*in 15 minutes

Heavy-ion physics at the HL-LHC*

Florian Jonas

for the **ALICE**, ATLAS, CMS and LHCb collaborations

LHCP 2024 - Boston

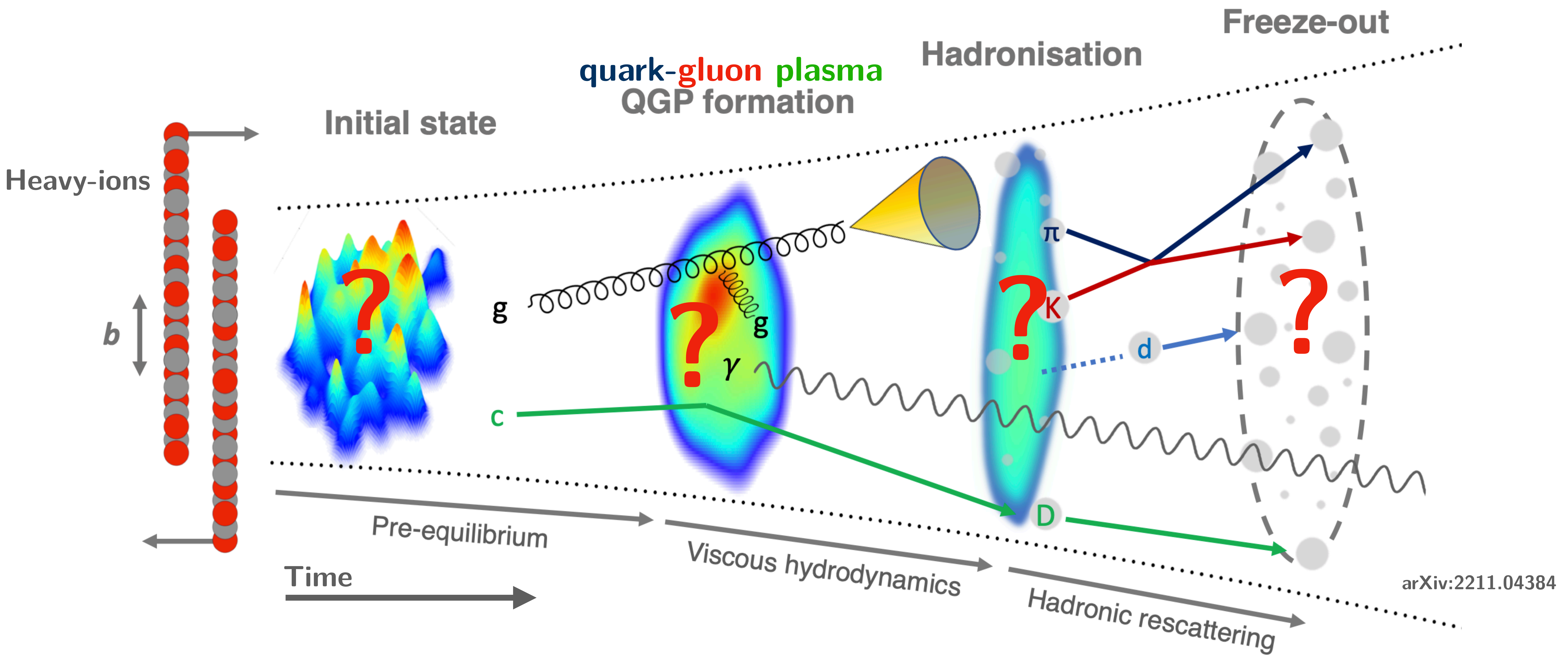
Berkeley
UNIVERSITY OF CALIFORNIA

BERKELEY LAB
Lawrence Berkeley National Laboratory

(High energy) Heavy-ion physics

By colliding heavy-ions we can learn about the evolution of QCD matter in extreme conditions (high temperature and/or high density)

using a toolbox of probes produced in all stages of collision



High-Luminosity LHC → higher precision & opportunities for new observables

The HL-LHC: Heavy-ion program

	2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041
Run 1	Run 2	LS 2	Run 3	LS 3	Run 4	LS 4	Runs 5&6
	Pb-Pb 2.2/nb p-Pb 0.18/pb		Pb-Pb 6.2/nb O-O 500/μb		Pb-Pb 6.8/nb p-Pb 0.6/pb		Pb-Pb 35/nb (tbd)

High-Luminosity LHC

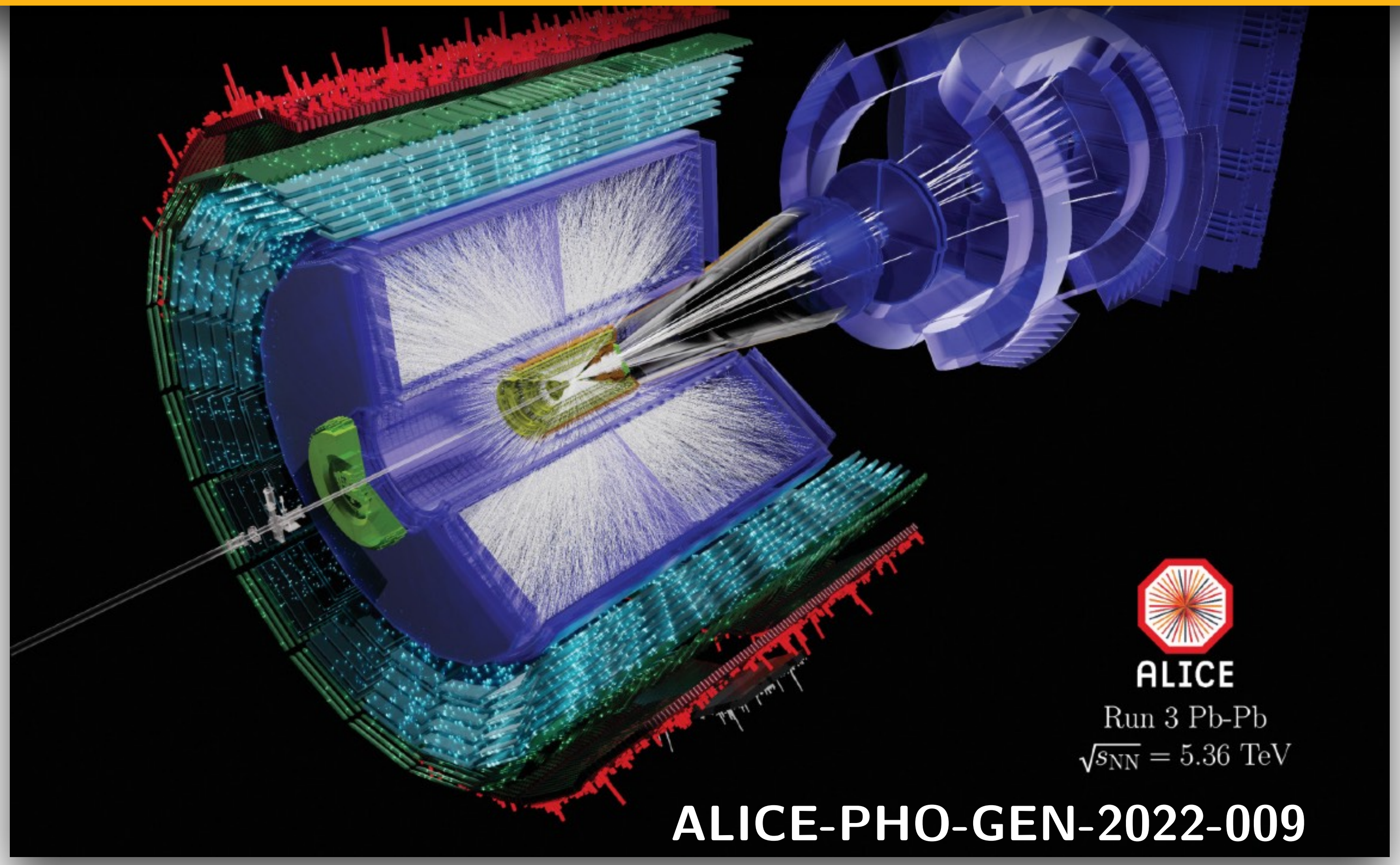
The High Luminosity LHC: CERN-2020-010

- **LS2:** LHC injector upgrades; Pb-Pb rate ~10kHz → 50kHz
- **LS3:** HL-LHC installation; pp ~460/fb → 3000/fb (HL-LHC)

Trigger/Readout compared to Run 2:

- ALICE: increase of MB Pb-Pb x100 **compared to Run 2**
- ATLAS/CMS: increase of **MB (rare triggers)** x5 (x10)
- LHCb: full delivered luminosity (up to 30% central Pb-Pb in Run 3 & 4)

HL for heavy-ions is already ongoing ...



Detector upgrades

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	2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041

High-Luminosity LHC (Run 4 onwards)

ALICE: See talk: Felix Reidt - 06/06 @ 16:48

- LS 2
  - new ITS & new Muon Forward Tracker (MFT)
  - TPC upgrade + continuous readout
- LS 3
  - Forward Calorimeter (FoCal)
  - ITS3: ultralight cylindrical vertexer
- LS 4
  - ALICE 3: completely new detector

LHCb: See talk: Elisabeth Niel - 06/06 @ 17:12

- LS 2
  - VELO & Upstream tracker upgrades
  - Calorimeter. & muon upgrades
- LS 3
  - Smaller detector consolidation & enhancements
- LS 4
  - LHCb Upgrade II

ATLAS: See talk: Yasuyuki Okumura - 06/06 @ 16:24

- LS 2
  - Muon New Small Wheels (MSW)
  - Re-designed AFP TOF
- LS 3
  - Upgraded triggers & DAQ
  - New Inner Tracker + new μ chambers + lumi detectors

CMS: See talk: Thiago Tomei Fernandez - 06/06 @ 16:00

- LS 2
  - New GEM detectors
  - New innermost barrel pixel layer
- LS 3
  - Upgraded triggers & DAQ
  - New Inner tracker + calo. endcap + μ detector

Detector upgrades

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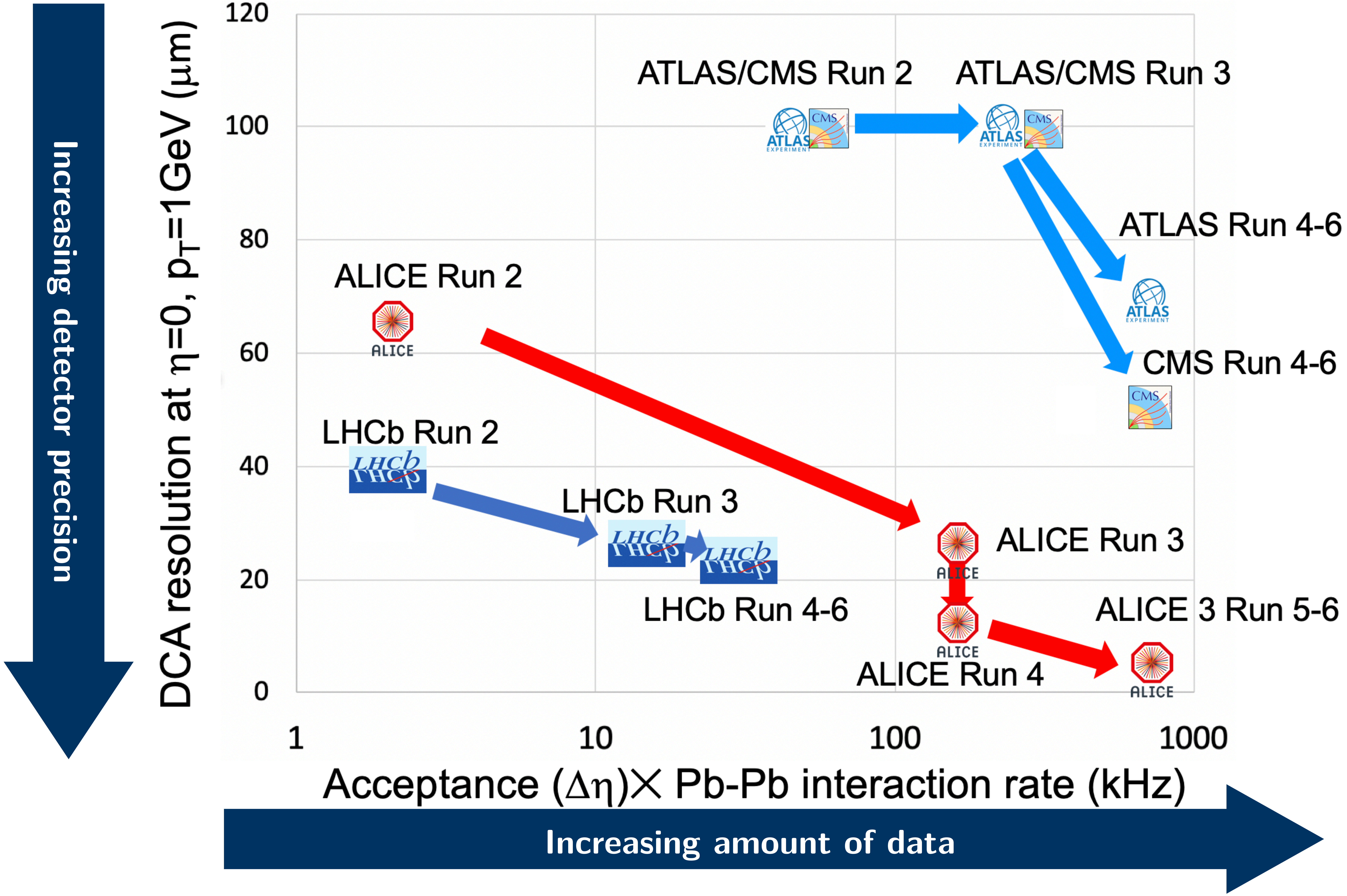
Upgrades allow for:

1. Higher luminosity
2. Higher precision
3. Novel phase space
4. More differential measurements
5. New observables

Detector & Interaction rate improvements



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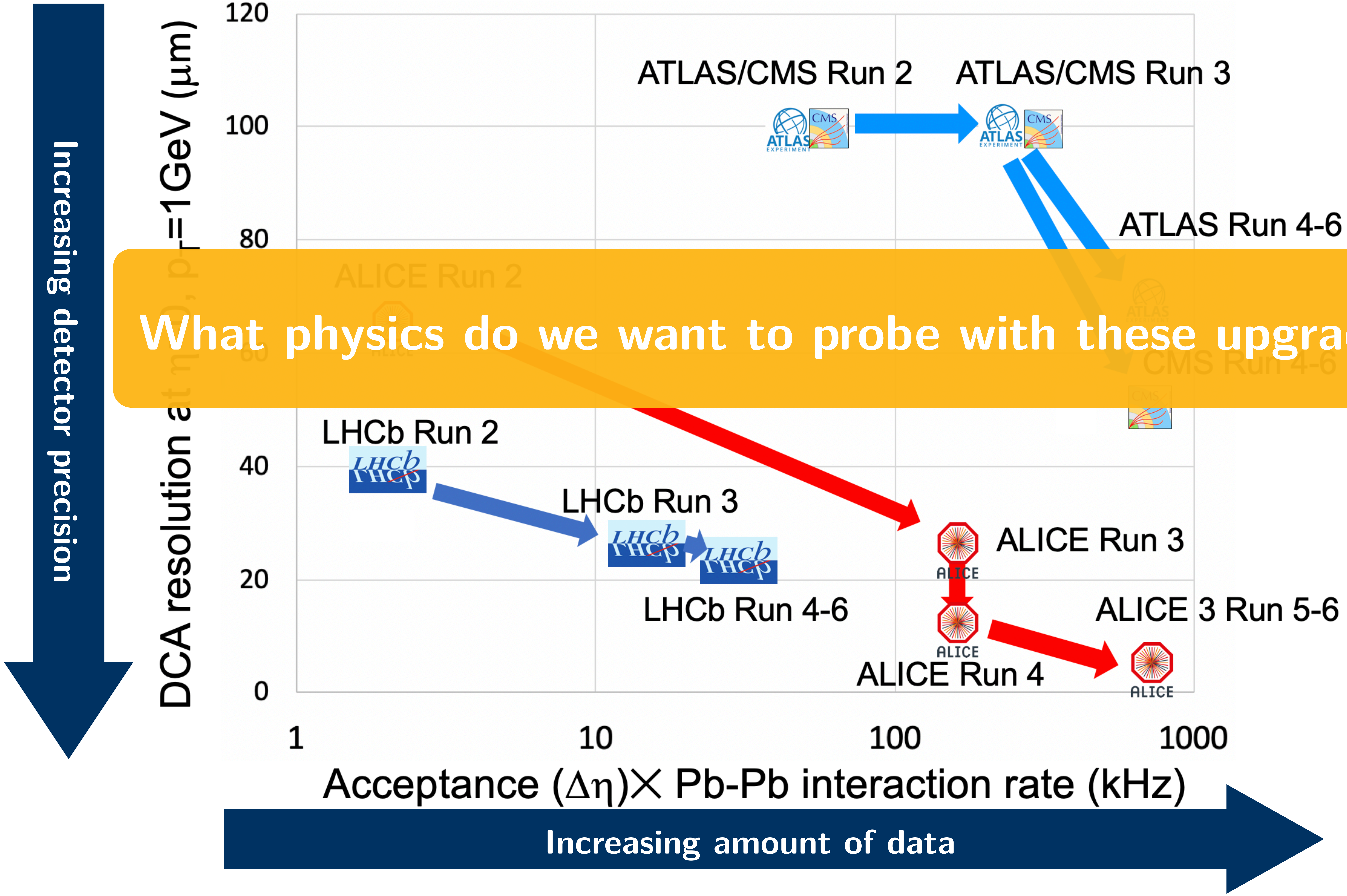


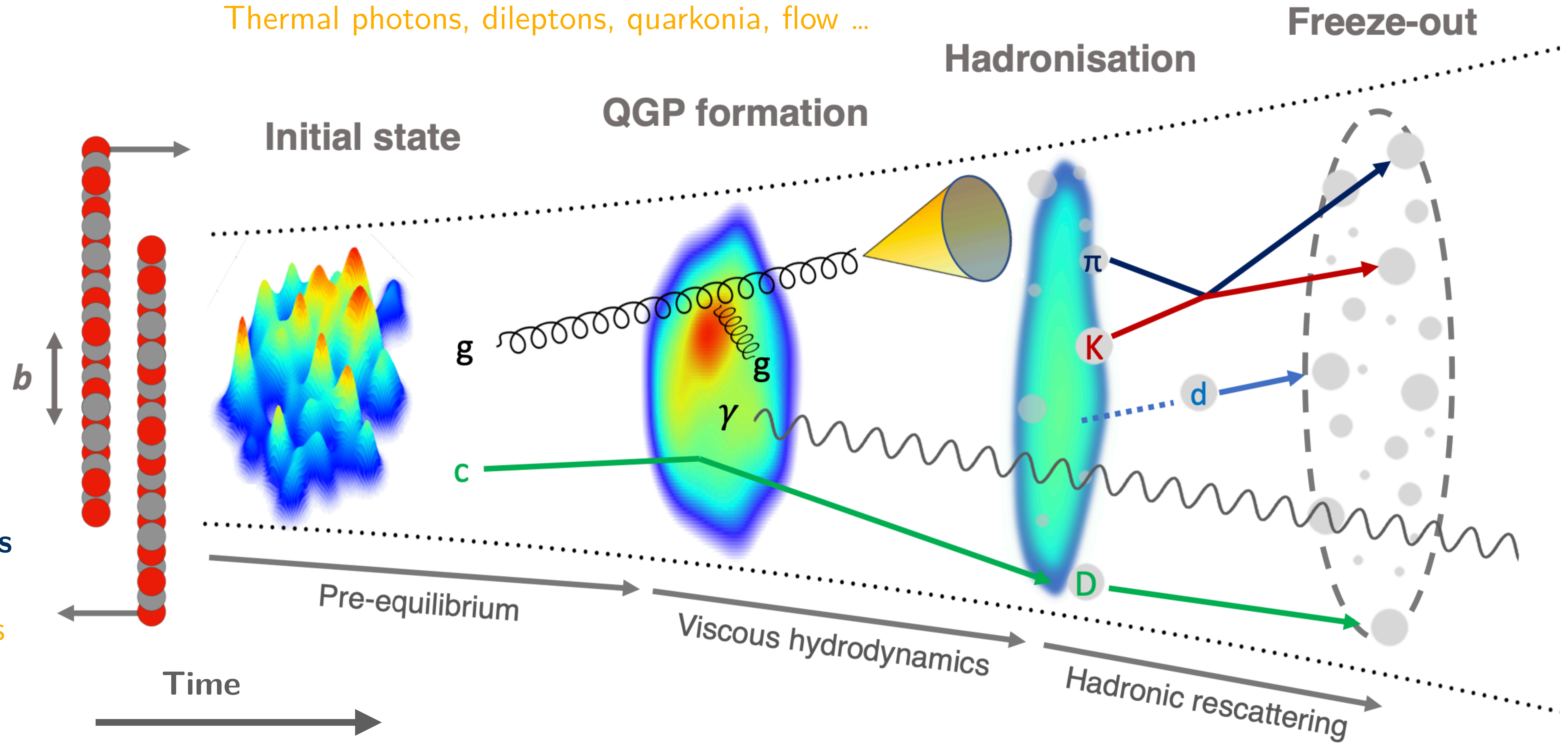
What physics do we want to probe with these upgrades?

Heavy-ion physics: The big questions

What are the macroscopic properties of the QGP? Temperature? Viscosity? QCD phase transition?
Thermal photons, dileptons, quarkonia, flow ...

What are the initial conditions of a collision? nPDFs & Saturation?
DY, UPC, forward LHC ...

Collectivity of QCD across system sizes?
Flow in pp, p-A; strangeness production, energy loss, thermal radiation



arXiv:2211.04384

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Jets (substructure), γ/Z-jet correlations, heavy flavour, quarkonia, hadronization

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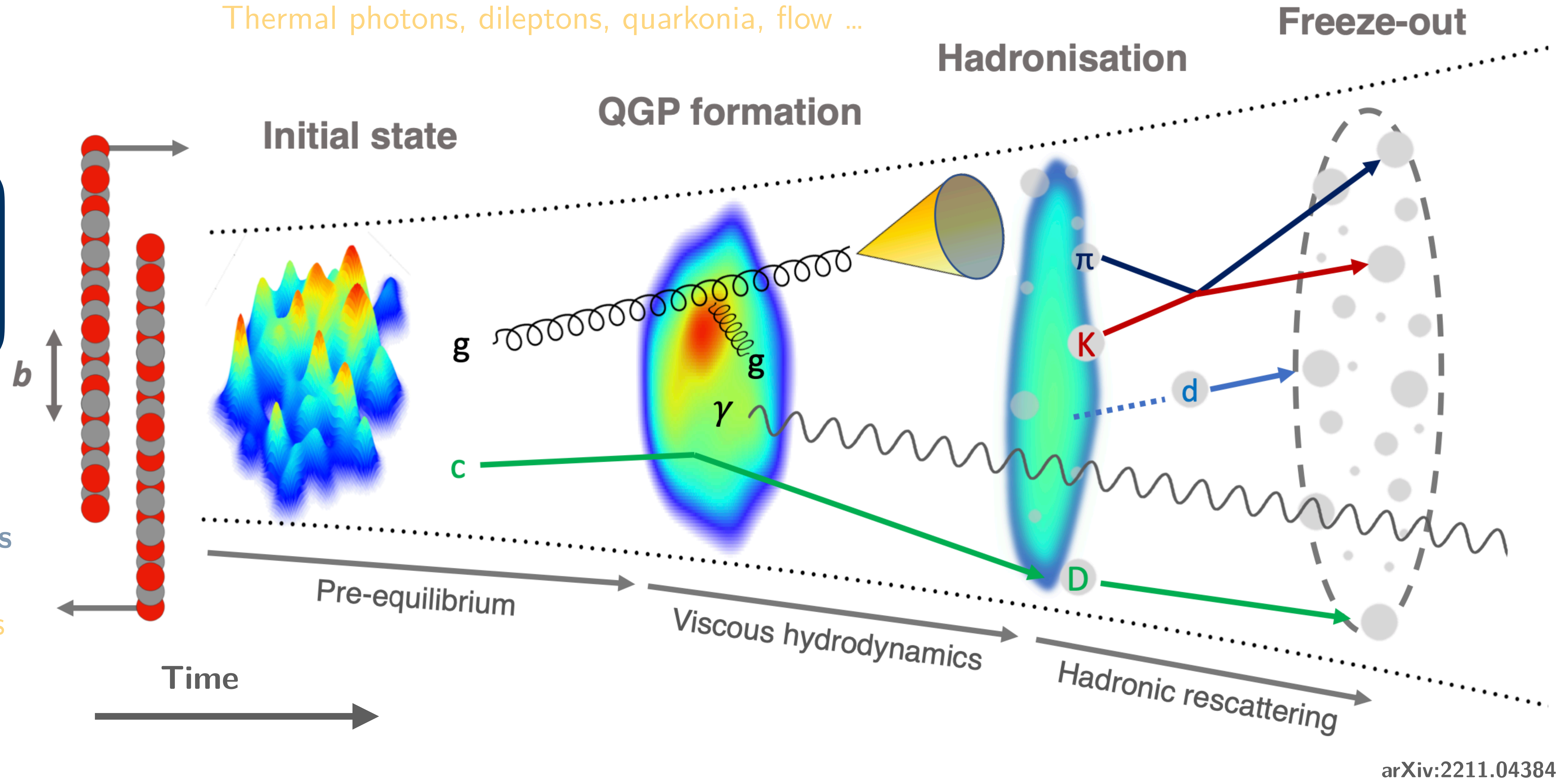

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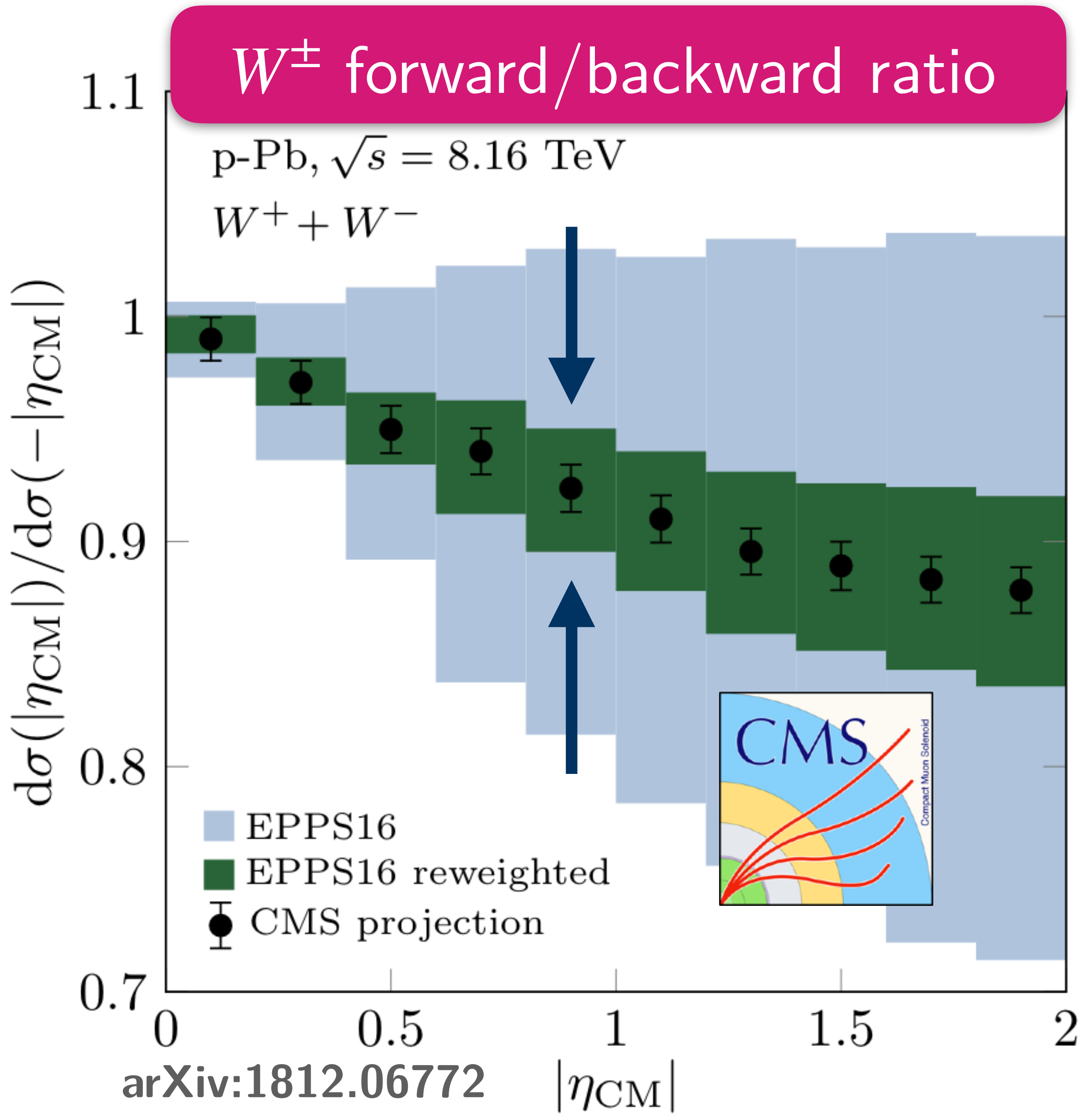
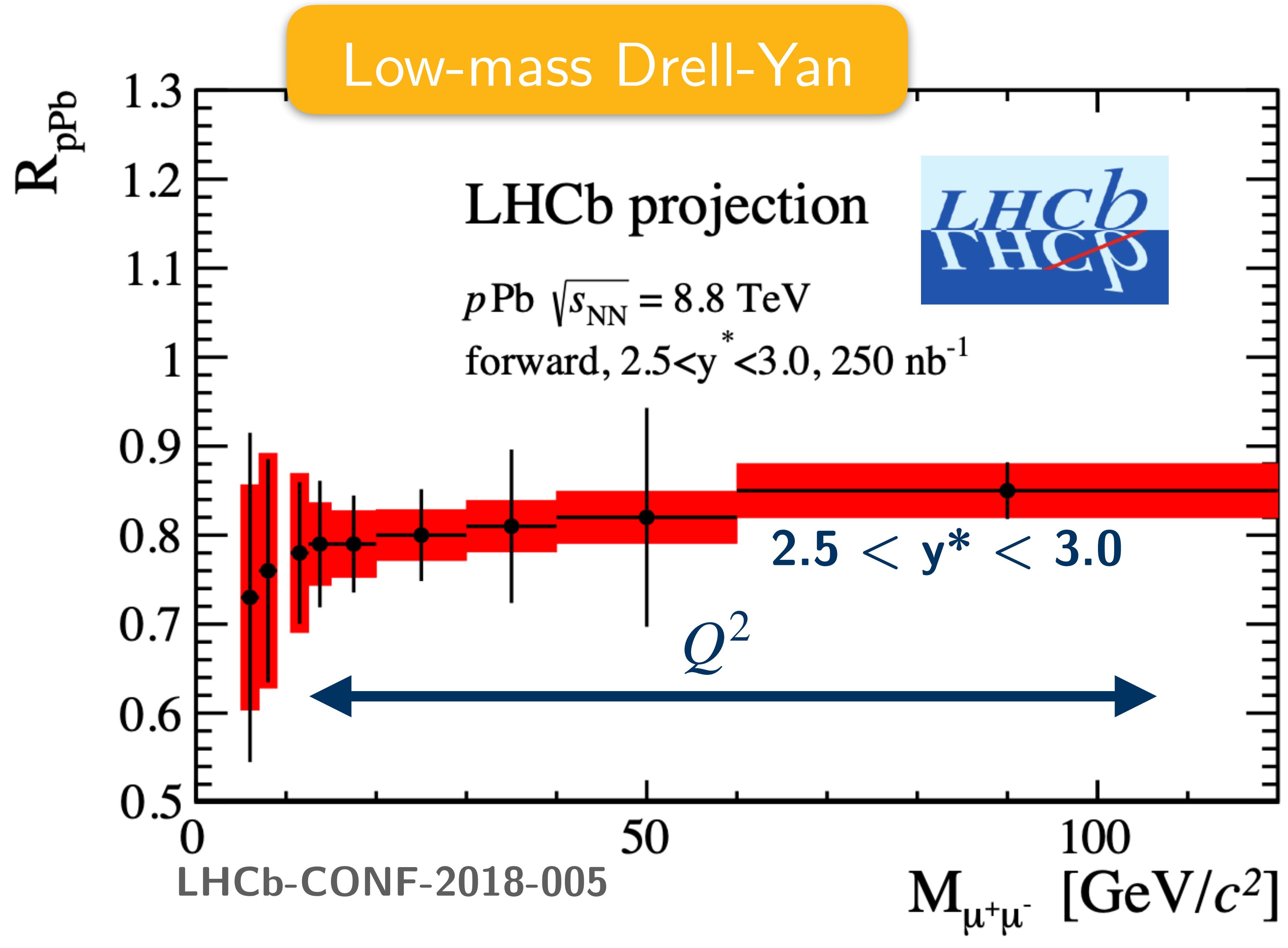
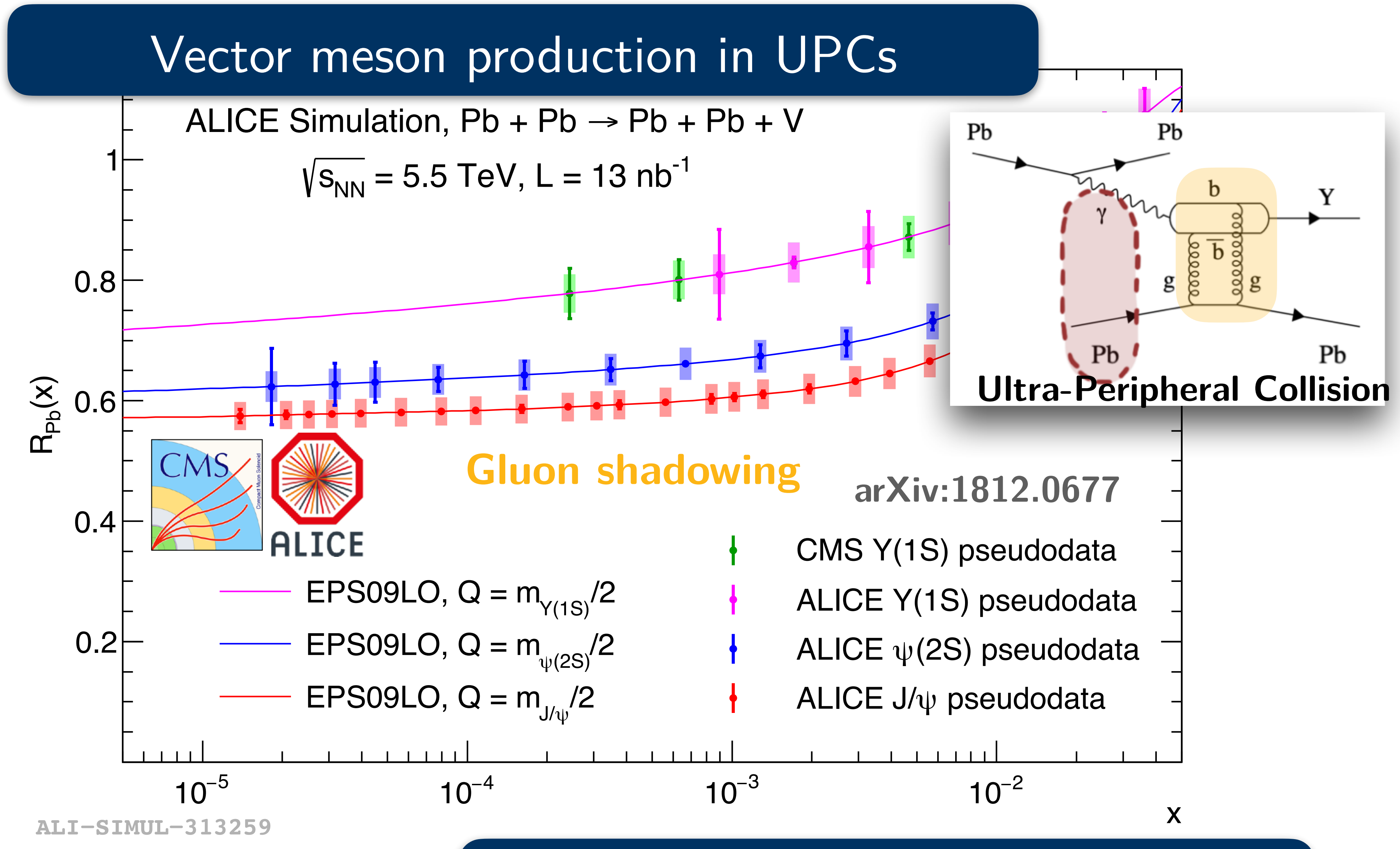
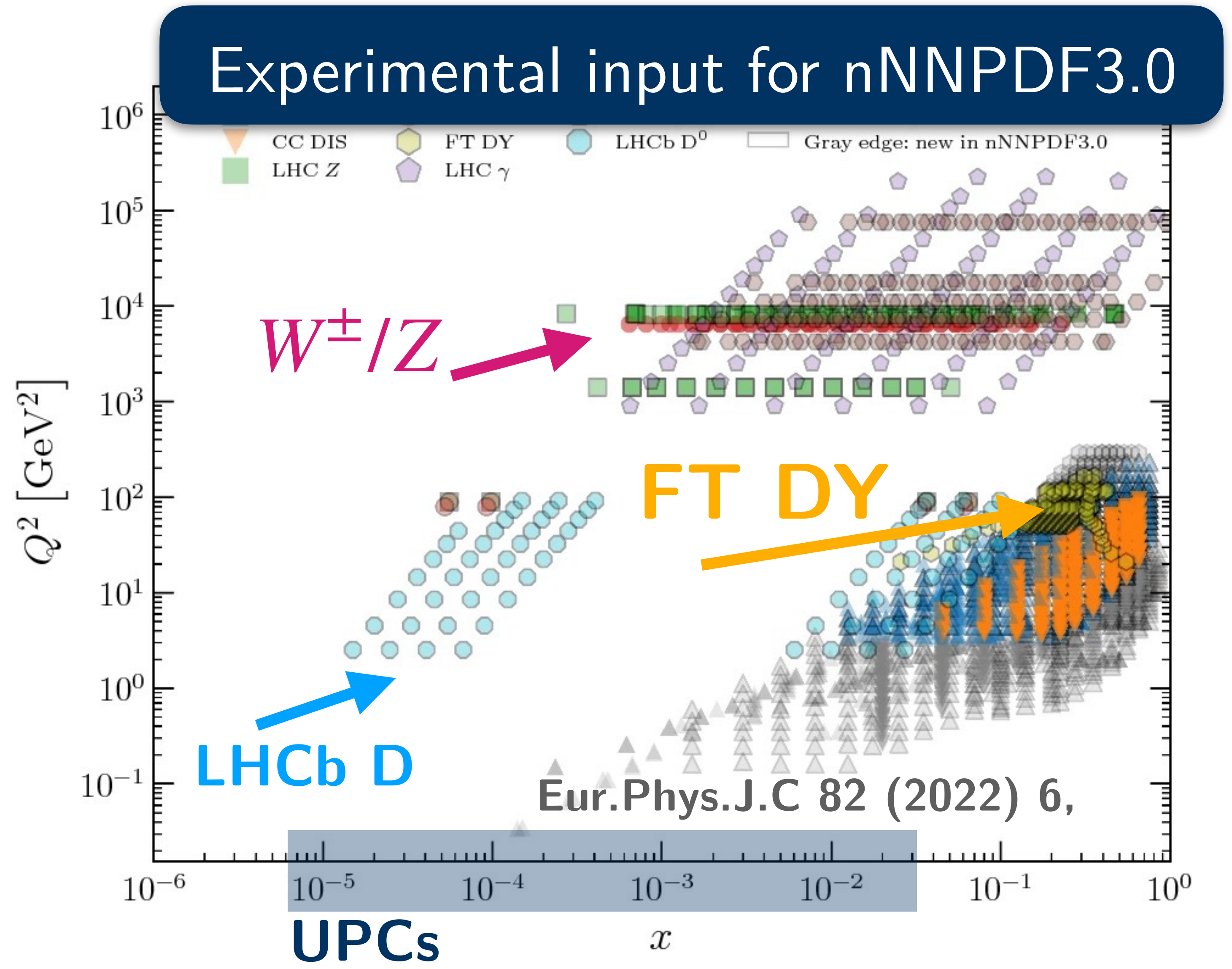






Probing (nuclear) matter in a novel phase-space with high precision:

- $W^{\pm}/Z$ **production:** sensitive to quark (n)PDF and heavy flavours
- **Low-mass Drell-Yan:** precision measurement over wide mass range & differential in y offer possibility to test Q^2 evolution of nPDFs
- **Vector meson, dijet & open charm prod. in UPCs:** gluon densities at low-x



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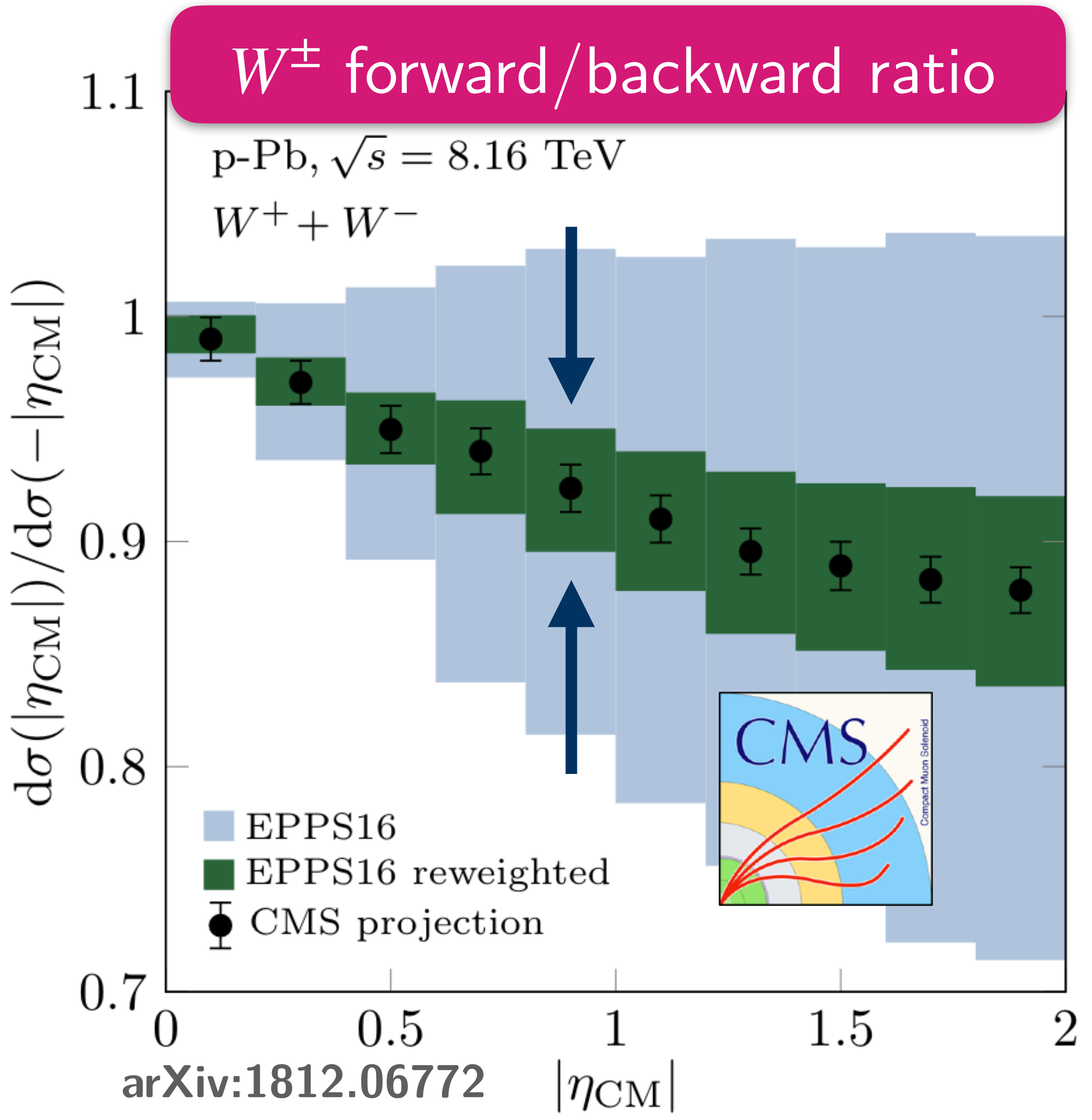

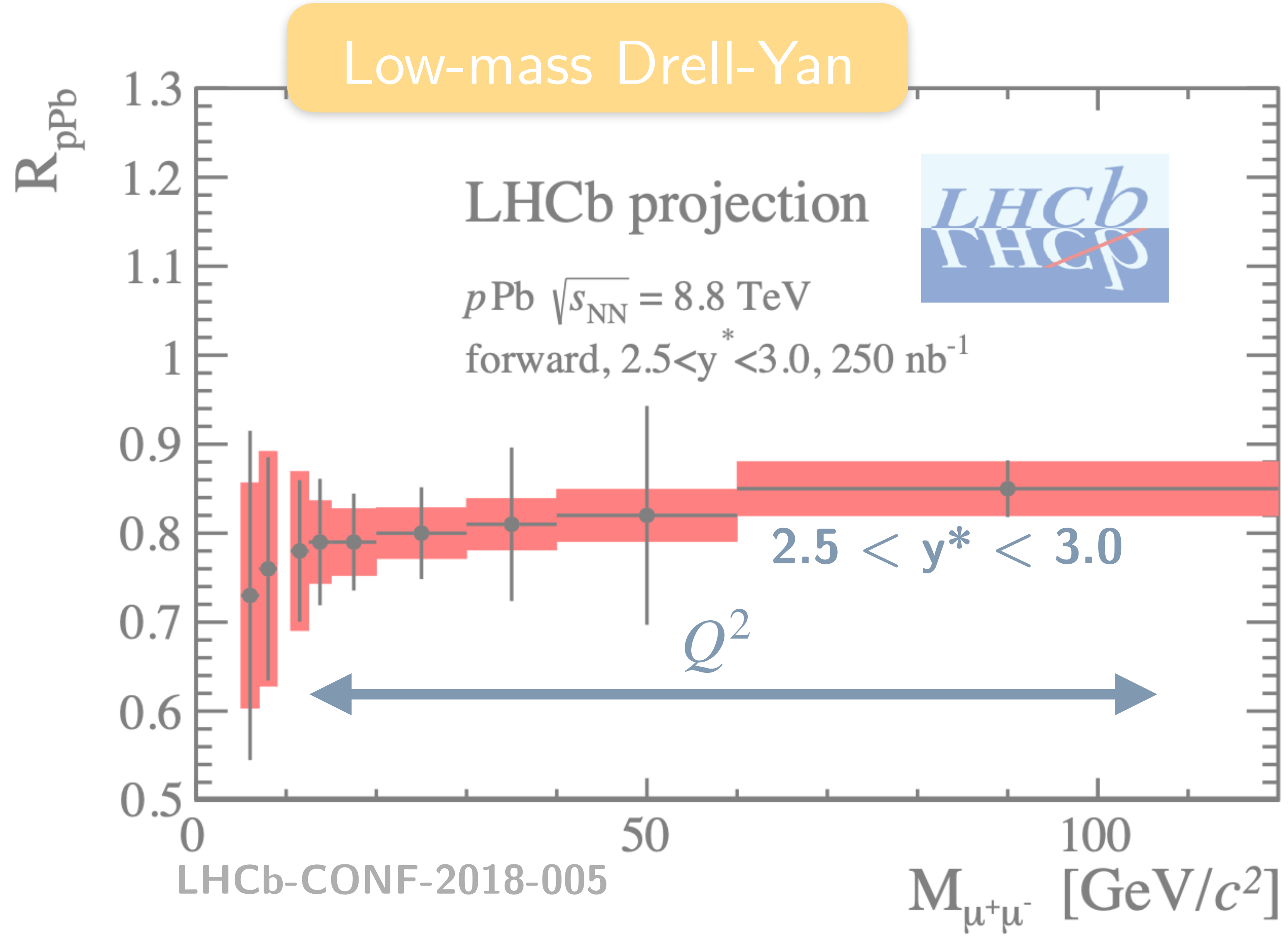

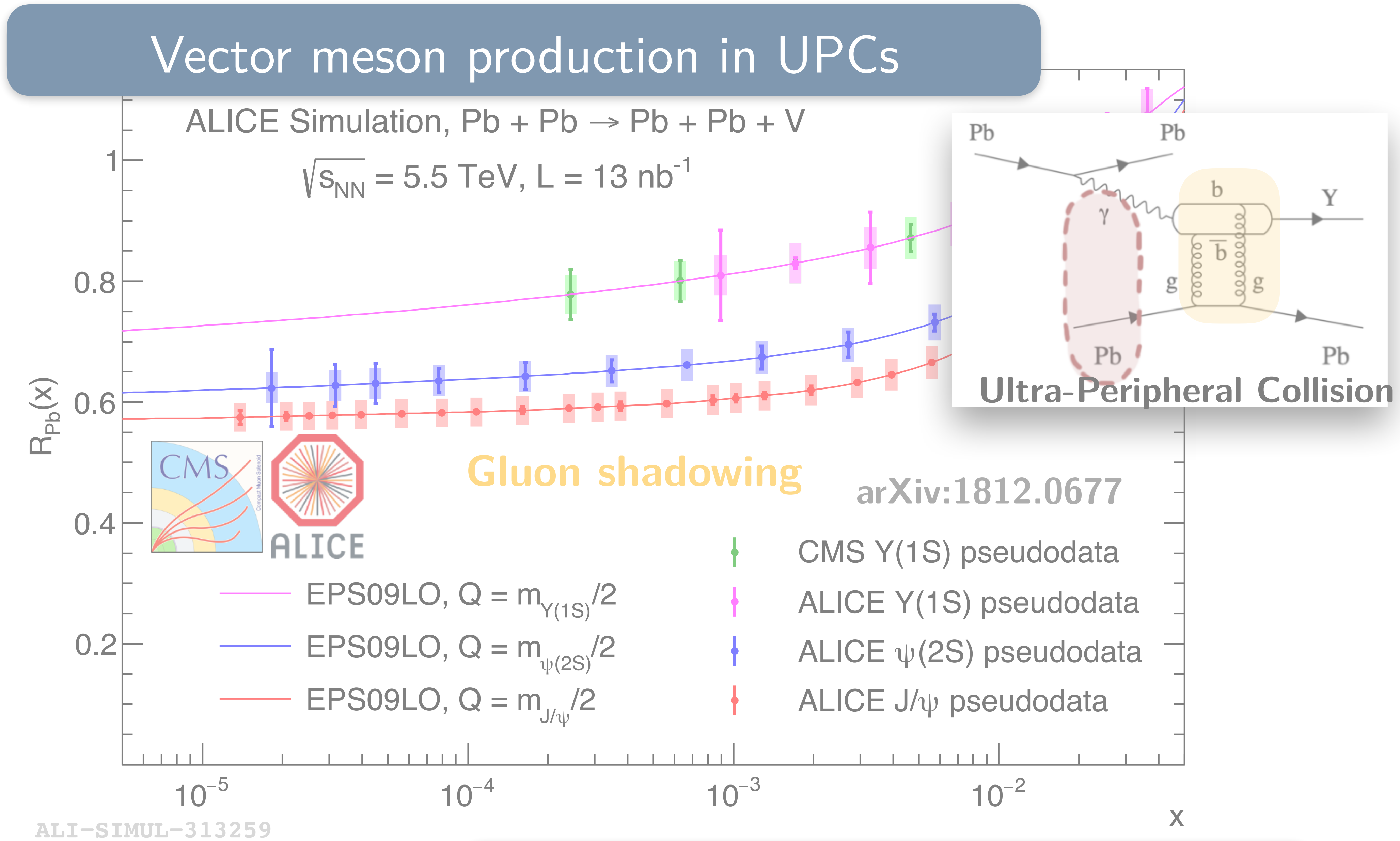

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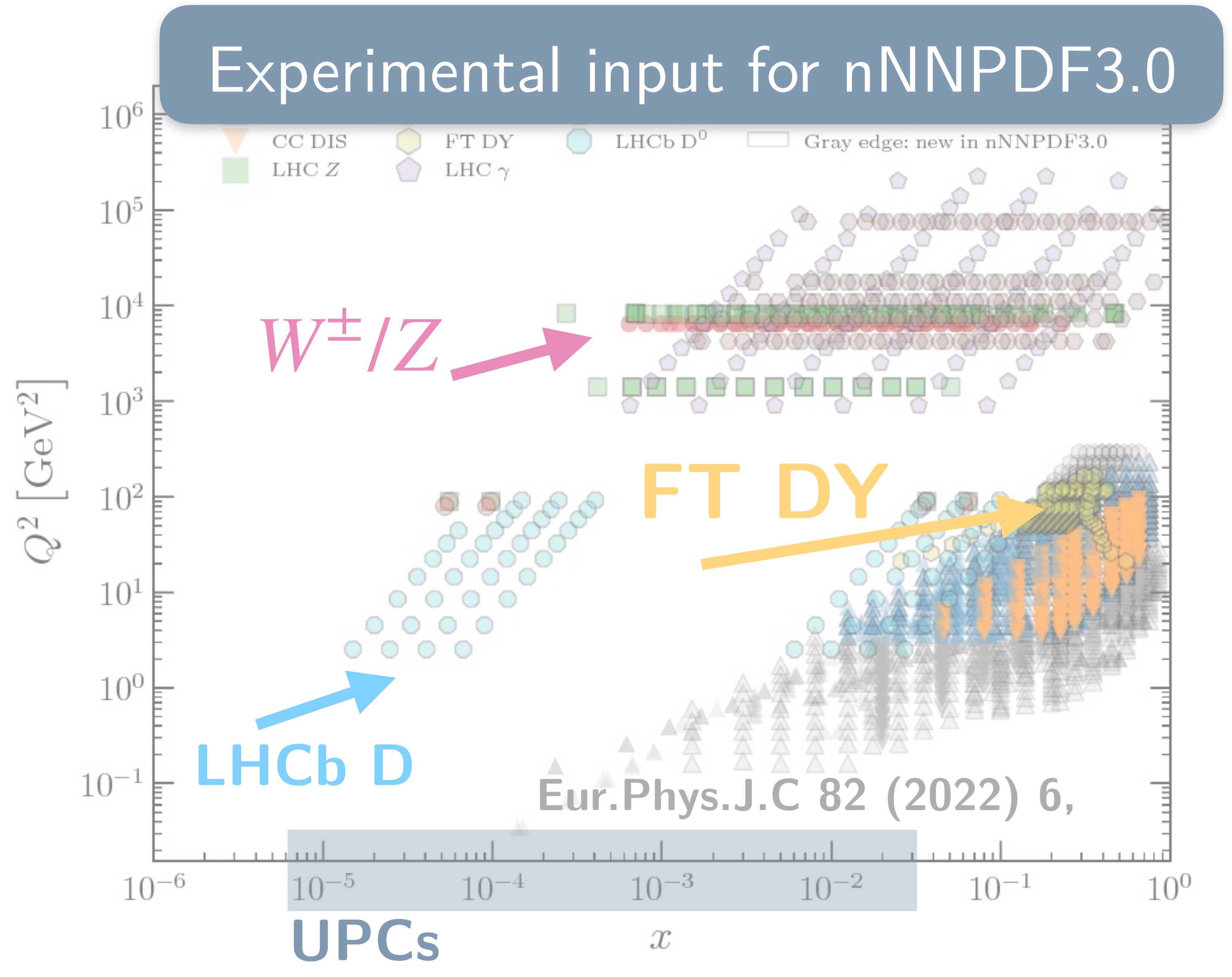

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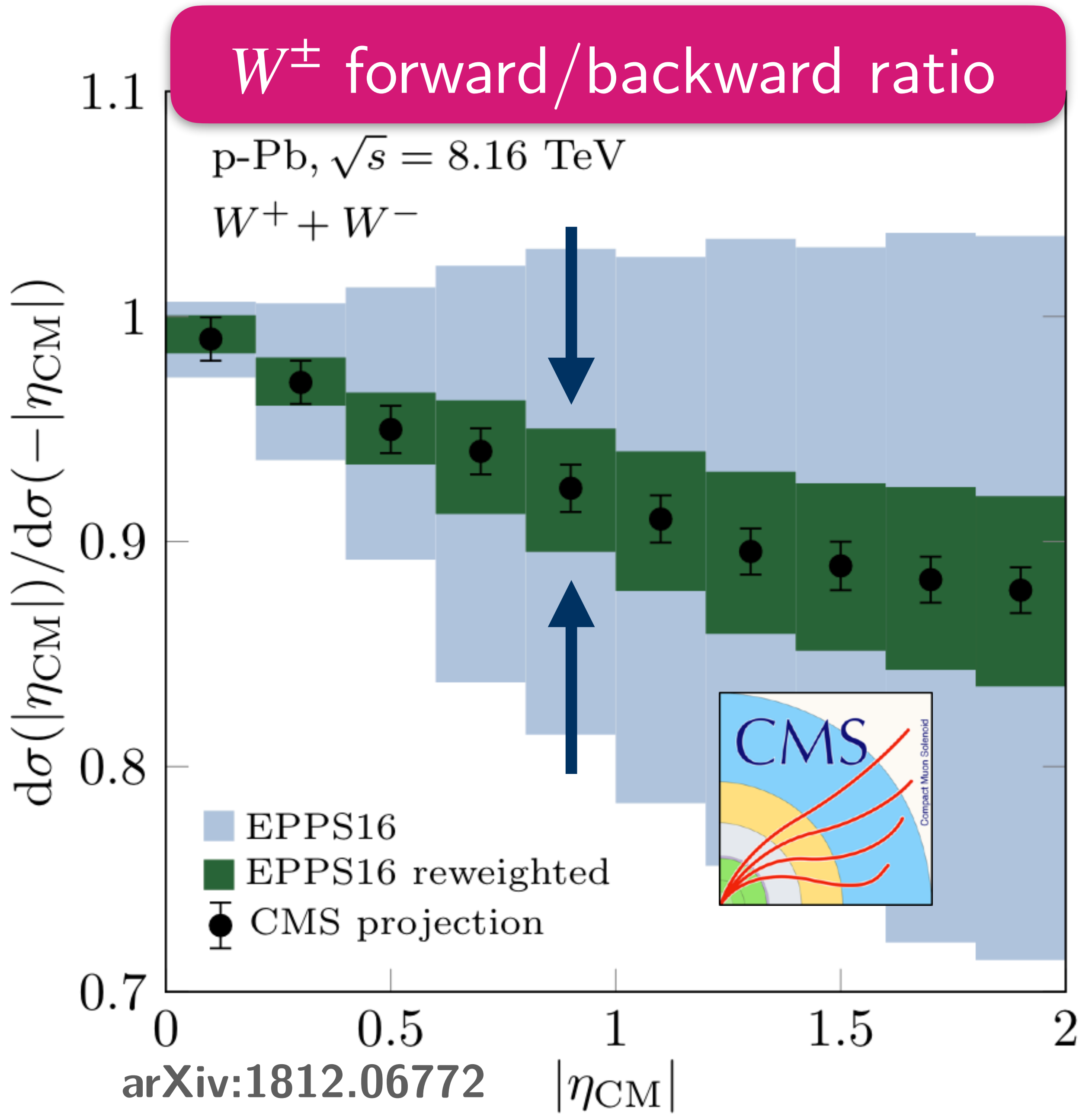

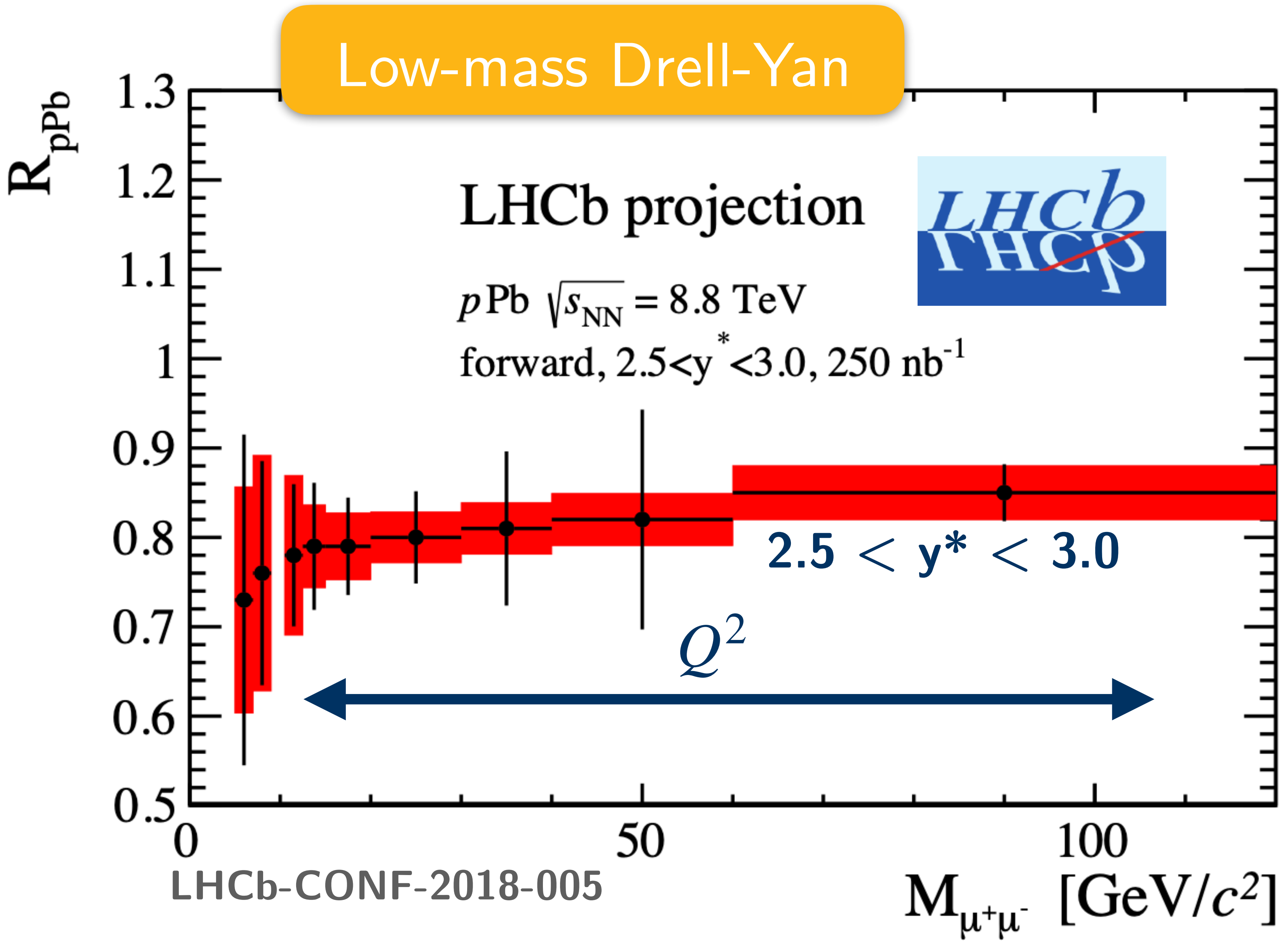

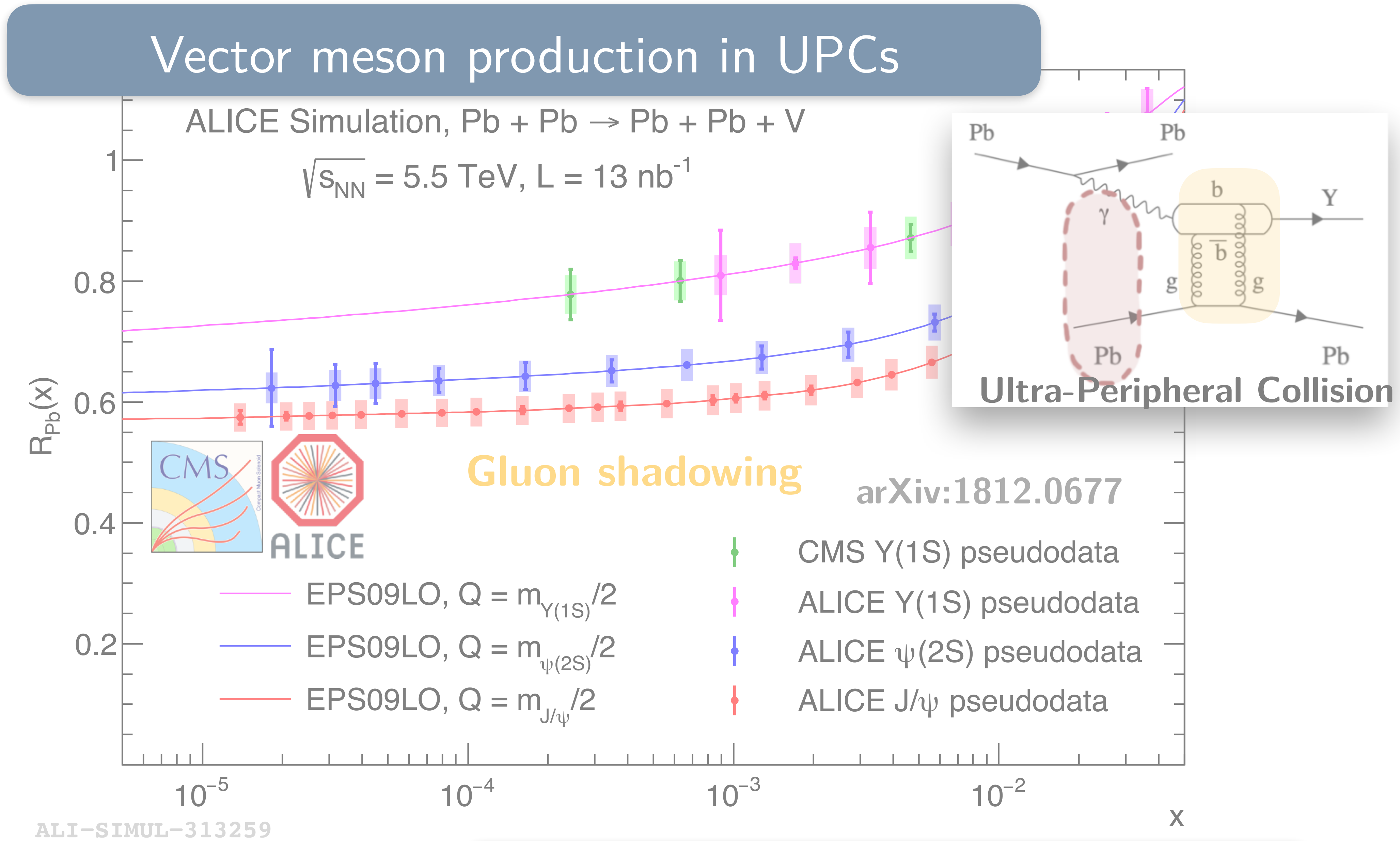

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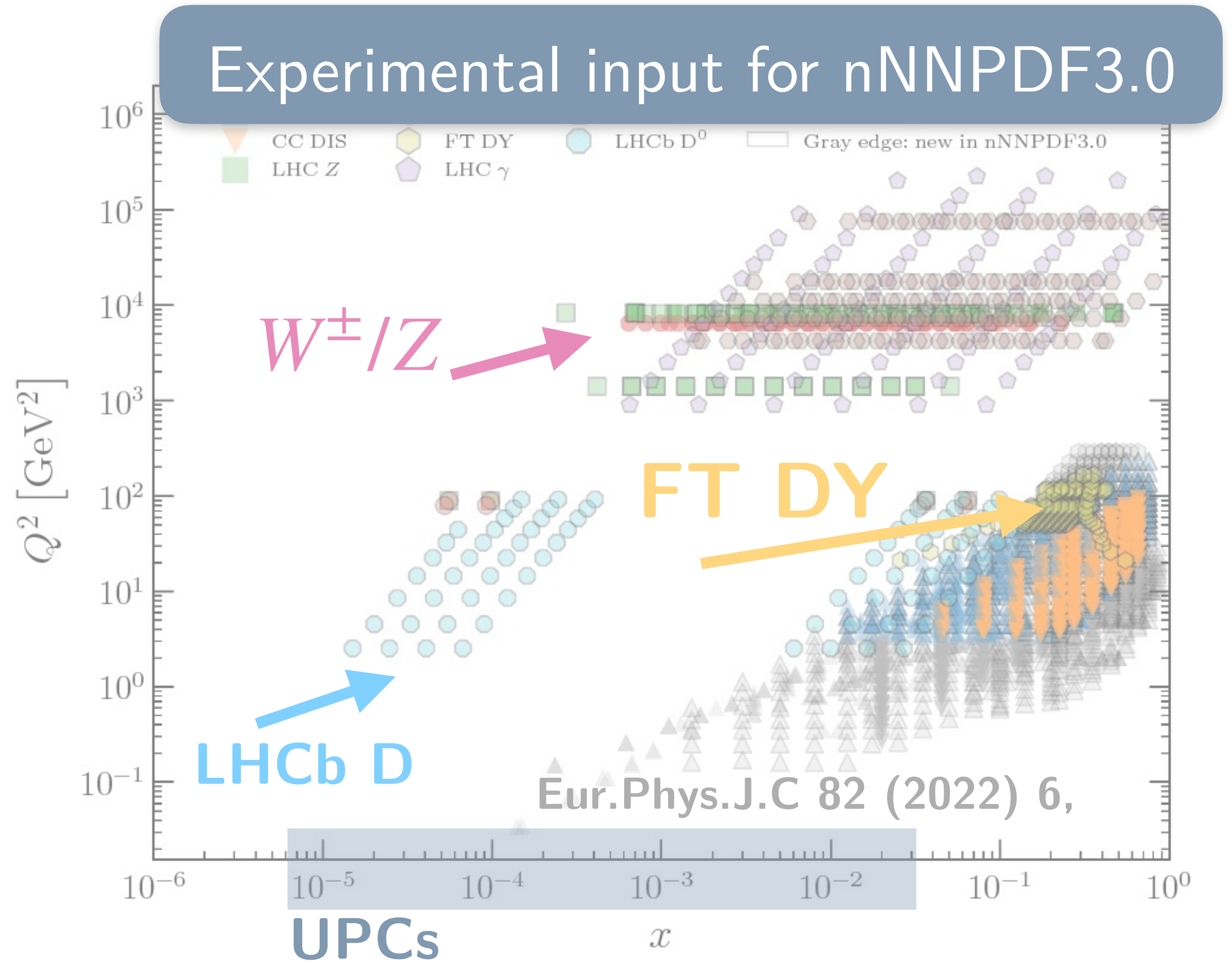

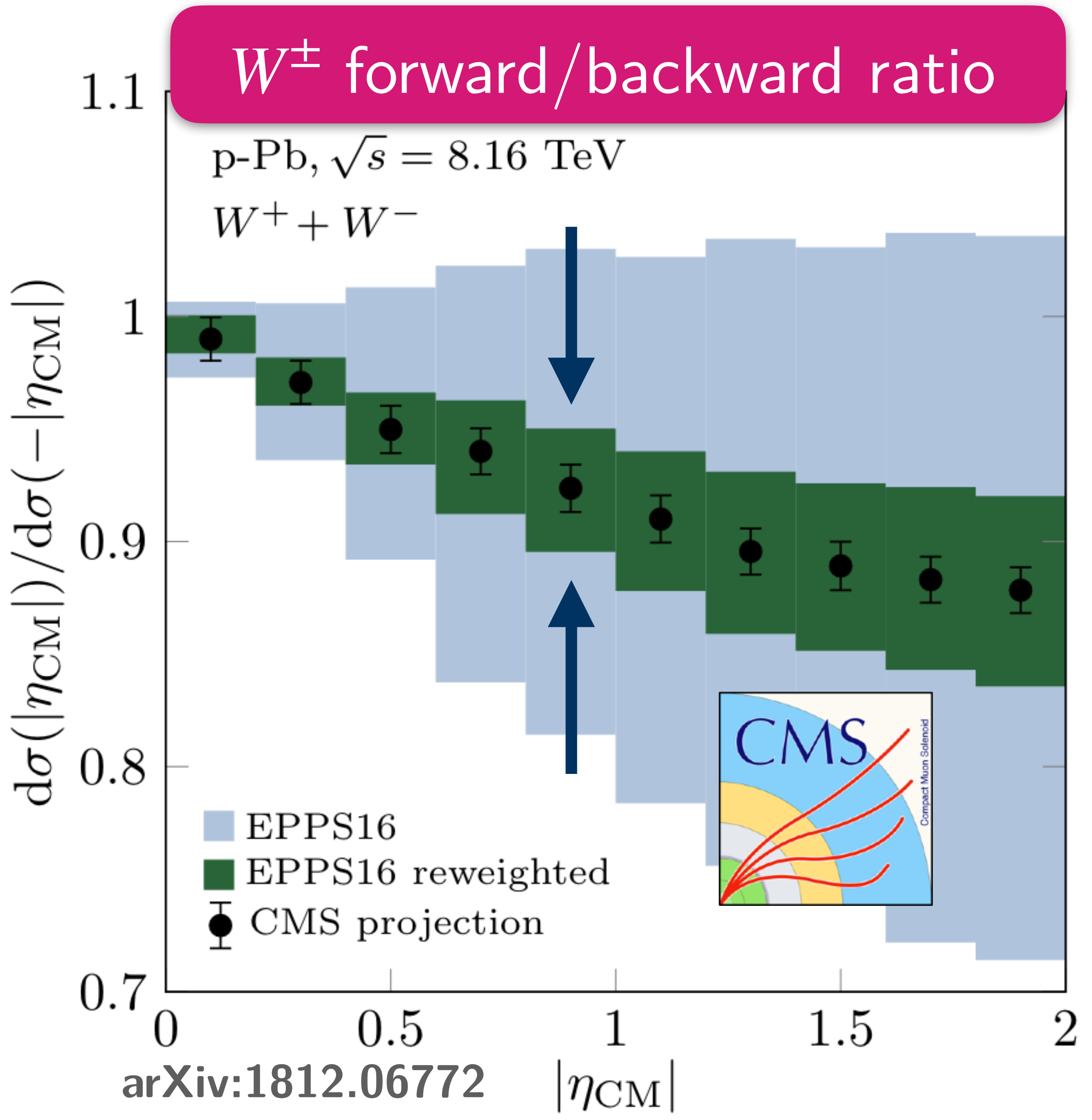

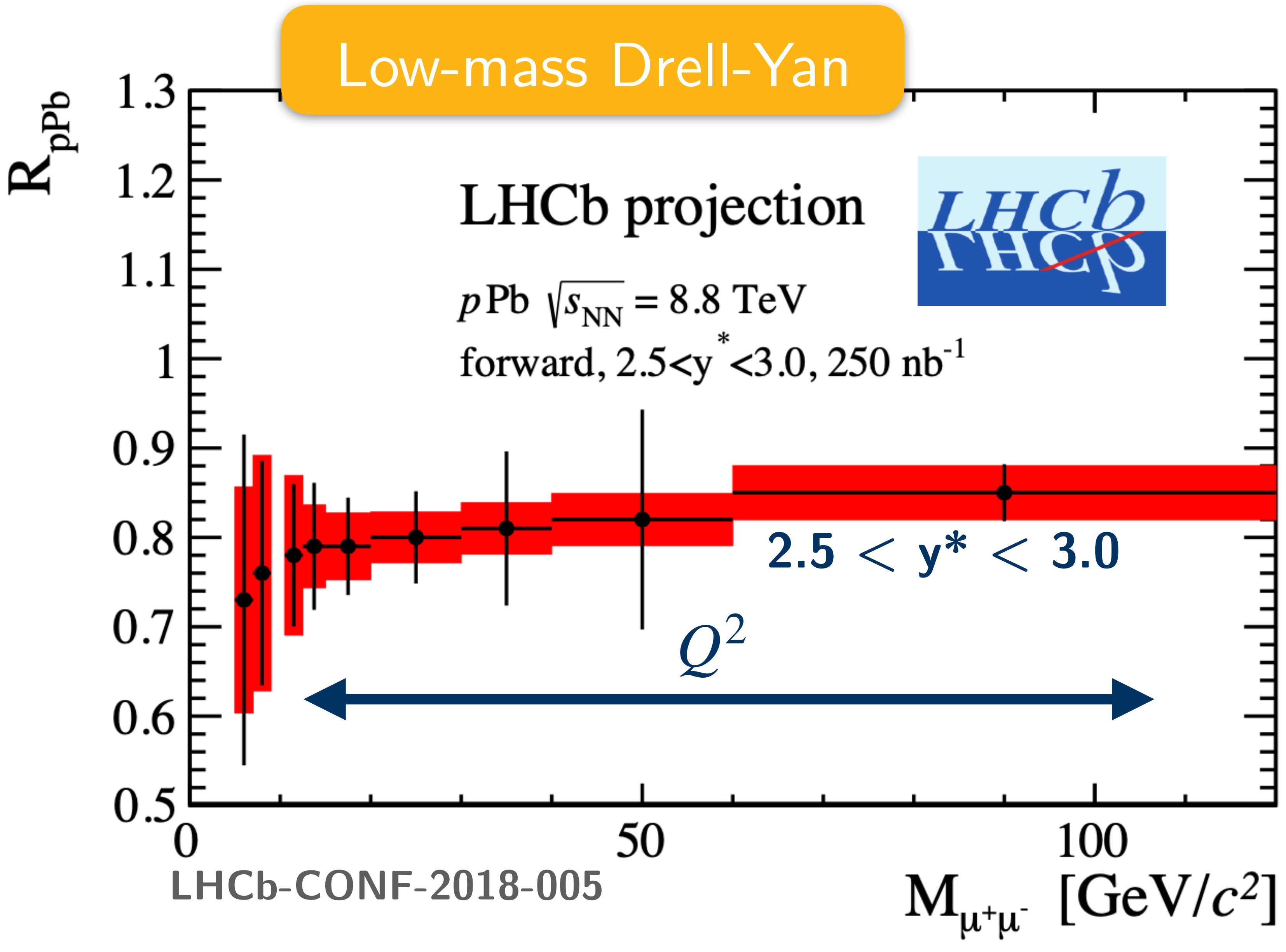

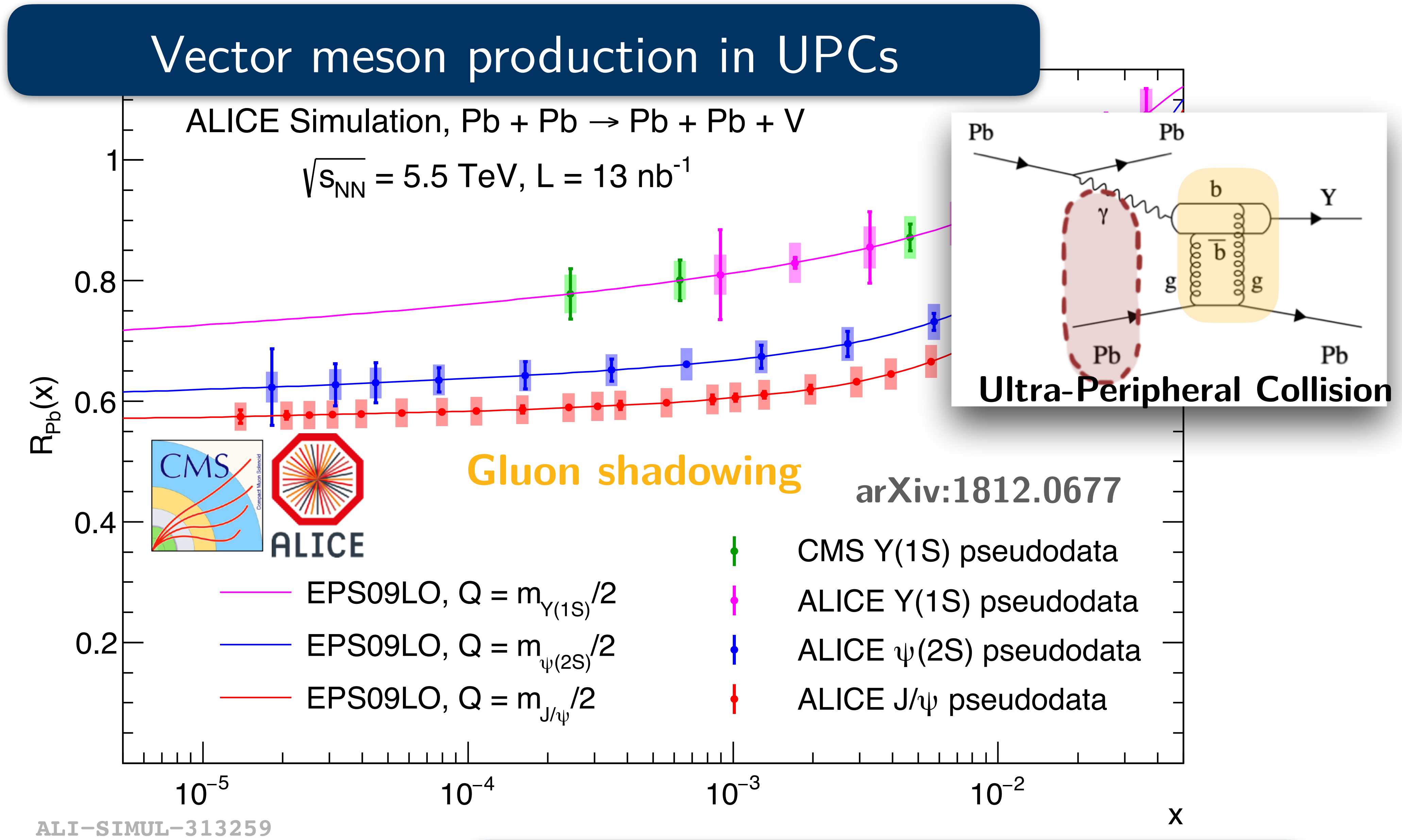

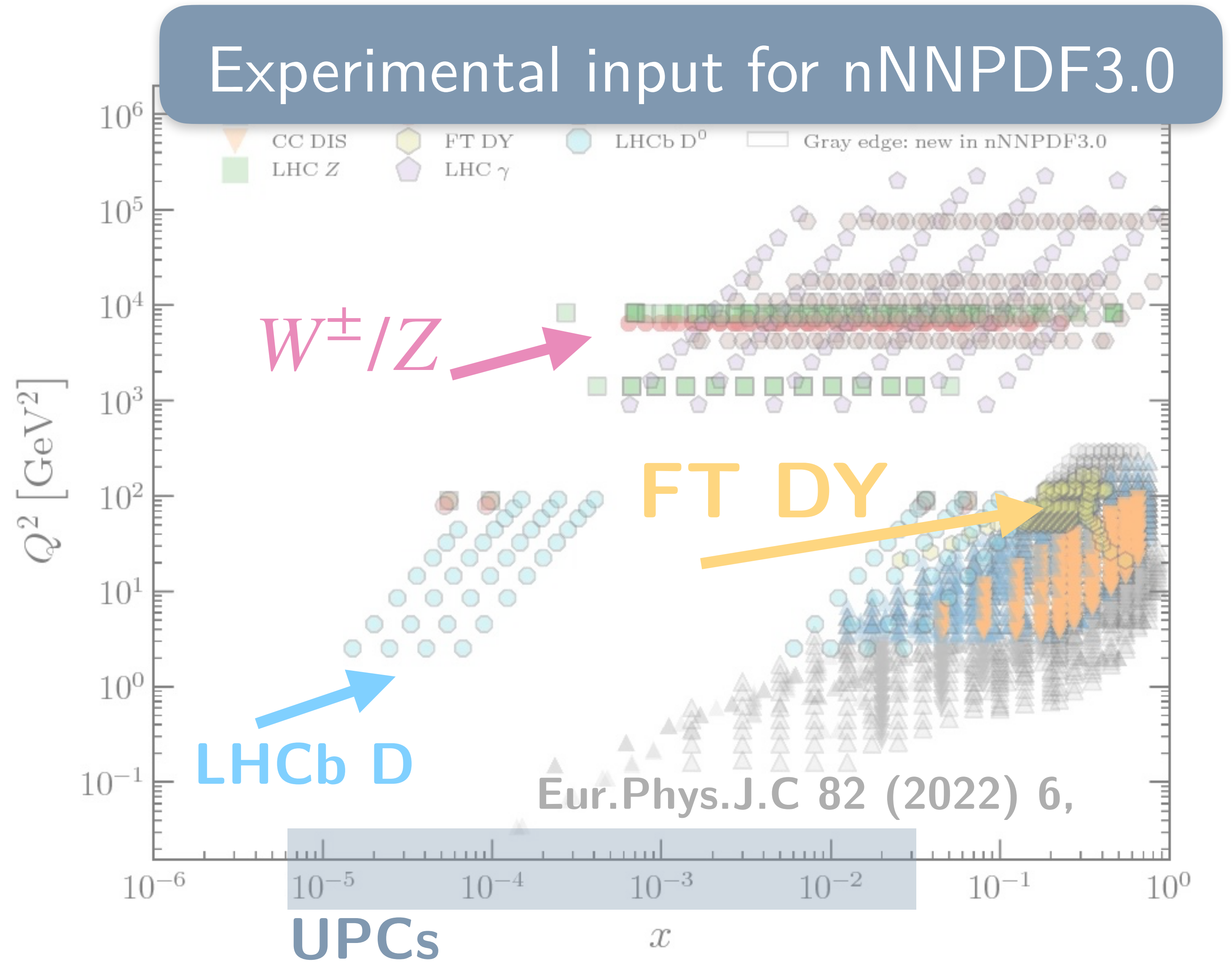

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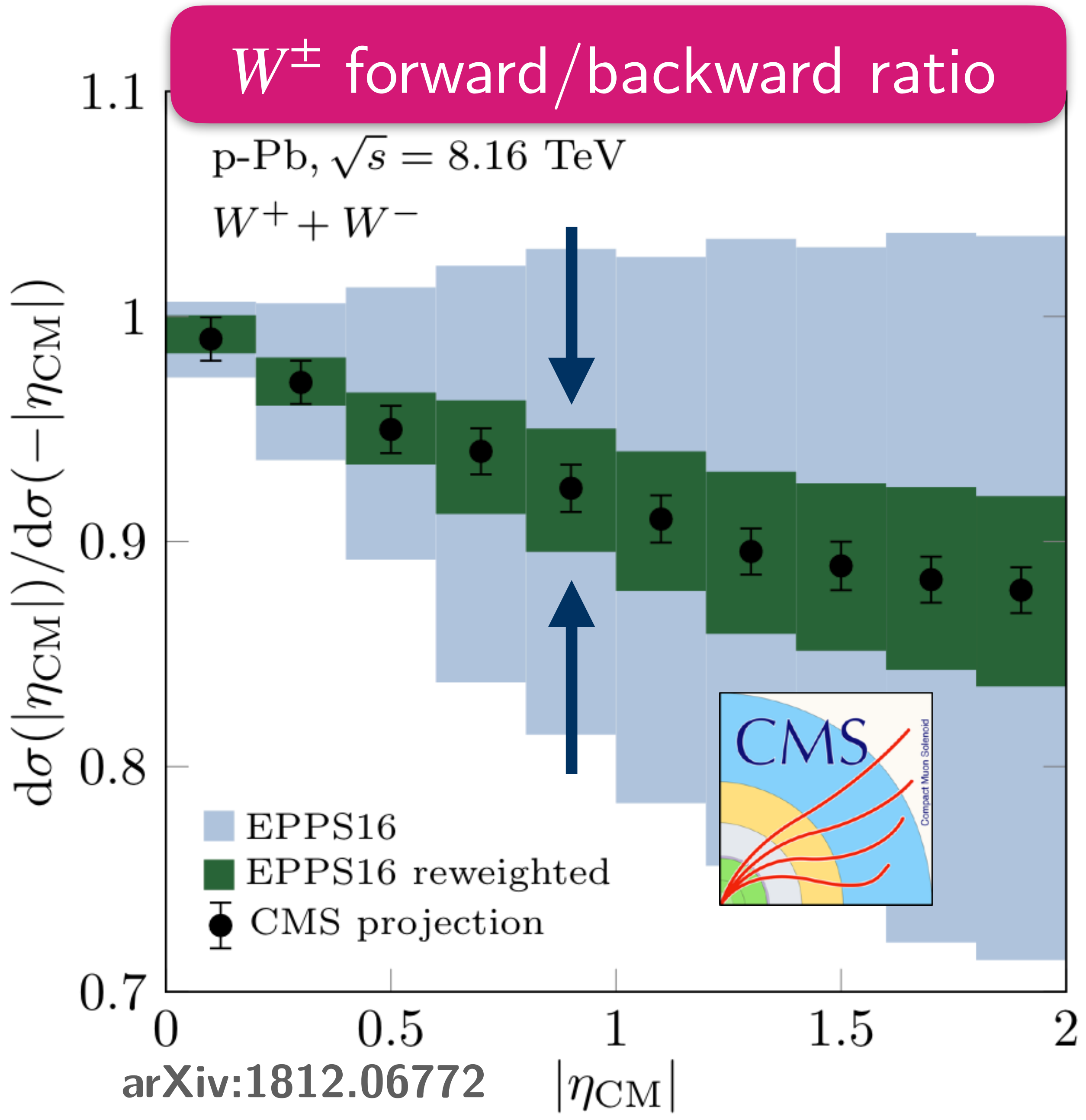

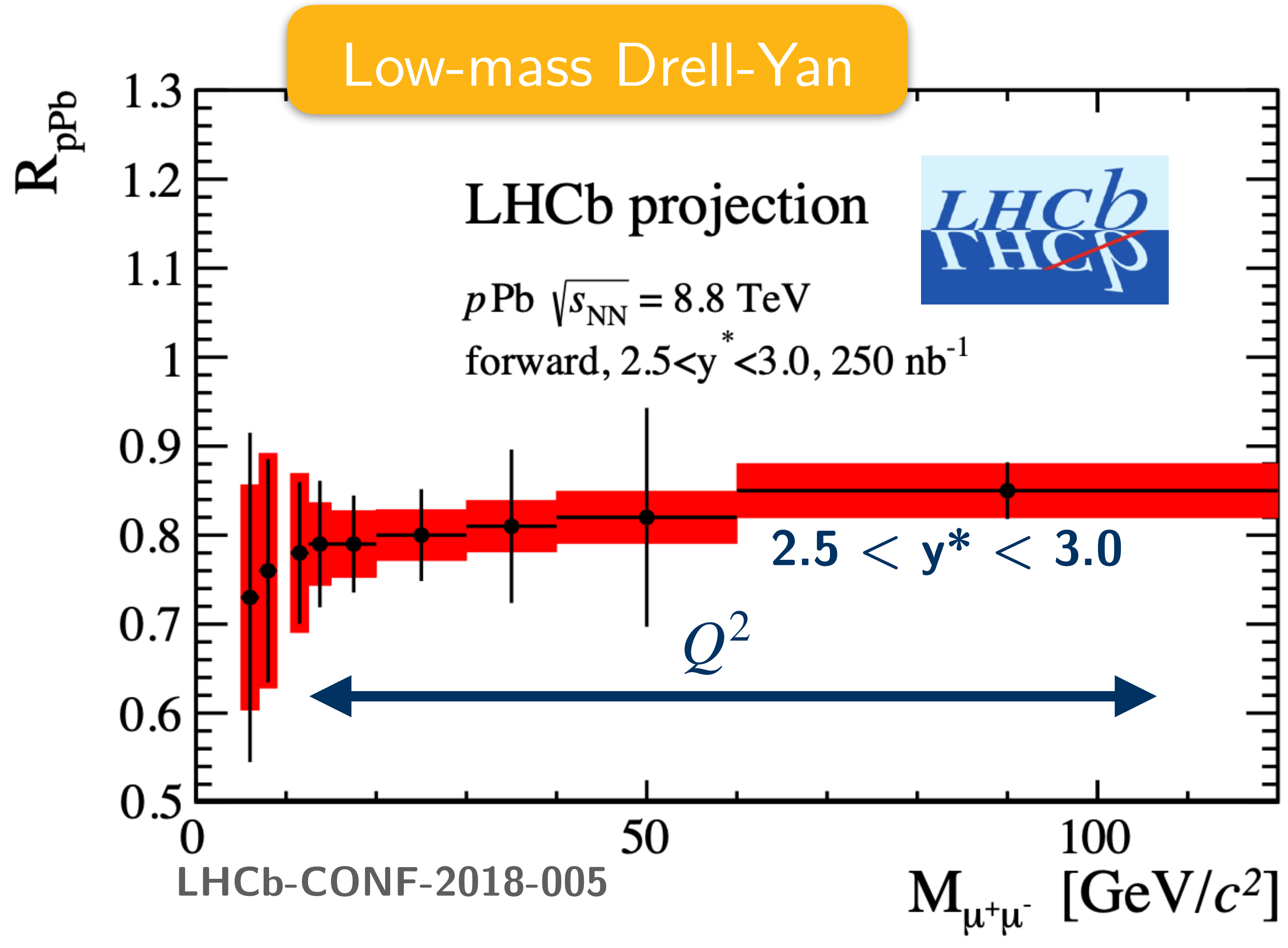

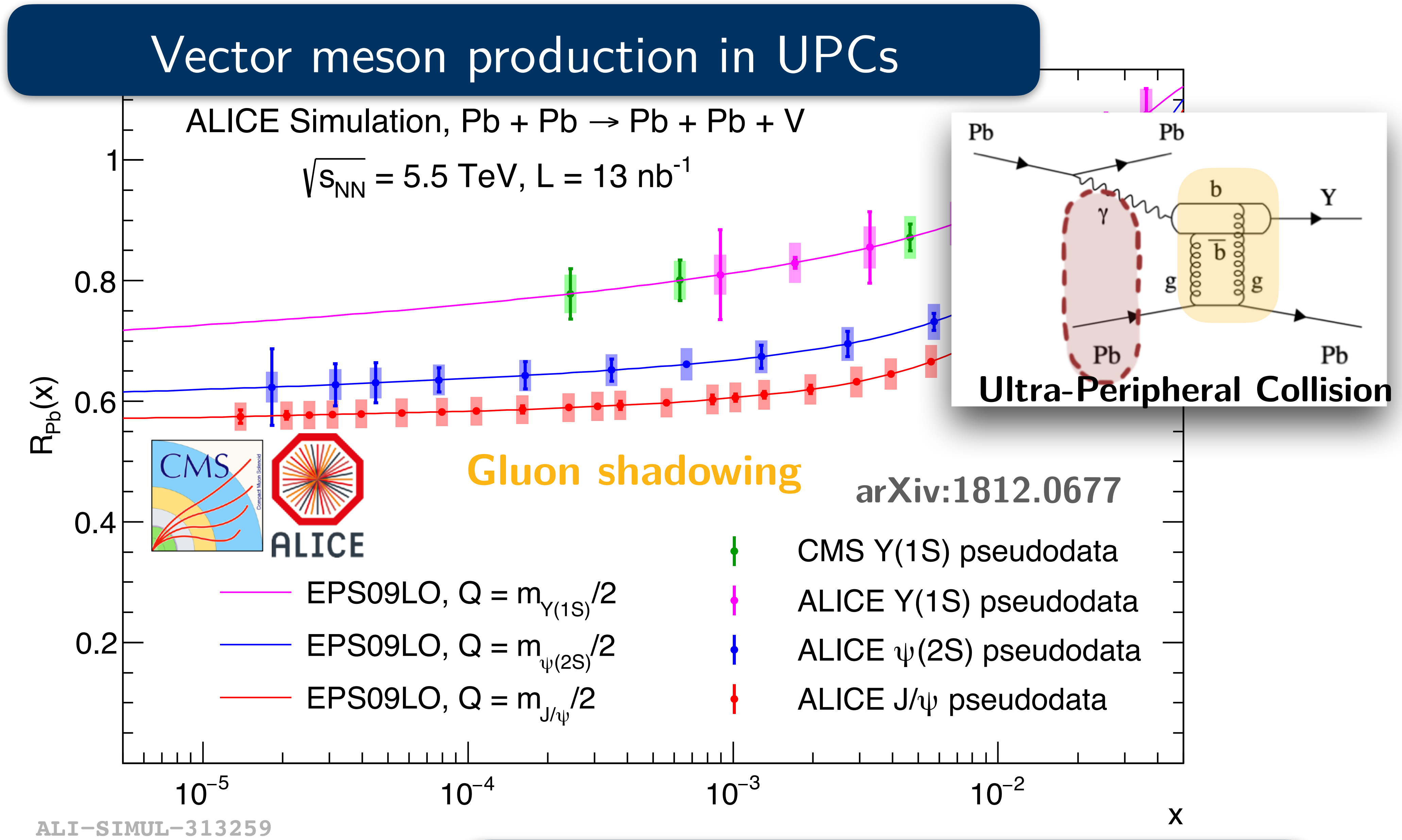

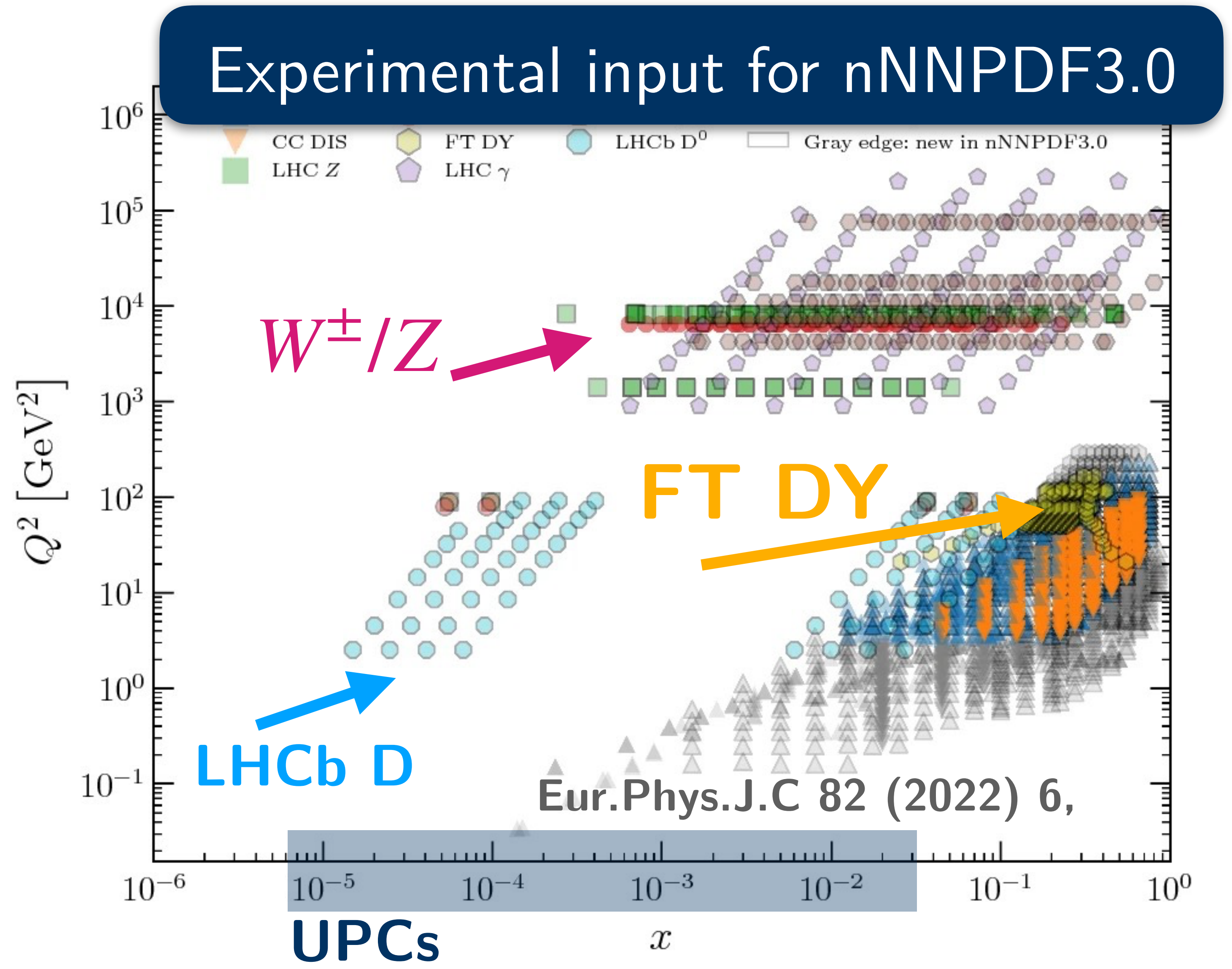

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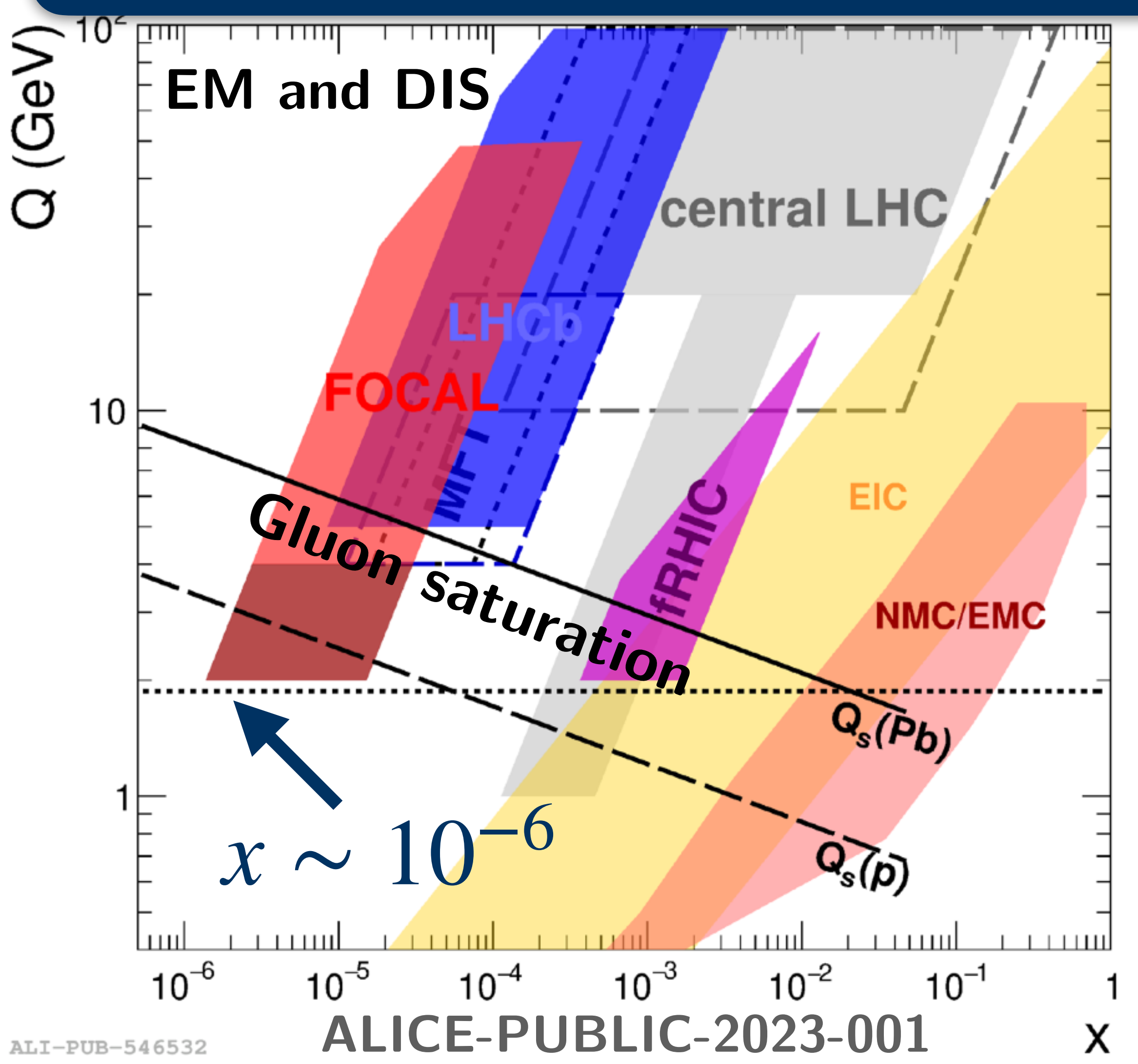
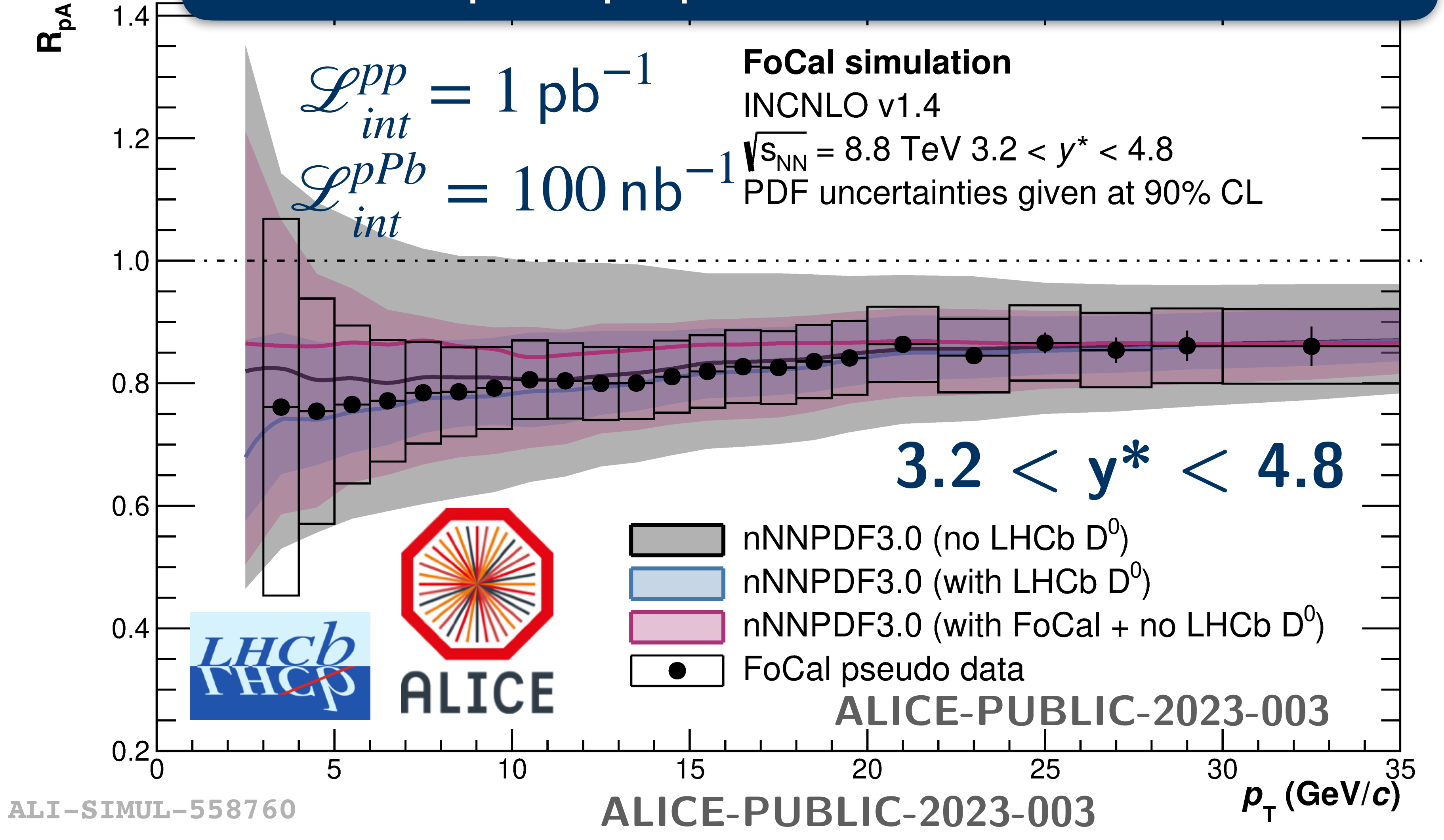
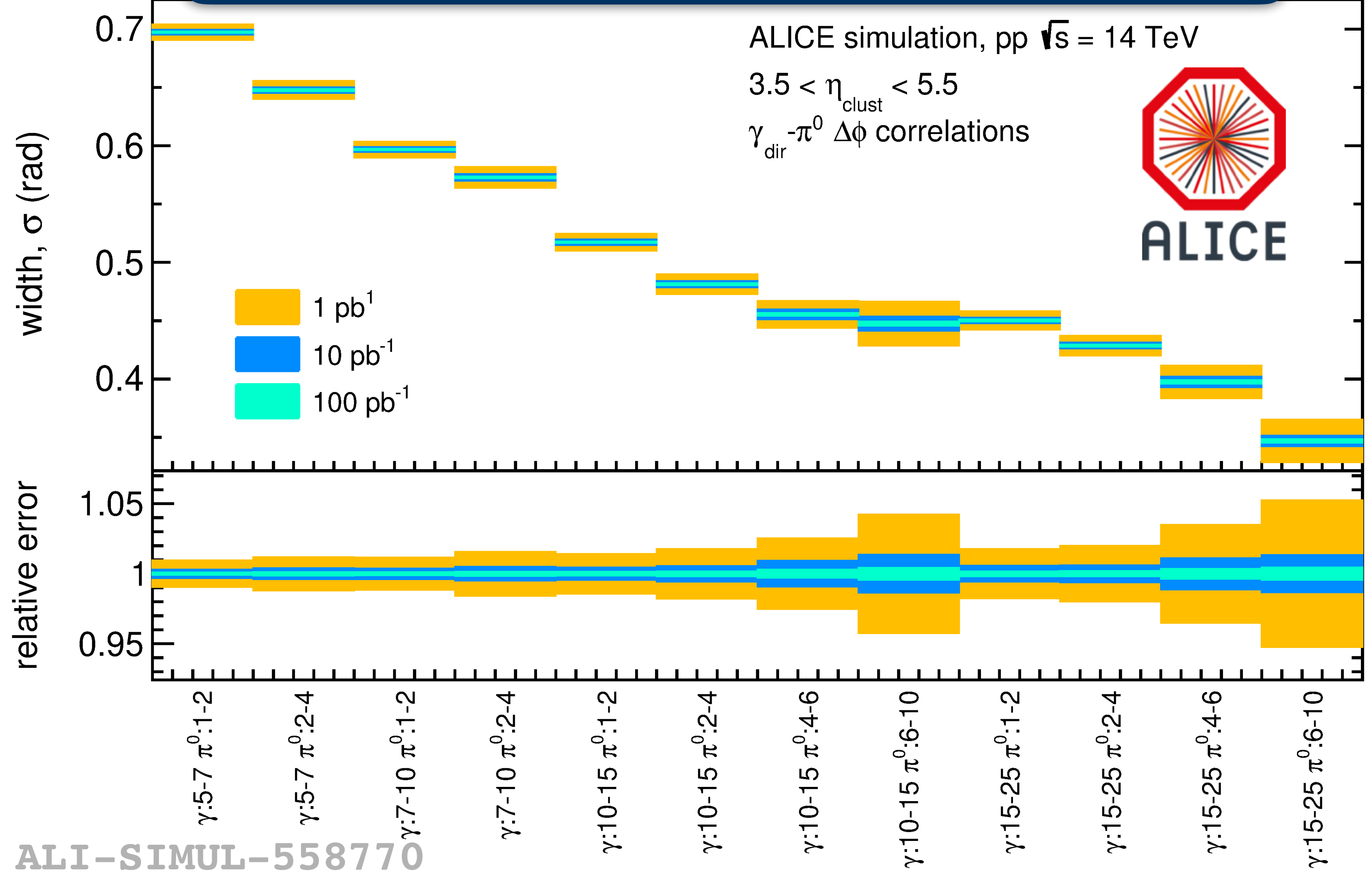


Forward prompt photons with ALICE FoCal



$\gamma_{iso} - \pi^0$ correlations with ALICE FoCal



Unprecedented low-x reach at forward LHC

deep theoretical connection to EIC physics

- Multiple processes in **e-A DIS** and **forward p-A** collisions are described using the **same dipole/quadrupole scattering amplitudes!**

	Inclusive DIS	SIDIS	DIS dijet	Inclusive in p+A	γ+jet in p+A	dijet in p+A
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Nucl. Phys. A 1026 (2022) 122447

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→ **test universal description of gluon saturated matter**

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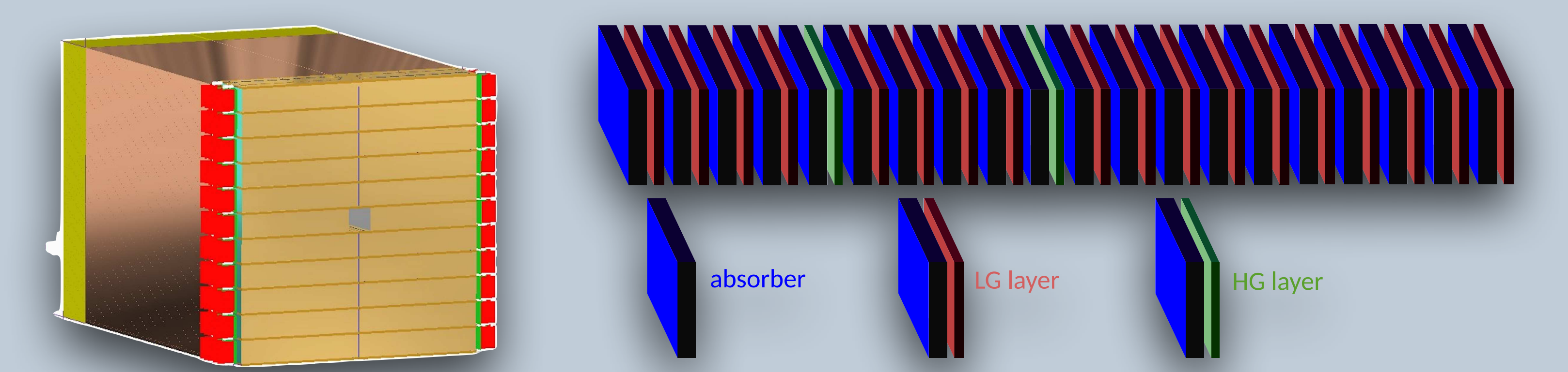

$3.2 < \eta < 5.8$

Pad

Pixel

FoCal-E

TDR: CERN-LHCC-2024-004

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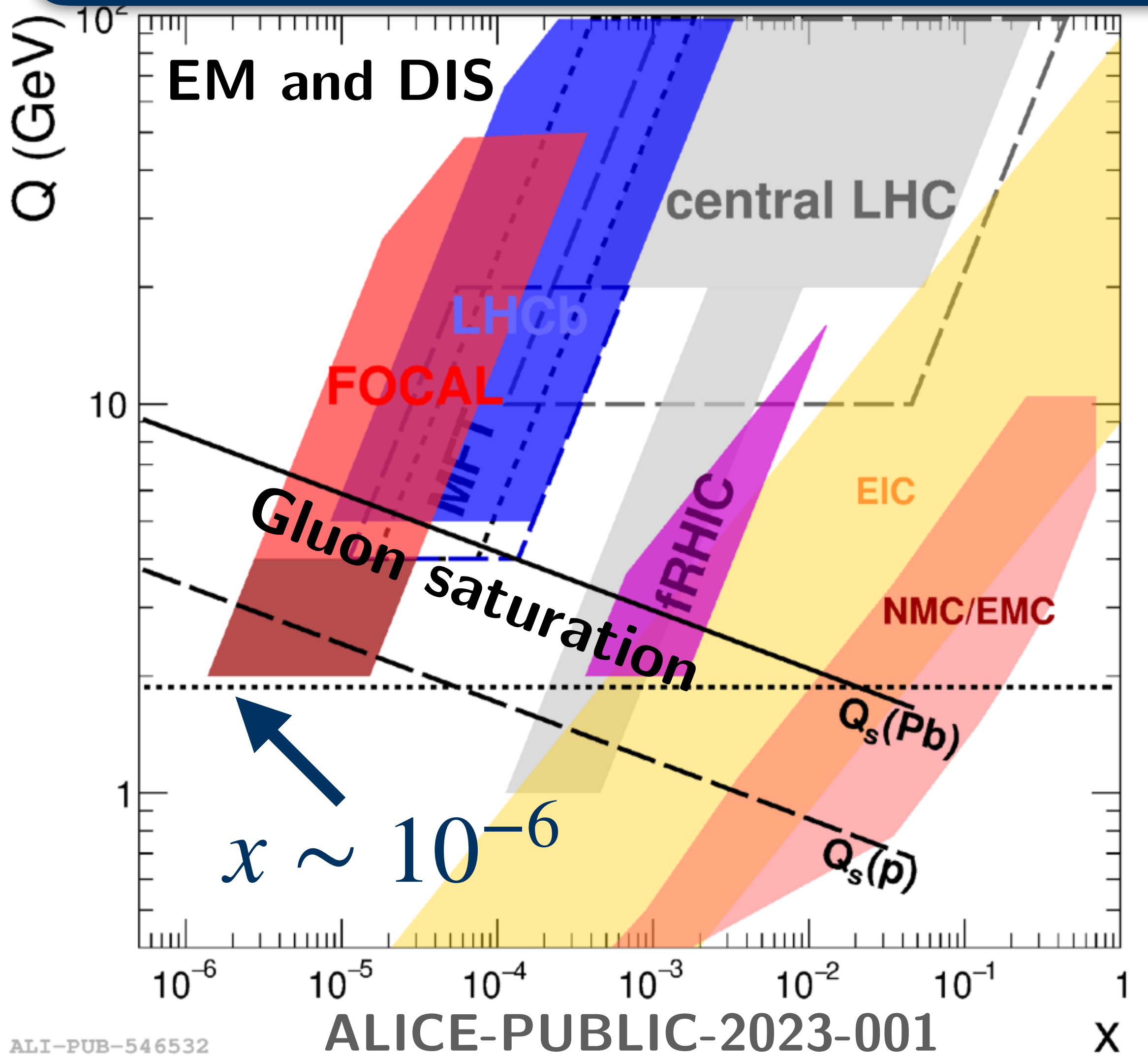

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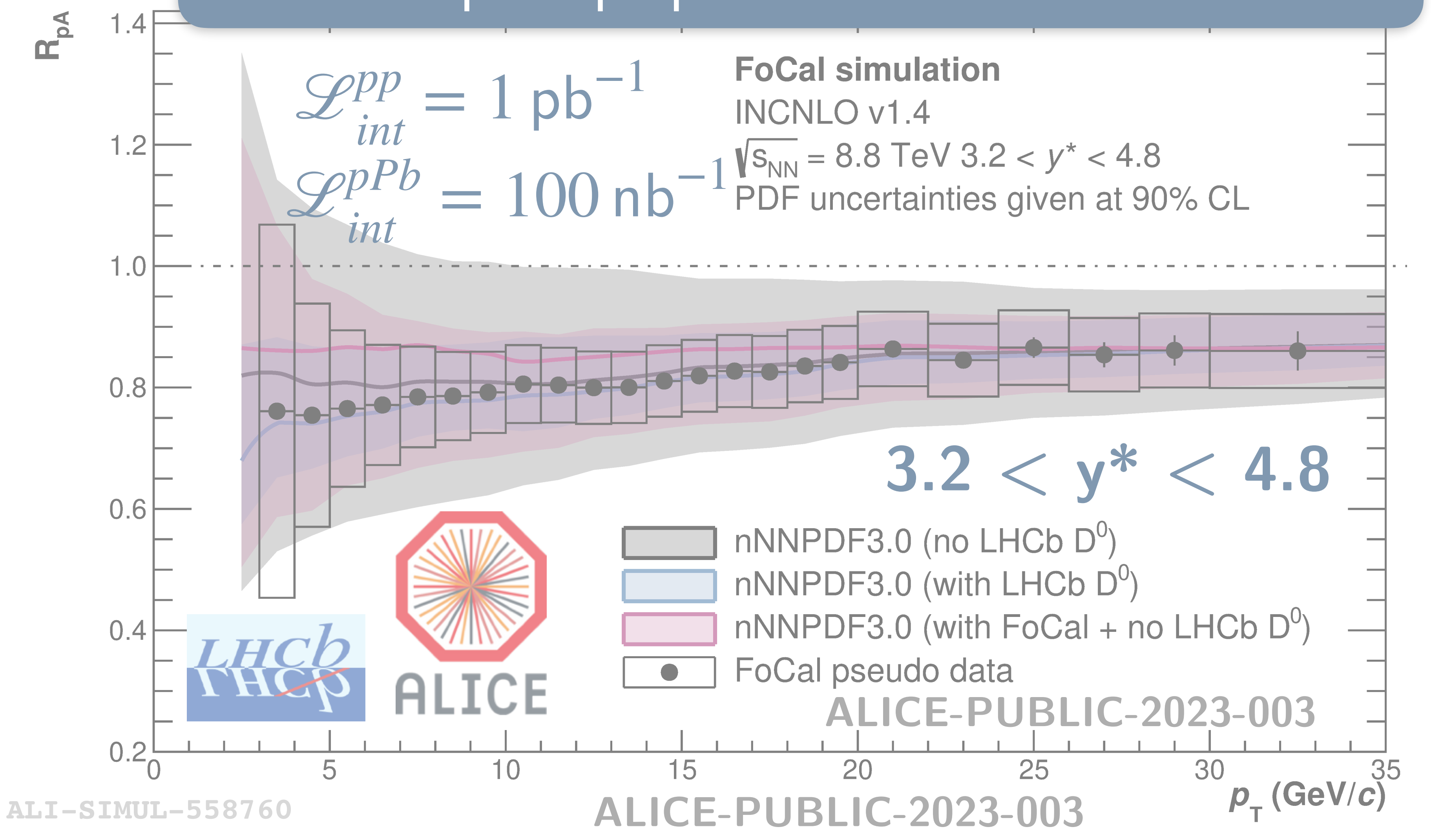

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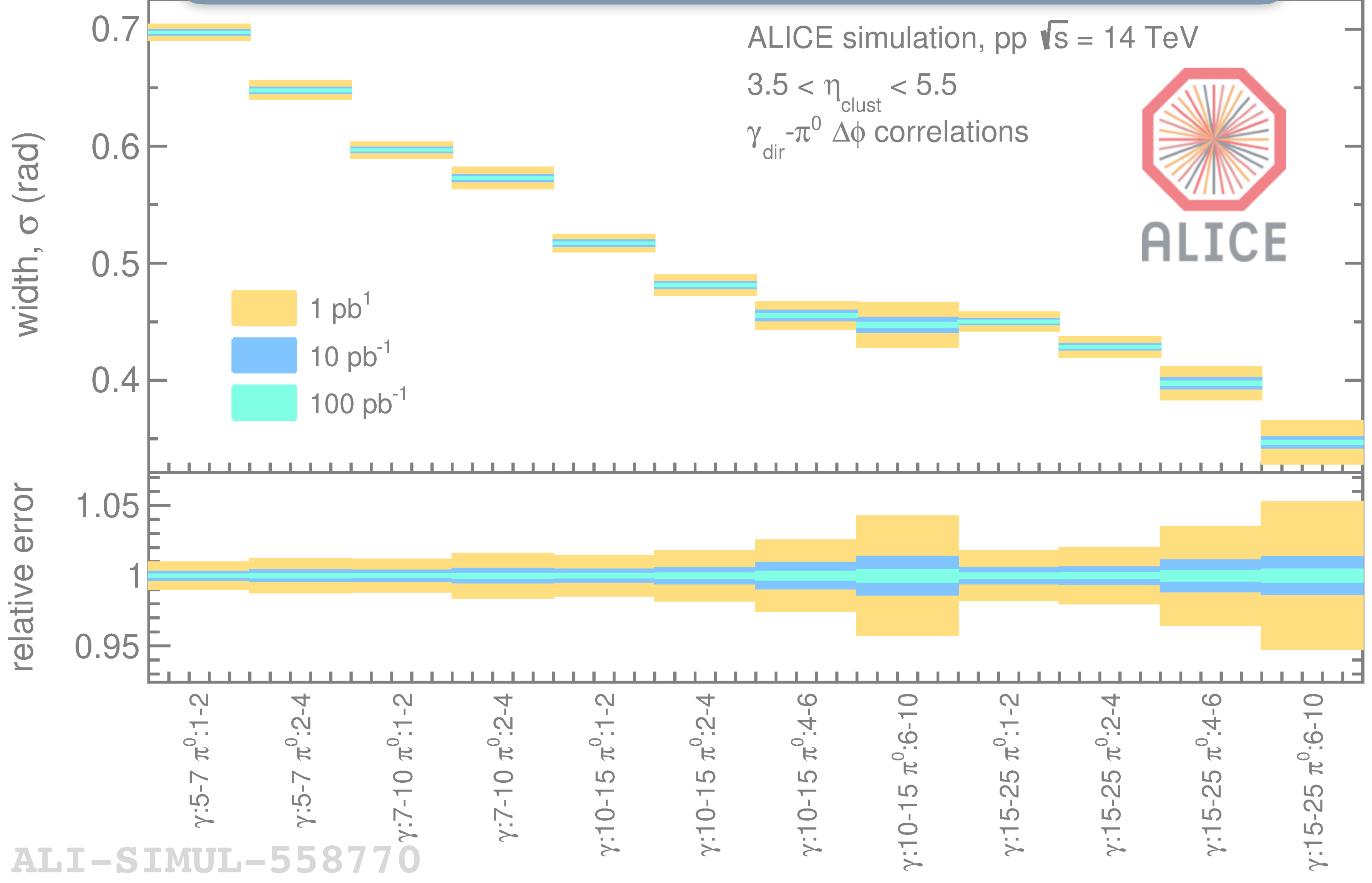

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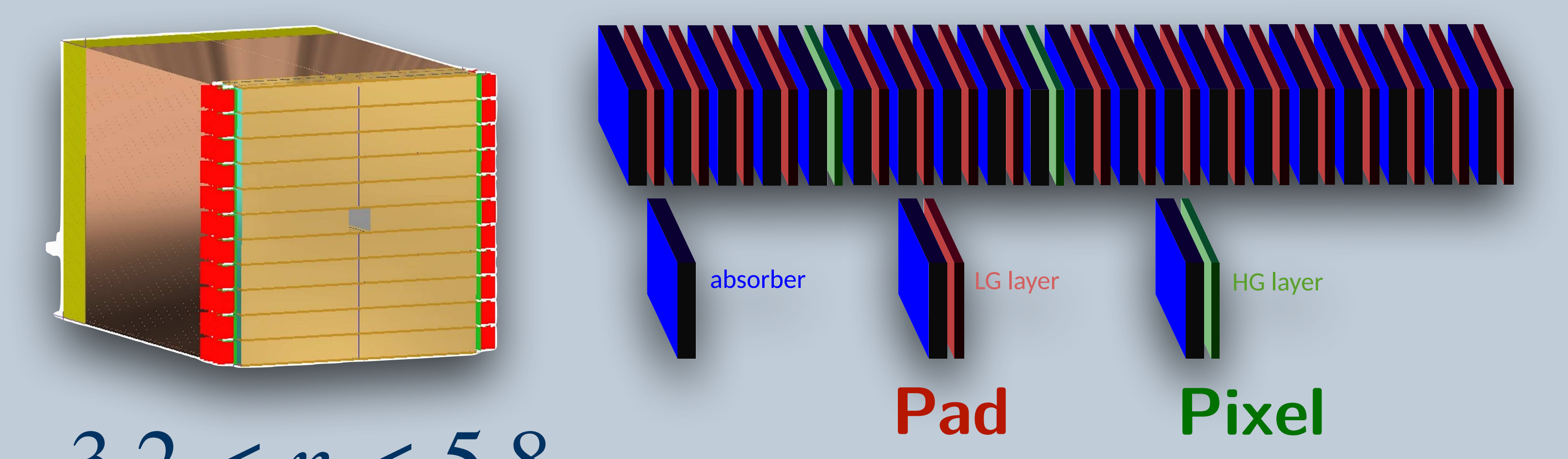

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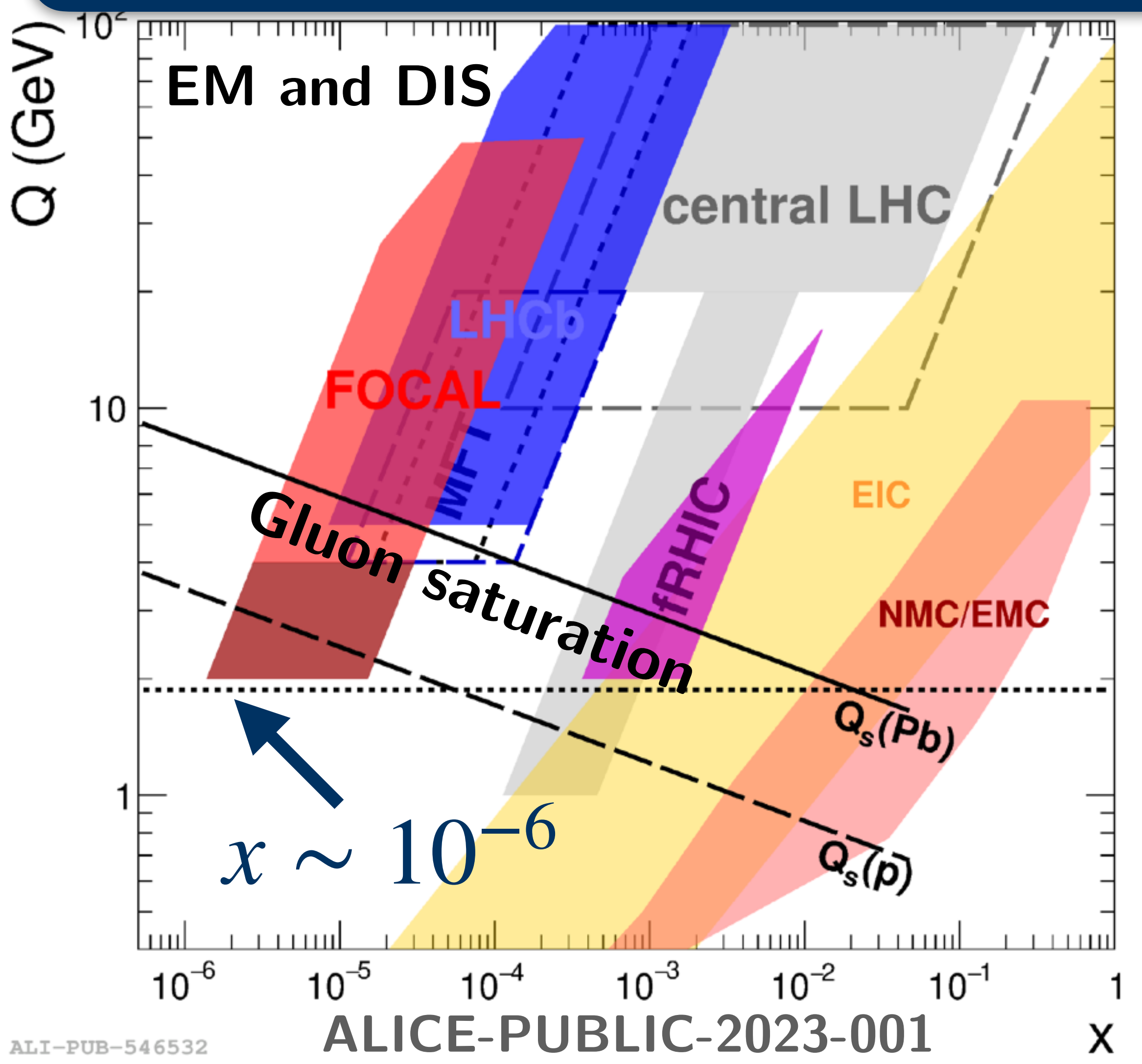

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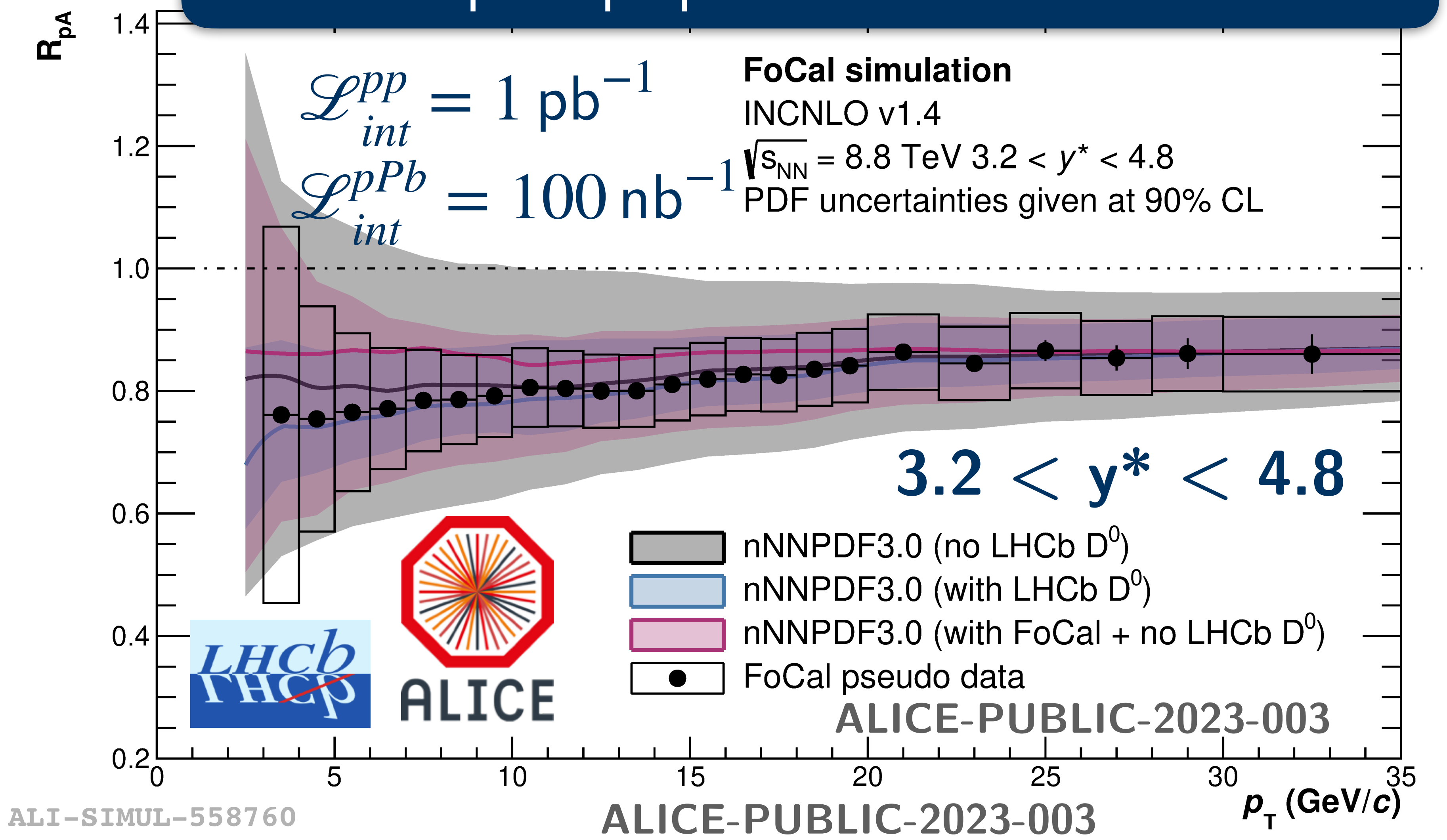

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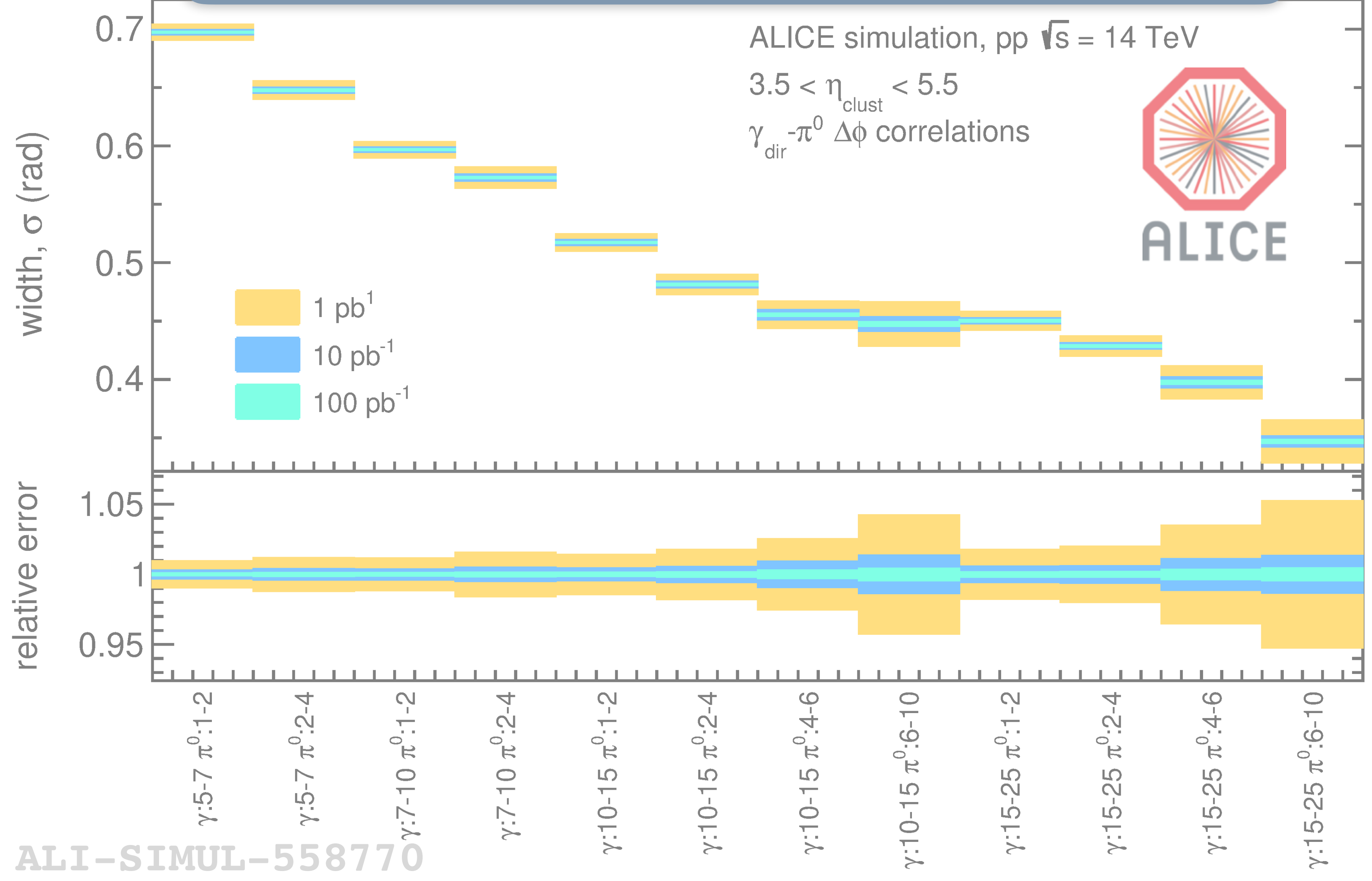

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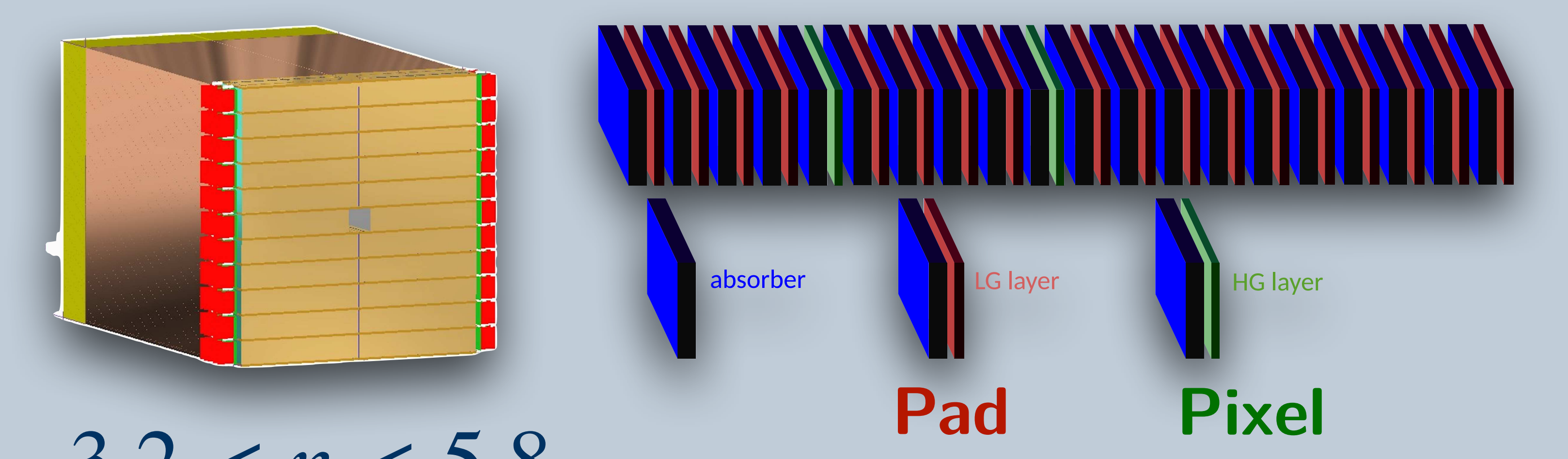

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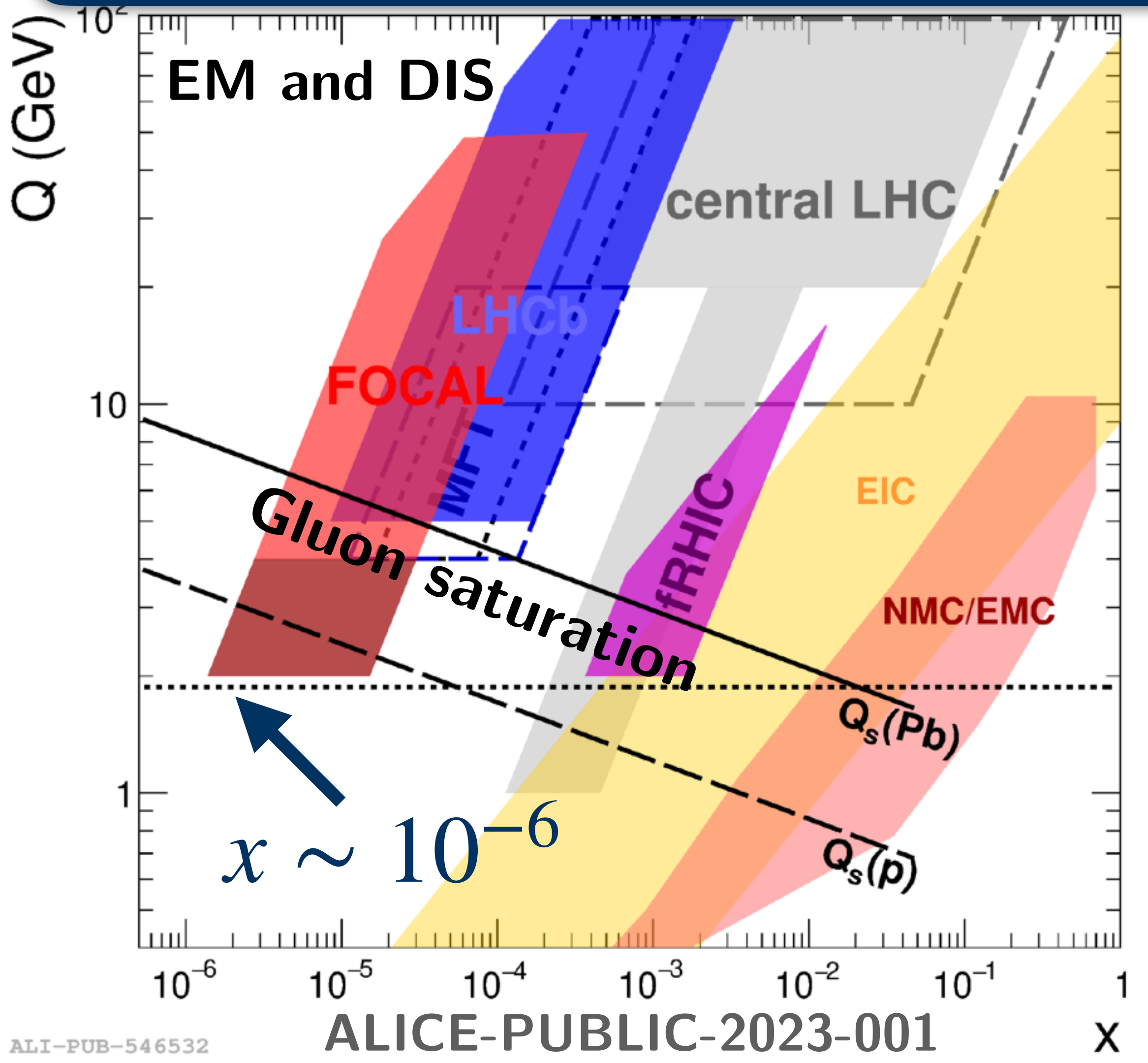

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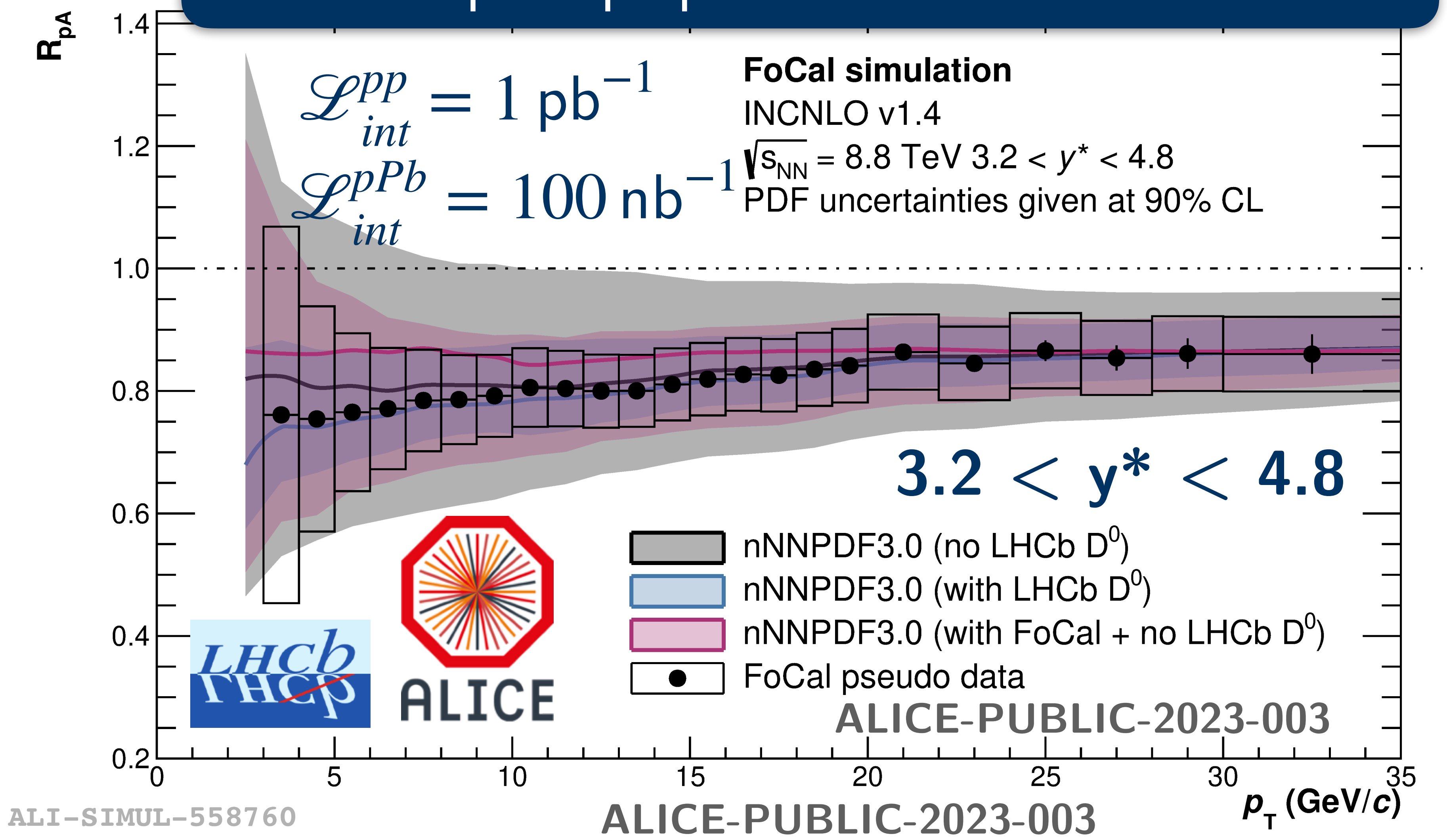

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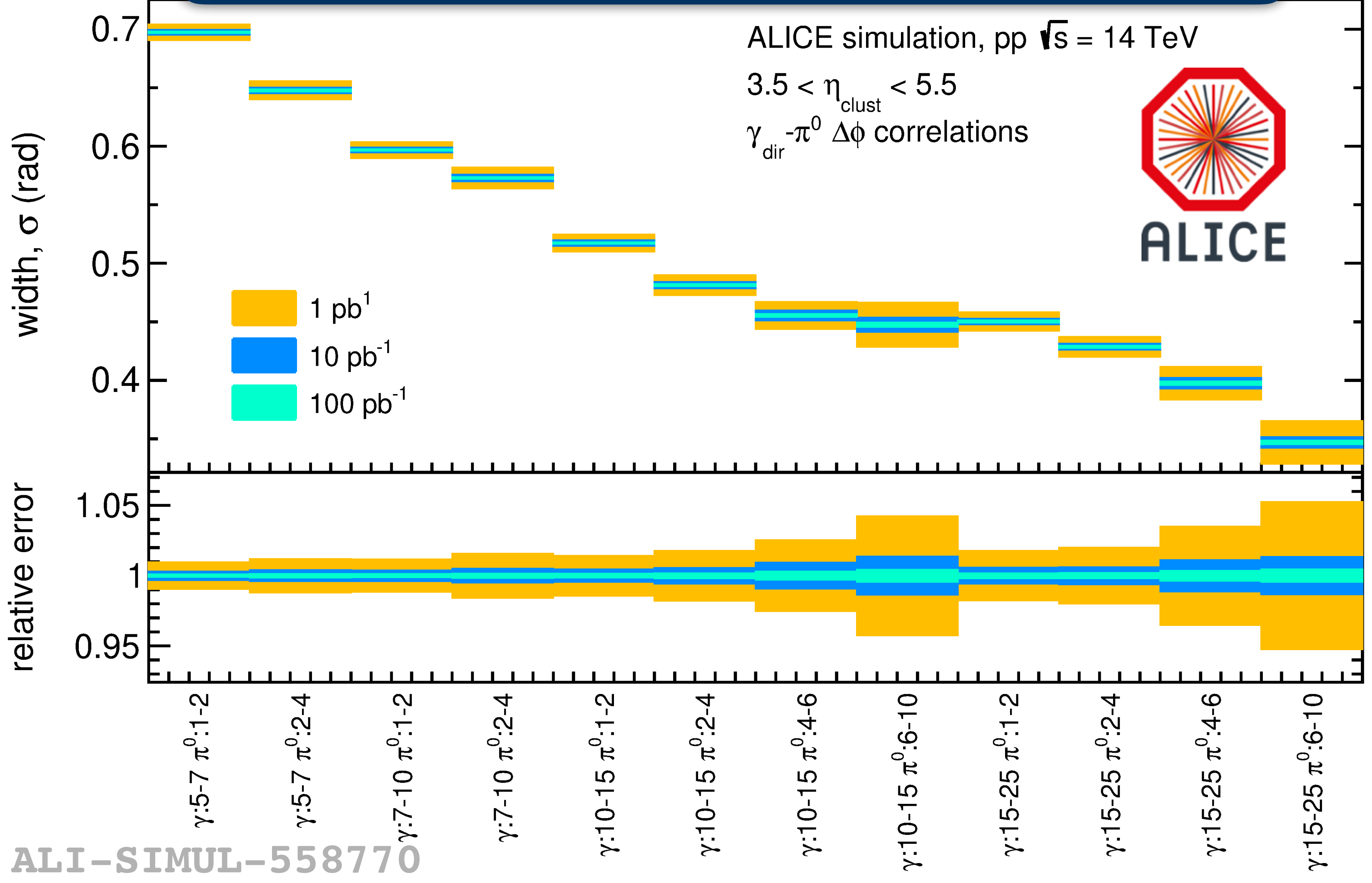

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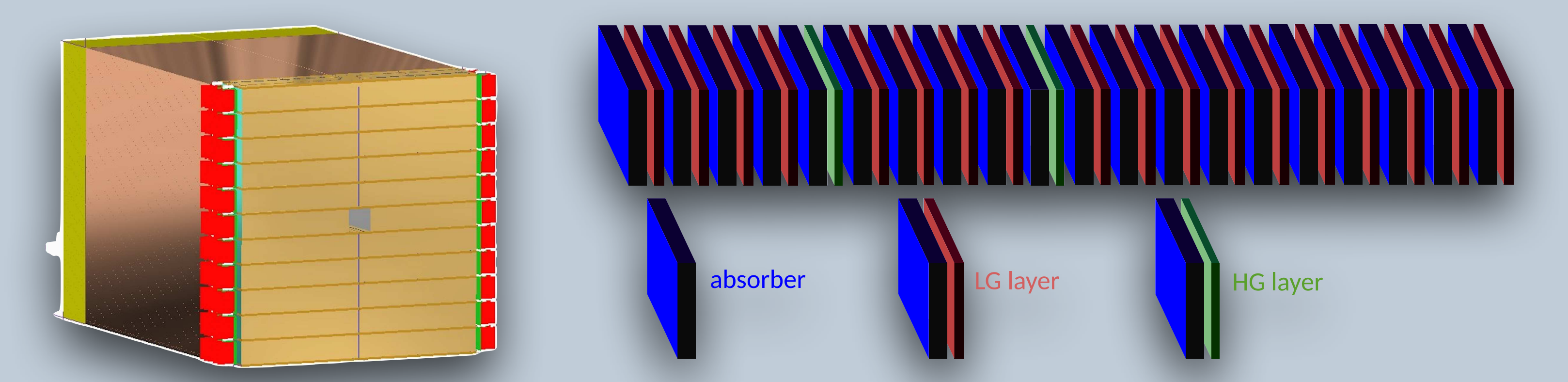

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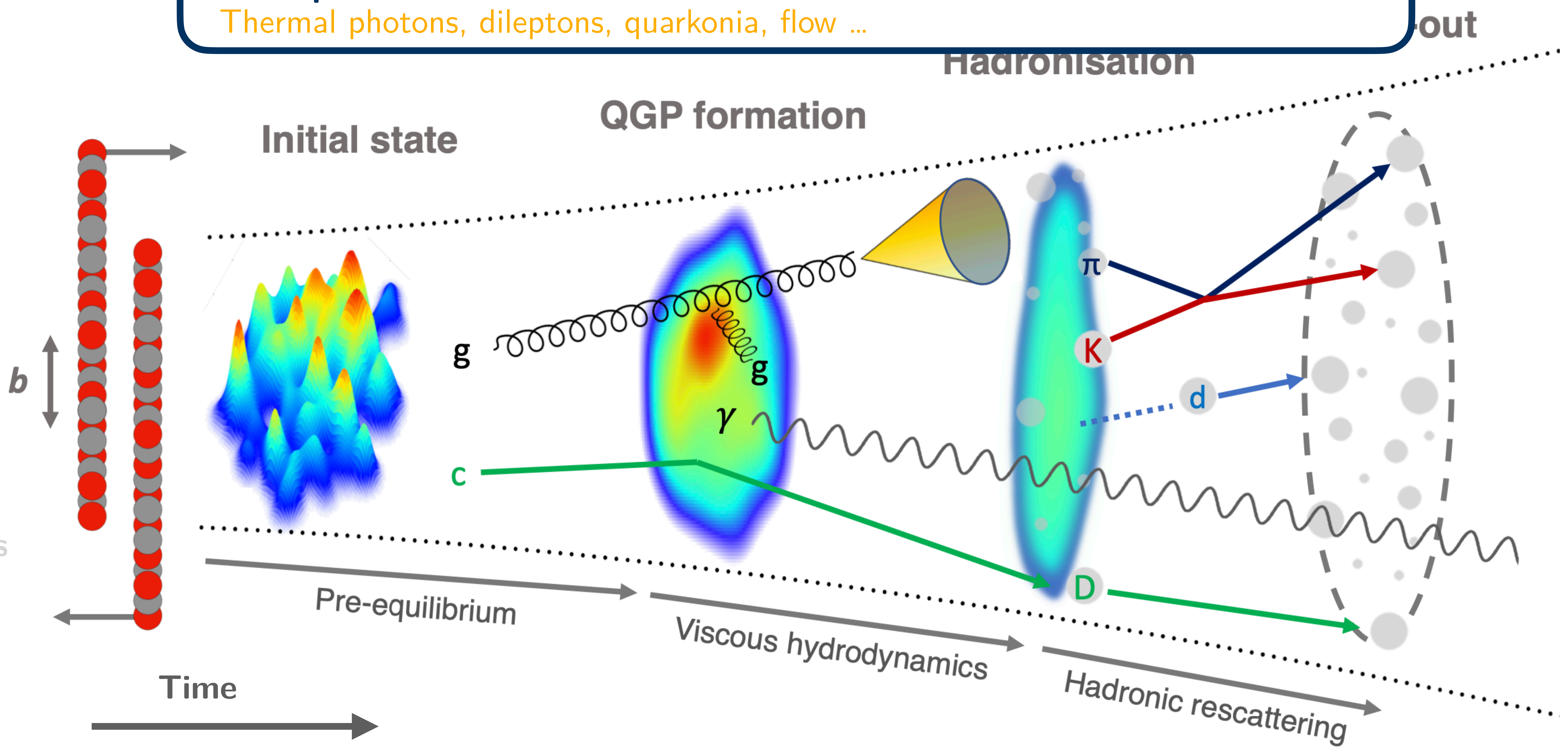

arXiv:2211.04384

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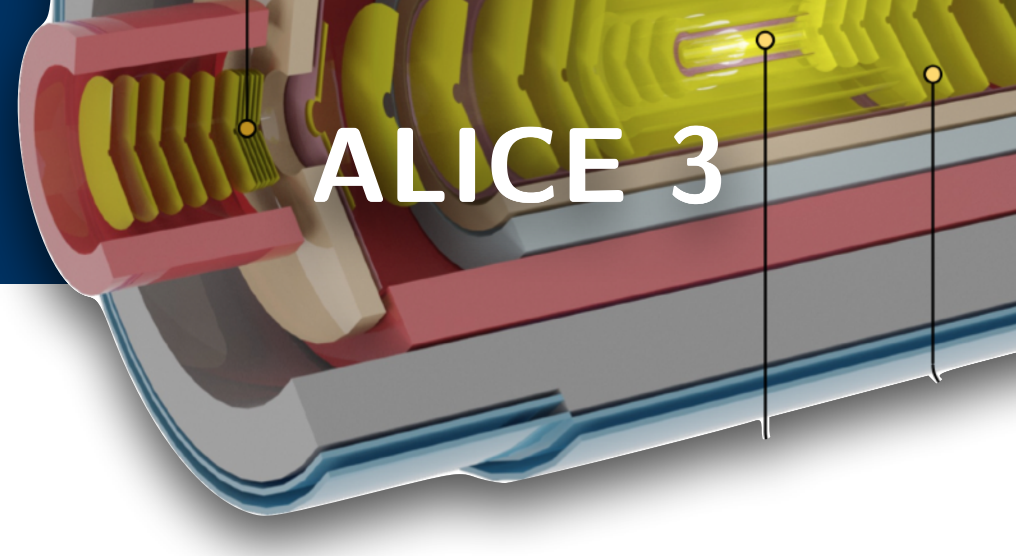
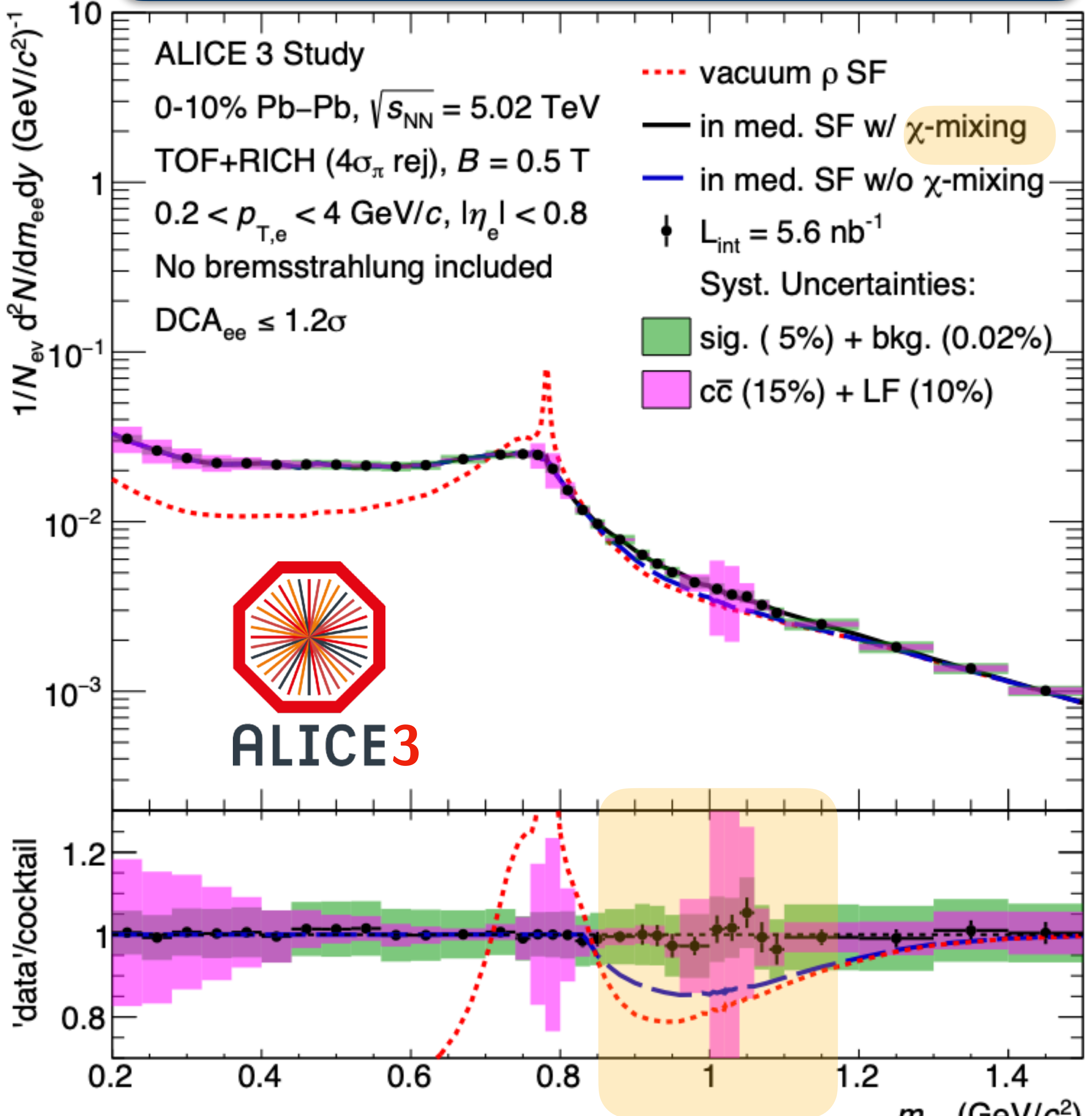
Electromagnetic probes: thermal photons & dileptons

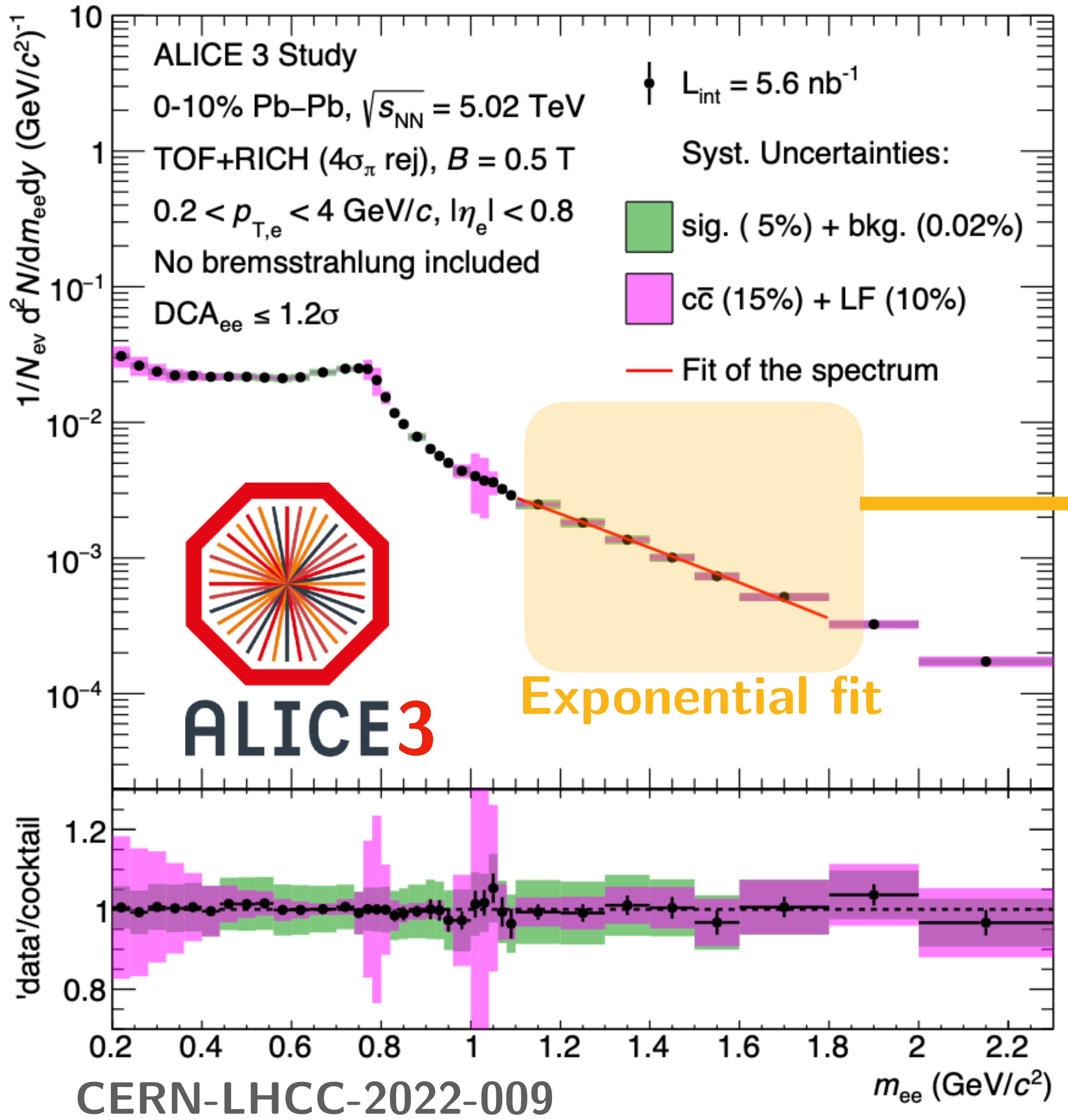


Probing chiral symmetry restoration with dileptons

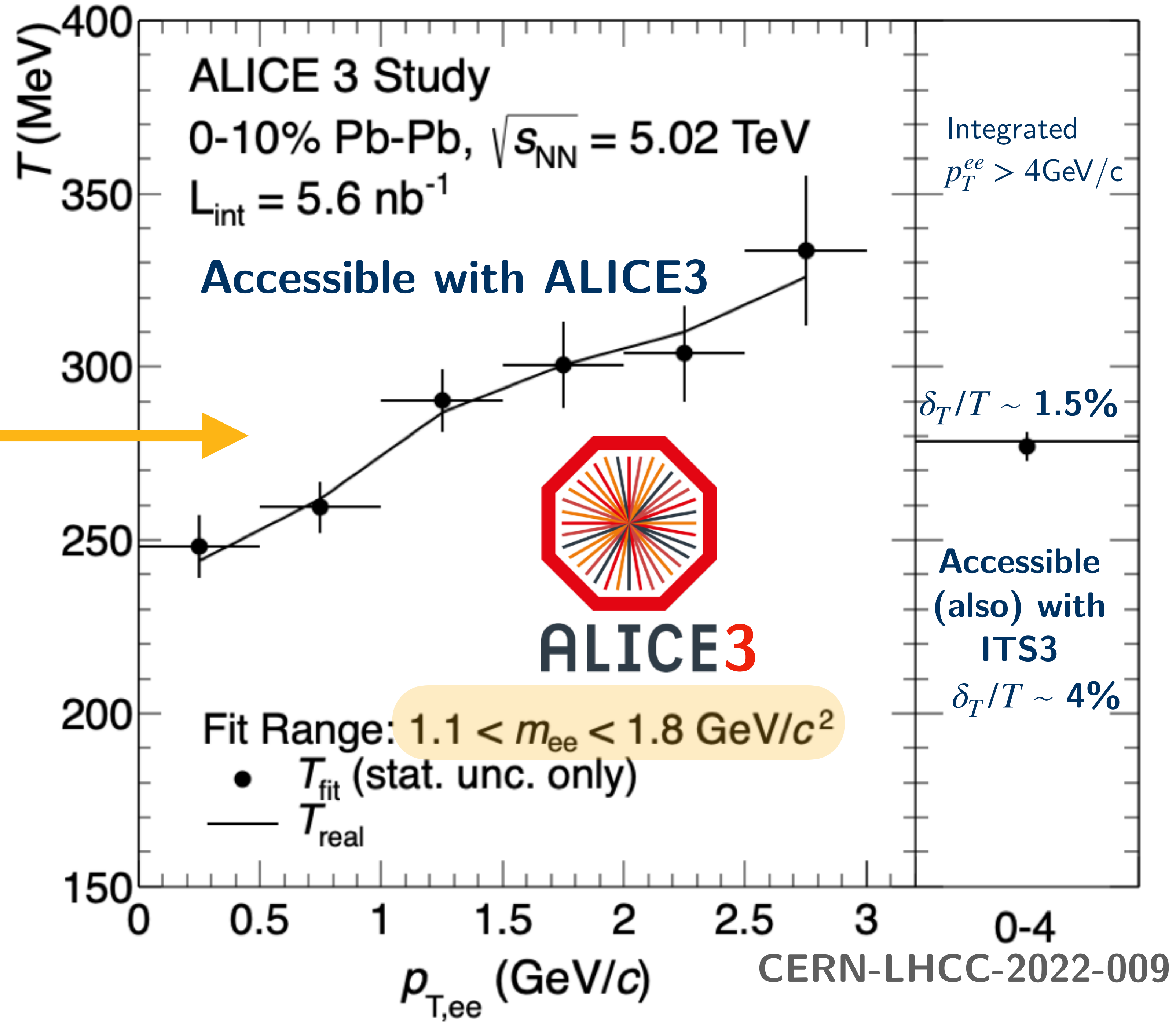


CERN-LHCC-2022-009

Determining the QGP temperature with dileptons

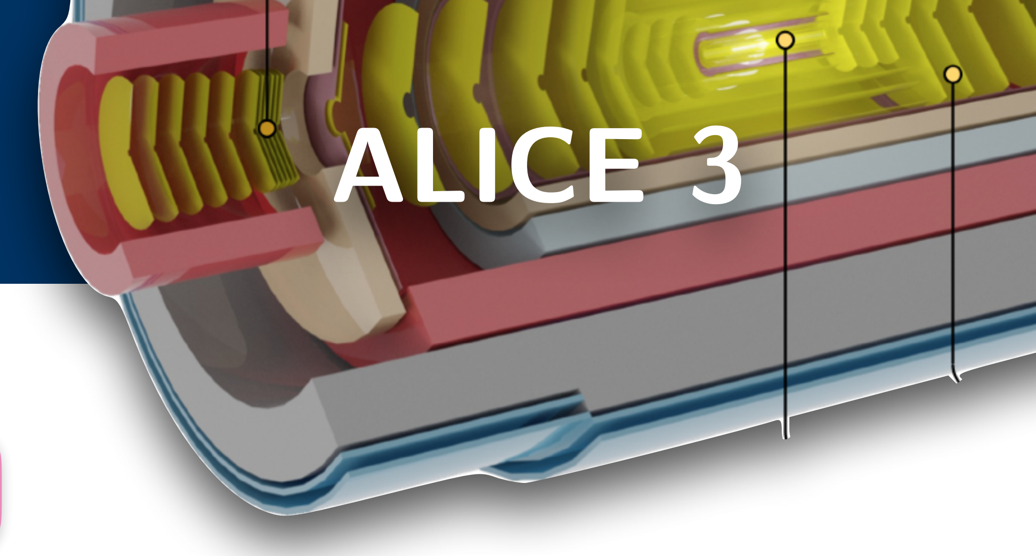


CERN-LHCC-2022-009

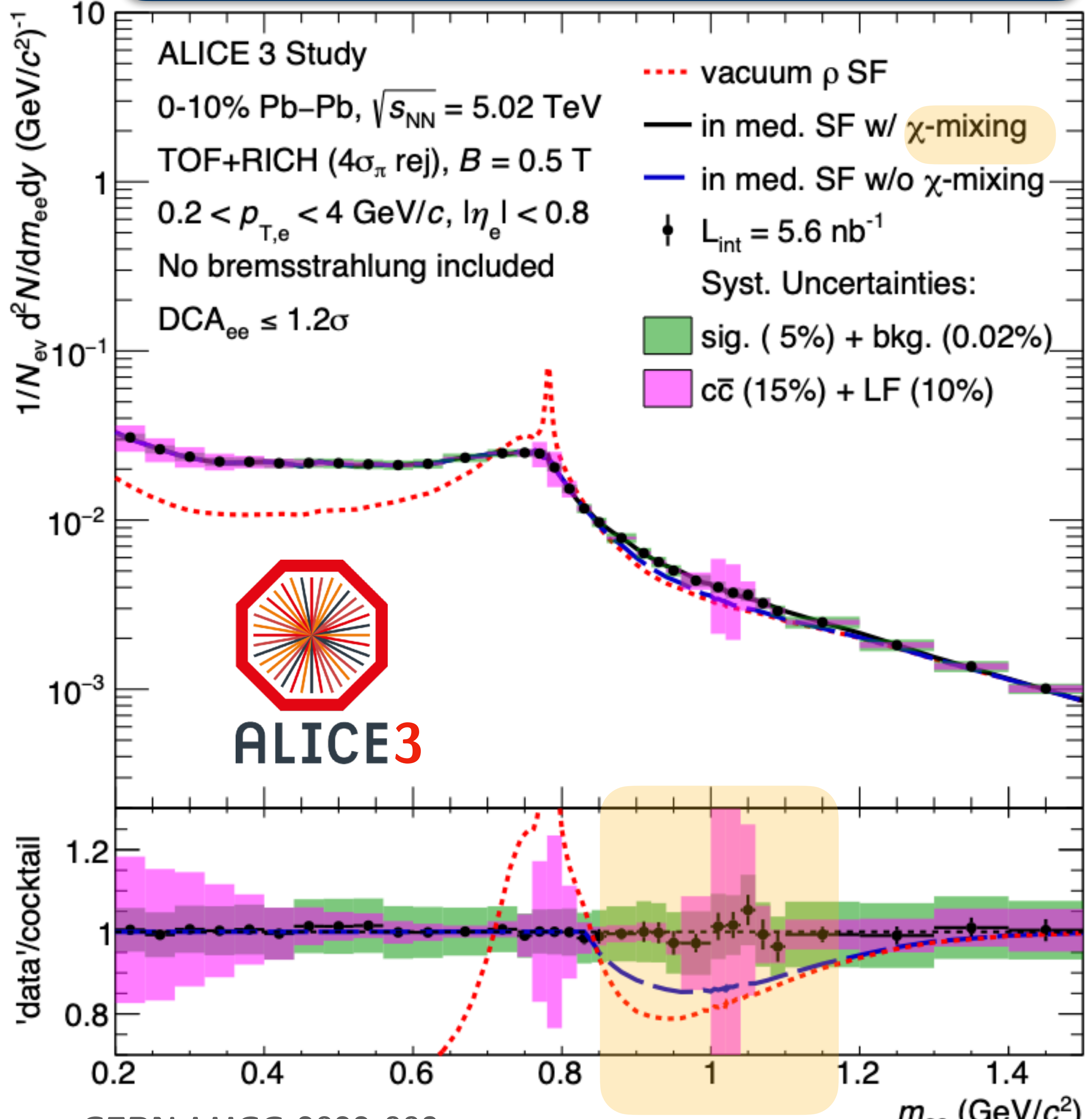


CERN-LHCC-2022-009

- Measurement of spectral shape ρ and chiral partner a_1 is **unambiguous way to measure chiral symmetry restoration.**
  $\rightarrow \rho - a_1$ mixing: enhancement of ~15% at 1 GeV (exp. unc. ~ 6-8%!)
- **Effective QGP temperature determination** with stat. unc. $< 1.5\%$ (integrated case) & differential in p_T^{ee}



Probing chiral symmetry restoration with dileptons



CERN-LHCC-2022-009

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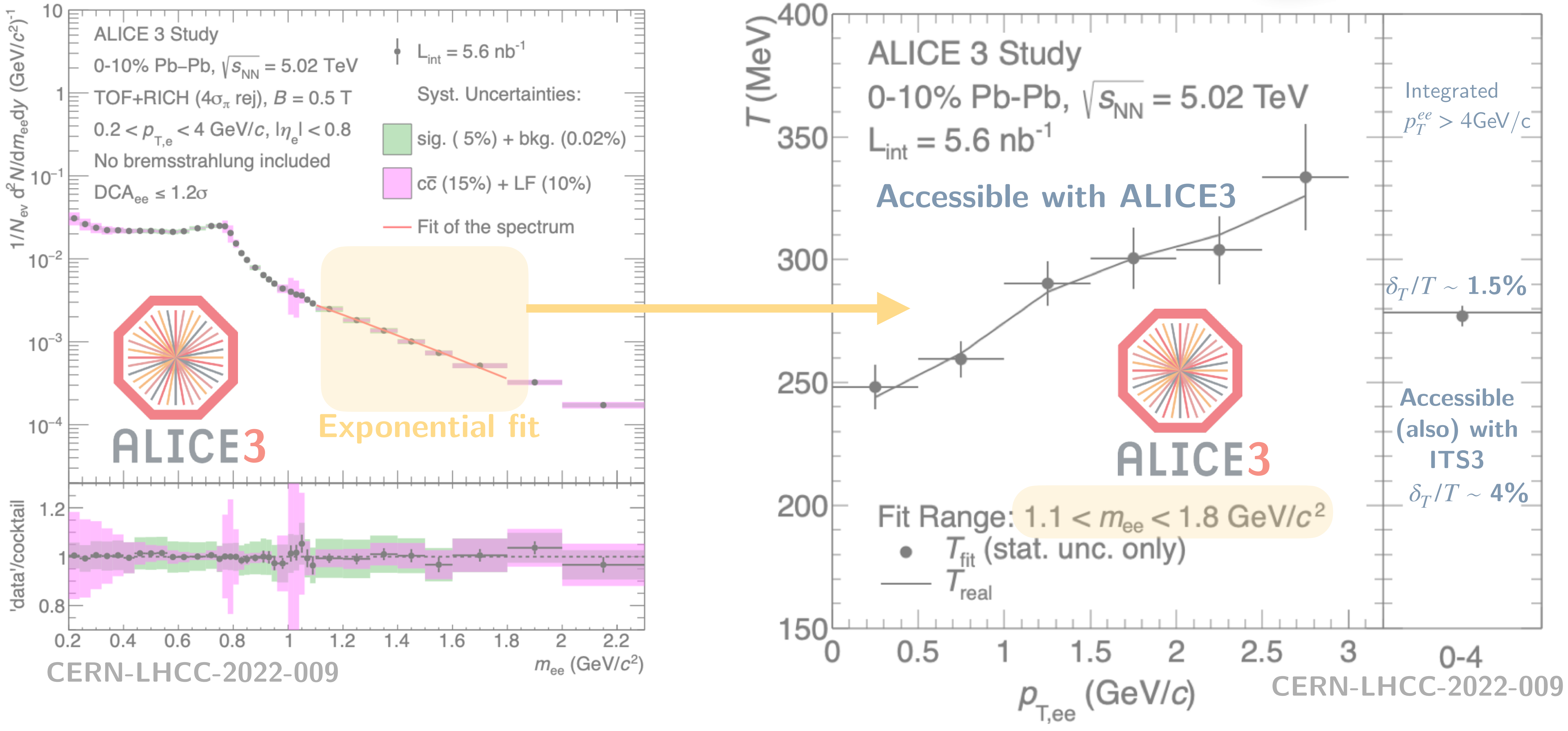

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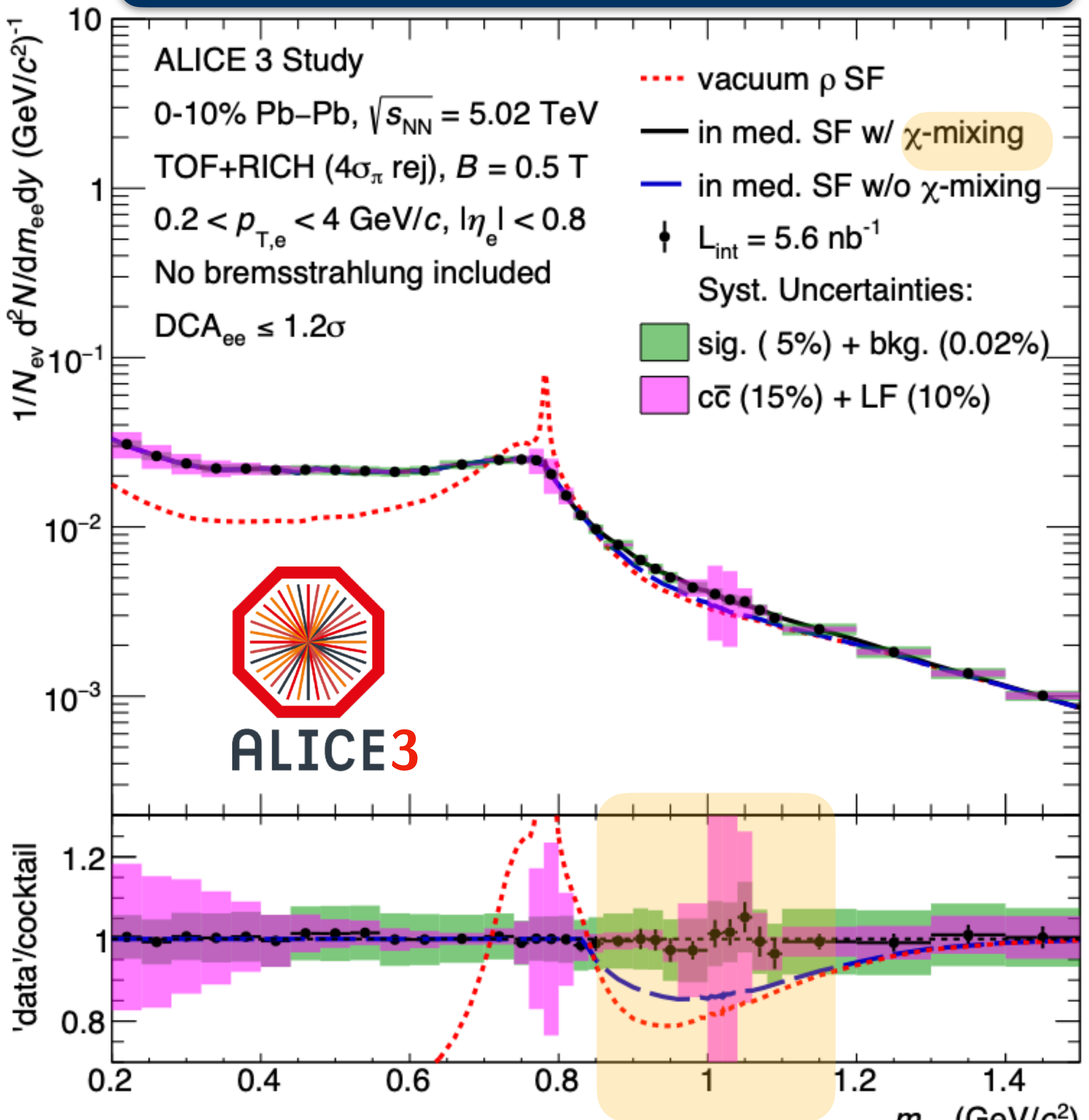
Electromagnetic probes: thermal photons & dileptons

ALICE 3

Probing chiral symmetry restoration with dileptons



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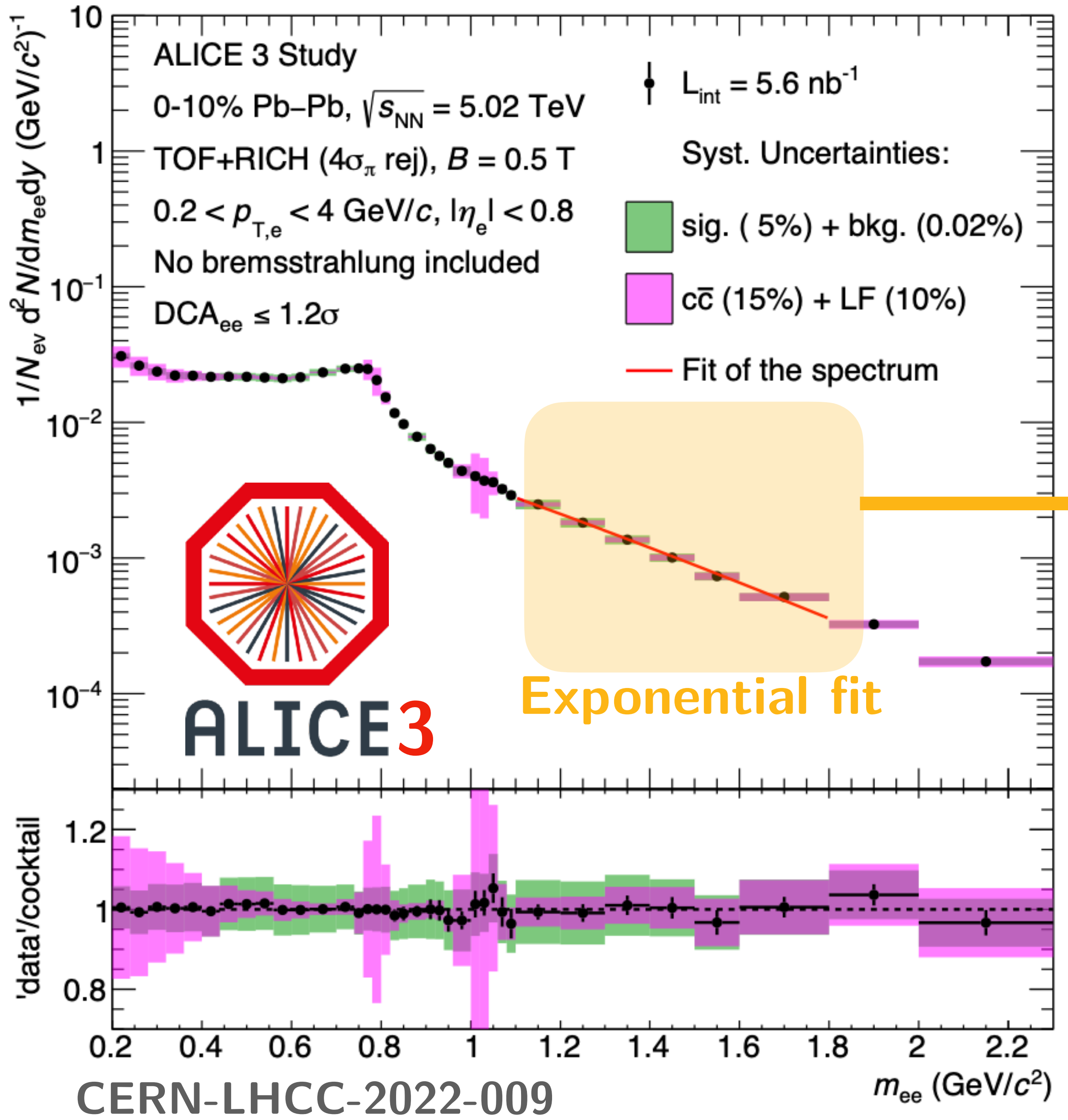

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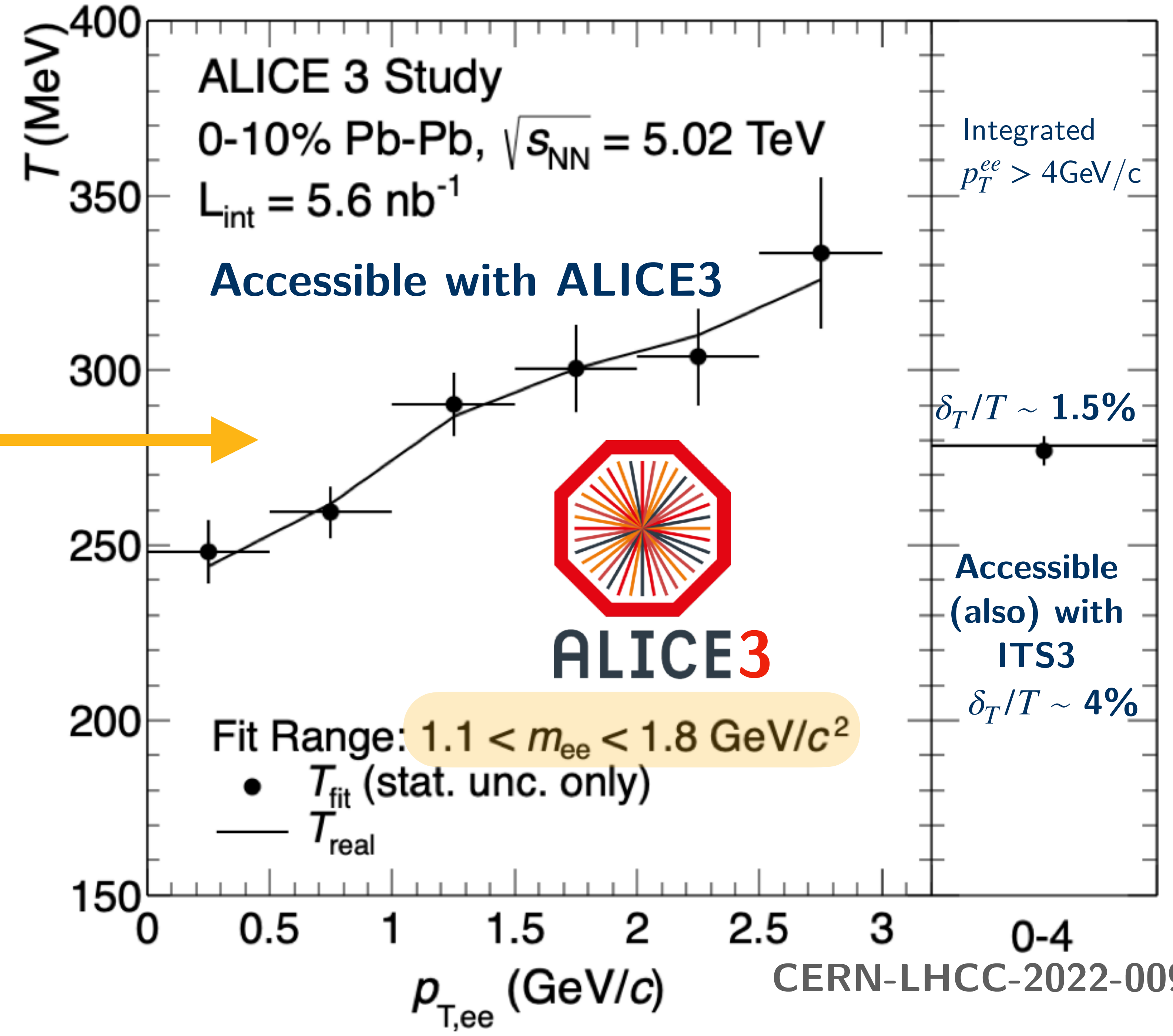

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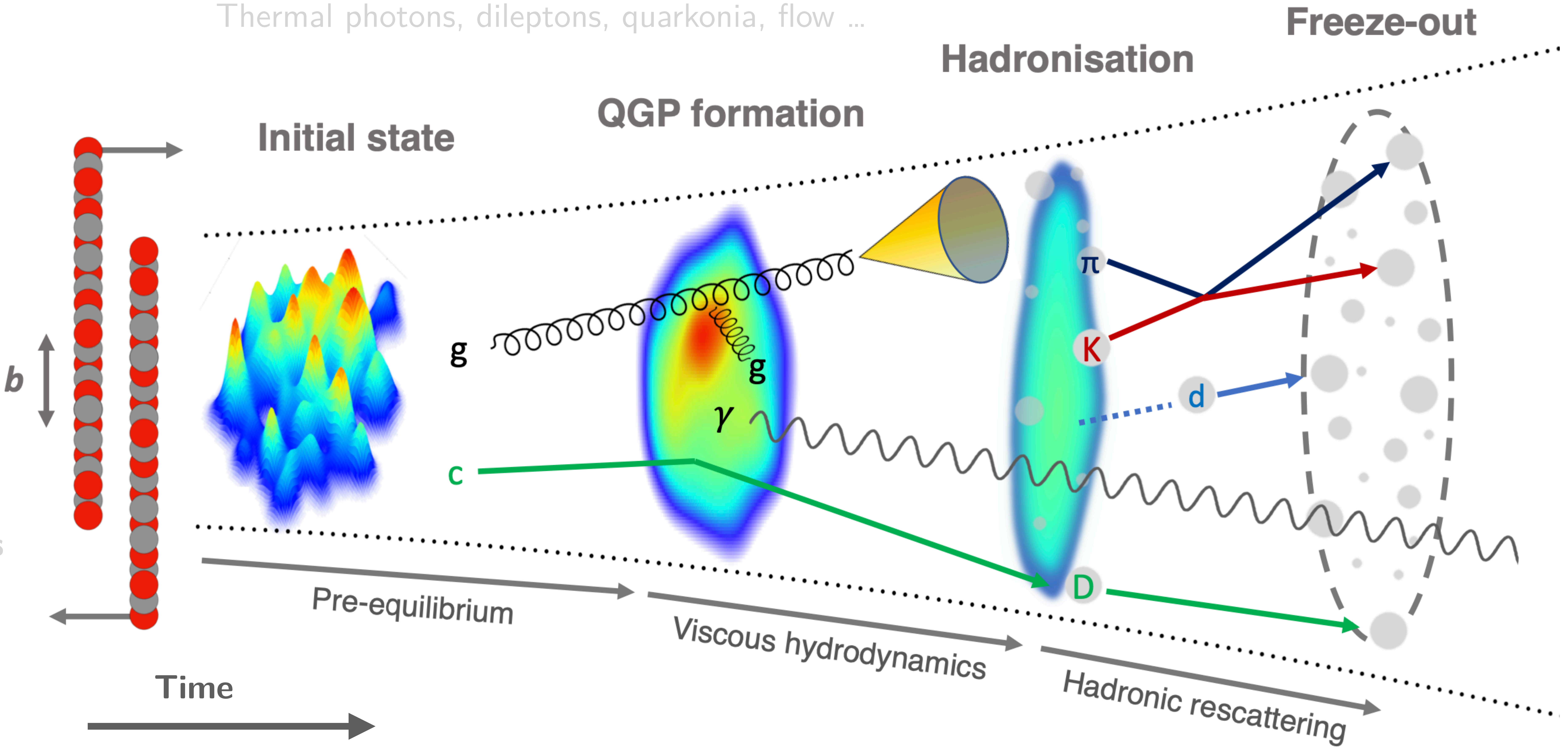
Heavy-ion physics: The big questions

What are the macroscopic properties of the QGP? Temperature? Viscosity? QCD phase transition?
Thermal photons, dileptons, quarkonia, flow ...

What are the initial conditions of a collision? nPDFs & Saturation?
DY, UPC, forward LHC ...

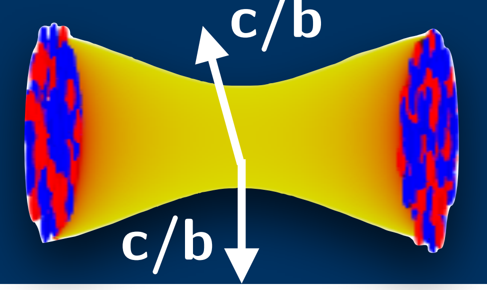
Collectivity of QCD across system sizes?
Flow in pp, p-A; strangeness production, energy loss, thermal radiation



arXiv:2211.04384

What is the microscopic dynamics of QGP at various length scales?
Jets (substructure), γ/Z-jet correlations, heavy flavour, quarkonia, hadronization

Heavy flavour



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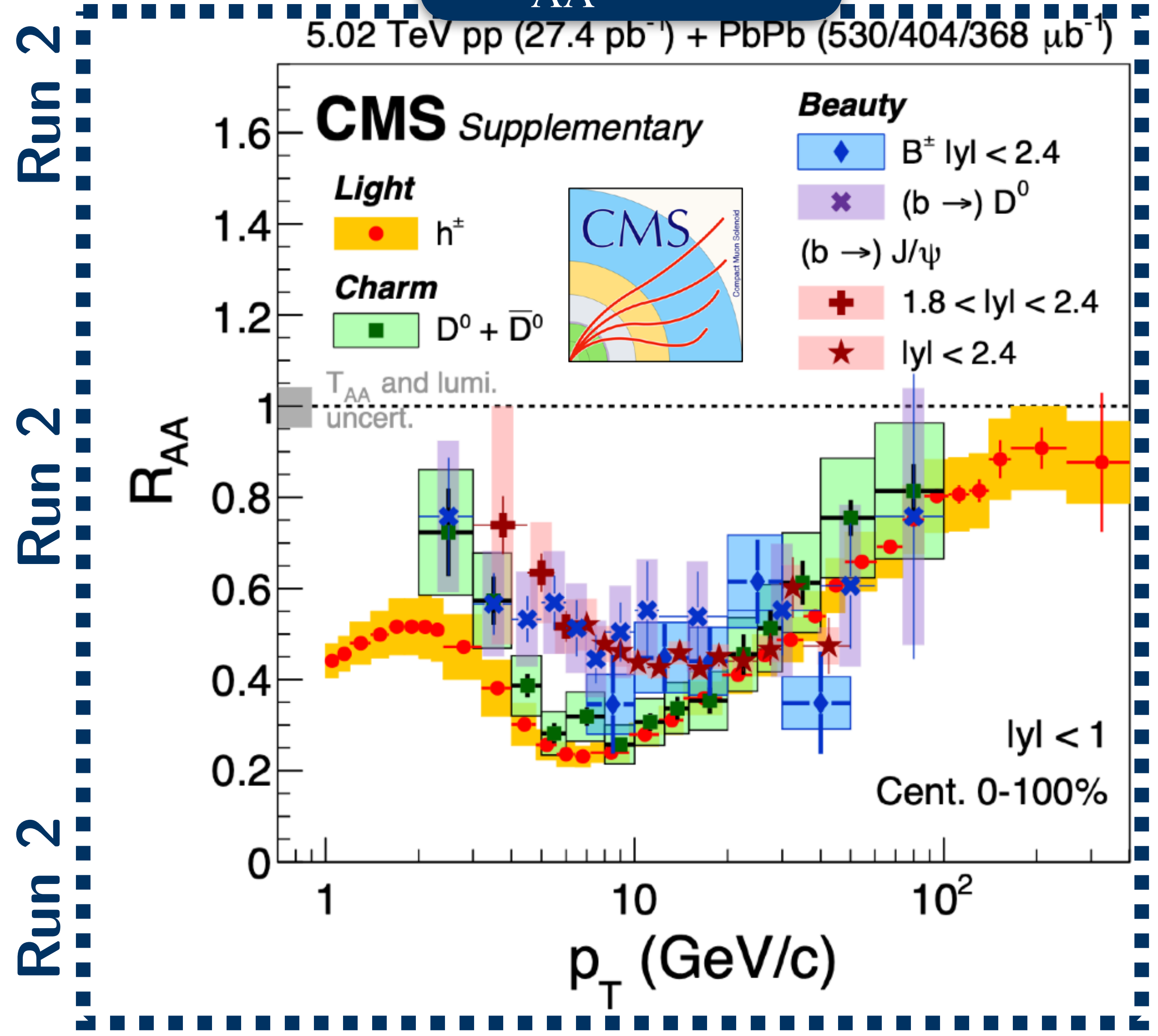
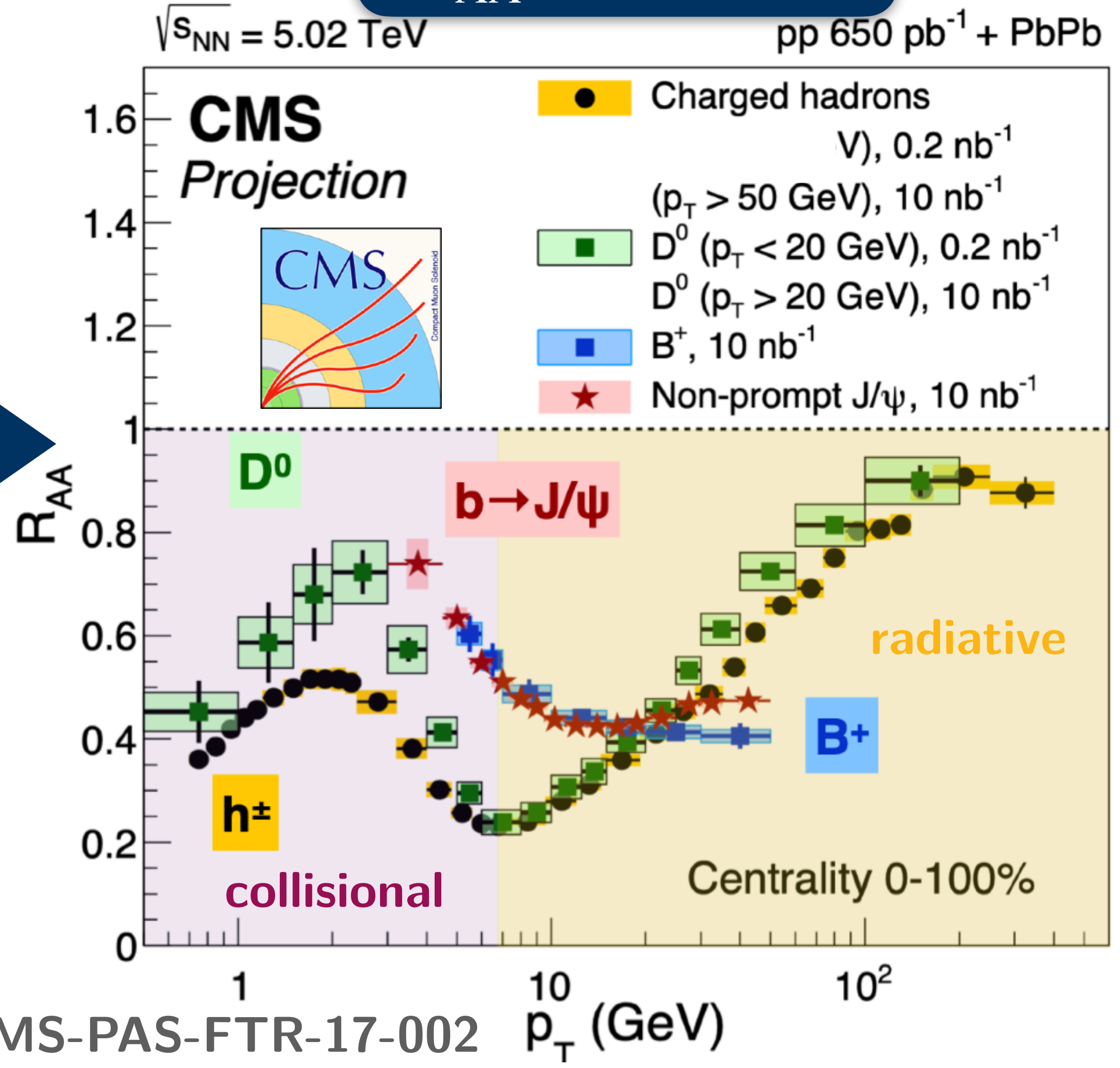
R_{AA} Run 2



R_{AA} at HL-LHC



CMS-PAS-FTR-17-002

- **What microscopic mechanisms drive HF interactions in QGP?**
  precision measurements of R_{AA} & flow
  → stronger constrains on QGP transport coefficient
  → importance of radiative vs. collisional energy loss
  → degree of thermalisation of heavy quarks
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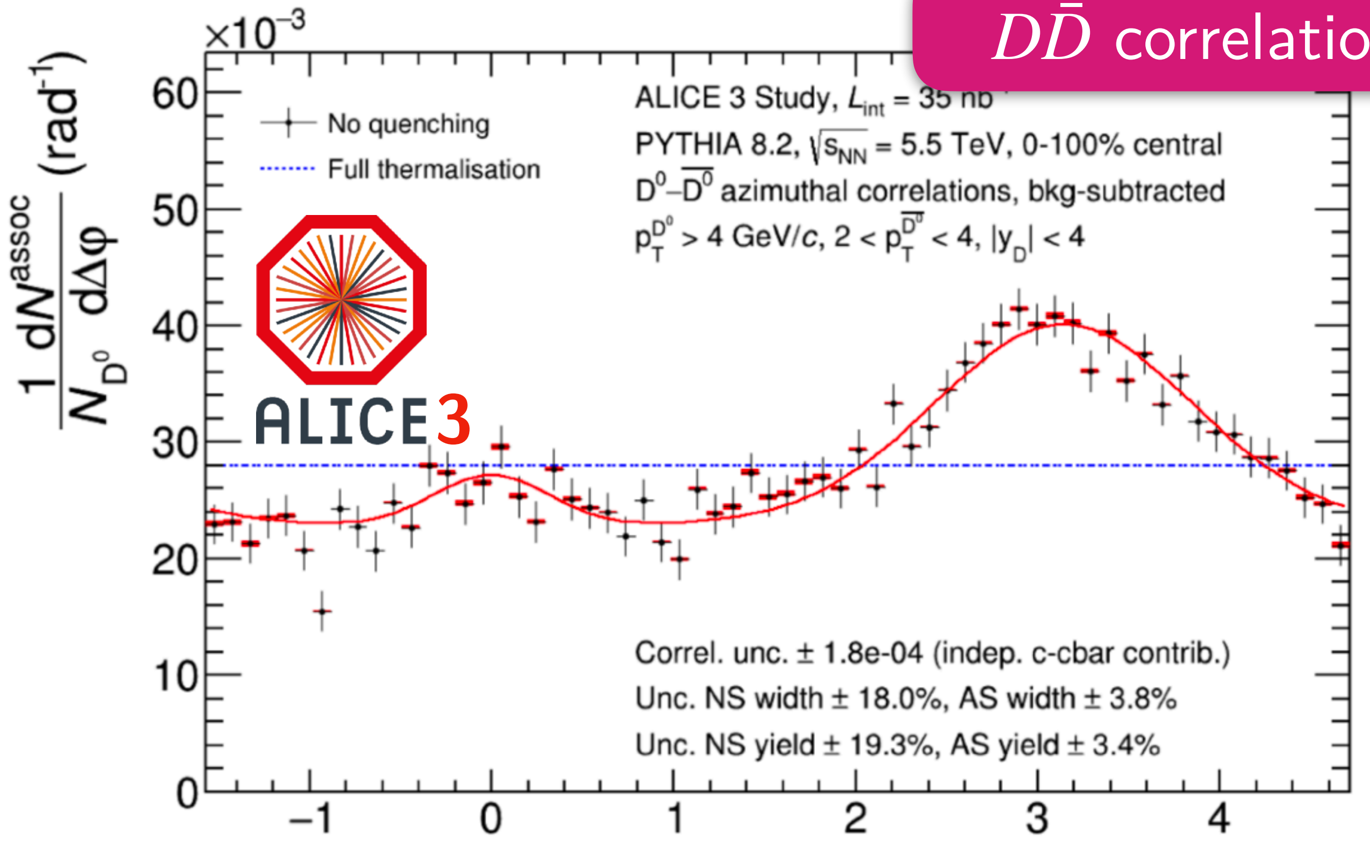
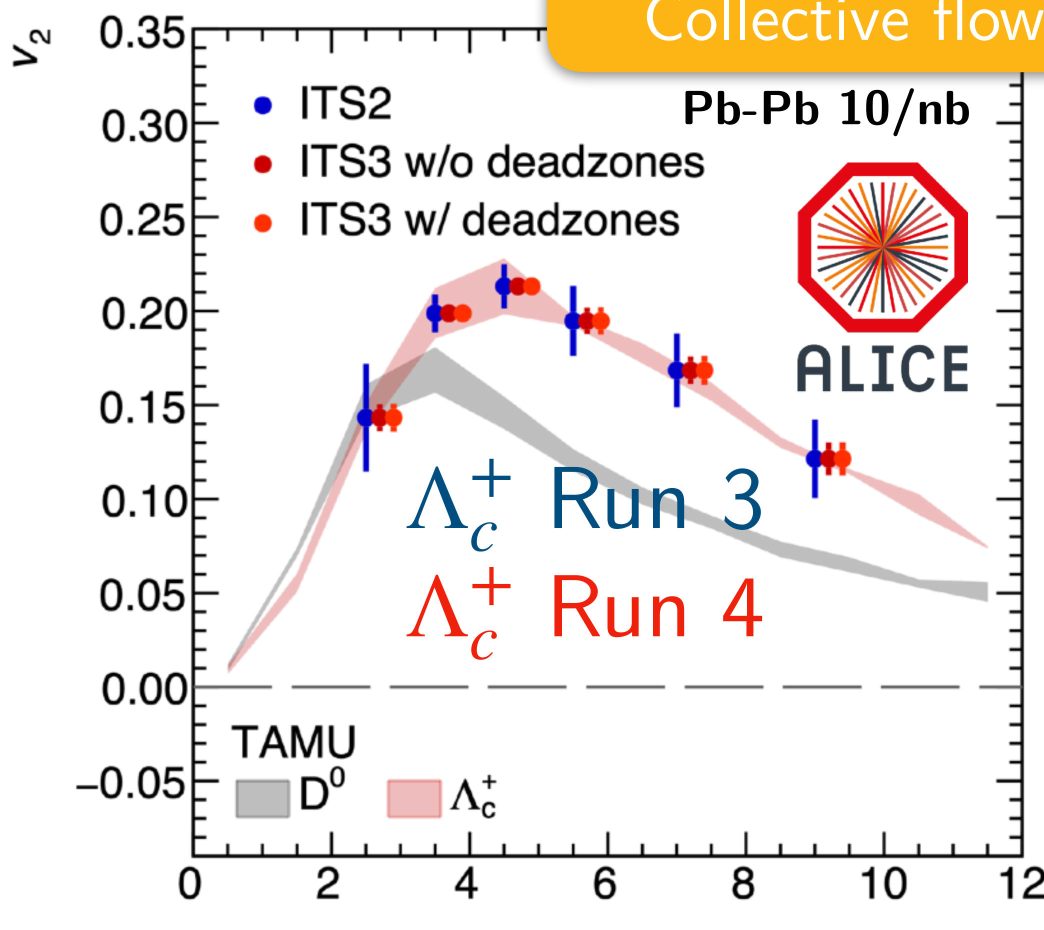
$D\bar{D}$ correlation



CERN-LHCC-2022-009

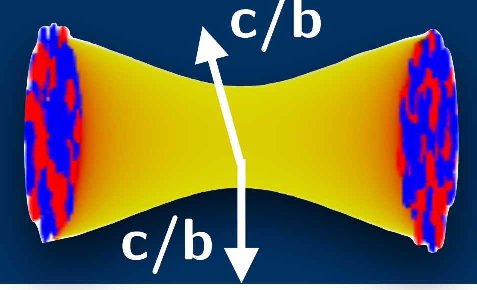
Collective flow v_2



CERN-LHCC-2024-003

Not shown: LHCb HF capabilities for full centrality range in Pb-Pb thanks to "mighty tracker" in Run 5+

Heavy flavour



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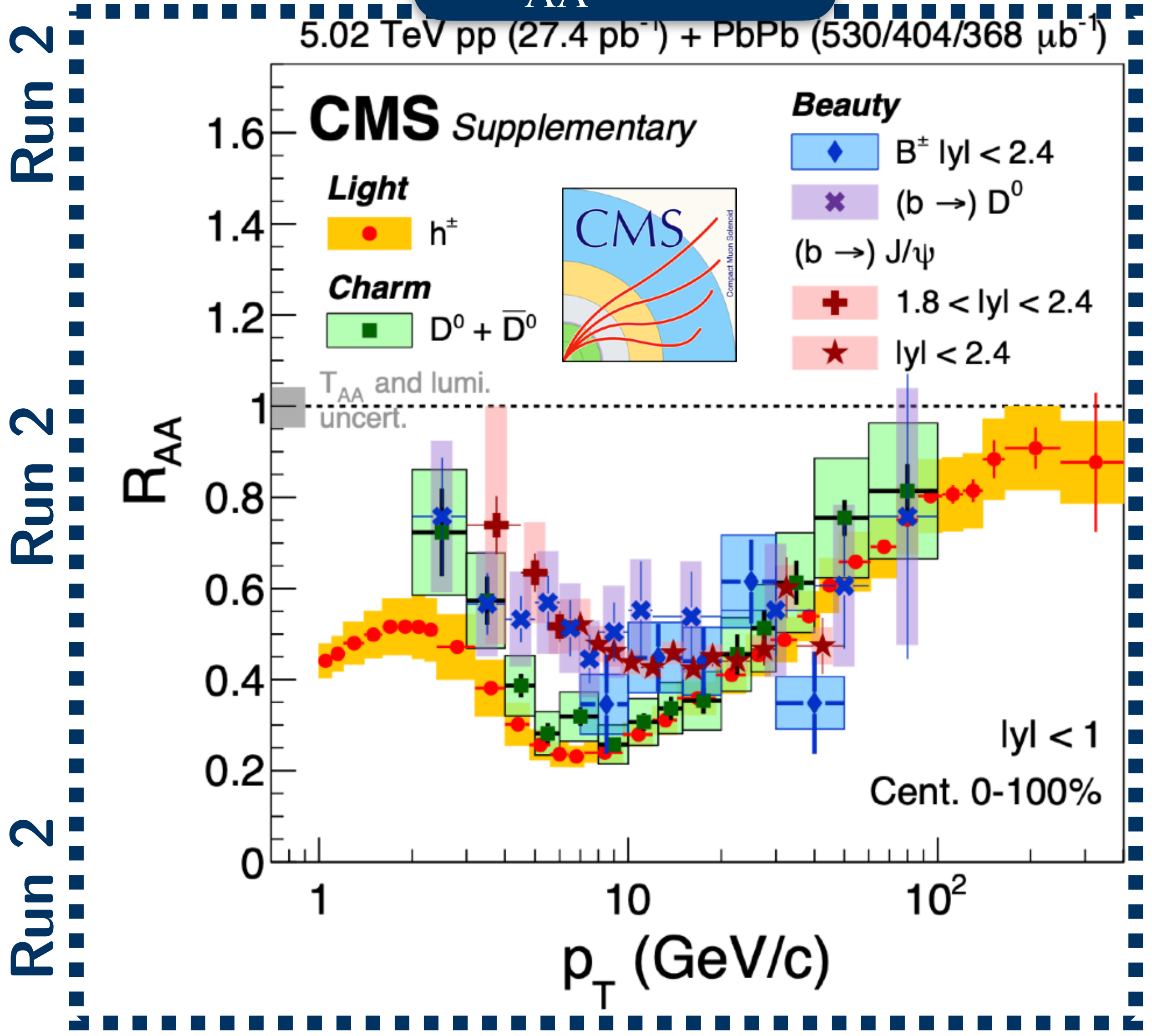

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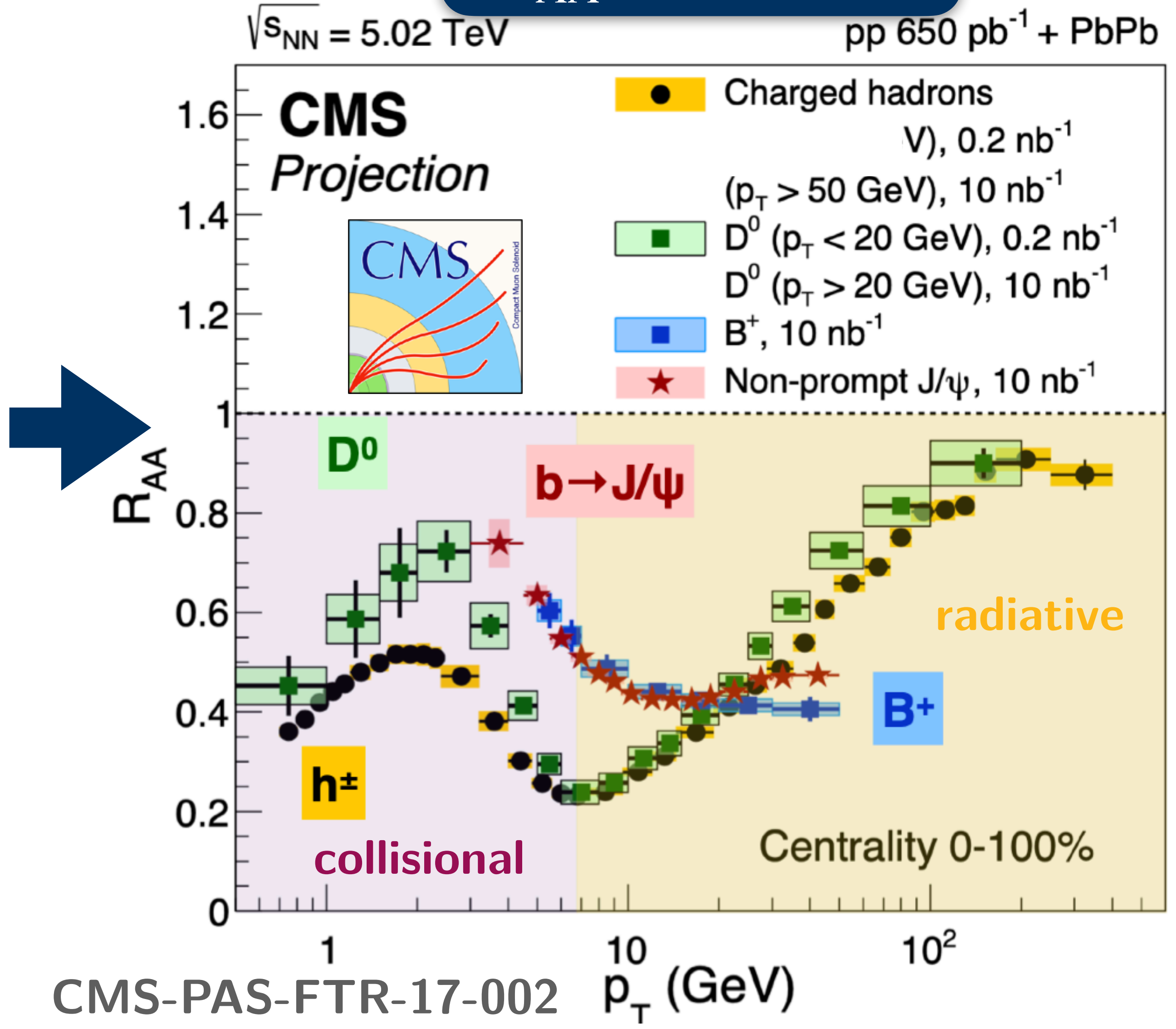

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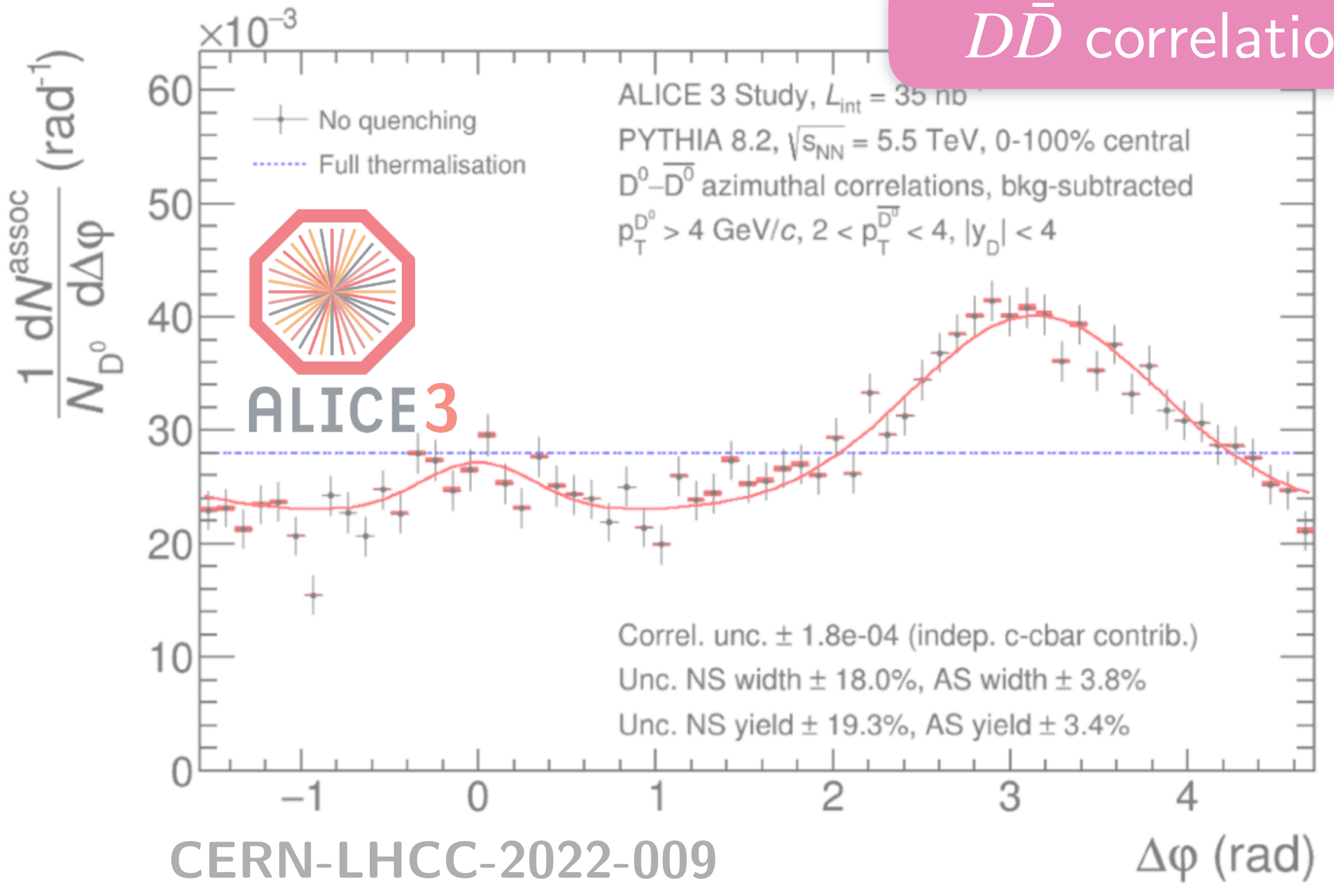

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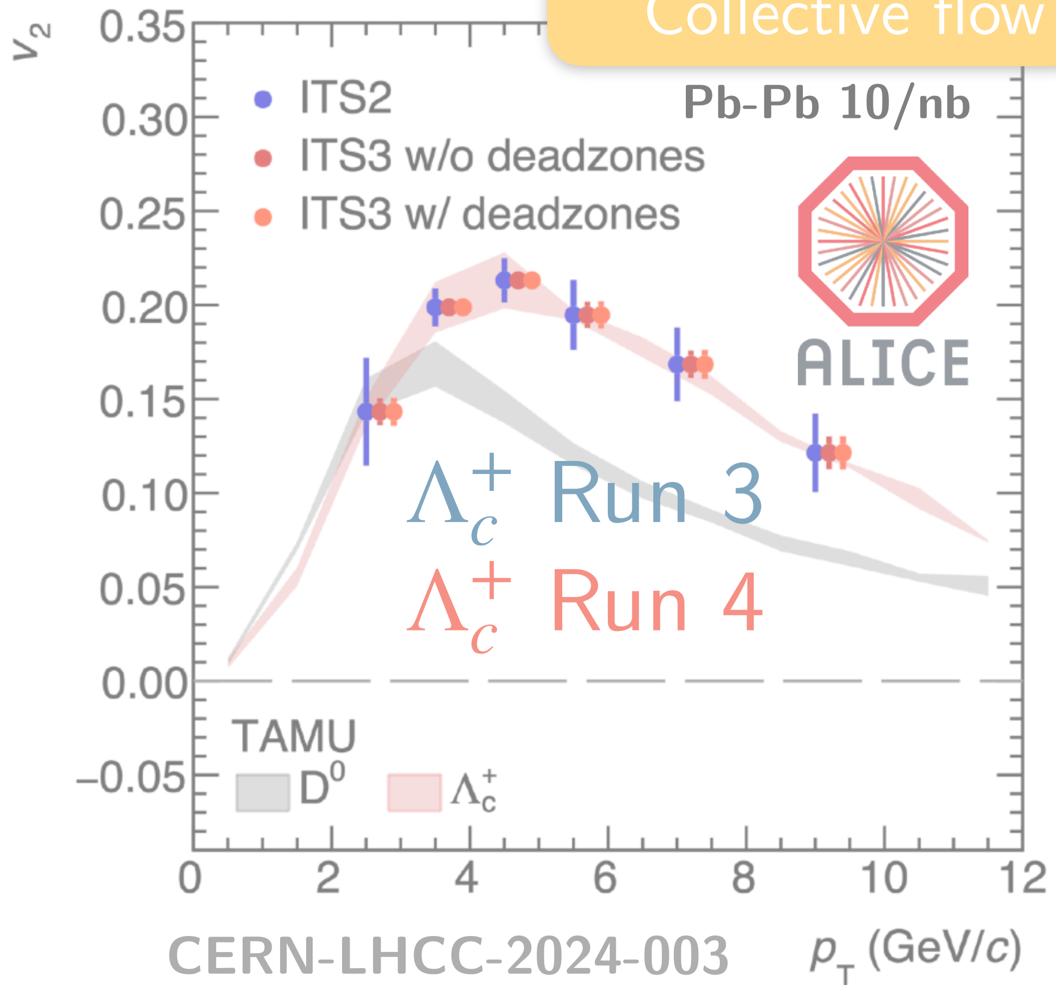

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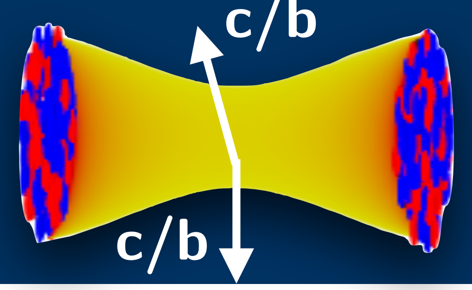

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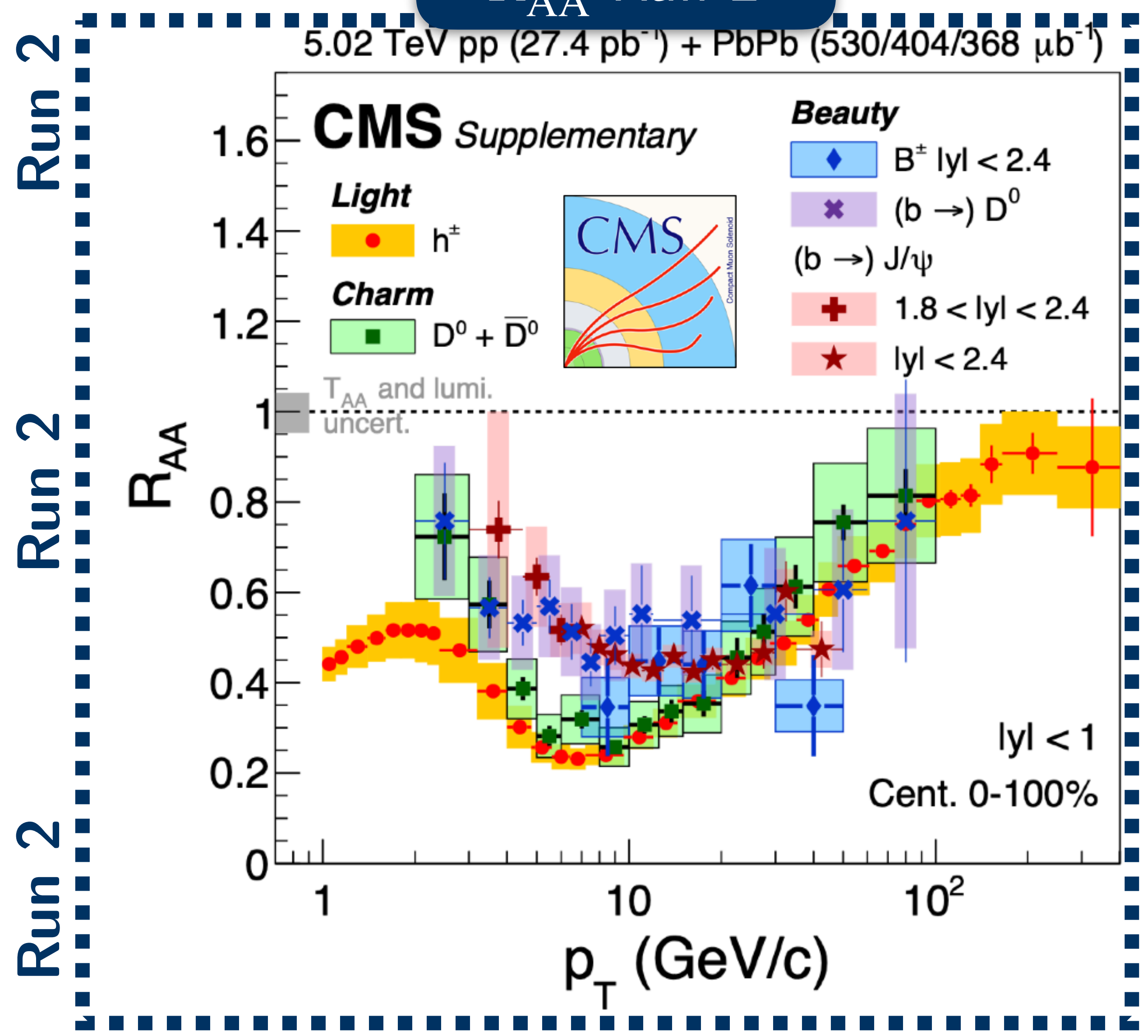

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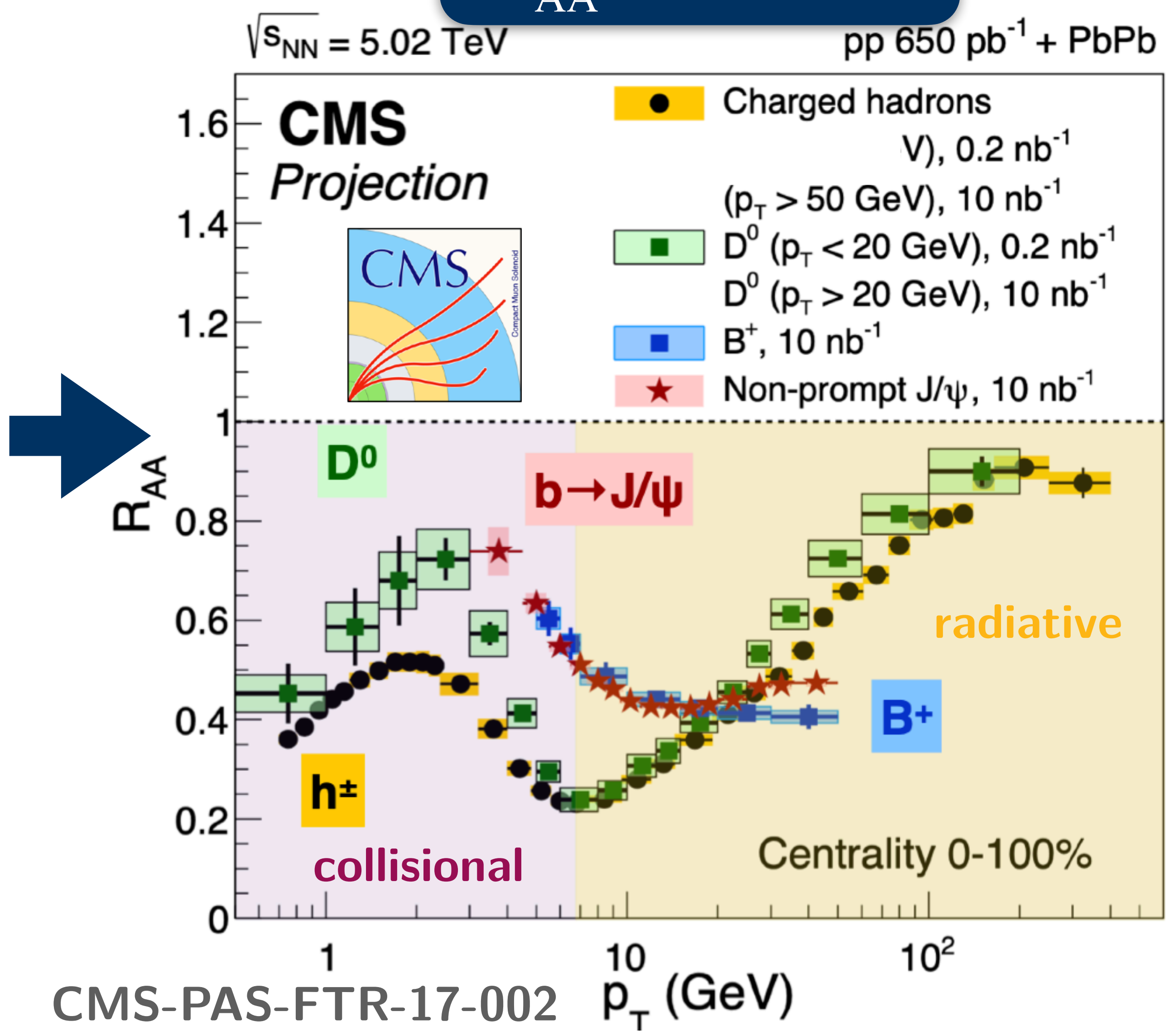

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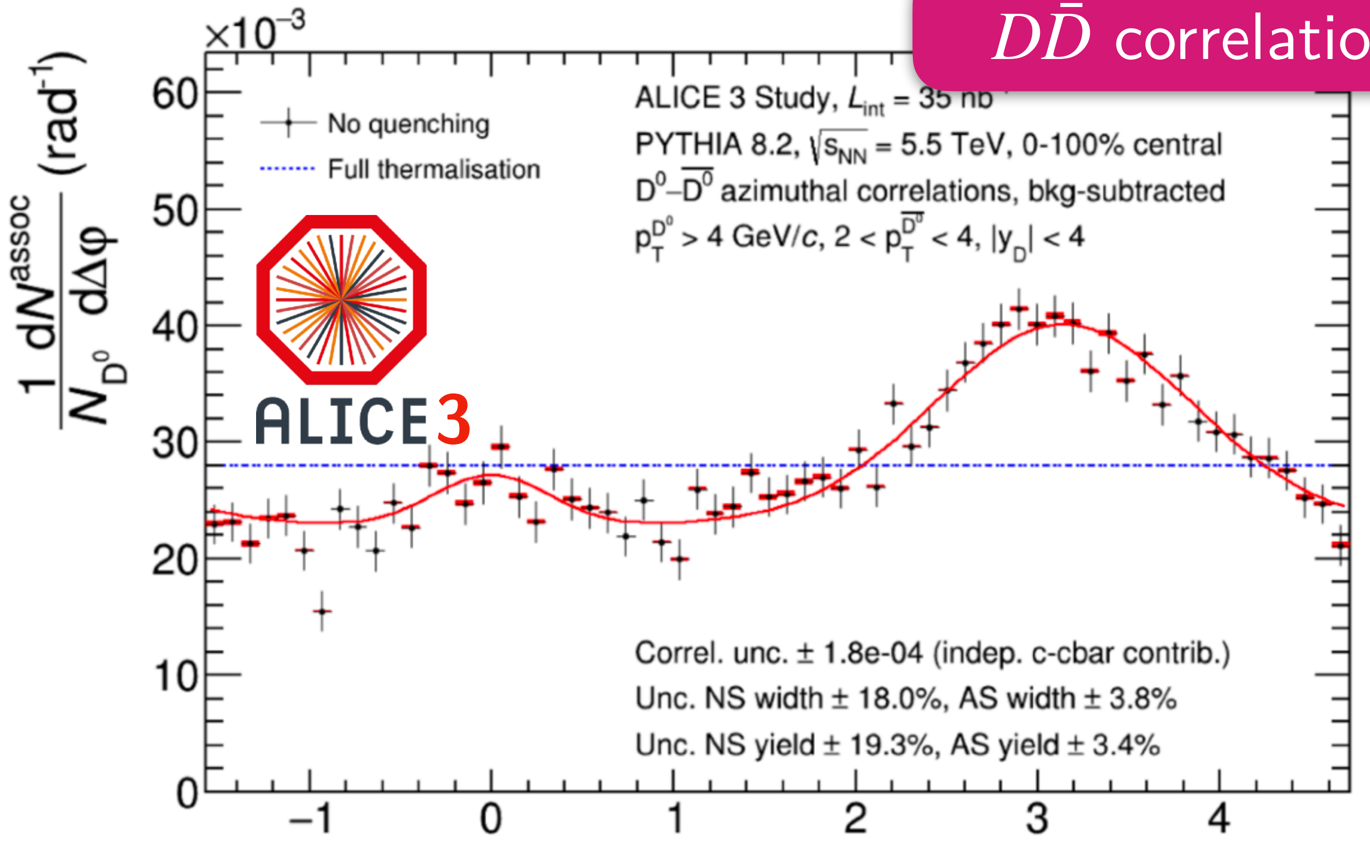

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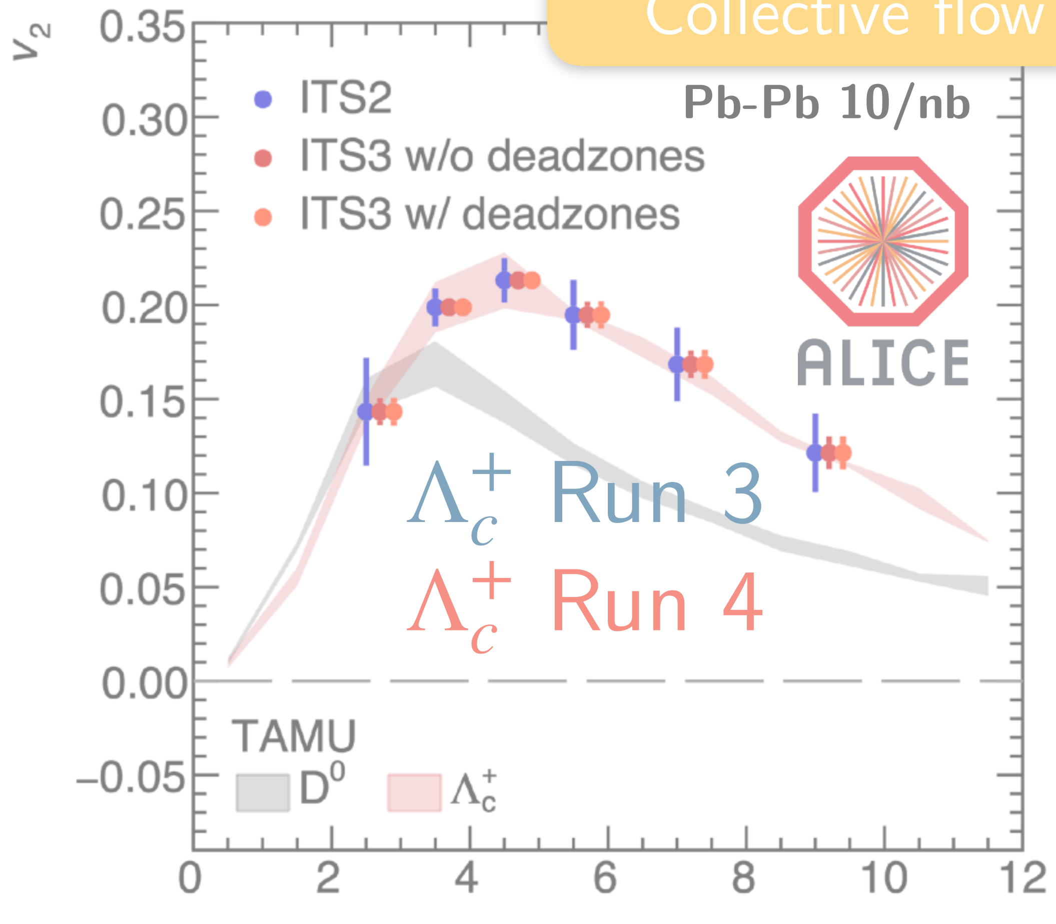

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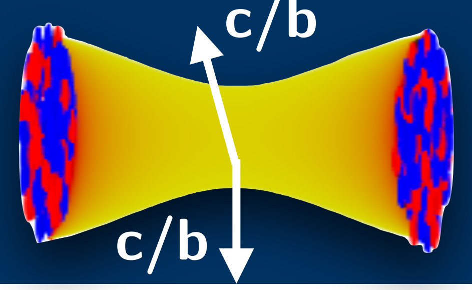

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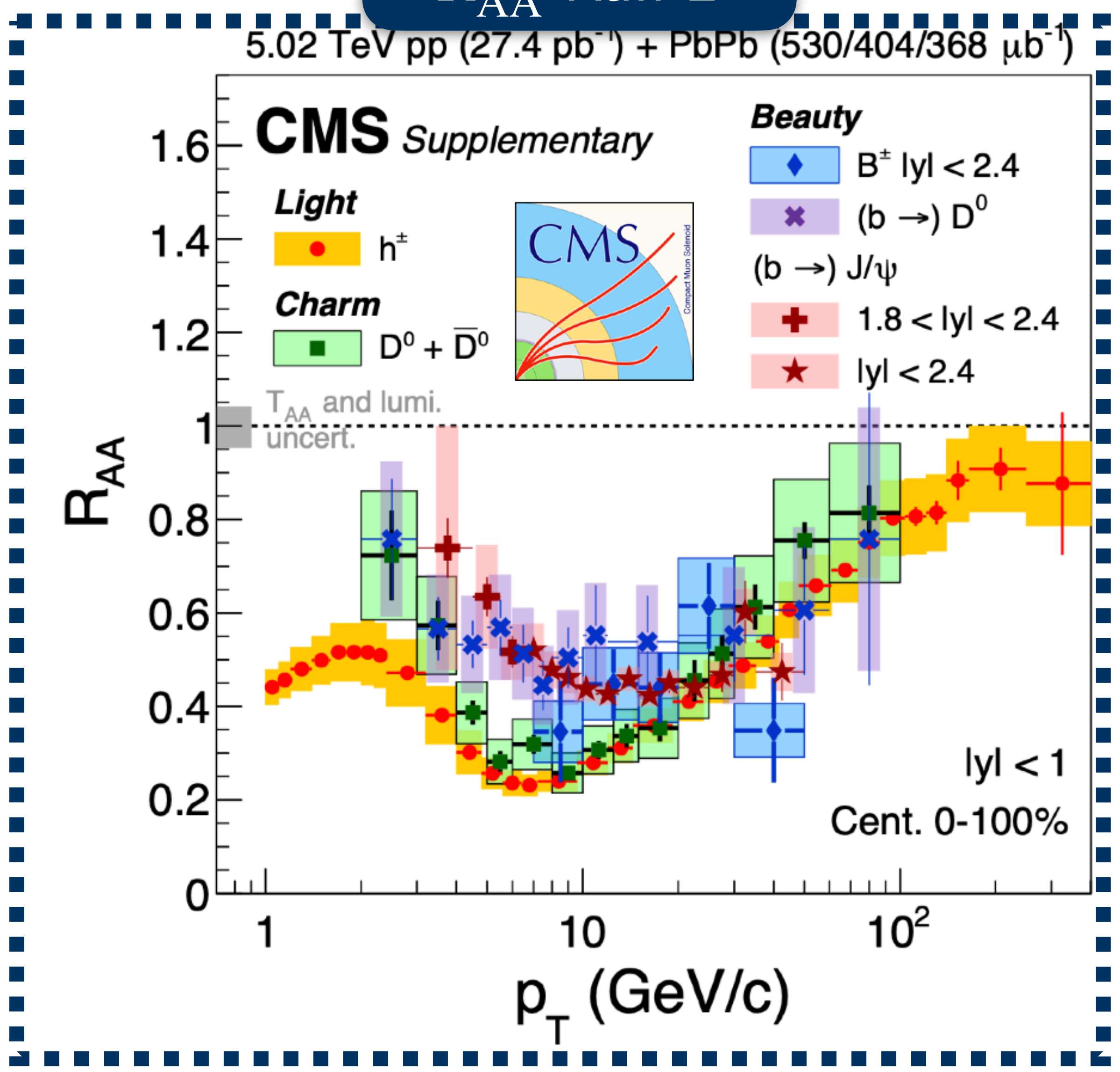

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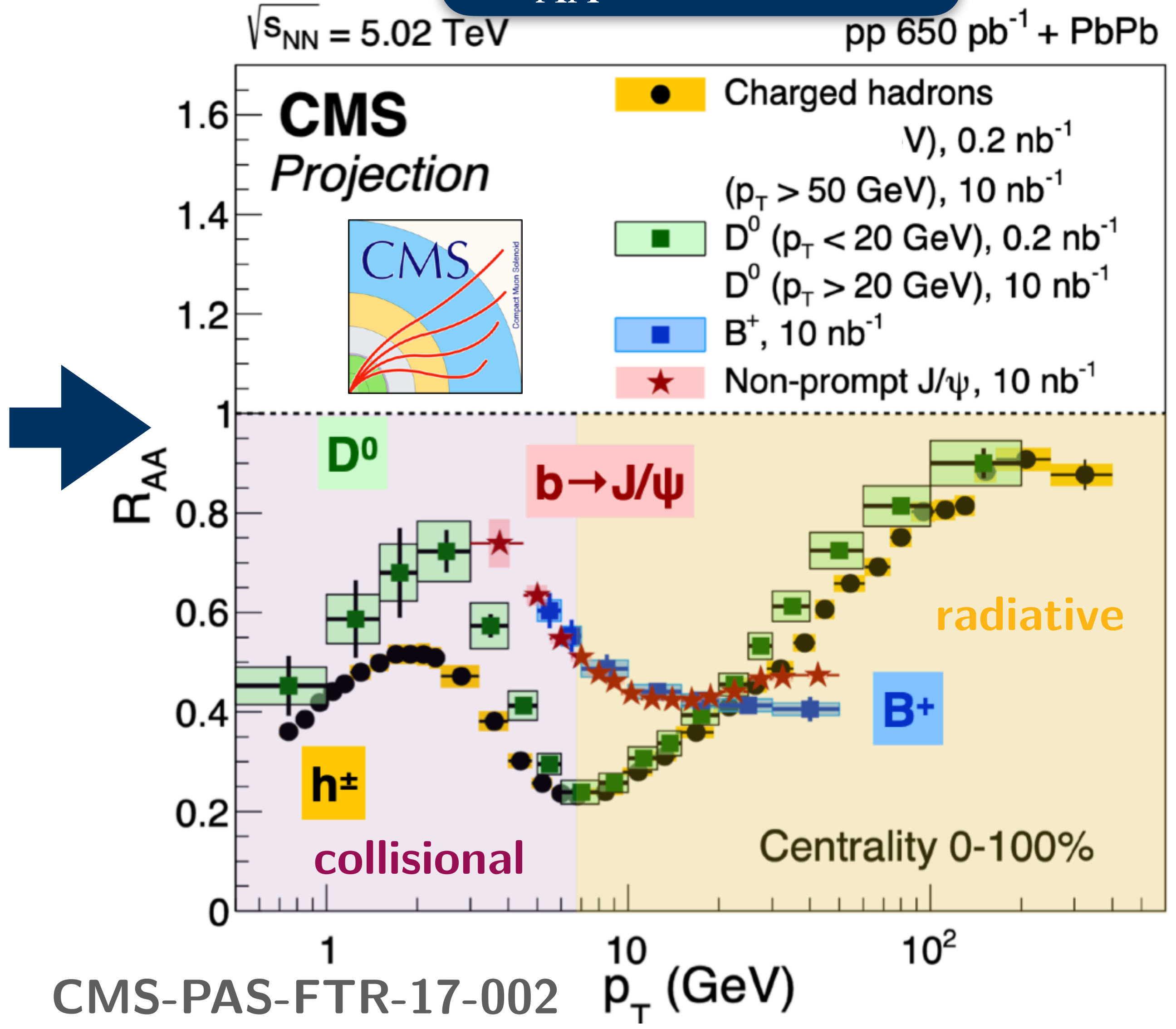

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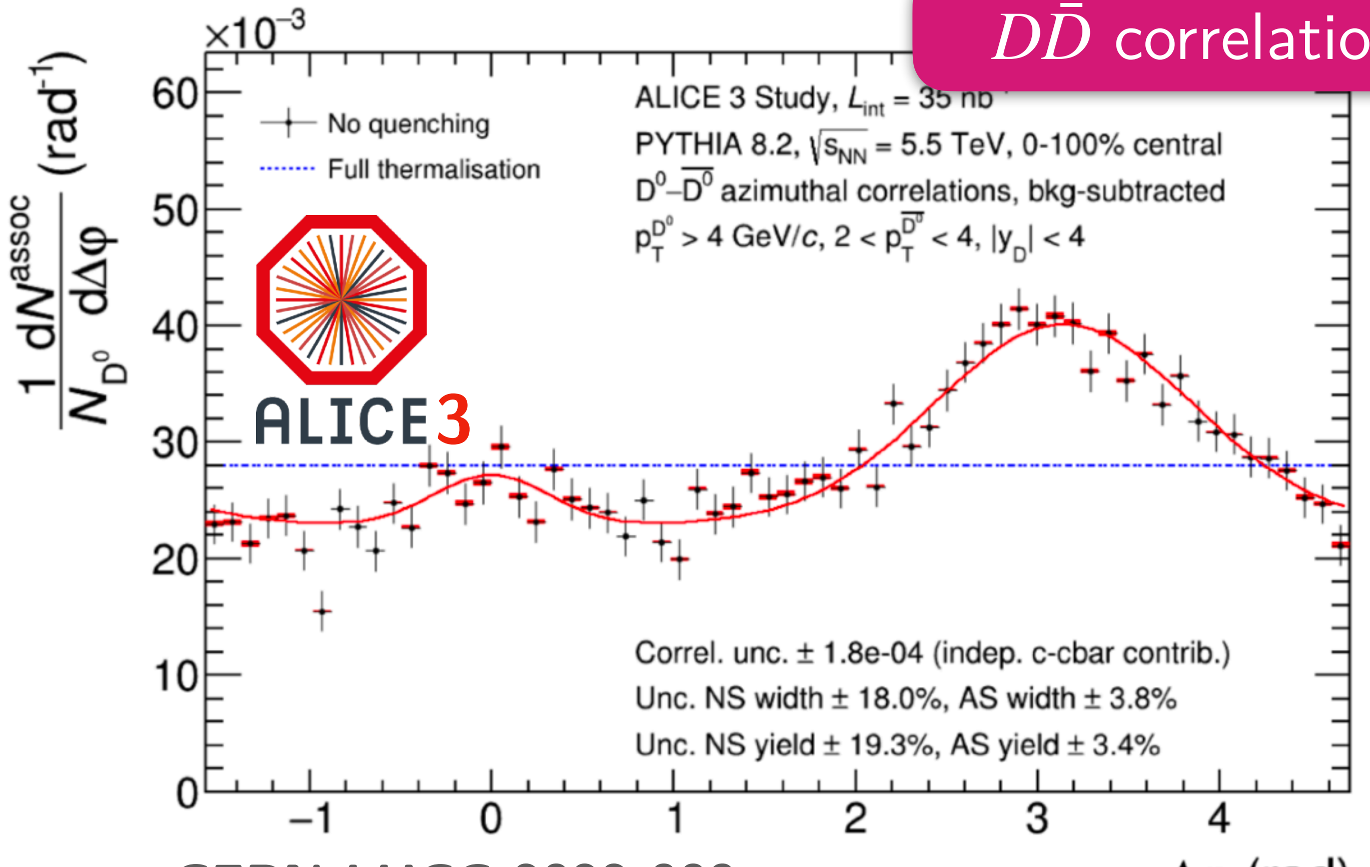

CERN-LHCC-2022-009

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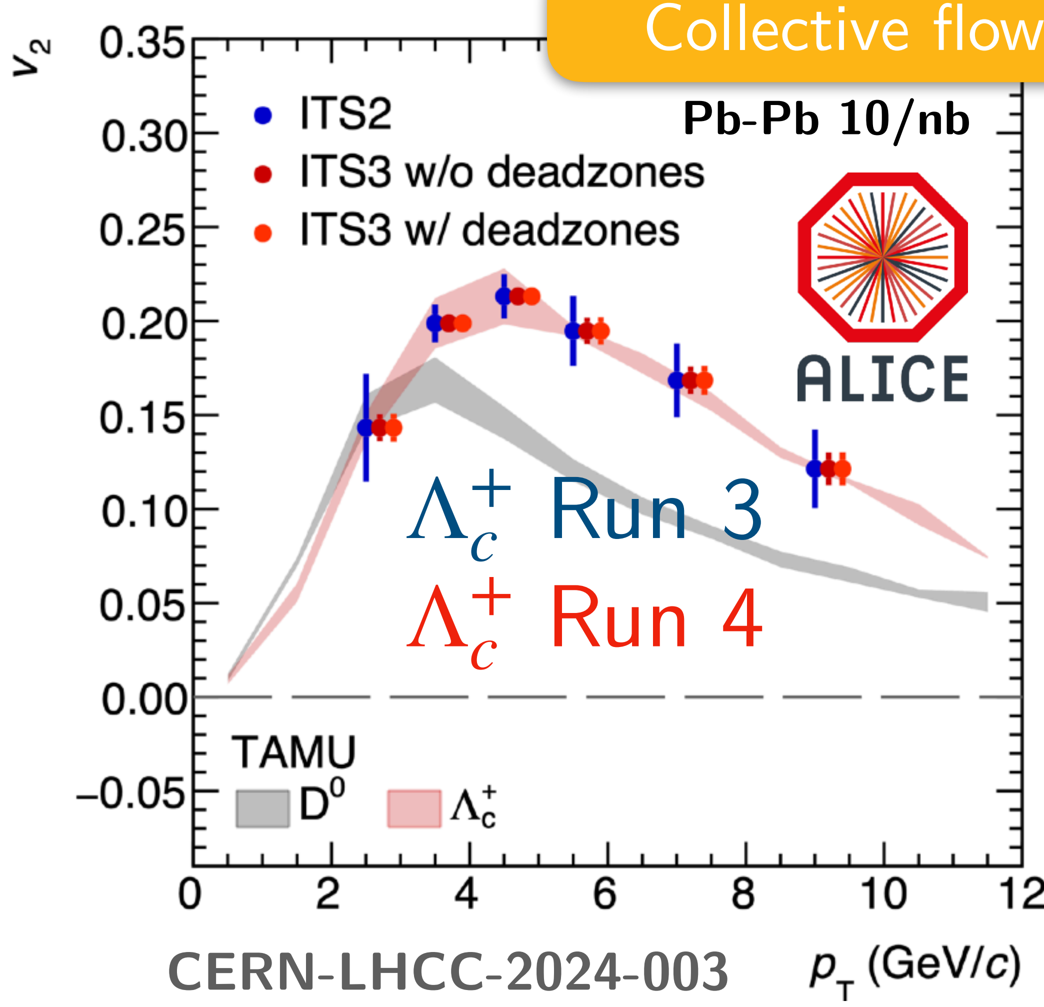


CERN-LHCC-2024-003

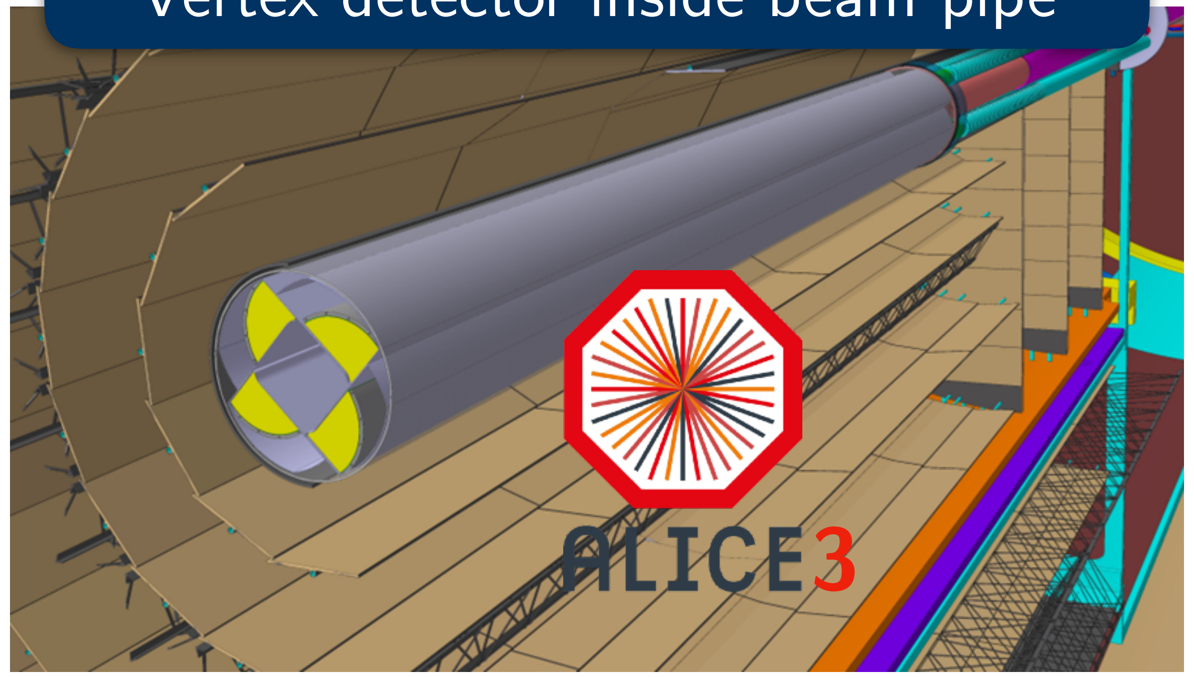
Not shown: LHCb HF capabilities for full centrality range in Pb-Pb thanks to "mighty tracker" in Run 5+

Novel insights into charm recombination using multi-charm hadrons

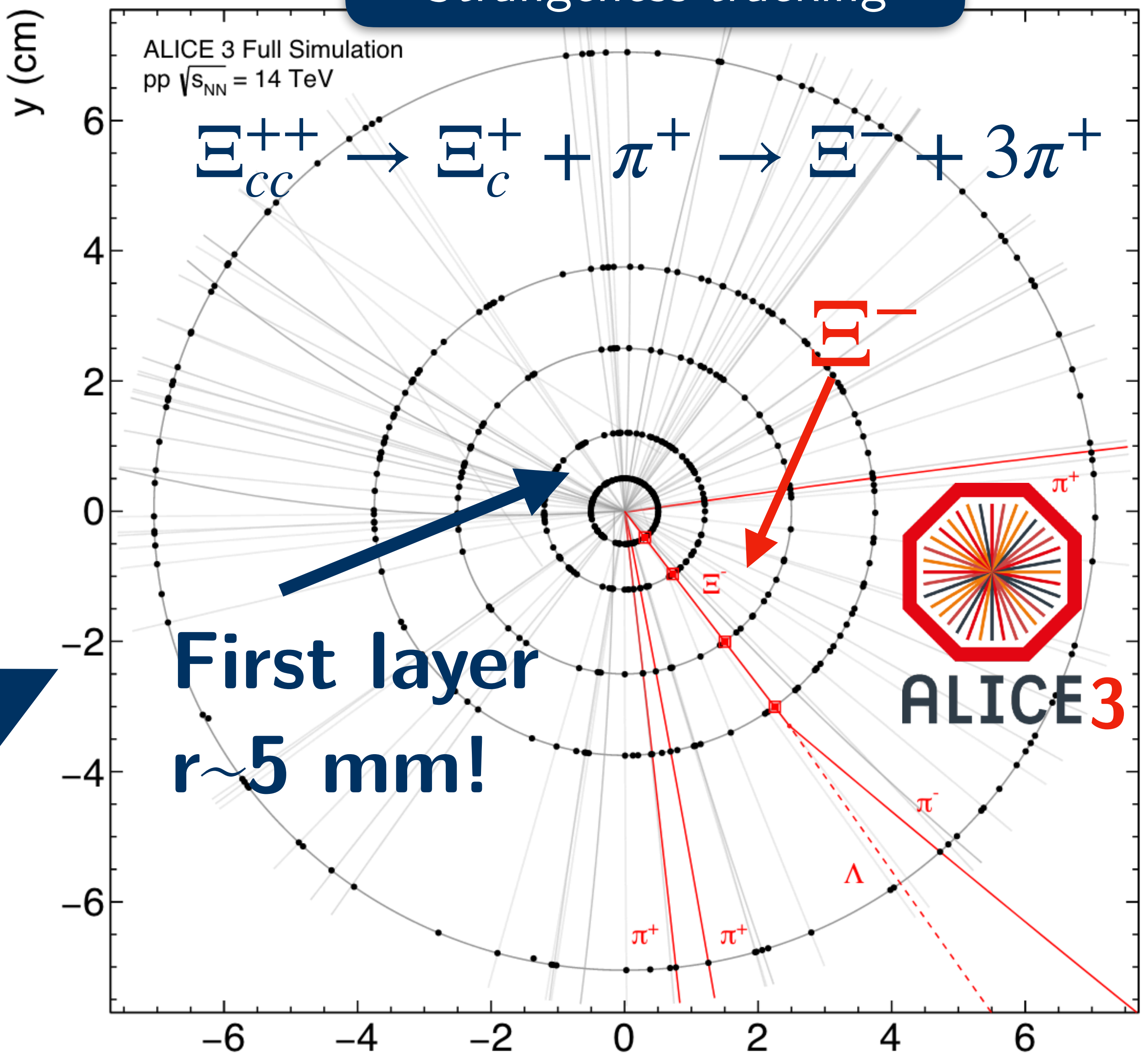
- **Present:** **multi-strange baryon yield** enhancement in Pb-Pb; first evidence Λ_C/D enhancement → **coalescence**
- **Run 3 & Run 4:** precision studies in charm sector: **single charm baryons**
- **Beyond Run 4:** **multi-charm baryons** → only produced by combination of uncorrelated charm quarks → **novel insights into production mechanism**

ALICE3: unique opportunities to study $\Xi^{+}_{cc}(ccd), \Xi^{++}_{cc}(ccu), \Omega^{+}_{cc}(ccs), \Omega^{++}_{ccc}(ccc)$ thanks to "strangeness tracking" in silicon pixel tracking layers

Vertex detector inside beam pipe

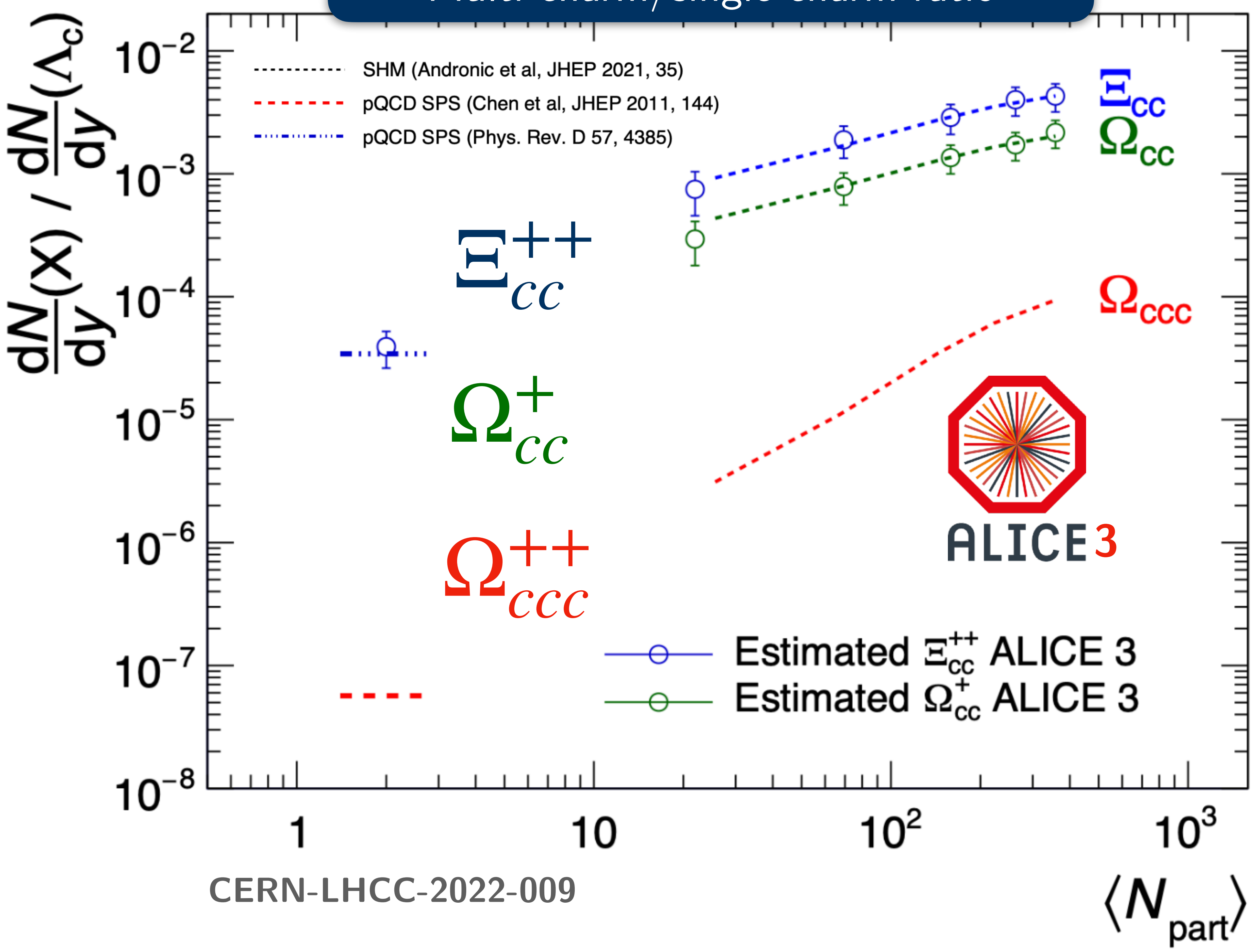


Strangeness tracking



CERN-LHCC-2022-009

Multi-charm/single charm ratio



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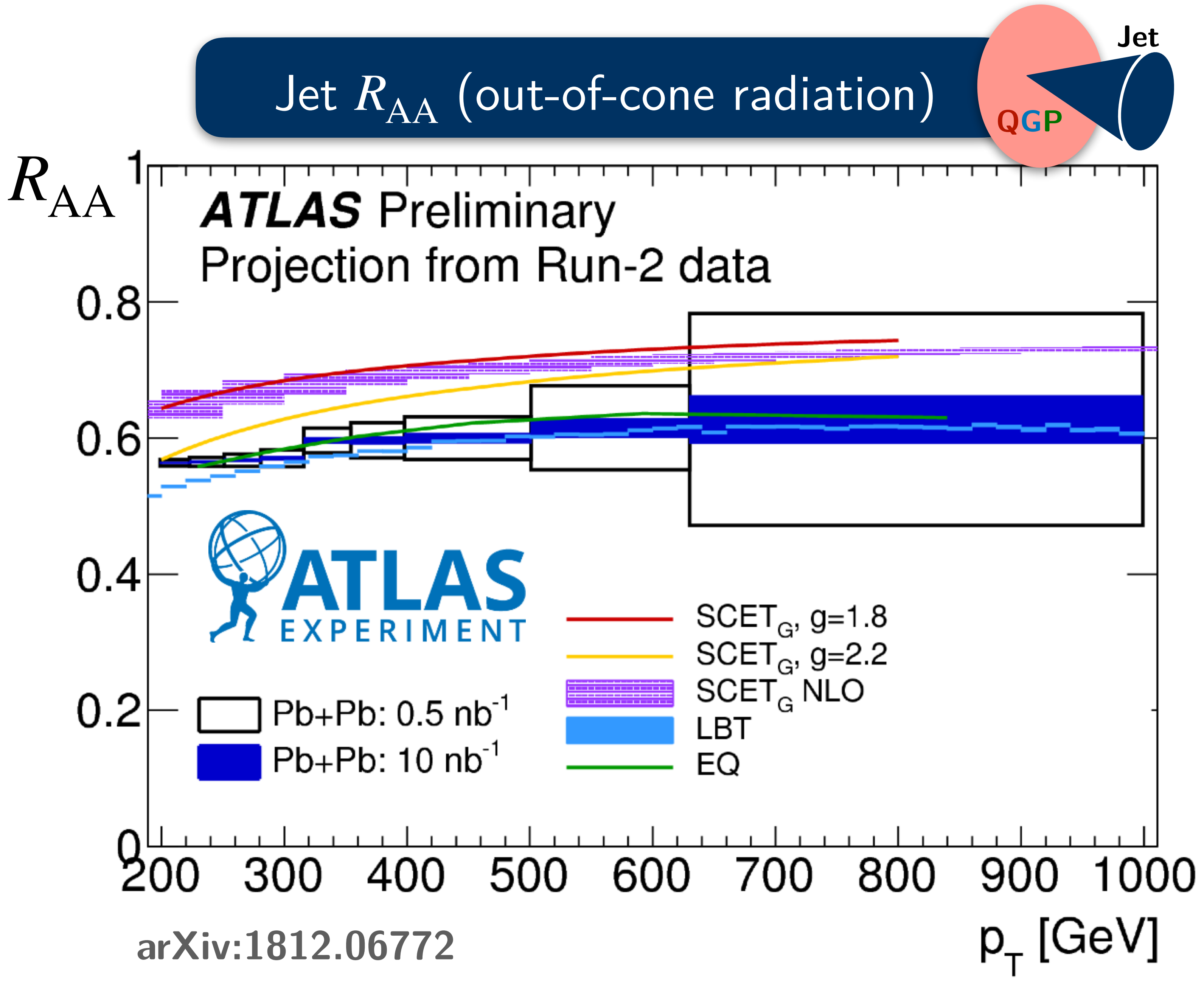
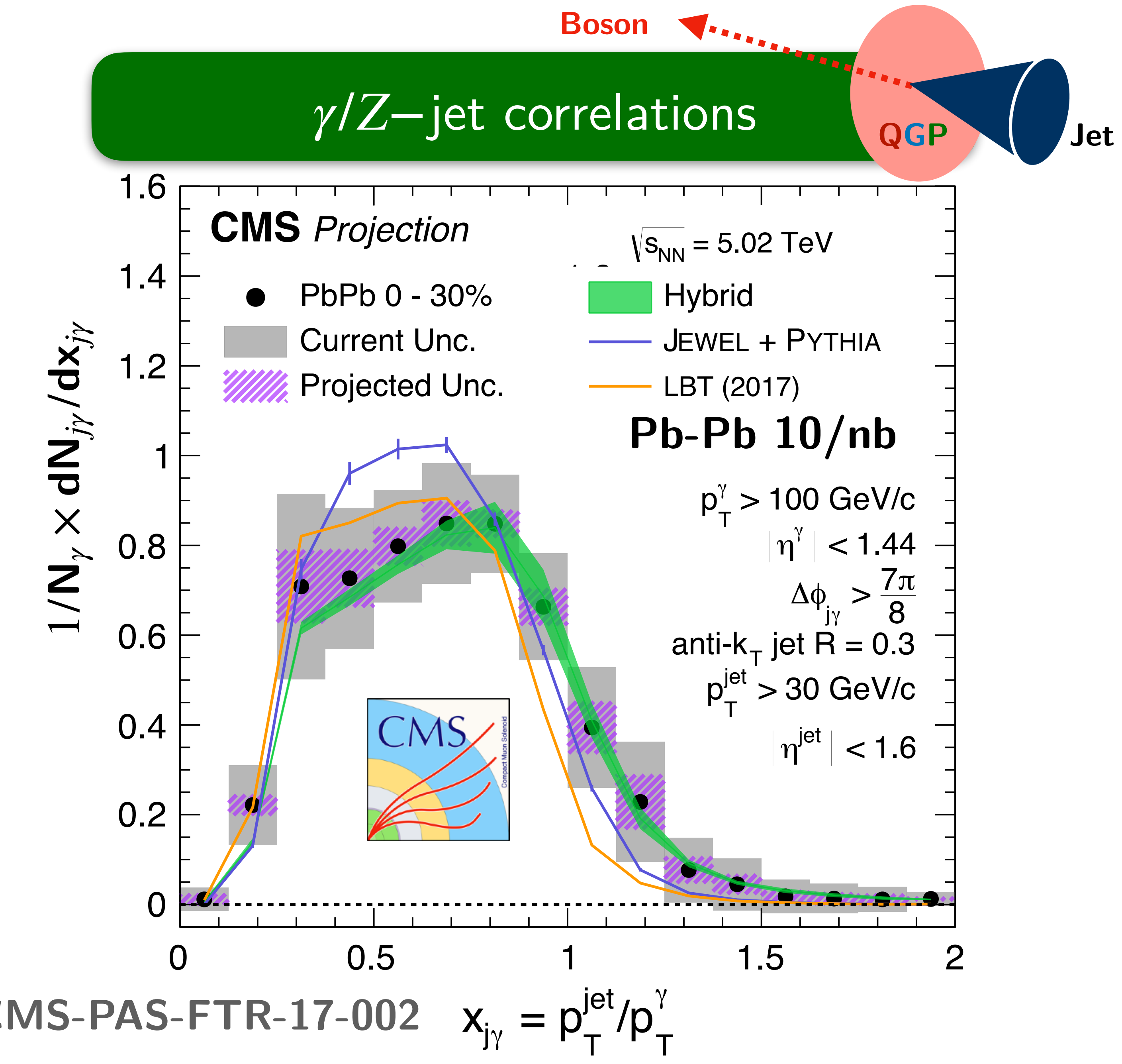
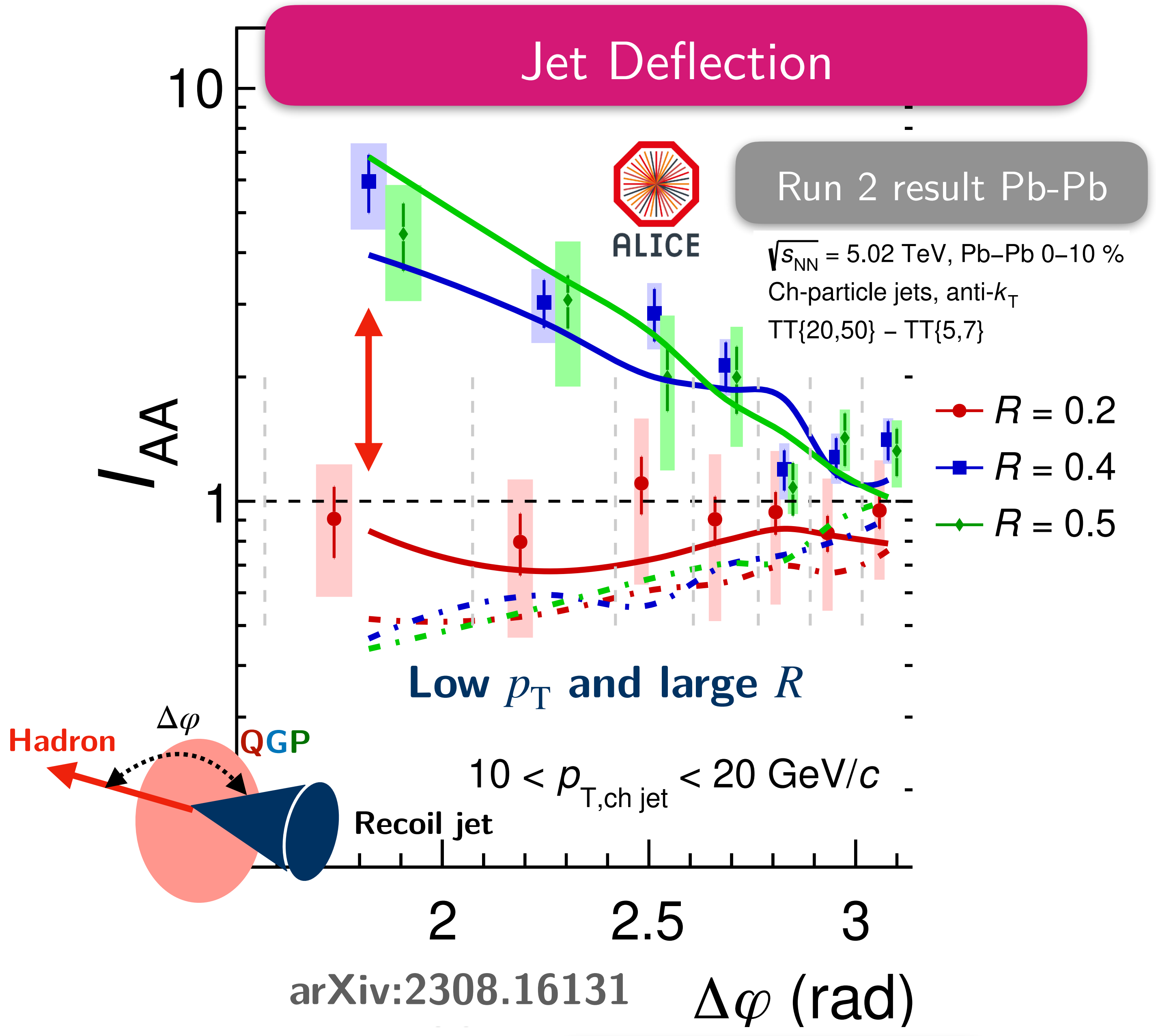
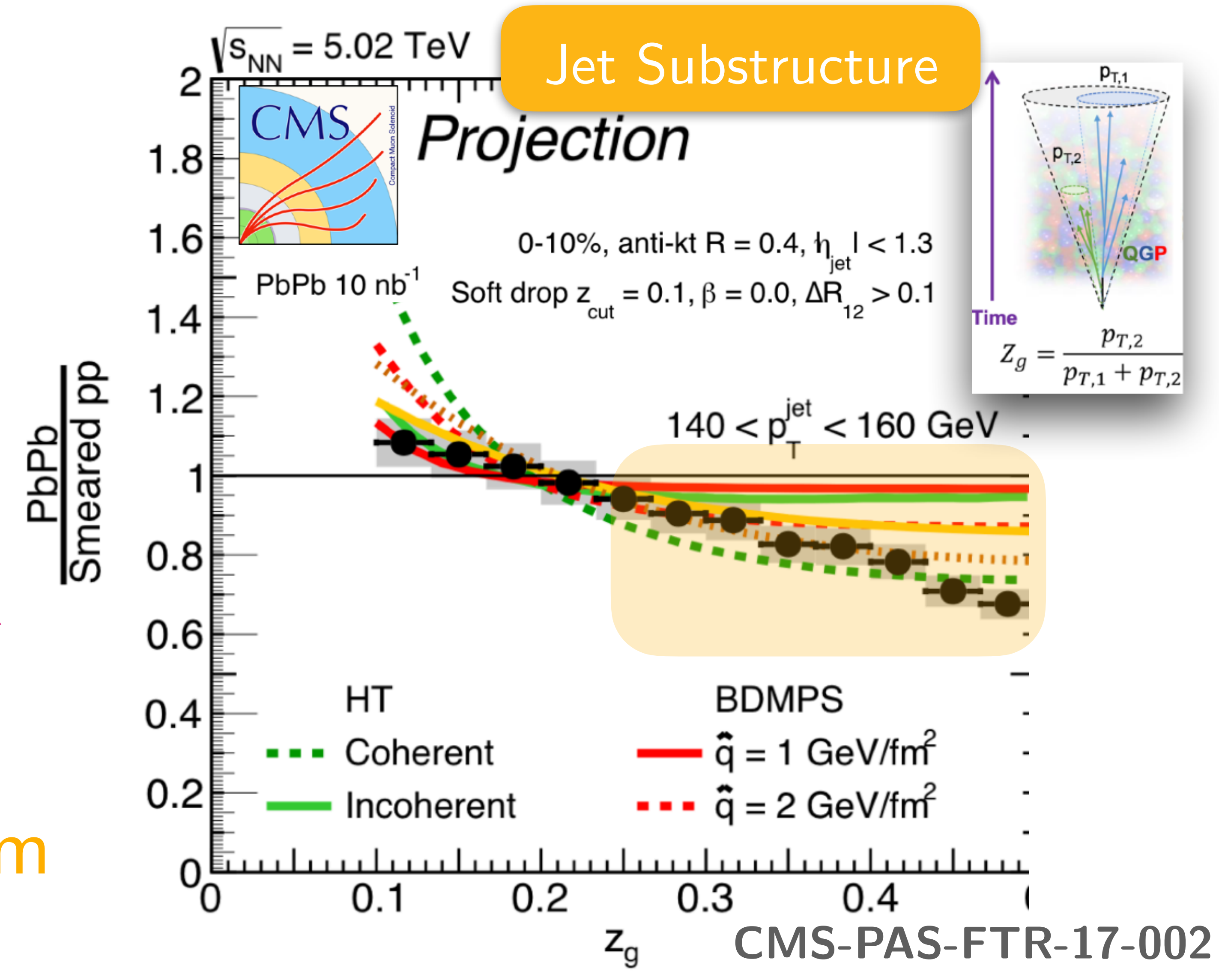
Jet physics

Physics: Microscopic QGP properties, extraction of transport coefficient $\hat{q}$, multi-scale probe for QGP









Jet physics: probing the short distance structure of QGP through scattering of a hard probe

- Precision measurements of R_{AA} at high-p_T: significant quenching & low UE
- γ/Z-jet corr.: well calibrated probe for absolute energy loss; high amount of quark jets
- Run 2 results show first indication of medium-induced jet deflection at low-p_T and large R → HL-LHC allows more differential studies in p_T, R ...
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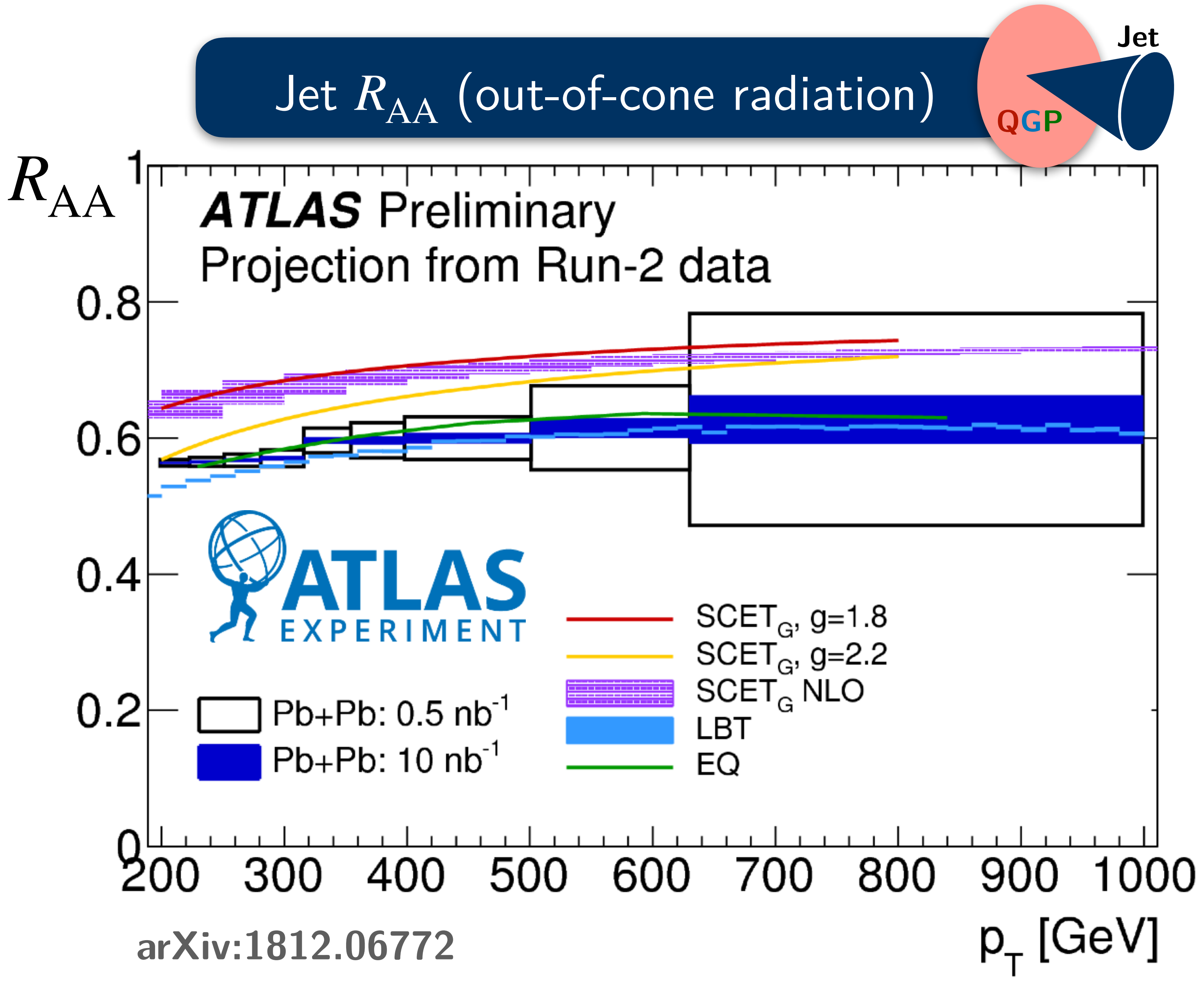
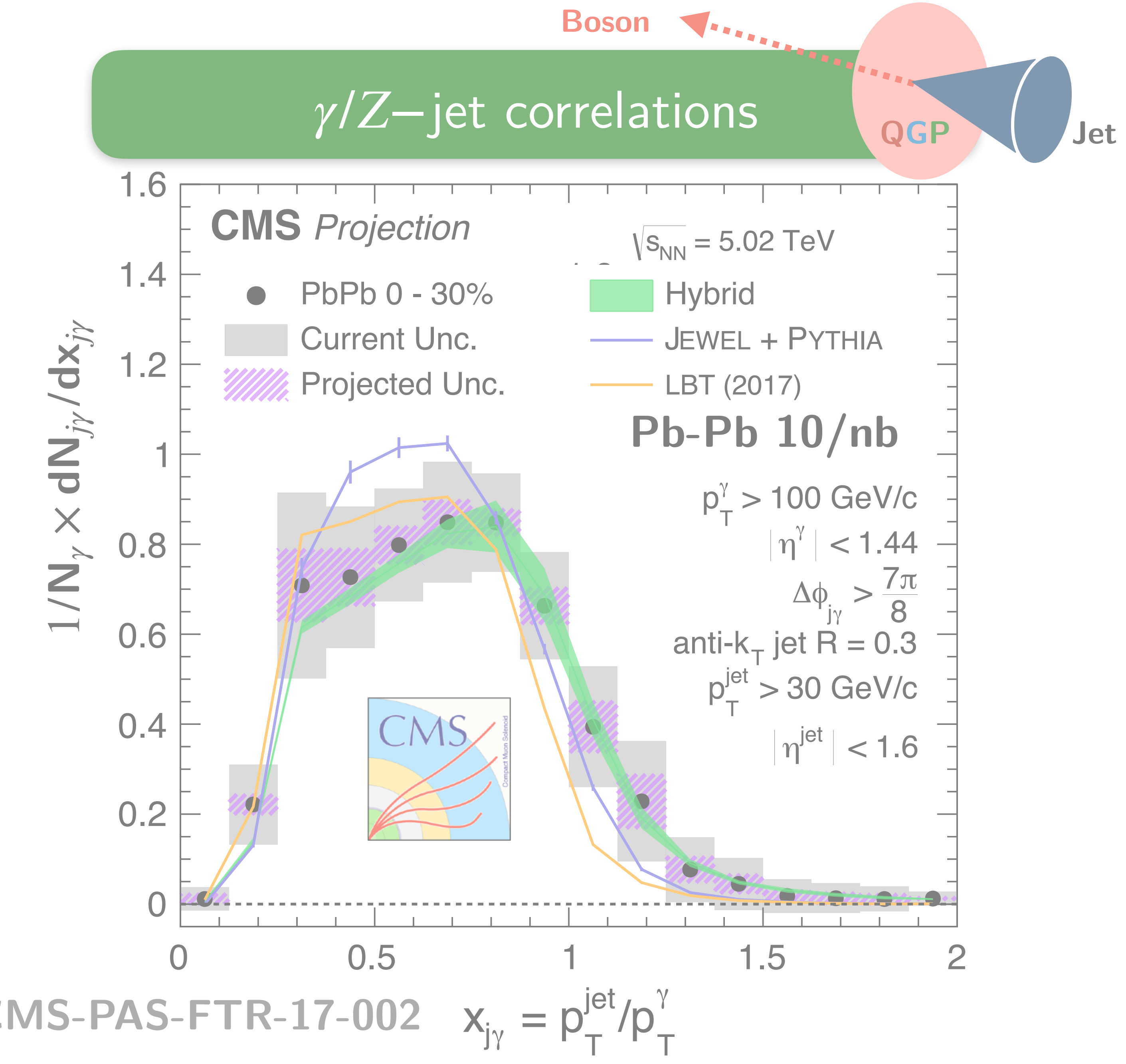
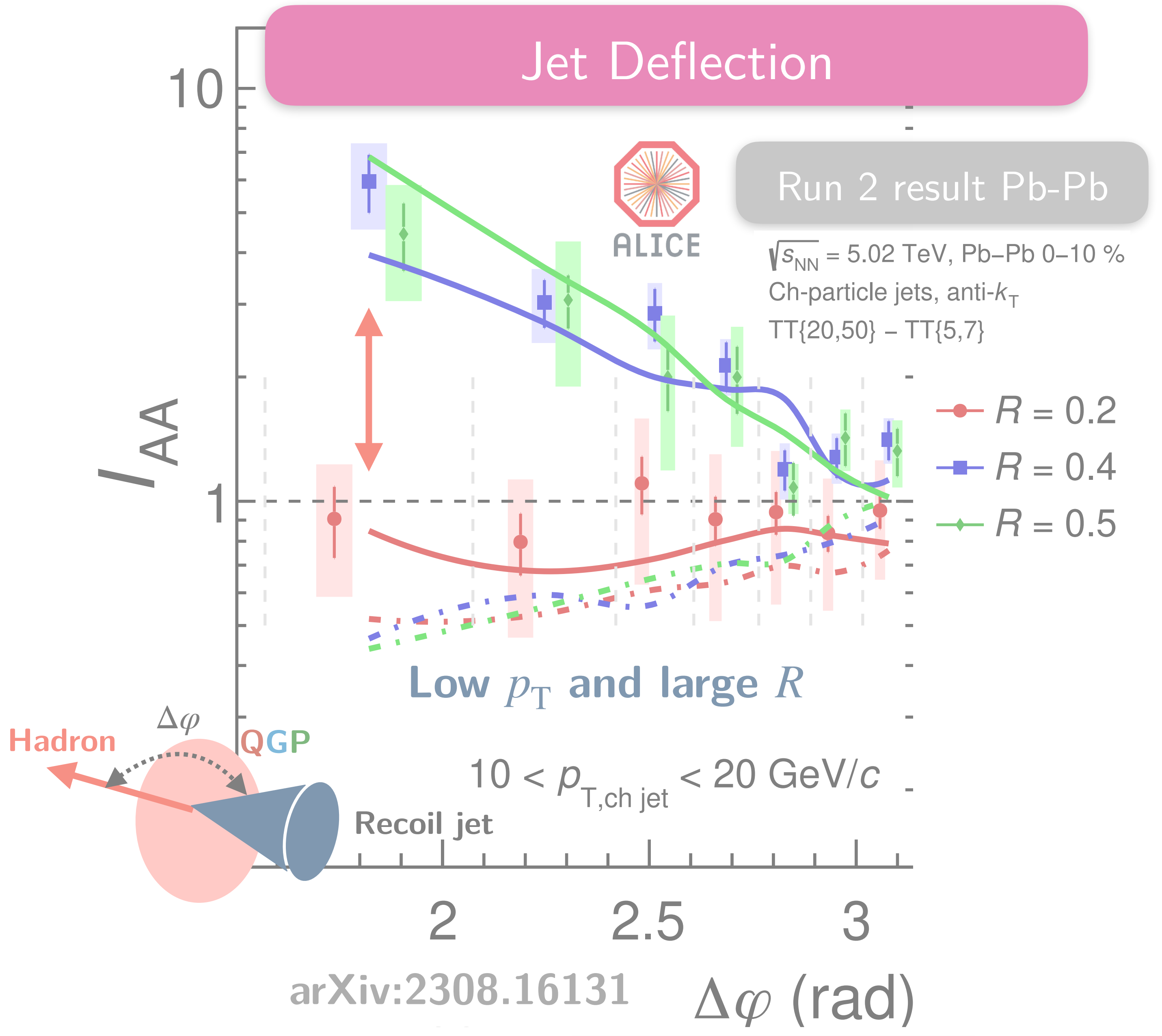
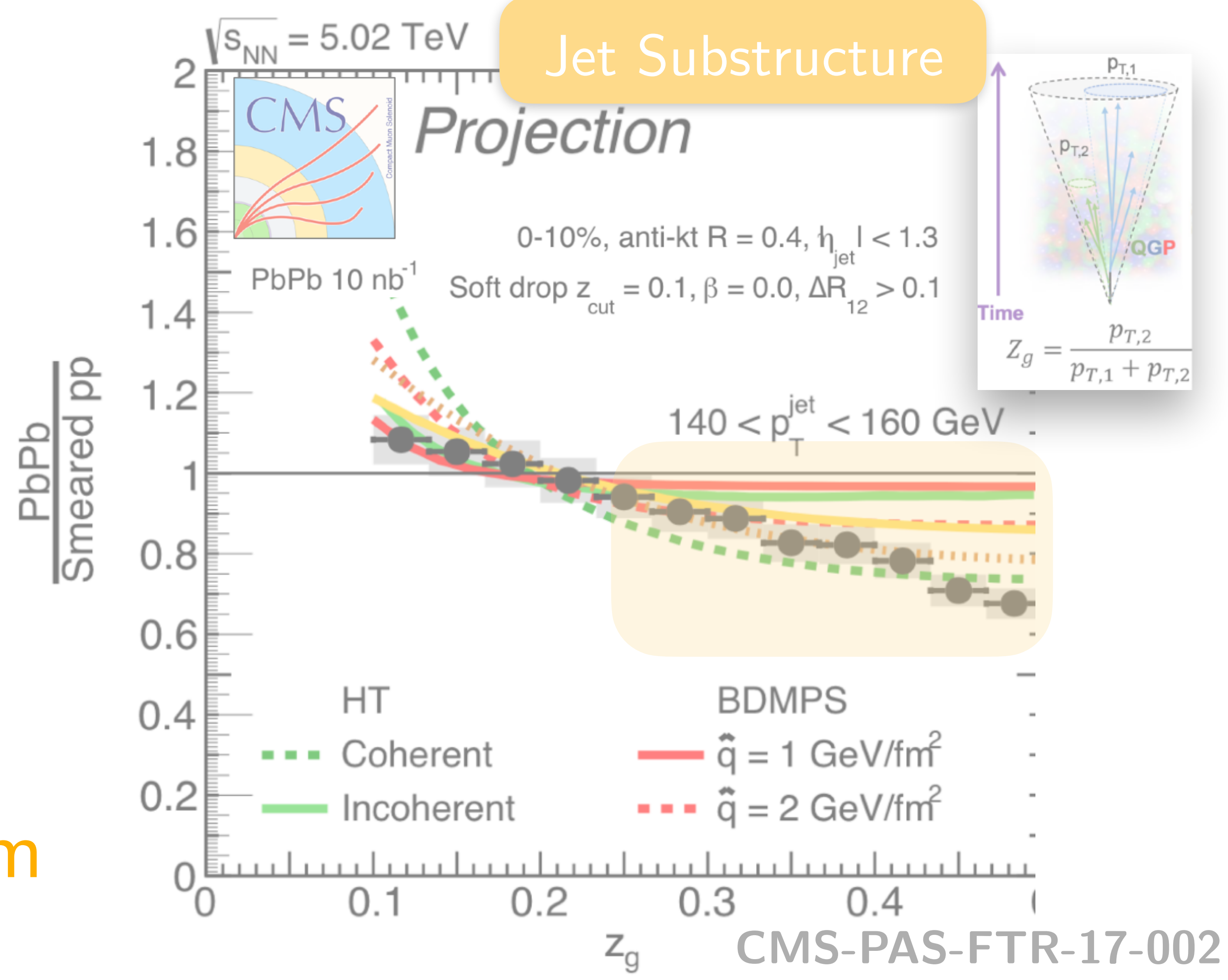
Jet R_{AA} (out-of-cone radiation)



γ/Z–jet correlations







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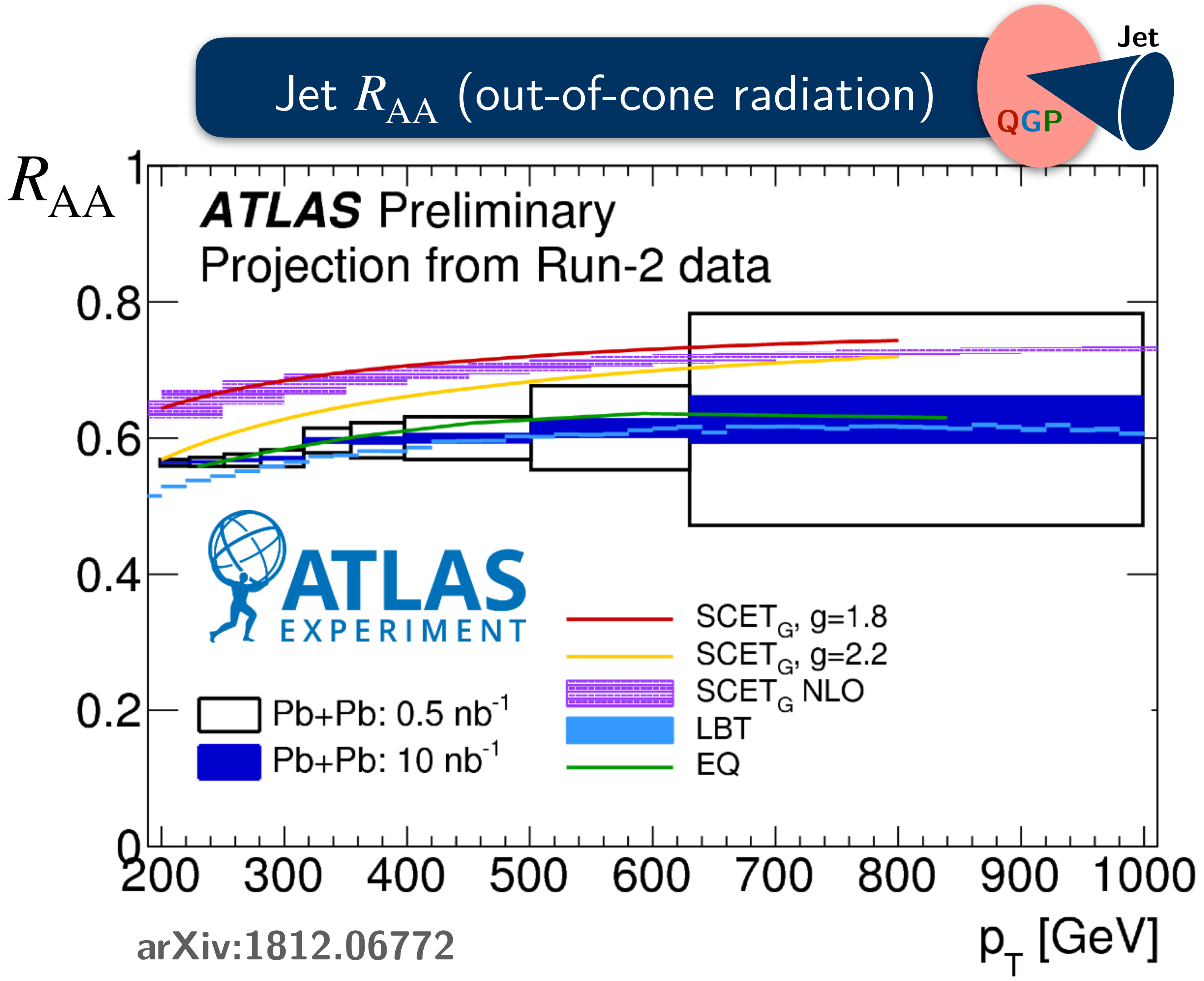

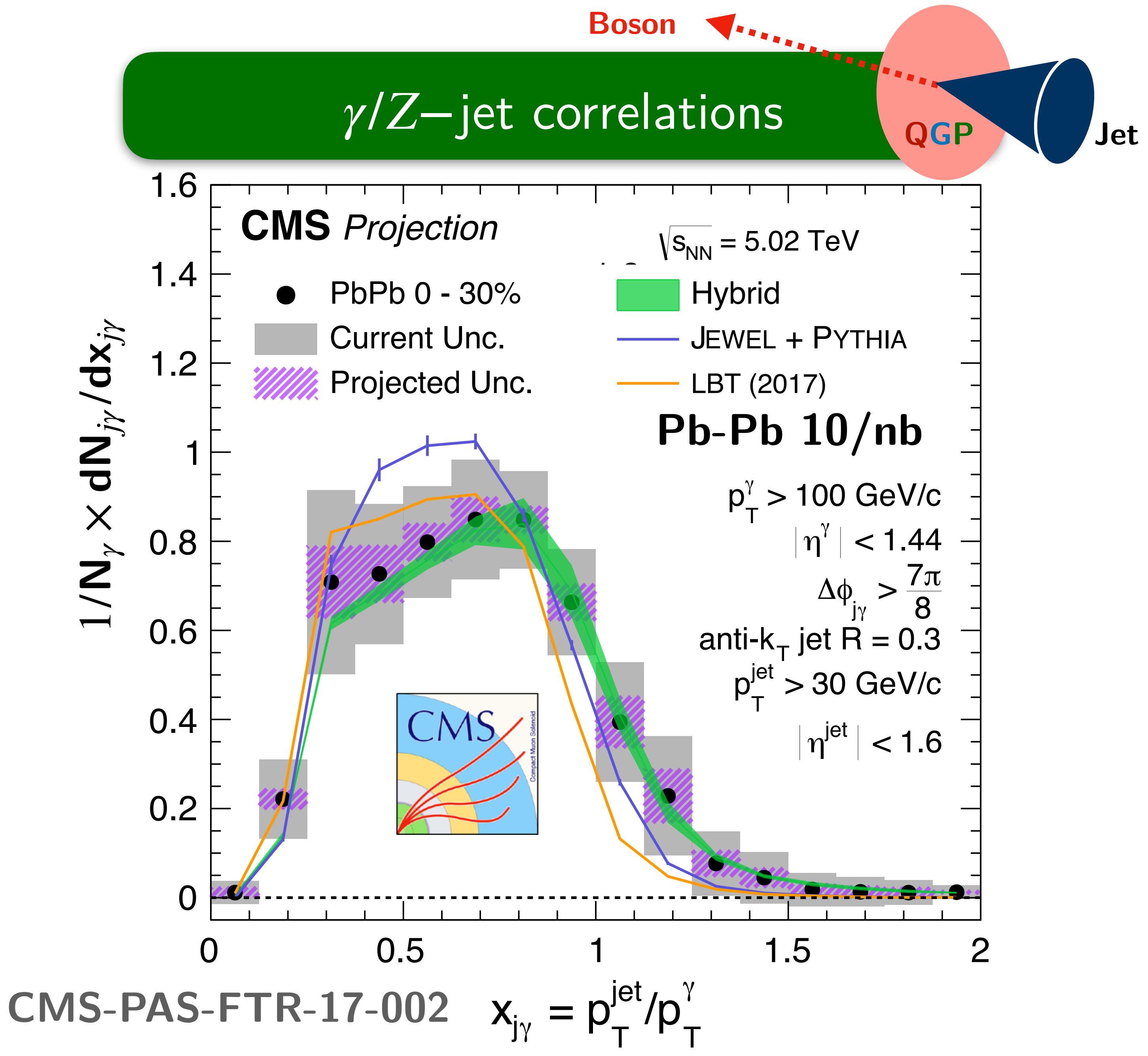

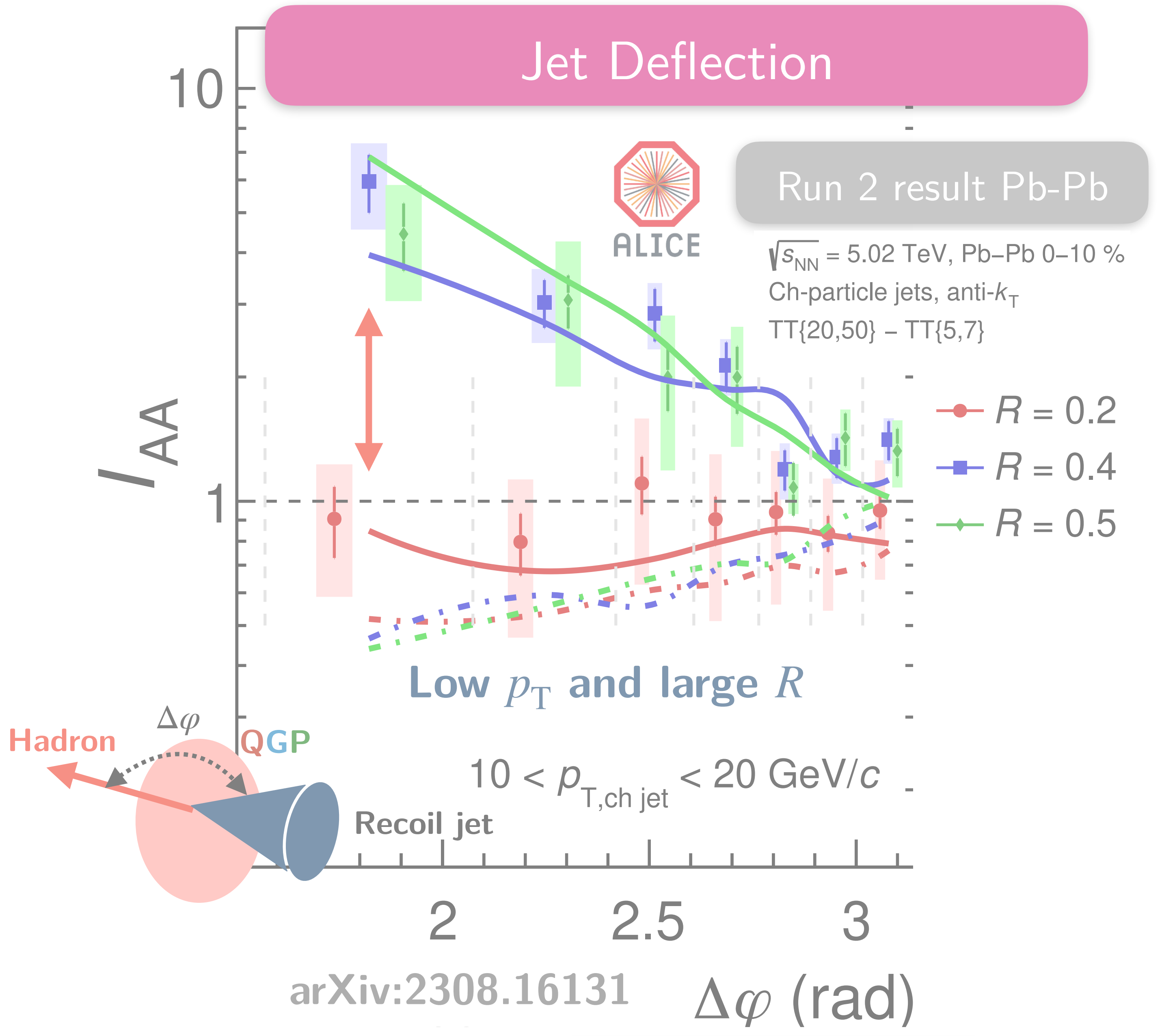

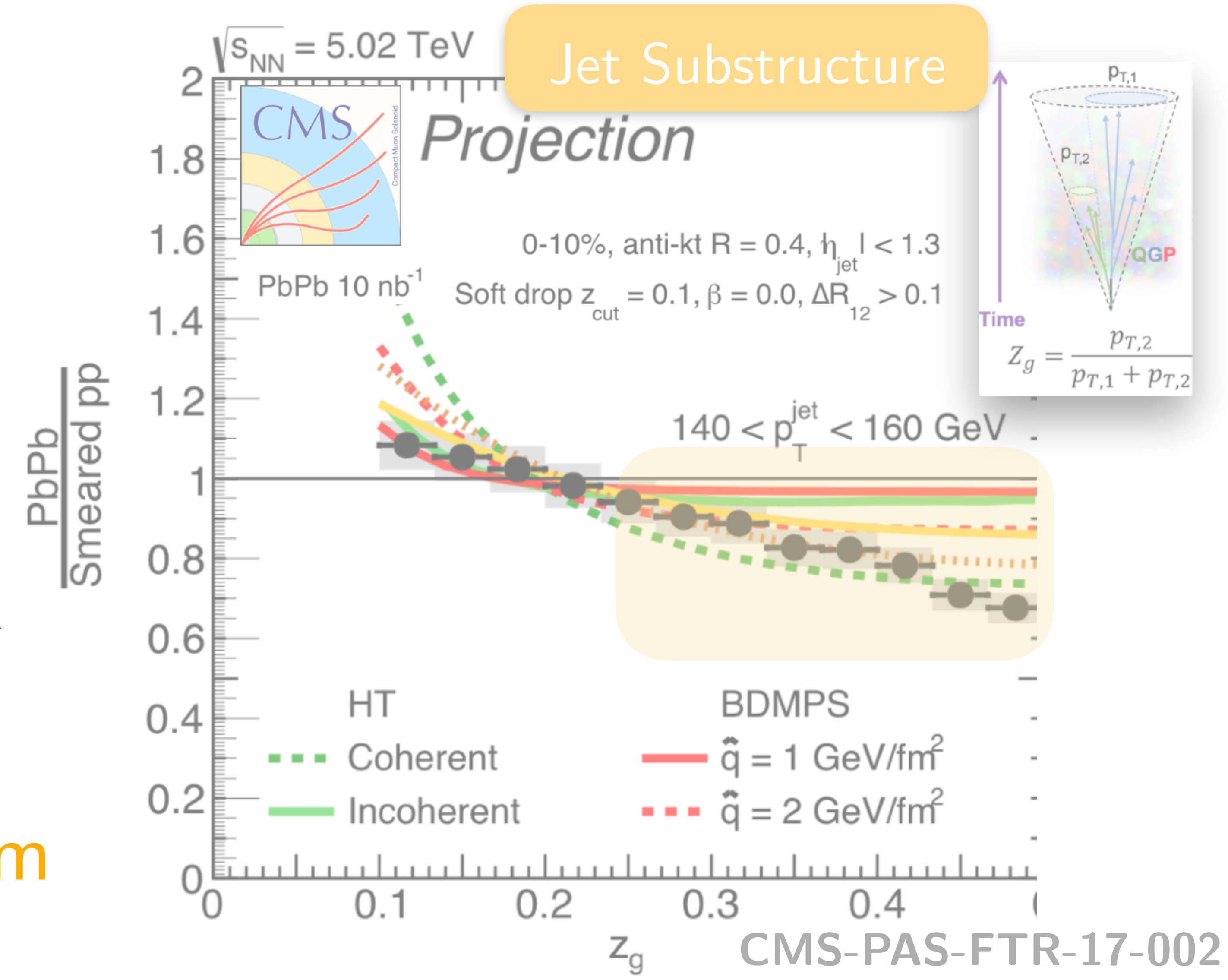

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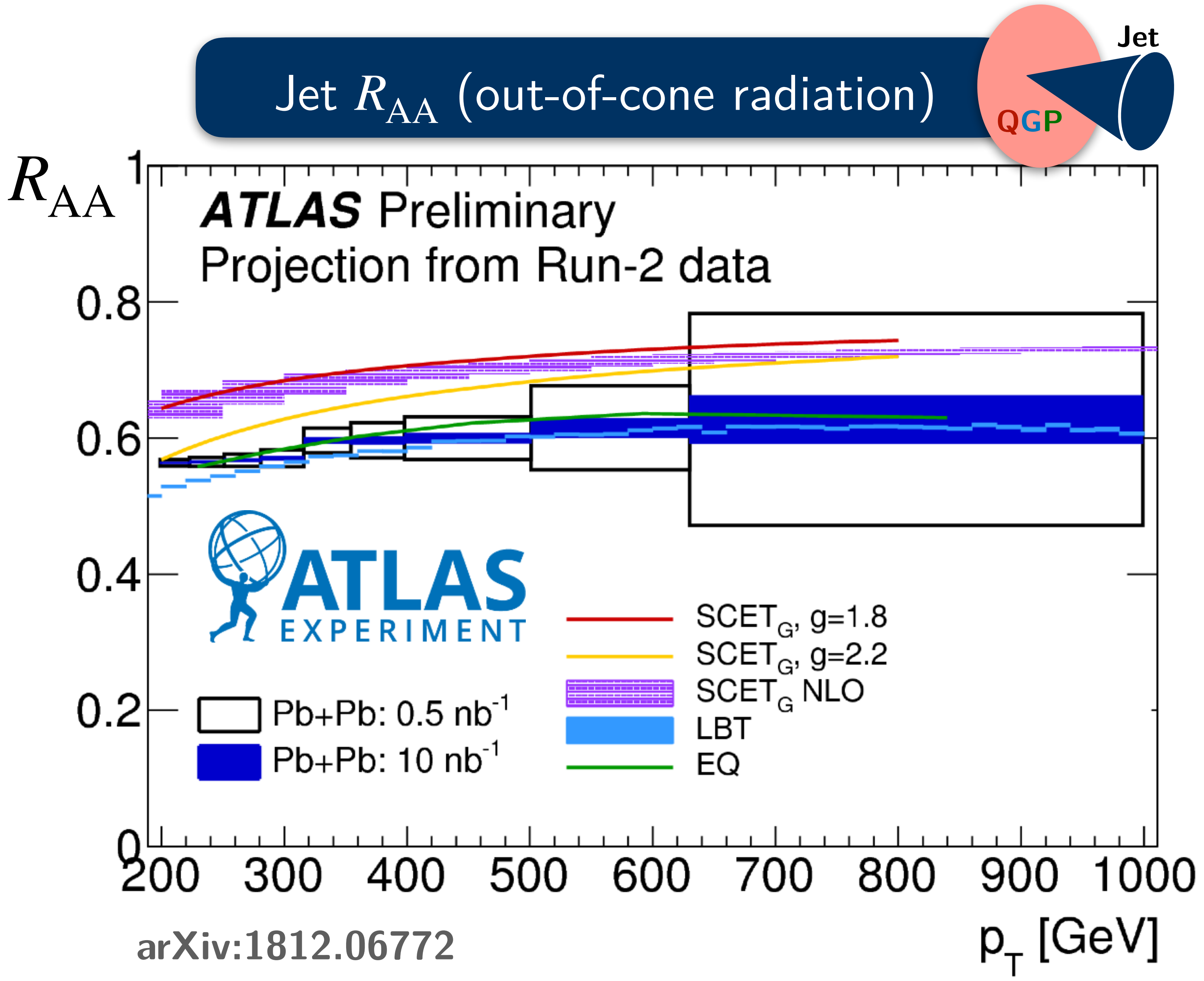

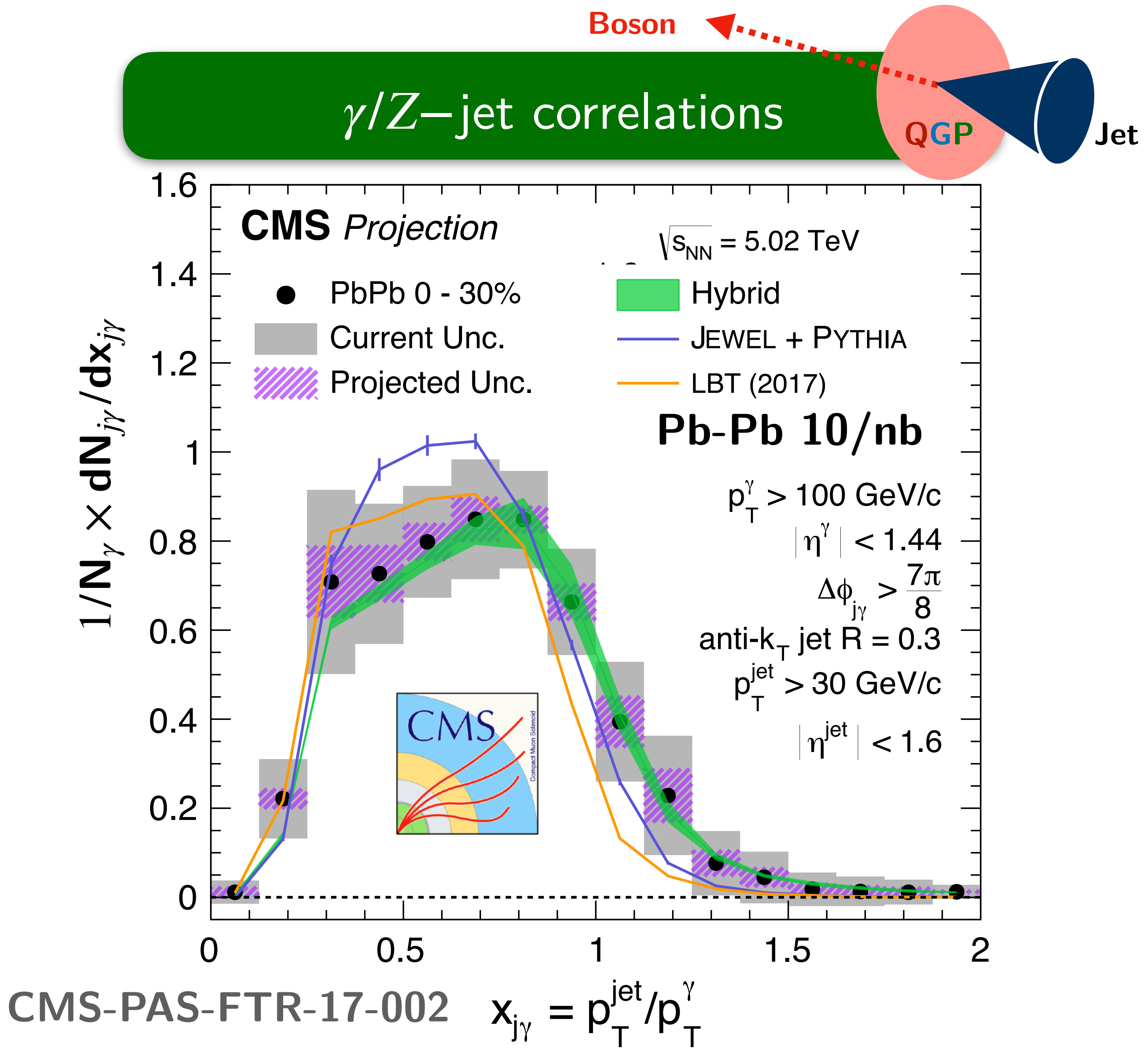

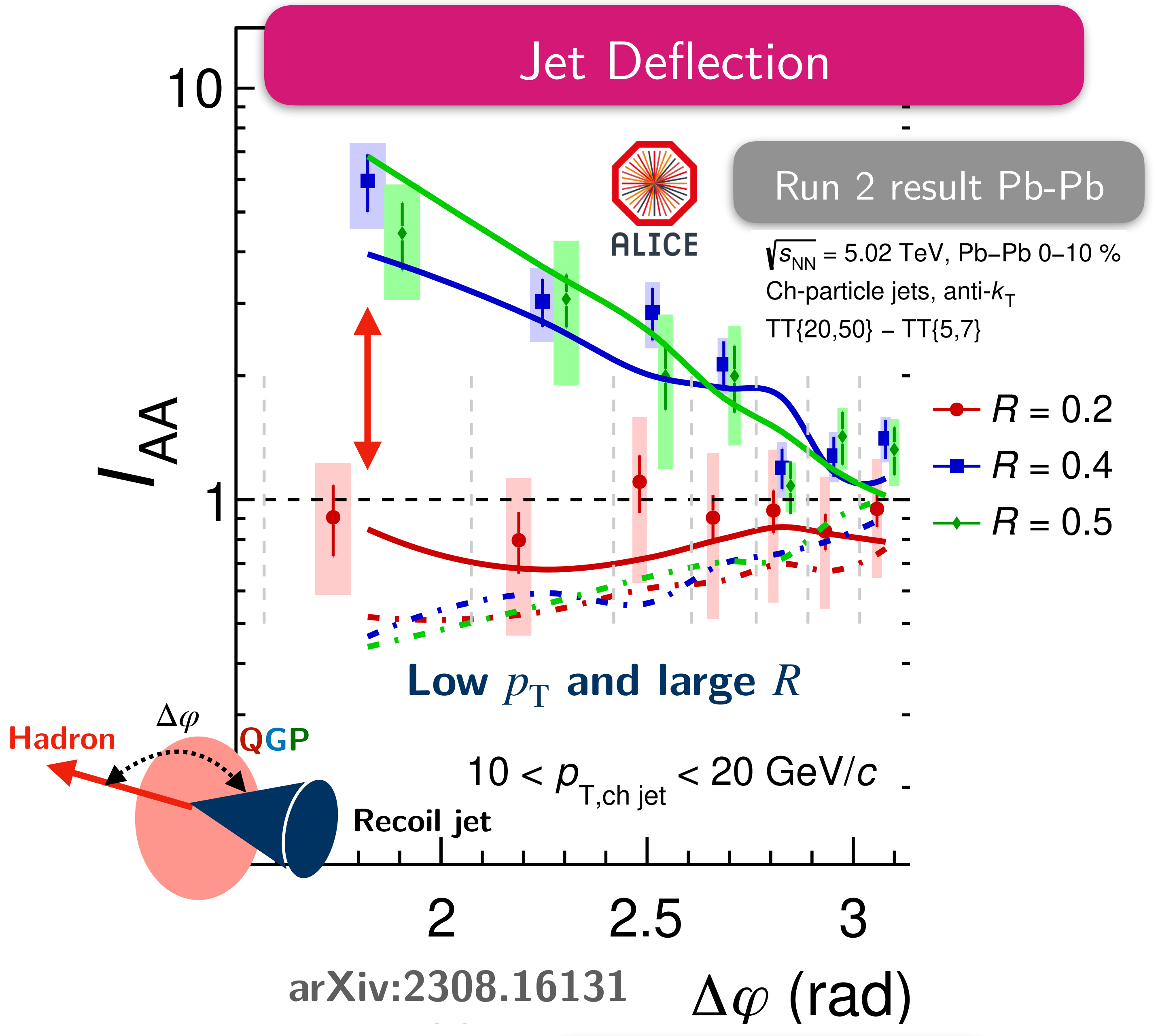

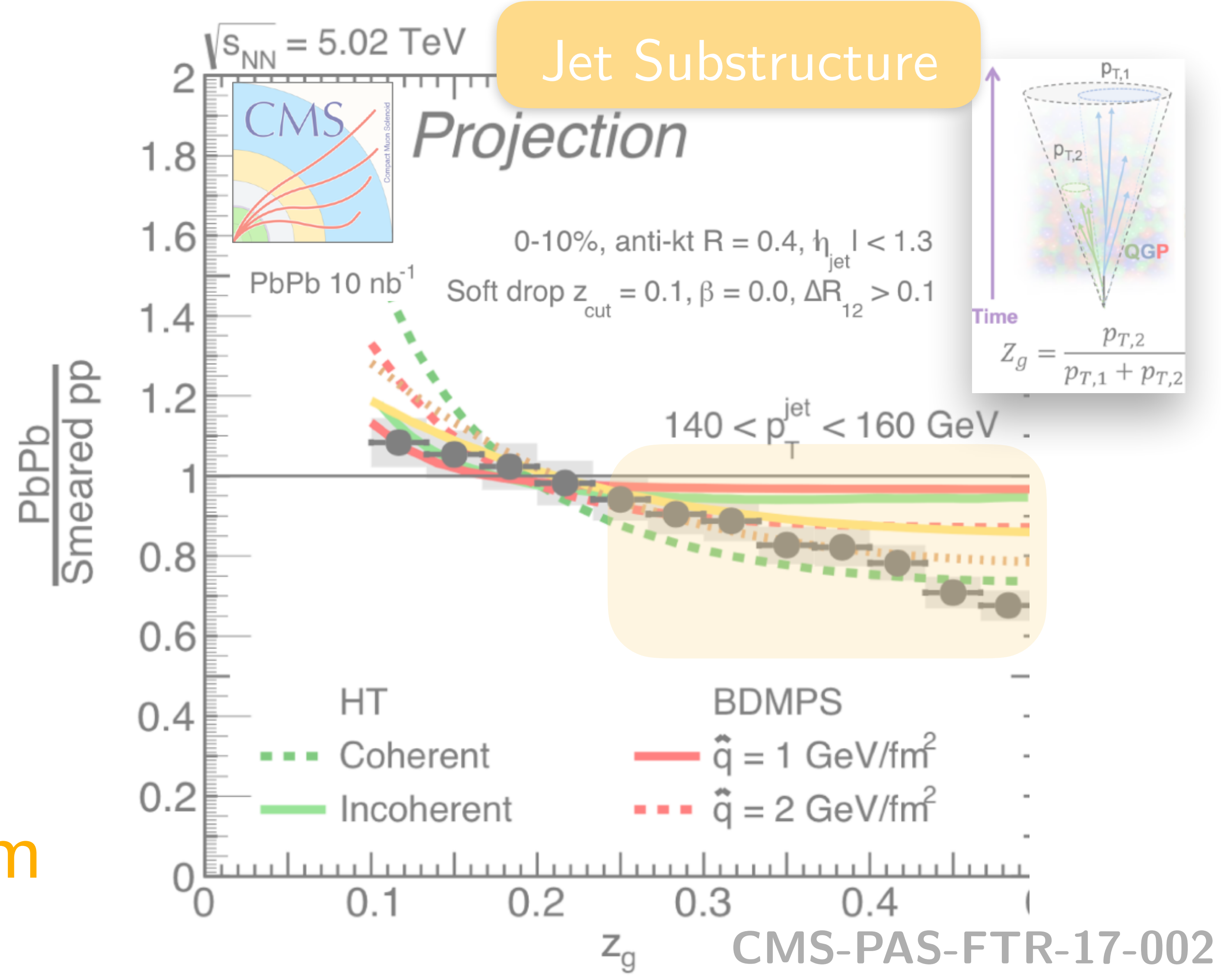

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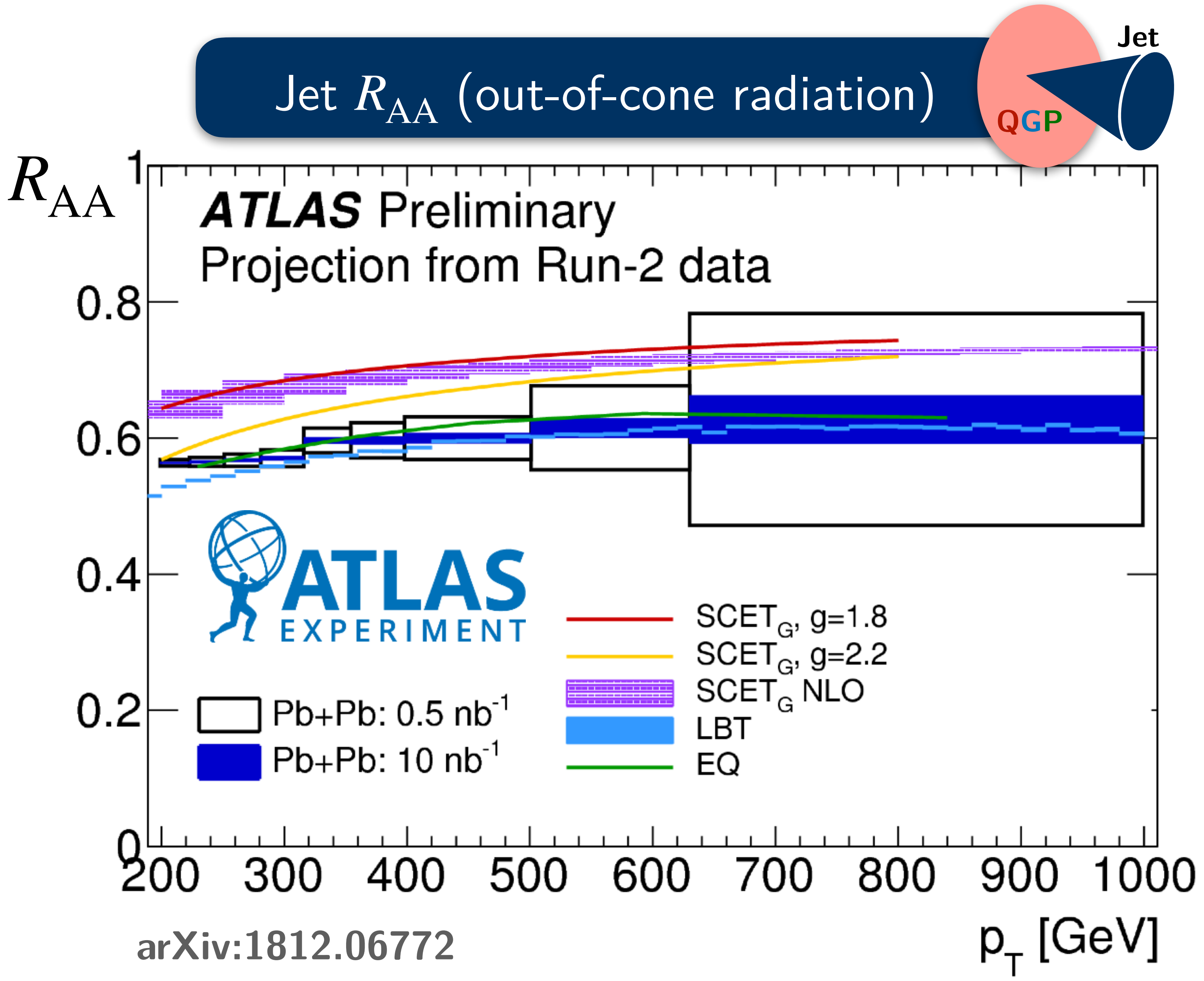
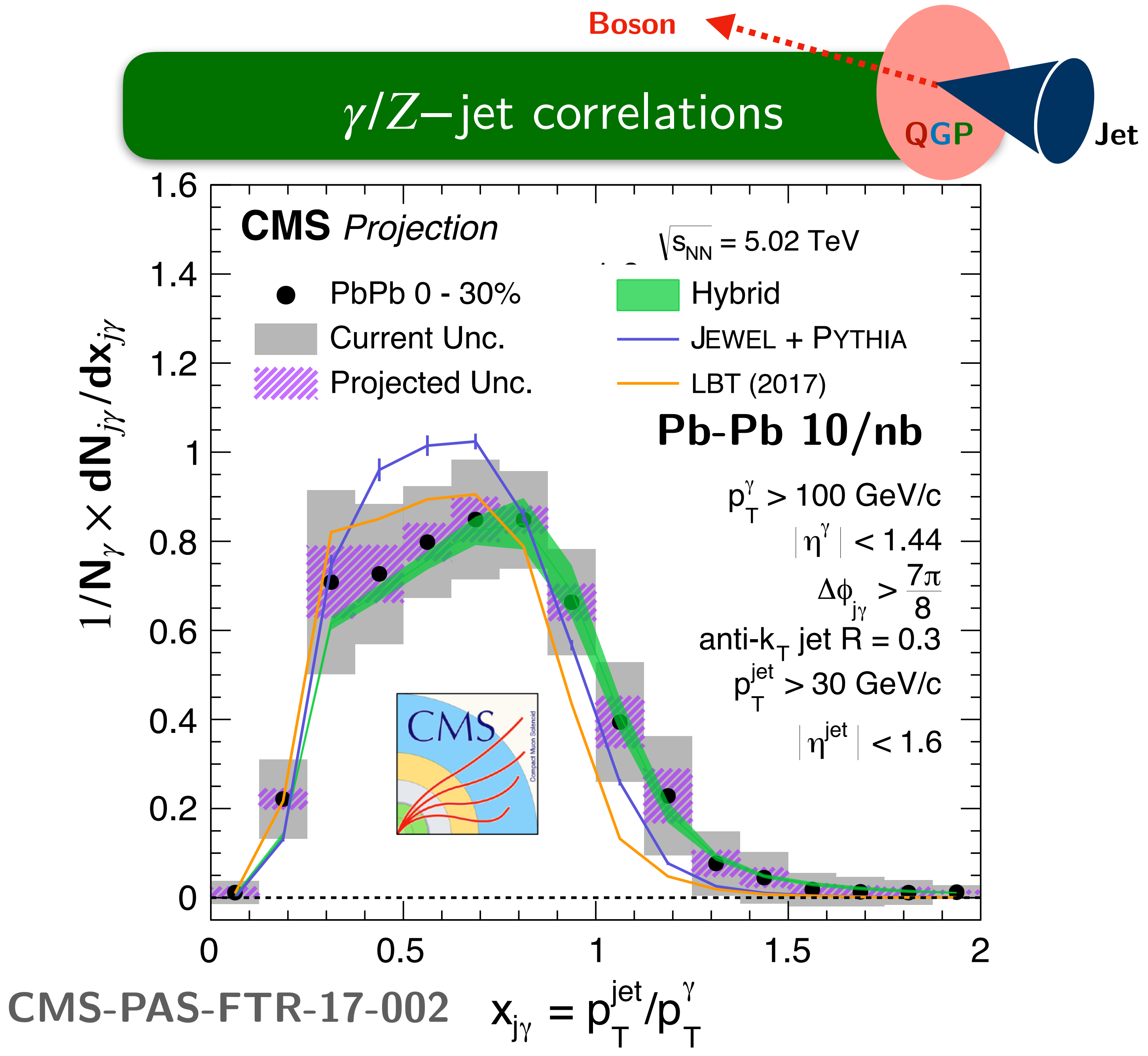
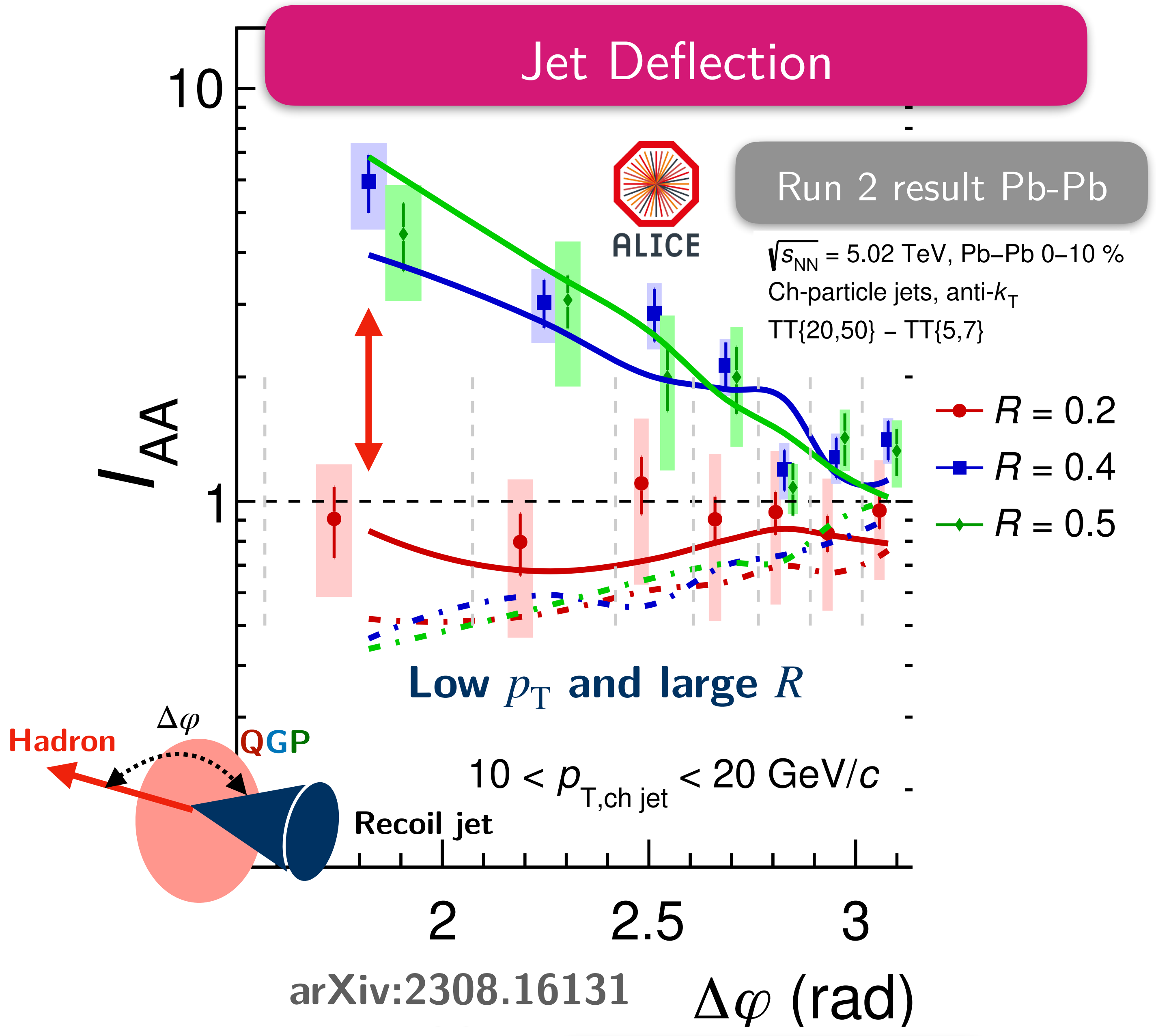
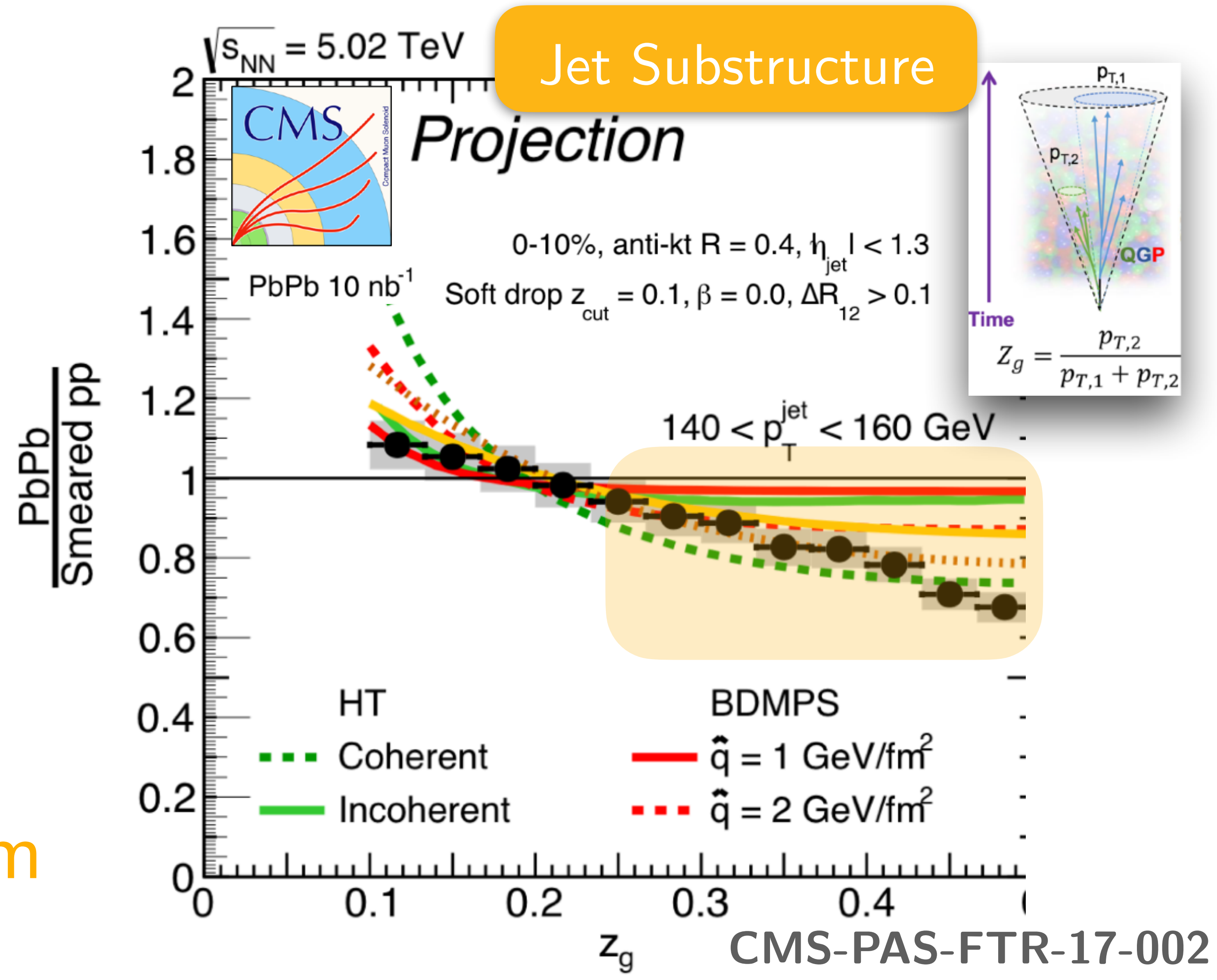






Jet physics: probing the short distance structure of QGP through scattering of a hard probe

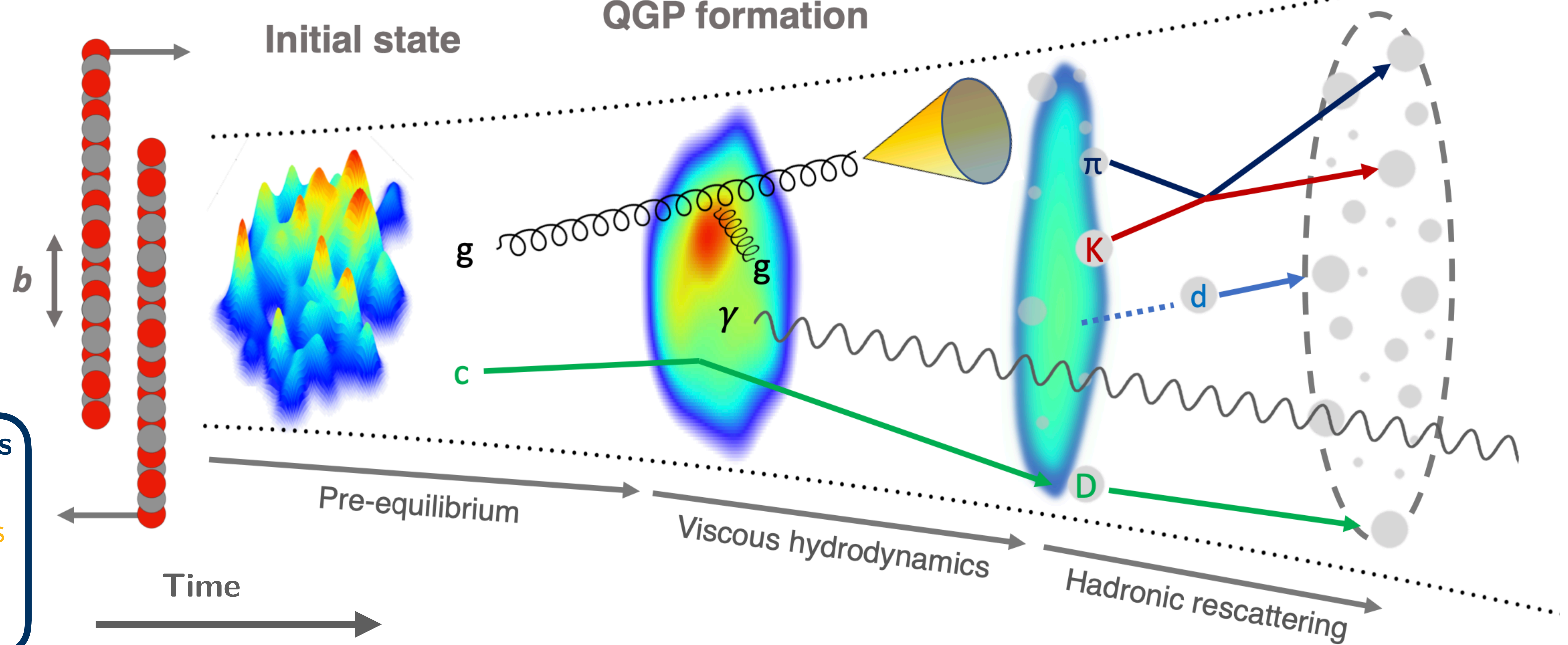
- Precision measurements of R_{AA} at high-p_T: significant quenching & low UE
- γ/Z-jet corr.: well calibrated probe for absolute energy loss; high amount of quark jets
- Run 2 results show first indication of medium-induced jet deflection at low-p_T and large R → HL-LHC allows more differential studies in p_T, R ...
- Jet substructure: resolving energy loss on the level of parton evolution through the medium



Heavy-ion physics: The big questions

What are the macroscopic properties of the QGP? Temperature? Viscosity? QCD phase transition?
Thermal photons, dileptons, quarkonia, flow ...

What are the initial conditions of a collision? nPDFs & Saturation?
DY, UPC, forward LHC ...



arXiv:2211.04384

Collectivity of QCD across system sizes?
Flow in pp, p-A; strangeness production, energy loss, thermal radiation

What is the microscopic dynamics of QGP at various length scales?
Jets (substructure), γ/Z-jet correlations, heavy flavour, quarkonia, hadronization

QGP in small systems?

Run 1 & Run 2: Full of surprises

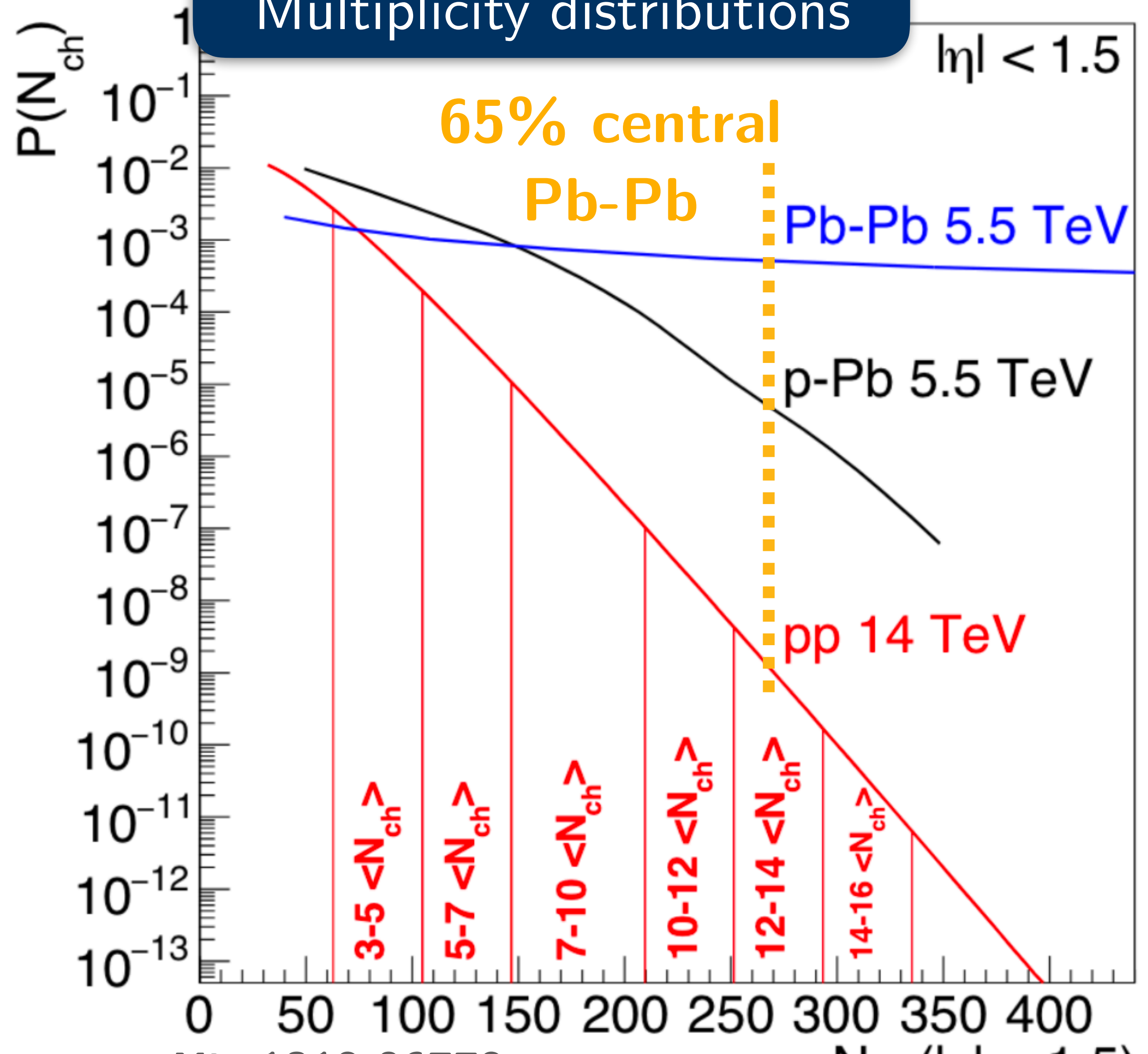
1. Long-range correlations observed in high mult. pp collisions and p-Pb collisions
2. Strangeness enhancement observed in pp and p-Pb collisions → smooth as a function of multiplicity

Do we have QGP in small systems?
(applying HI modelling in novel regimes?)

Is our understanding/description of pp physics still accurate?
(additions to pp modeling?)

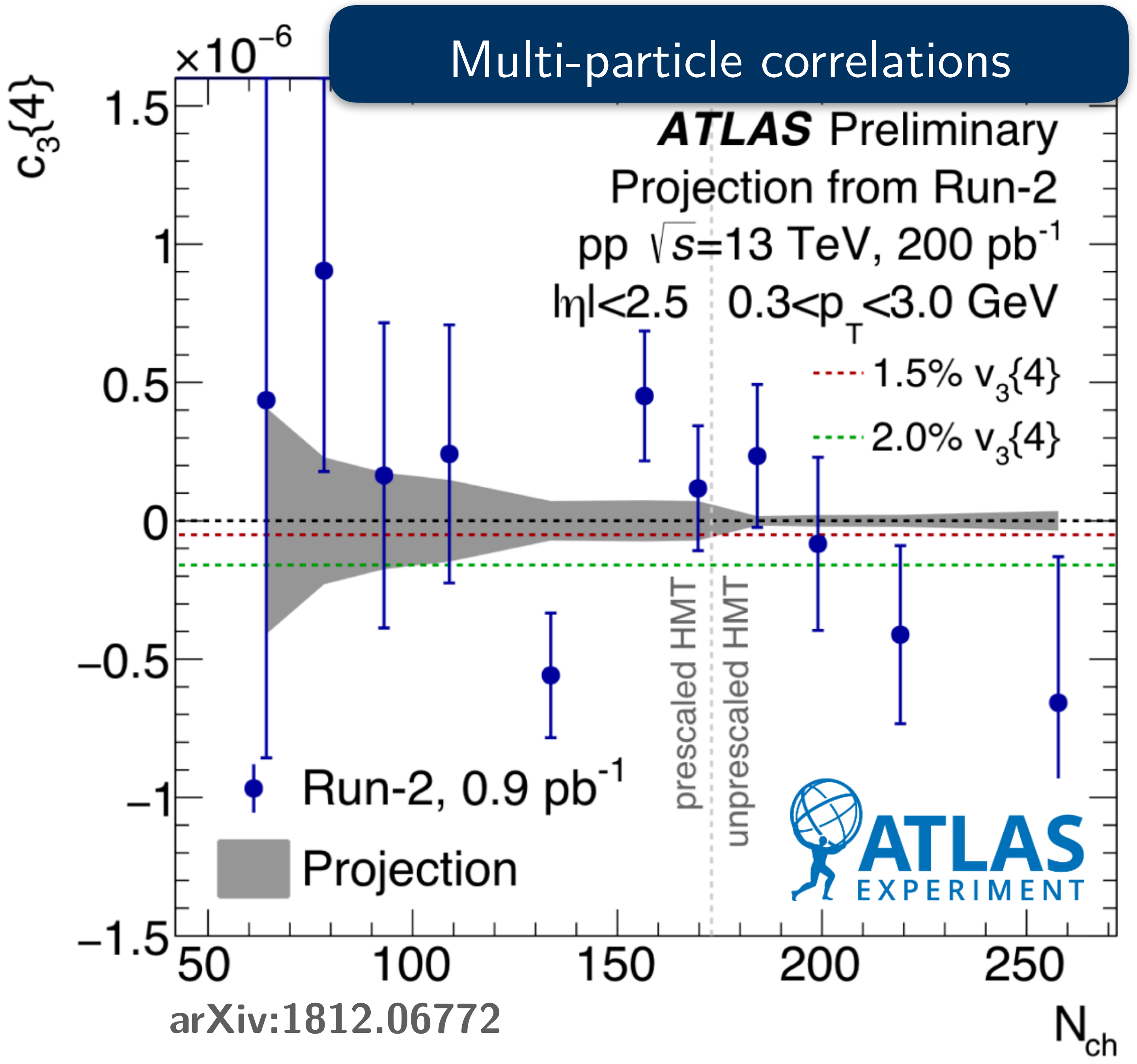
Run 3 and beyond: systematic study of "QGP signals" in pp, p-Pb and Pb-Pb collisions

Multiplicity distributions



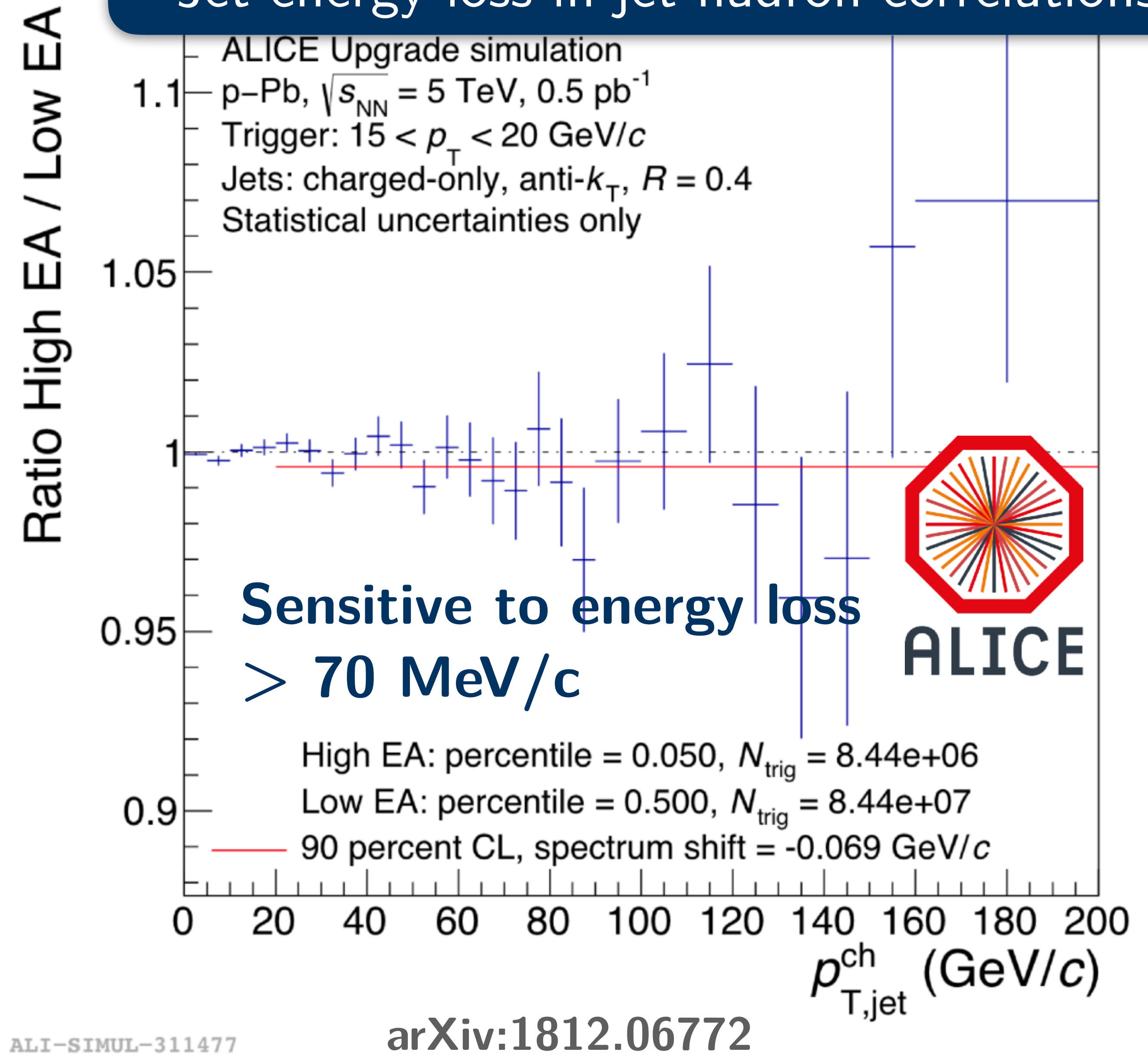
arXiv:1812.06772

Multi-particle correlations



arXiv:1812.06772

Jet energy loss in jet-hadron correlations



arXiv:1812.06772

\+ Strangeness enhancement

Thermal radiation

Connections to other fields / Additional perspectives

Neutron stars
QCD Equation of State
Neutron skin thickness
Hypernuclei production
arXiv:2112.05323

Air shower modelling for cosmic rays
forward LHC and low-x constrains
arXiv:2203.08129

Hadron physics
Residual interaction in pairs and triplets of hadrons, including charm
Nature 588 (2020) 232-238

Heavy-Ion collisions

Dark-matter searches
Search for anti-nuclei in space: measurement of anti-^{3}He cross section
Nature Phys. 19 (2023) 1, 61-71

Black Holes and gravitational radiation
interesting theoretical connections between Color Glass Condensate and Black Holes
Phys.Lett.B 853 (2024) 138669

Beyond the Standard Model Physics Searches
Searches for axion-like particles in ultra-peripheral heavy-ion collisions
Phys.Lett.B 797 (2019) 134826

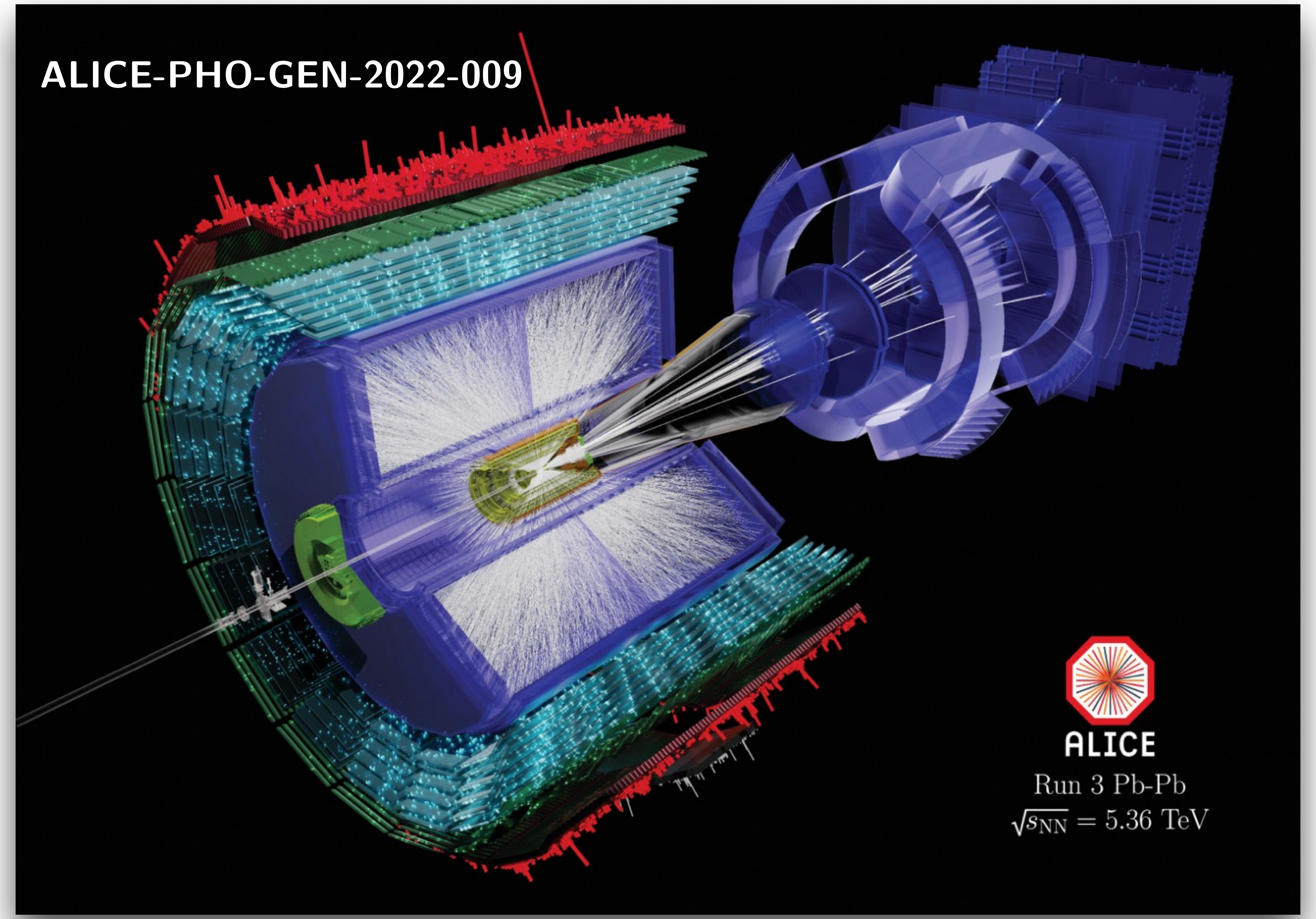
Summary

The HL-LHC & detector upgrades allow for up to 100 times more statistics in Pb-Pb collisions than $<$ Run 3

All four experiments will undergo major upgrades allowing to exploit this data

We have the tools to explore all stages of a heavy-ion collisions, including the QGP ...

- ... with unprecedented precision
- ... in a wider phasespace
- ... more differentially
- ... with entirely new observables



The whole picture painted at the HL-LHC will improve our understanding of QCD in extreme conditions (wherever they occur in nature!)

Selection of related heavy-ion talks at LHCP 2024:

R. Ehlers: *Investigating QGP with jets and heavy flavour*
J. Nystrand: *Studying initial-state effects with UPCs*
P. M. Jacobs: *Modification of jet substructure*
Y. Go: *Medium response to jet propagation in QGP*
F. Krizek: *Search for jet quenching in small systems*

Thank you for your attention!

Backup

Heavy-ion physics: The big questions

What are the initial conditions of a collision?
nPDFs & Saturation?
DY, UPC, forward LHC ...

Collectivity of QCD across system sizes?
Flow in pp, p-A; strangene... production, energy loss, thermal radiation

Interlude: How do we improve?

HL-LHC offers ...

... increased data sample

... detector upgrades: increased precision and/or coverage

This allows to ...

... repeat existing measurements with higher precision

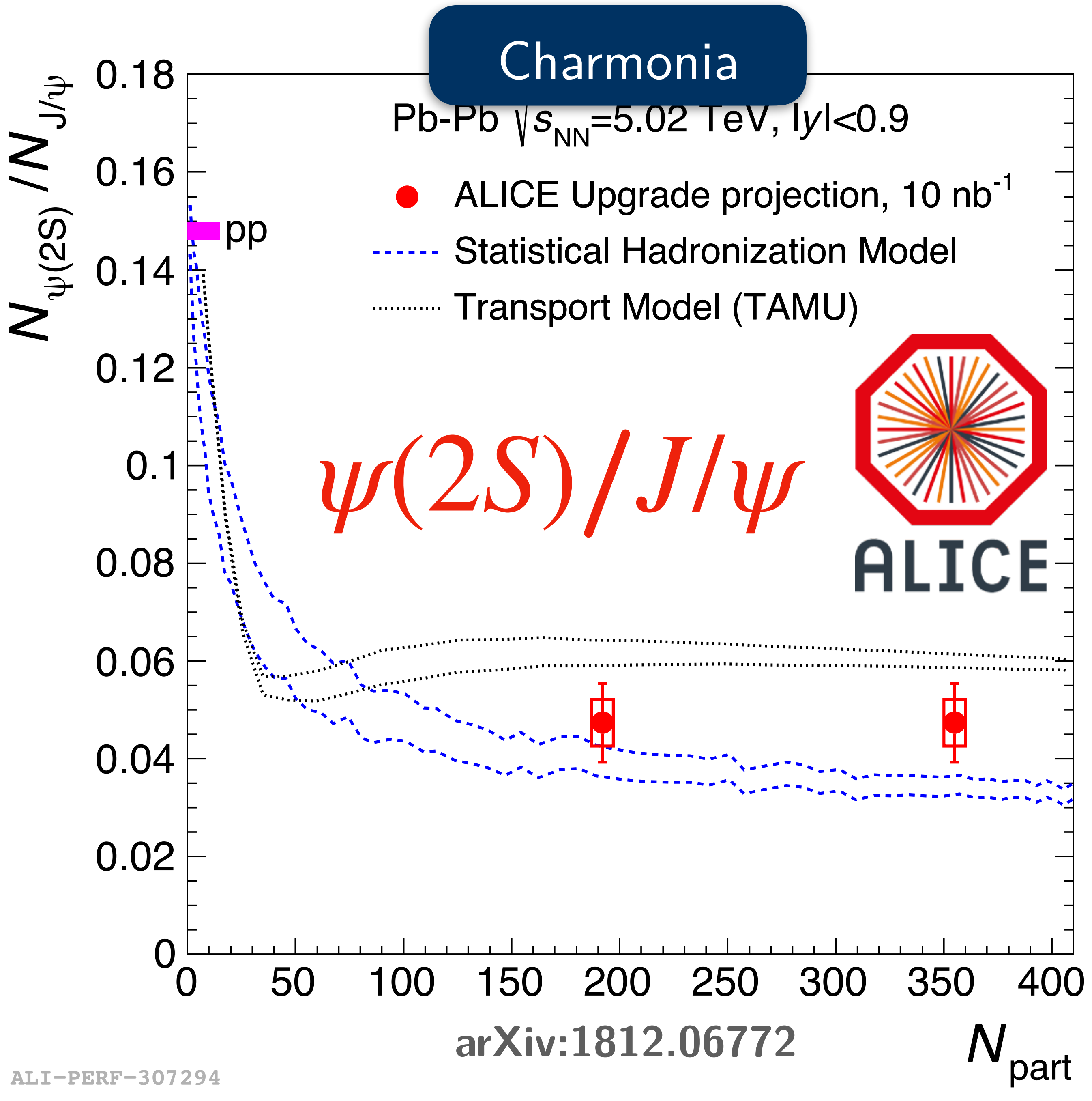
... measure existing observables more differentially

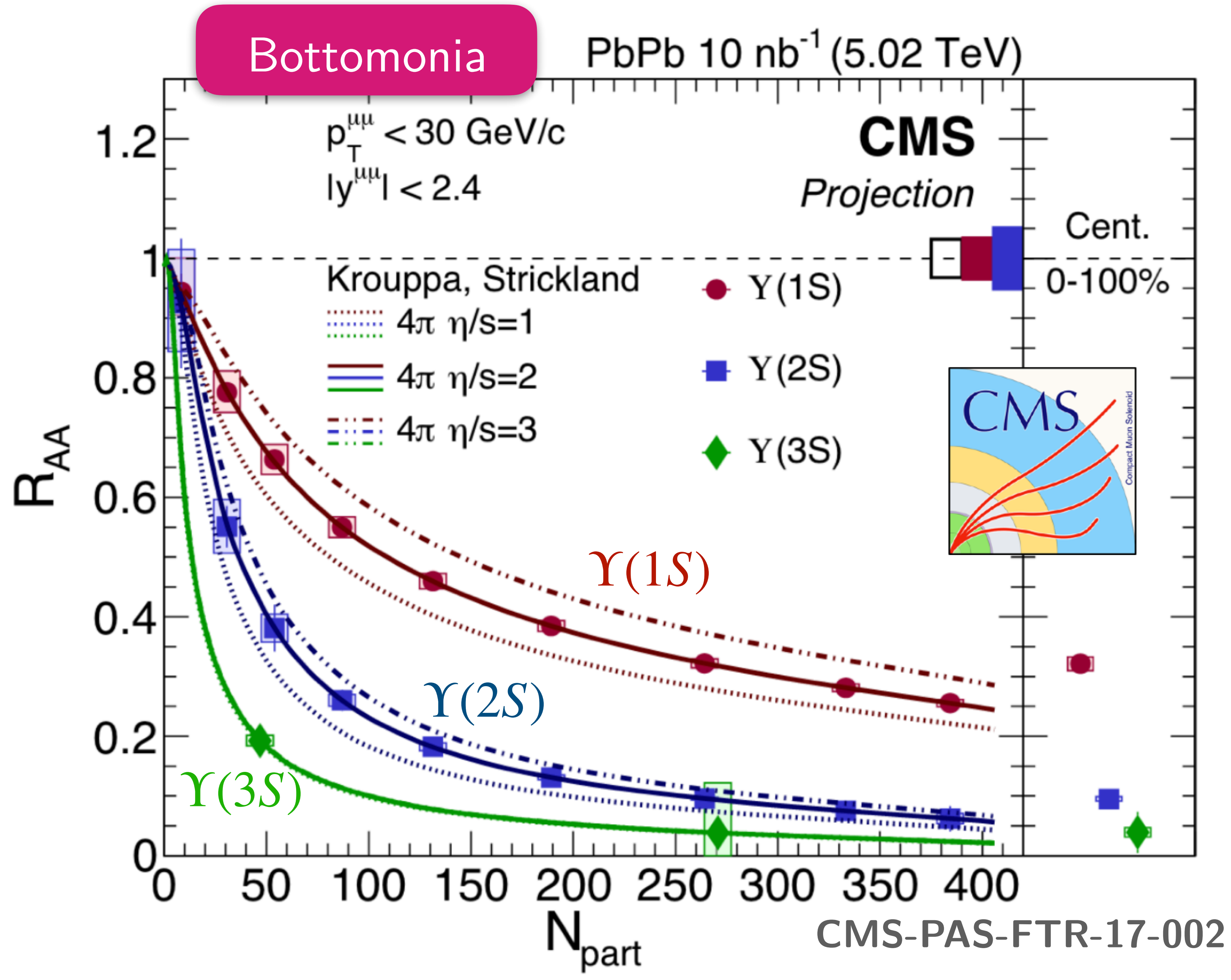
... explore observables in a new phasespace

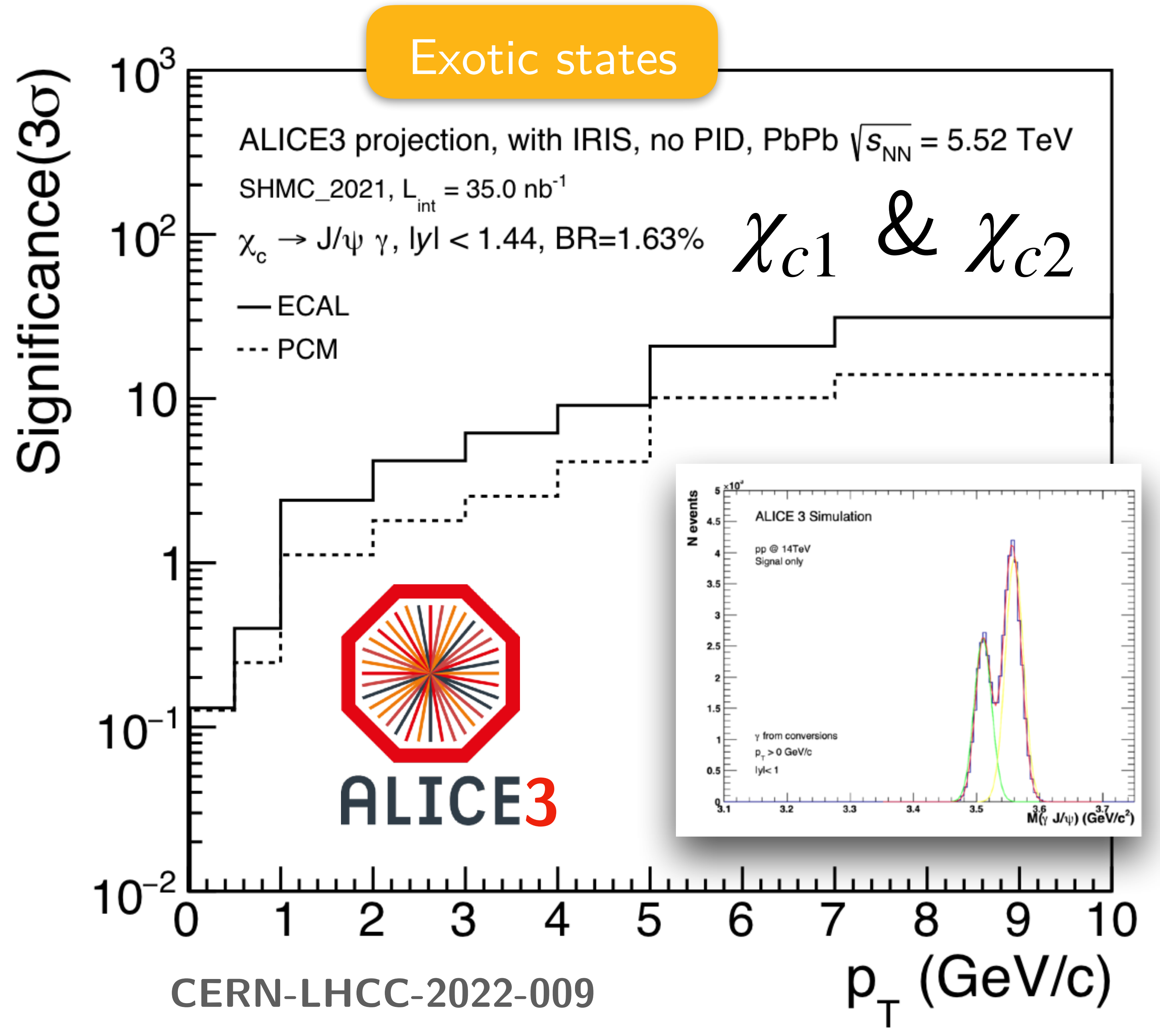
... access to entirely new observables

The full set of measurements tests our understanding of heavy-ion collision and QCD matter (and the universality of our models!)

Physics: probing in-medium color force of strongly interacting medium







Systematic investigation of **in-medium force through spectroscopy of bound states** that dissolve/re-generate in QGP

- **Charmonia:** charm diffusion in QGP & recombination:
  → precision studies of J/ψ suppression and flow; access to rare excited states
- **Bottomonia:** lower importance of regeneration; access to $\Upsilon(3S)$ and Bottomonia flow!
- **Exotica:** access to exotic states in heavy-ion collisions in reach → properties, binding potential, hadronisation mechanism

Theoretical connections between EIC and forward p-A collision

EIC Yellow Report Sec. 7.5.4:

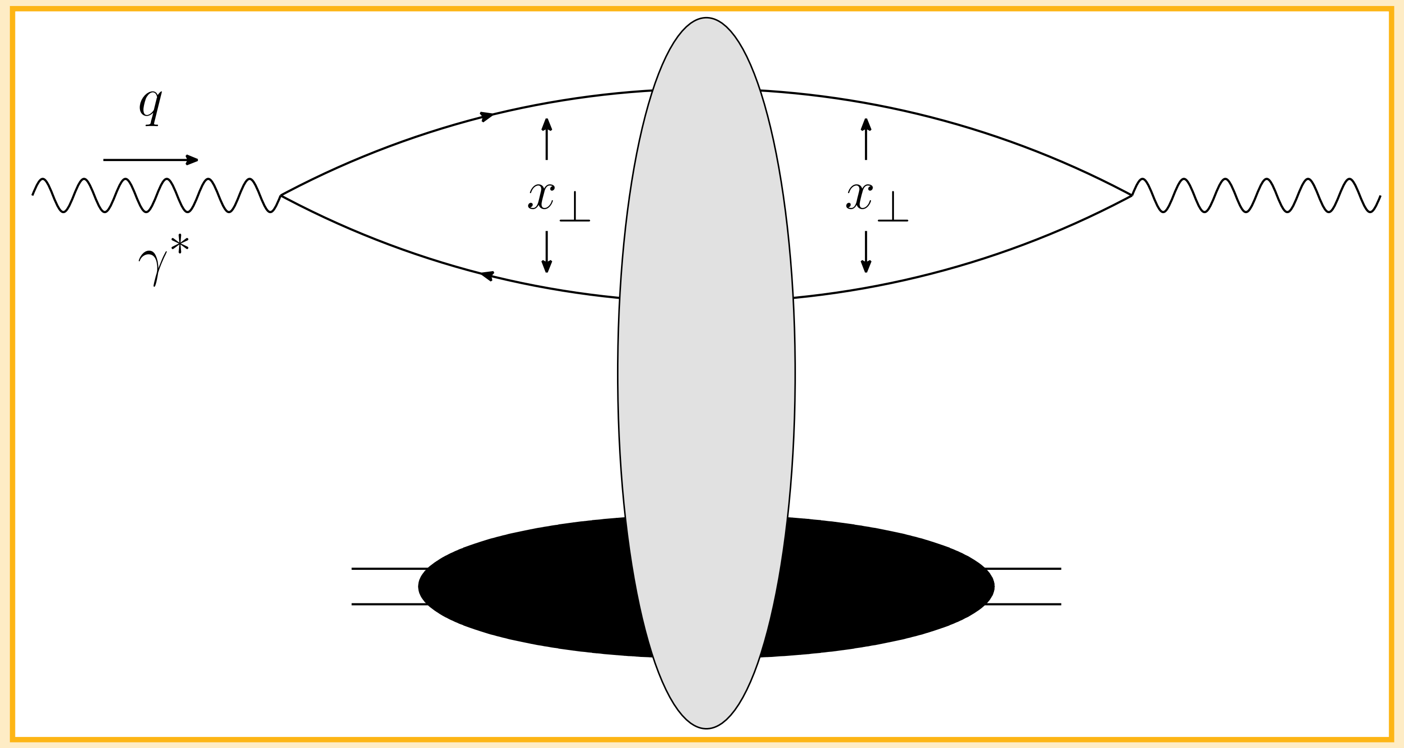
*"Meanwhile, **pA collisions can serve as a gateway to the EIC** as far as saturation physics is concerned, and it also plays an **important and complementary role** in the study of these two fundamental gluon distributions."* *Nucl.Phys.A* 1026 (2022) 122447

	Inclusive DIS	SIDIS	DIS dijet	Inclusive in p+A	γ+jet in p+A	dijet in p+A
xG_{WW}	−	−	+	−	−	+
xG_{DP}	+	+	−	+	+	+

- Multiple processes in **e-A DIS** and **forward p-A** collisions are theoretically described using the **same dipole/quadrupole scattering amplitudes!**

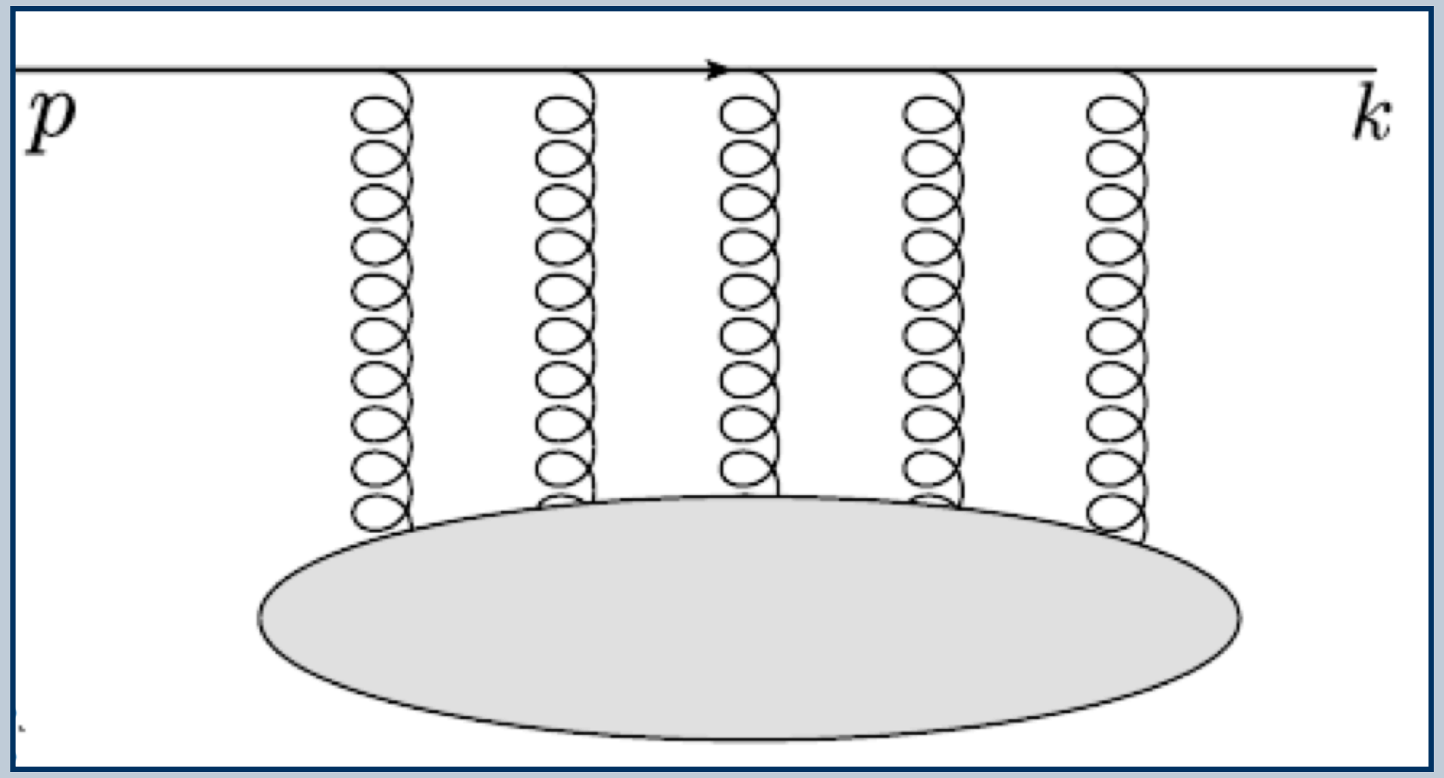
measurements in e-A DIS and forward p-A collisions
→ **test universal description of gluon saturated matter**

e+A Deep Inelastic Scattering (DIS)



JETP 30 (1970) 709-717, Phys. Rev. D 8 (1973) 1341, Nucl. Phys. B 335 (1990) 115

Forward p+A collisions



Phys. Rev. C 59 (1999) 1609, Phys. Rev. D66 (2002) 014021, Phys. Lett. B 503 (2001) 91

The Forward Calorimeter (FoCal)

Acceptance:
$3.2 < \eta < 5.8$

General:

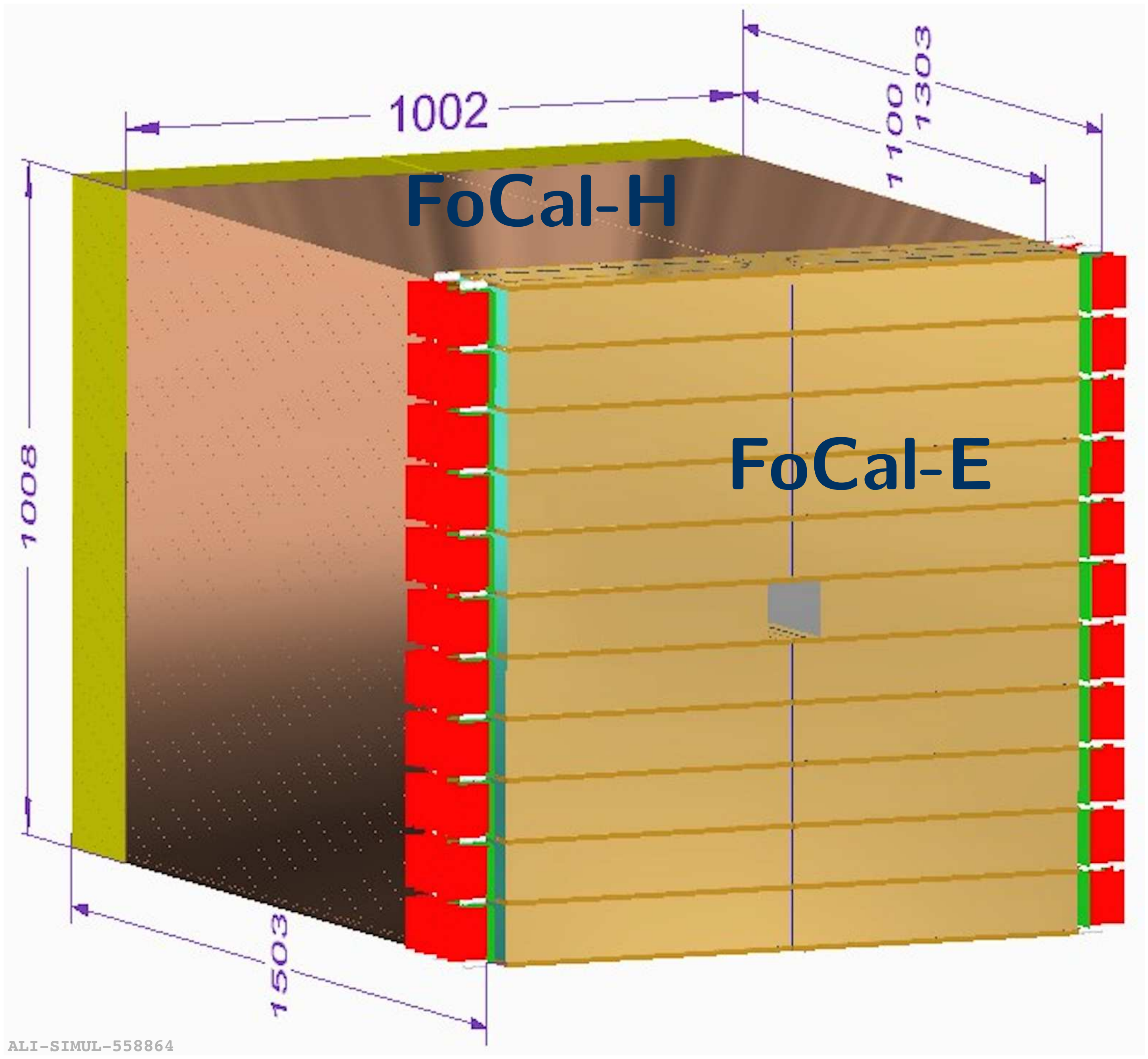
- Very forward calorimeter consisting of two parts (FoCal-E and FoCal-H) located $\approx$ 7m from IP of ALICE

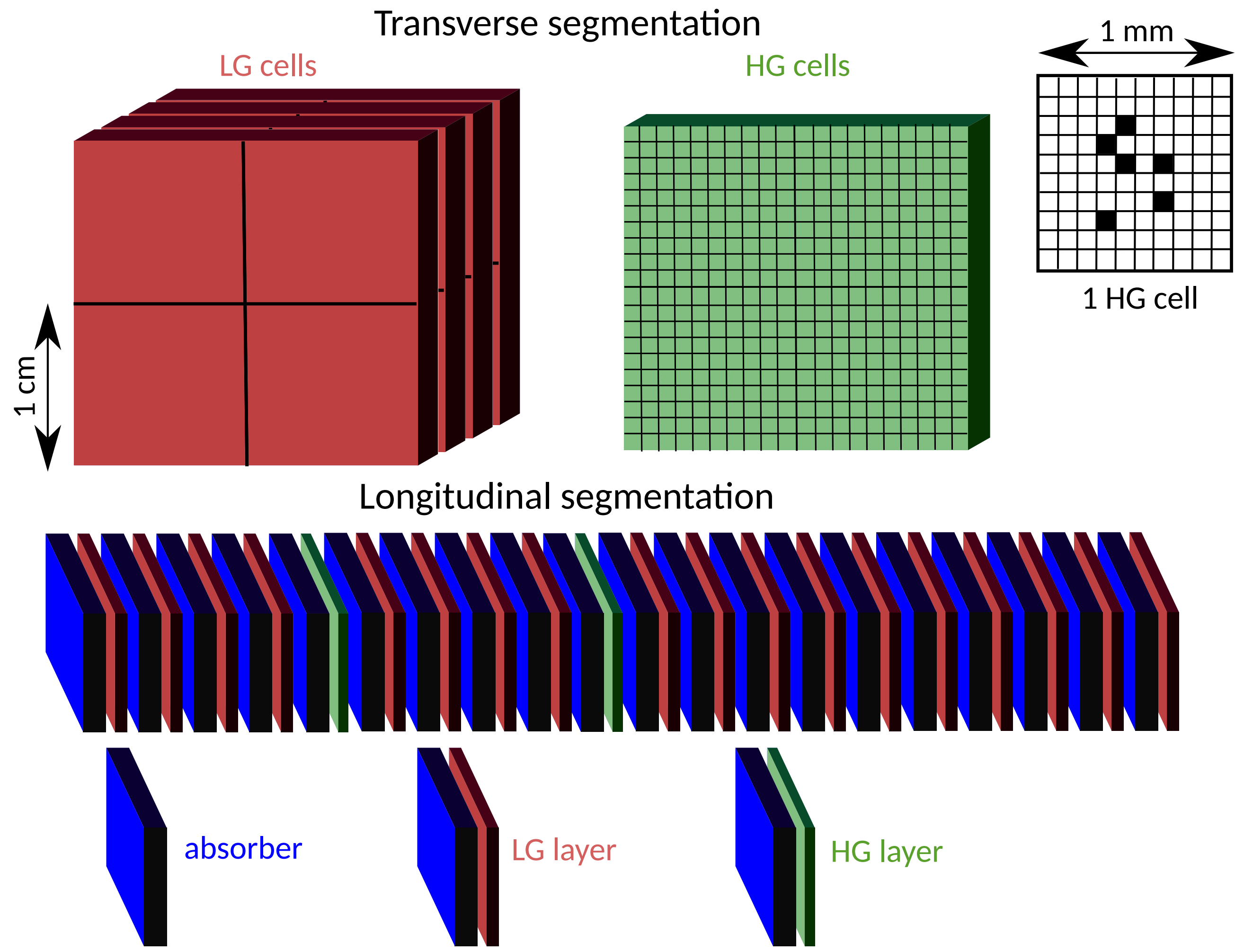
FoCal-E (electromagnetic):

- High-granularity Si-W sampling calorimeter combining two sensor granularities
  - 18 pad layers with silicon pads $(1 \times 1\text{cm}^2)$
  - Two pixel layers with digital readout $(30 \times 30\mu\text{m}^2)$
- Ability to "track" longitudinal component of shower!
- Used to measure photons and π^0 (40μm position rec.)

FoCal-H (hadronic):

- Conventional metal-scintillator hadronic calorimeter behind FoCal-E
- Design using scintillating fibres embedded in Cu tubes
- Used to measure photon isolation, jet energy etc.

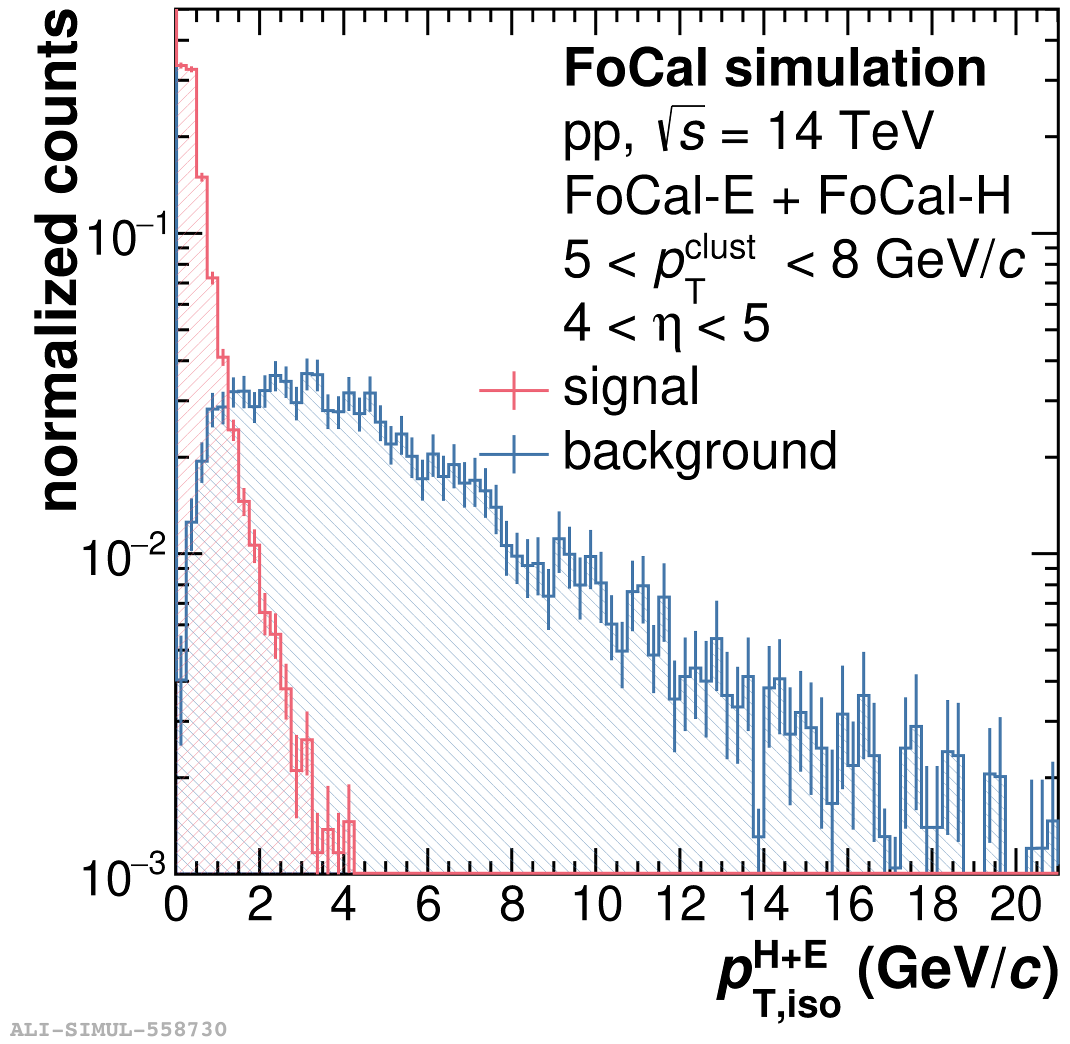




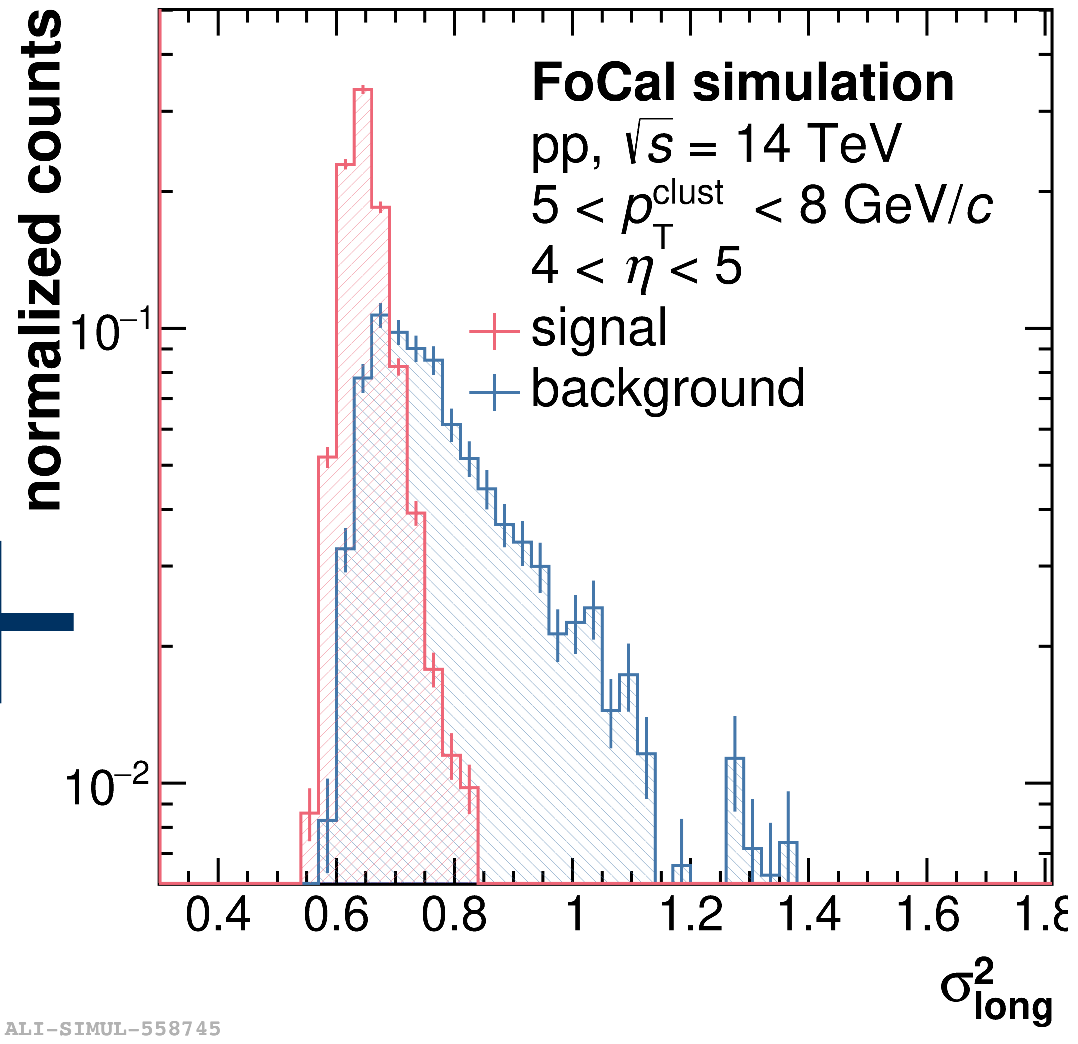
Prompt photon identification

PYTHIA8 pp at $\sqrt{s} = 14$ TeV + GEANT3

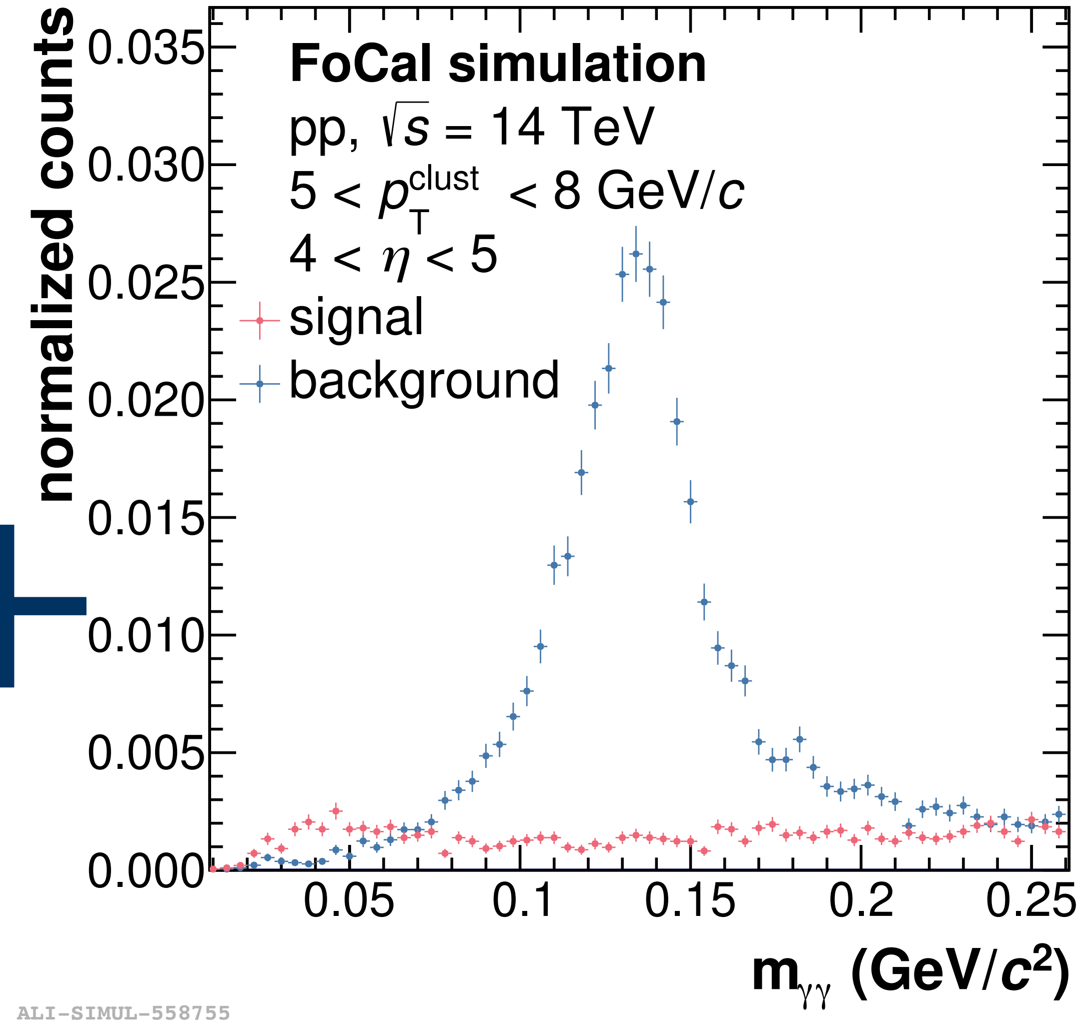
Isolation



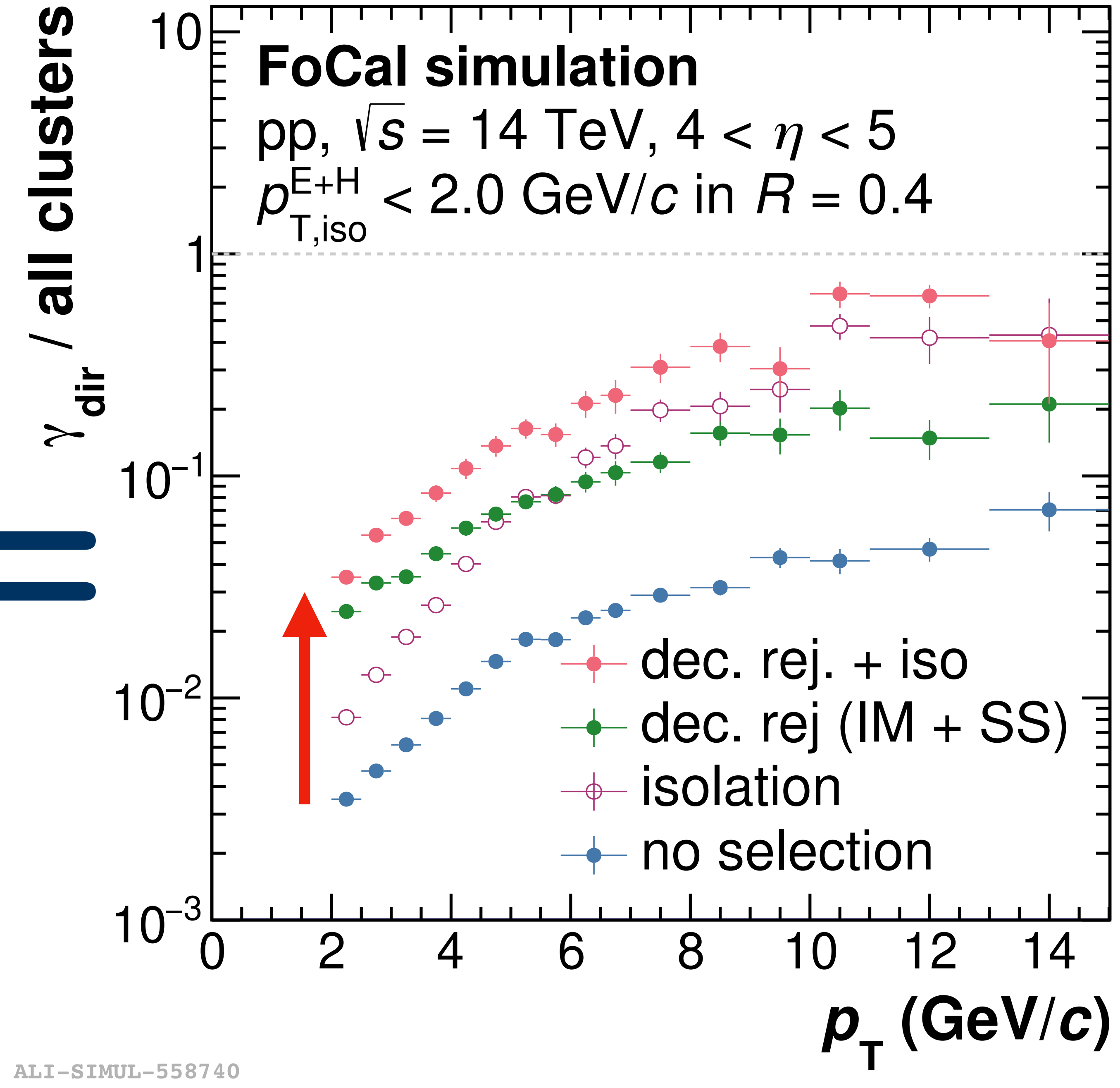
Shower shape

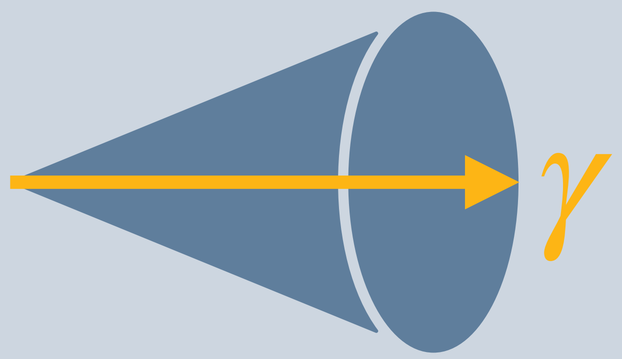


Invariant mass tagging:

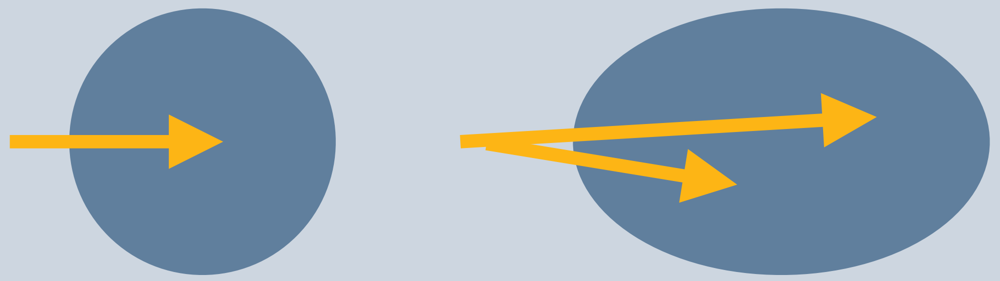


Signal fraction:





E_T sum within cone with $R = 0.4$ allows to discriminate sig. and bck.



Decay photons may produce elongated showers in pad layers due to shower overlaps

Highly granular pixel layers enable large π^0 reconstruction efficiency

→ tag decay photons according to inv. mass of clust. pairs

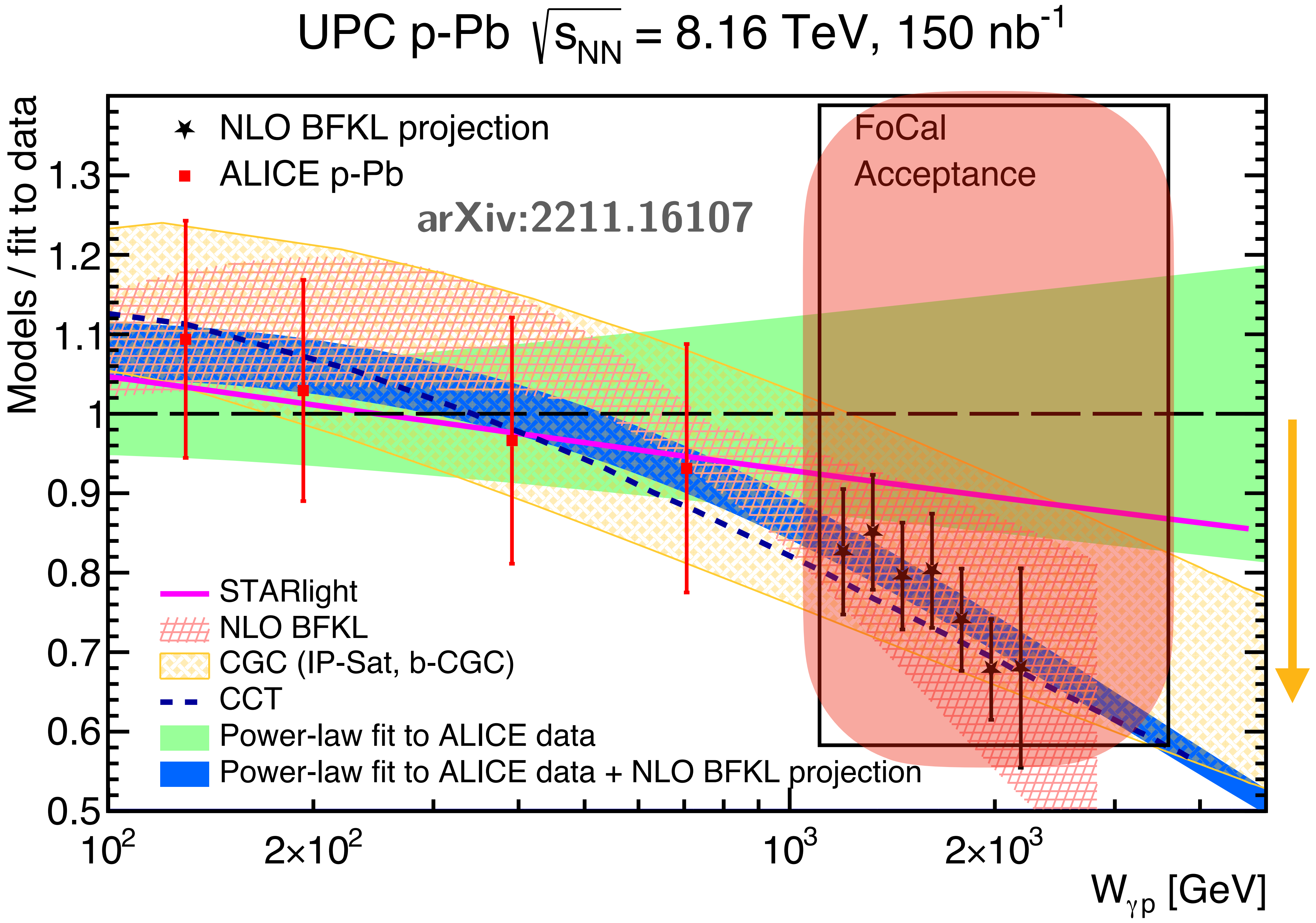
Employed selections increase signal fraction by a factor 11!

Comparable performance in p-Pb collisions at $\sqrt{s_{NN}} = 8.8$ TeV

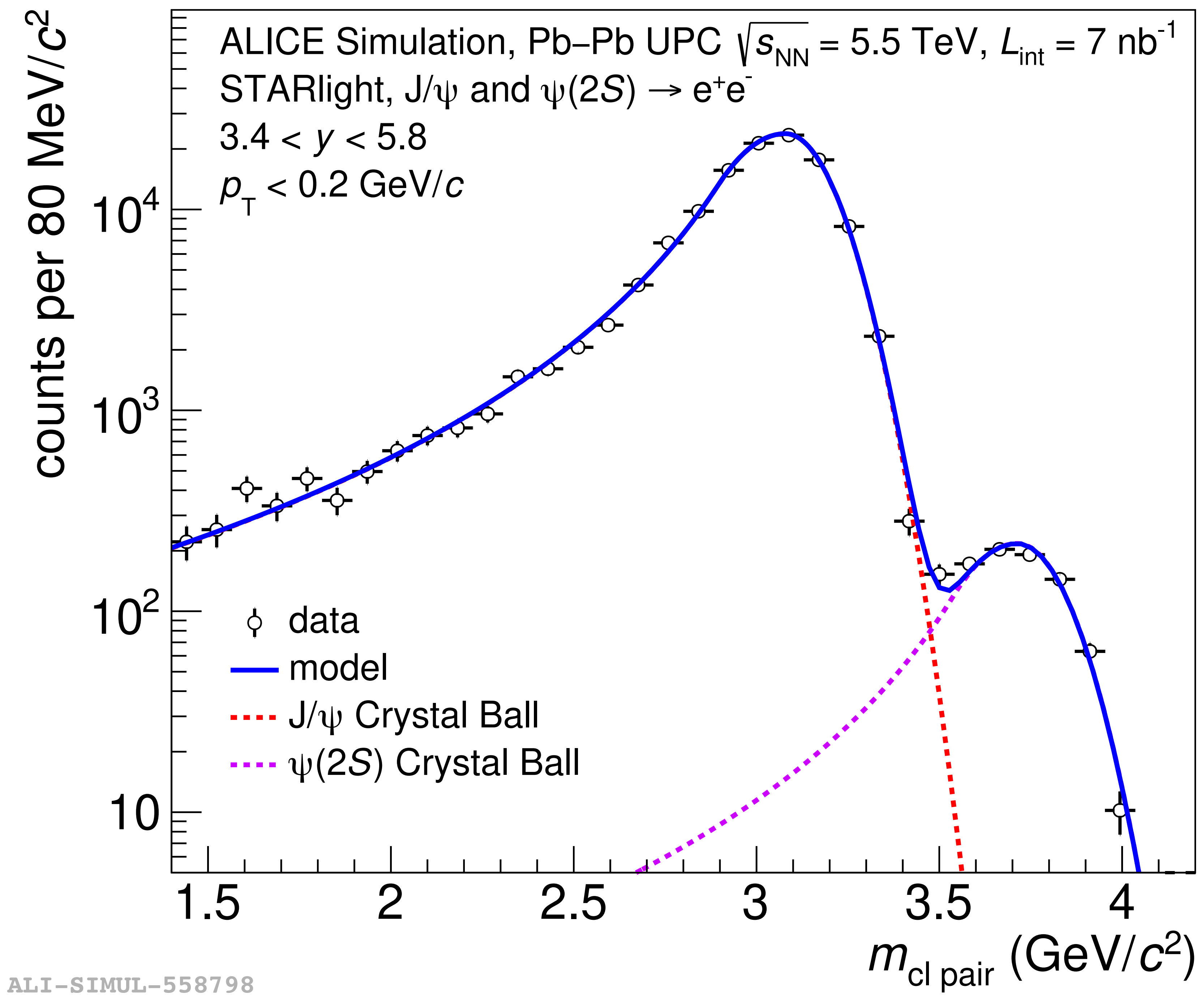
Vector meson photoproduction in UPCs

Theory:

- Photoproduction cross section of vector mesons (e.g. J/ψ) in ultra-peripheral collisions (UPCs) **proportional to gluon density squared** at LO
- **Deviation from power-law** growth of cross section with increasing $W_{\gamma p}$ expected due to **saturation effects**

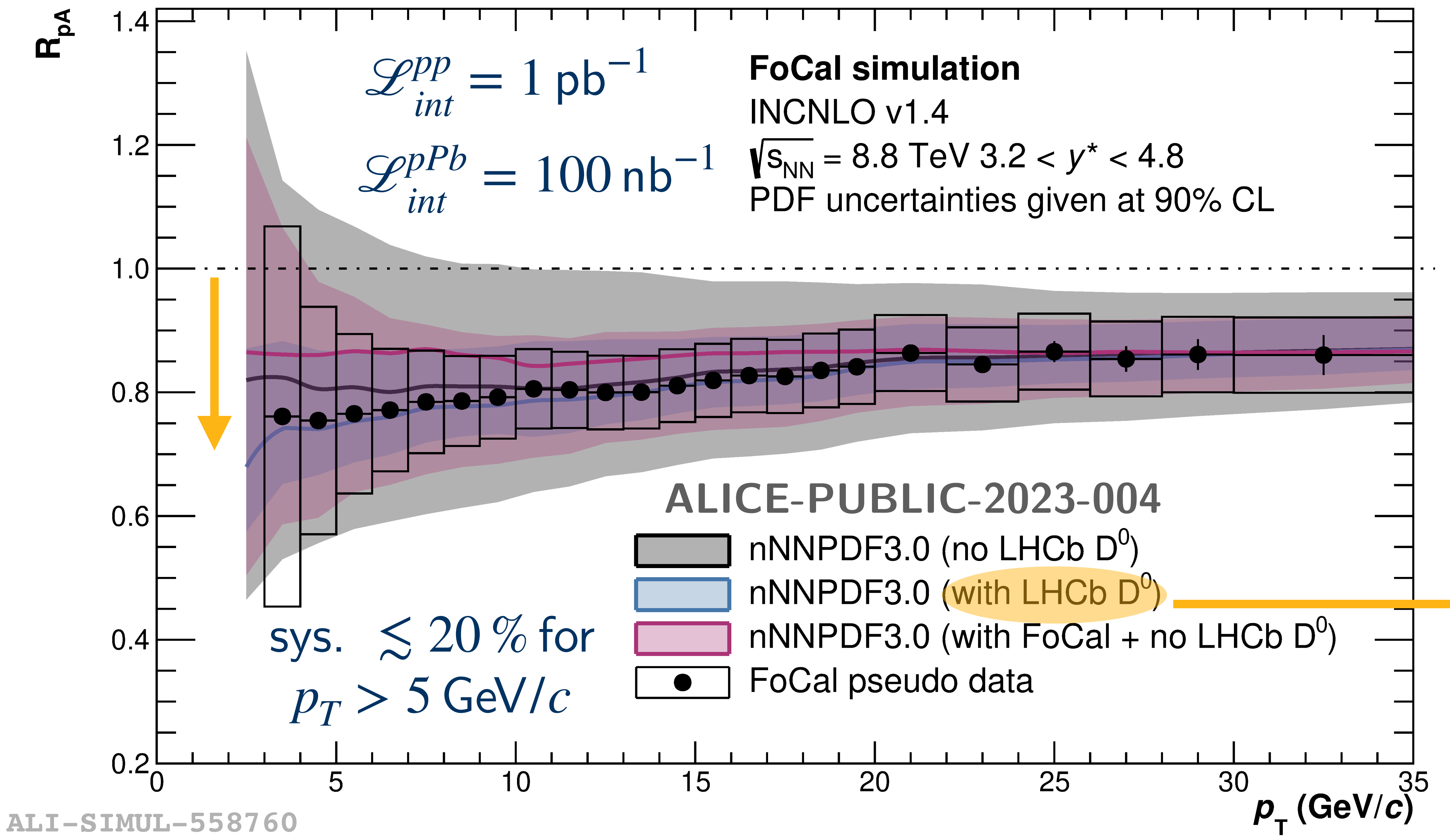


FoCal performance:

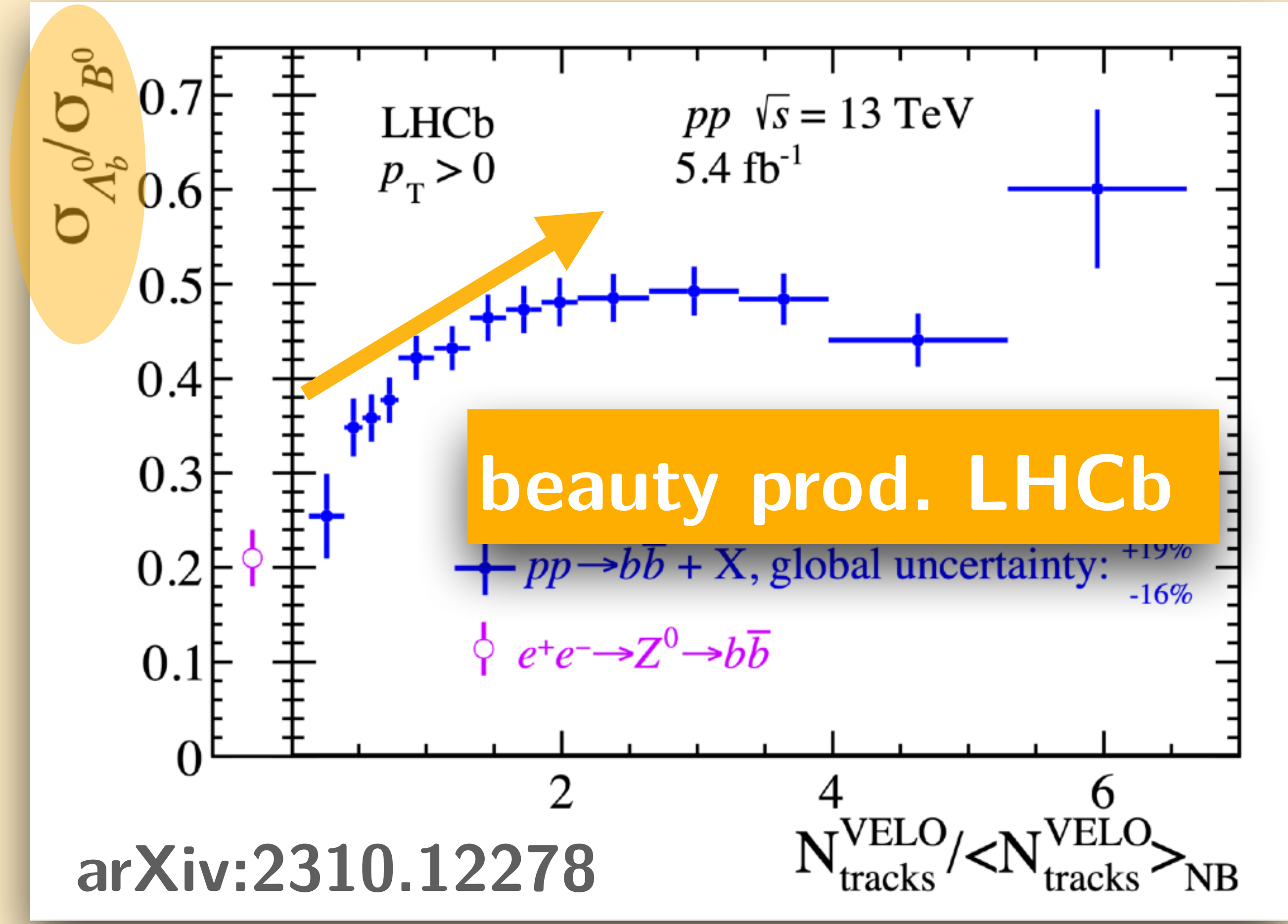


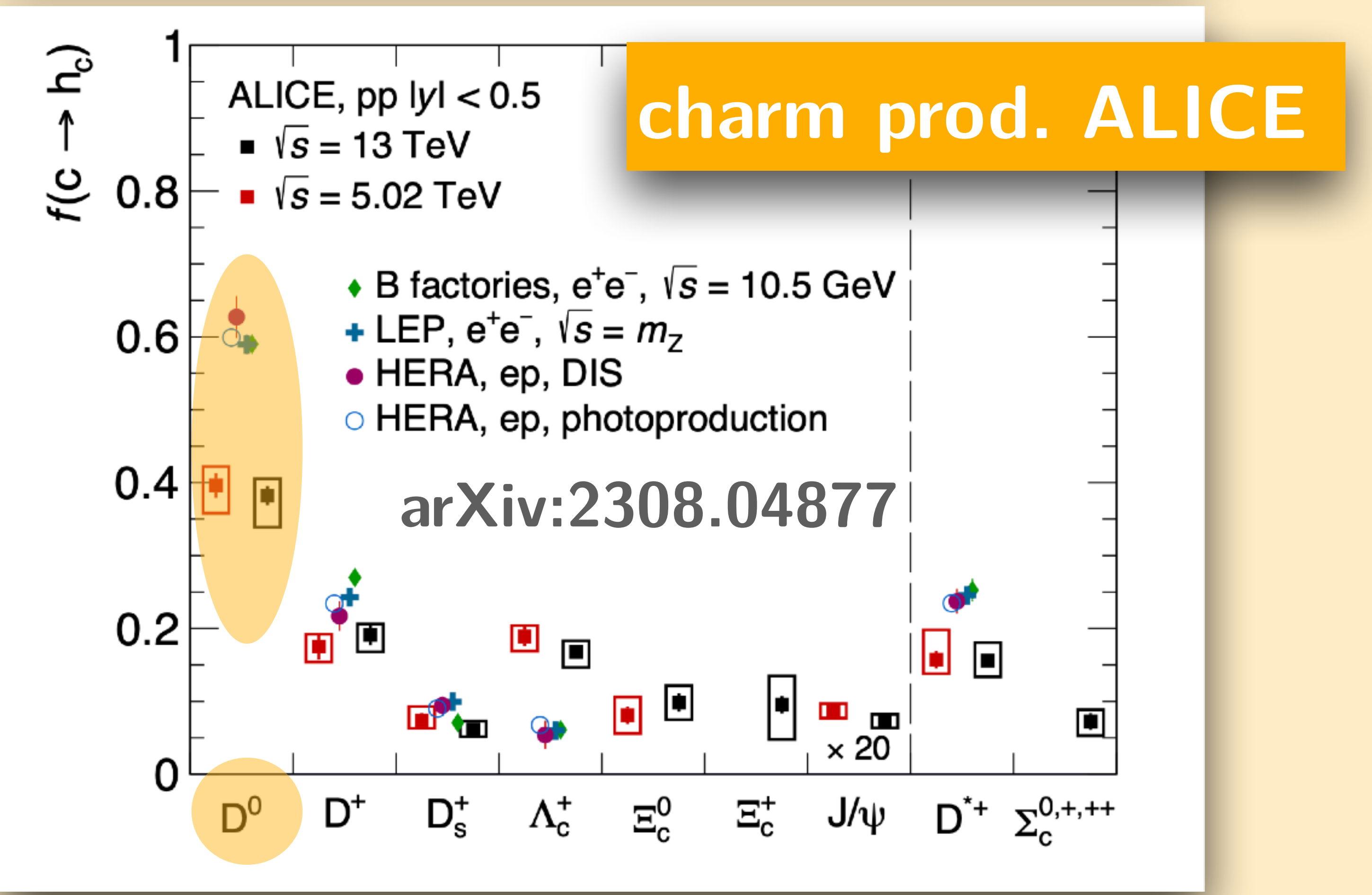
- FoCal allows to access unprecedented low-x, extending existing measurements to $W_{\gamma p} \approx$ 2 TeV (10 GeV) in p-Pb (Pb-p) collisions + Pb-Pb collisions
- Studies with STARlight + GEANT show successful reconstruction of J/ψ and $\psi(2S)$

Prompt photon physics impact



Are fragmentation functions universal?





- **FoCal pseudo-data** of nuclear modification factor R_{pA} constructed using input from NLO+nPDF and assumptions on stat. and sys. uncertainties from perf. studies
- **Bayesian re-weighting of nNNPDF30** prediction showcases **significant reduction of nPDF uncertainties** when including FoCal data; comparable to D meson measurement by LHCb

Prompt photons → no final state and hadronisation effects → universality test of low-x formalism