Heavy-ion collision experiment (Lecture 3)

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1. Introduction for relativistic heavy-ion collisions
2. Particle yields and statistical model
3. Hard probes of QGP: jets
4. Hard probes of QGP: heavy-flavors
5. Quarkonia
6. Highlights from small systems
7. Summary and outlook

4. Hard probes of QGP: heavy-flavors

Heavy Quarks: charm and beauty

Charm (m ~ 1.3 GeV/c^2)) and Beauty (m ~ 4.7 GeV/c^2)

- produced in **initial hard parton scatterings**

  τ_b(~ 0.02) < τ_c(~0.07) < τ_{QGP}(~0.1-1) fm/c

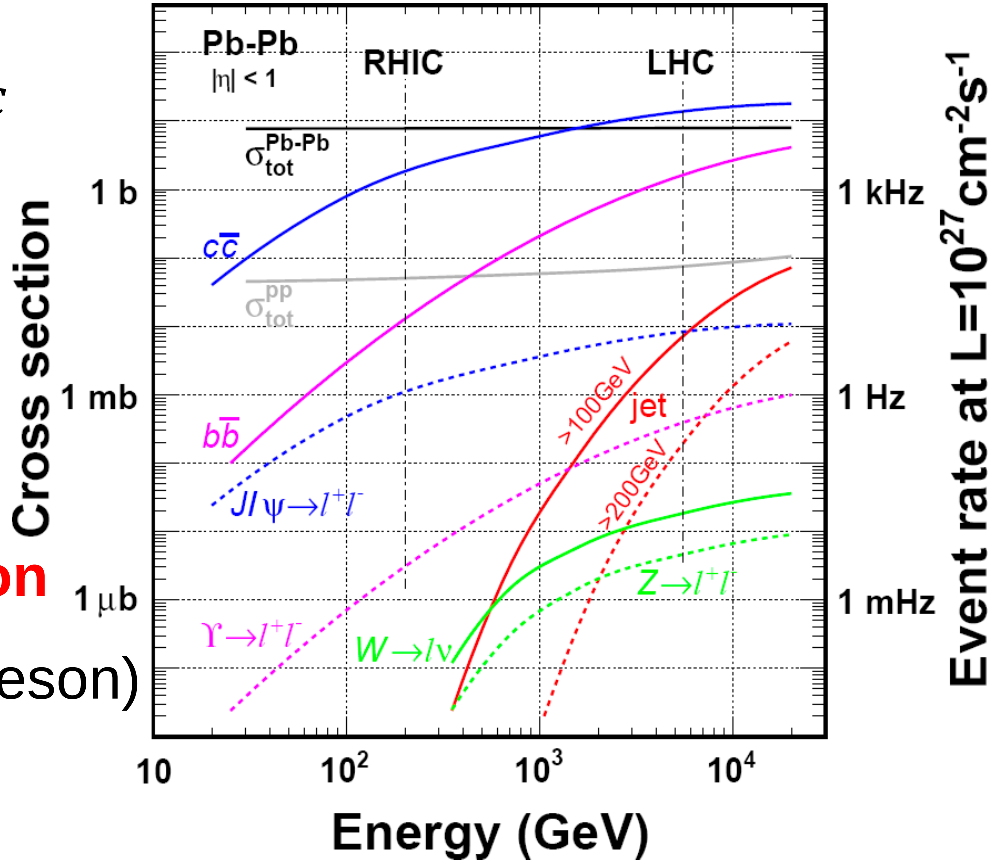
- **large production cross sections**

  (~7 D > 2 GeV/c per central event)

- Essentially not produced in the QGP

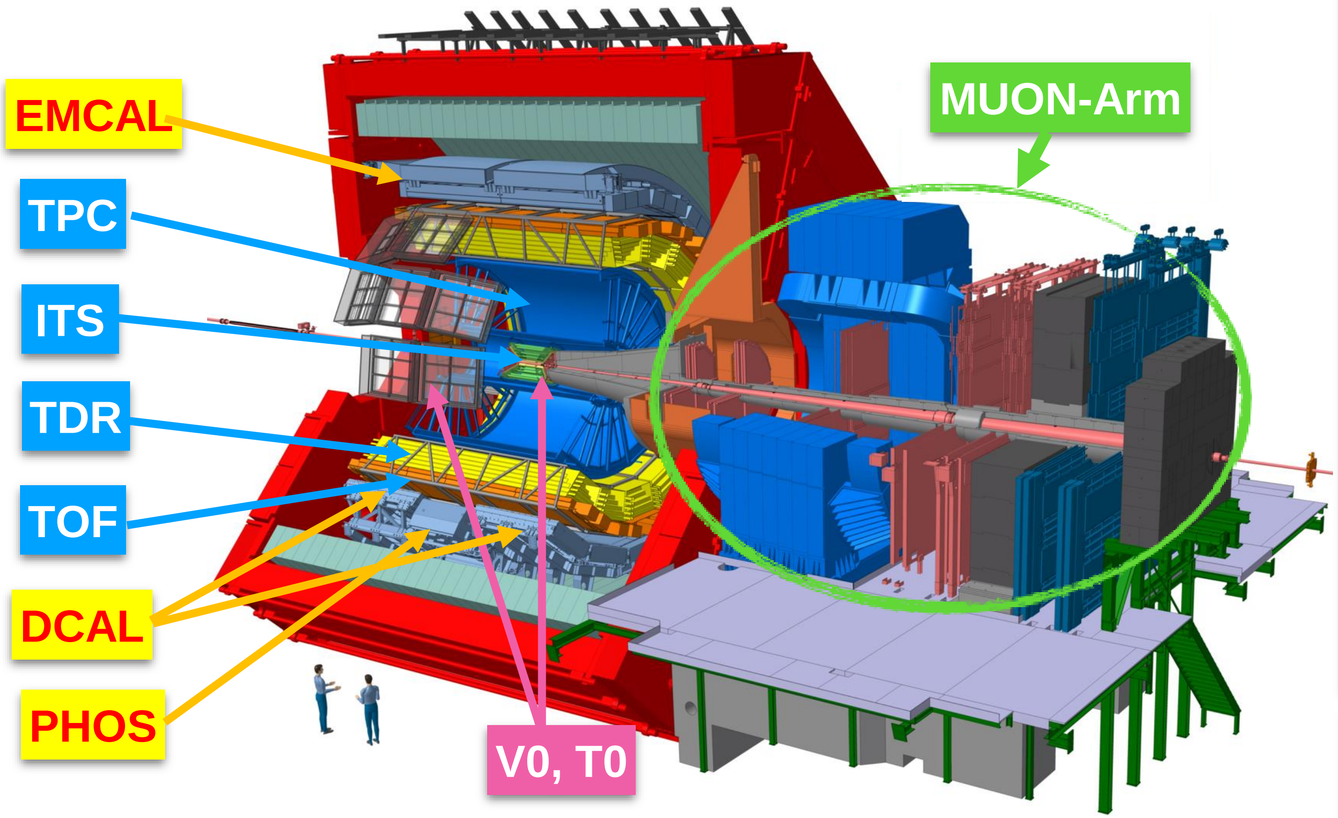
  ➡ ideal probes of the QGP at the LHC

- “brownian” motion through the medium, **diffusion**
- sensitive to QGP **hadronisation** (into baryon/meson)
- **Expectation** $R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$



ALICE heavy quark programme

Collisions systems (so far) :
Pb-Pb, pp, p-Pb, Pb-p, Xe-Xe



Hadronic decays ($|y| < 0.8$)

- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
- $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$
- $\Lambda_c^+ \rightarrow pK^- \pi^+$
- $\Sigma_c^{0,++} \rightarrow \Lambda_c^+ \pi^\mp$
- $\Xi_c^{0(+)} \rightarrow \Xi^- \pi^+ (\pi^+)$
- $\Omega_c^+ \rightarrow \Omega^0 \pi^+$

Semi-leptonic decays

- $c, b \rightarrow e^\pm$ ($|y| < 0.7$)
- $c, b \rightarrow \mu^\pm$ ($2.5 < y < 4$)

D^0 reconstruction

- **D^0 meson: m = 1.87 GeV/c^2 ; cτ = 123 μm**
  - Rather short lived
  - Many decay modes
  - $D^0 \rightarrow K\pi$ (branching ratio 3.9%)

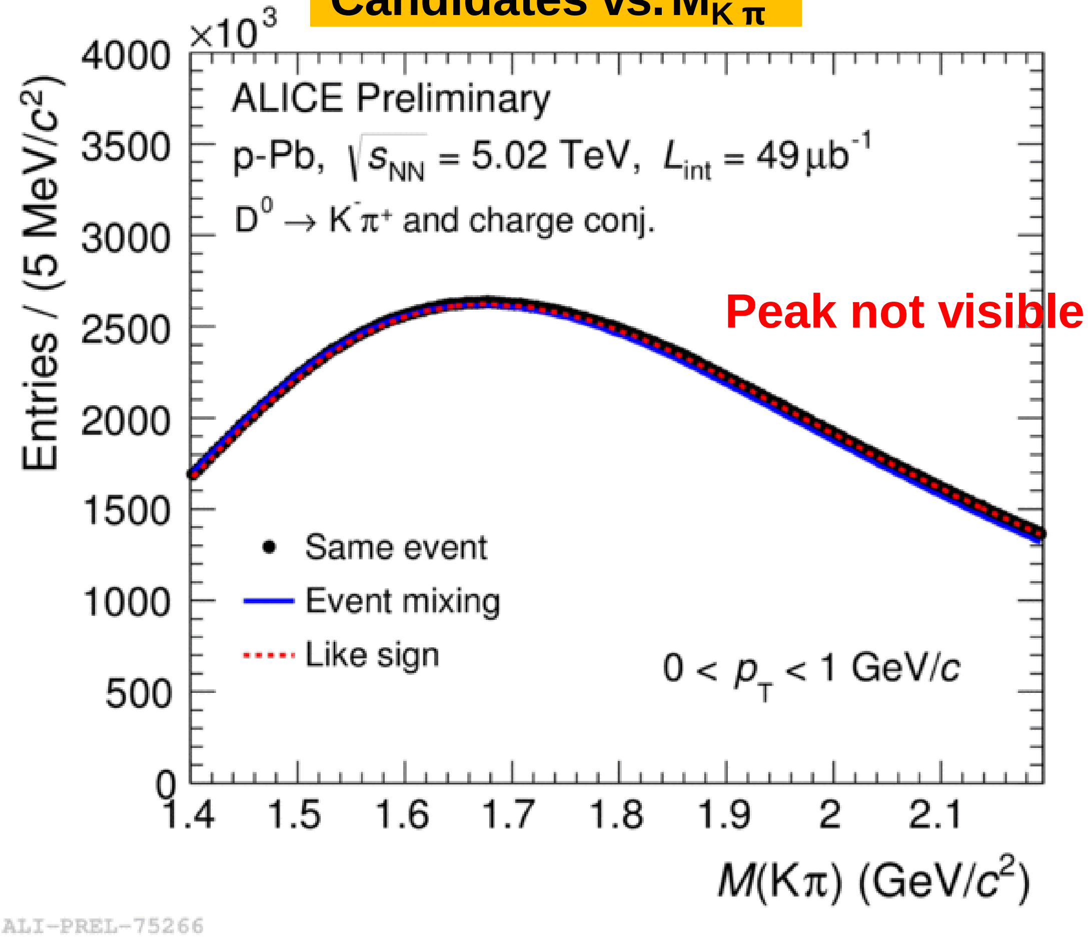
- **Standard method:** **invariant mass of opposite charge pairs**
  - Per central event ($D^0 \rightarrow K\pi$, > 2 GeV/c, incl. efficiencies):
    0.001 compared to ~700 K and up to ~2500 π
  - Signal over background far too small to extract a peak

- **Method to reduce combinatorial background** (see next slides)
  - Topological cuts
  - Particle identification (**PID**) of K and π

Invariant mass

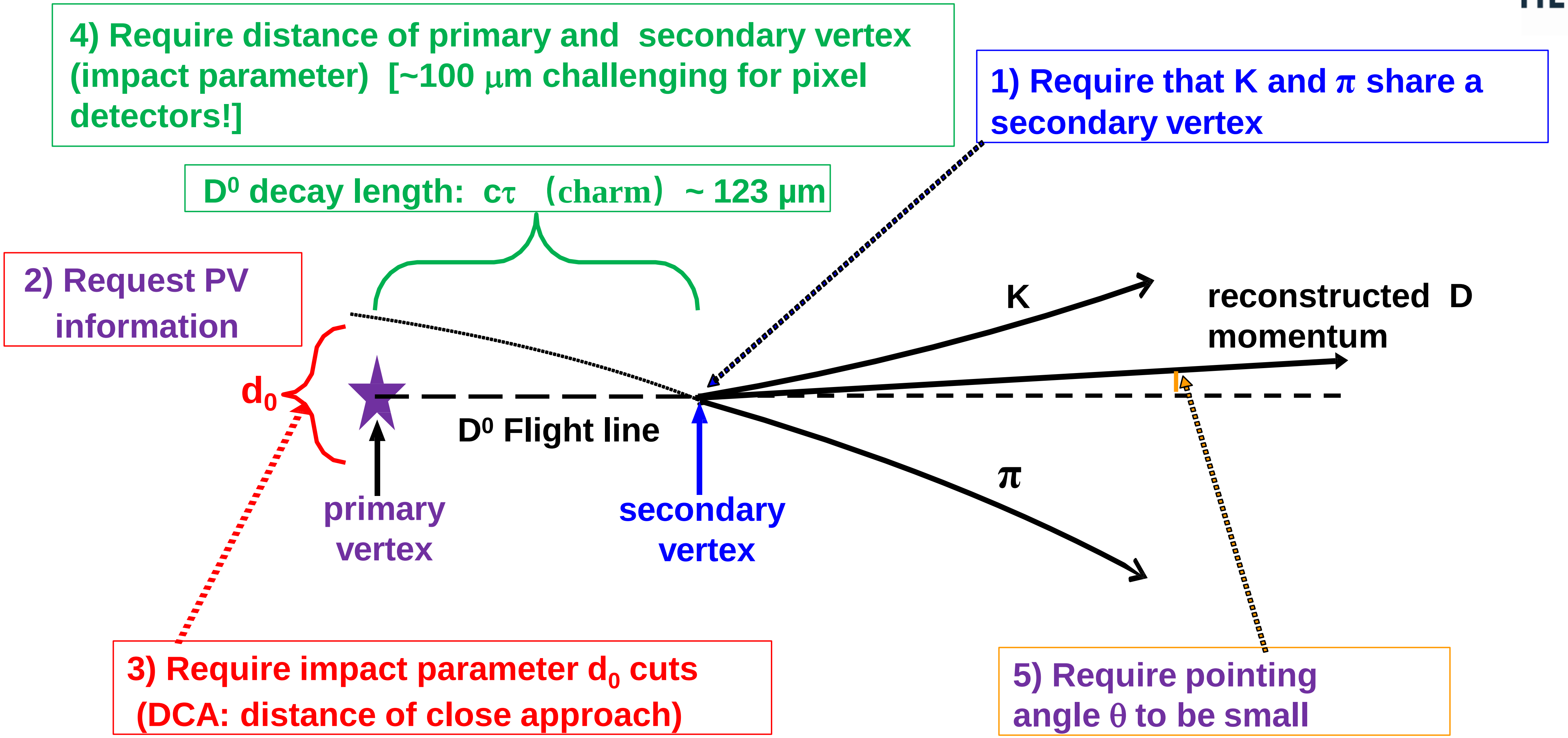
- $D^0 \rightarrow K\,\pi$ without PID and without topological cuts

Candidates vs. $M_{K\,\pi}$



Peak not visible without cuts

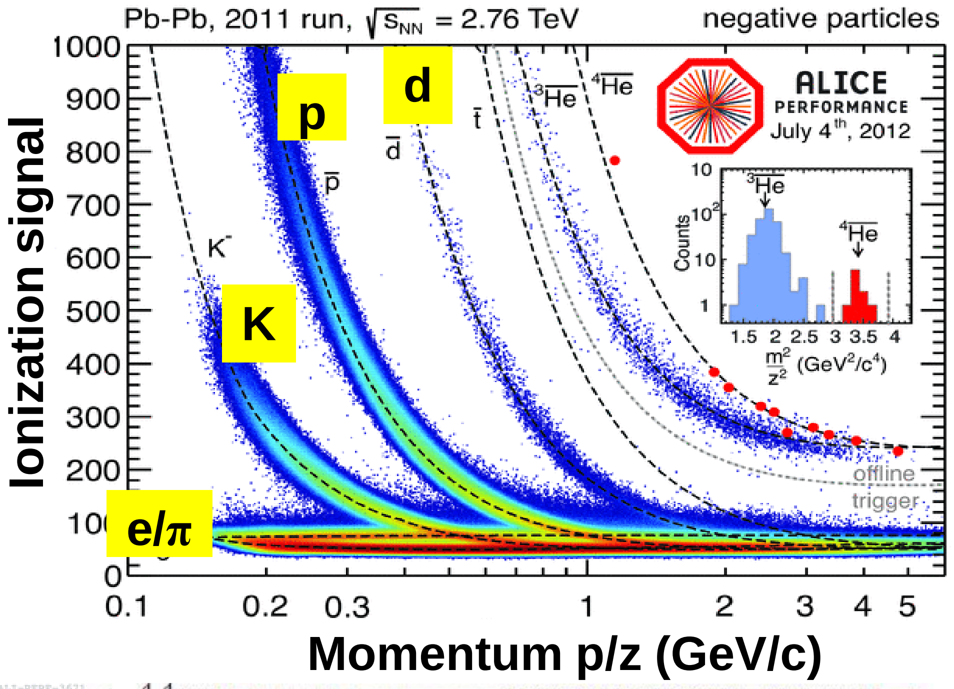
Topological cuts



Plane transverse to beam

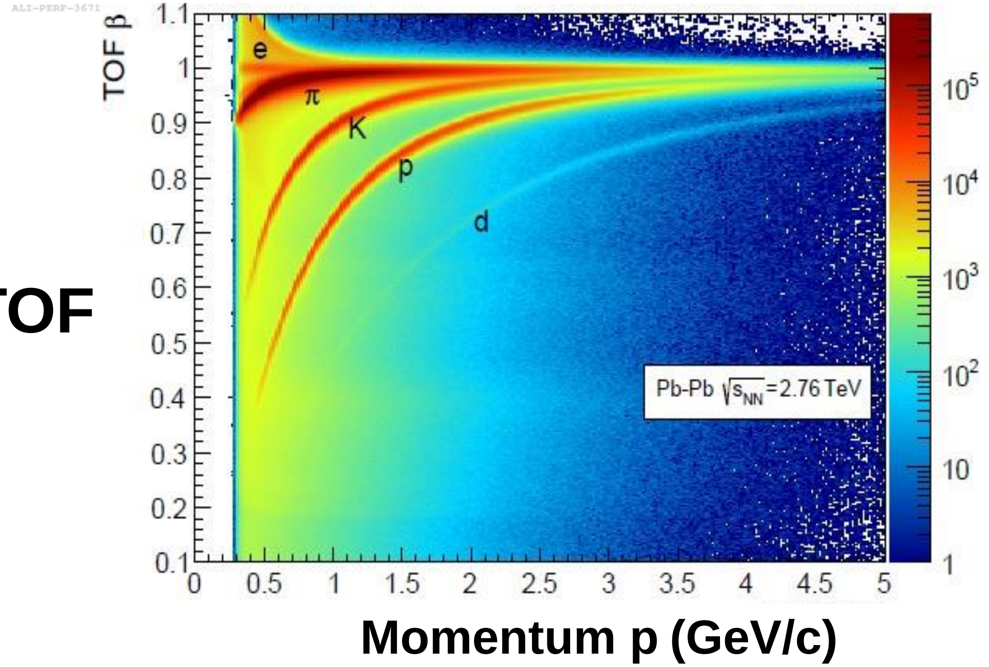
PID

- **Specific Energy Loss**
  - Particles passing through matter loose energy mainly by ionization
  - Average energy loss calculated with Bethe-Bloch formula
  - Identify particle by measuring energy deposition and momentum
- **Time Of Flight**
  - Particles with the same momentum have slightly different speed due to their different mass
  - Needed flight time precision, e.g. for a particle with p = 3 GeV/c, flying length 3.5 m: t(π) ~ 12 ns | t(K) – t(π) ~ 140 ps
- **Methods can be combined**



TPC

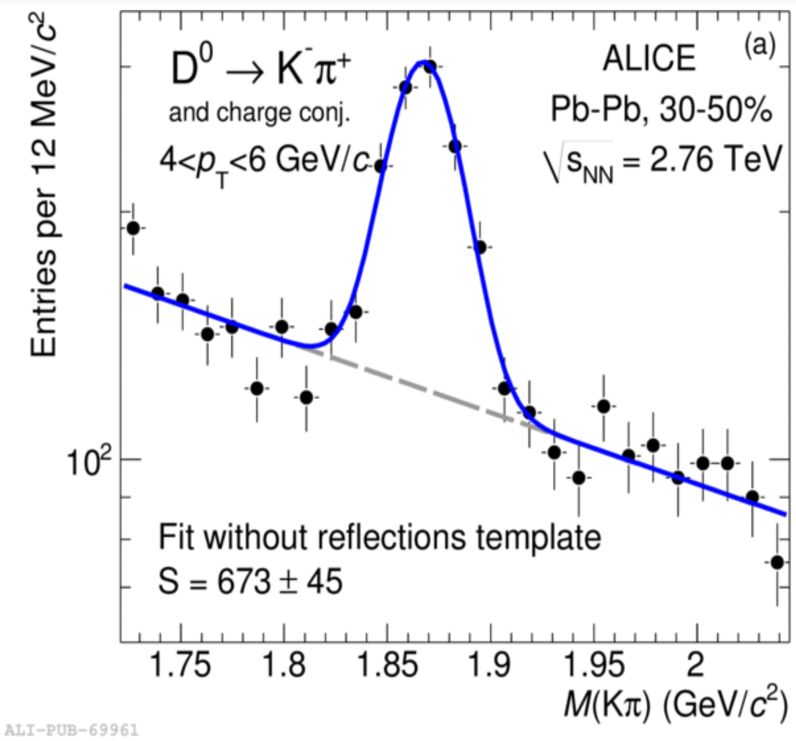
TOF



Invariant mass

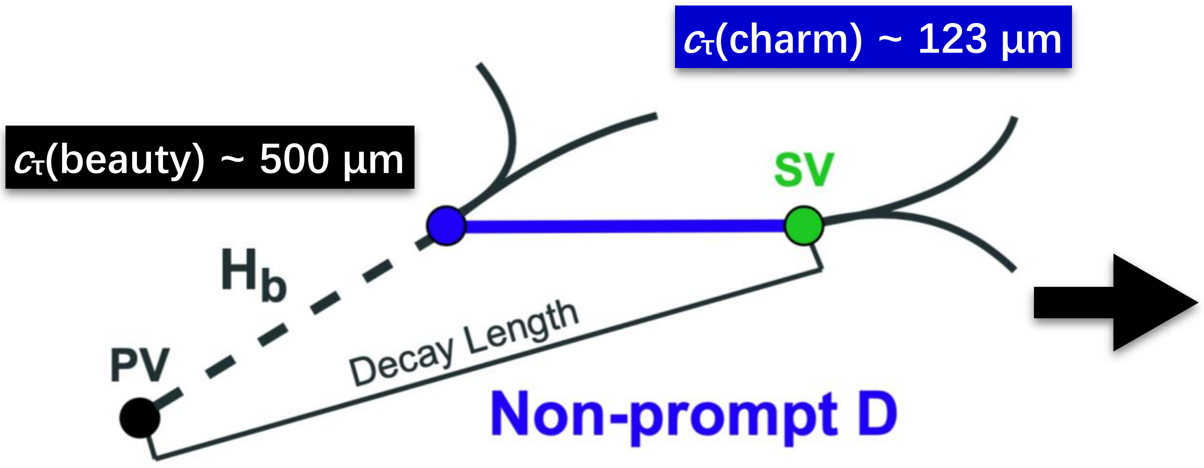
- Reconstruct D meson decay to K, π based on the following methods
  - Combinatorial pairs
  - background reduced with particle identification and topological cuts
  - Invariant mass distribution
  - Background subtraction with like-sign combinations
  - Apply fitting to extract yield

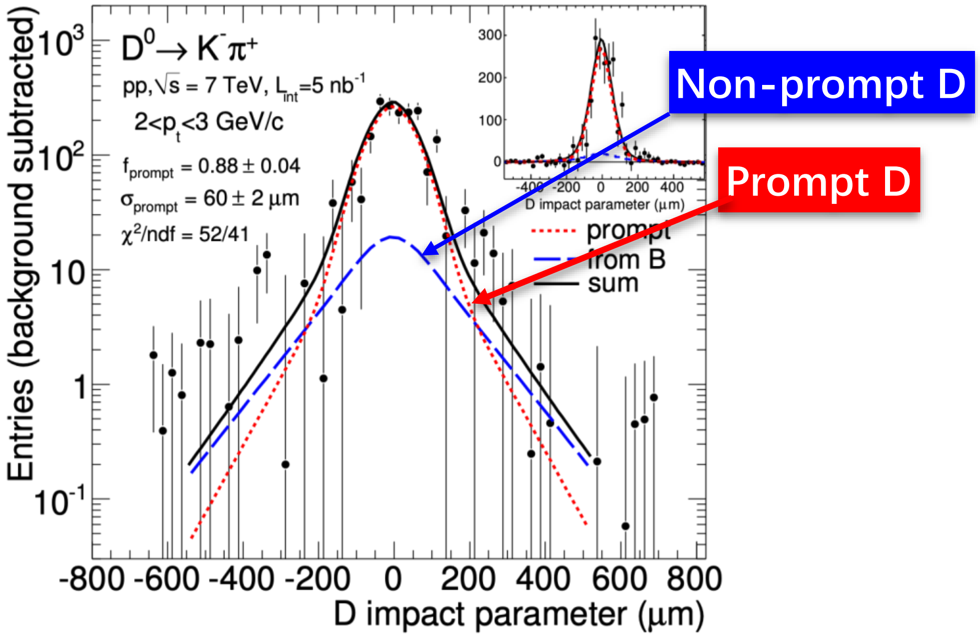
$$M_{\mathrm{inv}} = \sqrt{(E_{\mathrm{K}} + E_{\pi})^2 - (p_{\mathrm{K}} + p_{\pi})^2}$$



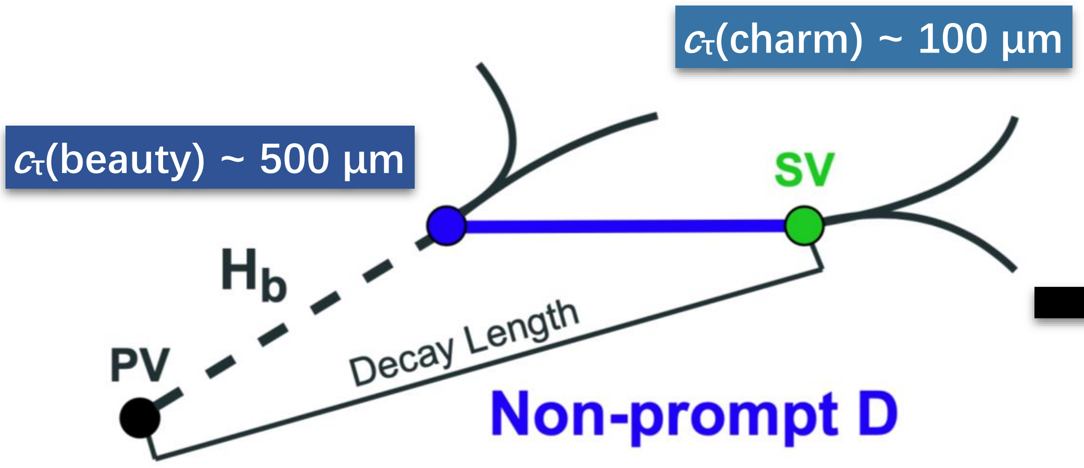
Similar procedure apply to $D^{\pm}$, $D^{*\pm}$ and $D_s^{\pm}$

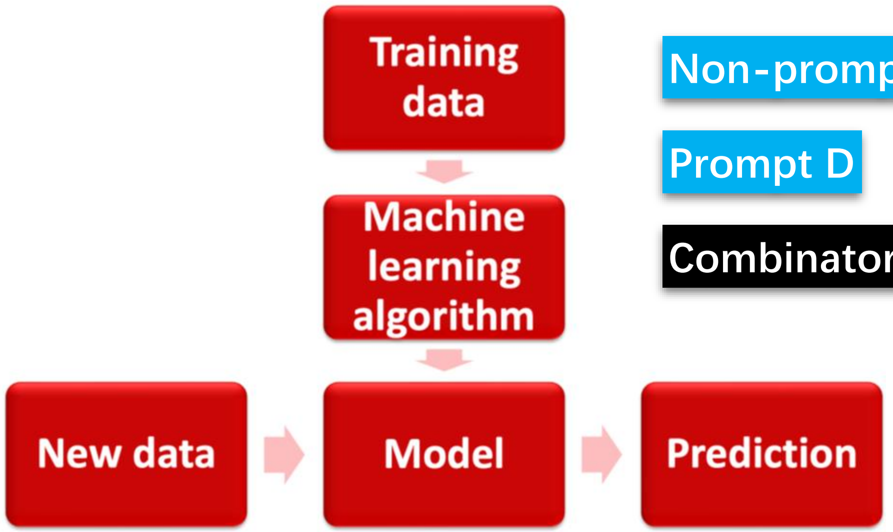
Non-promt D^0 signal extraction





Non-promt D^0 signal extraction



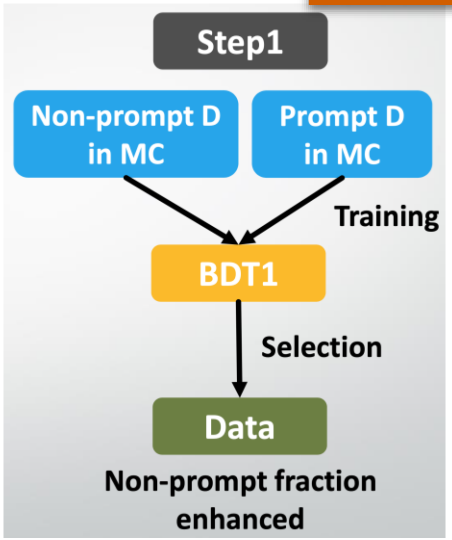


Non-prompt D

Prompt D

Combinatory background

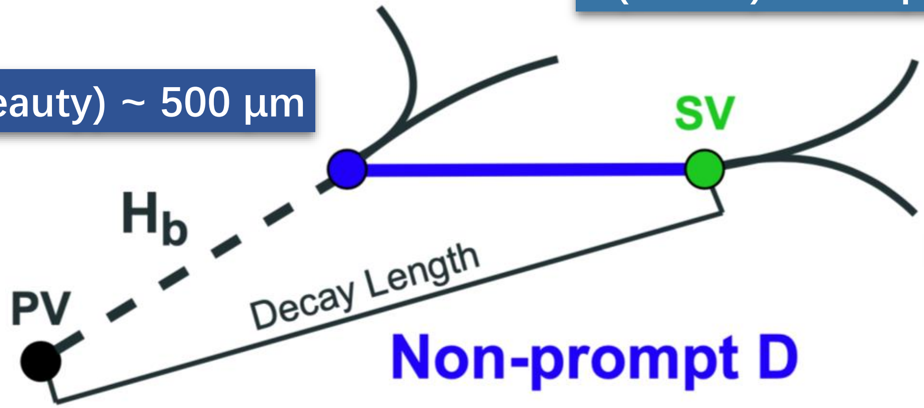
Select significant



Non-promt D^0 signal extraction

$c\tau$(charm) ~ 100 μm

$c\tau$(beauty) ~ 500 μm



Training data → Machine learning algorithm → Model

New data → Model → Prediction

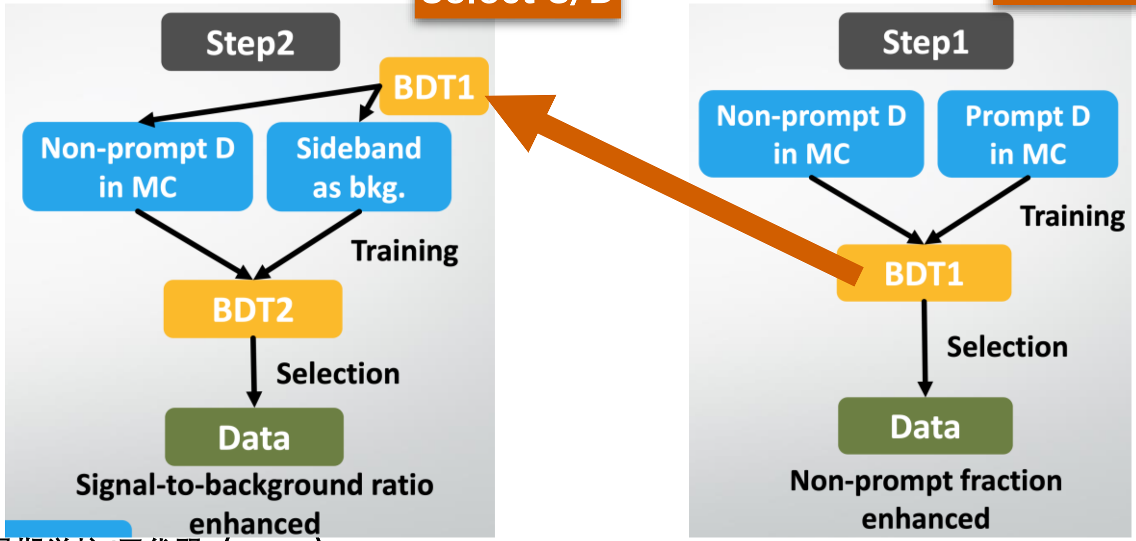
Non-prompt D

Prompt D

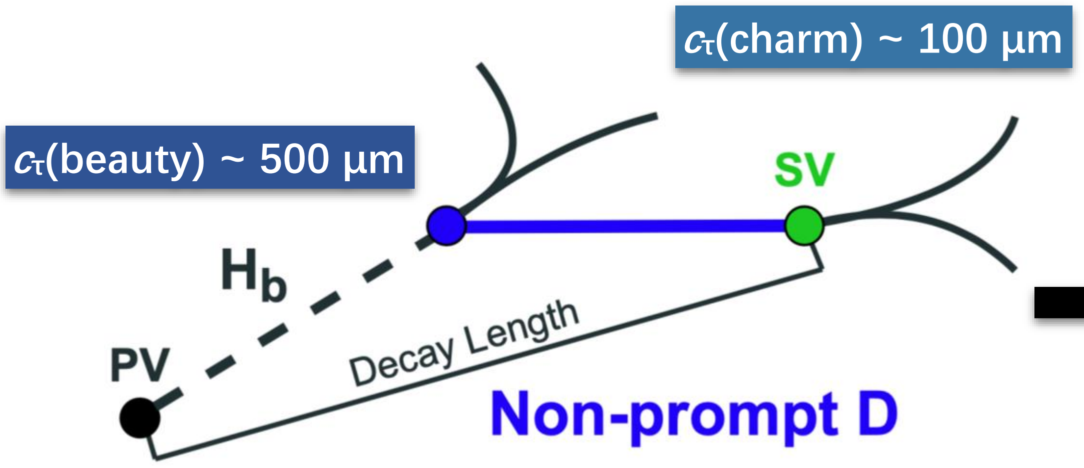
Combinatory background

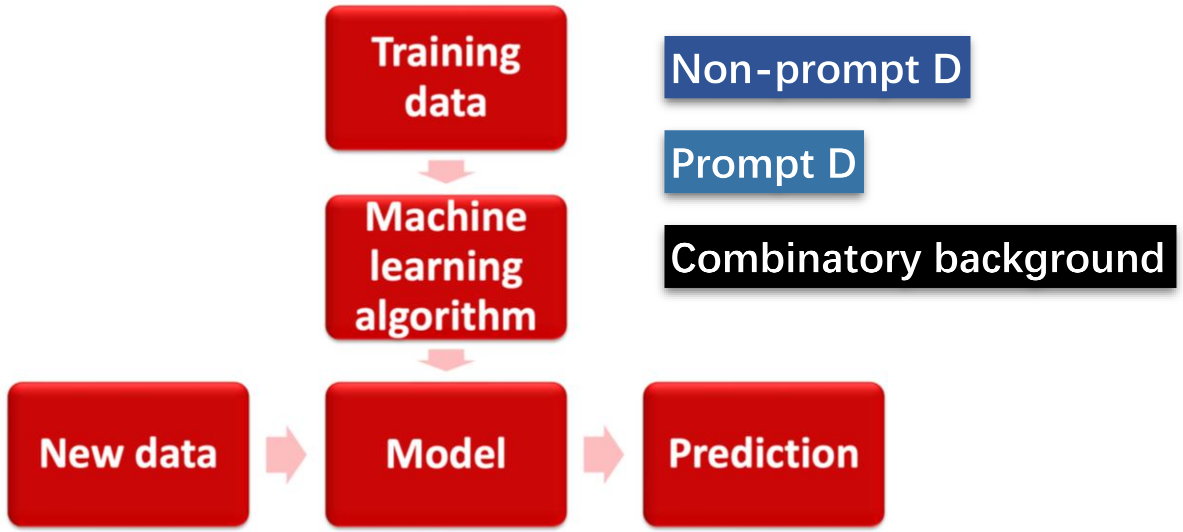
Select S/B

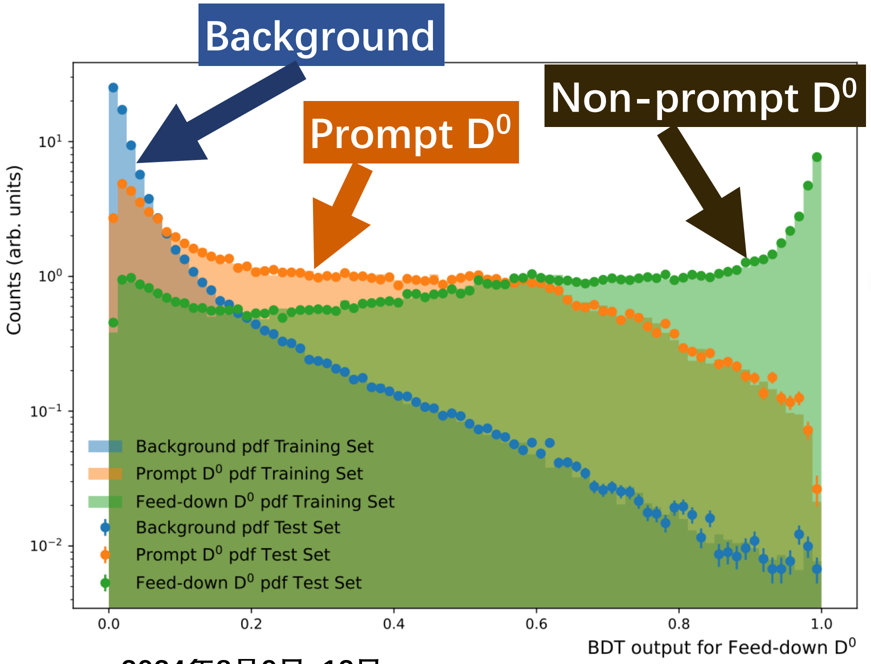
Select significant

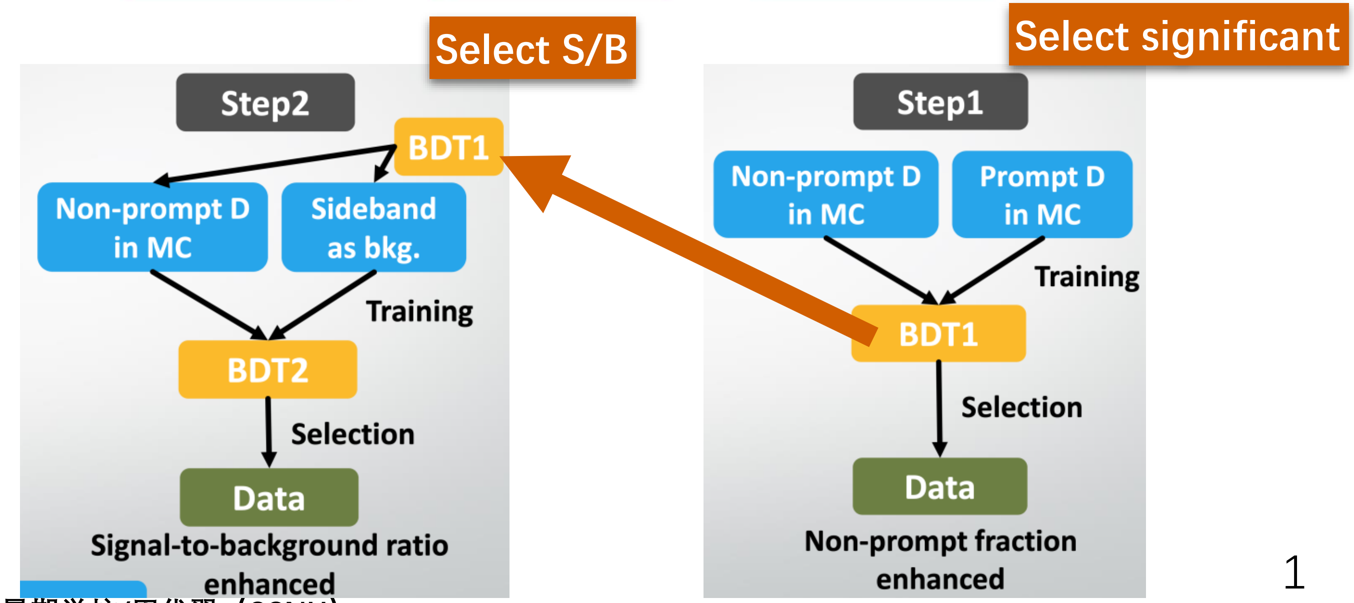


Non-promt D^0 signal extraction

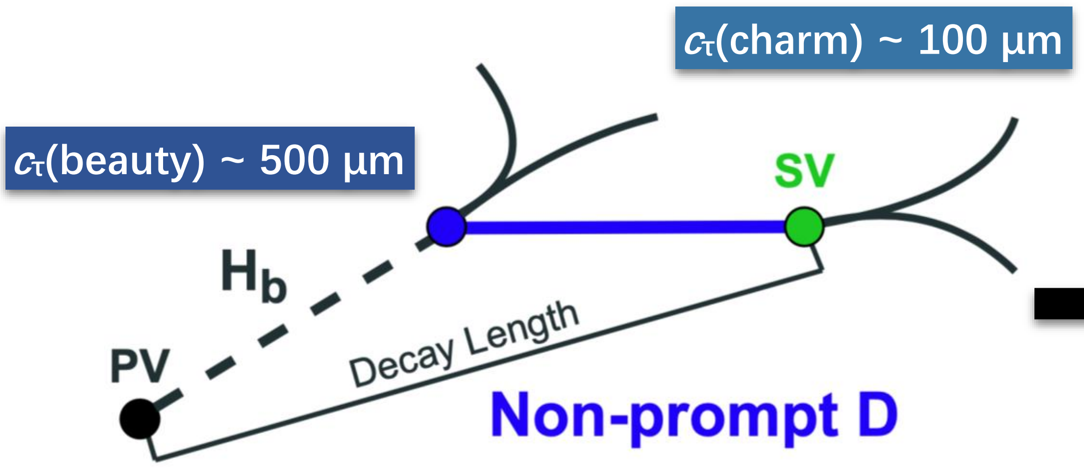


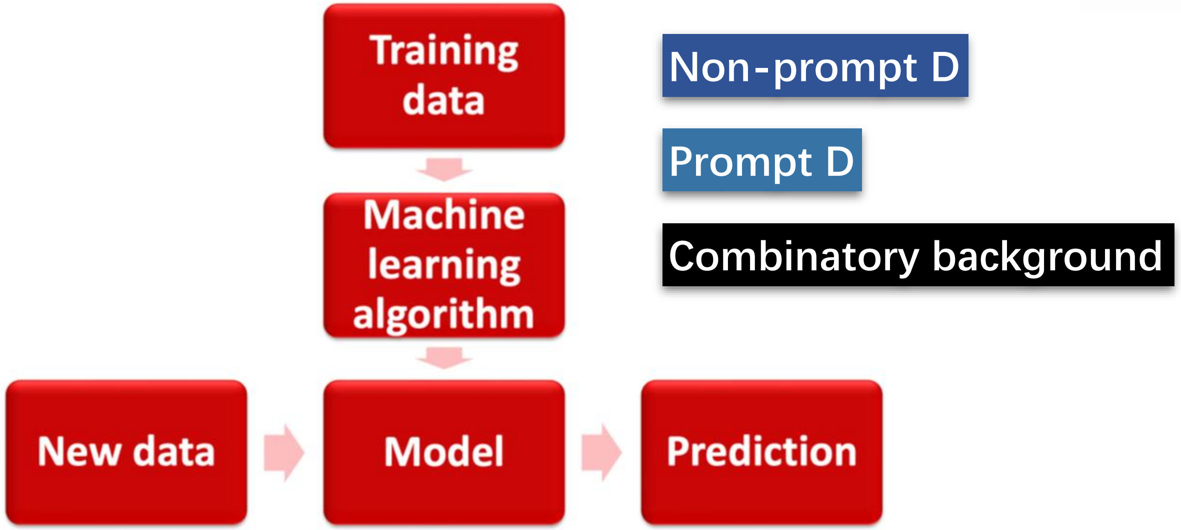


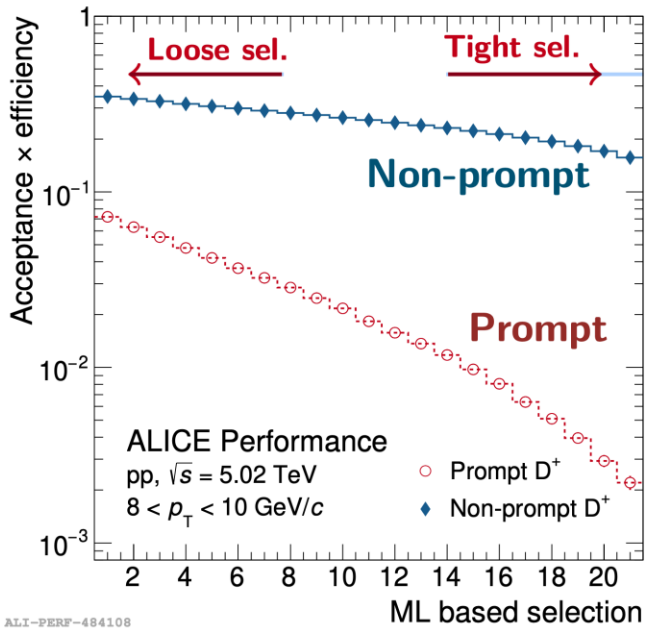


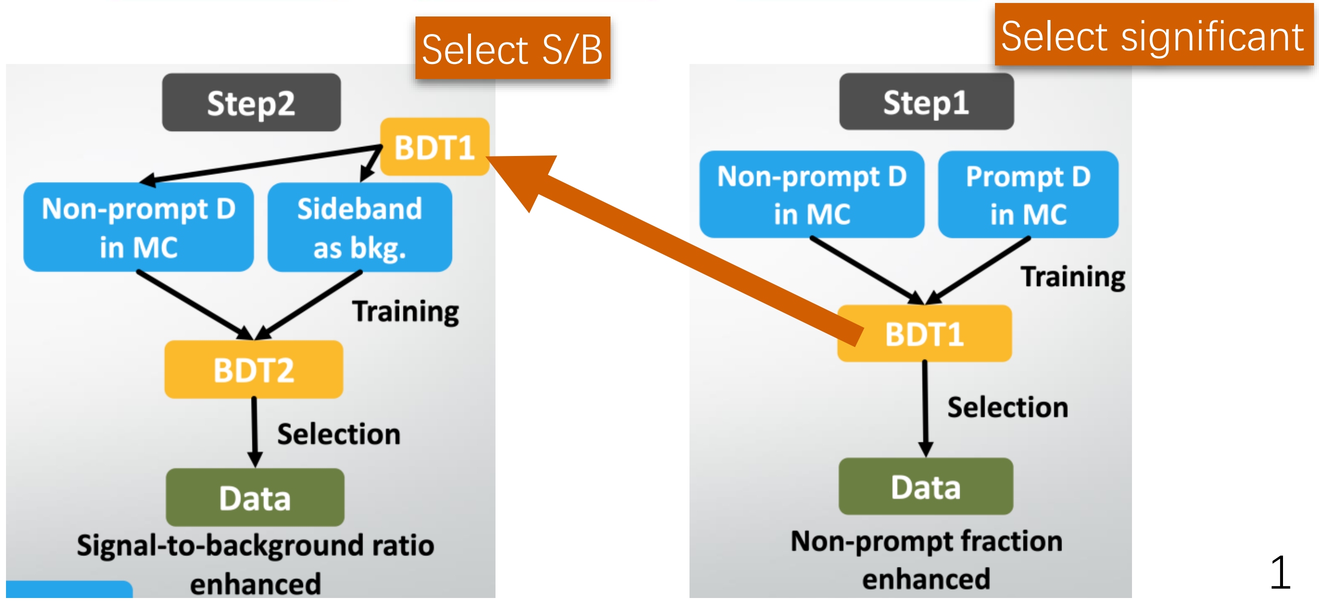


Non-promt D^0 signal extraction

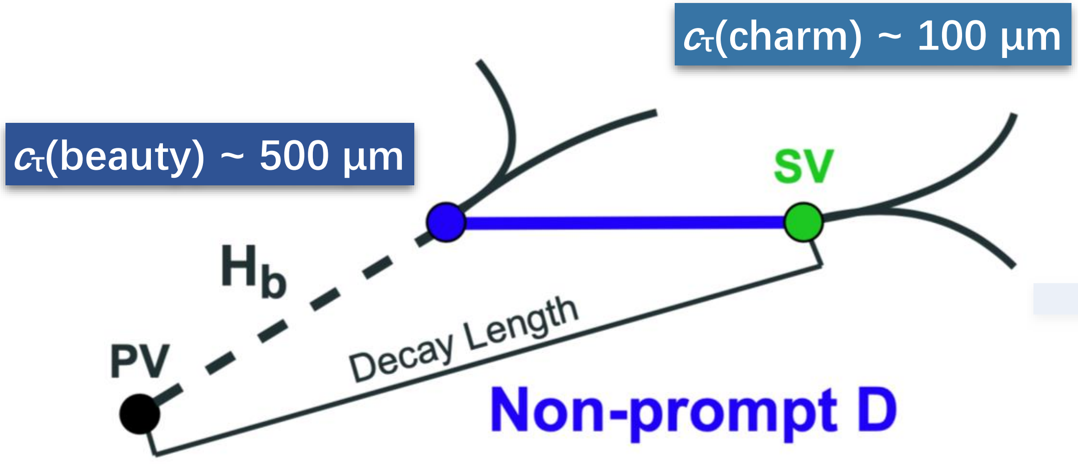


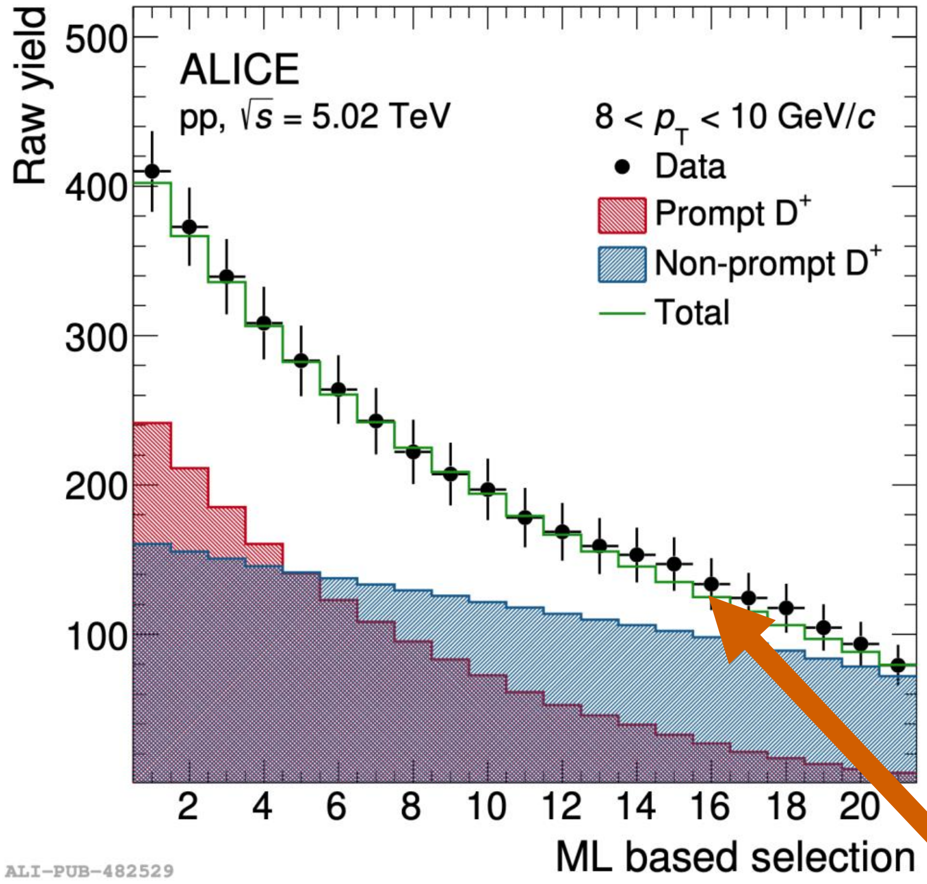


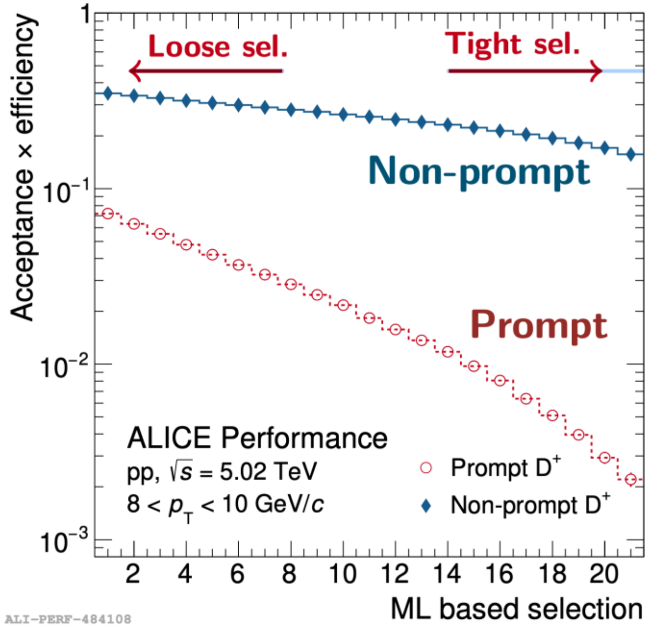




Non-promt D⁰ signal extraction

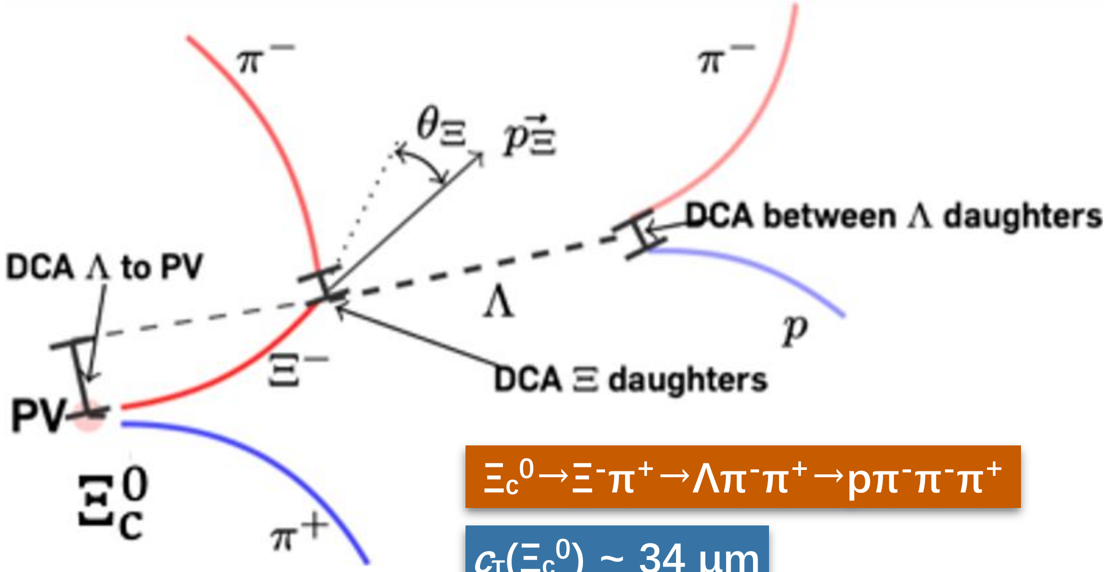






$$\begin{cases} (\mathrm{Acc}\times\epsilon)_1^{\mathrm{prompt}}\cdot N_{\mathrm{prompt}} + (\mathrm{Acc}\times\epsilon)_1^{\mathrm{non\text{-}prompt}}\cdot N_{\mathrm{non\text{-}prompt}} = Y_1 \\ \dots \\ (\mathrm{Acc}\times\epsilon)_n^{\mathrm{prompt}}\cdot N_{\mathrm{prompt}} + (\mathrm{Acc}\times\epsilon)_n^{\mathrm{non\text{-}prompt}}\cdot N_{\mathrm{non\text{-}prompt}} = Y_n \end{cases}$$

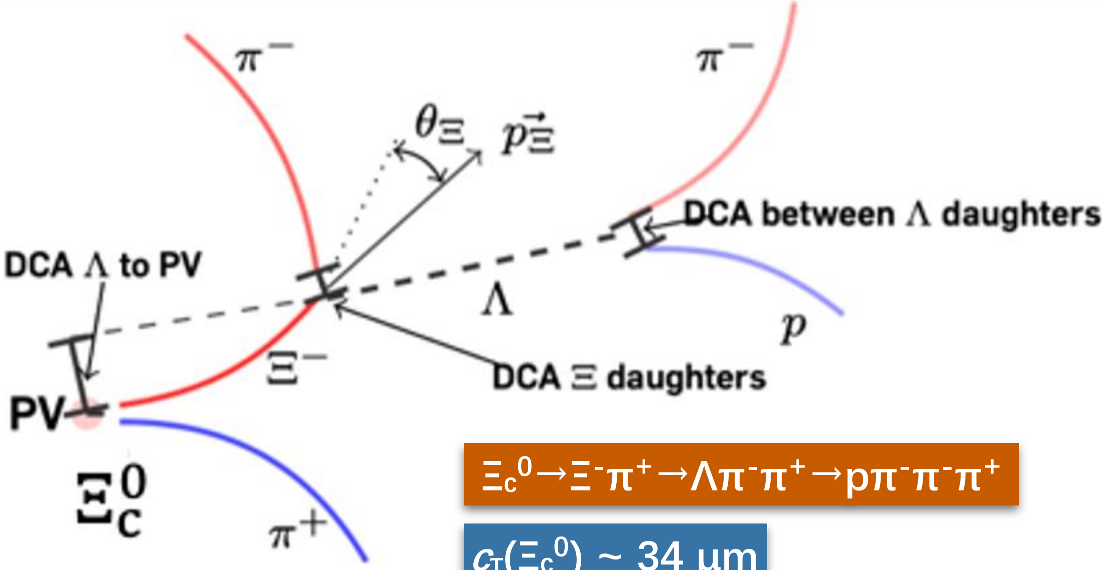
Cascade decay reconstruction



$\Xi_c^0 \rightarrow \Xi^- \pi^+ \rightarrow \Lambda \pi^- \pi^+ \rightarrow p \pi^- \pi^- \pi^+$

$c\tau(\Xi_c^0)$ ~ 34 μm

Cascade decay reconstruction



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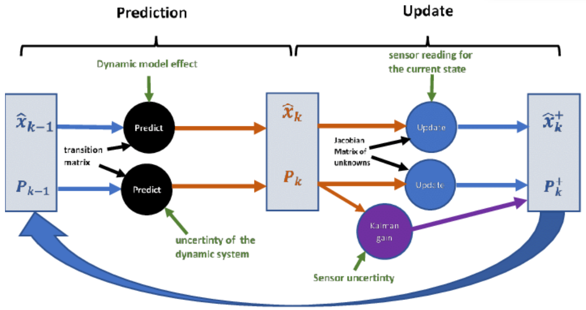
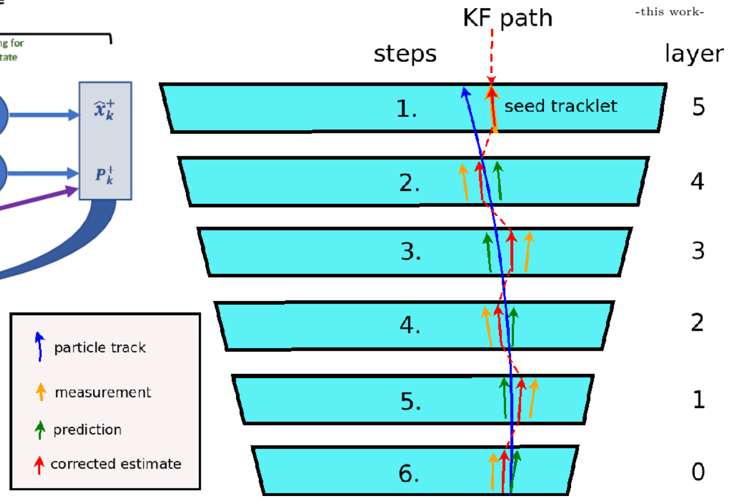
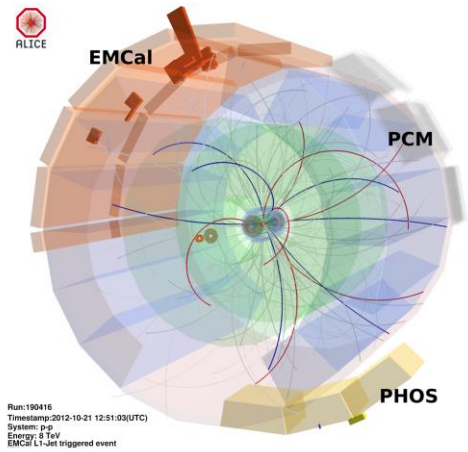
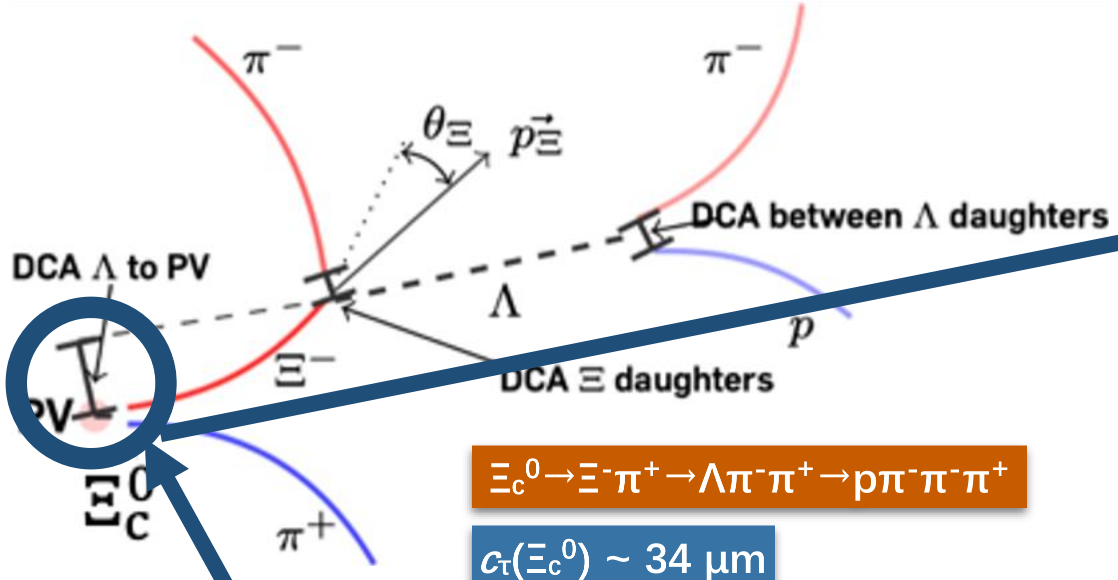




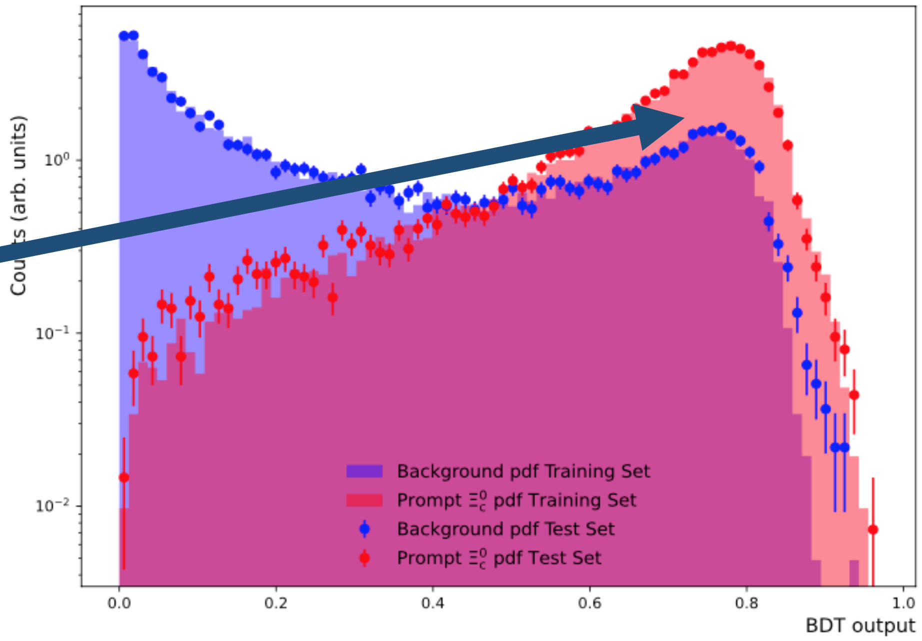


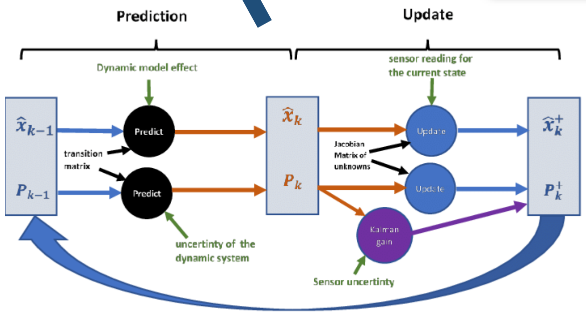
Cascade decay reconstruction

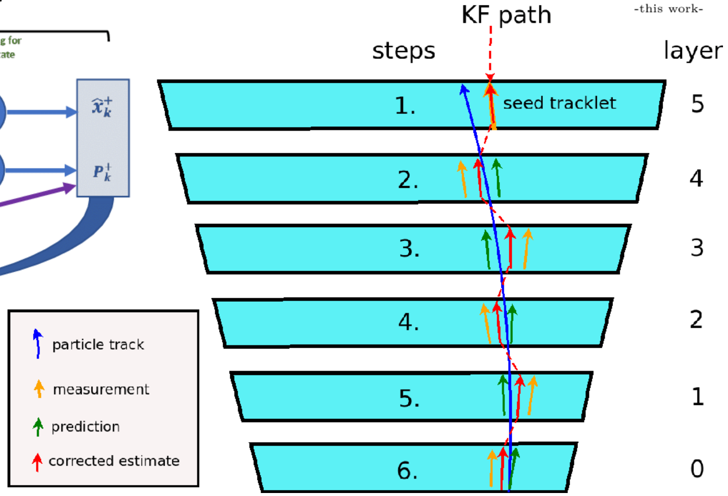


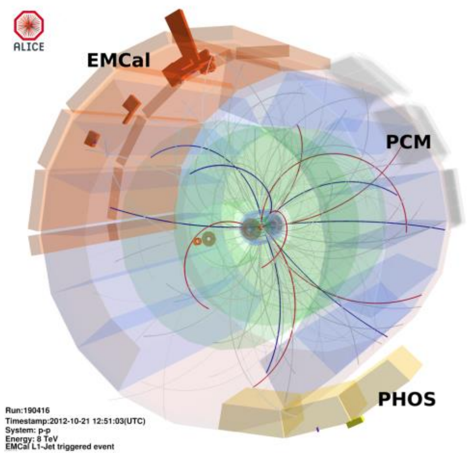
$\Xi_c^0 \to \Xi^- \pi^+ \to \Lambda \pi^- \pi^+ \to p \pi^- \pi^- \pi^+$

$c\tau(\Xi_c^0) \sim 34\ \mu m$

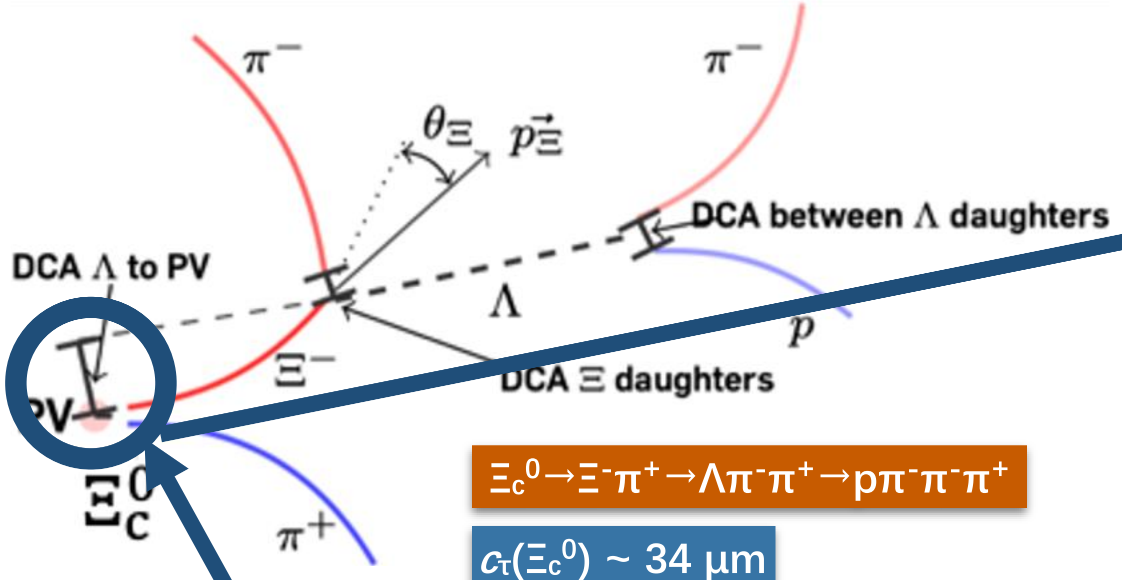








Cascade decay reconstruction



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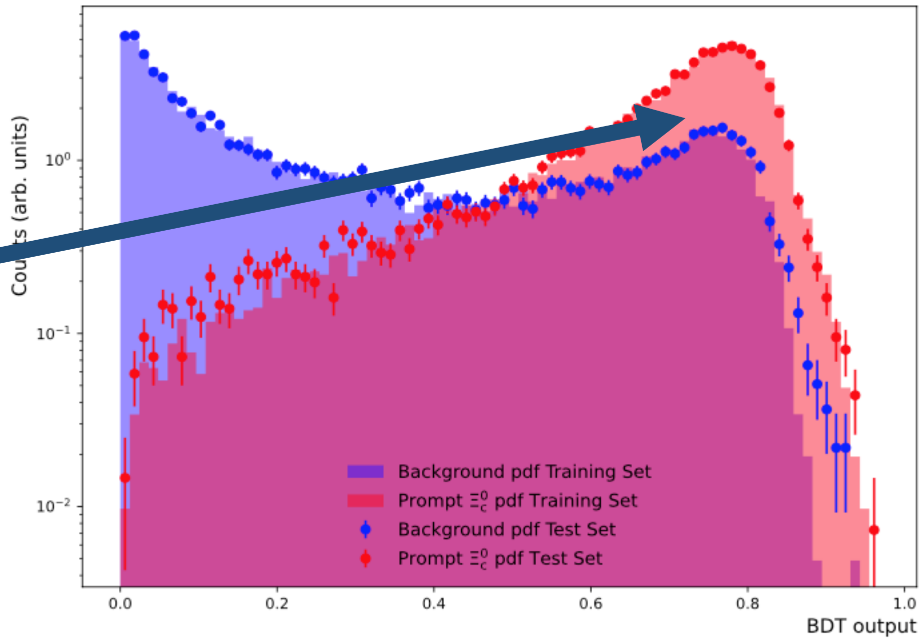
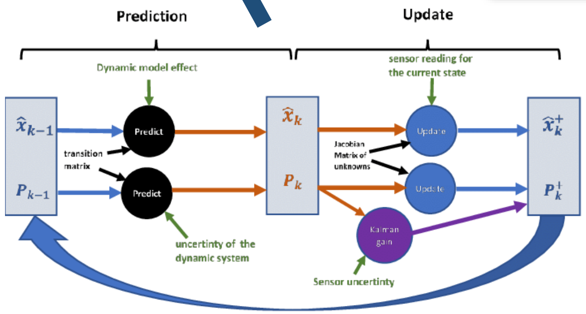
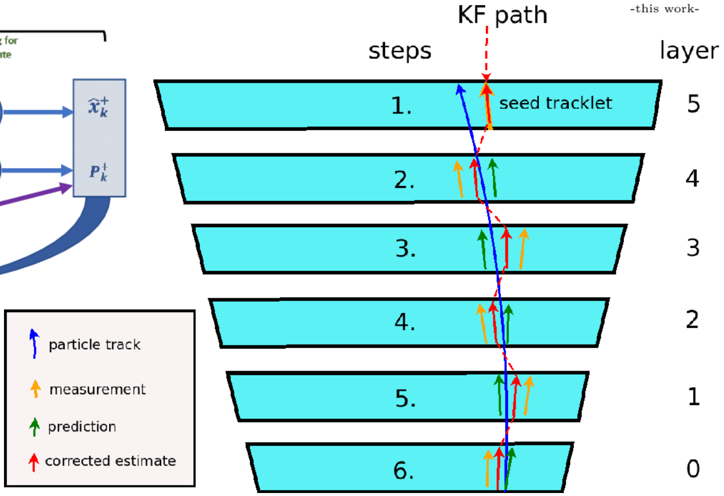
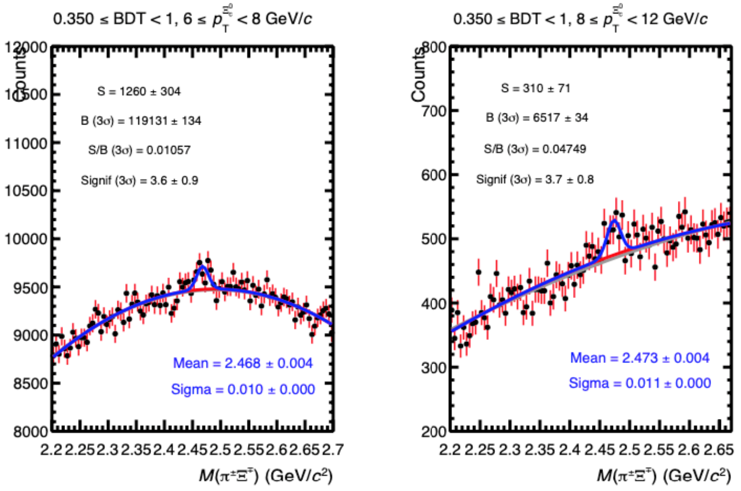


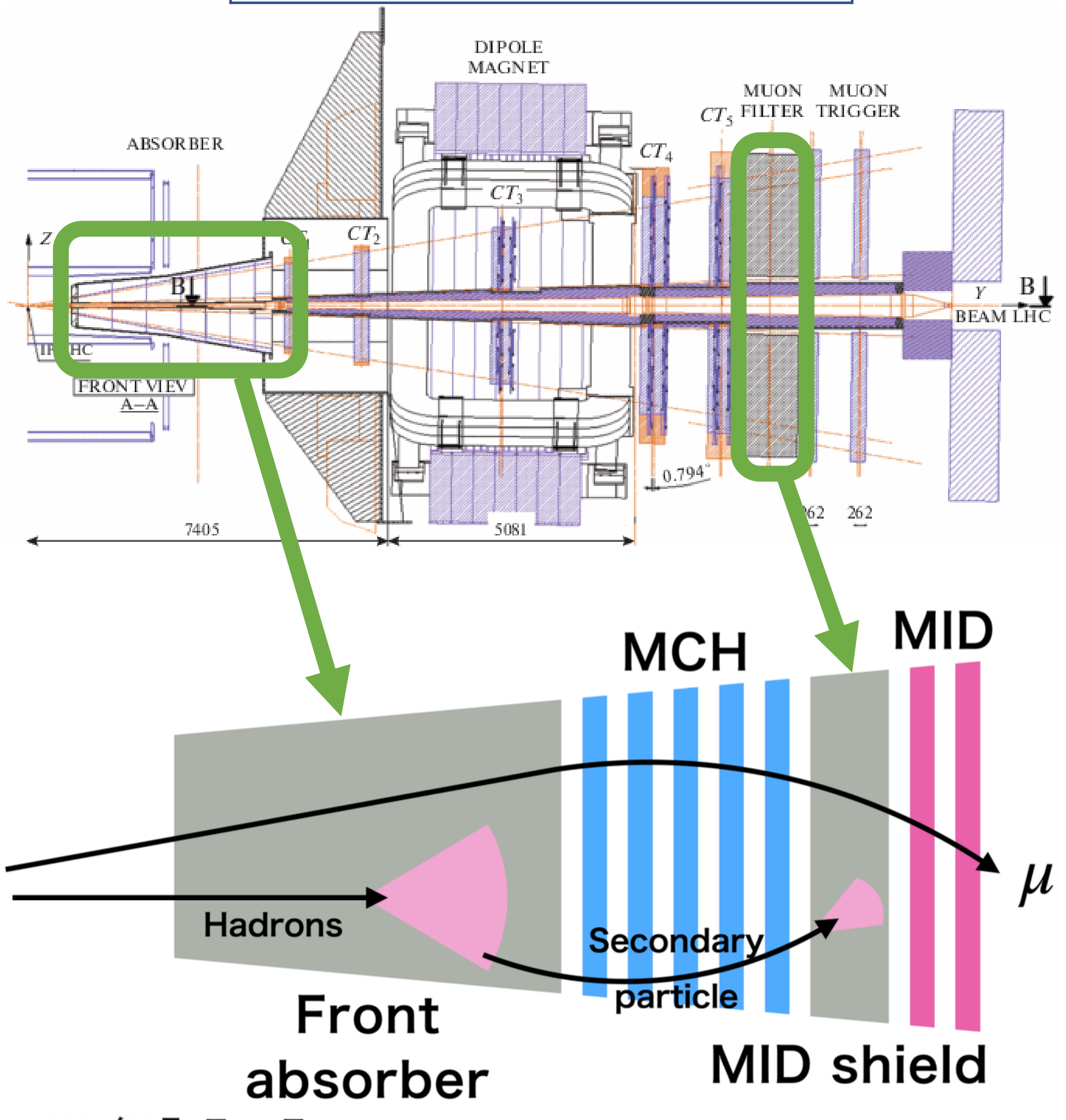




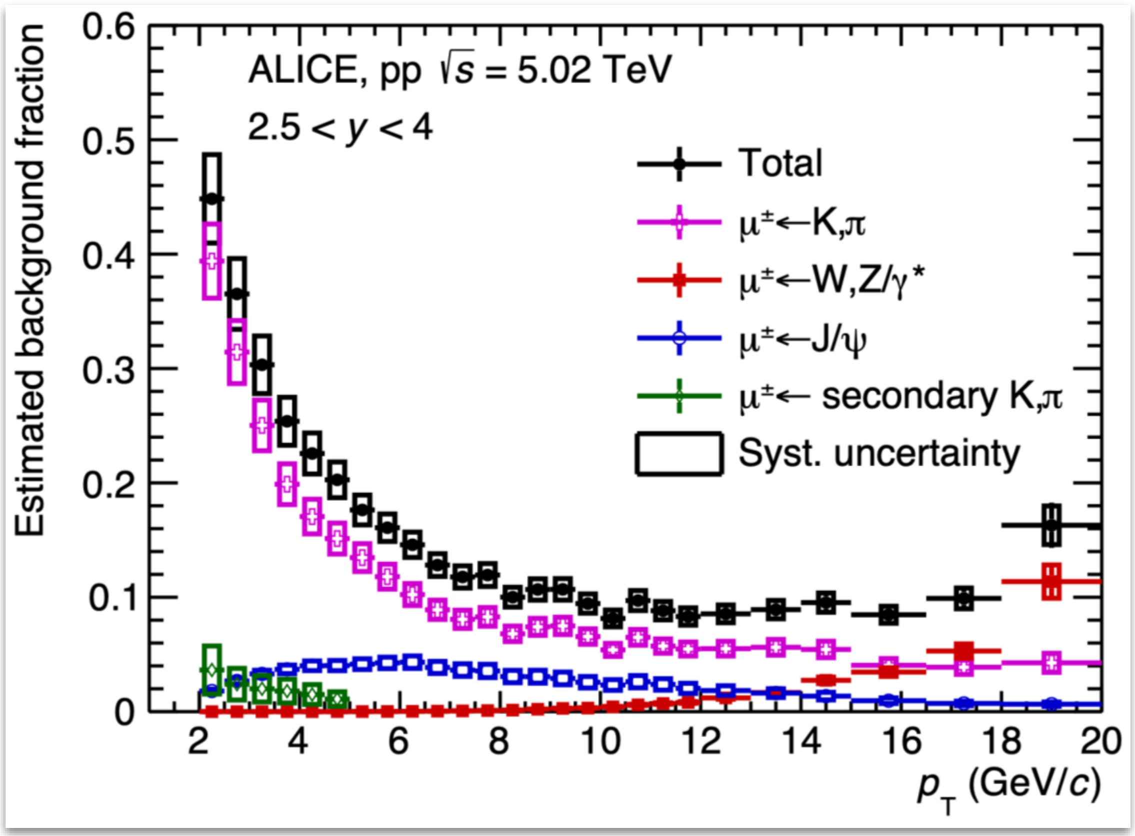


Heavy flavor decay muons

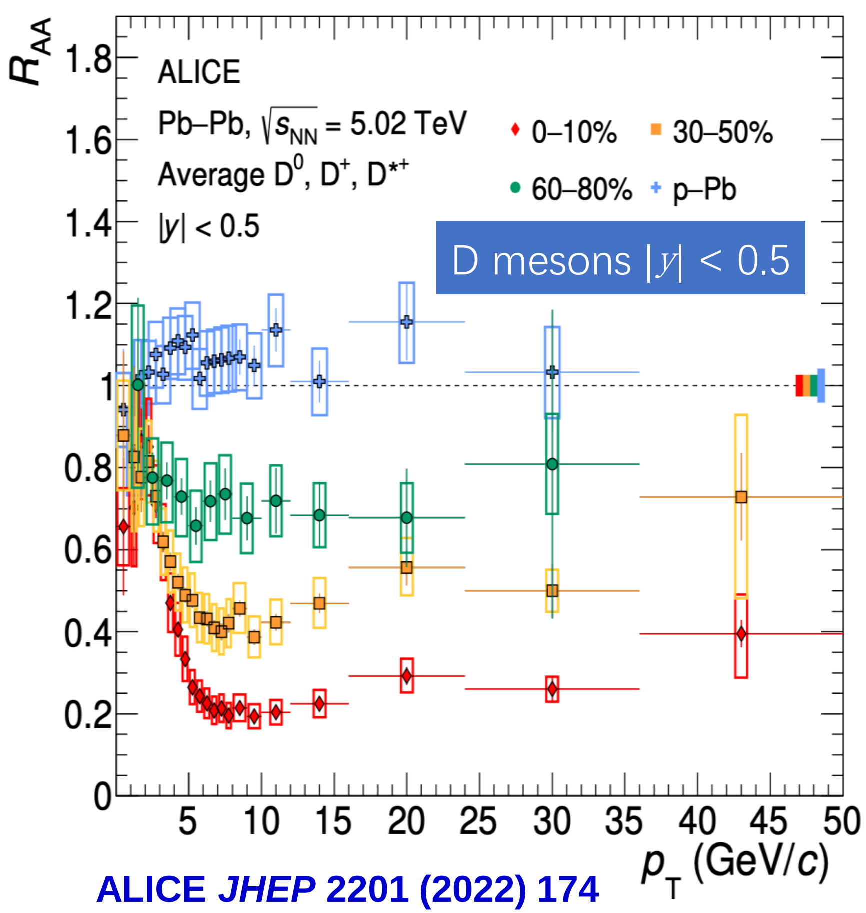
ALICE Muon-Detector



Background muon sources



Charm particle R_{AA}



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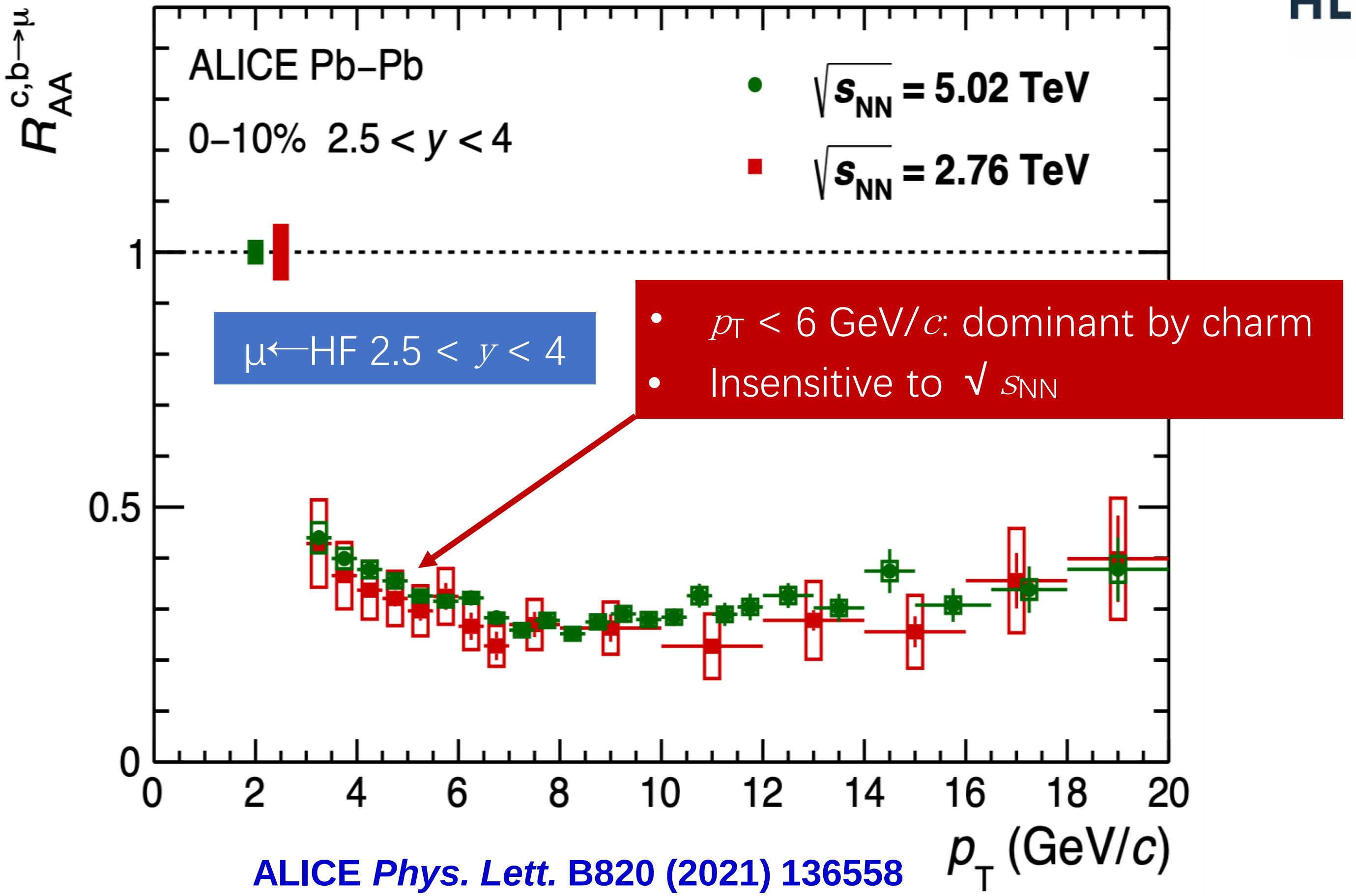
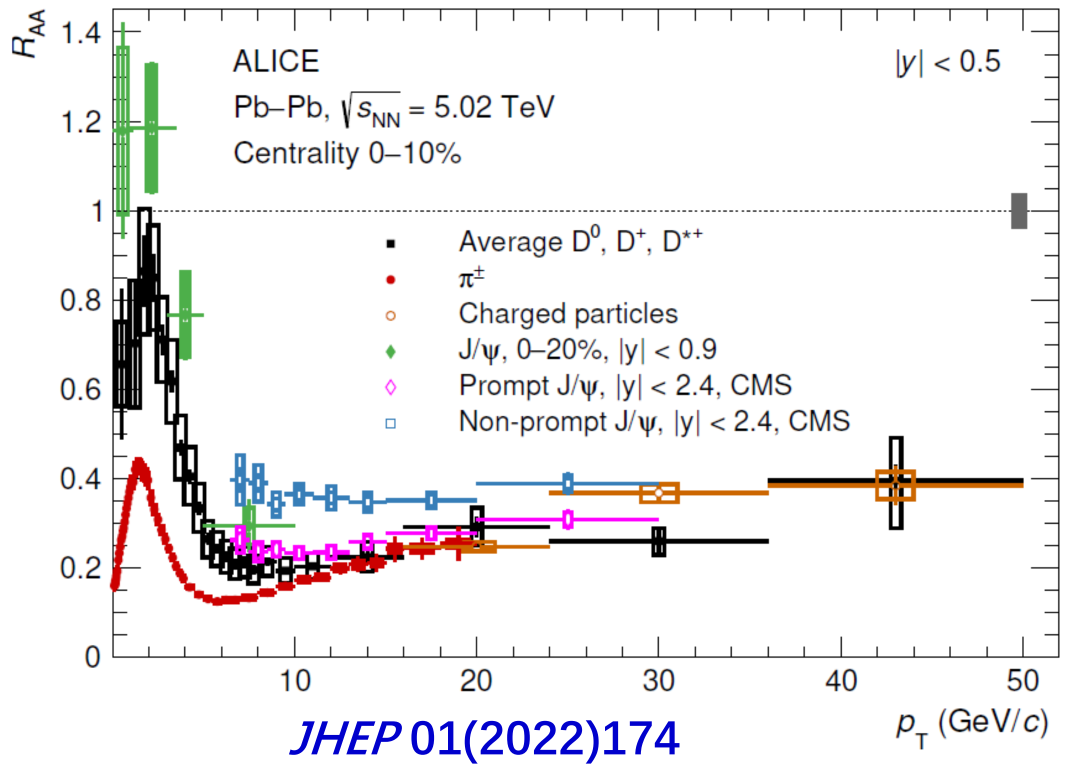


ALICE *Phys. Lett.* B820 (2021) 136558

- Suppression increases from peripheral to central collisions
- Similar suppression in the most central collisions between mid- and forward-rapidity

→ Charm quarks undergo strong energy loss in a wide rapidity range

Light floavor, charm and beauty R_{AA}



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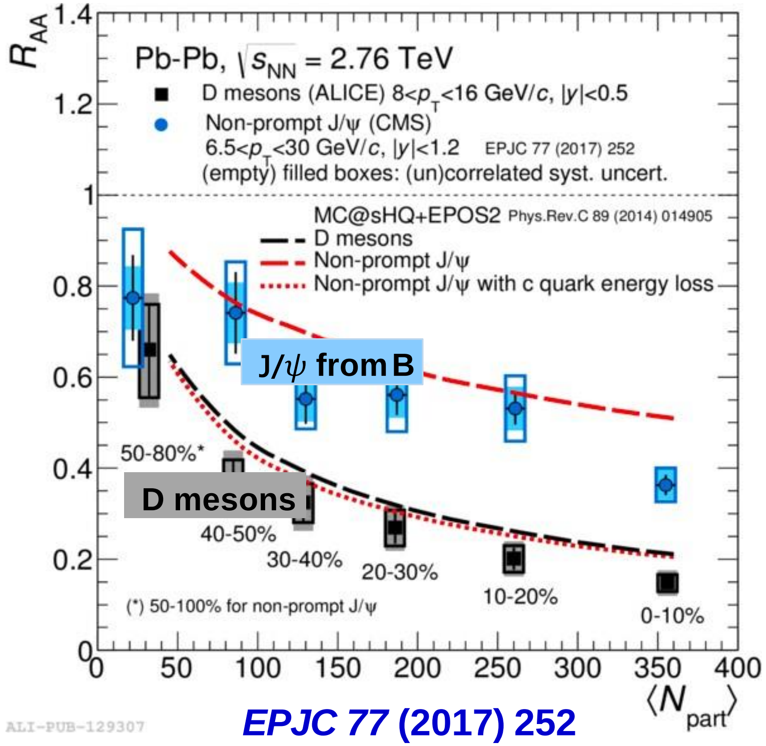

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- A strong suppression is observed in the R_{AA} of D mesons, J/psi from b decay
- J/ψ from beauty is less suppressed than D mesons from charm

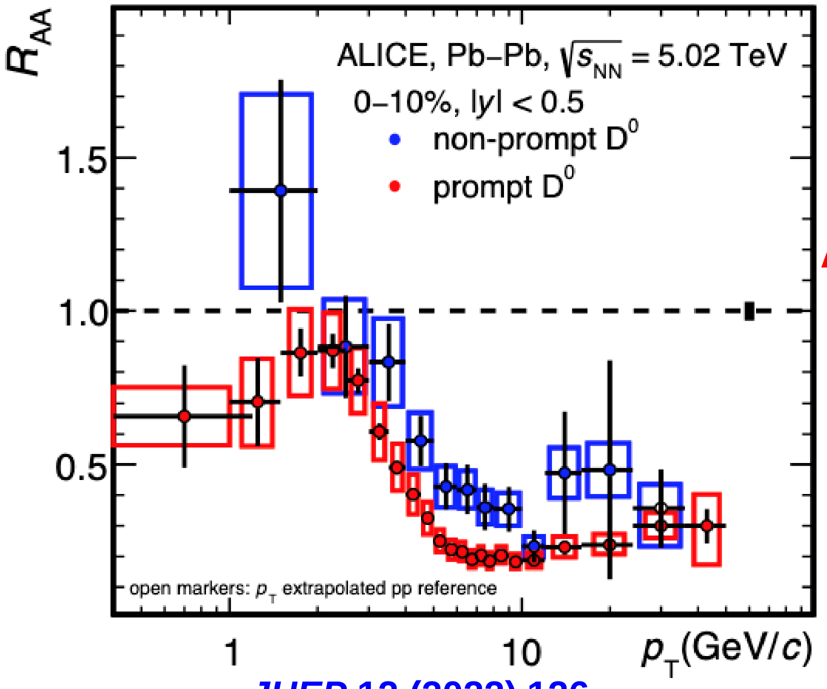
➢ $\Delta E\pi > \Delta E_c > \Delta E_b$

重夸克能量损失的质量依赖性和集体性

Mass matters when quarks cross a quark–gluon plasma

A new analysis by the ALICE collaboration confirms the expected role of quark mass in the interactions of quarks with a quark–gluon plasma

25 MARCH, 2022 | By ALICE collaboration



JHEP 12 (2022) 126
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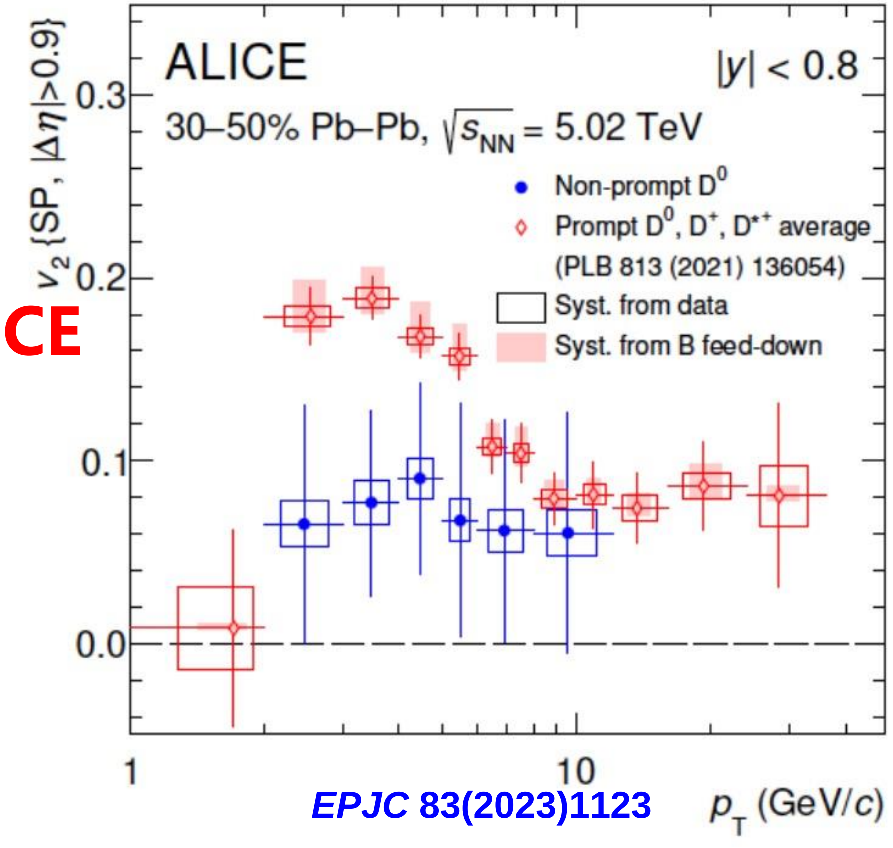
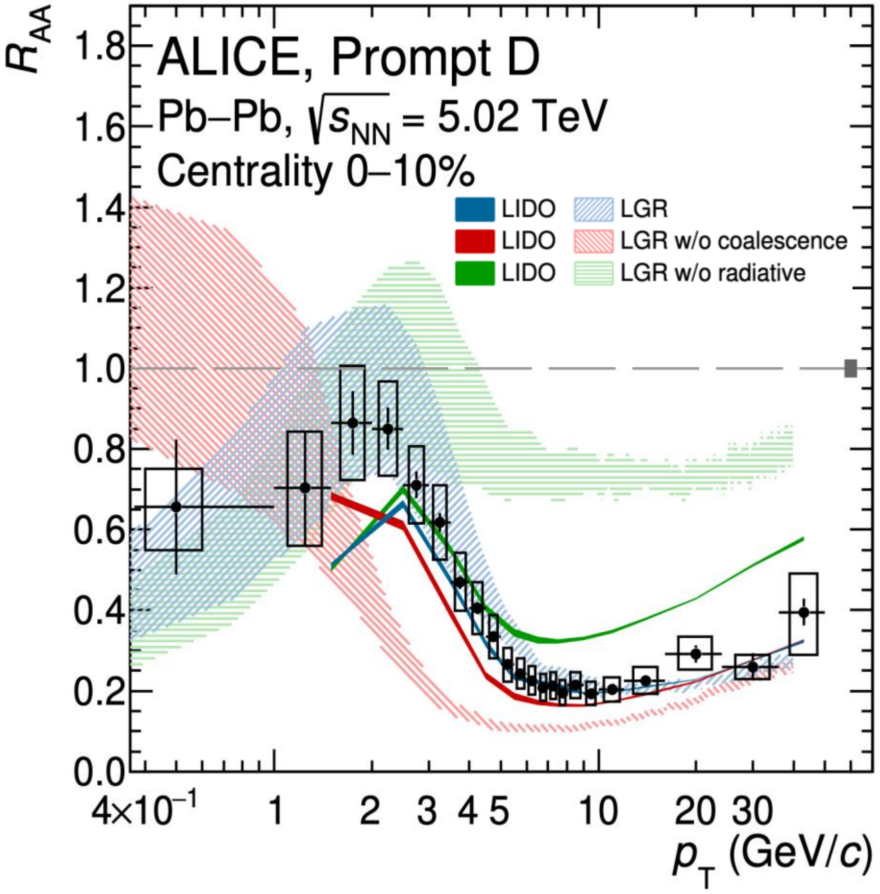
ALICE



EPJC 83(2023)1123

- 粲、底夸克穿越QGP物质遭受了很强的能量损失，但二者有明显差别，ΔE（粲）> ΔE（底），质量效应明显
- 粲、底夸克椭圆流不为零，参与了解禁闭部分子的集体运动，被部分热化，但二者热化程度不相同

Charm quark energy loss: comparison with models



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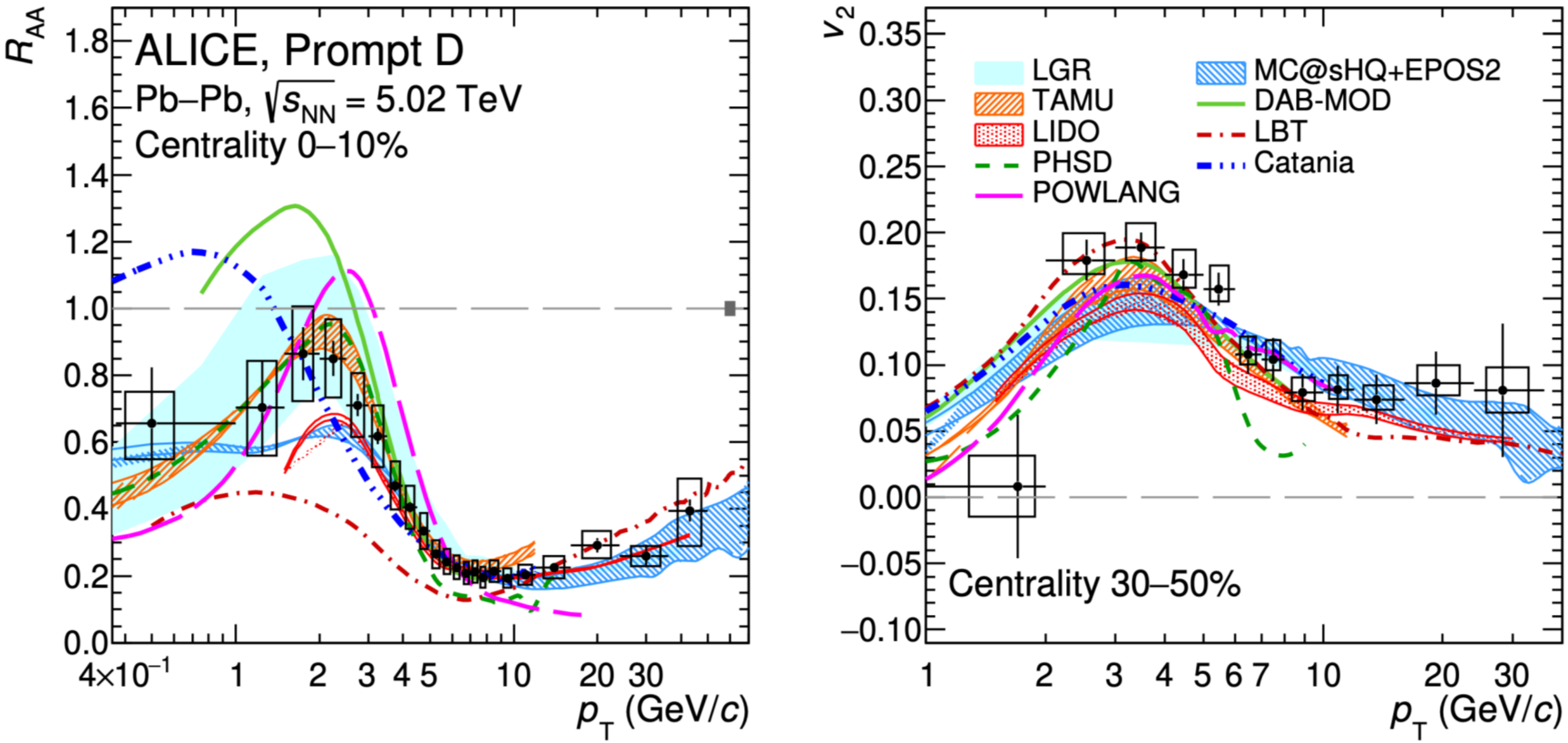
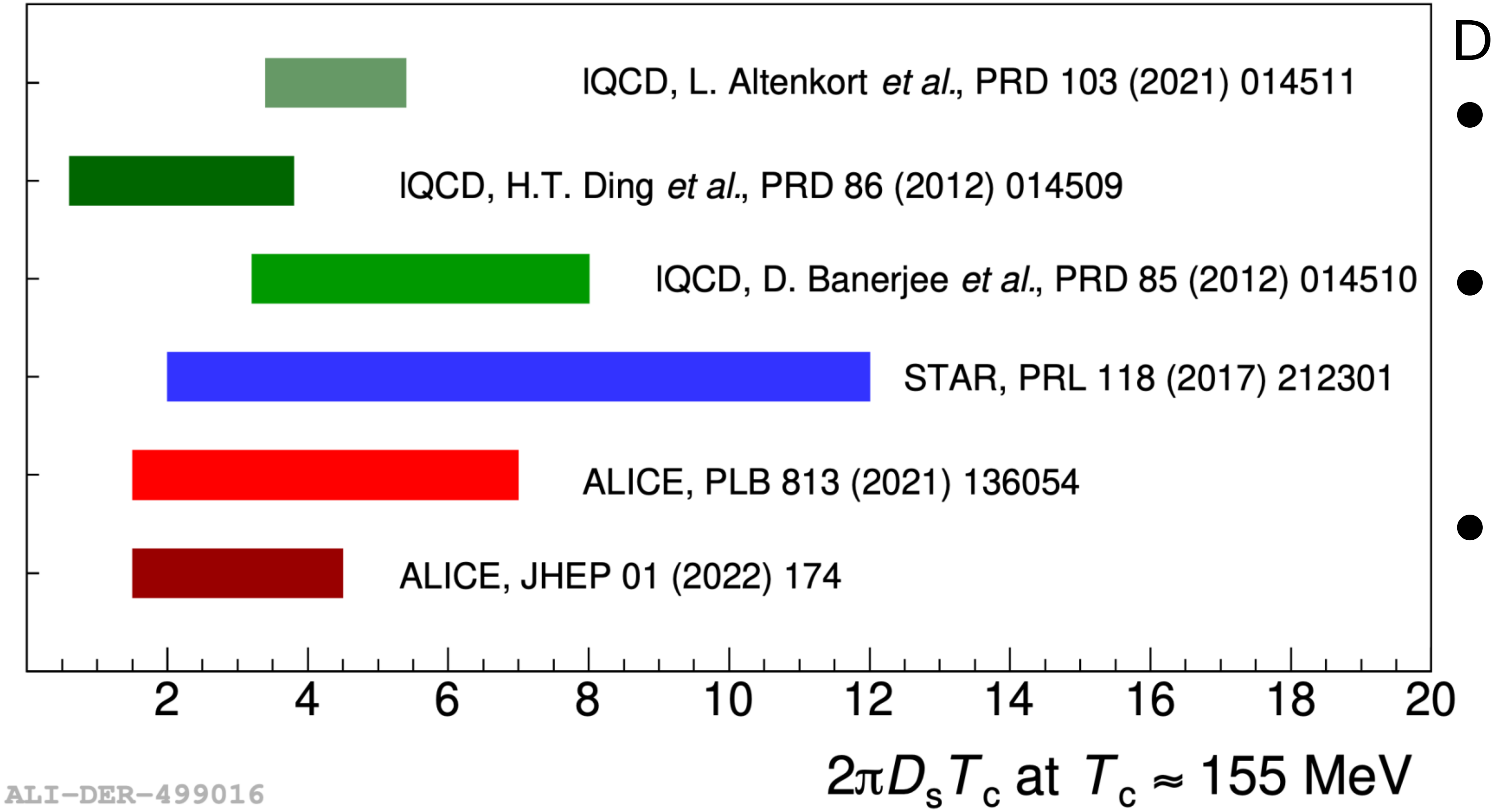
- **W/o coalescence**: large deviation from data
  - ➞ Hadronization via coalescence is important to interpret data
- **W/o radiative energy loss**: reasonably describe data in p_T < 5 GeV/c, but largely overestimate data at high p_T
  - ➞ Radiative energy loss is dominant at high p_T, while collisional energy loss is predominant at low and intermediate p_T

Charm quark transform



- Most charm quark transport models able to describe both the R_{AA} and v_2
- Use to estimate the spatial diffusion coefficient *Ds*

Charm quark transport



Diffusion coefficient D_s

- Almost independent of quark mass
- Characterization of the transport properties of the medium
- Constrains the specific shear viscosity η / s

The newest constraints from ALICE by combining D meson R_{AA} and v_2

- $1.5 < 2\pi D_s(T) < 4.5$, $\tau_{charm} = (m_{charm} / T)\, D_s(T) = 3–9$ fm/c < $\tau_{medium} \approx 10$ fm/c
- Indicate charm may thermalize in the medium

Summary for lecture 2

- Strong nuclear suppression of particle production observed in central heavy ion collisions, which provides the evidence that a dense strongly coupling medium is produced in HI collisions

- Mass dependence of energy loss of colored partons in the QGP is observed:

$$R_{AA}^{\pi} \approx R_{AA}^{D} < R_{AA}^{B}$$

- Radiative energy loss dominates at high p_T for light flavors u, d, gluons and charm

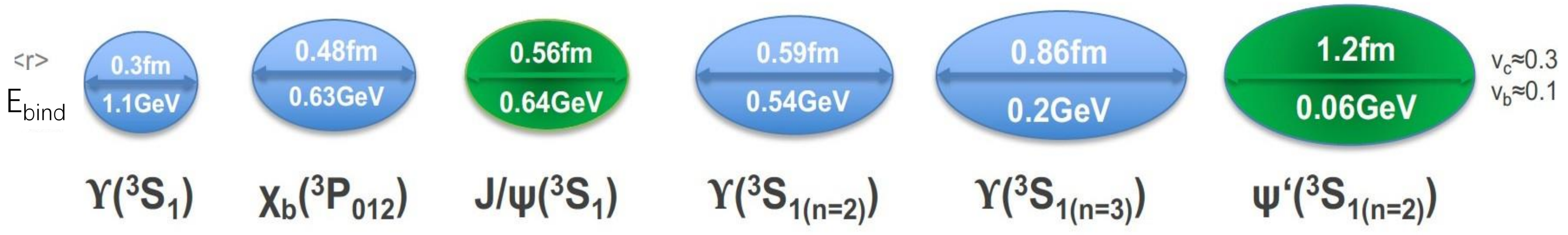
5. Quarkonia

Quarkonia

c-cbar (J/Ψ, Ψ',..) and b-bar (Υ', Υ'',Υ''') pairs from hard process

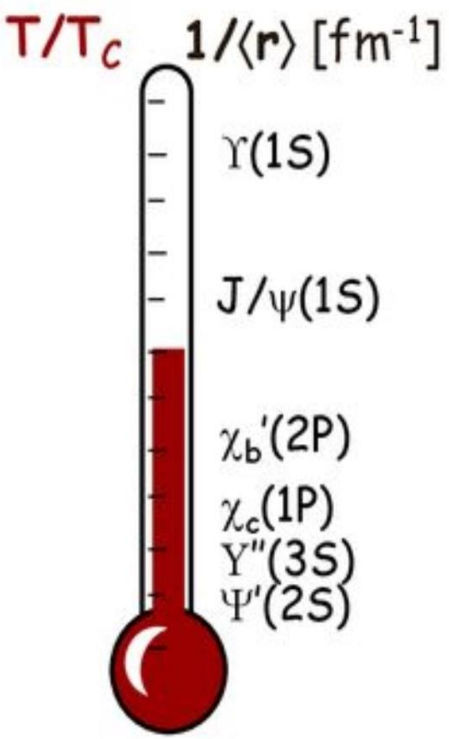
- Small decay width (~keV), significant BR into dileptons
- Intrinsic separation of energy scales: E
- A variety of states characterized by different binding energies $m_Q >> \Lambda_{QCD}$

→ Goal: understand mechanisms of **dissociation and regeneration** in QGP



To larger radius →

To lower binding energy →



Quarkonium as a thermometer for QGP

Charmonium suppression (J/ψ, ψ',...) suggested as ''smoking gun'' signatures for the QGP back in the 1980's.

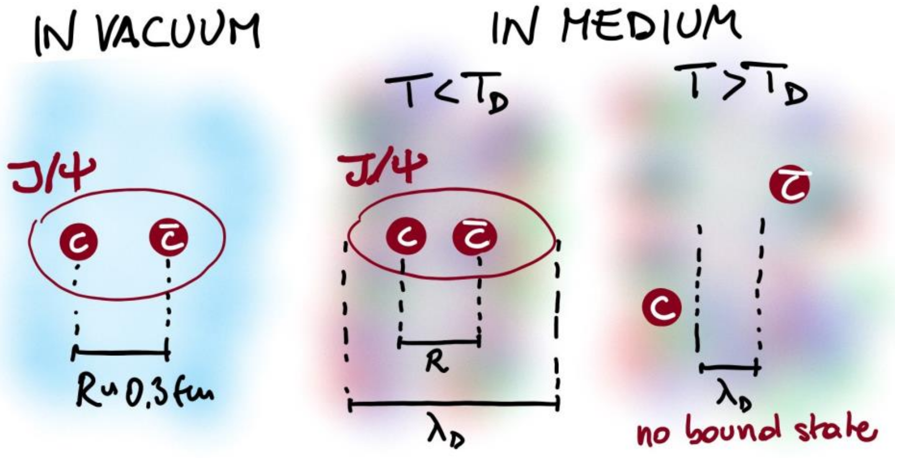
In vacuum (T=0), qqbar is bound by the Cornell potential

$$V(r) = -\frac{\alpha}{r} + kr$$

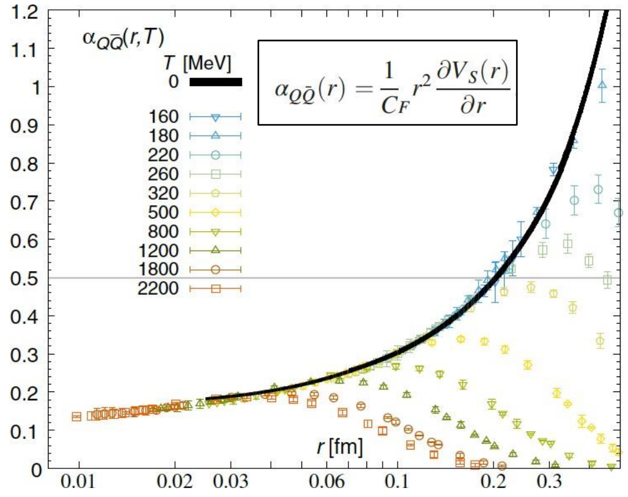
When the qqbar is immersed in the high density of quarks and gluons (QGP) **(T>0)**, the surrounding color charges screen the binding potentials (color Debye screening), resulting in

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

The effective coupling between q and qbar at large distances gets reduced → q-qbar melting

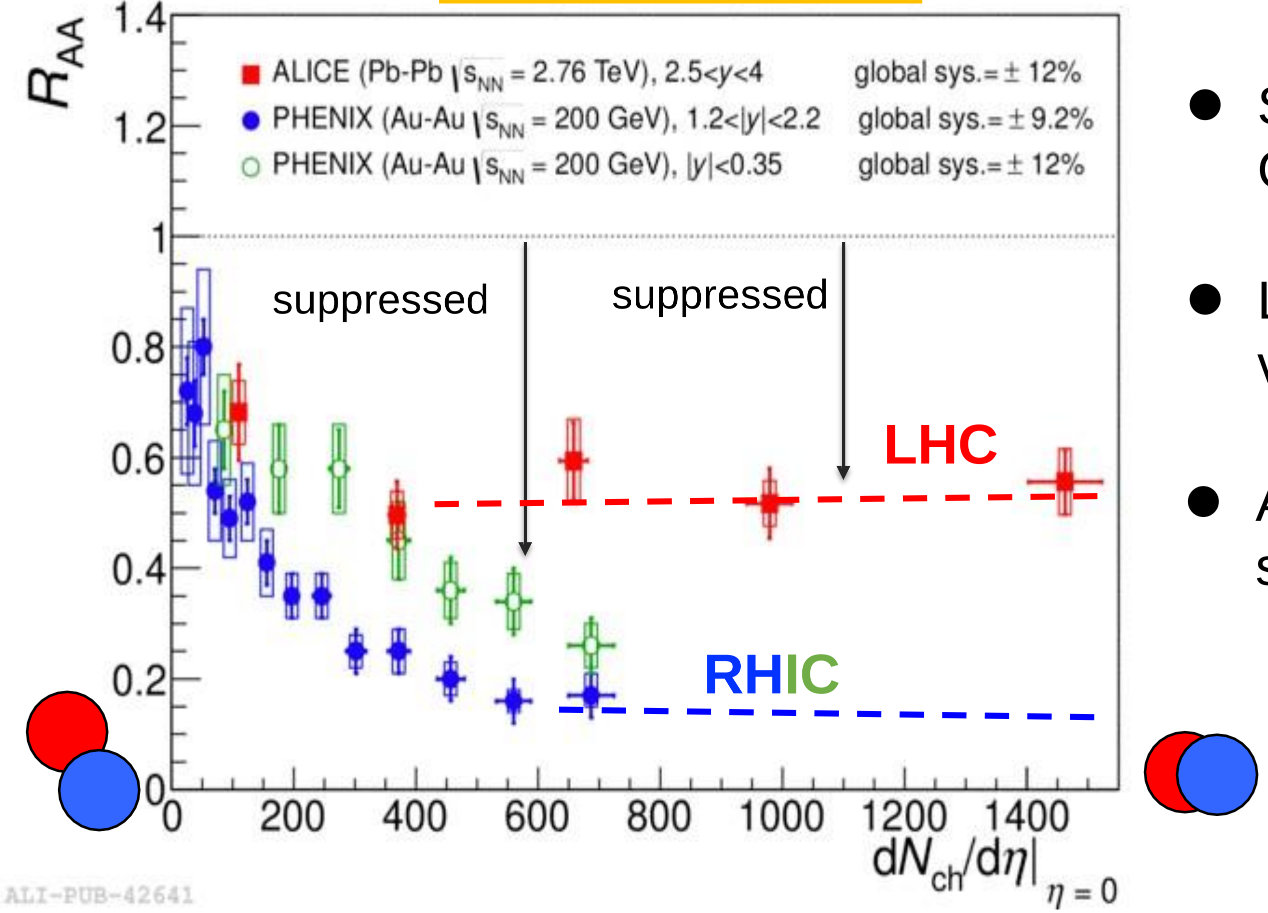


Effective coupling from (2+1) QCD at various T



J/ψ suppression

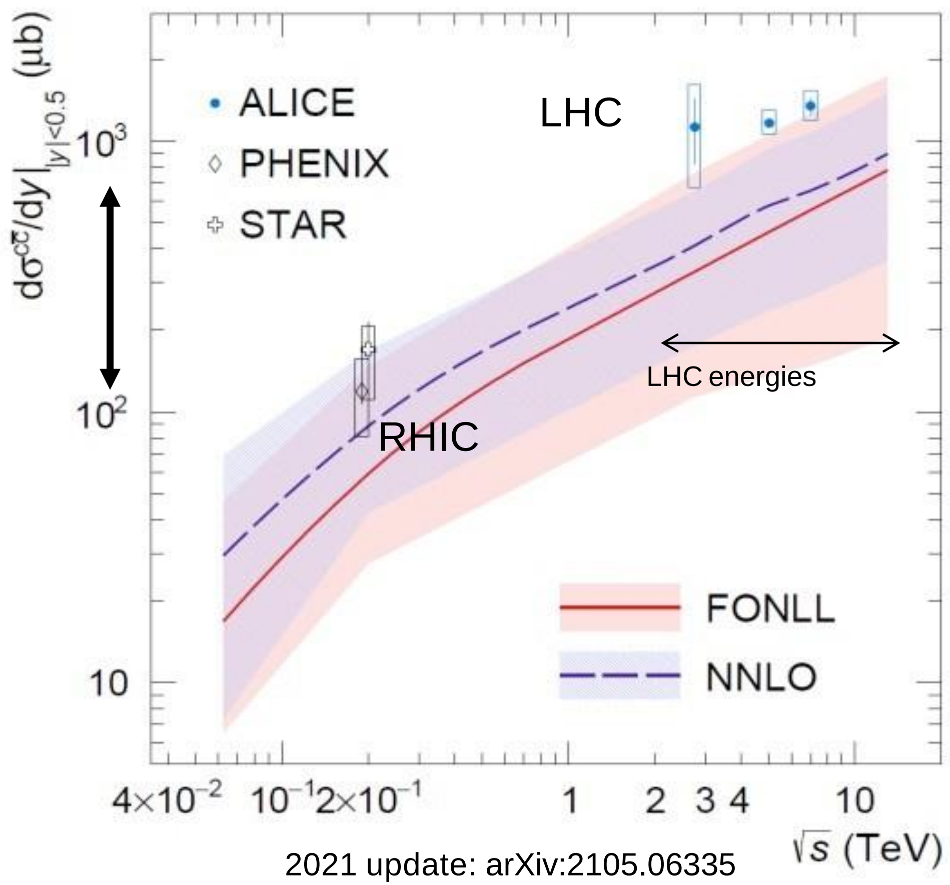
R_{AA} vs. multiplicity



- Suppression early observed at the SPS ($\sqrt{s_{NN}}$ = 17 GeV), due to Debye screening
- Later measured at RHIC ($\sqrt{s_{NN}}$=200 GeV) up to very high multiplicities
- At the LHC, $\sqrt{s_{NN}}$ = 2.76 TeV, yet J/ψ is less suppressed, due to the larger charm cross section

c-cbar production vs Collision energy

c-cbar production cross section



2021 update: arXiv:2105.06335

The cross section for producing a c-cbar pair increases with collision energy

In a central event

at SPS ~ 0.1 c-cbar

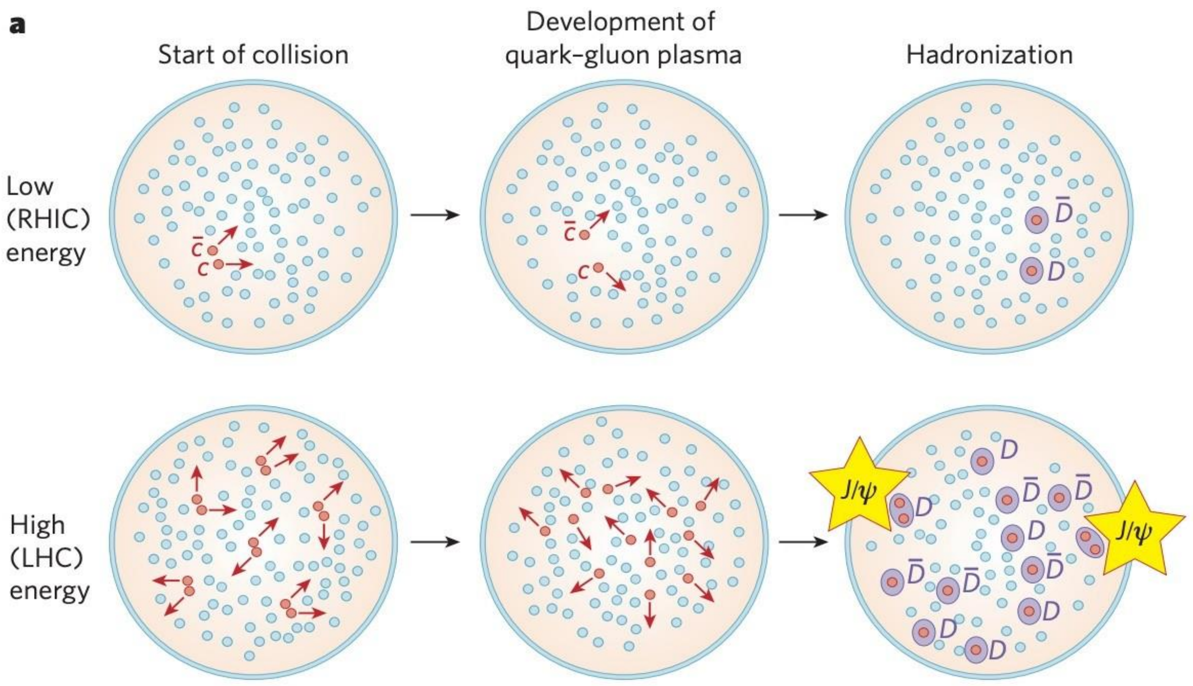
at RHIC ~ 10 c-cbar

at LHC ~ 100 c-cbar

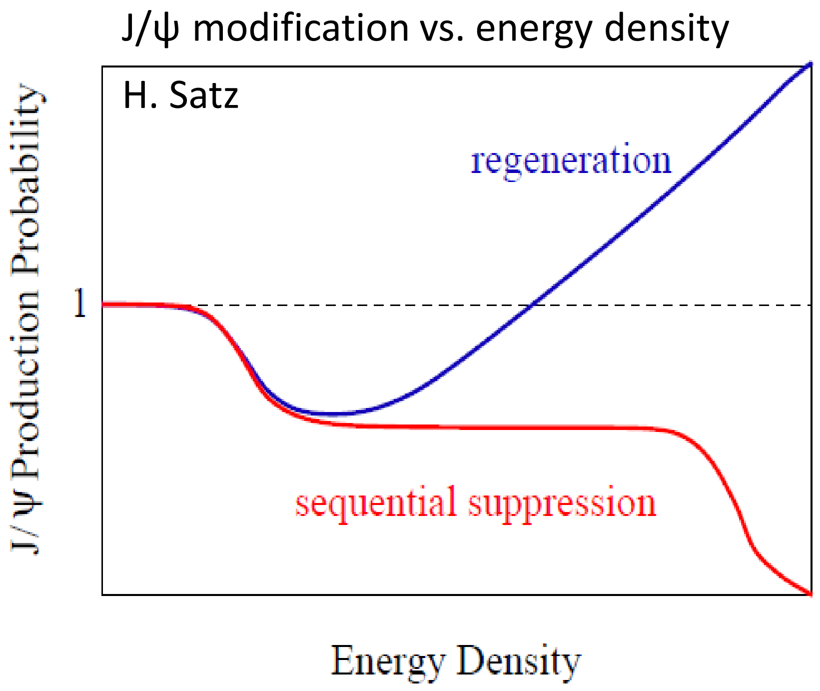
c from one c-cbar pair may combine with cbar from another c-cbar pair at hadronization to form a J/ψ

→ **regeneration!**

J/ψ suppression & regeneration



P. Braun-Munzinger, J. Stachel., Nature 448, 302–309 (2007)

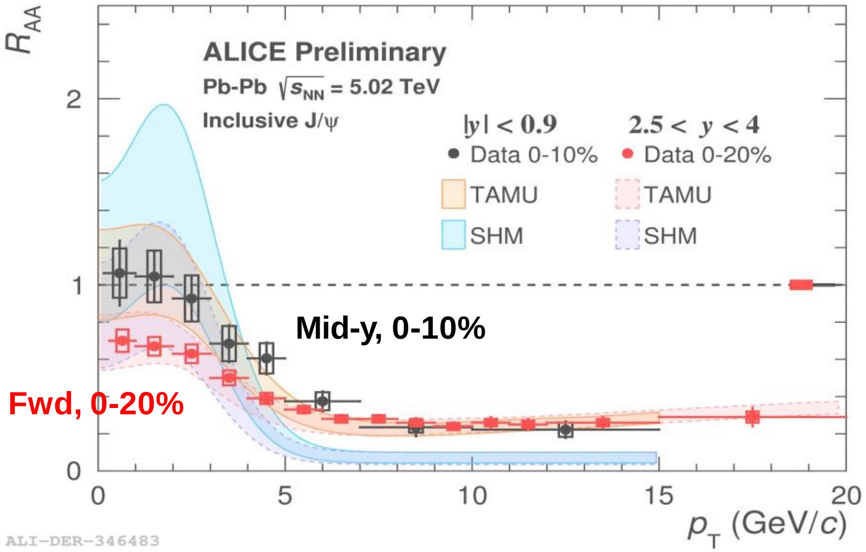


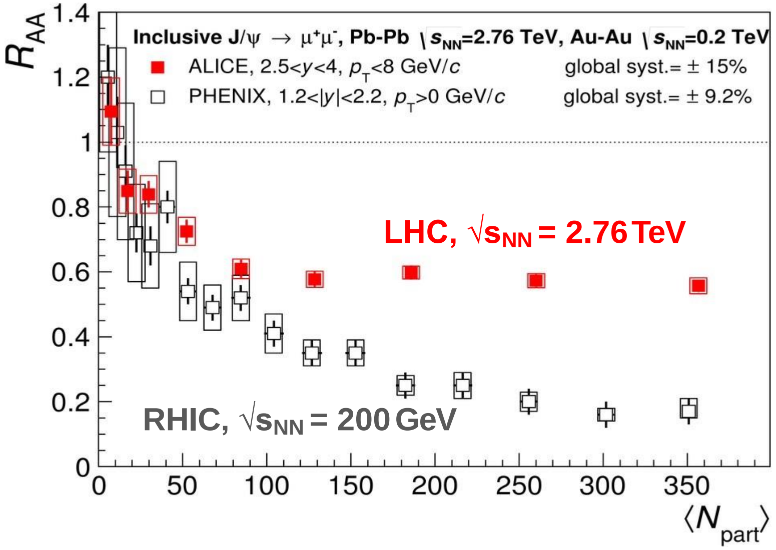
Regeneration of charmonium and charmed hadron production take place at the phase boundary or in QGP.

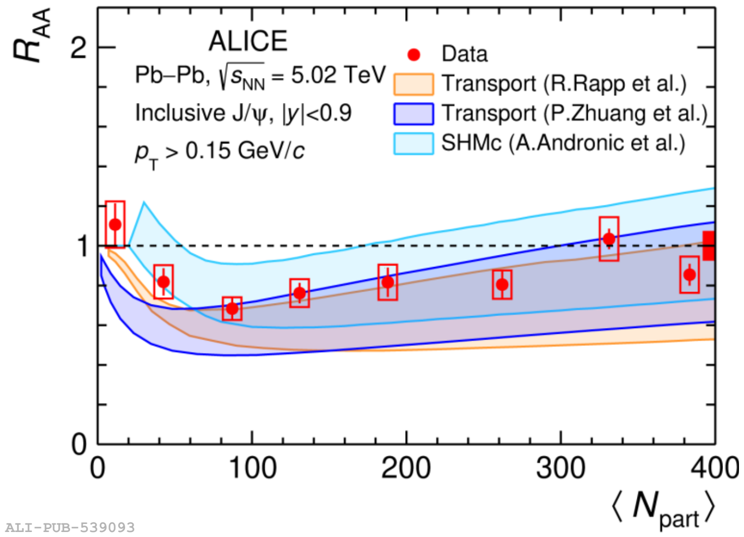
Dissociation and regeneration take place in opposite directions vs energy density.

J/ψ suppression vs regeneration

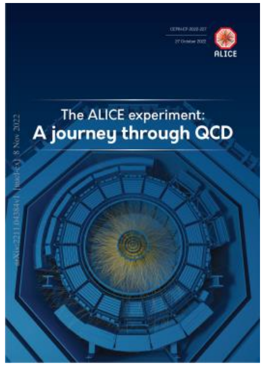
[1] *Phys. Lett.* B 849 (2024) 138451;
[2] *JHEP* 02 (2024) 066



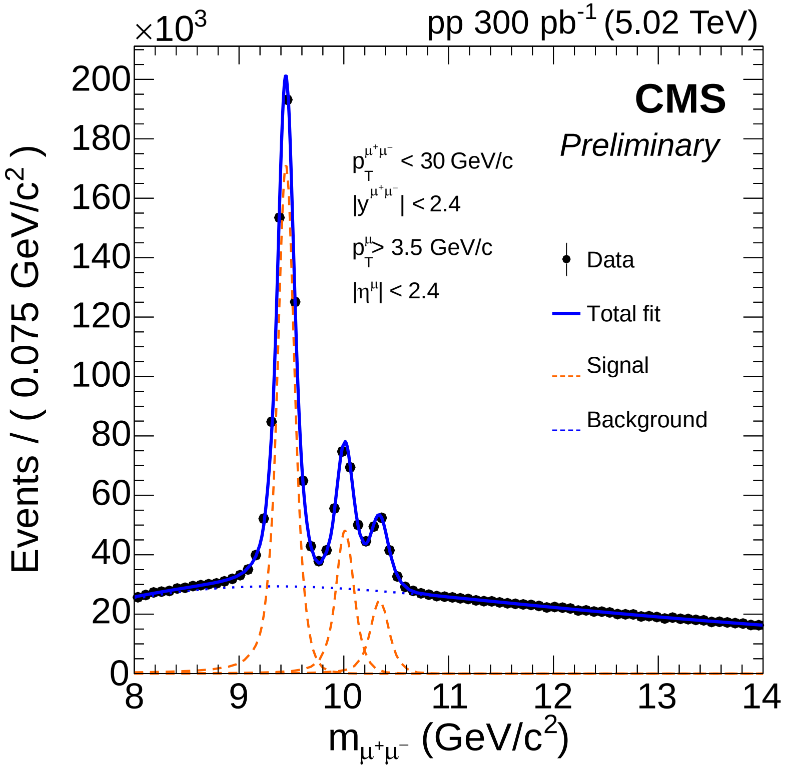


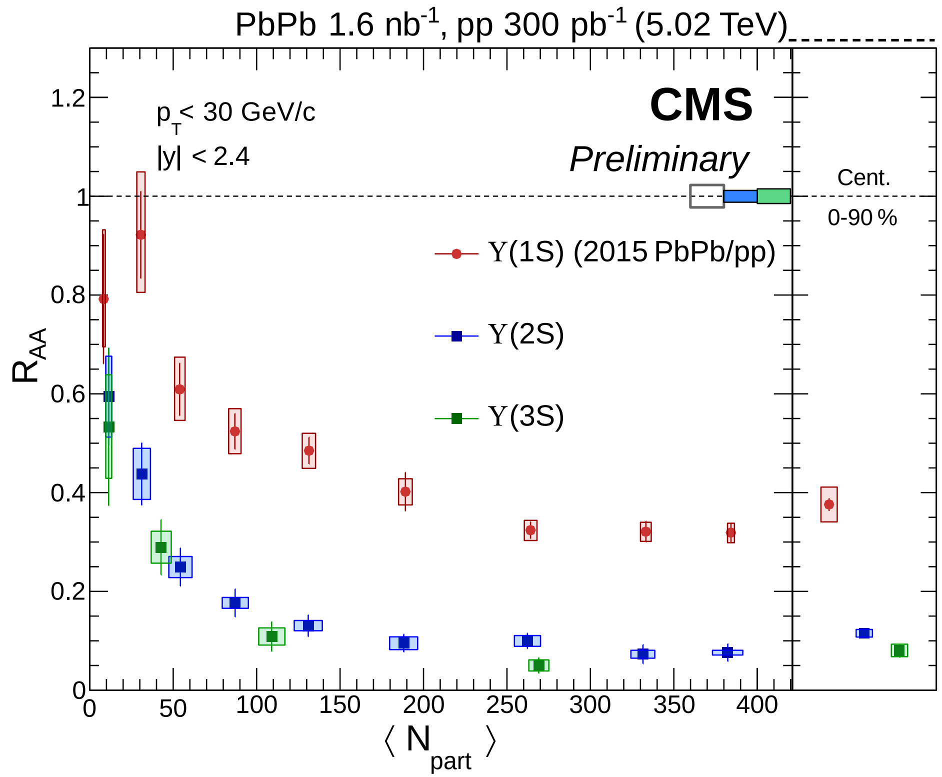


- ALICE data from 5.02 TeV Pb-Pb collisions confirm the J/ψ recombination picture:
  - R_{AA}(LHC) > R_{AA}(RHIC)
  - R_{AA} midrapidity > R_{AA} forward rapidity, increase with centrality
- Evidence for the deconfinement and (re)generation



Sequential melting of quarkonia

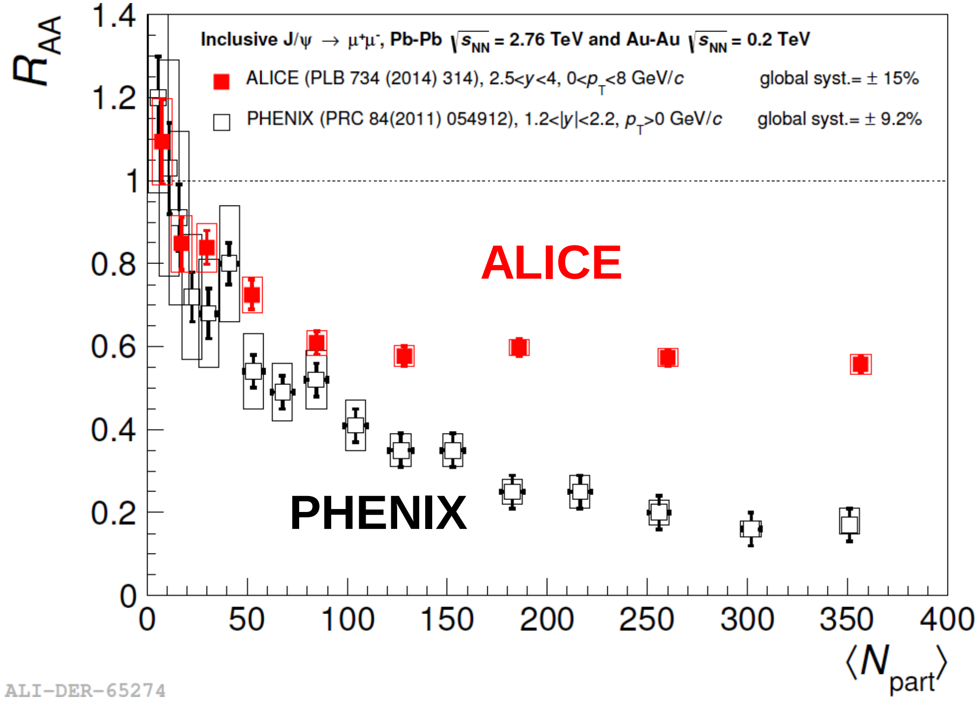




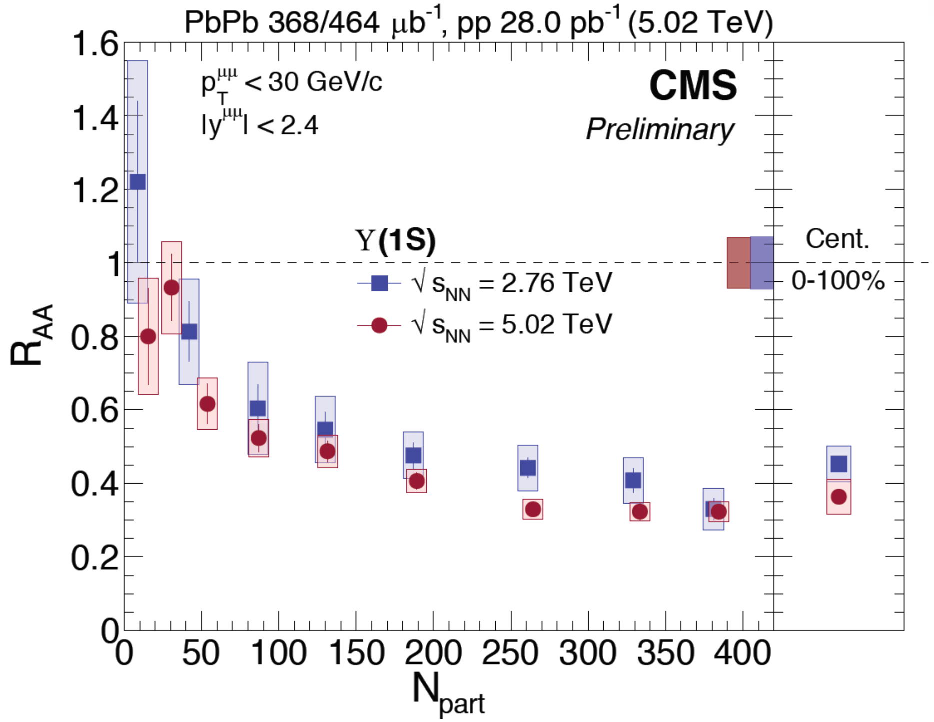
- Measurements reveal a sequential suppression of high mass bottomonium states.
- The centrality dependence of the asymptotical suppression in a hotter medium is observed.

Quarkonia as probes

Charmonium R_{AA}



Bottomonium R_{AA}



Charm is partially equilibrated (thermalized) with the medium

- ➢ A partially-equilibrated probe of the late hadronization stages

Beauty/bottomonia: no evidence that beauty is even partially equilibrated with the medium

- ➢ Non-equilibrium probe (open question)

Summary for Quarkonia

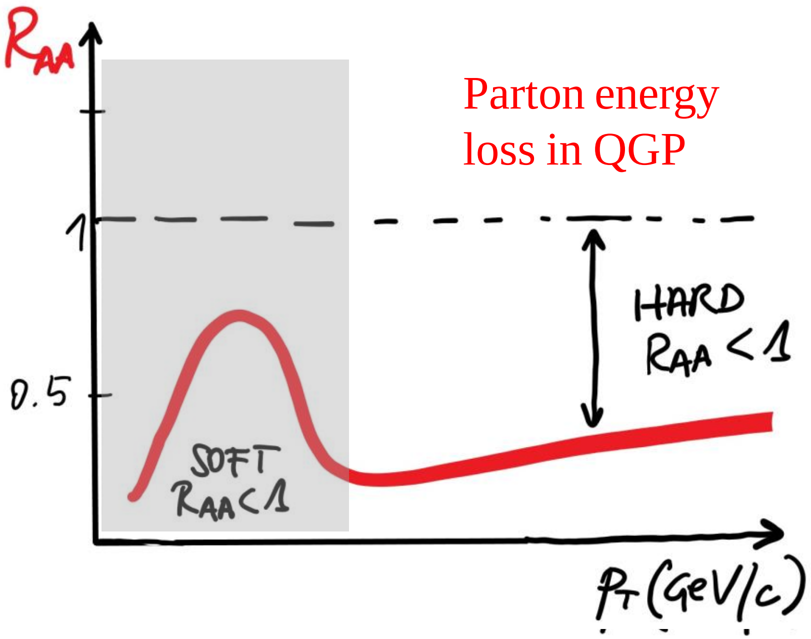
The study of quarkonium (ccbar, bbar) states provides information on the mechanisms of **dissociation and regeneration** of strongly-bound state in a medium (T>0).

- The high density of color charges in the QGP leads to melting of quarkonia
- The large abundance of charm quarks at LHC results in regeneration of the amount of J/ψ
- States with smaller binding energies are more suppressed (“QGP thermometer”)

Backup

The nuclear modification factor, R_{AA}

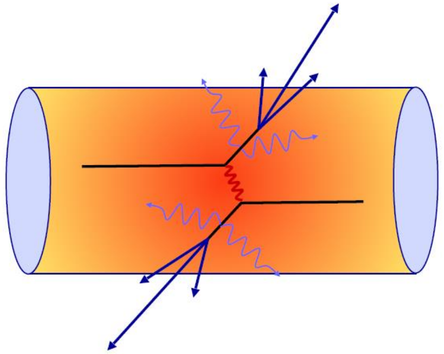
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



If a AA collision is a incoherent superposition of independent pp collisions, the p_T spectra in AAcollisions can be obtained by scaling the p_T spectra in pp collisions by the number of nucleon-nucleon collisions, N_{coll} :

$$\mathrm{d}N_{AA}/\mathrm{d}p_T = N_{coll} \times \mathrm{d}N_{pp}/\mathrm{d}p_T$$

and $R_{AA} = 1$ at high p_T
→ the medium is transparent to the passage of partons



If $R_{AA} < 1$ at high p_T
→ the medium is opaque to the passage of partons
→ **parton-medium final state interactions, energy loss, modification of fragmentation in the medium**