TMD Studies at the LHC: Overview of results

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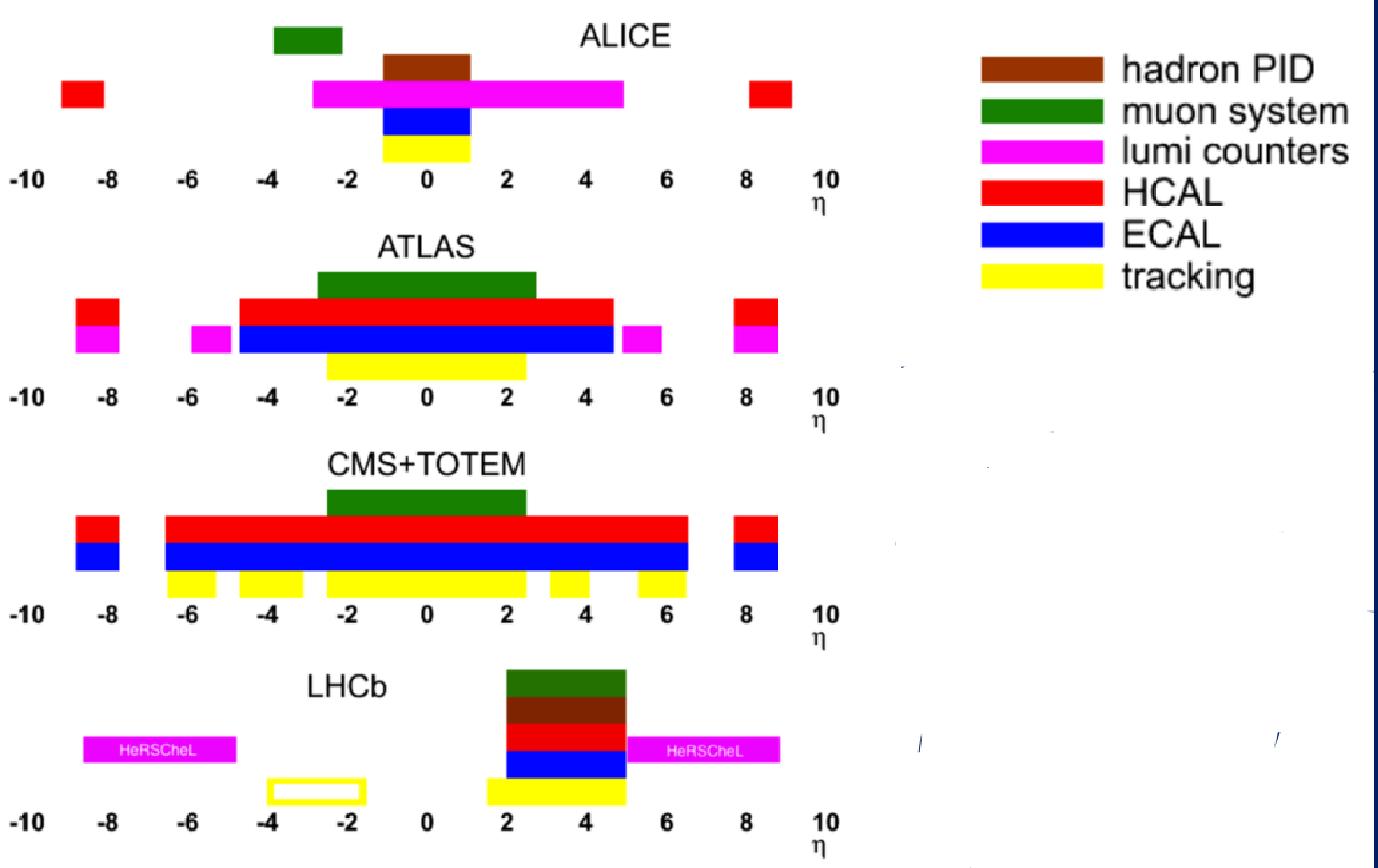
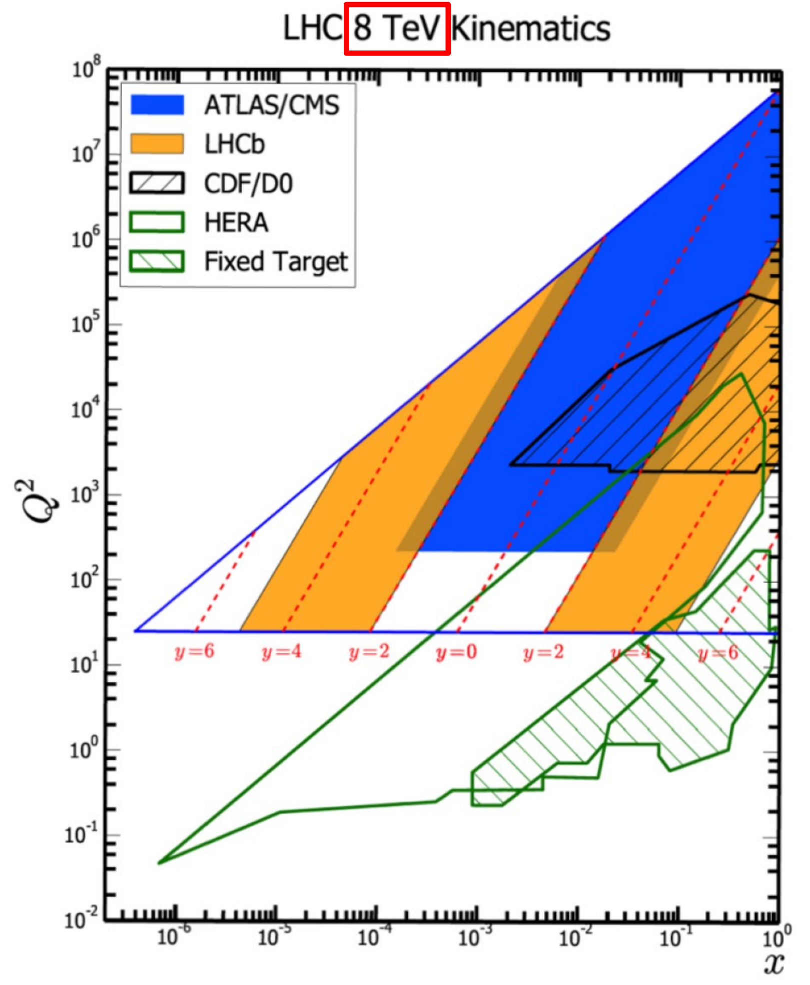
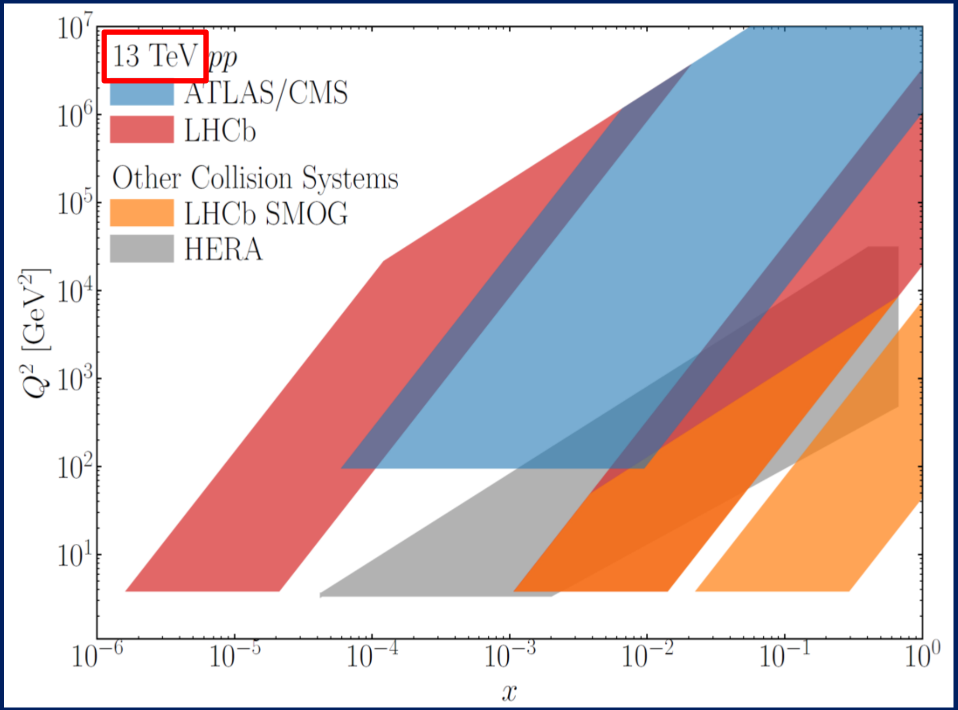
Sardinian Workshop on Spin
Cagliari (I'm there in spirit!)
September 6-8, 2021

Pseudorapidity coverage at LHC

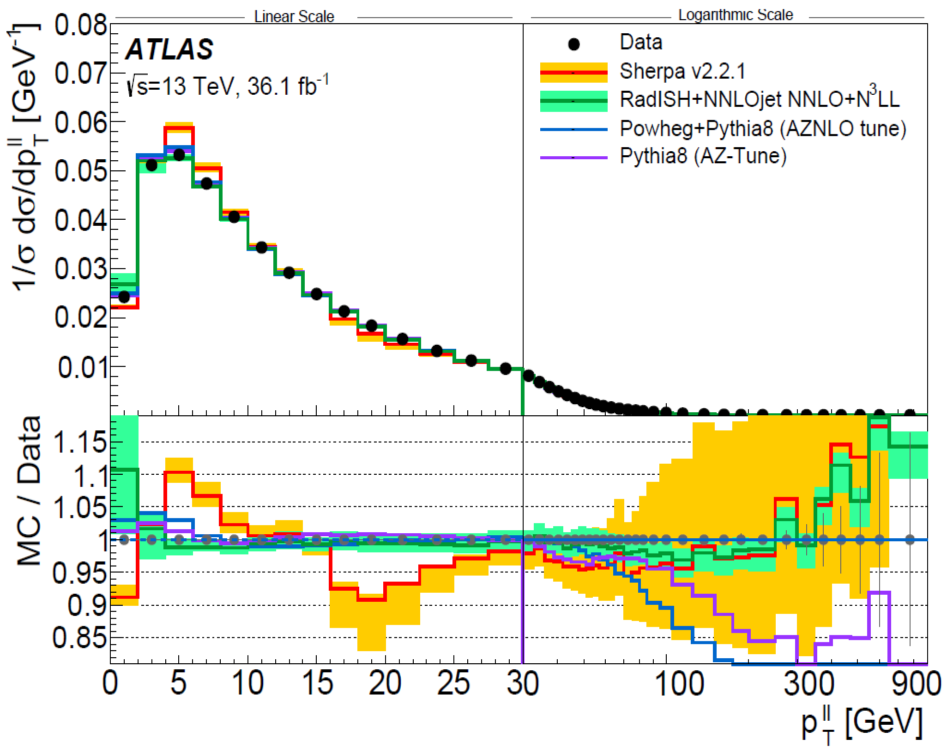


x-Q^2 *coverage*

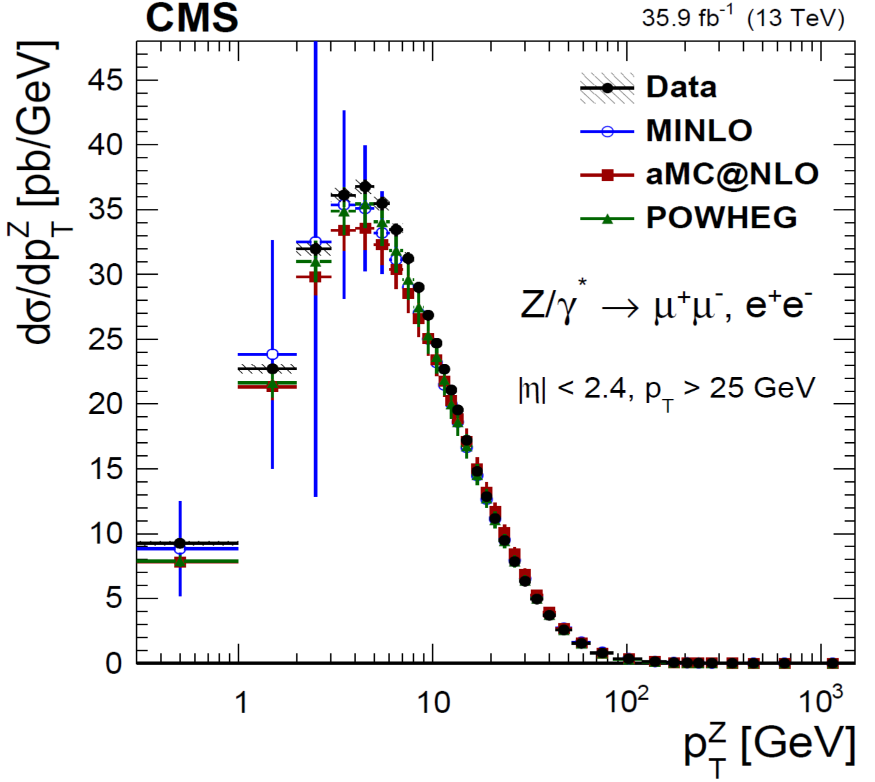




(Anti-)Quark TMDs: Drell-Yan/Z

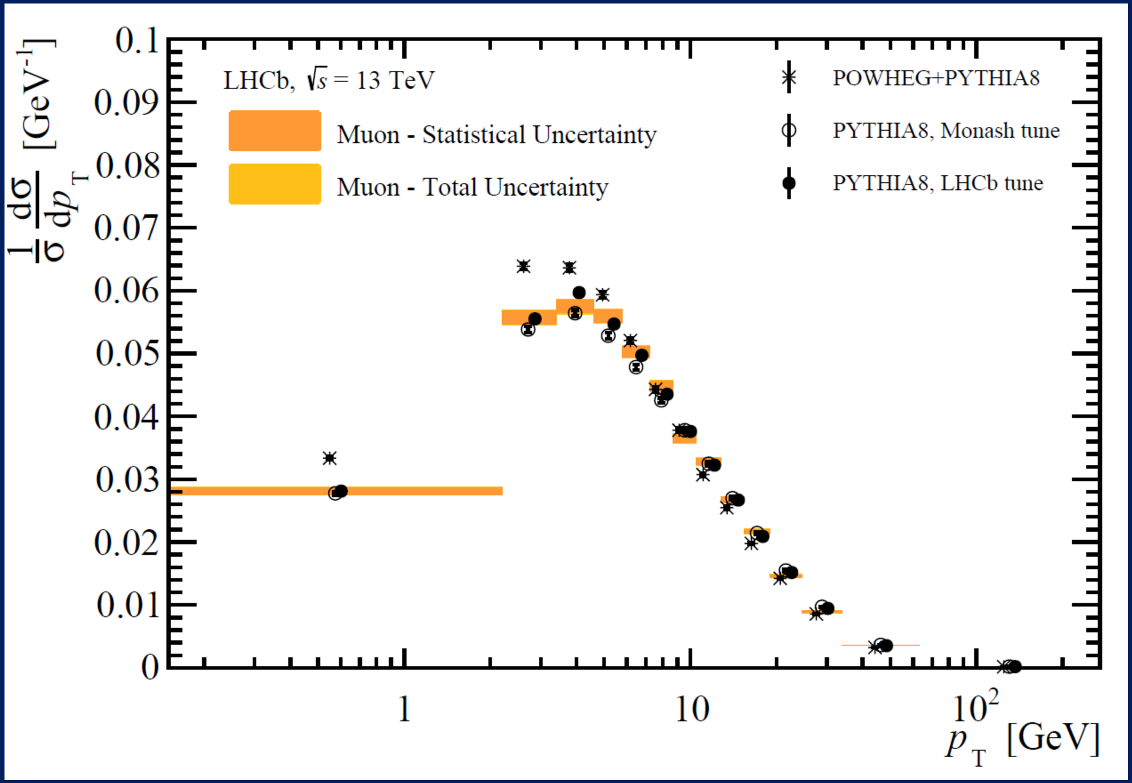


EPJ C80, 616 (2020)
arXiv:1912.02844
$66 < m < 116$ GeV



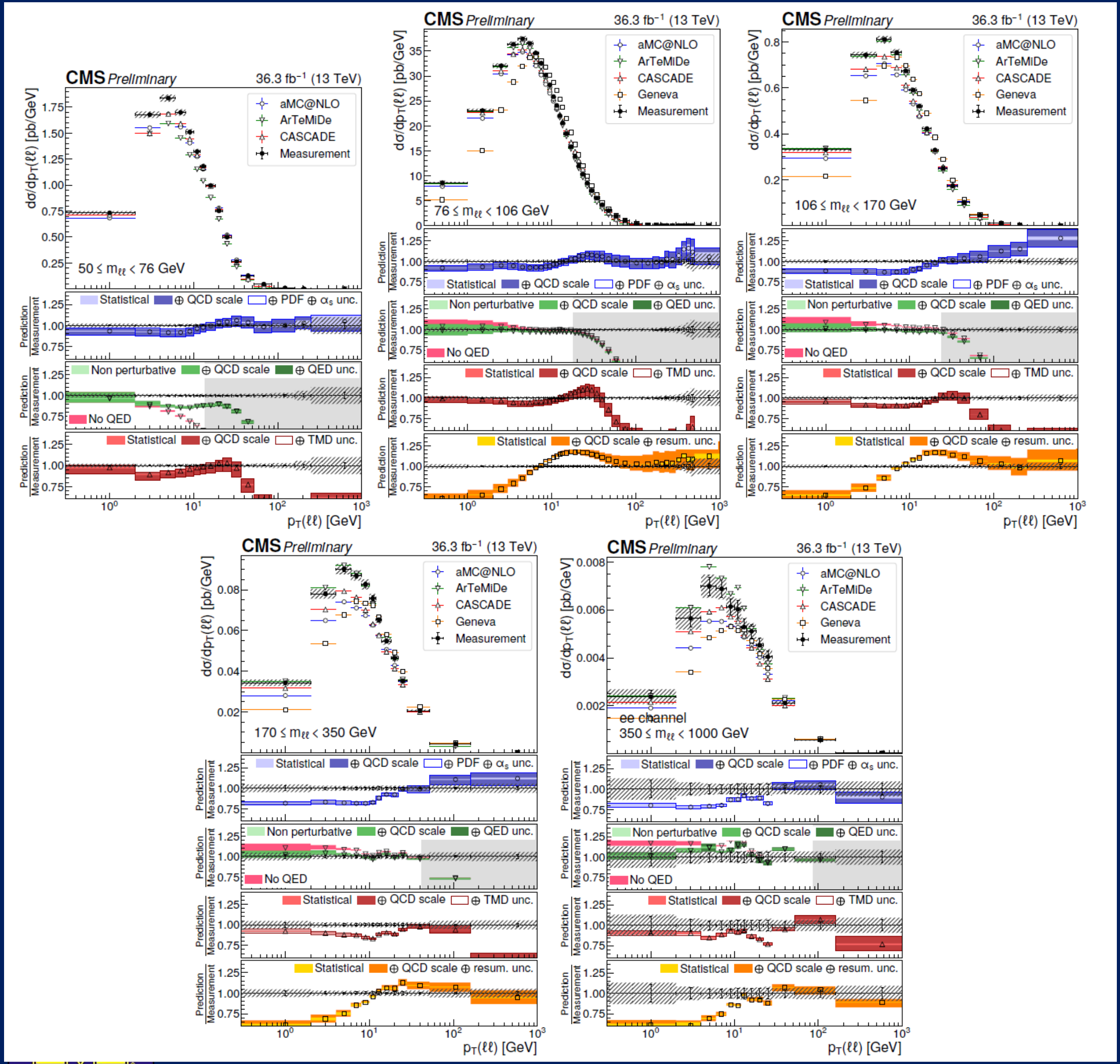
JHEP 12, 061 (2019)
arXiv:1909.04133
$76 < m < 106$ GeV

(Anti-)Quark TMDs: Drell-Yan/Z



JHEP 09, 136 (2016)
arXiv:1607.06495
$60 < m < 120$ GeV
$2.0 < \eta < 4.5$

Double-differential Drell-Yan



Different mass bins as a function of p_T, with relatively fine binning at low p_T.

- Should be useful for studying TMD evolution

CMS PAS SMP-20-003

(Anti-)Quark TMDs: Z angular distributions

$\cos 2\phi$ angular modulation at low p_T sensitive to Boer-Mulders TMD PDF

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\boxed{\nu}}{2} \sin^2\theta \cos 2\phi$$

$$\lambda = \frac{2 - 3A_0}{2 + A_0}, \qquad \mu = \frac{2A_1}{2 + A_0}, \qquad \nu = \frac{2A_2}{2 + A_0}$$

- Angular coefficients λ, μ, ν or A_i typically used

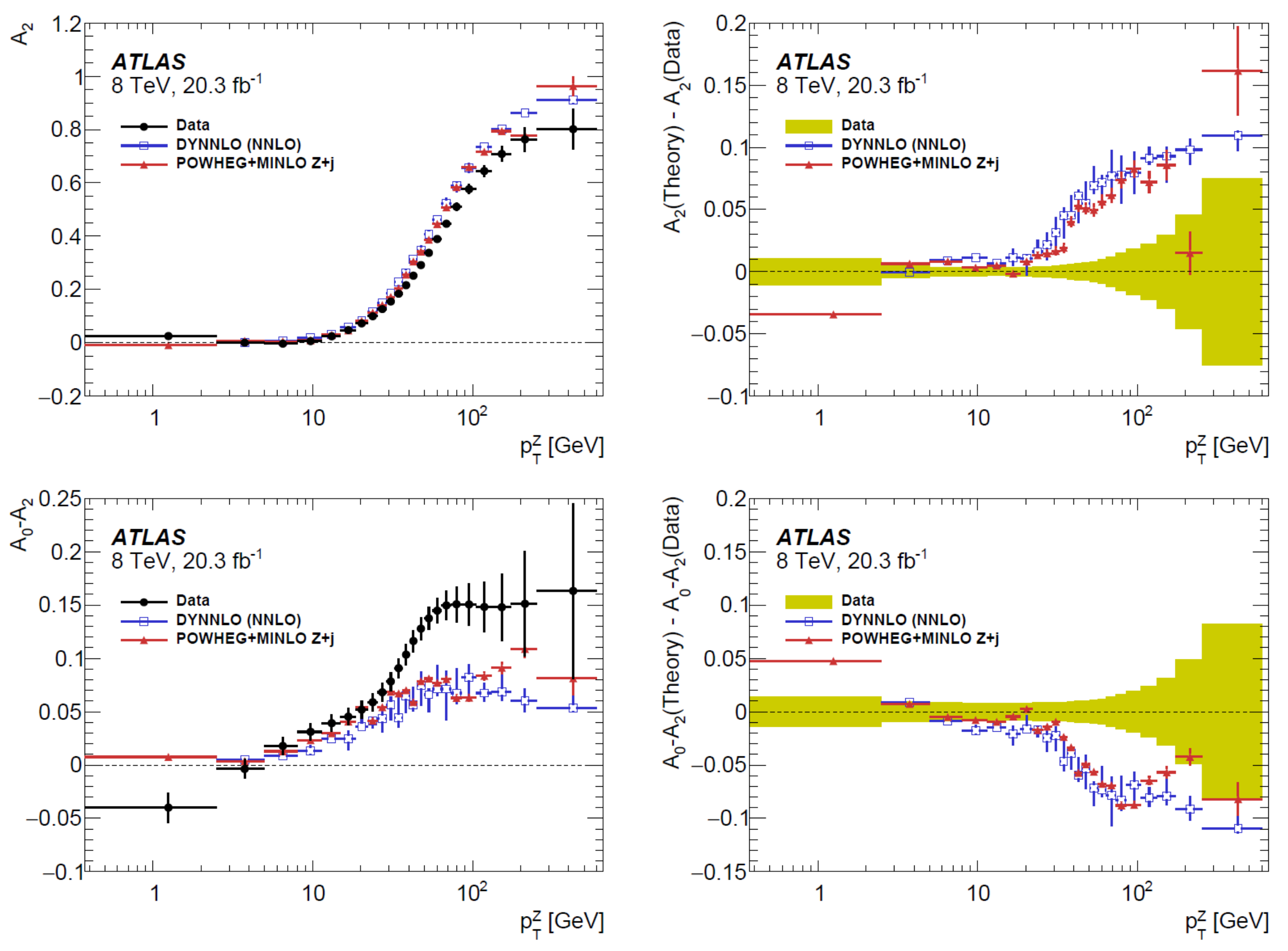
$$A_0 = \frac{2W_L}{2W_T + W_L}, \qquad A_1 = \frac{2W_\Delta}{2W_T + W_L}$$

$$\boxed{A_2} = \frac{4W_{\Delta\Delta}}{2W_T + W_L}.$$

See e.g. Boer and Vogelsang, PRD74, 014004 (2006)

(Anti-)Quark TMDs: Z angular distributions

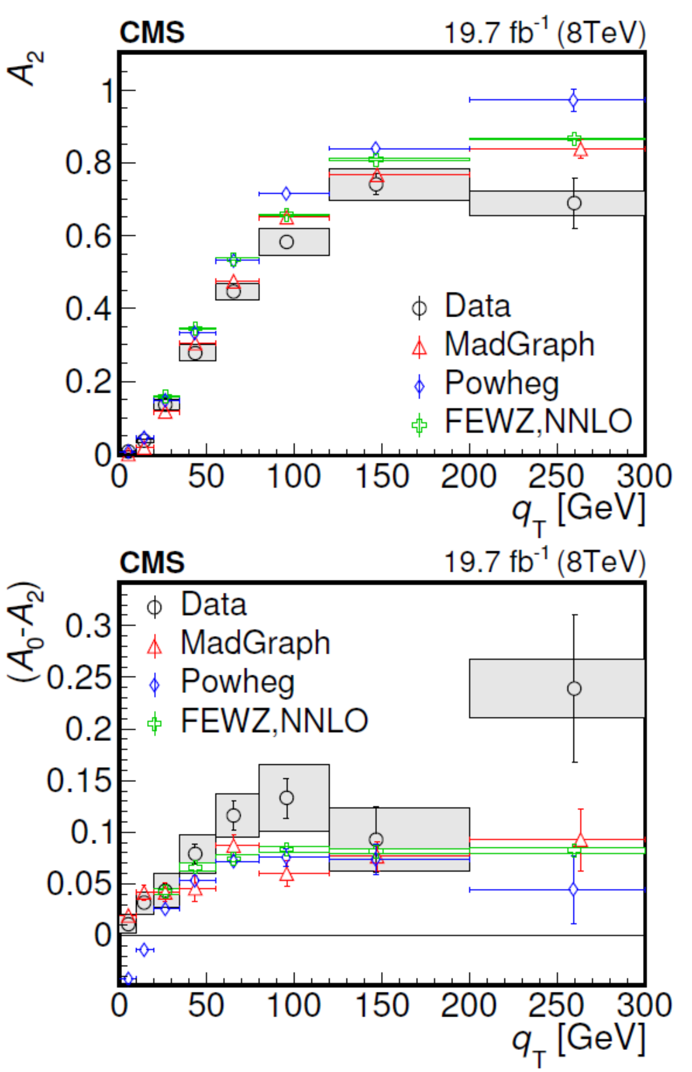
Interesting behavior in first p_T bin, up to 2.5 GeV?



JHEP 08, 159 (2016)
arXiv:1606.00689

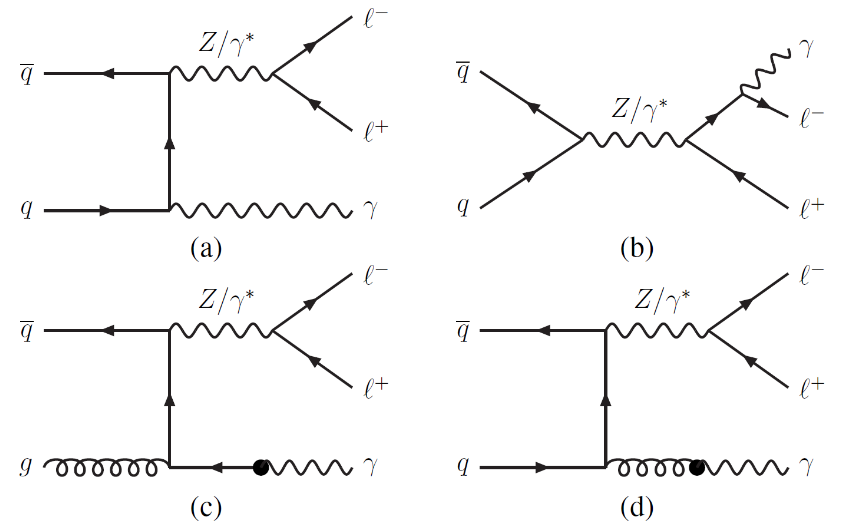
(Anti-)Quark TMDs: Z angular distributions

CMS lowest p_T bin extends up to 10 GeV—less sensitive to any TMD effects

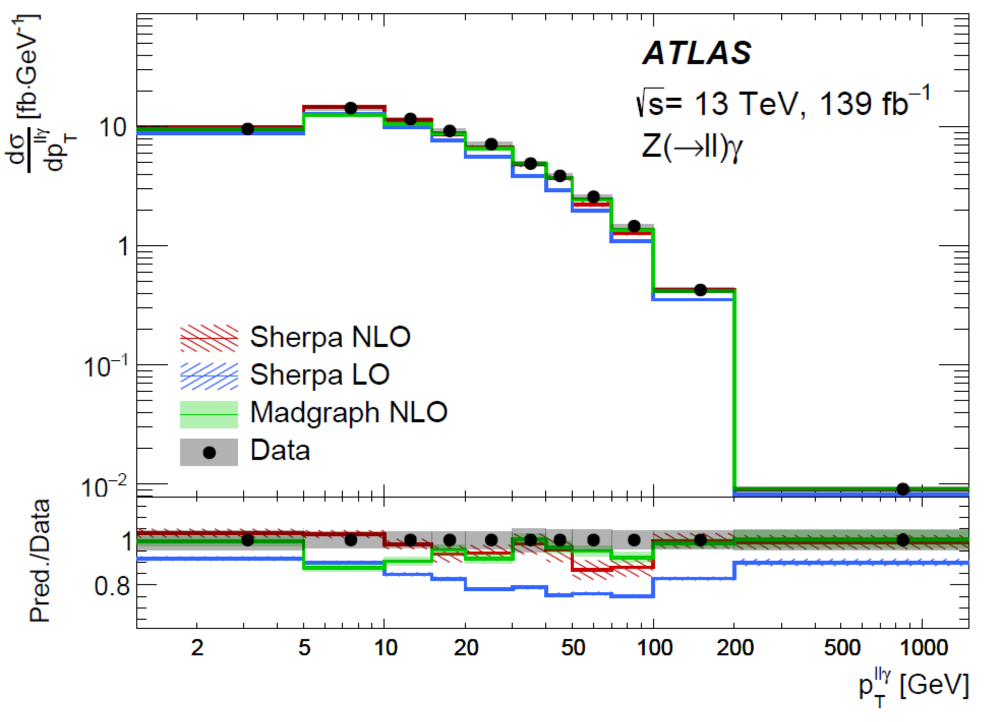


PLB 750, 154 (2015)
arXiv:1504.03512

Can anything be learned from $p + p \to Z\gamma + X$?

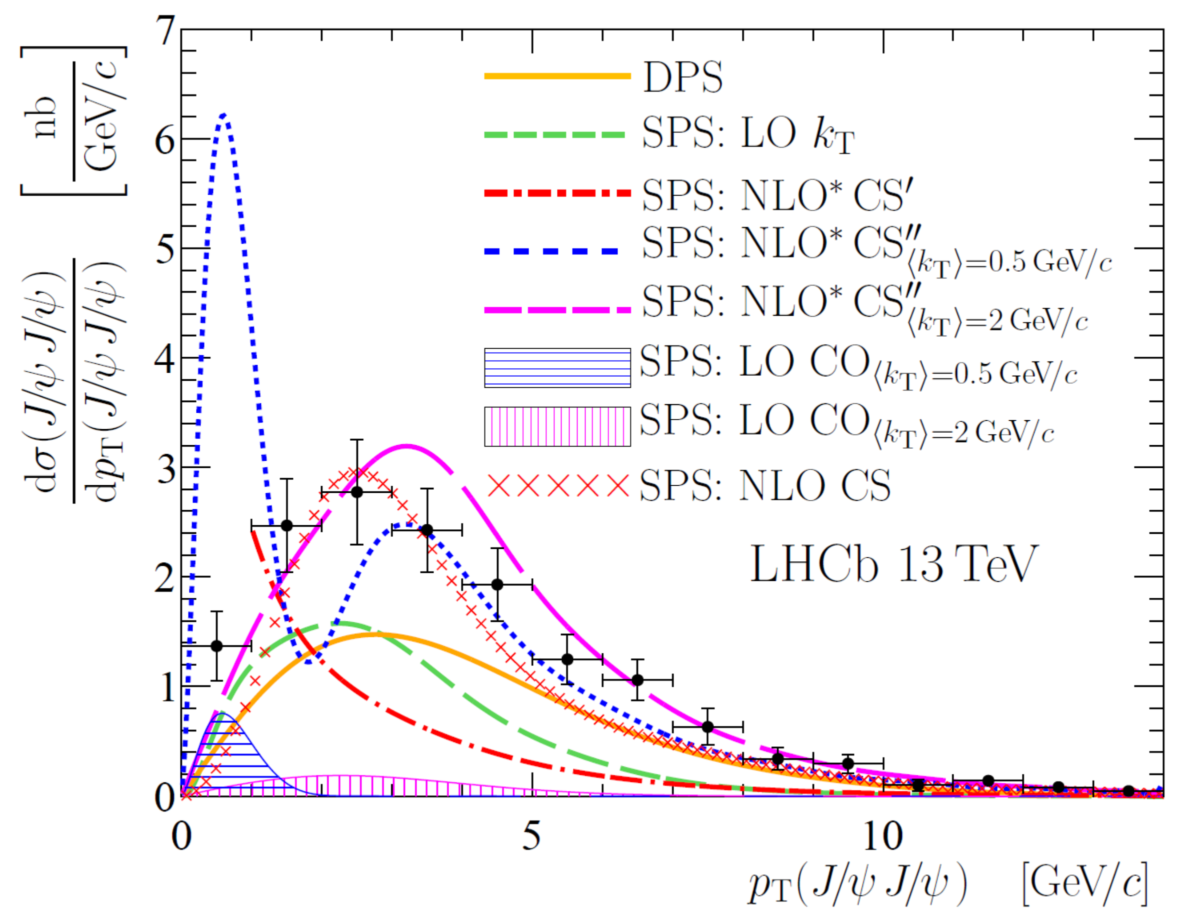


(a) (b) (c) (d)



JHEP 03, 054 (2020)
arXiv:1911.04813

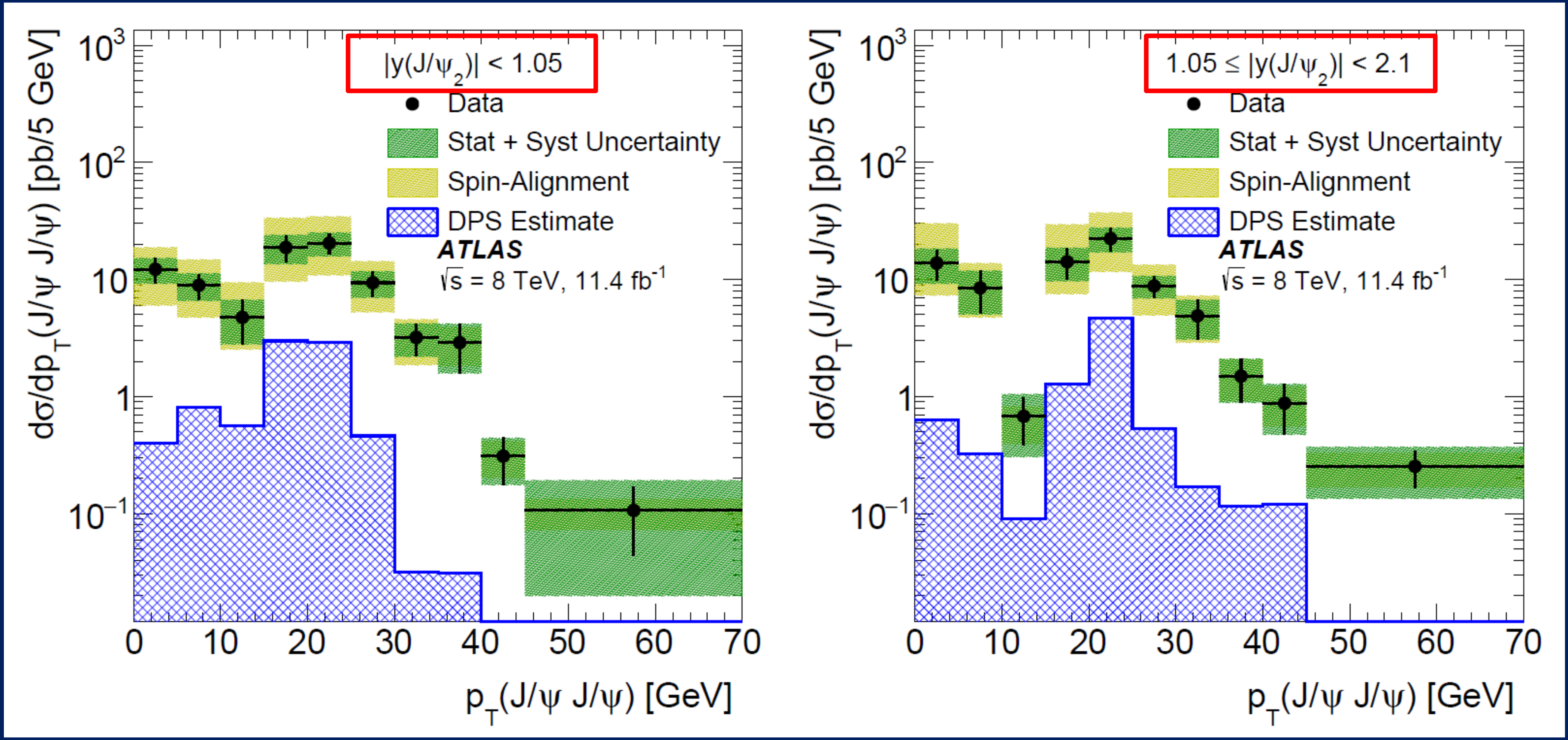
Gluon TMDs: Double J/ψ production



- Sensitive to unpolarized and linearly polarized gluon TMDs
- LHCb measurement $2.0 < y < 4.5$

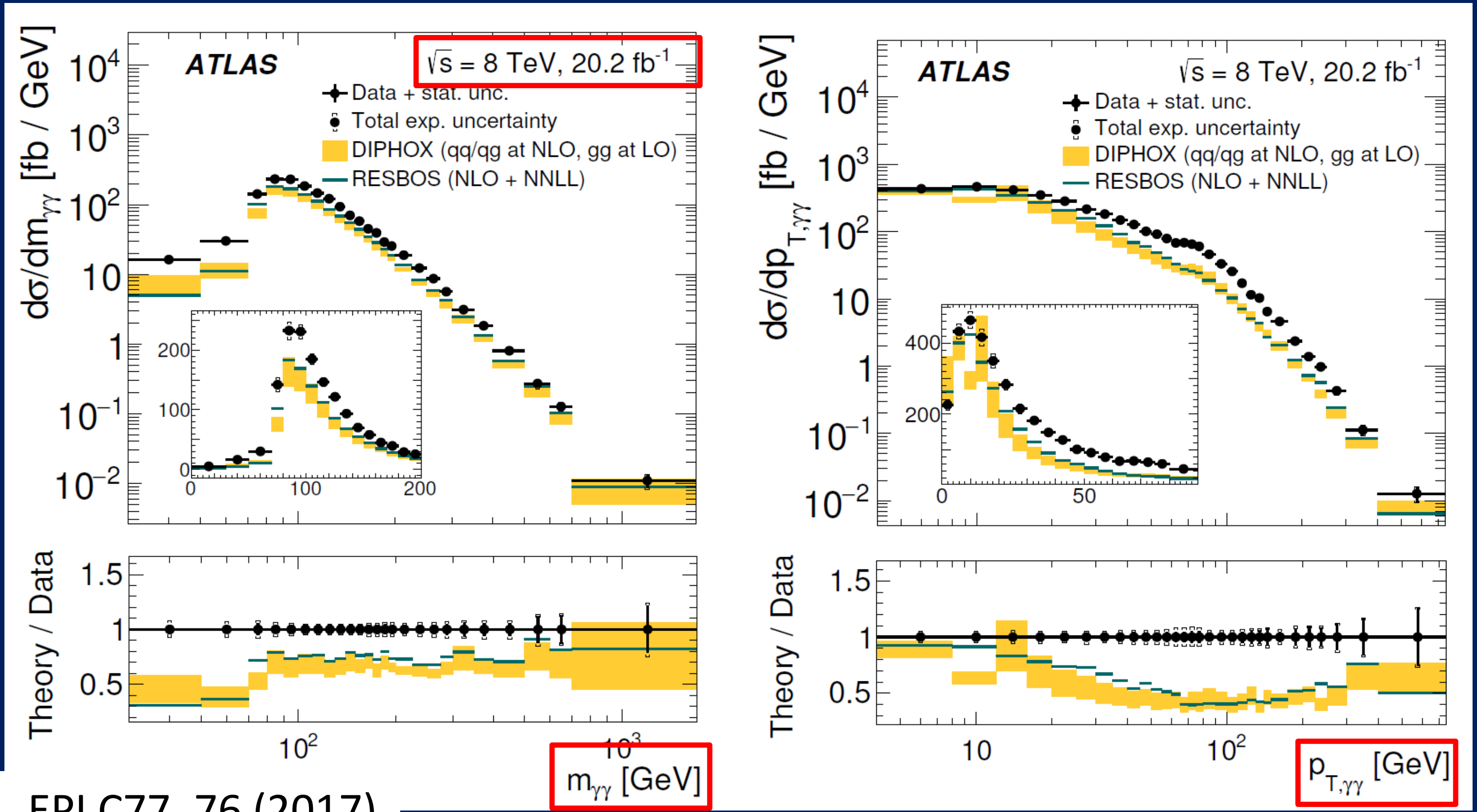
JHEP 06, 047 (2017)
arXiv:1612.07451

Double J/ψ production



EPJ C77, 76 (2017)
arXiv:1612.02950

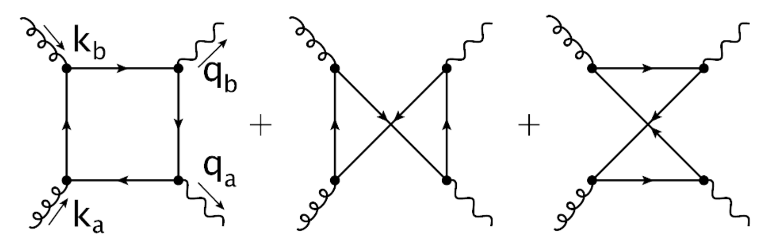
Gluon TMDs: Isolated photon pairs



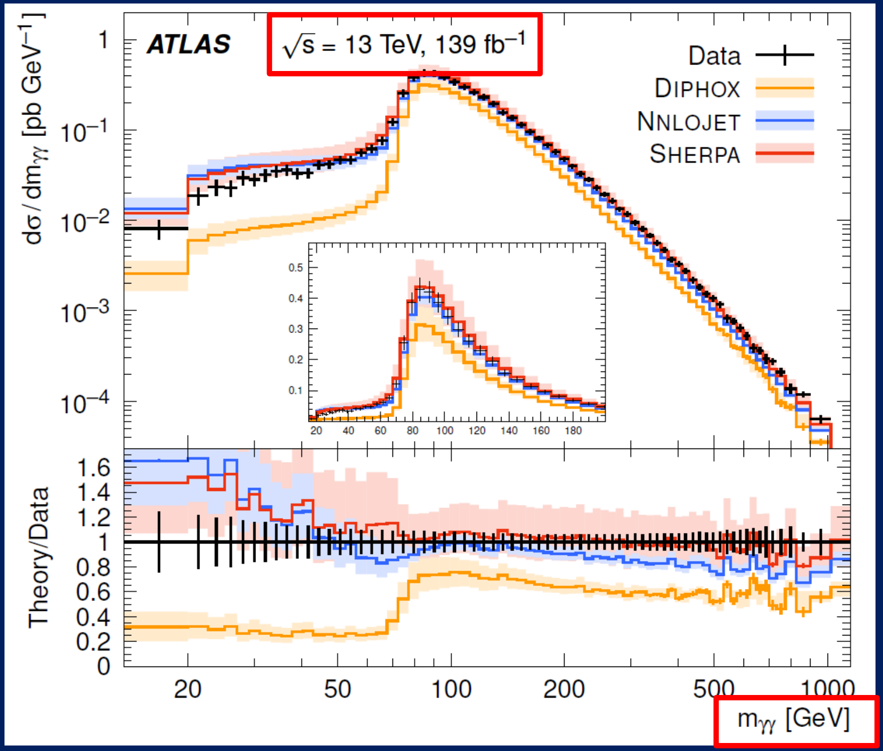
EPJ C77, 76 (2017)
arXiv:1704.03839

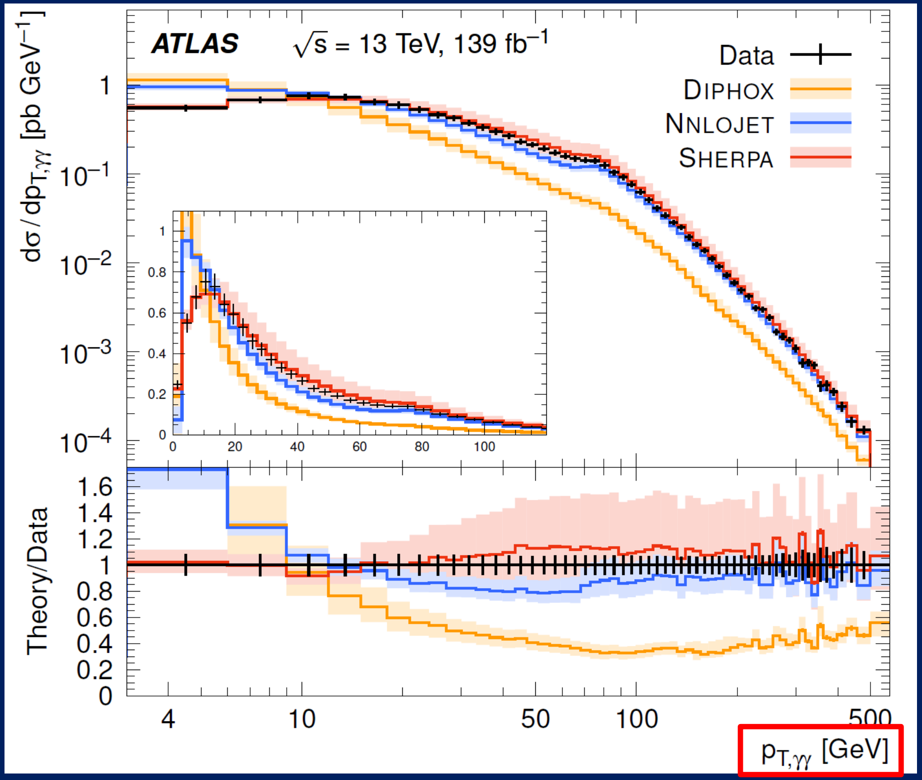
Mass shape due to photon E_T cuts. Low-mass region populated by $\gamma\gamma$ + multijet events.
Bump below ~100 GeV in p_T due to $\gamma j + j\gamma + jj$ events.

Sensitive to unpolarized and linearly polarized gluon TMDs via:
(PRL 107, 062001, arXiv:1108.3861)



Isolated photon pairs

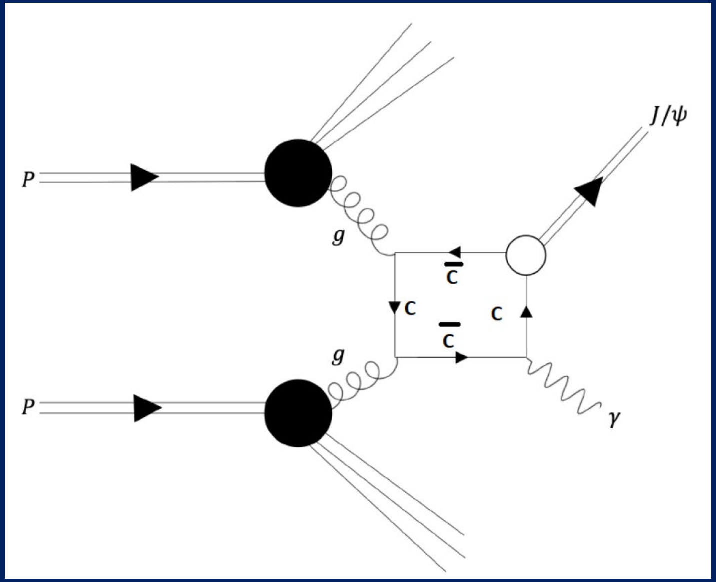


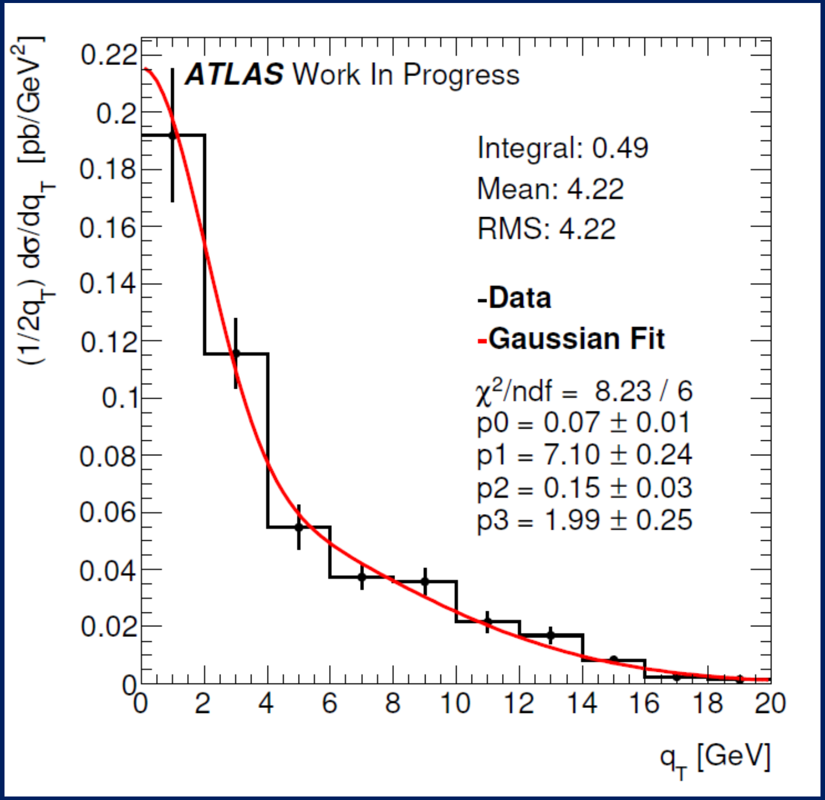


Mass shape due to photon E_T cuts. Low-mass region populated by $\gamma\gamma$ + multijet events

arXiv:2107.09330

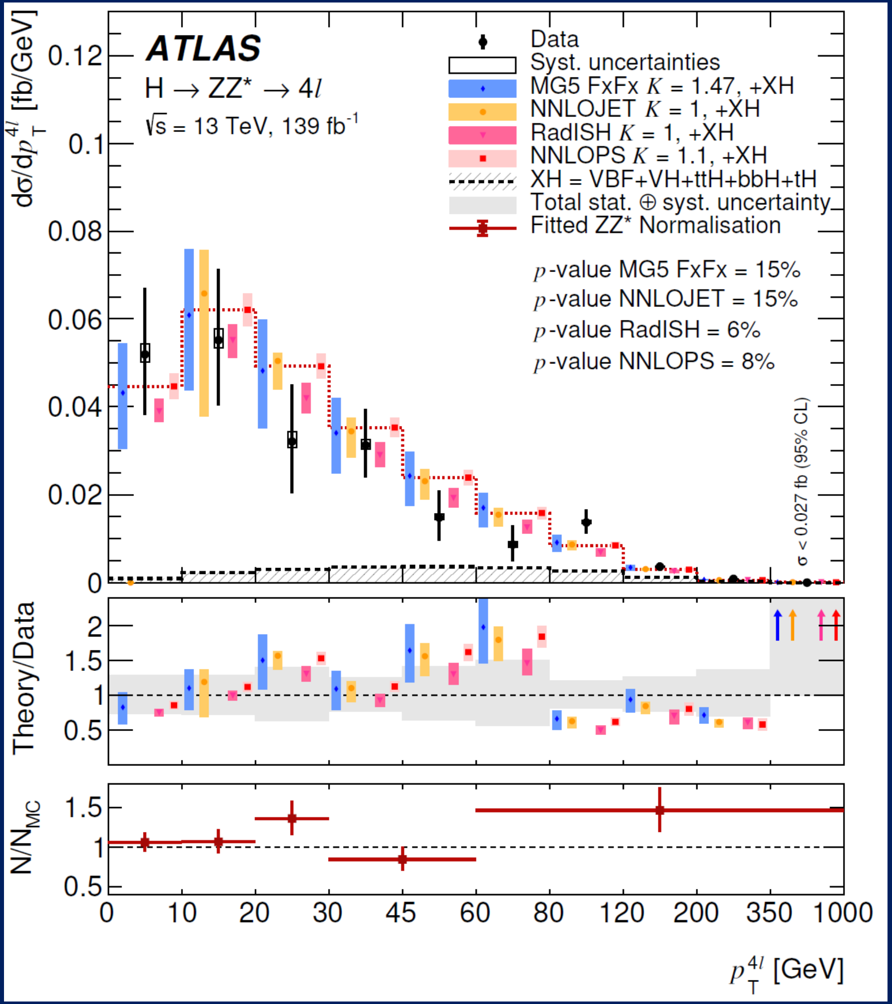
Gluon TMDs: $p + p \rightarrow J/\psi + \gamma + X$

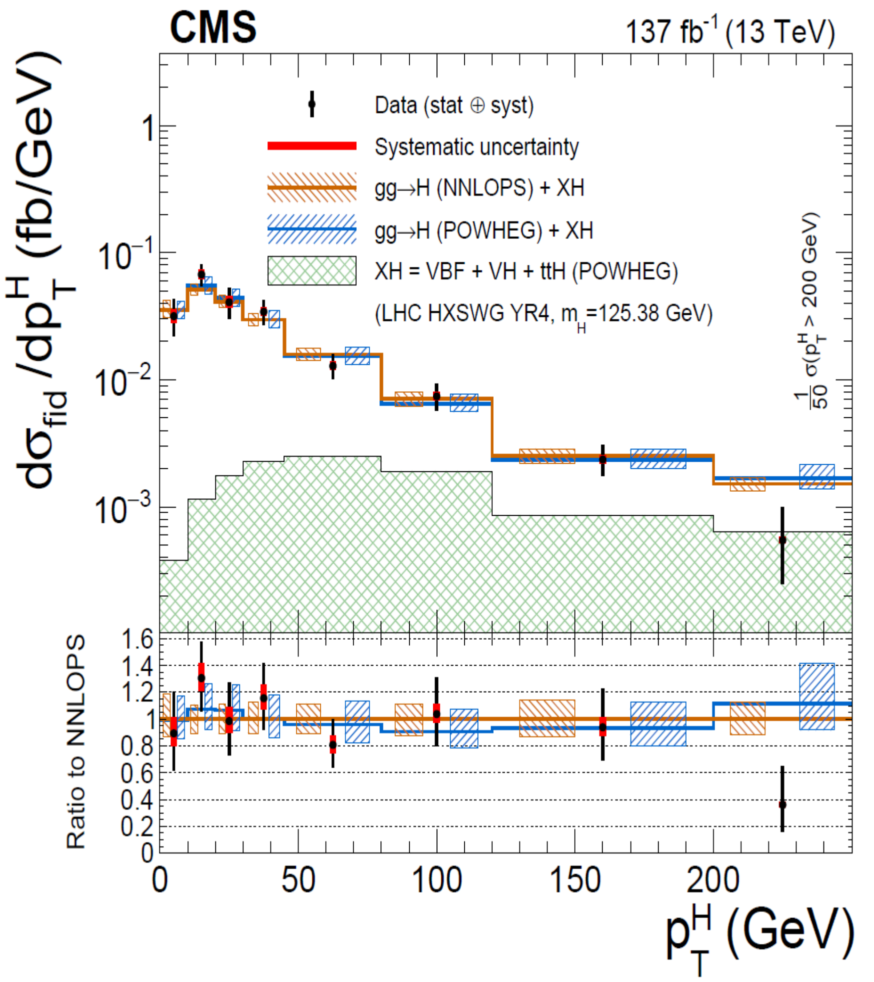




ATLAS Work-in-progress results (13 TeV) from dissertation of Amy Tee, Lancaster U. 2020 (Kartvelishvili)

Gluon TMDs: Higgs production vs. p_T





EPJ C80, 942 (2020)
arxiv:2004.03969

EPJ C81, 488 (2021)
arxiv:2103.04956

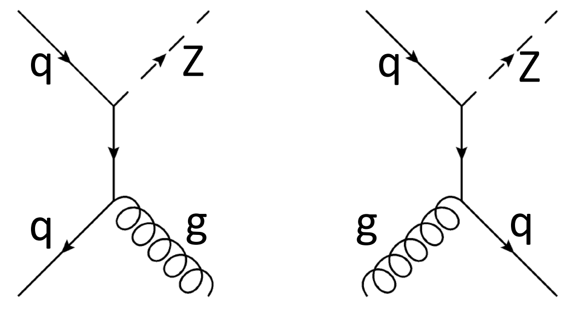
TMD fragmentation functions: Hadrons in jets

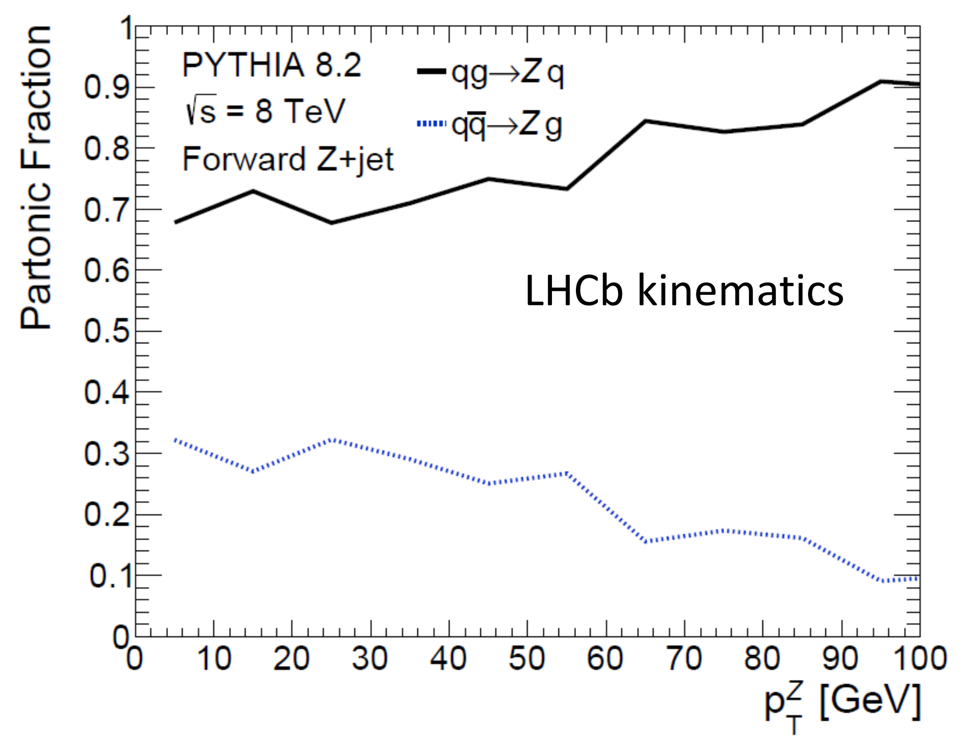
- Driven by multiple physics communities (BSM and heavy ions as well as TMD), a number of measurements relevant to TMD fragmentation in jets have been coming out in recent years

Enriched quark-jet samples

- Z+jet or γ+jet is predominantly sensitive to quark jets

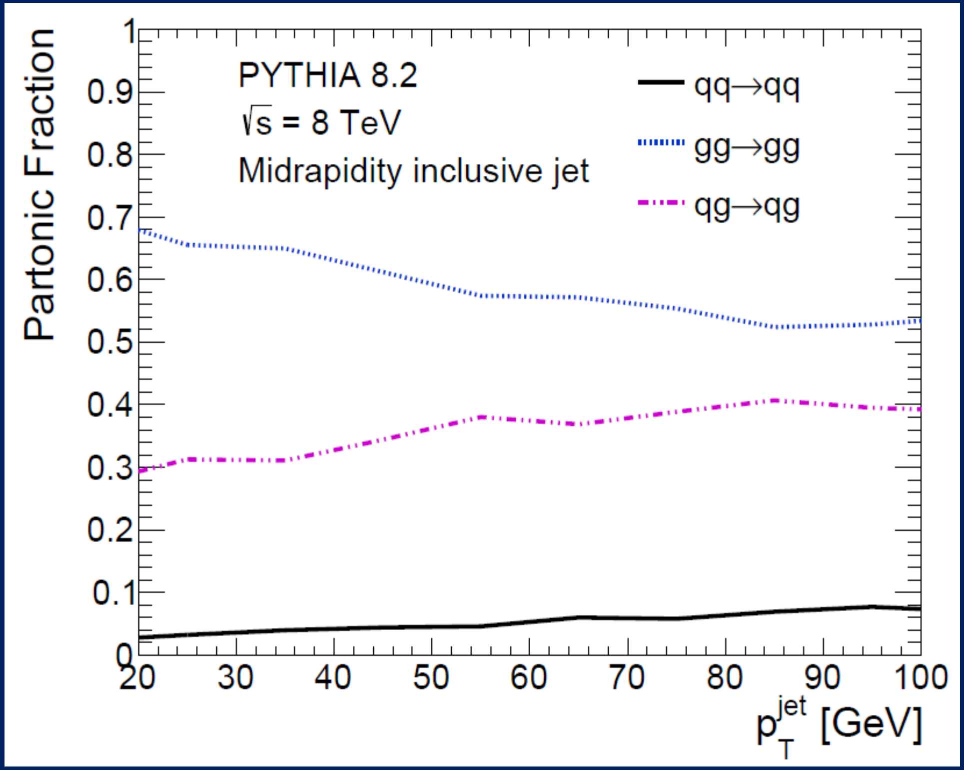
- At LHCb, forward kinematics increases fraction of light quark jets





Enriched gluon-jet samples

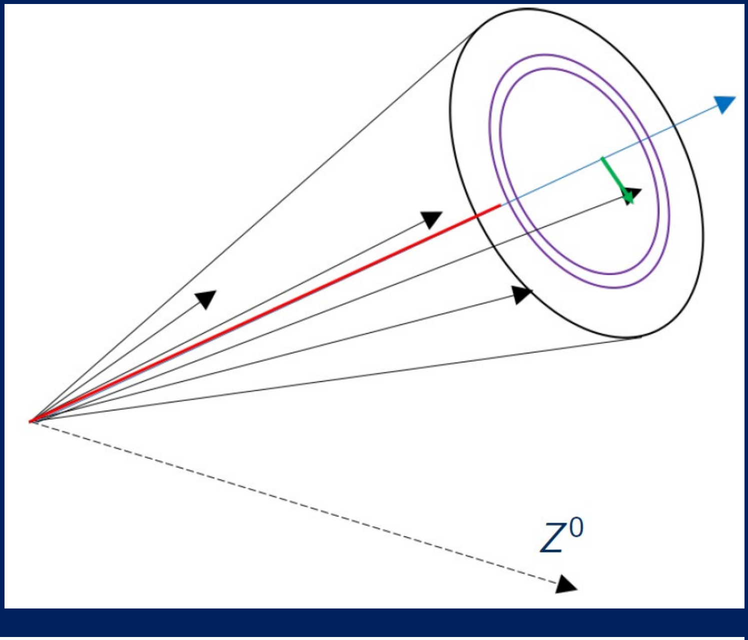
- Midrapidity inclusive jets are instead dominated by gluons
- Opportunity to study light quark vs. gluon jets
  - Hadronization dynamics
  - Jet properties



Note modest jet p_T range

Charged hadrons in forward Z+jet at LHCb: Observables

- Longitudinal momentum fraction z
- Transverse momentum with respect to jet axis j_T
- Radial profile r



$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

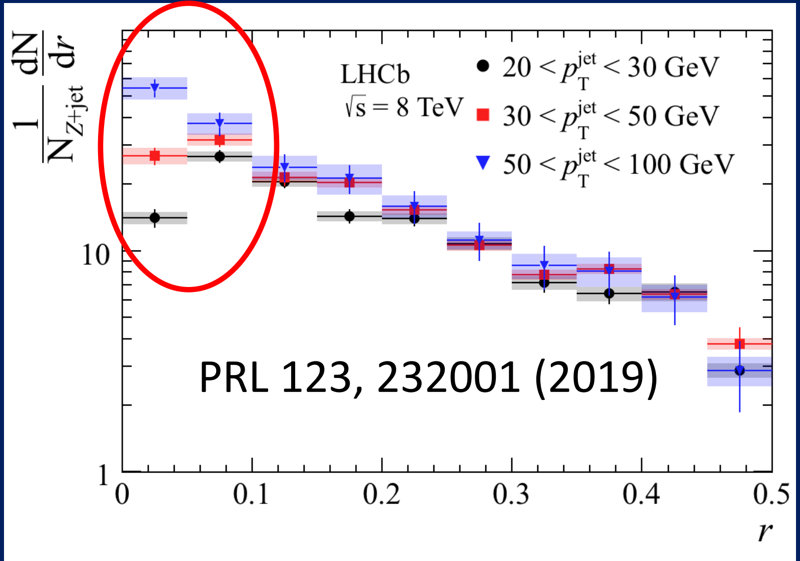
$$j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}$$

$$r = \sqrt{(\phi_h - \phi_{jet})^2 + (y_h - y_{jet})^2}$$

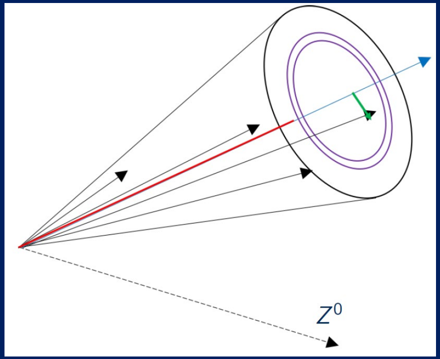
PRL 123, 232001 (2019)
arXiv:1904.08878

Radial profiles

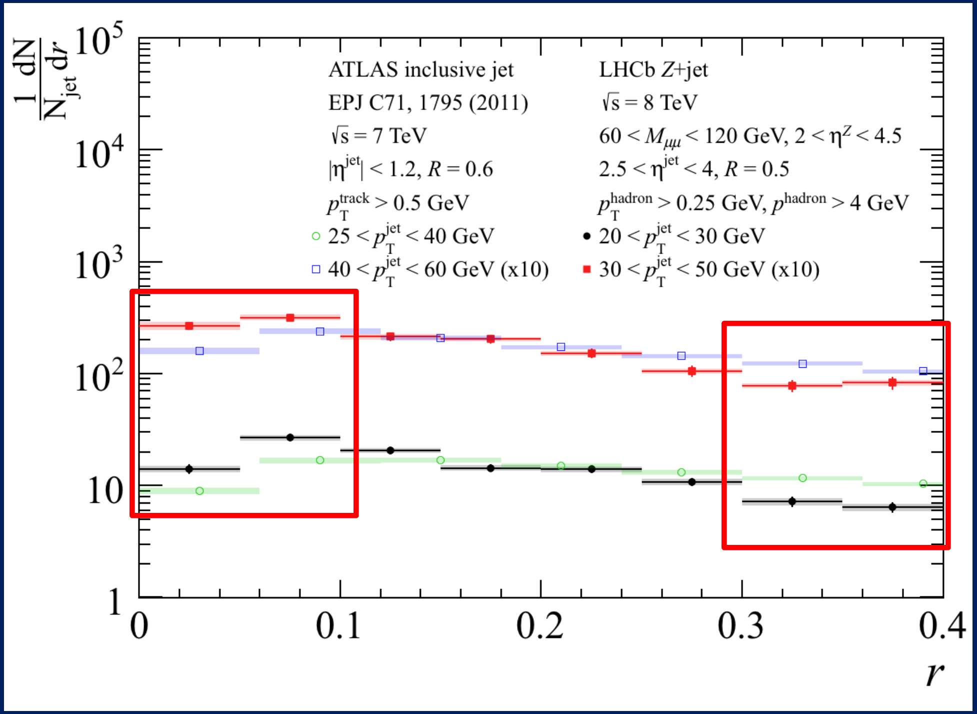
- Observe that the greater energy available in higher transverse momentum jets leads to more hadrons produced (logical)
- Note: ~All of the additional particles are produced close to the jet axis, and go from a depletion close to the axis to an excess



PRL 123, 232001 (2019)



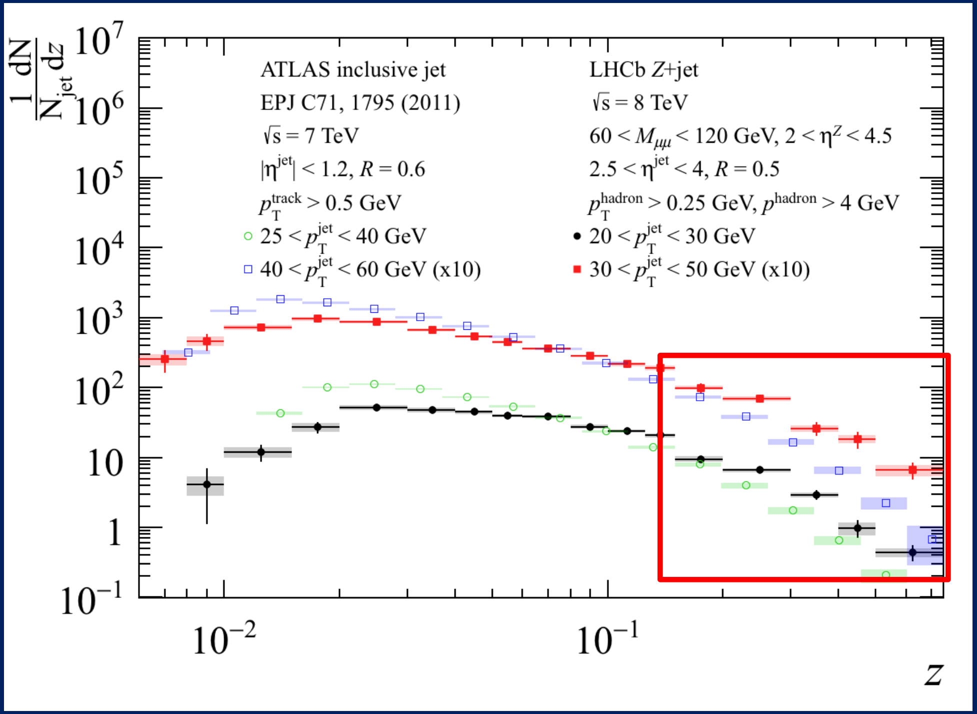
Differences between quark- and gluon-dominated jet samples: Radial profile



PRL 123, 232001 (2019)
LHCb-PAPER-2019-012

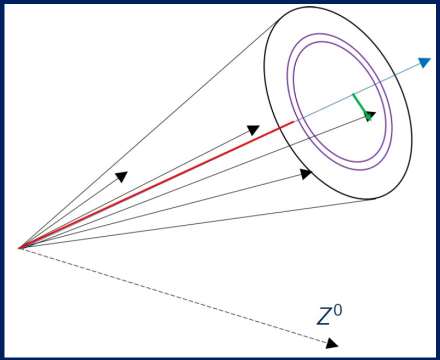
- Quark-dominated jets more collimated than gluon-dominated jets measured by ATLAS
  - I.e. more charged hadrons at small radii, fewer at large radii
  - Qualitatively agrees with conventional expectations, but this shows clear and quantitative evidence from data

Differences between quark- and gluon-dominated jet samples: Longitudinal profile

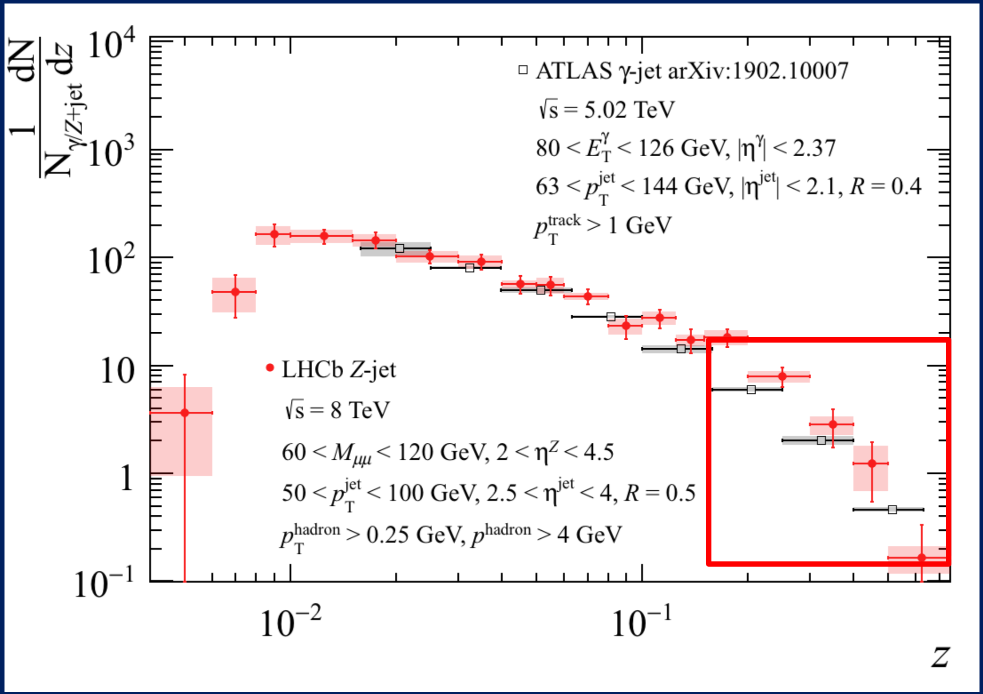


- Quark-dominated jets have relatively more hadrons produced at higher longitudinal momentum fractions than gluon-dominated jets

PRL 123, 232001 (2019)
LHCb-PAPER-2019-012



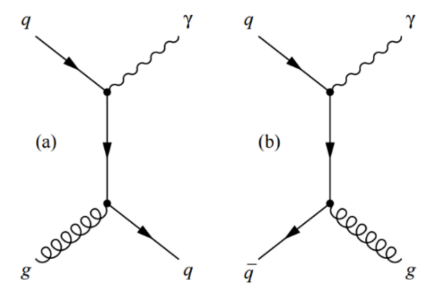
Differences between quark- and gluon-dominated jet samples: Longitudinal profile



- ATLAS midrapidity γ+jet and LHCb Z+jet longitudinal momentum distributions are more similar
  - γ+jet, like Z+jet, enhances quark jet fraction
  - Further evidence that differences observed between LHCb results and ATLAS gluon-dominated results are due to differences in quark and gluon hadronization

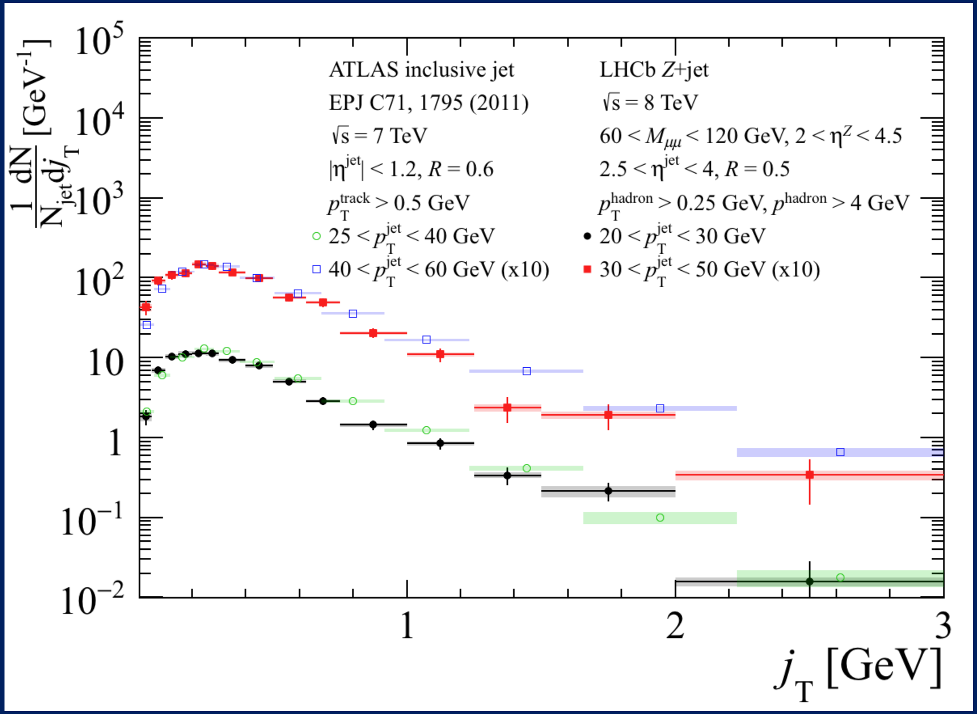
LHCb: PRL 123, 232001 (2019)
LHCb-PAPER-2019-012

ATLAS: PRL 123, 042001 (2019)



Differences between quark- and gluon-dominated jet samples: Transverse momentum distributions

- Transverse momentum distributions similar but show slightly smaller $\langle j_T \rangle$ in Z+jet vs. inclusive jet at small j_T



LHCb: PRL 123, 232001 (2019)

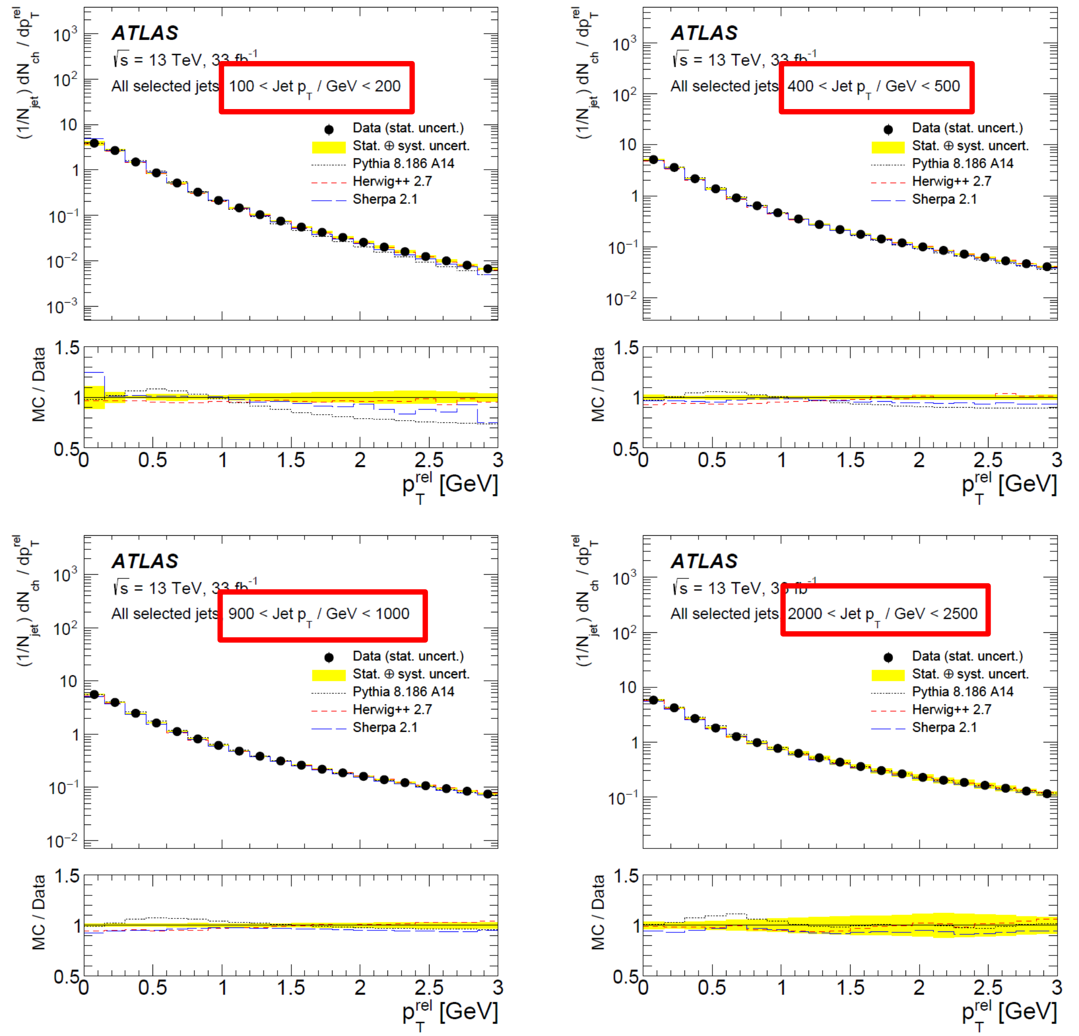
Midrapidity inclusive jet transverse momentum profile, 13 TeV

The two leading jets in each event are studied.

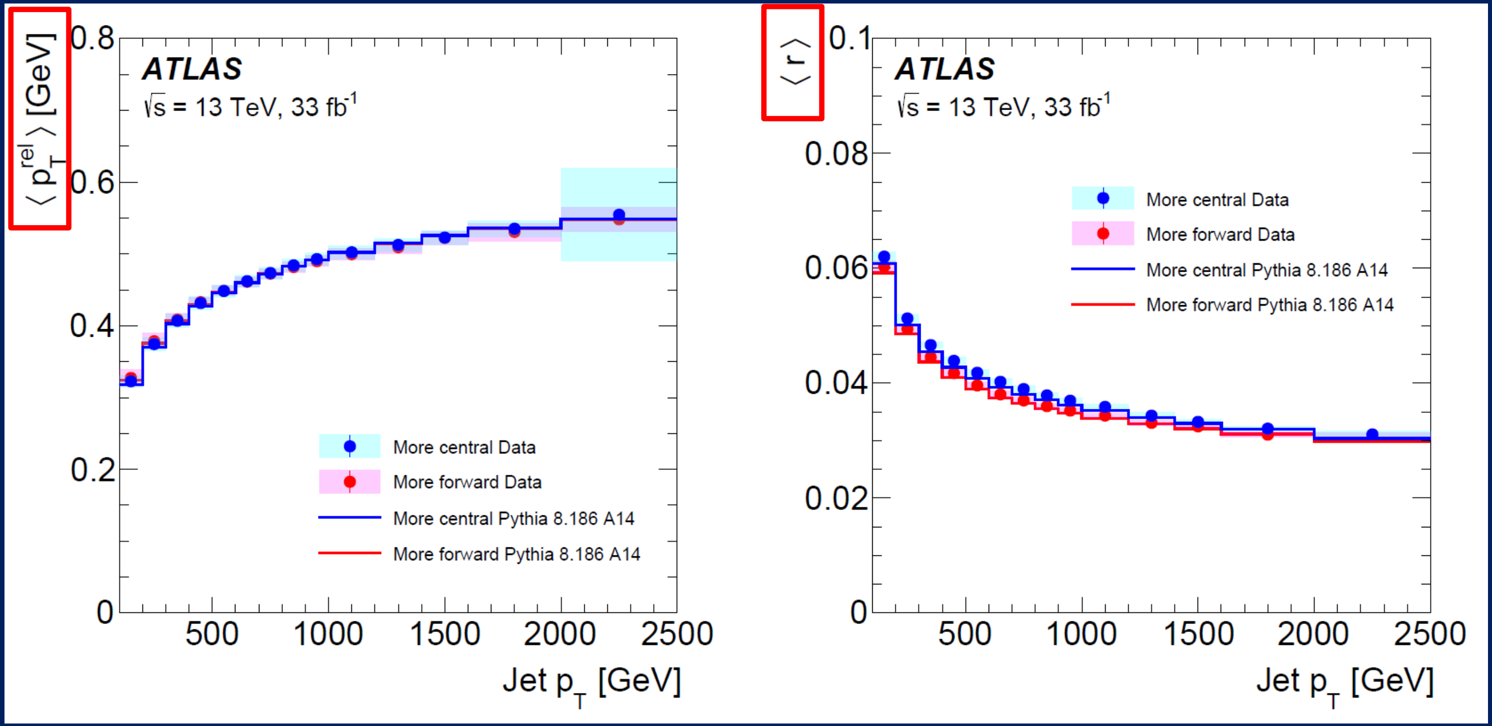
$|\eta| < 2.1$

Four bins of jet p_T

PRD 100, 052011 (2019)
arXiv:1906.09254



Midrapidity inclusive jet fragmentation, 13 TeV

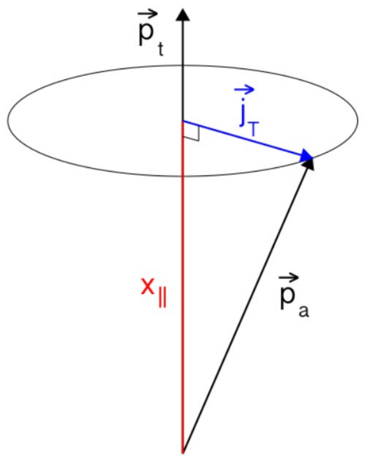


PRD 100, 052011 (2019)
arXiv:1906.09254

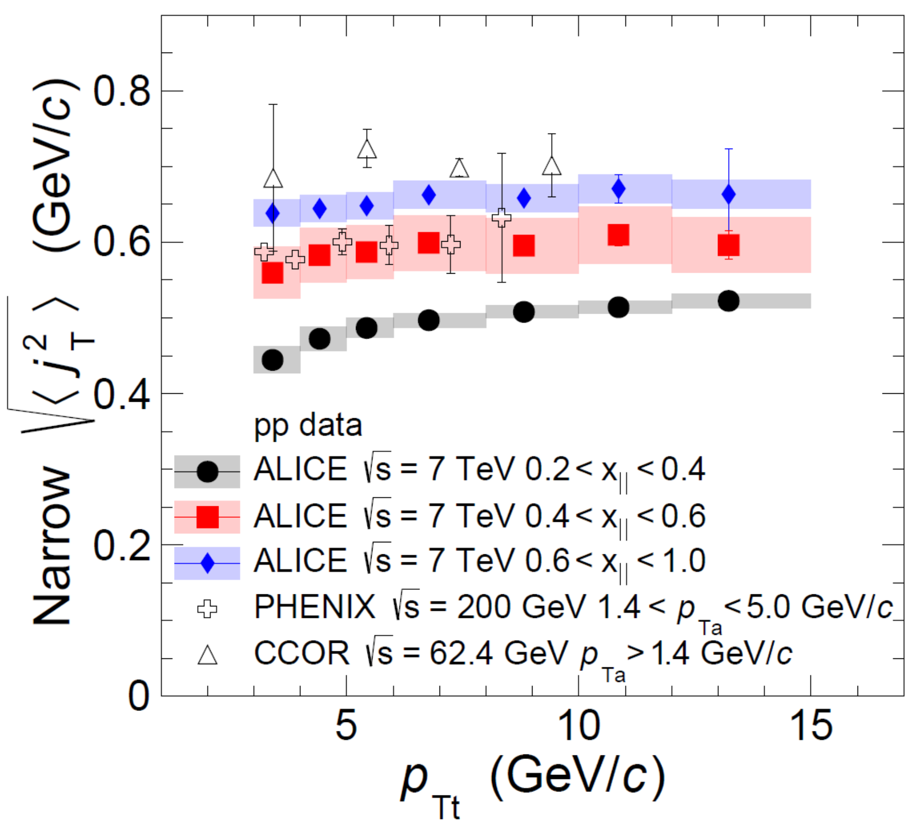
Mean p_T^{rel} and r vs. jet p_T.

Separated for the more central or forward of the two leading jets

Jet fragmentation transverse momentum measurements from dihadron correlations

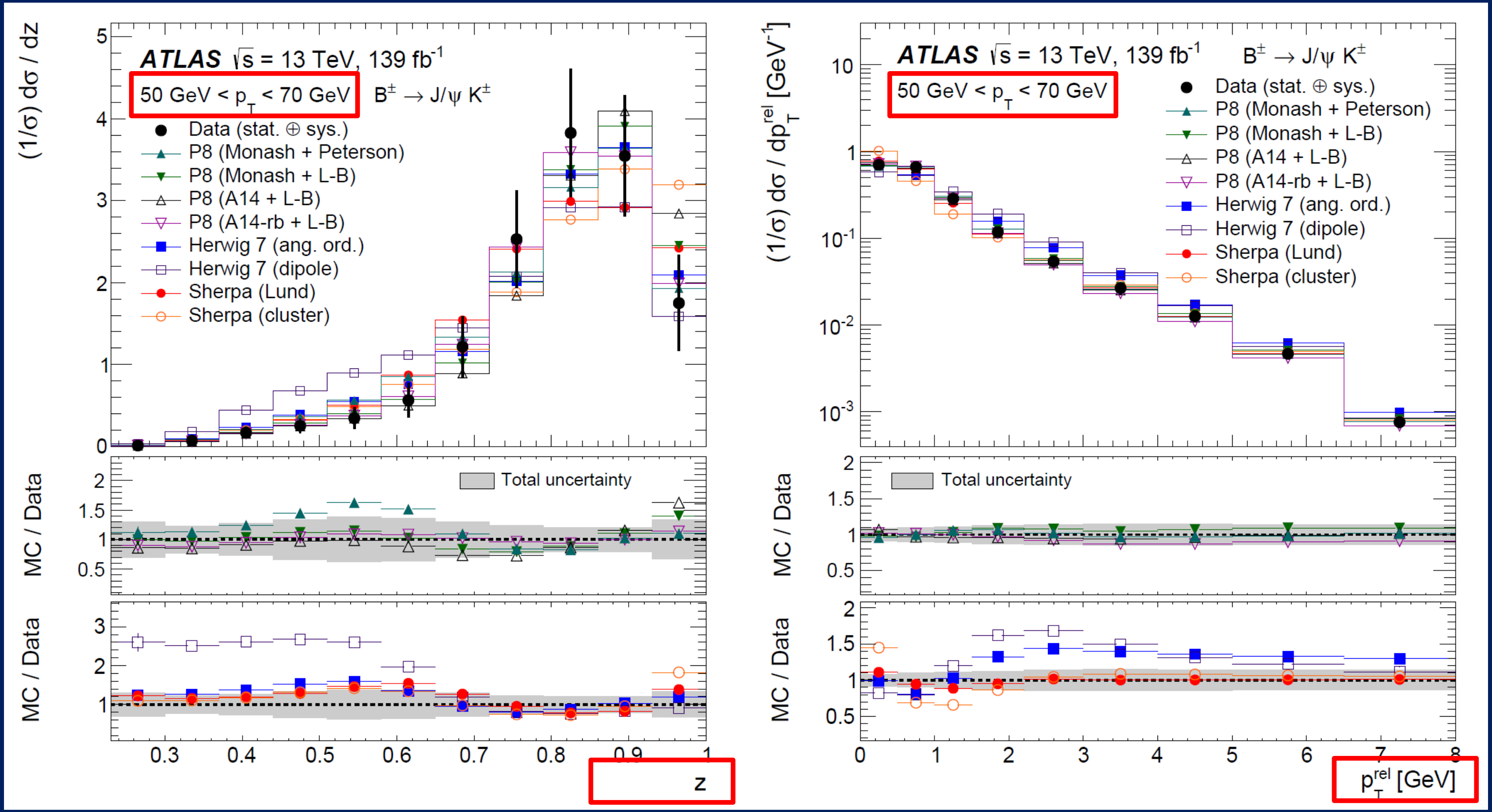


- No explicit jet reconstruction.
- p_t = momentum of the "trigger" reference hadron
- p_a = momentum of the "associated" hadron



JHEP 03, 169 (2019)
arXiv:1811.09742

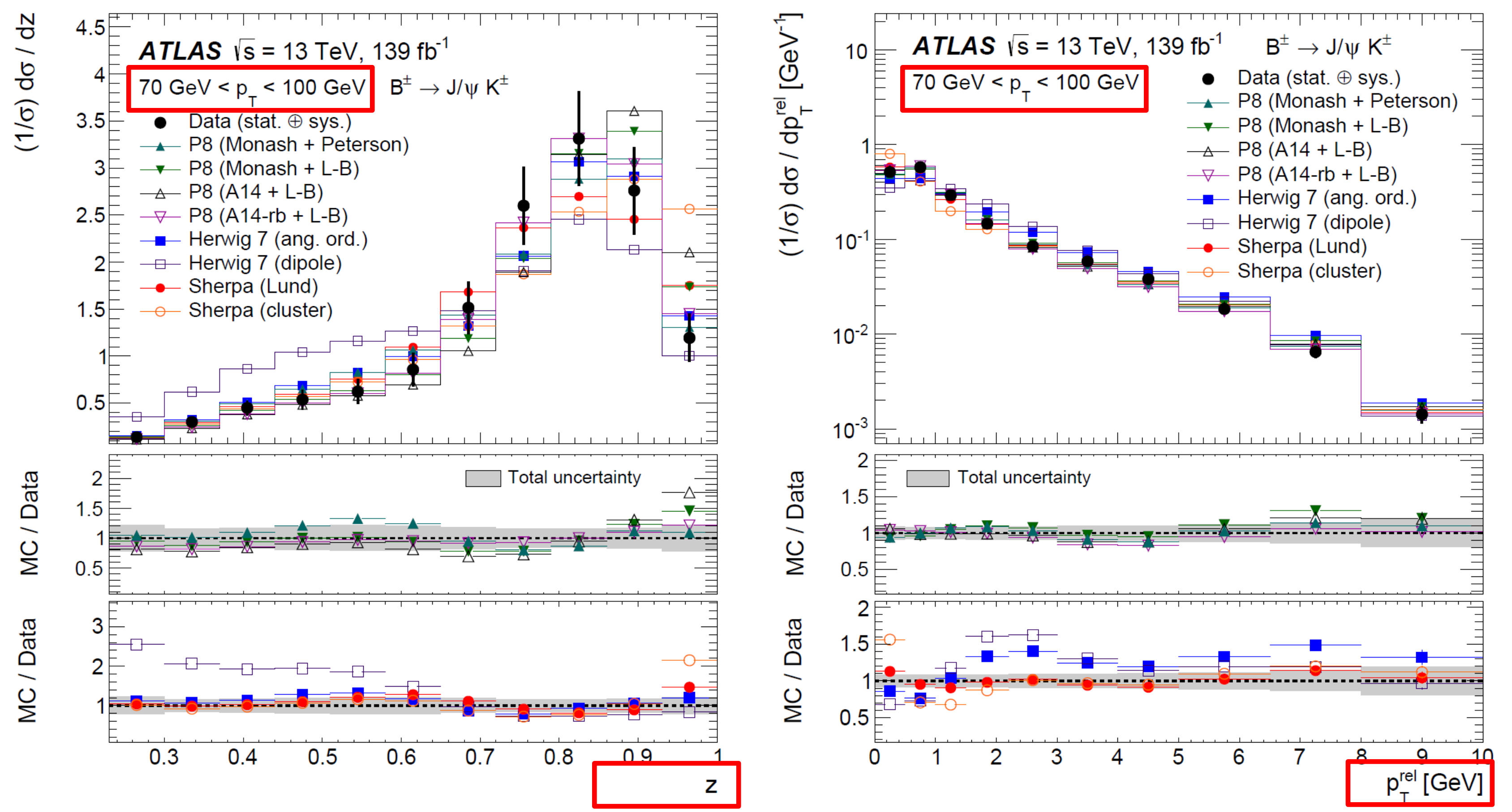
b quark fragmentation in jets via $B^{\pm} \rightarrow J/\psi K^{\pm}$



Heavy flavor hadronization peaked at high *z*.

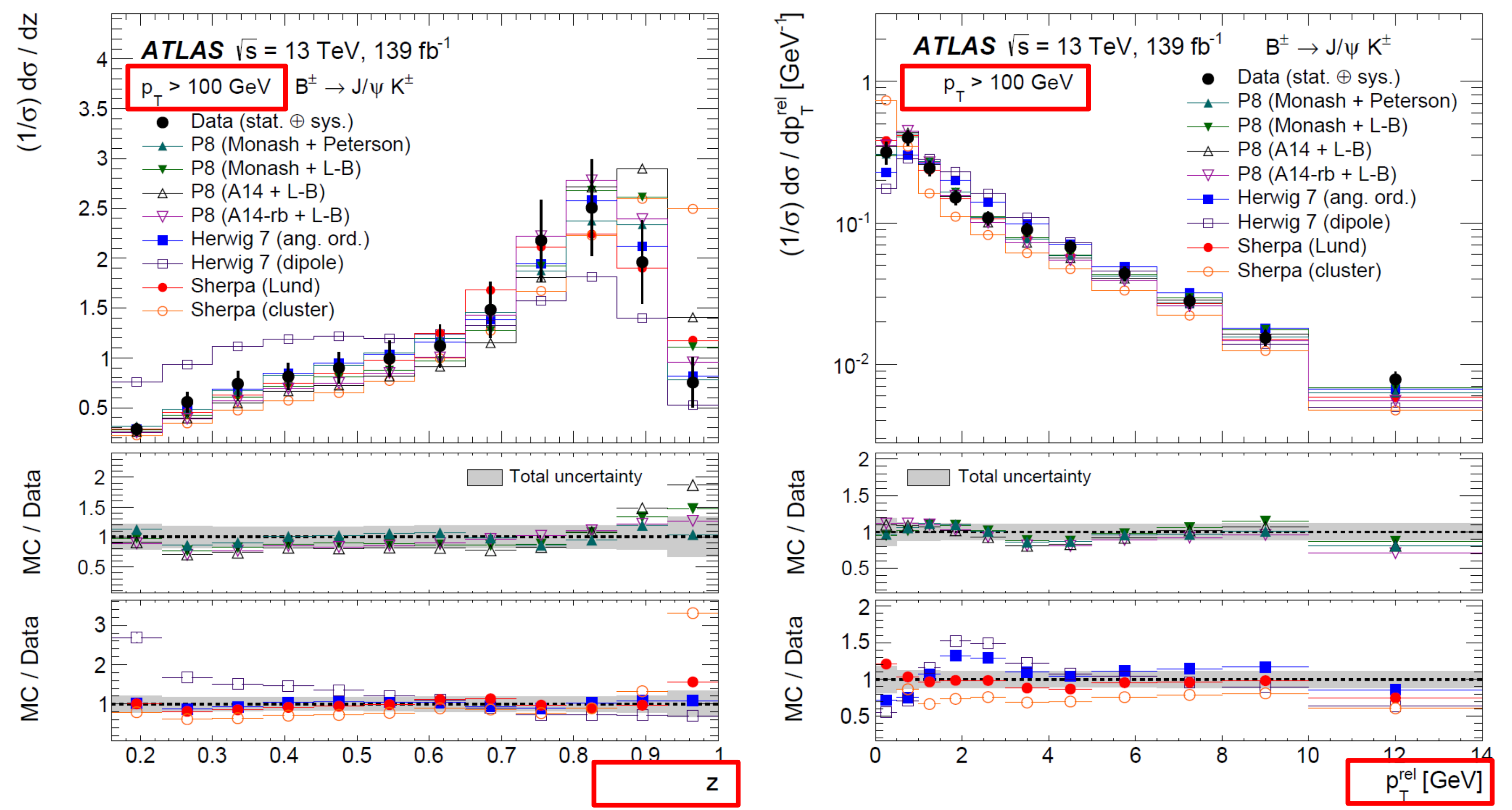
arXiv:2108.11650

b quark fragmentation in jets via $B^{\pm} \rightarrow J/\psi K^{\pm}$



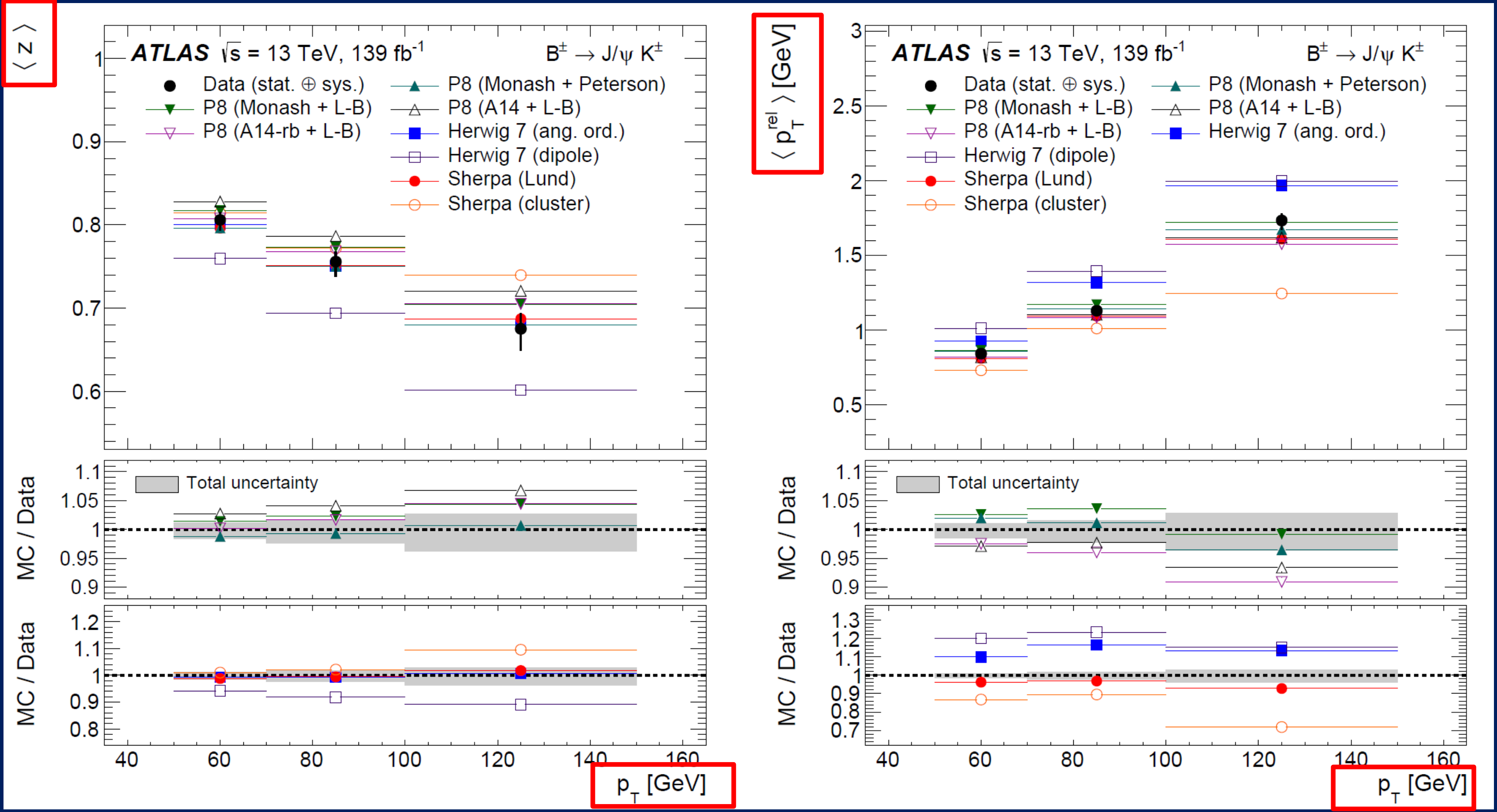
arXiv:2108.11650

b quark fragmentation in jets via $B^{\pm} \rightarrow J/\psi K^{\pm}$



arXiv:2108.11650

b quark fragmentation in jets via $B^{\pm} \to J/\psi K^{\pm}$

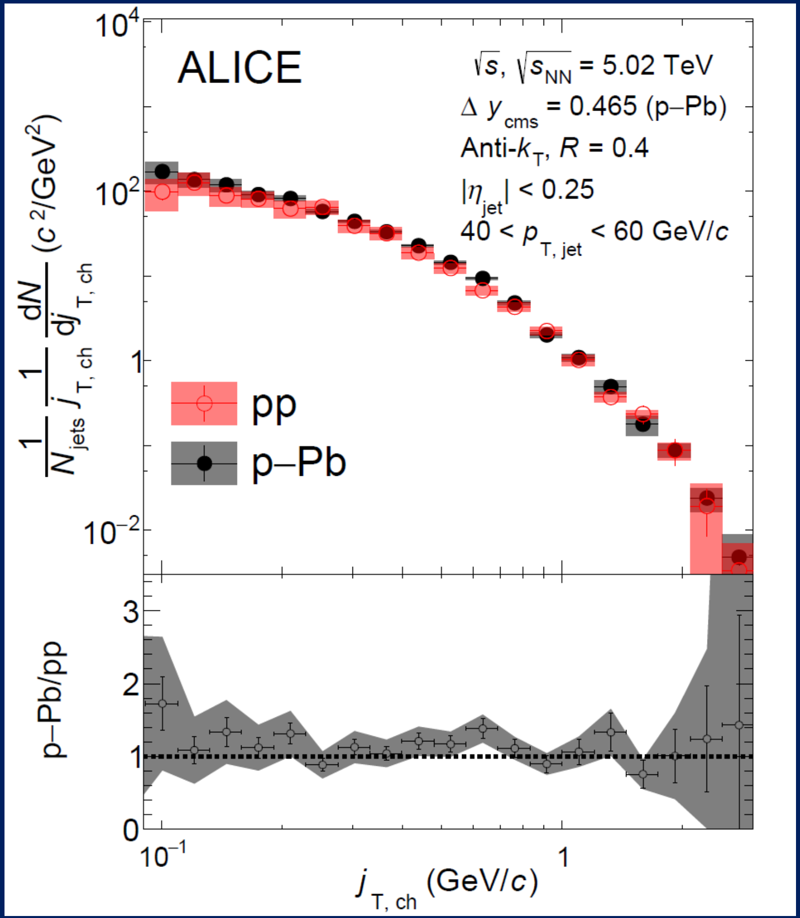


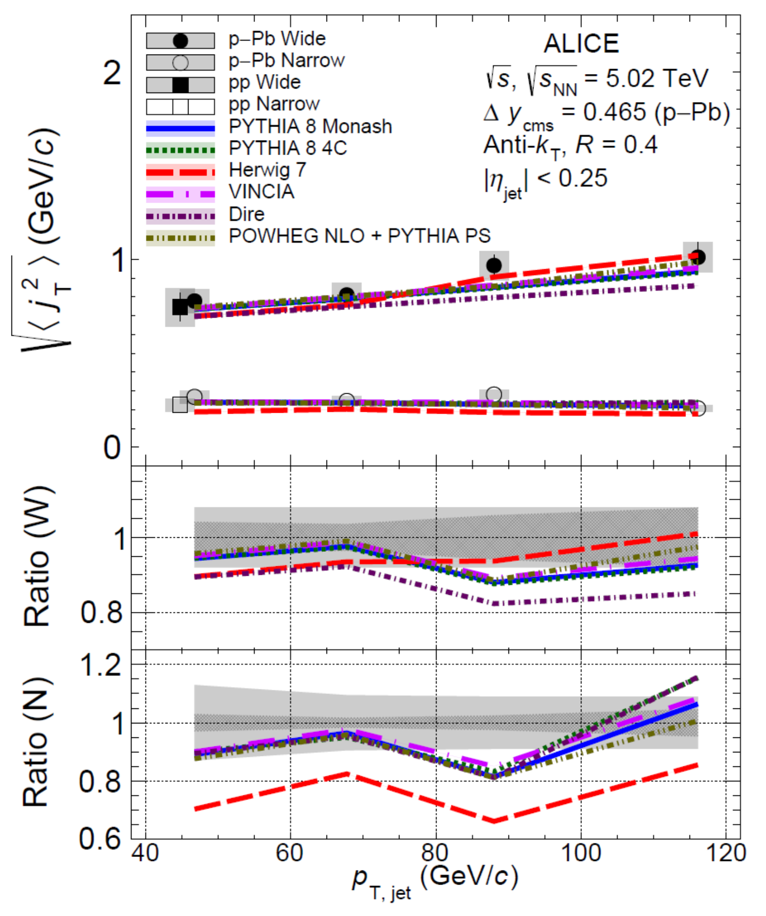
Mean z and p_T^{rel} vs. jet p_T

arXiv:2108.11650

Midrapidity inclusive jet fragmentation in p+p and p+Pb

arXiv:2011.05904





j_T distributions consistent between p+p, p+Pb

"Narrow" (open symbols): Gaussian part of distribution at low j_T

Some forthcoming measurements from LHCb

- Z angular analysis down to low p_T

- Hadronization in jets
  - Nonidentified charged hadrons in Z+jet at 13 TeV, double-differential in (z, j_T)
  - Identified $\pi^{\pm}, K^{\pm}, p^{\pm}$ in Z+jet
  - Nonidentified charged hadrons in b-tagged jets

- Search for evidence of TMD-factorization breaking in Z+jet

- Spontaneous lambda polarization in p+Pb collisions
  - Polarizing TMD FF / twist-3 counterpart

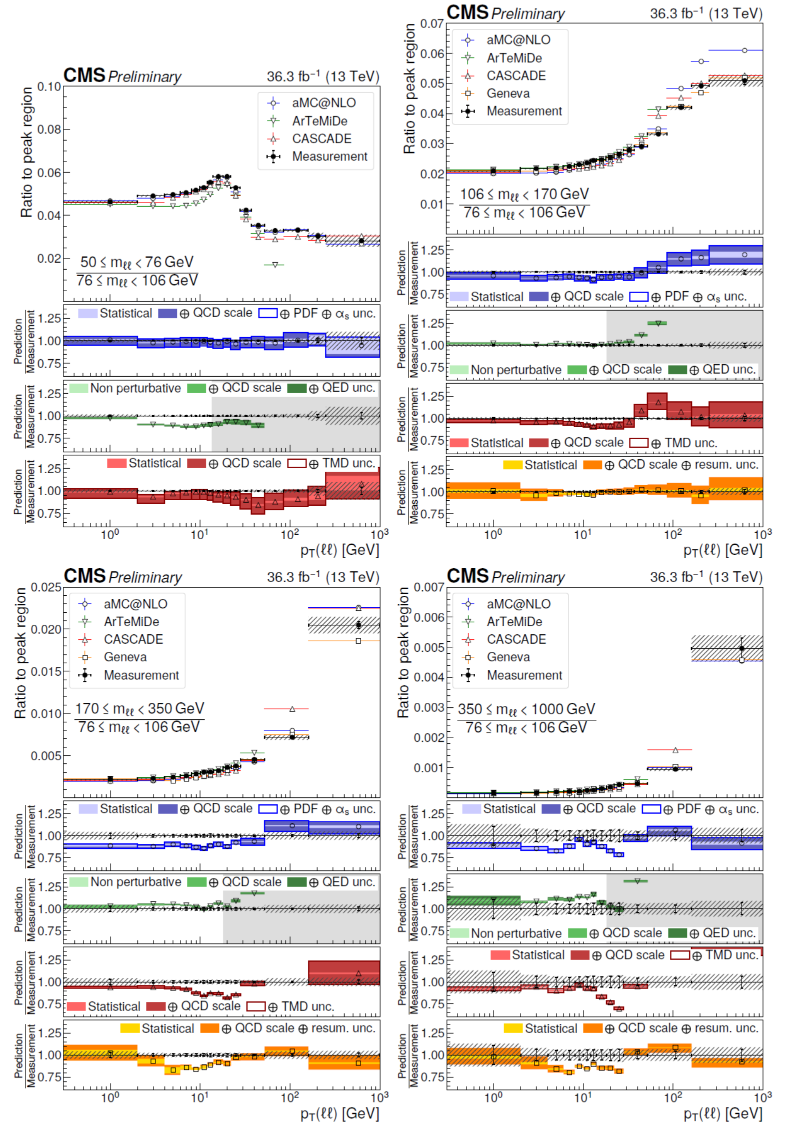
- Fixed-target measurements – see talk by Marco Santimaria, earlier today!

Conclusions

- A wealth of data and results available from the LHC, with even more data about to arrive with the start of Run 3 in 2022
- Suggestions for additional observables relevant to TMD physics welcome!

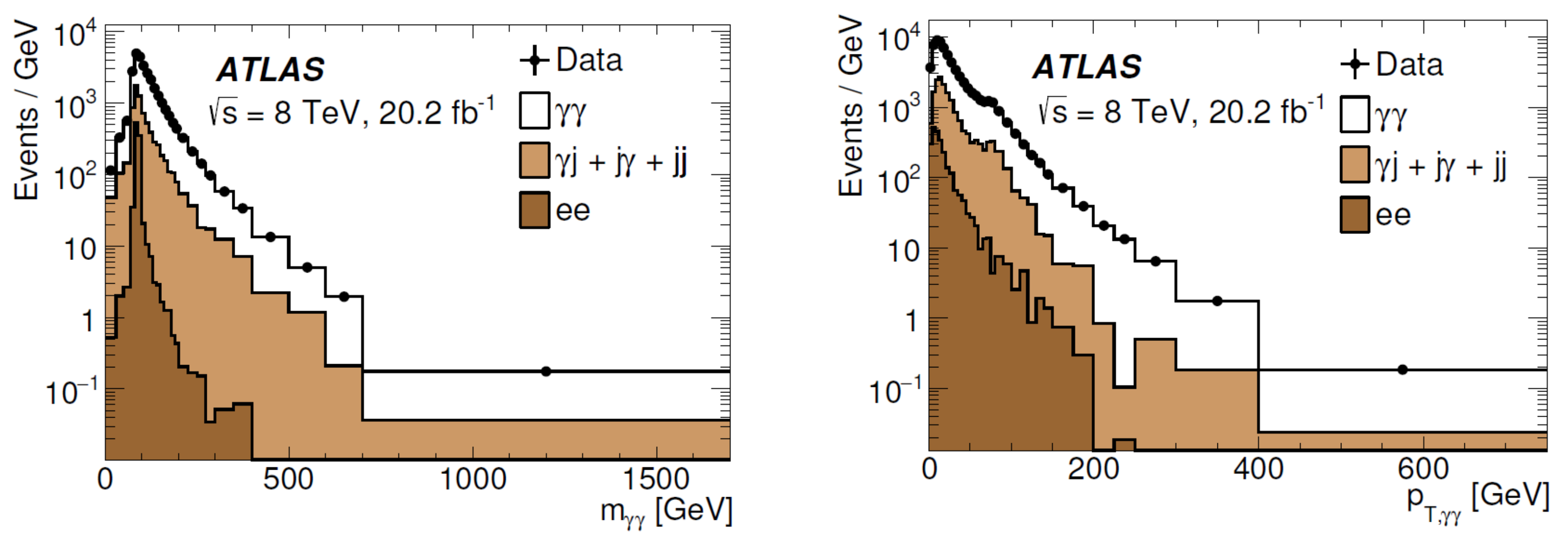
Backup

Double-differential Drell-Yan: Ratios of different mass bins to Z peak region



CMS PAS SMP-20-003

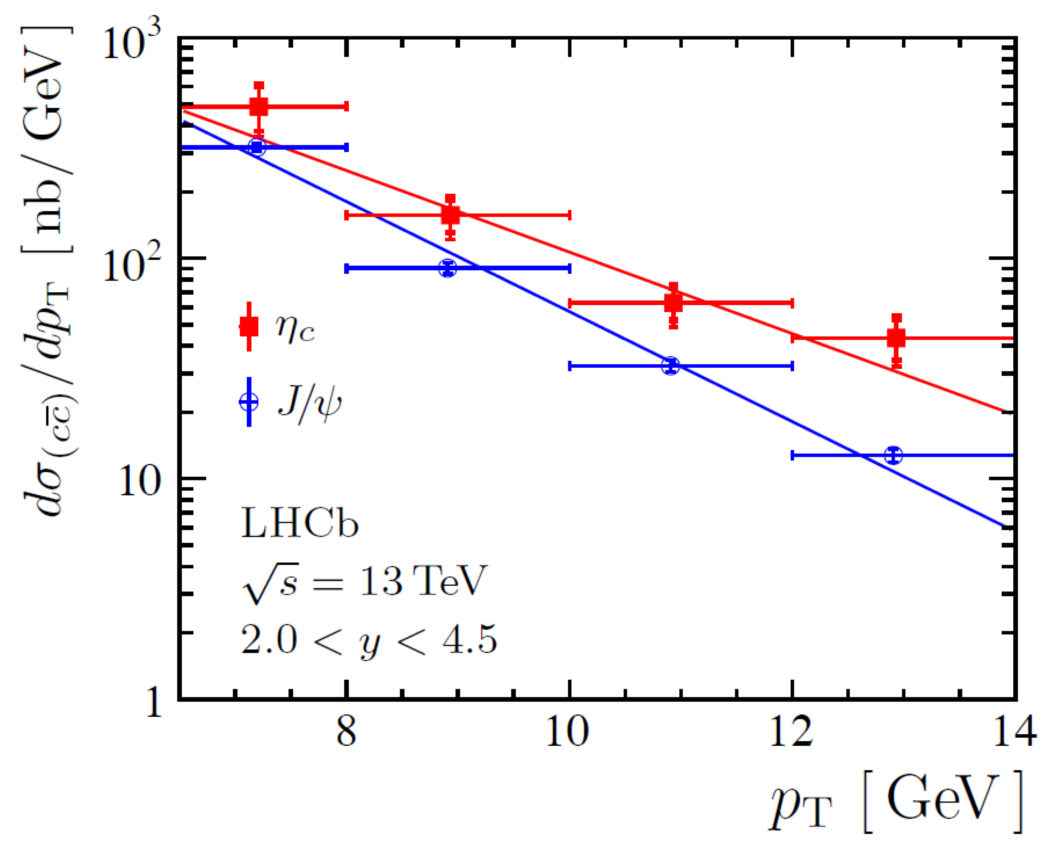
ATLAS 8 TeV isolated diphoton sample composition



EPJ C77, 76 (2017)
arXiv:1704.03839

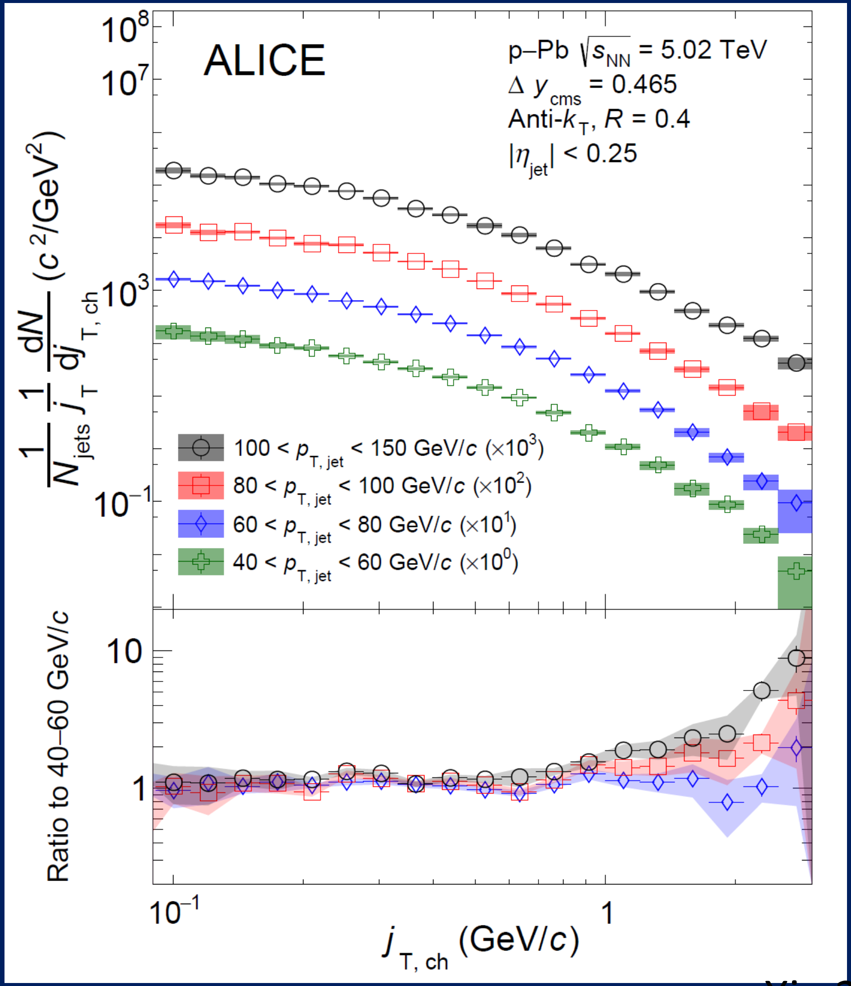
Gluon TMDs: Pseudoscalar charmonium

Need to push measurement of the η_c down to lower p_T…



EPJ C80, 191 (2020)
arXiv:1911.03326

Jet fragmentation in p+Pb



arXiv:2011.05904

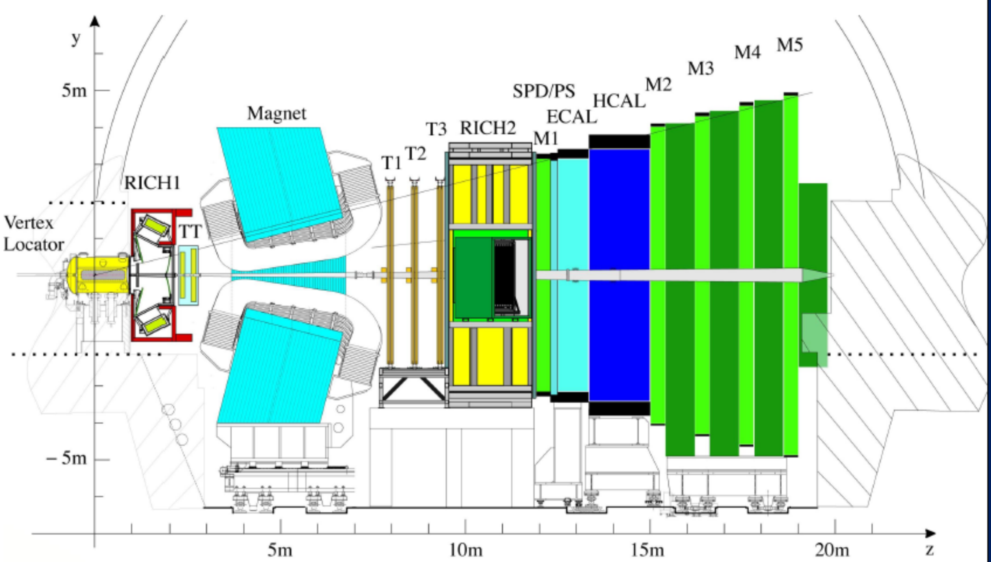
arXiv:2011.05904

LHCb: Opportunities for hadronization measurements in p+p

LHCb is the experiment devoted to heavy flavor at the LHC

Detector design:

- Forward geometry to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- Tracking: Momentum resolution <1% for $p < 200$ GeV/c
- Particle ID: Excellent capabilities to select exclusive decays



JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

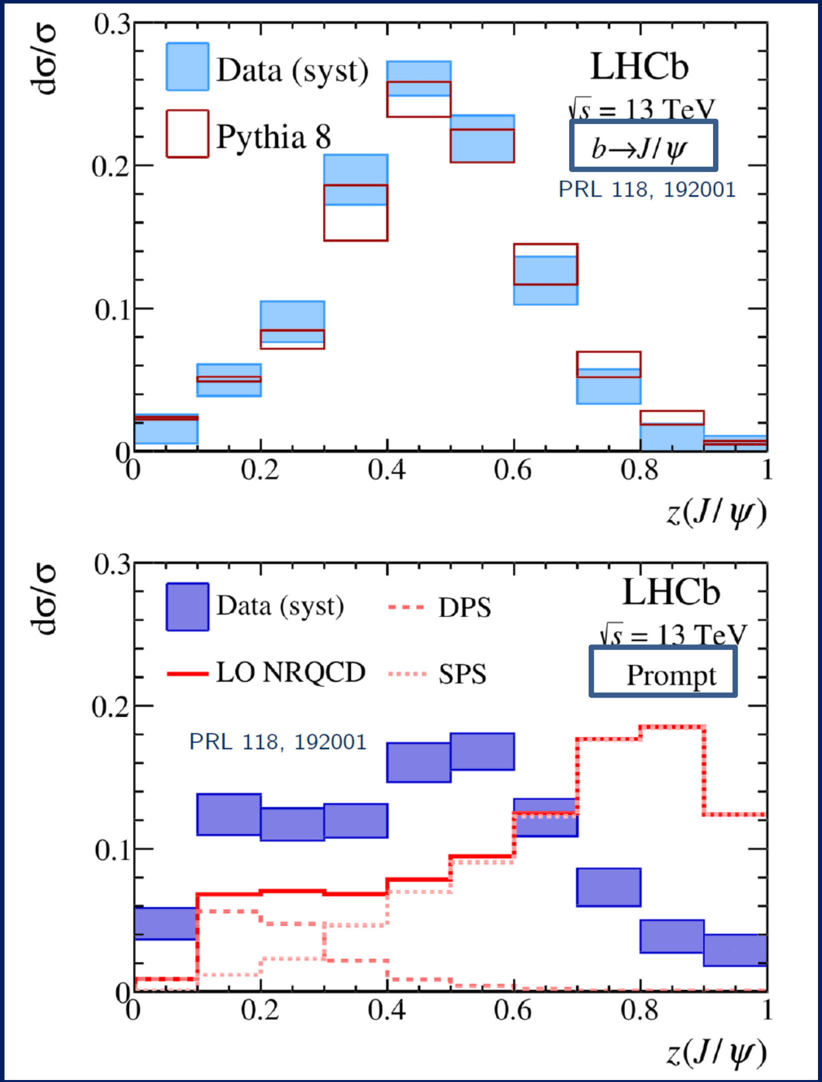
Some features specifically attractive for hadronization:

- Full jet reconstruction with tracking, ECAL, HCAL
  - Heavy flavor tagging of jets
- Charged hadron PID from $2 < p < 100$ GeV

Can study identified particle distributions within jets!

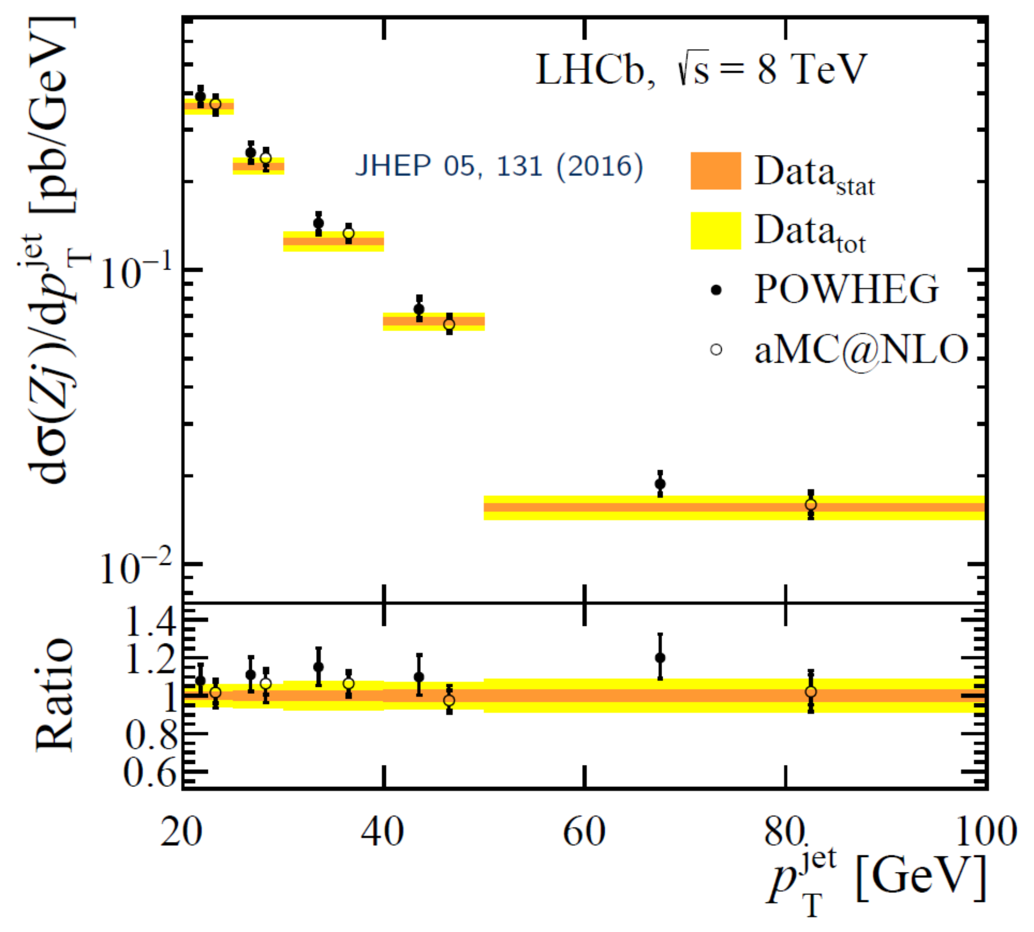
J/Ψ production in jets at LHCb

- First LHCb jet substructure measurement was J/ψ-in-jet production
  - J/ψ from b decay well described by PYTHIA
  - Prompt J/ψ-in-jet not! Can shed light on prompt J/ψ production mechanism(s). How is a prompt J/ψ produced within a jet?



Forward Z+jet

- LHCb previously measured the forward Z+jet cross section
  - JHEP 05, 131 (2016)
- Now have measured charged hadron distributions within the jet, in the same data set
  - arXiv:1904.08878
- First LHC measurement of charged hadrons within Z-tagged jets
- First LHC measurement of charged hadrons-in-jets at forward rapidity



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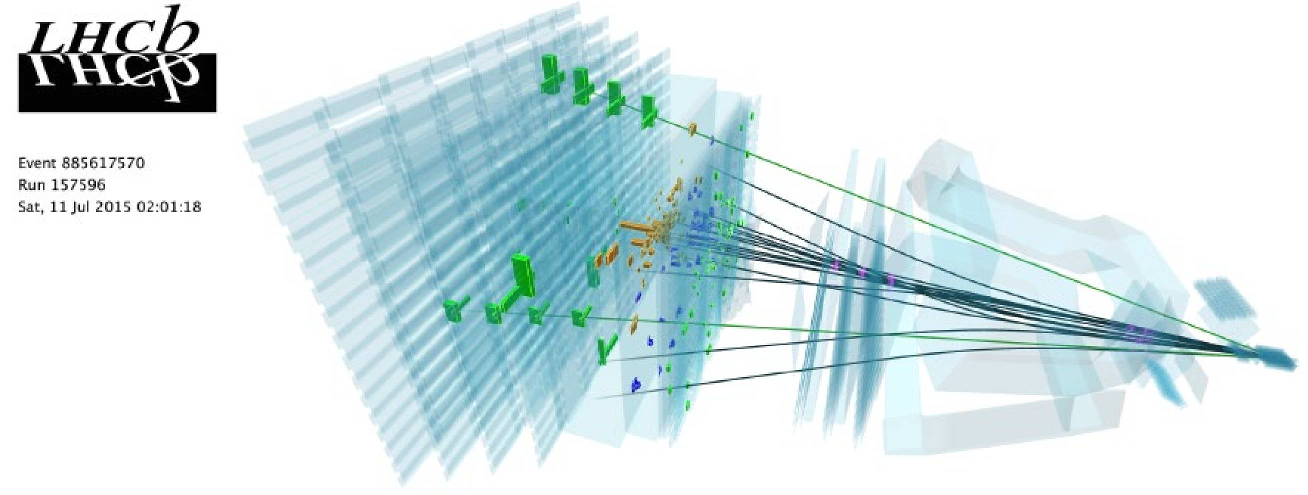
Analysis details

- Follow similar analysis strategy to ATLAS and previous LHCb papers
  - ATLAS: EPJC 71, 1795 (2011), NPA 978, 65 (2018)
  - LHCb: PRL 118, 192001 (2017)

- $Z \rightarrow \mu^+\mu^-$ identified with $60 < M_{\mu\mu} < 120$ GeV, in $2 < \eta < 4.5$
- Anti-k_T jets are measured with $R = 0.5$, $p_T^{jet} > 20$ GeV, in $2 < \eta < 4.5$
- $|\Delta\phi_{Z+jet}| > 7\pi/8$ selects 2→2 event topology
- Charged hadrons selected with $p_T > 0.25$ GeV, $p > 4$ GeV, $\Delta R < 0.5$

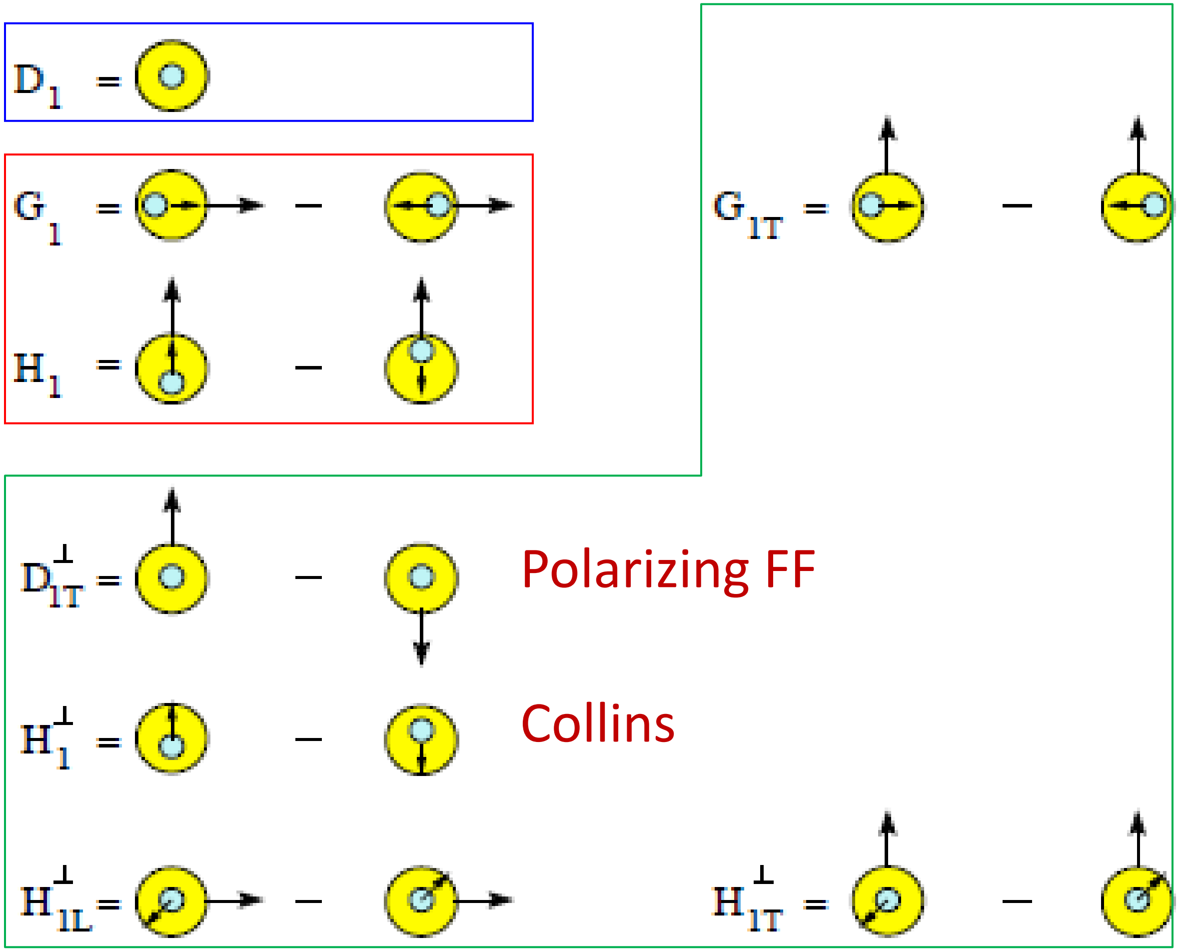


Twist-2 fragmentation functions

Unpolarized

Spin-spin correlations

Spin-momentum correlations



Polarizing FF

Collins