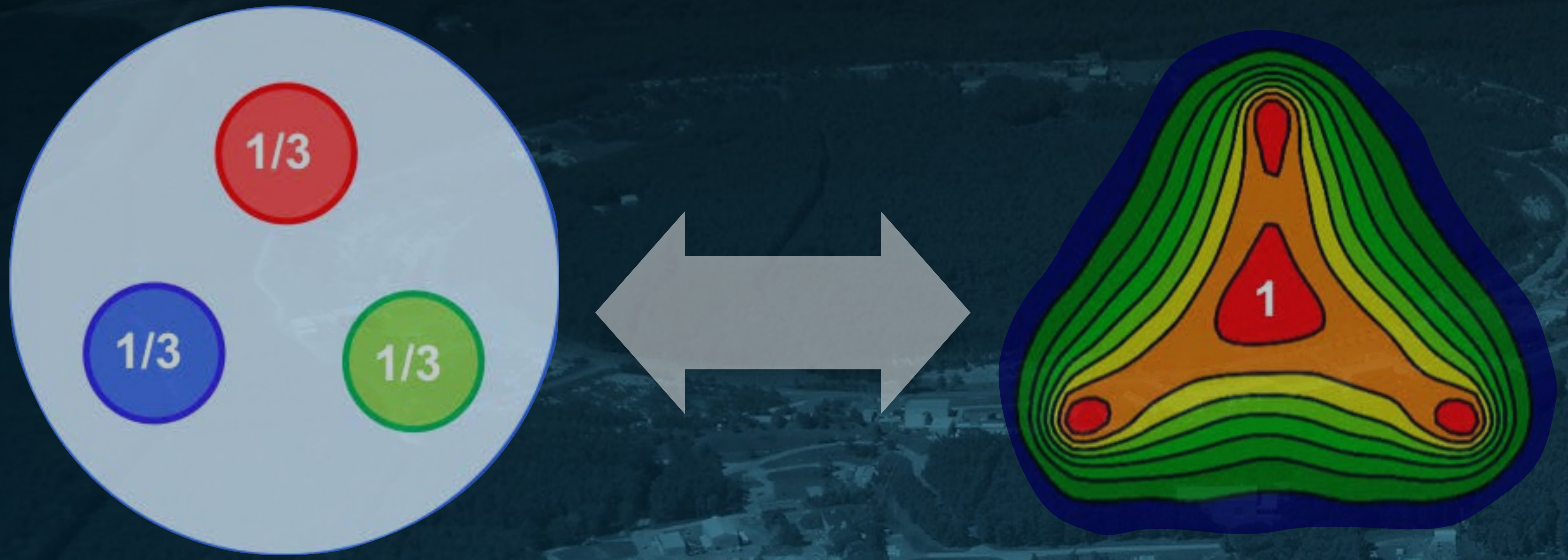


RHIC topics informative towards EIC science

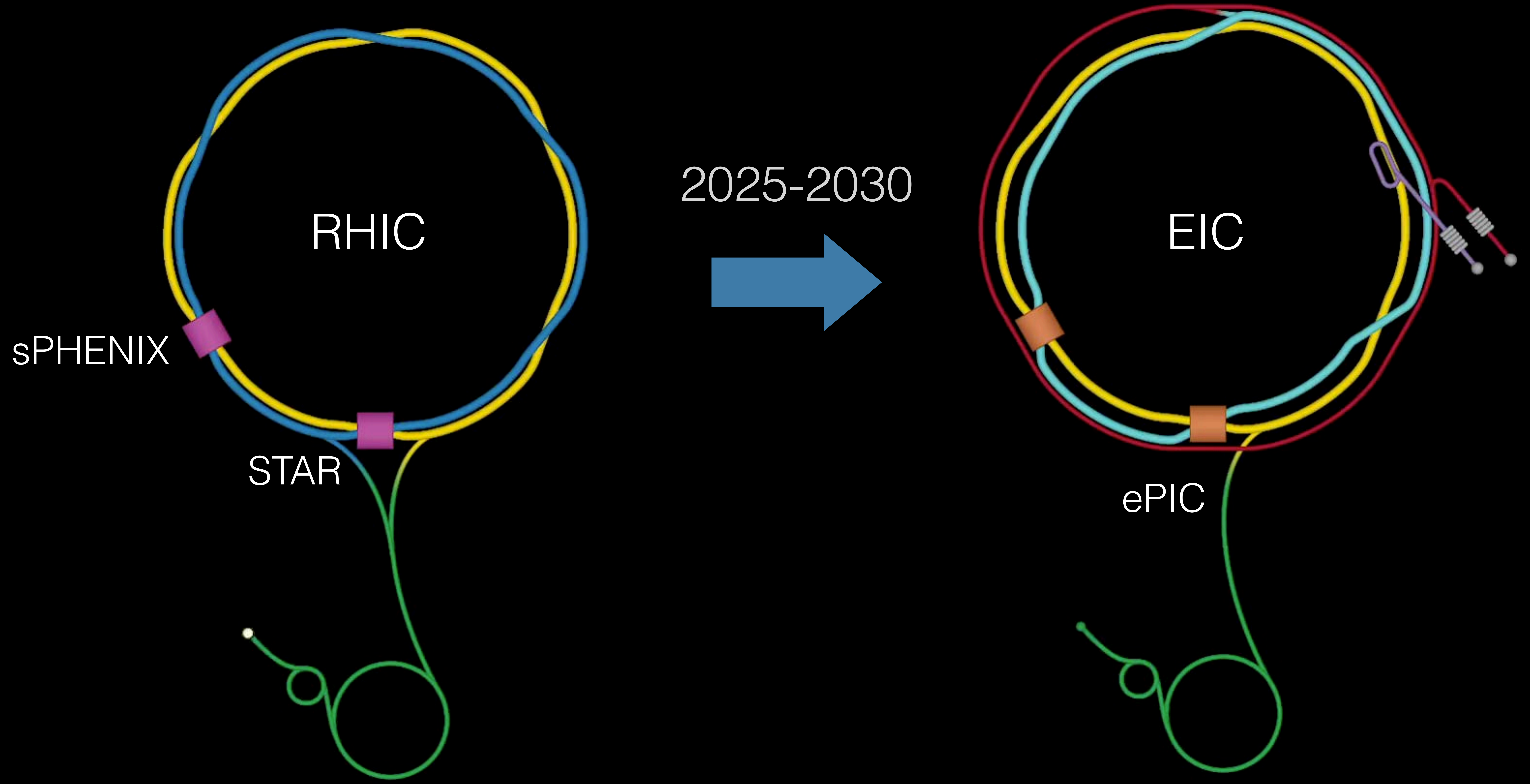
Prithwish Tribedy

Brookhaven National Laboratory

DAE-BRNS symposium on
Contemporary and Emerging Topics in High Energy Nuclear Physics

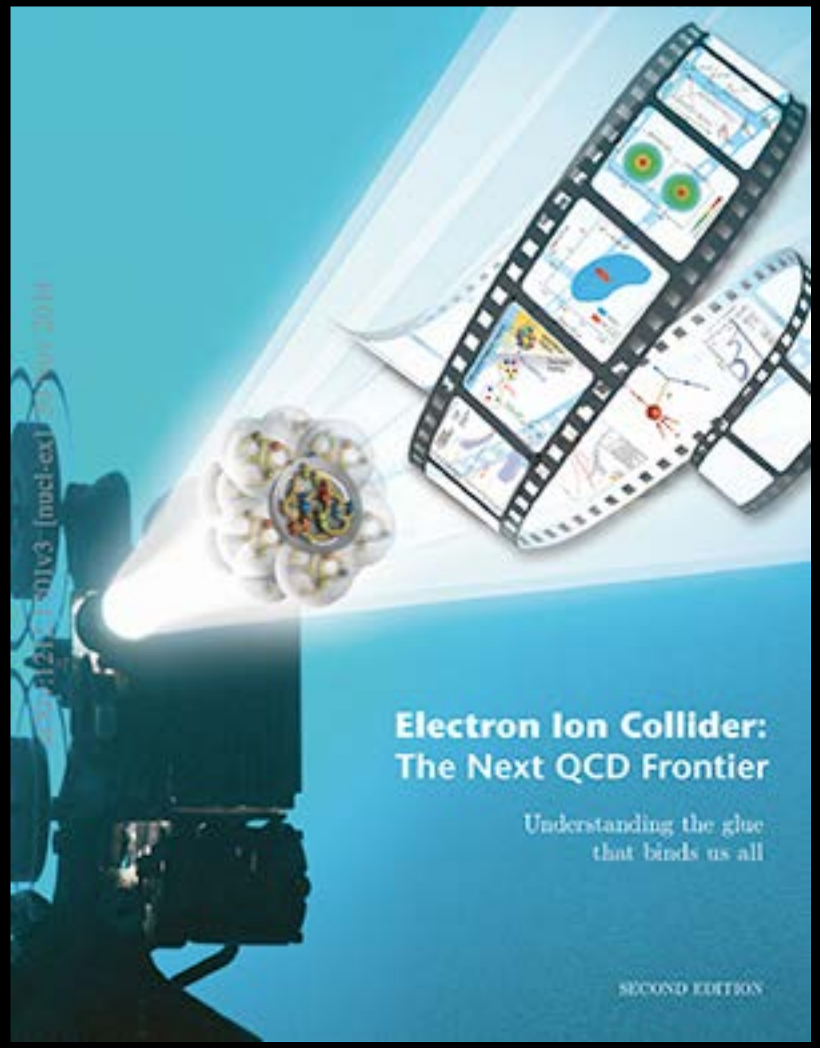
15-17 November 2022, Variable Energy Cyclotron Centre, Kolkata, India

RHIC making transition to Electron Ion Collider

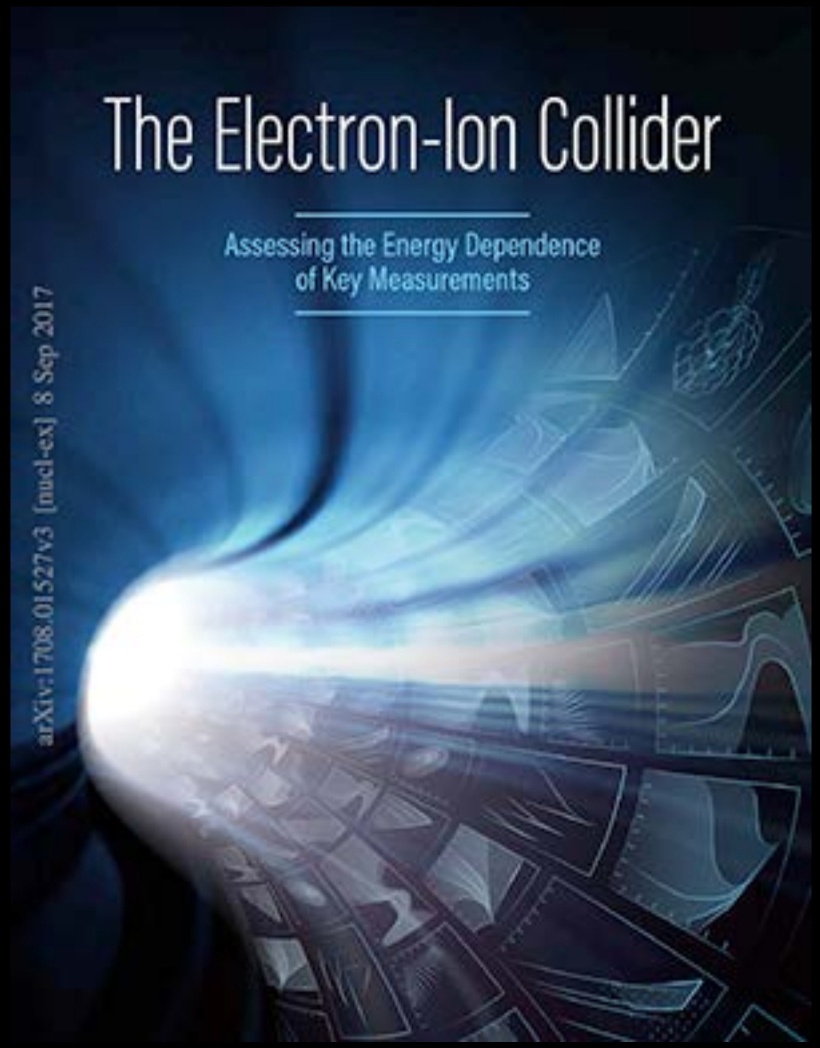


EIC science case

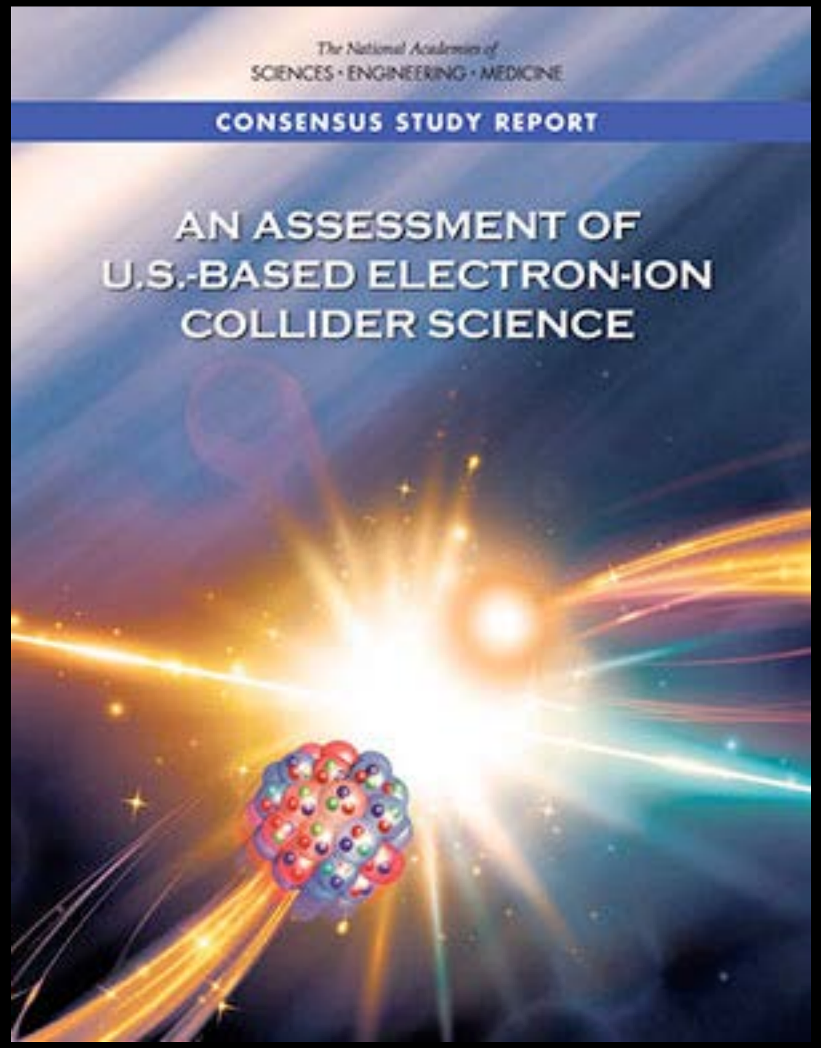
https://www.bnl.gov/eic/science.php



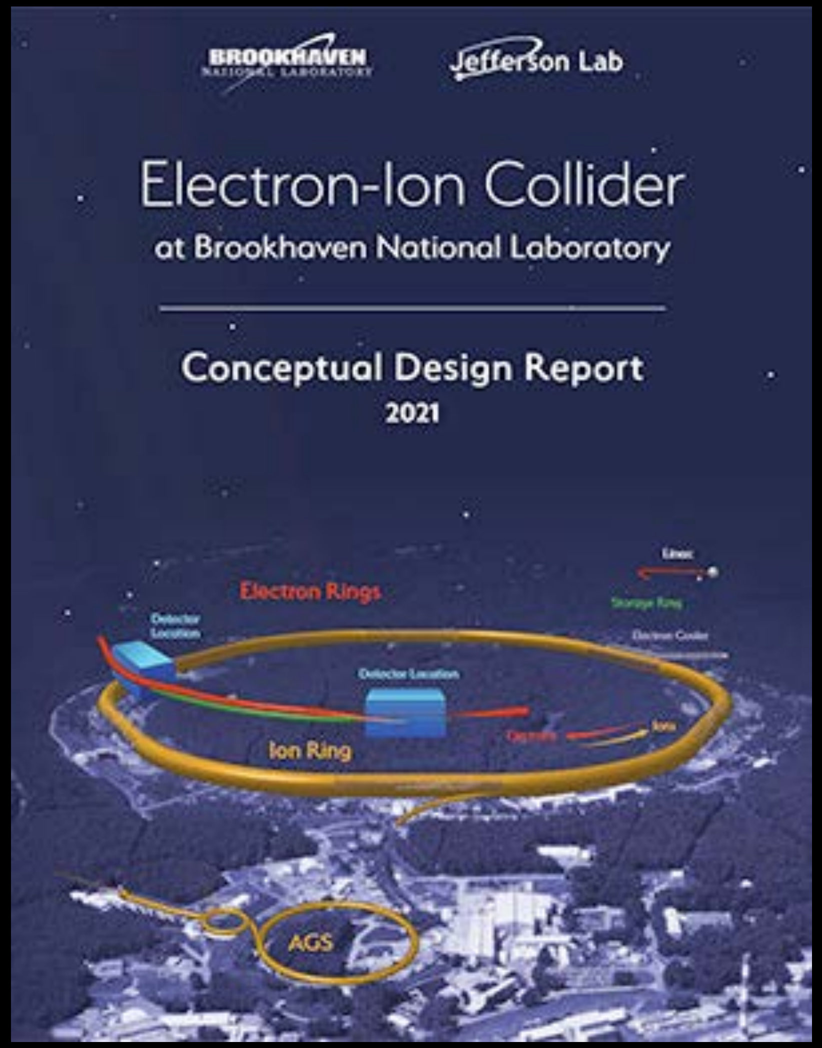
http://arxiv.org/pdf/1212.1701v3.pdf



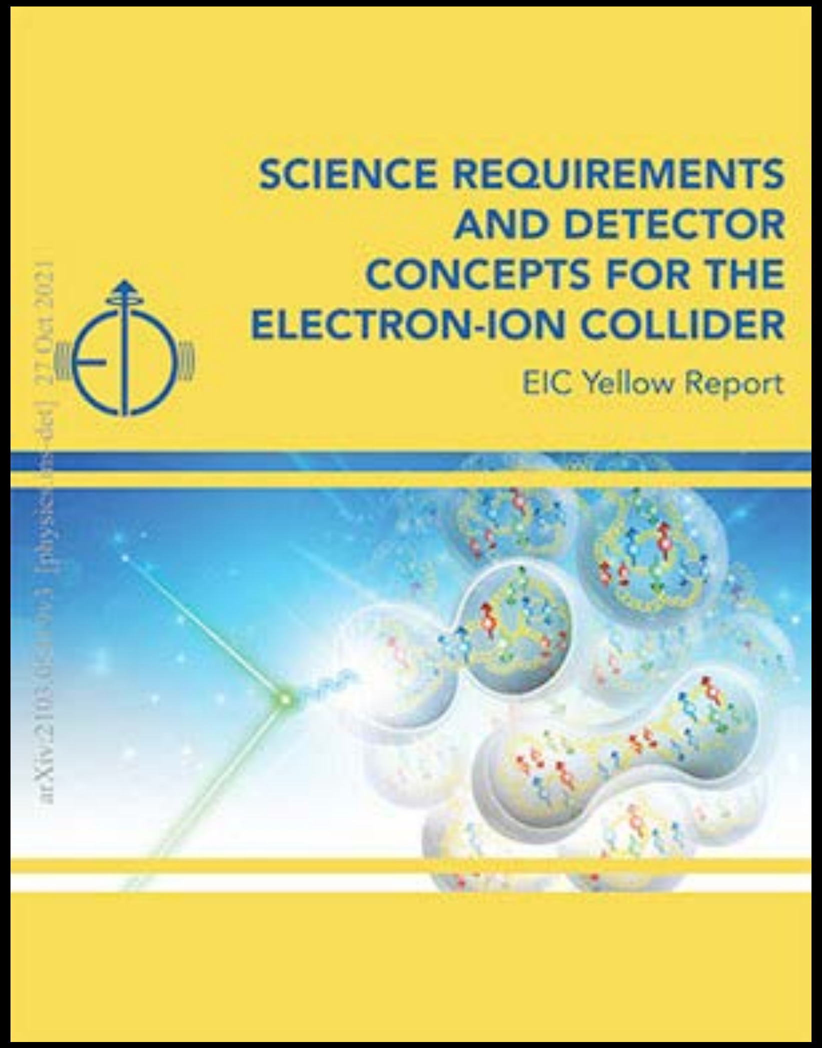
https://arxiv.org/pdf/1708.01527.pdf



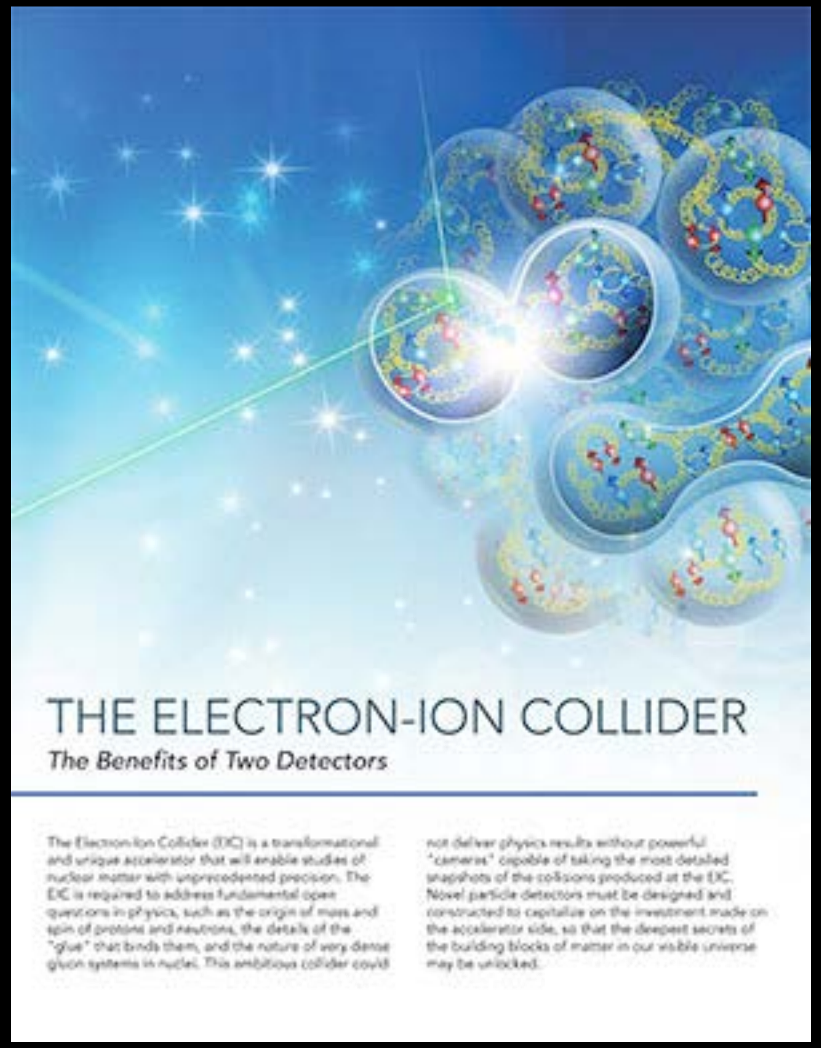
https://www.nap.edu/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science



https://www.bnl.gov/ec/files/eic_cdr_final.pdf



https://arxiv.org/pdf/2103.05419.pdf

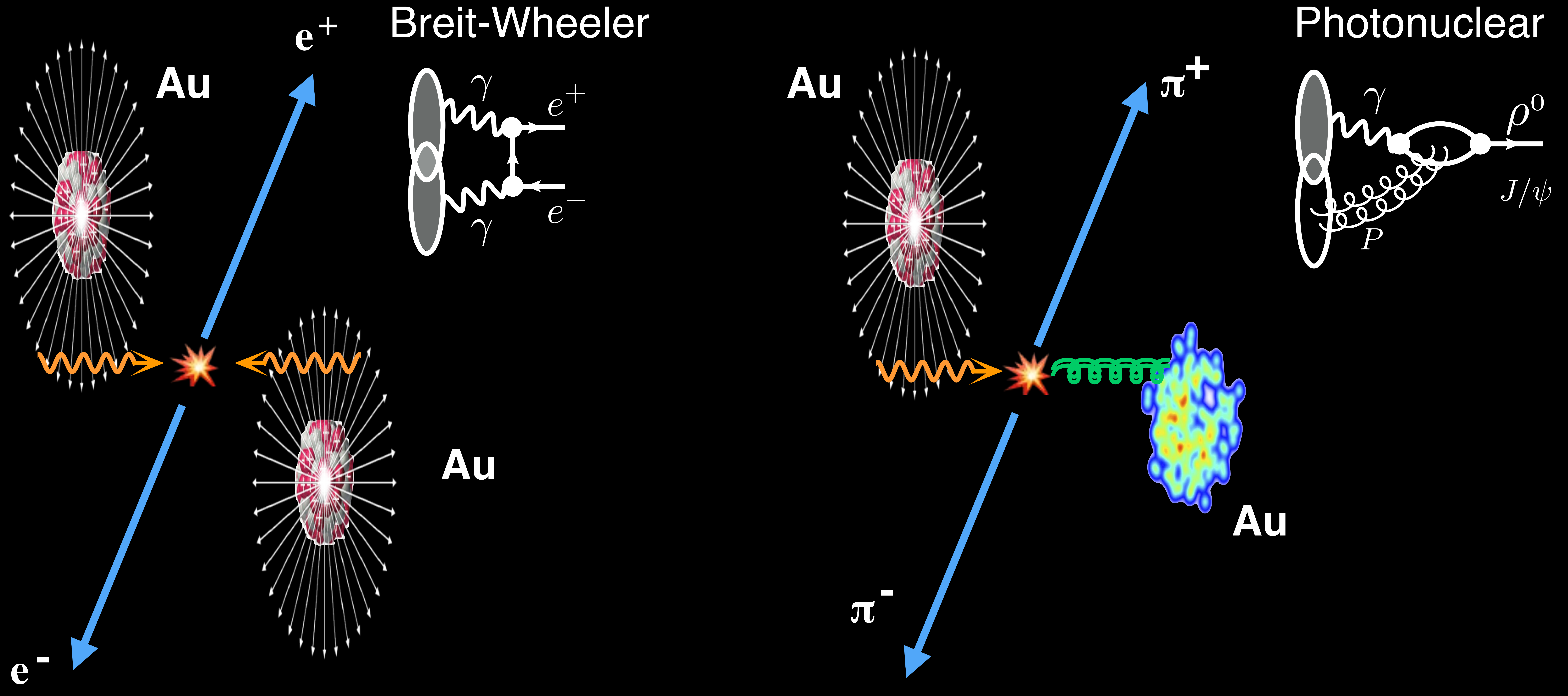


https://indico.bnl.gov/event/15297/contributions/61818/attachments/40377/67413/EIC-brochure2021_D11.pdf

- Precision 3D imaging of protons and nuclei
- Solving the proton spin puzzle
- Search for gluon saturation
- Insights on Quark and gluon confinement
- Nuclear modification of quark & gluon distribution

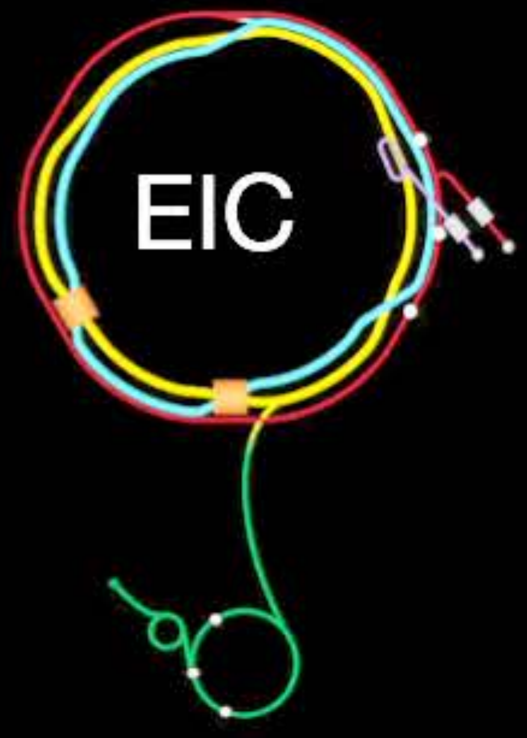
Photon-induced processes before EIC era

Talk by Ashik Ikbal

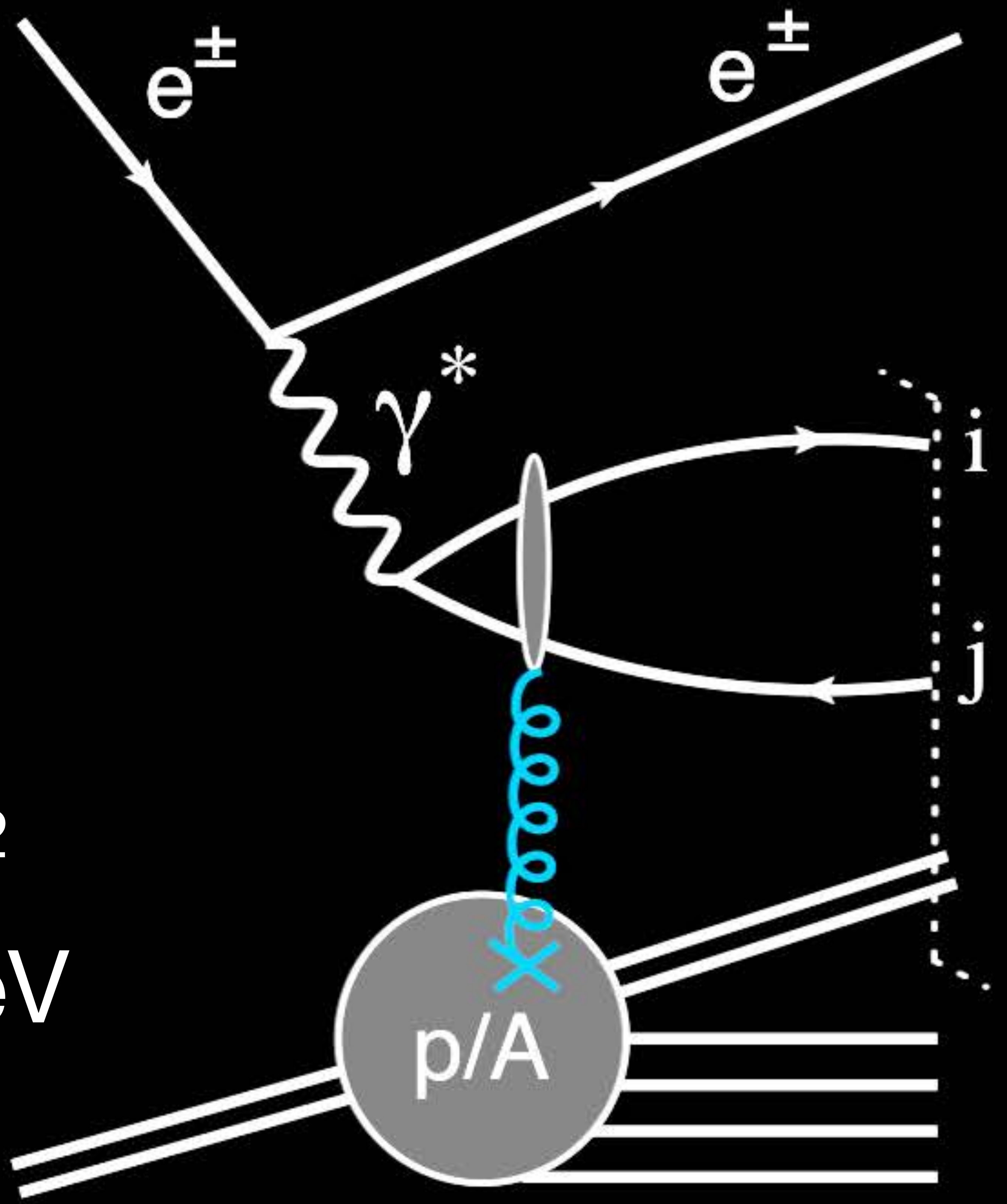


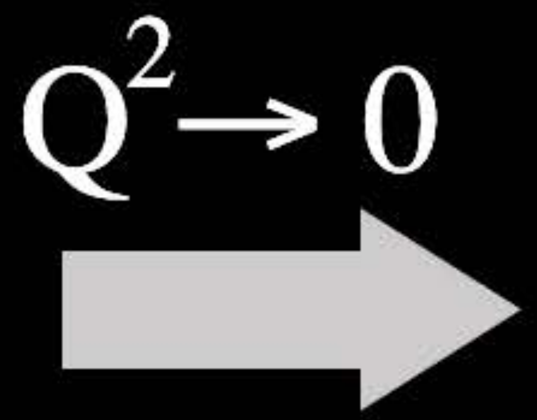
Ultra-peripheral heavy ion collisions can be used to trigger γ-γ or γ+Au collisions

Photon induced processes at EIC vs. RHIC

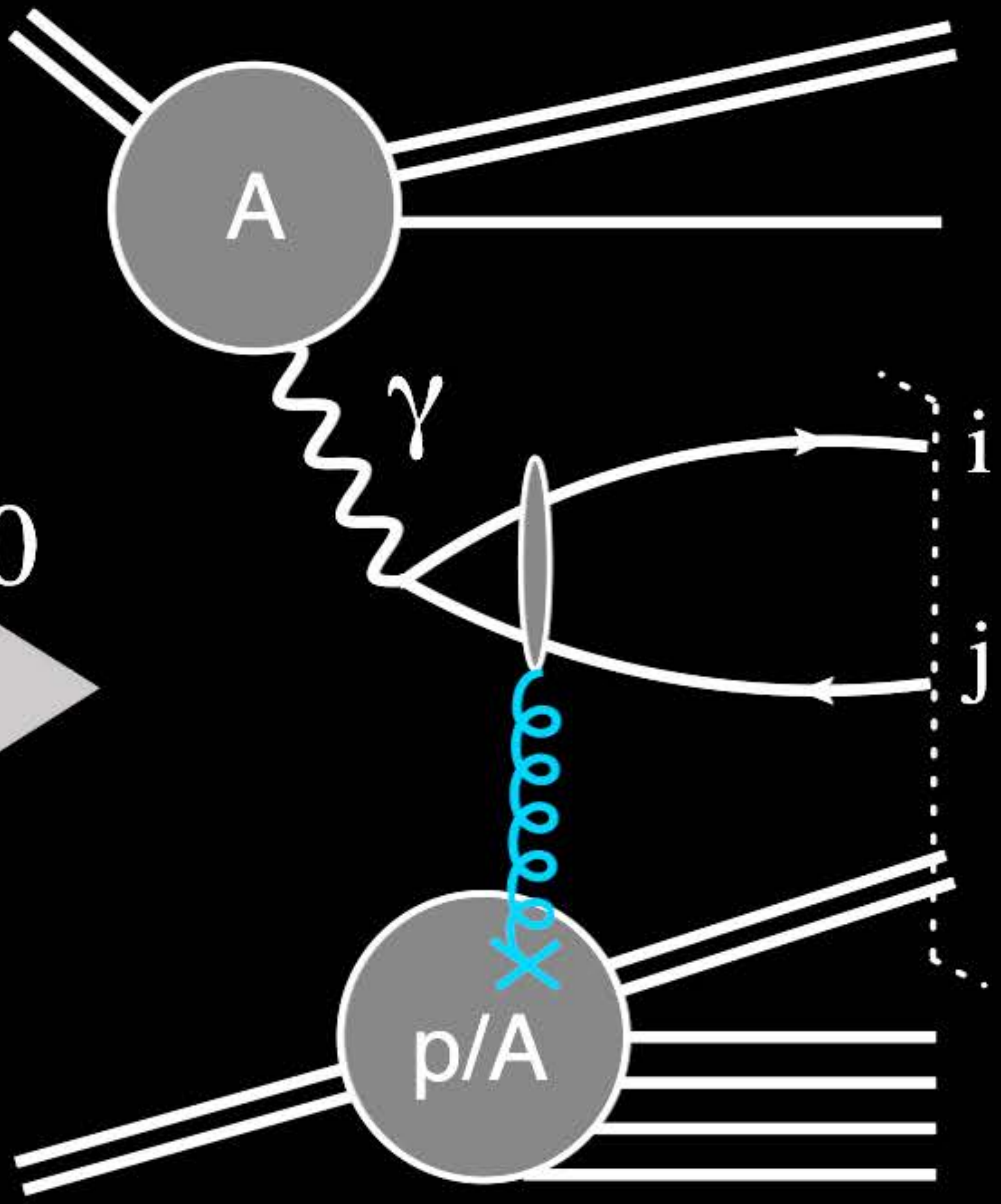


Deep Inelastic Scattering





Ultra-peripheral Collisions



Typical kinematics:

$Q^2 = 10\ \mathrm{GeV}^2$

$W_{\gamma N} = 100\ \mathrm{GeV}$

$x = 10^{-4}$

Approximate kinematics:

$Q^2 \sim 0.001\ \mathrm{GeV}^2$

$W_{\gamma N} \sim 10\text{-}40\ \mathrm{GeV}$

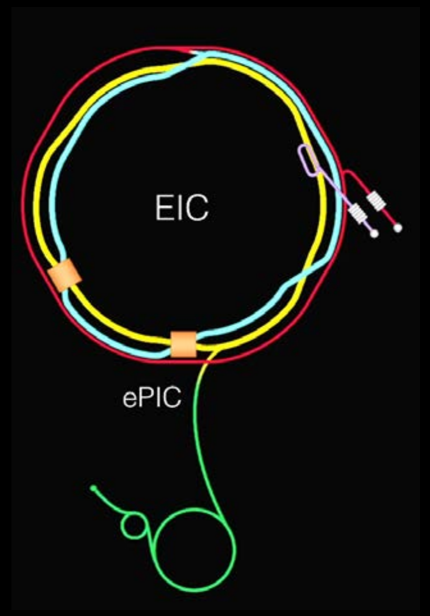
$x \sim 10^{-3} - 10^{-2}$

Ultra-peripheral p/A+A collisions provide opportunities to study photoproduction

Hot QCD topics that bridge RHIC and EIC science

- Microscopic structure of the baryons ✓
- Collectivity in small system ✓
- Imaging nuclei in the pre-EIC era
- Forward hadron production

Imaging a proton at the EIC

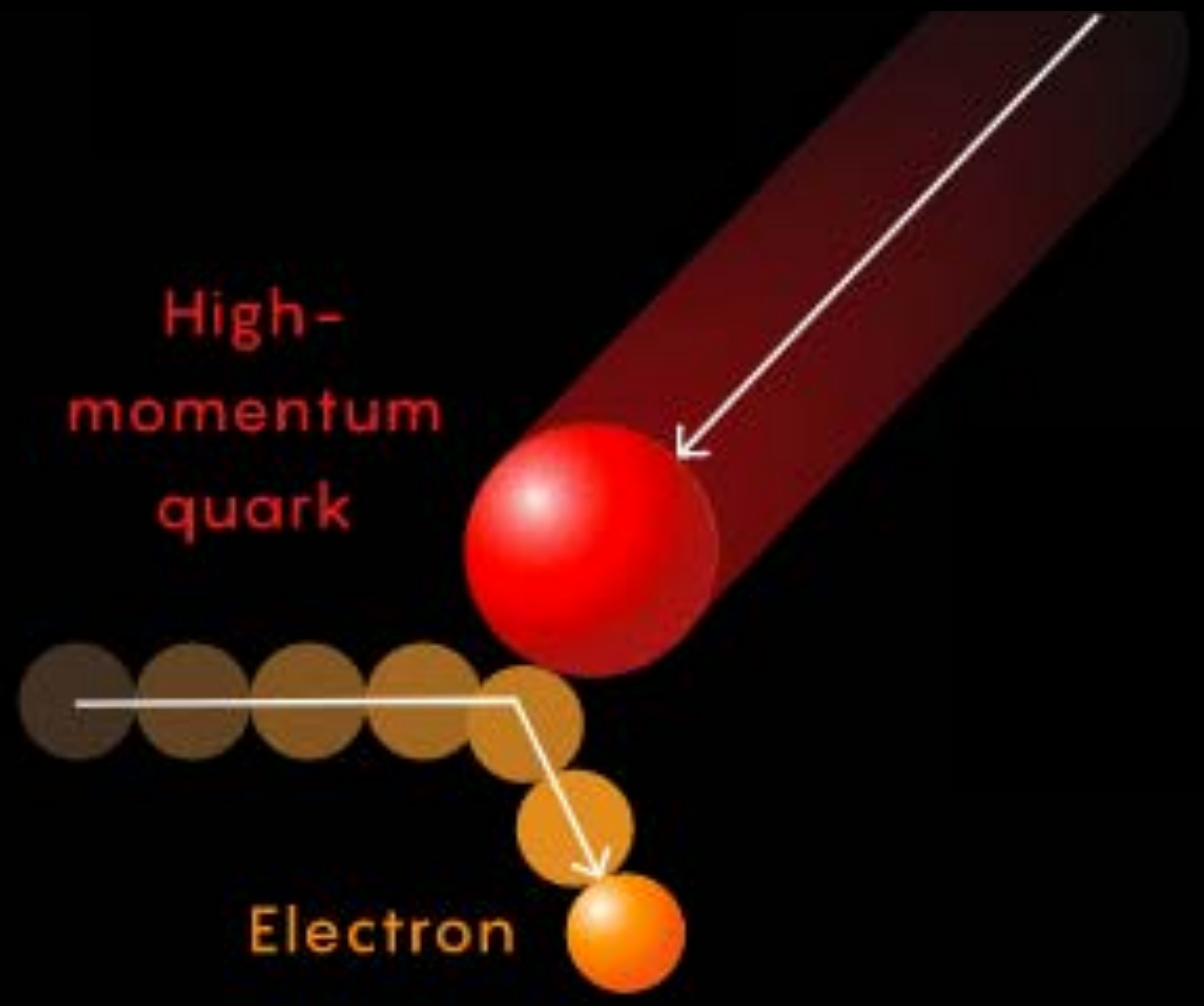


Deep Inelastic Scattering terminology

High Virtuality Q^2, Large Bjorken x

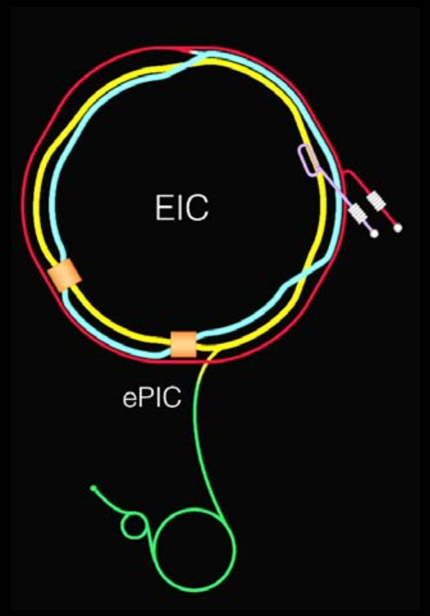
Camera terminology

High Pixel, Low shutter speed



https://www.quantamagazine.org/inside-the-proton-the-most-complicated-thing-imaginable-20221019/

Imaging a proton at the EIC

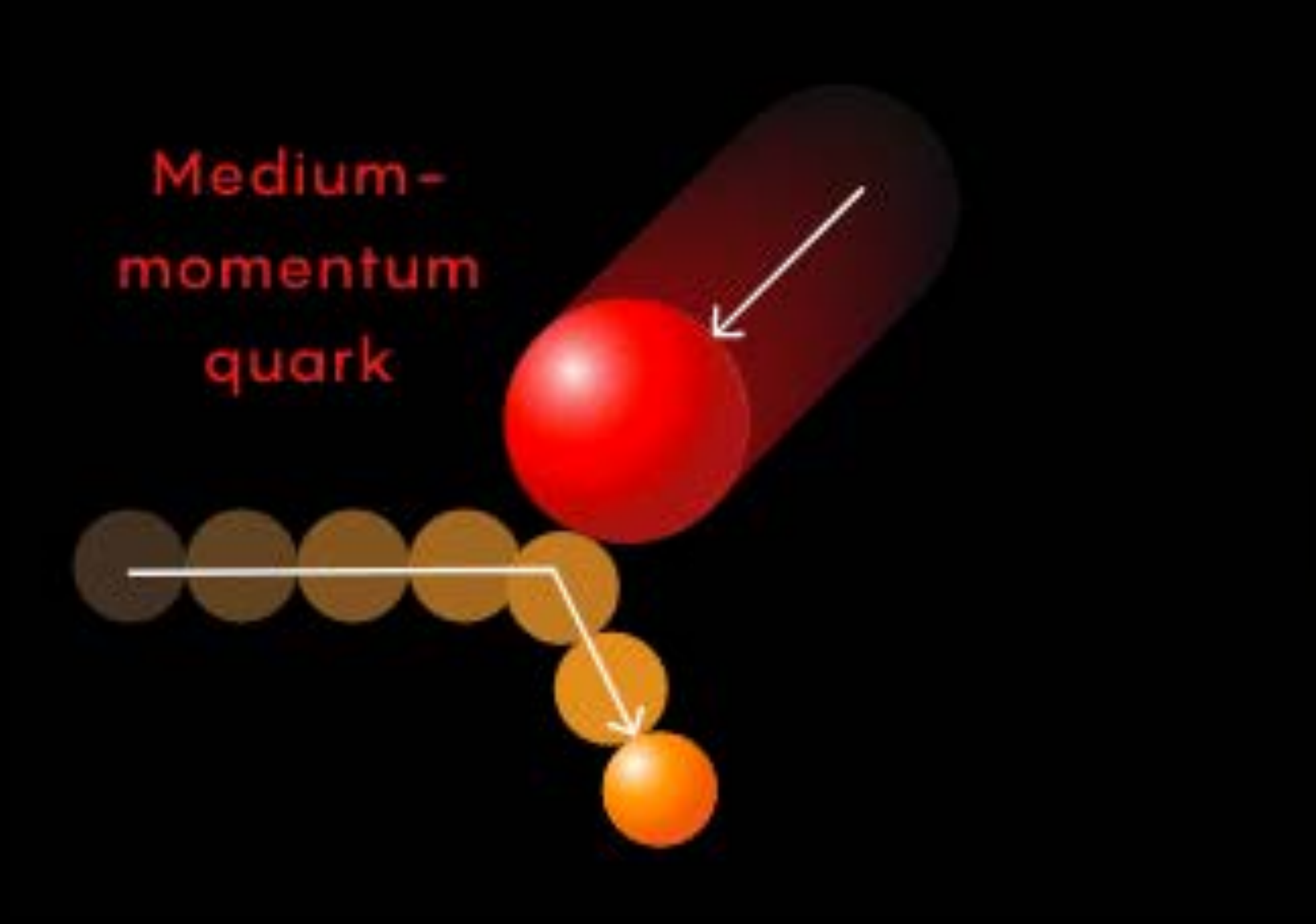


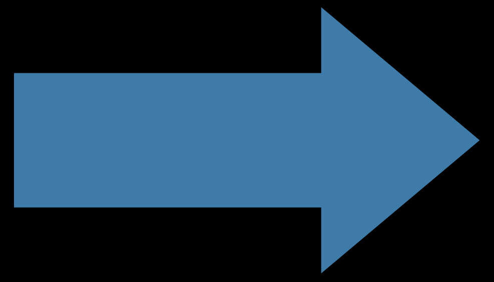
Deep Inelastic Scattering terminology

High Virtuality Q^2, Medium Bjorken x

Camera terminology

High Pixel, Medium shutter speed





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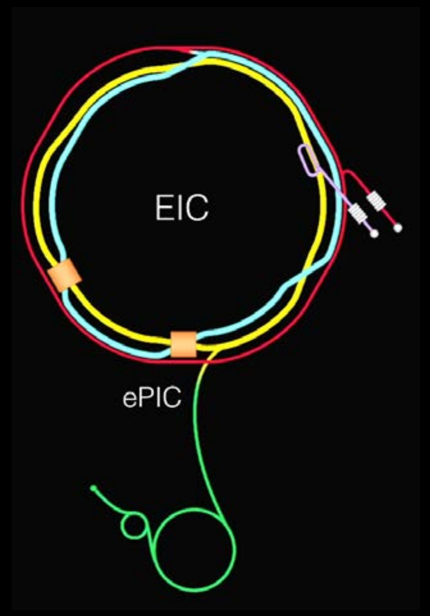
Imaging a proton at the EIC



Deep Inelastic Scattering terminology

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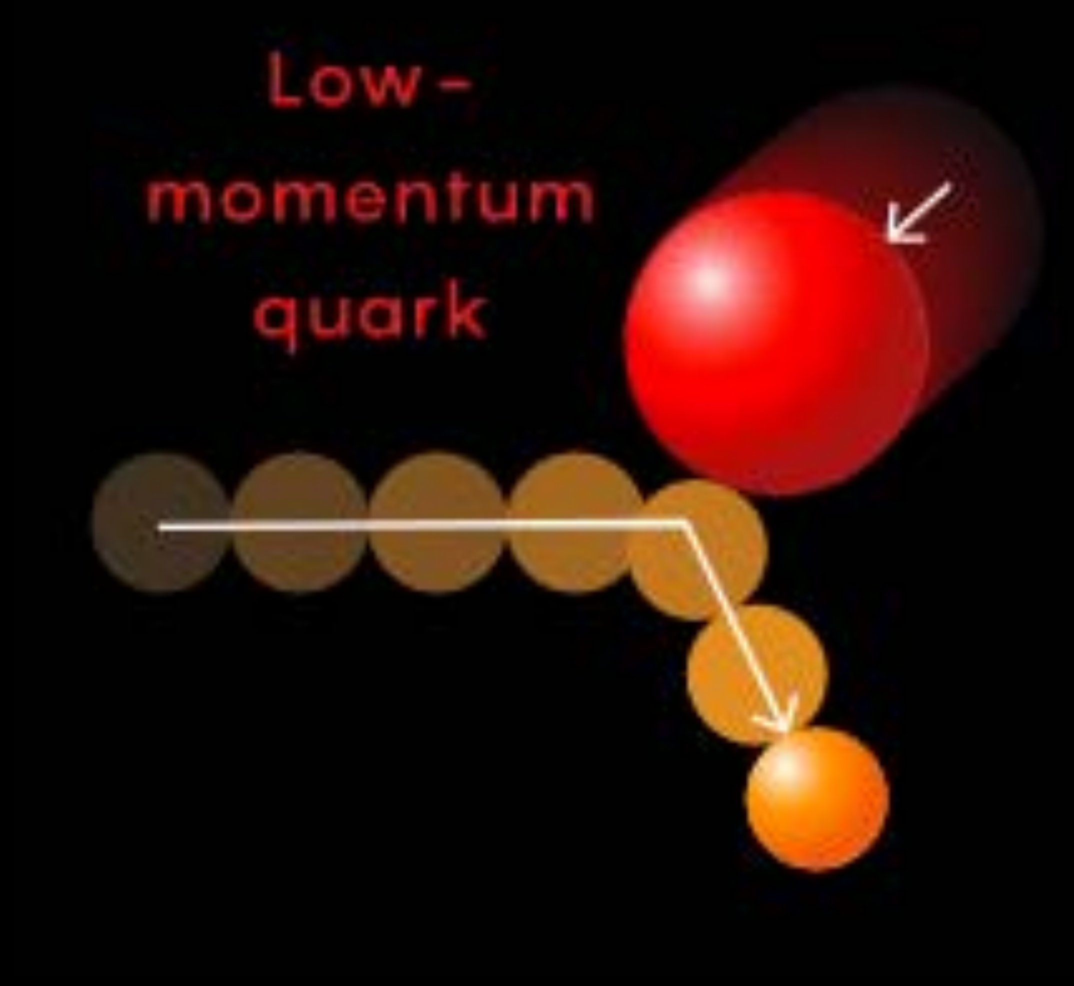
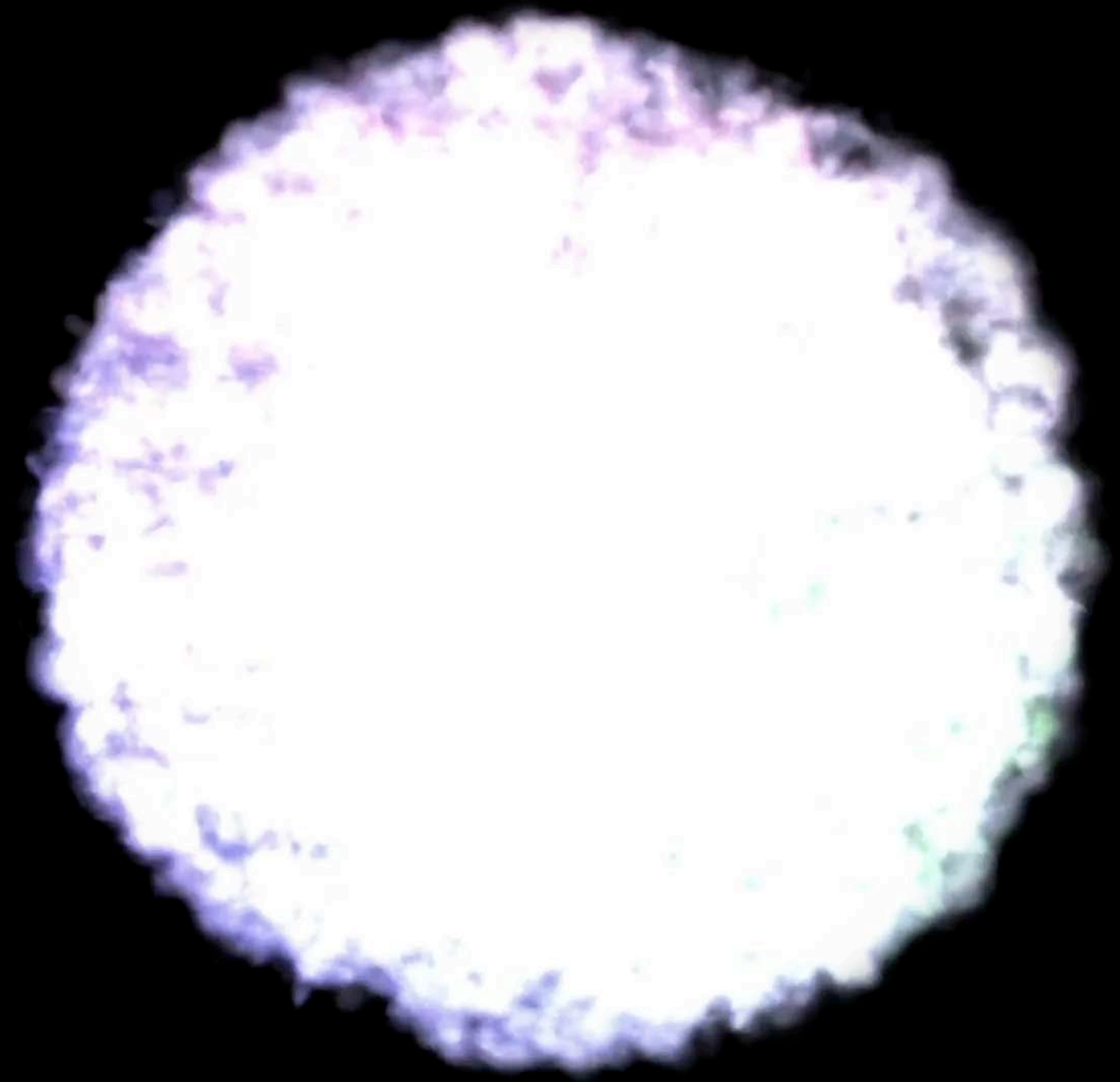
High Pixel, High shutter speed



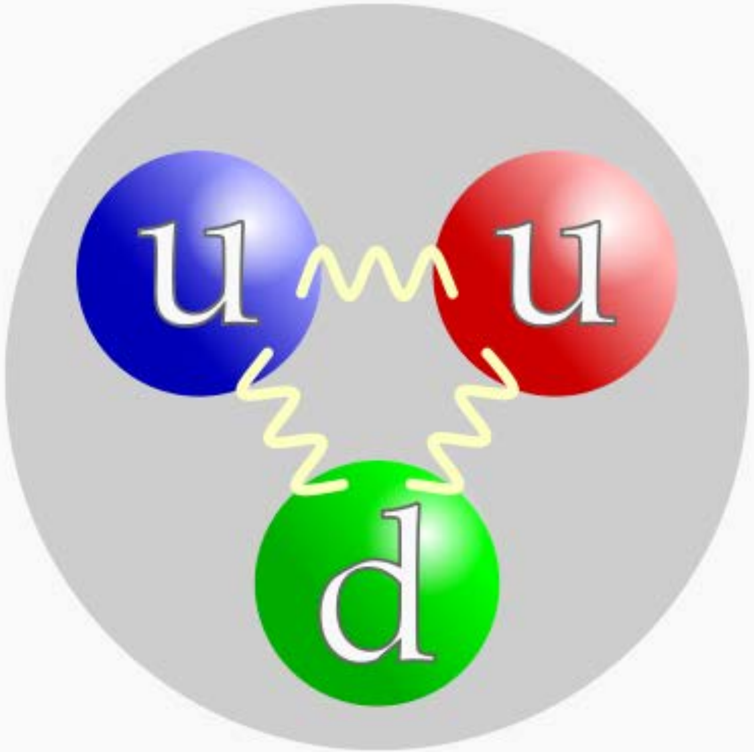


https://www.quantamagazine.org/inside-the-proton-the-most-complicated-thing-imaginable-20221019/

Structure of a proton (baryon)

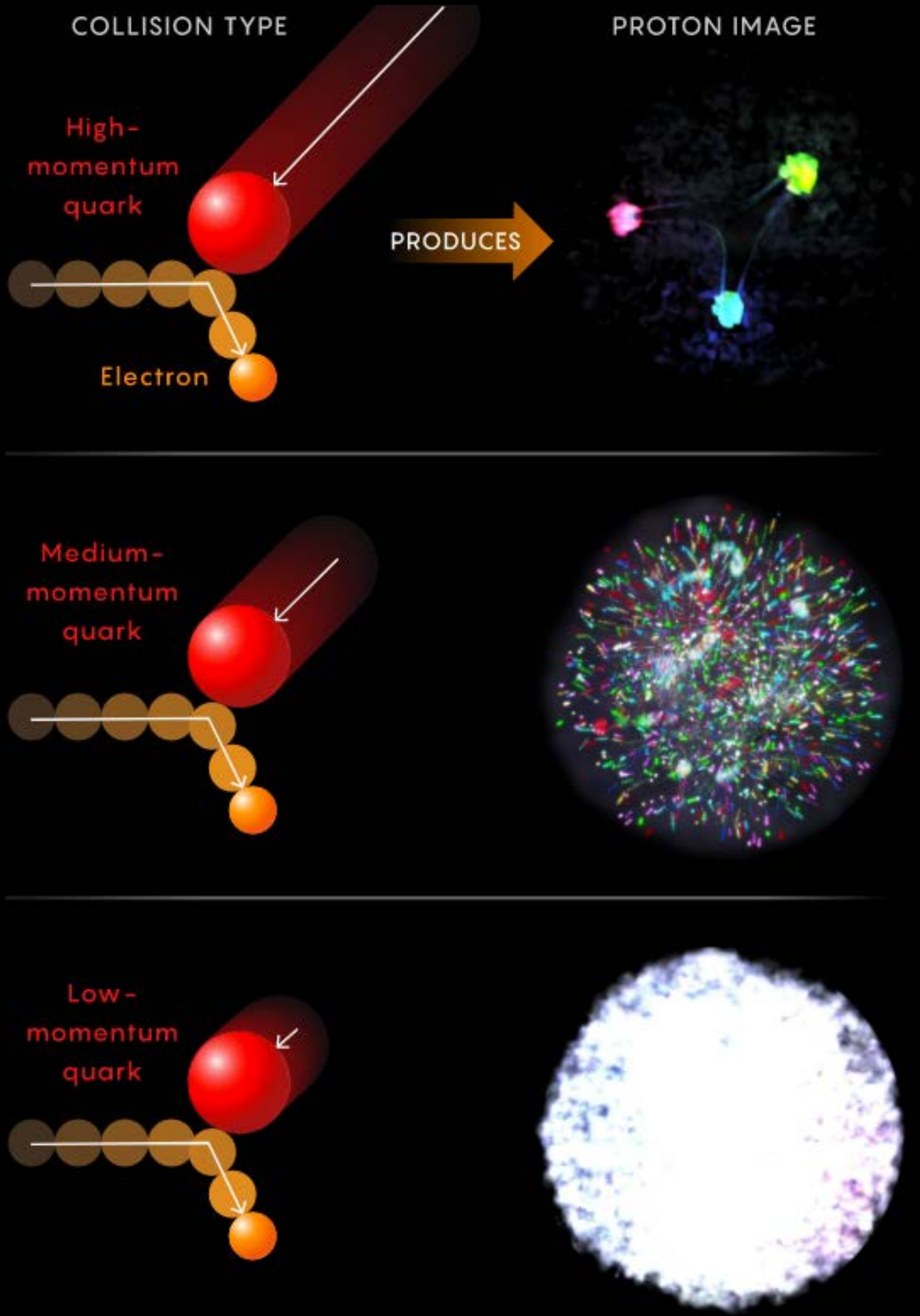
https://en.wikipedia.org/wiki/Proton
https://en.wikipedia.org/wiki/Baryon

Proton



The quark content of a proton. The color assignment of individual quarks is arbitrary, but all three colors must be present. Forces between quarks are mediated by gluons.

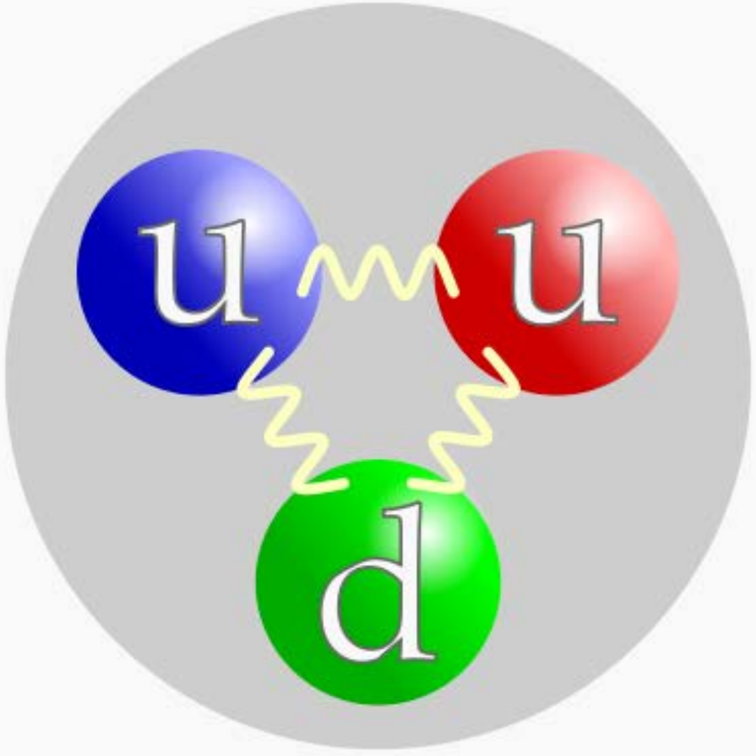
Classification	Baryon
Composition	2 up quarks (u), 1 down quark (d)
Statistics	Fermionic
Family	Hadron
Interactions	Gravity, electromagnetic, weak, strong



Outline: What carries the baryon quantum number ?

https://en.wikipedia.org/wiki/Proton
https://en.wikipedia.org/wiki/Baryon

Proton



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Classification	Baryon
Composition	2 up quarks (u), 1 down quark (d)
Statistics	Fermionic
Family	Hadron
Interactions	Gravity, electromagnetic, weak, strong

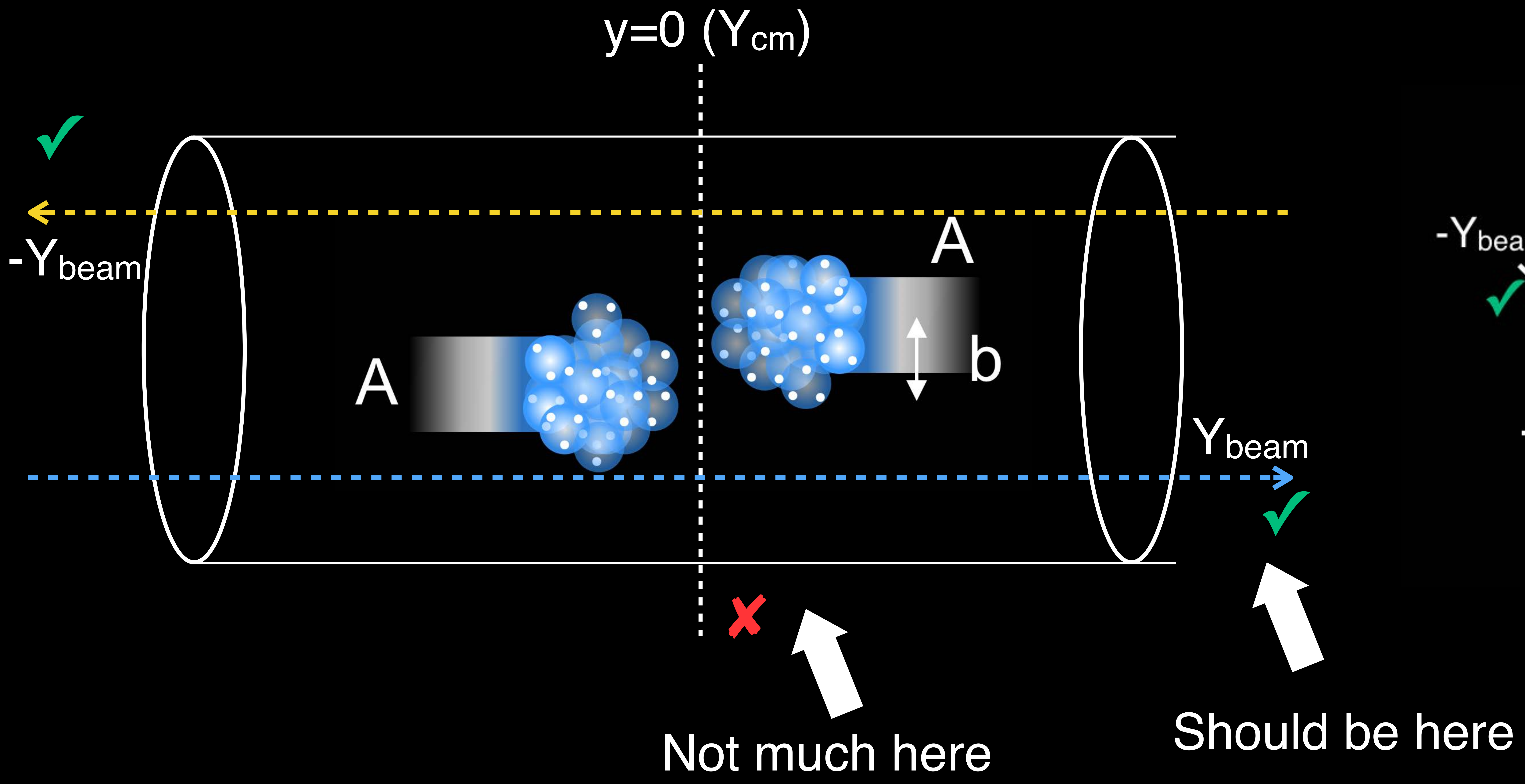
Baryons, along with mesons, are hadrons, particles composed of quarks. Quarks have baryon numbers of $B = \frac{1}{3}$ and antiquarks have baryon numbers of $B = -\frac{1}{3}$. The term "baryon" usually refers to *triquarks*—baryons made of three quarks ($B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$).

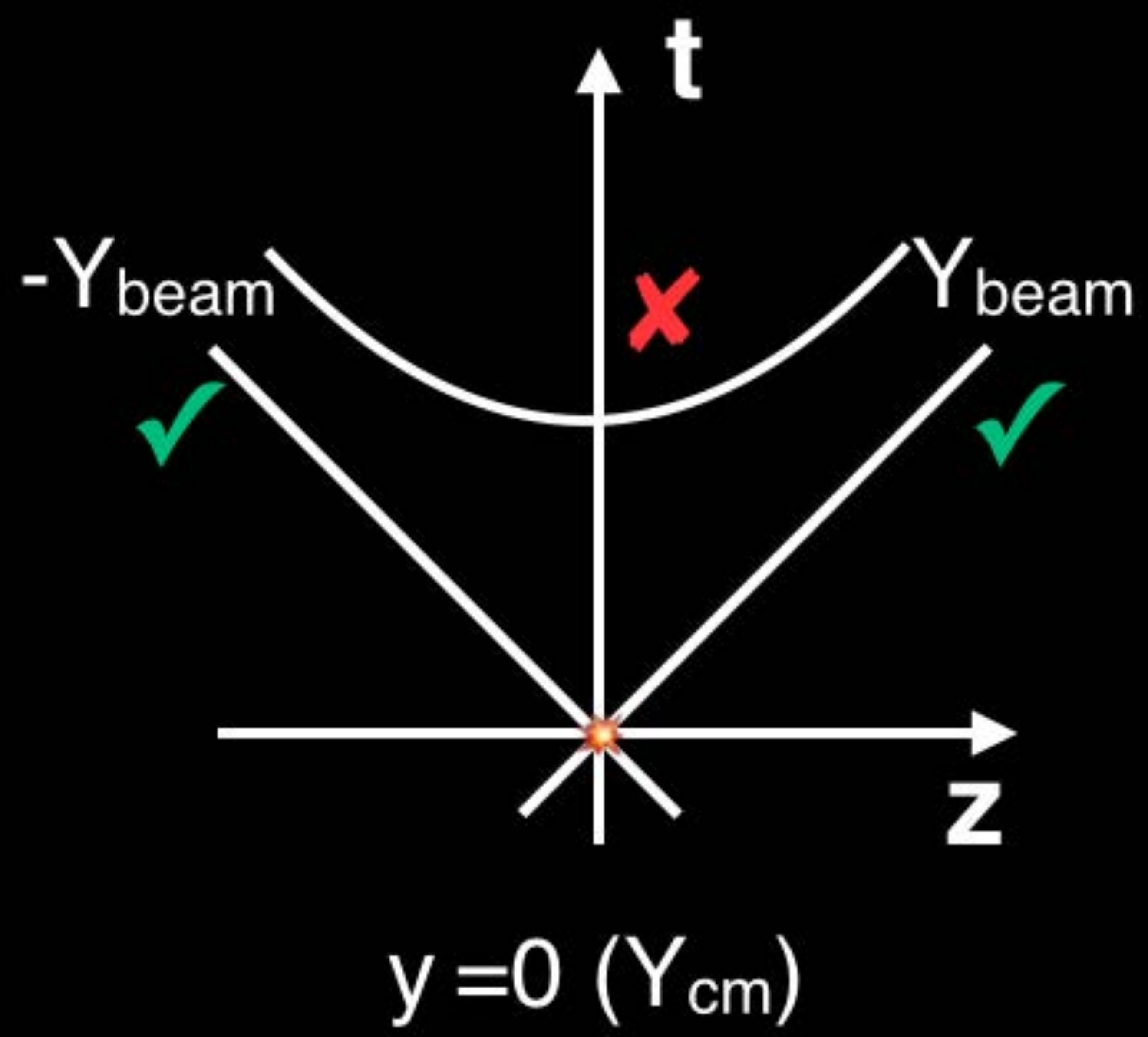
Baryon number is a strictly conserved quantum number & assumed to be carried by the quarks but never proven

G.C. Rossi and G. Veneziano, Nucl. Phys.B123(1977) 507; Phys. Rep.63(1980) 149
Kharzeev, Phys. Lett. B, 378 (1996) 238-246

Puzzle with how a baryon is stopped during collision

Kharzeev, Phys. Lett. B, 378 (1996) 238-246



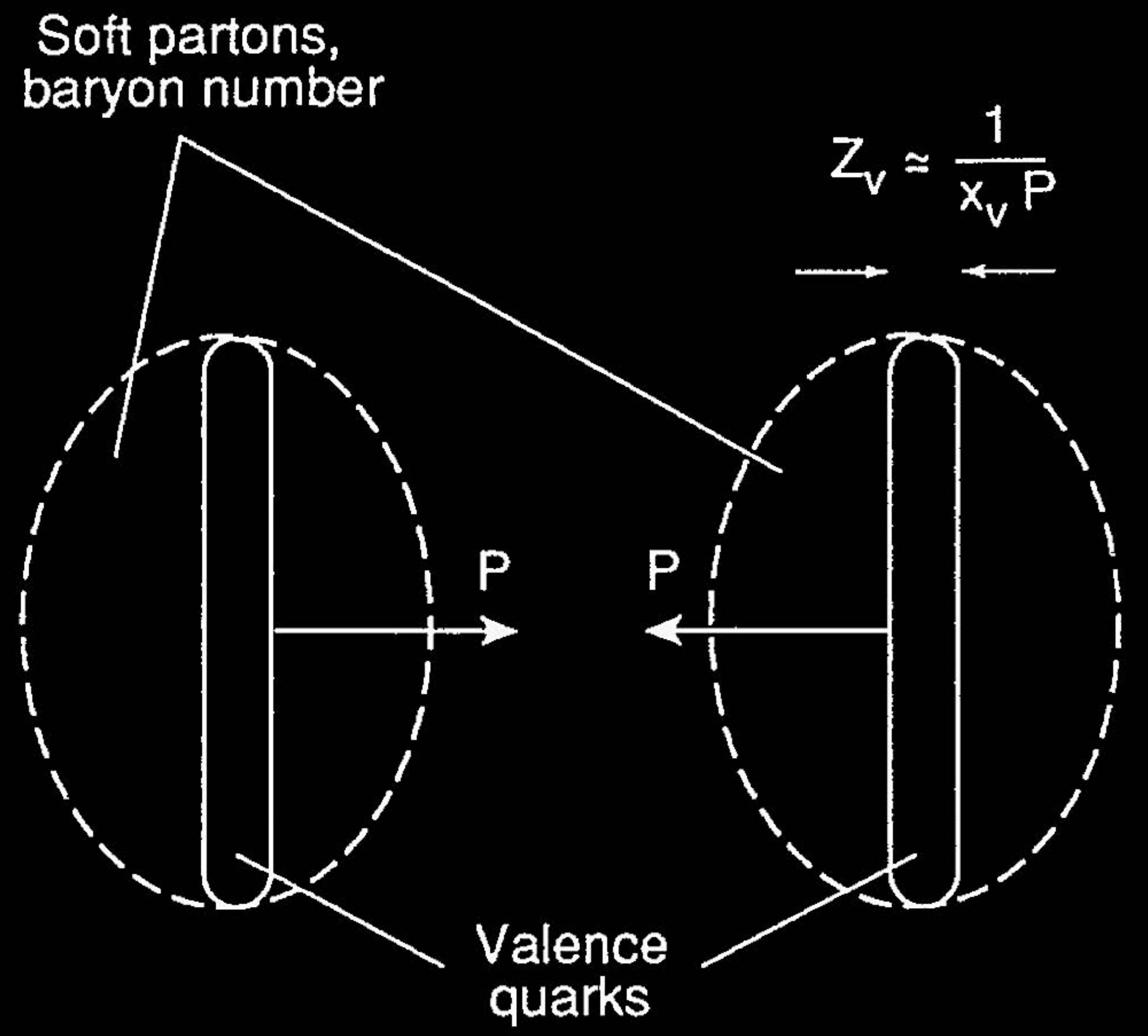


If baryon number flows with valence quarks, then they should end up near Y_{beam} and not near y=0 or Y_{cm}

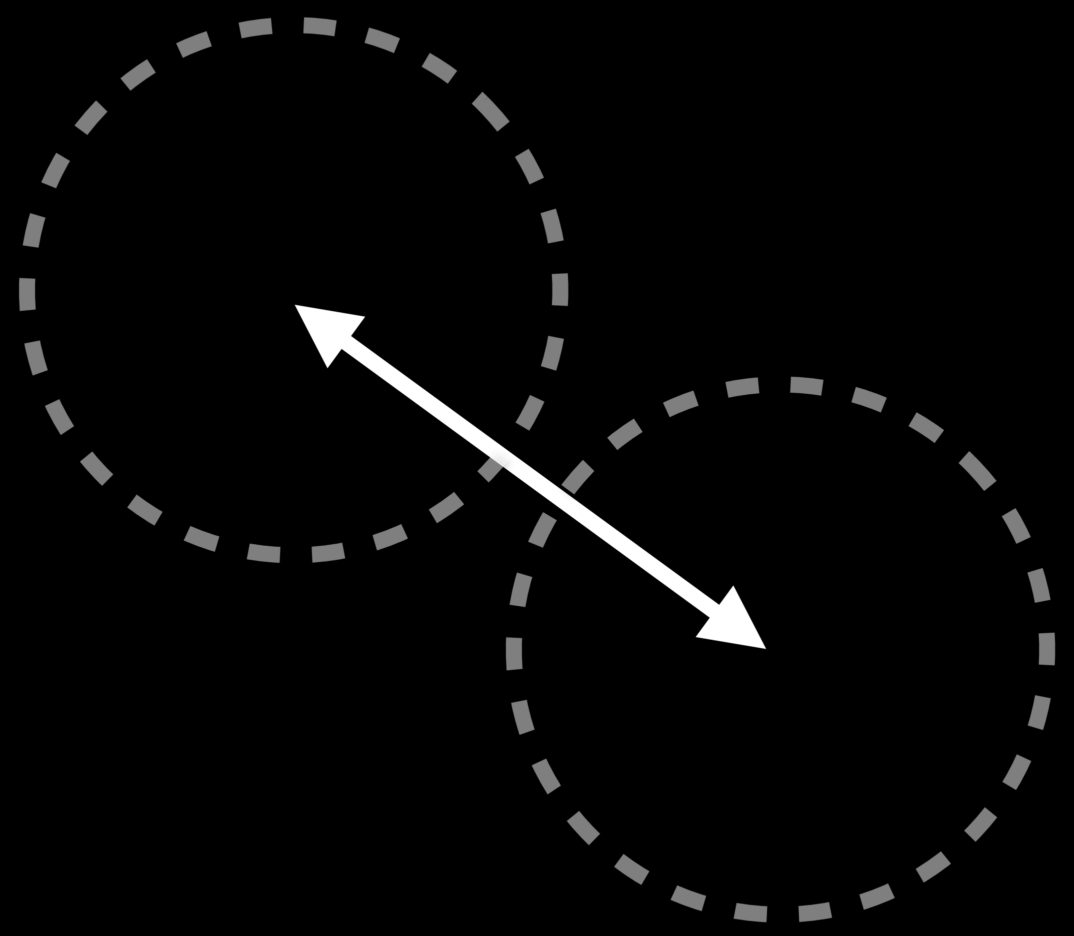
Stopping the valence quarks during collision

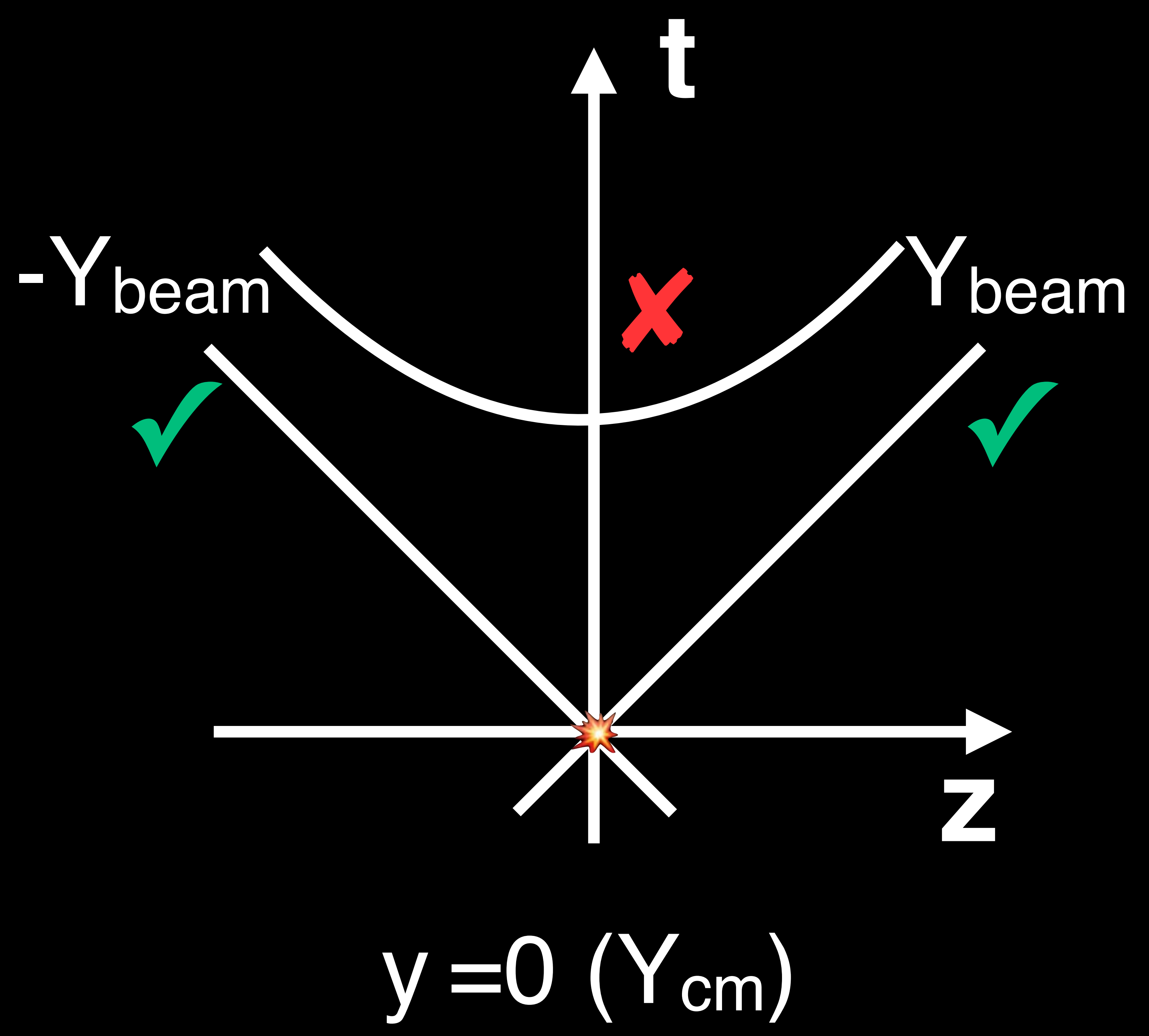
Kharzeev, Phys. Lett. B, 378 (1996) 238-246

Longitudinal direction



Transverse plane





Time available

$$t_{\rm coll} \sim (x_V P)^{-1} = (1/3 \times 100)^{-1}\ \mathrm{GeV}^{-1}$$
$$= 0.006\ \mathrm{fm}$$

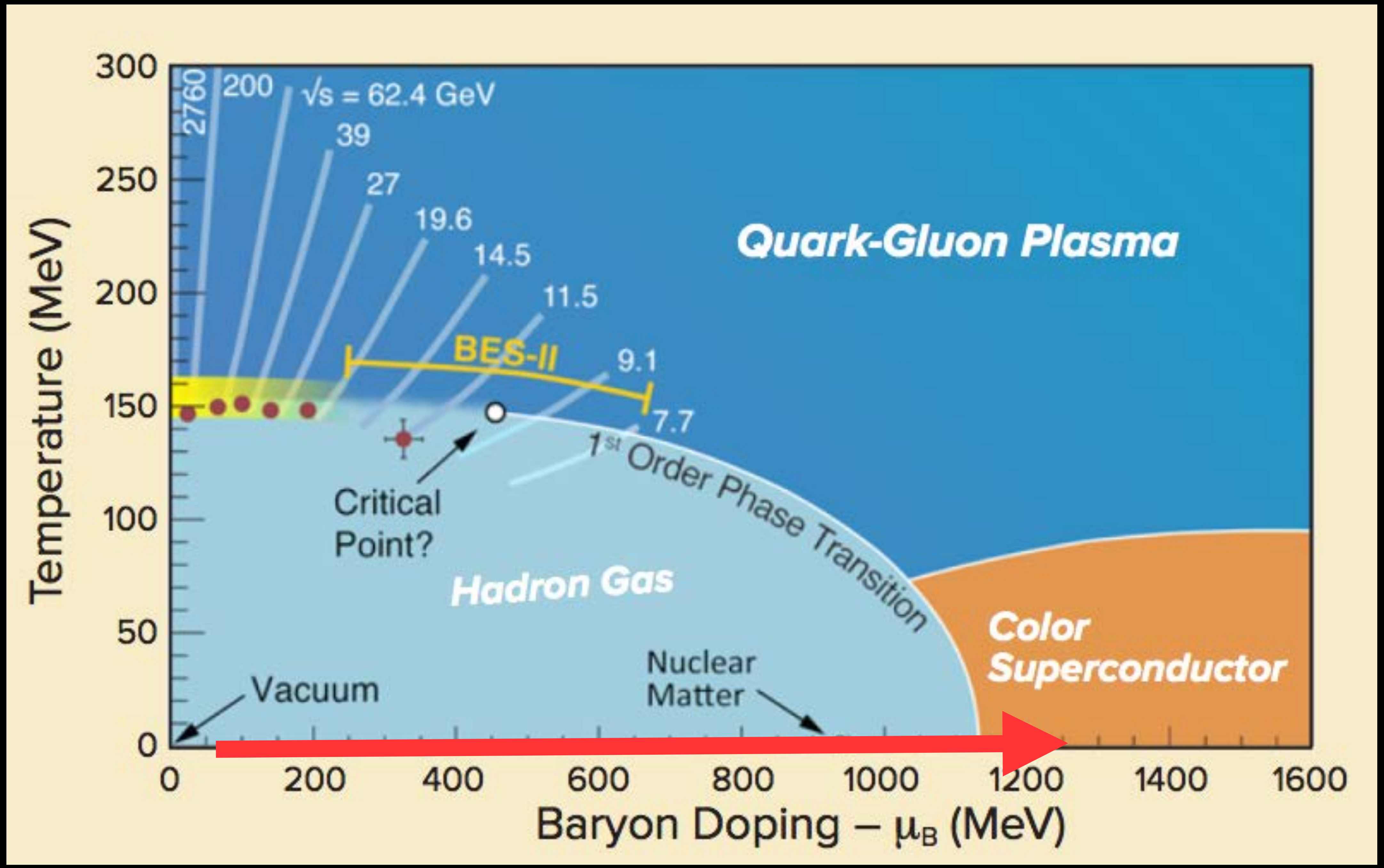
Time required

$$t_{\rm int} \sim \mathcal{O}(1)\ \mathrm{fm}$$

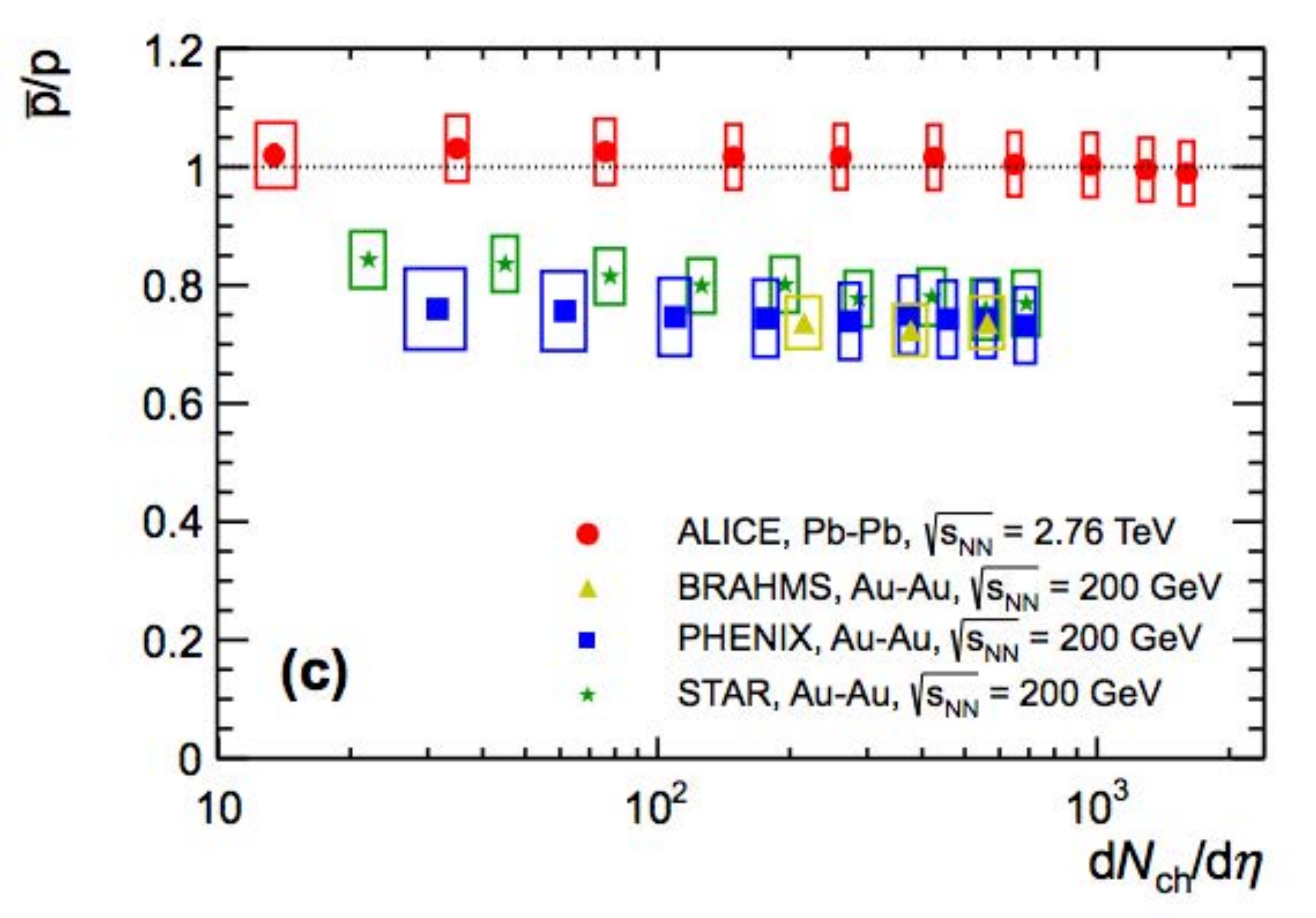
Available time for valence quark stopping is too short

What makes is possible to scan along the μ_B axis ?

Baryon stopping helps dope the QGP & map the QCD phase diagram



Midrapidity net-baryon density

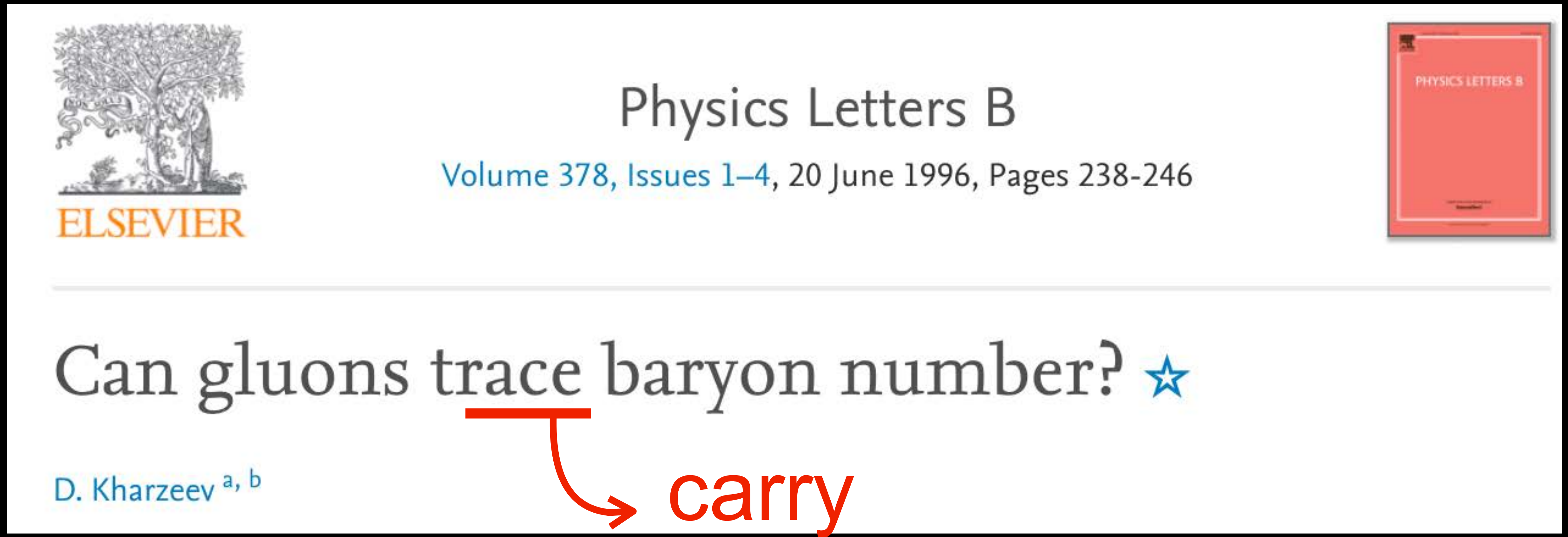


ALICE Collaboration, Phys. Rev. C 88, 044910 (2013)

Global data show exponential dependence of baryon density with rapidity shift

Can gluons trace the flow of baryon number?

G.C. Rossi and G. Veneziano, Nucl. Phys.B123(1977) 507; Phys. Rep. 63(1980) 149
Kharzeev, Phys. Lett. B, 378 (1996) 238-246


ELSEVIER

Physics Letters B

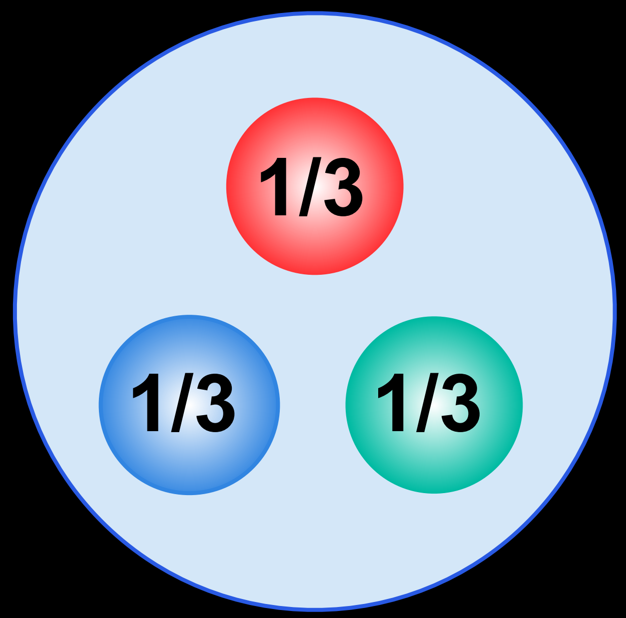
Volume 378, Issues 1–4, 20 June 1996, Pages 238-246

Can gluons trace baryon number? ☆

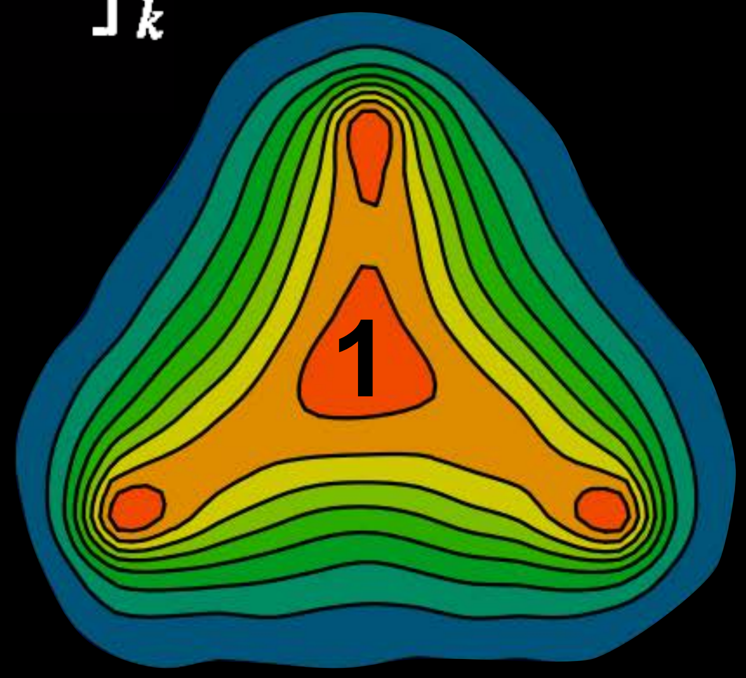
D. Kharzeev [a, b]

carry

$$B = \epsilon^{ijk}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu dx^\mu\right)q(x_1)\right]_i \times \left[P\exp\left(ig\int_{x_2}^{x} A_\mu dx^\mu\right)q(x_2)\right]_j \times \left[P\exp\left(ig\int_{x_3}^{x} A_\mu dx^\mu\right)q(x_3)\right]_k$$



Baryon number flows with the valence quarks

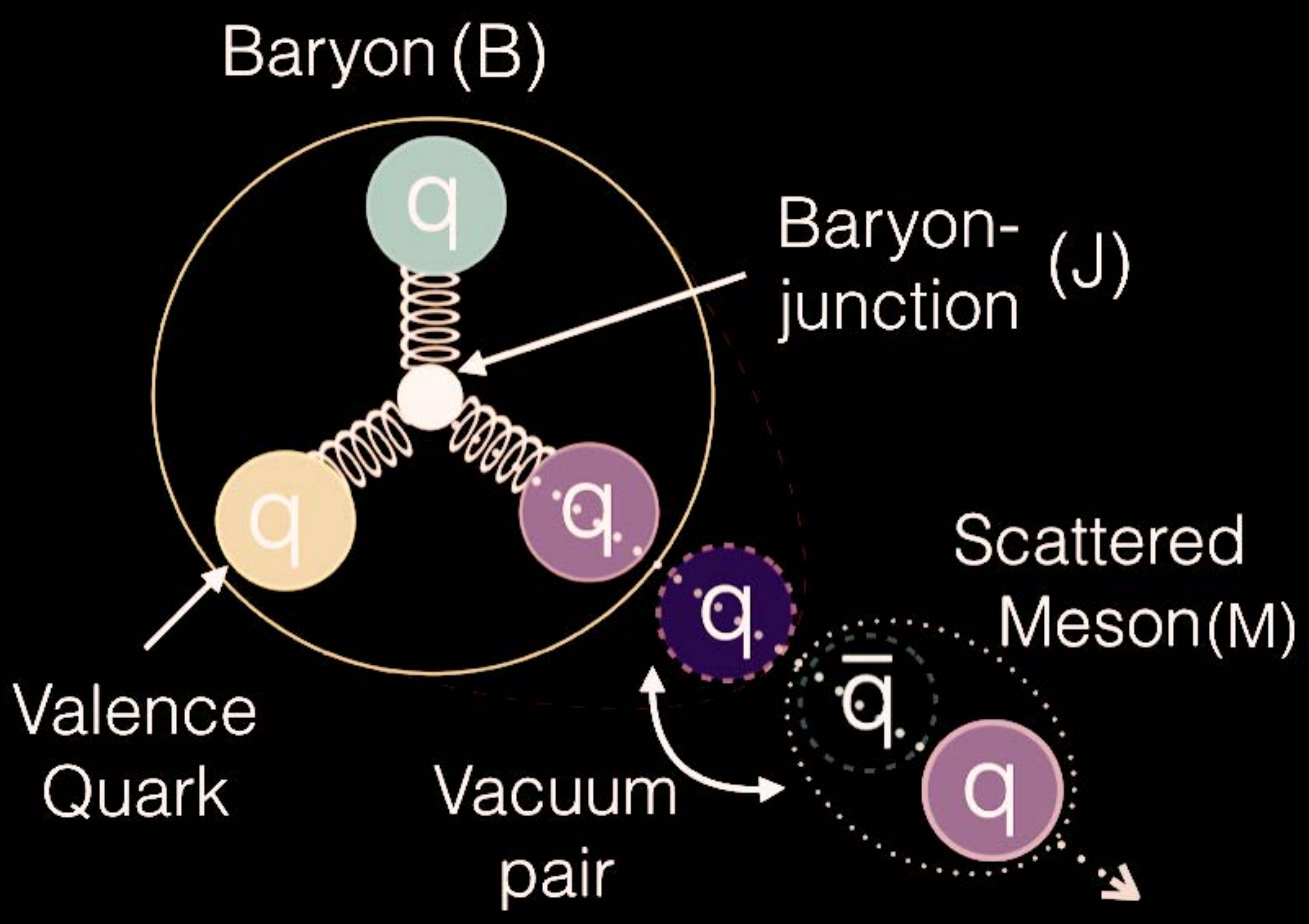


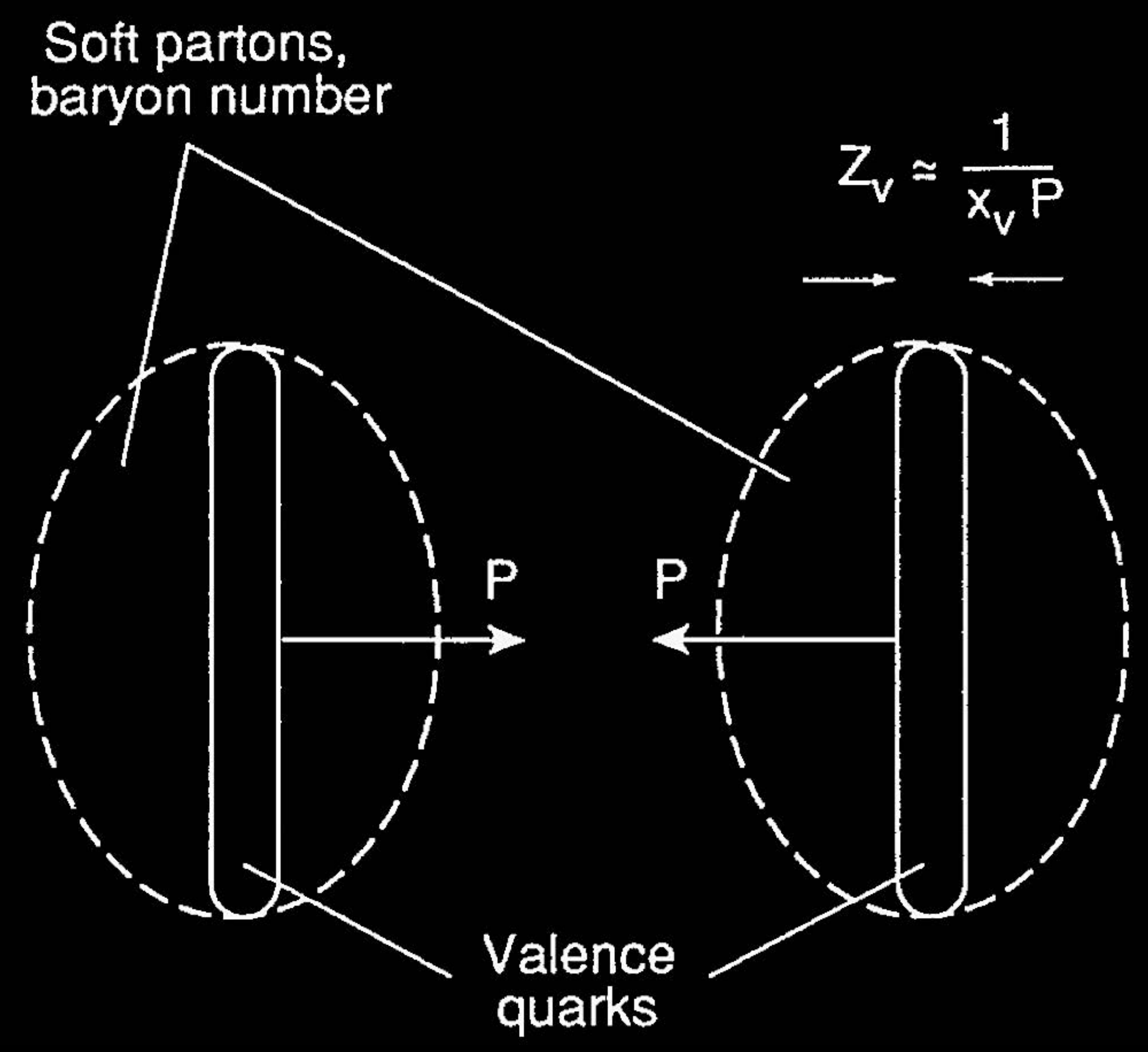
Baryon number flows with the junction

String-junction made of gluons

What happens if baryon number is carried by the string-junction?

What if string-junctions carry baryon number instead of valence quarks?





$$t_{\rm coll} \sim (x_V P)^{-1} = (1/3 \times 100)^{-1}\ {\rm GeV}^{-1} = 0.006\ {\rm fm}$$

$$t_{\rm int} \sim \mathcal{O}(1)\ {\rm fm}$$

Pulling a quark stops a meson not a baryon, you have to stop the junction to stop a baryon

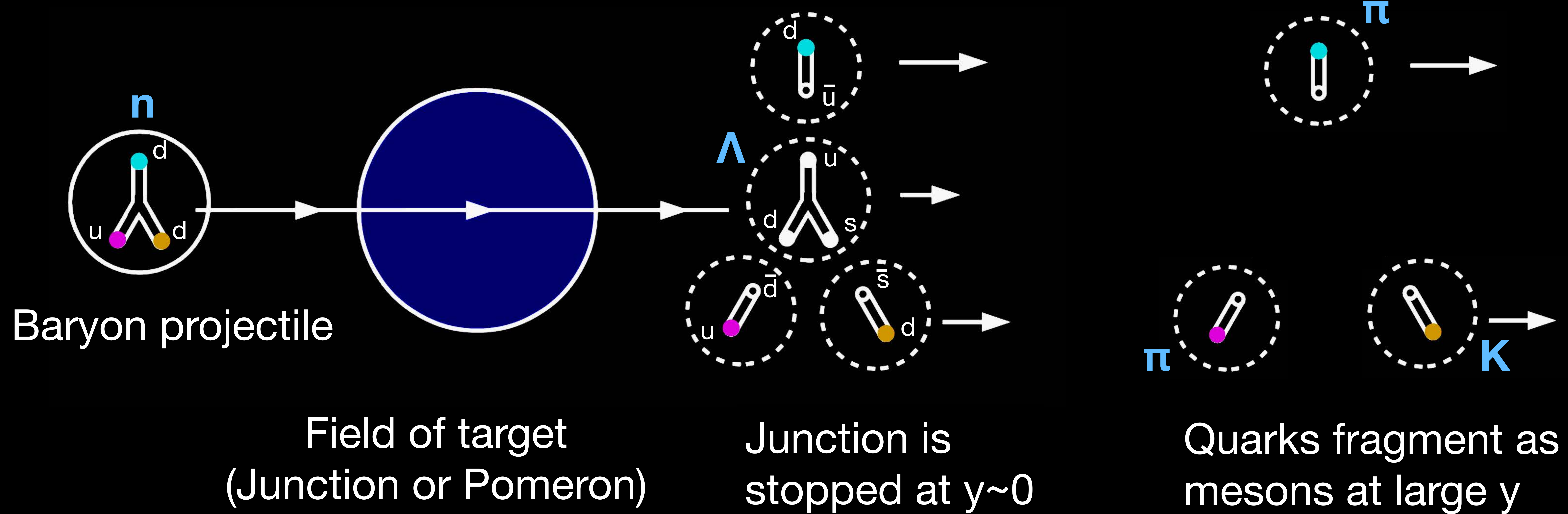
Junction is made of infinite low-x gluons so they have enough time to be stopped

$$x_J \ll x_V \qquad ((x_J P)^{-1} \gg (x_V P)^{-1})$$

How a baryon junction can be stopped?

Kharzeev, Phys. Lett. B, 378 (1996) 238-246

fig: Navarra

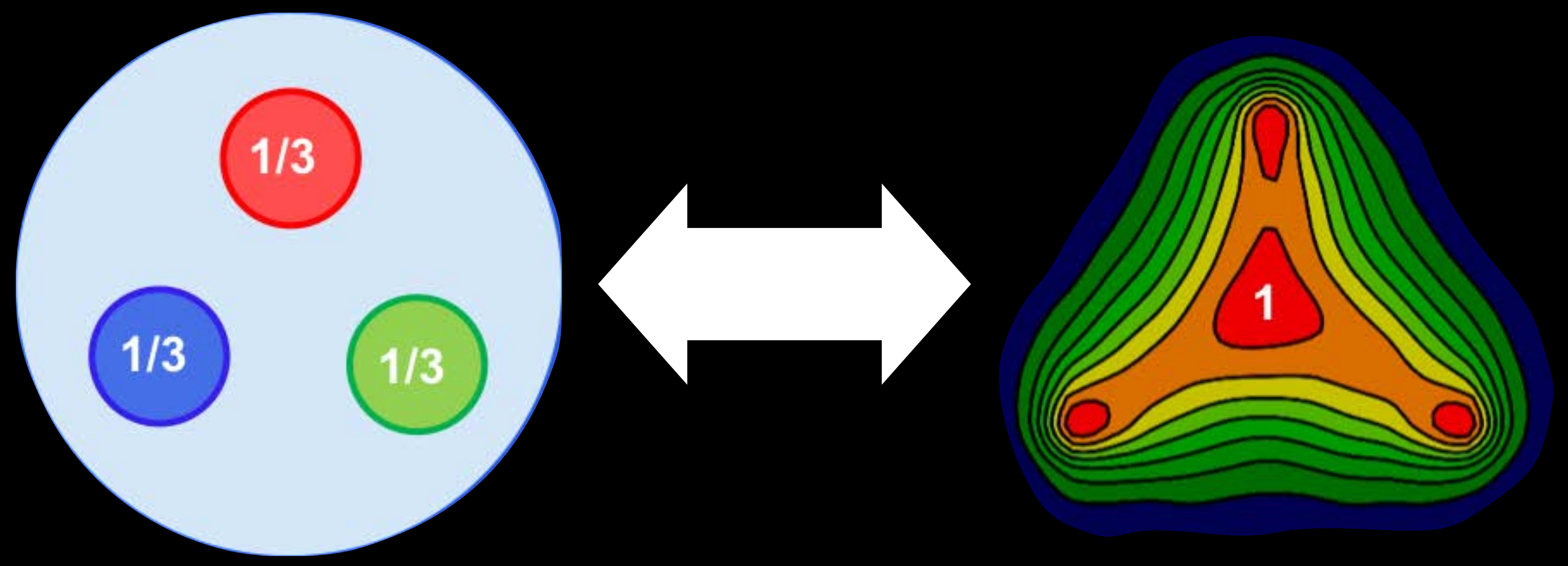


Three features: stopped baryon at y~0 will be soft (low p_T), can have different flavor and many mesons will be produced in the process between y=0 & y=Y_{beam}

Testing the baryon junction conjecture in experiment

How do we test it experimentally ?

Brandenburg, Lewis, Tribedy, Xu, arXiv: 2205.05685



arXiv > hep-ph > arXiv:2205.05685

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High Energy Physics – Phenomenology

[Submitted on 12 May 2022 (v1), last revised 13 May 2022 (this version, v2)]

Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

James Daniel Brandenburg, Nicole Lewis, Prithwish Tribedy, Zhangbu Xu

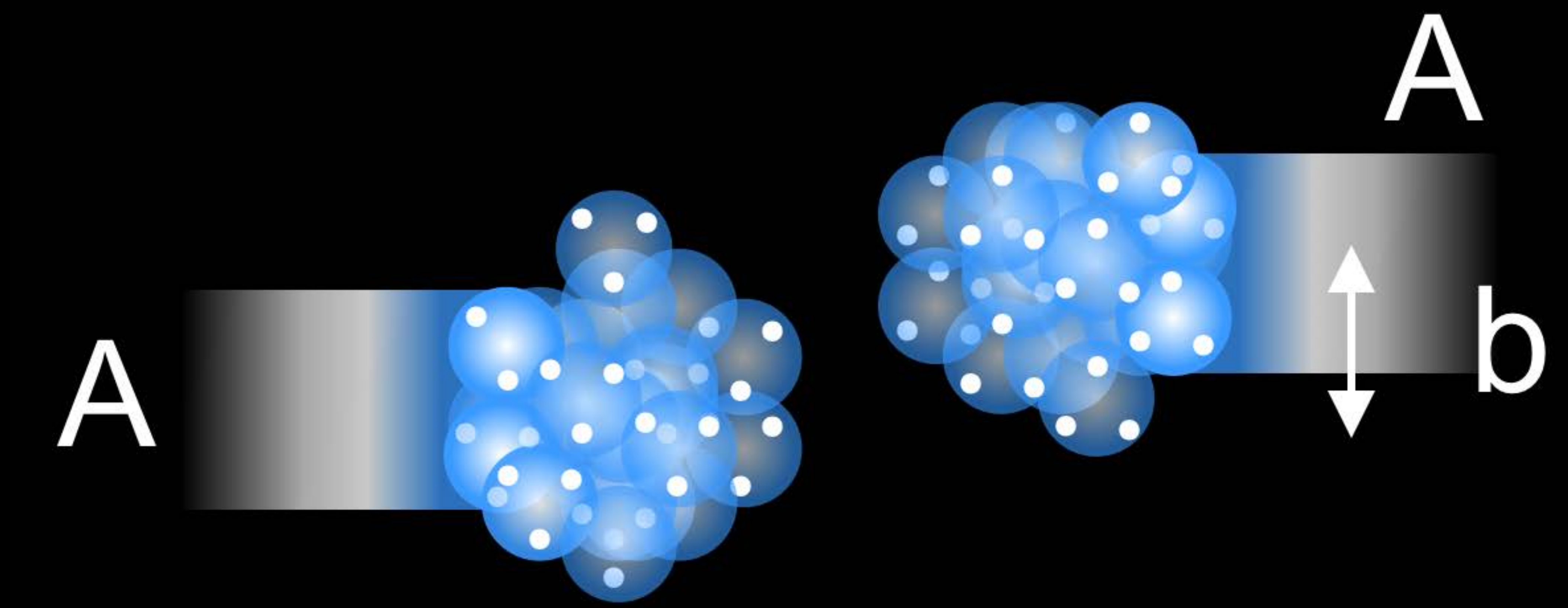
A puzzling feature of ultra-relativistic nucleus-nucleus collisions is the apparent substantial baryon excess in the midrapidity region. It was proposed that baryon number could be carried by a non-perturbative Y-shaped topology of gluon fields, called the baryon junction, rather than by the valence quarks. The stopping of baryon junctions is predicted to lead to a characteristic exponential distribution of net-baryon density with rapidity and could resolve the puzzle. In this context we point out that the rapidity density of net-baryons near midrapidity indeed follows an exponential distribution with a slope of -0.61 ± 0.03 as a function of beam rapidity in the existing global data from A+A collisions at AGS, SPS and RHIC energies. To further test if quarks or gluon junction carry the baryon quantum number, we propose to study the absolute magnitude of the baryon vs. charge stopping in isobar collisions at RHIC. We also argue that semi-inclusive photon-induced processes ($\gamma + p$/A) at RHIC kinematics provide an ideal opportunity to search for the signatures of the baryon junction and to shed light onto the mechanisms of observed baryon excess in the mid-rapidity region in ultra-relativistic nucleus-nucleus collisions. Such measurements can be further validated in $e + p$/A collisions at the EIC.

1. Charge vs. baryon stopping in isobar collisions at RHIC
2. Rapidity dependence of baryon density in photon-induced processes

Correlation between charge and baryon stopping

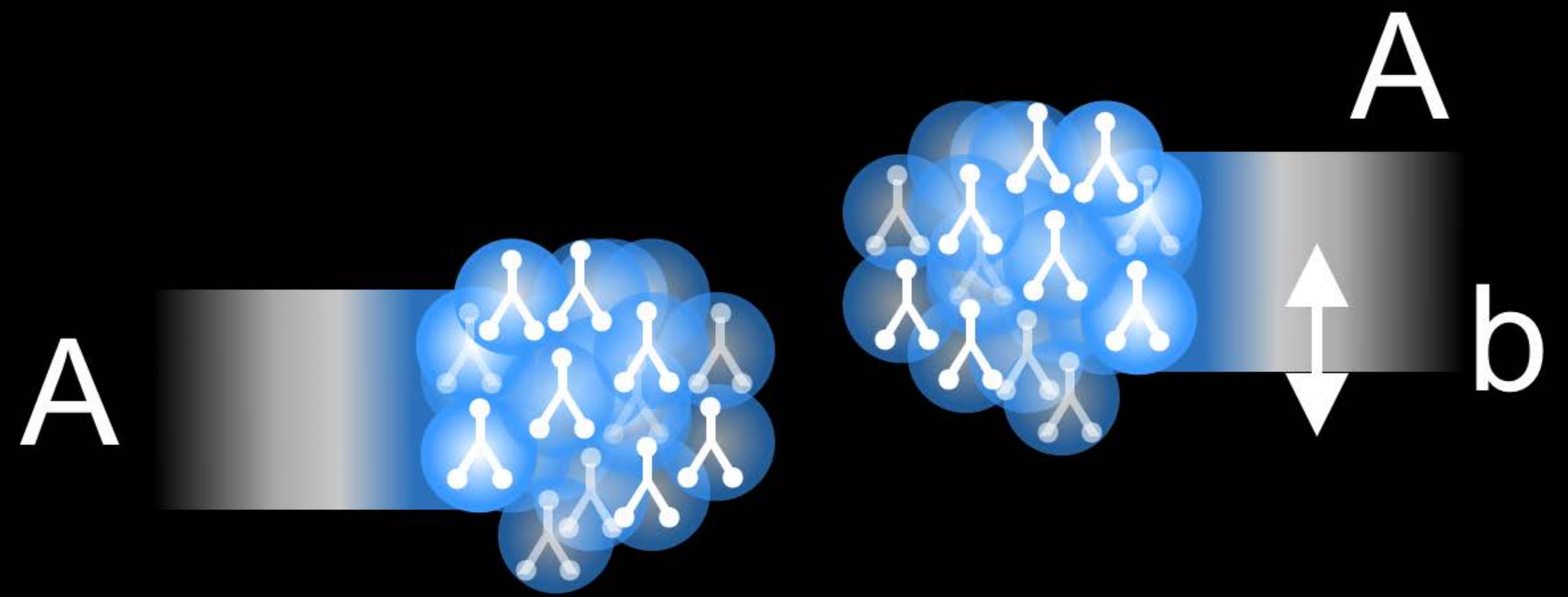
1. Valence quarks carry charge & baryon number

A=Mass number $\Longrightarrow$ Baryon
Z=Atomic number $\Longrightarrow$ Charge



$$\text{Charge stopping} \simeq \frac{Z}{A} \times \text{Baryon stopping}$$

2: Valence quarks carry charge & junctions carry baryon number



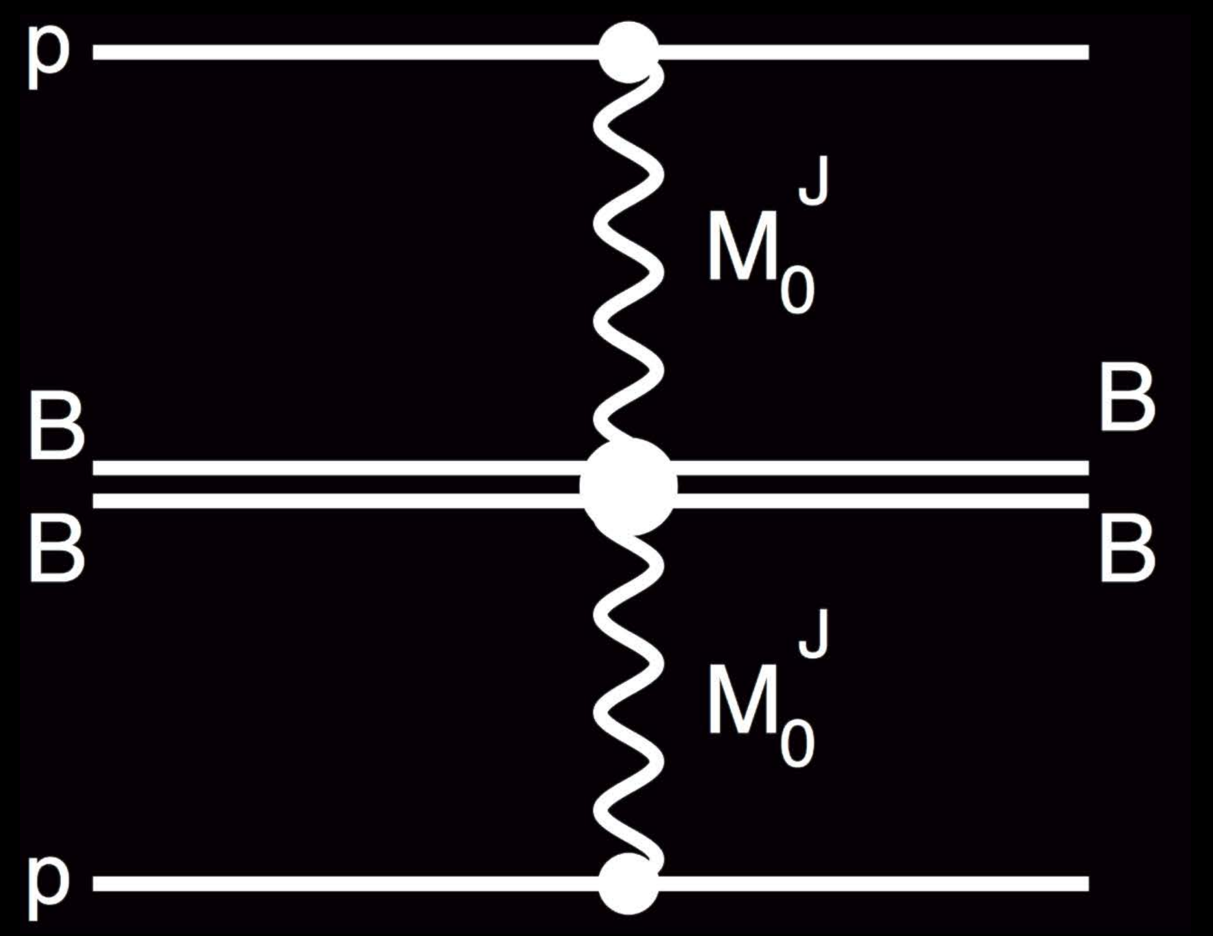
$$\text{Charge stopping} < \frac{Z}{A} \times \text{Baryon stopping}$$

Isobar systems can be used to reduce systematics

Predictions from Regge Theory

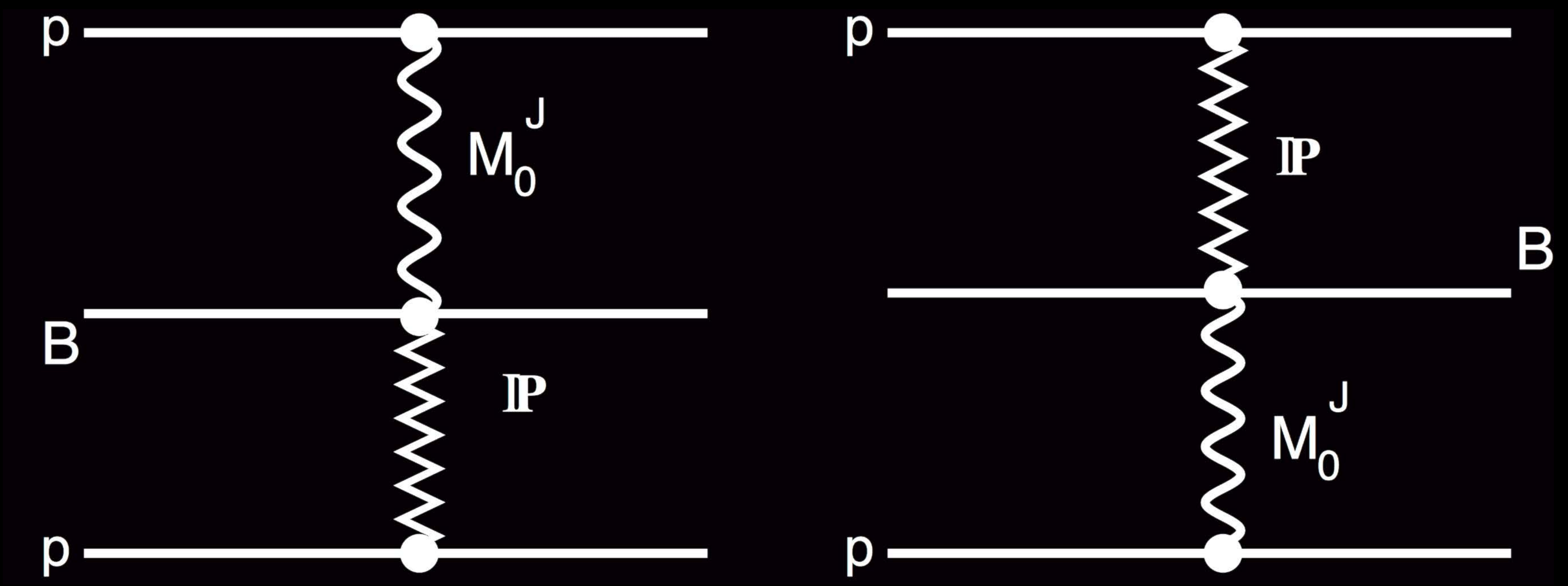
Kharzeev, Phys. Lett. B, 378 (1996) 238-246

Junction stops another junction



$$\sigma \sim e^{\pm Y_{\mathrm{beam}}}$$

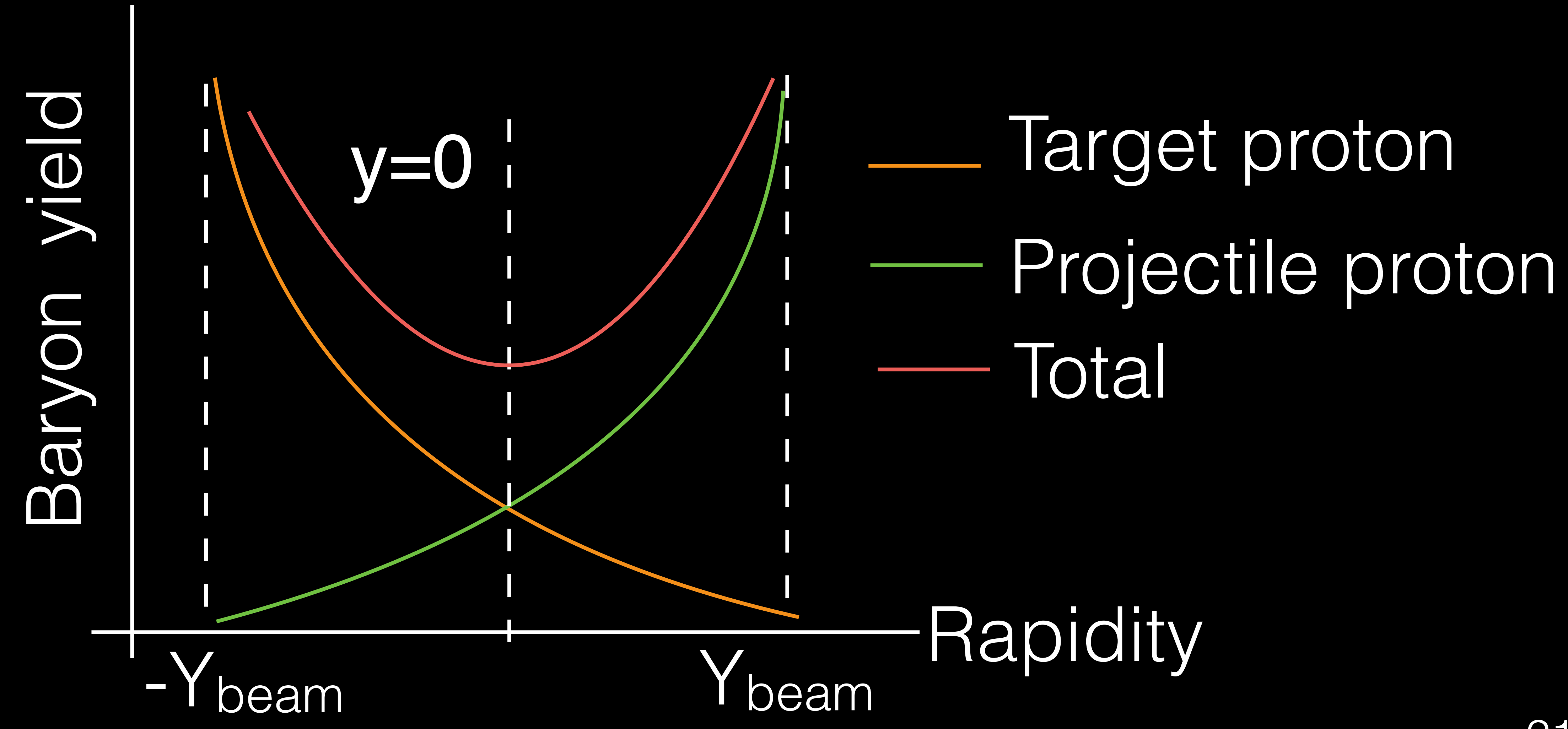
Junction stopped by Pomeron



$$e^{0.16\,Y_{\mathrm{beam}}} \times \left(e^{-0.58(y+Y_{\mathrm{beam}})} + e^{0.58(y-Y_{\mathrm{beam}})}\right)$$

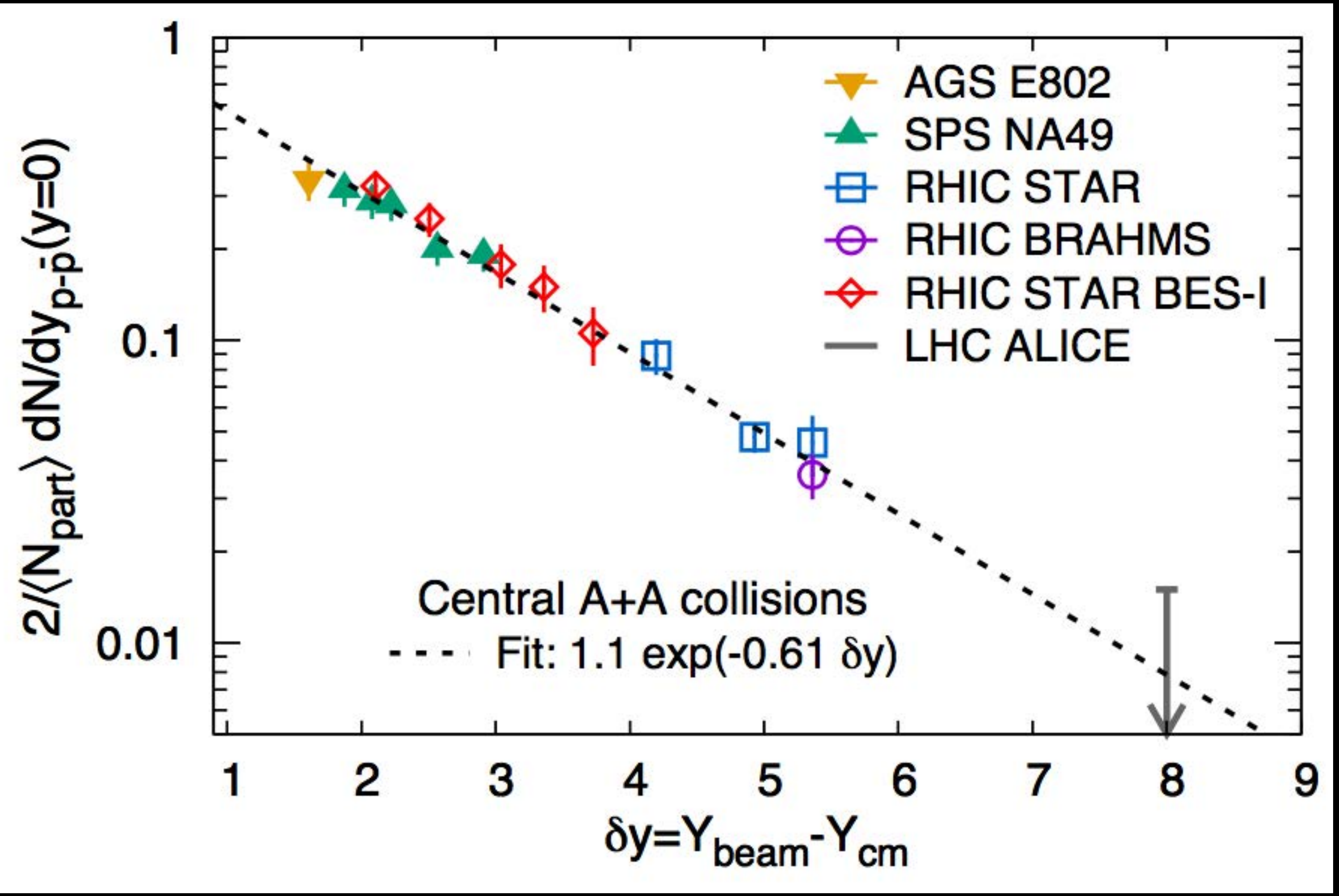
Cross section follow exponential rapidity (y) dependence with specific values of the exponent ~ 0.5

Difficult to see exponential fall in symmetric collisions



Midrapidity baryon production in A+A collisions

Brandenburg, Lewis, Tribedy, Xu, arXiv:2205.05685



Fit to global data on central A+A:

$$\frac{2}{N_{\text{part}}}\left.\frac{dN_{\mathrm{p}-\bar{\mathrm{p}}}}{dy}\right|_{A+A} = N_B\, e^{-\alpha_B (Y_{\text{beam}} - Y_{\text{cm}})}$$

$$\boxed{\alpha_B = 0.61 \pm 0.03}$$

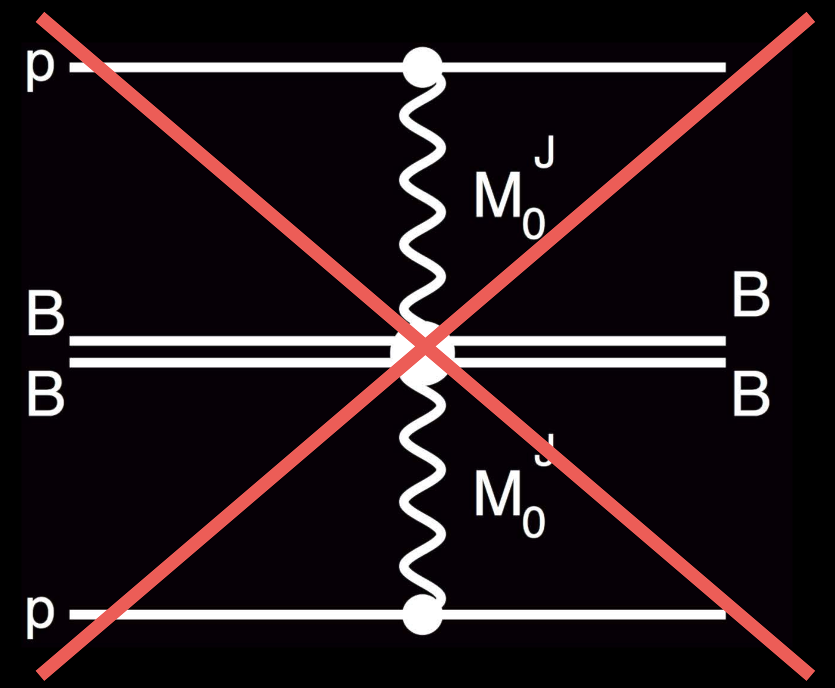
Predictions form Regge theory & baryon junction picture:

$$\boxed{0.42 \leq \alpha_B \leq 1}$$

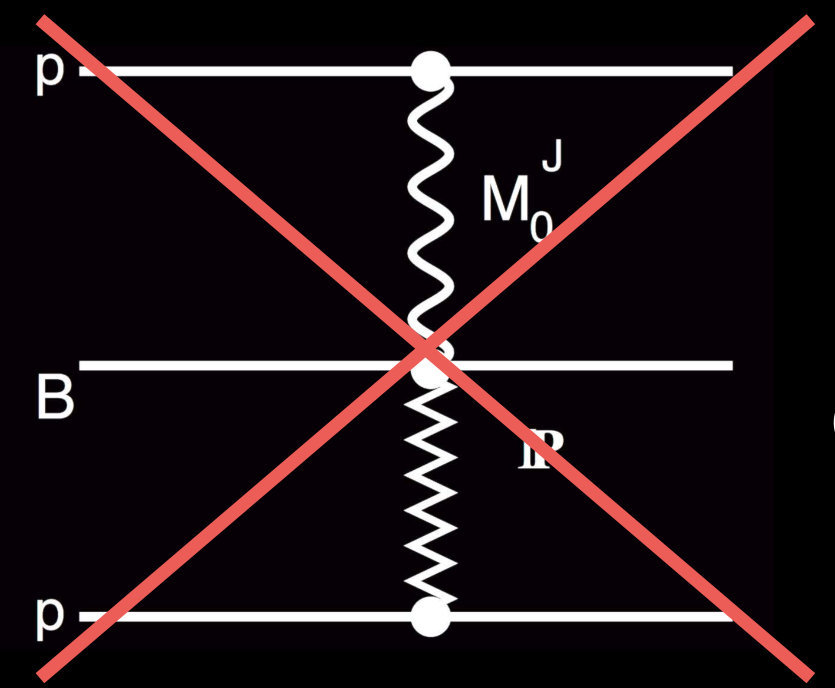
Midrapidity baryon density slope is consistent with baryon junction prediction

Baryon free projectile: photon-induced processes

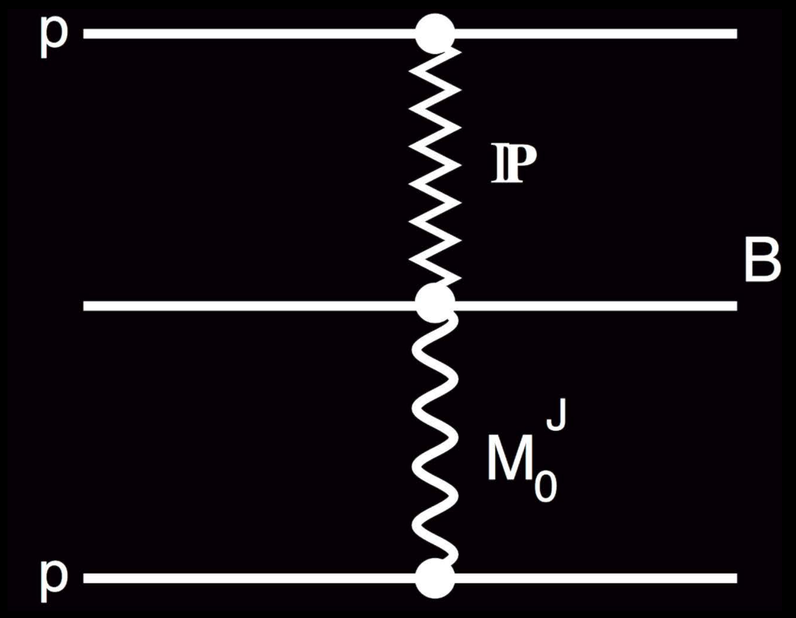
Brandenburg, Lewis, Tribedy, Xu, arXiv:2205.05685



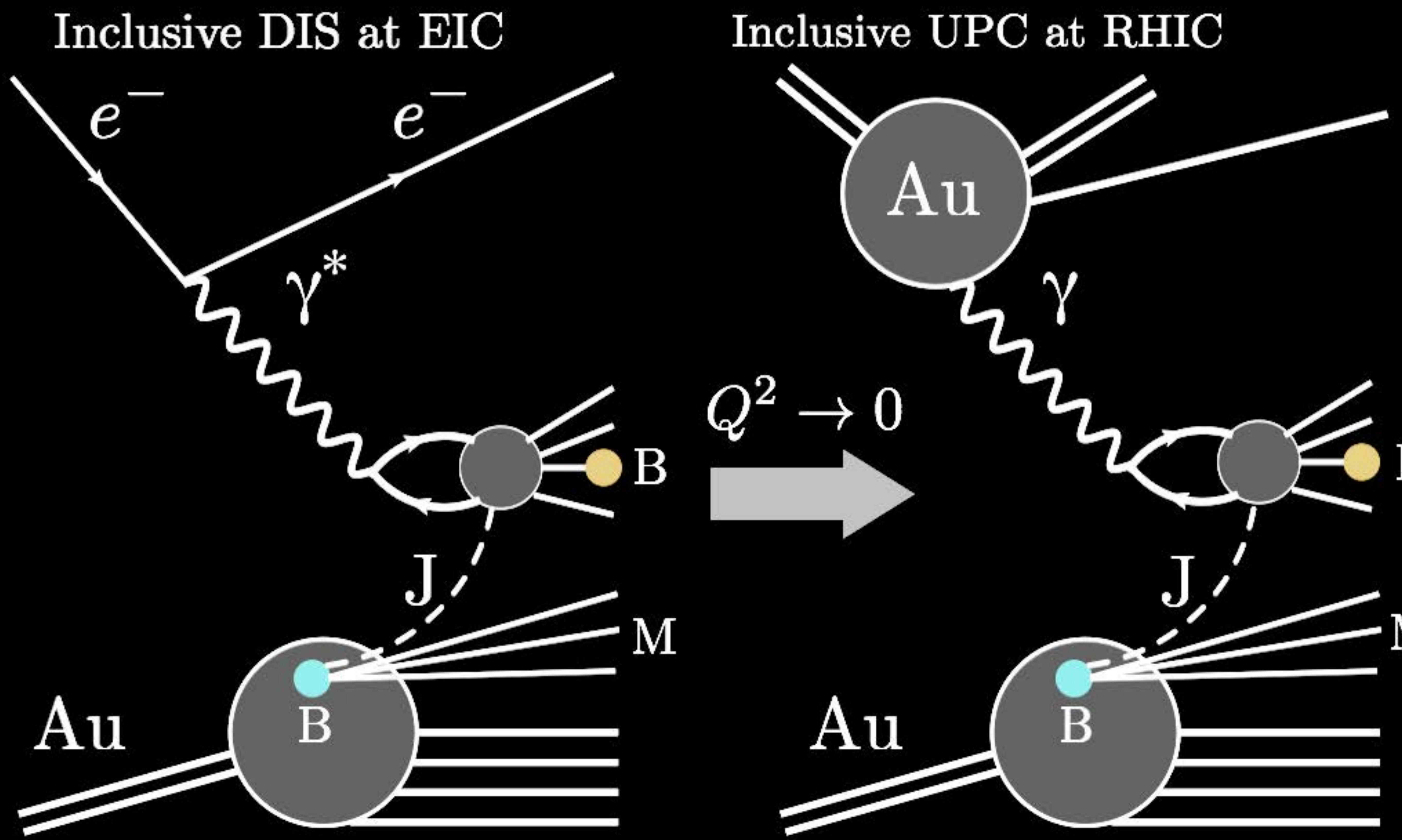
✘ $\sim e^{\pm Y_{\mathrm{beam}}}$



✘ $e^{-0.58(y+Y_{\mathrm{beam}})}$

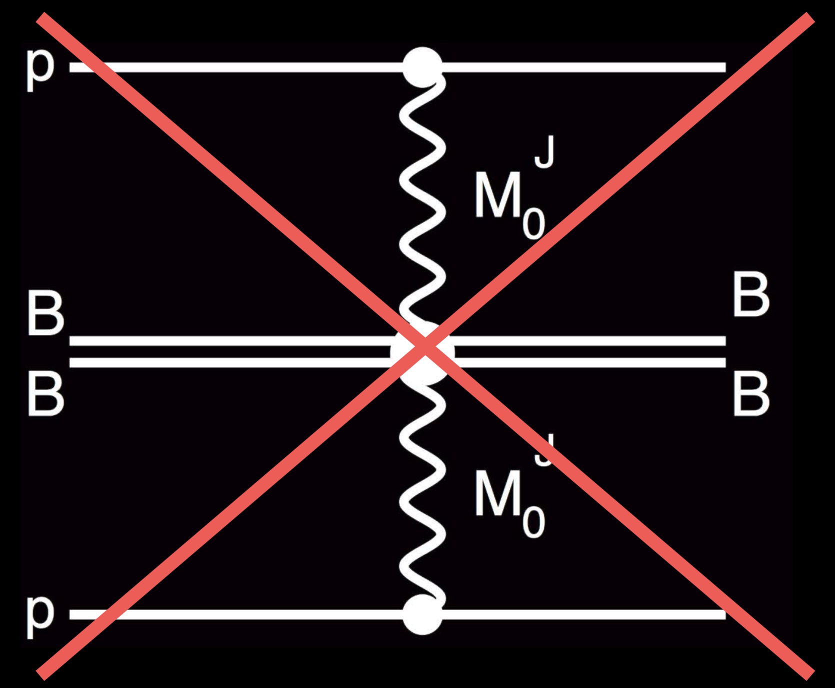


✓ $e^{0.58(y-Y_{\mathrm{beam}})}$

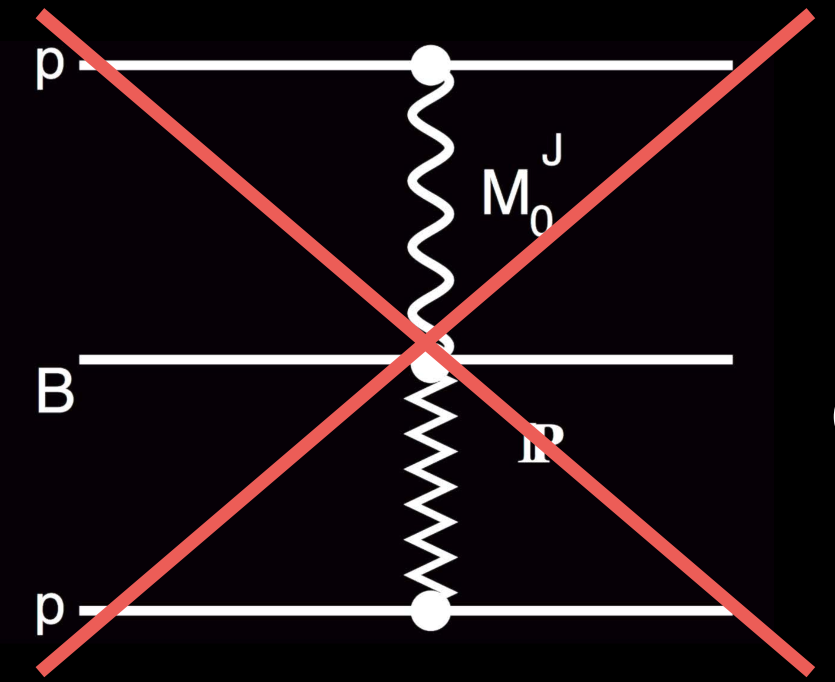


Baryon free projectile: photon-induced processes

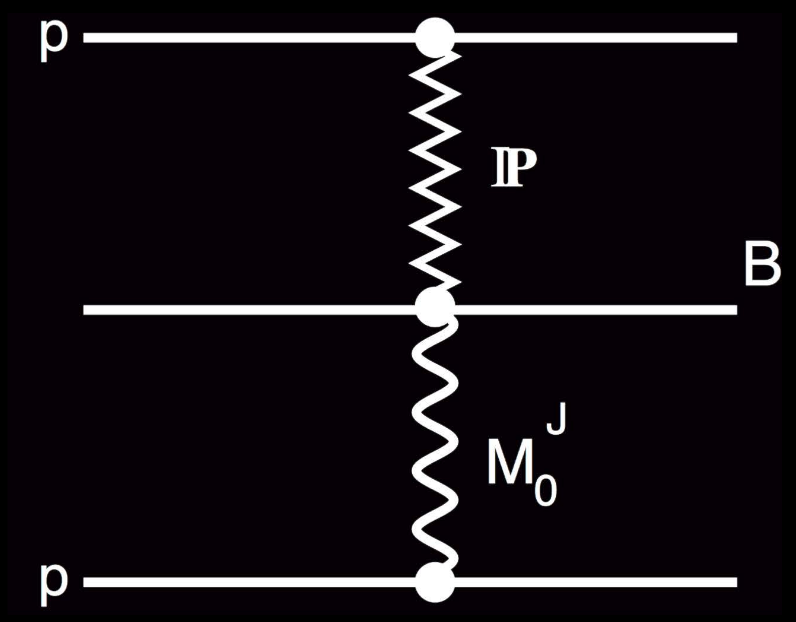
Brandenburg, Lewis, Tribedy, Xu, arXiv:2205.05685



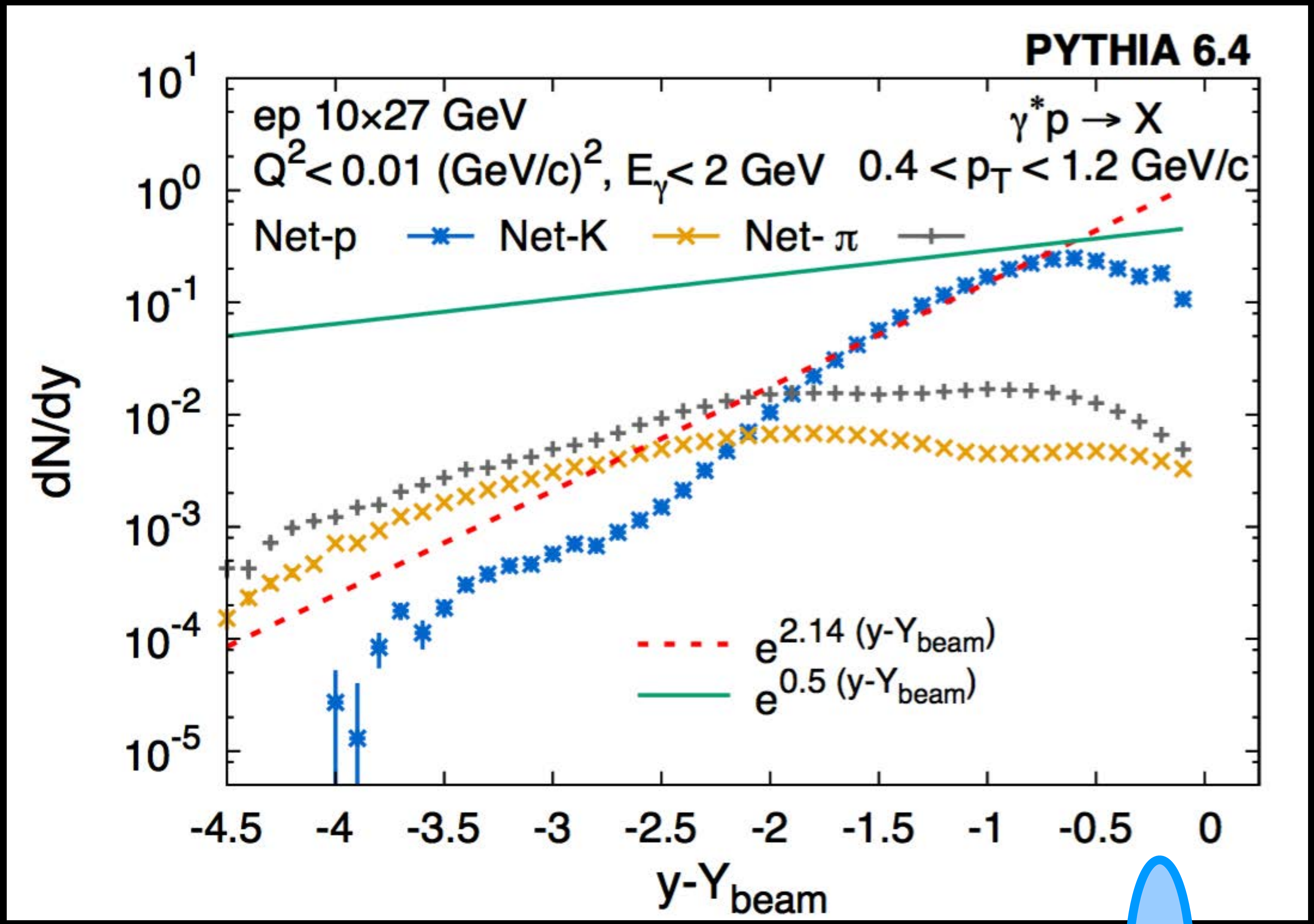
$\sim e^{\pm Y_{\mathrm{beam}}}$



$e^{-0.58(y+Y_{\mathrm{beam}})}$



$e^{0.58(y-Y_{\mathrm{beam}})}$



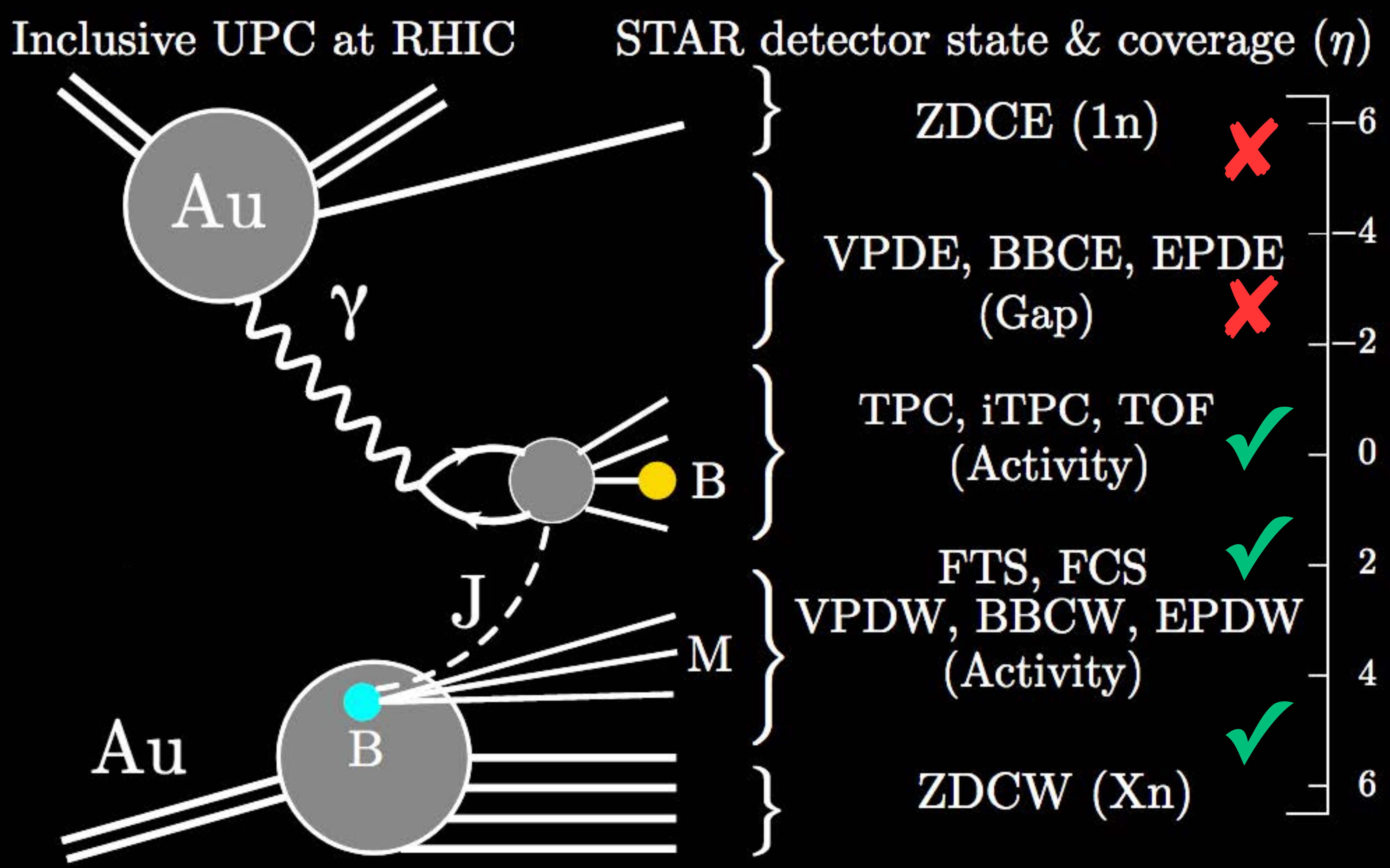
Junction as baryon carrier: $\sim e^{0.58(y-Y_{\mathrm{beam}})}$

PYTHIA (Quark as baryon carrier): $\sim e^{2.14(y-Y_{\mathrm{beam}})}$

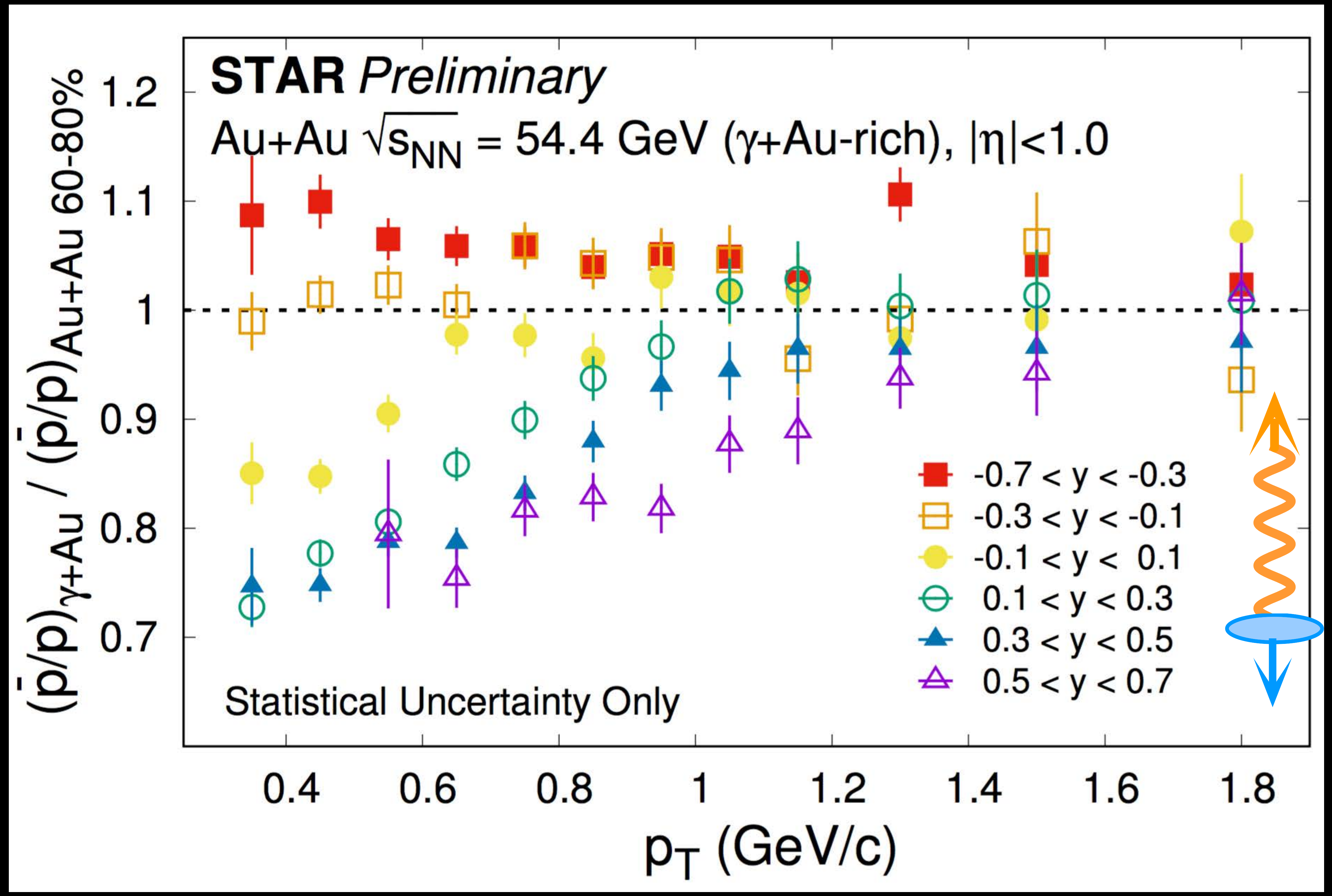
Measurements in ultra-peripheral collisions from STAR

Nicole Lewis (STAR collaboration), QM 2022

Triggering photonuclear processes with STAR detector

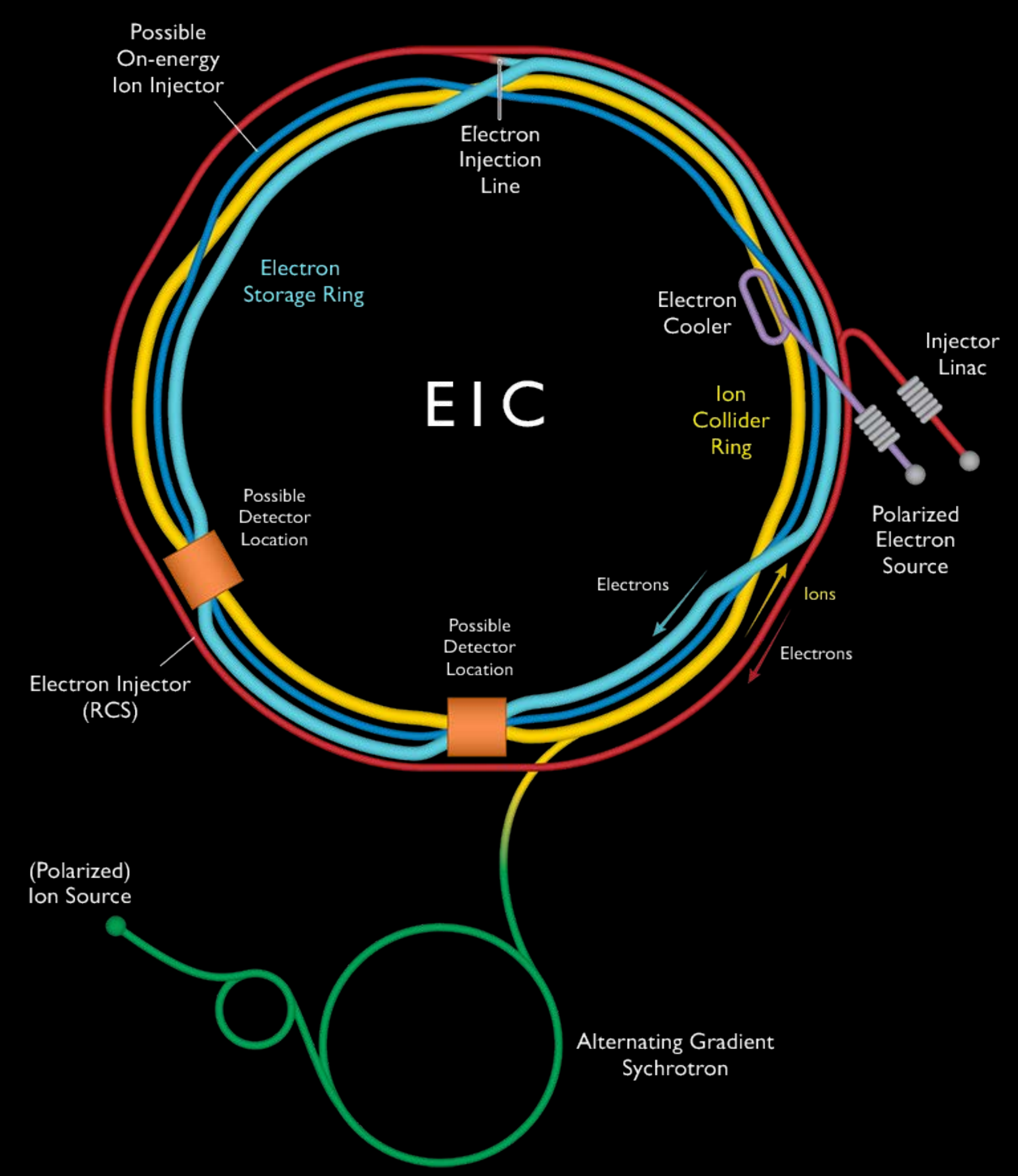


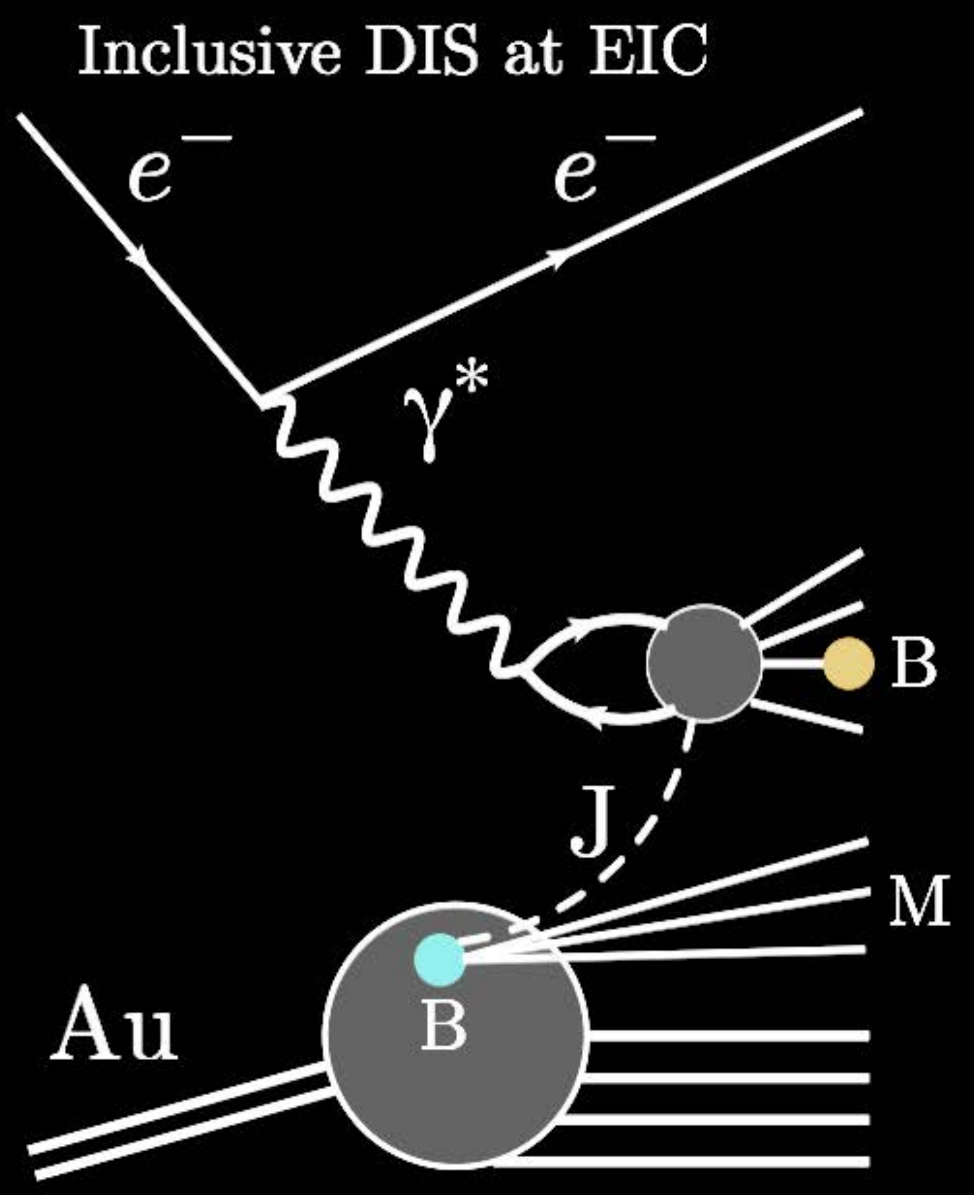
Stronger rapidity dependent stopping in γ+Au ≫ Au+Au



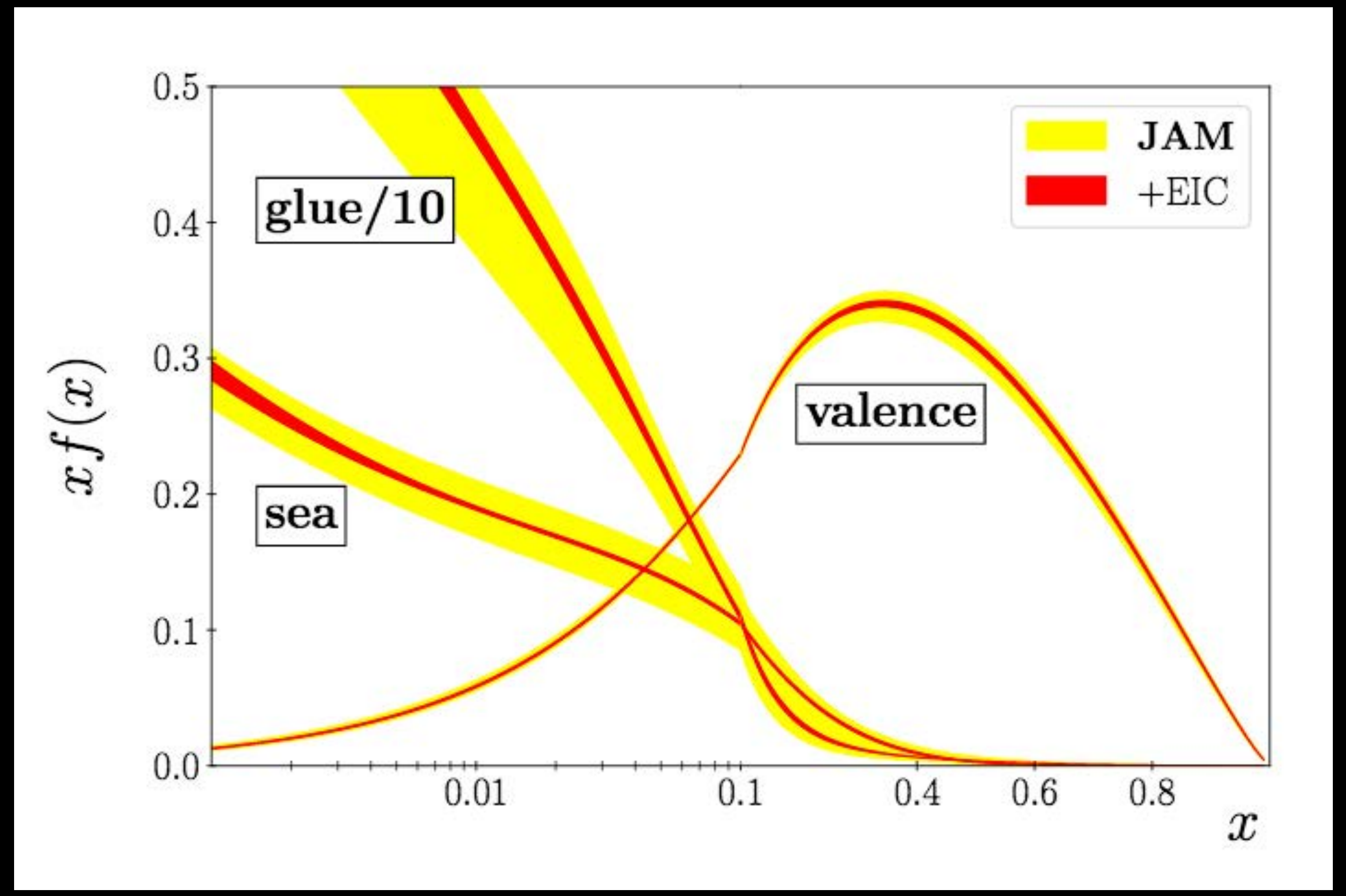
Interesting rapidity dependence of soft baryon stopping observed in RHIC photonuclear events, stay tuned for more results

Opportunities at the EIC

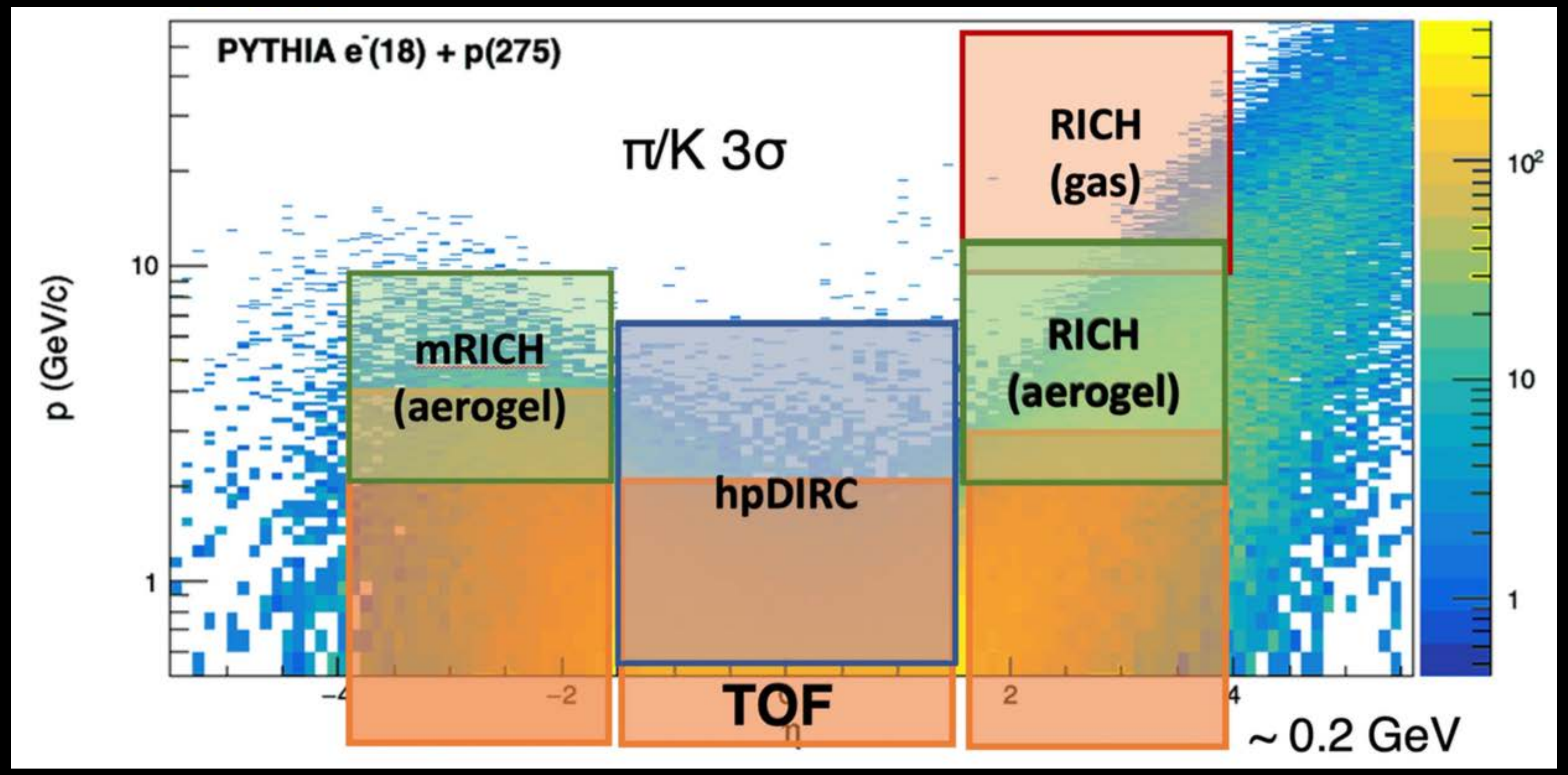


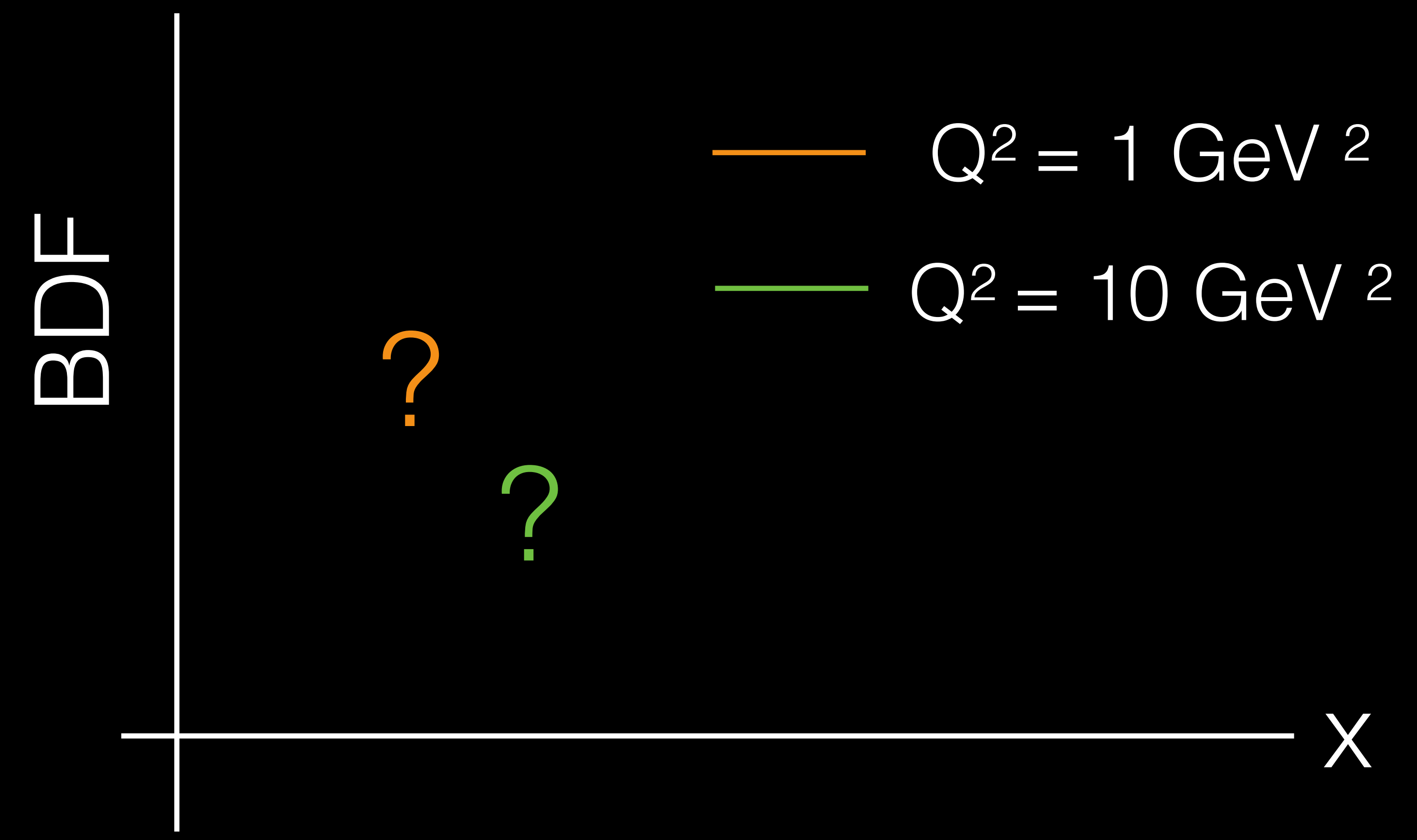


EIC yellow report, arXiv:2103.05419



PDF equivalent of baryons ?

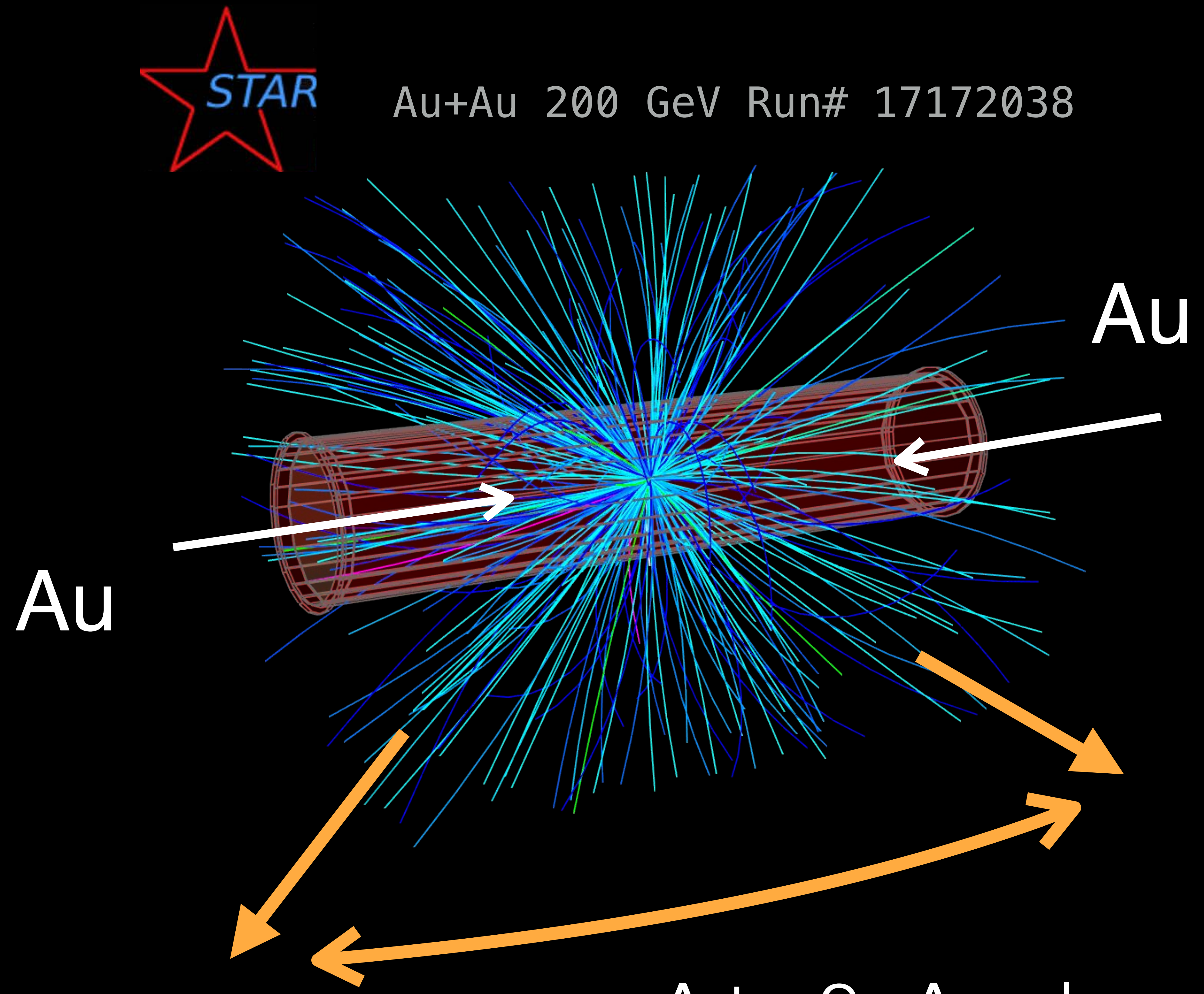




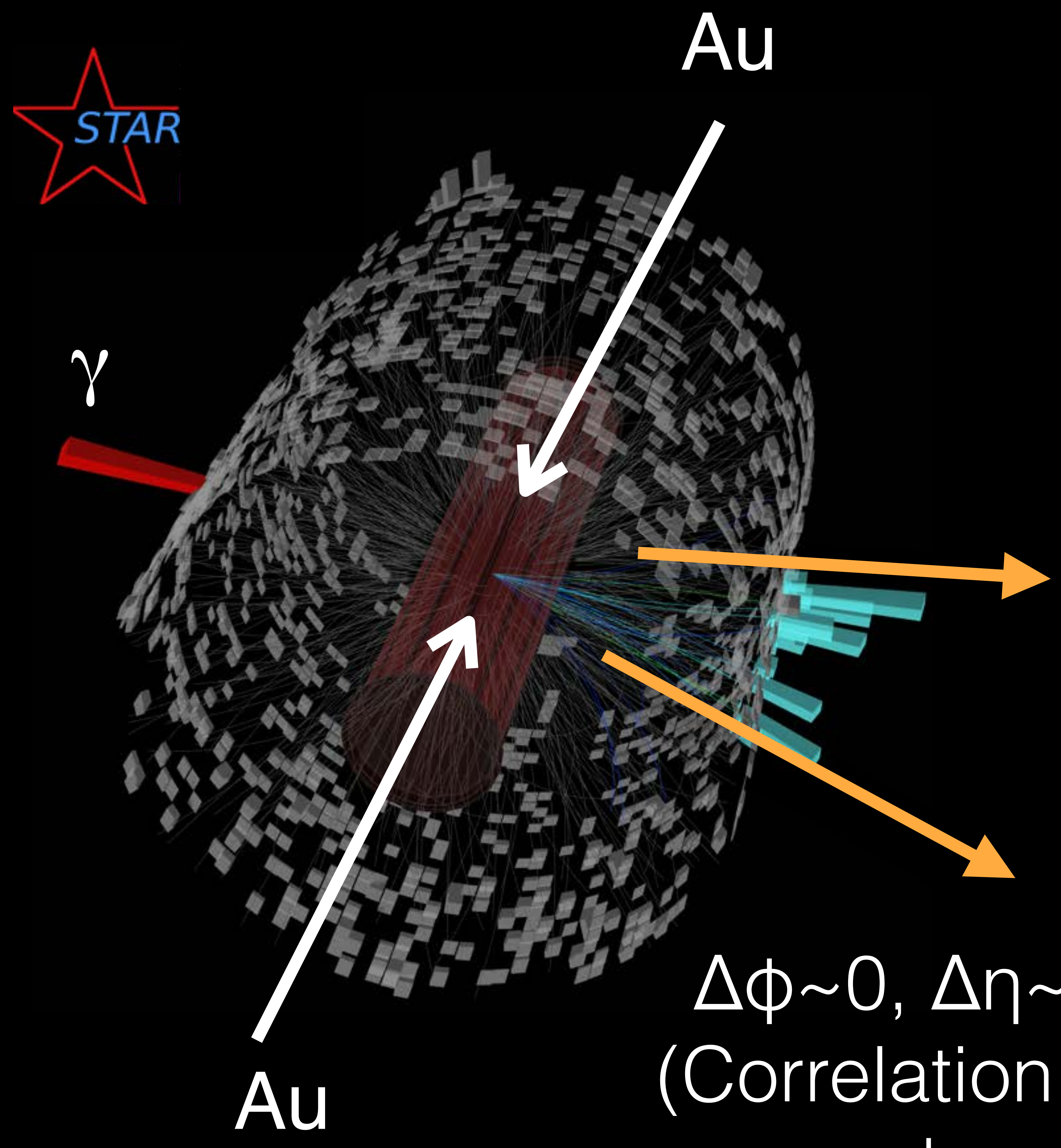
Low momentum PID detector (TOF) needed

Origin of collectivity in small collision system

What is collectivity?



Δϕ~0, Δη~large
(Correlation pattern repeated over **wide** phase space)

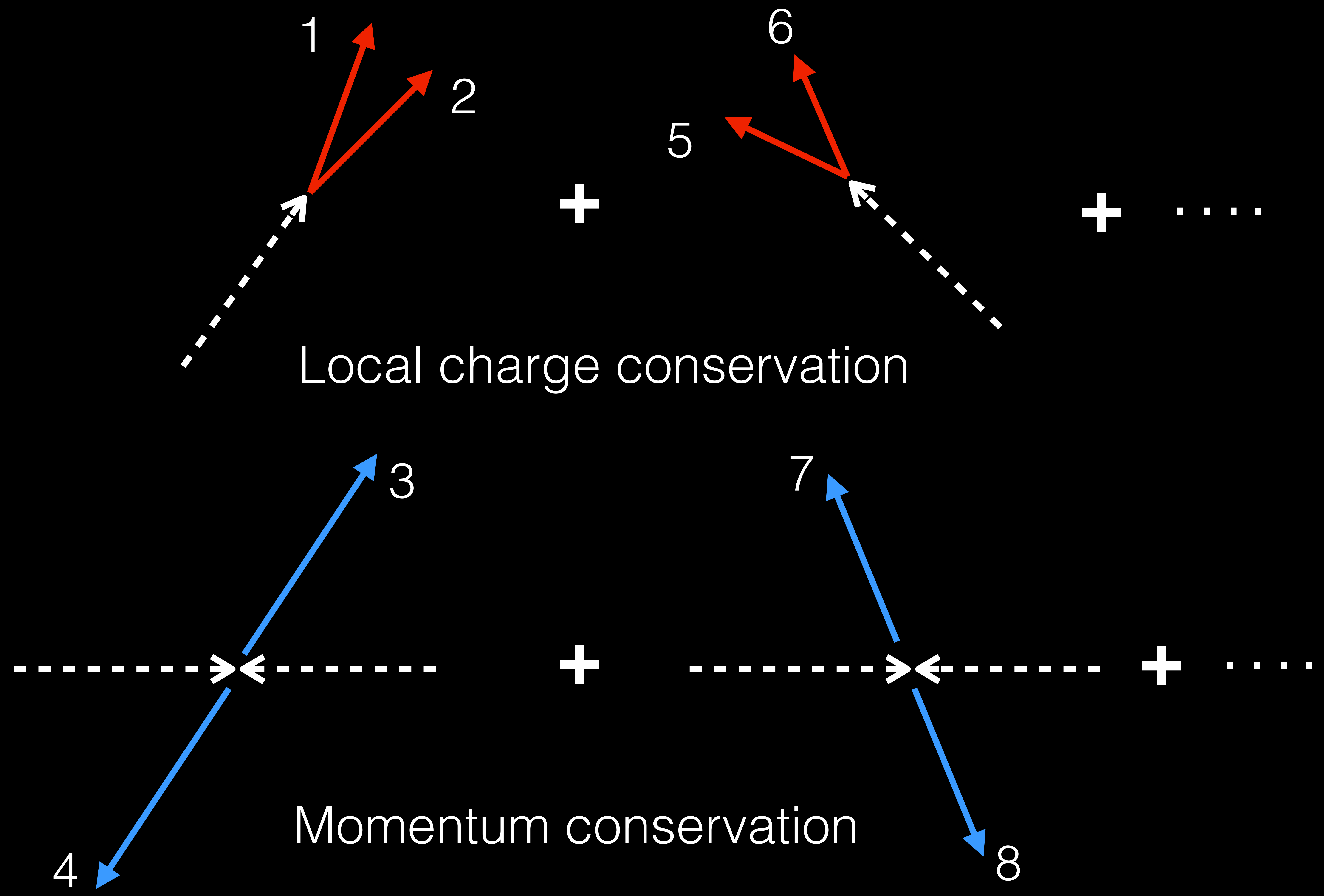


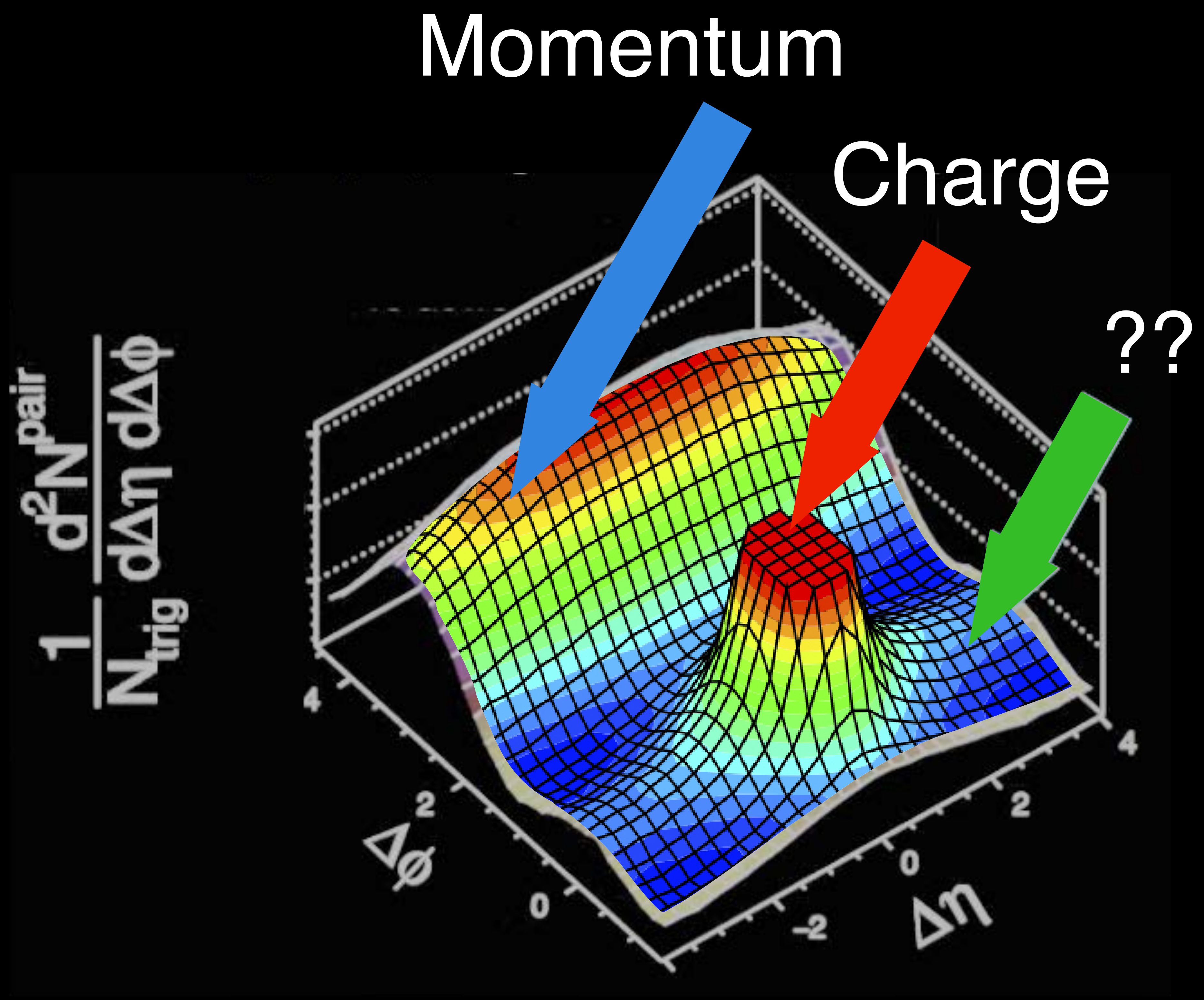
Δϕ~0, Δη~small
(Correlation over a **narrow** phase space)

Collectivity ⟹ observation of a specific pattern or behavior that is followed by most of its constituents in a system

What is collectivity: NOT at common phenomenon

At fundamental levels conservation laws determine correlation among few particles



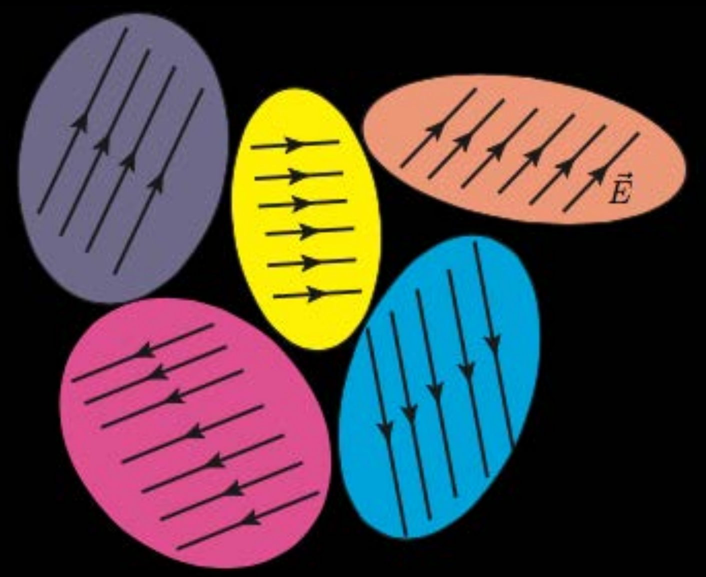


Conservation processes lead to perfect configurations,collectivity is different & associated with deviation from such a pattern

A+A → p+A → p+p → e(γ)+A → e(γ)+p → e+e: at what size does it set in?

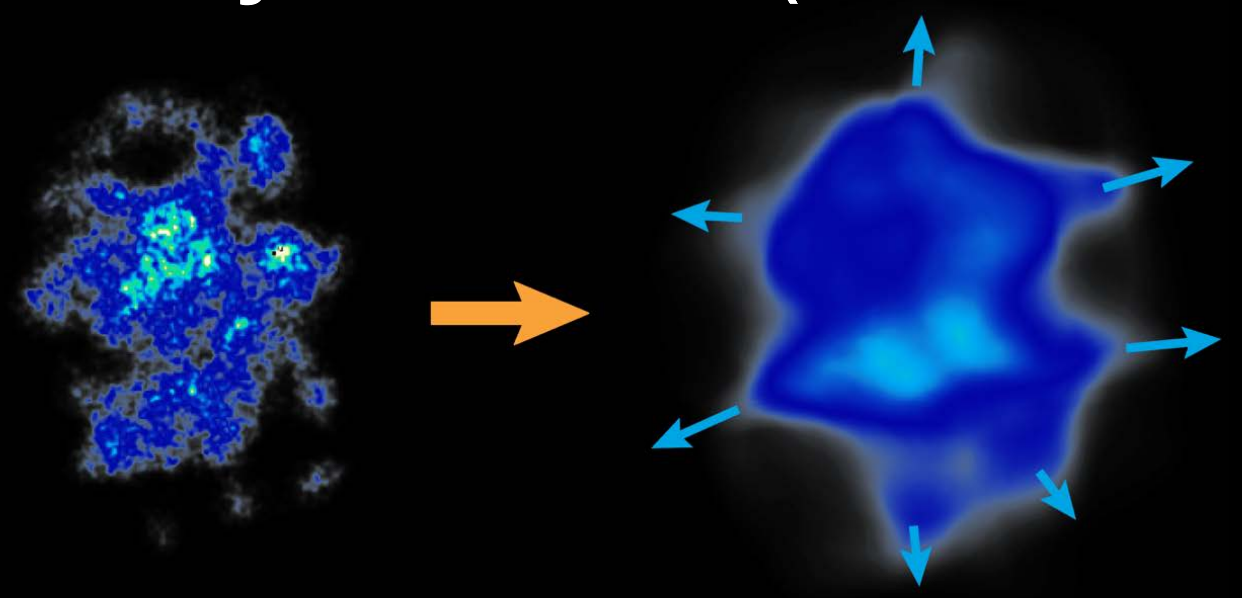
What drives it in small system?

Color Glass Condensate
(initial state momentum)



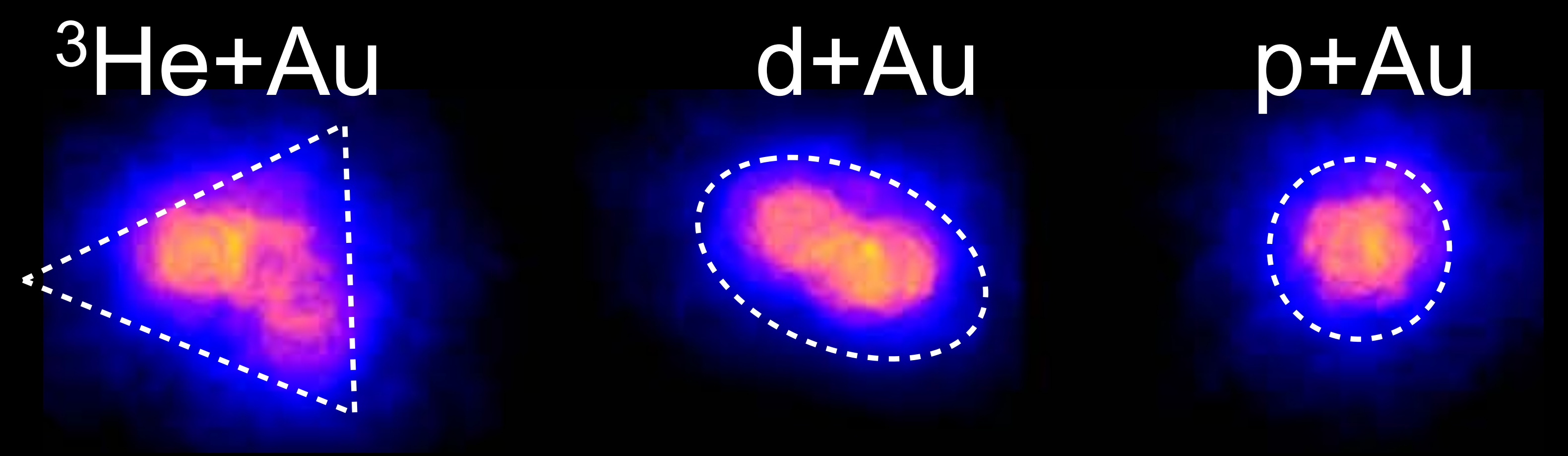
$v_2(^3He+Au) < v_2(d+Au) < v_2(p+Au)$

Hydrodynamics (final state)

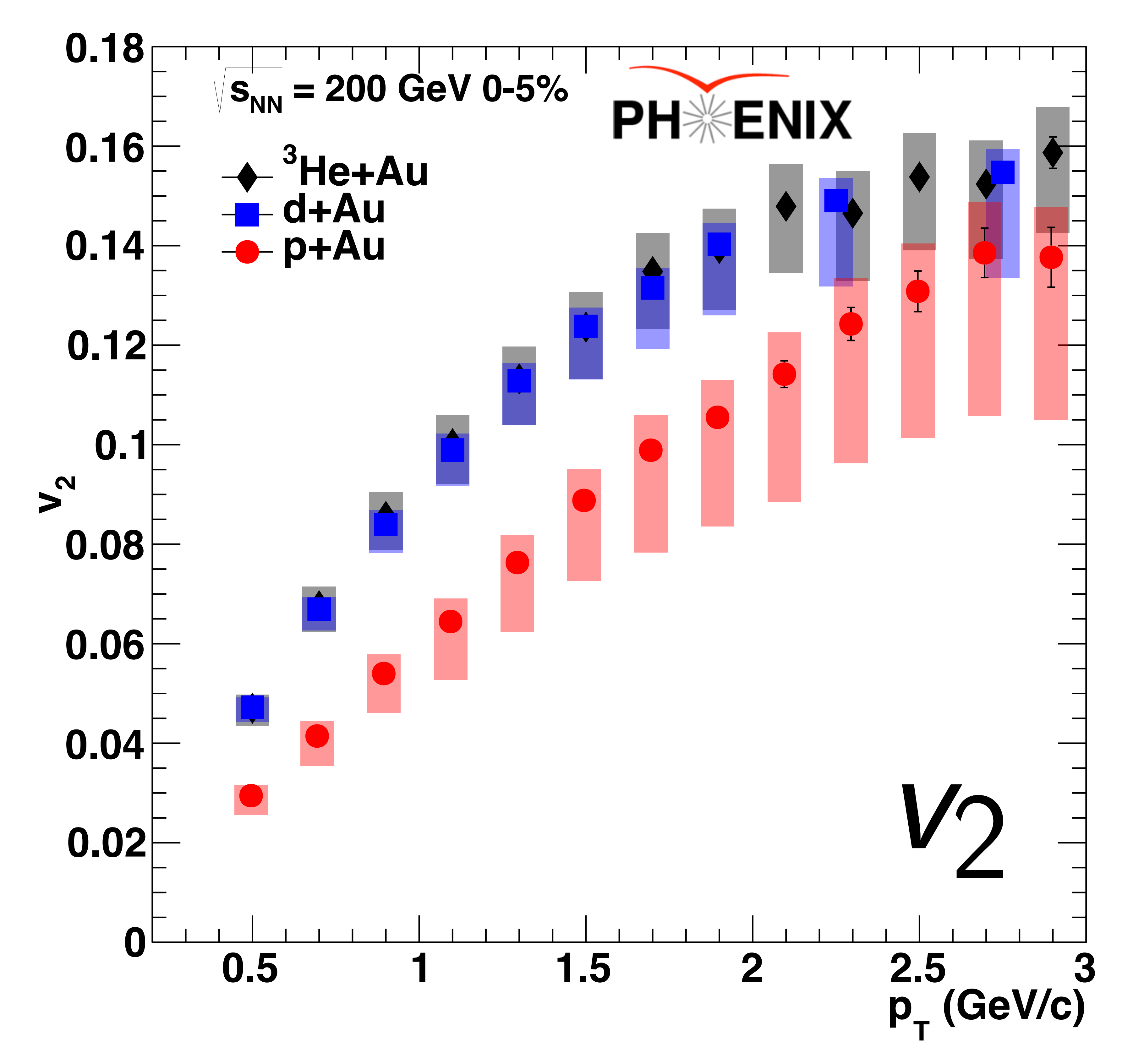


$v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$

PHENIX collab, Nature Physics 15, 214–220 (2019), Phys. Rev. C 105, 024901 (2022)



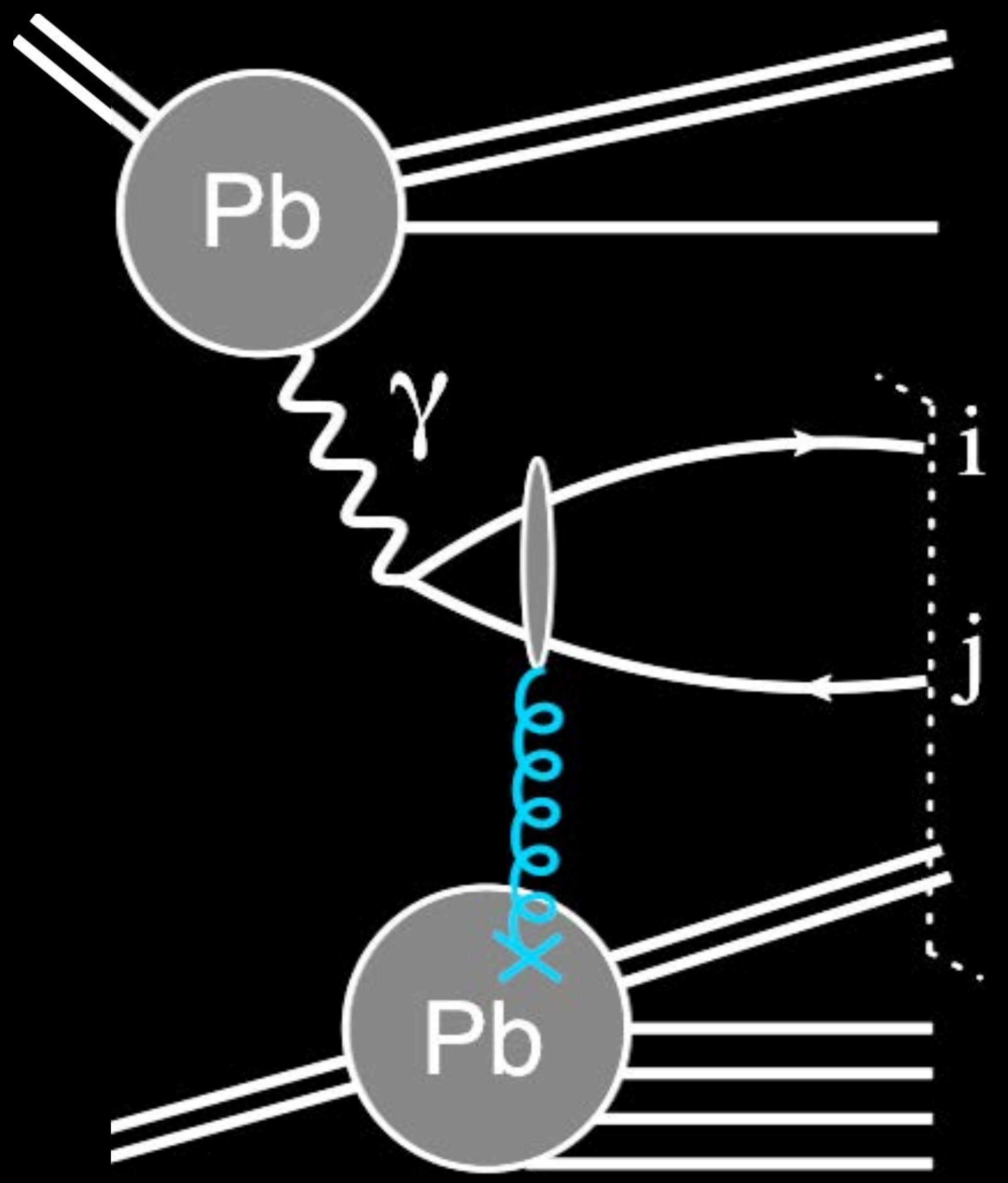
$v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$

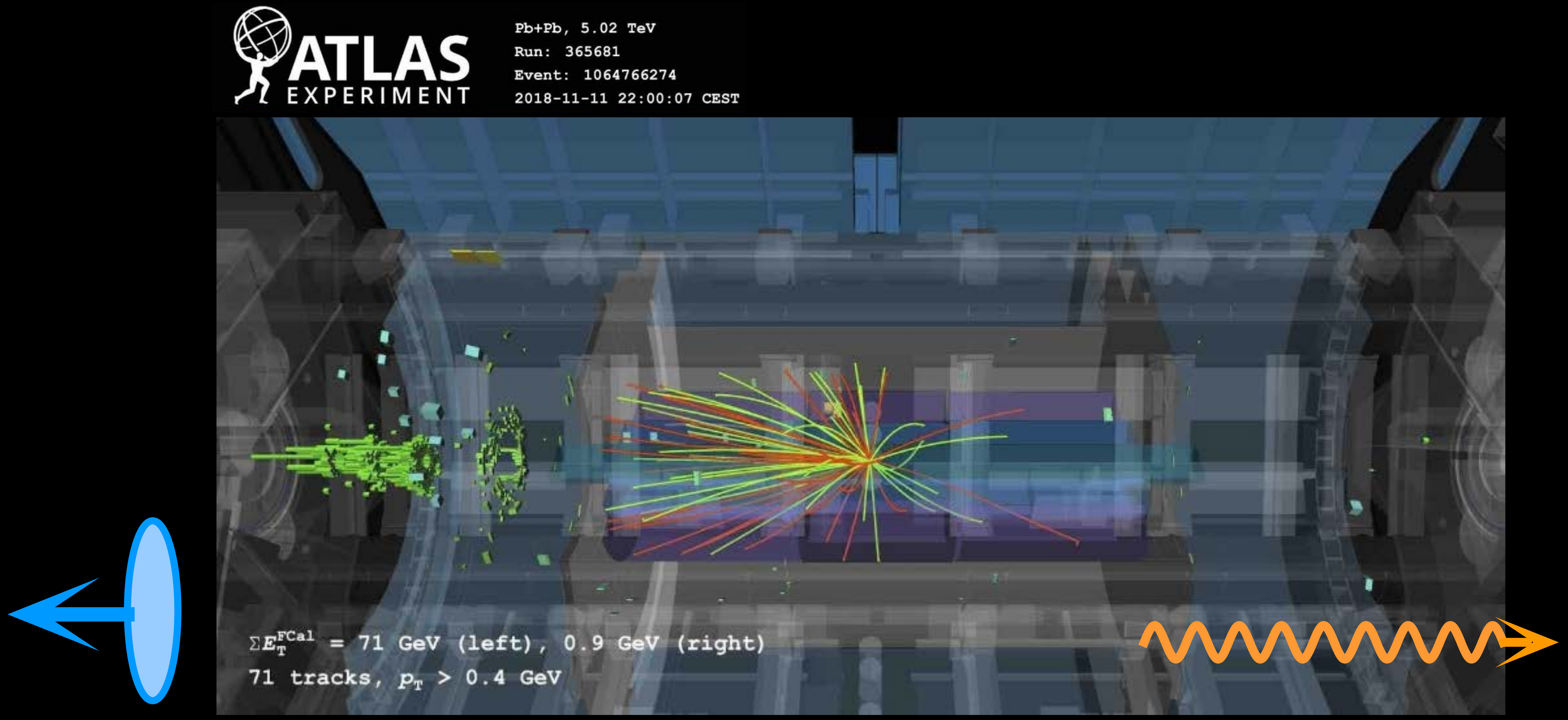


PHENIX results decisively establishes hydrodynamic final state is essential

Collectivity in photon-induced process

γ+Pb event by trigged in ultra-peripheral Pb+Pb collisions by ATLAS

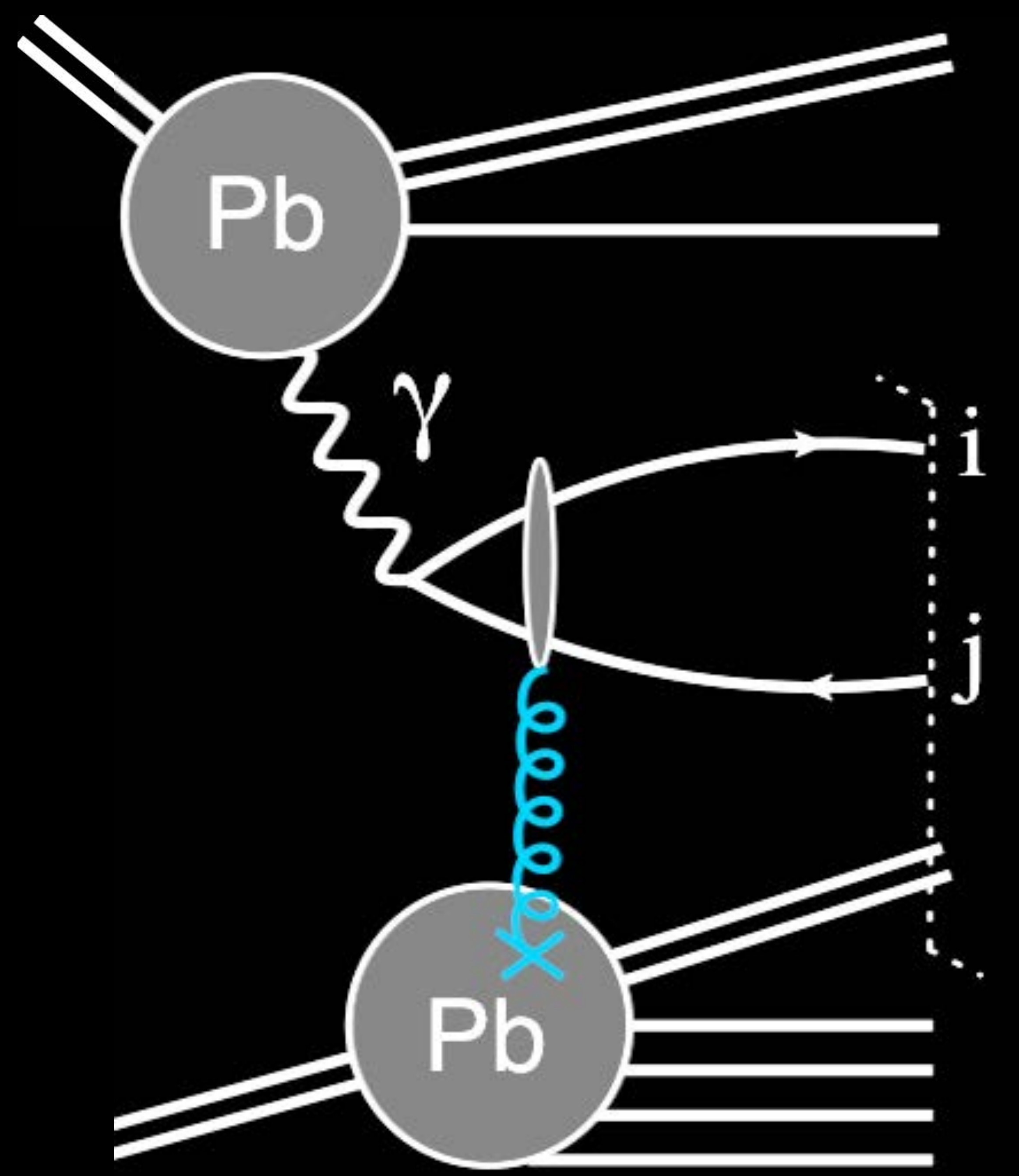


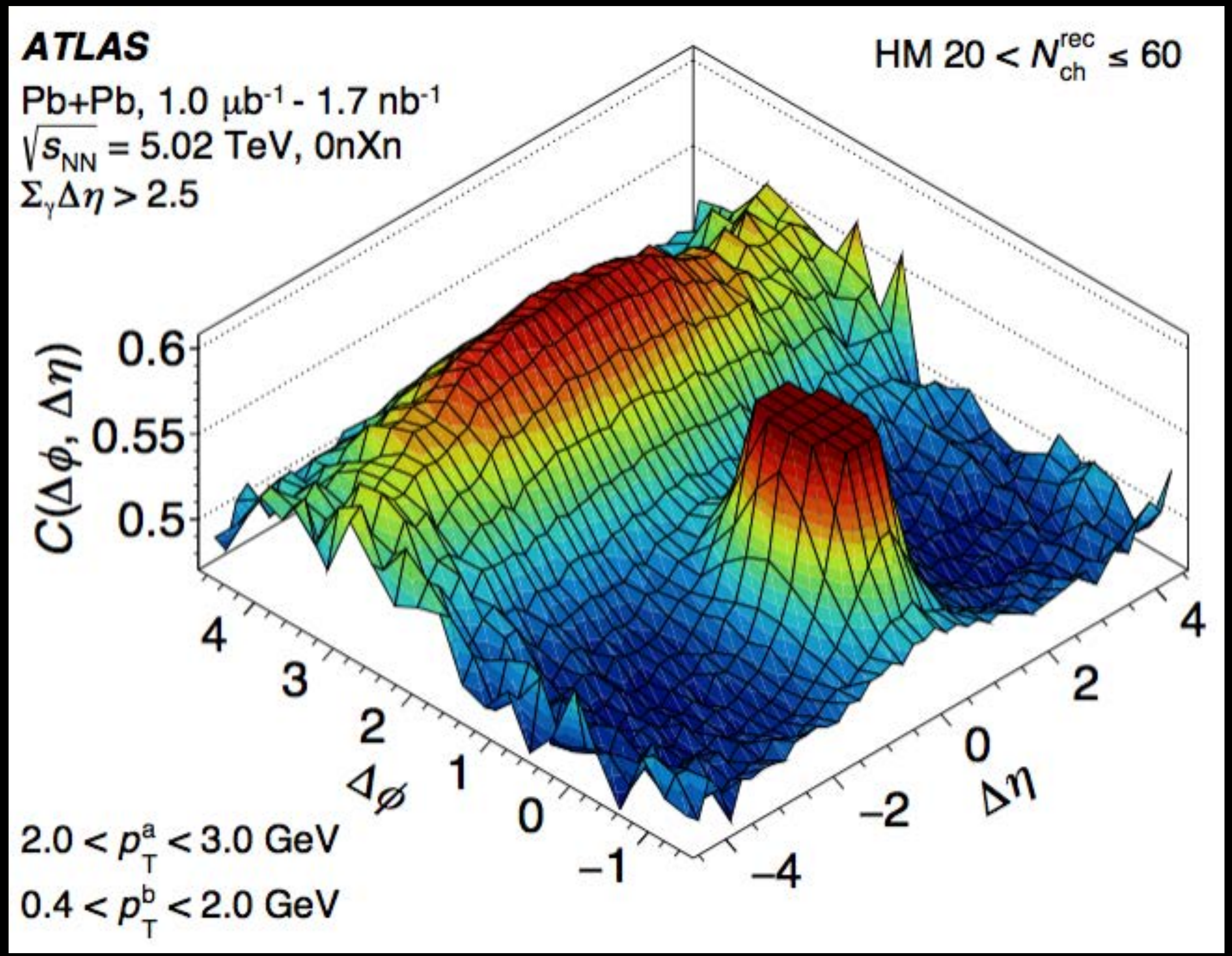


$W_{\gamma Pb}$ (LHC) ~ 844 GeV, $dN_{trk}/d\eta$ (HM) > 10

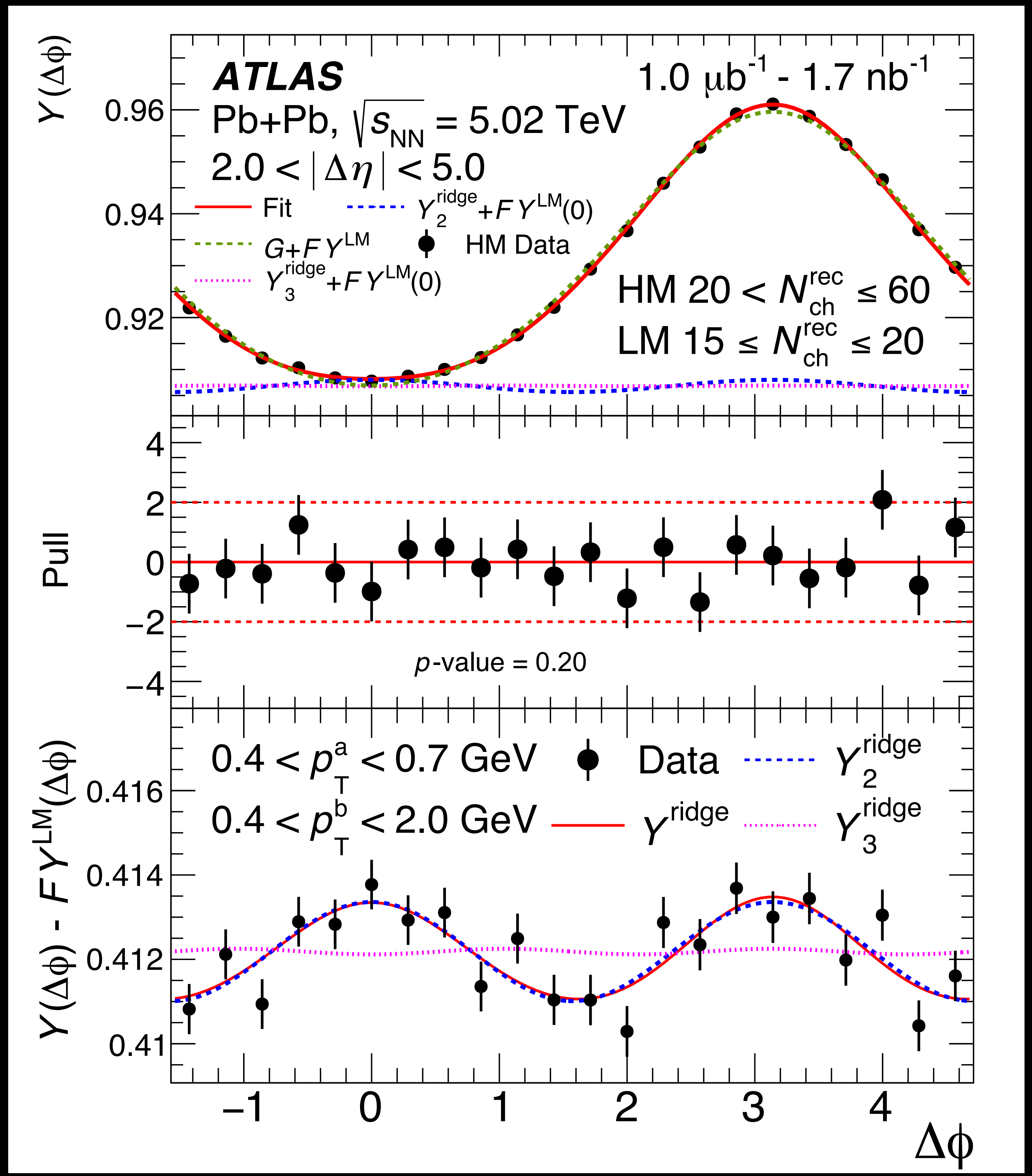
Do we observe collectivity in such collisions ?

Search for collectivity UPC collisions at the LHC





ATLAS collab., Phys. Rev. C 104, 014903 (2021)



$$Y(\Delta\phi, 2<|\Delta\eta|<5) = \frac{1}{N_{\mathrm{trig}}}\frac{d^2N_{\mathrm{pair}}}{d\Delta\phi} = \frac{N_{\mathrm{asco}}}{2\pi}\left(1+\sum_n 2a_n\cos(n\Delta\phi)\right)$$

$$Y(\Delta\phi)^{\mathrm{template}}(HM) = FY(\Delta\phi)(LM) + Y(\Delta\phi)^{\mathrm{ridge}}(HM)$$

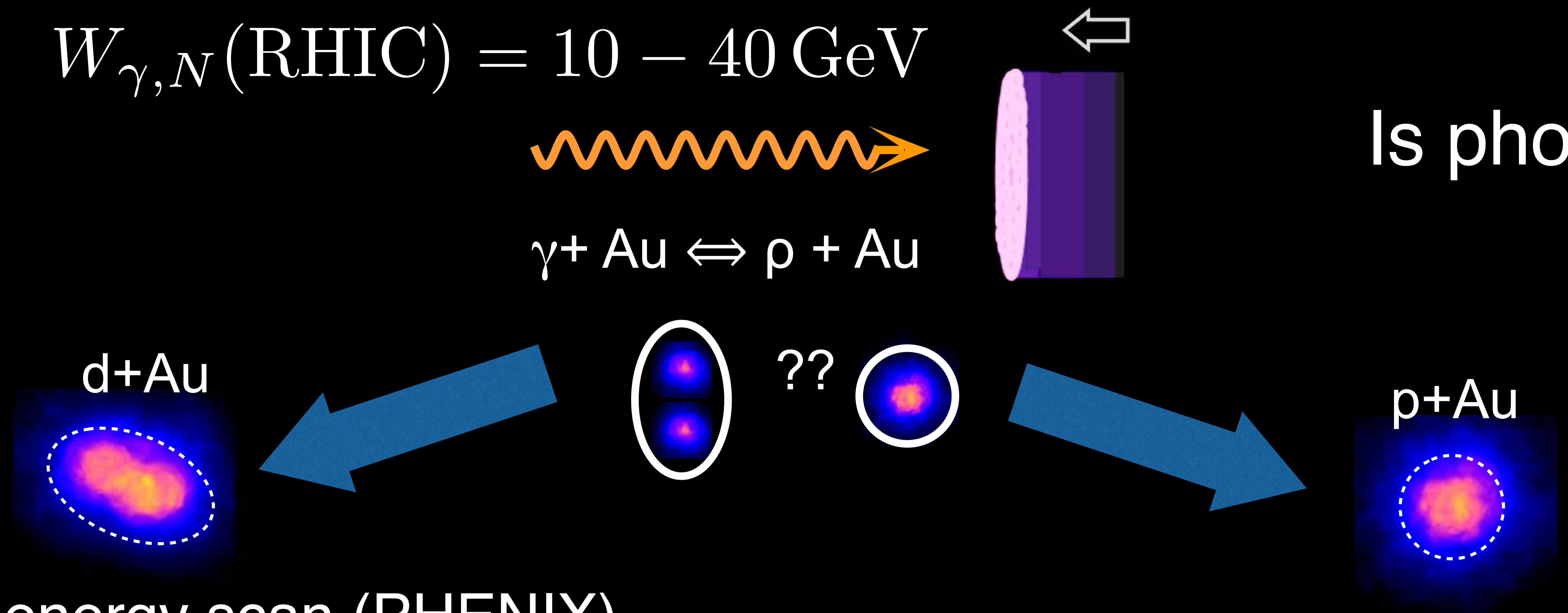
$$Y(\Delta\phi)^{\mathrm{ridge}}(HM) = G\{1+2a_2\cos(2\Delta\phi)+2a_3\cos(3\Delta\phi)+2a_4\cos(4\Delta\phi)\}$$

long-range di-hadron correlations observed

Hints of collectivity observed, does the medium experience fluid dynamic evolution ?

Small system collectivity: future measurements

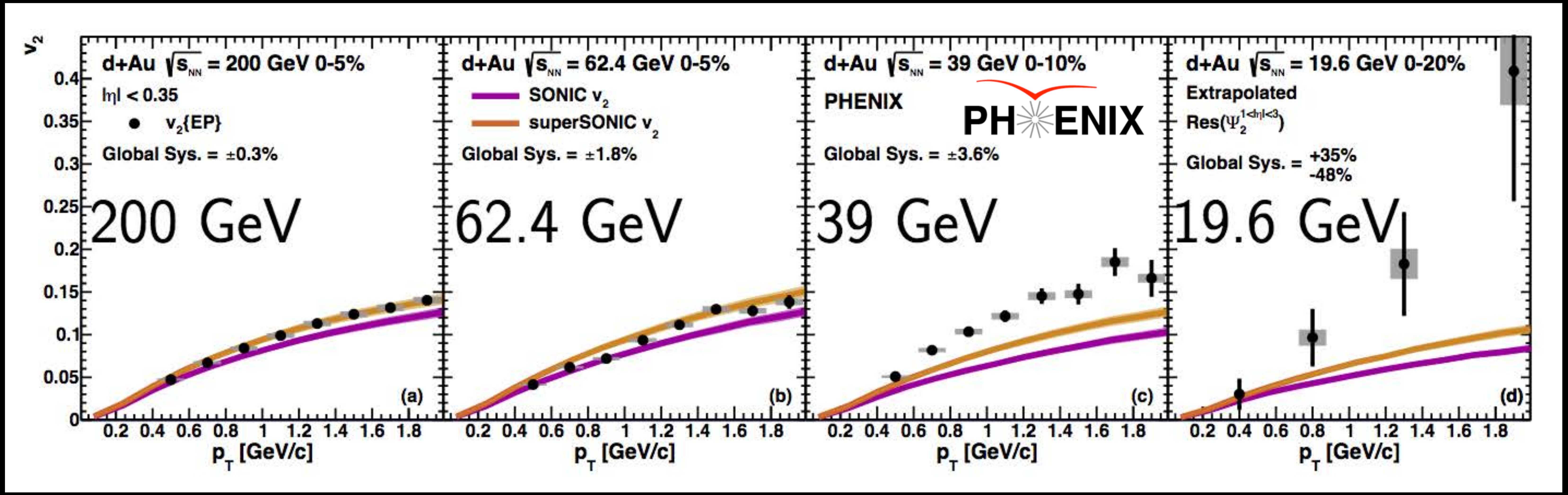
STAR BUR for Run 23-25
sPHENIX BUP 2022 (sPH-TRG-2022-001)
ATLAS Collab,Phys. Rev. C 104, 014903 (2021)



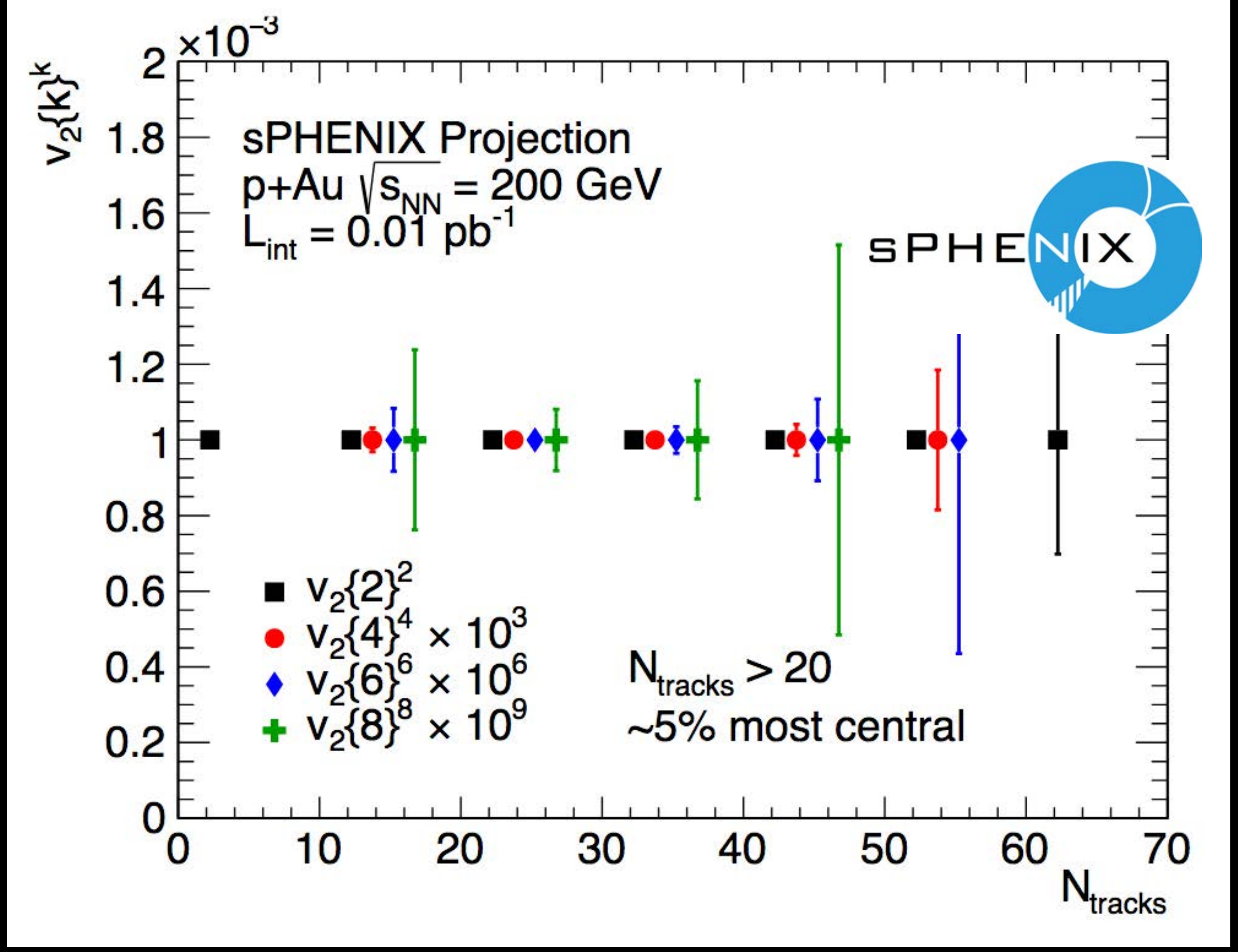
Is photon-ion collision like d+Au or p+Au ?

p+Au rapidity scan (sPHENIX + STAR 2024)

d+Au beam energy scan (PHENIX)



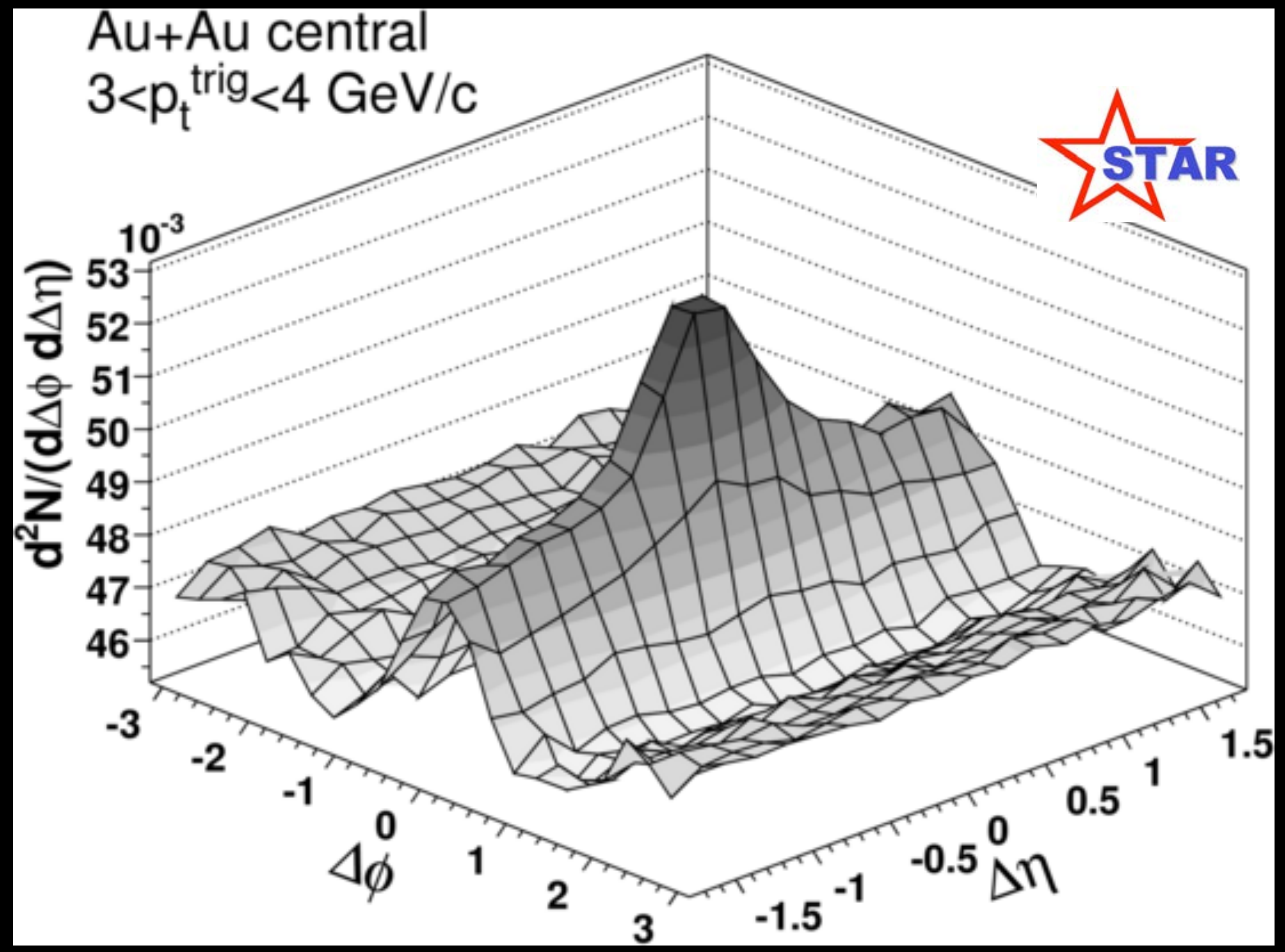
C. Aidala et al. (PHENIX Collab), Phys. Rev. C 96, 064905



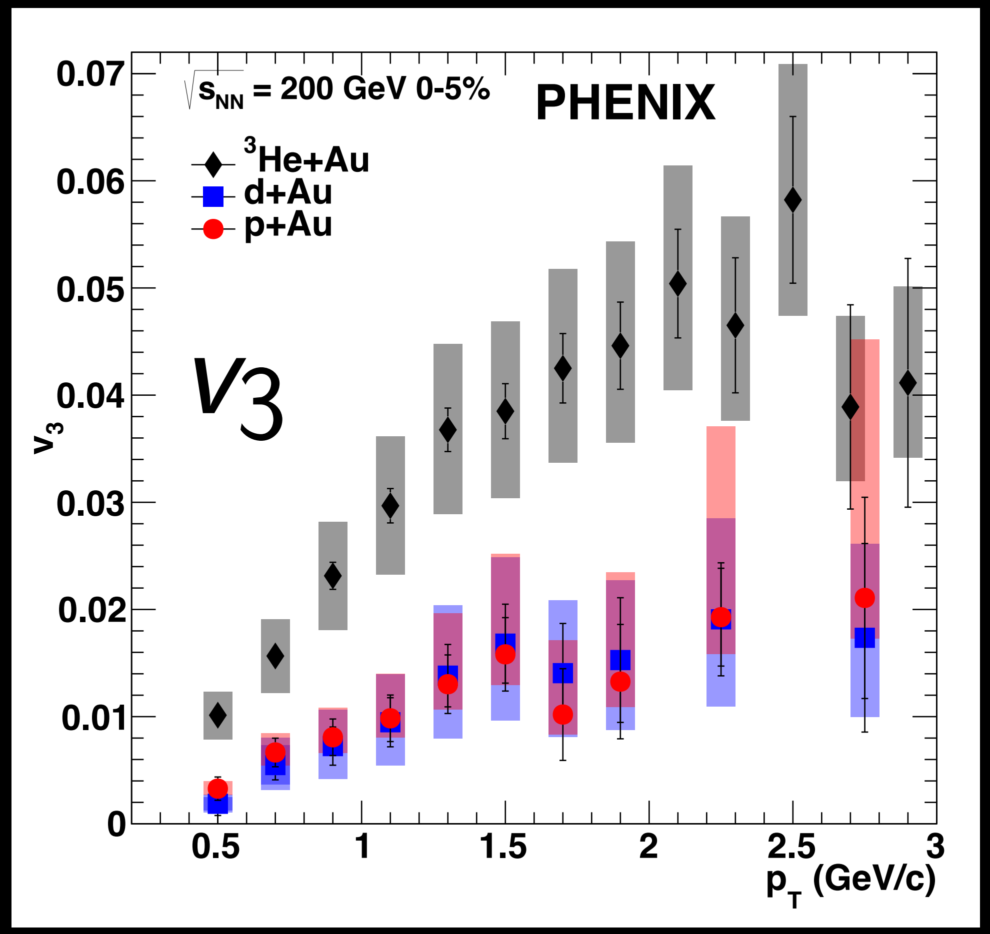
We can test if photon-ion collision system exhibit fluid behavior

Collectivity search from RHIC to EIC

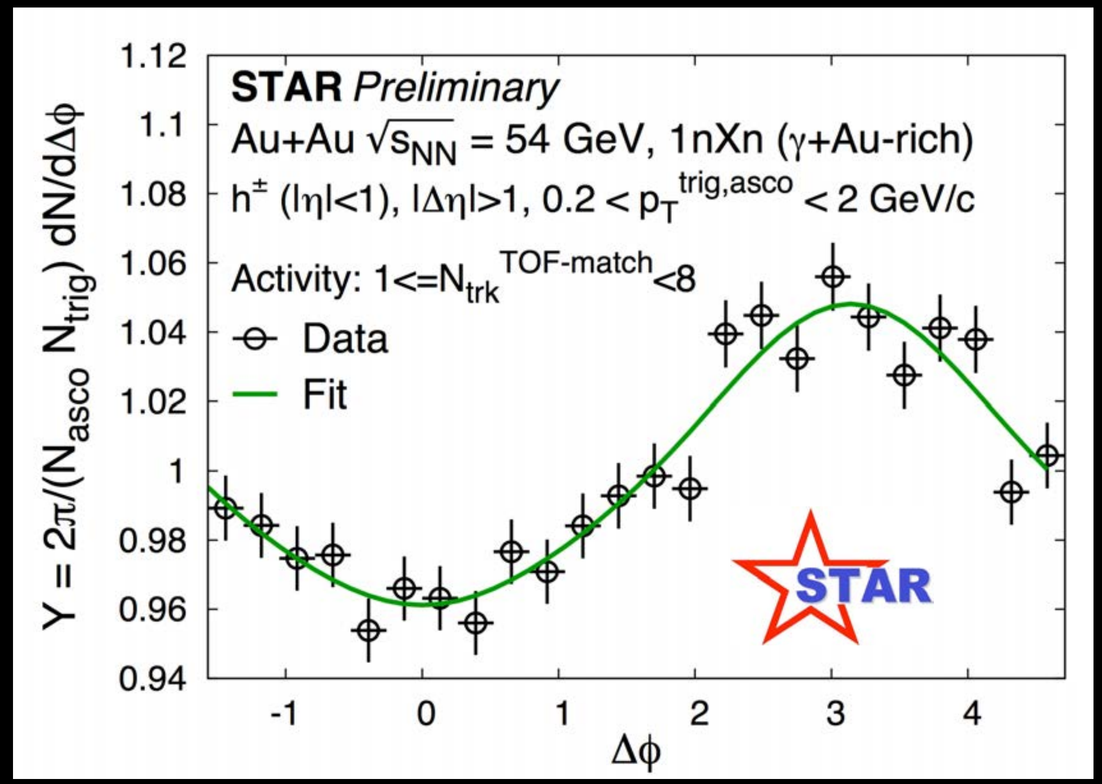
U+U | Au+Au | Ru+Ru | O+O | ^{3}He+Au | d+Au | p+Au | ρ + Au | dipole+A (EIC)



STAR collaboration, Phys. Rev. Lett. 95, 152301
Phys. Rev. C 80 (2009) 64912



PHENIX collab, Nature Physics 15, 214–220 (2019)



STAR Collab. QM 2022

Will γ*+A be the next small system ?

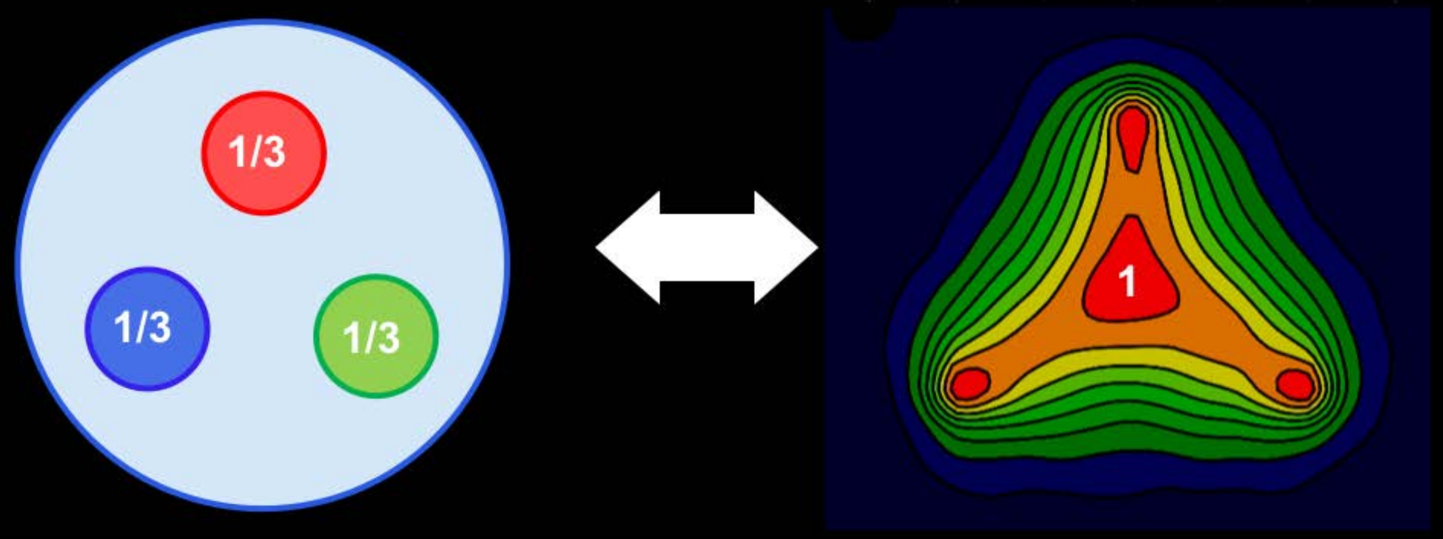
EPIC collaboration, 2030+

RHIC system scan sets the stage for collectivity search at EIC

Summary

What carries the baryon number and how it is stopped?

Two approaches identified to explore:

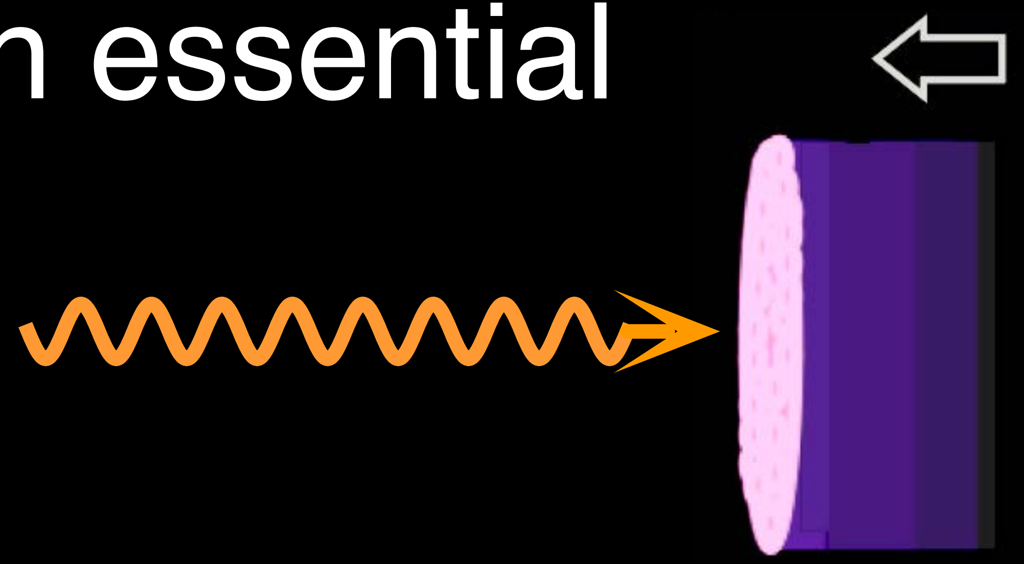


1. Charge vs. baryon stopping in isobar collisions at RHIC
2. Baryon stopping in γ+A processes (RHIC/LHC UPC & EIC)

What drives collectivity? Will fluid-like behavior be seen in photon-induced events?

RHIC small system collision established that fluid-dynamic evolution essential

UPC can be a doorway to study collectivity at the future EIC



Many exciting new opportunities for young students:

1. RHIC took data on O+O, d+Au, possible O+O run at the LHC
2. RHIC run 2023-25 will collect large dataset on γ+Au collisions