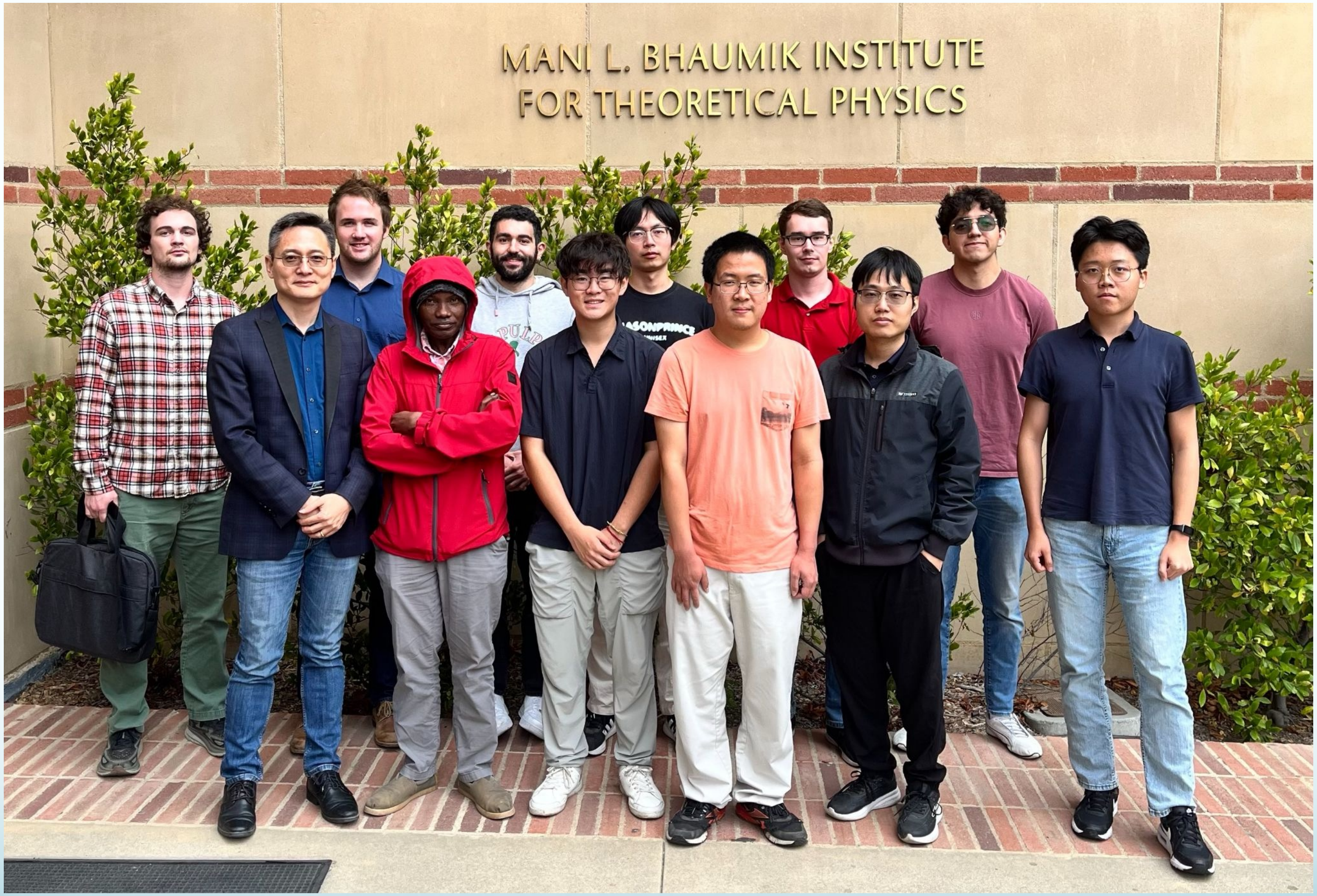
UCLA QCD and EIC Theory 4 Year Overview

Zhongbo Kang
UCLA

@ZhongboK

California EIC Consortium Collaboration Meeting
January 9 – 10, 2025

Current group picture



Group Members

- Staff/postdocs
  - Jani Penttala (09/2023): joint with SURGE small-x collaboration
  - Farid Salazar (10/21 – 11/23): joint with LBNL, next: research assistant professor at UW INT, now a faculty at Temple U. (01/2025)
  - Andrew Larkoski (09/22 – 09/23): next: associate editor at PRD

- Graduate students:
  - Kyle Lee (closely worked with us, at LBNL, now at MIT)
  - John Terry (now a Director's Postdoc Fellow at LANL)
  - Fanyi Zhao (graduated in 08/2023, next MIT, story)
  - Jared Reiten (graduated in 12/2023, now industry)
  - Luke Sellers (machine learning)
  - Diego Padilla (EIC theory and small-x physics)
  - Robert Kao (small-x physics)
  - Xoan Mayo Lopez (visited us, will join MIT CTP)

Group Members

- Undergraduate students
  - Current: Congyue Zhang, Peter Nguyen, Curtis Zhou, Sofia Behzadi
  - Past: Rares Fota, Grace Garmire, Tejes Gaertner, Sky Shi, Miranda Li, Parth Bbatnagar, Philip Velie, Yuxuan Tee, Jesson Pulido, Amanda Wei

TMD Handbook

TMD Handbook

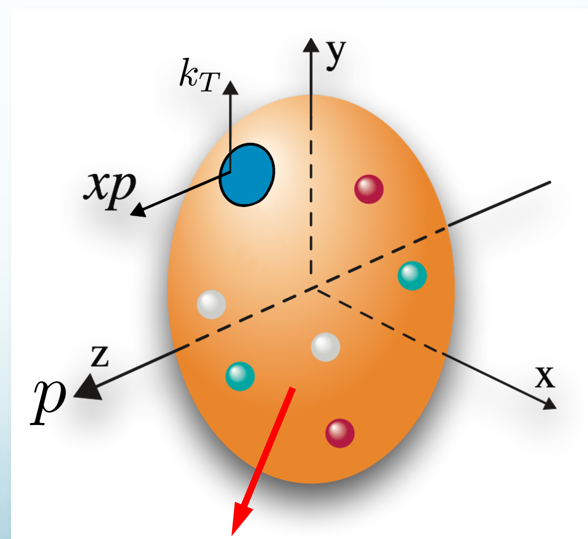
A modern introduction to the physics of Transverse Momentum Dependent distributions

arXiv:2304.03302

TMD Collaboration

Renaud Boussarie
Matthias Burkardt
Martha Constantinou
William Detmold
Markus Ebert
Michael Engelhardt
Sean Fleming
Leonard Gamberg
Xiangdong Ji
Zhong-Bo Kang
Christopher Lee
Keh-Fei Liu
Simonetta Liuti
Thomas Mehen *
Andreas Metz
John Negele
Daniel Pitonyak
Alexei Prokudin
Jian-Wei Qiu
Abha Rajan
Marc Schlegel
Phiala Shanahan
Peter Schweitzer
Iain W. Stewart *
Andrey Tarasov
Raju Venugopalan
Ivan Vitev
Feng Yuan
Yong Zhao

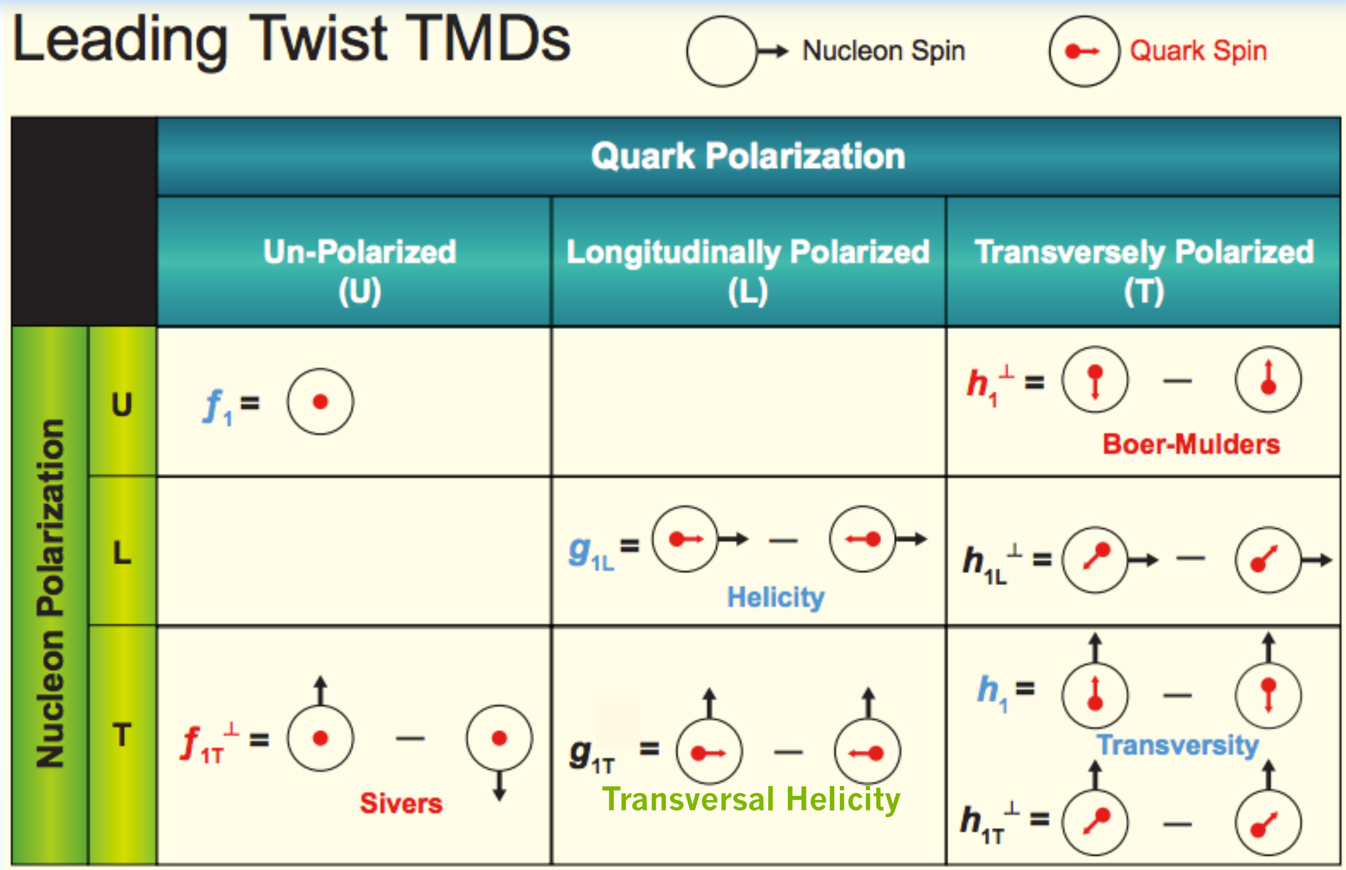
* - Editors



Proton spin

TMDs with polarization

TMD PDFs

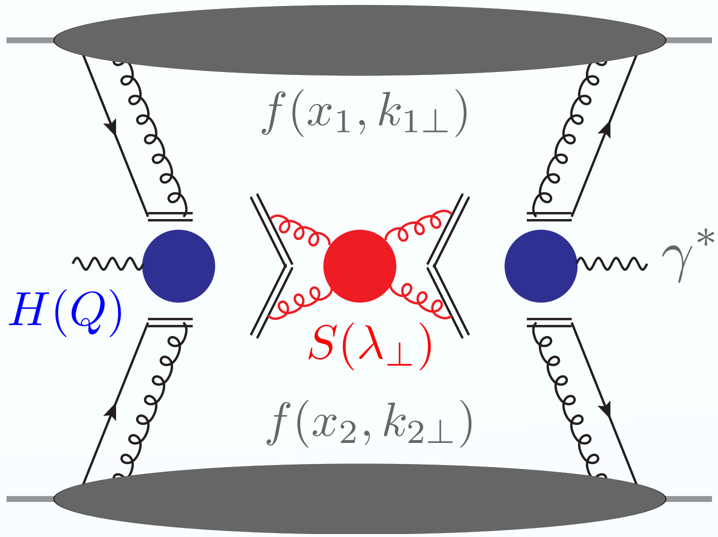


TMD FFs

	Quark Polarization U	L	T
Pion	D_1		$H_1^{\perp}$ **Collins**

TMD factorization

- Drell-Yan production $p + p \to [\gamma^* \to \ell^+ \ell^-] + X$



$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} \propto \int d^2k_{1\perp}\, d^2k_{2\perp}\, d^2\lambda_\perp H(Q) f(x_1, k_{1\perp}) f(x_2, k_{2\perp}) S(\lambda_\perp) \delta^2(k_{1\perp} + k_{2\perp} + \lambda_\perp - q_\perp)$$

$$= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) f(x_1, b) f(x_2, b) S(b)$$

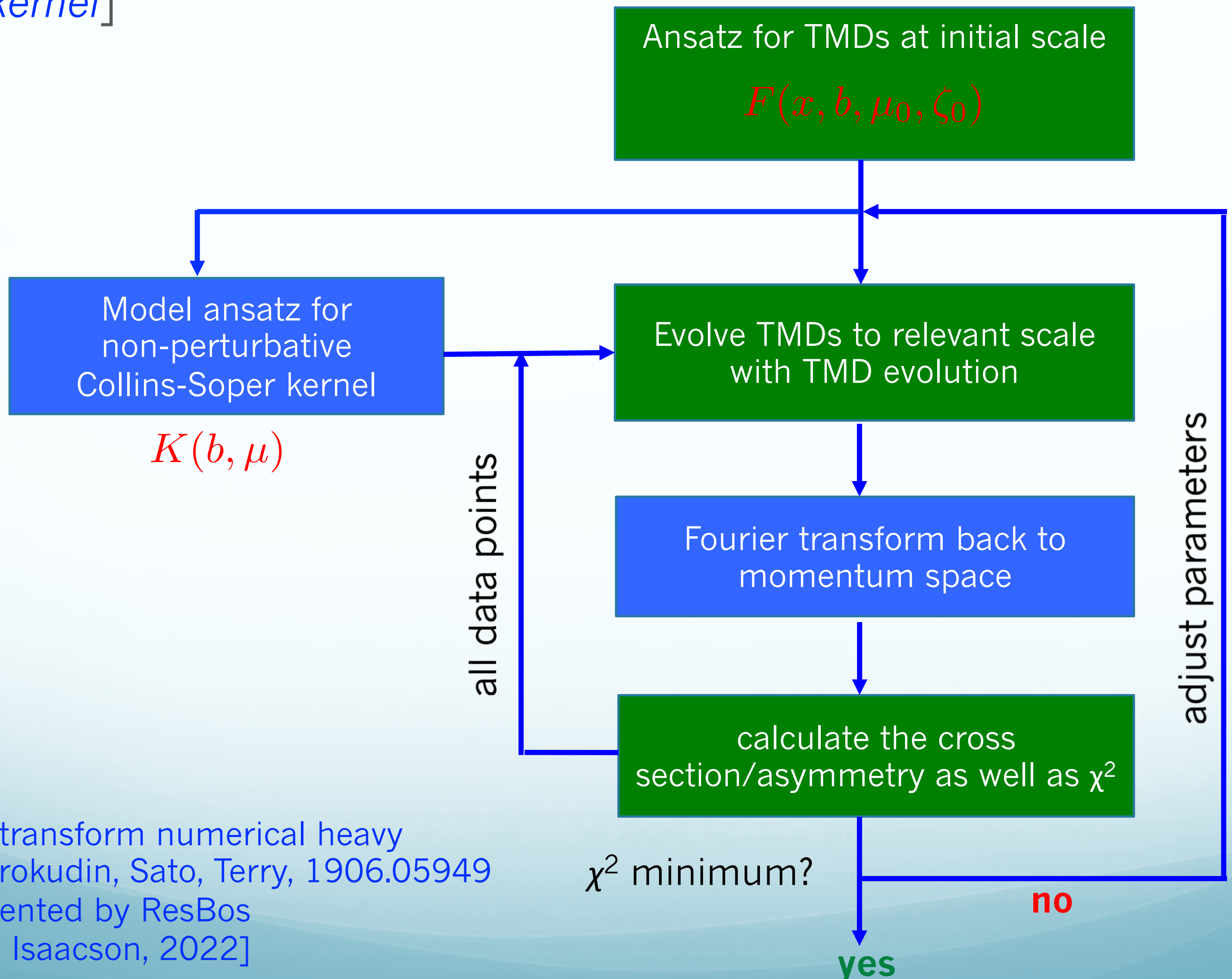
$$F(x, b) = f(x, b)\sqrt{S(b)}$$

$$= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)$$

mimic “parton model”

TMD global analysis

- Outline of a TMD global analysis [*lattice input on initial TMD and CS kernel*]

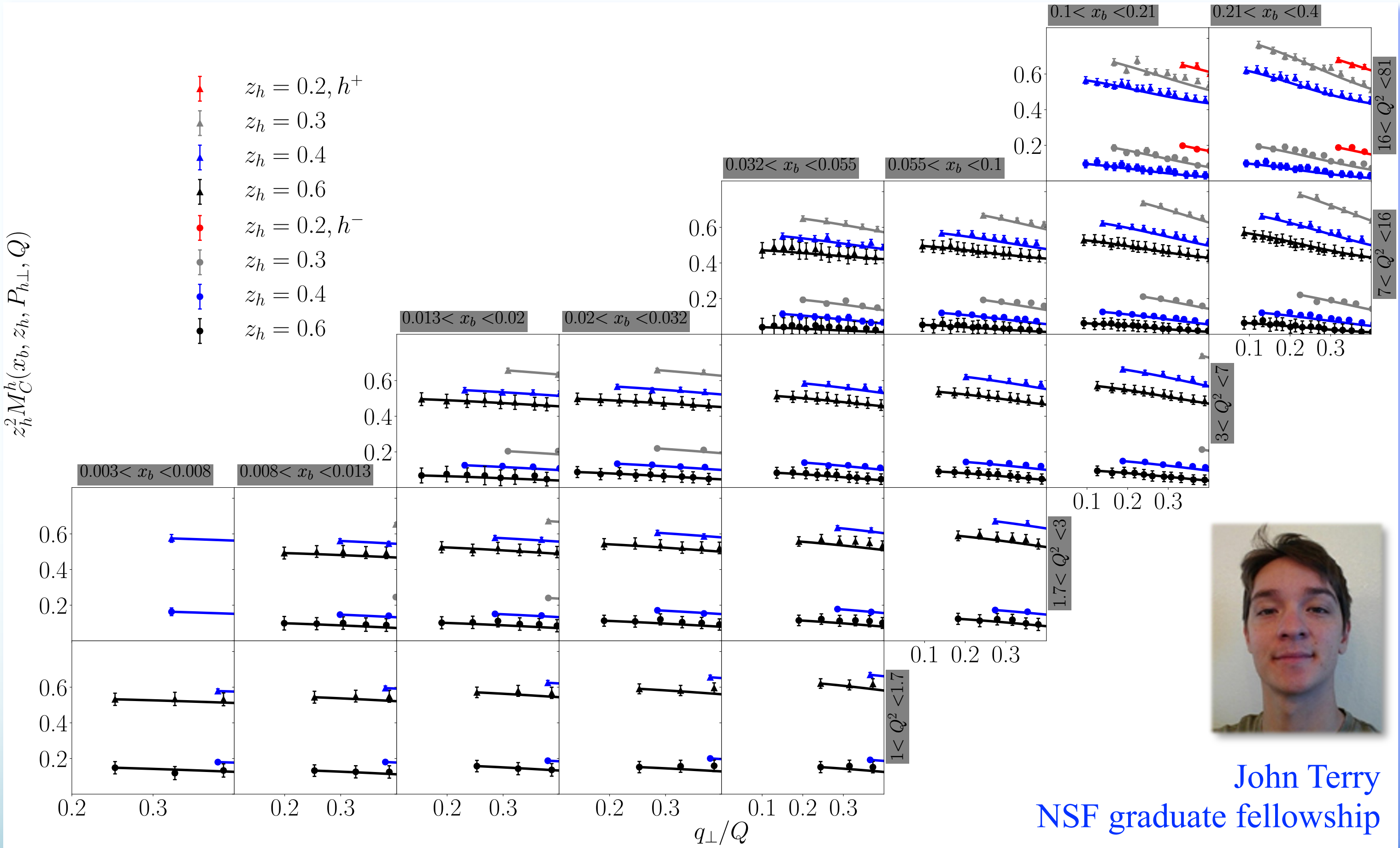


Fourier transform numerical heavy
Kang, Prokudin, Sato, Terry, 1906.05949
Implemented by ResBos
[Joshua Isaacson, 2022]

Unpolarized cross section

- Hadron distribution in SIDIS

Echevarria, **Kang**, Terry, 20

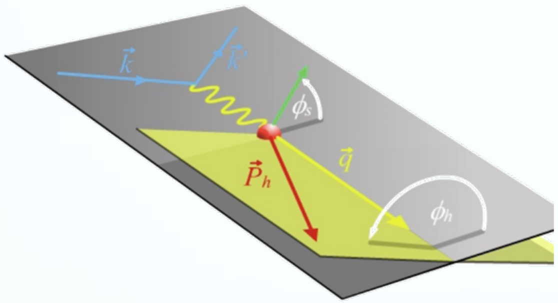


John Terry
NSF graduate fellowship

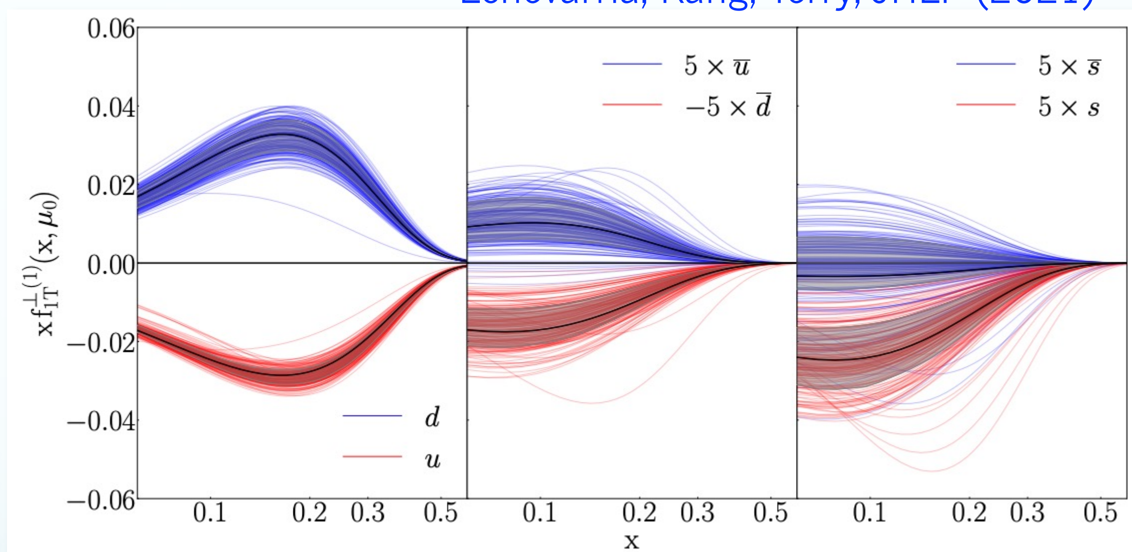
Progress from polarized TMDs

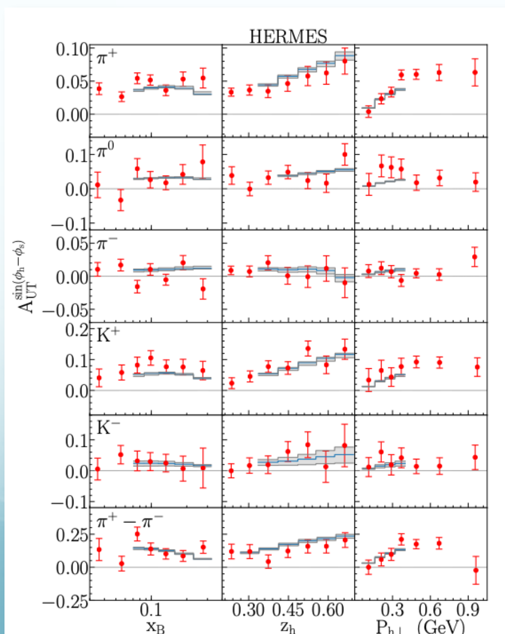
- Sivers function
  - Data: Jlab 12, HERMES, COMPASS, RHIC W boson

$$f_{q/P^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \equiv f_{q/P}(x,k_\perp) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp)\,\vec{S}\cdot(\hat{p}\times\mathbf{k}_\perp)$$



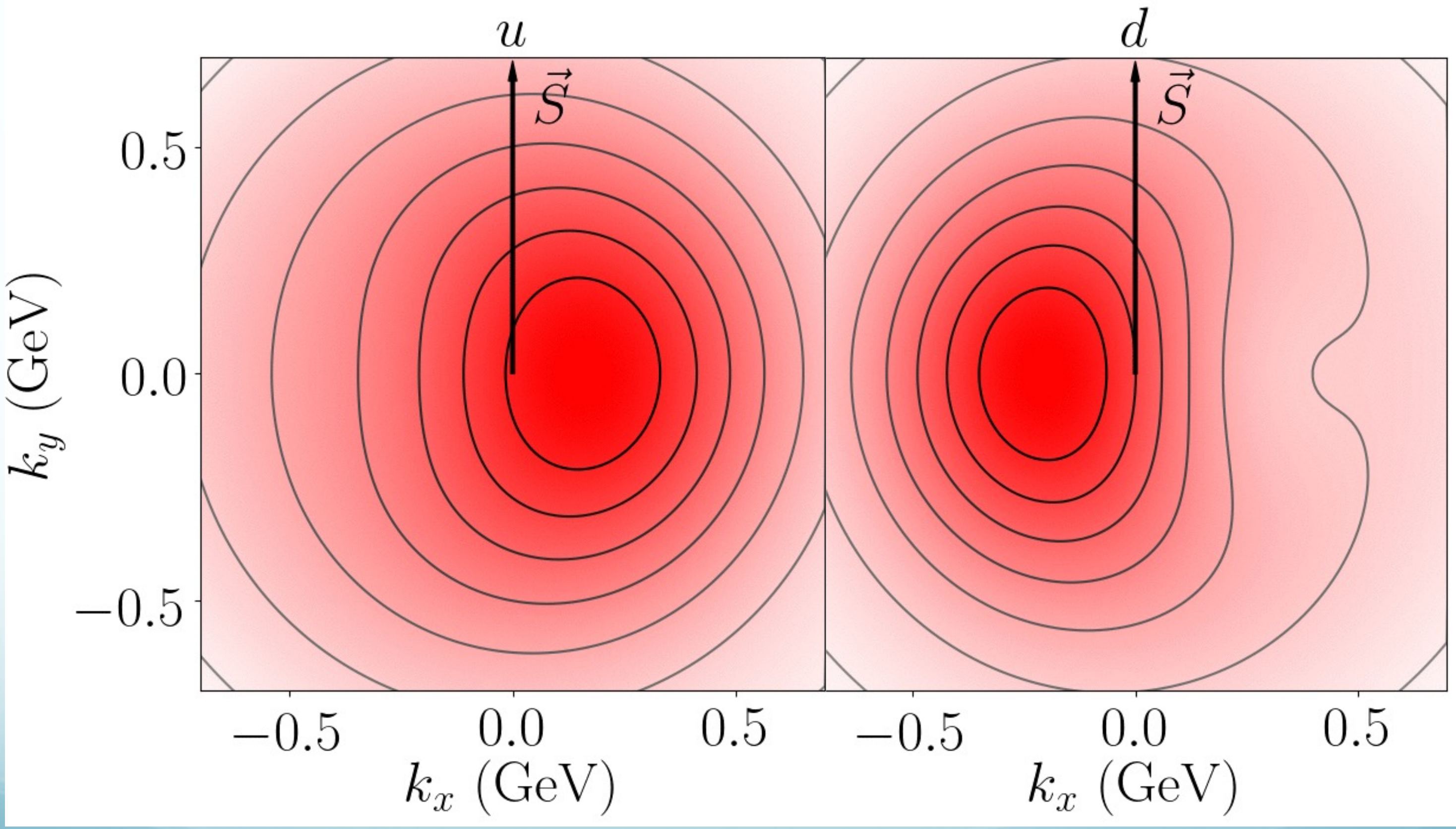
Echevarria, Kang, Terry, JHEP (2021)





Distorted distribution

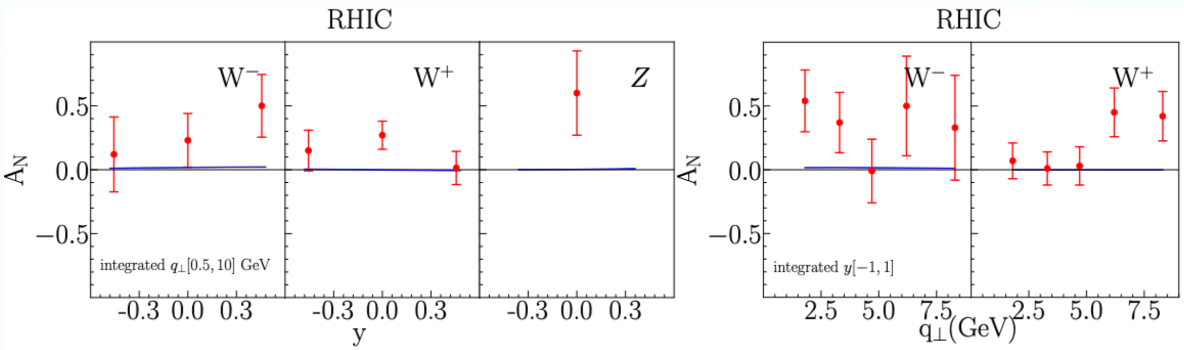
- Sivers correlation leads to a distortion in u/d quark distribution
  - Left or right shift



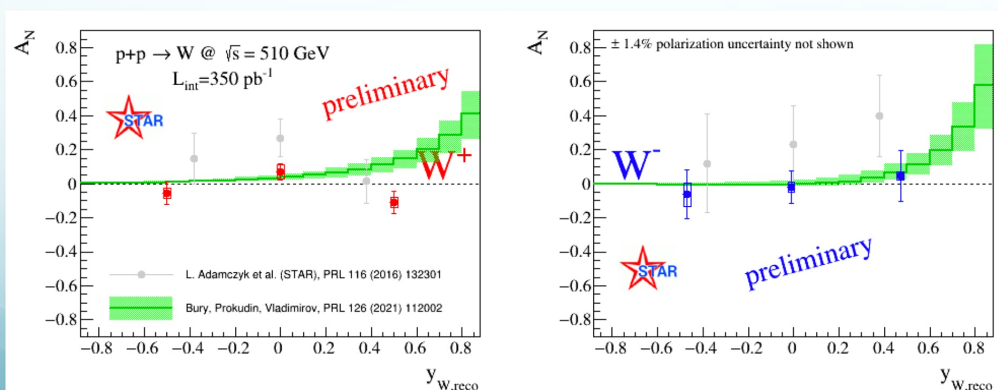
RHIC data: update

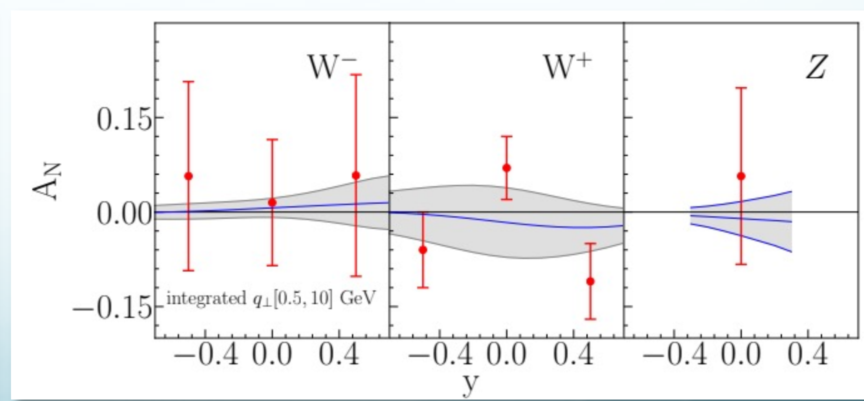
- Previously, some tension in fitting (2016) RHIC W/Z data (very large asymmetry), but consistent with 2021 preliminary data
  - Emphasizing the importance of the precision measurement

OLD data



NEW data





Bury, Vladimirov, Prokudin

Echevarria, Kang, Terry

Threshold logs

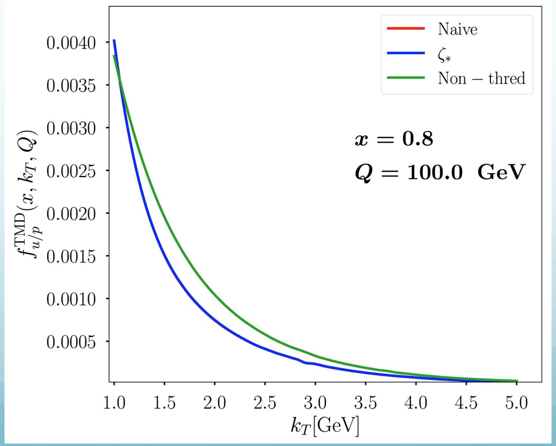
- Threshold logs ln(1-x) arises
  - Handle it in Mellin space [becomes ln(N)]

$$f_{i/h}^{\mathrm{TMD}}(x, b_T, \mu, \zeta) = \sum_j \int_x^1 \frac{\mathrm{d}y}{y} C_{ij}(z, b_T, \mu, \zeta) f_{j/h}(y/z, \mu)$$

$$\tilde{f}_{i/h}^{\mathrm{TMD}}(N, b_T, \mu, \zeta) \equiv \int_0^1 \mathrm{d}x\, x^{N-1} f_{i/h}^{\mathrm{TMD}}(x, b_T, \mu, \zeta).$$

  - Find out the usual rapidity log $\ln\zeta$, would become $\ln(\zeta/\bar{N}^2)$
    - Check up to three loops
  - Suggests us to replace the usual zeta by zeta/N^2 in the TMD evolution functions
    - This new evolution equation (the replacement) would lead to the joint resummation of both TMD logs and threshold logs

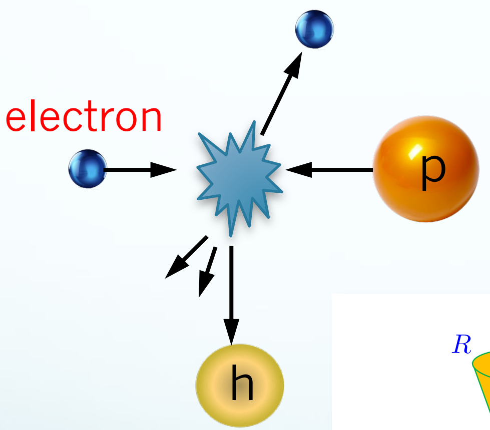
Kang, Samanta, Shao, Zeng, 2211.08341, JHEP 2023

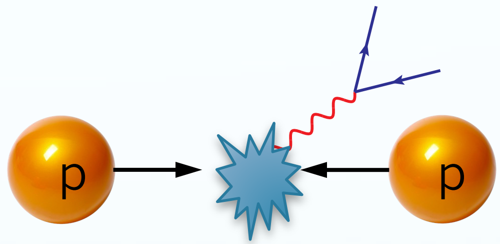


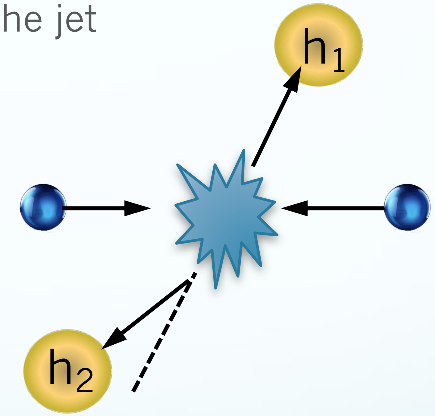
Many more processes

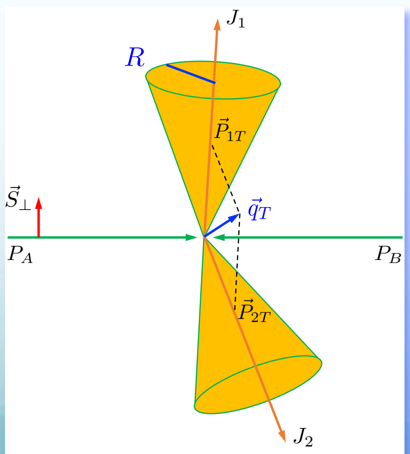
- Standard processes: SIDIS, Drell-Yan, e+e-
  - One could combine unpolarized + polarized scattering data
  - Unpolarized cross section + spin asymmetry data to determine the Collins-Soper evolution kernel, further compare with the lattice data

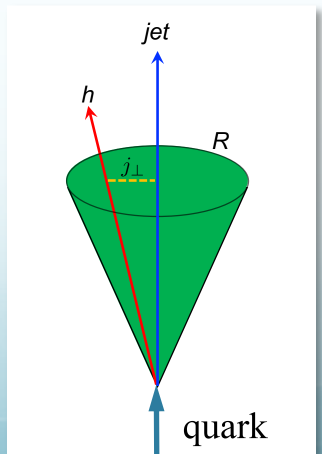
- In principle, one could further include jet production and hadron-in-jet
  - e.g. back-to-back dijet production for TMDPDFs
  - both unpolarized and polarized hadron distribution inside the jet





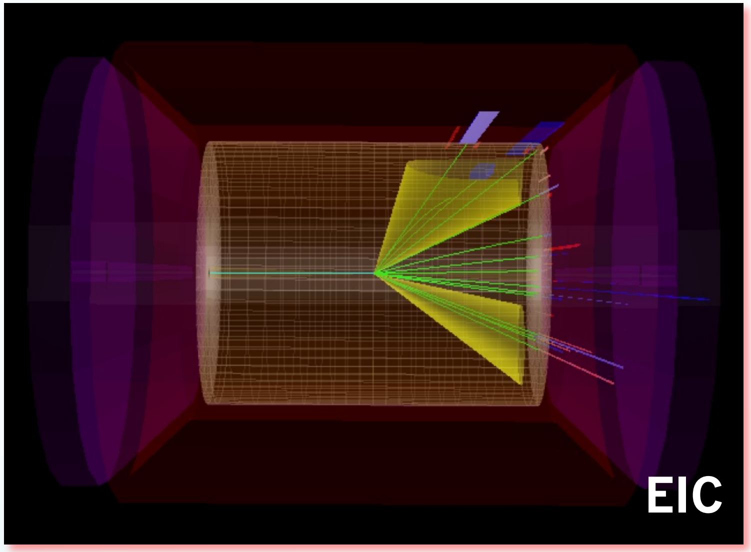


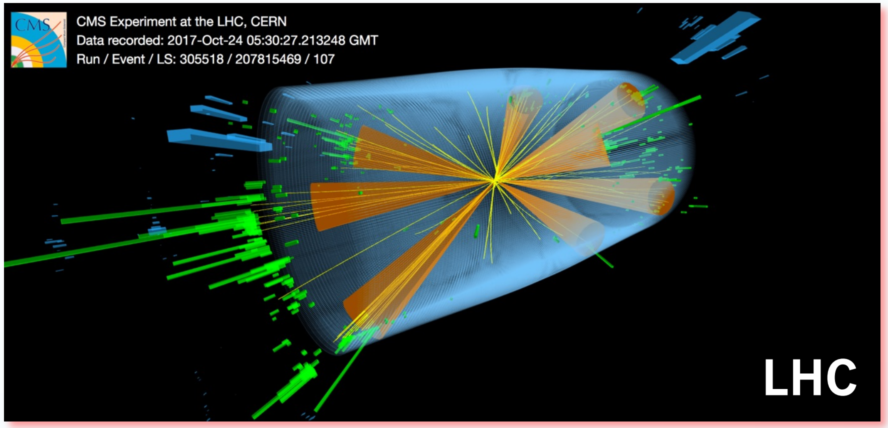




Jets are useful tools for TMD physics

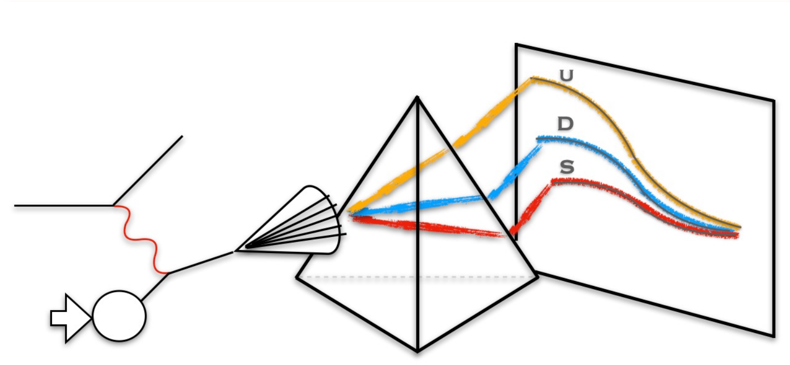
- Active study at the RHIC, LHC, and the future EIC



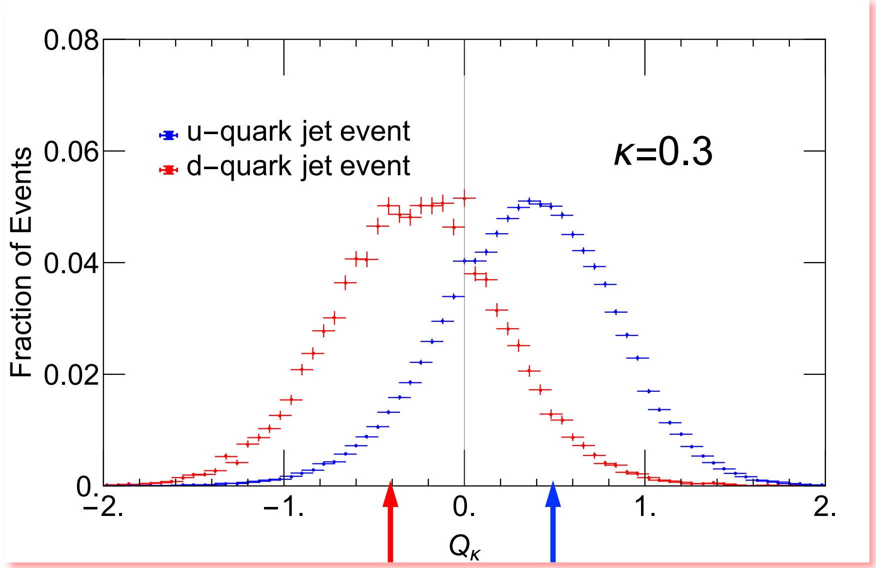


Jet charge at the EIC

- To get started, we decide to first look at jet production at the EIC
  - e+p collisions: simpler



- Jet charge distribution of u and d jets



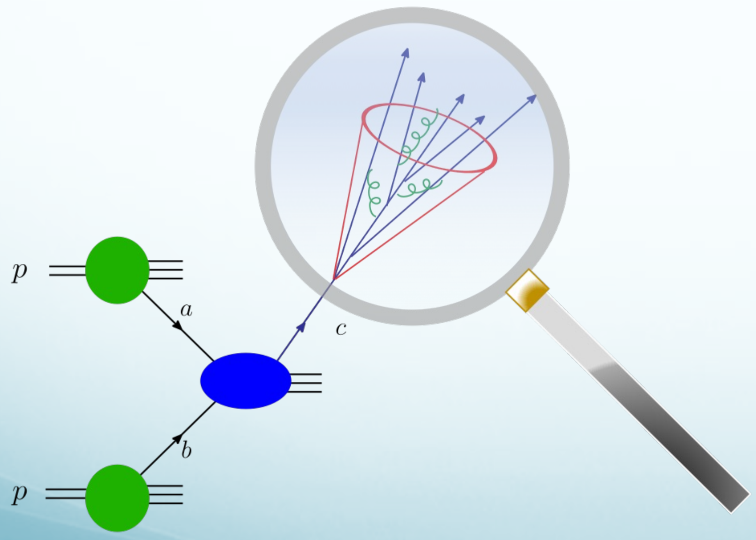
- Organize the cross section via jet charge bin

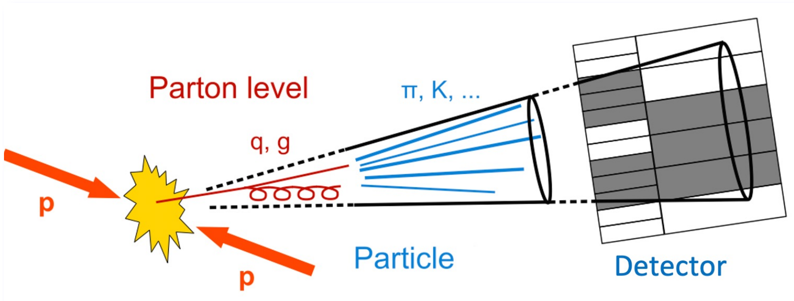
Kang, Liu, Mantry, Shao, 20

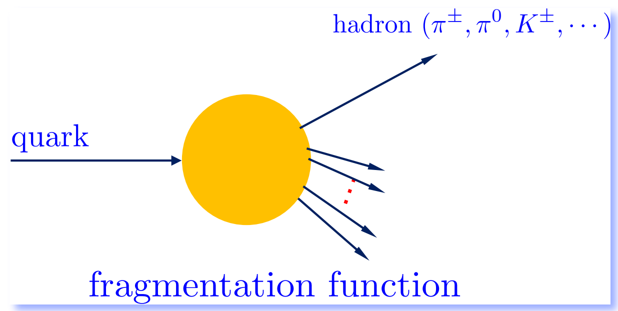
$$\frac{d^6\sigma^i_{UU}}{dy_e d^2p_T^e d^2q_T dQ_\kappa} = \frac{d^5\sigma^i_{UU}}{dy_e d^2p_T^e d^2q_T} \frac{\mathcal{G}_i(Q_\kappa, p_T R, \mu)}{\mathcal{J}_i(p_T R, \mu)}$$

Jet substructure

- The jet charge example suggests
  - Looking into the constituents inside the jet could give you novel insights [jet substructure], help us achieve what is not possible otherwise
- The inverse problem
  - 3D imaging of a proton: proton → quark/gluon distribution [parton distribution]
  - Hadronization: quark/gluon → hadron [fragmentation function]



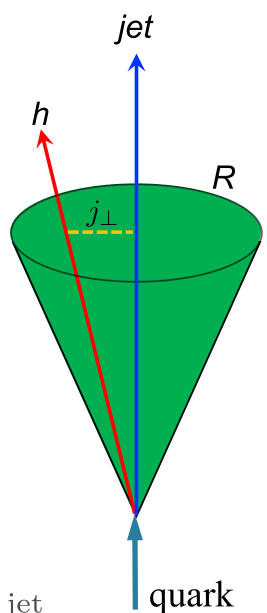




❑ Fragmentation functions would help us understand the elusive hadronization process

Hadron distribution inside the jet

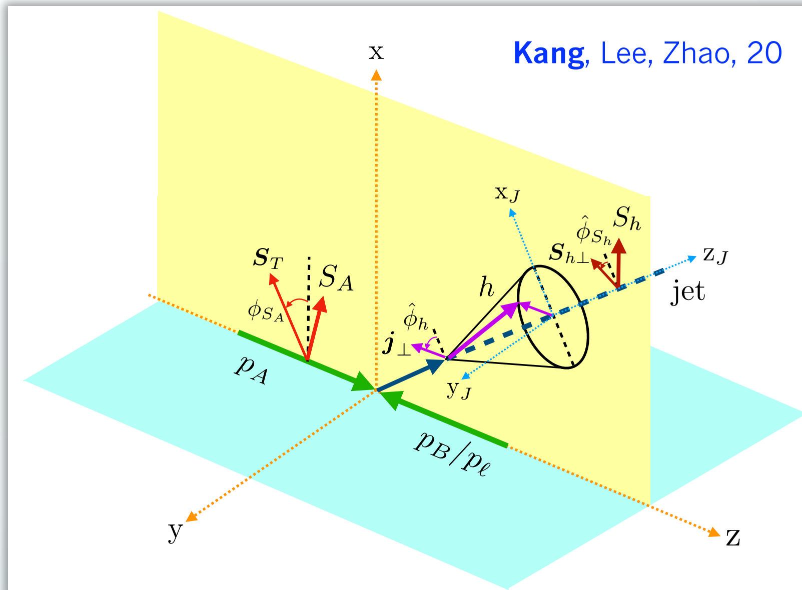
- A theoretical framework has recently been developed
  - Referred to as *polarized jet fragmentation function*
  - Imagine both the initiating quark/gluon and the hadron have general polarization, it will provide the most information on the hadronization process



$z_h = p_T^{\rm h}/p_T^{\rm jet}$

$j_\perp$: hadron transverse momentum with respect to the jet

Kang, Lee, Zhao, 20



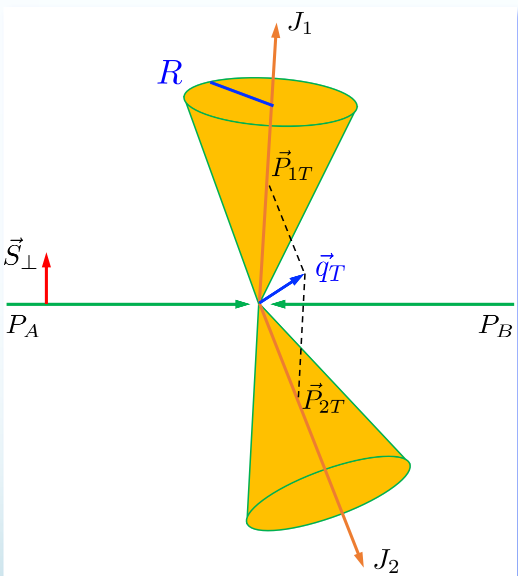
Fanyi Zhao
Bhaumik Institute
Nina Byers graduate fellowship

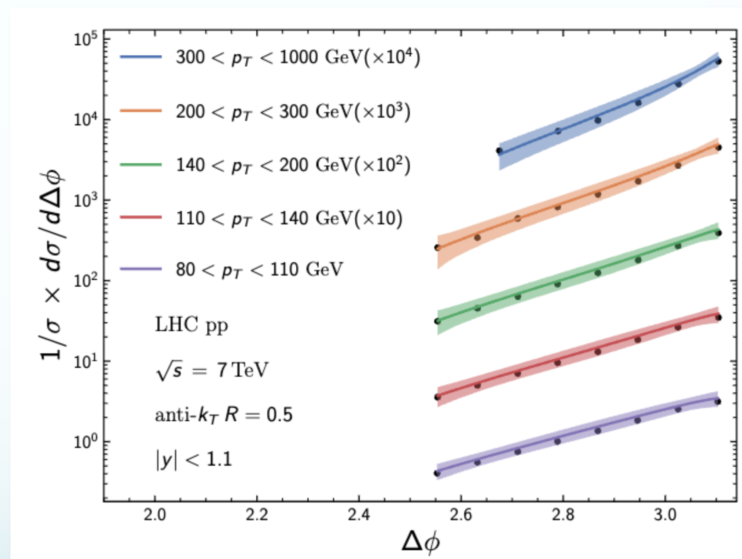
Dijet production: cross section

- Take into account soft gluon radiation, and thus include TMD evolution

- It seems to be working well with experimental data
  - TMD factorization breaking is small?!

Kang, Lee, Shao, Terry, JHEP 2021, Gao, Kang, Shao, Terry, Zhang, JHEP 2023





$$\sigma \propto f_a(x_a, k_{aT}) \otimes f_b(x_b, k_{bT})$$
$$\otimes \mathrm{Tr}[\boldsymbol{S}_{ab}(q_T)\boldsymbol{H}_{ab\to cd}(P_T)] \otimes S_c^{\mathrm{cs}}(q_T R) S_d^{\mathrm{cs}}(q_T R) J_c(P_T R) J_d(P_T R)$$

What about p+A collisions

- TMD PDFs get modified in nuclear matter
  - Modified the non-perturbative collinear PDFs [nuclear PDFs]
  - Modified the non-perturbative Sudakov facor [S_{NP}]

$$f_q(x,b,Q,Q^2) = C(x,b,\mu_{b_*}) \otimes f_q(x,\mu_{b_*}) \exp\left[\int_{\mu_{b_*}}^{Q} \frac{d\mu'}{\mu'} \gamma_\mu^q \left[\alpha_s(\mu'), Q^2/\mu'^2\right]\right]$$
$$\times \exp\left[-S_{NP}(b,Q,Q_0)\right]$$

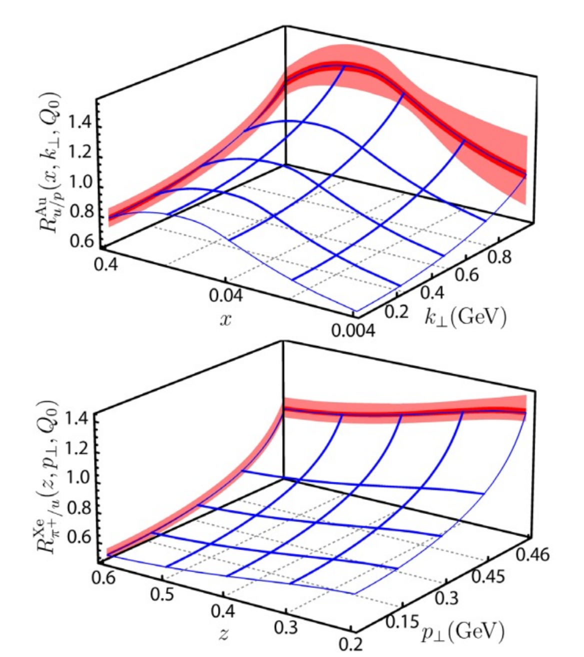
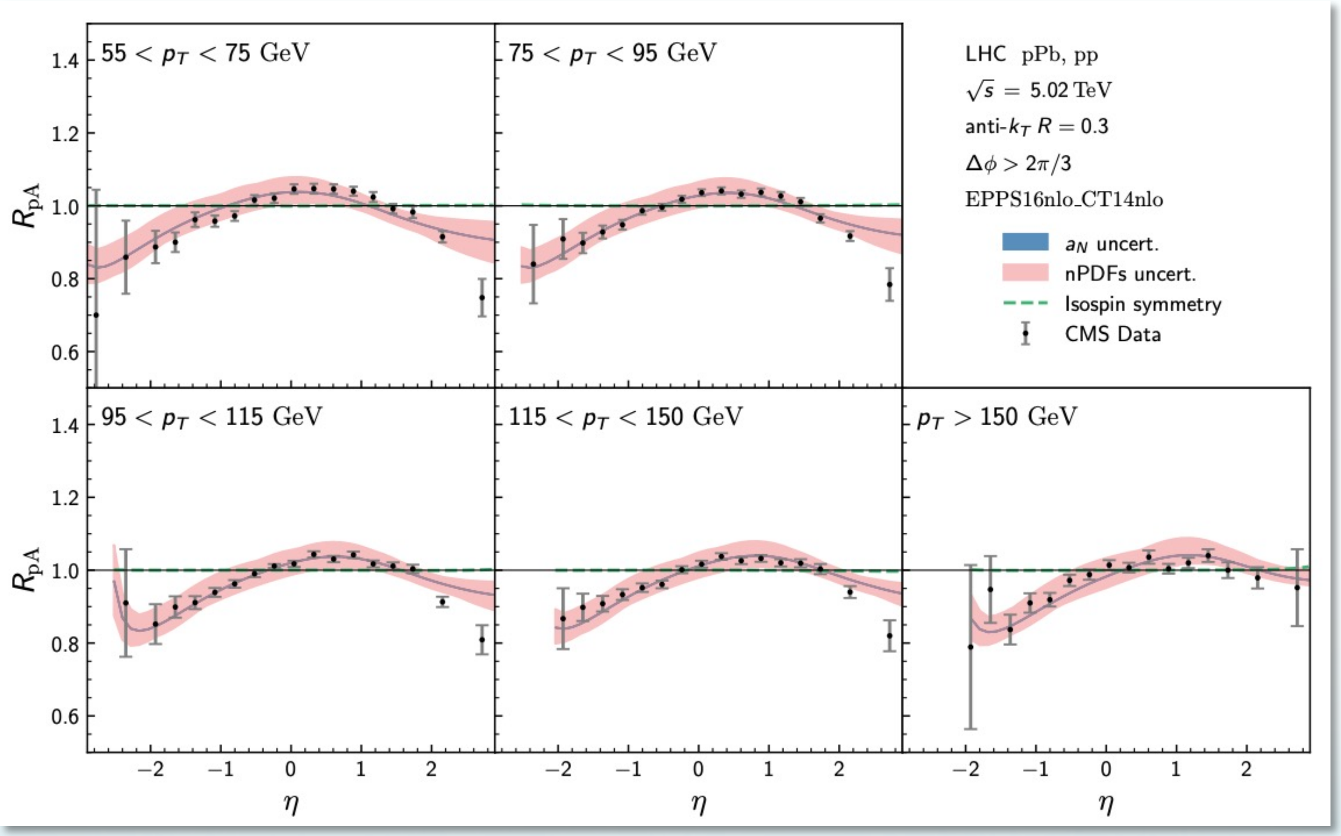


FIG. 3. The extracted nuclear ratio for the TMDPDF (top) and the TMDFF (bottom) at $Q_0 = \sqrt{2.4}$ GeV. The light and dark bands are the same as in Fig. 2.

Alrashed, Anderle, Kang, Terry, Xing, PRL 2022
Alrashed, Kang, Terry, Xing, Zhang, include Jlab data

Dijet production in p+A collisions

- The modification describes the LHC data well

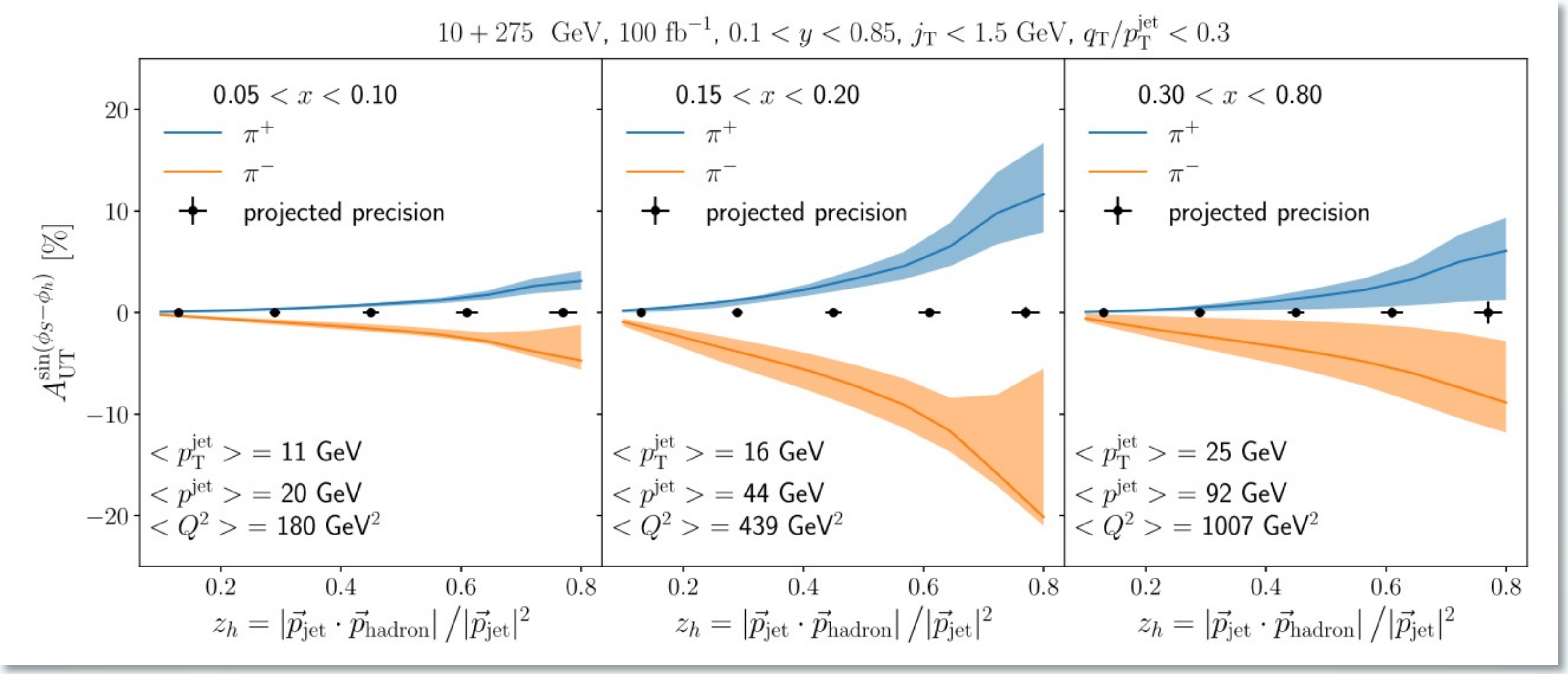


Gao, Kang, Shao, Terry, Zhang, JHEP 2023

Joint theory and exp studies

- Study QCD dynamics via jets at the EIC

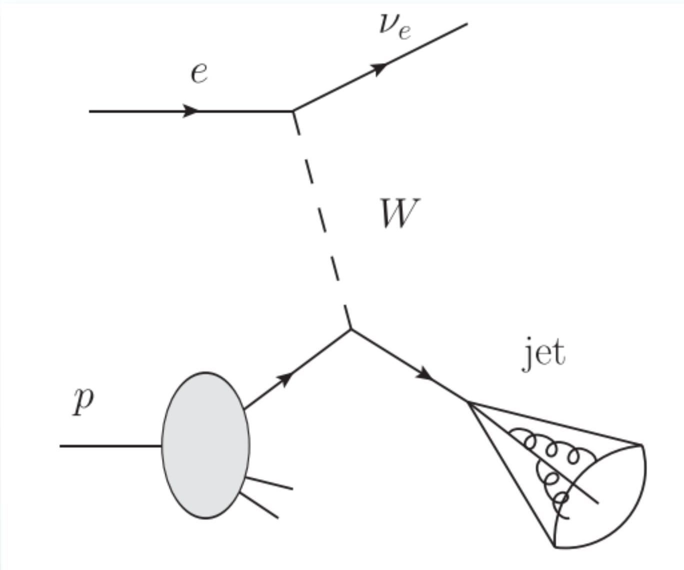
Arratia, **Kang**, Prokudin, Ringer, 20

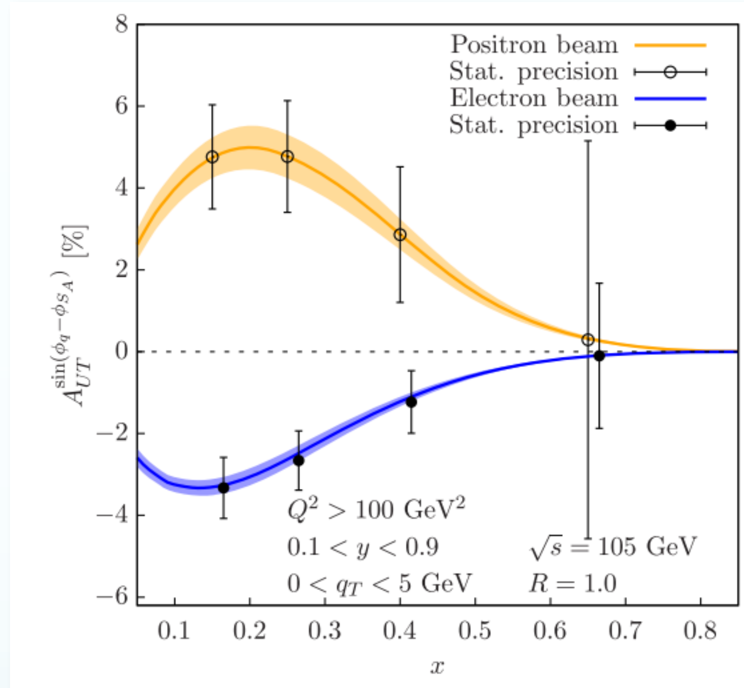


Neutrio-tagged jets at EIC

- Neutrino-tagged jets at the EIC

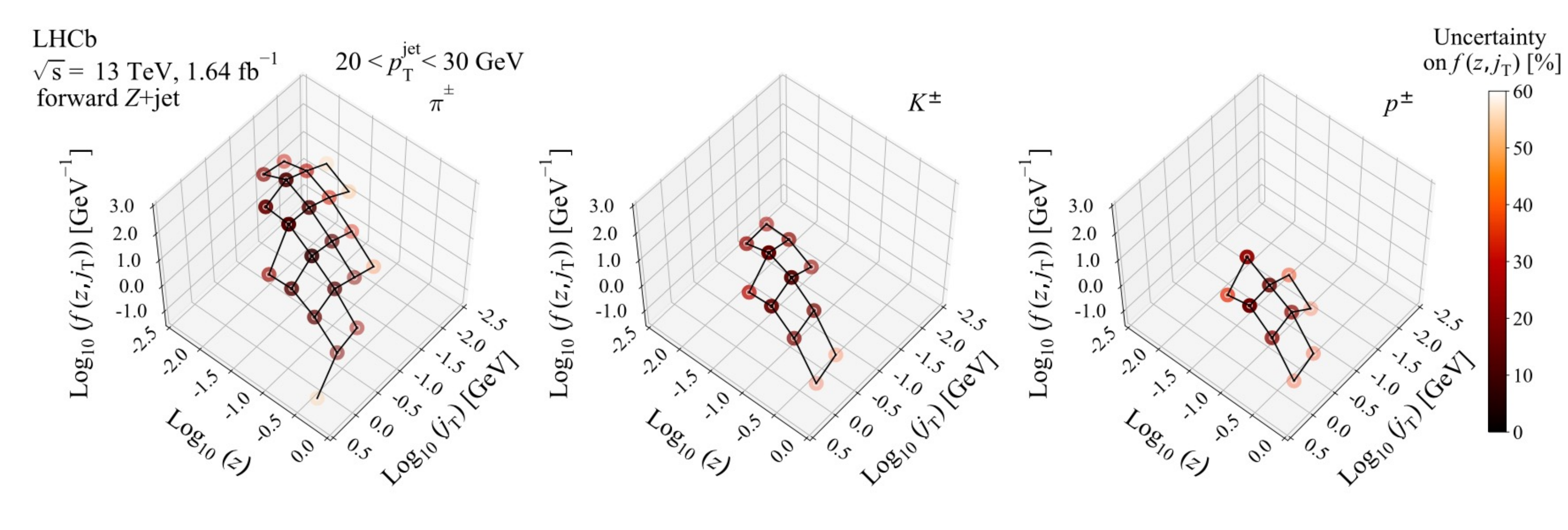
Arratia, **Kang**, Paul, Prokudin, Ringer, Zhao, 2023





Jet fragmentation function at LHC

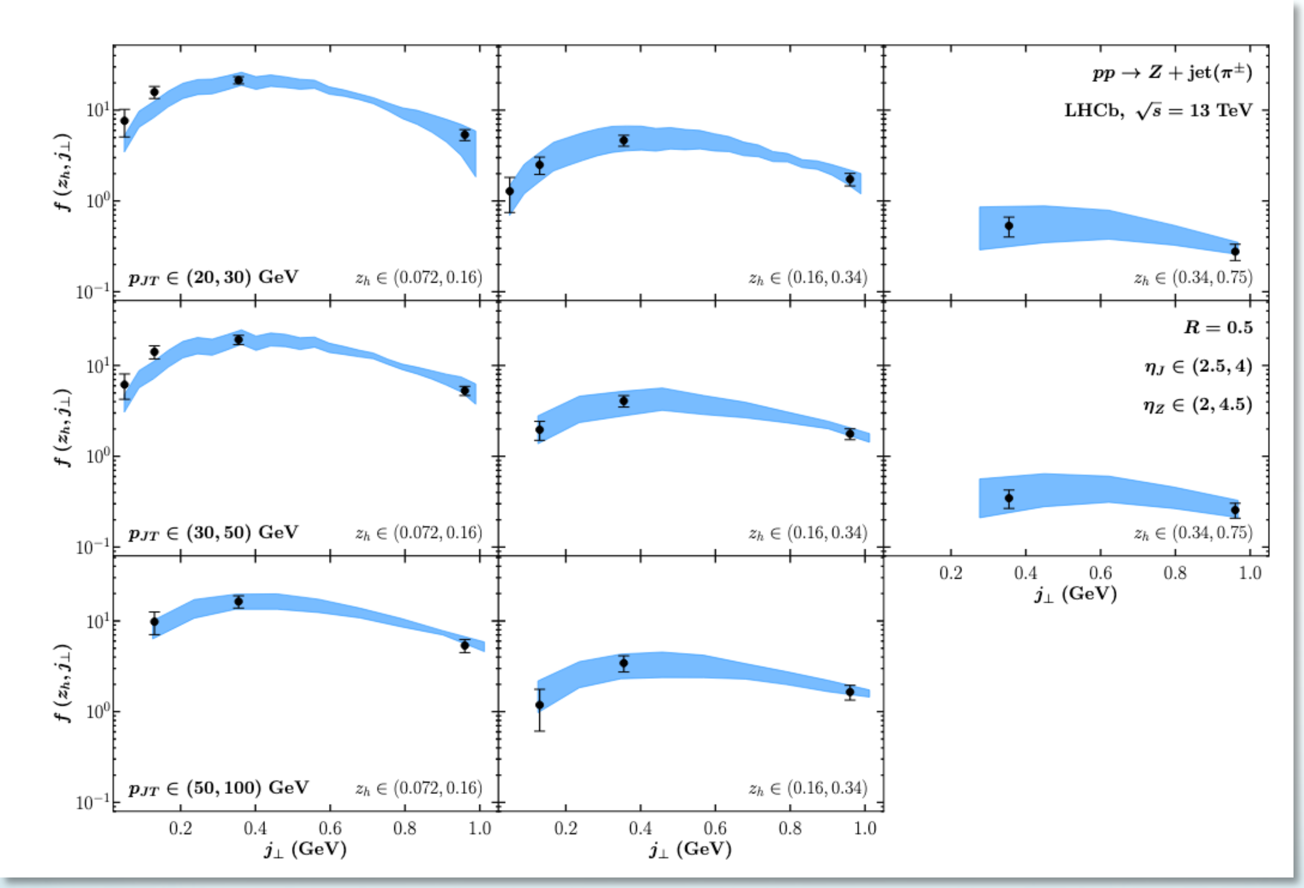
- LHCb measurement Z-tagged jet production in pp collisions



LHCb, 2208.11691

Comparison with Z-tagged jets

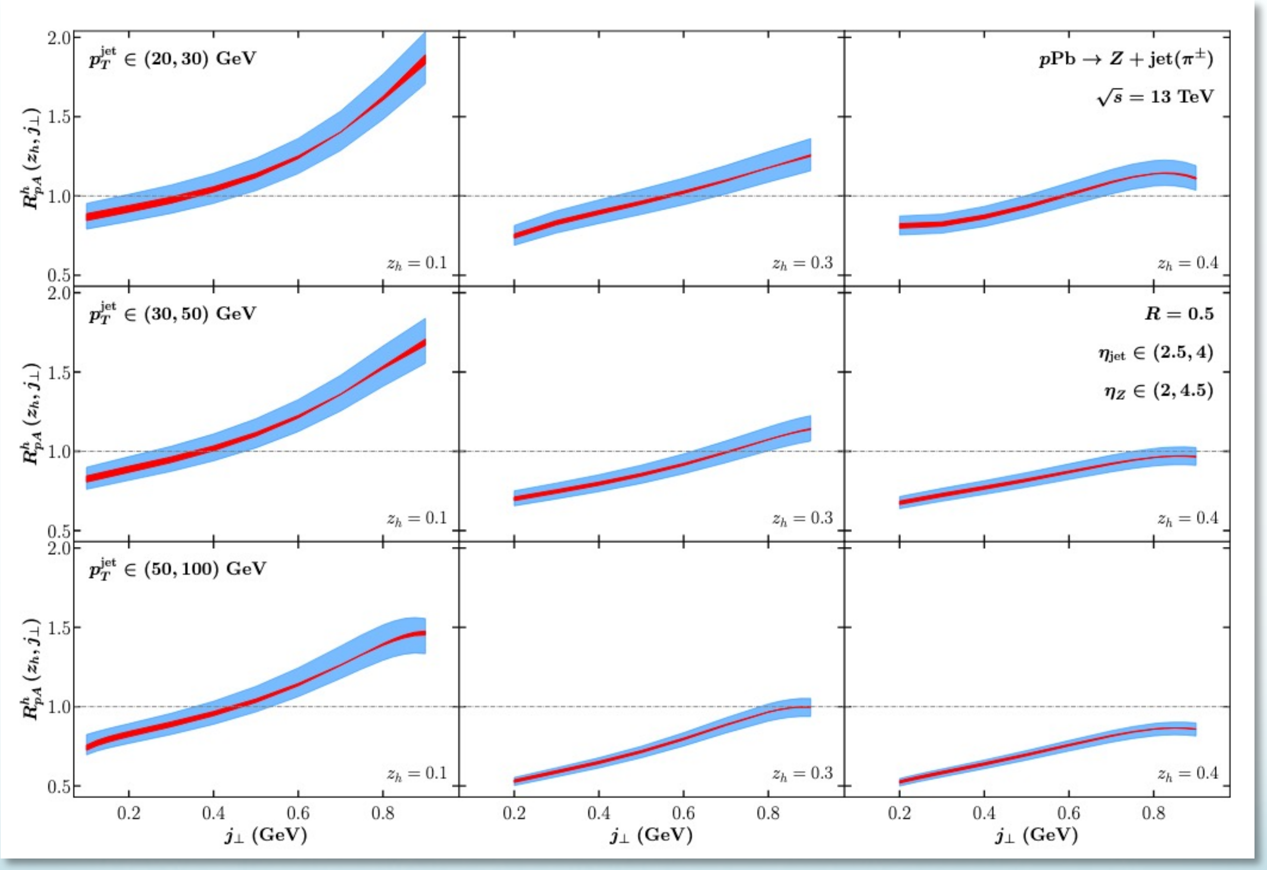
- Hadrons inside the jets



Kang, Xing, Zhao, Zhou, to appear

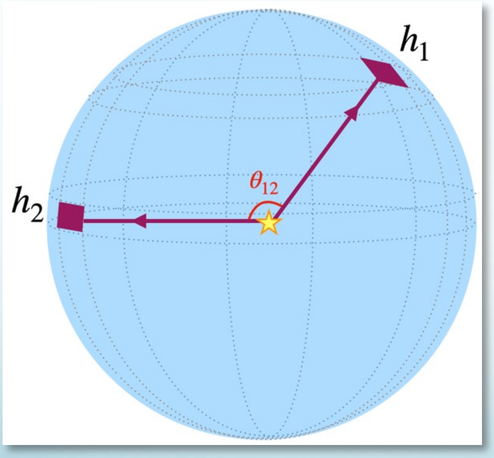
Nuclear modification of jet fragmentation

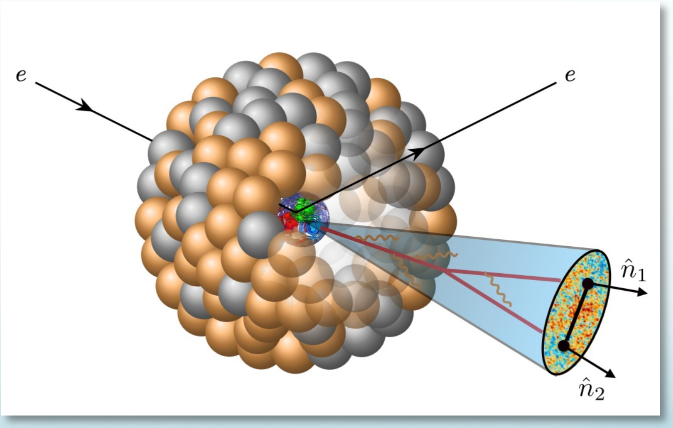
- Distribution of hadron in jets: back-to-back Z+jet production in p+A collisions



Energy Energy Correlator

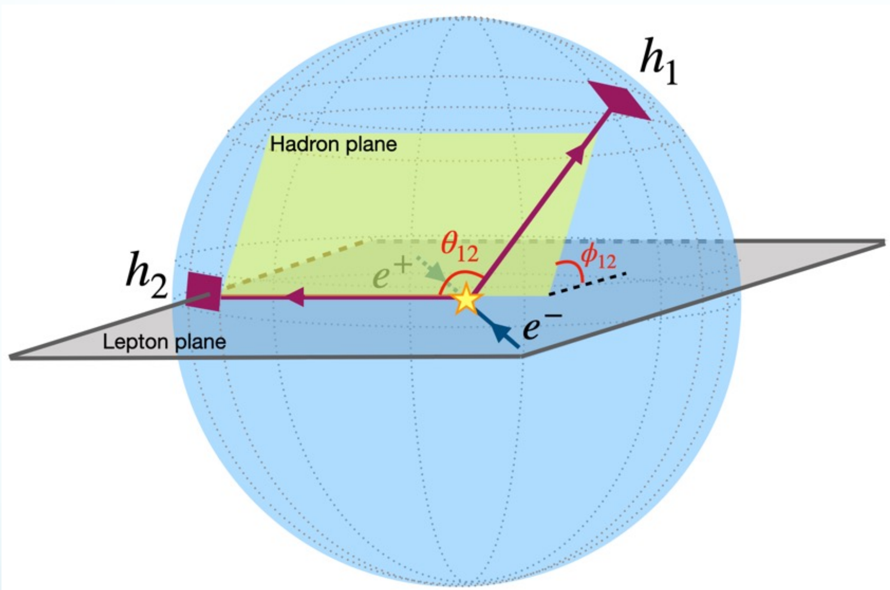
- Two types
  - Global EEC
    - One of the earliest infrared safe event shape observables
    - Measure energy correlation as a function of the opening angle between pairs of particles
  - Local EEC
    - In-jet EEC: measure energy correlations for particles inside the jet





Azimuthal angle dependence of the EEC

- Azimuthal angle dependence of EEC would allow us to probe TMD structure
  - Azimuthal dependence is in the original paper, but forgotten afterwards



VOLUME 41, NUMBER 23 PHYSICAL REVIEW LETTERS 4 DECEMBER 1978

Energy Correlations in Electron-Positron Annihilation: Testing Quantum Chromodynamics

C. Louis Basham, Lowell S. Brown, Stephen D. Ellis, and Sherwin T. Love
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 21 August 1978)

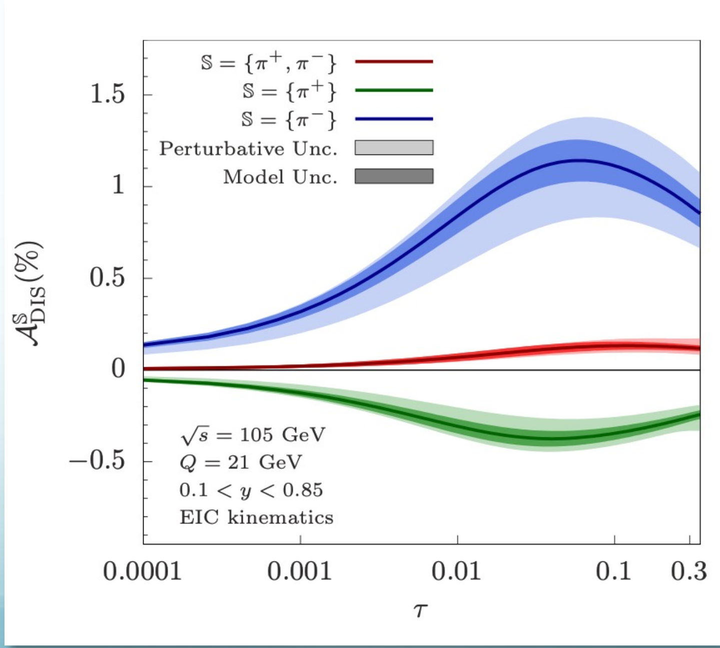
$$\frac{d^2\Sigma}{d\Omega\, d\Omega'} = \frac{\alpha^2}{4W^2}\sum_f 3Q_f^{\,2}\,\frac{\bar{g}_W^{\,2}}{3\pi^2}\,\frac{1}{32\pi}\,\frac{1}{1-\zeta}\left\{\left[\left(\frac{36}{\zeta^5}-\frac{96}{\zeta^4}+\frac{72}{\zeta^3}-\frac{16}{\zeta^2}\right)\ln(1-\zeta)+\frac{36}{\zeta^4}-\frac{78}{\zeta^3}+\frac{36}{\zeta^2}\right](1+\cos^2\theta)\right.$$
$$+4\zeta(1-\zeta)\left[\left(\frac{6}{\zeta^5}-\frac{8}{\zeta^4}\right)\ln(1-\zeta)+\frac{6}{\zeta^4}-\frac{5}{\zeta^3}-\frac{2}{\zeta^2}\right]\left[\cos^2\varphi-\cos^2\theta\,(1+\cos^2\varphi)\right]$$
$$\left.+2[\zeta(1-\zeta)]^{1/2}\left[\left(-\frac{36}{\zeta^5}+\frac{72}{\zeta^4}-\frac{40}{\zeta^3}\right)\ln(1-\zeta)-\frac{36}{\zeta^4}+\frac{54}{\zeta^3}-\frac{16}{\zeta^2}-\frac{8}{\zeta}\right]\cos\theta\sin\theta\cos\varphi\right\}. \quad (5)$$

Kang, Lee, Shao, Zhao, 2310.15159

Azimuthal angle dependence of the EEC

- EEC in DIS now can probe all unpolarized and polarized TMDs

$$\begin{aligned}
\mathrm{EEC}_{\mathrm{DIS}}(\tau,\phi) = \frac{d\Sigma_{\mathrm{DIS}}}{dx_B dy d\tau d\phi} &= \sigma_0 \int d^2\boldsymbol{q}_T \delta(\tau - \frac{\boldsymbol{q}_T^2}{Q^2})\delta(\phi-\phi_h)\int \frac{db\, b}{2\pi}\Big\{\mathcal{F}_{UU} \\
&+ \cos(2\phi_h)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UU}^{\cos(2\phi_h)} + S_\parallel \sin(2\phi_h)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UL}^{\sin(2\phi_h)} \\
&+ |\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_s)\mathcal{F}_{UT}^{\sin(\phi_h-\phi_s)} + \sin(\phi_h+\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(\phi_h+\phi_s)} \\
&\quad + \sin(3\phi_h-\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(3\phi_h-\phi_s)}\Big] \\
&+ \lambda_e\Big[S_\parallel \frac{y(2-y)}{1+(1-y)^2}\mathcal{F}_{LL} + |\boldsymbol{S}_\perp|\cos(\phi_h-\phi_s)\mathcal{F}_{LT}^{\cos(\phi_h-\phi_s)}\Big]\Big\}, \qquad (2.21)
\end{aligned}$$

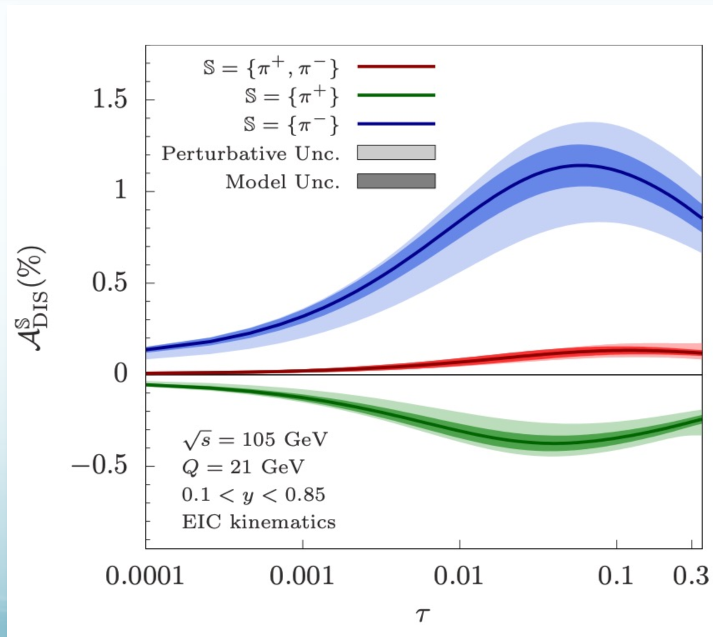


Kang, Lee, Shao, Zhao, 2310.15159

Azimuthal angle dependence of the EEC

- EEC in DIS now can probe all unpolarized and polarized TMDs

$$\begin{aligned}
\mathrm{EEC}_{\mathrm{DIS}}(\tau,\phi) &= \frac{d\Sigma_{\mathrm{DIS}}}{dx_B\,dy\,d\tau\,d\phi} = \sigma_0 \int d^2\boldsymbol{q}_T\,\delta\Big(\tau - \frac{\boldsymbol{q}_T^2}{Q^2}\Big)\delta(\phi-\phi_h)\int \frac{db\,b}{2\pi}\Big\{\mathcal{F}_{UU} \\
&+ \cos(2\phi_h)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UU}^{\cos(2\phi_h)} + S_\parallel \sin(2\phi_h)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UL}^{\sin(2\phi_h)} \\
&+ |\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_s)\mathcal{F}_{UT}^{\sin(\phi_h-\phi_s)} + \sin(\phi_h+\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(\phi_h+\phi_s)} \\
&\quad + \sin(3\phi_h-\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(3\phi_h-\phi_s)}\Big] \\
&+ \lambda_e\Big[S_\parallel\frac{y(2-y)}{1+(1-y)^2}\mathcal{F}_{LL} + |\boldsymbol{S}_\perp|\cos(\phi_h-\phi_s)\mathcal{F}_{LT}^{\cos(\phi_h-\phi_s)}\Big]\Big\}, \qquad (2.21)
\end{aligned}$$



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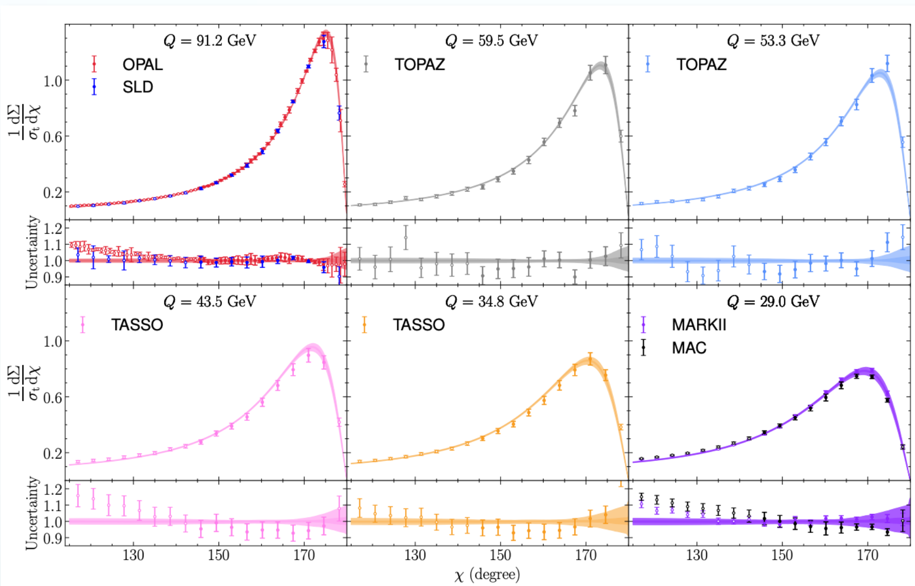
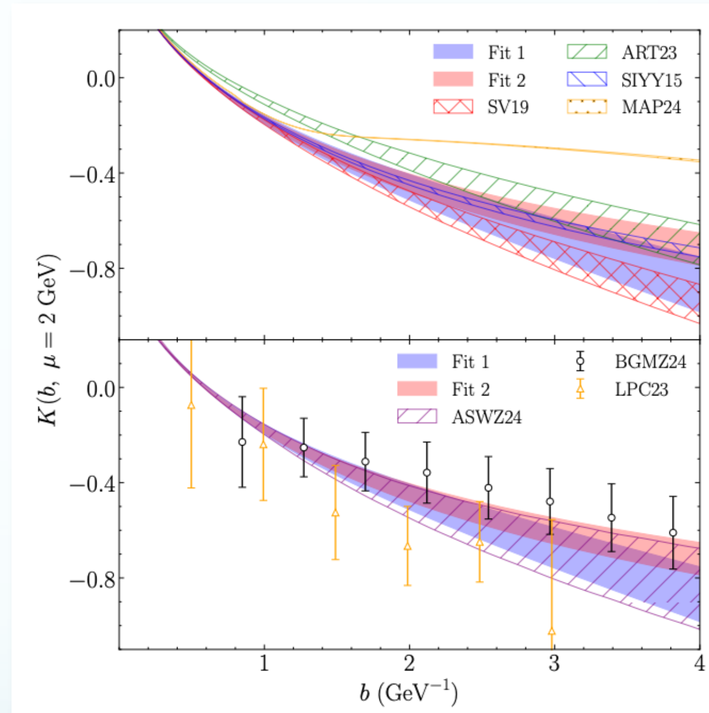
EEC in back-to-back region

- EEC in back-to-back regime

Kang, Penttala, Zhang, 2024



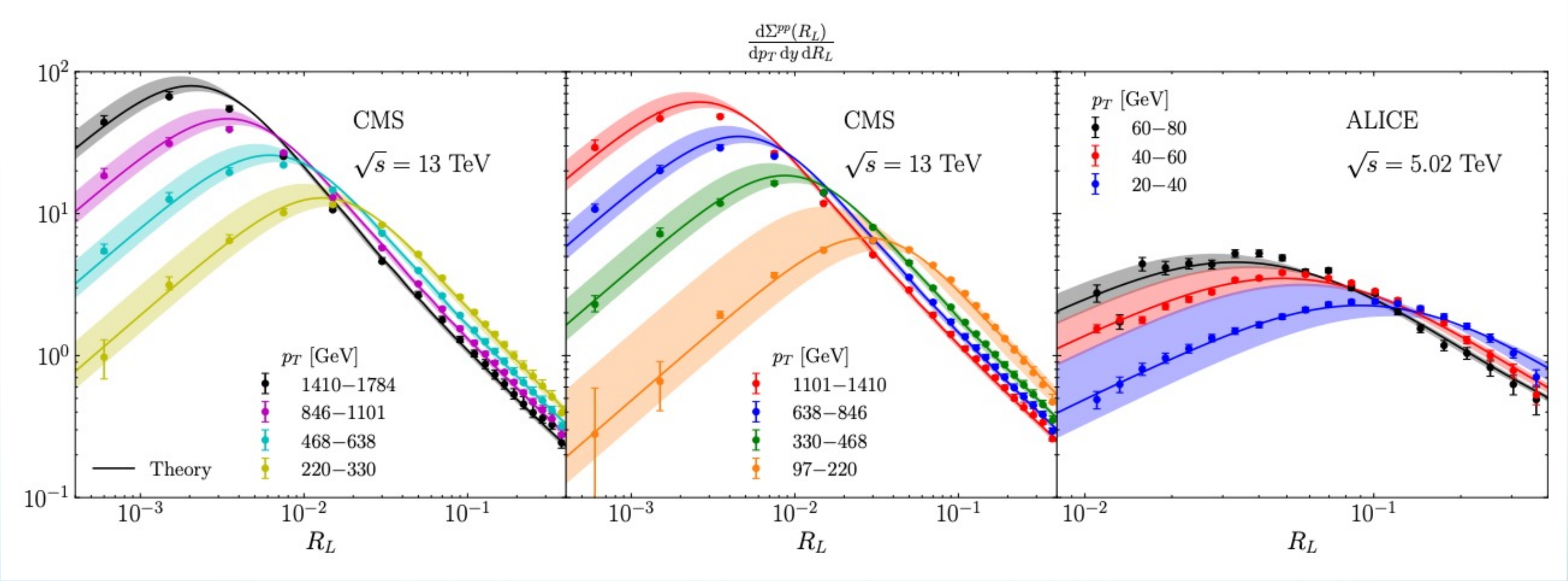


EEC in the collinear regime

- EEC in collinear regime

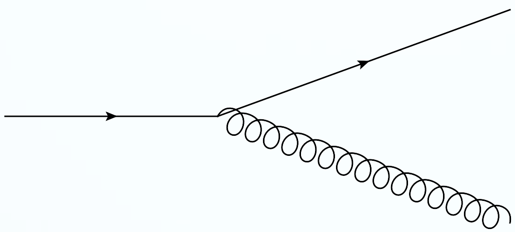
Barata, Kang, Lopez, Penttala, 2024

$$\frac{d\Sigma^{pp}}{dp_T\,dy\,dR_L} = R_L p_T^2 \int_0^\infty db\, b\, J_0(R_L p_T b)\, j_{\rm np}(b)\, \widetilde{\Sigma}(b)$$

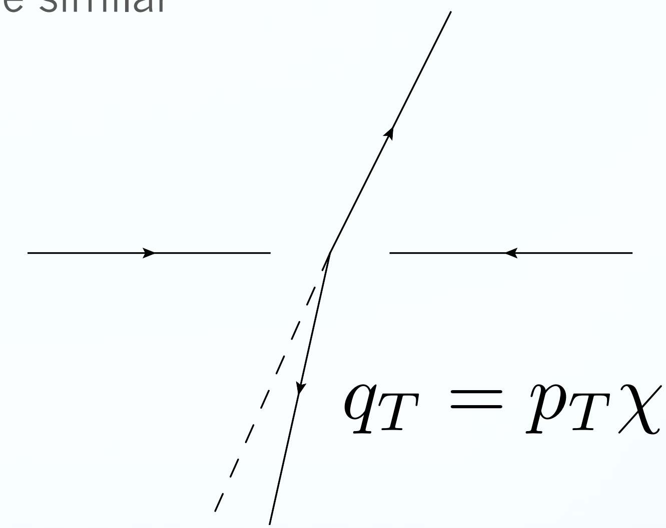


EEC in the collinear and back-to-back regime

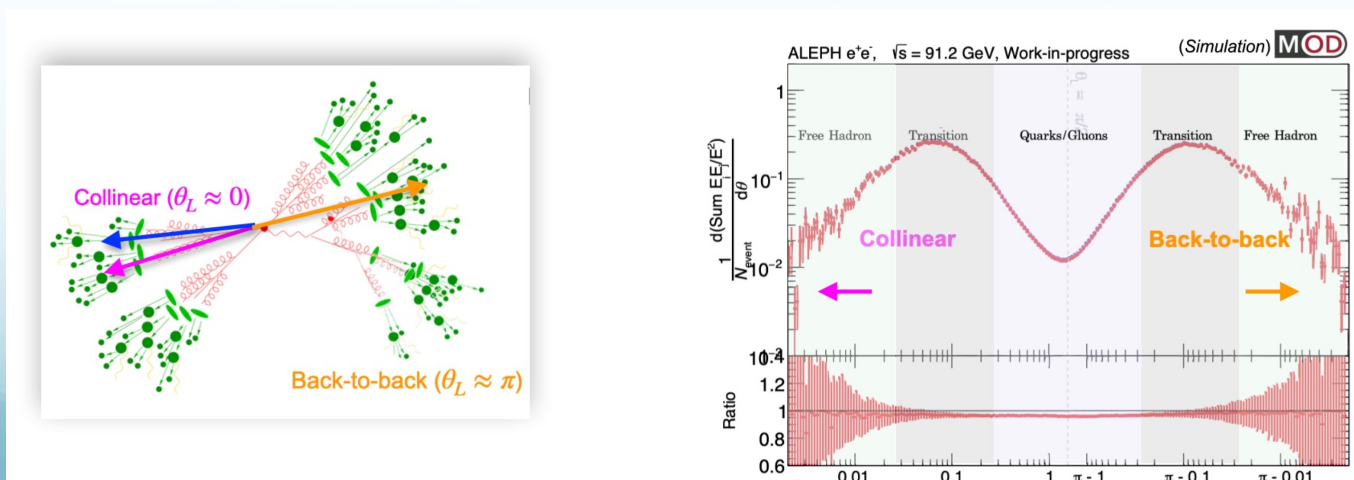
- Related but not the same
  - EEC integrated over z and sum over all hadrons
  - Their non-perturbative contribution can be similar



$$k_T = z(1-z)p_T R_L$$

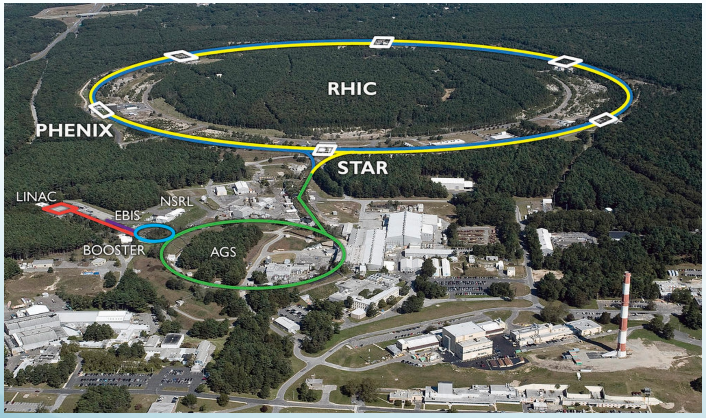


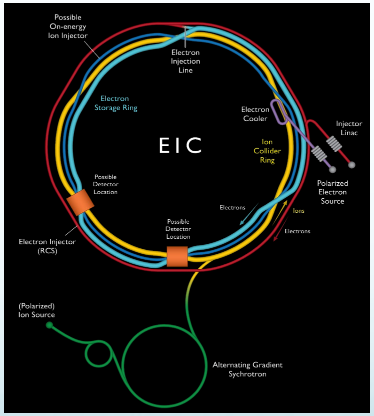
$$q_T = p_T \chi$$



Summary

- We had significantly enjoyed being part of the California EIC consortium
- We have enjoyed working on joint experiment and theory EIC work
- We look forward to the continued collaborations in the coming years





Thank you!