Jets and Heavy Flavor
Part 2

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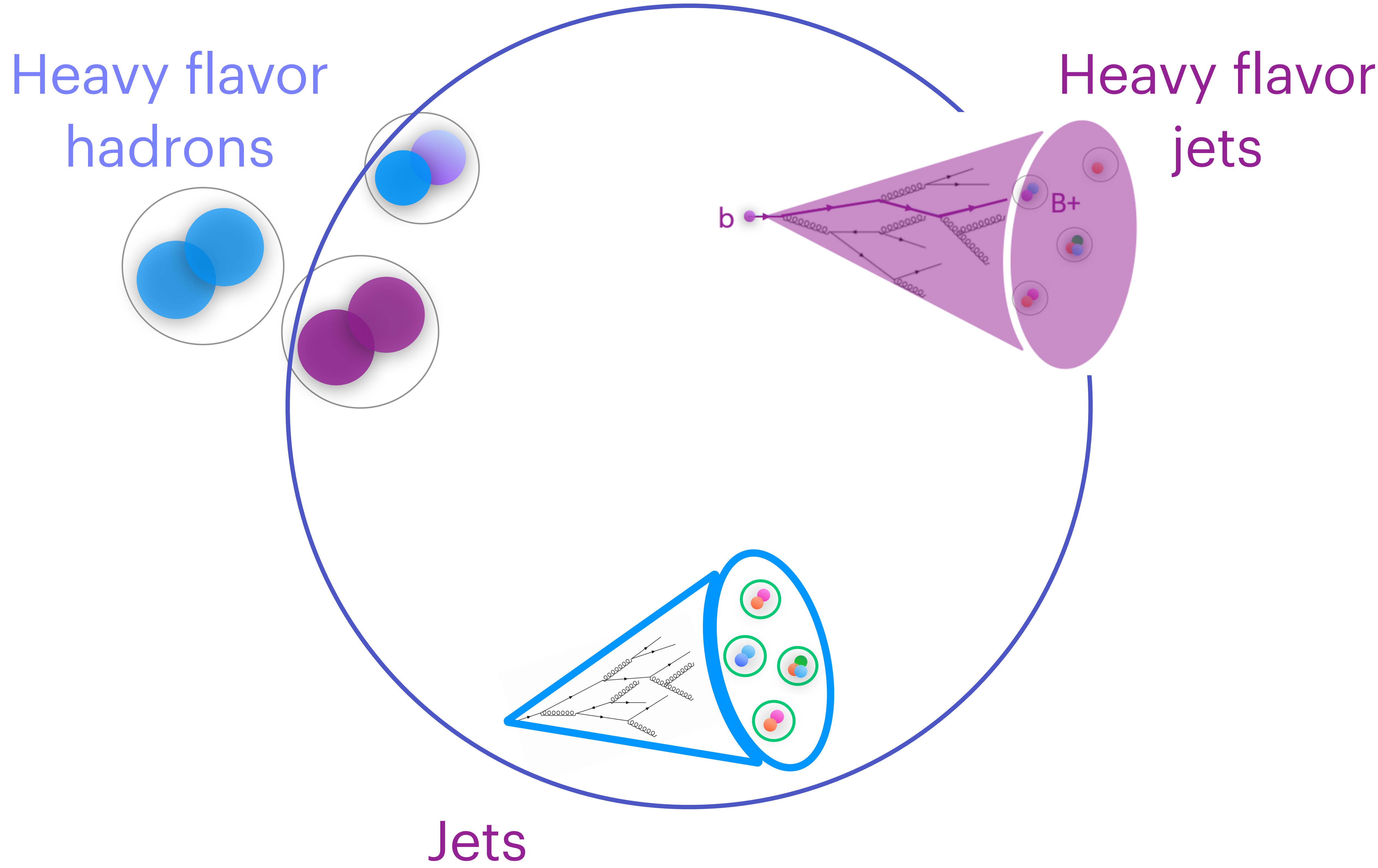
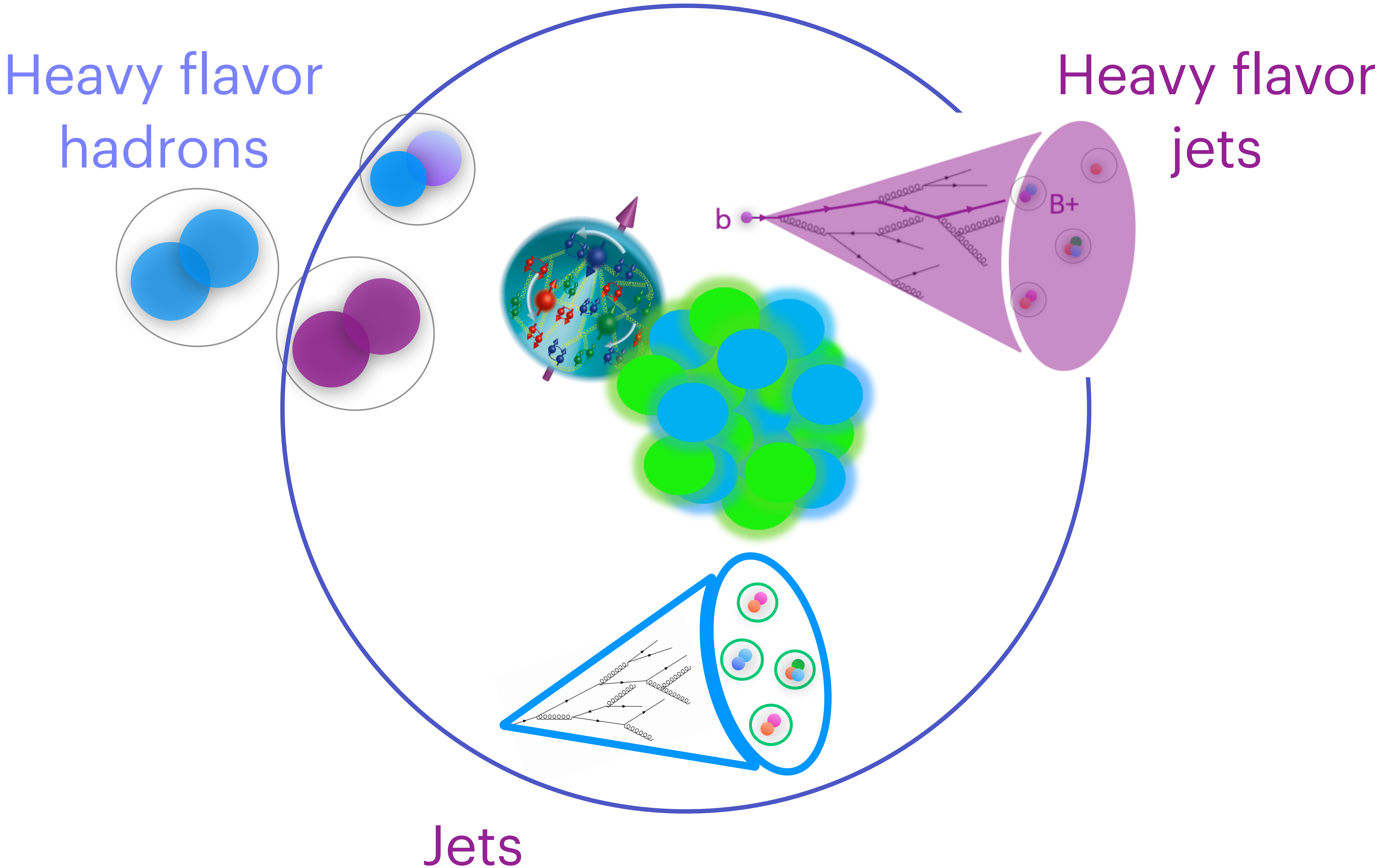
Last time



This lecture: how can we use jets and heavy flavor at the EIC?



This lecture: how can we use jets and heavy flavor at the EIC?

Today (Part 2):
Focus on measurements involving jets and heavy flavor at the EIC

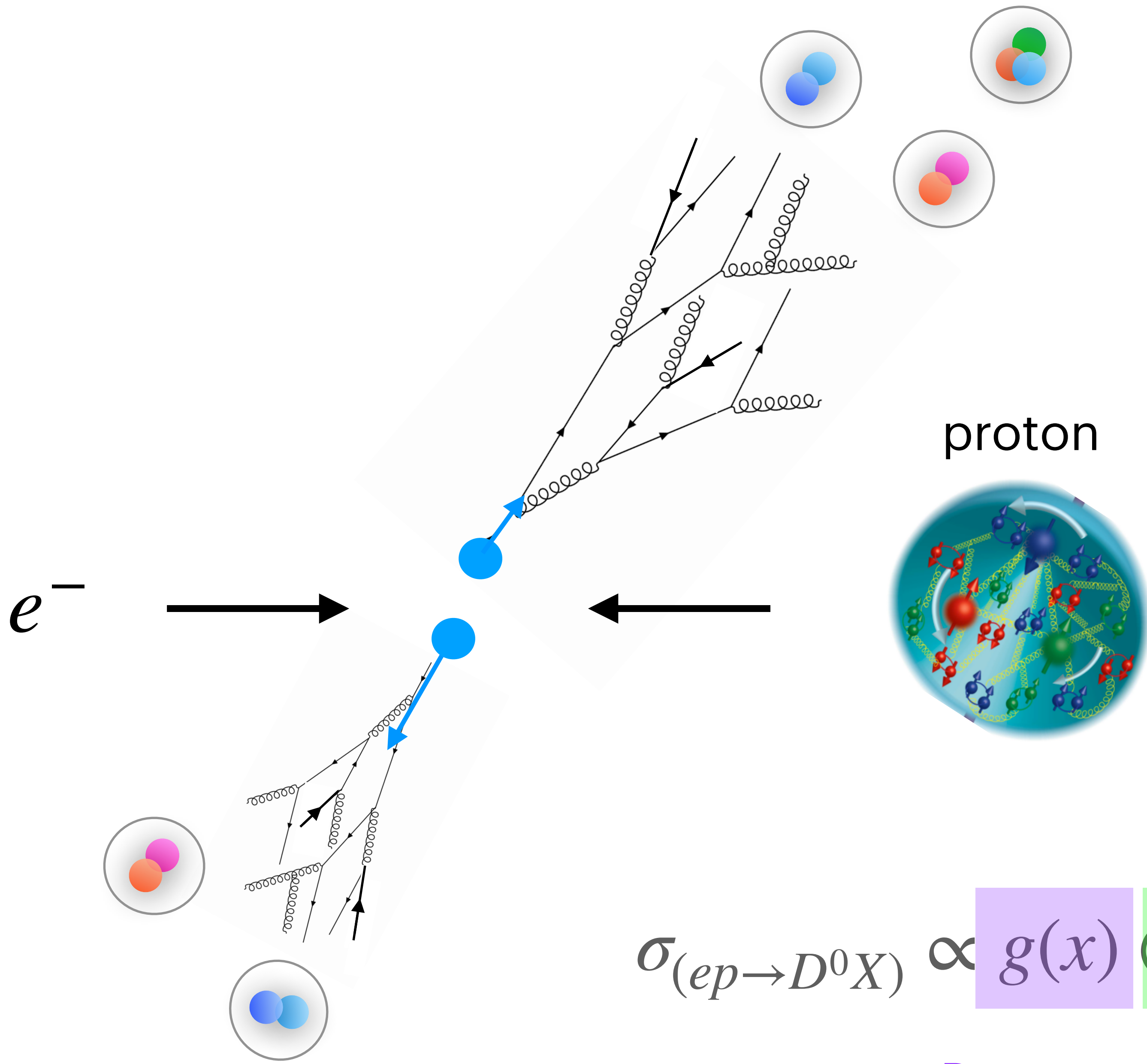
- How can we use jets and heavy flavor to probe nucleon structure?
- How can we use jets and heavy flavor to study cold nuclear matter?

More caveats:

- There are many studies of possible measurements with jet and heavy flavor probes at the EIC! This is NOT intended to be a review of all possible measurements at the EIC, it's just meant to give you a taste of what is planned/possible at the EIC :)
- I will not be covering photoproduction of J/ψ, because Charlotte will discuss it in her talk!

Heavy quark production in *ep* collisions

- What can we probe with this process?



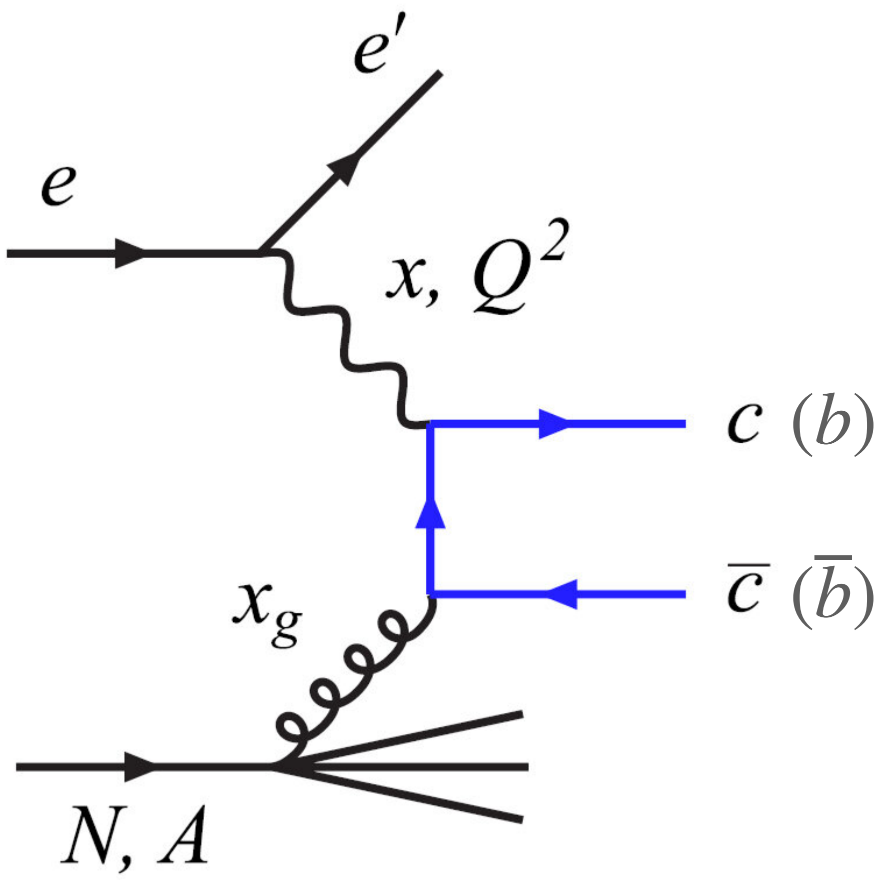
Fragmentation Function

$$\sigma_{(ep\rightarrow D^0X)} \propto g(x) \otimes \sigma_{\gamma g\rightarrow c\bar{c}} \otimes D_c^{D^0}(z)$$

Parton Distribution Function

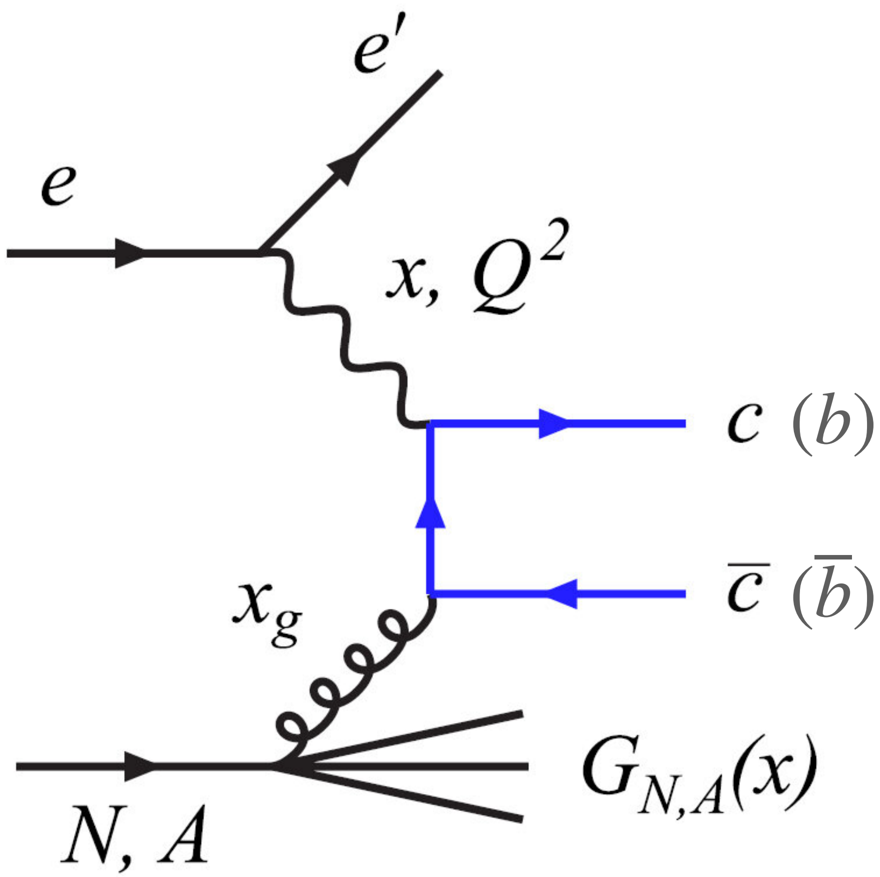
hard scattering cross section

Photon gluon fusion



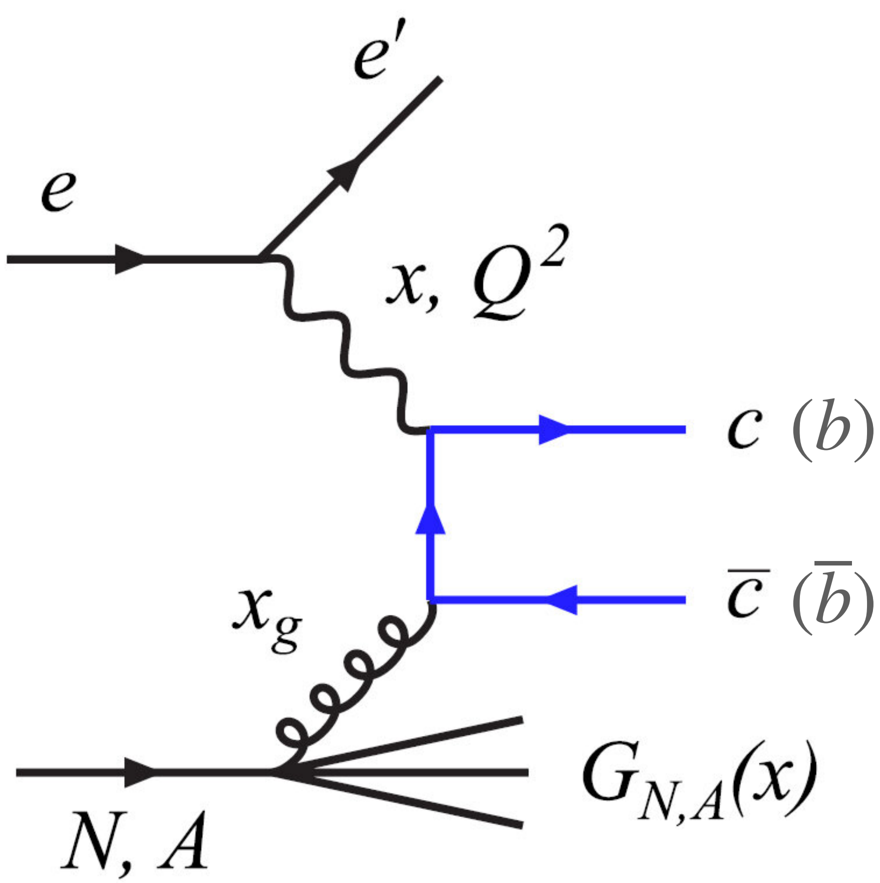
- Leading order process for heavy quark production at the EIC

Photon gluon fusion



- Leading order process for heavy quark production at the EIC
- **Heavy quark production at the EIC is directly sensitive to the gluon PDF** (collinear + TMD)
- How can we reconstruct the heavy quark pair experimentally? What are our proxies for heavy flavor quarks?

Photon gluon fusion



- Leading order process for heavy quark production at the EIC
- **Heavy quark production at the EIC is directly sensitive to the gluon PDF** (collinear + TMD)
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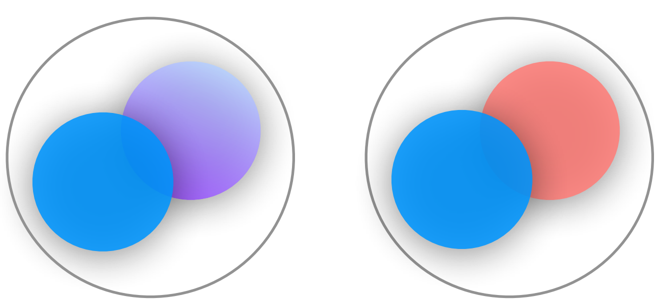
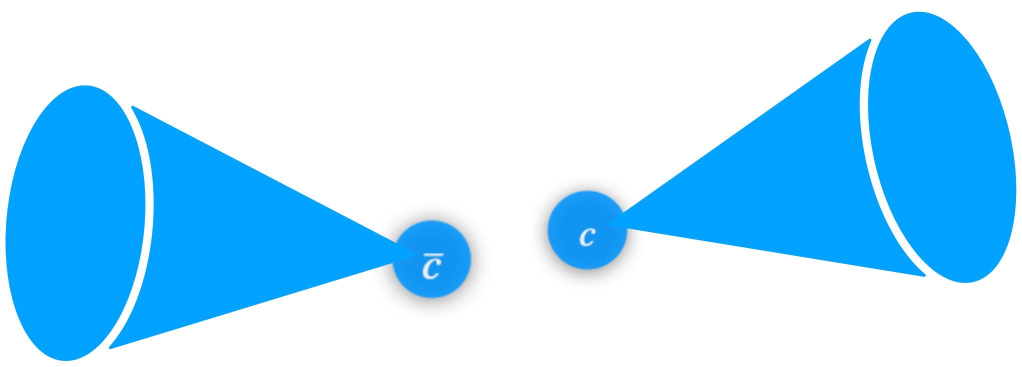
Charm and anti-charm hadron pair



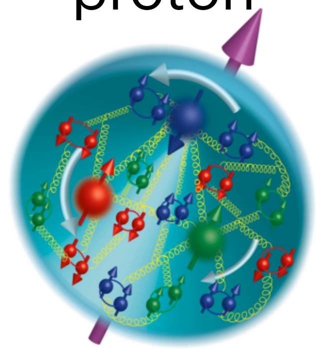
Charm dijet



Accessing gluon TMD PDFs with heavy quarks

e^- $\longrightarrow$ $\longleftarrow$

proton



- Gluon Sivers Function: spin-momentum correlation between the gluon’s transverse motion and the spin of the proton

Single Spin Asymmetry is proportional to the gluon Sivers function

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

Unpolarized electron

Transversely polarised proton

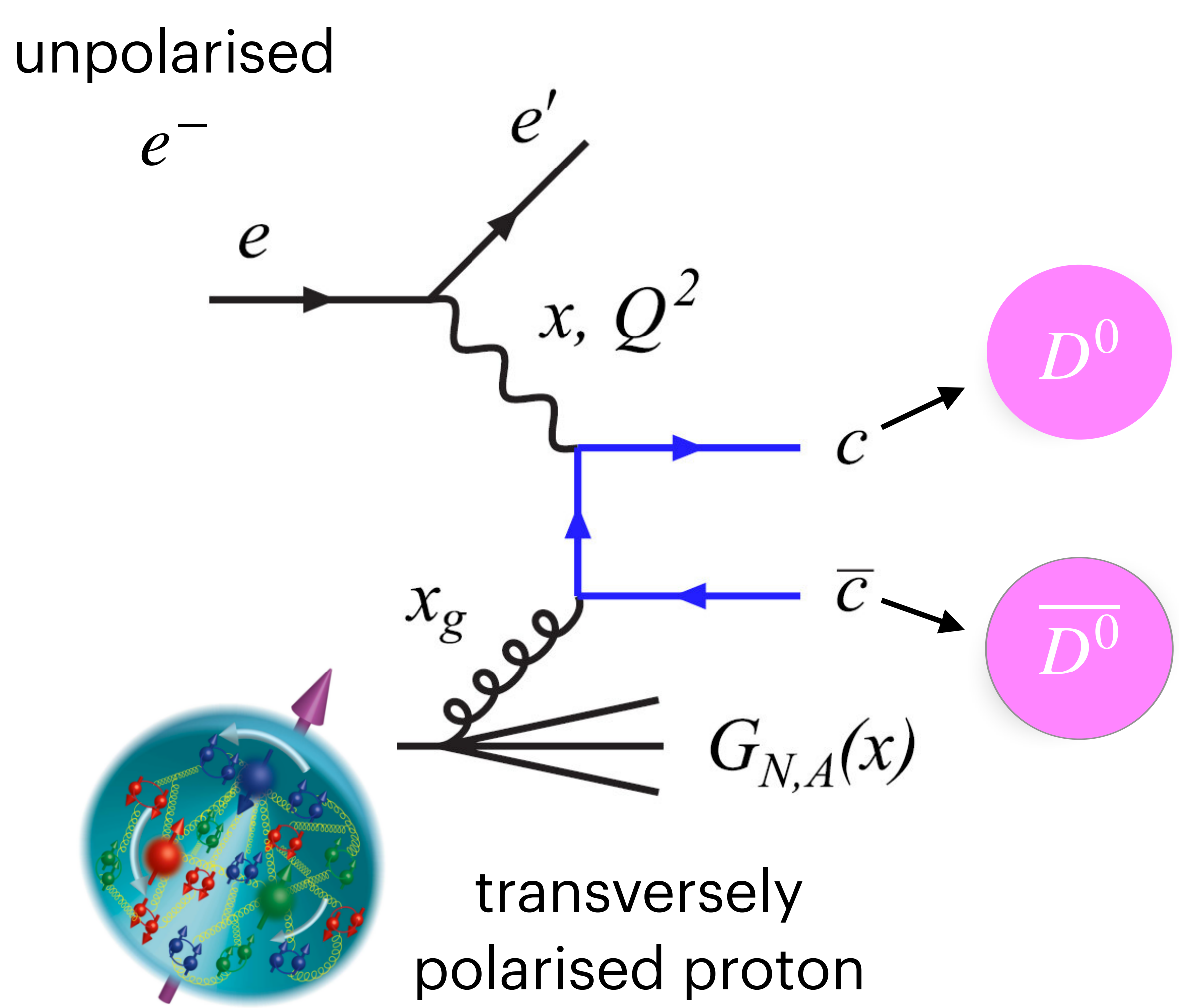
$d\sigma^{\uparrow}$ = cross section when proton beam is transversely polarised “up”

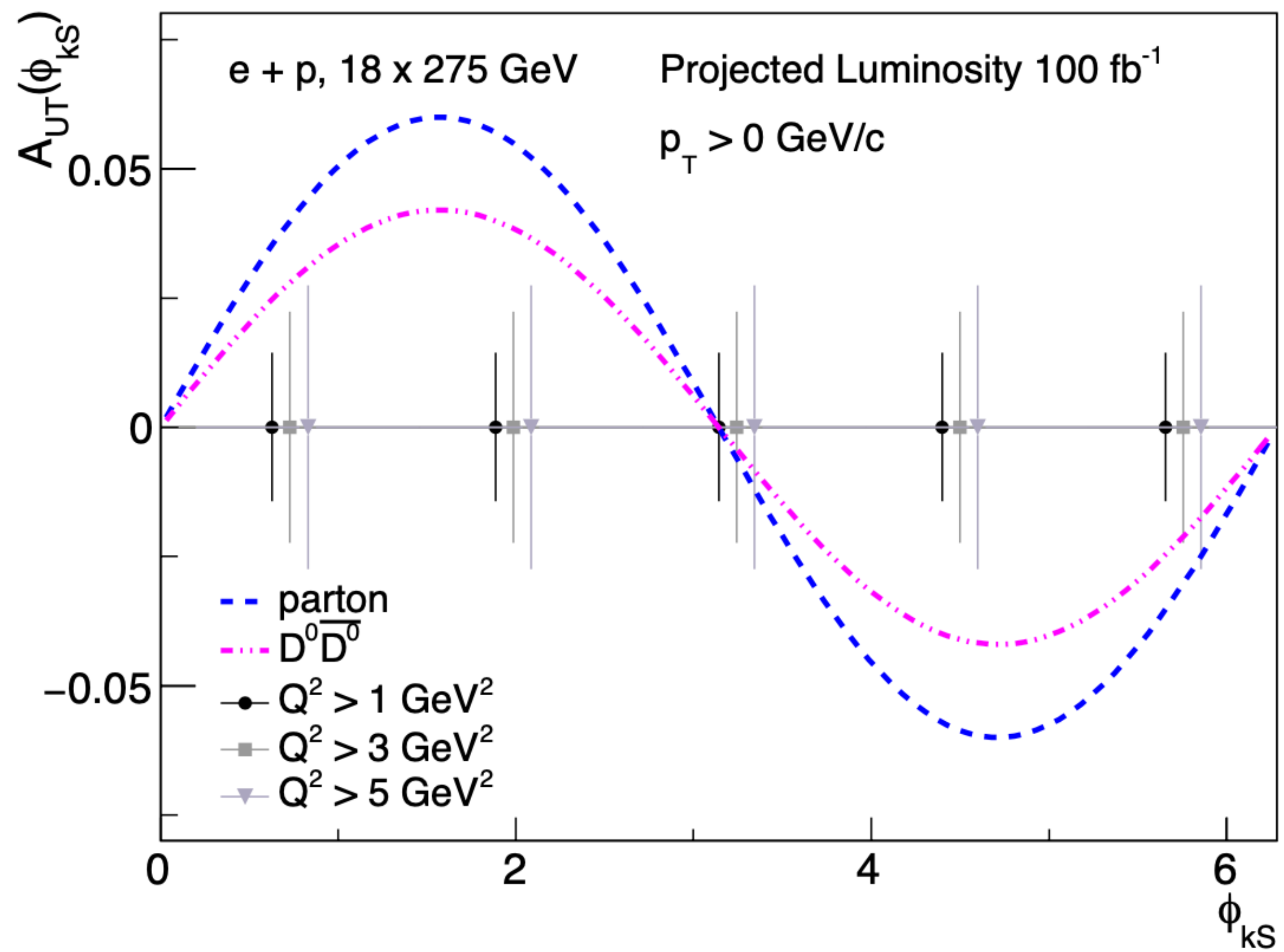
$d\sigma^{\downarrow}$ = cross section when proton beam is transversely polarised “down”

Accessing the gluon Sivers function with heavy flavor hadrons

Measure cross sections for charm hadron pair production to compute the SSA

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$





arxiv: 2102.08337

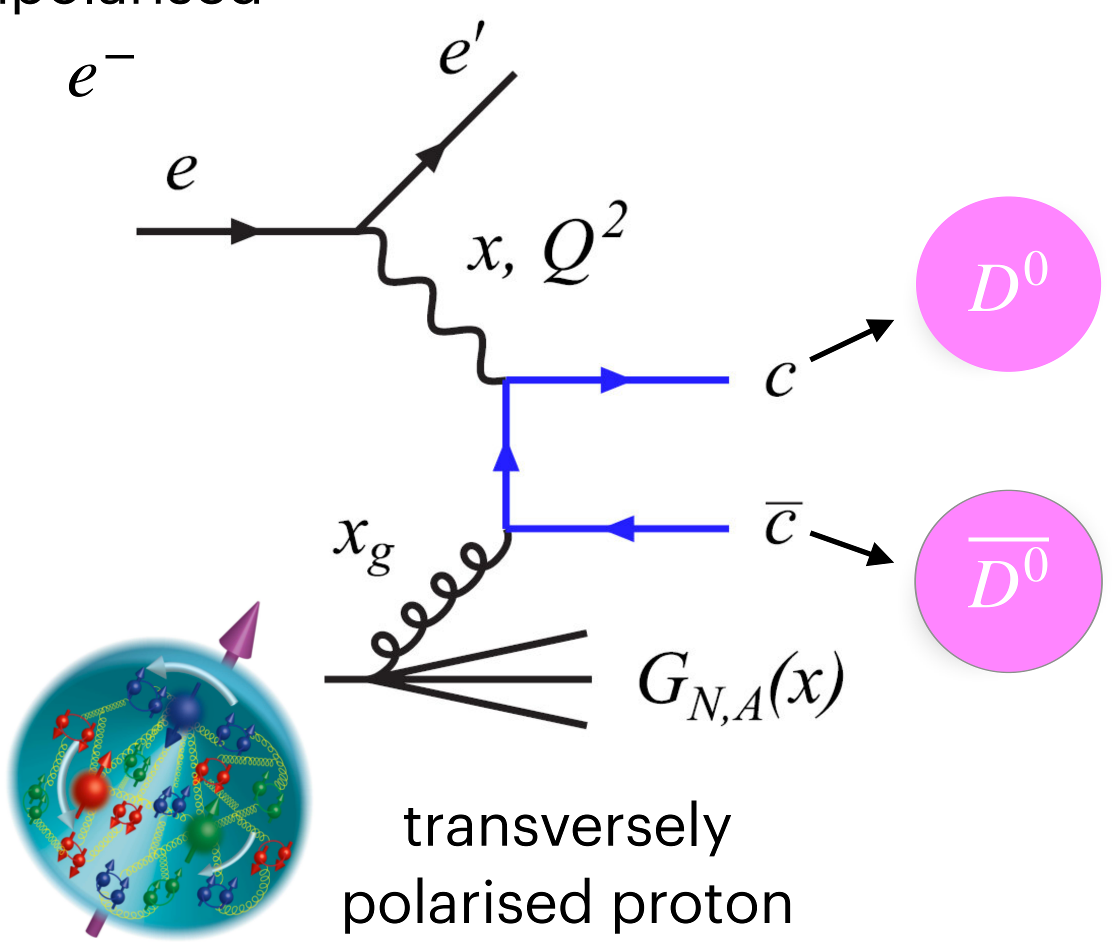
$\phi_{kS} =$ Angle between polarized proton spin direction and momentum of charm hadron pair

Accessing the gluon Sivers function with heavy flavor hadrons

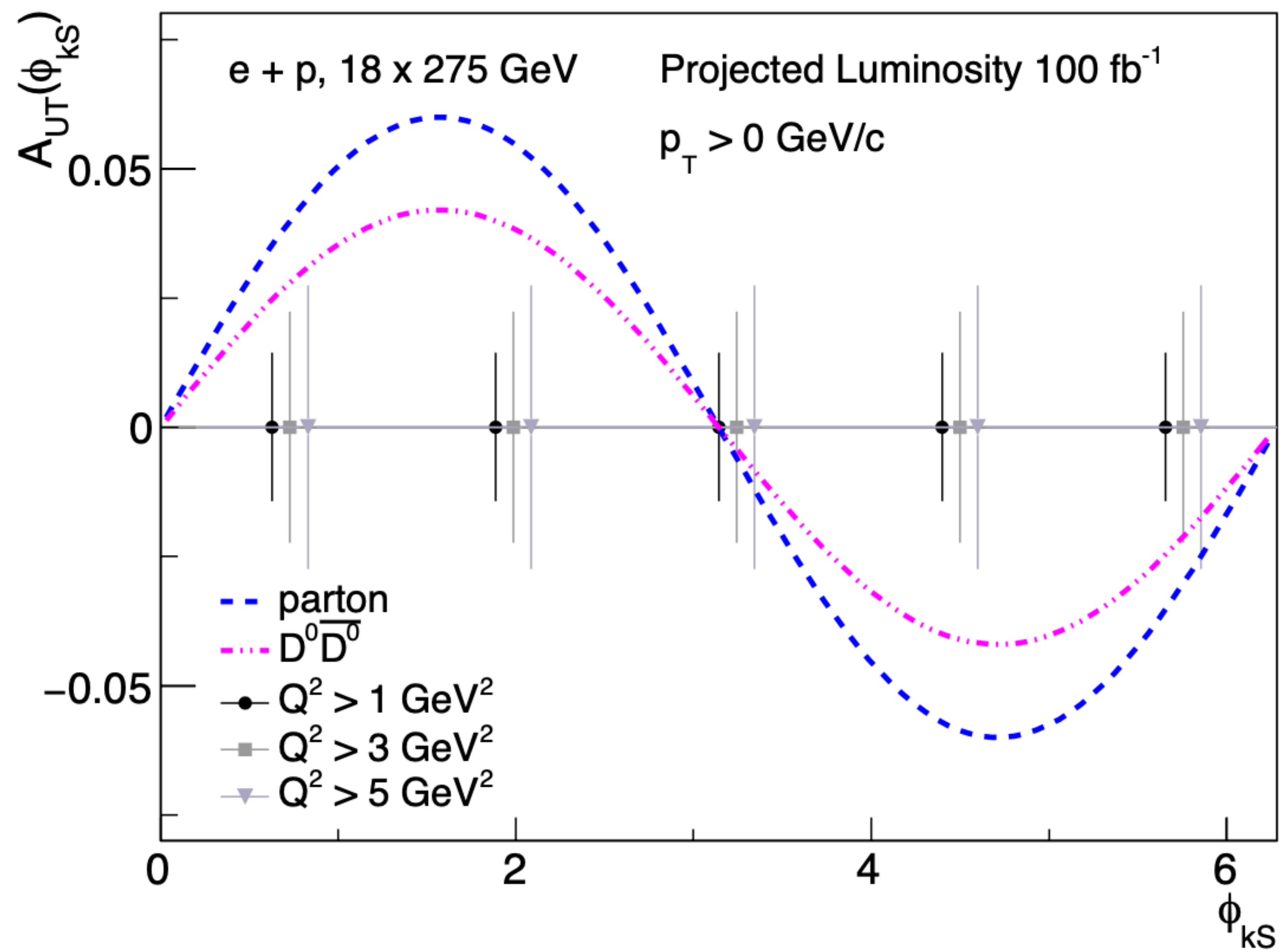
Measure cross sections for charm hadron pair production to compute the SSA

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

unpolarised



transversely polarised proton



arxiv: 2102.08337

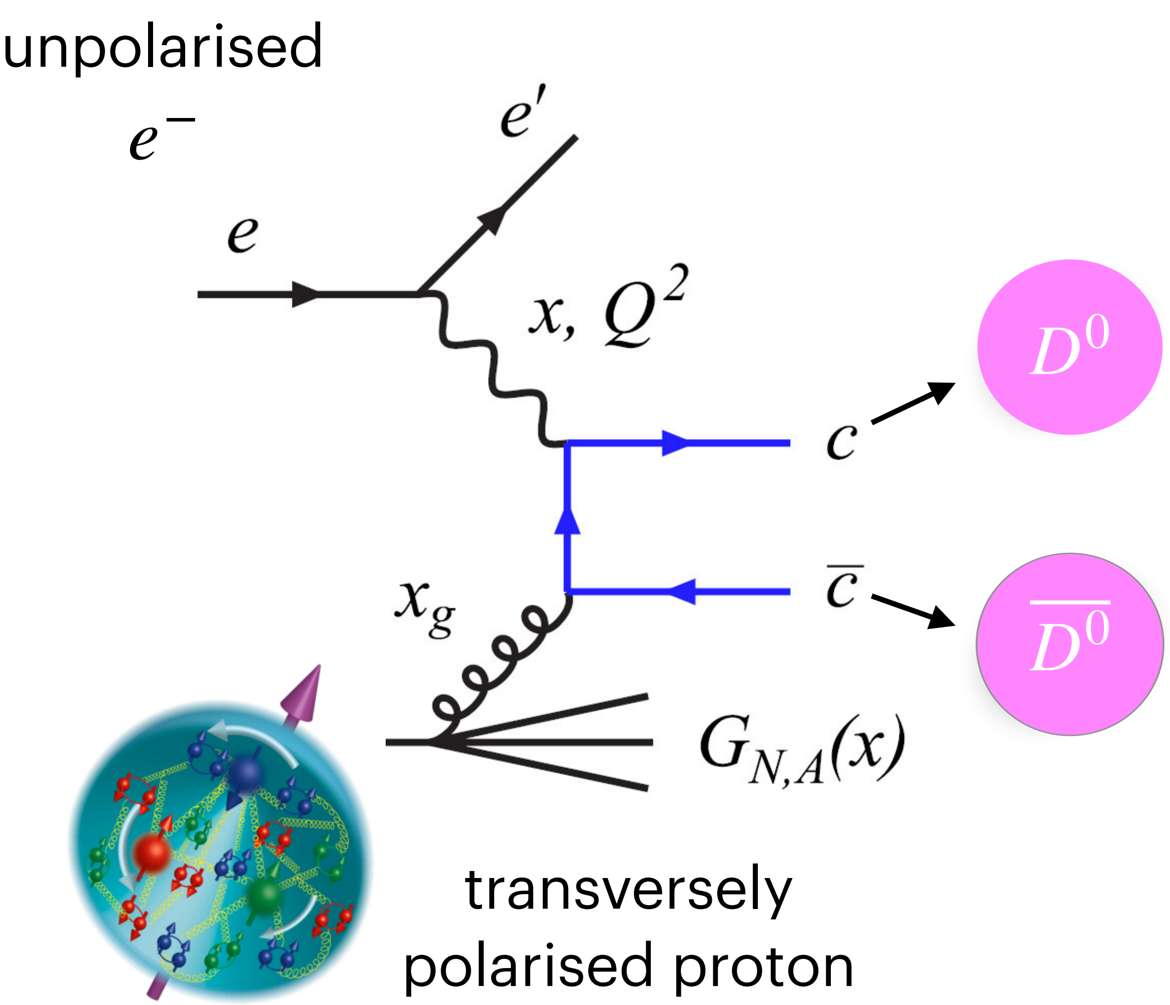
Parton level = the maximum sensitivity possible

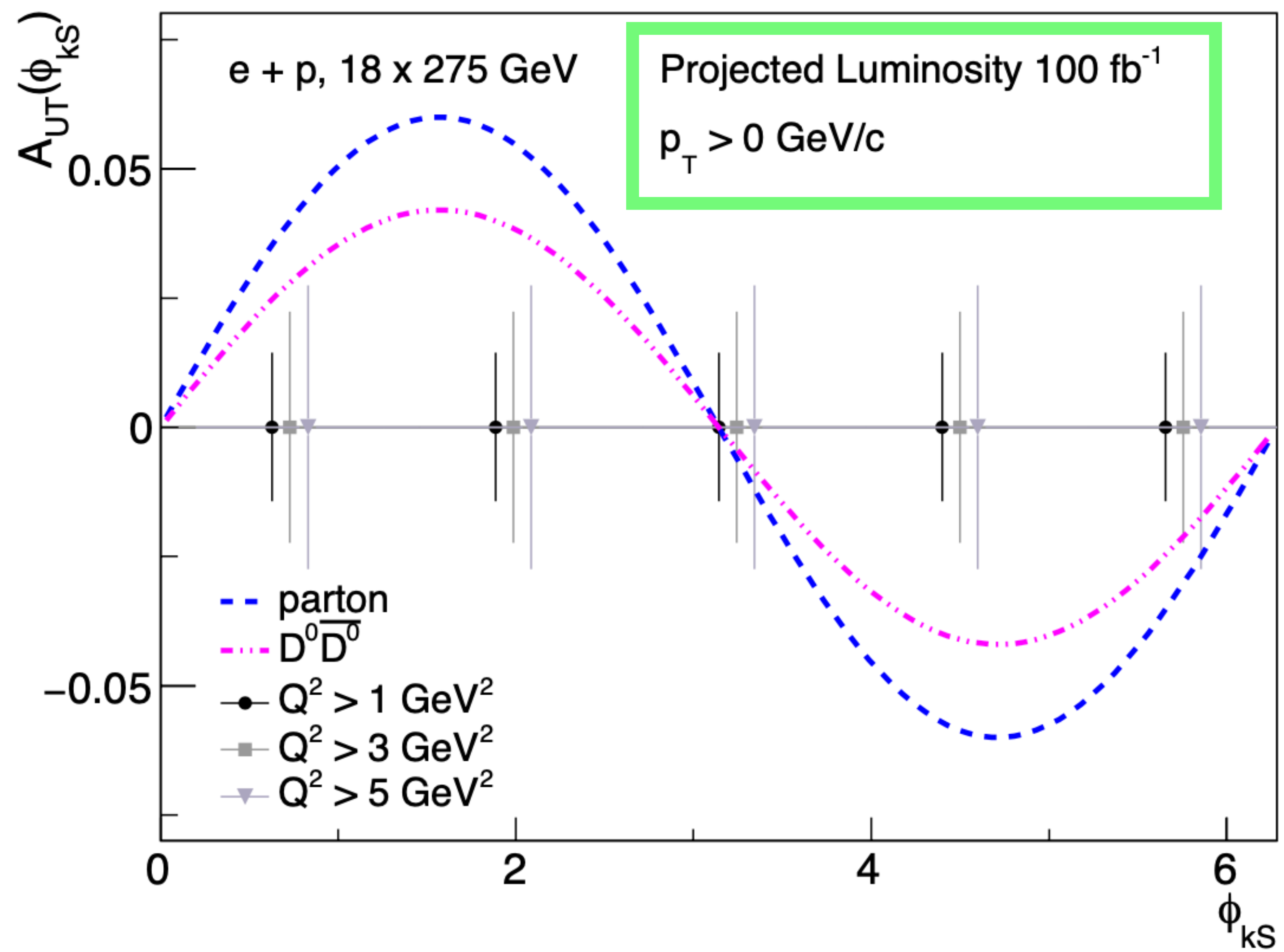
Decrease between parton level and hadron level -> why?

Accessing the gluon Sivers function with heavy flavor hadrons

Measure cross sections for charm hadron pair production to compute the SSA

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$





arxiv: 2102.08337

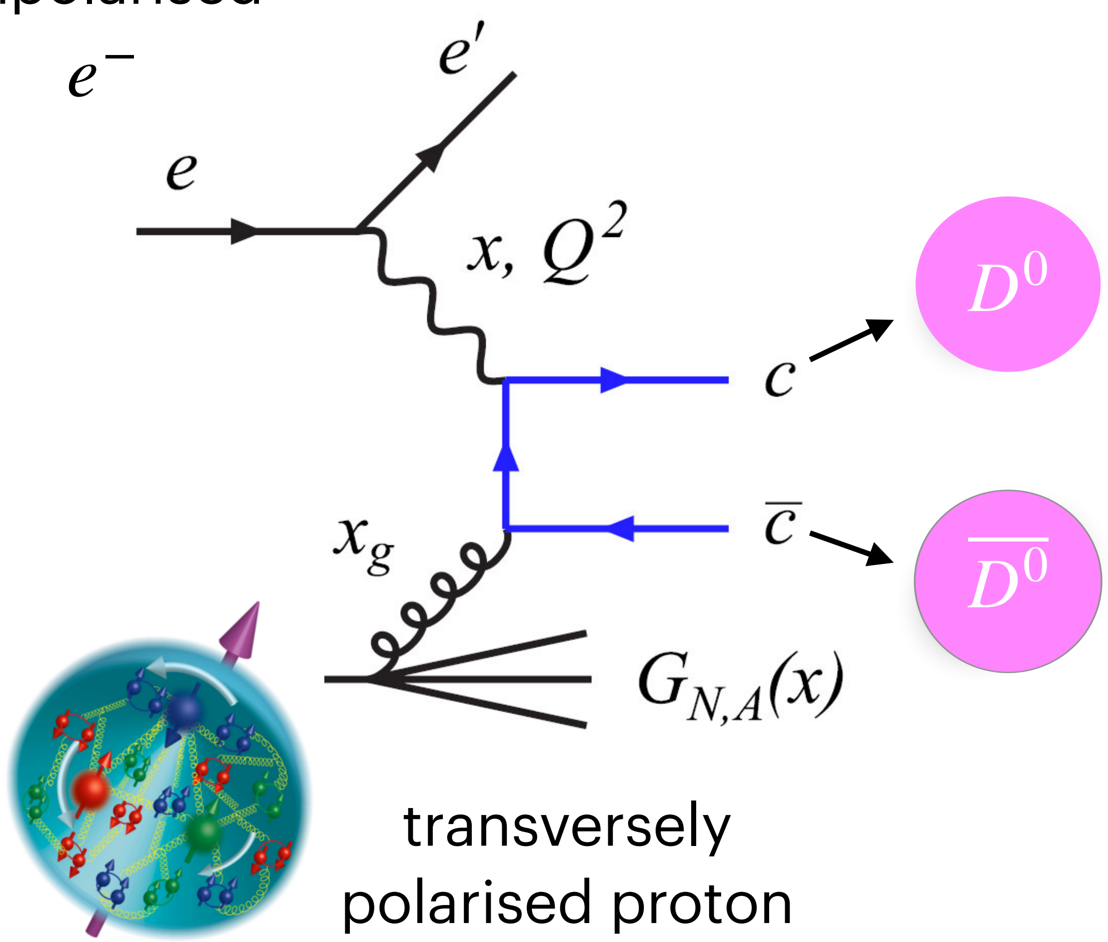
- This measurement needs a lot of statistics (~ several years of data-taking)
- Statistical error bars are still a bit large. Why?

Accessing the gluon Sivers function with heavy flavor hadrons

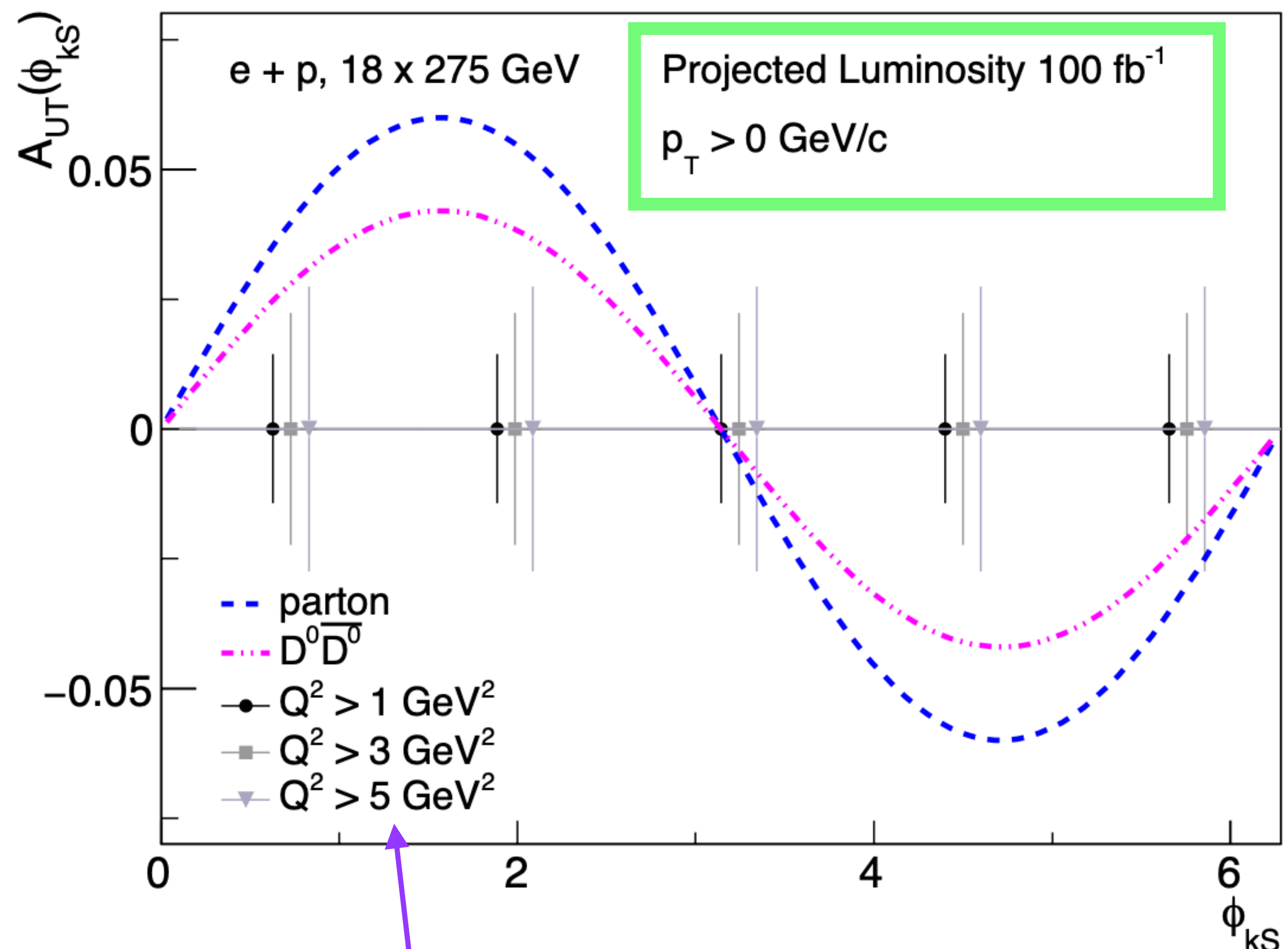
Measure cross sections for charm hadron pair production to compute the SSA

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

unpolarised



transversely polarised proton



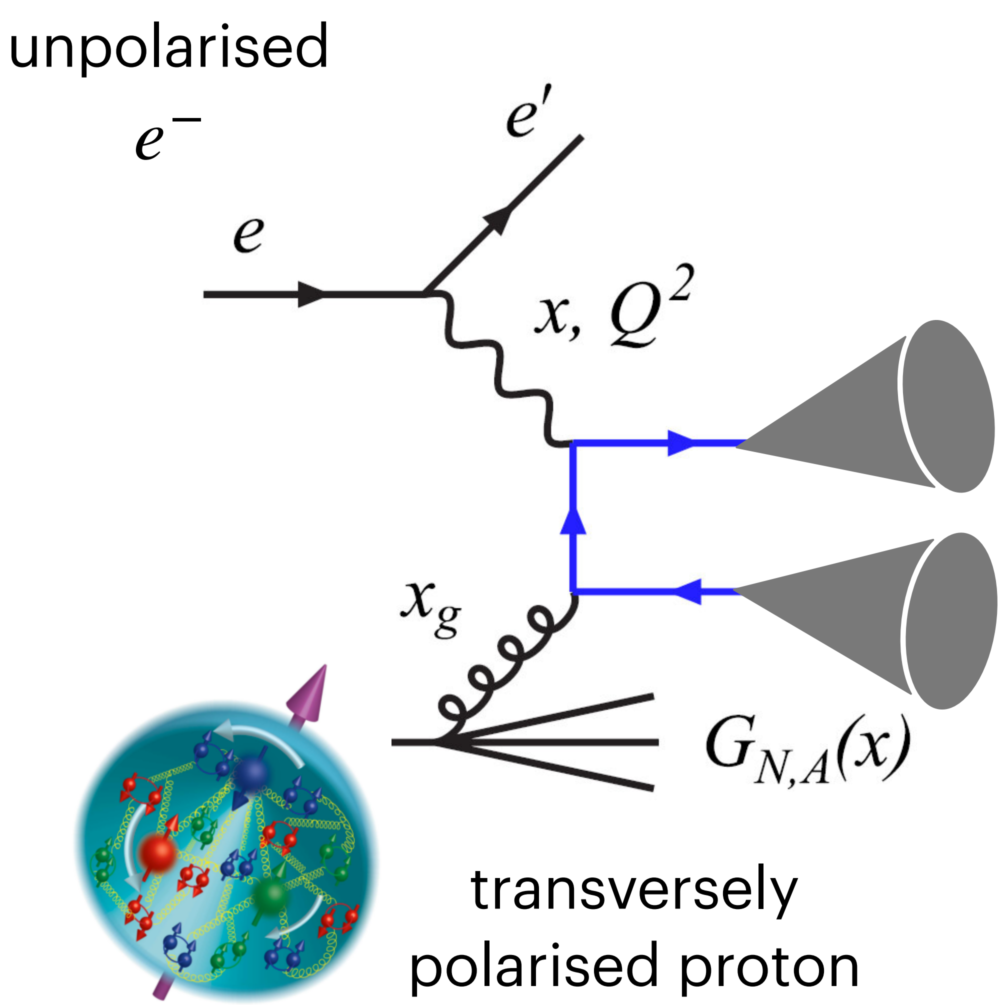
arxiv: 2102.08337

- Why do we want to measure this for different Q² bins?

Accessing the gluon Sivers function with dijets

Measure cross sections for dijet production to compute the SSA

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



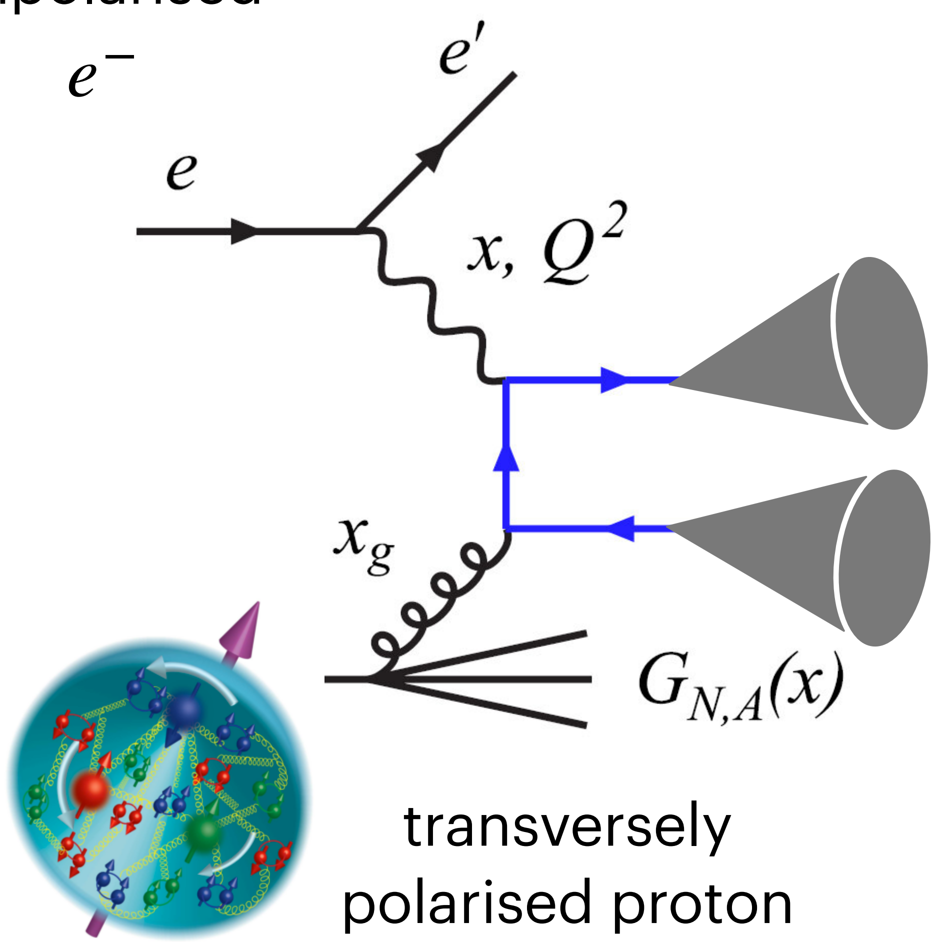
What is the problem if we measure **inclusive dijets**, instead of heavy flavor dijets?

Accessing the gluon Sivers function with dijets

Measure cross sections for dijet production to compute the SSA

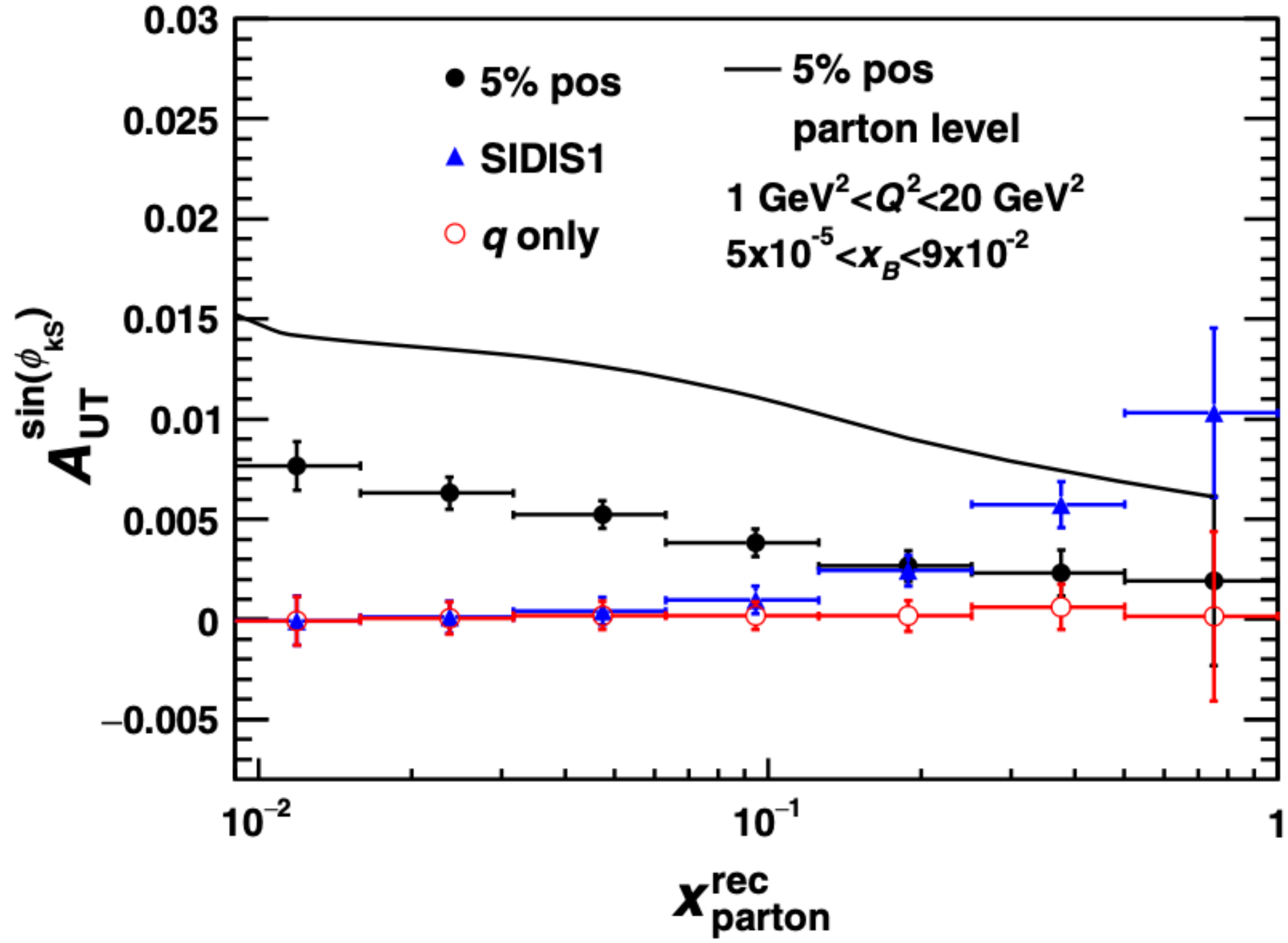
$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

unpolarised



transversely polarised proton

PRD **98** (2018) 034011



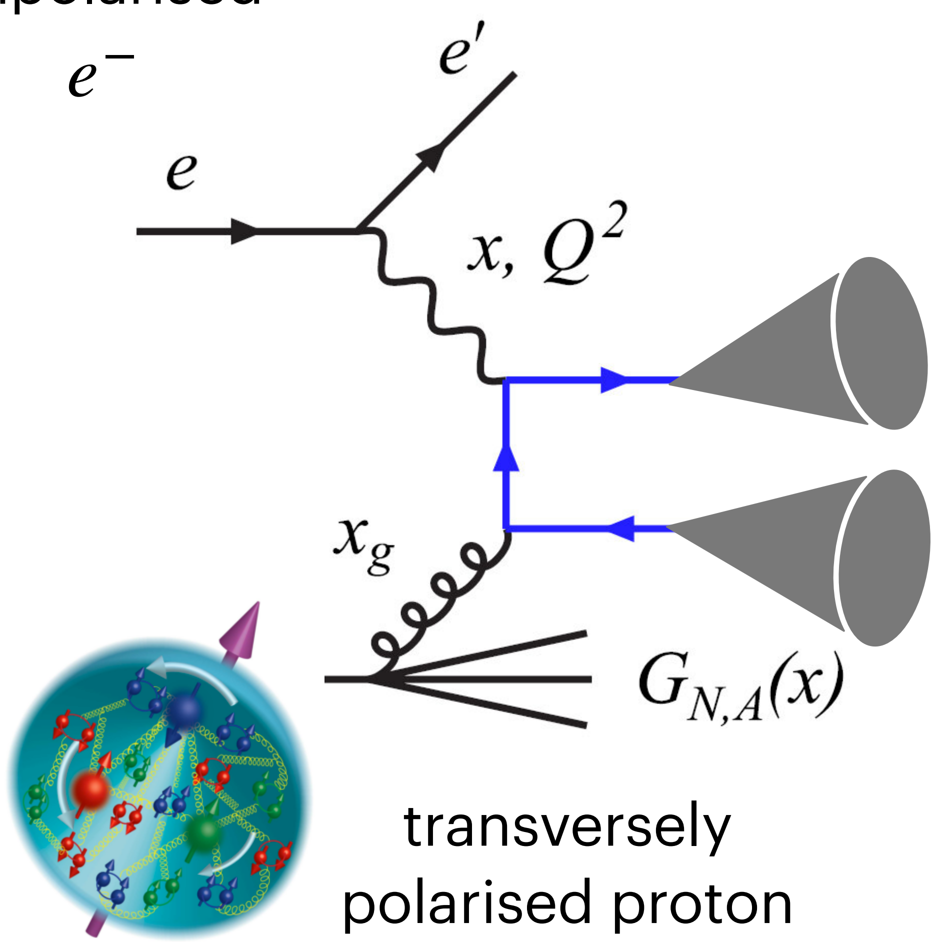
With inclusive dijets, you are not only probing photon-gluon fusion, so you have some quark-initiated contributions

Accessing the gluon Sivers function with dijets

Measure cross sections for dijet production to compute the SSA

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

unpolarised



transversely polarised proton

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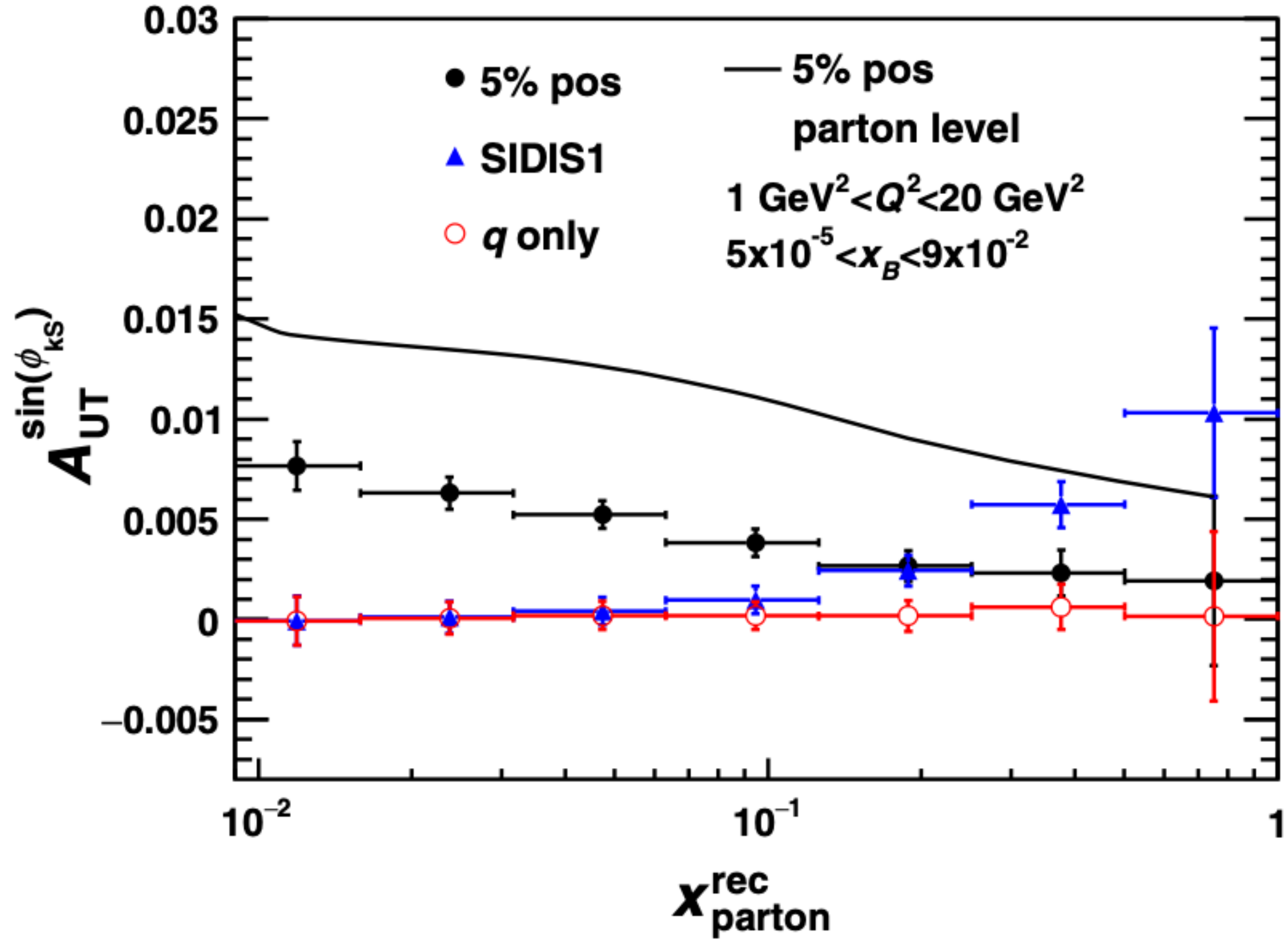


x_{parton}^{rec} = reconstructed x of gluon using the dijet kinematics

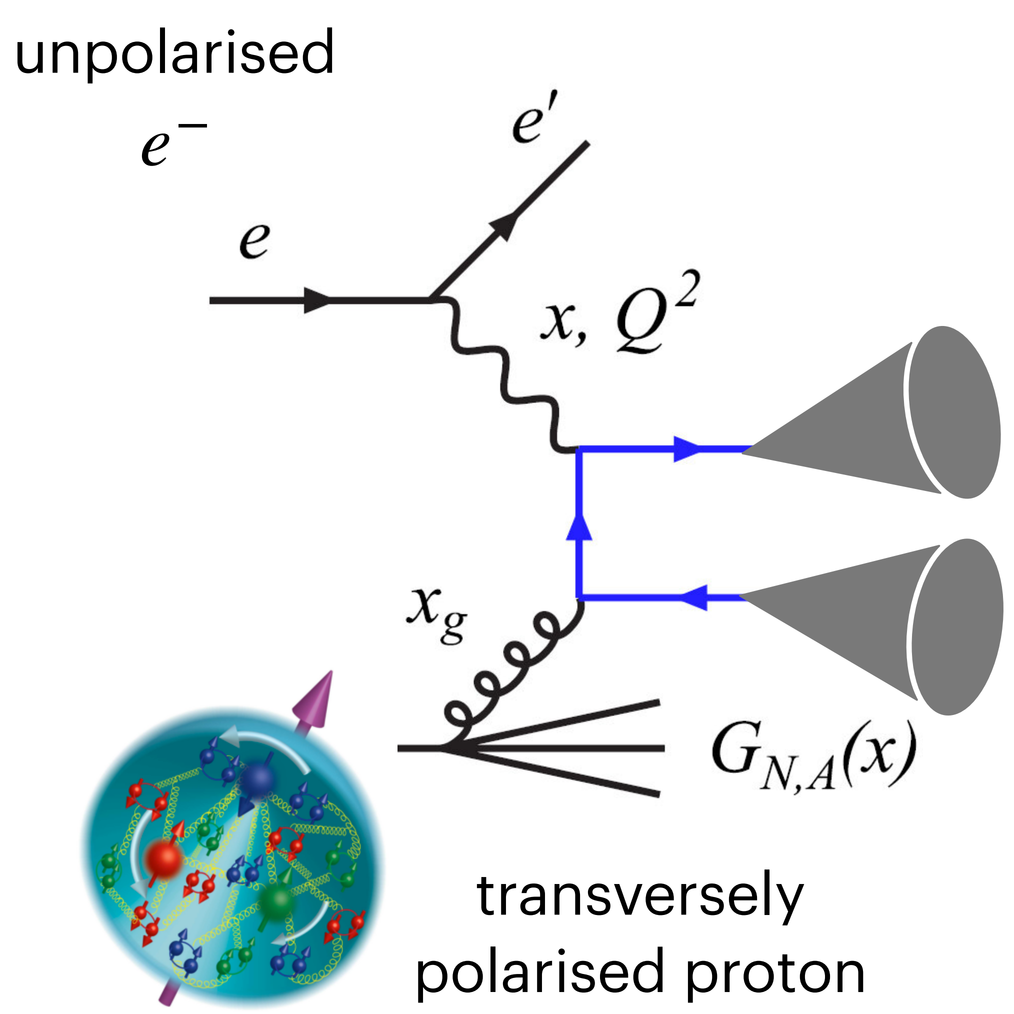
SSA measured with inclusive dijets still generally follows the parton-level trend

What else can you notice?

Accessing the gluon Sivers function with dijets

Measure cross sections for dijet production to compute the SSA

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



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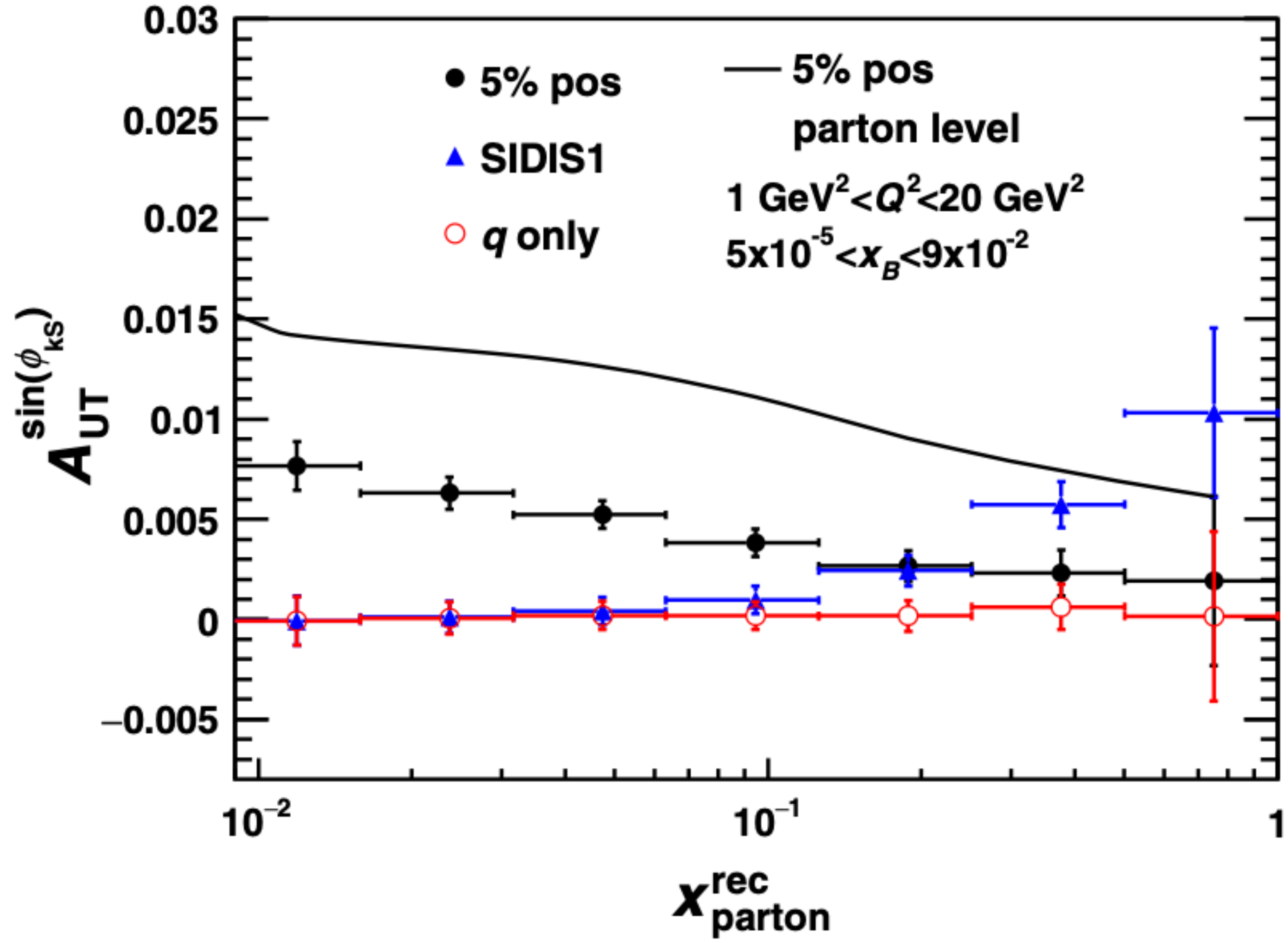


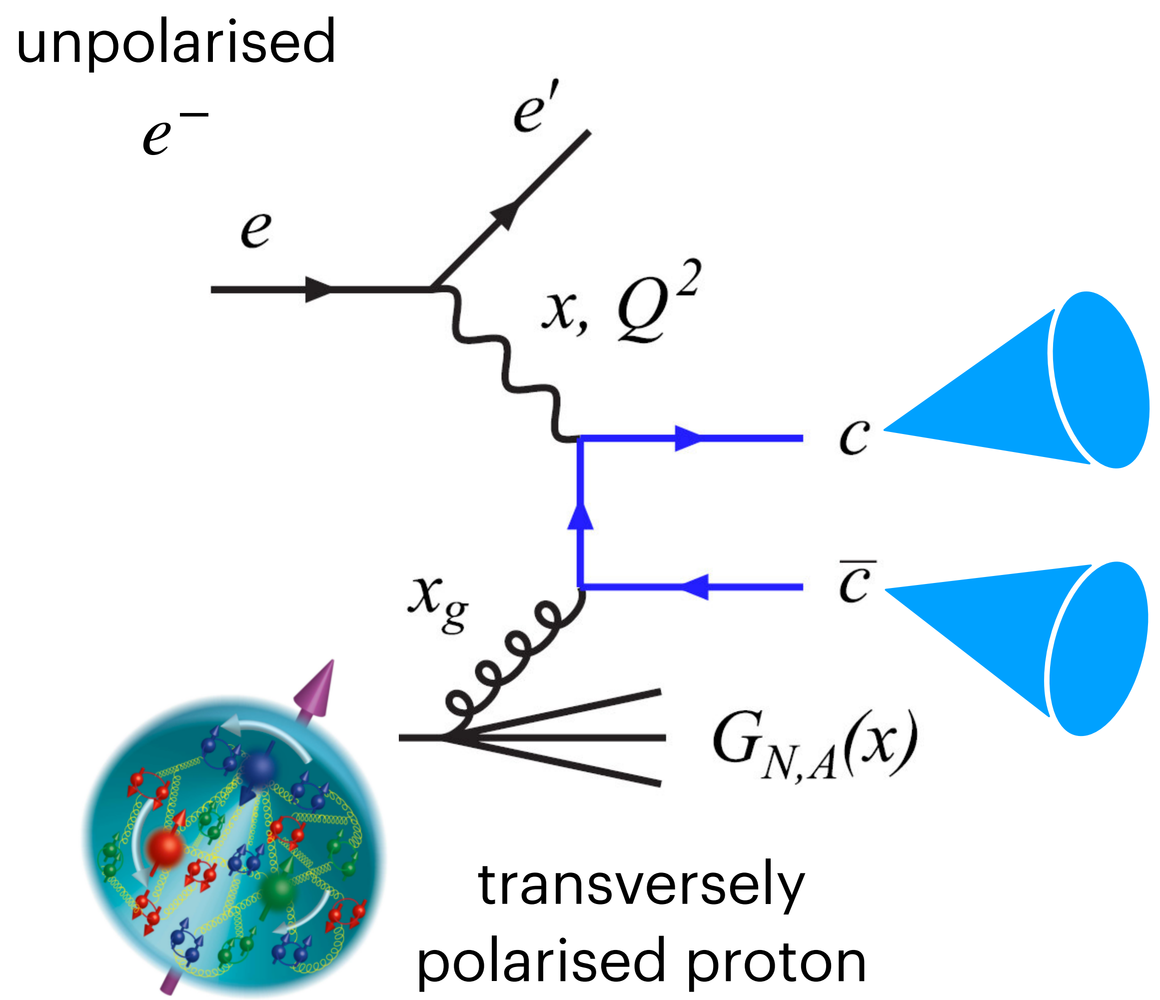
SSA measured with inclusive dijets still generally follows the parton-level trend

Statistical uncertainties are much lower!

Accessing the gluon Sivers function with heavy flavor dijets

Measure cross sections for dijet production to compute the SSA

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



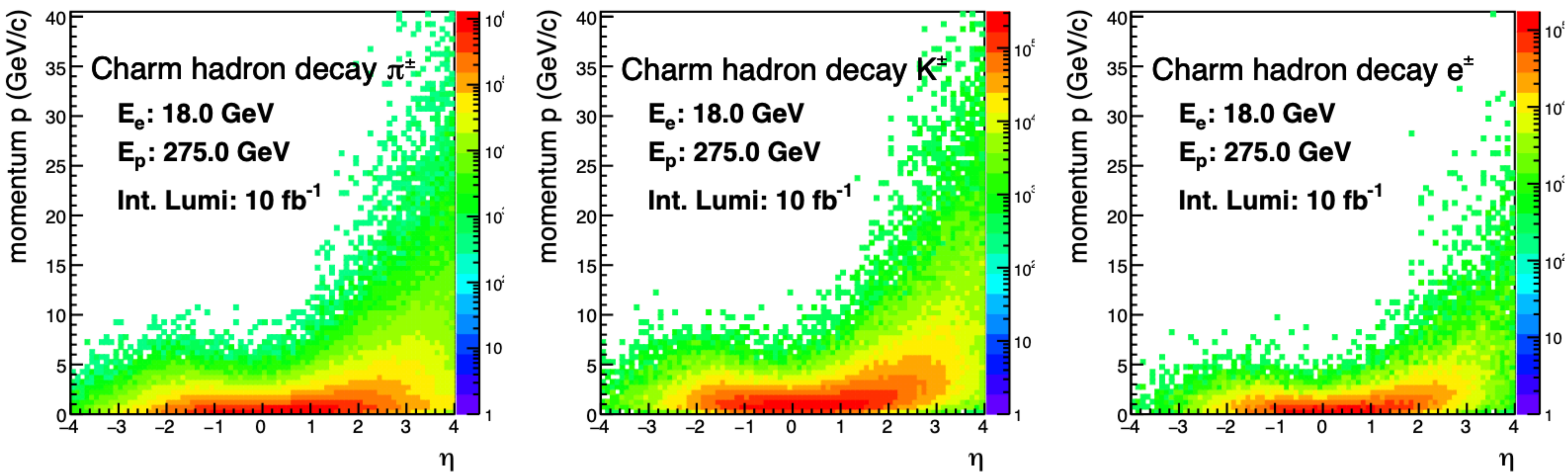
It would be interesting to see if using heavy flavor dijets gets you even closer to parton-level.

Of course, also need to take into account statistics here too!

Theory study already performed, see *JHEP* 05 (2021) 286

Heavy flavor hadron production at the EIC

For 18 GeV e^- beam and 275 GeV proton beam:

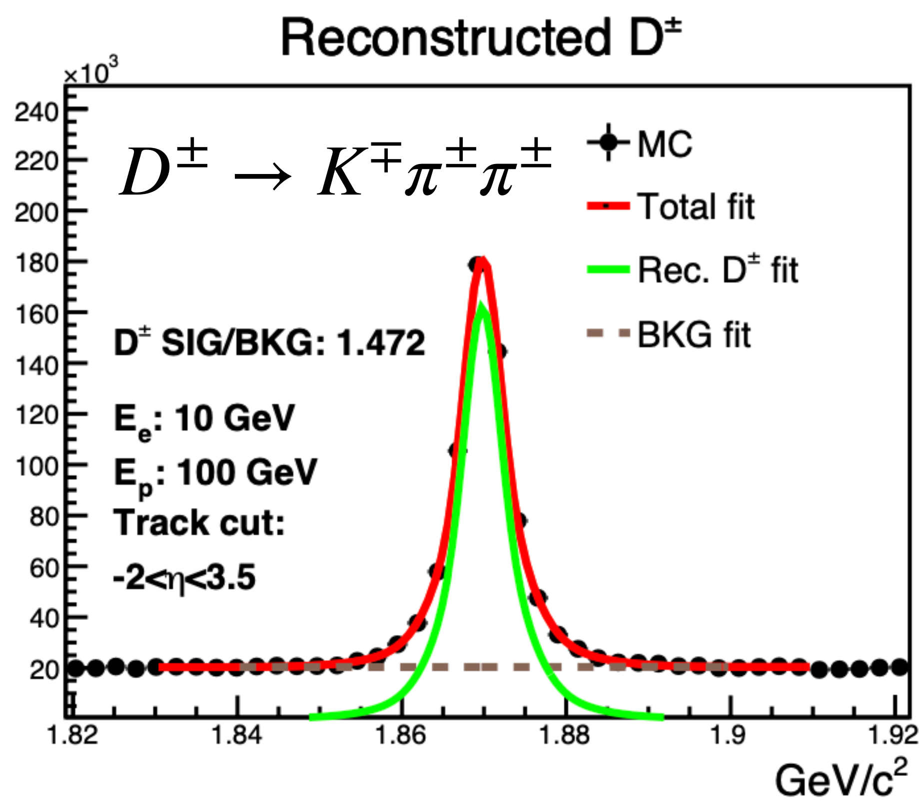


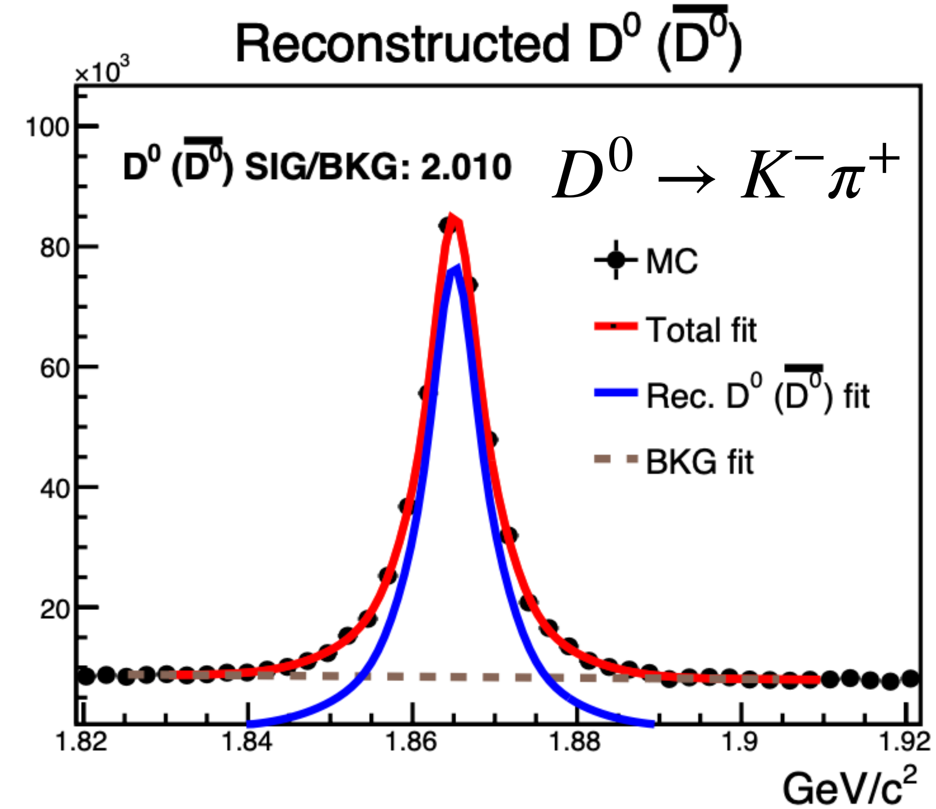
Most charm hadron decay products are produced at midrapidity or in the forward (proton-going) direction

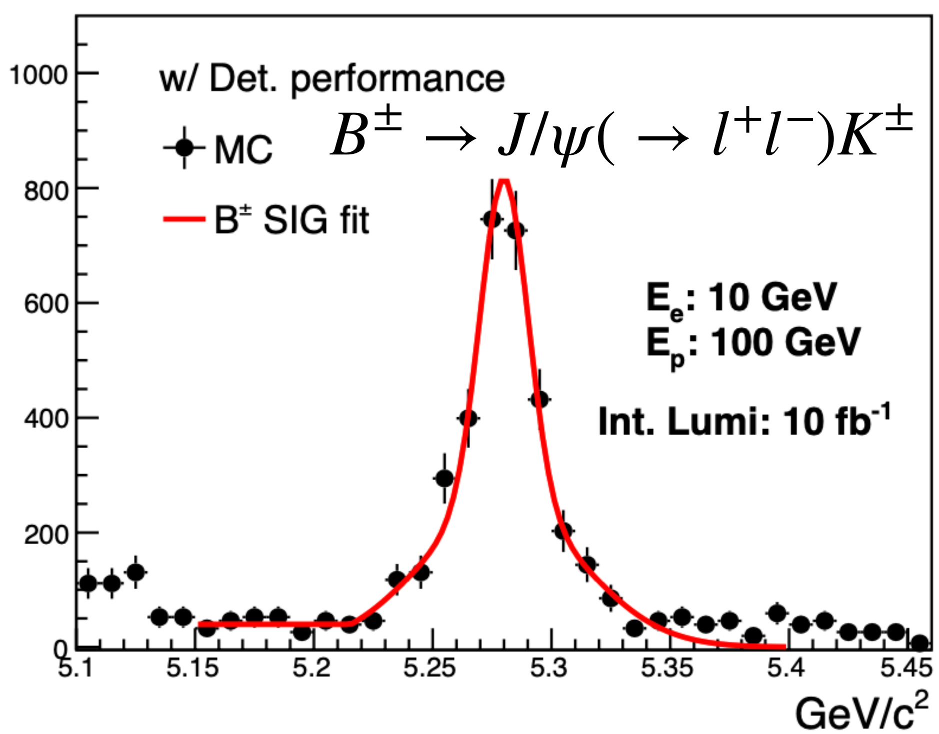
→ Motivates choice of where to put particle identification and precision tracking detectors

Nucl. Phys. A 1026 (2022) 122447

How well can we reconstruct heavy flavor hadrons at the EIC?







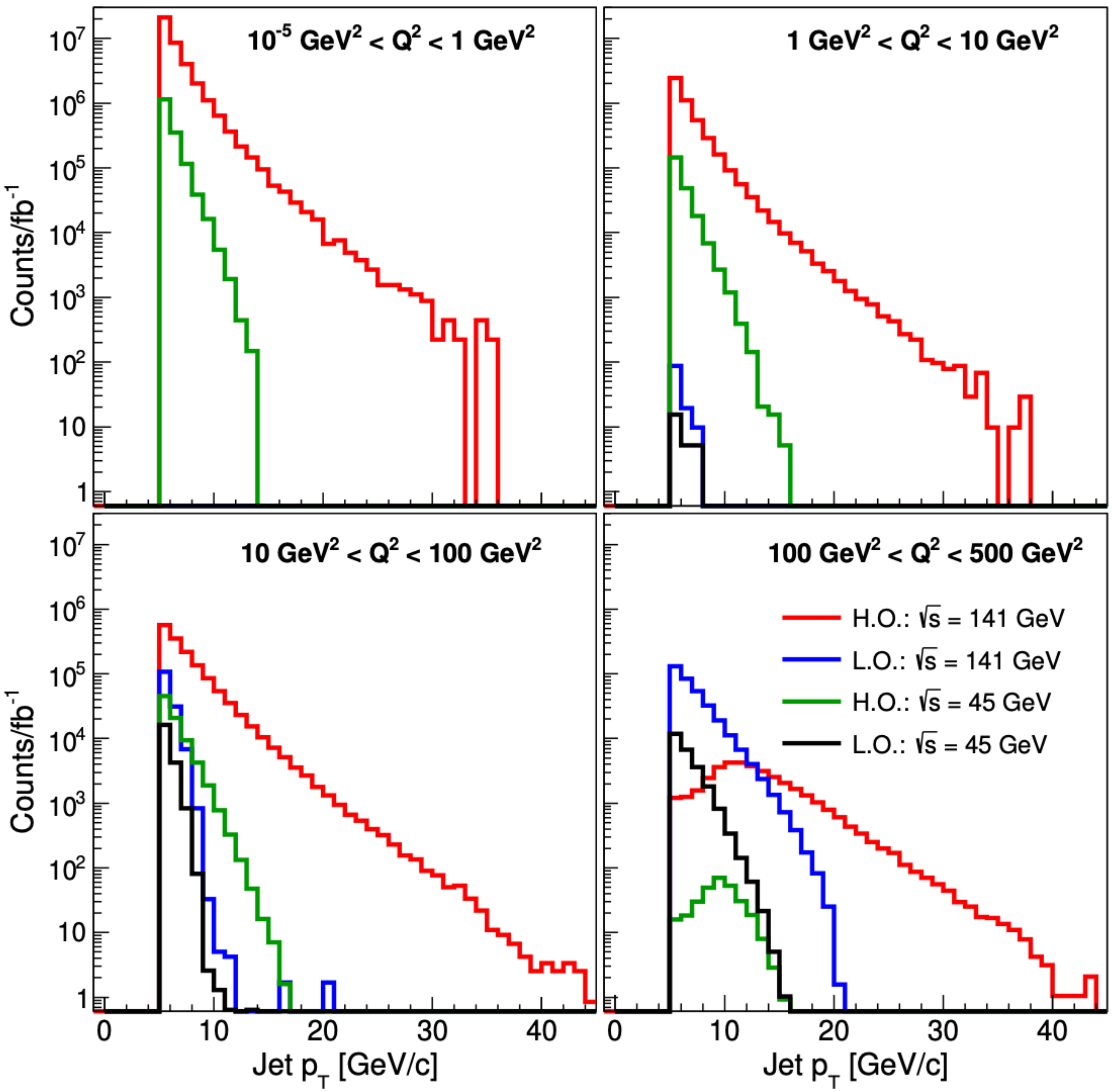
- Preliminary studies with detector simulations show that the heavy flavor reconstruction is very good!
- Low background, precision tracking and PID all help obtain good resolution

PoS QNP2024 (2025) 113

Nucl. Phys. A 1026 (2022) 122447

Jet kinematics at the EIC

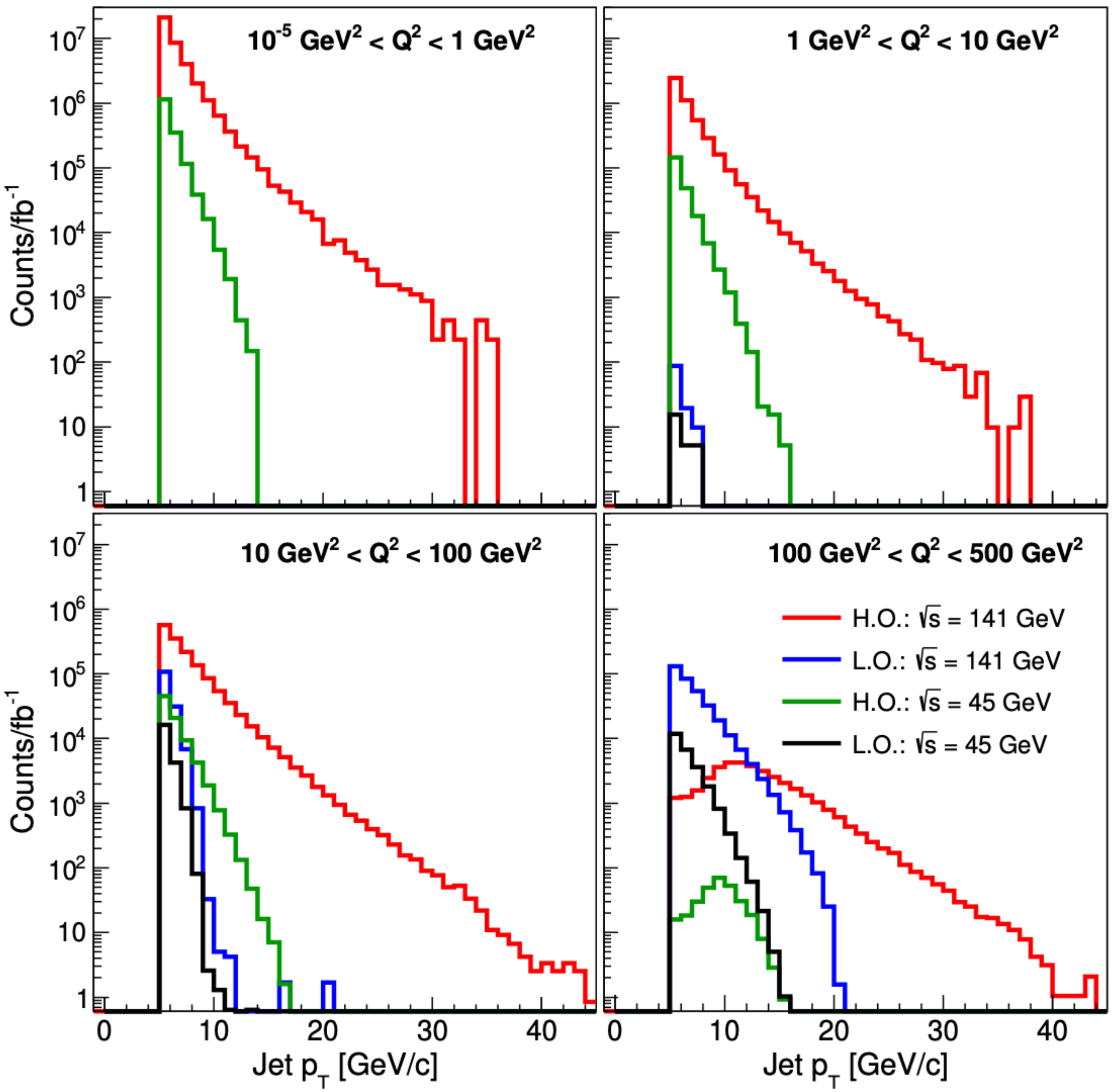
Phys. Rev. D **101**, 072003 (2020)   Int. luminosity 1 fb^{-1}



- Inclusive jet p_T spectra for different partonic processes
- LO = Leading order DIS process
- HO = all other higher order processes
- What do you notice about this plot?

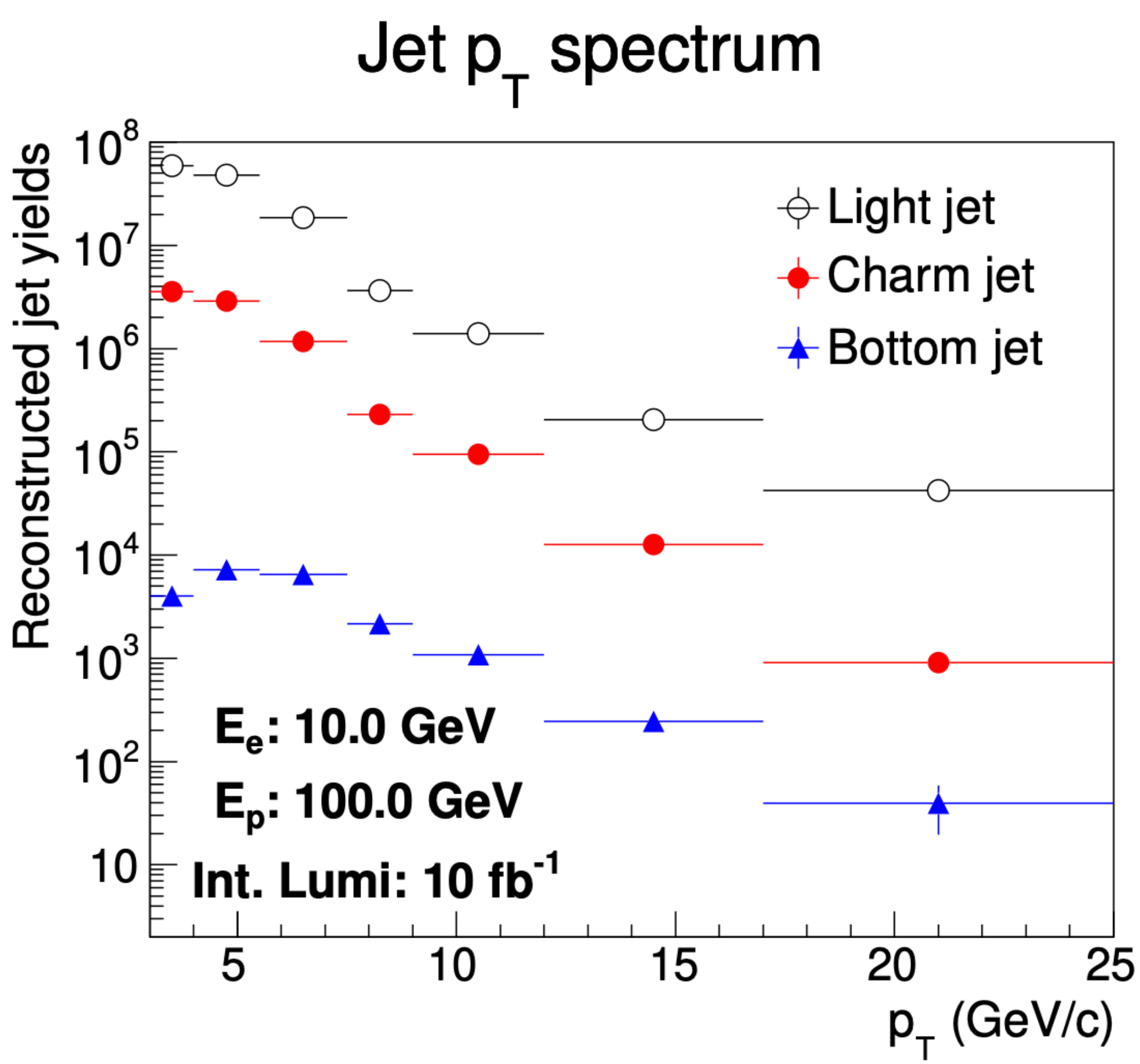
Jet kinematics at the EIC

Phys. Rev. D **101**, 072003 (2020)   Int. luminosity 1 fb^{-1}



- Inclusive jet p_T spectra for different partonic processes
- LO = Leading order DIS process
- HO = all other higher order processes
- What do you notice about this plot?
  - Steeply falling jet spectra! Fewer high p_T jets at EIC
  - High $\sqrt{s}$ is important in order to have more jets
  - Jet production from LO DIS is strongly dependent on Q^2

Heavy flavor jets at the EIC

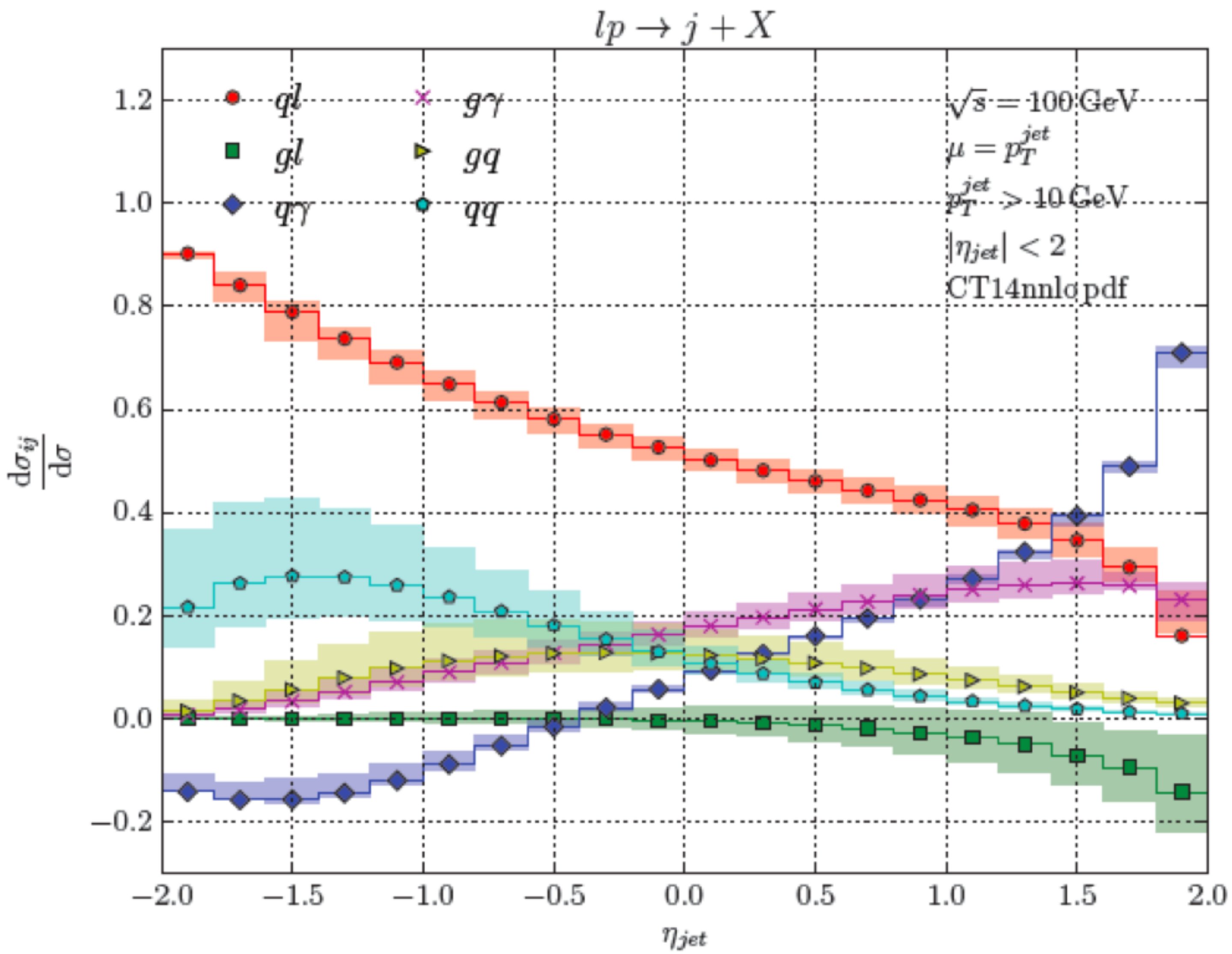


PoS QNP2024 (2025) 113

- Heavy flavor jets are more difficult to produce at the EIC, due to the lower collision energy
- Charm jets will be more easily accessible than beauty jets, which will require very large statistics
- However, heavy flavor jets are still accessible at the EIC! They will be very interesting to study due to the cleaner EIC events → less “underlying” event, will be interesting to compare substructure with that measured at other colliders

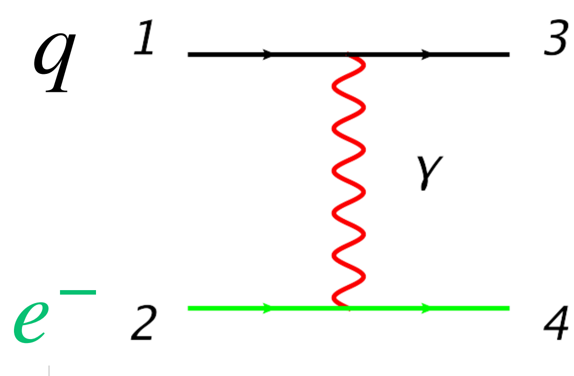
Constraining PDFs with inclusive jet production

- Usually in EIC measurements we want to reconstruct the scattered electron, but for some measurements we don't always need to. One example: inclusive jets



G. Abelof, R. Boughezel, X. Liu, F. Petriello
PLB **763**, 52 (2016)

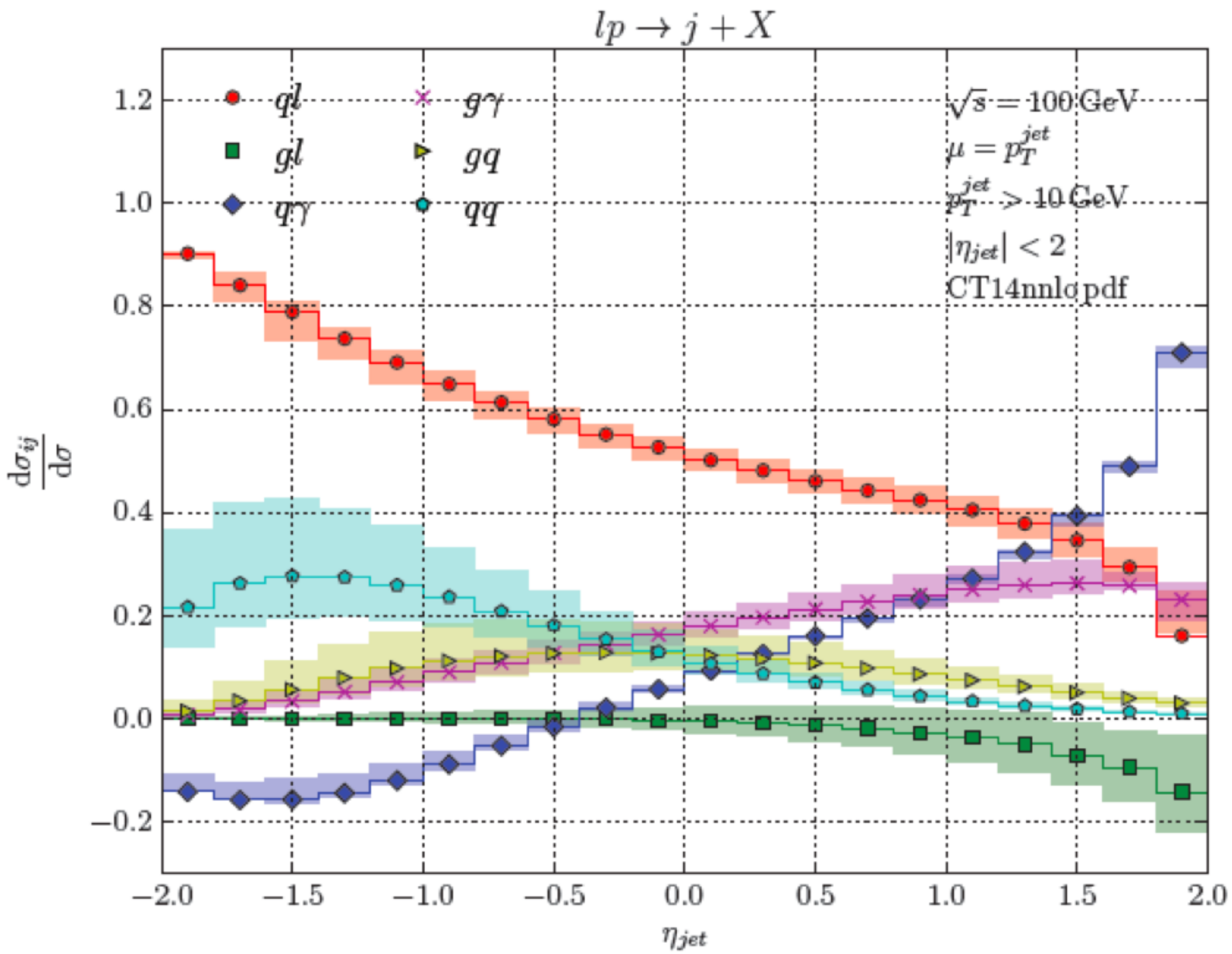
- Inclusive jet production at the EIC probes a variety of subprocesses!
- NNLO calculation
- $ql =$ LO Deep Inelastic Scattering



Produces one jet

Constraining PDFs with inclusive jet production

- Usually in EIC measurements we want to reconstruct the scattered electron, but for some measurements we don't always need to. One example: inclusive jets



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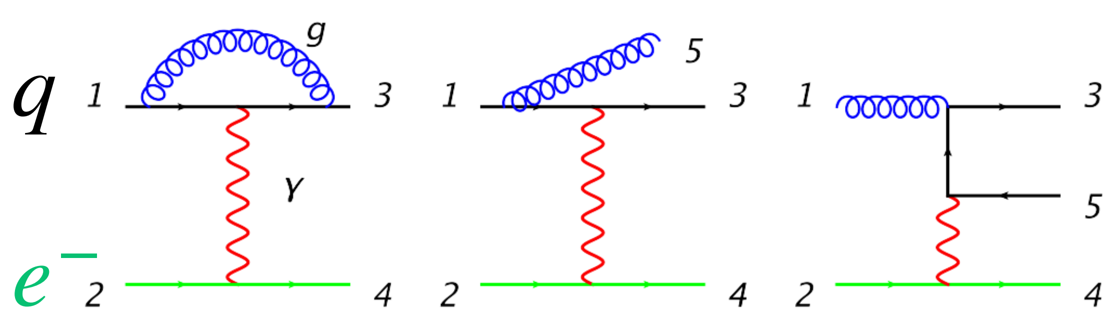
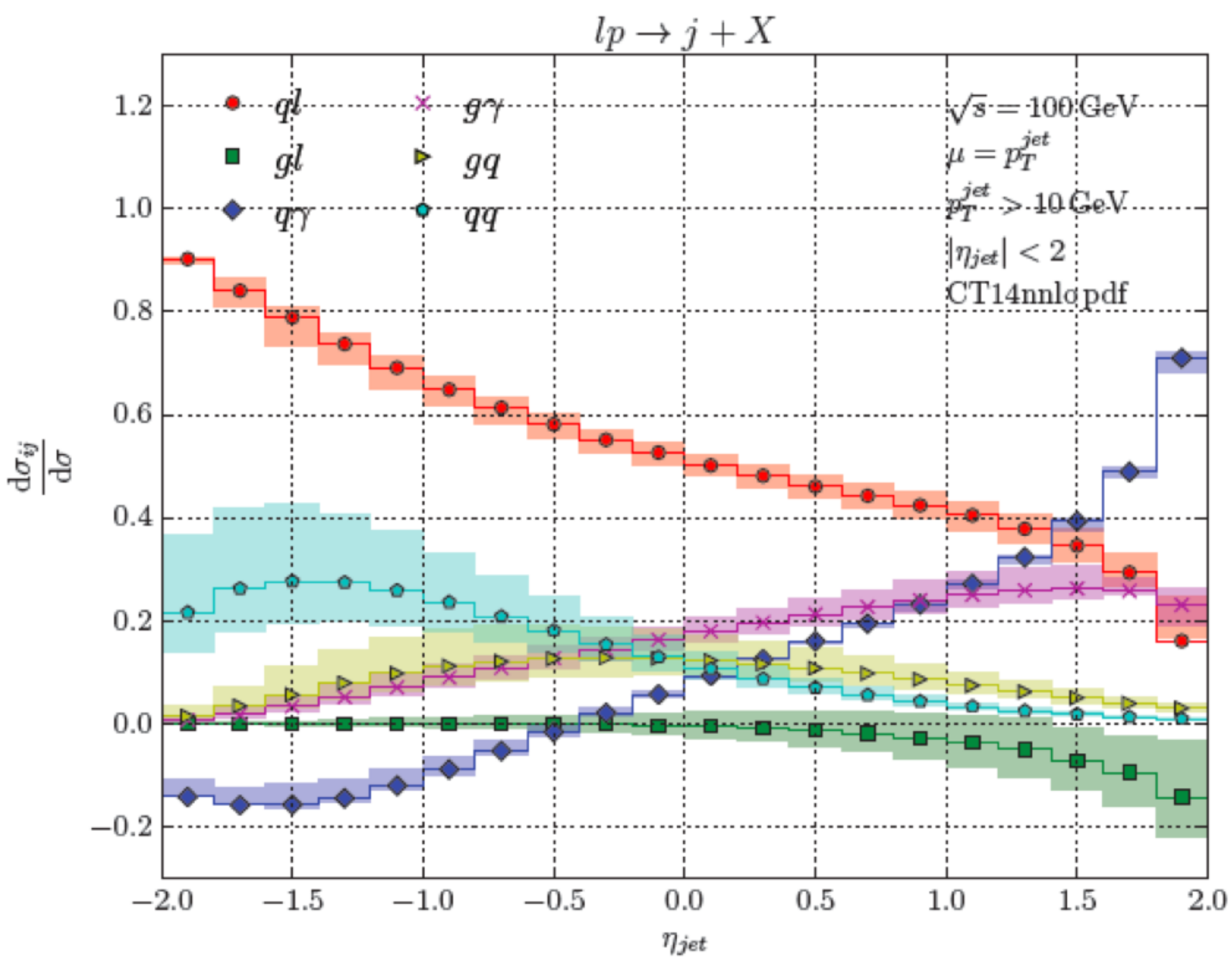
- Inclusive jet production at the EIC probes a variety of subprocesses!
- NNLO calculation
- $gl =$ NLO correction to LO process



Can sometimes have more than one jet

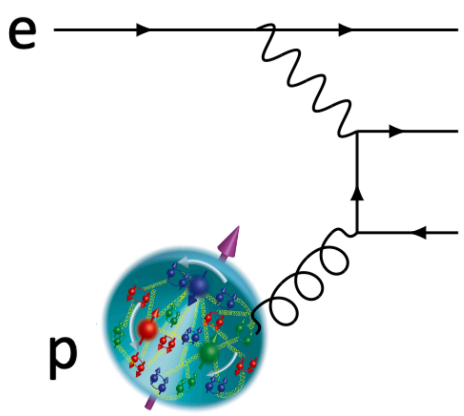
Constraining PDFs with inclusive jet production

- Usually in EIC measurements we want to reconstruct the scattered electron, but for some measurements we don't always need to. One example: inclusive jets

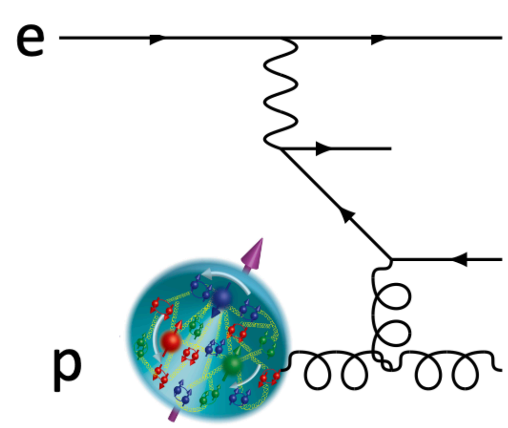


G. Abelof, R. Boughezel, X. Liu, F. Petriello
PLB **763**, 52 (2016)

- Inclusive jet production at the EIC probes a variety of subprocesses!
- $g\gamma =$ "direct" photon, acts like a point particle
- $gq =$ "resolved" photon, treat like photon has a PDF



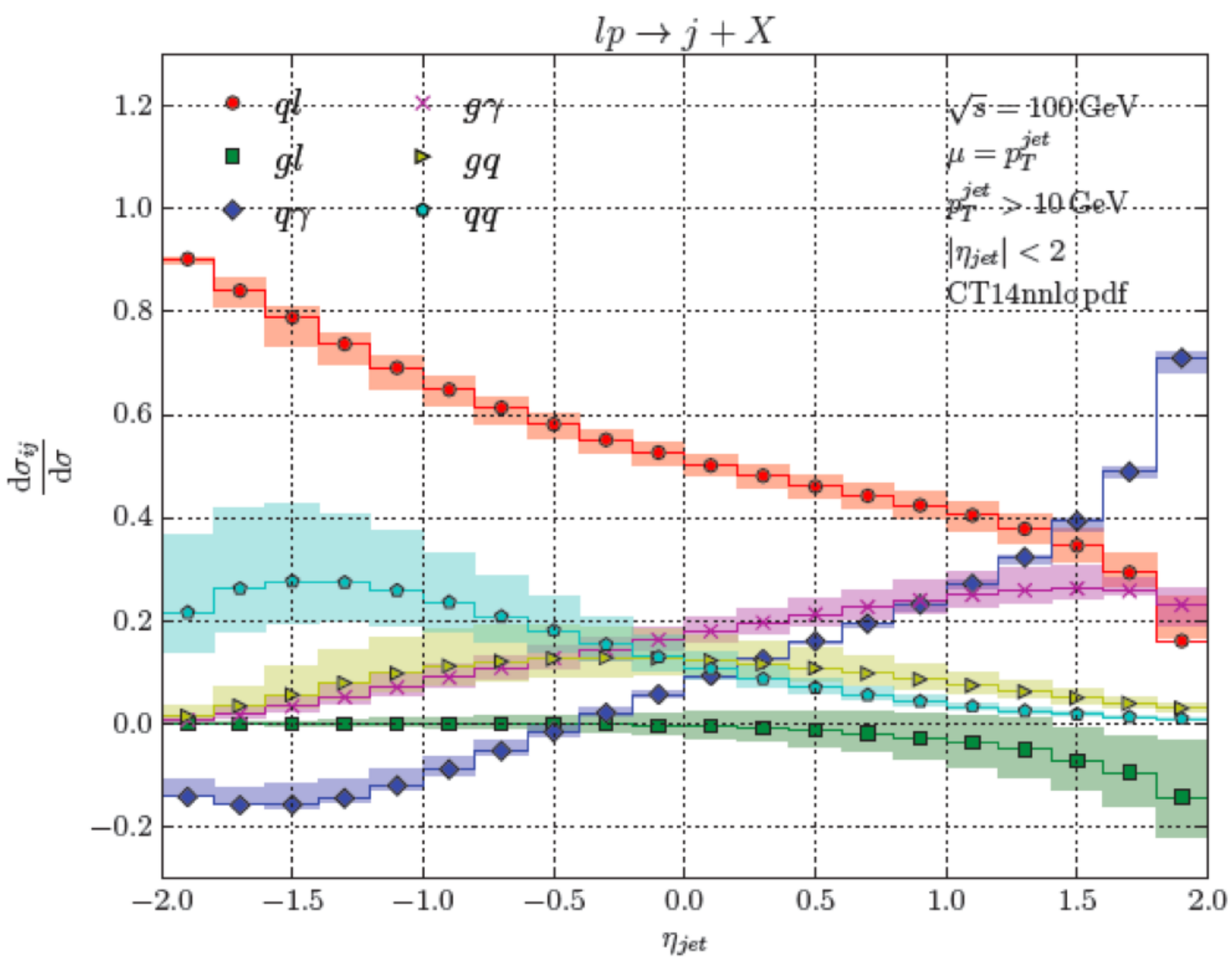
Nearly on-shell photon, scattered e⁻ not detected



Resolved photon splits into $q\bar{q}$ pair that participates in hard scattering

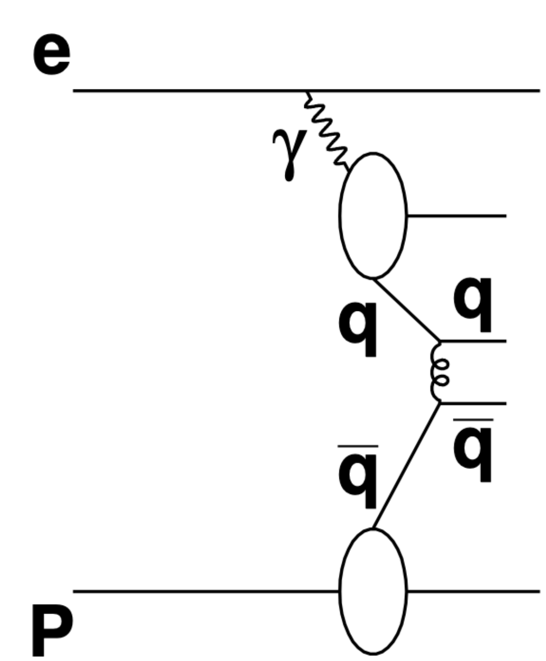
Constraining PDFs with inclusive jet production

- Usually in EIC measurements we want to reconstruct the scattered electron, but for some measurements we don't always need to. One example: inclusive jets



G. Abelof, R. Boughezel, X. Liu, F. Petriello
PLB **763**, 52 (2016)

- Inclusive jet production at the EIC probes a variety of subprocesses!
- $qq =$ another resolved photon process

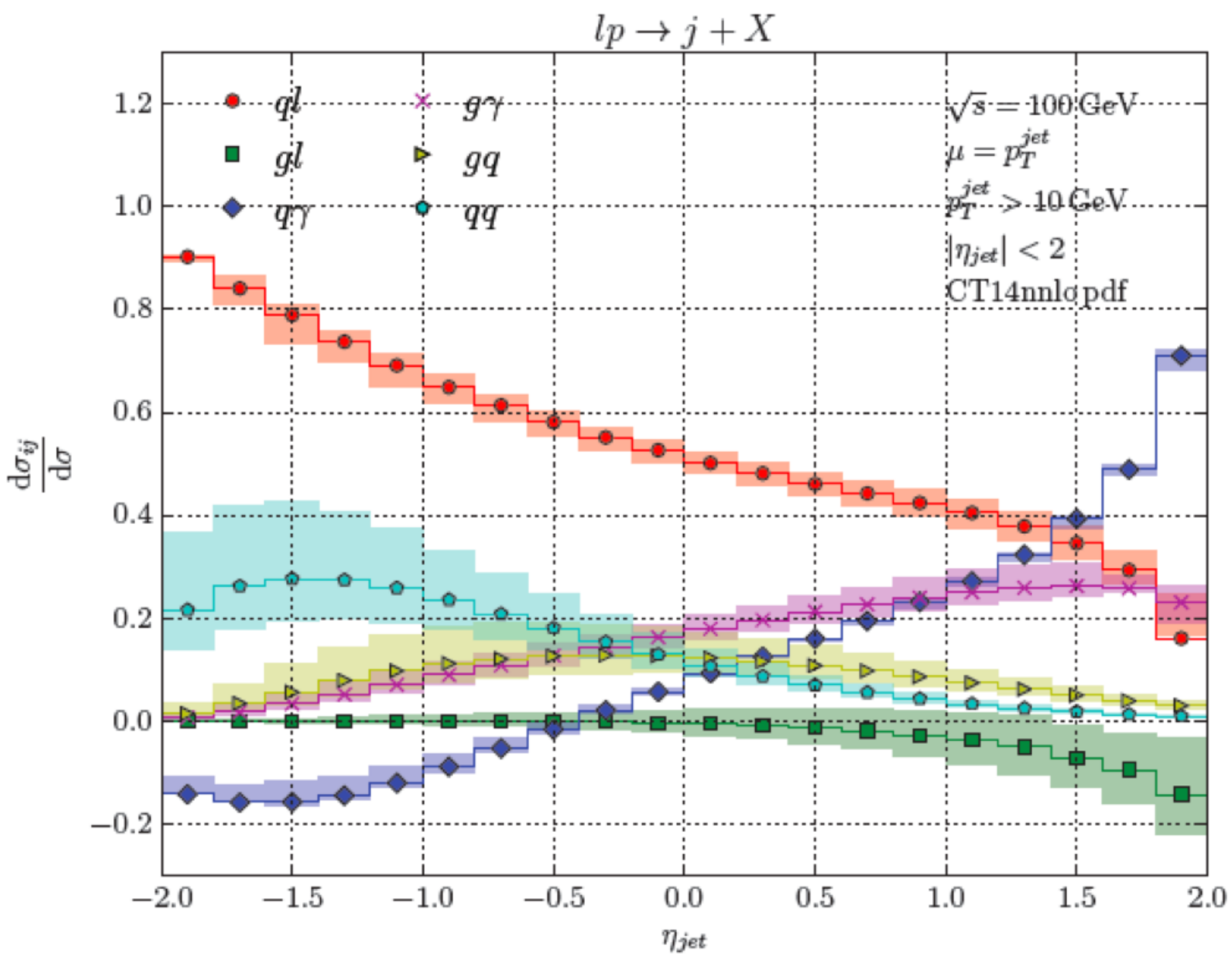


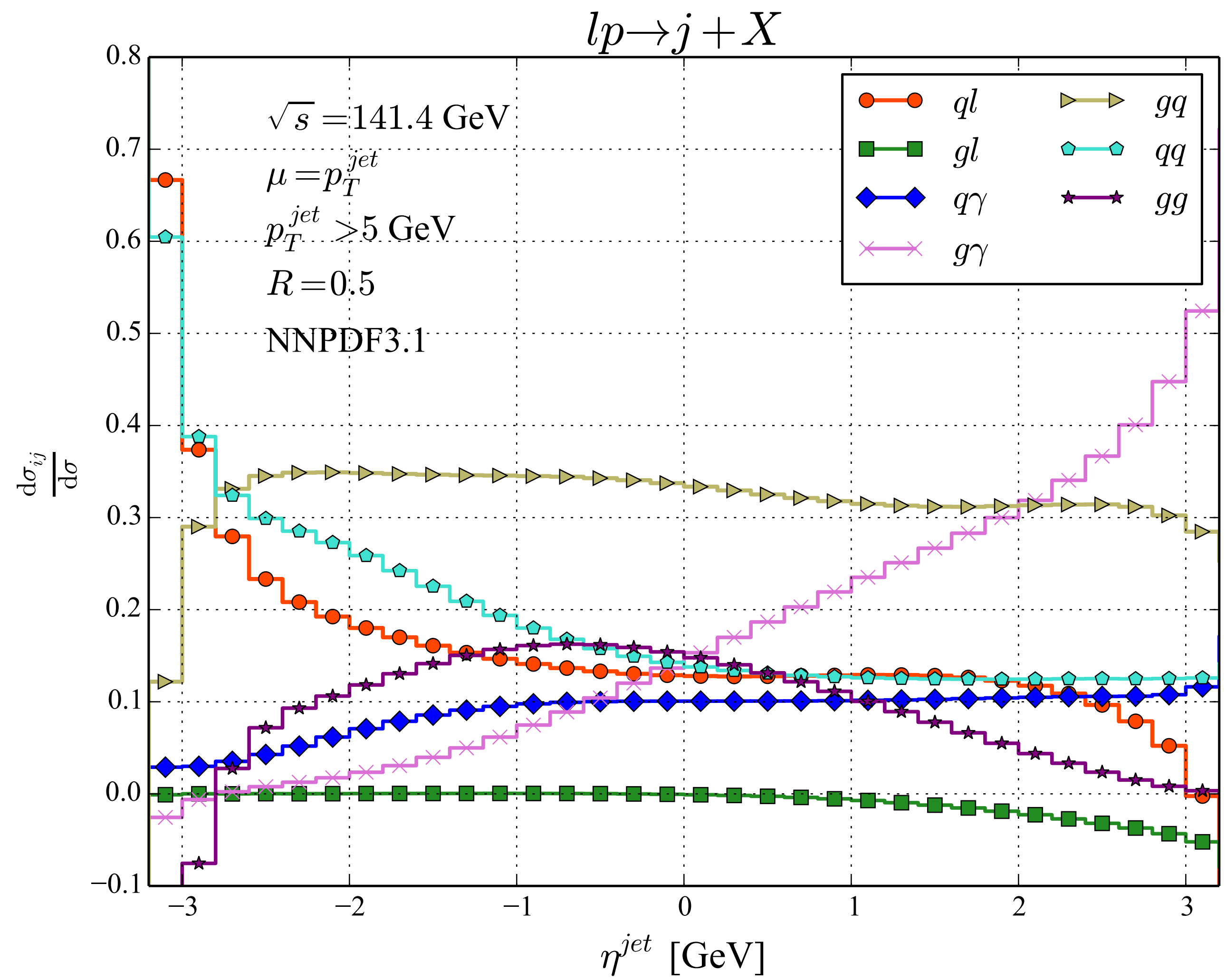
X. Chu, E. Aschenauer, J. H. Lee, L. Zheng
PRD **96**, 074035 (2017)

Constraining PDFs with inclusive jet production

$\sqrt{s} = 100$ GeV, $|\eta_{jet}| < 2$
minimum jet p_T = 10 GeV

$\sqrt{s} = 141.4$ GeV, $|\eta_{jet}| < 3$
minimum jet p_T = 5 GeV



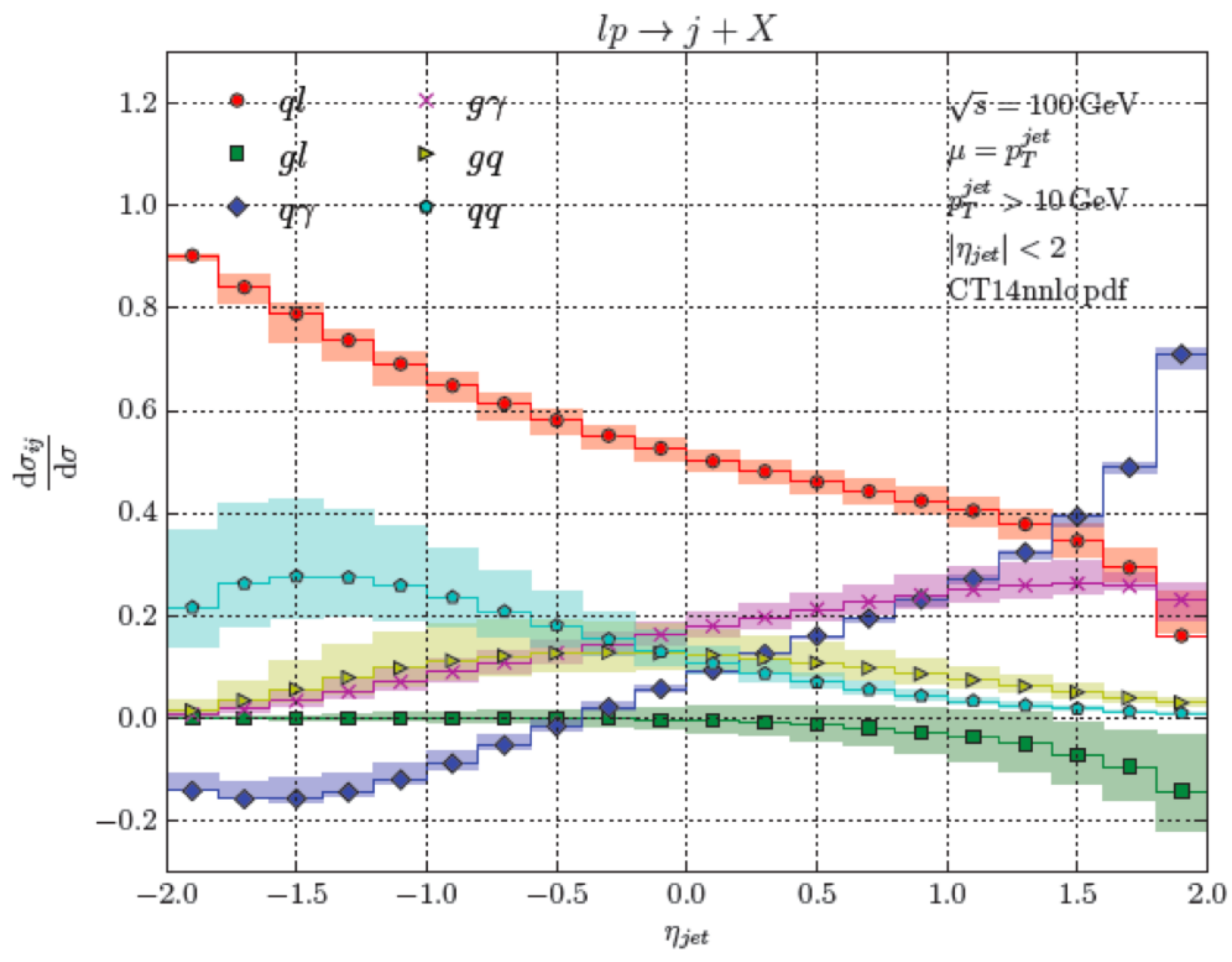


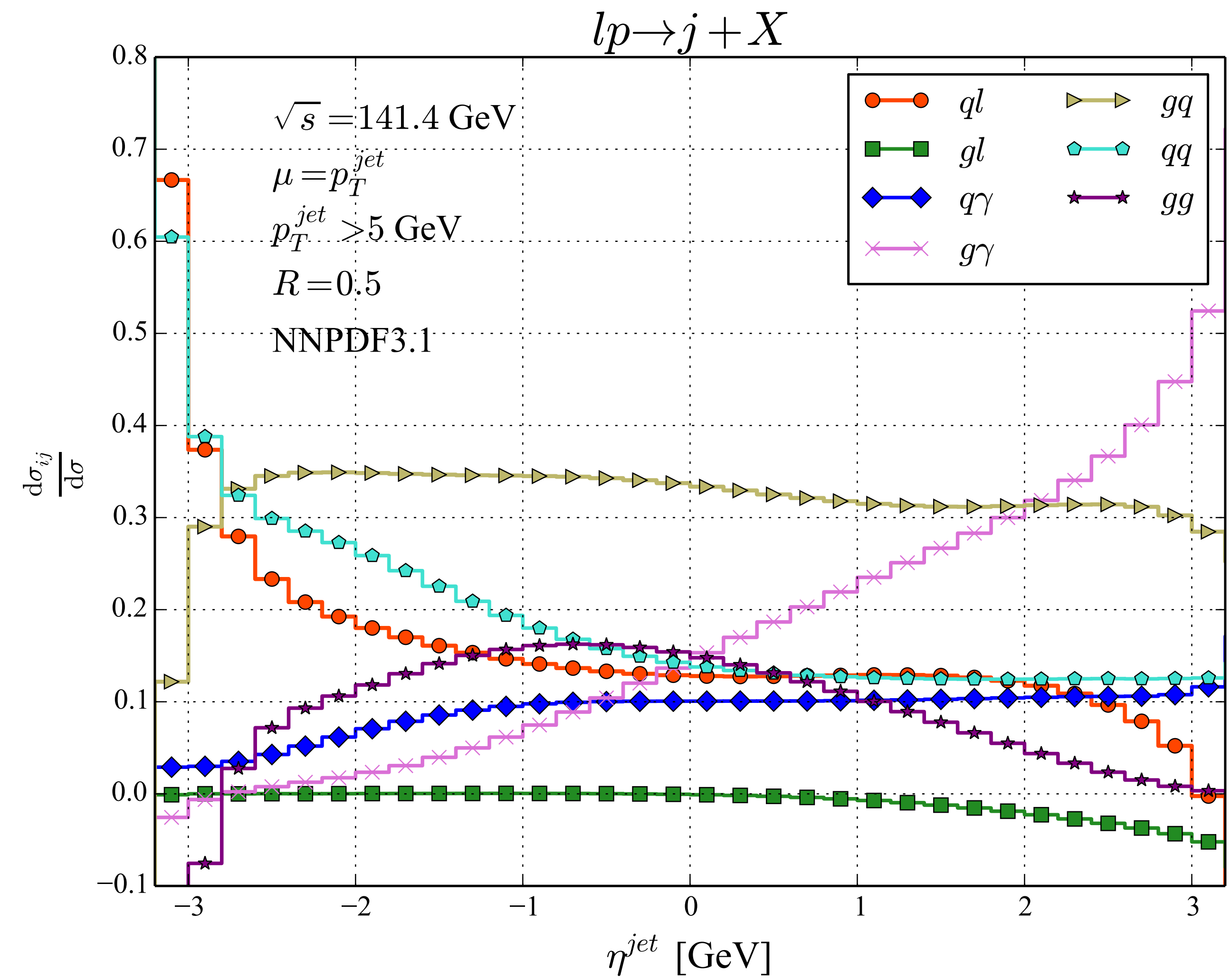
G. Abelof, R. Boughezel, X. Liu, F. Petriello
PLB **763**, 52 (2016)

Plot courtesy of Frank Petriello

Constraining PDFs with inclusive jet production

- Sensitivity to different subprocesses depends strongly on choice of jet kinematics (p_T, η) and the $\sqrt{s}$. Forward region dominated by $g\gamma$ and gq processes





G. Abelof, R. Boughezel, X. Liu, F. Petriello
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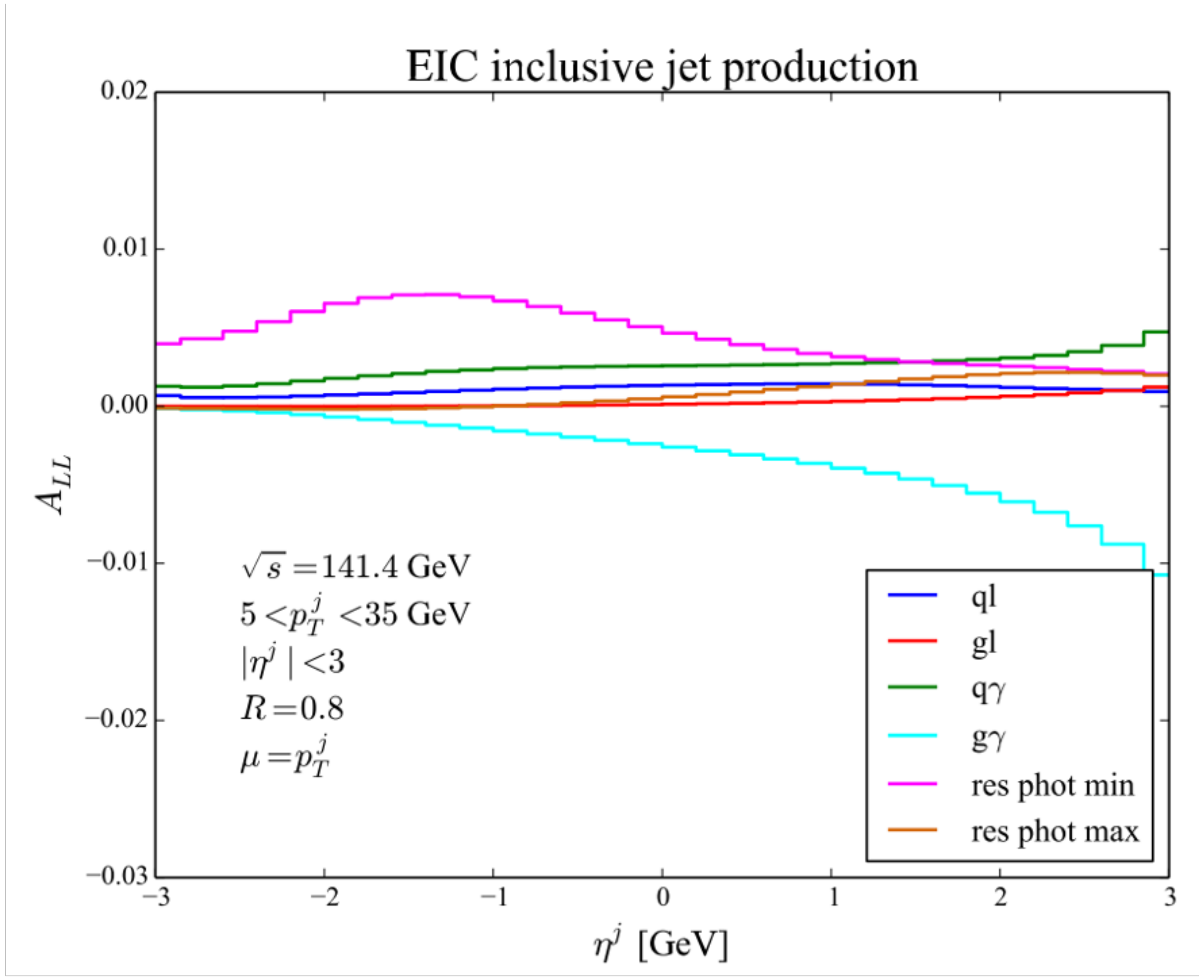
Plot courtesy of Frank Petriello

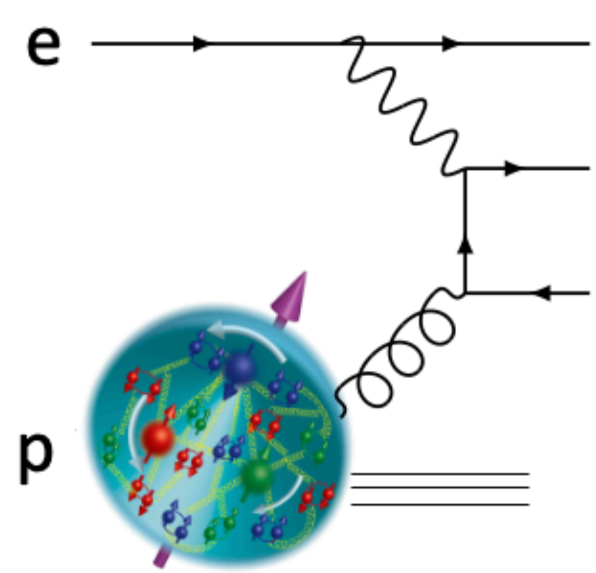
Accessing polarized PDFs with jets



•In the forward region, inclusive jet production from photon-gluon scattering is predicted to give a ~-1% double-longitudinal spin asymmetry (A_{LL})

$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-} - d\sigma^{-+} + d\sigma^{--}}{d\sigma^{++} + d\sigma^{+-} + d\sigma^{-+} + d\sigma^{--}}$$

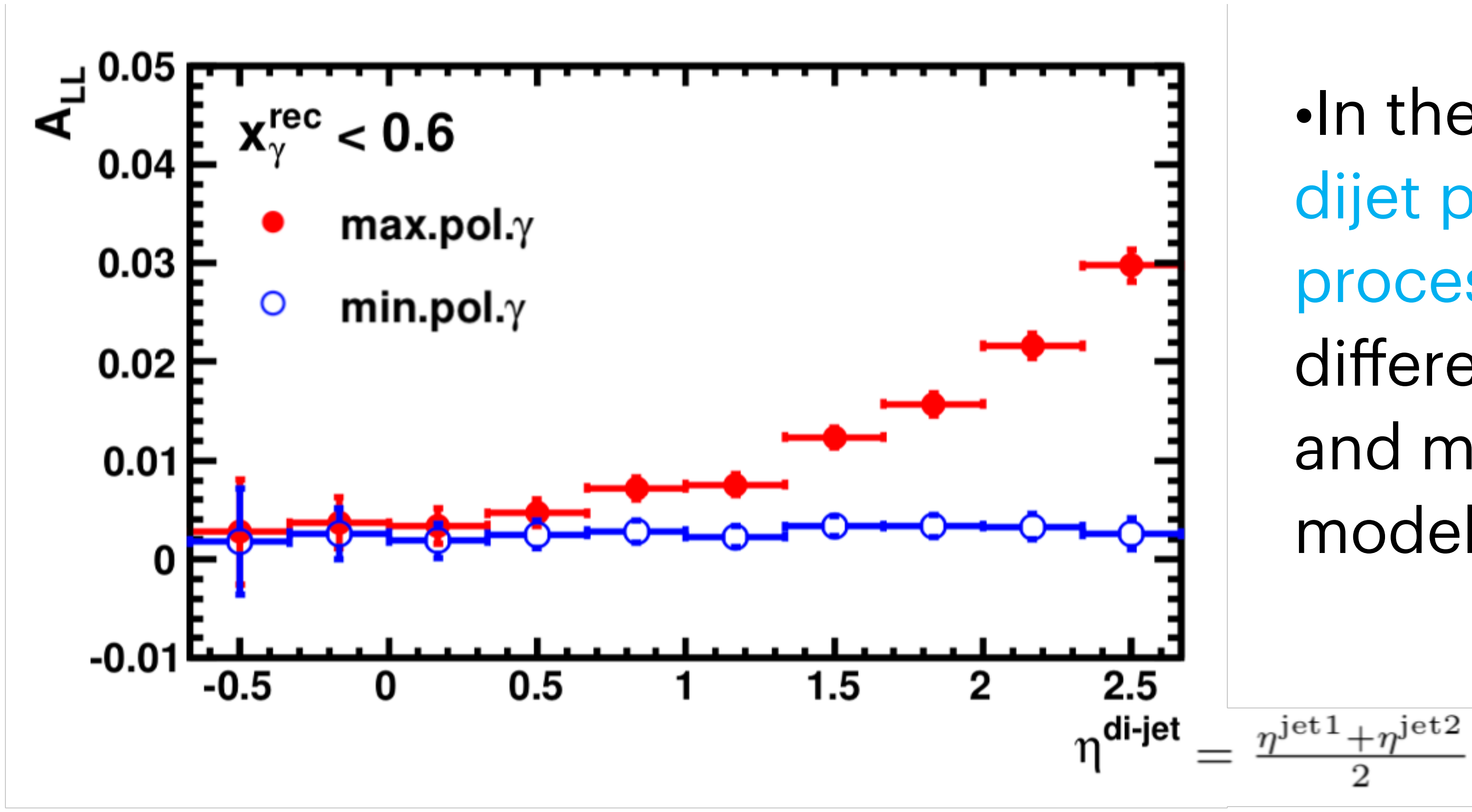
Photon-gluon scattering is sensitive to polarized and unpolarized gluon PDFs



Nearly on-shell photon, scattered e⁻ not detected – only sensitive to this channel with inclusive jet measurements!

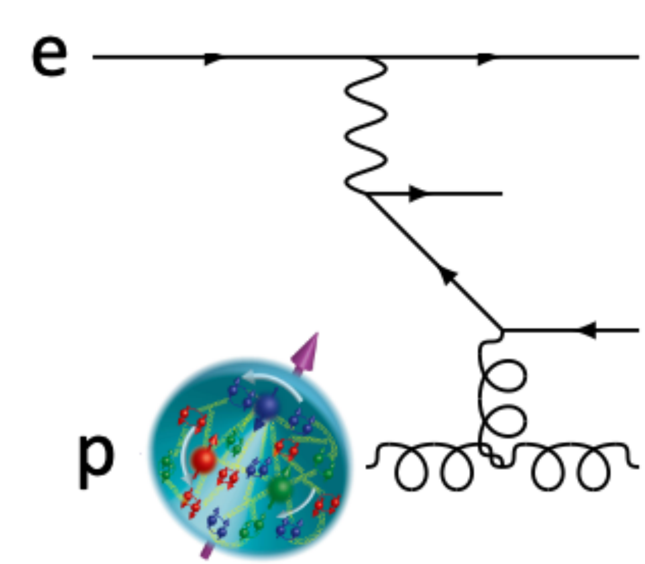
R. Boughezel, F. Petriello, H. Xing
PRD **98**, 054031 (2018)

Accessing photon structure with jets



- In the forward region, the A_{LL} from dijet production in resolved photon processes is predicted to differentiate between the minimal and maximal photon polarization models

Example of resolved process:
qg -> qg channel

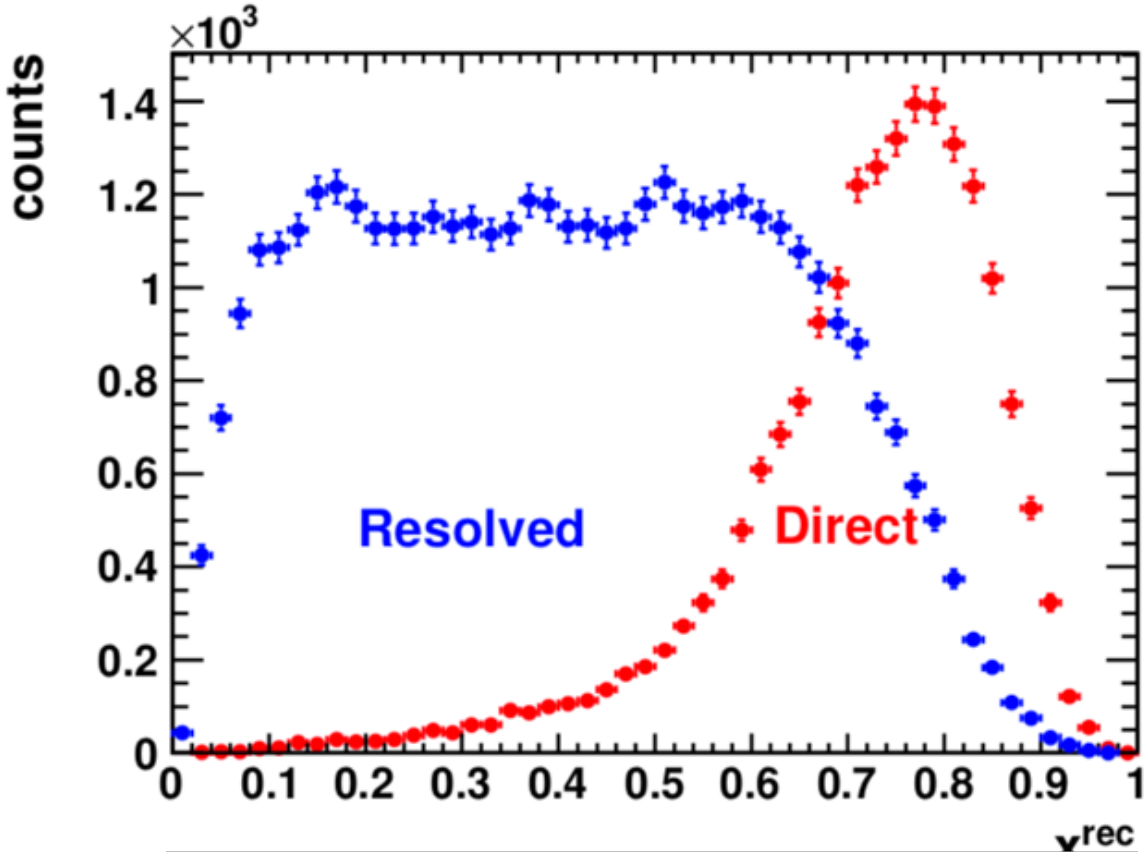


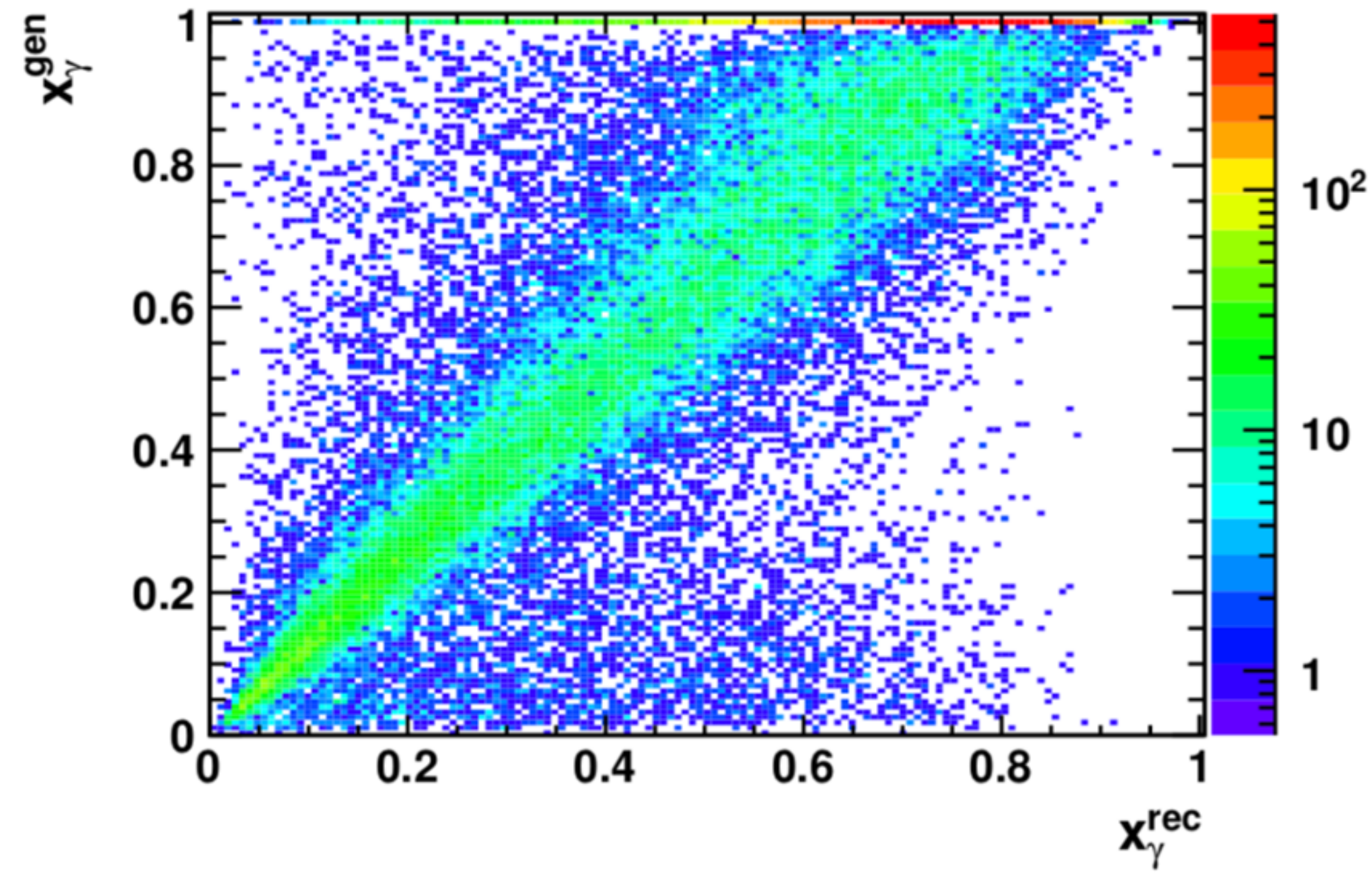
Reconstructed momentum fraction x_γ of parton in photon:

$$x_\gamma^{\text{rec}} = \frac{1}{2E_e y}\left(p_{T,1}e^{-\eta_1} + p_{T,2}e^{-\eta_2}\right)$$

X. Chu, E. Aschenauer, J. H. Lee, L. Zheng
PRD **96**, 074035 (2017)

Accessing photon structure with jets





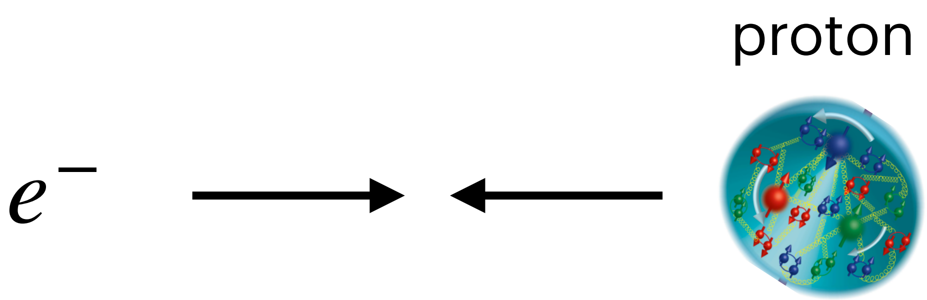
$$x_\gamma = \frac{1}{2E_e y}(p_{T,1}e^{-\eta_1} + p_{T,2}e^{-\eta_2})$$

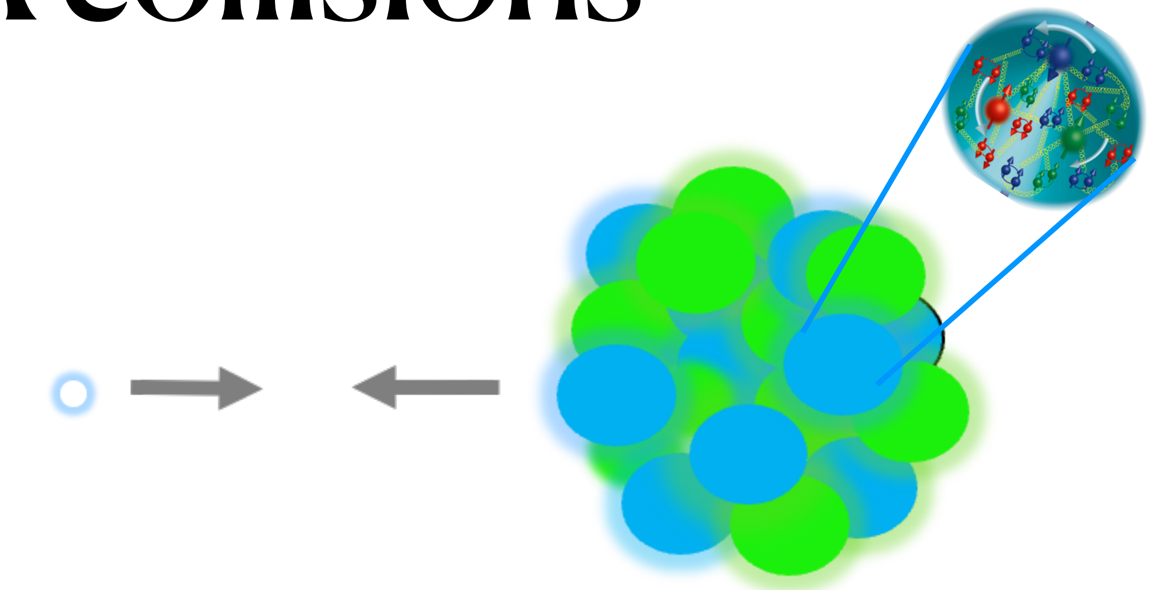
- Reconstruct photon kinematics with dijet p_T and η
- Cut on x_γ separates resolved from direct processes

- Excellent reconstruction of true x_γ with dijets

X. Chu, E. Aschenauer, J. H. Lee, L. Zheng
PRD **96**, 074035 (2017)

From *ep* to *eA* collisions





- Let's make one thing clear: **eA collisions are very interesting in their own right!** They are more than just "a baseline" for other collision systems, but the reason why they are a baseline is also important to understand

- So, let's understand the broader context for heavy flavor and jet probes in nuclear collisions, and see where *e*A fits in to this picture, then we will also look at what is fascinating about eA

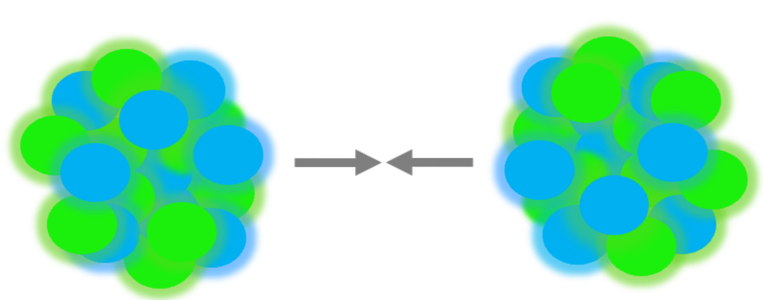
Let's take a short detour into heavy ion physics, and back to quarkonia probes...

Quarkonia "melting" as a signature of Quark Gluon Plasma

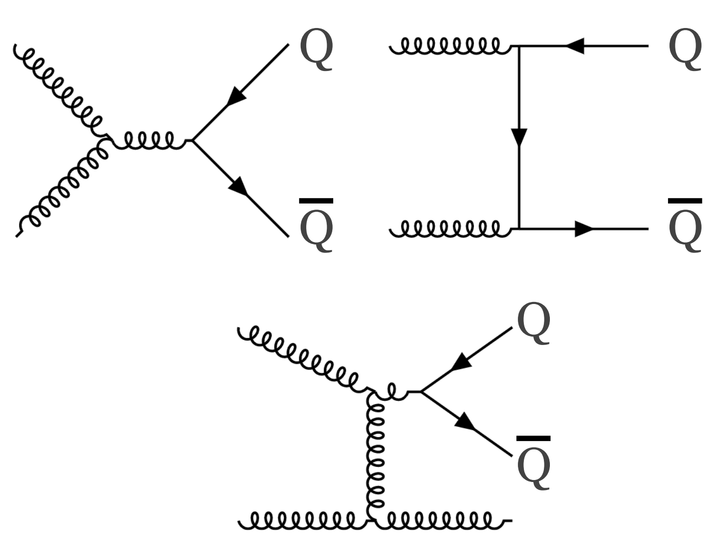
- Quark-gluon plasma (QGP) is a state of matter formed in high-energy nucleus-nucleus collisions in which quarks and gluons are completely deconfined from hadrons

- The QGP medium behaves as a nearly perfect liquid and theory predicts that the deconfined colour charges "screen" or prevent the formation of $c\bar{c}$ bound states

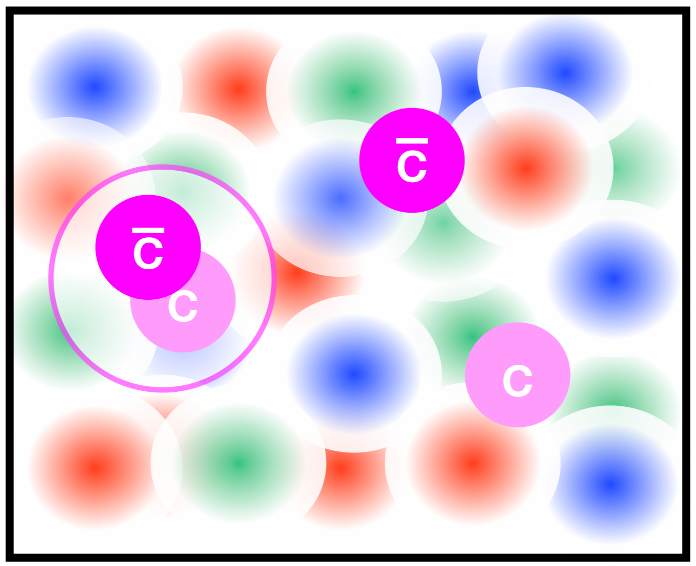
Central PbPb Collision (nuclei head-on)



Hard $c\bar{c}$ and $b\bar{b}$ production



Quarkonia "melting" in a thermalised QGP



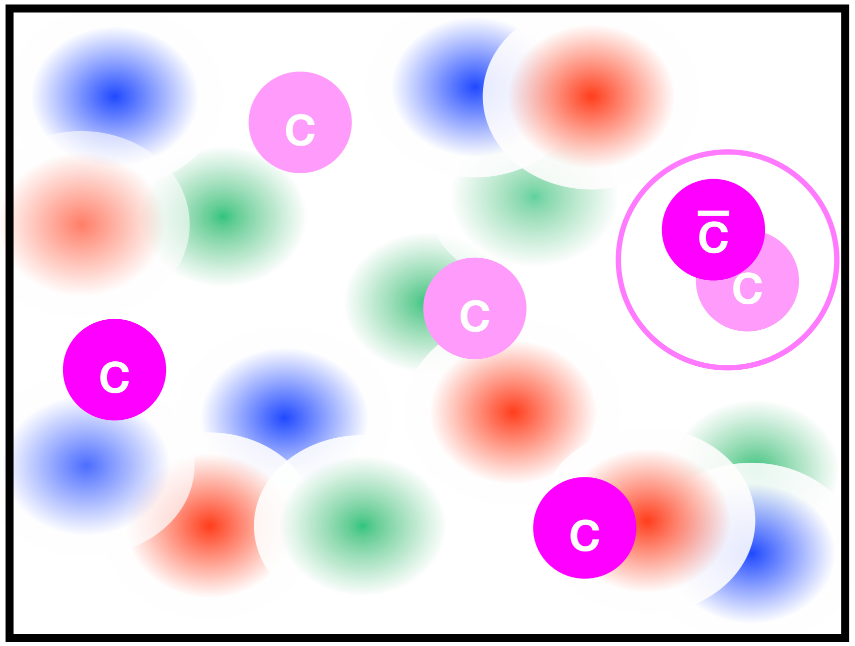
PLB 178 (1986) 416

time

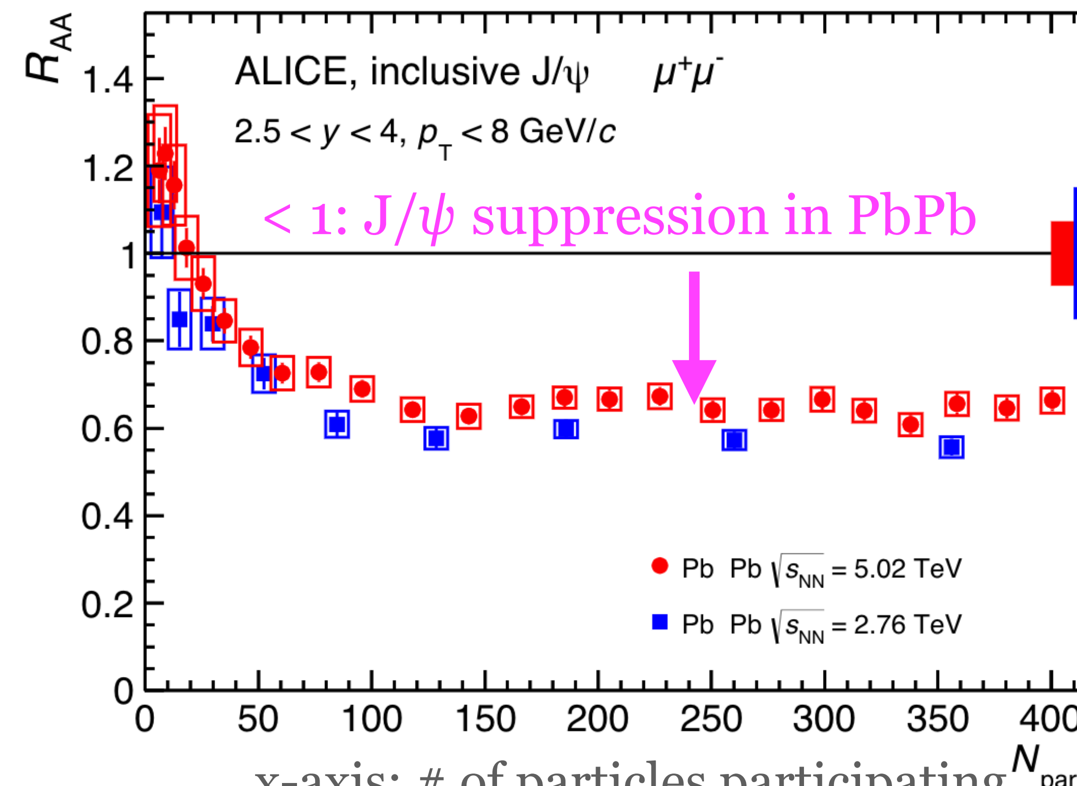
Quarkonia "melting" as a signature of Quark Gluon Plasma

Individual c and $\bar{c}$ quarks can also recombine to form charmonium bound states as the temperature of the QGP medium cools, which partly counteracts the suppression from melting

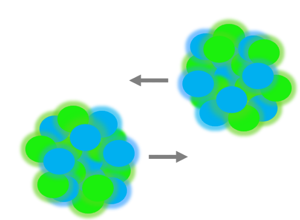
J/ψ "recombination" in a QGP



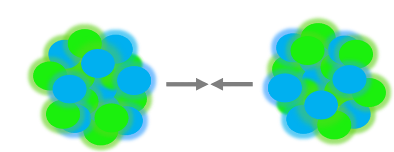
PLB 766 (2017) 212-224



x-axis: # of particles participating in the collision



low N_{part}: "peripheral" collisions, where less QGP is formed



high N_{part}: head-on "central" collisions, where the most QGP is formed

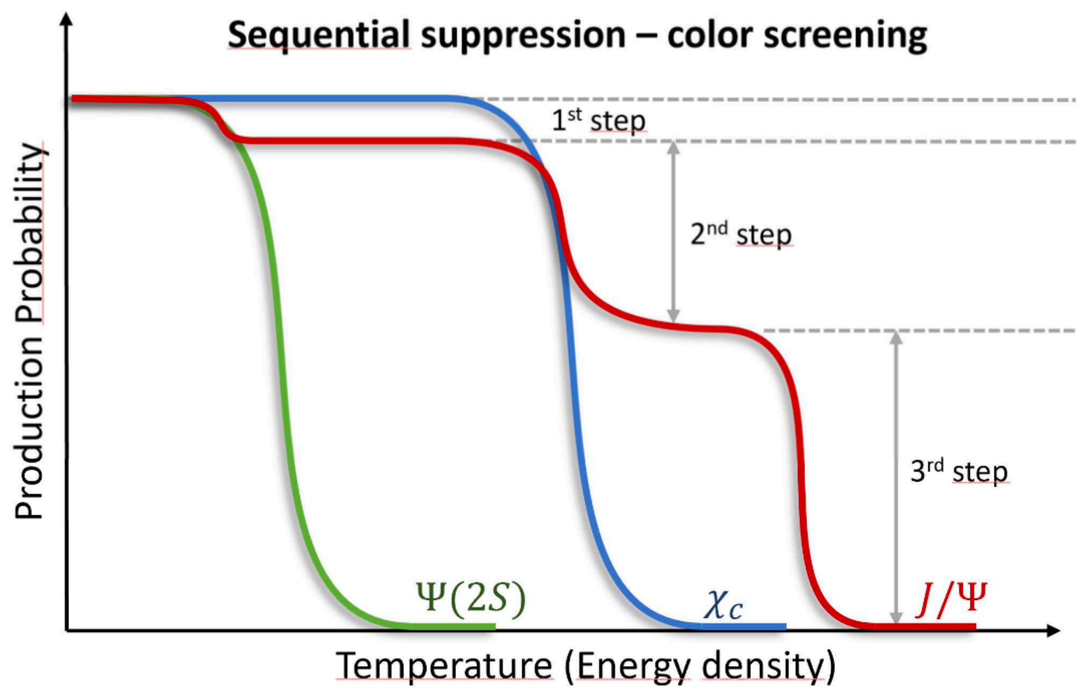
The observable we use to measure the suppression of particles in PbPb compared to pp collisions is the **nuclear modification factor, R_{AA}:**

$$R_{AA}\,(J/\psi) = \frac{J/\psi \text{ yield in PbPb}}{J/\psi \text{ yield in pp x Avg. \# of interactions in PbPb}}$$

PLB 178 (1986) 416

Quarkonia as "thermometers" of QGP

Different quarkonia states are predicted to "melt" at different temperatures of the QGP, according to their binding energies



Example: "sequential suppression" for charmonium states

- never been experimentally confirmed because χ_c production has not been measured in heavy ion collisions!

If we understood quarkonia production and "melting"/recombination well, we could use different quarkonia states to study the QGP evolution as a function of temperature!

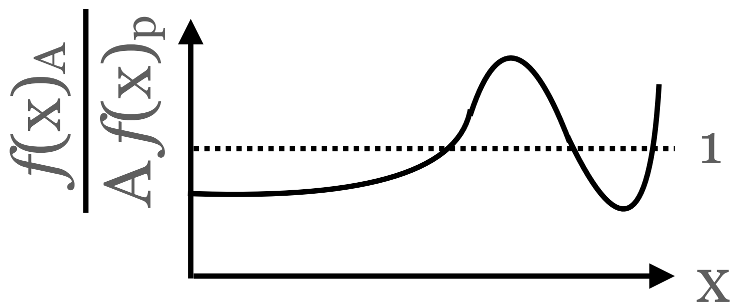
What more do we need to understand, since we know that the J/ψ R_{AA} is less than 1, proving that J/ψs are suppressed in PbPb collisions? Well, there's more to the story!

What else might "break up" quarkonia states?

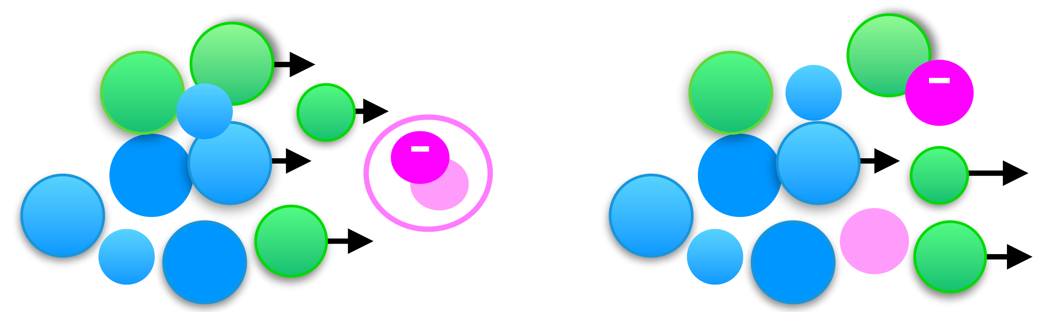
What else might "break up" quarkonia states?

Other effects besides interaction with a QGP can cause quarkonia to dissociate, or not to form at all:

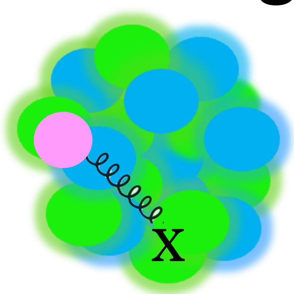
Nuclear structure & internal parton dynamics: nuclear parton distribution functions



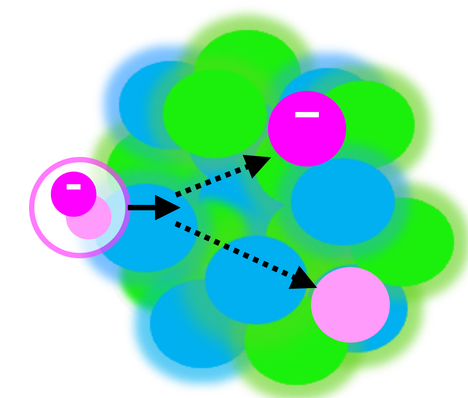
Breakup due to "co-moving" particles



Parton energy loss



Nuclear "absorption" - breakup by the interaction with the nucleus



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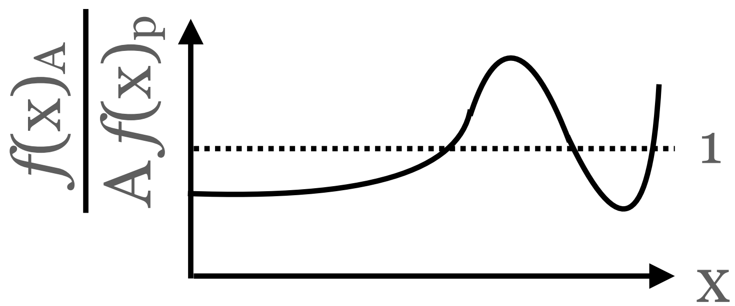

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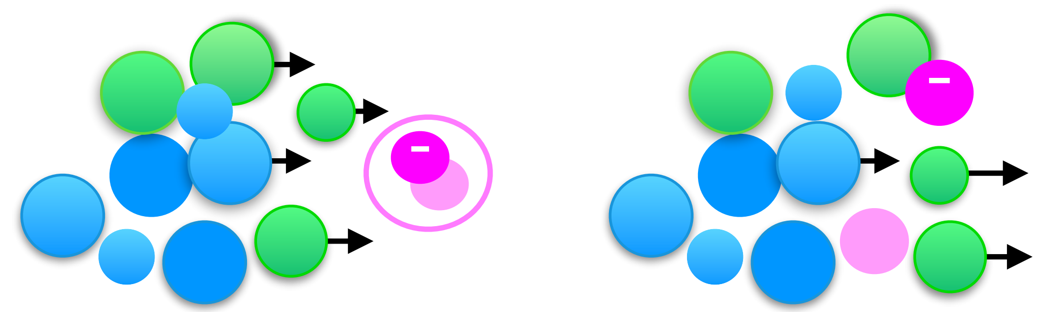

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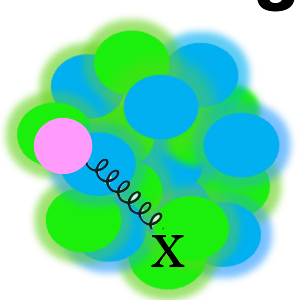

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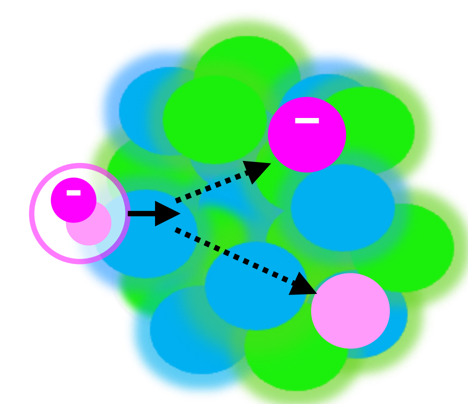
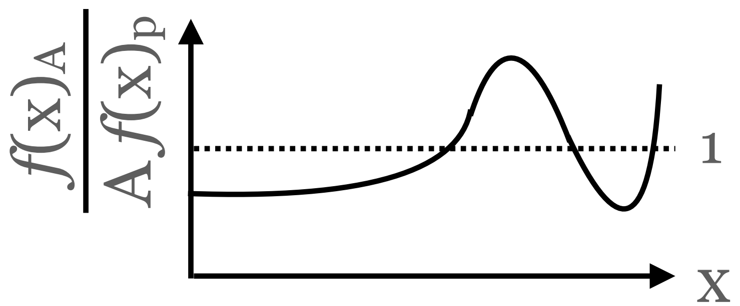


What do these effects have in common? They don't require any QGP. These can all happen in Cold Nuclear Matter (CNM), nuclear matter that is not in the hot plasma phase

What else might "break up" quarkonia states?

Other effects besides interaction with a QGP can cause quarkonia to dissociate, or not to form at all:

Nuclear structure & internal parton dynamics: nuclear parton distribution functions



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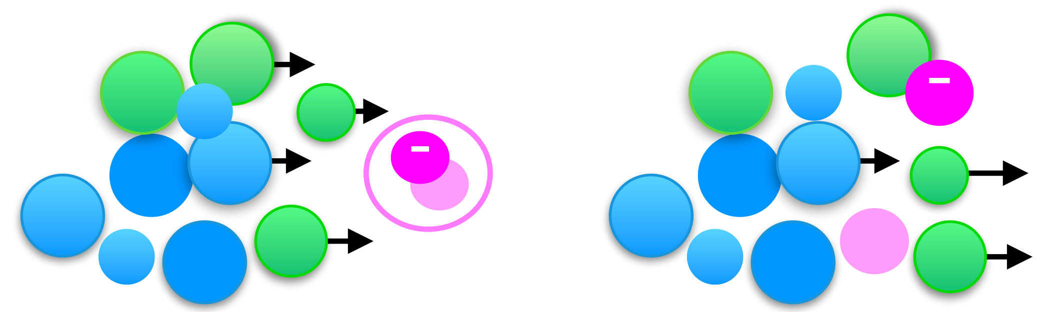

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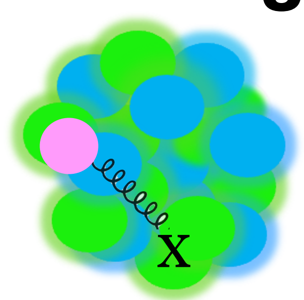
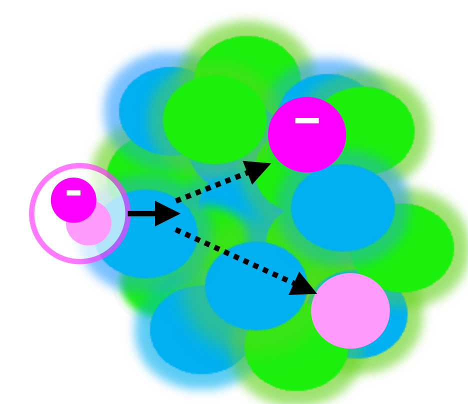
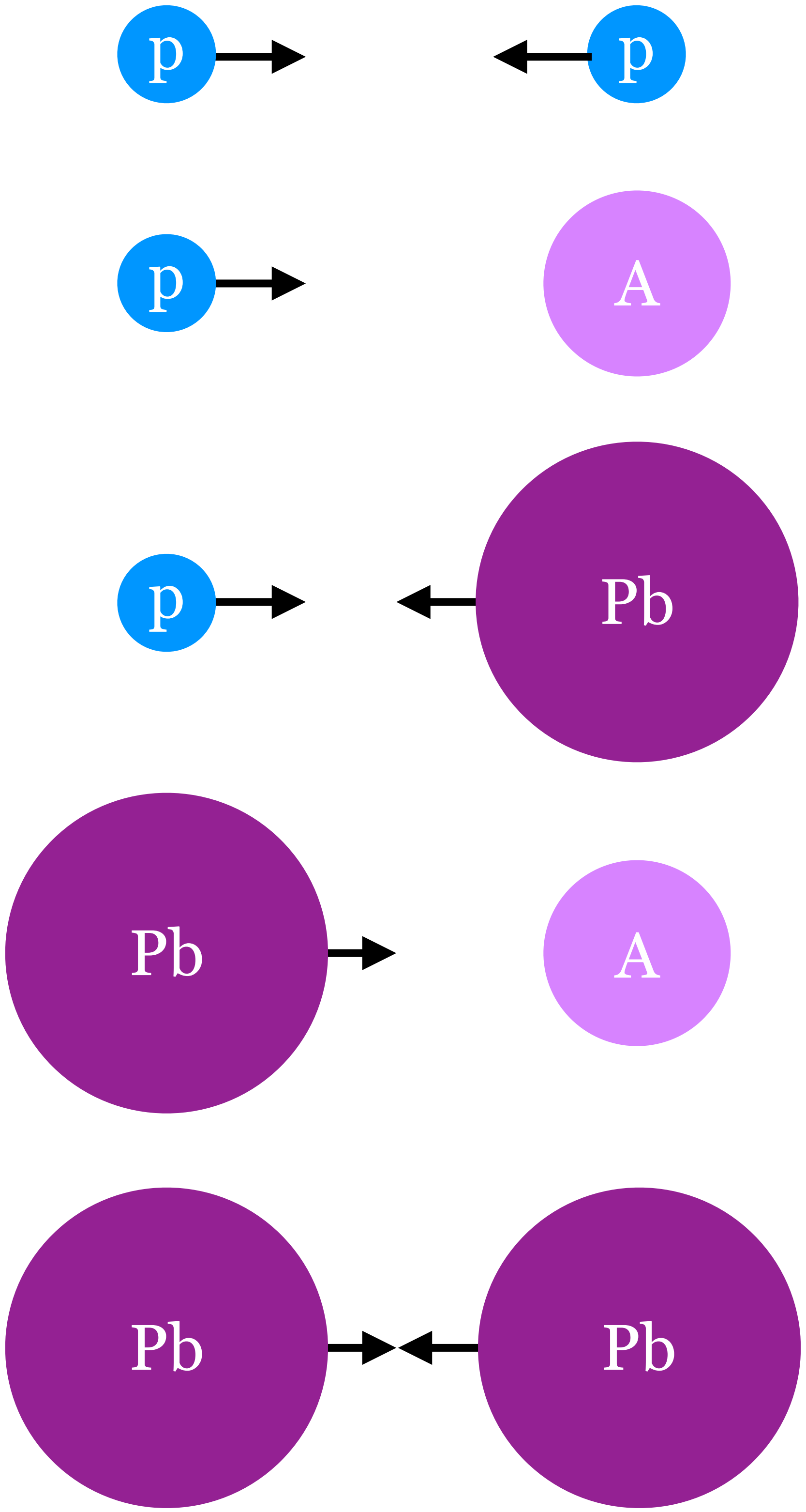


Nuclear "absorption" - breakup by the interaction with the nucleus



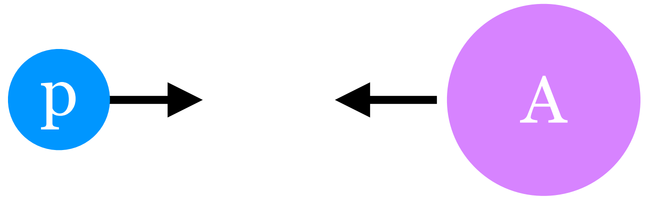
To correctly interpret measurements (quarkonia, jets, heavy flavor...) in a QGP, these other Cold Nuclear Matter (CNM) effects must be understood!

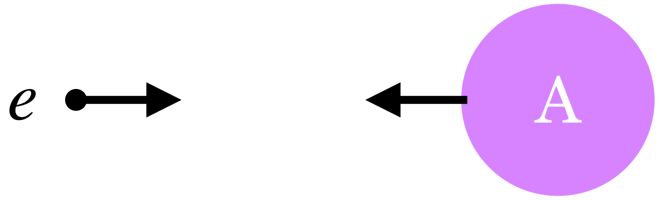
A guide to collision systems



pp	Our baseline system: QGP not expected
pA	"Cold" nuclear matter: QGP not expected
pPb, Pbp (or pAu)	"Cold" nuclear matter: QGP not expected, study CNM effects in Pb/Au
PbA fixed target (LHCb)	"Hot" or "Cold" depending on choice of A: QGP can be formed
PbPb (or AuAu at RHIC)	"Hot" nuclear matter: QGP expected

Why is *e*A necessary?





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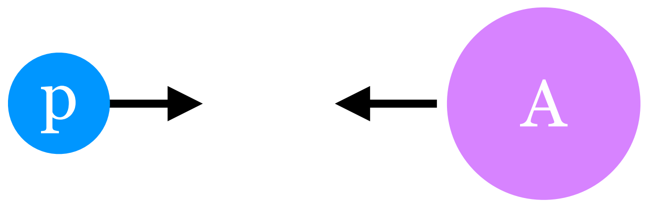
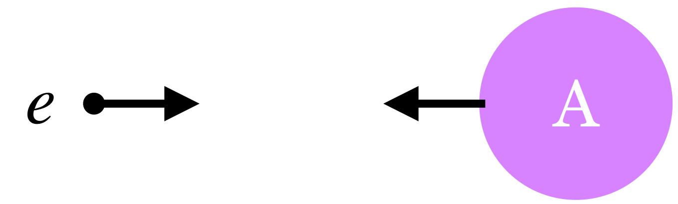
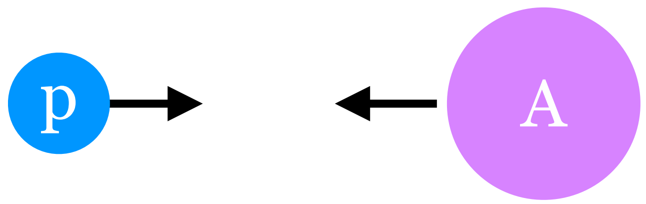


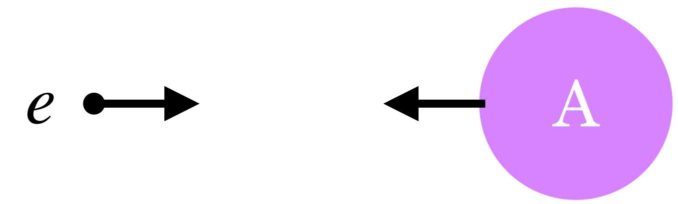
- Measure CNM effects arising from the nucleus *and* additional QCD interactions in the initial state
- The proton is an important "building block" to work our way up to understanding what is happening in a heavy ion collision



- Necessary to isolate nuclear effects
- Precisely measure CNM effects due to the nucleus (nPDF, absorption, etc.)

Why is *e*A necessary?





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- The proton is an important "building block" to work our way up to understanding what is happening in a heavy ion collision

- Necessary to isolate nuclear effects
- Precisely measure CNM effects due to the nucleus (nPDF, absorption, etc.)

Both necessary "baselines"! With many synergies & complementarity between them

Understanding CNM is not a "one and done" measurement per nuclear species. CNM includes a lot of rich, dynamical physics that we can only understand by studying as a function of A and as multi-dimensionally as possible!

How can we compare *e*A to *e*p?

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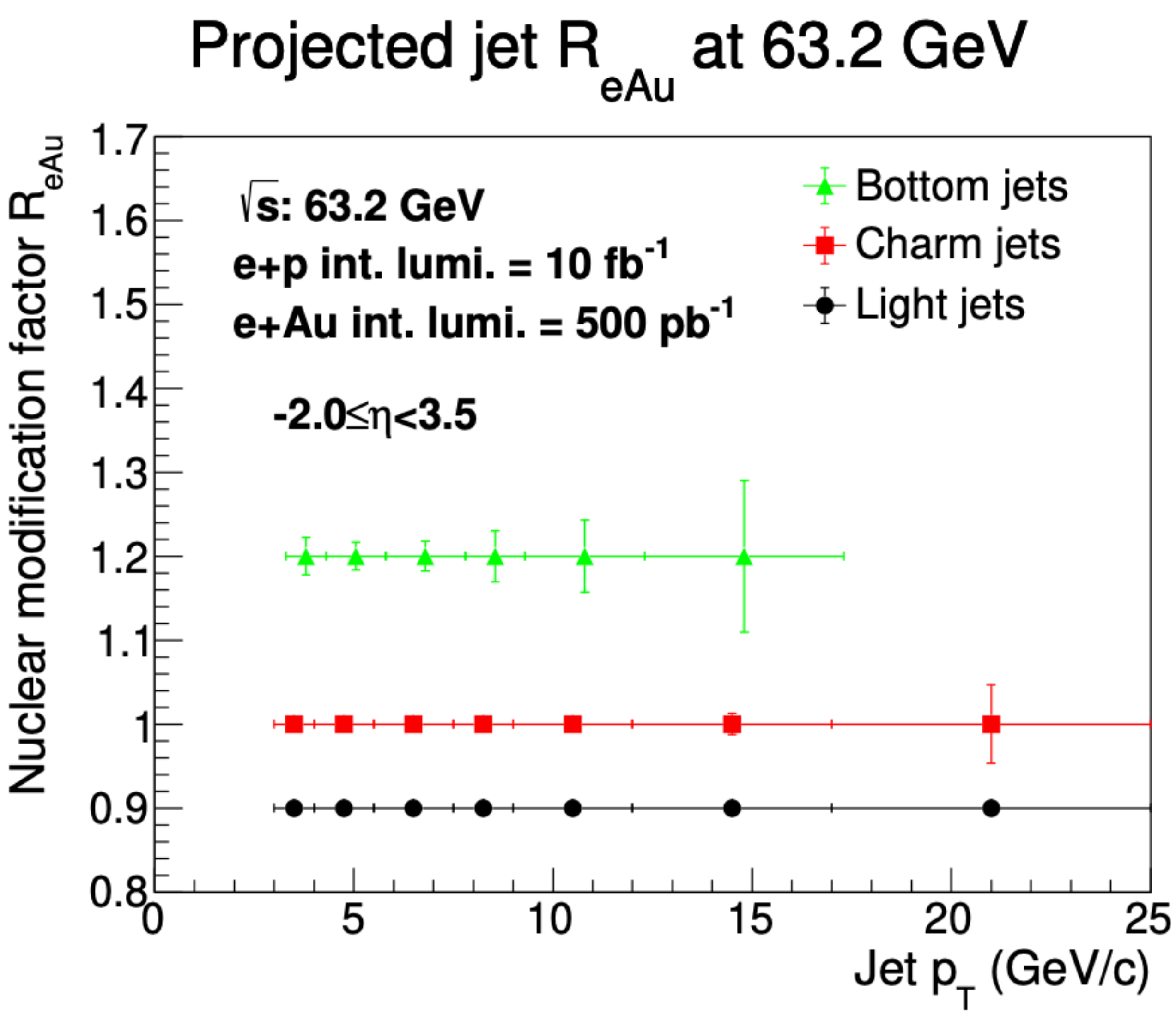
Use the nuclear modification factor!



$$R_{eA} = \frac{\sigma_{eA}}{A\sigma_{ep}}$$

What does R_{eA} tell us?

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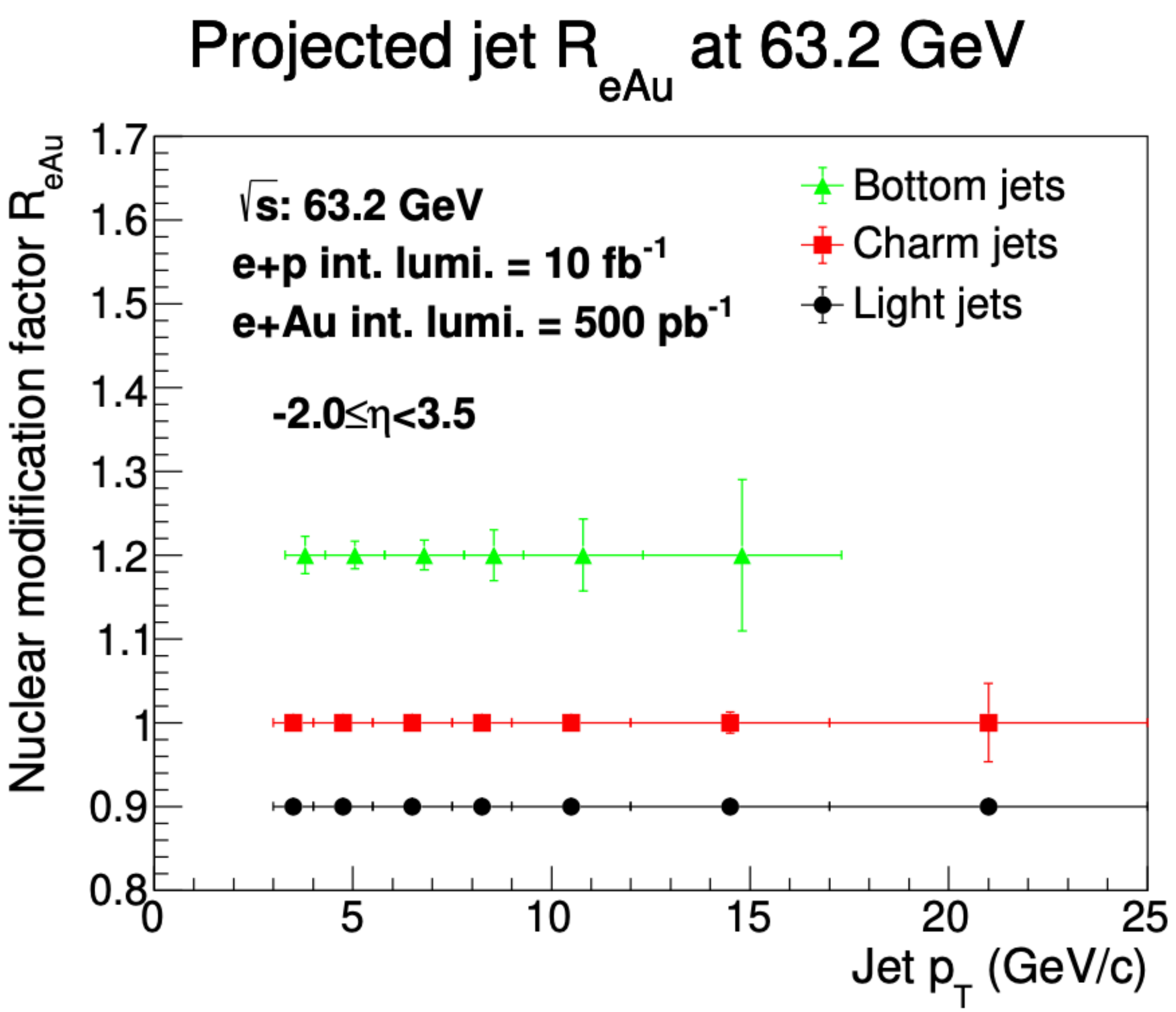
How can we compare *eA* to *ep*?

Use the nuclear modification factor!



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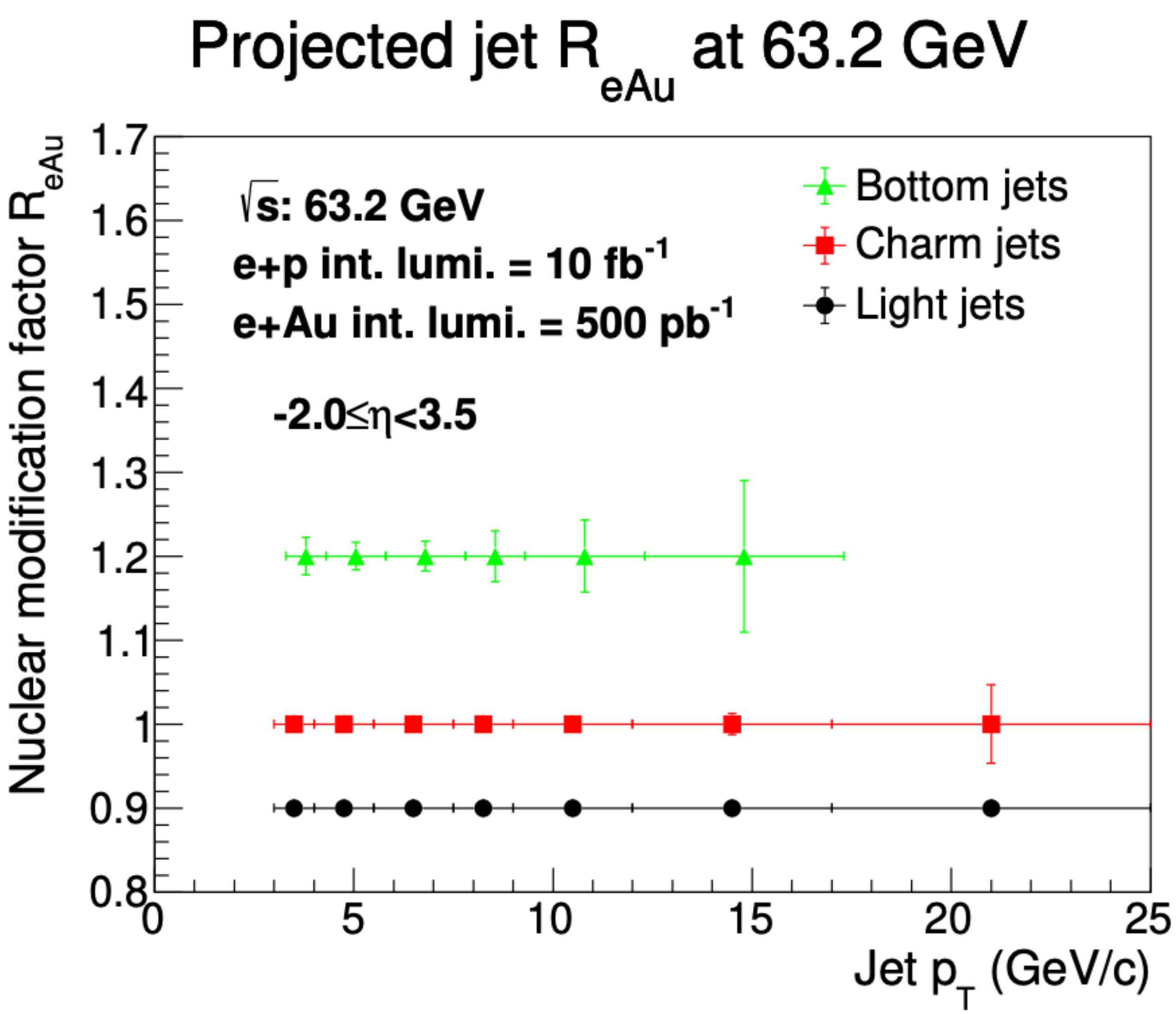

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Why are heavy flavor probes particularly useful for studying cold nuclear matter?

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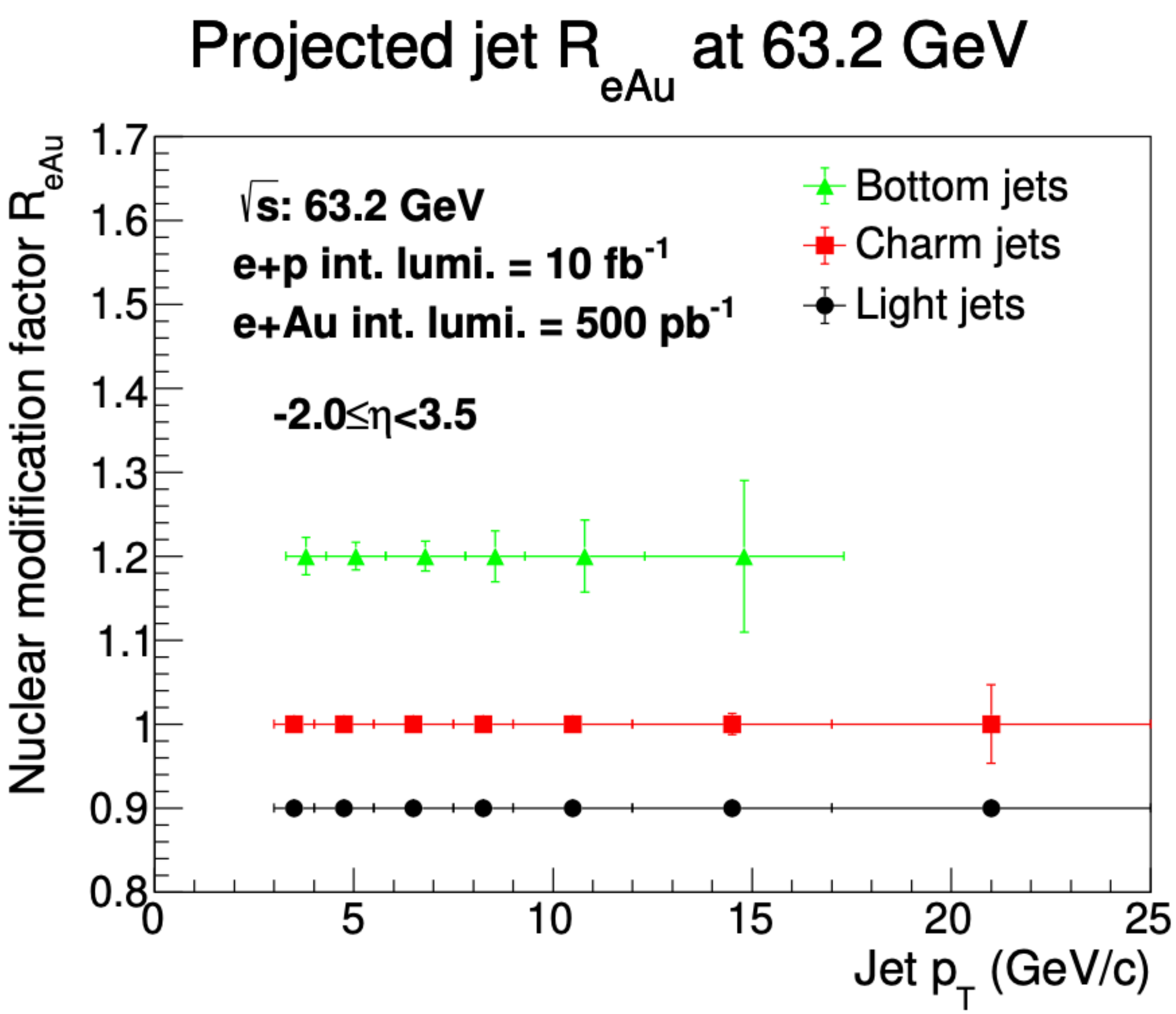

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$$R_{eA} = \frac{\sigma_{eA}}{A\sigma_{ep}}$$

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A nucleus with total number of nucleons A is not the same thing as A *ep* collisions → nuclei are different!

Why are heavy flavor probes particularly useful for studying cold nuclear matter?

Perturbative probes, and produced early → they are in the medium longer than other probes

What is an energy-energy correlator?

What is an energy-energy correlator?

$$\Sigma_{\mathrm{EEC}}(R_{\mathrm{L}}) = \frac{1}{N_{\mathrm{jet}} \cdot \Delta} \int_{R_{\mathrm{L}}-\frac{1}{2}\Delta}^{R_{\mathrm{L}}+\frac{1}{2}\Delta} \sum_{\mathrm{jets}} \sum_{i,j} \frac{p_{\mathrm{T},i} p_{\mathrm{T},j}}{(p_{\mathrm{T}}^{\mathrm{jet}})^2} \delta(R'_{\mathrm{L}} - R_{\mathrm{L},ij}) dR'_{\mathrm{L}}$$

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It is a multi-particle correlation function (above defines the two-particle correlation)

Energy-weighted sum over all pairs of particles in the jet

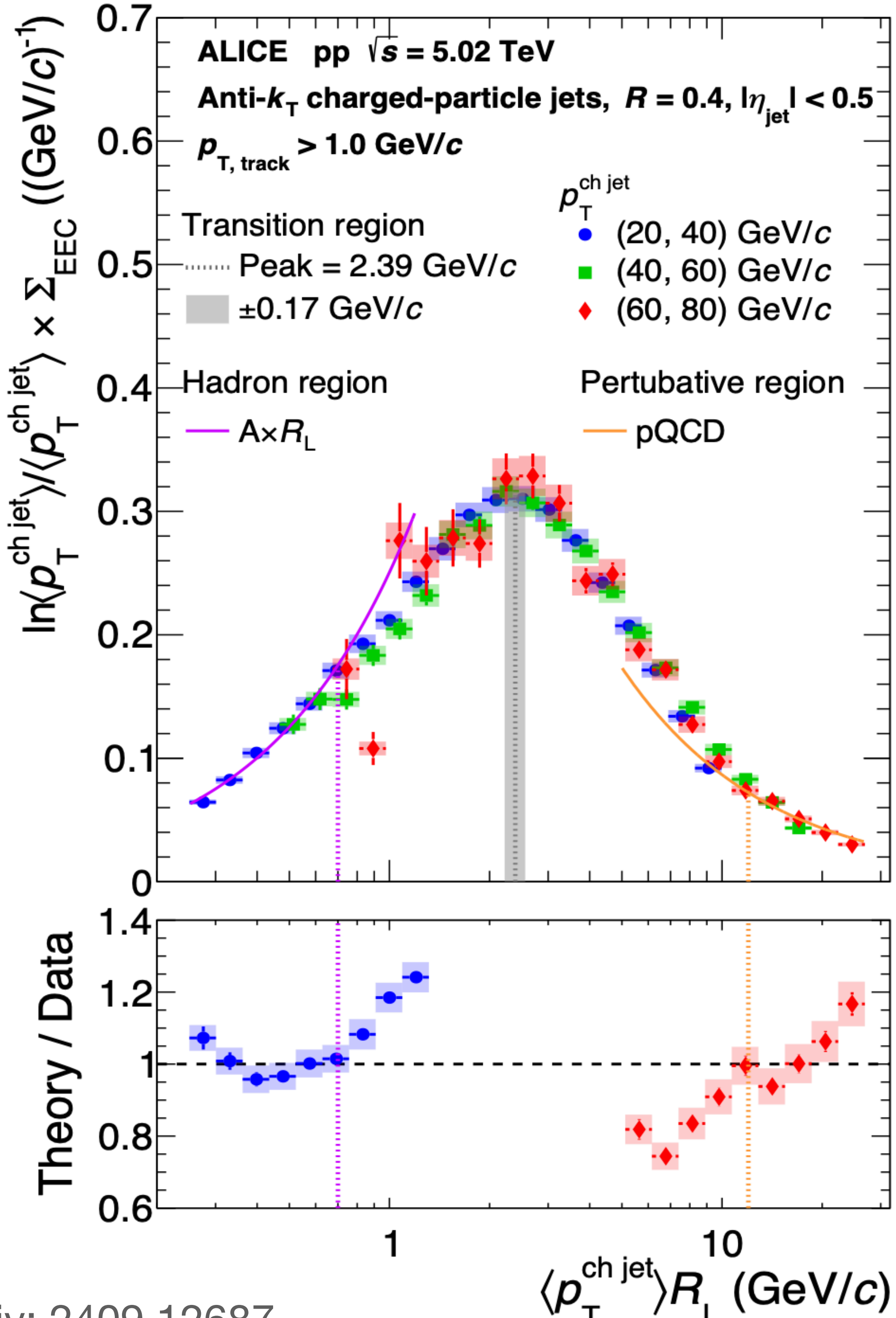
Binned as a function of the distance between the particles in the (η, ϕ) plane

$$R_{L,ij} = \sqrt{(\phi_j - \phi_i)^2 + (\eta_j - \eta_i)^2}$$

Bin size Δ

Normalised by the number of jets you measured

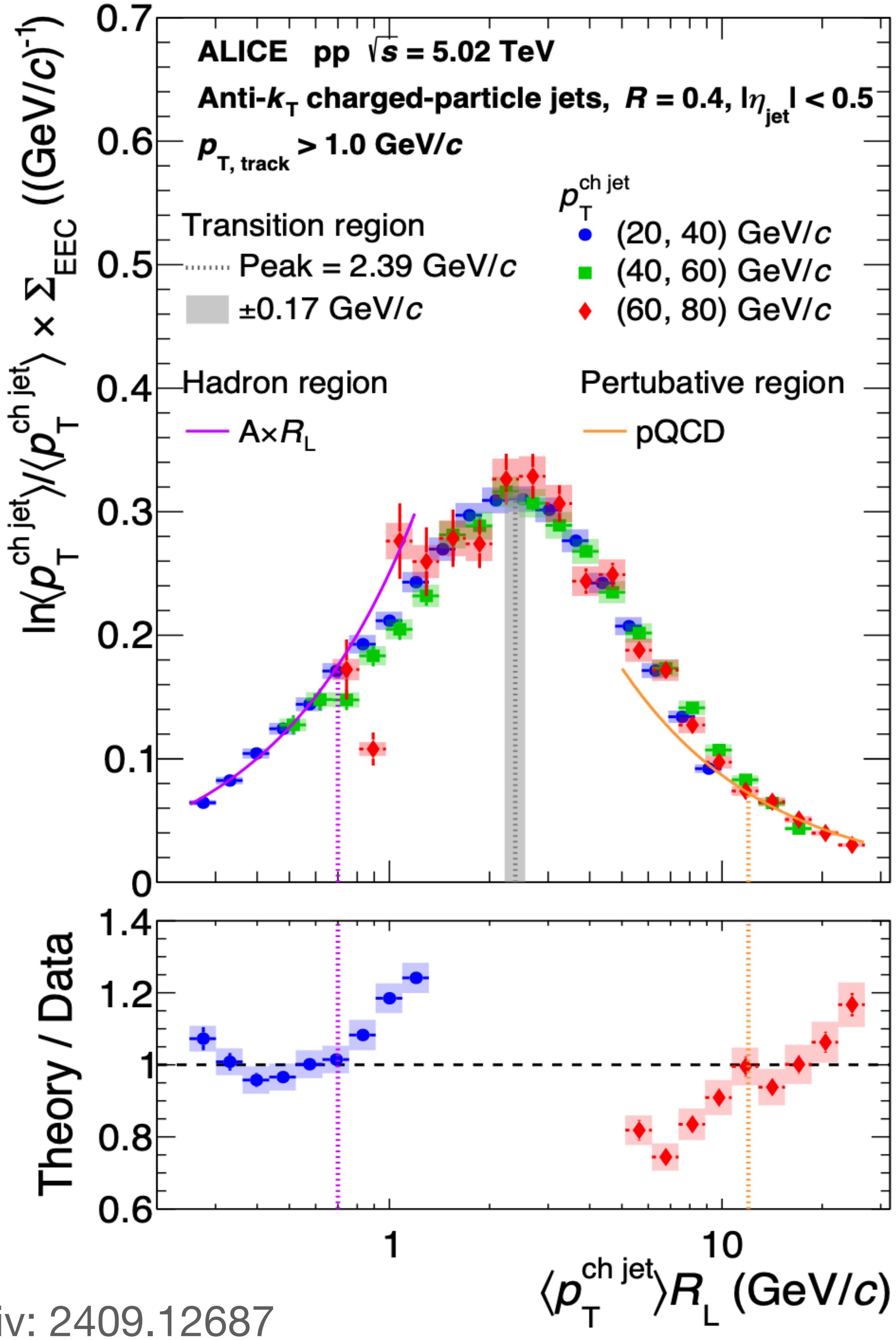
Why are energy-energy correlators interesting?



arXiv: 2409.12687

- Energy-energy correlators are sensitive to the transition between partons and hadrons
- Time scale of parton splitting
  $\tau \sim 1/(p_T^{jet} \times R_L^2)$

Why are energy-energy correlators interesting?



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- Large R_L region corresponds to the parton shower and is described by perturbative QCD
- Small R_L region (smaller angles) corresponds to hadronization and is non-perturbative

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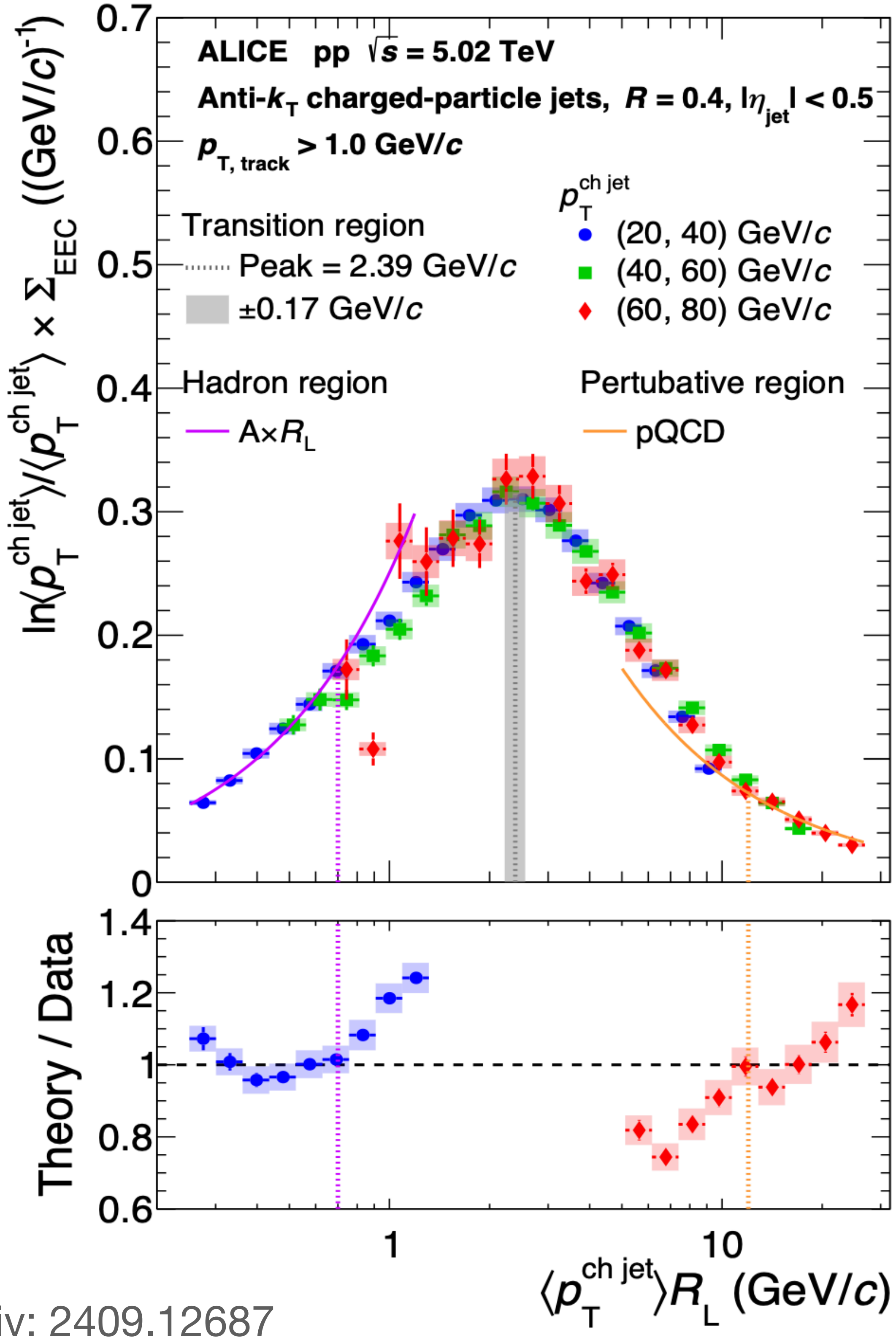

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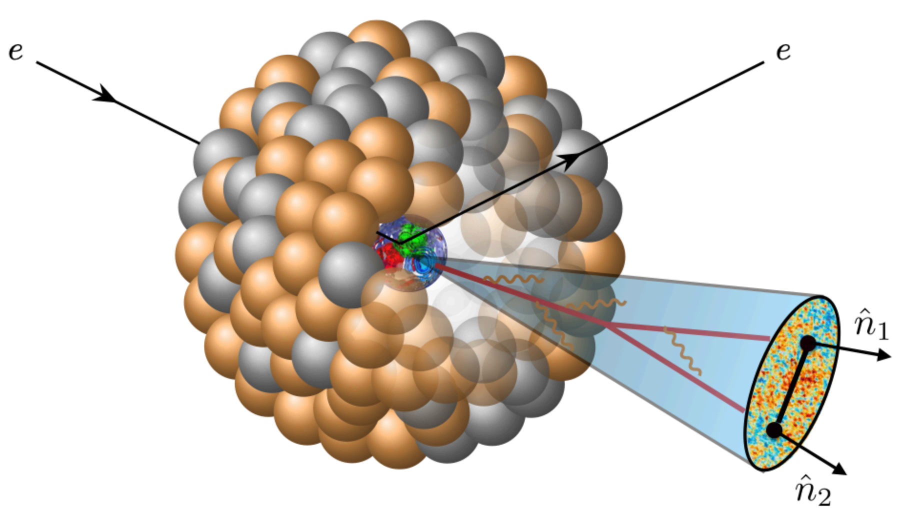
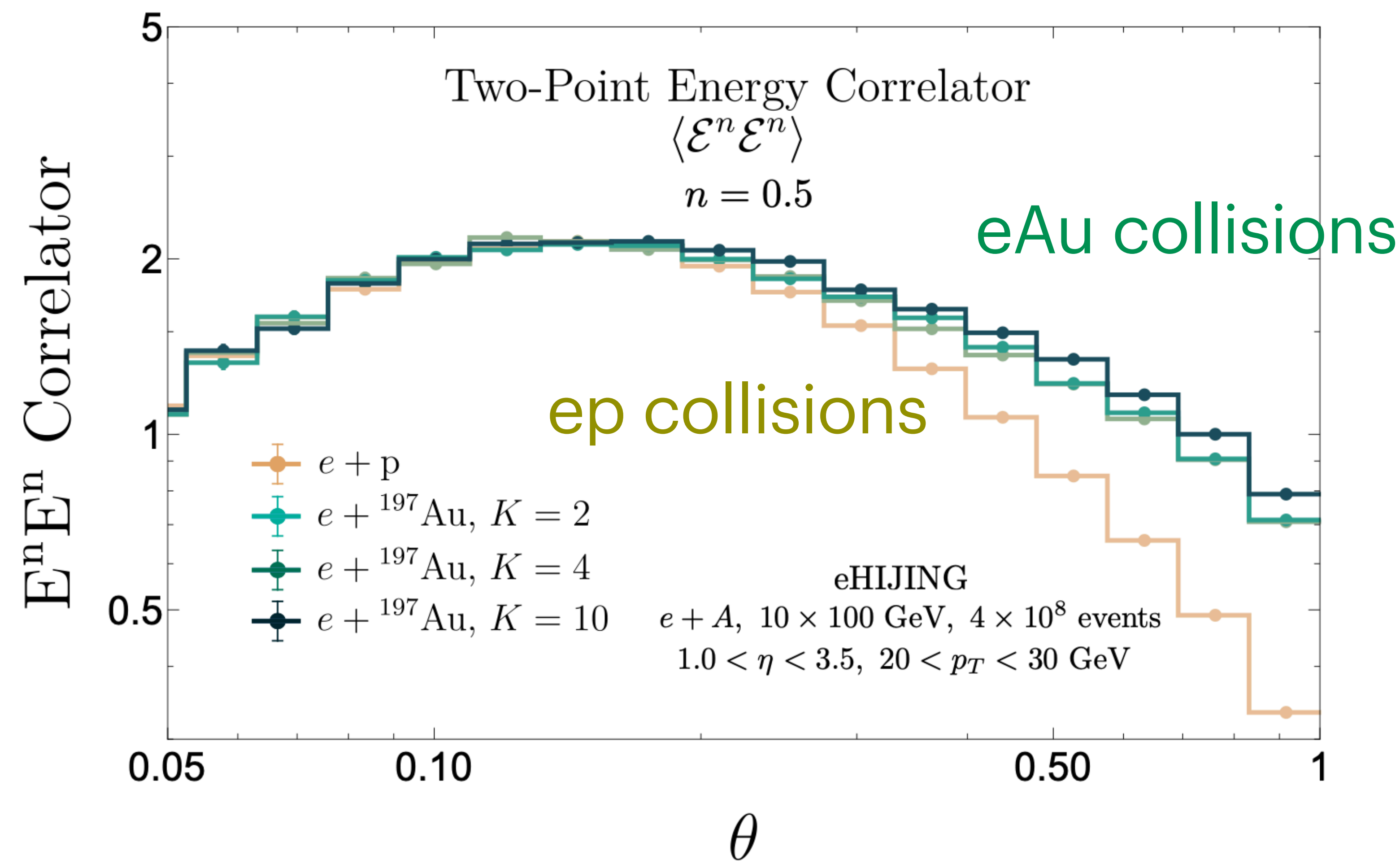
- Large R_L region corresponds to the parton shower and is described by perturbative QCD
- Small R_L region (smaller angles) corresponds to hadronization and is non-perturbative
- "Turnover" at the angular scale where the parton to hadron transition occurs!

Probing cold nuclear matter with EECs

- EECs cleanly separate physics occurring at different angular scales → rich phenomenology now being applied to many other fields!
- In eA collisions, EECs are sensitive to the scale at which medium modifications (cold nuclear matter effects) take place
- A new tool to better understand cold nuclear matter!



arXiv: 2303.08143

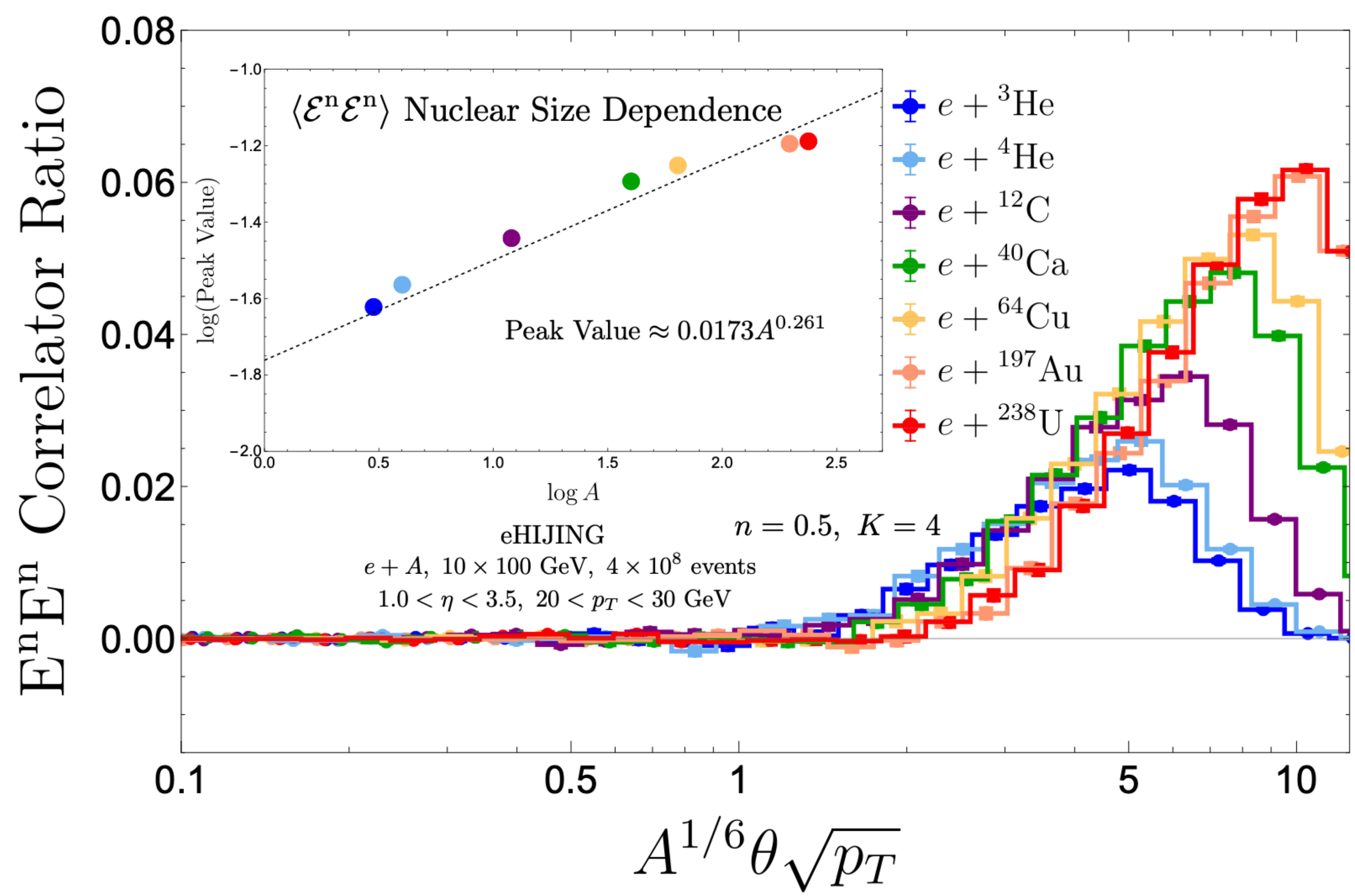


Probing cold nuclear matter with EECs

- EEC ratios have even been shown to be directly proportional to the size of the nucleus!
- Opportunity to start connecting partonic interactions to "macroscopic" nuclear physics, one of the goals of QCD and the EIC

$$\frac{\langle \mathcal{E}^n \mathcal{E}^n \rangle_{e+^{197}\mathrm{Au}} - \langle \mathcal{E}^n \mathcal{E}^n \rangle_{e+\mathrm{p}}}{\langle \mathcal{E}^n \mathcal{E}^n \rangle_{e+\mathrm{p}}}$$

Ratio to vacuum ep



arXiv: 2303.08143

Summary: Lecture 2

- Heavy flavor probes at the EIC are sensitive to the gluon PDFs (collinear and TMDs). Measurements of open heavy flavor production and heavy flavor jet production can help constrain unpolarised and polarised gluon PDFs

- Jet production at the EIC probes a variety of subprocesses → important for constraining PDFs both in protons and in nuclei

- eA collisions are a crucial piece towards understanding QCD interactions in nearly every collision system. They allow to isolate cold nuclear matter effects from other complex QCD interactions that can arise in pA collisions

- Energy-energy correlators are another type of jet substructure observable that have a strong potential to illuminate cold nuclear matter at the EIC, and to potentially connect QCD partonic interactions to low-energy nuclear structure