Heavy Ion Physics in the EIC Era

Yang-Ting Chien

Institute for Nuclear Theory
Seattle, August 23rd, 2024

U.S. DEPARTMENT OF ENERGY | Office of Science

Jefferson Lab

Georgia State University

Outline

- An attempt to string together the talks
  - Highlighting some points emphasized at the workshop
  - I apologize if I miss also some important points!
- Sneak in some of my personal perspectives

Disclaimer:
I work mostly on jets so I don't know everything in HI and EIC. I won't risk pretending that I can summarize experiment and theory efforts.

I will try not going into technical details due to lack of knowledge and/or time, and as Olga said, I also don't want to bore you with physics cases and things you already know.

It’s all on internet?

I asked ChatGPT: what should we study about heavy ion physics in the EIC era?

- Quark-Gluon Plasma (QGP) Properties
  - Understanding QGP Formation and Evolution
  - Phase Transition Dynamics
- Nuclear Parton Distributions
  - Probing the Nucleon's Internal Structure
  - Shadowing and Saturation Effects
- Gluon Dynamics and the Color Glass Condensate
  - Understanding Gluon Saturation
  - Small-x Physics
- Strong Force and Confinement
  - The Role of Gluon Fields
- Hadronization and Jet Quenching
- Spin and Orbital Angular Momentum
  - Nucleon Spin Structure
  - Spin-Dependent Phenomena
- Electromagnetic Probes and Exotic States
  - Photons and Dileptons
  - Exotic Hadrons and States of Matter
- Applications and Implications
  - Astrophysical Connections
  - Fundamental Symmetries and Anomalies

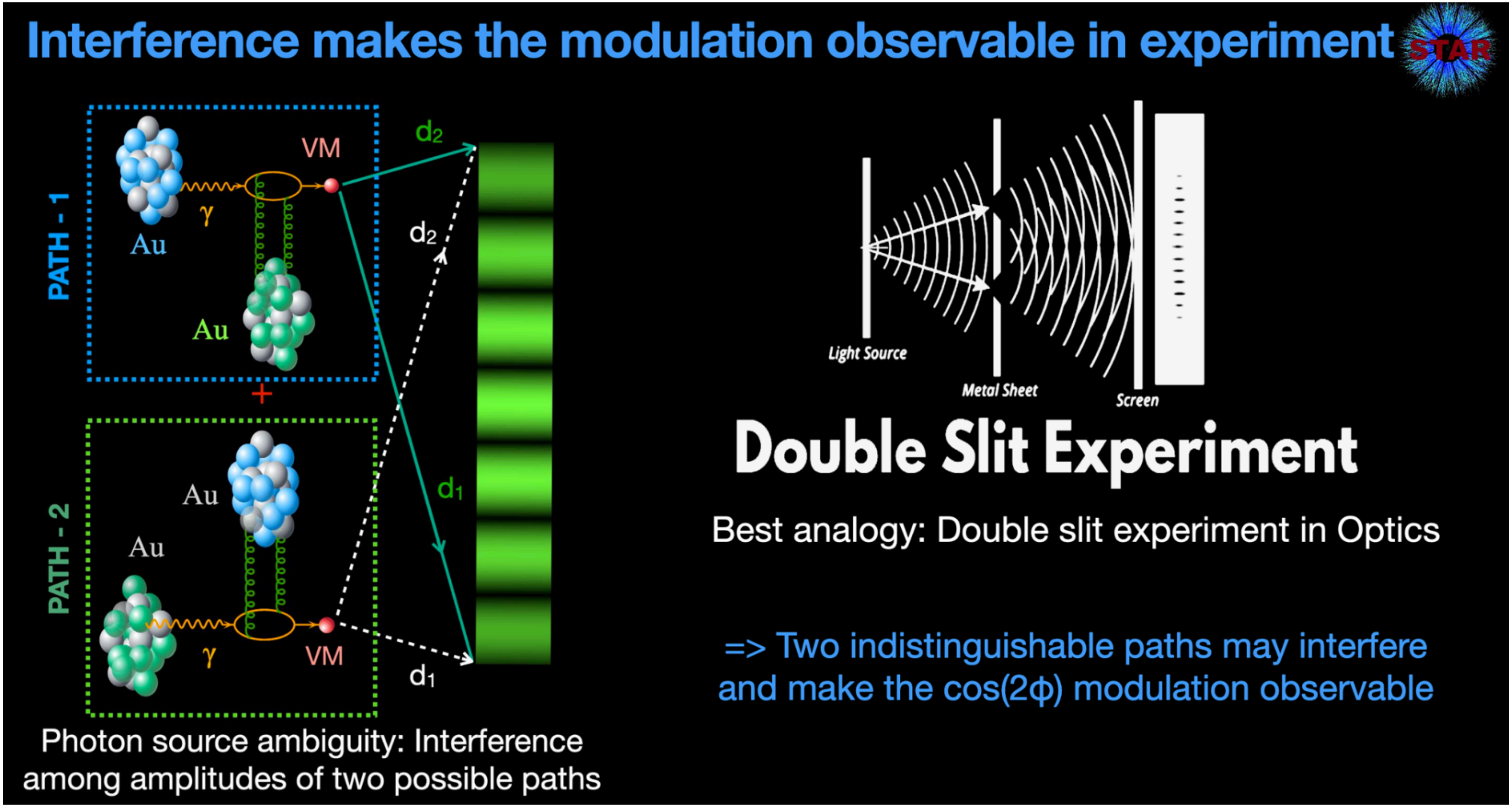
I gave ChatGPT the workshop link and asked it to summarize. Here is what it told me:

For more details, visit the workshop page.

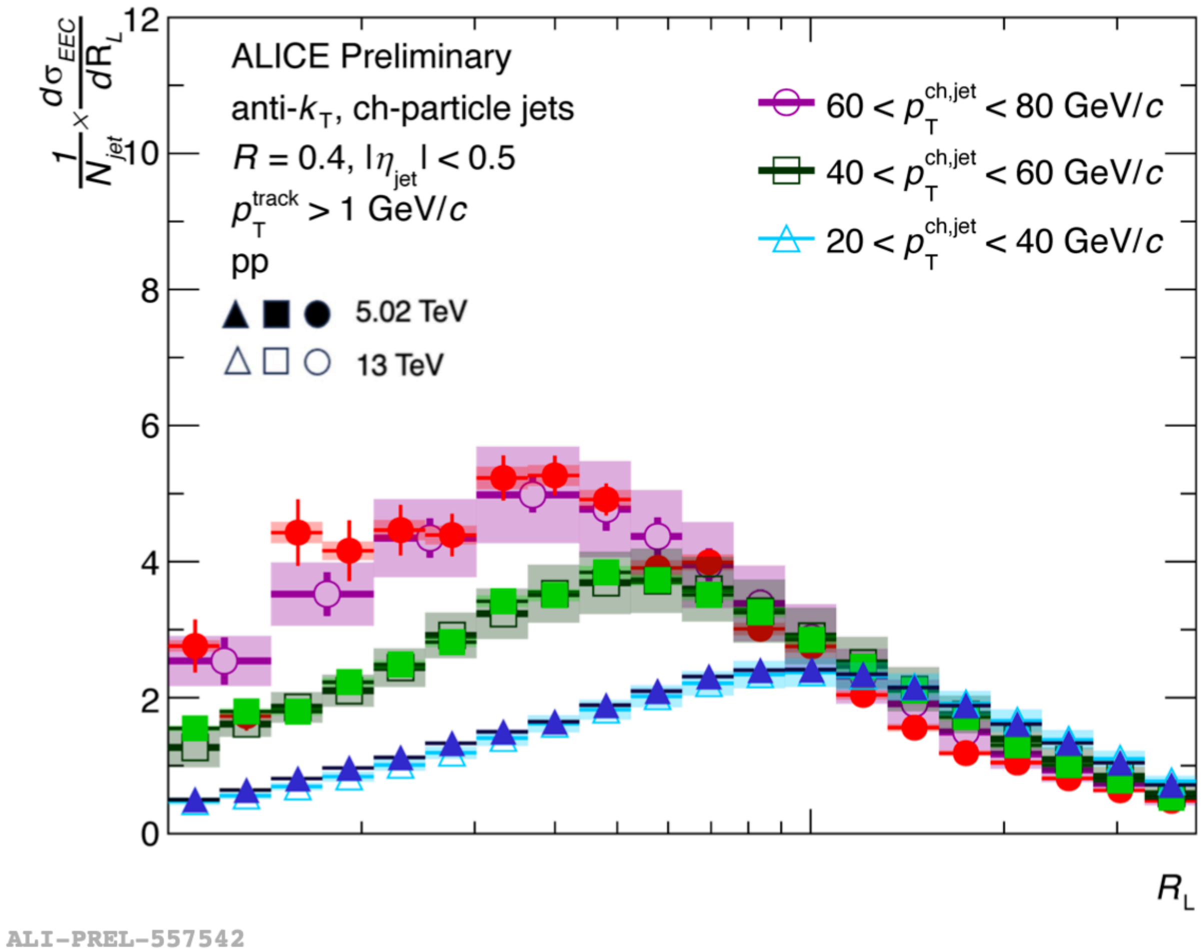
Emphasis on UPC

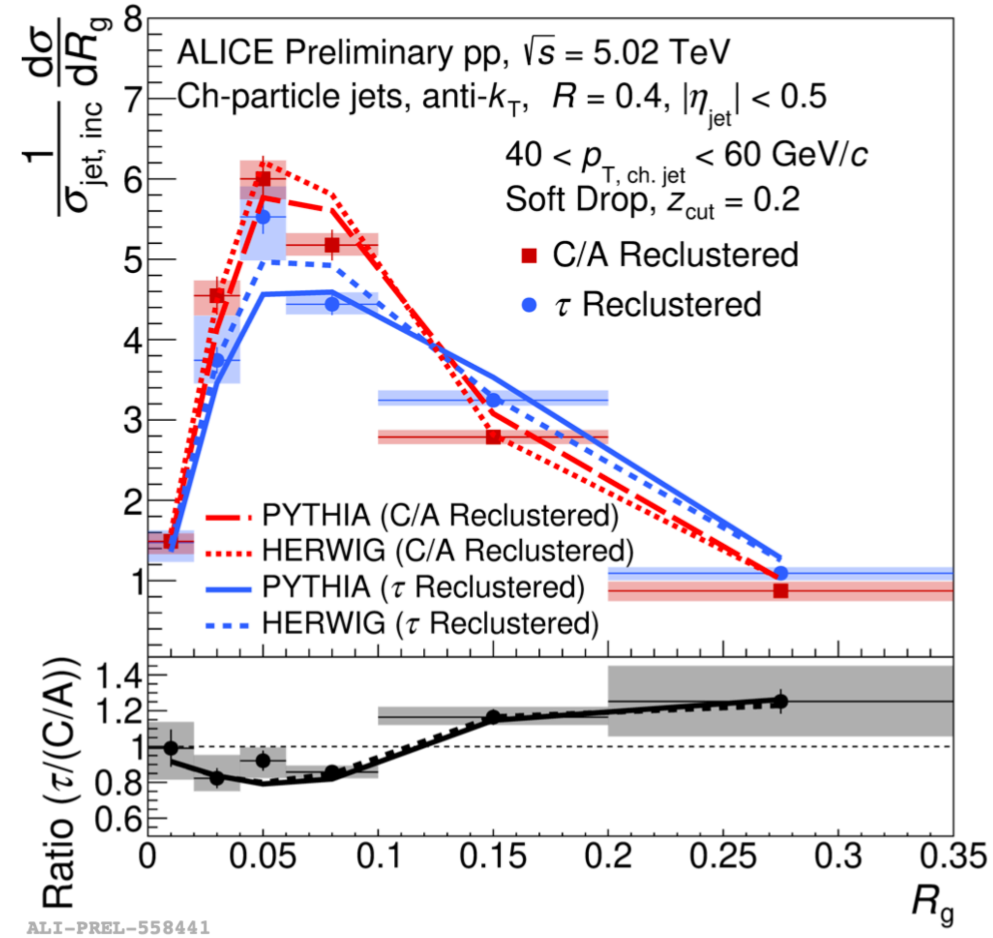
- This came out spontaneously when inviting official talks from experimental collaborations
  - we had dedicated UPC talks from CMS (thanks to Jing Wang), ALICE and ePIC (thanks to Maria Zurek)
  - why did we do that? Because heavy ion physics is still mostly dominated by experiments
- UPCs are clean processes, allowing precision studies
  - Photon-nucleus collisions therefore closely connected with EIC
- UPCs at higher energies give the opportunities to scrutinize, e.g. forward dijets, in many ways, in preparation for EIC
  - Jet tagging
  - Heavy flavor

Classic quantum physics



Precision studies

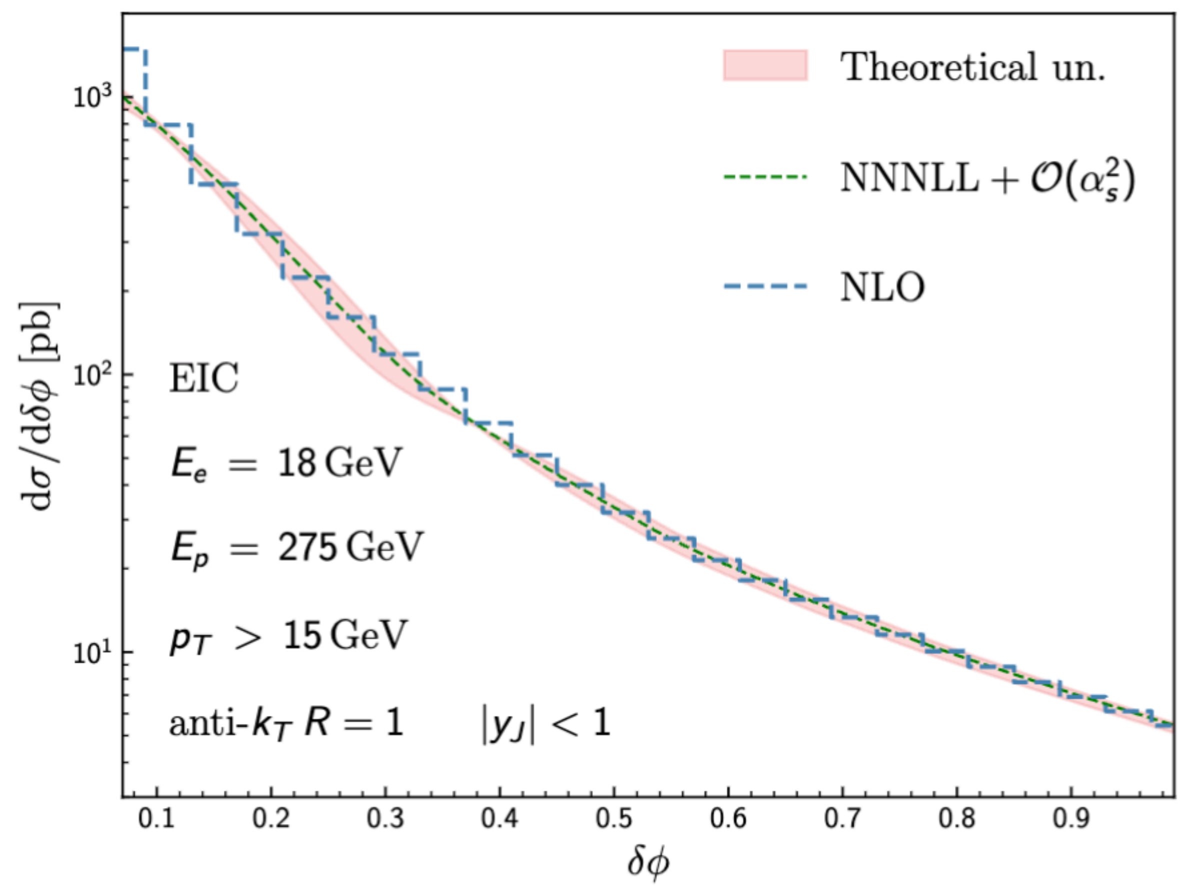




We have been making great progress measuring more and more jet substructure observables!

Some are more challenging than the others

Precision studies



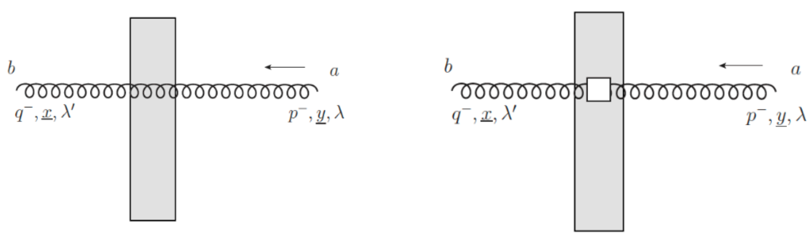
$N^3LL + O(\alpha_s^2)$ has been state of the art precision (at LEP) for many years.
Already achieved for the EIC with recoil free observables!

Expect $N^4LL + O(\alpha_s^3)$ within the EIC timeline

Theory development for precision studies

Gluon double spin asymmetry

Wilson Lines at Sub-eikonal Order



$$M^{g\to g} = (2\pi)2p^-\delta(p^- - q^-)\delta_{\lambda\lambda'}\left[\delta^{(2)}(\underline{x}-\underline{y})U_{\underline{x}} + \lambda\delta^{(2)}(\underline{x}-\underline{y})U_{\underline{x}}^{G[1]} + U_{\underline{x},\underline{y}}^{G[2]}\right]^{ba} + \delta_{\lambda\lambda'}\delta^{(2)}(\underline{x}-\underline{y})(2\pi)(p^- + q^-)\delta'(p^- - q^-)\left(U_{\underline{x}}^{G[3]}\right)^{ba} + \mathcal{O}(1/s^2)$$

M. Li, JHEP 07 (2023) 158.

Chirilli (2019), Kovchegov et al. (2022), Altinoluk and Beuf (2022)

Improved evolution

Collinearly improved BK (real term): $x \ll x'$

$$S(\rho_{\boldsymbol{xy}},\eta,Y) = \bar{\alpha}\int_0^Y \mathrm{d}Y' \int_0^\eta \mathrm{d}\eta' \int \mathrm{d}\boldsymbol{z} K^{BK}_{\boldsymbol{xz},\boldsymbol{zy}} \times \delta(Y'-\eta'-\hat{\rho})\,[S(\rho_{\boldsymbol{xz}},\eta',Y') + S(\rho_{\boldsymbol{zy}},\eta',Y') + \ldots]$$

Where are the sea quarks in the CGC?

CGC-TMD correspondence

CGS v.s. higher twist, again sub-eikonal precision

Missing energy loss mechanism

ENERGY LOSS DUE TO CHIRAL CHERENKOV

Hansen KT, 2405.0897

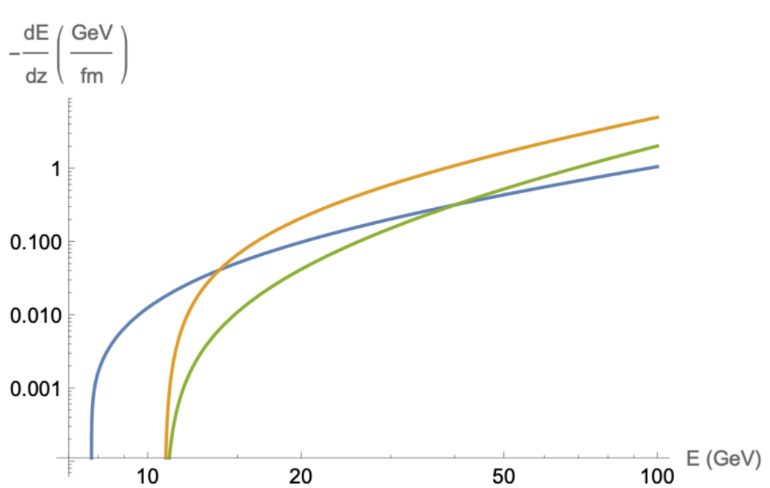


Fig. 3. The rate of energy loss due to the Color Chiral Cherenkov radiation for $q \to qg$ (blue), $g_R \to gg$ (orange), and $g_L \to gg$ (green). Parameters: $g = 2$, $T = 300$ MeV, $b_0 = 50$ MeV.

More theory control over in-medium evolution

The final result

Modified p beam function

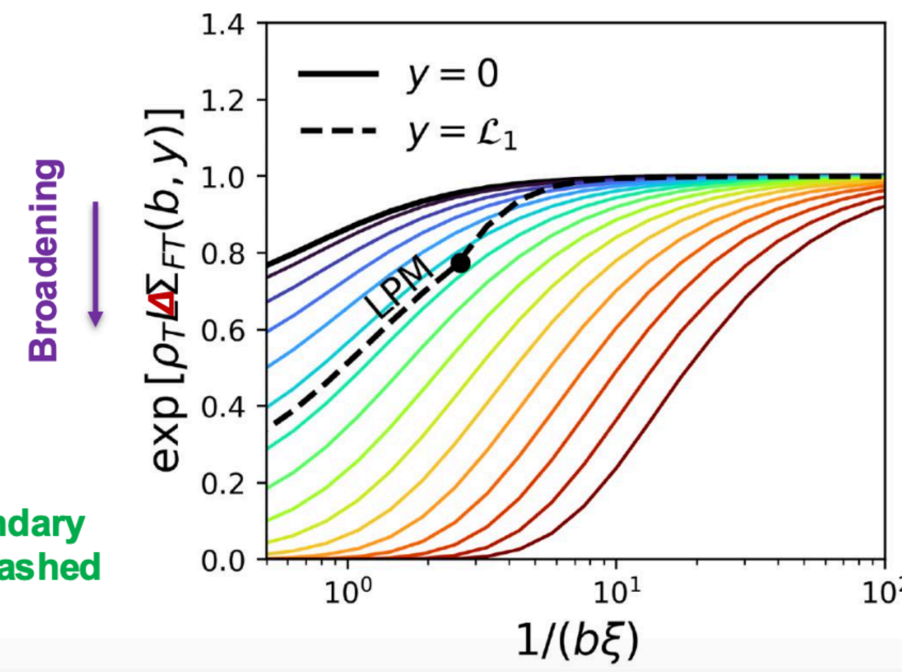
$$\mathcal{B}^{\rm CNM}_{q/a}\left(x_1, b, \mu, \frac{\zeta_1}{\nu^2}; \mu_E, \mathcal{L}_1\right) = \sum_i \int_{x_1}^1 \frac{dx}{x} f_{i/a}\left(\frac{x_1}{x}, \mu_b^*, \mu_E\right) C_{q/i}\left(x, b, \mu_b^*, \frac{\zeta_1}{\nu^2}\right) e^{-S^f_{\rm NP}(b,\zeta_1)}$$

$$\times \exp\left\{\rho_0^- L^+ \sum_j \int dx_t f_{j/N}(x_t) \left[\tilde{\Sigma}_{ij}(b, \mathcal{L}_1) - \tilde{\Sigma}_{ij}(0, \mathcal{L}_1)\right]\right\}$$

$\Delta\Sigma$

$$\times \left(1 + \rho_0^- L^+ \sum_j \int dx_t f_{j/N}(x_t) \Delta\sigma^{\rm NLO}_{ij\to q}\right).$$

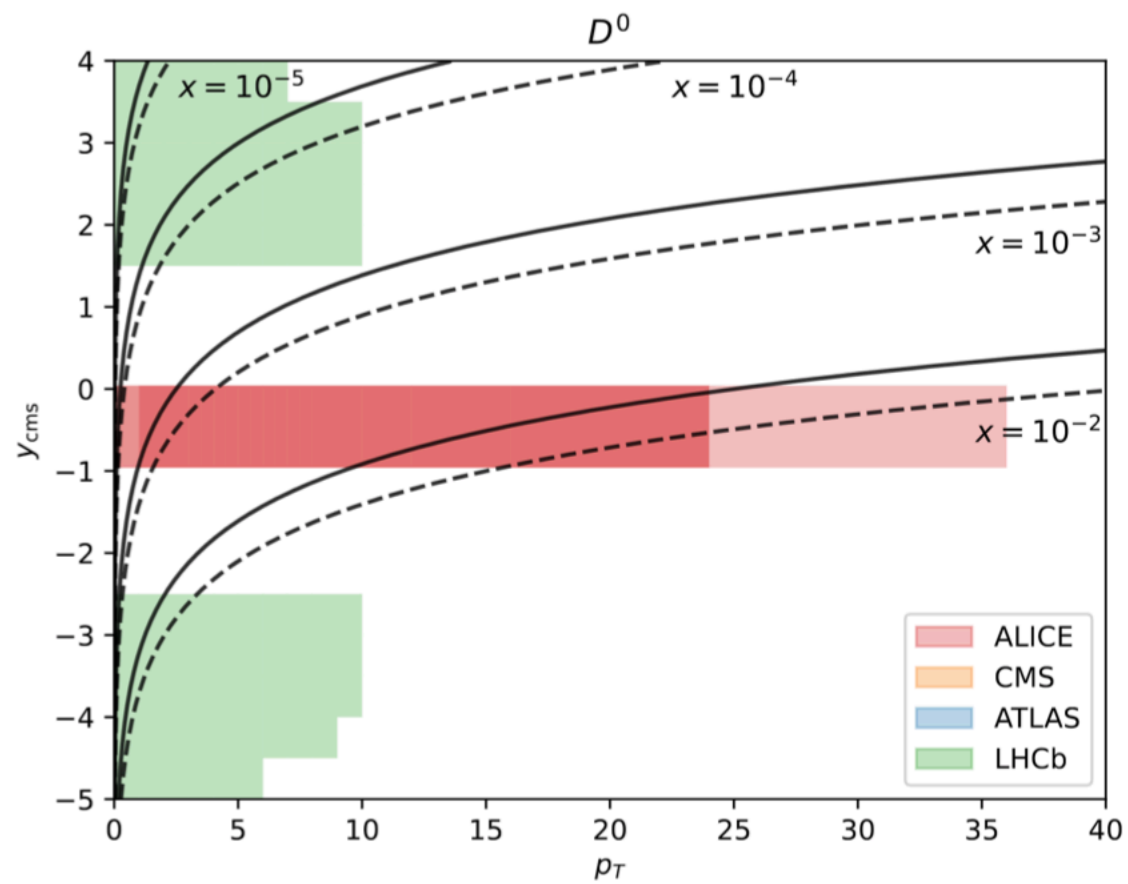
- Collinear evolution (RG) modifies the PDF in the proton (including LPM).
- Multiple Glauber gluons exponentiate (including unitarity corrections)
- Radiation enhances broadening, renormalizes (RRG) the forward scattering cross section.
- There are finite contributions



Rapidity evolution of the forward scattering in impact parameter space. Solid line is the boundary condition from tree level Glauber exchange, dashed – the physical boundary.

TMDs in pA collisions

PDF, small x at LHC before EIC



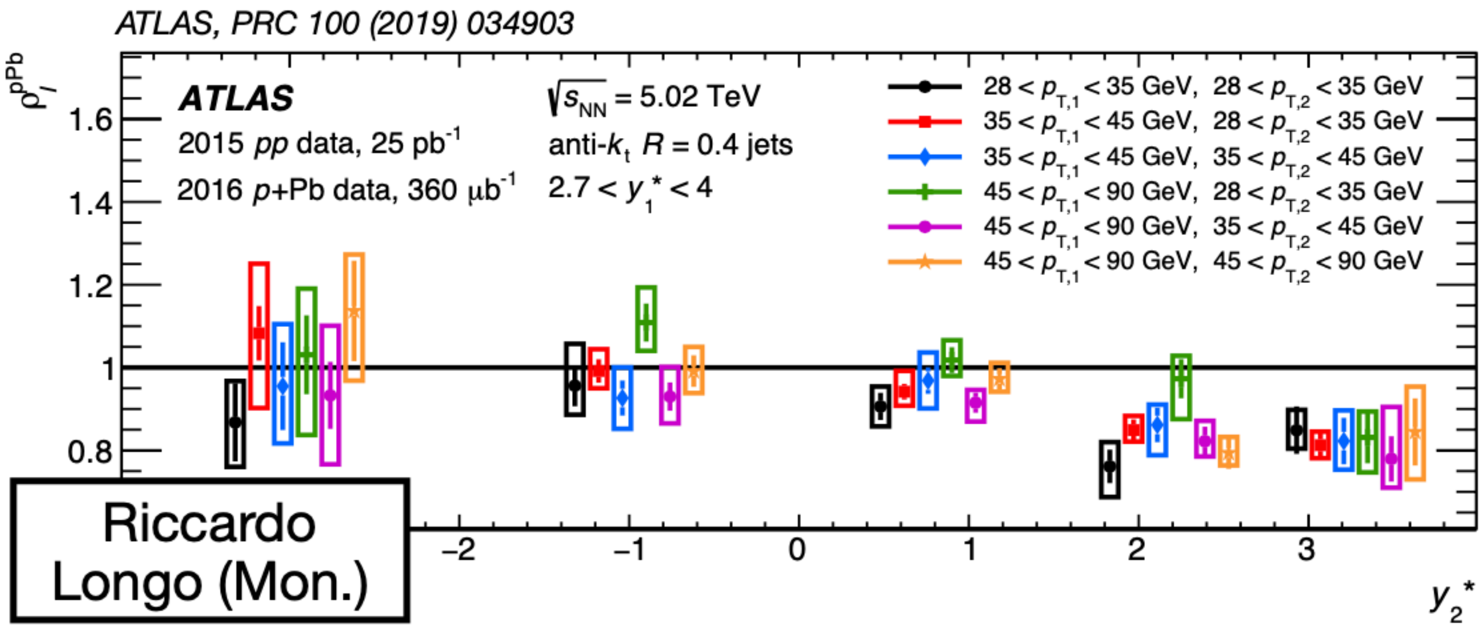
Plot from Pit Duwentaster's talk, Week 3

Matt Durham

We don't need to wait for the EIC to probe small x

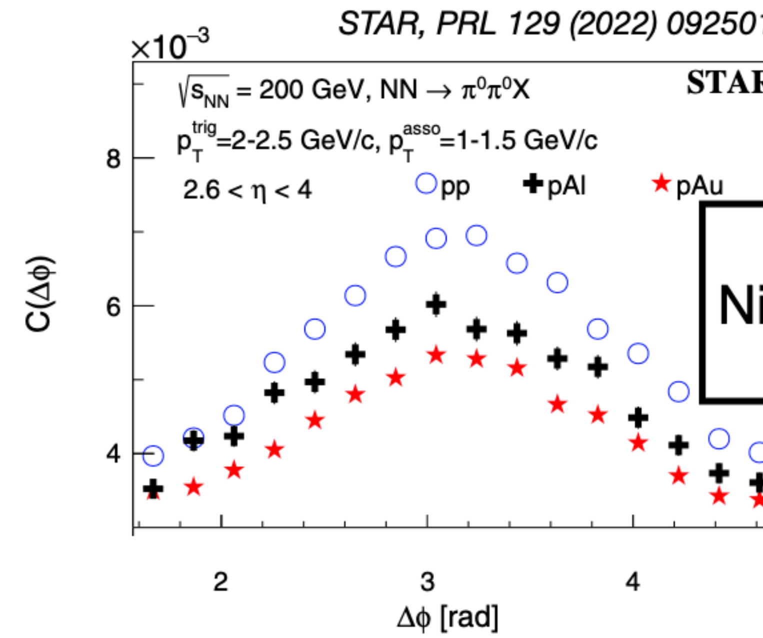
Can EIC reach small enough x?

nPDF, saturation, pA dijet/hadrons



Riccardo Longo (Mon.)

Forward di-jets in *p*+Pb by ATLAS



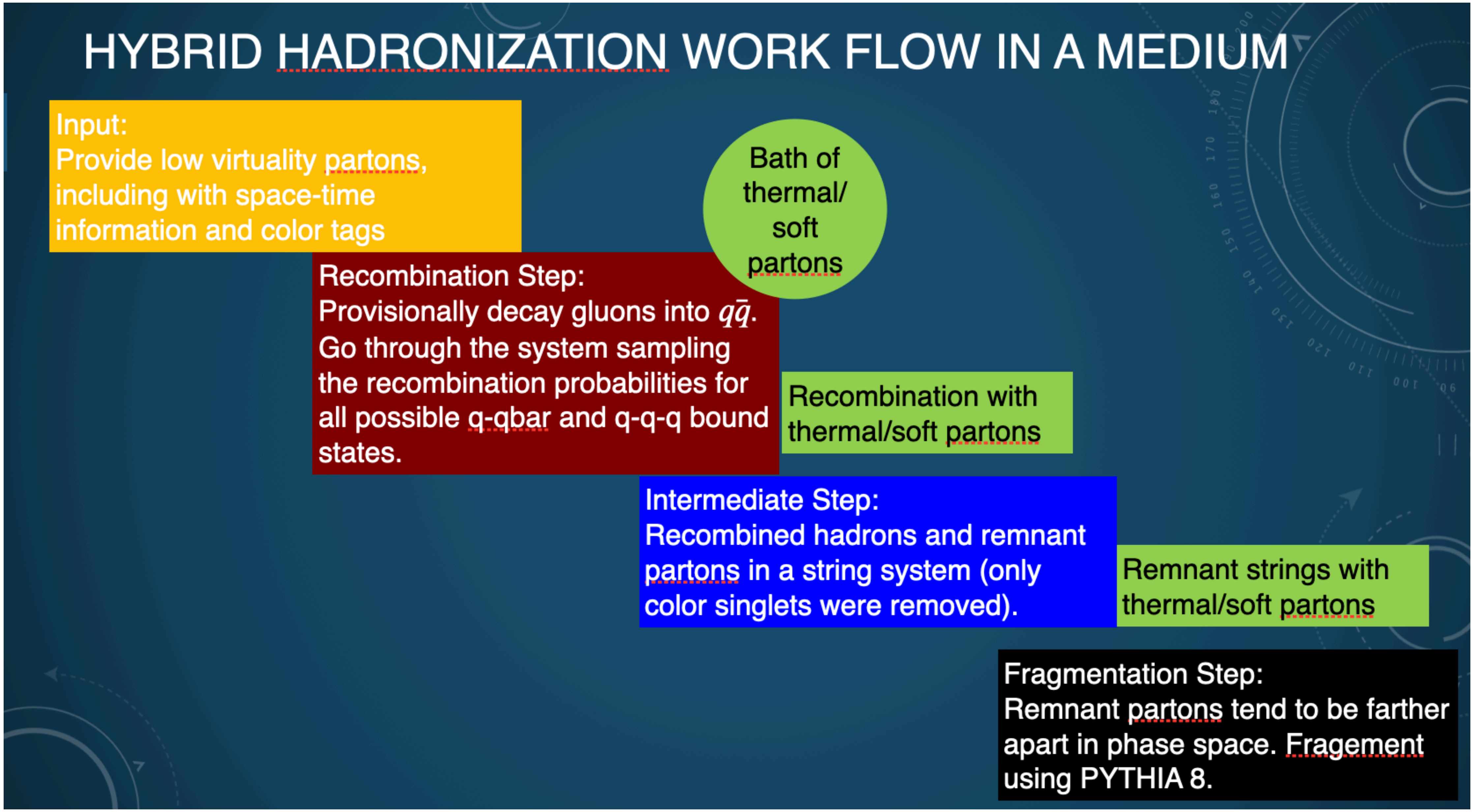
Grigory Nigmatkulov (Wed.)

Forward di-hadrons in *p*+Au by STAR

Compatibility between nPDFs and saturation studies

Peter: what do we mean by observing saturation?

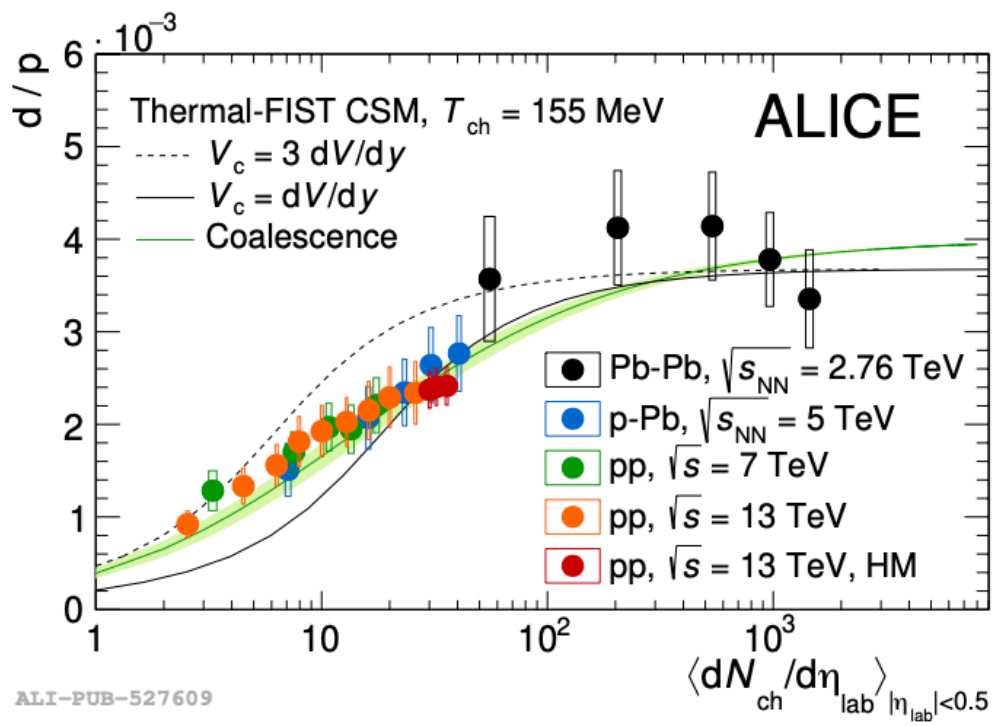
Hadronization and fragmentation

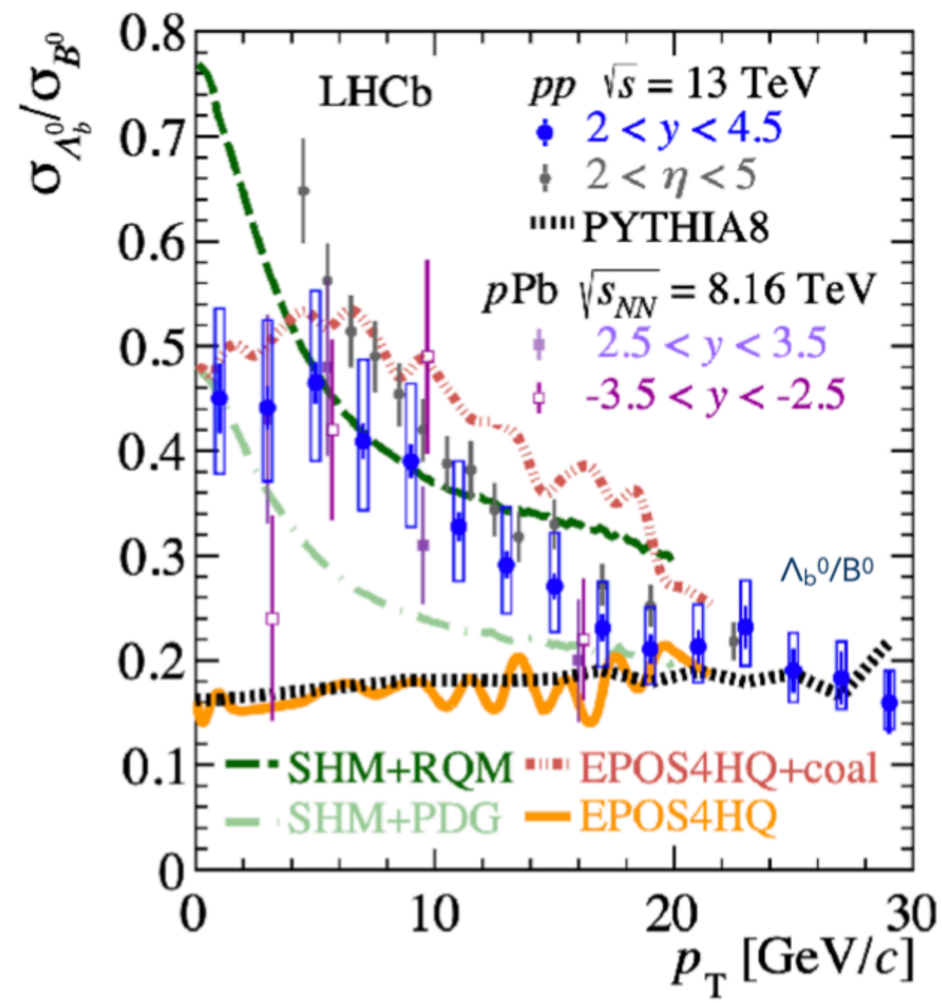


A state-of-the-art hadronization model tackling different environments!

Comparison to Angantyr?

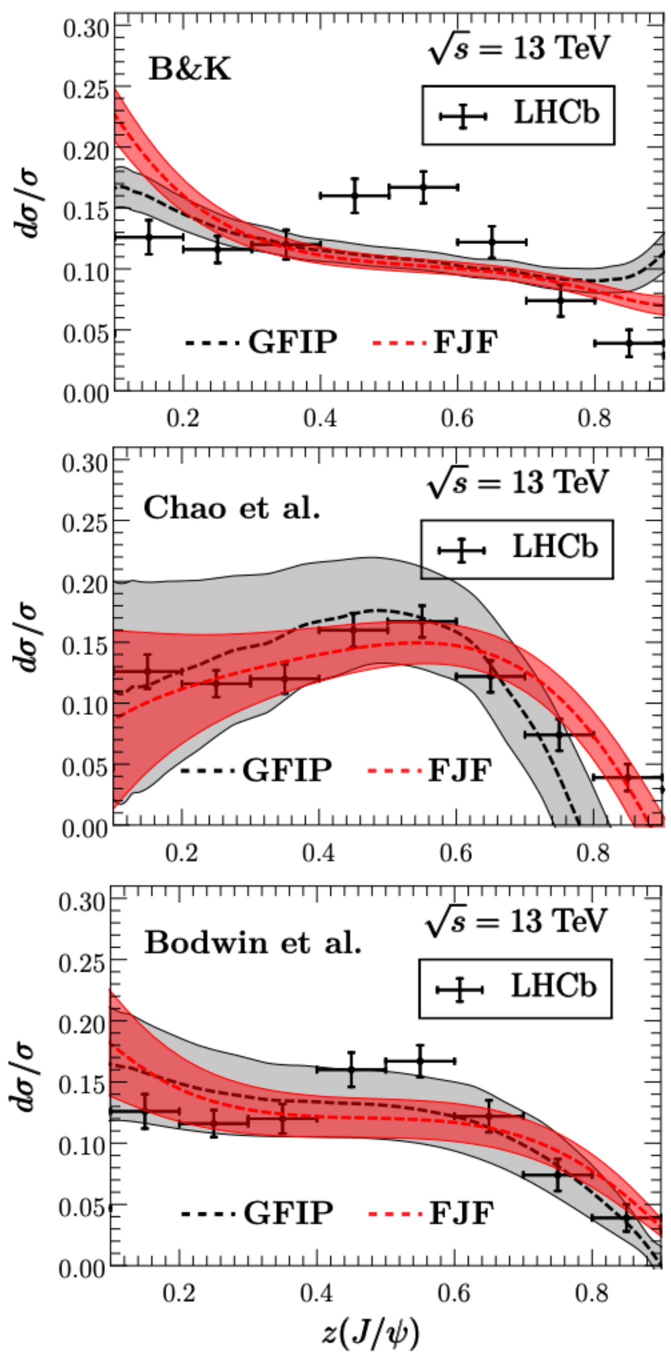
Hadronization and fragmentation

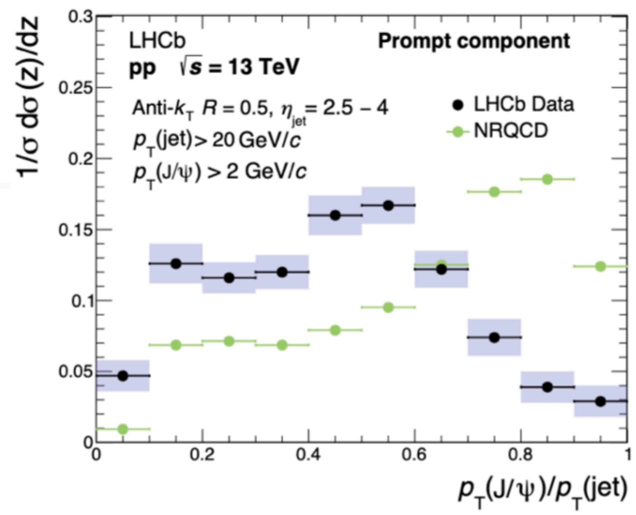




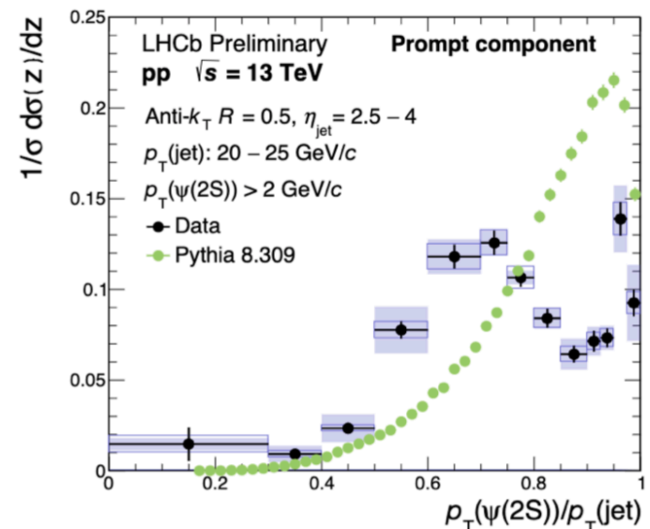
Light nuclei, baryon, quarkonium, “exotic” particles production being studied!

Hadronization and fragmentation

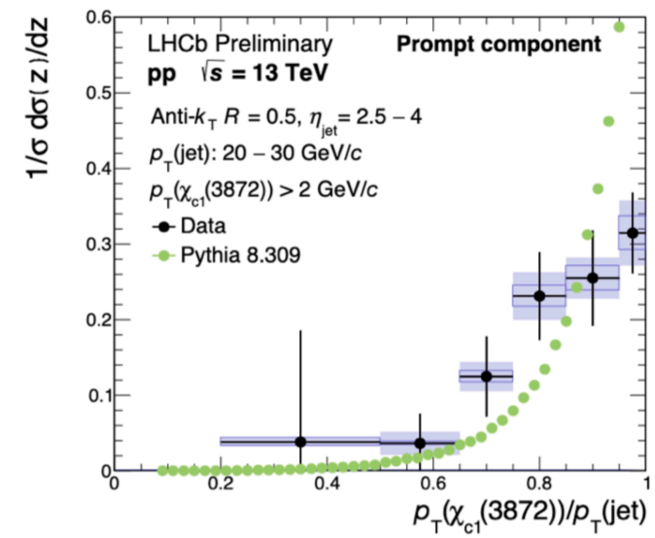




Prompt J/ψ: less isolated than expected



Prompt $\psi(2S)$:
Two component structure:
Different production mechanisms?

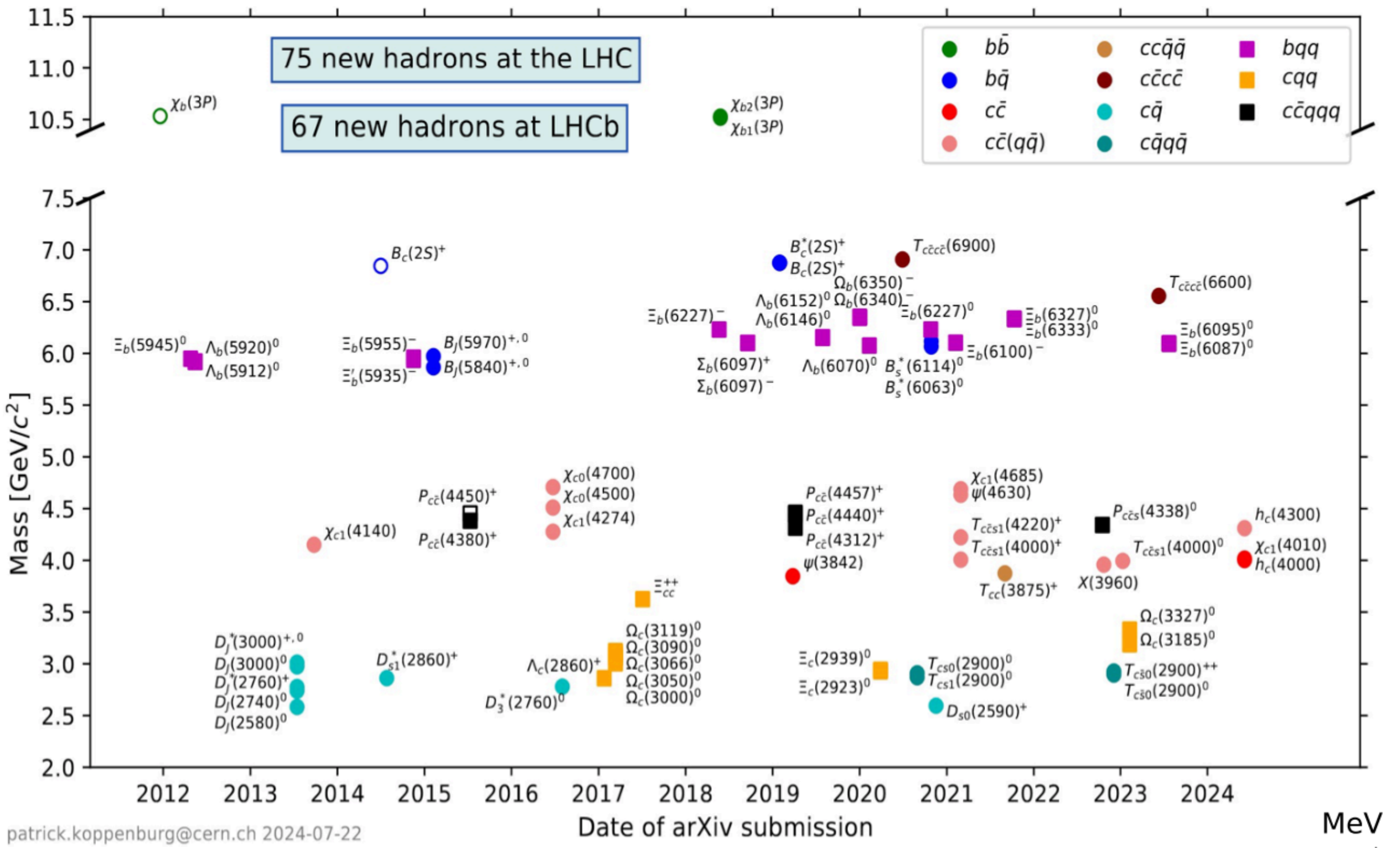


Prompt $X(3872)$:
More isolated than conventional charmonia

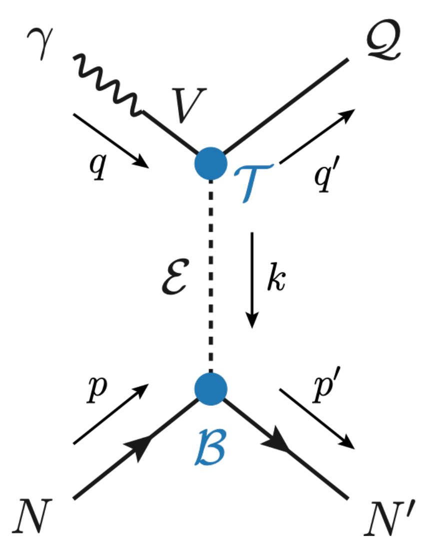
Exciting discrepancy! Something to learn and improve!

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

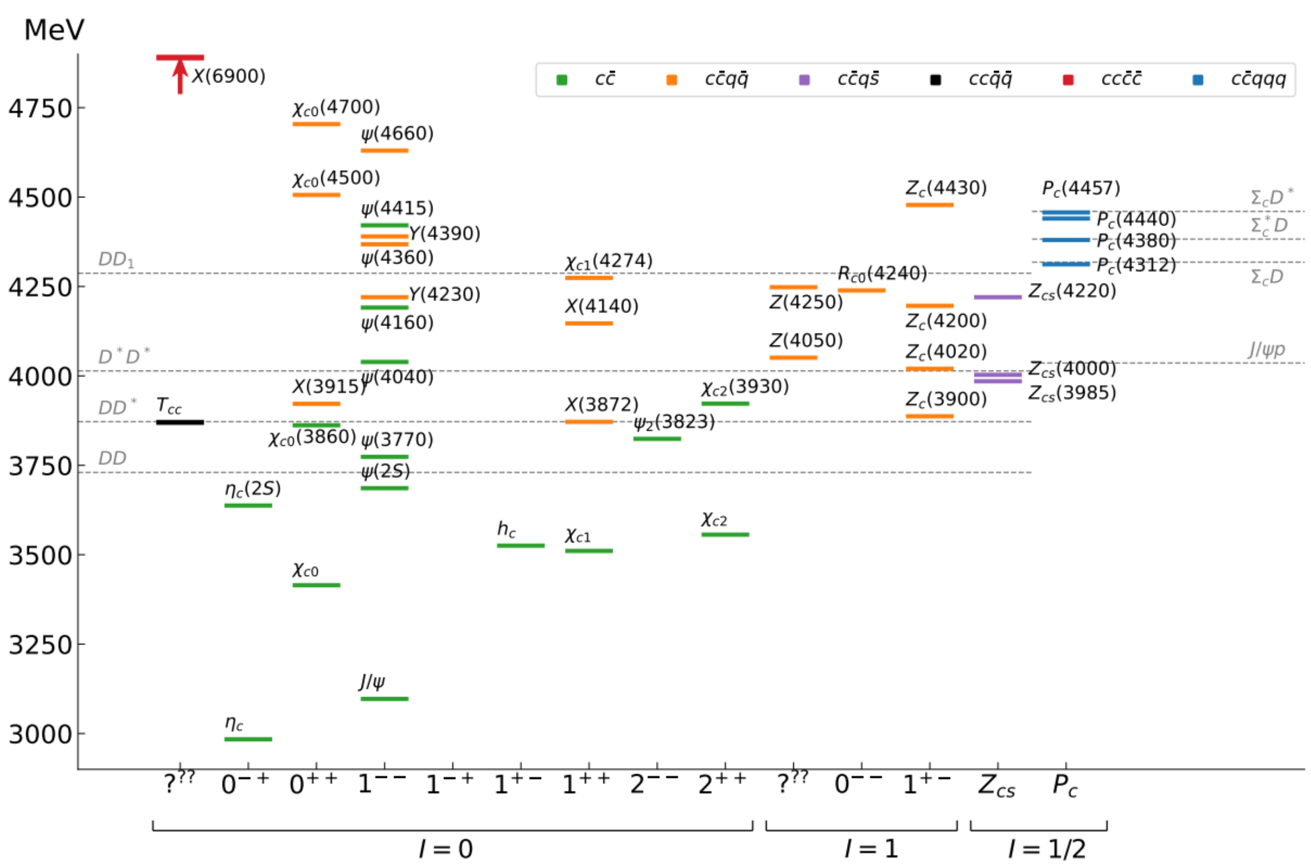
Spectroscopy



More and more QCD bound states discovered. Hadron chemistry



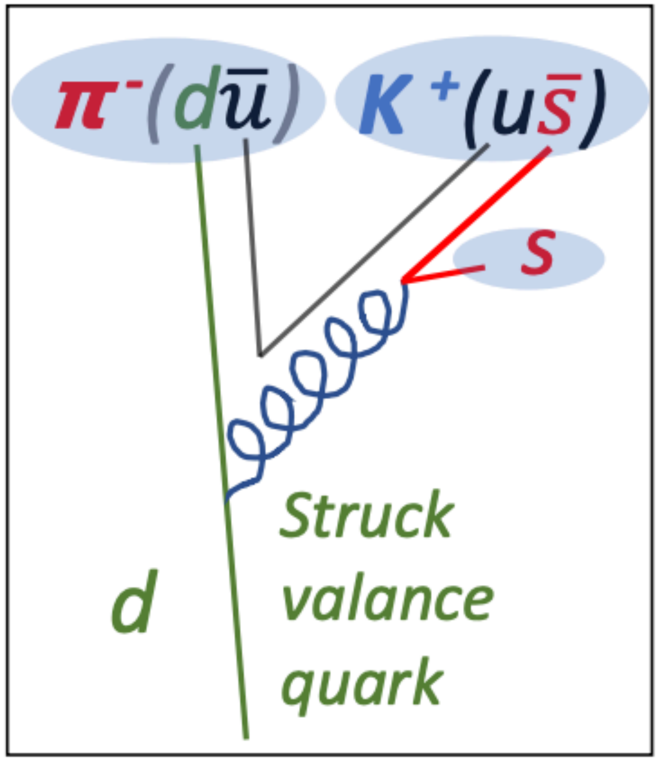
Theory catching up!

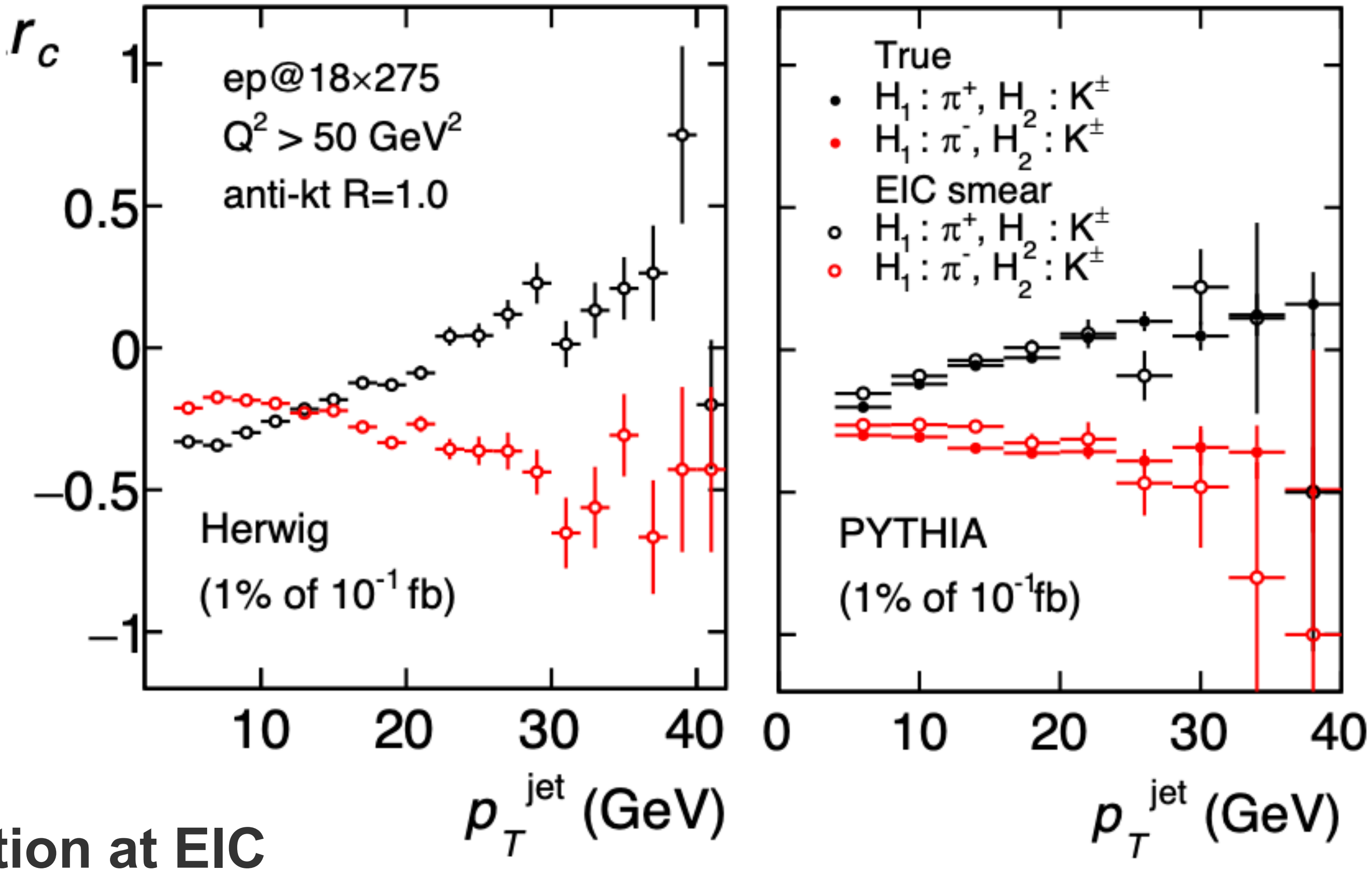


Hadronization and correlation

How about flavor correlations? The conditional probability of observing hadron A near hadron B

An attempt to probe microscopic processes of hadronization: string breaking?

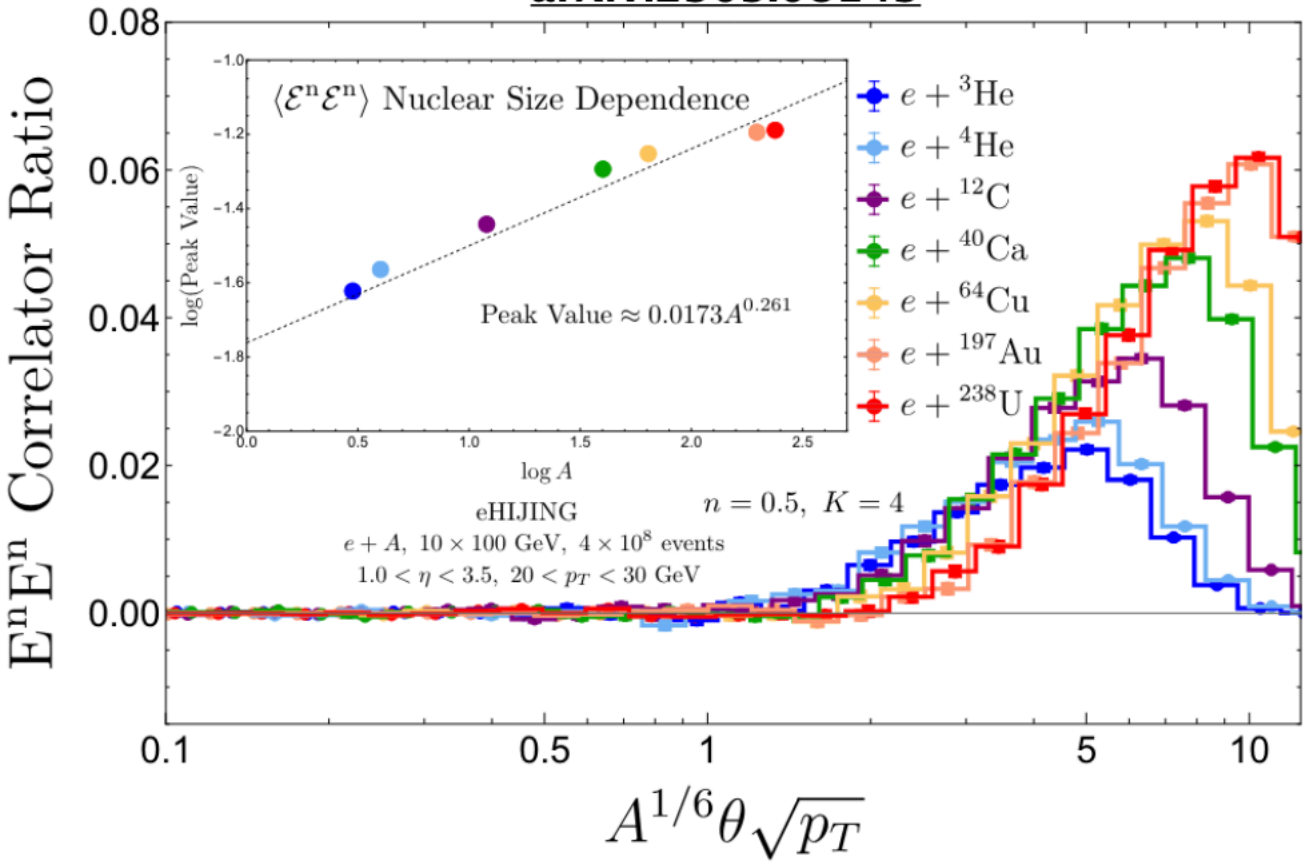




Charge correlation in hadronization at EIC
PRD 105 (2022) 5, L051502

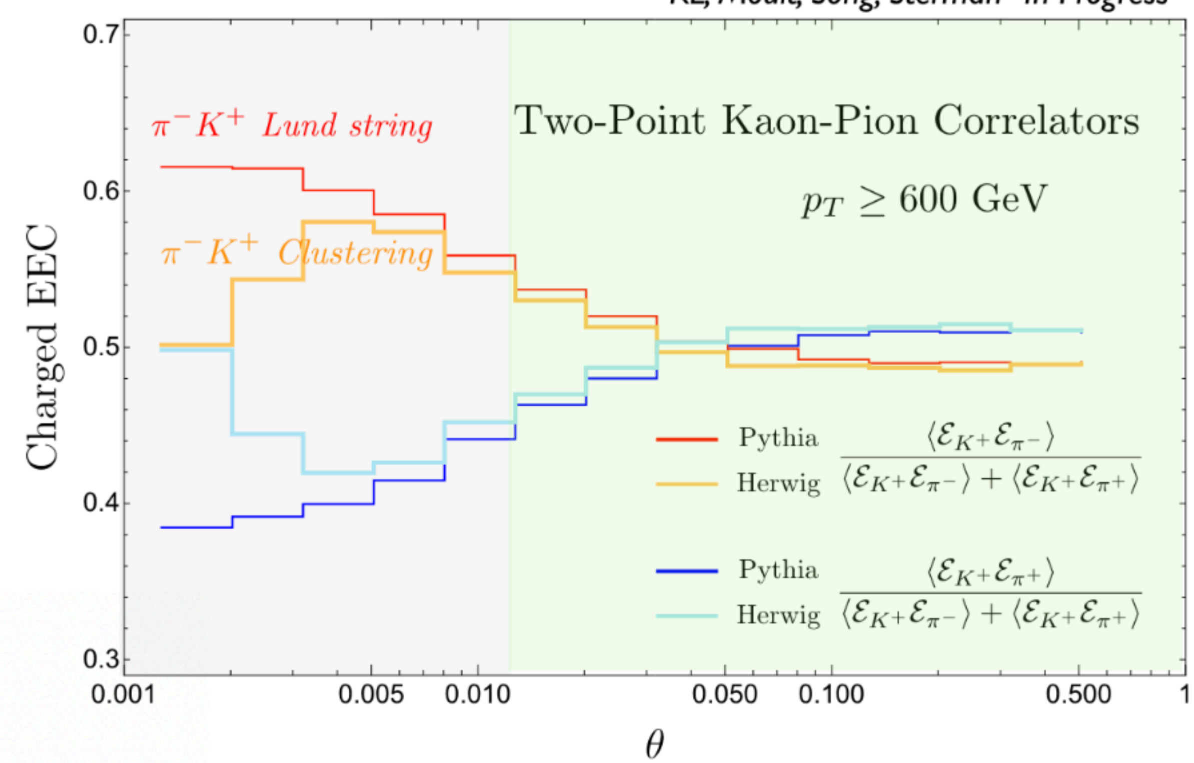
Testing hadronization models

arXiv:2303.08143

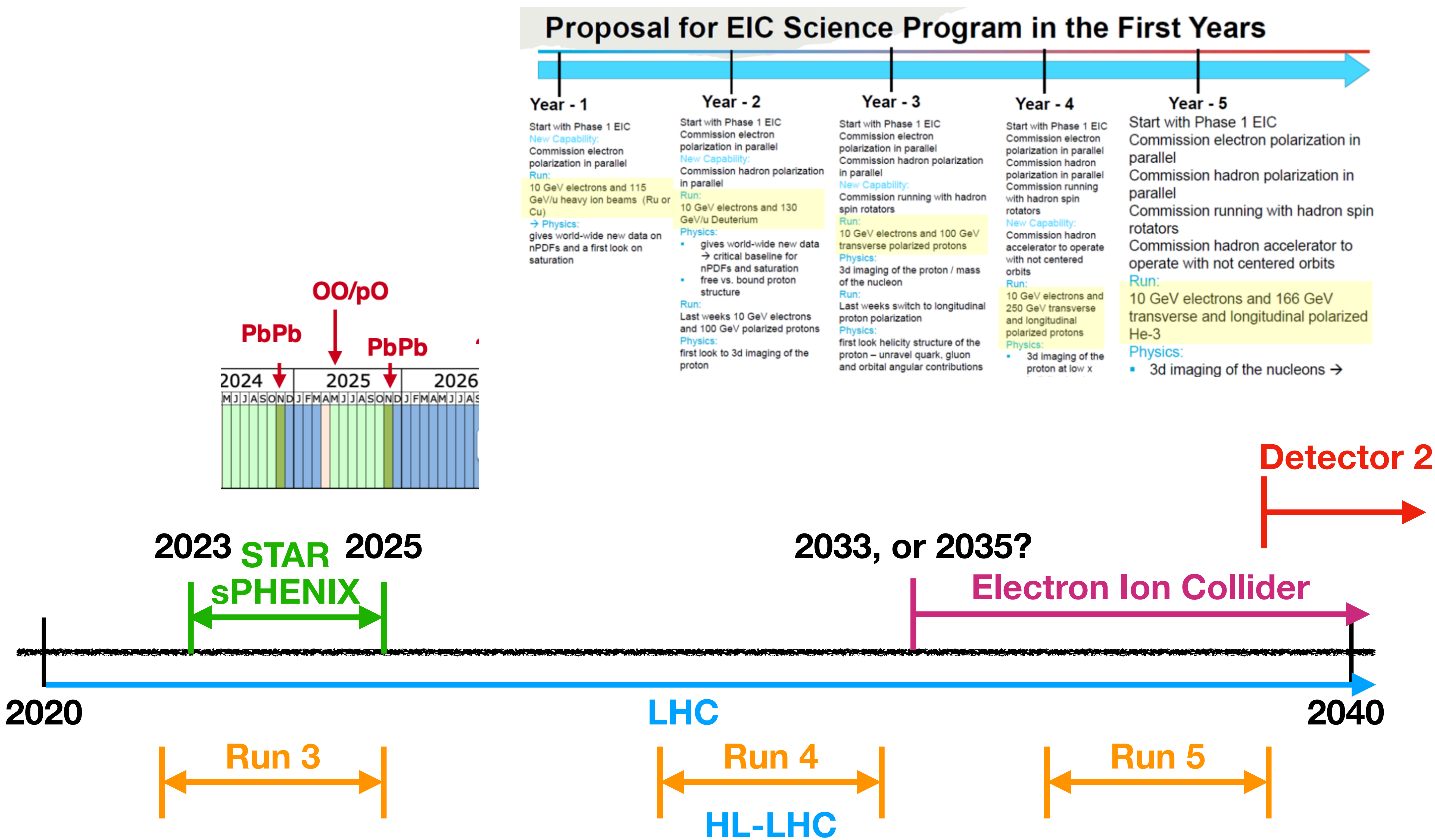


Kyle Lee's Presentation at 2024 EICUG Meeting (LeHigh University)

KL, Moult, Song, Sterman `In Progress



Timeline



Proposal for EIC Science Program in the First Years
Year - 1
Start with Phase 1 EIC
New Capability:
Commission electron polarization in parallel
Run:
10 GeV electrons and 115 GeV/u heavy ion beams (Ru or Cu)
→ Physics:
gives world-wide new data on nPDFs and a first look on saturation
Year - 2
Start with Phase 1 EIC
Commission electron polarization in parallel
New Capability:
Commission hadron polarization in parallel
Run:
10 GeV electrons and 130 GeV/u Deuterium
Physics:
gives world-wide new data → critical baseline for nPDFs and saturation
free vs. bound proton structure
Run:
Last weeks 10 GeV electrons and 100 GeV polarized protons
Physics:
first look to 3d imaging of the proton
Year - 3
Start with Phase 1 EIC
Commission electron polarization in parallel
Commission hadron polarization in parallel
New Capability:
Commission running with hadron spin rotators
Run:
10 GeV electrons and 100 GeV transverse polarized protons
Physics:
3d imaging of the proton / mass of the nucleon
Run:
Last weeks switch to longitudinal proton polarization
Physics:
first look helicity structure of the proton – unravel quark, gluon and orbital angular contributions
Year - 4
Start with Phase 1 EIC
Commission electron polarization in parallel
Commission hadron polarization in parallel
Commission running with hadron spin rotators
New Capability:
Commission hadron accelerator to operate with not centered orbits
Run:
10 GeV electrons and 250 GeV transverse and longitudinal polarized protons
Physics:
3d imaging of the proton at low x
Year - 5
Start with Phase 1 EIC
Commission electron polarization in parallel
Commission hadron polarization in parallel
Commission running with hadron spin rotators
Commission hadron accelerator to operate with not centered orbits
Run:
10 GeV electrons and 166 GeV transverse and longitudinal polarized He-3
Physics:
3d imaging of the nucleons →
OO/pO
PbPb
PbPb
2024
2025
2026
Detector 2
2023
STAR
sPHENIX
2025
2033, or 2035?
Electron Ion Collider
2020
LHC
2040
Run 3
Run 4
Run 5
HL-LHC

Two paradigms challenged at once

Particle Physics

How can short distance scattering generate collective behavior, while collective behavior is a manifestation over long distance?

What is lacking in the simulation?

What does it mean when Pythia agrees with data?

How much multi-parton interaction (MPI) can explain heavy ion collisions?

Nuclear Physics

How can small systems behave hydrodynamically, while hydrodynamics is supposed to be a description over long distance?

How small can a droplet of liquid be?

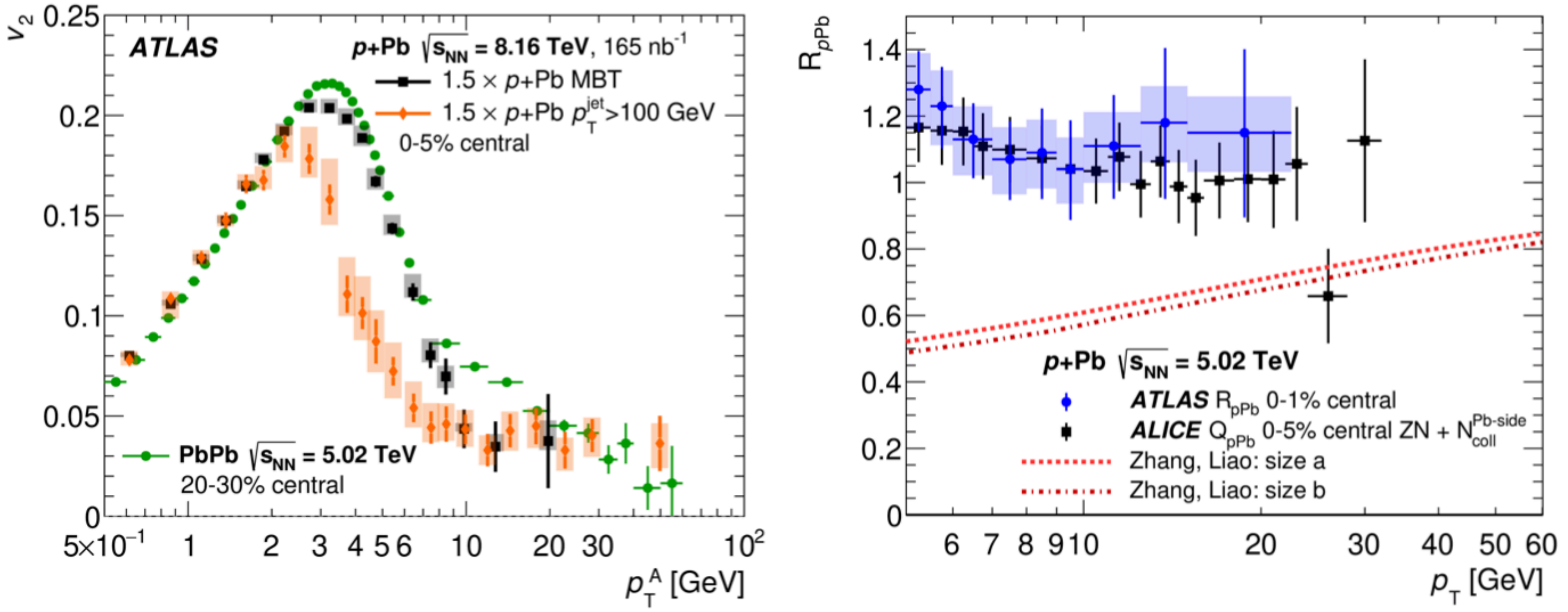
QGP can not be turned off.

Hydro is not supposed to "work" in small systems but it "works".

Hard probes puzzles also!

HIGH PT PUZZLE: NO ENERGY LOSS BUT COLLECTIVITY

Eur. Phys. J. C 80 (2020) 73

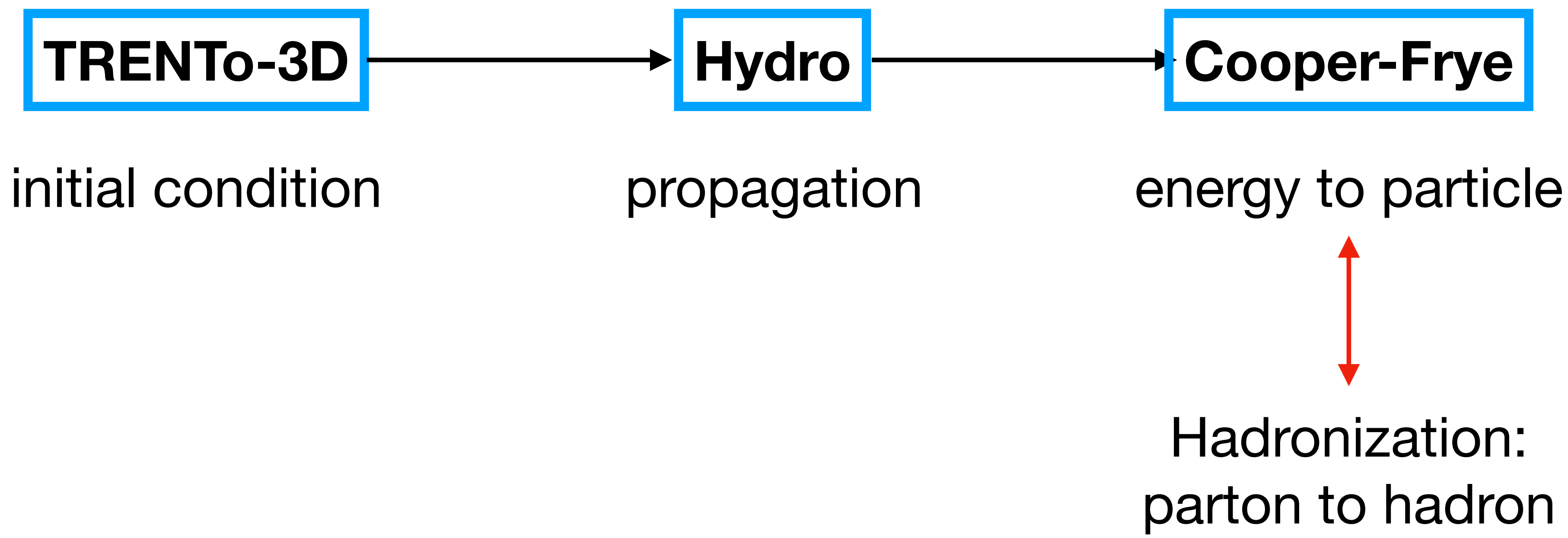


High p_T puzzle in small-systems

- No jet quenching
- Clear v_2 signal - similar to mid-central Pb-Pb
- Models that predict collective behavior largely overestimate R_{pPb} suppression

Systematic improvement of medium effective theory (MET)

What does it mean when hydro agrees with data?



We have tested a lot of bulk properties. What new observables can test this framework in the corner of phase space we haven't probed?

- Local properties of the medium
- Response to an external current, or hard probes
- How correct is Cooper-Frye?
- How much theory control on initial condition?

Inner-working of QGP — from MET

An analogy: how do we systematically study water flows (hydro) to approach the conclusion that it consists of H_2O molecules with EM interaction (inner working)?

- Keep looking into smaller distances (not necessarily smaller water droplet). Before reaching atomic length scale hopefully one will see something nontrivial

QGP: Hydro energy-momentum constructed above some length scale (1 fm? 0.1fm?). When does continuity stop working? How does this translate to final state signatures in AA (or pA, pp)? Bulk flow fluctuation moments? Local properties?

How does this long-distance medium effective theory match to a microscopic theory, or microscopic theories?

Hydrodynamics EFT

Versions of causal stable hydrodynamics

- Mueller-Israel-Stewart (MIS) and DNMR:
  - **fluxes of conserved charges evolve independently** of the respective densities and relax after a **relaxation time** τ
- Bemfica-Disconzi-Noronha-Kovtun (BDNK)
  - **redefinitions of hydrodynamic fields** to introduce the **relaxation time** τ into the hydrodynamic equations
- Schwinger-Keldysh (SK) EFT of hydrodynamics
  - **covariant renormalized** generating functional

➡ **all versions provide UV-regularization of the EFT (hydrodynamics)**

How do nonlinear ***quantum-statistical fluctuations*** modify diffusion when taking into account the ***slowest UV-mode***?

[Abbasi, Kaminski, Tavakol; PRL (2024)]

Hydrodynamics starts to tackle questions in the UV: inner working of QGP!

Inner-working of QGP — from hard probes

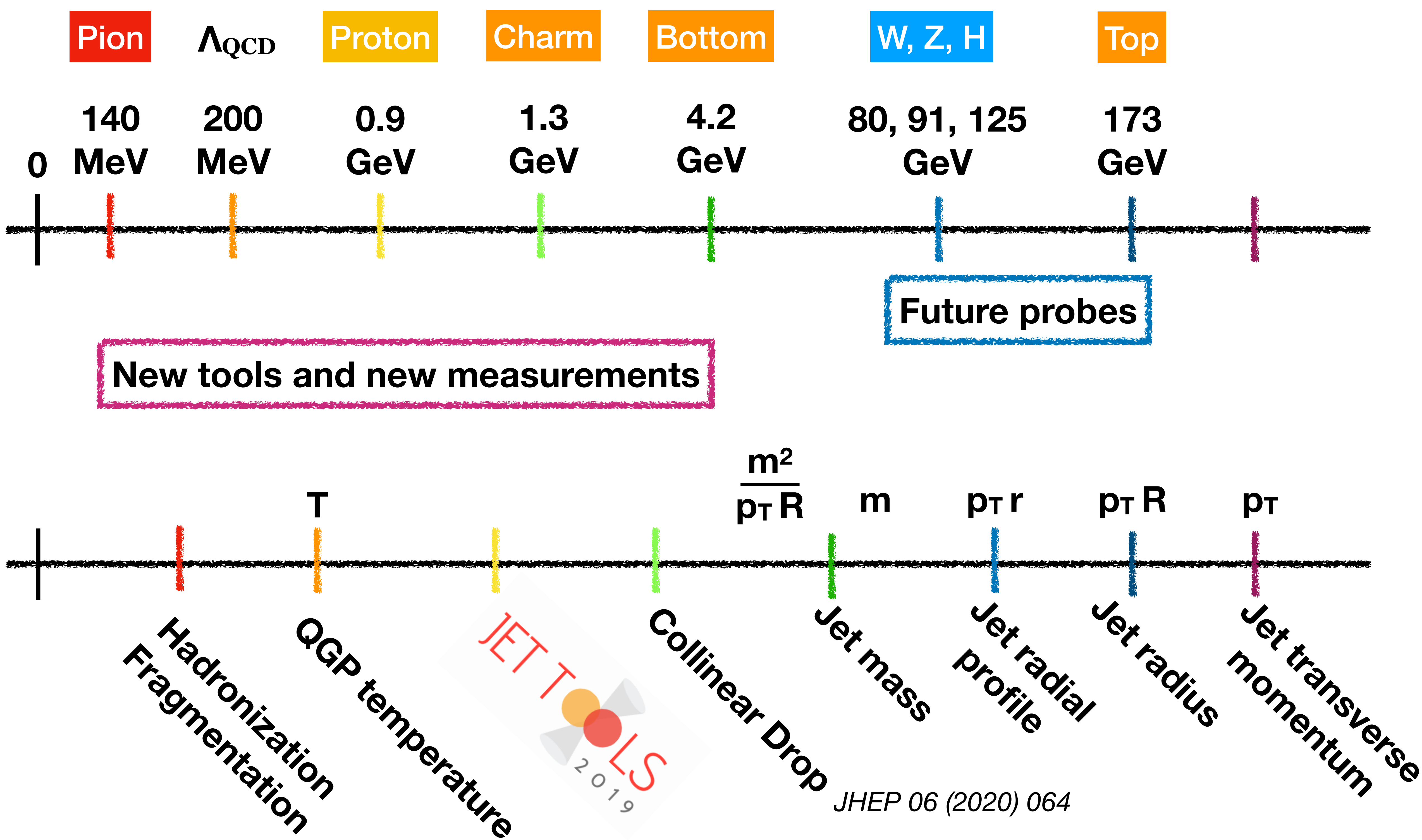
An analogy: how do we systematically shoot water with something (hard probes) to approach the conclusion that it consists of H_2O molecules with EM interaction (inner working)?

- Hard probe with EM waves? What happens when we keep reducing the wavelength of the EM wave down to atomic length scale?

QGP: jets evolve from the shortest distance scales up to a few fm, or the highest energy scales down to Λ_{QCD}. The jet-medium interaction should leave fingerprints during certain stages of the evolution. In principle a systematic scanning of jet substructure should characterize jet-medium interaction

How do modifications of a basis of jet substructure observables map to the inner working of QGP?

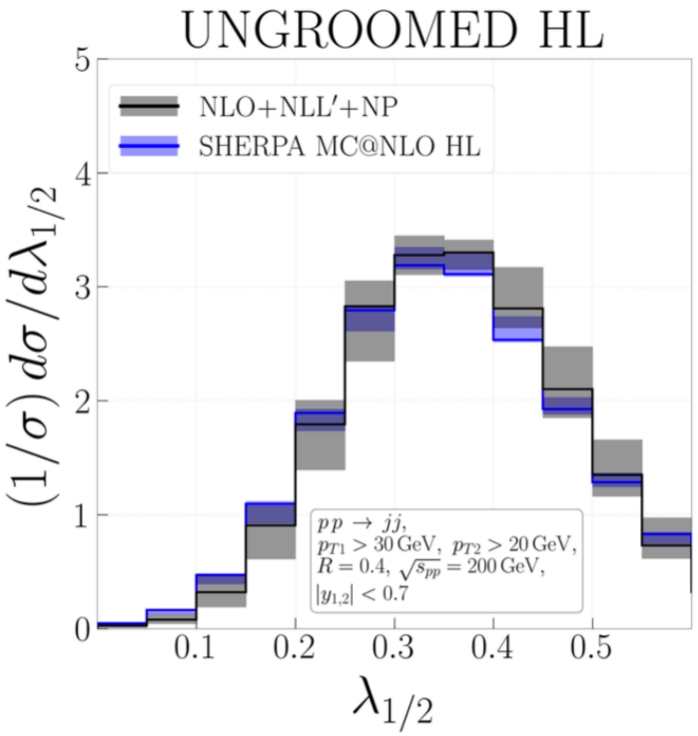
Jet substructure are multi-scale probes

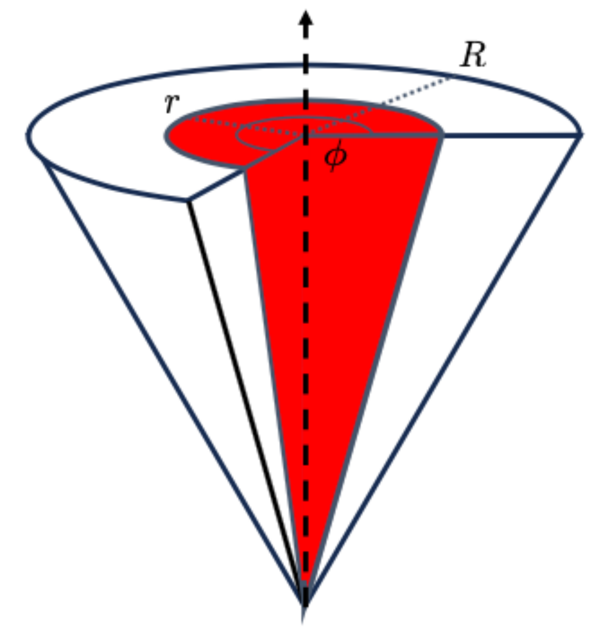


JHEP 06 (2020) 064

J.Phys.G 47 (2020) 6, 065102

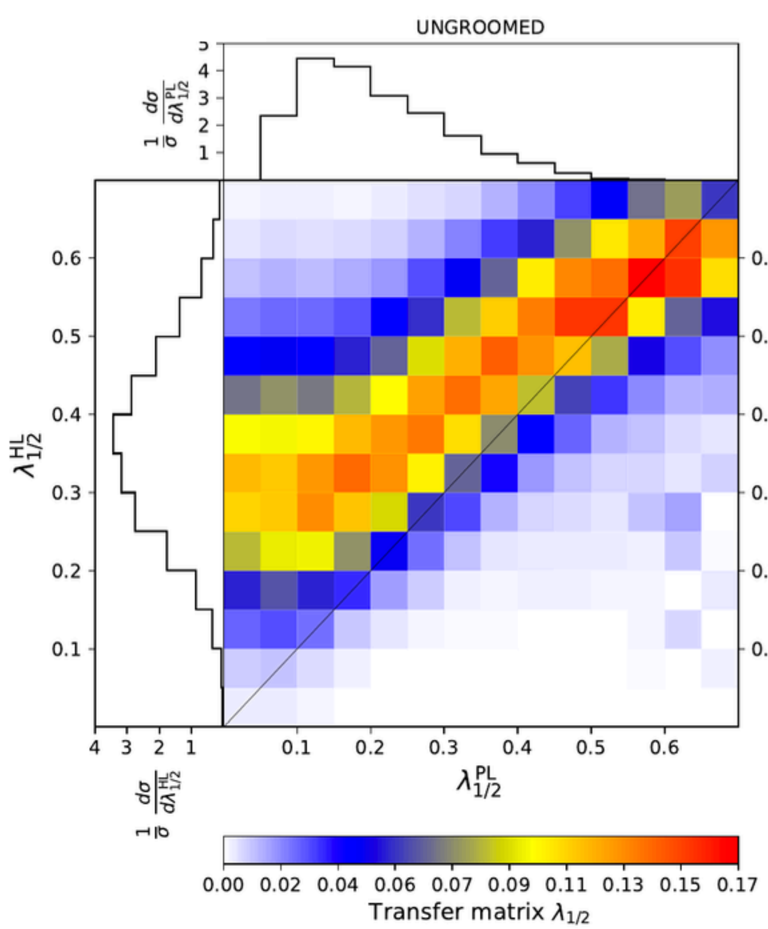
Classics done carefully and new observables





$$\psi(r, R, \varphi_i, \varphi_f)$$

Hadron level results



Parton level results

Comprehensive quantification of hadronization using transfer matrix

As spin and polarization get more emphasized in the EIC era, jet observables sensitive to azimuthal dependence are further developed

Bayesian analysis and speed up

Machine-learned normalizing flow

Find an approximate normalizing flow

$$\mathcal{N}\prod_{i=1}^{N} dx_i\, e^{-x_i^2/2} = d\boldsymbol{\alpha}\, Q(\boldsymbol{\alpha}) \approx d\boldsymbol{\alpha}\, P(\boldsymbol{\alpha})$$

by optimizing parameters in the neural network.

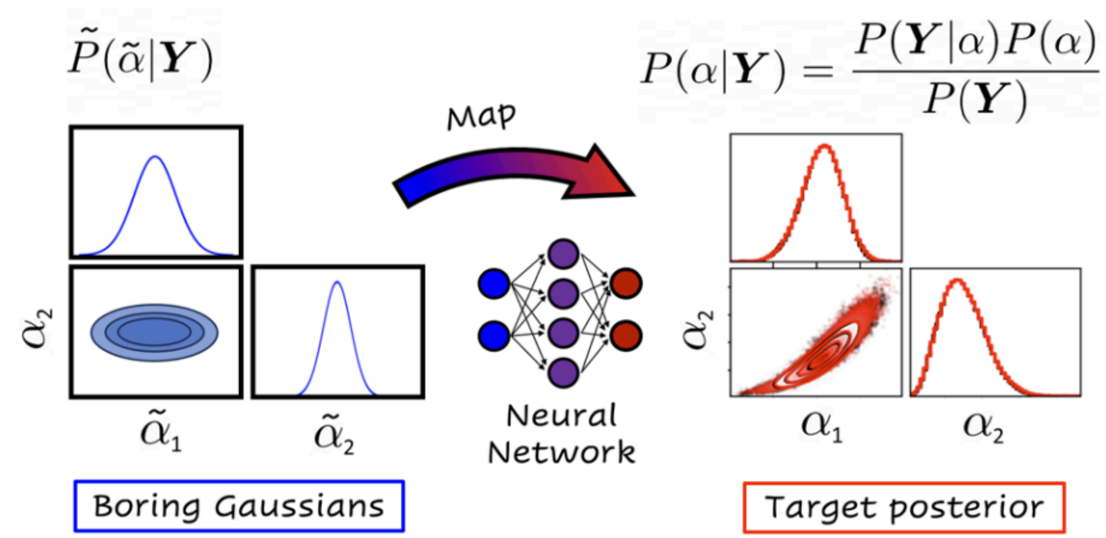
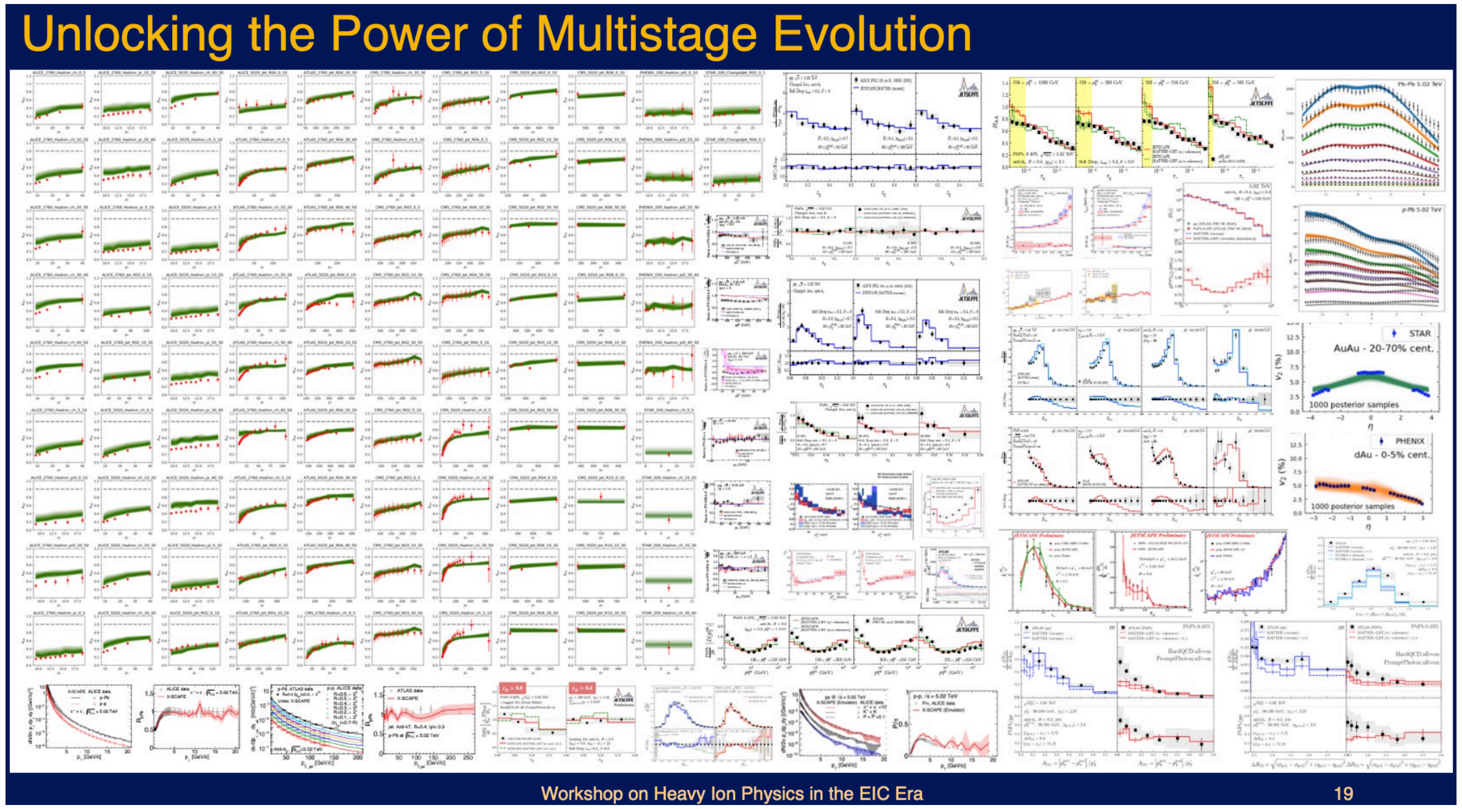
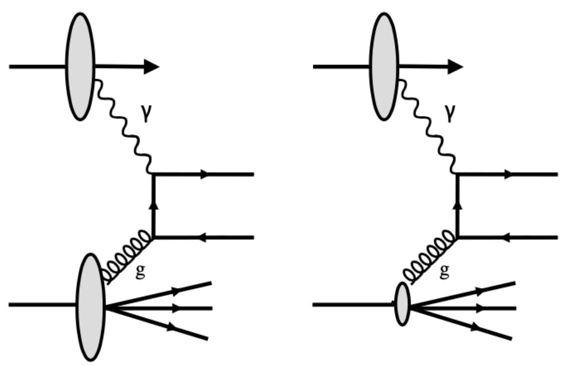


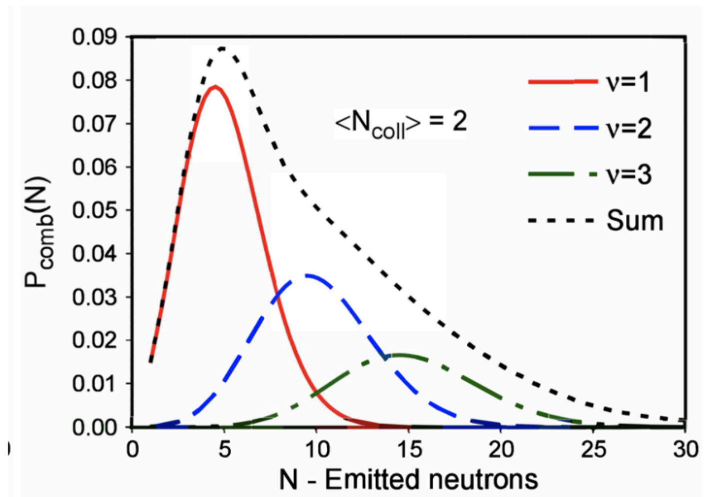
Image credit: Pablu Giuliani



Emphasis on forward physics

Basic concept: “over-constraining” low-x models by measuring both barrel and very forward observables
M. Strikman, V. Guzey et al., arXiv.2402.19060

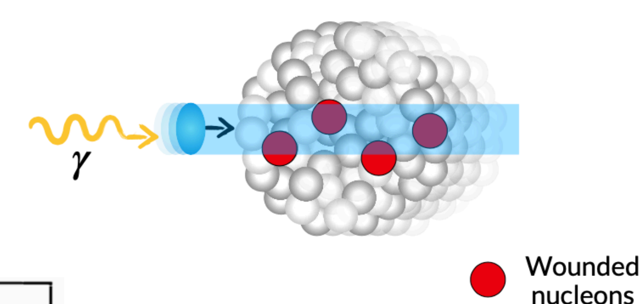




How well do we understand the nuclear breakup in *e*+A collisions?

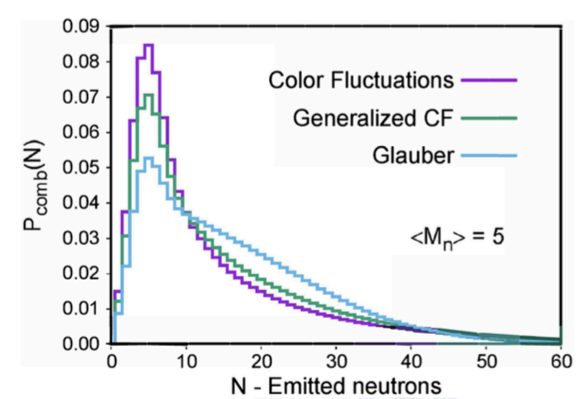
- Can we rely on forward neutrons to characterize the event geometry in *e*+A collisions (approach proposed by Zheng et al, **Eur. Phys. J. A (2014) 50: 189**) or could there be biases from kinematic-driven effects?

Also:
γA in $e^- + A$ collisions via resolved photon



Characterization of neutron multiplicities in p+A and in UPCs at the LHC can inform geometry determination in e+A

PRC 110, 025205 (2024)



CFs are also relevant for result interpretation at RHIC energies, see D.Perepelitsa, **Phys. Rev. C 110, L011901** , for a recent use of the CF model to interpret PHENIX data

ZDC may provide valuable information on nuclear dynamics!

Target jet substructure and correlation

Yang-Ting Chien

INT program: Heavy Ion Physics in the EIC Era
University of Washington, Seattle, August 14th, 2024

In collaboration with Kai-Feng Chen, Roli Esha, Meng-Hsiu Kuo, to appear soon

國立臺灣大學 National Taiwan University
Center for Frontiers in Nuclear Science
Georgia State University
Jefferson Lab
U.S. DEPARTMENT OF ENERGY Office of Science

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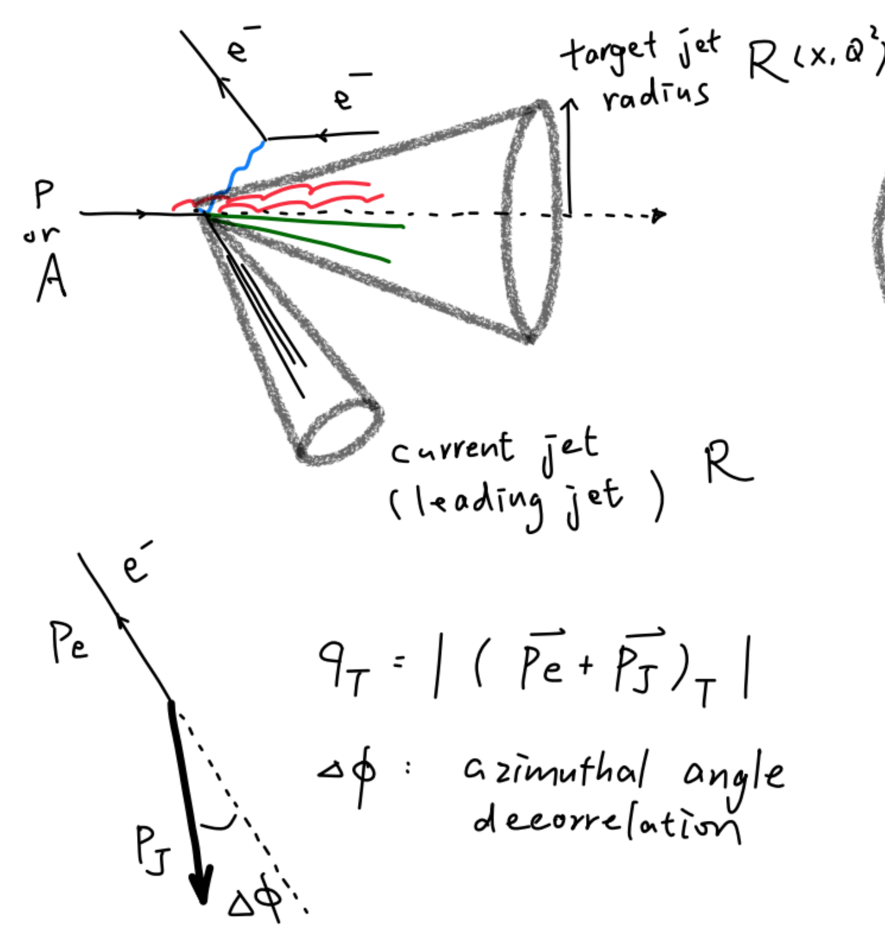
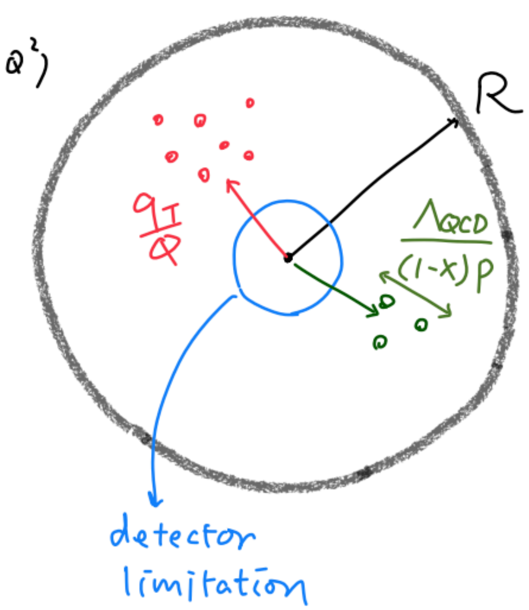
Electron-leading jet and target jet





- Carving out two collinear energy flows

Connection between MET and hard probes

How do jets couple to the medium?

Perturbative emissions with formation time overlapping medium evolution should couple to medium: how does apparently perturbative (weakly-coupled) parton shower coupled to strongly-coupled medium?

Hard probes people

- Postulate effective color sources
- Draw gluons between the sources and the jet partons
- Postulate scattering probability with some medium parameters
- Calculate with sometimes inaccurate approximations (because calculations are usually very hard)

Medium people

- Postulate effective probabilistic color currents (can be sophisticated)
- Work out the (linear) responses
- Quantify the responses by some local observables

Synergy between MET and hard probes

A systematic scanning of jet substructure from hard to soft

The more toward the softer substructure, the more complicated the situation will be. The bottleneck of this program is the lack of knowledge of medium local properties (fluctuations within a patch of size R), making background subtraction less and less reliable. Jet-medium correlation also makes subtraction fundamentally invalid

So not only medium local properties may test the regime of validity of MET, but also become essential knowledge for jet substructure studies

A unified framework for studying medium local fluctuation and jet substructure will help facilitate the synergy

To begin, recoil free observables can be good candidates to benchmark jet quenching studies

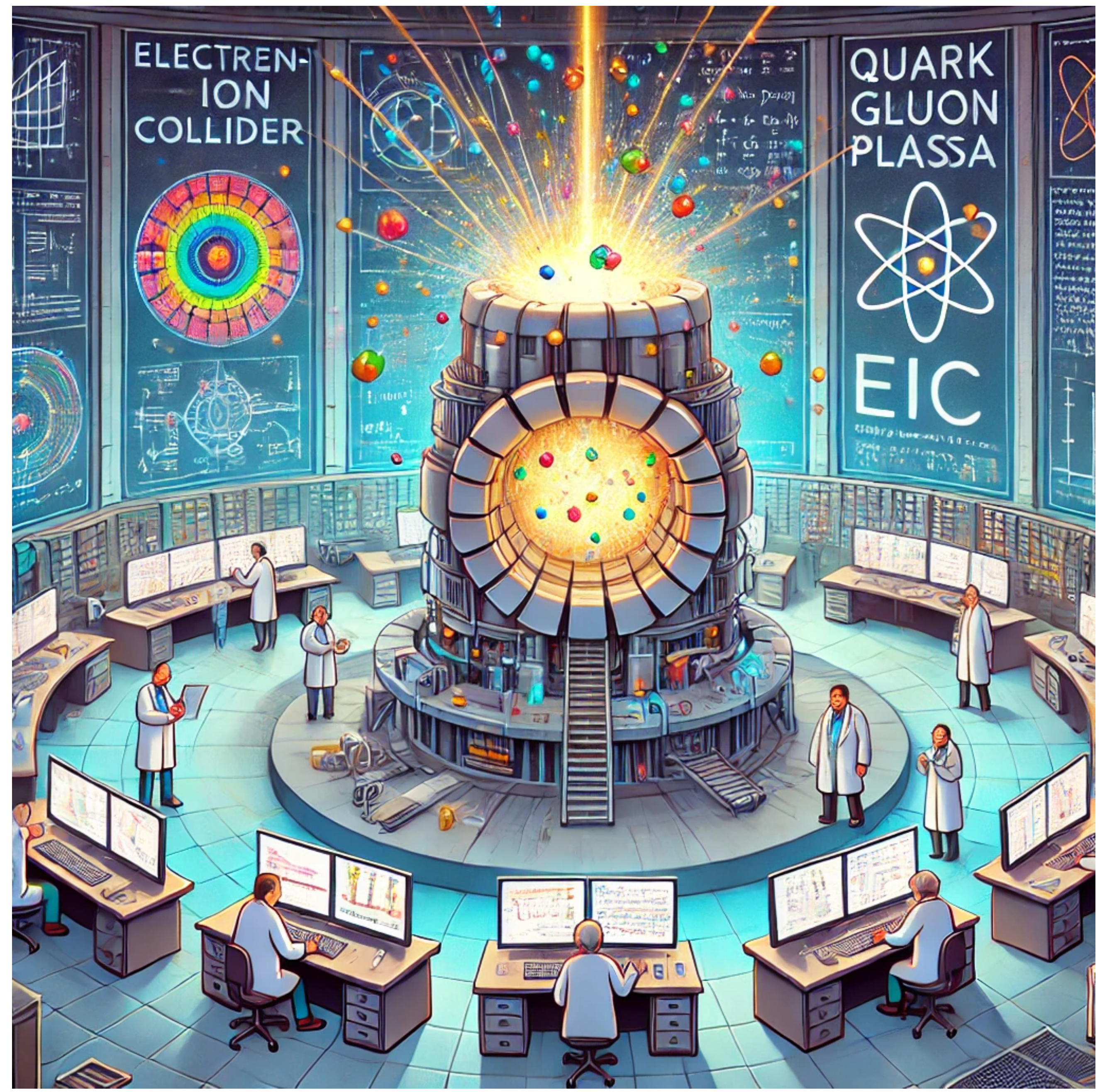
Heavy Ions Collide

In the collider's gleaming hall,
Ions smash with mighty force,
Quark-gluon plasma forms and falls,
Recreating cosmic source.

Strong fields rise, intense and bright,
Gluons freed, in streams they surge,
Probing matter's ancient might,
Where the universe did emerge.

Jets and hadrons mark the tale,
As symmetry breaks and twists,
New particles without fail,
Appear from quantum mists.

A fleeting glimpse of early time,
Revealed in each embrace,
Heavy ions, in their prime,
Unlock the fabric of space.



Acknowledgements

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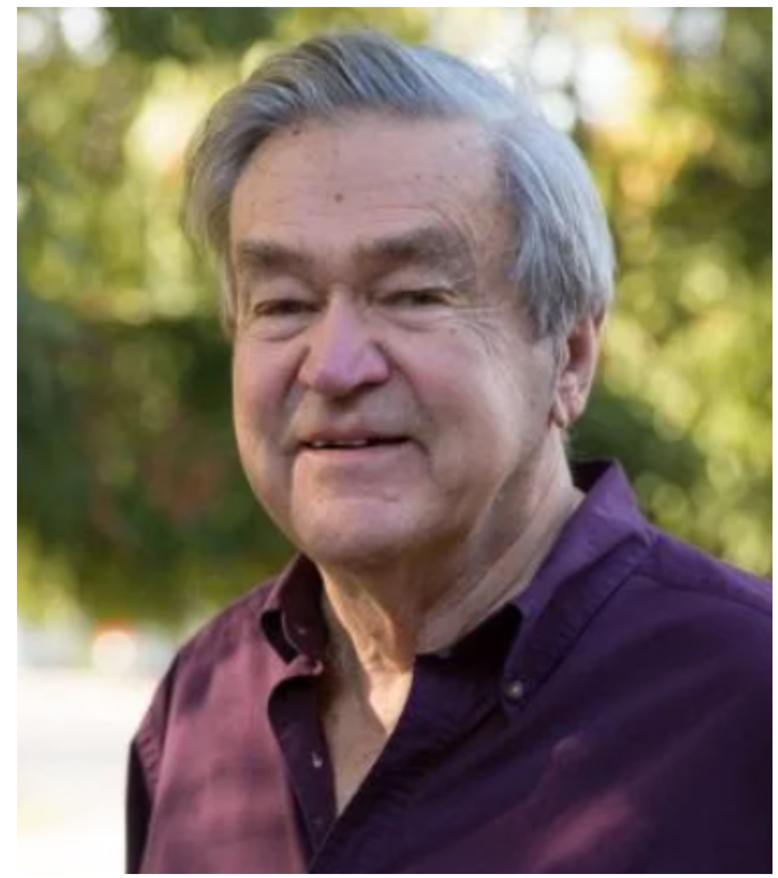
Please consider requesting preprint numbers from INT for the work benefiting from this INT program

sPHENIX working!

AGUA VERDE CAFÉ

In memory of two great physicists

Tsung-Dao Lee
1926-2024



James Bjorken
1934-2024