LP2019

QCD at the LHC

Lauren Tompkins for the TOTEM, ALICE, ATLAS, CMS and LHCb collaborations

TOTEM

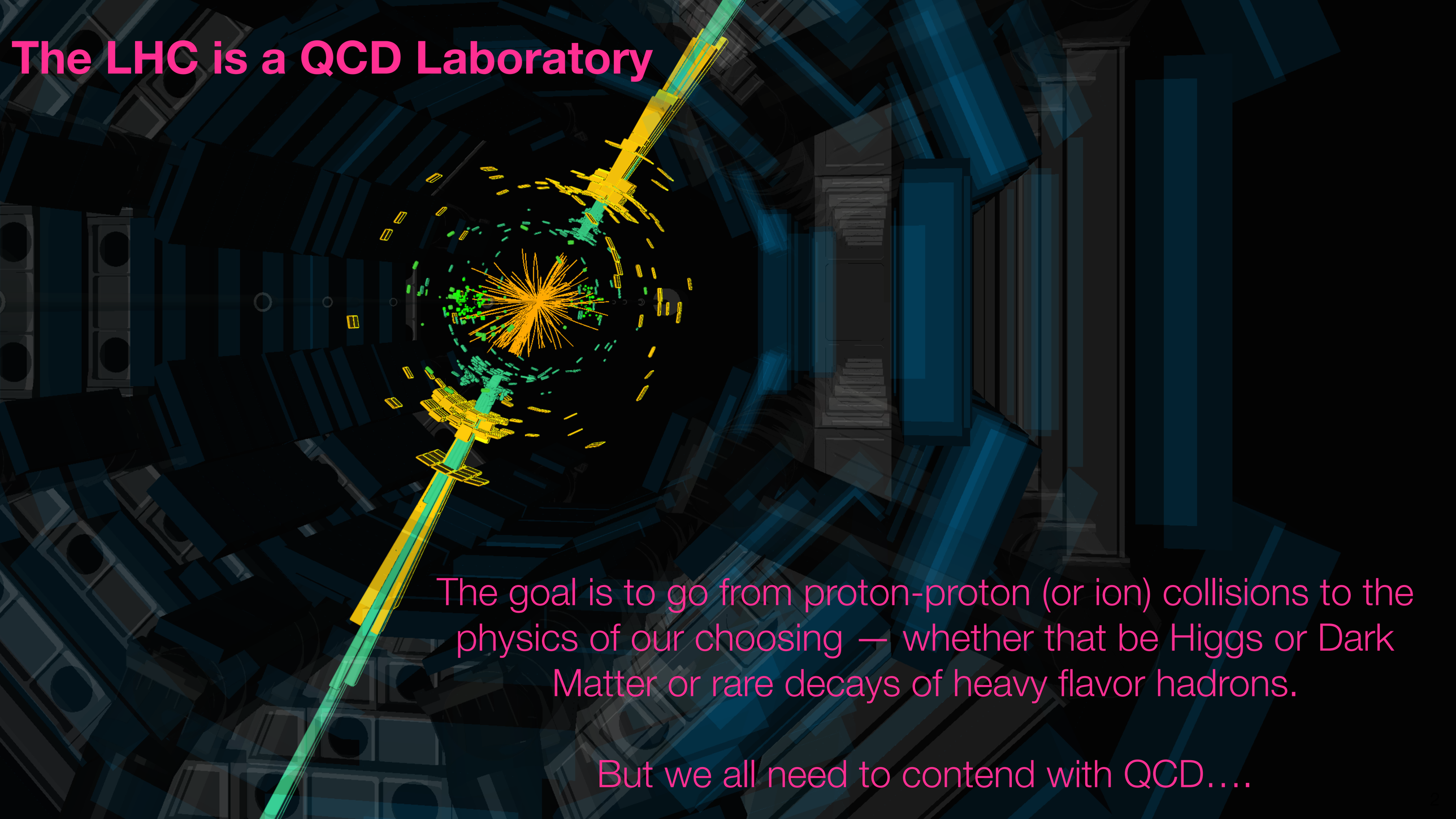
ALICE

ATLAS EXPERIMENT

CMS

LHCb

The LHC is a QCD Laboratory



The goal is to go from proton-proton (or ion) collisions to the physics of our choosing — whether that be Higgs or Dark Matter or rare decays of heavy flavor hadrons.

But we all need to contend with QCD….

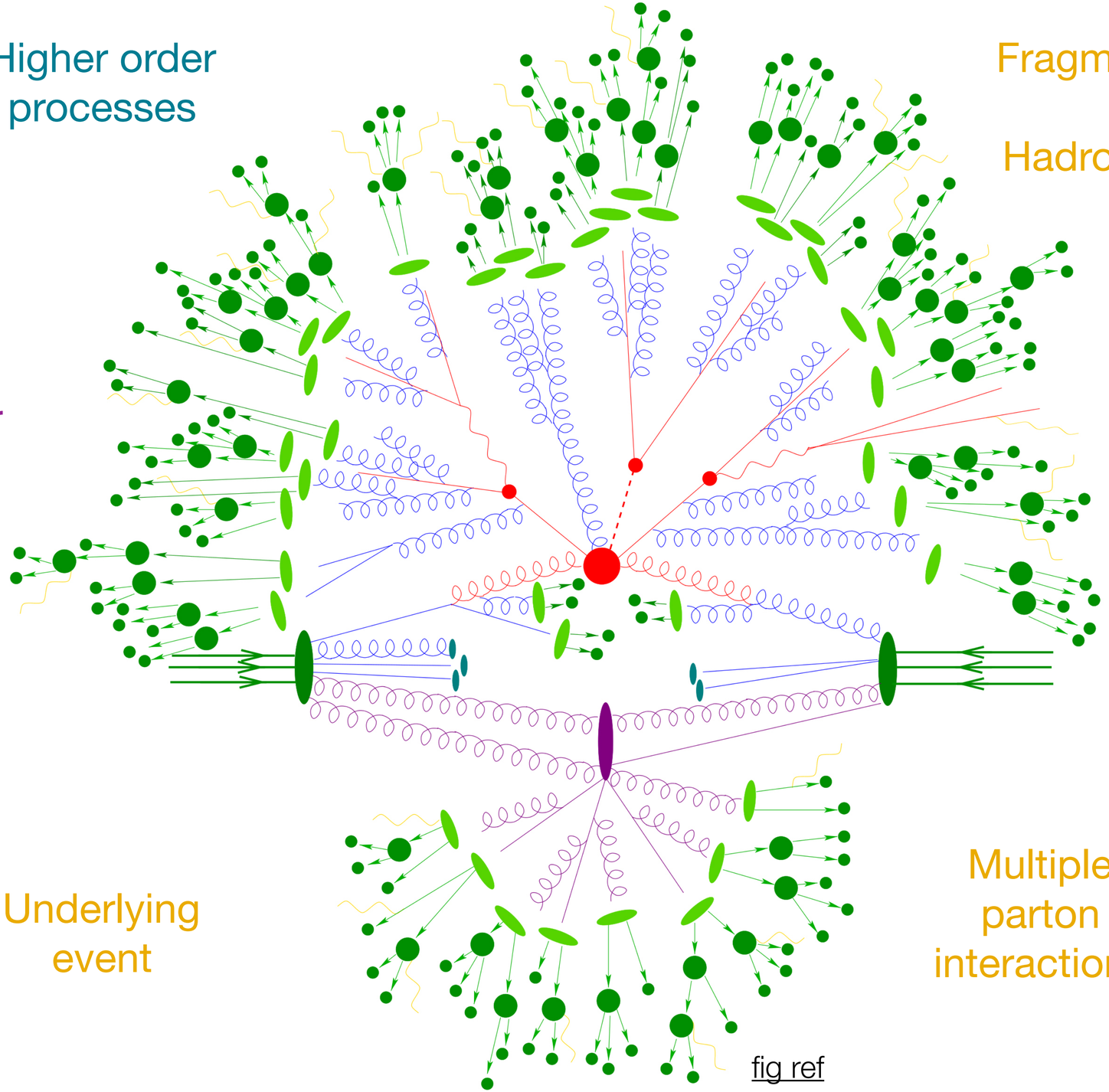

Higher order processes
Fragmentation & Hadronization
Factorization Scale
Renormalization Scale
Parton Shower
Initial & Final State Radiation
Hard Scatter/ Partonic cross-section
Parton Distribution Functions
Underlying event
Multiple parton interactions

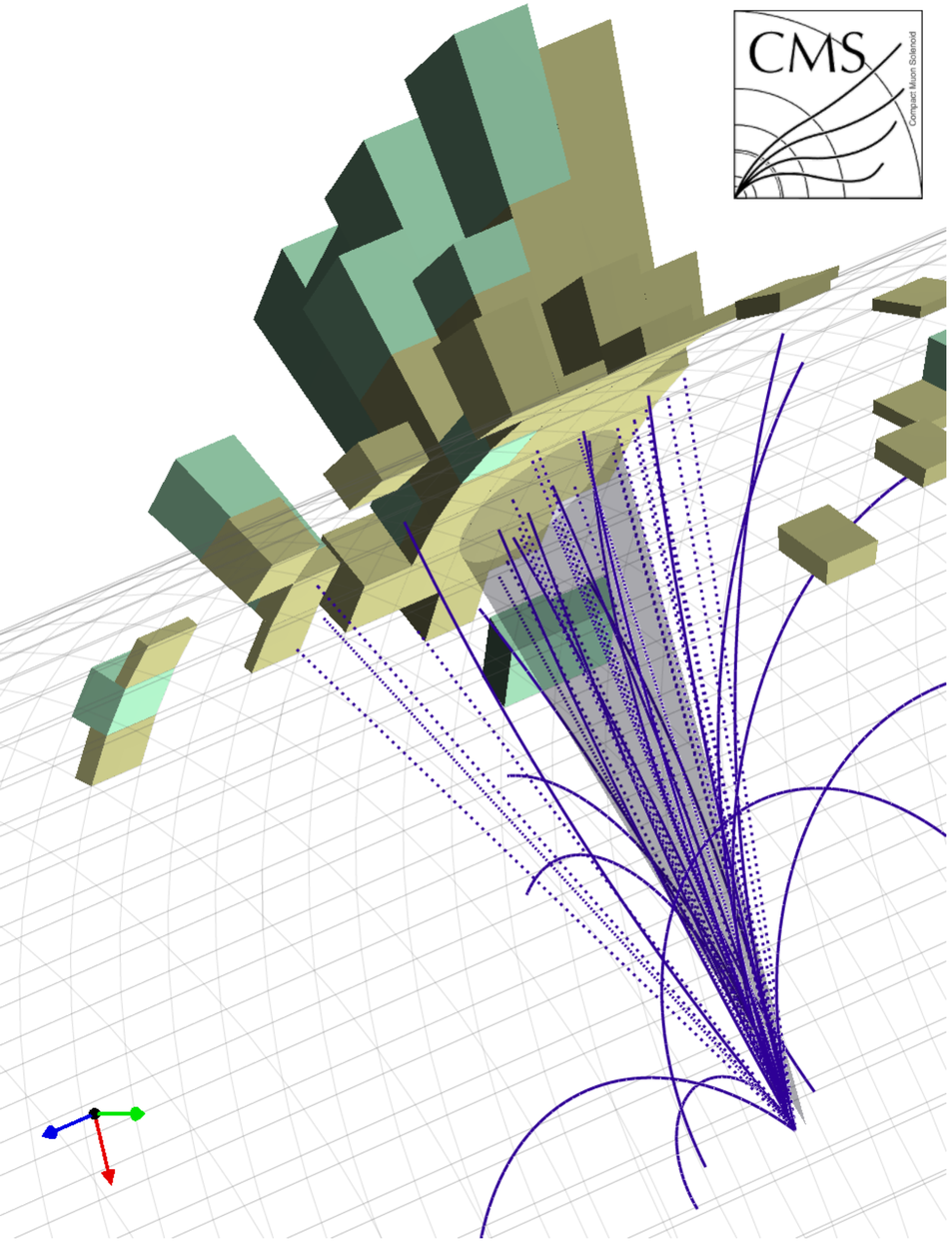
fig ref

The QCD @ LHC Lab Tour Itinerary

- Soft and forward physics
- Partonic structure of the proton
- Multi-scale dynamics of jet-based observables
- Measurements Sensitive to pQCD

Highlighting a ***selection of results*** from the past year.
Please visit the references for more information!

Experimental tools for probing QCD



- Building blocks:
  - Charged hadrons from tracking detectors
  - Calorimeters to capture full hadronic interactions
- Look at event level quantities *or* build ***jets:***
  - Made out of tracks, calorimeter deposits or combination of both
  - Probe different physics by tweaking algorithmic parameters: effective radius, treatment of soft radiation
  - Build sensitive quantities out of jet constituents
- Correct to particle level quantities by *unfolding*
- Sometimes use high energy, colorless particles as probes:
  - Photons, Ws, Zs

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Elastic p-p cross-section @ 2.76 & 13 TeV— TOTEM
arXiv:1812.08610; arXiv:1812.08283 *

Inclusive single diffractive dissociation — ATLAS
ATLAS-CONF-2019-012 *

Forward energy vs pseudo rapidity & track multiplicity— CMS
Eur. Phys. J. C 79 (2019) 391; *
CMS-PAS-FSQ-18-001

Underlying event in Z boson events—ATLAS
arXiv:1905.09752 *
Particle production vs UE activity — ALICE *

Forward jet cross-sections in p-Pb — CMS
JHEP 05 (2019) 043
Dijet production with leading proton — CMS
CMS-PAS-FSQ-12-033

* = result presented here

Forward and Soft QCD

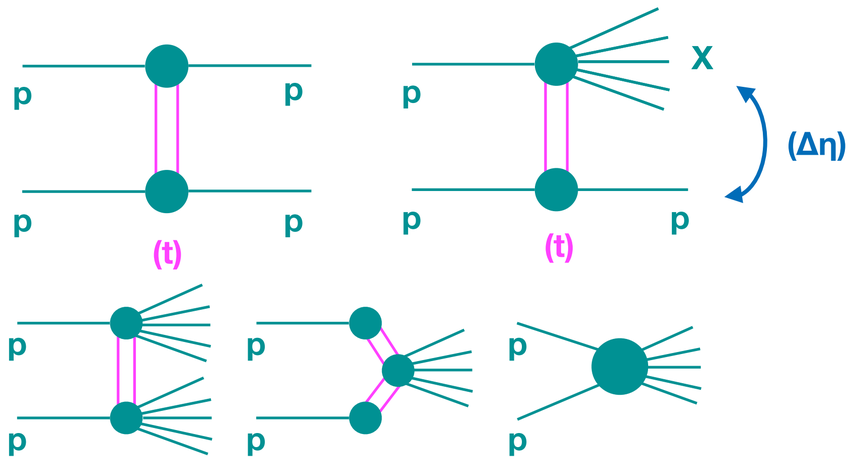
- Realm of non-perturbative or semi-perturbative QCD:
  - Low momentum transfer processes in a strong(er) coupling regime
  - Important for understanding cosmic ray showers, proton structure, has theoretical connections to string theory [ref]
- What's interesting?
  - Testing models of interactions via colorless exchange
  - Differential distributions of energy and particle multiplicities for generic pp collisions
  - Properties of soft radiation accompanying hard processes (underlying event)

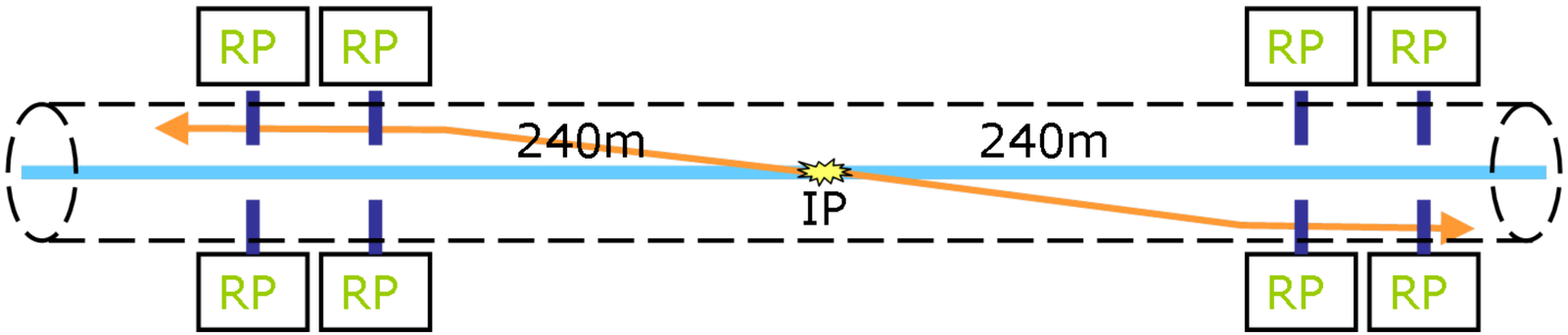
Particle Zoo

Forward and Soft QCD: Elastic and Diffractive processes

arXiv:1812.08610
ATLAS-CONF-2019-012

- ~20% of pp collisions are elastic, ~20% are inelastic but involve the exchange of colorless objects: diffractive processes
- Can study through *tagging and measuring* out-going protons





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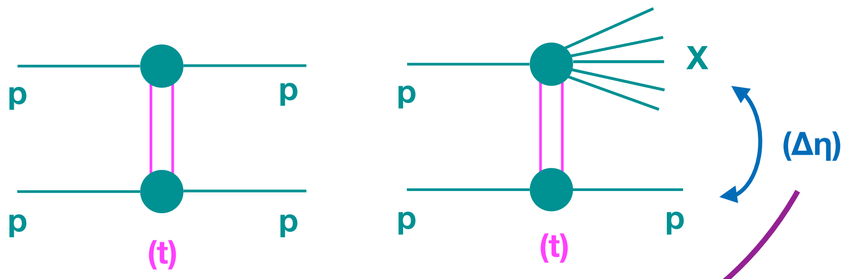

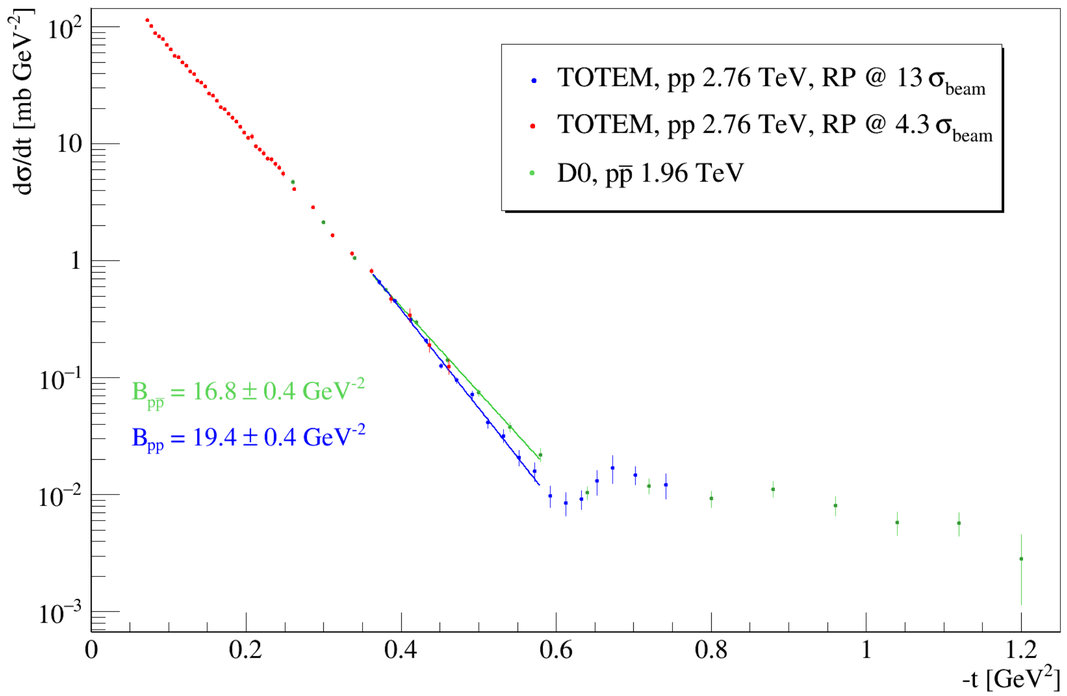

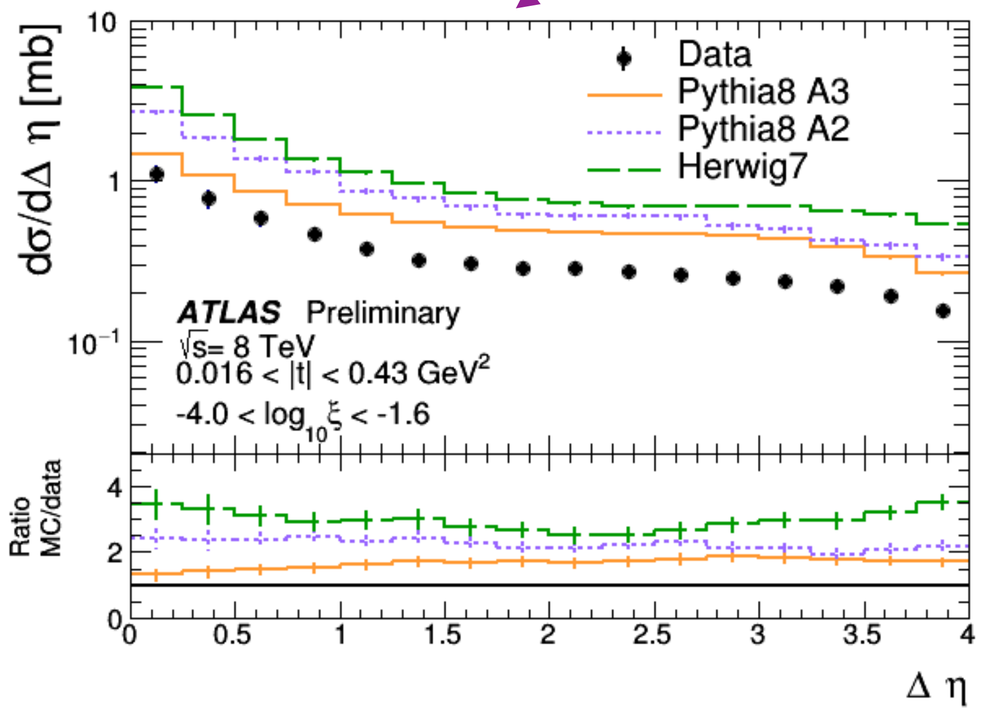

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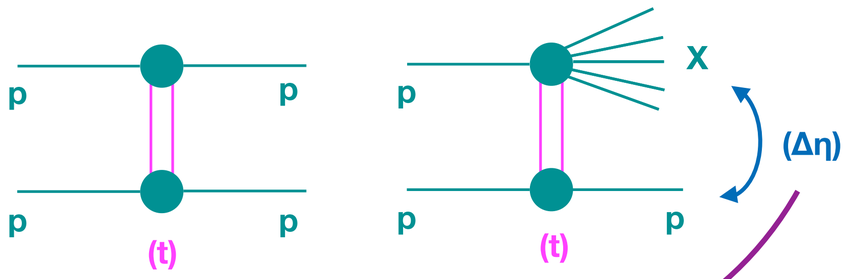
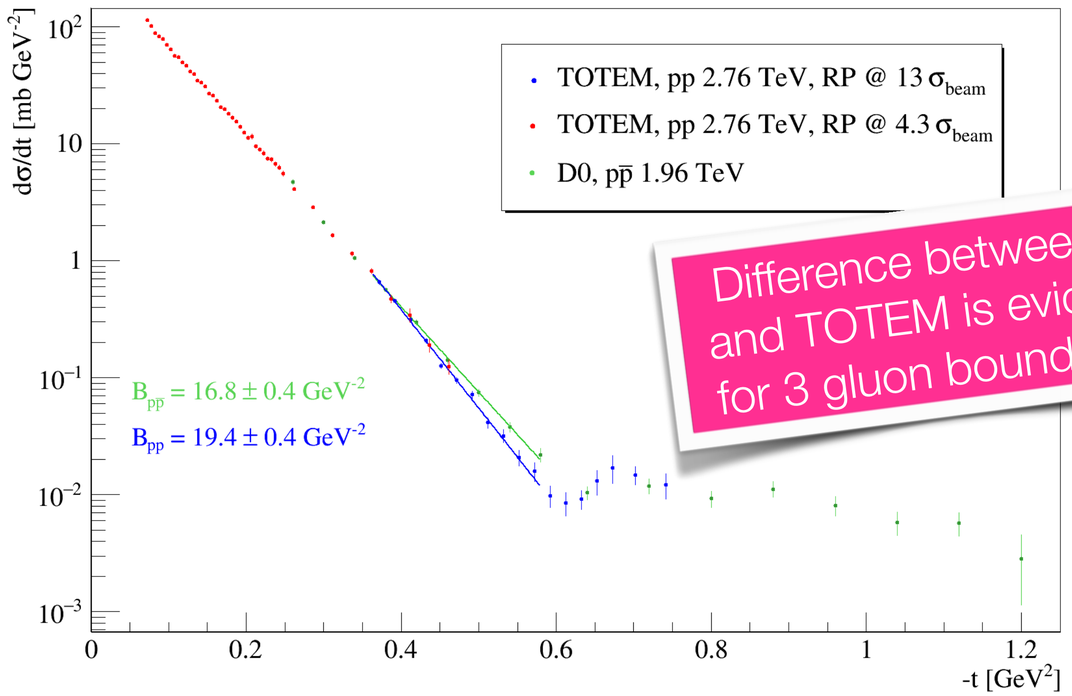
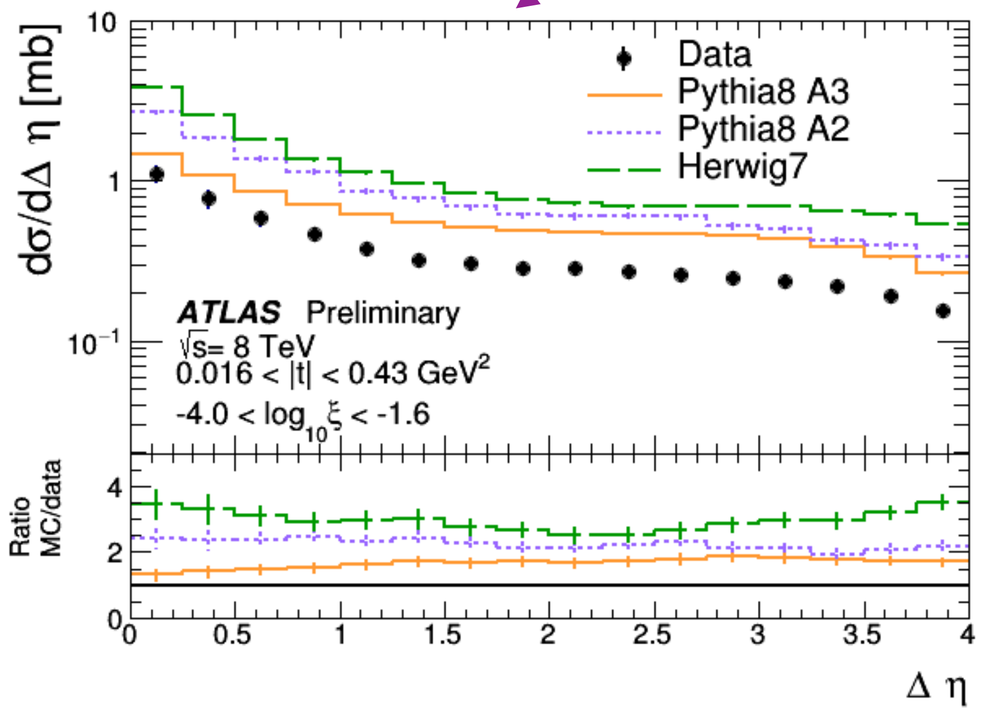




Difference between D0 and TOTEM is evidence for 3 gluon bound-state



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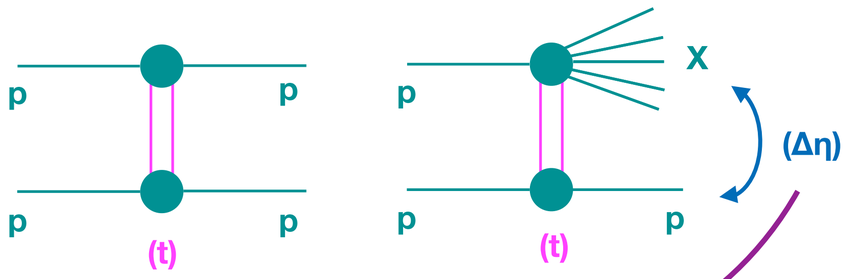

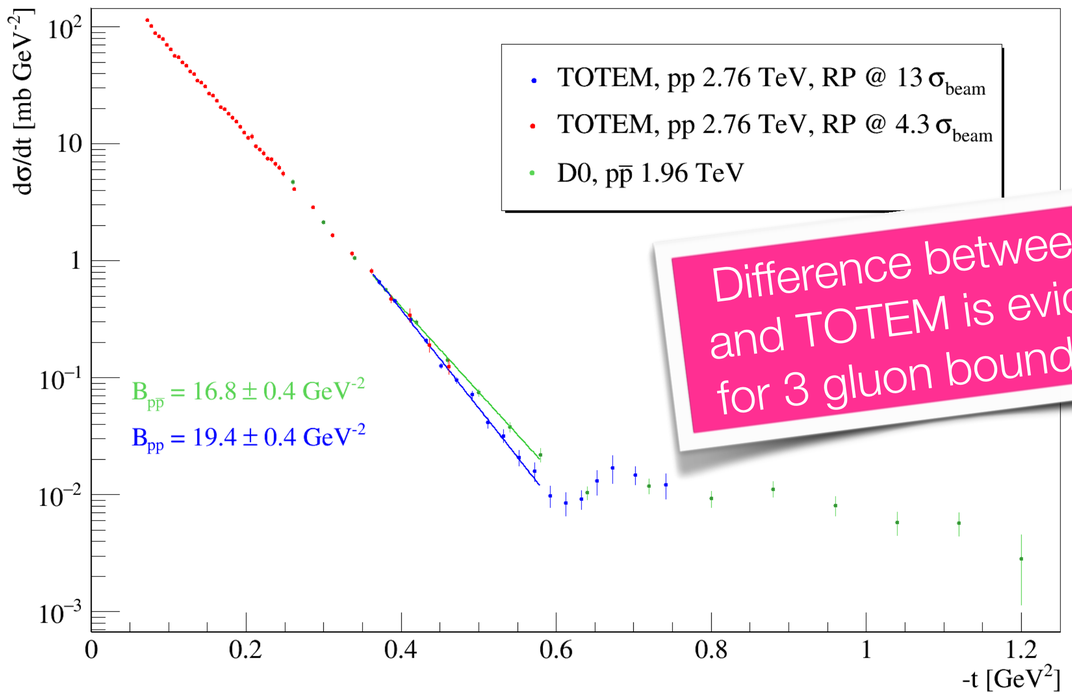

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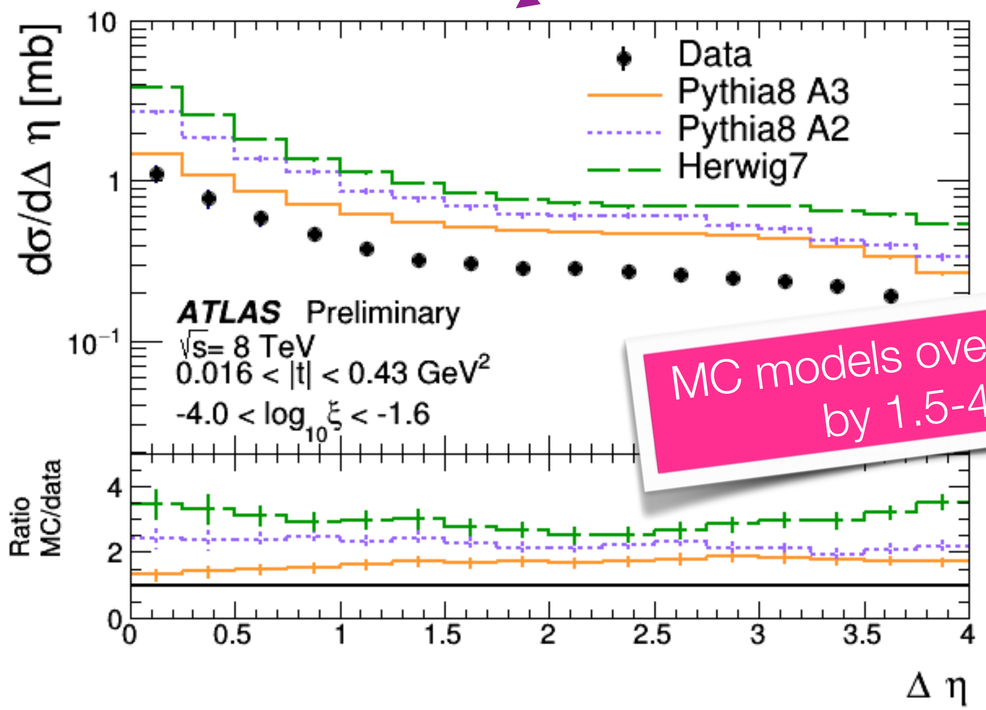
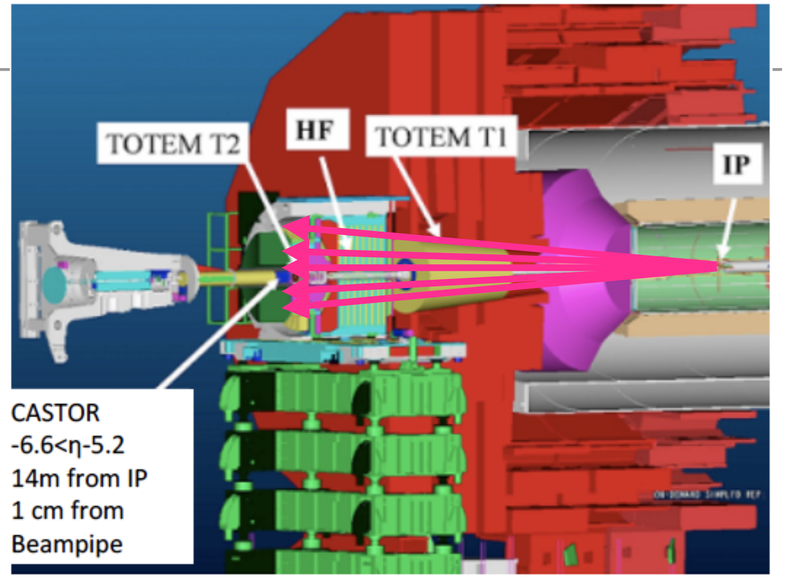


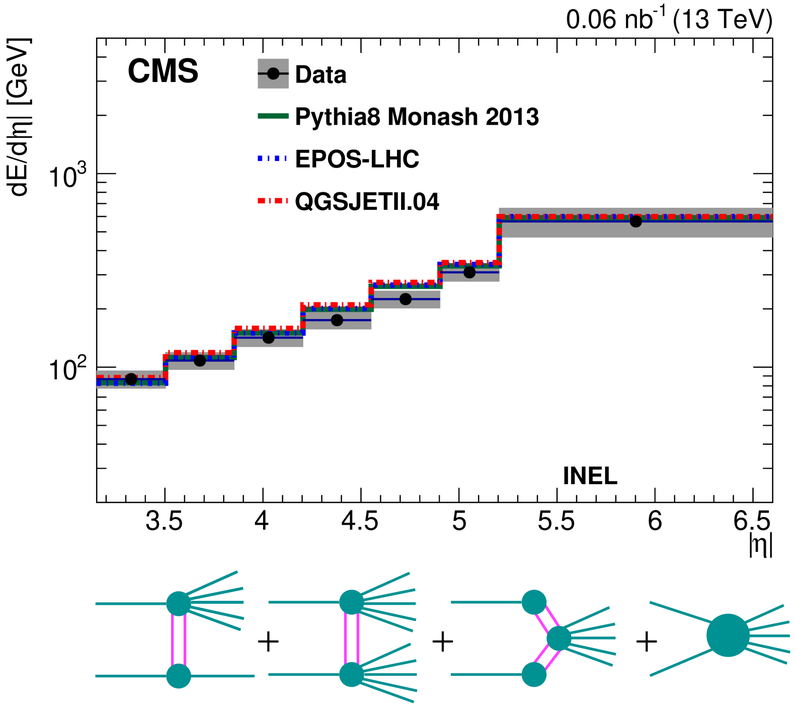
MC models over predict by 1.5-4x

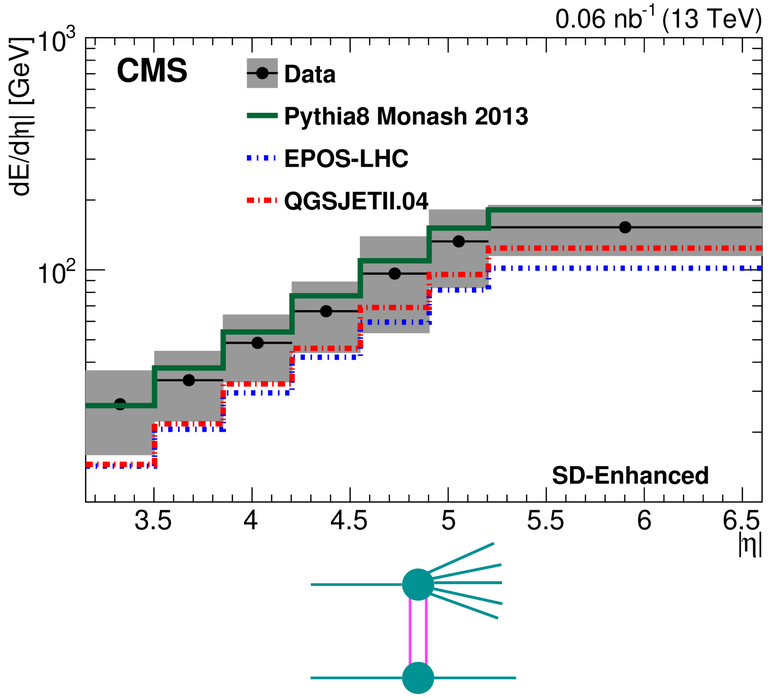
Eur. Phys. J. C 79 (2019) 391

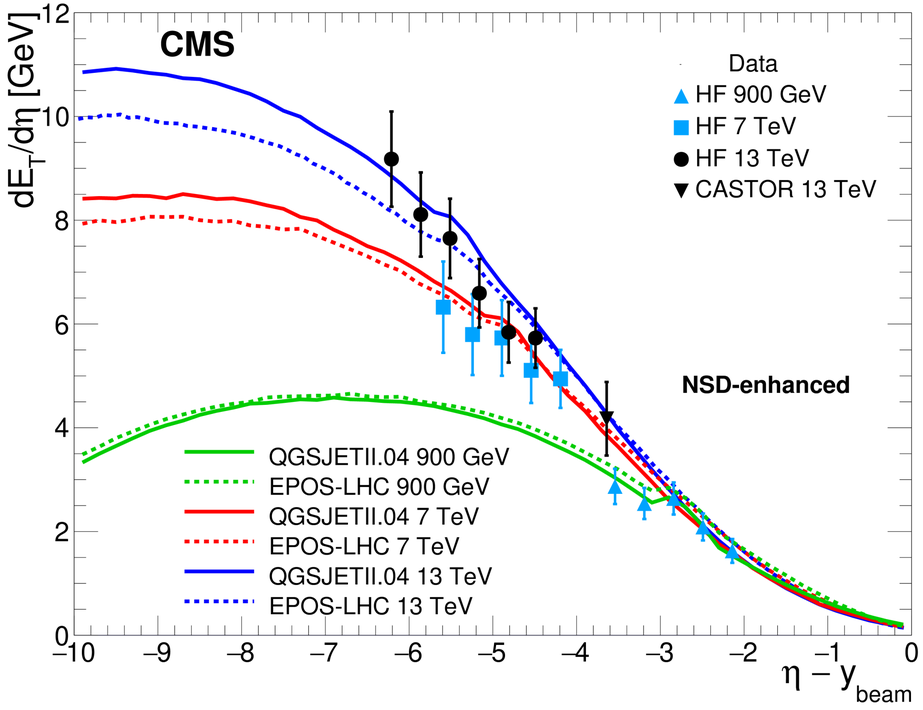
Forward and Soft QCD: Forward Energy Density

- Measurements of forward energy flow relatively unexplored, particularly in “soft” phase space
- Inclusive measurements agree well with models but discrepancies exist in single diffractive phase space
- Data support limiting fragmentation hypothesis: *forward energy flow independent of* $\sqrt{s}$









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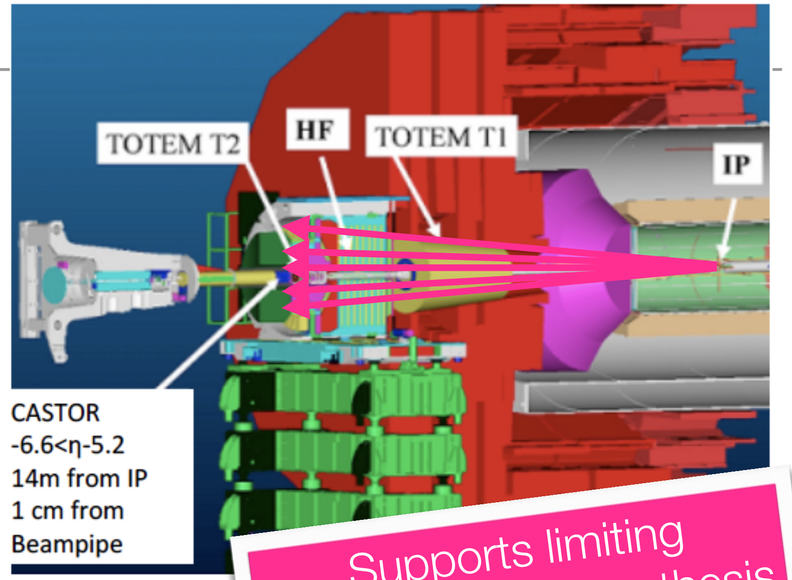
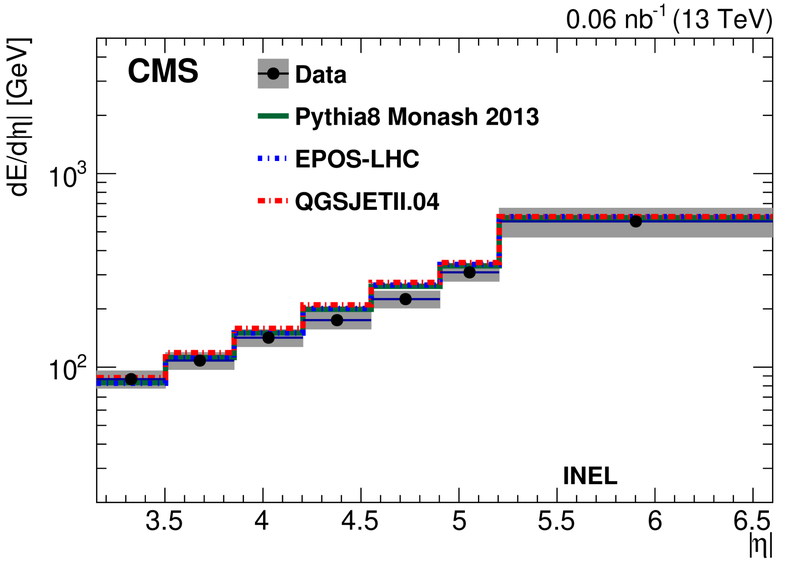
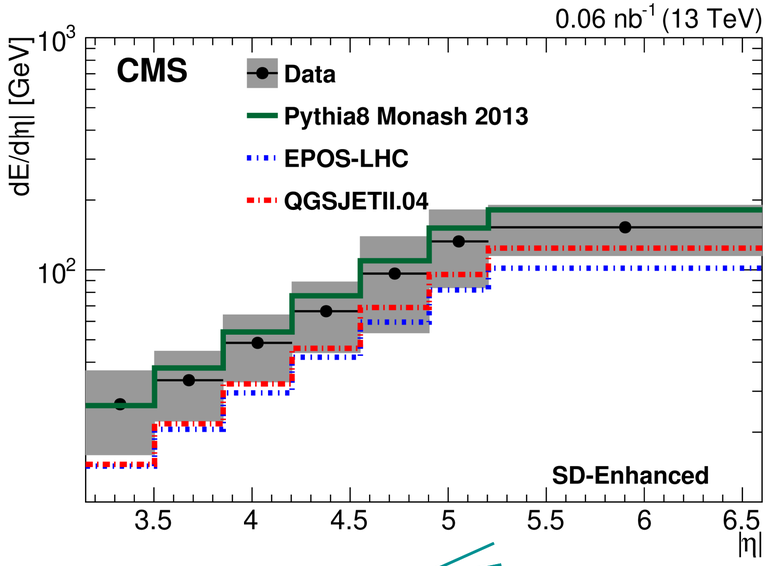
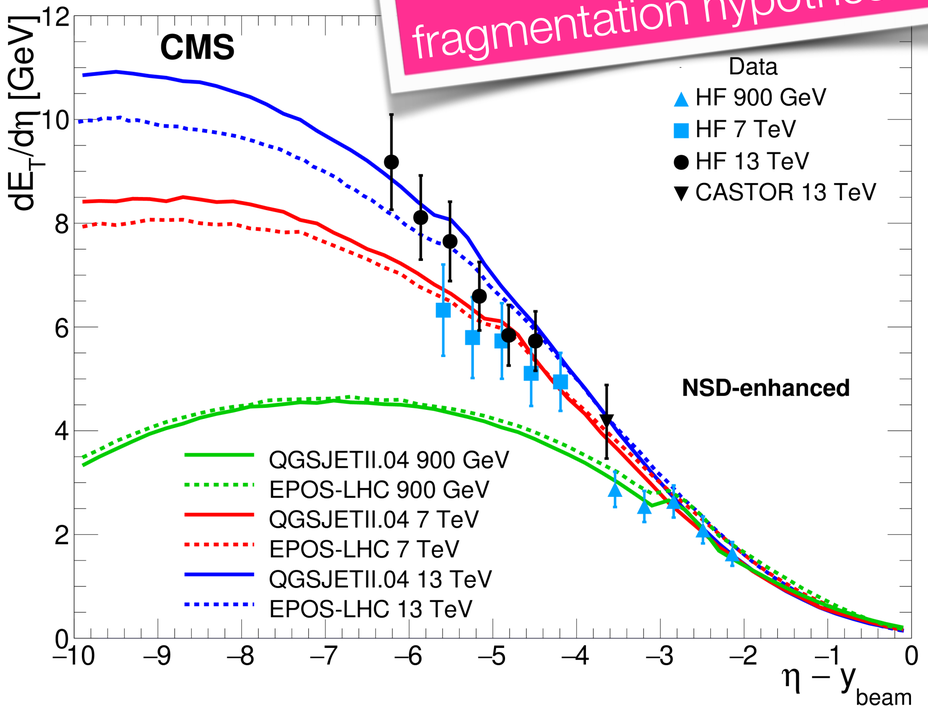


Supports limiting fragmentation hypothesis



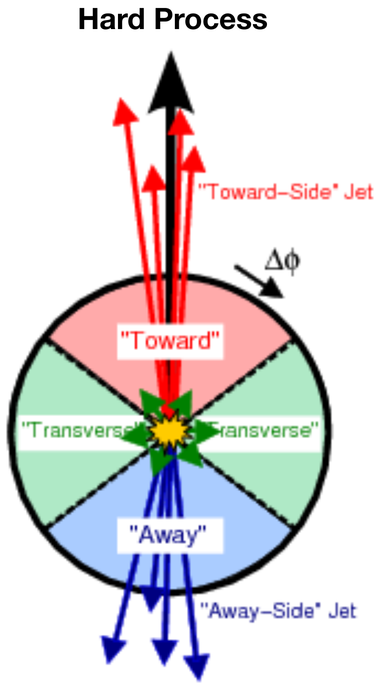


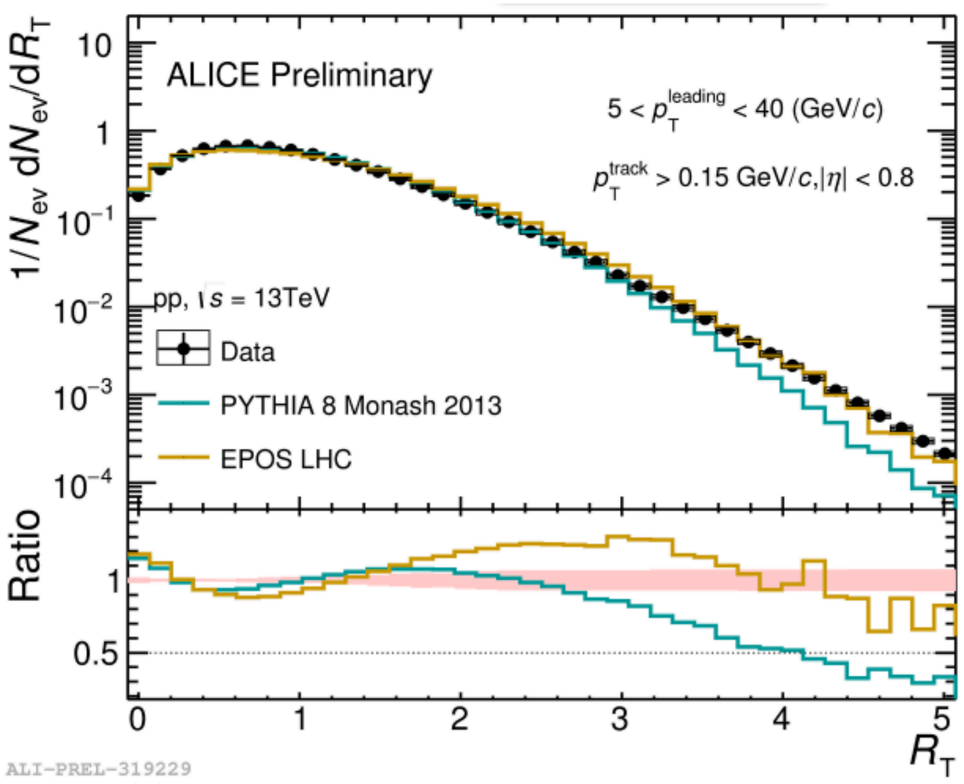


ATLAS-CONF-2019-012
ALI-PREL-319229

Forward and Soft QCD: Underlying Event

- Underlying event measures hadronic activity not related to the primary "hard" scattering process:
  - Important for measurements sensitive to generic hadronic activity: W mass, rapidity gap based selections, etc.





$$R_T = \frac{N_{inclusive}}{< N_{inclusive} >}$$

- Main contribution to UE is multiple parton interactions (MPI)
  - R_T can select hard scatterings with different MPI activity

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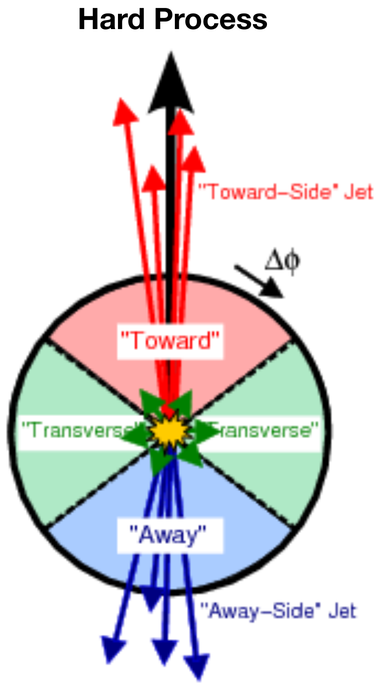
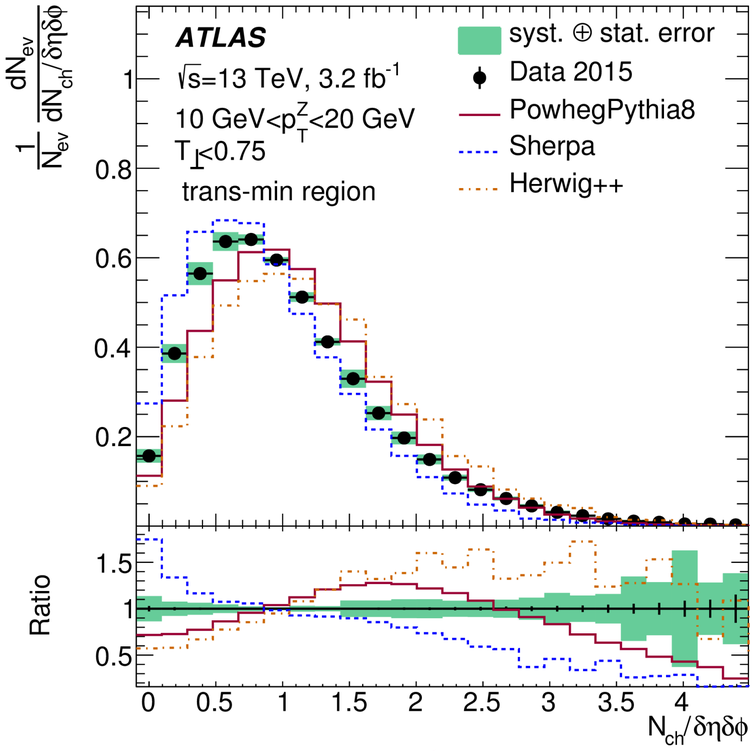
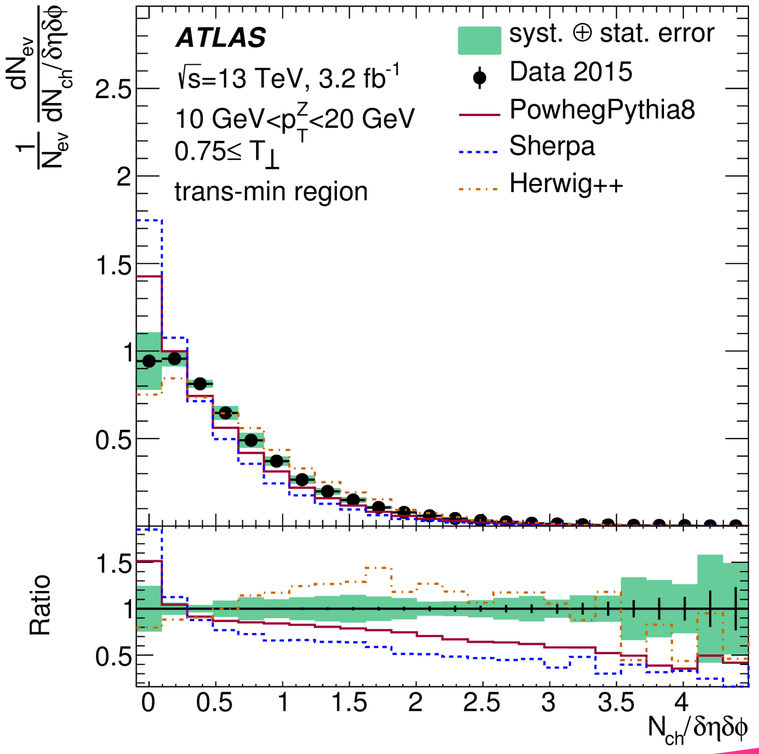
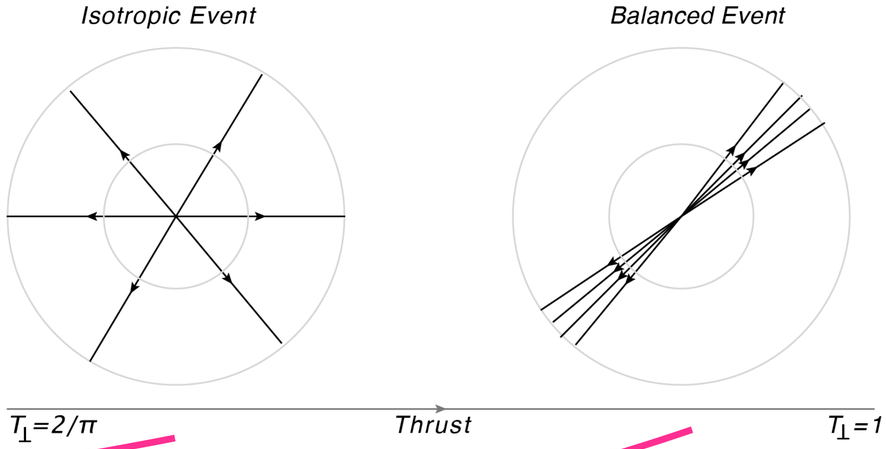








The QCD @ LHC Lab Tour Itinerary

- Soft and forward physics
- Partonic structure of the proton
- Multi-scale dynamics in jet-based observables
- Measurements Sensitive to pQCD

W+charm @ 8 TeV — CMS—
CMS-PAS-SMP-18-013 ✱
W+charm @ 8 TeV —ATLAS —
ATL-PUB-2019-016 ✱
W+charm @ 13 TeV — CMS—
Eur. Phys. J. C 79 (2019) 269 ✱
W&Z production @ 2.76TeV —ATLAS
arXiv:1907.03567

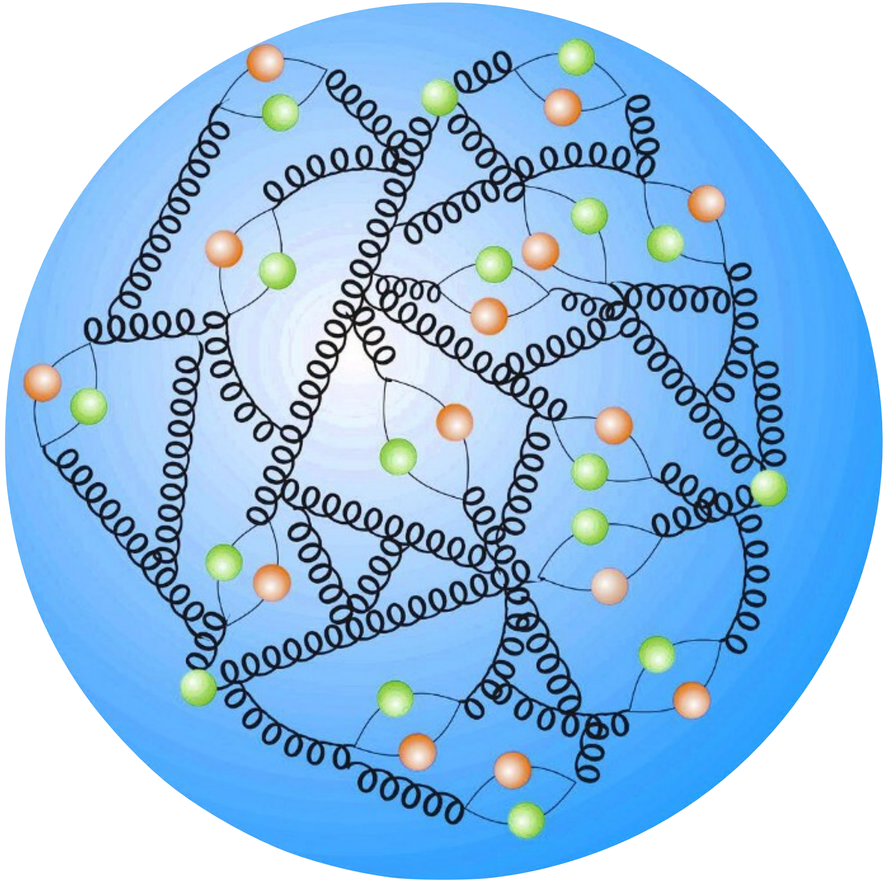
Forward top quark production — LHCb —
J. High Energ. Phys. (2018) 2018: 174

Double parton scattering (DPS) in ZZ —ATLAS—
Phys. Lett. 790 (2019) 595
Evidence for DPS in WW — CMS —
CMS-PAS-SMP-18-015

✱ = result presented here

Partonic Structure of the Proton

- Experimental probes of the dynamics of protons:
  - See into the proton using probes which are unique to the partonic structure
- What's interesting?
  - Uncertainty in parton distribution functions critical in theory comparison for many cross-section measurements
  - Flavorful content of proton becoming important at LHC energies
  - Multiple simultaneous parton interactions can be perturbative at LHC energies, allowing for precise comparisons with data

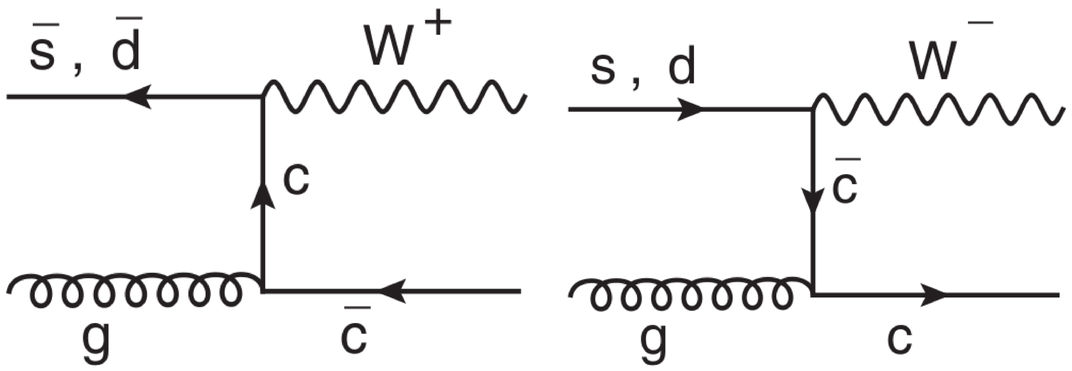


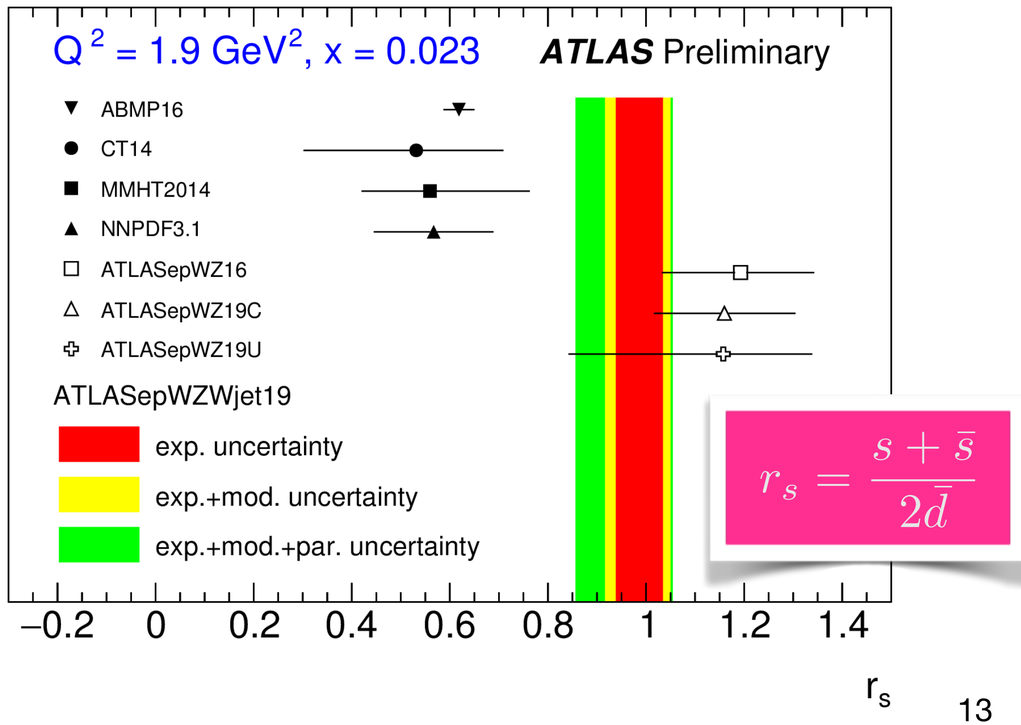
DESY

Partonic Structure of the Proton: Strange quark content

ATL-PUB-2019-016

- W+c production sensitive to strange quark content in proton:
  - Tag with leptonic Ws and D* mesons
  - Can be used to constrain strange quark parton distribution functions
- Previous ATLAS measurements @ 7 TeV showed tension with global PDF fits on strange quark suppression
  - Global fits include neutrino charm production data — neutrino-iron DIS and inclusive charm production measurements
  - 2019 ATLAS update with inclusive W data at 8 TeV maintains tension





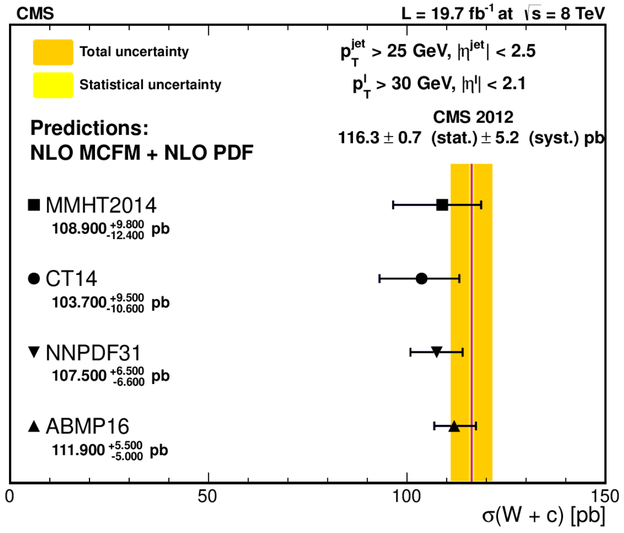
$$r_s = \frac{s + \bar{s}}{2\bar{d}}$$

CMS-PAS-SMP-18-013
Eur. Phys. J. C 79 (2019) 269

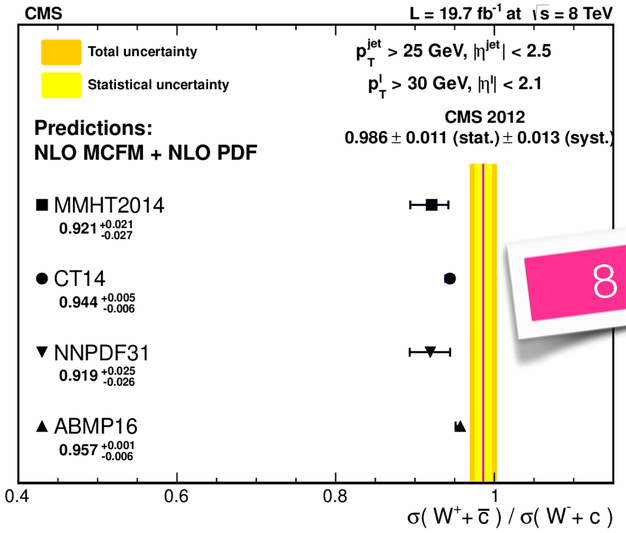
Partonic Structure of the Proton: Strange quark content

- 8 TeV CMS measurements:
  - Cross-section agrees with global PDFs, although high
  - Ratio of W^+/W^- disagrees with global PDFs
- 13 TeV CMS measurements:
  - Good agreement with PDFs except ATLAS-derived one
  - Note: parameterization uncertainty for ATLAS PDF not used in the comparison, recent paper shows CMS and ATLAS data not in tension*

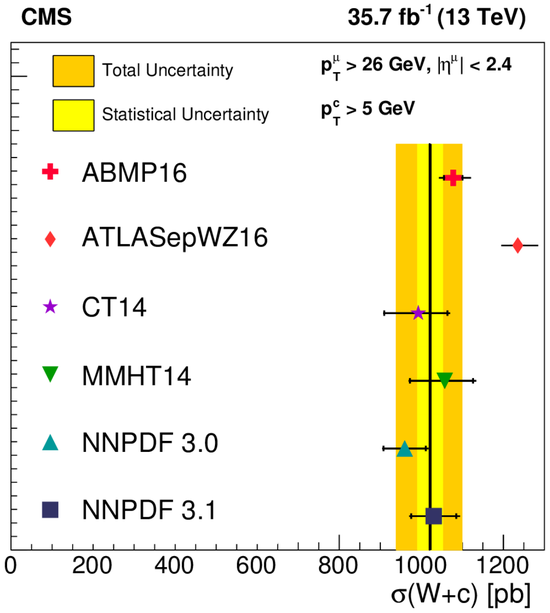
$\sigma(W + c)$

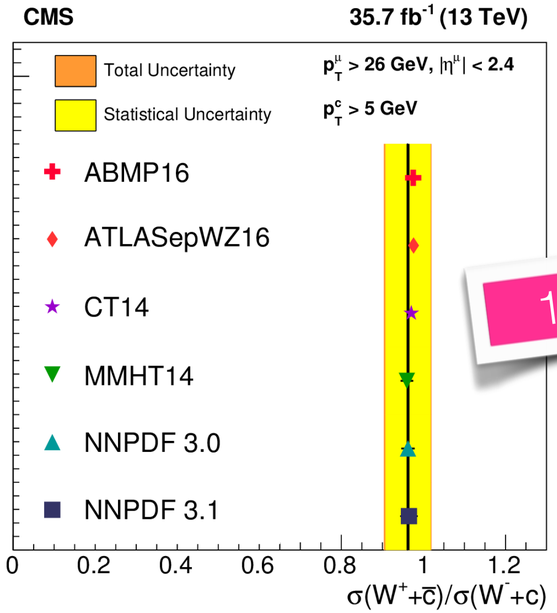


$\sigma(W^+ + \bar{c})/\sigma(W^- + c)$



8 TeV





13 TeV

*Phys. Rev. D 98, 014027 (2018)

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Eventshapes —CMS
JHEP 12 (2018) 117 ✱
Jet Fragmentation In Z Events — LHCb
arXiv:1904.08878 ✱
Jet Fragmentation, Quark Gluon Properties— ATLAS
arXiv:1906.09254 ✱
Gluon splitting to b-quarks — ATLAS
Phys. Rev. D 99 (2019) 052004 ✱
Charm-quark jet properties — ALICE
arXiv:1905.02510
Azimuthal separation of 2&3-jet events —CMS
arXiv:1902.04374 ✱
kT splitting scales — ALICE—
ALI-PREL-310018-43 ✱
Measurement of Lund Plane—ATLAS
ATLAS-CONF-2019-035 ✱
Λ_c^+ production — ALICE
JHEP04(2018)108
Ks & Λ_0 production in t-tbar — ATLAS
arXiv:1907.10862
Jet cross-sections versus anti-kT jet size — CMS
CMS-PAS-SMP-19-003 ;
ALICE — ALI-PREL-315682-725
Substructure for Dijet, W and Top jets — ATLAS
arXiv:1903.02942

✱ = result presented here

Multi-scale dynamics in jet-based observables

- Exploring the evolution of high energy quarks and gluons into hadrons
  - Multi-scale problem which straddles perturbative and non-perturbative effects
  - Good understanding necessary for precise control over observables in *many* physics analyses
- What's Interesting?
  - Testing showering and hadronization models against event shape and individual jet observables
  - Measuring how these variables evolve in a wide range of phase-space and with different jet flavors
  - Probing the structure of hadronic resonances

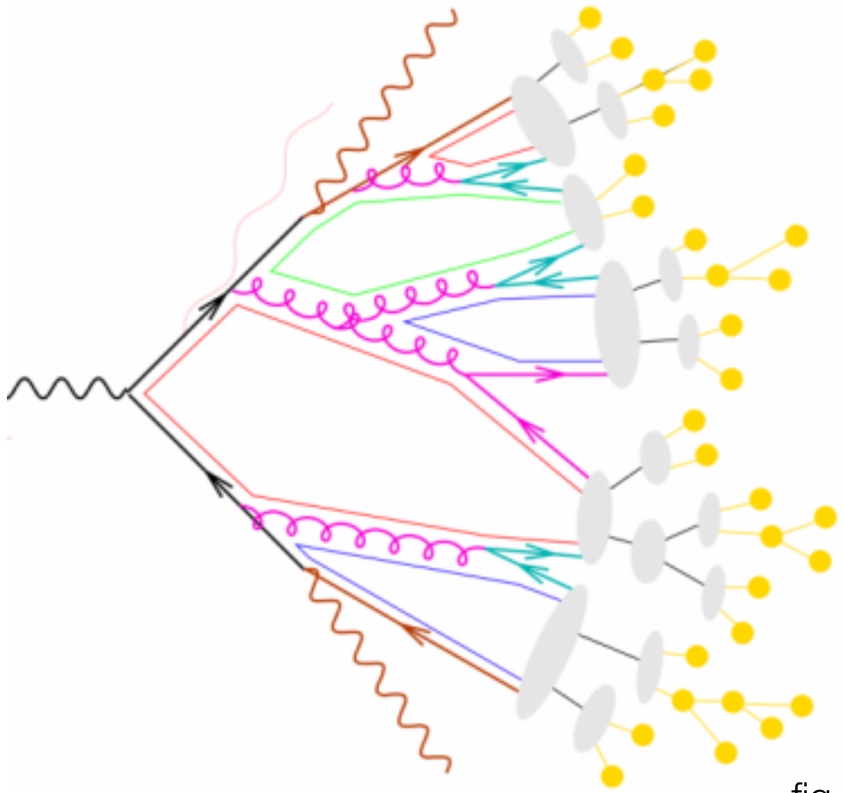


fig ref

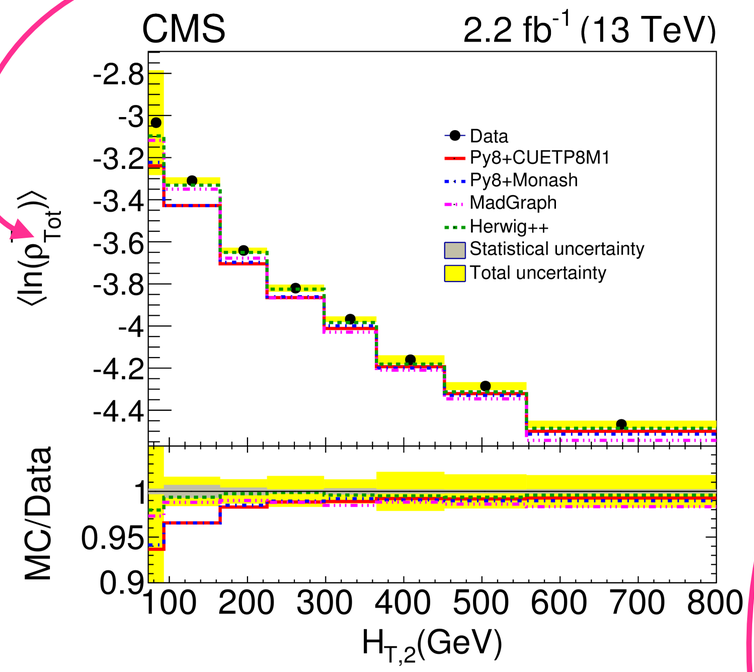
Λ_X Λ_{parton} Λ_{QCD}

JHEP 12 (2018) 117

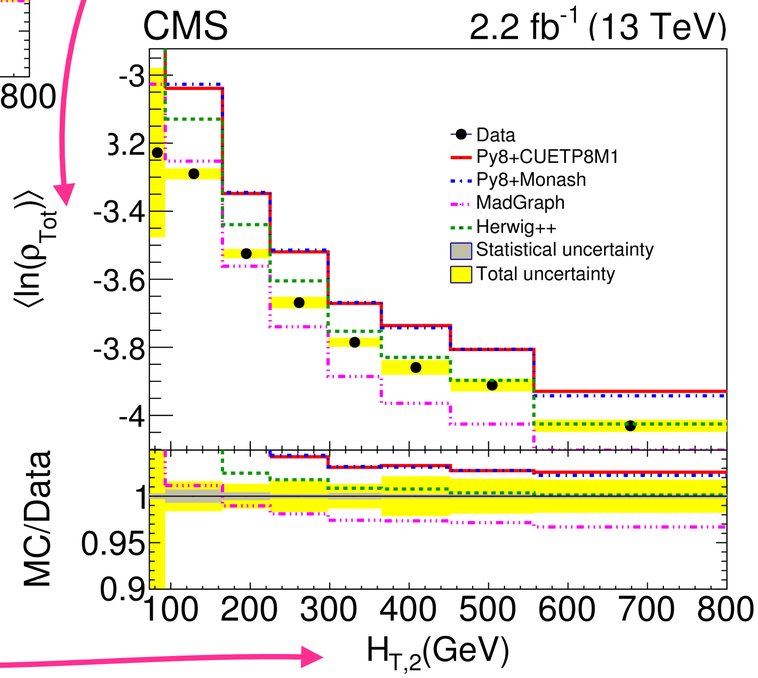
Multiscale Dynamics: Event Shapes

- CMS analysis uses event shape variables calculated using 3-jet events
  - Evaluated versus average of 2 highest p_T jets ($H_{T,2}$) in order to reduce theoretical uncertainties
- Modeling:
  - *Transverse flow* variables well described by all MC models
  - *Total flow* variables best described by Herwig++ (angular ordered parton shower) not well described by Pythia8 (p_T ordered shower). Madgraph (matrix element approach) is more accurate than Pythia
- Distributions (including transverse thrust and jet broadening) in bins of $H_{T,2}$ evaluated in detail in paper!

Transverse Total Jet Mass



Total Jet Mass

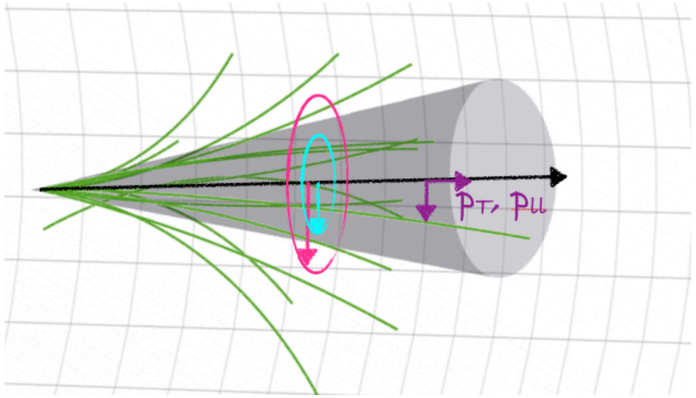


$H_{T,2} = (p_T^{j1} + p_T^{j2})/2$

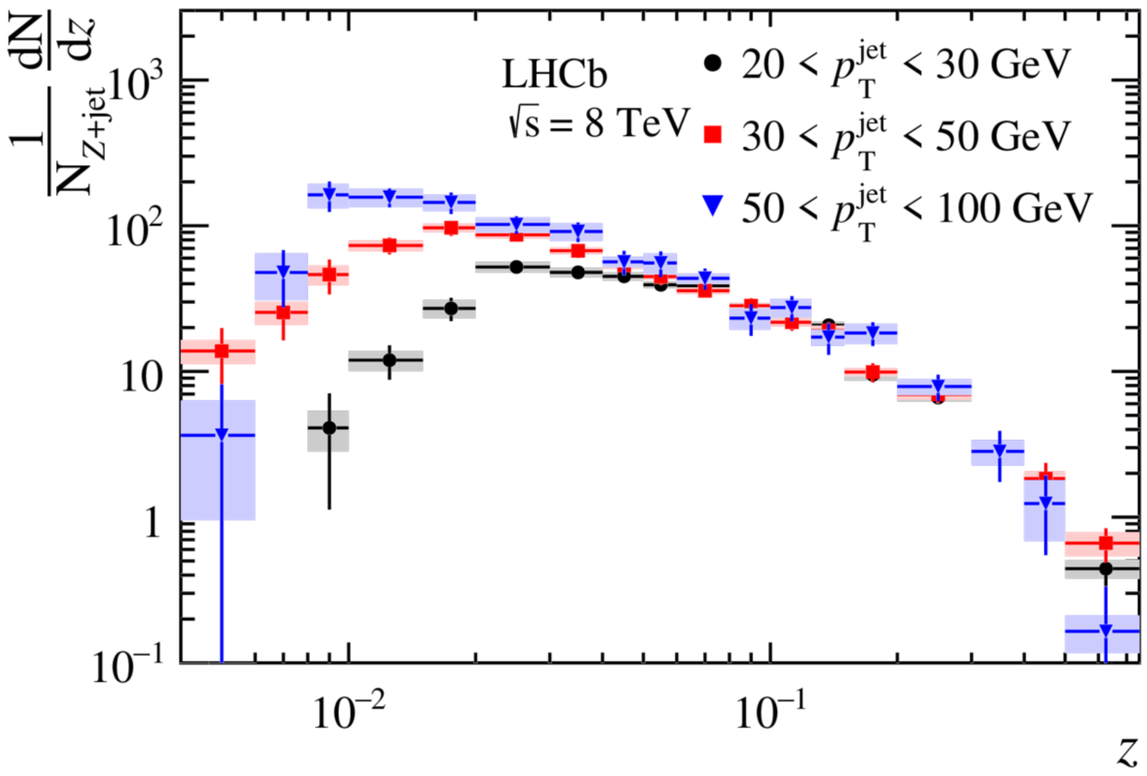
arXiv:1904.08878

Multiscale Dynamics: Jet Constituent Characteristics

- LHCb analysis uses charged hadron properties of jets in Z+jet events in the forward region:



$$z = \frac{\vec{p}_{\rm jet} \cdot \vec{p}_{\rm hadron}}{|\vec{p}_{\rm jet}|^2}$$



- Sample is light quark dominated — useful for q/g discrimination studies

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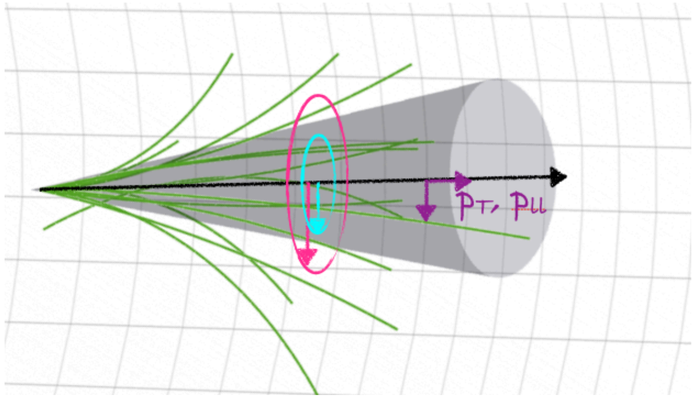
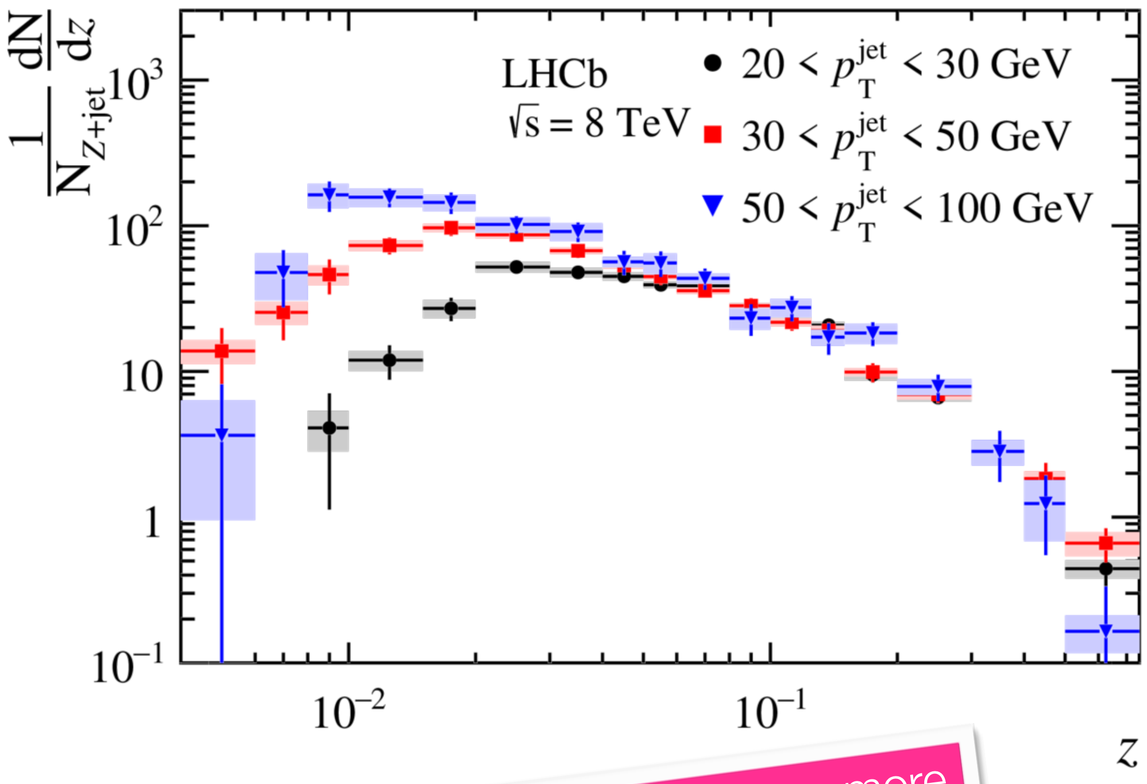
Multiscale Dynamics: Jet Constituent Characteristics

- LHCb analysis uses charged hadron properties of jets in Z+jet events in the forward region:



$$z = \frac{\vec{p}_{\rm jet} \cdot \vec{p}_{\rm hadron}}{|\vec{p}_{\rm jet}|^2}$$

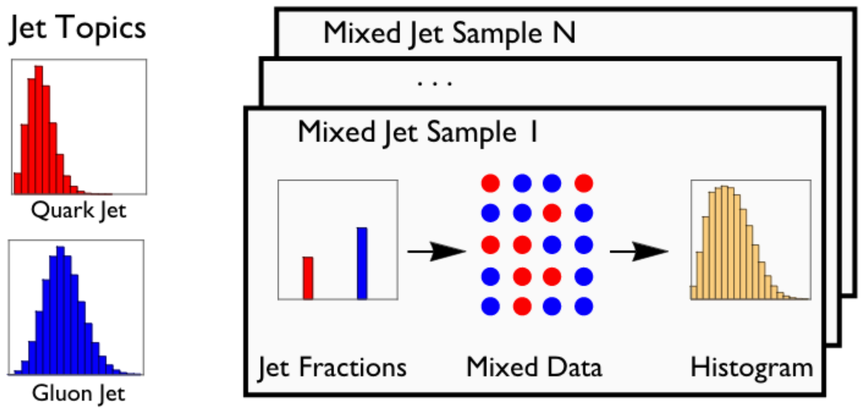


- Sample is light quark dominated — useful for q/g discrimination studies

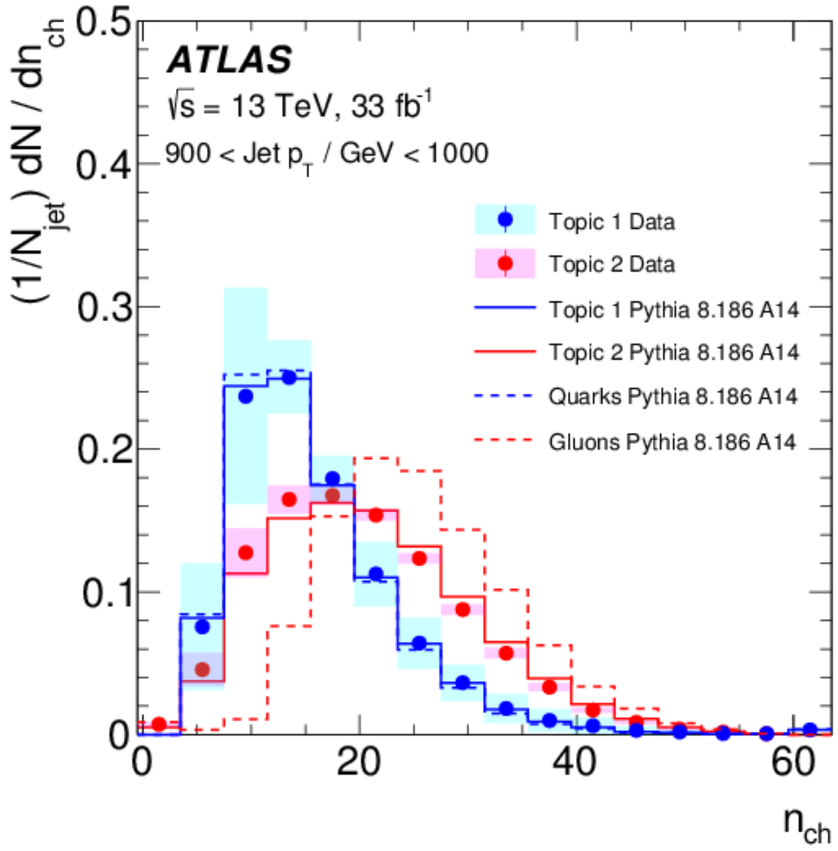
Higher pT jets have more consituents and populate lower z values

Multiscale Dynamics: Jet Constituent Characteristics

- By exploiting the fact that forward jets tend to be quark dominated, can extract *in situ* quark & gluon distributions
  - Utilize ML technique, topic modeling, to extract distributions without dependence on MC models



Phys. Rev. Lett. 120, 241602 (2018)



- Paper has detailed comparisons of jet fragmentation quantities in forward and central regions, compares q/g distributions extracted with MC fractions to N^{3}LO predictions

arXiv:1906.09254

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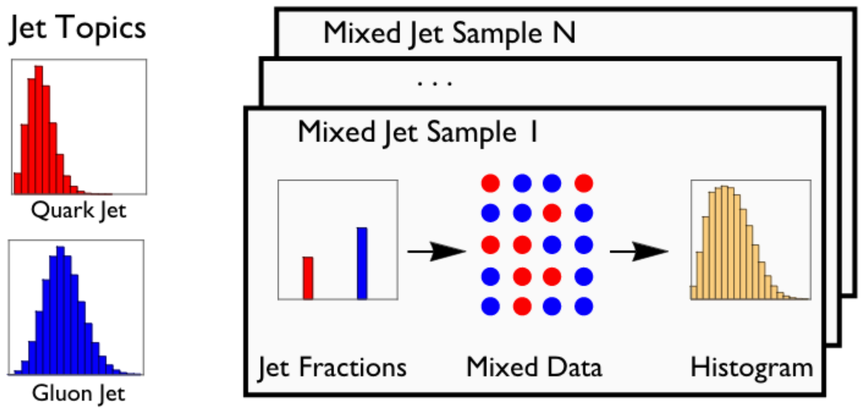

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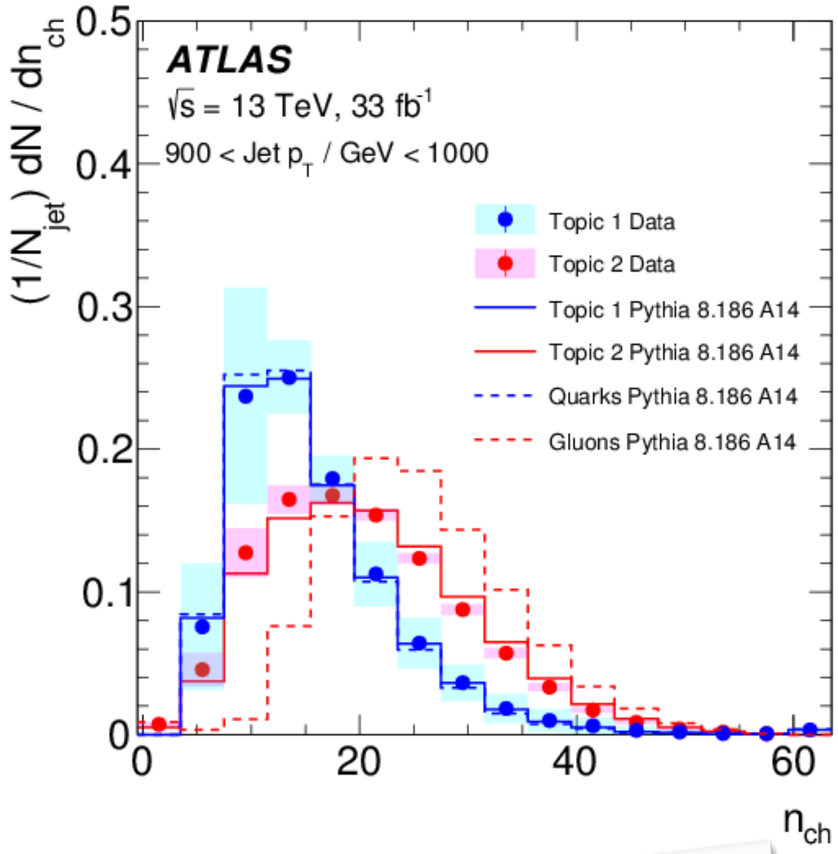

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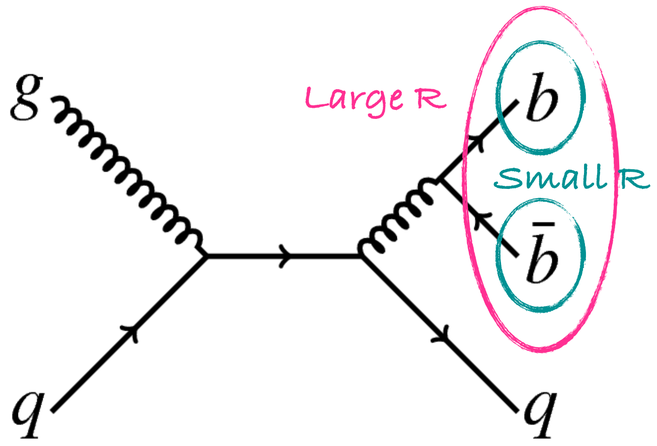
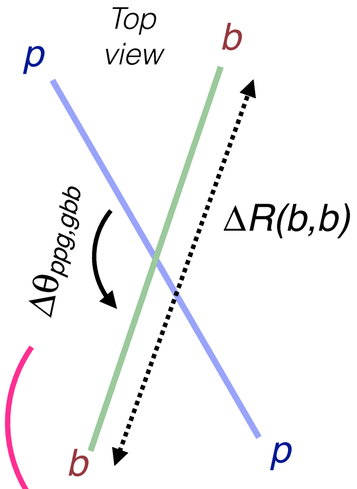
Data topic 2 (gluon-*like*) matches topic 2 extracted from MC, but not parton matched MC due to some quark contamination

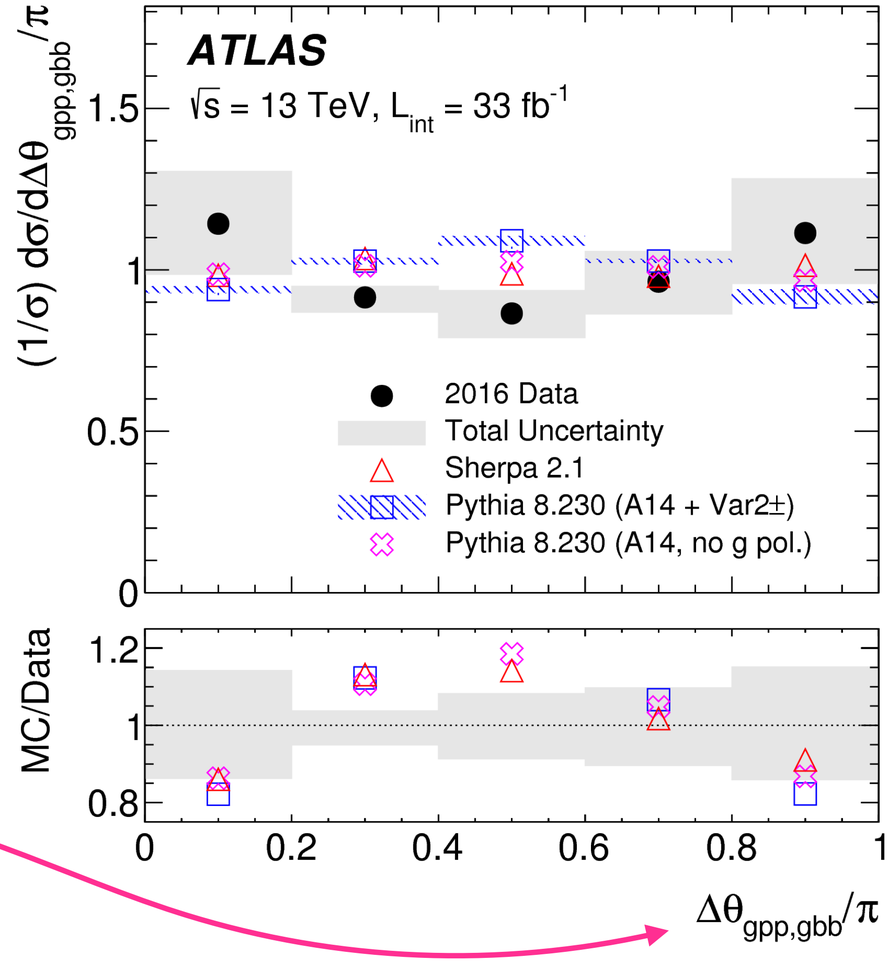
Phys. Rev. D 99 (2019) 052004

Multiscale Dynamics: Gluon splitting

- Select sample rich in g➛bb by large radius jet with 2 small radius sub-jets, at least 1 b-tag
  - Probe quantities related to b-b system





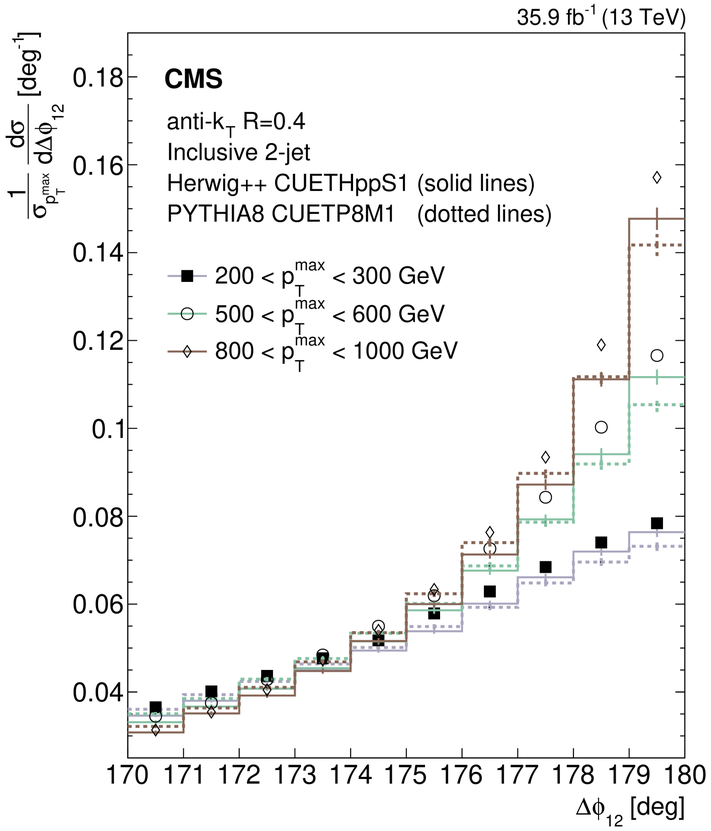


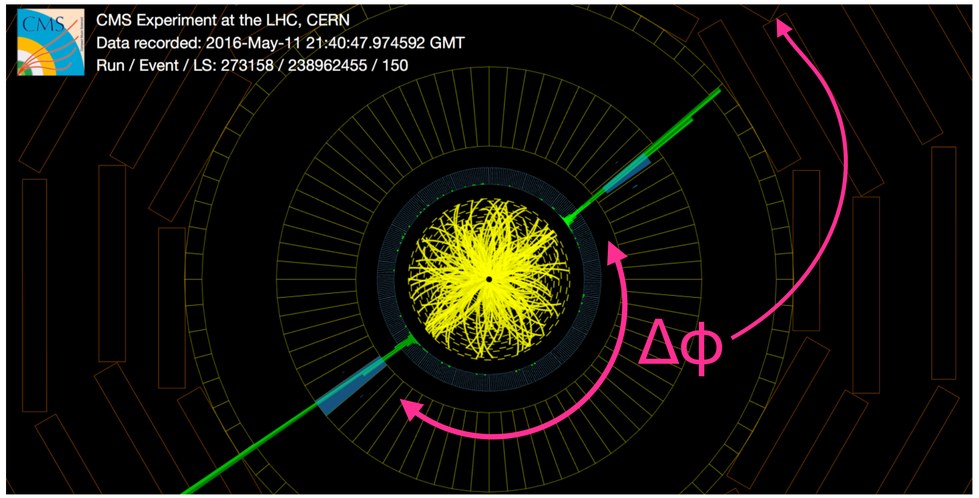
- Data shows significant deviation from models in angle related to gluon polarization (largely unconstrained from prior data)

arXiv:1902.04374

Multiscale Dynamics: Resummation Effects

- Accurately modeling parton showers requires resummation of soft gluon emission
  - Need measurements sensitive to these effects
- For 2 & 3-jet events, look at Δϕ of 2 leading jets in back-to-back topology
  - Cross-section dominated by soft gluon emission in this phasespace
- Models deviate for Δϕ ≳ 177°
  - Different combinations of $N_{partons}$ & parton showers describe data best in various jet p_T ranges





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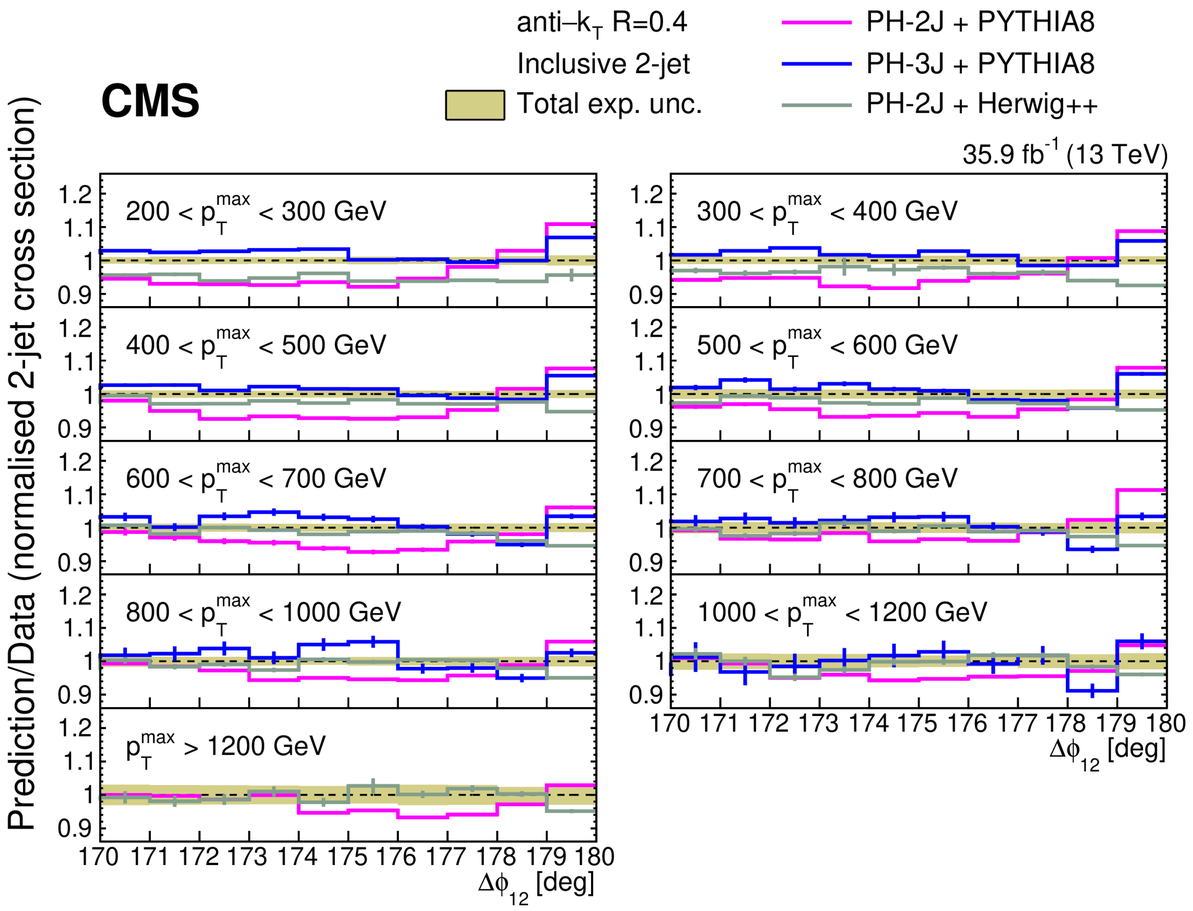
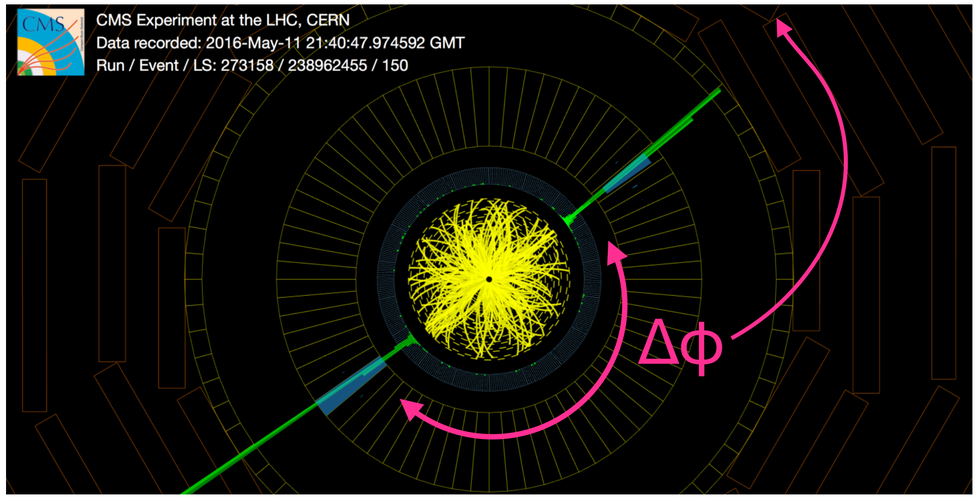
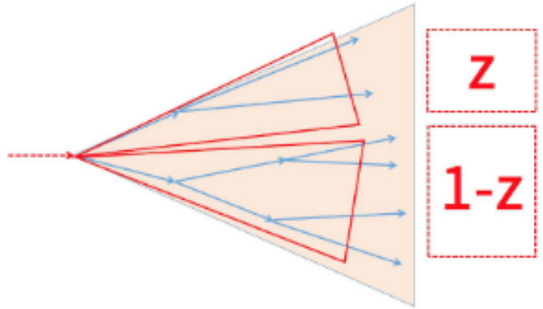




Multiscale Dynamics: Shower Evolution

- Soft-drop method removes soft radiation not fulfilling minimum p_T requirement (z_g) [ref,ref]
  - Relates to parton splitting function
- Sources of R-dependence of z_g:
  - Perturbative: δpt ~ ln(R)
  - Hadronization: δpt ~ -1/R
- ALICE measures cross-section as a function of k_T splitting scale for different cone sizes & p_T to probe these effects
  - more asymmetric splitting for larger R at low p_T
  - larger z_g values at low p_T for small R

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{cut}$$



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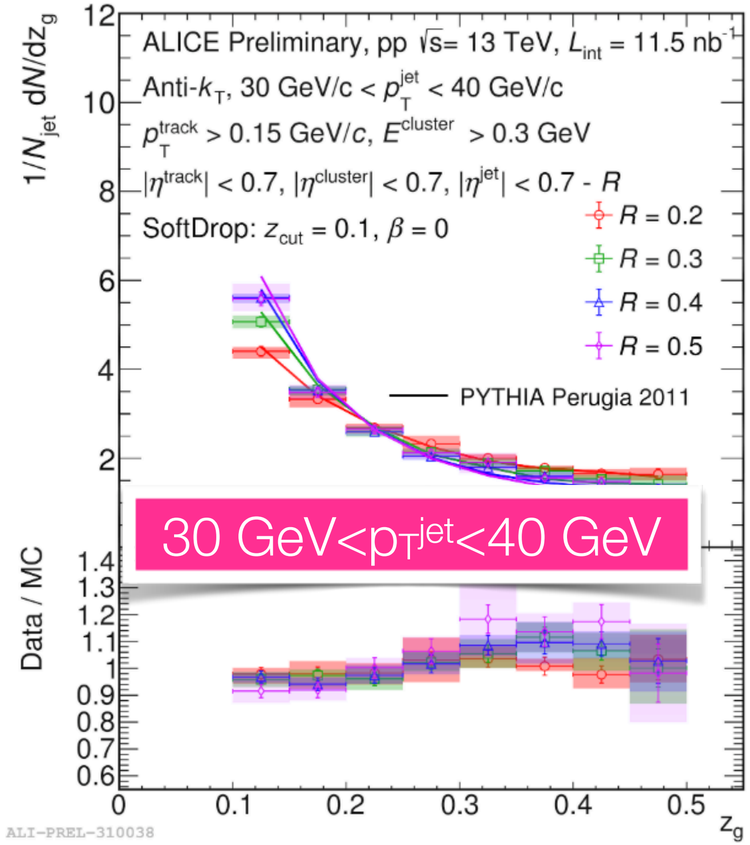
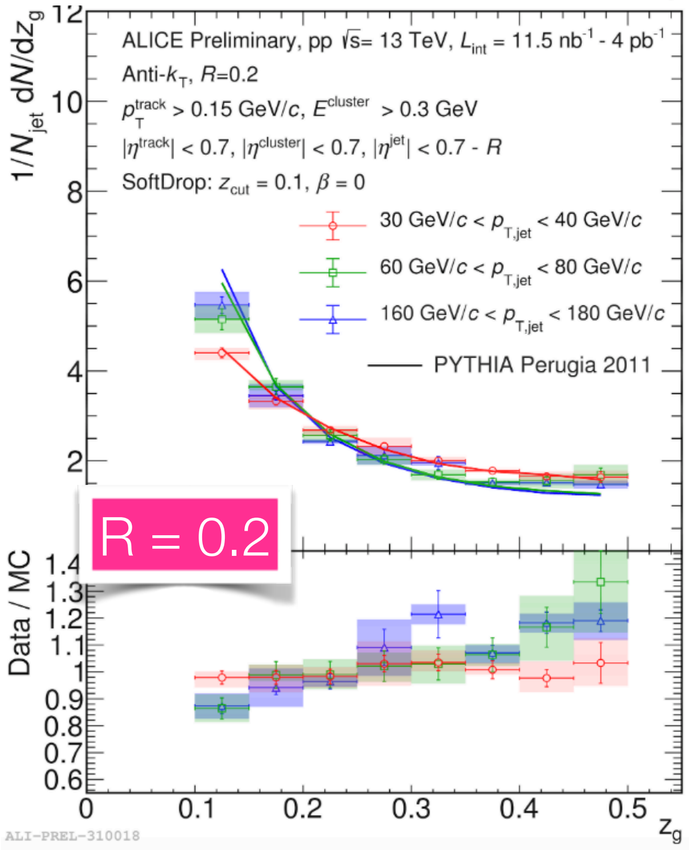
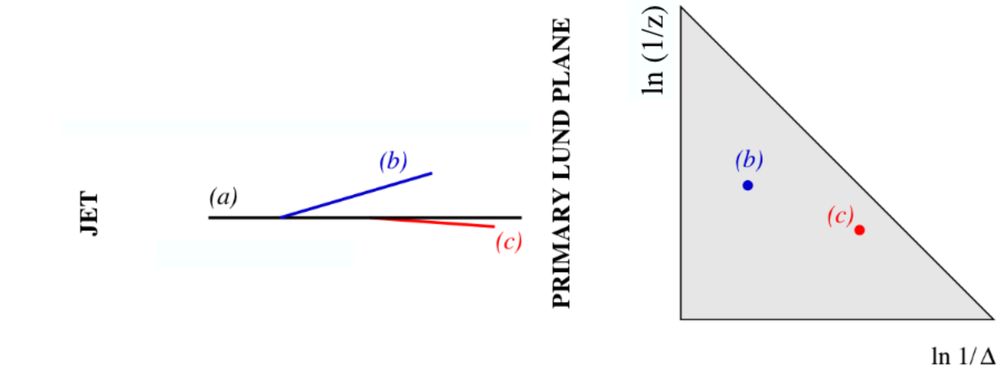
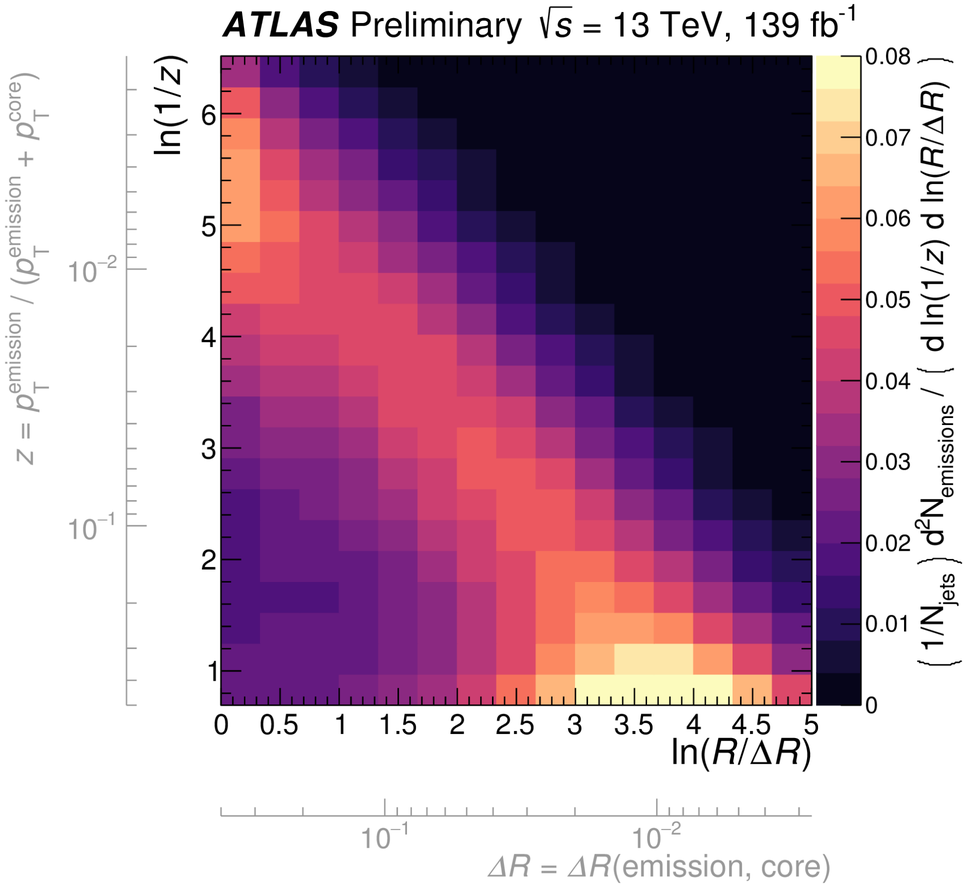


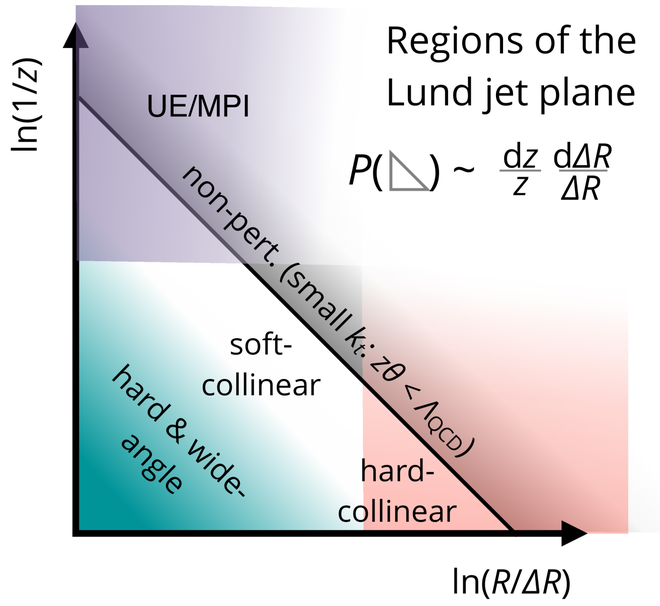


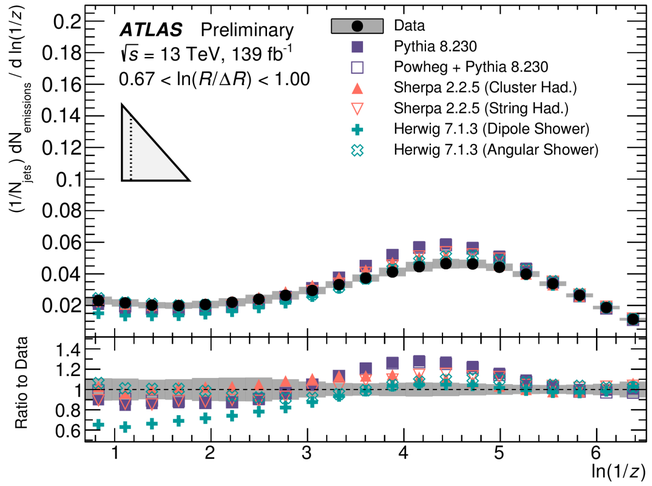
Multiscale Dynamics: Lund Plane

- New proposal to represent internal structure of jets*:
  - Lund Plane: ln(1/z) vs ln(1/θ)
- Recluster jet using Cambridge/ Aachen alg, plot history
- Utilize tracks associated to anti-kT (R = 0.4) jets, recluster with C/A, plot history
- Powerful test of MCs against shower and hadronization history
  - Can distinguish perturbative and non-perturbative effects in same measurement
- Can be used in ML-based jet discriminants









* J. High Energ. Phys. (2018) 2018

The QCD @ LHC Lab Tour Itinerary

- Soft and forward physics
- Partonic structure of the proton
- Multi-scale dynamics in jet-based observables
- Measurements Sensitive to pQCD

Inclusive photon production — ATLAS
ATL-PHYS-STDM-2017-29 *
Differential Isolated photon production @ 8 TEV—CMS
arXiv:1907.08155

-
W&Z cross-sections — CMS *
CMS-PAS-SMP-17-010

Z+heavy flavor — CMS
CMS-PAS-SMP-19-004

Inclusive Z cross-sections — ATLAS
arXiv:1907.06728

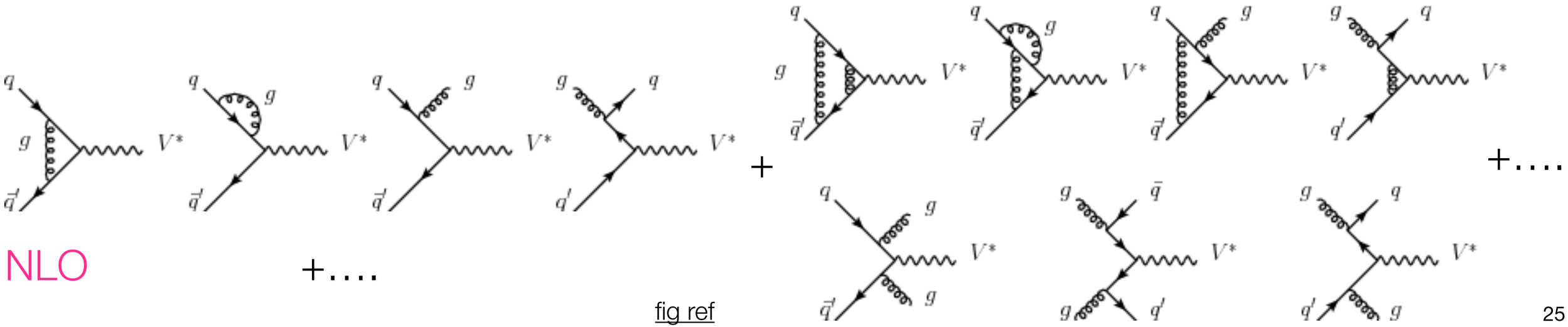
Photon cross-section ratios at 8/13 TeV —ATLAS
JHEP 04 (2019) 093

* = result presented here

Measurements Sensitive to pQCD

- Comparison of QCD phenomena with precise theoretical calculations
  - Choose hard, colorless probe and measure cross-sections and properties
  - Many searches for new physics (e.g. deviations in Higgs p_T measurements) rely on precise theoretical pQCD calculations
- What's interesting:
  - Testing state of the art (NLO, NNLO) calculations against data
  - Tests of resummation in parton showers at NNLL

NNLO



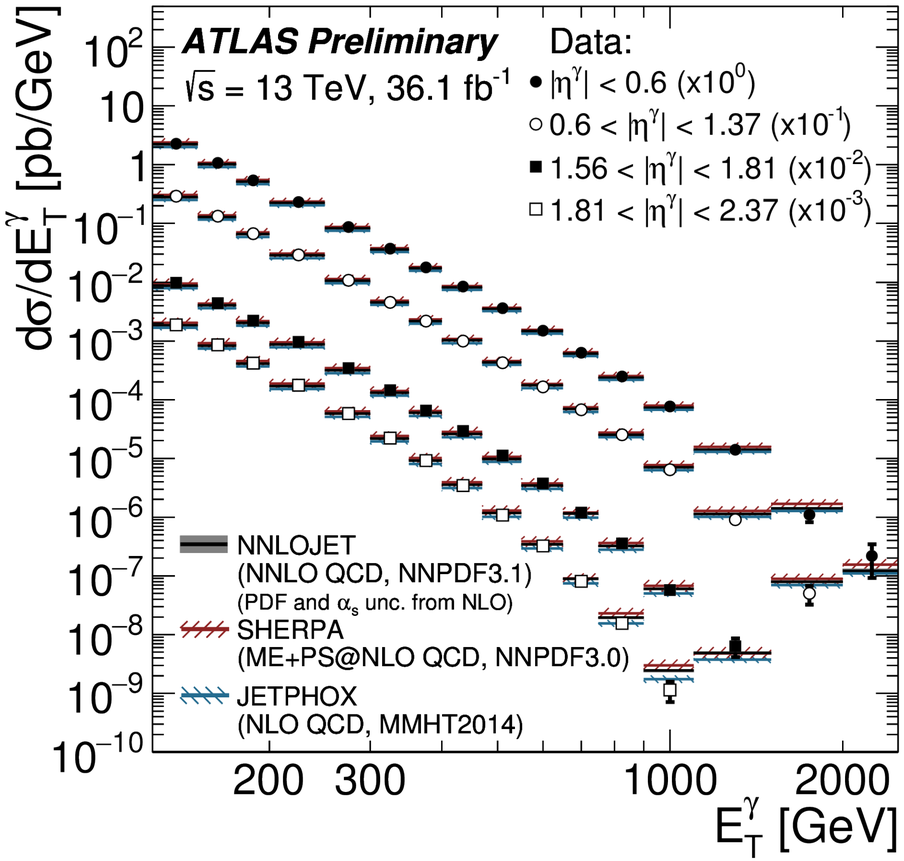
NLO

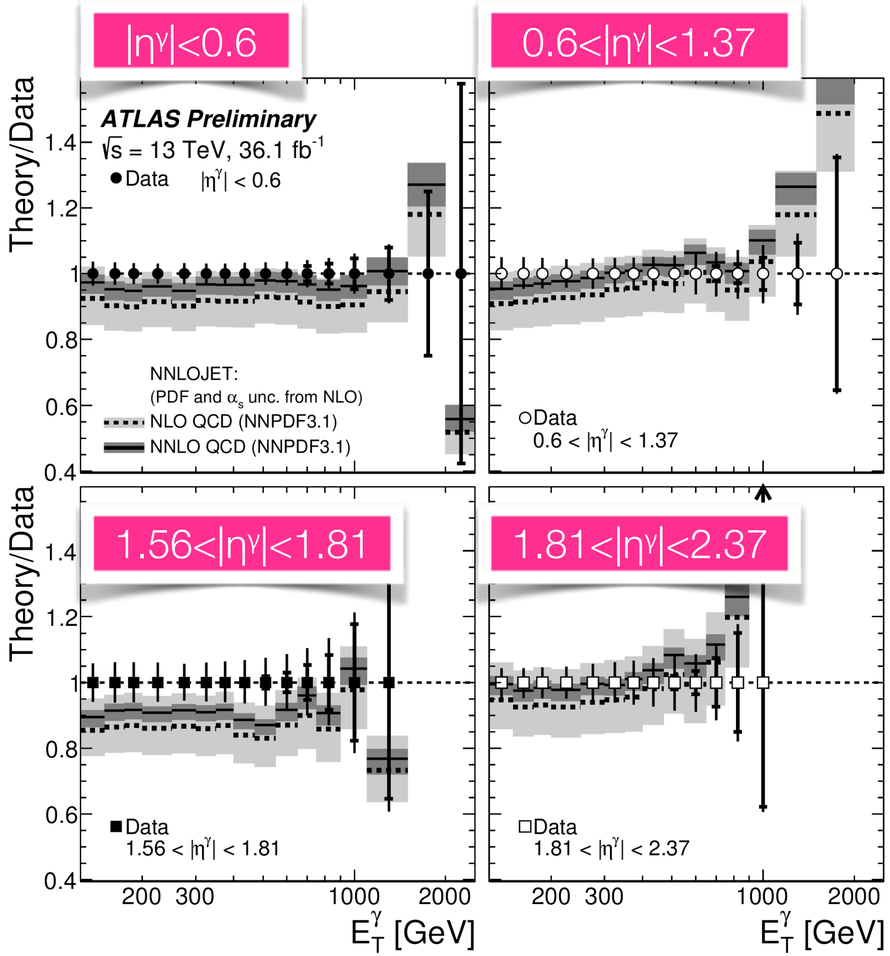
fig ref

Measurements Sensitive to pQCD

ATL-PHYS-STDM-2017-29

- ATLAS measurement of inclusive photon production up to E^{γ}_{T} ~1 TeV with < 10% experimental & theoretical uncertainties
- Excellent NLO & NNLO agreement with data; NNLO uncertainties comparable to data uncertainties

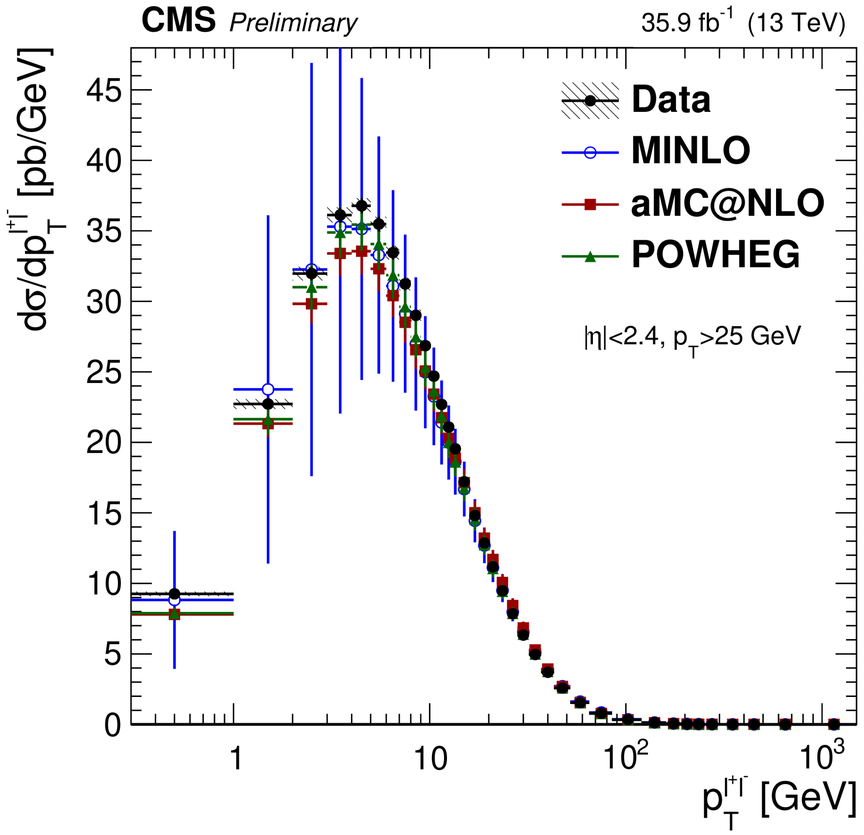


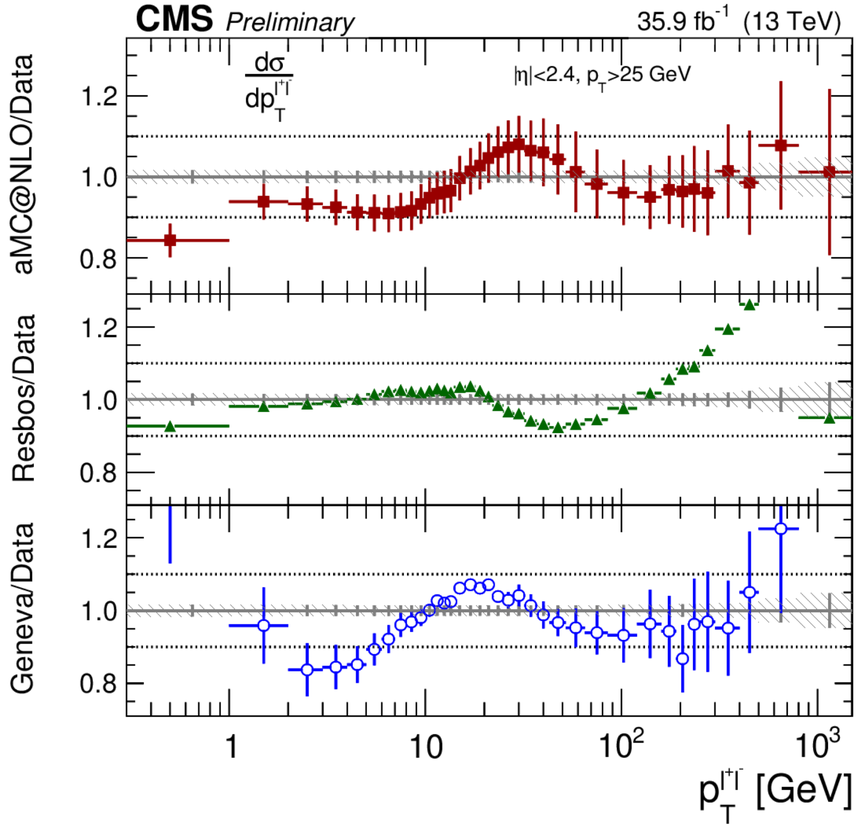


Measurements Sensitive to pQCD

CMS-PAS-SMP-17-010

- CMS measured W&Z production cross-sections as a function of p_T & *y*.
  - Compare to resumed NNLL at low p_T and NLO, NNLO at high p_T
  - Important for W mass measurements





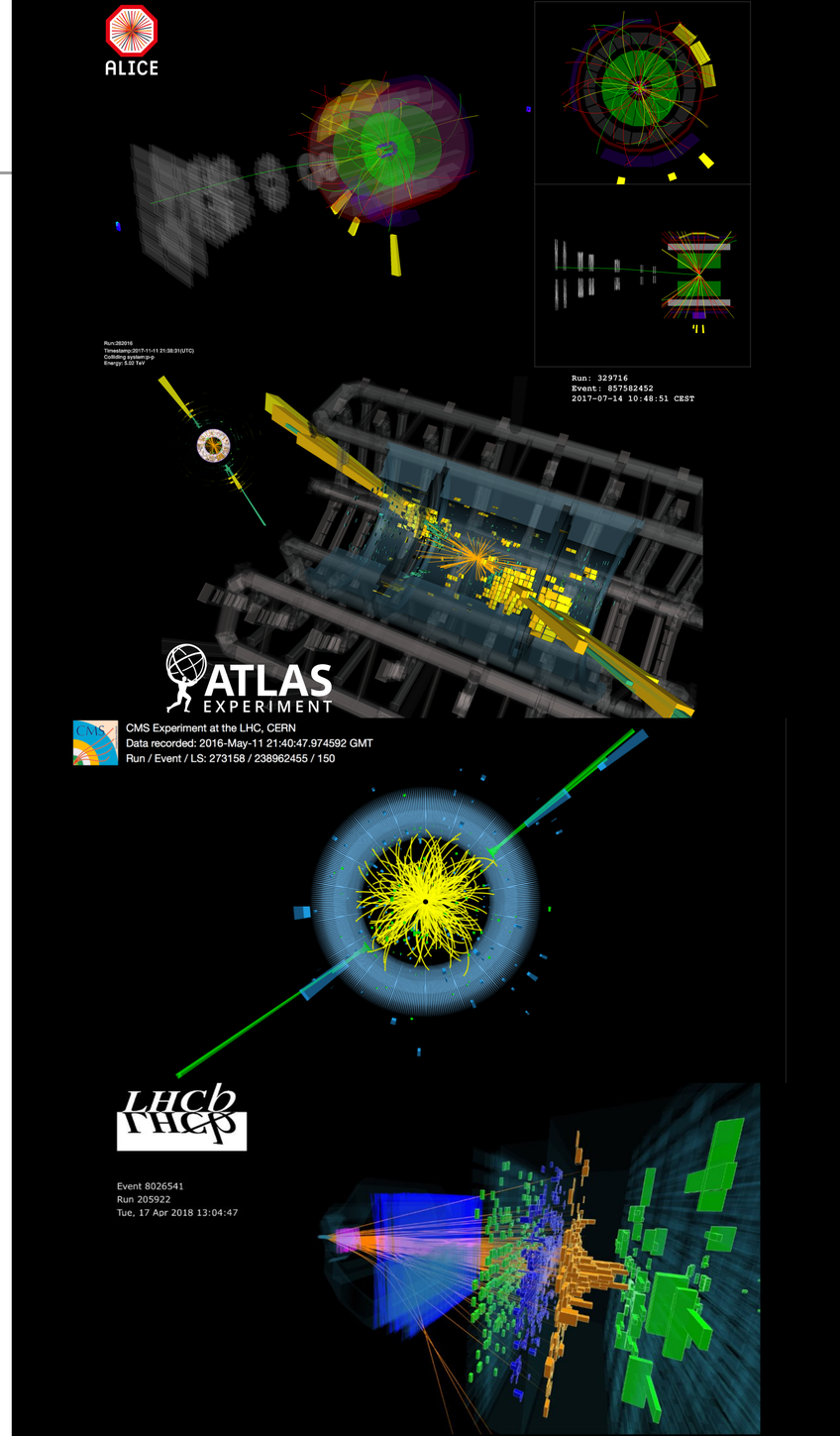
aMC@NLO (NLO+FxFx)

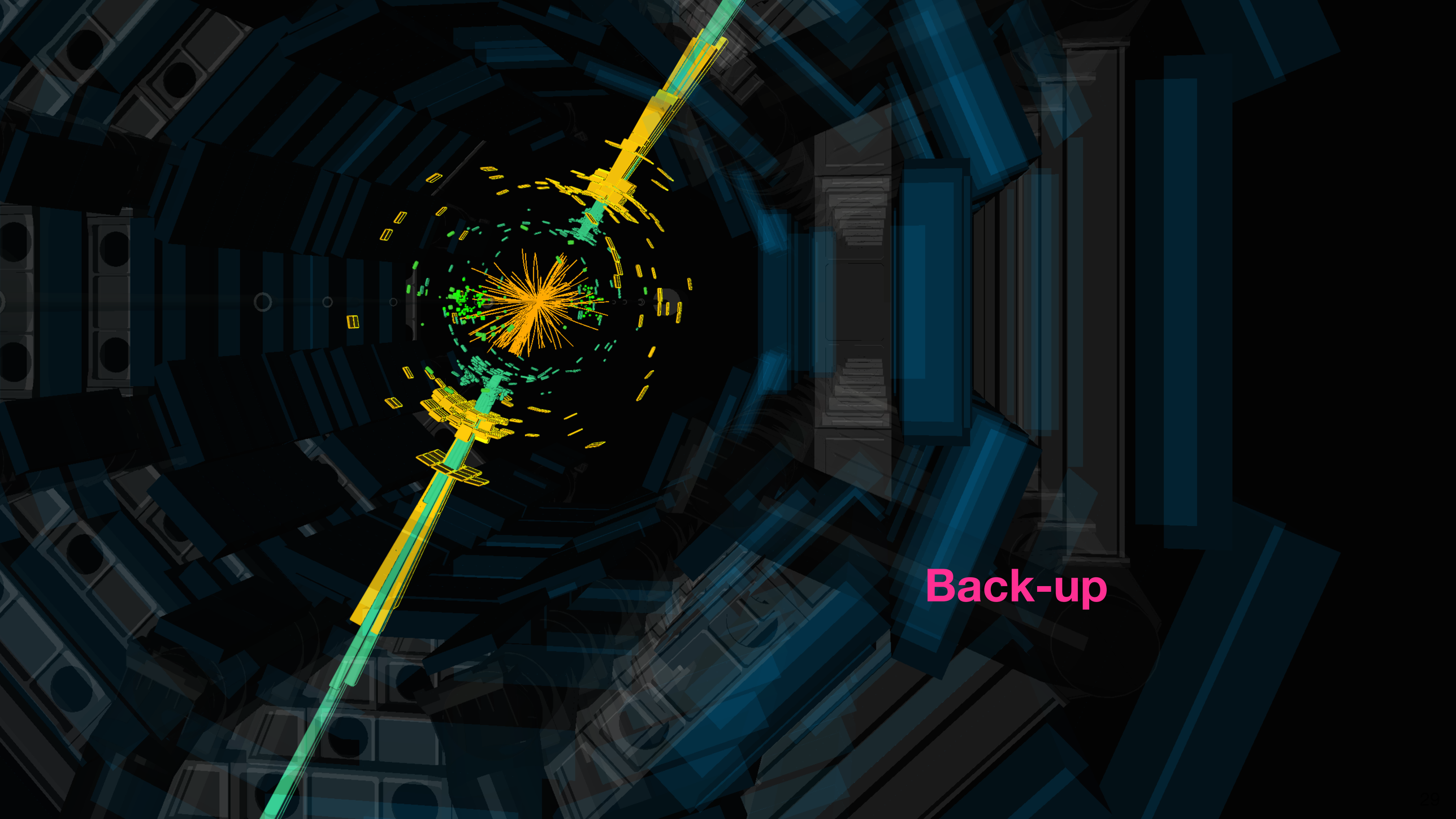
Resbos (NLO+NNLL)

Geneva (NNLO +NNLL)

Conclusions

- The LHC is a rich QCD laboratory probing physics at a huge range of energy scales
- Experimental measurements are increasing in precision and informing models of non-perturbative physics as well as providing stringent tests of detailed perturbative calculations
- LHC future is trending towards indirect searches → precise QCD predictions will be critical. Effort needed now to improve our predictions.
- Stay tuned for more Run 2 results!

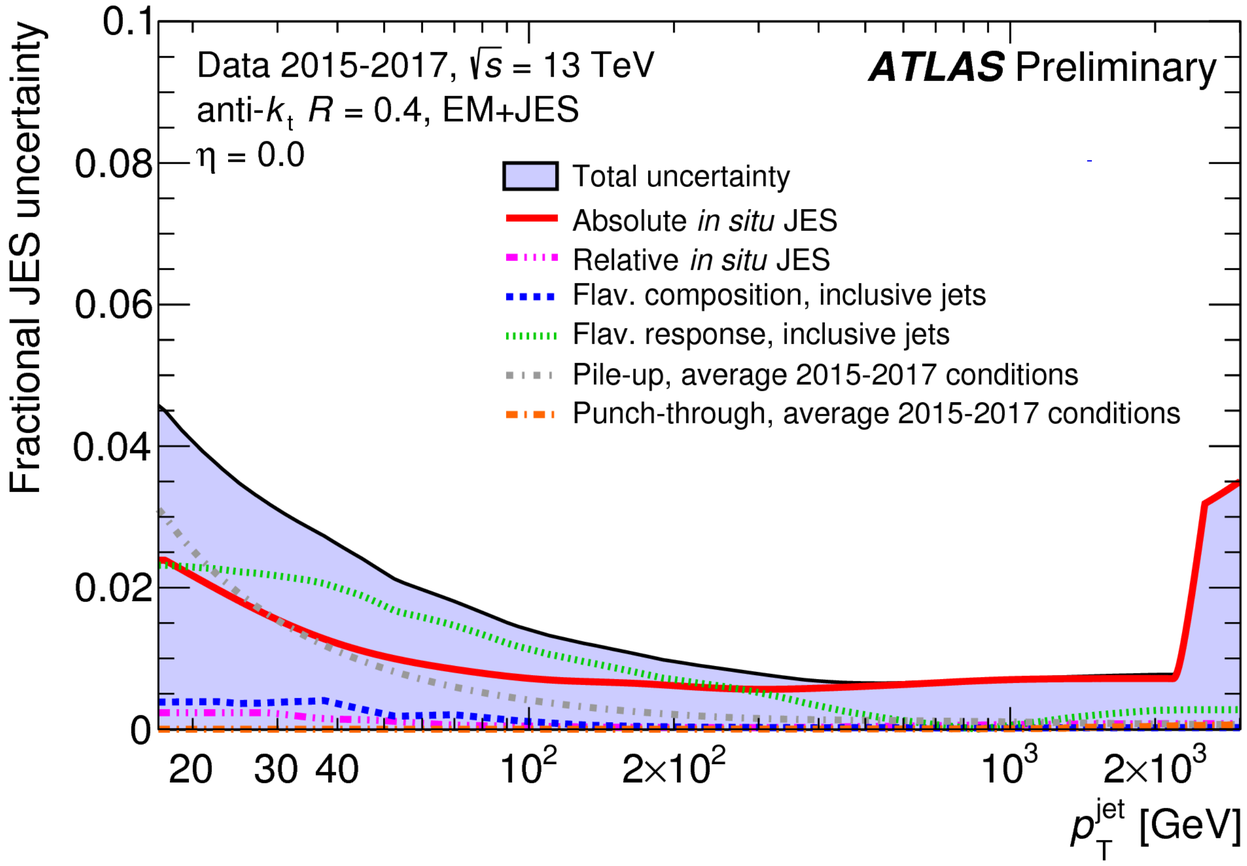


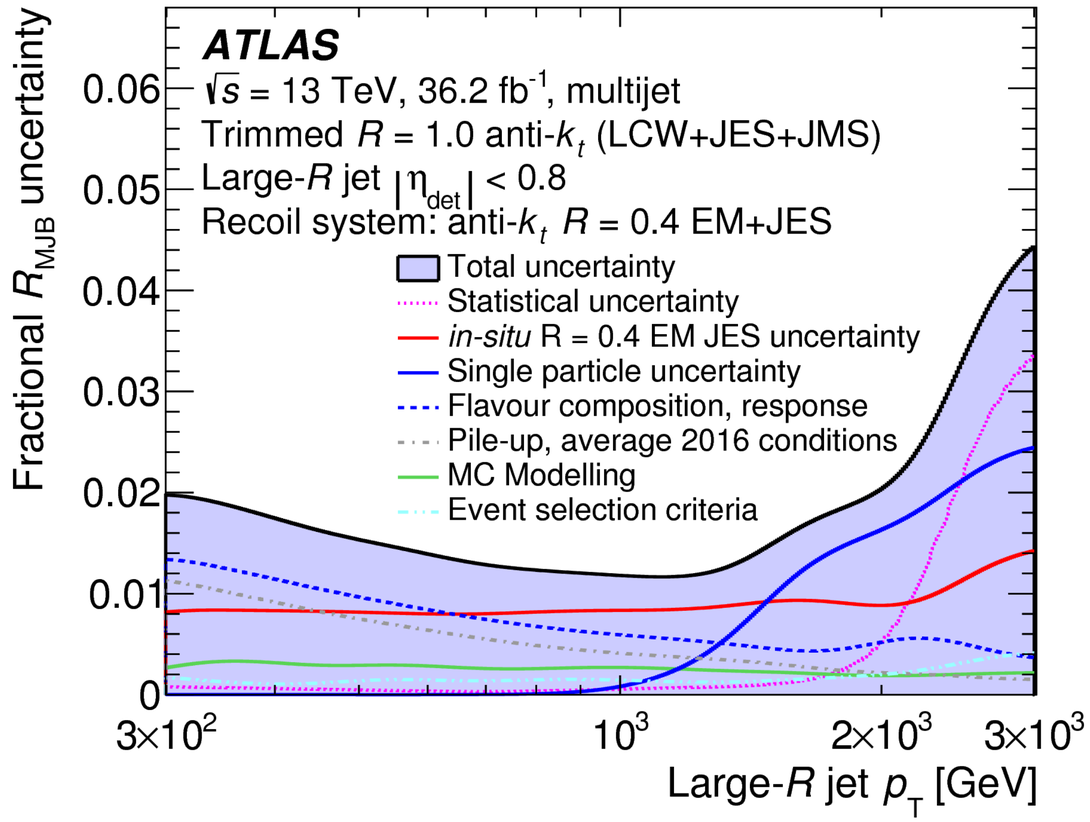


Back-up

Jet Energy Scale: ATLAS

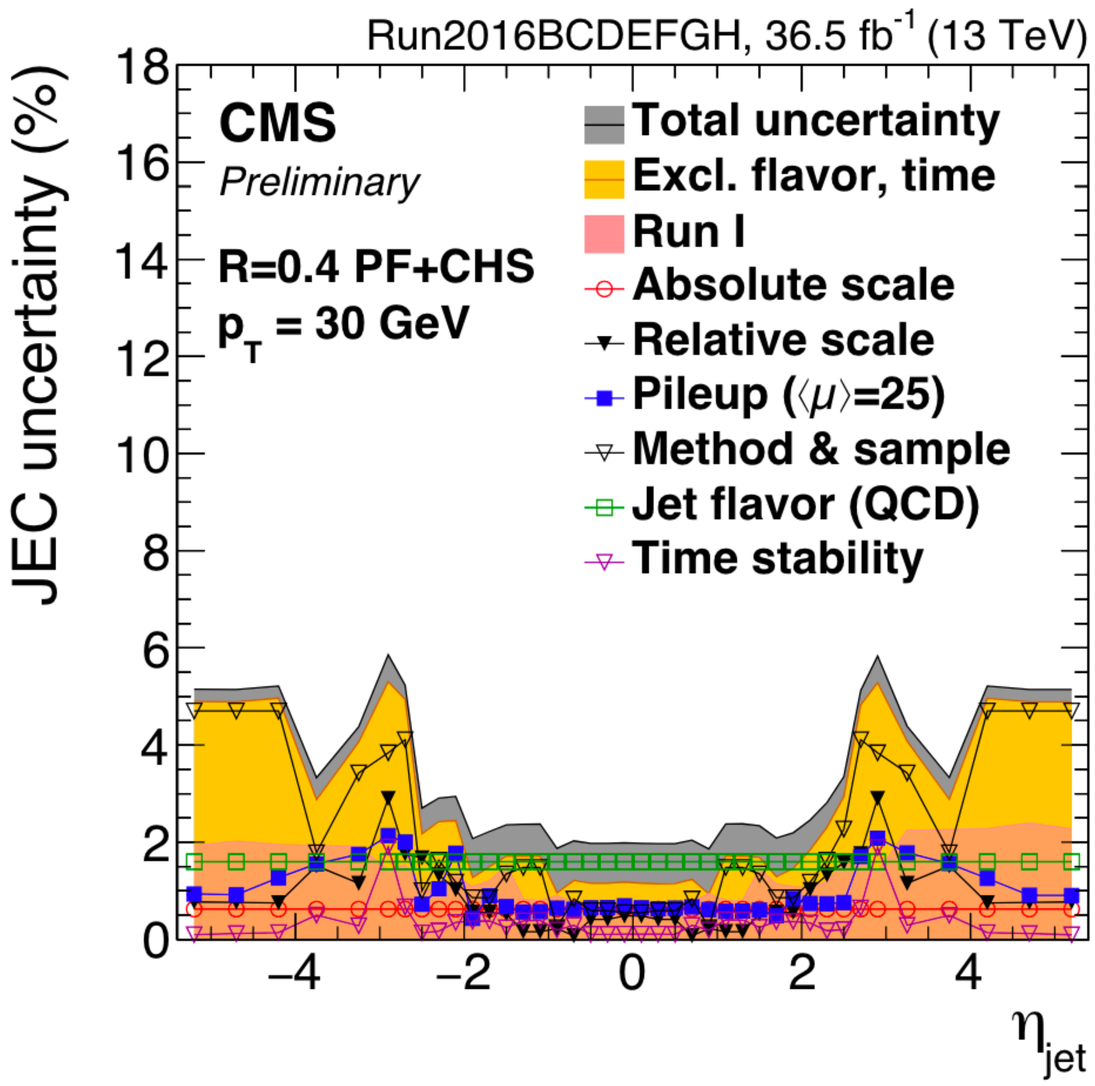
JETM-2018-006
ATLAS-CONF-2017-063

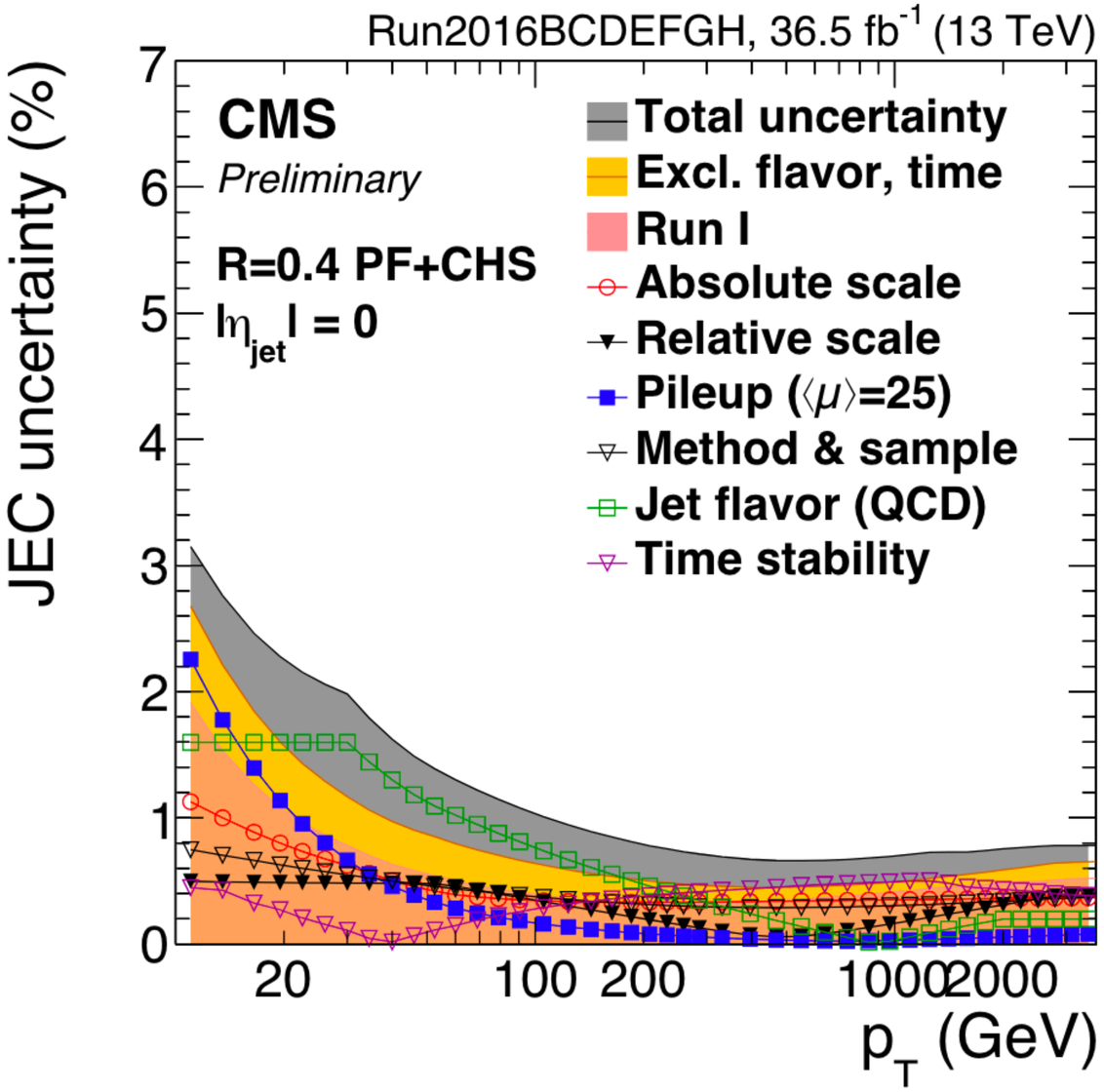




Jet Energy Scale: CMS

CMS-DP-2018-028
ATLAS-CONF-2017-063

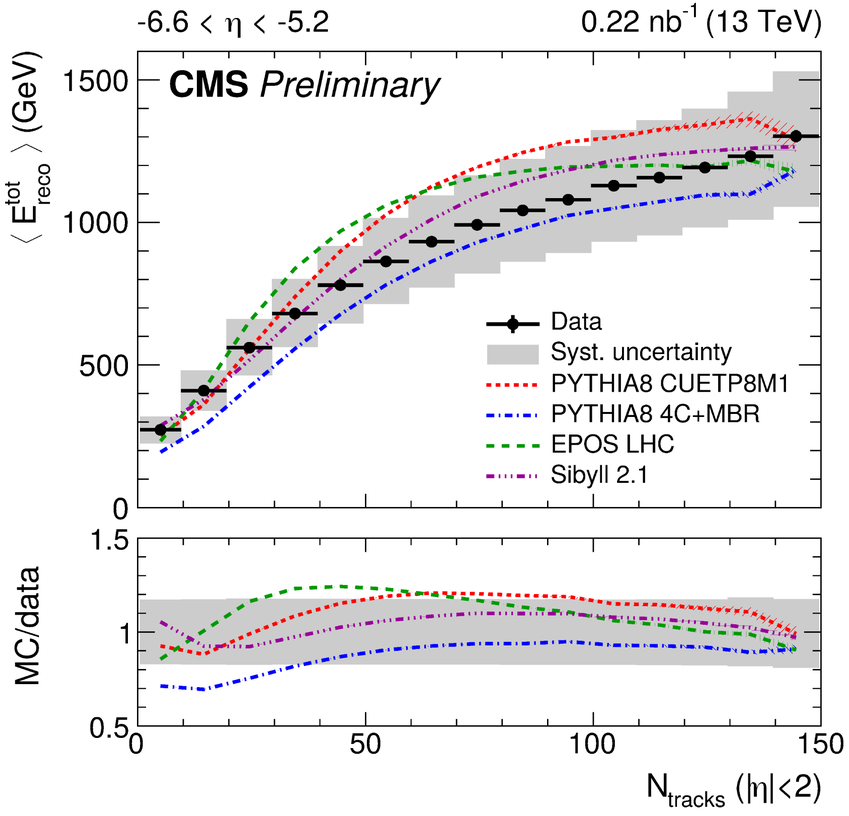


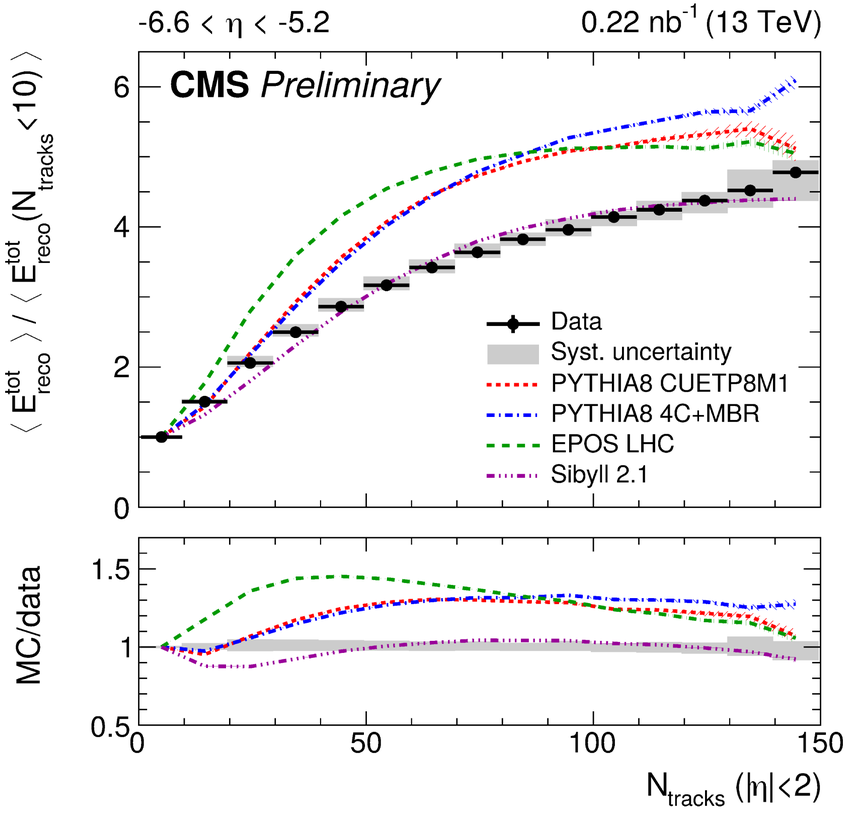


Forward and Soft QCD: Forward Energy Density

CMS-PAS-FSQ-18-001
arXiv:1812.04095

- When normalizing to the energy flowing events with < 10 central tracks (first bin uncertainties decrease significantly and discrepancies arise

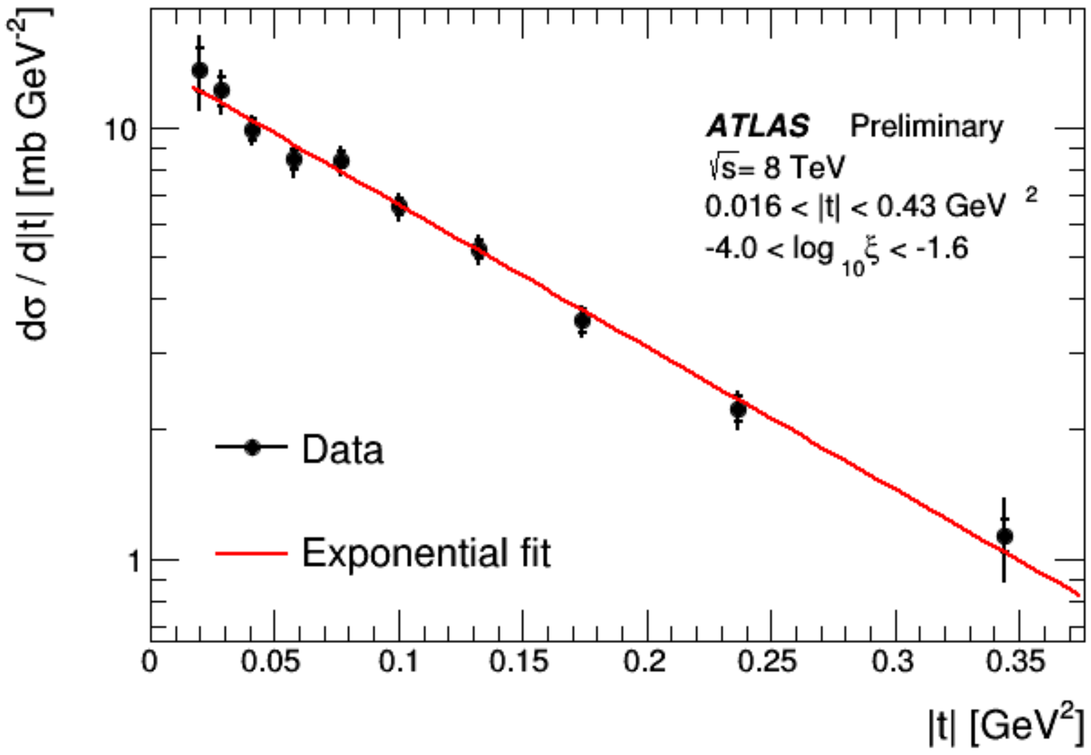


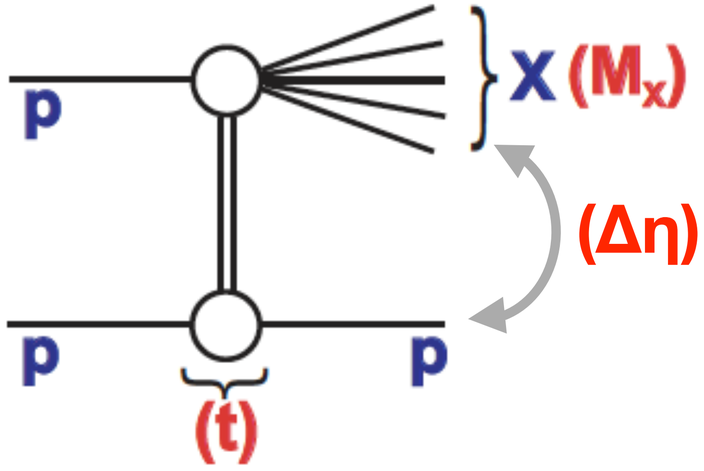


Forward and Soft QCD: Diffractive processes

ATLAS-CONF-2019-012

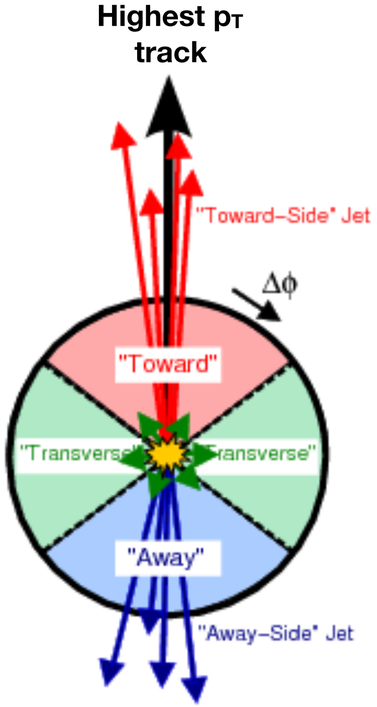
- ATLAS single diffractive measurement t-dependence well described by exponential
  - Slope parameter of B = 7.60±0.32 GeV^{-2}
  - Fractional proton dissociation well described by triple pomeron Regge trajectory with slope α(0) = 1.07±0.09

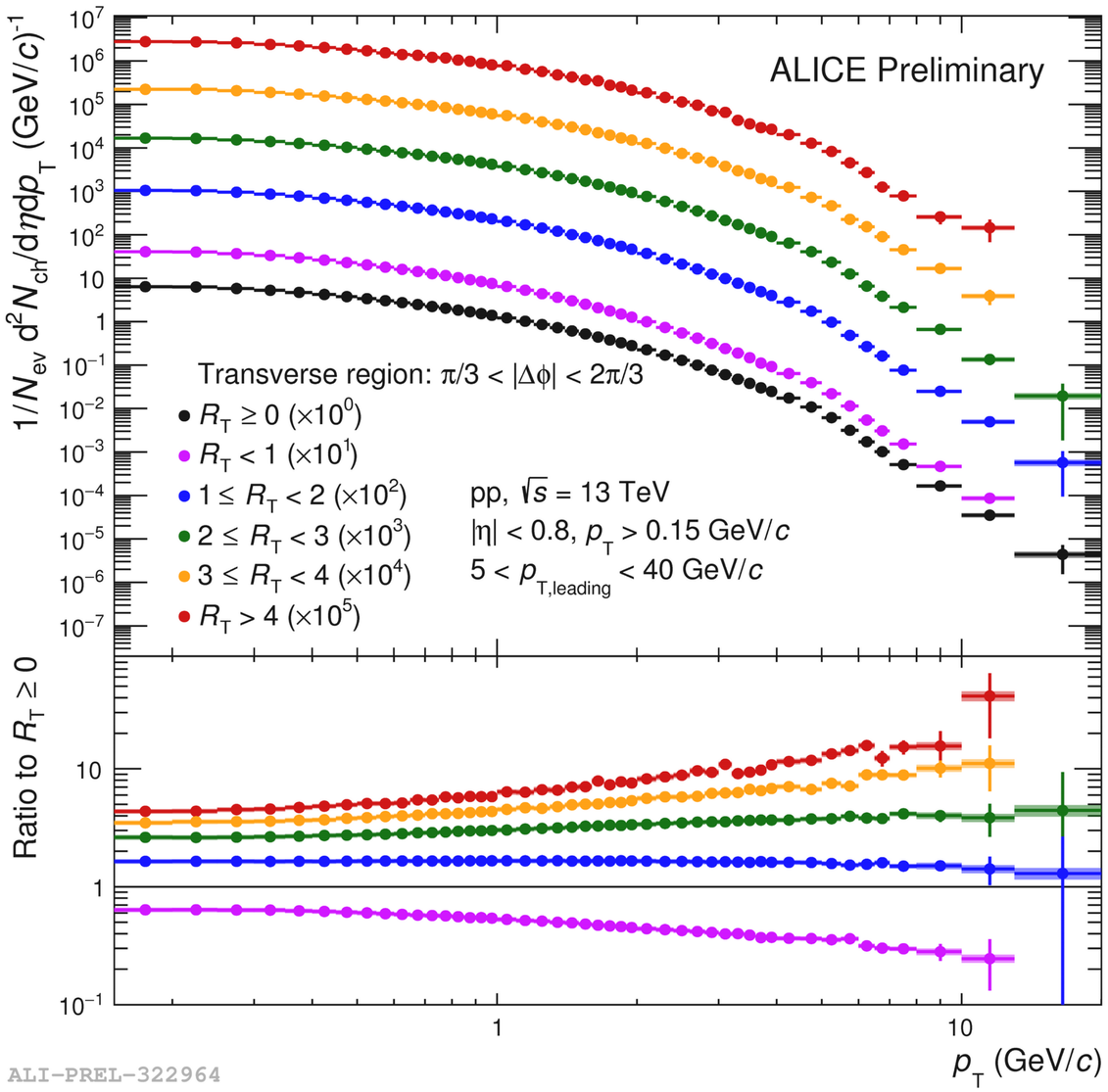




Forward and Soft QCD: Underlying Event

- ALICE: Measure $R_T = \frac{N_{inclusive}}{< N_{inclusive} >}$ in transverse region defined by highest p_T track in event [ref]
  - High R_T corresponds to high UE activity
  - Track spectrum harder in higher UE activity events





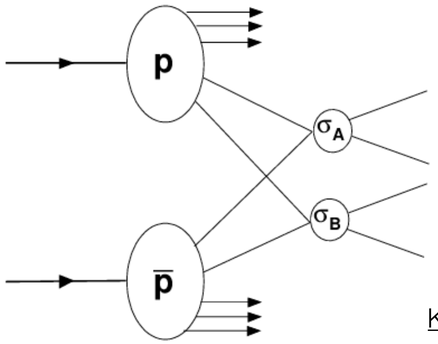
Partonic Structure of the Proton: Double Parton Scattering

CMS-PAS-SMP-18-015
arXiv:1811.10021

- Double Parton Scattering: two pairs of partons from one single pp collision interact

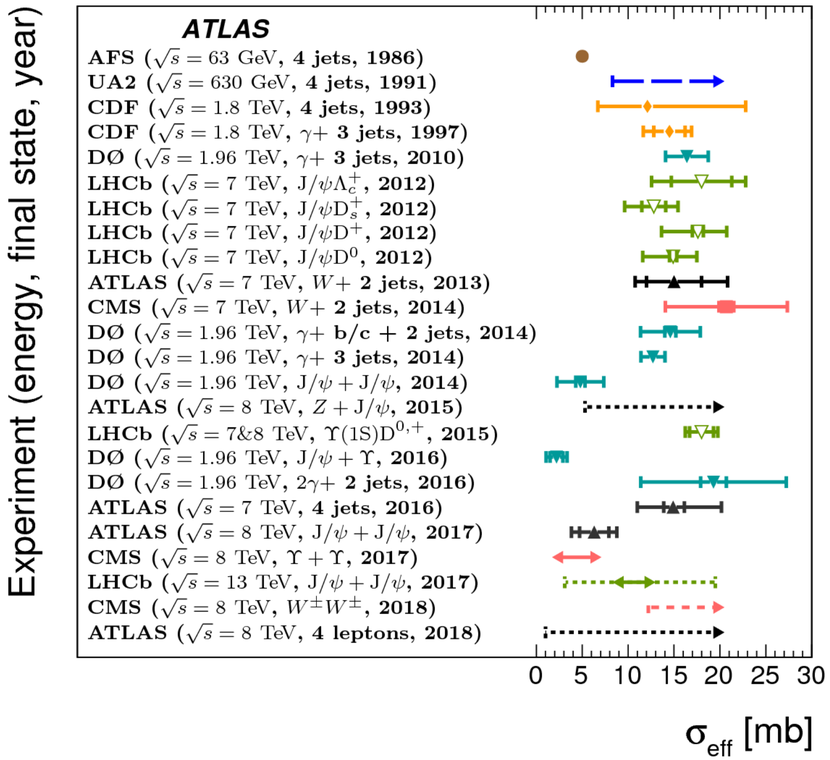
$$\sigma_{AB}^{DPS} = \frac{k}{2} \cdot \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

- DPS measurements test universality of σ_{eff}
- ATLAS: measure lower limit on σ_{eff} (≥ 1mb) in ZZ events, consistent with DPS interpretation
- CMS: Evidence for DPS in same sign WW production (3.9σ) at 13 TeV



Klundert

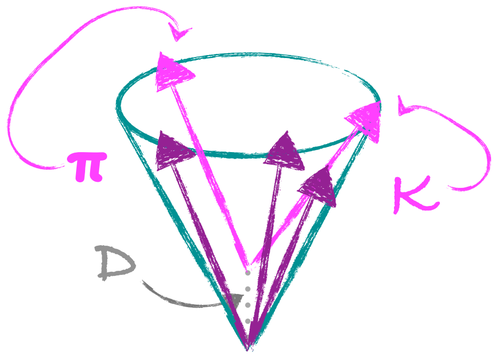
$W^{\pm}W^{\pm}$	Pythia 8	Factorized (N)NLO	Measured
$\sigma(pb)$	1.92	0.87	$1.41 \pm 0.28(\text{stat.}) \pm 0.28(\text{sys.})$
Significance	5.4	2.5	3.9
σ_{eff}		20.7	$12.7^{+5.0}_{-2.9}$

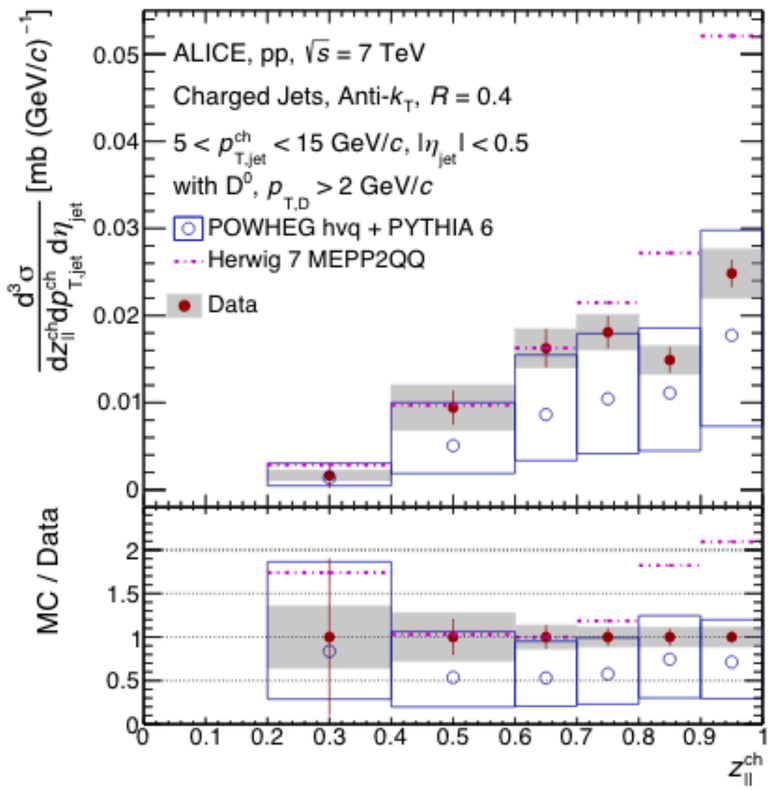


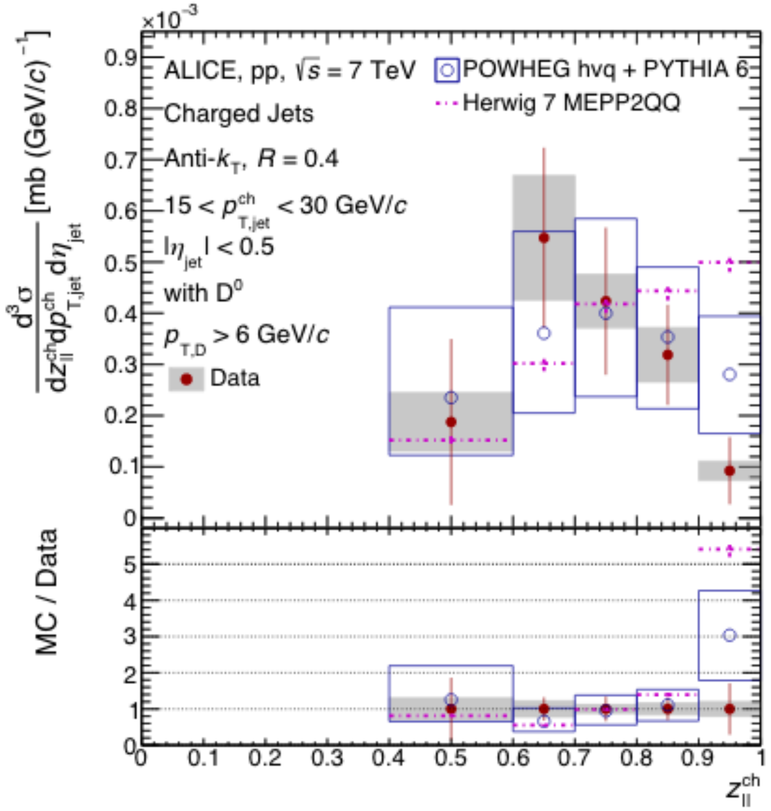
Hadronization and Fragmentation: jet flavor

arXiv:1905.02510

- Select sample rich in c-quarks by tagging track jets with D mesons (ALICE)
  - Study cross-sections for fragmentation distributions and overall production; good agreement within uncertainties
  - Note: ALICE can access low energy jets and give unique information







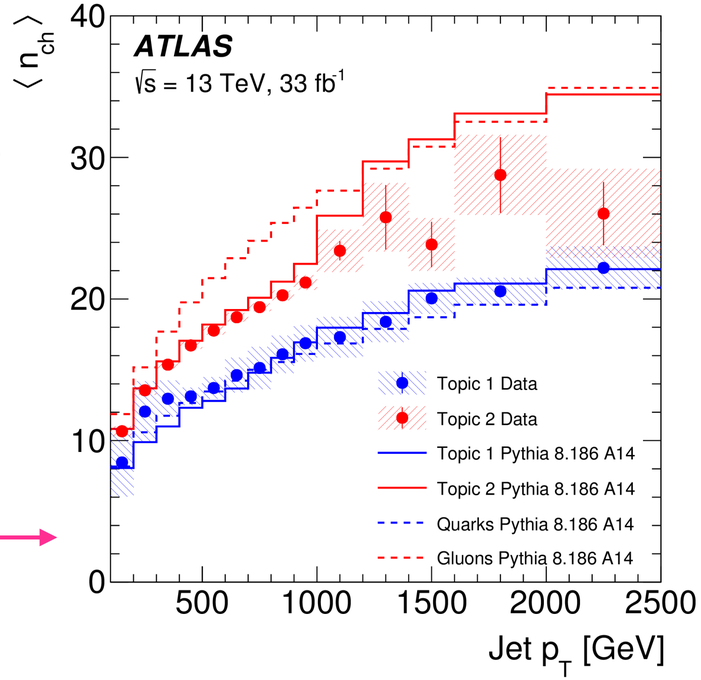
Q/G Jet Extraction

arXiv:1906.09254

- Topics converge to quark/gluon definitions in the case that there are some bins in the dataset which are purely quark or purely gluon
  - Basically true for quarks, not quite true for gluons, but converges at high pT
  - Only true for Nch

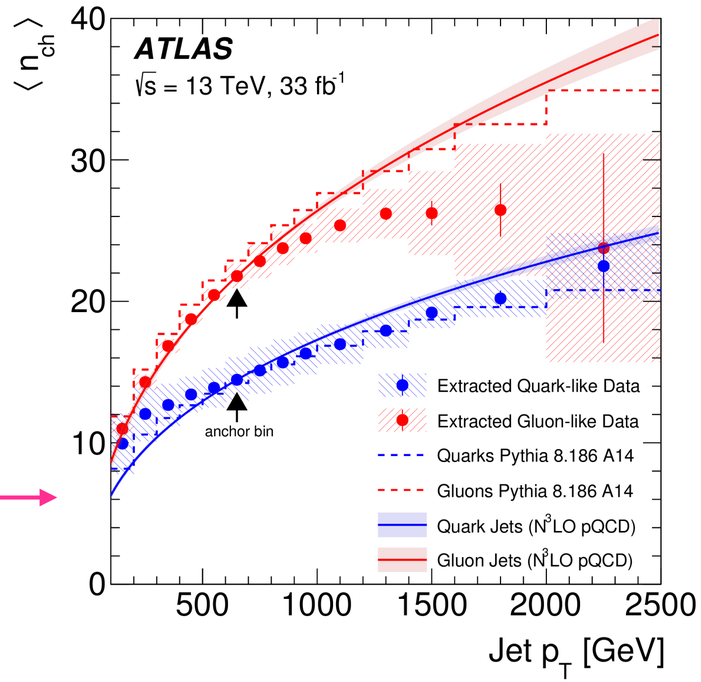
$$h_i^{T_1} = \frac{h_i^f - \left(\min_j\{h_j^f/h_j^c\}\right) \times h_i^c}{1 - \min_j h_j^f/h_j^c},$$

$$h_i^{T_2} = \frac{h_i^c - \left(\min_j\{h_j^c/h_j^f\}\right) \times h_i^f}{1 - \min_j h_j^c/h_j^f}.$$



- Extraction relying on MC fractions shows good agreement with N3LO at low pT, diverges at high pT
  - Used for Nch & fragmentation variables

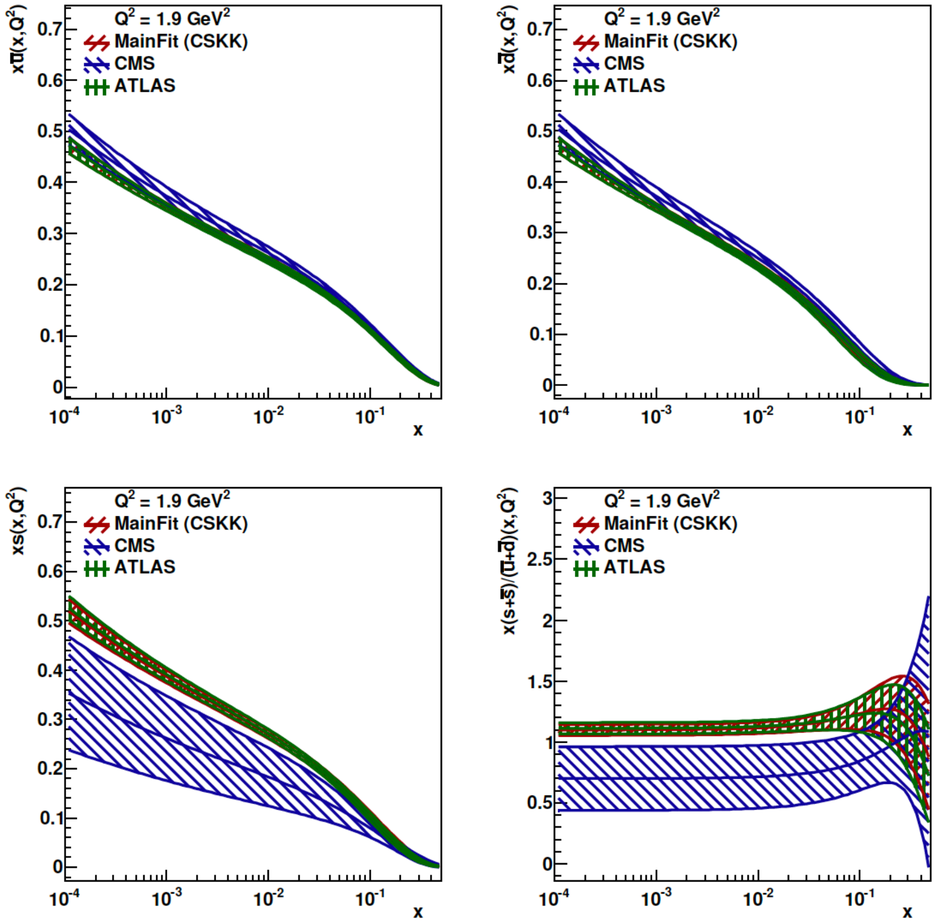
$$h_i^f = f_q^f h_i^q + (1 - f_q^f) h_i^g,$$
$$h_i^c = f_q^c h_i^q + (1 - f_q^c) h_i^g,$$



ATLAS & CMS PDF Compatability

Phys. Rev. D 98, 014027 (2018)

- Using ATLAS & CMS *inclusive* W&Z data
- All datasets have good chi2 w.r.t. fits
- ATLAS data more constraining for s-quark content
- CMS data prefers slightly higher anti-u/d contributions



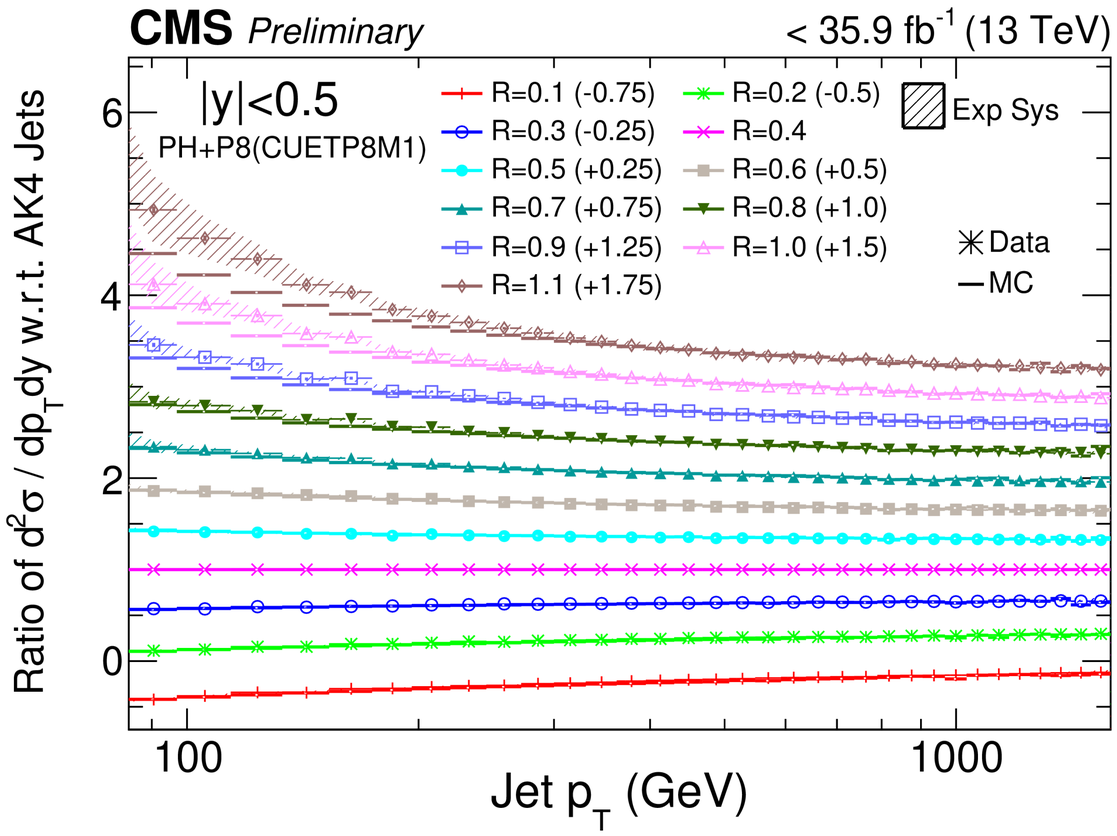
	ATLAS and CMS W and all Z bins		CMS W and
	Z at 7 TeV	Z at 7 and 8 TeV	all Z bins
Total χ^2/NDF	1481/1243 = 1.19	1814/1351 = 1.34	1596/1290 = 1.24
Data set, χ^2/NDP			
HERA	1163/1056	1178/1056	1186/1056
ATLAS W^+	13/11	12/11	
ATLAS W^-	9/11	15/11	
ATLAS central CC Z	15/12	26/12	
ATLAS central CF Z	7/9	8/9	
ATLAS CC Z, $116 < M_z < 150$ GeV	8/6	7/6	
ATLAS CF Z, $116 < M_z < 150$ GeV	4/6	4/6	
ATLAS CC Z, $46 < M_z < 66$ GeV	28/6	34/6	
CMS 7 TeV W-asym.	14/11	14/11	18/11
CMS 8 TeV W^+, W^-	5/22	7/22	5/22
CMS 7 TeV Z central	12/24	13/24	16/24
CMS 7 TeV Z, $120 < M_z < 200$ GeV	31/24	28/24	25/25
CMS 7 TeV Z, $200 < M_z < 1500$ GeV	20/12	19/12	17/12
CMS 7 TeV Z, $30 < M_z < 45$ GeV	35/24	35/24	36/24
CMS 7 TeV Z, $45 < M_z < 60$ GeV	22/24	20/24	20/24
CMS 8 TeV Z central		74/24	66/24
CMS 8 TeV Z, $120 < M_z < 200$ GeV		73/24	56/24
CMS 8 TeV Z, $200 < M_z < 1500$ GeV		14/12	12/12
CMS 8 TeV Z, $30 < M_z < 45$ GeV		38/24	37/24
CMS 8 TeV Z, $45 < M_z < 60$ GeV		29/24	20/24

Table 4: Total and partial χ^2 for data sets entering the extended PDF fits of the ATLAS and CMS data to include off-peak Drell-Yan data. Full details are given in the text

Multi-scale: Jet production

CMS-PAS-SMP-19-003

- CMS measures jet cross-sections as a function of anti-kT jet clustering parameter, R, w.r.t. R= 0.4 default
  - Experimental jet corrections extrapolated from R = 0.4
- Compare to MC generators and QCD calculations at different orders
  - Need both higher fixed order and non-perturbative effects to describe data



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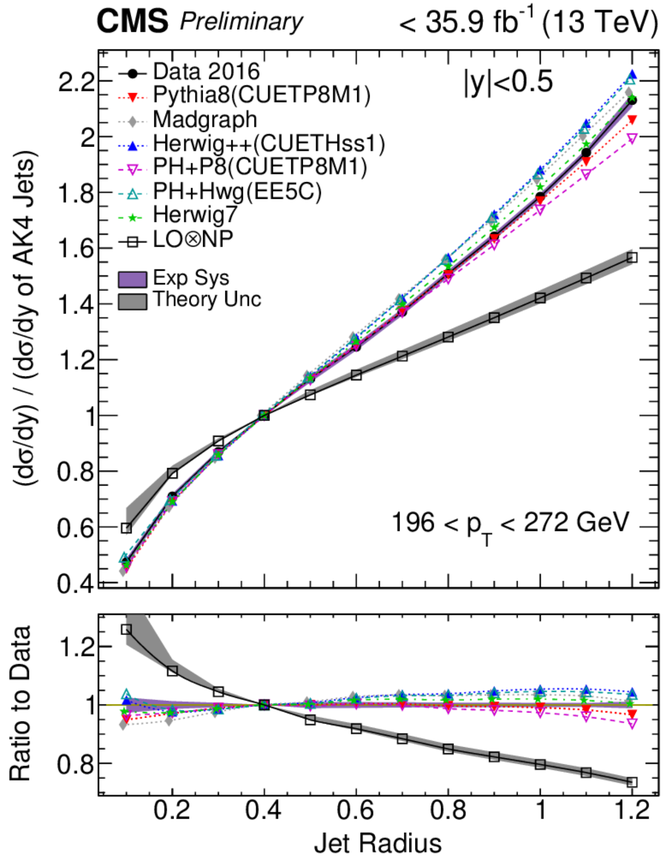
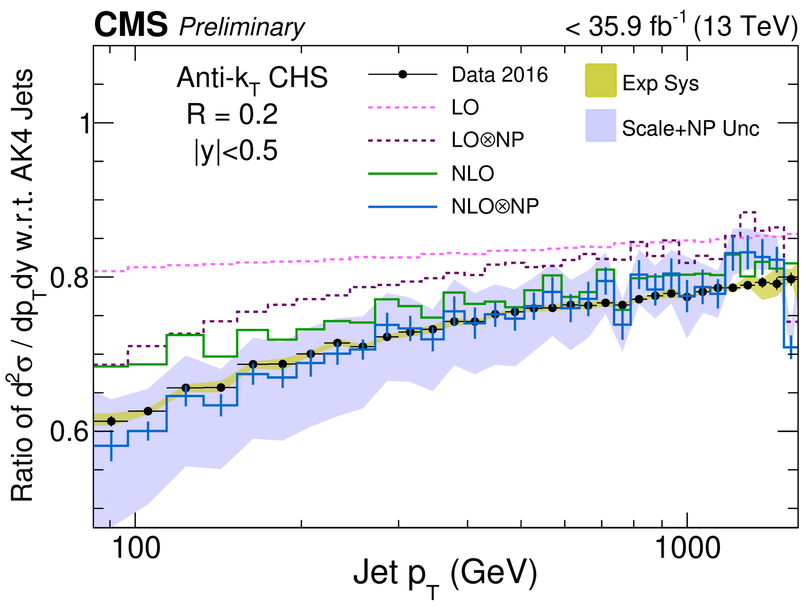
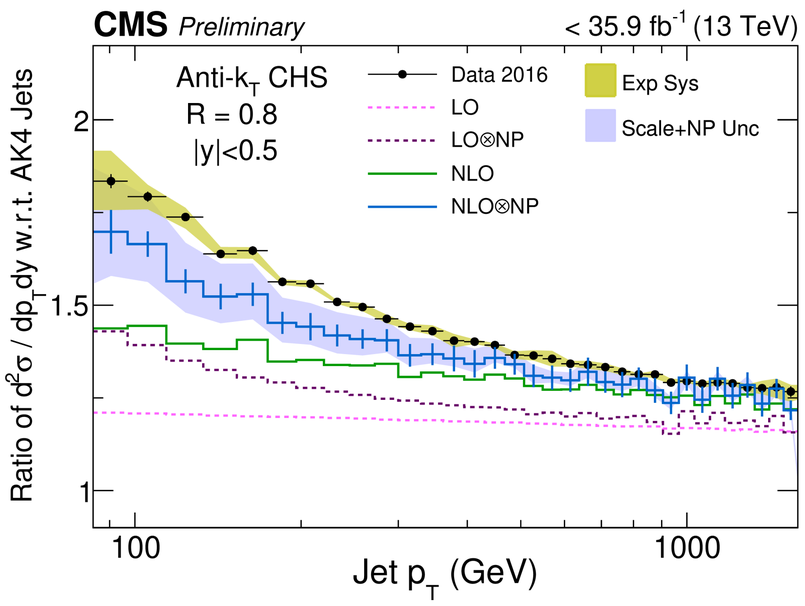


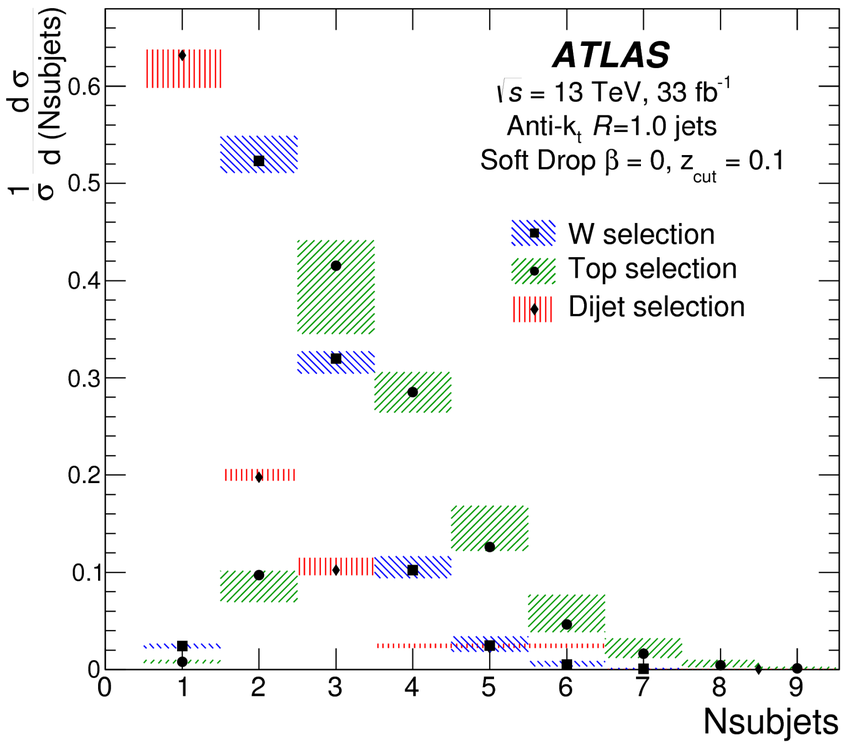


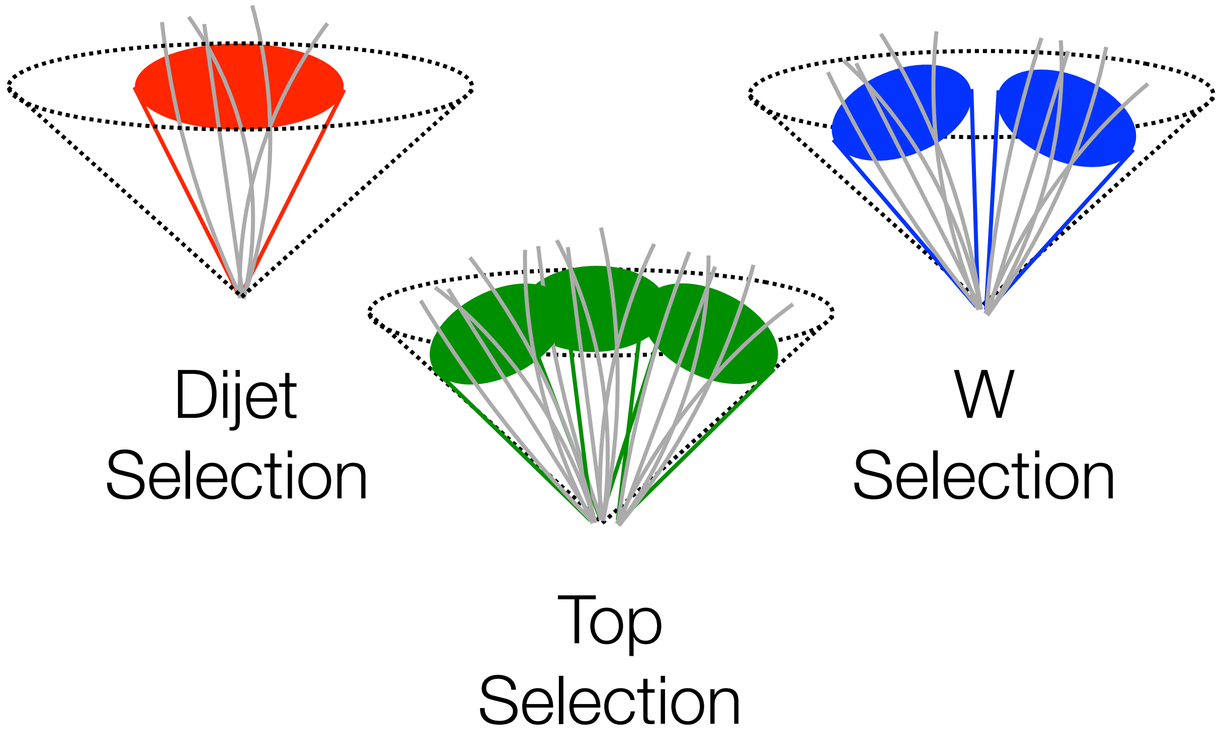


Multi-scale: Jet production

arXiv:1903.02942

- ATLAS selects hadronic top, W and dijet events and compares jet substructure variables for data and standard generators





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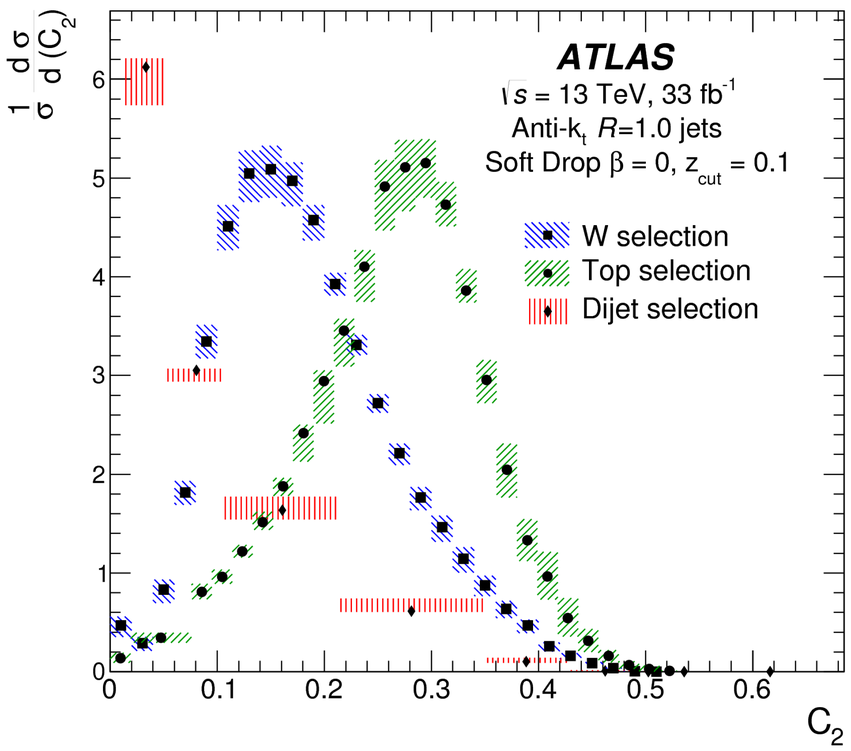

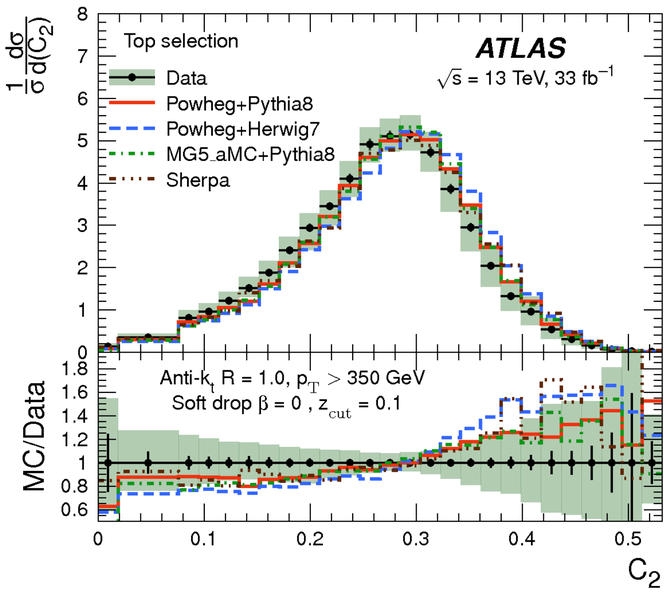

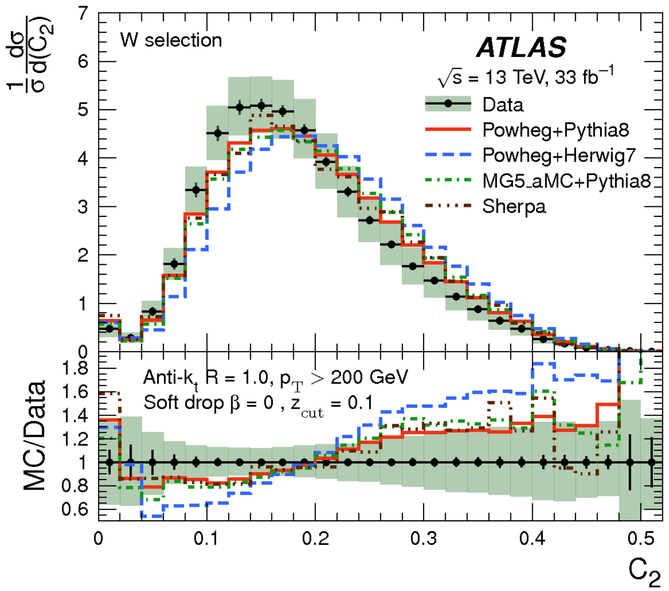

C2 ref