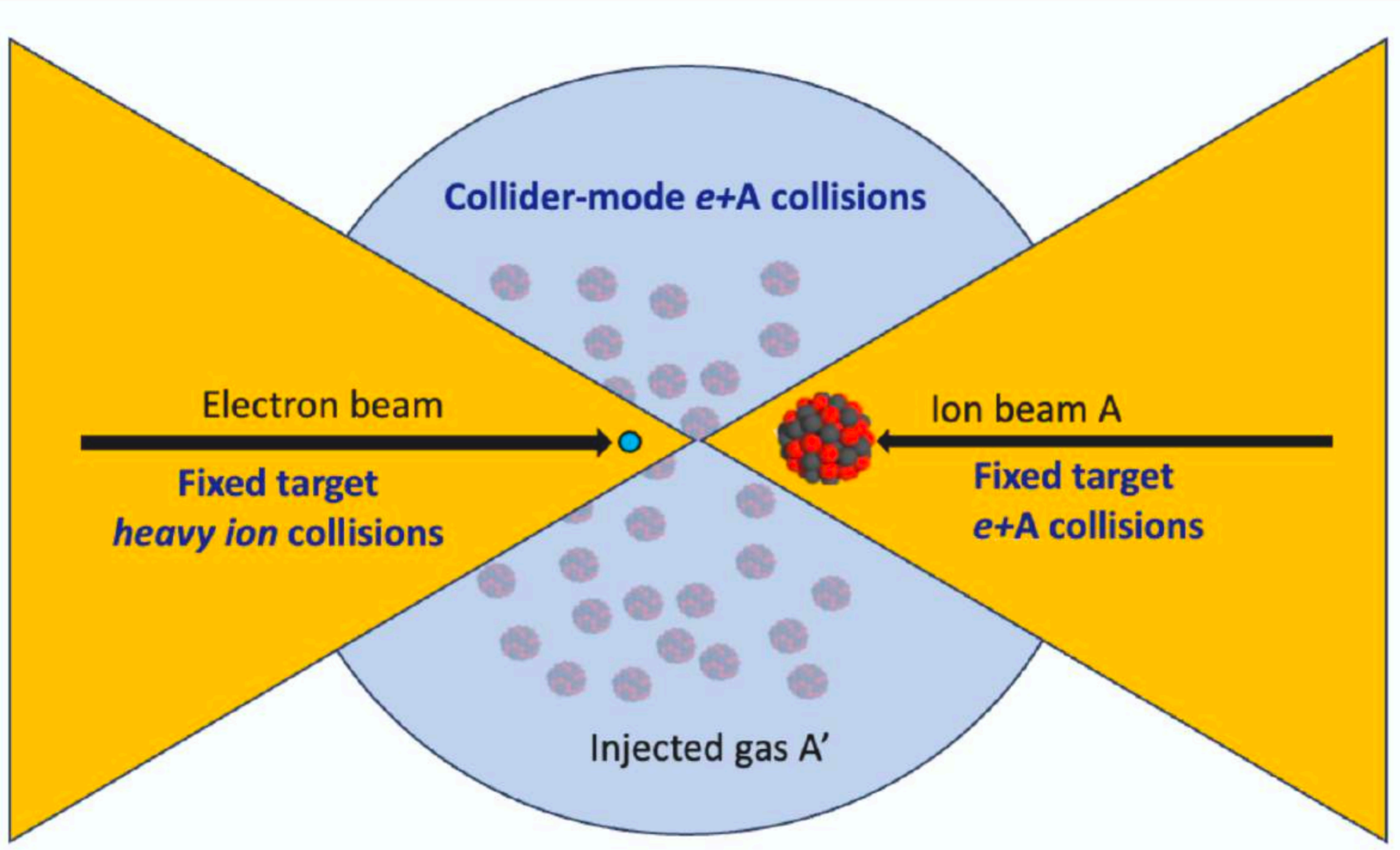
Exploring a fixed-target program at ePIC@EIC

September, 30, 2025

C-J. Naïm



Stony Brook University

Center for Frontiers in Nuclear Science

Physics Motivations to a Physics Case?

What can we learn with a fixed-target program?

- **Access to large-**x **region** → essential to study nuclear effects across extended phase space
- **Small-pT coverage** → probe TMD dynamics, resummation, and non-perturbative QCD effects
- **Charm production** → intrinsic charm, open-charm production
- **Variety of nuclear targets** → enables systematic studies and direct tests of **A-dependence**
- **Complementary to collider mode** → extends reach to extreme kinematics with high luminosity

The Strategy

A+A

Fixed-target

p+A

Heavy Ion

EIC

Cold QCD

QCD transition
Nuclear data
Nasa's studies (new fundings)

Large-x physics
Hadronization studies
Nuclear medium modification

Societal Program for EIC
A goal for NSAC 2023

Collider

e+A

QCD

The EIC must be thought as a cornerstone of QCD

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It is not a new experiment

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Physics Motivations to a Physics Case?

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It is not a new experiment

It is not two physics programs in competition

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Physics Motivations to a Physics Case?

It is **not** a new experiment

It is **not** two physics programs in competition

It is **not** an expensive program

The EIC must be thought as a cornerstone of QCD

It is **not** a new experiment

It is **not** two physics programs in competition

It is **not** an expensive program

It is **not** a different community

Physics Motivations to a Physics Case?

It is a new mode

It is the same community

The cost remains minimal

It is a synergy

It is EIC

A+A

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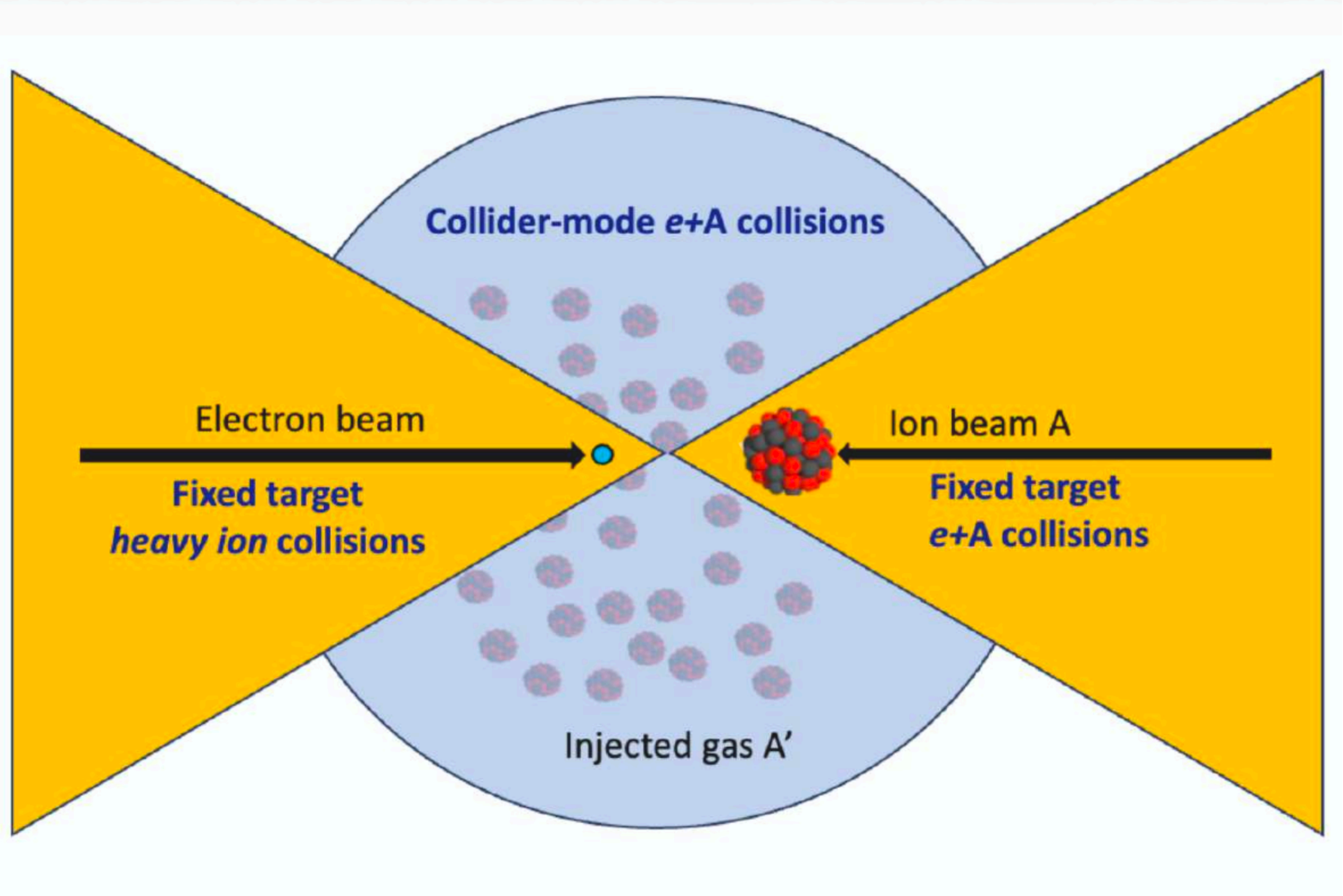


p (beam) +A (target) collisions

$\sqrt{s} = 6.8 - 22.2$ GeV

$I \sim 10^{18}$ p/s

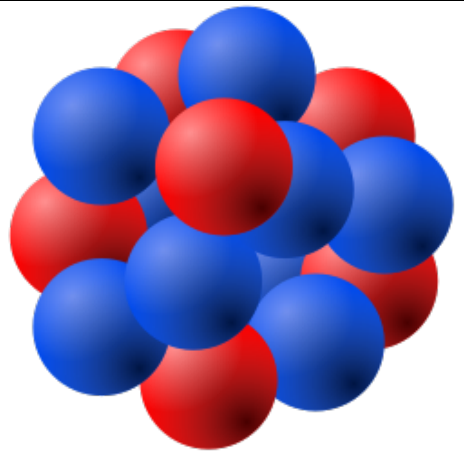
A (beam) +A (target) collisions

$\sqrt{s} = 4.2 - 14.0$ GeV

$I \sim 10^{17}$ Au/s

Unique complementary beam types

Physics Motivations to a Physics Case?



QCD Nuclear Matter studies – p+A collisions

- **Objective** – Provide A-dependance measurements at large x
- **Interest** – Complementary to small-x physics, CNM effects
- **Physics processes**
  - Light & Heavy flavor production
  - Quarkonium production (feed-down)
- **EIC Role** – Delivers unique FT data in a large energy range and at large rapidity

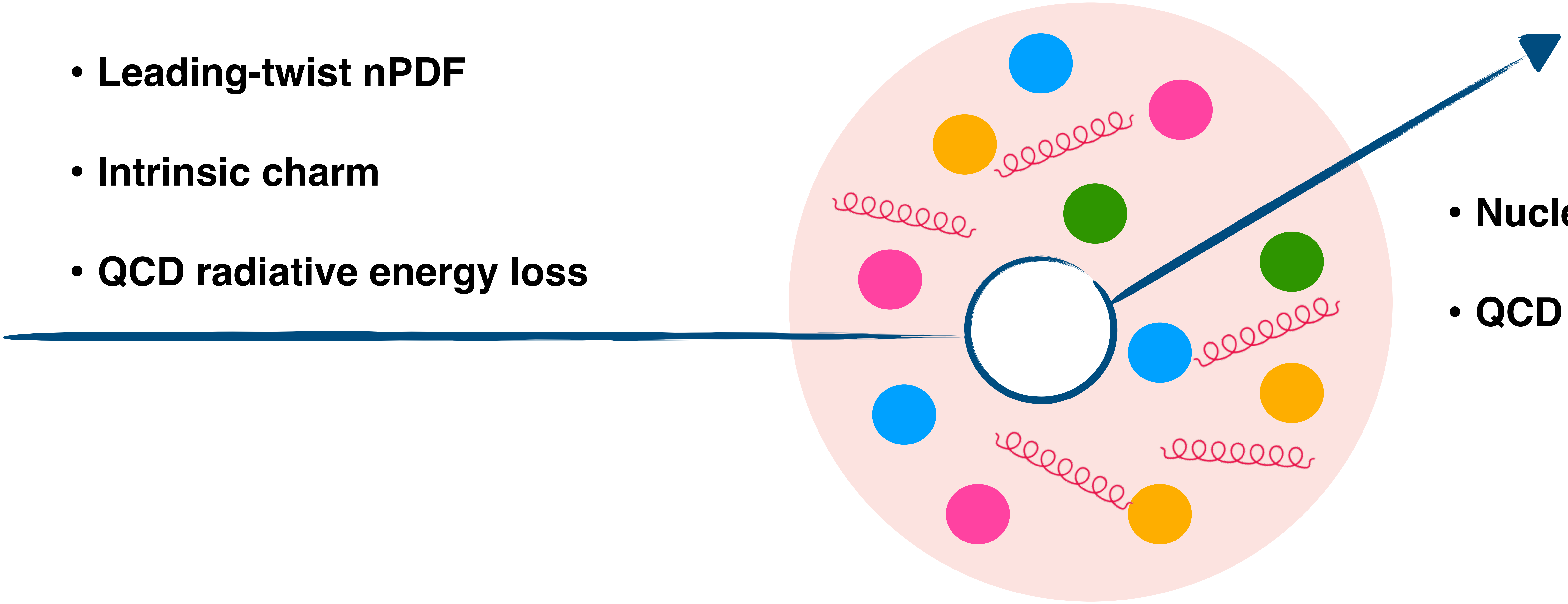
Physics Motivations to a Physics Case?

White Paper: Cold Nuclear QCD

F. Arleo et al., arXiv:2506.17454

Accepted in PRC, Perspective Article

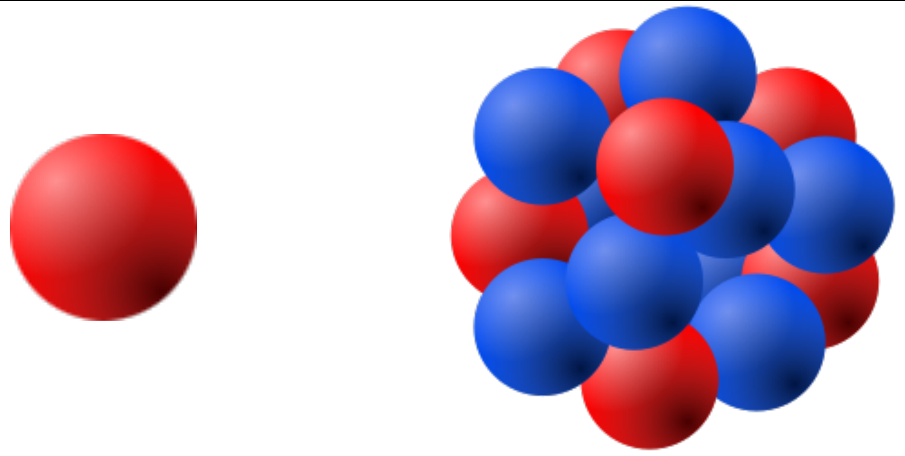
- Leading-twist nPDF
- Intrinsic charm
- QCD radiative energy loss

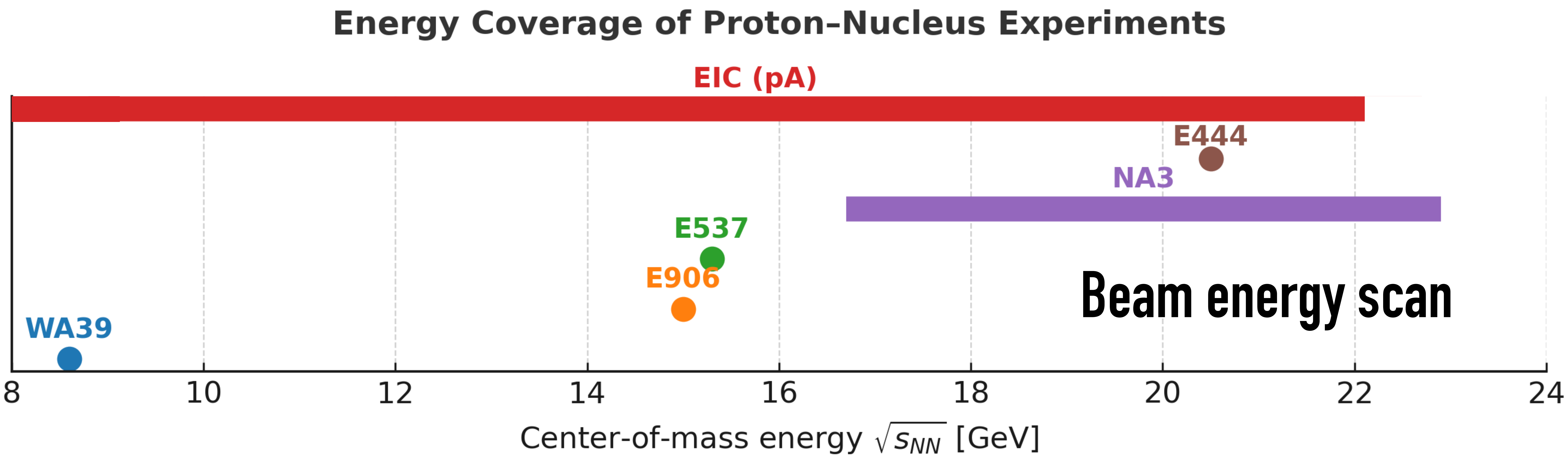


- Nuclear absorption
- QCD radiative energy loss

Cold Nuclear Matter effects are stronger at large rapidity and low beam energy

Data in fixed-target experiments





- Old data from WA39 1982, NA3 1980, E537 1990
- **Large empty energy gap!**
- Good hardware:
  - **New detectors**
  - **New analysis methods**

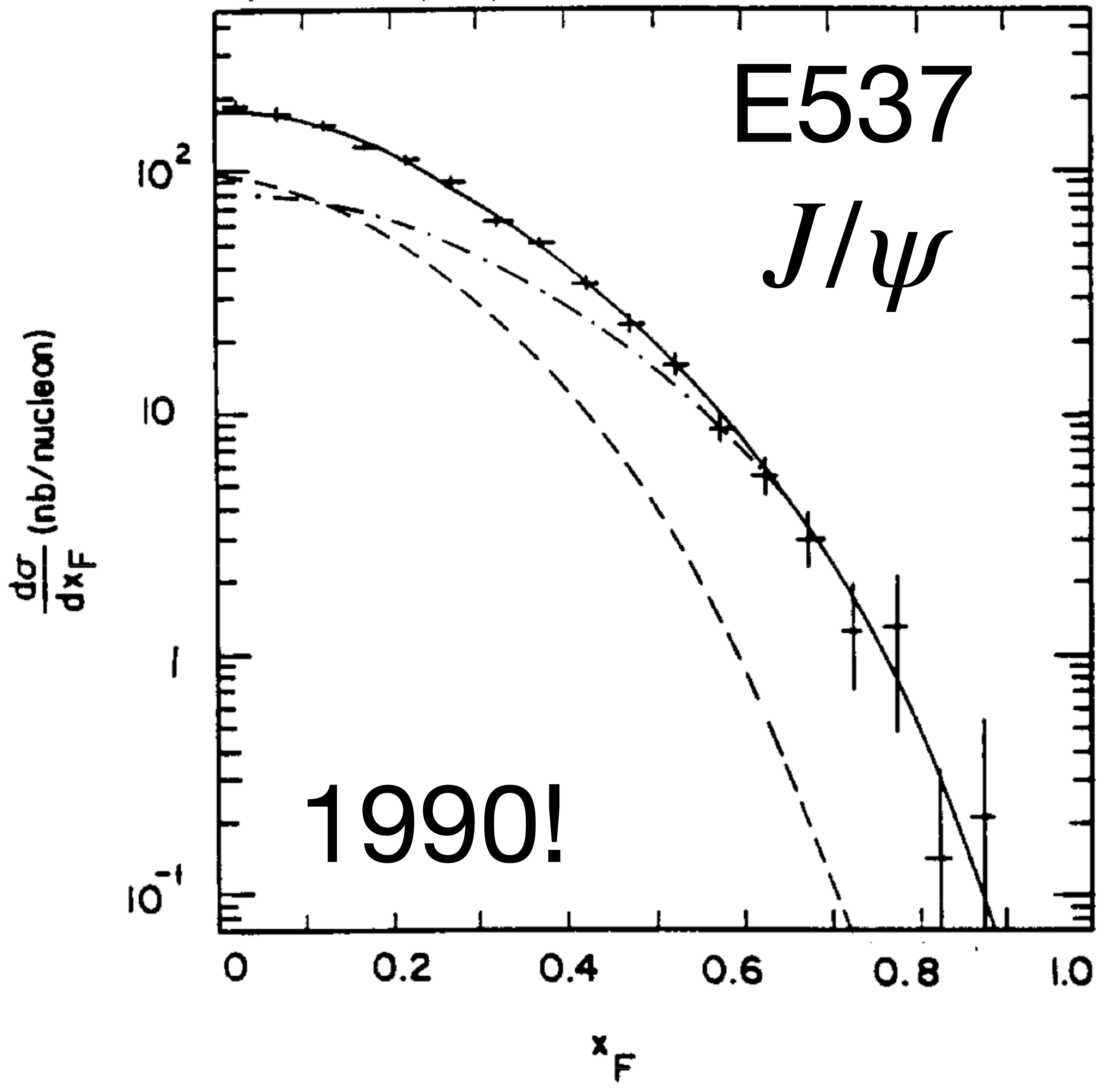
EIC data in pA collisions

$$\sqrt{s} = 6.8 - 22.2 \text{ GeV}$$

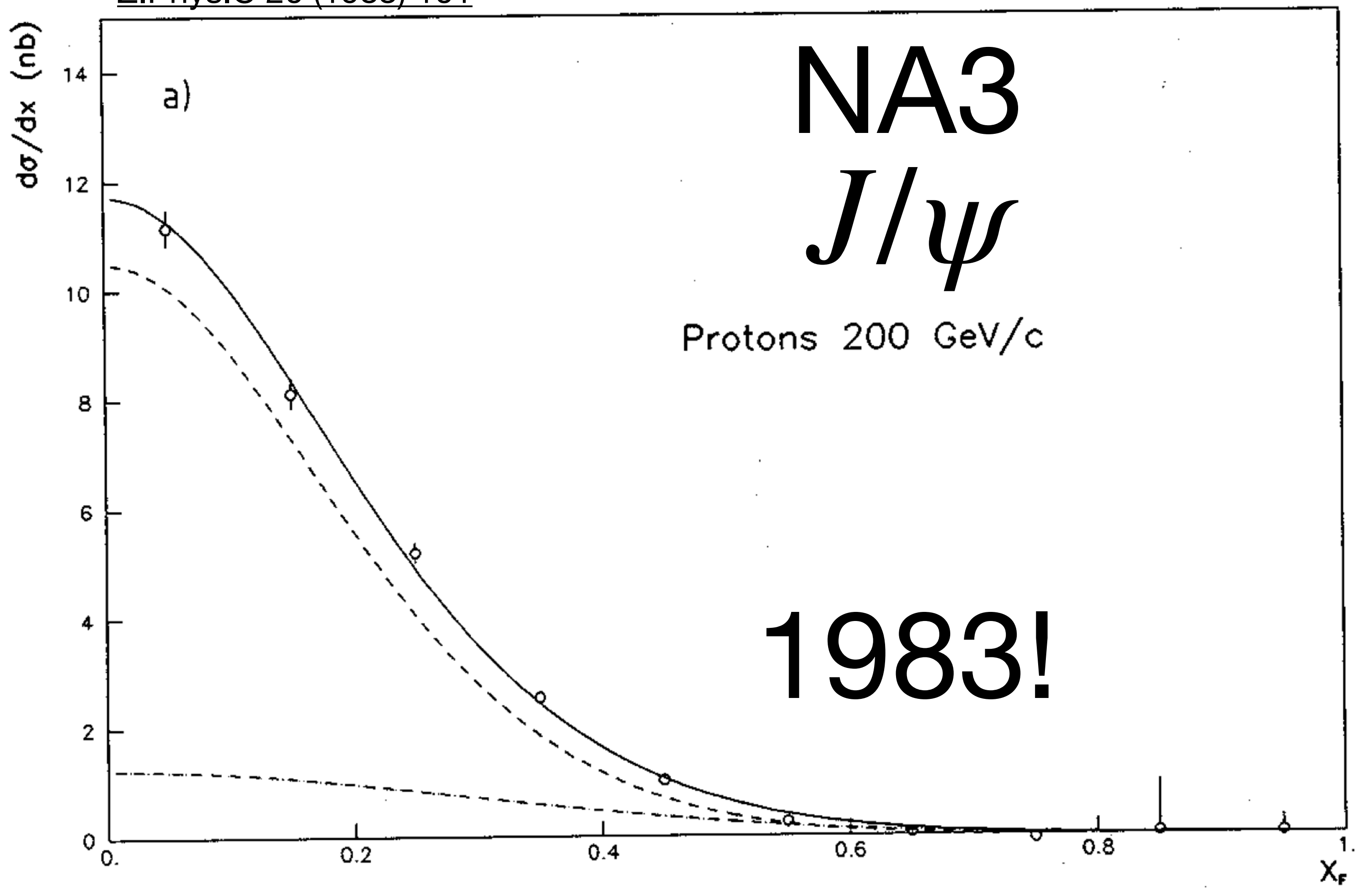
Data in nuclear fixed-target

- **E906/SeaQuest: J/ψ data *not yet* published**
- **COMPASS (pion): J/ψ data *not yet* published**
- **NA3: J/ψ data published**
- **E537: J/ψ data published**

Phys.Rev.D 48 (1993) 5067-5080

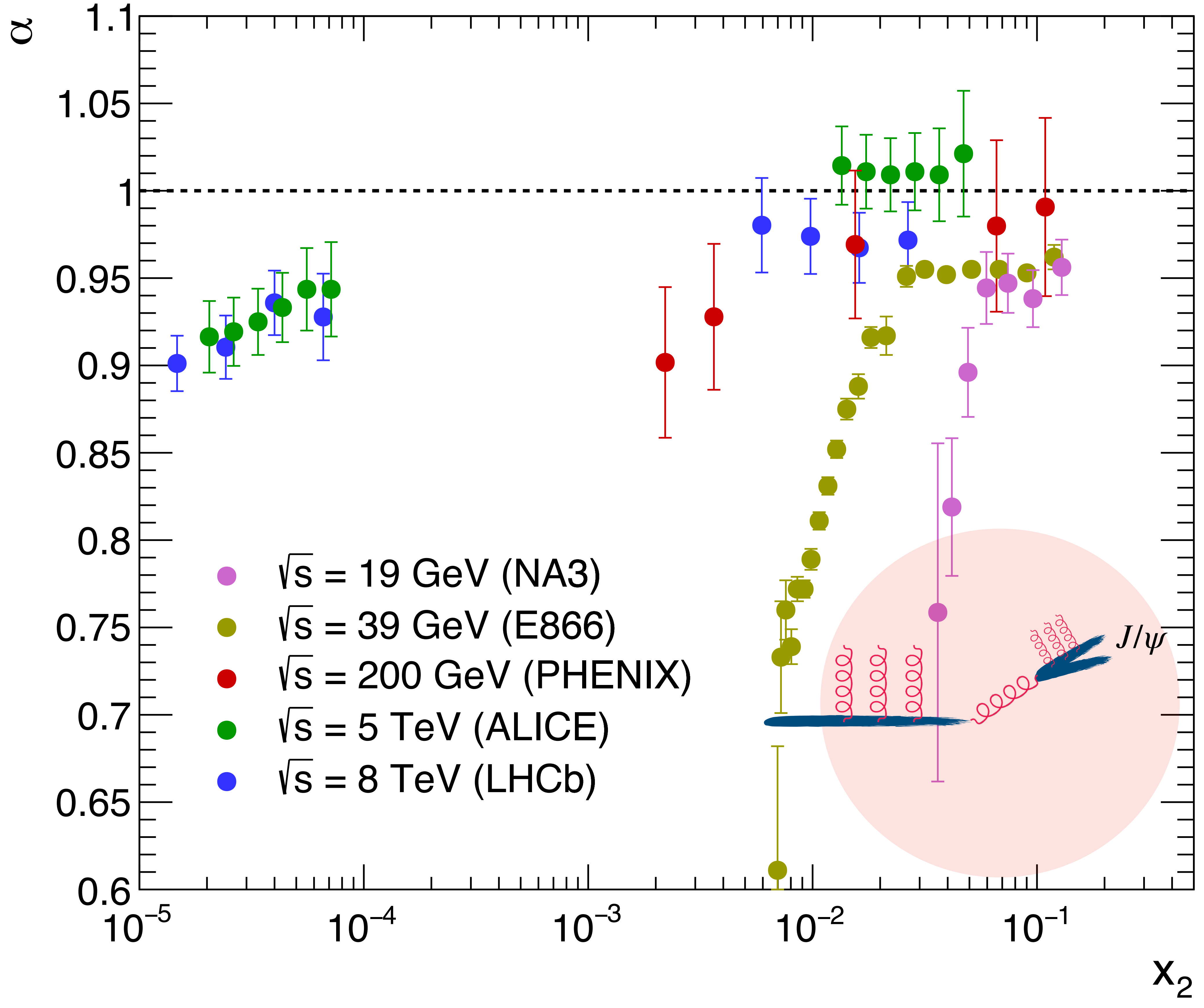


Z.Phys.C 20 (1983) 101

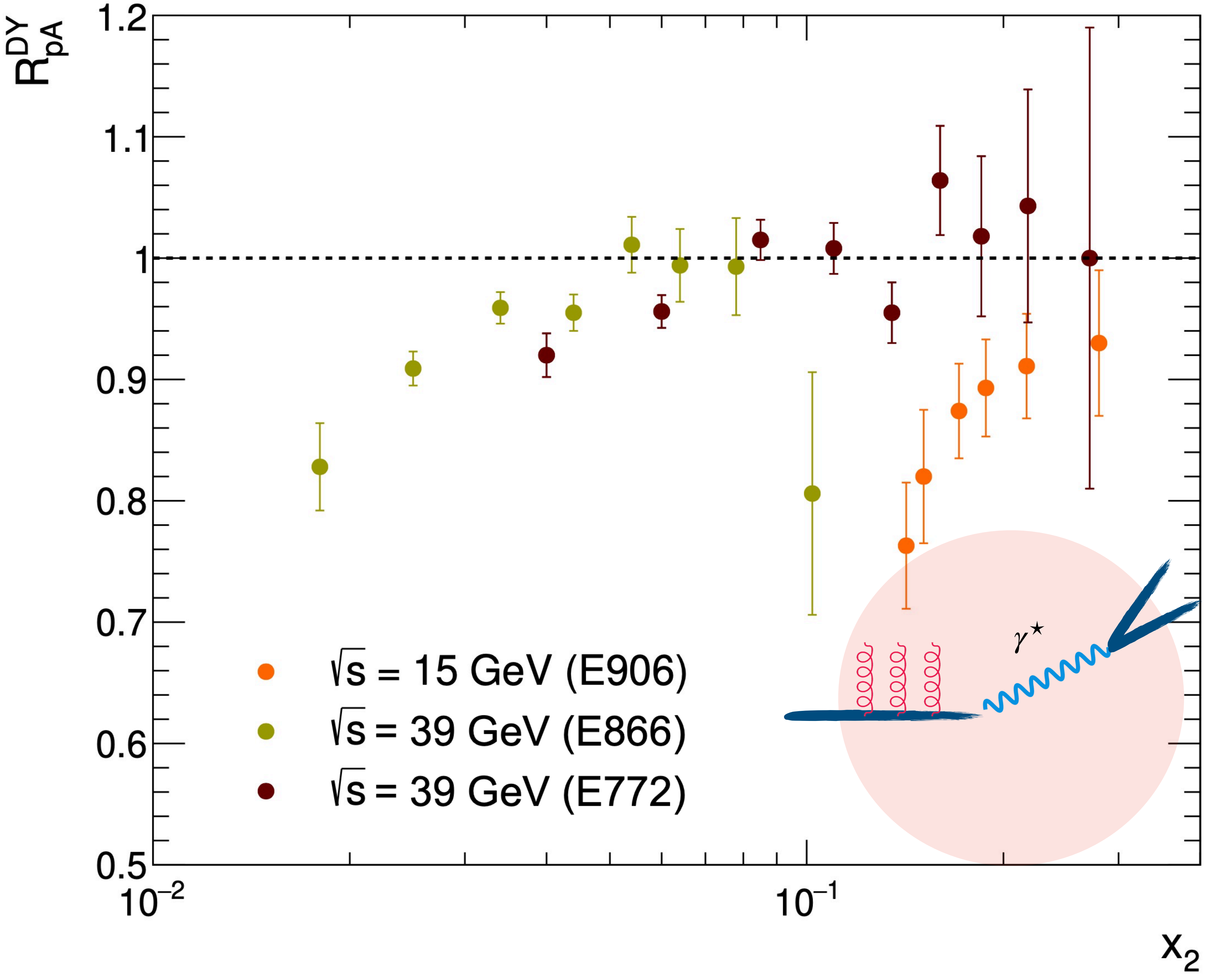


$$R_{\rm pA} \equiv \frac{1}{A}\frac{d\sigma_{\rm pA}}{d\sigma_{\rm pp}}$$

J/ψ



Drell-Yan



No scaling as a function of x_2, **no universality** of $R_{\rm pA}$

Someone can explain it?

QCD Radiative Energy Loss

Initial-state (LPM)

$\Delta E \sim qL^2 \ln(E)$

- **h+A**: Drell-Yan
- E906, COMPASS

Fully Coherent (FCEL)

$\Delta E \sim \sqrt{qL} \cdot E/M_T$

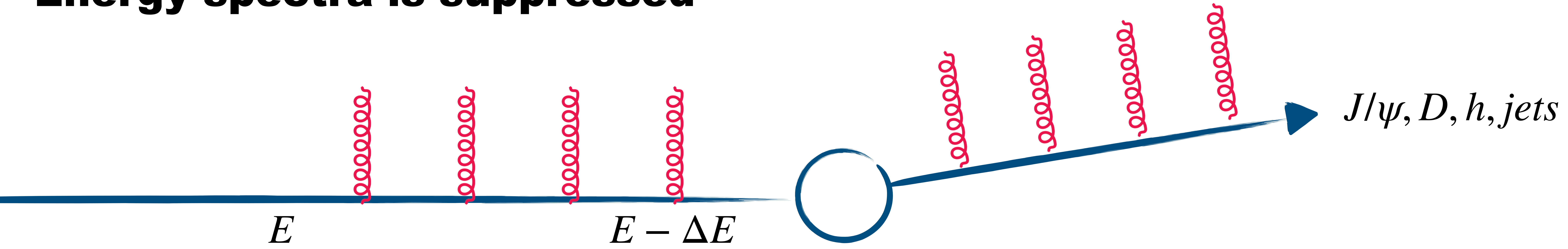
- **h+A**: h, jets
- SPS, FINAL, RHIC, LHC

Final-state (LPM)

$\Delta E \sim qL^2 \ln(E)$

- **e+A**: h, jets
- CLASS, HERMES, EIC

Energy spectra is suppressed

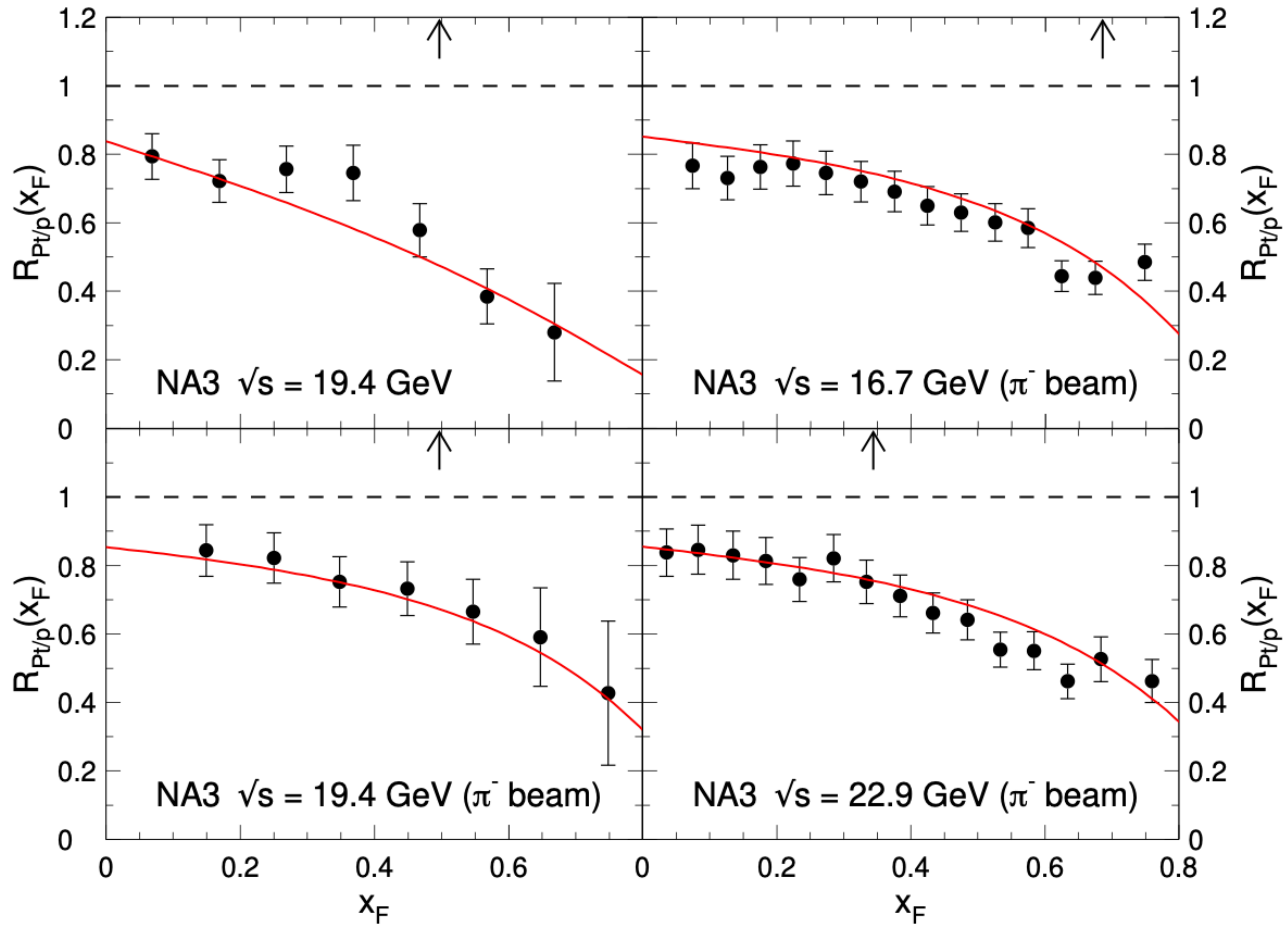


QCD Radiative Energy Loss

Fully Coherent (FCEL)

J/ψ

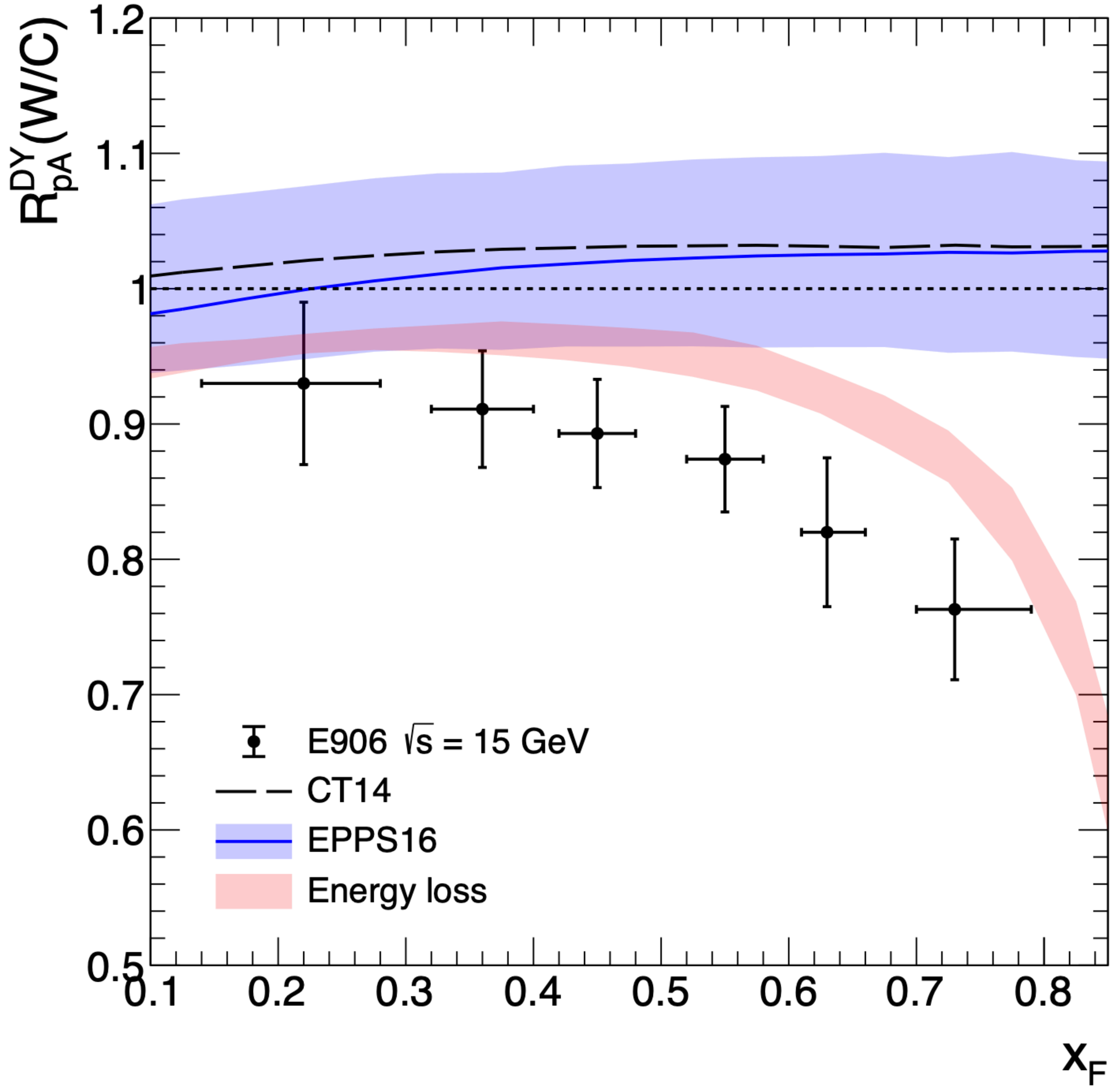
$\hat{q}_0 = 0.075\ \text{GeV}^2/\text{fm}$ Arleo Peigne 10.1007/JHEP03(2013)122



LPM

DY

F. Arleo, C-J Naïm 1810.05120



QCD Radiative Energy Loss

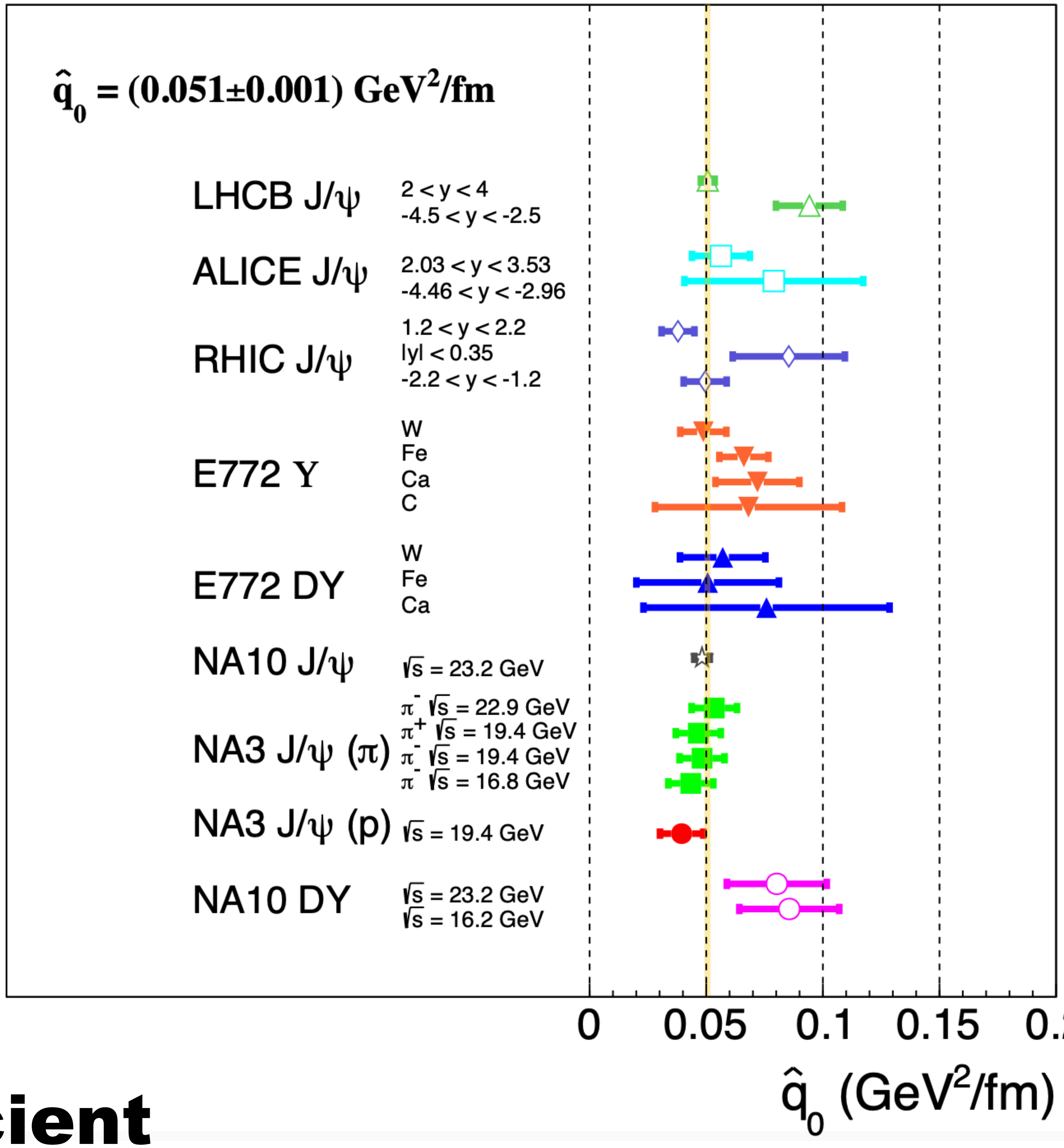
- Governs induced gluon radiation
- Related to gluon distribution at $Q^2 \sim \Delta p_T^2$

$$\hat{q} \equiv \frac{\mu^2}{\lambda} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \rho\, xG(x, Q^2)$$

- Determined from transverse momentum broadening

$$\Delta p_T^2 = \langle p_T^2 \rangle_{hA} - \langle p_T^2 \rangle_{hp}$$

- **Origin: multiple parton scattering**



Universal coefficient

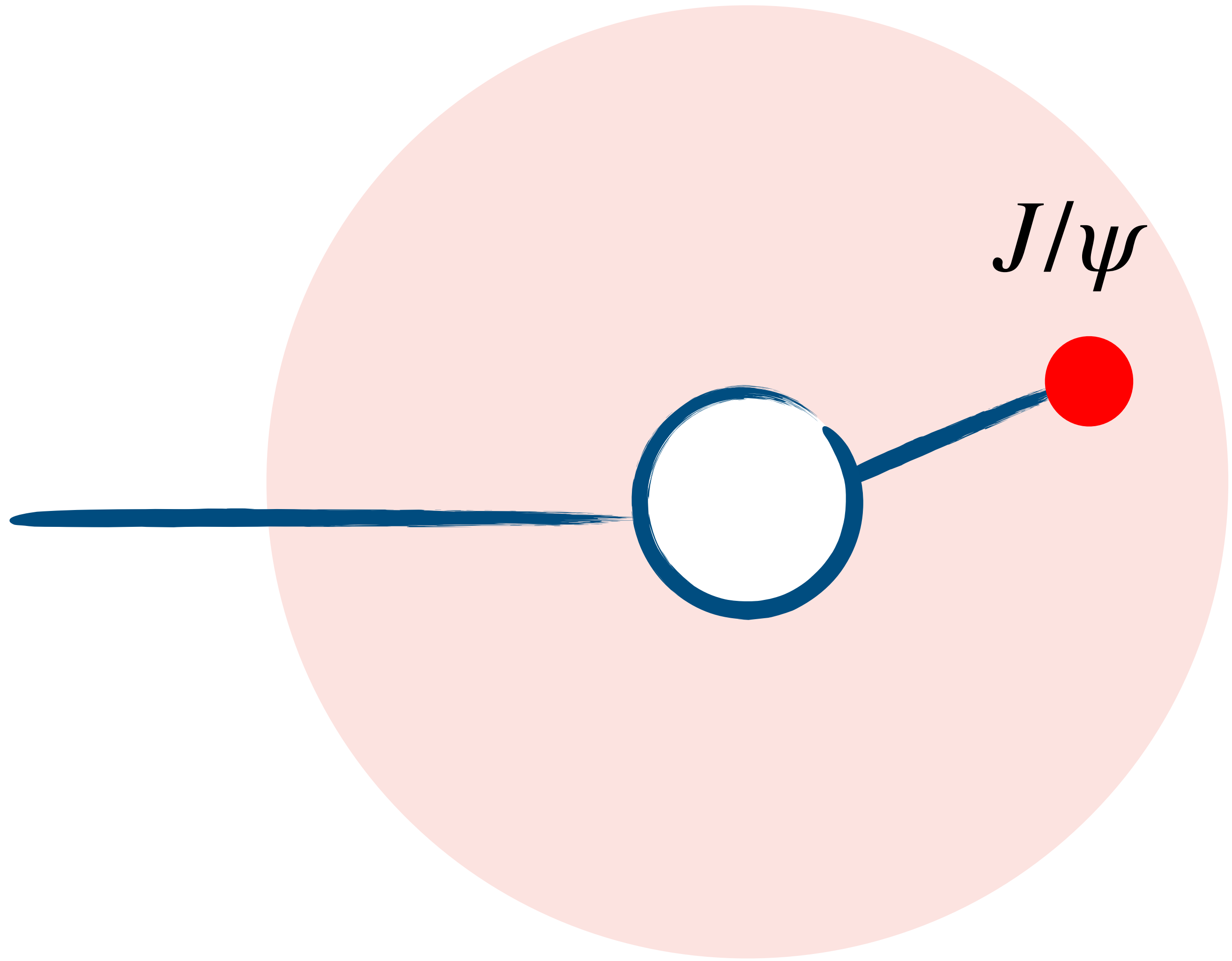
QCD Radiative Energy Loss

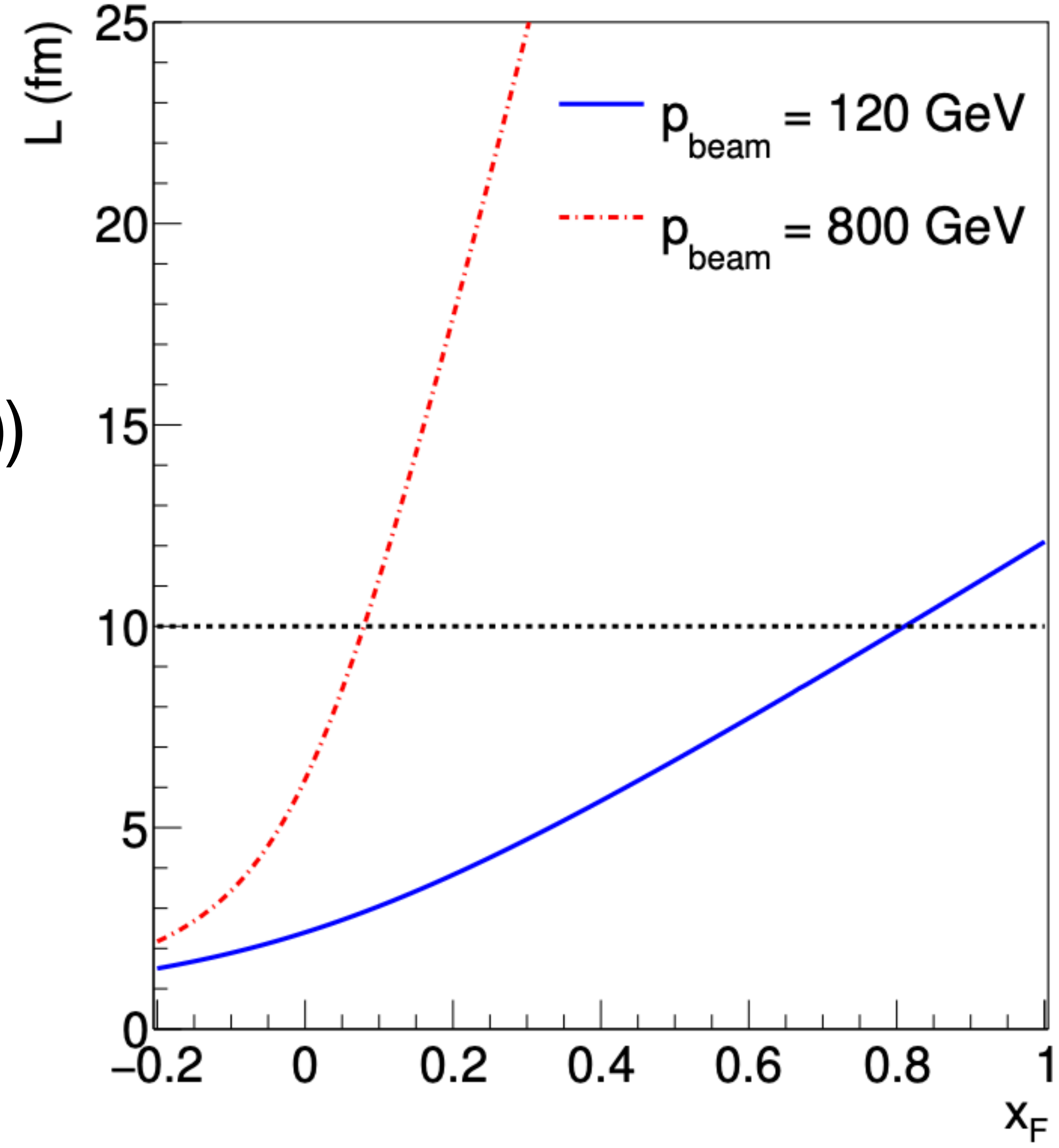
- **Drell–Yan at high x_F** → LPM energy loss
- **J/ψ in e+A vs. p+A** → test non-universality of energy loss regime
- **Photo-production (jets, hadrons)** → resolved sensitive to FCEL
- **Ratios $R_{pA}^{J/\psi}/R_{pA}^{DY}, R_{pA}^{J/\psi}/R_{pA}^{\Upsilon}$** → sensitive to FCEL vs. nPDF, mass dependence
- p_T **broadening** → constrains $\hat{q}$, impacts DY, quarkonium, SIDIS …
- **Light hadrons & heavy flavors at large xF** → strong suppression

Cold nuclear effects require a global, coherent approach

Nuclear Absorption

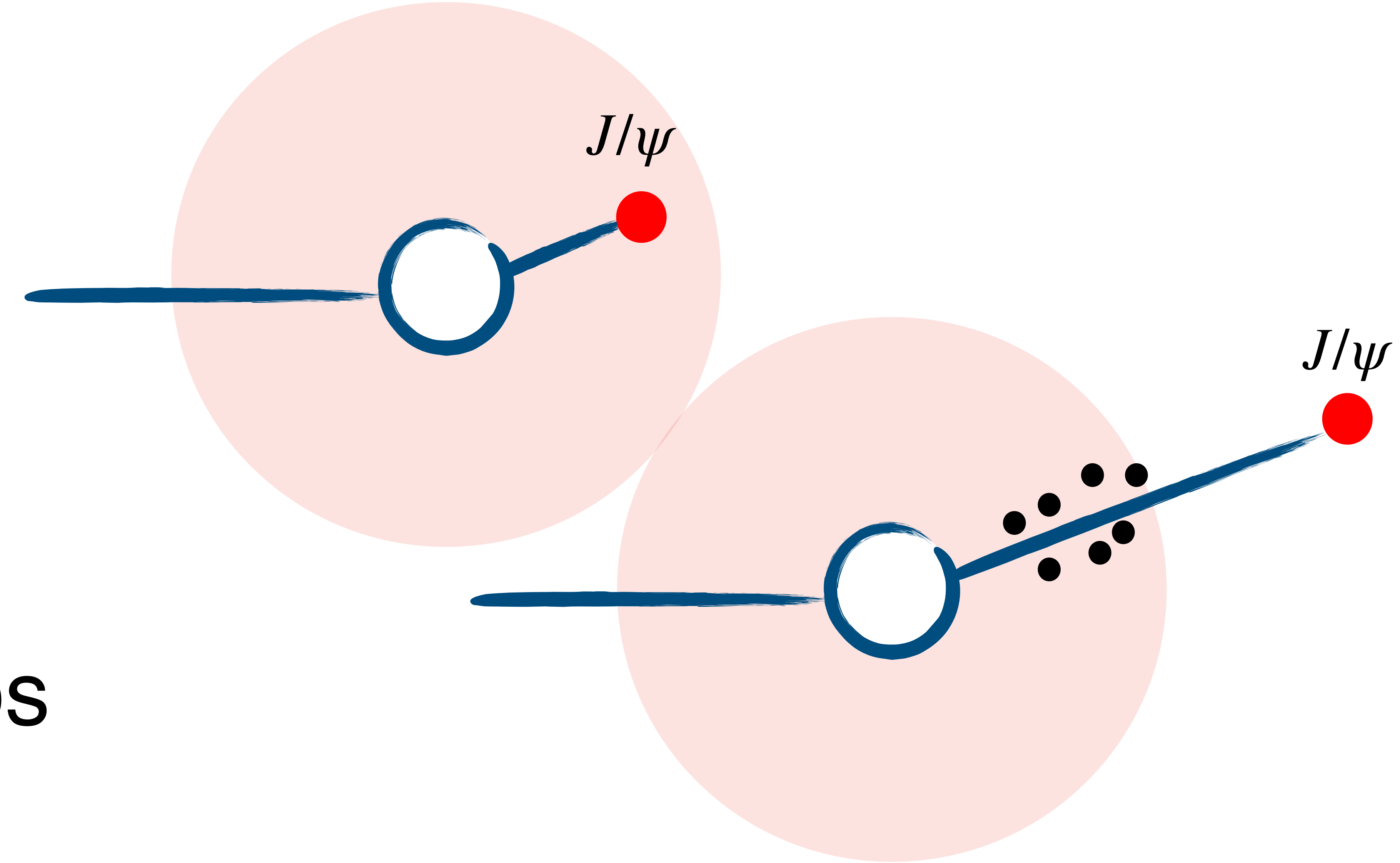
- **Absorption depends on formation length** of the J/ψ in the medium
- **Different extraction methods** → different values of σ_{abs}
- **Comovers**: similar A-dependence,
  - but **distinguish better between states** (e.g. J/ψ vs. ψ(2))

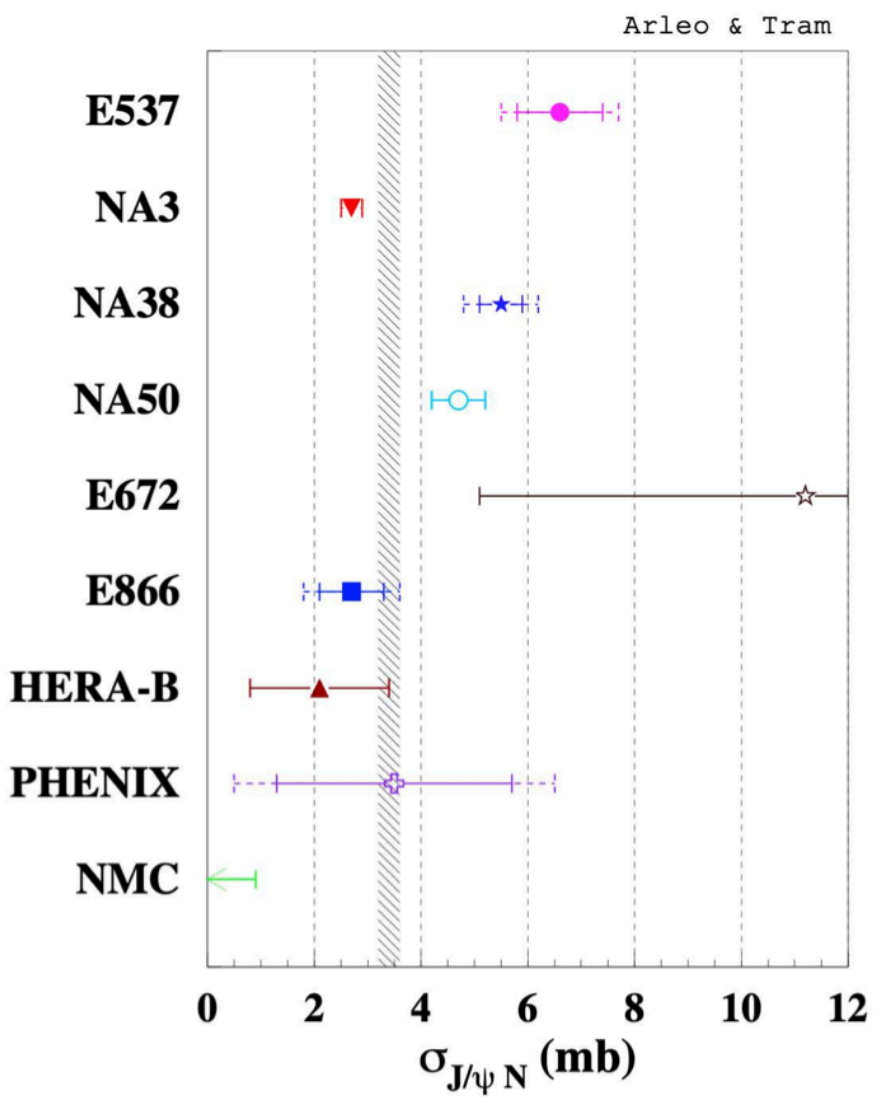


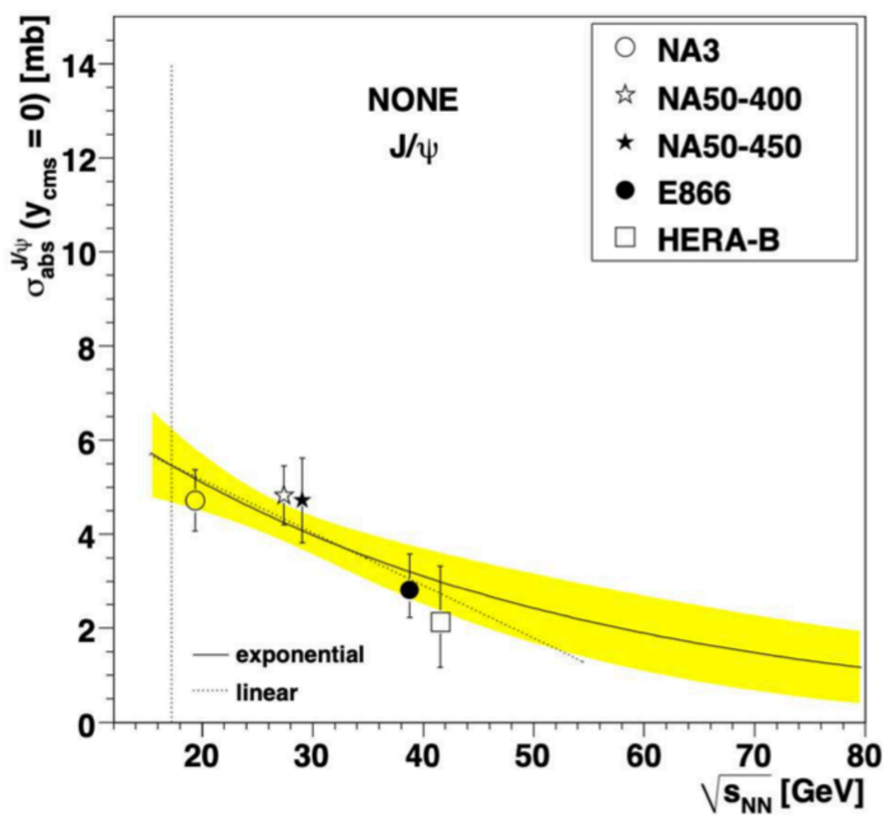


Nuclear Absorption

- **Double ratios (quarkonium states)**
  - Low energy → isolate absorption ($t_{\text{form}} \leq L$)
  - High energy → isolate comovers ($t_{\text{form}} \gg L$)
- $R^{J/\psi}$ **vs.** R^{χ_c} → color state dependence → different σ_{abs}

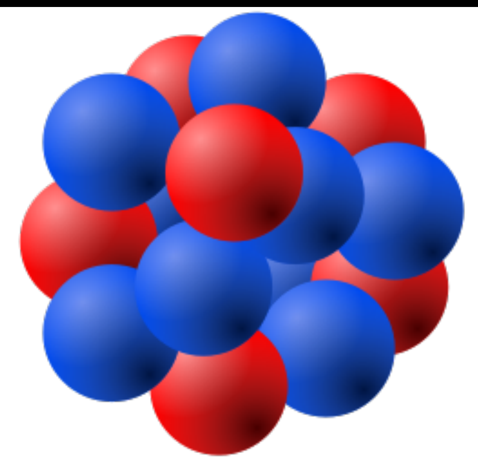






The contribution remains unclear

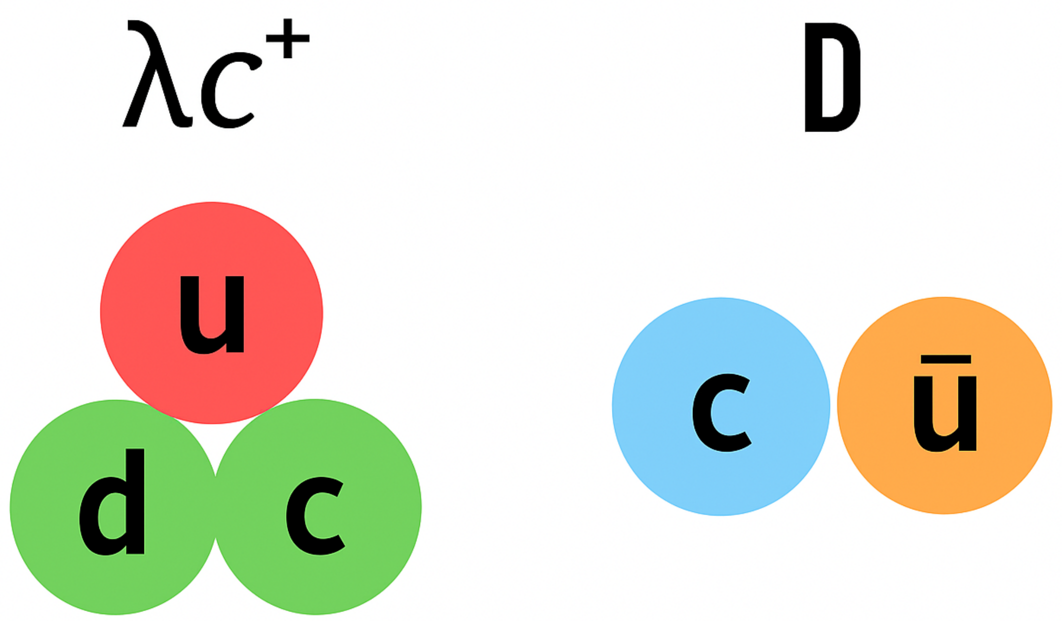
Baryon – meson ratios

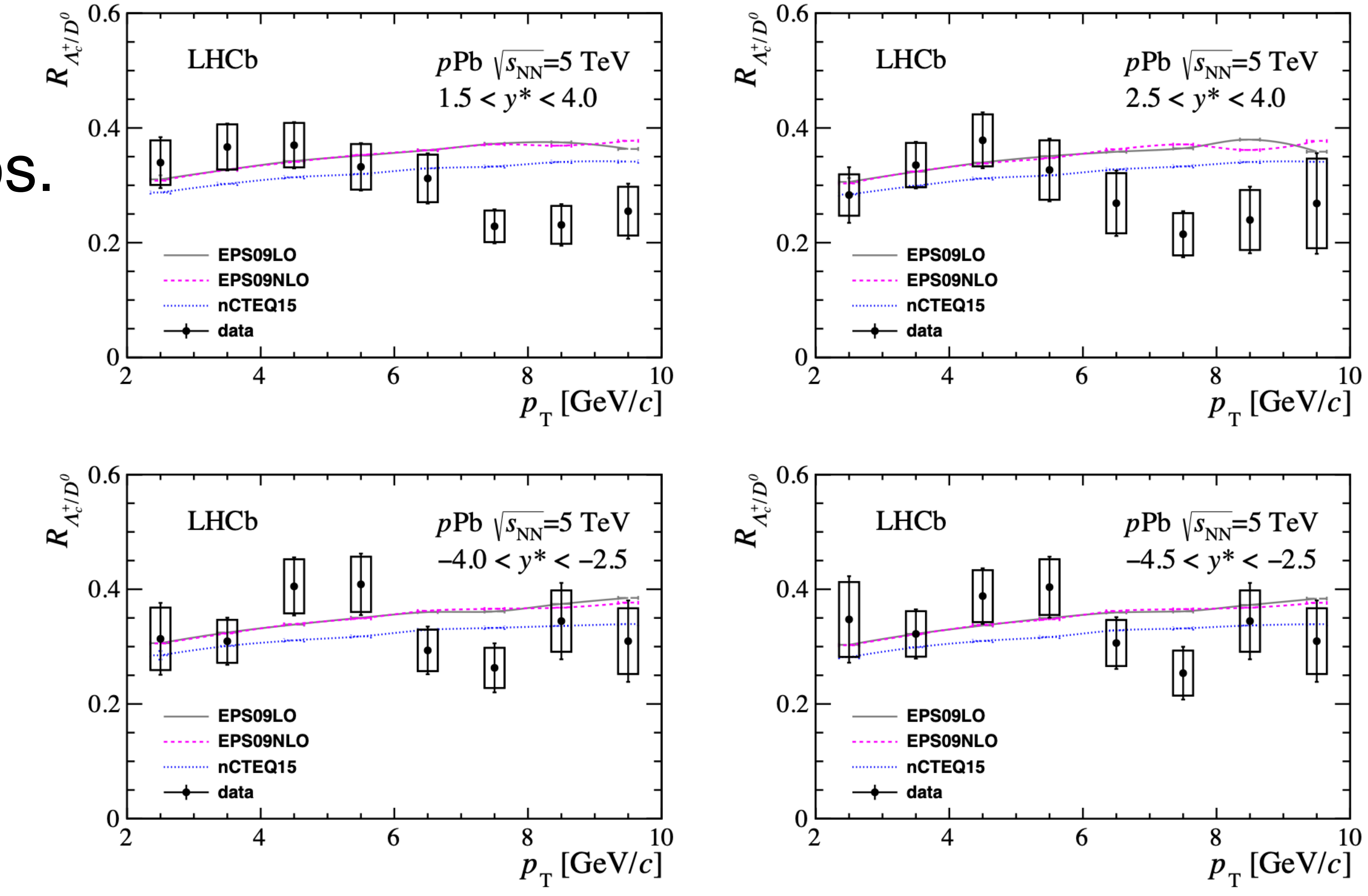


Charm production

LHCb data (collider)

- **Intrinsic charm:** low-energy p+A enhances sensitivity
- **Hadronization:** D, Λc test CNM effects & baryon/meson ratios.
- **Mass & flavor dependence** – study how charm quarks lose energy vs light/heavy hadrons in CNM

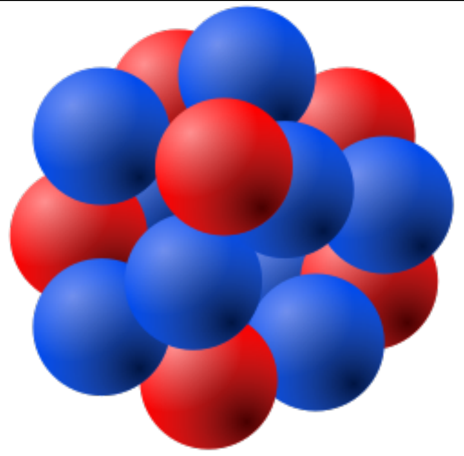




Clear enhancement

Physics Motivations to a Physics Case?

See <u>Helen</u>
And <u>Jaki's</u> talk

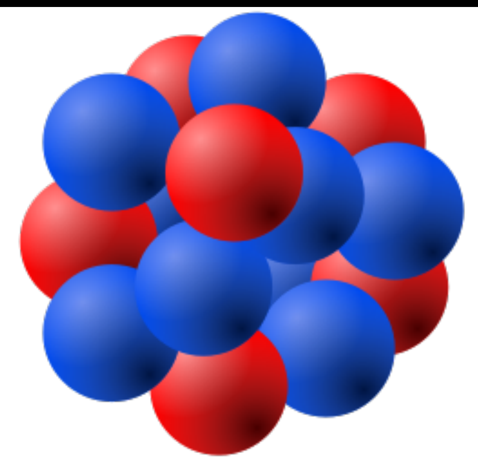


QCD Nuclear Matter studies – A+A collisions

- **Objective** – Provide precise cross sections measurements (light ions, mesons)
- **Interest** – QGP transition, nuclear interaction, radiations studies
- **Physics processes**
  - Strangeness enhancement and multi-strange hadrons
  - Collective flow observables (v_1, v_2)
  - Fluctuations and correlations (critical point search)
  - Fragmentation and secondary-production models
- **EIC Role** – Delivers unique FT data in this range, complementing low-energy gaps

Physics Motivations to a Physics Case?

See Ramona and David's talks



NASA's Space Radiation Lab

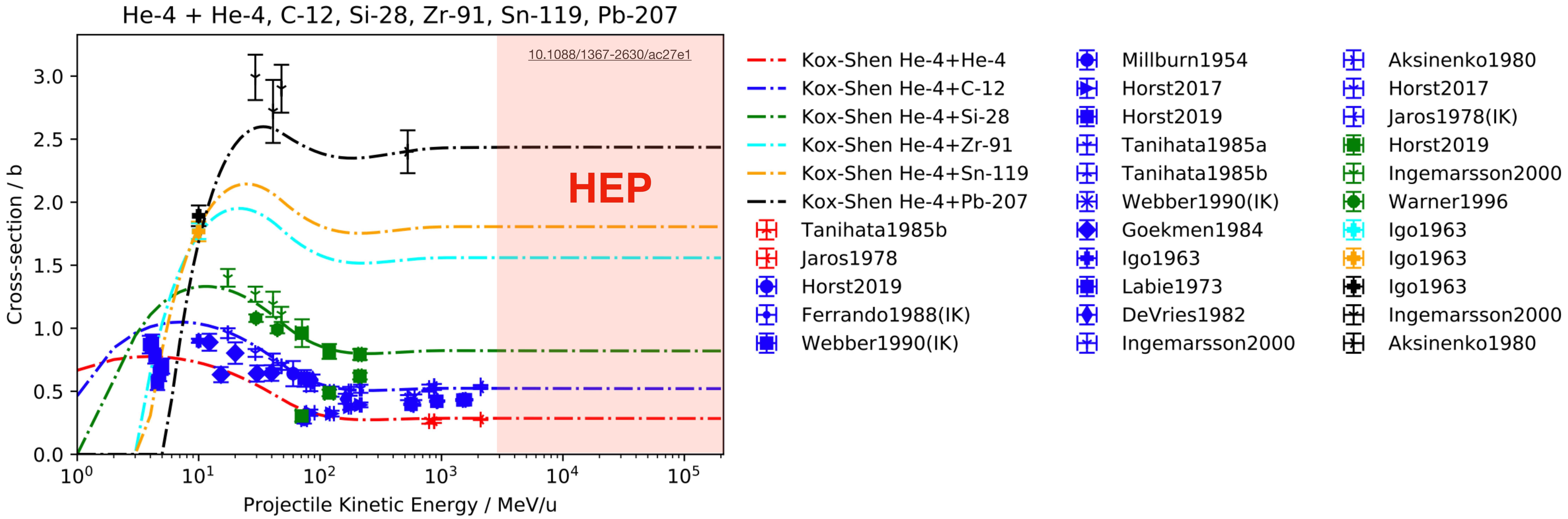
- **Objective** – Provide reliable nuclear cross sections for space radiation transport
- **Interest** – High-energy GCR ions (C, O, Fe) reach 100 GeV/n, driving astronaut dose
- **Need** – Benchmark fragmentation and secondary production models
- **EIC Role** – Delivers unique FT data in this range, complementing low-energy gaps

"NASA has not made an adequate effort to collect, catalogue and categorize existing experimental data obtained by the worldwide heavy ion research community and make it available in appropriate form to the shielding engineering community."

National Research Council of the National Academy of Sciences, Managing space radiation risk in the new era of space exploration, The National Academies Press, Washington D.C. (2008).

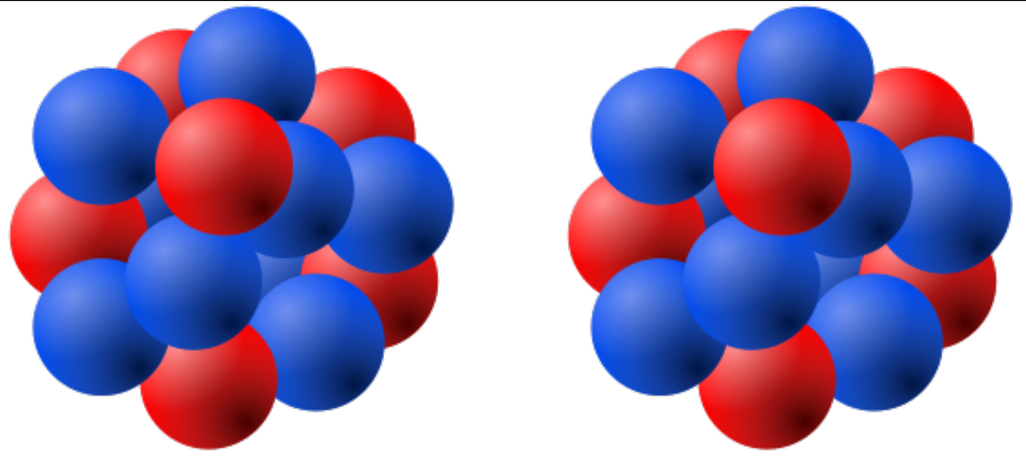
Physics Motivations to a Physics Case?

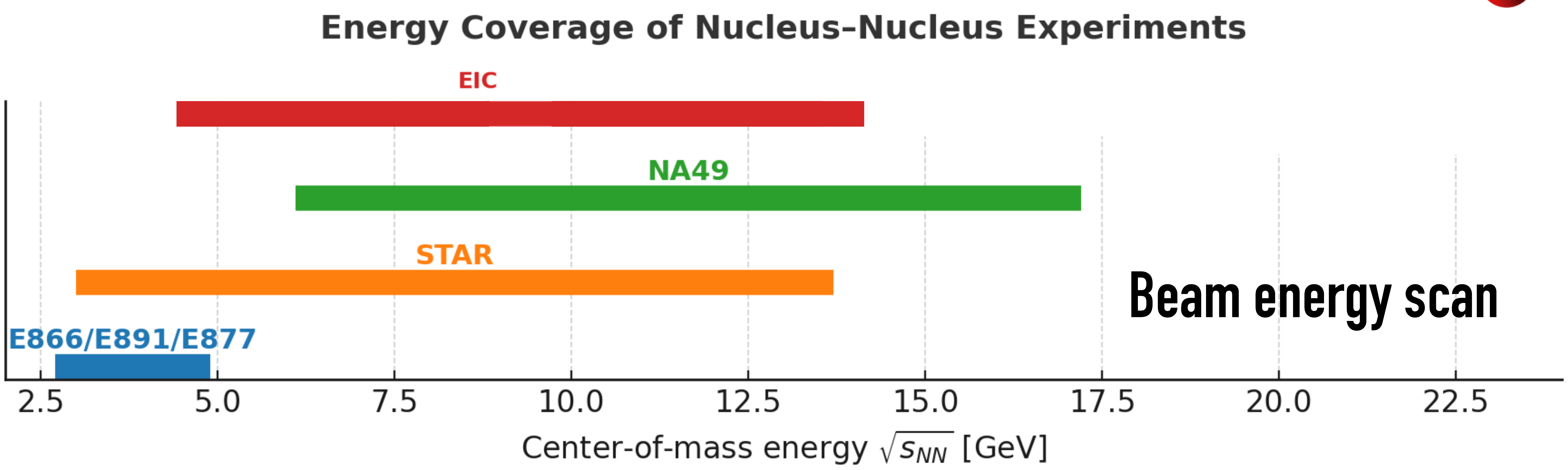
Total nuclear reaction cross-section database



A unique opportunity to centralize high-energy nuclear data: a new data bank?

Data in fixed-target experiments





Beam energy scan

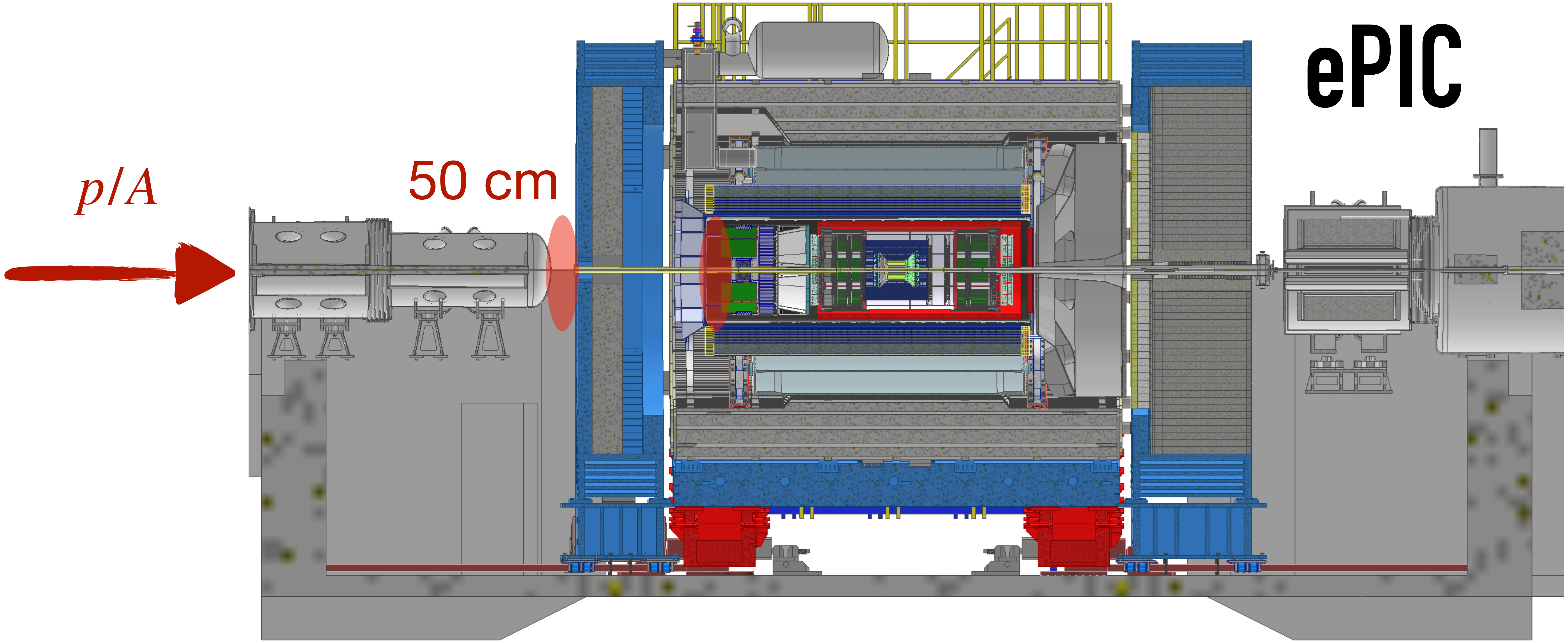
- EIC FT can reach similar energy compared to STAR
- Lack of (precise) data in this energy range
- NA49 (2000s)
- Precise beam scan + a wide variety of nuclei

EIC data in A+A collisions

$$\sqrt{s} = 4.2 - 14.0 \text{ GeV}$$

A setup design

ePIC



Polarized p:
E = 26 to 275 GeV
Au:
E =10 to 110 GeV

- **Target position:** Impact the geometry acceptance
- **Type of Target? (not enough place for polarized target)**
  - Solid, high luminosity, heavy nuclei
  - Gaz, lower luminosity, light nuclei

The cost is minimal

See Elke's talk

FT@EIC is not a new experiment, but a new mode

- **Bridge physics gap:** EIC FT uniquely covers a unique energy window — the missing link between SPS/RHIC fixed-target and collider programs
- **Cross-cutting impact:** Enables a broad QCD program (cold nuclear matter, nuclear structure, space-radiation models), fostering DOE–NSF–NASA synergies
- **Continuity & connection:** Provides continuity between cold nuclear matter studies, low-energy heavy-ion dynamics, and beam energy scans
- **Balanced focus: Small-x physics** is fundamental, but **large-x physics** is equally critical for a complete picture of QCD

The EIC must be thought as a cornerstone of QCD