université PARIS-SACLAY

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Co-funded by the European Union

Energy Correlators:

A New Lens on Nuclear Structure

IJCLab seminar

Jani Penttala

IJCLab, November 4 2026

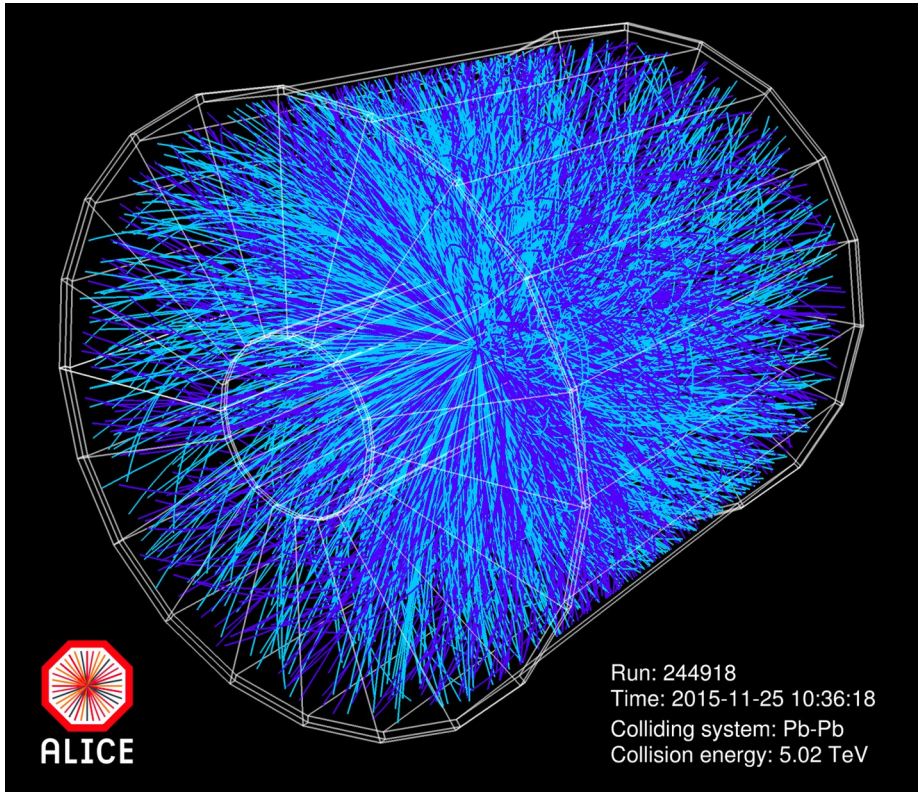
Event-shape observables

- Particle colliders:

  Break nucleons into pieces to study their internal structure

  - Can be inferred from the produced particles

- But: understanding the collision process can be very difficult
  - Huge number of particles produced at every collision
  - Additional contributions from nonperturbative physics
- **Event-shape observables**
  - Instead of individual particles, focus on the geometry of the final state
  - Less sensitive to nonperturbative contributions



ALICE collaboration

Energy correlators

- Measure energy flow instead of individual particles
- Can be defined in terms of energy flow operators

$$\mathcal{E}(\hat{n})|X\rangle = \sum_{i \in X} E_i \delta^{(2)}(\Omega_n - \Omega_i)|X\rangle$$

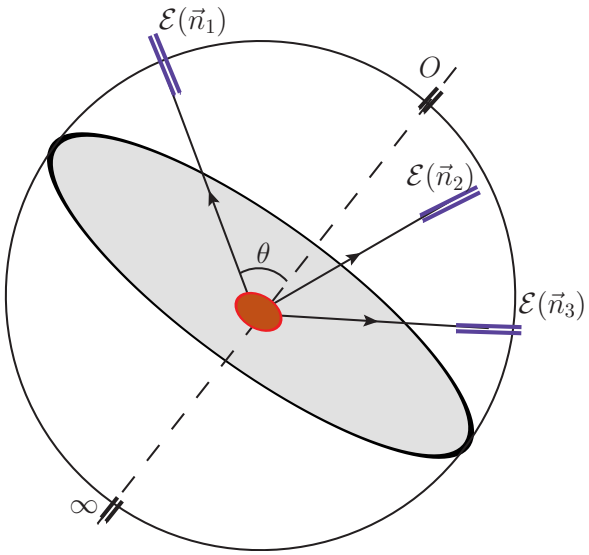
- Energy correlators in terms of flow operators:

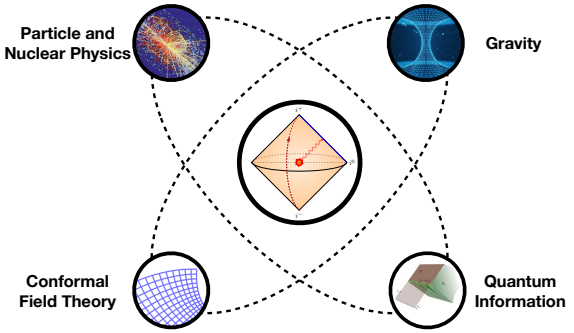
$$\langle \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) \rangle$$

- Allows for a definition in very generic field theories
  - Can be studied in many separate areas of physics
- Focus of this talk:

  Energy correlators for nuclear structure

Yan, Zhang (2203.04349)





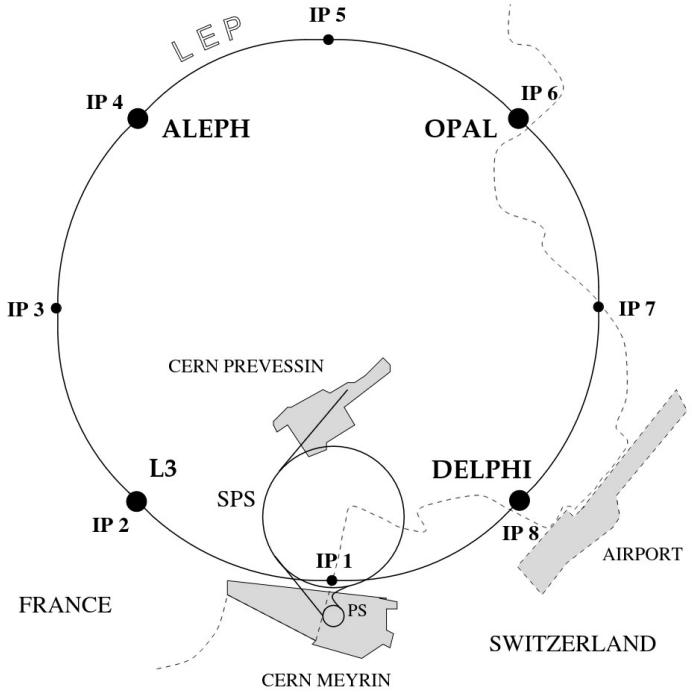
Moult, Zhu (2506.09119)

Energy correlators: Brief history

- One of the first infrared-safe event shapes in QCD
  - Introduced in the late 70's Basham et al. (Phys.Rev.Lett. 41 (1978))
- Measured and studied in the e^+e^- colliders during 90's
- "Forgotten" for a long time
  - Renewed interest due to the seminal paper:

    Hofman, Maldacena (0803.1467)

    Systematized the study of energy correlators



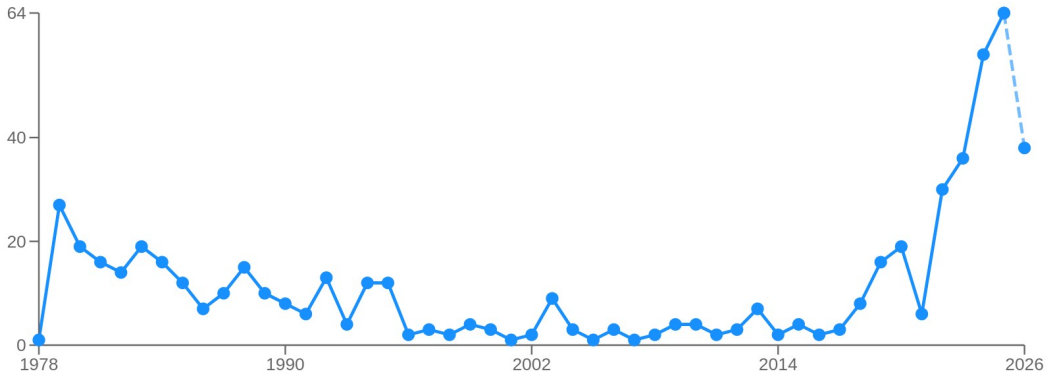
Energy Correlations in electron - Positron Annihilation: Testing QCD

C.Louis Basham (Washington U., Seattle), Lowell S. Brown (Washington U., Seattle), Stephen D. Ellis (Washington U., Seattle), Sherwin T. Love (Washington U., Seattle)
Aug, 1978

13 pages
Published in: *Phys.Rev.Lett.* 41 (1978) 1585
DOI: 10.1103/PhysRevLett.41.1585
Report numbers: RLO-1388-759
View in: OSTI.GOV, ADS Abstract Service

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Citations per year



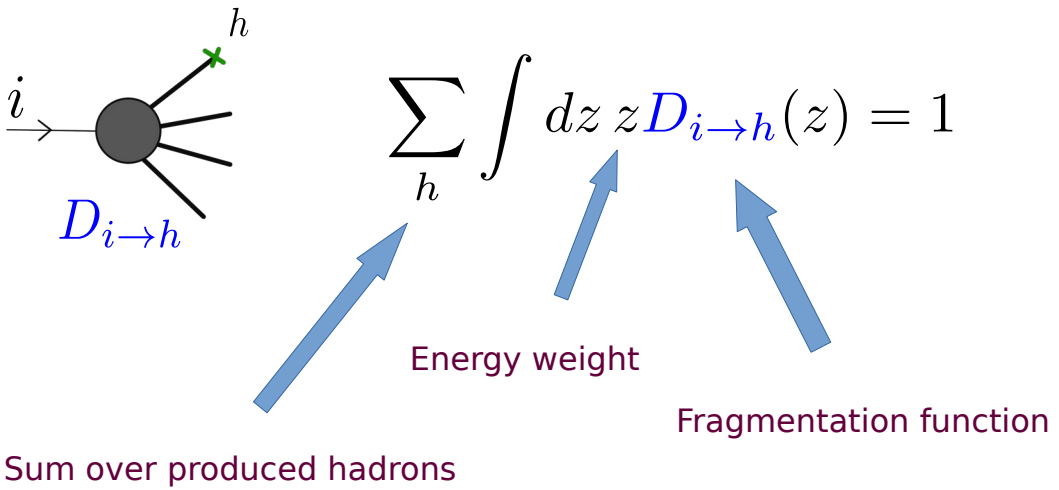
Energy correlators: Connection to cross sections

- Formal definition in terms of the energy flow operators
- More intuitive: an energy-weighted cross section
- Connection to particle production:
  - Weight by energy and sum over all particles
- Hadronization: intermediate partons into measurable hadrons
  - Described by NP *fragmentation functions*

Cross section: $$\sigma^h \sim \int \hat{\sigma}^i \otimes D_{i\to h}$$

Energy correlator: $$\Sigma \sim \sum_h E_h \sigma^h \sim \sum_h E_h \times \int \hat{\sigma}^i \otimes D_{i\to h}$$

Momentum-sum rule:



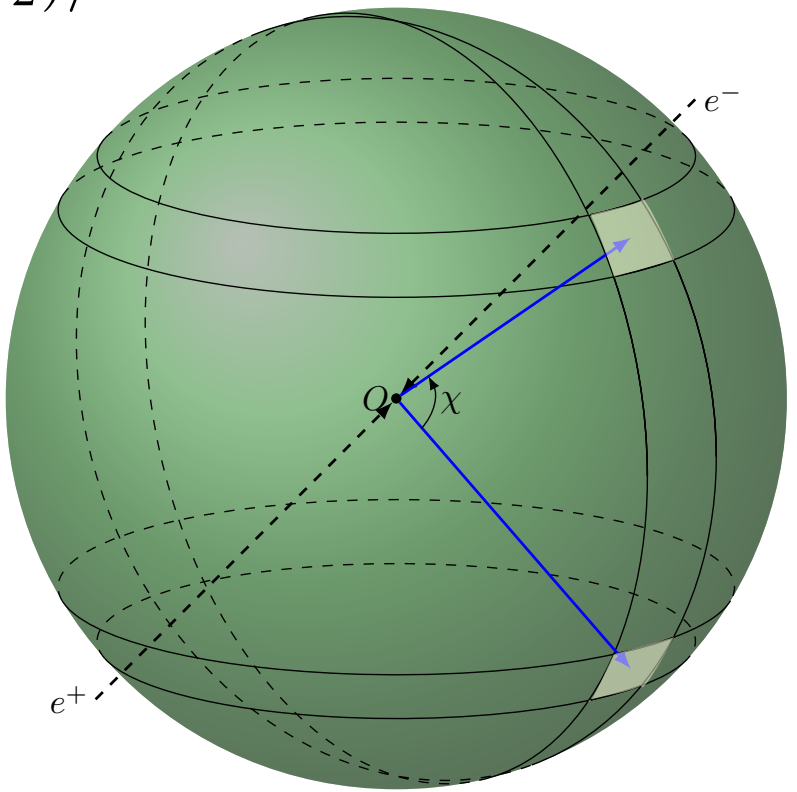
- Follows from momentum conservation
- Fragmentation function cancelled identically

⇒ Reduced sensitivity to NP physics!

Energy–energy correlator

$$\langle \mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)\rangle$$

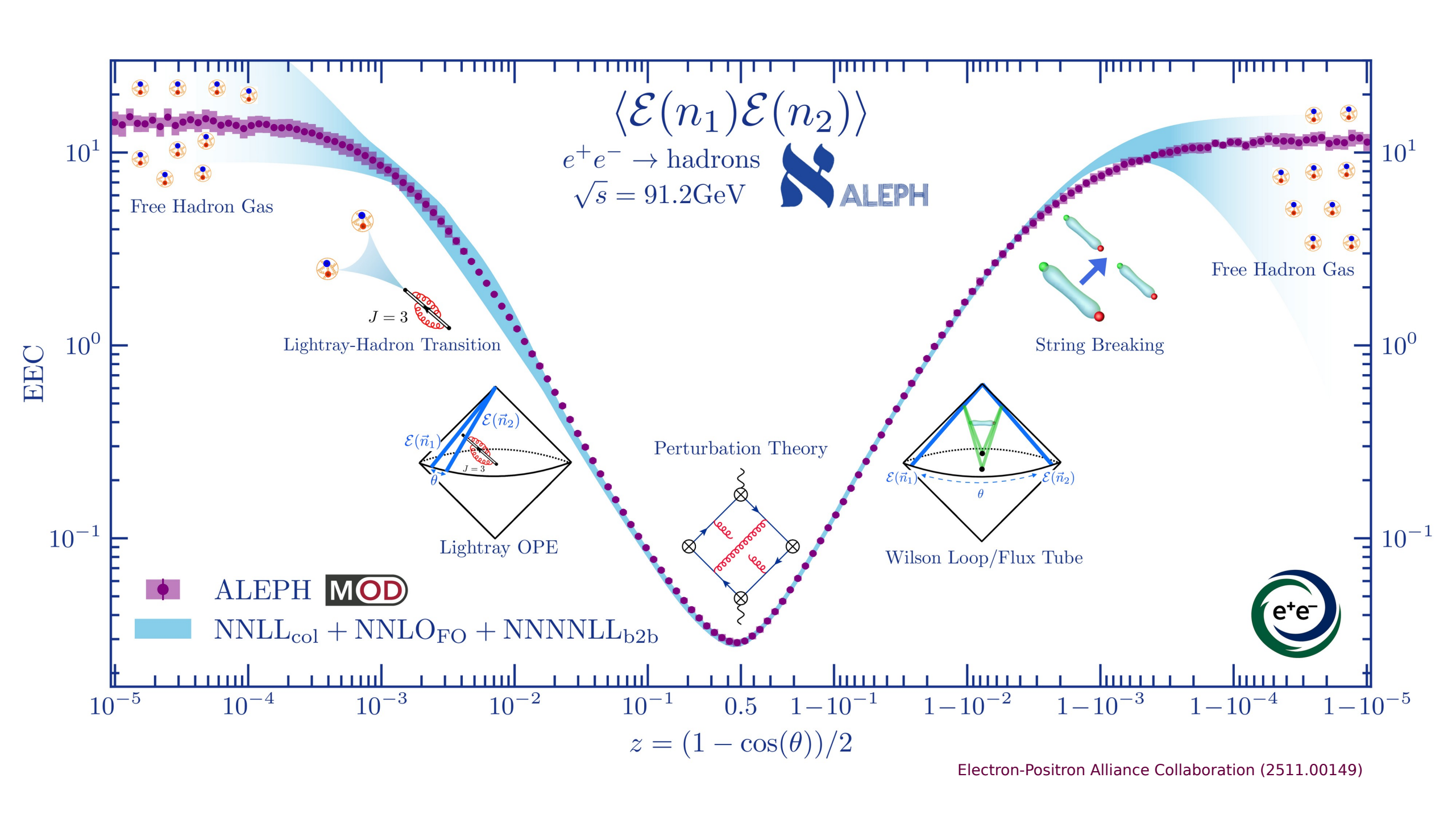
- Measure energy flow at two points
- Can be measured as a function of the *angle* χ
- Especially clean in e^+e^- collisions:
  - Spherical symmetry



Moult, Zhu (1801.02627)

$$e^+ + e^- \to h + h + X:$$

$$\frac{d\Sigma}{d\cos\chi} = \sum_{ij}\int d\sigma \frac{E_i E_j}{Q^2}\delta(\cos\theta_{ij} - \cos\chi)$$

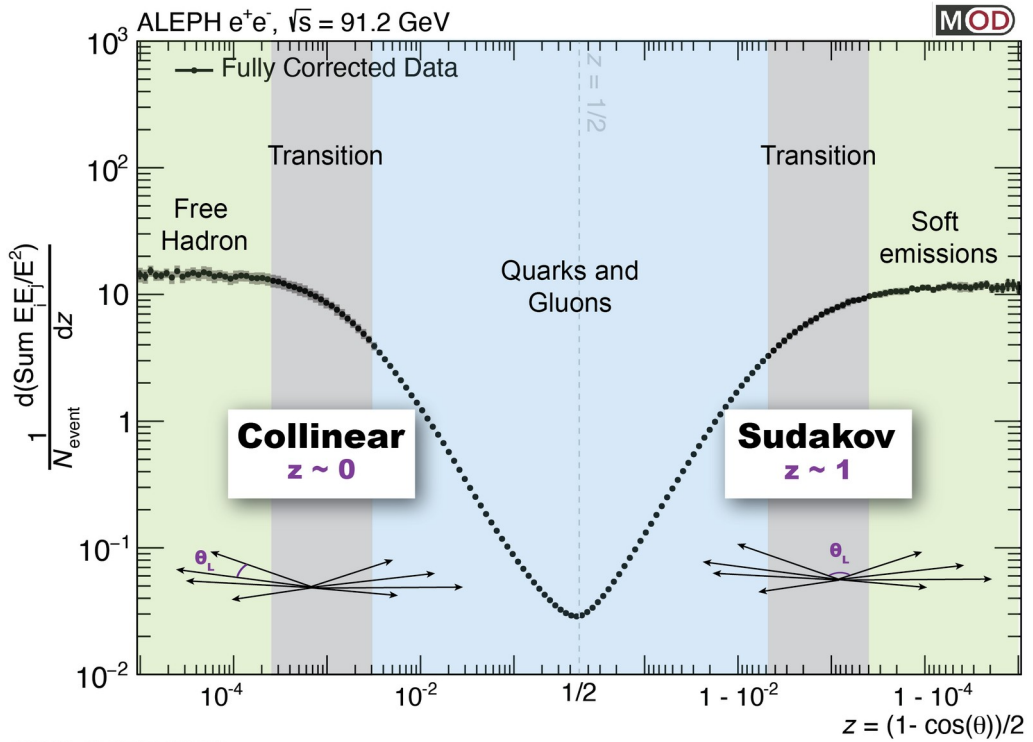


Electron-Positron Alliance Collaboration (2511.00149)

EEC: Different regions

- Angular dependence: probes different physics
- Back-to-back limit: $\theta \approx \pi$
  - Transverse momentum of the partons becomes important: $D_{i\to h}(z) \Rightarrow D_{i\to h}(z, k_T)$

    ⇒ Access to transverse-momentum-dependent (TMD) distributions
- Collinear limit: $\theta \approx 0$
  - Probes jet substructure
  - Transition from perturbative to nonperturbative physics



Electron-Positron Alliance Collaboration (2505.11828)

EEC: Back-to-back region and TMD factorization

$$\Sigma_{\text{back-to-back}} = H \times \mathcal{J}_q \otimes \mathcal{J}_{\bar{q}}$$

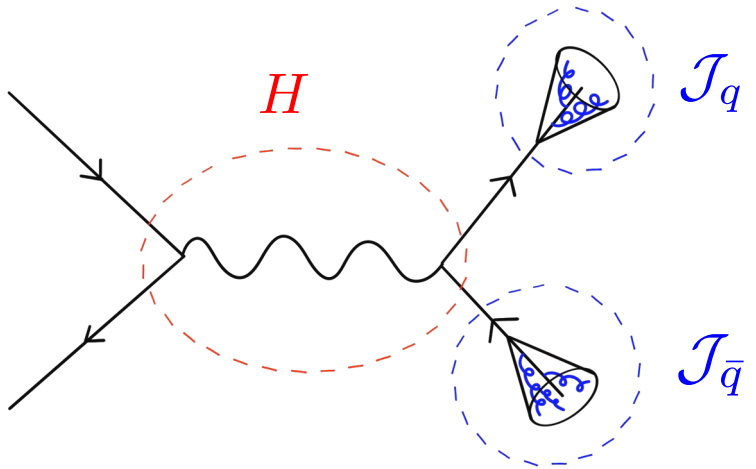
- Back-to-back limit: Separation into different parts

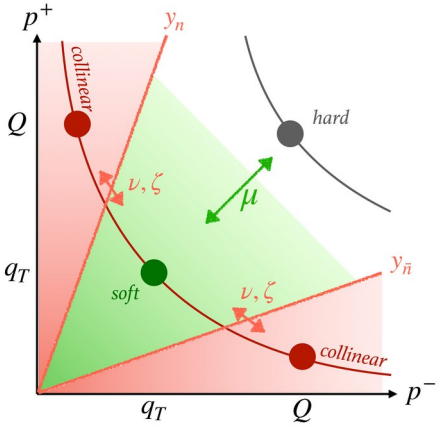
  ⇒ Can be described through TMD factorization

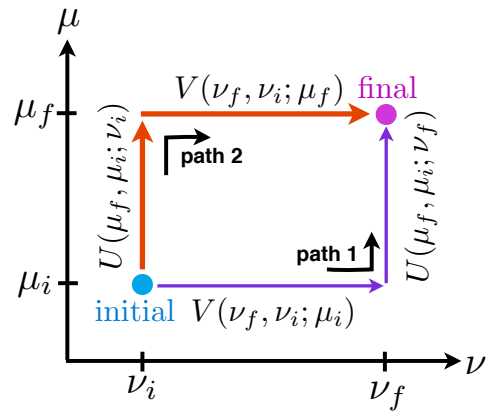
- Separation given in terms of the factorization scale
  - Not unique ⇒ Renormalization group evolution
- TMD factorization: two renormalization scales

$$\frac{d}{d\log\mu}\log H(Q,\mu) = \gamma_\mu^H(\mu,Q) \qquad \frac{d}{d\log\mu}\log \mathcal{J}_q(x,b,\mu,\zeta) = \gamma_\mu^J(\mu,\zeta)$$

$$\frac{d}{d\log\sqrt{\zeta}}\log \mathcal{J}_q(x,b,\mu,\zeta) = K(b,\mu) \quad = \text{ Collins–Soper (CS) kernel}$$





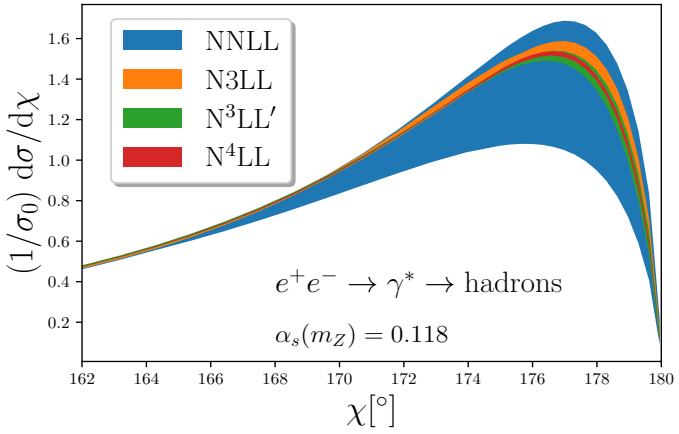


TMD Handbook (2304.03302)

EEC: Ingredients for the TMD factorization

Perturbative part:

Can be calculated to very high orders!



Duhr, Mistlberger, Vita (2205.02242)

Accuracy	H, $\mathcal{J}$	$\Gamma_{\rm cusp}(\alpha_s)$	$\gamma_H^q(\alpha_s)$	$\gamma_r^q(\alpha_s)$	$\beta(\alpha_s)$
LL	Tree level	1-loop	–	–	1-loop
NLL	Tree level	2-loop	1-loop	1-loop	2-loop
NLL$'$	1-loop	2-loop	1-loop	1-loop	2-loop
NNLL	1-loop	3-loop	2-loop	2-loop	3-loop
NNLL$'$	2-loop	3-loop	2-loop	2-loop	3-loop
N^{3}LL	2-loop	4-loop	3-loop	3-loop	4-loop
N^{3}LL$'$	3-loop	4-loop	3-loop	3-loop	4-loop
N^{4}LL	3-loop	5-loop	4-loop	4-loop	5-loop
N^{4}LL$'$	4-loop	5-loop	4-loop	4-loop	5-loop

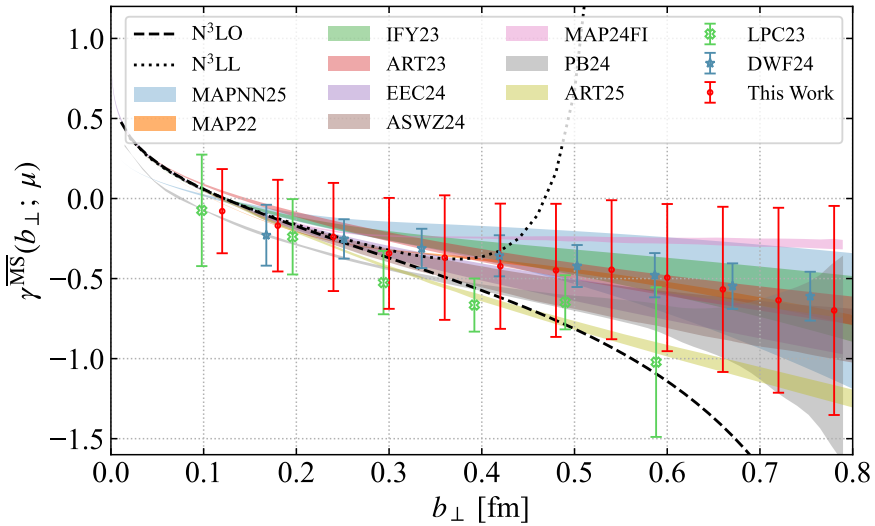
Nonperturbative (NP) part:

1) NP jet function

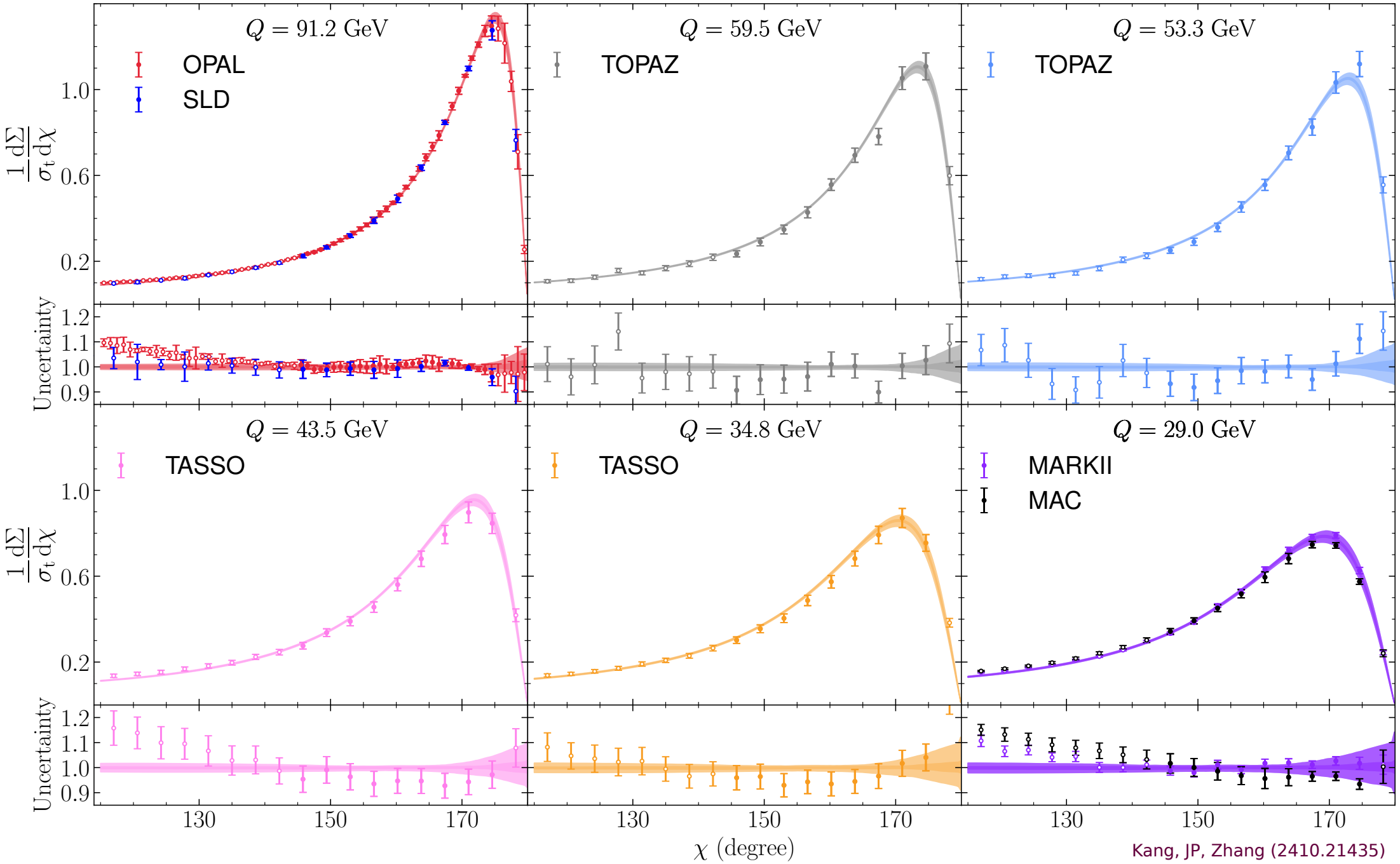
2) NP CS kernel

Cannot be calculated using perturbation theory

- Lattice calculations
- Phenomenological fits



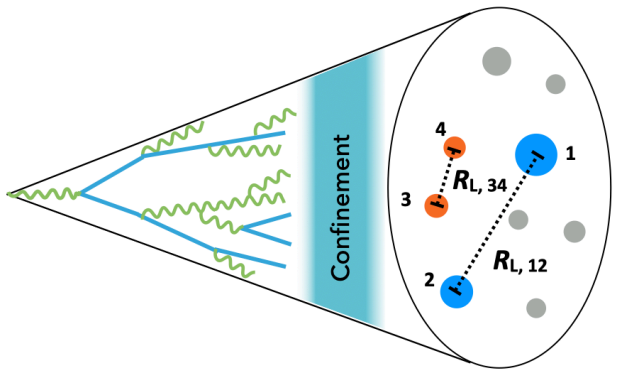
Bollweg et al. (2504.04625)



Kang, JP, Zhang (2410.21435)

EEC: Collinear limit

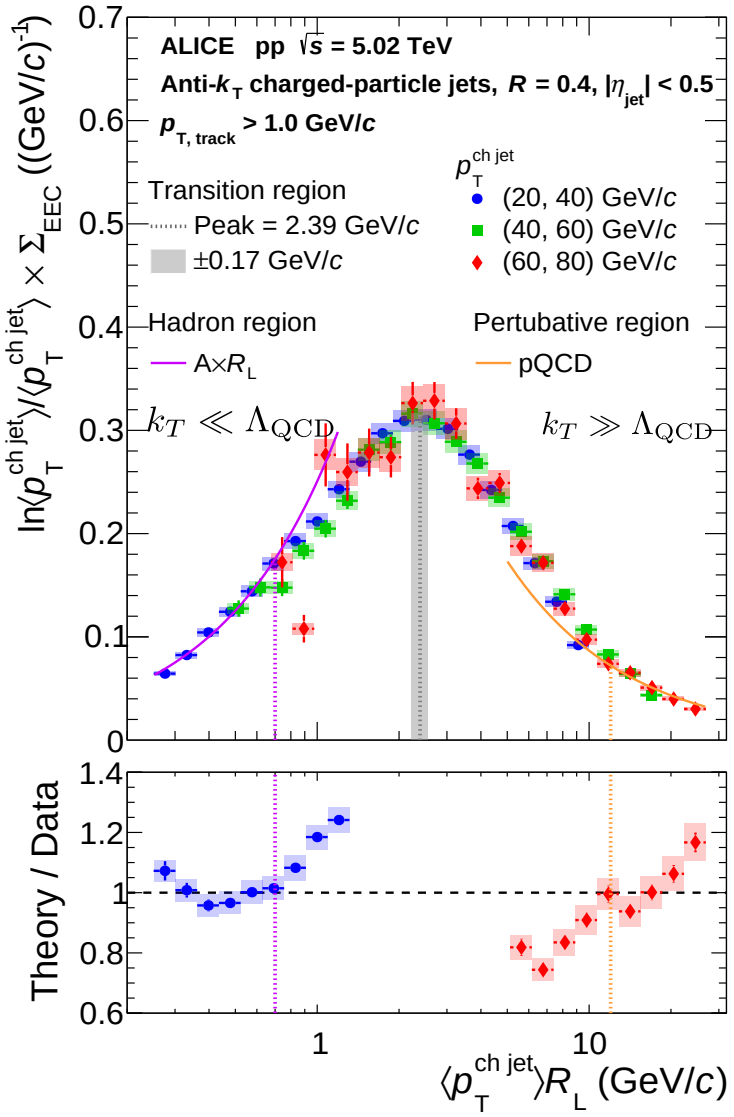
- Small angles ⇒ Perturbative splittings become important
  - Described through **collinear factorization**
- Can be measured both in e^+e^- and hadronic collisions
  - Hadronic colliders: defined inside **jets**
- How to understand the transition from perturbative to nonperturbative regions?



Relevant scale: transverse momentum between the produced pair

$$k_\perp \sim p_T R_L$$

R_L = Angular variable for a pair inside a jet



ALICE Collaboration (2409.12687)

EEC: Collinear limit and factorization

- Collinear factorization:

$$\Sigma_{\text{collinear}} = H_i \otimes J_{i\to jk}$$

Hard scattering and the final-state splitting (jet function)

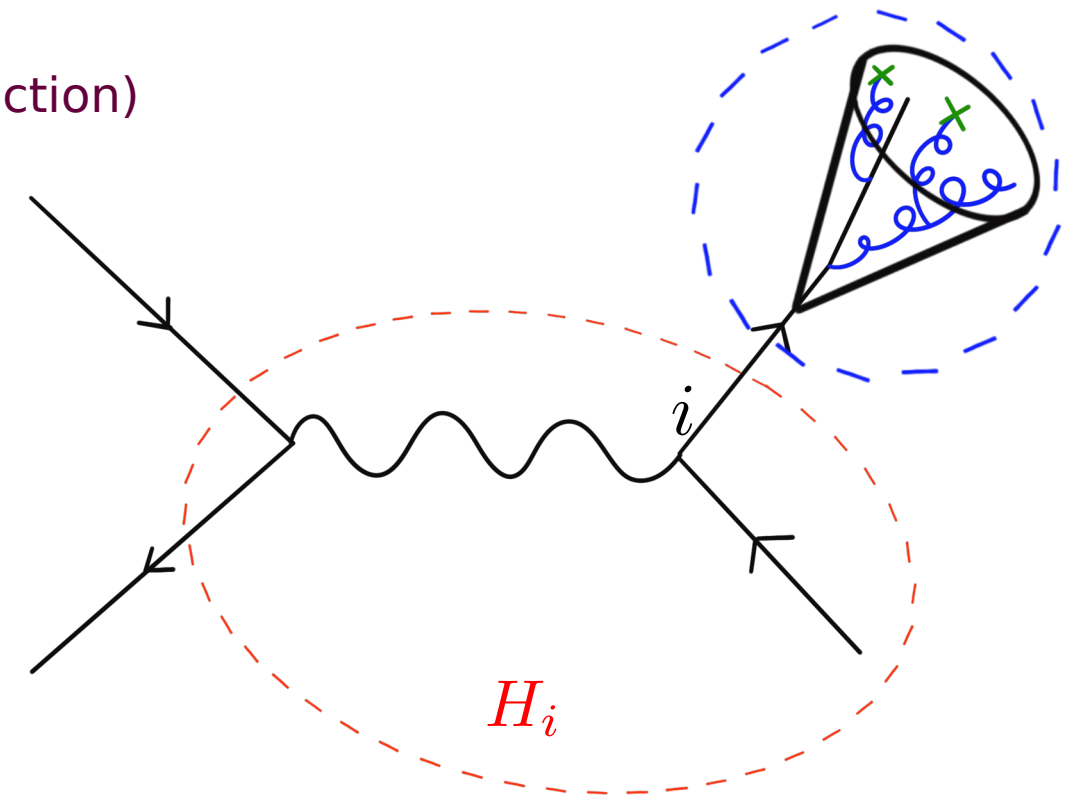
  - Hard function: Process dependent
  - Jet function: Universal!

- As in TMD factorization:

Separation given by the factorization scale μ

- Choice of factorization scale not unique

⇒ Evolution equations (DGLAP)



$$\frac{d}{d\log\mu^2}\mathbf{H}(x,Q\mu) = -\int_x^1 \frac{dy}{y}\mathbf{P}(y,\mu)\cdot\mathbf{H}\left(\frac{x}{y},Q,\mu\right)$$

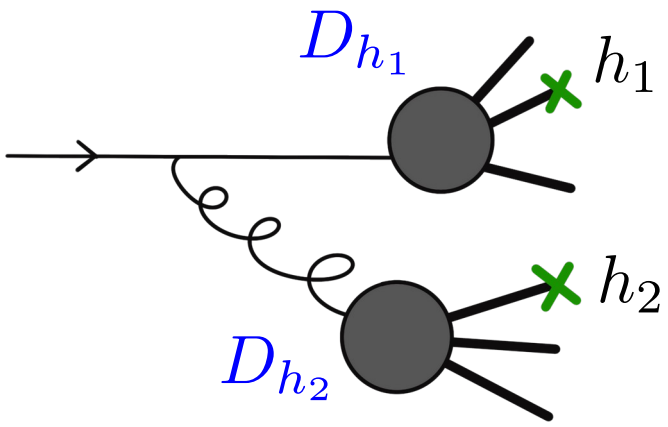
$$\frac{d}{d\log\mu^2}\mathbf{J}(p,\mu) = -\int_0^1 dy\, y^2\mathbf{J}(yp,\mu)\cdot\mathbf{P}(y,\mu)$$

EEC: Collinear jet function and nonperturbative physics

- Perturbative region:

  Parton splits into two partons ⇒ Independent fragmentation

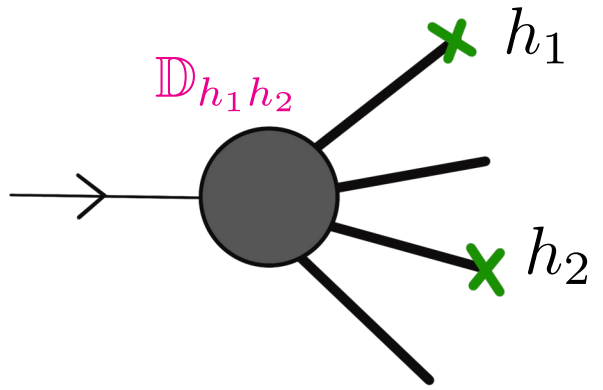
$$J \sim \sum_{h_1} \int dz_1\, z_1 D_{h_1}(z_1) \times \sum_{h_2} \int dz_2\, z_2 D_{h_2}(z_2) \sim 1$$



- Nonperturbative region:

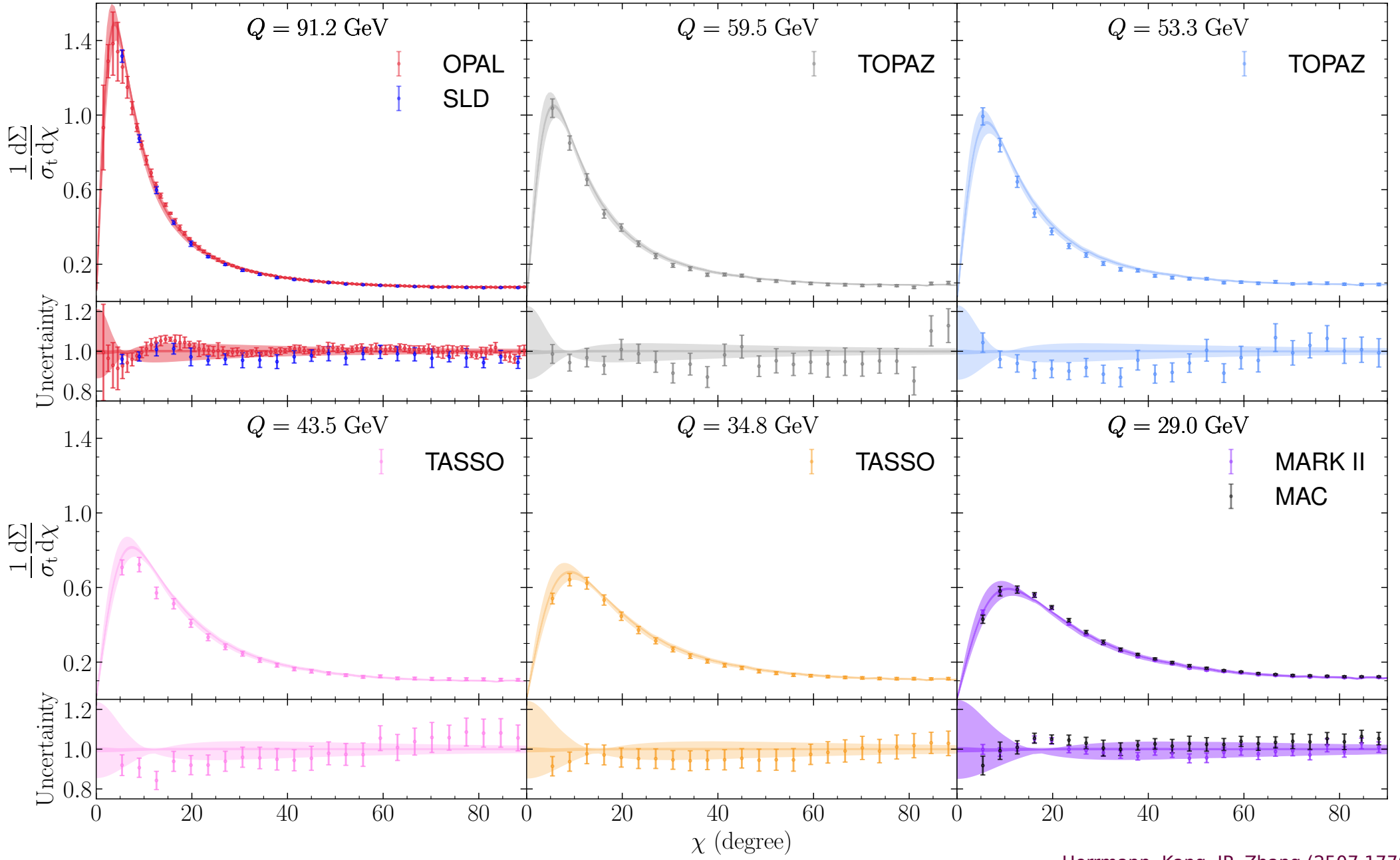
  Parton directly into two hadrons ⇒ *Dihadron fragmentation*

$$J \sim \sum_{h_1,h_2} \int dz_1 dz_2\, z_1 z_2 \mathbb{D}_{h_1,h_2}(z_1, z_2, k_T)$$



  - Has to be modelled

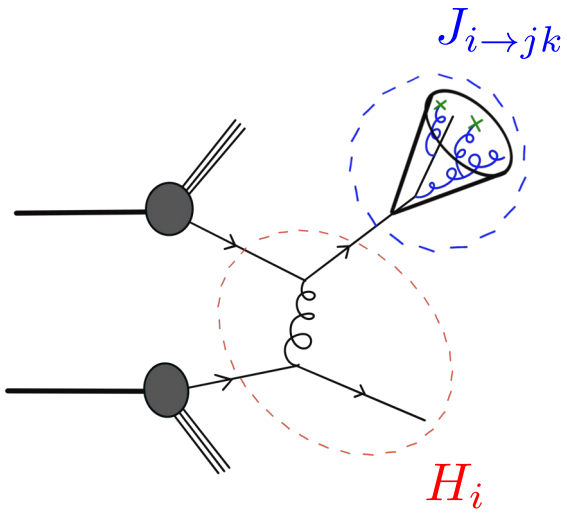
Lee, Stewart (2507.11495)
Guo, Yuan, Zhao (2507.15820)
Chang et al ({2507.15923)
Kang, Metz, Pitonyak, Zhang (2507.17444)
Guo, Vogelsang, Yuan, Zhao (2512.15896)



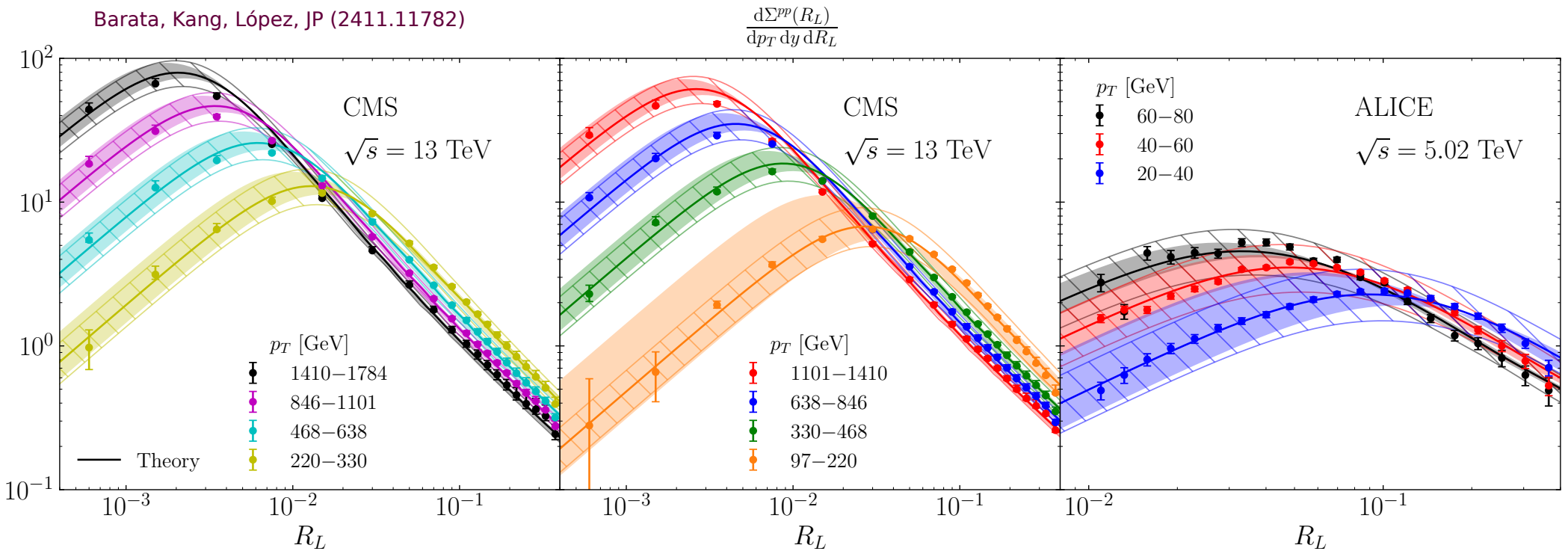
Herrmann, Kang, JP, Zhang (2507.17704)

EEC: Collinear limit in pp collisions

- Going from e^+e^- to pp collisions: only changes the hard function
- *pp* collisions: EEC measured inside jets with momentum p_T
- Good description across a wide range of angles and transverse momenta!



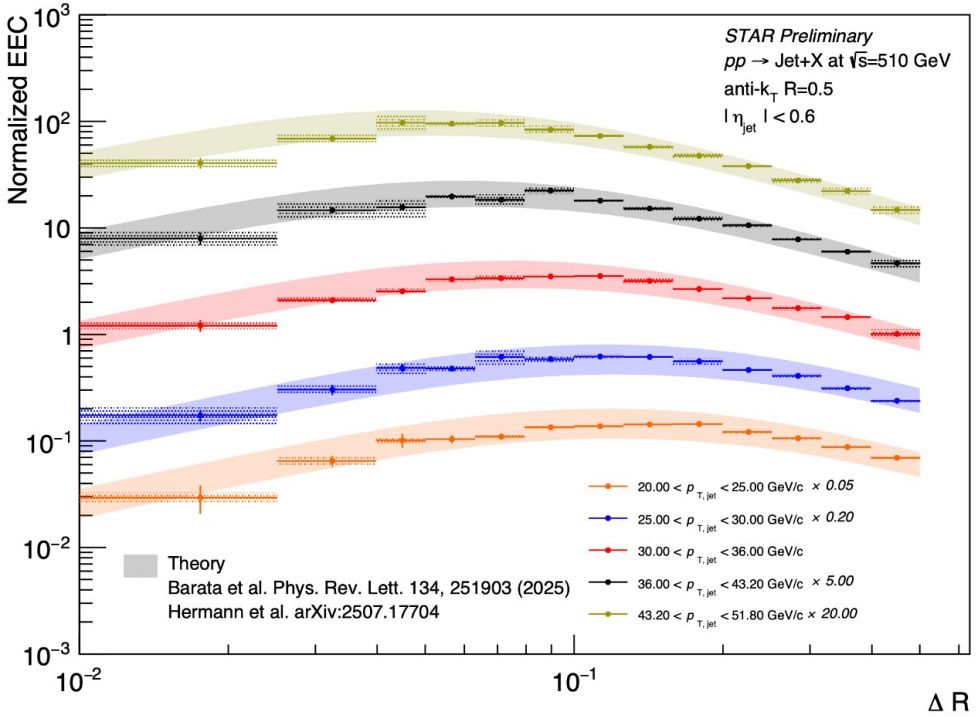
Barata, Kang, López, JP (2411.11782)



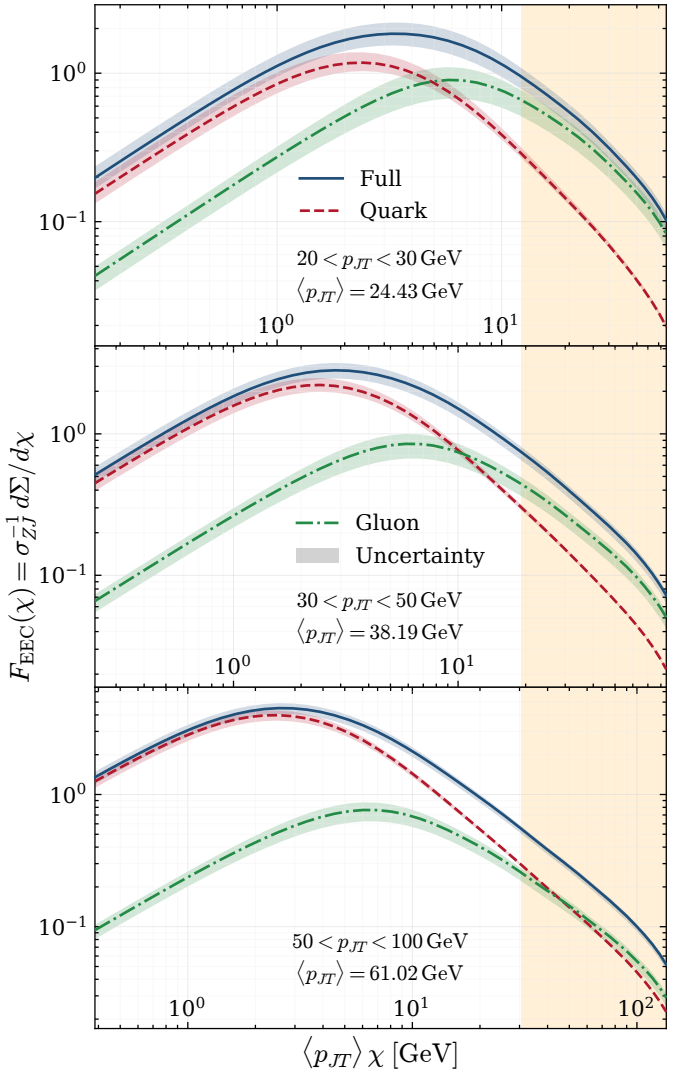
EEC: Collinear limit and universality of the jet function

- Factorization: collinear jet function should be universal across different collisions environments
- e^+e^- (LEP): sensitive to quark jets
- pp (LHC): sensitive to gluons jets
- Combine fits for the quark and gluon jets to produce ***predictions*** for RHIC

  ⇒ Good description of the data!



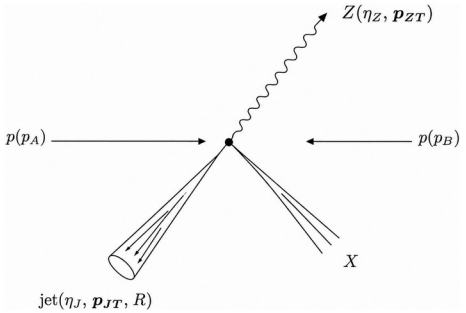
EEC: Collinear limit and universality of the jet function



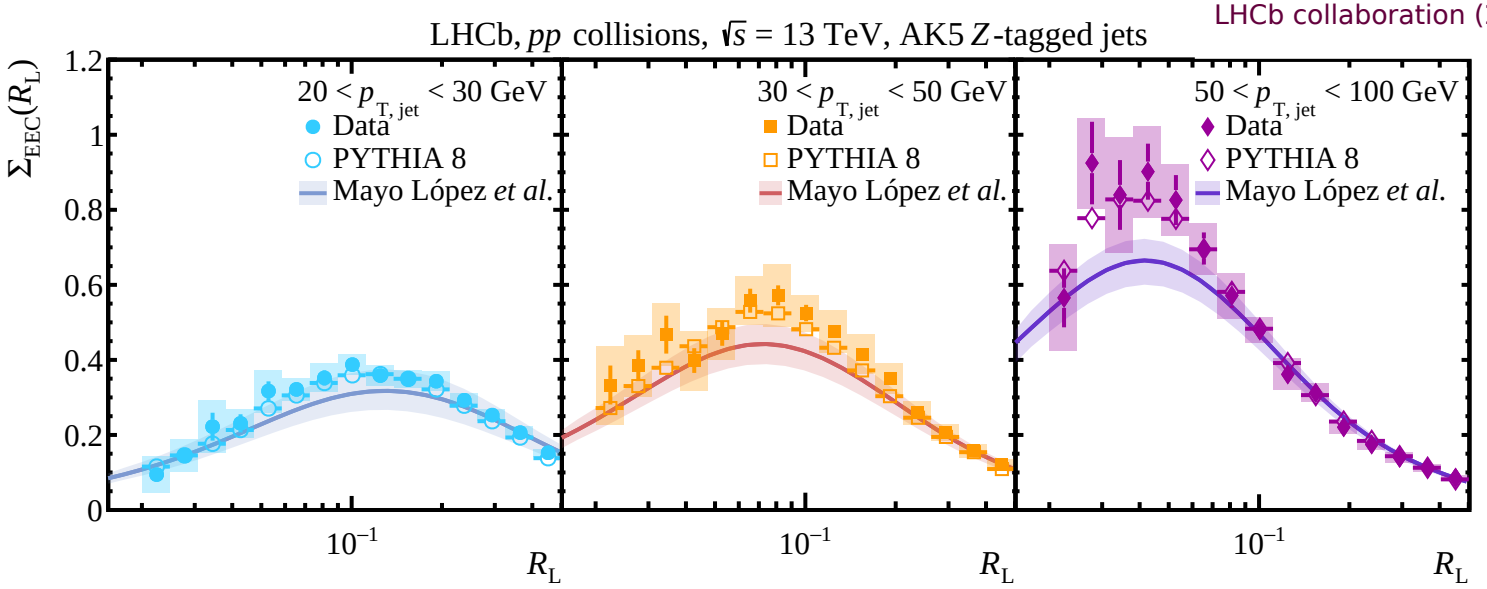
Barata, Kang, Mayo López, JP, Zhou (2609.03072)

- Quark and gluon contributions can be further studied in different processes
  - *Z*-boson production: more sensitive to ***quarks***

$$p + p \to Z + \text{jet}$$



LHCb collaboration (2610.14221)

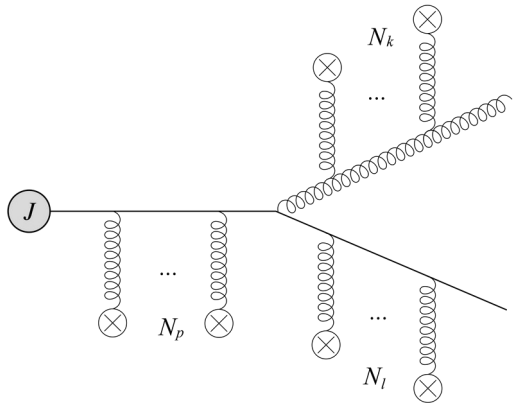


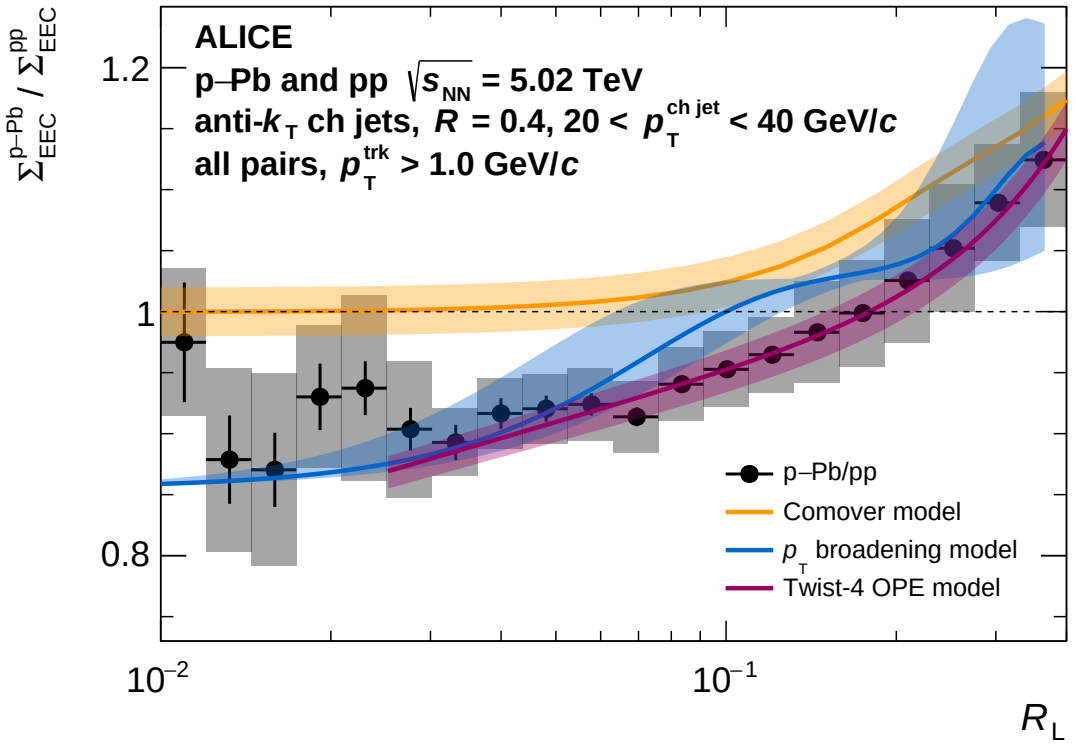
EEC: Collinear limit and nuclear modification

- Going from pp to pA collisions:

  Modifications from the nuclear environment

- Nonperturbative region $(p_T R_L \ll \Lambda_{\mathrm{QCD}})$
  - Modifications to the dihadron fragmentation
- Perturbative region $(p_T R_L \gg \Lambda_{\mathrm{QCD}})$
  - Interactions with the background gluons





ALICE Collaboration (2606.18143)

One-point energy correlator

"Simplest" energy correlator:

$$\mathrm{OPEC}_{n_0}(\chi) = \int d\vec{n} \frac{\langle \mathcal{E}(\vec{n}) \rangle}{Q} \delta(\vec{n} \cdot \vec{n}_0 - \cos\chi)$$

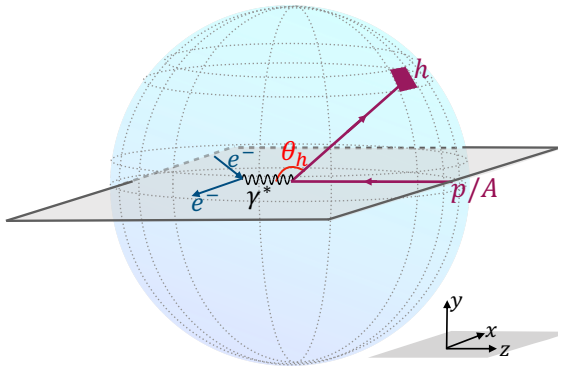
Measure energy flow with respect to a reference direction

- Study nuclear modification:

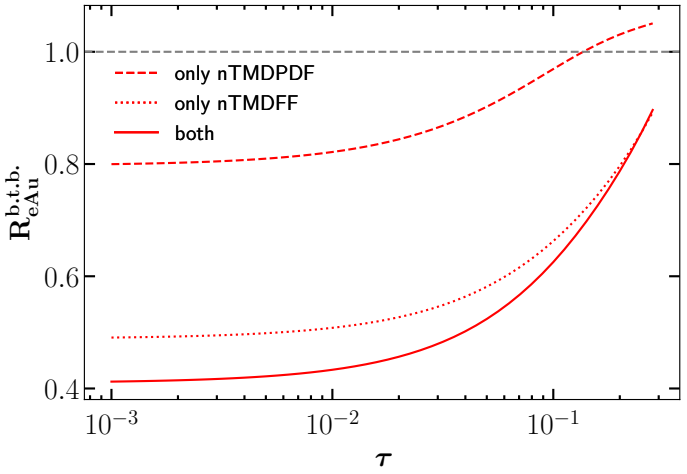
$$\mathrm{R} \sim \frac{\Sigma^{eA}}{A \times \Sigma^{ep}}$$

Energy flow with respect to the virtual photon

$$e + p/A \to e + h + X$$

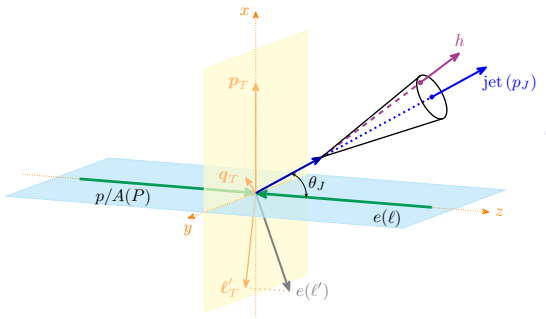


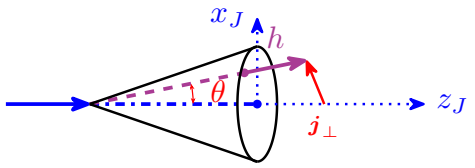
$$\tau = \frac{1+\cos\theta}{2}$$



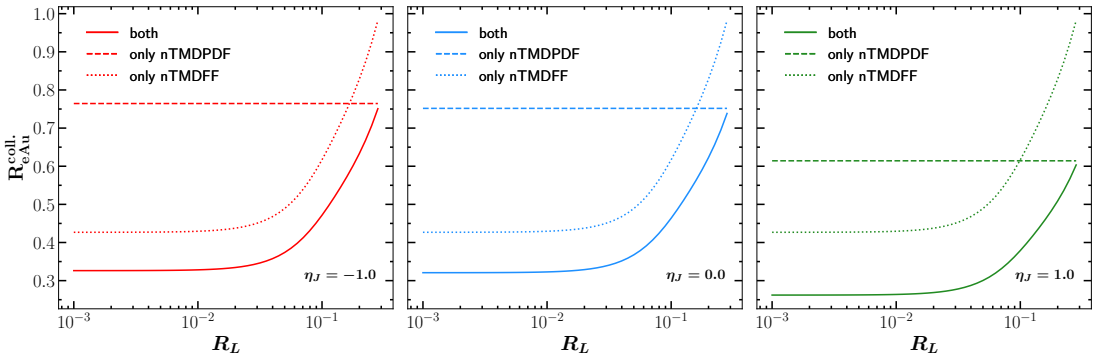
Energy flow inside a jet

$$e + p/A \to e + \mathrm{jet}(h) + X$$





Fu, Kang, JP, Zhou (2512.16847)

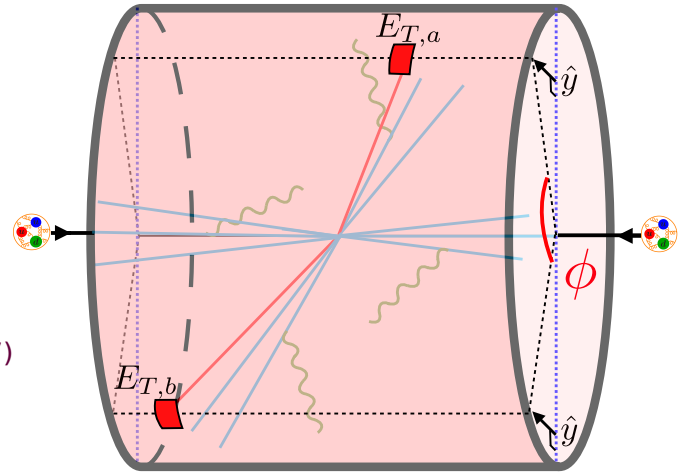


Transverse energy correlators

- Hadronic colliders: beam direction specifies a direction
  - No spherical symmetry as in e^+e^-
  - However, azimuthal symmetry retained

⇒ Look at transverse energy correlators instead

Ali, Pietarinen, Stirling (Phys.Lett.B 141 (1984) 447-454)



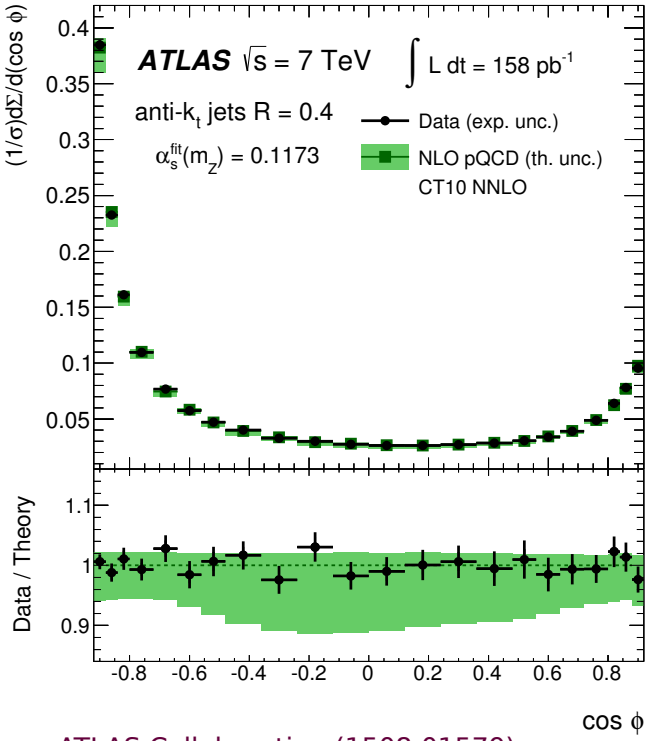
Gao et al. (1901.04497)

- Analogous to standard energy correlators:

$$E \mapsto E_T = \sqrt{p_T^2 + m^2}$$
$$\theta \mapsto \phi$$

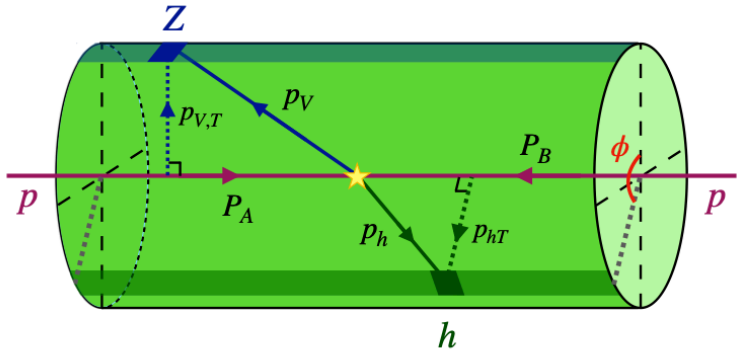
- More suitable for hadronic colliders

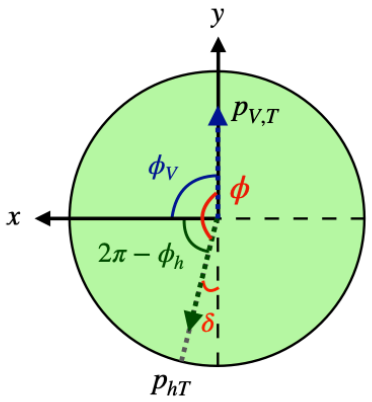
⇒ Enables similar studies as energy correlators in e^+e^-

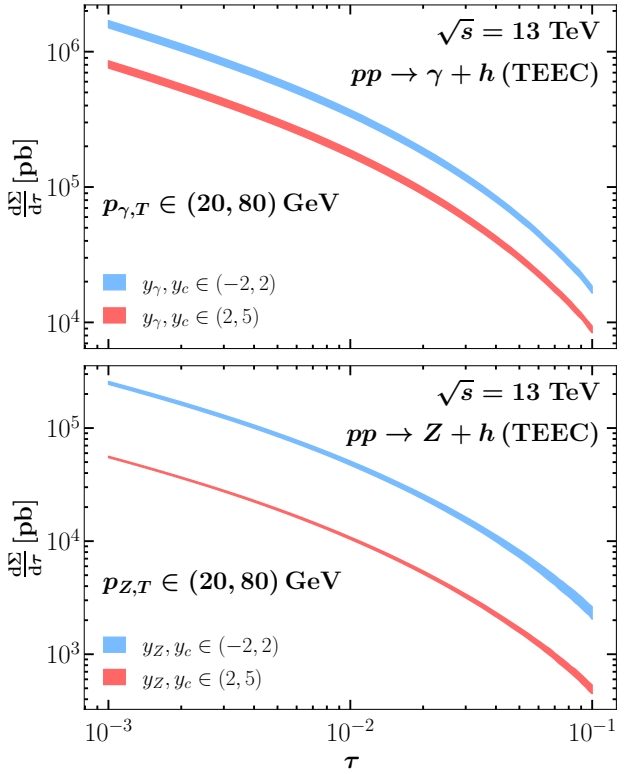


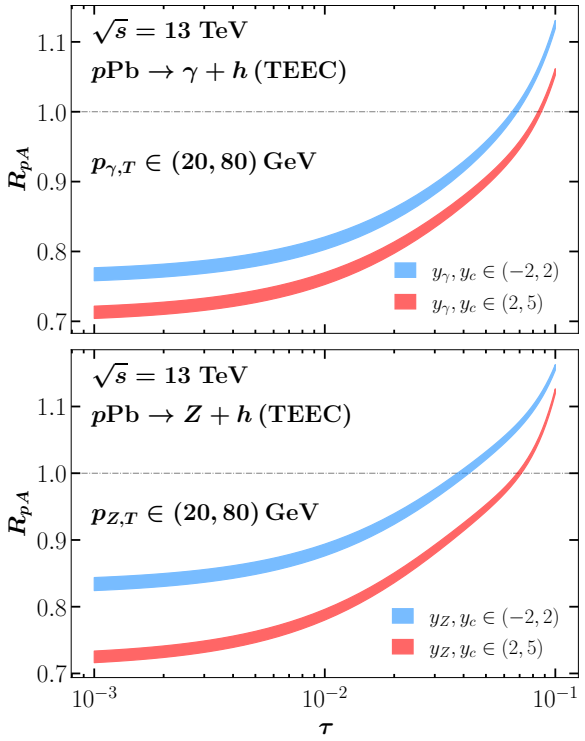
ATLAS Collaboration (1508.01579)

Vector-boson tagged TEEC in pp and pA collisions









- Back-to-back in the azimuthal angle

  ⇒ TMD factorization!

- Possible to examine nuclear corrections

- Can be studied at RHIC and LHC

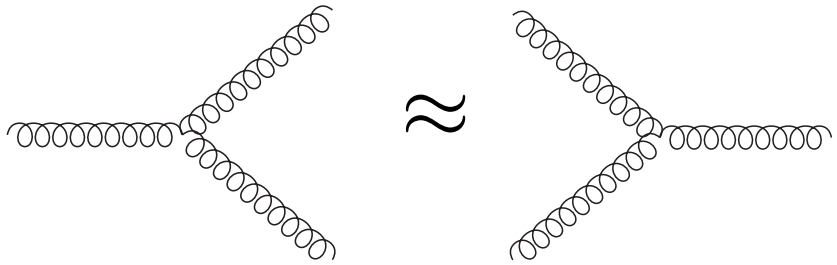
$$\tau = \frac{1 + \cos\phi}{2}$$

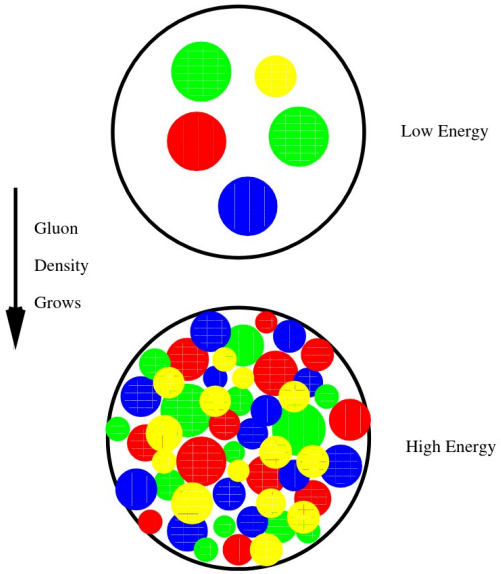
Kang, Lee, JP, Zhao, Zhou (2410.02747)

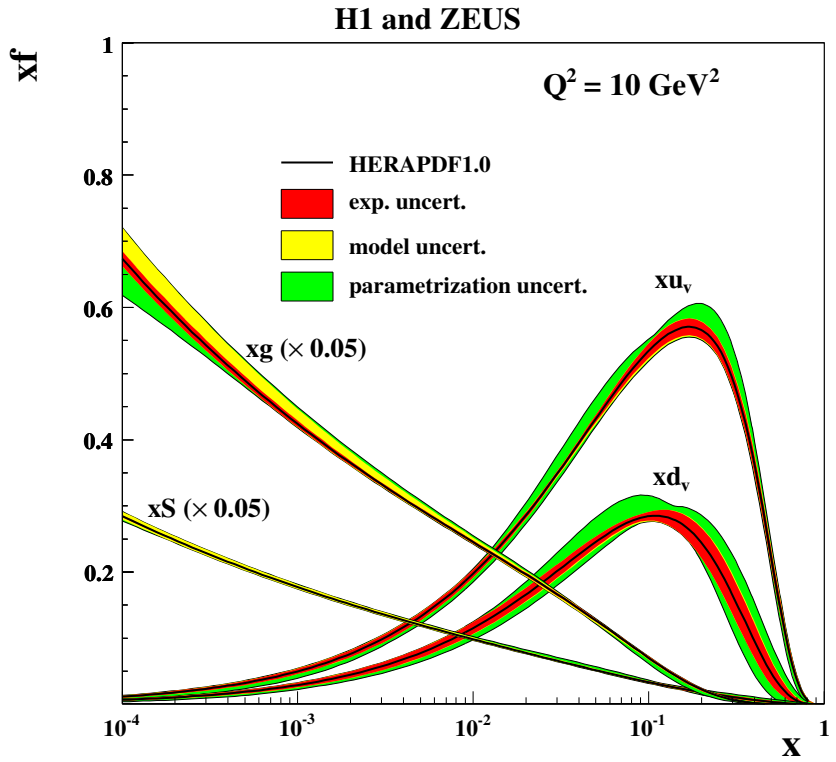
Energy correlators in the high-energy limit

- High energies = Small momentum fraction x
  - Gluon distribution starts to dominate
- Eventually would break unitarity

  ⇒ Tamed by nonlinear gluon recombination
- Leads to ***gluon saturation***





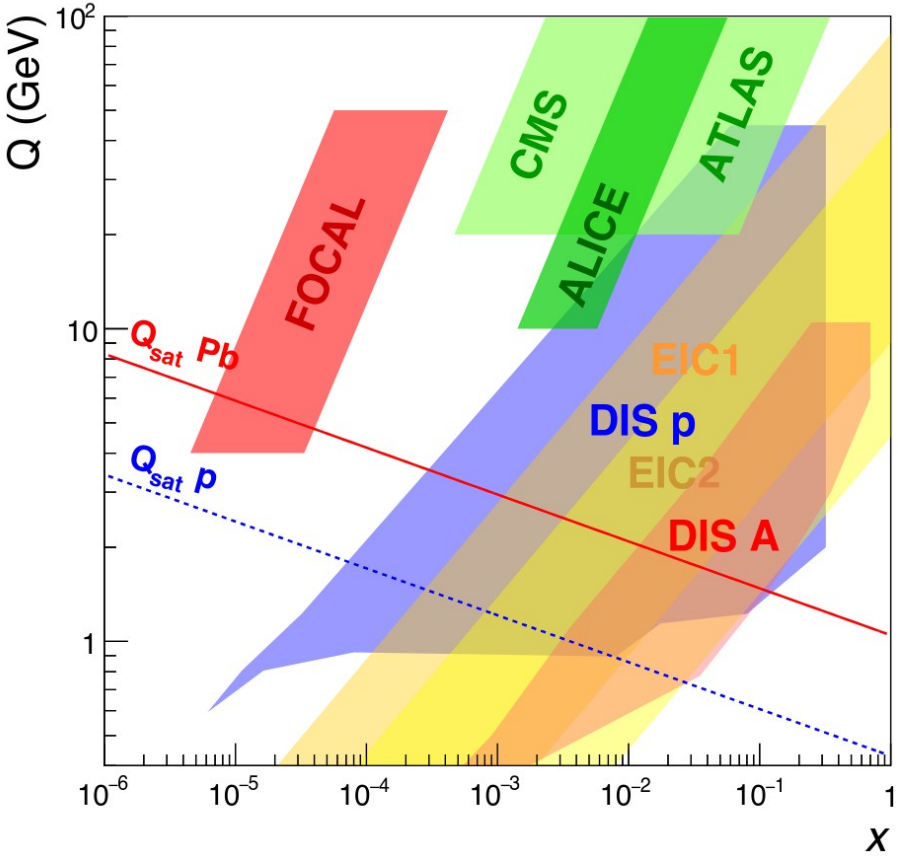


H1 and ZEUS (0911.0884)

Gluon saturation

- Characterized by the saturation scale Q_s
- For protons: $Q_s \lesssim 1$ GeV ⇒ Small effect at perturbative scales
  - Increases at higher energies: $Q_s^2 \sim 1/x^{0.3}$
  - Enhanced in heavy nuclei: $Q_{s,A}^2 \sim A^{1/3} Q_{s,p}^2$
- Very difficult to measure
  - No clear definite experimental signal evidence yet!
- Need clean observables to distinguish from other effects
  - Energy correlators insensitive to final-state hadronization

  ⇒ Potential for measuring gluon saturation



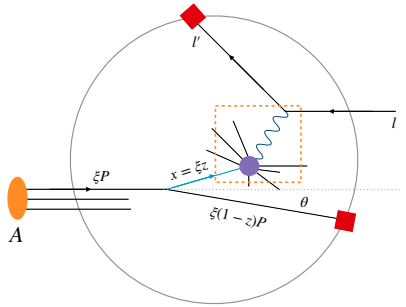
Searching for gluon saturation with energy correlators

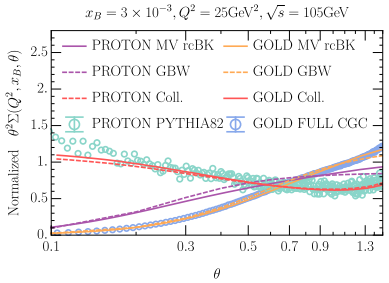
Saturation hard to distinguish from just one observable:

⇒ Look at many different processes

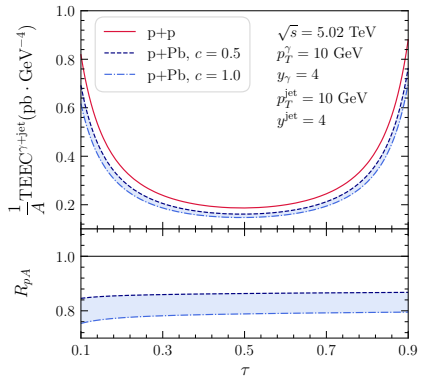
Possible to measure at RHIC, LHC and EIC

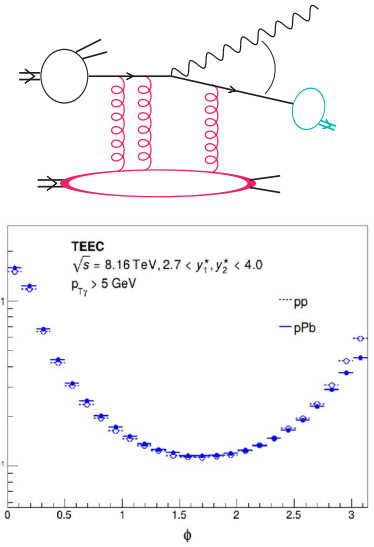
$e + p/A \to e + h + X$ Liu at al. (2301.01788)





$p + p/A \to \gamma + h + X$



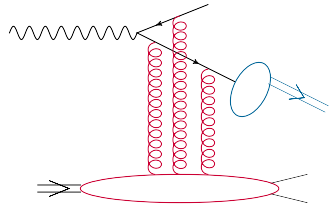


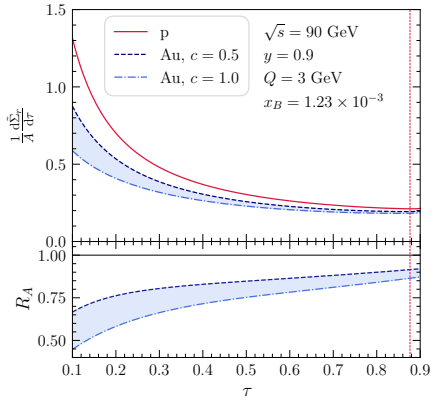
Kang, Kao, Li, JP (2504.00069)

$$\tau = \frac{1 + \cos\phi}{2}$$

Ganguli, Kotko (2507.23435)

$\gamma^* + p/A \to h + X$





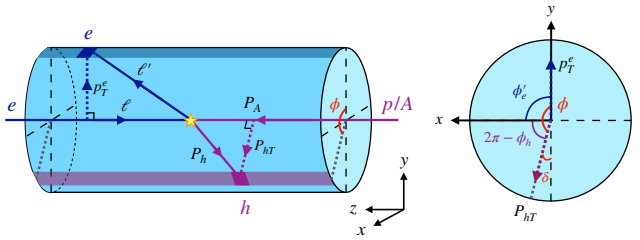
Kang, Kao, Li, JP (2603.02300)

Searching for gluon saturation with TEEC

Back-to-back limit especially sensitive to saturation ⇒ Need to combine small x with TMD factorization

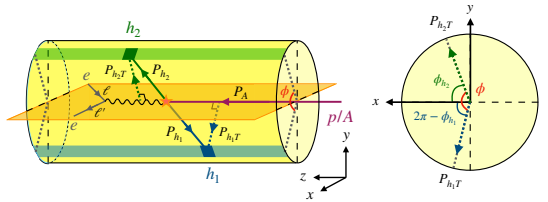
$e + p/A \to e + h + X$

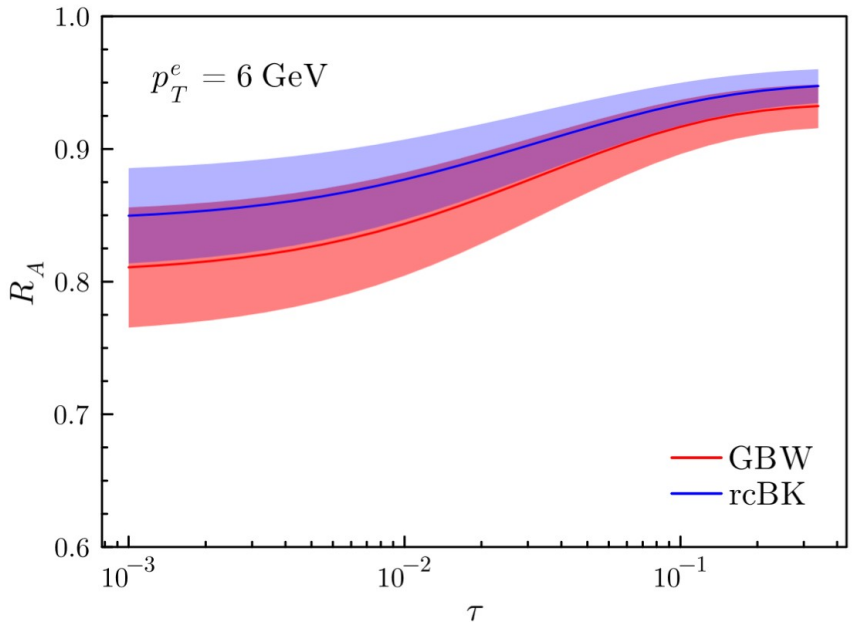
Kang, JP, Zhao, Zhou (2311.17142)



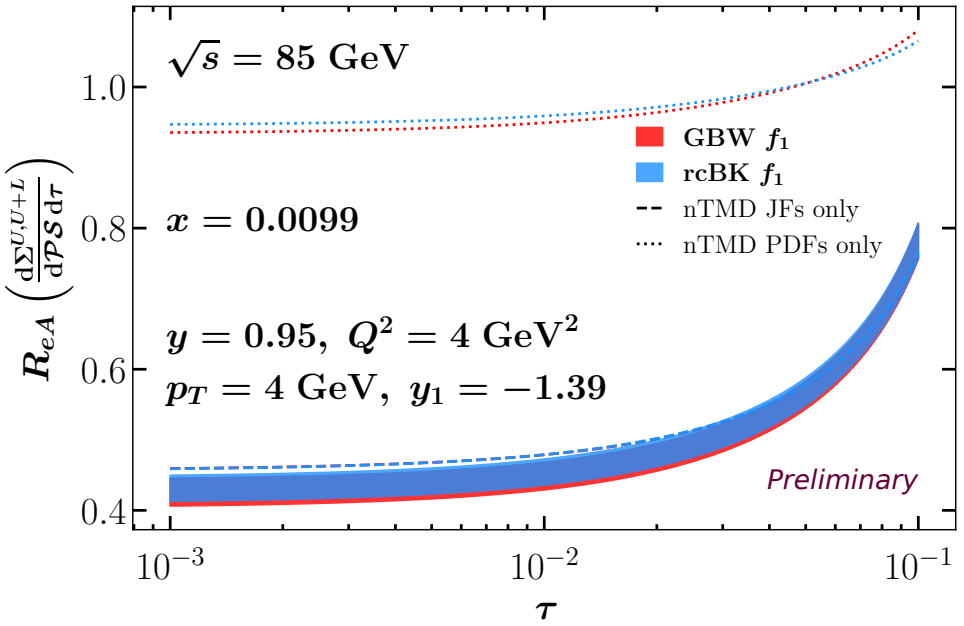
$\gamma^* + p/A \to h + h + X$

Kang, JP, Zhao, Zhou (in preparation)

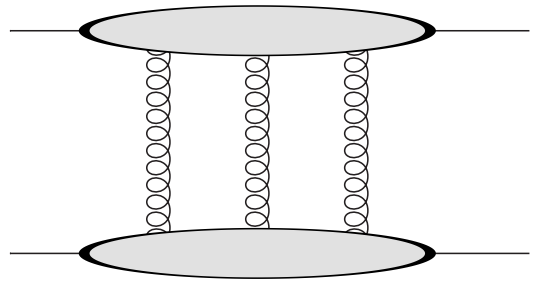




$$\tau = \frac{1 + \cos\phi}{2}$$



Odderon with (energy) correlators



Polarized beams at the EIC:

Possible to study also the spin asymmetries

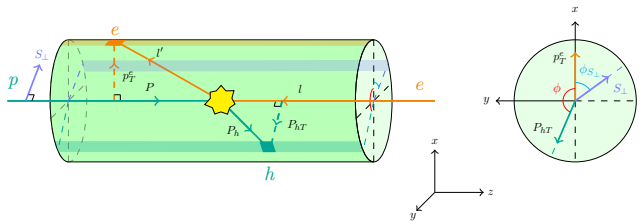
- Small x: Described by the ***odderon*** interaction

Odderon: C-odd interaction with the target

- Discovered only recently: D0, Totem Collaborations (2012.03981)

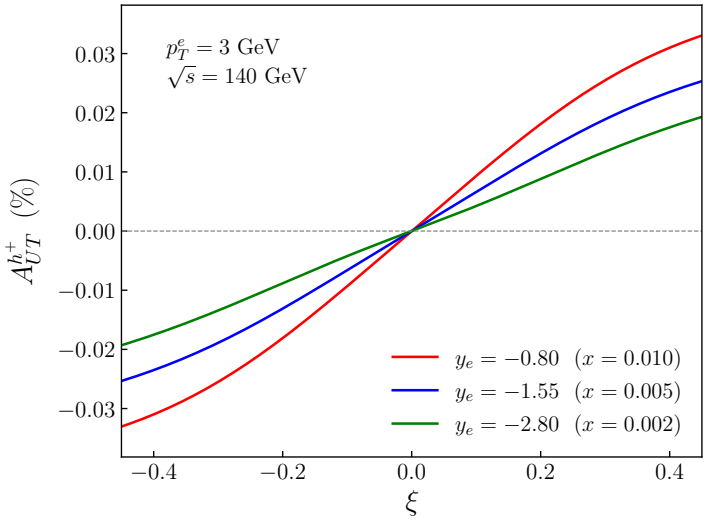
$$e + p/A \to e + h + X$$

$$A_{UT} \sim \frac{\text{Polarized}}{\text{Unpolarized}}$$



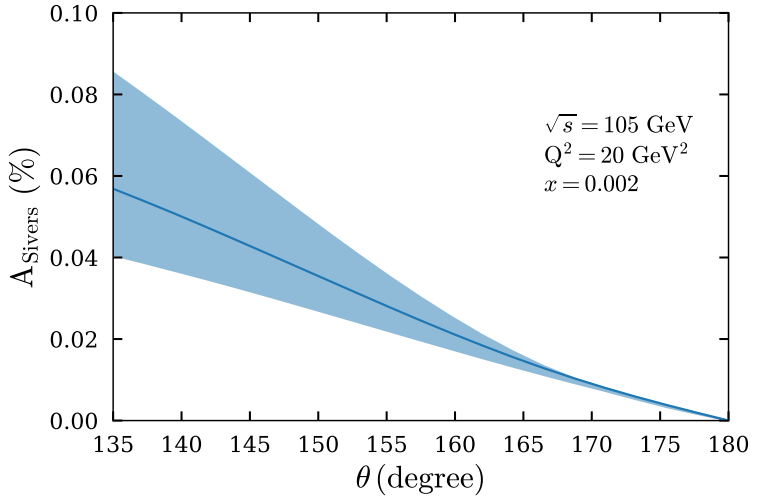
$$\xi = \pi - \phi$$

EC + charge weight



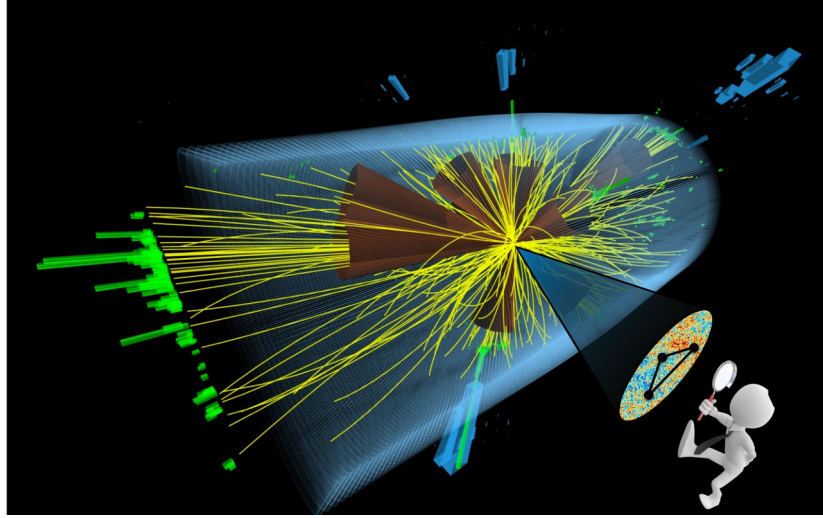
Bhattacharya, Kang, Padilla, JP (2504.10475)

Charge correlator



Cao, Kang, Padilla, JP (2609.12064)

Summary



- Energy correlators:

  Measure energy flow instead of individual particles

  - Provides a clean probe of quantum field theories
- Experimentally simple
- Possible to study different aspects of nuclear physics:
  - Jet substructure
  - Transverse-momentum-dependent distributions
  - Gluon saturation
  - Nuclear modification

- Lots of topics not discussed
  - Higher-point energy correlators
  - Light-ray operator product expansion
  - Energy correlators with charge
  - Boosted energy correlators
  - Energy correlators with heavy quarks
  - Hot nuclear effects (quark–gluon plasma)
  - Power corrections
  - Energy correlators in conformal theories
  - Energy correlators in gravity
  - List goes on...

Many processes still unexplored ⟹ Opportunities at the current and future colliders!