NONPERTURBATIVE DYNAMICS IN PROTON STRUCTURE AND HADRONIZATION IN PP COLLISIONS AT RHIC AND LHC ENERGY AND PATH TOWARDS EIC

Sookhyun Lee (University of Michigan)

Sep 21, 2022

CFNS workshop, Stony Brook

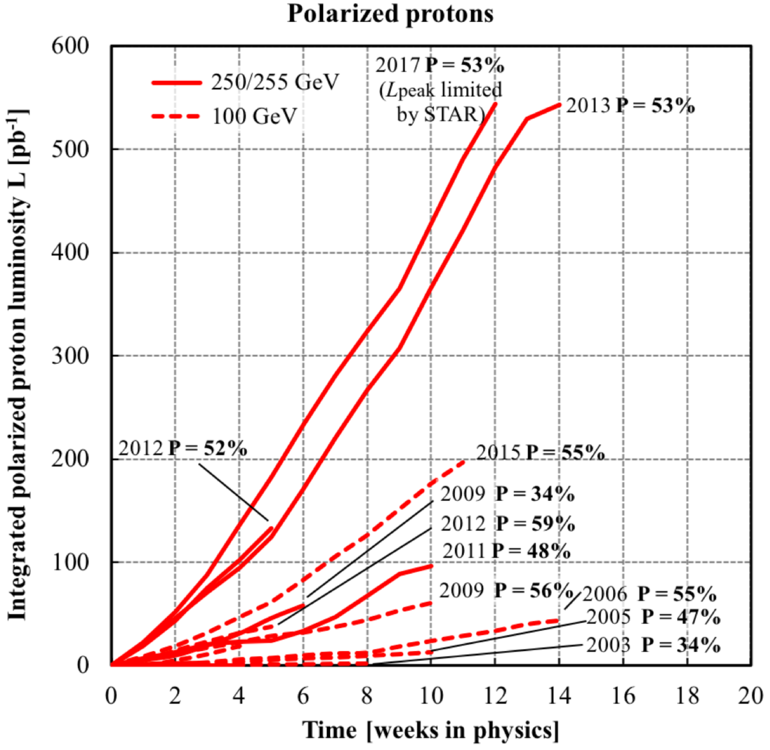
CONTENTS

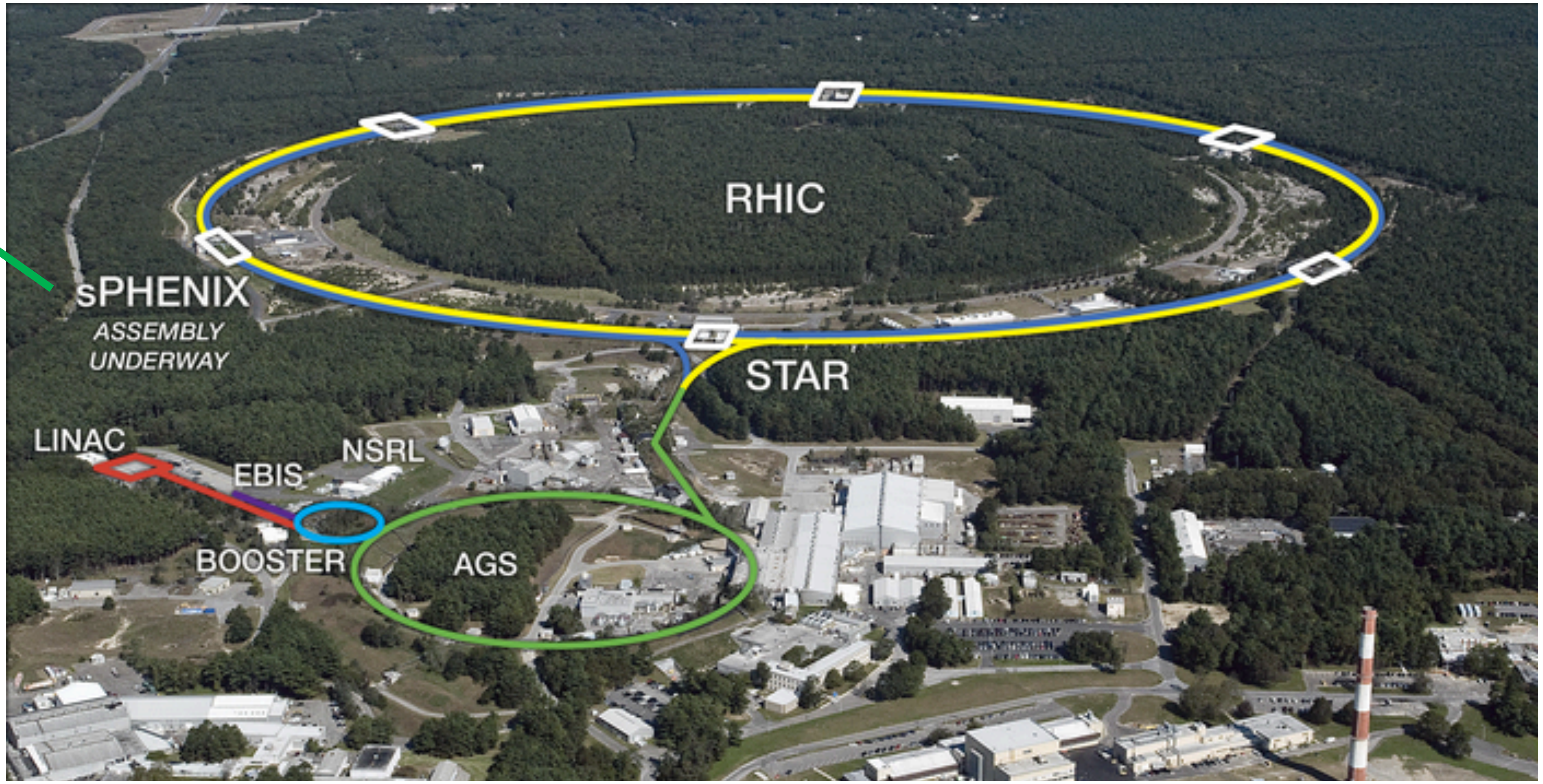
- Nonperturbative dynamics inside proton at RHIC
  - Proton spin and nucleon-parton spin-momentum correlations
  - Cross section asymmetries with polarized protons data
- Proton structure and hadronization in jets at LHCb at LHC
  - s-quark content, intrinsic charm and quark spin-momentum correlations.
  - Jet fragmentation functions
- Event shapes at HERA and EIC
  - Strong coupling constant and hadronization.
  - 1-jettiness
  - Groomed event shapes

RELATIVISTIC HEAVY ION COLLIDER

PHENIX
was here
taking data
until 2016

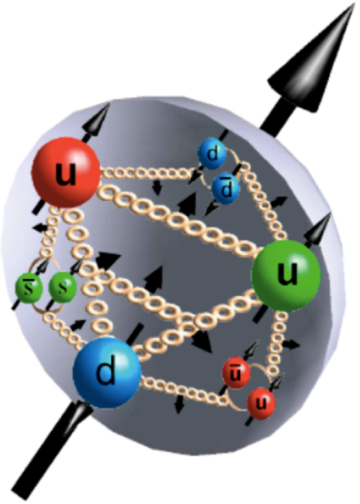
STAR
polarized p+p
running in 2022



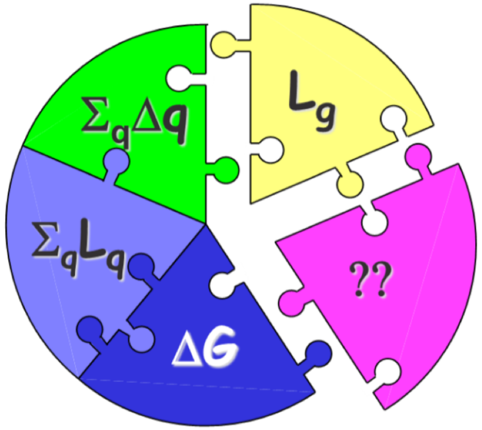


- Located at Brookhaven National Laboratory in Long Island, NY.
- World's only polarized synchrotron collider.
- Spin patterns are predetermined for each bunch.

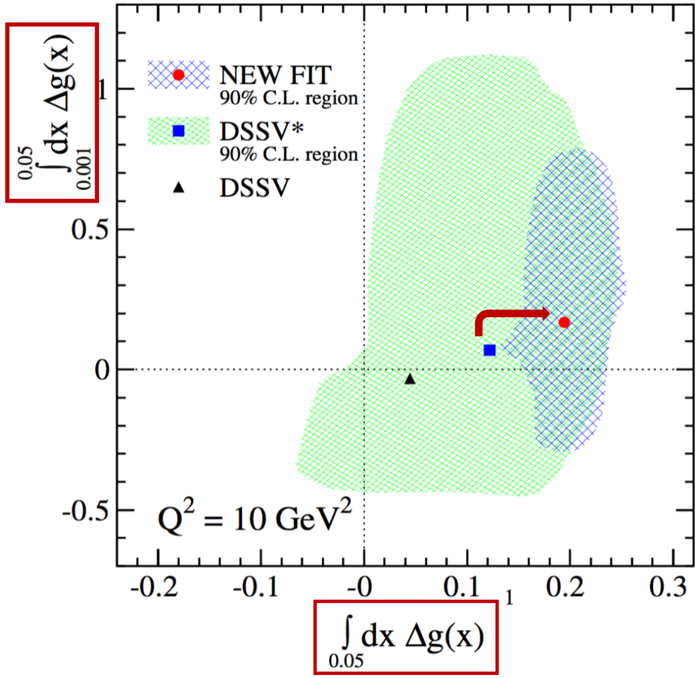
NONPERTURBATIVE DYNAMICS INSIDE PROTON AT RHIC



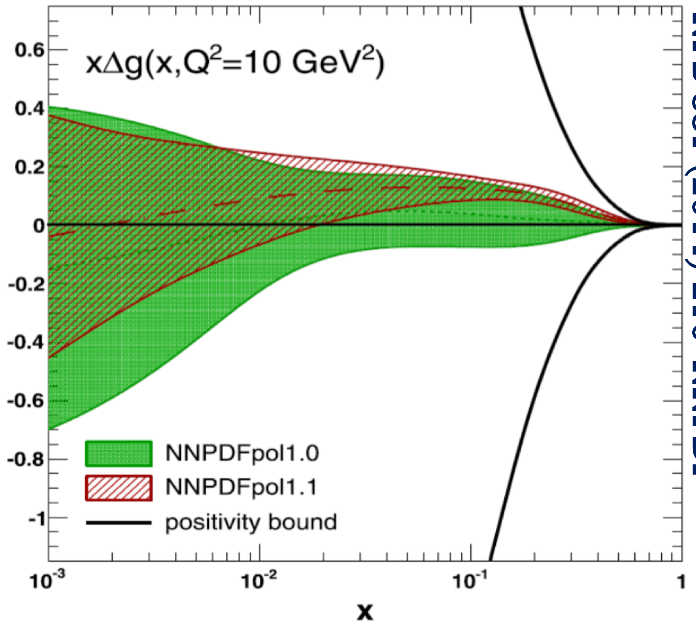
- Global analyses of longitudinal double spin asymmetry data taken at RHIC since early 2000 confirmed sizable gluon polarization inside proton.



$$J_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$



PRL 113 (2014) 012001, DSSV

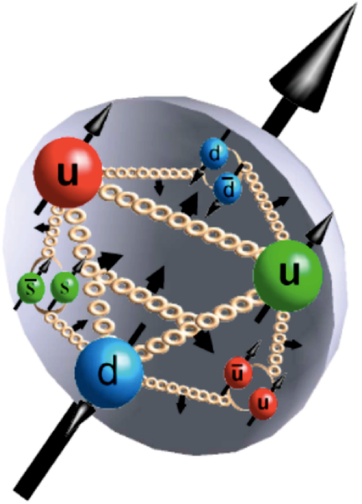


NPB 887 (2014) 276 NNPDF

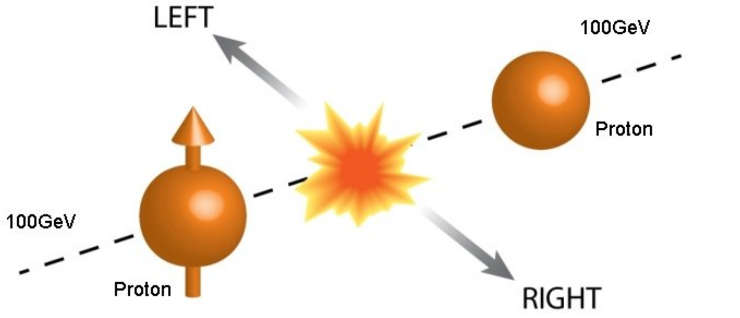
DSSV $\int_{0.05}^{1} \Delta g(x)dx = 0.20^{+0.06}_{-0.07}$

NNPDF $\int_{0.05}^{1} \Delta g(x)dx = 0.17^{+0.06}_{-0.06}$

NONPERTURBATIVE DYNAMICS INSIDE PROTON AT RHIC



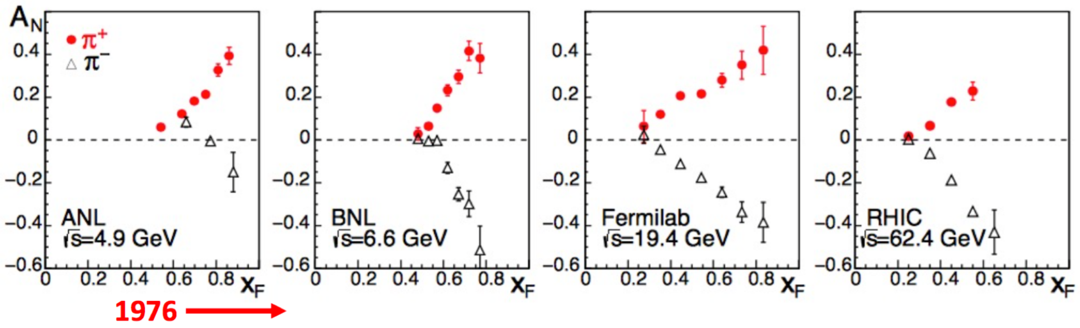
- Global analyses of longitudinal double spin asymmetry data taken at RHIC since early 2000 confirmed sizable gluon polarization inside proton.
- Spin and transvers momentum degrees of freedom gained increasing attention to explain large transverse single spin asymmetries.



Transverse Single Spin Asymmetry (TSSA)

$$A_N \equiv \frac{\sigma^{\uparrow 0}-\sigma^{\downarrow 0}}{\sigma^{\uparrow 0}+\sigma^{\downarrow 0}}$$

↑ or ↓ : proton transverse spin states.



$$x_F = \frac{2p_z}{\sqrt{s}}$$

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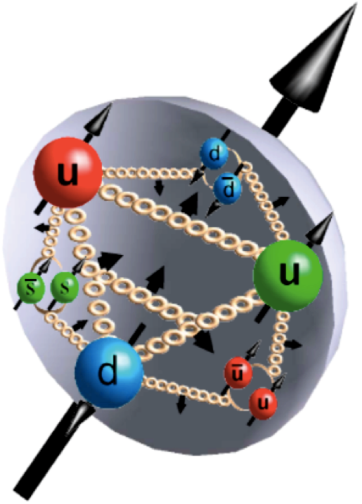
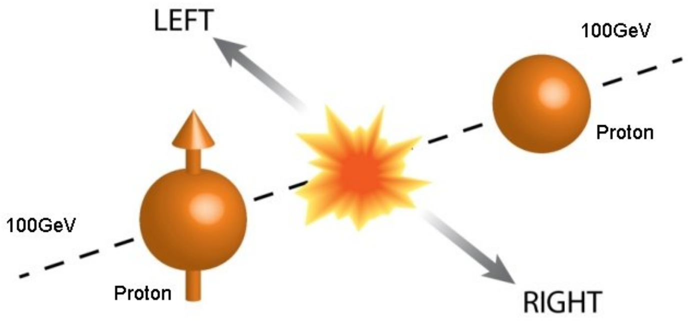
NONPERTURBATIVE DYNAMICS INSIDE PROTON AT RHIC

- Global analyses of longitudinal double spin asymmetry data taken at RHIC since early 2000 confirmed sizable gluon polarization inside proton.
- Spin and transvers momentum degrees of freedom gained increasing attention to explain large transverse single spin asymmetries.
- Probes diversified from mostly single inclusive kinds to multi-differential or substructure ones.





Transverse Single Spin Asymmetry (TSSA)

$$A_N \equiv \frac{\sigma^{\uparrow 0}-\sigma^{\downarrow 0}}{\sigma^{\uparrow 0}+\sigma^{\downarrow 0}}$$

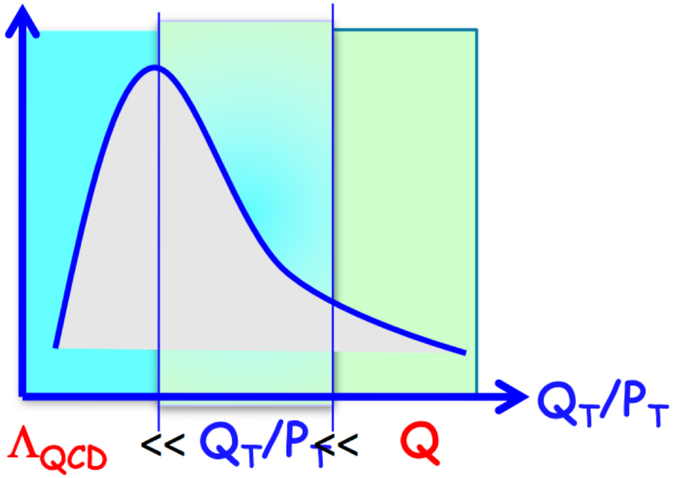
$\uparrow$ or $\downarrow$: proton transverse spin states.

TMD

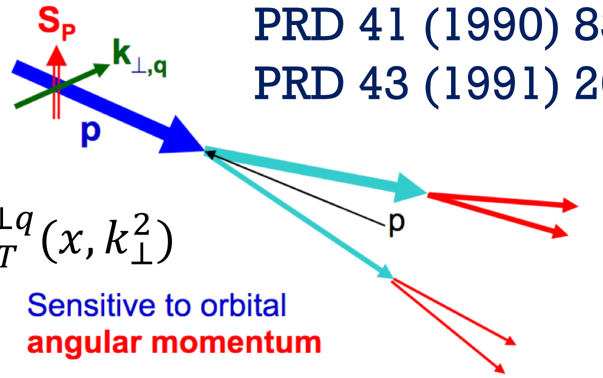
- Requires 2 scales:
  - Hard scale Q
  - Soft scale $p_T \ll Q$
- Suitable for
  - SIDIS, DY, W/Z and hadrons in jets

Collinear Twist-3

- Only require single scale
  - Hard scale: $p_T \sim Q$
- Suitable for
  - Inclusive π^0, jet, γ and Λ



e.g. Sivers Fn:



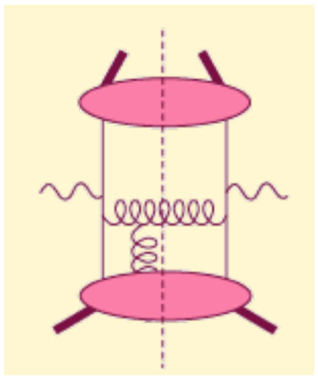
PRD 41 (1990) 83
PRD 43 (1991) 261

$f_{1T}^{\perp q}(x, k_\perp^2)$

Sensitive to orbital **angular momentum**

$$T_{q,F}(x,x) = \frac{1}{M_p} \int d^2\vec{k}_\perp \vec{k}_\perp^2 \, q_T(x, k_\perp)$$

Nucl. Phys. B **667** (2003) 201
Phys. Rev. Lett. **97** (2006) 082002



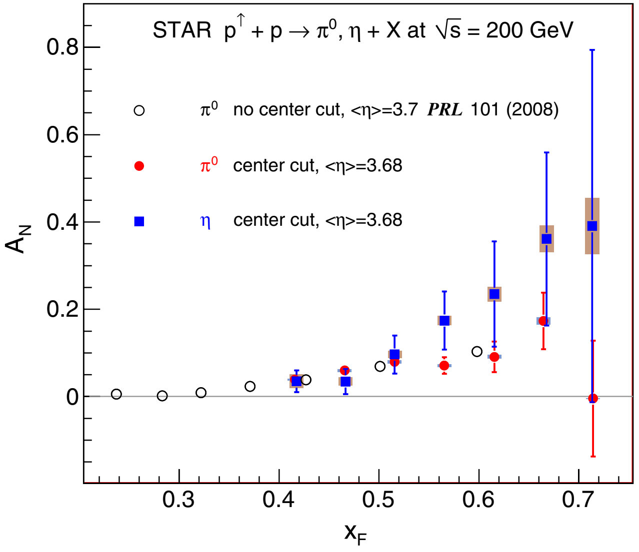
Efremov, Teryaev; Sterman, Qiu

qgq correlator

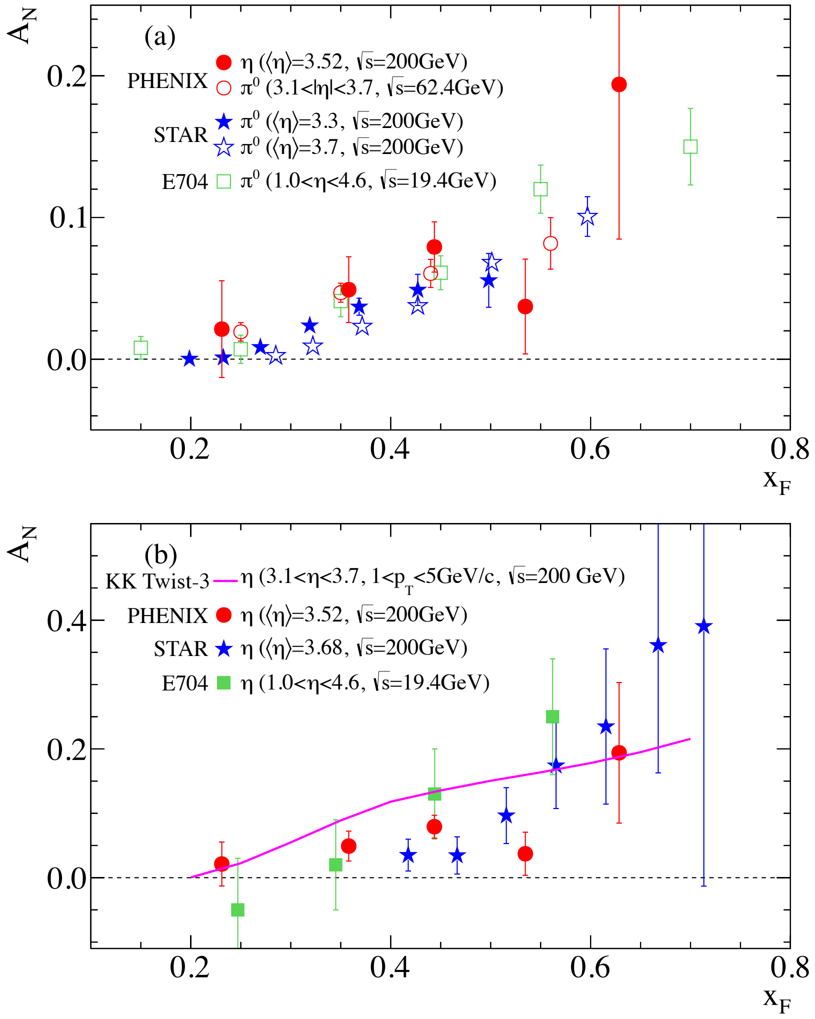
*Similar relation holds for **gluon** Sivers Fn and **ggg** correlator.*

FORWARD η AND π^0 A_N FROM PHENIX AND STAR

PRD 86 (2012) 051101 (R)

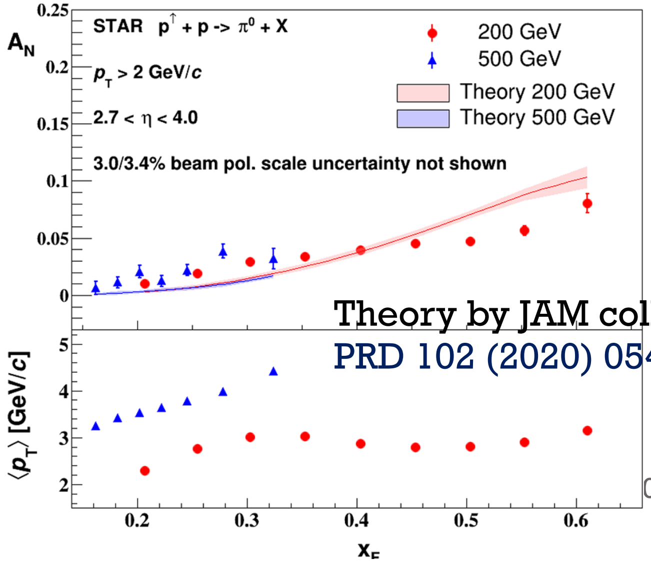


PRD 90 (2014) 072008



- Increasing A_N with x_F.
- A_N^{η} similar in magnitude to $A_N^{\pi^0}$
  : no significant isospin, strangeness and/or mass effects seen.
- Theoretical studies show initial-state effects are small and final-state effects dominate these asymmetries.
  PRD 89 (2014) 111501(R); PRD 96 (2017) 034027
- Detailed studies being done on effects of different mechanisms; Diffractive, Collins effects using π^0 and/or EM-jet.

PRD 103 (2021) 092009

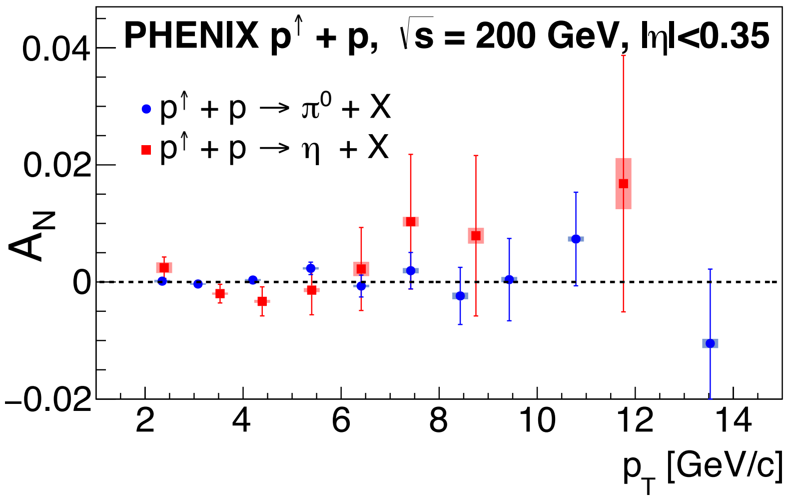


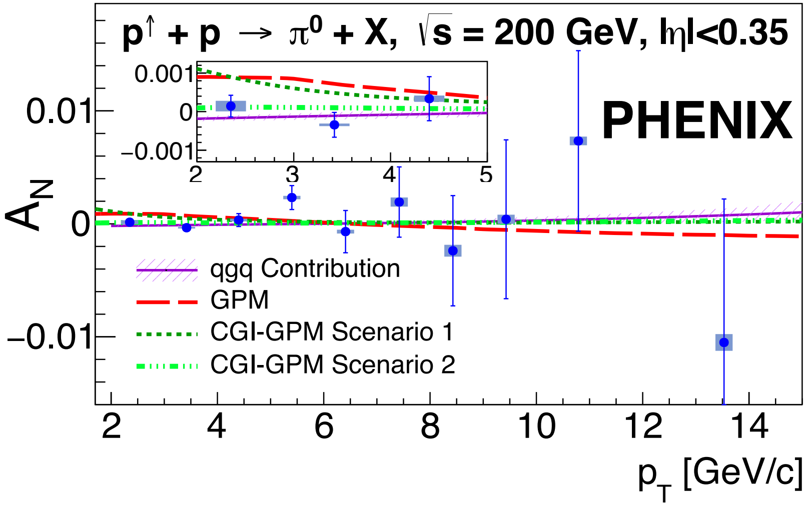
Theory by JAM collab.
PRD 102 (2020) 054002

022

MIDRAPIDITY π^0, η AND $\pi^{\pm}$ A_N

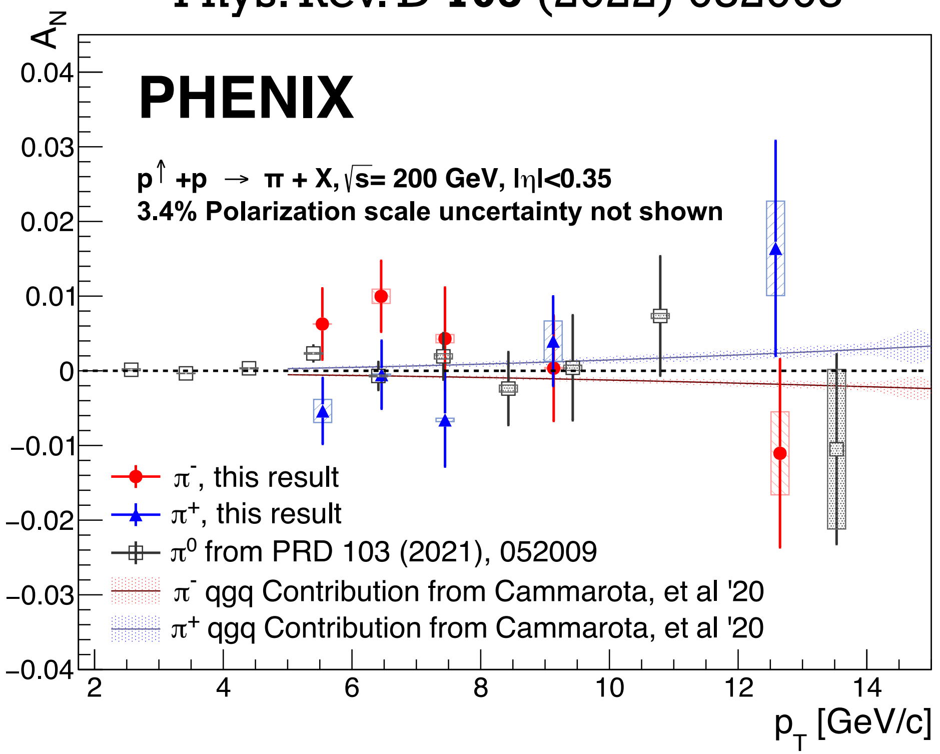
Phys. Rev. D **103** (2021) 052009





- Measured asymmetries consistent with zero and with previous measurements.
- A_N (π^0) ***vs.*** A_N (η): no evidence of differences due to strangeness, isospin or mass.
- A_N $(\pi^{\pm})$ ***vs.*** A_N (π^0): charged pions provide different flavor sensitivities than neutral particles via fragmentation functions
- Moderately sensitive to trigluon correlator and gluon Sivers fn.

Phys. Rev. D **105** (2022) 032003

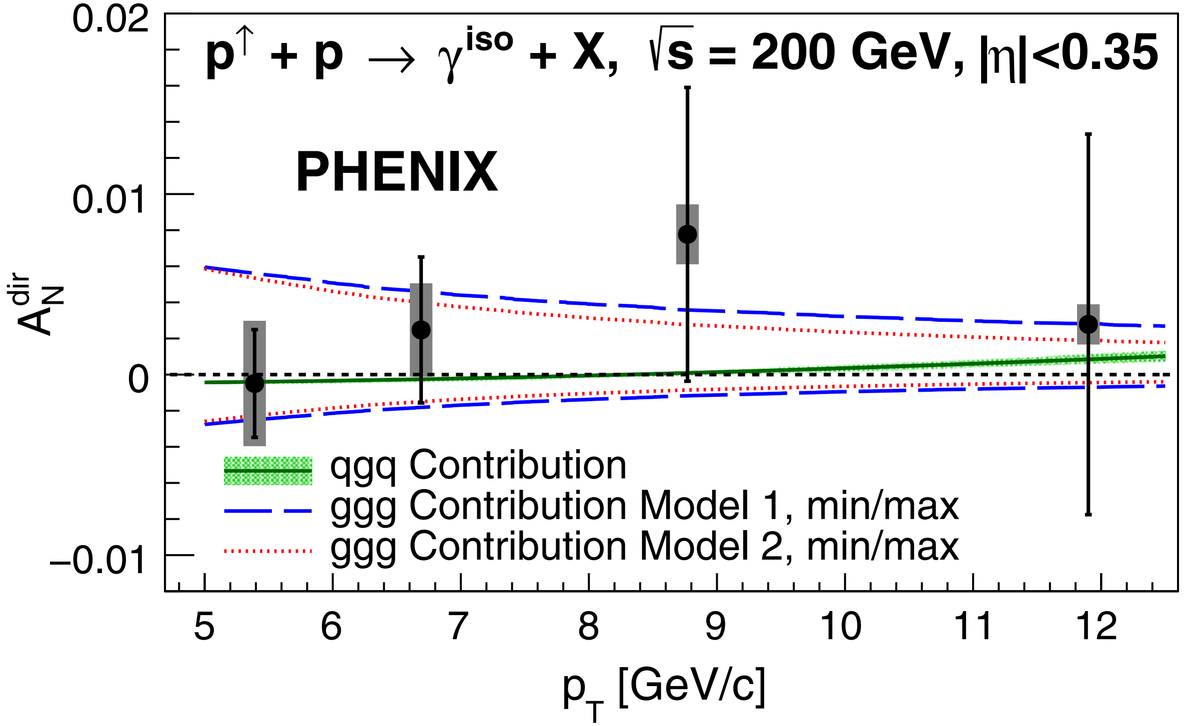


- Difference between π^+ and π^- at 2σ deviation level.
- Increasing qgq contribution predicted with hard scale and opposite sign for oppositely charged $\pi's$ (which is seen cancelled in π^0 A_N).

DIRECT PHOTON A_N

- Measured asymmetry consistent with zero.
- Sensitive to transverse gluon structure inside proton
  - Direct photon production predominantly from QCD Compton scattering.
  - Small contribution from qgq correlation function predicted at midrapidity.
- Clean probe for extraction of trigluon correlator and sensitive to gluon Sivers fn.

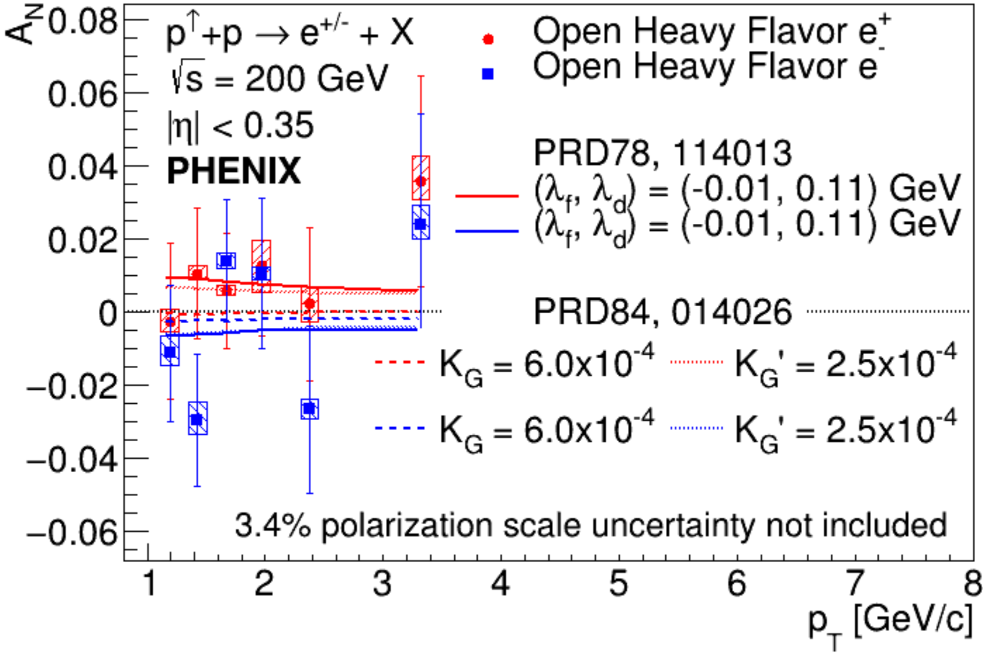
Phys. Rev. Lett. **127** (2021) 162001

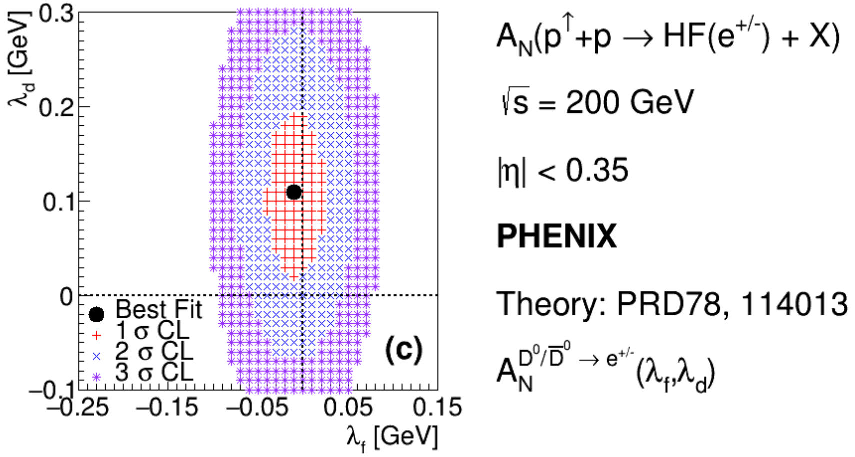


OPEN HEAVY FLAVOR A_N

- Charge separated e^+ and e^- A_N.
- Measured asymmetries consistent with zero.
- Most sensitive probe of trigluon correlator; $gg \to Q\bar{Q}$ dominance relative to $q\bar{q} \to Q\bar{Q}$.
- Model calculations provided by two groups rely on normalizing symmetric and antisymmetric trigluon correlators $T_G^{(f,d)}$ to unpolarized gluon PDF.
- First quantitative extraction of trigluon correlators.

arXiv:2204.12899





$$T_G^{(f,d)}(x,x) = \lambda_{f,d}\, G(x)$$

Best fit results:

PRD78, 114013 Kang-Qiu-Vogelsang-Yuan

λ_f = -0.01 ± 0.03 GeV

λ_d = 0.11 ± 0.09 GeV

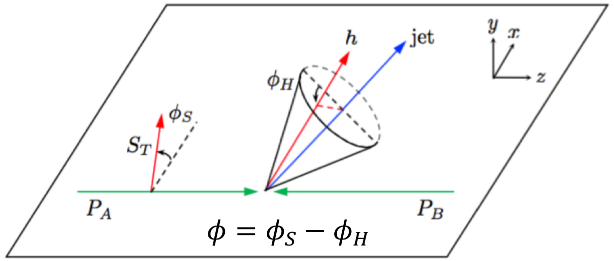
PRD84, 014026 Koike-Yosida model

K_G = 6.0x10-4 (+0.0014 -0.0017)

$K_{G'}$ = 2.5x10-4 (± 0.00025)

STAR HADRONS-IN-JET

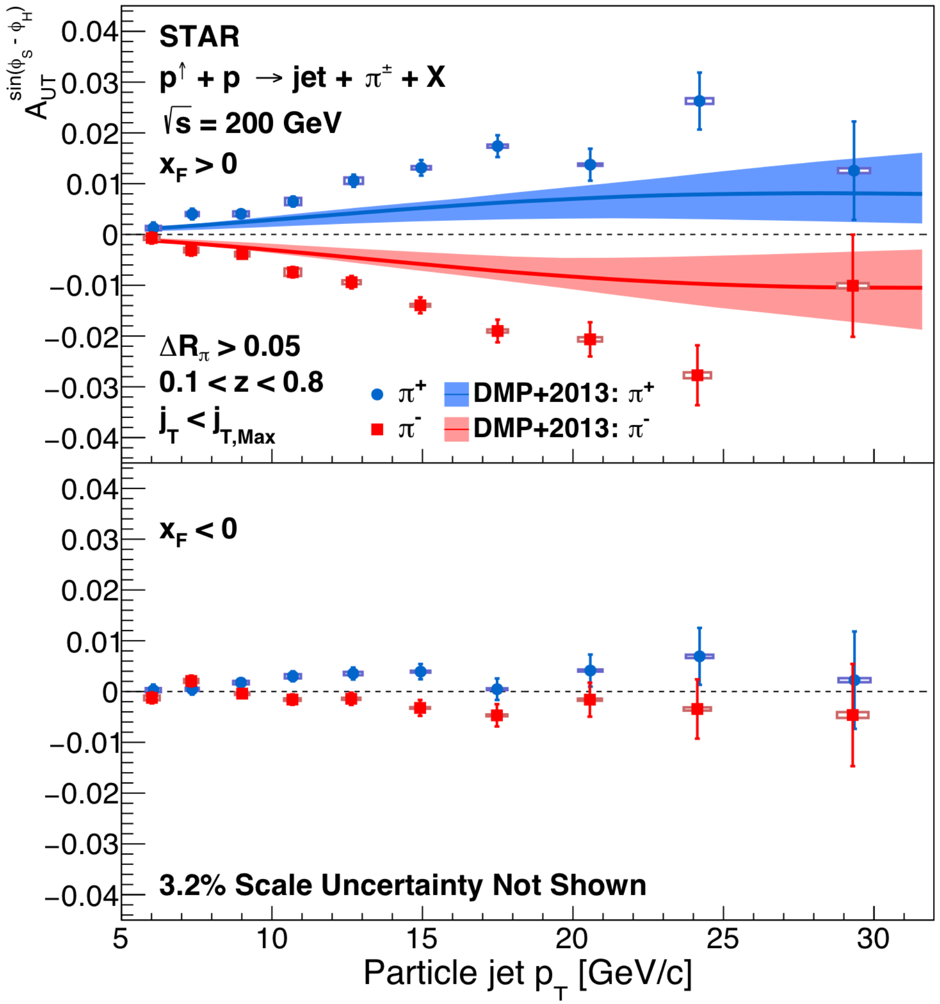
- Hadron distributions in jets produced from single-transversely polarized proton collisions, a novel approach to final state effects to transverse spin asymmetries.
- $\mathrm{Sin}(\phi_s - \phi_h)$ modulation sensitive to Collins effects, i.e. access transversity TMD PDF × Collins FF.
- Recent measurements include z, j_T, jet p_T and x_F dependence.



$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)} \propto H_{1\,h/c}^{\perp}(z_h, j_{\perp}^2; Q)$$

Phys. Rev. D**97** (2018) 032004

arXiv.2205.11800



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  - **s-quark content, intrinsic charm and quark spin-momentum correlations.**
  - **Jet fragmentation functions**
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  - Strong coupling constant and hadronization.
  - 1-jettiness
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PROTON STRUCTURE & HADRONIZATION IN JETS AT LHCB

- ❑ What constitutes proton?
- ❑ How do partonic momentum and spin degrees of freedom interplay?

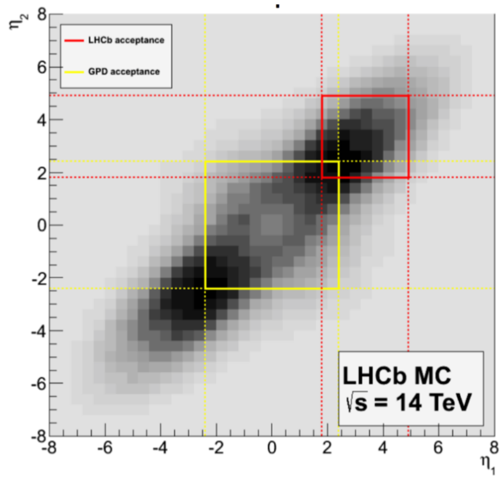
- W+b/c jet – s quark PDF
- Z+charm jet – intrinsic charm in proton
- Drell Yan production and angular coefficients – TMD PDF, Lam-Tung relation

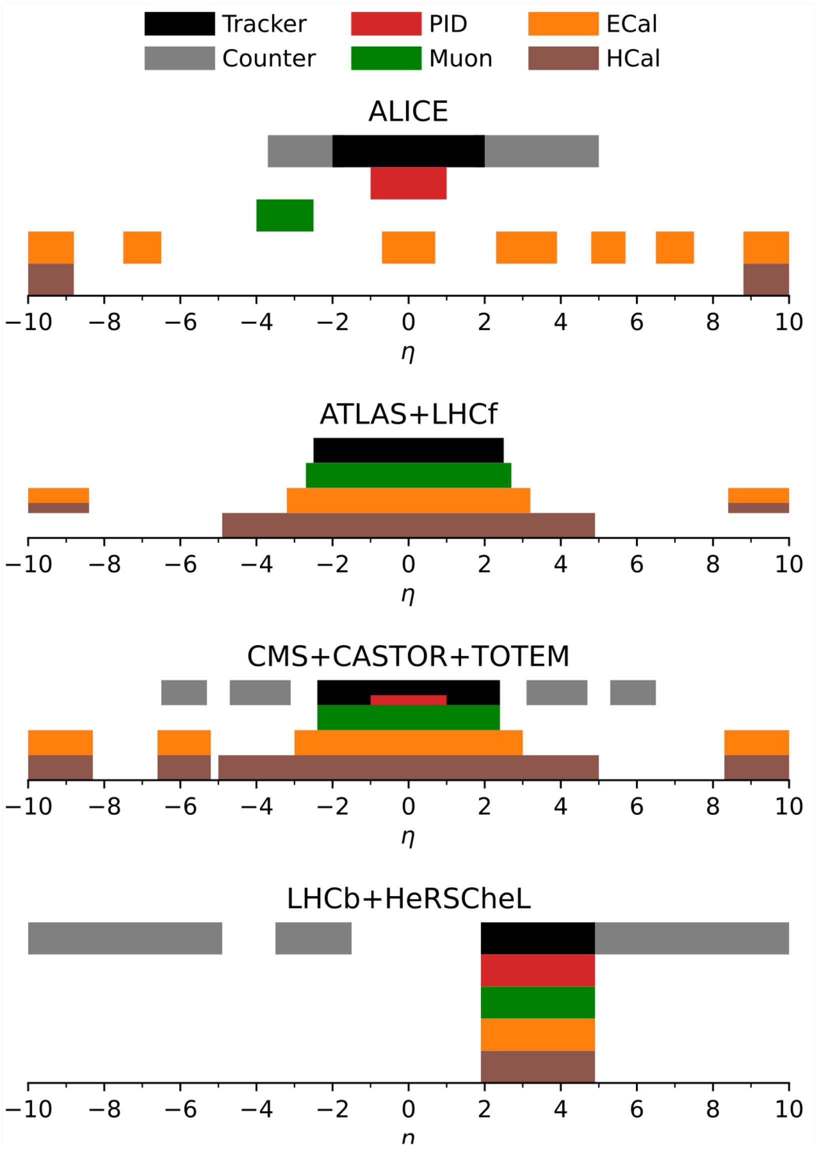
- ❑ How does a parton evolve through shower process?
- ❑ What governs characteristics of hadron formation? Mass and flavor contents of hadron, partons initiating shower?

- Qurakonia in jets – quarkonia production mechanisms
- Z+light quark jet – TMD fragmentation functions
- c/b-tagged jets , exotic states in jets

LHCB DETECTORS

- Forward spectrometer
- PID up to p~100 GeV/c
- Ecal+Hcal and tracking detectors
  → Full jet reconstruction
- Muon reconstruction
- ~40% of all produced $c\bar{c}$ and $b\bar{b}$ pairs are in LHCb acceptance.



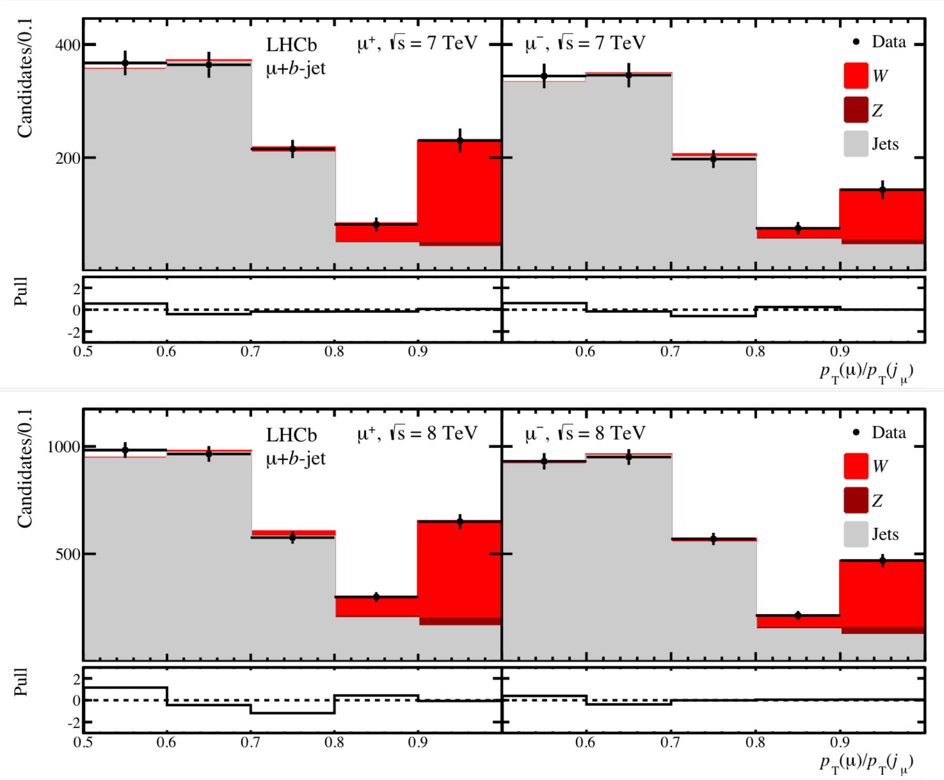


Astrophys. Space Sci. **367**, 27 (2022)

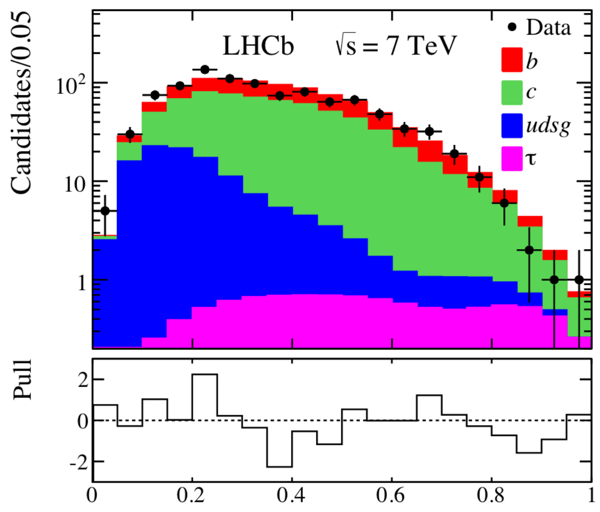
Phys. Rev. D 92, 052001 (2015)

W+B/C JET

- Excellent b-/c-tagging capabilities at LHCb using BDT technique.
- c-tagged jets in association with W boson sensitive to s-quark PDF via gs→Wc.
- W+b jets predominatly from gluon splitting.
- Results consistent with SM predictions



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



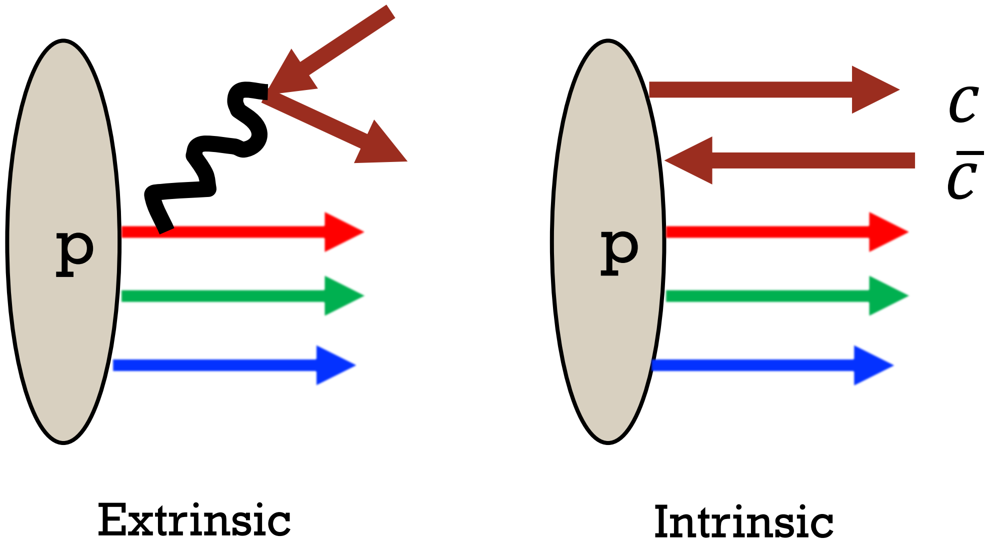
$p_T(\mu)/p_T(j_\mu) > 0.9$ and $\mathrm{BDT}(bc|udsg) > 0.2$

INTRINSIC CHARM IN PROTON

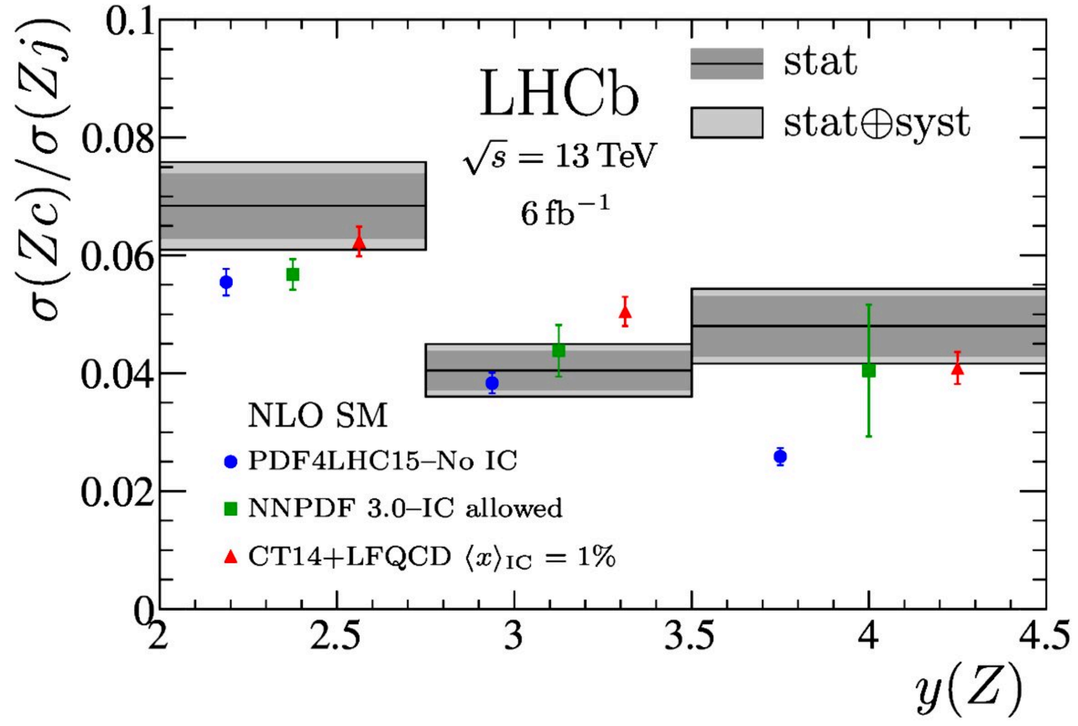
Phys. Rev. D **93** (2016) 074008

$$\mathcal{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$$

Phys. Lett. B **93** (1980) 451
Phys. Rev. D **23** (1981) 2745

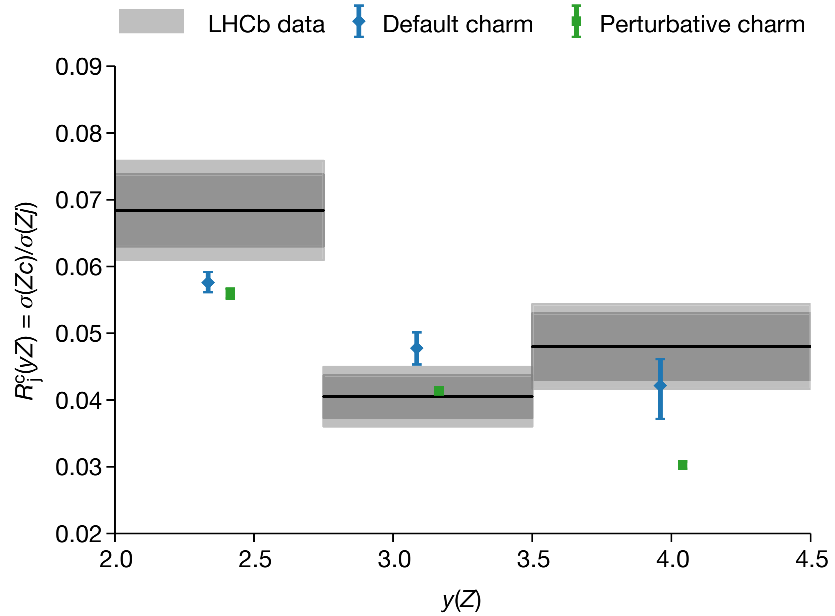


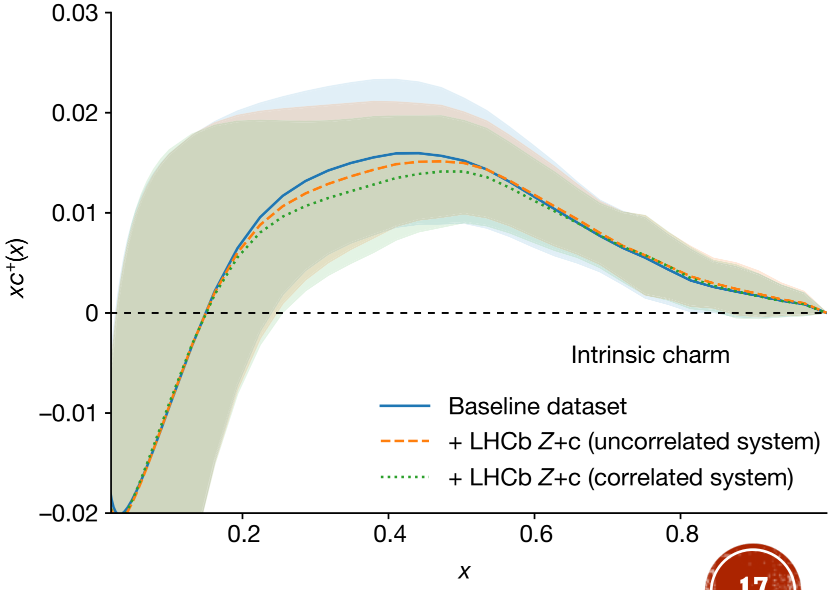
- 'Fraction of charm jet in jets in association with Z' proposed to be measured at LHCb.
- Large momentum transfer Q above EW scale, hence small nuclear and hadronic effects.
- $Z + c$ to $Z + j$ ratio to reduce sensitivities to experimental and theoretical uncertainties.



Phys. Rev. Lett. **128** (2022) 082001

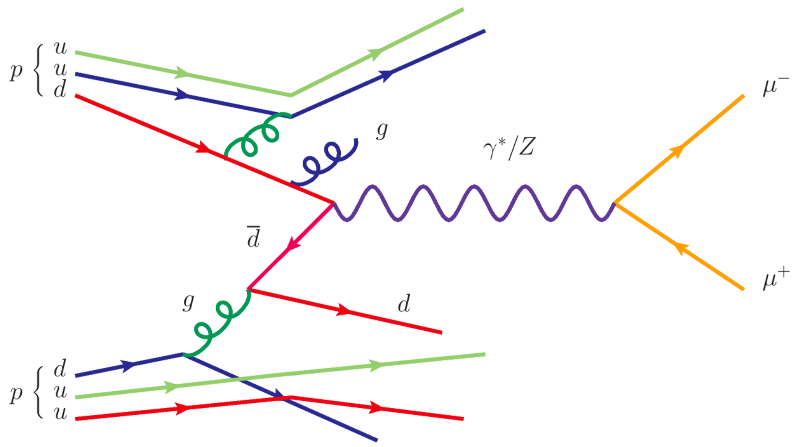
Nature **608** (2022) 483





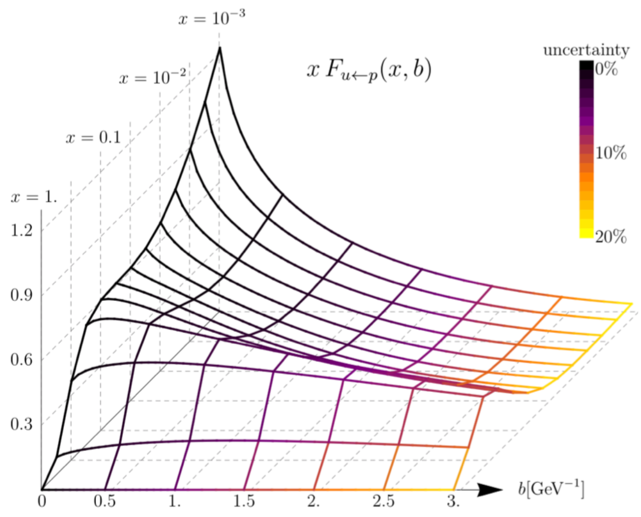
- Three scenarios, assuming no IC, IC allowed and valence-like IC (BHPS).
- A sizable enhancement at forward Z rapidities, consistent with the effect expected if the proton wave function contains the $|uudc\bar{c}>$ component.
- LHCb results rule out no IC prediction from global analysis performed by NNPDF group at 3σ deviation level, supporting existence of IC.
- Consistency between prediction and the measurements indicates success of DGLAP evolution from low Q in DIS to EW scale at LHC.

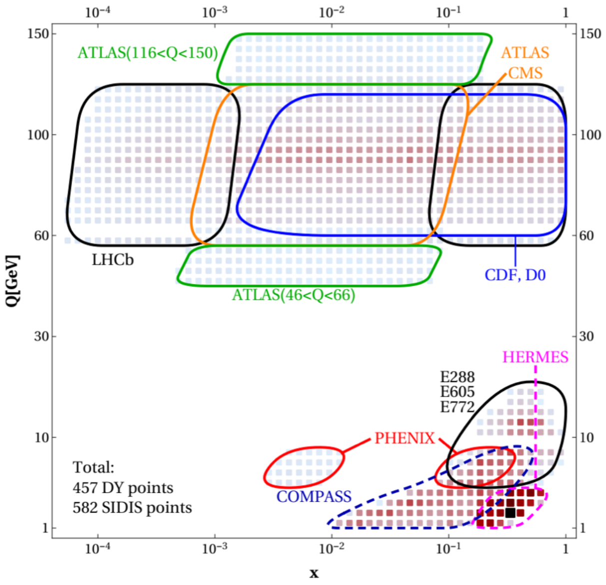
DY NEUTRAL CURRENT PROCESS



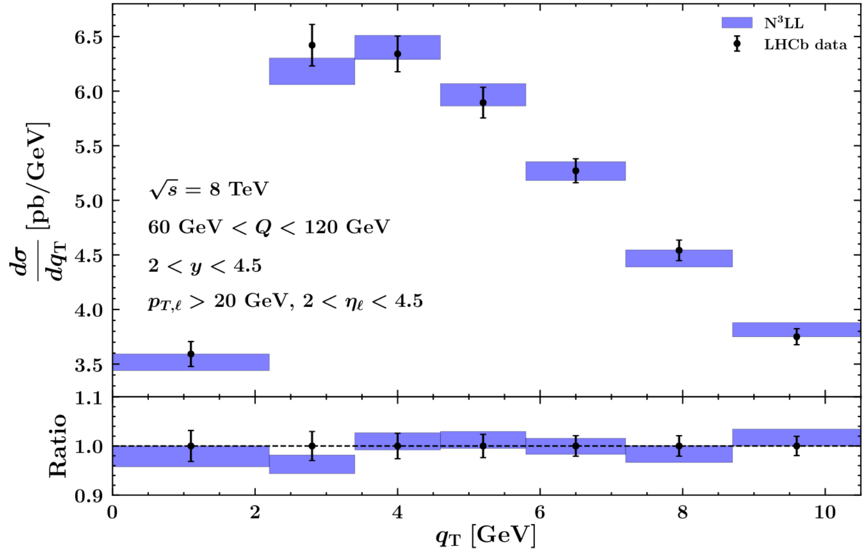
- Rich physics encoded in angular distribution of muons from $\gamma^*/Z \to \mu^+\mu^-$ decay in the forward region.
- Z-boson cross-section measurements at low Z p_T ($< 0.2\ m_Z$) already used for global analyses of unpolarized TMD PDFs.

JHEP **06** (2020) 137 Scimemi, Vladimirov

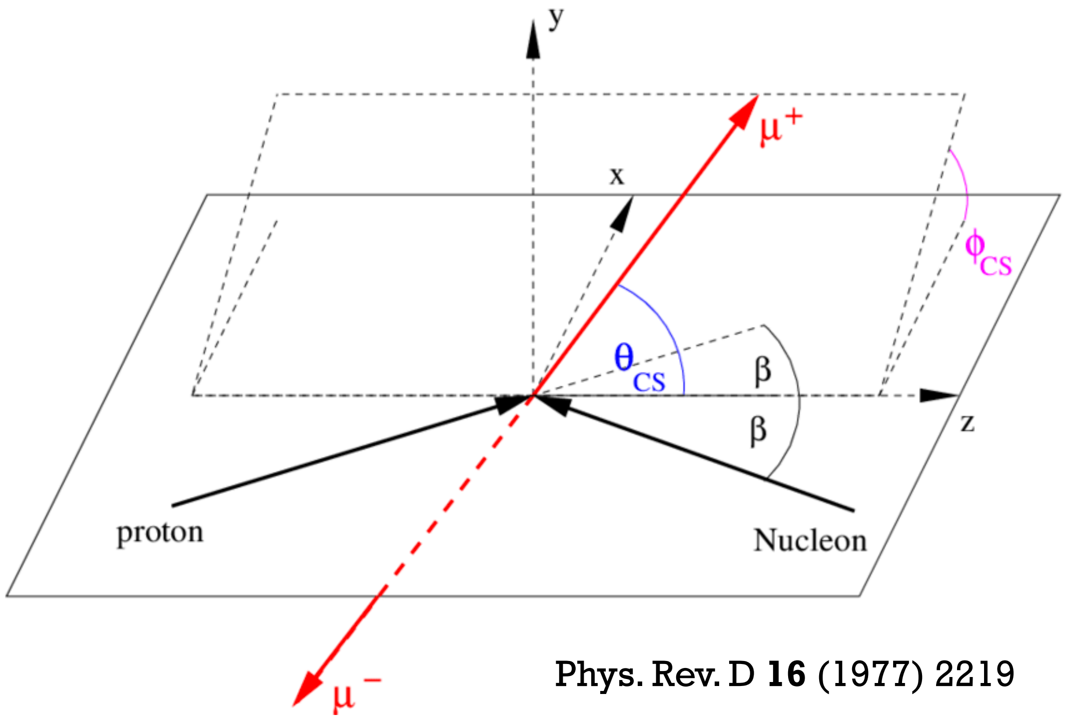




JHEP **07** (2020) 117 Bacchetta et al.



DY ANGULAR COEFFICIENTS



Phys. Rev. D **16** (1977) 2219

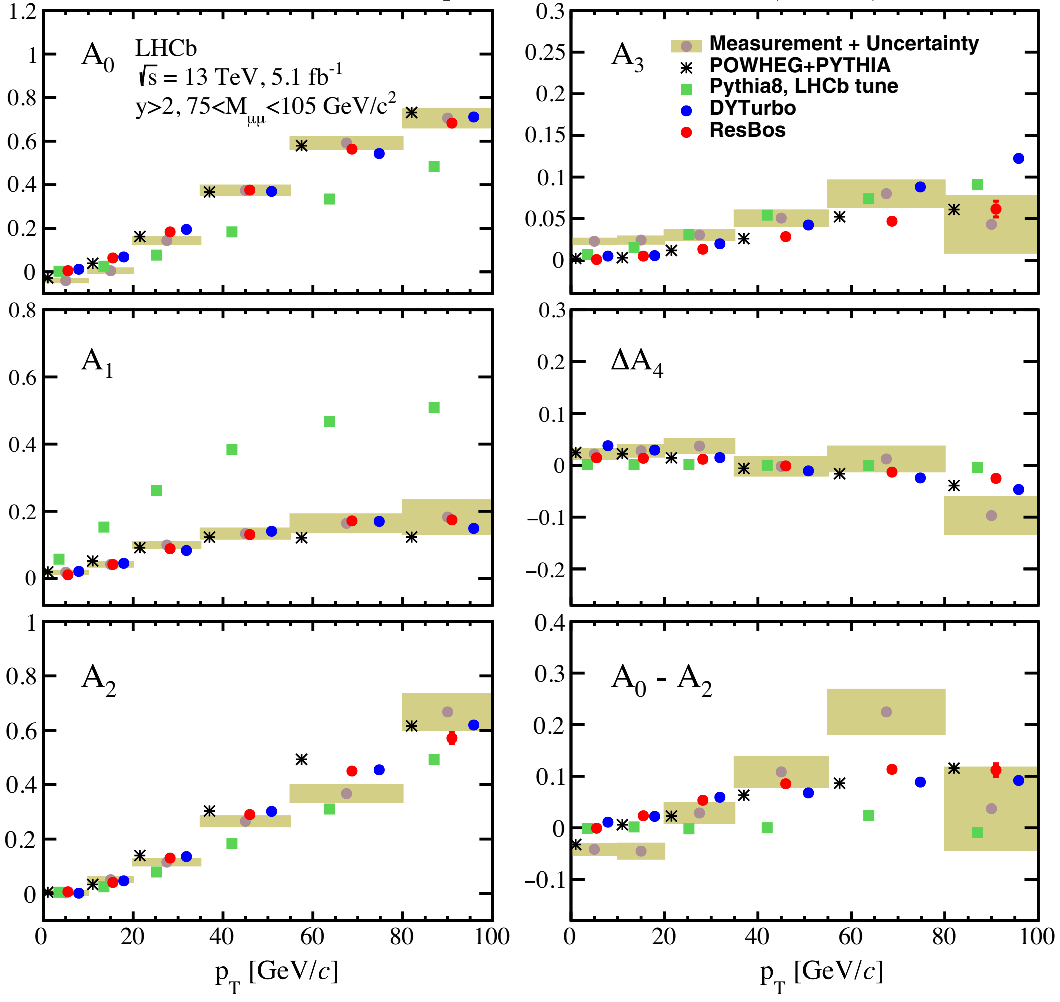
- Production mechanisms for spin 1 particles decaying into dileptons can be expressed using 8 angular coefficients A_i (i =0,… 7).
- *Lam-Tung* relation $A_0 = A_2$ at LO; can be violated by NP effects, e.g. Boer-Mulders TMD PDF, or even perturbatively at higher order in FO as well as resummation pQCD calculation.
- A_3, A_4 : V-A structure.

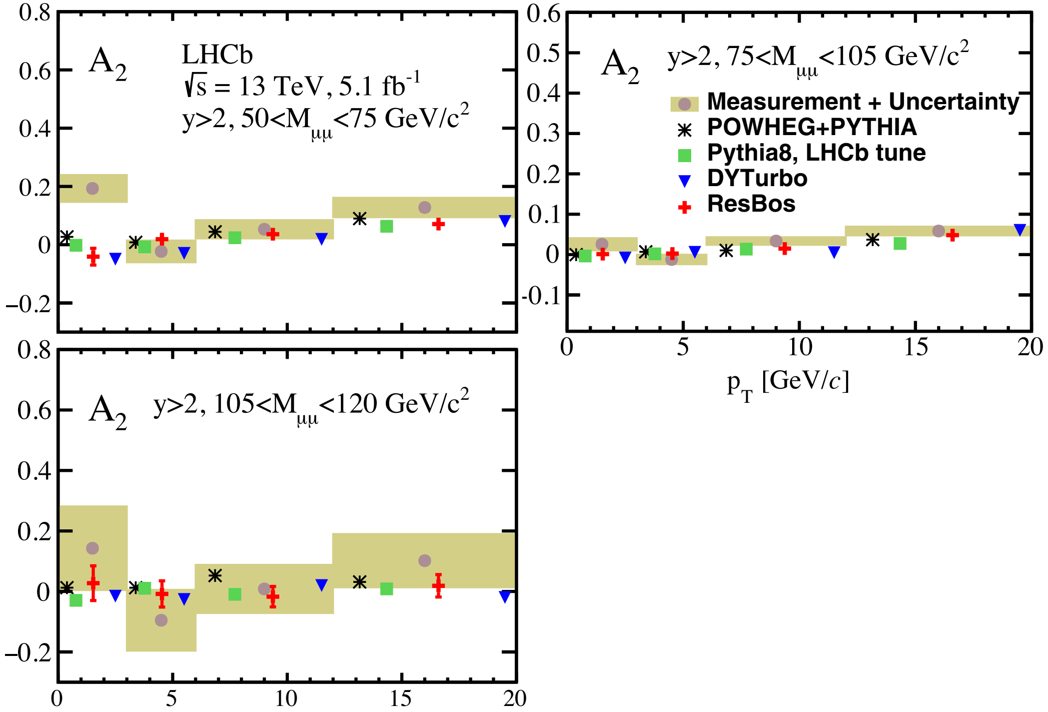
Lepton angular distribution

$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi$$
$$+A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi,$$

- Overall agreement in trends between data and predictions with an exception of Pythia.
- Significant violation of *Lam-Tung* relation observed.

Phys. Rev. Lett. **129** (2022) 091801





- A_2 in the low p_T region sensitive to the *Boer-Mulders TMD PDF.*
- At $p_T(Z) < 3$ GeV/c, A_2 measured to be ~ 5 times all predictions.
- No phenomenological calculations available.

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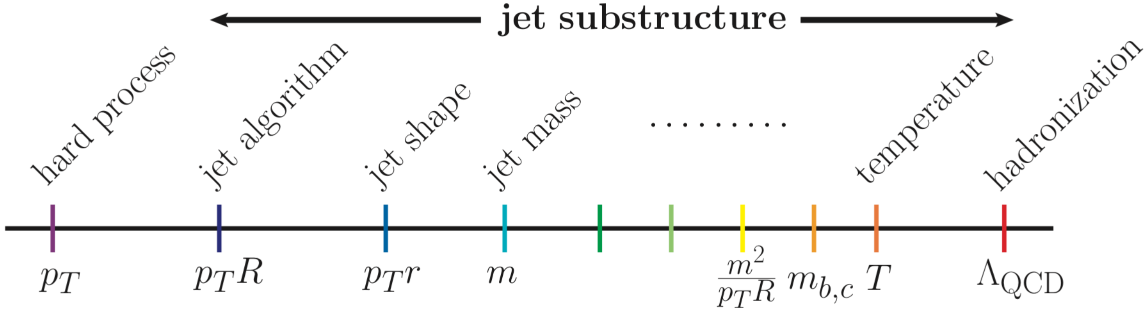
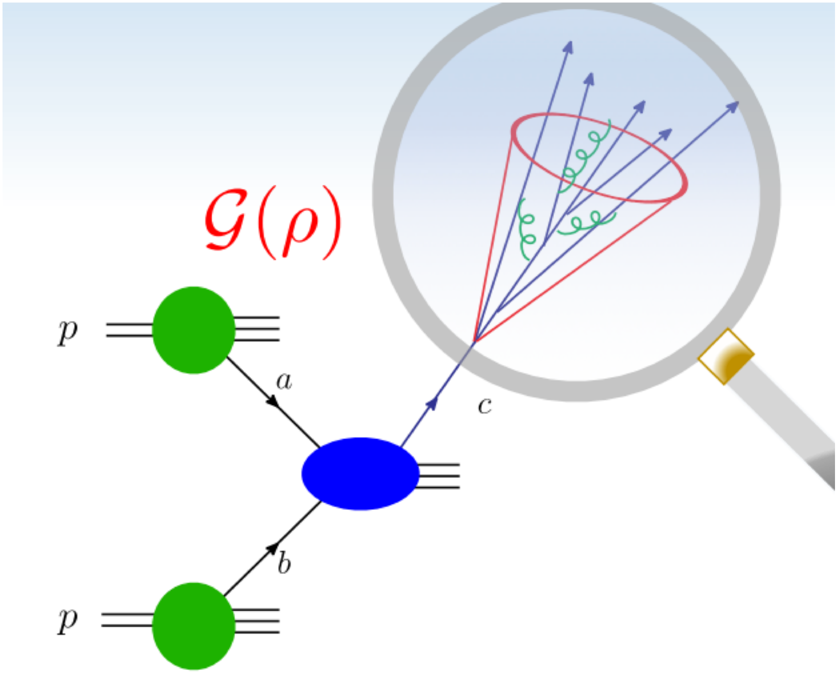
JET SUBSTRUCTURE

- Jet substructure ρ
  - Jet mass
  - Jet angularity
  - fragmenting jet function (FJF)
  - TMD FJF
  - …



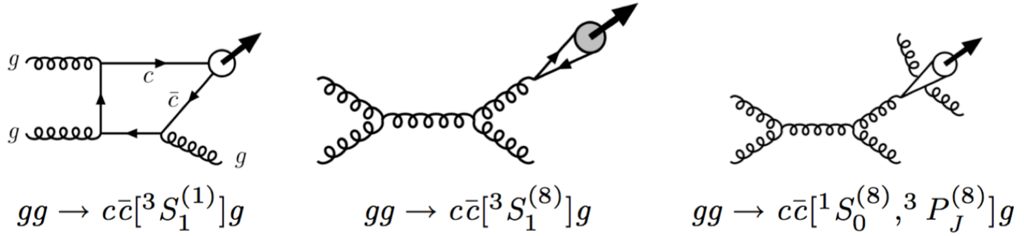
Courtesy by Y-T Chien

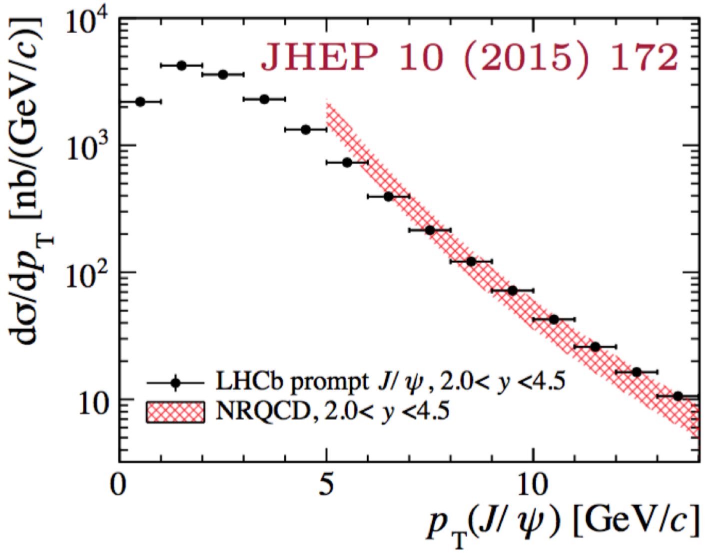


$$\frac{d\sigma^{pp\to jet\ (\rho)X}}{dp_T d\eta\ d\rho} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes \mathcal{G}_c(\rho)$$

Phys. Rev D **81** (2010) 074009
Phys. Rev. D **92** (2015) 054015
JHEP **11** (2016) 155
JHEP **1804** (2018) 110

QUARKONIA IN JETS

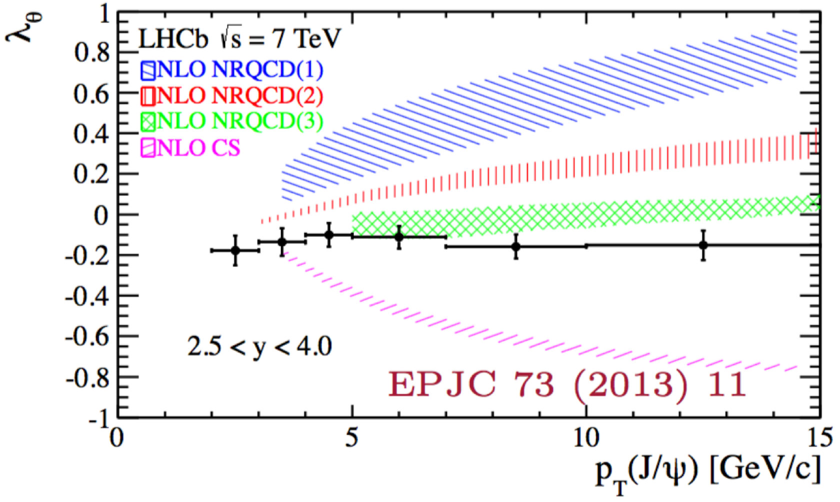




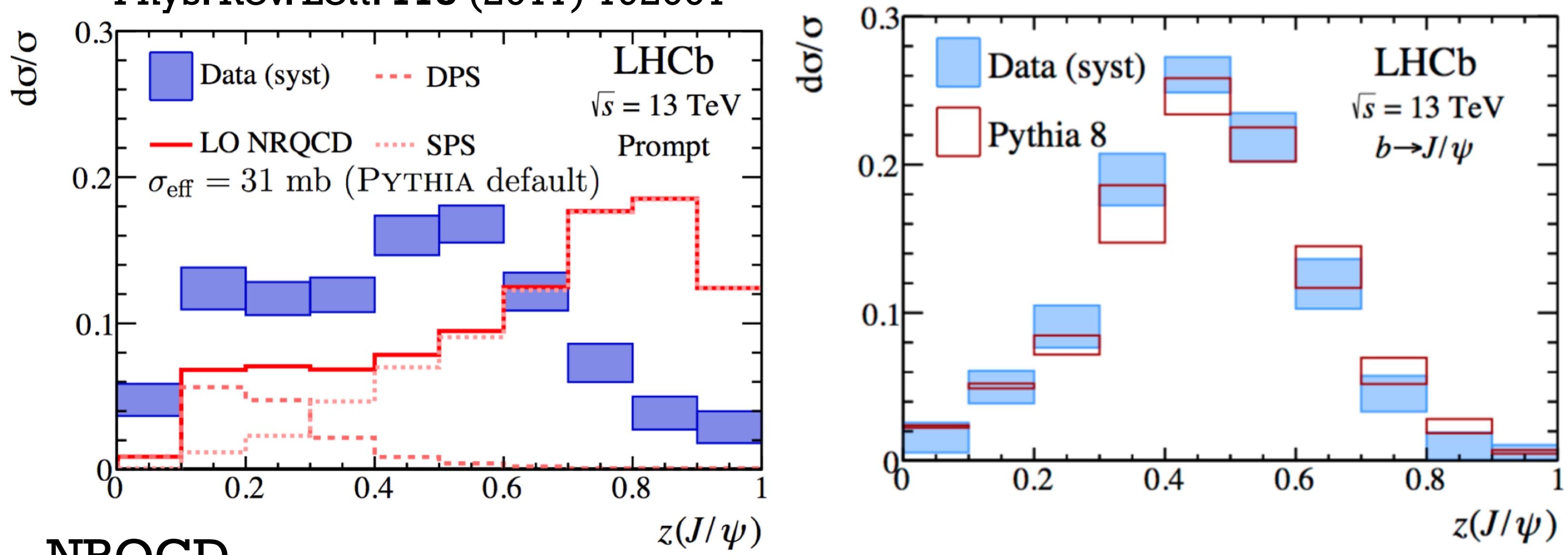
- Hadronization mechanisms of energetic heavy quark into $Q\bar{Q}$ bound states not well understood with limited success from NRQCD.

Phys. Rev. Lett. **119** (2017) 032002

- Charmonium fragmentation-in-jet measurements confirmed predominant production mechanism by gluon fragmentation.



Phys. Rev. Lett. **118** (2017) 192001



NRQCD

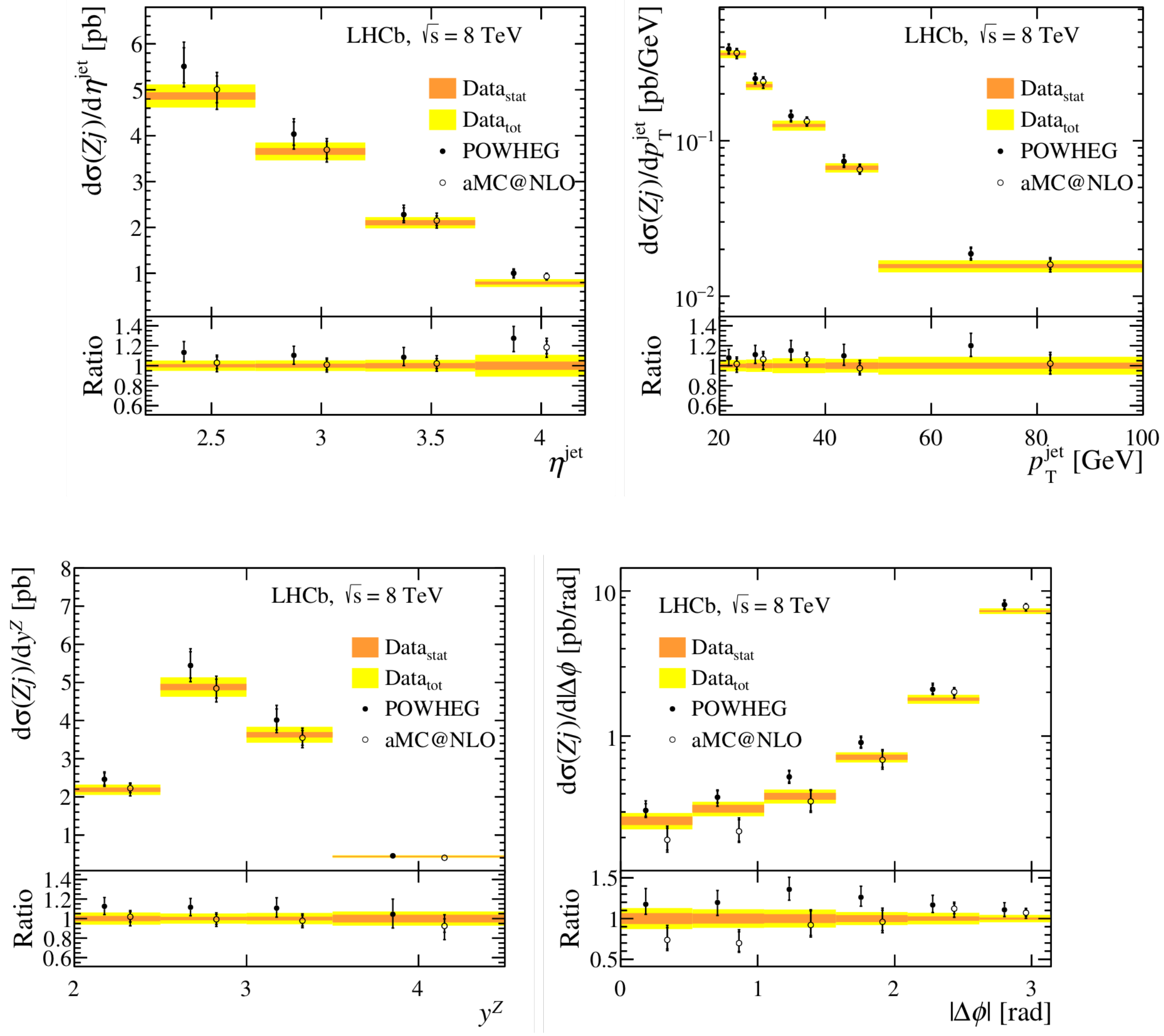
$$d\sigma(pp \to H + X) = \sum_{s,L,J} d\hat{\sigma}(pp \to Q\bar{Q}[^{2s+1}L_J] + X)\langle \mathcal{O}^H[^{2s+1}L_J]\rangle$$

Sookhyun Lee, CFNS workshop 2022

Z+LIGHT QUARK JET

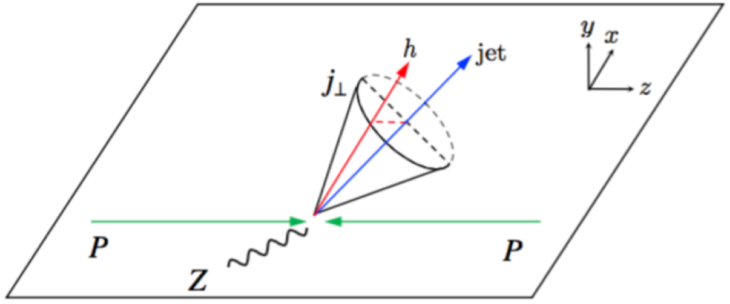
- Z boson + jet production is predominantly sensitive to quark initiated jets with further enhancement of up and down flavor due to forward kinematics.
- Jet production in association with Z measured with high precision at LHCb.
- LHCb does not have jet trigger; events triggered by high p_T muons.

JHEP **05** (2016) 131



LIGHT QUARK FRAGMENTATION INTO JET

JHEP **05** (2011) 035
JHEP **11** (2017) 068
Phys. Lett. B **798** (2019) 134978



$$\frac{d\sigma^{pp\to \mathrm{jet}(h)X}}{dp_T d\eta dz_h d^2 \boldsymbol{j}_\perp} = \sum_{a,b,c} f_{a/A} \otimes f_{b/B} \otimes H_{ab}^c \otimes \mathcal{G}_c^h(z_h, \boldsymbol{j}_\perp)$$

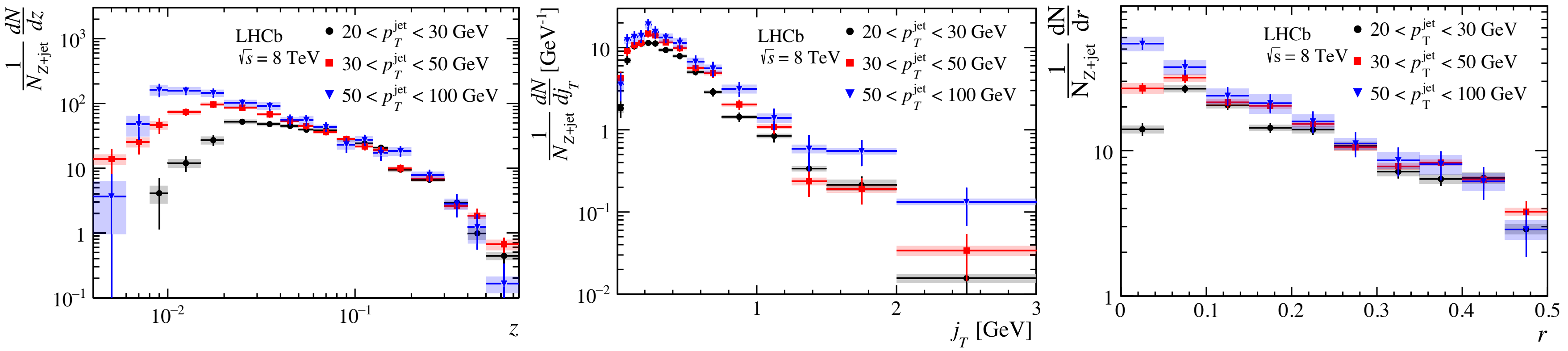
$\sim \widehat{D}_{h/c}(z_h, j_\perp, \mu_J)$
: TMD FF

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

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

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

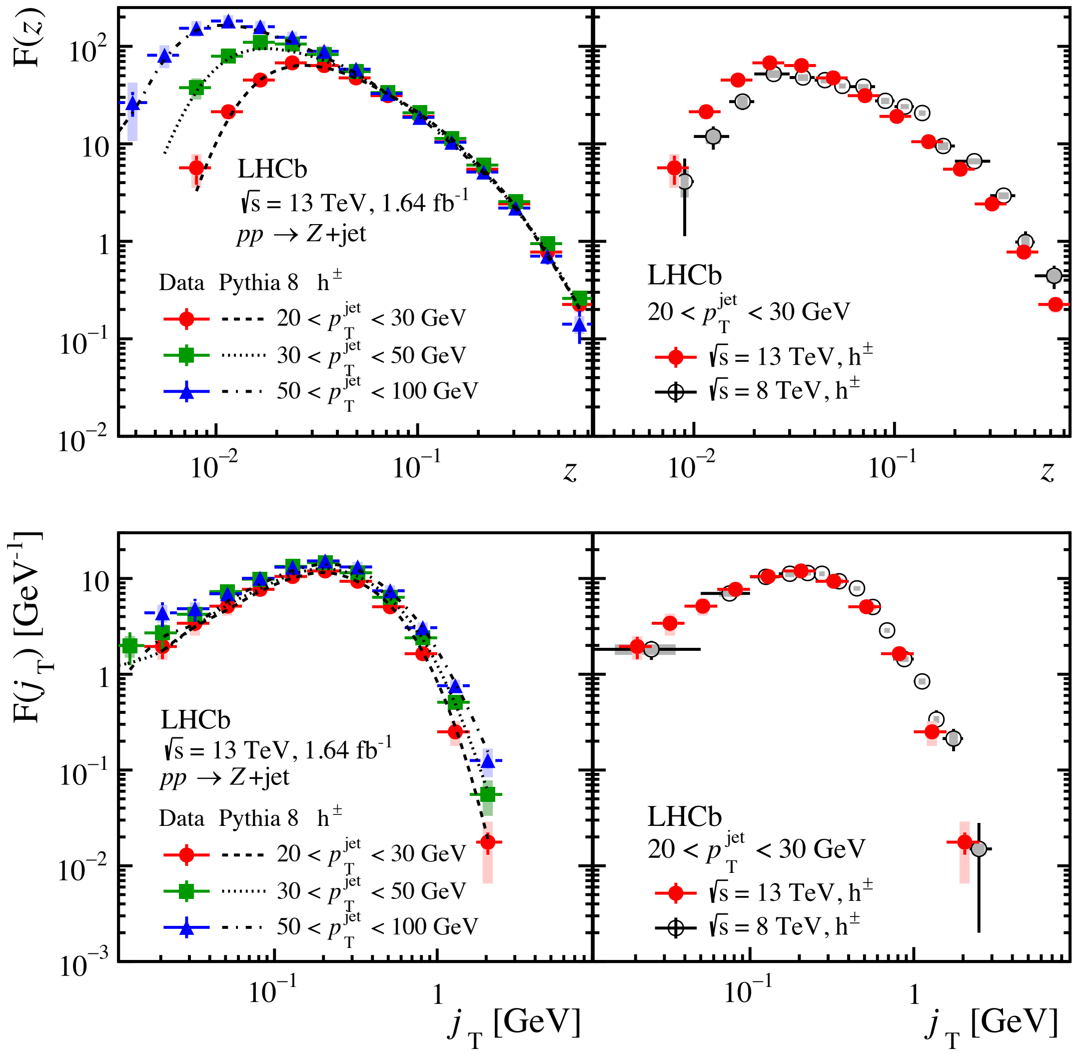
1D measurements of nonidentified $h^{\pm}$ in Z+jets



Phys. Rev. Lett. **123** (2019) 232001

LIGHT-QUARK JFF AT LHCB

arxiv:2208.11691

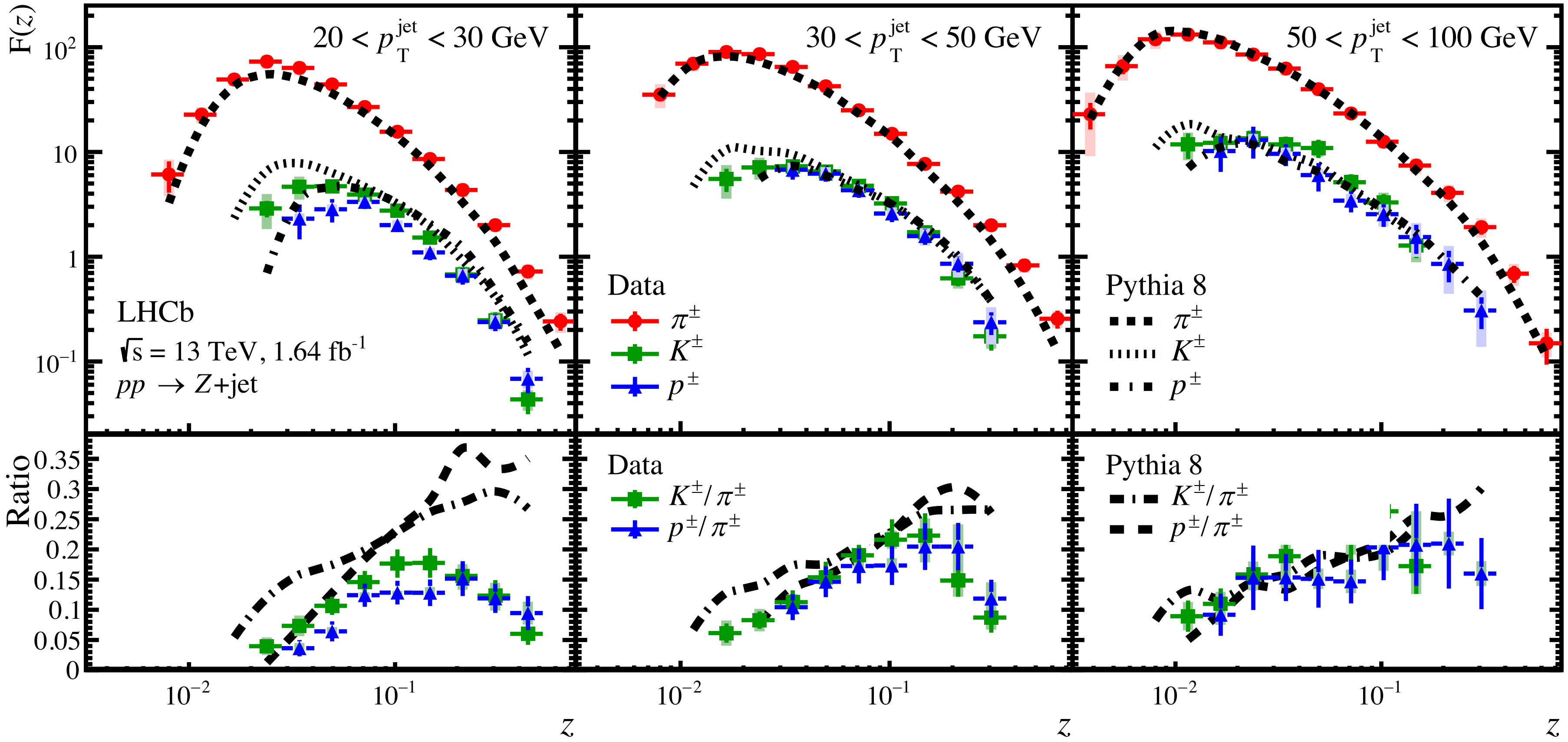


- Charged hadrons in Z–tagged jets.
- At small $z < 0.02$, effects of color coherence as well as kinematic cuts manifest as a humped-back structure.
- Harder jets, higher p_{T} or higher $\sqrt{s}$, produce an excess of soft particles per jet; access smaller z .
- Scaling behavior at large $z > 0.04$.
- Similar pattern in j_{T} between $\sqrt{s} = 8$ TeV vs 13 TeV.

LIGHT-QUARK JFF FOR $\pi^{\pm}, K^{\pm}$ AND $p^{\pm}$

arxiv:2208.11691

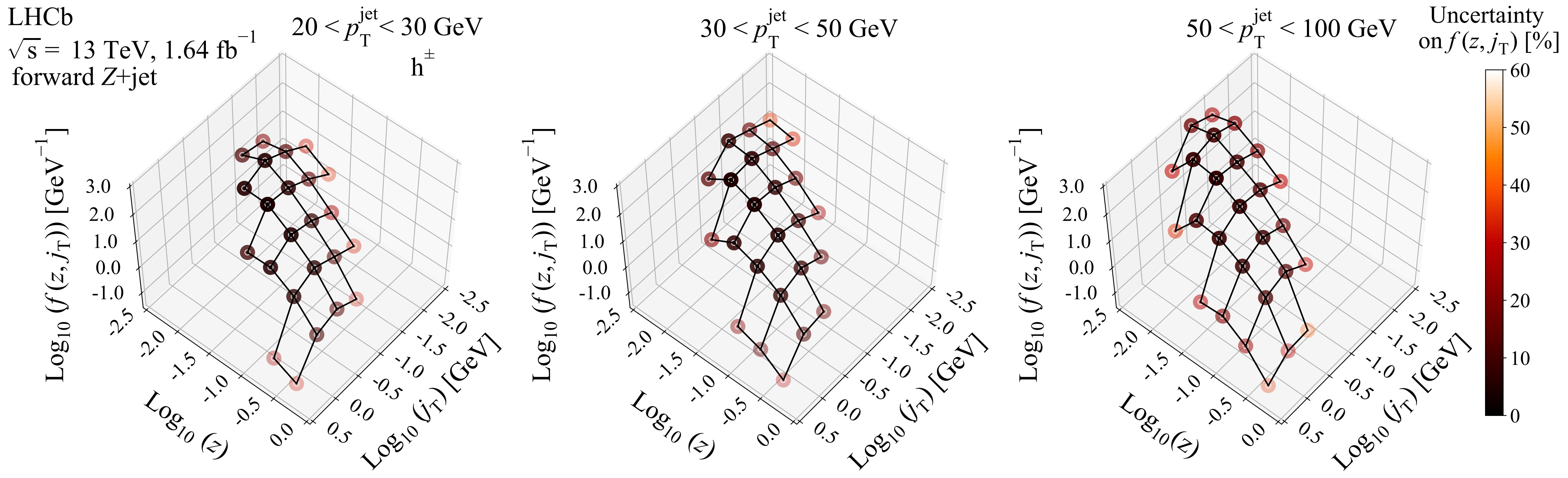
- Charged hadron formation within jets predominantly by $\pi^{\pm}$ due to its low mass and flavor content of initial-state proton.
- Hadrons with higher mass require a larger z threshold for their formation. Delayed scaling behavior shown in heavier charged particles.



- In lowest jet p_T interval:
  - Proton production relative to kaons clearly suppressed at lower z.
  - Pythia 8 overestimates $K^{\pm}, p^{\pm}$ production relative to $\pi^{\pm}$.

MULTI-DIFFERENTIAL TMD JFF FOR CHARGED HADRONS $h^{\pm}$

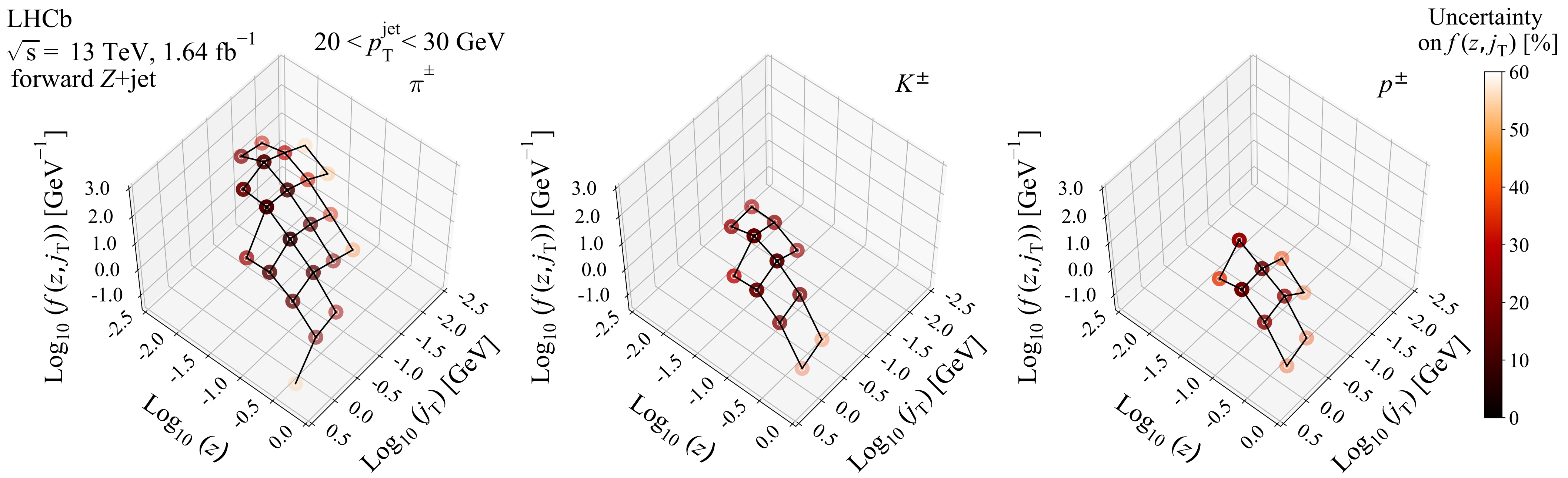
arxiv:2208.11691



- Hadrons carrying large momentum fraction along jet axis tend to have large transverse momentum w.r.t. jet axis.
- Centroid of harder jets shifted towards smaller z (soft particle production) and larger j_T (wider jet).
- Larger j_T for given z in jets with higher p_T; consistent with Markov chain fragmentation models, e.g. string or cluster models.

MULTI-DIFFERENTIAL TMD JFF FOR $\pi^{\pm}, K^{\pm}$ AND $p^{\pm}$

arxiv:2208.11691

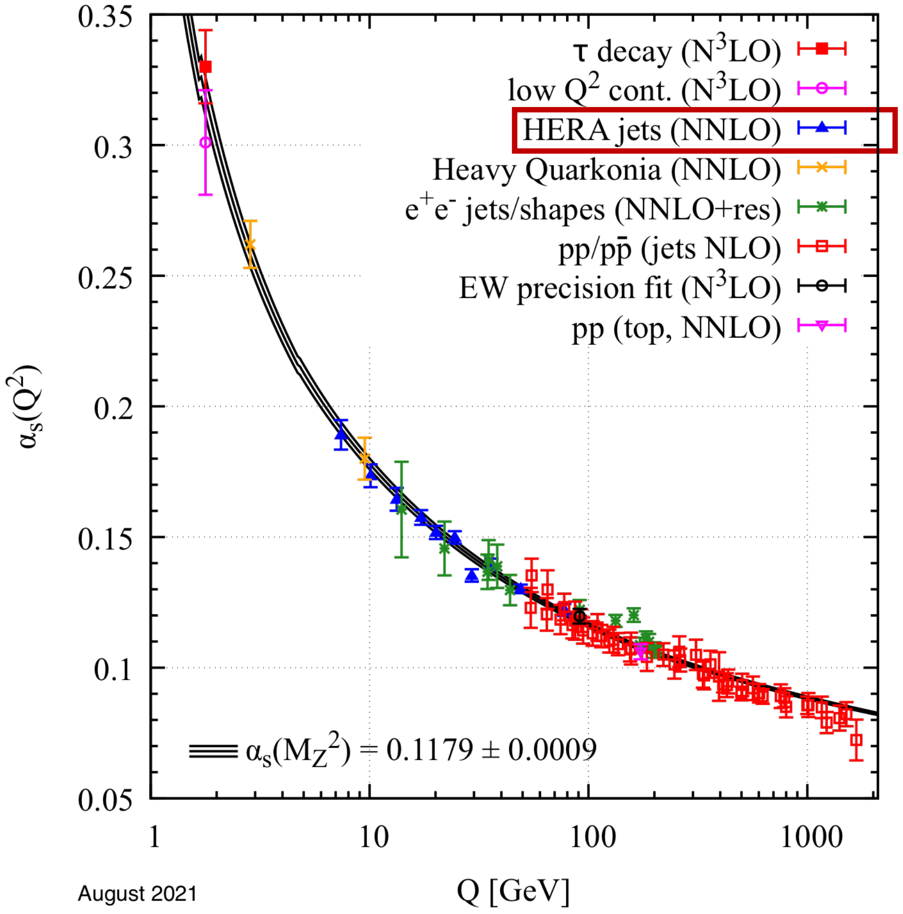


- Multidifferential distributions for pions, kaons and protons at 20 < jet p_T < 30 GeV/c
- Heavier hadrons produced from harder partons, i.e. larger j_T as well as larger z .

CONTENTS

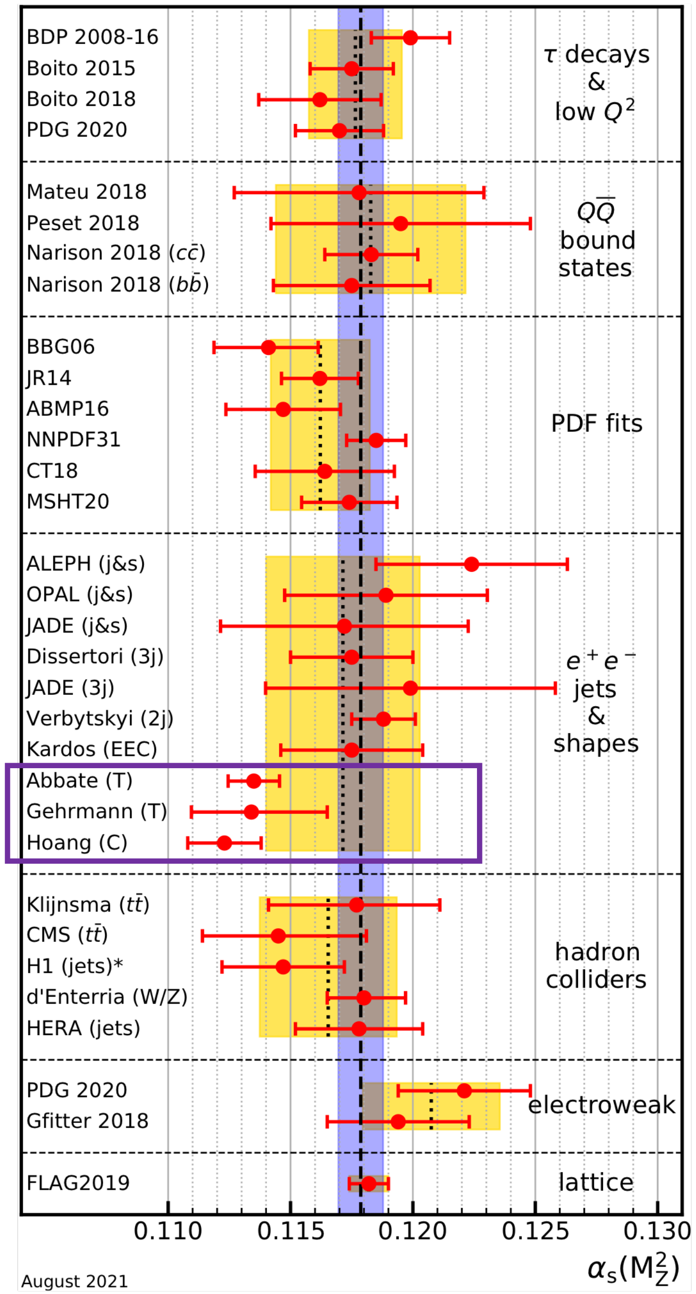
- Nonperturbative dynamics inside proton at RHIC
  - Proton spin and nucleon-parton spin-momentum correlations
  - Cross section asymmetries with polarized protons data
- Proton structure and hadronization in jets at LHCb at LHC
  - s-quark content, intrinsic charm and quark spin-momentum correlations.
  - Jet fragmentation functions
- **Event shapes at HERA and EIC**
  - **Strong coupling constant and hadronization.**
  - **1-jettiness**
  - **Groomed event shapes**

PRECISION MEASUREMENTS OF RUNNING α_S



Recently updated with NNLO fit: reduced theory uncertainty, still dominant

Event Shapes : relatively large deviations from lattice results

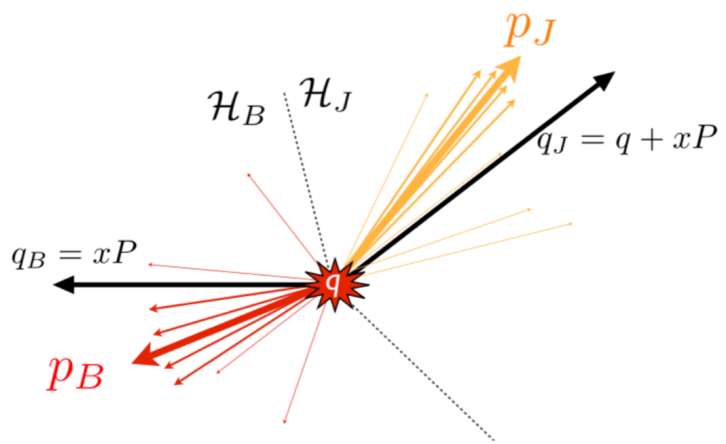


Sookhyun Lee, CFNS workshop 2022

1-jettiness

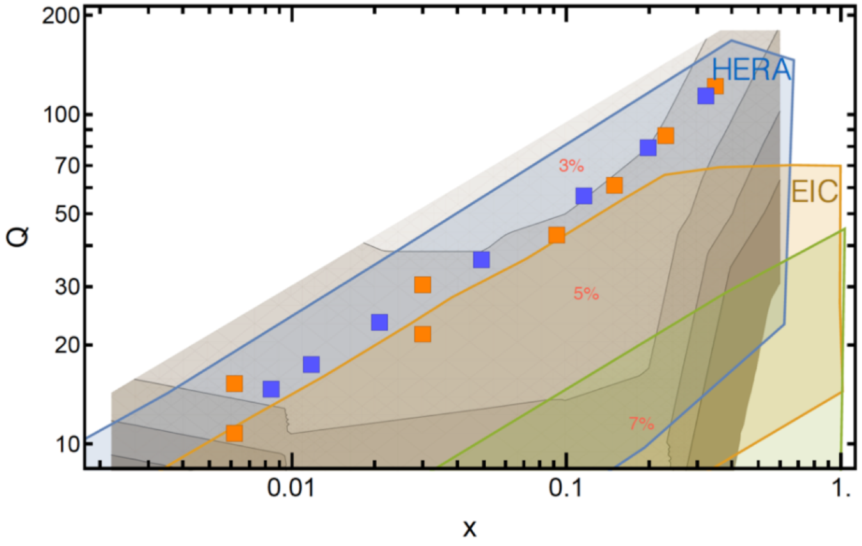
- $\tau_1^b = \frac{2}{Q^2} \Sigma_{i \in X} \min\{q_J \cdot p_i, q_B \cdot p_i\}$,

  where $q_J = xP + q, q_B = xP$
- Global, Lorentz invariant and infrared-safe observable
- Sensitive to strong coupling constant α_s and PDFs

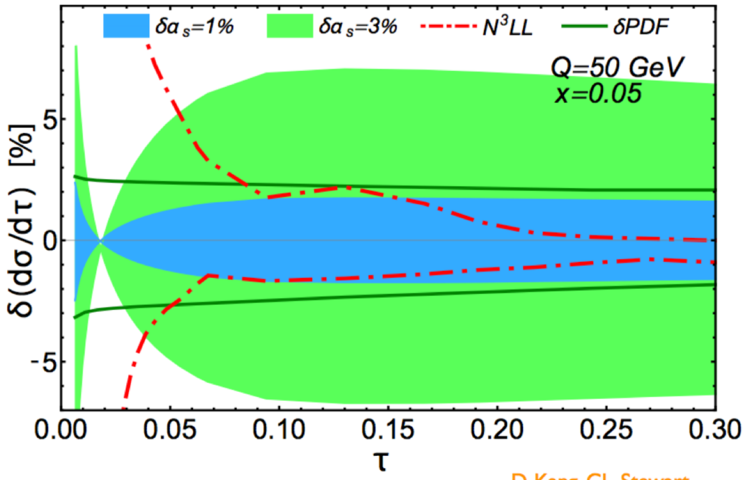


Phys. Rev. D **88** (2013) 054004 D. Kang, C. Lee, I. Stewart.

Current theoretical uncertainty vs. HERA or EIC coverage:



Current theoretical uncertainty on the order of 1% sensitivity to α_s and PDF uncertainties:



D. Kang, CL, Stewart
(2015 and in progress)

N2LL published, N3LL WIP

Proposed to pursue at EIC

D. Kang, C. Lee, I. Stewart + L. Cunqueiro, P. Jacobs, H. Klest, SL

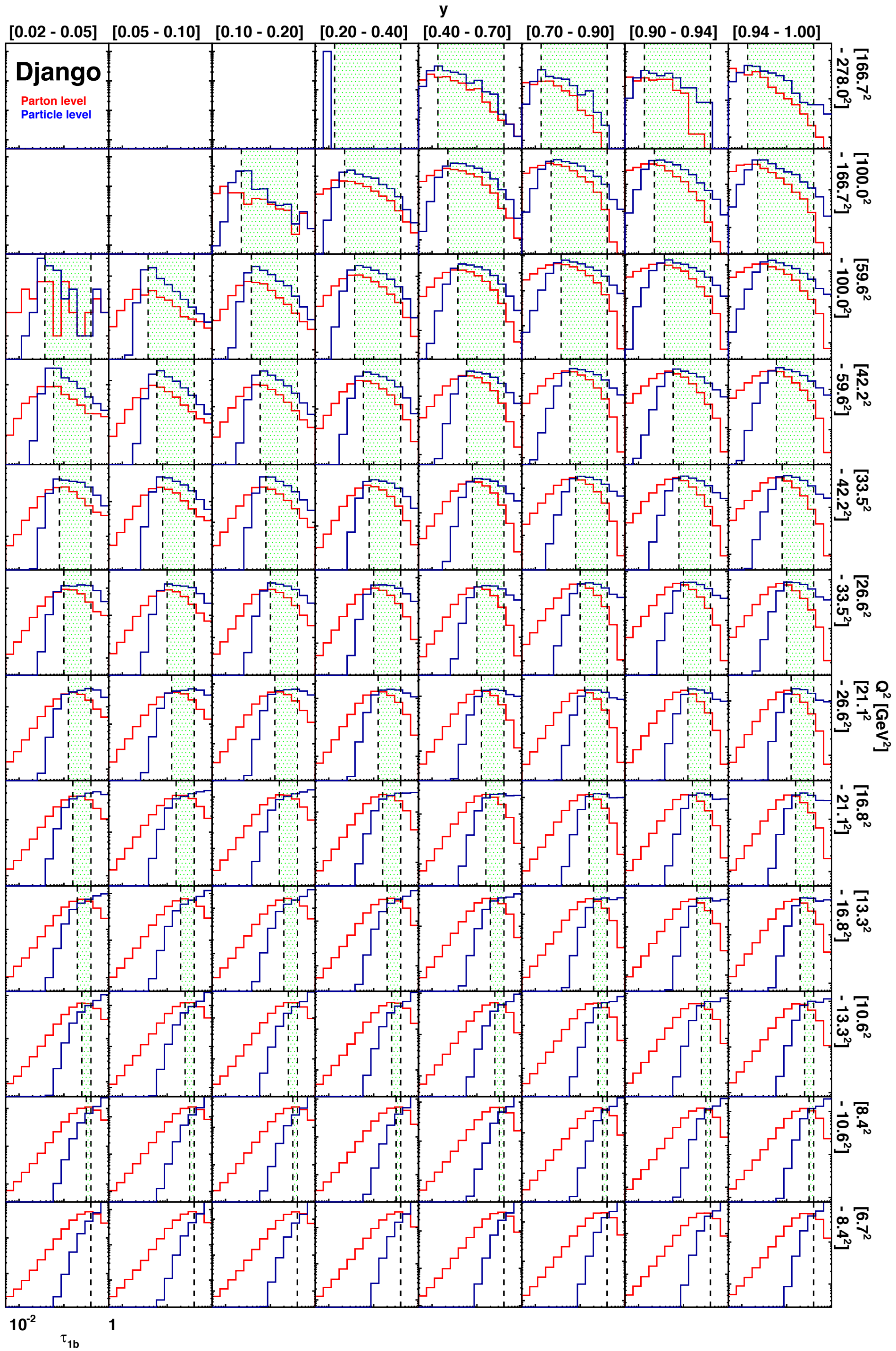
UNIVERSALITY OF NONPERTURBATIVE SECTOR

- Soft hadronic activities
  - Hadronization
  - Perturbative soft radiation
  - Multiple parton interaction
- Nonperturbative shift in event shapes; universality established across various shapes in e+e-.

G. Korchemsky, G. Sterman;
C. Bauer, C. Lee, A. Manohar, M. Wise

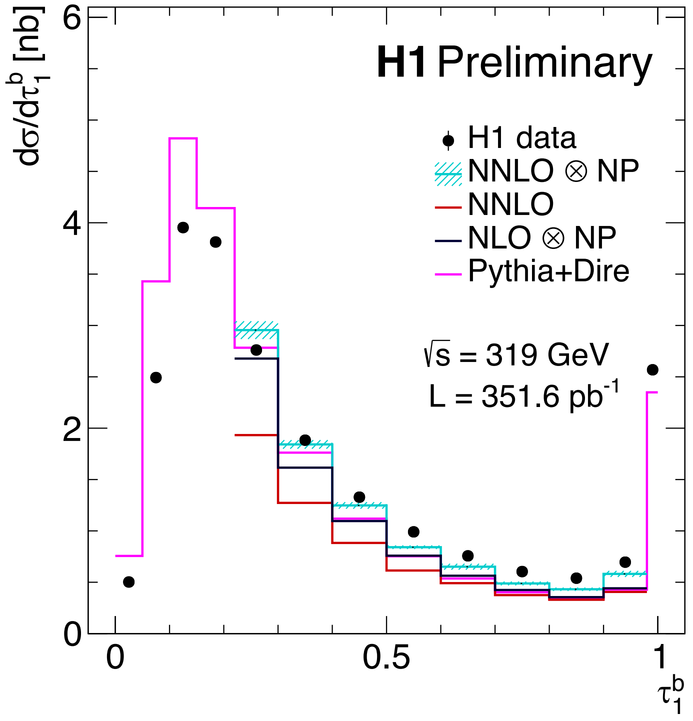
- Test universality of hadronization in DIS as well as across collision systems.

C. Lee, Y. Makris + L. Cunqueiro, P. Jacobs, H. Klest, SL, B. Nachman (In preparation)

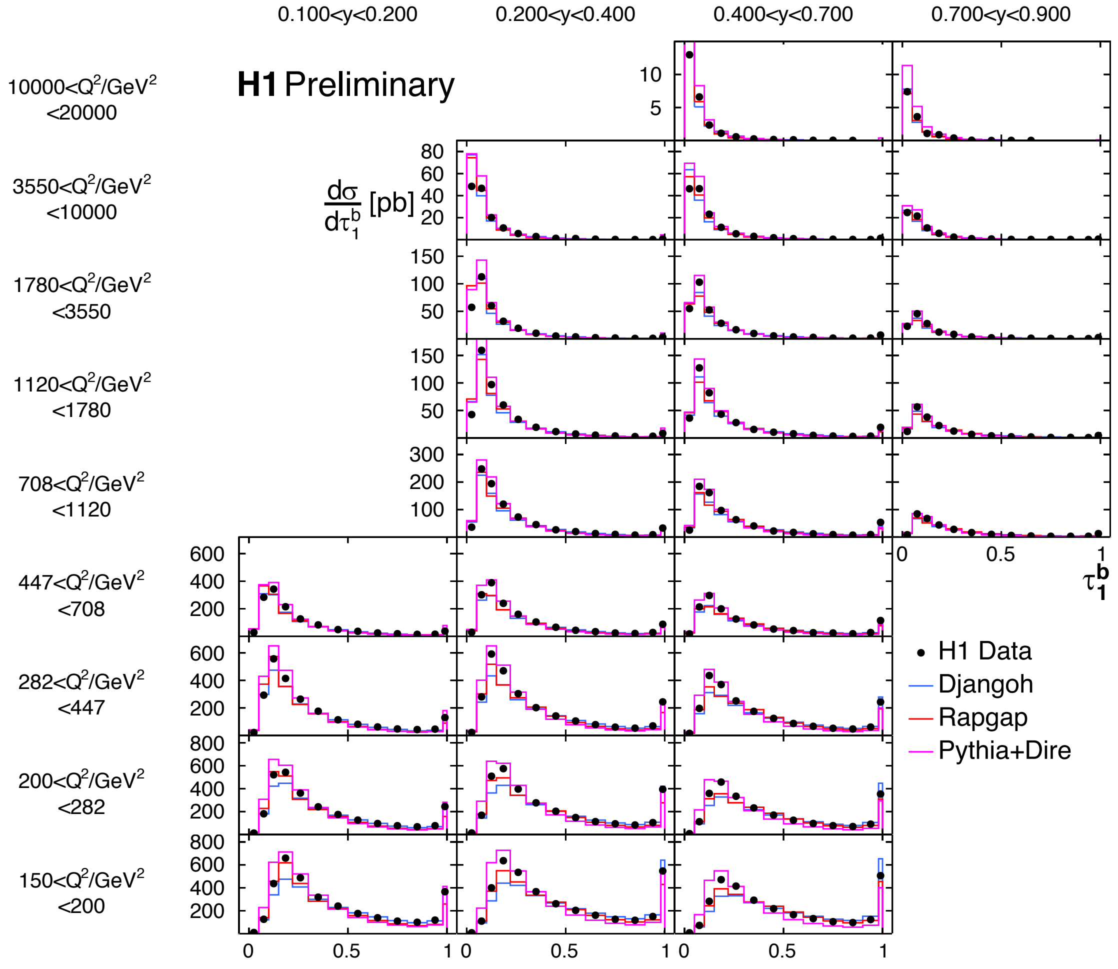


1-JETTINESS FROM H1 AT HERA

H1prelim-21-032



H1prelim-21-032

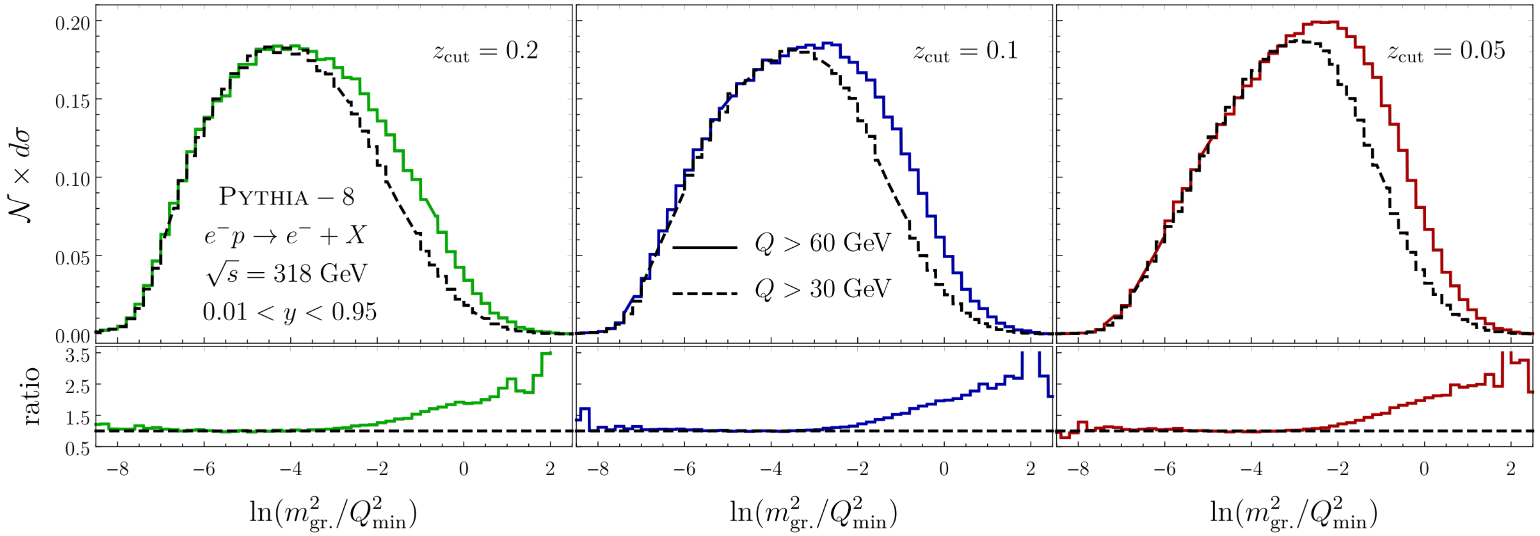


Well preserved data and analysis tools available at H1 allow us to explore possibilities. Special thanks to D. Britzger!

GROOMED EVENT SHAPES

- Groomed invariant mass and groomed 1-jettiness.
- New observables insensitive to ISR and beam remnants.
- Nonperturbative effects can be controlled by grooming parameters z_{cut}.
- In back-to-back limit, no x & Q^2 dependence in groomed invariant mass shape – experimentally favorable.

arXiv:2101.02708



$$z_i = \frac{P \cdot p_i}{P \cdot q} \qquad \min = \frac{\min(z_i, z_j)}{z_i + z_j} > z_{cut}$$

See H. Klest's talk later today !

SUMMARY & OUTLOOK

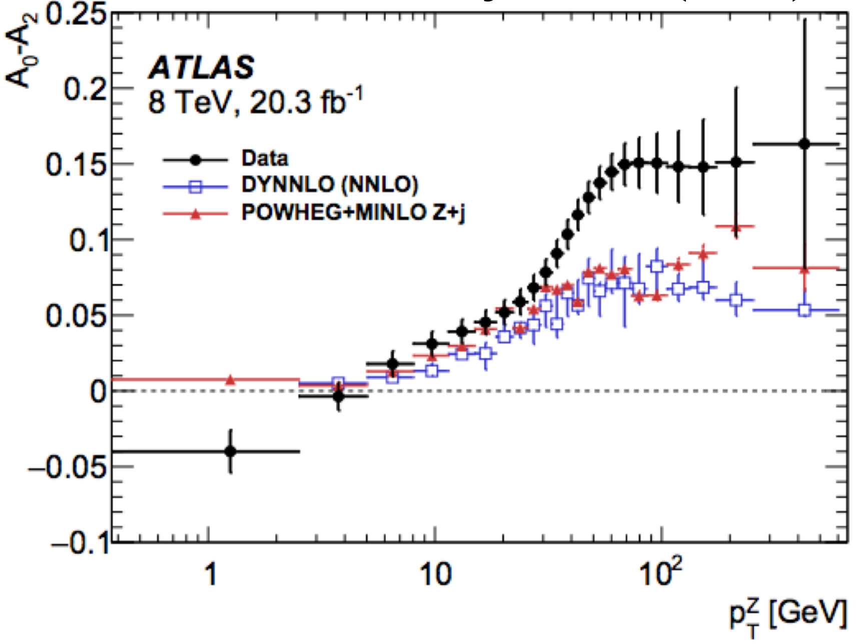
- Spin degrees of freedom plays a crucial role in NP QCD.
- Both initial state and final state effects studied at RHIC.

- Electroweak boson productions and jets in association with them at LHCb access partonic momentum structure and its interplay with spin.
- Jet fragmentation function
- Heavy flavor and exotic states in jets under study.

- Event shape measurements promising to shed light on hadronization.
- Higher theoretical precision in groomed observables can provide much stronger handle on studying NP effects.
- Revisiting e^+e^- and making conserted efforts will be beneficial.

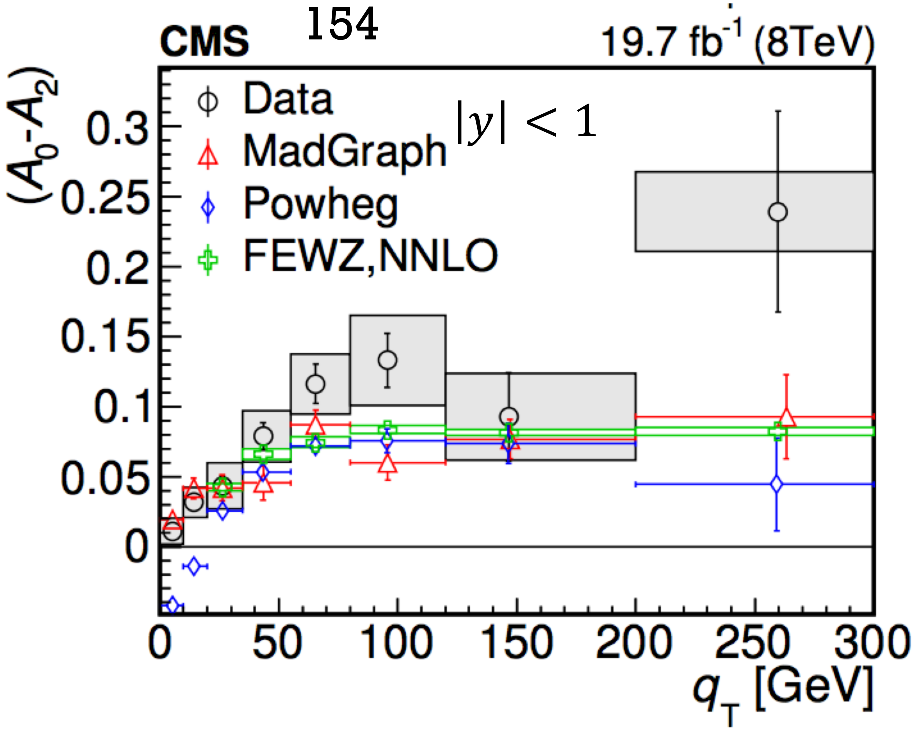
THANK YOU!

JHEP **08** (2016) 159



- Significant violation of Lam-Tung relation observed.
- Consistent with measurements by CMS and ATLAS.

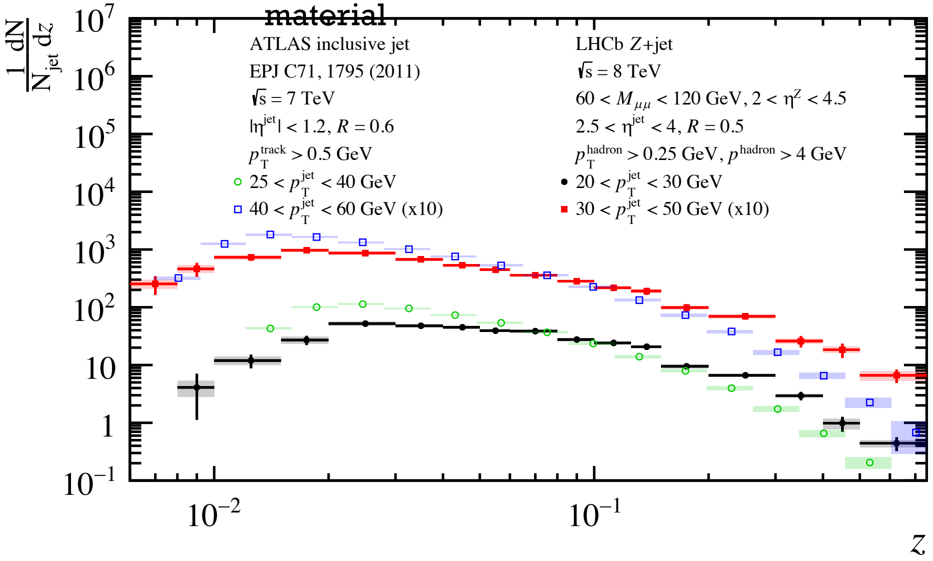
Phys. Lett. B **750** (2015) 154



GLUON- VS. QUARK-INITIATED JETS

- LHCb Z+jets (quark jet) vs. ATLAS inclusive jets (gluon jet)
- Quark-initiated jets are more collimated and takes a larger partonic momentum fraction than gluon jets.

PRL 123, 232001 (2019) - Supplemental material



PRL 123, 232001 (2019) - Supplemental material