

# Recent results with ALICE at the LHC

**LXXI International conference Nucleus 2021**

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on behalf of the ALICE collaboration

23.09.2021



# Collisions at the LHC: a laboratory for QCD matter

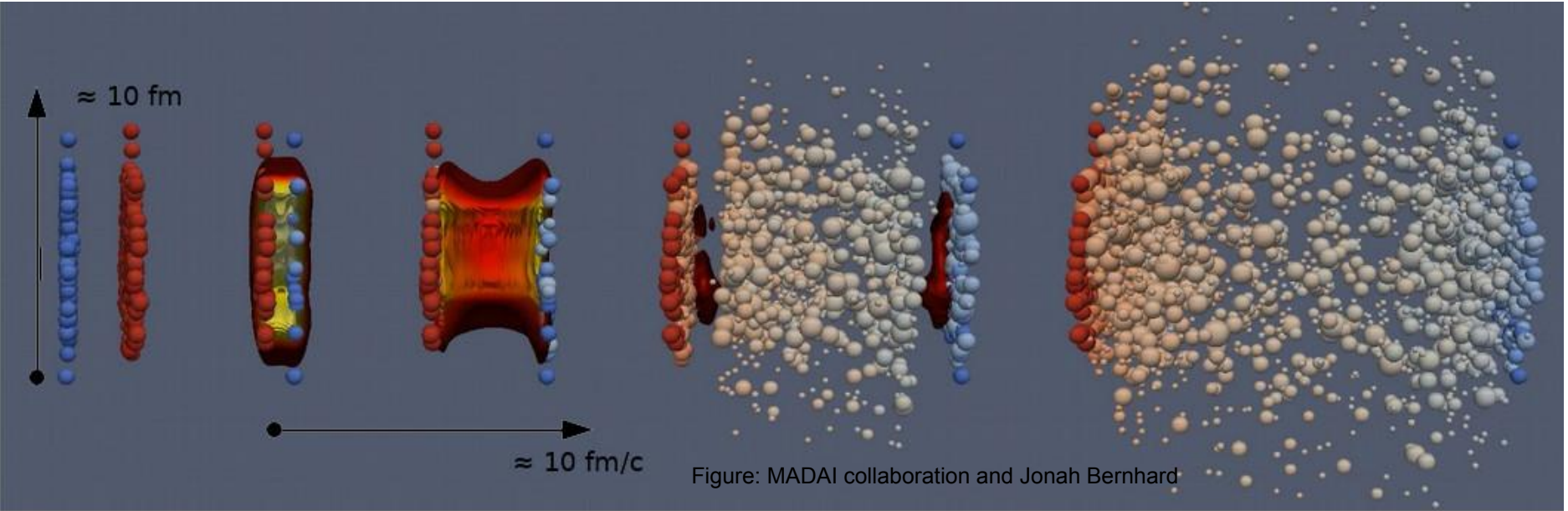
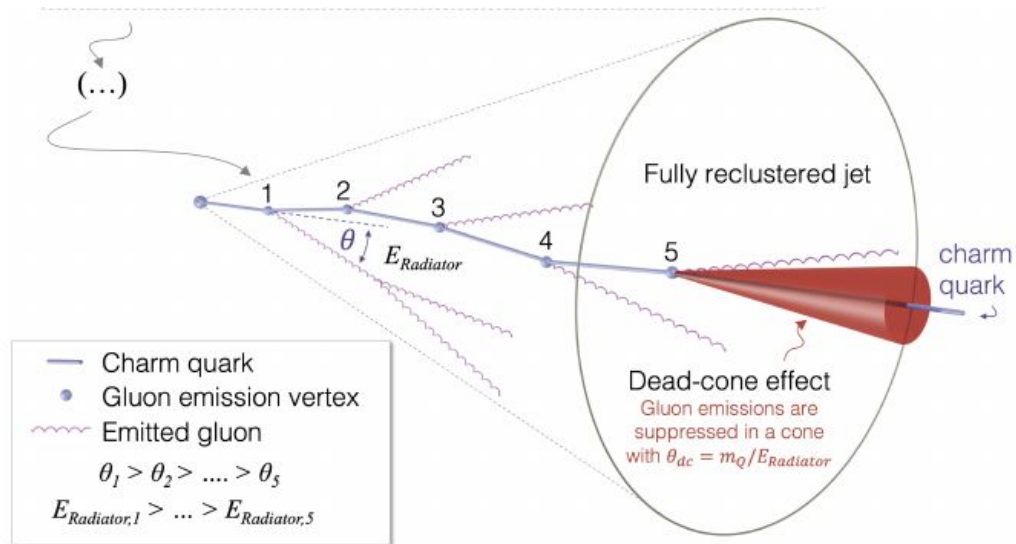
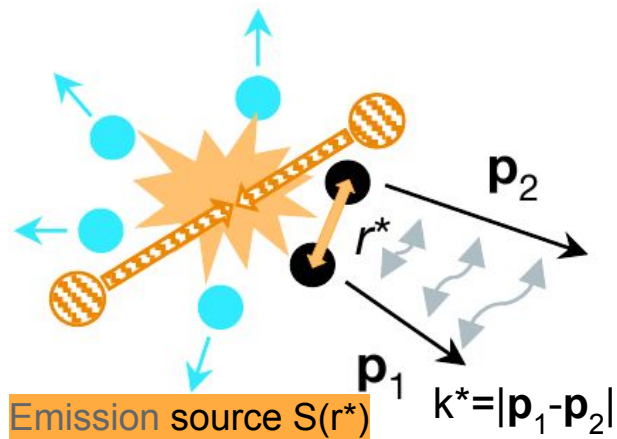


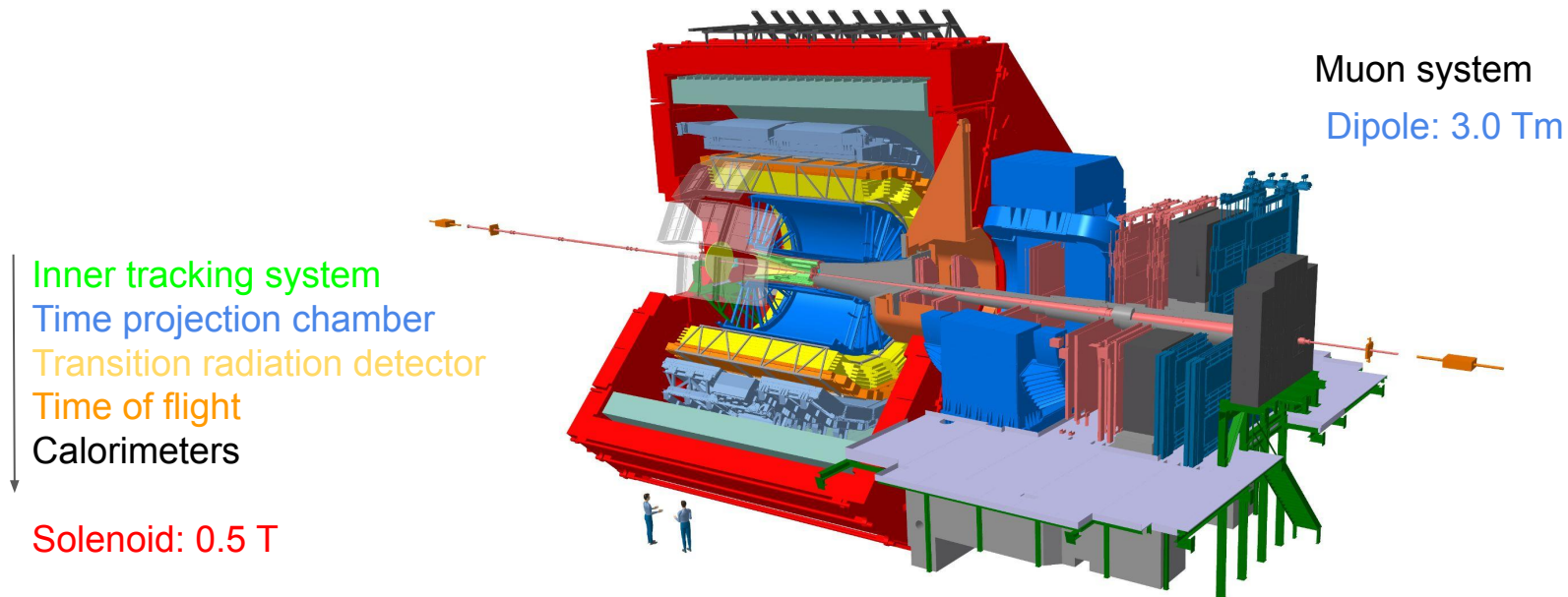
Figure: MADAI collaboration and Jonah Bernhard

- ALICE: derive properties of produced QCD matter and the initial wave function

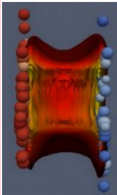


- Processes involving multiple scales: advance our understanding of strong interaction
  - impact beyond quark-gluon plasma physics

# ALICE setup

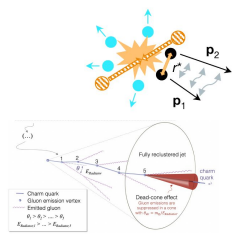


- Precise tracking and particle identification over a large momentum range at midrapidity
- Muon spectrometer: quarkonium and semileptonic decays of heavy-flavour hadrons
- Forward: trigger, event characterisation and correlation measurements



# QCD matter studies and the initial wave function

# Understanding of strong interaction

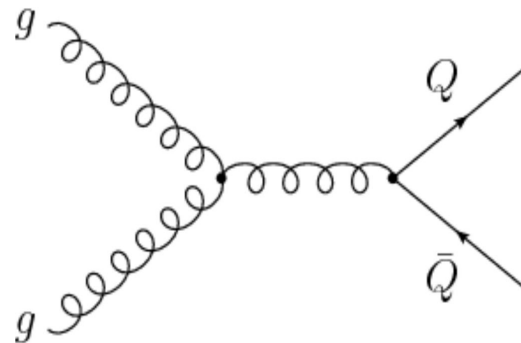
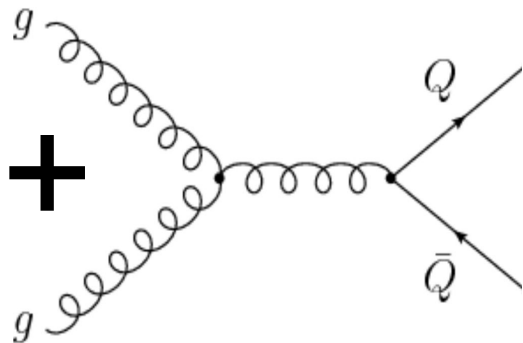
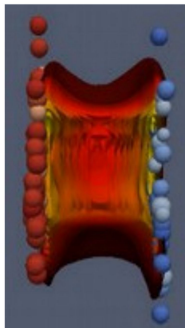


Heavy quarks and jets in hadronic collisions

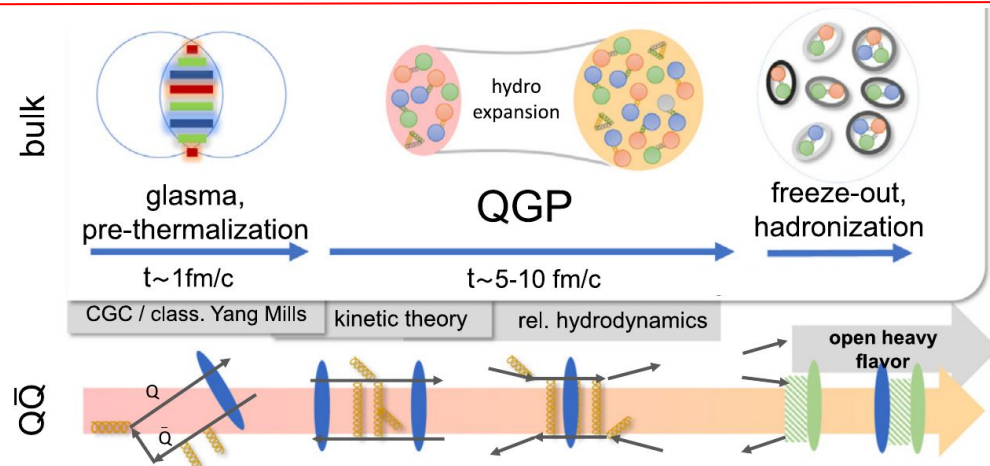
Photoproduction with ALICE at the LHC

Precise measurements of strong interaction at soft scales

# Heavy quarks and jets in hadronic collisions



# Quarkonium to study the quark-gluon plasma



[A. Rothkopf, Phys.Rept. 858 \(2020\) 1-117.](#)

- Bound states of heavy quarks
  - test system for strong interaction
- Heavy-quark-antiquark pairs produced early in hadronic collision
  - witness the time evolution of the collision system
- Production modifications: signatures of deconfinement in heavy-ion collisions
- ALICE: measured via decay to  $\mu^+\mu^-$  or  $e^+e^-$  pairs

# Charmonium production in Pb-Pb collisions at the LHC

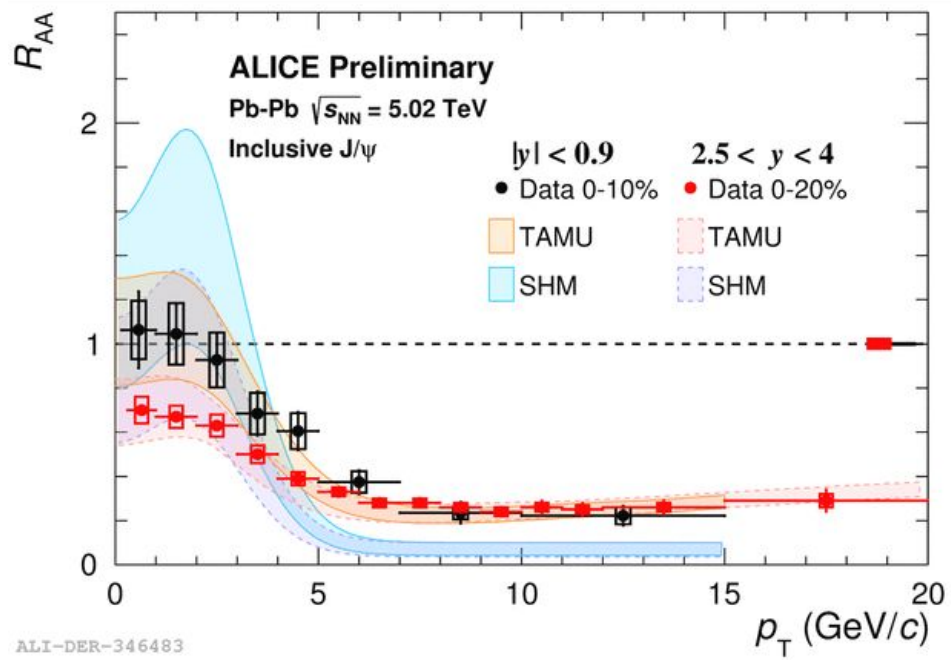
## Proposed bound state production mechanisms

- Formation & destruction in QGP  
Thews, Schroedter, Rafelski: [PRC 63 \(2001\)](#)
- Formation at common freeze-out  
Braun-Munzinger, Stachel: [Phys.Lett. B490 \(2000\)](#)

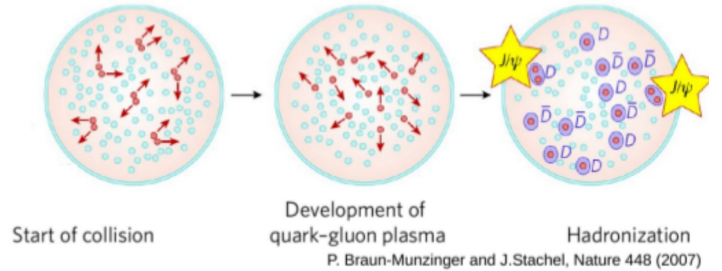
## Charm quark density large at the LHC

- increase of nuclear modification factor w.r.t. lower energies in both scenarios due to regeneration
- observed by ALICE including expected  $p_T$  & rapidity dependence

$$R_{AA} = \frac{N_{AA}^{J/\psi} / N_{AA}^{\text{events}}}{\langle N_{\text{coll}} \rangle \cdot N_{pp}^{J/\psi} / N_{pp}^{\text{events}}}$$

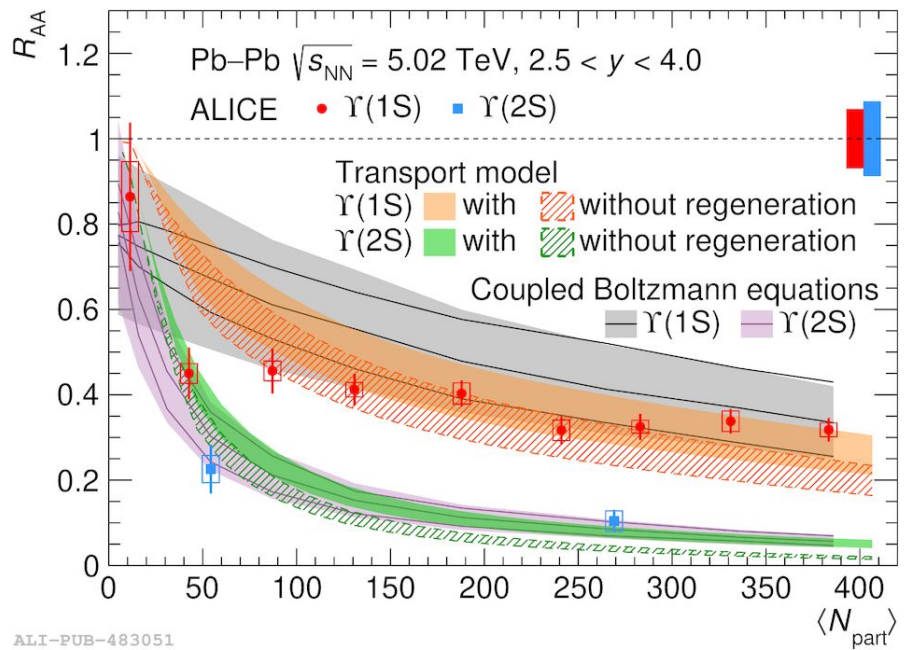


ALI-DER-346483

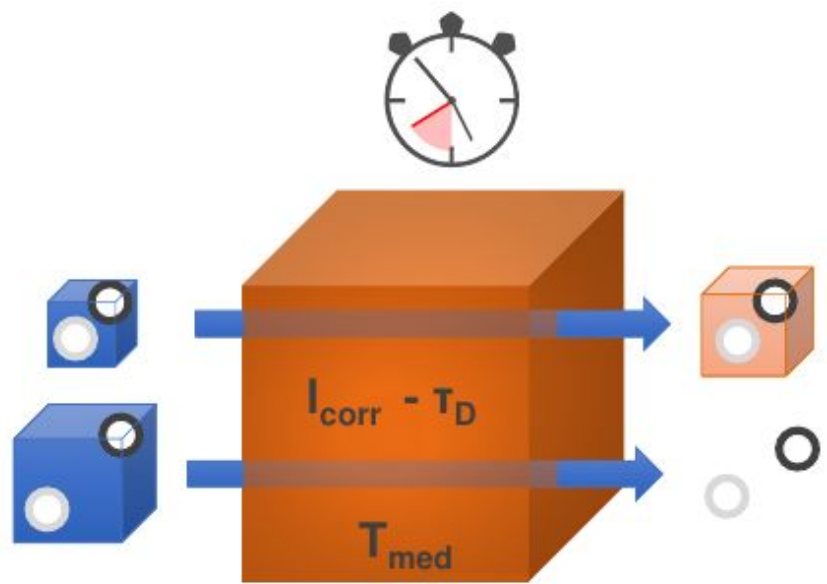




# Bottomonium production in Pb-Pb collisions at the LHC



ALI-PUB-483051  
[arXiv:2011.05758](https://arxiv.org/abs/2011.05758), accepted by PLB



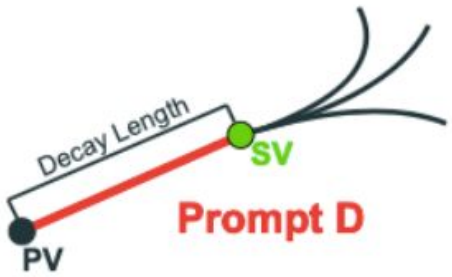
QGP as sieve acting on quarkonium  
[A. Rothkopf, Phys.Rept. 858 \(2020\) 1-117.](https://arxiv.org/abs/1907.08771)

- Strong modifications from pp to Pb-Pb
- Consistent with calculations based on modified quark-antiquark interaction in QGP

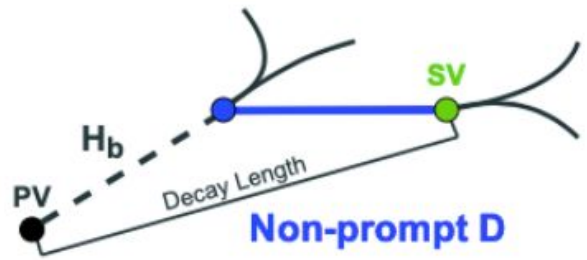
# Heavy quarks: access partons in the QGP

Most of produced heavy quarks hadronise in open-heavy flavour

- Study interaction of single heavy quark with QGP
- Heavy-quark reservoir for quarkonium formation



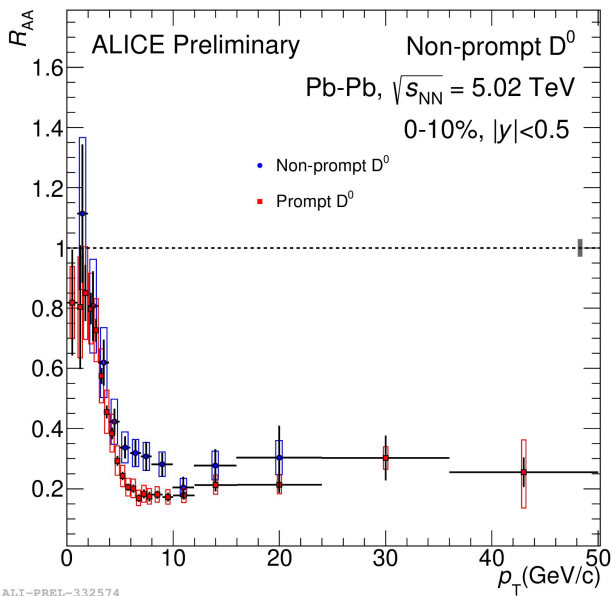
**Prompt** D-mesons:  
sensitive to **c-quark**



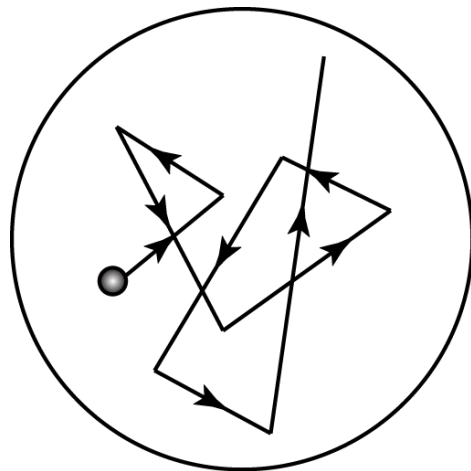
**Non-prompt** D-mesons from weak decays of hadrons containing a b-quark:  
sensitive to **b-quark**

Precise measurements thanks to weak decays: displacement from primary vertex

# Heavy-quark hadrons: dragged by the medium



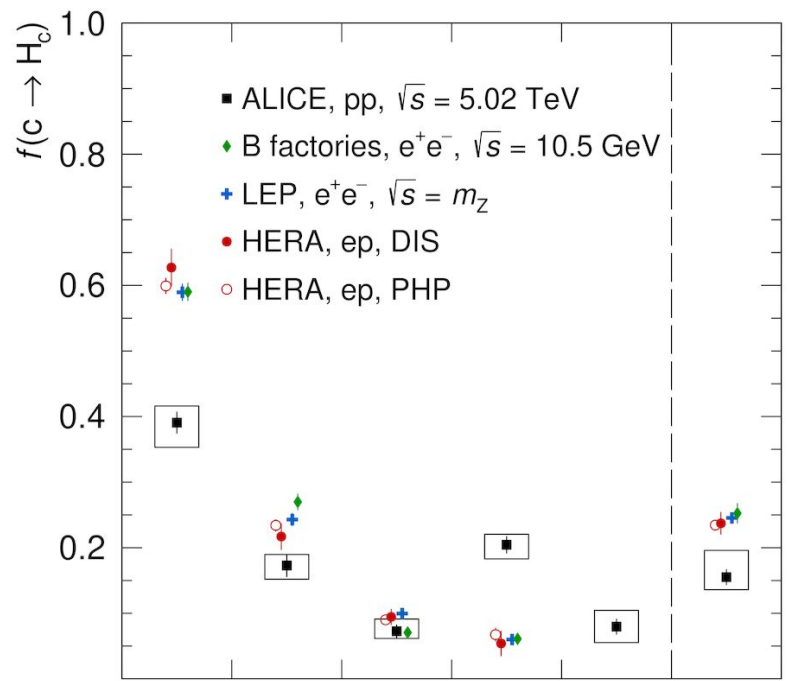
**Non-prompt:** sensitive to b-quark  
**Prompt:** sensitive to c-quark



“Brownian motion”: heavy quarks described Langevin and Fokker-Planck equations

- Described by models with “Brownian motion” of quarks and radiative energy loss in QGP: sensitive to diffusion of heavy quarks in medium
- Separate D-mesons from beauty-hadron decays: consistent with smaller energy loss of beauty with respect to charm quarks
- First measurement down to 0 transverse momentum  $p_T$

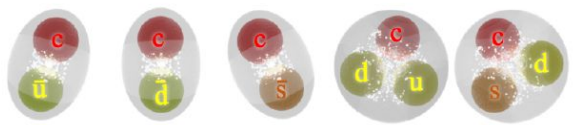
# Charm baryons: non-universal fragmentation fractions



Hadronization non-universal between e<sup>+</sup>e<sup>-</sup>/ep and pp

- Important to calibrate heavy quarks observables for QCD matter studies
- additional constraint to hadronization: heavy quarks created in hard scattering

D<sup>0</sup>   D<sup>+</sup>   D<sub>s</sub><sup>+</sup>   Λ<sub>c</sub><sup>+</sup>   Λ<sub>c</sub><sup>0</sup>   D<sup>\*+</sup>



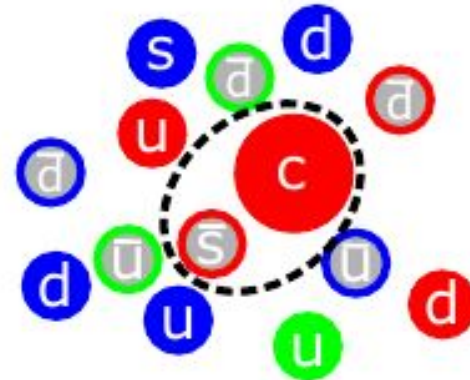
ALI-PUB-48

[arXiv:2105.06335](https://arxiv.org/abs/2105.06335)



## Color reconnection topologies

Picture from P. Skands [link](#)  
Christiansen, Skands, JHEP 1508 (2015) 003



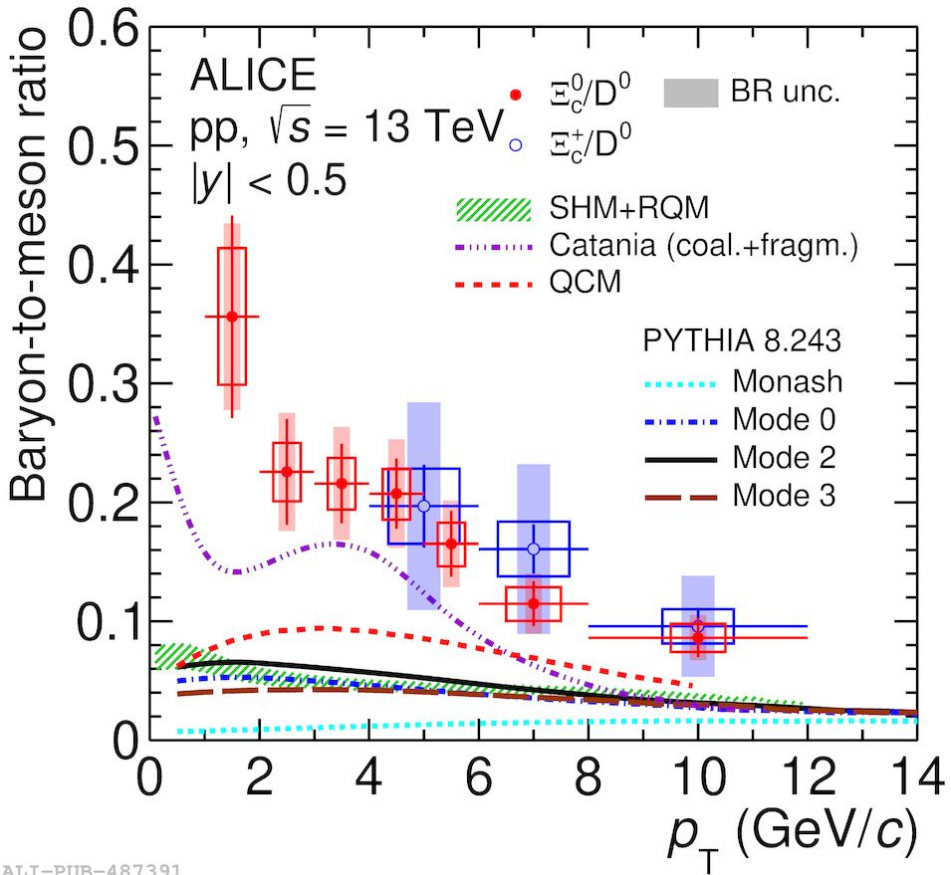
## Quark coalescence in phase space

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

Statistical hadronization and a large number of high-mass baryon resonances beyond those experimentally observed

He, Rapp, PLB 795 (2019) 117

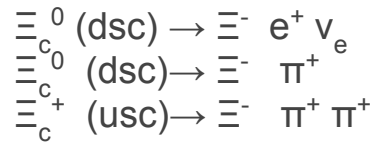
# Non-universal hadronization: new measurements



$\Lambda/D^0$ : unprecedented low  $p_T$  measurements described by all model variants

[arXiv:2011.06079](https://arxiv.org/abs/2011.06079), [arxiv:2106.08278](https://arxiv.org/abs/2106.08278)

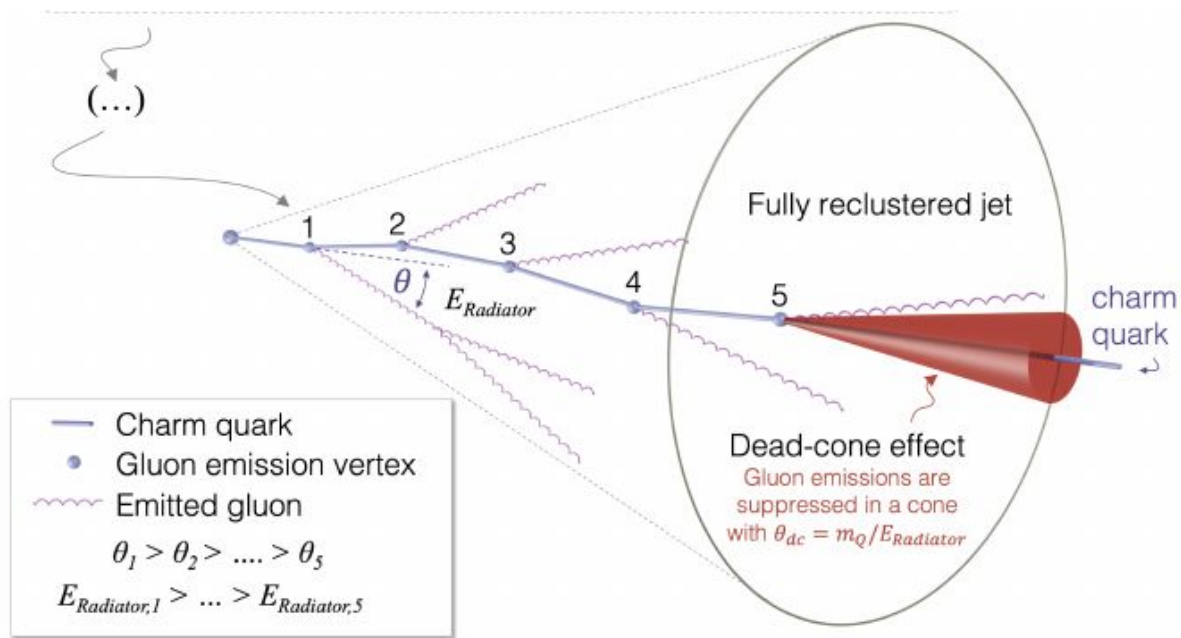
- $\Xi_c^0$  (dsc) and  $\Xi_c^+$  (usc) to test models



- $\Xi_c/D^0$  ratio not described: coalescence model closest

[arXiv:2105.05187](https://arxiv.org/abs/2105.05187)

# Gluon radiation from heavy quarks in pp collisions

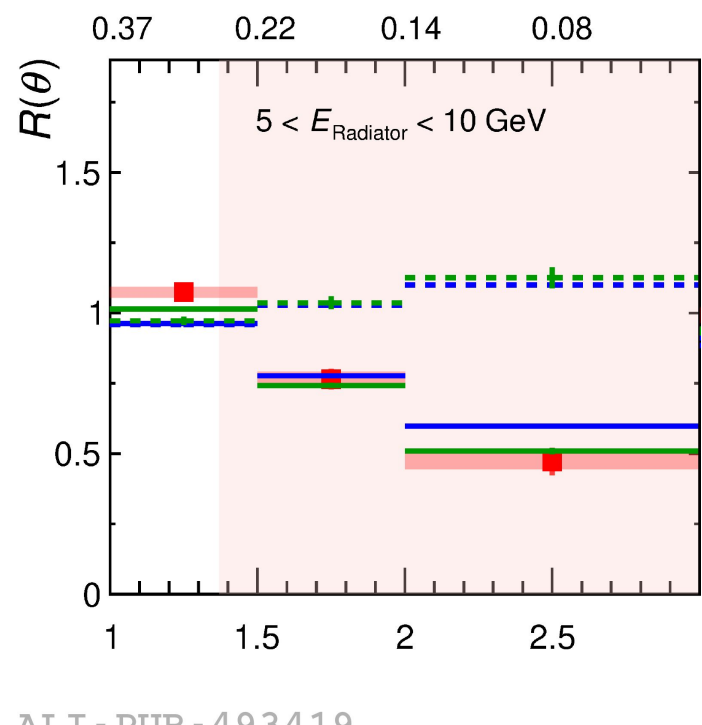


Perturbative QCD: small angle radiation suppressed for heavy quarks

Directly accessible by declustering via angular ordered Cambridge-Aachen algorithm

L. Cunqueiro M. Ploskon, [PRD 99, 074027 \(2019\)](#)

# Gluon radiation from heavy quarks in pp collisions



$$R(\theta) = \frac{dn/d \ln 1/\theta|_{\text{D0jets}}}{dn/d \ln 1/\theta|_{\text{incl.,jets}}} \quad k_T > \Lambda_{\text{qcd}} = 200 \text{ MeV}/c$$

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

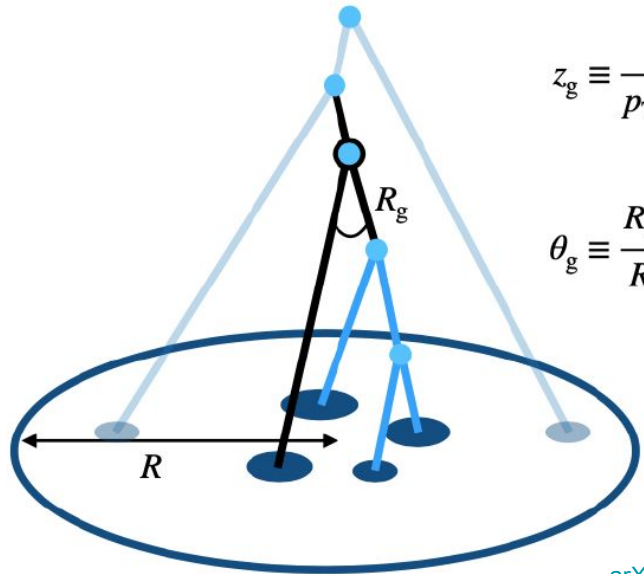
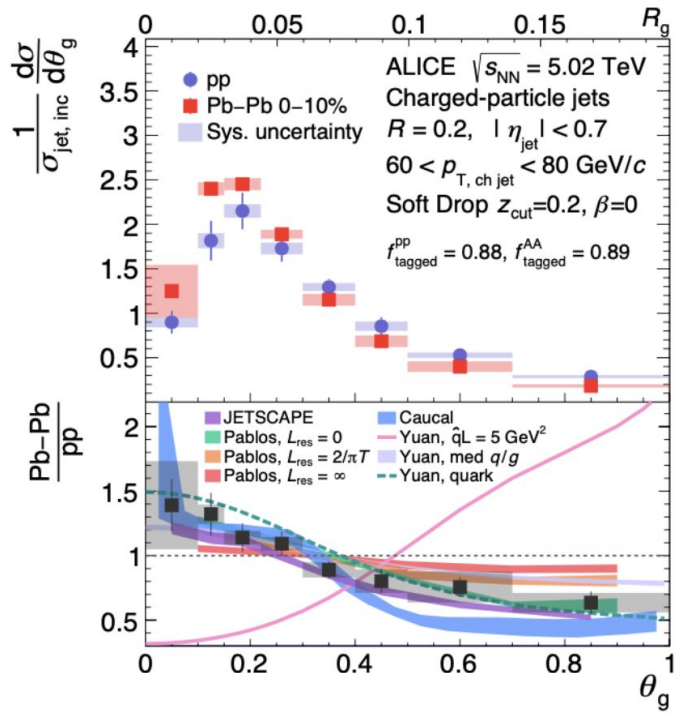
ALI - PUB - 493419

[arXiv:2106.05713](https://arxiv.org/abs/2106.05713)

First direct observation of dead-cone effect in pp collisions:  
 Small angle splitting suppressed for heavy quarks



# QCD radiation in medium: modified splittings



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

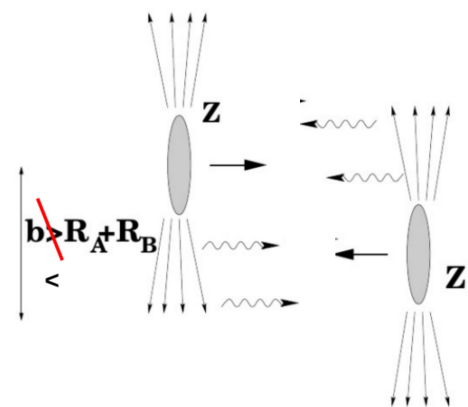
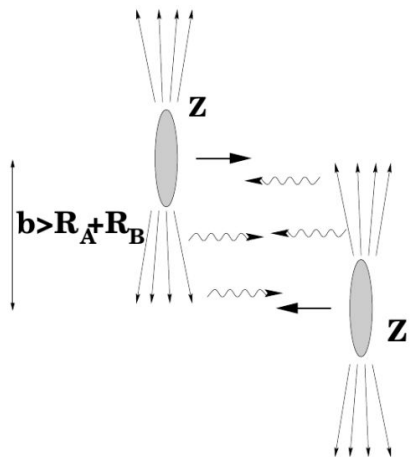
$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta \phi^2}}{R}$$

[arXiv:2107.12984](https://arxiv.org/abs/2107.12984)

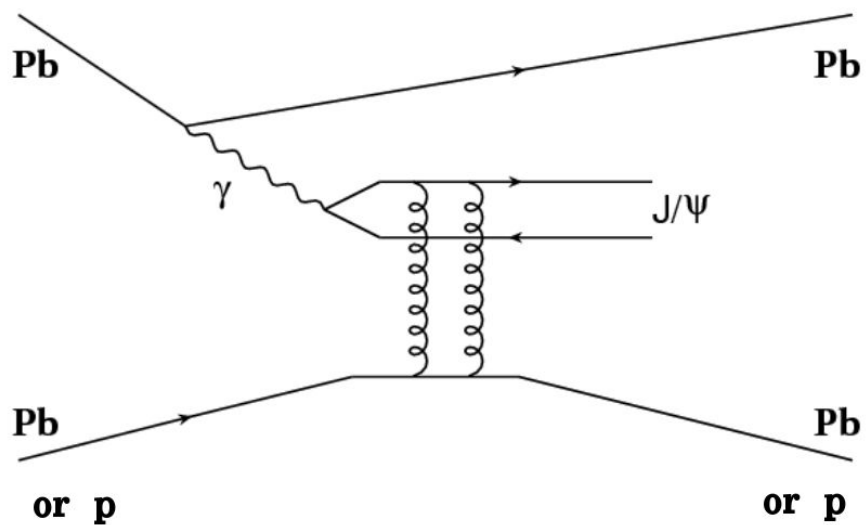
Cores of jets narrower in Pb-Pb than in pp

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

# Photoproduction with ALICE at the LHC



# Photoproduction: hadron structure at high energy



Heavy-ion collision:  
large flux of quasi-real photons

Enables photoproduction studies  
in analogy to deep-inelastic scattering facilities  
including nuclei as target

Focus on  $J/\psi$  production:  
Hard scale amenable to perturbative QCD

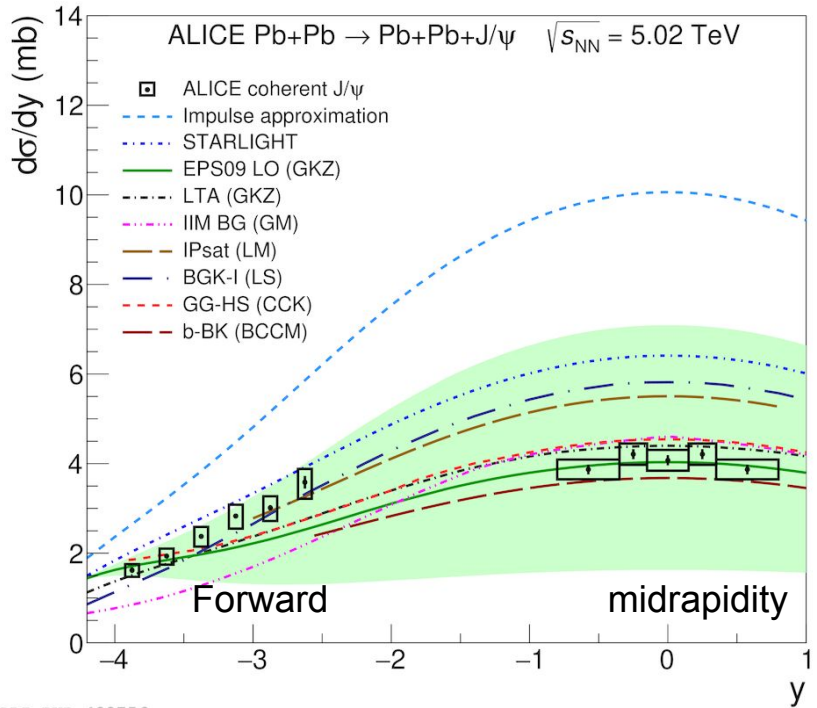
For small  $q\bar{q}$  at leading twist, leading  $\ln(1/x)$ ,  $t \rightarrow 0$ :  $\sigma \propto (\text{gluon PDF})^2$

Brodsky et al.: [PRD50 \(1994\) 3134-3144](#)

See also: t-dependence of  $J/\psi$  production in PbPb collisions by ALICE [Phys. Lett. B 817 \(2021\) 136280](#)

approaching the black disk limit with  $\rho$  - meson in XeXe collisions by ALICE [Phys. Lett. B 820 \(2021\) 136481](#)

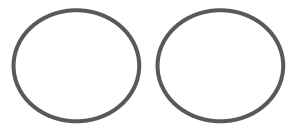
# Photoproduction at the LHC: nucleus gluon density



## Ultra-peripheral collisions

- Photon direction ambiguity forward: sensitive to high- and low-x combination
- Measurement at midrapidity: sensitive to  $x \approx 6 \times 10^{-4}$   
Consistent with moderate gluon shadowing of 0.65

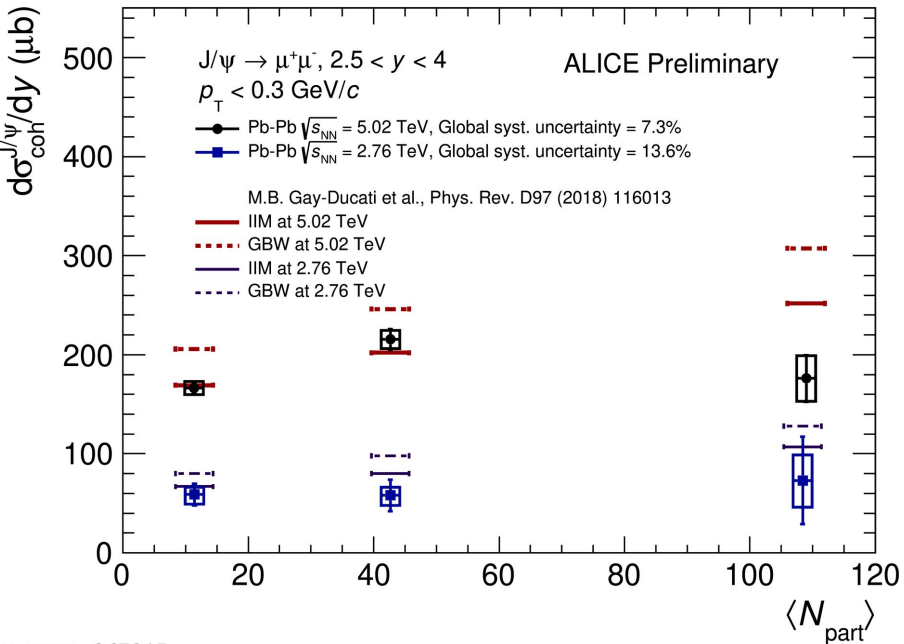
Starting point to connect exclusive production with collinear parton densities



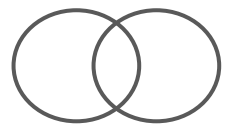
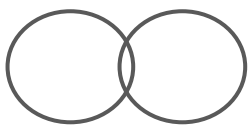
Midrapidity: [arXiv:2101.04577](https://arxiv.org/abs/2101.04577)

Forward rapidity: [Phys.Lett. B798 \(2019\) 134926](https://arxiv.org/abs/1907.134926)

# Photoproduction at the LHC: nucleus gluon density



ALI-PREL-367215

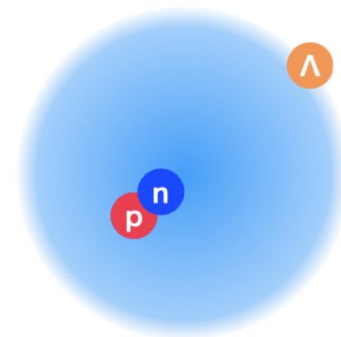
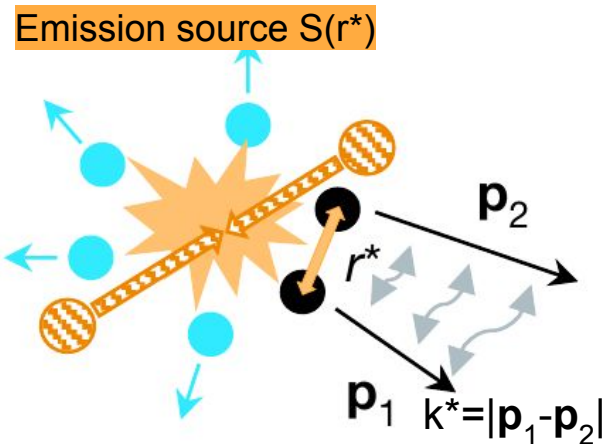


## Hadronic collisions

Measurement of low- $p_T$  excess at forward rapidity above hadronic production in peripheral collisions

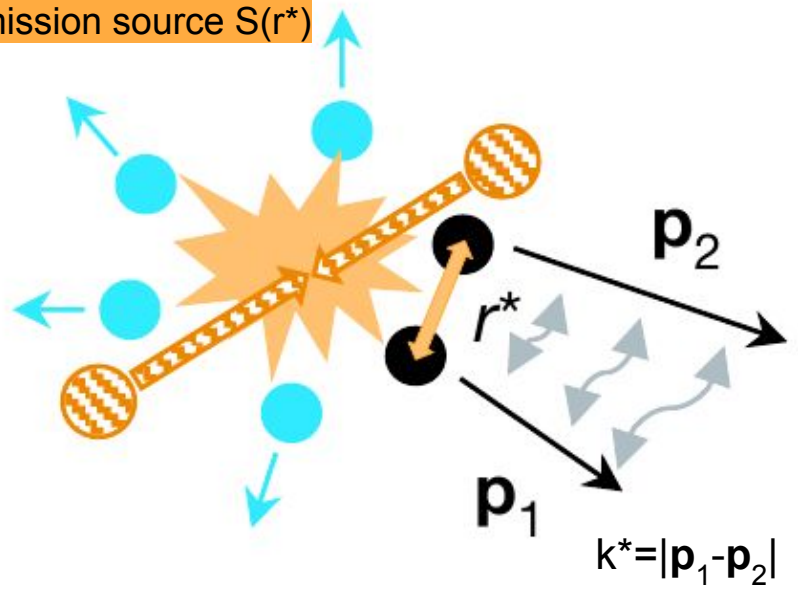
- Extended up to semicentral collisions
  - Input to understand coherence condition
  - Peripheral collisions: resolve photon direction ambiguity in conjunction with ultra-peripheral collisions
- J. G. Contreras: [Phys. Rev. C 96, 015203 \(2017\)](https://arxiv.org/abs/1705.08001)

# Precise measurements of strong interaction at soft scales



# Precision soft QCD: interactions via correlations

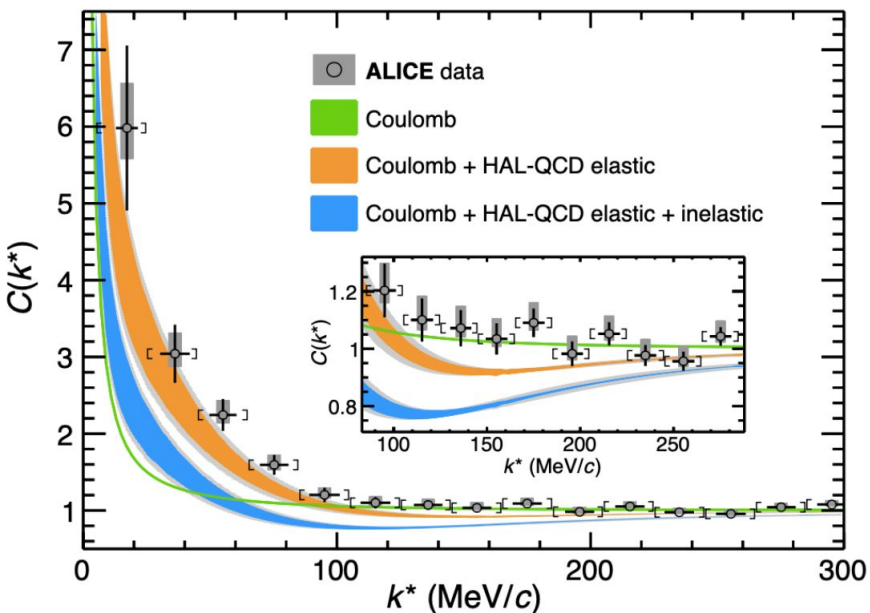
Emission source  $S(r^*)$



1. Source geometry Input
2. Measure correlation function  $C(k^*)$   
 → Study hadron-hadron interaction

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

# Extract information on unknown $p$ - $\Omega^-$ interaction



$p$ - $\Omega^-$  correlation function in pp collisions: [Nature v. 588, p. 232–238 \(2020\)](#)

Further publication exploiting the same concept:

$p$ -K: [arXiv:2105.05683](#)

$p$ - $\Phi$ : [arXiv:2105.05578](#)

$p$ - $\bar{p}$ ,  $p$ - $\bar{\Lambda}$ ,  $\Lambda$ - $\bar{\Lambda}$ : [arXiv:2105.05190](#)

Input to study common source in pp: [PLB 811 \(2020\) 135849](#)

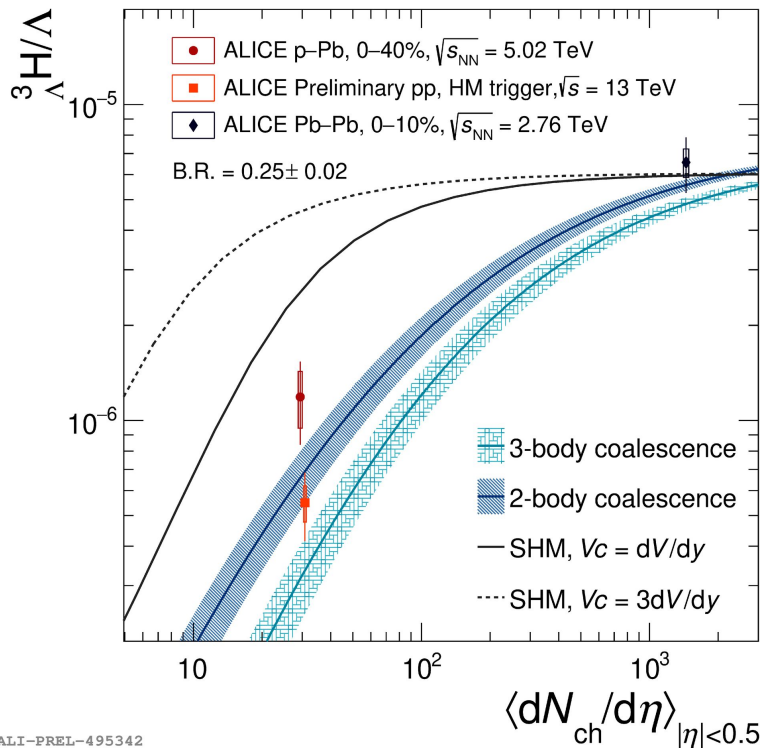
- Critical test for lattice QCD calculations of the strong h-h interaction
- A new avenue for high-precision tests of the strong interaction at the LHC:



- Important input for the equation of state of neutron stars



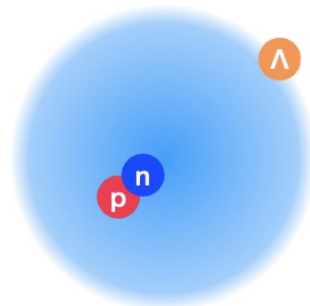
# Understanding the production of fragile objects



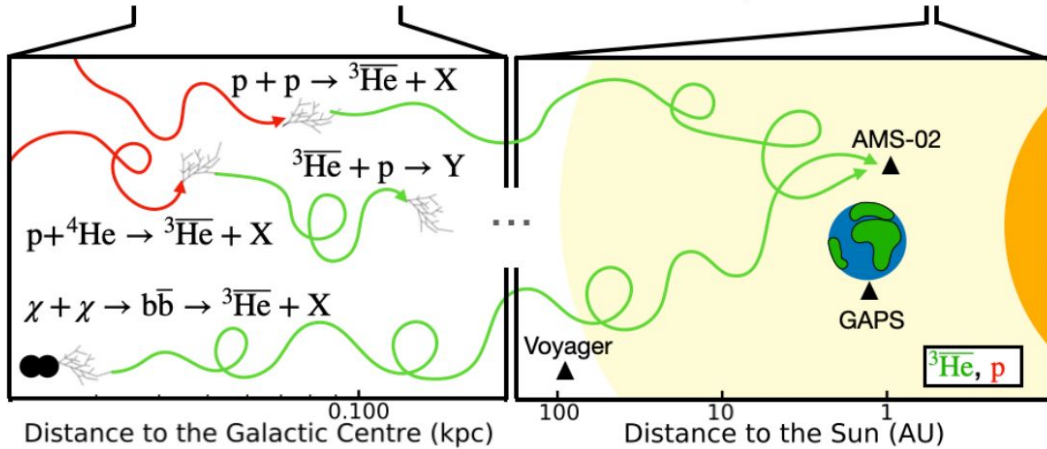
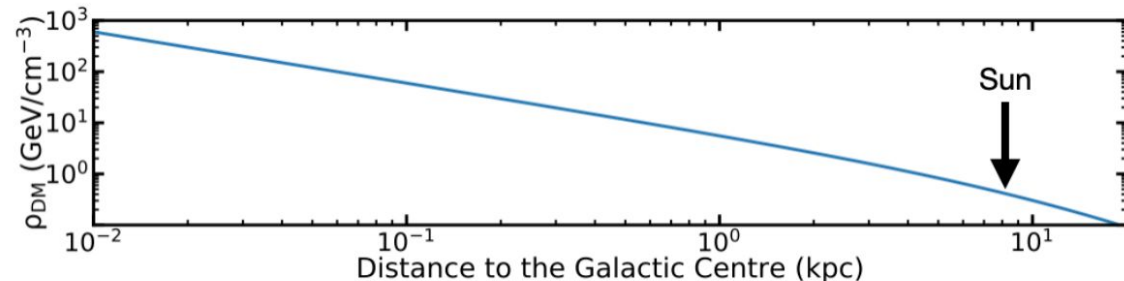
ALI-PREL-495342

[arXiv:2107.10627](https://arxiv.org/abs/2107.10627)

- Hypertriton production in pp, p-Pb and in Pb-Pb  
Very weakly bound, large size object
- Test formation pictures by varying emission source
- Impacts our picture of hadron formation in dense environments



# LHC as antimatter factory: constrain its interaction

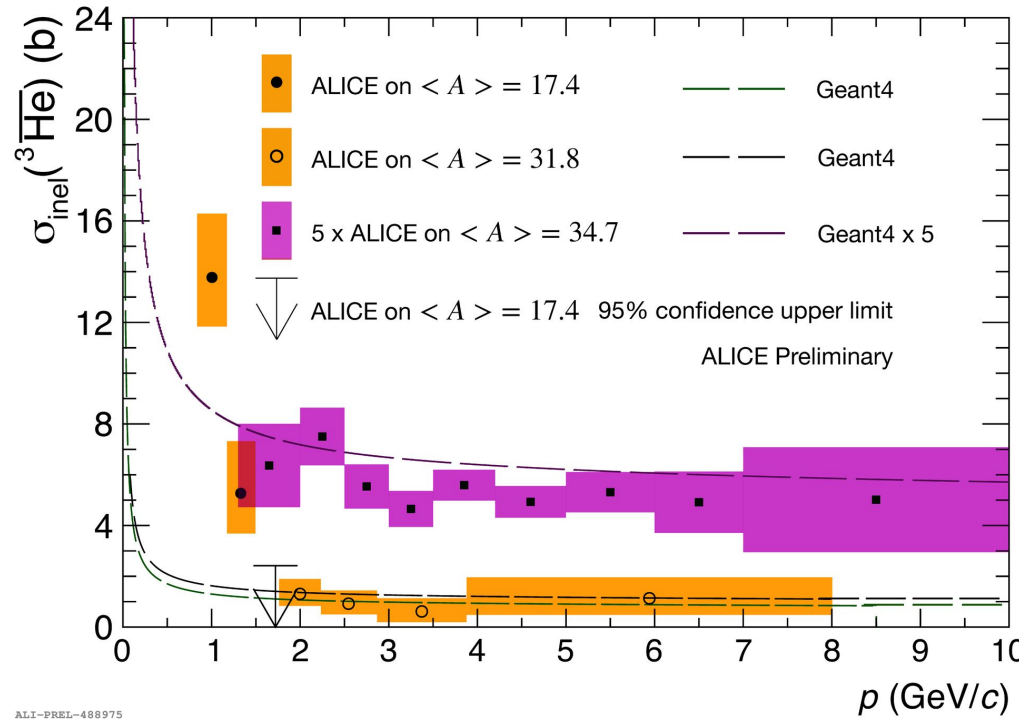


- Indirect dark matter searches
  - $\chi + \chi \rightarrow b \bar{b} \rightarrow \bar{d} + X$
  - $\chi + \chi \rightarrow W^+ W^- \rightarrow d \bar{d} + X$
  - $\chi + \chi \rightarrow b \bar{b} \rightarrow \bar{^3\text{He}} + X$
  - $\chi + \chi \rightarrow W^+ W^- \rightarrow \bar{^3\text{He}} + X$

- Small astrophysical backgrounds
- Important input: cross sections of  $\bar{d}$  on matter measured by ALICE

[PRL 125 \(2020\) 16.162001](https://arxiv.org/abs/2001.16201)

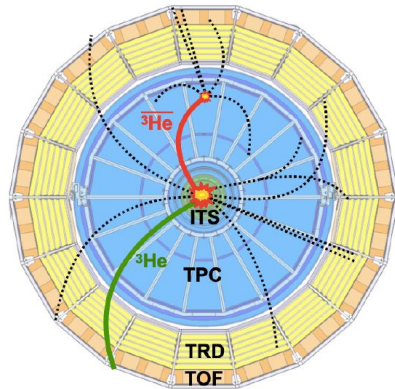
# LHC as antimatter factory: constrain its interaction



ALI-PREL-488975

pp collisions  
PbPb collisions

First measurement of  $^3\overline{\text{He}}$  interaction



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

Indications of deviations from GEANT 4 at low momentum  $p$

ALICE: the dedicated experiment for heavy-ion physics

- QCD matter studies: constraining the QGP-parton interaction  
The fate of bound states in the QGP, gluon radiation and “Brownian motion”
- Learn about different aspects of strong interaction and hadron structure  
From exotic nuclei built from nucleons & hyperons up to high energetic partons