# Heavy Flavour & Quarkonia

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# Heavy quarks: probes through the full system history

- Large mass ($m_c$~1.5 GeV, $m_b$~5 GeV) → produced in large virtuality ($Q^2$) processes at the initial stage of the collision with short formation time

$$\Delta t < 1/(2m_c) \sim 0.1 \text{ fm/c} \ll \tau_0 \sim 1 \text{ fm/c} \ll \tau_{QGP} \sim 10 \text{ fm/c}$$

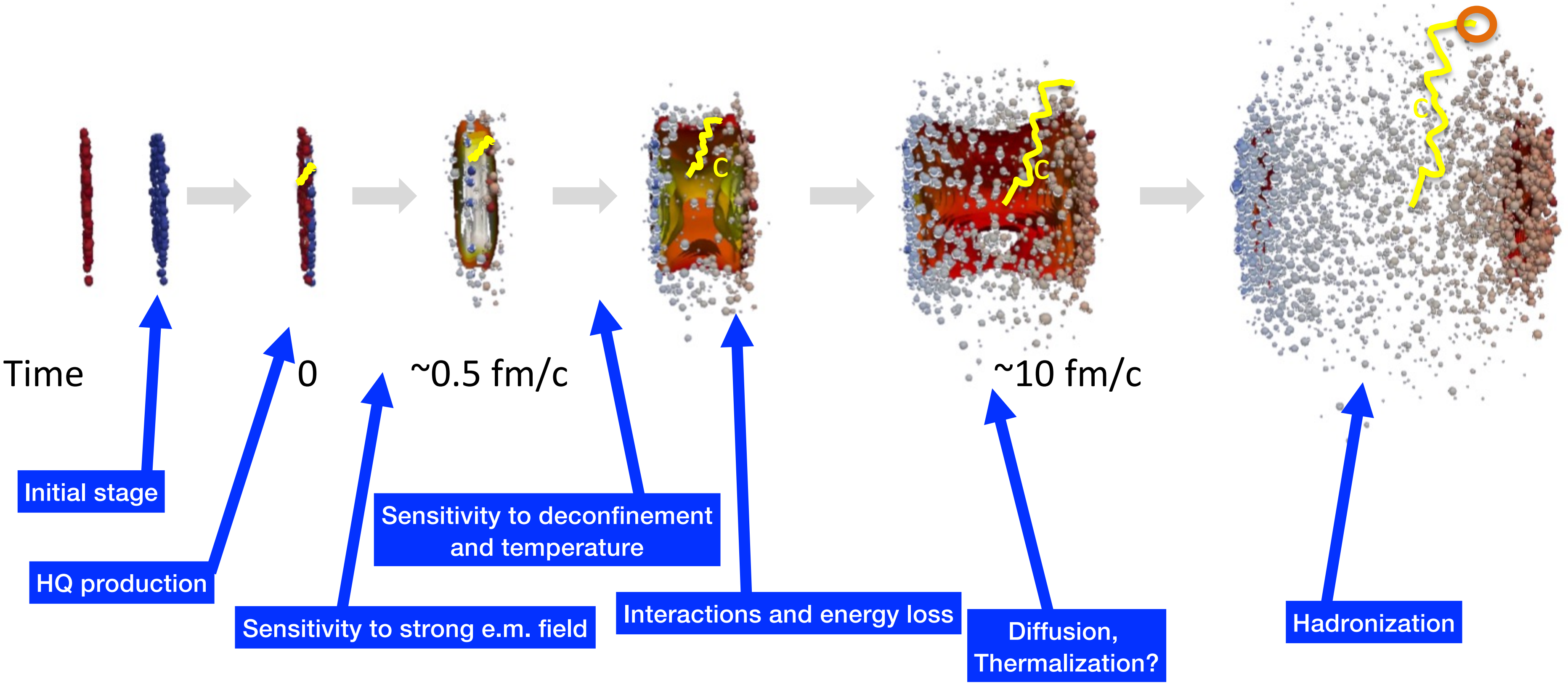
- Production in QGP expected to be ~negligible (<< 10% at LHC)
- Strong interactions with QGP conserve flavour

→ Uniqueness of heavy quarks: “see” full system evolution

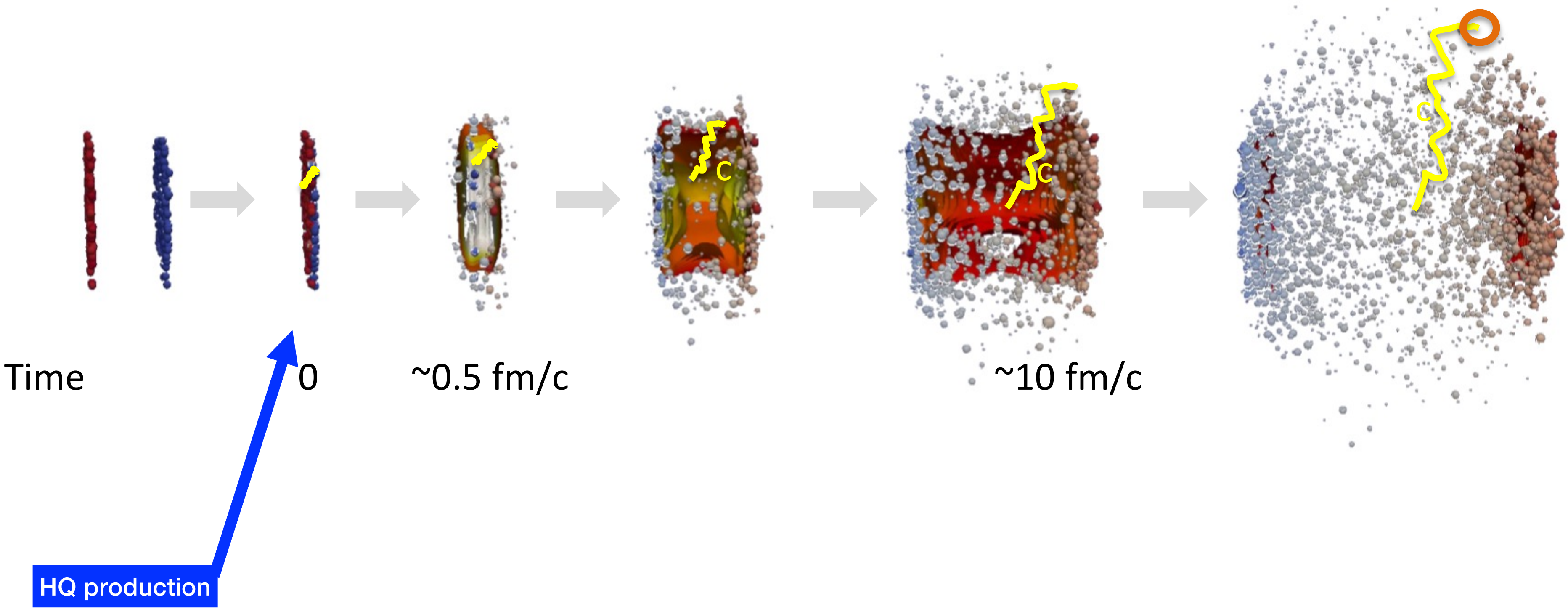
- **Effective probes of:**
  - **Presence of deconfined colour charge and QGP temperature**
  - **The mechanisms of quark-medium interaction: energy loss (and gain)**
  - **The strength of the collective expansion of the system**

# Outline of this lecture:

Heavy Quarks as messengers from all stages of heavy-ion collisions

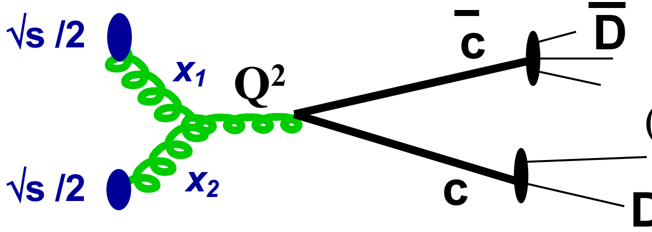


# Heavy quark production in pp collisions



# Heavy-flavour production: pp

***proton-proton collisions:*** **factorised perturbative QCD approach**




$(x_1 x_2 s \sim Q^2 \sim M^2_{c\bar{c}})$

$$\frac{d\sigma^D}{dp_T^D}(\mu_F,\mu_R) = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T^c} \otimes D_{c\to D}(z = p_D / p_c)$$

$\mu^2_{F,R} \sim Q^2$

***Parton Distribution Functions:***

- $Q^2$ evolution calculated in pQCD
- initial condition from data (ep DIS)

***Fragmentation Functions:***

- non-perturbative
- phenomenolgy + fit to data ($e^+e^-$)

***Partonic cross section:***

*calculable* as perturbative series of strong coupling $\alpha_s(\mu_R)$

# pp → $Q\bar{Q}$+X: partonic cross section

- Fixed-order massive quark calculations: perturbative expansion in powers of $\alpha_s$
  - Fixed-order massive calculation

$$\frac{d\sigma}{dp_T} = A(m)\,\alpha_s^2 + B(m)\,\alpha_s^3 + O(\alpha_s^4) \qquad B(m) = \beta(m) + \gamma(m)\log(\mu/m)$$

$\mu \approx p_T$

**NLO: Mangano, Nason, Ridolfi (1992)**
**NNLO: Czakon et al. (2013), Catani et al. (2020)**

**→ state-of-the-art for total cross section, but not $p_T$ differential**

  - Fixed-order next-to-leading log (FONLL)

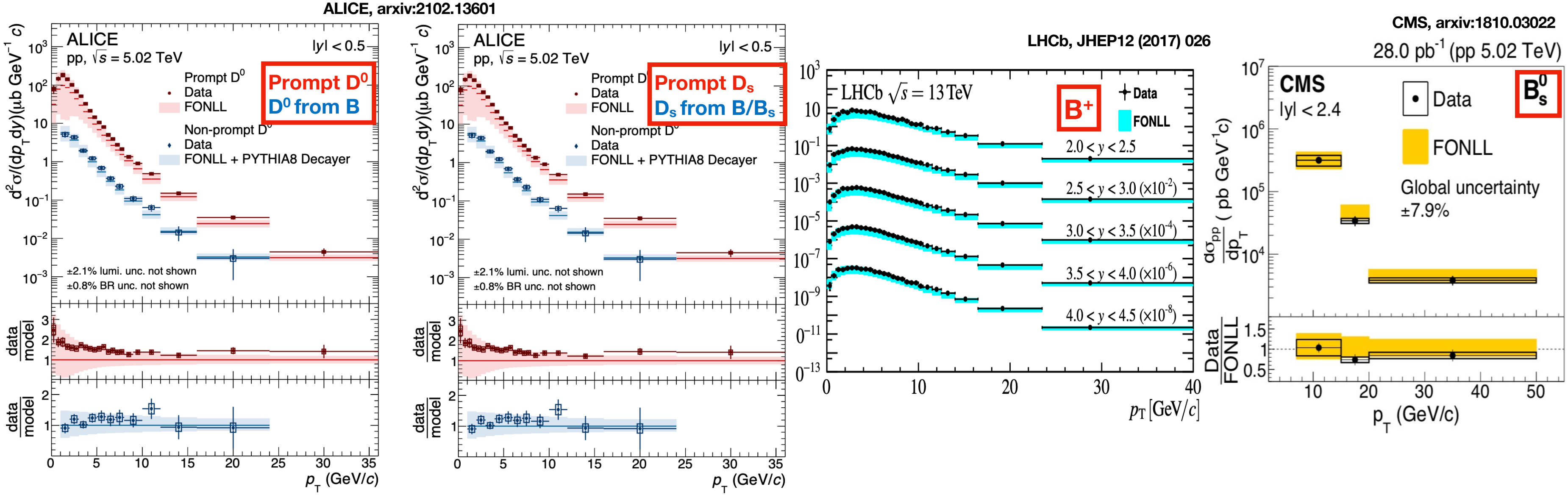
$$\frac{d\sigma}{dp_T} = A(m)\,\alpha_s^2 + B(m)\,\alpha_s^3 + G(m,p_T)\left[\alpha_s^2 \sum_{i=2}^{\infty} a_i [\alpha_s \log(\mu/m)]^i + \alpha_s^3 \sum_{i=1}^{\infty} b_i [\alpha_s \log(\mu/m)]^i\right]$$

**FONLL: Cacciari, Nason, Frixione, Mangano (1998)**

**→ more accurate than NLO at high $p_T$**

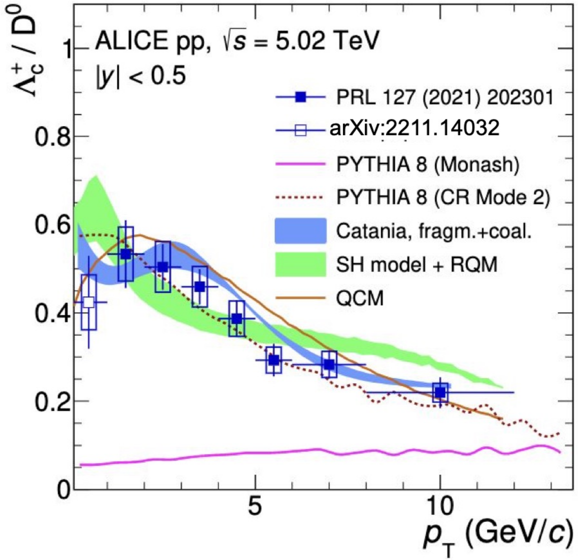
- Other approaches: Variable Flavour Number Scheme (Kniehl et al.), $k_T$-factorization (Maciula, Szczurek)

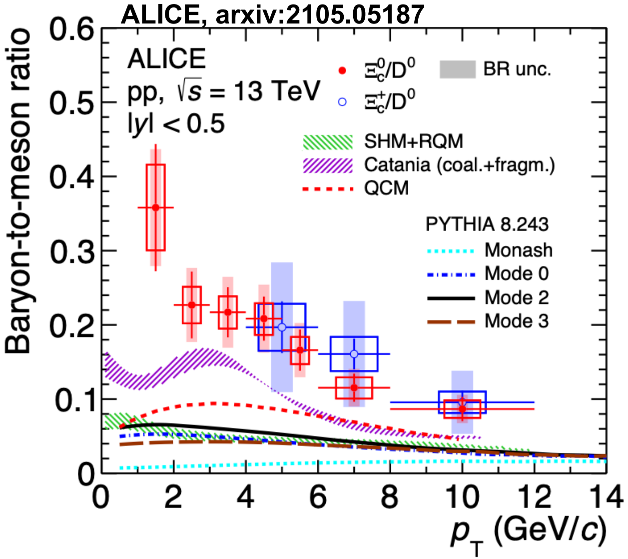
# D and B production in pp collisions: data vs theory




- Measurements from 0 to ~50-100 GeV/c for both charm and beauty hadrons
- **Systematic comparison with FONLL calculations**: charm data close to upper FONLL limit; beauty data close(r) to central value
- **Important for QGP studies: HQs are well-calibrated probes; most models of HQ-QGP interactions use FONLL for the baseline production**

# The big surprise of HF baryons at the LHC




- Baryon fraction ($\Lambda_c$ and $\Xi_c$) at low $p_T$ much larger than predicted by string fragmentation models tuned on e+e- data, e.g. $\Lambda_c/D^0$ ~0.6, $\Xi_c/D^0$ ~0.3
- Qualitatively described by models with baryon junctions (PYTHIA 8) or with hadronization via coalescence

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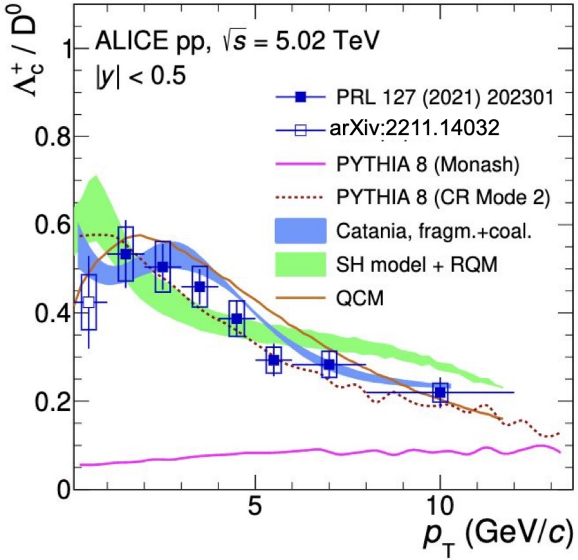
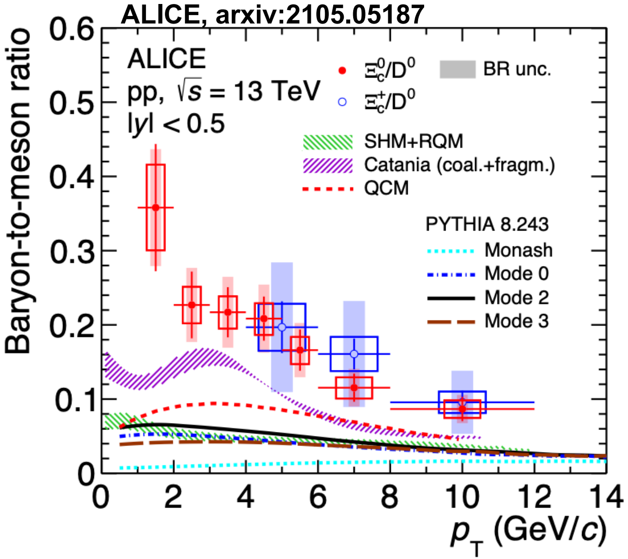
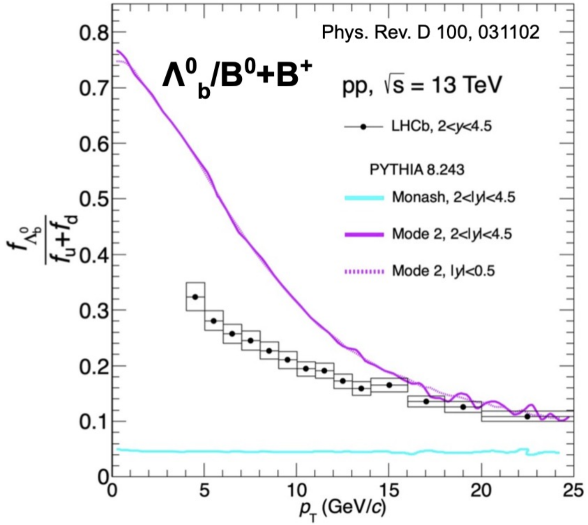
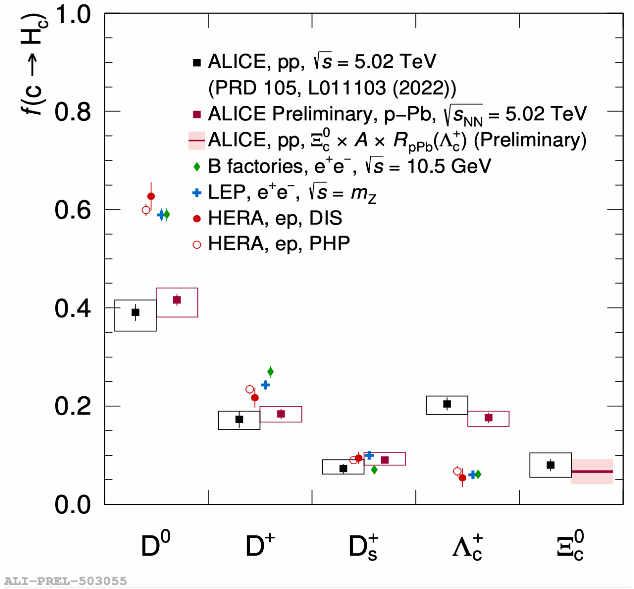


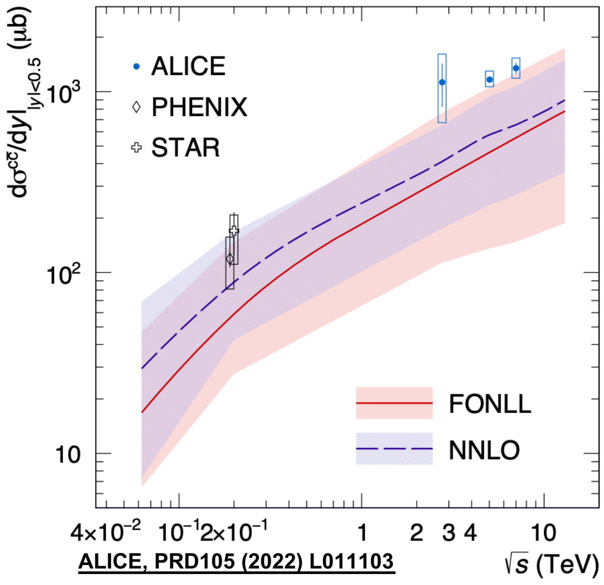




- **Baryon fraction ($\Lambda_c$ and $\Xi_c$) at low $p_T$ much larger than predicted by string fragmentation models tuned on e+e$^-$ data, e.g. $\Lambda_c/D^0$ ~0.6, $\Xi_c/D^0$ ~0.3**
- Qualitatively described by models with **baryon junctions (PYTHIA 8)** or with hadronization via **coalescence**
- Large baryon/meson ratio also measured in the beauty sector

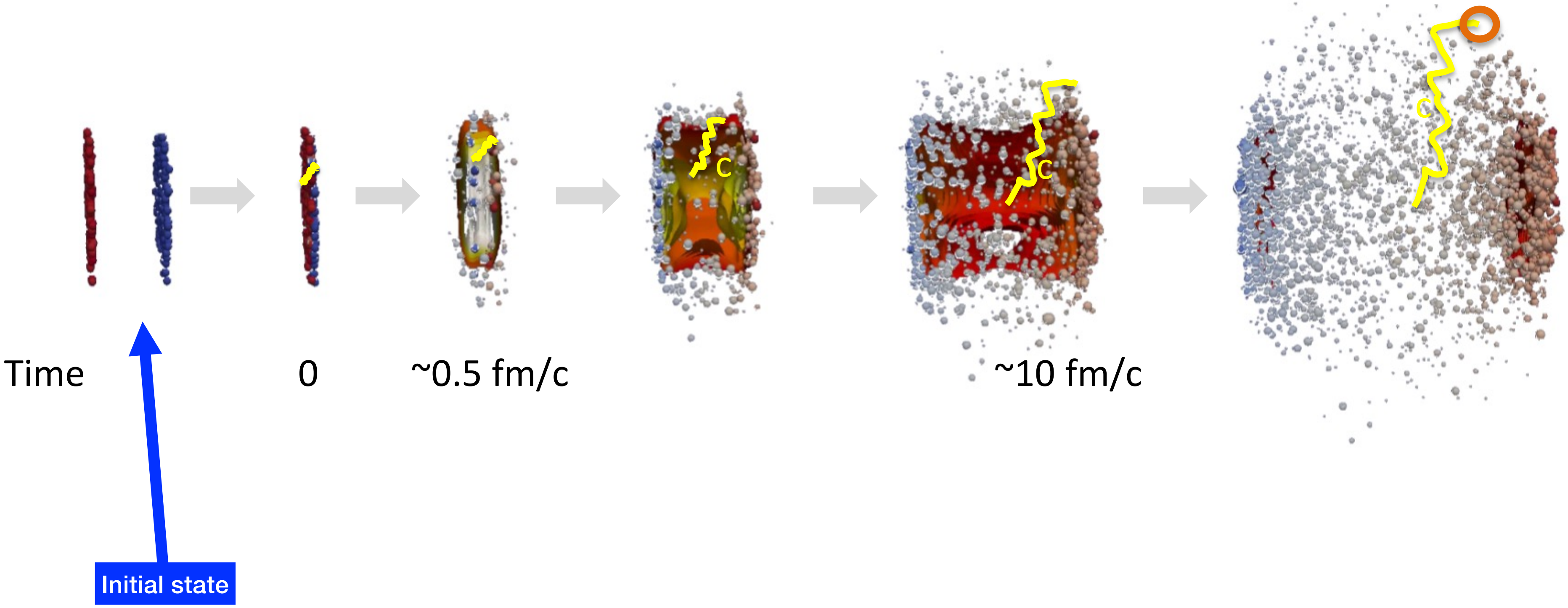
# Charm-anticharm cross section



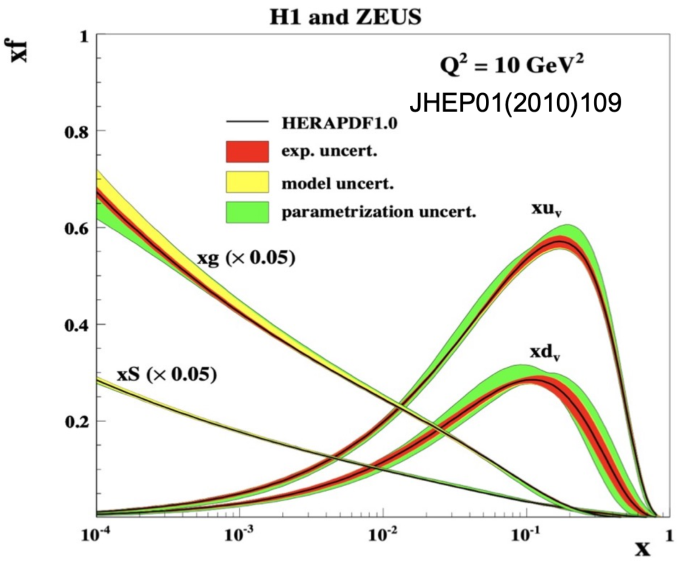

- **Measurement of charm cross section needs baryons!**
- Recent measurements (at mid-rapidity) that use the sum of observed mesons ($D^0$, $D^+$, $D_s$) and baryons ($\Lambda_c$ and $\Xi_c$) give a cross section ~30% larger than early measurements based on mesons and $e^+e^-$ fragmentation fractions
- Forward rapidity charm baryon measurements needed to obtain total cross section

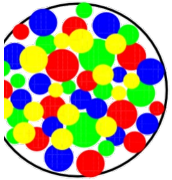
# Heavy quarks as probes of the initial state



# Parton densities in nuclei at small $x_{Bjorken}$

- Initial state: high-$p$ nucleus = set of gluons with $p^g$ distribution according to PDF $g(x_{Bjorken},Q^2)$, with $x=p^g/p^N$ and $Q^2$ the scale of the process (~ 1/"area" of the gluon)
- HERA DIS (ep) data: strong rise of $xg(x,Q^2)$ at low-$x$ & low-$Q^2$
- New (unknown) regime of QCD: when gluons are numerous enough (low-$x$) & extended enough (low-$Q^2$) to overlap → ***Limits the low-x rise, lead to saturation?***



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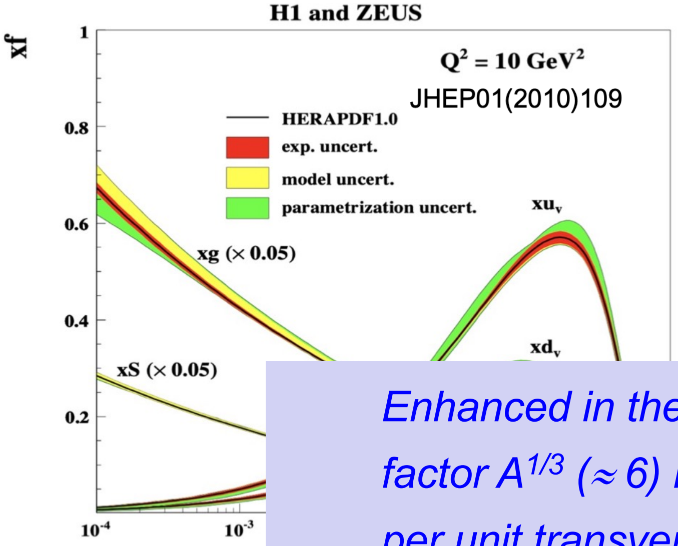
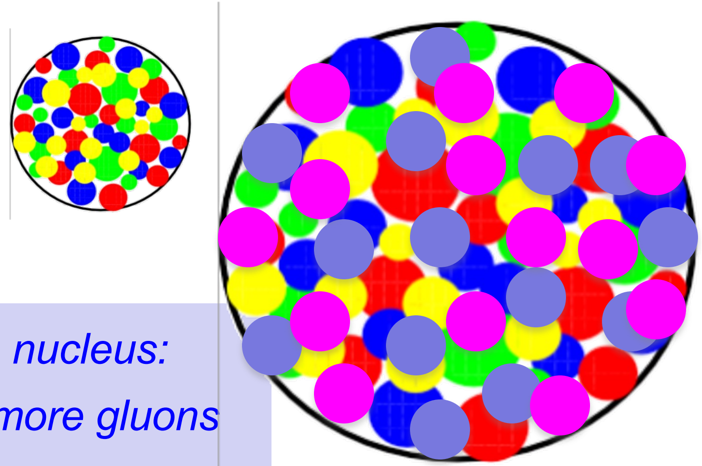
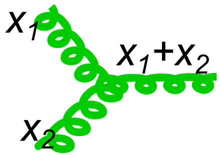


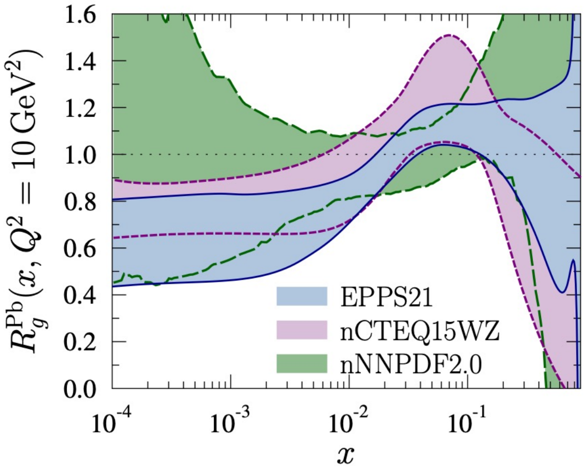
*Enhanced in the nucleus: factor $A^{1/3}$ ($\approx$ 6) more gluons per unit transverse area*

# Nuclear PDFs

Effective reduction of the parton flux at small x(shadowing)
→ can described with nuclear-modified PDFs



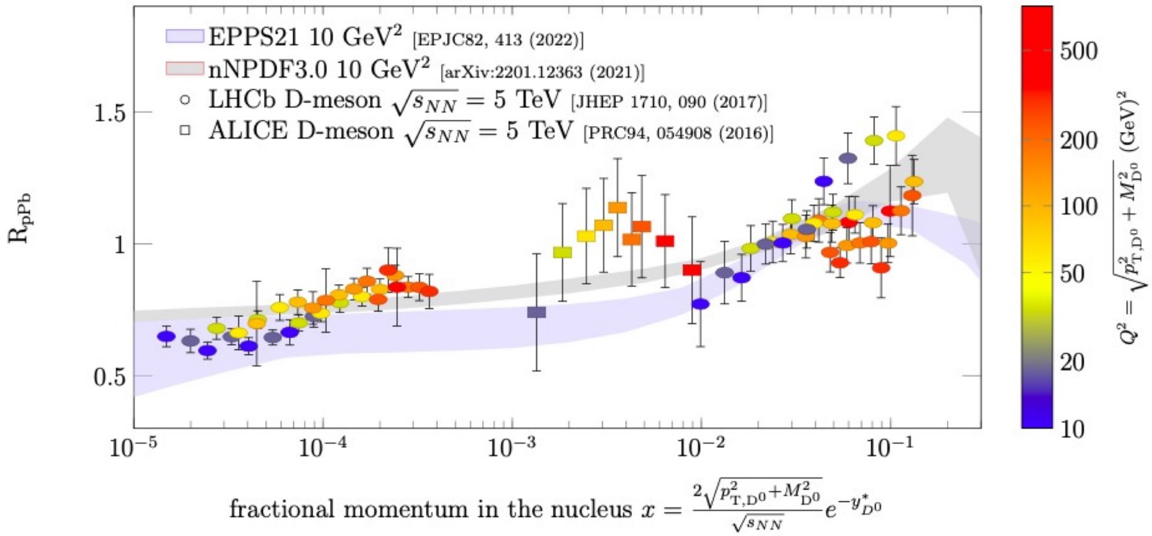

- Shadowing ≈ small-x gluon "fusion": $g_{x1} + g_{x2} \rightarrow g_{x1+x2}$
- Shadowing factor for PDFs: $xG_A(x,Q^2) = A\, xg(x,Q^2)\, R_G^A(x,Q^2)$




see e.g. Eskola et al. Eur.Phys.J.C 82 (2022) 5, 413

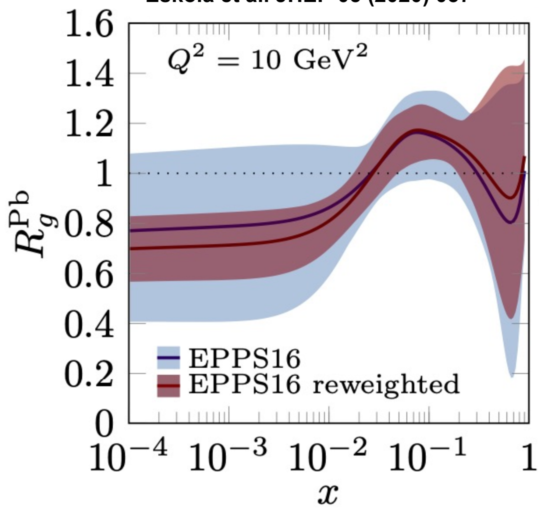
- Limited data at small-*x* (esp. before the LHC era) → large uncertainties and large differences between approaches **→ uncertainty in initial HQ production in AA**

# Initial-state effects on charm in proton-nucleus




Cesar Luiz da Silva, QCD Challenges 2023 workshop

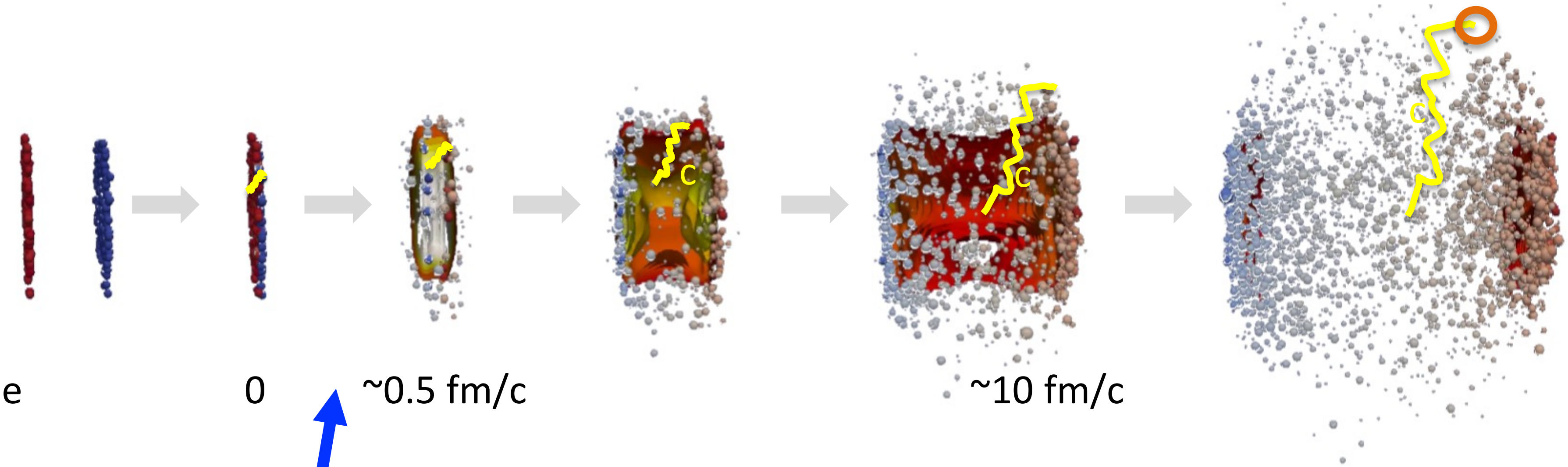
Eskola et al. JHEP 05 (2020) 037




- nPDFs with shadowing describe D-meson p-Pb 5 TeV data: reduction of forward y (small x) and possible enhancement at backward y (large x)

- Precise LHCb fwd-y data constrain nPDFs down to small x
- However, the p-Pb charm data may be affected by final-state effects as well

# Heavy quarks as probes of the early e.m. field

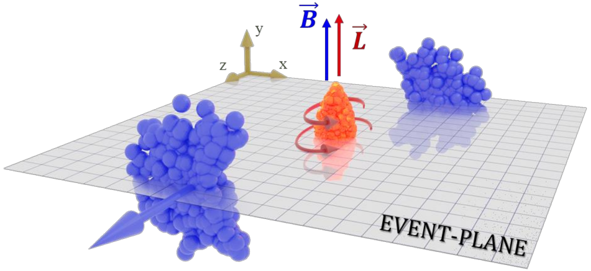


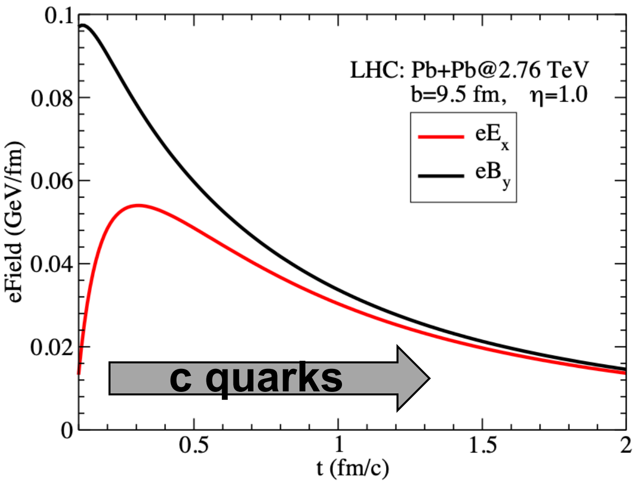

Time 0 ~0.5 fm/c ~10 fm/c

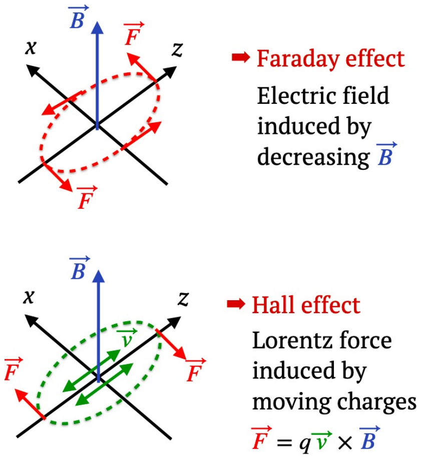
Sensitivity to strong e.m. field

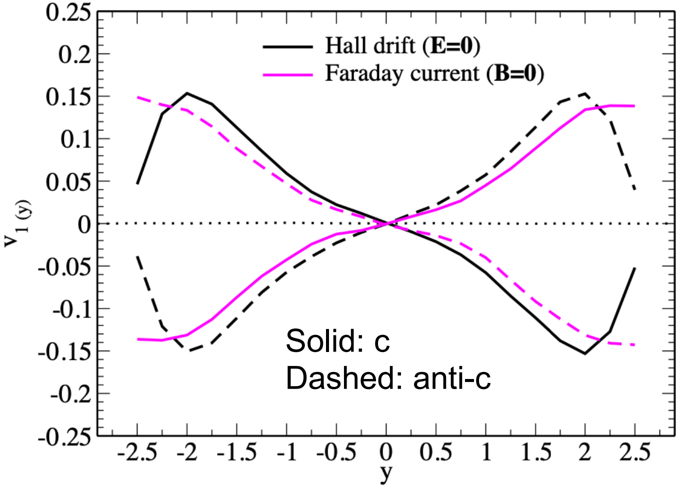
# Large magnetic field (B) in heavy-ion collisions

- B up to $10^{14}$ T produced by crossing positive ions, and rapidly decreasing after crossing
- Expected to induce asymmetry vs rapidity or event plane for particle with opposite charge
- **Charm quarks produced at t < 0.1 fm/c → sensitive to the highest field values**



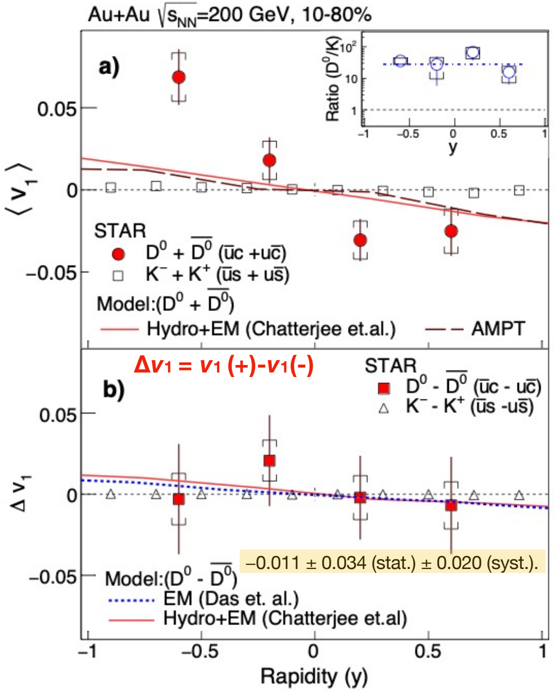




K. Das et al. PLB 768 (2017) 260

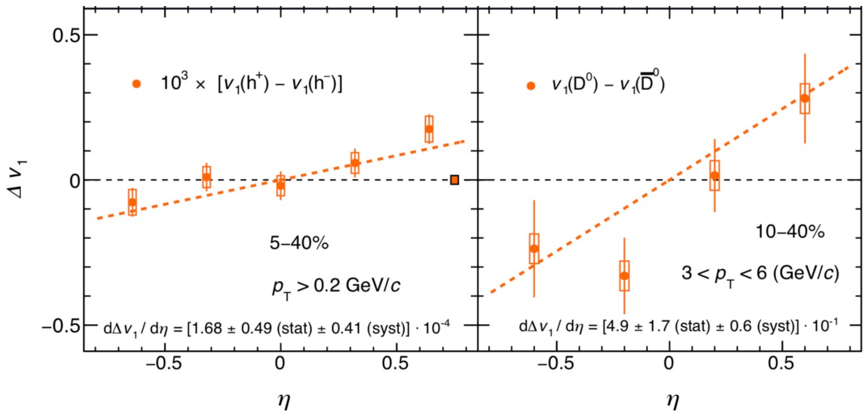
# Rapidity asymmetry: $v_1$(D)- $v_1$(anti-D)

[STAR arXiv:1905.02052](#)




LHC: larger slope w.r.t. RHIC, effect due to larger B than the induced E?

**ALICE, arXiv:1910.14406**

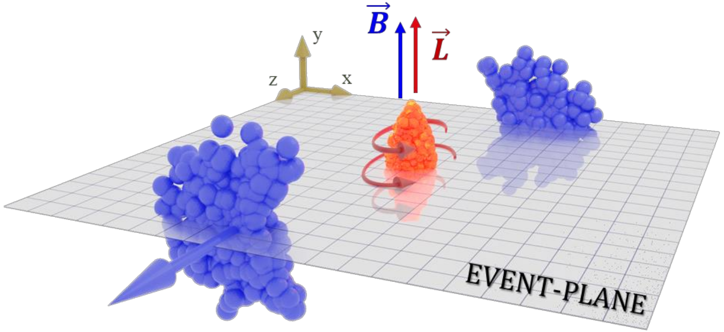



Slope ≠ 0 significance 2.7σ

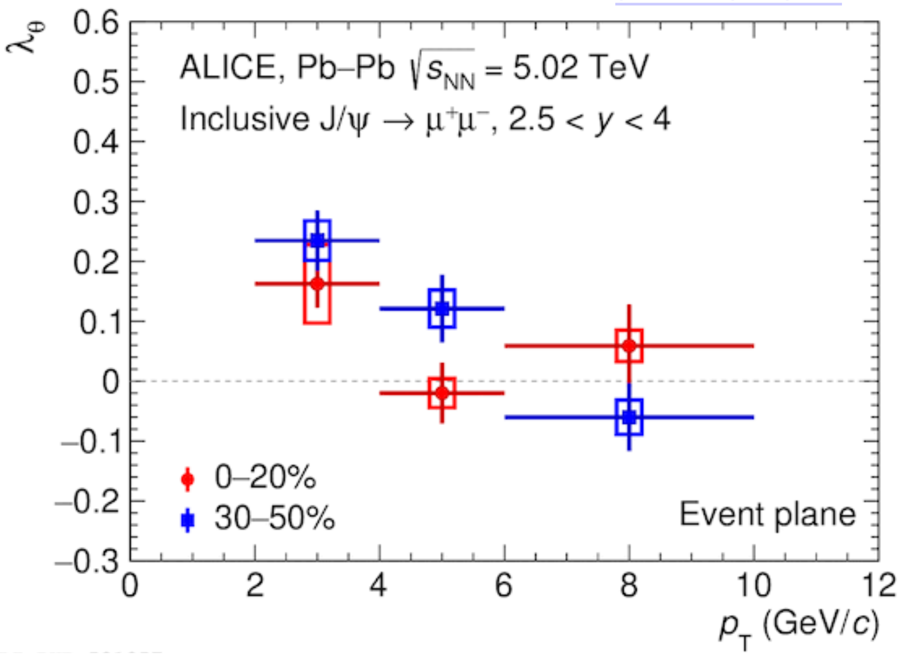
3 orders of magnitude larger slopes w.r.t. **charged hadrons**

# J/ψ polarization w.r.t. event plane

- J/ψ polarization with respect to event plane in Pb-Pb at the LHC
- Increases in less central collisions and at low $p_T$ (reaching 3.9σ effect)
- Interpretation in terms of early B field and/or angular momentum needs detailed theory calculations



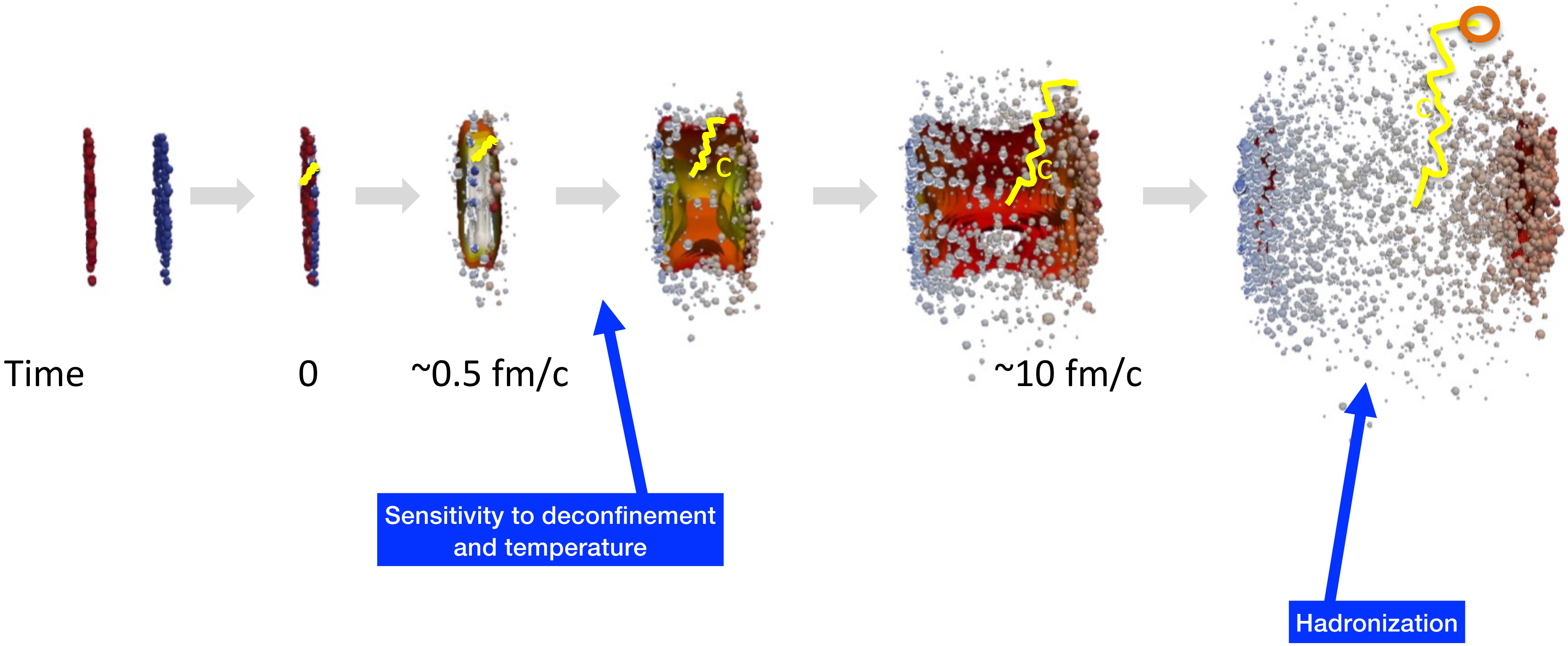

arXiv:2204.10171




$$W(\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta)$$

**polar angular distribution of dimuon decay**

# Quarkonia: probing the strong force in the QGP



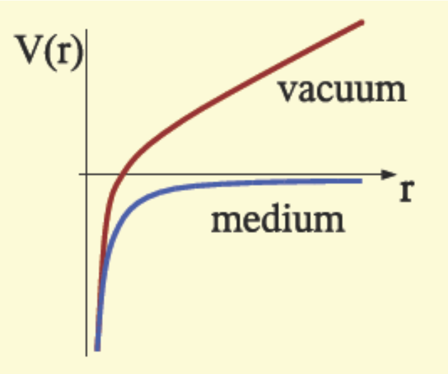
# Quarkonium melting due to colour screening

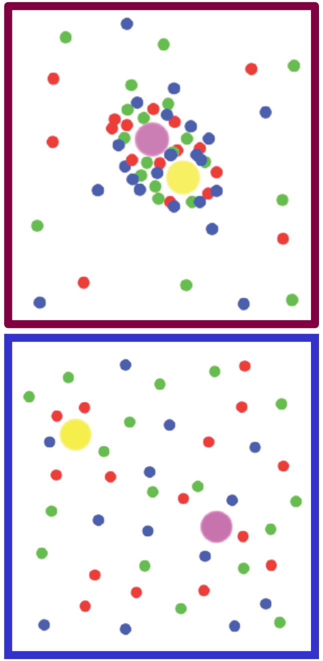
- QGP signature proposed by Matsui and Satz, 1986 Matsui, Satz, PLB178 (1986) 416

- In the plasma phase the interaction potential is expected to be screened beyond the Debye length $\lambda_D$ (analogous to e.m. Debye screening)

$$V(r) = -\frac{\alpha}{r} + kr \quad \Rightarrow \quad V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

- Charmonium ($c\bar{c}$) and bottonium ($b\bar{b}$) states with r > $\lambda_D$ will not bind; their production will be suppressed



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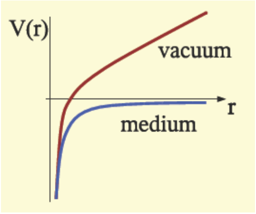


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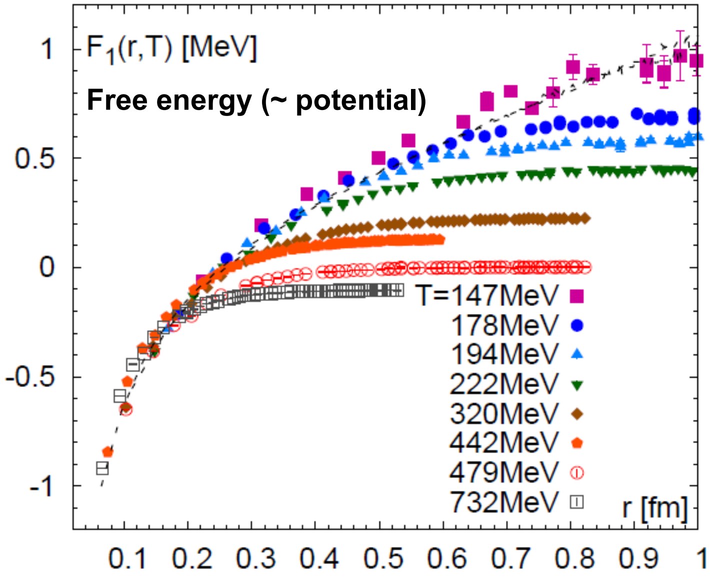
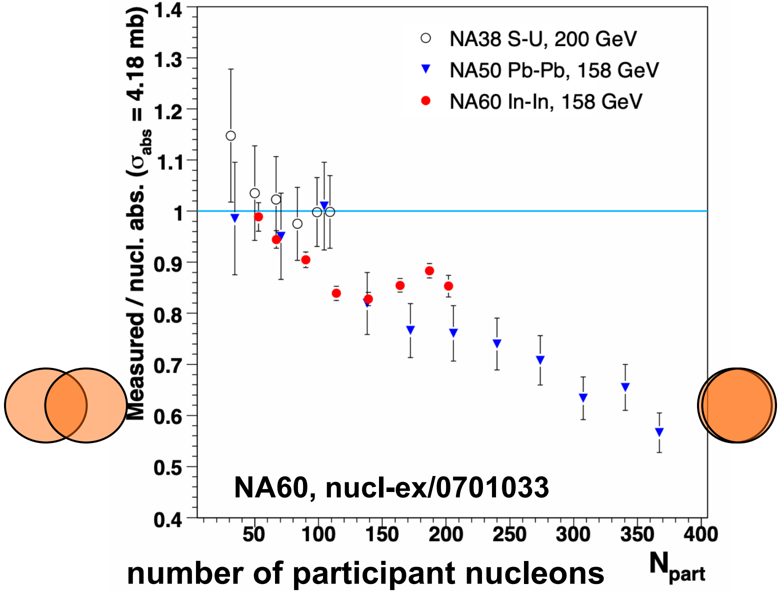
- In-medium potential calculated in lattice QCD:




Lattice QCD: e.g. Bazavov et al. 2013

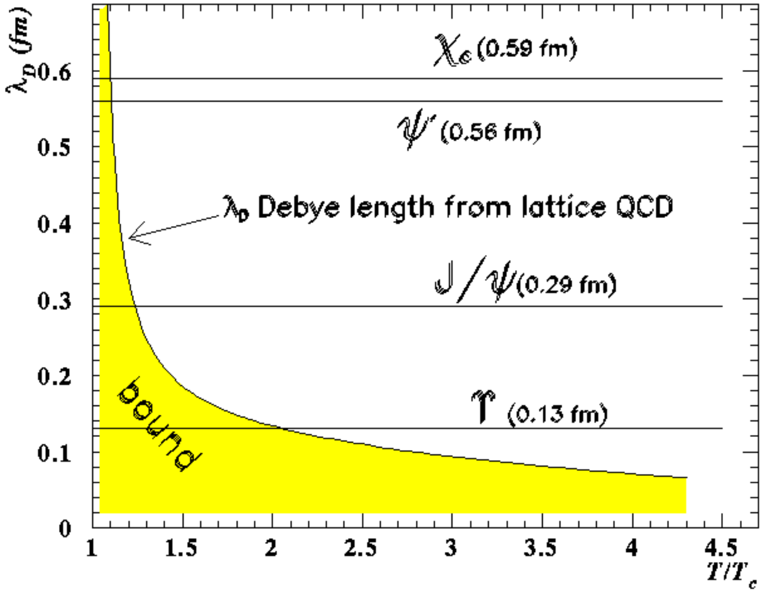
# J/ψ suppression at the SPS

- **Suppression observed by the NA50 and NA60 experiments** in Pb-Pb and In-In at the SPS ($\sqrt{s_{NN}}$ ~ 17 GeV)
- "Measured / Expected" J/ψ yield vs. centrality drops below unity towards more central collisions



# Sequential quarkonium melting due to colour screening

Debye screening length $\lambda_D$ rapidly decreases when T > $T_c$ (T/$T_c$ > 1):




Digal,Petrecki,Satz PRD 64(2001) 0940150

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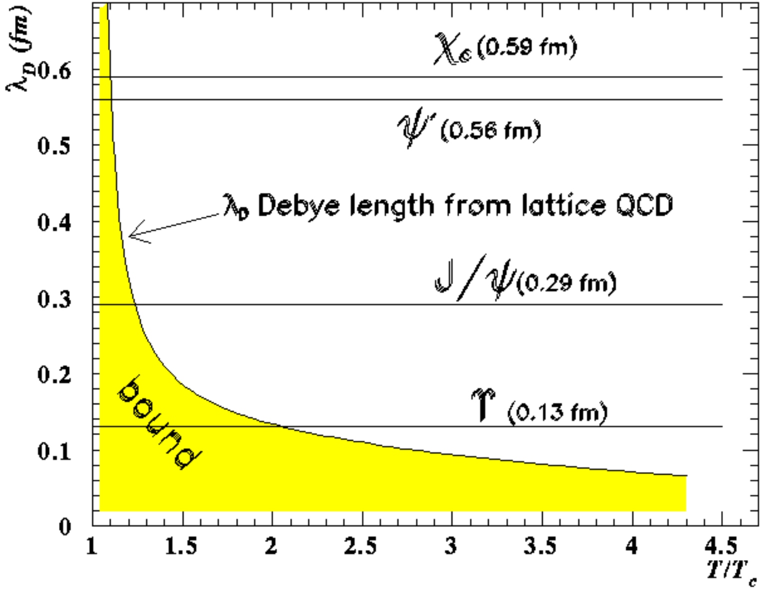
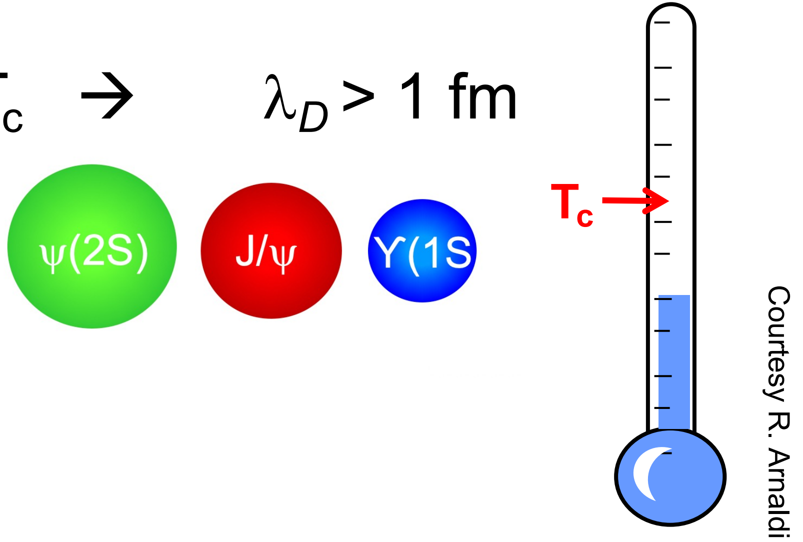



$T < T_c \rightarrow \lambda_D > 1$ fm

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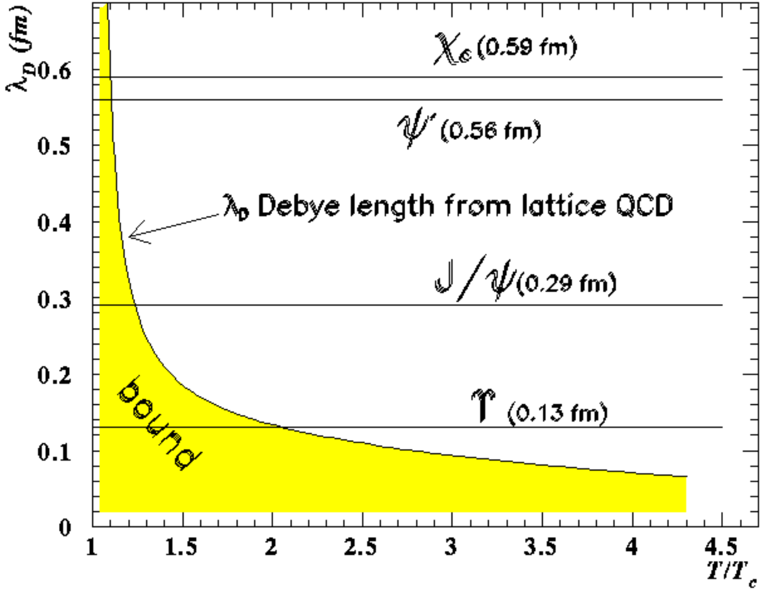
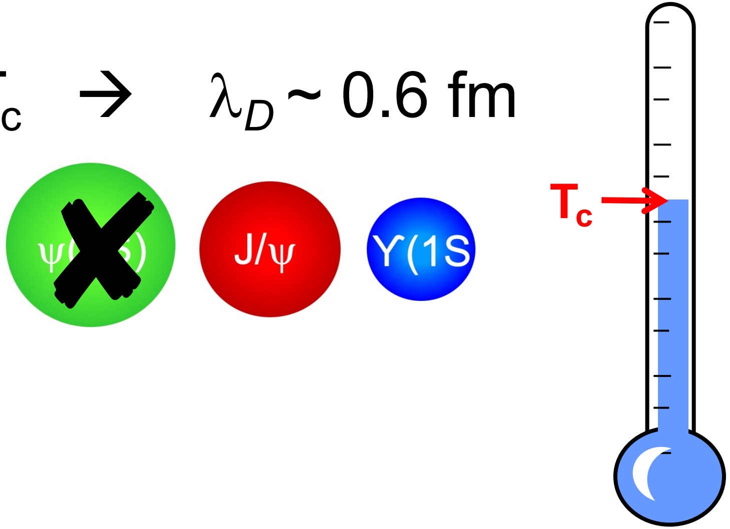



$T \sim T_c \rightarrow \lambda_D \sim 0.6$ fm




Courtesy R. Arnaldi

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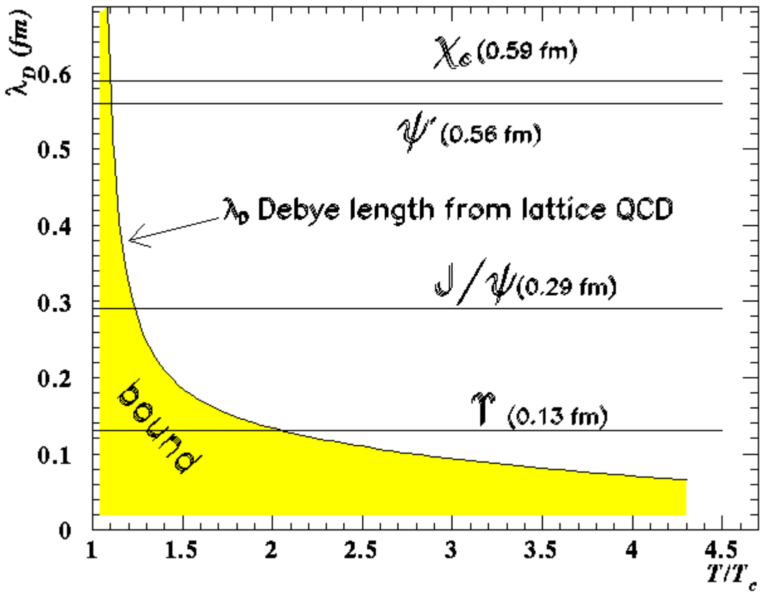
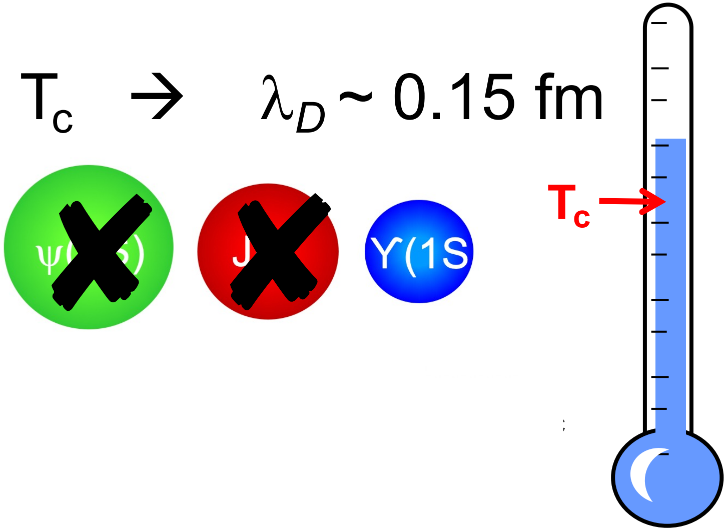



$T \sim 2\, T_c \;\rightarrow\; \lambda_D \sim 0.15$ fm

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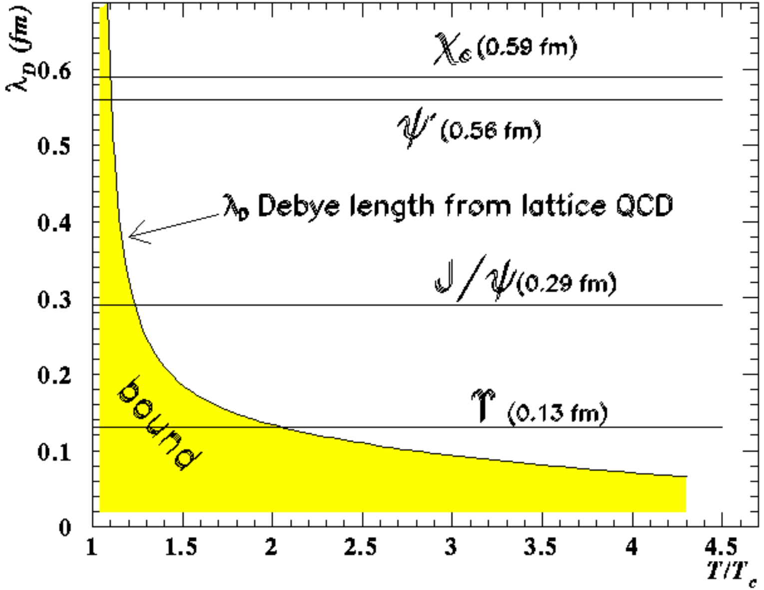
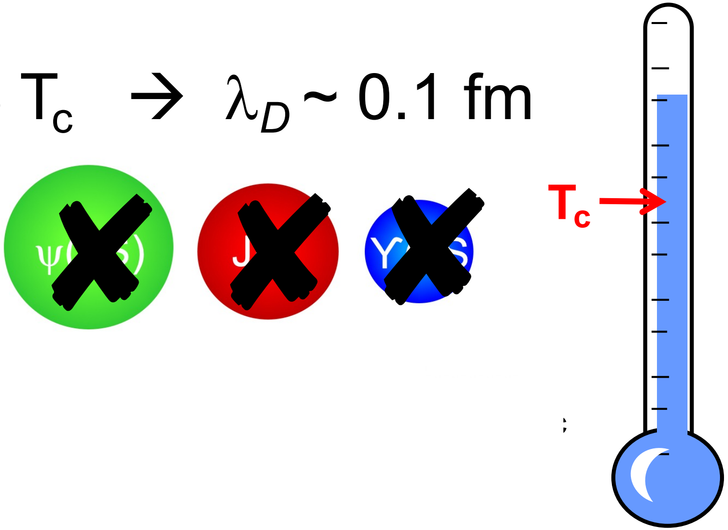



$T \sim 3\,T_c \;\rightarrow\; \lambda_D \sim 0.1$ fm



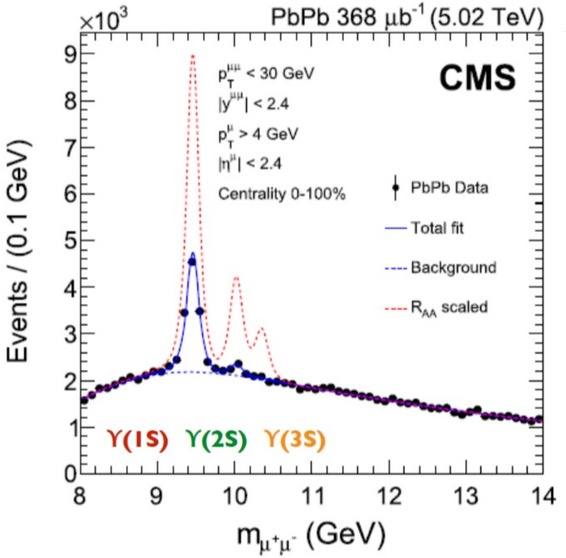

Courtesy R. Arnaldi

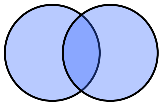
Digal, Petrecki, Satz PRD 64(2001) 0940150

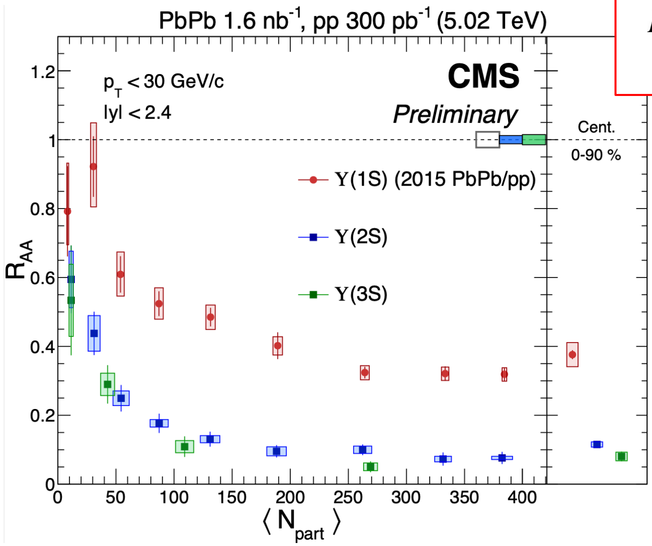
# Bottonium sequential suppression: Υ(1S), Υ(2S), Υ(3S)

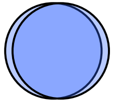
***Binding energy: ~1.1 ~0.5 ~0.2 GeV***

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$



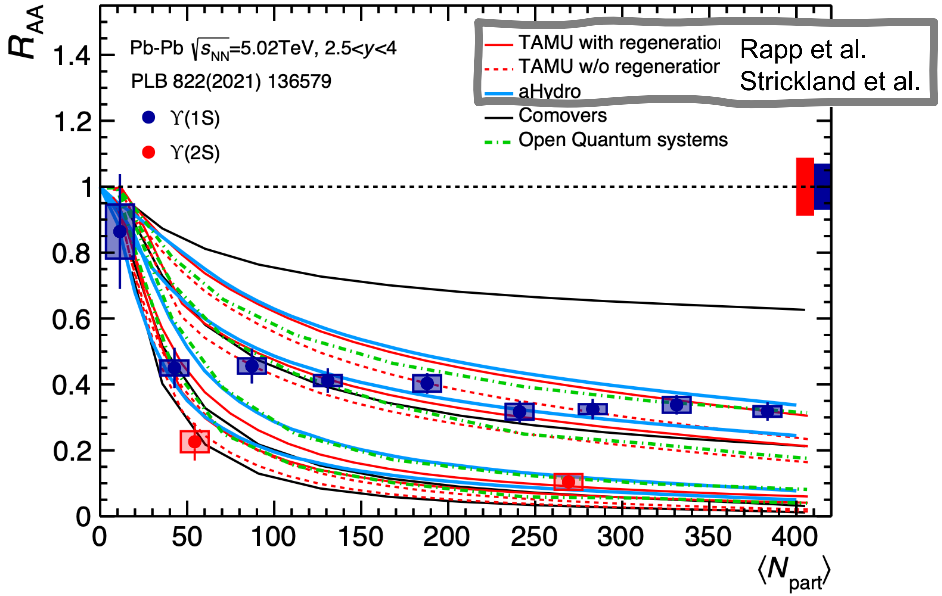


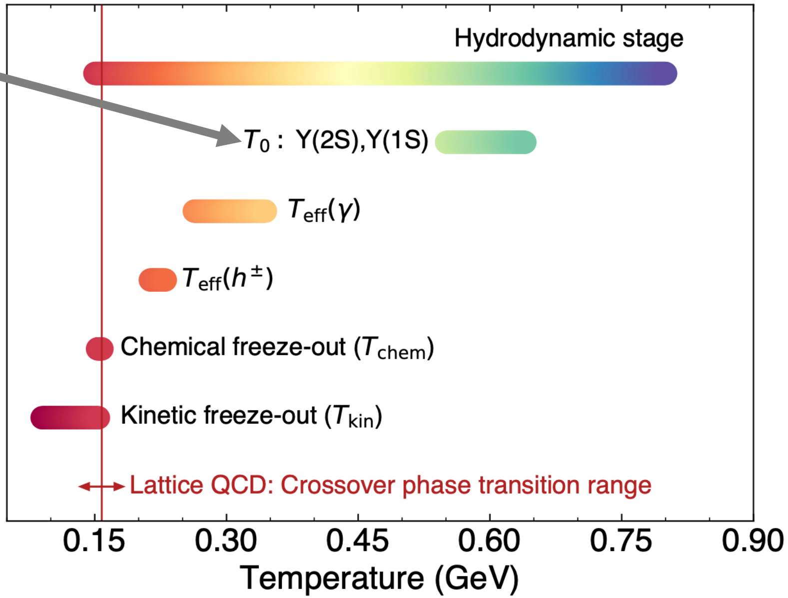



**CMS-HIN-21-07**

- Υ(2S) 4x more suppressed than Υ(1S); Υ(3S) 2x more suppressed than Υ(2S)
- **Consistent with sequential suppression, ordered with binding energy** (or radius of bound state)

# Towards QGP temperature from bottonium suppression?




ALICE, A journey through QCD, arXiv:2211.04384

- Two **model calculations**, that describe Y suppression at the LHC, implement colour screening in hydro medium with **initial $T_0$ ~ 550-650 MeV**

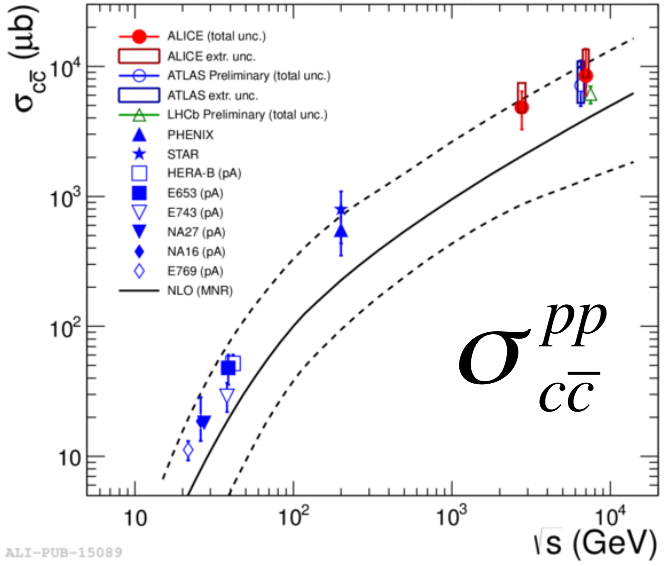
# Charmonium regeneration

- Uncorrelated c quarks from the medium could bind during QGP evolution and/or at hadronization (chemical freeze-out) and form charmonium
- At LHC, about 100 $c\bar{c}$ pairs in central collisions:

$$N_{c\bar{c}} = \frac{\sigma_{c\bar{c}}^{pp}}{\sigma_{inel}^{pp}} \cdot N_{coll} \sim \frac{\sigma_{c\bar{c}}^{pp}}{65\ \text{mb}} \cdot 1600$$

| In most central A-A collisions | SPS 20 GeV | RHIC 200 Gev | LHC 2.76 TeV |
|---|---|---|---|
| $N_{ccbar}$/event | ~0.1 | ~10 | ~100 |

P. Braun-Munzinger and J. Stachel, Phys. Lett. B490(2000) 196
R. Thews et al, Phys. ReV. C63 (2001) 054905

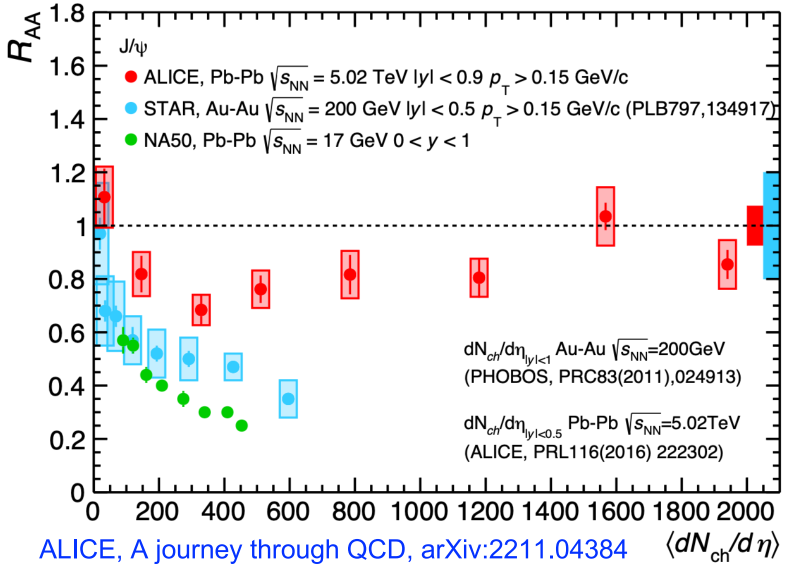



ALICE, JHEP1207 (2012) 191

To first approximation:

$$\frac{dN_{J/\psi}}{dy} \propto \left(\frac{dN_{c\bar{c}}}{dy}\right)^2$$

# J/ψ suppression + regeneration: SPS, RHIC, LHC

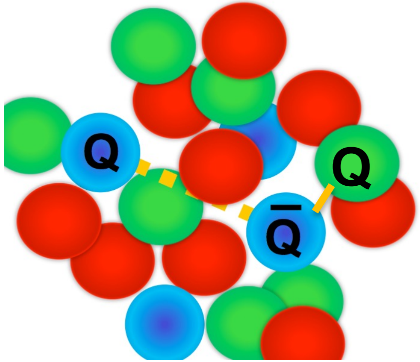


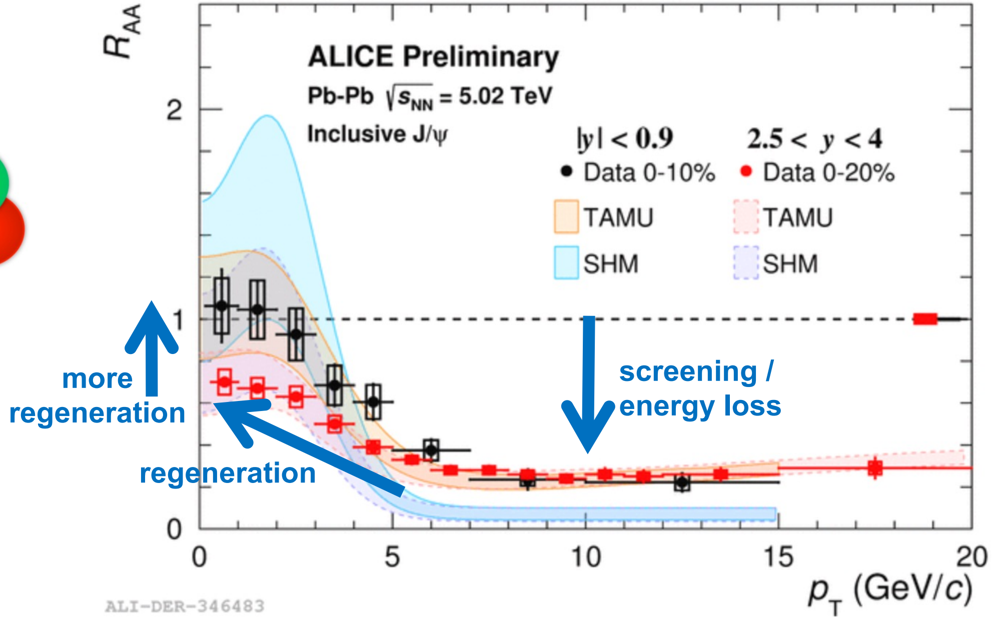

ALICE, A journey through QCD, arXiv:2211.04384

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$

- Suppression expected from increasing temperature is countered by the **rapid increase of regeneration**: $\left(\frac{dN_{c\bar{c}}}{dy}\right)^2$ increases by ~$10^6$ from SPS to LHC
- J/ψ $R_{AA}$ ~ 1 at mid-rapidity in central collisions at LHC

# J/ψ regeneration at LHC: $p_T$ and rapidity dependence

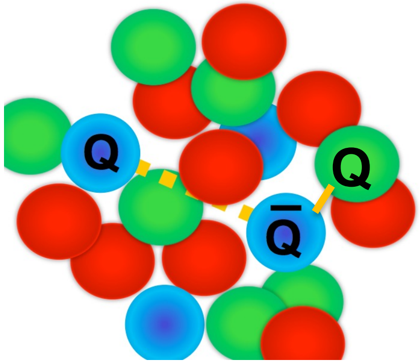


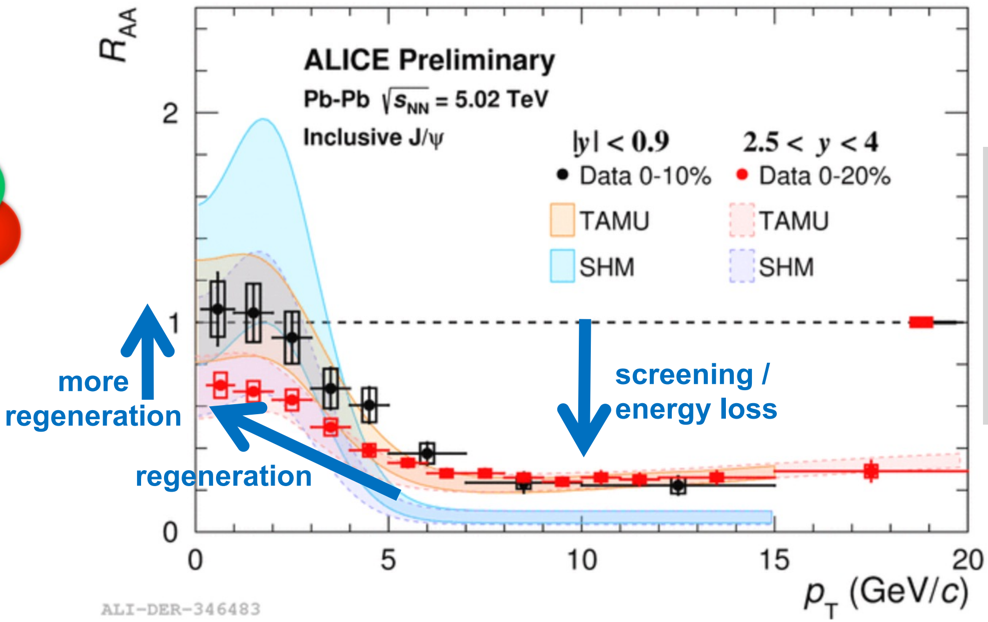




- J/ψ suppression reduced at low $p_T$
  - $c\bar{c}$ regeneration balancing the dissociation in the QGP

- At low $p_T$, modification decreases from forward to central rapidity
  - Reflects rapidity dependence of the $c\bar{c}$ cross section → regeneration probability

# J/ψ regeneration at LHC: $p_T$ and rapidity dependence





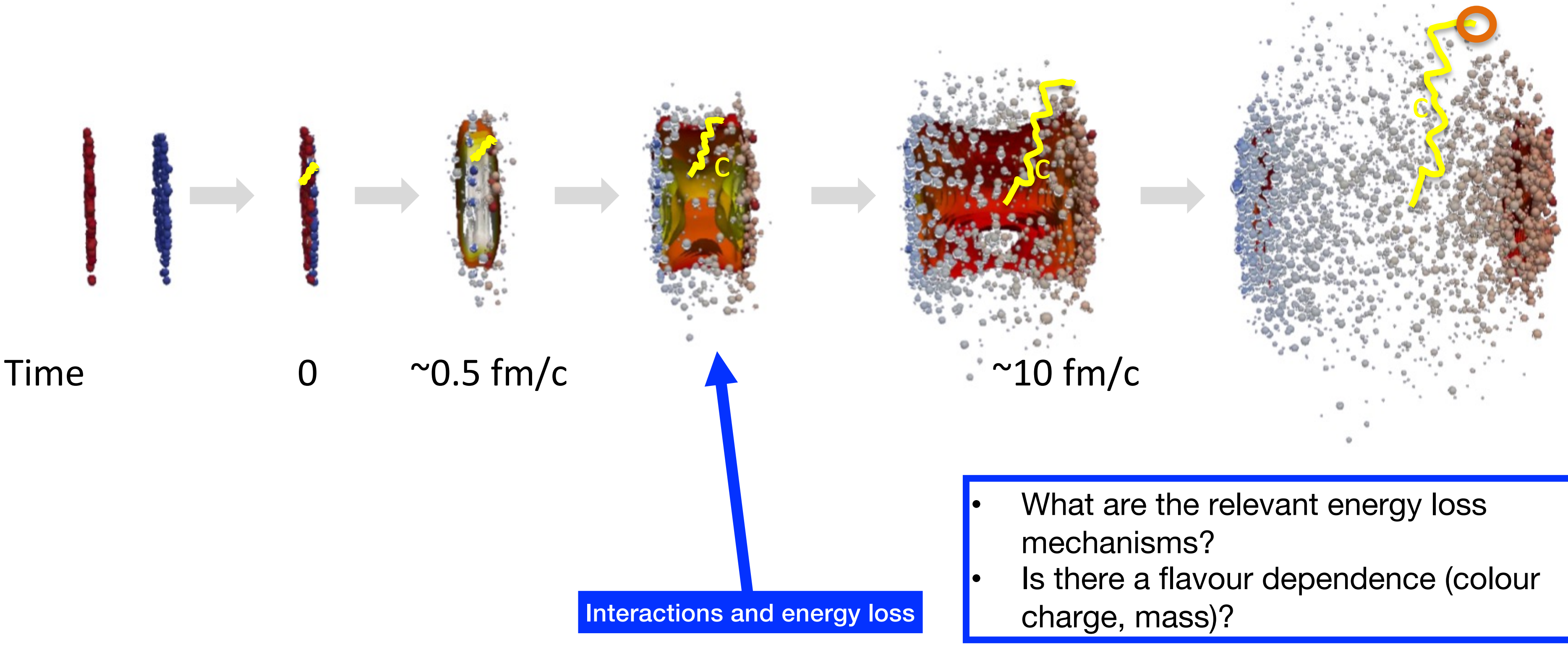

Large "theory" uncertainty mostly from $\sigma_{c\bar{c}}$

Crucial to measure this precisely in AA!

- J/ψ suppression reduced at low $p_T$
  - $c\bar{c}$ regeneration balancing the dissociation in the QGP

- At low $p_T$, modification decreases from forward to central rapidity
  - Reflects rapidity dependence of the $c\bar{c}$ cross section → regeneration probability

# Heavy quark interactions: energy loss



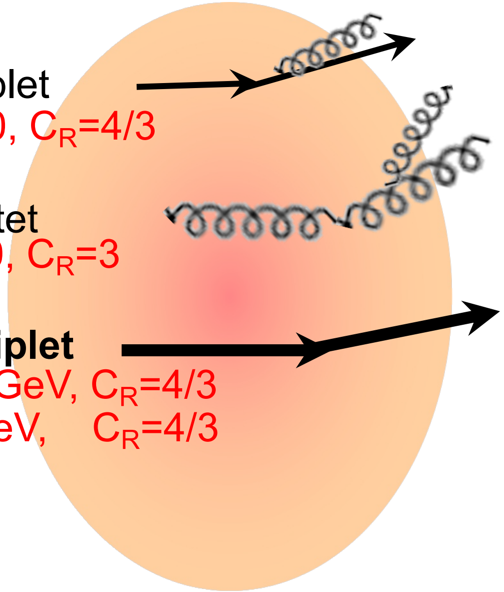

- What are the relevant energy loss mechanisms?
- Is there a flavour dependence (colour charge, mass)?

# The parton palette and the properties of QCD energy loss

q: colour triplet
**u,d,s:** m~0, $C_R$=4/3

g: colour octet
**g:** m=0, $C_R$=3

**Q: colour triplet**
**c:** m~1.5 GeV, $C_R$=4/3
**b:** m~5 GeV, $C_R$=4/3



**'QCD medium'**

***Parton Energy Loss*** by
- medium-induced gluon radiation
- collisions with medium gluons

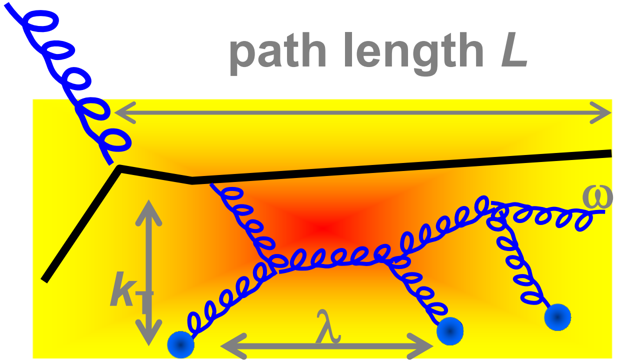
$$\Delta E(\varepsilon_{medium}; C_R, m, L)$$

*$C_R$*: colour charge dep.
*m*: mass dependence

➔ $\Delta E_g > \Delta E_{c \approx q} > \Delta E_b$

See e.g.:
Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.
Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

# Radiative energy loss: colour charge dependence




***Example: BDMPS-Z formalism***

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$ transport coefficient

Radiated-gluon energy distrib.:

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q}L^2}{\omega}}$$

$C_R$ = Casimir coupling factor: 4/3 for q, 3 for g

→ Colour charge dependence of radiative energy loss

$$\Delta E_g > \Delta E_{c \approx q}$$

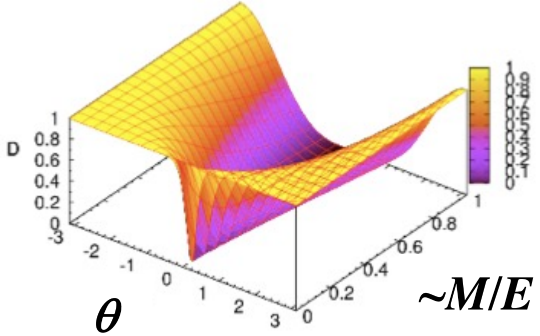
Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

# Radiative energy loss: mass dependence

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$
  → "dead cone" effect

Gluonsstrahlung probability

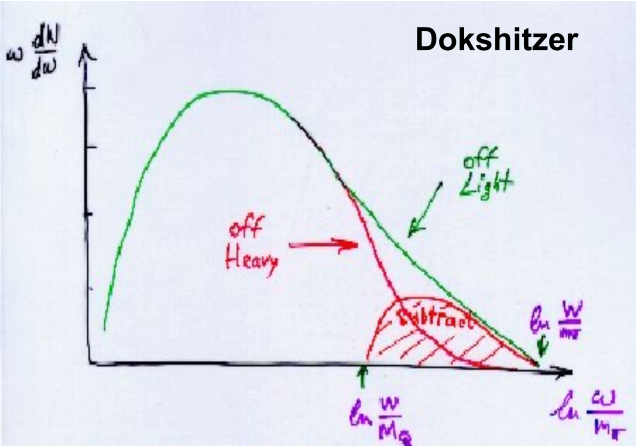
$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$




- ***Dead cone implies lower energy loss***:
  - energy distribution $\omega dI/d\omega$ of radiated gluons suppressed by angle-dependent factor
  - suppresses high-$\omega$ tail

$$\omega \frac{dI}{d\omega}\bigg|_{HEAVY} = \omega \frac{dI}{d\omega}\bigg|_{LIGHT} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

$$\Delta E_c > \Delta E_b$$




Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

# Mass dependence in collisional energy loss

## *Example: Langevin formalism*

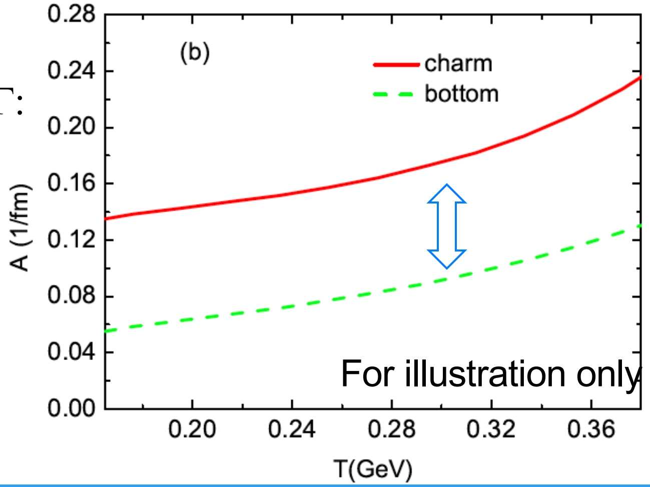
- Langevin equation gives momentum ($\mathbf{p}$) evolution vs. time ($t$) for a HQ with mass $m_Q$:

$$d\mathbf{p} = -\Gamma(p)\ \mathbf{p}\ dt + \sqrt{2D(\mathbf{p}+d\mathbf{p})\,dt}\ \rho$$

Loss term → energy loss    Gain term

- Both $\Gamma$ (drag) and $D$ (diffusion) ~ $1/m_Q$

Thermal relaxation rate A ~ $\Gamma$:




$$\Delta E_c > \Delta E_b$$

See e.g.: He, Rapp, Fries, PRC86 (2012) 014903

# From energy loss to $R_{AA}$

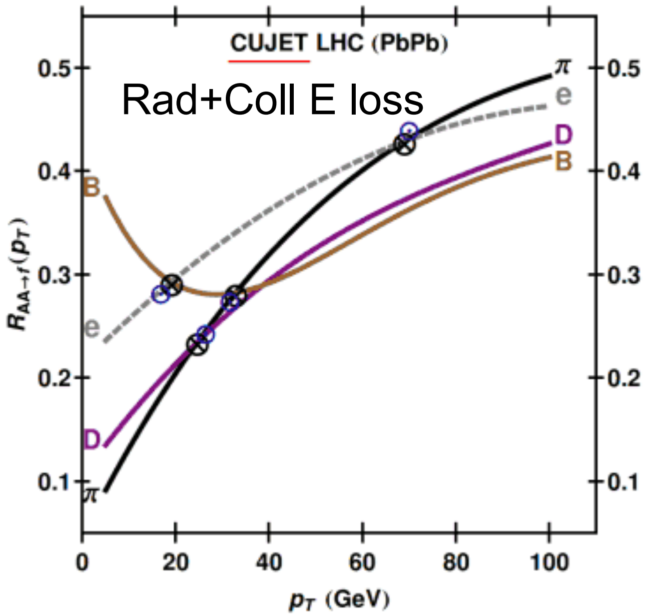
$$\Delta E_g > \Delta E_{c\approx q} > \Delta E_b$$

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

- What is the expected $R_{AA}$ pattern?
  - No trivial relation between ΔE and $R_{AA}$
  - Need to account for different steepness of partonic $p_T$ spectrum, different hadronization mechanisms, effects of radial flow (system collective expansion)

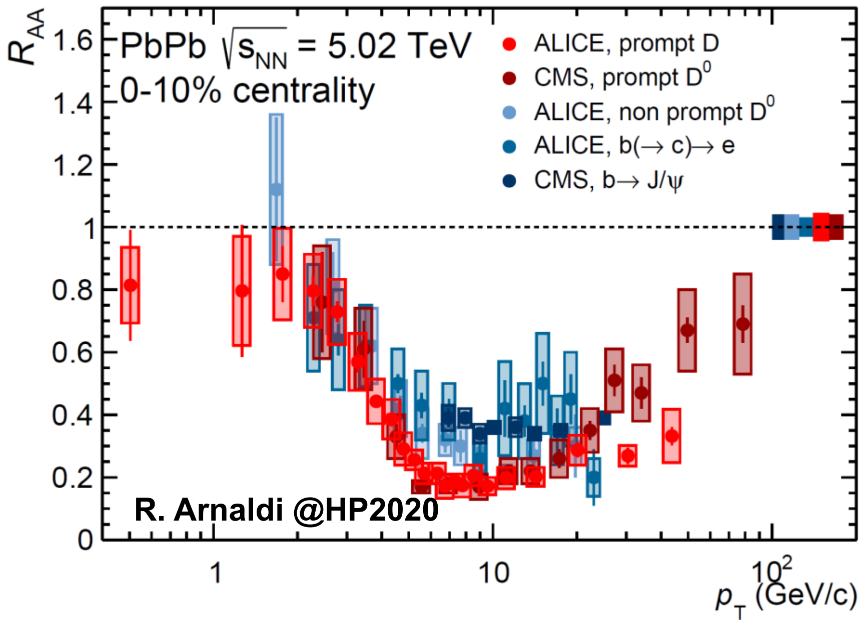
$R^D_{AA} < R^B_{AA}$ → **Clear prediction**

$R^\pi_{AA} \leq R^D_{AA}$ → **Difficult to observe**



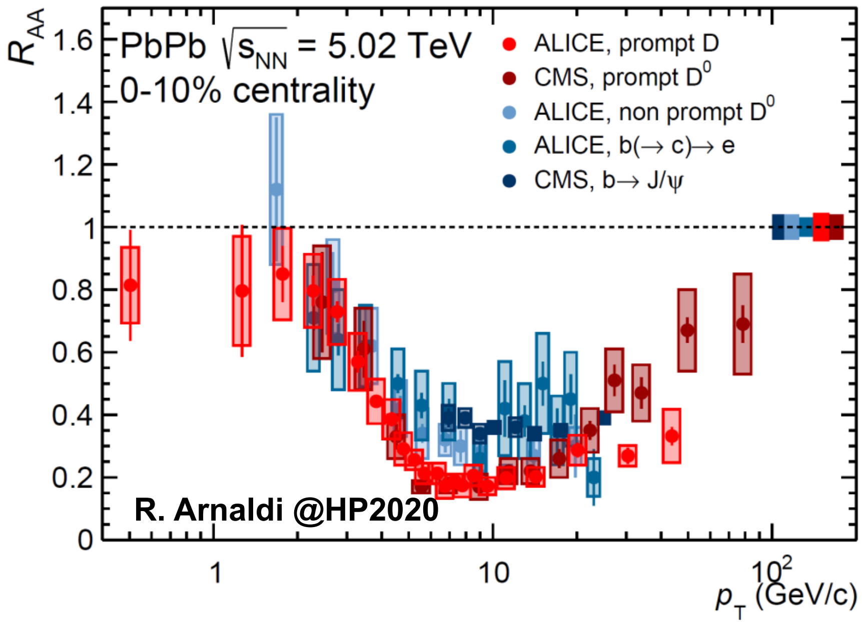

e.g.: A.Buzzatti et al., NPA904-905 (2013) 779c

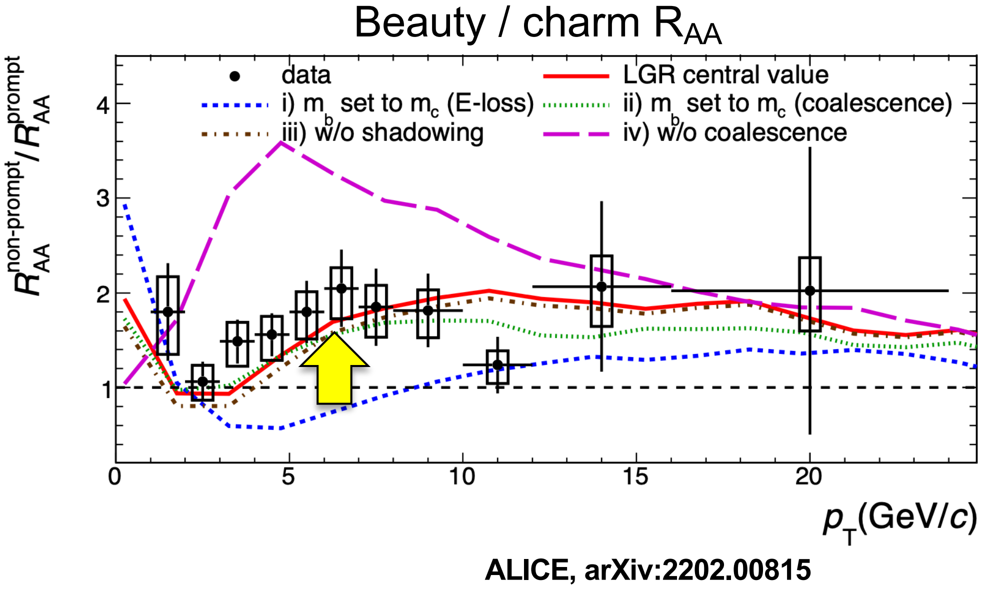
# Beauty vs charm $R_{AA}$




- Beauty $R_{AA}$ > Charm $R_{AA}$ at $p_T$ ~ 5-15 GeV/c

# Beauty vs charm $R_{AA}$



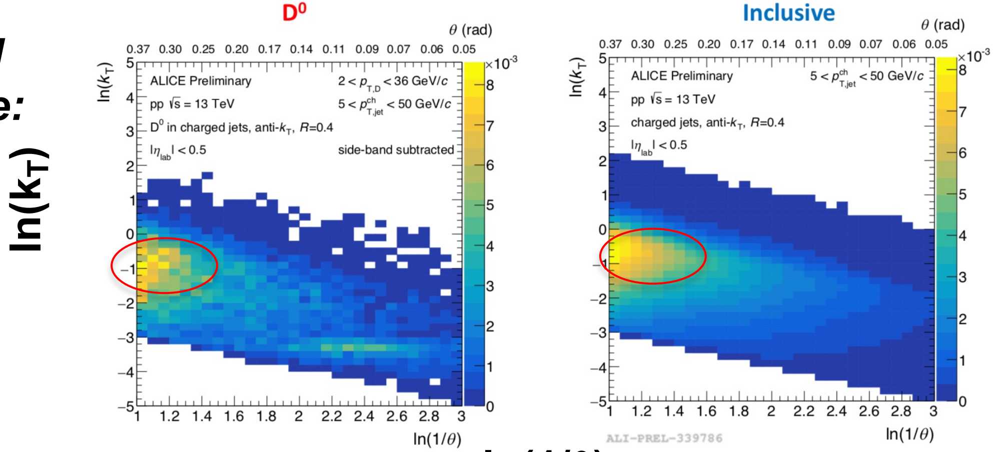




- Beauty $R_{AA}$ > Charm $R_{AA}$ at $p_T$ ~ 5-15 GeV/c
- Described by models with **smaller elastic coupling + dead cone for gluon radiation**

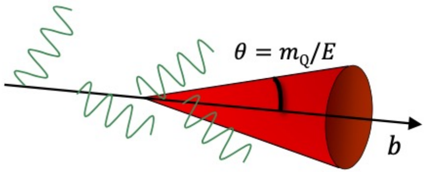
# Meanwhile: dead cone 'seen' in D-jets in pp

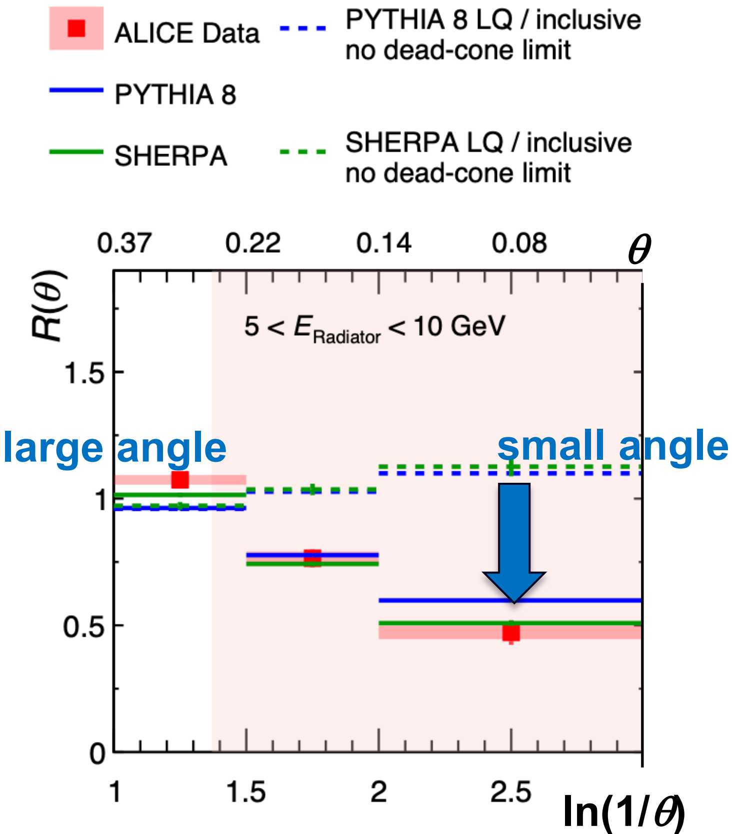
- First direct observation using jet iterative declustering and **Lund plane** analysis of jets that contain a soft $D^0$ meson

***Lund plane:***



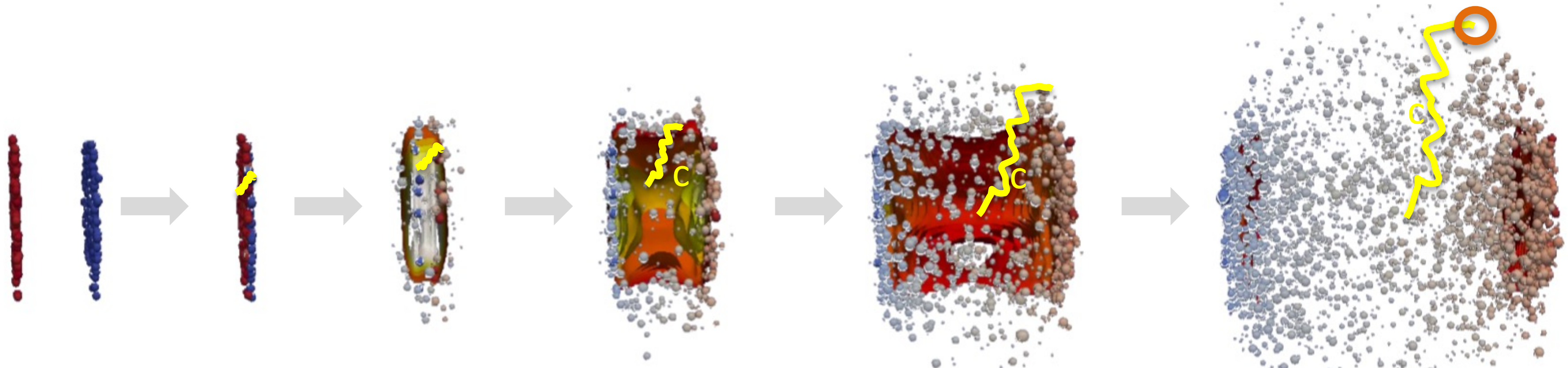

ln(1/θ)




ALICE, Nature 605 (2022) 7910, 440

# Heavy quark interactions: diffusion, thermalization?, hadronization




Time 0 ~0.5 fm/c ~10 fm/c

- Low-pT HQs could take part in QGP expansion:
  - Collisional E loss → Diffusion
- Could they thermalize in the QGP?
- This also affects the hadronization mechanisms

**Diffusion, Thermalization?**

**Hadronization**

# Mass dependence in collisional ~~energy loss~~ *interactions*

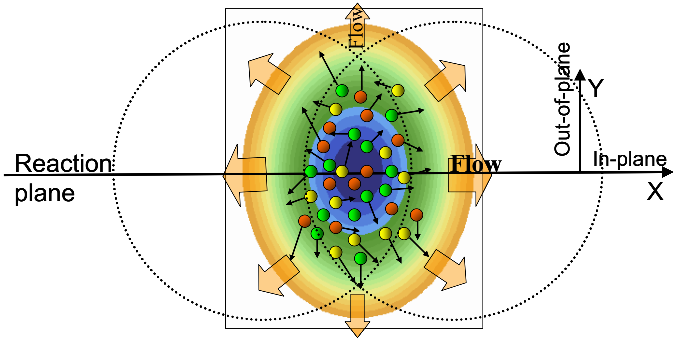
### ***Example: Langevin formalism***

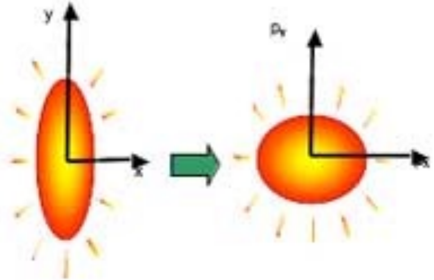
- Langevin equation gives momentum (**p**) evolution vs. time (*t*) for a HQ with mass $m_Q$:

$$d\mathbf{p} = -\Gamma(p)\ \mathbf{p}\ dt + \sqrt{2D(\mathbf{p}+d\mathbf{p})\,dt}\ \rho$$

Loss term → energy loss    Gain term

- If a low-*p* heavy quark is embedded in an expanding QGP, the gain term $d\mathbf{p}$ :
  - Increases significantly its momentum → radial flow (i.e. increase of $\langle p_T \rangle$)
  - Imparts azimuthal asymmetry → anisotropic flow ($v_2$, and higher harmonics)



# Heavy quark diffusion coefficient

## *Example: Langevin formalism*

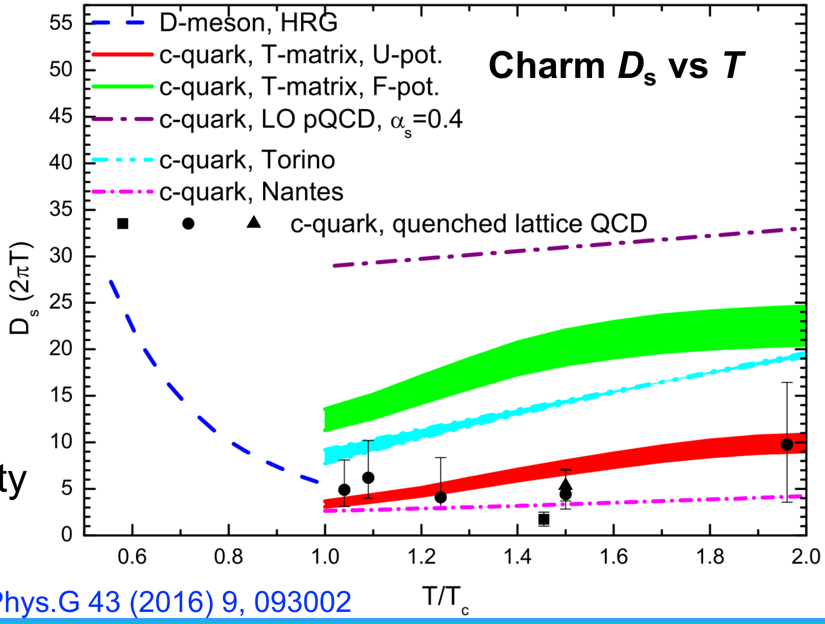
- Langevin equation gives momentum (**p**) evolution vs. time ($t$) for a HQ with mass $m_Q$:

$$d\mathbf{p} = -\Gamma(p)\,\mathbf{p}\,dt + \sqrt{2D(\mathbf{p}+d\mathbf{p})\,dt}\;\rho$$

- Diffusion coefficient $D$: one of the characterizing properties of the QGP
- Spatial diffusion coefficient: $D_S \propto \dfrac{T}{m_Q\Gamma} \sim T$
  - ~ same for charm and beauty
  - Hard scale ($m_Q$) enables calculations on the lattice
- Heavy quark thermalization time:

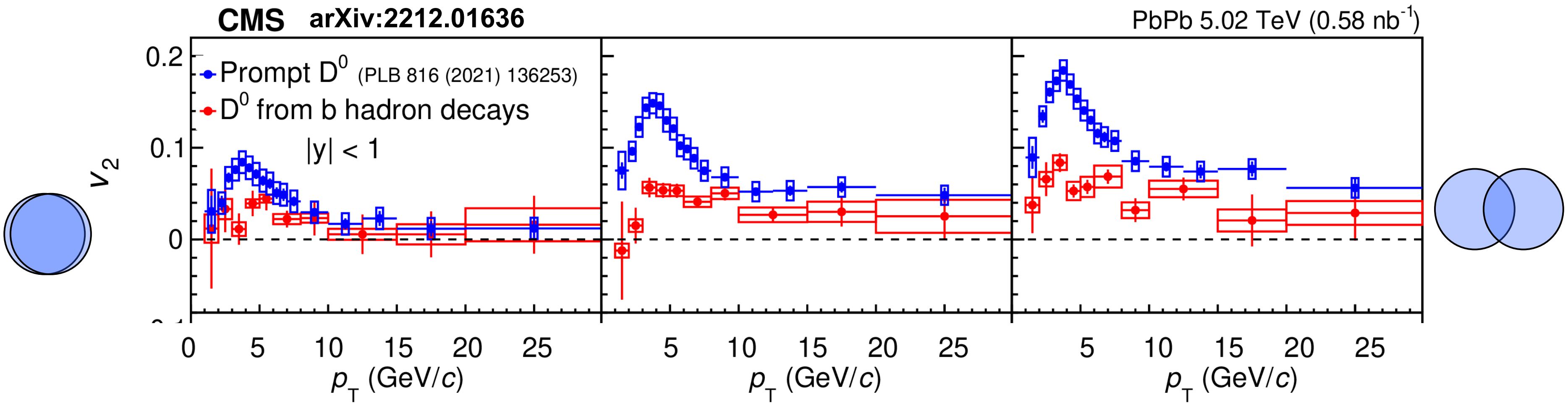
$$\tau_Q = (m_Q/T)D_s$$

  - Charm expected to thermalize x 3-4 faster than Beauty




Prino, Rapp, J.Phys.G 43 (2016) 9, 093002

# Open charm and open beauty elliptic flow

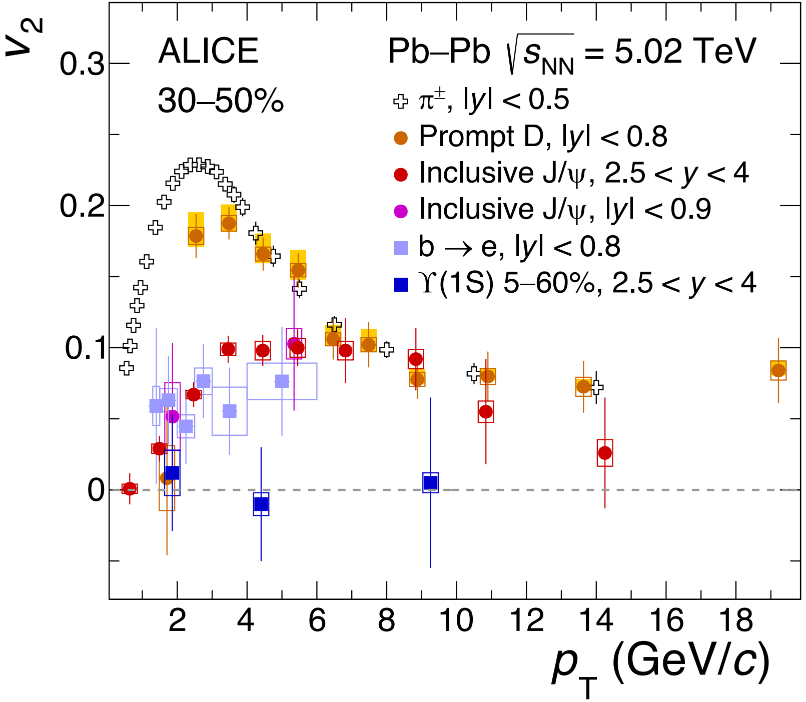



- Prompt D mesons (charm) have large $v_2$ at LHC (and RHIC)
- Non-prompt D mesons (beauty) have $v_2$>0
- Low $p_T$: indication of 0 < beauty $v_2$ < charm $v_2$
  - → Smaller thermalization for beauty?
- High $p_T$: 0 < beauty $v_2$ ~ charm $v_2$
  - → $v_2$ from path-length dependence of energy loss?

# Open and hidden HF $v_2$

- **J/ψ** have clear $v_2 > 0$
  - ➢ confirms formation by regeneration from flowing c and $\bar{c}$ quarks
- No indication of **Y(1S)** flow
  - ➢ consistent with large Y mass and small $b\bar{b}$ regeneration probability
- At intermediate $p_T$, **J/ψ < D < pions**

→ What is the role of the hadronization mechanism?




π: JHEP1809(2018)006
D: arXiv:2005.11131
J/ψ: arXiv:2005.14518
b→e: arXiv:2005.11130
Y(1S): PRL123(2019)192301

# HQ hadronization in heavy-ion collisions ?

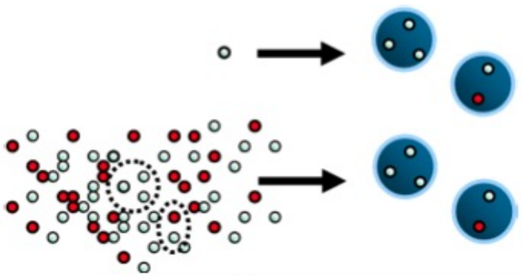
- Even in high-energy pp collisions HQ hadronization differs from e+e⁻-like fragmentation
- High parton density in QGP favours hadronization by recombination (or coalescence) of quarks

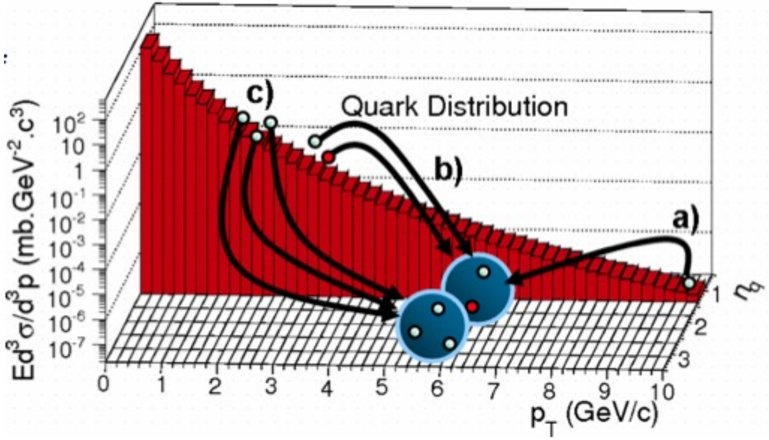
$$\vec{p}_{hadron} = \sum \vec{p}_{quark}$$

- Recombination dominant at low *p* for light quarks
- It affects the momentum distributions, enhances the baryon/meson ratios at intermediate $p_T$, and the azimuthal anisotropy of hadrons

$$v_{n,hadron} = \sum v_{n,quark}$$

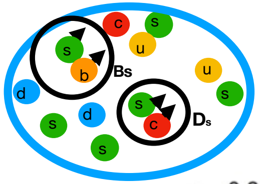
**What about HQs in HI?**



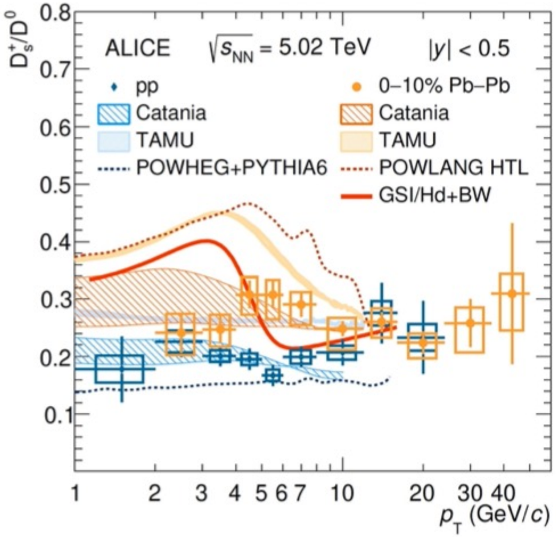


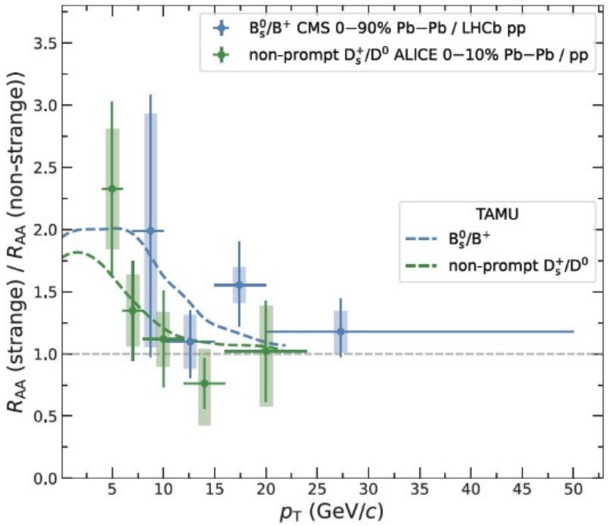

a) 6 GeV/c pion from 1x 10 GeV/c quark fragmentation
b) 6 GeV/c pion from 2x 3 GeV/c quark recombination
c) 6 GeV/c proton from 3x 2 GeV/c quark recombination

# Strange-HF mesons




Expected to be enhanced, because QGP is strangeness-rich



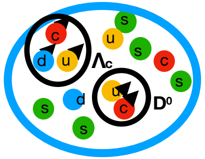

$D_s/D^0$ larger in central Pb-Pb w.r.t pp measurements

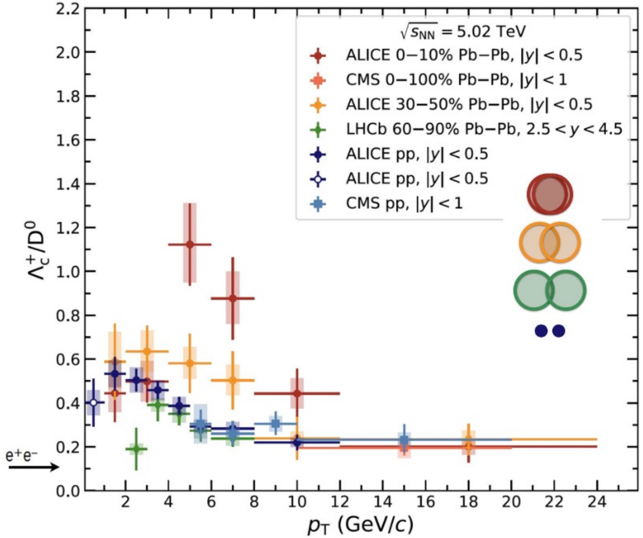
**ALICE, arXiv:2110.10006**

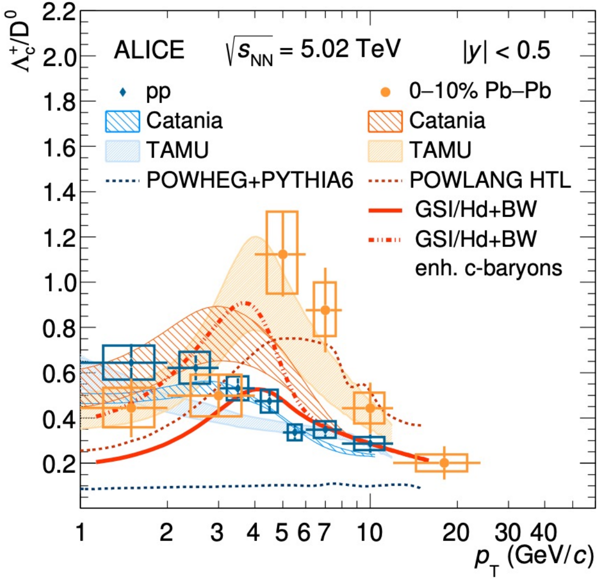
Hint of $R_{AA}(B_s) > R_{AA}(B)$

**CMS, arxiv:1810.03022**
**ALICE, arXiv:2204.10386**

# Charm baryon-to-meson ratio




**ALICE pp arxiv:2011.06079**
**ALICE Pb-Pb arXiv:2112.08156**
**CMS, arXiv:1906.03322**
**LHCb, arXiv:2210.06939**

$\Lambda_c/D^0$ larger in central and semi-central Pb-Pb than in pp at intermediate $p_T$

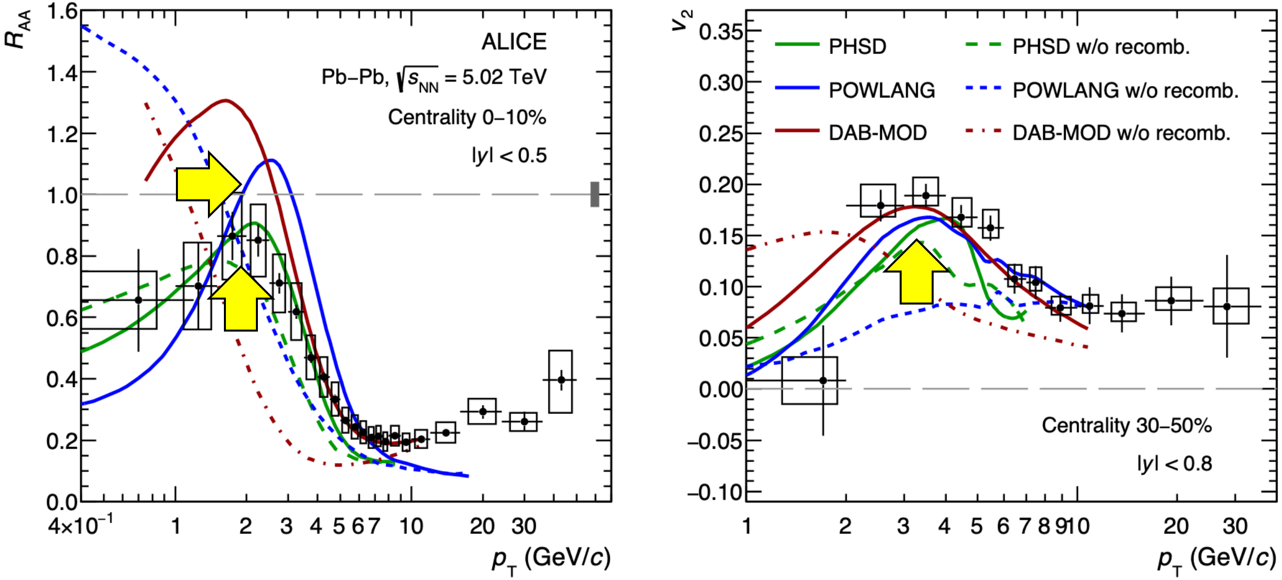
**Described by models with different implementations of quark recombination**

RHIC energy: $\Lambda_c/D^0$ ~1 in Au-Au at low $p_T$ (3-6 GeV/c), but no pp measurement

**STAR, arXiv:1910.1462**

# HF hadronization ⟷ HF diffusion

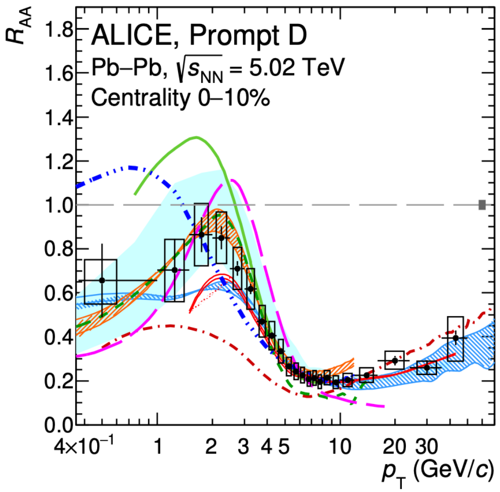
- Understanding HF hadronization in a high-density partonic environment
  → fundamental, and one of the handles on the emergence of collectivity in QCD
  → instrumental to measuring the QGP diffusion coefficient with HF flow

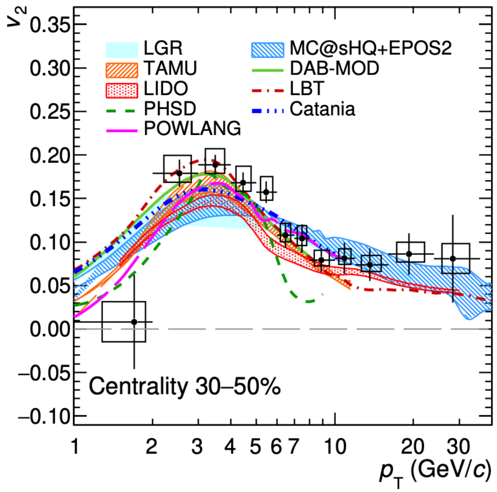


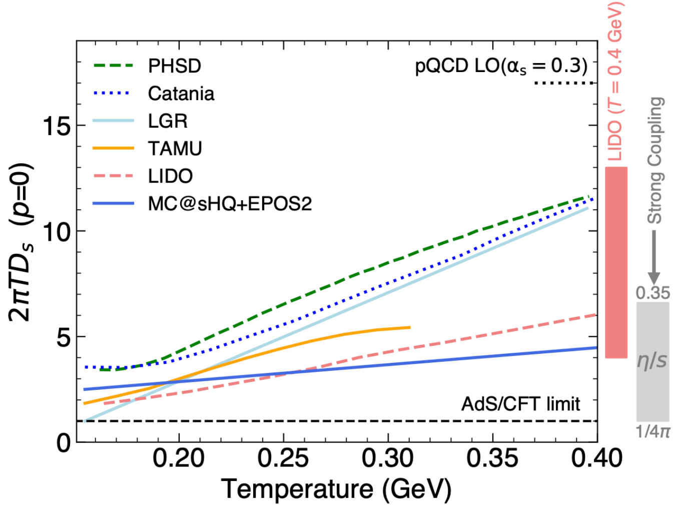

**D-meson $R_{AA}$ and $v_2$ only described when including recombination**

**ALICE, arXiv:2110.09420**

# Charm diffusion coefficient from "LHC data"



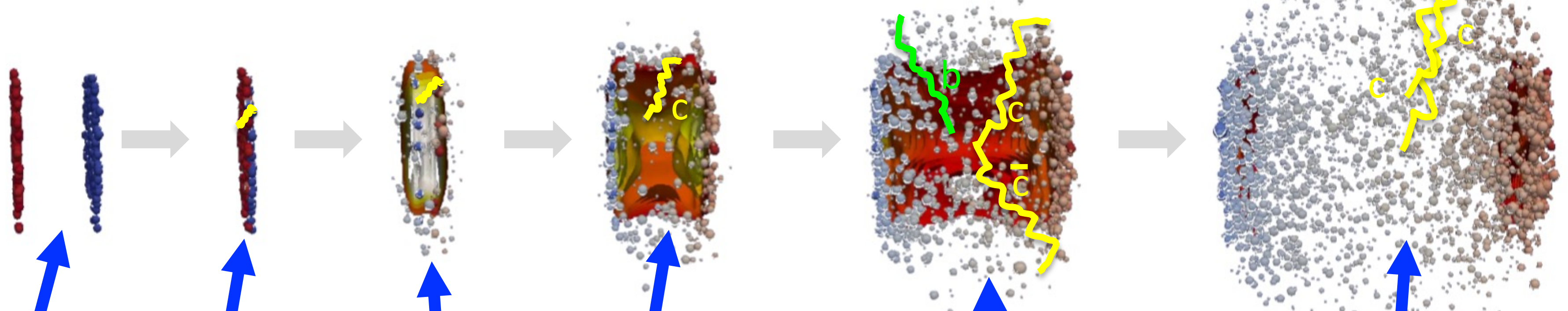




ALICE, A journey through QCD, arXiv:2211.04384

- Estimates of $D_s$ vs $T$ using the inputs of models that describe the LHC data
  - E.g. latest ALICE estimate: $1.5 < 2\pi D_s(T)T < 4.5$ at $T_c$ ⟶ $\tau_{charm} = 3\text{–}9$ fm/c
- Next steps: $D_s$ and other parameters from global Bayesian analyses of light and heavy flavour observables

# Outlook: (some) future goals and challenges




**Initial stage**

Initial gluons vs. final-state effects in p-Pb

**Sensitivity to magnetic field**

Precise D $v_1$ to constrain B-field

**Sensitivity to deconfinement and temperature**

Interplay of melting and regeneration vs. binding energy → access to modified QCD potential in QGP

**Interactions and energy loss**

Mass effects in QCD-induced radiation: dead cone and substructure with D/B-tagged jets

**Diffusion, Thermalization?**

Collisional interaction regime via angular (de)correlation of soft D-Dbar pairs

QGP diffusion coefficient with b quarks: larger mass → further from thermalization

**Hadronization**

Precise measurements of charm and beauty baryons in AA (including charm-strange baryons), across systems / multiplicity

Multi-HF hadrons as ultimate probe ("pure recombination" particles)

# Outlook: (some) future goals and challenges


**Comprehensive theory frameworks**
**→ global analyses (Bayesian, ML, …)**

**Initial stage**
Initial gluons vs. final-state effects in p-Pb

**Sensitivity to magnetic field**
Precise D $v_1$ to constrain B-field

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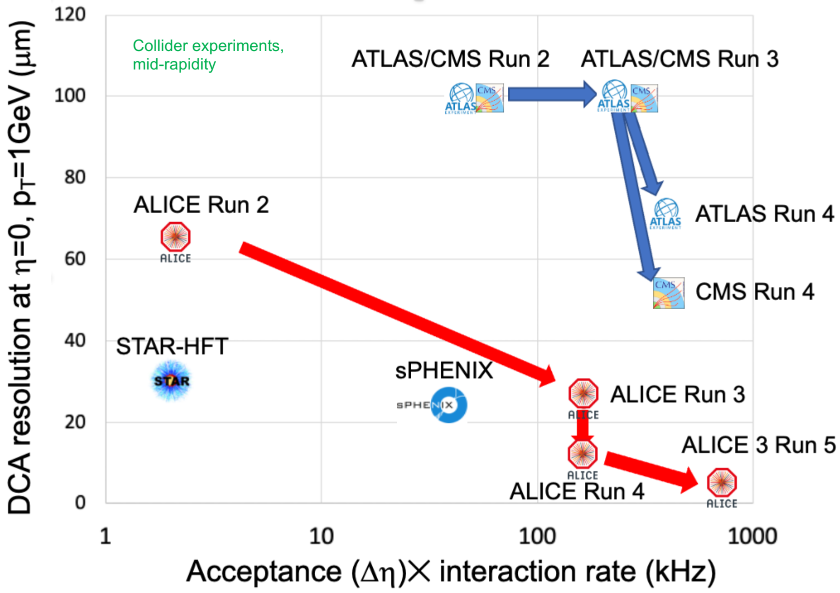
Precise measurements of charm and beauty baryons in AA (including charm-strange baryons), across systems / multiplicity

Multi-HF hadrons as ultimate probe ("pure recombination" particles)

# Outlook: experiment → faster and "sharper"

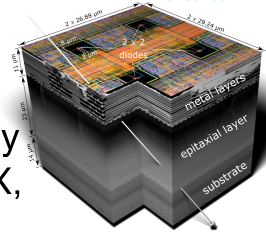
- Main frontiers to enhance HF physics reach:
  - **rate capabilities & acceptance**
  - **tracking precision**

→ high precision, reduce backgrounds, access to rarer processes




- x10-100 in "statistics" at RHIC and LHC
  - Increased interaction rate at both machines
  - Faster readout and larger acceptance
- Monolithic pixel trackers bring DCA resolution to 20-30 μm at $p_T$=1 GeV/c
  - Pioneered by STAR; key development by ALICE, will be adopted also by sPHENIX, CBM, NA61, NA60+

Monolithic Active Pixel Sensor



Thanks for your attention!
Questions?

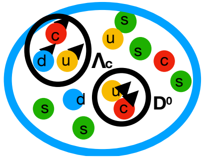
Have an interesting and productive
Hard Probes 2023!

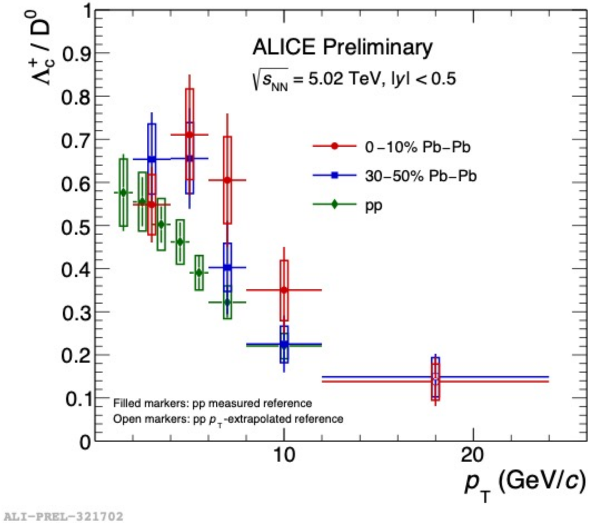
# Don't miss these plenary talks!

| Day | Talk | Speaker | Location | Time |
|---|---|---|---|---|
| Monday PM | **Open heavy flavors: Theory** | *Santosh Kumar Das* | *Cranach-Saal, Stadthalle* | 15:15 - 15:40 |
| | **Open heavy flavors: Experiment** | *Zaida Conesa del Valle* | *Cranach-Saal, Stadthalle* | 15:40 - 16:05 |
| Thursday AM | **Quarkonia: Theory** | *Miguel Angel Escobedo Espinosa* | *Cranach-Saal, Stadthalle* | 11:10 - 11:35 |
| | **Quarkonia: Experiment** | *Krista Smith* | *Cranach-Saal, Stadthalle* | 11:35 - 12:00 |
| | **Nuclear PDFs: new results from global fits** | *Tomas Jezo* | *Cranach-Saal, Stadthalle* | 12:00 - 12:25 |
| Thursday PM | **Hadronization mechanism (via heavy-flavor hadrons): Experiment** | *Andrea Rossi* | *Cranach-Saal, Stadthalle* | 14:25 - 14:45 |
| | **Hadronization mechanism (via heavy-flavor hadrons): Theory** | *Andrea Beraudo* | *Cranach-Saal, Stadthalle* | 14:45 - 15:05 |
| Friday AM | **Highlights, open questions and perspectives: Heavy flavors and quarkonia** | *Andrea Dubla* | *Cranach-Saal, Stadthalle* | 11:15 - 11:40 |

# EXTRA SLIDES

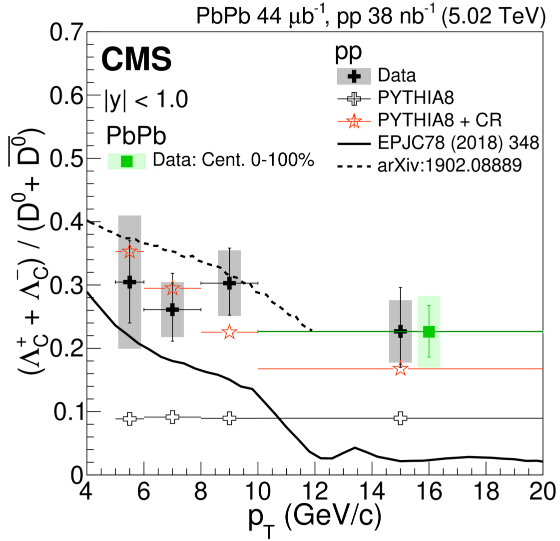
# Charm baryons vs mesons



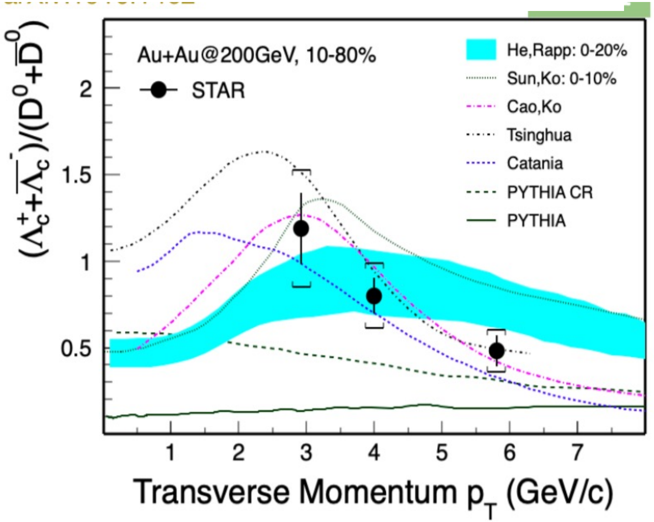

ALICE: hint of larger $\Lambda_c/D^0$ in Pb-Pb w.r.t. to pp for 4 <$p_T$< 6 GeV/c

arXiv:1906.03322



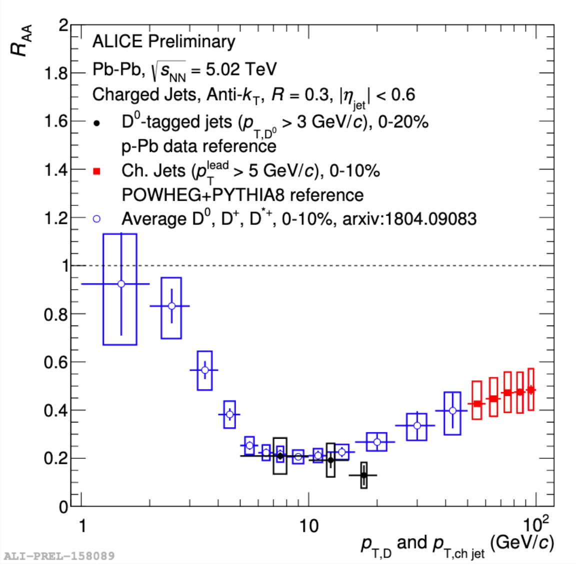

CMS: similar $\Lambda_c/D^0$ in Pb-Pb and pp at high $p_T$

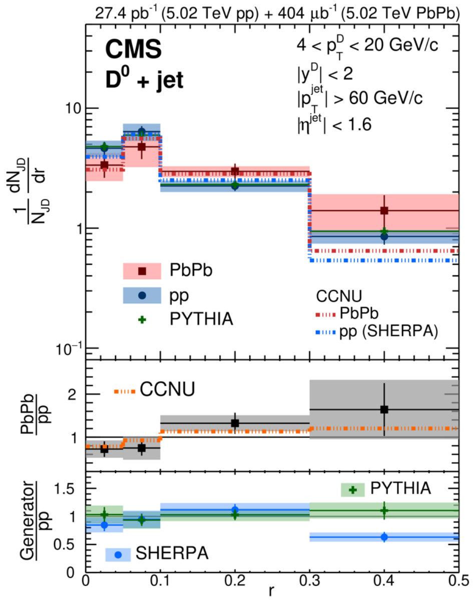
arXiv:1910.1462



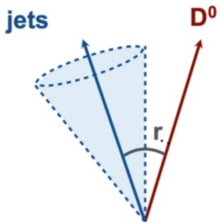

STAR shows higher value for $\Lambda_c/D^0$ ~1 in Au-Au at low $p_T$ (3-6 GeV/c), but no pp comparison

# D-jets also studied in Pb-Pb




arXiv:1911.01461

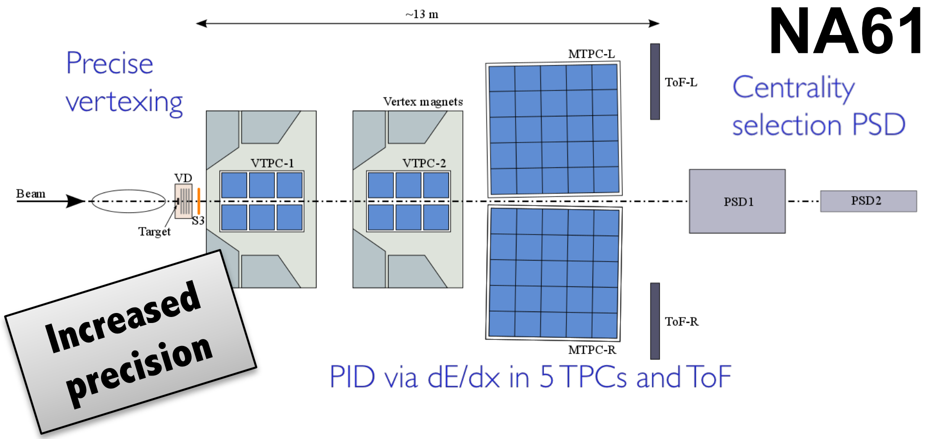


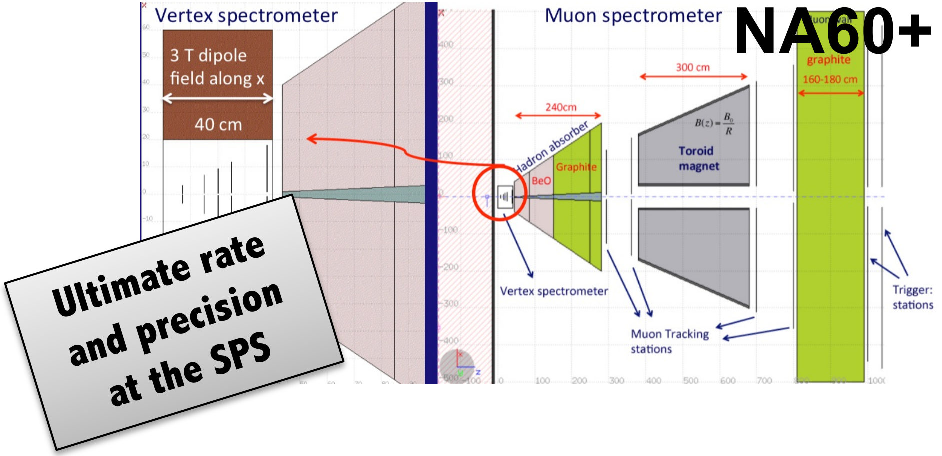

- **D-meson tagged jets *R*AA** consistent with **D-meson *R*AA**
- Hint of larger suppression for **low *p*T D-jets** than **high *p*T charged jets**

- Broader radial distribution of D meson with respect to the jet axis in Pb-Pb?

# Experimental outlook

# NA61/SHINE (2022), NA60+ (>2029?) @ SPS

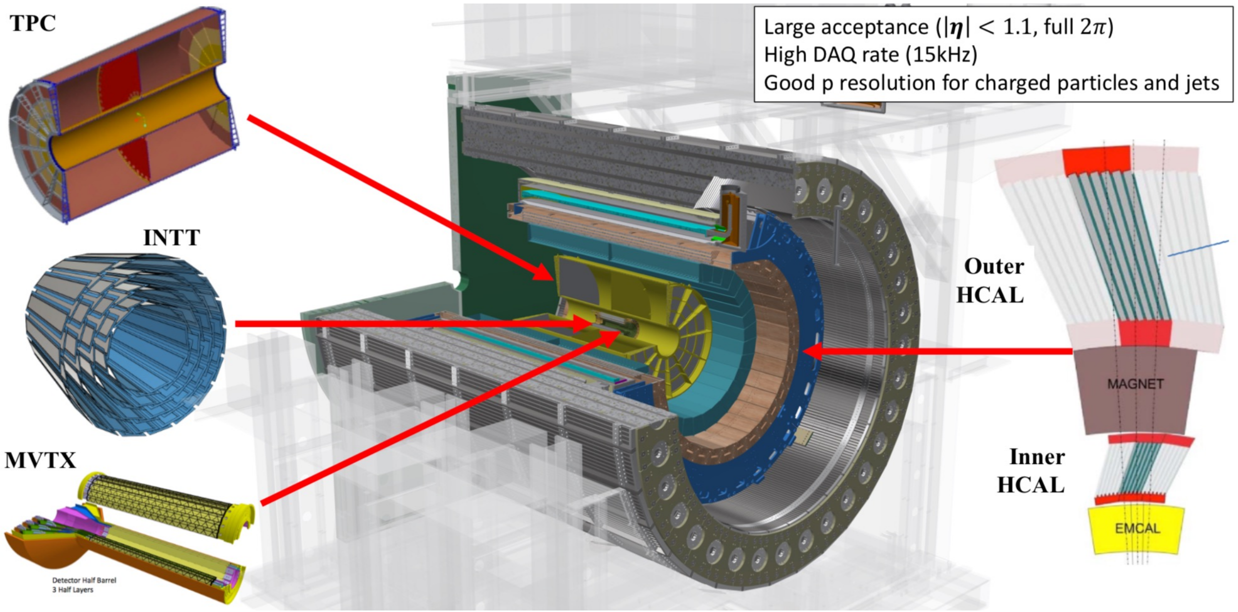



- Ongoing upgrade: pixel tracker, TPC readout at 1 kHz
- Pb-Pb at $\sqrt{s_{NN}}$ = 5 and 17 GeV in 2022-24
- Main goals: **open charm cross section with ~10% precision**, critical fluctuations with higher precision

- Proposal for a high-rate dimuon spectrometer with a silicon pixel tracker
  - EoI submitted to SPSC, LoI in prep.
- 10 MHz Pb-Pb at $\sqrt{s_{NN}}$ = 5-17 GeV
- Main goals: caloric curve with thermal dimuons, characterize $\chi$-symmetry restoration, **charmonia and open charm (~1% precision)**

# sPHENIX @ RHIC (2023)



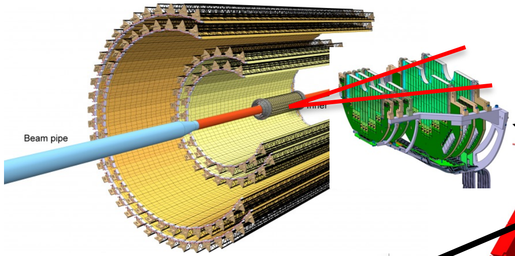

**Ultimate performance for jets and HQs at RHIC**

- Compact and hermetic design
- Continuous readout at 15 kHz
  - ~100B Au-Au events per year

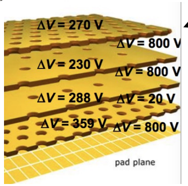
- Focus on:
  - Fully reconstructed jets, with HCAL
  - Bottomonium states
  - HF mesons and baryons, with MAPS

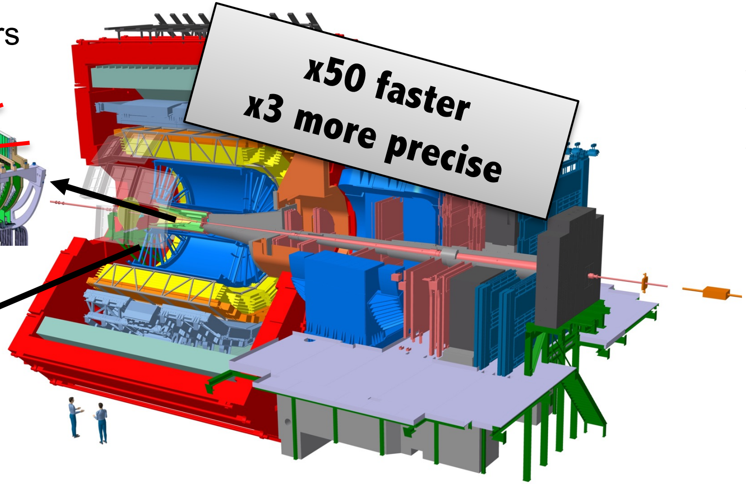
# ALICE in Run 3 (2022) and ideas for Run 4 (2029)

All-pixel central and fwd trackers




GEM-based TPC readout



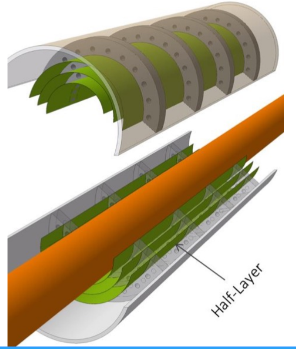

… and more:

- Fast Interaction Trigger
- New Online-Offline system
- Readout upgrade of several detectors

- ◆ x3 better tracking precision
- ◆ Continuous readout at 50 kHz

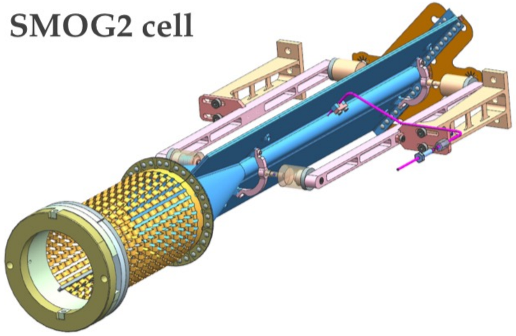
→ ~100B Pb-Pb in Runs 3+4

- ◆ Upgrade proposal for LS3 (2026): replace **inner barrel** with a **truly-cylindrical ultralight** one: x3 less material
  - ➢ e.g. improves by a factor 4 the precision for the $\Lambda_c$
  - ➢ More HF studies ongoing: $\Lambda_b$, $B_s$, search for “super-nuclei”

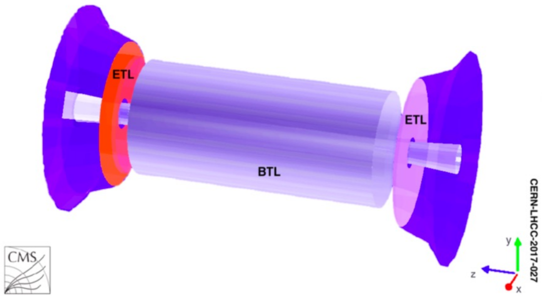


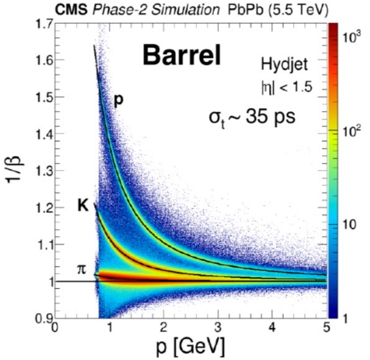
# LHCb (2022), ATLAS and CMS (2029) Upgrades

- LHCb: LS2 upgrade:
  - Tracker with higher granularity
    → **Pb-Pb 30-100%**
  - New **storage cell for fixed-target collisions** at up to x100 higher rates (p … Ne … Xe)

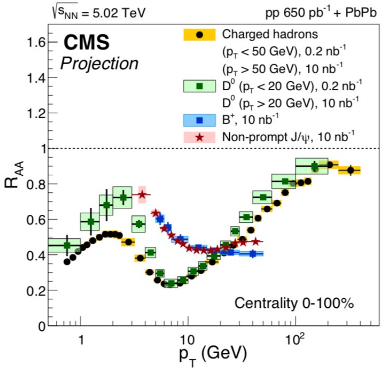


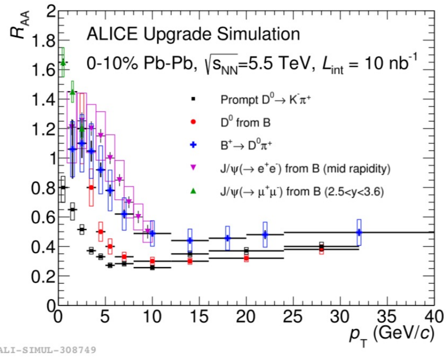

- ATLAS and CMS: major Phase-2 upgrades for HL-LHC
  - Extension of tracker acceptance to $|\eta|<4$
  - Precise timing detectors for pile-up rejection → t.o.f. PID
    - ATLAS $2.5 < |\eta| < 5$
    - CMS $|\eta| < 4$

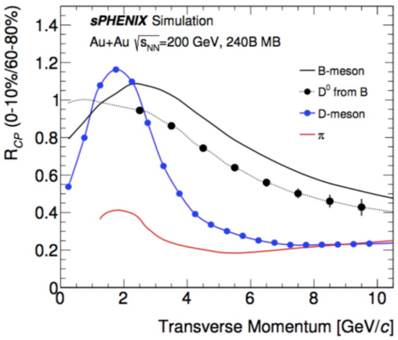


# HF performance outlook: energy loss and transport



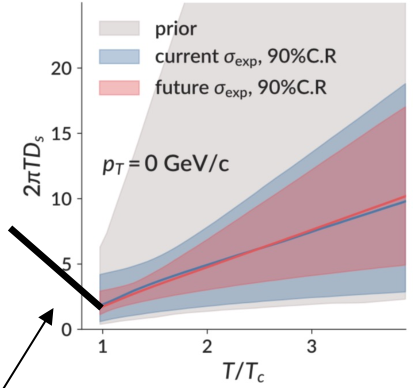




D and B at LHC and RHIC

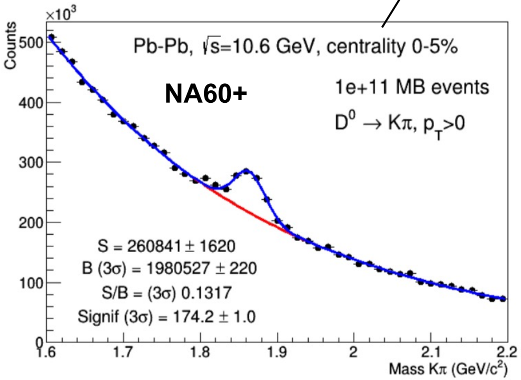
→ **Heavy quark diffusion coefficients** $2\pi TD_S(T)$

- e.g. Bayesian analysis with modified Langevin (Bass et al.)

$2\pi TD_S$ in hadronic matter ($T<T_c$) with NA60+ at SPS?

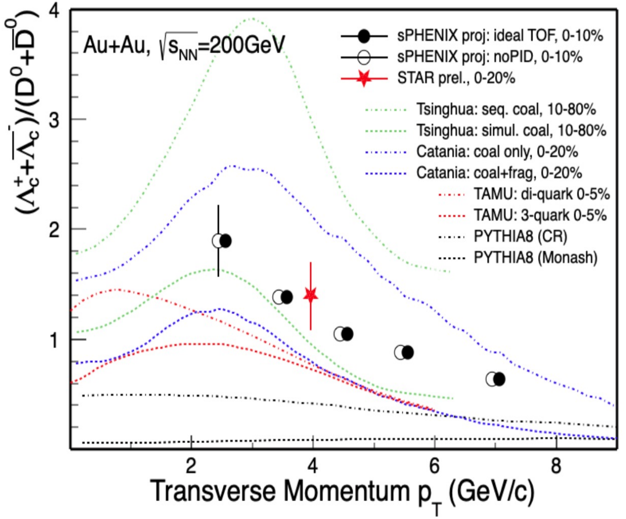



arXiv:1812.06772

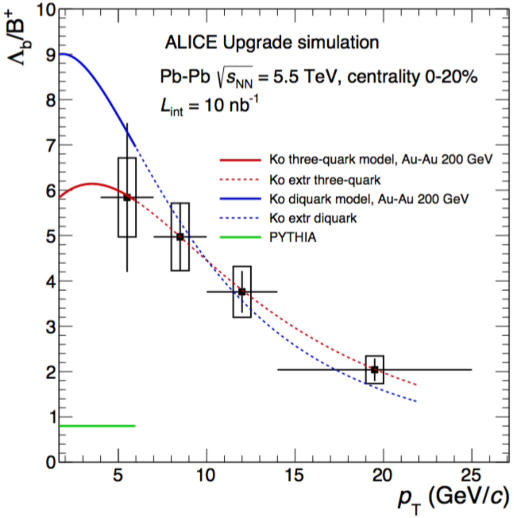


# HF performance outlook: hadronisation of HQs

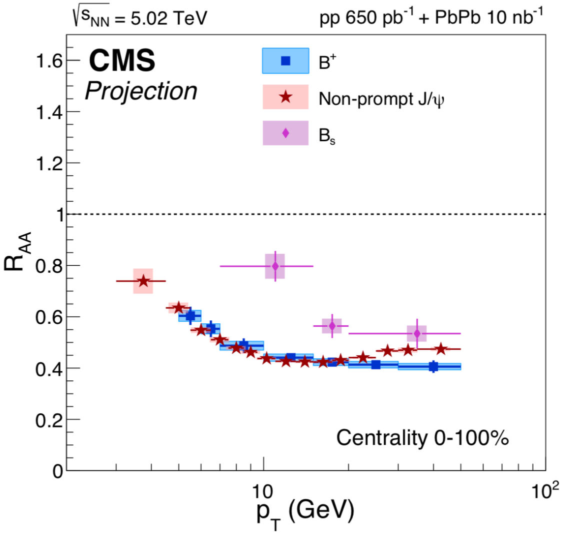
**sPHENIX $\Lambda_c$ / D**




**ALICE $\Lambda_b$ / B**




**CMS B and $B_s$**




Some examples, many more studies available and ongoing

# Next-generation HI detector for LHC Runs 5-6

- Fast, ultra-thin detector with precise tracking and timing
  - Exploit full AA lumi
  - Ultimate performance for (multi-)HF, thermal radiation and soft hadrons (<50 MeV)

- All-pixel tracking and PID detector $|\eta|<4$
- Timing layers $\sigma$~20 ps for t.o.f. ID of hadrons and low-*p* electrons
- RICH, Muon ID, ECal
- Insertable converter layer for photon detection
- Innermost layers inside the beam pipe

arXiv:2211.02491