Highlights from the ALICE experiment

Particle Physics Seminar, University of Birmingham
Dec 8, 2021

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Physikalisches Institut
Heidelberg University

Quark-gluon plasma physics: QCD thermodynamics

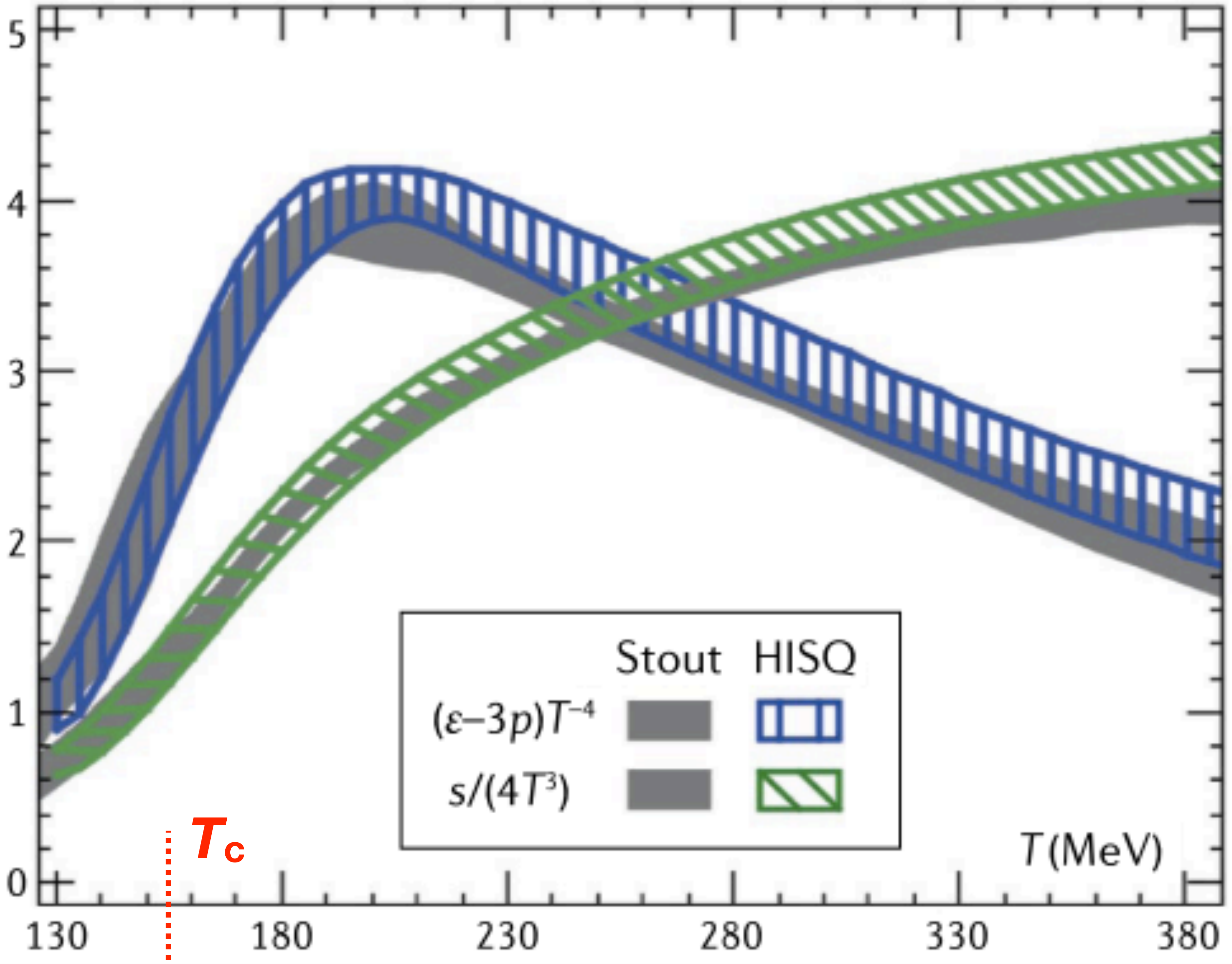
figure credit: MADAI collaboration, Hannah Petersen and Jonah Bernhard

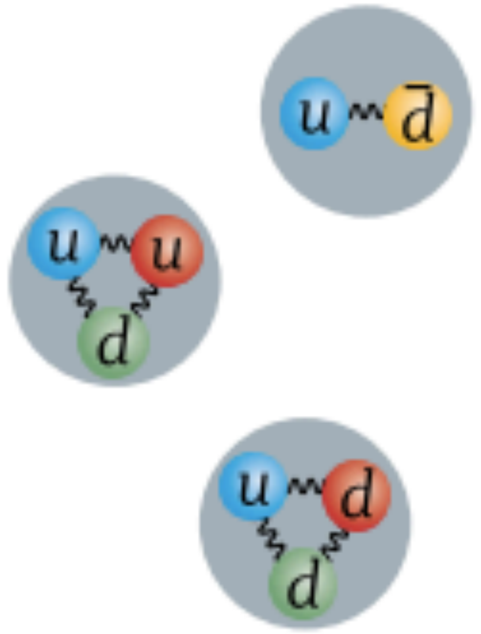
QCD matter properties enter in hydro modeling of the QGP phase

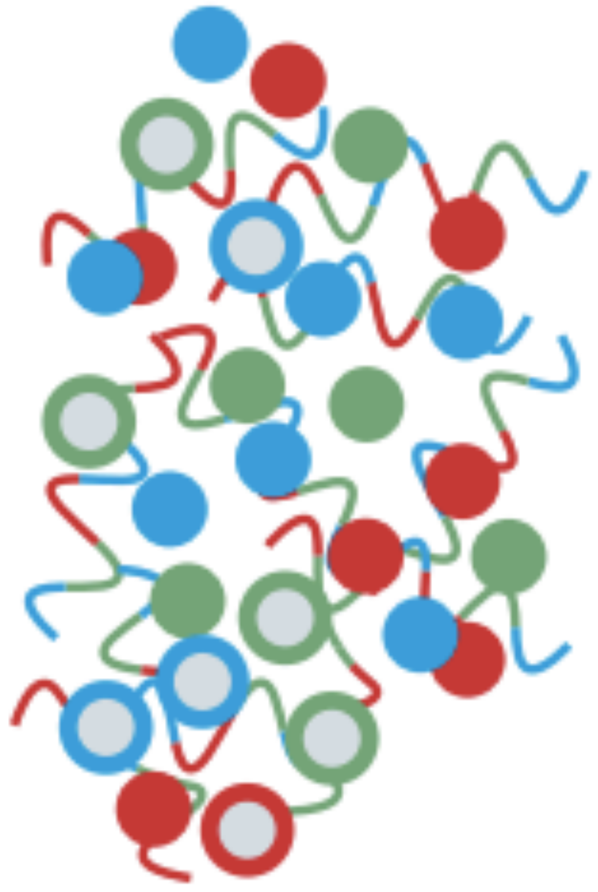
Quark-gluon plasma physics: QCD thermodynamics

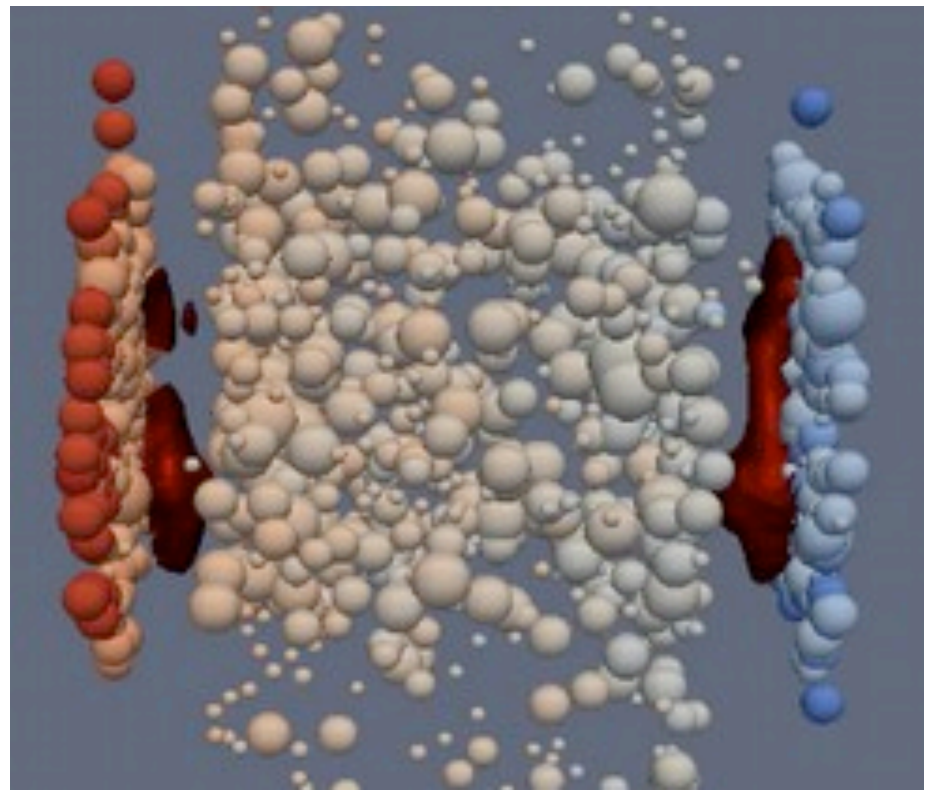
Borsany et al, Phys. Lett. B 730, 99–104 (2014)
Bazavov et al., Phys. Rev. D 90, 094503 (2014)

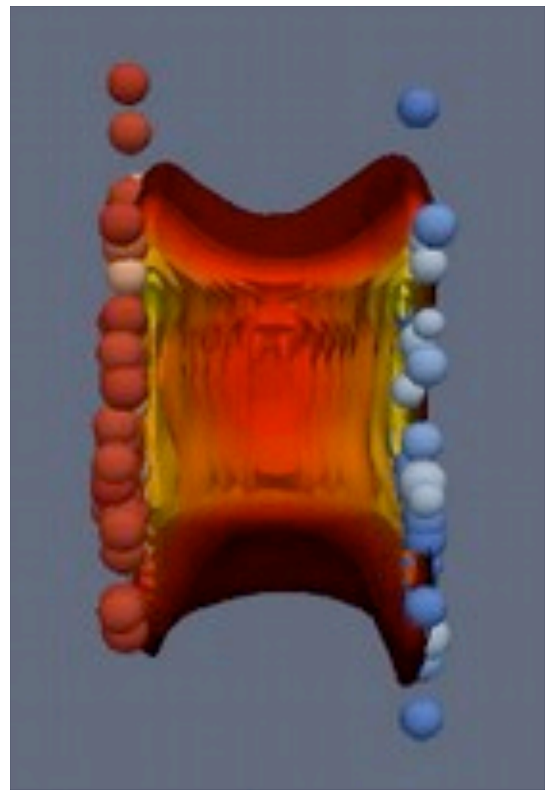
Kharzeev, Liao, Nature Reviews Physics volume 3, 55 (2021)











Hadron gas ⟵ **~10^{12} K** ⟶ **Quark-gluon plasma**

Contact with first-principles calculations (lattice QCD)

Some of the driving questions

Precise determination of QGP properties
Equation-of-state, transport coefficients, microscopic structure at different momentum scales

Heavy quarks as QGP probes
Do heavy quarks thermalize, too? Do they go with the flow? How much energy do they lose?

QGP-like effects in pp and p-A
QGP in small systems? Reassessment of some QGP signatures in Pb-Pb?

Exploring QCD with ALICE (3)

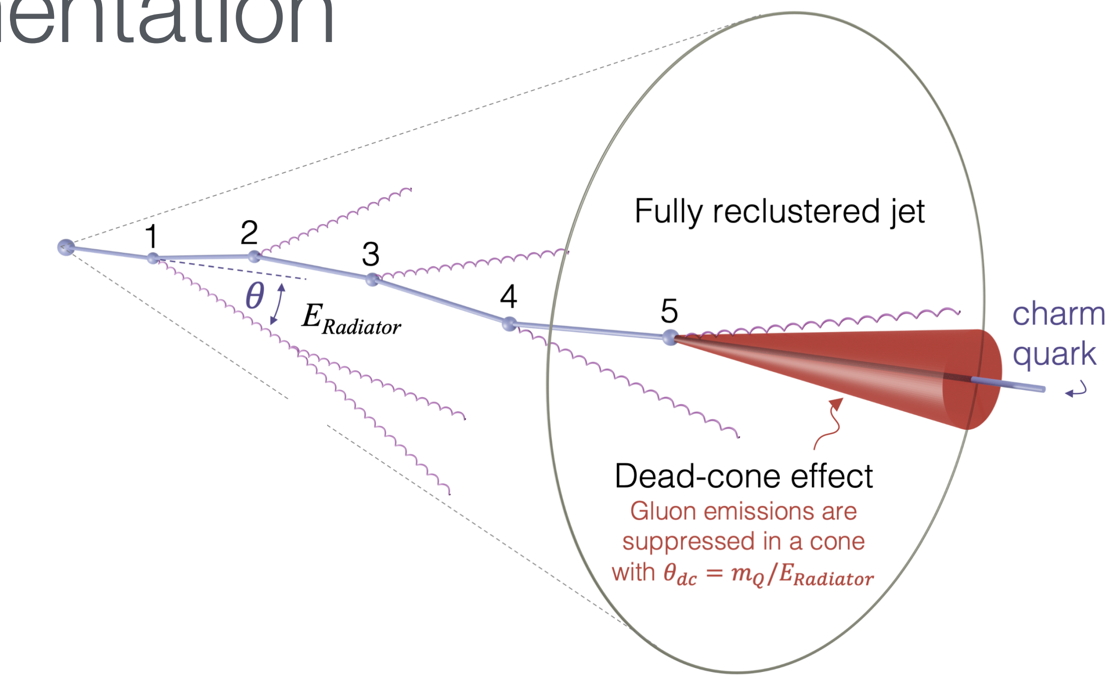
Beyond QGP physics

QCD in pp / p-Pb

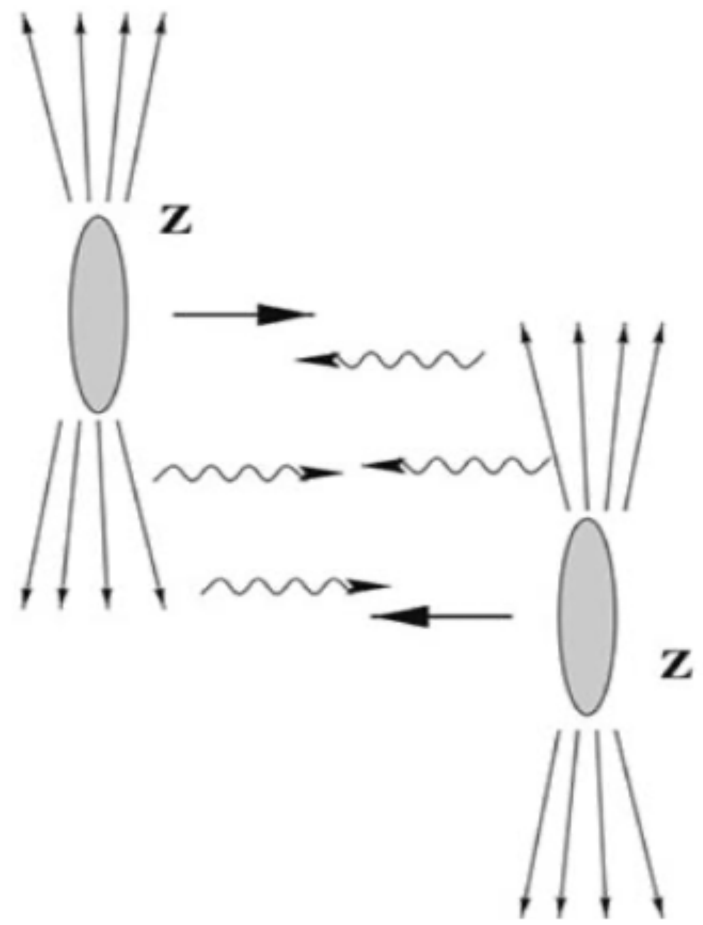
Charm hadronization

Jet fragmentation

…

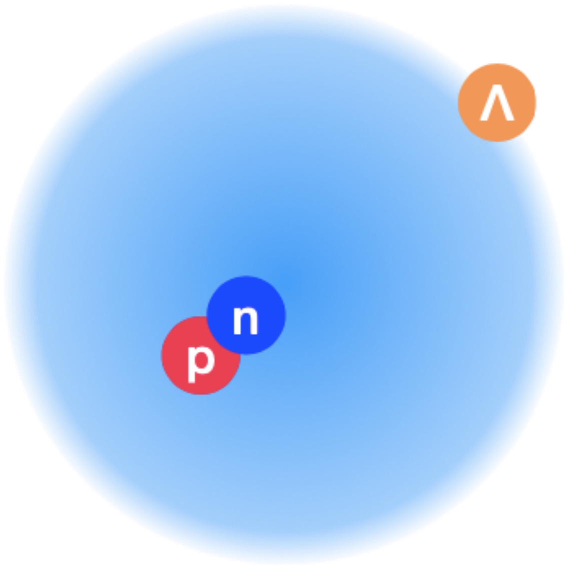


Photon-nucleus scattering



Properties of light nuclei and hypernuclei

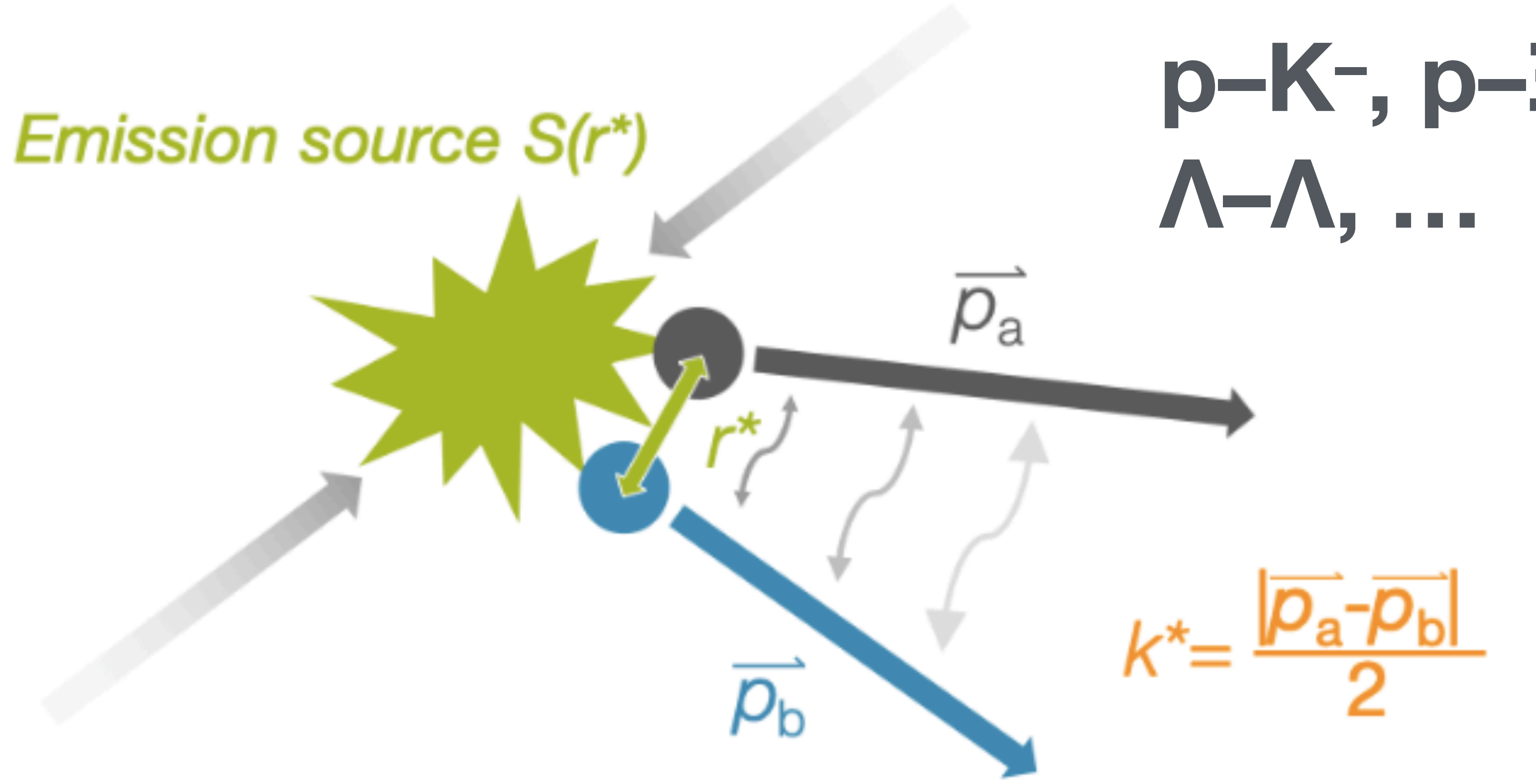
$^{3}_{\Lambda}\mathrm{H}$ structure



$\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ for indirect dark matter search

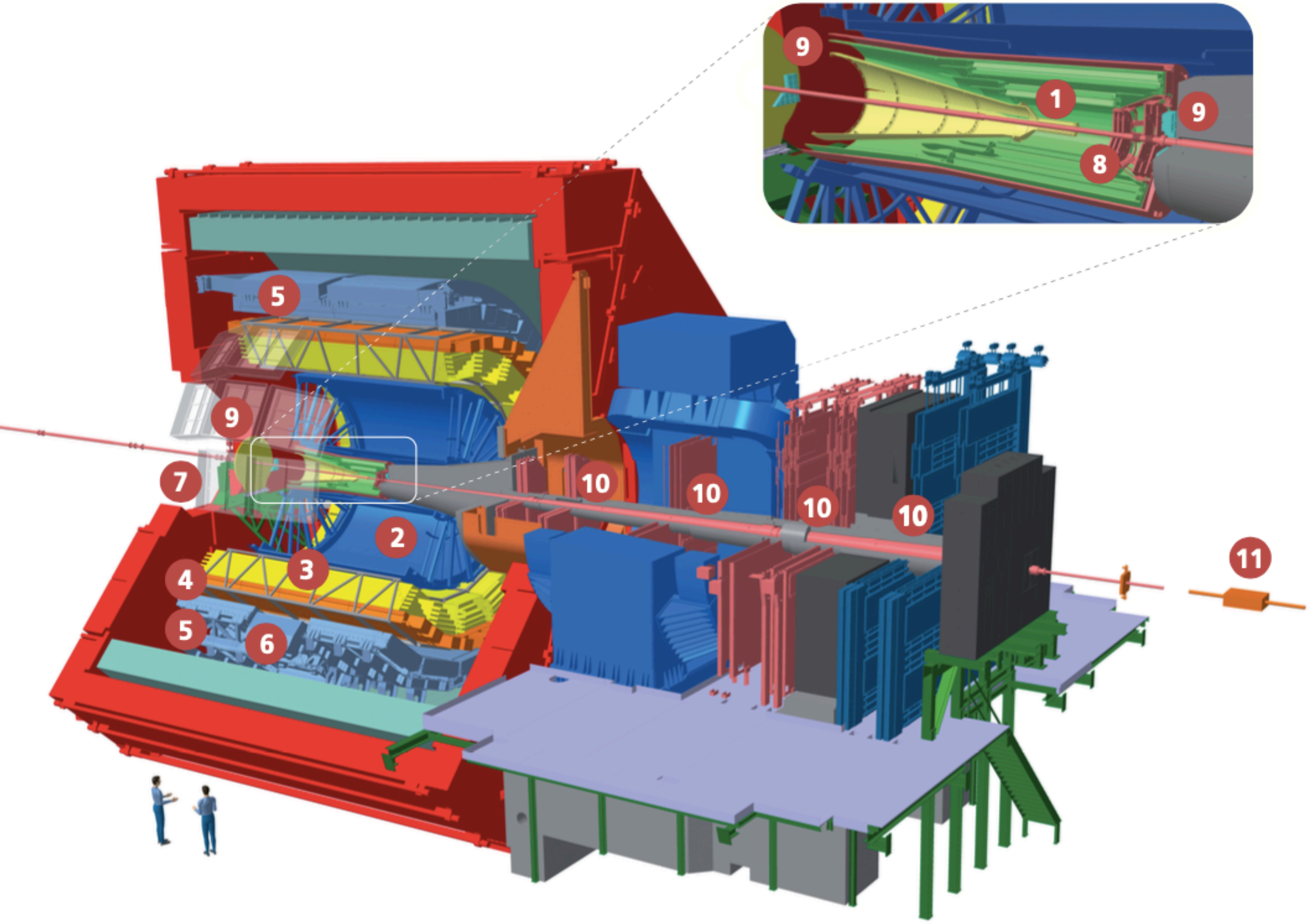
Nuclear force between (unstable) hadrons

p–K⁻, p–Ξ⁻, p–Ω⁻, Λ–Λ, …



Run 3 & 4:
ALICE 2

Faster readout, improved tracking, and very good PID



ALICE 2 (Run 3 & 4)

1 **ITS** | Inner Tracking System
2 **TPC** | Time Projection Chamber
3 **TRD** | Transition Radiation Detector
4 **TOF** | Time Of Flight
5 **EMCal** | Electromagnetic Calorimeter
6 **PHOS / CPV** | Photon Spectrometer
7 **HMPID** | High Momentum Particle Identification Detector
8 **MFT** | Muon Forward Tracker
9 **FIT** | Fast Interaction Trigger
10 **Muon Spectrometer**
11 **ZDC** | Zero Degree Calorimeter

LS2 upgrade

- **new** TPC detectors (GEMs)
- **new** silicon trackers (ITS & MFT)
- **new** fast interaction trigger (FIT)
- **new** online/offline system (O2)
- **new** readout for all detectors

Continuous readout: 50 times higher readout rate for min. bias Pb-Pb

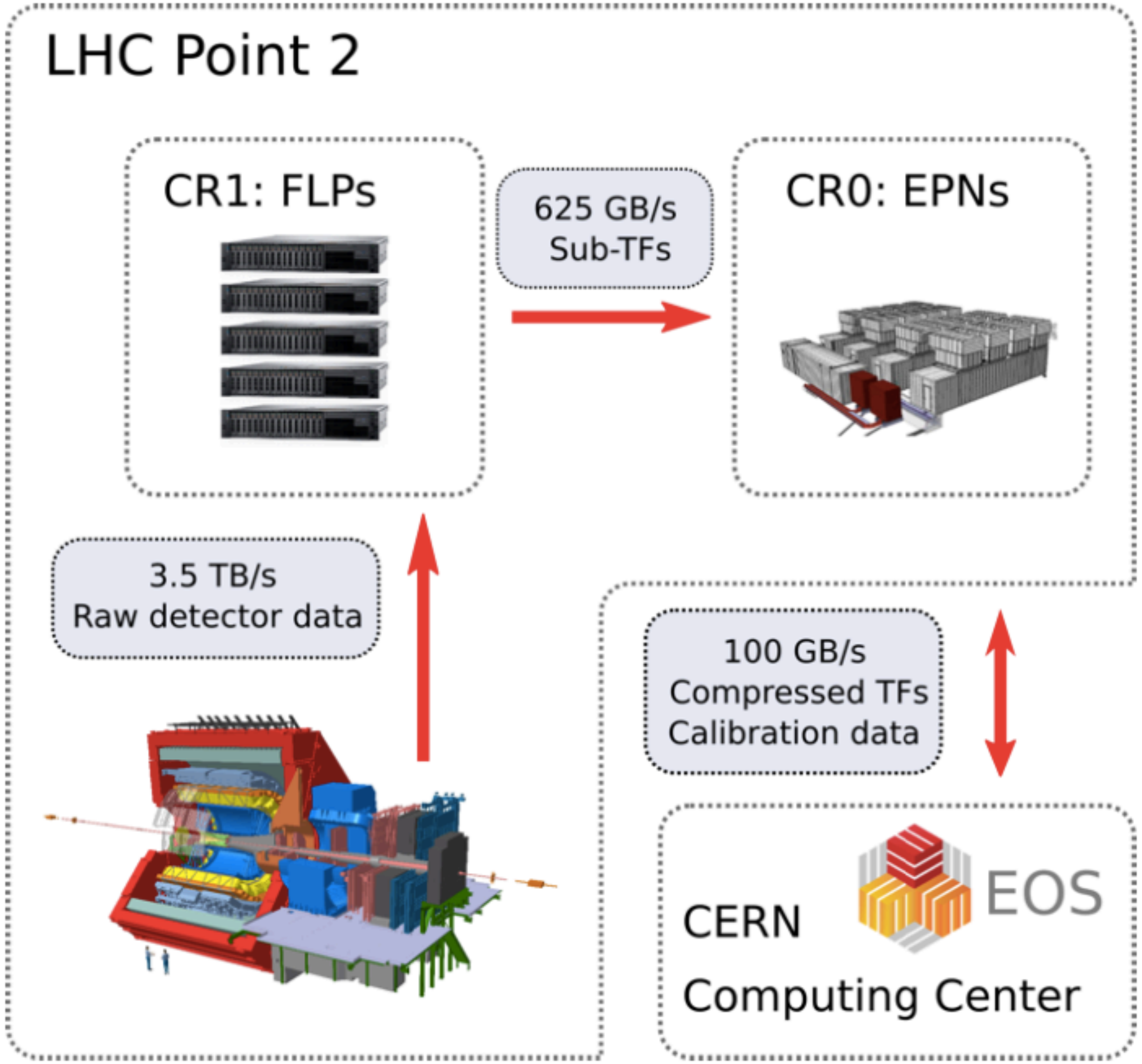


figure credit: Marten Ole Schmidt, CERN-THESIS-2020-071

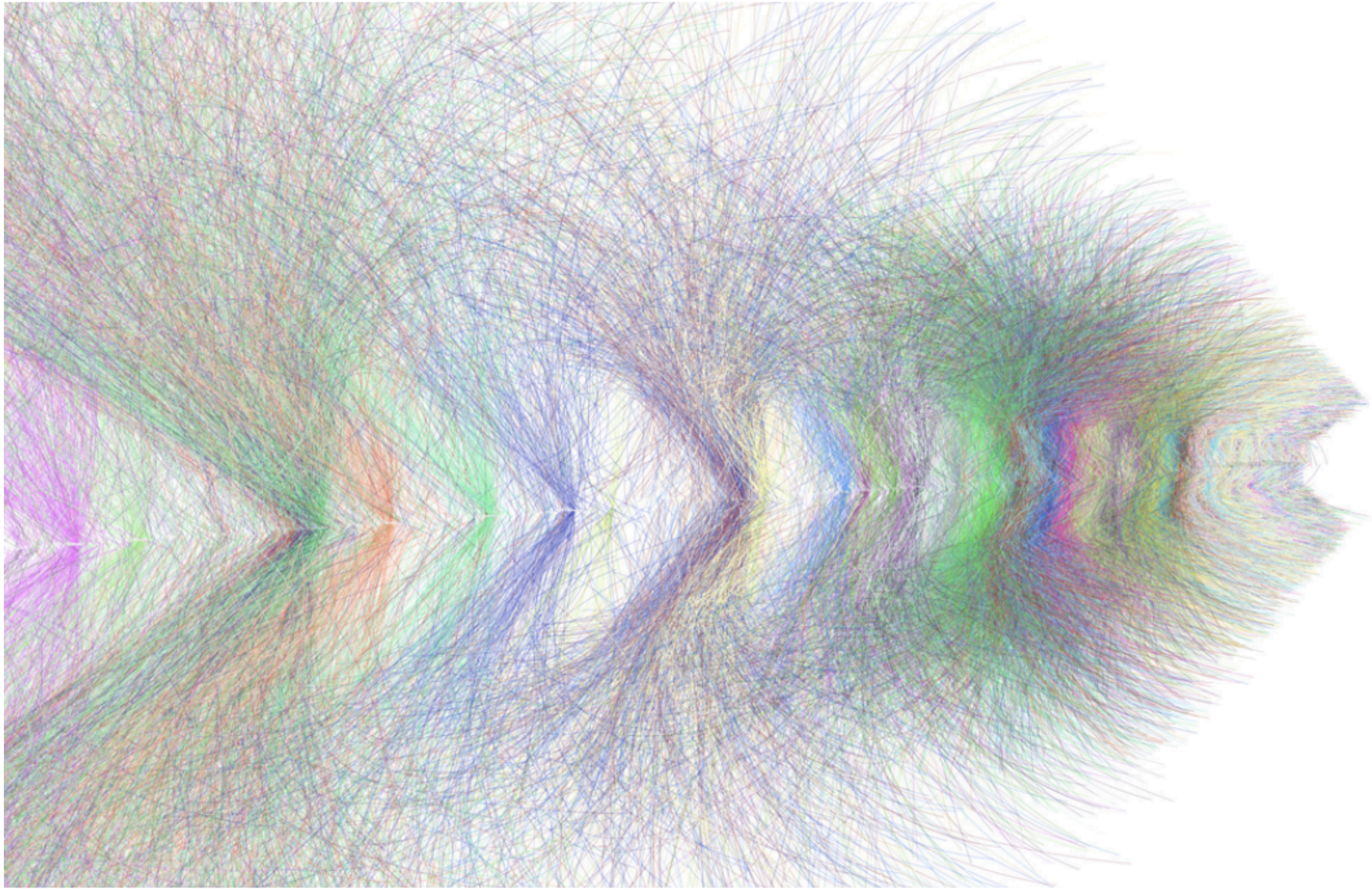
Run 1 & 2

- 8 kHz Pb-Pb interaction rate
- 1 kHz Pb-Pb readout rate
- total of 1 nb^{-1} Pb-Pb collisions

Run 3 & 4: continuous readout

- readout rate 50 kHz Pb-Pb (1 MHz pp)
- expect 13 nb^{-1} Pb-Pb collisions
  - × 50 min. bias Pb-Pb Run 1 & 2
- 0.6 pb^{-1} p-Pb collisions
  - × 200 min. bias p-Pb Run 2
- 200 pb^{-1} pp top energy
  - with software selection for rare events
- small O-O sample (1 nb^{-1})

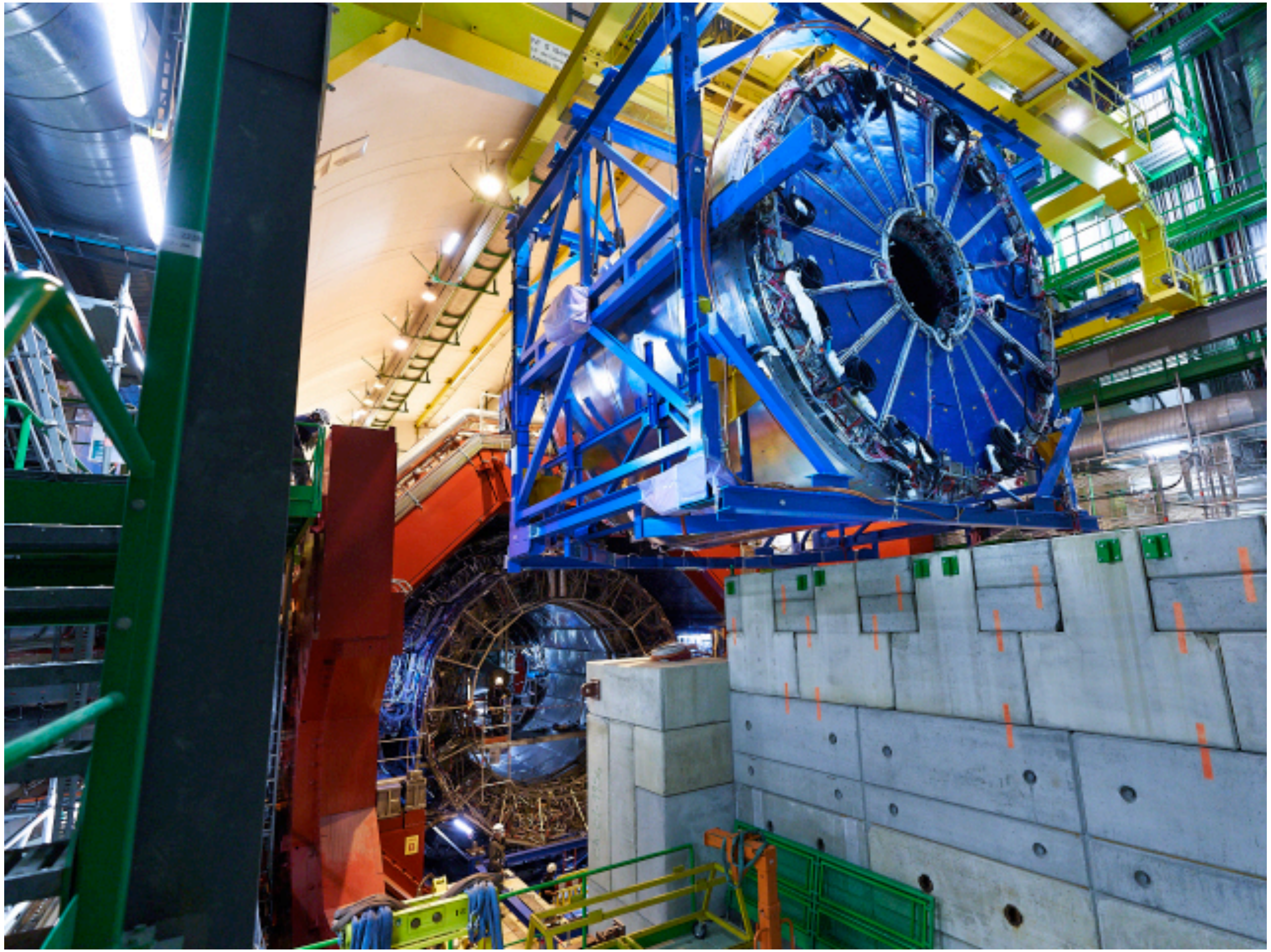
Visualization of a 2 ms time frame with Pb–Pb collisions at 50 kHz



Time frame of ~10 ms with ~500 Pb-Pb collisions reconstructed in one shot

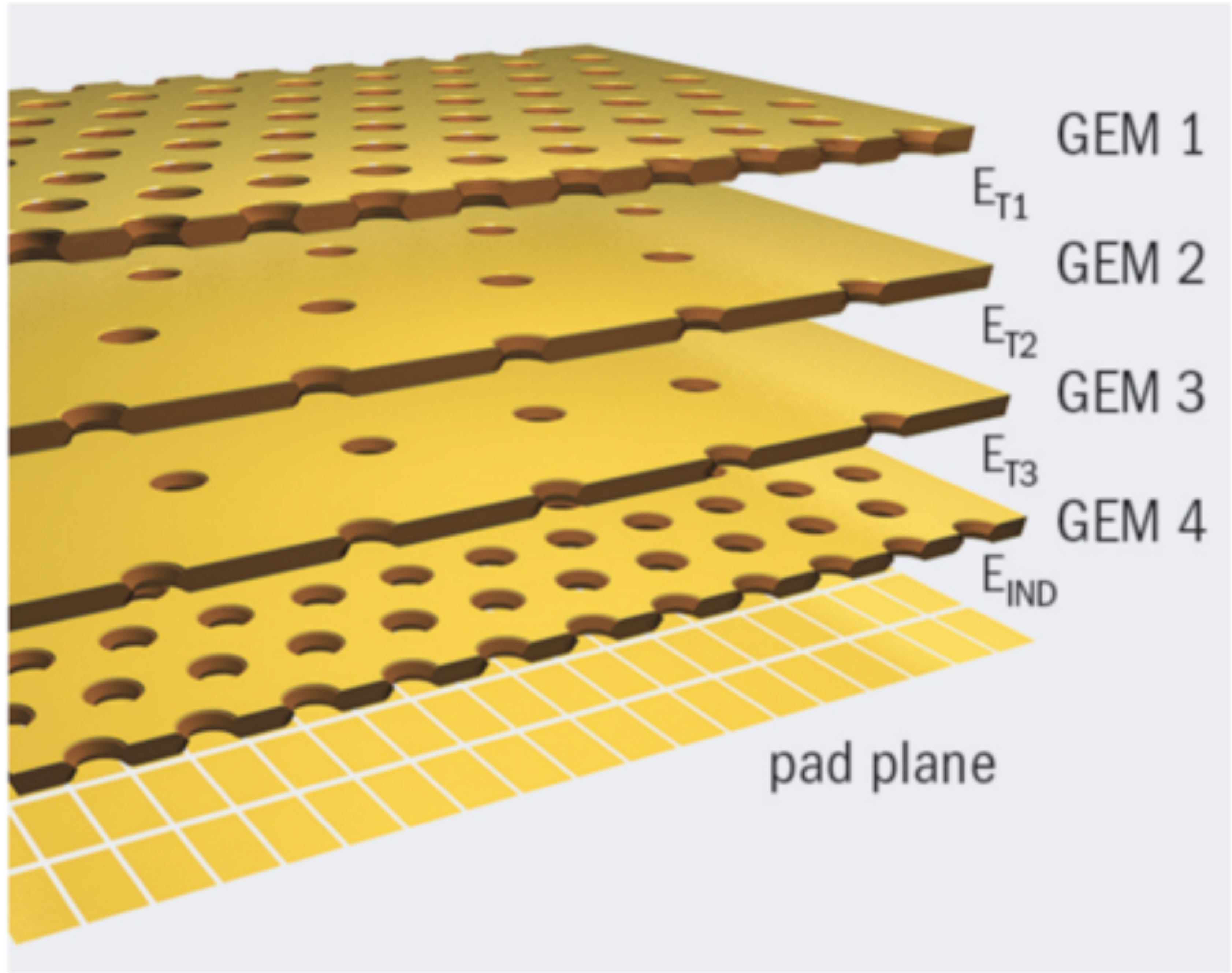
95% of reconstruction on GPUs

High rates with GEMs (replacing MWPCs)

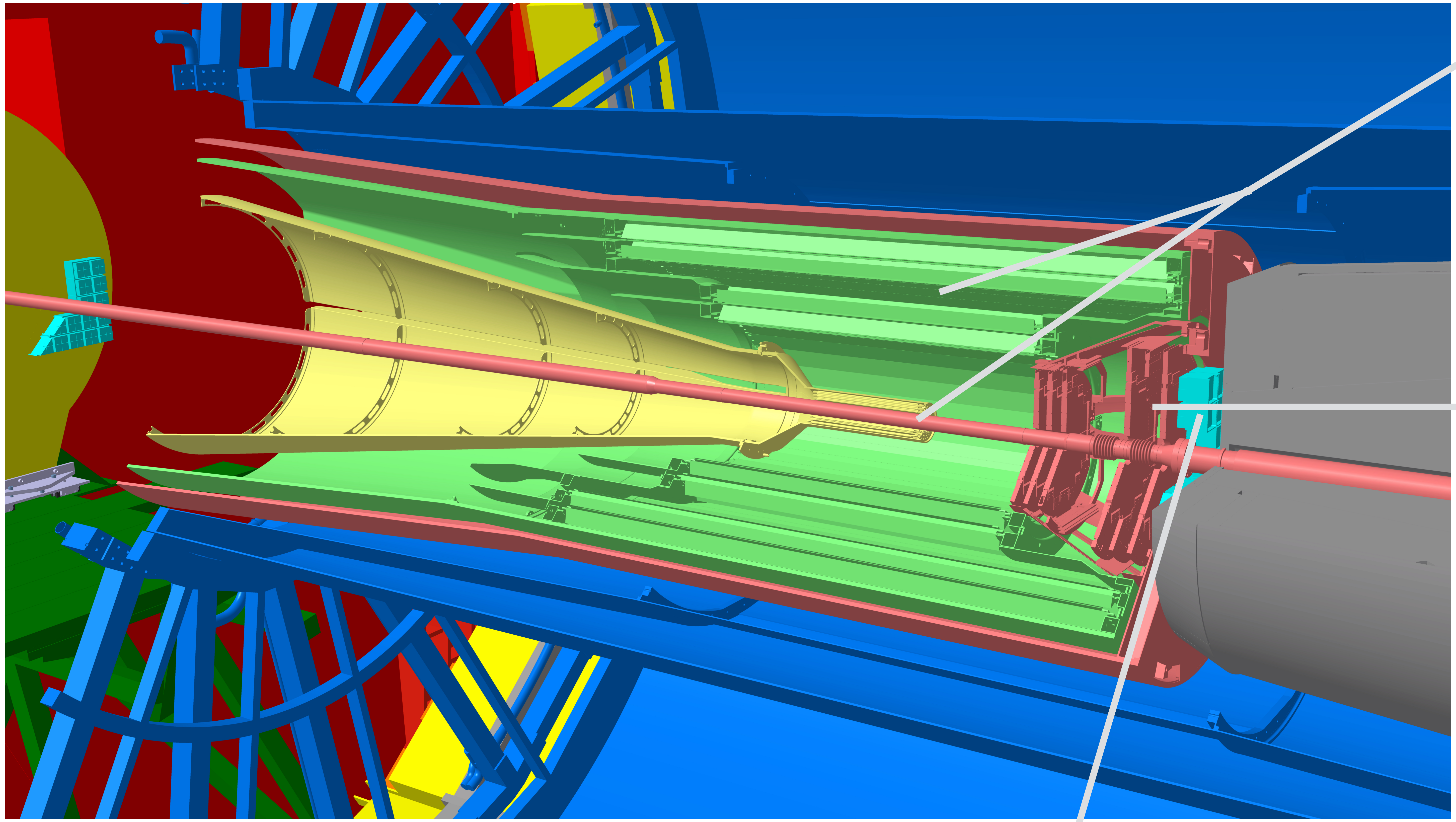


Continuous readout at 50 kHz Pb-Pb interaction rate possible due to GEMs

Fully installed in August 2020



New technology for tracking detectors: CMOS MAPS (ALPIDE)



ITS2: new inner tracking system

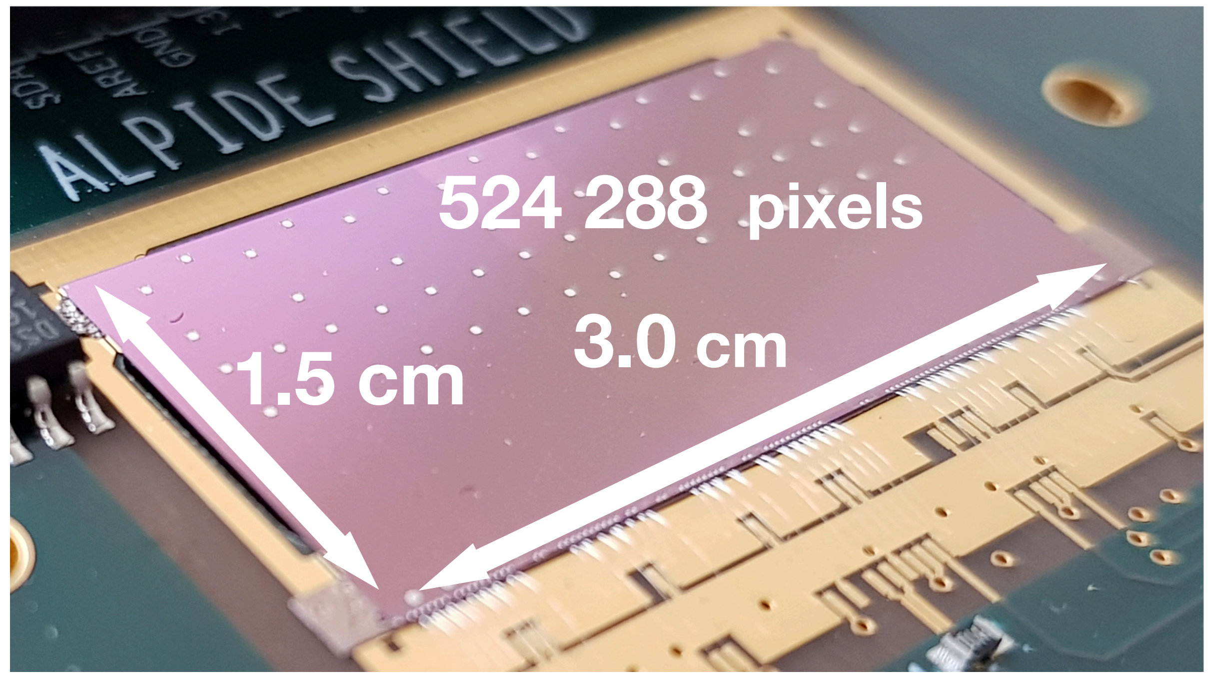
- Improved pointing resolution (× 3)
- Inner barrel: 0.35% X_0 per layer
- Smaller beam pipe, 1st layer closer (22 mm)

MFT: muon forward tracker

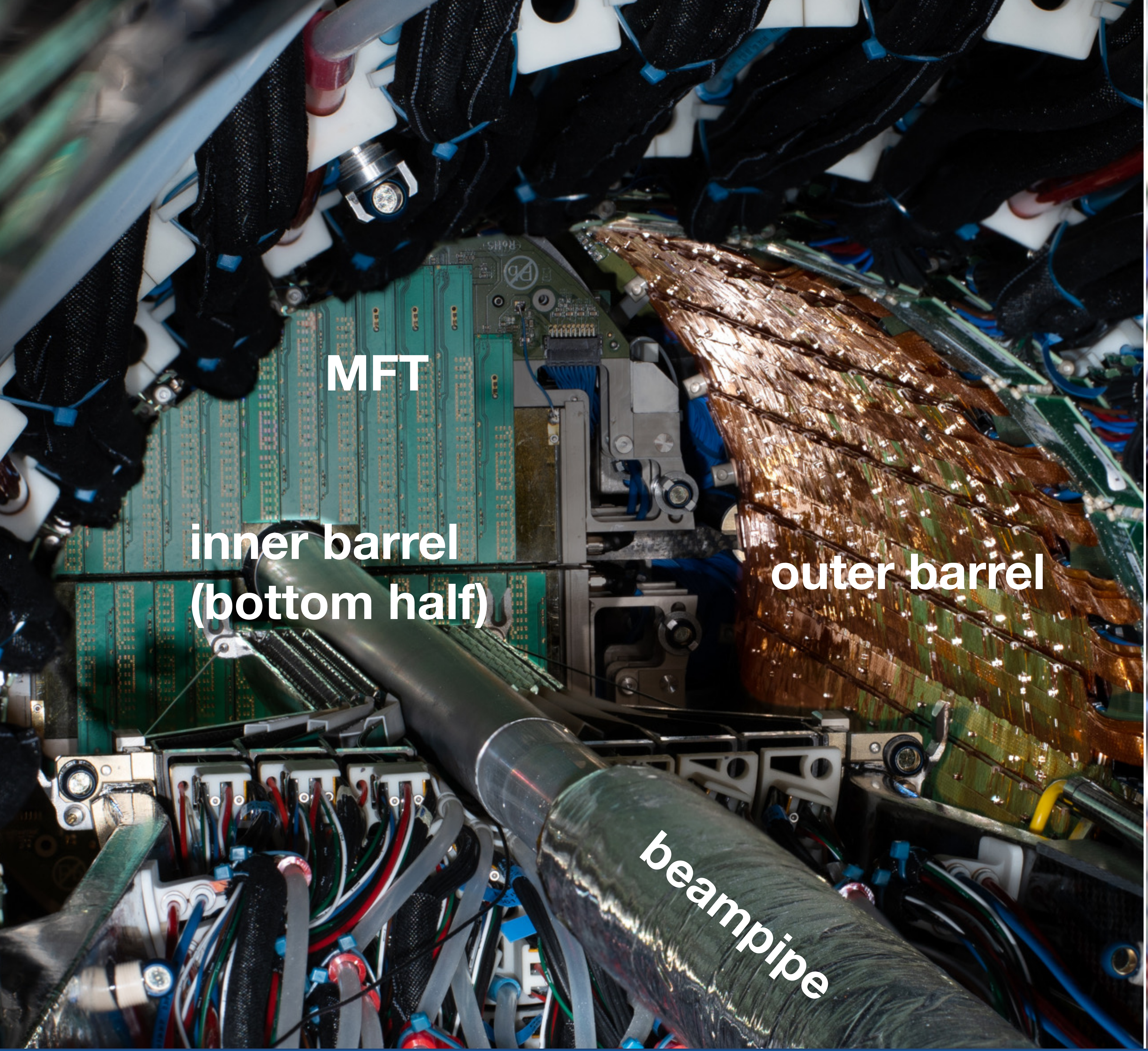
- New tracker based on ALPIDE
- Now tracking before the absorber: Improved muon pointing

FIT: new trigger system

ALPIDE



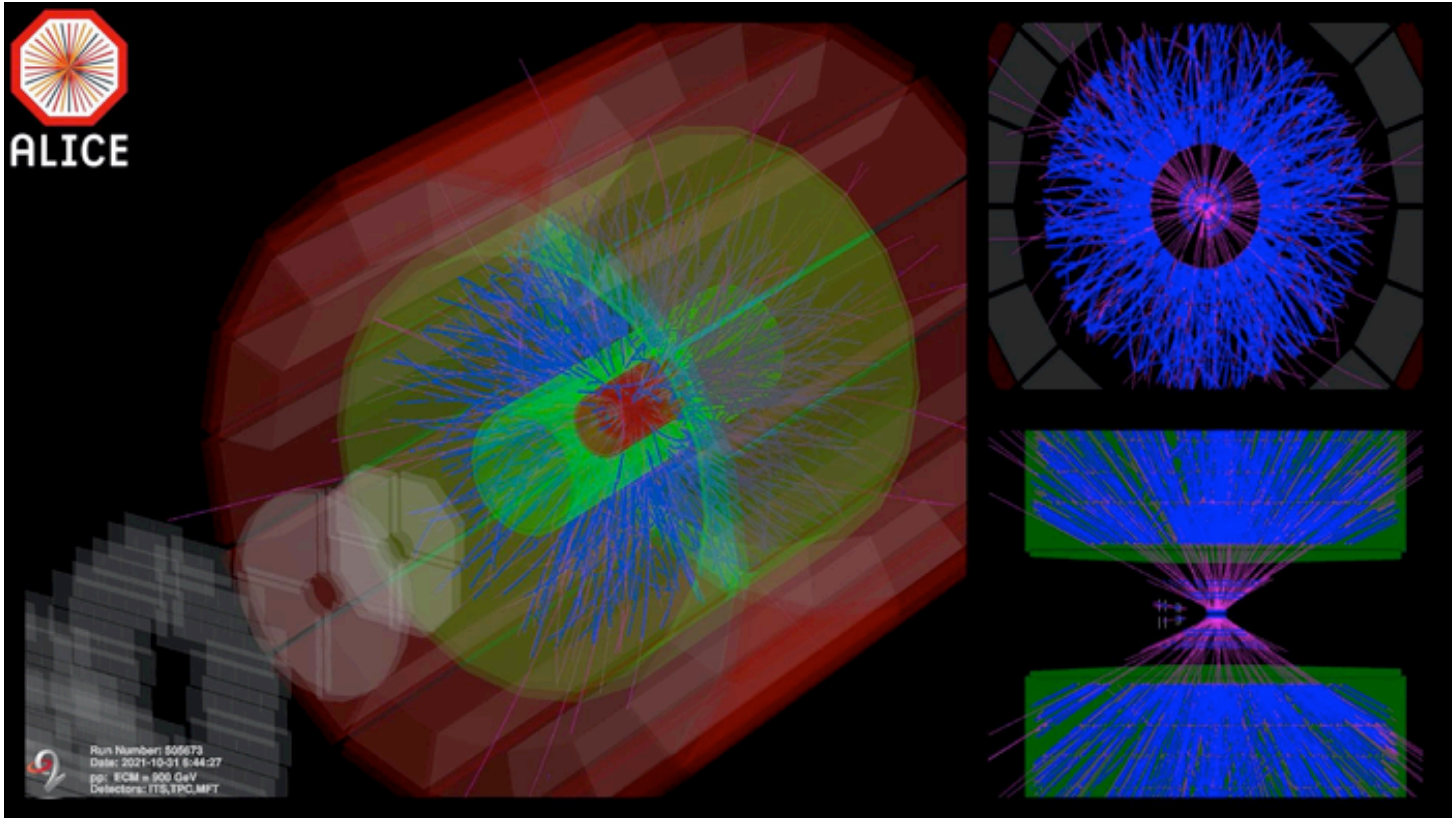
talks Jian Liu, Solangel Rojas Torres



ITS2: 10 m², 12.5×10⁹ pixels,
fully installed in May 2021

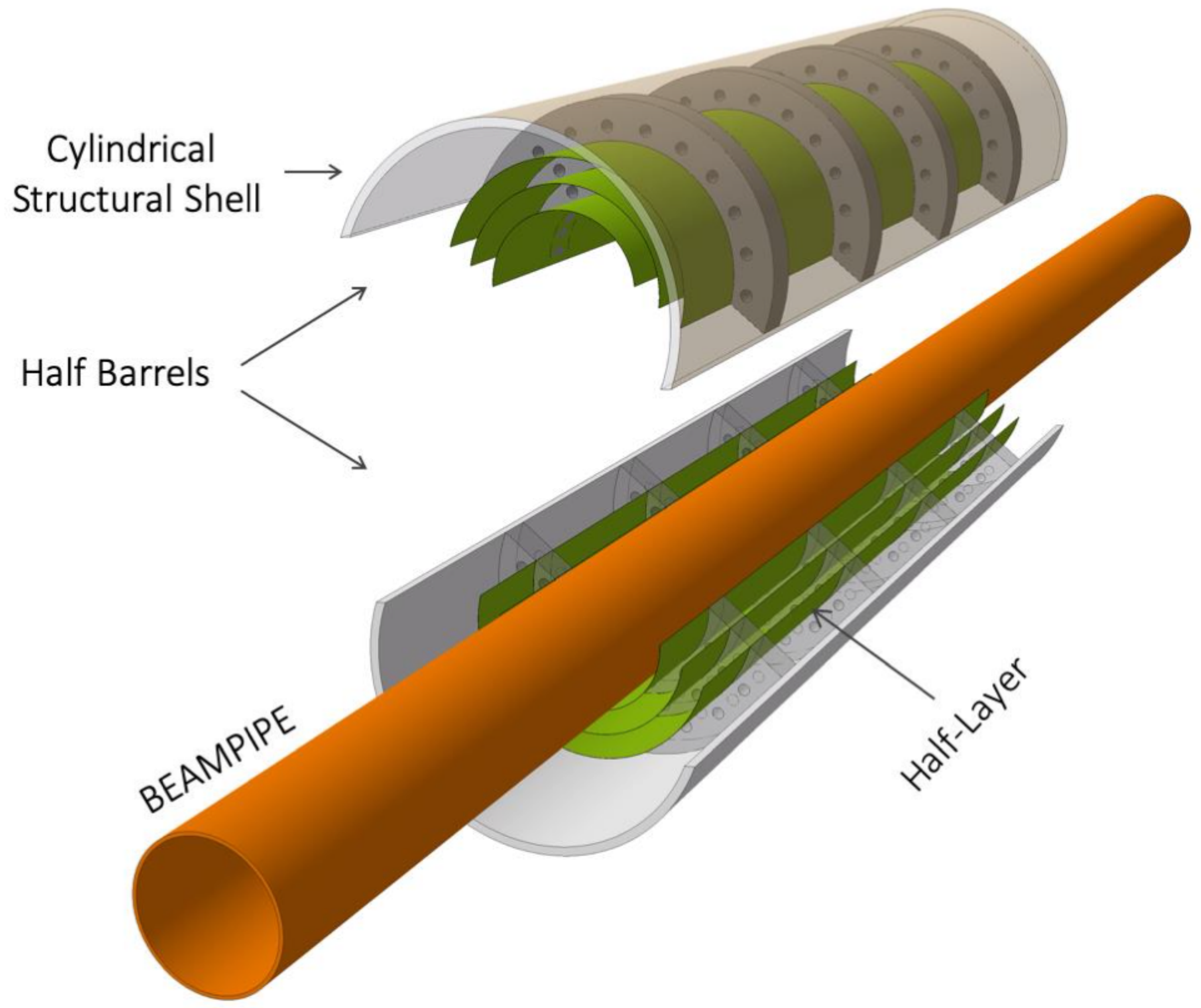
LHC pilot run (pp @ 900 GeV, 19-31 October 2021)

First events with ALICE 2

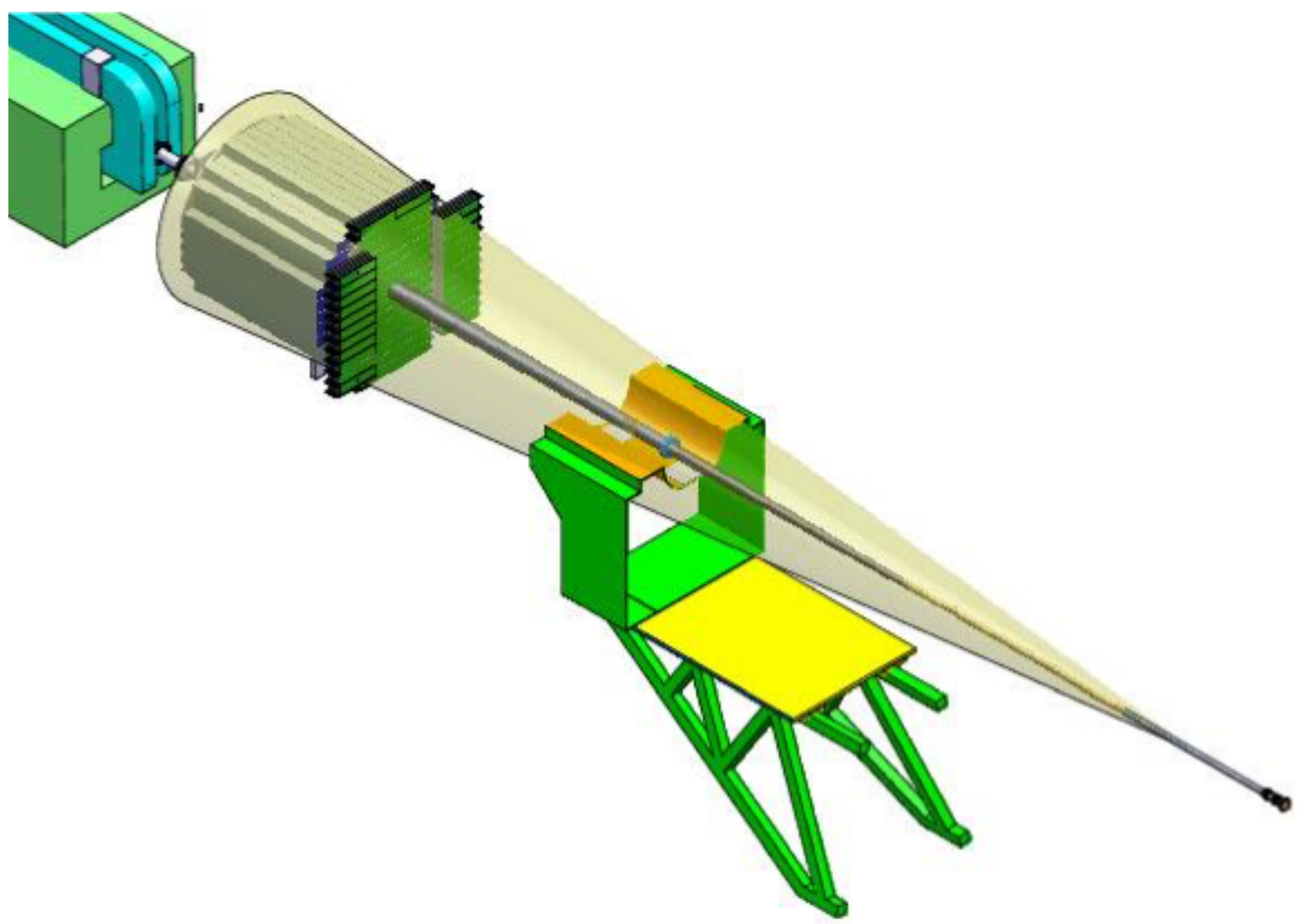


ALICE upgrades in LS3 & LS4

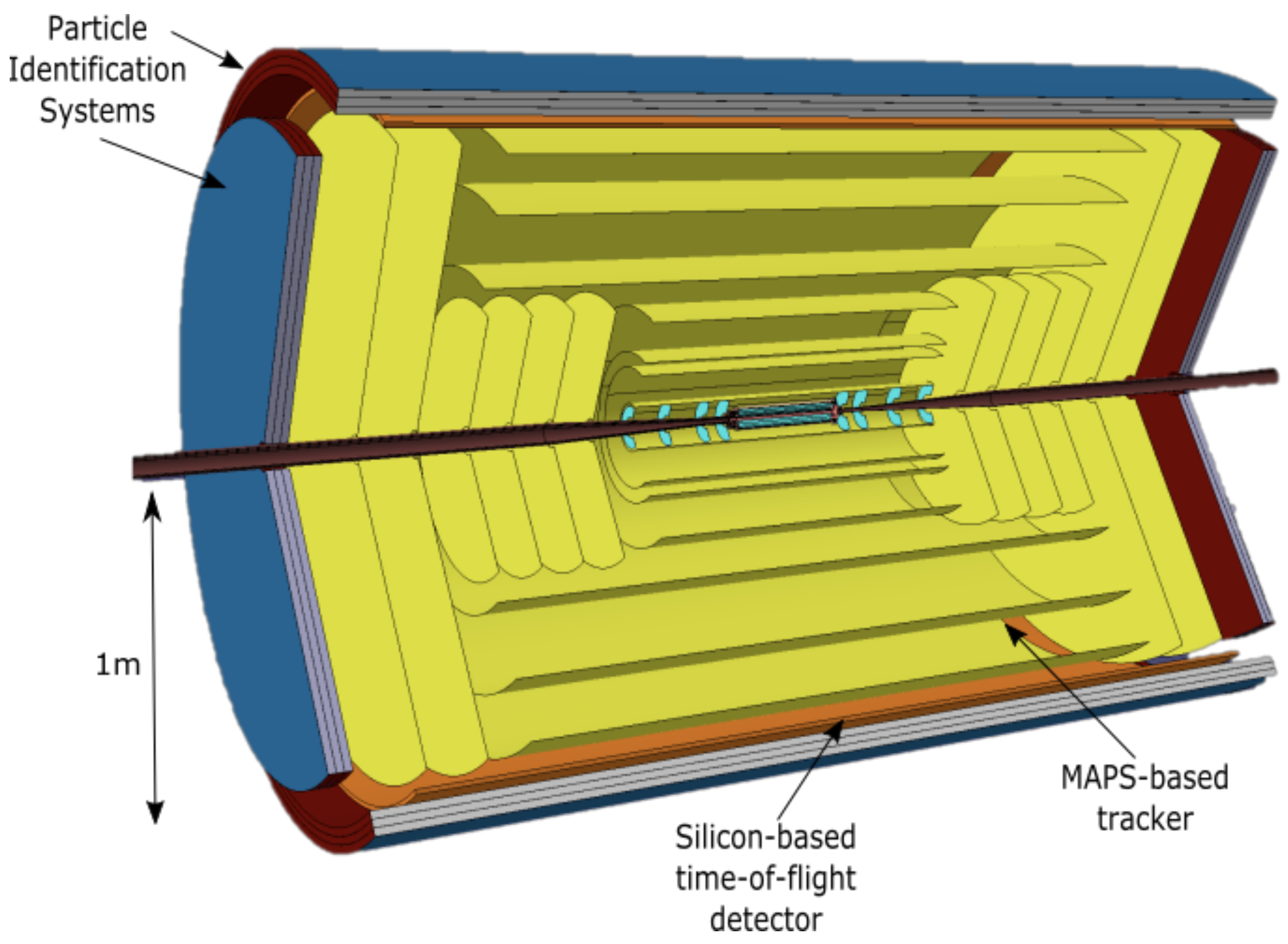
ITS3



FoCal



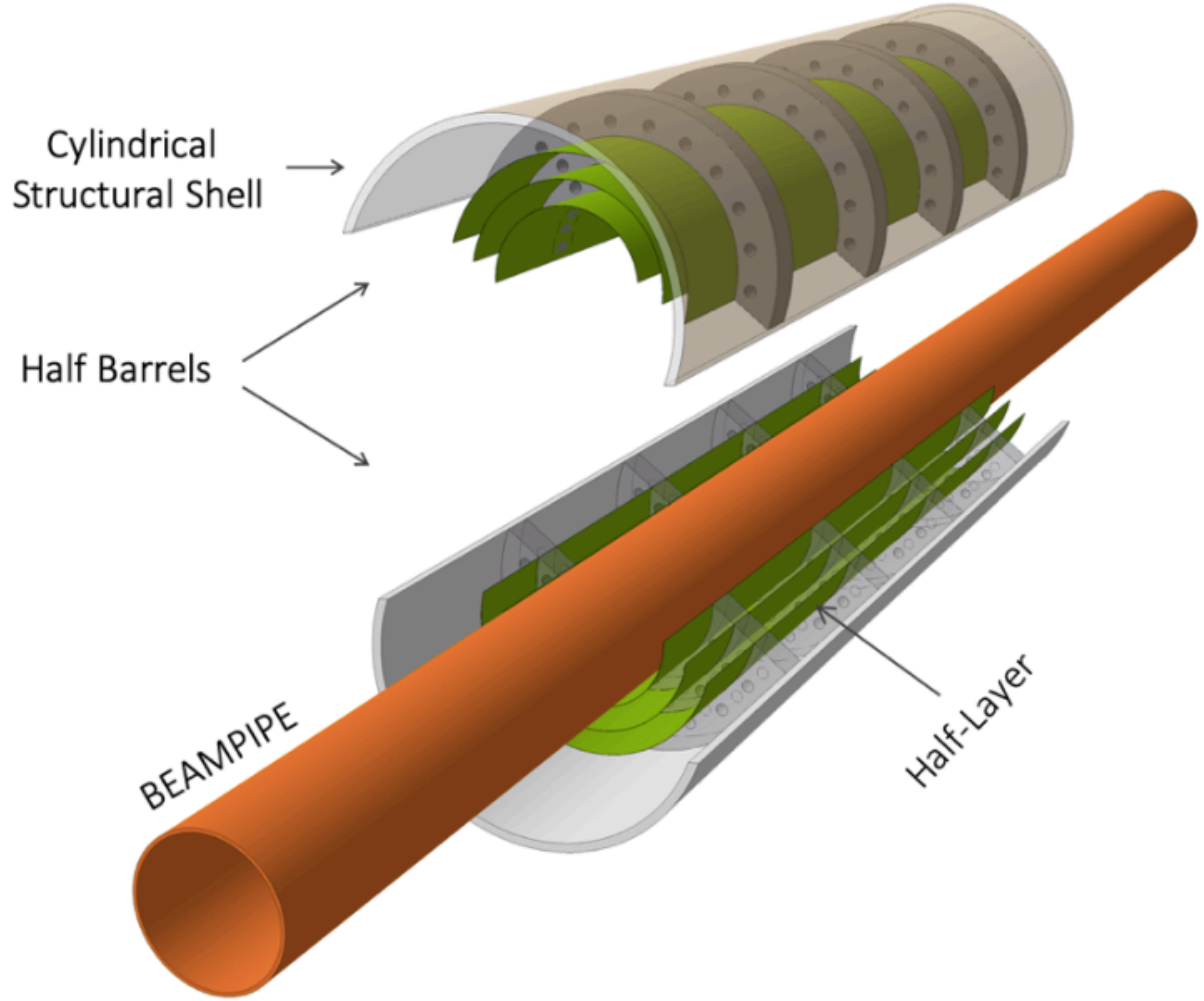
ALICE 3



talks Filip Krizek, Gian Michele Innocenti

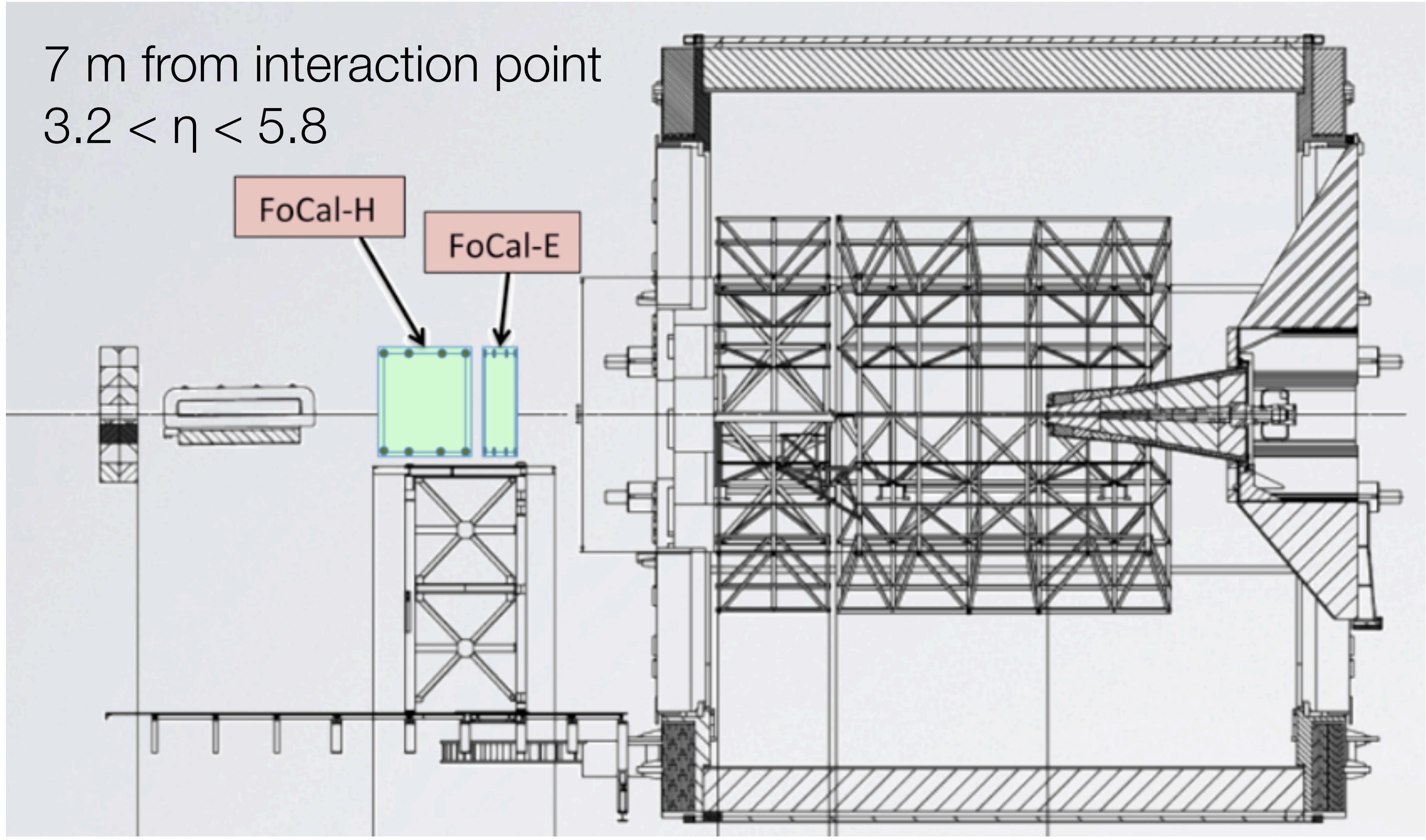
Wafer-scale, ultra-thin, bent MAPS: lowest possible material budget

"sensors maintain their excellent performance after bending",
ALICE ITS team, arXiv:2105.13000

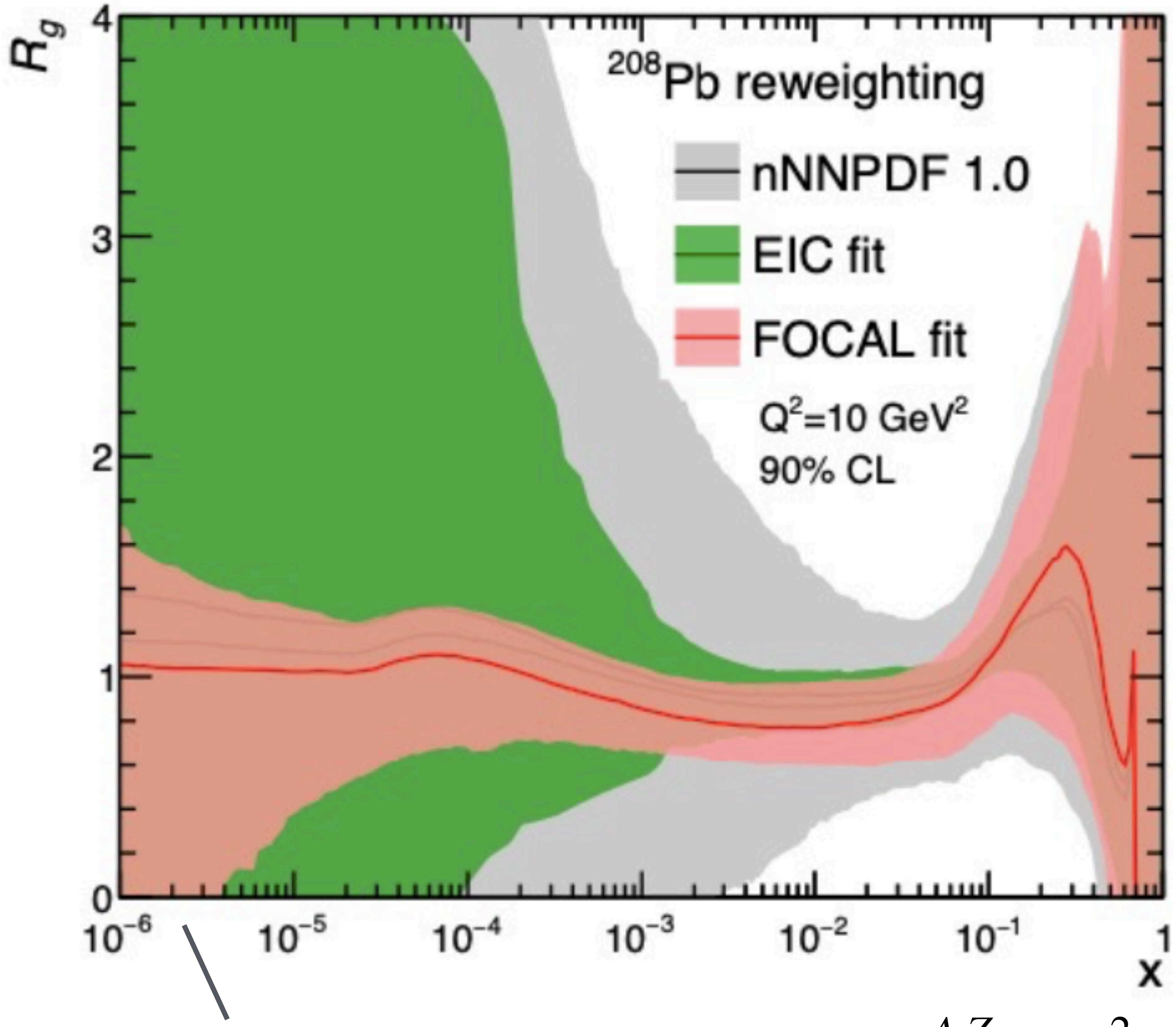


Significant improvement in the measurement of low momentum charm and beauty hadrons and low-mass dielectrons

Shadowing/saturation of small-*x* gluons in Pb with forward photons



CERN-LHCC-2020-009



FoCal-E: high-granularity Si-W sampling sandwich calorimeter for photons and π^0

down to $x \approx 10^{-6}$ $$R_g(x, Q^2) = \frac{g^{A,Z}(x, Q^2)}{g^N(x, Q^2)}$$

FoCal-H: conventional sampling calorimeter for photon isolation

In addition: jets, jet quenching, J/ψ, Υ, long-range correlations in pp, p-Pb, …

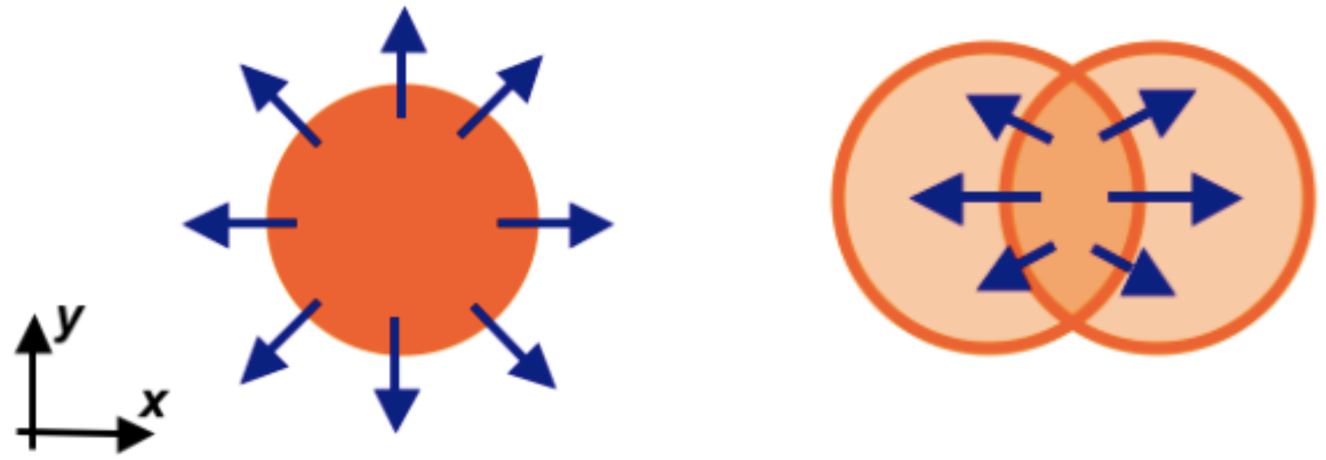
Physics highlights
Pb-Pb: Exploring the QGP

Expected effects in the presence of a QGP

c and b quarks from initial hard scatterings (prior to QGP formation, $m_Q \gg T_{QGP}$: no thermal production)

Low p_T ($p_T \lesssim$ 10 GeV/c)

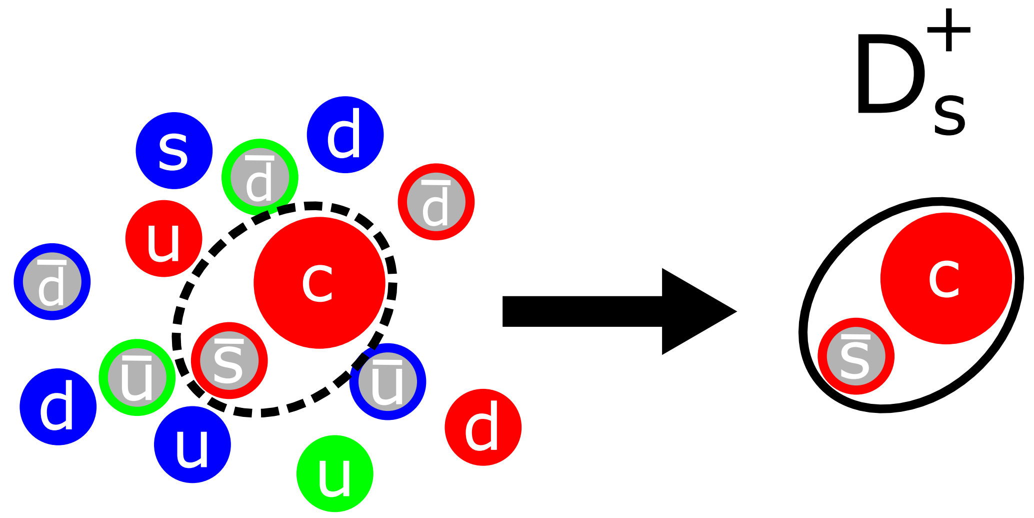
Collective motion like for u,d,s (?)



Mass-dependent p_T shift:

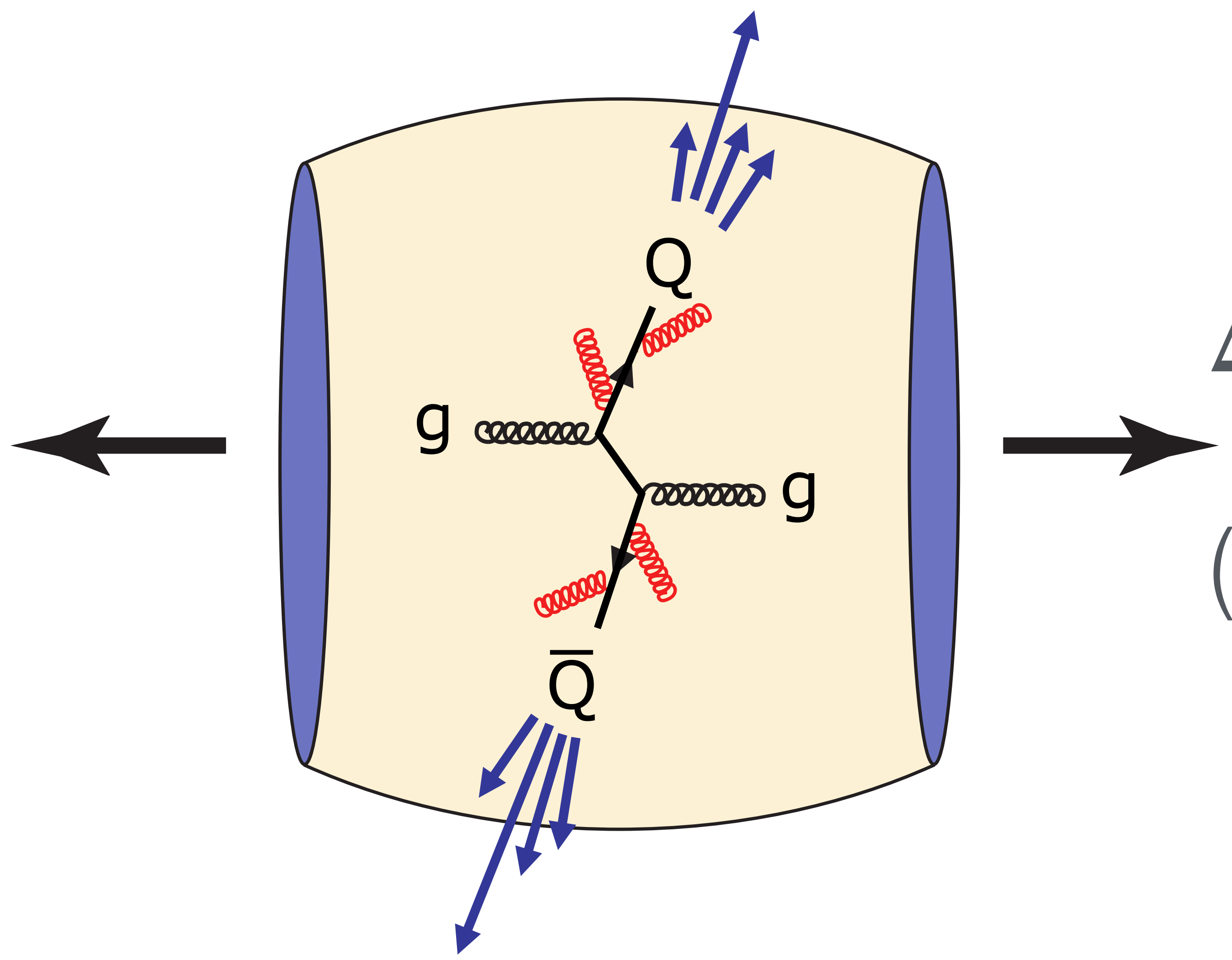
$$p_{\mathrm{T,flow}} = \beta_{\mathrm{flow}} \gamma_{\mathrm{flow}} m$$

Hadronization via coalescence?



High p_T ($p_T \gtrsim$ 10 GeV/c)

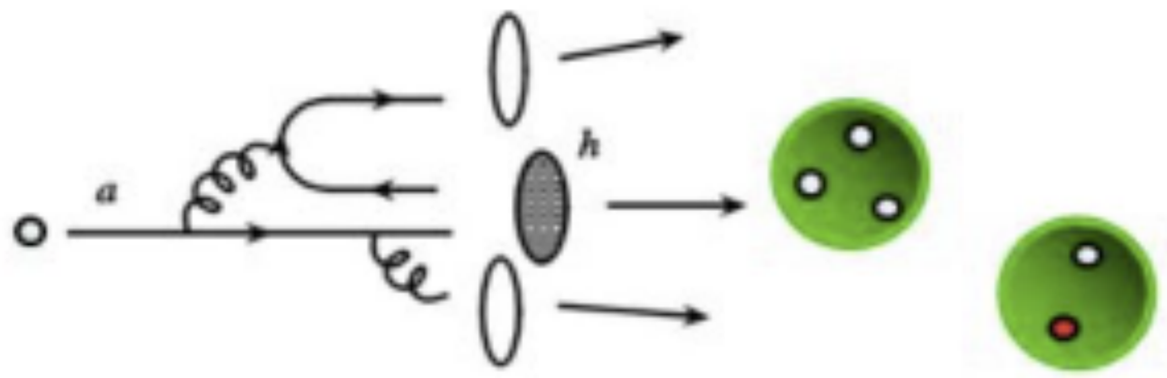
Parton energy loss:



$$\Delta E_b < \Delta E_c < \Delta E_{u,d,s}$$

(→ **dead-cone effect!**)

Hadronization in vacuum (like in e^+e^-)



parameterized by fragmentation function

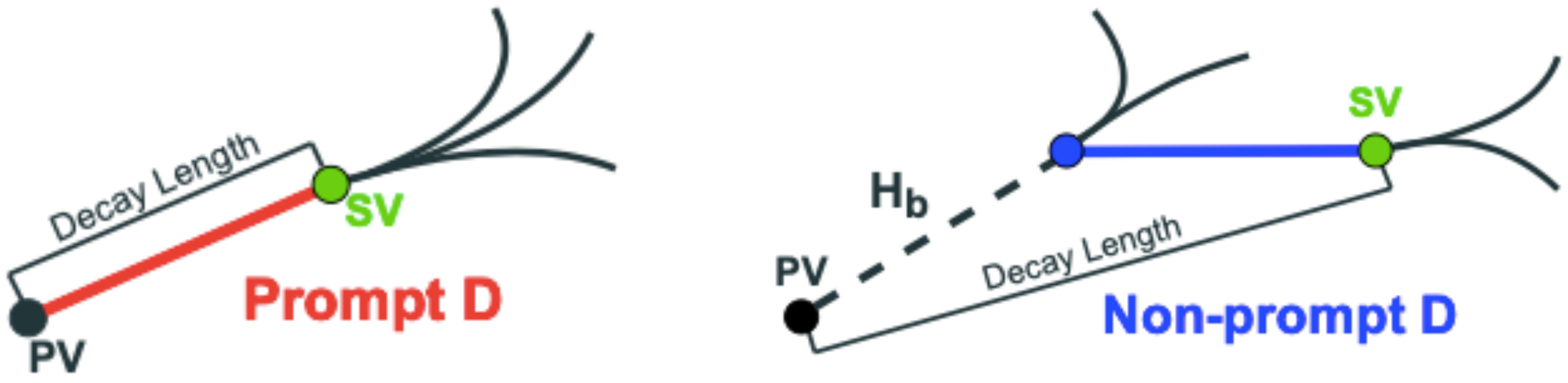
Observable and techniques

Quantifying medium effects in A-A:
Comparison to simple superposition of pp collisions

$$R_{AA}(p_T) = \frac{dN/dp_T|_{AA}}{N_{coll} \times dN/dp_T|_{pp}}$$

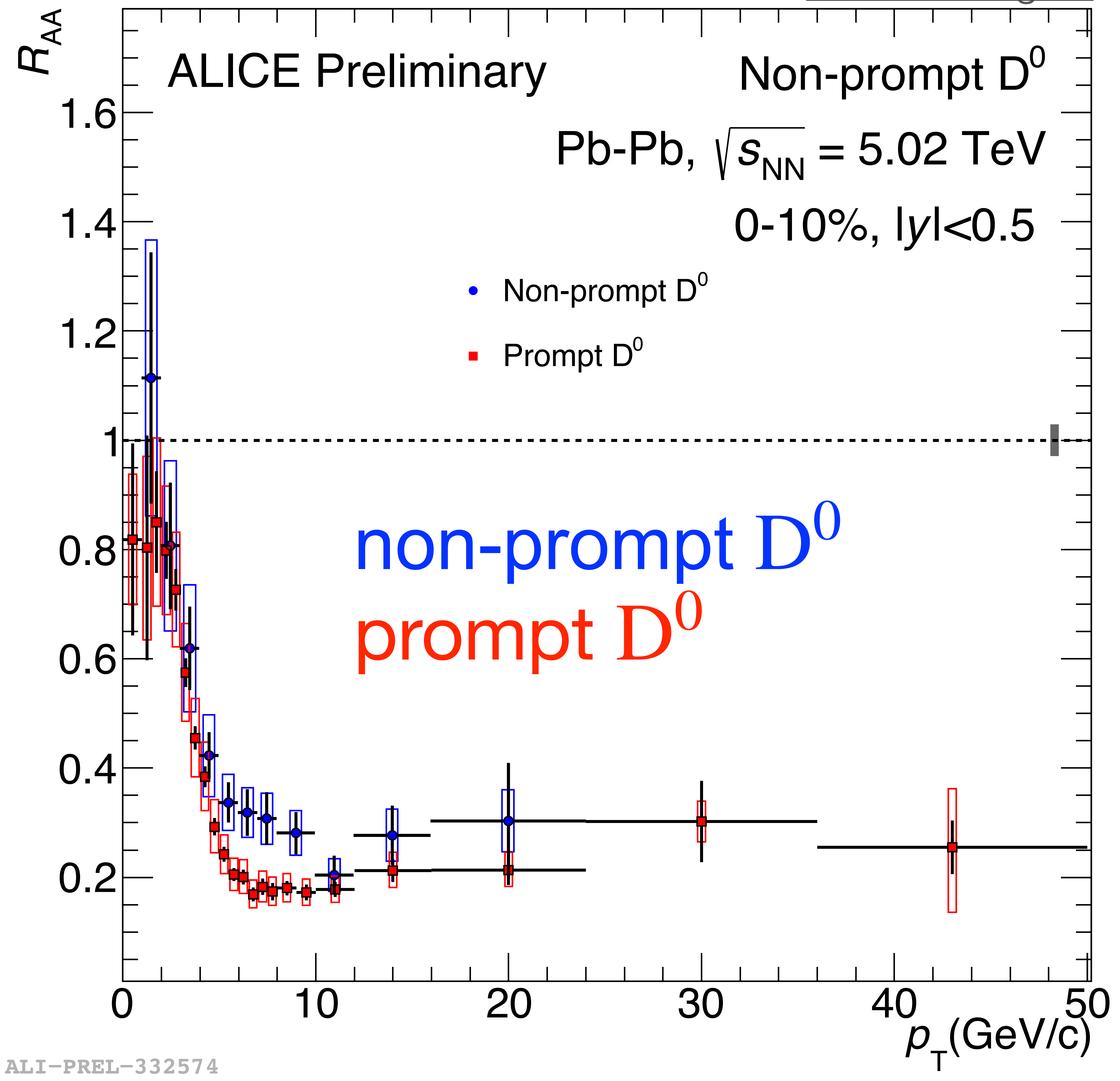
b quark energy loss:
Accessible via non-prompt D

$$B \to D + X$$



Prompt vs non-prompt D^0 R_{AA} consistent with $\Delta E_b < \Delta E_c$

talk Stefano Trogolo



First measurement of D meson production down to zero p_T in Pb-Pb

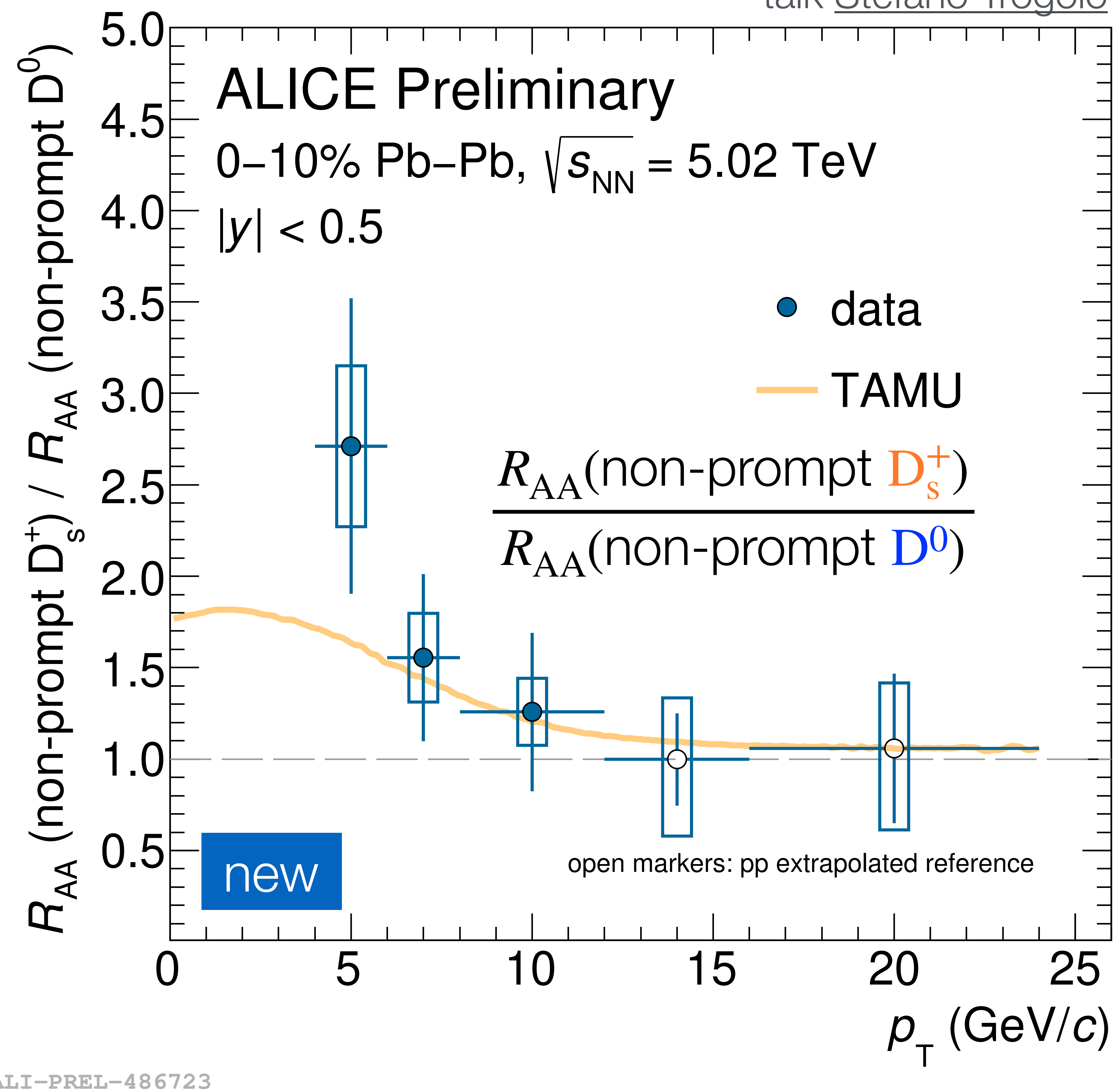
D^0 from B less suppressed than prompt D^0

Consistent with $\Delta E_b < \Delta E_c$ (dead-cone effect)

More precise measurement with new ITS in Run 3

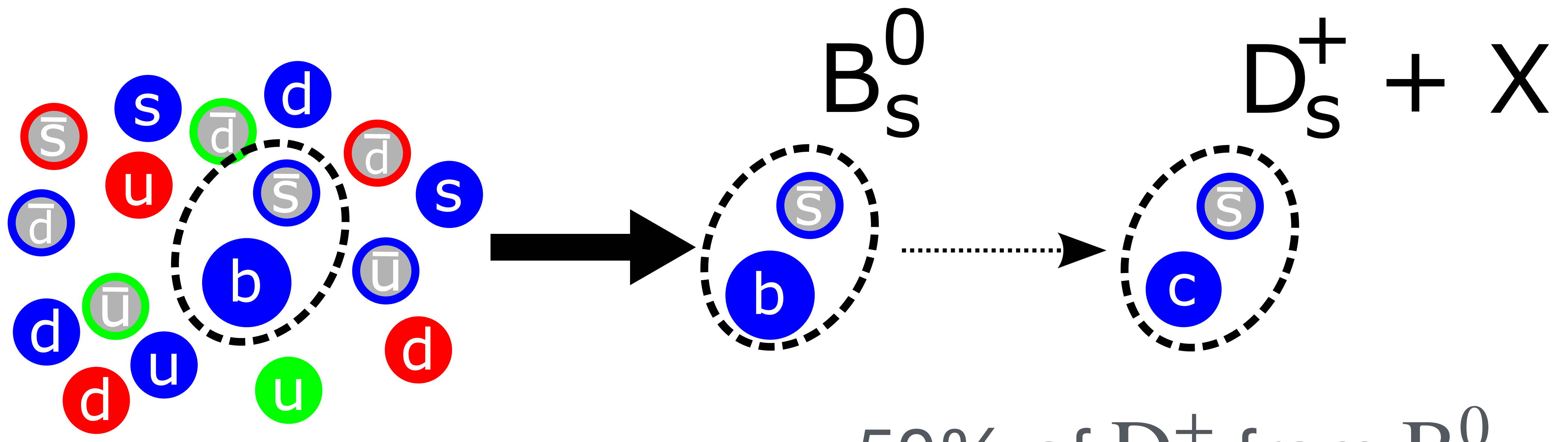
R_{AA}(non-prompt D_s^+) > R_{AA}(non-prompt D^0) in line with coalescence picture

talk Stefano Trogolo



Non-prompt D_s^+ less suppressed than non-prompt D^0 at low p_T

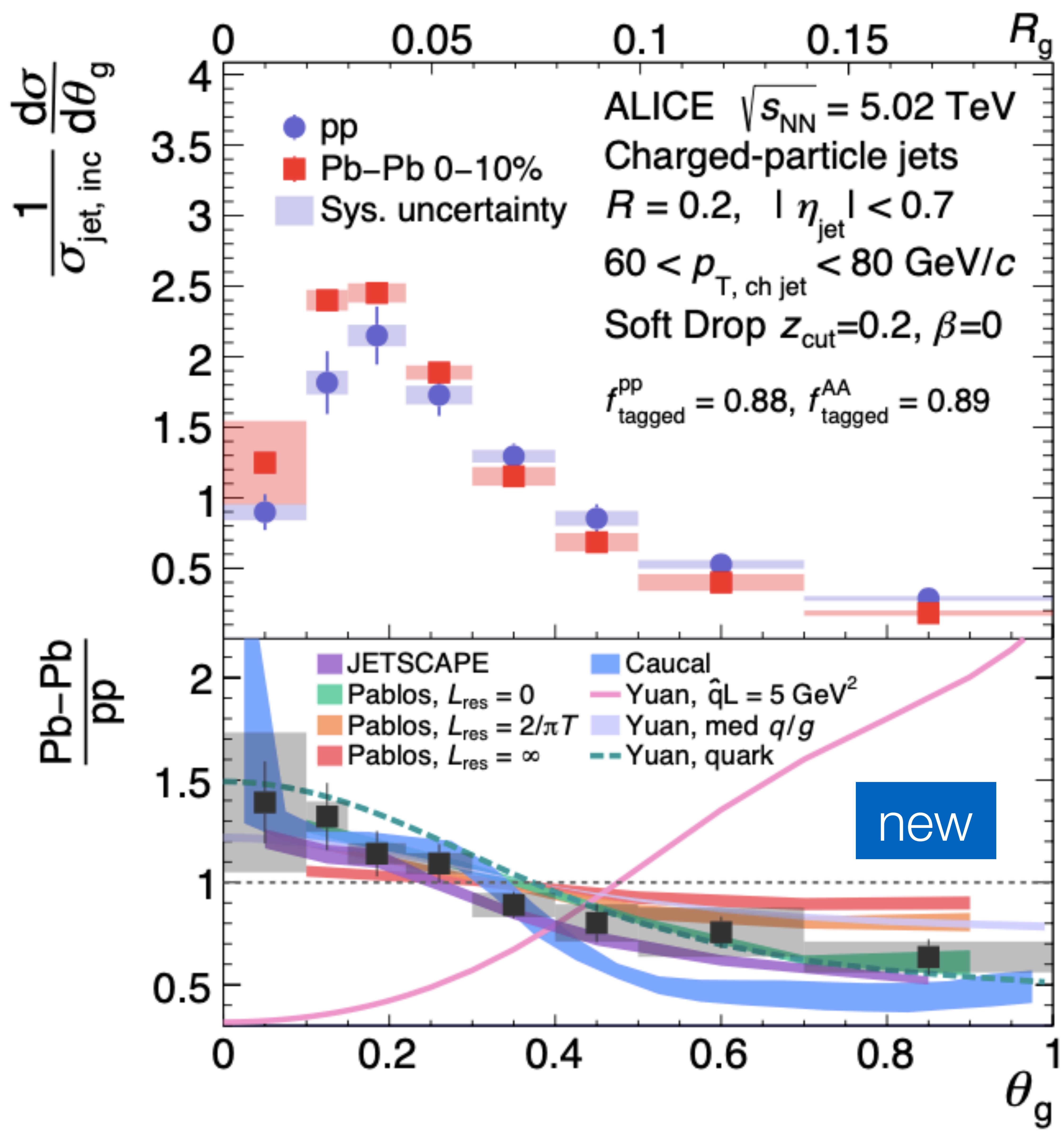
Points to B_s^0 production via coalescence

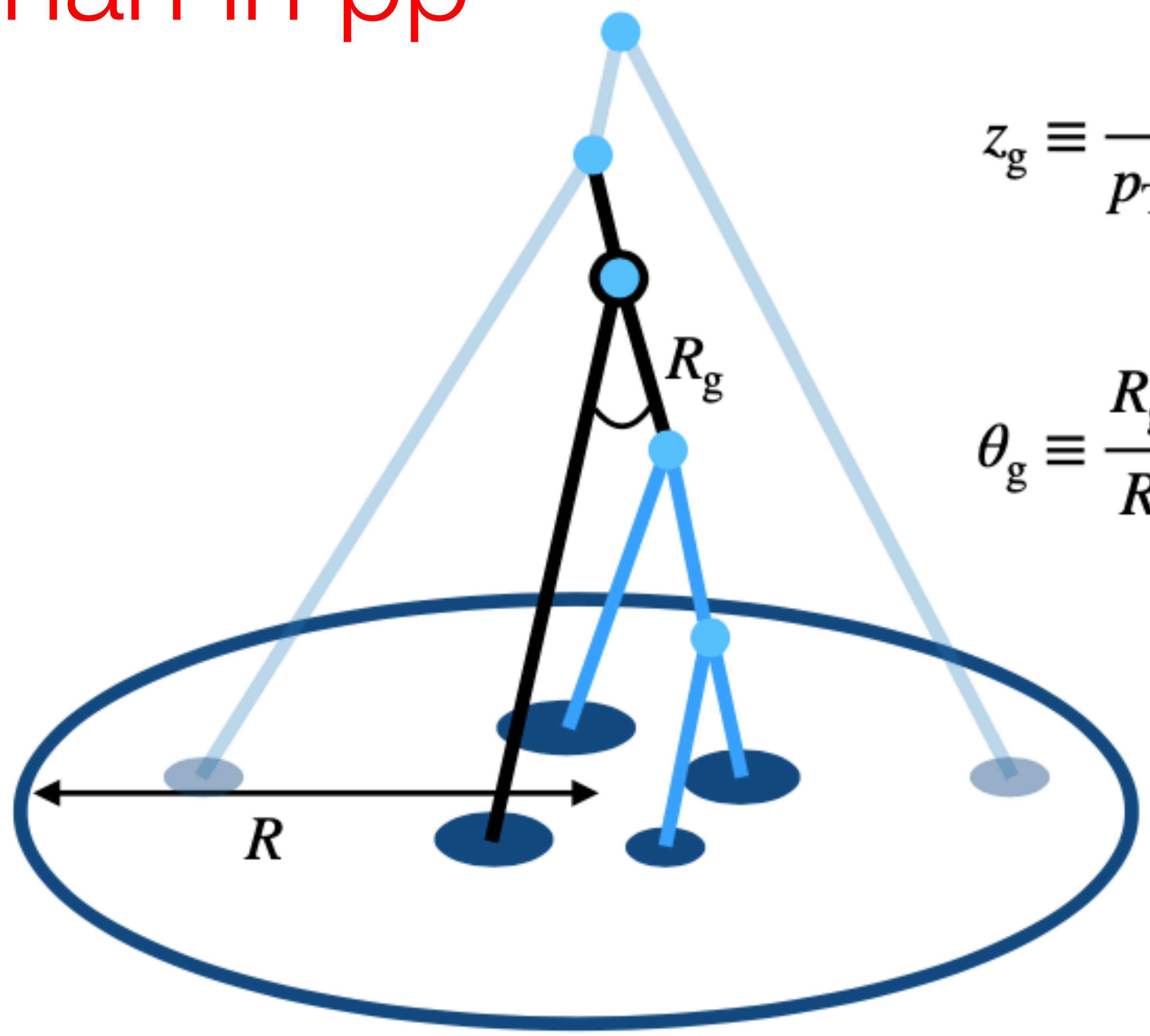


~50% of D_s^+ from B_s^0,
~50% from non-strange B

TAMU model, He, Fries, Rapp, PLB 735 (2014) 445

Groomed jet radius narrower in Pb-Pb than in pp





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

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

The cores of jets are narrower in Pb-Pb compared to pp collisions

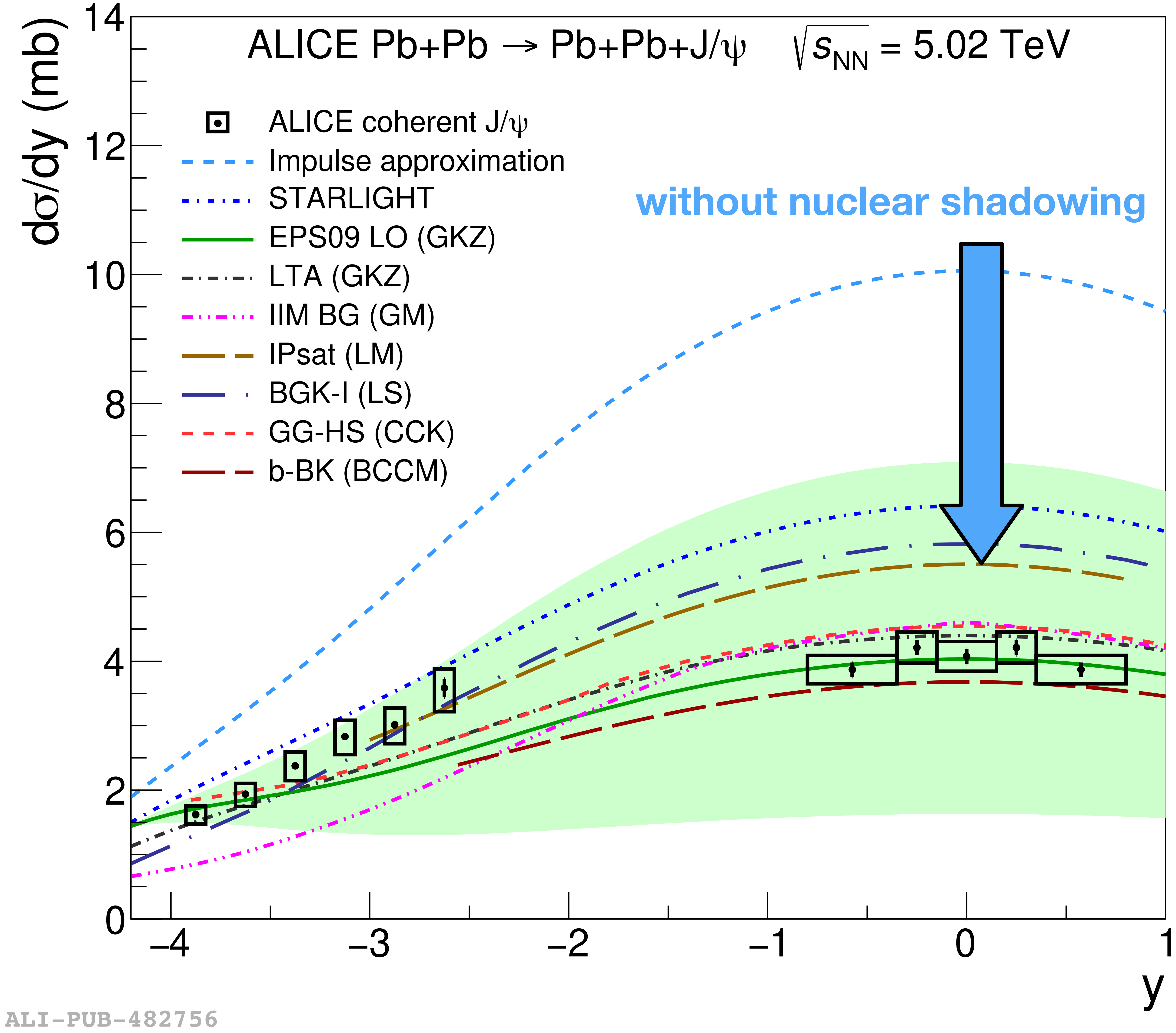
First direct experimental evidence for the modification of the angular scale of groomed jets in heavy-ion collisions

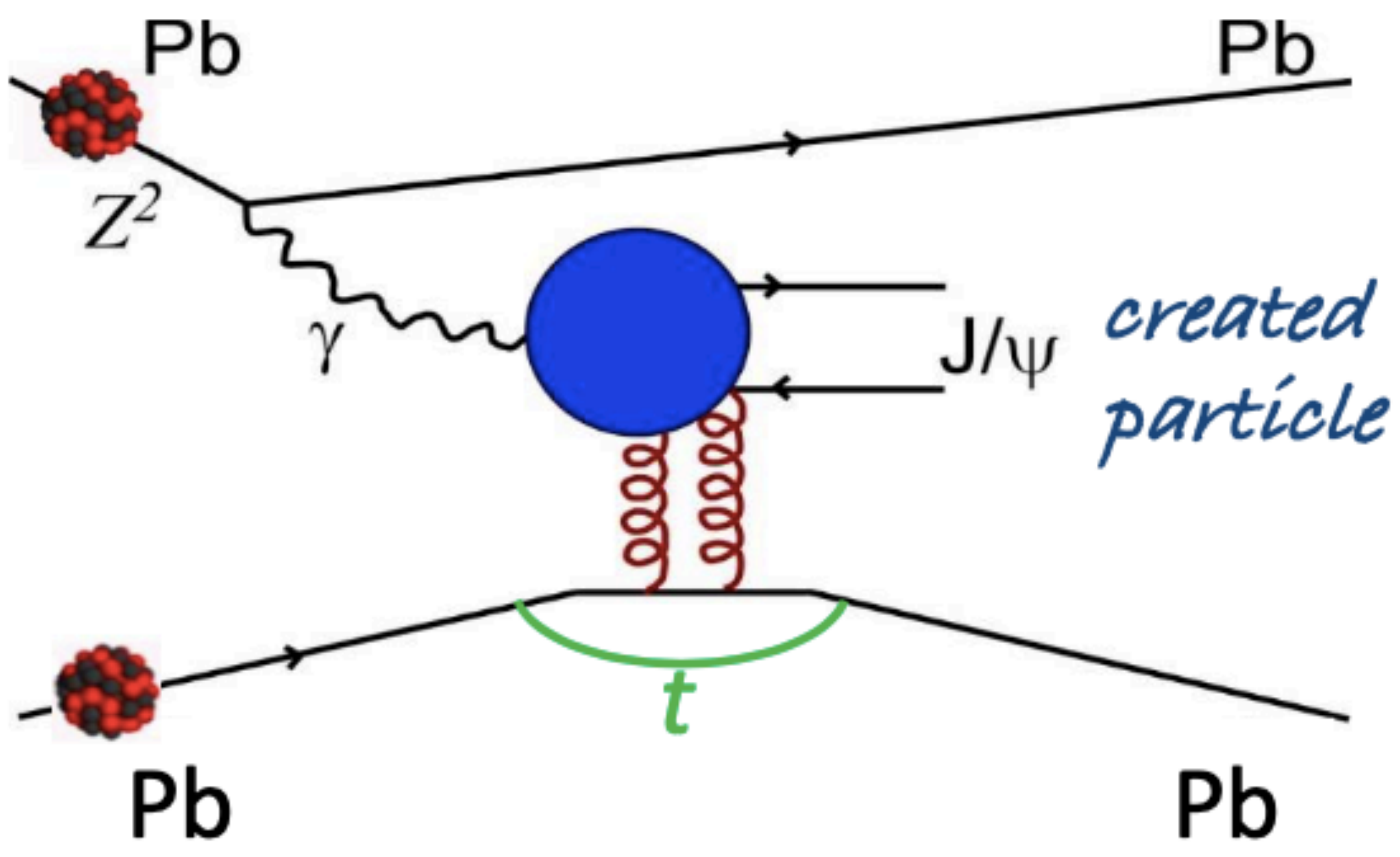
arXiv:2107.12984 talks James Mulligan, Laura Havener γ-Pb scattering in ultra-peripheral collisions

Gluon distribution at low *x*

talks Hermann Degenhardt, Kunal Garg, Yvonne Pachmayer

arXiv:2101.04577



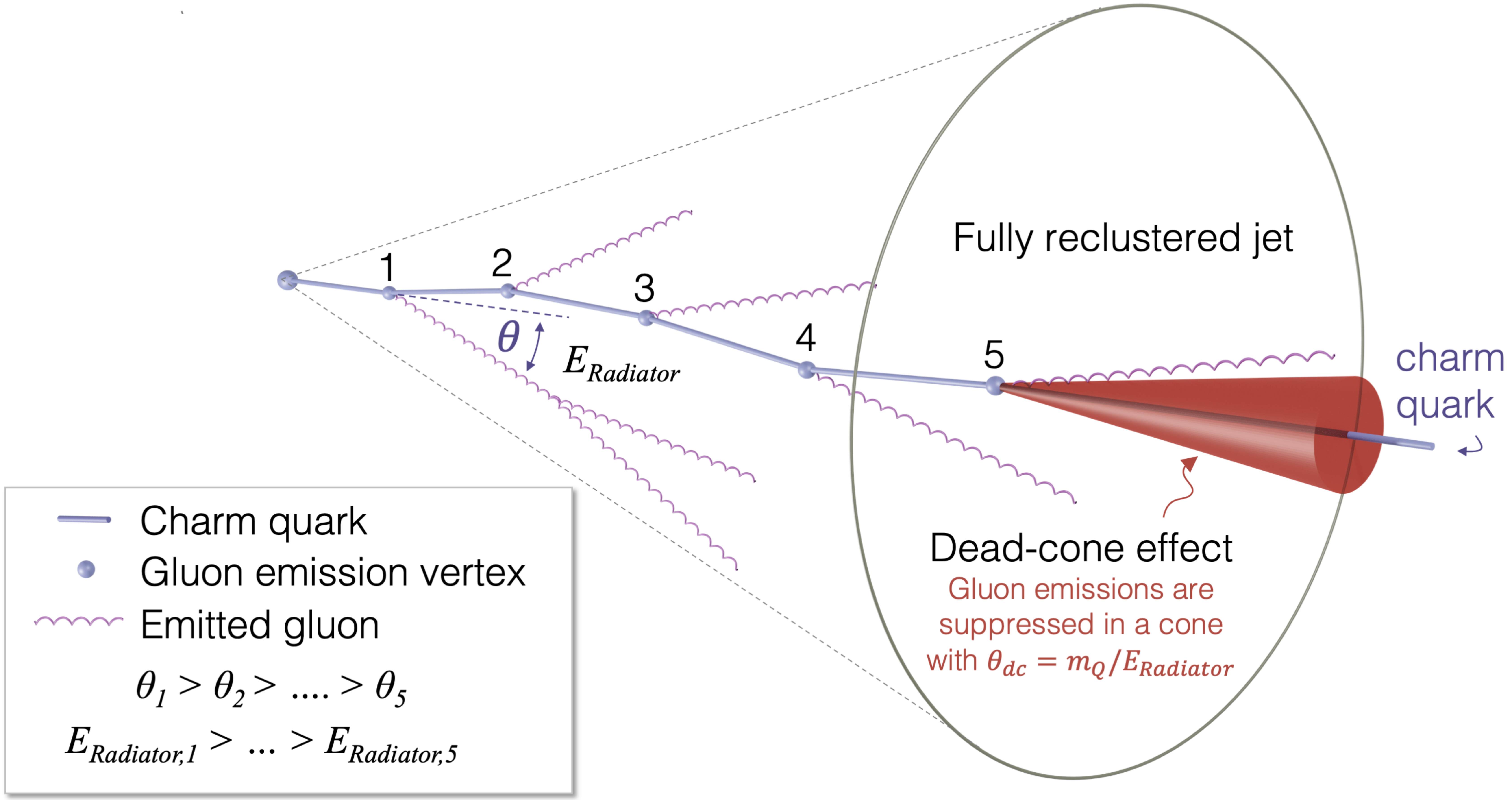


$$\left.\frac{d\sigma_{\gamma A \to J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$

Consistent with moderate gluon shadowing of 0.65 at $x \approx 6\times10^{-4}$

Physics highlights:
pp / p-Pb collisions

Gluon emission by a heavy quark



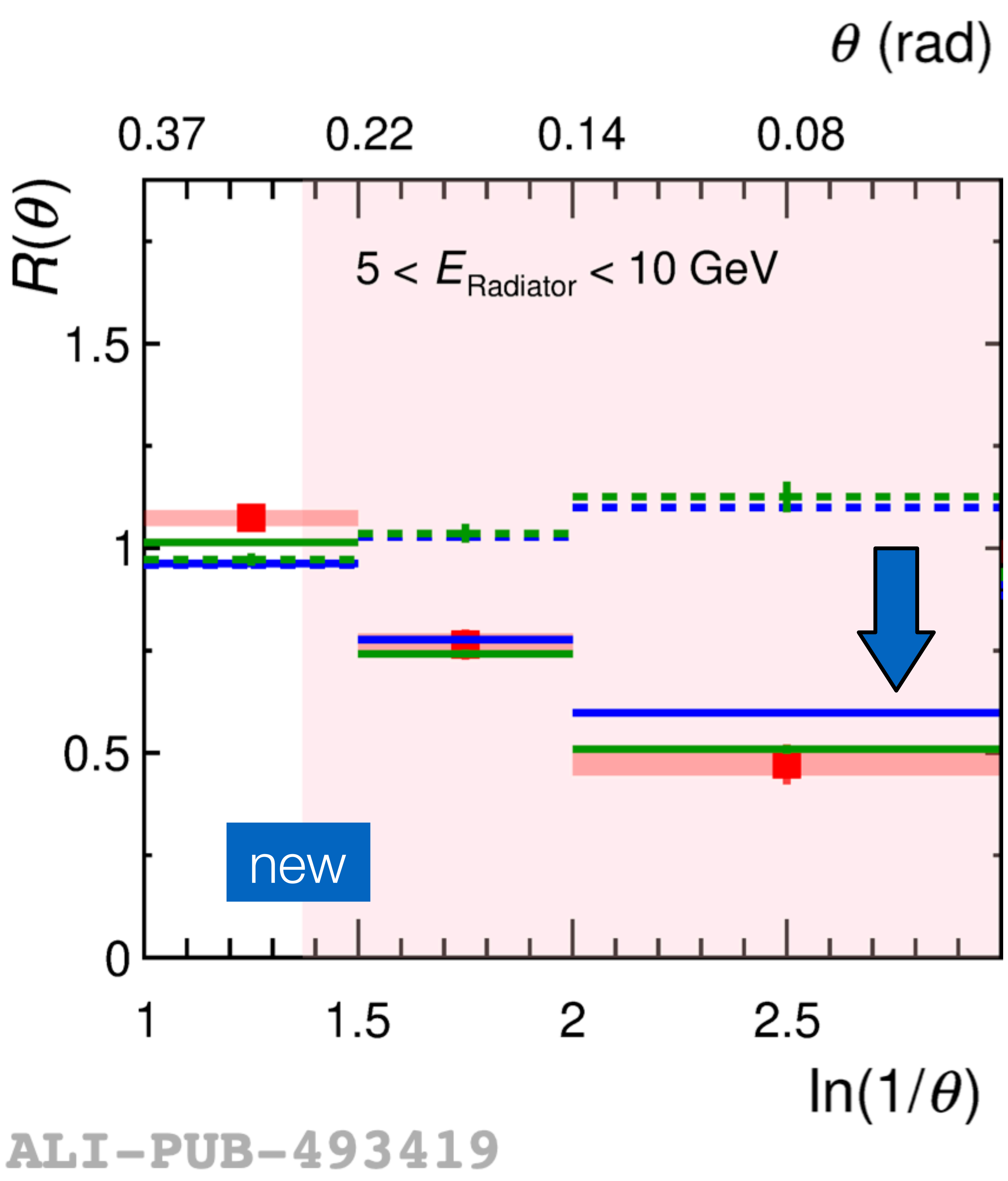
Dead-cone effect:
Gluon emission suppressed in a cone with $\theta_{dc} = m_Q / E_{radiator}$

A fundamental QCD feature (holds for all gauge quantum field theories)

Dokshitzer, Khoze, Troian, J. Phys. G17 (1991) 1602

arXiv:2106.05713 **new**

Significant suppression of small-angle splittings for small E_{charm}



$$R(\theta) = \frac{dn/d\ln 1/\theta|_{\text{D0 jets}}}{dn/d\ln 1/\theta|_{\text{incl.,jets}}} \qquad k_T > \Lambda_{\text{qcd}} = 200\,\text{MeV}/c$$

- ALICE Data
- PYTHIA 8
- SHERPA
- PYTHIA 8 LQ / inclusive no dead-cone limit
- SHERPA LQ / inclusive no dead-cone limit

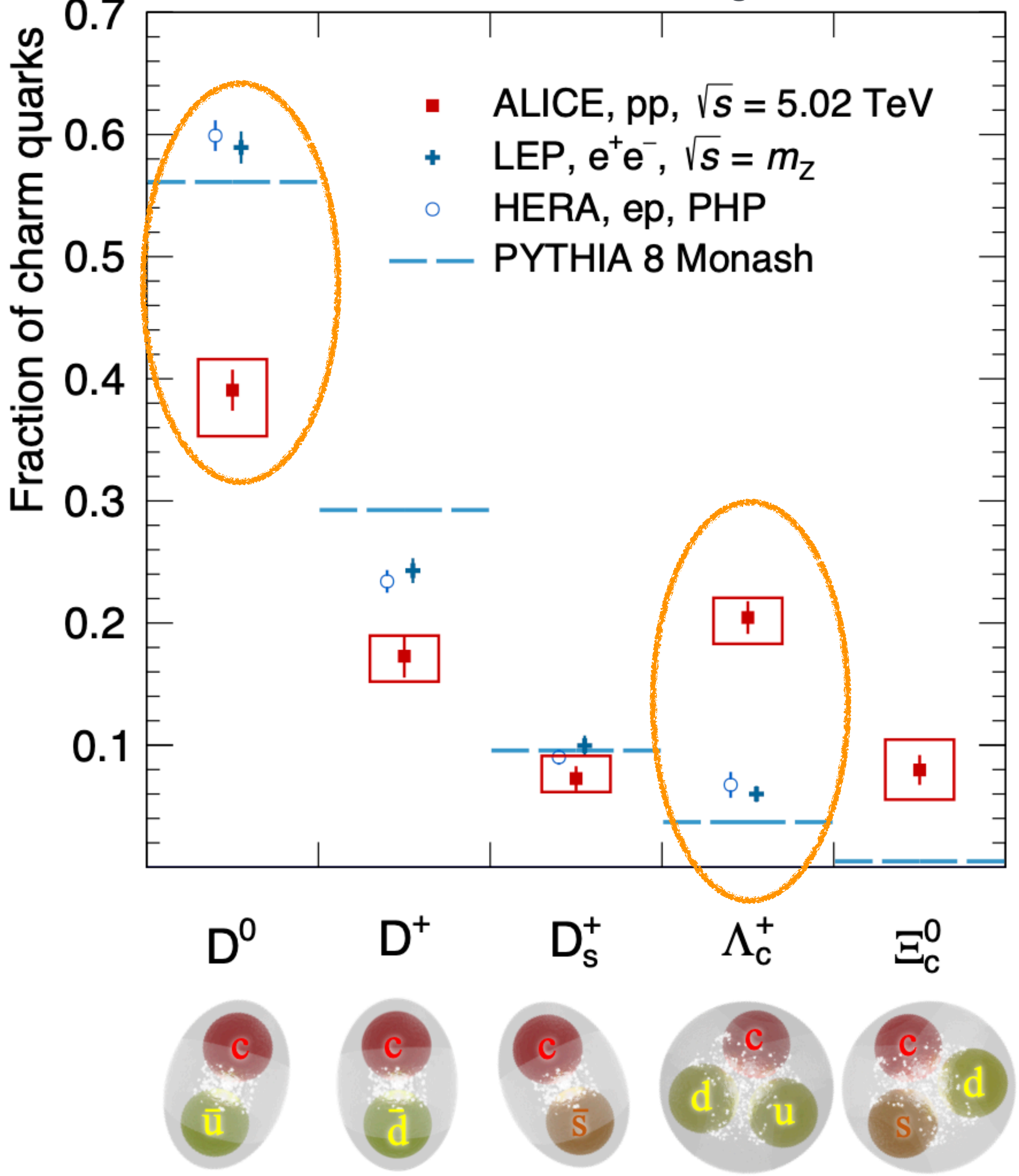
Dead-cone effect results in
$\Delta E_b < \Delta E_c < \Delta E_{u,d,s}$ in the QGP

arXiv:2106.05713 talk Vít Kučera

Charm hadronization in pp (1):

More charm quarks in baryons in pp than in e^+e^- and ep collisions

arXiv:2105.06335 talk Luigi Dello Stritto



Charm quarks hadronize into baryons 40% of the time

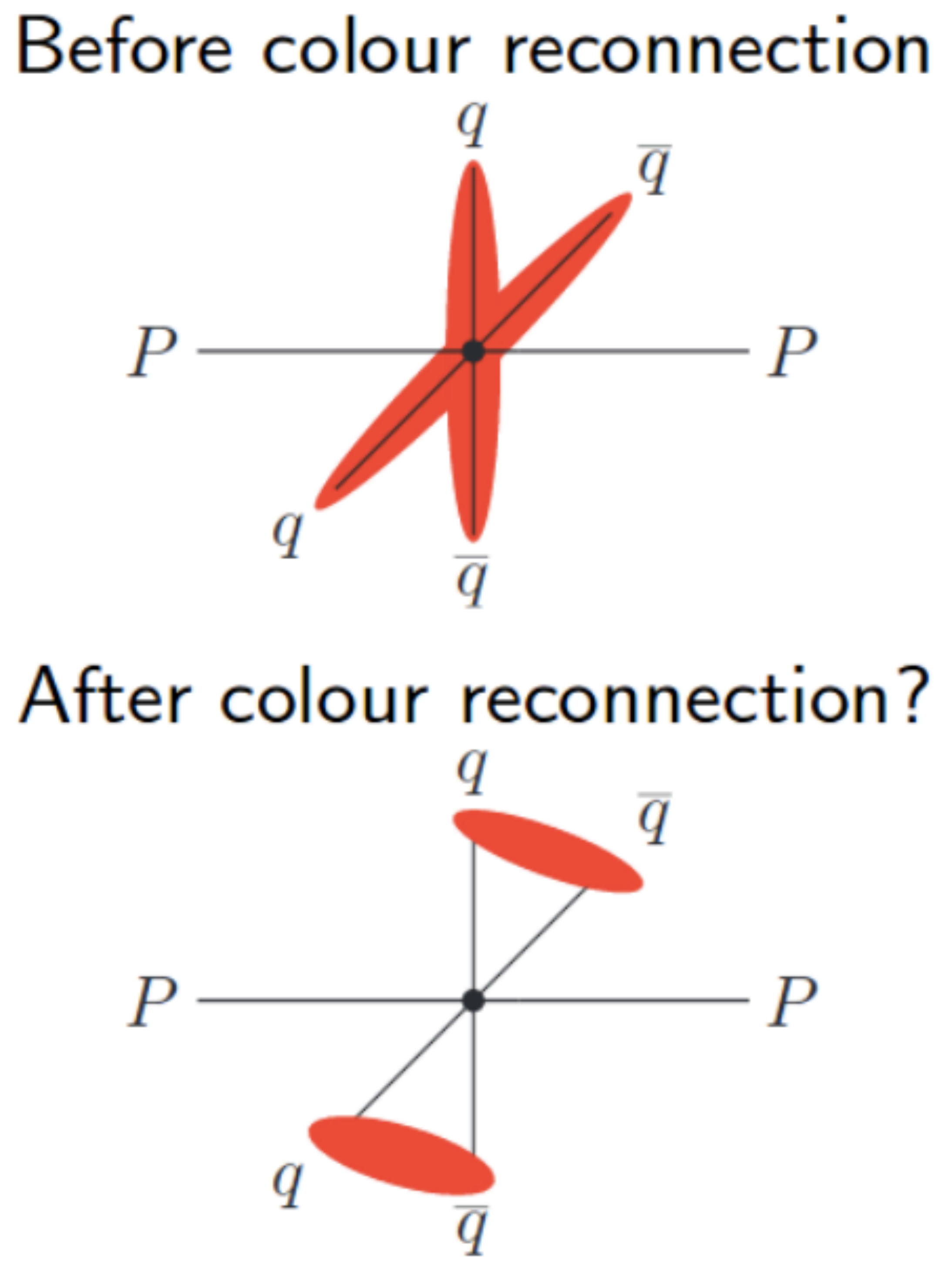
~ 4 times more than in e^+e^-

H_c	$f(c \to H_c)[\%]$
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$
Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$

Competing theoretical ideas

Color reconnections

String configuration that minimizes potential energy

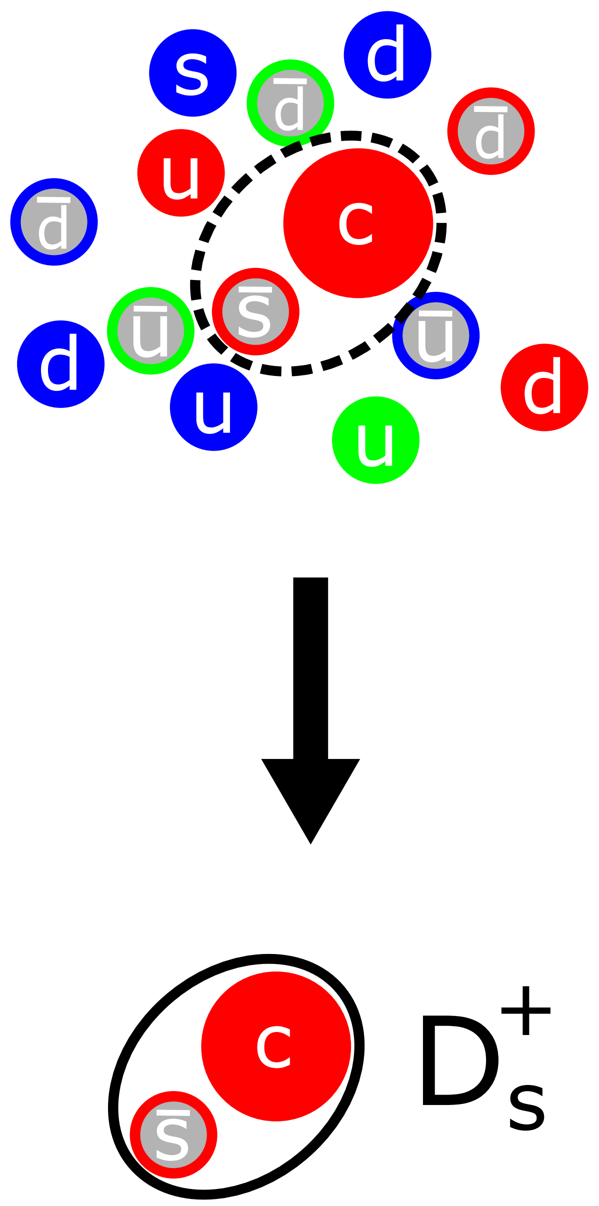


Christiansen, Skands, JHEP 1508 (2015) 003

Quark coalescence in phase space

Convolve quark distributions and hadron wave function

Assumes a high-density partonic system



Plumari et al., Eur.Phys.J.C 78 (2018) 348

SH model + RQM

Independent statistical hadronization + extra charm-baryon states predicted by rel. quark model (RQM)

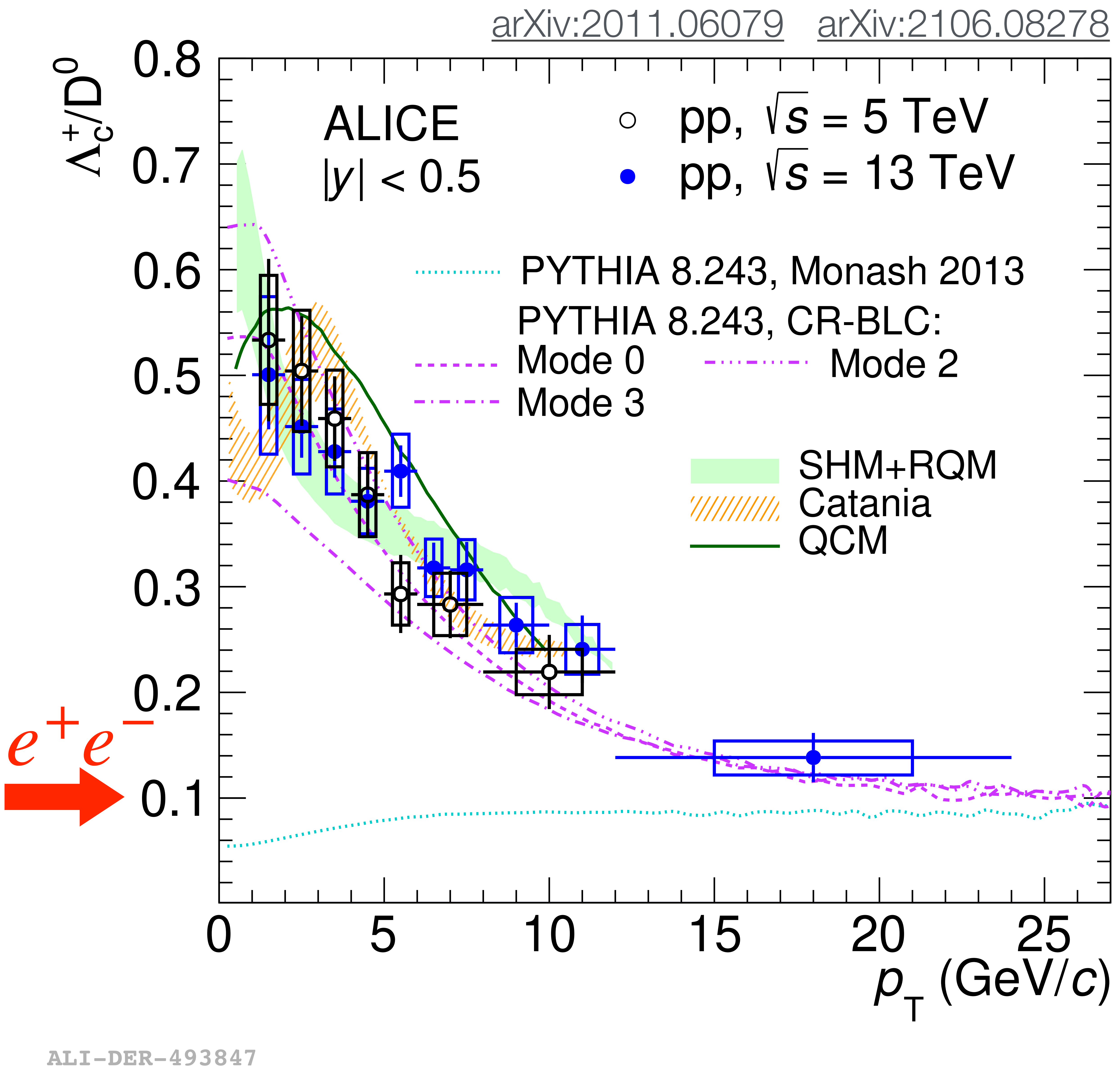
$I(J^P)$	Qd state	$Q = c$ M	$Q = c$ M^{exp} [1]	$Q = b$ M	$Q = b$ M^{exp} [1]
$\frac{1}{2}(\frac{1}{2}^+)$	1S	2476	$2470.88(^{34}_{80})$	5803	5790.5(2.7)
$\frac{1}{2}(\frac{1}{2}^+)$	2S	2959		6266	
$\frac{1}{2}(\frac{1}{2}^+)$	3S	3323		6601	
$\frac{1}{2}(\frac{1}{2}^+)$	4S	3632		6913	
$\frac{1}{2}(\frac{1}{2}^+)$	5S	3909		7165	
$\frac{1}{2}(\frac{1}{2}^+)$	6S	4166		7415	
$\frac{1}{2}(\frac{1}{2}^-)$	1P	2792	2791.8(3.3)	6120	
$\frac{1}{2}(\frac{1}{2}^-)$	2P	3179		6496	

⋮

(many states …)

He, Rapp, PLB 795 (2019) 117

Λ_c^+/D^0 ratio in pp significantly higher than in e^+e^-



$\Lambda_c^+ (udc) \to pK^-\pi^+$

$\to pK_s^0$

Measurement of charmed hadrons down to unprecedentedly low p_T at midrapidity

Charm quark fragmentation not universal!

Standard PYTHIA 8 below data

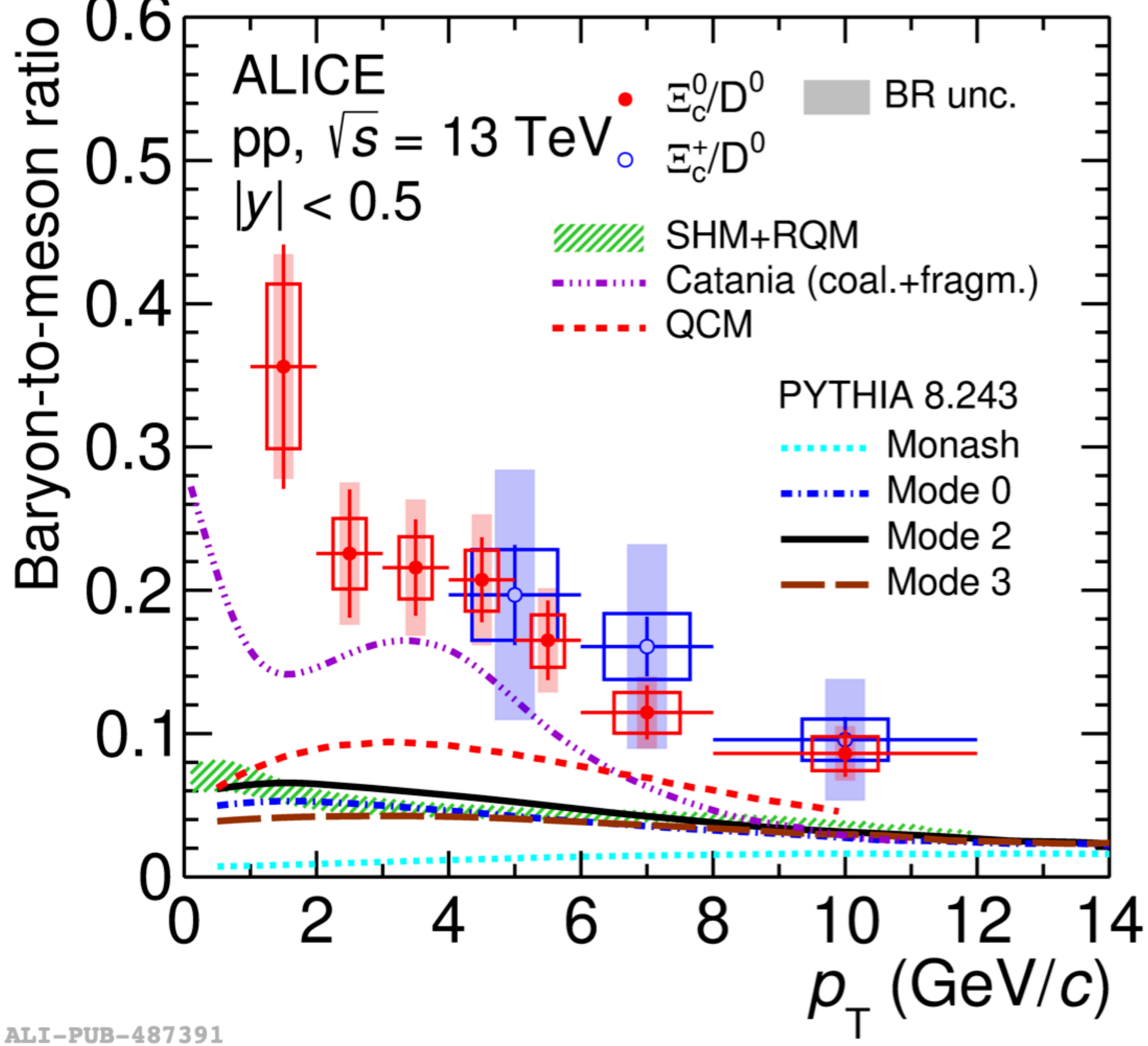
Fair description by

- PYTHIA 8 with CR
- Coalescence + fragmentation (Catania)
- SH mode + RQM
  (T = 170 MeV, additional states crucial)

Charm hadronization in pp (4):

Ξ_c^0/D^0 not described by models that get Λ_c^+/D^0 right!

arXiv:2105.05187 talk Luigi Dello Stritto



ALI-PUB-487391

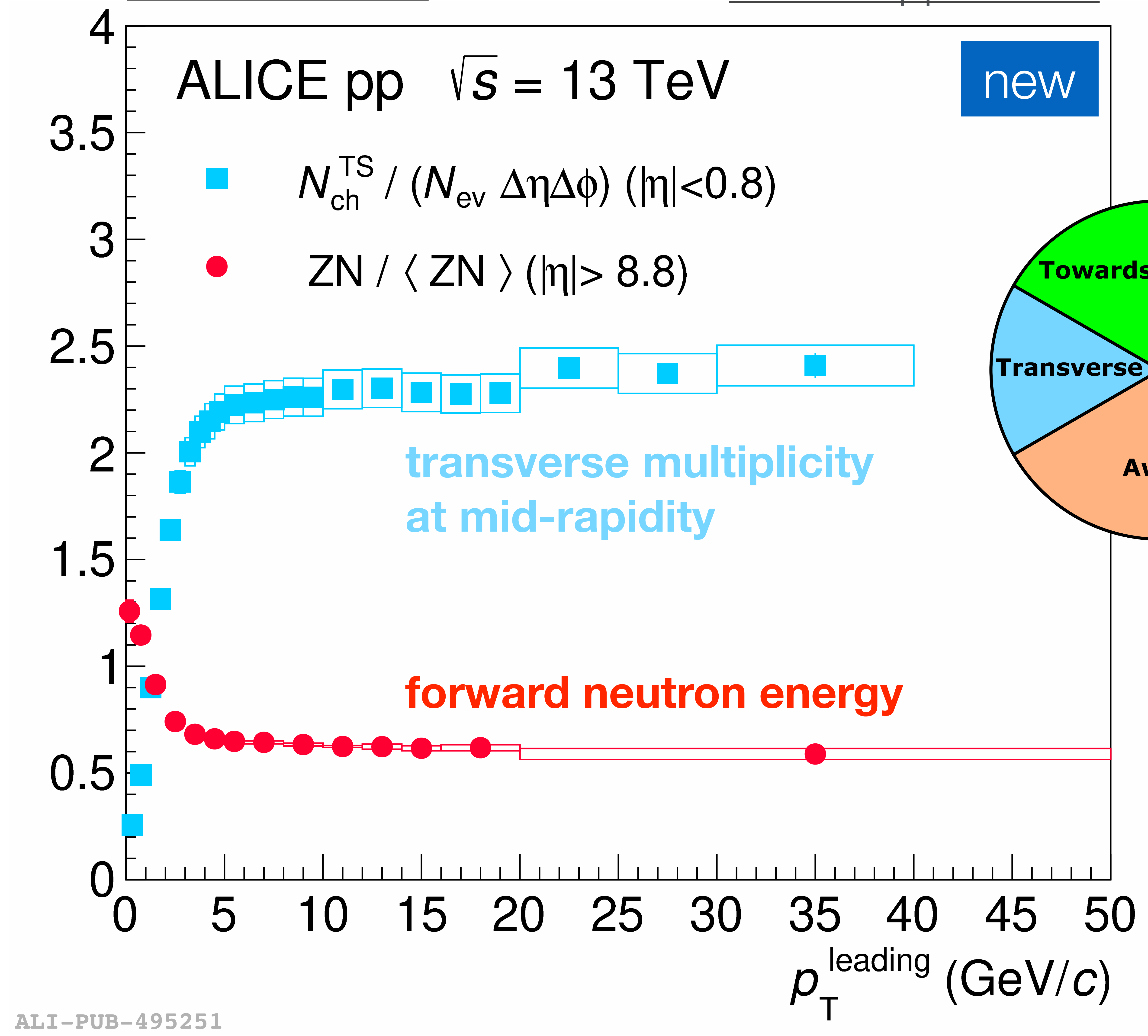
$$\Xi_c^0\,(dsc) \to \Xi^- e^+ \nu_e$$
$$\to \Xi^- \pi^+$$

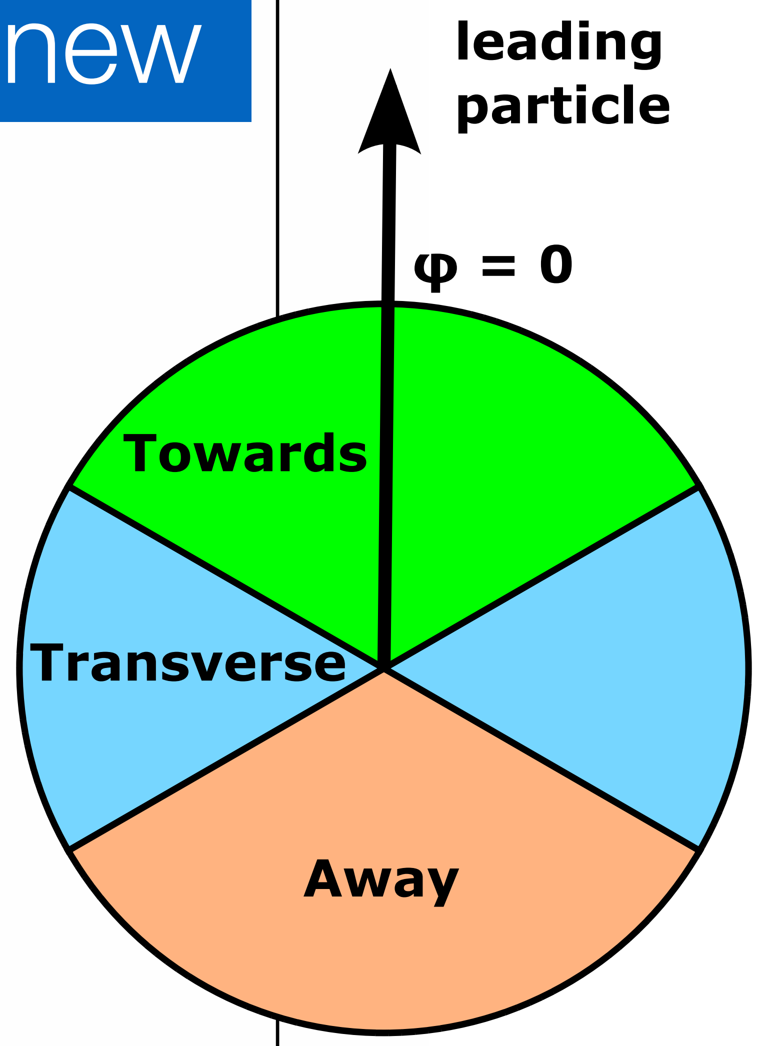
PYTHIA 8 with CR (mode 2) below data, even though this model describes Λ_c^+/D^0

Coalescence model comes closest to data

Small E_{ZDC} correlates with high $dN_{ch}/d\eta|_{\eta=0}$ and high p_T particle at $\eta = 0$

arXiv:2107.10757 talk Chiara Oppedisano





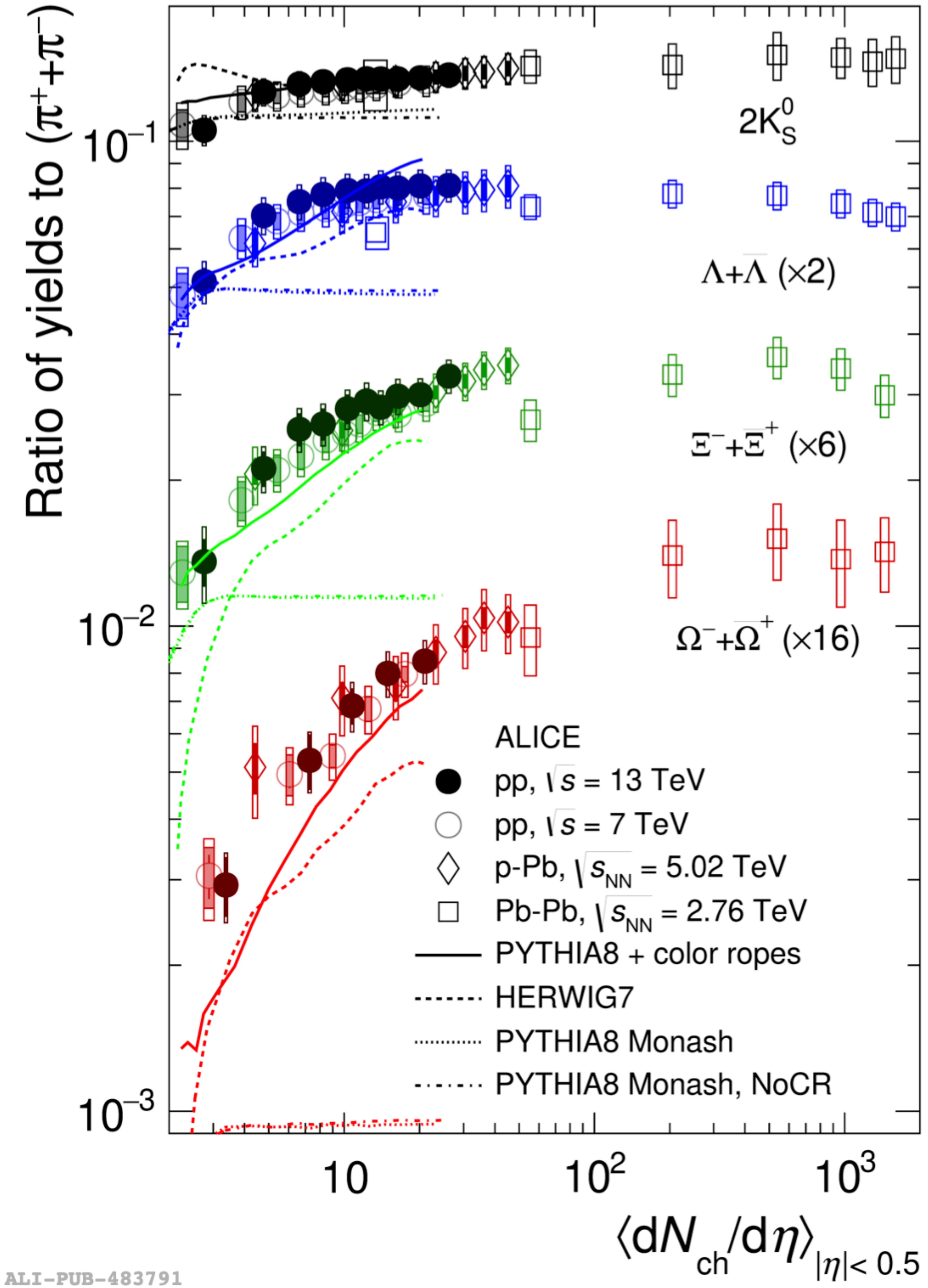
Explore concept of "centrality" in pp collisions

Zero degree calorimeters:
ZN ($|\eta|$ > 8.8) for neutrons
ZP (6.5 < η < 7.4) for protons

Observation 1:
Forward proton and neutron energy **anticorrelated** with $dN_{ch}/d\eta|_{\eta=0}$

Observation 2:
Transverse multiplicity at η = 0 and forward neutron energy both saturate for $p_T^{leading} > 5\,\mathrm{GeV}/c$

Nature Physics 13 (2017) 535-539



ALI-PUB-483791

Strangeness enhancement in pp (1)

Setting the stage

(Multiple-strange) baryon yields increase faster with $dN_{ch}/d\eta$ than pions

Not reproduced by PYTHIA 8 Monash tune

Modified strings?

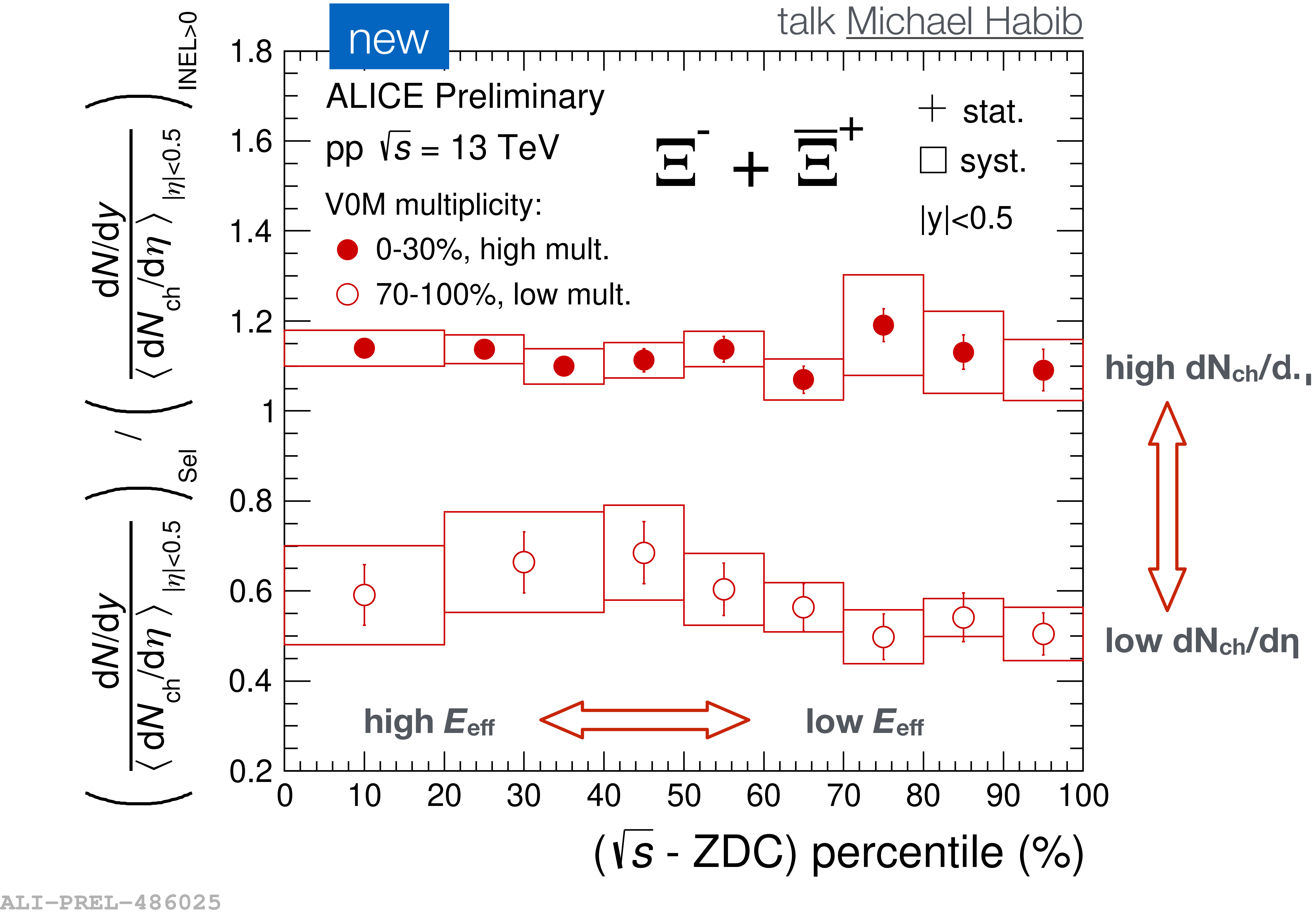
(PYTHIA 8 + ropes, string tension, color reconnection)

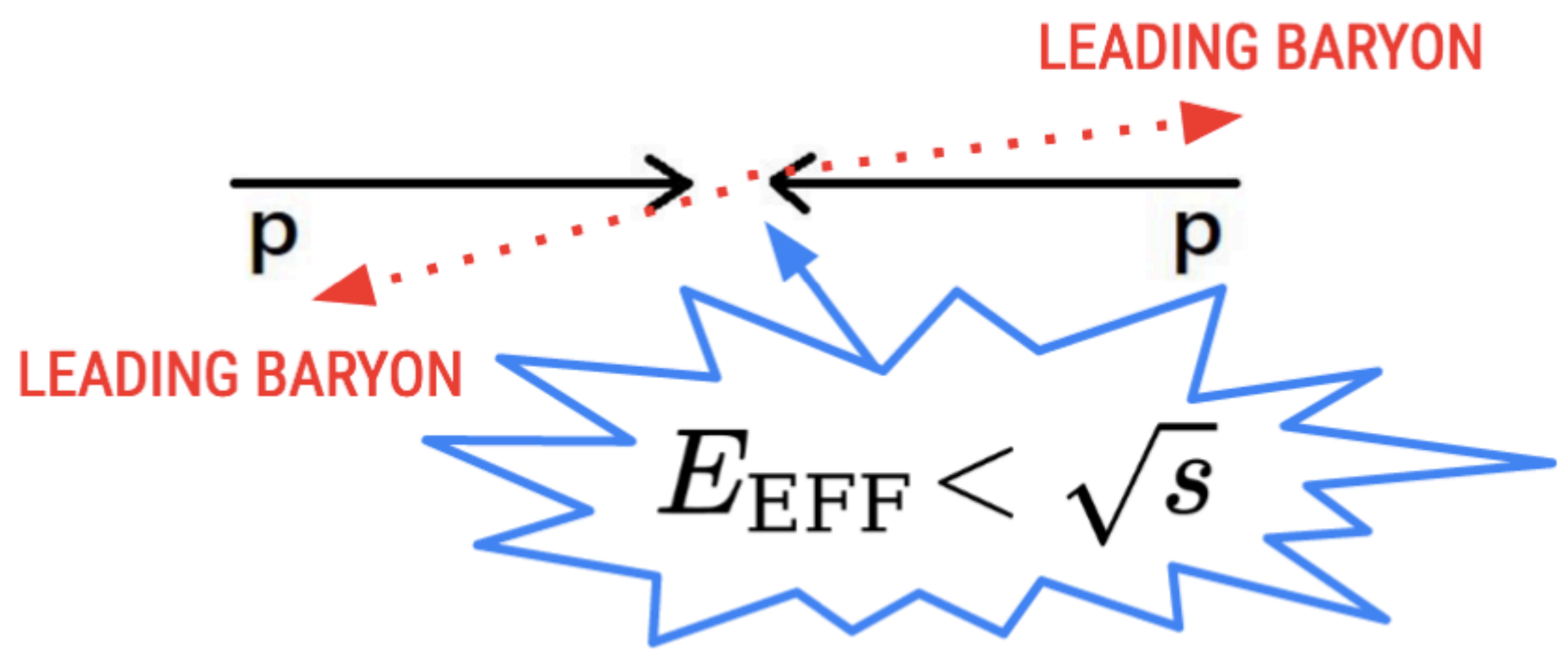
“Canonical strangeness suppression” in thermal models

(Grand-canonical description only correct for large enough volumes)

Or a sign of QGP formation in pp collisions?

Enhancement driven by final-state multiplicity, not by effective energy





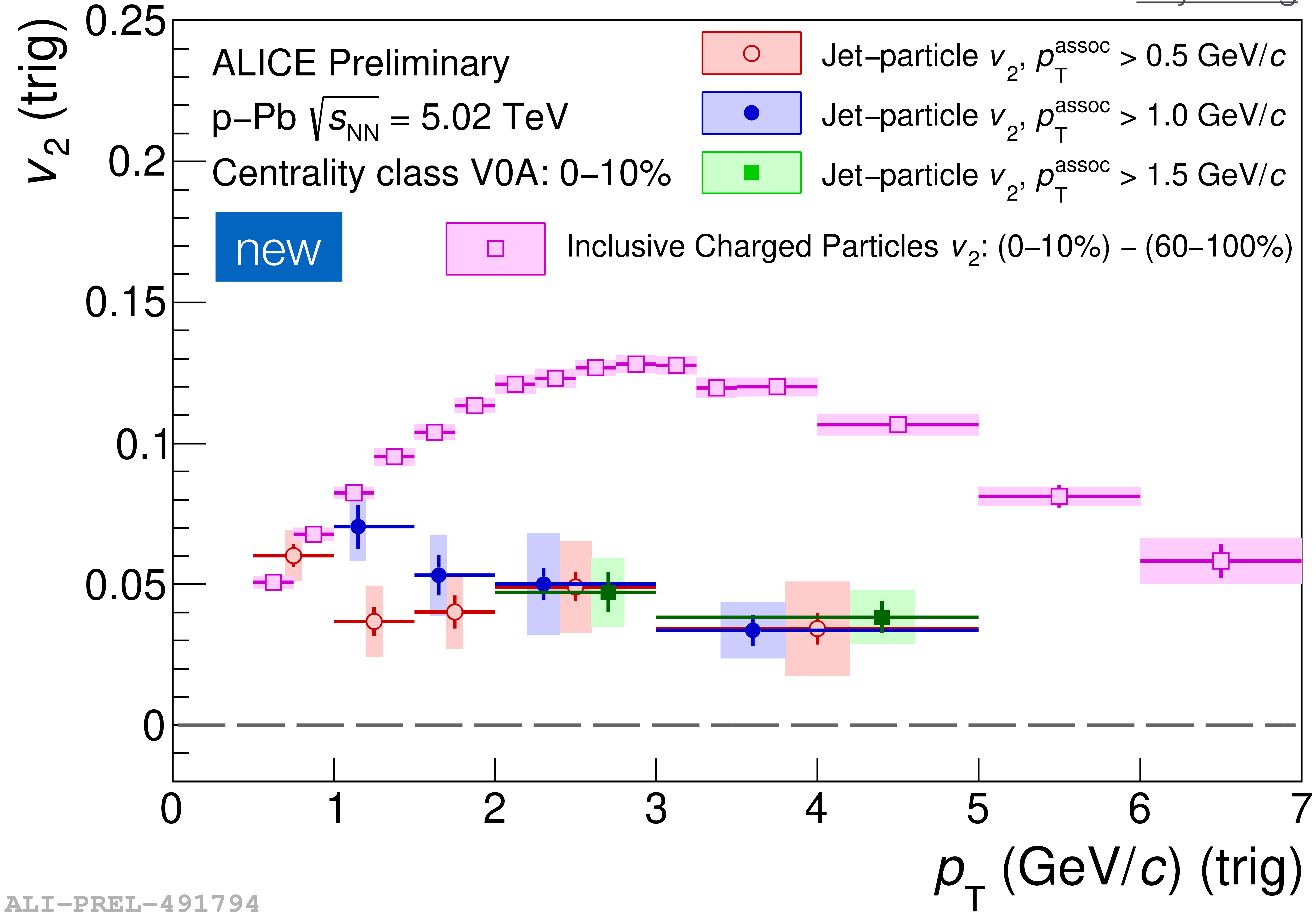
$$E_{\mathrm{eff}} = \sqrt{s} - (E_{\mathrm{leading1}} + E_{\mathrm{leading2}})$$

from energy in zero degree calorimeters

v_2 of soft jet particles in p-Pb

Non-zero v_2 could indicate parton energy loss in p-Pb

talk Siyu Tang

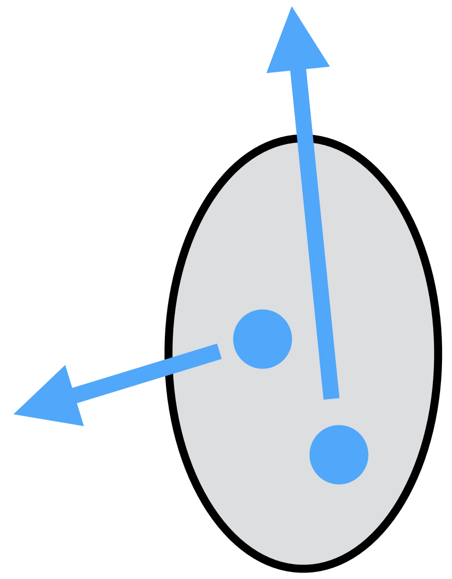


Azimuthal anisotropy

$$\frac{dN}{d\phi} \sim (1 + 2v_2 \cos(\phi - \phi_{ref}))$$

A-A at high p_T:

$v_2 > 0 \longleftrightarrow$ jet quenching ($R_{AA} < 1$)



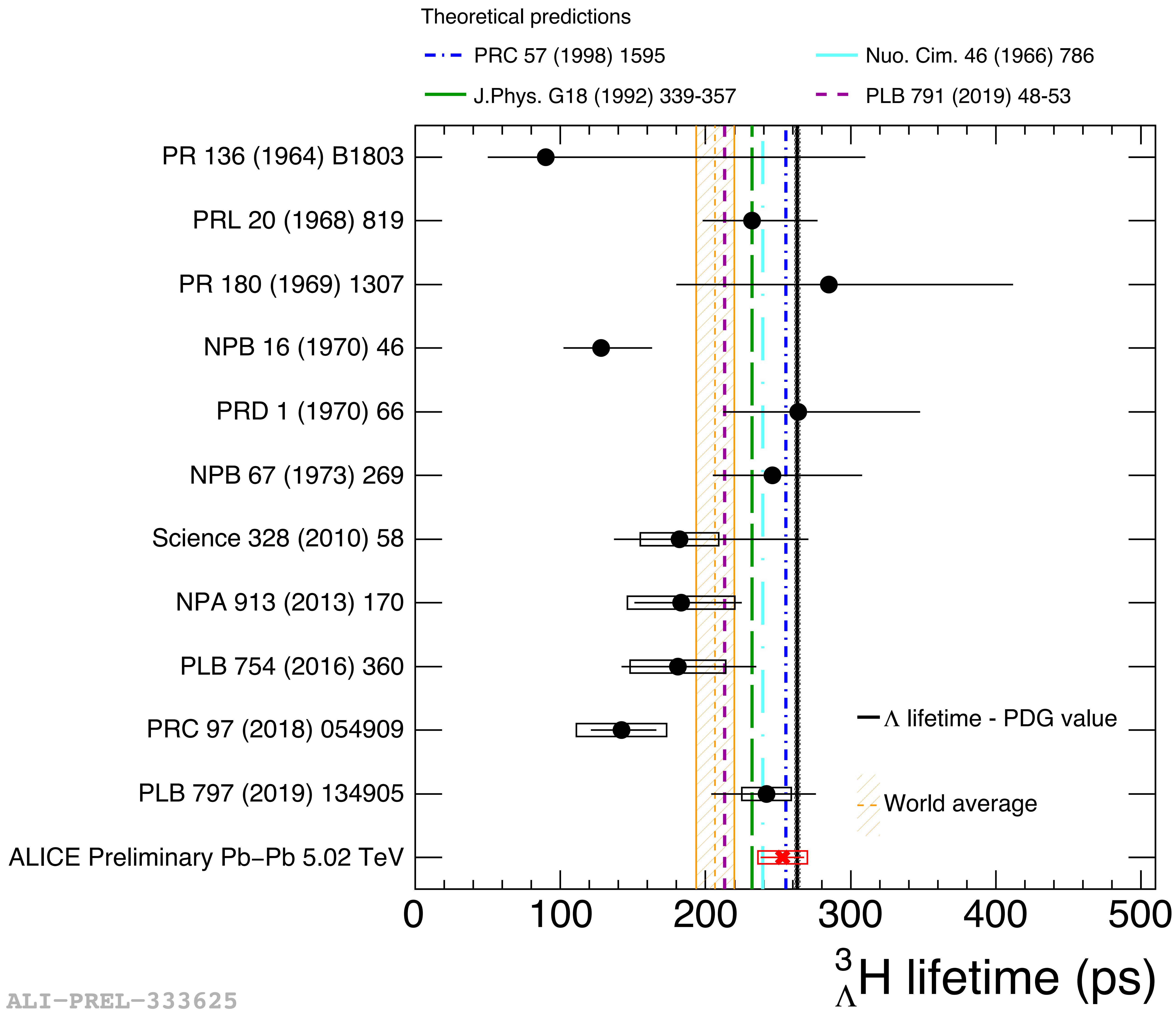
p-Pb at high p_T:

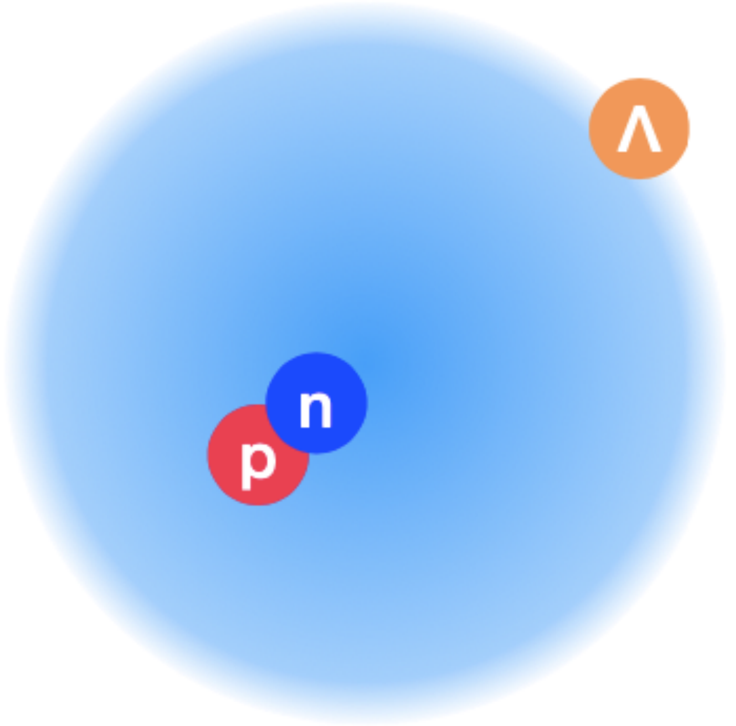
$v_2 > 0 \longleftrightarrow$ jet quenching? (but $R_{AA} \approx 1$!)

Higher sensitivity to parton E loss in p-Pb by studying soft jet particles

Physics highlights:
the LHC as a versatile particle source

Hypertriton properties





Mass: $m \approx 2.991$ GeV/c^2

Large RMS radius: about 10.3 fm

Molecular structure: (p + n) + Λ

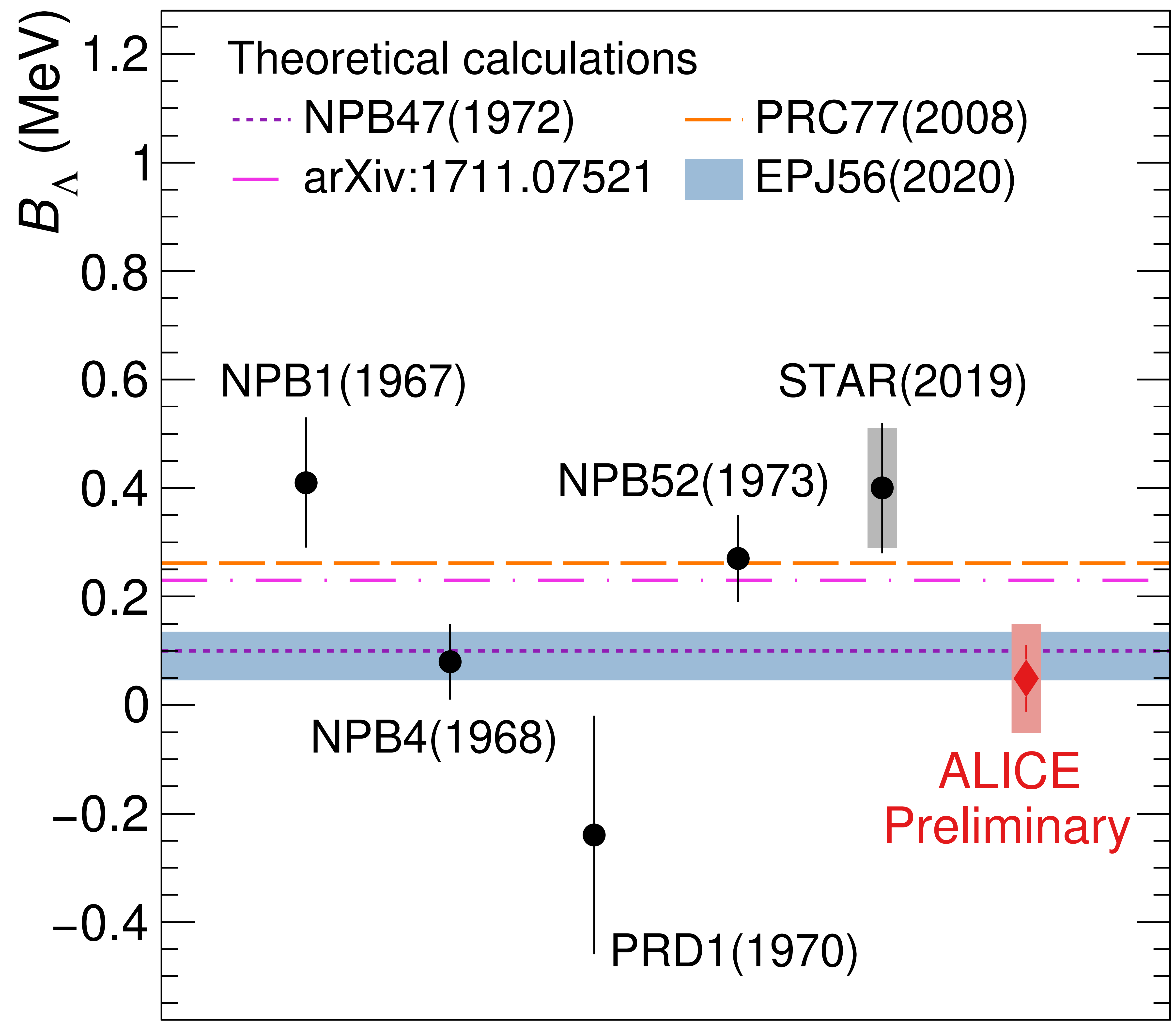
Quantum mechanical formation time: about 100 fm/c

$^{3}_{\Lambda}\mathrm{H}$ lifetime:
ALICE result consistent with free Λ lifetime

Very interesting to study hypertriton production in different systems (pp, p-Pb, Pb-Pb)

Precision measurement of Λ separation energy B_Λ

talk Janik Ditzel



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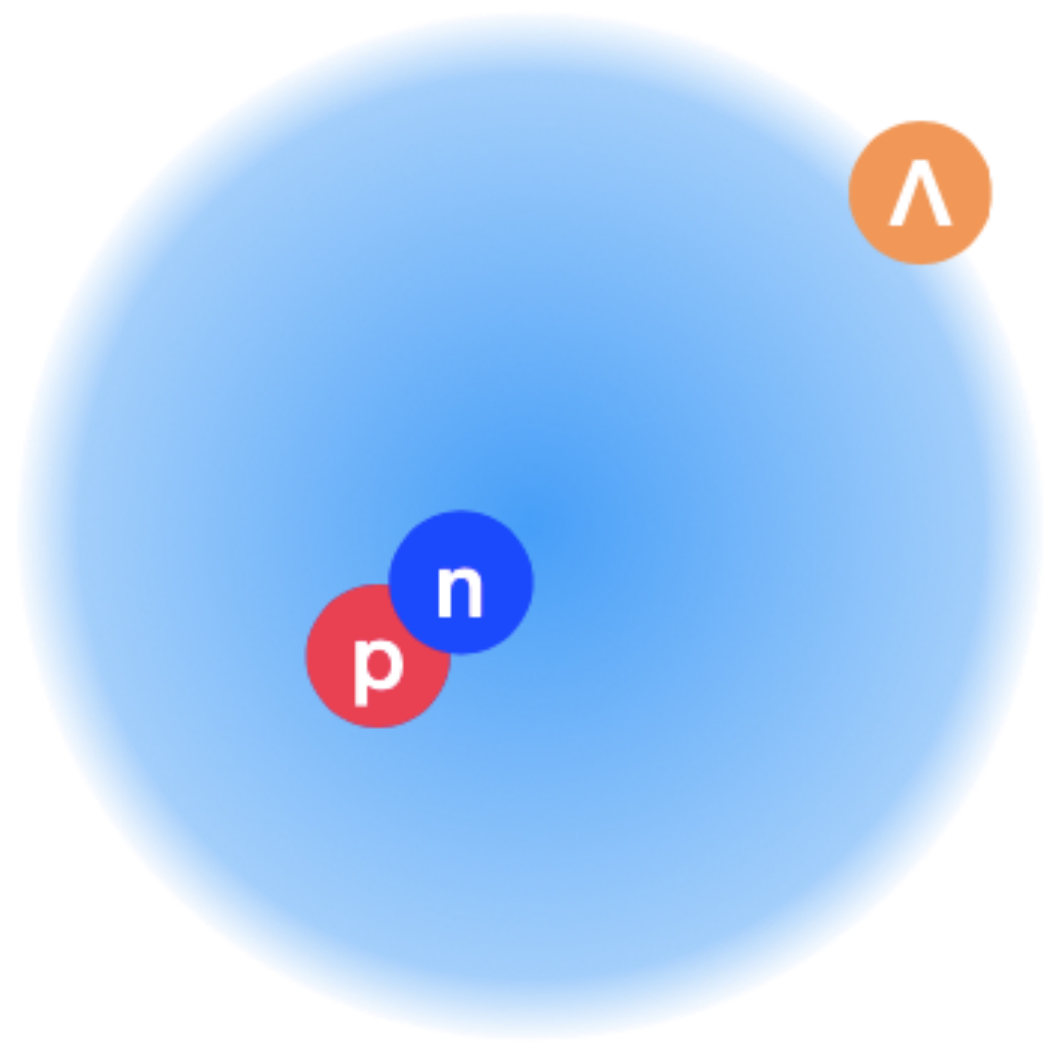
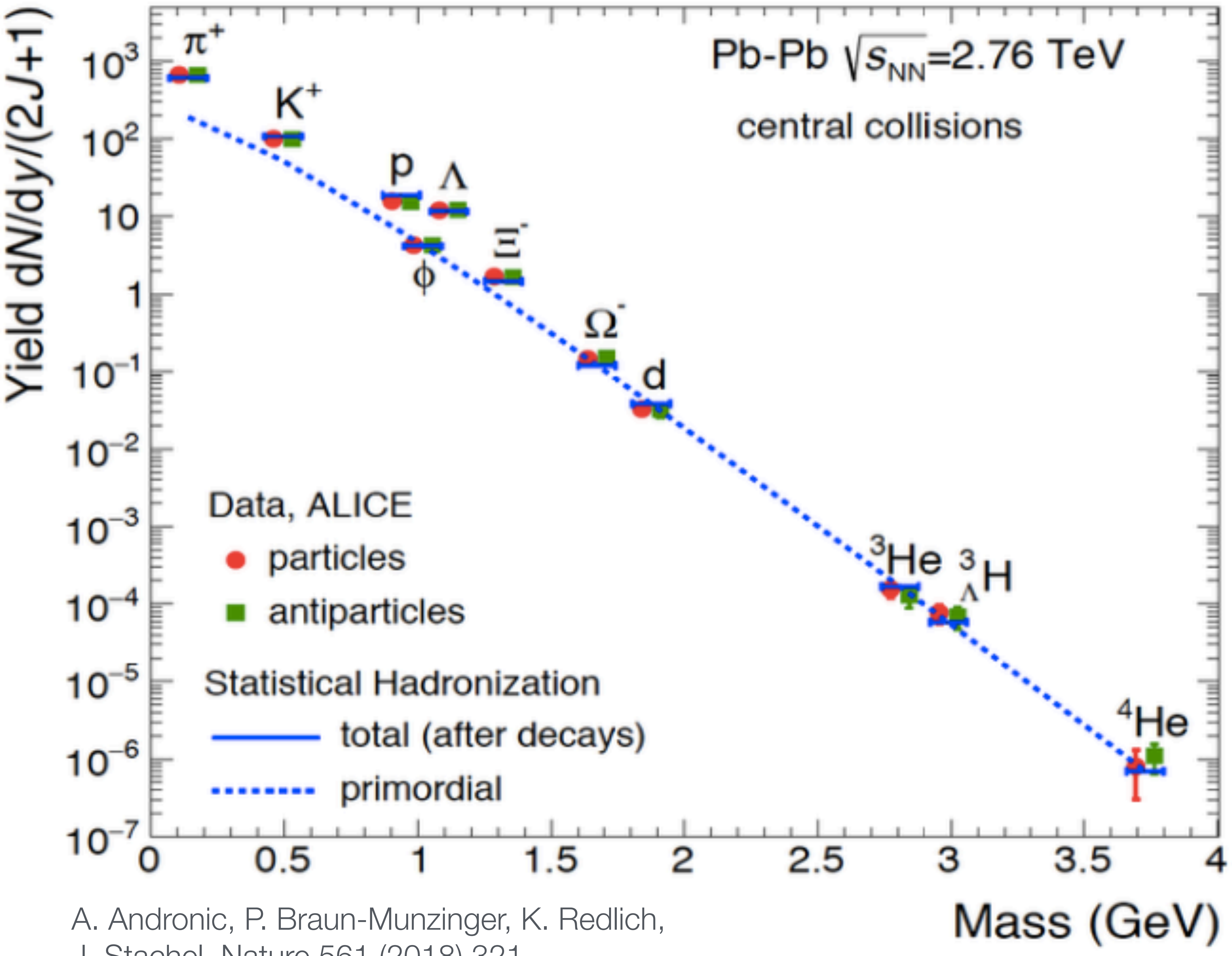


$${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$$

Precise measurement of B_Λ and lifetime sheds light on hypertriton structure

Λ separation energy:
Supports loosely bound nature of the hypertriton

Interlude: Statistical hadronization model (SHM)



A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) 321

Statistical hadronization model:

$$n_i = N_i/V = \frac{g_i}{2\pi} \int_0^\infty \frac{p^2\,dp}{\exp\left((E_i - \mu_i)/T\right) \pm 1}$$

Measured yields described with

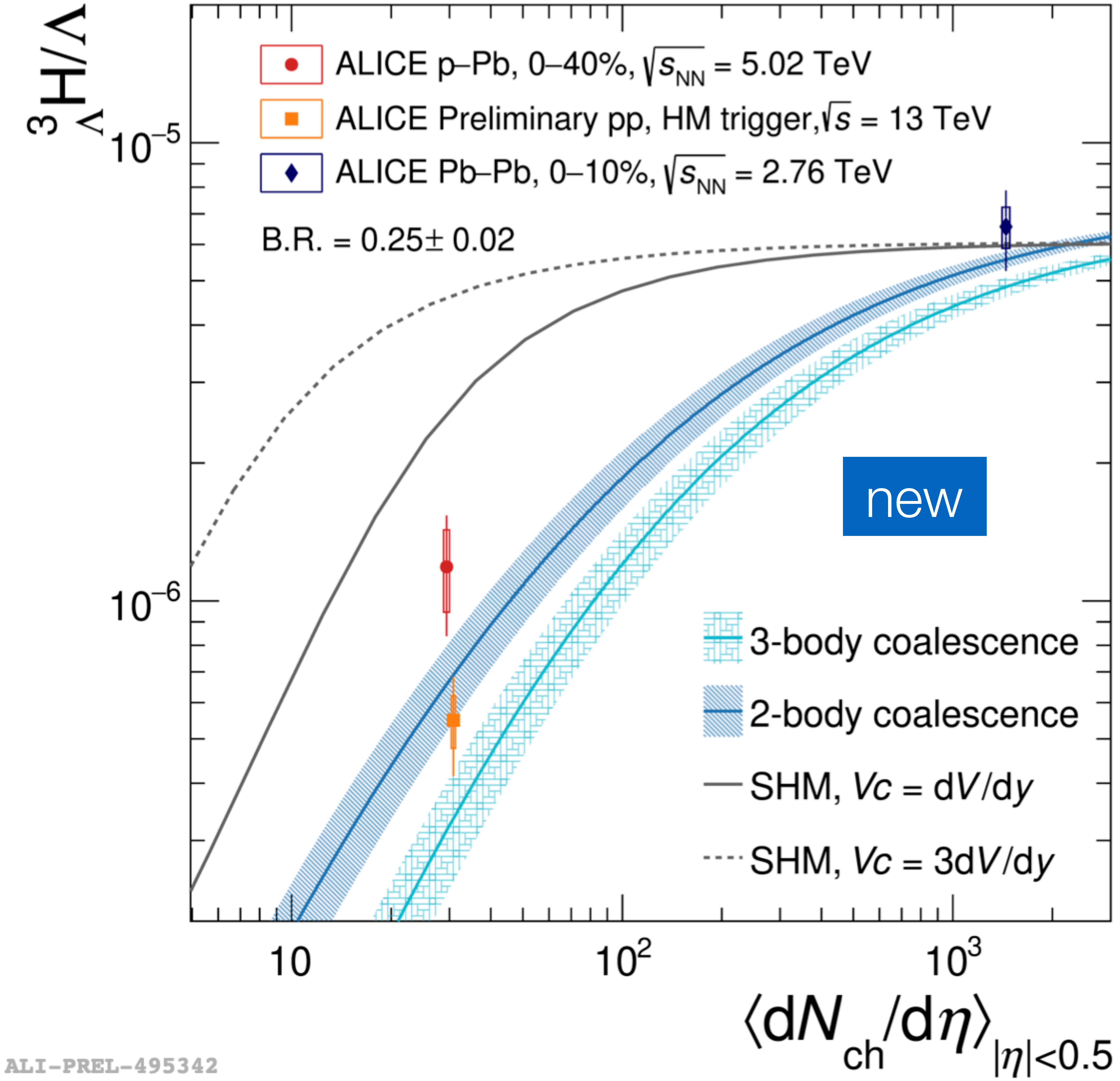
$$T = (156 \pm 2)\,\text{MeV}, \quad \mu_i \approx 0$$

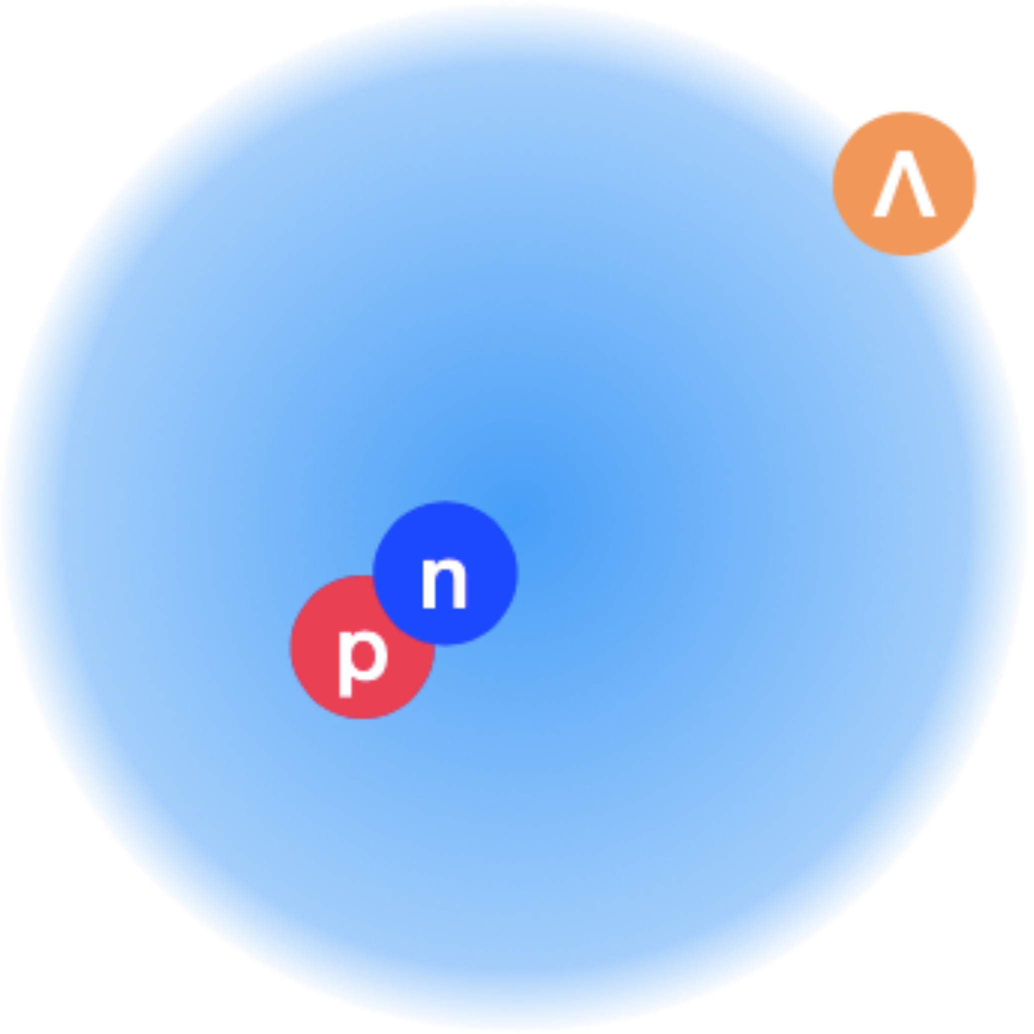
A surprise: production yields of loosely bound objects and strongly bound objects simultaneously described in the statistical hadronization approach

d, $^3_\Lambda$He: "snowballs that survive in hell"

${}^{3}_{\Lambda}H/\Lambda$ yield ratio consistent with formation through coalescence

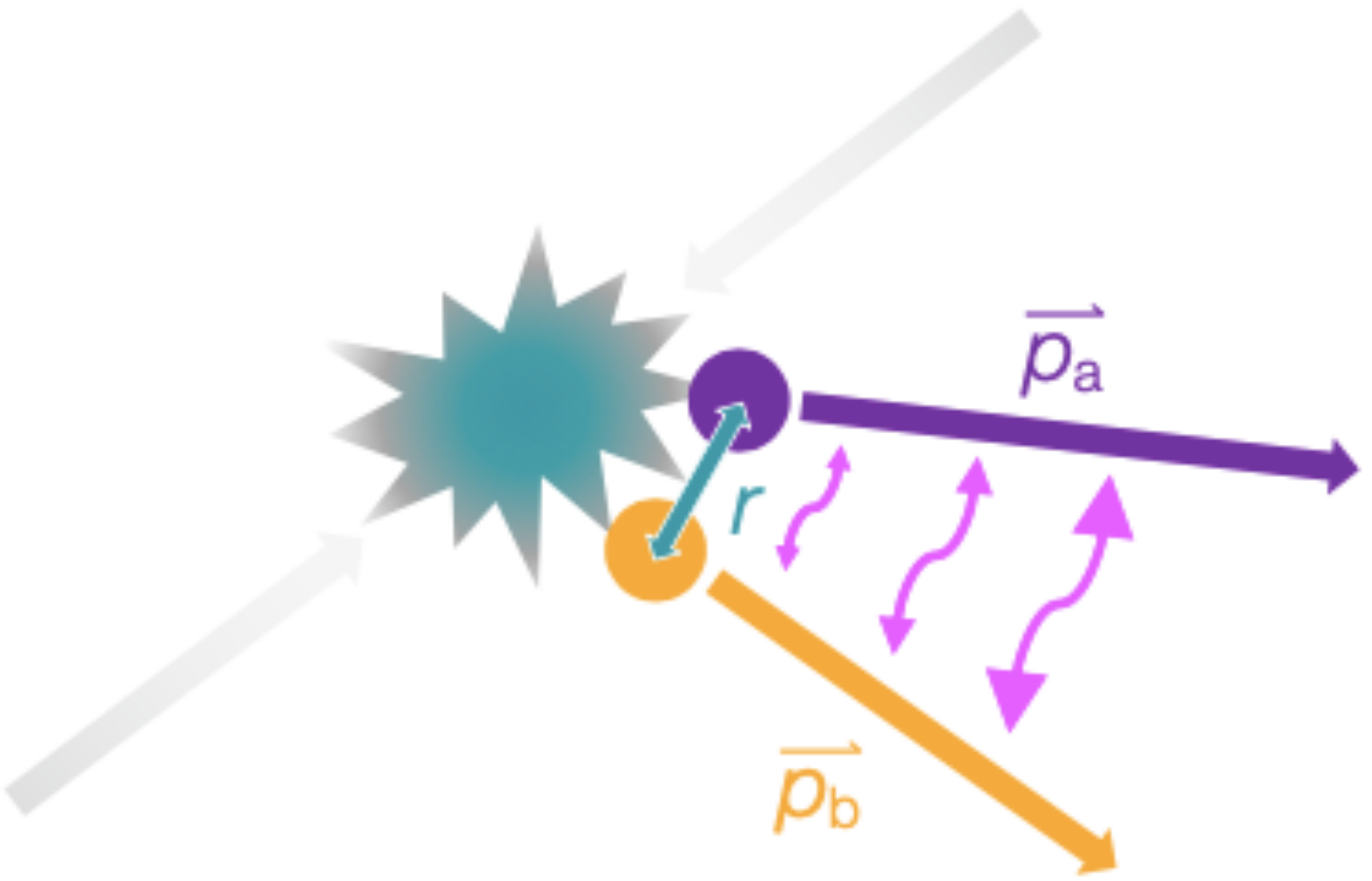
arXiv:2107.10627 talk Janik Ditzel





Formation mechanism provides insight into hypertriton structure
(in addition to lifetime and Λ separation energy)

Correlation function sensitive to interaction potential



1. **Fix source geometry**
2. **Measure correlation fct. C(k^*)**

→ study the strong interaction

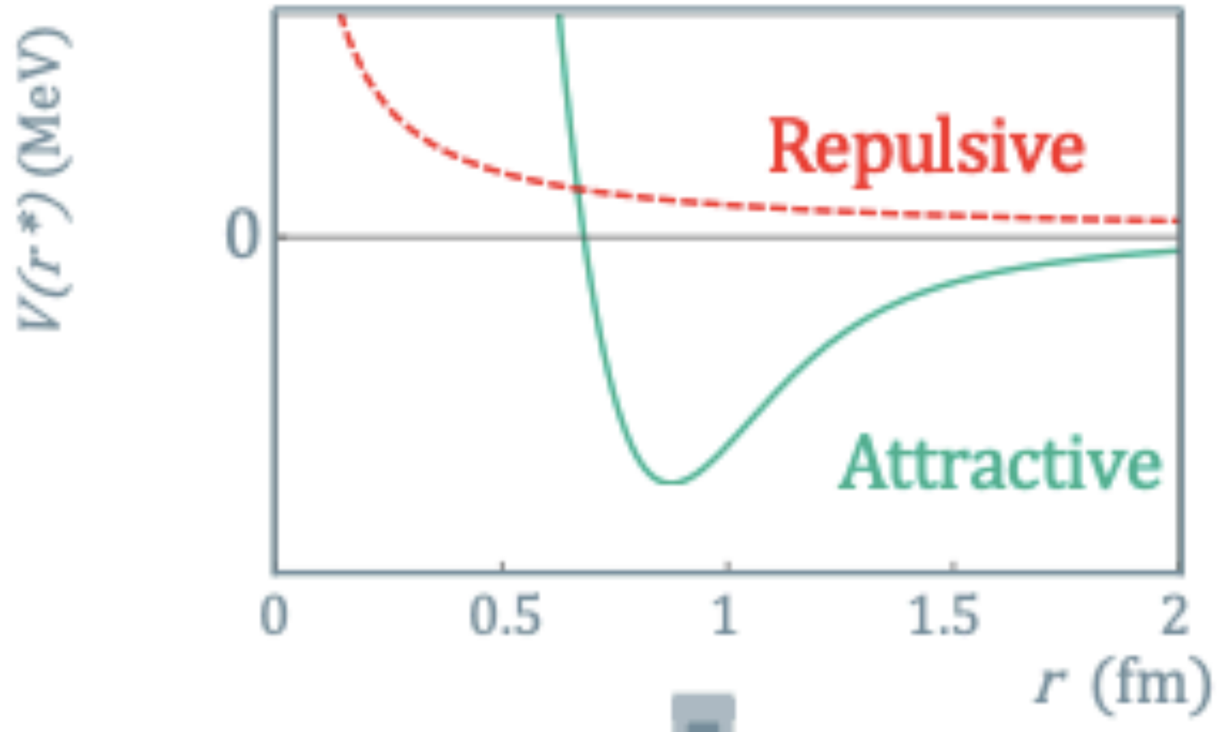
$$C(k^*) = \int S(r)\, |\psi(\vec{k}^*, \vec{r})|^2\, d^3r$$

Emission source   Two-particle wave function

Source parametrisation

Gaussian source

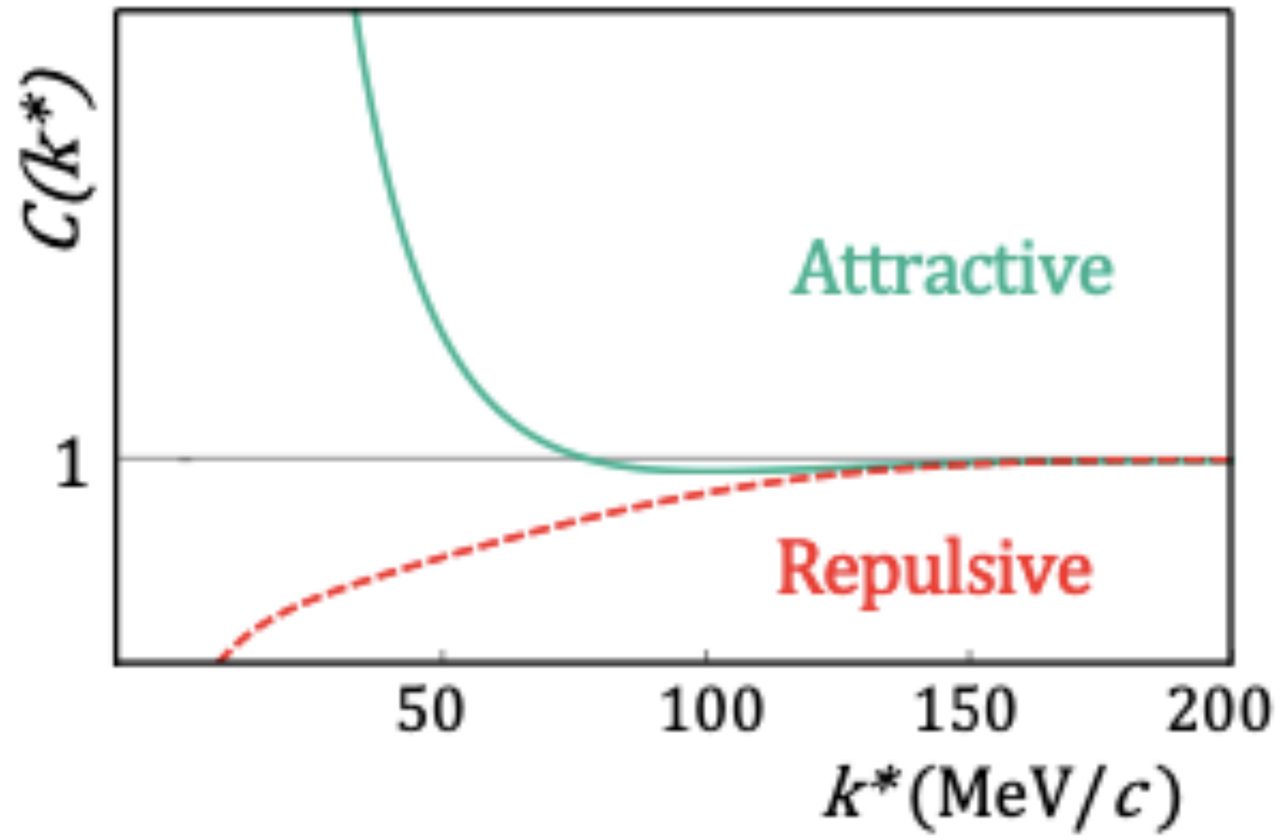
Interacting potential



Schrödinger equation**

Two-particle wave function $|\Psi(k^*, r)|$

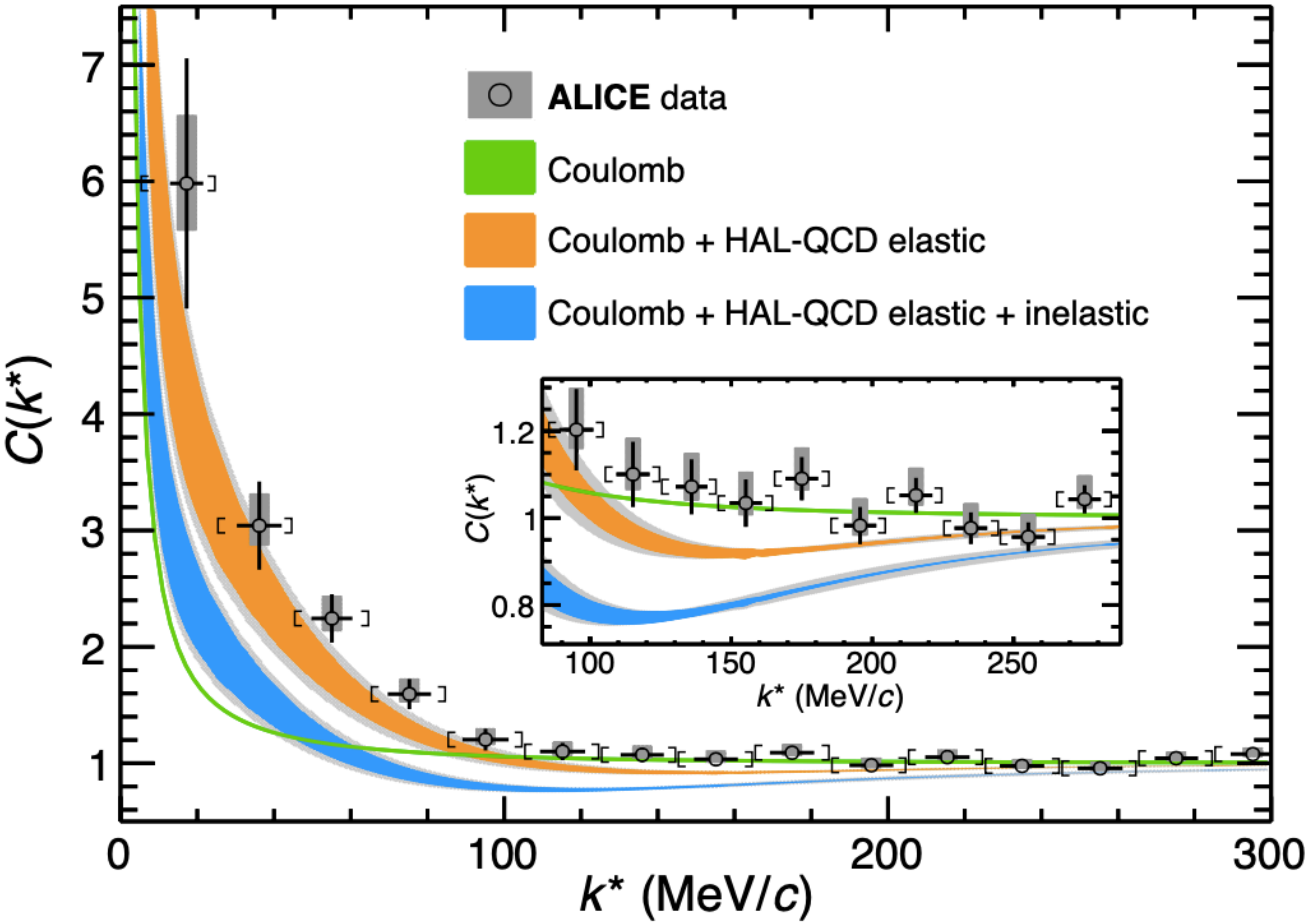
Correlation function



talk Bhawani Singh

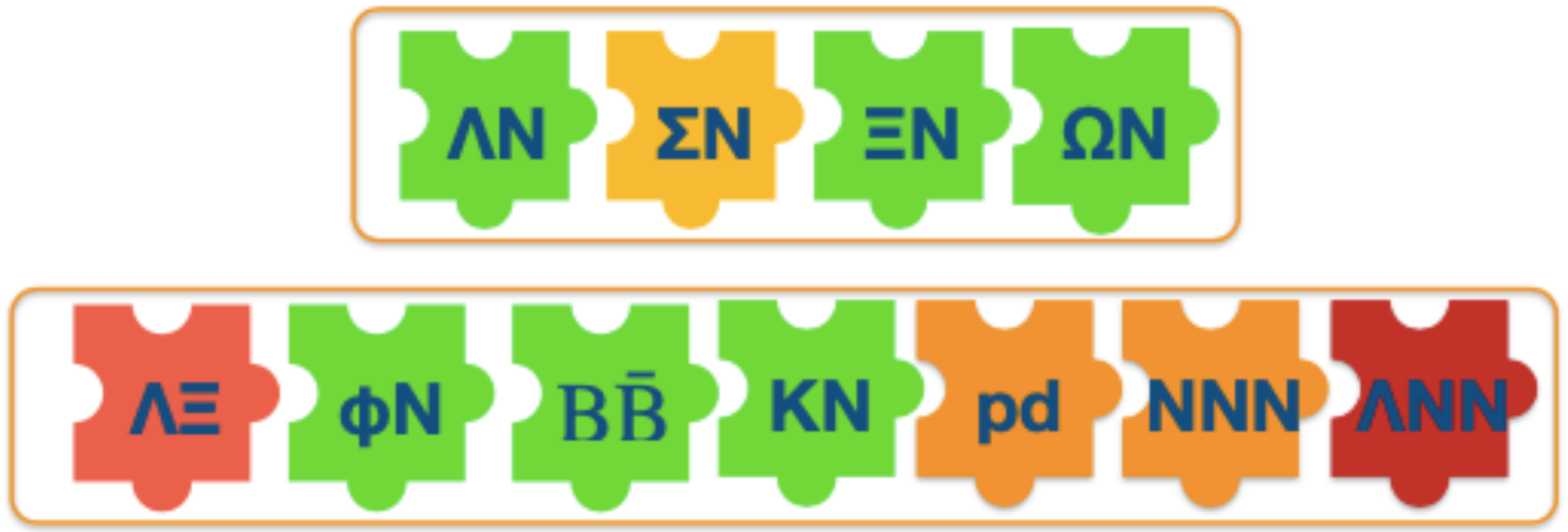
Precise information on the as-yet-unknown p-Ω⁻ interaction

Nature 588, 232 (2020)



Critical test for lattice QCD calculations of the strong h-h interaction

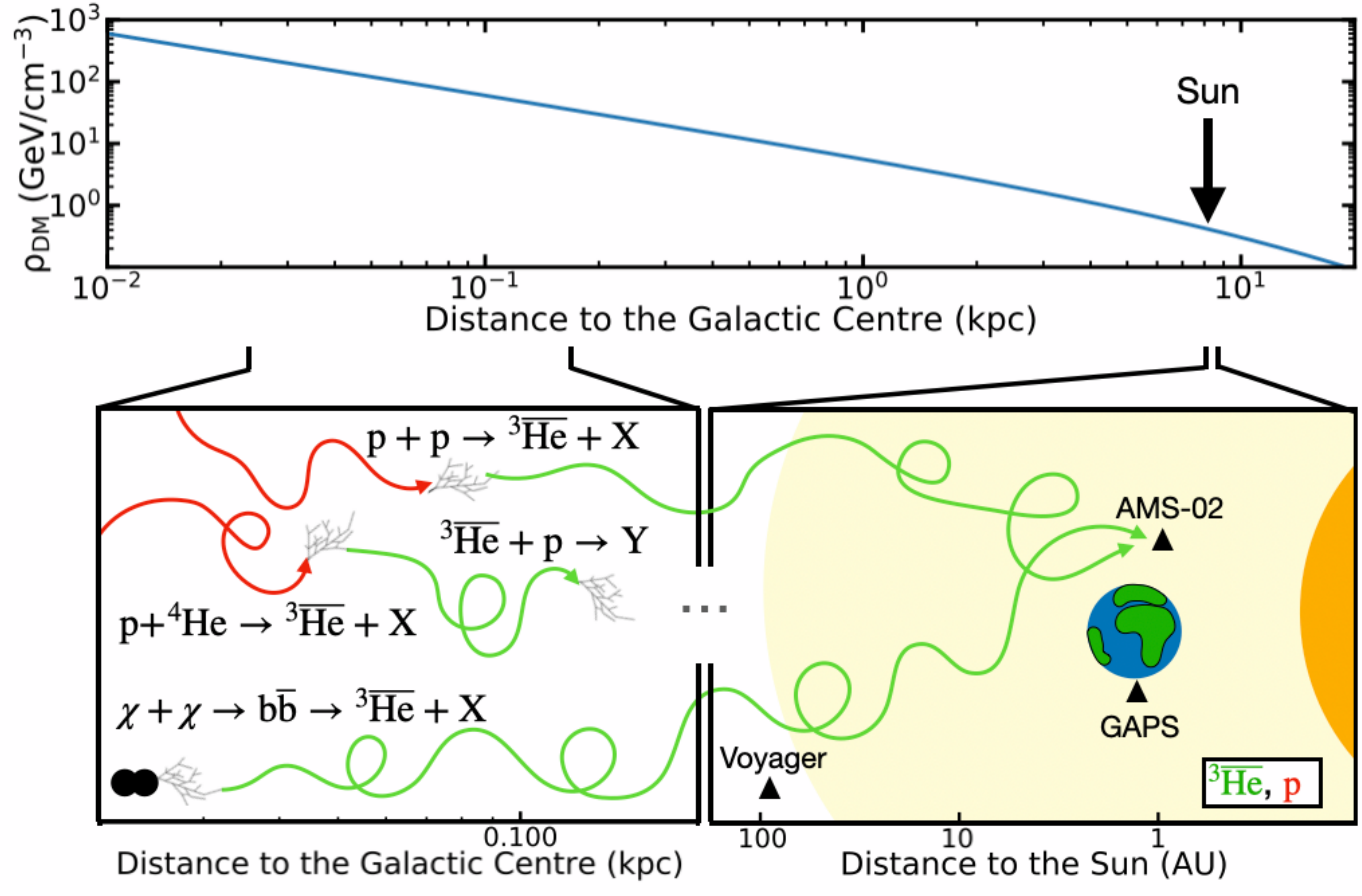
A new avenue for high-precision tests of the strong interaction at the LHC:



Important input for the equation-of-state of neutron stars (which contain hyperon-rich matter)

Inelastic cross section of $\bar{\mathrm{d}}$ and $^3\overline{\mathrm{He}}$ (1)

Input for dark matter searches in space



Indirect dark matter search:

$$\chi + \chi \rightarrow b\bar{b} \rightarrow \bar{\mathrm{d}} + X$$
$$\chi + \chi \rightarrow W^+W^- \rightarrow \bar{\mathrm{d}} + X$$

$$\chi + \chi \rightarrow b\bar{b} \rightarrow {}^3\overline{\mathrm{He}} + X$$
$$\chi + \chi \rightarrow W^+W^- \rightarrow {}^3\overline{\mathrm{He}} + X$$

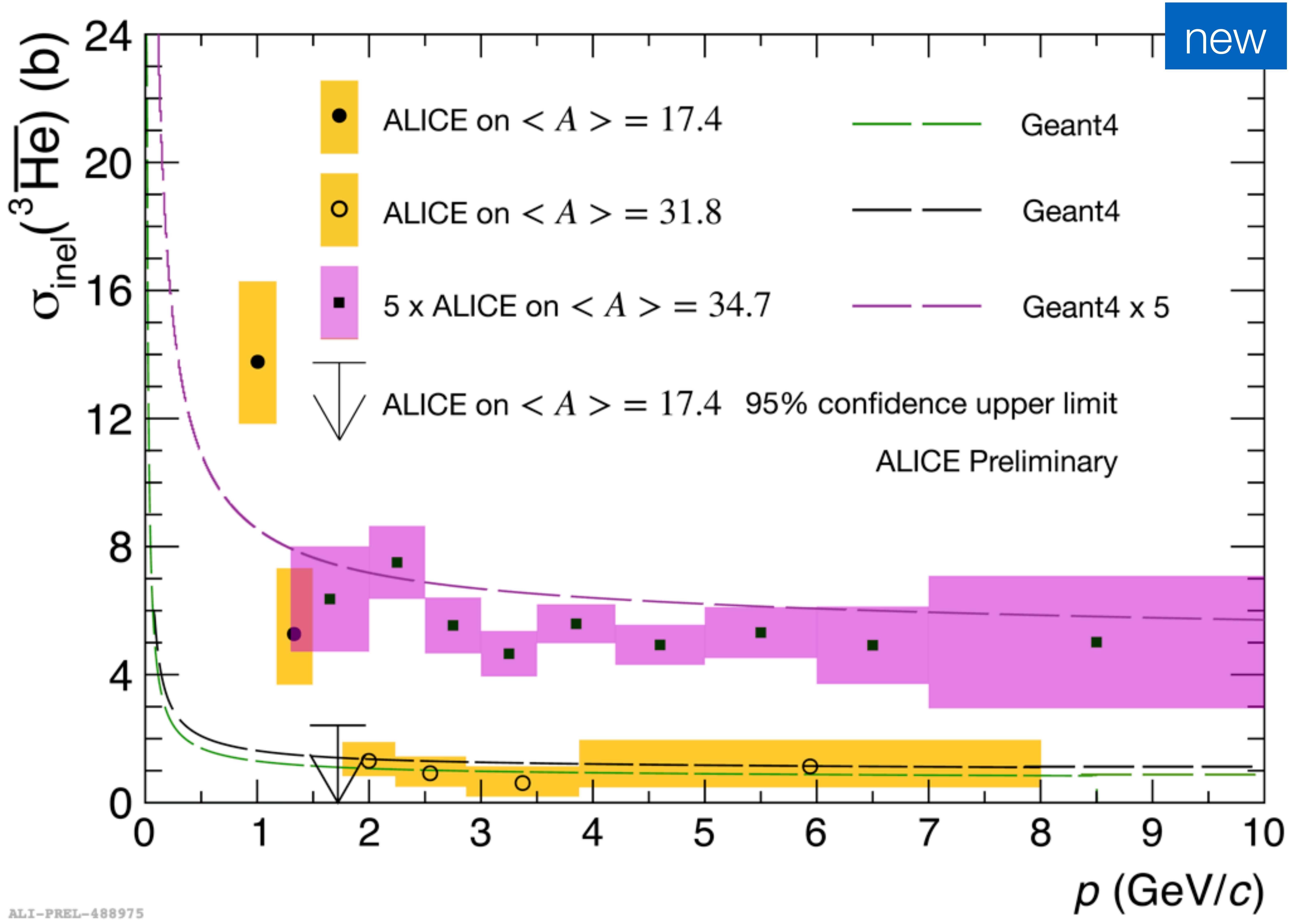
Small astrophysical background

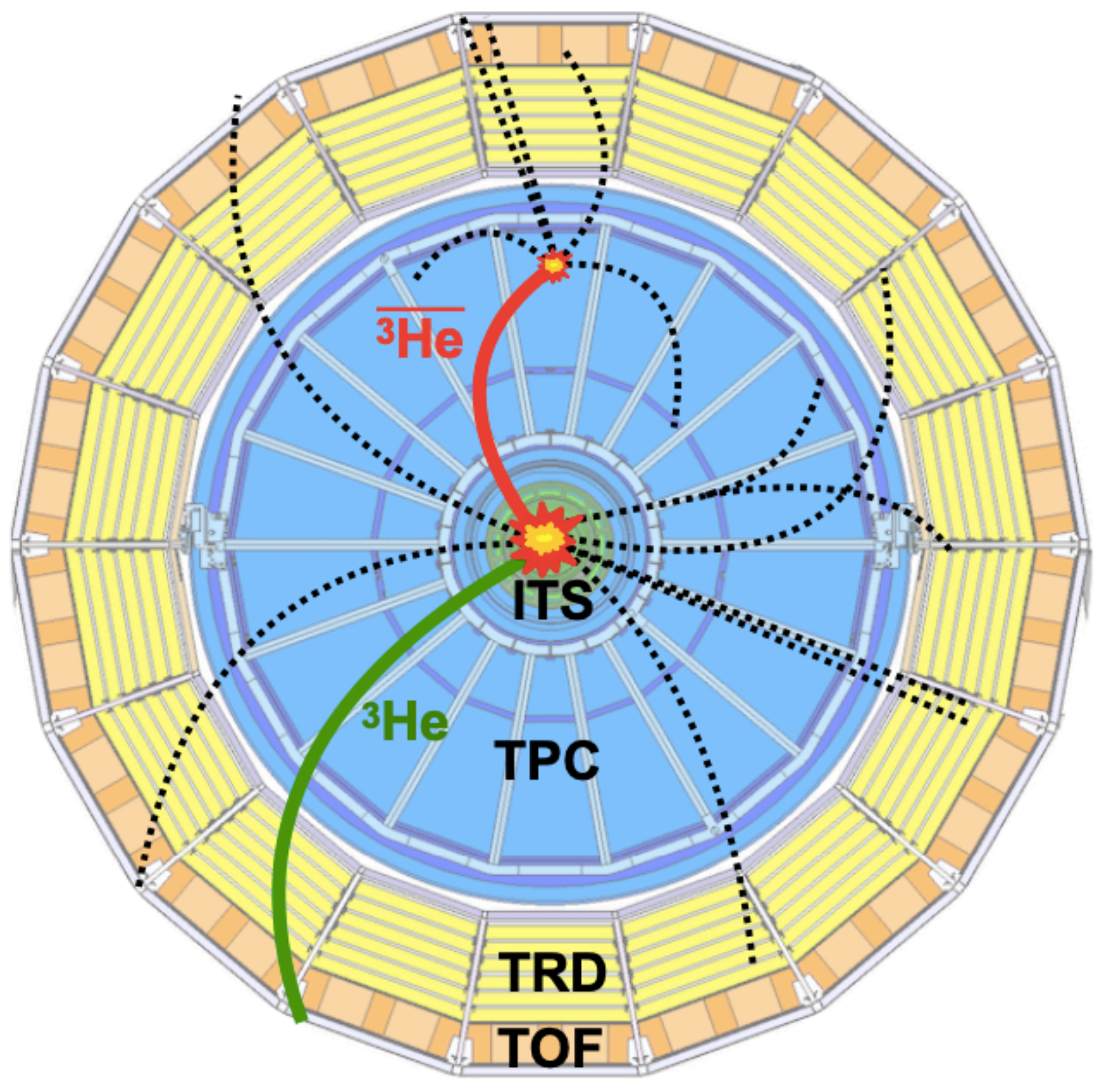
Critical input:
inelastic cross section

$\bar{\mathrm{d}}$ + A inelastic cross section:
PRL 125 (2020) 16, 162001

Inelastic cross section of $\bar{\mathrm{d}}$ and $^3\overline{\mathrm{He}}$ (3)

First-ever measurement of the interaction of antihelium with matter





Adjust inelastic cross section in GEANT 4 until reconstructed $^3\overline{\mathrm{He}}/^3\mathrm{He}$ ratio is reproduced

Indications of deviations from GEANT 4 at low p

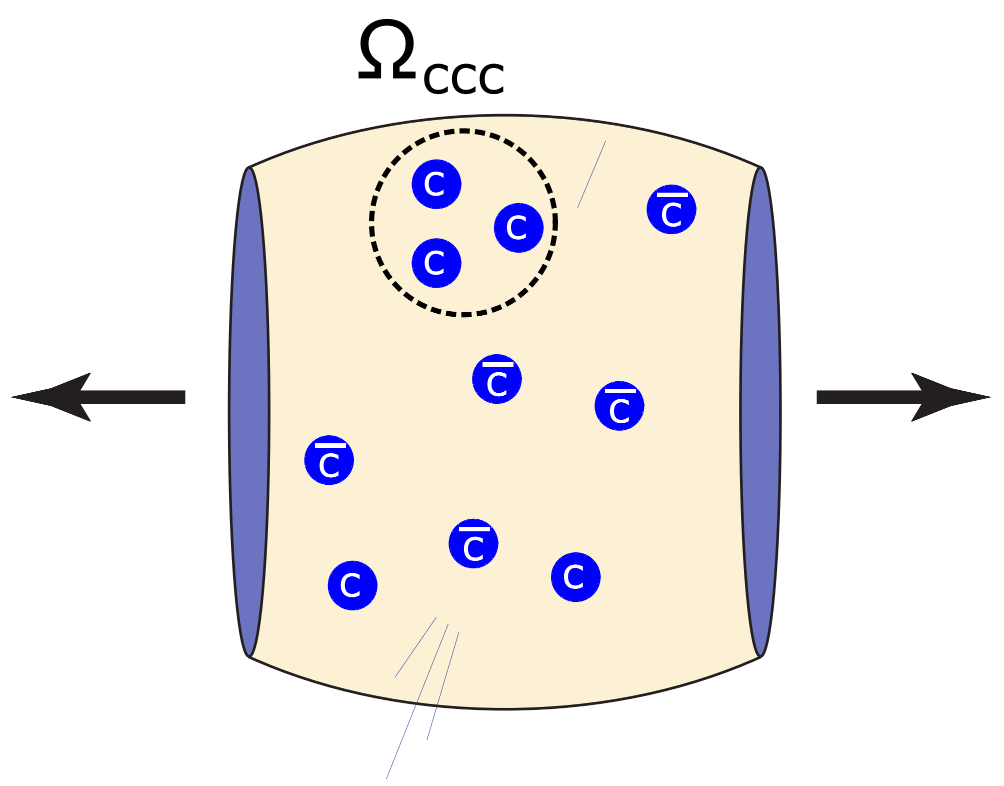
Run 5 and beyond:
ALICE 3

New ways to study the QGP

Deconfinement and hadronization

Multiple charm hadrons, quarkonia, X(3872): extremely enhanced in the QGP

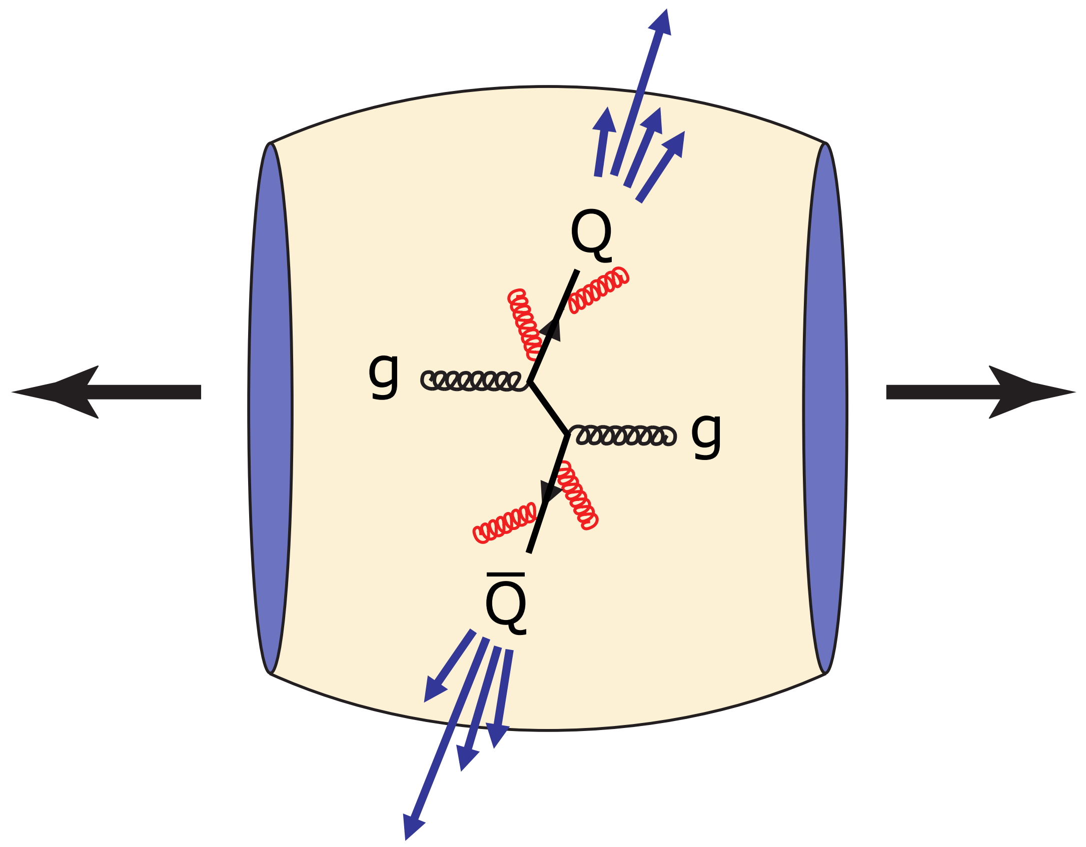
Vary charm quark density through large rapidity coverage



Precision QGP tomography with $c\bar{c} \rightarrow D\bar{D}$ correlations

Nature of quasi-particles in the QGP

Collisional vs. radiative energy loss

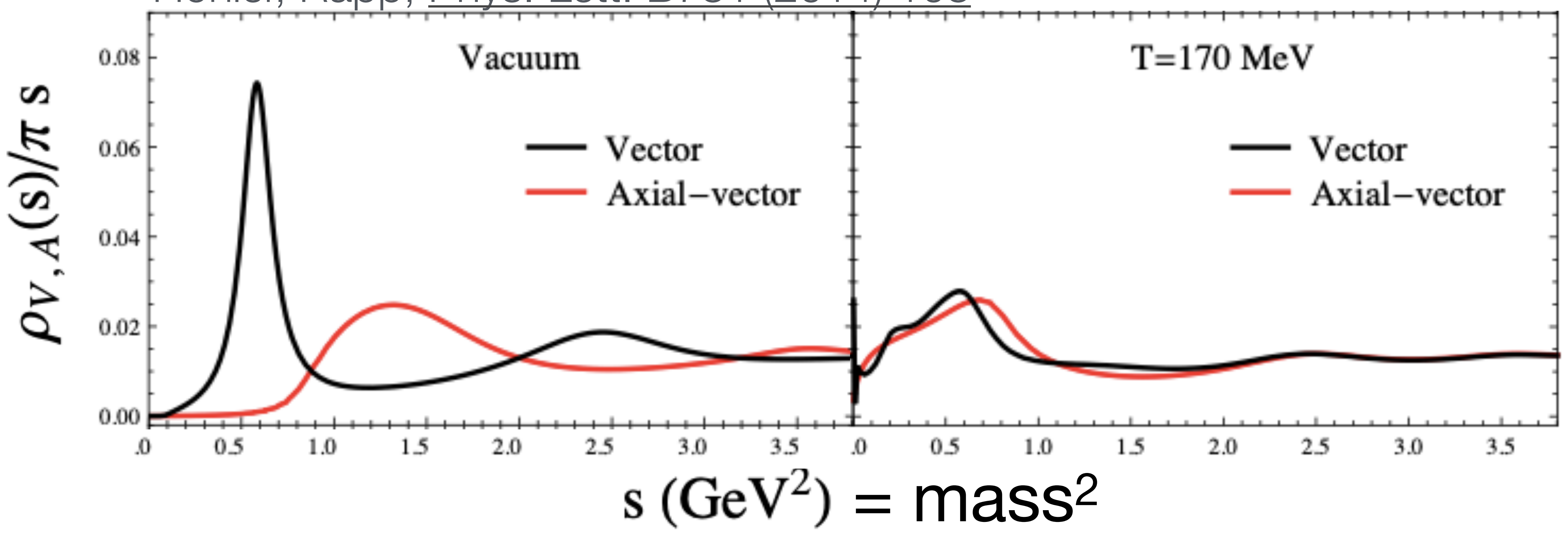


Observation of chiral symmetry restoration

Dileptons with m_{ee} > 1 GeV with high precision

Discover ρ-a_1 chiral mixing

Hohler, Rapp, Phys. Lett. B731 (2014) 103



Further physics goals

Pre-QGP stage: how does the medium thermalize?
→ dileptons yield and v_2 at high masses and p_T

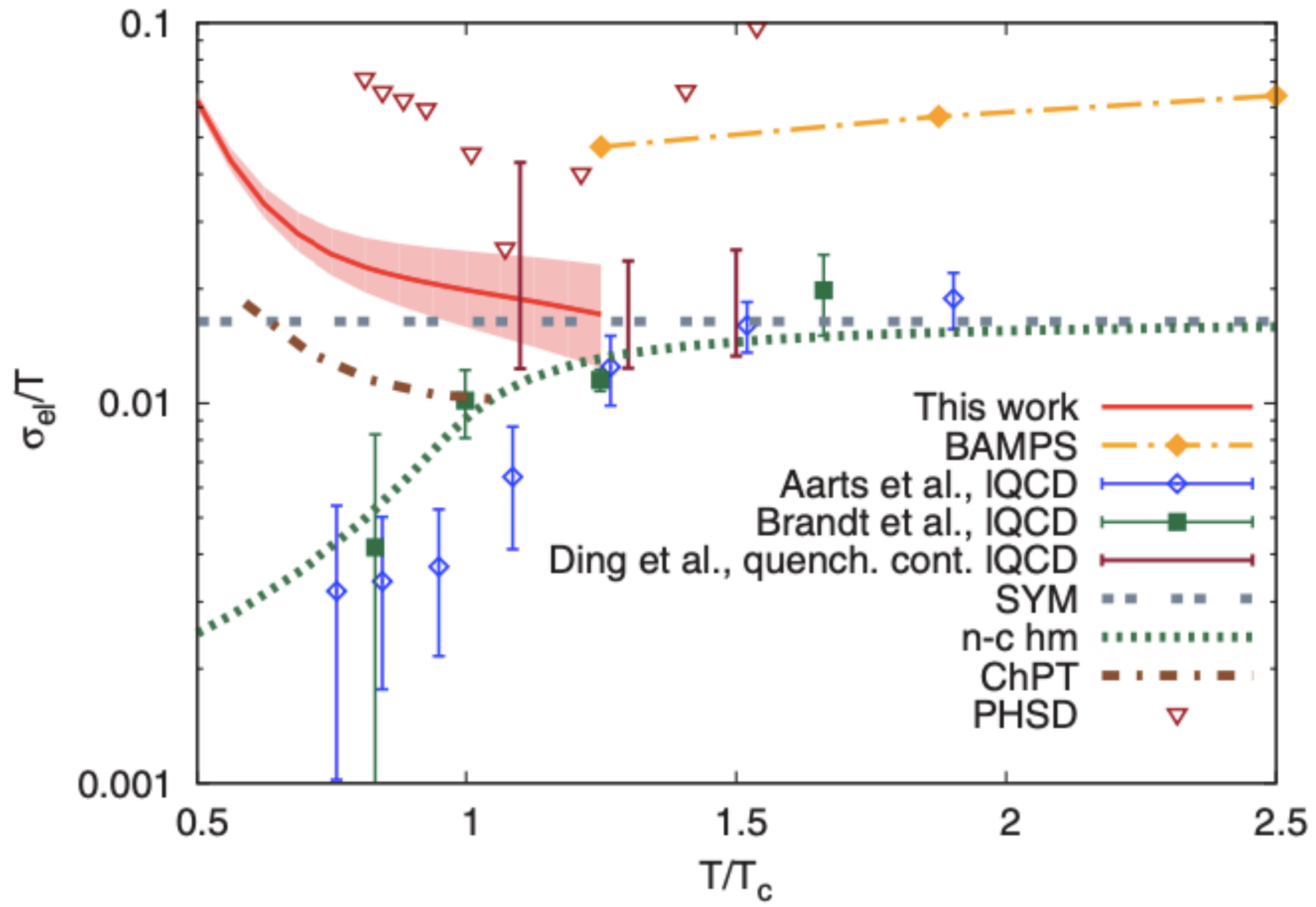
Electrical conductivity of the QGP
→ dileptons yield ultra-low masses and p_T

Onset of collective/QGP effects
from small to large systems

Ultra soft photons (p_T < 10 MeV/c)
Low's theorem, soft photon puzzle

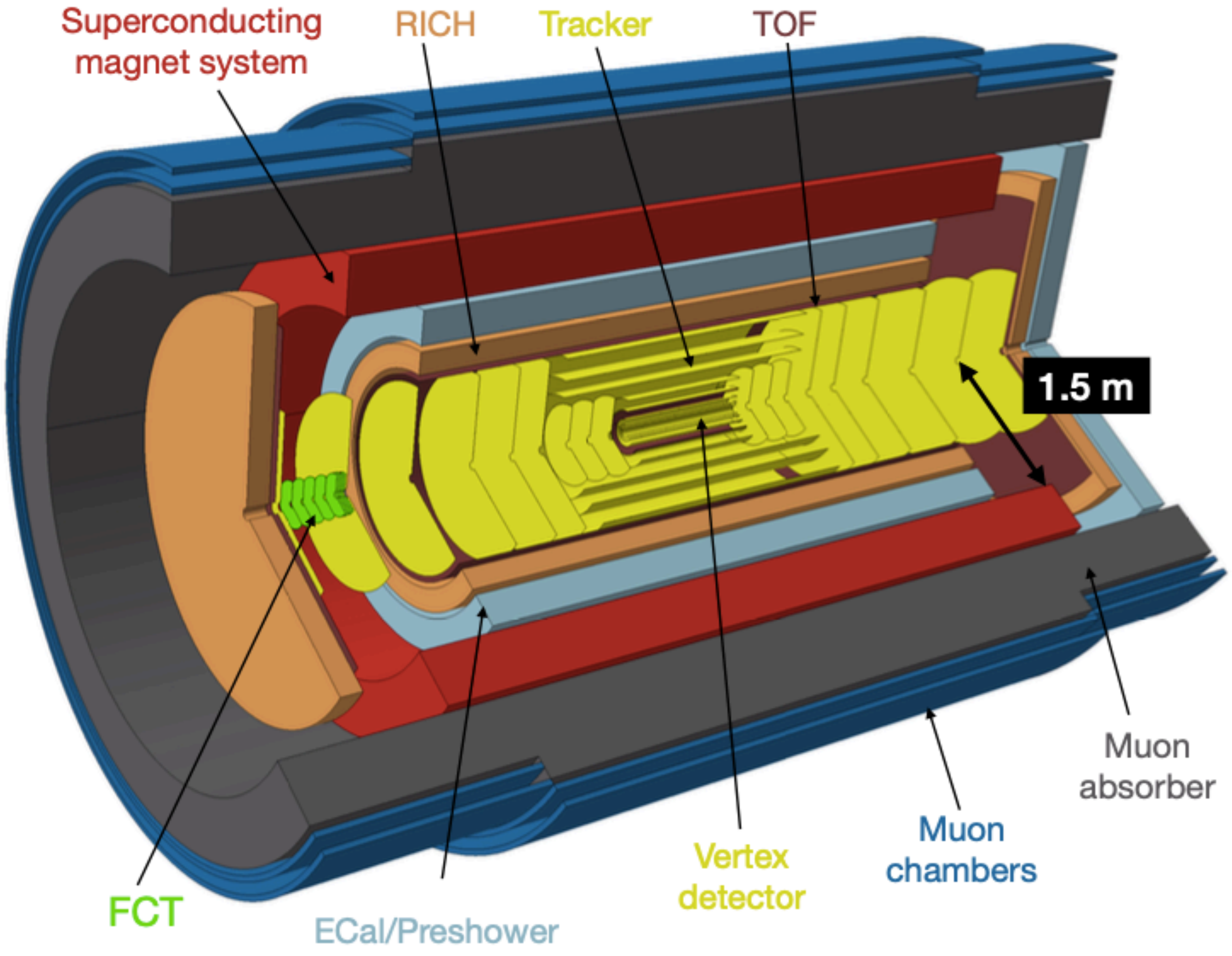
And more …

Electrical conductivity of the QGP:
large variations in existing literature



M. Greif, C. Greiner, and G. S. Denicol,
Phys. Rev. D 96 059902

A new dedicated QGP physics detector for Run 5+ (> 2030)



Fast and ultra-thin detector with precise tracking and particle ID

First tracking layer very close to primary vertex

Kinematic range down to very low p_T

Large acceptance (barrel + endcap Δη ≈ 8)

Letter of Intent by end of 2021

Public ALICE 3 workshop Oct 19/20

talk Gian Michele Innocenti, expression of interest: 1902.01211

Summary

New insights from c and b quarks on QGP hadronization and parton energy loss

Charm hadronization in pp very different from e^+e^-

Direct observation of the dead-cone effect in pp for charm quarks

Hadron physics
Hadron structure, strong hadron-hadron interaction, formation of hadrons and nuclei

ALICE 2
Run 3: installation and commissioning of major upgrades complete, verified in pilot run
Run 4: upgrades on track

ALICE 3
Plans for a next-generation dedicated QGP experiment for Run 5+