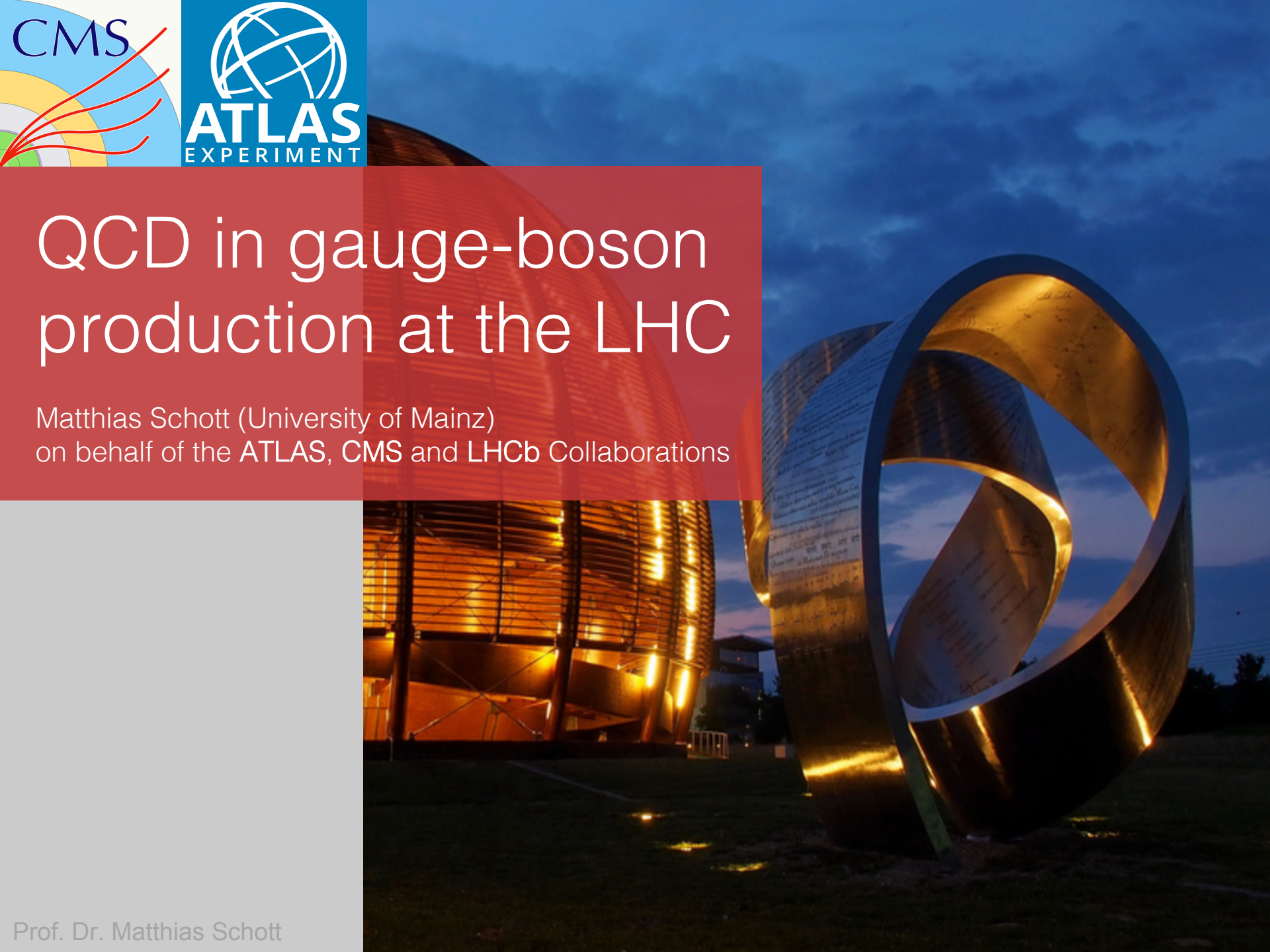
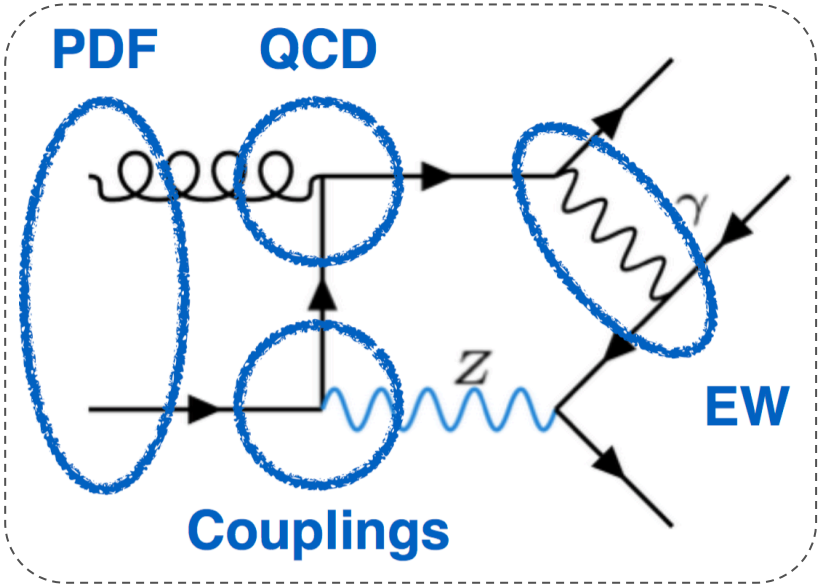


QCD in gauge-boson production at the LHC

Matthias Schott (University of Mainz)
on behalf of the ATLAS, CMS and LHCb Collaborations

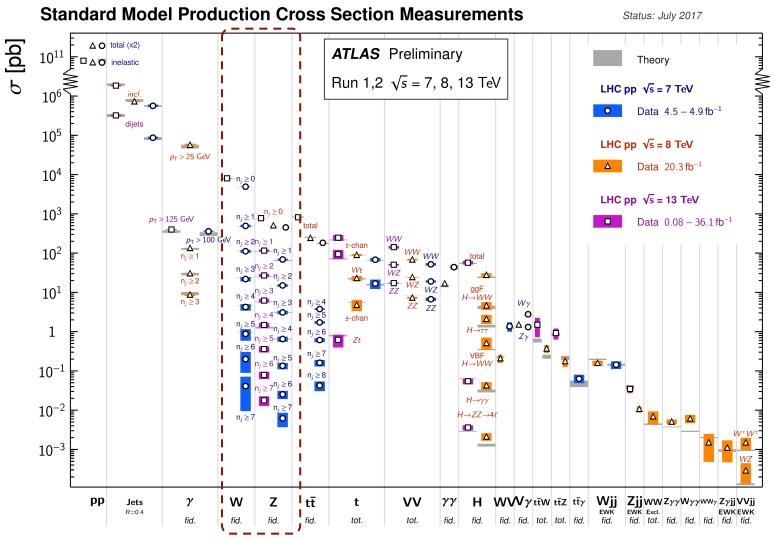
What can we learn from those tests?

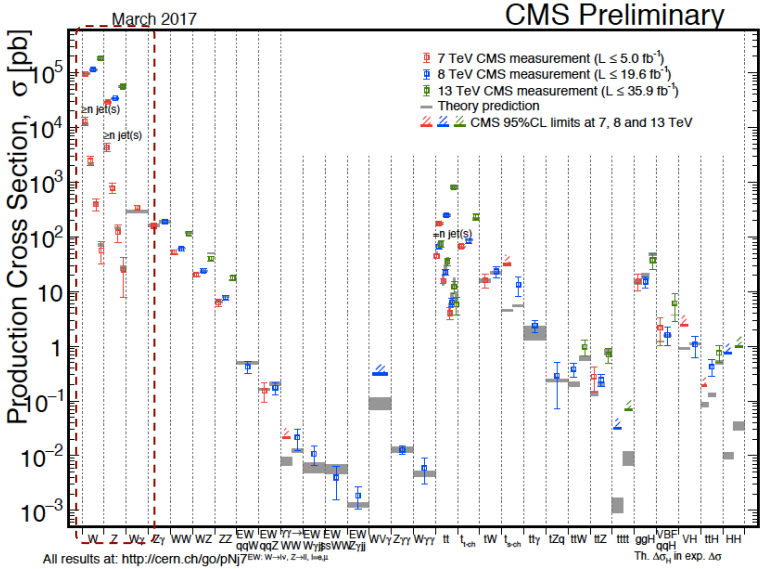
- Inclusive and differential cross-sections are sensitive to proton PDFs
- Vector bosons with jets
  - can test perturbative QCD
  - their interplay with parton shower approaches
  - Sensitive to gluon density
  - Introduces scales larger than the mass of the Z boson
- W/Z transverse momentum measurements probe resummation
- Electroweak corrections become important in the high p_T regime



What we will discuss today?

- Plenty of results from ATLAS and CMS available
  - Vector boson papers are among the most cited ones at the LHC
- Focus on precision measurement and innovative measurement
  - Keep in mind that precision takes time, i.e. many of the results are still based on the run-1 data-sets
- A full overview can be found at
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  - https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
  - http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html





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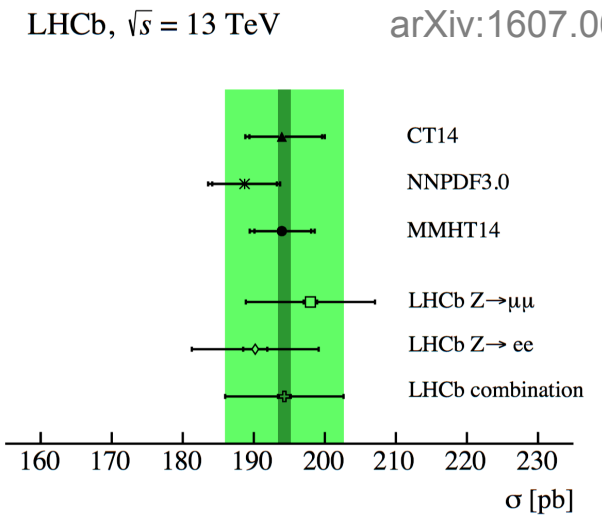
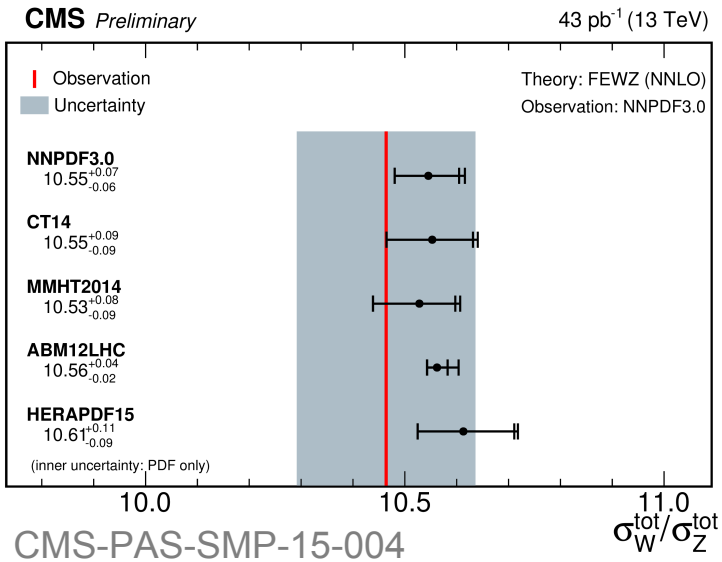
Inclusive Vector Boson Production

Cross-Section Measurements at 13 TeV

- First thing to be done at each new energy: Rediscover W/Z bosons
  - Gives confidence in detector operation
  - Test for unexpected behaviours in the energy dependence
  - Important: LHCb perfectly covers forward region!

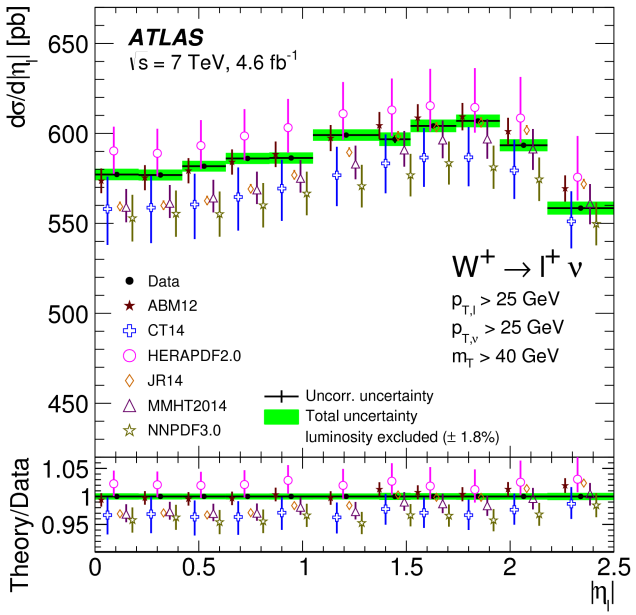
- High statistics allow for first precision measurements on sub-% level even looking at ratios
  - W^+/W^-: ratio sensitive to u_v-d_v quark distributions
  - $W^\pm/Z$ ratio: sensitive to s-quark distribution

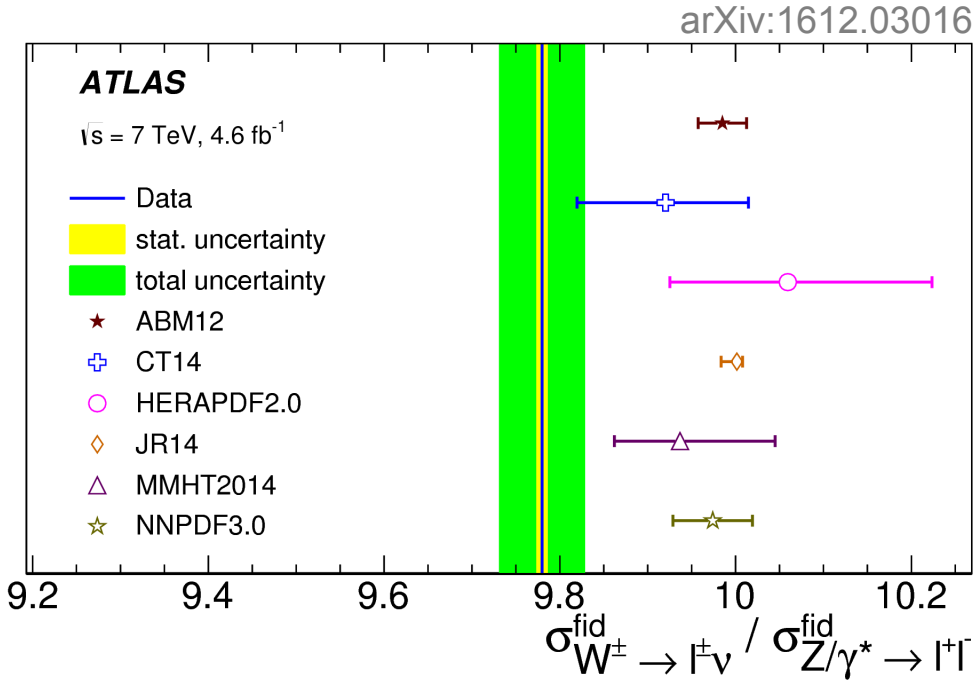




CMS-PAS-SMP-15-004

Precision Measurements and PDFs



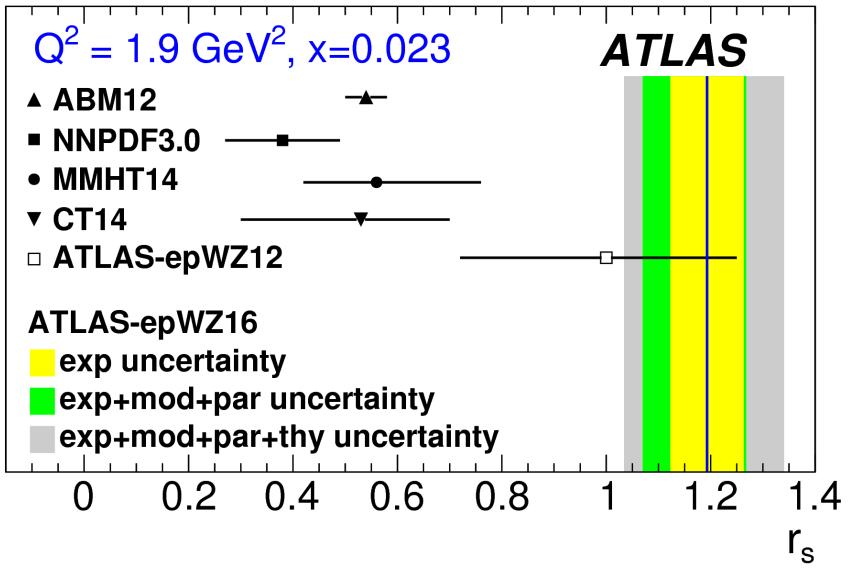


- W/Z differential cross-section measured at 7 TeV with highest precision in a >5 years effort.
  - Important input for future PDF sets
  - General trend of W/Z ratio confirmed by ATLAS and CMS at 7/8/13 TeV

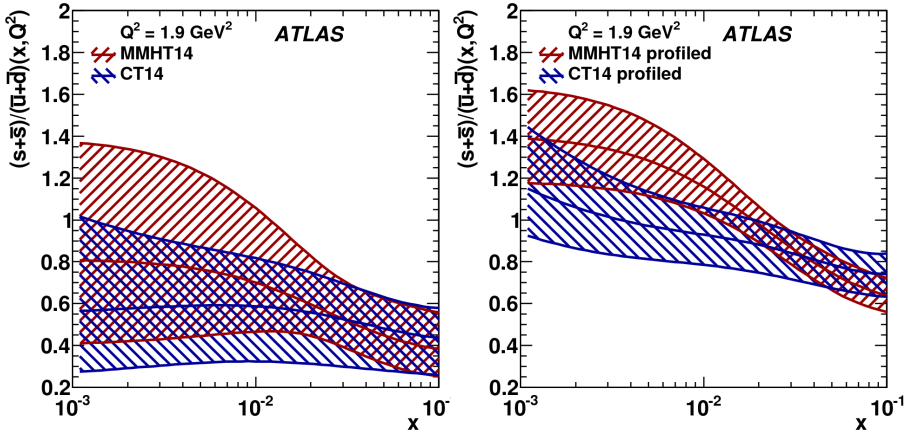
Strangeness of the Proton?

- ATLAS PDF fit on W/Z precision data suggests enhanced strangeness content of the proton
  - Strange content seems at same level as light-flavour sea quarks
  - Large (10%) uncertainty on r_s from QCD scale choice
    - $(\mu_f, \mu_r) = (1/2, 1/2) * m_V$ favored over (1, 1) by 24 units of $\chi 2$

arXiv:1612.03016

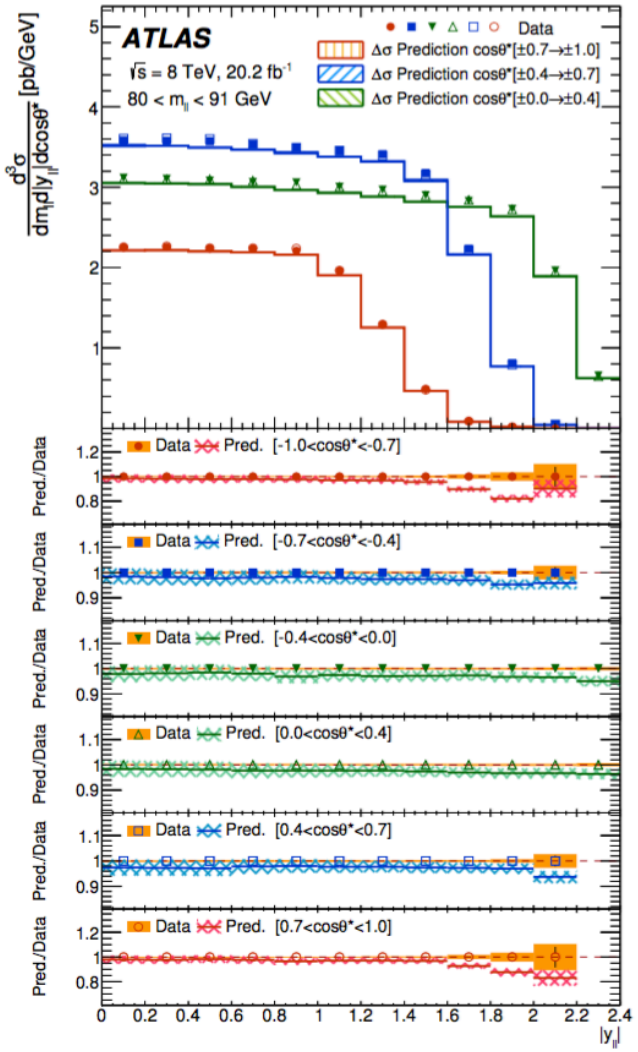


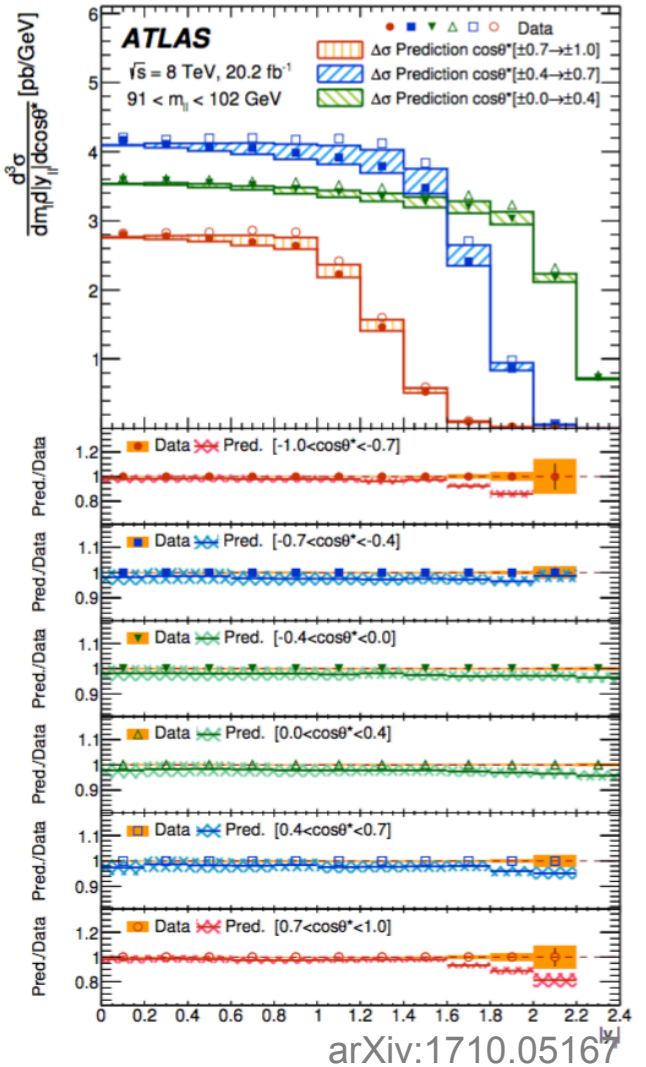
- Enhanced strangeness only an artifact of PDF parameterization?
  - parameterization bias was tested
  - sensitivity to the assumptions on the low-x behavior or light-sea quarks
  - W+c production with same hint
  - ATLAS and CMS data is consistent



Triple-Differential Cross-Sections

- New triple-differential measurement of Z/γ^*
  - m_{ll}, $|y_{ll}|$, $\cos\theta^*$ in the Collins–Soper frame
- Can be used to simultaneously fit PDFs and electroweak mixing angle
  - EWK corrections have to be considered for $\sin^2\theta_W$ extraction

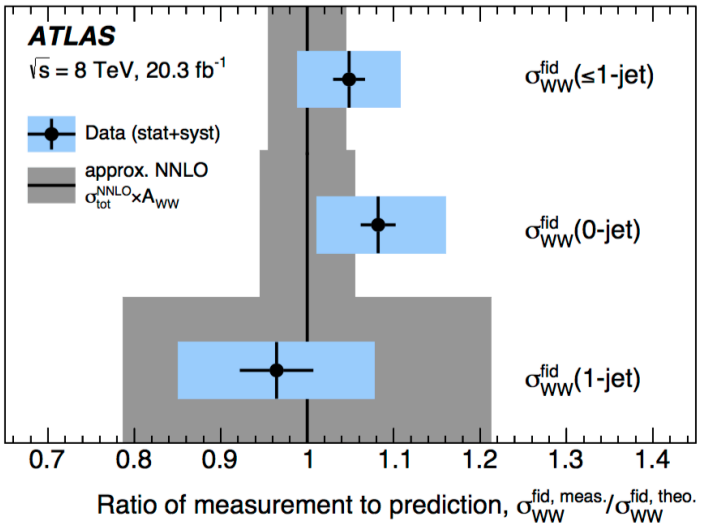




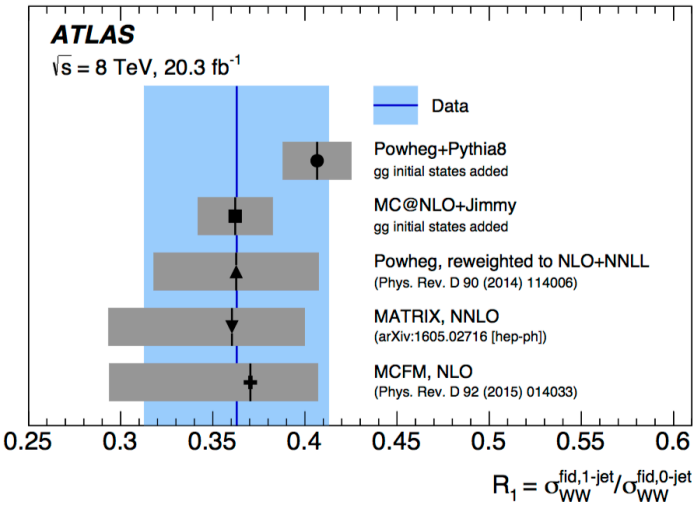
arXiv:1710.05167

QCD in DiBoson processes

- Diboson processes typically used to test the SM Abelian gauge structure
  - In need for high precision predictions of cross-sections
- Large progress in predictions over the past years
  - pp→WW at NLO and NNLO (differentially)
  - dedicated NLO predictions for jet-associated WW production
  - gg→WW process available at order $O(\alpha_S^3)$
- Dominant measurement uncertainty due to jet calibration



arXiv:1608.03086



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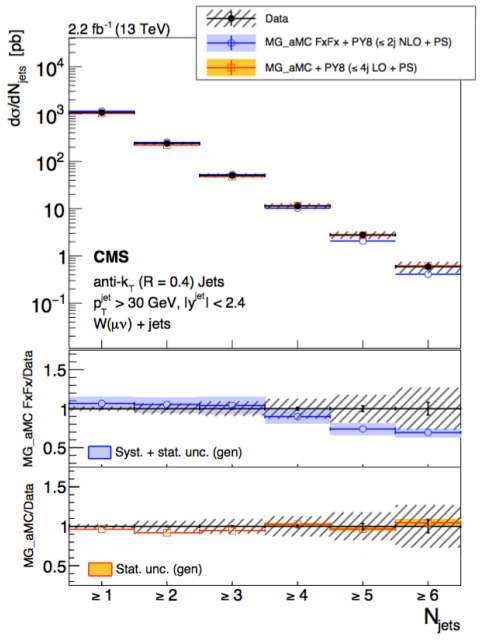
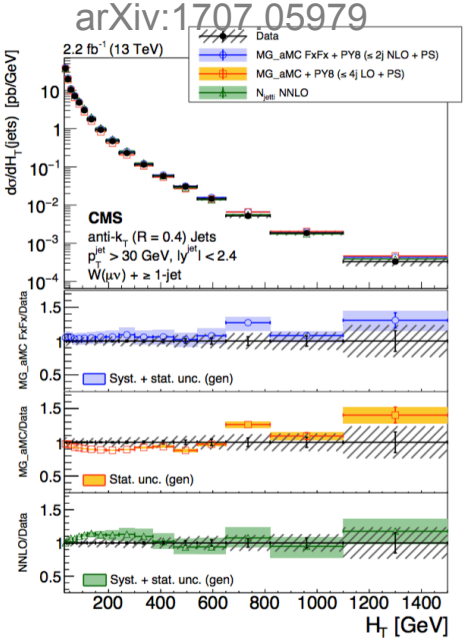
Vector Boson and Jets

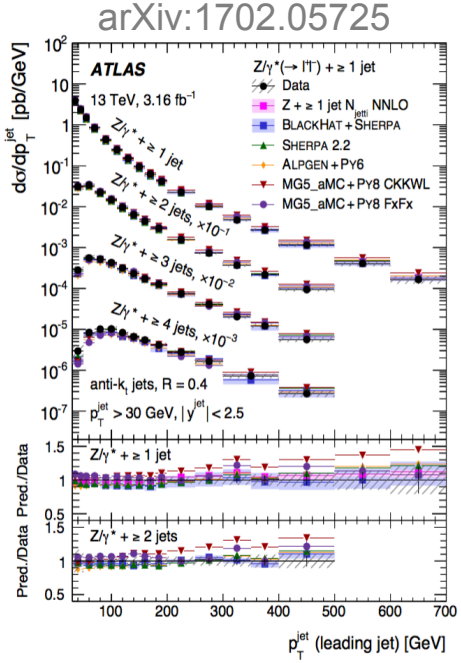
Standard W/Z+jets measurements

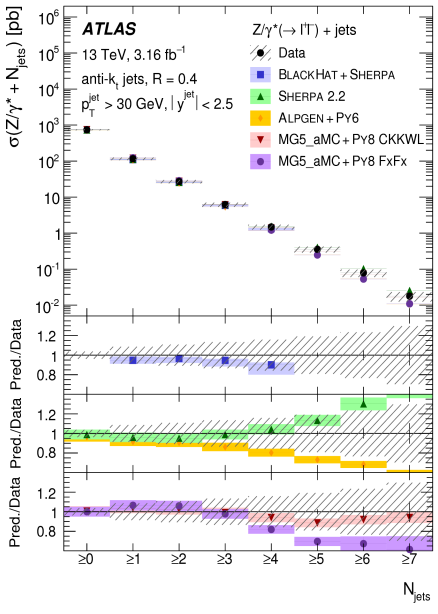


arXiv:1707.05979



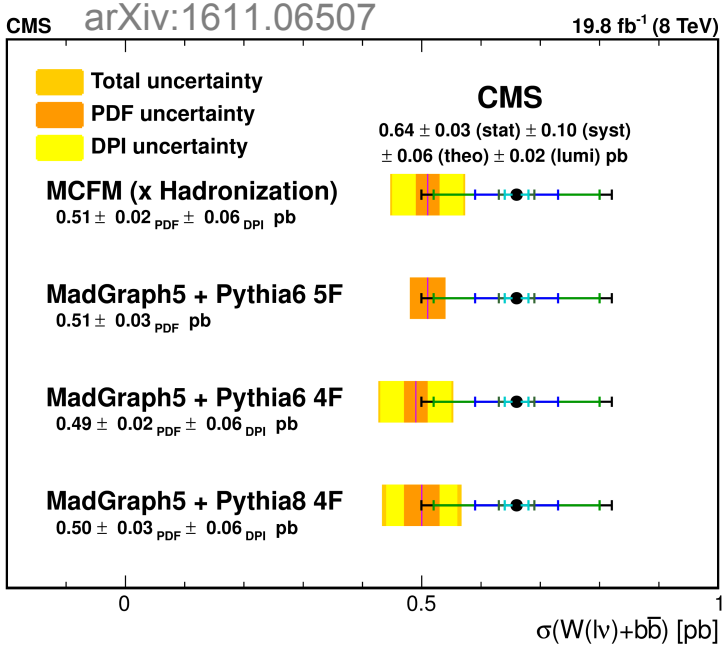
arXiv:1702.05725

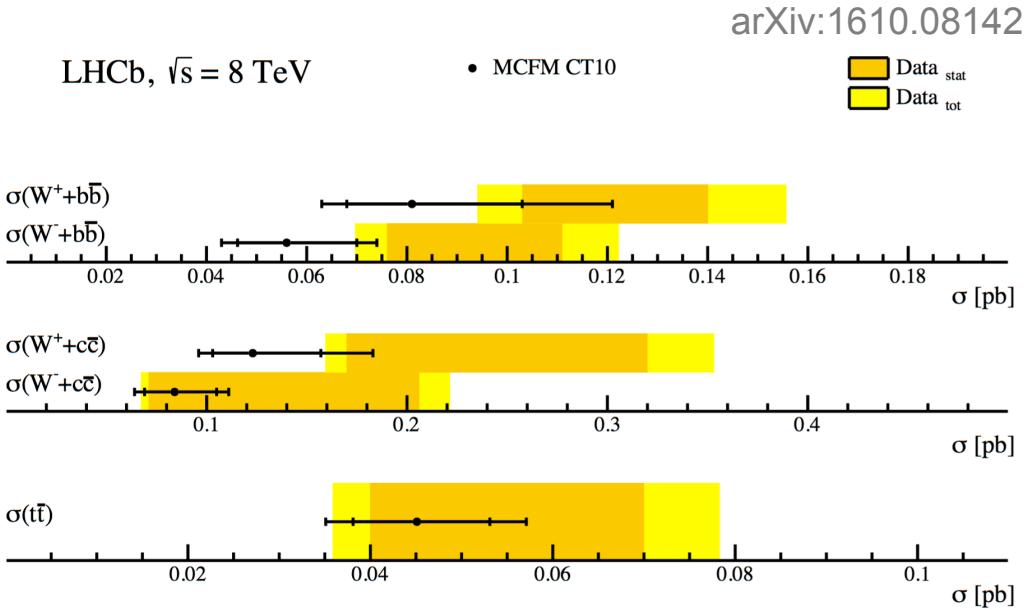




- Test fixed-order at NLO$^{BlackHat+Sherpa}$, at NNLO^{Njetti} and different generators
  - Sherpa 2.2, Alpgen+Py6, MG5_aMC+Py8 FxFx do not describe data for high jet multiplicity, where large fraction of jets produced by PS
  - Distributions dominated by a single jet multiplicity are modelled well by fixed-order NLO calculations, even in the presence of a jet veto at a low scale
  - The ME+PS generator MG5_aMC+Py8 CKKWL, which is based on LO matrix elements, models a too-hard jet spectrum (similar at 7 TeV): scale-treatment?

Vector Bosons and Heavy Flavors

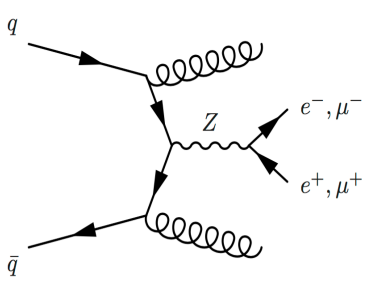




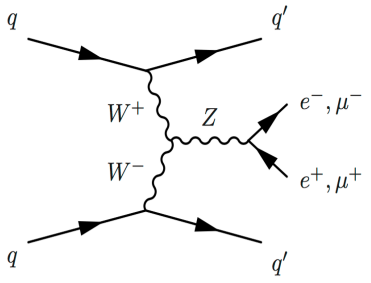
- Testing b-hadron production
  - Compare to 4-/5-flavour PDF scheme
  - Effects from DPI to be considered
- W+b production
  - Agreement within 1σ with predictions
- Similar trend for b- and c-hadron production observed by LHCb
  - Agreement within 1σ with predictions
- Also studies for Z+b available

QCD Contribution to single vector boson production in VBF processes

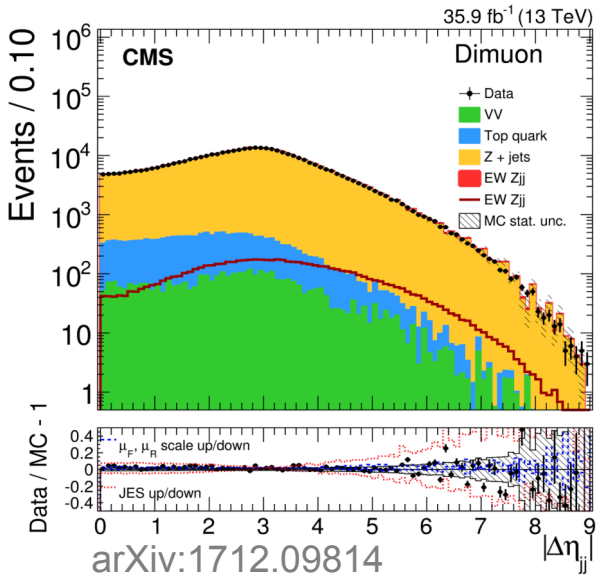
- ATLAS and CMS: Study of EWK Vector-Boson Fusion processes to search aTGGs
  - Shape of m_{jj} distribution for QCD-Zjj production poorly modeled (overestimate by up to 100% for large m_{jj})
  - ATLAS uses data-driven method to extract QCD-Zjj background



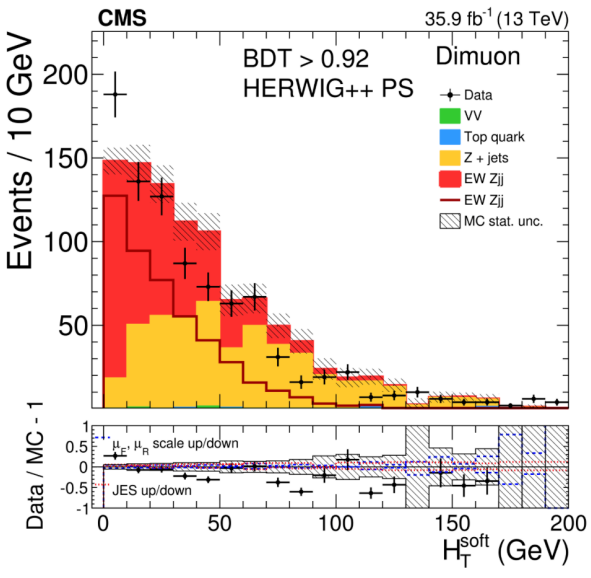
(a) QCD-Zjj.

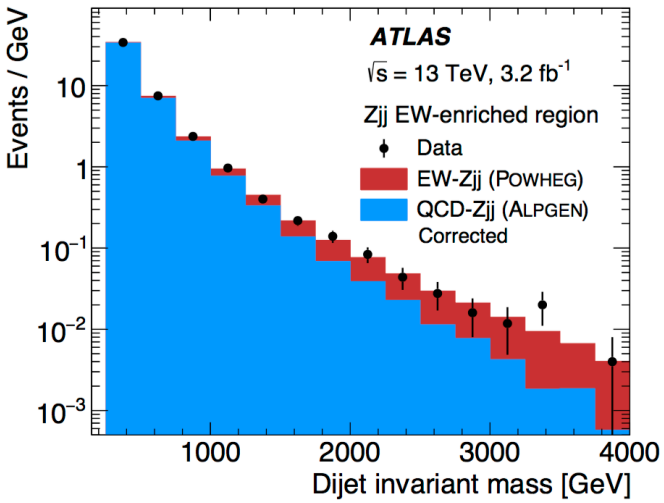


(b) EW-Zjj.



arXiv:1712.09814

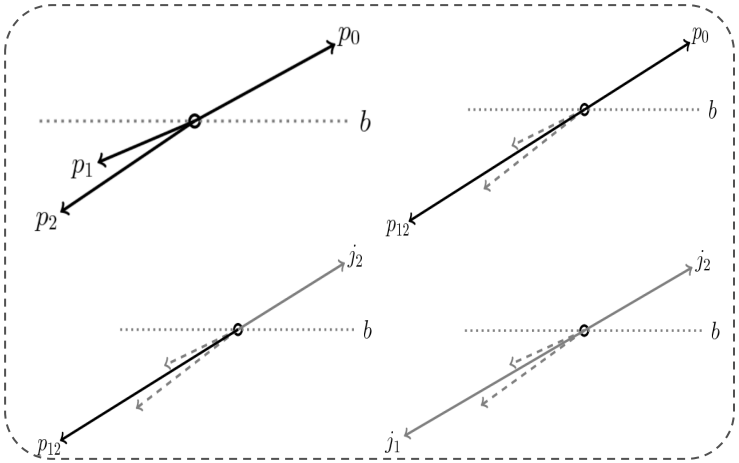




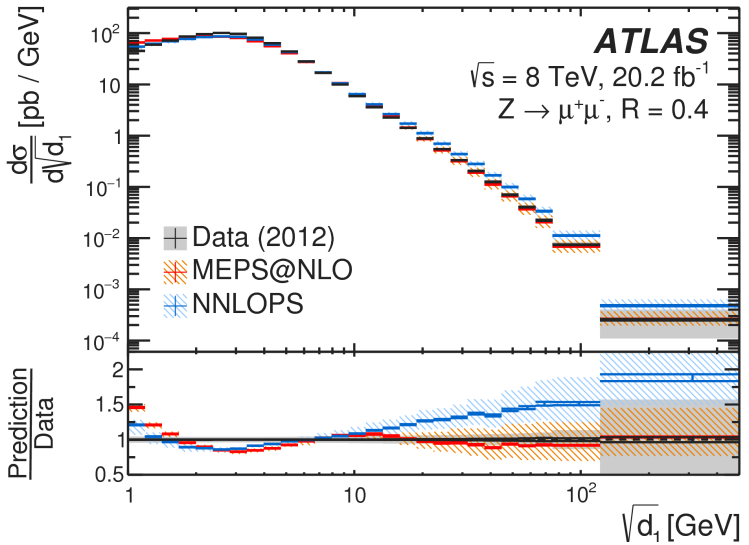
arXiv:1709.10264

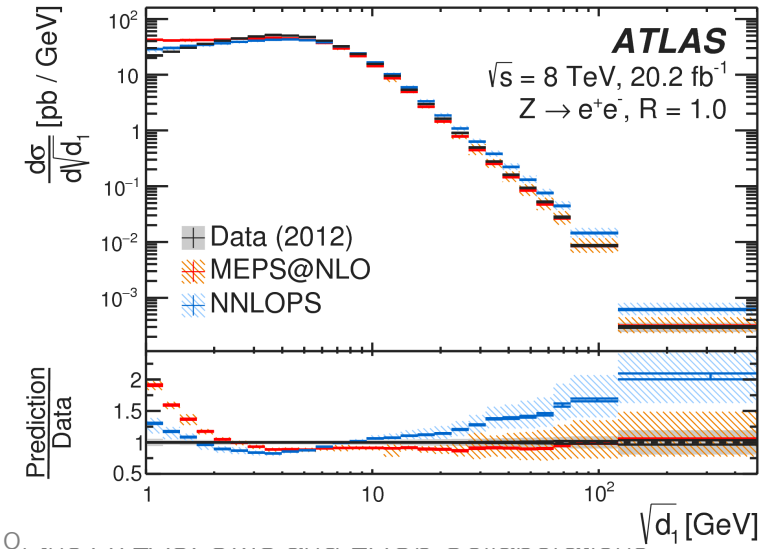
Study of Splitting Scales

- Probing the transition between perturbative and non-perturbative QCD by study the splitting scales of the kt jet-algorithm
  - $\sqrt{d_0}$, corresponds to the p_T of the leading kt-jet
  - N_{th} splitting scale, $\sqrt{d_N}$, as the distance measure at which an N-jet event is resolved as an (N+1)-jet event.



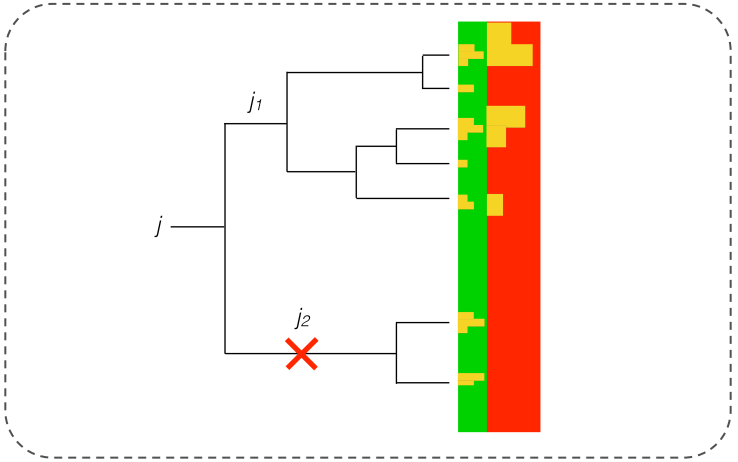
arXiv:1704.01530

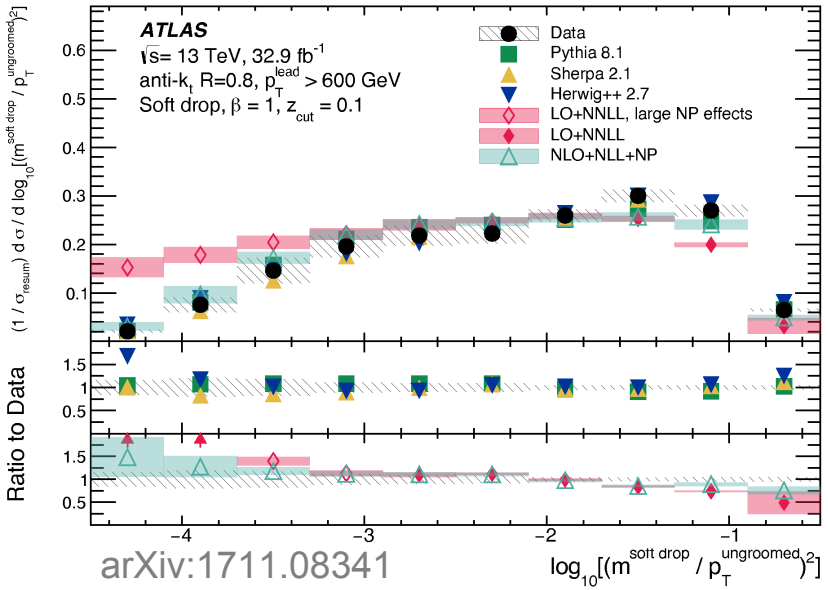




Future: Measurements with the SoftDrop Algorithm

- First jet substructure quantities can be predicted at next-to-next-to-leading-logarithm accuracy
- Soft-drop grooming algorithm
  - insensitive to resummation terms associated with particles that radiate out of, and then radiate back into, a jet
- Measurement of the ratio of the soft-drop mass over ungroomed jet-momentum in dijet events
- Maybe also interesting to study in V+jets events





arXiv:1711.08341

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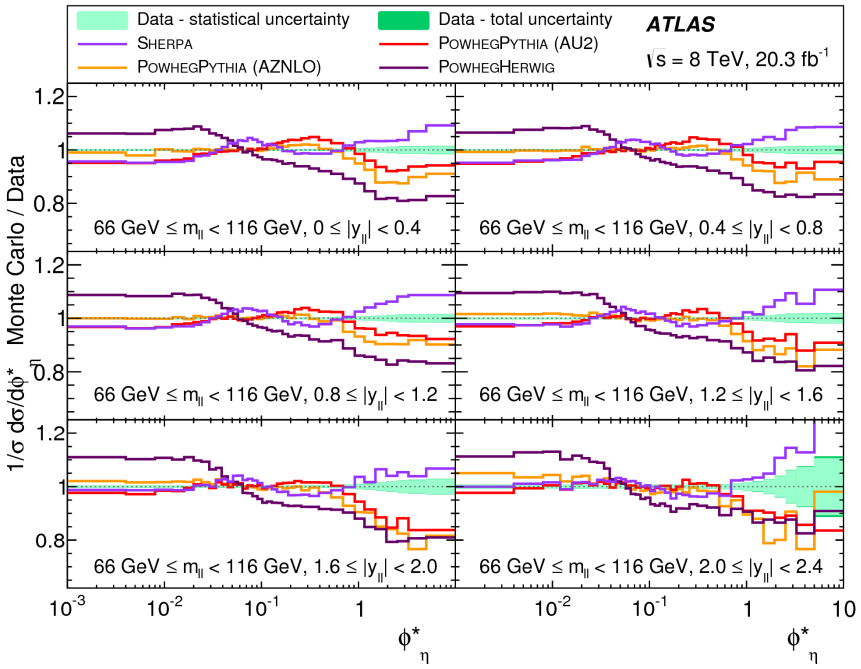
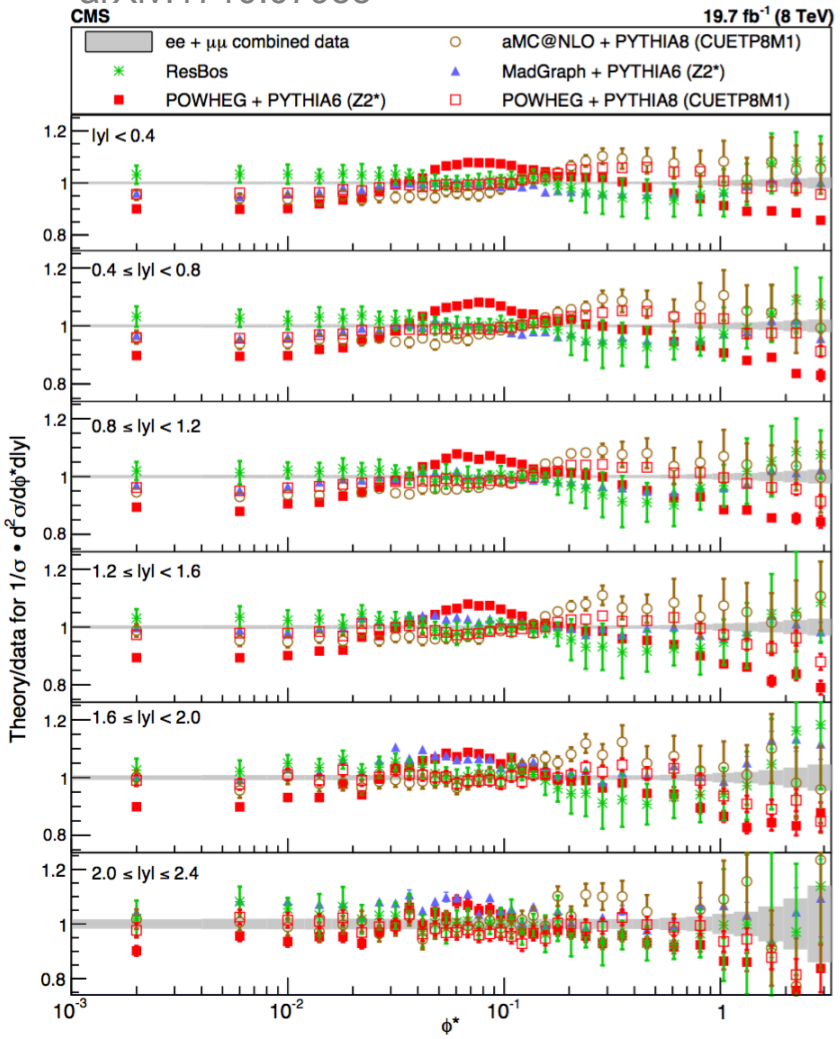
Resummation and Angular Coefficients

Z Boson Transverse Momentum

arXiv:1512.02192



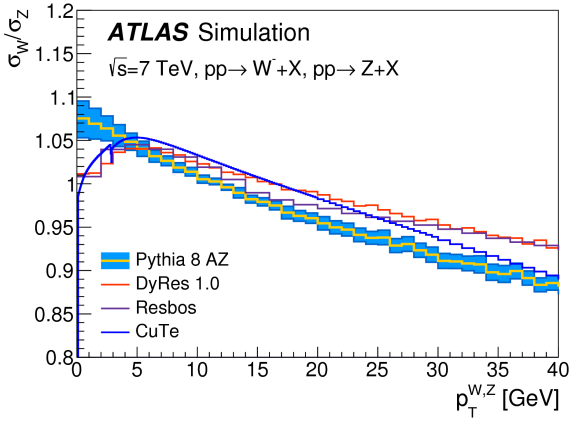
arXiv:1710.07955

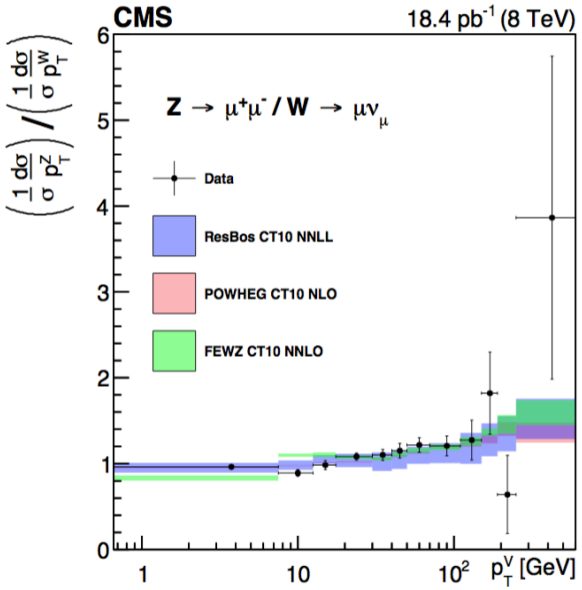


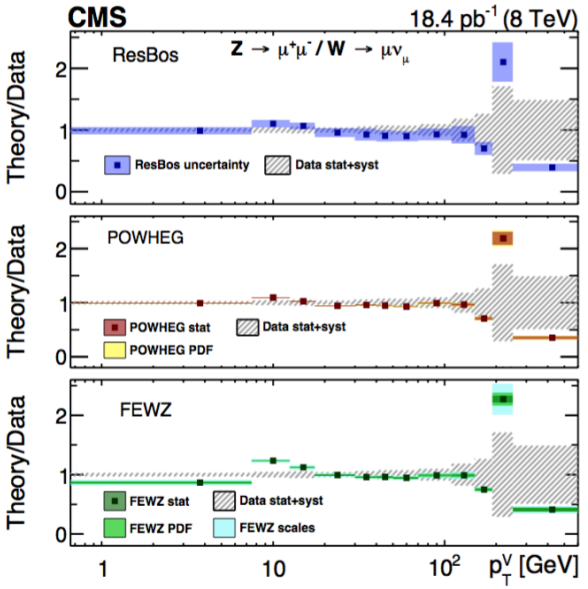
- Probe $p_T(Z)$ either directly or via ϕ^*
  - Reduced lepton res. uncertainties
  - Precision <% level
  - Very good description via resummed predictions but also PS

W Boson Transverse Momentum

- Modelling of $p_T(W)$ crucial to know for m_W
  - Transfer from Z to W modelling not trivial
  - Experimental input crucial to distinguish models
- Measurement of $p_T(W)$ significantly more complicated, due to neutrino in final state
  - Use hadronic recoil
- Uncertainties 1-2% in 1st bin
  - Bin range from 0 to 7.5 GeV too large to resolve differences in $p_T(W)/p_T(Z)$ modelling
  - Dominated by unfolding bias





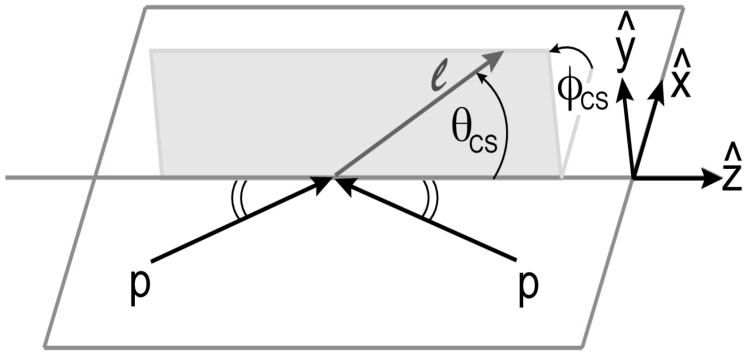


arXiv:1606.05864

Angular Coefficients (1/2)

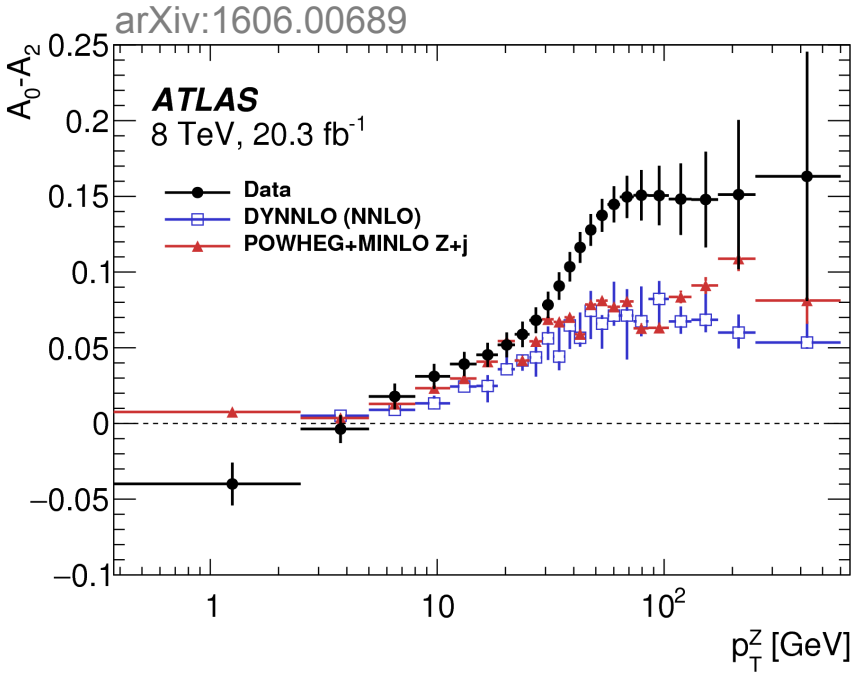
- The fully differential DY cross section can be reorganised by factorising the dynamic of the boson production, and the kinematic of decay (CS-Frame)

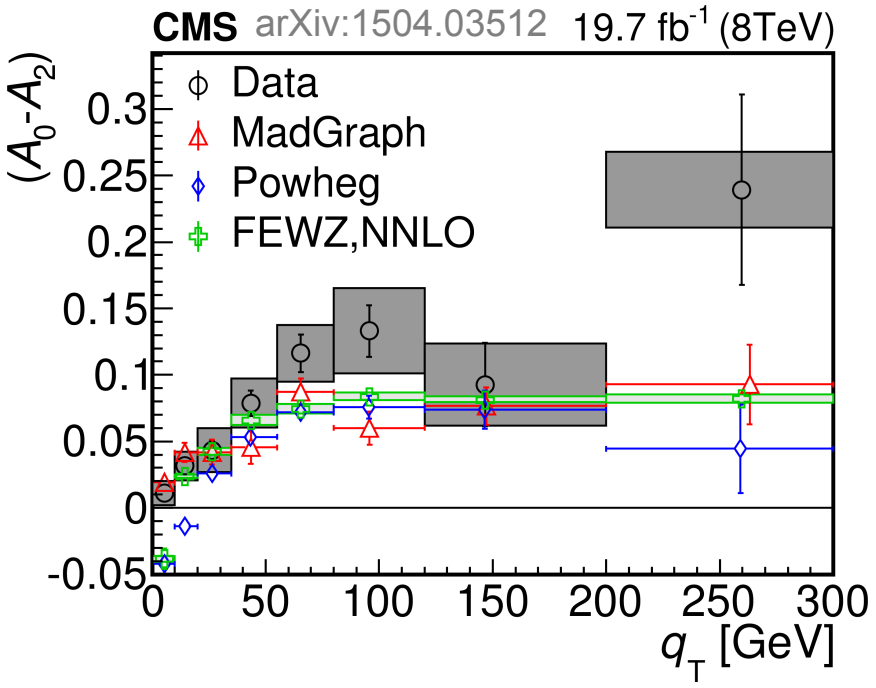
$$\frac{d\sigma}{dp_T^2 dy dM d\cos\theta d\phi} = \frac{3}{16\pi}\frac{d\sigma}{dp_T^2 dy dM} \times [(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi]$$



- LQ QCD: only the annihilation diagram qq→Z is present; only A_4 is non-zero
- NLO QCD: A_{0-3} also non-zero
- The Lam–Tung relation: $A_0 - A_2 = 0$ at NLO QCD due to the spin-1 of the gluon in the qg→Zq and qq→Zg diagrams
- NNLO QCD $A_{5,6,7}$ are expected to become non-zero but small
- A_3 and A_4 sensitive to $\sin^2\theta_W$

Angular Coefficients (2/2)





- ATLAS observes significant deviation from the $O(\alpha_s^2)$ predictions from DYNNLO for $A_0 - A_2$
  - Higher-order QCD corrections required?

- Evidence at the 3σ level is found for non-zero $A_{5,6,7}$ coefficients
  - consistent with expectations from DYNNLO at $O(\alpha_s^2)$.

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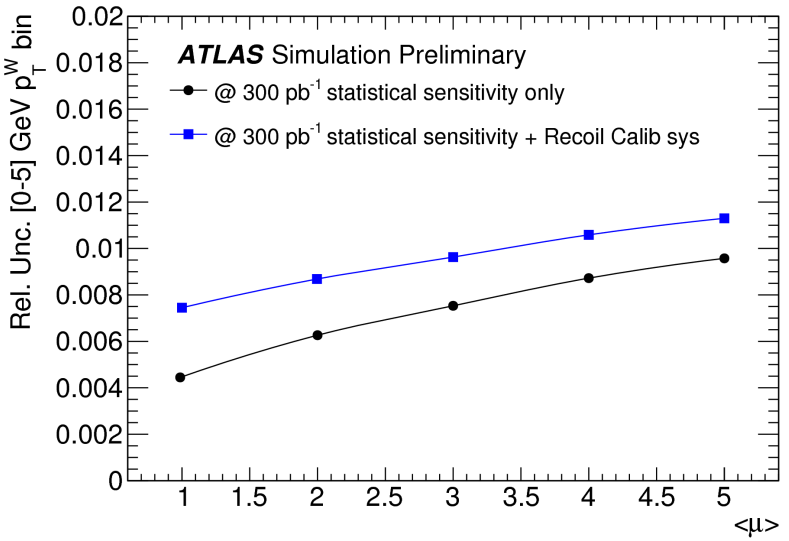
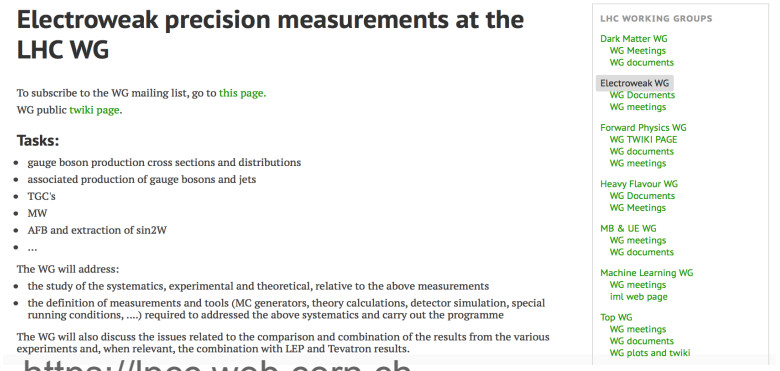
What to do next?

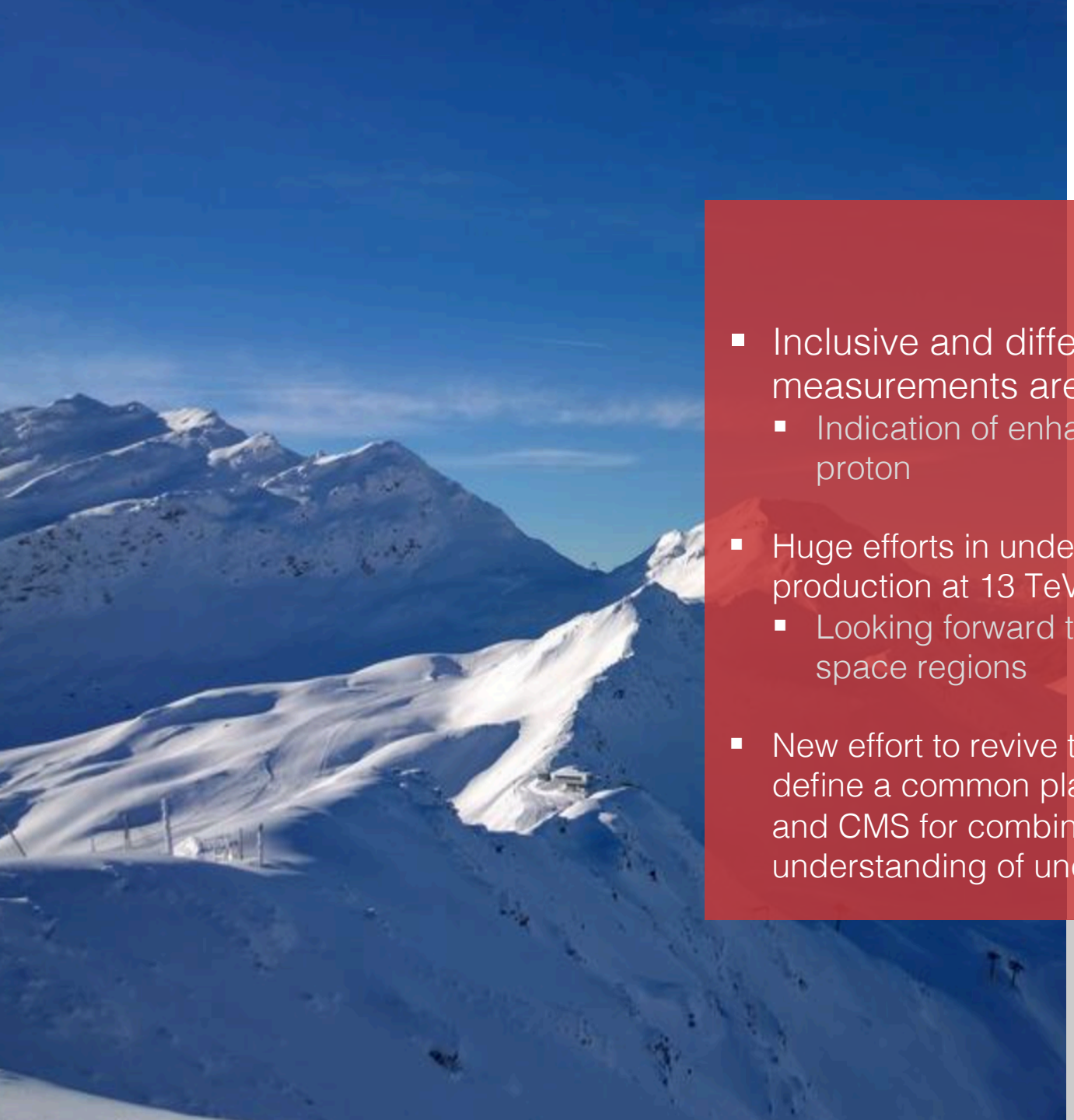
ATLAS and CMS consistency and outlook for more 13 TeV measurements

- Full Run-2 statistics will allow to test extreme regions of phase space and high scales
  - Challenging to reach/overpass the precision of previous measurements
  - Focus on measurement of new observables e.g. soft-drop-mass
- Low pile-up run at 5/13 TeV allows for precise p_T(W) measurement
- ATLAS and CMS urgently have to develop an infrastructure to cross-check their results for consistency and even combination
  - Scale-choices, phase-spaces, …
  - Revive the LPPC Working Group





https://lpcc.web.cern.ch



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Summary

- Inclusive and differential W/Z measurements are at <% level precision
  - Indication of enhanced strangeness of the proton
- Huge efforts in understanding W/Z+jets production at 13 TeV with first precision results
  - Looking forward to probe extreme phase-space regions
- New effort to revive the LPPC Working group to define a common plattform between ATLAS and CMS for combinations and common understanding of uncertainties