QCD Studies at High and Low Energies (Including PDFs)

Division of Particles and Fields, Meeting 2017

3rd August 2017, Fermilab

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on behalf of Alice, ATLAS, CMS, and LHCb Collaborations

Why to Study QCD?

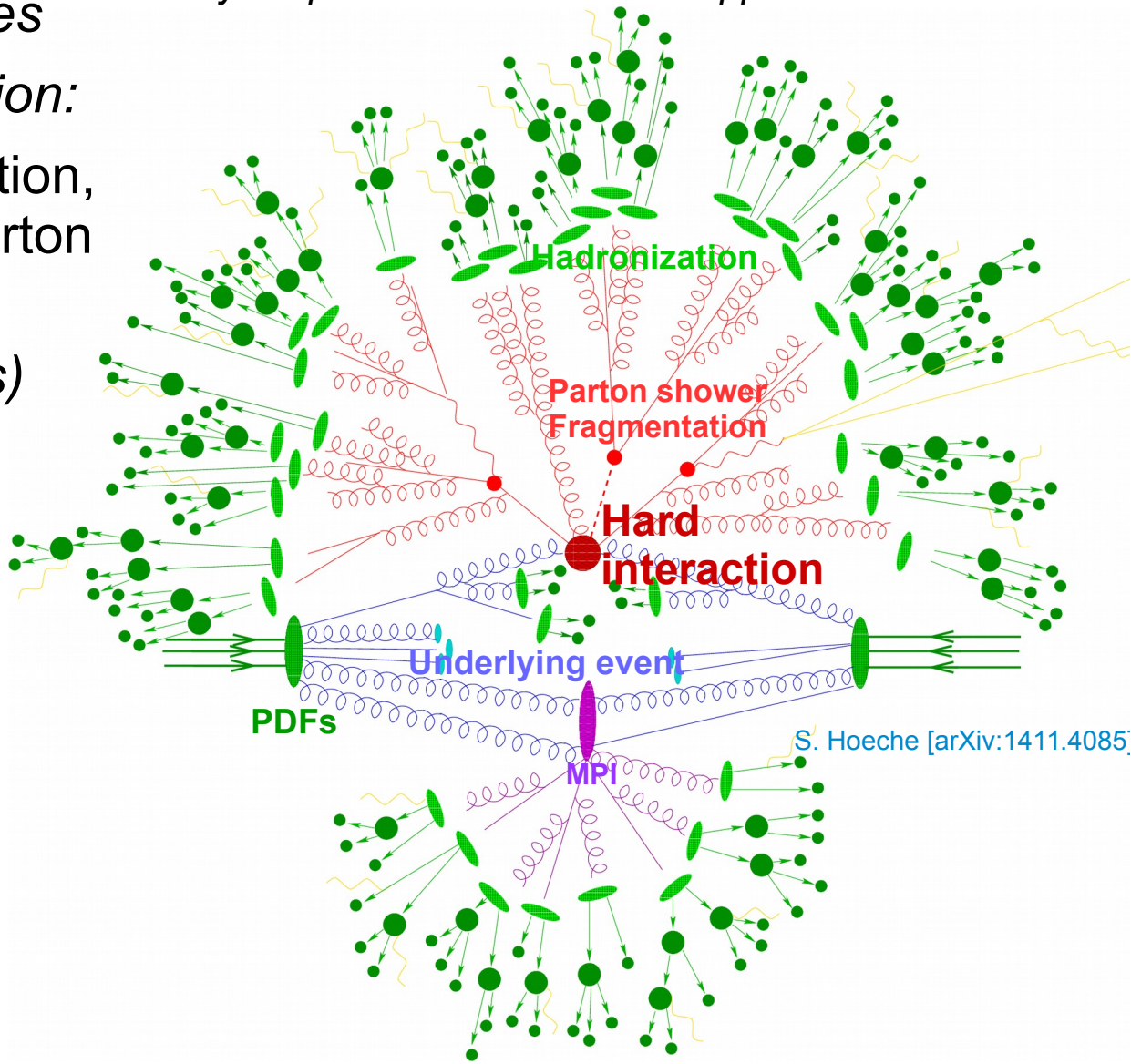
QCD is everywhere at LHC:

- *Study of soft QCD observables*
- *Element of MC event simulation:*

parton-shower (PS), hadronization, underlying event (UE), multi parton interactions (MPI), ...

- *Structure of the proton (PDFs)*
- *Hard QCD interactions*

Very simplified visualization of a pp collision simulation:



Why to Study QCD?

LHC now in the era of precision QCD measurements:

- Control and reduce syst. errors
- Improvements BSM searches
- Precision EWK physics
- Test state-of-the-art predictions
- Constraints on fundamental parameters
- ...

Impossible to cover everything…

Presenting only a small *personal* selection of mainly LHC results from last two years

(Also note the plenary talks about flavor and QGP measurements, by Steve Blusk and James Dunlop)

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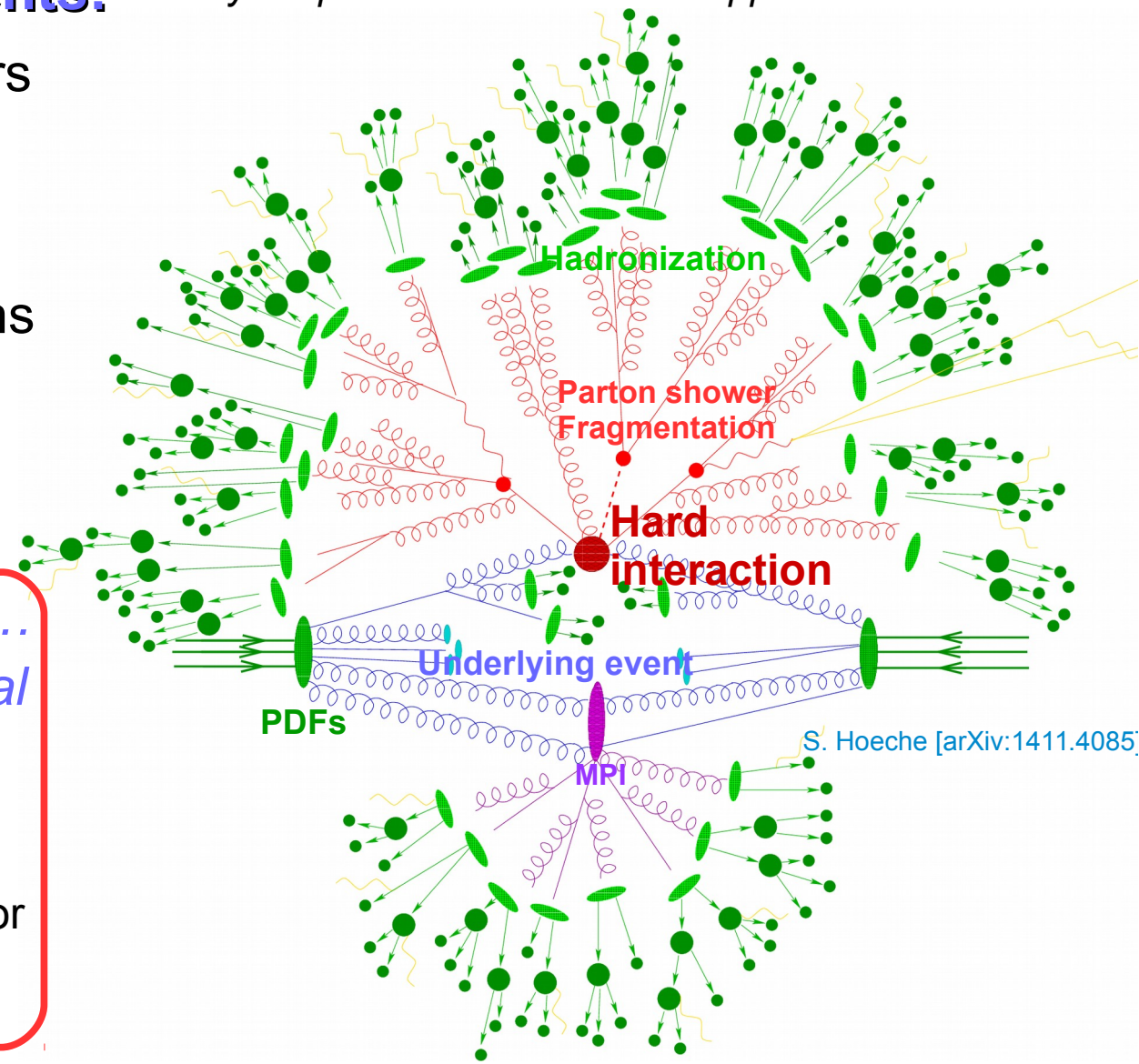
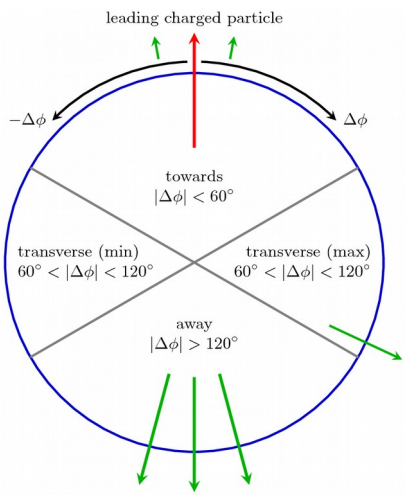


Soft QCD and MC Tuning

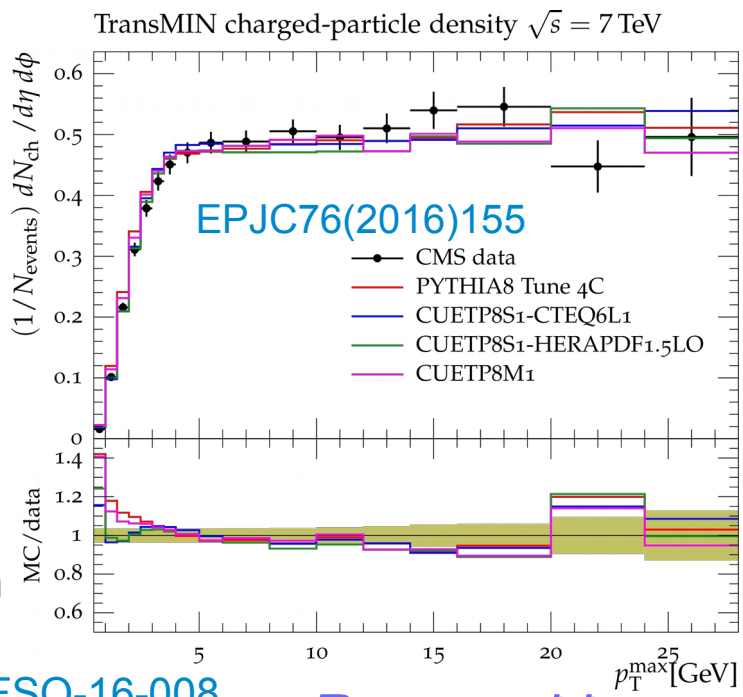
Let's start from soft QCD:

- Non-perturbative effects in hadron collisions:
  hadronization, UE, MPI, beam-remnant interactions, long-range color-exchange
- Pheno models used in all MC generators → ***correct "tuning" essential at LHC!***
- Possible thanks to a set of recent (and less recent) dedicated measurements

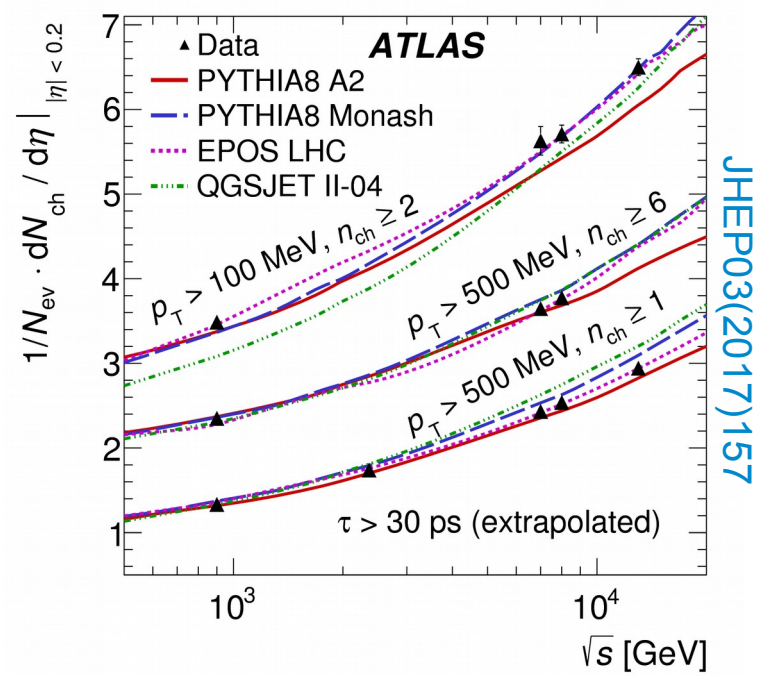


UE measurement in region "transverse" to hard-event

MC tuning from UE at different $\sqrt{s}$: CMS @7 TeV plus lower $\sqrt{s}$ @CDF



Charged particle multiplicity in min-bias down to p_T=100 MeV:



Recent UE measurements in "special" hard-processes:

- DY events: CMS-PAS-FSQ-16-008
- $t\bar{t}$ events: CMS-PAS-TOP-15-017

Reasonable agreement but none of the tuned models describes data perfectly

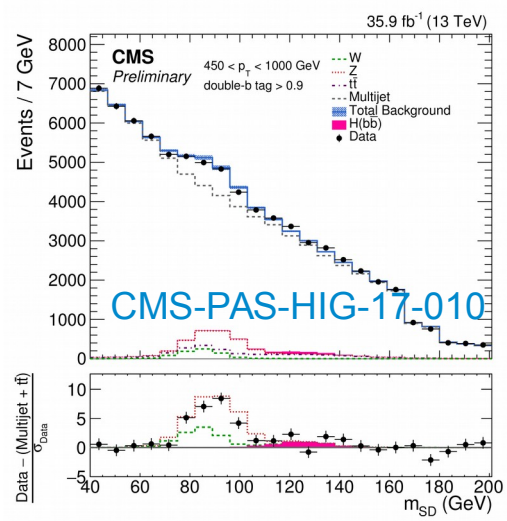
Soft QCD and High-p_T Jets

Soft QCD at the basis of jet sub-structure:

→ *important new tool for BSM searches and SM in boosted environments!*

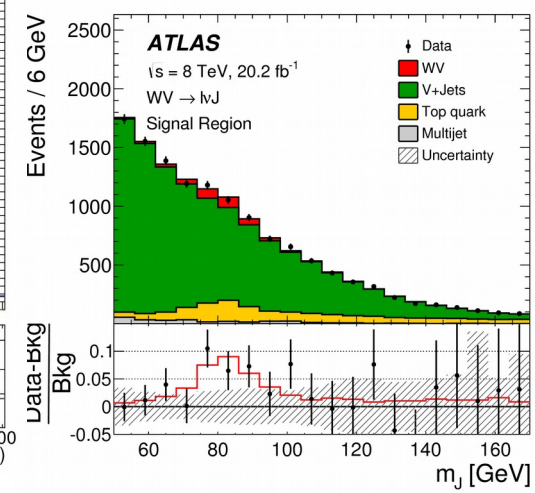
How to understand this new tool?

Best way: *differential measurement of sub-structure sensitive observables*



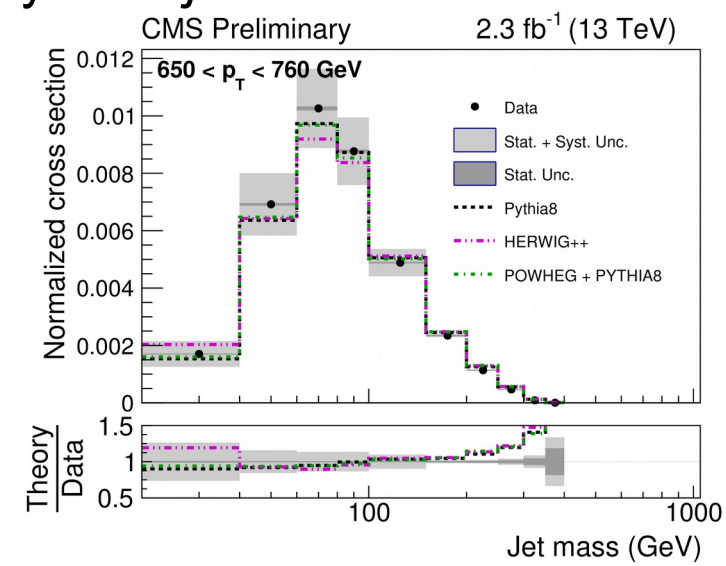
CMS-PAS-HIG-17-010

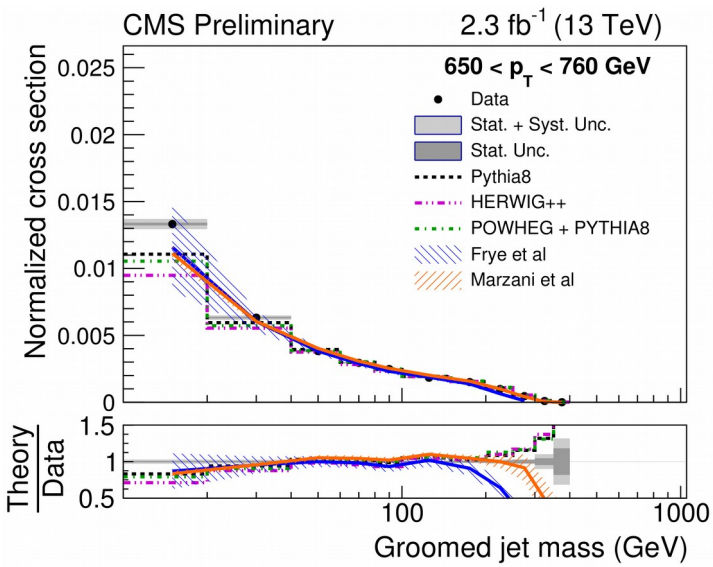
[arXiv:1706.01702]



New CMS analysis (CMS-PAS-SMP-16-010):

- Analysis of *jet-mass*
- Groomed jets *softdrop mass* (insensitive to non-global logs)

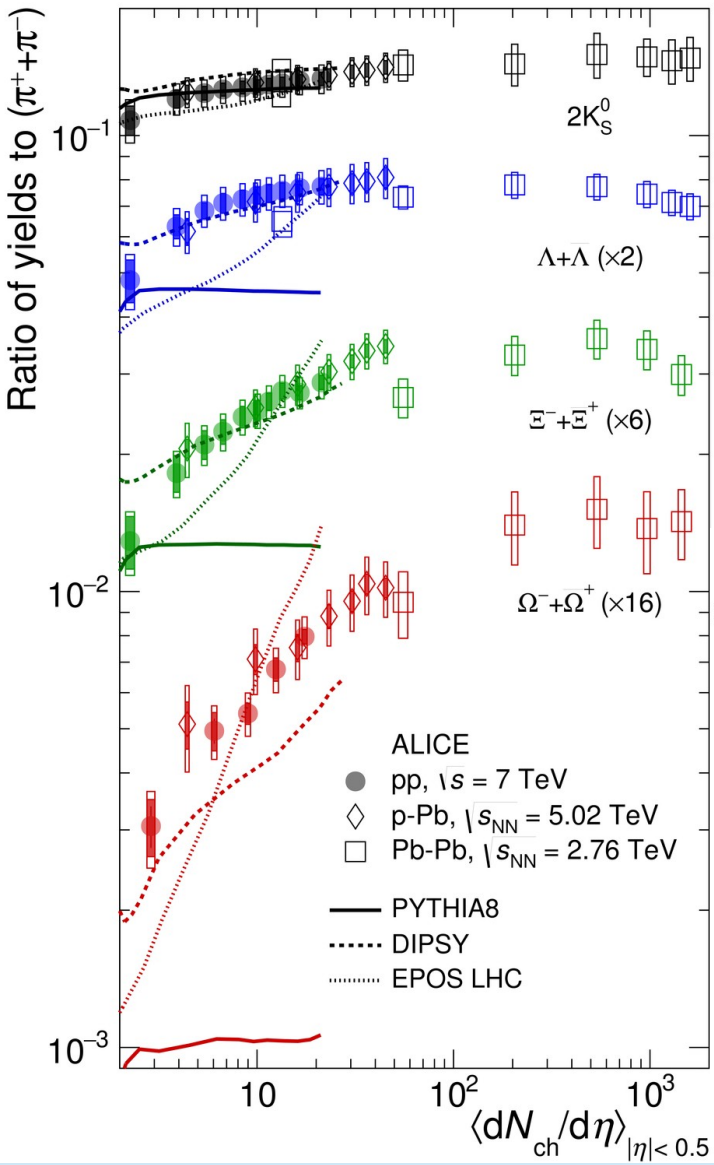




- Precision improvement for groomed jets in region $0.1<m/p_T<0.3$
- These are first steps, but can be used for tuning

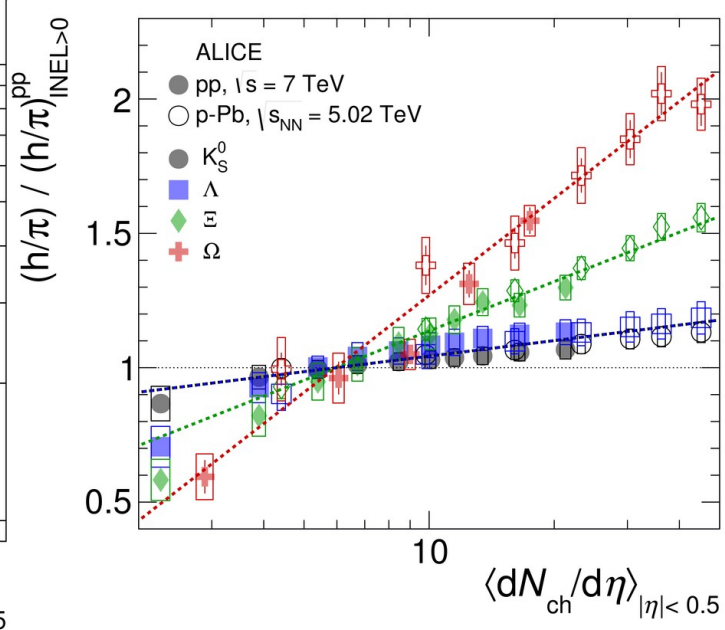
Strangeness in Soft QCD

Current approach to MC simulations plus tuning is *powerful, working fine...*
→ *Could new studies re-define the basis of our models?*

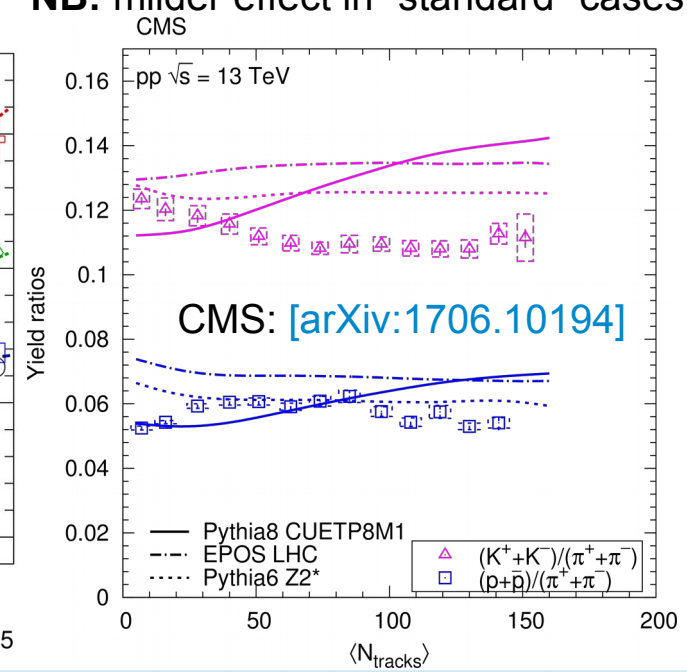


- ALICE measurement of N. strange vs N. charged particles (π^+, π^-) production in pp, pPb, PbPb collisions
- Strangeness-dependent production-rate increase
- Discrepancy with respect to standard PS models
- *Sign of initial-state correlation (QGP in jets?)*
- Tested in *new dipole-evolution PS models*

Nat.Phys.13(2017)535

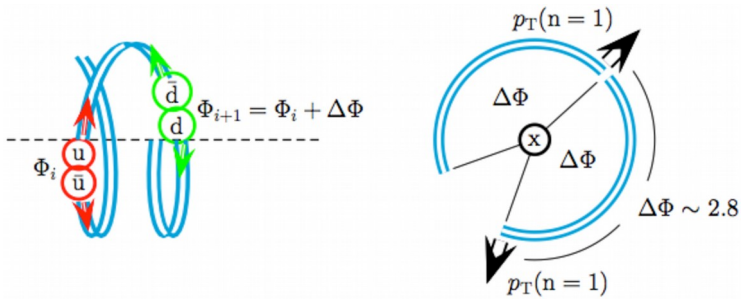


NB: milder effect in "standard" cases



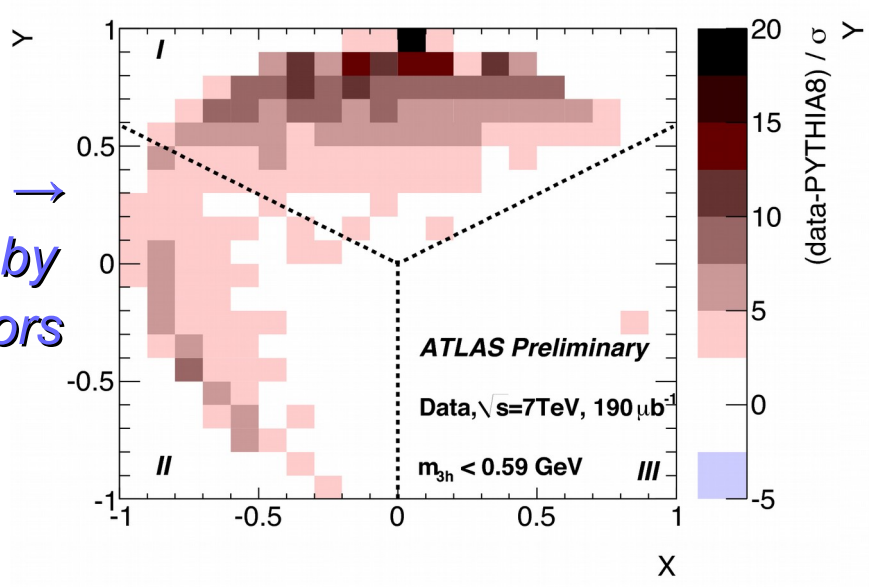
Hadron Correlations in Soft QCD

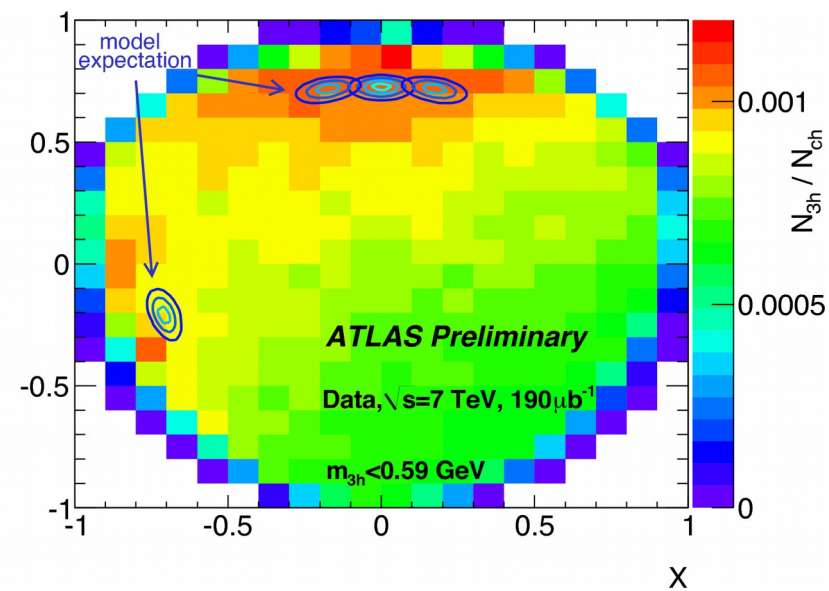
- Shed light on early phases of hadronization → beyond pheno models
- One specific example: *excess of nearby same charge hadrons explained by Bose-Einstein interference, could other models be better?*



- **New** ALTAS study of ordered hadron chains (STDM-2014-08)
- Test model of quantized fragmentation of 3D color strings

Daliz plot of 3-hadron chain: → *not reproduced by current generators*





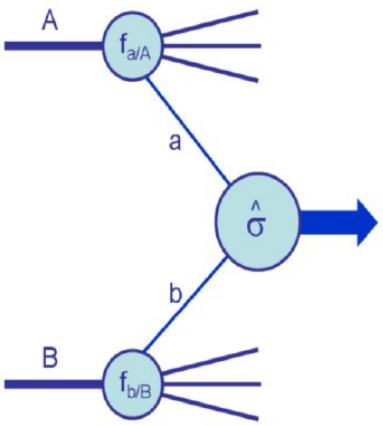
Soft QCD take-home questions: Are current models satisfactory? How can we understand deep mechanics? Which uncertainties will be reduced?

Analysis of Hard Collisions at LHC

Next step: accurate study of hard-scattering

- Possible thanks to running of α_s and factorization theorem:

$$\sigma(P_1,P_2) = \sum_{i,j} \int dx_1\, dx_2 f_i(x_1,\mu_F) f_j(x_2,\mu_F) \hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2,\mu_R\mu_F)$$



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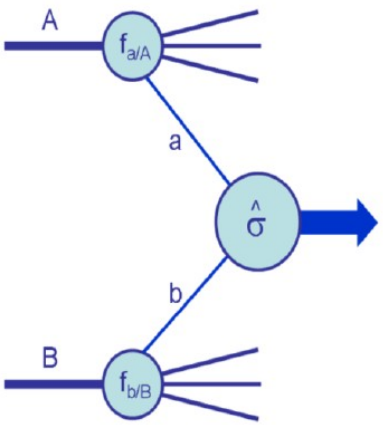

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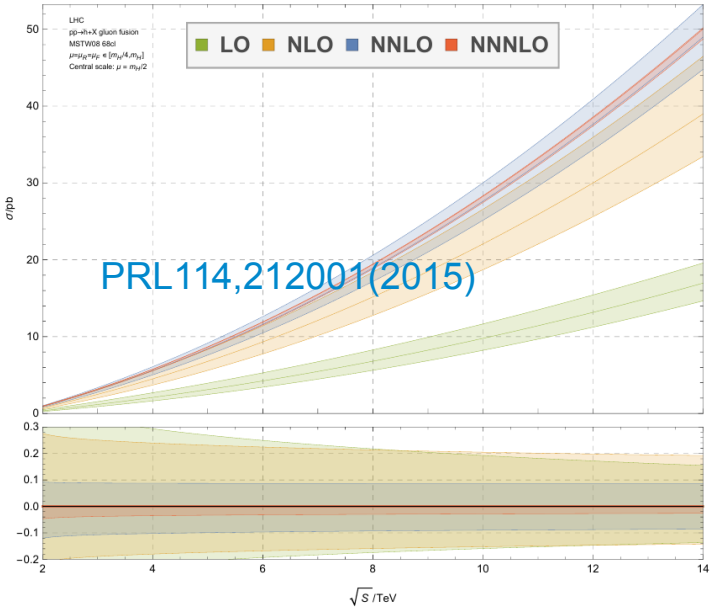
$\hat{\sigma}_{ij}$ represents hard production of:

- di-jet, multi-jets, γ + jets
- single V (V=W, Z), V+ jets, V+ HF-jets
- top-quark, Higgs, etc. etc.

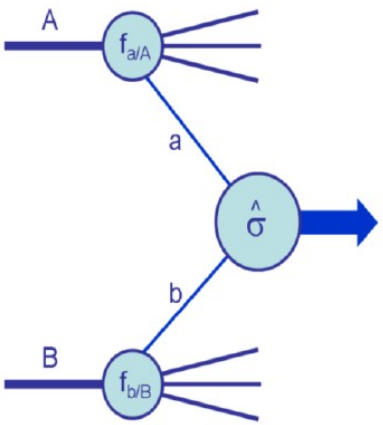
Example, Higgs production:
~70% NLO to LO QCD correction,
~30% NNLO, N3LO also available!



- All rely on *perturbative QCD (pQCD)* calculations
  → ***are they good enough?***
- Higher order (HO) corrections can be large for inclusive or differential (selection dependent) observables

Analysis of Hard Collisions at LHC

Next step: accurate study of hard-scattering



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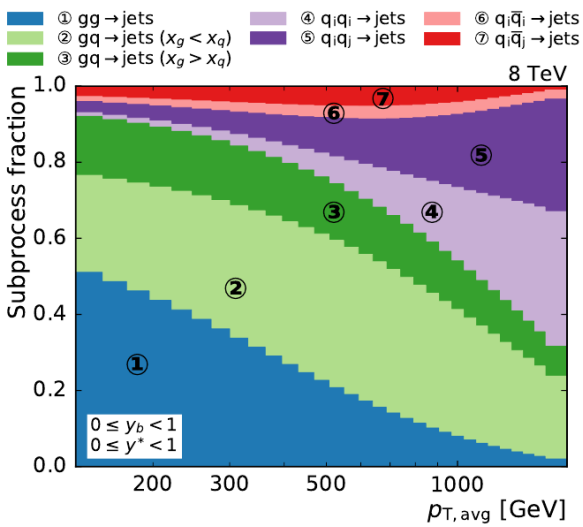
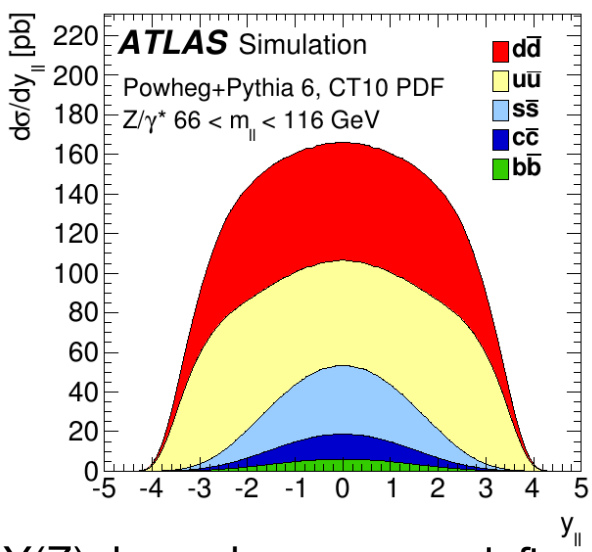
PDFs are the other fundamental ingredient:

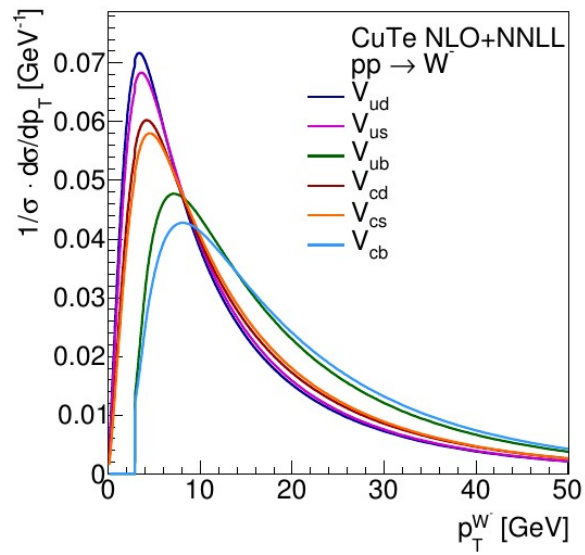
- Different processes can probe contribution form all partons
- ***Test of proton structure, reduction of syst. errors, SM couplings***



di-jet: kinematic dependent fraction of involved partons



Y(Z) dependence vs quark flavor

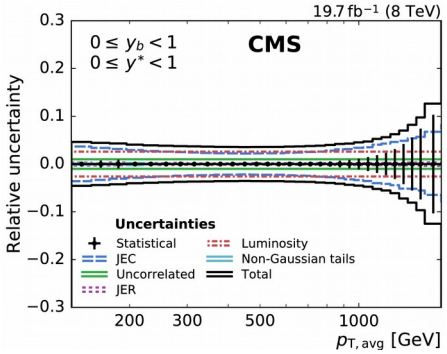


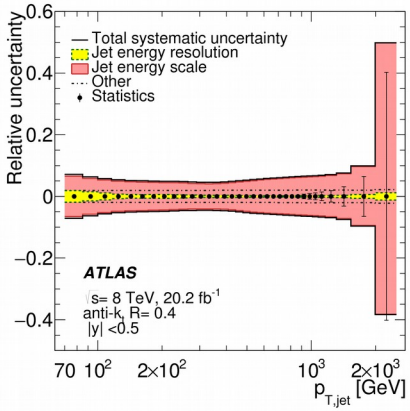
HF-quark couplings vs W-p_T

Di-jet Cross Section Measurements

Jets: most abundant process at LHC

- Differential measurements probe pQCD at the multi-TeV scale
- Analysis of Anti-k_t jets with ΔR= 0.4, 0.6/0.7
- 5-10 % experimental syst. mostly JES & JER



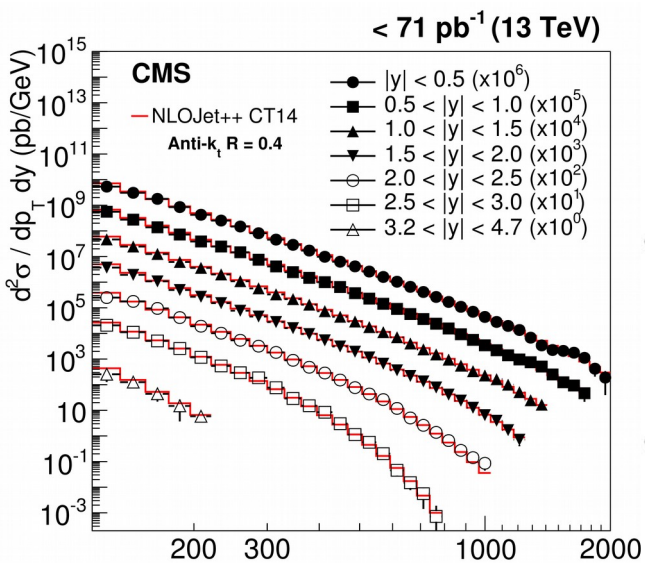


CMS 13 TeV, 1st paper:

- CMS: EPJC76(2016)451
- And ATLAS preliminary ATLAS-CONF-2015-034

Final experimental precision reached at 8 TeV:

- CMS 8 TeV measurement and ratio at 7, and 2.76 TeV: JHEP03(2017)156
- ATLAS 8 TeV: [arXiv:1706.03192]



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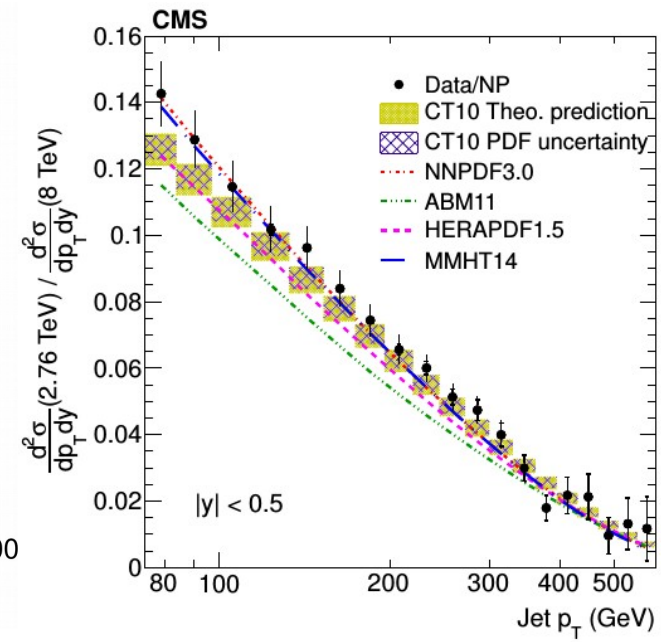

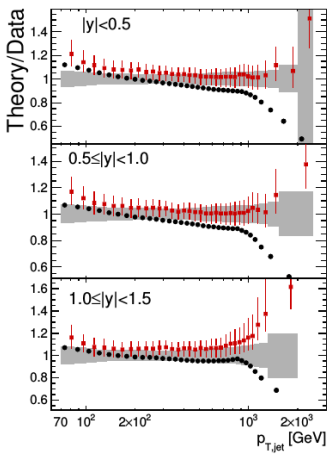

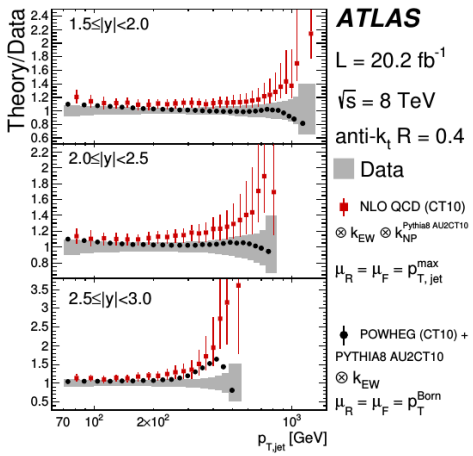

ATLAS data vs NLO predictions showing some tension

Di-jet Cross Section Measurements

Jets: most abundant process at LHC

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- Analysis of Anti-k_t jets with ΔR= 0.4, 0.6/0.7
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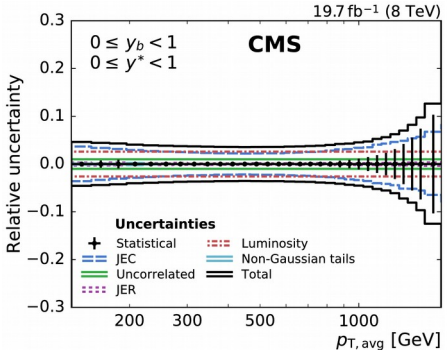

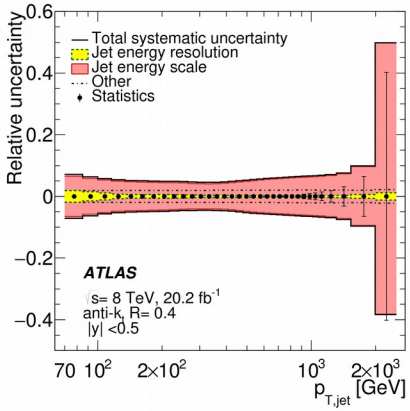

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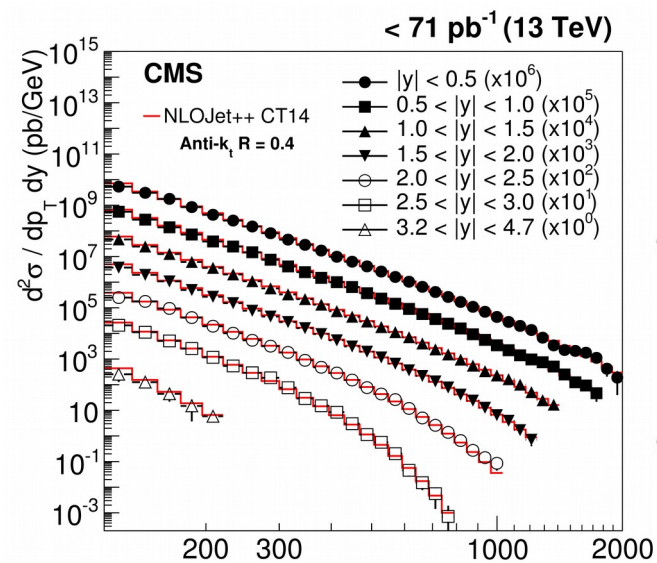
No tension vs NNLO predictions in 13 TeV preliminary analysis

ATLAS-CONF-2017-048



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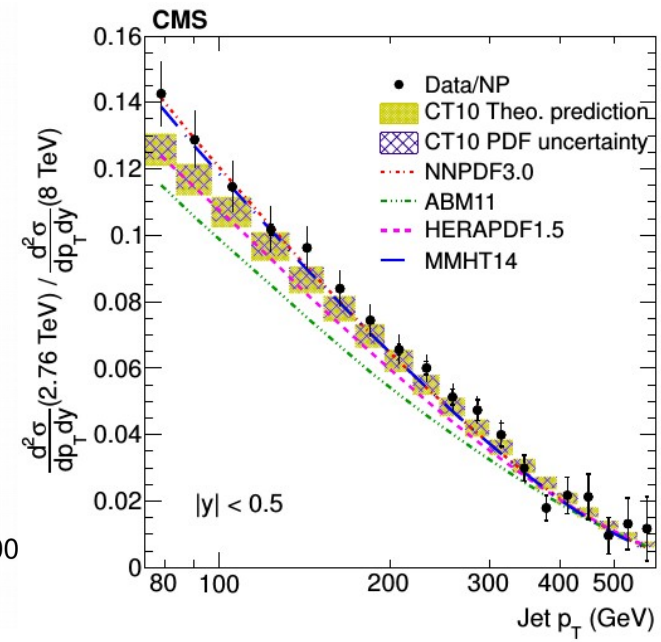
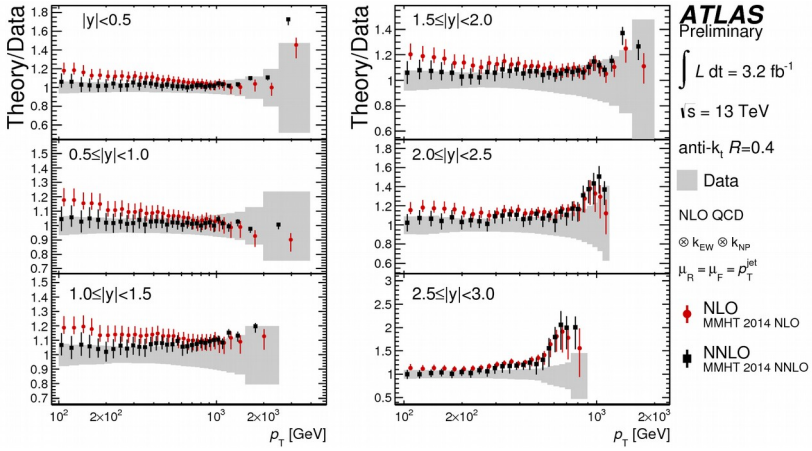
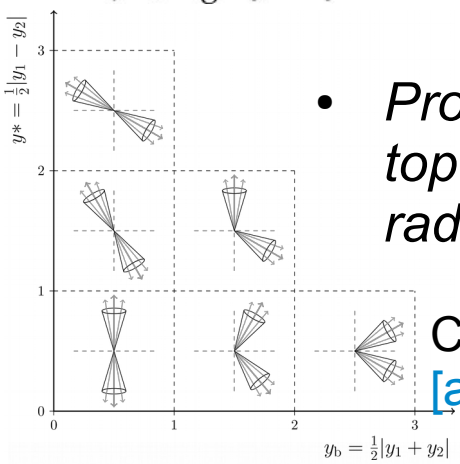




In-depth Analysis of Jet Production

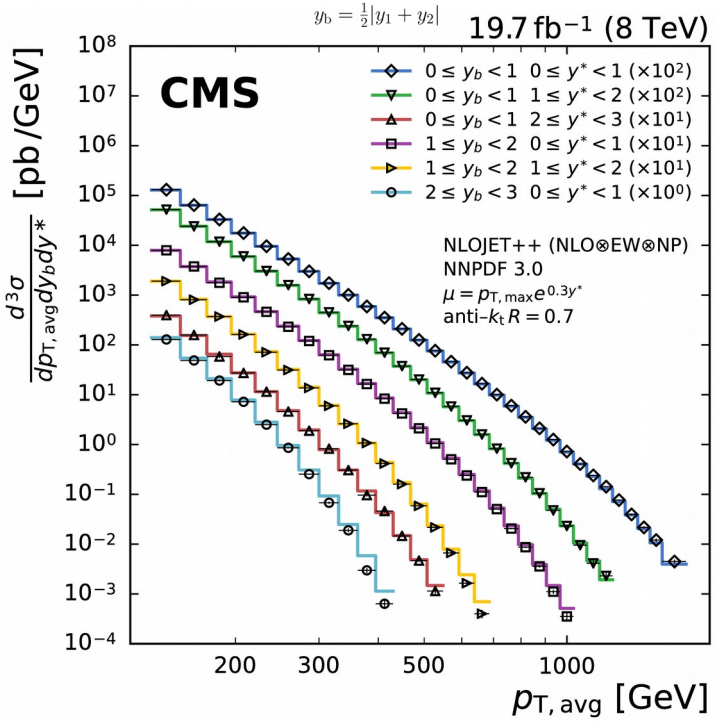
3D differential cross section:

$$\frac{d^3\sigma}{dp_{T,avg}dy^*dy_b} = \frac{1}{\epsilon\mathcal{L}^{eff}_{int}}\frac{N}{\Delta p_{T,avg}\Delta y^*\Delta y_b}$$



- *Probe of different topologies and radiation patterns*

CMS: [arXiv:1705.02628]

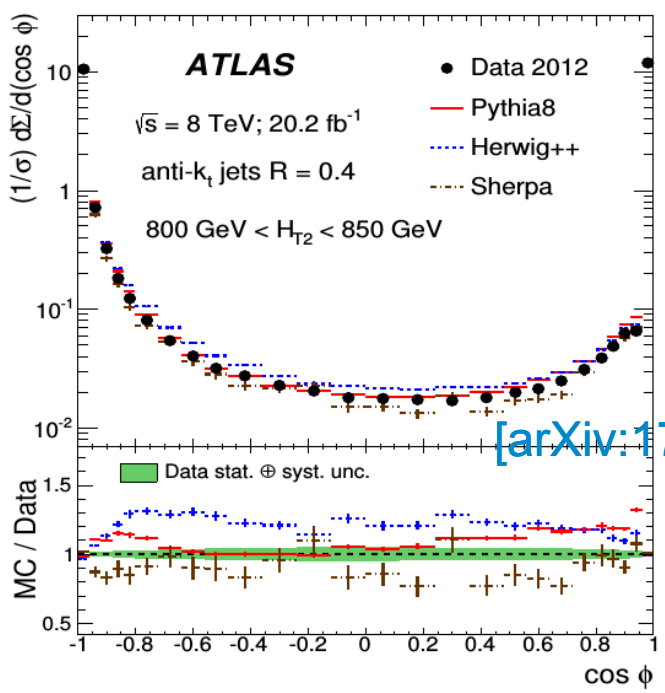


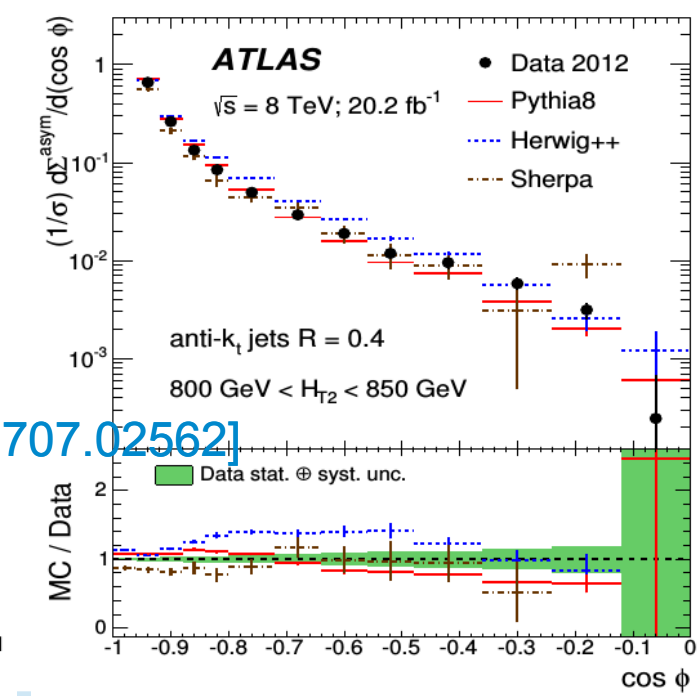
Study of jet-jet correlations:

- Energy-energy-correlation in transverse plane (TEEC) and its asymmetry (ATEEC)

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{Ti}E^A_{Tj}}{\left(\sum_k E^A_{Tk}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

- Jet-angular correlations (up to 3,4 jets in CMS-PAS-SMP-014)
- Sensitive to HO corrections away from back-to-back topology



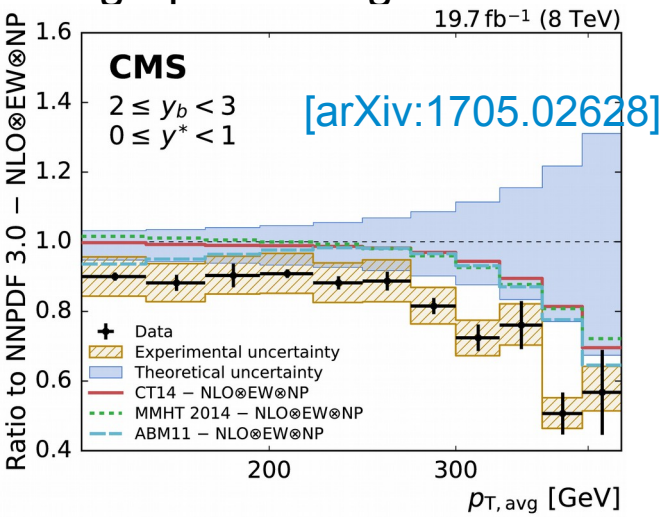


[arXiv:1707.02562]

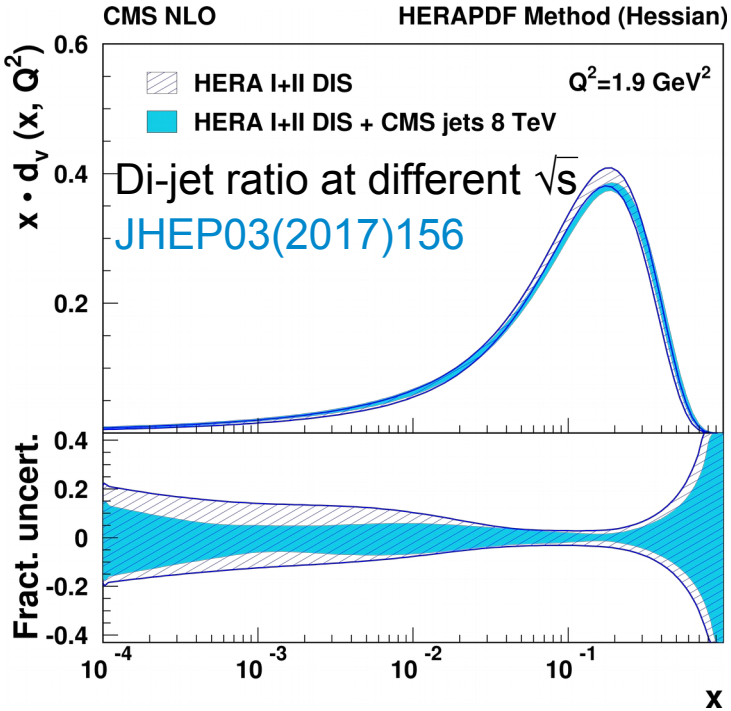
Constraints on PDFs

- Theoretical uncertainties on predictions are often larger than experimental ones
- PDFs uncertainties dominate at high p_T
- *Measurements can constrain theory*

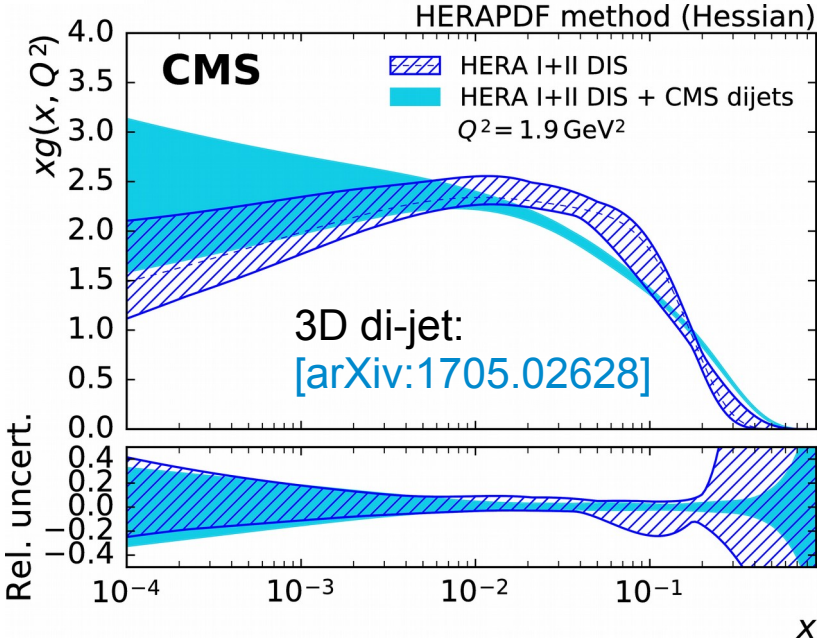
E.g. data/theory discrepancy at high-pT and high boost:



- QCD analysis of jet data with DIS data (HERA)
- Fit of free parameters of PDFs models
- xFITTER routines [arXiv:1410.4412]



- Constraints on valence quark PDF

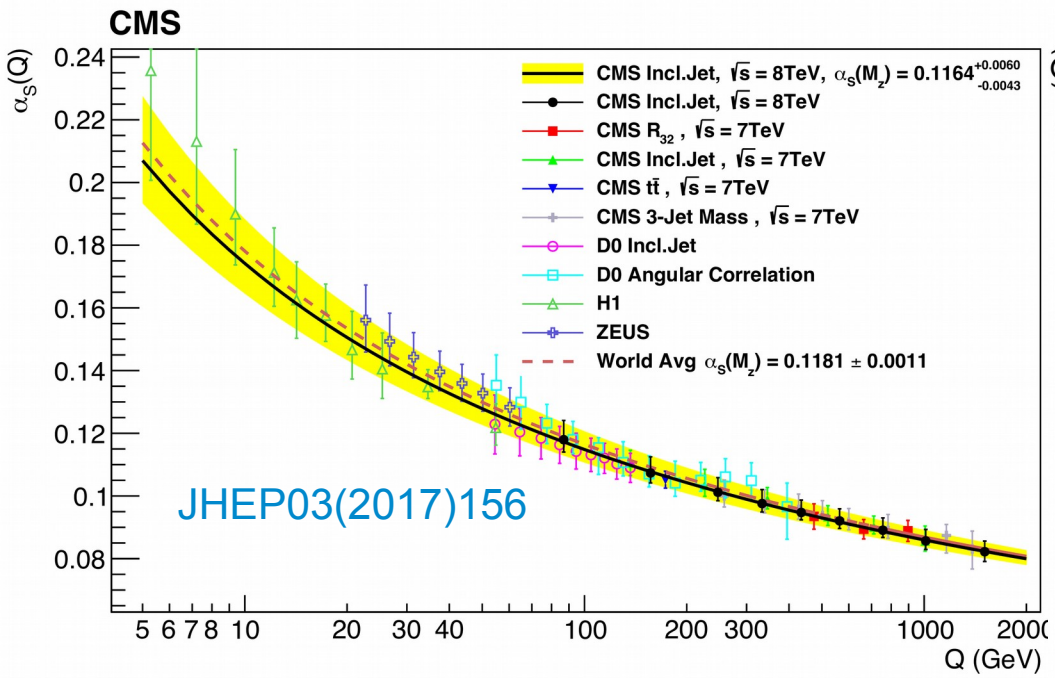


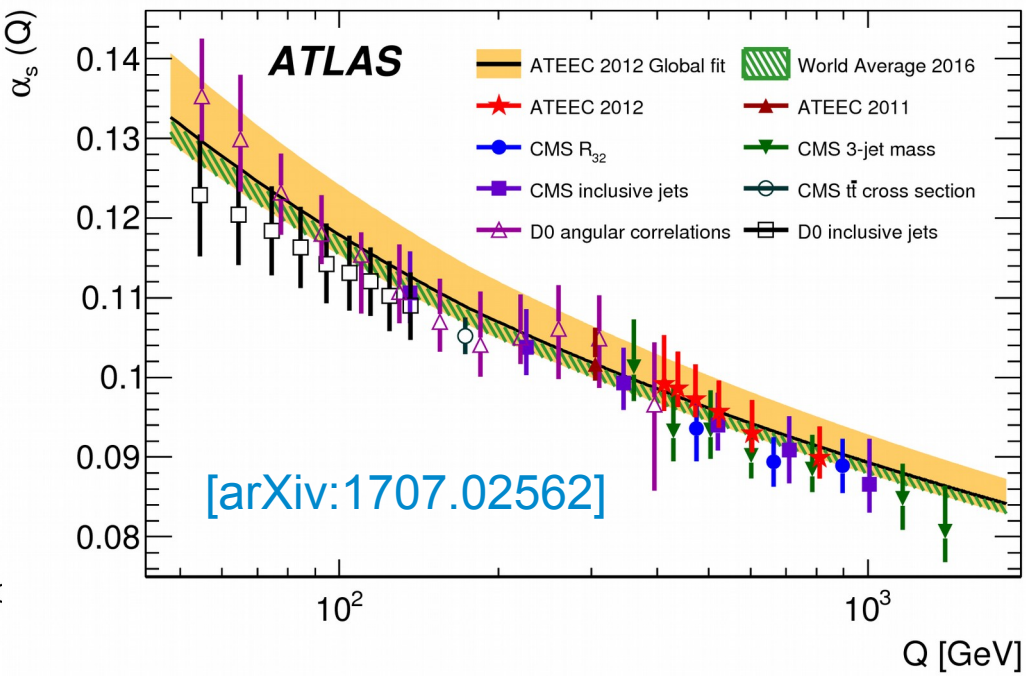
- Significant impact on gluon PDF

Extraction of a Fundamental Constant: α_S

- Jet cross section measurements are probing the fundamental nature of pQCD

Direct measurement of α_S





Analysis	$\alpha_S(M_Z)$	Exp. error	scale	PDFs	
Inclusive jets	0.1164	+/- 0.0015	+0.0053 / -0.0028	+0.0025 / -0.0029	JHEP03(2017)156 (CMS)
3D jet cross sec.	0.1199	+/- 0.0015	+0.0031 / -0.0020		[arXiv:1705.02628] (CMS)
TEEC	0.1162	+/- 0.0011	+0.0076 / -0.0061	+/-0.0017	[arXiv:1707.02562] (ATLAS)
ATEEC	0.1196	+/- 0.0013	+0.0061 / -0.0013	+/-0.0017	

V plus Jet Associate Production

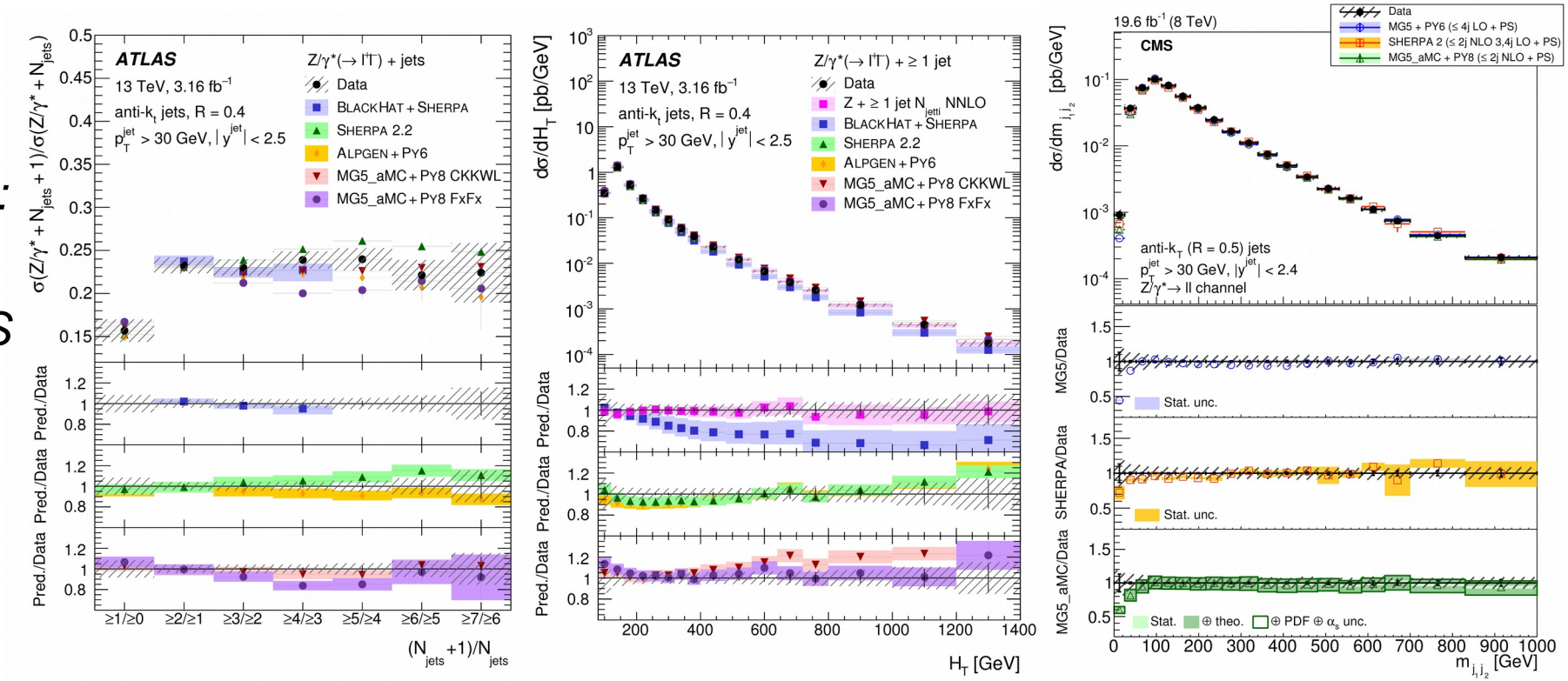
- LHC hadronic initial states means that jets are *always produced,* also together with other particles undergoing investigation
- Associate production of W, Z bosons and hard-jets is often the main background for BSM and Higgs physics → *need of reliable simulation*
- *Comparison of unfolded distributions sensitive to MC modeling & pQCD*

First analysis of Z+jets 13 TeV on early 3 fb^{-1} data (ATLAS EPJC77(2017)361)

… and full-glory analysis of Z+jet 8 TeV **20 fb^{-1}** data (CMS JHEP04(2017)022)

Prediction comparison:

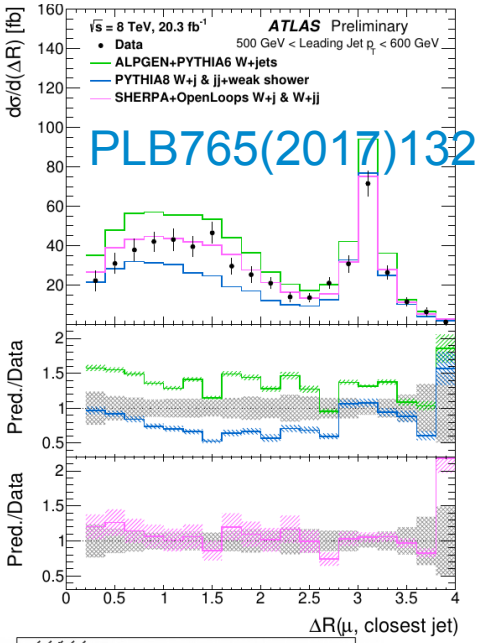
- *LO+PS*
- *NLO+PS*
- ***NNLO***



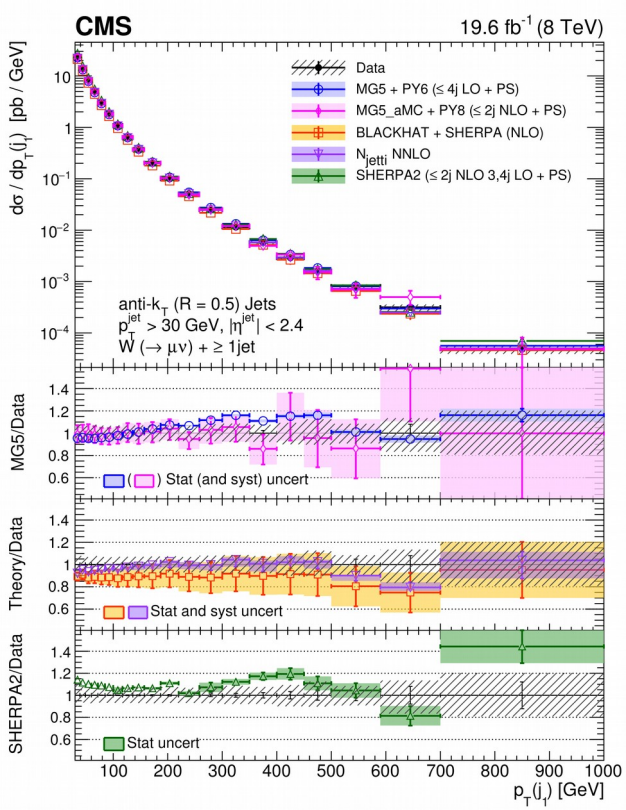
W plus Jets Production

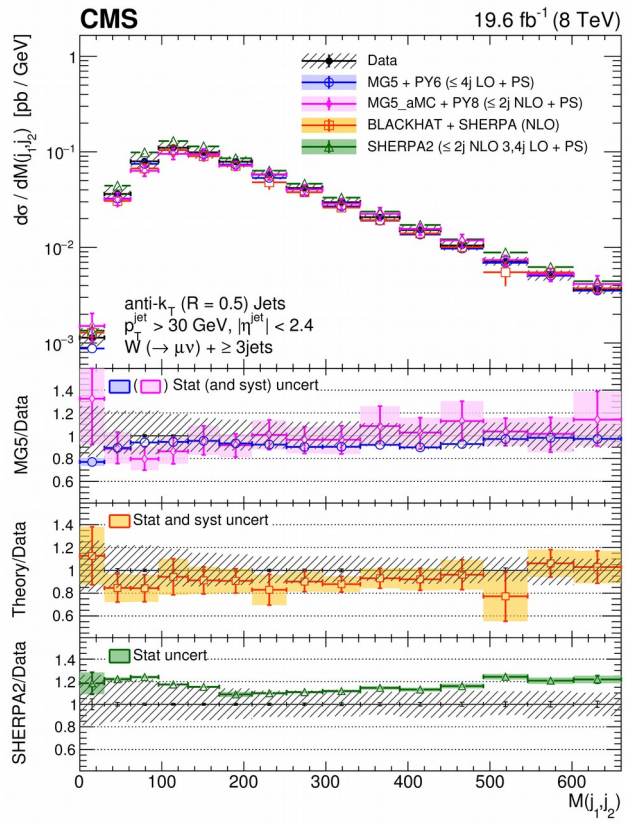
W(→lν) + jets analyses :

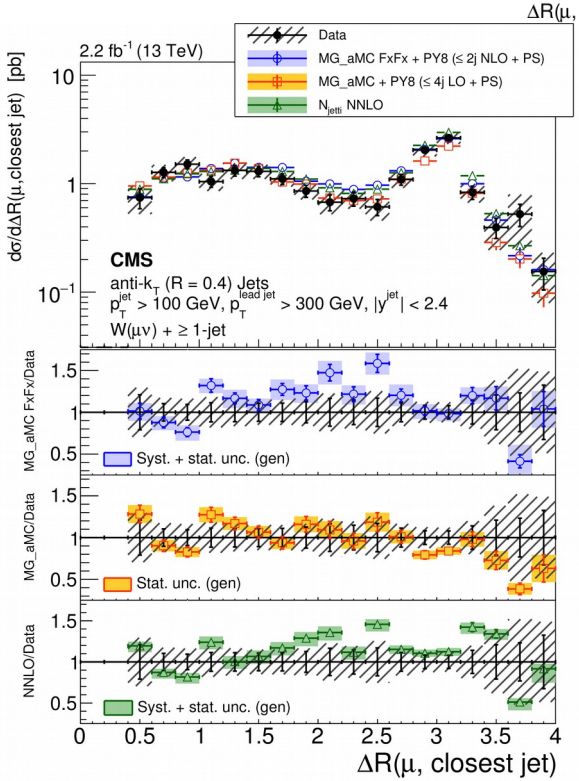
- ν escapes direct detection, signaled by E_T imbalance
- Slightly larger syst. & larger backgrounds (top, multi-jet)
- ***But:*** complementary Z+jets & larger stat. → investigation of phase space corners e.g. collinear emission, *jet-jet correlations, etc.*
- CMS W+jets 8 TeV (*PRD95(2017)052002*) > *40 distributions!*
- ***New!*** *W+jets CMS 13 TeV also available: [arXiv:1707.05979]*



PLB765(2017)132







PRD95(2017)052002

W plus Heavy-Flavor Jets

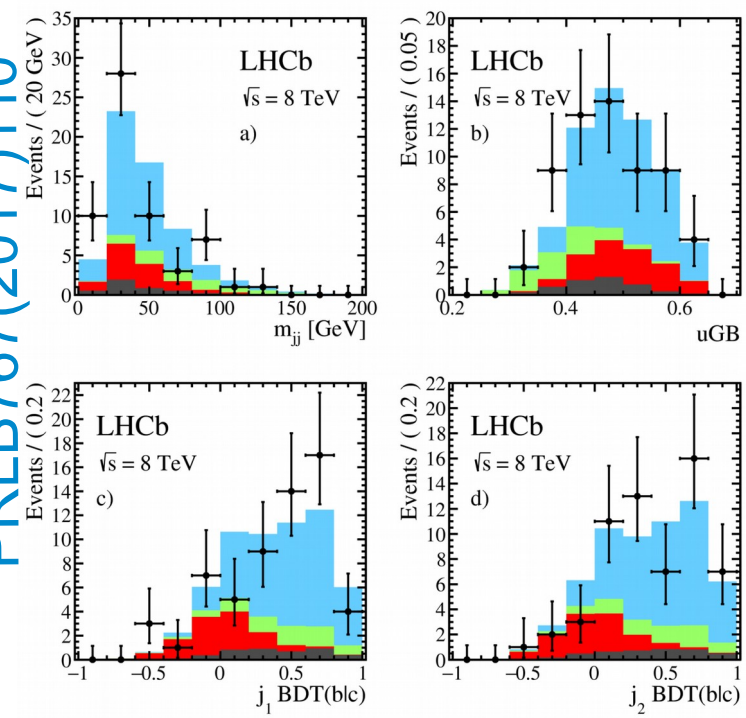
- V+HF jets smaller cross section means larger relative background contributions

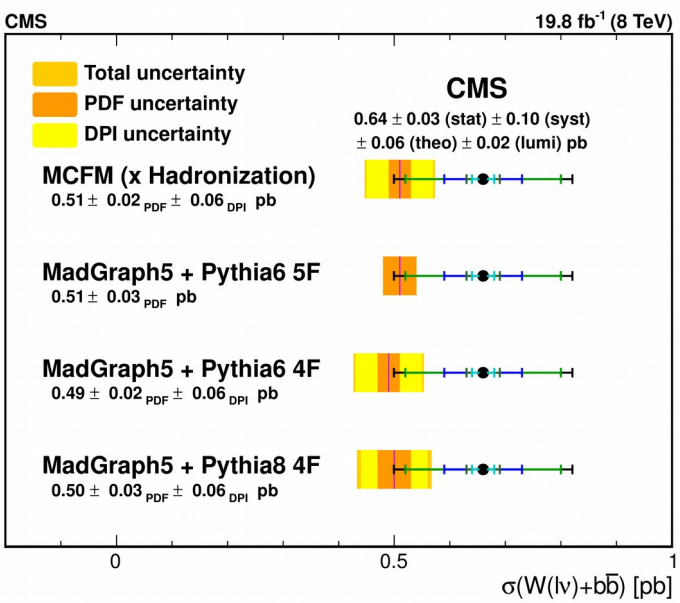
- HF jets identified using secondary vertexing, track impact-parameter, etc. Often combined using MVA

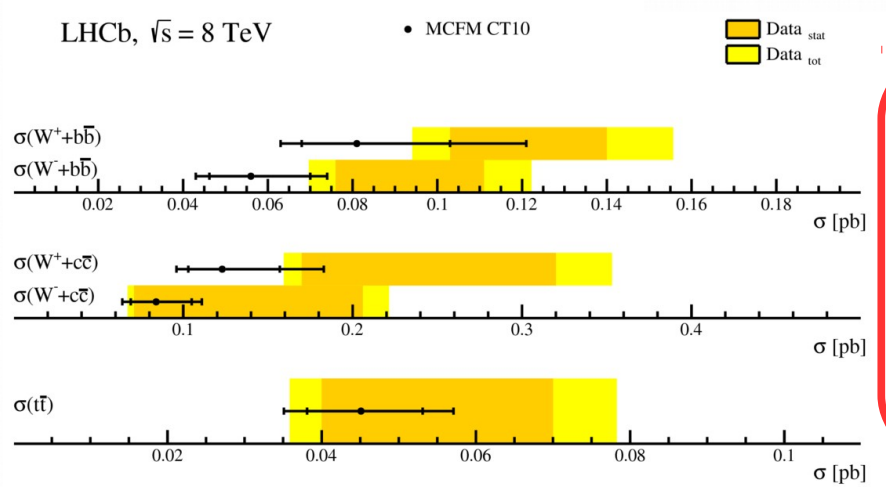
Experimentally challenging!

- *W+$b\bar{b}$@8 TeV CMS results: EPJC77(2017)92*
- **LHCb** outstanding vertexing capability but limited jet reconstruction → succeeded in simultaneous extraction of W+$b\bar{b}$, W+$c\bar{c}$, $t\bar{t}$ using a 4D fit @8TeV!

PRLB767(2017)110





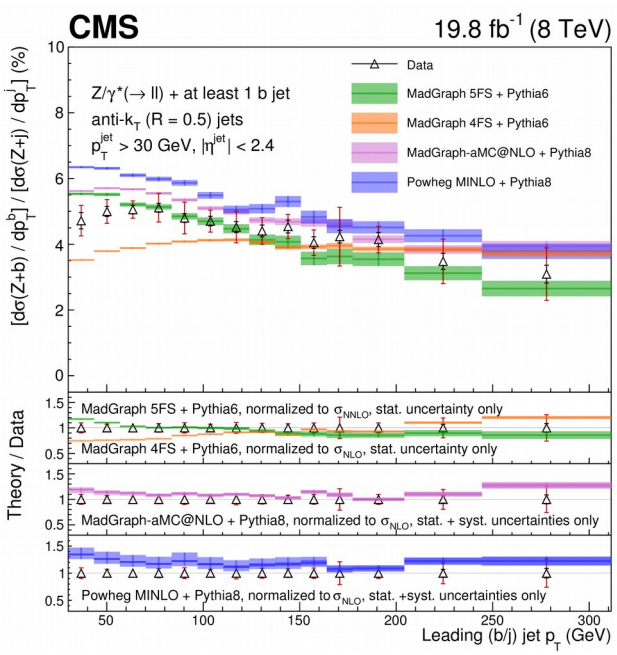


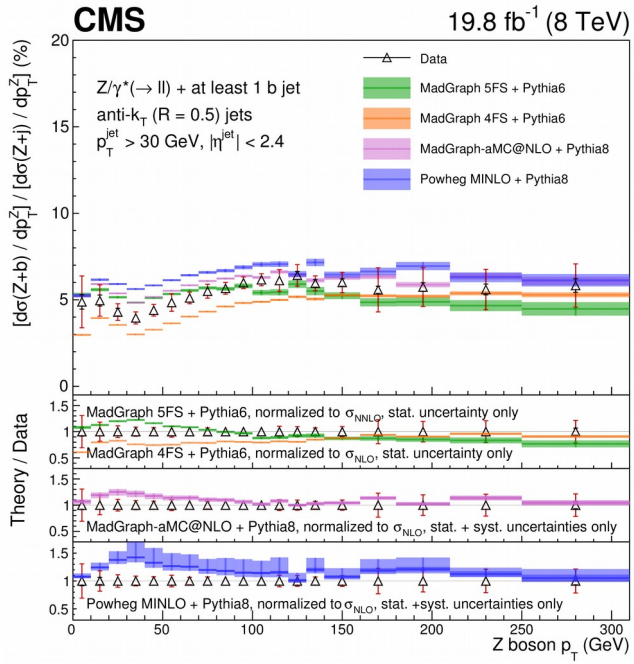
Agreement on the edge of inclusive cross section NLO predictions...

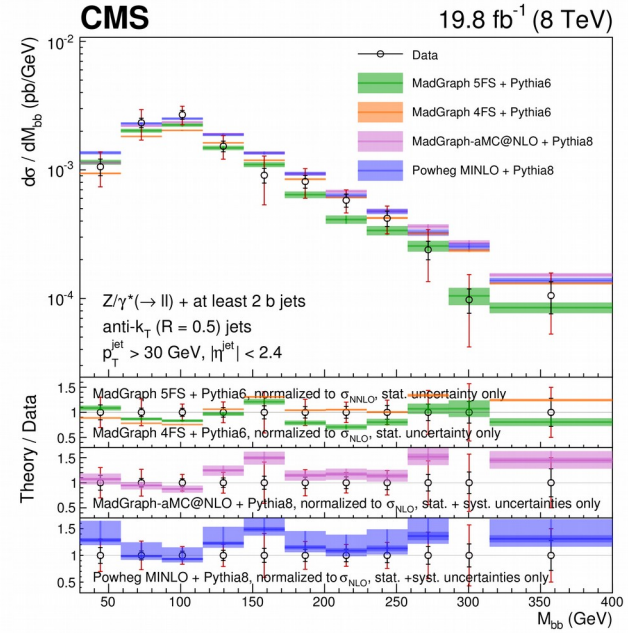
Need for more measurements!

Z plus Heavy-Flavor Jets

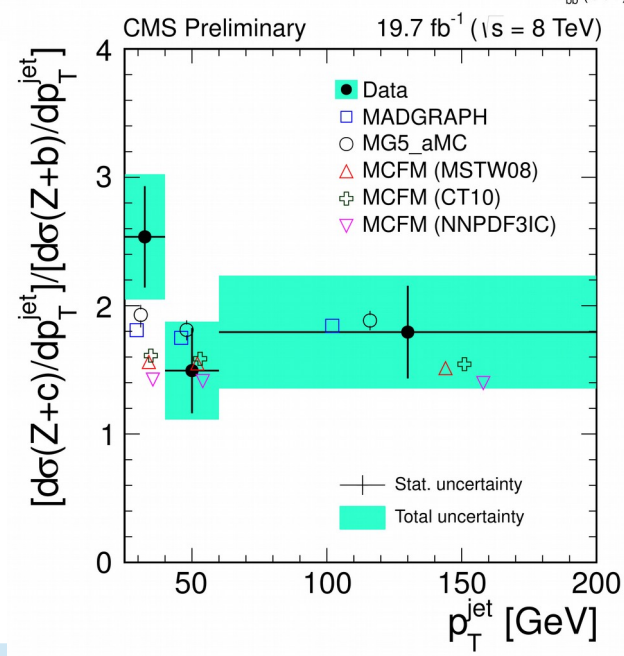
- Multi-differential Z+HF measurement @8 TeV, CMS [arXiv:1611.06507]







- Smaller background for Z+HF jets than W+HF
- Use of ratio w.r.t. to light jets to cancel experimental syst.
- Test of 5FS vs 4FS ME calculations: b-quark from PDFs evolution or only from gluon splitting (mass-effects)
- ***Predictions differ but none describe data perfectly***



Analysis of Z+c production: CMS-PAS-SMP-15-009

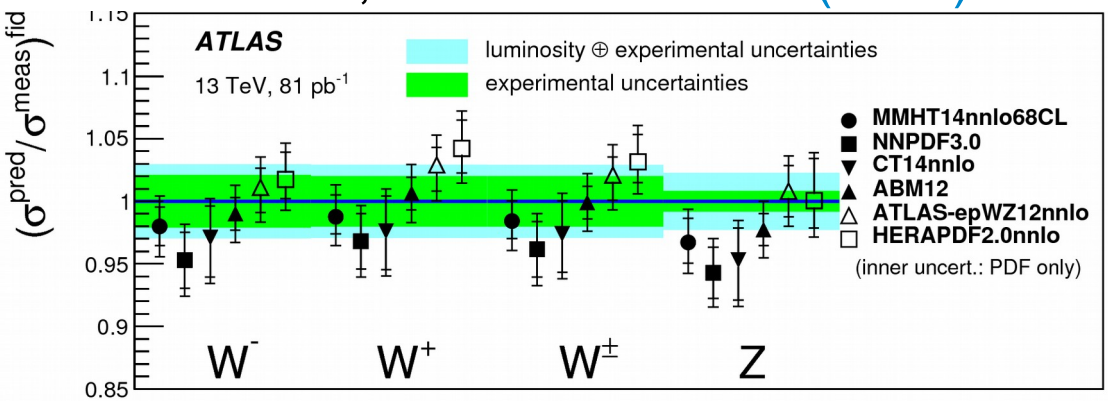
- c-jet extraction using semileptonic and D-meson decays
- *Some tension at low p_T → but still large exp. uncertainties*

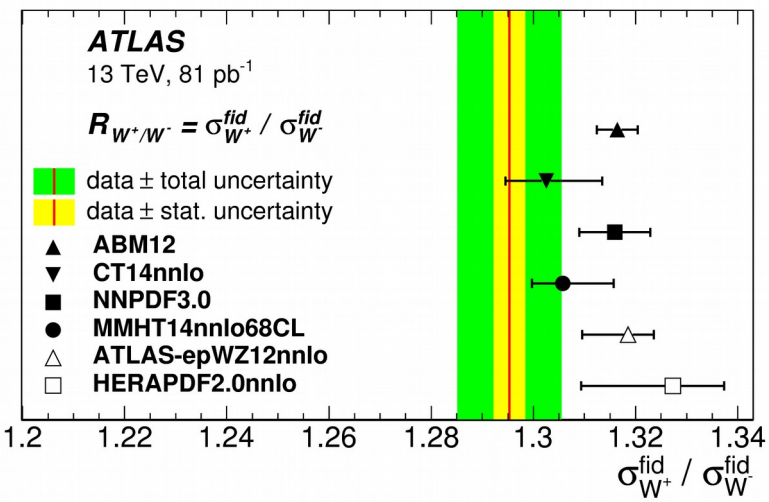
Analysis of Single W, Z/γ* Production

- *Ultimate experimental precision in QCD measurements from single boson identification in leptonic final states → clean & high stat. samples*

- Also partially covered in Andreas Jung's plenary talk
- % level accuracy already in early 13 TeV analyses
- Dominant uncertainty from lumi. determination (~2%)

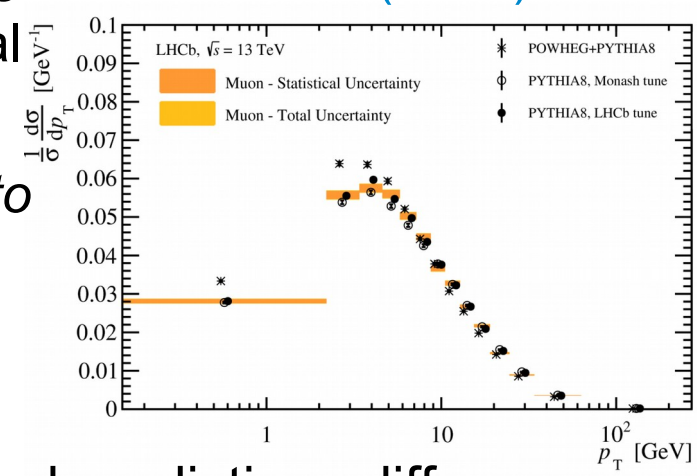
ATLAS W, Z 13 TeV: PLB759(2016)601





- Reduced impact of syst. uncertainties using ratios or considering differential observables
- *Also LHCb contributing to precision W, Z physics!*

LHCb Z 13 TeV: JHEP09(2016)136



- Constraints on proton PDFs (valence and sea quarks)
- V-p_T high sensitivity to fixed-order, ME+PS, or resummed predictions differences

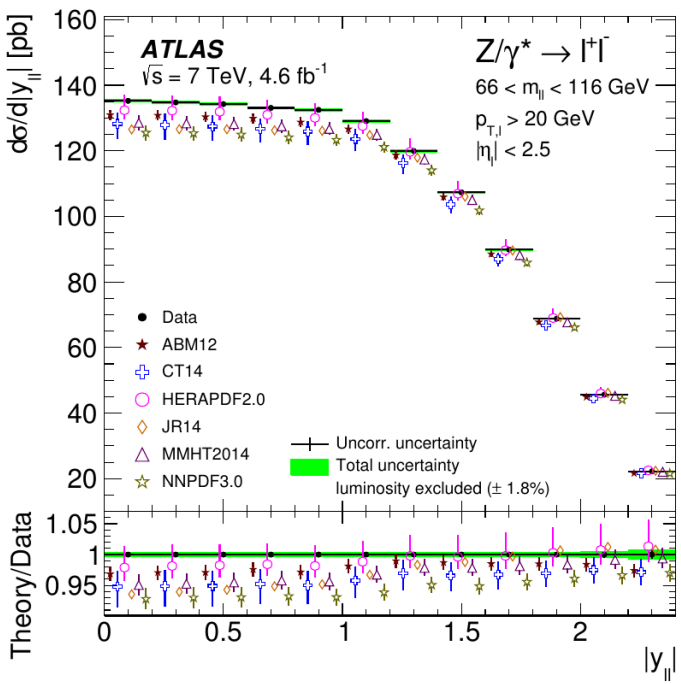
Drell-Yan Precision Analysis

Unfortunately reaching the final precision takes time… Run I still fundamental!

- Differential analysis of DY events at 7 and 8 TeV from ATLAS and CMS

Multi-differential high-precision measurements:

- DY kinematics described by 5 independent variables
- M_{ll} & |Y| in Z→ll used to maximize PDFs sensitivity



Notable examples:

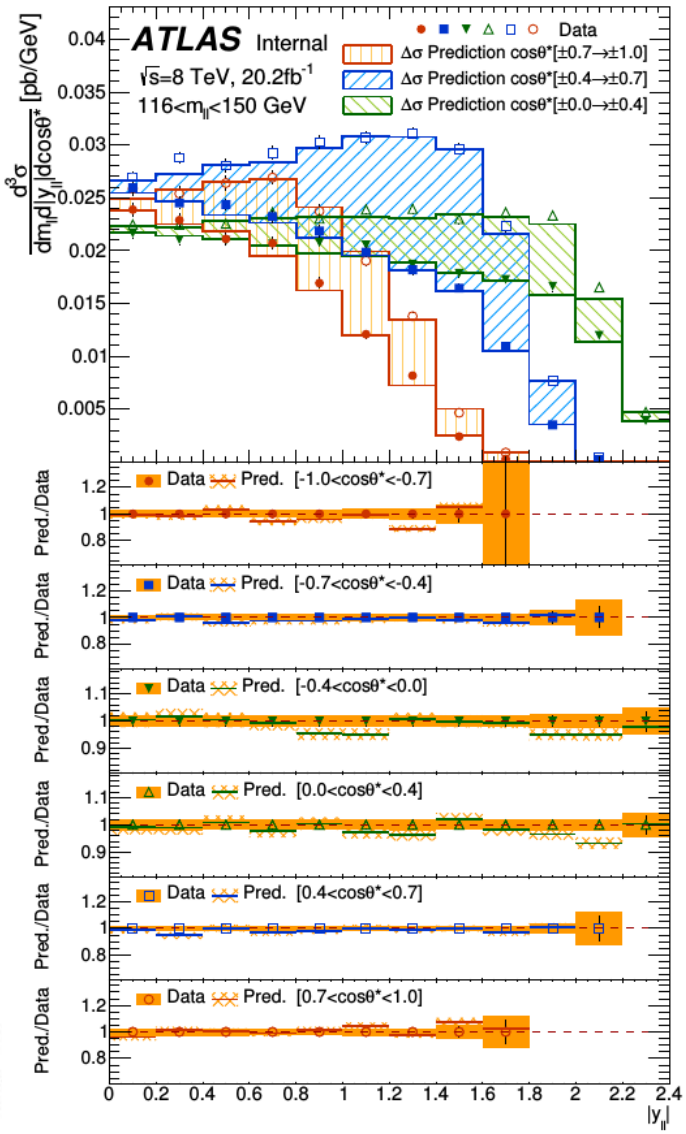
- ATLAS W, Z 7 TeV ATLAS EPJC77(2017)367
- CMS W at 8 TeV EPJC76(2016)469
- *Both resulting in strong constraints on PDFs*

- **New** ATLAS at 8 TeV **Z3D**:

$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*}$$

- **20 fb^{-1}** also allows fine binning
- *Sensitivity to AFB:*

$$A_{FB} = \frac{d^3\sigma(\cos\theta^* > 0) - d^3\sigma(\cos\theta^* < 0)}{d^3\sigma(\cos\theta^* > 0) + d^3\sigma(\cos\theta^* < 0)}$$



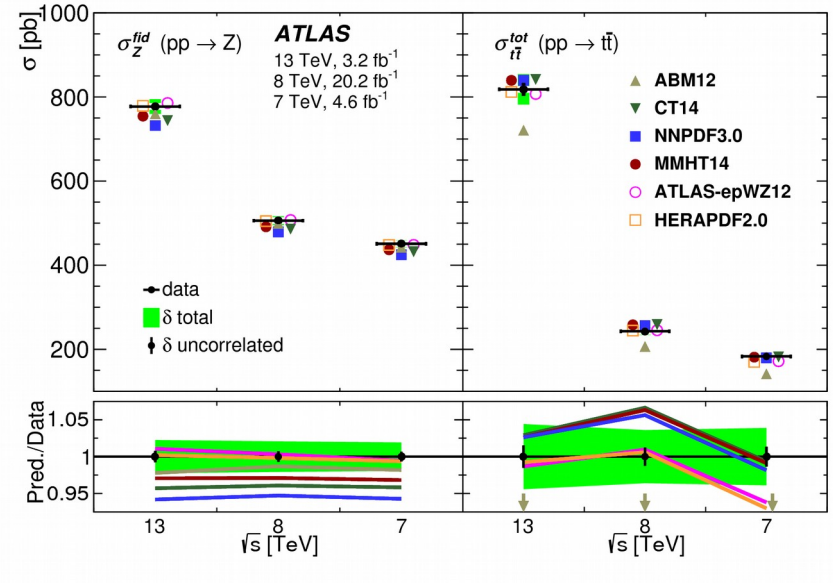
More Information Using 7,8,13 TeV

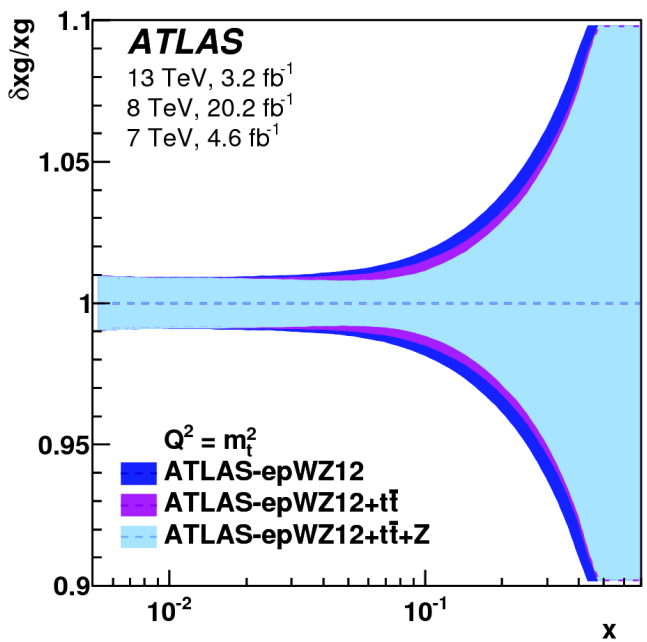
How to achieve an even better precision?

- Ratio & double ratios at different $\sqrt{s}$
- *First example of this kind of measurement: JHEP02(2017)117*

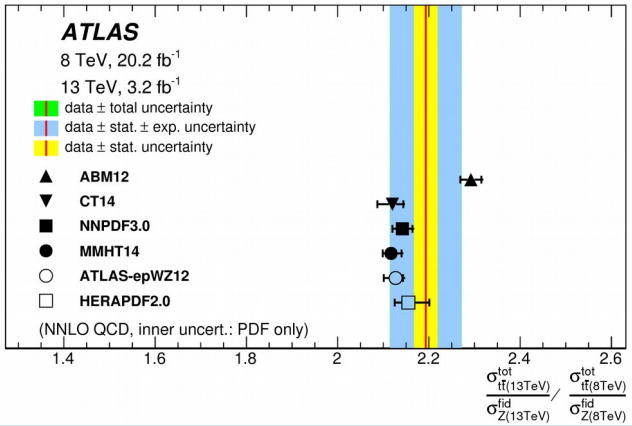
$$R^{\mathrm{tot/fid}}_{t\bar{t}/Z}(i/j) = \left[\sigma^{\mathrm{tot}}_{t\bar{t}(i\mathrm{TeV})}/\sigma^{\mathrm{fid}}_{Z(i\mathrm{TeV})}\right] \Big/ \left[\sigma^{\mathrm{tot}}_{t\bar{t}(j\mathrm{TeV})}/\sigma^{\mathrm{fid}}_{Z(j\mathrm{TeV})}\right]$$

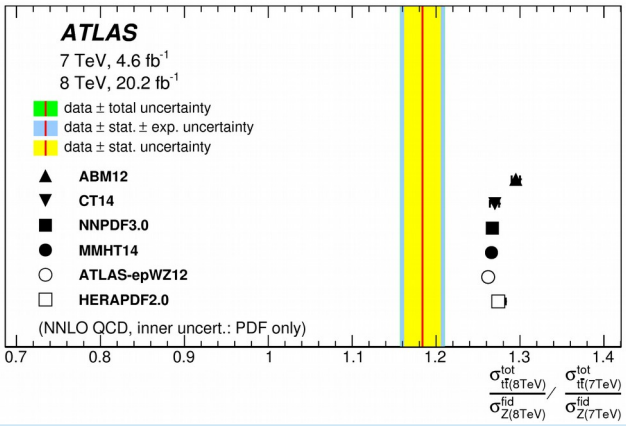
- Luminosity syst. cancels → we are using Z cross section to normalize events





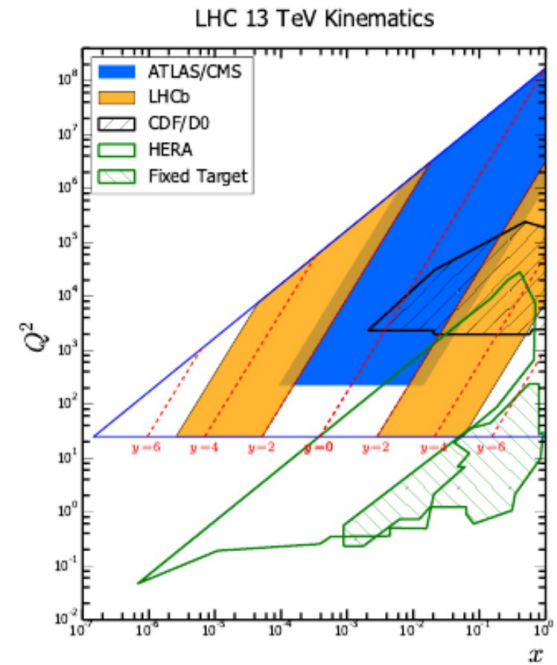
- $t\bar{t}$ + lever arm from multi-$\sqrt{s}$: *constraints on gluon PDF*
- Good agreement with prediction for data including 13 TeV measurements (~3% error on $R_{t\bar{t}/Z}$)
- *Some tension in 7/8 TeV results* (~1% error on $R_{t\bar{t}/Z}$)

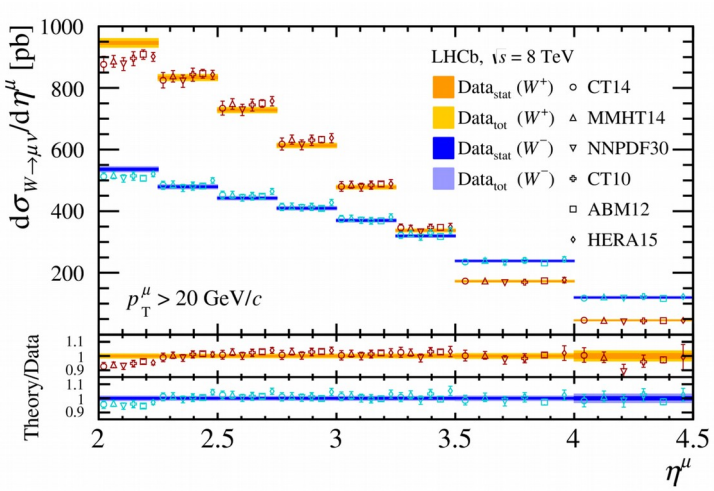


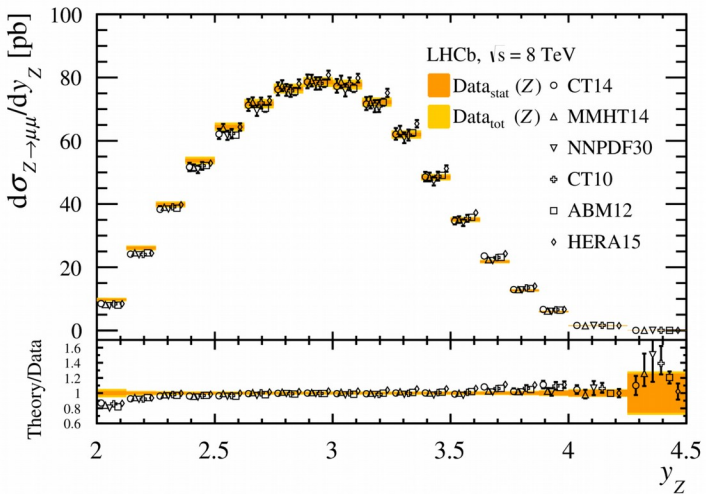


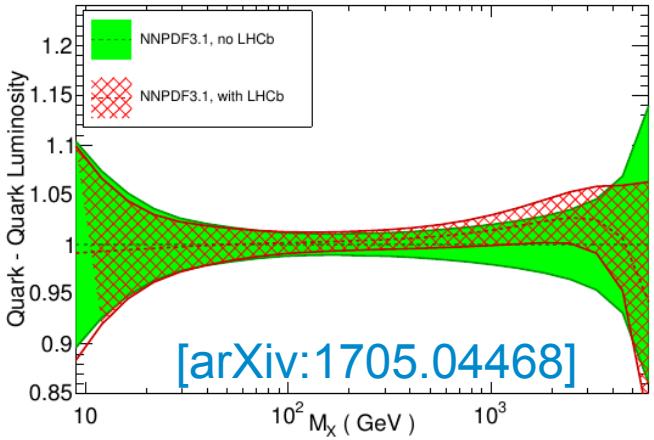
LHCb W, Z Precision Measurements

- 7, 8 TeV W, Z fiducial and differential cross section measurements in phase space complementary to ATLAS/CMS: $2.0<\eta_{lep}<4.5$ JHEP01(2016)155
- Use of *W, Z ratio and double ratio* at different $\sqrt{s}$ to cancel experimental uncertainties (<1% precision)

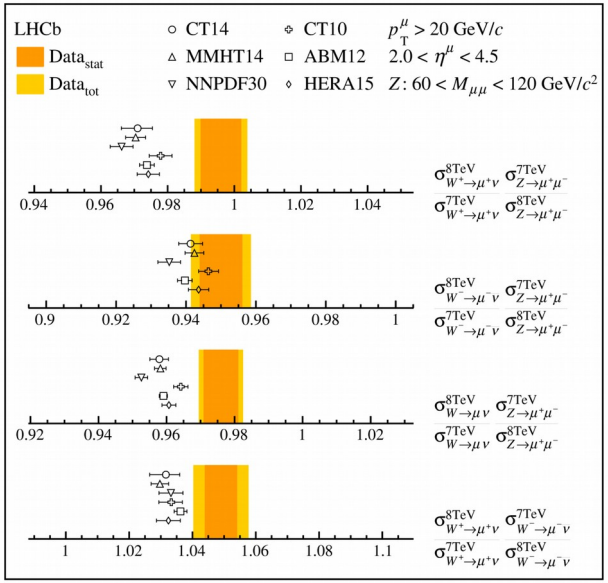








- Double ratio shows some tension with predictions
- Extend sensitivity in PDFs in (x,Q^2) plane

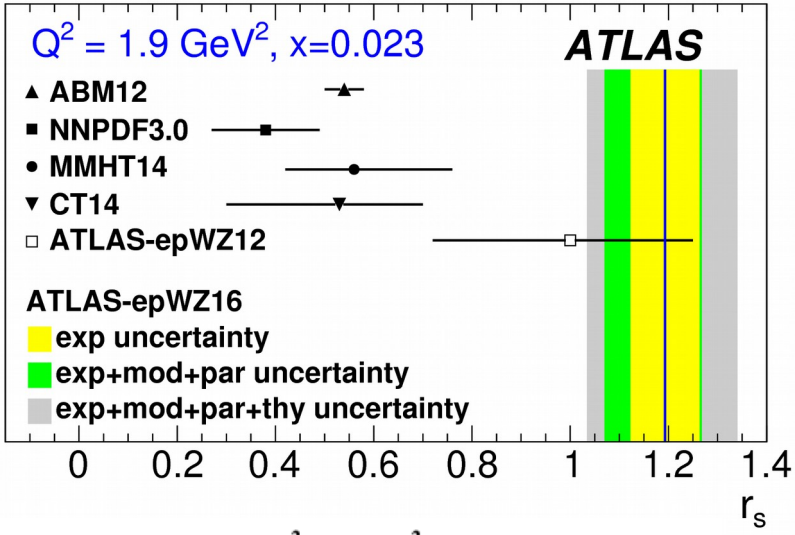


Strangeness Content of the Proton

What else can we learn given the amount of information we have?

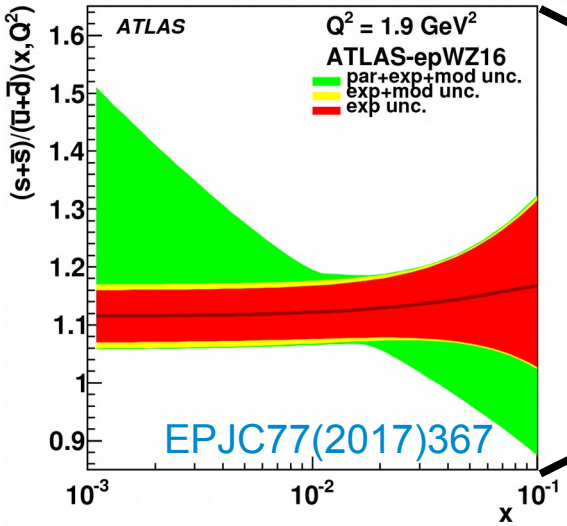
- Early (2010) Run I W, Z ATLAS results pointed to possible enhancement of strangeness in PDFs
- Strangeness fraction (r_s) now measured in W, Z 7TeV EPJC77(2017)367:

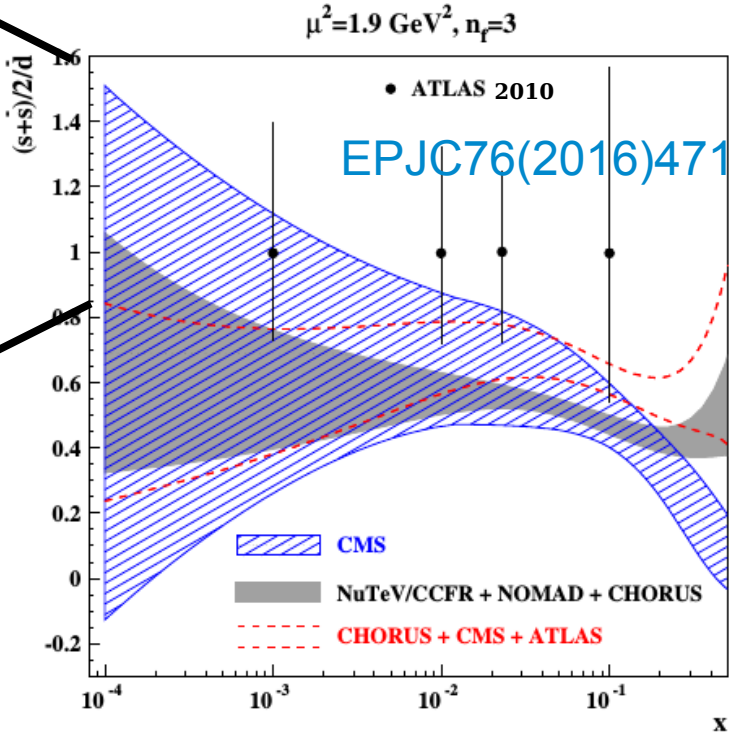
$$r_s = \frac{s+\bar{s}}{2\bar{d}} = 1.19 \pm 0.07\,(\text{exp}) \;\pm 0.02\,(\text{mod})\; {}^{+0.02}_{-0.10}\,(\text{par})$$



Proton strangeness:

- Tension confirmed when comparing latest ATLAS data vs results to ν-DIS experiments
- No strong constrains from CMS





- Previously accepted r_s value was about ~0.5
- ***LHC now points to r_s~1 and changing our view of the proton!***

More About Extraction of Fundamental SM Parameters

Indirect:

- Precise QCD measurements indirectly help any kind of measurement of fundamental parameters (or BSM search) at the LHC and beyond
- *ATLAS W-mass is a recent example* [arXiv:1701.07240]: several measurements (Vp_T, PDFs, etc.) allowed to pin down systematic uncertainties to the current level of precision (still QCD related systematics are dominant)

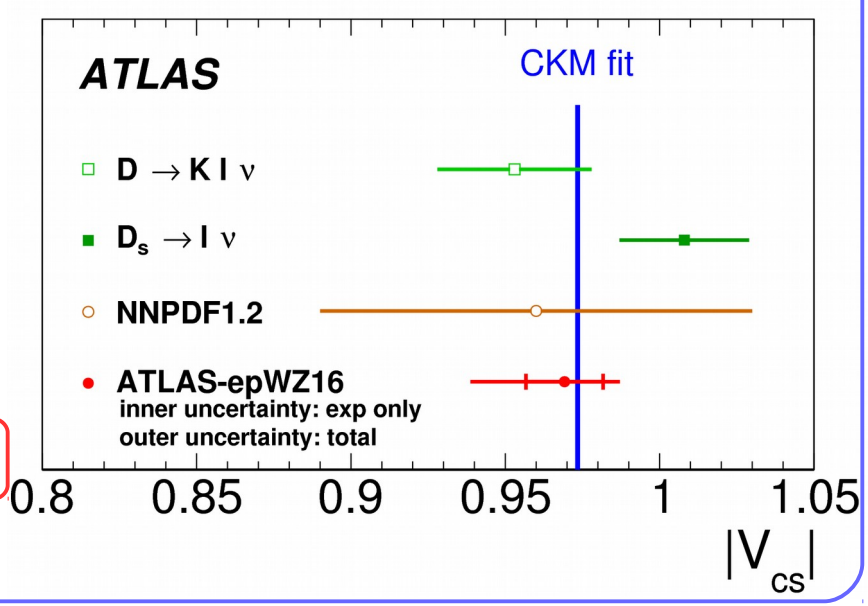
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Direct:

- $|V_{cs}|$ element of CKM matrix related to strange density because of cs→W
- ~25% of W cross section at 7 TeV due to it
- CKM elements can be extracted from QCD analysis of precision W, Z measurement!

$$|V_{cs}| = 0.969 \pm 0.013\,(\text{exp})\,^{+0.006}_{-0.003}\,(\text{mod})\,^{+0.003}_{-0.027}\,(\text{par})\,^{+0.011}_{-0.005}\,(\text{thy})$$

- Measurement competitive with D-meson decays



Conclusions

QCD, at the basis of every interaction at the LHC, is a pervasive element of modern particle physics:

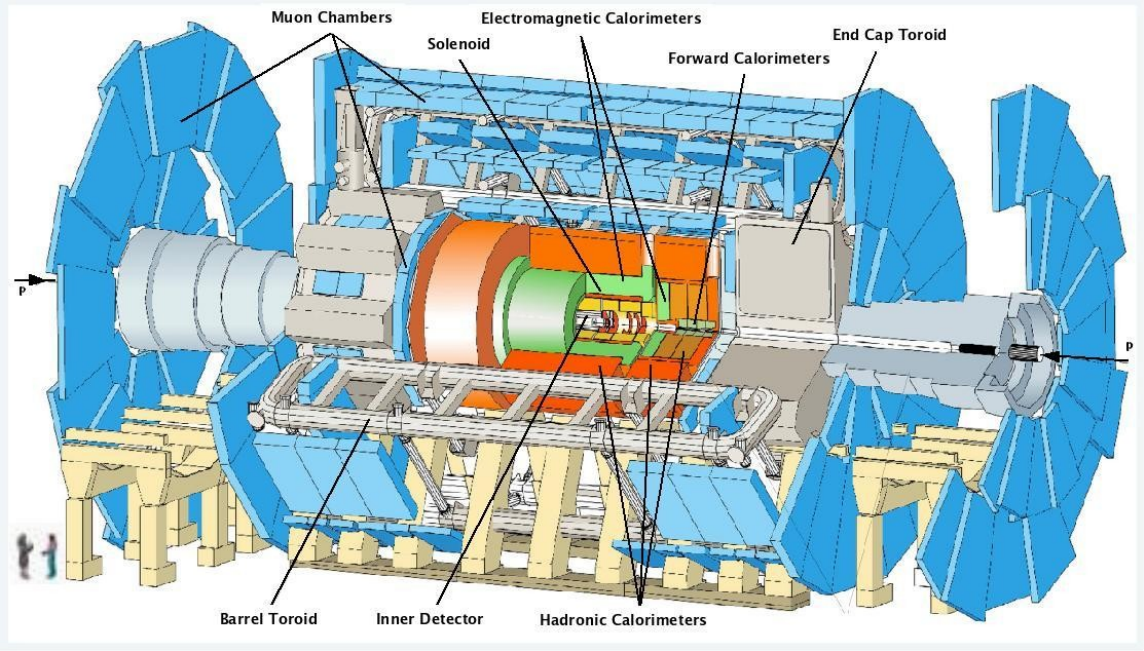
- Subject of a variety of challenging experimental measurements… only a small sub set shown
- Each measurement usually delivers an important message to the experimental and theoretical communities
- Comparison against state-of-the-art theory predictions
- Understanding of hadron properties and proton structure
- Reduction of uncertainties needed for “not easy” BSM searches
- Fundamental part of any SM precision measurements
- Probe of fundamental constants of Nature

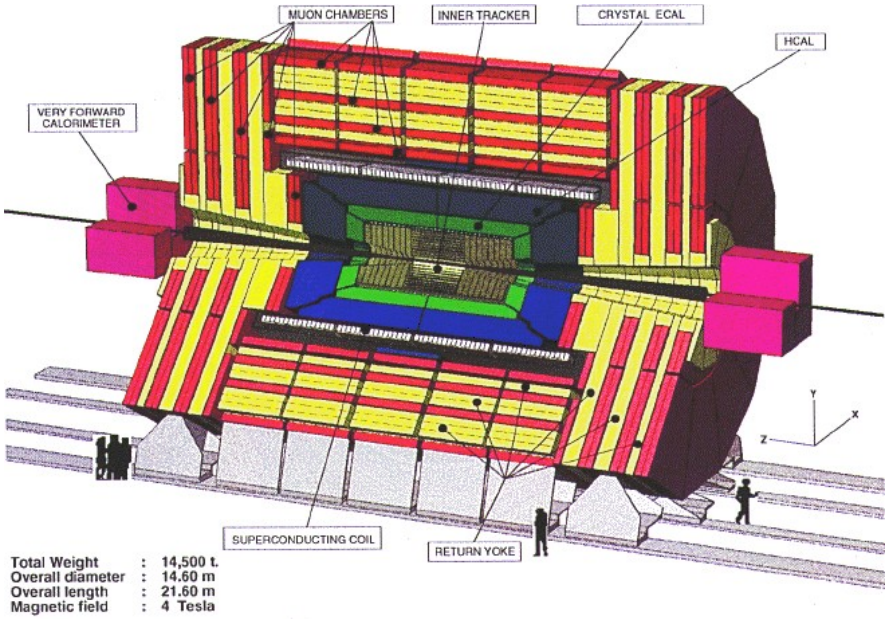
Mastering QCD is both essential for the future of the LHC program and for the advancement of our knowledge

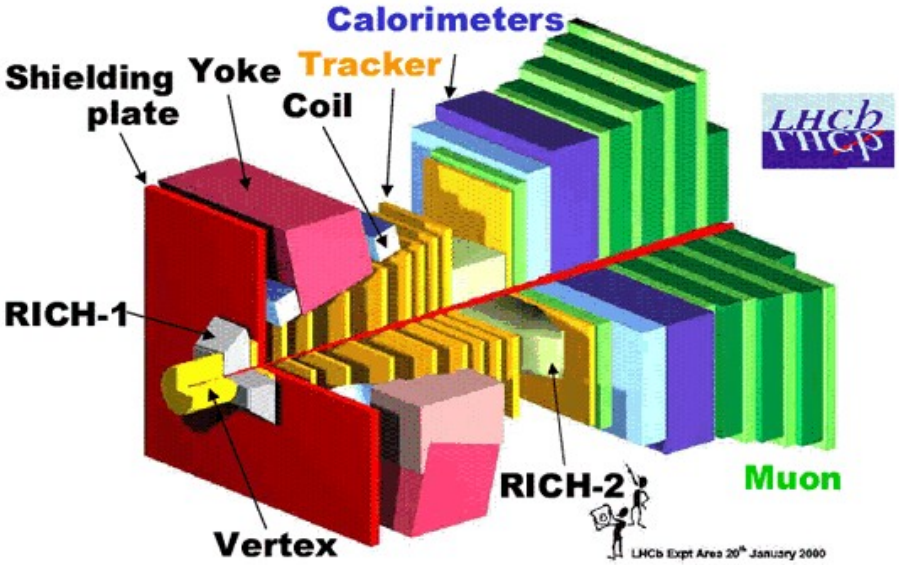

Thanks for your attention!
Questions?

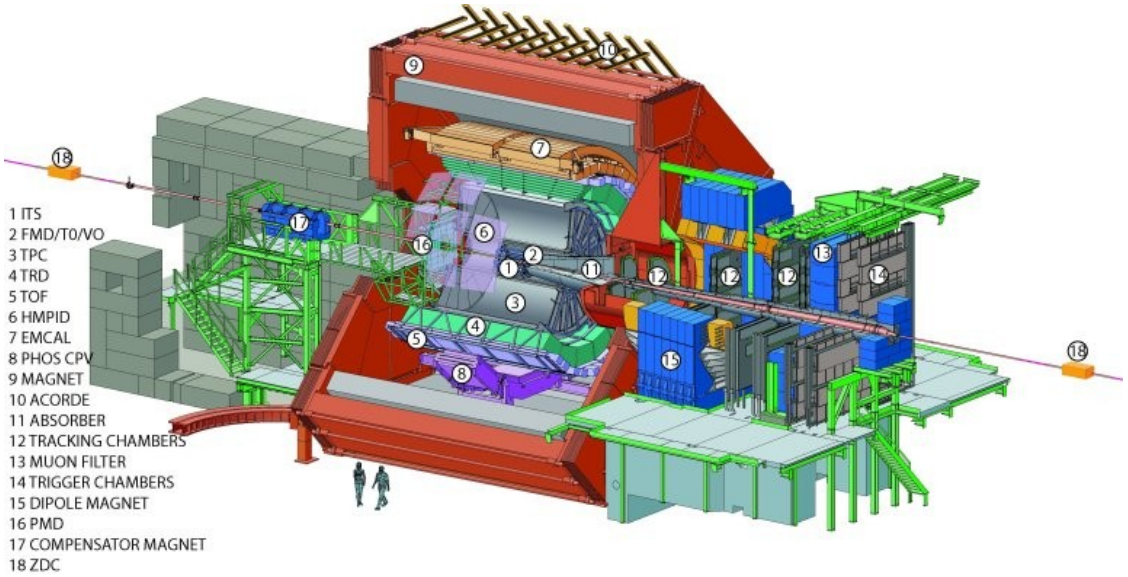
Backup

Detectors

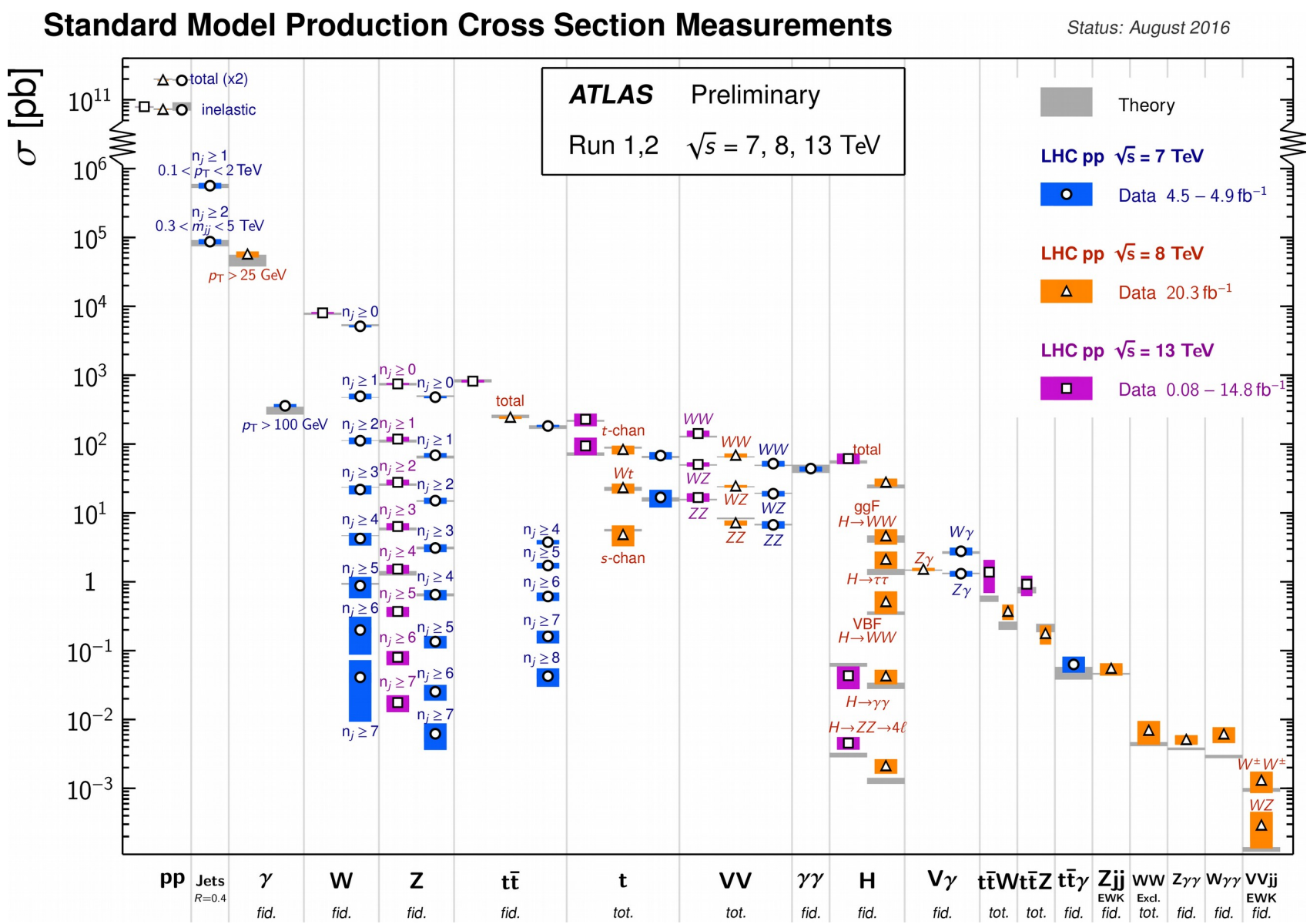

Muon Chambers
Electromagnetic Calorimeters
Solenoid
End Cap Toroid
Forward Calorimeters
Barrel Toroid
Inner Detector
Hadronic Calorimeters


MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla


Calorimeters
Shielding plate
Yoke
Tracker
Coil
RICH-1
RICH-2
Muon
Vertex
LHCb
LHCb Expt Area 20th January 2000


1 ITS
2 FMD/T0/VO
3 TPC
4 TRD
5 TOF
6 HMPID
7 EMCAL
8 PHOS CPV
9 MAGNET
10 ACORDE
11 ABSORBER
12 TRACKING CHAMBERS
13 MUON FILTER
14 TRIGGER CHAMBERS
15 DIPOLE MAGNET
16 PMD
17 COMPENSATOR MAGNET
18 ZDC

The QCD Domain at LHC



Proton-proton Cross Section

Total pp cross-section:

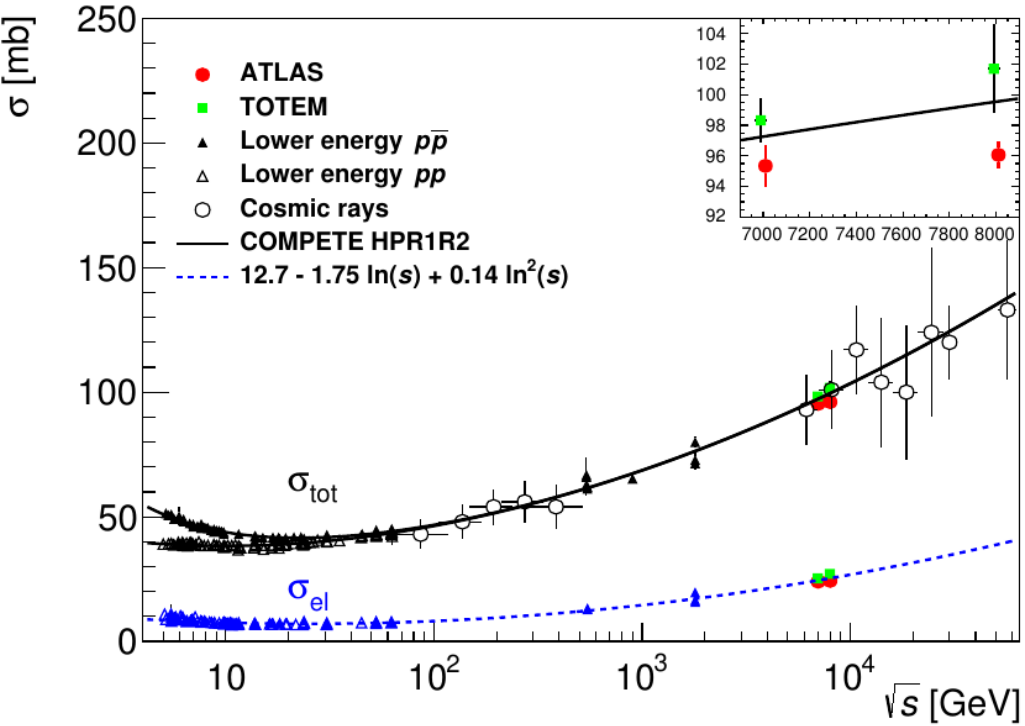
ATLAS: [arXiv:1607.06605]

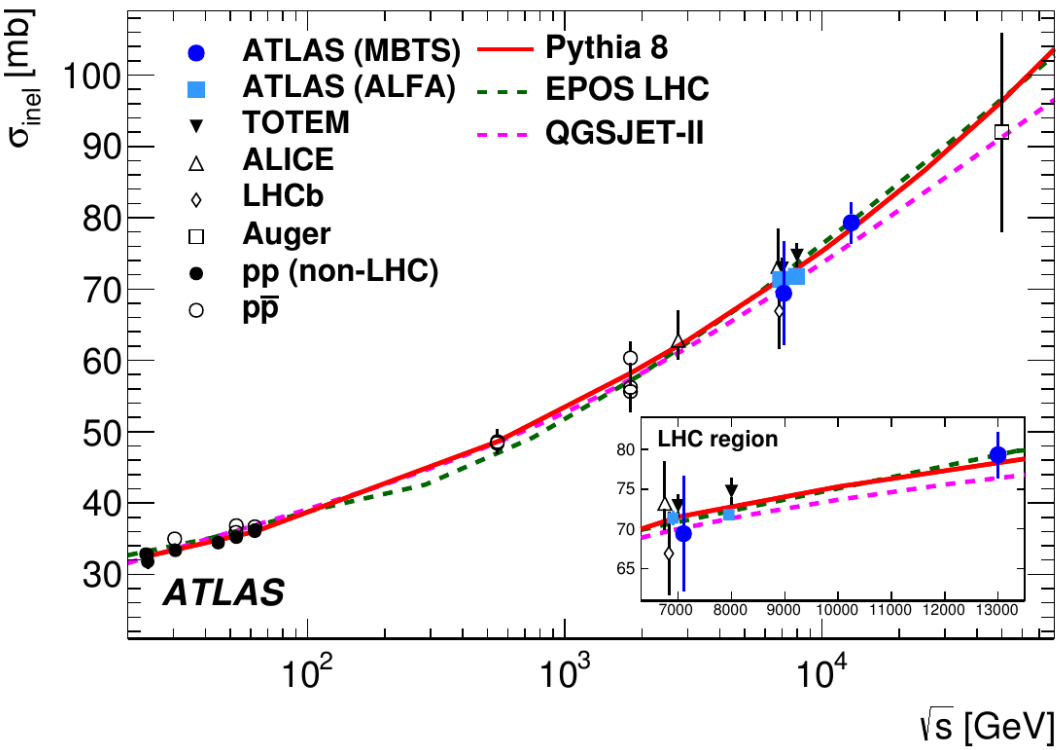
TOTEM: [arXiv:1610.00603]

Inelastic pp cross-section:

ATLAS, [arXiv:1606.02625]

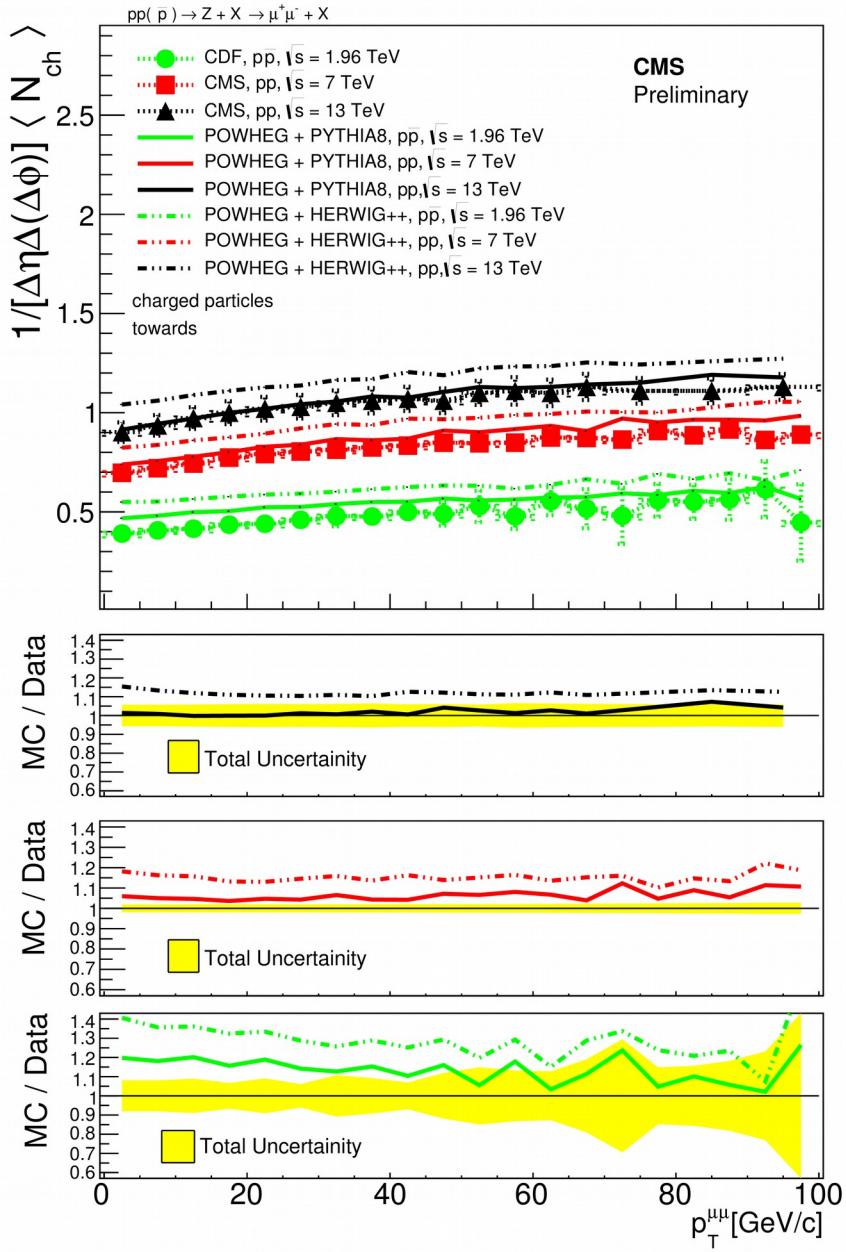
CMS-PAS-FSQ-15-005



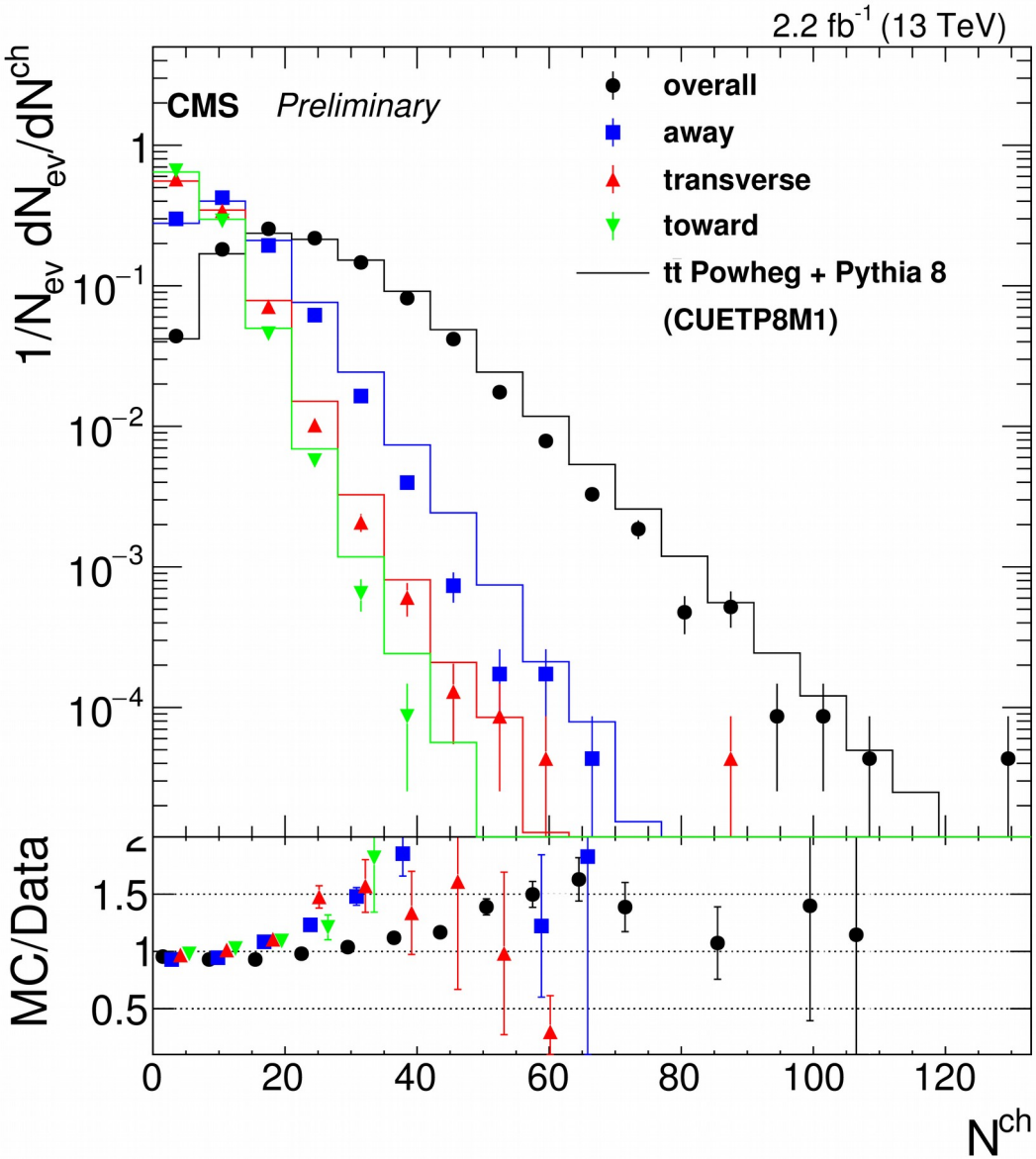


UE In Z+jets and ttbar Events

CMS-PAS-FSQ-16-008



CMS-PAS-TOP-15-017



Jet Grooming & Softdrop Mass

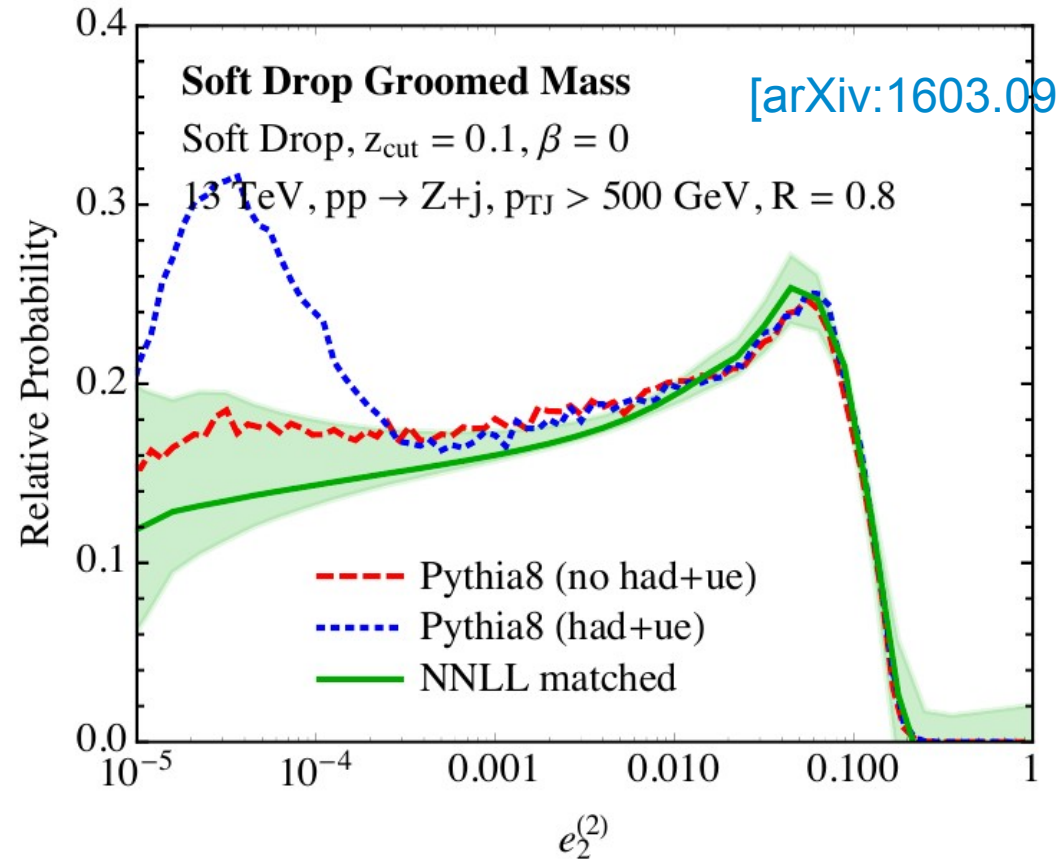
- Softdrop is a jet grooming procedure to remove soft and wide angle radiation from a jet
- Formally insensitive to non-global logarithms

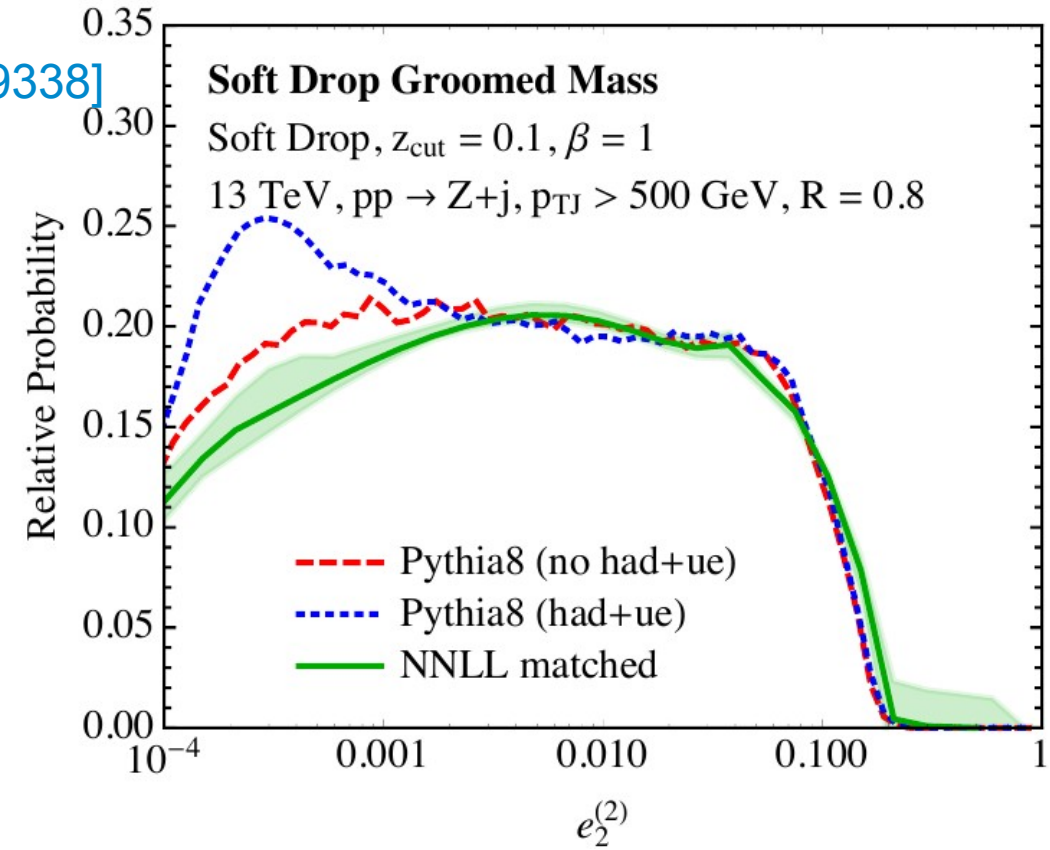
Observable: groomed jet mass over p_T: $e_2^{(2)} = \frac{m_g^2}{E_g^2}$

Soft-drop condition:

$$\frac{\min[p_{Ti}, p_{Tj}]}{p_{Ti} + p_{Tj}} > z_{\rm cut} \left(\frac{R_{ij}}{R}\right)^{\beta}$$

[arXiv:1603.09338]

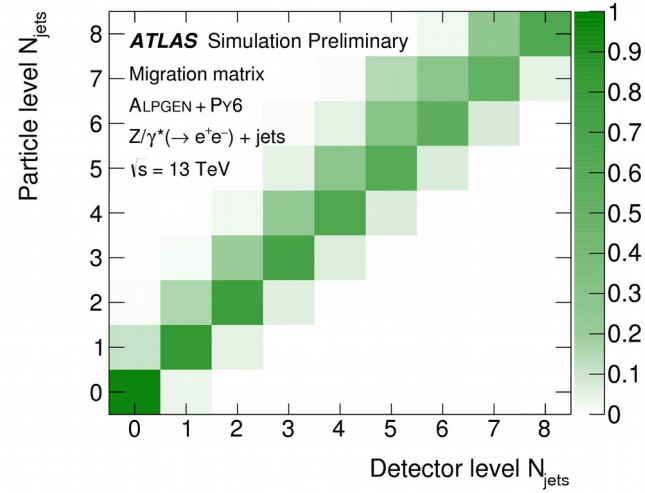




V+jets: Unfolding & Prediction Comparison

- Define fiducial volume of the measurement in phase space similar to experimental acceptance
- Use signal MC to remove *detector* effects (efficiencies, resolution, scales) on background subtracted data
- Compare unfolded data to available MC simulations or to fixed-order calculations (after correction for non-perturbative effects as fragmentation, underling event, etc.)

E.g. n-jets reco-vs-particle jets:



Type of Prediction	MCs & Calculations "label"	Usage & Notes
multi-partons (Np) LO ME+PS	Sherpa 1.X (up to Np = 4)	Wide usage in ATLAS Run I analyses
	Madgraph5 (up to Np = 4)	Wide usage in CMS Run I analyses
	ALPGEN (up to Np = 5)	Run I (and Run II) "workhorse"
multi-parton (Np) NLO and LO ME+PS	Madgraph5 aMC@NLO (NLO up to Np = 2)	"Standard" in many Run II CMS analyses
	Sherpa 2.X (NLO up to Np = 2)	"Standard" in many Run II ATLAS analyses
	Powheg (NLO Np = 1)	Tested in Run I by CMS
Fixed order NLO calculation	BlackHat + Sherpa (NLO up to Np = 5)	Tested in Run I, II (both ATLAS and CMS)
Approximate NNLO	LoopSim (approx. NNLO for W+>=1jets)	Tested in Run I by ATLAS
	HEJ (approx. to all orders for W+>=2 jets)	
Fixed order NNLO calculation	N-Jettiness (full NNLO QCD)	**!! NEW !! Tested for fist time in Run II**

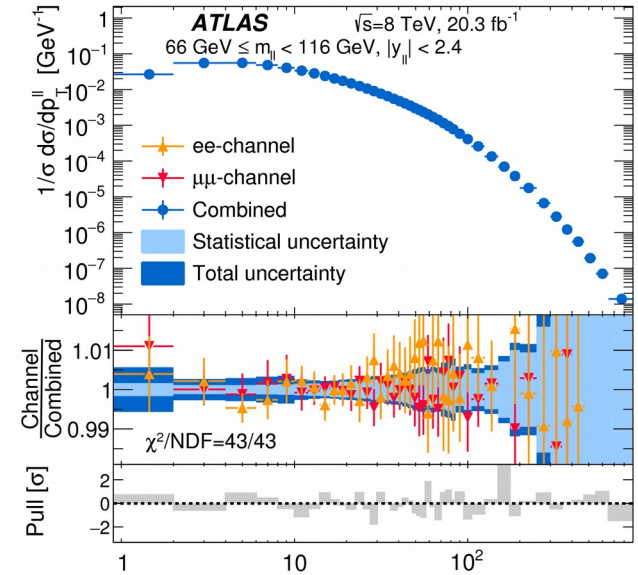
Drell-Yan Precision Analysis

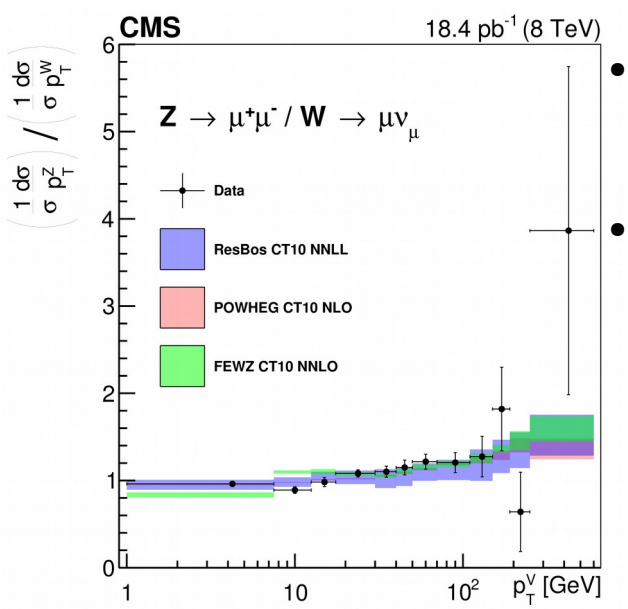
Unfortunately reaching the final precision takes time… Run I still fundamental!

- Differential analysis of DY events at 7 and 8 TeV from ATLAS and CMS

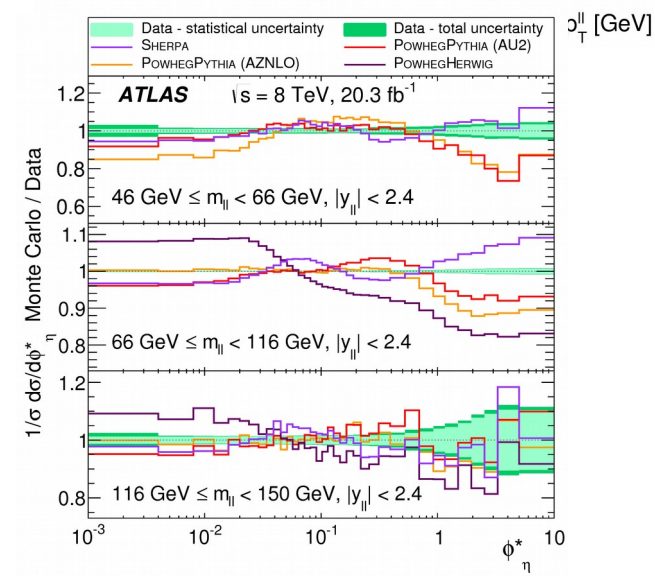
A notable example: boson p_T

- ATLAS: EPJC76(5)1(2016) CMS: JHEP02(2016)096
- Sub-percent precision on differential shape, analysis of Z-peak and off-peak regions
- $p_T << M_Z \rightarrow$ soft-resummation, non-perturbative regime
- $p_T \sim M_Z \rightarrow$ fixed order calculations



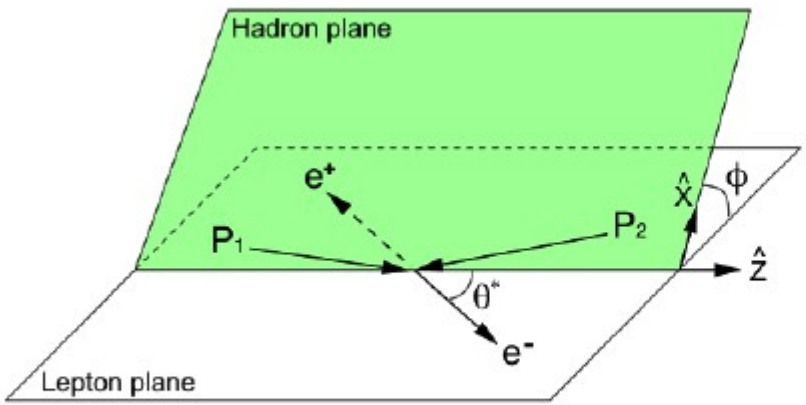


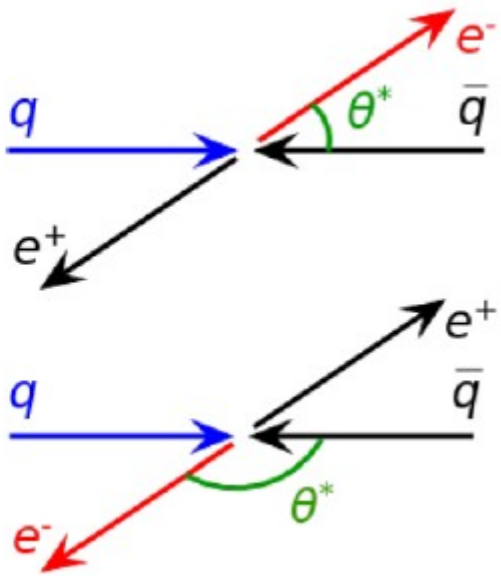
- Full boson p_T spectrum hard to model with a single prediction
- Ratio of Z to W p_T is important for W-mass measurement at LHC: $\rightarrow$ Needed to transfer calibrations from Z to W with MeV accuracy



Collins-Soper frame

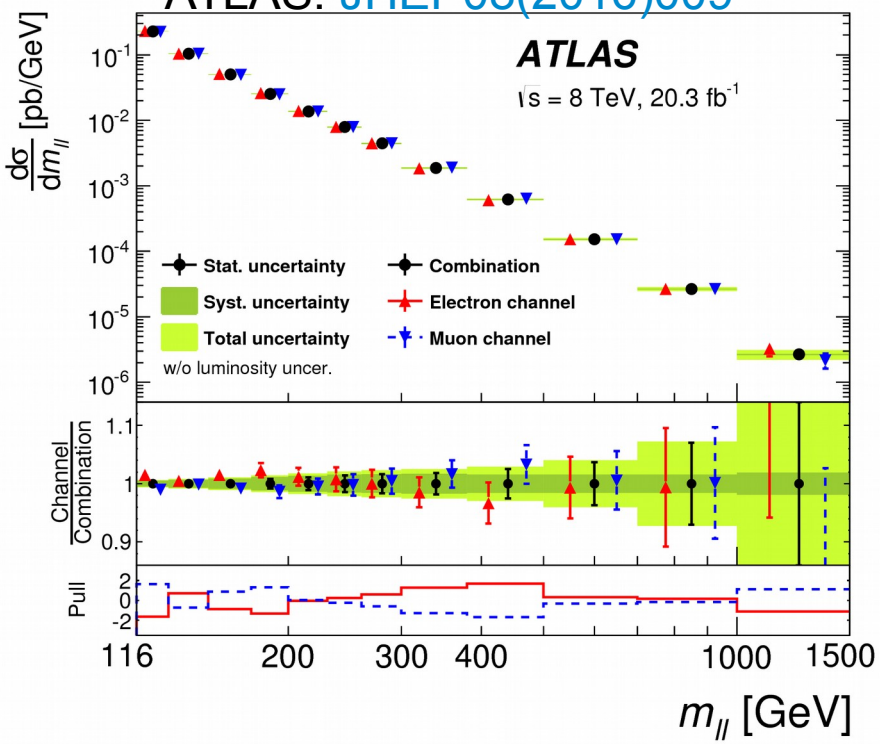
- Decay angle measured from an axis symmetric with respect to the two incoming partons
- Decay angle uniquely defined
- avoids potential ambiguity in the case that one or both partons have non-zero transverse momentum in the lab frame.



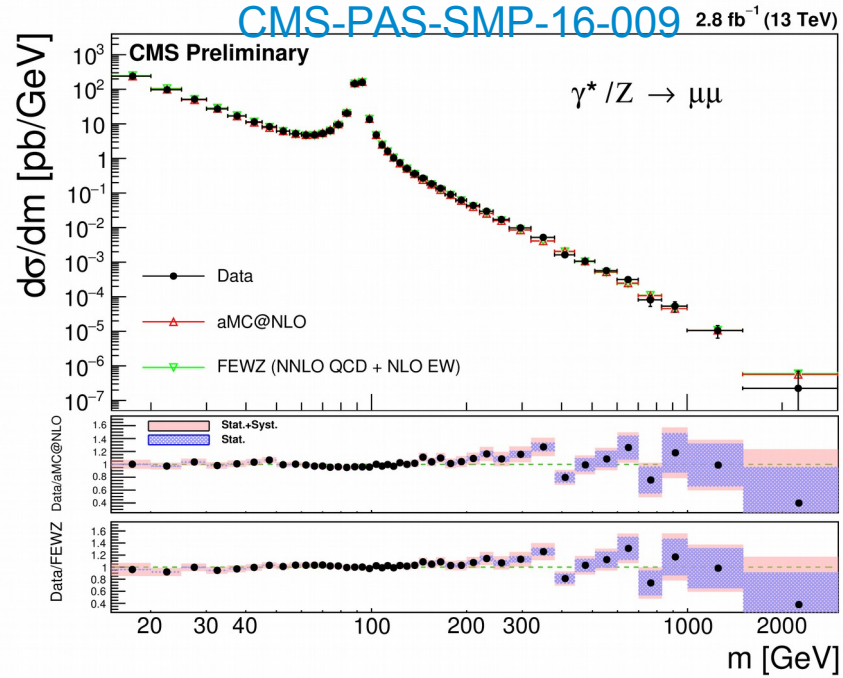


High-Mass Drell-Yan Analysis

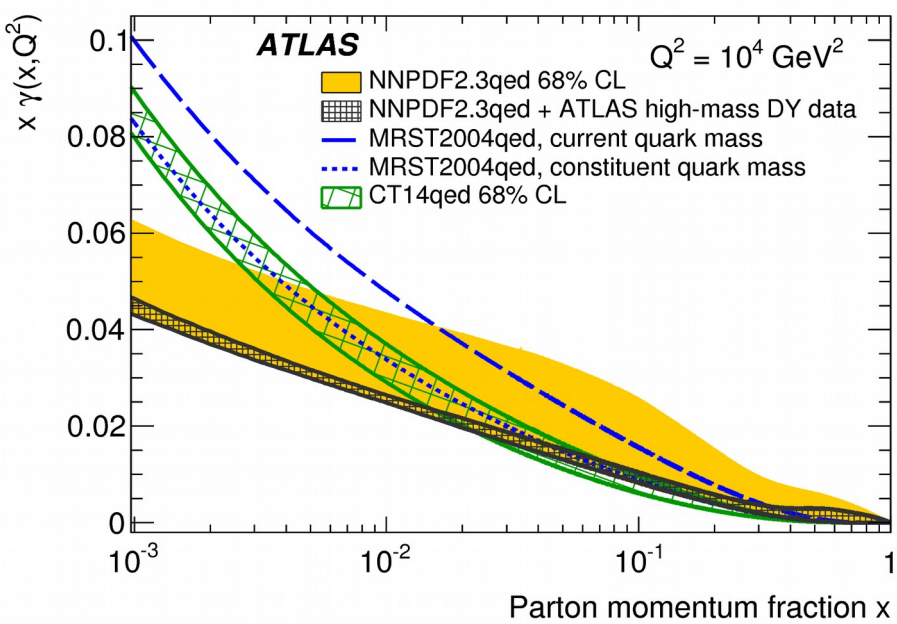
ATLAS: JHEP08(2016)009



CMS-PAS-SMP-16-009

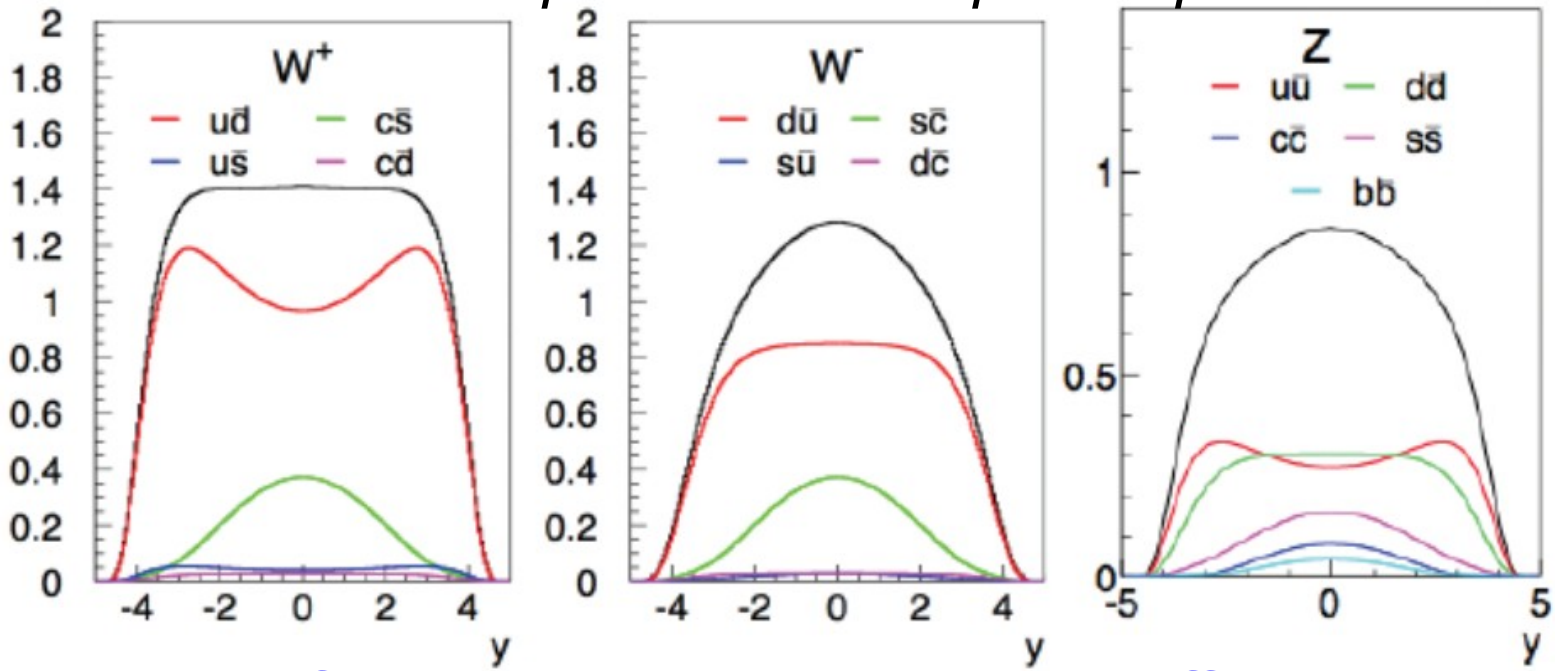


- Sensitive to γγ → ℓℓ, significant constraining power vs NNPDF2.3QED



Differential Measurement and PDFs

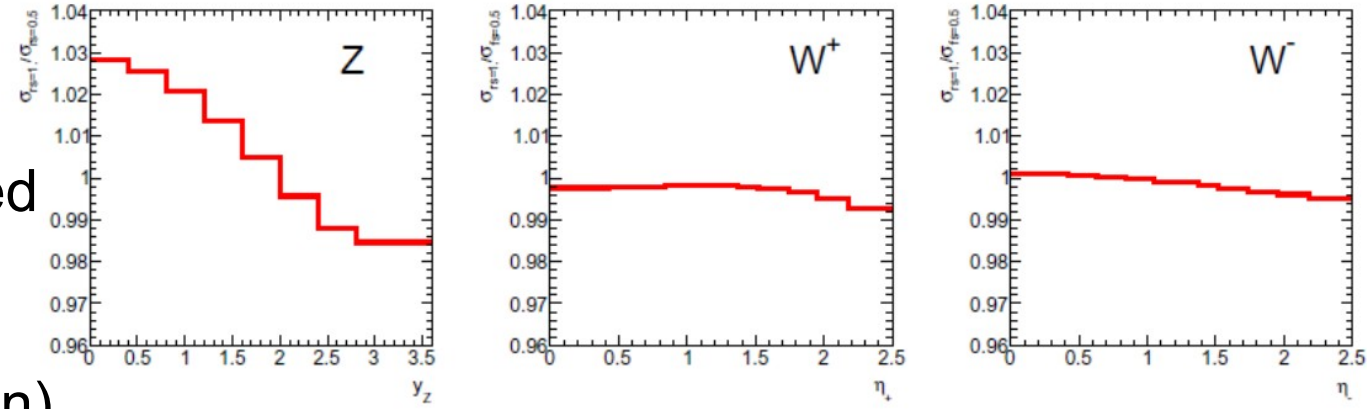
Differential cross-sections (e.g. vs rapidity) can disentangle contribution form different quark flavors in proton-proton collisions:



A practical example of shape sensitivity to peculiar effects:

Believed (i.e. in all PDFs) that strange-sea suppressed w.r.t. down-sea, ***what if not true?***

- Shape of Z rapidity affected (~4% difference)
- W distributions not (may give absolute normalization)



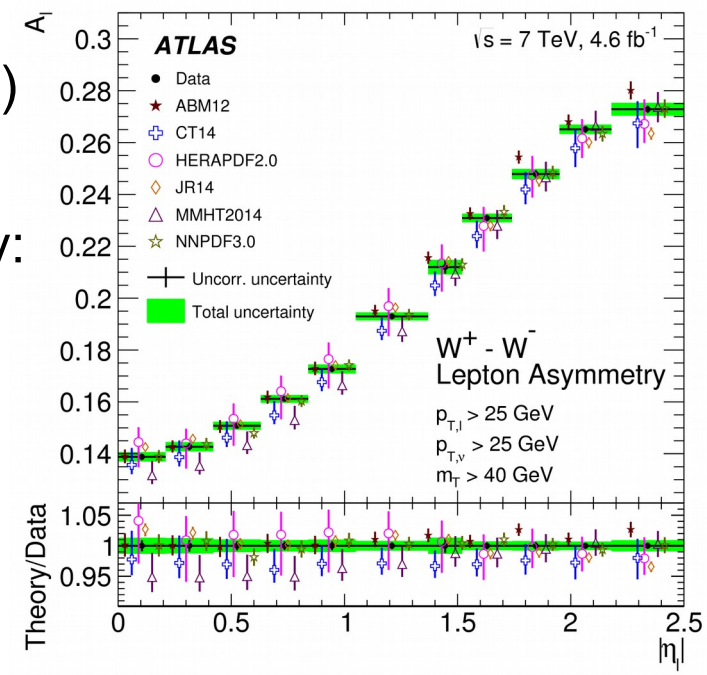
PDFs Measurement Using W, Z

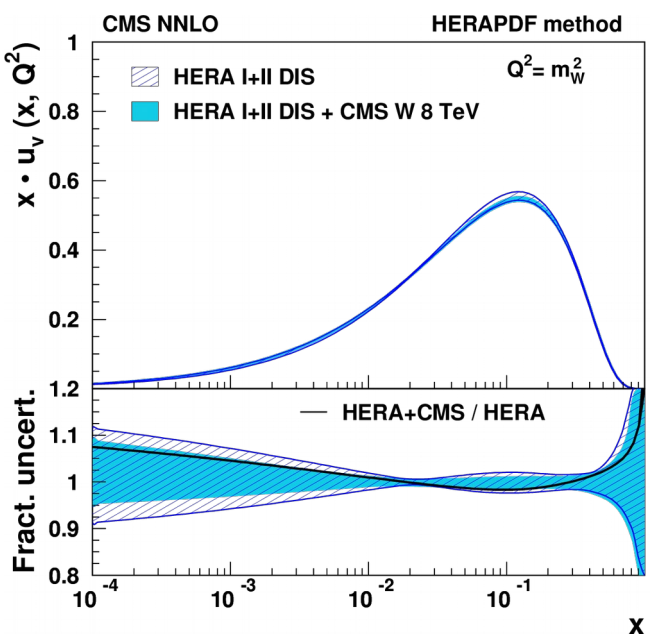
The most precise W analyses:

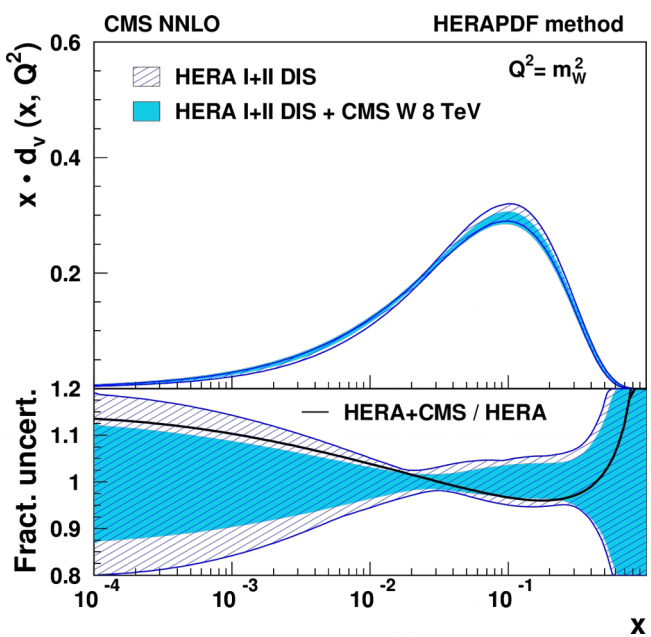
- ATLAS W at 7 TeV EPJC77(2017)367 (together with Z)
- CMS at 8 TeV EPJC76(2016)469
- W^+, W^- production difference encoded in W-asymmetry:

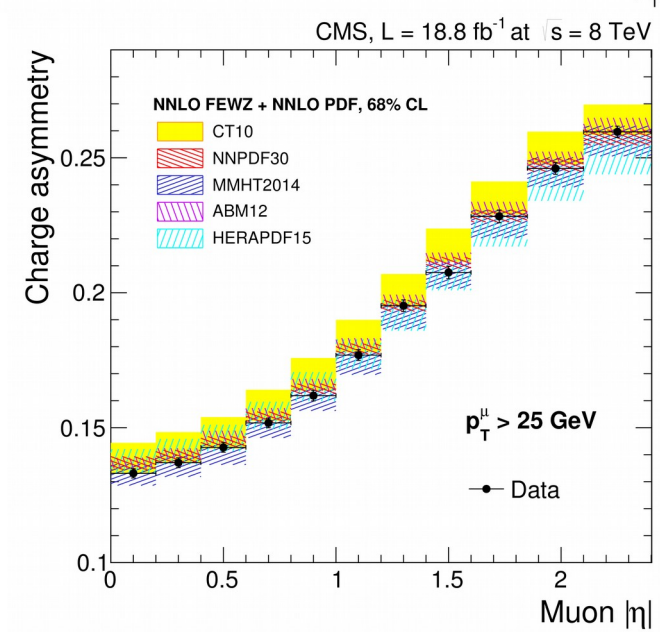
$$A_\ell = \frac{d\sigma_{W+}/d|\eta_\ell| - d\sigma_{W-}/d|\eta_\ell|}{d\sigma_{W+}/d|\eta_\ell| + d\sigma_{W-}/d|\eta_\ell|}$$

- Dedicated QCD analysis allows extraction of PDFs for valence and sea quarks



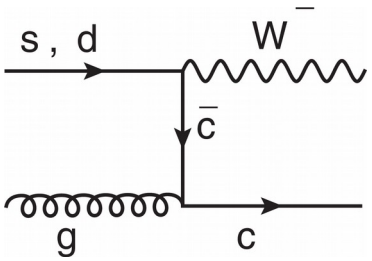




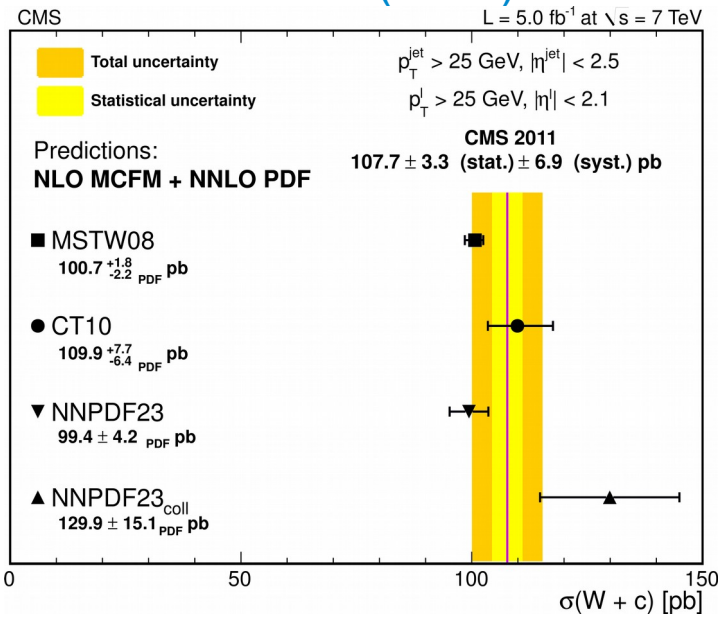


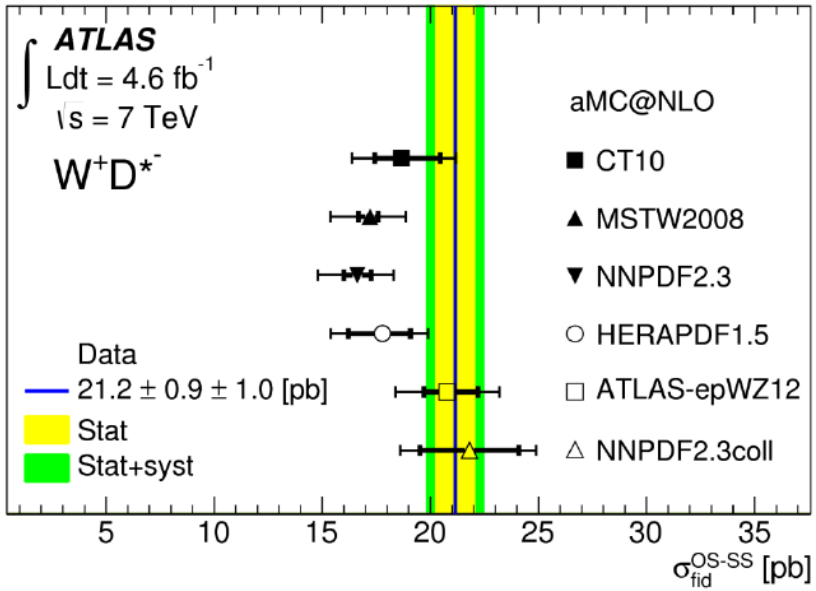
W plus c-jets

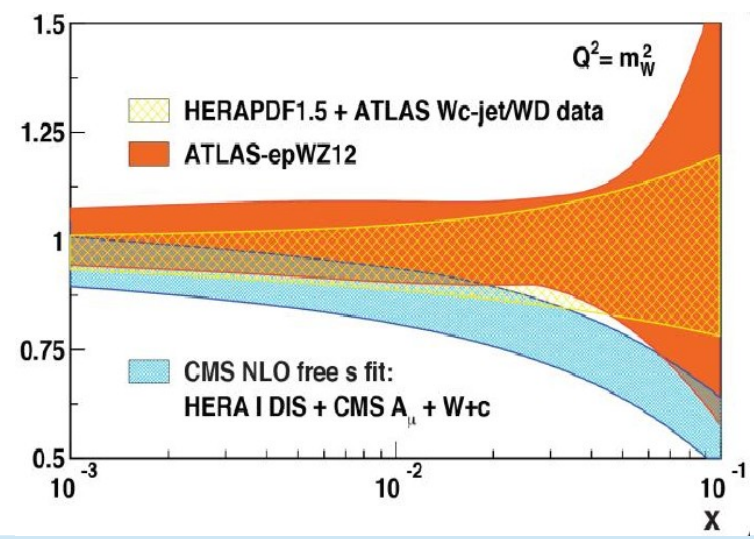
ATLAS data for W+D*- prefer equal (i.e. enhanced) strangeness: JHEP05(2014)068



CMS JHEP02(2014)013



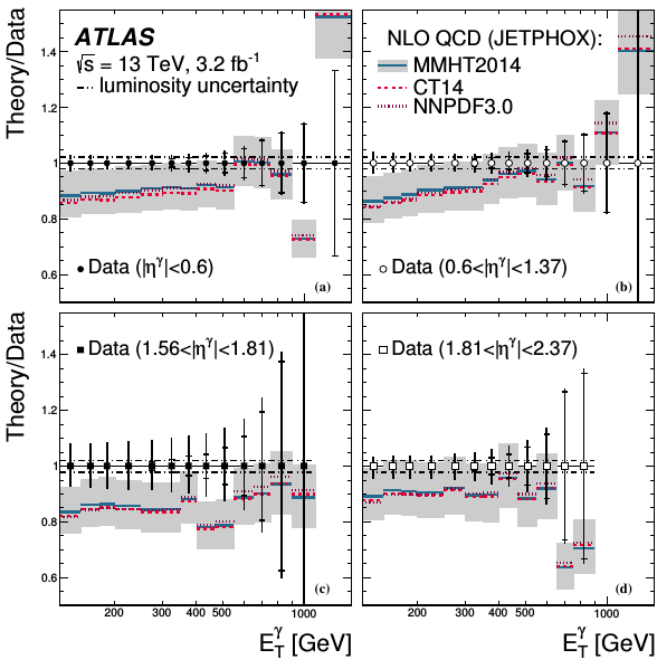




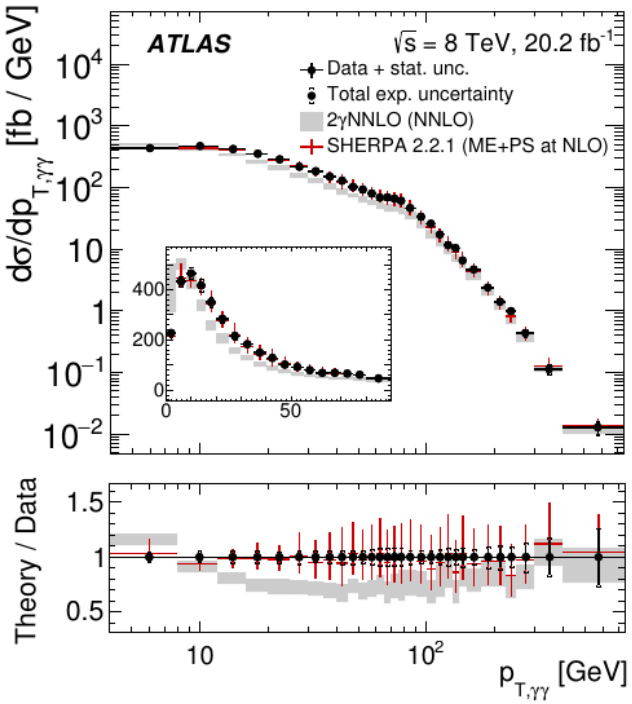
CMS favours the CT10 level of strangeness suppression rs ~0.7 rather than either rs ~0.5 or equal rs =1.0

Photon and Photon plus Jets

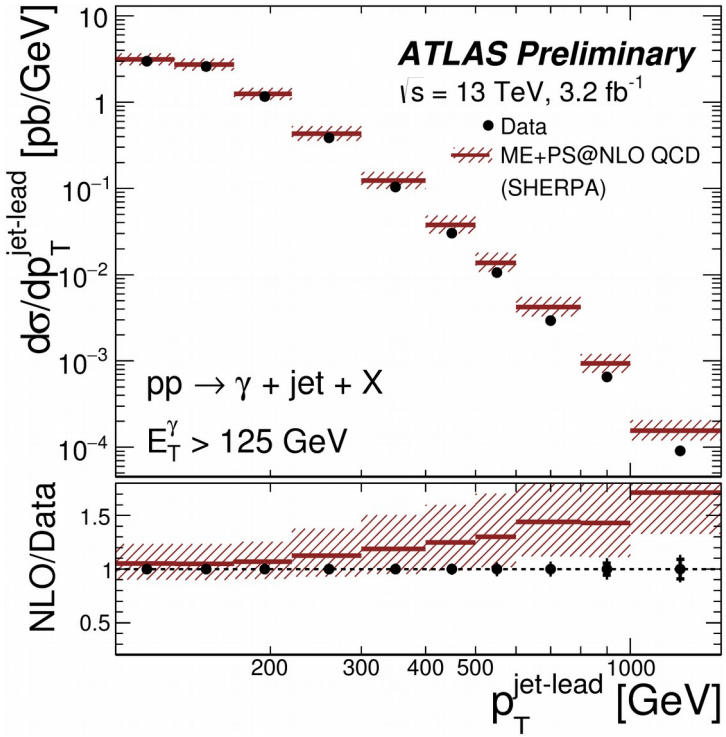
Inclusive photons:
PLB770(2017)473



di-photon:
PRD95(2017)112005



Photon+jets:
ATLAS-CONF-2017-059



- Inclusive photon cross section well reproduced by Pythia8 and Sherpa2 LO except for very high ET (>500 GeV)
- NNLO prediction available!
- Sherpa 2 with NLO has good description of photon kinematic
- But too hard Jet pT in gamma+jets events