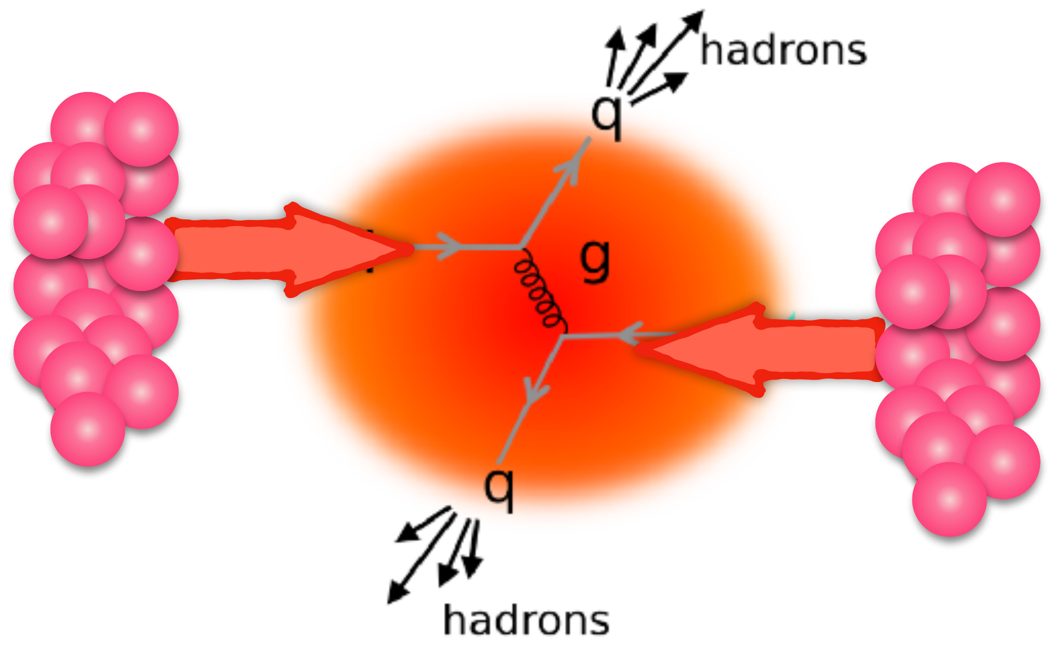
La Thuile 2021 – Les Rencontres de Physique de la Vallée d'Aoste

Overview of recent ALICE results

Chiara Oppedisano
on behalf of the ALICE Collaboration

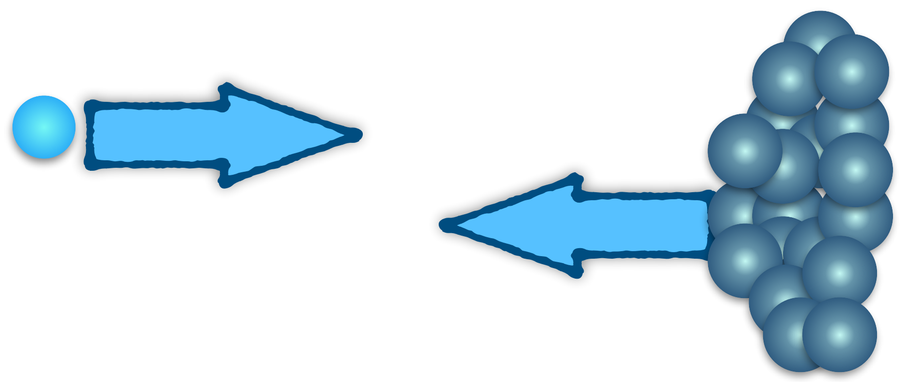
Heavy ions…and beyond

A-A



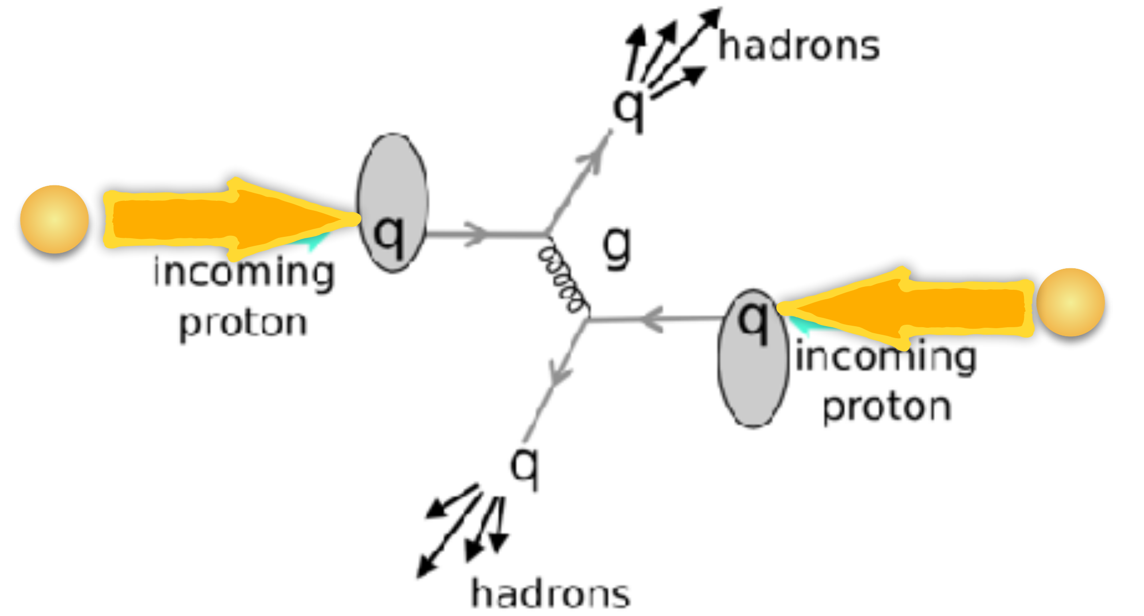
QGP CHARACTERIZATION

p-A



COLD NUCLEAR MATTER (CNM) EFFECTS

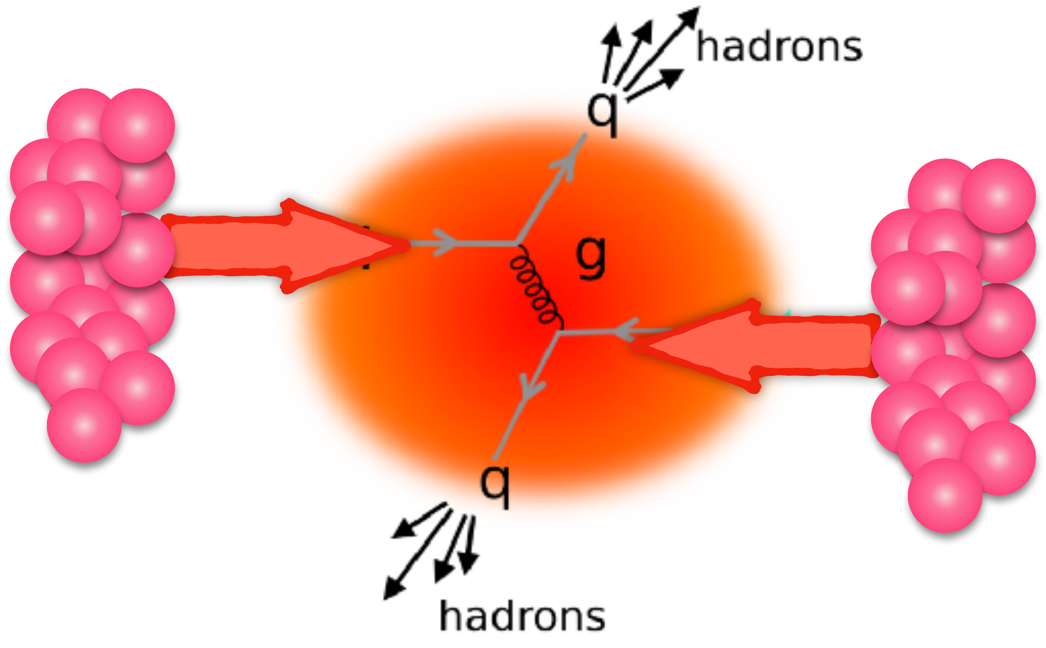
pp



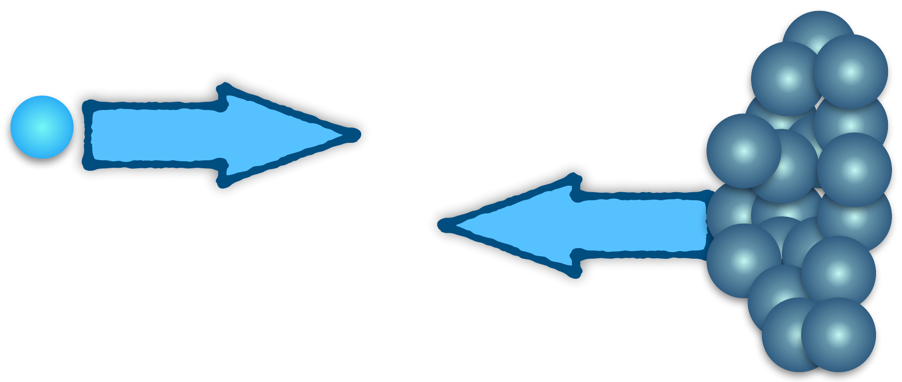
IN-VACUUM QCD

Heavy ions...and beyond

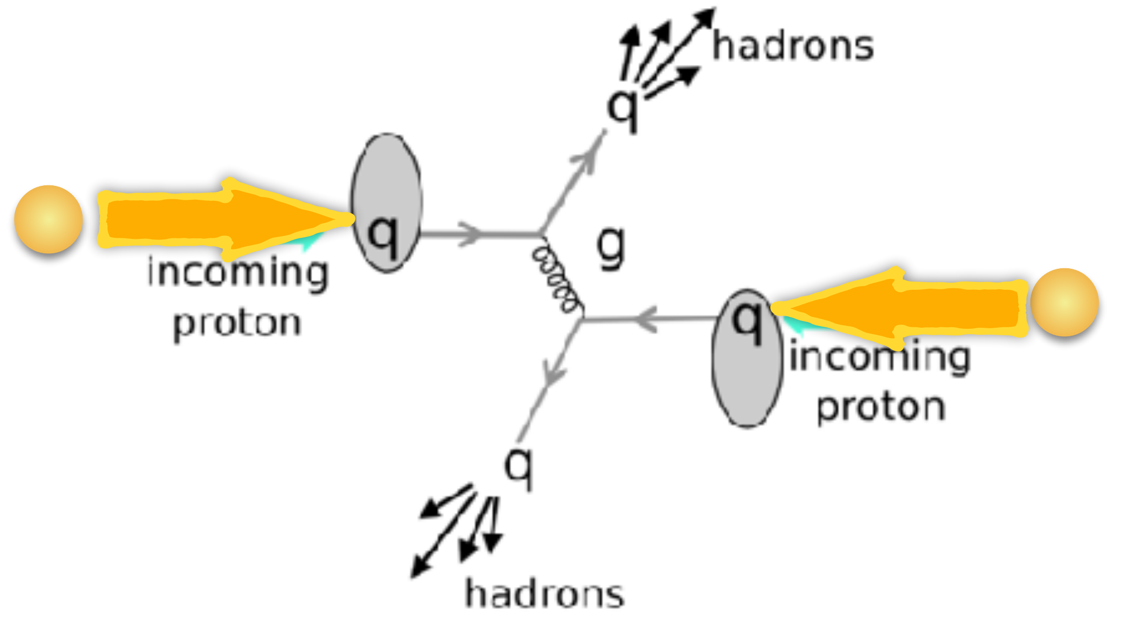
A-A



p-A



pp



QGP CHARACTERIZATION

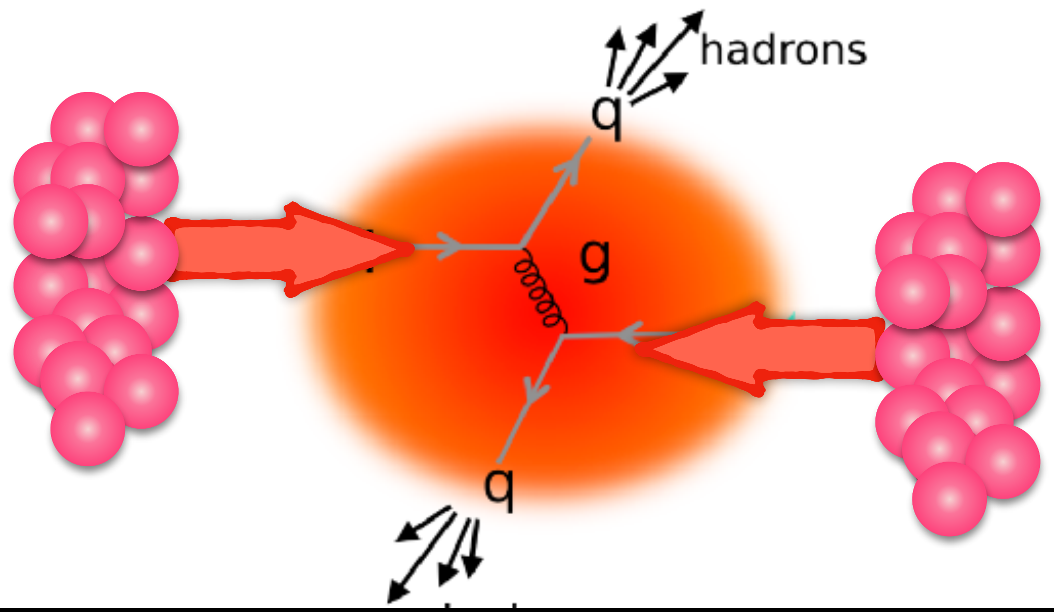
COLD NUCLEAR MATTER (CNM) EFFECTS

IN-VACUUM QCD

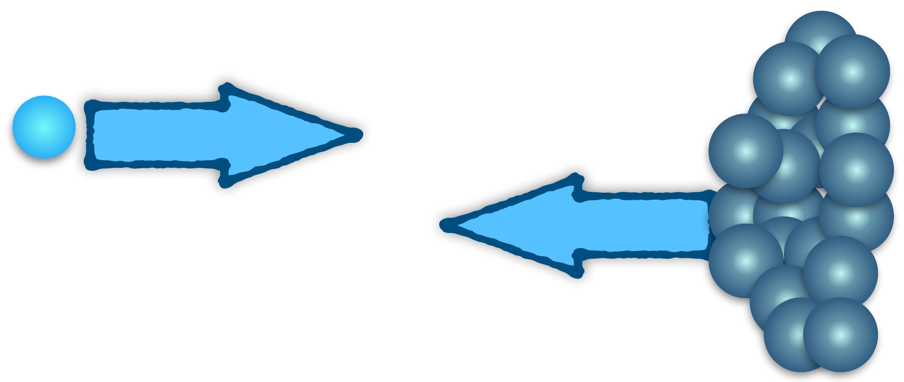
SMALL SYSTEMS vs. MULTIPLICITY ➧ A-A

Heavy ions...and beyond

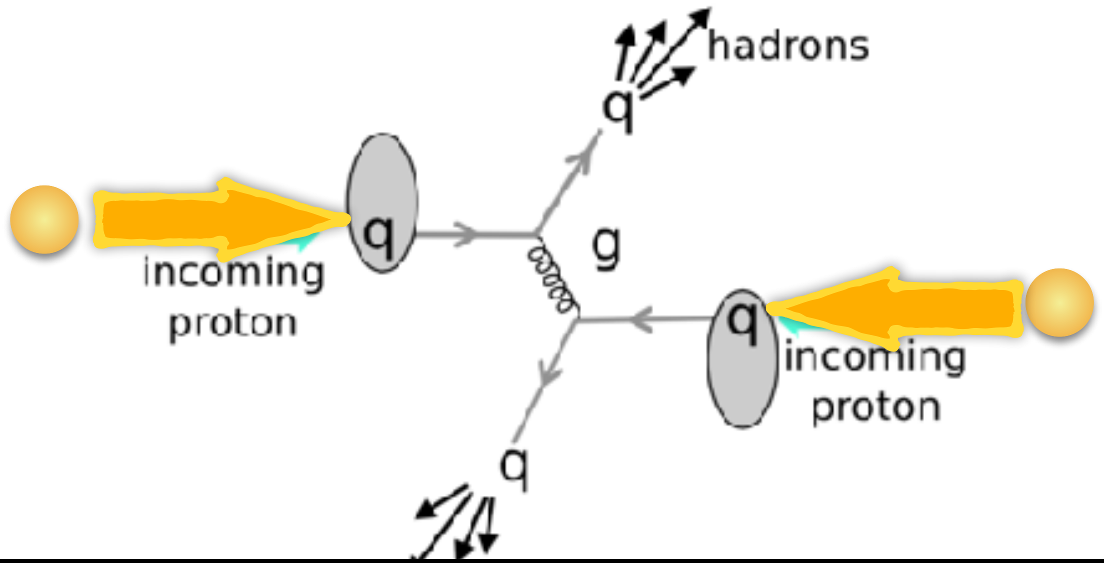
A-A

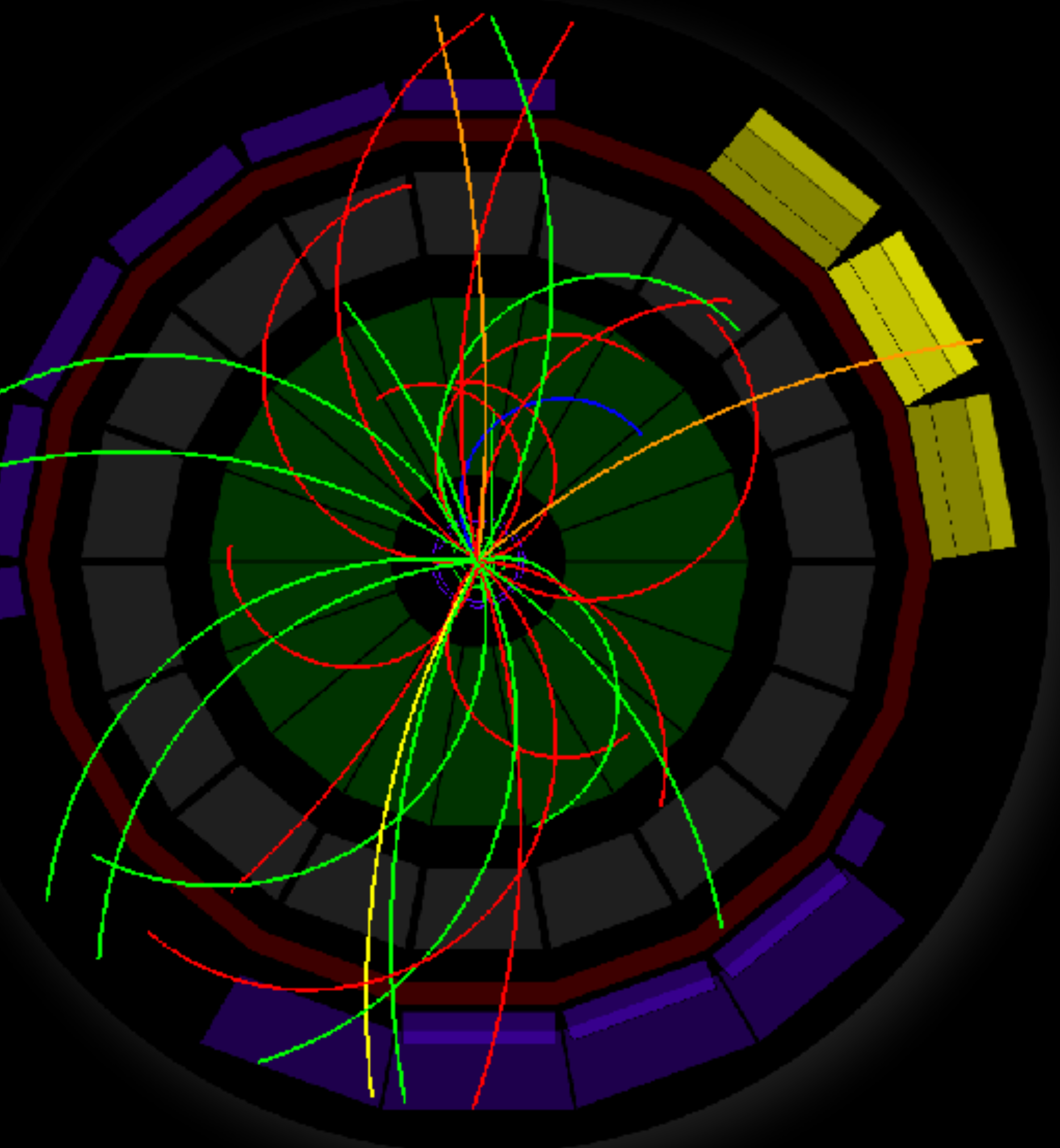


p-A

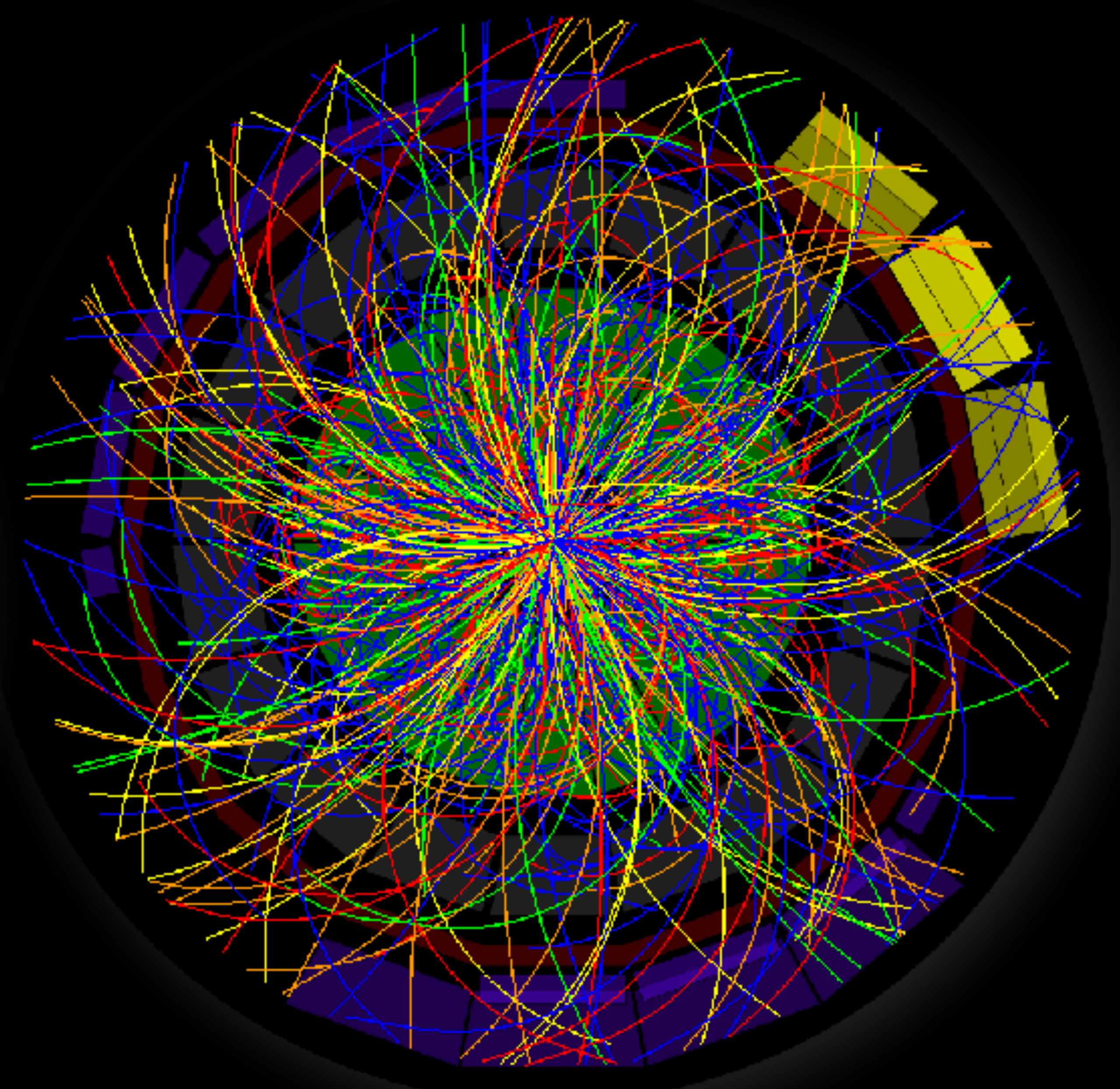


pp

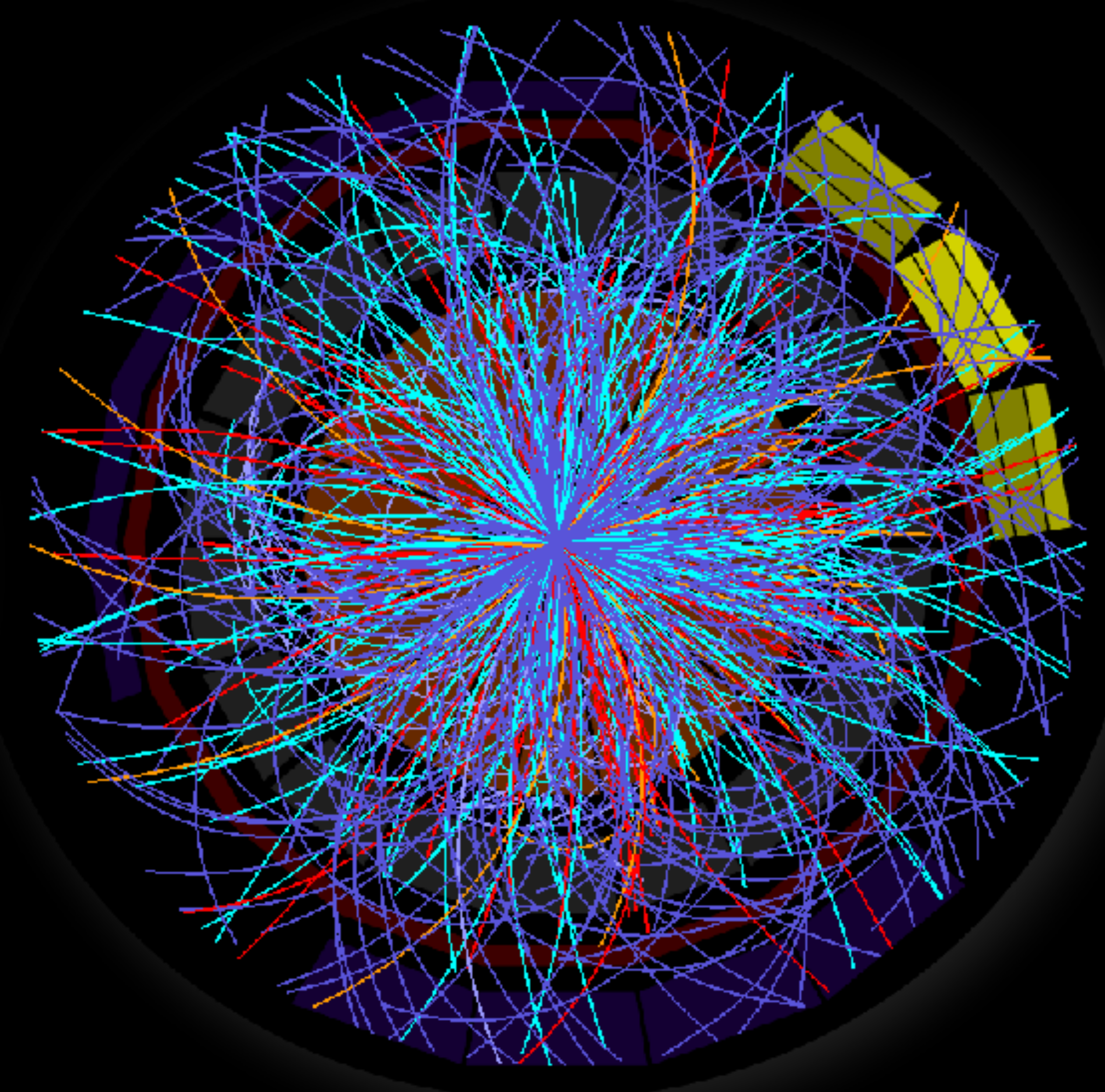




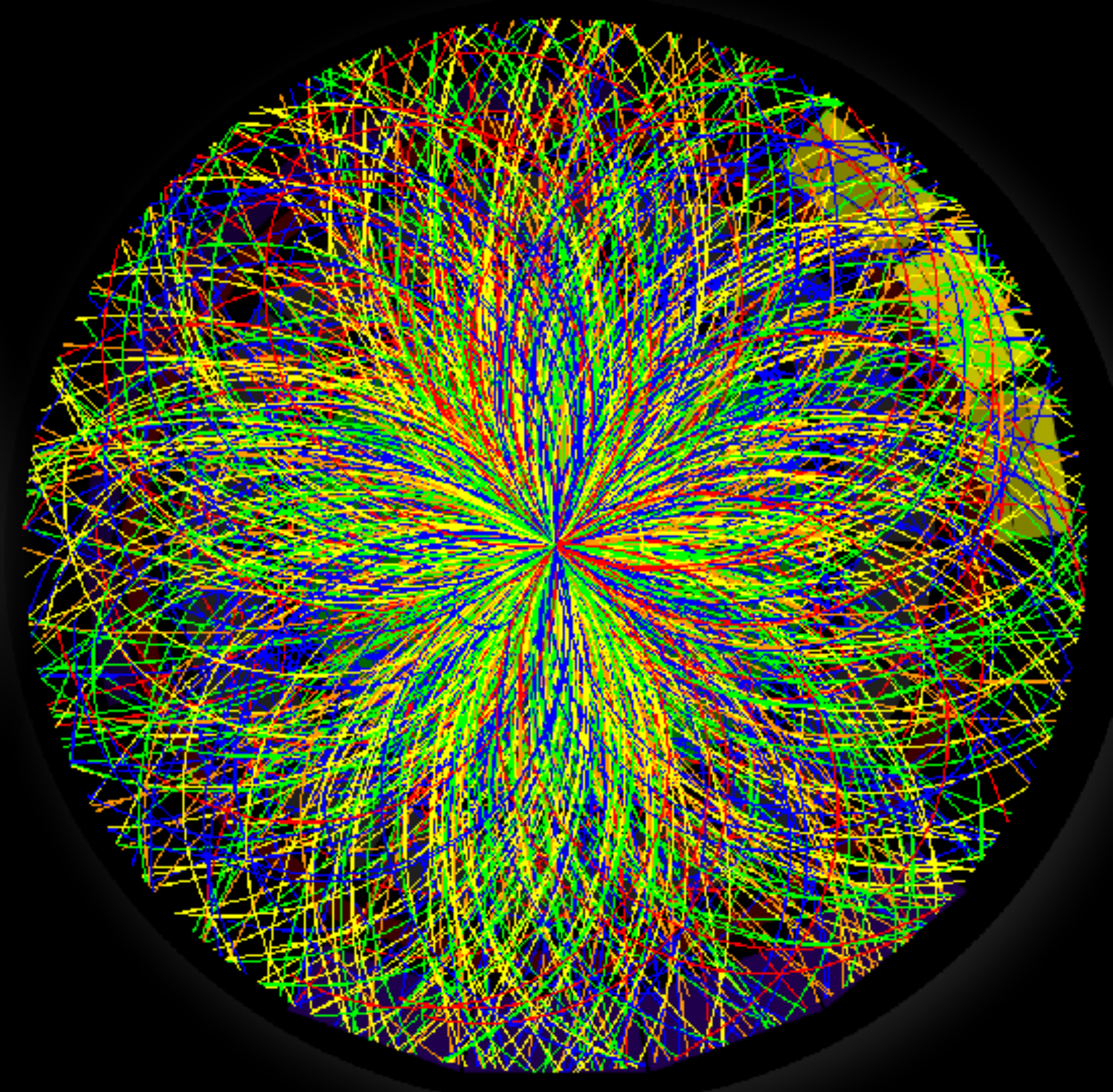
pp
0.9, 5.02, 7, 13 TeV



p-Pb
5.02 TeV and 8 TeV



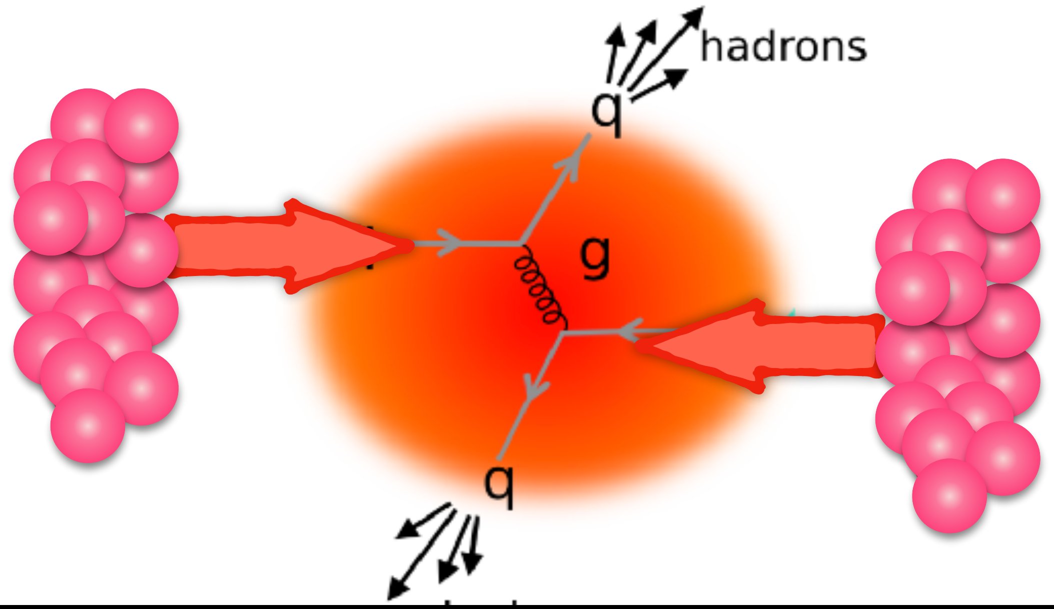
Xe-Xe
5.44 TeV



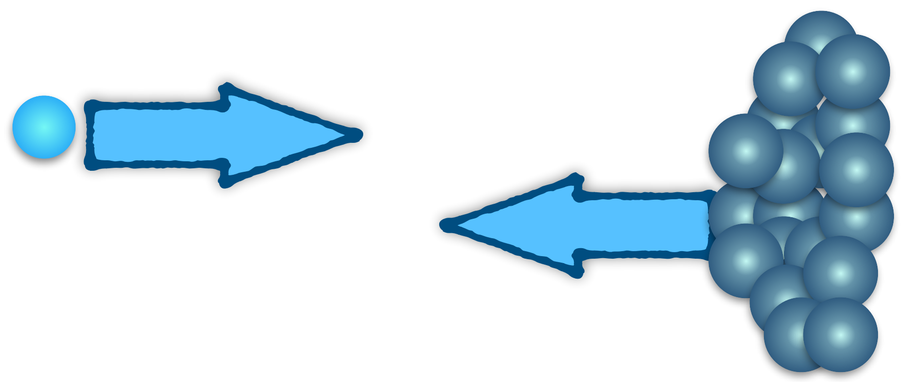
Pb-Pb
2.76 and 5.02 TeV

Heavy ions...and beyond

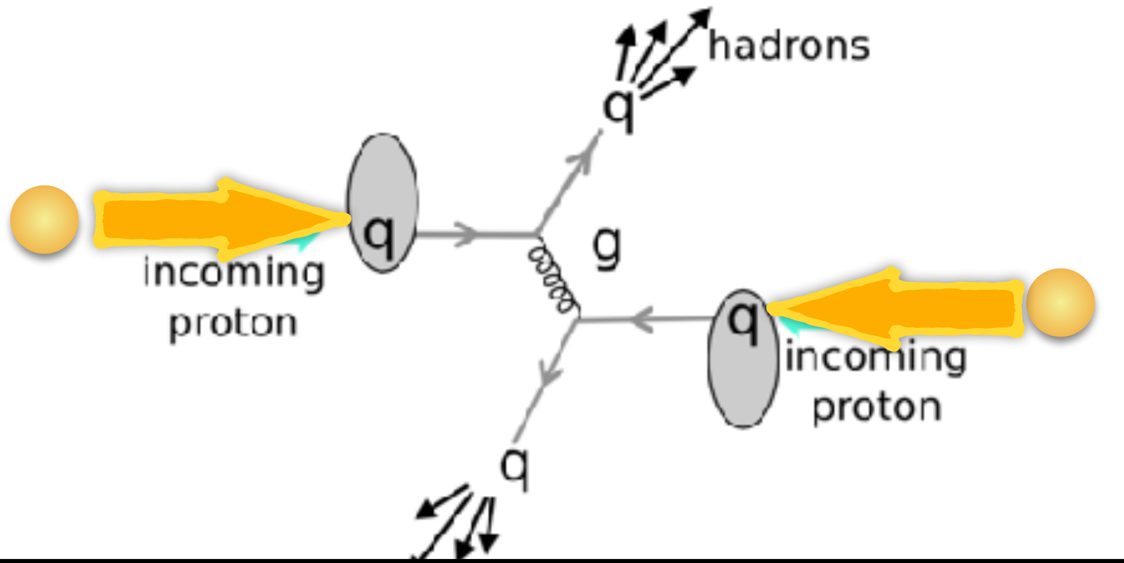
A-A

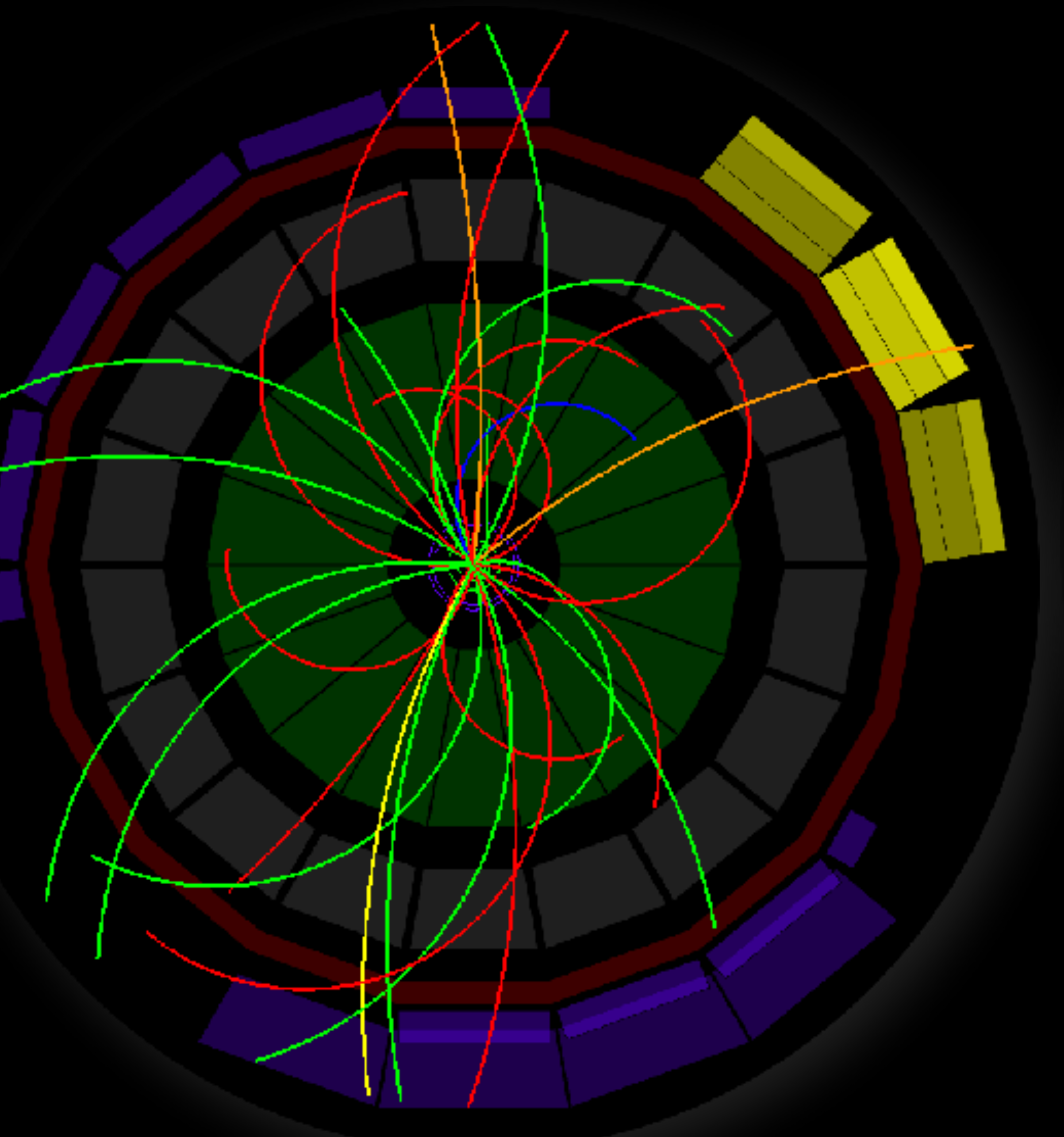


p-A

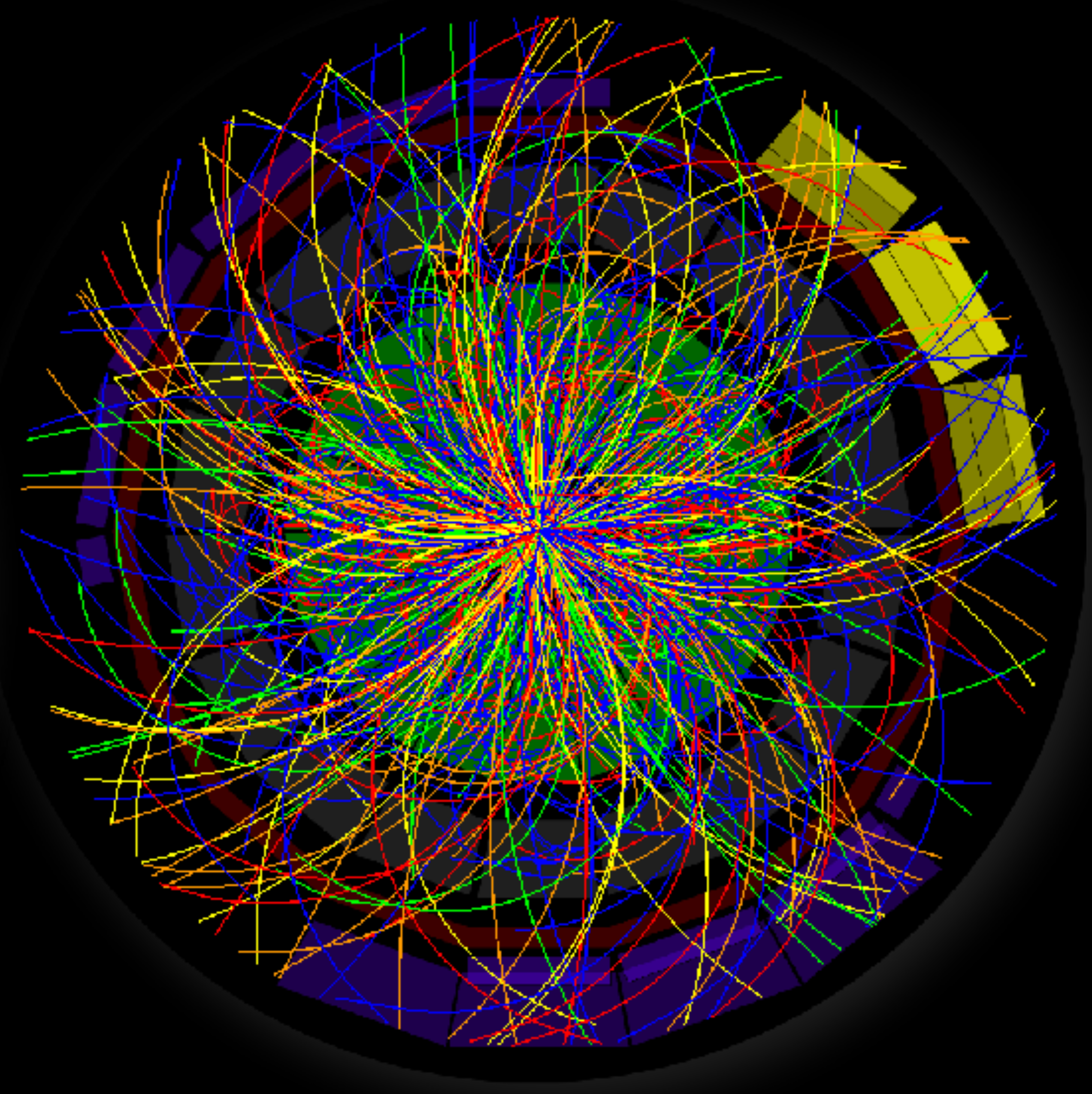


pp

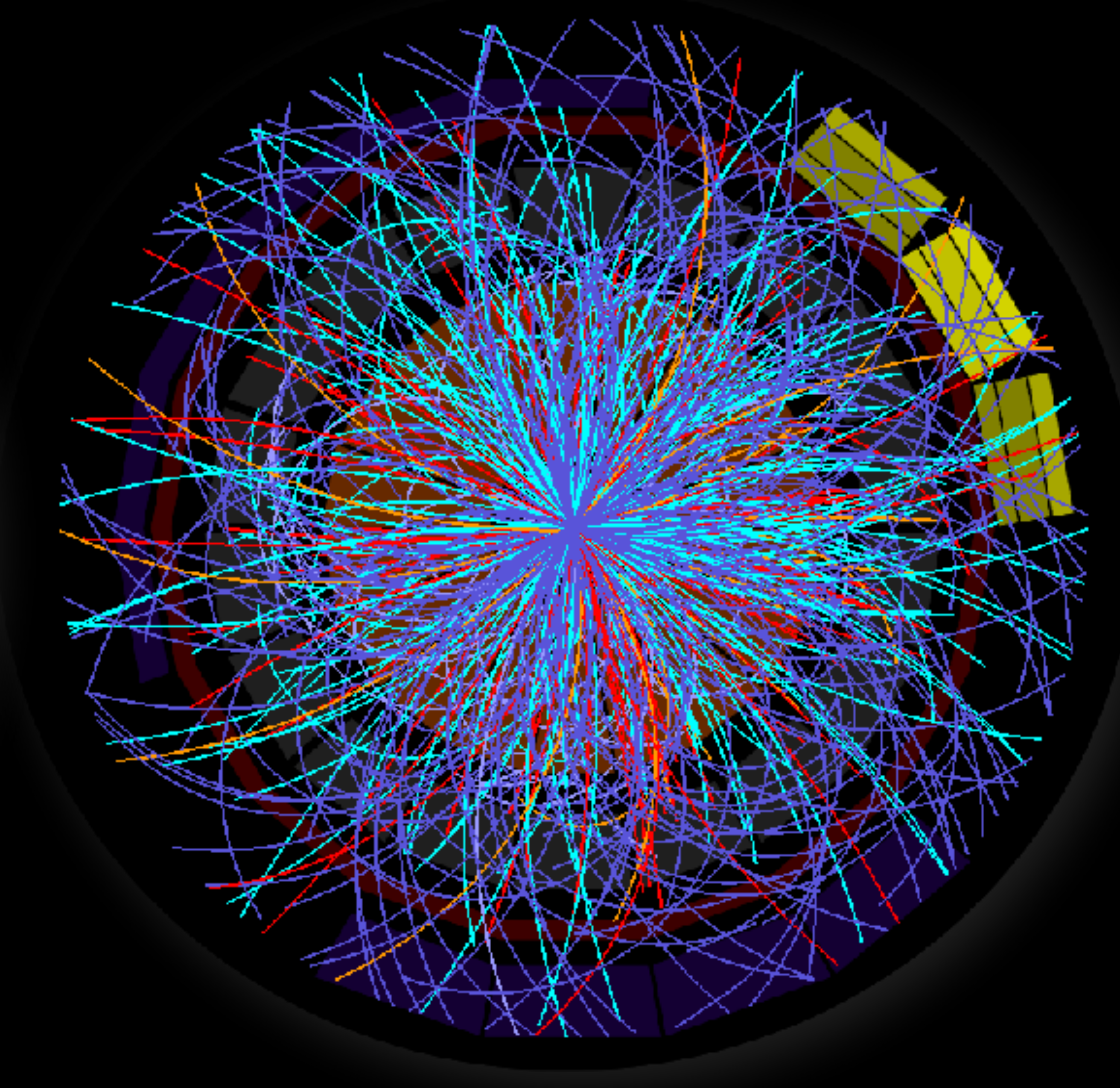




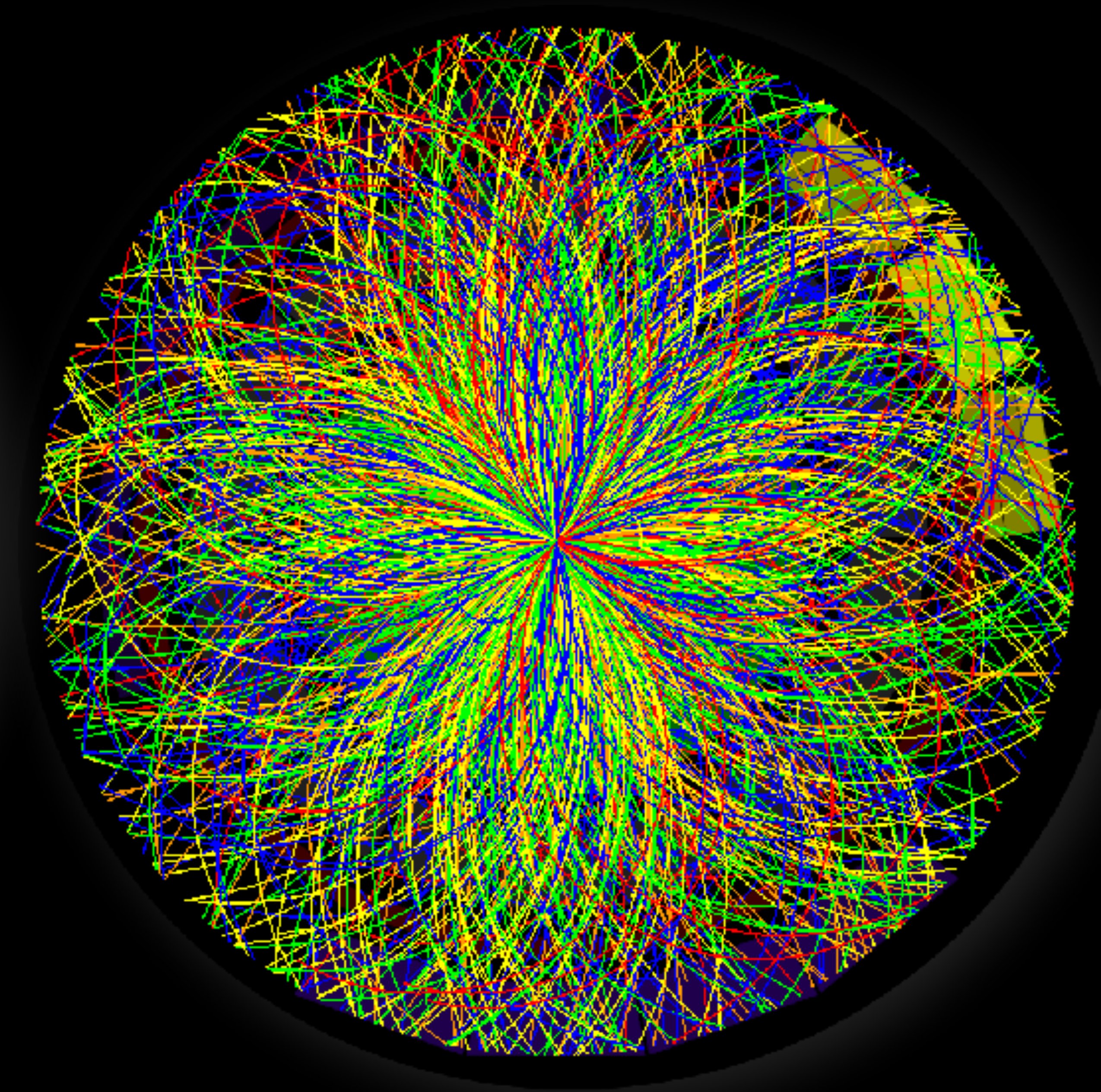
pp
0.9, 5.02, 7, 13 TeV



p-Pb
5.02 TeV and 8 TeV

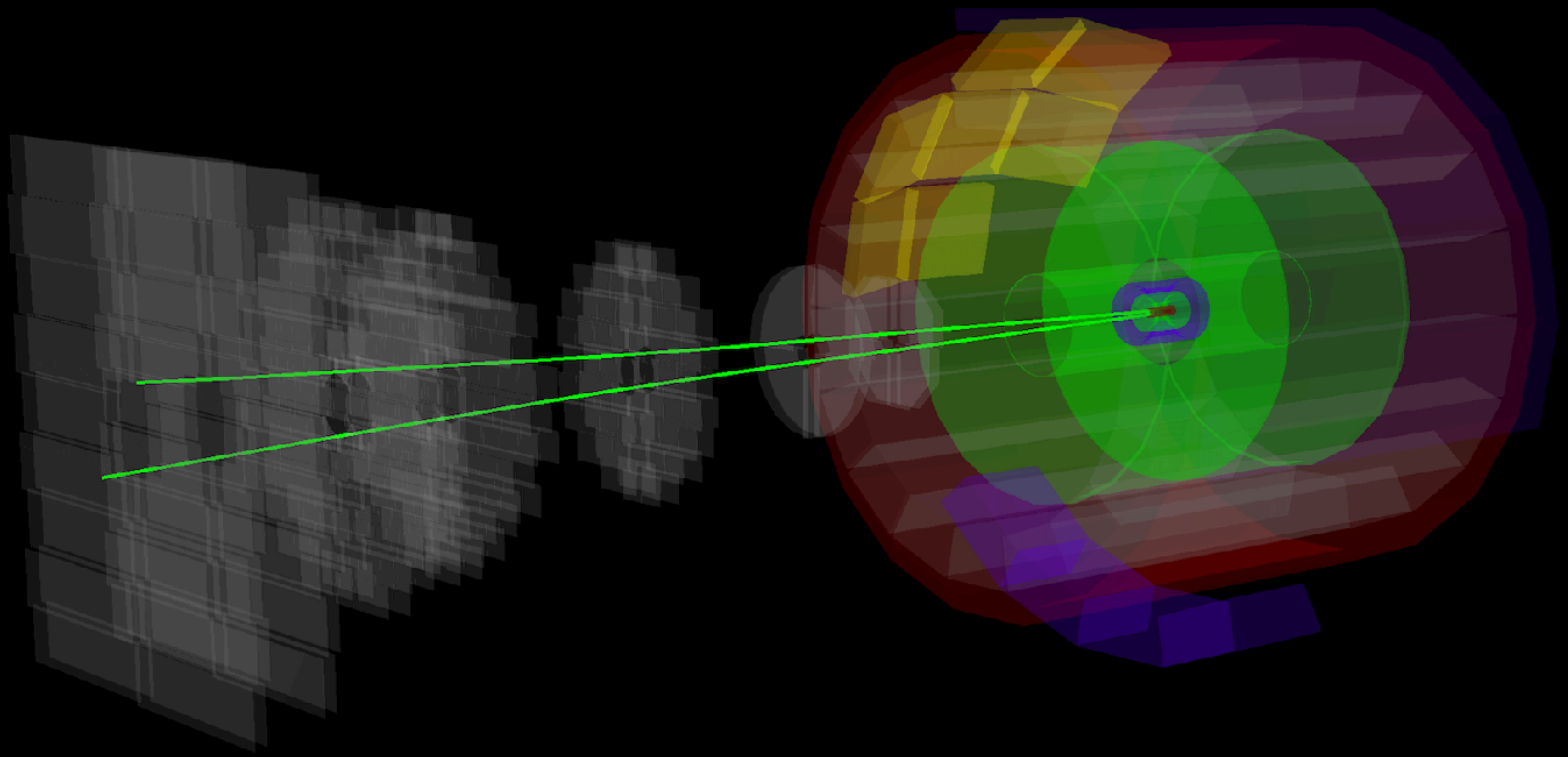


Xe-Xe
5.44 TeV



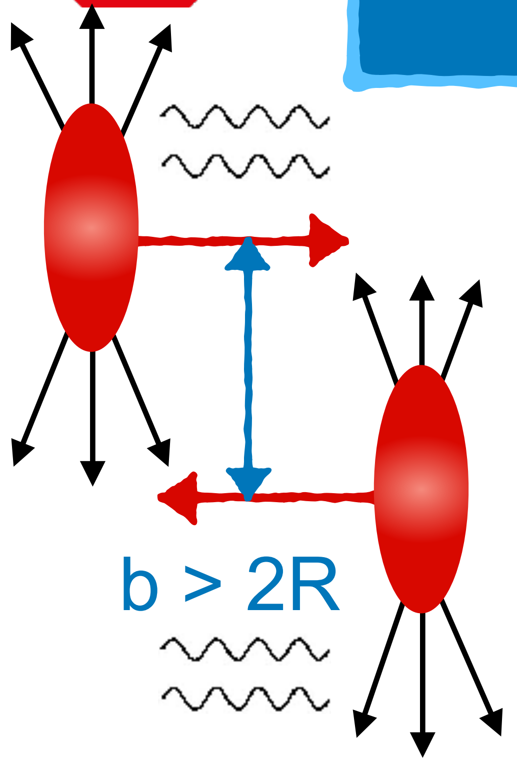
Pb-Pb
2.76 and 5.02 TeV

This presentation ➧ topic driven selection of ALICE experimental results



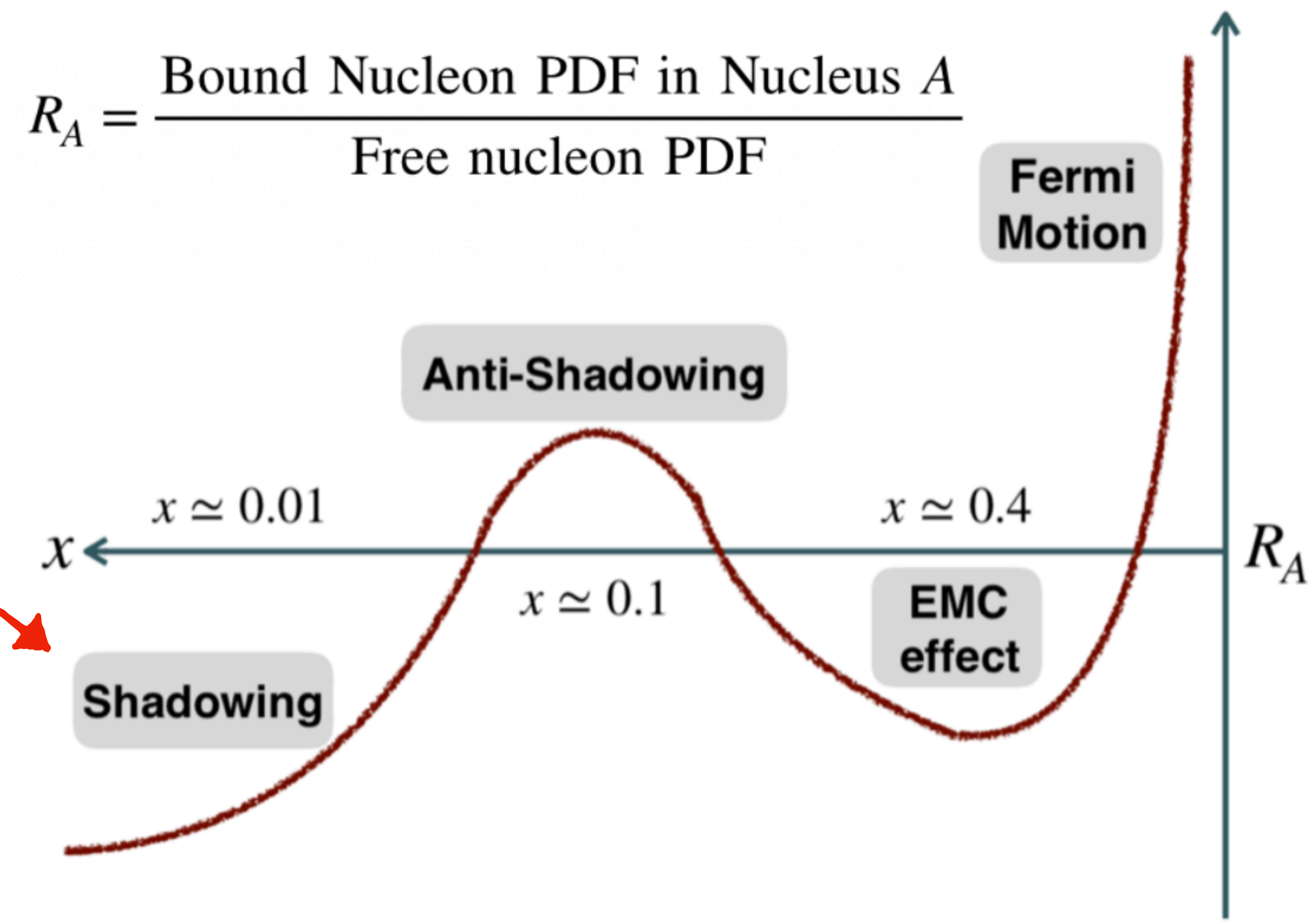
Initial stage of heavy-ion collisions

J/ψ coherent photoproduction



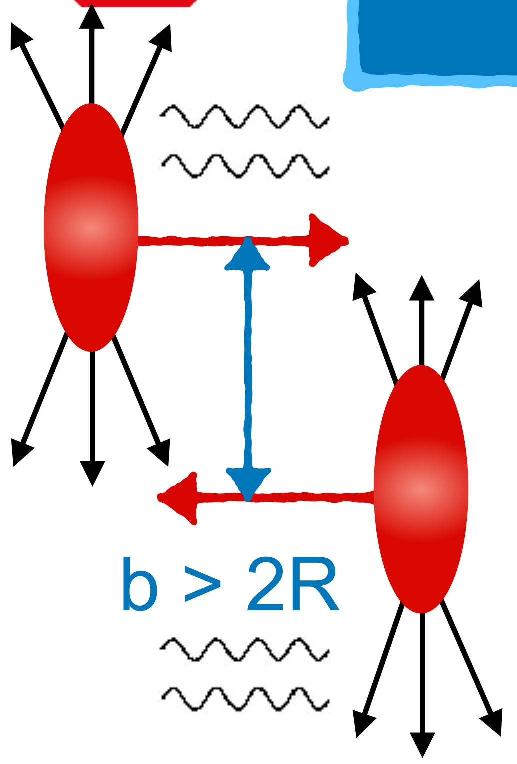
Ultra-peripheral heavy-ion interactions ➧ nuclei interact via virtual photons

Coherent vector meson (J/ψ, ψ') photoproduction is sensitive to gluon PDF ➧ study the modification of PDFs for bound nucleons (nPDFs) compared to free nucleons (ie shadowing effects) at low x values $x = (0.3\text{-}1.4)10^{-3}$

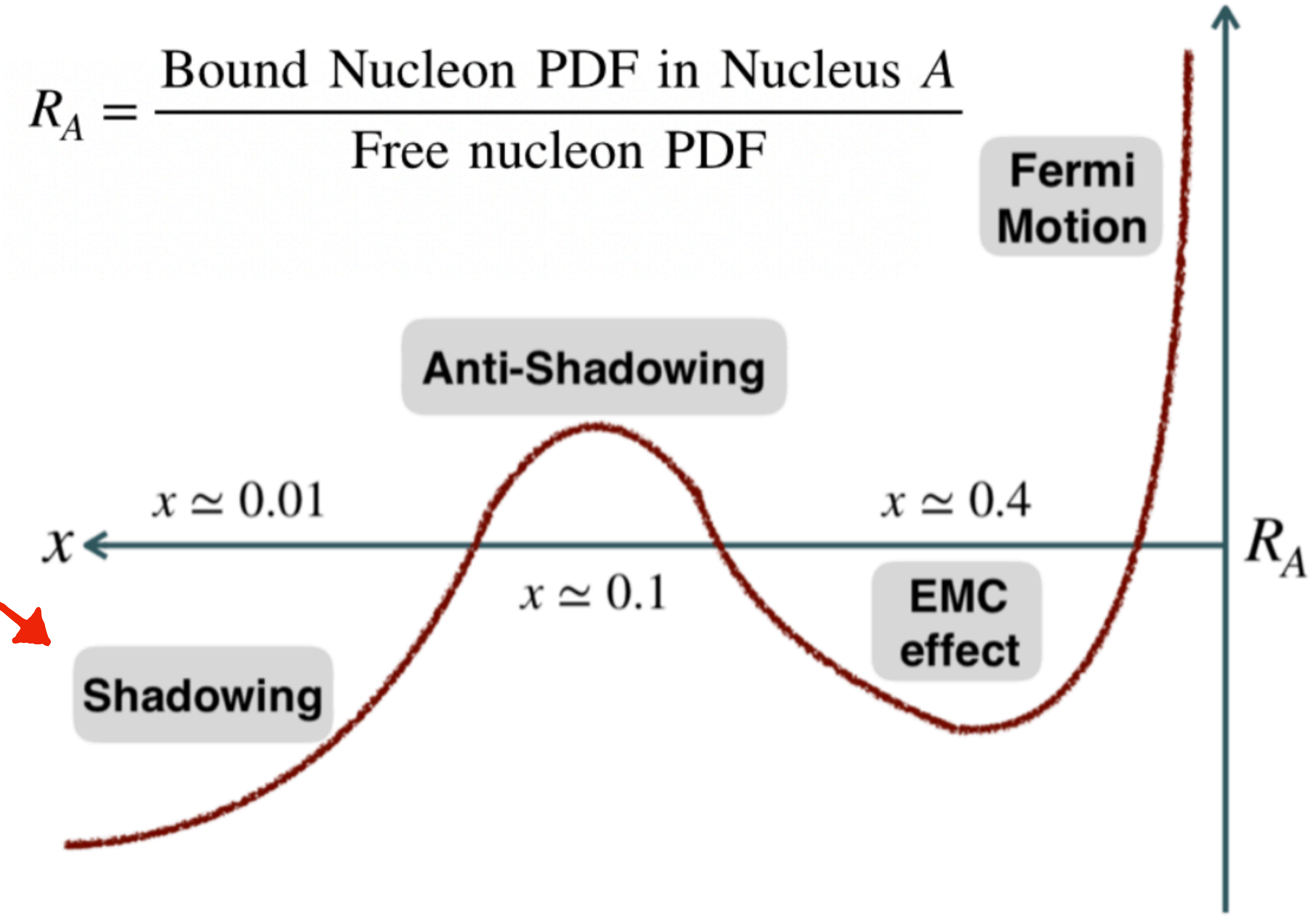


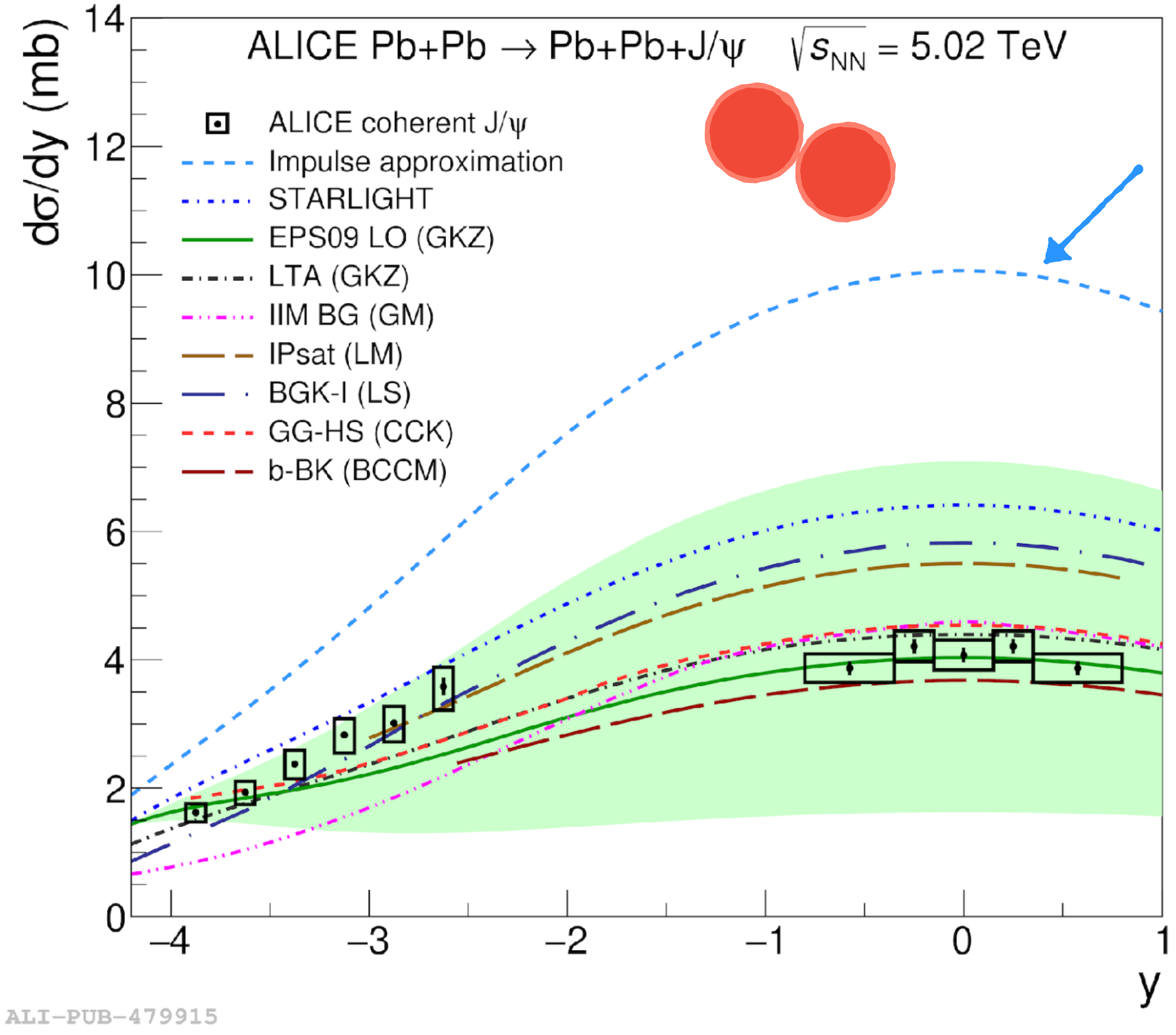
arXiv:2101.04577

J/ψ coherent photoproduction



Ultra-peripheral heavy-ion interactions ➧ nuclei interact via virtual photons
Coherent vector meson (J/ψ, ψ’) photoproduction is sensitive to gluon PDF
➧ study the modification of PDFs for bound nucleons (nPDFs) compared to free nucleons (ie shadowing effects) at low x values x = (0.3-1.4)10^{-3}





Photoproduction on p target

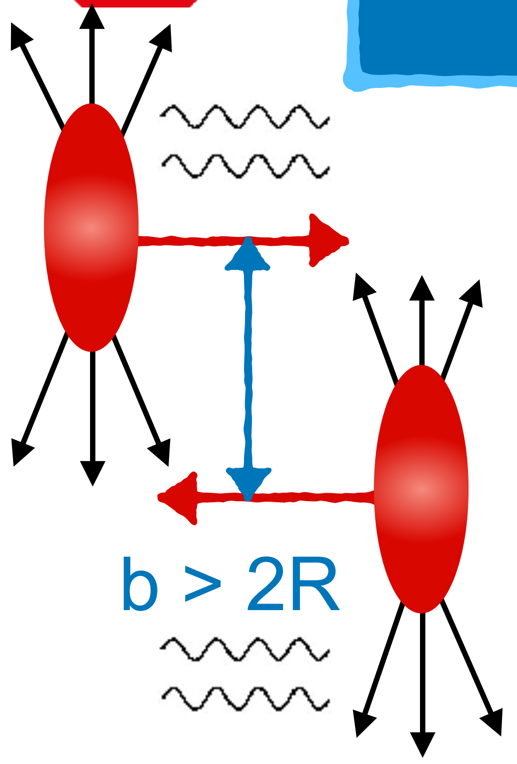
Photoproduction cross section

➧ shadowing from J/ψ photo production on Pb relative to exclusive photoproduction on p target = 0.65 ± 0.03

Constraint on nuclear gluon-shadowing models
➧ none of the models describes measured cross section over the whole y interval

arXiv:2101.04577

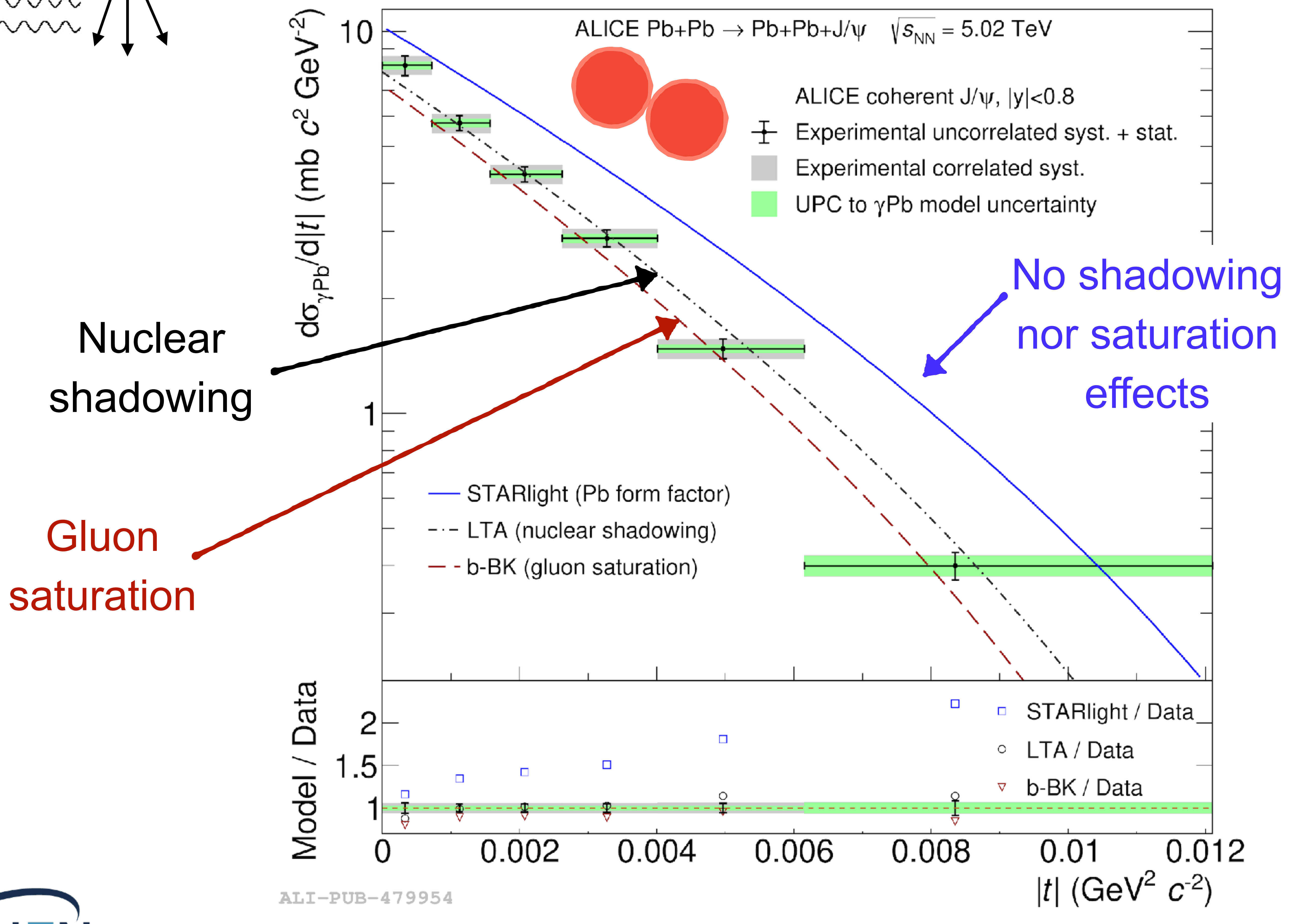
J/ψ coherent photoproduction



arxiv.2101.04623

First measurement of |t|-dependence of coherent J/ψ photoproduction cross section

|t| = square of momentum transferred to the target nucleus
➧ related to the gluon distribution in the plane transverse to the interaction

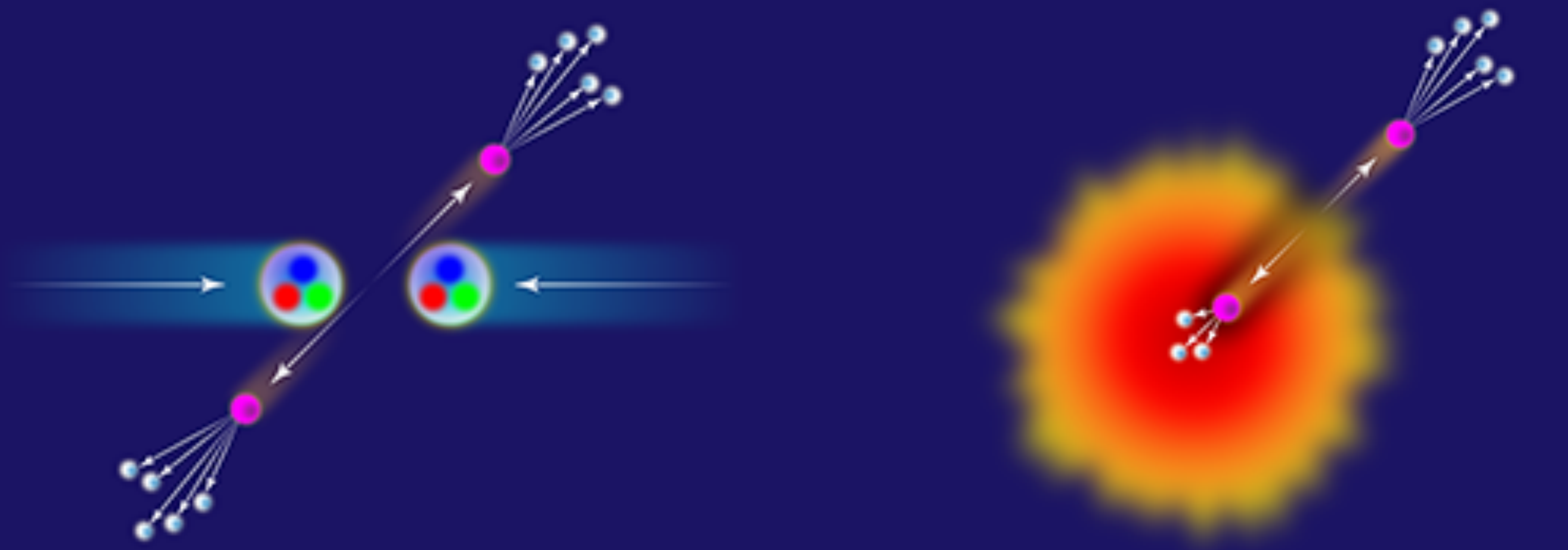


$$\left.\frac{d^2\sigma^{coh}_{J/\psi}}{dy\,dp_T^2}\right|_{y=0} = 2n_{\gamma Pb}(y=0)\frac{d\sigma_{\gamma Pb}}{d|t|}$$

Measured differential cross section | Computed photon flux | Extract γ-Pb cross section

Data are closer to model including saturation or shadowing effects

More precise measurements needed to discriminate between the two effects ➧ Run 3



Medium characterization in A-A collisions

Flavour dependent energy loss

Nuclear modification factor $R_{AA} = \frac{AA}{N_{coll} \cdot pp} = \frac{dN_{AA}/dp_T}{N_{coll} \cdot dN_{pp}/dp_T}$

$R_{AA} = 1$ ➧ N_{coll} scaling

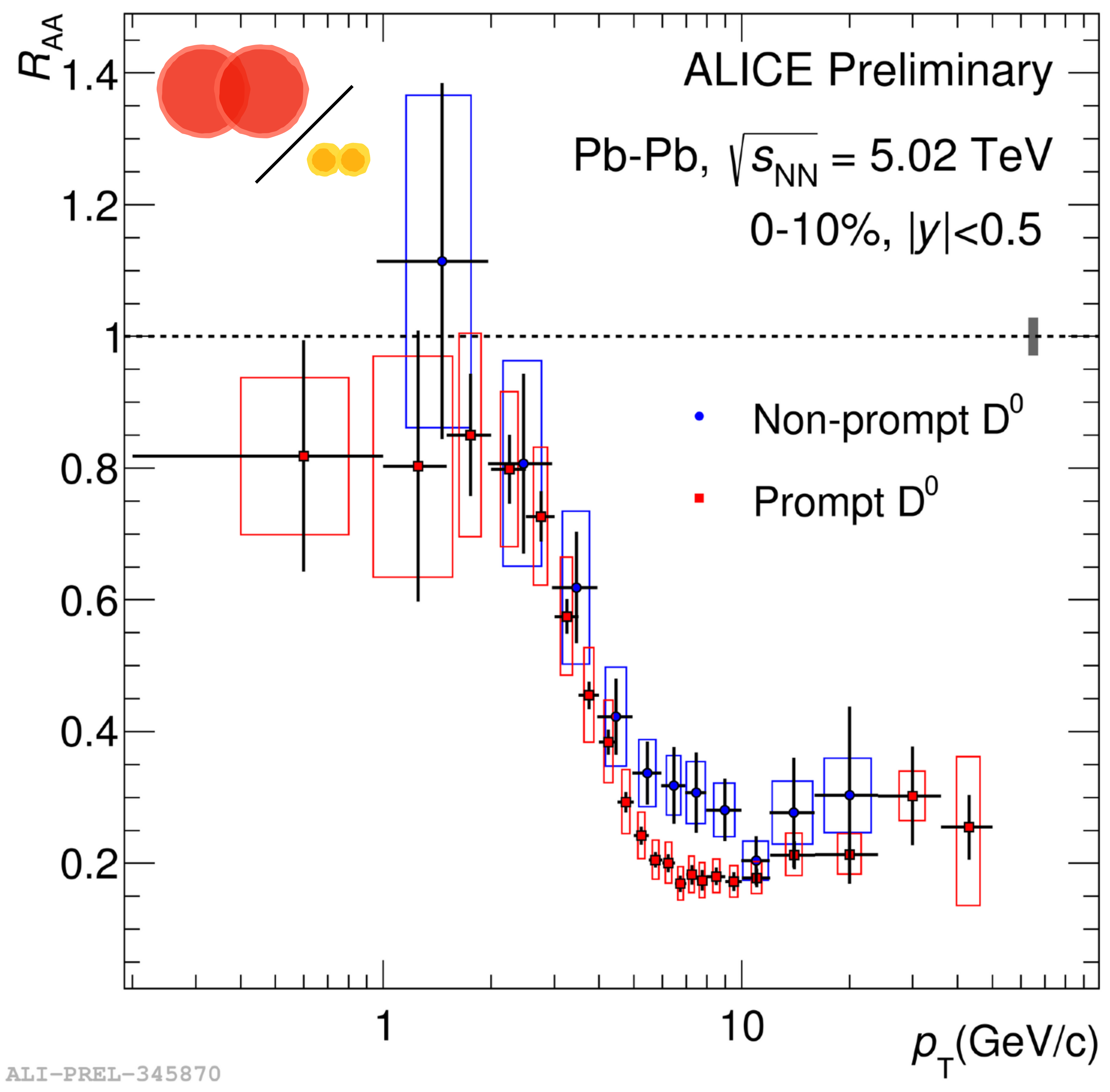
$R_{AA} < 1$ ➧ in-medium modification

Flavour dependent energy loss

Nuclear modification factor $R_{AA} = \frac{AA}{N_{coll} \cdot pp} = \frac{dN_{AA}/dp_T}{N_{coll} \cdot dN_{pp}/dp_T}$

$R_{AA} = 1$ ➧ N_{coll} scaling

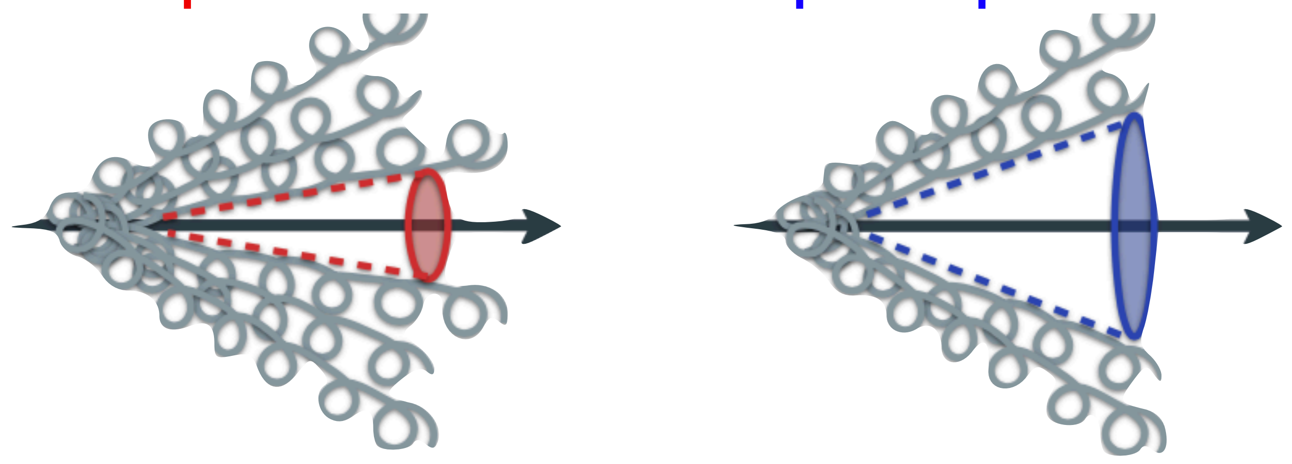
$R_{AA} < 1$ ➧ in-medium modification



E loss depends on parton mass through dead-cone effect

$\Delta E_c > \Delta E_b$

Prompt: c → D   Non-prompt: b → B → D



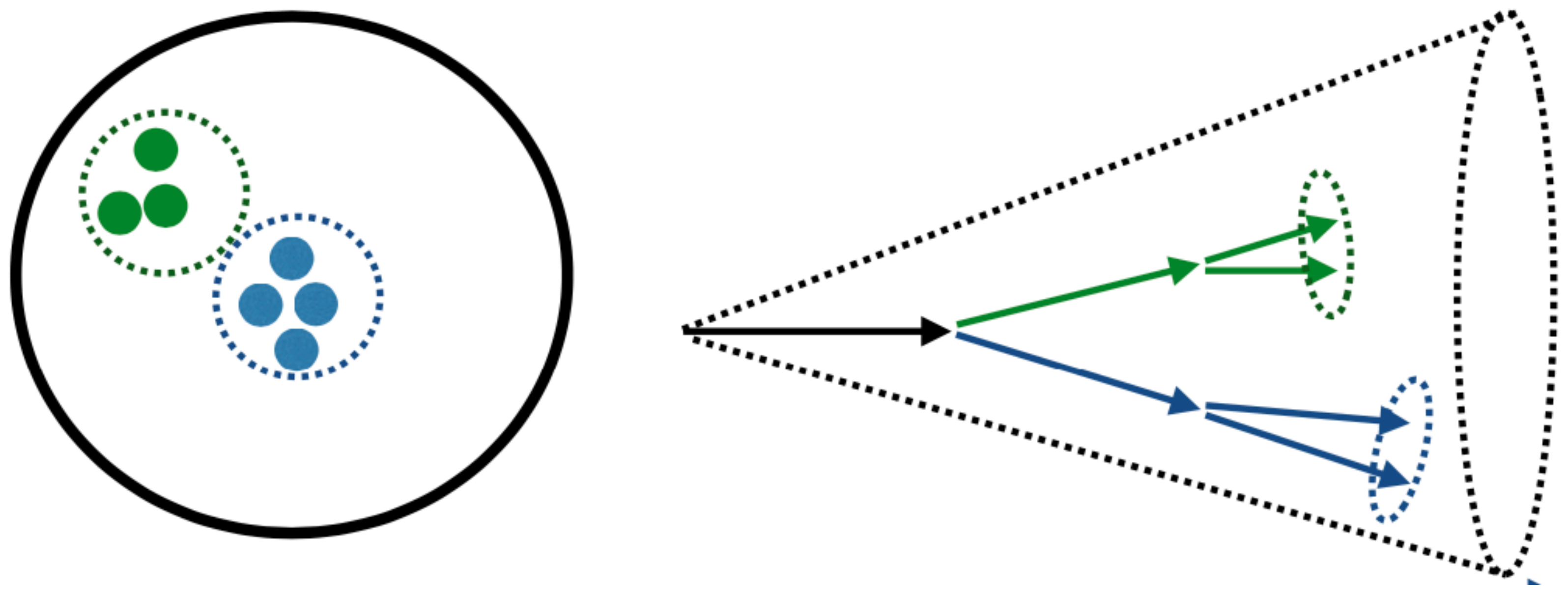
Smaller suppression of D meson from B than from prompt production at intermediate p_T expected

➧ mass dependent energy loss observed

Jet substructure in Pb-Pb

Remove soft radiation at large angles from the jets to isolate the hard structure

- tool to investigate jet quenching effect



Fully correct measurement of the groomed jet radius θ_g:

$$R_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

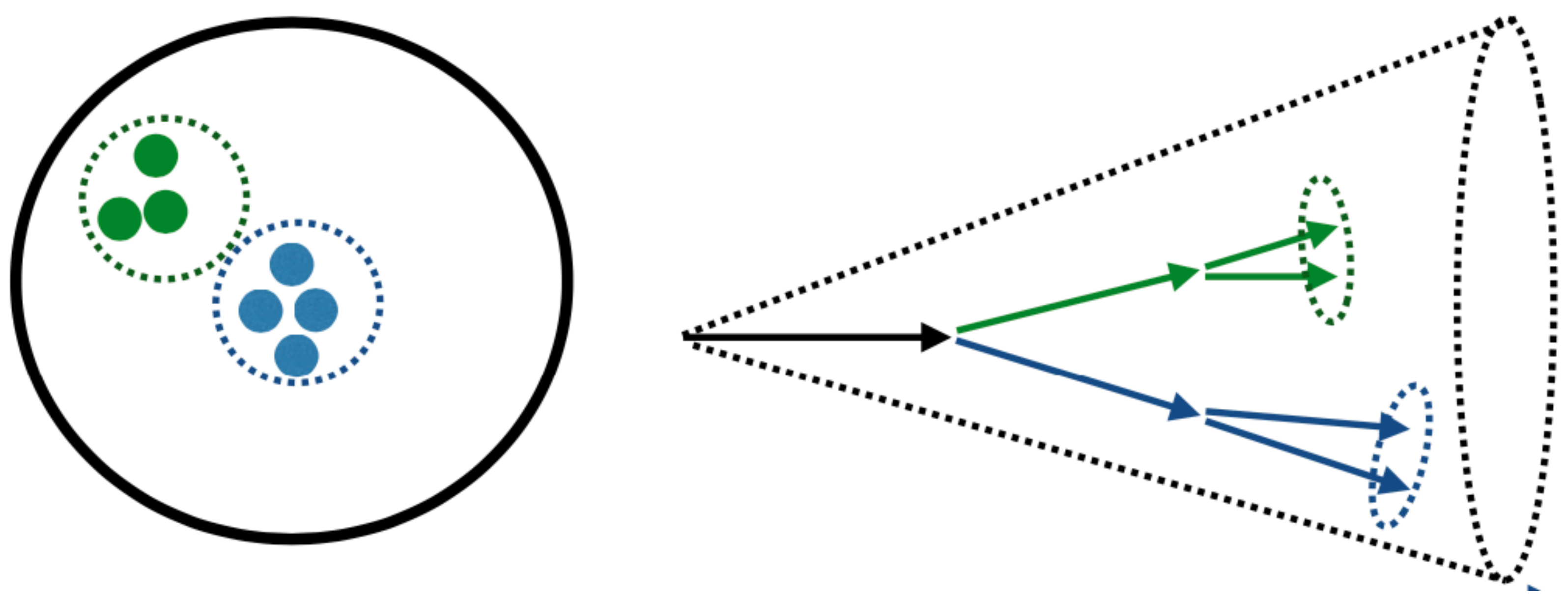
$$\theta_g \equiv \frac{R_g}{R}$$

sensitive to path length
and coherence effects

Jet substructure in Pb-Pb

Remove soft radiation at large angles from the jets to isolate the hard structure

- tool to investigate jet quenching effect

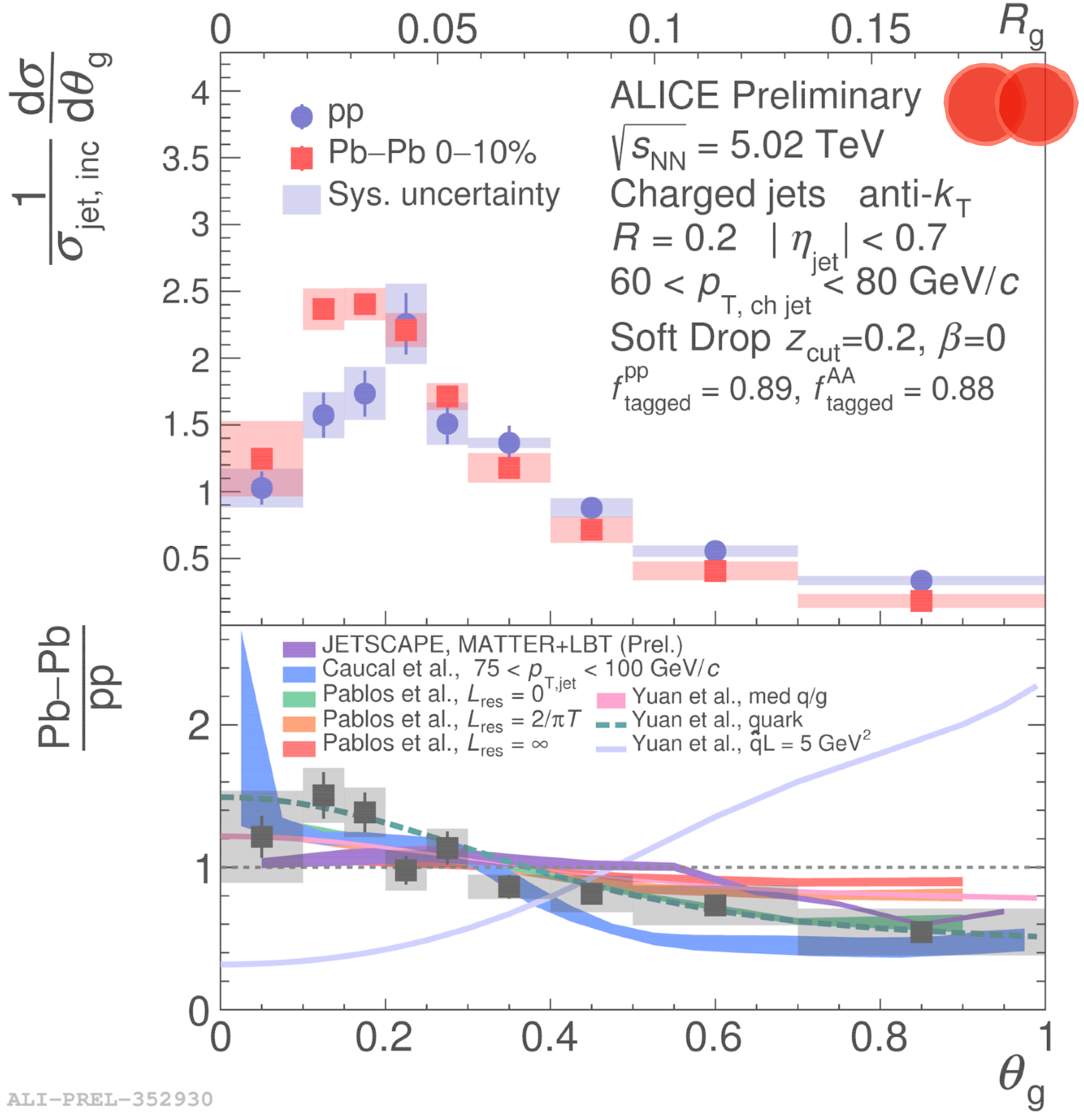


Fully correct measurement of the groomed jet radius θ_g:

$$R_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

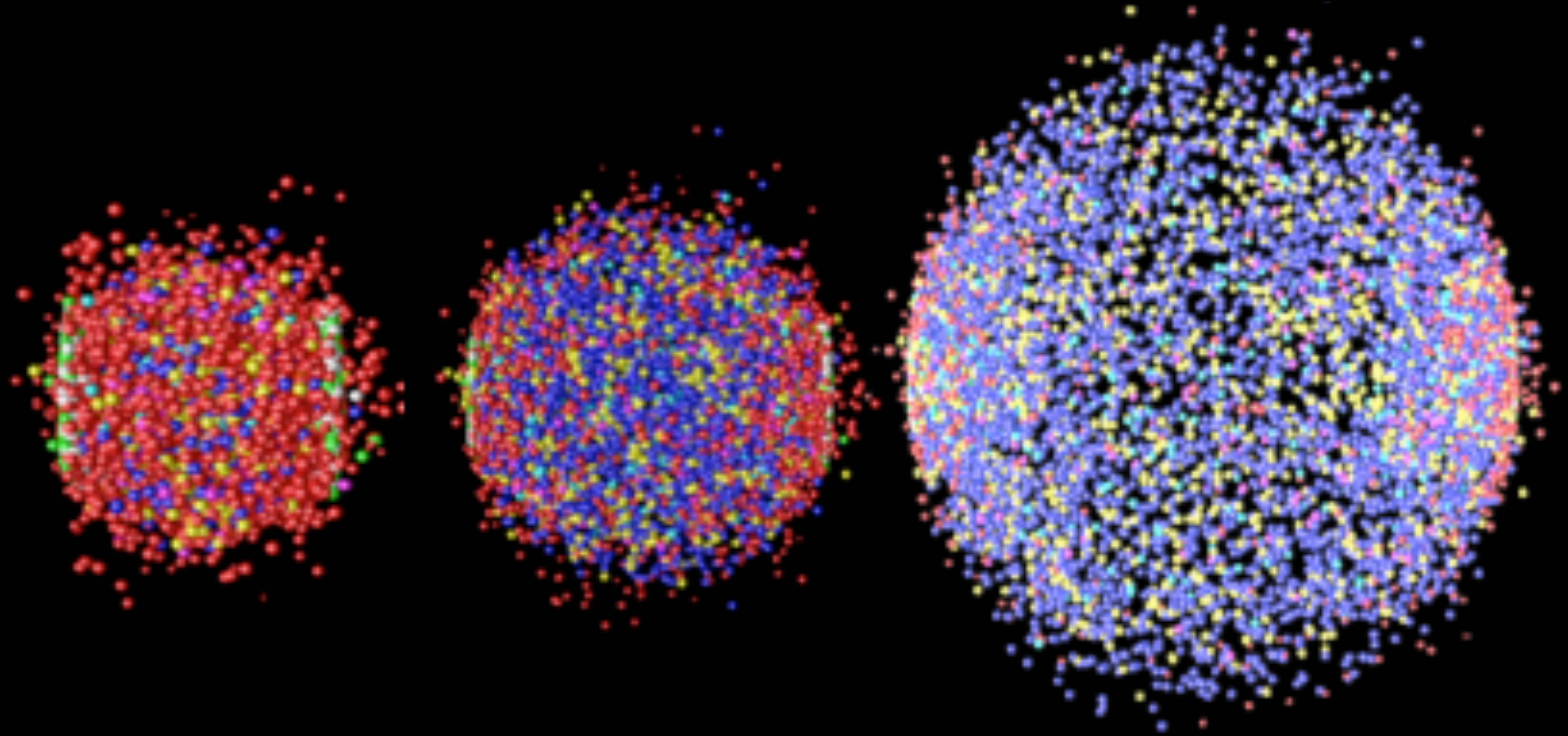
$$\theta_g \equiv \frac{R_g}{R}$$

sensitive to path length and coherence effects



Jet hard core is narrower in Pb-Pb collisions relative to pp

- first direct experimental evidence of a modification of the angular scale of jets in Pb-Pb collisions



Collective evolution

Light flavour flow

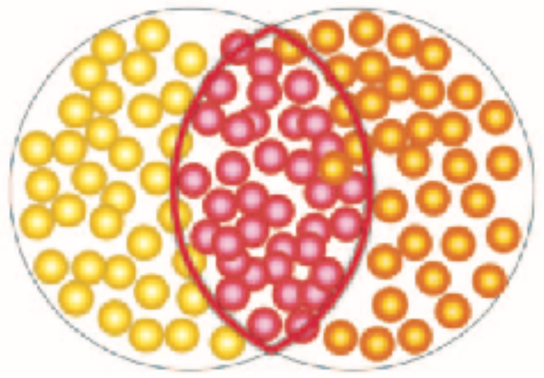
Anisotropies in the initial state are mapped in final state particle spectra

Fourier decomposition of azimuthal distributions relative to the Reaction Plane (RP):

$$\frac{dN}{d\phi} \sim 1 + 2\sum_{n} v_n cos\left[n\left(\phi - \Psi_{RP}\right)\right]$$

Fourier coefficients $v_n(p_T, y) = \langle cos[n(\phi - \Psi_{RP})]\rangle$

v_2 elliptic flow ➧ related to the geometry of the overlap zone expansion
asymmetry between in-plane and out-of-plane emission



Light flavour flow

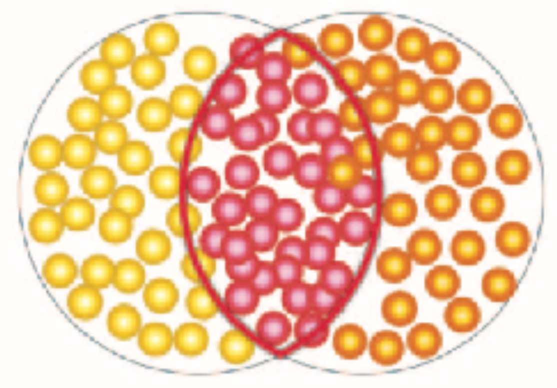
Anisotropies in the initial state are mapped in final state particle spectra

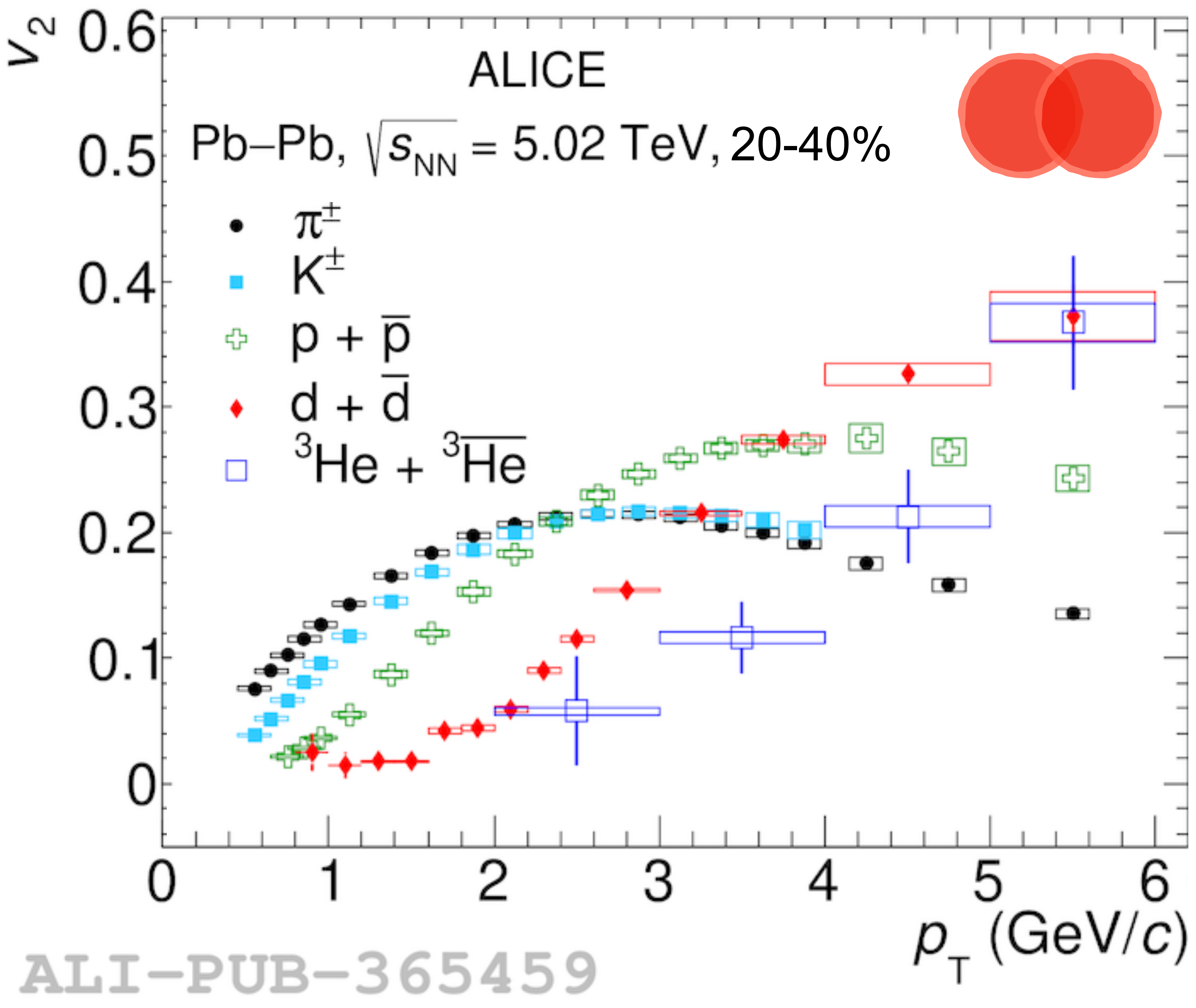
Fourier decomposition of azimuthal distributions relative to the Reaction Plane (RP):

$$\frac{dN}{d\phi} \sim 1 + 2\sum_n v_n cos\left[n\left(\phi - \Psi_{RP}\right)\right]$$

Fourier coefficients $v_n(p_T, y) = \langle cos[n(\phi-\Psi_{RP})]\rangle$

v_2 elliptic flow ➧ related to the geometry of the overlap zone expansion asymmetry between in-plane and out-of-plane emission



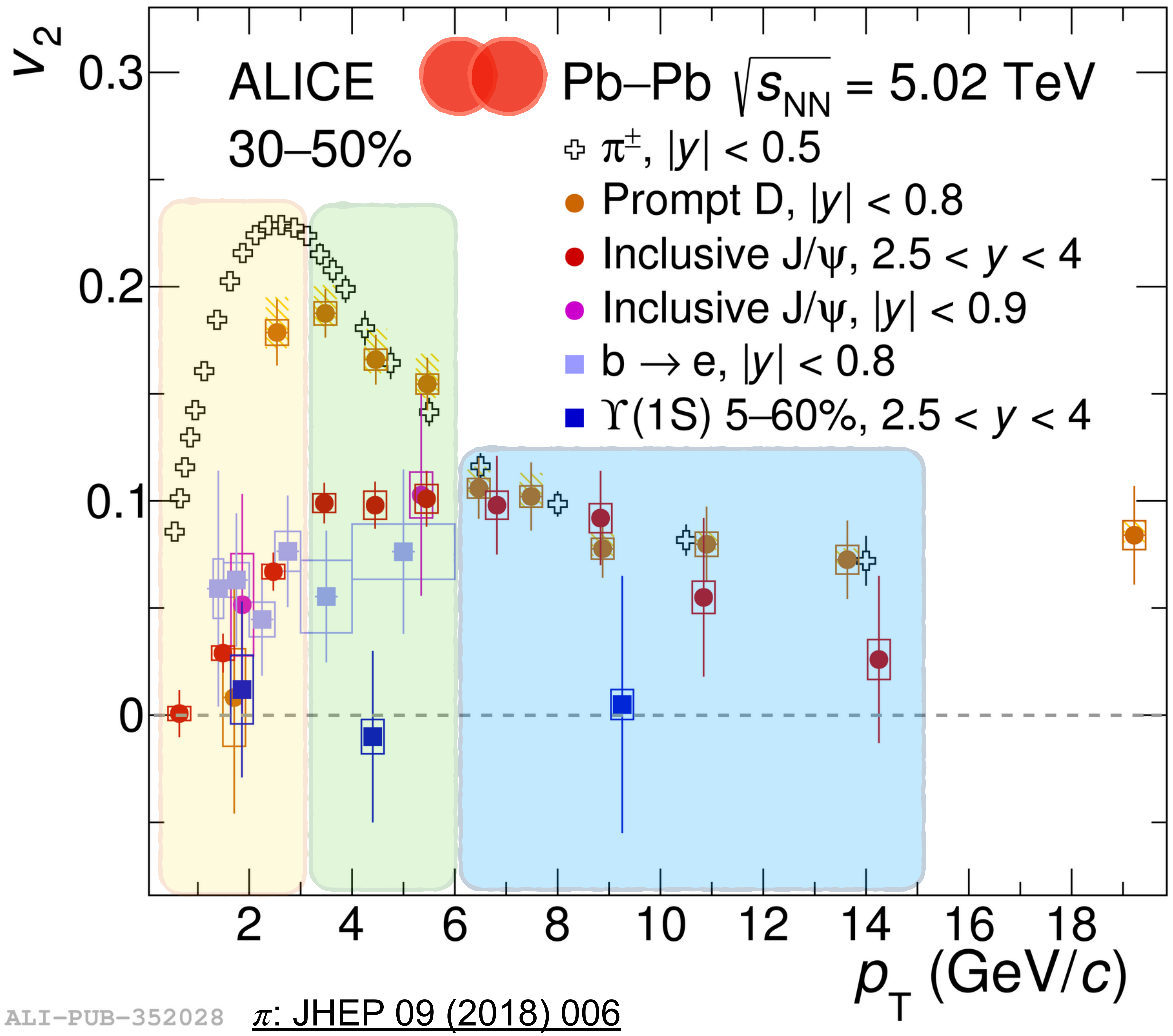


For $p_T < 3$ GeV/c mass ordering as expected from hydrodynamic evolution, with heavier hadrons v_2 shifted to higher p_T

➧ collective expansion of the medium confirmed up to ^{3}He

Phys.Rev. C 102 (2020) 055203

Heavy flavour flow?



π: JHEP 09 (2018) 006

D: arXiv:2005.11131

b->e: arXiv:2005.11130

J/ψ: arXiv:2005.14518

Υ(1S): PRL 123 (2019) 192301

p_T < 3 GeV/c ➧ $v_2(J/\psi) < v_2(D) < v_2(\pi^{\pm})$

mass ordering consistent with expectations from hydrodynamics

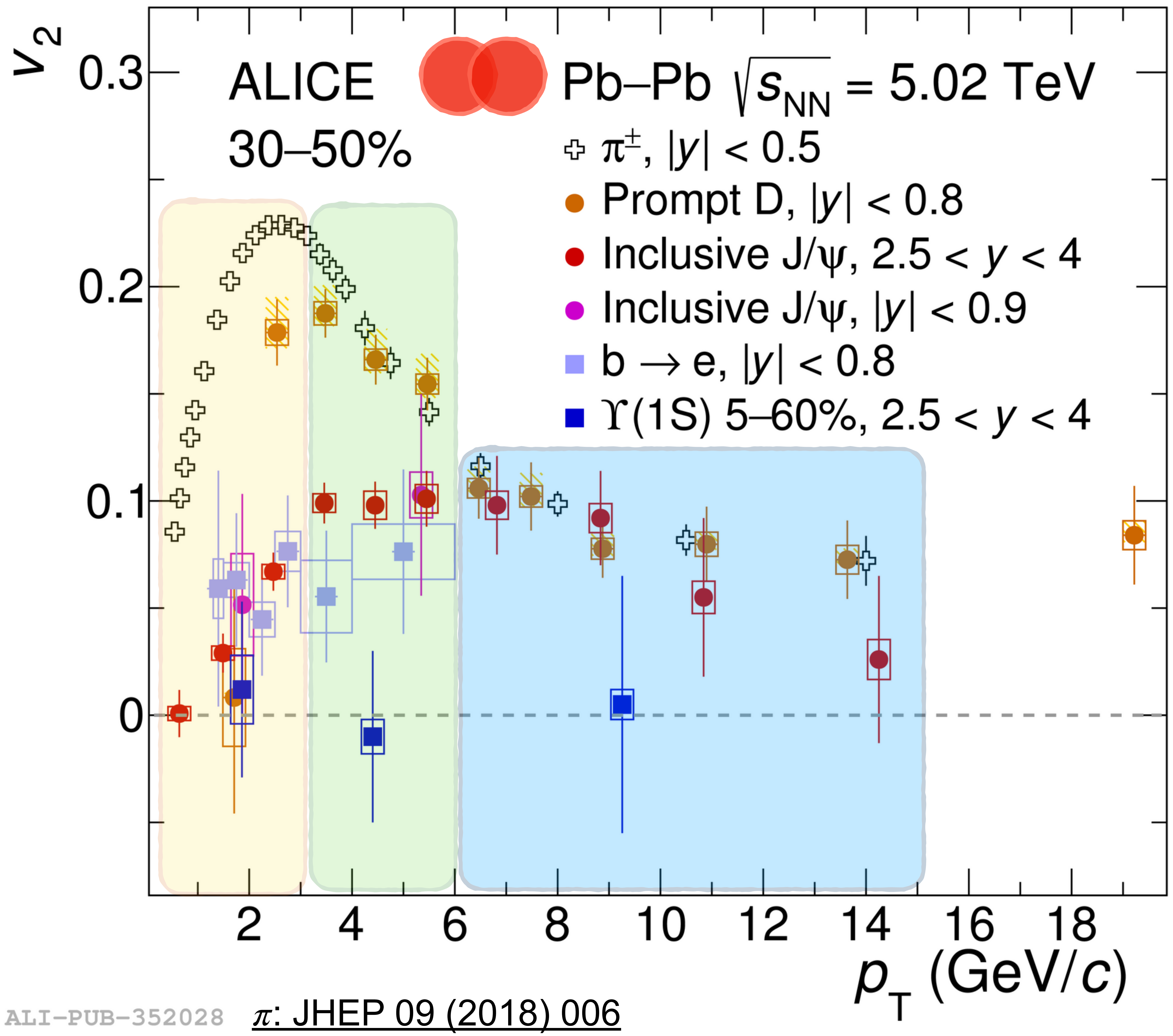
3 < p_T < 6 GeV/c ➧ $v_2(J/\psi) < v_2(D) \approx v_2(\pi^{\pm})$

heavy-quark hadronization via coalescence with flowing light quarks

p_T > 6-8 GeV/c ➧ $v_2(J/\psi) \approx v_2(D) \approx v_2(\pi^{\pm})$

similar path-length dependence of energy loss for heavy and light partons?

Heavy flavour flow?



π: JHEP 09 (2018) 006
D: arXiv:2005.11131
J/ψ: arXiv:2005.14518
b->e: arXiv:2005.11130
ϒ(1S): PRL 123 (2019) 192301

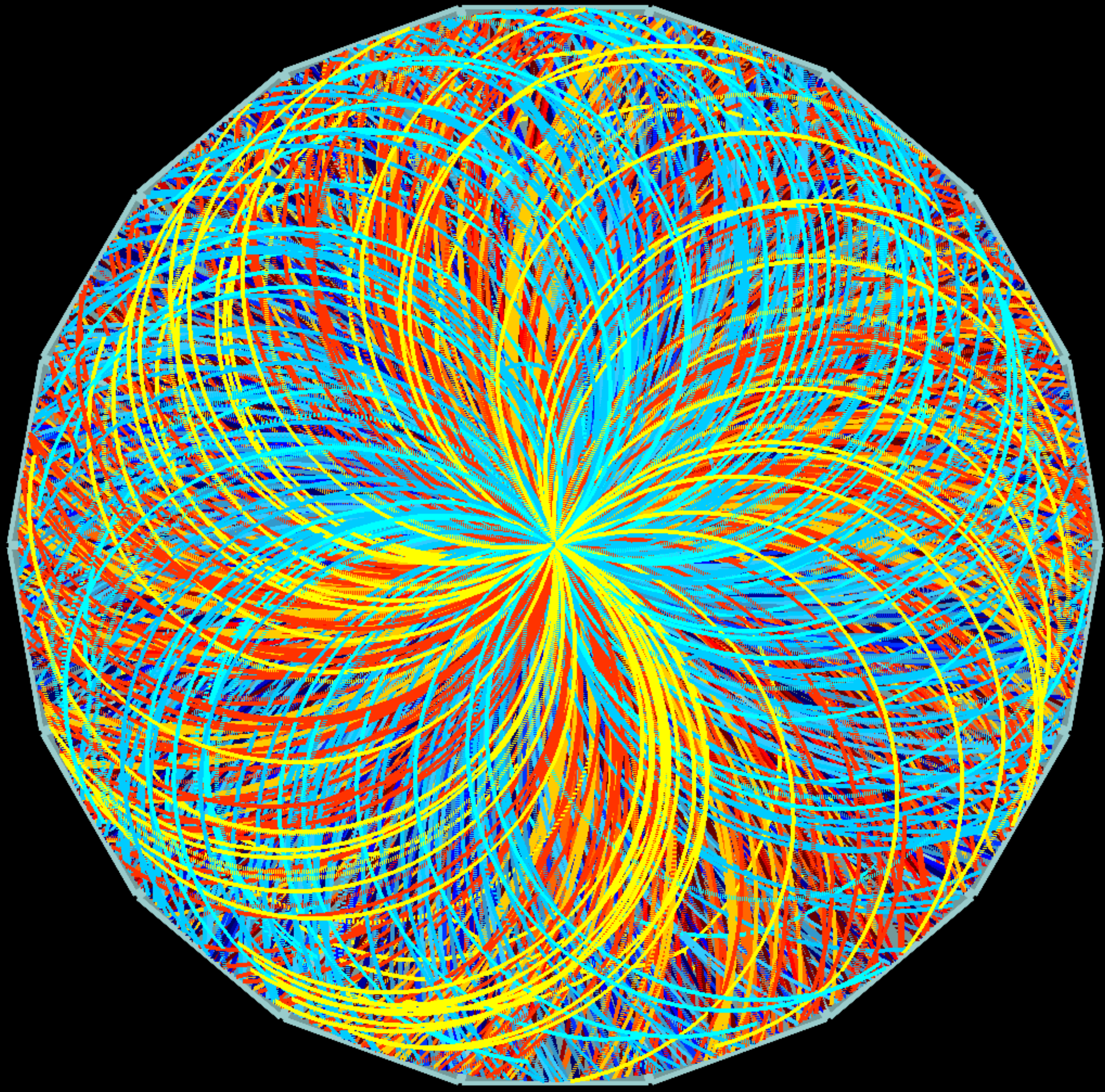
p_T < 3 GeV/c ➧ $v_2(J/\psi) < v_2(D) < v_2(\pi^{\pm})$
mass ordering consistent with expectations from hydrodynamics

3 < p_T < 6 GeV/c ➧ $v_2(J/\psi) < v_2(D) \approx v_2(\pi^{\pm})$
heavy-quark hadronization via coalescence with flowing light quarks

p_T > 6-8 GeV/c ➧ $v_2(J/\psi) \approx v_2(D) \approx v_2(\pi^{\pm})$
similar path-length dependence of energy loss for heavy and light partons?

v_2>0 for open HF and J/ψ
v_2 compatible with 0 for ϒ(1S)
(expected from a smaller regeneration contribution for bb)

➧ c and b quarks participate in collective motion of the system



Particle production & hadronization

Underlying Event in pp

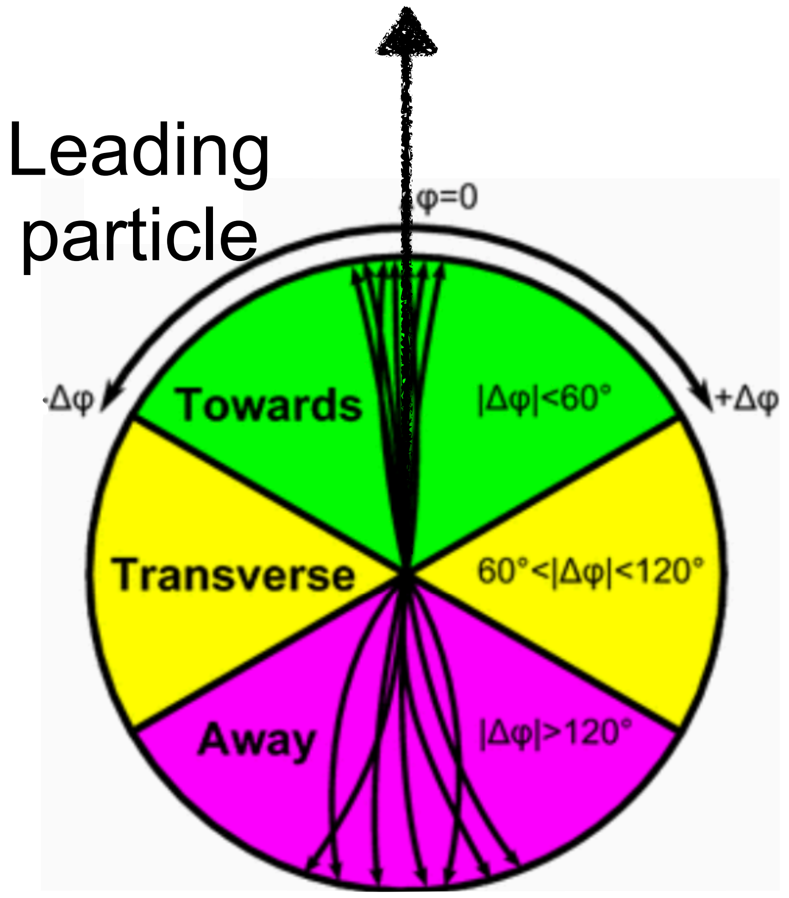
Analysis of particle multiplicity and momentum density in the presence of a leading particle (hard scattering) in different regions:

- TOWARDS ($|\Delta\varphi|<60°$)
- AWAY ($|\Delta\varphi|>120°$)

→ Fragmentation products from hard scatterings

- TRANSVERSE ($60°<|\Delta\varphi|<120°$)

→ Underlying Event (UE), MultiParton Interactions (MPI), ISR/FSR, beam remnants



Underlying Event in pp

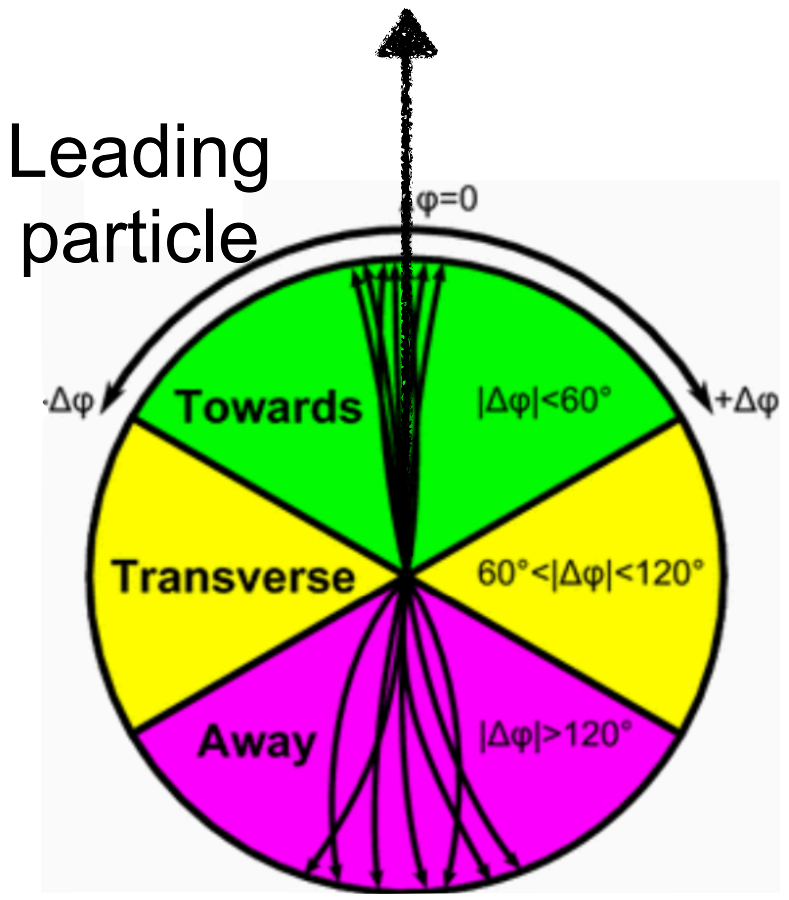
Analysis of particle multiplicity and momentum density in the presence of a leading particle (hard scattering) in different regions:

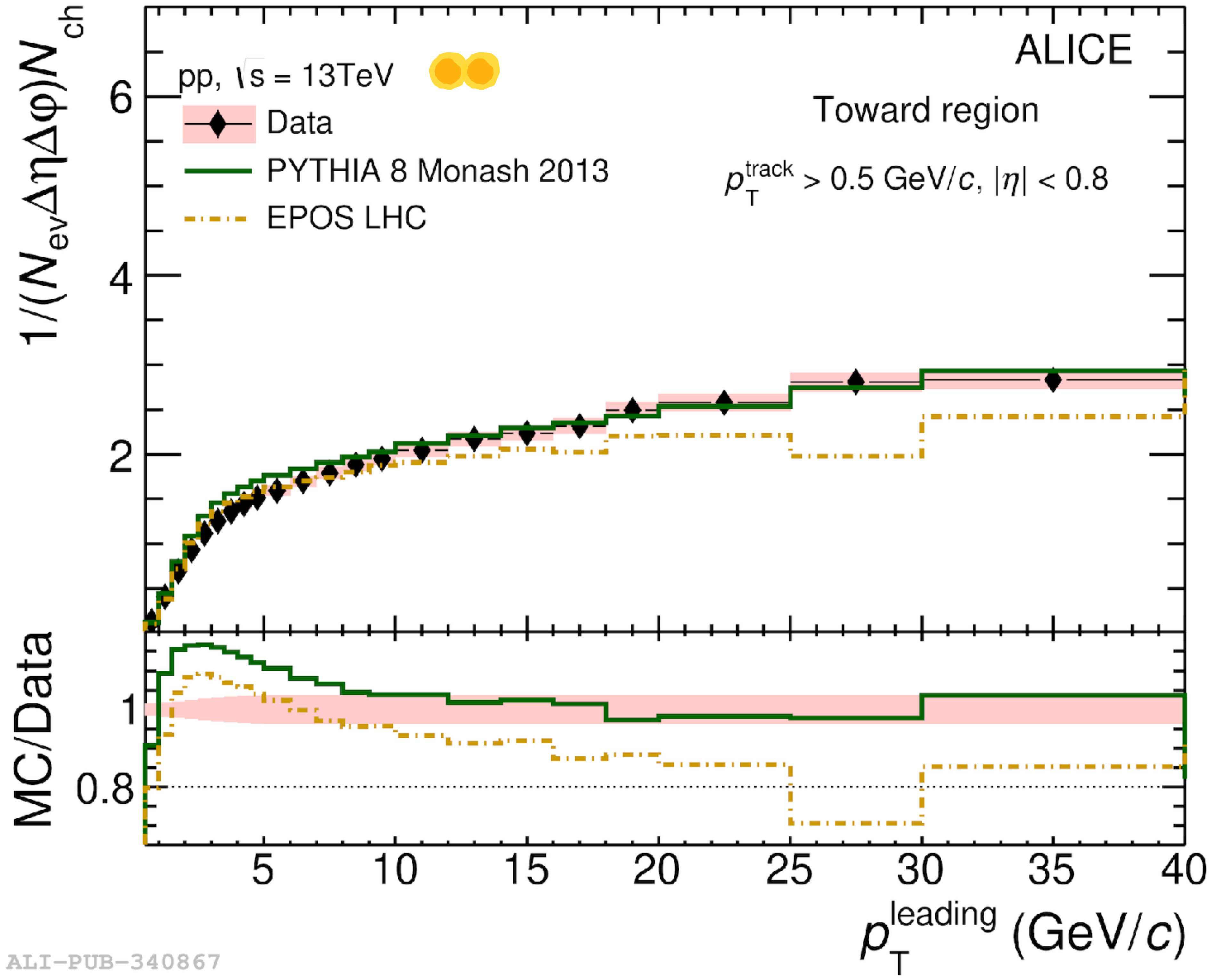
- TOWARDS ($|\Delta\varphi|<60°$)
- AWAY ($|\Delta\varphi|>120°$)

→ Fragmentation products from hard scatterings

- TRANSVERSE ($60°<|\Delta\varphi|<120°$)

→ Underlying Event (UE), MultiParton Interactions (MPI), ISR/FSR, beam remnants





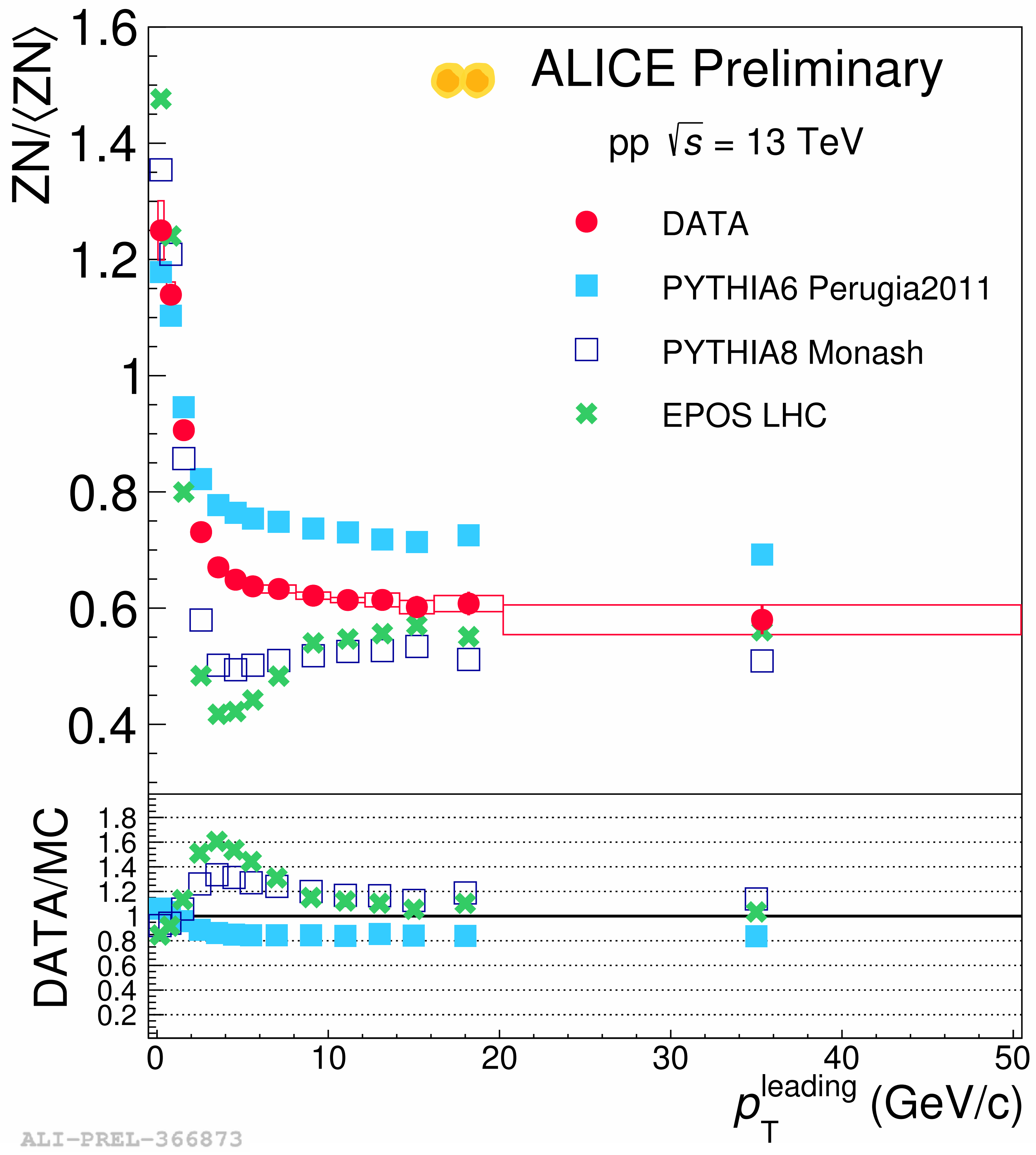
In the TRANSVERSE REGION:

- UE saturate for p_T>5 GeV/c both in pp and in p-Pb collisions
- pedestal effect reproduced by MPI with impact parameter dependence

JHEP 04 (2020) 192

Very forward energy in pp

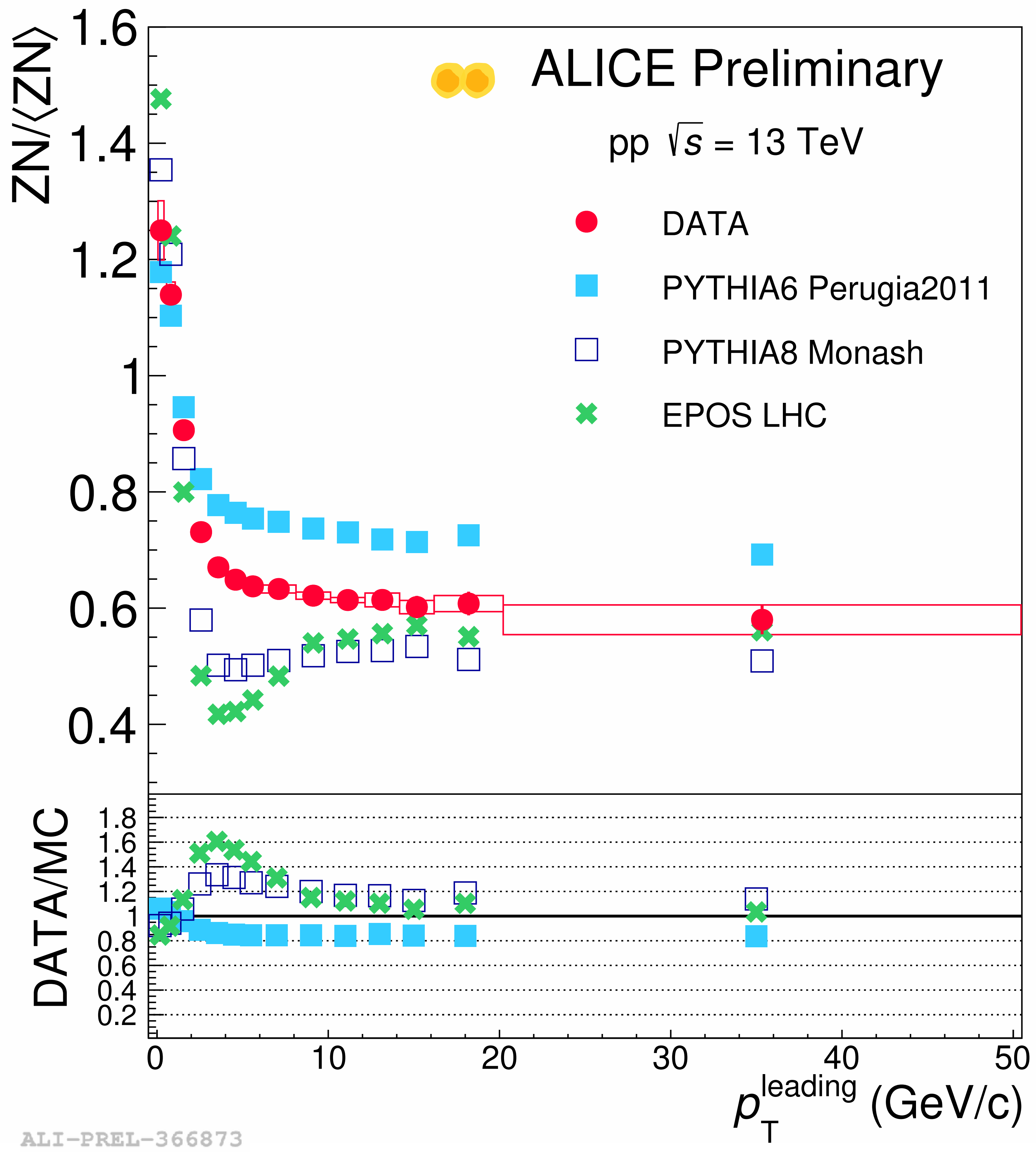
First measurement at LHC energies of very forward (|η|>8.8) energy in combination with midrapidity activity

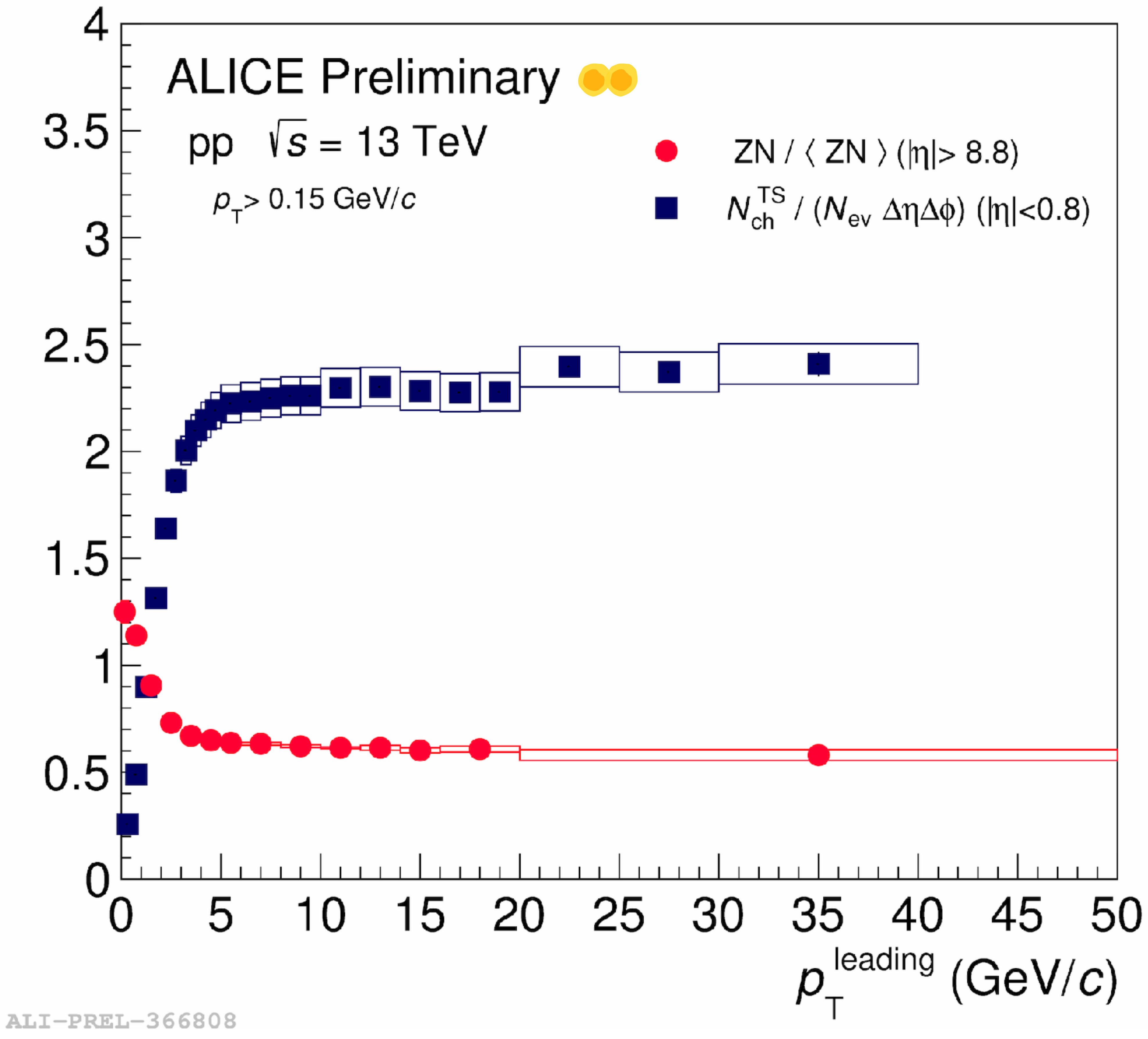


Forward energy decreases with midrapidity activity
Constraints for hadronic interaction models, largely used in high energy cosmic ray simulations

Very forward energy in pp

First measurement at LHC energies of very forward (|η|>8.8) energy in combination with midrapidity activity





Midrapidity

Very forward rapidity

Forward energy decreases with midrapidity activity
Constraints for hadronic interaction models, largely used in high energy cosmic ray simulations

- both UE and very forward energy saturate at the same p_T scale
- the saturation is built in the initial stages of the collision and is in both cases related to a higher number of MPIs

Heavy flavours

Heavy flavours (c, b) produced in hard-scattering processes at very early stages ➧ test pQCD

Production cross section can be described with perturbative QCD calculations based on the collinear factorisation

$$\sigma_{hh \to Hh} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{ab \to q\bar{q}} \otimes D_{q \to h}(z_q, Q^2)$$

Parton Distribution Functions (non perturbative)

Partonic x-section (perturbative)

Fragmentation functions (non perturbative)

Heavy flavours

Heavy flavours (c, b) produced in hard-scattering processes at very early stages ➧ test pQCD

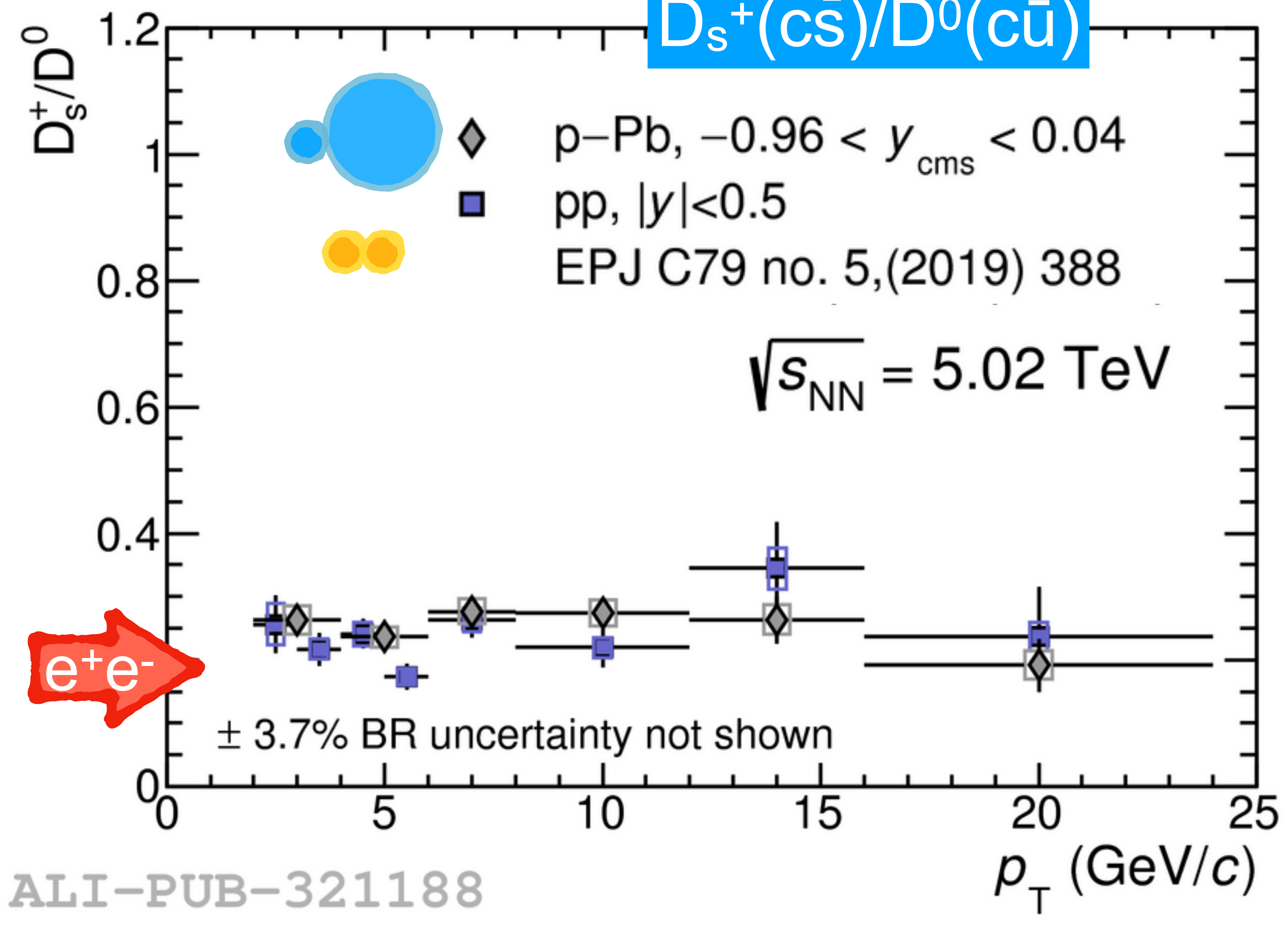
Production cross section can be described with perturbative QCD calculations based on the collinear factorisation

$$\sigma_{hh\rightarrow Hh} = PDF(x_a, Q^2)PDF(x_b, Q^2) \otimes \sigma_{ab\rightarrow q\bar{q}} \otimes D_{q\rightarrow h}(z_q, Q^2)$$

Parton Distribution Functions (non perturbative) | Partonic x-section (perturbative) | Fragmentation functions (non perturbative)

JHEP 12 (2019) 092

$D_s^+(c\bar{s})/D^0(c\bar{u})$



D_s^+ to non-strange D meson abundances in pp and p-Pb are unmodified and compatible with values measured in e^+e^- collisions

➧ confirm assumed universality of fragmentation functions between energies and collision systems

Heavy flavours

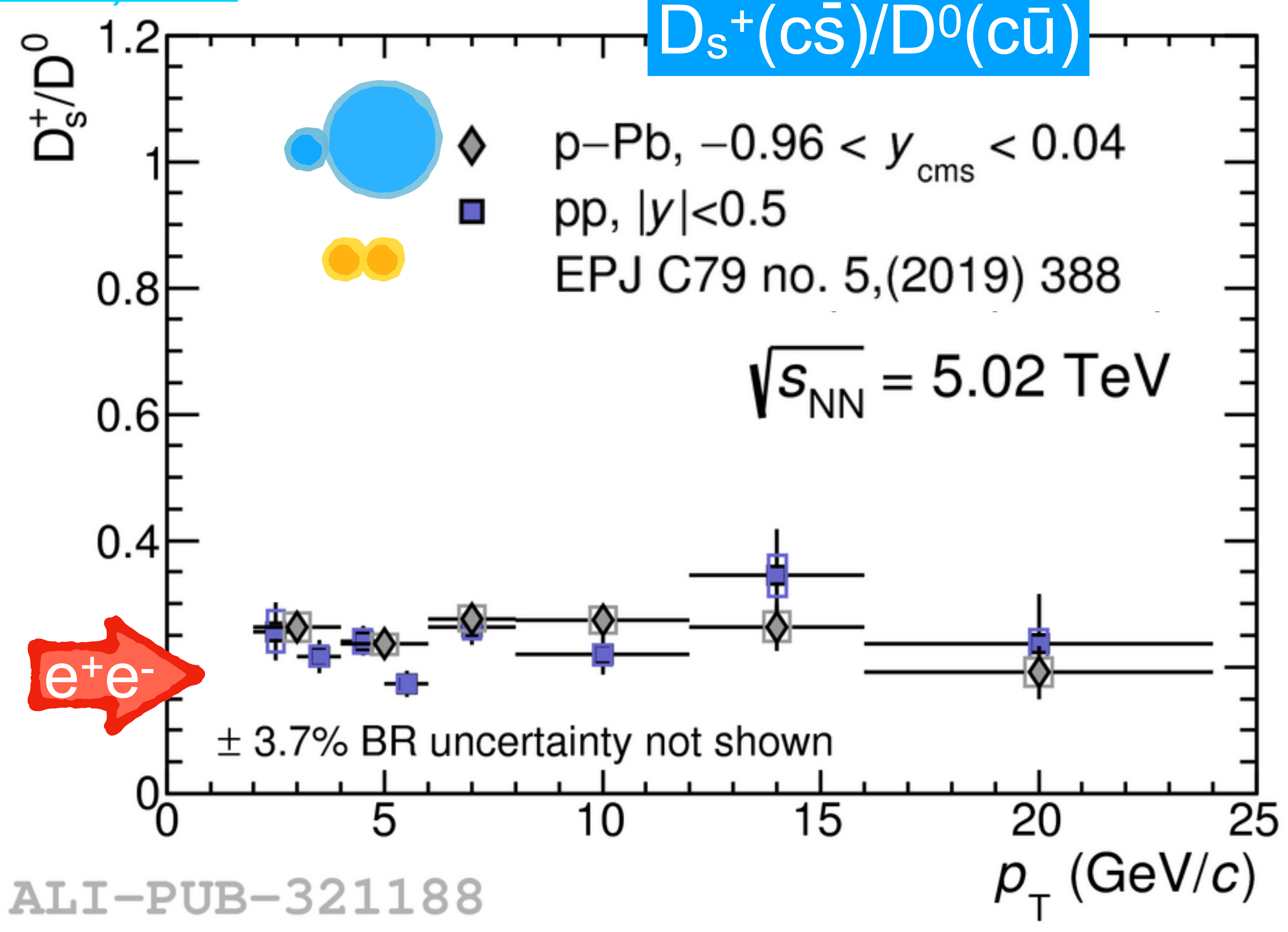
Heavy flavours (c, b) produced in hard-scattering processes at very early stages ➧ test pQCD

Production cross section can be described with perturbative QCD calculations based on the collinear factorisation

$$\sigma_{hh\to Hh} = PDF(x_a, Q^2)PDF(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to h}(z_q, Q^2)$$

JHEP 12 (2019) 092

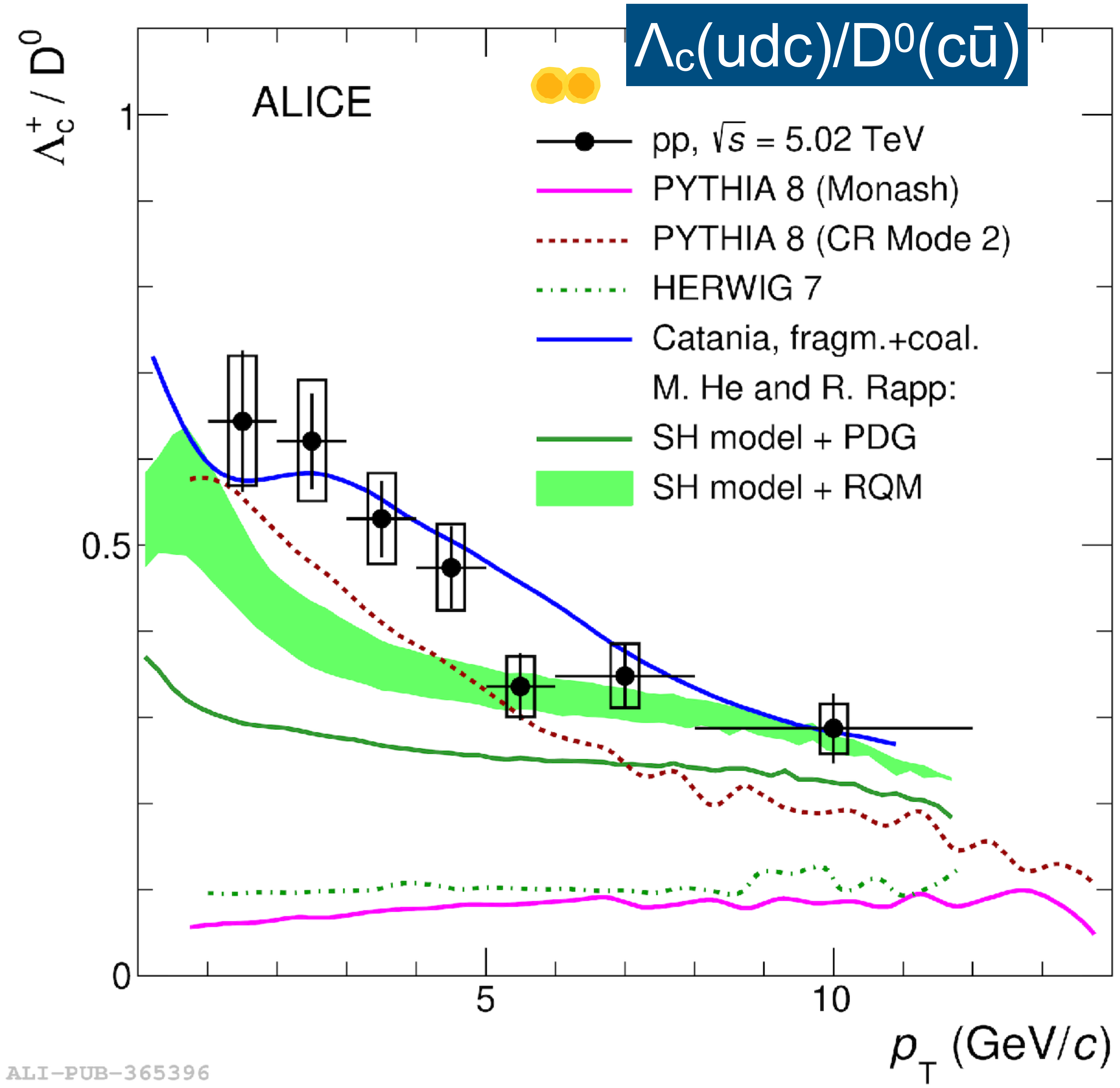
$D_s^+(c\bar{s})/D^0(c\bar{u})$



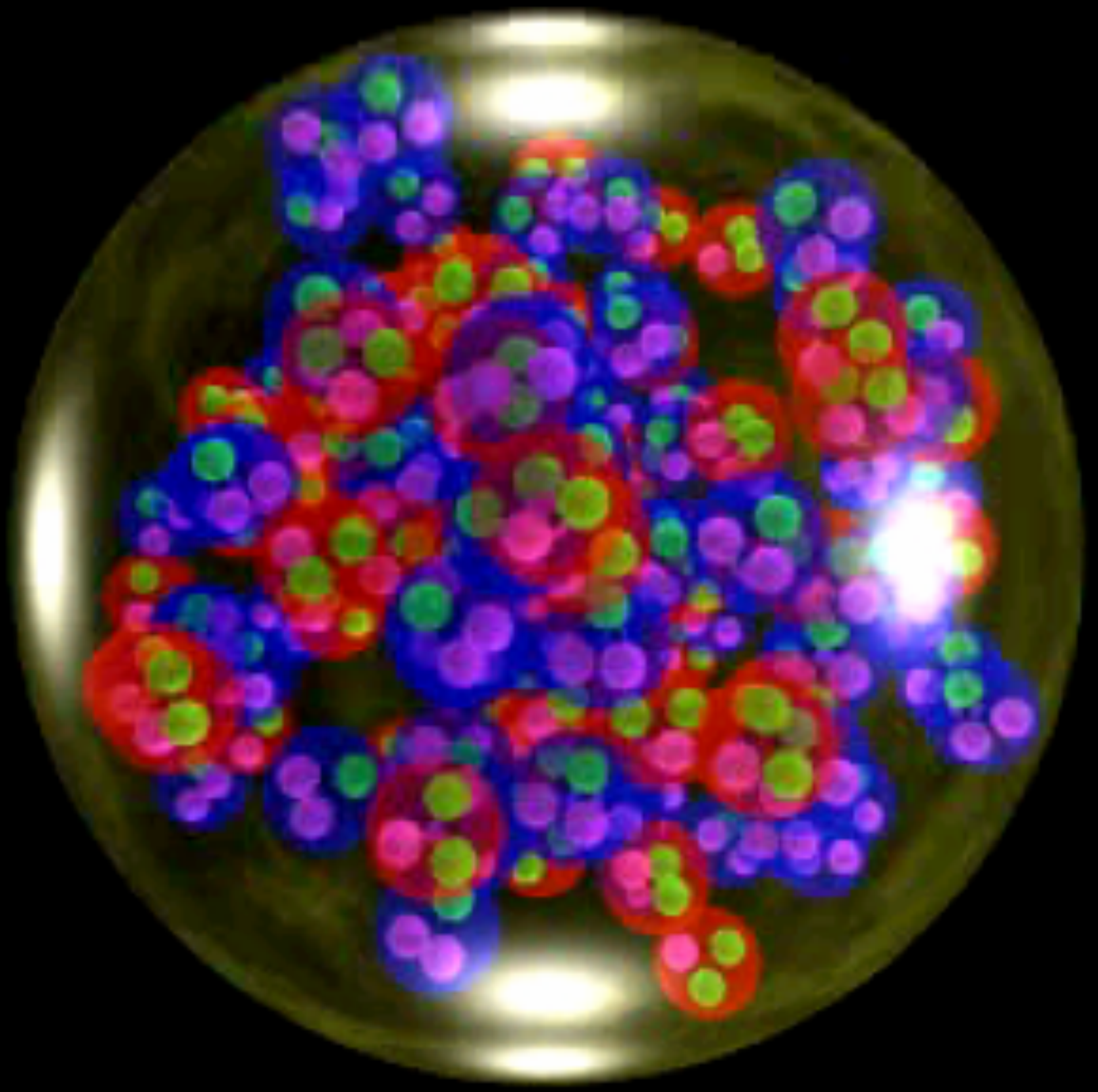
➧ confirm assumed universality of fragmentation functions between energies and collision systems

$\Lambda_c(udc)/D^0(c\bar{u})$

arXiv 2011.06078



Λ_c/D^0 shows a large increase w.r.t e^+e^- ➧ strong indication of a very different fragmentation in pp!

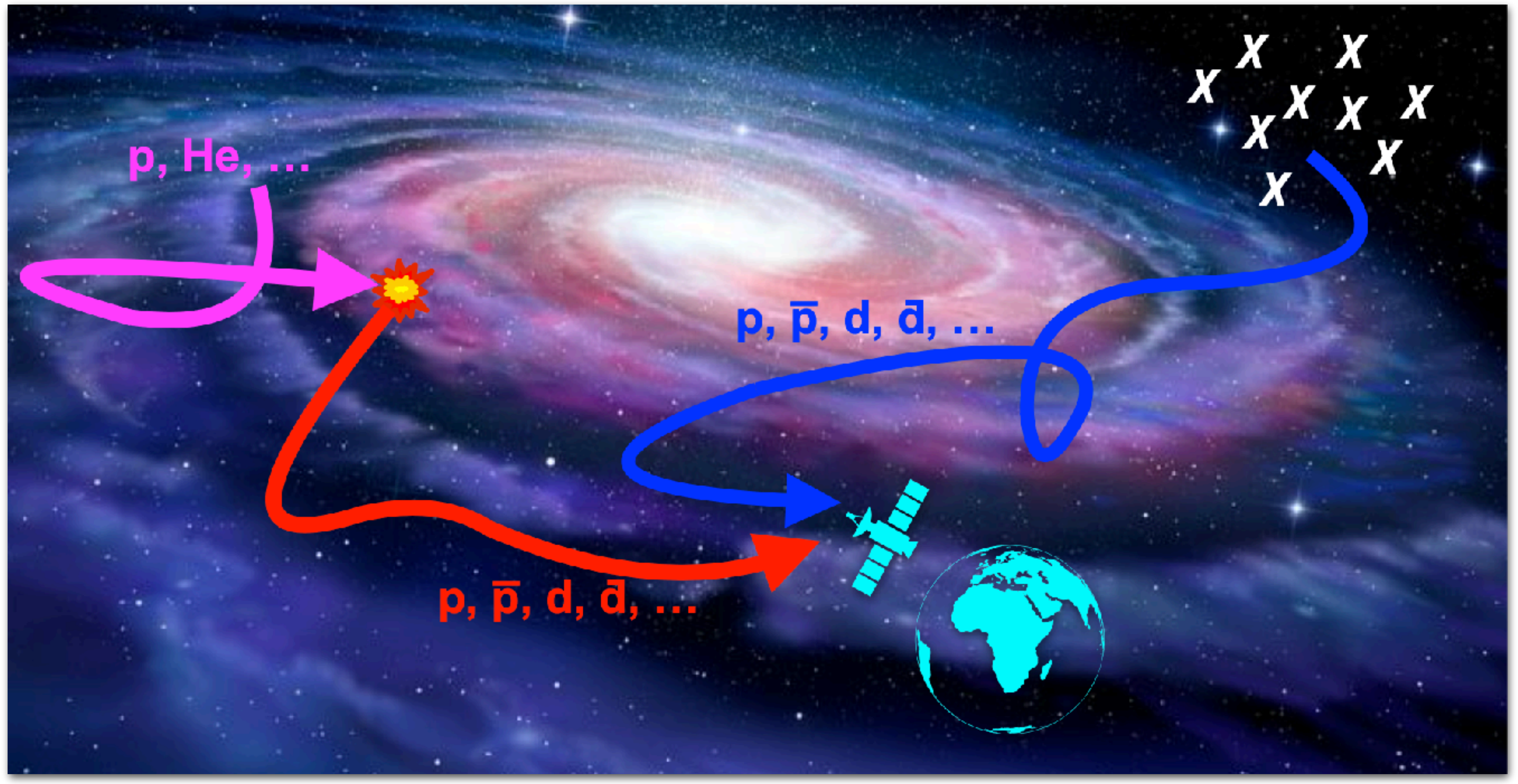


Hadronic interactions

Antideuteron cross section

Measurement relevant to understand antinuclei production from cosmic ray interaction with ISM, heliosphere and Earth environment

Antideuterons are a promising probe for indirect DM searches (low background from secondary production) ➧ crucial to determine precisely primary and secondary antideuteron flux



Ingredients for flux calculation

$$\nabla \cdot \left(-K \nabla N_{\bar{d}} + V_c N_{\bar{d}}\right) + \partial_t \left(b_{tot} N_{\bar{d}} - K_{EE} \partial_t N_{\bar{d}}\right) + \Gamma_{ann} N_{\bar{d}} = q_{\bar{d}}$$

Propagation term

Annihilation term ➧ constrained by measurement of inelastic cross section

Production term ➧ constrained by measurement of production

Strategy:

LHC ➧ antimatter factory

ALICE detector material ➧ target ➧ ALICE detector to study antideuteron absorption in material

Antideuteron cross section

➧ first measurement of antideuteron absorption cross section at low momentum

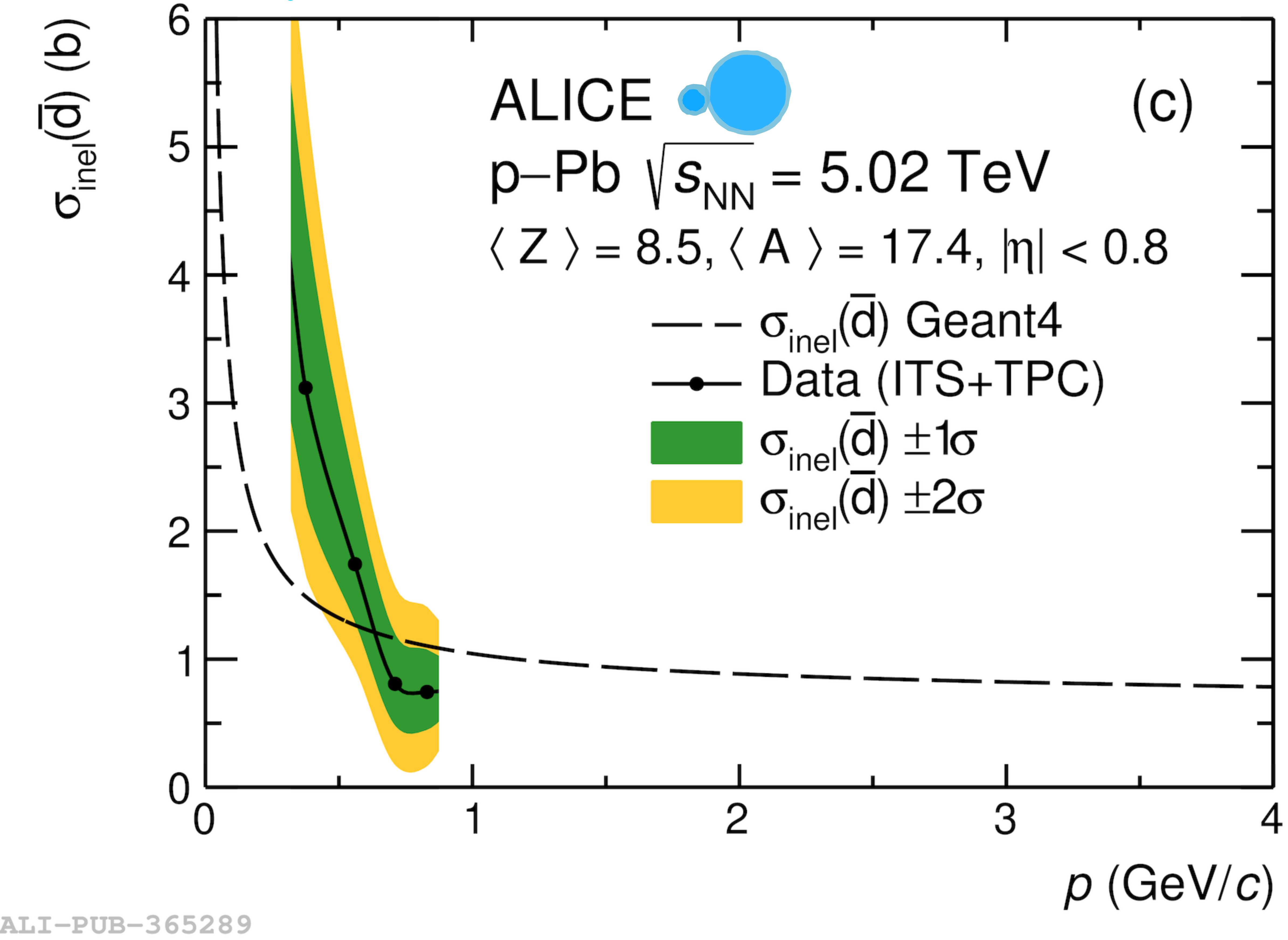
Phys. Rev. Lett. 125, 162001

Low *p* region ➧ hint for a steeper rise of $\sigma_{INEL}(\bar{d})$ than expected from Geant4

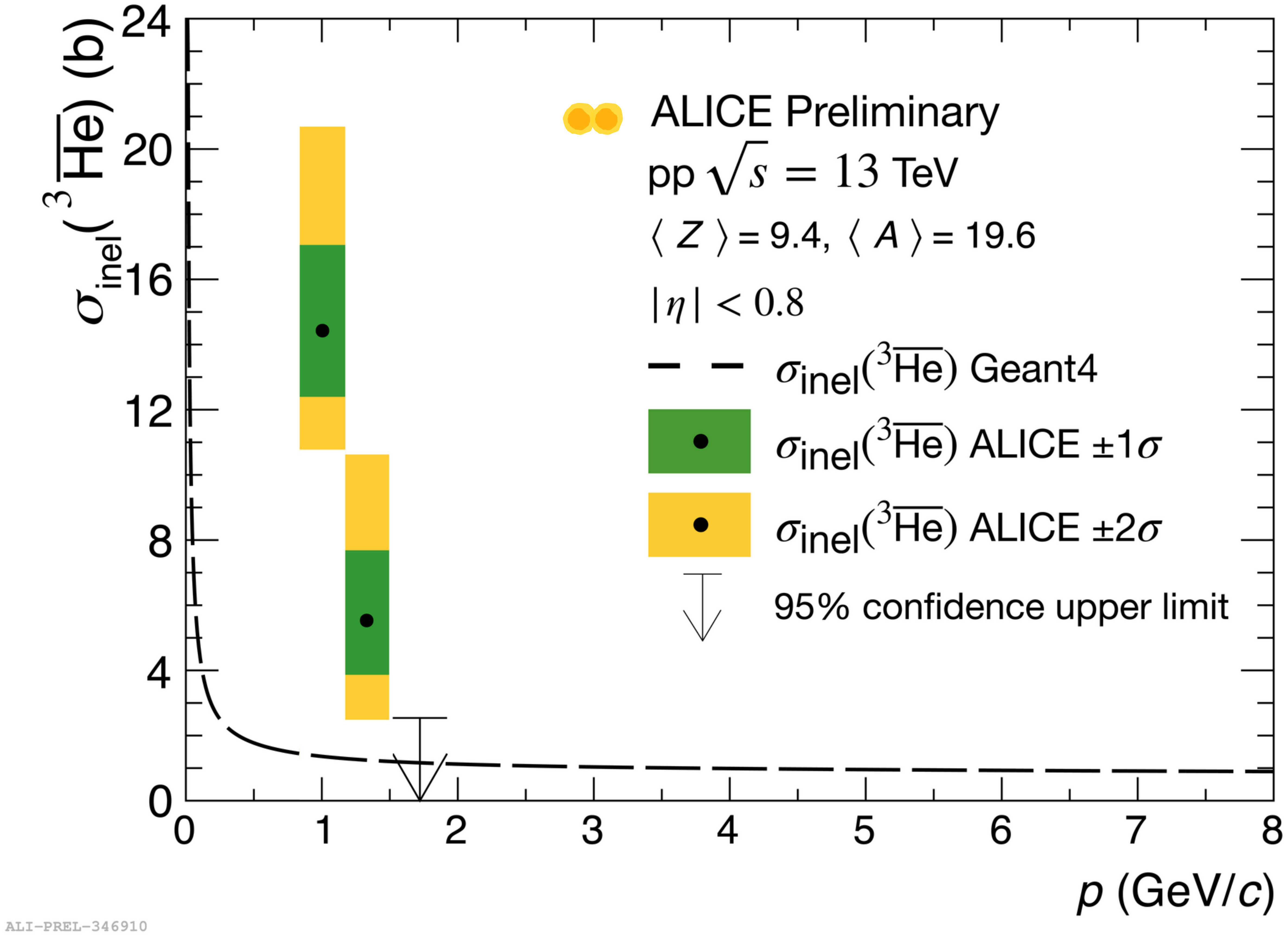
Antideuteron cross section

- first measurement of antideuteron absorption cross section at low momentum

Phys. Rev. Lett. 125, 162001



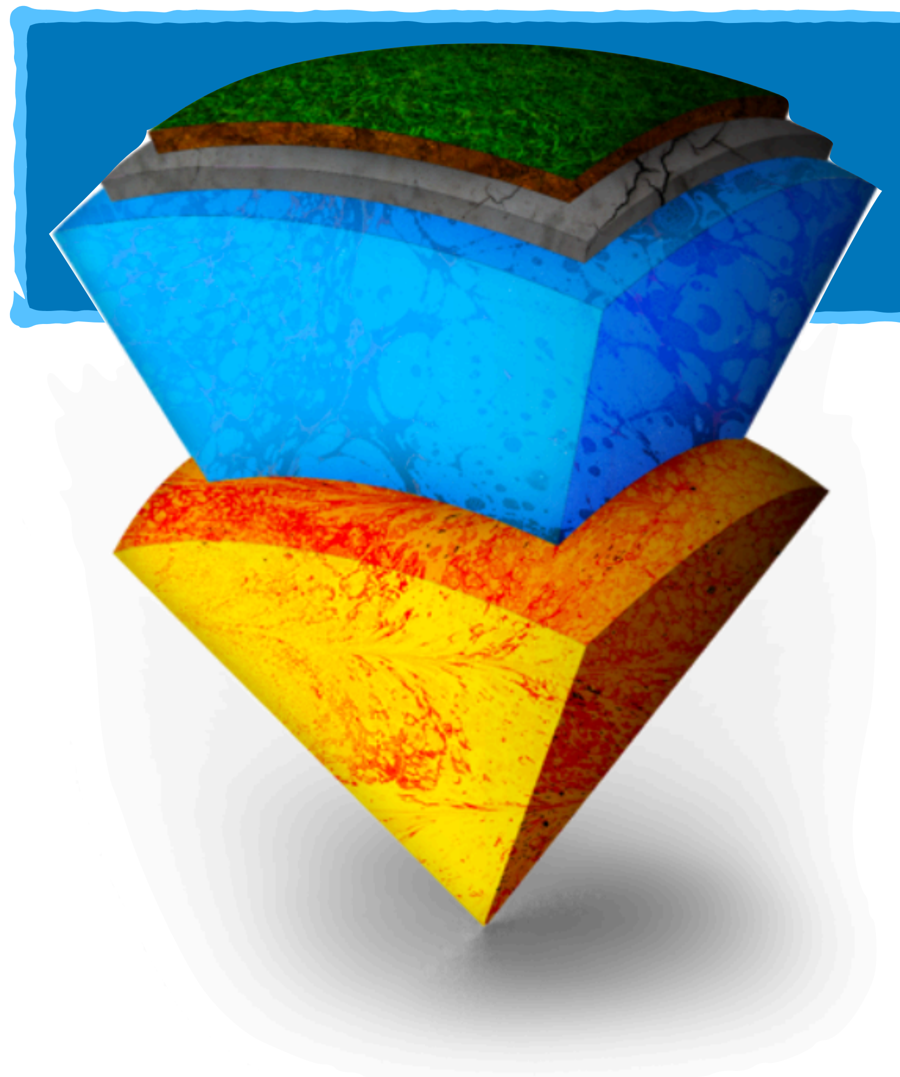
- first measurement of anti^{3}He inelastic cross section

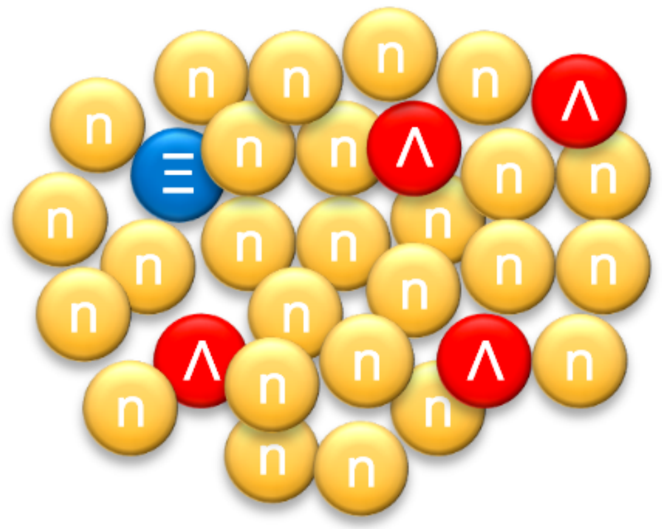


Low p region ➧ hint for a steeper rise of $\sigma_{INEL}(\bar{d})$ than expected from Geant4

Significant deviation from GEANT 4 at low momentum!

Hadron-hyperon interaction



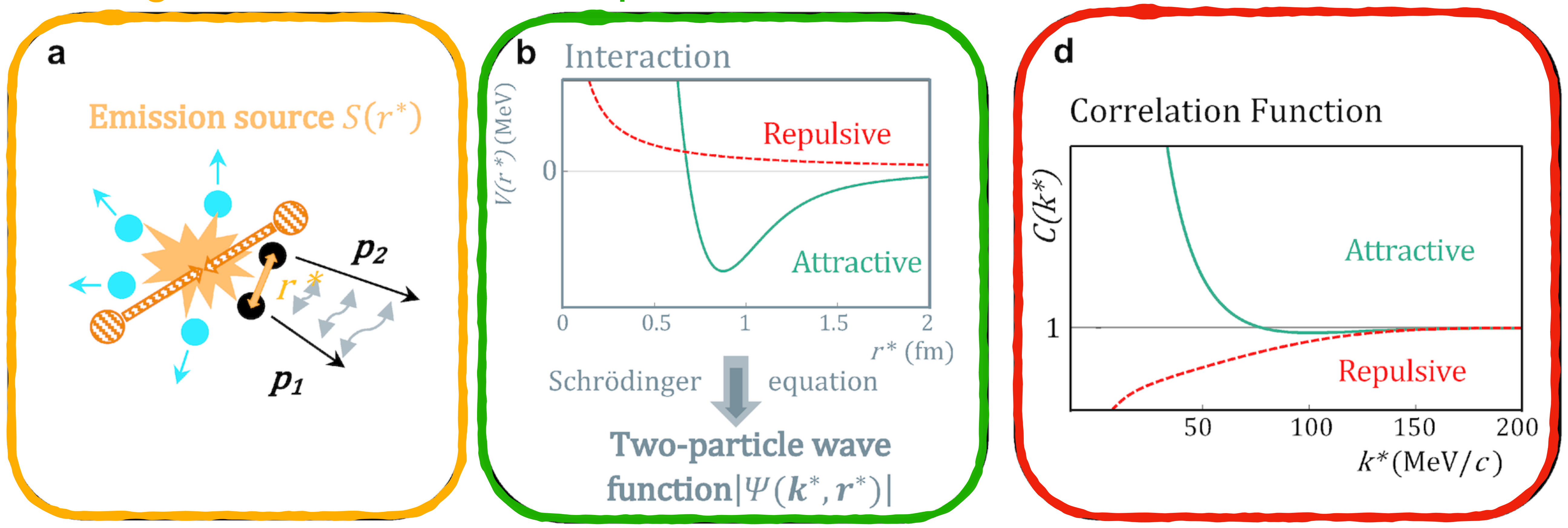


Neutron star inner core

- composition still unknown (neutrons, protons, hyperons, quark matter?)
- depends on constituent interactions and couplings

Hadron-hyperon interaction investigated in ALICE with femtoscopic techniques

Model emitting source — Interaction potential from LQCD — Measure correlation function



Correlation function C(k*)

c

$$C(k^*) = \int S(r^*) \, |\Psi(k^*, r^*)|^2 \, d^3r^* = \xi(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

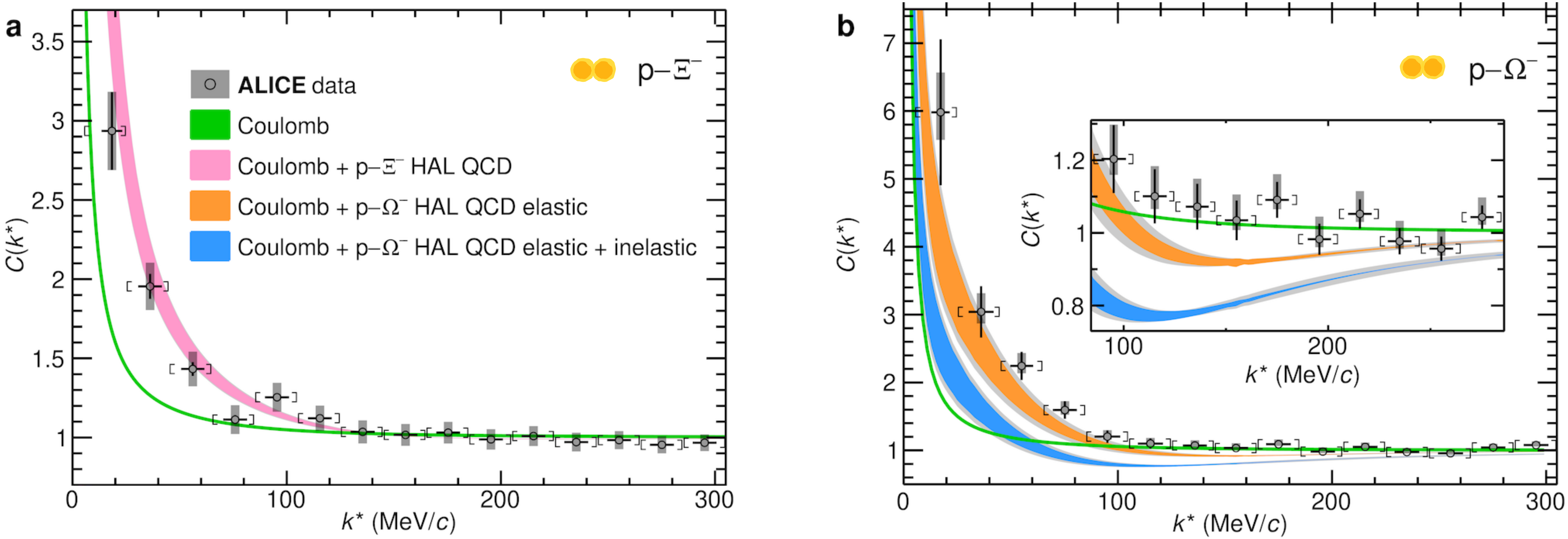
- >1 attractive interaction
- =1 no interaction
- <1 repulsive interaction

ALI-PUB-367339

Nature 588 (2020) 232-238

Strong interaction among hadrons

Nature 588 (2020) 232-238



Attractive interaction + enhancement above Coulomb interaction for both p-Ξ^- and p-Ω^-

- effect of residual strong interaction
- unprecedented constraint on hadronic interaction
- Λ-d Ω^--Ω^- correlations will be studied in Run 3

Wrap up

Many channels and measurements to put further constraint on existing models

Topics to be further investigated to shed light on not fully understood mechanisms

Measurements with relevant impact in other fields

Wrap up

Many channels and measurements to put further constraint on existing models

Topics to be further investigated to shed light on not fully understood mechanisms

Measurements with relevant impact in other fields

ALICE is ready for Run 3, with upgraded or new detectors:

- upgraded ITS
- TPC based on GEM technology
- muon forward tracker

50x faster readout rate, access to rarer probes, improved tracking resolution down to low p_T, new capabilities (muon vertexing)…

many more interesting results in the near future!

Wrap up

Many channels and measurements to put further constraint on existing models

Topics to be further investigated to shed light on not fully understood mechanisms

Measurements with relevant impact in other fields

ALICE is ready for Run 3, with upgraded or new detectors:

- upgraded ITS
- TPC based on GEM technology
- muon forward tracker

50x faster readout rate, access to rarer probes, improved tracking resolution down to low p_T, new capabilities (muon vertexing)…

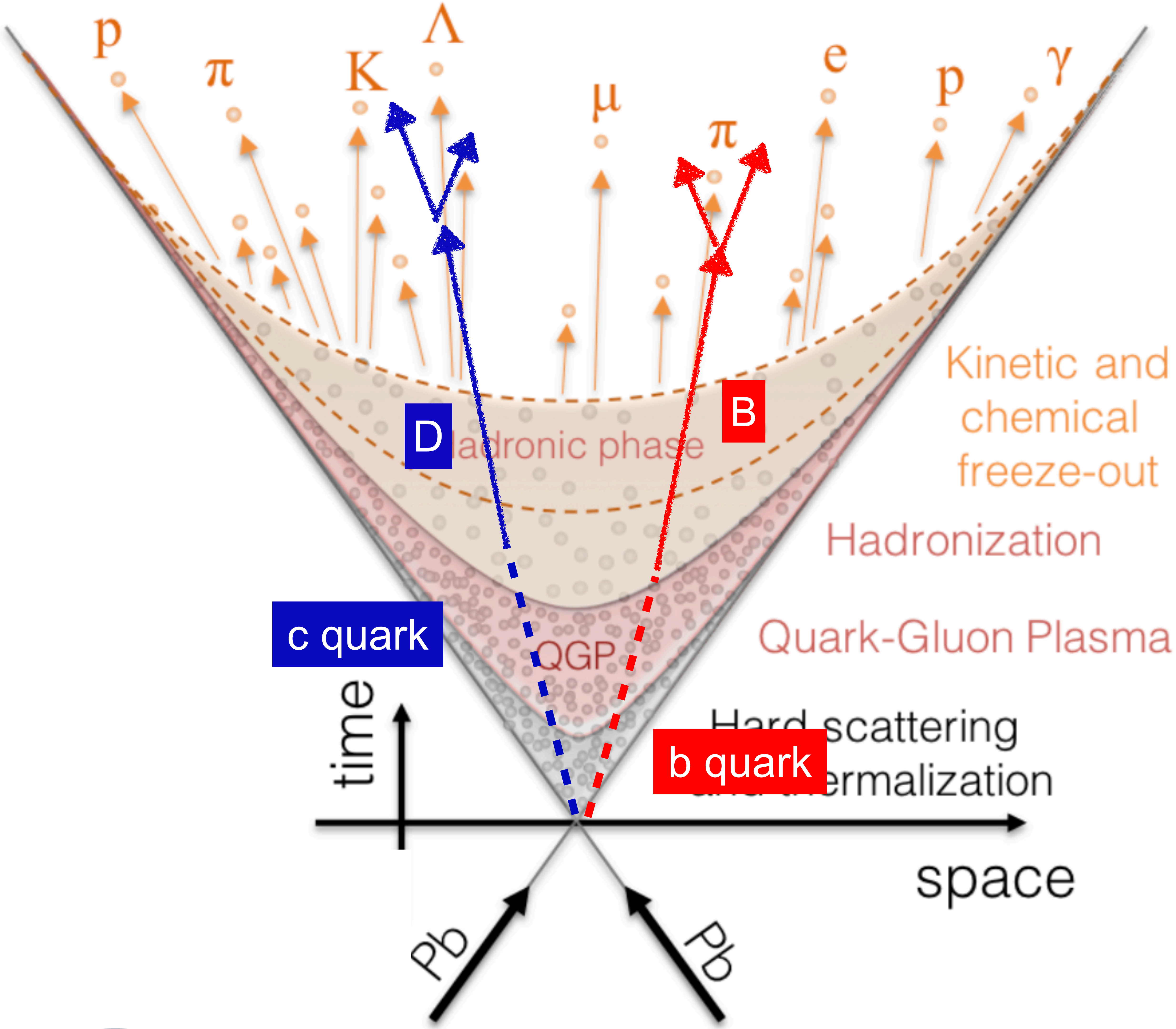
many more interesting results in the near future!

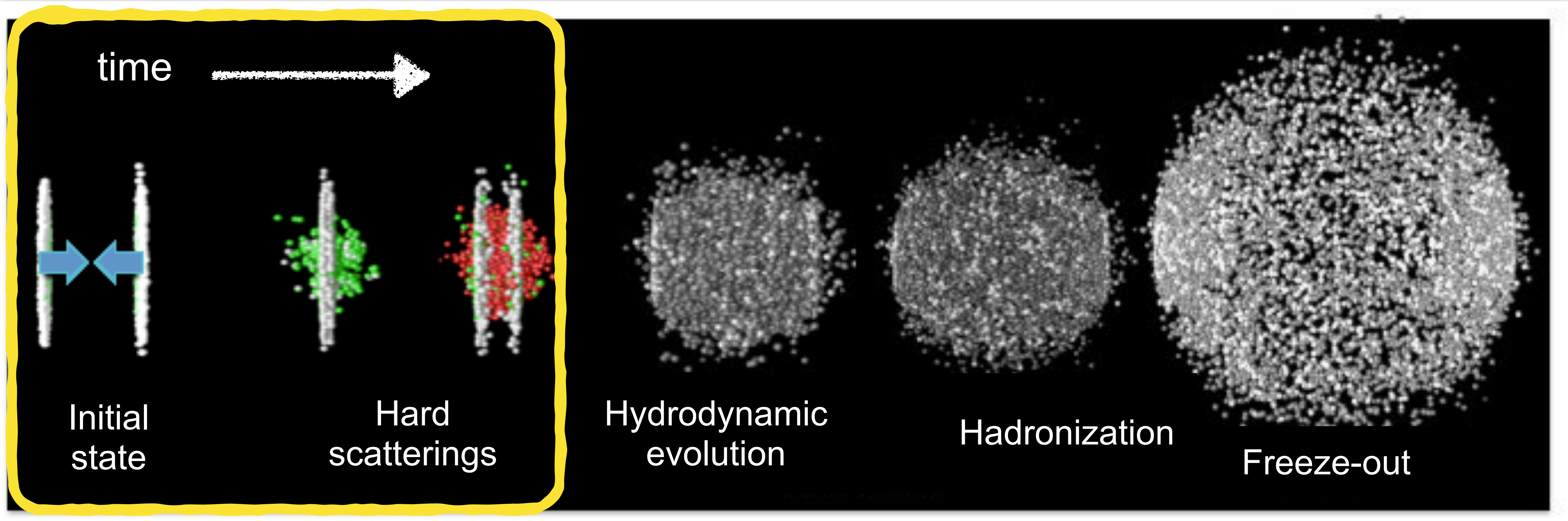
Ongoing: preparation of a new detector proposal (ALICE3) for LHC Run 5

Compact and new Si tracker with unprecendented tracking and vertexing capabilities at high rates

Thanks for your attention!

Heavy probes

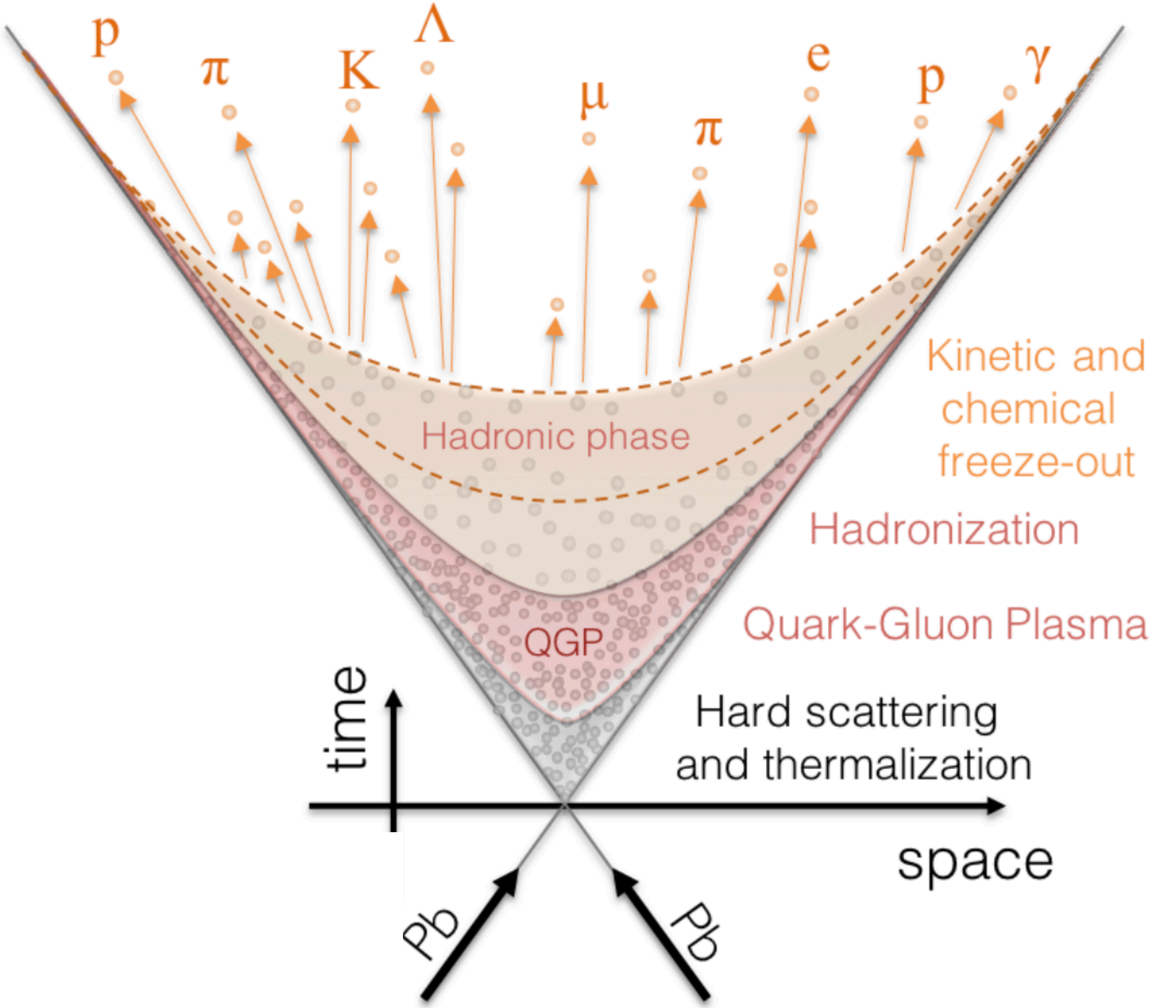


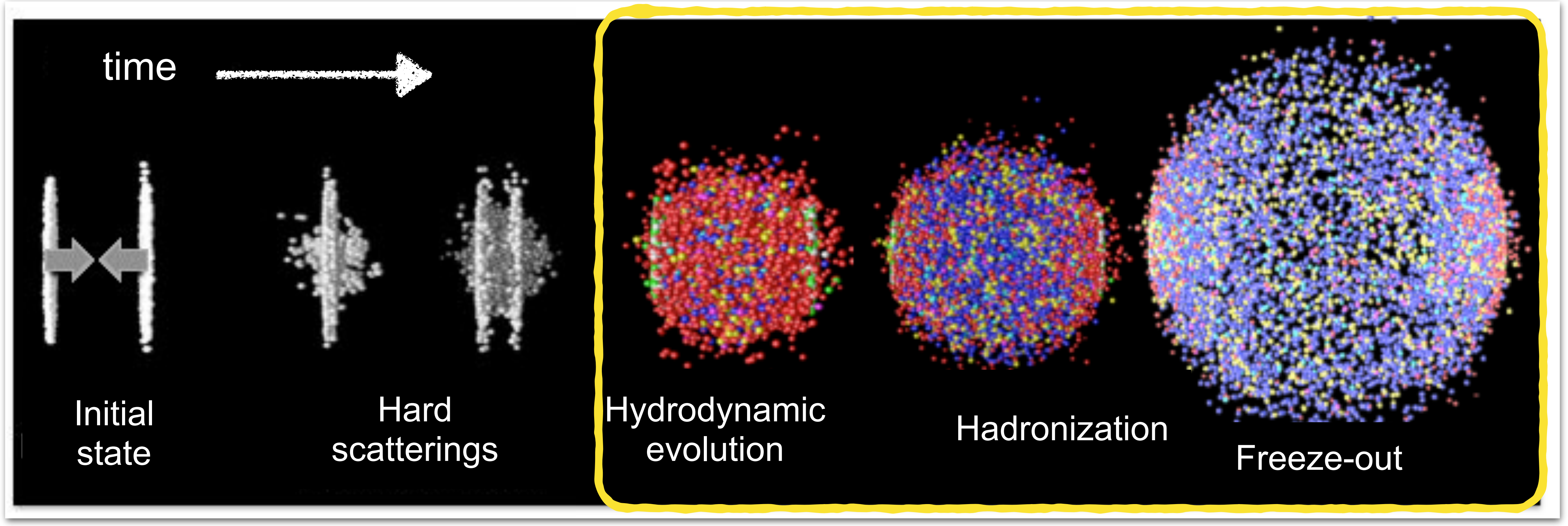


Heavy flavours

- mainly produced in hard-scattering processes in shorter time scales than the QGP formation time
- experience the system evolution, interacting with the medium constituents both via elastic (collisional) and inelastic (gluon radiation) processes
- can probe the strong interacting medium formed in A-A collisions

Soft probes

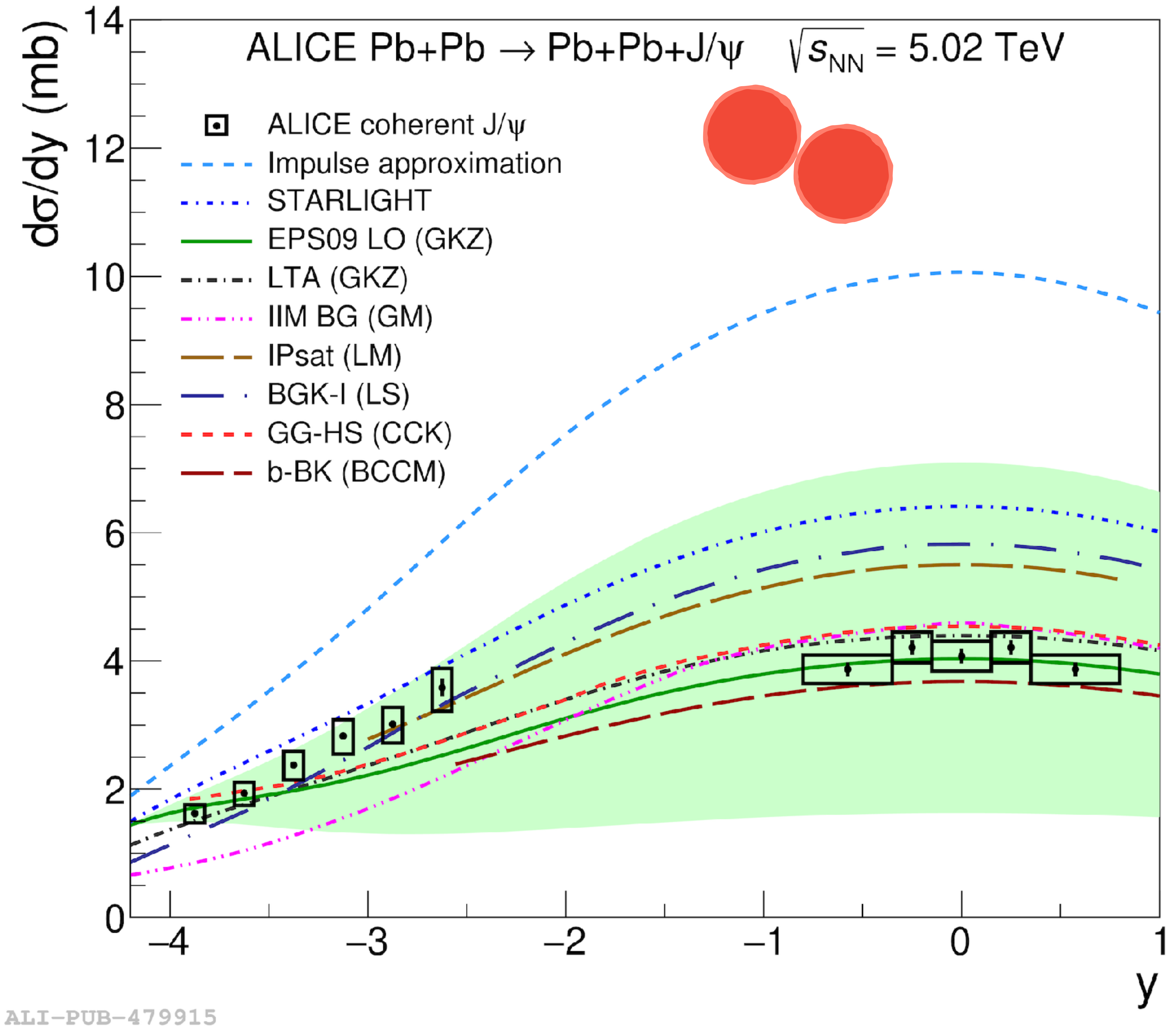




Soft probes

- produced at late stages with lower transverse momentum, p_T
- exchanged momentum Q: non-perturbative phenomenological models, statistical models, effective theories, transport models
- tool to characterize the strongly interacting medium

J/ψ coherent photoproduction



Impulse approximation ➧ exclusive photoproduction data off protons, neglecting all nuclear effects except coherence.

STARlight ➧ Vector Meson Dominance model with Glauber-like formalism to calculate cross section in Pb-Pb

GKZ: EPS09 LO ➧ parametrization of the nuclear shadowing data

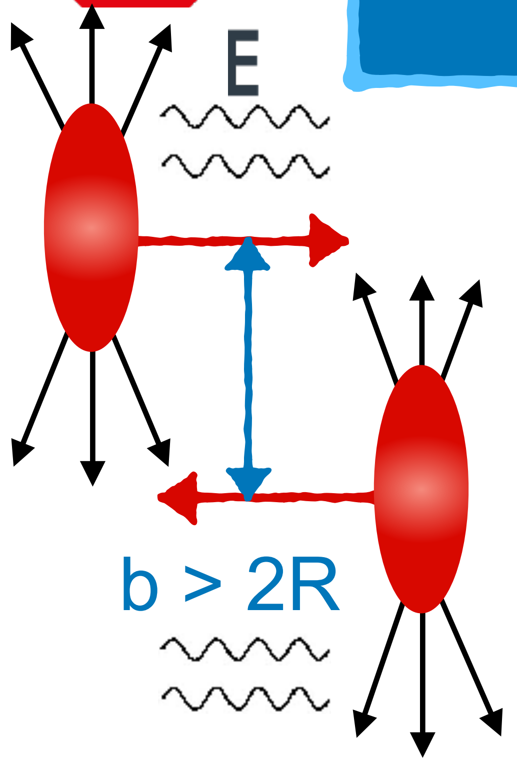
GKZ ➧ Leading twist approximation (LTA) of nuclear shadowing

CCK ➧ Color dipole model with the structure of the nucleon described by the hot spots

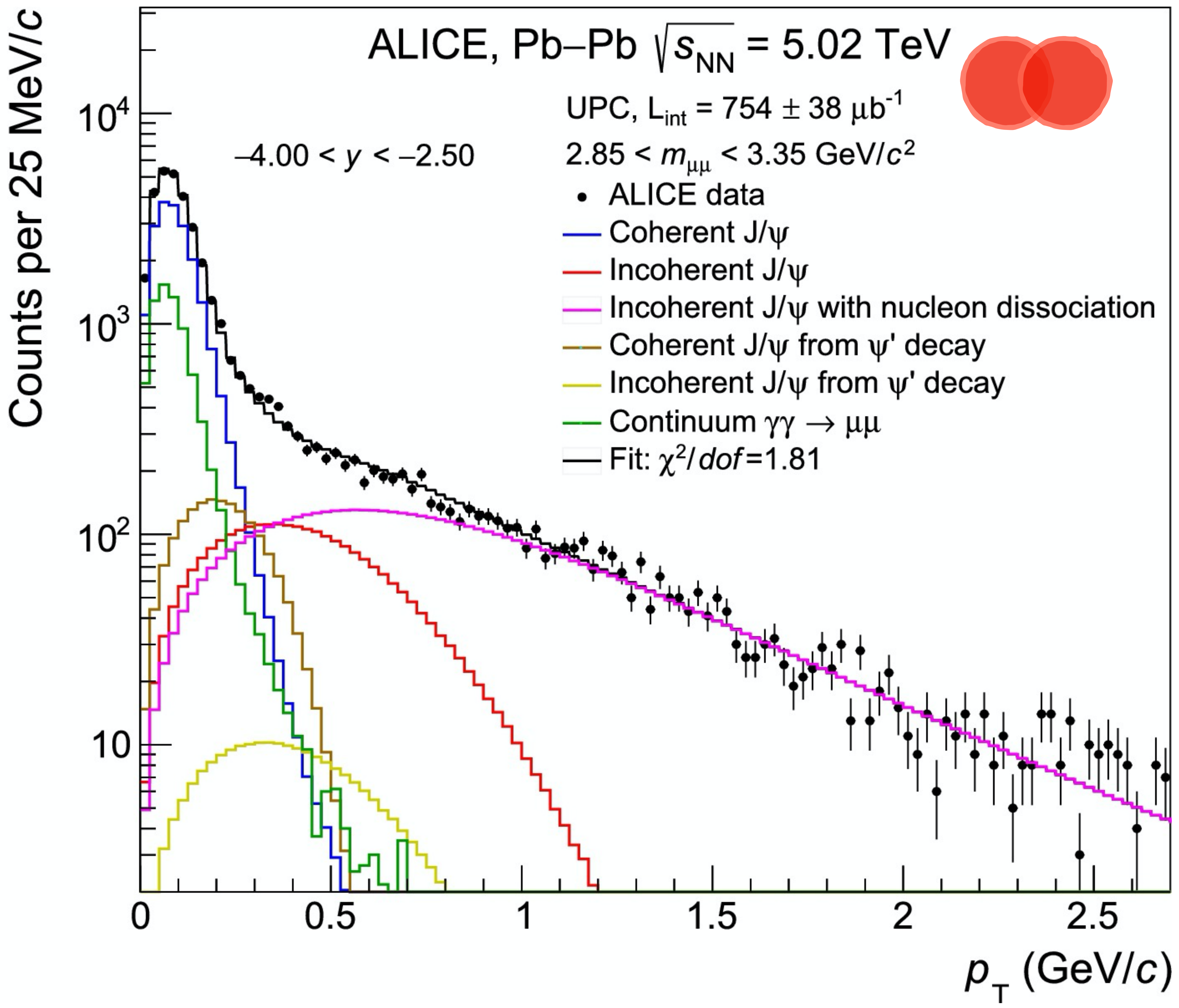
BCCM ➧ Color dipole approach coupled to the solutions of the Balitsky-Kovchegov equation

GM, LM, LS ➧ Color dipole approach coupled to the Color Glass Condensate formalism with different assumptions on the dipole-proton scattering amplitude

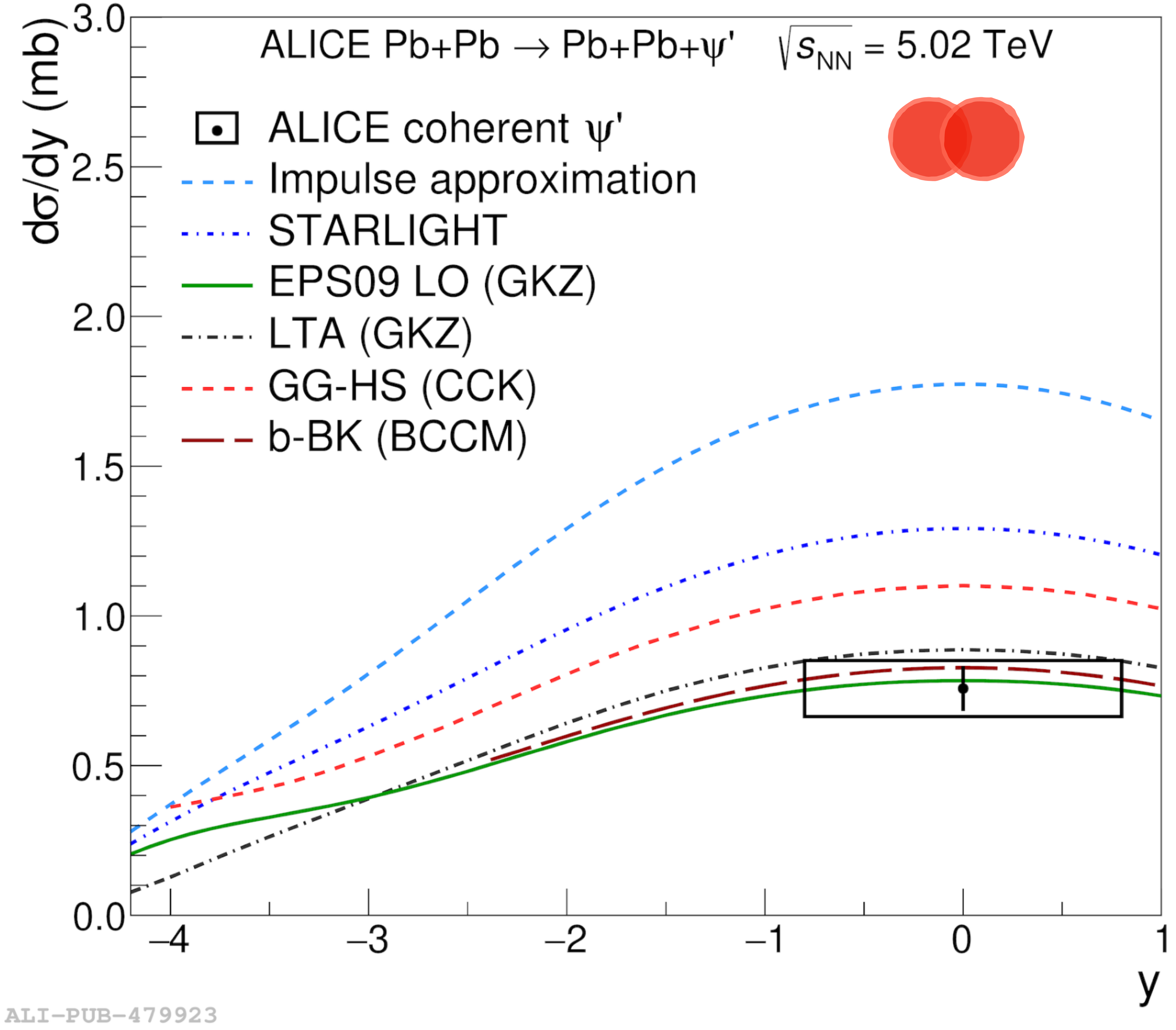
J/ψ, ψ’ coherent photoproduction



Phys.Lett. B 798 (2019) 134926



arXiv:2101.04577



Ψ’ well described by models with moderate shadowing

Jet substructure in Pb-Pb

Remove soft radiation at large angles from the jets to isolate the hard structure

➧ tool to investigate jet quenching effect

Fully correct measurement of:

Groomed jet momentum fraction

$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

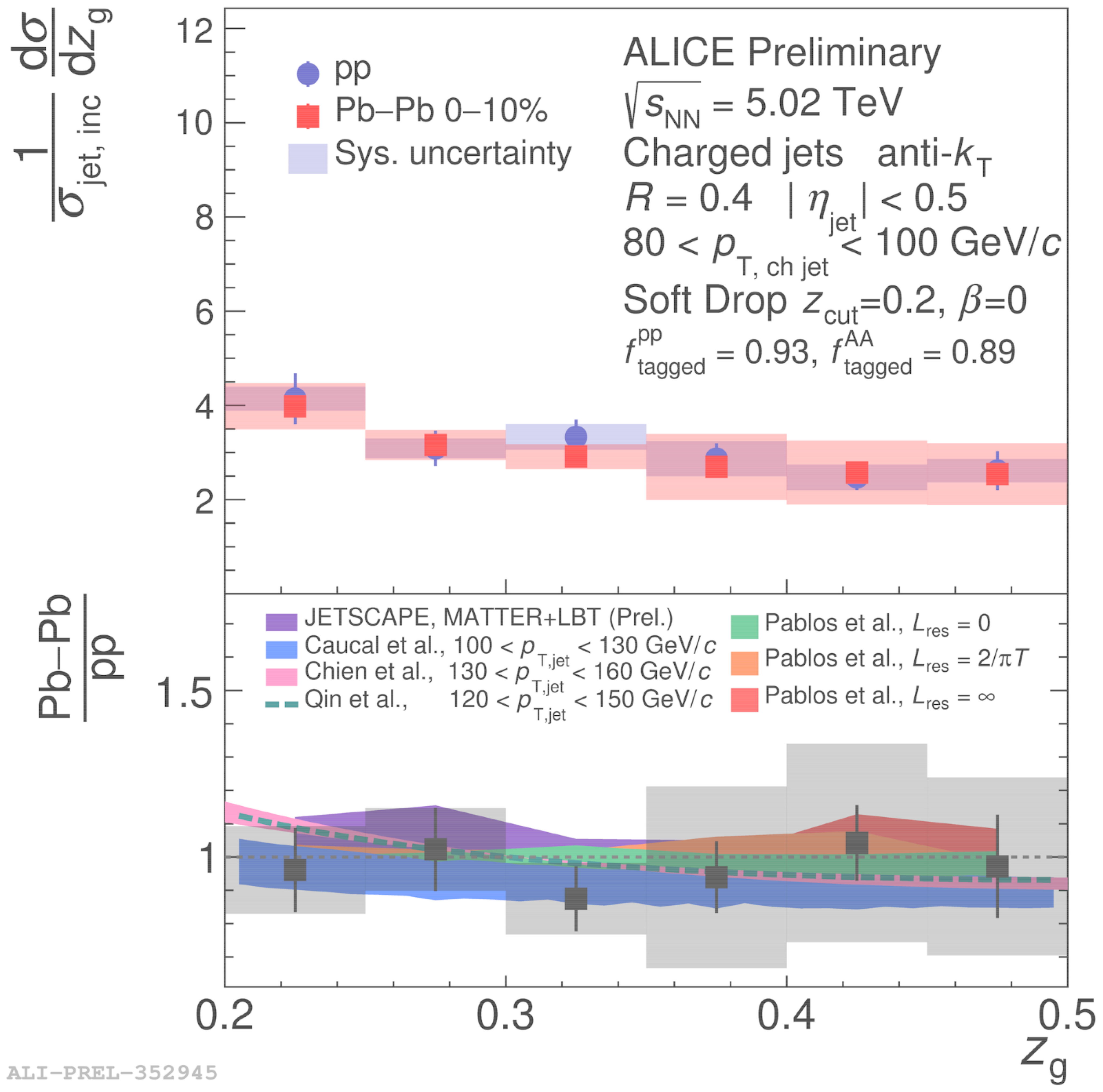
sensitive to jet quenching

Groomed jet radius

$$R_g = \sqrt{\Delta y^2 + \Delta \varphi^2}$$

$$\theta_g \equiv \frac{R_g}{R}$$

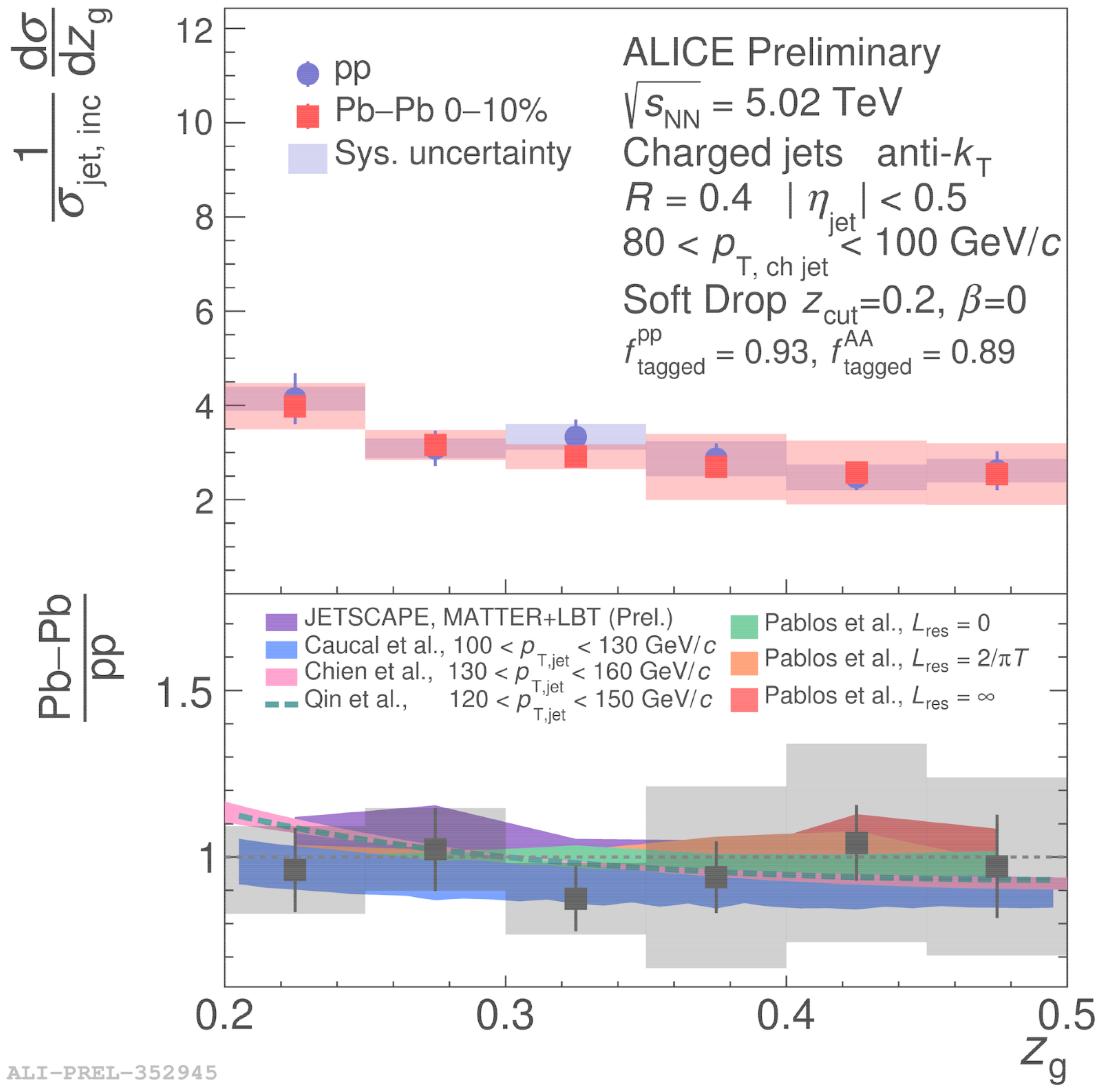
sensitive to both path length and coherence effects



Jet substructure in Pb-Pb

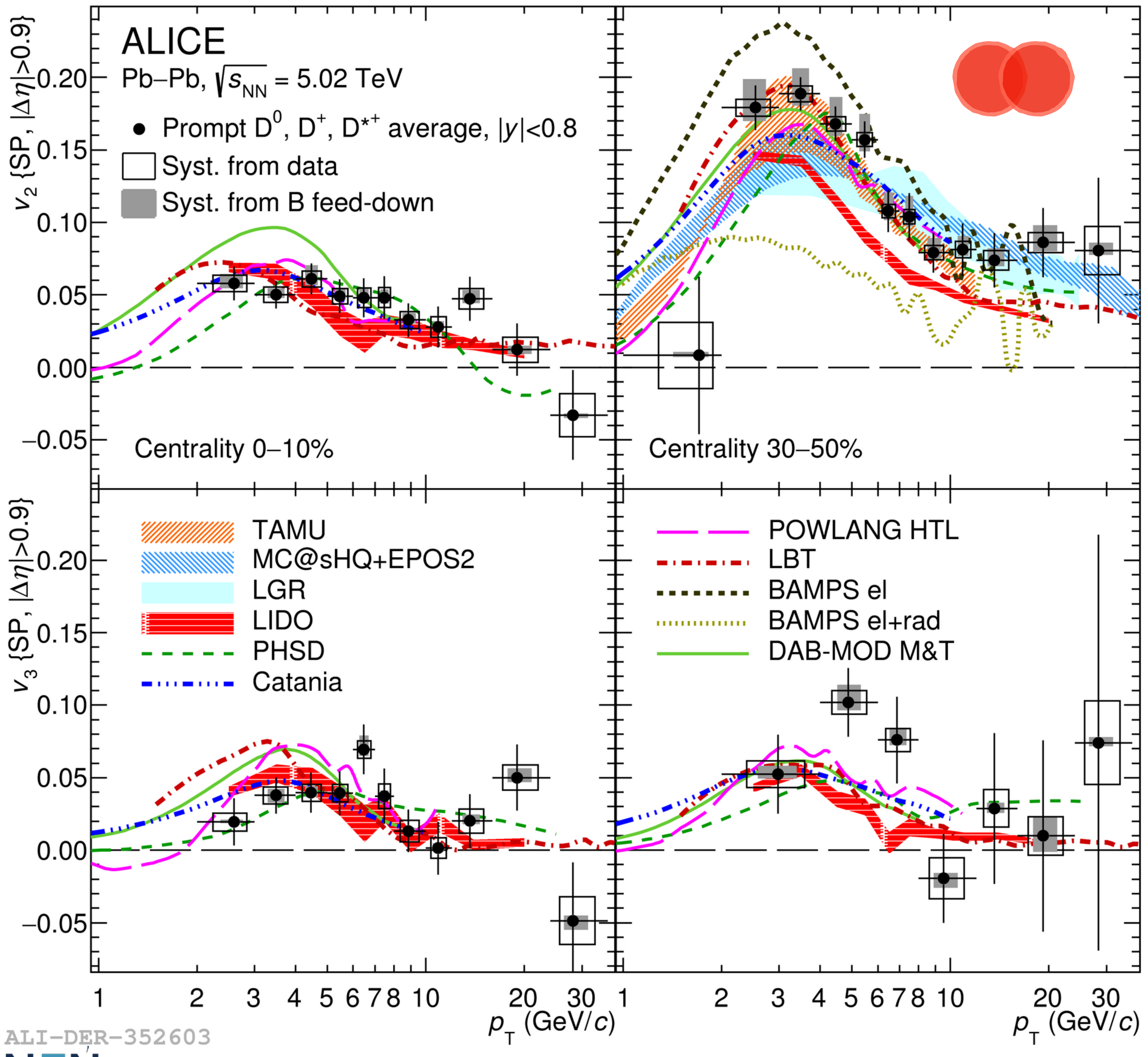
Remove soft radiation at large angles from the jets to isolate the hard structure

➧ tool to investigate jet quenching effect



➧ no modification in groomed jet momentum fraction

D meson v_2

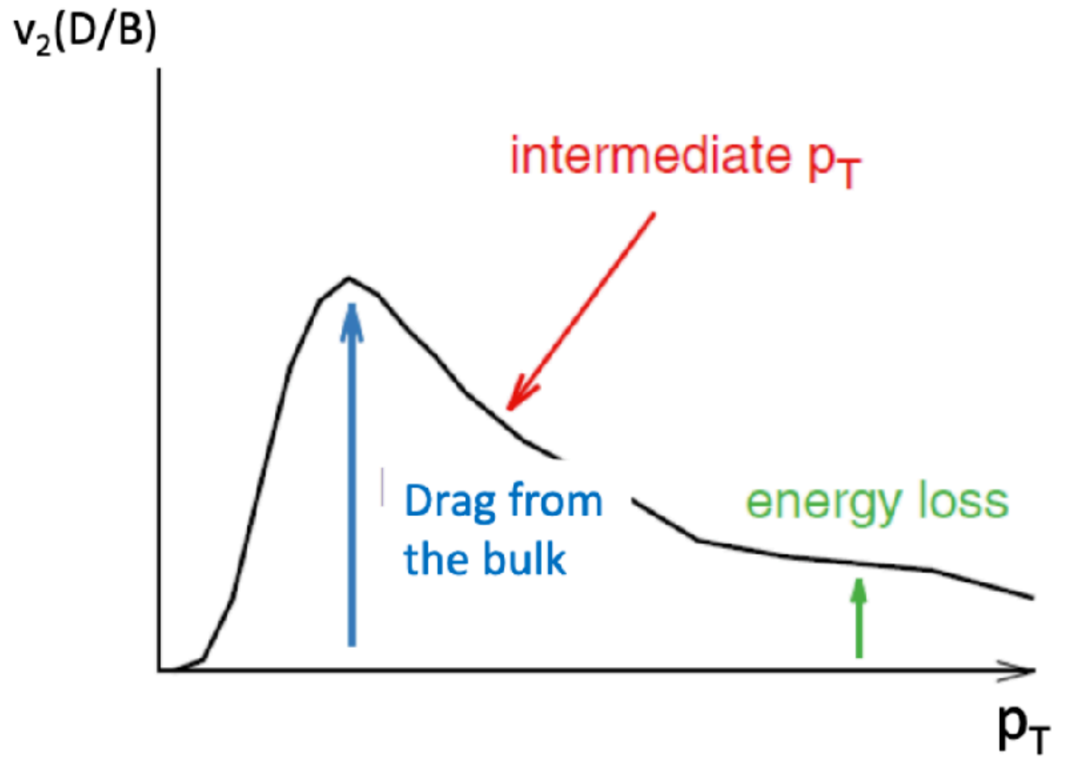


D-meson v_n harmonics are reproduced by theoretical models

Model ingredients:

- transport of charm quarks in an hydrodynamically expanding medium ➧ diffusion coefficient D_S related to thermalisation time of charm quark
- charm-quark hadronisation via coalescence
- charm-quark energy loss (elastic and/or inelastic collisions)

Collisional processes
Collisional + radiative processes
All models except BAMPS include both fragmentation and coalescence

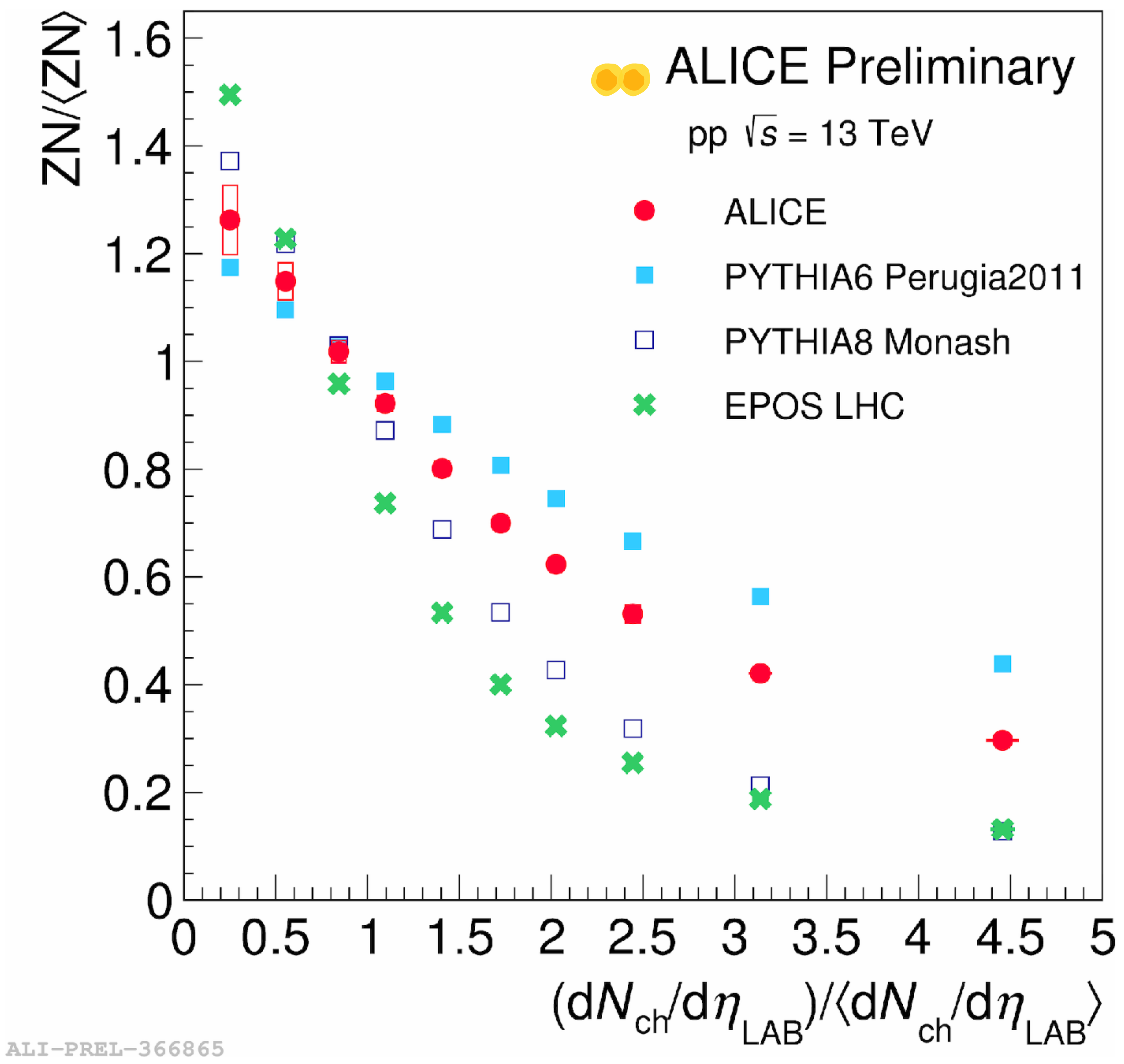


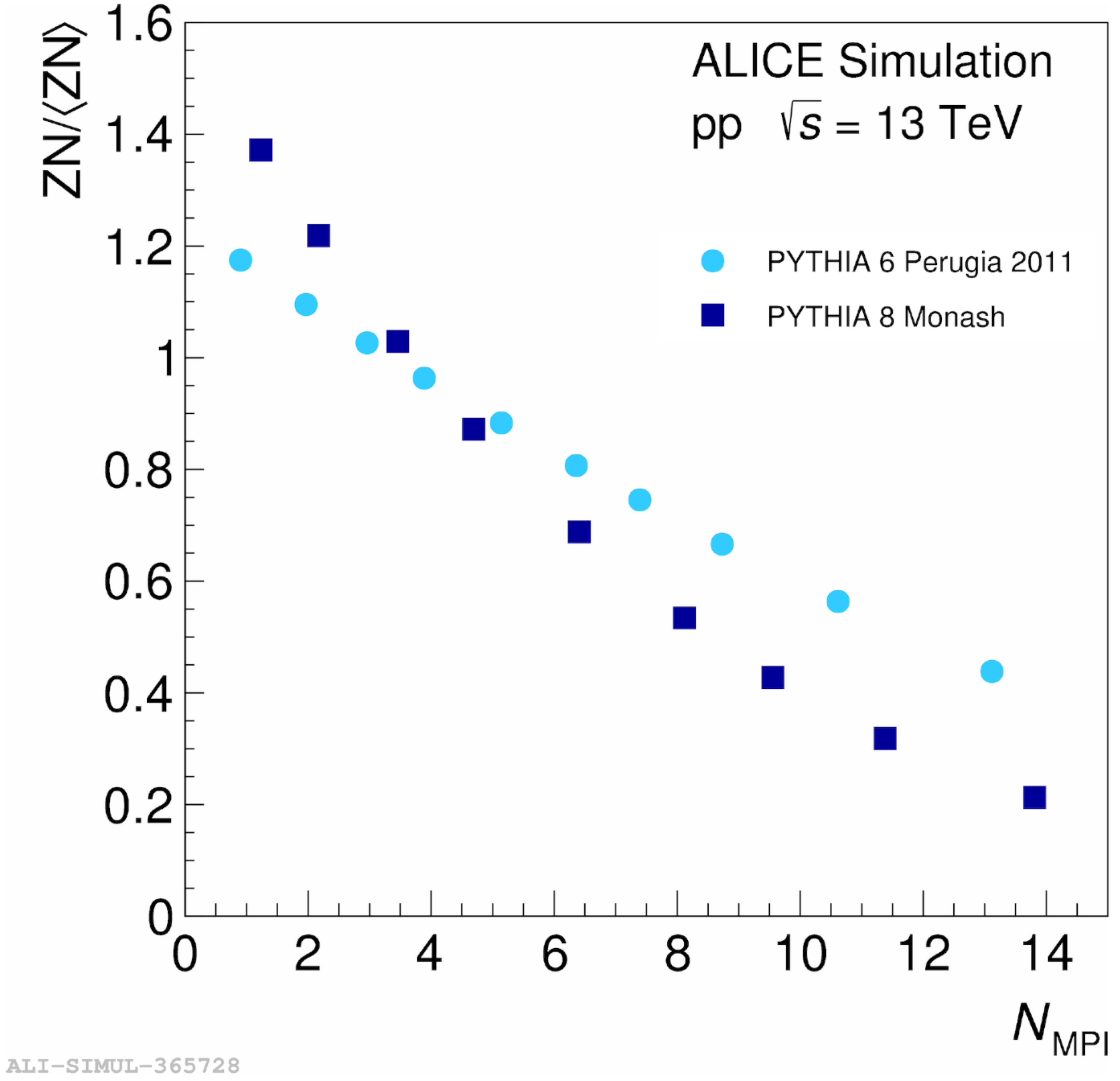
Model in better agreement with data have:

$1.5 < 2\pi D_S T < 7$ at T=155 MeV

Very forward energy

First measurement at LHC energies of very forward (|η|>8.8) energy in combination with midrapidity activity





Forward energy decreases:

- with increasing multiplicity at midrapidity
- vs. leading particle p_T measured in |η|<0.8

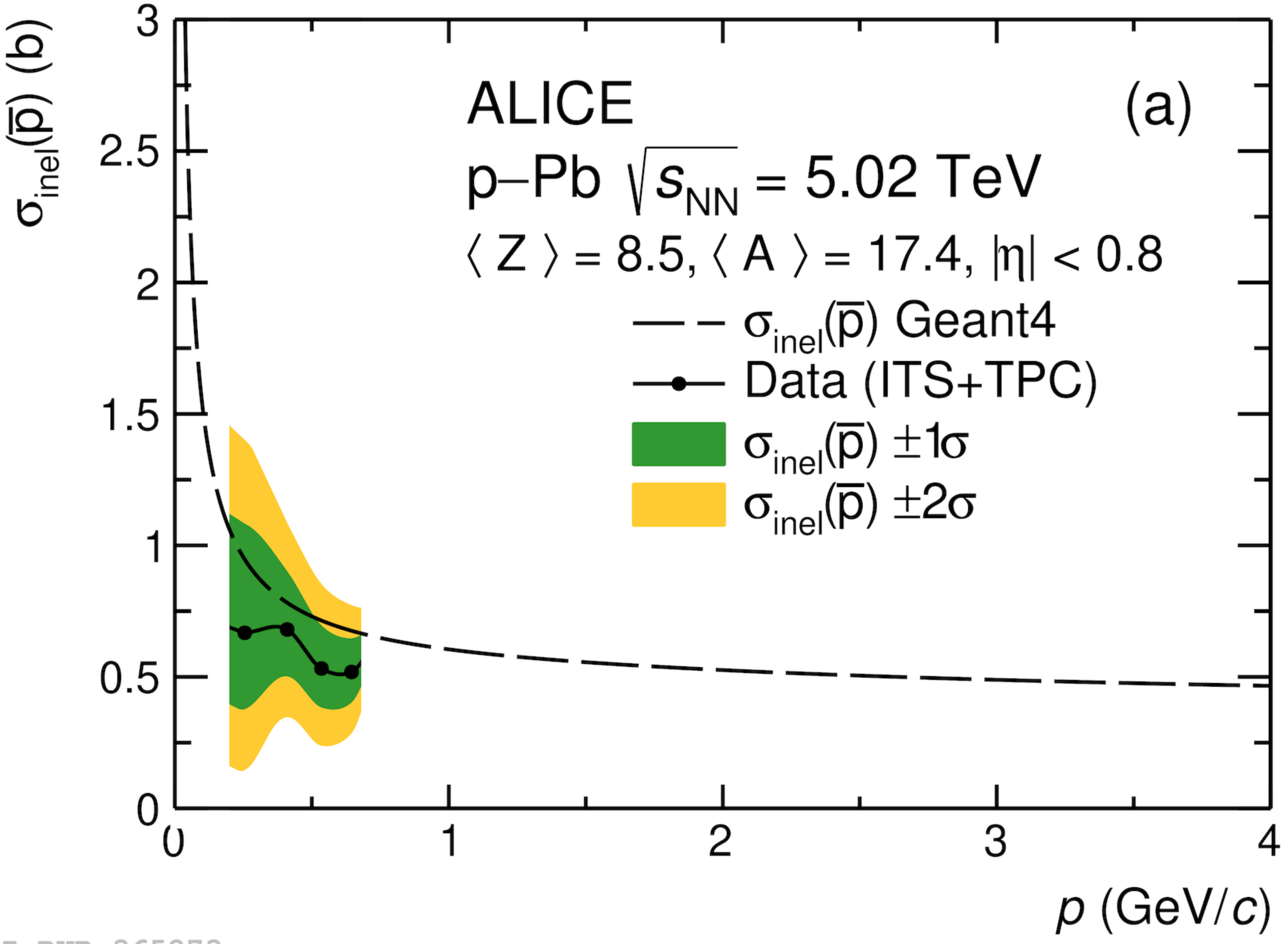
Antiproton cross section

Phys. Rev. Lett. 125, 162001

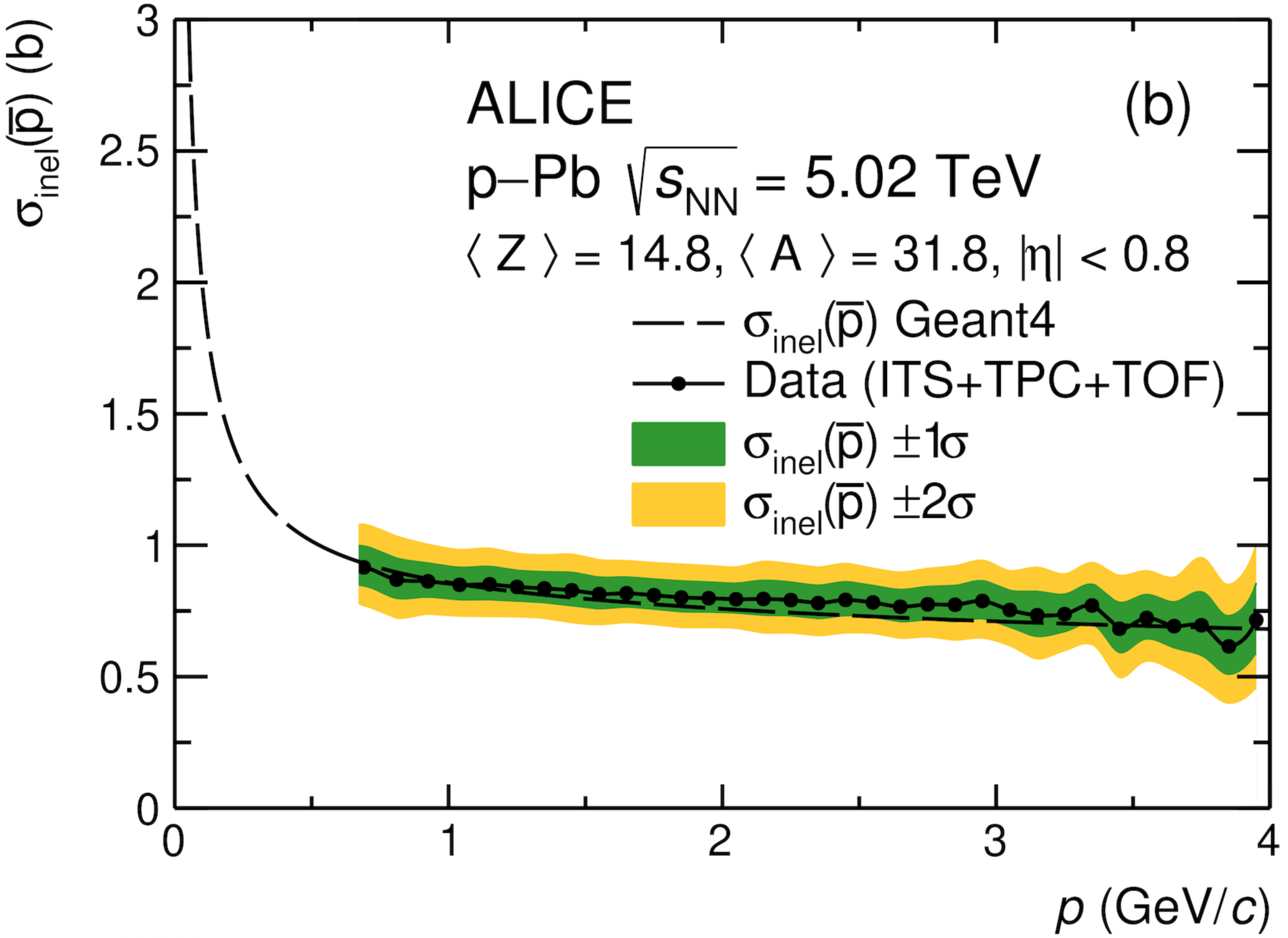
Antideuteron inelastic cross section is poorly known at low energies

Antiparticle/particle ratio is sensitive to variations of the inelastic cross section

➧ the ratio can be used to measure inelastic cross section



ALI-PUB-365273



ALI-PUB-365281

Strong interaction between hadrons