Hadronization in the EIC

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smash

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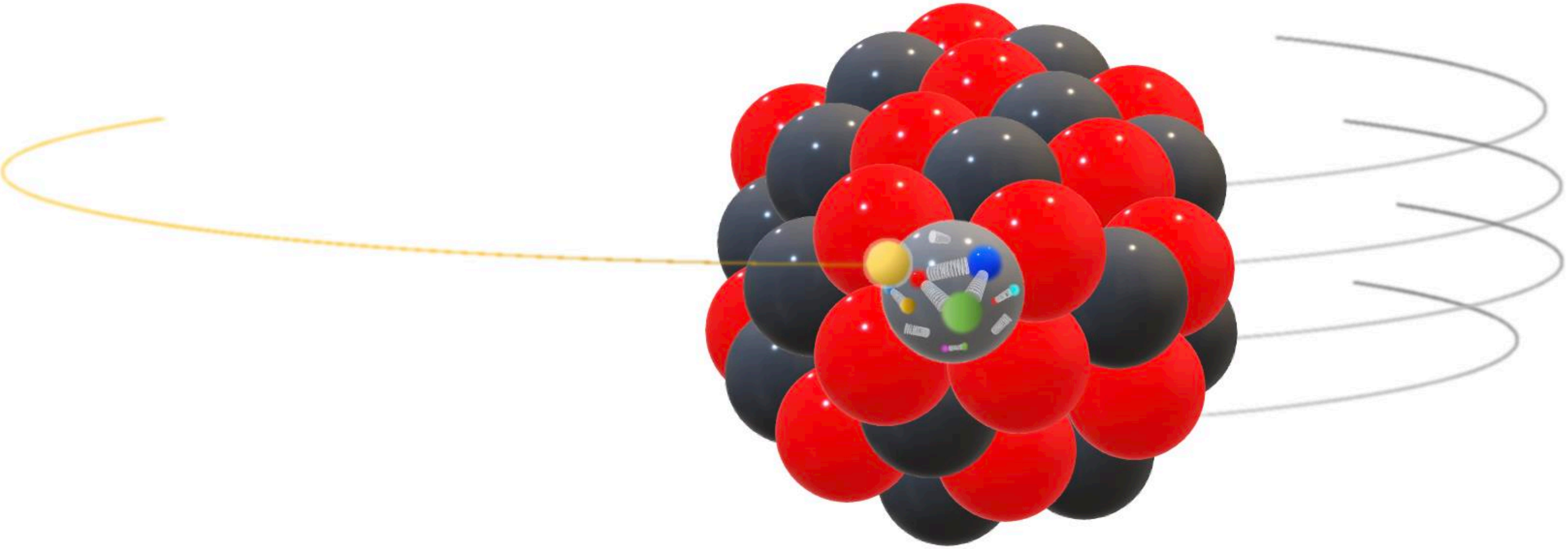
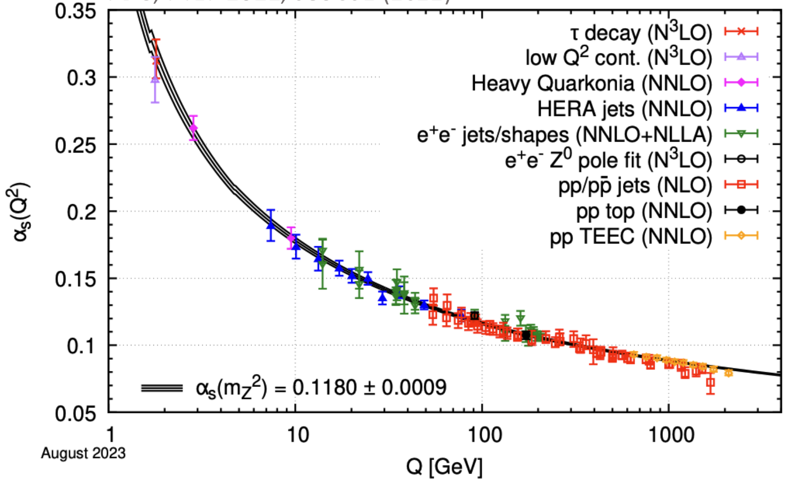
Illinois Center for Advanced Studies of the Universe



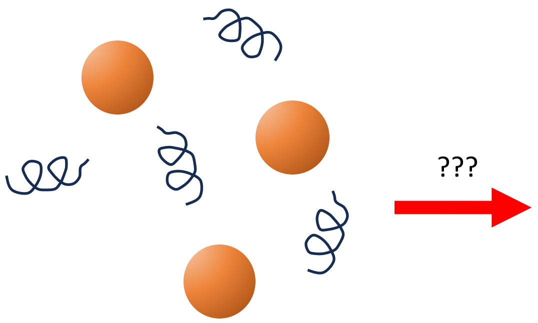
Color confinement

Question: Why do we observe only color neutral hadrons?

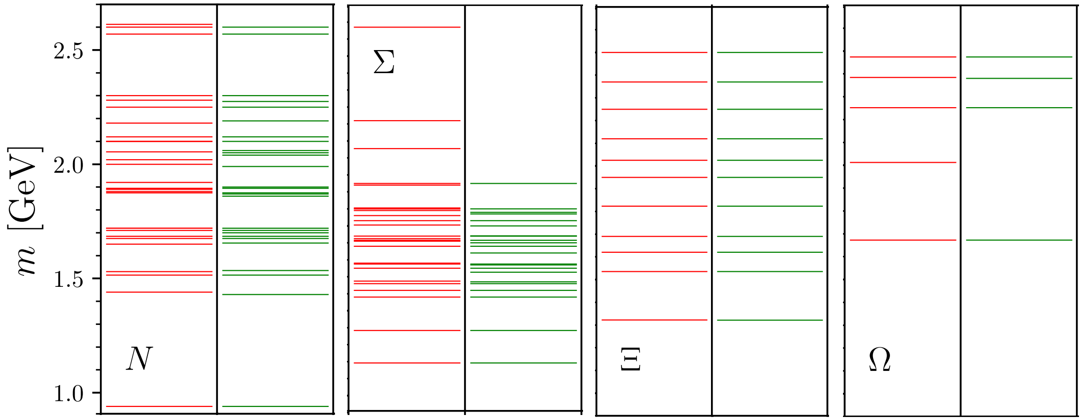


- Color confinement is tightly related to *hadronization*
- Gluon self-coupling leads to asymptotic freedom
- Perturbative methods fail at long distances (where $\alpha_s \sim 1$)

Hadronization is a non-perturbative phenomena and is poorly understood



Quarks and gluons



Hadron spectrum

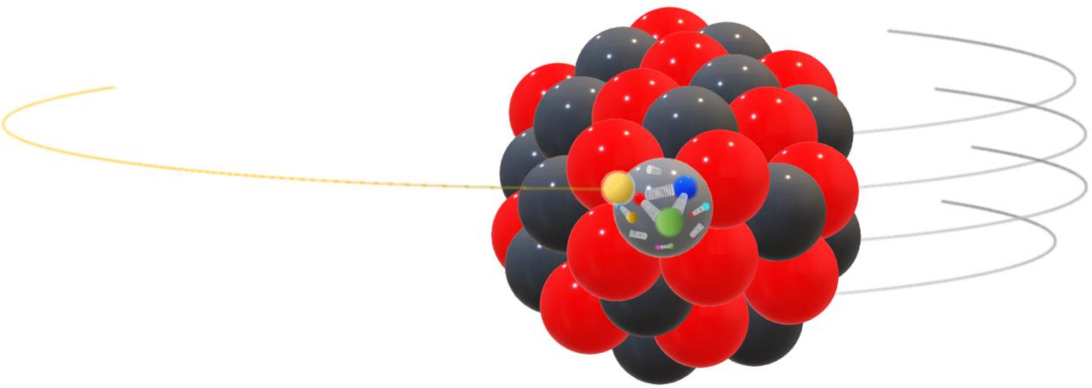
PDG: PTEP **2022**, 083C01 (2022), CPC **38**, 090001 (2015)

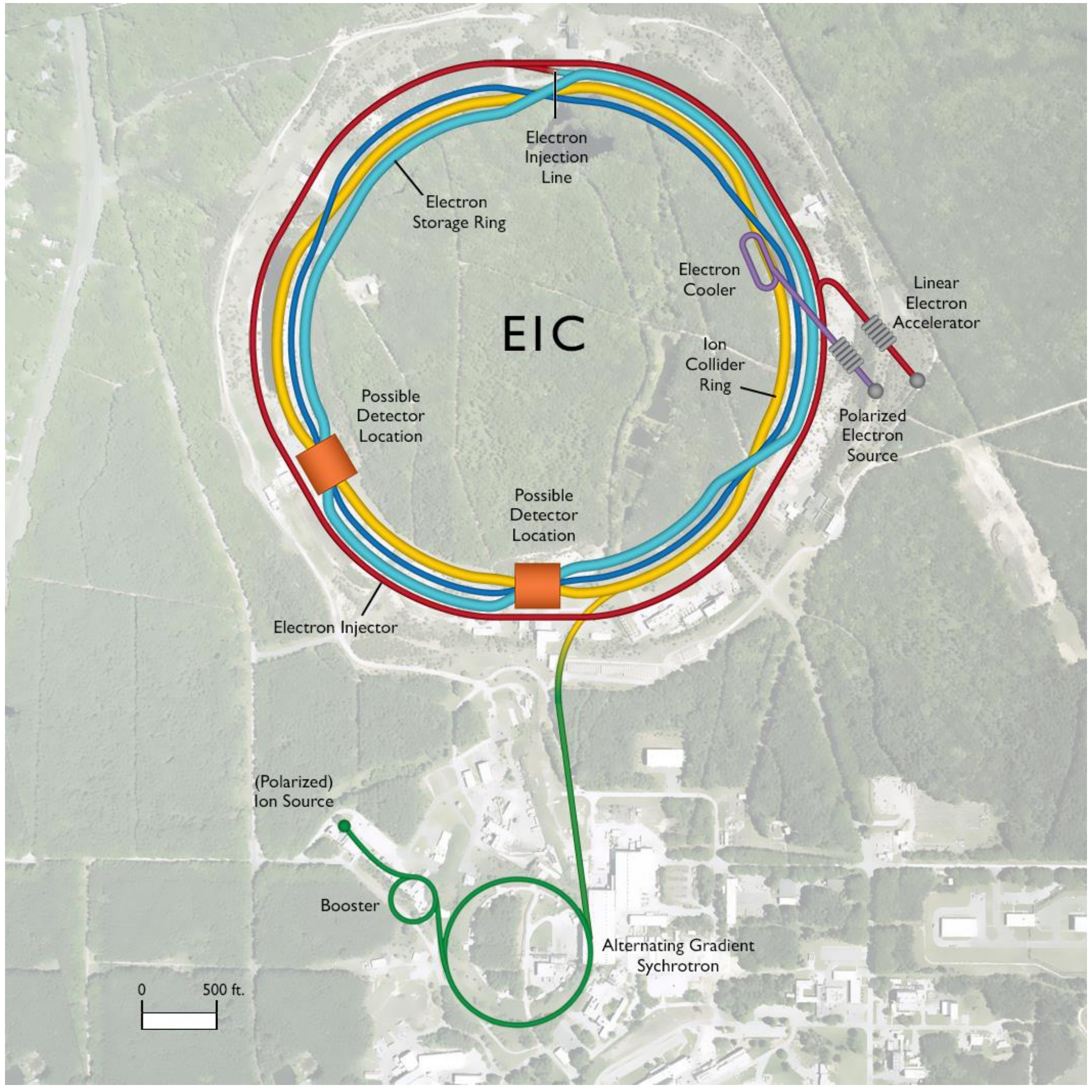
- How can we produce **hadrons from partons** (quarks or gluons) in a consistent dynamical picture?
- How can we **improve** current knowledge on hadronization/color confinement?

Hadronization at the EIC

Unique opportunity due to the ”simple” kinematics and the surrounding nuclear medium

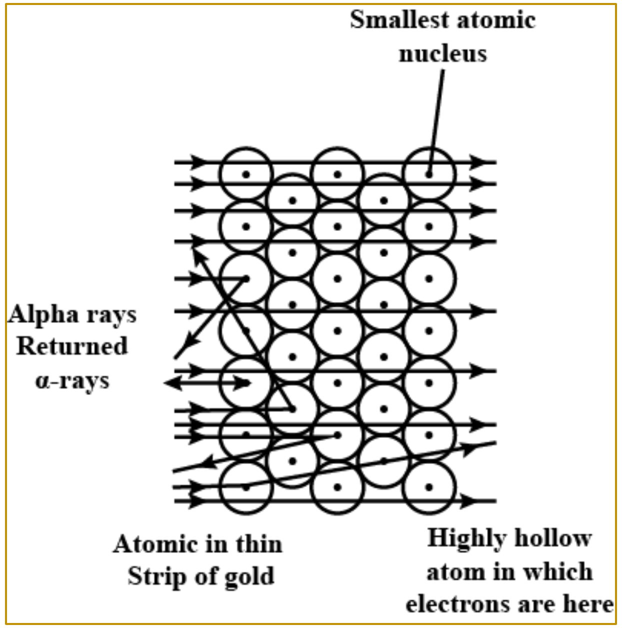
We can import the tools from from Heavy-Ions to the the EIC!



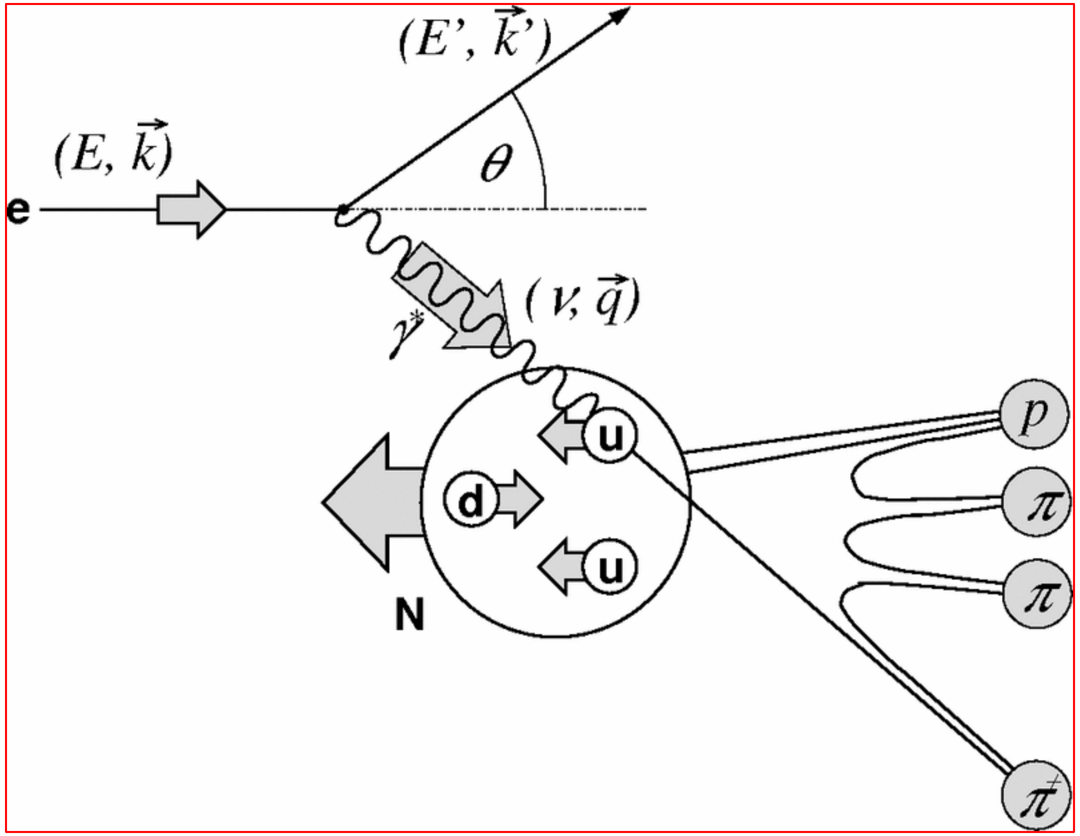


https://www.bnl.gov/newsroom/news.php?a=116998

Hadronization in Deep Inelastic Scattering



The Rutherford gold foil experiment



Deep Inelastic Scattering (DIS)

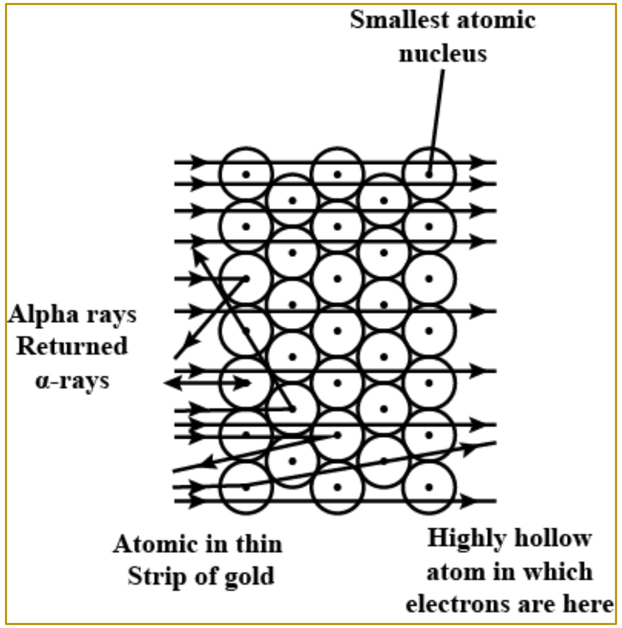
DIS is the evolution of Rutherford's idea

Hit the target with a very energetic projectile and see what happens with it!

time

- ep/en (FT) @ SLAC
- ν's (FT) @ Fermilab and CERN
- μ's (FT) @ Fermilab and CERN
- ep (Collider) @ HERA
- Pol. μp (FT) @ CERN
- Pol. ep @ JLAB and HERA

Hadronization in Deep Inelastic Scattering



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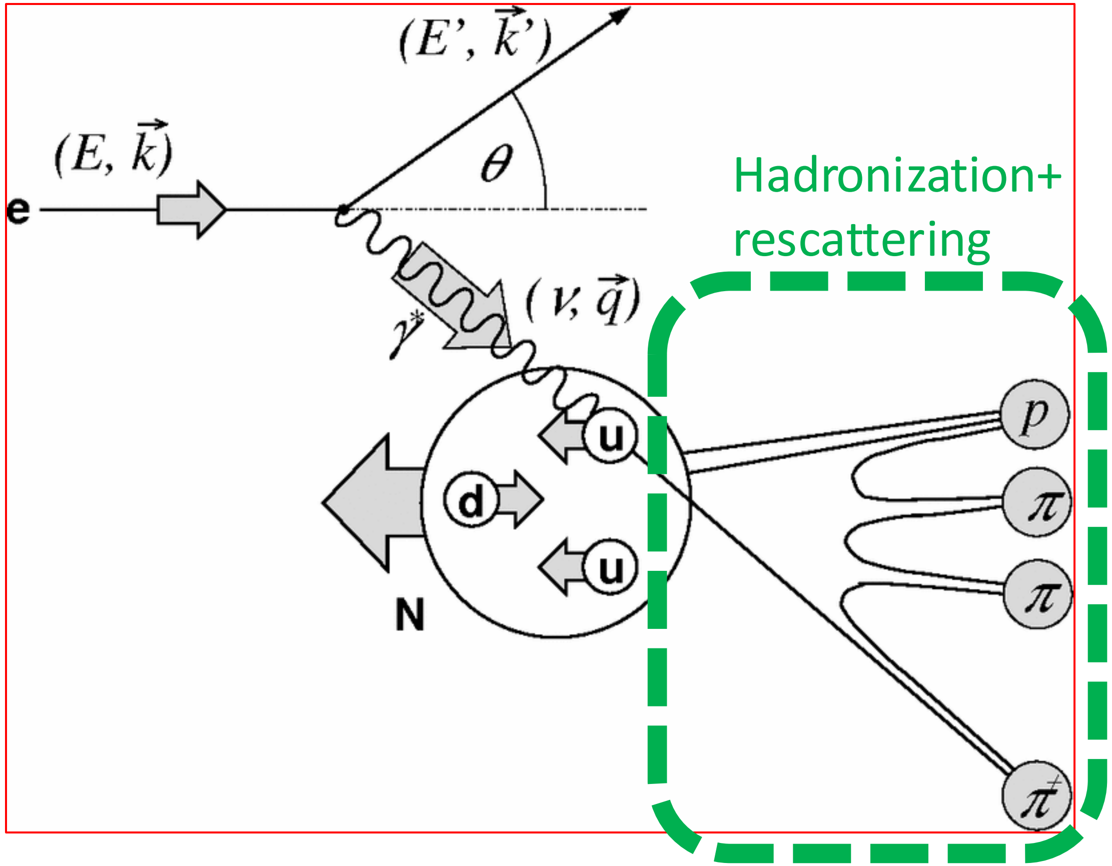

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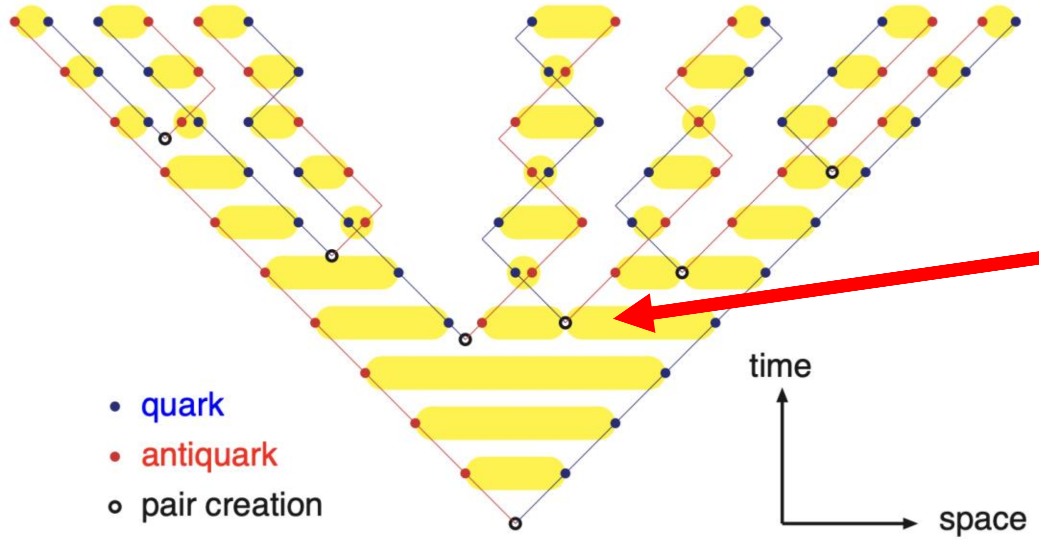
time

Hadronization in practice: Lund string model

Question: how can we create hadrons from our initial partons?

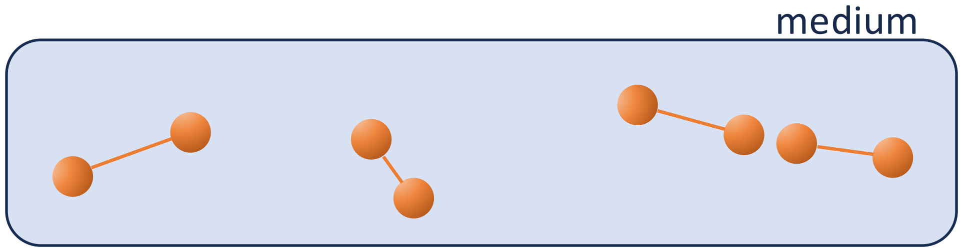
P. Skands, 1207.2389 (2012)



- The Lund string fragmentation model provides a hadronization picture
- For large charge separations, field lines seem to be compressed to tubelike regions or strings
- Confinement is realized as a linear string tension between a quark/anti-quark pair
- String fragments, forming new quark/anti-quark pairs – color conserving process
- **Currently implemented in the PYTHIA event generator (most used)**

Effect of the nuclear medium on hadrons

Question: How do hadrons (strings) interact with the medium?

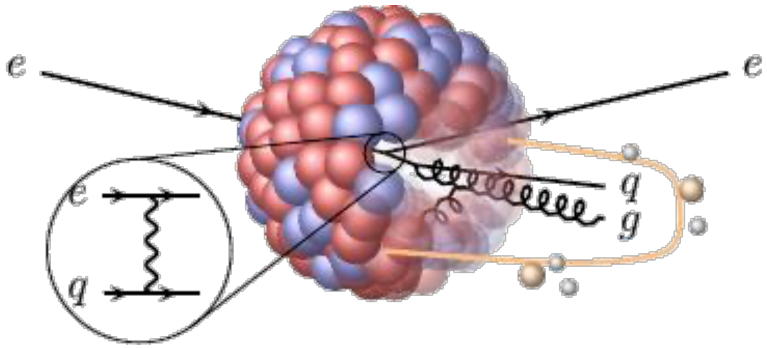


Question: Do hadrons have time to interact with the medium (at all)?

$$\ell \sim \frac{1}{\Lambda_{\mathrm{QCD}}} \sim 1 \text{ fm}$$

Question: Are the hadrons created in an *eA* collision formed inside or outside the nuclei?

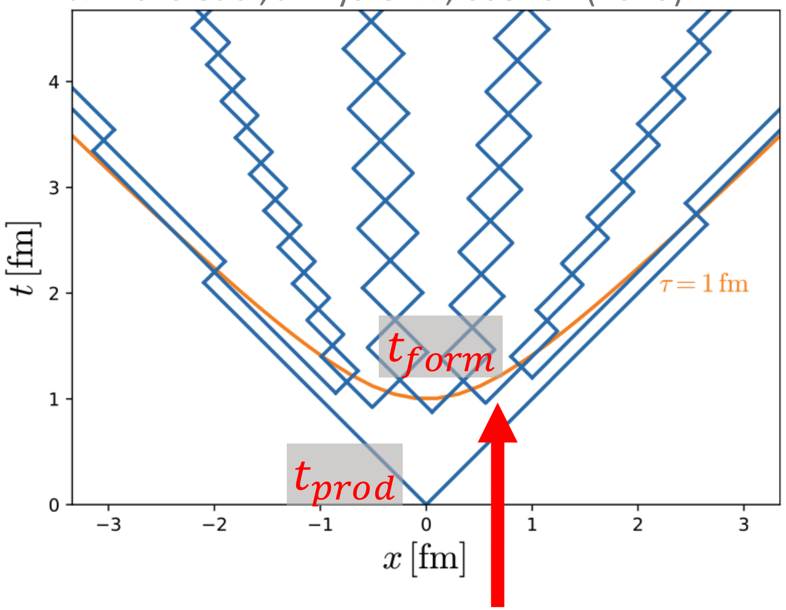
$$r_{\mathrm{A}} \sim A^{1/3} \sim 6 \text{ fm}$$



We do not know the answer to these questions!

Hadronization in practice: formation time

J. Mohs et al, J Phys G **47**, 065101 (2020)



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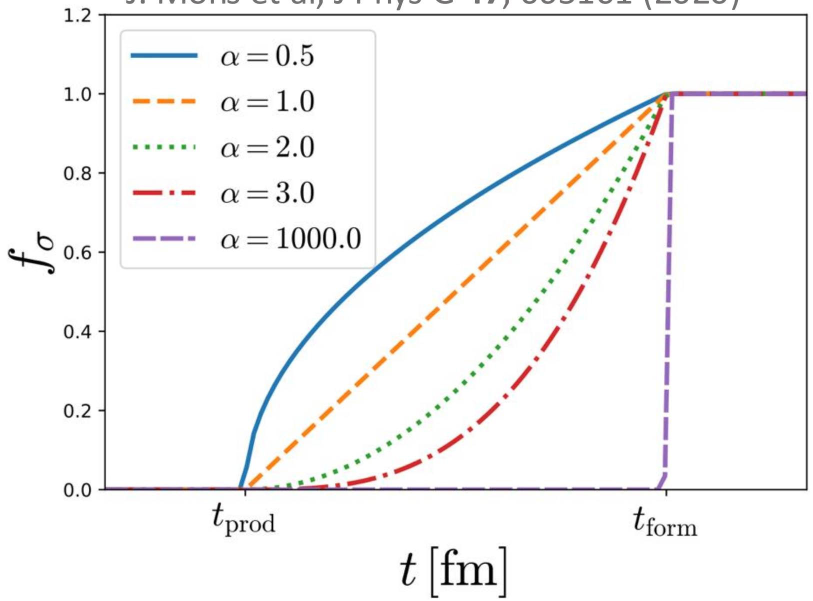

- The time between (initial) pair creation and hadron recombination is the formation time
- Natural laboratory to study in-medium modifications to hadronization

$$f_\sigma \equiv \frac{\sigma(t)}{\sigma(t_{\mathrm{form}})} = \left(\frac{t - t_{\mathrm{prod}}}{t_{\mathrm{form}} - t_{\mathrm{prod}}}\right)^\alpha$$

Pre-hadronic cross-sections can mimic a continuous formation process by increasing over time

- Previous results slightly prefer a linear scaling with free parameter α
- But results are <u>inconclusive</u>
- … and the analysis is <u>too simplistic</u>

K. Gallmeister and U. Mosel, Nucl Phys A **801**, 68 (2008)

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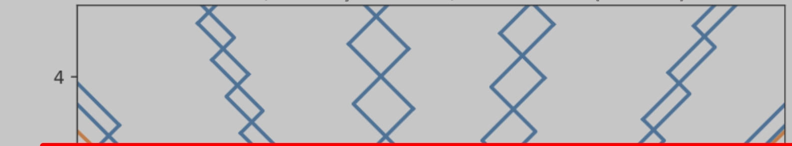

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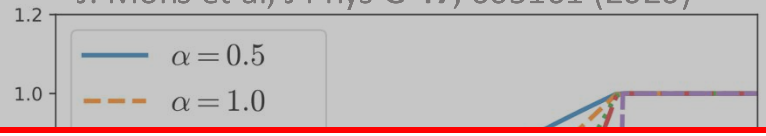

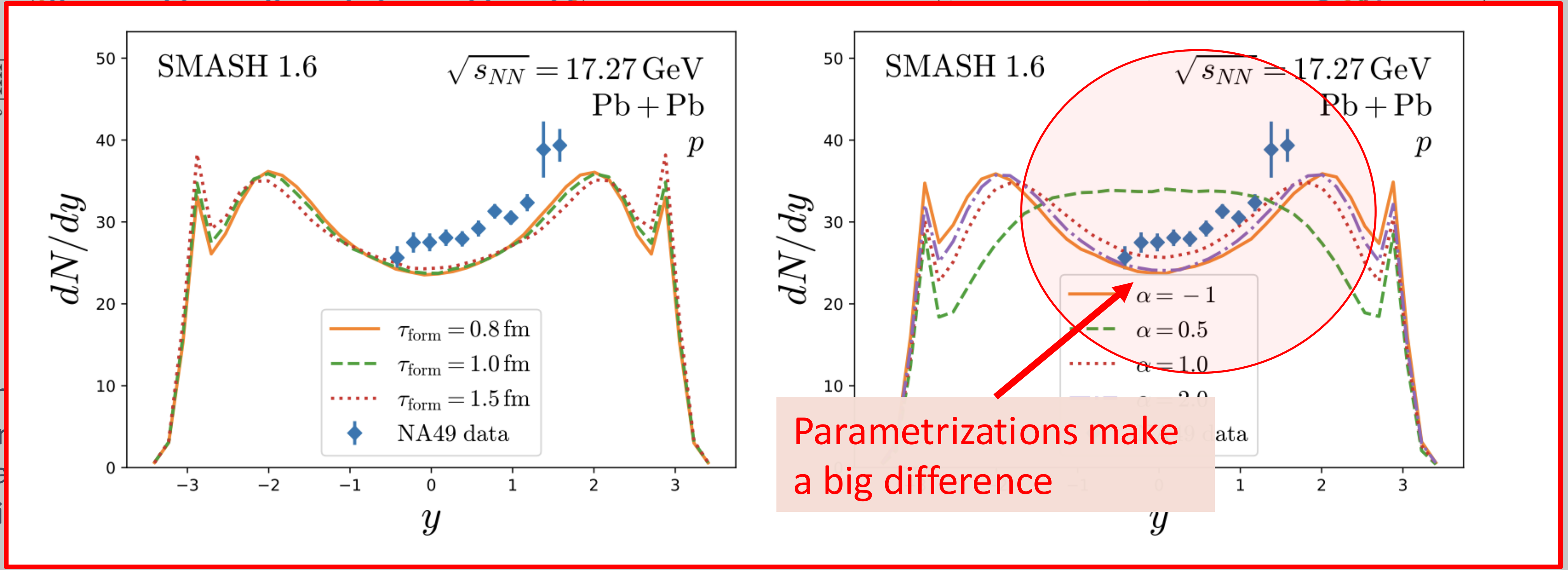

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Hadronization @ EIC: eHIJING+SMASH

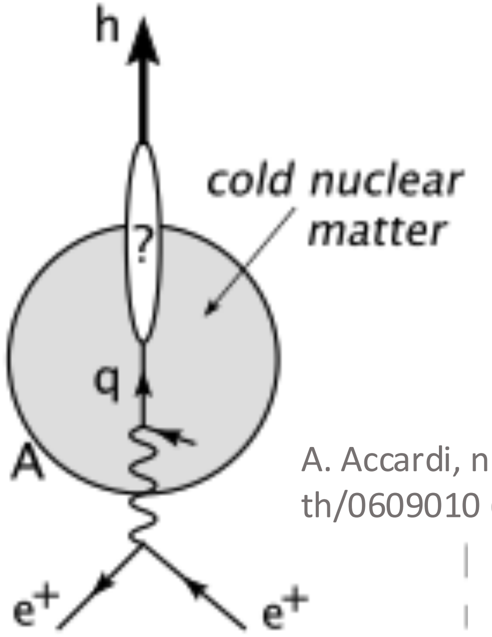
Goal: Study formation time in *eA* collisions

- Need to build an event generator for the SURGE Collaboration
- eHIJING simulates energetic jet partons produced from the initial hard scattering and how they undergo multiple collisions after

W. Ke et al, 2304.10779 (2023)

smash "soft"

HIJING "hard"



A. Accardi, nucl-th/0609010 (2006)

- eHIJING also includes nuclear effects!
- SMASH performs hadronization and hadronic re-scattering

Framework to study hadronization

Loop over cross-section functional forms

Create tabular time-dependent cross-sections → Feed SMASH with cross-section → Run eHIJING+SMASH and calculate observables → Bayesian analysis to determine allowable time-dependencies

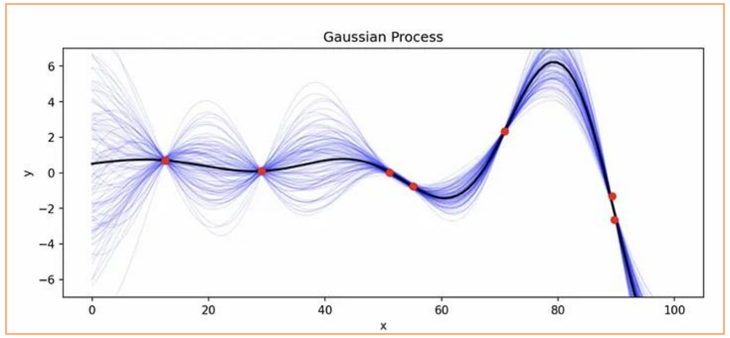
Formation time with Gaussian Processes

Formalism

Goal: Create model-agnostic functional forms for the time-dependent pre-hadronic cross-sections

→ Use Gaussian Processes

A **GP** is a stochastic process (a collection of random variables indexed by time or space), such that every finite collection of those random variables has a multivariate normal distribution



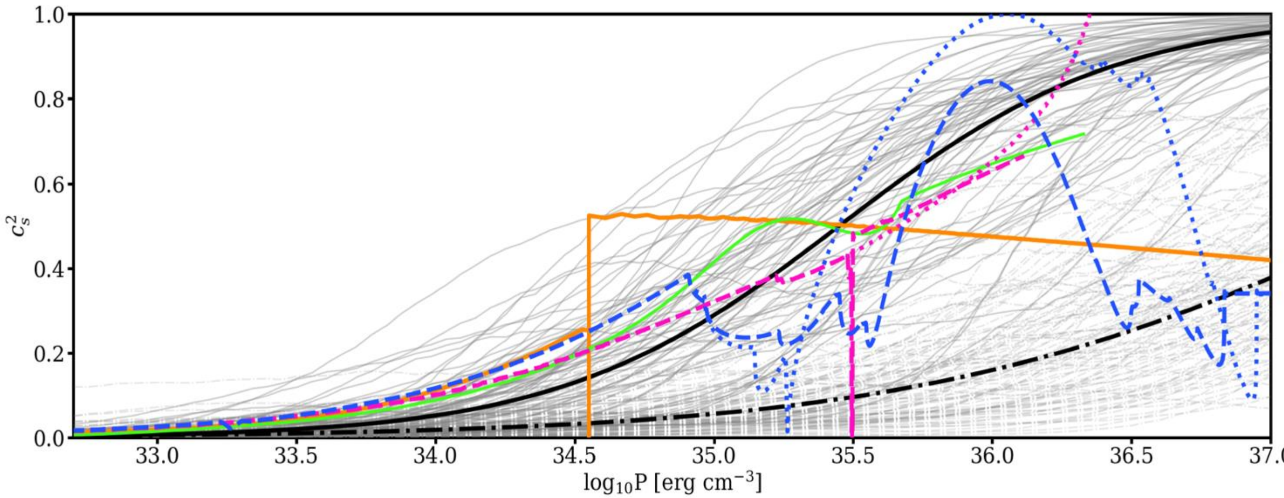
Collection of functions, behavior specified by a mean and covariance kernel

$$\phi \sim \mathcal{N}\left[\mu_i, \Sigma_{ij}\right]$$

- Auxiliary variables ϕ help imposing physical conditions (causality, etc…)
- In applications to neutron stars, e.g.,

$$\phi = \ln(d\varepsilon/dp - 1) = \ln(1/c_s^2 - 1)$$

D. Mroczek et al, 2309.02345 (2023)

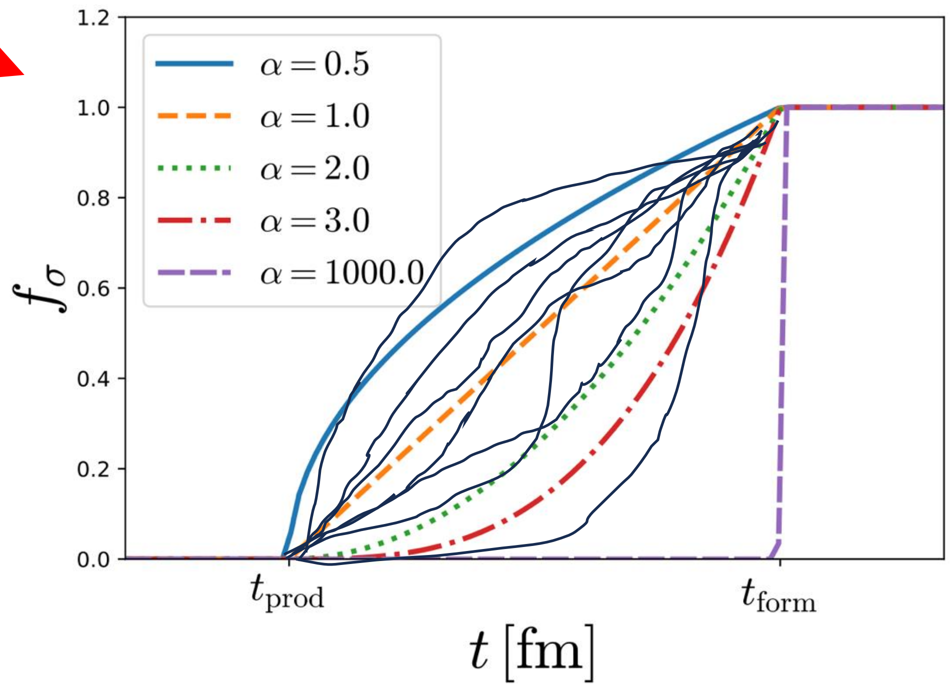


- Making these two equal allows us to find multiple $c_s^2(p)$ functional forms
- We seek to replicate this process for f_σ

Formation time with Gaussian Processes

Application to pre-hadronic cross-sections

Goal: Create model-agnostic functional forms for the time-dependent pre-hadronic cross-sections



$$f_\sigma(t) \equiv \frac{\sigma(t)}{\sigma(t_{\mathrm{prod}})}$$ "scaling factor"

$$\boxed{f_\sigma(t) = f_{\sigma,0} + \frac{df_\sigma}{dt}}$$

Constraints:

$$\frac{df_\sigma}{dt} > 0 \quad f_\sigma(t) \geq 0$$

$$f_\sigma(t_{\mathrm{form}}) = 1$$

$$\phi = \ln(d\varepsilon/dp - 1) = \ln(1/c_s^2 - 1)$$

Variable mapping

$$\frac{dp}{d\varepsilon} \to \frac{df_\sigma}{dt} \qquad \phi \to \ln\left(\frac{\mathcal{A}}{\frac{df_\sigma}{dt}} - 1\right)$$

This mapping provides the desired properties:

$$\frac{df_\sigma}{dt} > 0 \implies f_\sigma(t) \geq 0$$

We can obtain multiple functional forms that satisfy the physical constraints for the scaling factor using Gaussian Processes

Formation time with Gaussian Processes

Application to pre-hadronic cross-sections

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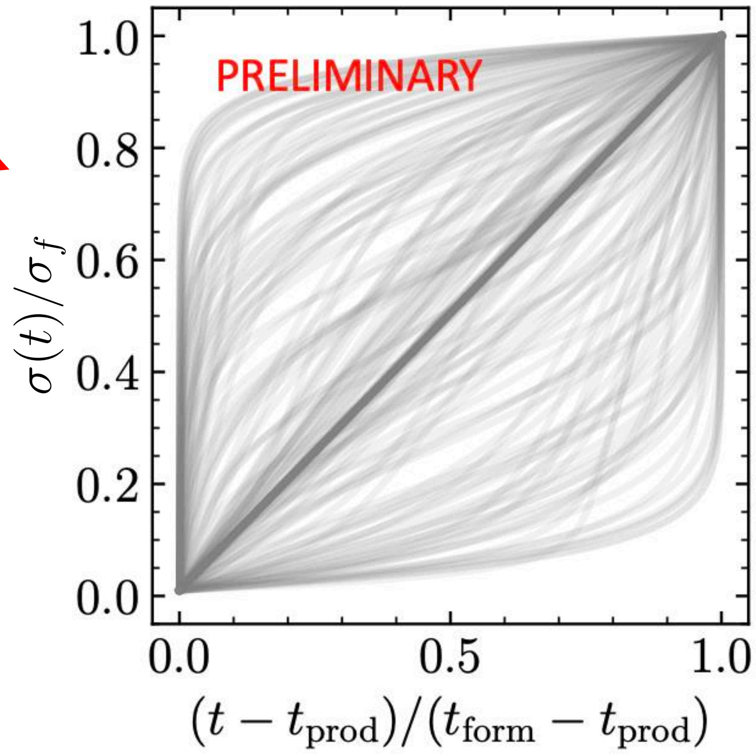
J. Salinas San Martin *et al.*, In Progress



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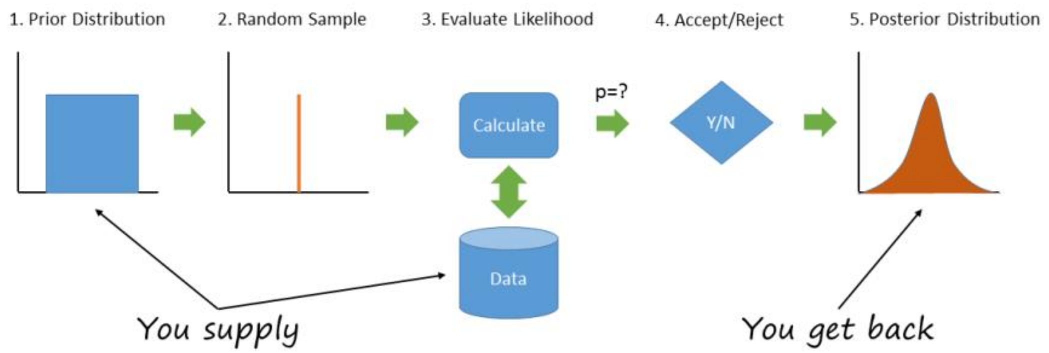
Formation time with Gaussian Processes

Bayesian analysis

Goal: Determine a scaling factor distribution that is favored by experimental data

→ We gain insight on pre-hadronic interactions

We will use Bayesian parameter estimation analysis



Prior := Prior information about model parameters,

i.e., parameters that characterize the covariance matrix

Posterior := Credibility interval of f_σ

Likelihood := How well predictions from f_σ match observed properties

Set of parameters that define a sampled f_σ

$$\underbrace{P_{f_\sigma}(\phi_k)}_{\text{Posterior}} \propto \underbrace{q(\phi_k)}_{\text{Prior}}\underbrace{\mathcal{L}(\phi_k)}_{\text{Likelihood}}$$

D. Mroczek et al, 2309.02345 (2023)

Conclusions

- We want to study QCD color confinement
- Need to understand the hadronic phase: statistical (HRG) and dynamical pictures (SMASH)
- Focus on hadronization in an *eA* collision (does it happen in or out the medium?)

- The eHIJING+SMASH framework can be used to generate *eA* events
- Formation time dictates **how pre-formed hadrons interact** between $q\bar{q}$ splitting and hadron formation
- Current knowledge on formation time dependence is scarce
- Will use **Gaussian Processes** to test various functional forms of the cross-section scaling factor
- Will use Bayesian parameter estimation analysis to determine a credible interval for f_σ as a function of time

eHIJING + SMASH will be the event generator for the SURGE Collaboration

Back-up

$$R_M^h(\nu, Q^2, z_h, p_T^2, \ldots) = \frac{[N_h(\nu, Q^2, z_h, p_T^2, \ldots)/N_e(\nu, Q^2)]_A}{[N_h(\nu, Q^2, z_h, p_T^2, \ldots)/N_e(\nu, Q^2)]_D}$$

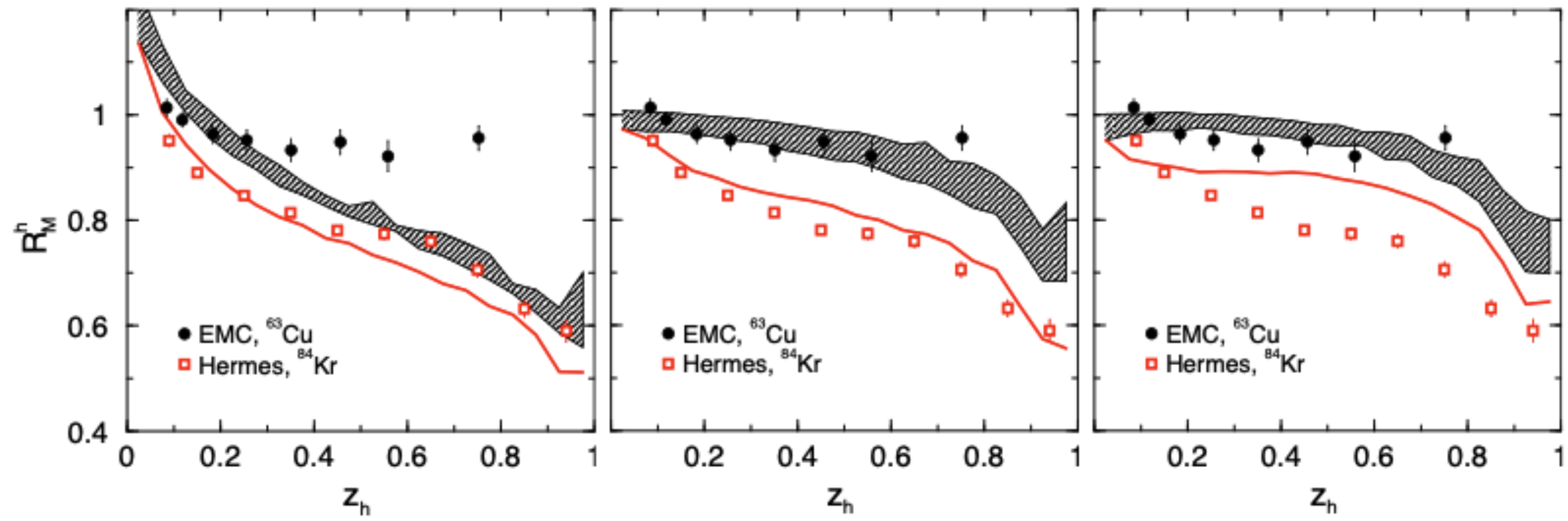
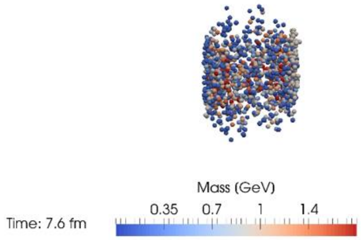


Fig. 1. *Nuclear modification factor for charged hadrons. Experimental data are for HERMES@27*GeV *(16) and EMC@100/280*GeV *(17). The predictions for the two EMC energies are given by the lower and upper bounds of the shaded band. The cross section-evolution-scenarios in the calculations are: constant, linear, quadratic (from left to right).*

SMASH Hadron Transport

A dynamical picture of hadrons



- We want to describe how hadron d.o.f. propagate, collide, and decay
- Monte-Carlo solutions of Boltzmann equations

J. Weil et al, PRC **94**, 054905 (2016)

$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial^p_\alpha f_i(x,p) = C^i_{\mathrm{coll}}$$

$f_i(x,p) :=$ single particle distribution for species i

$C^i_{\mathrm{coll}} :=$ collision term

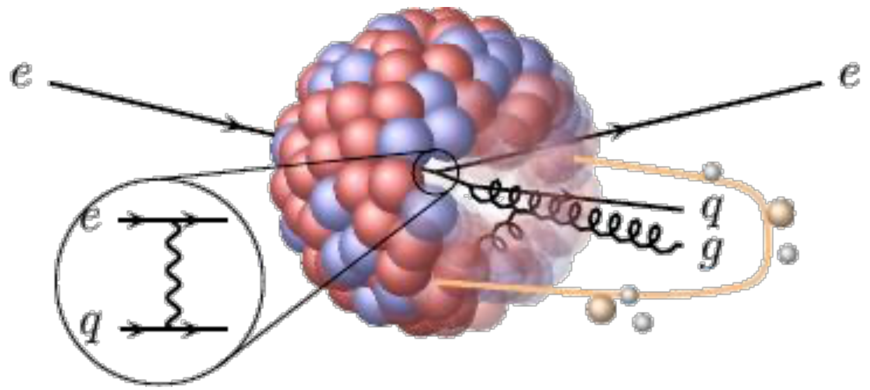
$F^\alpha :=$ force experienced by individual particles

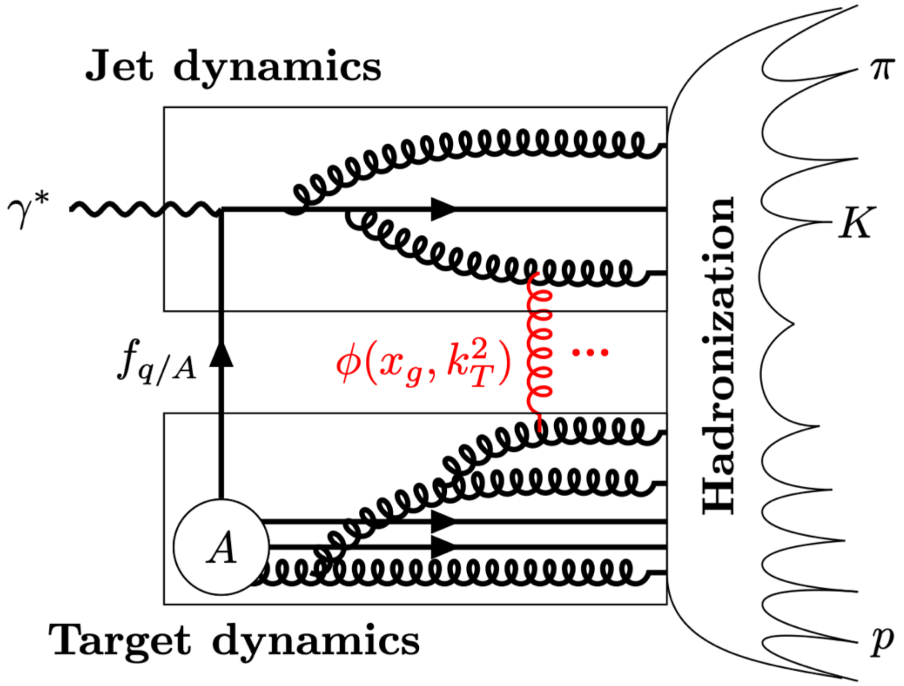
- Applicable at <u>low densities</u>: mean free path $\gg \lambda_{Compton}$
- Normally used standalone @ low energies and as afterburner @ higher energies in HICs
- SMASH is the **state-of-the-art hadron transport approach**

SMASH has two main limitations:

1. Default SMASH only includes ~ 400 hadrons → needs a better input (PDG2021+ ~ 800 hadrons)
2. Limited to 1 → 2 decays (in reality, particles can decay to 3 and 4 other hadrons)

Simulations @ EIC: Event Generator





- eHIJING (electron-Heavy-Ion-Jet-Interaction-Generator) simulates energetic jet partons produced from the initial hard scattering and how they undergo multiple collisions after
- The collision rate is proportional to the transverse-momentum-dependent (TMD) gluon density in the nuclei (i.e., considers **gluon density**)
- **Lund string model** is used for hadronization

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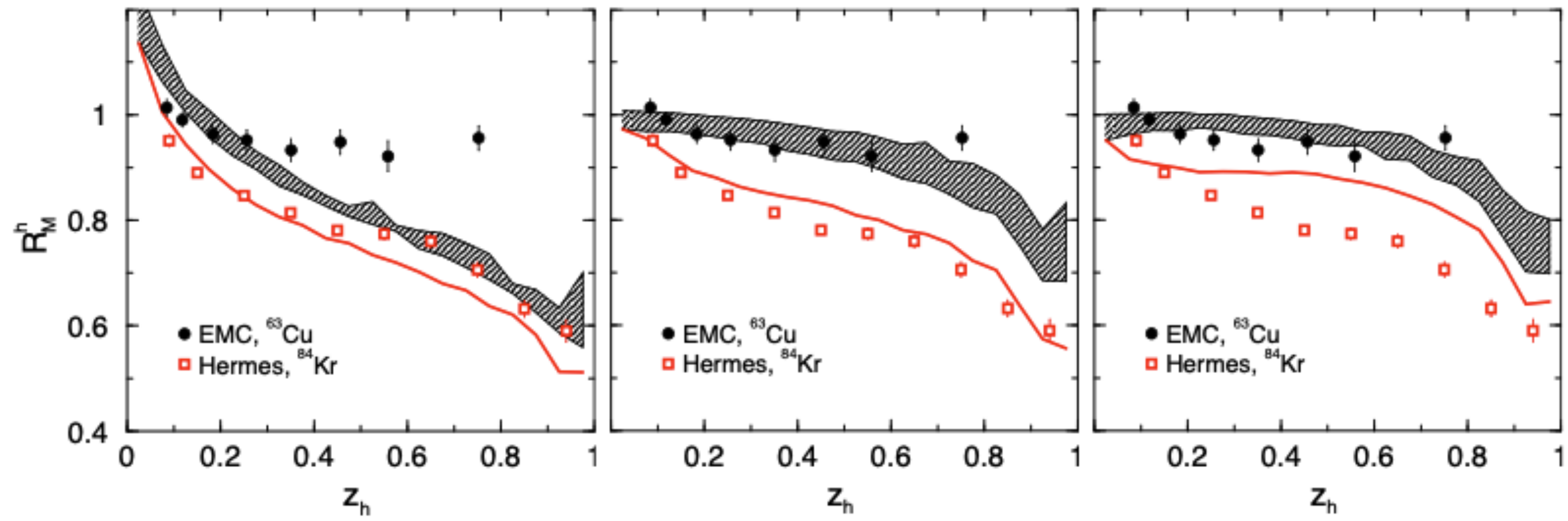
$$R_M^h(\nu, Q^2, z_h, p_T^2, \ldots) = \frac{[N_h(\nu, Q^2, z_h, p_T^2, \ldots)/N_e(\nu, Q^2)]_A}{[N_h(\nu, Q^2, z_h, p_T^2, \ldots)/N_e(\nu, Q^2)]_D}$$



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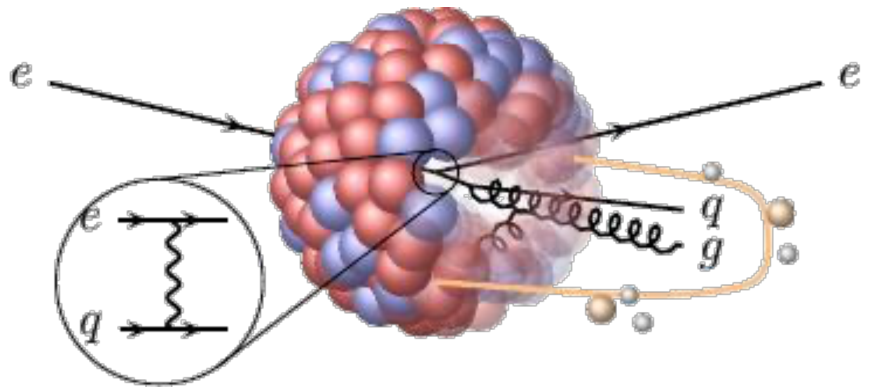

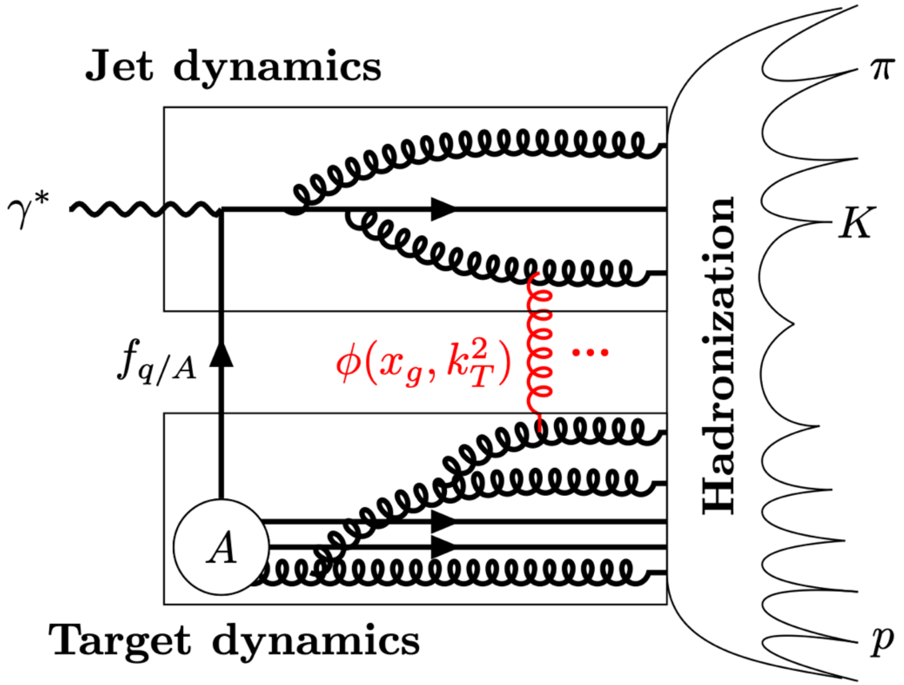

HIJING

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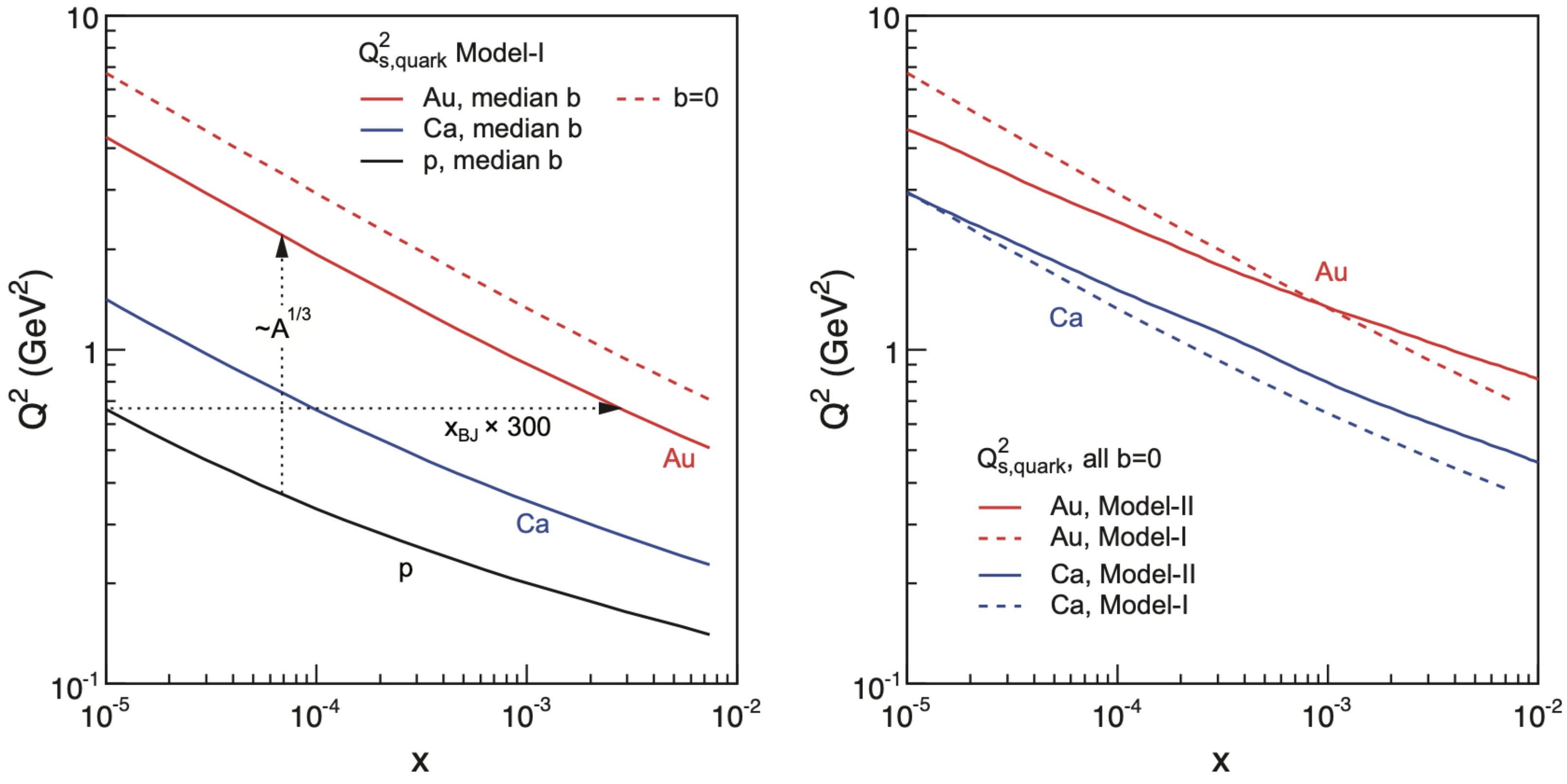


Theoretical expectations for the saturation scale as a function of Bjorken x for the proton along with Ca and Au nuclei

Back-up

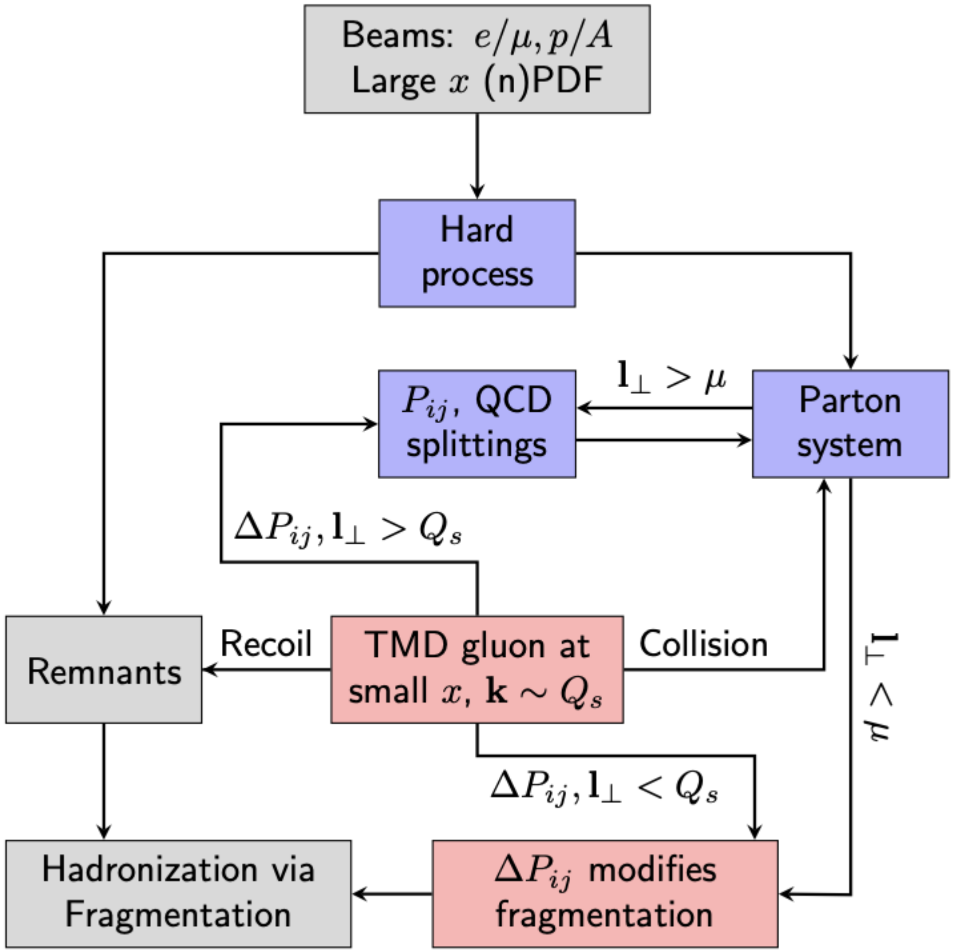
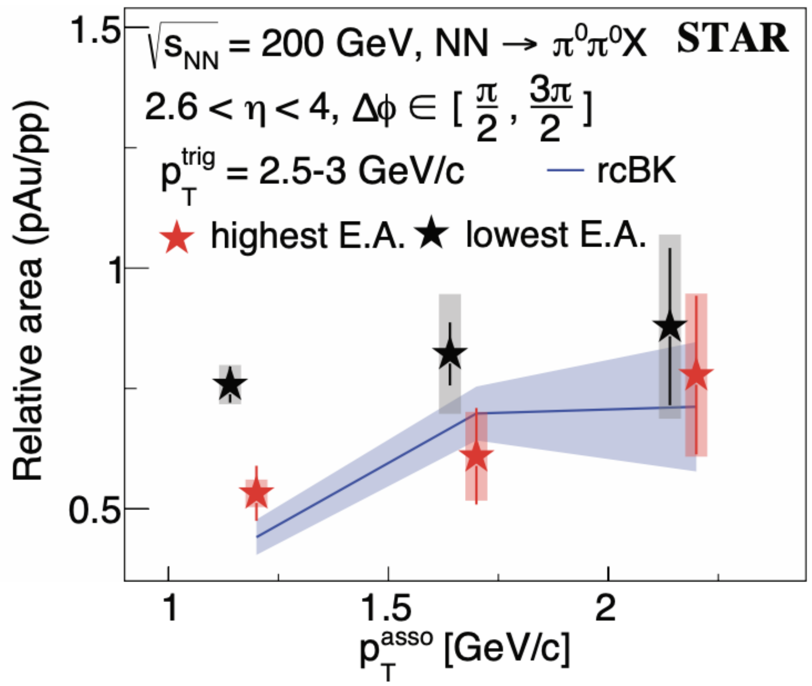
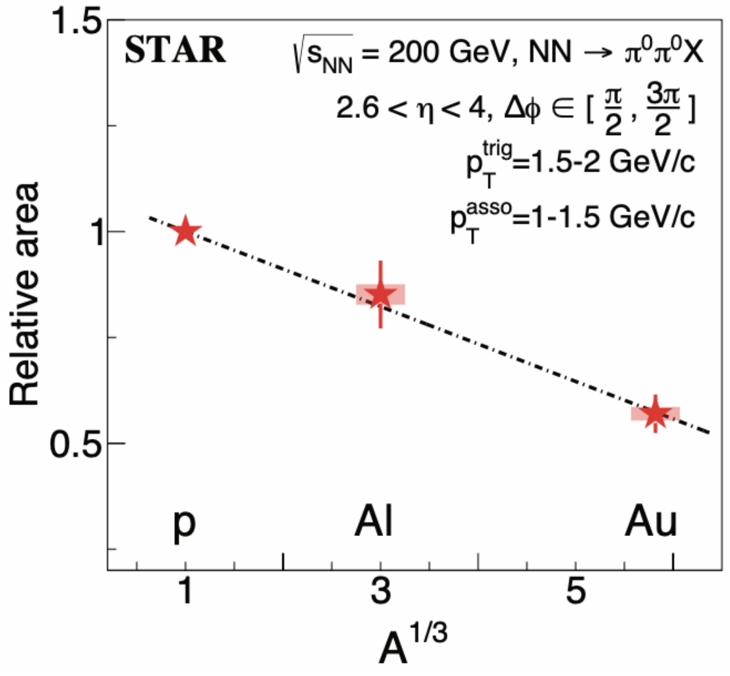


FIG. 2. Flow chart of eHIJING Monte Carlo model. Block colored in red are the key ingredients for including dynamica nuclear effects.

Back-up



$\sqrt{s_{NN}}$ = 200 GeV, NN → $\pi^0\pi^0$X
STAR
$2.6 < \eta < 4$, $\Delta\phi \in [\frac{\pi}{2}, \frac{3\pi}{2}]$
p_T^{trig} = 2.5-3 GeV/c
rcBK
highest E.A.
lowest E.A.
Relative area (pAu/pp)
p_T^{asso} [GeV/c]
1.5
1
0.5
1
1.5
2



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Relative area
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Al
Au
$A^{1/3}$
1.5
1
0.5
1
3
5