Photon-jet and Dijets from RHIC to the EIC

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Oak Ridge National Laboratory

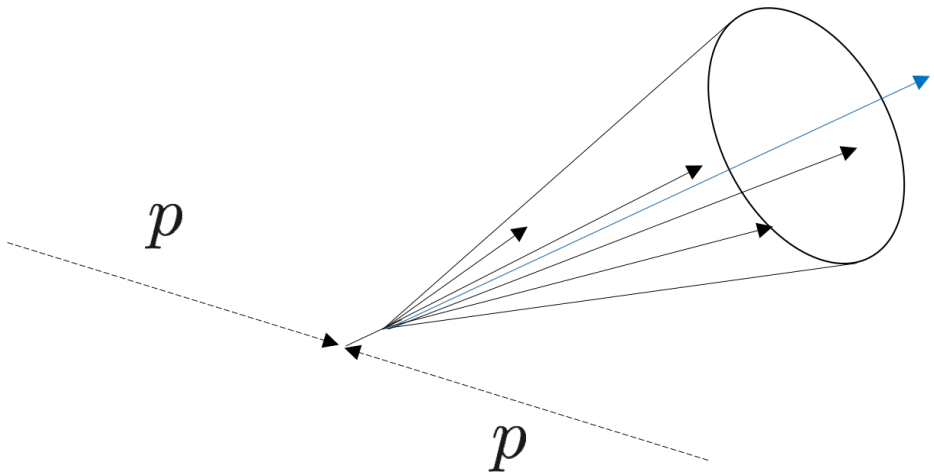
May 25, 2021

Photon-Jet and Dijet Physics

- A wide range of physics is accessible from photon-jets and dijets
  - Unpolarized PDFs and N^{n}LO physics
  - Spin physics - ΔG, TMDs, transversity etc. (See Renee Fatemi's talk)
  - Fragmentation and Hadronization - FFs, TMDFFs
  - Partonic energy loss
  - Diffractive structure functions
  - Possible effects from entanglement
  - ...
- Disclaimer: Impossible to robustly cover all of these topics in 30 minutes. I'll only discuss some which have been most covered by previous and upcoming RHIC measurements

Jets

- Jet physics is a broad experimental endeavor at RHIC and the LHC
- Enabled by more robust comparisons that can be made between theory and experiment with recent jet finding algorithms



Jets

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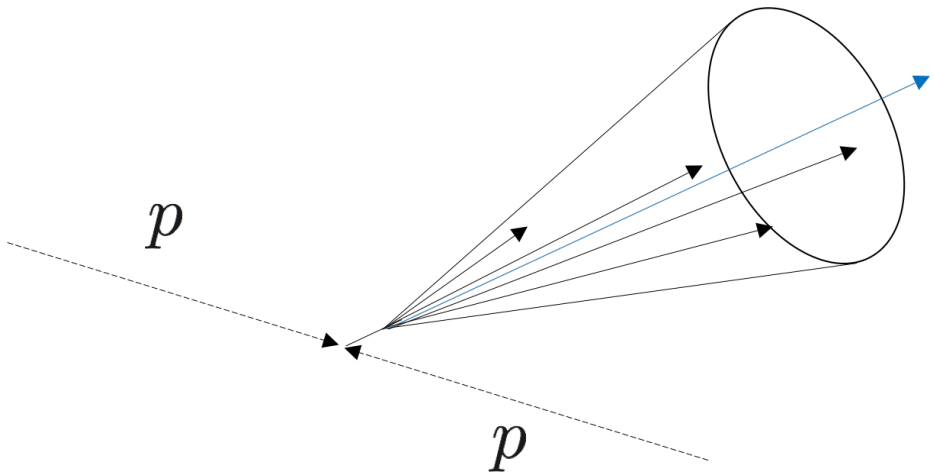
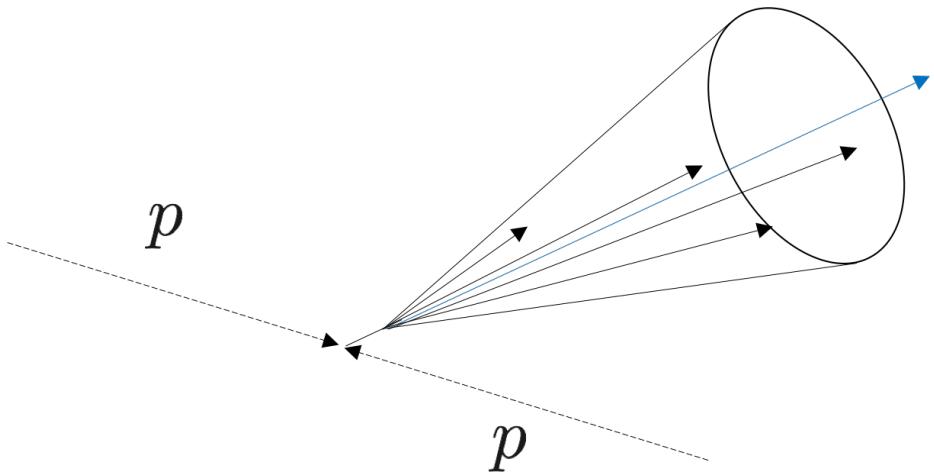
- Enabled by more robust comparisons that can be made between theory and experiment with recent jet finding algorithms
- Jets are a proxy for partons, and thus provide sensitivity to the underlying partonic dynamics
- Dijets and γ-jets are an optimal proxy for $2 \to 2$ scattering kinematics in hadronic collisions



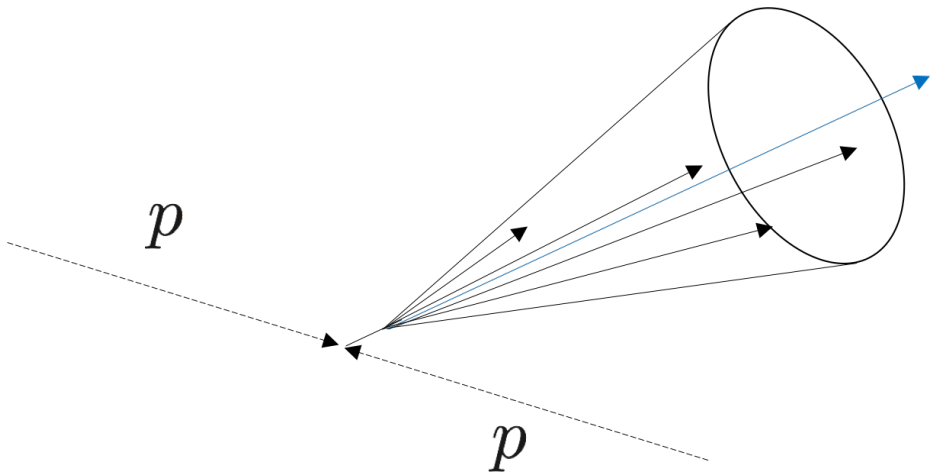
Jets

- BUT - jets are still formed from final-state hadrons!
- Nonperturbative elements of QCD still important in understanding perturbative jets

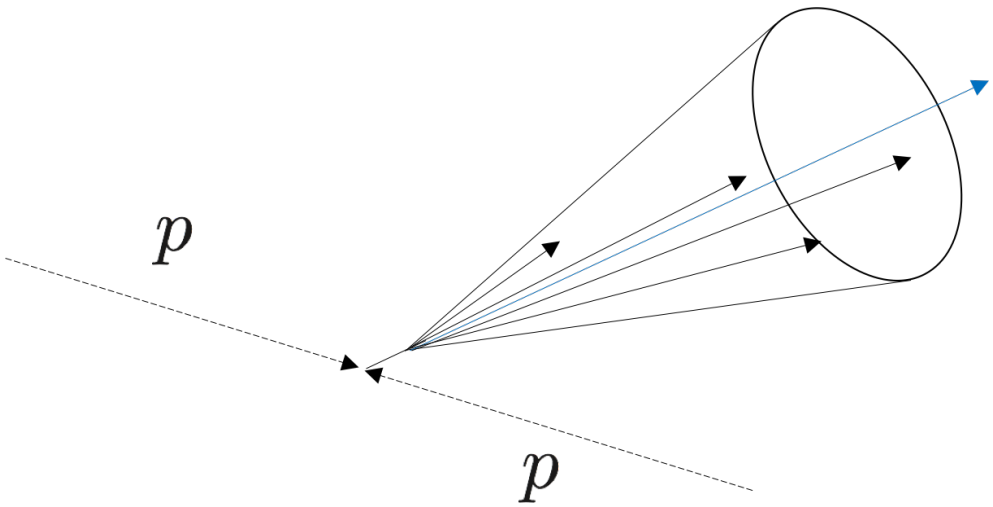


Jets

- BUT - jets are still formed from final-state hadrons!
- Nonperturbative elements of QCD still important in understanding perturbative jets
- We can use a perturbative object to learn about nonperturbative physics
- One of the fundamental questions we are all trying to answer - how do the nonperturbative and perturbative aspects of QCD lead to what we measure?
    - Jets are inherently a multiscale observable (making them interesting)

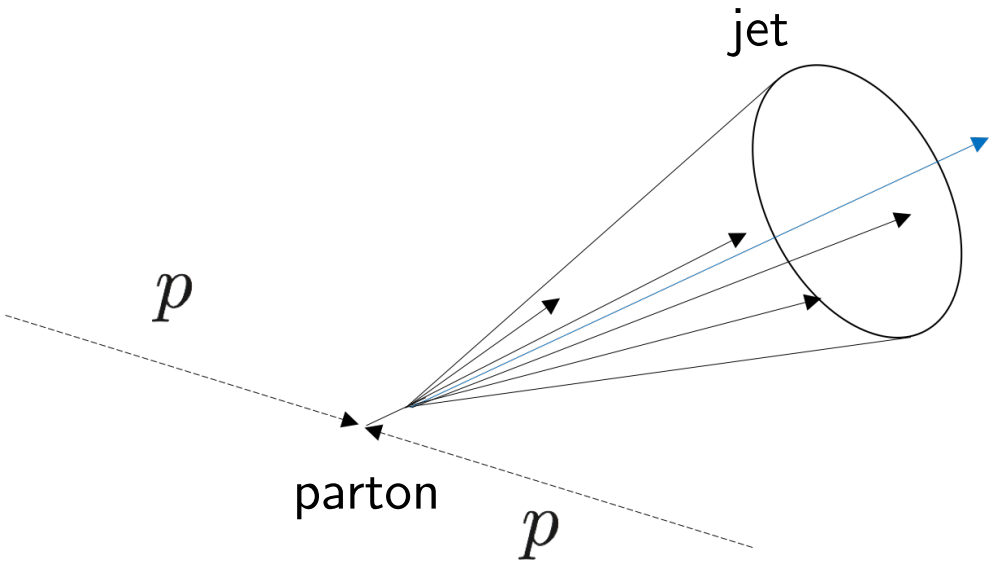


Jets: What do we want?



- What is on our wish list to *robustly* study jet production?

Jets: What do we want?



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     - Jets, as a proxy for a parton, are a tool to connect the perturbative to nonperturbative

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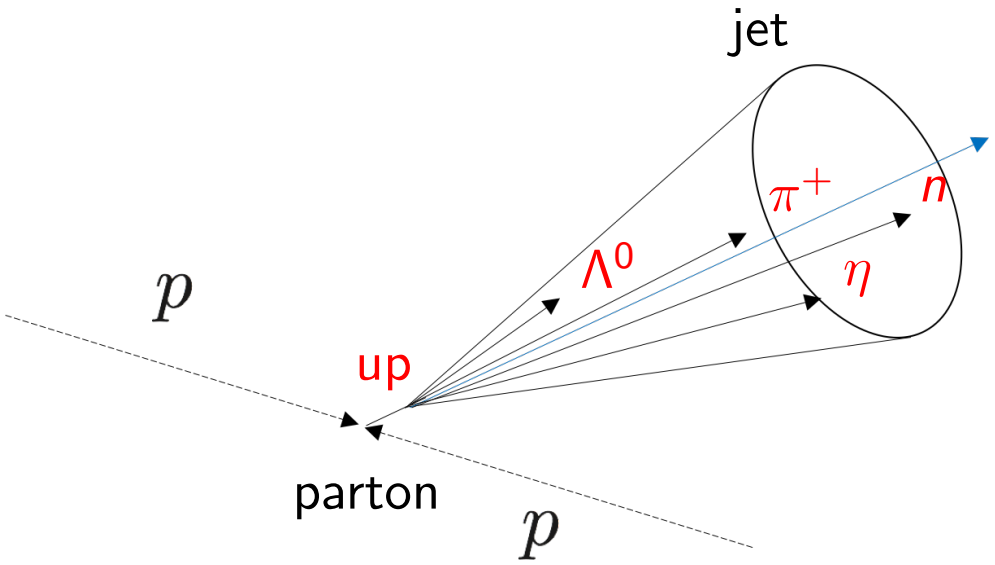

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     - Would allow for complete characterization of parton $\rightarrow$ hadron

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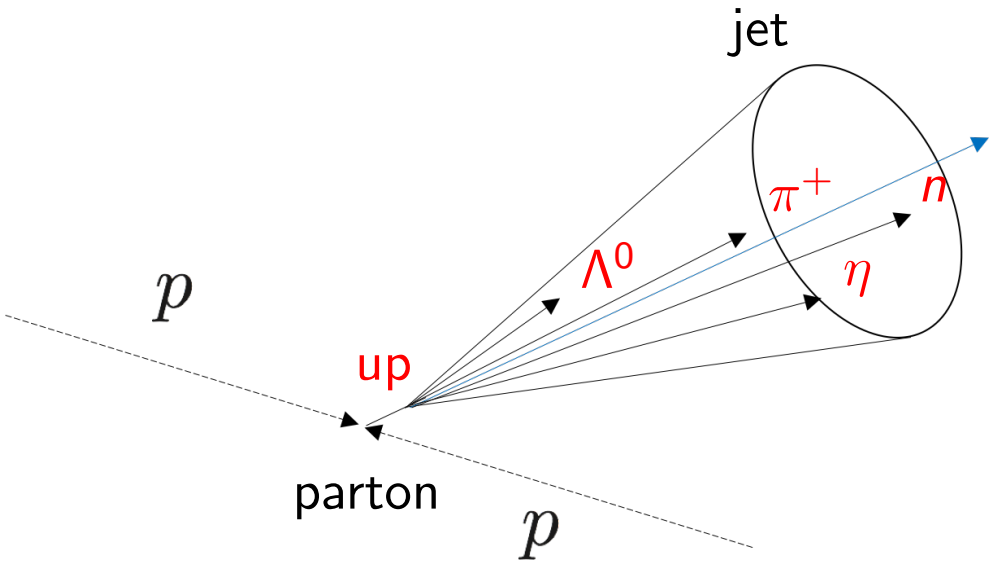

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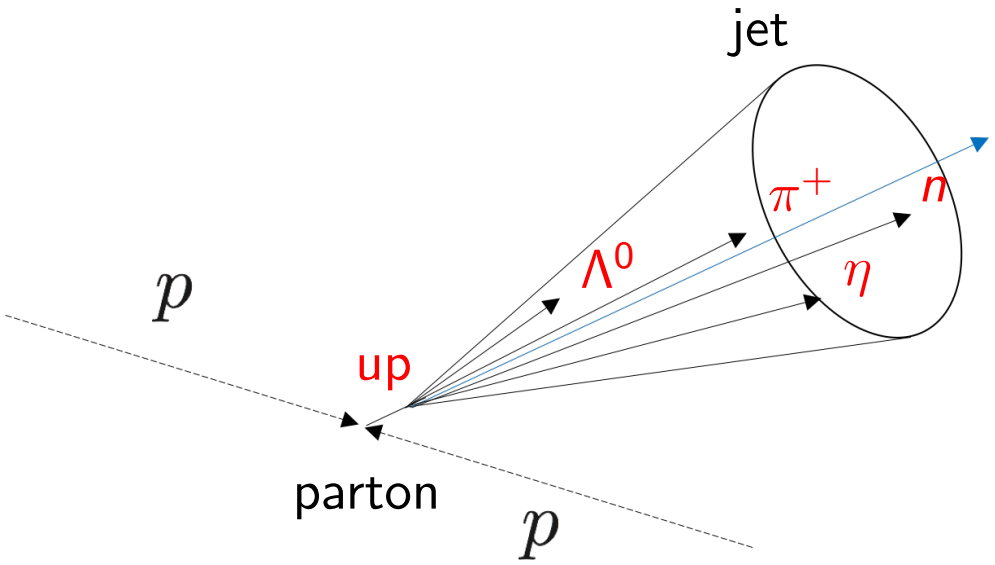

- Parton flavor studies
- Resonance production (ϕ, J/ψ, Υ)
- Correlations (e.g. kinematic, PIDed. . .)
- . . .

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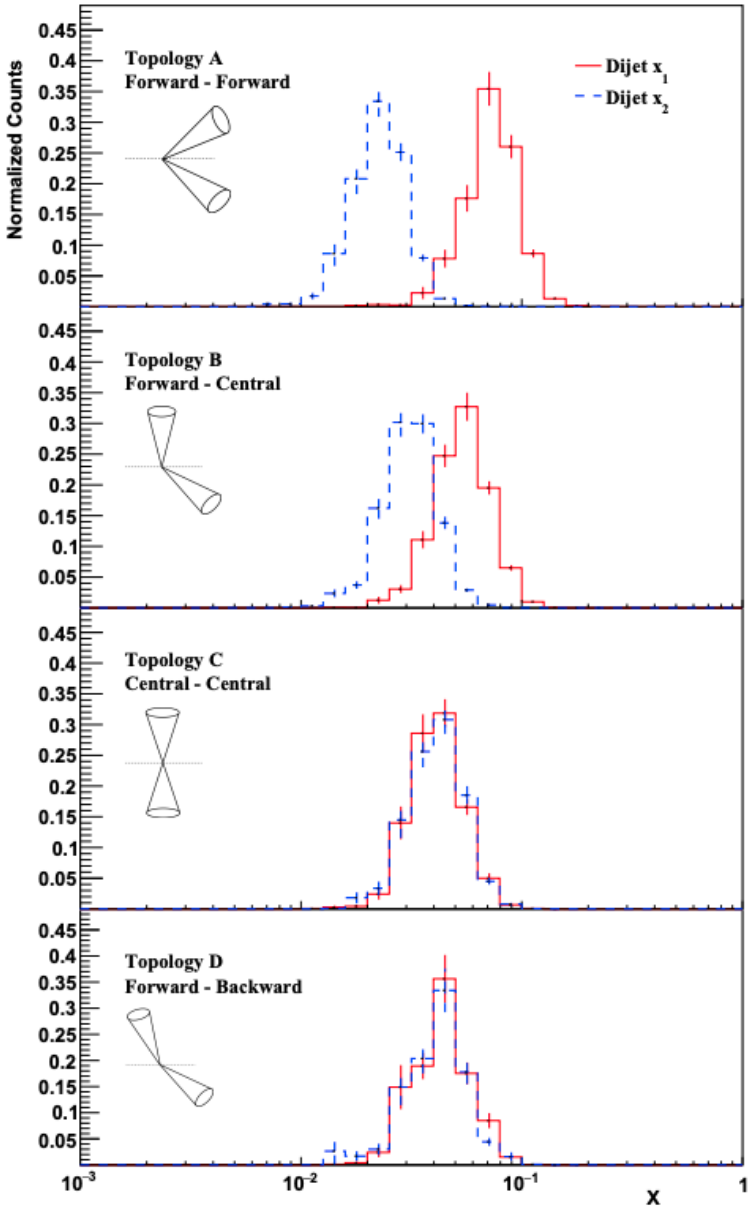
What can we do before EIC?

RHIC - the polarized collider

Measurements for ΔG

- A host of new jet A_{LL} measurements have recently been published
- STAR dijet at 200 and 510 GeV
  - Phys. Rev. D 100, 052005 (2019) (Run 12 @ 510 GeV)



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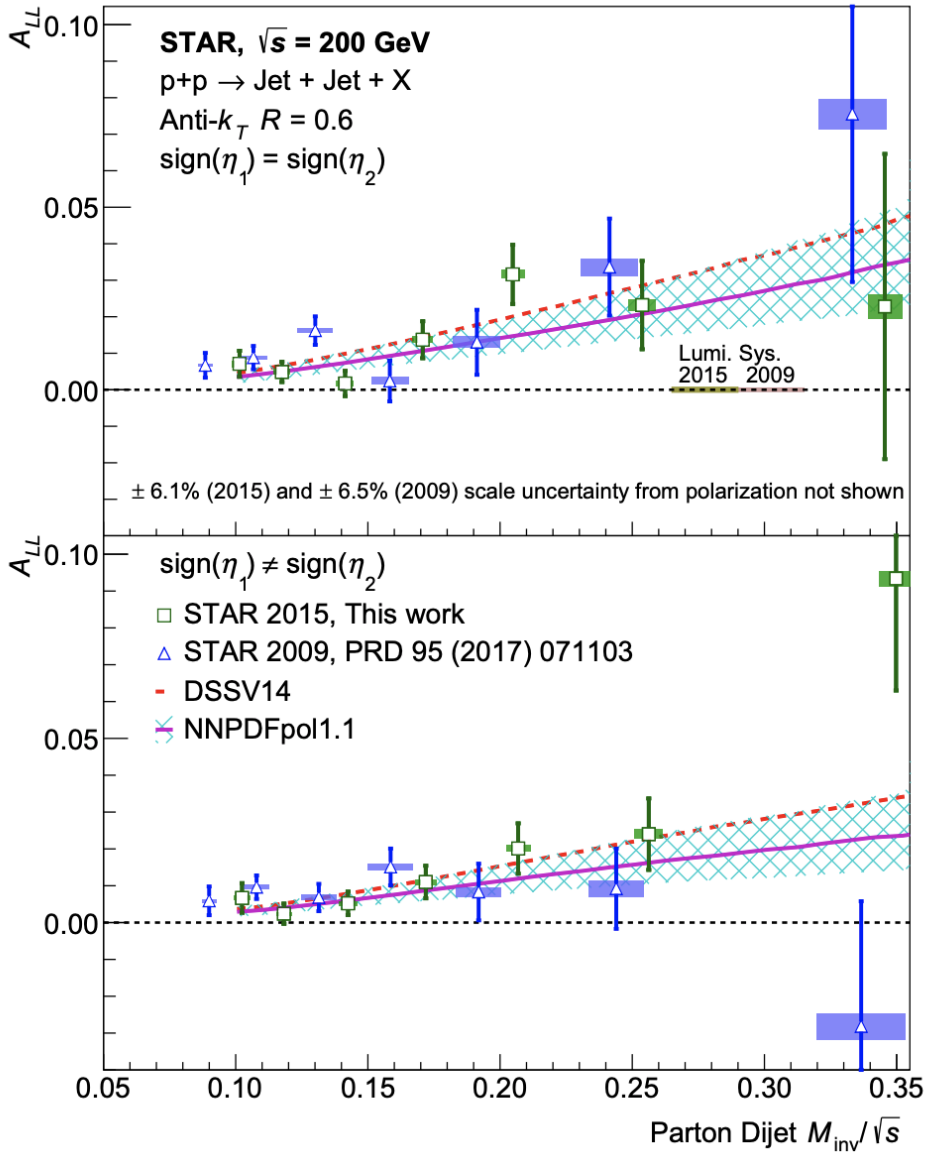

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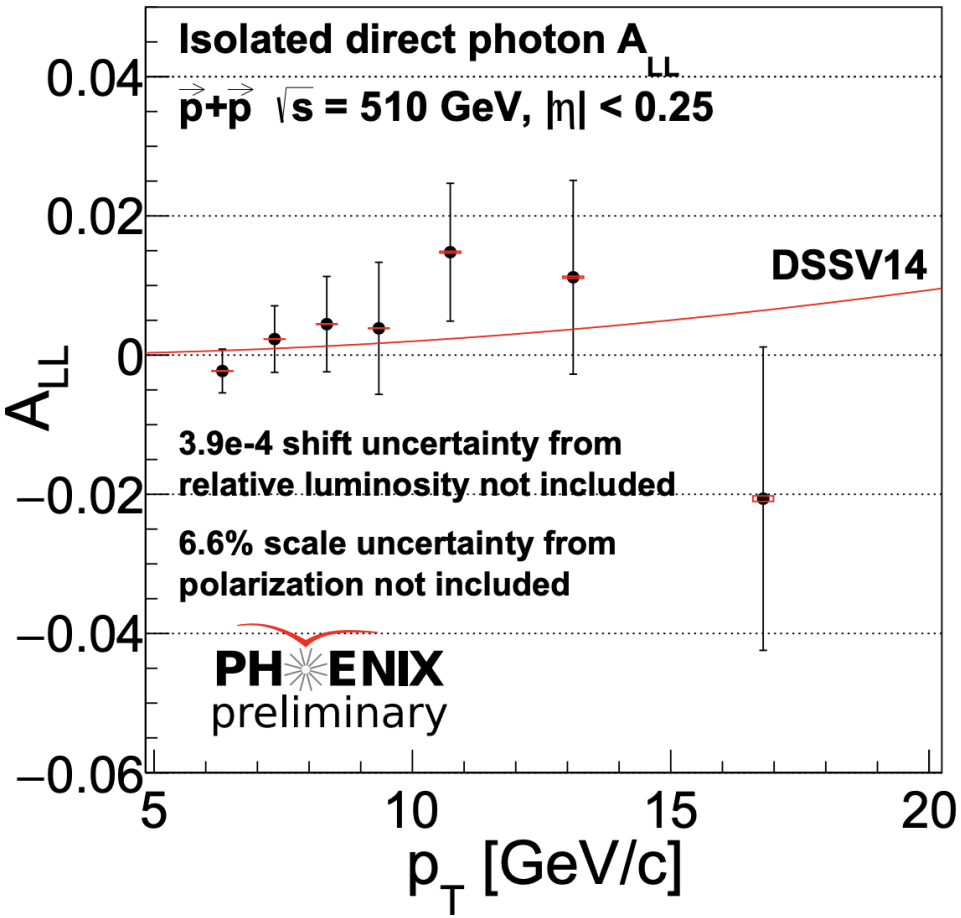

Z. Ji, DIS2021

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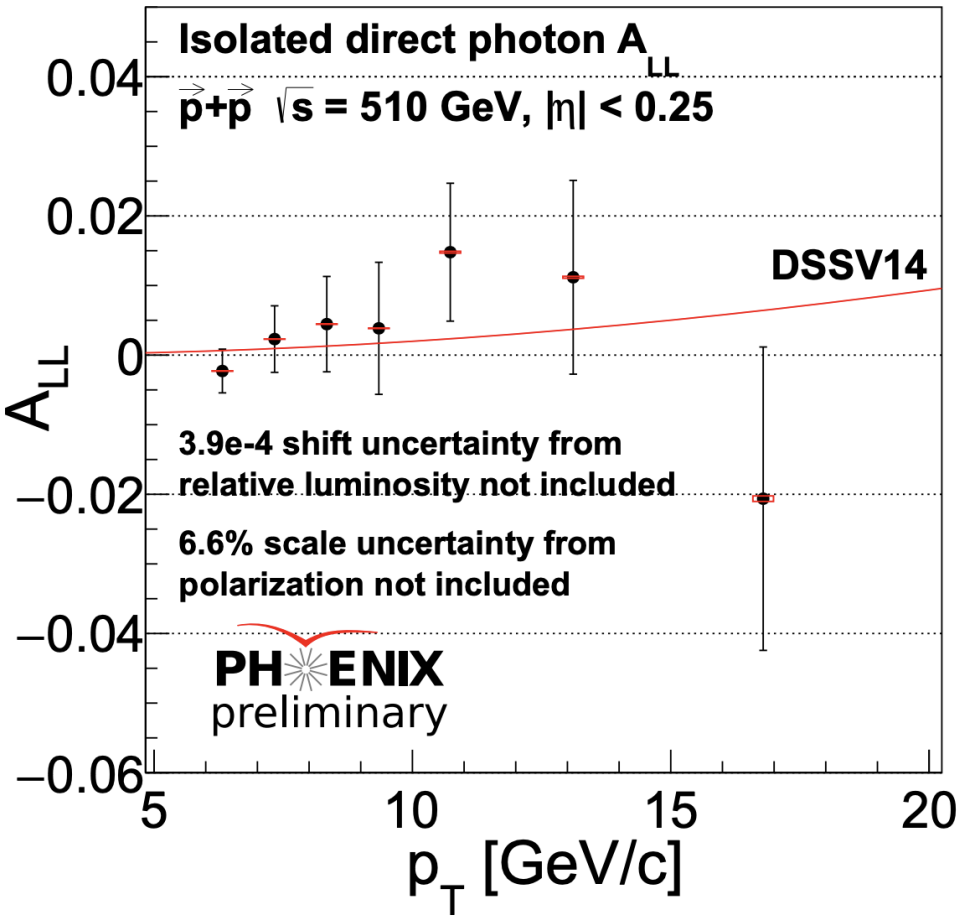
- Impact of Run 13 $\sqrt{s} = 510$ GeV data will be seen with latest results and STAR dijet results!



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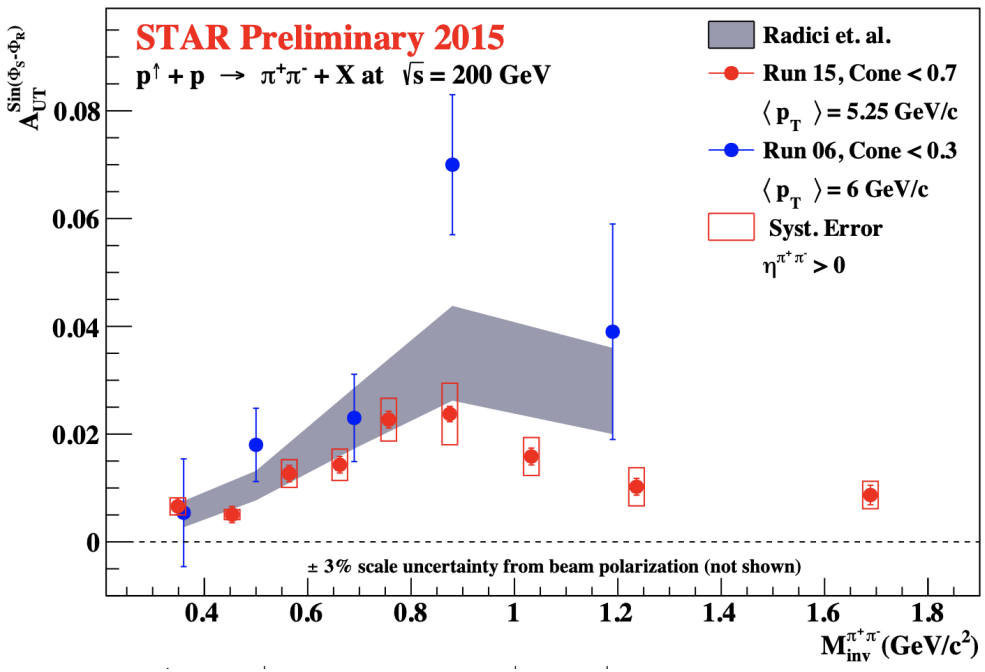
IFF Measurements

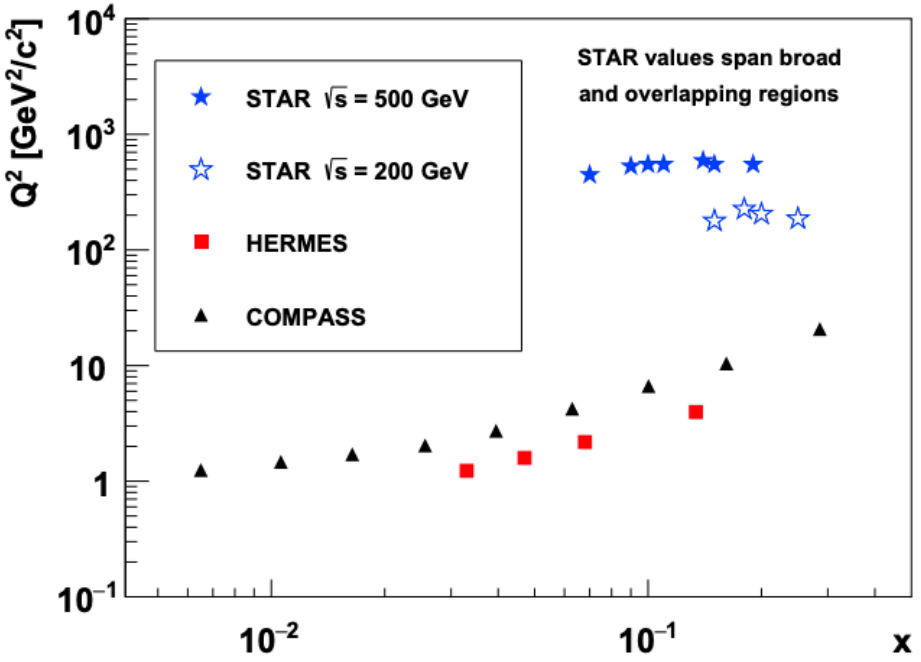
- New interference FF results from Run-15 STAR have much improved precision



B. Pokhrel, DIS 2021

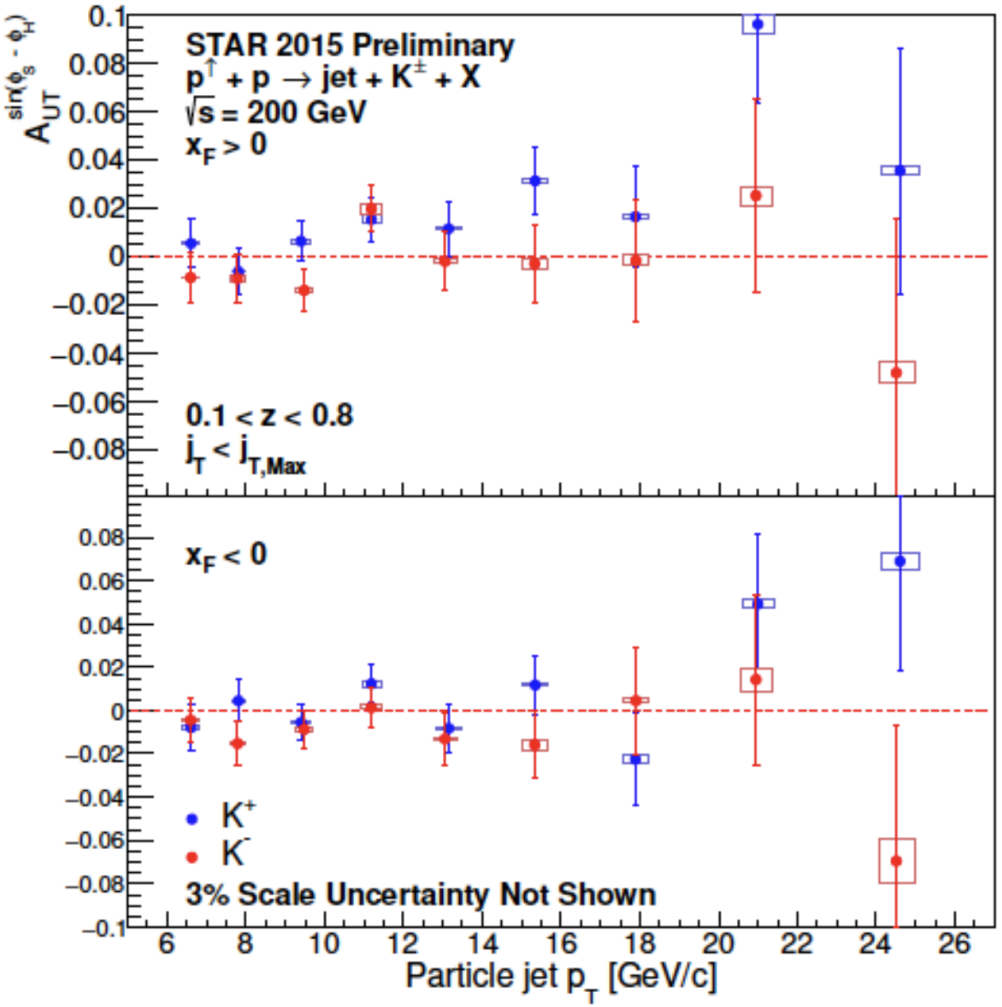
IFF Measurements

- New interference FF results from Run-15 STAR have much improved precision
- Important measurements to complement available SIDIS data
  - Cover similar x region but at high Q^2
  - Looking forward to EIC with broad $x - Q^2$ coverage



Phys. Lett. B 780, 332-339 (2018)

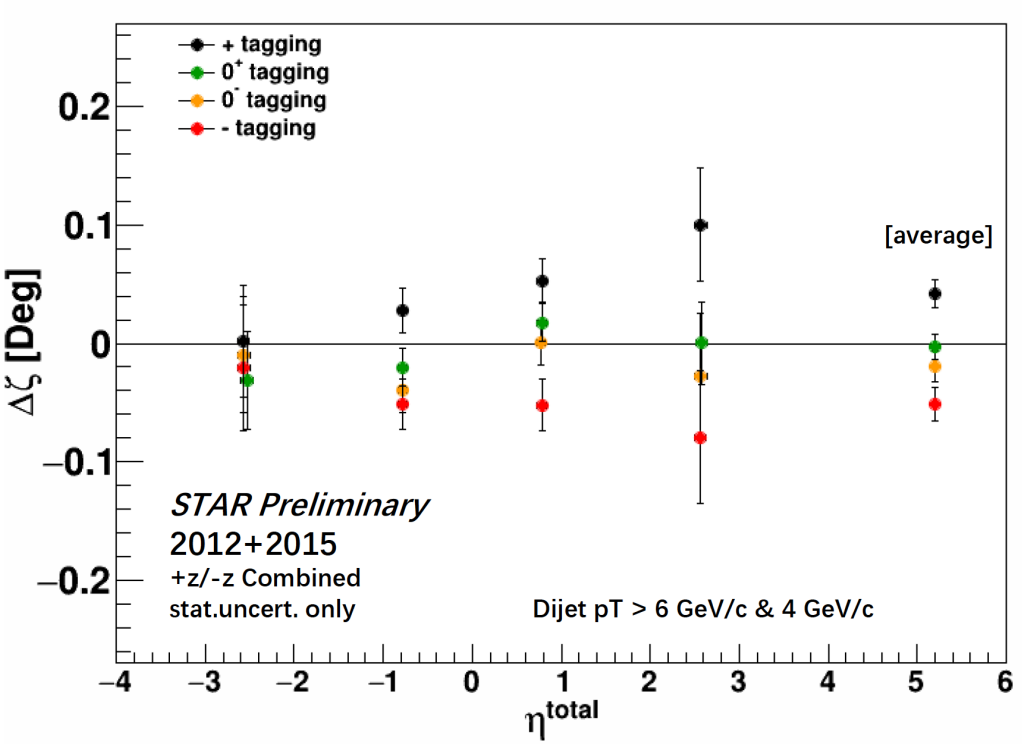
TMD Related Measurements



B. Pokhrel, DIS 2021

- New STAR Collins results with PID(!)
- Should make the most use of PID as possible towards EIC (e.g. at STAR, ALICE, LHCb)
- See more in hadronization, later

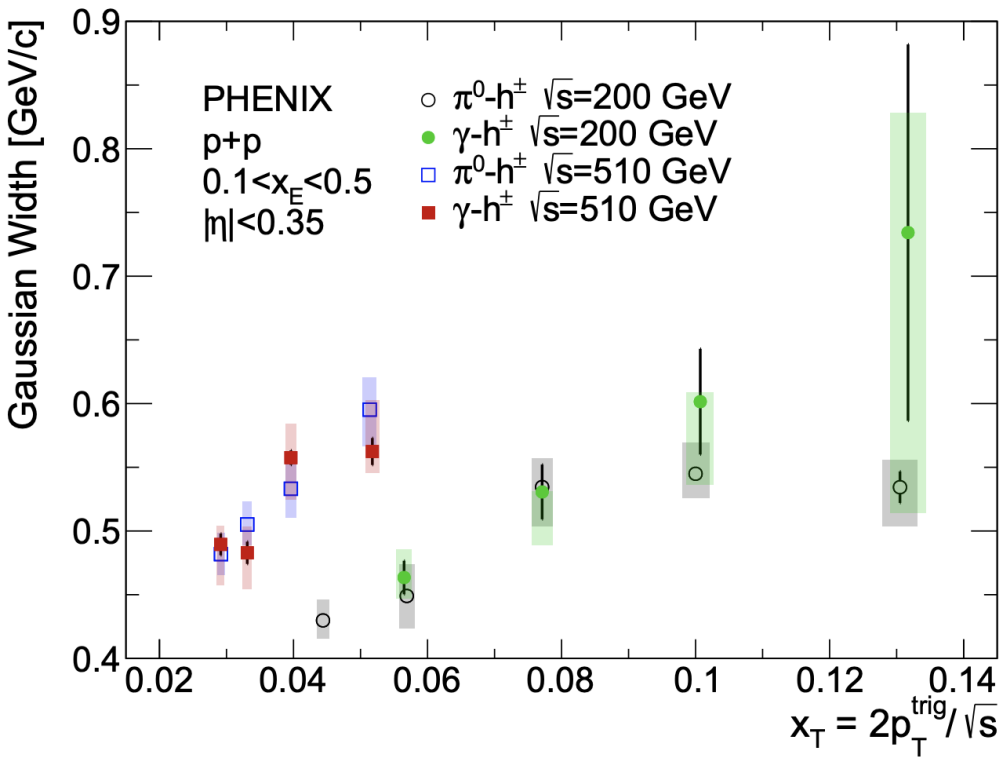
Dijet Sivers



- STAR has recently updated their dijet Sivers measurement from 2006
- Nonzero asymmetry when charge tagging is employed at the jet level
- See R. Fatemi's, Z. Kang's talks earlier today

QCD Color Effects

- QCD is unique due to non-abelian nature - gluon self coupling
- Leads to fundamental predictions of the field theory
  - Sign change of PT odd TMDPDFs (e.g. Sivers, Boer Mulders)
  - Factorization breaking of certain processes
- PHENIX measured direct $\gamma - h^{\pm}$ and $\pi^0 - h^{\pm}$ correlations to provide first measurements of TMD factorization breaking predictions
  - Calculations assuming factorization for comparison needed



Phys. Rev. D 98, 072004 (2018)

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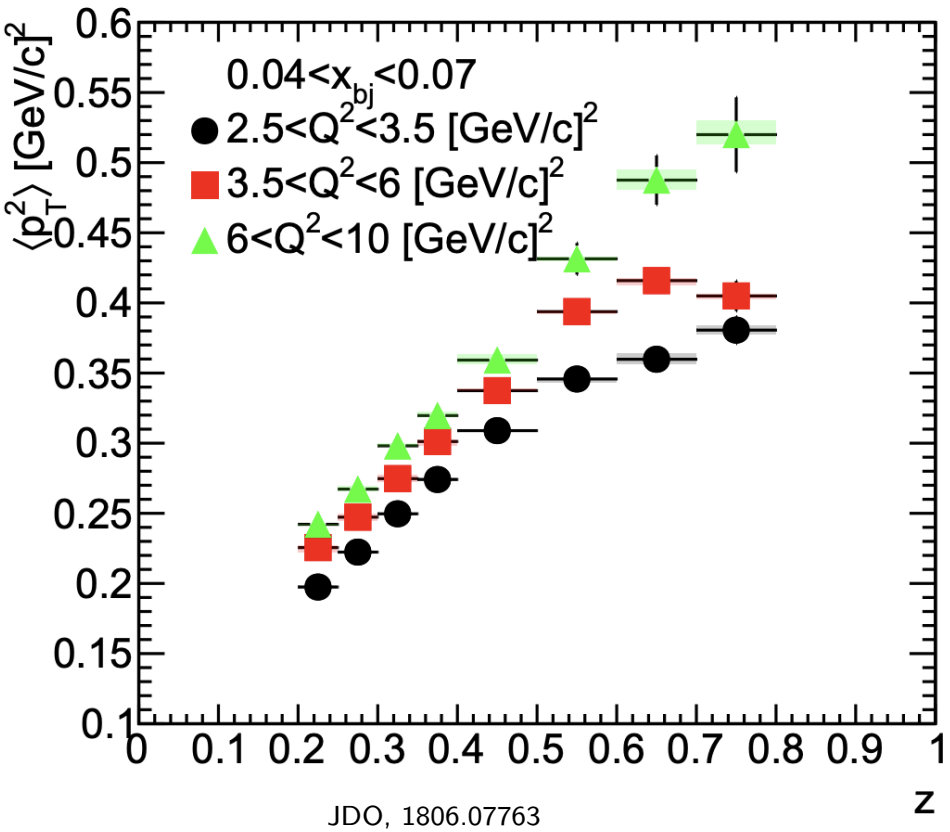
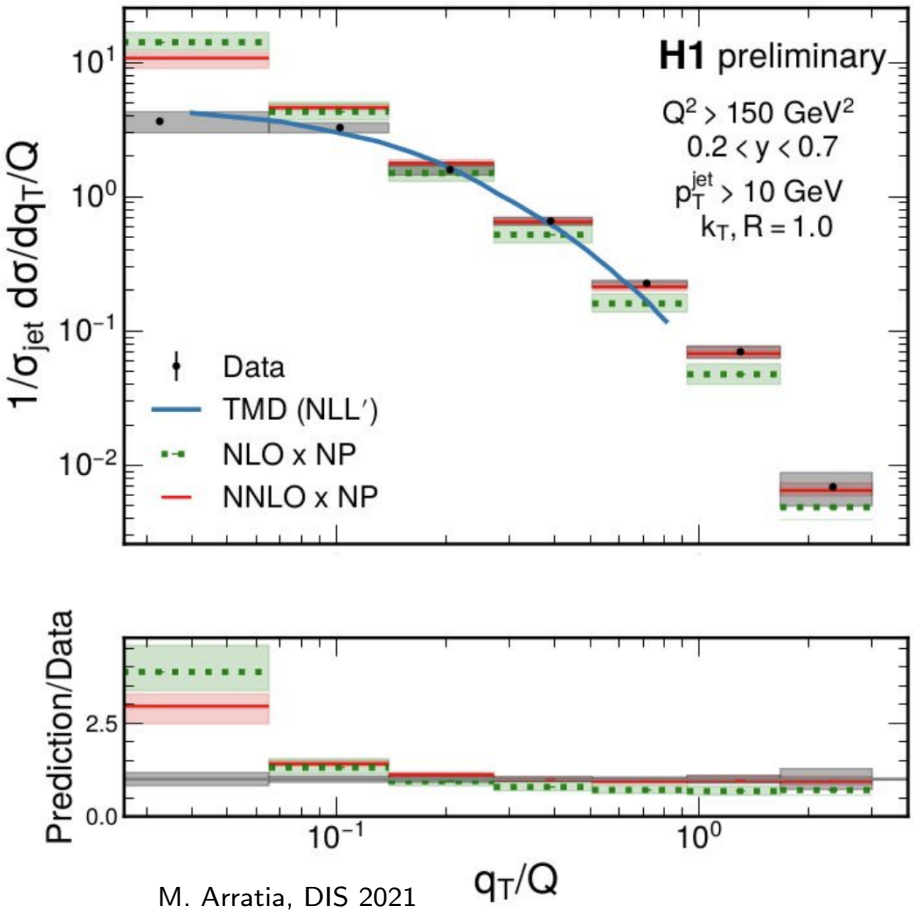


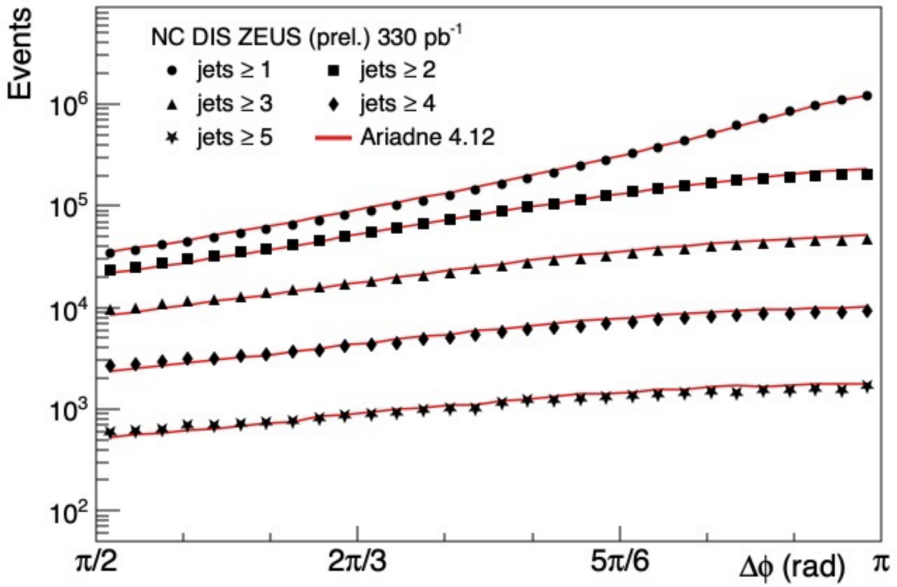
JDO, 1806.07763

- Towards EIC - what can we learn from comparing available RHIC data to current ep, e^+e^- data?
- Emphasizes making measurements that are as kinematically comparable as possible for robust systems comparisons

SIDIS TMD Data



M. Arratia, DIS 2021

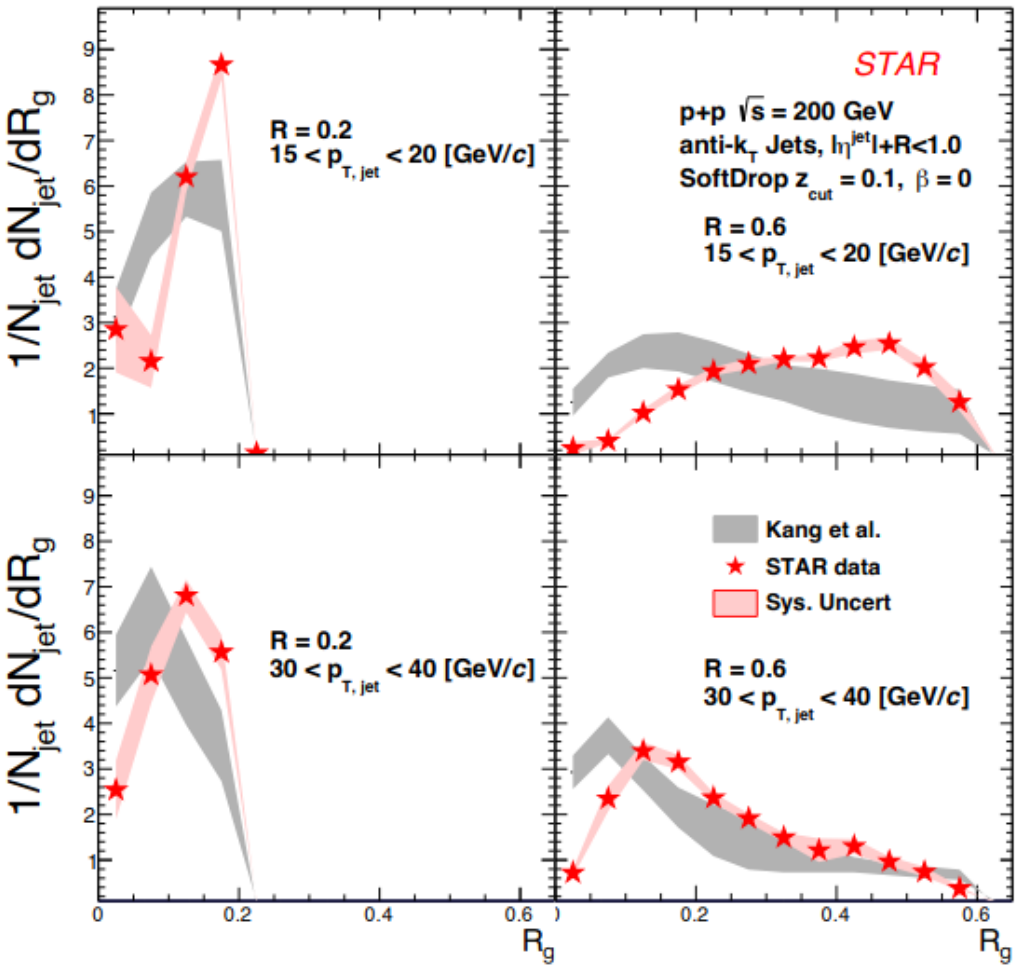


A. Quintero, DIS 2021

- HERA data being re-analyzed given new results from RHIC/LHC in last decade
- Emphasizes reusability of RHIC data! What will we want to re-analyze in the 2030s given new EIC information?

RHIC - the jet factory

STAR Soft Drop



Phys. Lett. B 811, 135846 (2020)

- New STAR results are first study at RHIC of Soft Drop splittings
- Highlight R_G, which shows need for more robust theory calculations relating fragmentation and hadronization effects

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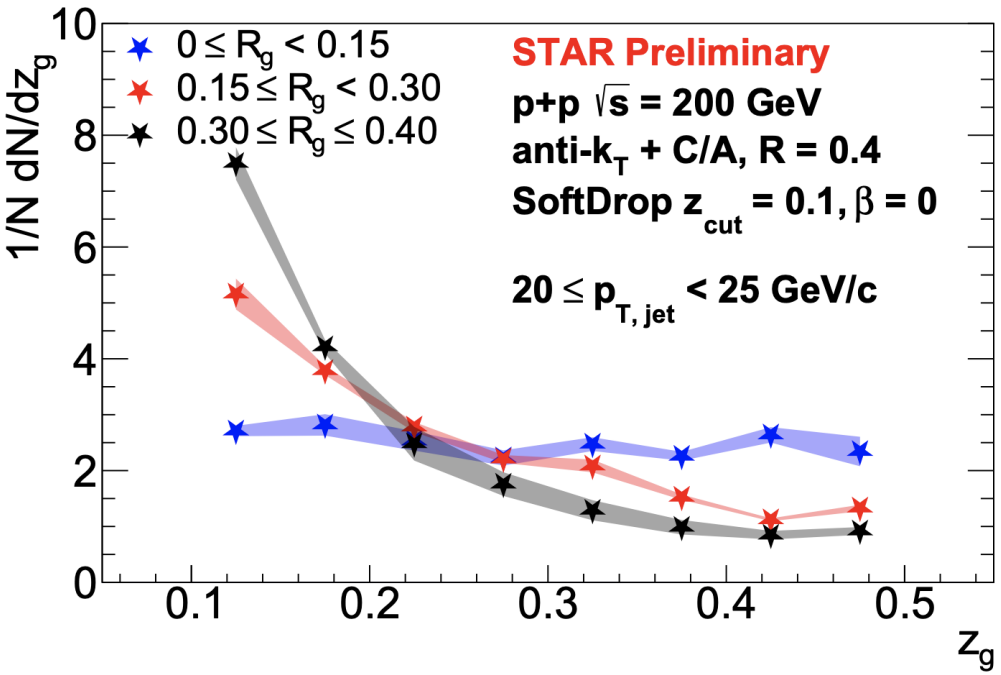
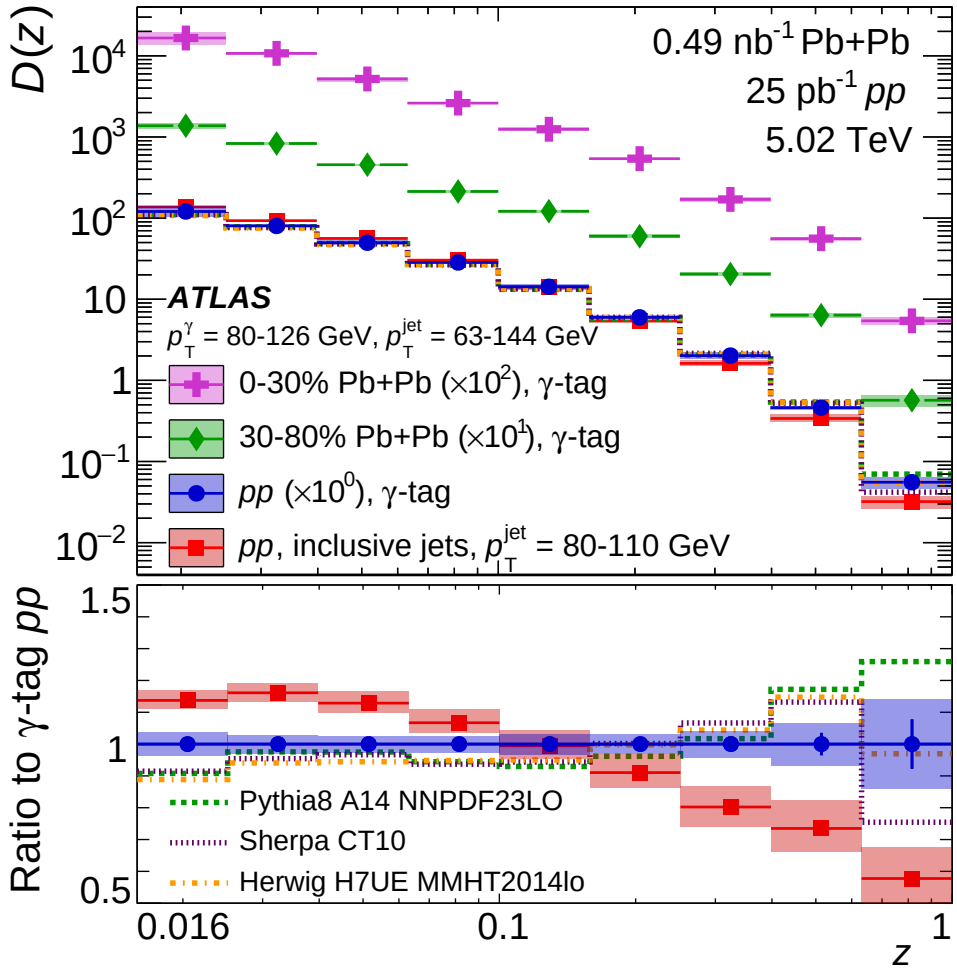


R. Elayavalli, DIS 2021

- New STAR results are first study at RHIC of Soft Drop splittings
- Highlight R_G, which shows need for more robust theory calculations relating fragmentation and hadronization effects
- Statistics allow for multi-differential measurements

Partonic Contributions

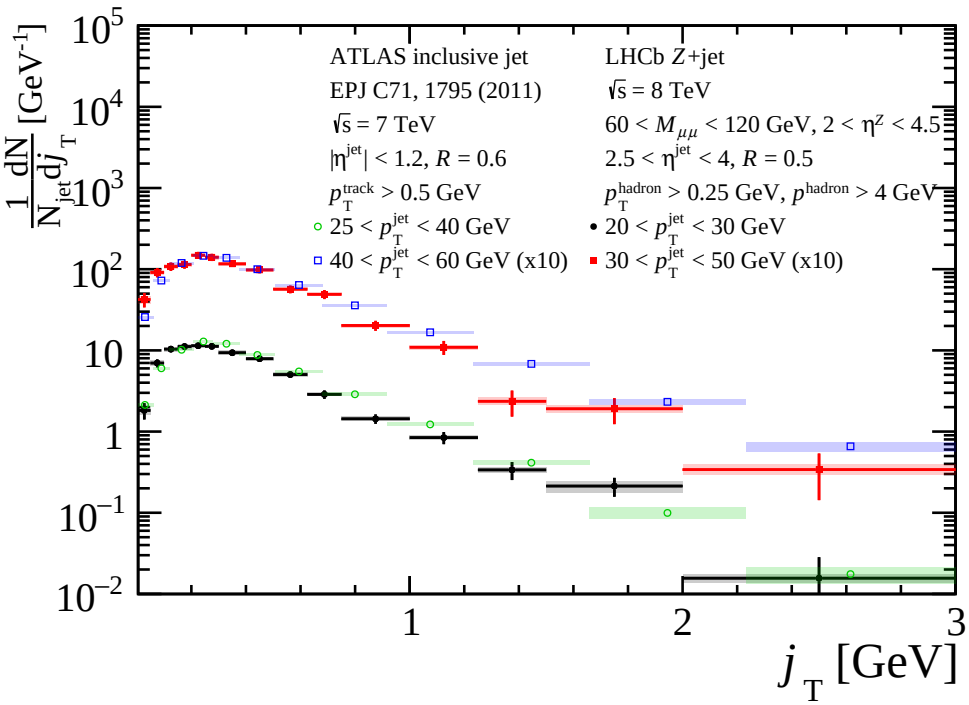
- Alter partonic contributions of underlying hard scattering processes
- ATLAS γ-jet compared to inclusive jet FFs



Phys. Rev. Lett. 123, 042001 (2019)

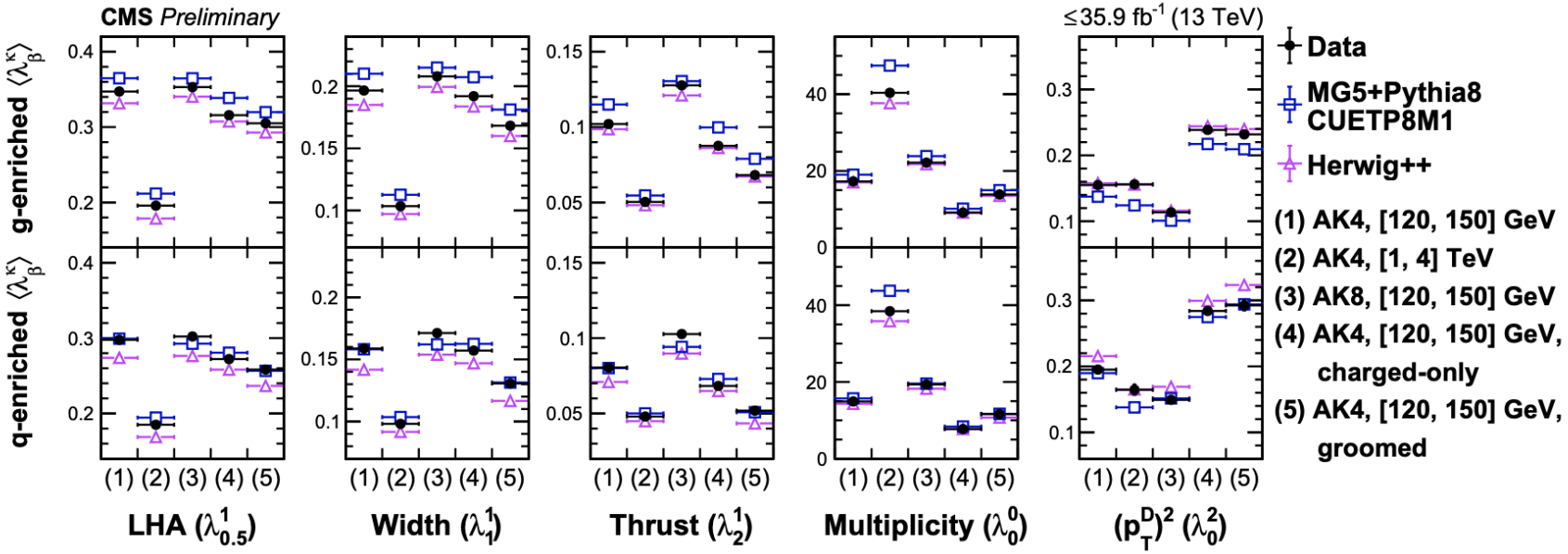
Partonic Contributions

- Alter partonic contributions of underlying hard scattering processes
- ATLAS γ-jet compared to inclusive jet FFs
- LHCb γ/Z^0-jet compared to inclusive jet TMD FFs



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

Partonic Contributions

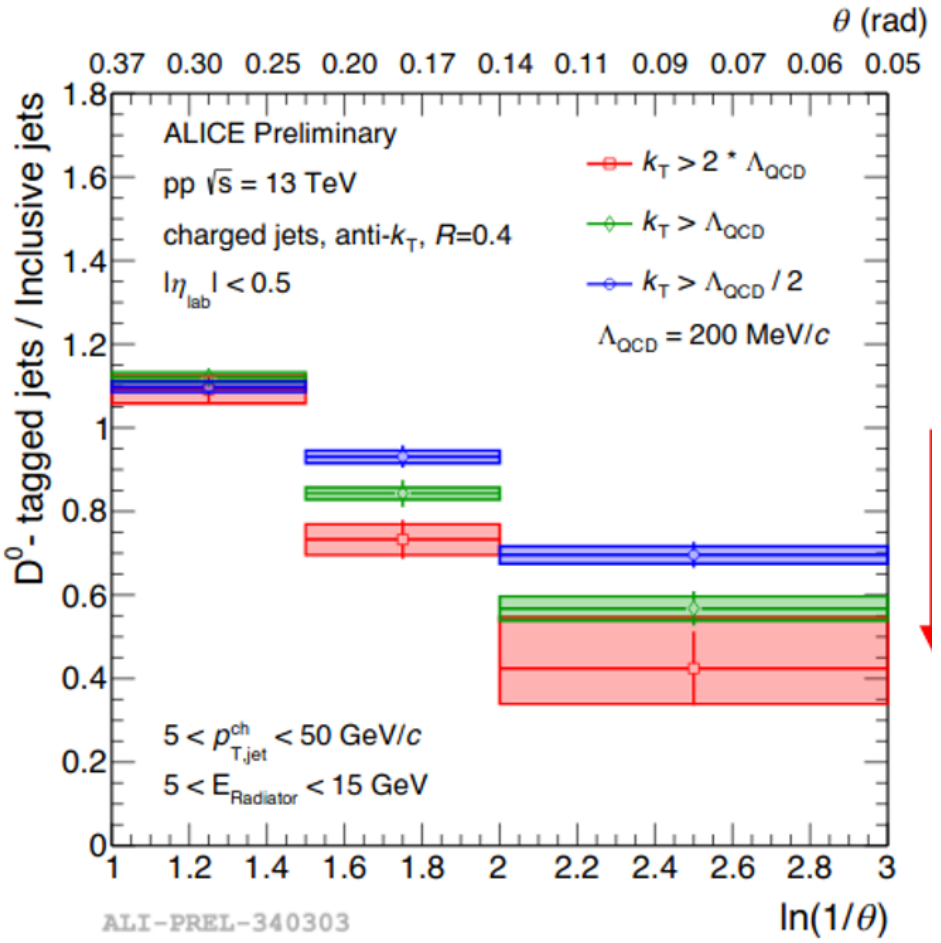


- CMS γ/Z^0-jet and inclusive jet generalized angularities

CMS-SMP-20-010 (2021)

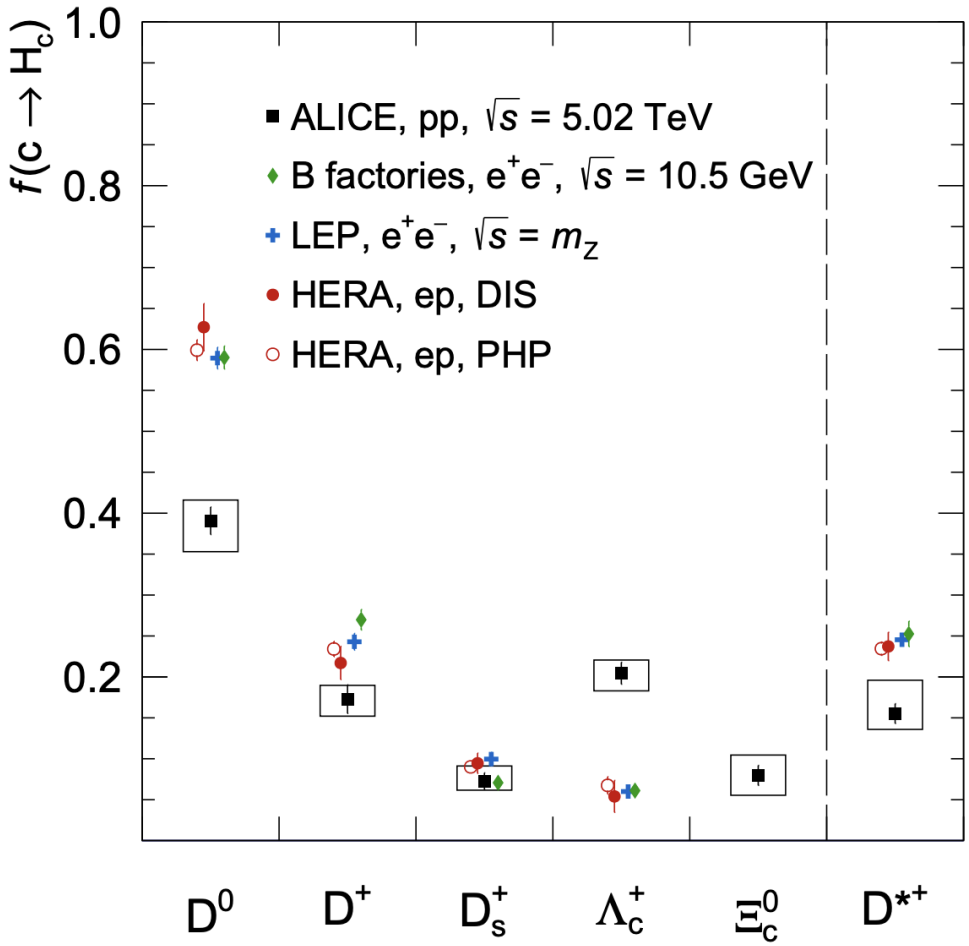
Flavor Dependence - Heavy Quarks

- First study trying to observe the dead cone effect
- Suppression of splittings at small angles comparing D^0 to inclusive jets



Universality of FFs

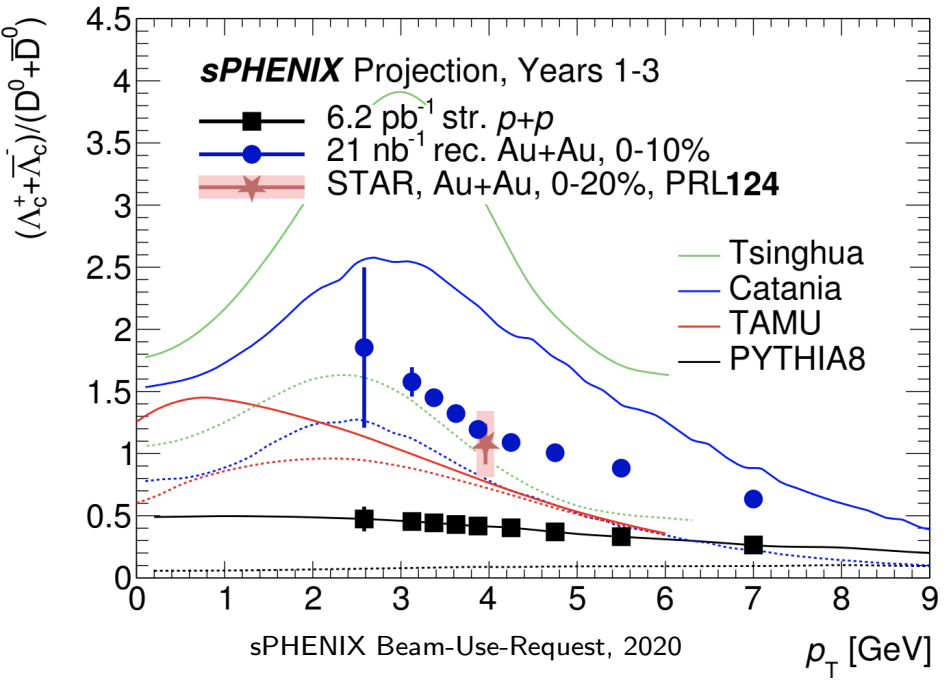
- New results from ALICE challenging universality of charm fragmentation fractions!
- More measurements like this needed, directly comparing observables between collision systems
- Can help guide EIC measurements

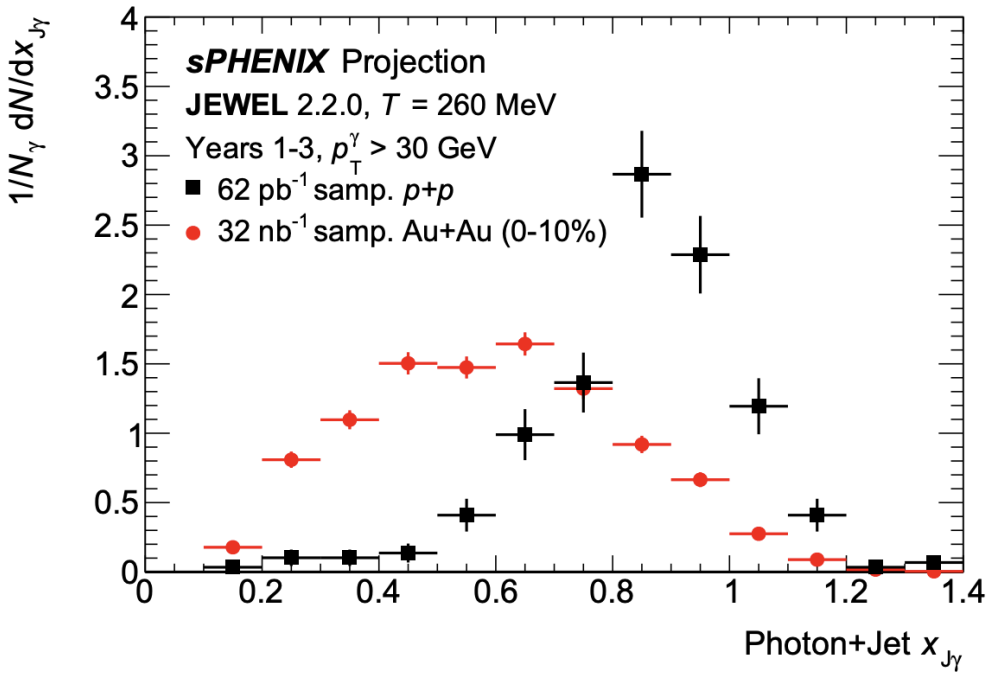


arXiv:2105.06335

LHC measurements $\rightarrow$ RHIC measurements

sPHENIX at RHIC

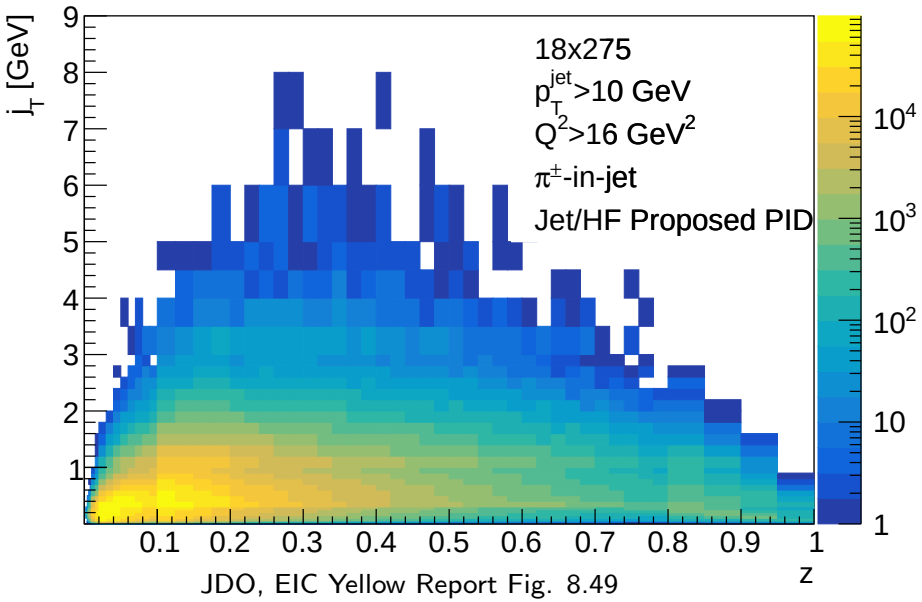




- Much of this points to sPHENIX capabilities, which will have dedicated $\gamma-$jet, c and b-jet (hadronization) studies
- I will not steal John's thunder, who will tell us about sPHENIX in the next talk!

Jet Substructure at the EIC

The available PIDed (z, j_T) phase space that could be probed with Jet/HF PWG PID requirements



- Jet substructure will play an important role in EIC physics
- See e.g. EIC Yellow Report, where jet substructure considerations were important for guiding detector requirements

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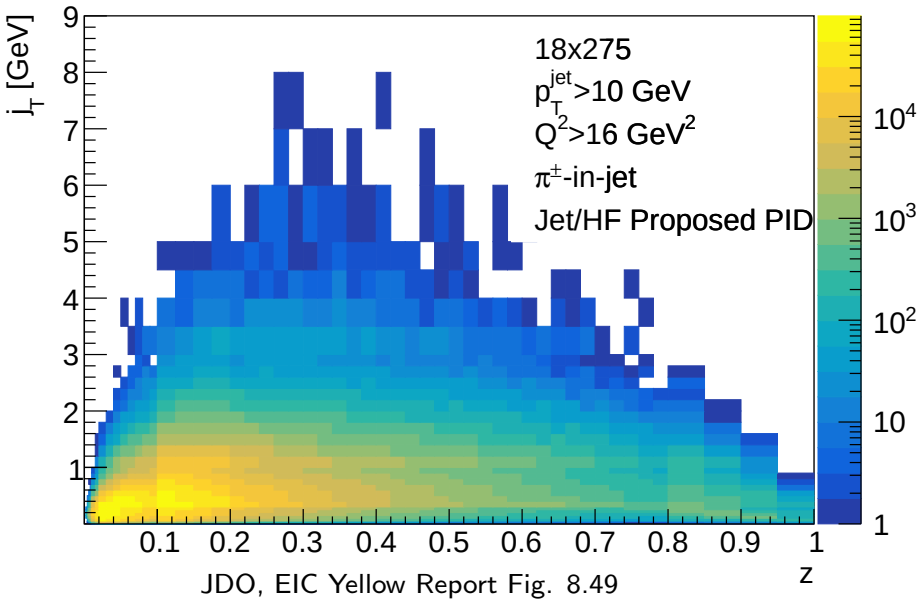
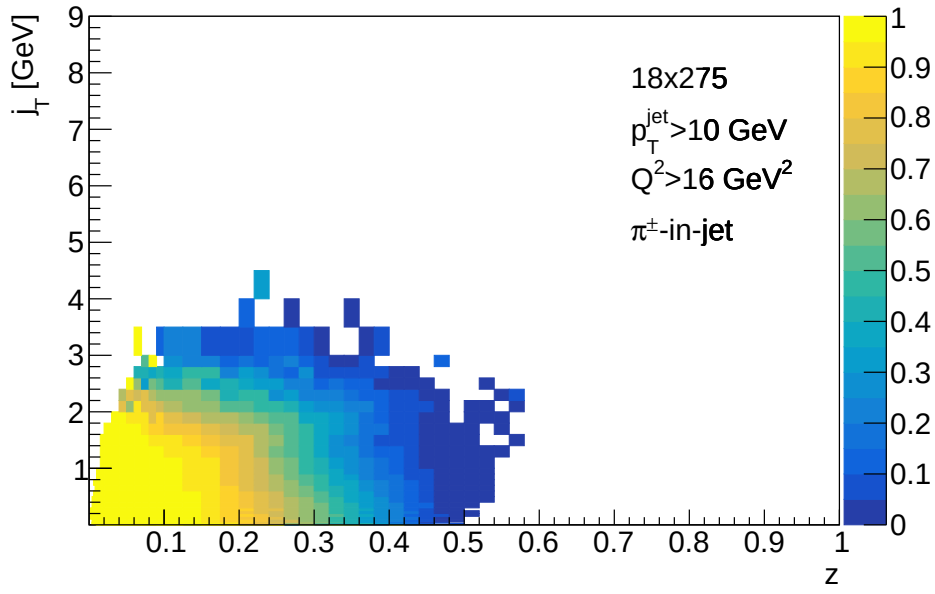


JDO, EIC Yellow Report Fig. 8.49

The ratio of the PID detector matrix requirements to Jet/HF PWG PID



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RHIC - the heavy ion collider

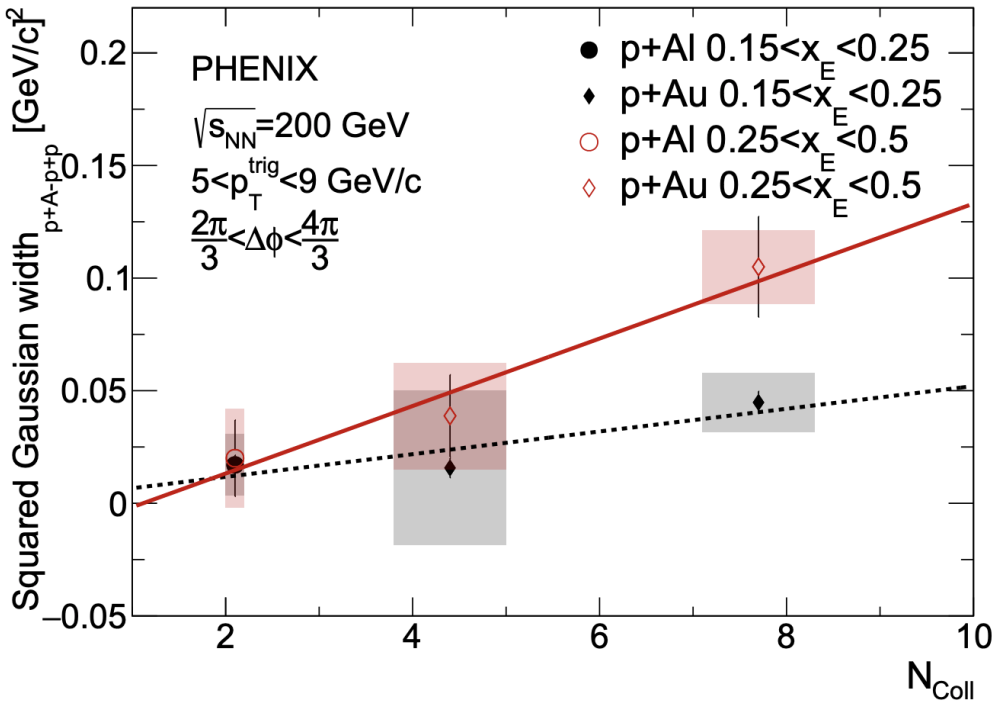
RHIC

$\sqrt{s}$ [GeV]	p+p	p+Al	p+Au	d+Au	^{3}He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

- RHIC is a versatile heavy ion machine (STAR has expanded this even further!)

Energy Loss and Gluon Saturation

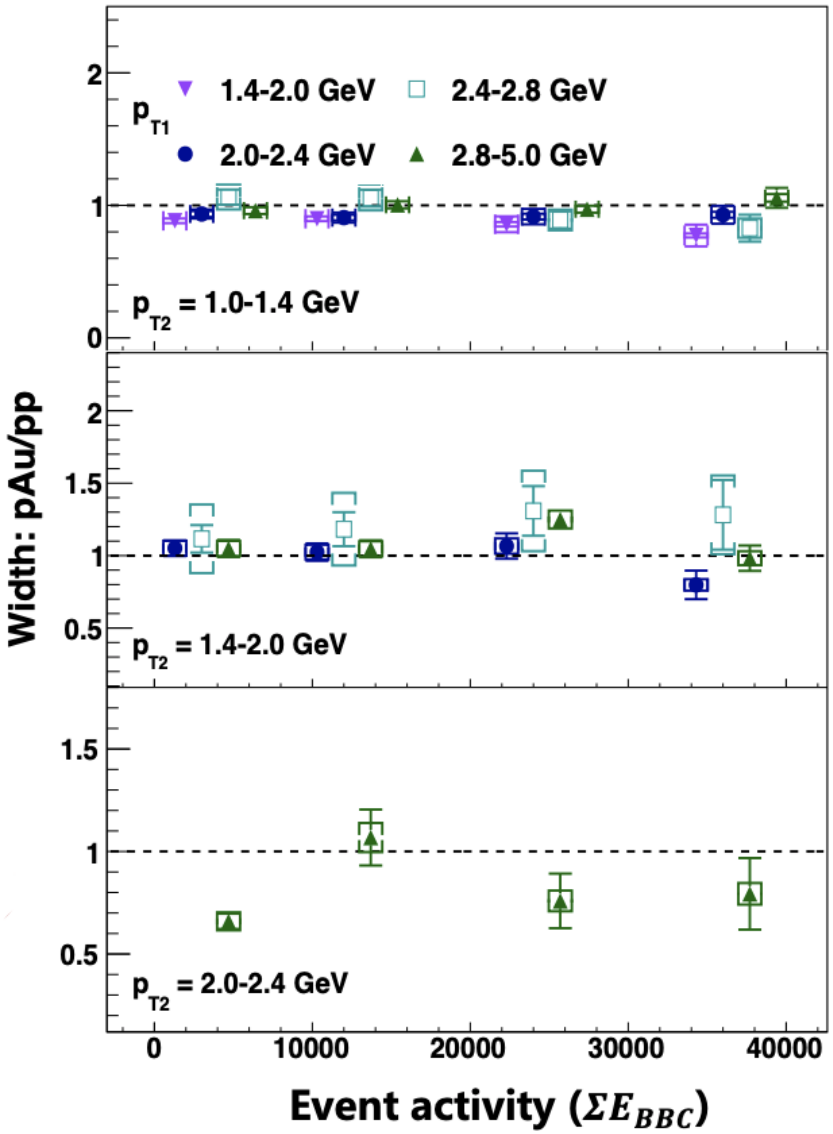
- PHENIX measured nuclear dependent charged hadron azimuthal widths at midrapidity



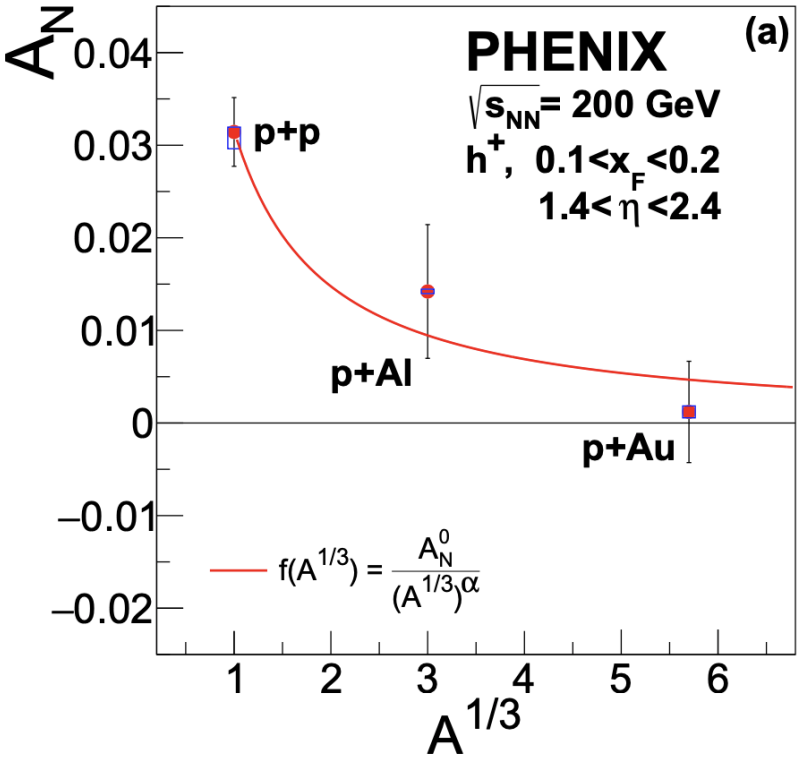
Phys. Rev. C 99, 044912 (2019)

Energy Loss and Gluon Saturation

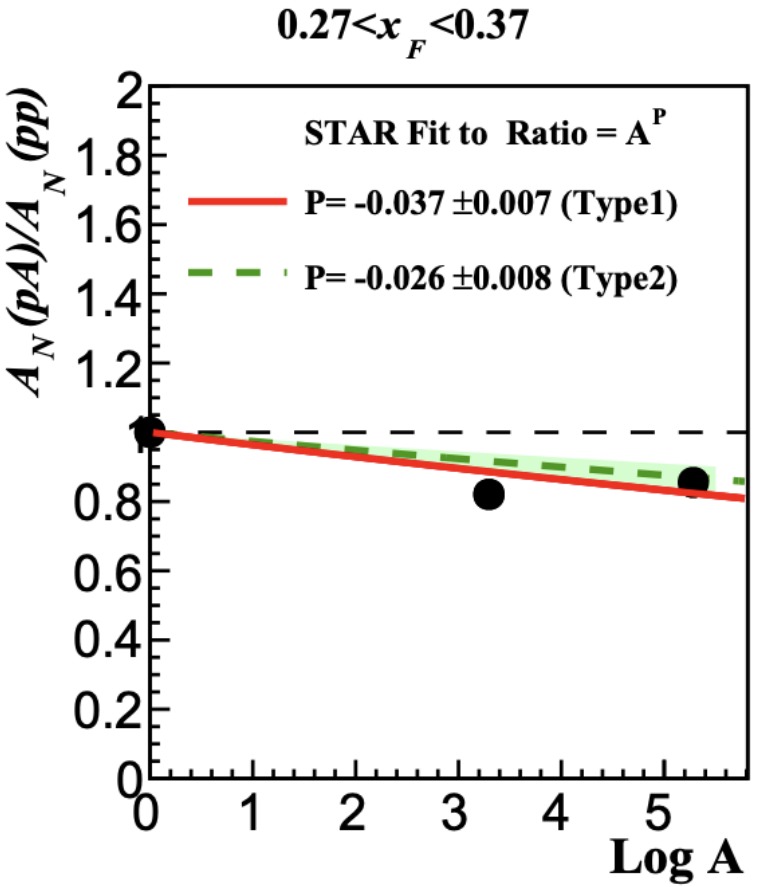
- PHENIX measured nuclear dependent charged hadron azimuthal widths at midrapidity
- STAR has measured nuclear dependence for di-π^0 production at forward rapidity
  - Maybe a small event activity dependence? Note different rapidities
- See Xiaoxuan's talk on Monday



Relation to A dependent A_N?



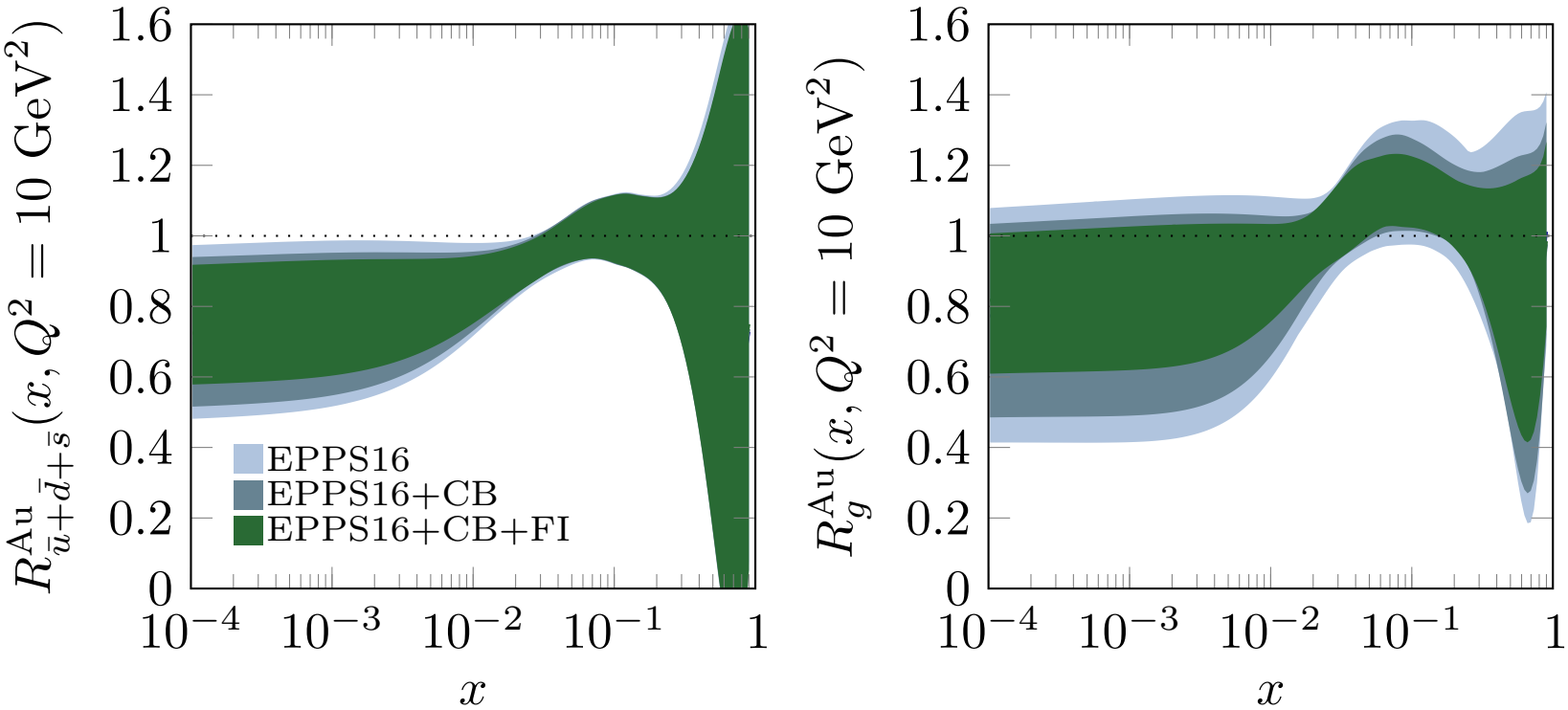
Phys. Rev. Lett. 123, 122001 (2019)



Phys. Rev. D 103, 172005 (2021)

- Differences in nuclear dependence of transverse single spin asymmetry also seen between charged/neutral and different rapidity regimes. What is the underlying physics relation?

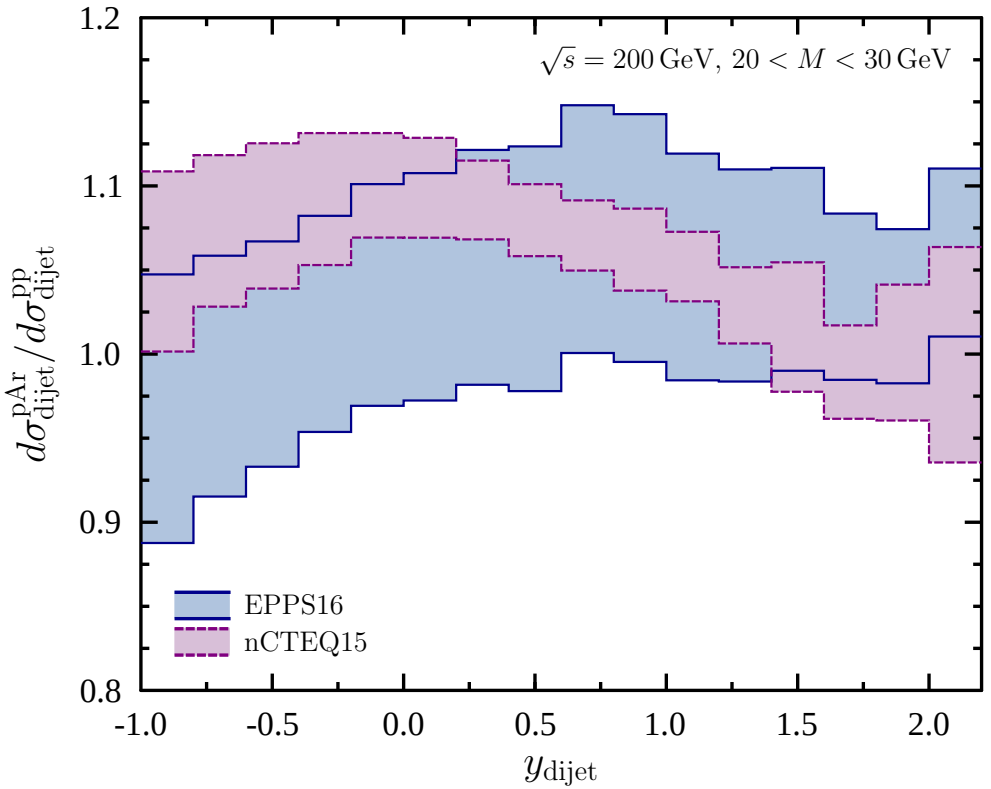
Towards the EIC



I Helenius, J. Lajoie, JDO, P. Paakkinen, H. Paukkunen - Phys. Rev. D 100, 014004 (2019)

- Utilize simultaneous observables to improve nPDF fits
  - Reduces overall normalization uncertainties in R_{pA} measurements
- Utilize versatility of RHIC as a heavy ion collider
- RHIC future experiments (fSTAR and sPHENIX) will have the capabilities to weigh in on this

Towards the EIC



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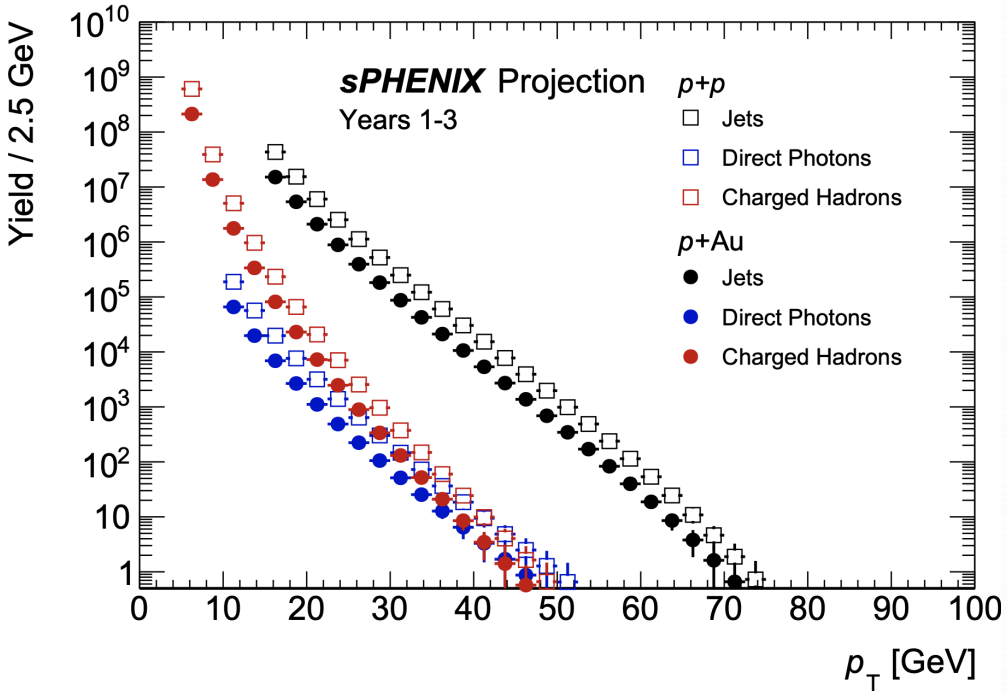
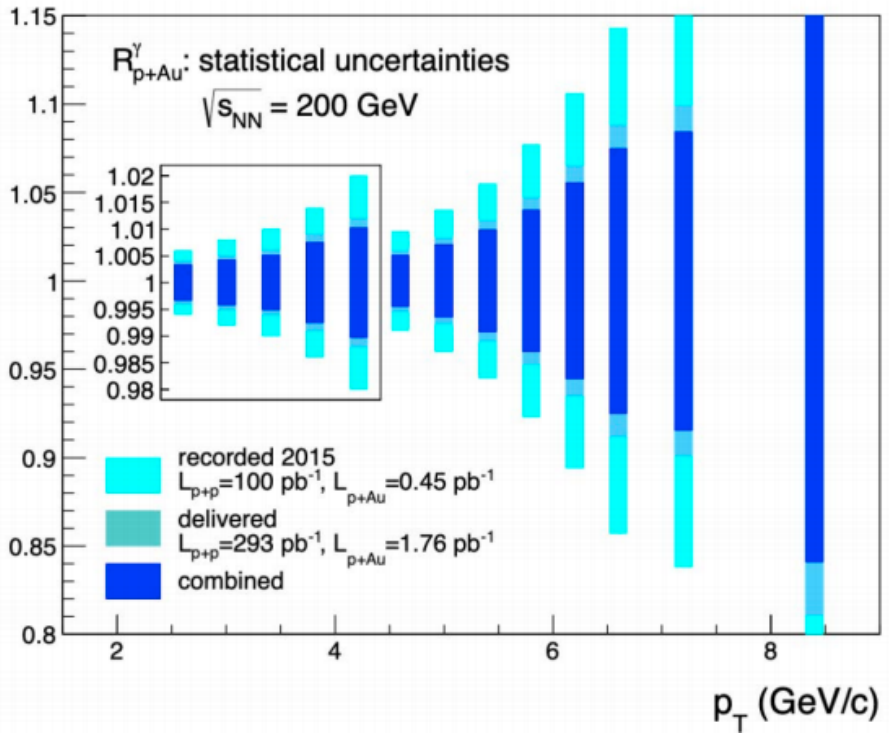
  - Reduces overall normalization uncertainties in R_{pA} measurements
- Utilize versatility of RHIC as a heavy ion collider
- RHIC future experiments (fSTAR and sPHENIX) will have the capabilities to weigh in on this

Towards the EIC





- sPHENIX and STAR will have robust p+A programs in the final years of RHIC
- Still much more to come from both experiments in preparation for EIC

Looking towards the EIC

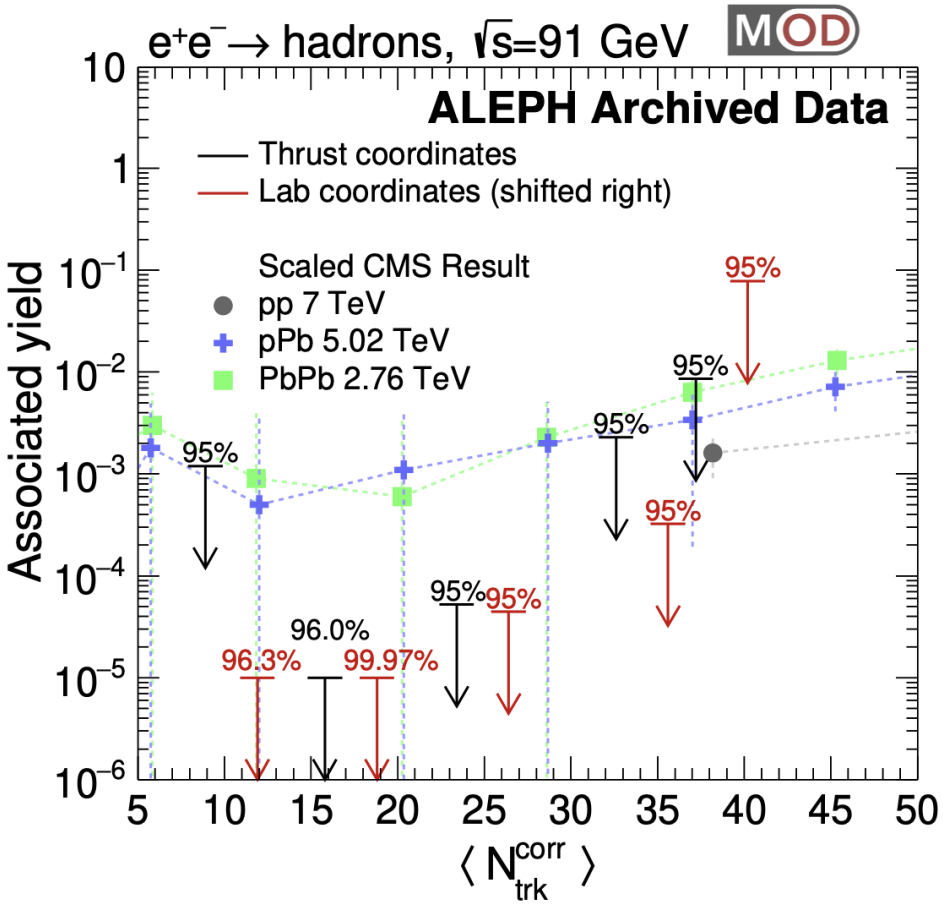
Conclusions

- Photon-jet and dijet probes have accessed a huge range of physics at RHIC
  - Unpolarized PDFs and cross sections
  - Fundamental questions of QCD
    - e.g. Sivers measurements, entanglement
  - Spin - ΔG, TMDPDFs, TMDFFs, transversity...
  - Nuclear modification of observables (or lack thereof...)
    - e.g. dihadrons, A_N, FFs
- Much more to come from both STAR upgrades and sPHENIX! Input from LHC will be important for guiding future measurements
- Emphasis towards EIC
  - What must we measure now when we will no longer have a hadronic collider operating in a similar $\sqrt{s}$ regime?
  - Data preservation - HERA/LEP data being reanalyzed now within context of RHIC/LHC results! What will we want to come back to when given the context of EIC data?

Back up

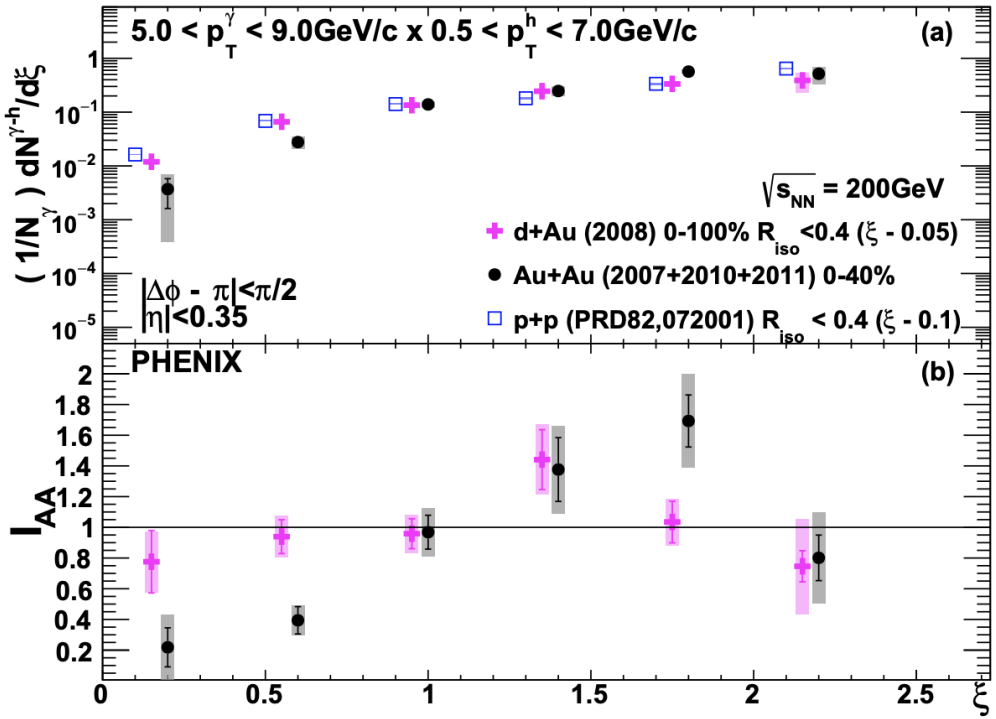
Long Range Correlations

- Archived ALEPH data used to compare long range correlation in e^+e^- to hadronic collisions
- Importance of (again)
  - Archiving data for later use (who knows what we will discover)
  - Comparison of different systems



Phys. Rev. Lett. 123, 212002 (2019)

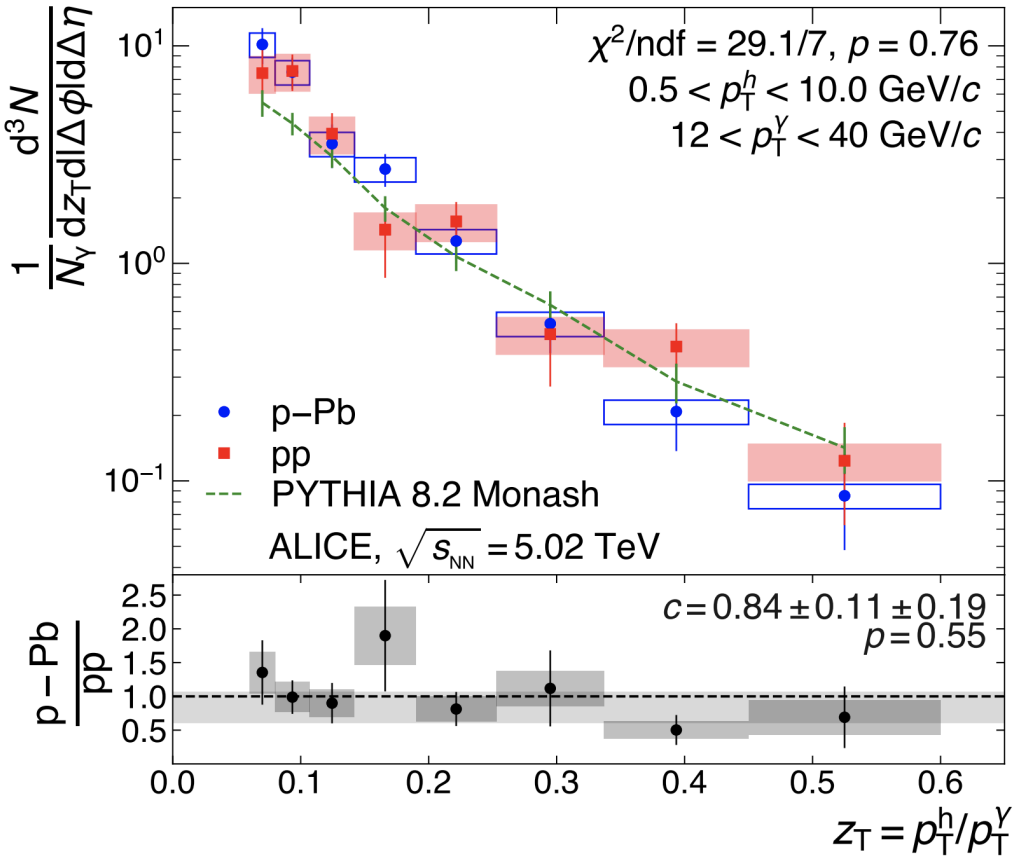
Nuclear Modification of Hadronization



- PHENIX has measured the nuclear modification of $\gamma - h^{\pm}$ correlations in d+Au and Au+Au

Phys. Rev. C 102, 054910 (2020)

Nuclear Modification of Hadronization



Phys. Rev. C 102, 044908 (2020)

- PHENIX has measured the nuclear modification of $\gamma - h^{\pm}$ correlations in d+Au and Au+Au
- Direct $\gamma - h^{\pm}$ studied at ALICE in $p + p$, $p + Pb$, results consistent with PHENIX d+Au
- At RHIC, look towards sPHENIX and STAR upgrade, which will provide both γ-jet and $\gamma-$hadron