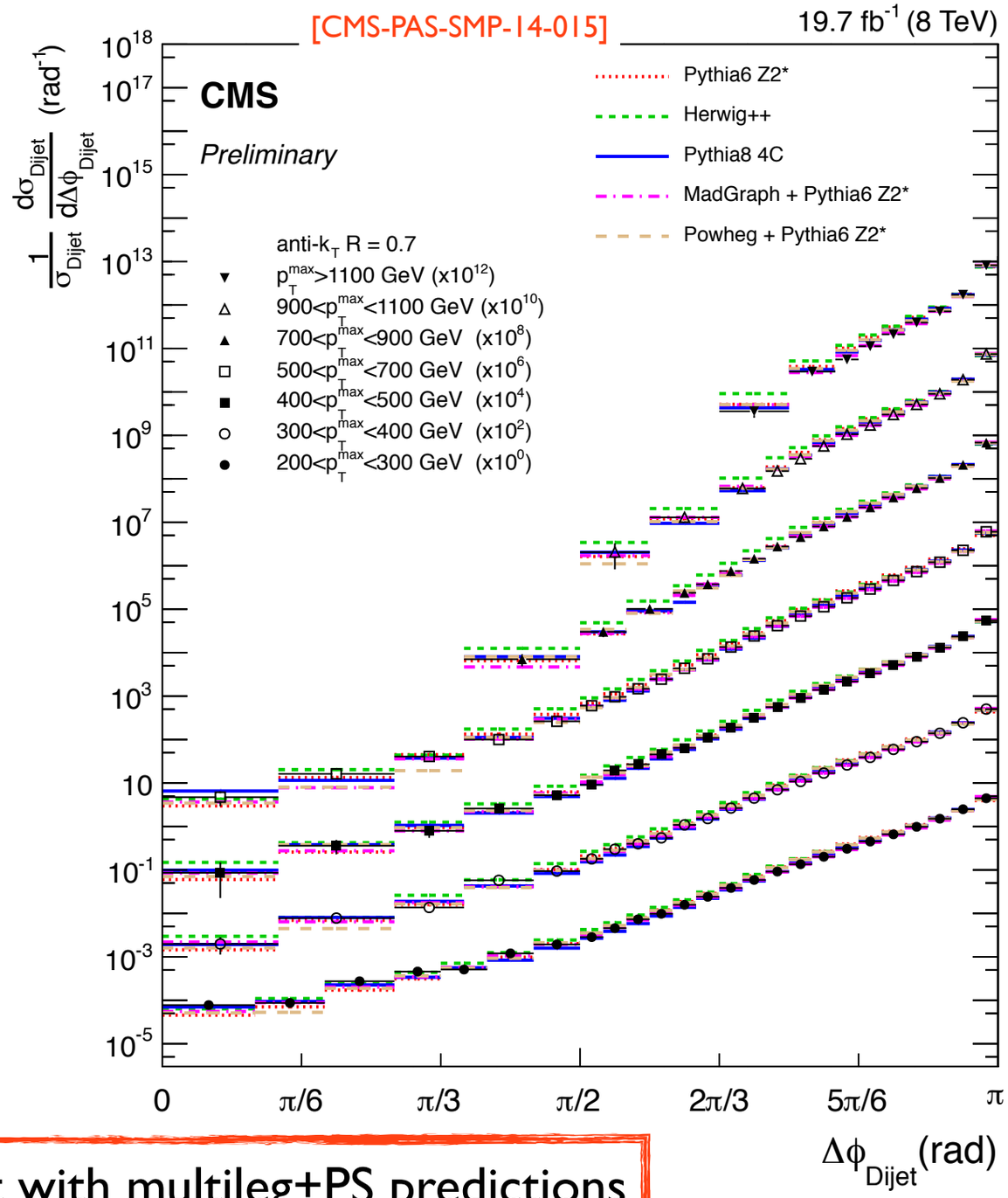
Azimuthal (de)correlation and jet veto

How well do we understand soft/collinear radiation?

[Eur. Phys. J.C74(2014)3177]

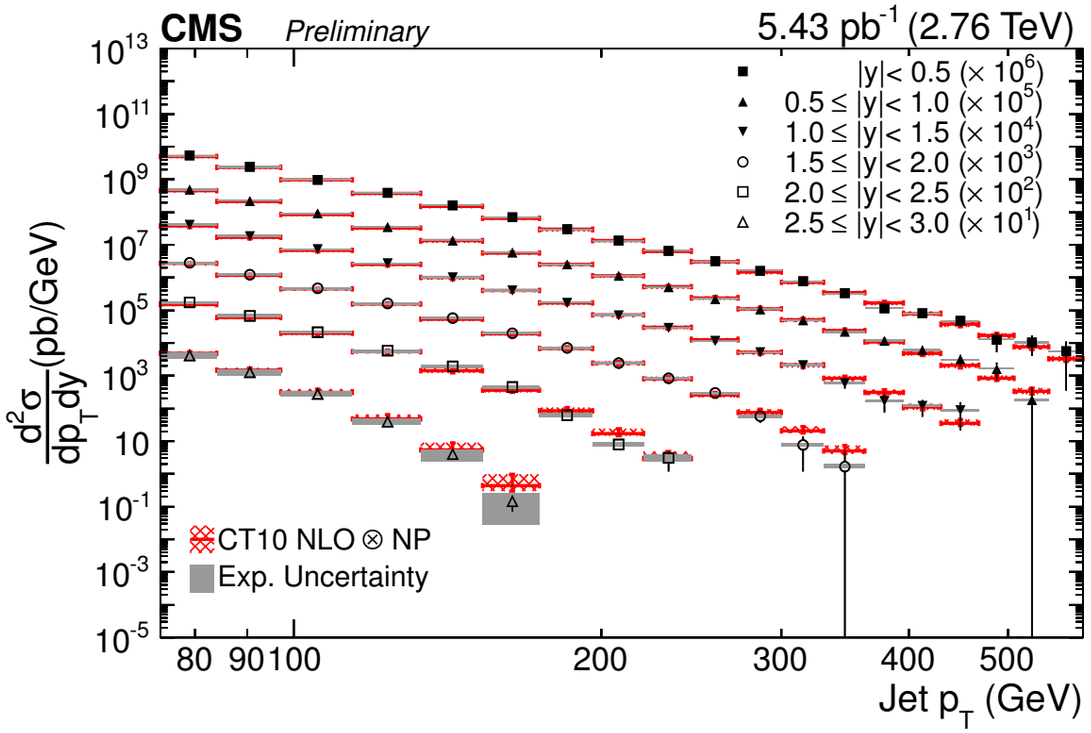


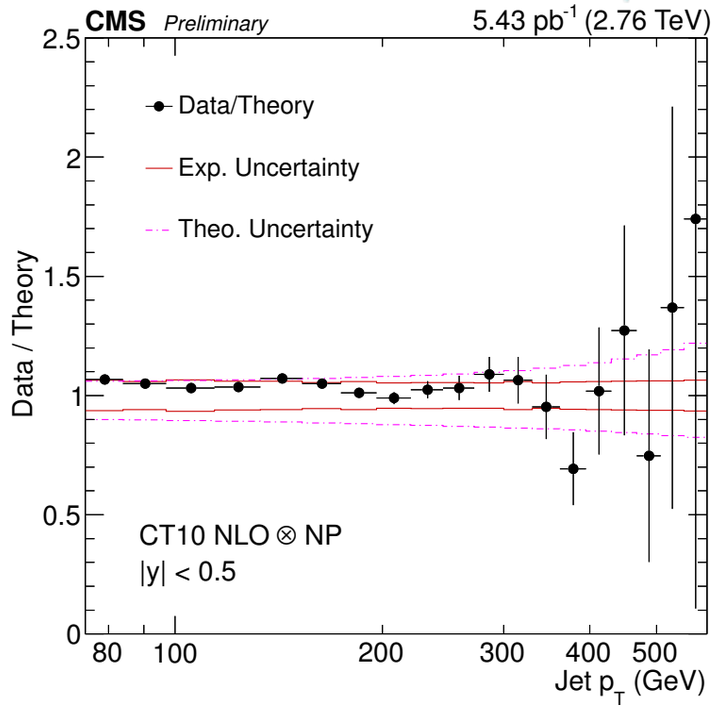
[CMS-PAS-SMP-14-015]



Generally an good agreement with multileg+PS predictions

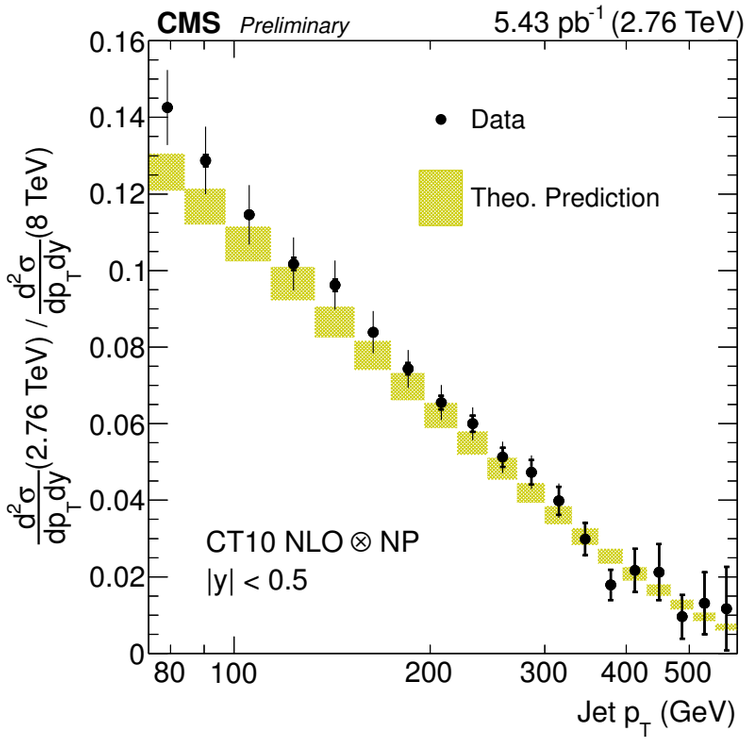
2.76 TeV (+ ratio to 8 TeV)





[CMS-PAS-SMP-14-017]

Additional measurement useful for PDF and α_s
Ratio cancels partially the exp. uncertainties, no significant deviation from NLOJet prediction

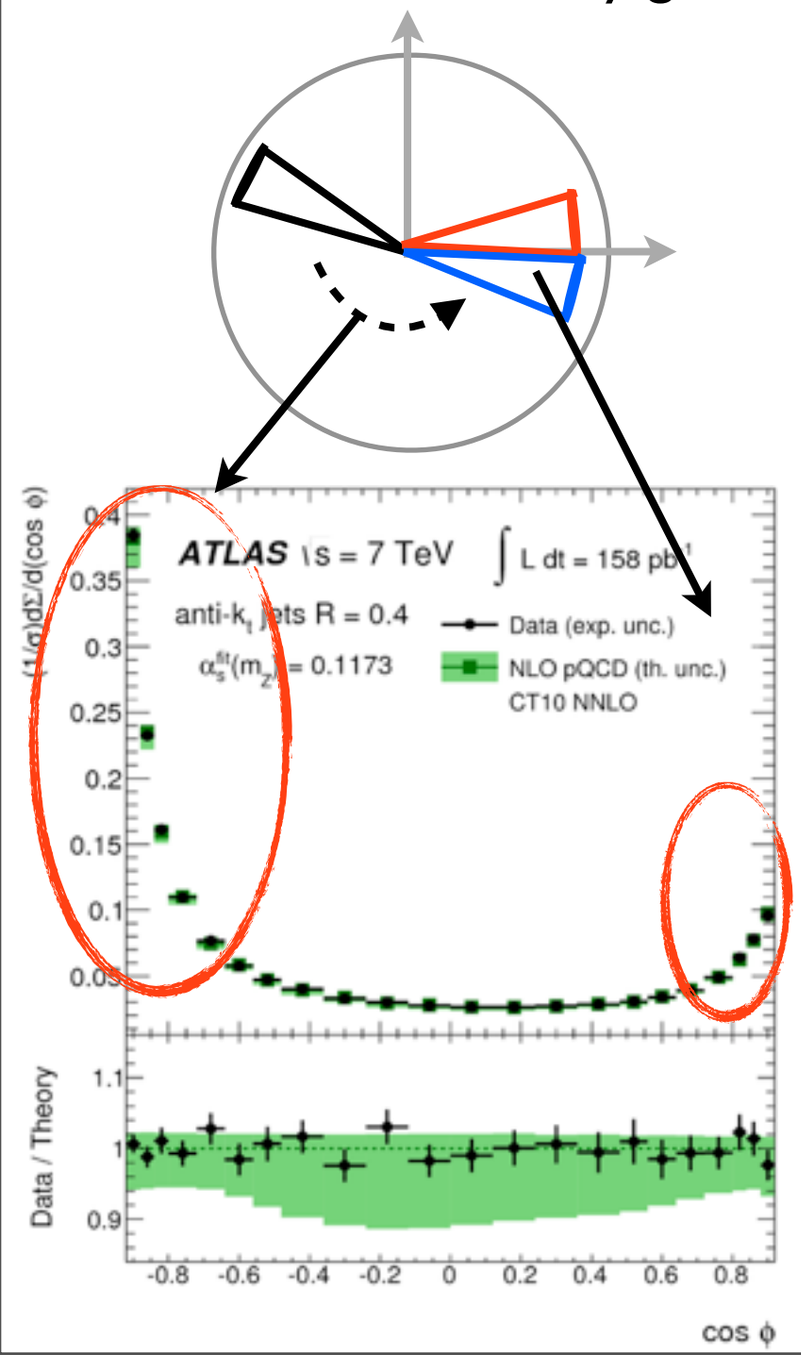


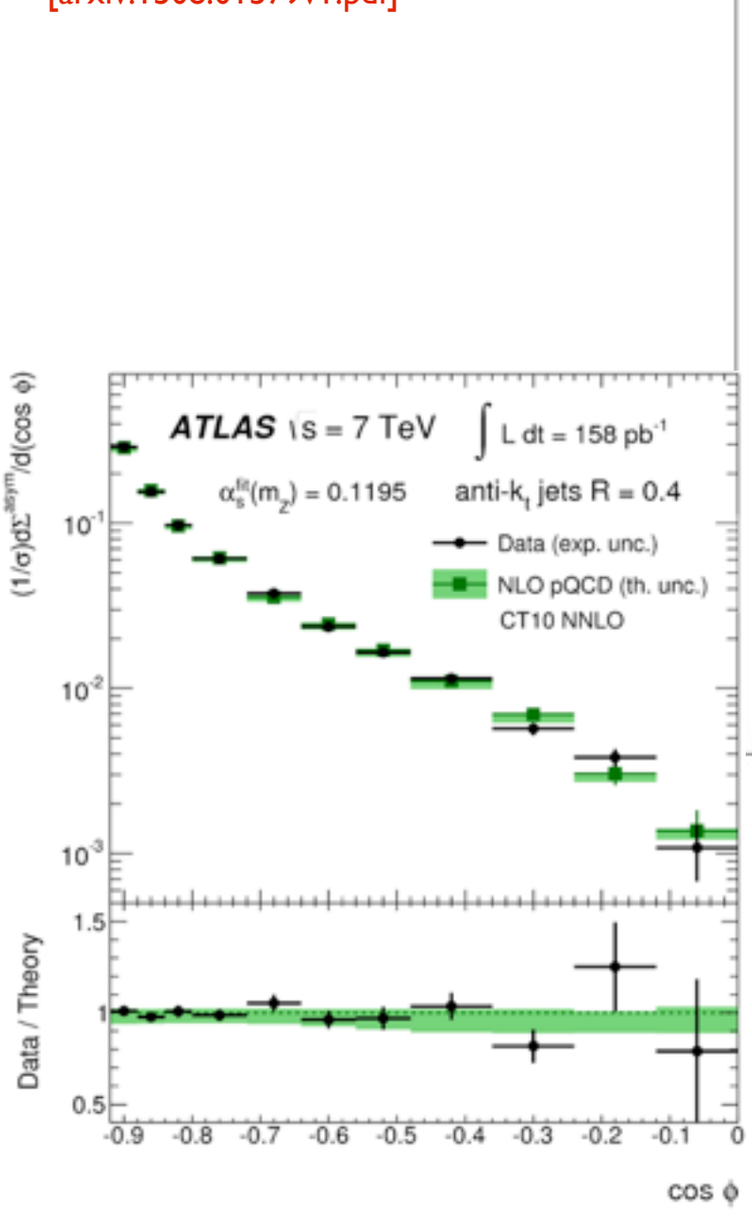
$\alpha_s(M_Z)$ from TEEC/ATEEC

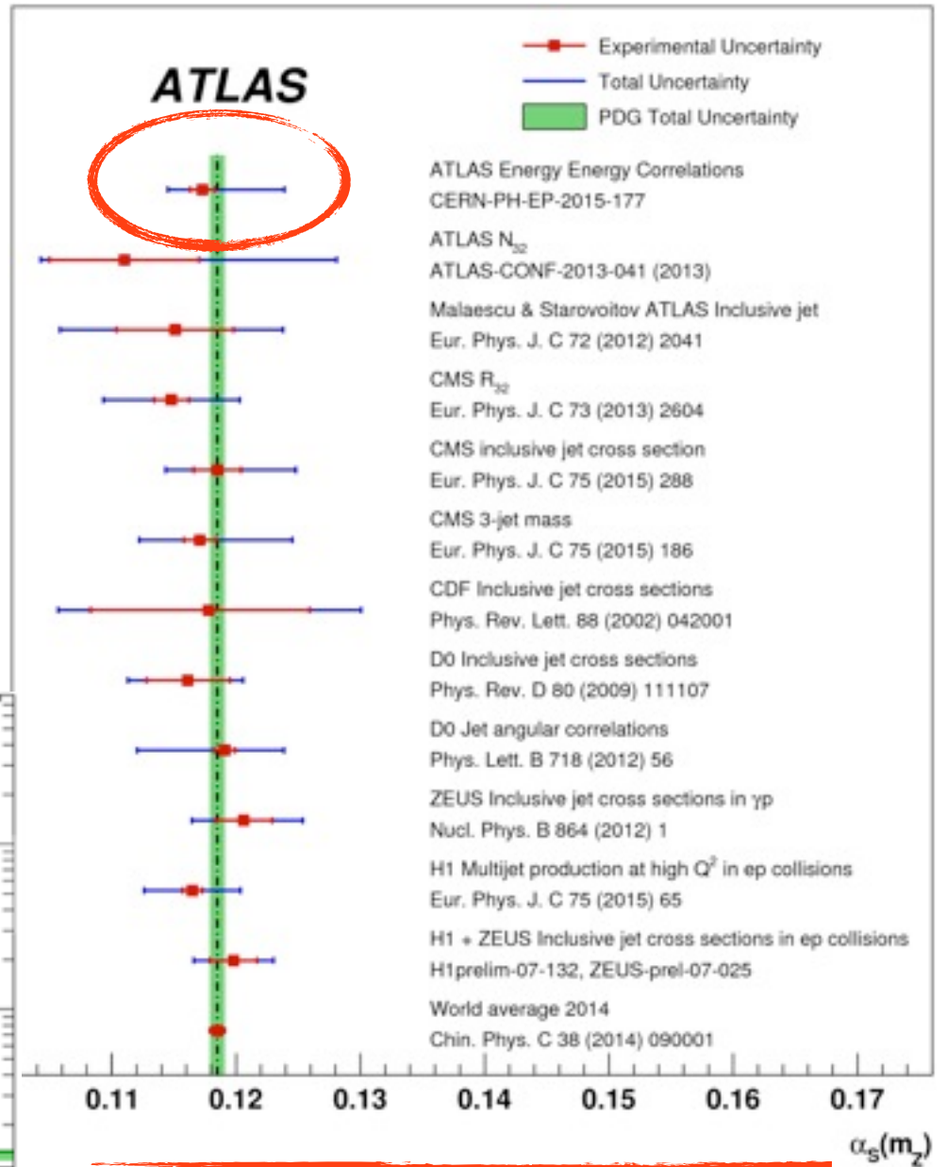
TEEC:angles between all (energy-weighted) combinations of jets.

ATEEC: removes contribution from 2 jets events. What remains is dominated by gluon contribution ⇒ α_s

[arxiv:1508.01579v1.pdf]







Excellent agreement with the world average (2014) α_s=0.1185+-0006

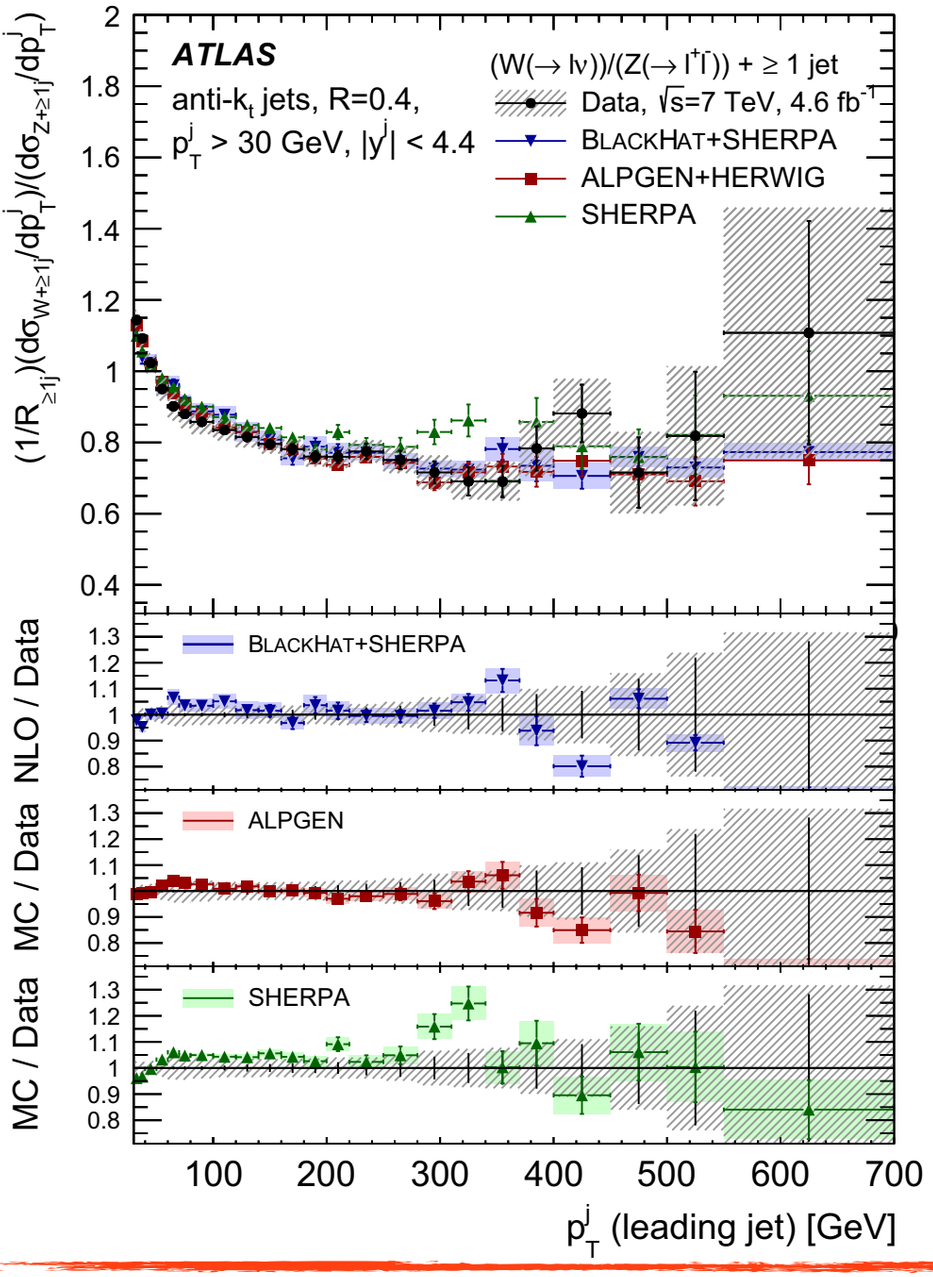
2015

V,V+jets

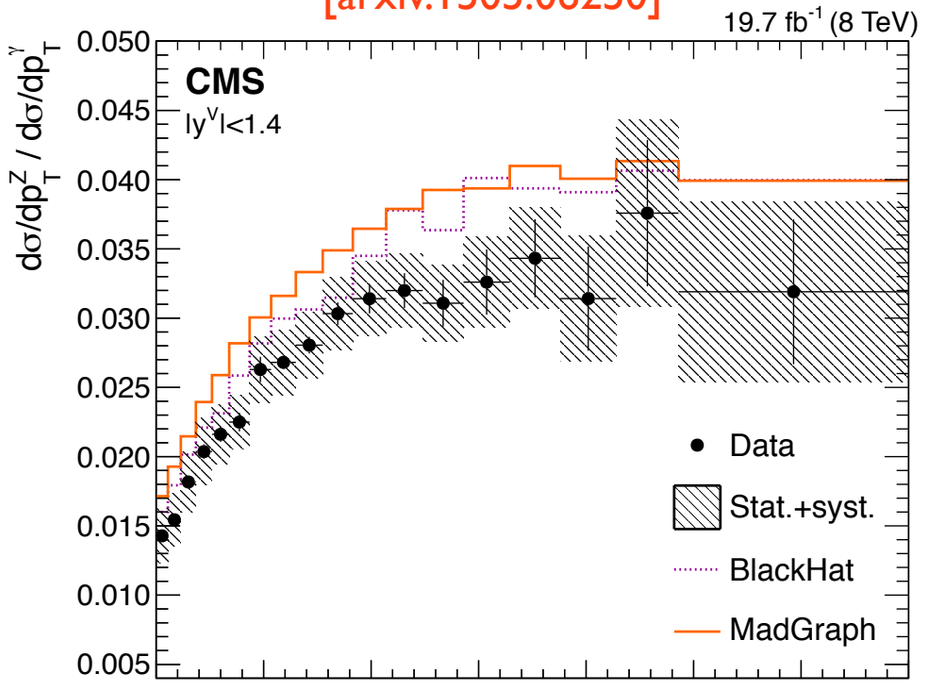
W/Z and Z/γ+jets ratio

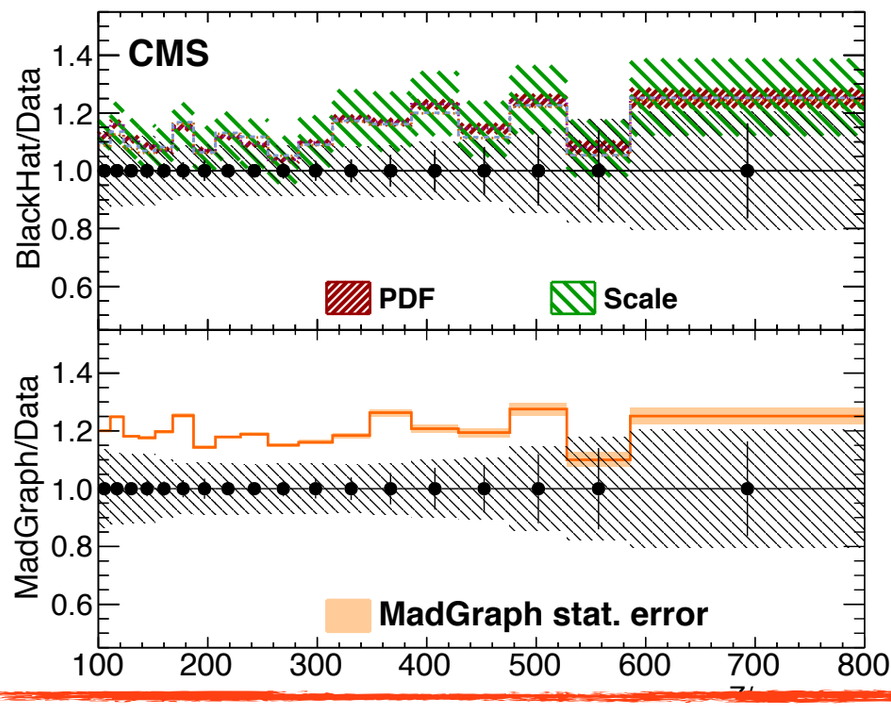
Use V+jets as precision measurement

[PLB708(2012)221-240]



[arxiv.1505.06250]



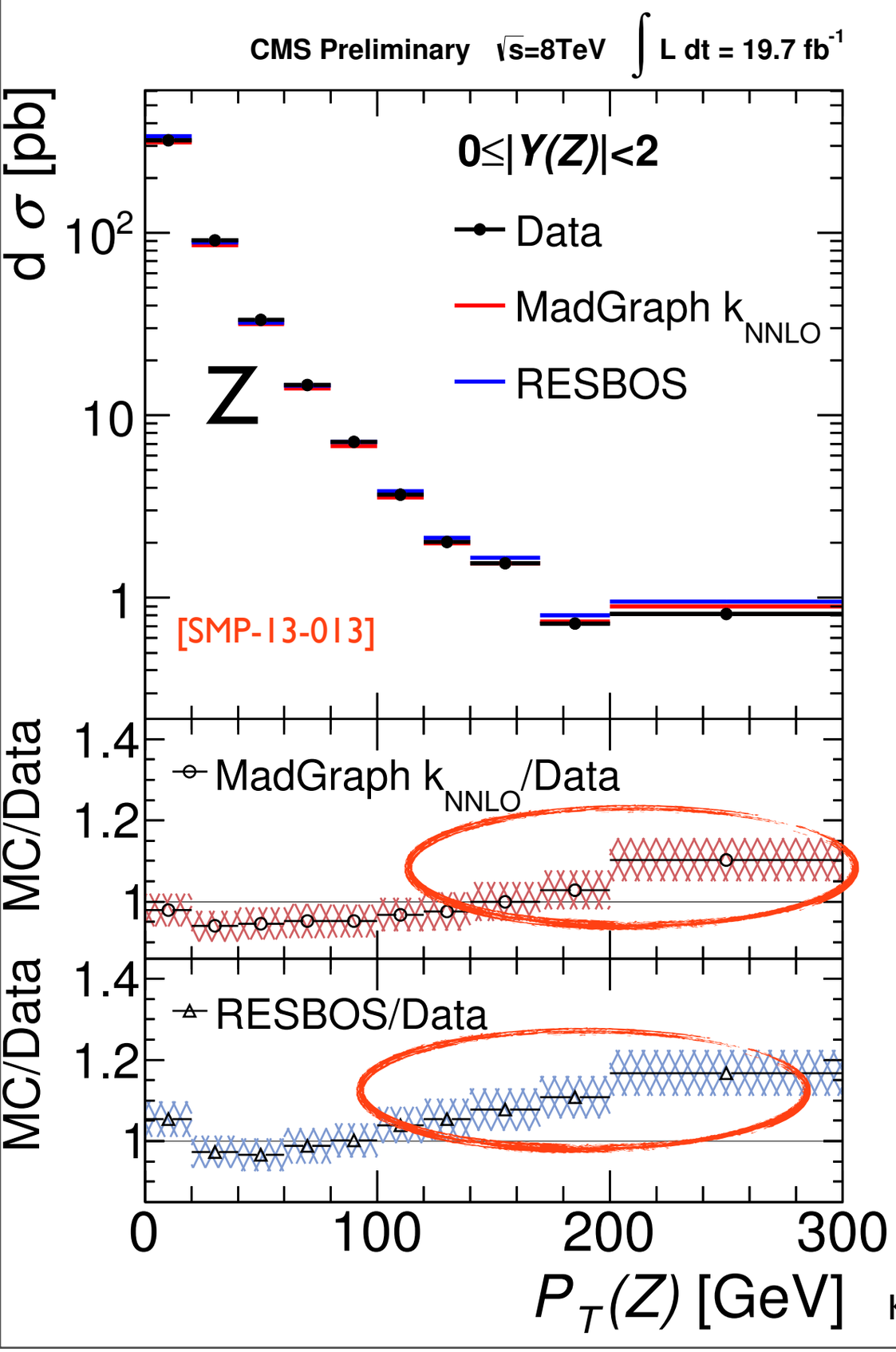


No severe disagreement between data and MC Tree-Level and NLO predictions show very similar behaviour

Data and MC agree within uncertainties.

Dynamics of W, Z bosons: dσ/dp$_T$

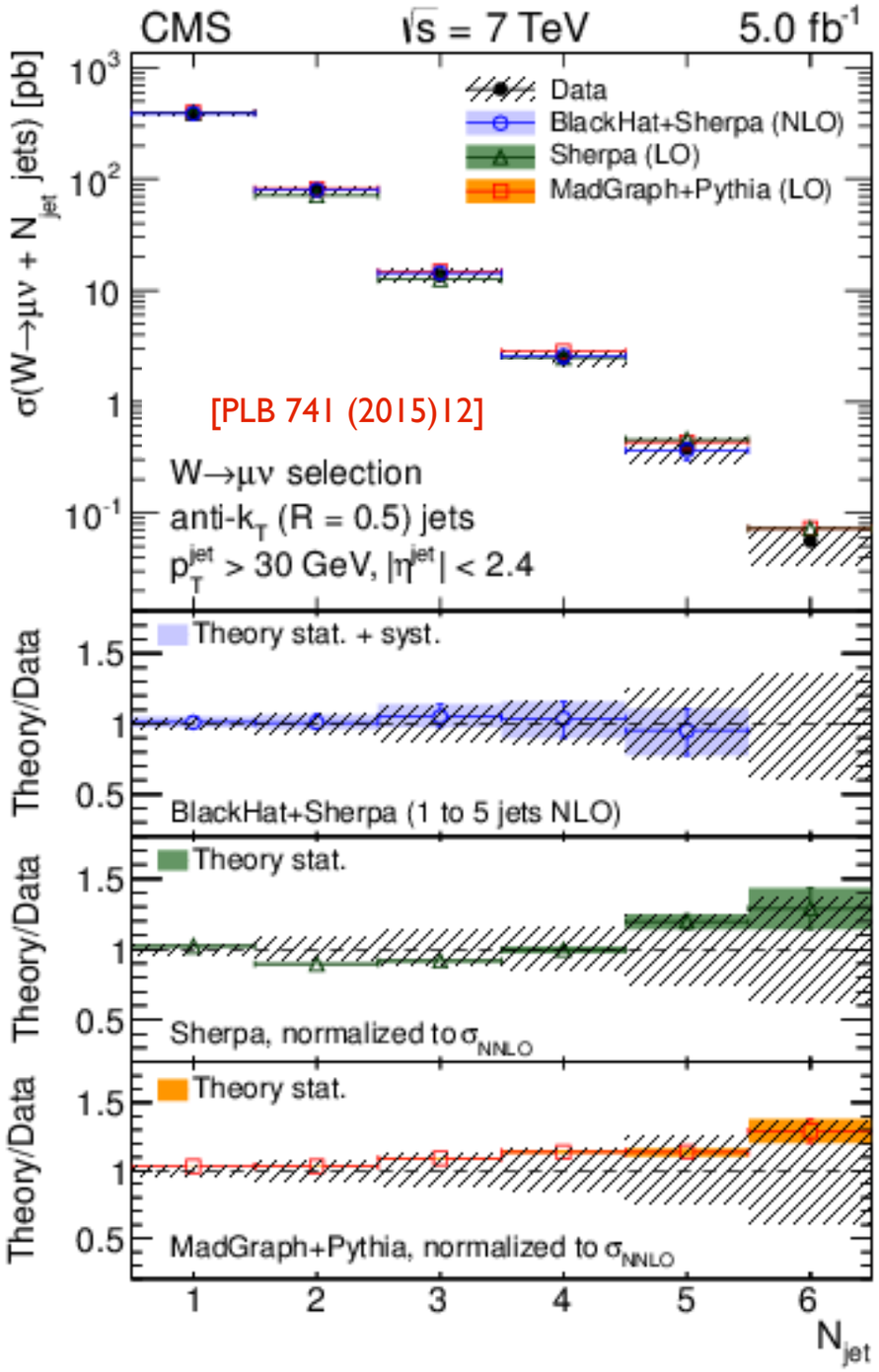
[SMP-13-006]

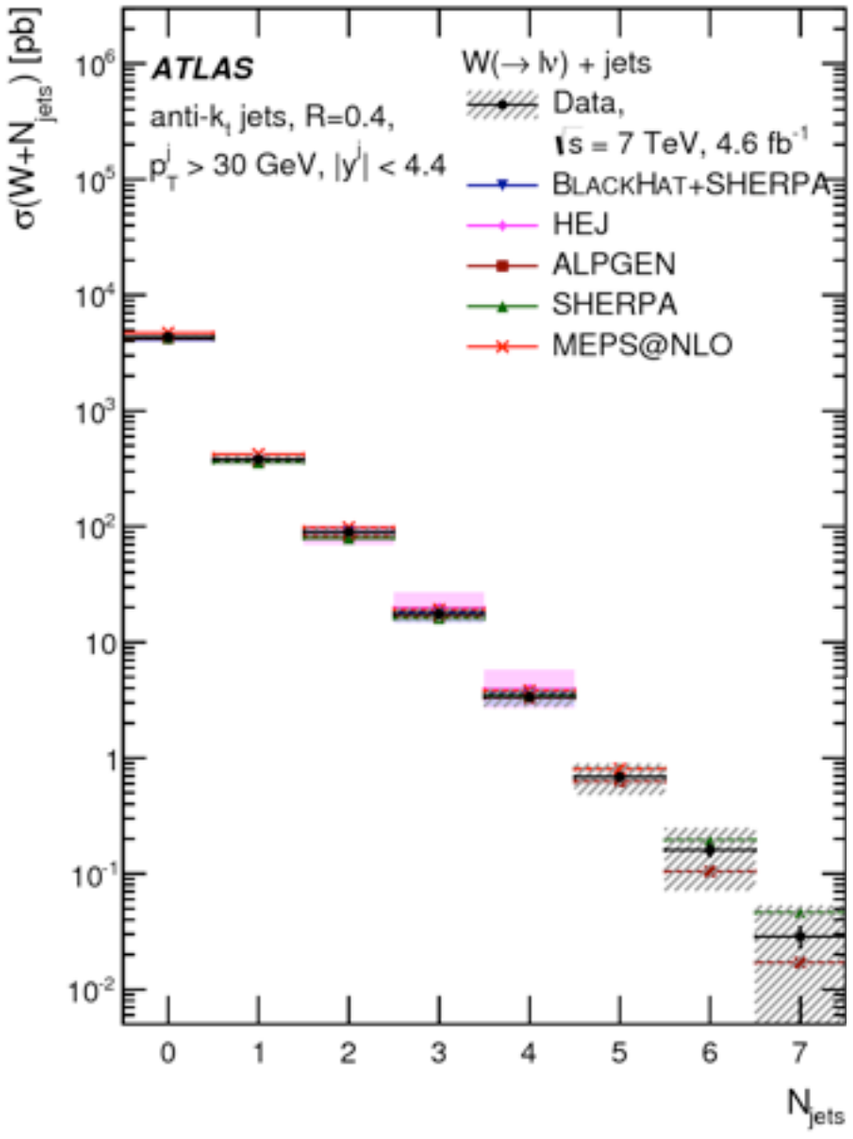


- Very simple final state
  - 1 or 2 leptons
- Large statistics
  - ~% level uncertainty

No prediction matches the data, LO or NLO

Number of jets: W+jets @ 7 teV

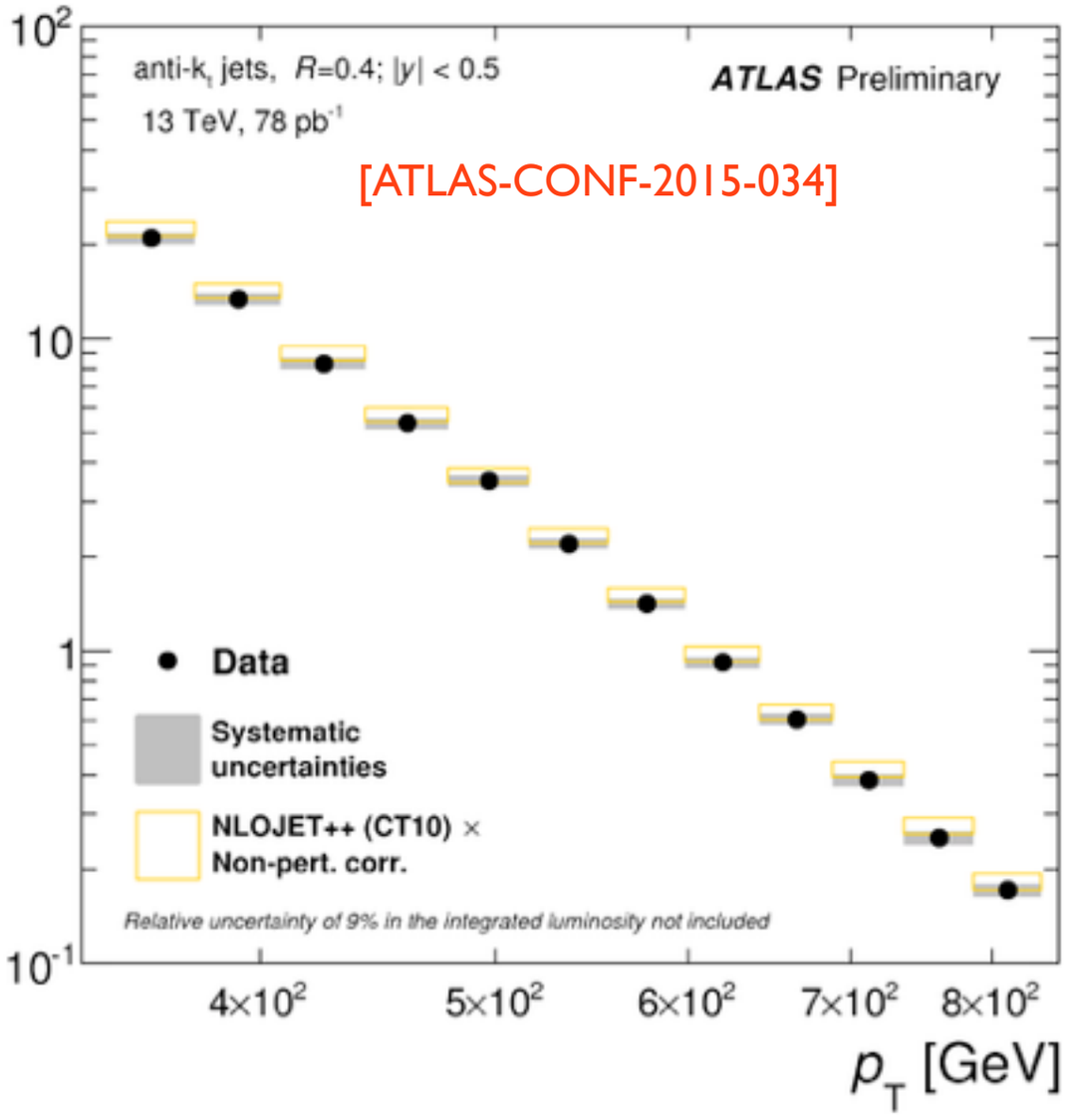


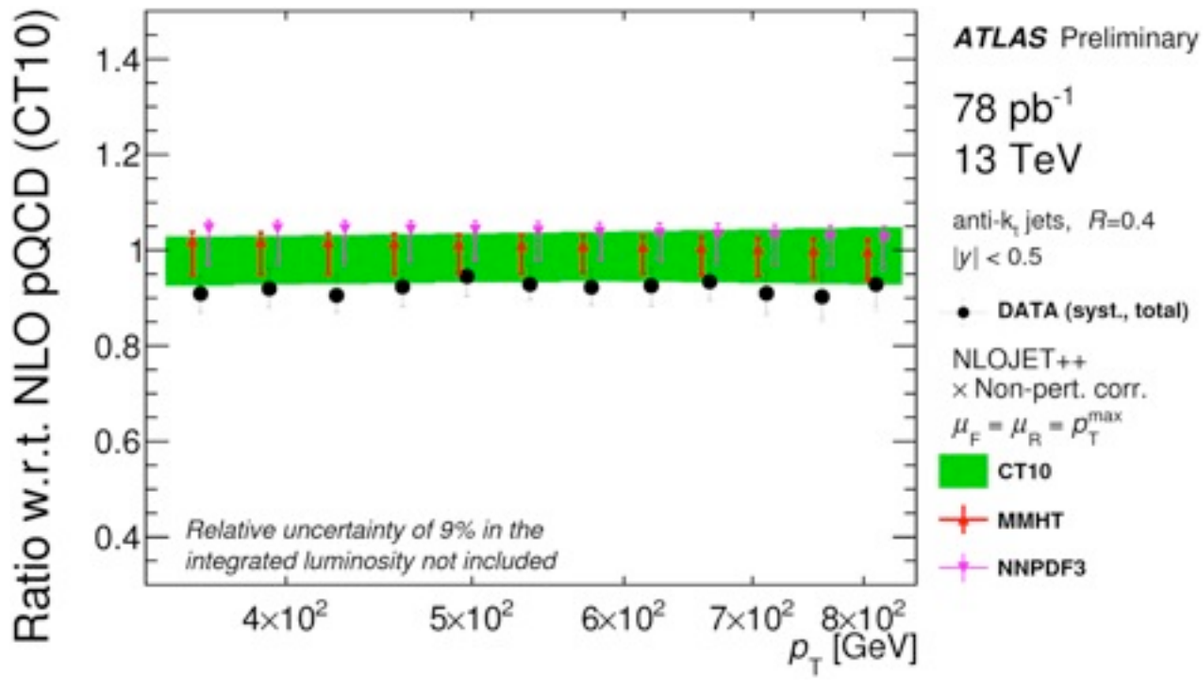


[Eur. Phys. J.C75(2015)82]

Final state up to 6/7 jets. Data generally well described

LHC Run II first QCD results

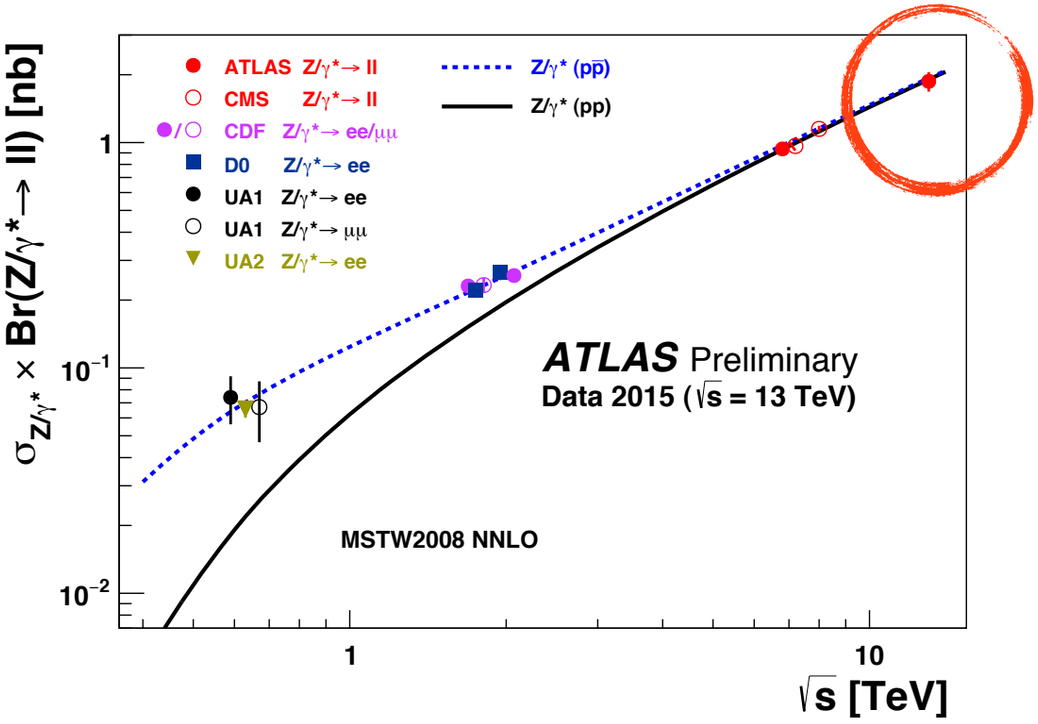




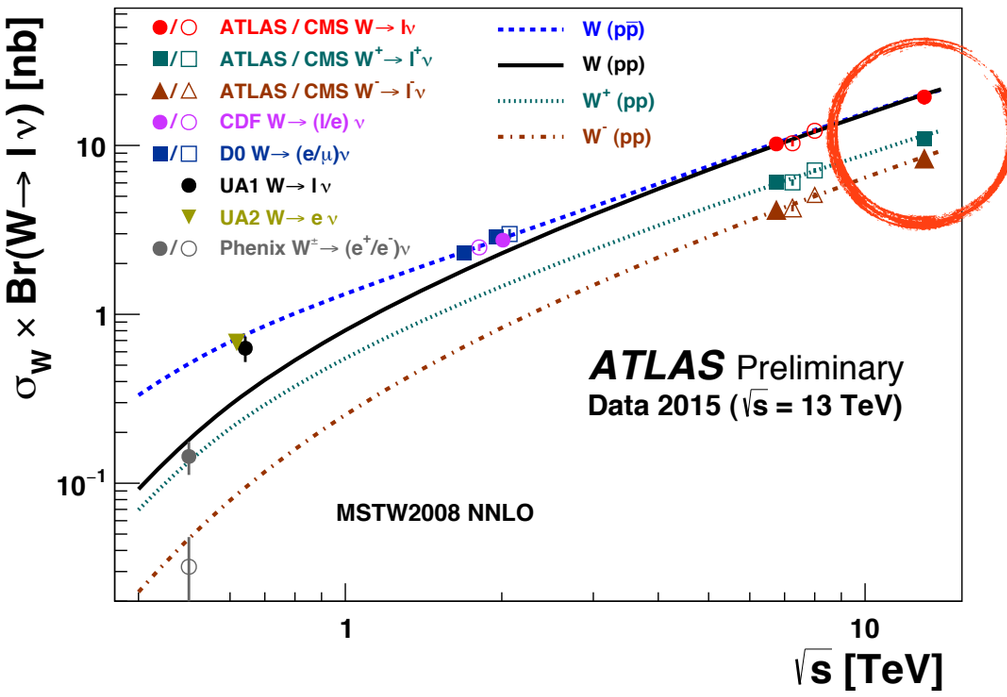
Normalisation: data and MC are in a reasonable agreement
Shape: very good agreement

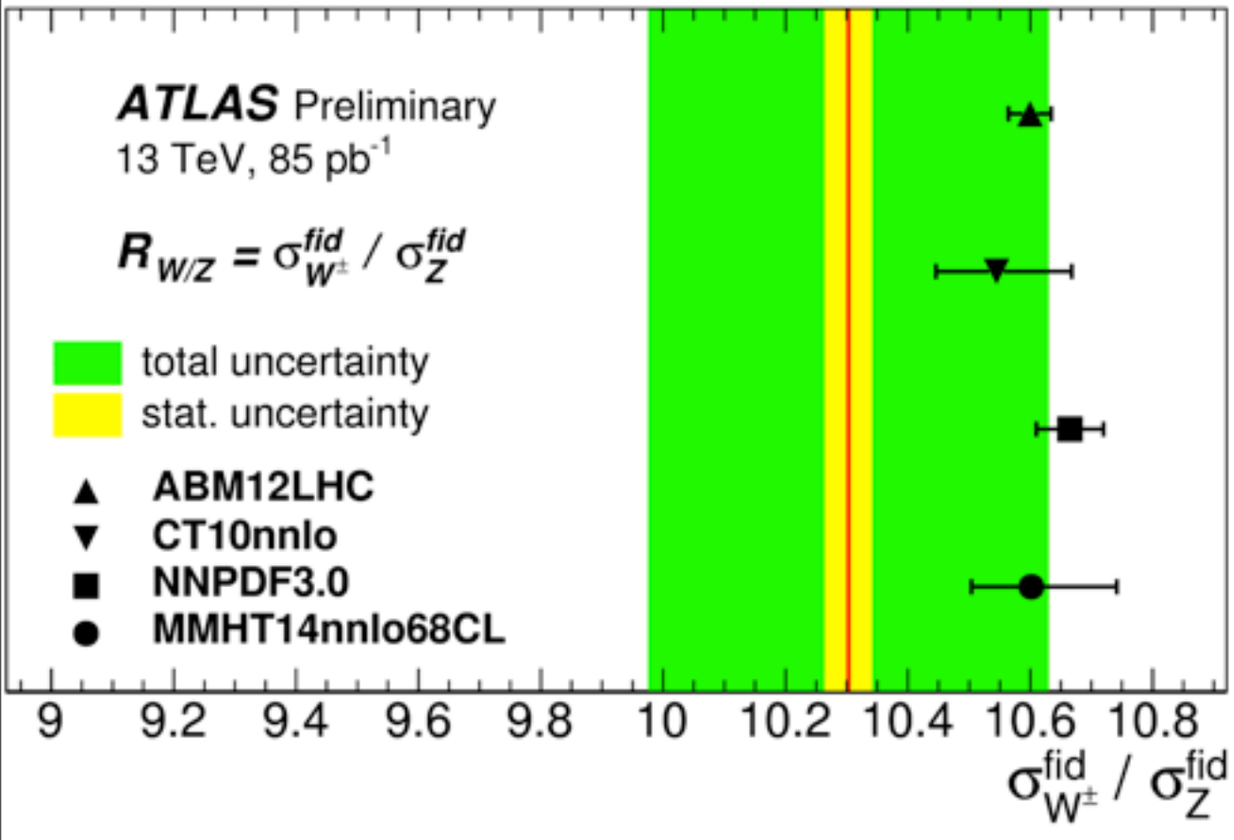
LHC Run II first QCD results: W/Z

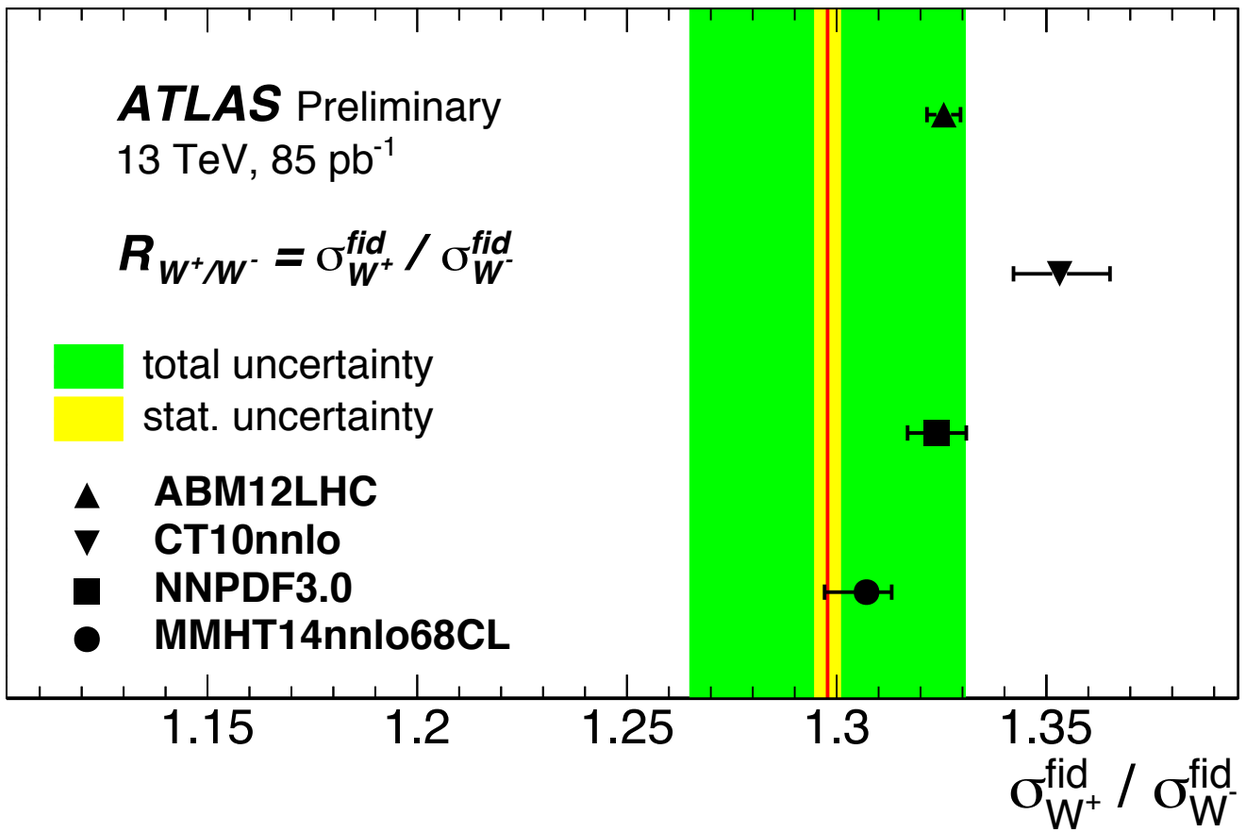
[ATLAS-CONF-2015-039]



Early result allow to already check if a dependence to V's inclusive xsec ratio.

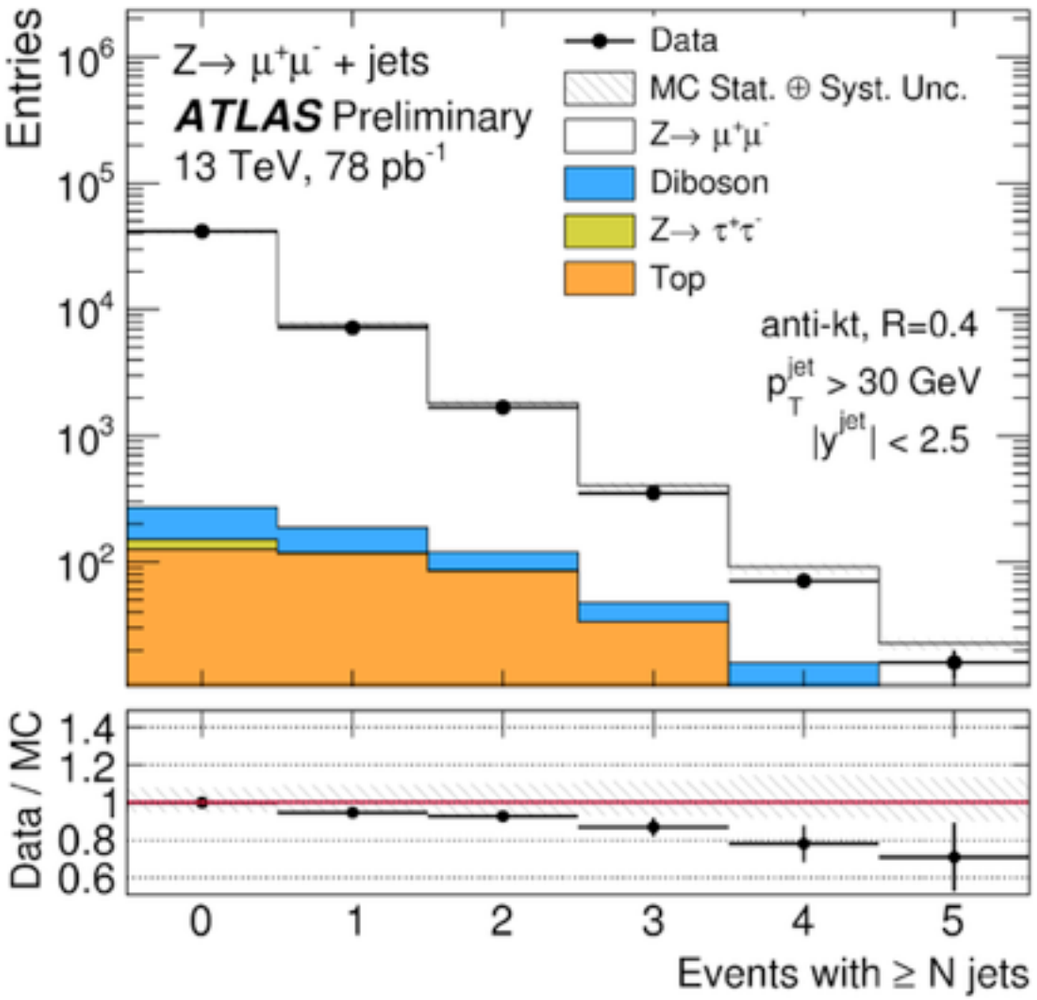


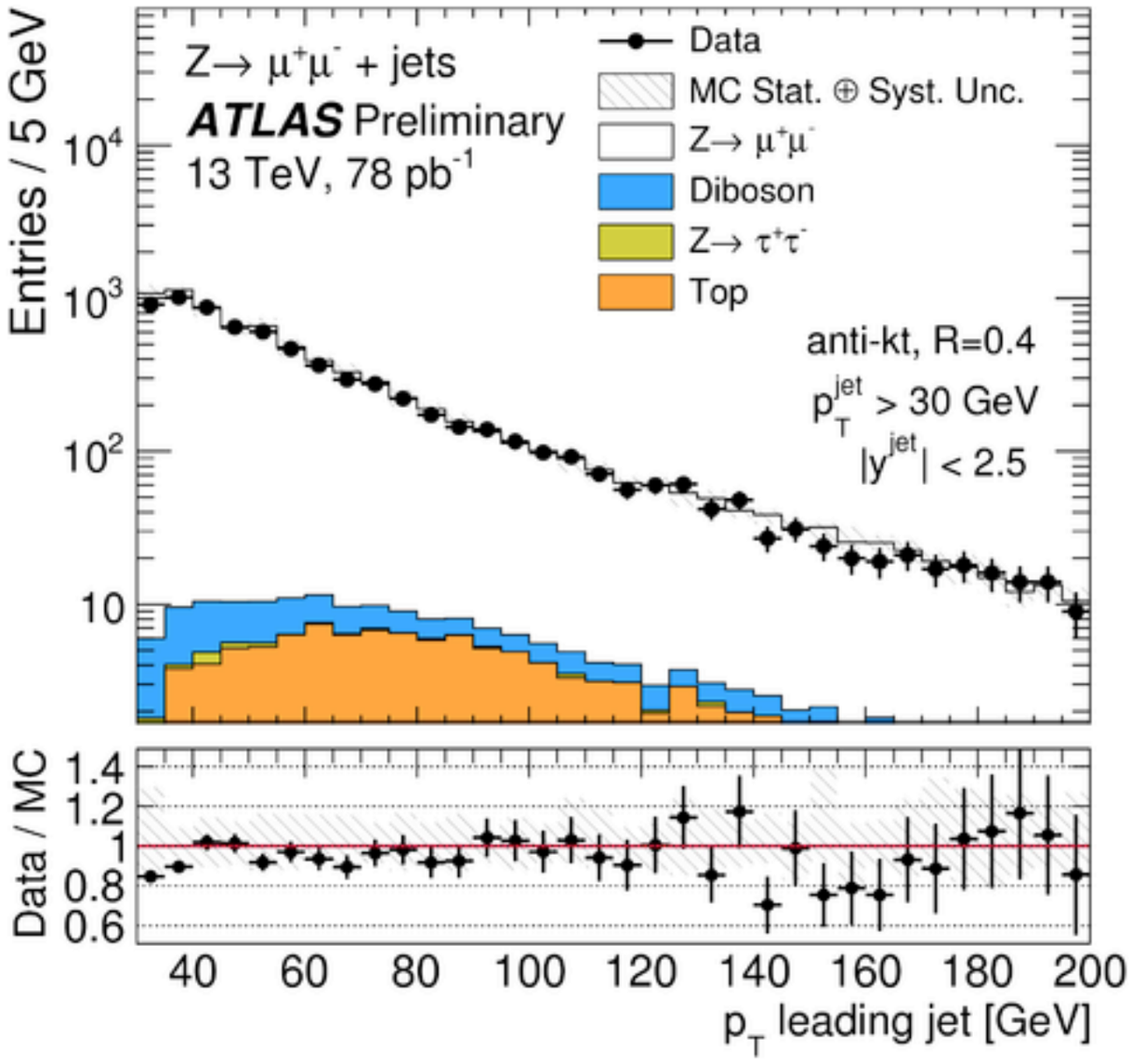




LHC Run II first QCD results: V+jets

[ATLAS-PHYS-PUB-2015-021]

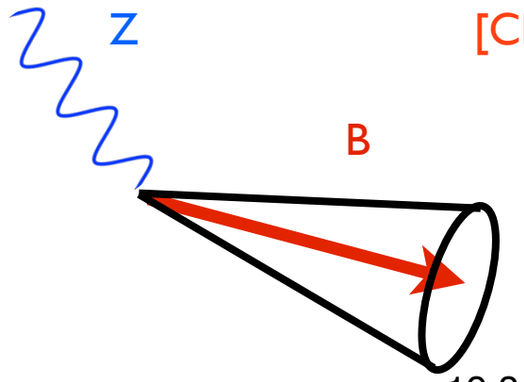


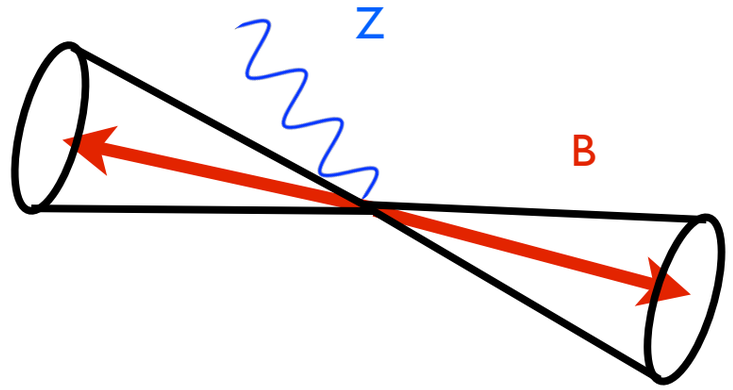


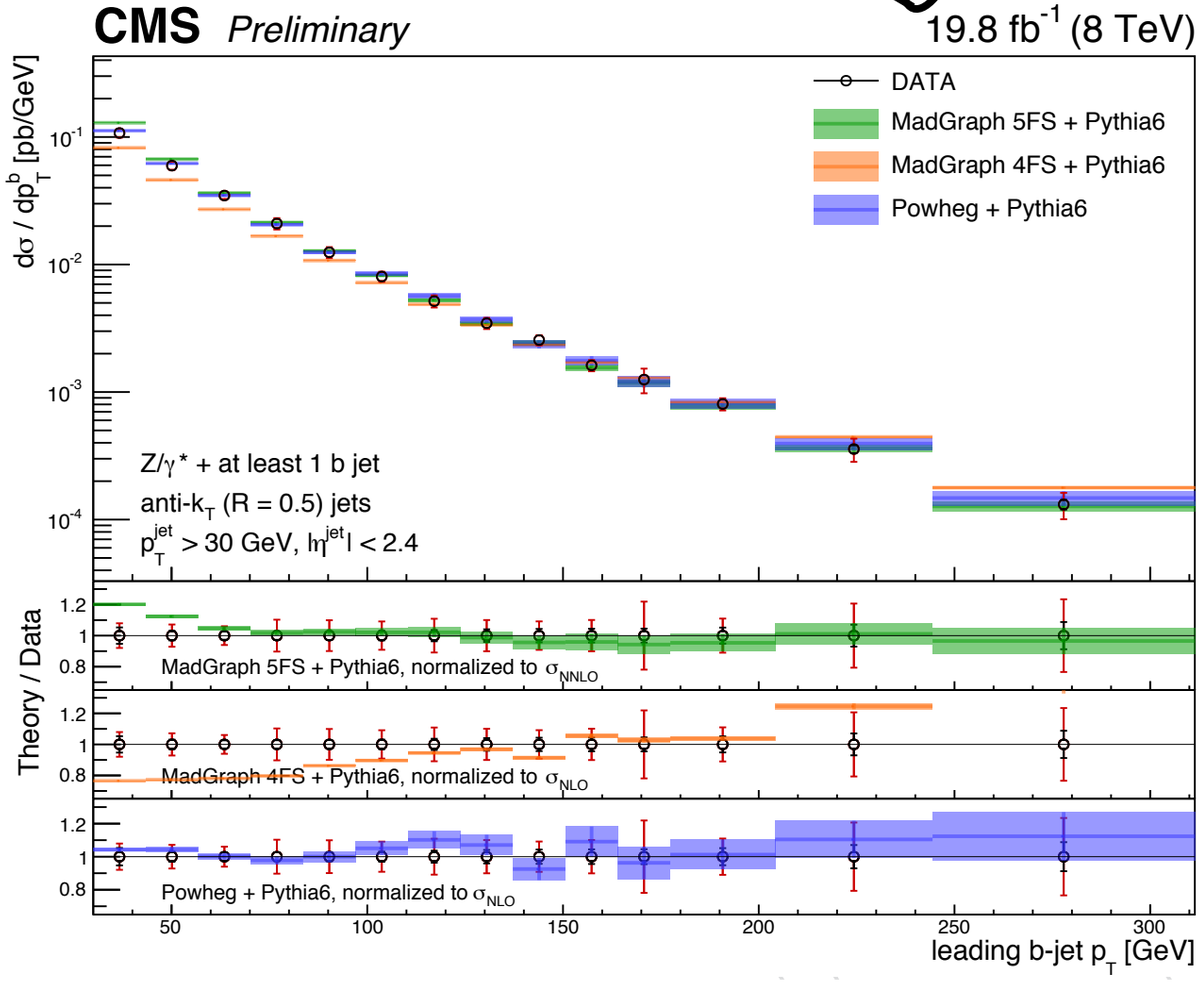
First detector-level comparison between data and MC!

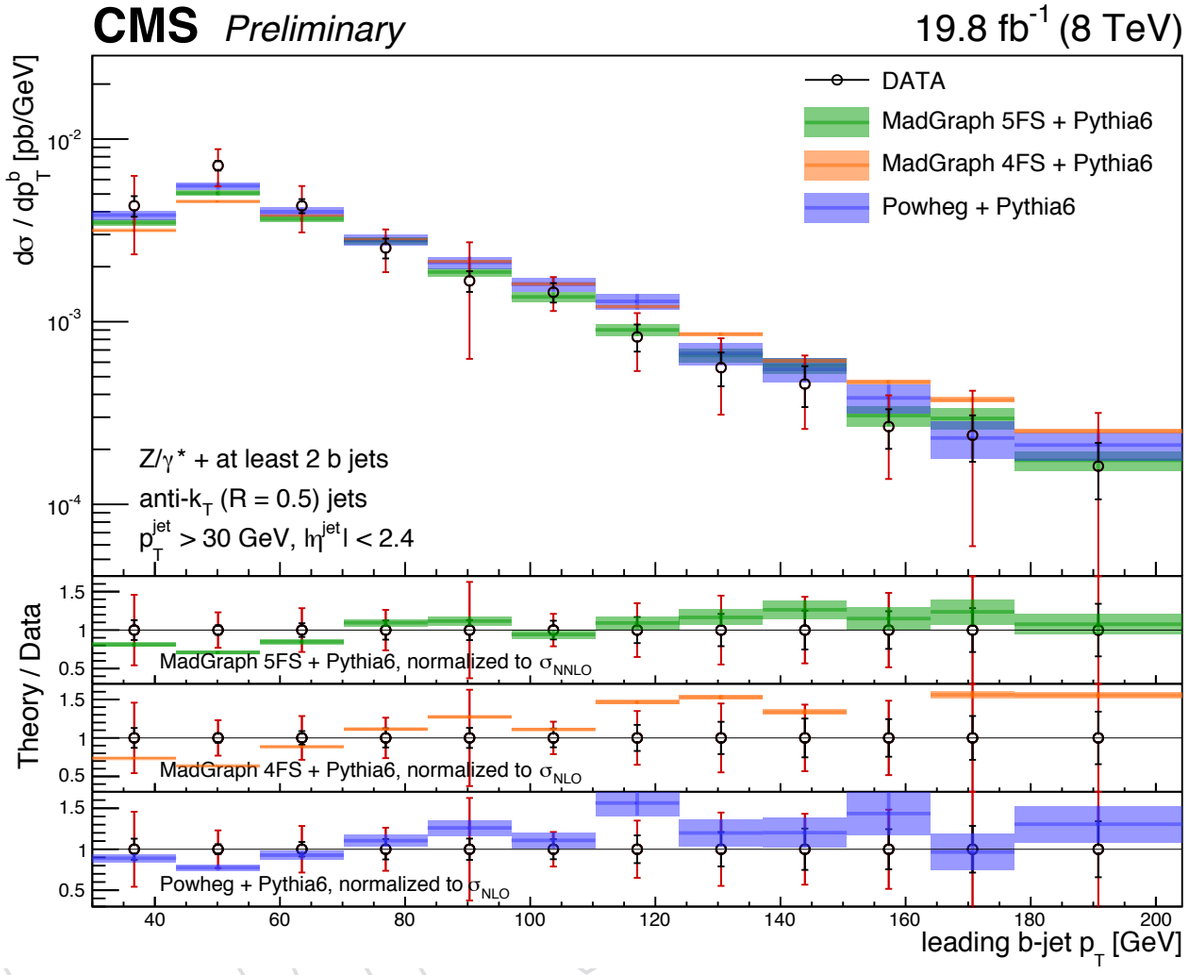
Z+2b

[CMS-PAS-SMP-14-10]





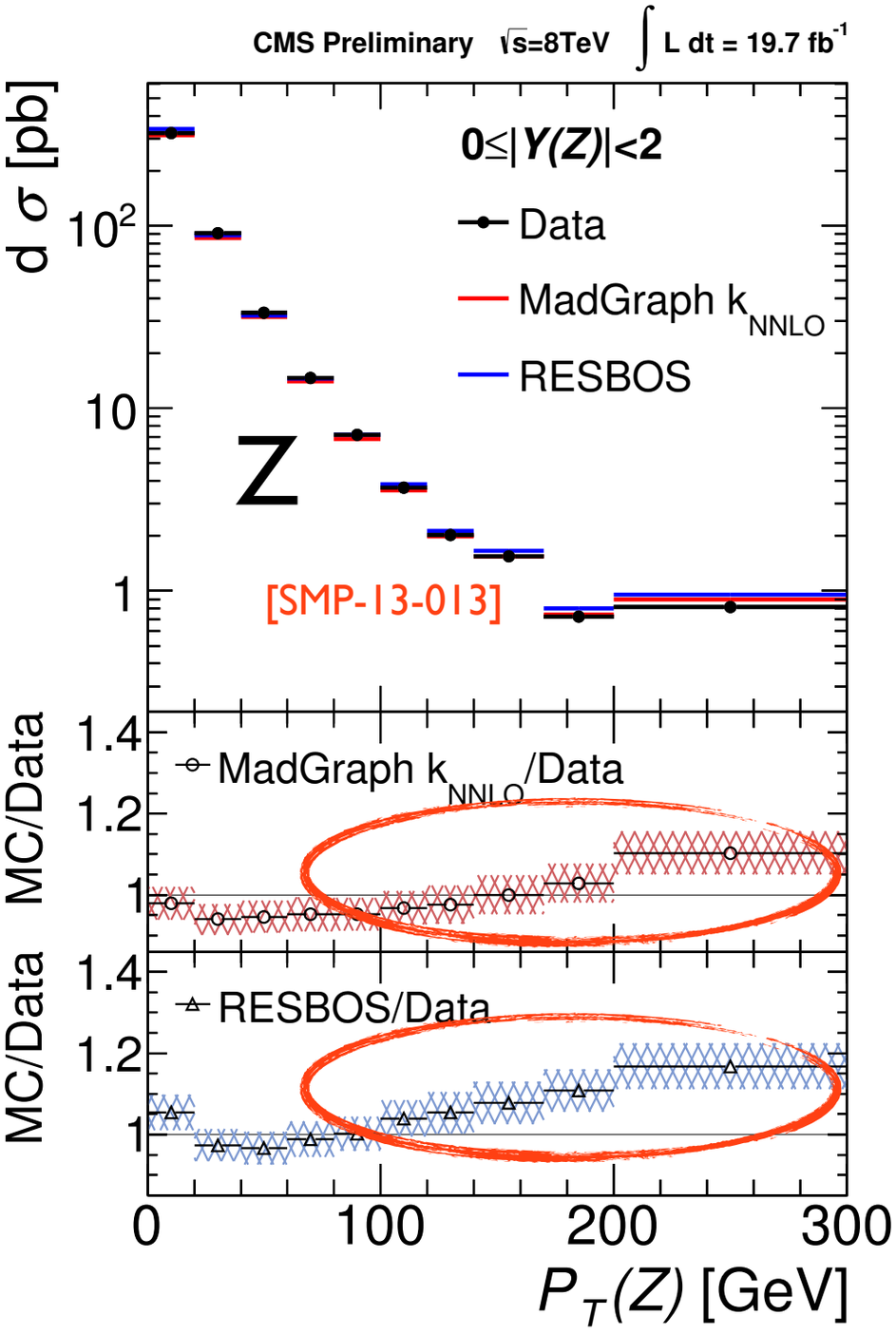




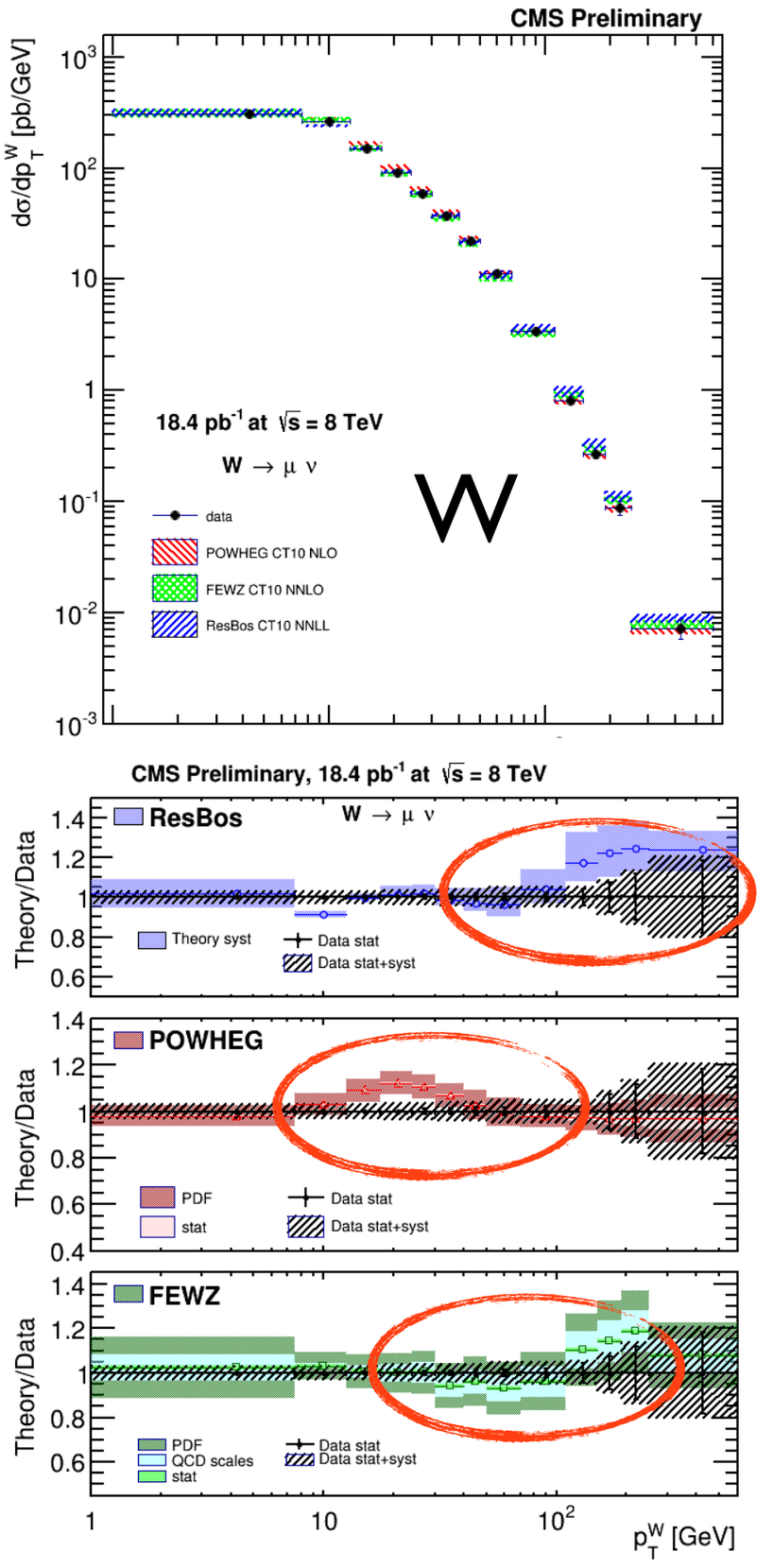
Z+>1b: powheg does the best job, MG 4F and 5F (P6) show trends
Z+2b: MG and PWG show the same trends

Dynamics of W, Z bosons: dσ/dp$_T$

[SMP-13-006]



- Very simple final state
  - 1 or 2 leptons



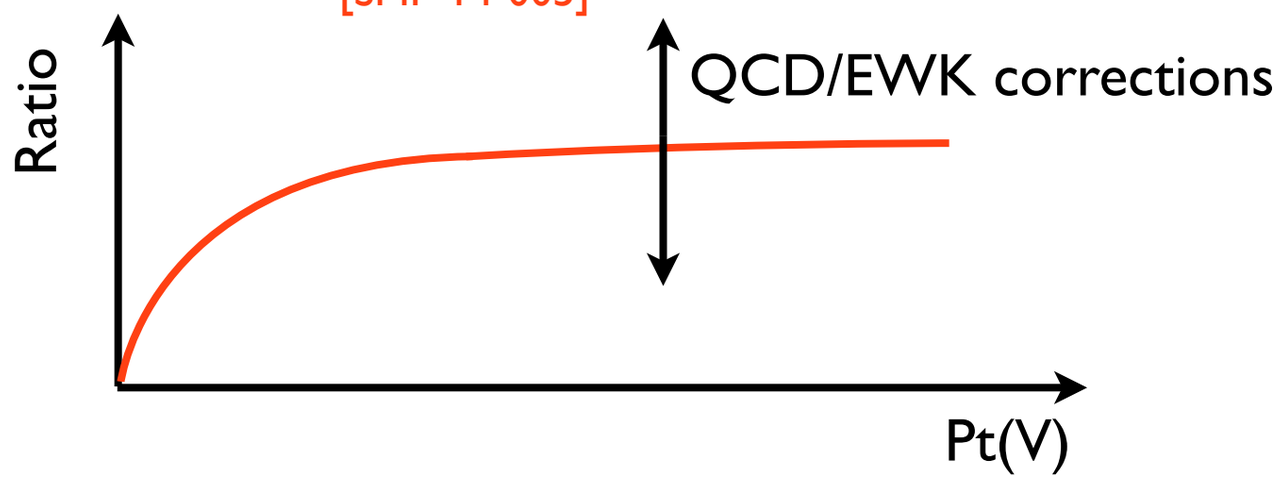
No prediction matches the data, LO or NLO

Belgian IUAP meeting, Antwerp, Dec 2015

Z/γ+jets ratio

- Why Z/γ?
  - In high Pt

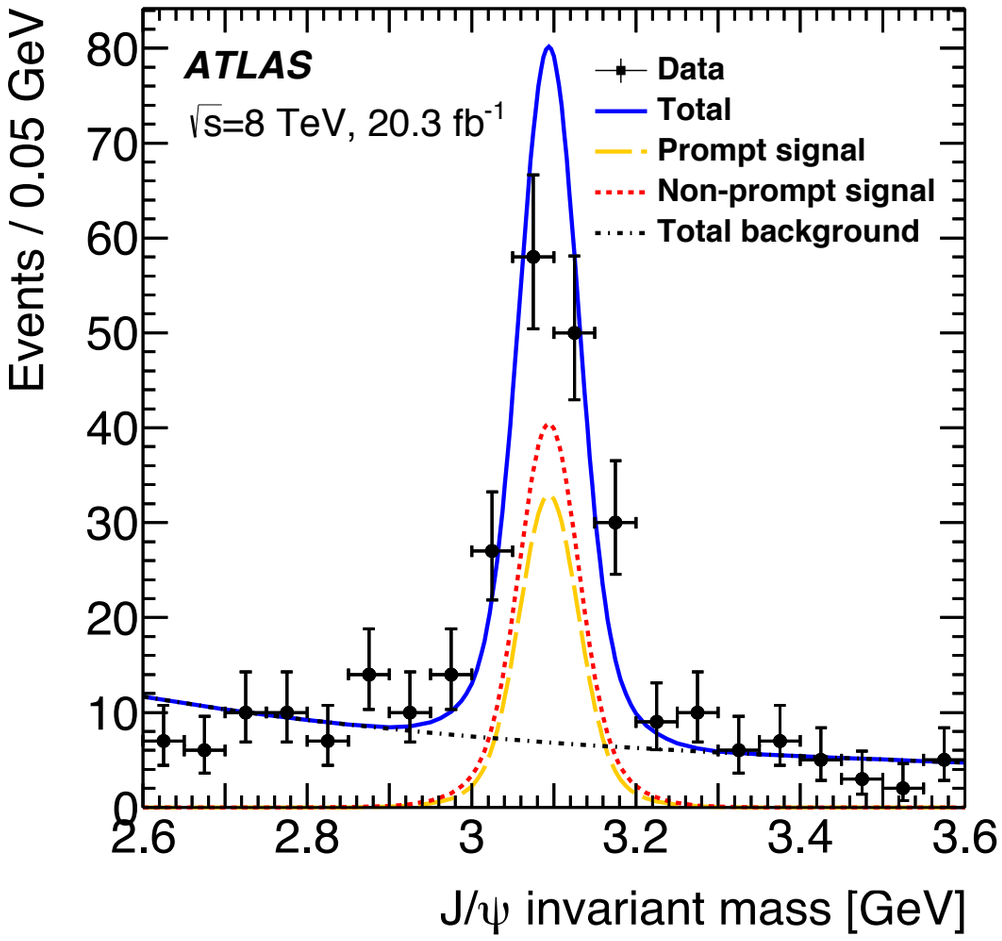
[SMP-14-005]

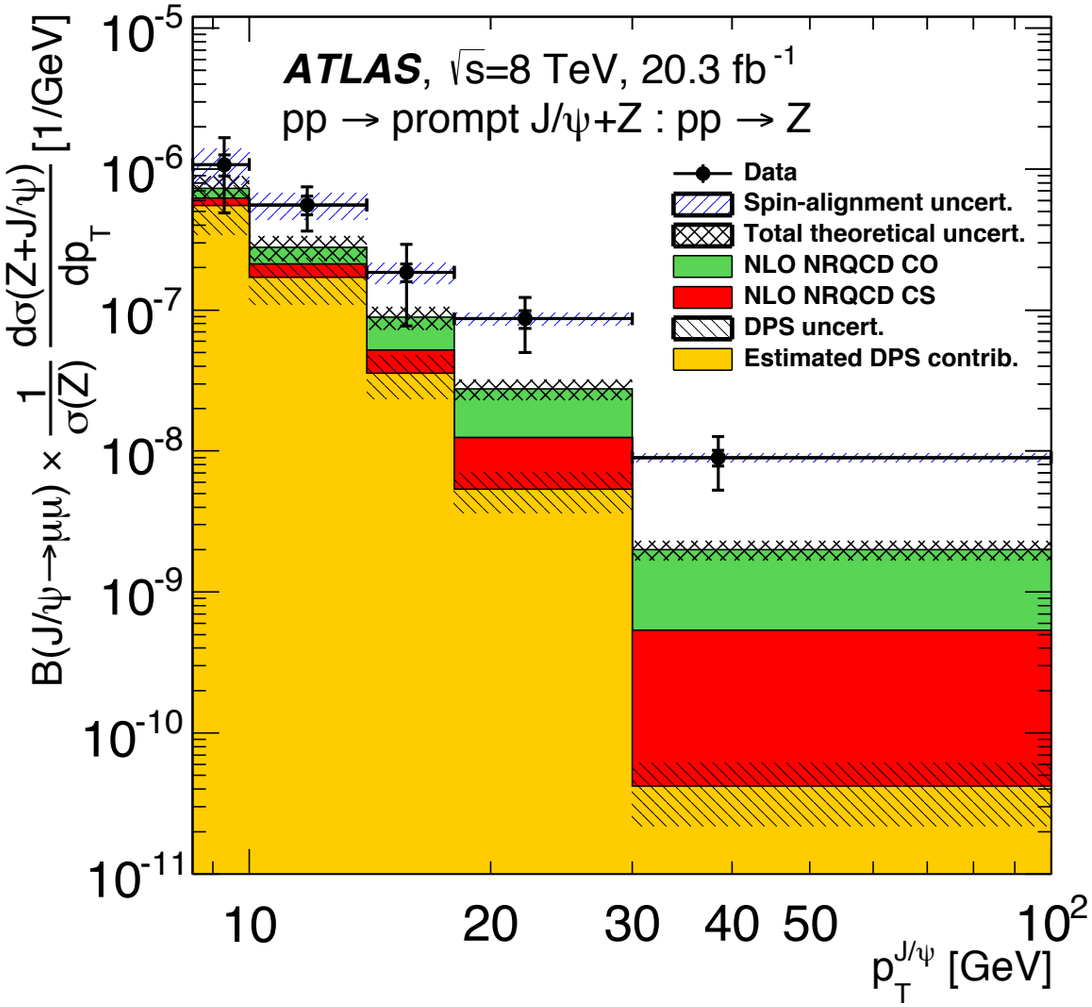


  - Both Z and γ+jets are large background processes for many searches
    - Particularly relevant for the modeling of $Z \rightarrow \nu\nu$+jets (SUSY) in MET +jets final state

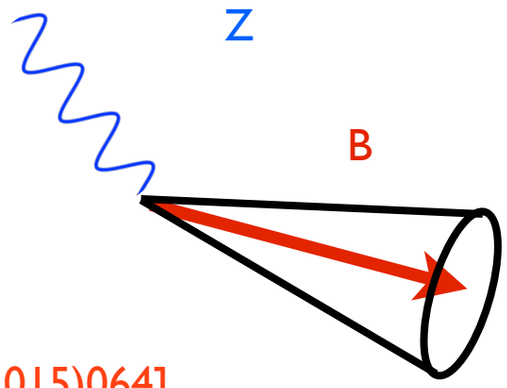
- Exp. final state:
  - 2 lept + >=1 jet, Pt>20 GeV, $|\eta|<2.4$, trigger match, $M(ll) \in [81,101]$ GeV
  - γ + >=1 jet, Pt>100 GeV, $|\eta_\gamma|<1.4$

Z+J/Psi

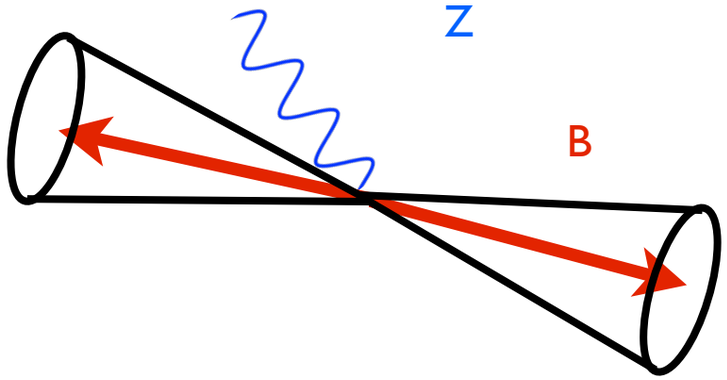

ATLAS
√s=8 TeV, 20.3 fb-1
Data
Total
Prompt signal
Non-prompt signal
Total background
Events / 0.05 GeV
J/ψ invariant mass [GeV]


ATLAS, √s=8 TeV, 20.3 fb-1
pp → prompt J/ψ+Z : pp → Z
Data
Spin-alignment uncert.
Total theoretical uncert.
NLO NRQCD CO
NLO NRQCD CS
DPS uncert.
Estimated DPS contrib.
B(J/ψ→μμ) × 1/σ(Z) dσ(Z+J/ψ)/dpT [1/GeV]
pT J/ψ [GeV]

Z+1, 2 b

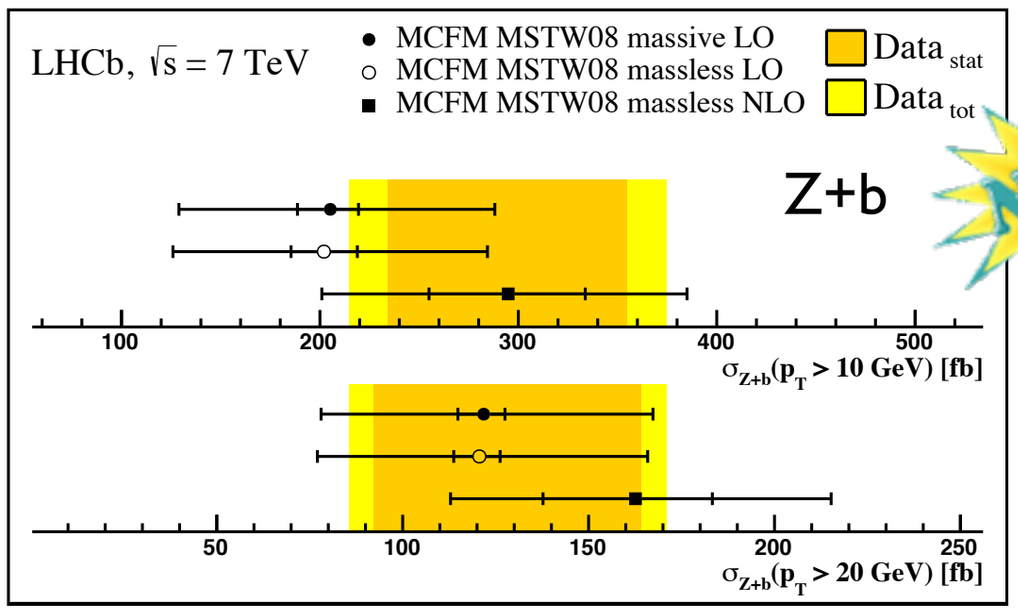


[JHEP 01(2015)064]

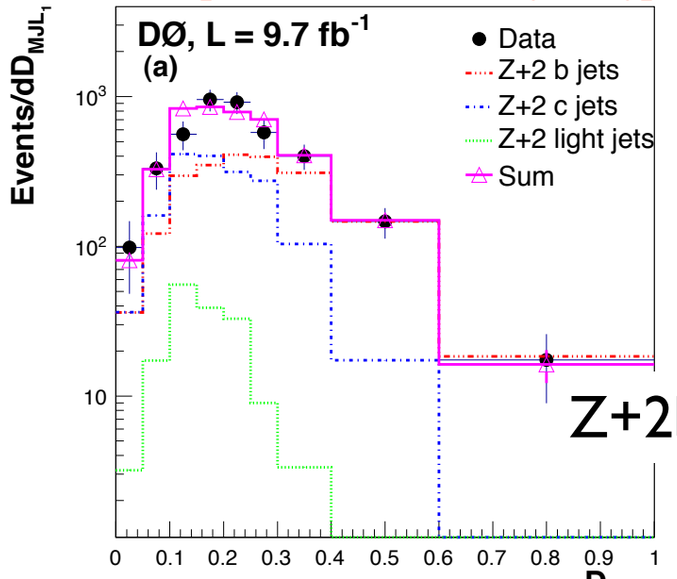


NEW!

[PRD 91, 052010 (2015)]



NEW!



$$\sigma(p\bar{p} \to Z + 2\ b\ \text{jet})/\sigma(p\bar{p} \to Z + 2\ \text{jet})$$

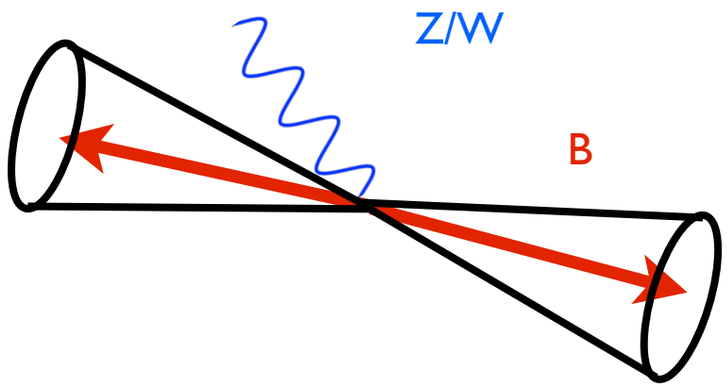
$$(2.36 \pm 0.32 \pm 0.35) \times 10^{-2}$$

NLO QCD(MSTW)	PYTHIA	ALPGEN
$(1.76 \pm 0.26) \times 10^{-2}$	2.42×10^{-2}	2.21×10^{-2}

Generally MCFM agrees quite well with data small deviation for LO Z+b prediction and soft Pt regime

Pythia and ALPGEN predictions match the data

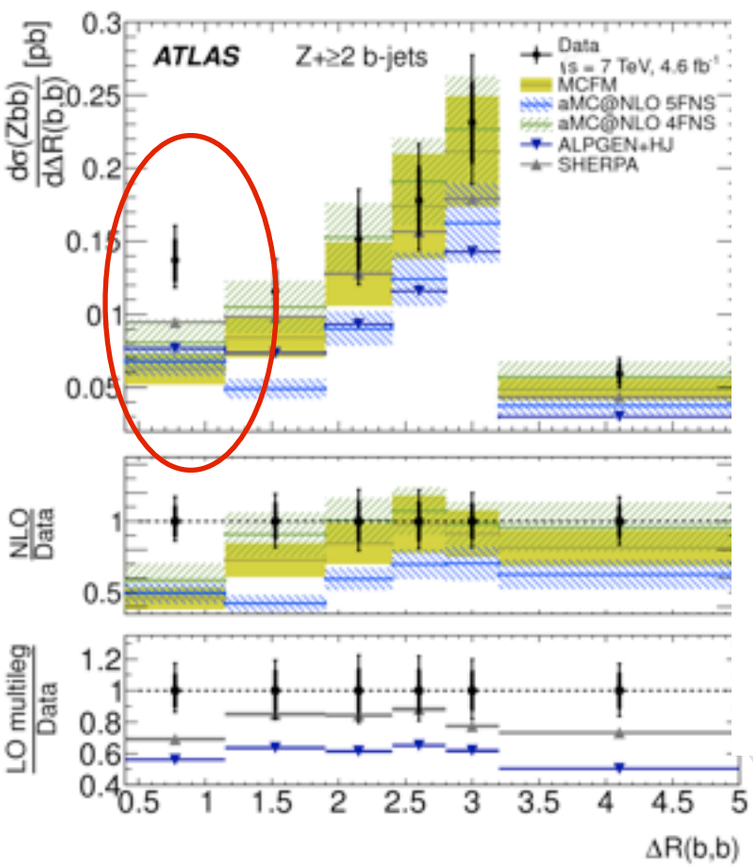
Z+2b

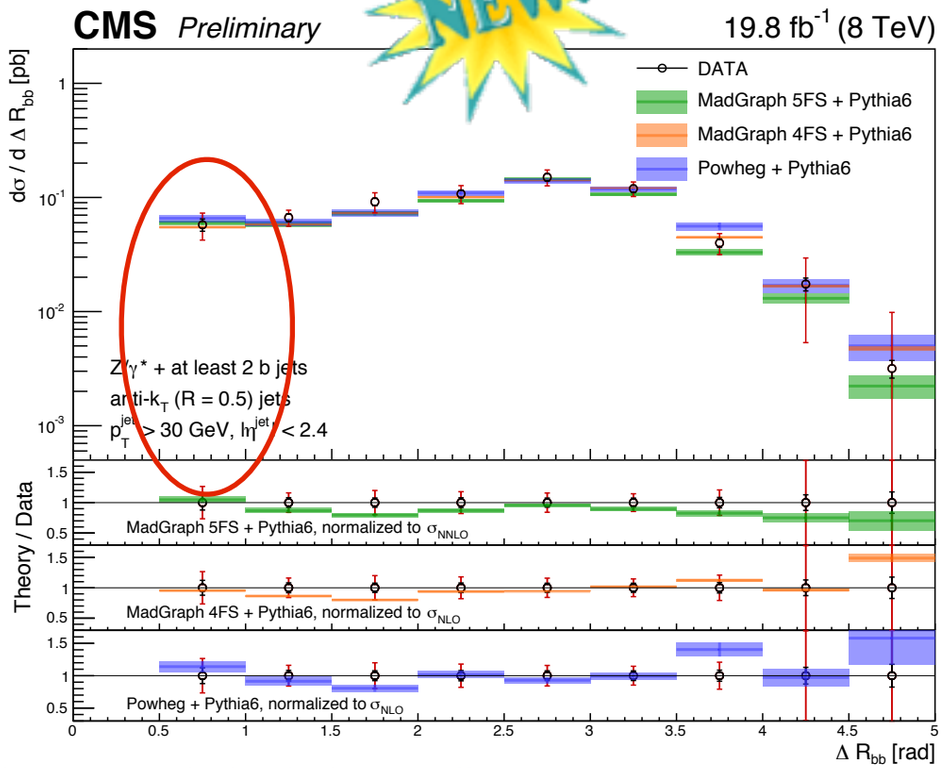


Jet radius 0.4

Z+2bj

[JHEP 10 (2014) 141]





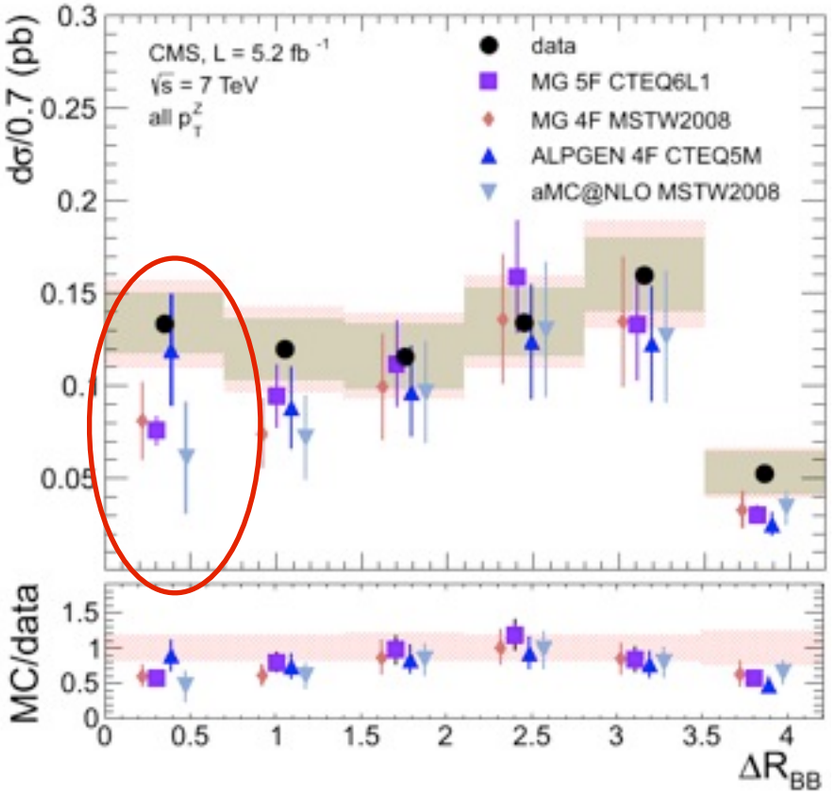
NEW!

Z/W

B

No use of jets

[JHEP 12 (2013) 39]

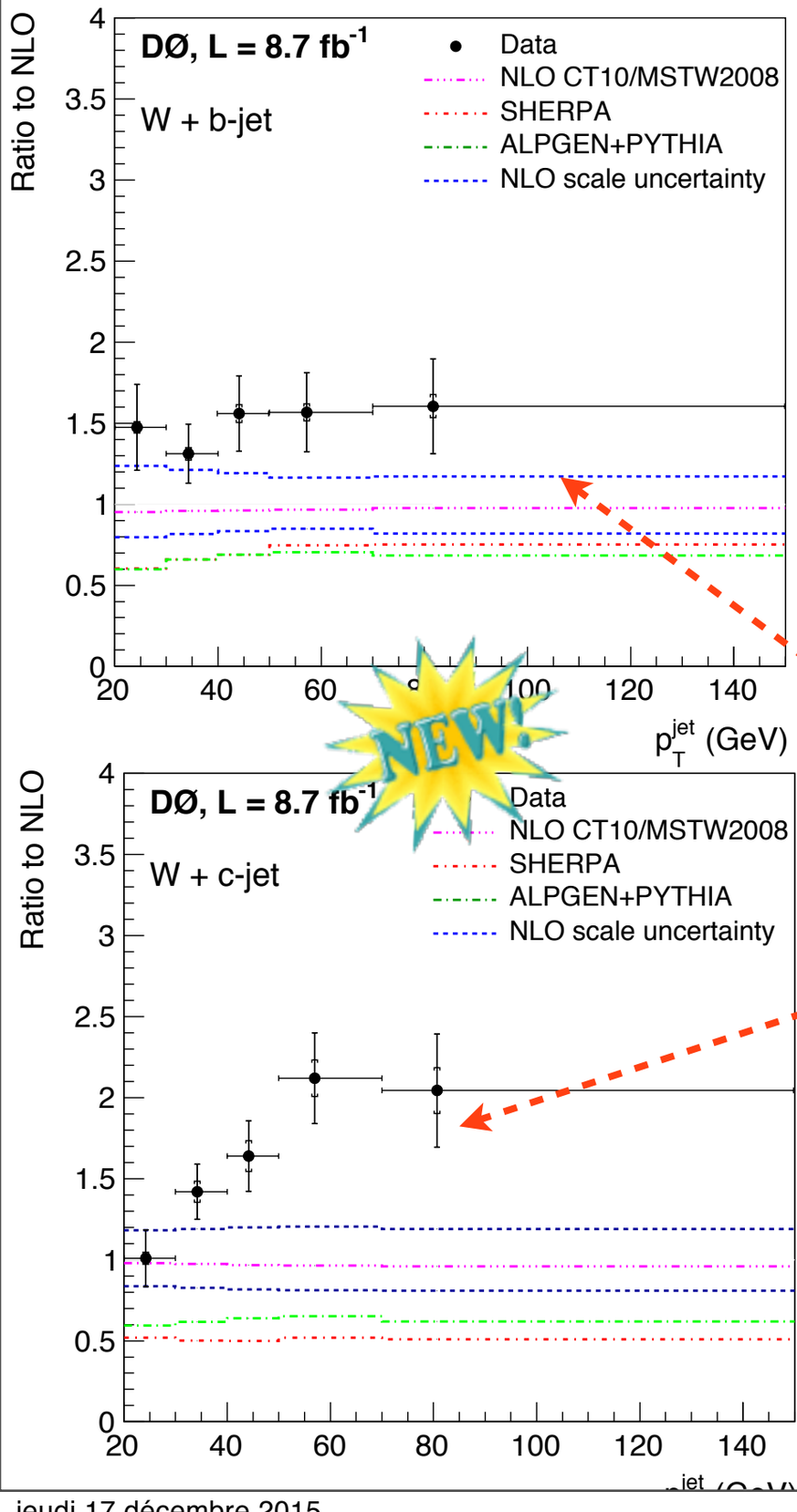


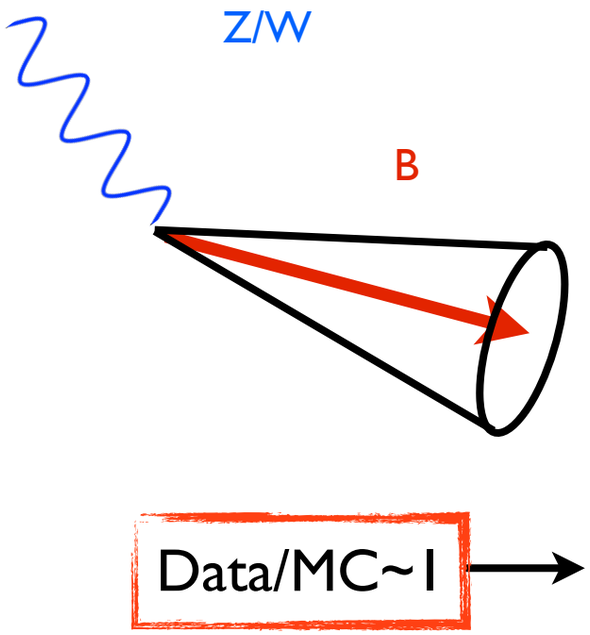
Z+2B

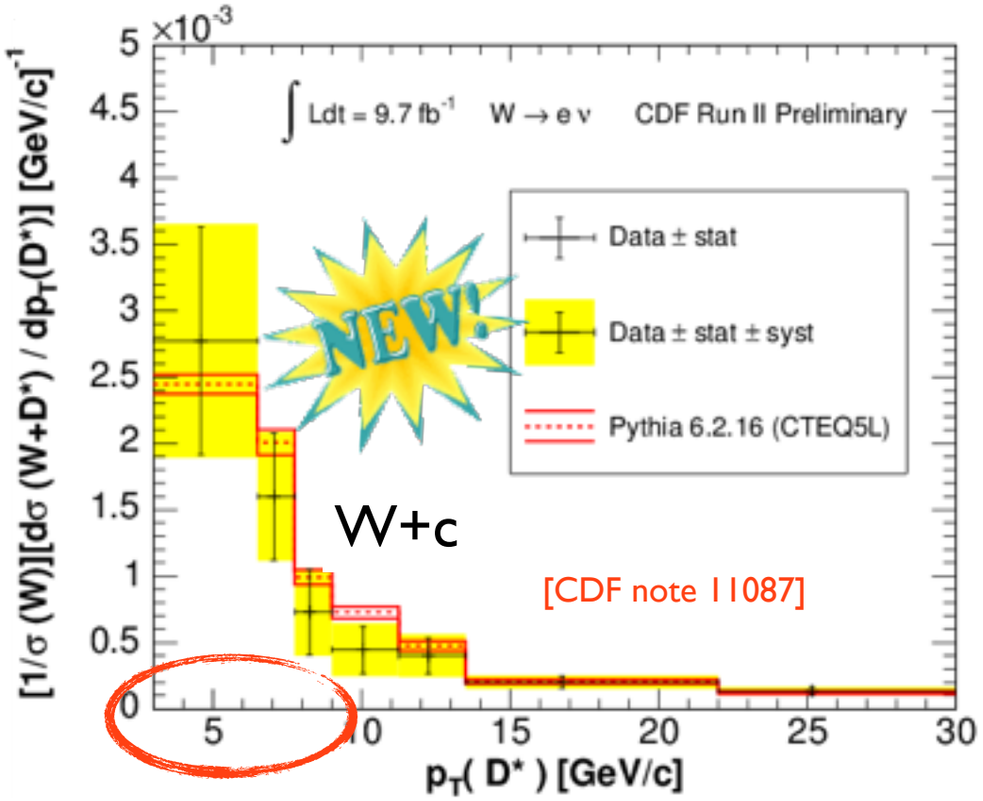
ATLAS and CMS 7 TeV measurements: excess of data around ~0.5 CMS (except ALPGEN)
Zbb @ 8 TeV: excess unseen with jet radius=0.5

W+1 b/c

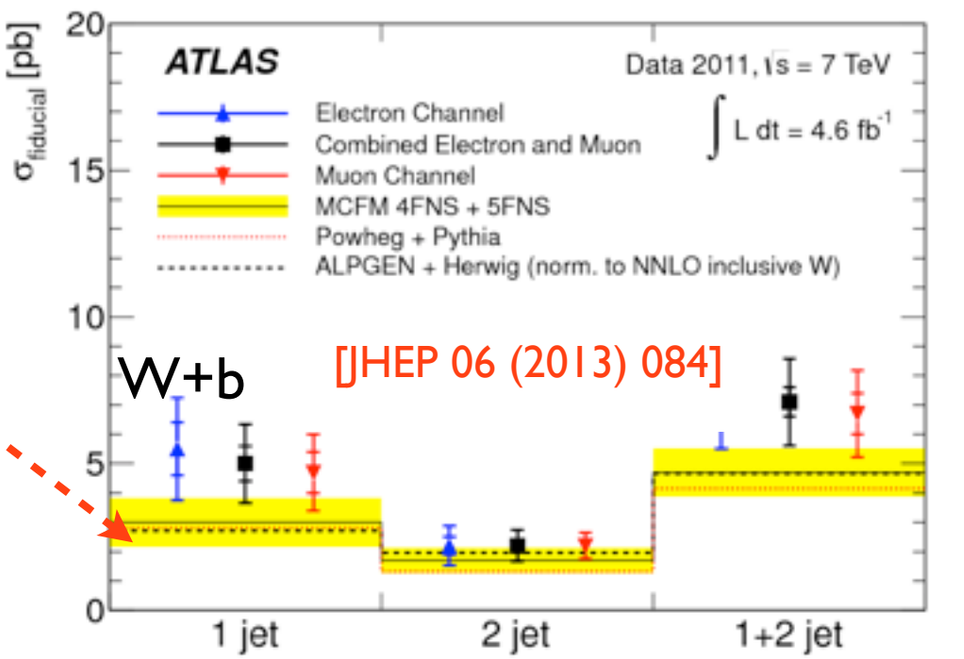
[PLB 743, 6 (2015)]



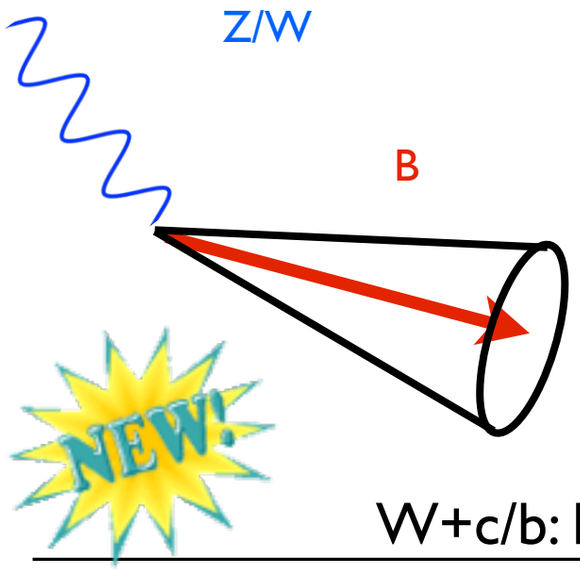


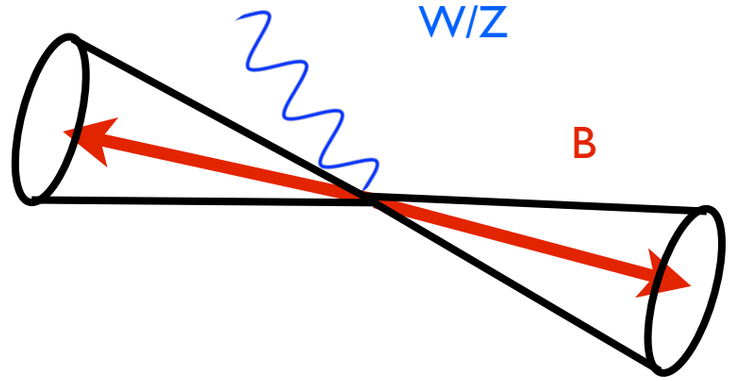


Large data/MC excess



W+b/c, W+2b





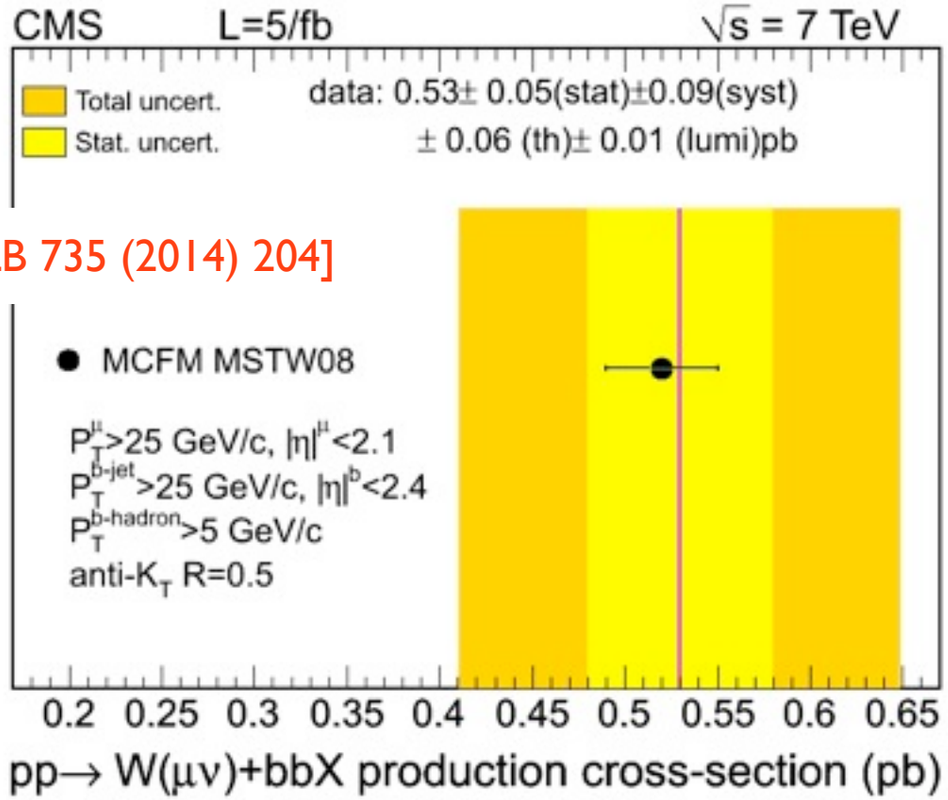
[CERN-PH-EP-2015-118]

W+c/b: LHCb

	Results 7 TeV	Results 8 TeV	SM prediction 7 TeV	SM prediction 8 TeV
$\frac{\sigma(Wb)}{\sigma(Wj)} \times 10^2$	$0.66 \pm 0.13 \pm 0.13$	$0.78 \pm 0.08 \pm 0.16$	$0.74^{+0.17}_{-0.13}$	$0.77^{+0.18}_{-0.13}$
$\frac{\sigma(Wc)}{\sigma(Wj)} \times 10^2$	$5.80 \pm 0.44 \pm 0.75$	$5.62 \pm 0.28 \pm 0.73$	$5.02^{+0.80}_{-0.69}$	$5.31^{+0.87}_{-0.52}$
$\mathcal{A}(Wb)$	$0.51 \pm 0.20 \pm 0.09$	$0.27 \pm 0.13 \pm 0.09$	$0.27^{+0.03}_{-0.03}$	$0.28^{+0.03}_{-0.03}$
$\mathcal{A}(Wc)$	$-0.09 \pm 0.08 \pm 0.04$	$-0.01 \pm 0.05 \pm 0.04$	$-0.15^{+0.02}_{-0.04}$	$-0.14^{+0.02}_{-0.03}$
$\frac{\sigma(W^+j)}{\sigma(Zj)}$	$10.49 \pm 0.28 \pm 0.53$	$9.44 \pm 0.19 \pm 0.47$	$9.90^{+0.28}_{-0.24}$	$9.48^{+0.16}_{-0.33}$
$\frac{\sigma(W^-j)}{\sigma(Zj)}$	$6.61 \pm 0.19 \pm 0.33$	$6.02 \pm 0.13 \pm 0.30$	$5.79^{+0.21}_{-0.18}$	$5.52^{+0.13}_{-0.25}$

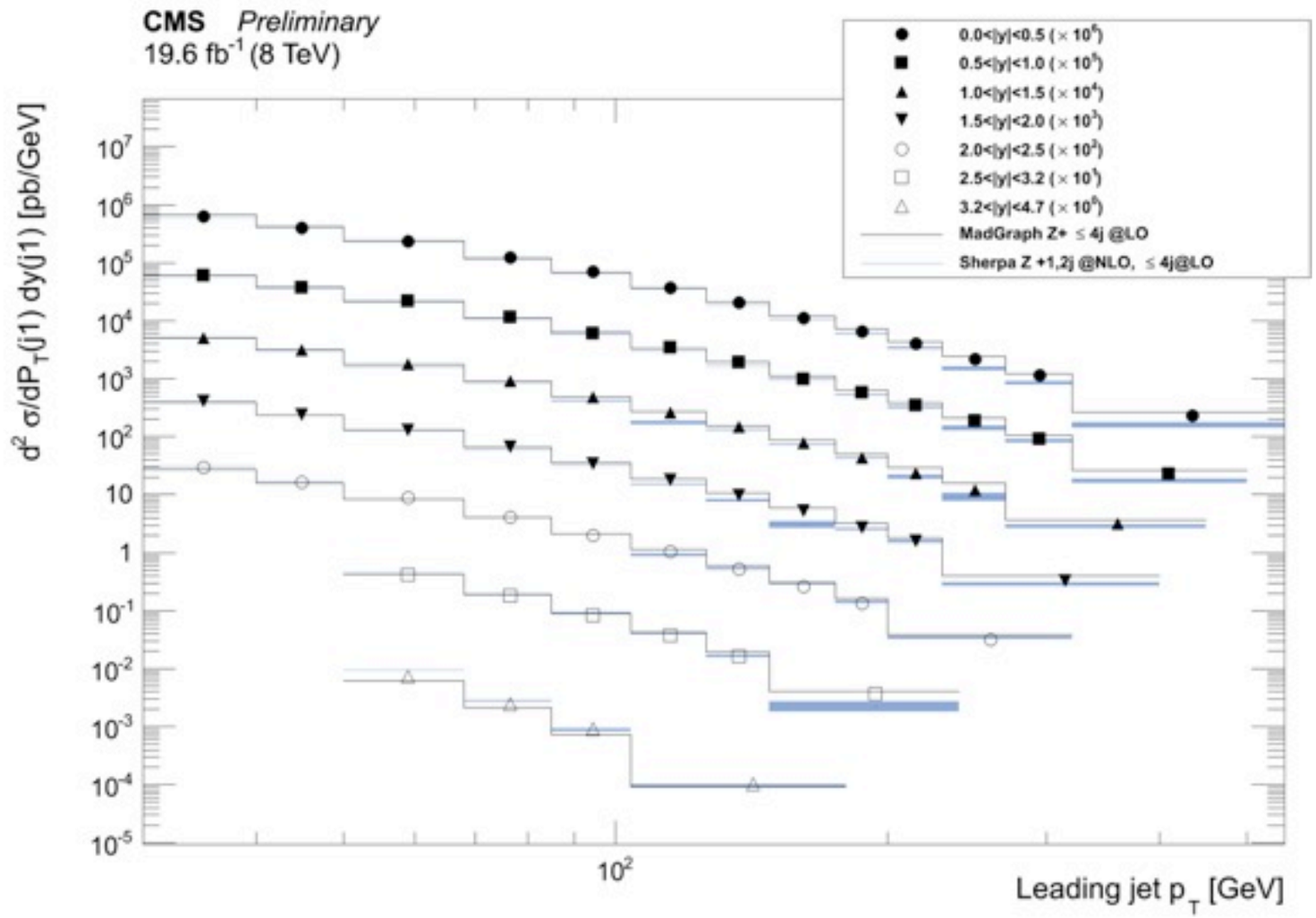
Good agreement between data and MCFM

[PLB 735 (2014) 204]



Good agreement MCFM

Z+jets @ 8 TeV

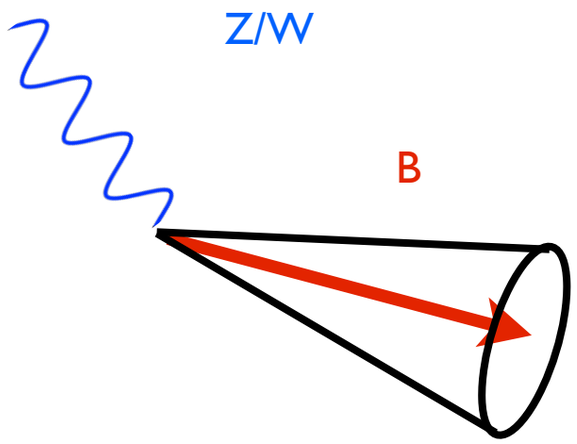


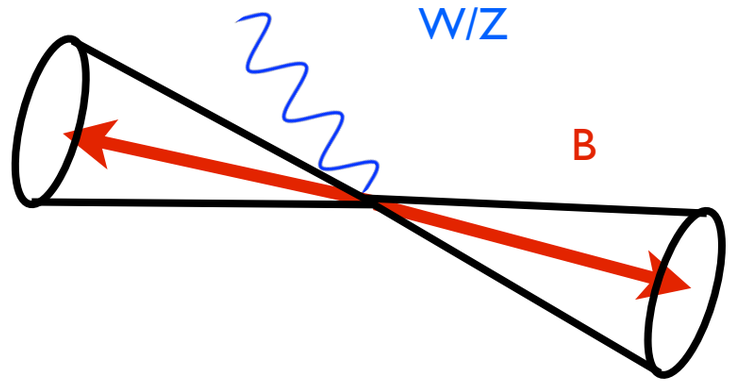
[CMS-PAS-SMP-14-009]

Double differential measurement of jet kinematics.
Eta coverage extended to 4.7

Severe trend for Sherpa
More reasonable for MG

W+b/c, W+2b @ 7,8 TeV





[CERN-PH-EP-2015-118]

W+c/b: LHCb

	Results		SM prediction	
	7 TeV	8 TeV	7 TeV	8 TeV
$\frac{\sigma(Wb)}{\sigma(Wj)} \times 10^2$	$0.66 \pm 0.13 \pm 0.13$	$0.78 \pm 0.08 \pm 0.16$	$0.74^{+0.17}_{-0.13}$	$0.77^{+0.18}_{-0.13}$
$\frac{\sigma(Wc)}{\sigma(Wj)} \times 10^2$	$5.80 \pm 0.44 \pm 0.75$	$5.62 \pm 0.28 \pm 0.73$	$5.02^{+0.80}_{-0.69}$	$5.31^{+0.87}_{-0.52}$
$\mathcal{A}(Wb)$	$0.51 \pm 0.20 \pm 0.09$	$0.27 \pm 0.13 \pm 0.09$	$0.27^{+0.03}_{-0.03}$	$0.28^{+0.03}_{-0.03}$
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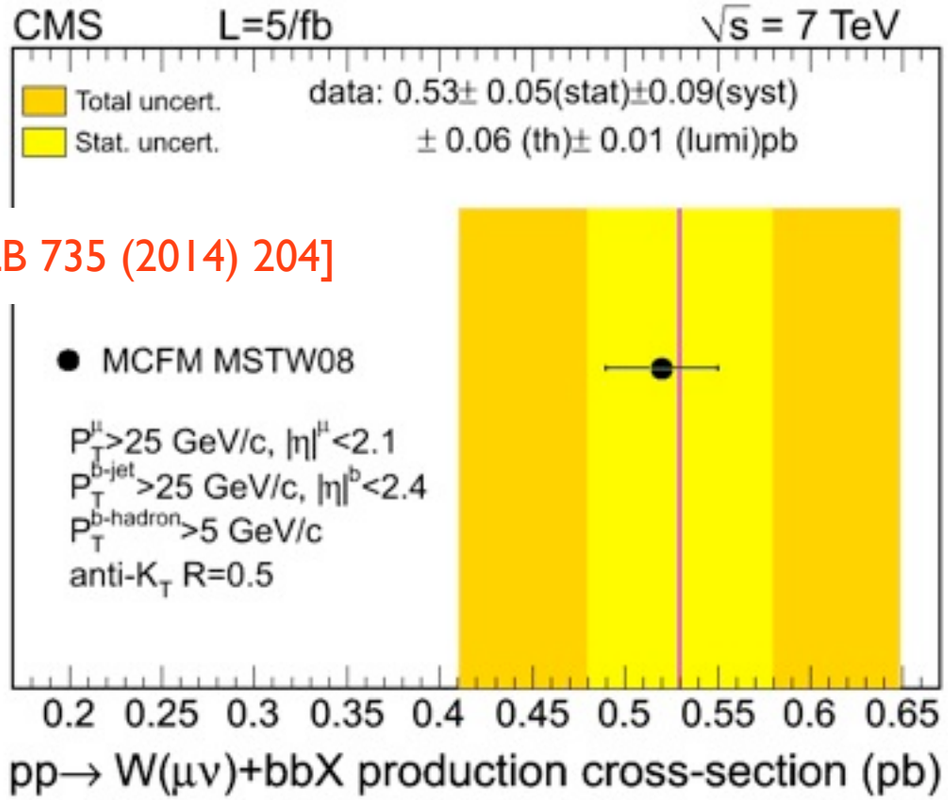
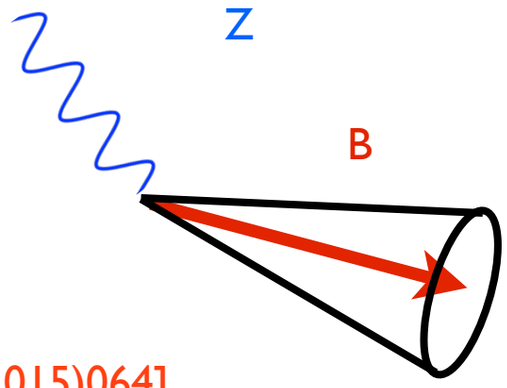
Good agreement between data and MCFM

[PLB 735 (2014) 204]

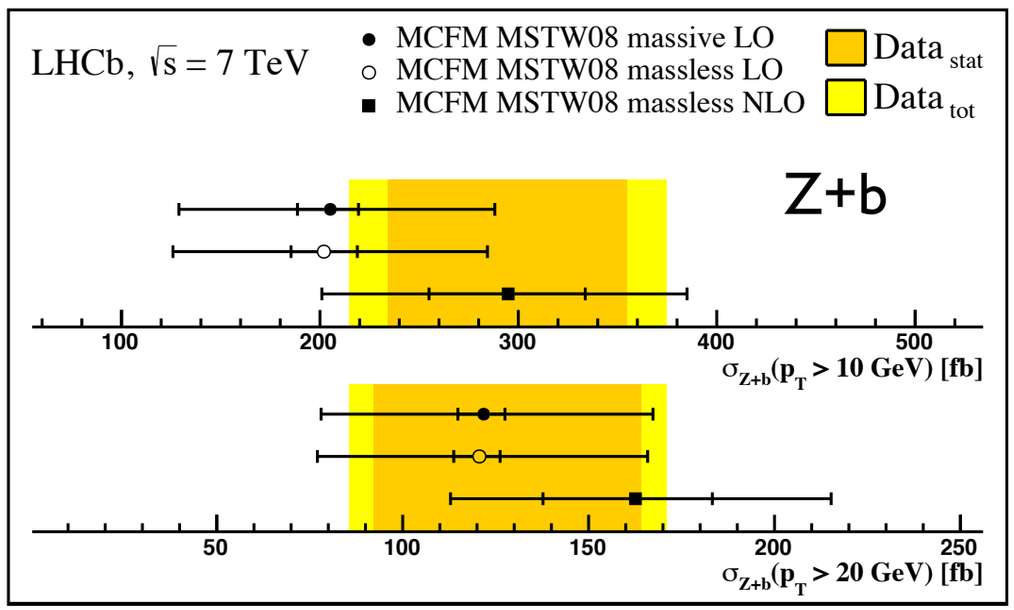


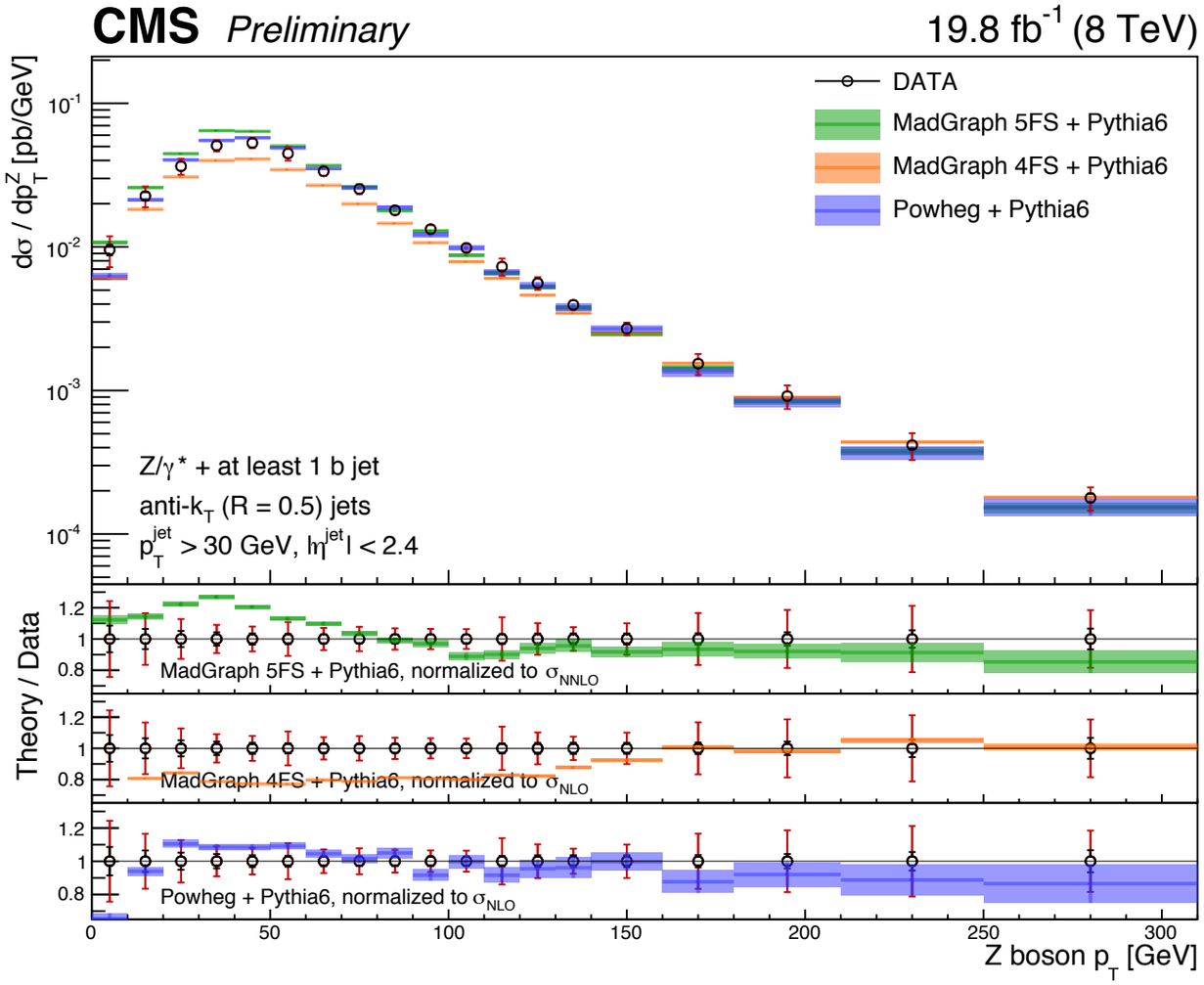
Good agreement MCFM

Z+>=1b-jet



[JHEP 01(2015)064]

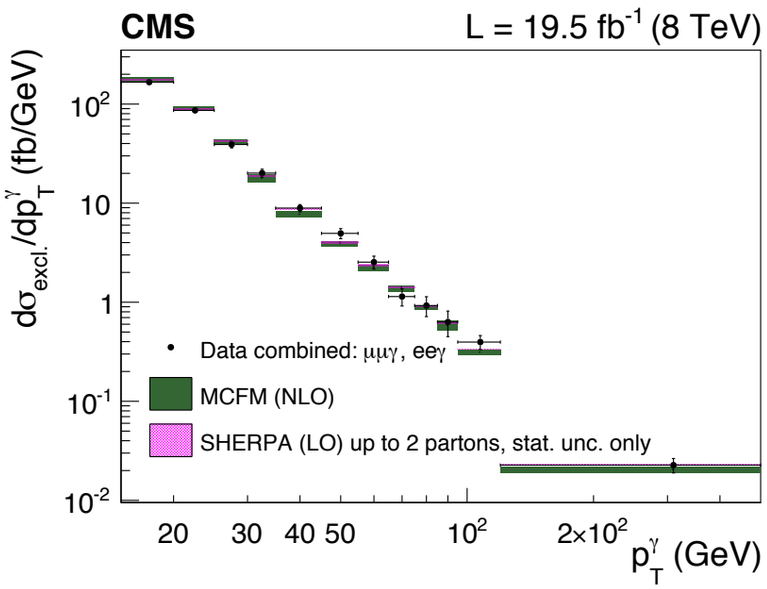


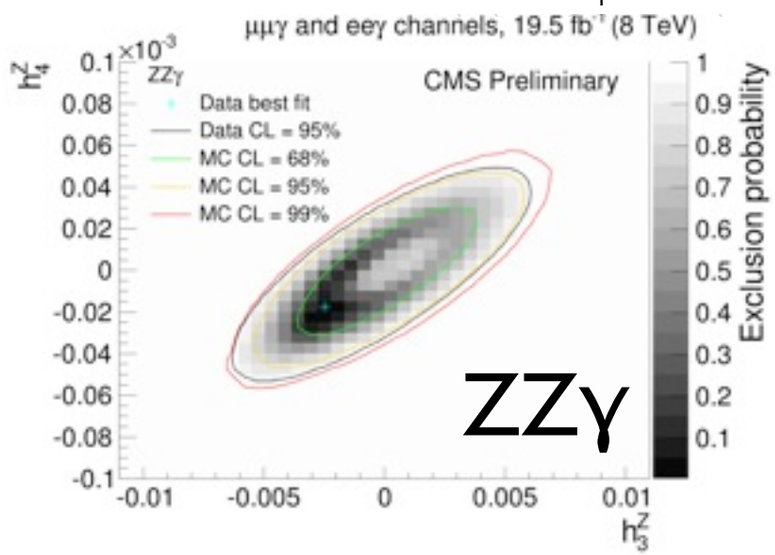


Generally MCFM agrees quite well with data small deviation for LO Z+b prediction and soft Pt regime

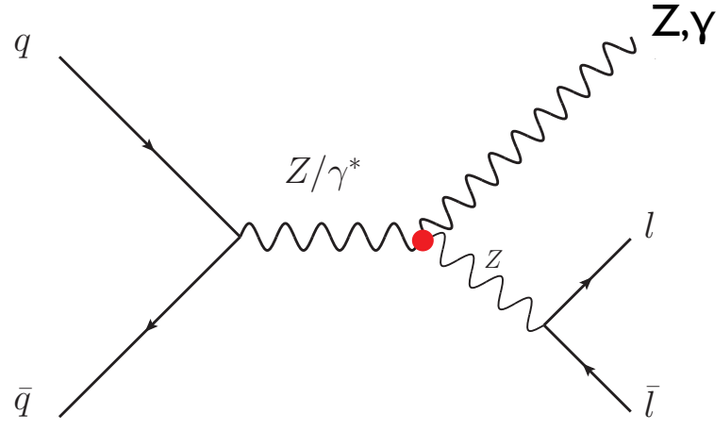
Neutral ZZγ and Zγγ aTGC: Zγ and ZZ

Zγ (llγ)

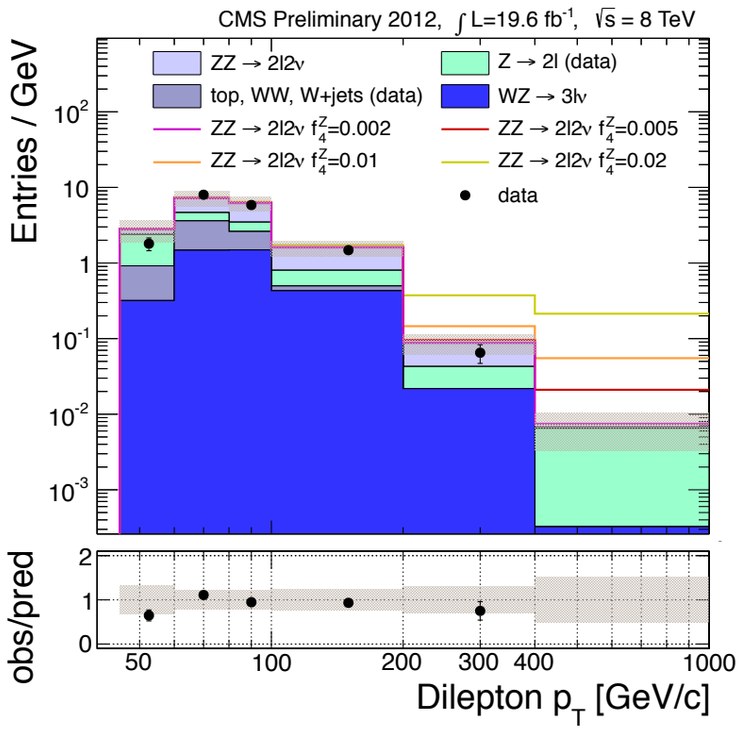




ZZγ

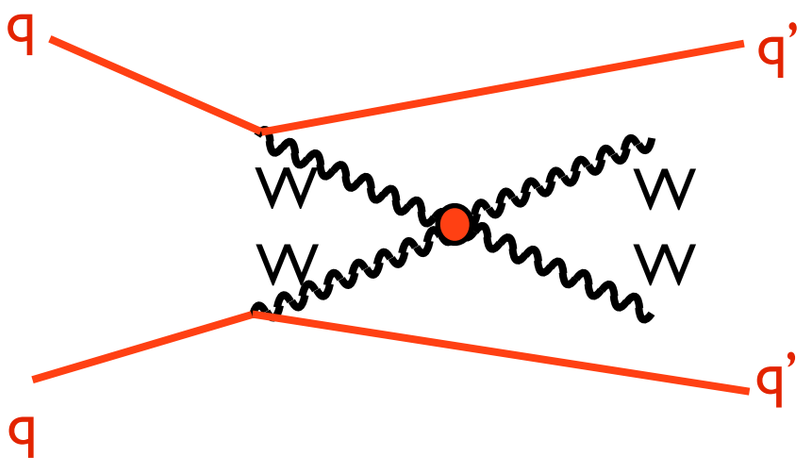


ZZ (2l2ν)



So far, no evidence for aTGC: new couplings compatible with 0

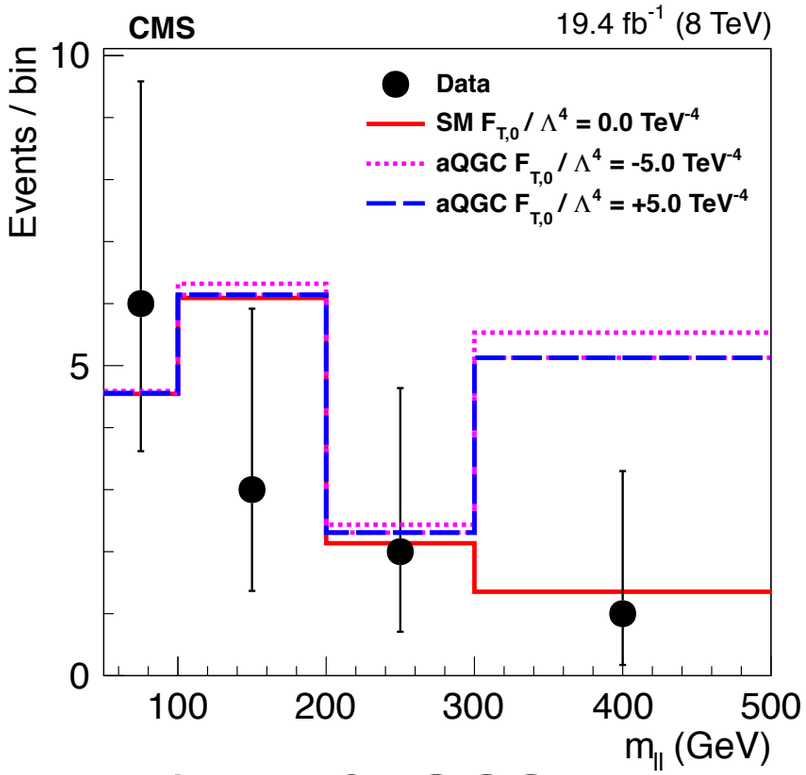
aQGC using same sign WW+2 jets



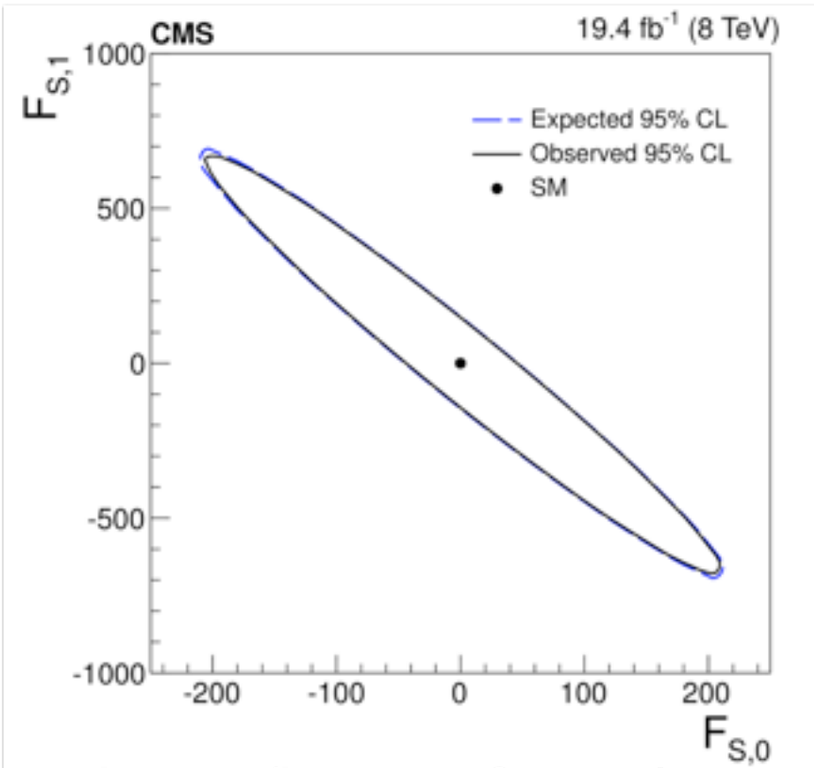
[SMP-13-015]

Same sign W bosons: suppresses QCD background

VBS⇒Large rapidity + high mass between forward jets



data vs 2 aQGC scenarios



Limits (here on 2 couplings only)

So far, no evidence for aQGC: new couplings (Phys. Rev. D 74 (2006) 073005) compatible with 0