Heavy Flavor and Quarkonia

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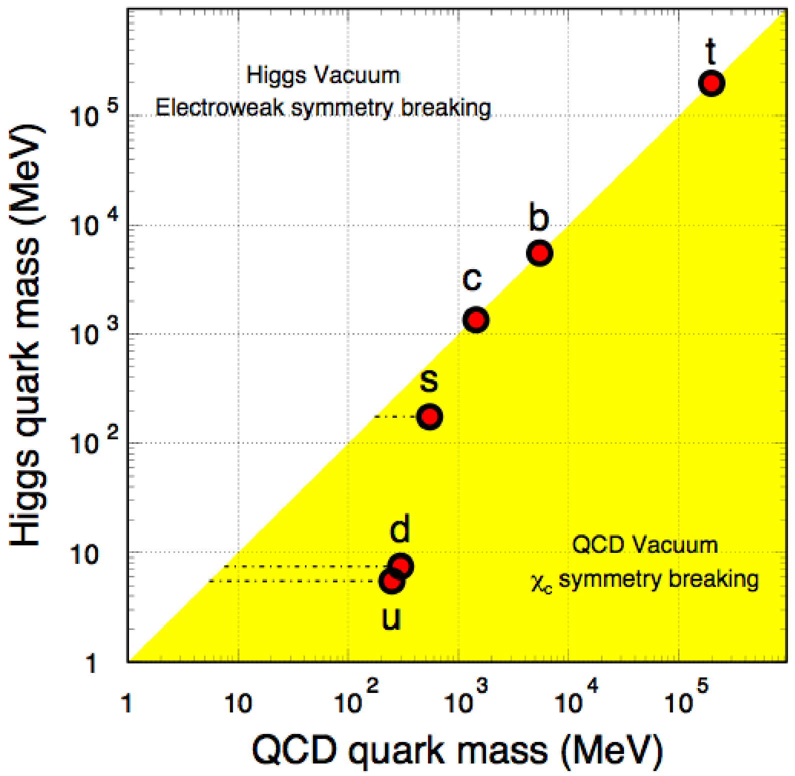
What Does "Heavy" Mean

Heavy Flavor: quarks with large masses, usually refer to charm and bottom quark



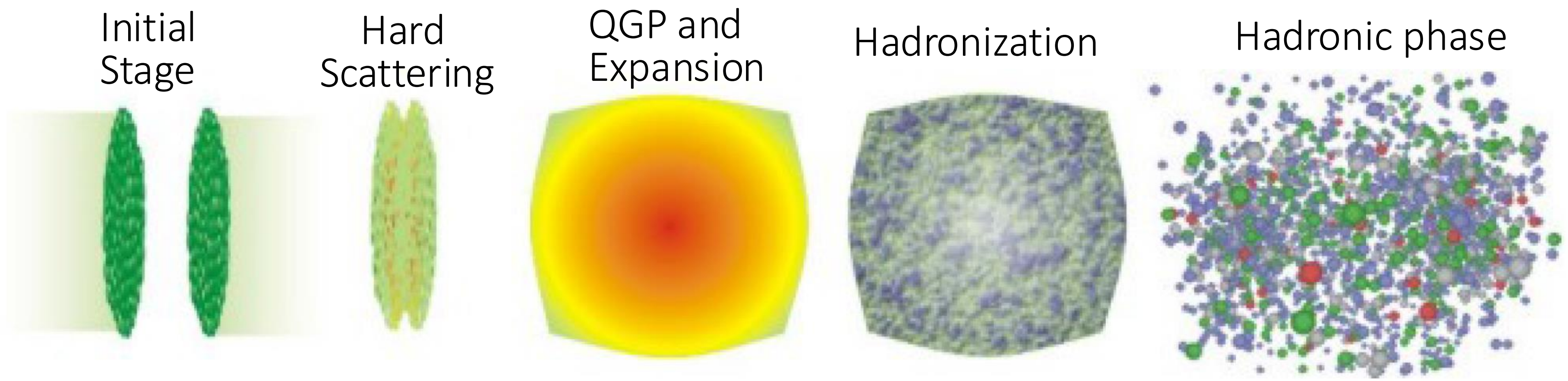
X. Zhu et al., PLB 647, 366 (2007)

Strong interactions do not affect heavy quark masses

Top quark has too short lifetime

- ~0.15 fm/c << QGP formation time
- Irrelevant to heavy ion collision physics (?)

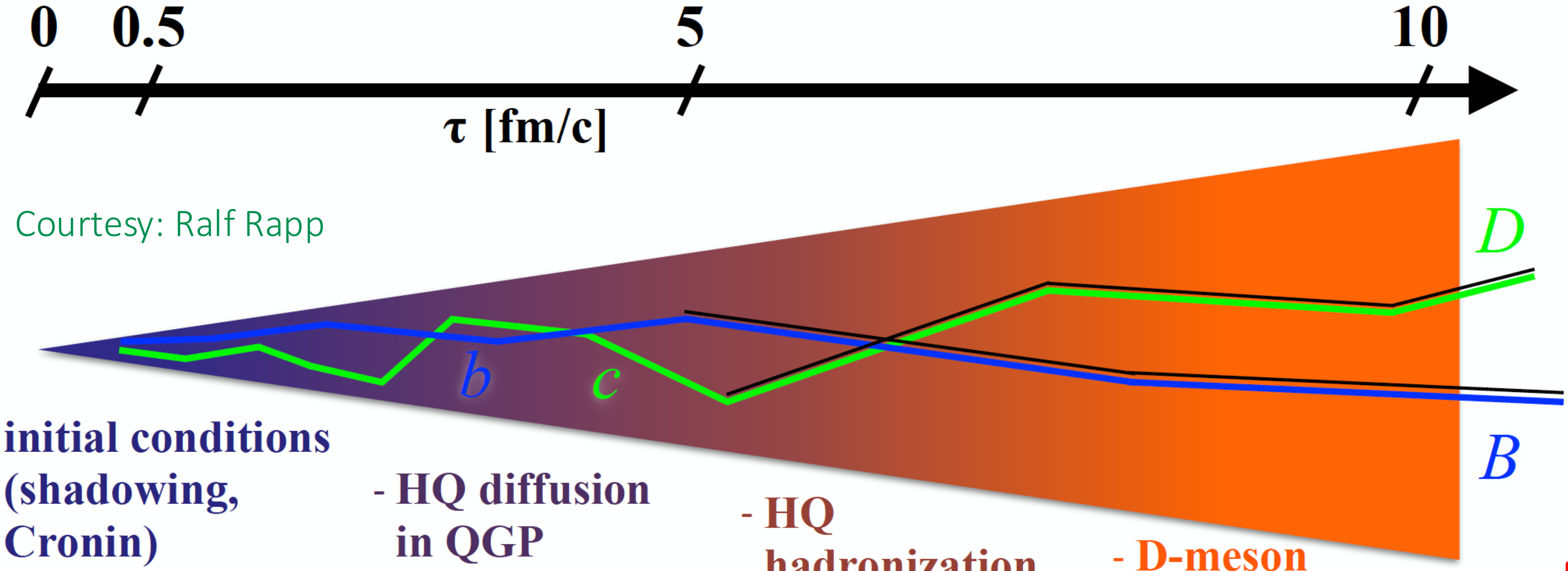
Pros of Being Heavy



- $t \sim \frac{1}{m_c}, \frac{1}{m_b} < \tau_{0,QGP}$: Produced early
- $m_c, m_b \gg \Lambda_{QCD}$: Produced in initial hard scattering calculable in pQCD
- $m_c, m_b \gg T_{QGP}$: Production in QGP is negligible

Penetrating probe: experience the whole evolution of QGP

A Journey of HQ in Heavy Ion Collisions



Courtesy: Ralf Rapp

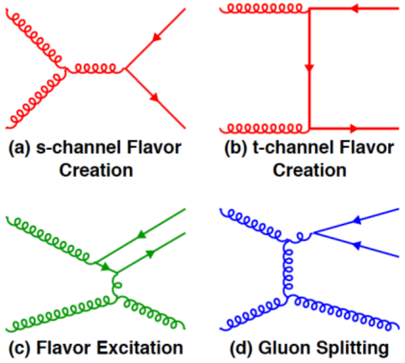
- initial conditions (shadowing, Cronin)
- Pre-equil. fields

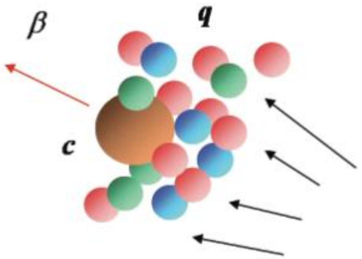
- HQ diffusion in QGP

- HQ hadronization

- D-meson diffusion at hadronic phase

# of heavy quarks is constant throughout the evolution





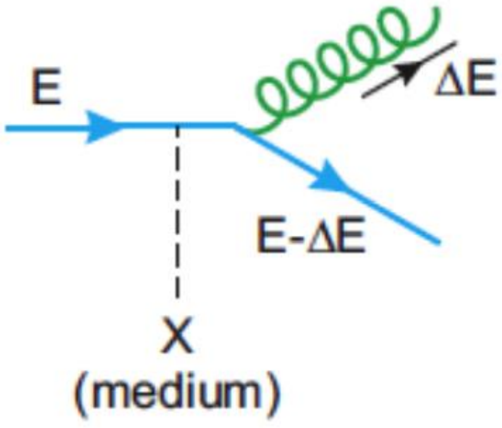
Fragmentation
+
Coalescence?

Probe the medium with final heavy flavor hadrons

Parton Energy Loss in QGP

Radiative energy loss

Inelastic scattering



D. d'Enterria and B. Betz,
Lect. Notes Phys. 785, 285 (2010)

Energy lost by radiation of gluons induced by interactions with the hot and dense medium

$$\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$$

$\hat{q}$: Transport coefficient of the QGP medium

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

Relate to the energy (gluon) density of the medium

C_R: Casmir coupling factor

4/3 for quark-gluon coupling

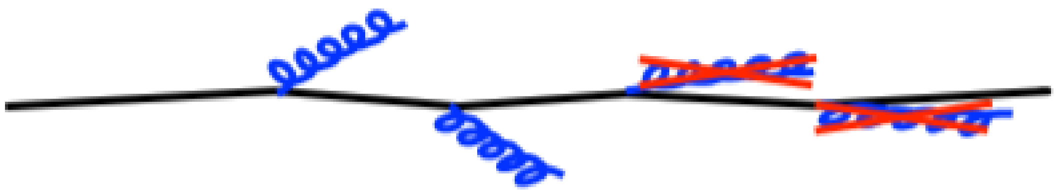
3 for gluon-gluon coupling

$$\langle \Delta E \rangle_g > \langle \Delta E \rangle_q$$

Heavy Quark Energy Loss in QGP

"Dead-Cone" effect: Gluon radiation in vacuum is suppressed for small angle due to kinematical constraints

Y. Dokshitzer, D. Kharzeev, PLB519, 199 (2001)

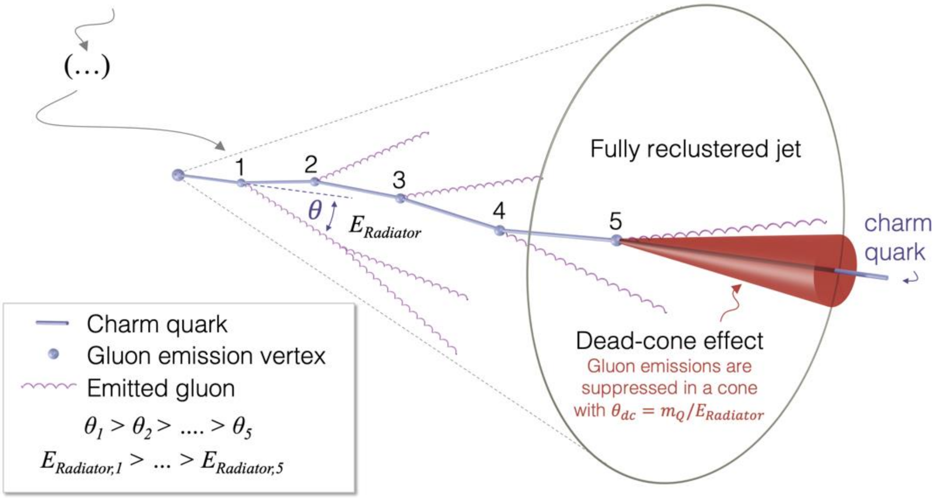


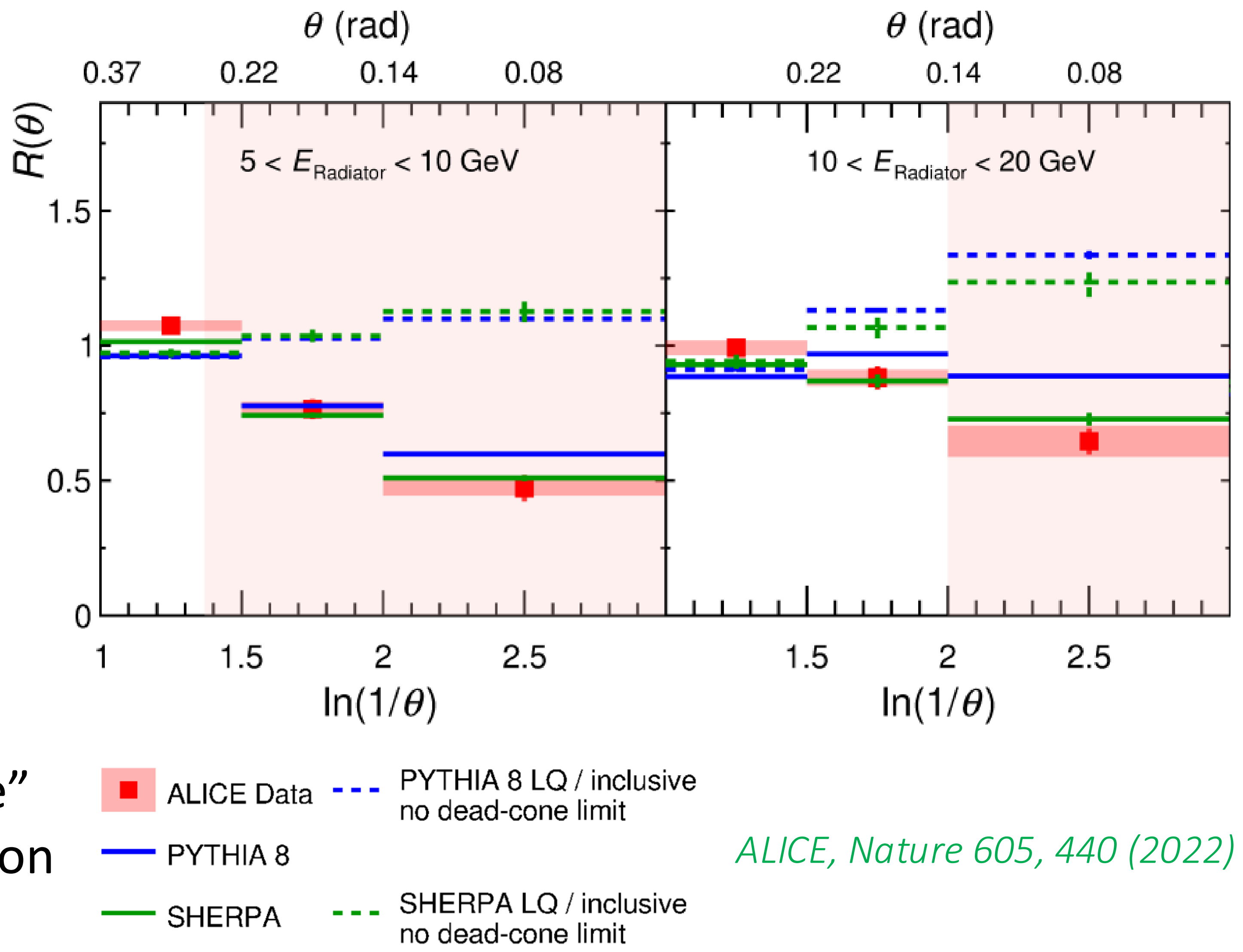
$$\langle \Delta E \rangle = \frac{\langle \Delta E \rangle_0}{(\theta^2 + \theta_0^2)^2} \qquad \theta_0 = \frac{1}{\gamma} = \frac{\boldsymbol{m_q}}{E}$$

Smaller energy loss for heavy quarks,
especially when the energy of a parton is close to its mass

$$\langle \Delta E \rangle_g > \langle \Delta E \rangle_{u,d,s} > \langle \Delta E \rangle_c > \langle \Delta E \rangle_b$$

Direct Observation of "Dead-Cone" Effect





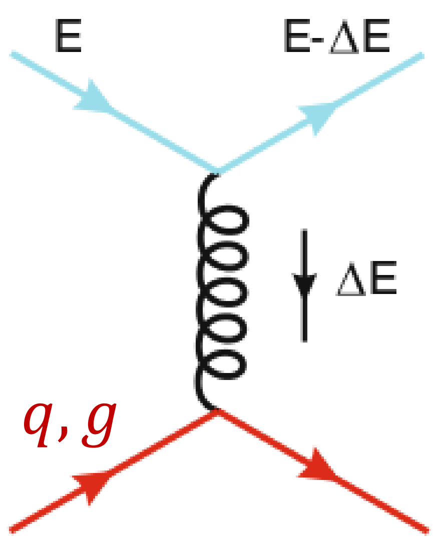
First direct observation of "dead-cone" effect in jets containing a soft D^0-meson

ALICE, Nature 605, 440 (2022)

Elastic Collision of Heavy Quark in QGP

Collisional energy "loss"

Elastic scattering



One-dimensional elastic collision in classic mechanics

$$\frac{\Delta E}{E} = \frac{4k}{(k+1)^2}, \qquad k = \frac{M}{m} \gg 1$$

High-energy object: Lose small energy per collision

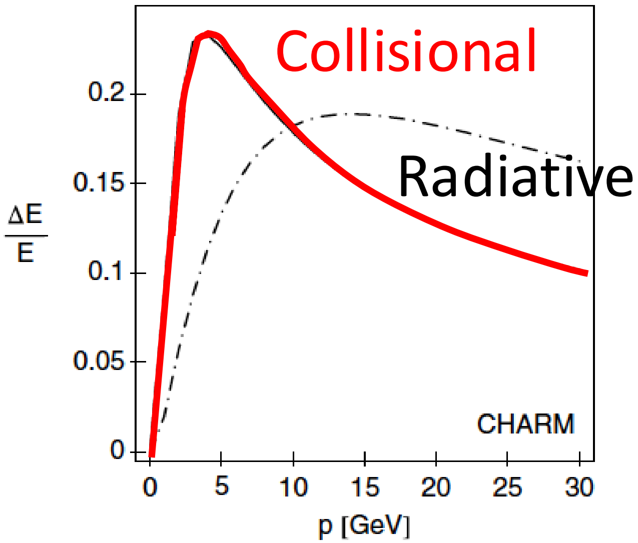
Low-energy object: May gain small energy from the medium

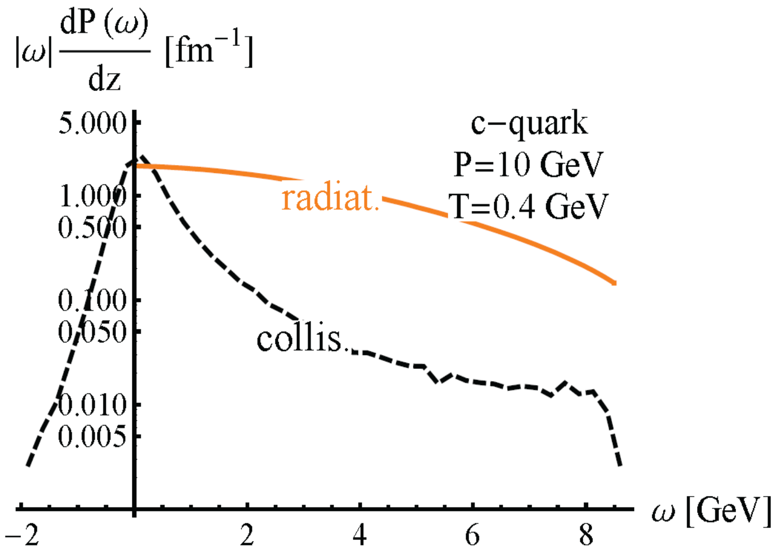
"Brownian motion"

Large relaxation time for heavy flavor quark, larger or comparable to QGP lifetime

→ Interactions at all stages are important (so-called memory?)

Elastic vs. Inelastic Collisions in QGP





M. Djordjevic, PRC74, 064907 (2006)

Elastic collision:

- Dominant at low-p_T
- Not aways energy "loss"
- Responsible for heavy quark collectivity

Inelastic collision:

- More important at high-p_T
- Main contributor of energy loss (jet quenching)

Both have much less effect on bottom than charm

Heavy Quarks Probe QGP

HF hadrons production affected by interaction between heavy quark and medium

They are sensitive to:

- Properties of the hot and dense medium
- Mechanism of heavy quark and medium interaction

Low-p_T:

- Thermalization of heavy quarks
- Diffusion coefficient

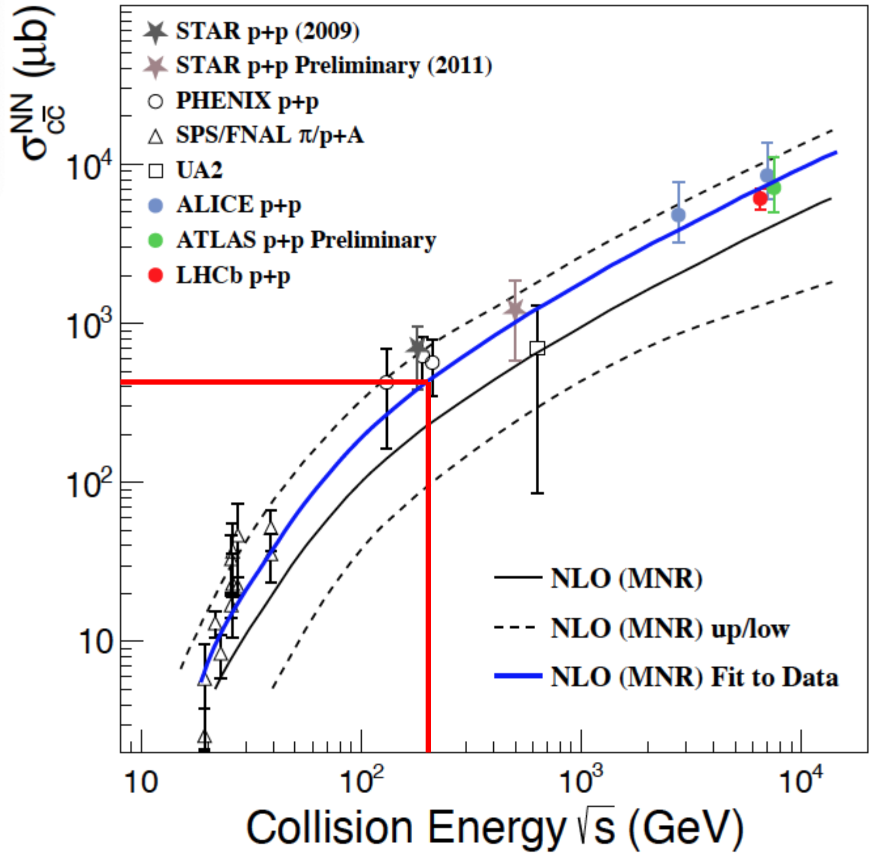
High-p_T:

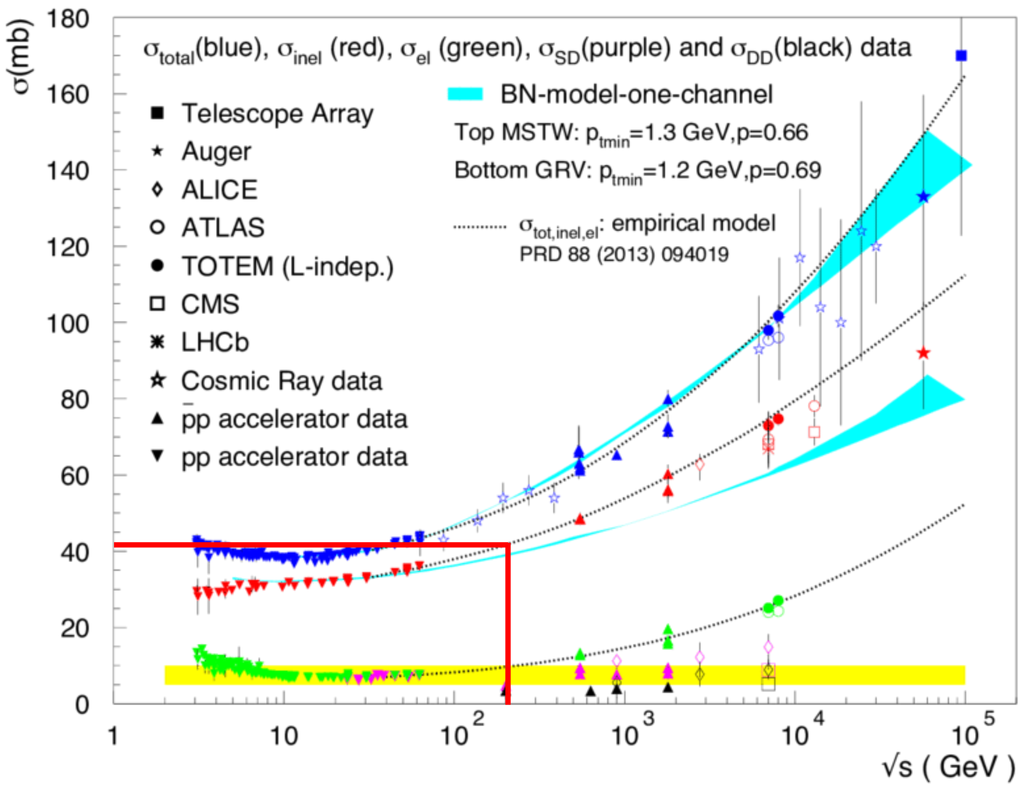
- Energy loss of heavy quarks
- Transport coefficient

Hadronization mechanism is essential for experiment and theory comparisons

How to Measure Heavy Flavor Hadrons

Charm Quark Pair Production Cross Section



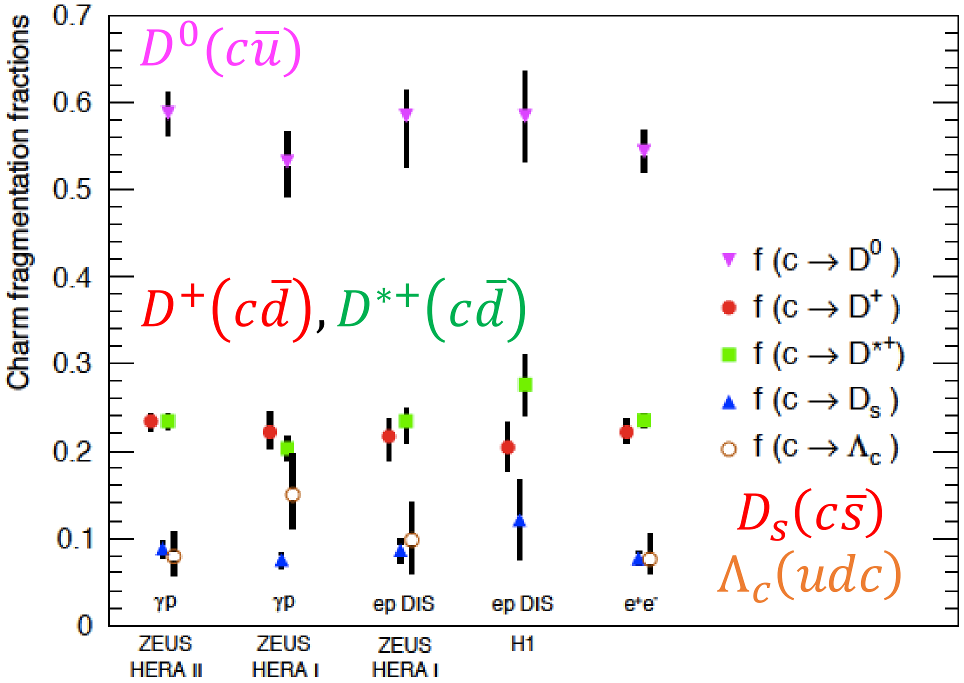


400 μb/40 mb = 1 $c\bar{c}$ per 100 Min. Bias p+p events @RHIC

~1/5 produced in one unit of rapidity at mid-rapidity

~0.6 $c\bar{c}$ at mid-rapidity per MB Au+Au collisions at RHIC, 10x more at LHC

Charmed Hadrons



ZEUS, JHEP 1309, 058 (2013)

QUESTION: Why D^0 is significantly higher than D^+?

Hadron	Abundance (fragmentation)
D^0	56%
D^+	24%
D_s	10%
Λ_c	10%

Short lifetime → Decay before tracker

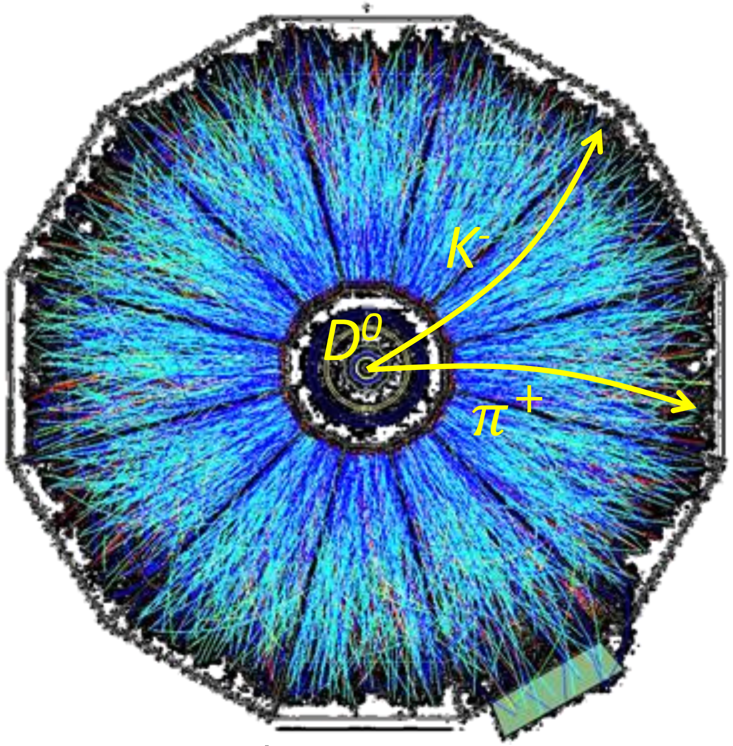
- Can not be detected directly
- Has to be reconstructed from decay products

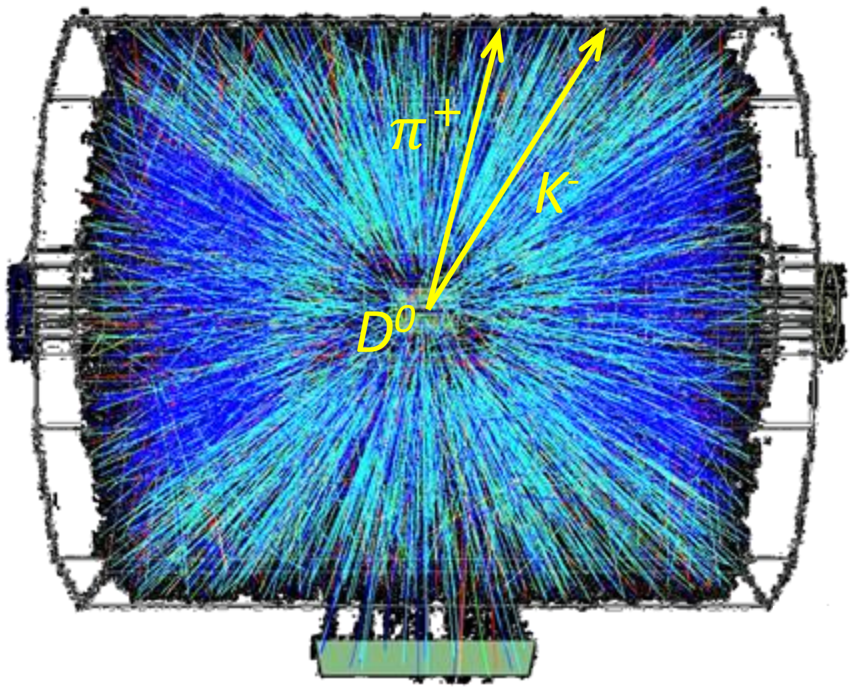
D^0-meson Reconstruction

Golden channel:

$D^0 \rightarrow K^-\pi^+$

Br. ~ 3.9%





- Need to pay all K^- with all π^+ in the same event

  $dN/dy(\pi^+) \sim 100 \quad dN/dy(K^-) \sim 20$

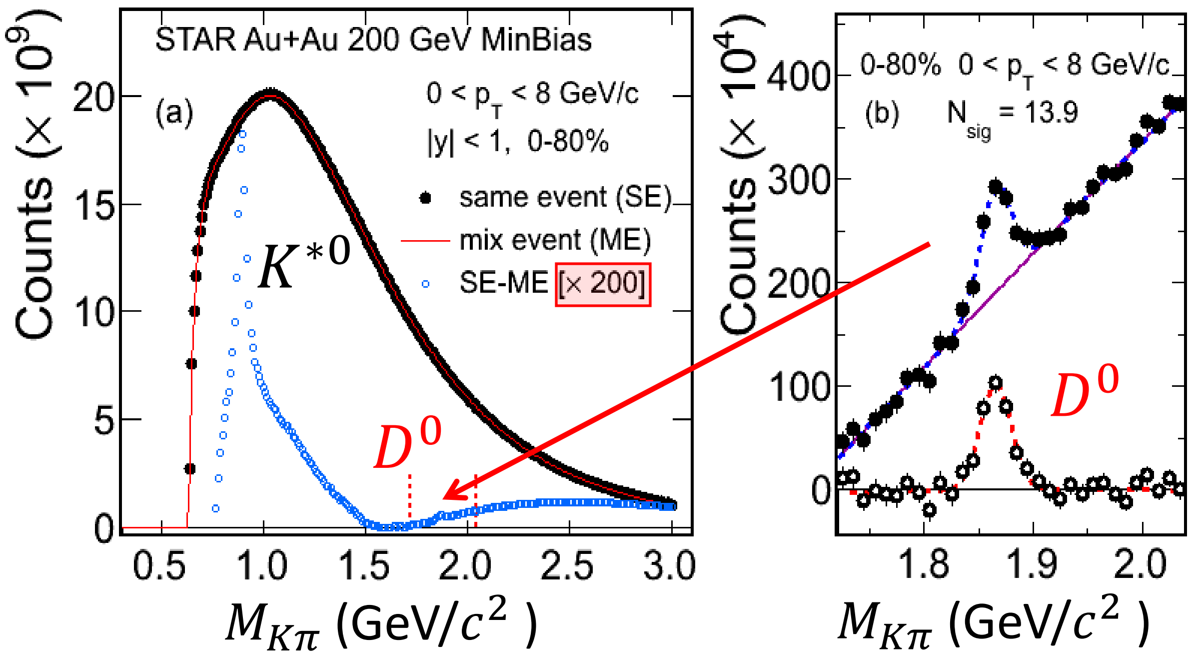
  STAR, PRC79, 034909 (2009)

  Signal-to-background ratio: 0.01 vs. 2000

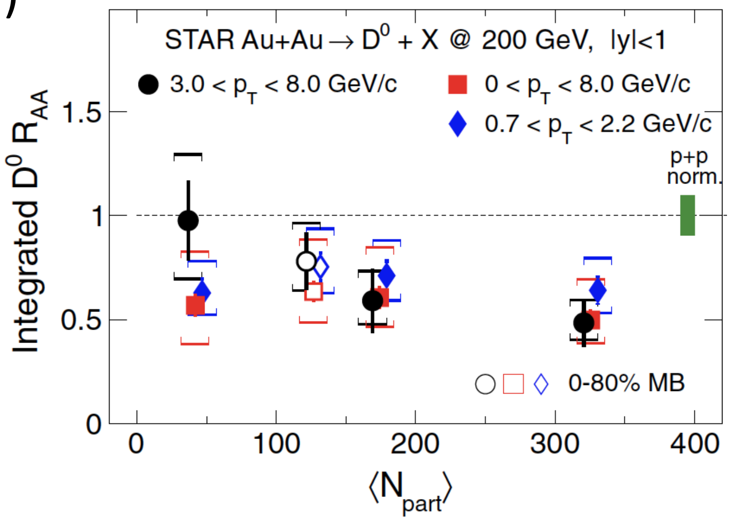
  Better if concentrate on narrow mass window

- Huge random combinatorial background may be *estimated* with the same data

D^0-meson Reconstruction



STAR, PRL113, 142301 (2014)



It is doable, but very challenging

- Rely on good particle (mainly kaon) identification
- The statistical and systematic uncertainties are large

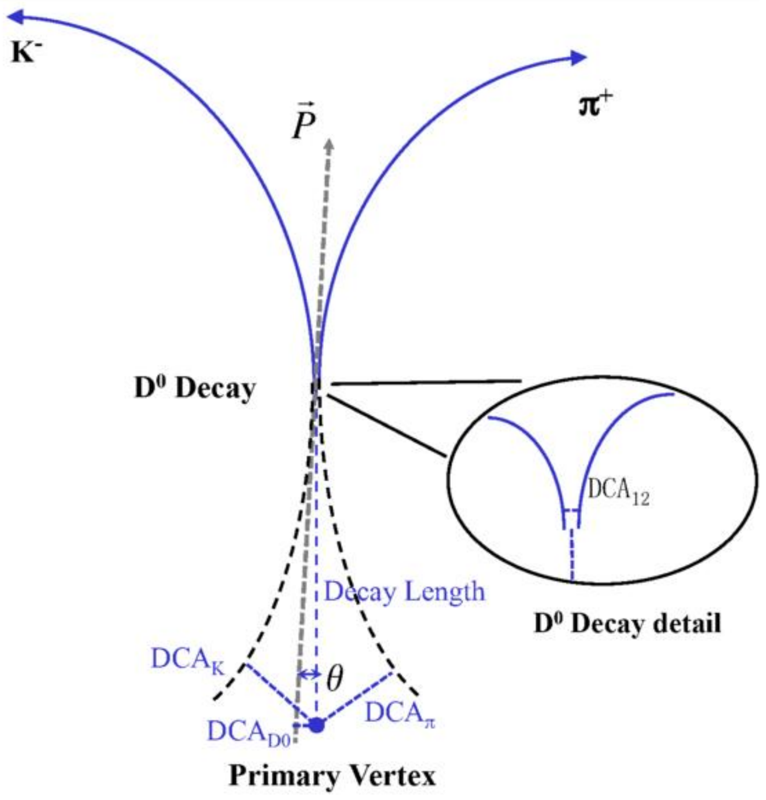
Topological Reconstruction

- Kaons and pions from D decay are originated from secondary vertex, *a little bit* away from primary vertex

Hadron	Abundance (fragmentation)	cτ (μm)
D^0	56%	123
D^+	24%	312
D_s	10%	150
Λ_c	10%	60

Less than 1/2 thickness of a fingernail!!!

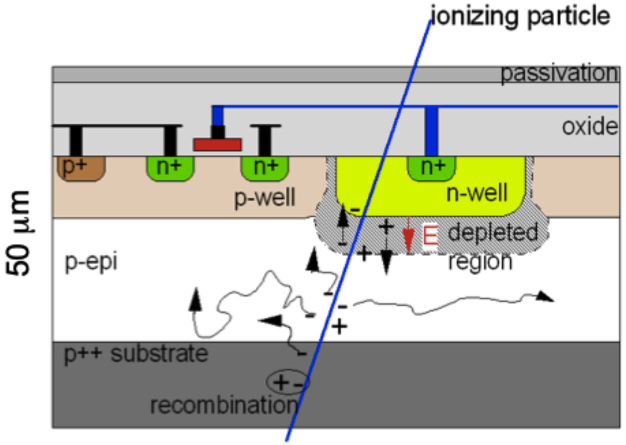
QUESTION: Does this method work for low-p_T D-mesons?

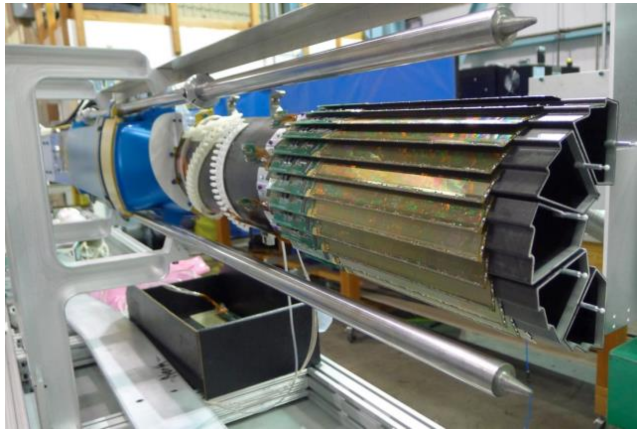


- Majority of kaons and pions are promptly produced and originate from primary vertex
- If the detectors can tell the tiny difference, significant backgrounds can be rejected
- Pointing resolution of tracker is crucial for this purpose

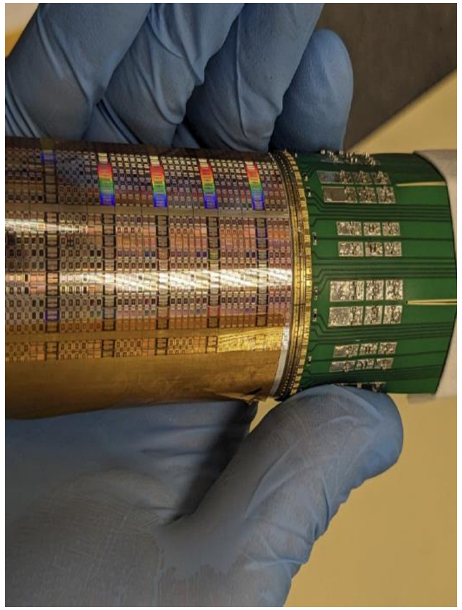
Silicon Pixel Detectors

Monolithic Active Pixel Sensor (MAPS)

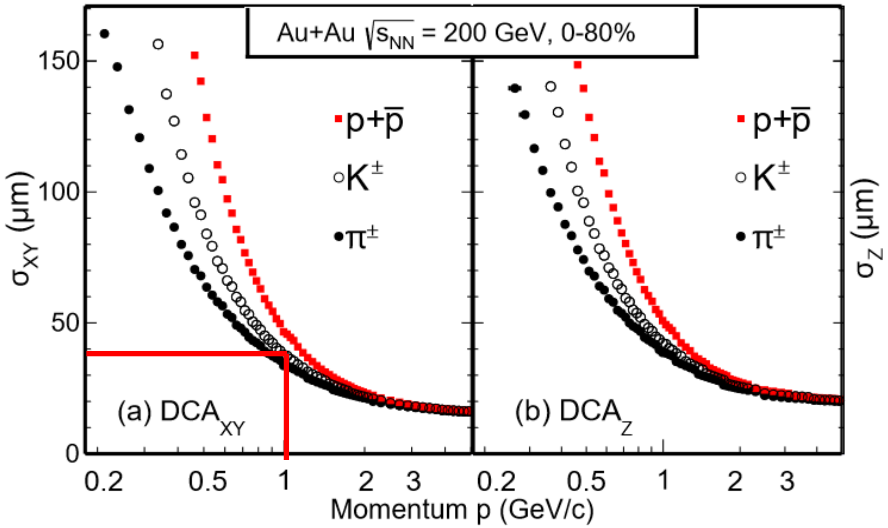


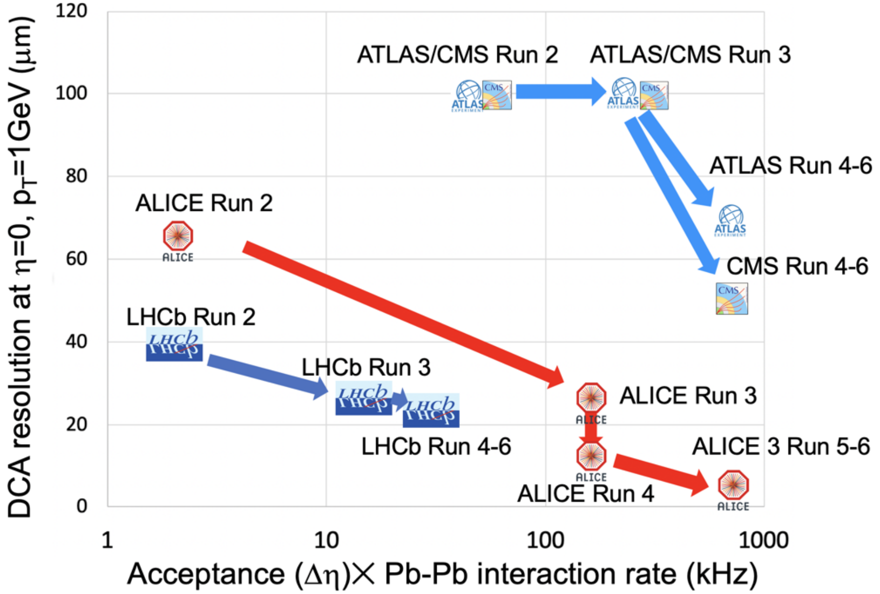


STAR Heavy Flavor Tracker



ALICE Inner Tracking System



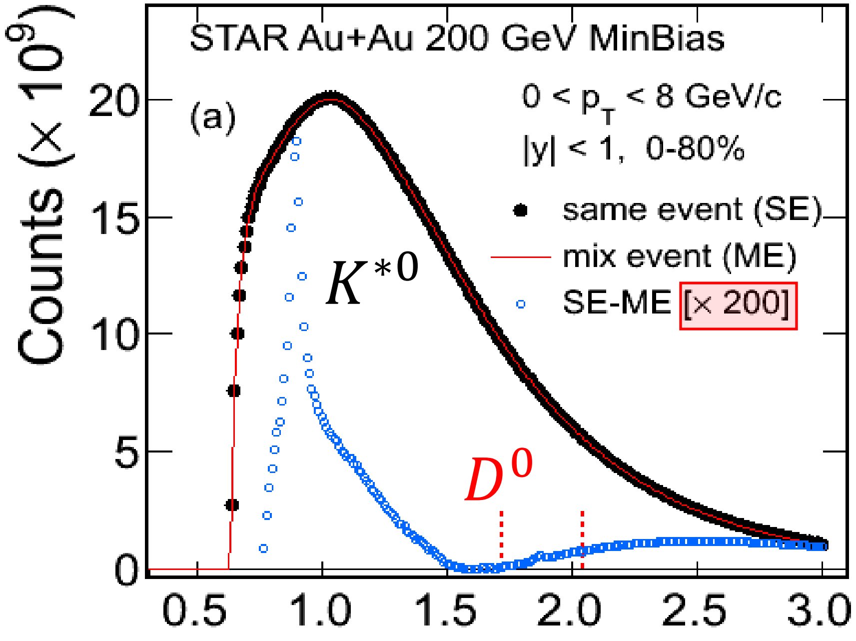


D^0 Signal with Topological Cuts

2010+2011

820M events

w/o HFT

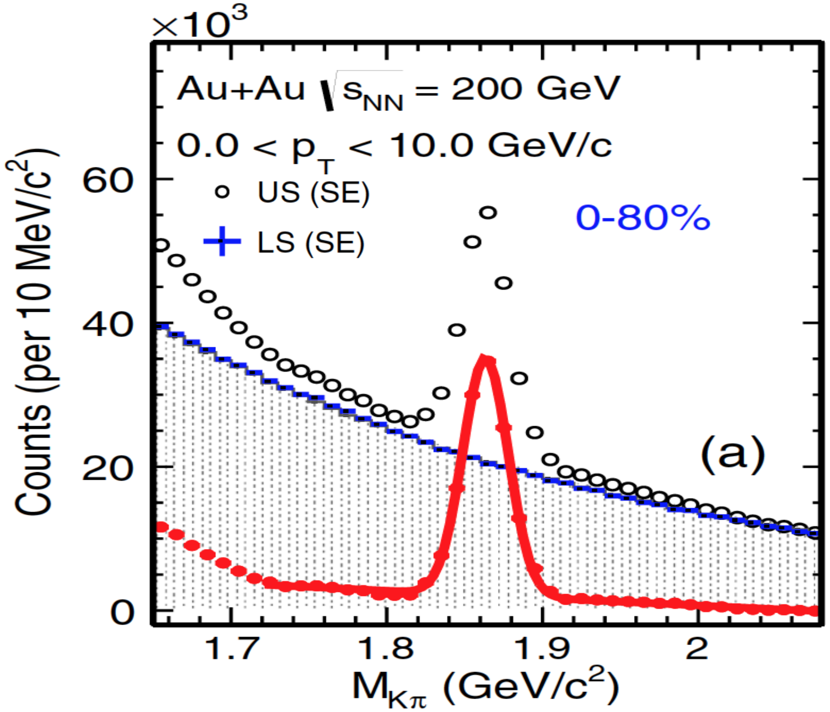


STAR, PRL113, 142301 (2014)

2014

900M events

w/ HFT



STAR, PRC 99, 034908 (2019)

S/B improved by $O(10^4)$

Feeddown Contribution

The measured charm hadrons have feeddown contributions

Inclusive D = prompt D + non-prompt D

Prompt D: D from vertex not distinguishable from primary vertex

- Direct D
- Strong/radiative decay products of heavier particle
  i.e. $D^{*+} \to D^0 + \pi^+, \quad D^{*+} \to D^+ + \pi^0, \quad D^{*0} \to D^0 + \pi^0/\gamma$

$D^0, D^{\pm}, D^{*0}, D^{*\pm}$ reflect similar physics, unnecessary to separate prompt

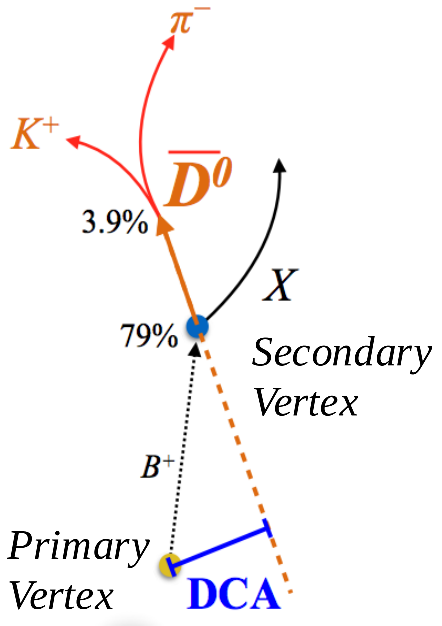
Non-prompt D: D from secondary vertex

- Weak decay products of heavier particle, mainly from B-hadrons

Flavor changed far later than QGP lifetime ($\tau \sim 500\ \mu m/c$)

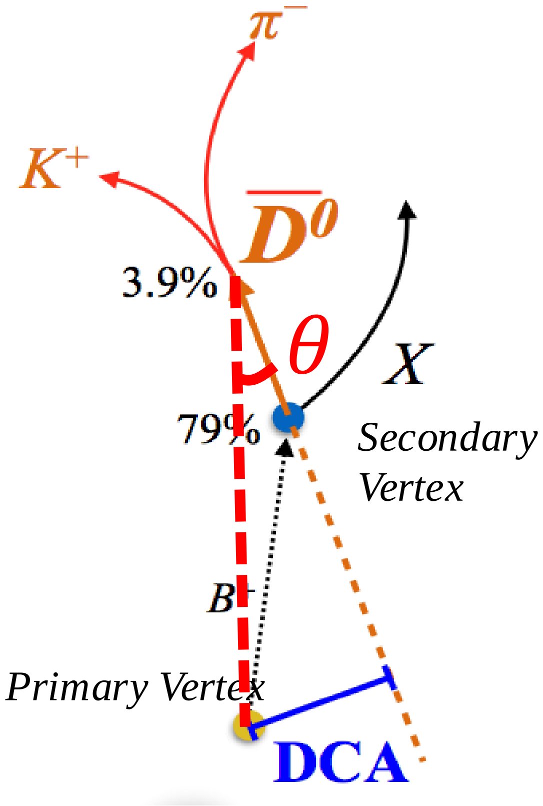
➔Reflect interaction of bottom instead of charm quark with the medium

A typical (good) proxy of B-hadrons



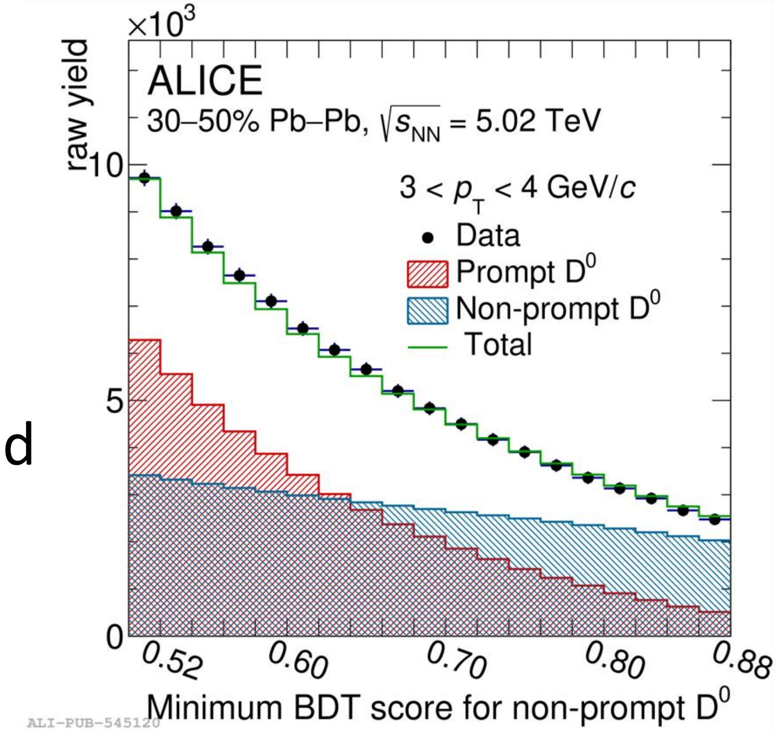
Prompt and Non-prompt Separation

Machine-learning approach with 3-class classification



Training variables mainly based on:

- DCA of D^0 daughters and D^0
- Distance between D^0 decay vertex and primary vertex
- Pointing angle between line of flight and momentum reconstructed



ALICE, EPJC83, 1123 (2023)

Non-prompt D yield obtained by combining measurements of *non-prompt fraction + inclusive measurements*

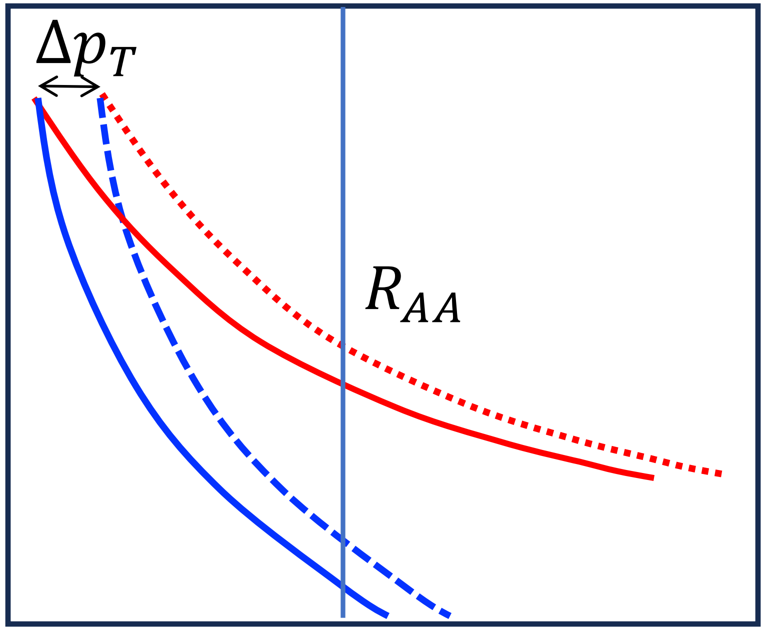
Experimental Results

Observable: Nuclear Modification Factor

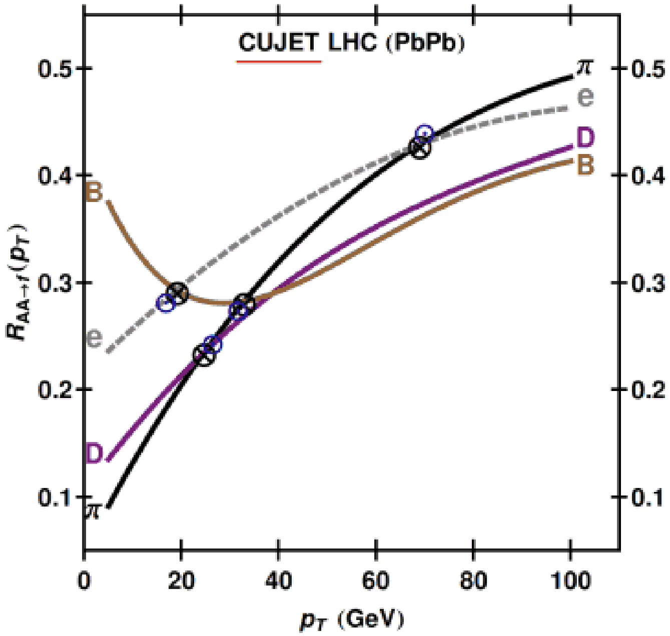
Nuclear Modification Factor: $$R_{AA} = \frac{dN_{AA}/dp_T dy}{\langle N_{bin}\rangle dN_{pp}/dp_T dy}$$

Conversion from R_{AA} measurements to energy loss is not so straight forward

- $R = \frac{f(p_T - \Delta p_T)}{f(p_T)}$ depends not only on Δp_T, but also the shape of $f(p_T)$



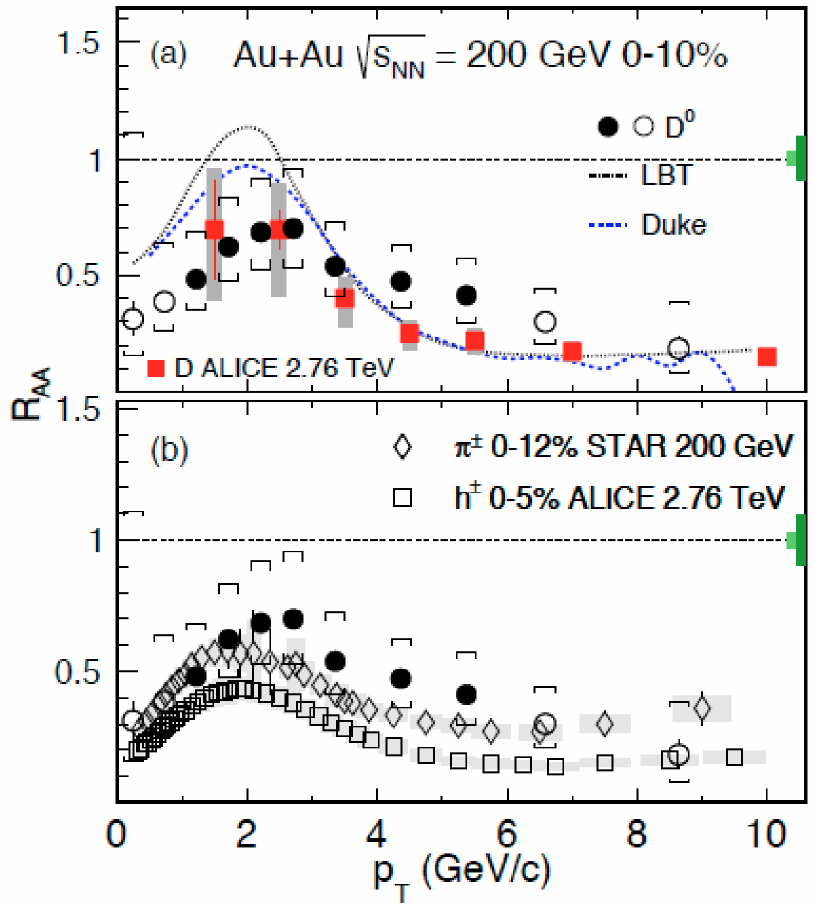
- And diluted by hadronization process ($q \rightarrow h$)



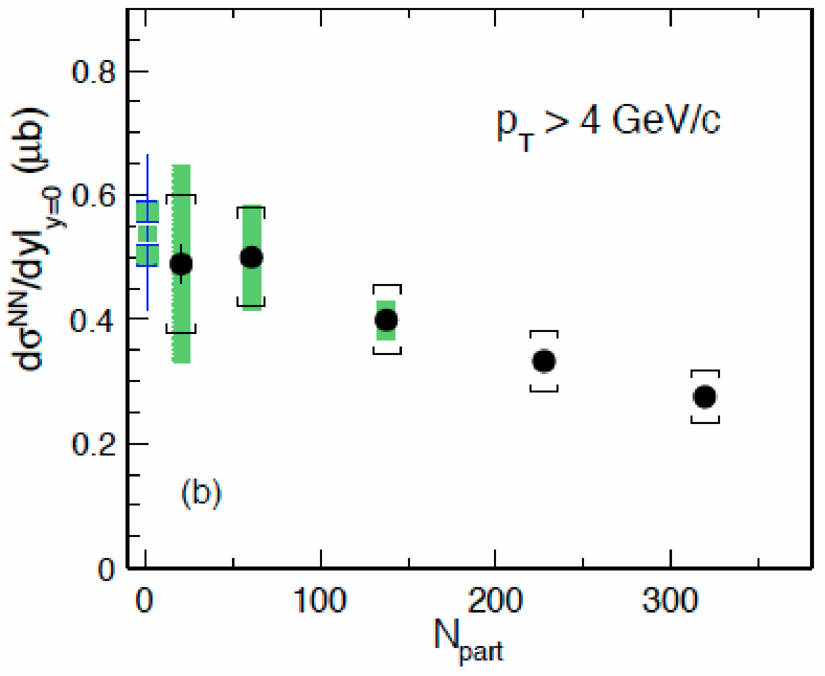
$R_{AA}(D) > R_{AA}(B)$
@low/intermediate p_T

A. Buzzatti et al., NPA904, 779c (2013)

D^0 Suppression at RHIC

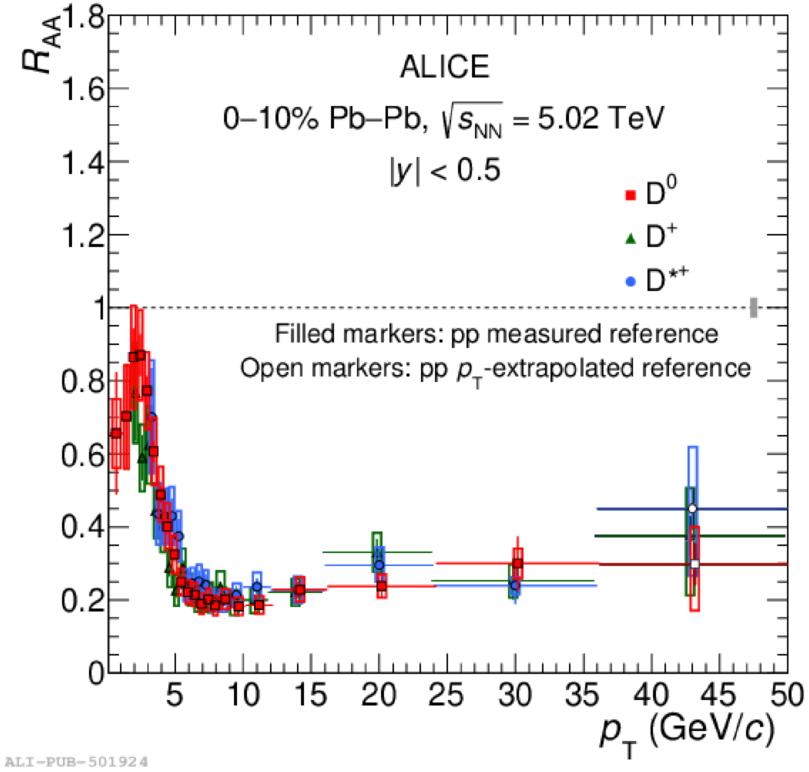


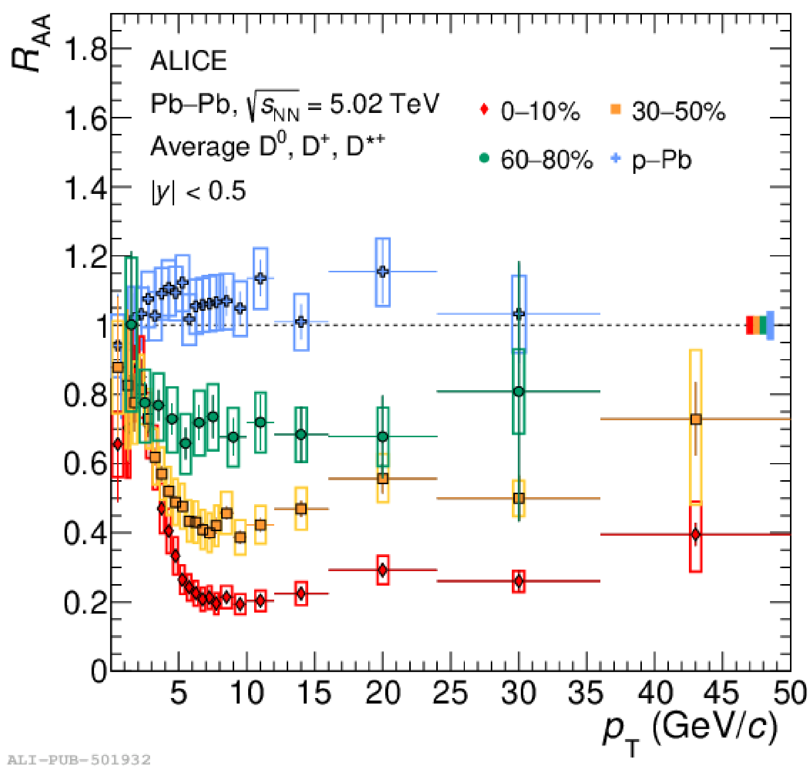
STAR: PRC 99, 034908 (2019)
LBT: PRC 97 (2018) 014907
Duke: PRC 94 (2016) 014909



- Significant suppression of D^0 yield at high-p_T observed in 200 GeV Au+Au collisions
- Stronger suppression towards central collisions
- Described by theoretical calculations

D-mesons Suppression at LHC



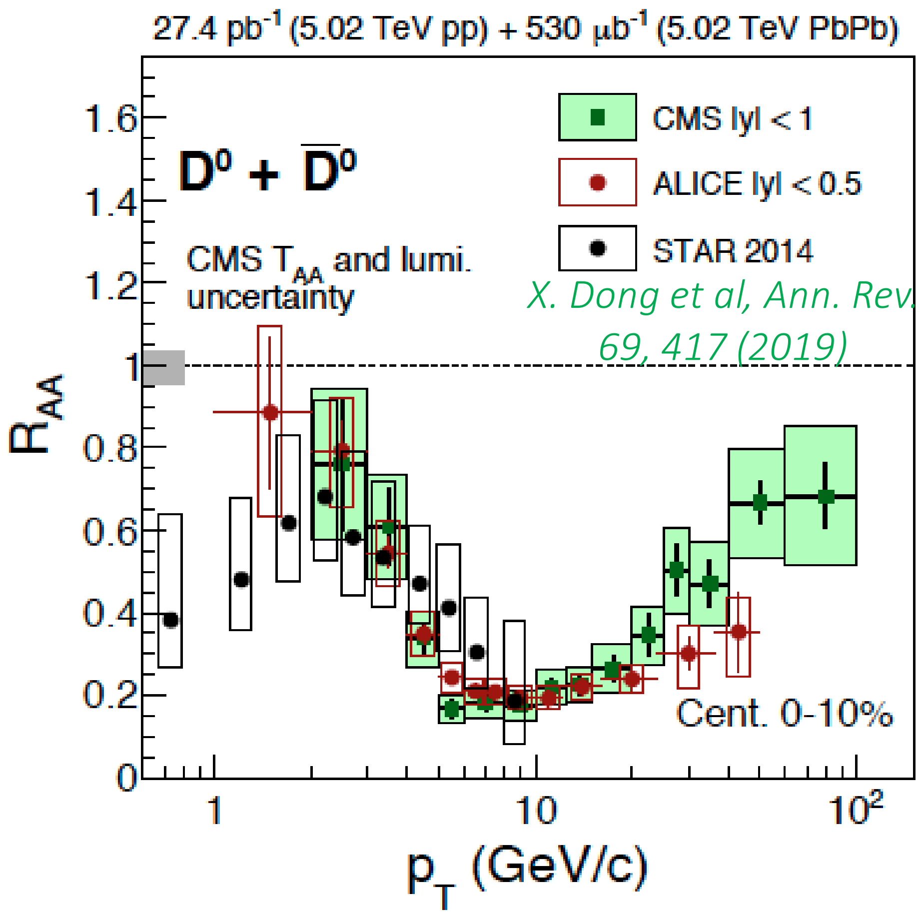


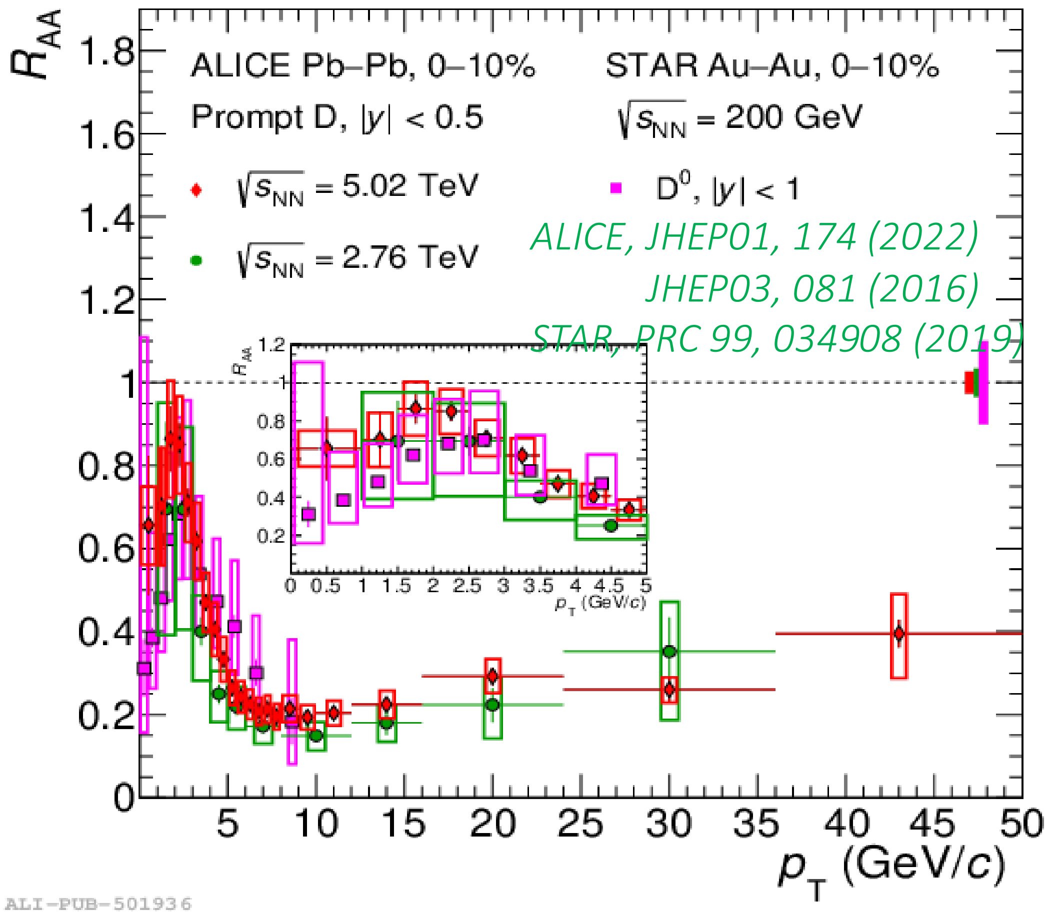
ALICE, JHEP01, 174 (2022)

- Prompt D^0, D^+, D^{*+} same suppression
- Dramatic decrease from 3-6 GeV/c
- Slight increase at high p_T

- Consistent with unity in pPb
- Clear increasing suppression towards central collisions at intermediate/high p_T
  ← Increasing energy density, size, lifetime

Energy Dependence

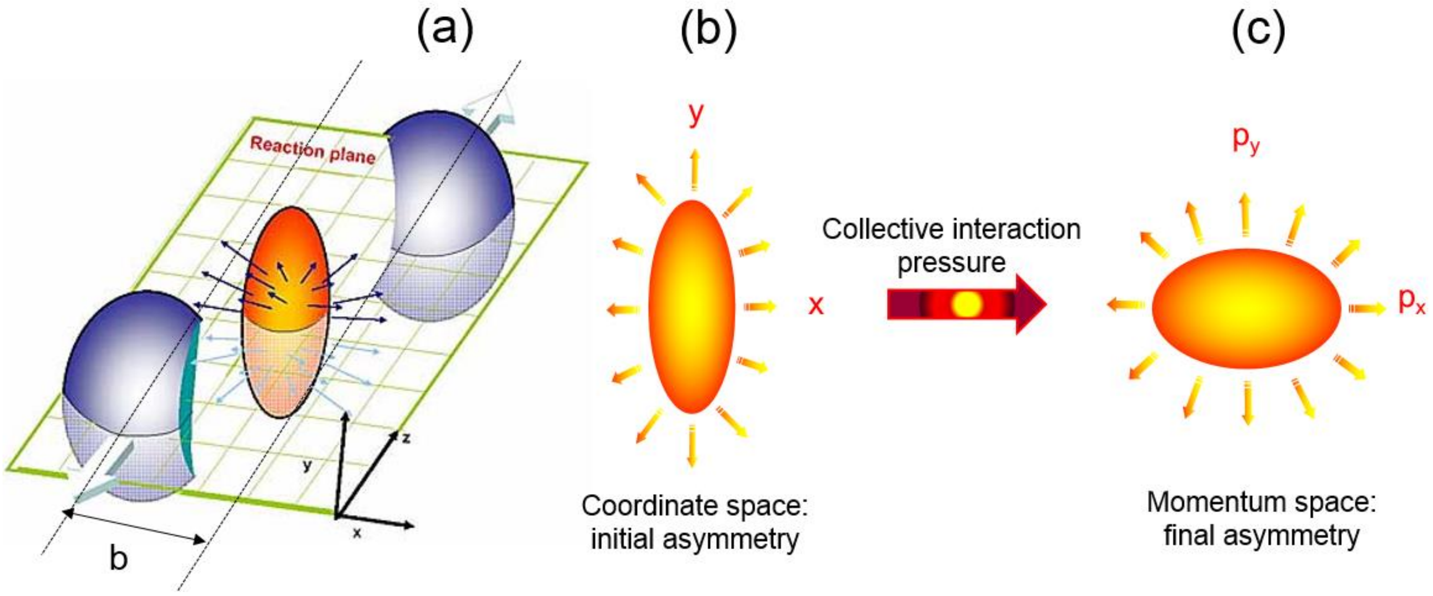


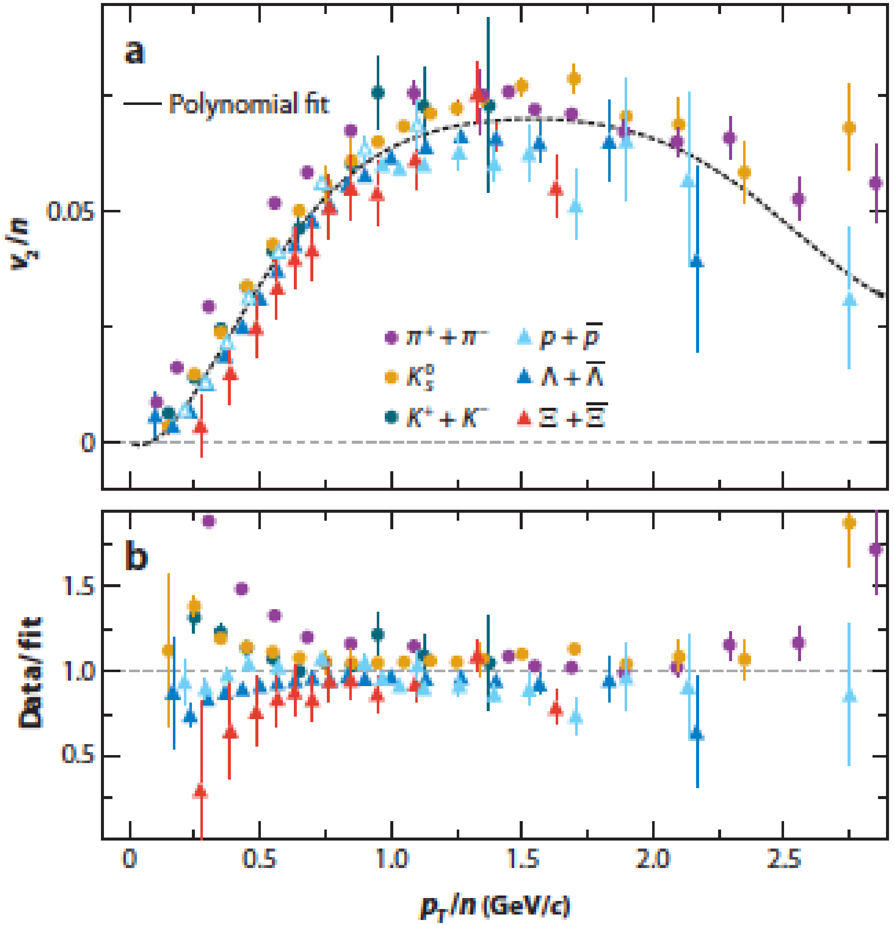


200 GeV ~ 2.76 TeV = 5.02 TeV

Counterbalance of temperature and medium density vs. p_T spectrum steepness

Observable: Collectivity



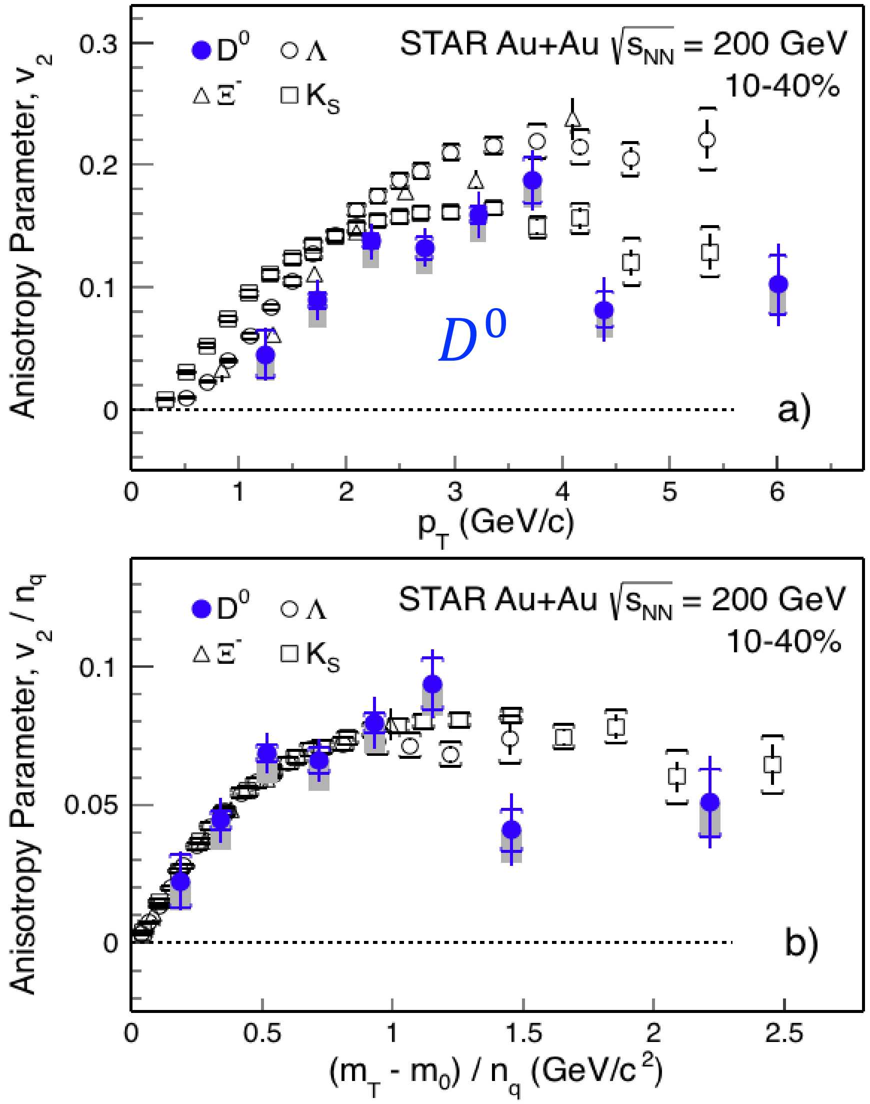


$$\frac{dN}{d\phi p_T dp_T} = \frac{dN}{p_T dp_T}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos(n\phi)\right]$$

Number-of-Constituent Quark scaling
→Partonic flow + Coalescence

Elliptic/Triangular Flow of D-meson

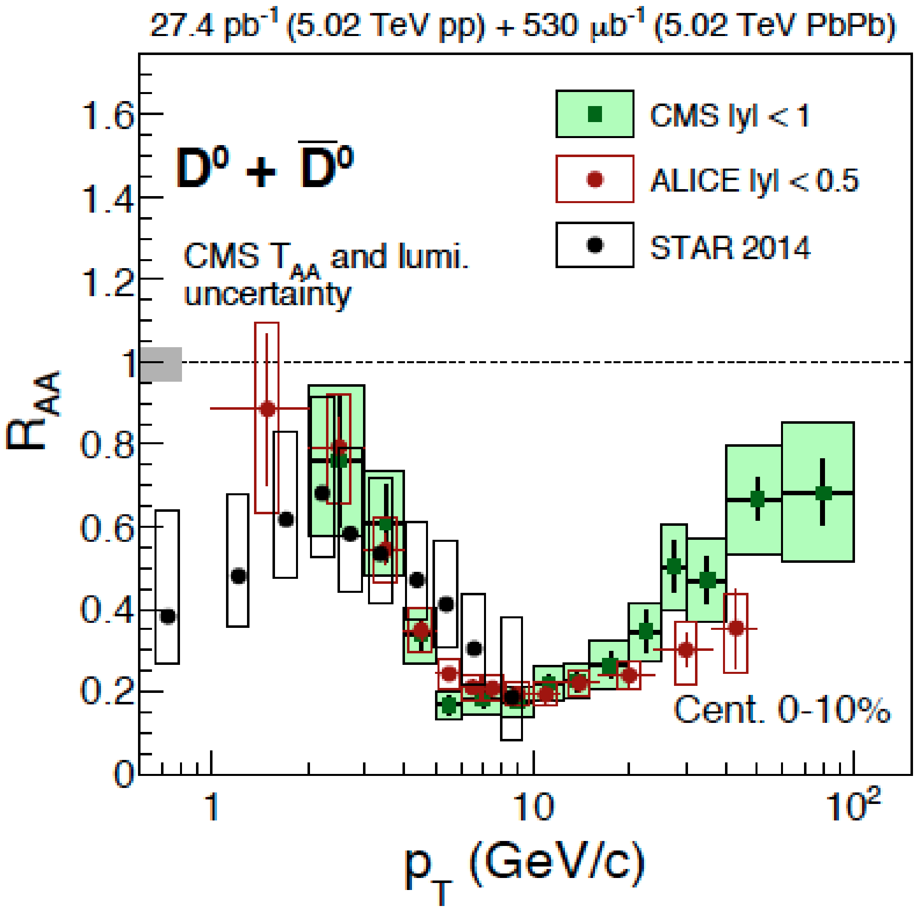
STAR, PRL 118, 212301 (2017)

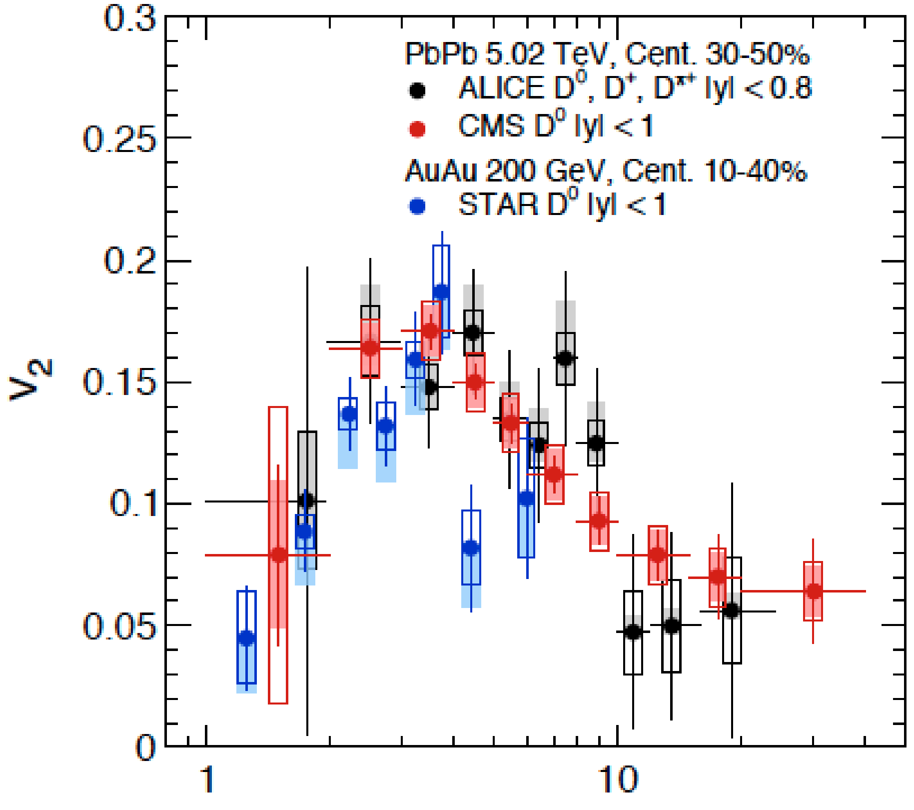


Significant v_2 observed for D^0-meson

- Mass ordering at low p_T
  – hydrodynamics behavior
- Follow mesons' flow at intermediated p_T
  – quark coalescence

Energy Dependence

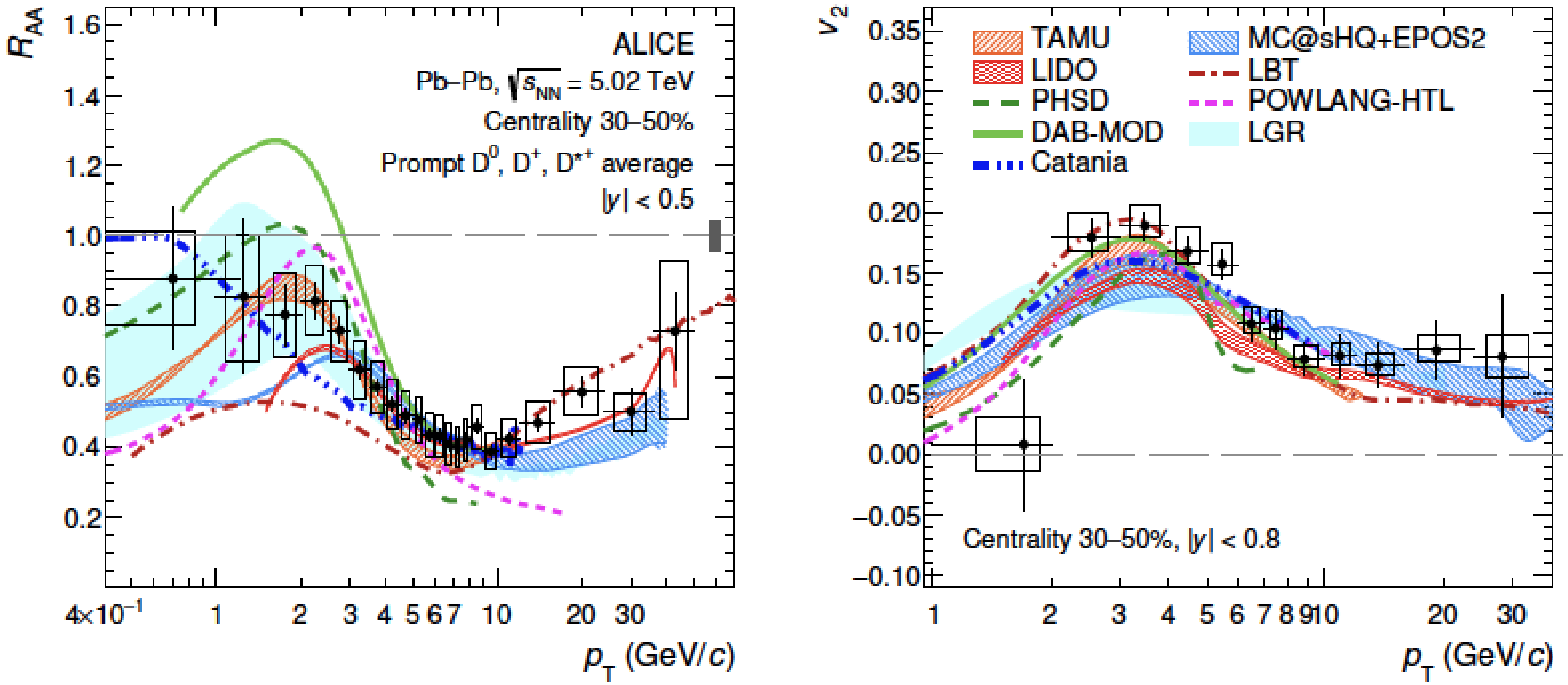




X. Dong et al, Ann. Rev. 69, 417 (2019)

No obvious energy dependence for both R_{AA} and v_2

Comparison with Theories



ALICE, JHEP01, 174 (2022)

- TAMU, MC@sHQ+EPOS2, LIDO, LGR and Catania able to describe R_{AA} and v_2 simultaneously
  All includes charm quark diffusion in the medium and quark coalescence hadronization
- Charm quark spatial diffusion coefficient is constrained by the comparisons

Spatial Diffusion Coefficient

The heavy quark distribution function can be written as (Fokker-Planck equation):

X. Dong et al, Ann. Rev. 69, 417 (2019)

$$\frac{\partial}{\partial t} f_Q = \frac{\partial}{\partial p} A(p) p f_Q + \frac{\partial^2}{\partial^2 \vec{p}} B(p) f_Q$$

Spatial diffusion coefficient

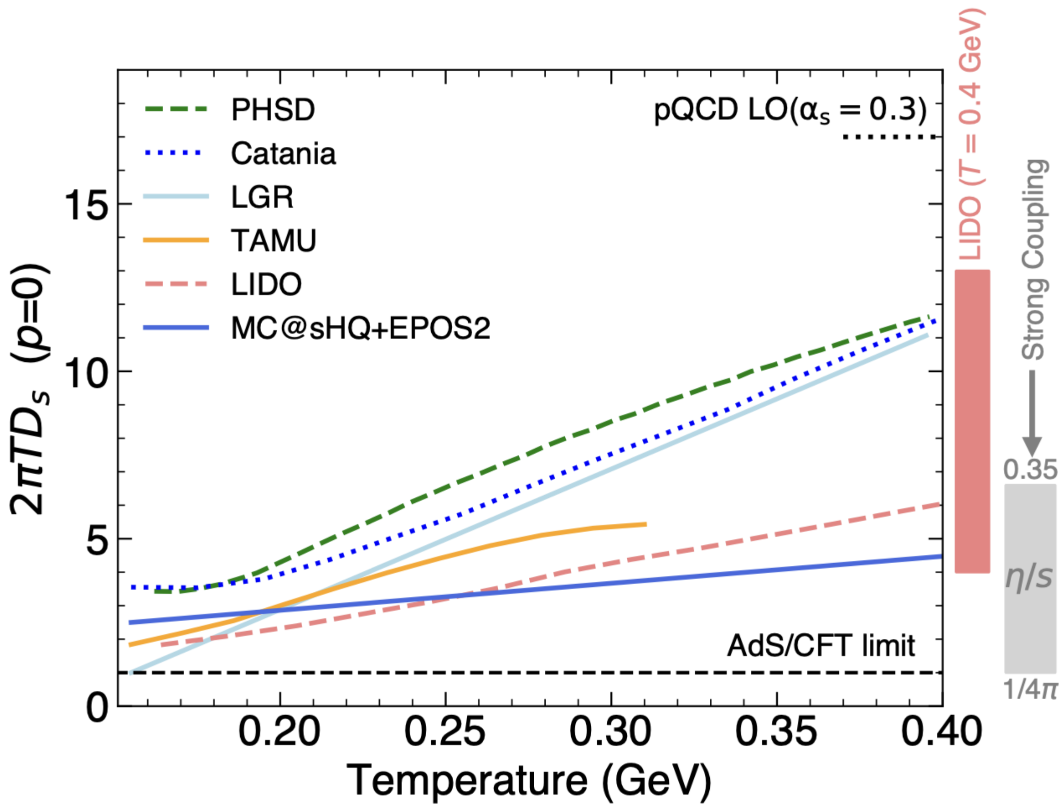
$$D_s = \frac{T}{m_Q A(p=0)}$$

Relaxation time

$$\tau_{relax} = \frac{1}{A} = \frac{m_Q}{T} D_s = 2\pi T D_s \times \frac{m_Q}{2\pi T^2}$$

$$\frac{m_c}{2\pi T_c^2} \sim 2 \text{ fm/c}$$

Charm Quark Diffusion Coefficient



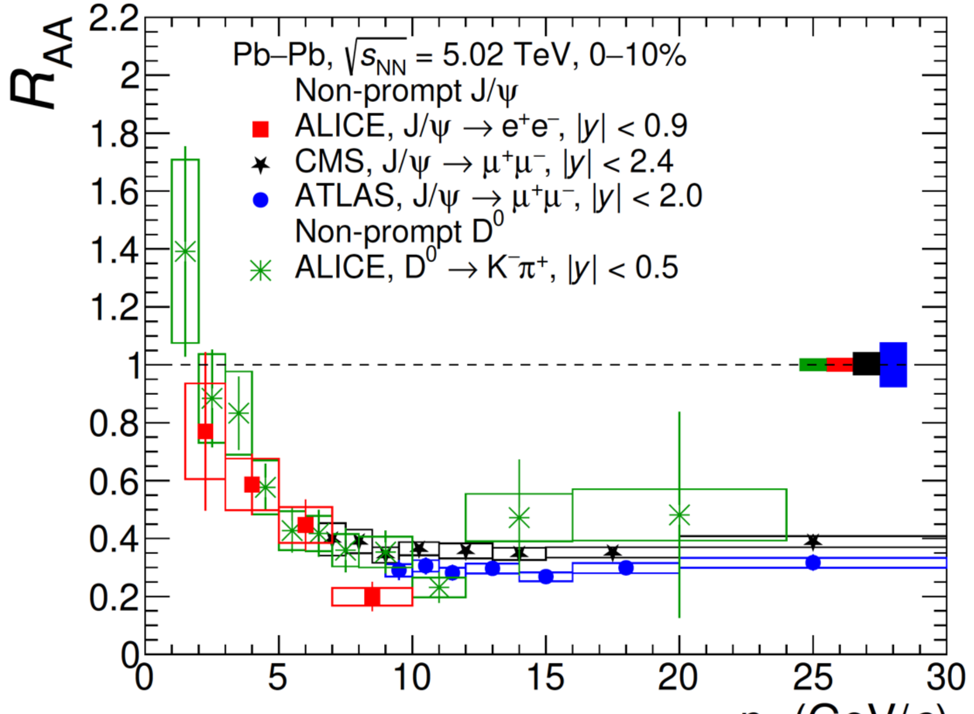
$1.5 < 2\pi T D_s < 4.5 \ @\ T_c$

$\tau_{relax} = (3 - 9)\ fm/c \lesssim \tau_{QGP}$

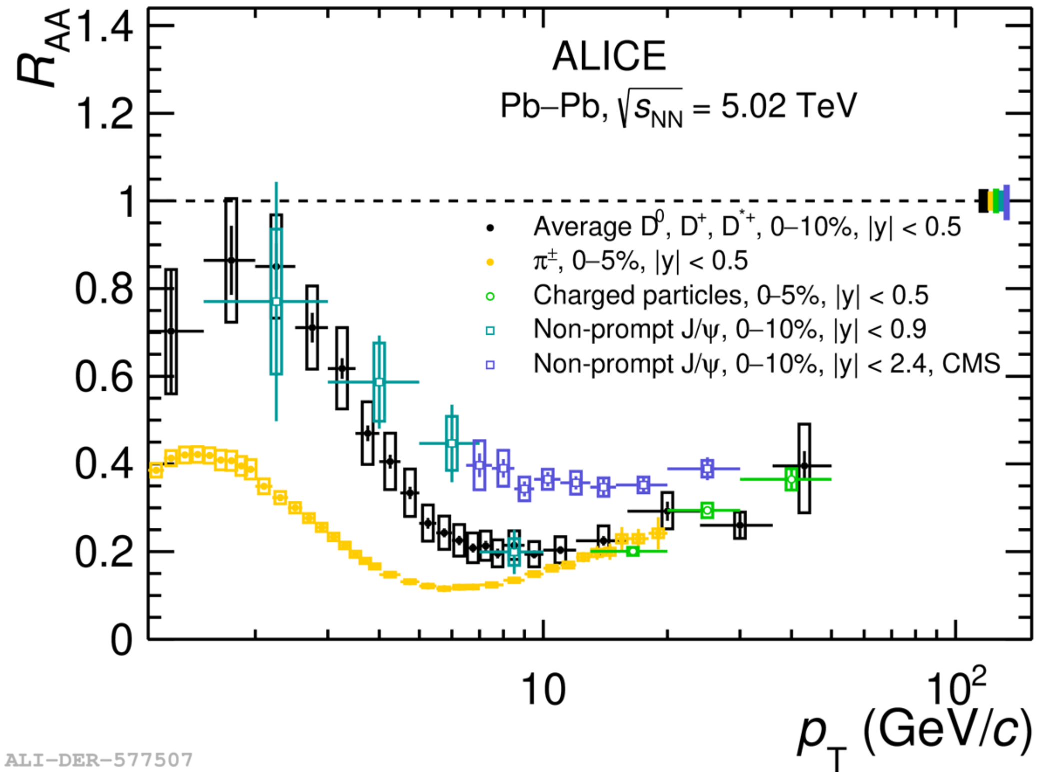
ALICE, arXiv:2211.04384

Charm is fully thermalized in QGP

Suppression of Bottom



ALICE, JHEP02, 066 (2024)



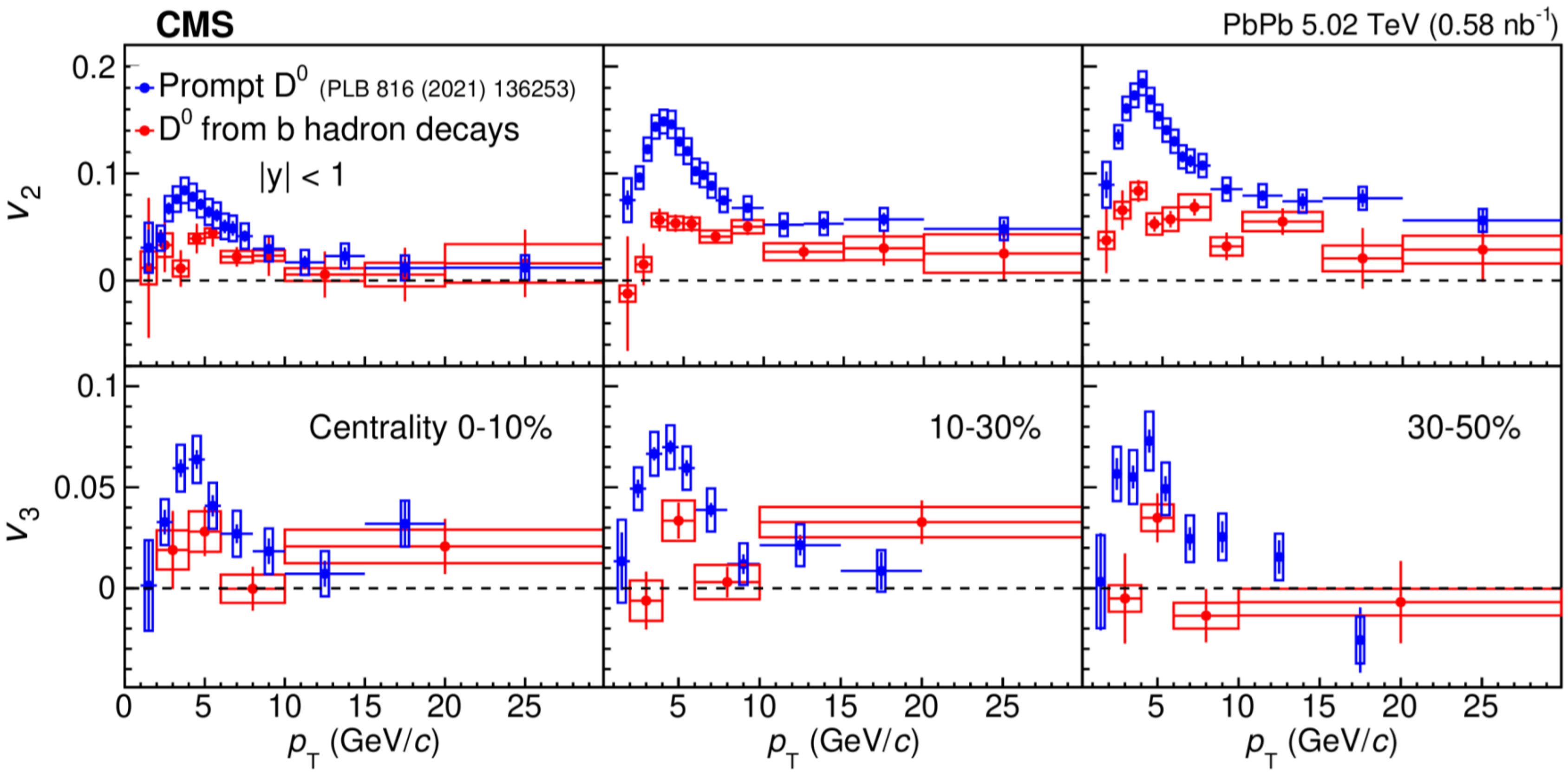
- Measured via non-prompt D^0 and J/ψ
  - D^0 has better statistics
  - J/ψ has better kinematics
- Strong suppression observed

- Clear mass hierarchy at intermediate p_T

  $R_{AA}(B) > R_{AA}(D) > R_{AA}(\text{light hadrons})$

- Converge at high p_T

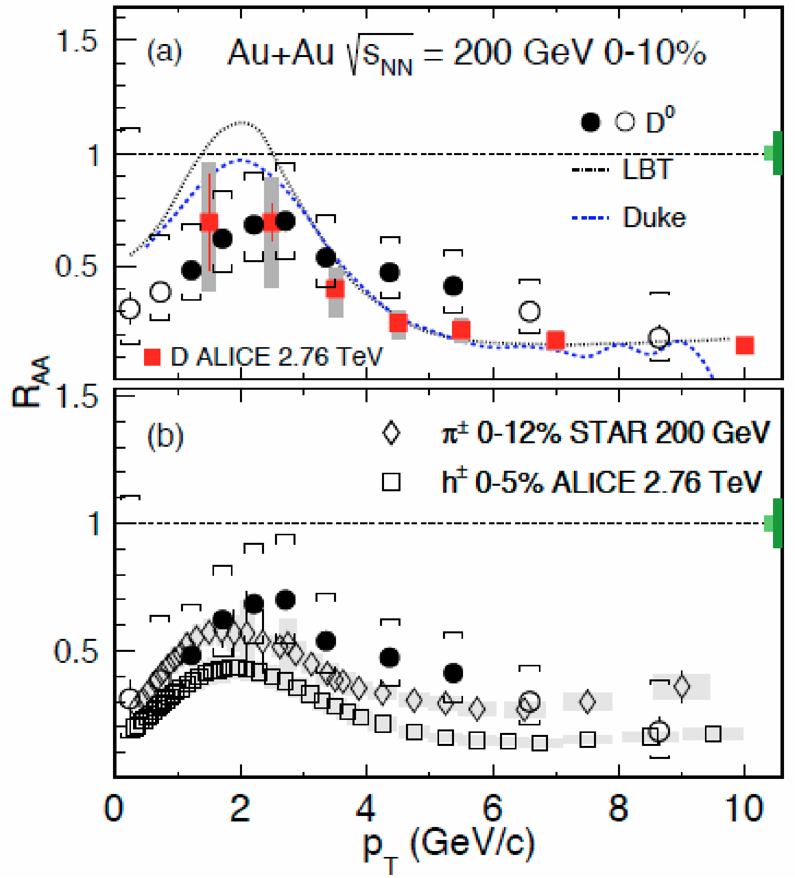
Collectivity of Bottom

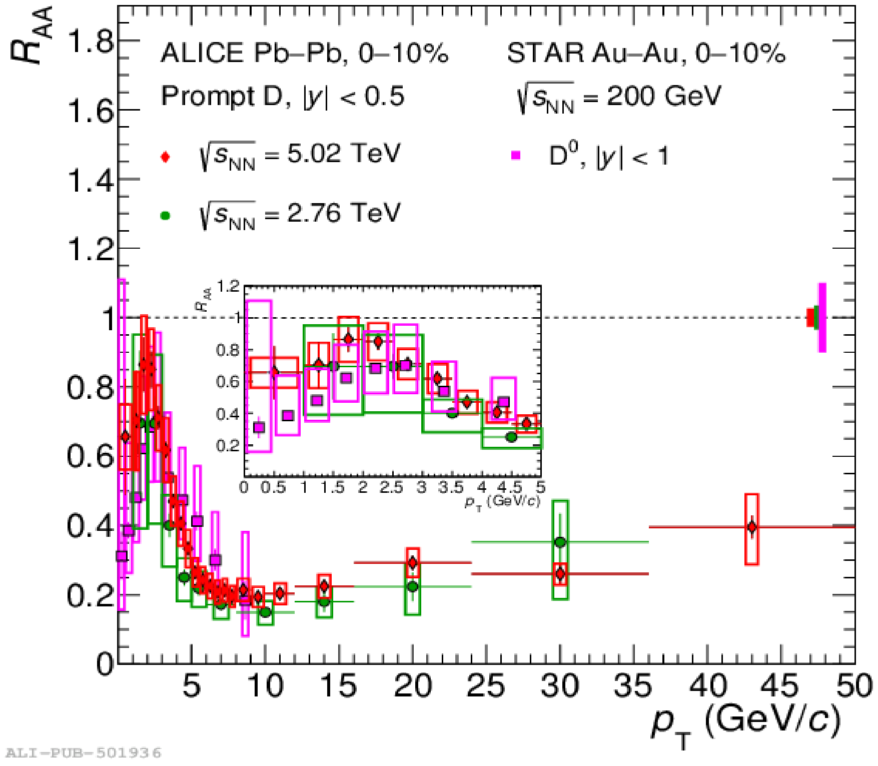


CMS, PLB850, 138389 (2024)

- Significant flow of D from B decay
- Much smaller than prompt D
- Different degree of thermalization of charm and bottom

Heavy Flavor Hadronization in QGP



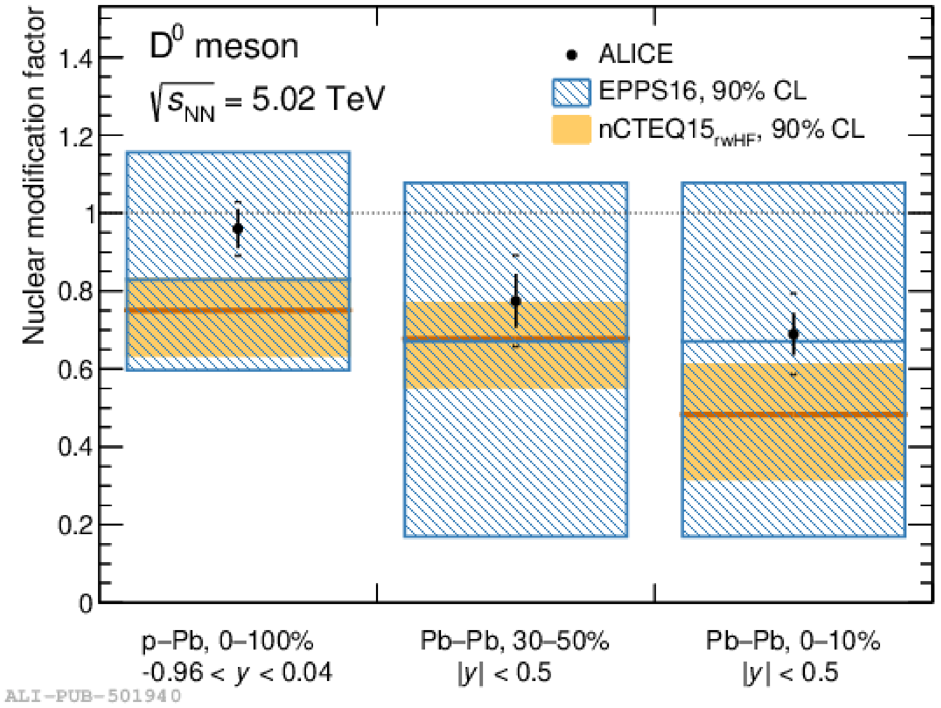


QUESTION:
Light hadrons have similar behavior, why we don't worry?

D is suppressed in all p_T at both RHIC and LHC $\rightarrow N^{AA} < N_{bin} \times N^{pp}$

Contradict to N_{bin} scaling of #ccbar ?!!

Cold Nuclear Matter Effect?



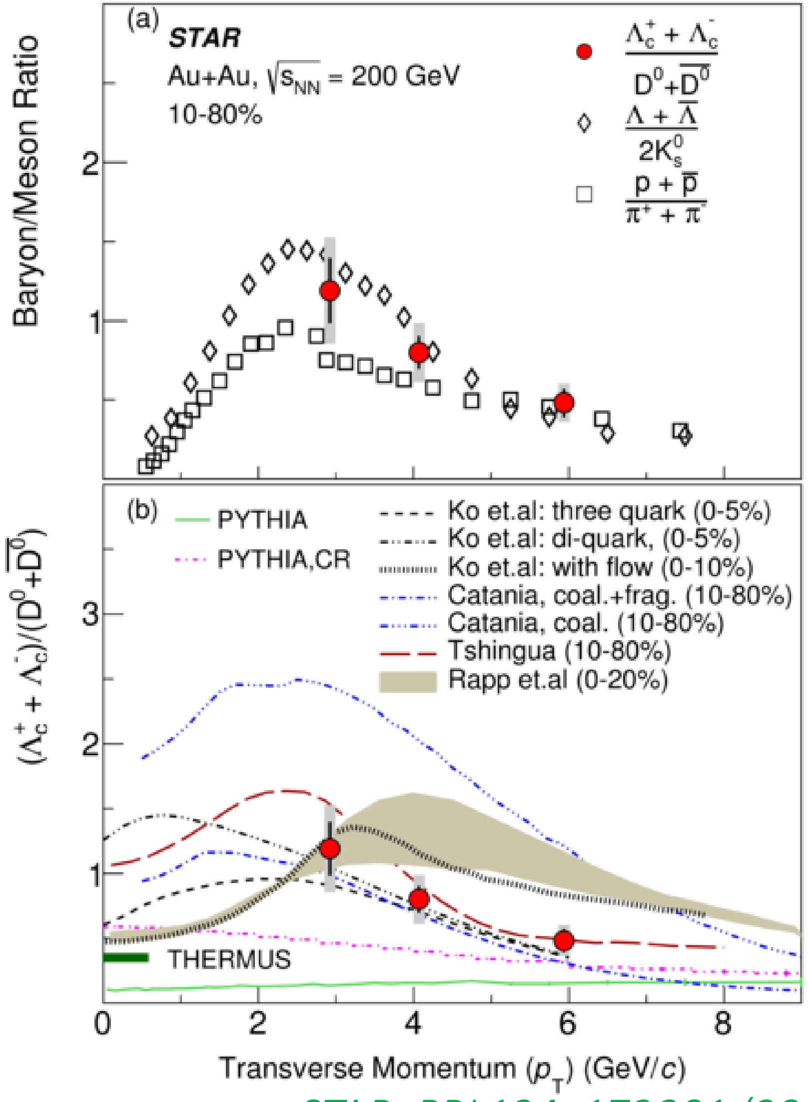
ALICE, PLB839, 137796 (2023)

~30% suppression in central PbPb collisions

Decreasing trend from pPb to central PbPb
Consistent with models implemented shadowing effect within large uncertainties

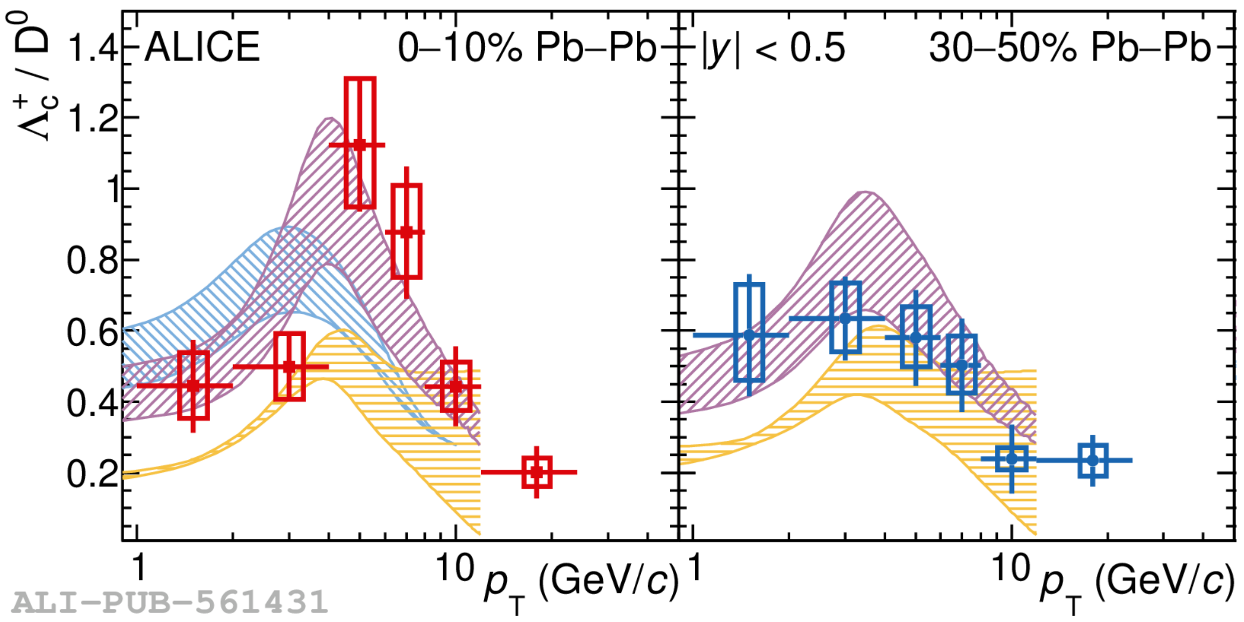
Purely from shadowing? Is there any other effects on top of it? --> Particle ratios

Charmed Baryon/Meson Ratio



STAR, PRL124, 172301 (2020)

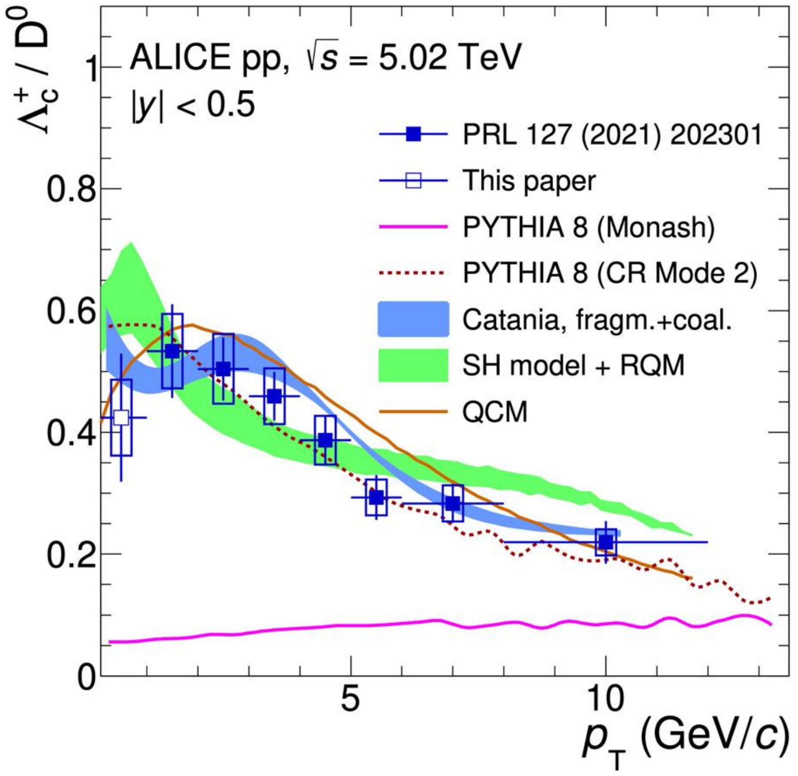
ALICE, PLB839, 137796 (2023)



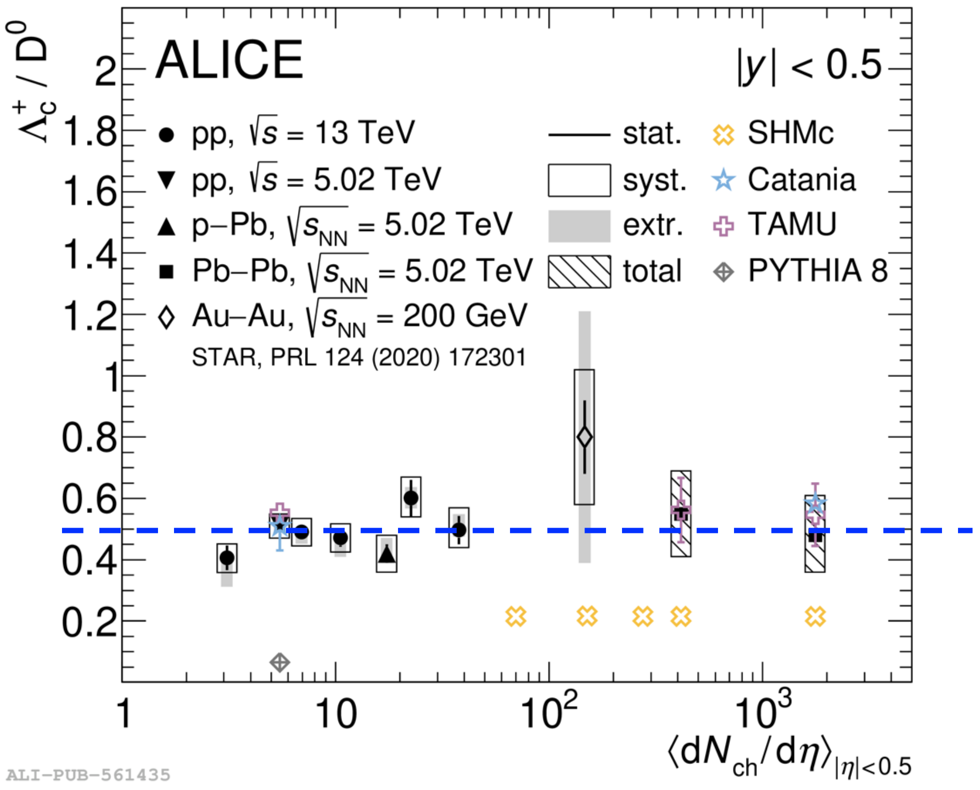
- Charmed baryon/meson ratio is similar to light hadrons
- Significantly higher than PYTHIA (constrained by ee/ep)
- Model including coalescence describe the enhanced ratios

Ratios in Small System

ALICE, PRC107, 064901 (2023)



ALICE, PLB839, 137796 (2023)



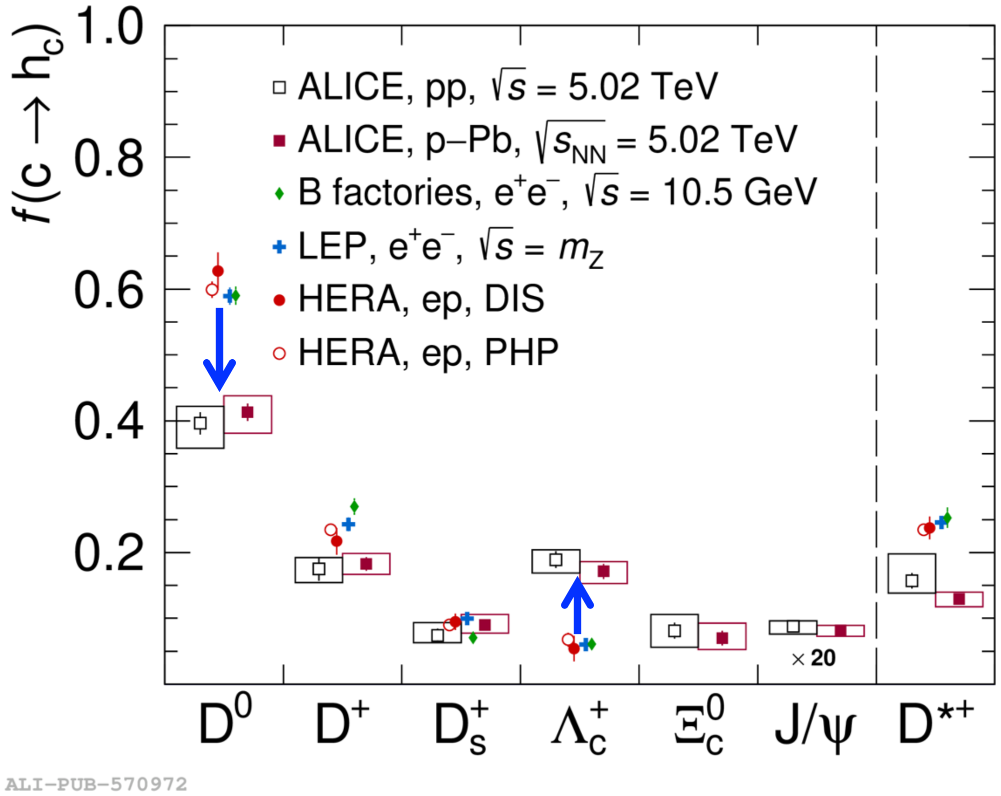
- Significantly larger than default PYTHIA
- Qualitatively described by models

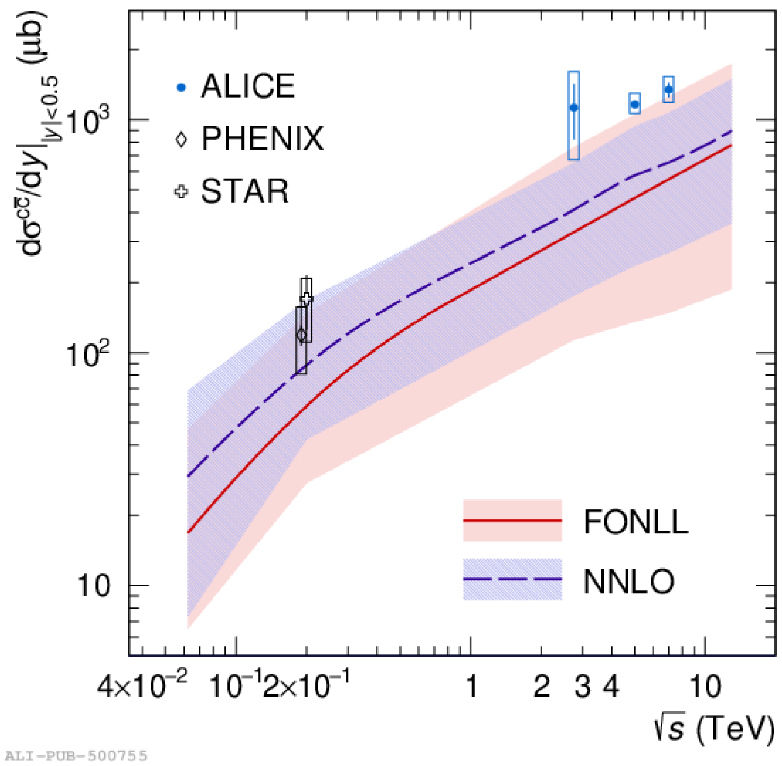
Smooth trend from pp to central AA

Same hadronization in pp and AA?

Coalescence ↮ QGP

Relative Abundance in Small System





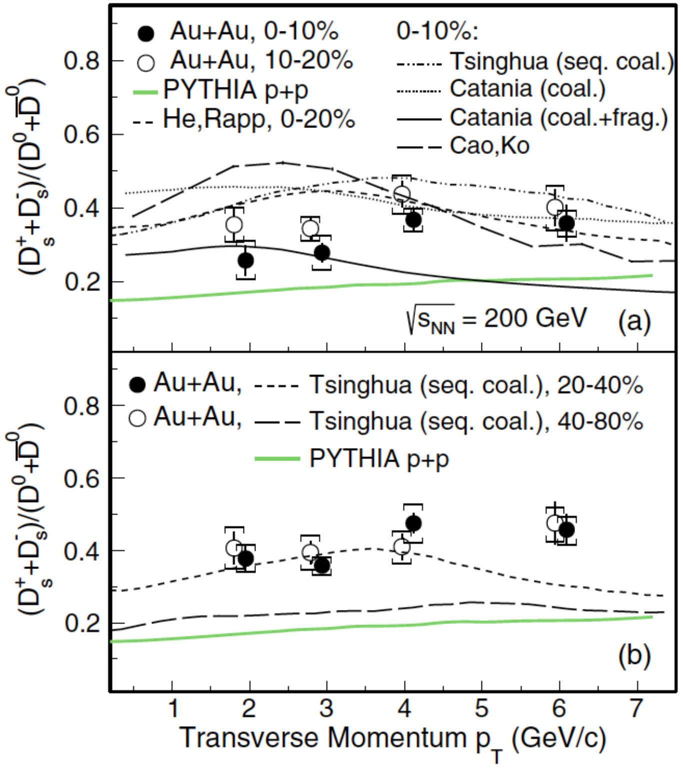
ALICE, arXiv:2405.14571
ALICE, PRD105, L011103 (2022)

Suppression of mesons and enhancement of baryons

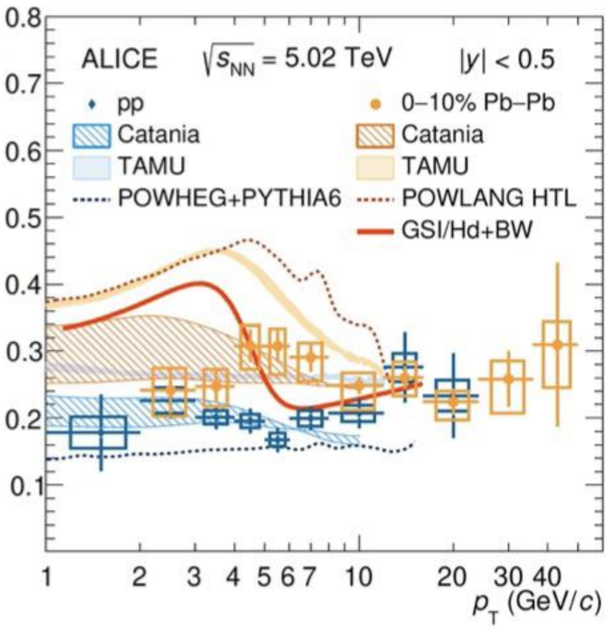
Total cross-section consistent with FONLL

Redistribution of charm quarks among hadrons

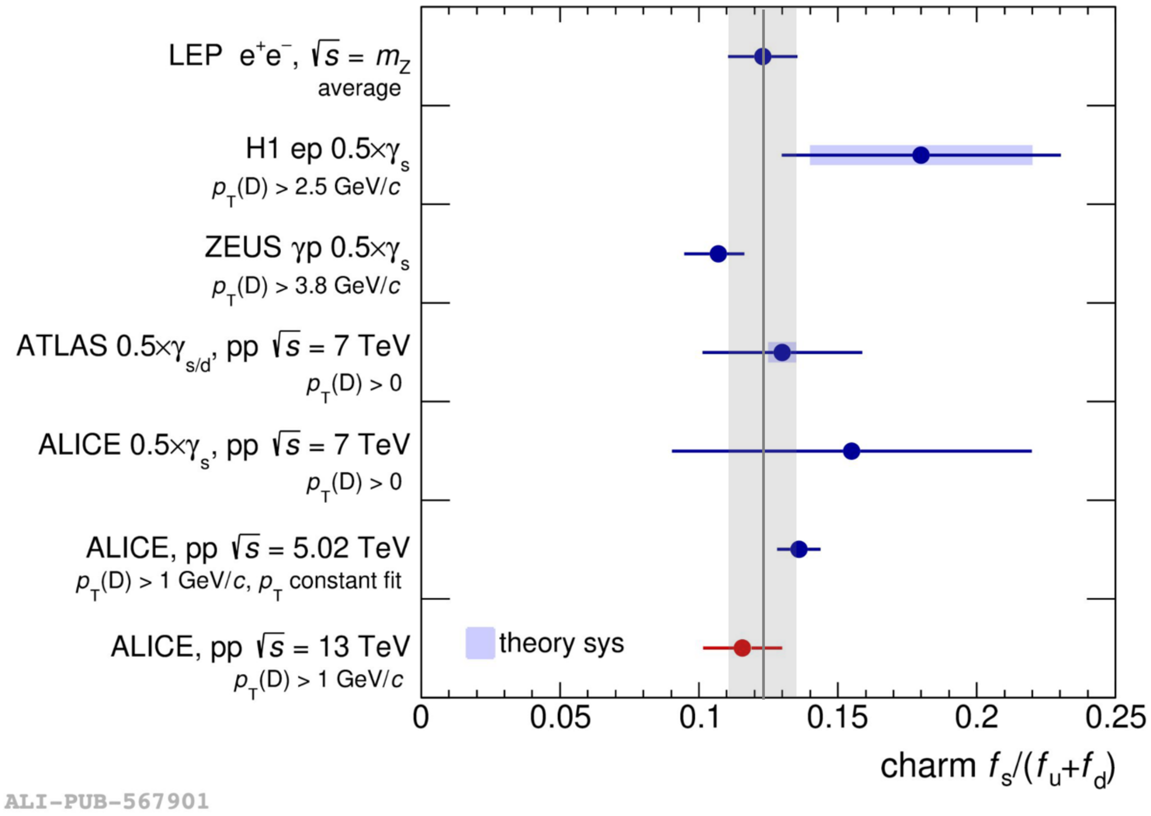
Ds/D0 Ratio



STAR, PRL127, 092301 (2021)



ALICE, PLB827, 136986 (2022)



D_s/D^0 in AA > D_s/D^0 in pp

D_s/D^0 in pp = D_s/D^0 in ee

Coalescence + Strangeness enhancement in QGP

Summary of Open Heavy Flavor

Heavy quarks are unique probes of QGP due to their large masses

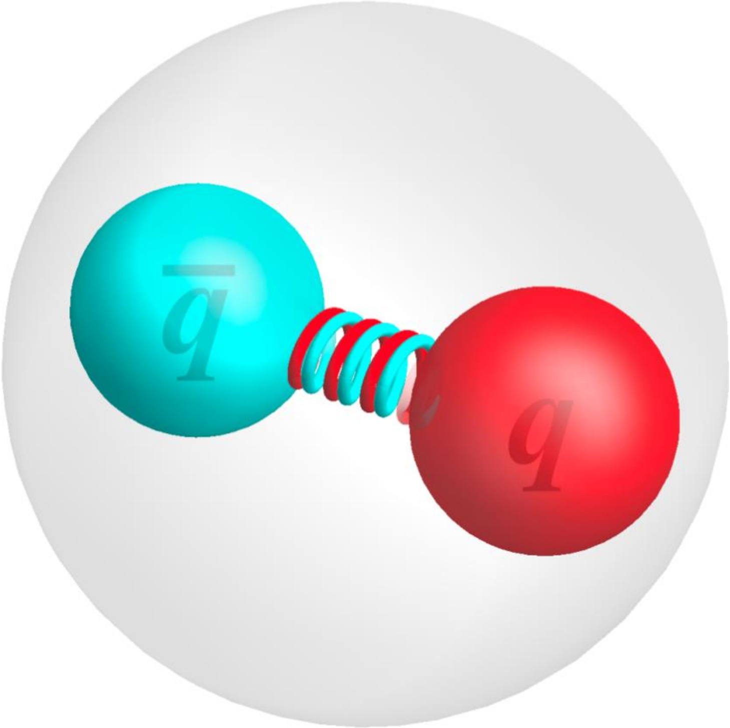
Extensive experimental studies have been conducted thanks to start-of-the-art silicon tracker

Experimental and theoretical studies show that

- Charm quark exhibit significant energy loss and collective motion
- Mass dependence of yield suppression and collective flow is observed
- Quark coalescence plays an impart role in heavy quark hadronization at low/mid p_T
- Dimensionless spatial diffusion coefficient of charm in the medium is constrained by comparing experimental results and theoretical calculations

Quarkonium

Bound state of quark and its own antiquark, usually refer to heavy quark



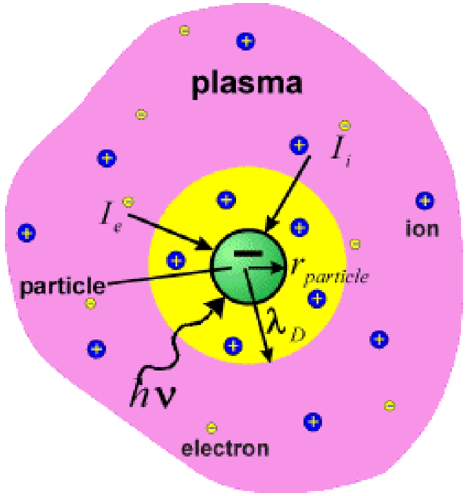
One of the simplest systems in QCD

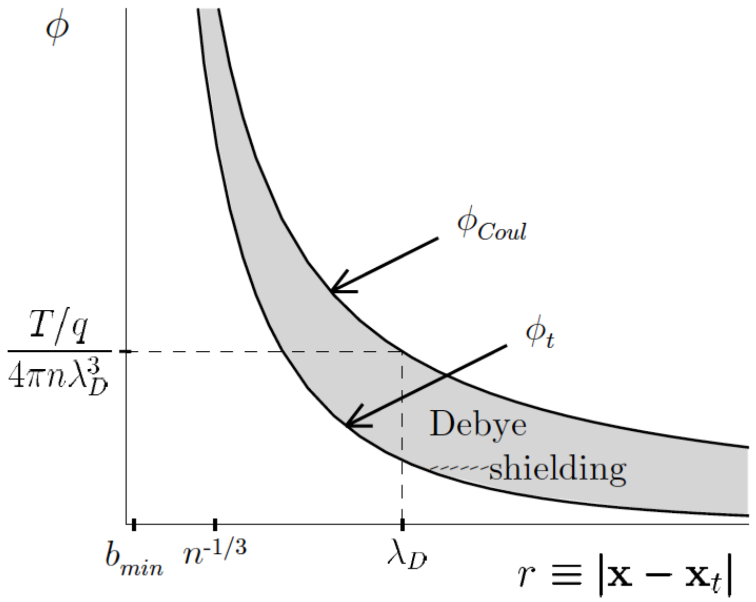
Analogue to hydrogen in atomic physics (QED)

State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
Mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	−0.03	0.03	0.06	−0.06	−0.06	−0.08	−0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

Please see also Enrico Scomparin's lecture at Quark Matter 2023: slides

Debye Screening in Plasma





Potential of point charge in vacuum:

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$

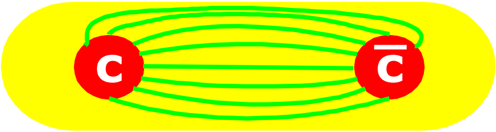
Potential of test charge in a plasma:

$$V = \frac{Q}{4\pi\varepsilon_0 r} e^{-r/\lambda_D}$$

Electromagnetic interaction limited in the Debye radius

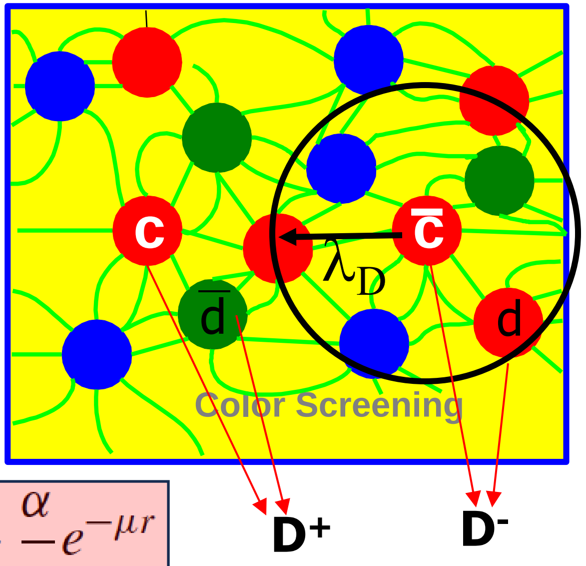
Debye Screening of Strong Interaction in QGP

Vacuum



$$V(r) = \sigma\, r - \frac{\alpha}{r}$$

QGP



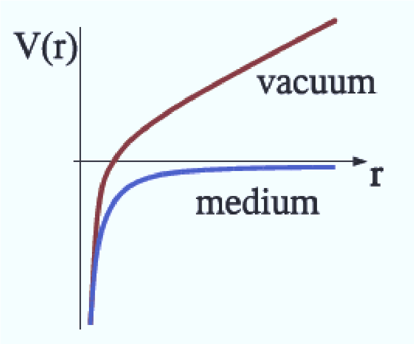
$$\frac{\sigma}{\mu}\{1 - e^{-\mu r}\} - \frac{\alpha}{r} e^{-\mu r}$$

$$\mu = 1/\lambda_D$$

Strong interaction between heavy quark and its antiquark is reduced in the deconfined medium due to the surrounding free quarks and gluons

Bound state will be dissociated into open heavy flavor hadrons when the Debye radius is smaller than the size of the bound state

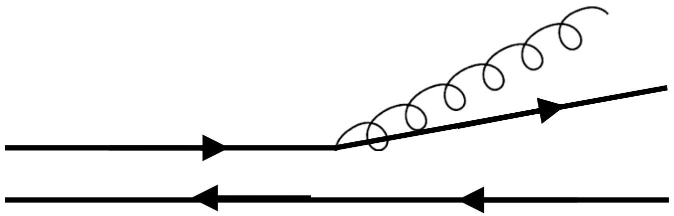
Suppression of quarkonium in relativistic heavy ion collisions should provide a "smoking-gun" signature of QGP formation

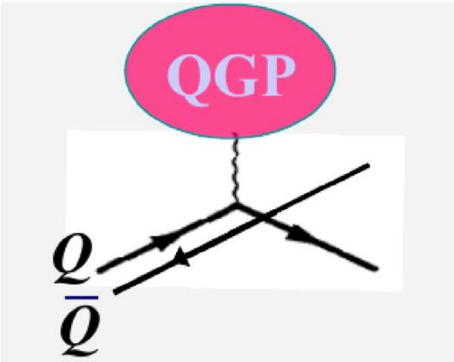


QUESTION:
Will light hadrons such as ϕ have the same effect?

T. Matsui, H. Satz, PLB174, 416 (1986)

Dynamic Dissociation in QGP



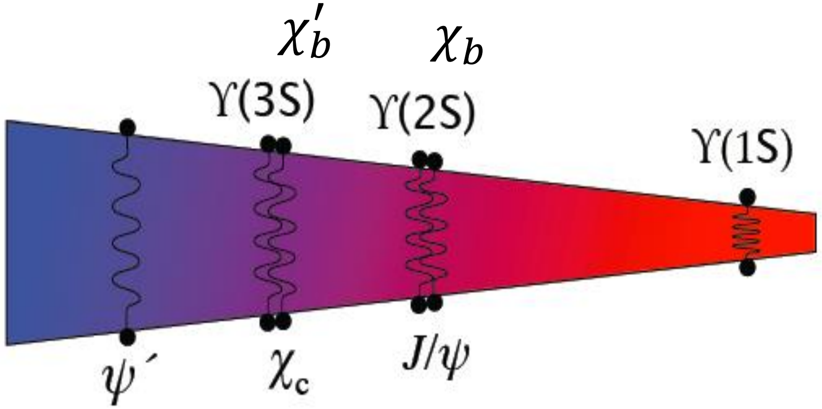


M. He, H. van Hees and R. Rapp, PPNP130, 104020 (2023)

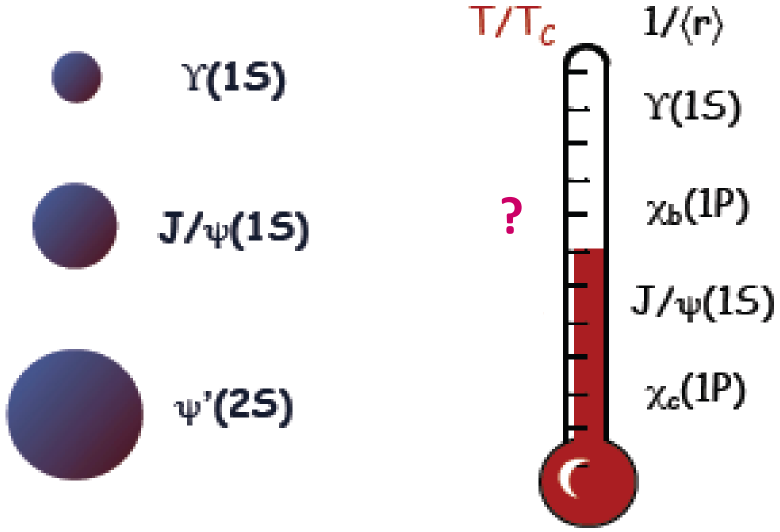
Quarkonium may absorb a gluon or interact with partons in QGP and dissociated

Dissociation rate depends also on QGP temperature, binding energy of quarkonium etc

Quarkonium Suppression: QGP Thermometer



Plasma thermometer



Debye radius is inversely proportional to the temperature of QGP

Different quarkonium states dissociate at different temperatures
→ Sequential melting

By measuring sequential melting, one get some information of QGP temperature

Quarkonium Reconstruction

QUESTION:
Why the dilepton decay branching ratios are different?

$J/\psi \rightarrow e^+e^- \ or \ \mu^+\mu^-$ Branching ratio ~ 6%

$\psi(2S) \rightarrow e^+e^- \ or \ \mu^+\mu^-$ Branching ratio ~ 0.8%

$\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ Branching ratio ~ 35% $35\% \times 6\% = 2.1\%$

$\Upsilon(1S) \rightarrow e^+e^- \ or \ \mu^+\mu^-$ Branching ratio ~ 2.4%

$\Upsilon(2S) \rightarrow e^+e^- \ or \ \mu^+\mu^-$ Branching ratio ~ 1.9%

$\Upsilon(3S) \rightarrow e^+e^- \ or \ \mu^+\mu^-$ Branching ratio ~ 2.2%

Typically need 1 million p+p events to reconstruct one J/ψ
Much less for other quarkonium states

Good trigger and PID detectors are crucial

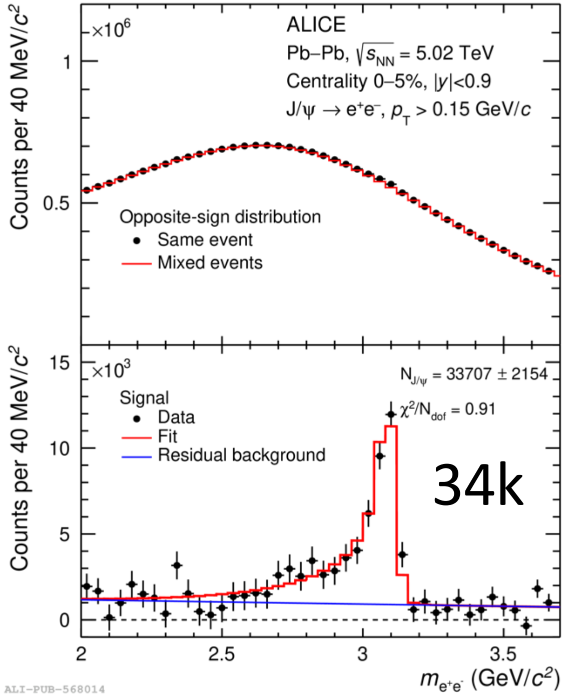
Quarkonium in ALICE @ Run2

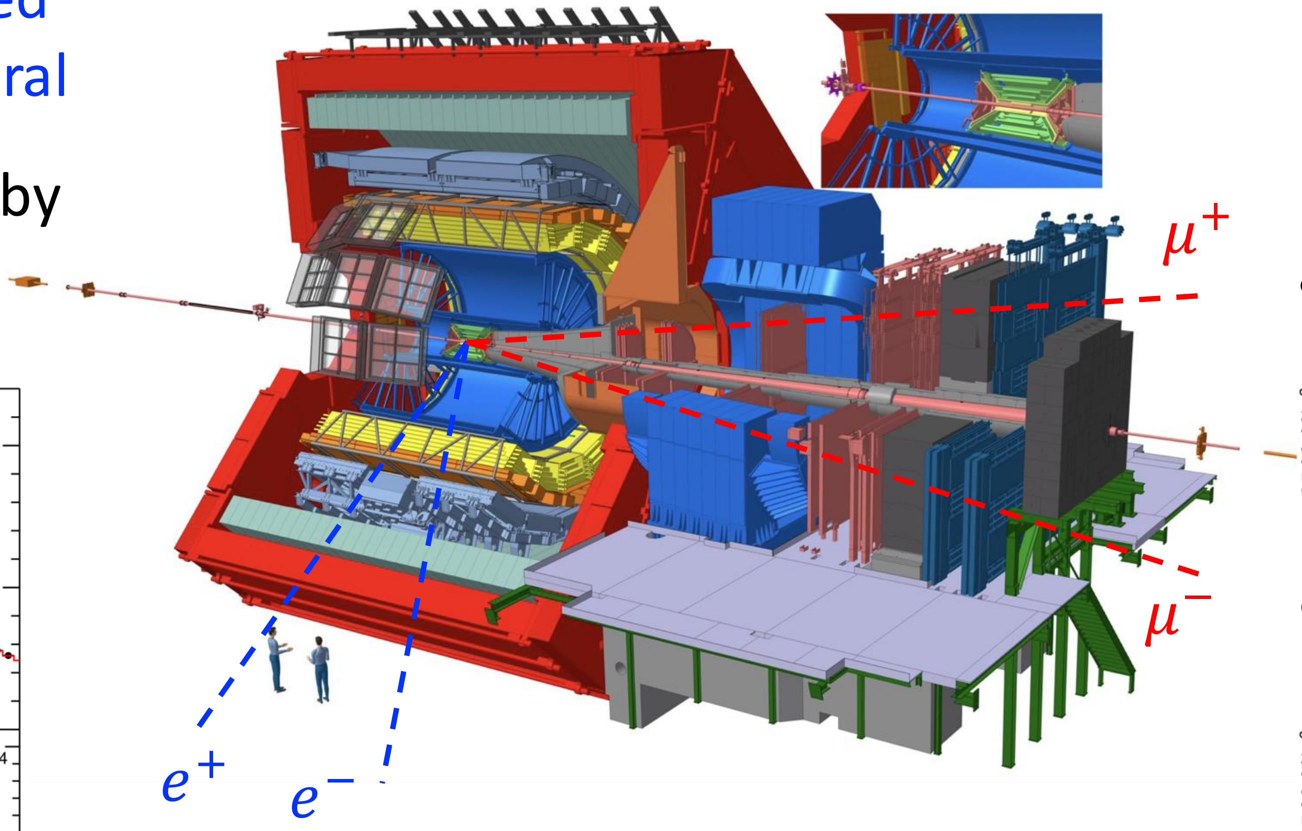
22 μb^{-1} MB triggered
105 μb^{-1} 0-10% central

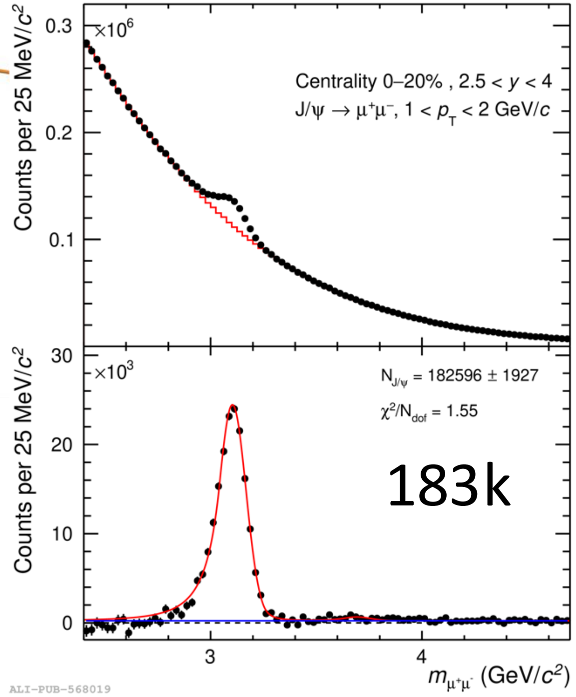
756 μb^{-1} $\mu^+\mu^-$ trigger

Electrons identified by dE/dx in TPC

Hadrons suppressed by absorbers (10+7.2 λ_I)





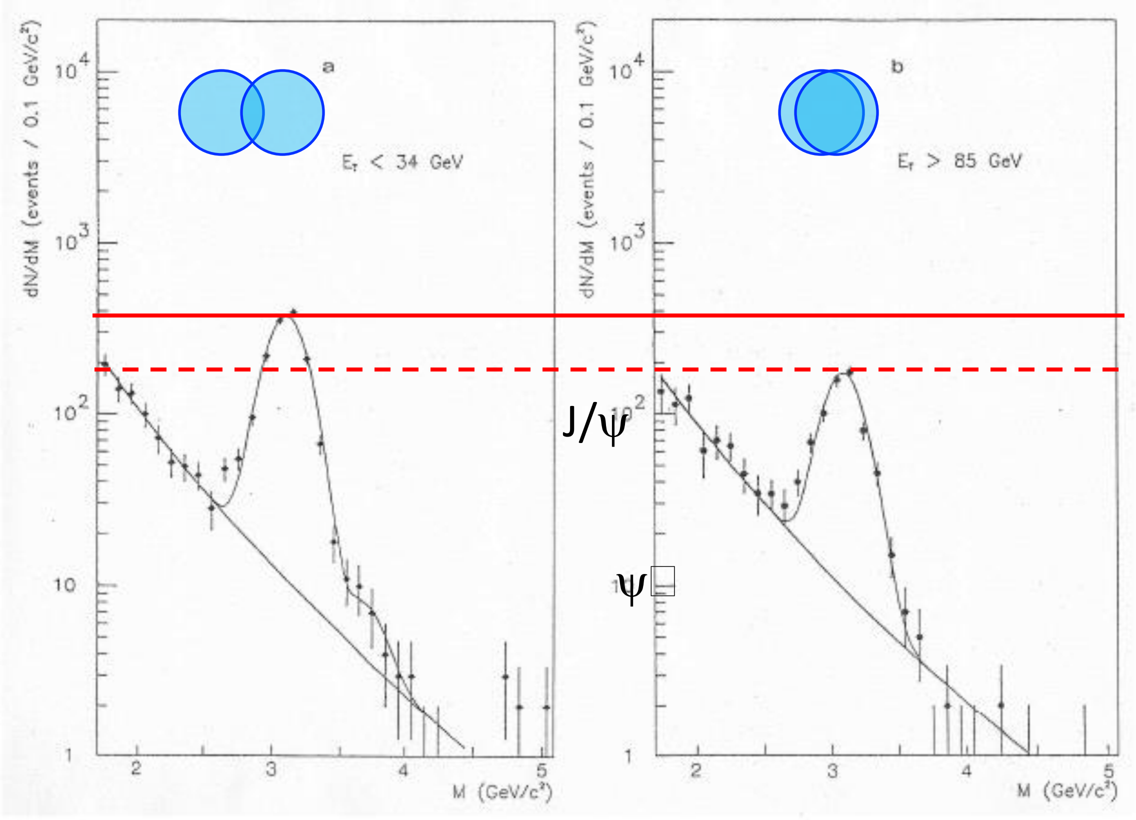


e^+e^- at mid-rapidity
$\mu^+\mu^-$ at forward rapidity

ALICE, JHEP02, 066 (2024)

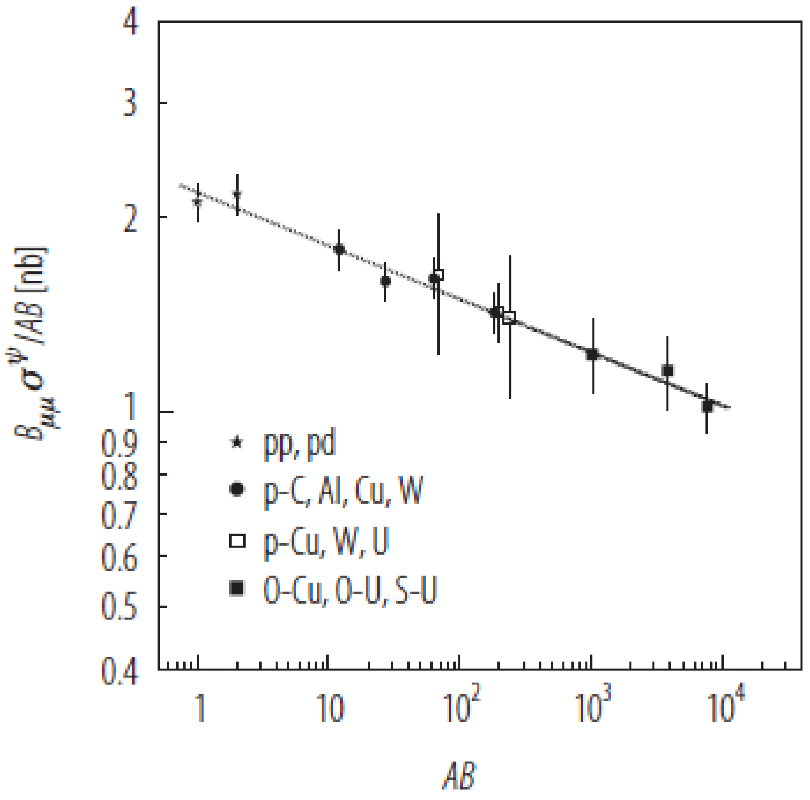
First Observation of J/ψ Suppression

200 AGeV O+U collisions



NA38, PLB220, 471 (1989)

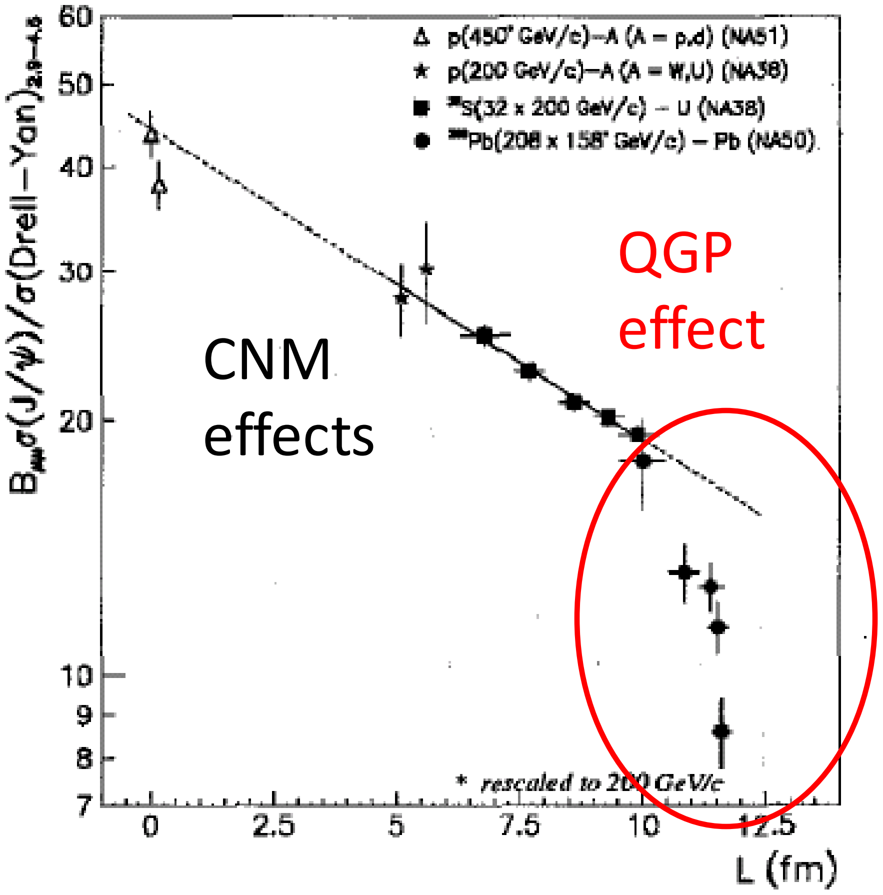
Figure 1: First observation of the J/ψ suppression effect in O(200 AGeV)-U collisions experiment at CERN-SPS. When comparing the invariant-mass spectrum of muon pair peripheral collisions (characterized by a small transverse energy $E_T < 34$ GeV; left panel central collisions (at high transverse energy, $E_T > 85$ GeV; right panel), a reduction of t over the Drell-Yan continuum is apparent (from [8]).

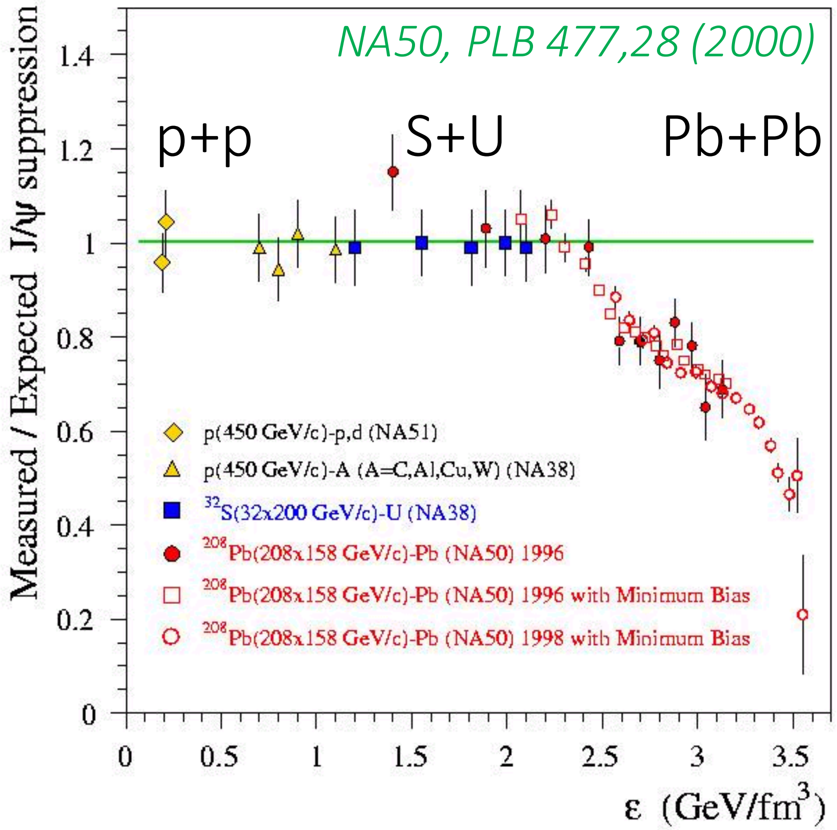


But observed also in p+A collisions

Explained by Cold Nuclear Matter (CNM effects)

Anomalous J/ψ Suppression at SPS



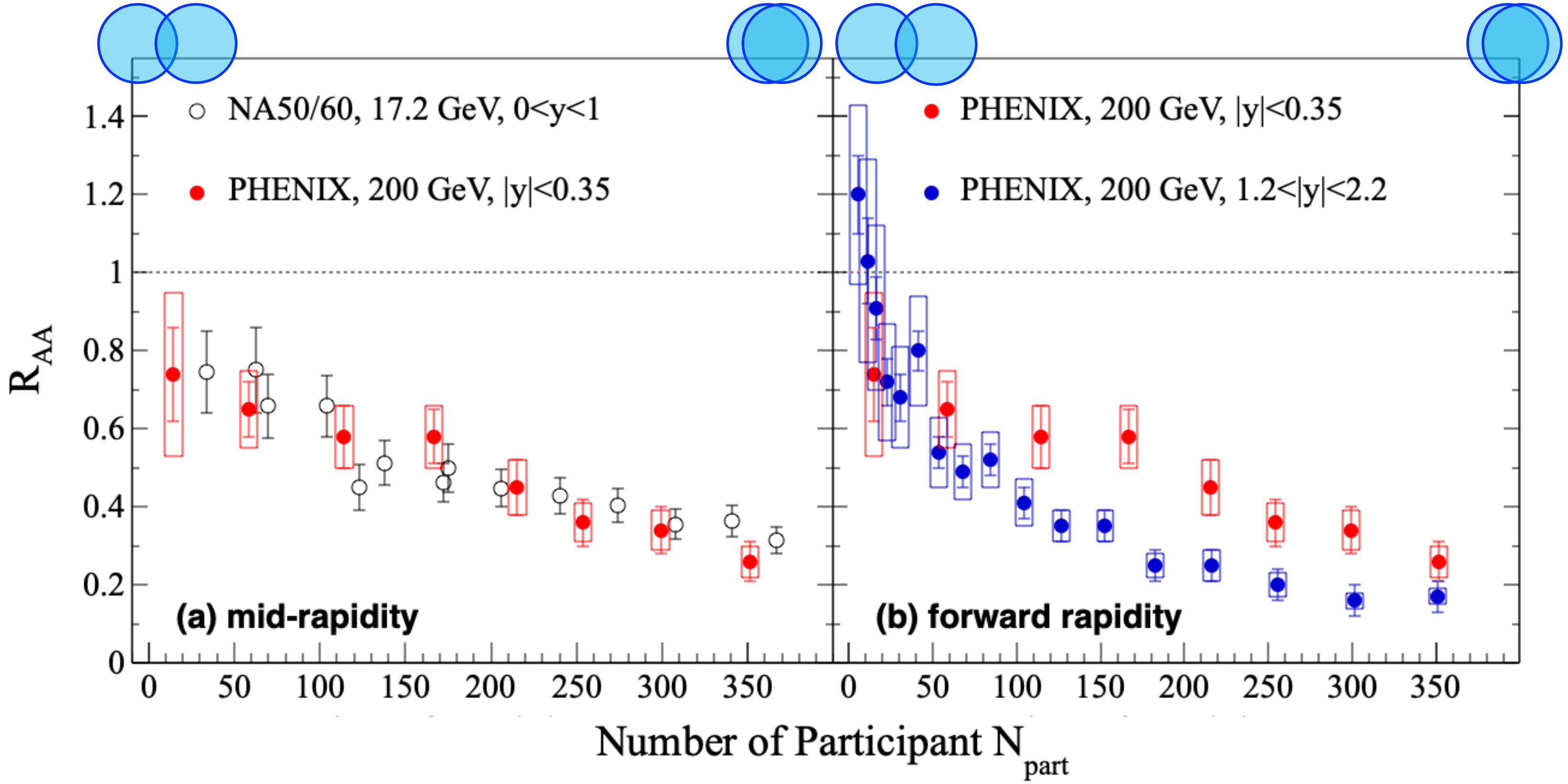


Beyond normal suppression observed in Pb+Pb

"Anomalous" suppression

gluons. Therefore, we must conclude that the J/ψ suppression pattern observed in our data provides significant evidence for deconfinement of quarks and gluons in the Pb-Pb collisions probed by NA50.

Suppression at RHIC

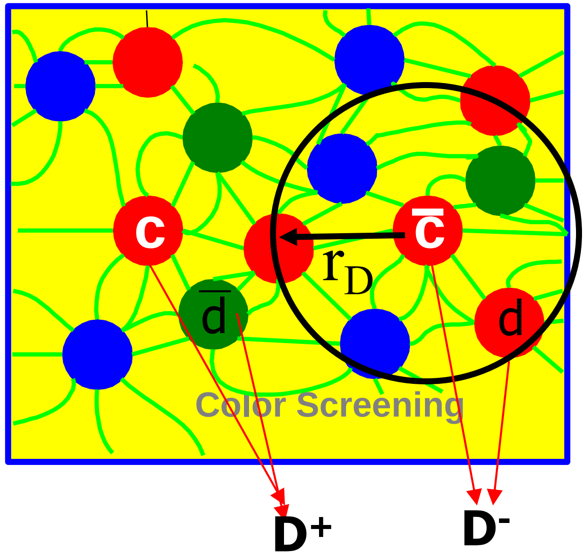


J/ψ suppression in 200GeV Au+Au at RHIC **similar** as J/ψ suppression in 17.2GeV Pb+Pb at SPS
Despite the increase of energy by a factor of 10+

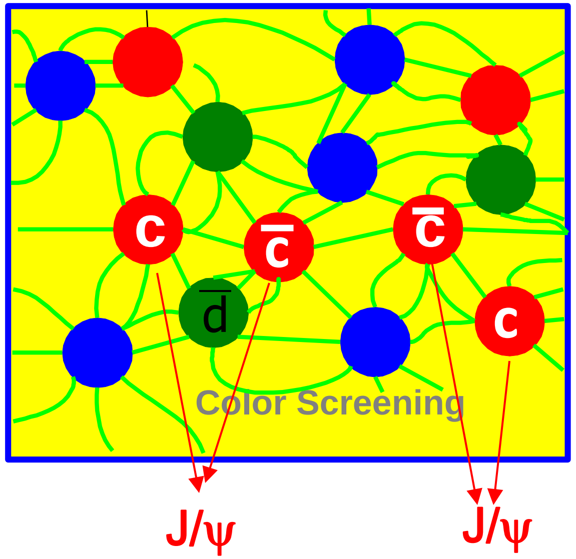
Stronger suppression at forward than at mid-rapidity

Puzzle!!

Color Screening vs. Regeneration



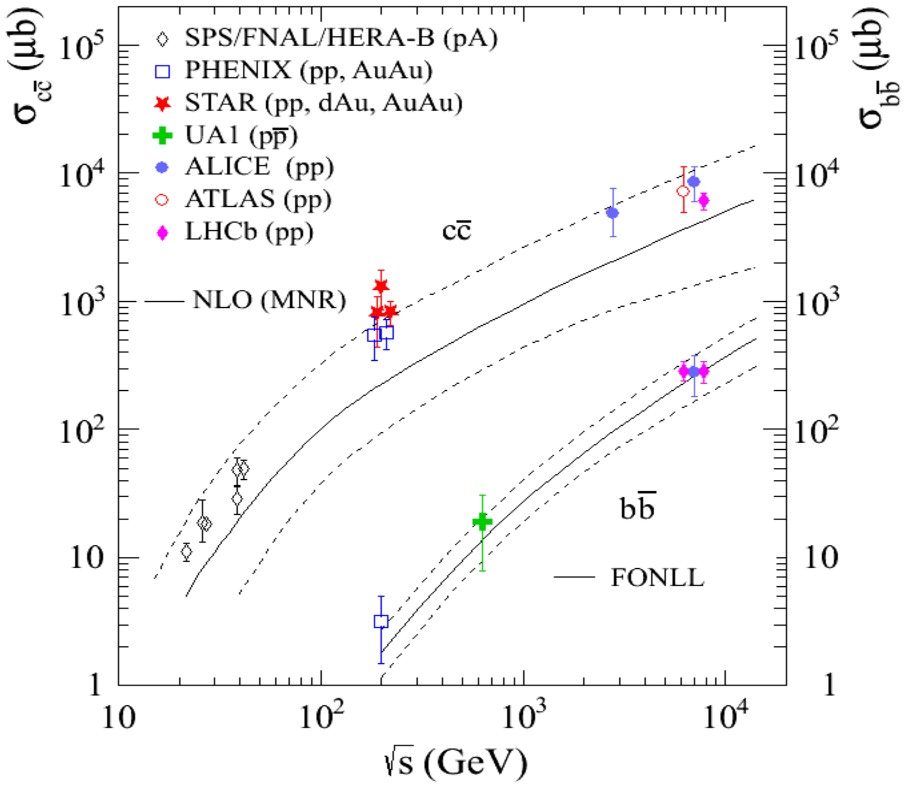
Quarkonium melting in QGP



Quarkonium regeneration in QGP

QGP formation is the prerequisite of both effects

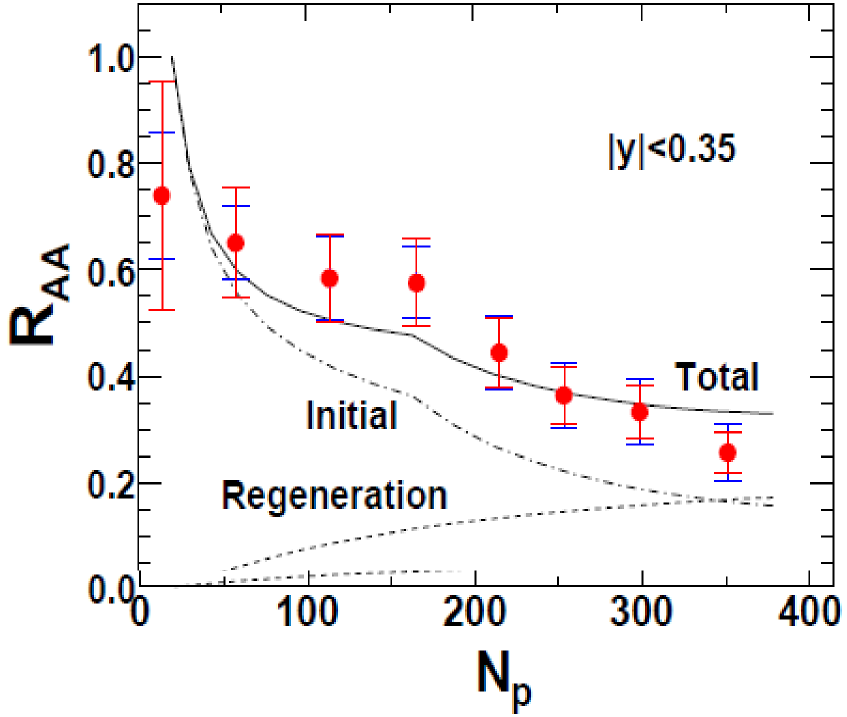
Puzzle Solved



Charm cross-section increases with energy

More regeneration at higher energy and in central collisions

Z. Qu, Y. Liu, N. Xu, P. Zhuang, NPA830, 335c (2009)

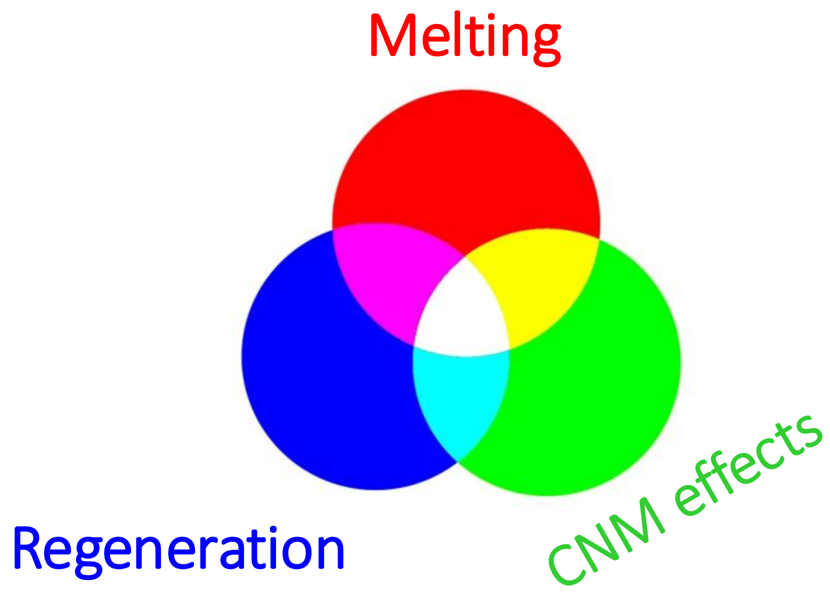


Theoretical calculations with regeneration can describe both RHIC and SPS data

In that the end?

Quarkonium in Heavy-Ion Collisions

Quarkonium production in heavy-ion collisions are the interplay of color-screening/melting, regeneration in QGP and CNM effects



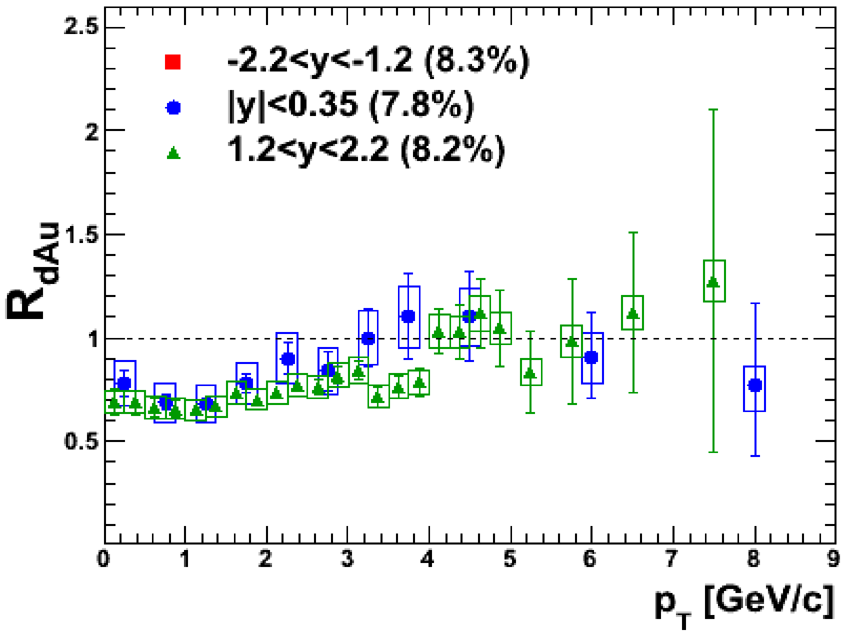
How to disentangle them?

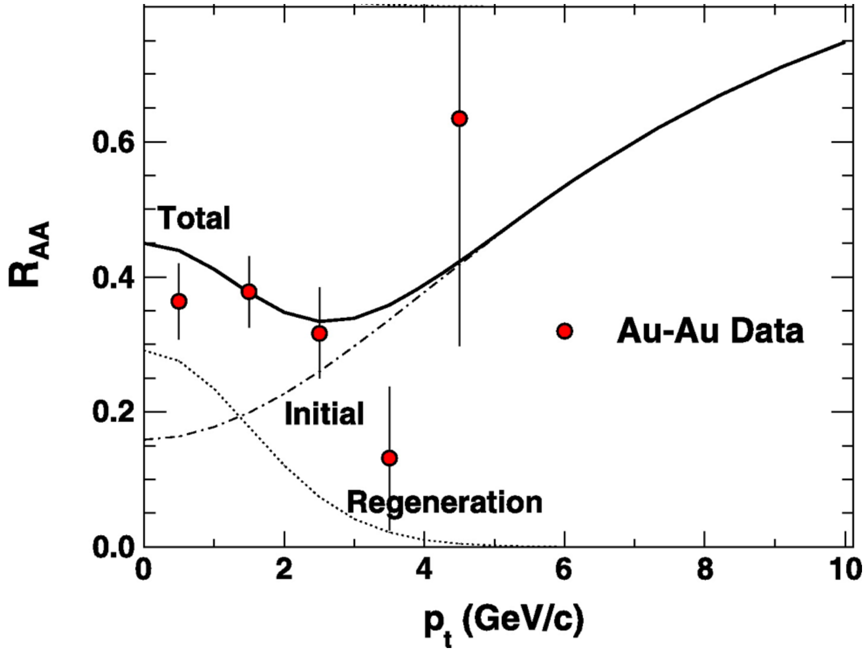
How to prob QGP with quarkonium?

Each of the effects have different dependence on

- p_T
- energy
- quarkonium size

Move to High p_T to Study Color Screening





At p_T>4 GeV/c,

CNM is negligible

At p_T>5 GeV/c,

regeneration is negligible

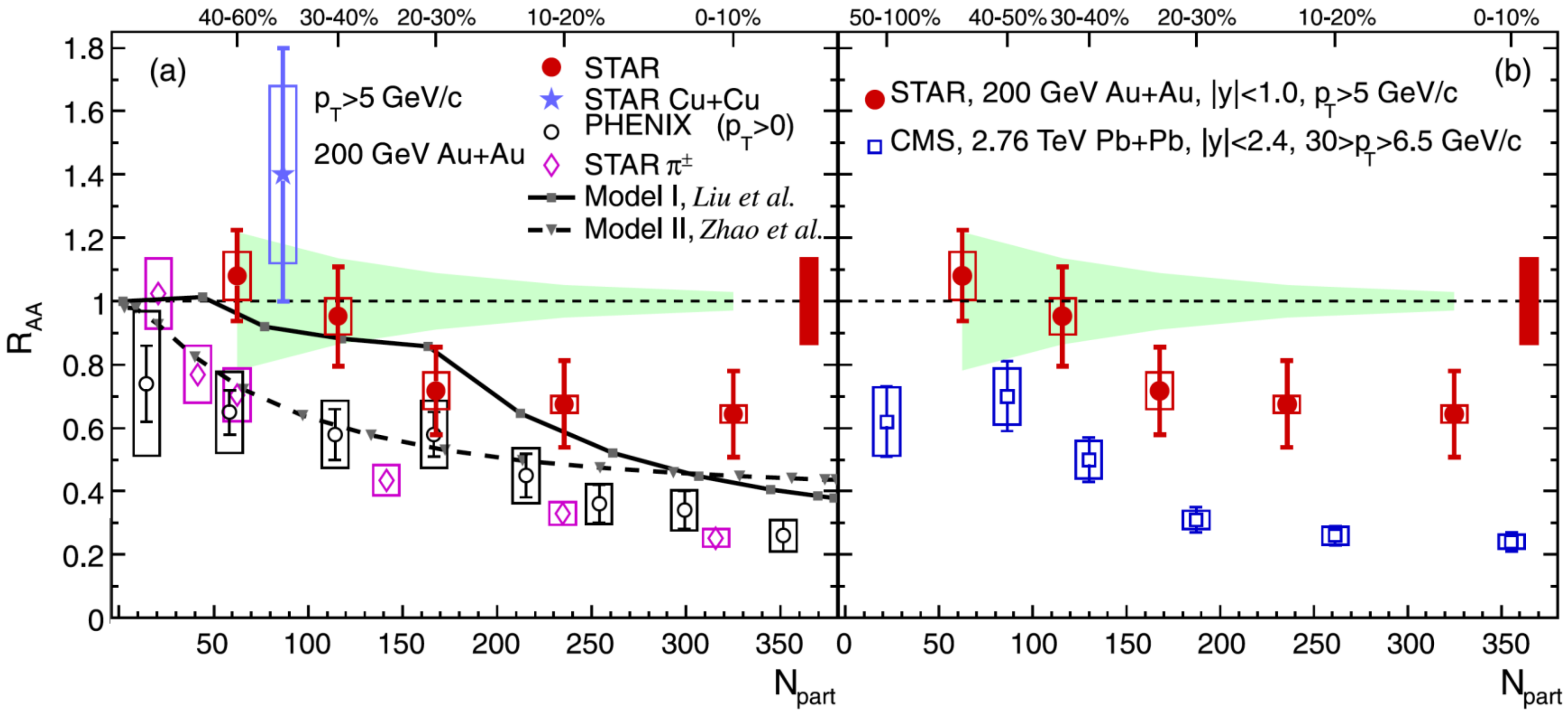
High-p_T J/ψ: clean probe of color screening

Very challenging measurement:

- Only < 1% of J/ψ are at high-p_T

Measurements in Au+Au Collisions

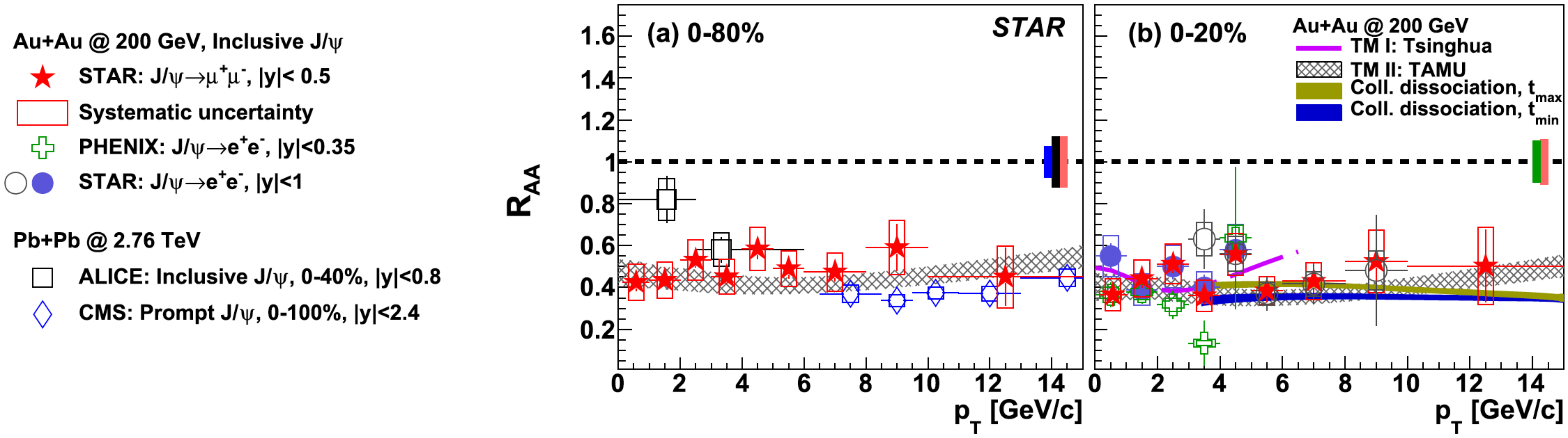
STAR, PLB722, 55 (2013)



Significant suppression of high-p_T J/ψ observed in central Au+Au collisions

"Points to the color screening feature"

Improved Measurements with Muons



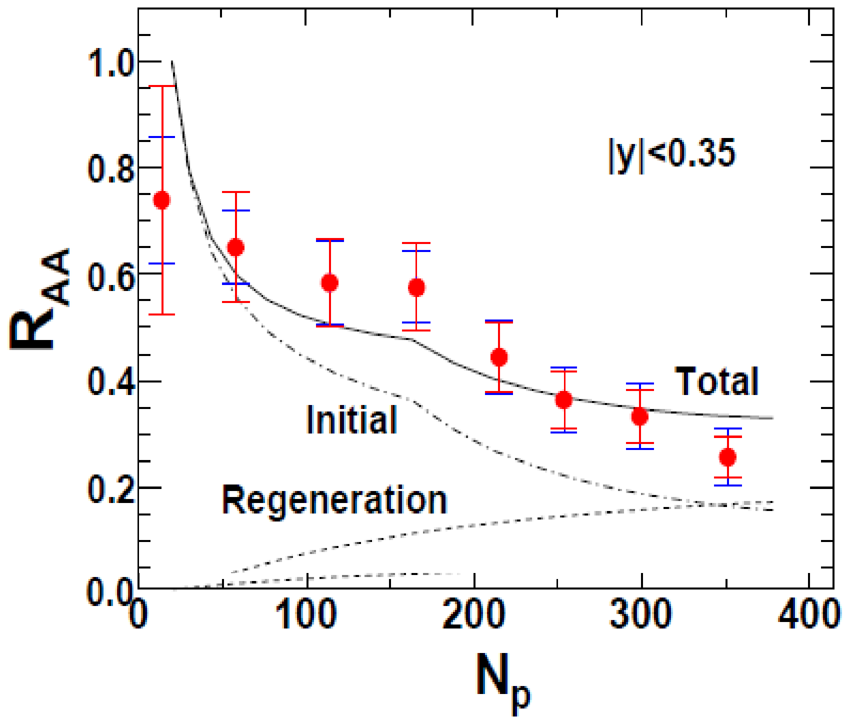
STAR, PLB797, 134917 (2019)

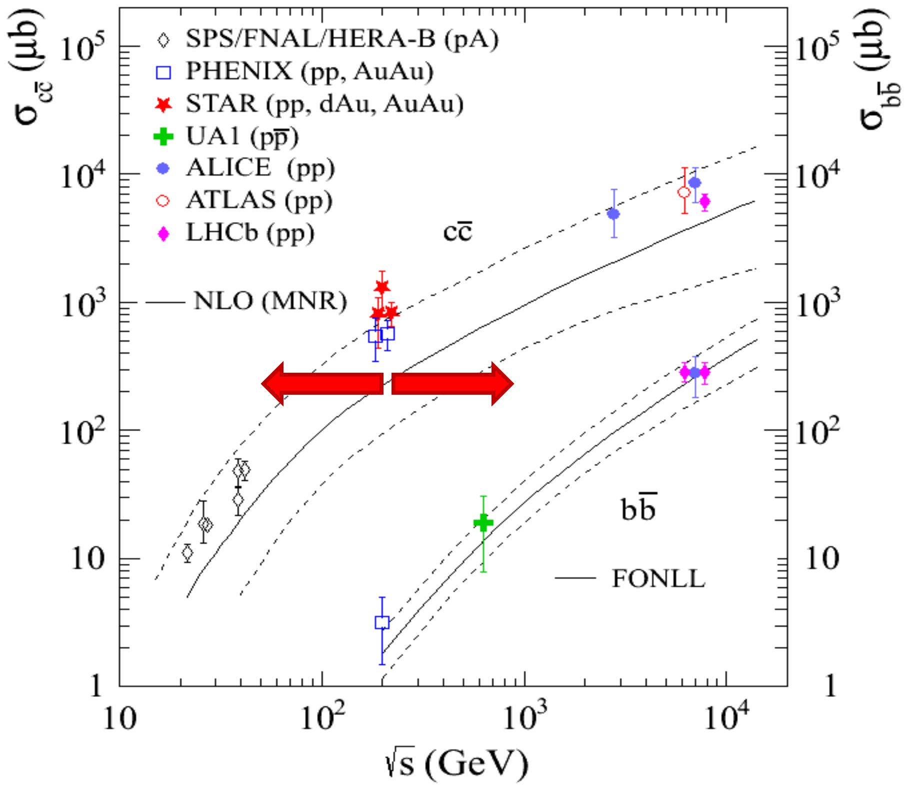
Significantly improves precision, and extends to low and higher p_T

Significant suppression observed at high p_T

"Providing strong evidence for the color-screening in the deconfined medium"

Energy Dependence of Charm Yield

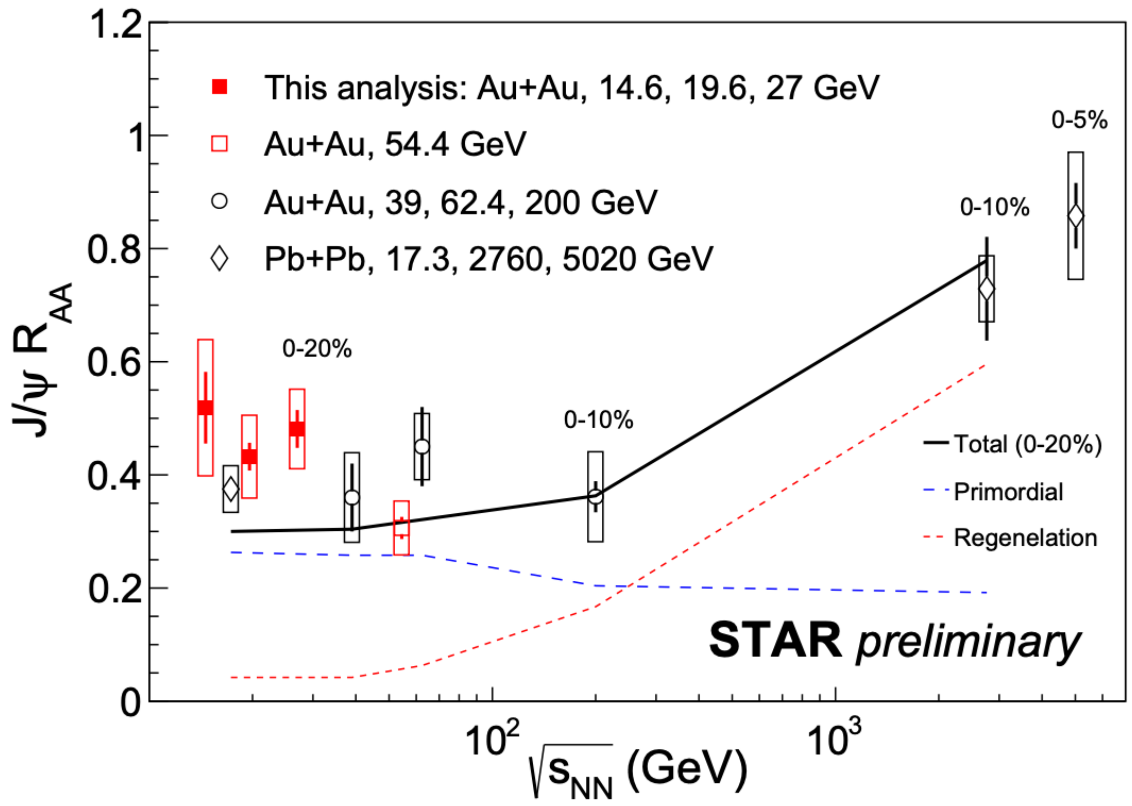




Theory predicts comparable contribution of color screening and regeneration in central collisions at RHIC

It's contribution should be less important at lower energy but dominant at LHC energy

Energy Dependence of J/ψ Suppression

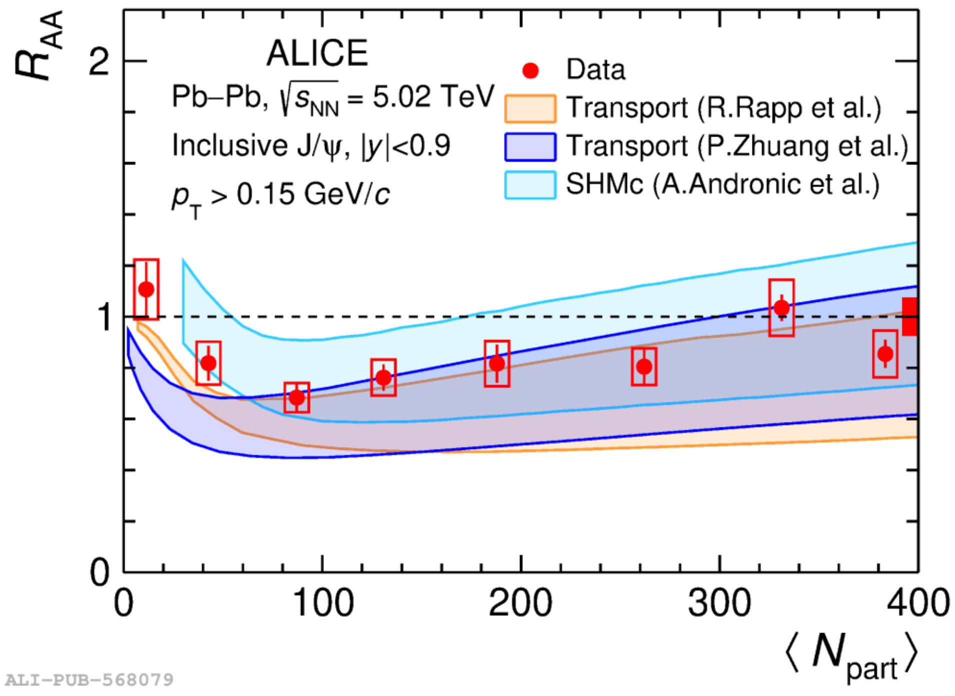


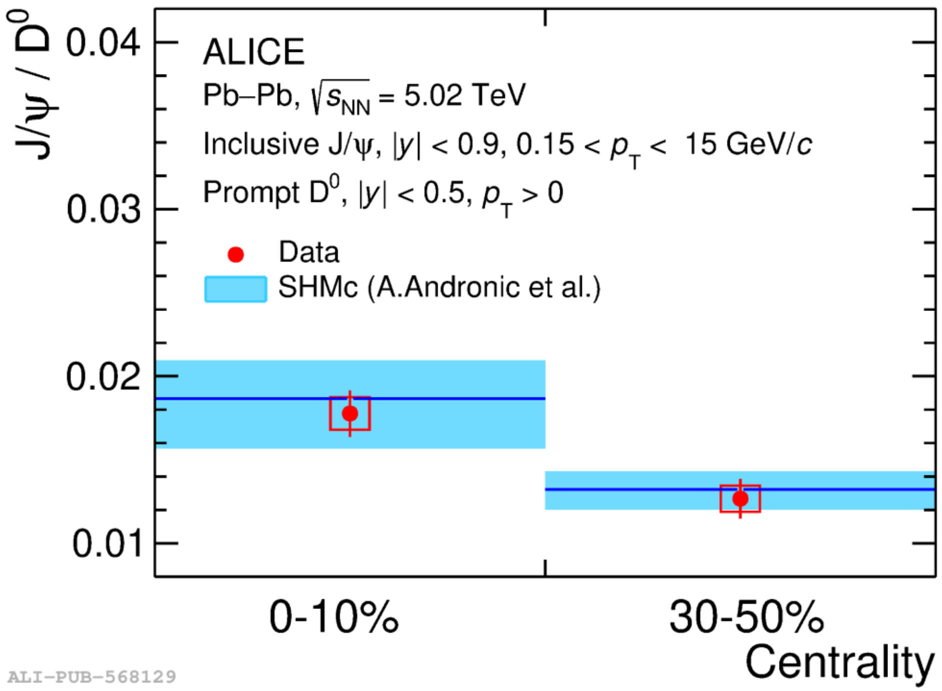
NA50, PLB 477, 28 (2000)
Wei Zhang, QM 2023
STAR, PLB 771, 13 (2017)
Kaifeng Shen, SQM 2021
ALICE, PLB 734, 314 (2014)
ALICE, PLB 849, 138451 (2024)

SPS	→	RHIC	→	LHC
CNM + screening		CNM + screening + regeneration		Regeneration domain

J/ψ Yield at LHC

ALICE, PLB 849, 138451 (2024)





Centrality dependence：

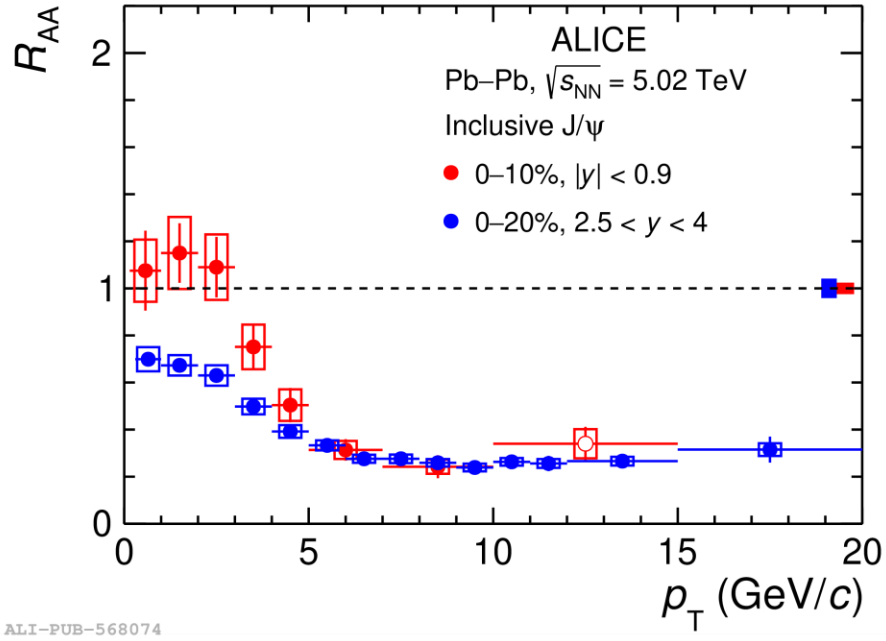
- Increase towards central collisions

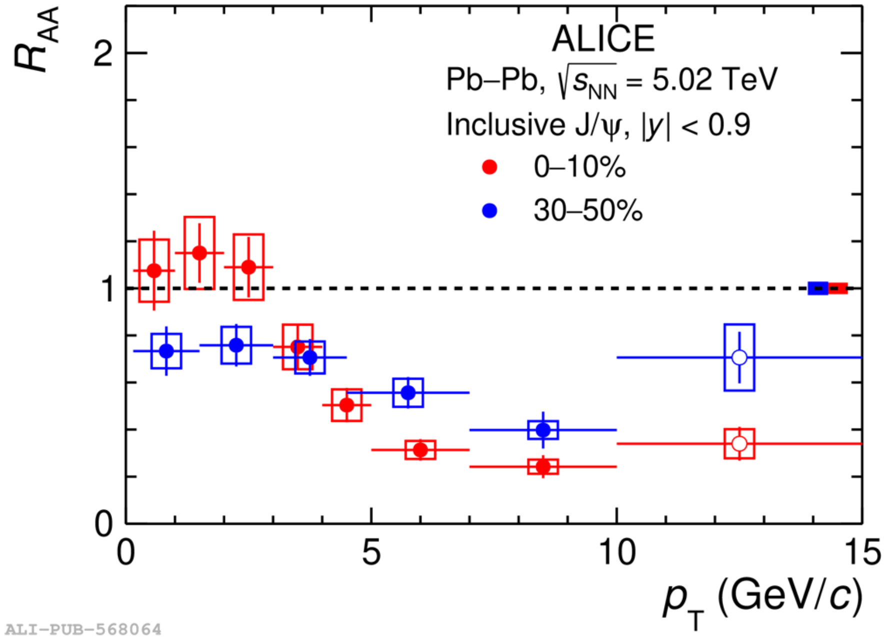
Particle ratio：

- Increase of J/ψ yield with respect to D^0 in central collisions

Differential Measurements at ALICE

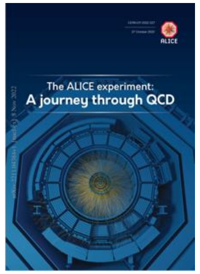
ALICE, PLB 849, 138451 (2024)





- Clear rapidity dependence at low-p_T
- Similar suppression at high-p_T

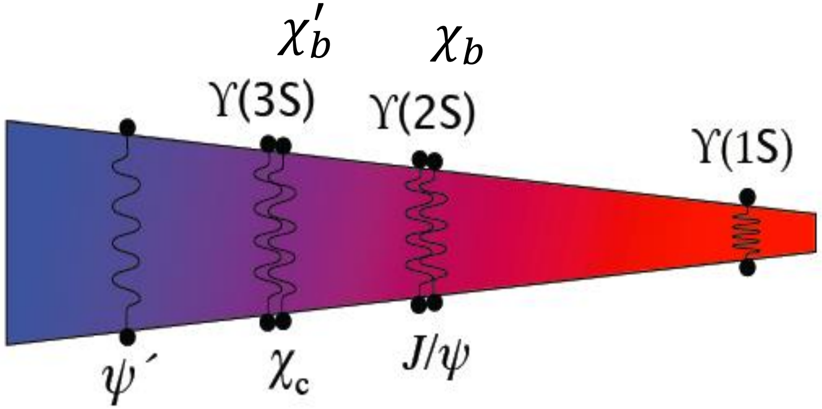
- Clear centrality dependence
- Opposite at low and high p_T region



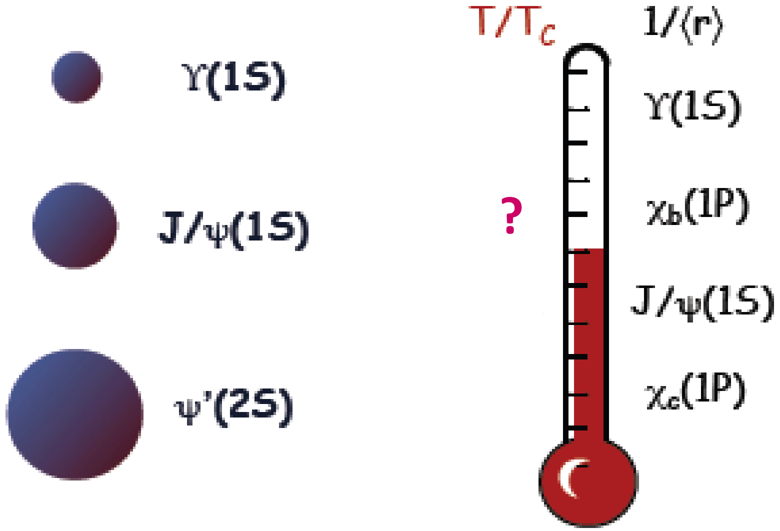
2.5.1 Study of the charmonium ground state: evidence for the (re)generation and demonstration of deconfinement at LHC energies

*Jet quenching might play an import role at high p_T

Quarkonium Suppression: QGP Thermometer



Plasma thermometer

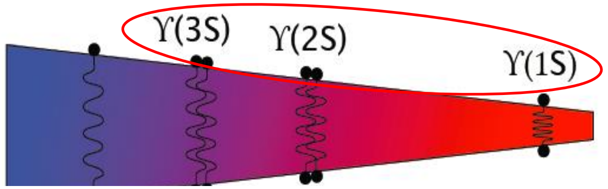


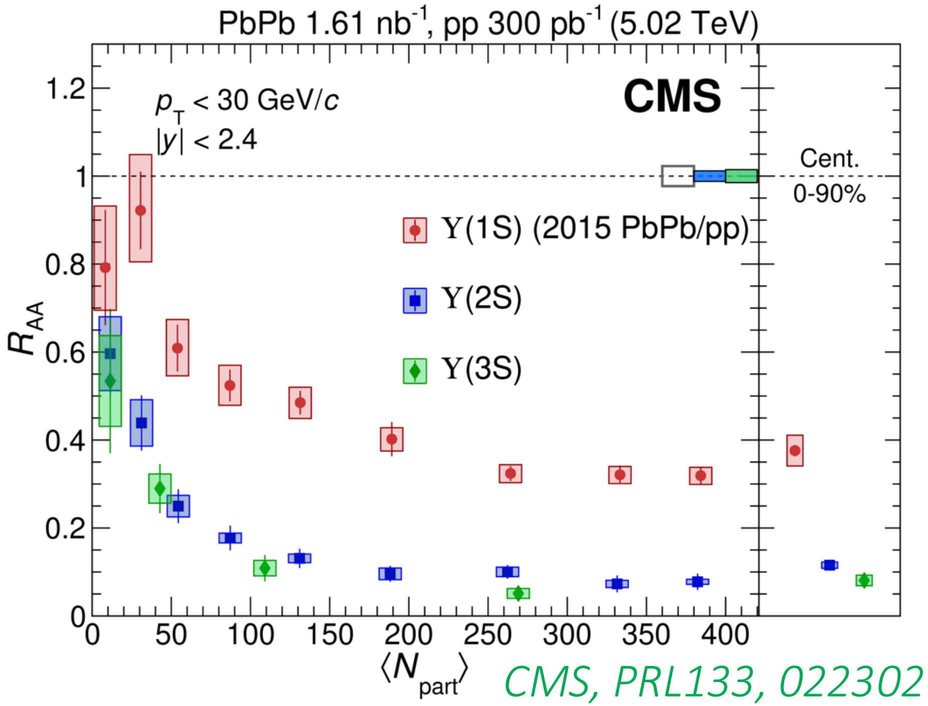
Debye radius is inversely proportional to the temperature of QGP

Different quarkonium states dissociate at different temperature
→ Sequential melting

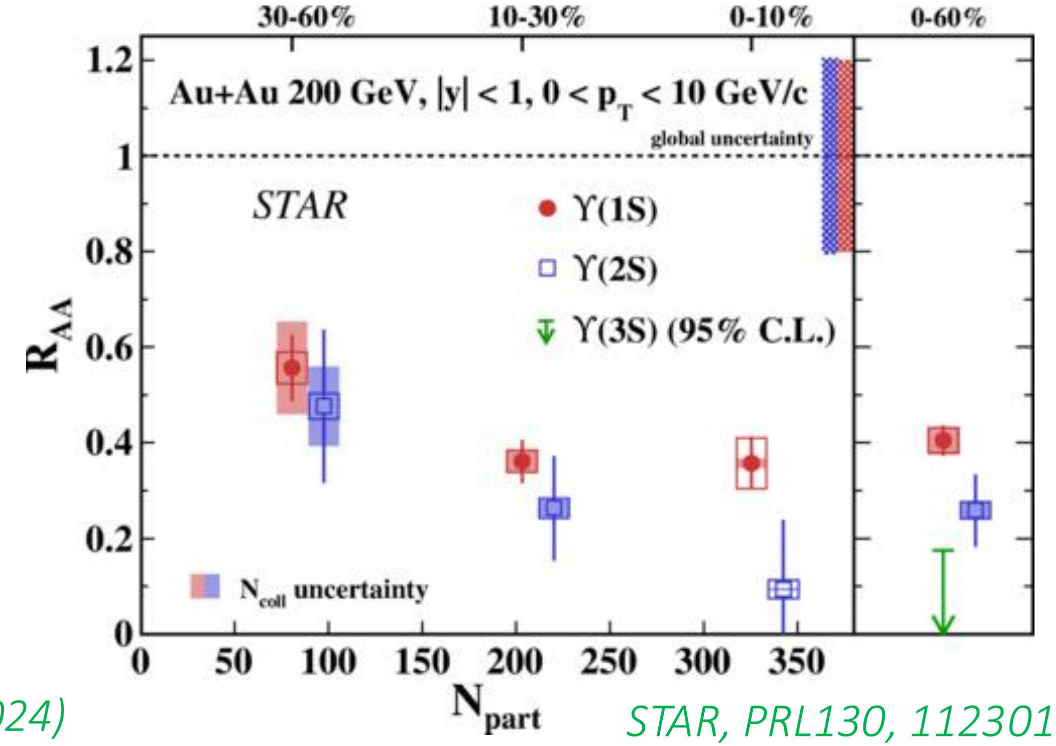
By measuring sequential melting, one get some information of QGP temperature

Sequential Melting in Bottom Sector





CMS, PRL133, 022302 (2024)

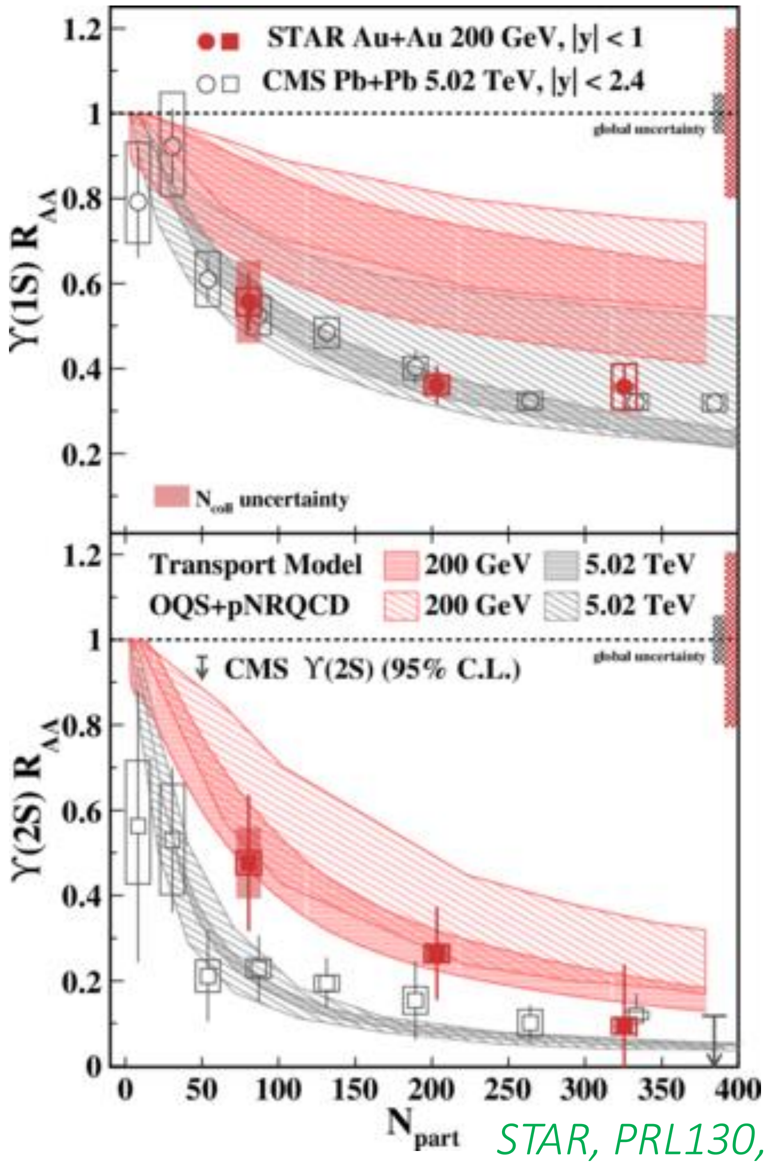


STAR, PRL130, 112301 (2023)

Precise measurement of "sequential melting" at LHC

First observation of "sequential melting" at RHIC

Sequential Melting in Bottom Sector



STAR, PRL130, 112301 (2023)

Upsilon(1S):

- Strong suppression, and similar at RHIC and LHC

→ Arises mainly from the suppression of excited states feed down to Upsilon(1S) and CNM effects

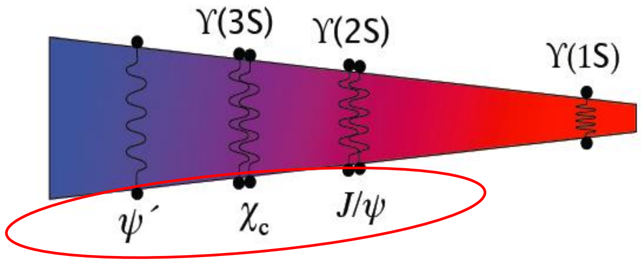
→ Primordial Upsilon(1S) not significantly suppressed

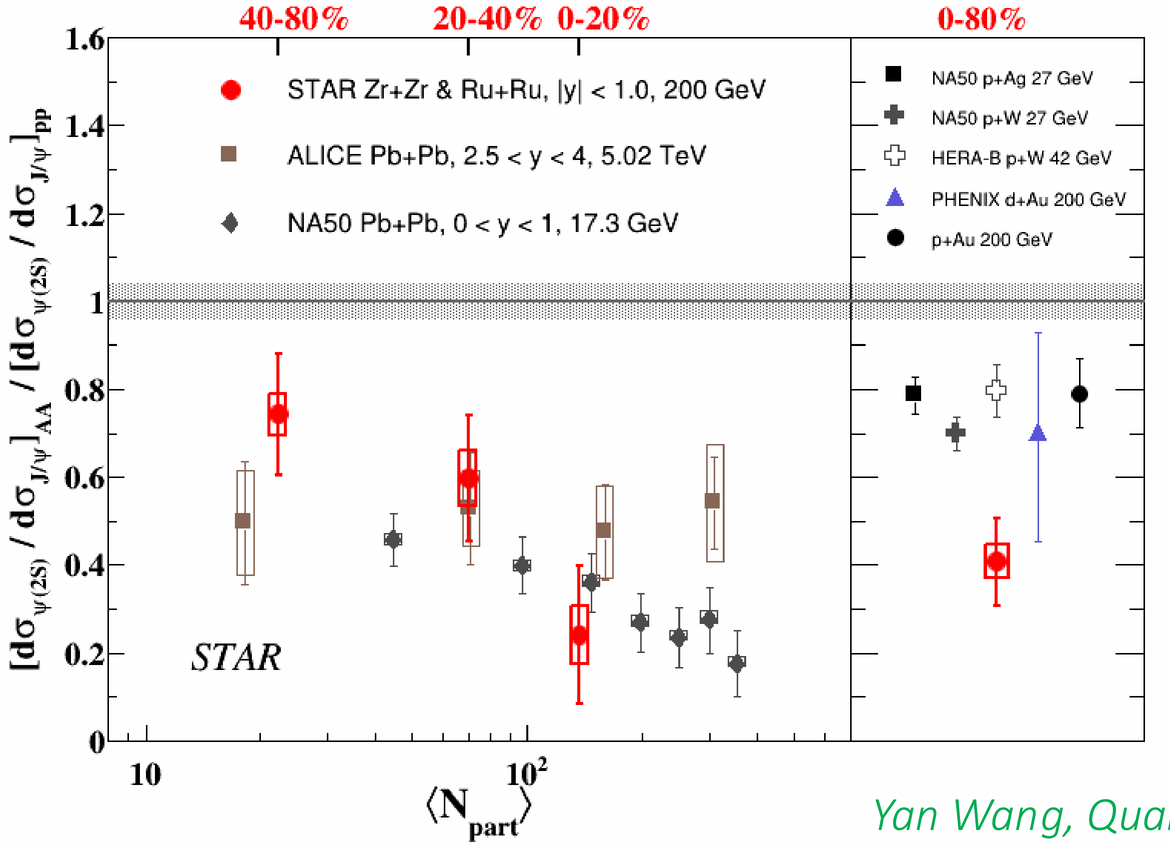
Upsilon(2S):

- Hints of less suppression at RHIC in peripheral collisions

QGP is formed, and its temperature is high enough to melt excited bottomonium states!!!

Sequential Melting in Charm Sector





Yan Wang, Quark Matter 2023

- Clearly stronger suppression for ψ(2S) than J/ψ from SPS to LHC
- “Sequential melting” in charm sector
- More data is needed to investigate collision energy dependence

Summary of Quarkonium

Quarkonium is an unique probe of QGP due to its large binding energy

Systematic experimental investigations provide strong evidence of

- Color screening in the deconfined medium
- And sequential melting (binding-energy-dependent suppression)

- Regeneration (coalescence) in the deconfined medium

➔ **All consistent with the formation of QGP**

➔ **Can be (Have been) used to extract QGP properties with precise data and theory**

Deep understanding the inner-working of QGP and quarkonium production mechanism in QGP requires further investigations

Plenary Talks

It is recommended to go to the following talks for latest developments and future plans

Wed 25/09

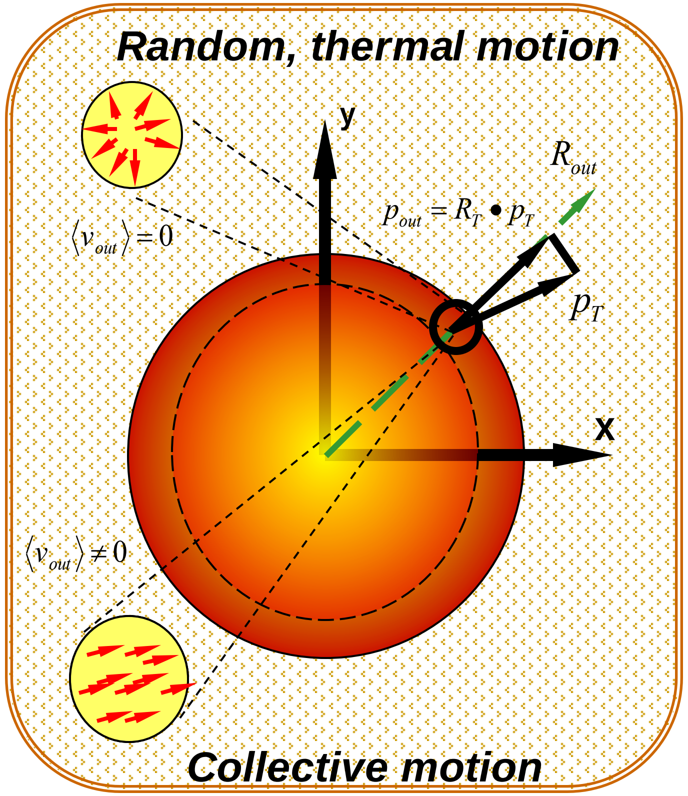
14:00	**Open Heavy Flavor: Theory** *Convention Hall 1*	*Dr Weiyao Ke* 14:00 - 14:25
	Open Heavy Flavor: Experiment *Convention Hall 1*	*Jing Wang* 14:25 - 14:50
	Quarkonia Theory: From Open Quantum System to Classical Transport *Convention Hall 1*	*Xiaojun Yao* 14:50 - 15:15
15:00	**Quarkonia: Experiment** *Convention Hall 1*	*Cristiane Jahnke* 15:15 - 15:40
16:00	**Coffee Break**	15:40 - 16:10

Fri 27/09

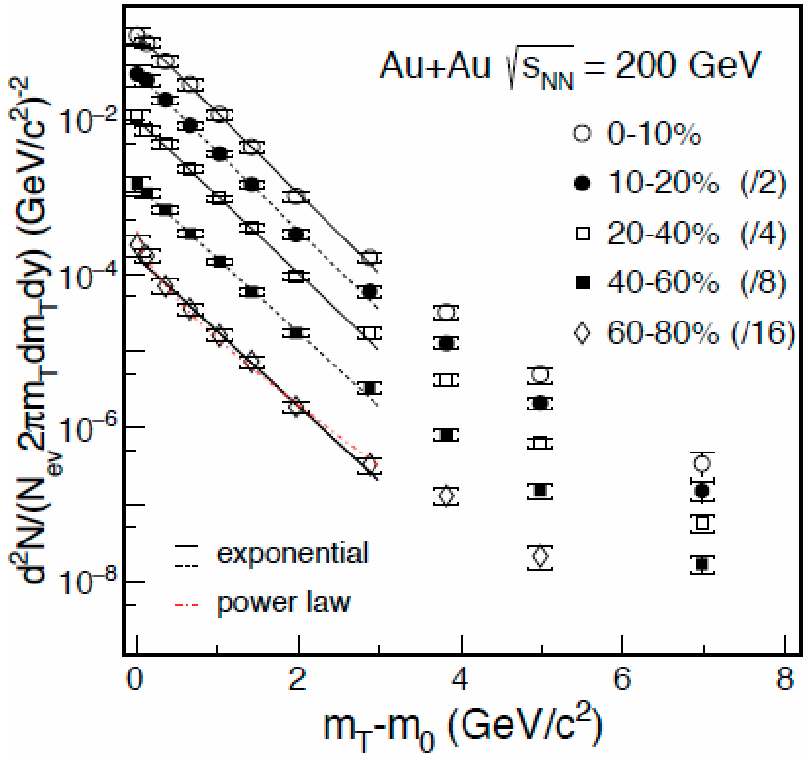
Conference Highlight: Heavy flavors *Convention Hall 1*	*Lijuan Ruan* 11:35 - 11:55

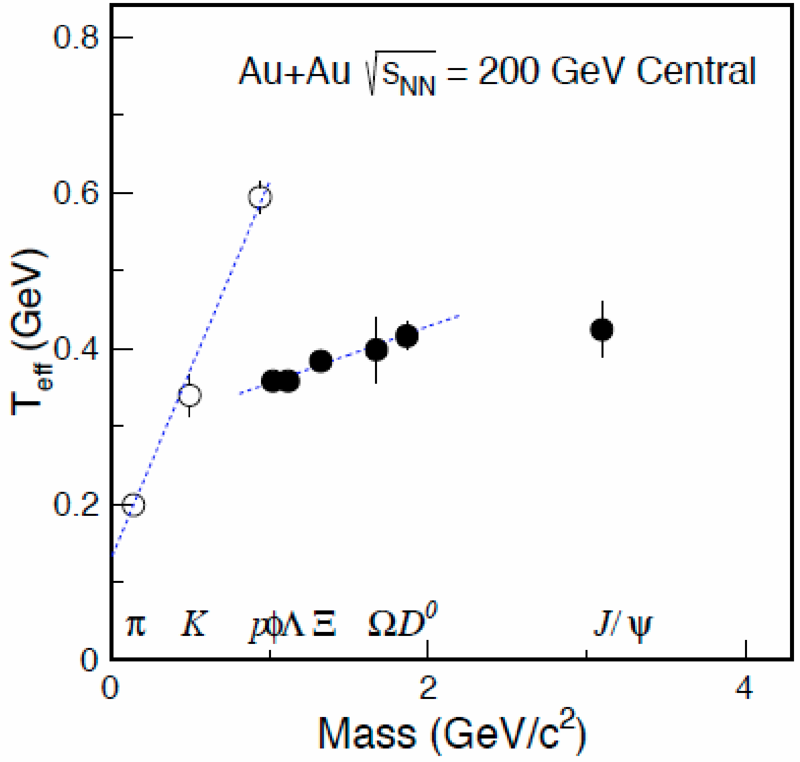
Thanks for your attention!

Radial Flow of D-meson



Courtesy of Nu Xu



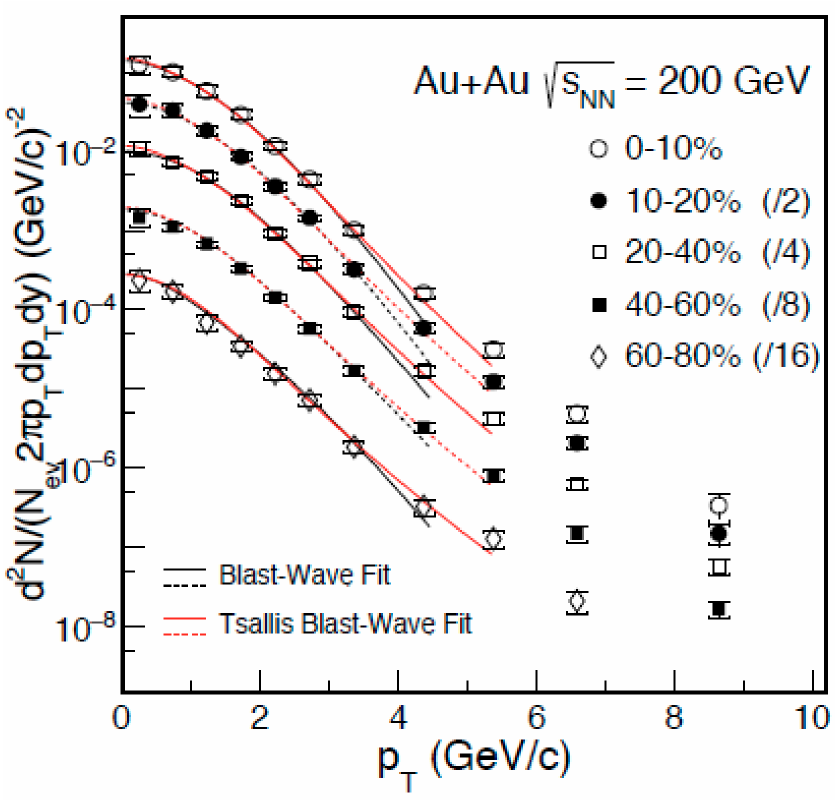


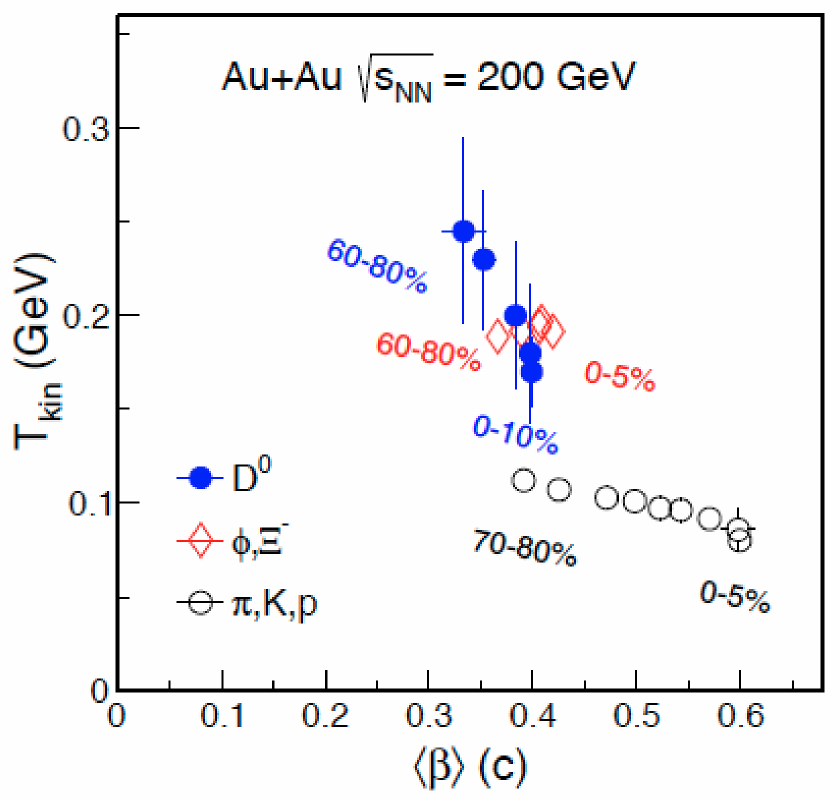
Charm should have blue shift if it has enough interactions with the expanding medium

$$T_{eff} \propto T_{thermal} + m \times \langle v_T \rangle^2$$

- D^0 follow the trend of strange particles
- Non-zero slop, but smaller than light flavor

Radial Flow of D-meson

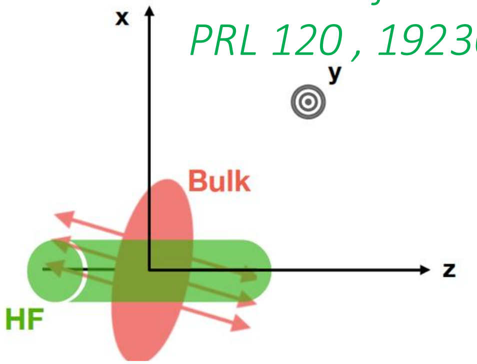


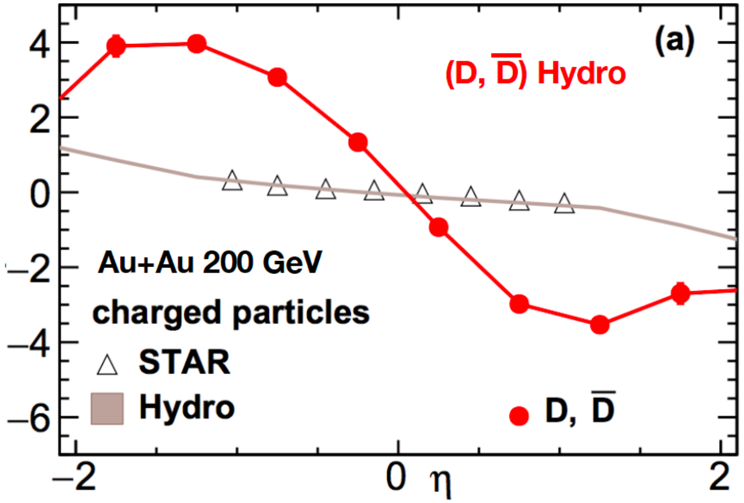


- Kinetic freezeout parameters can be extracted with (Tsallis) Blast-Wave model
- D^0 has similar parameters as strange particles

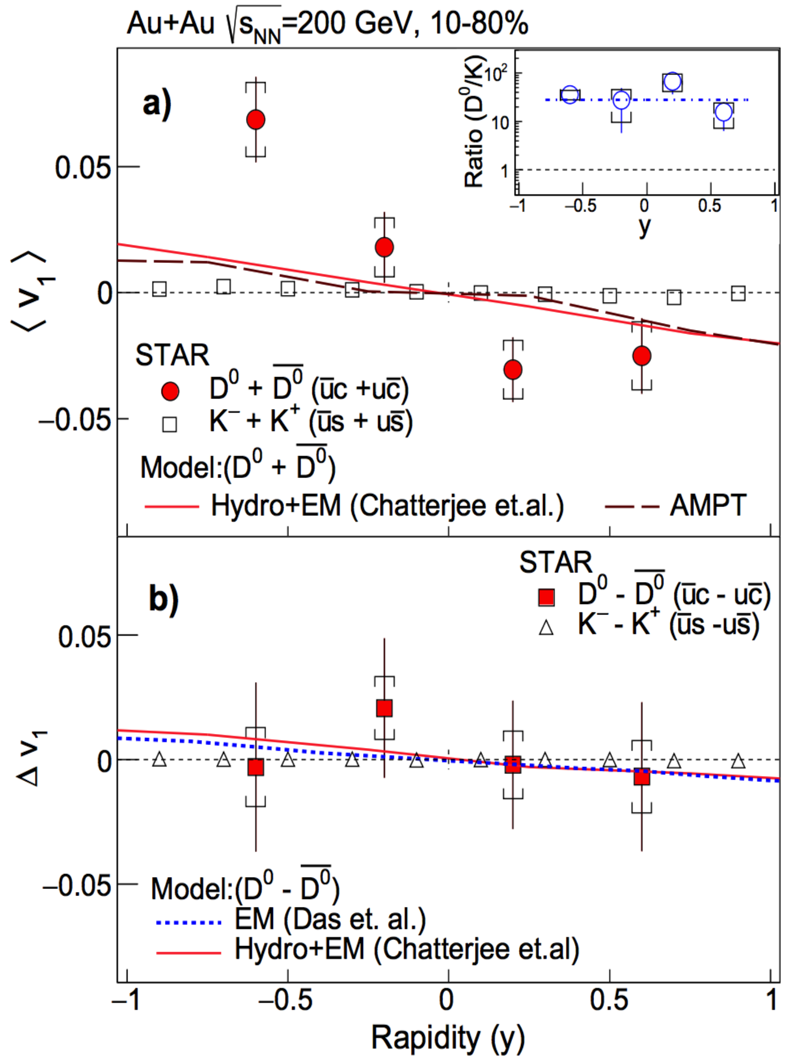
Directed Flow of D^0

S. Chatterjee and P. Bożek, PRL 120 , 192301 (2018)



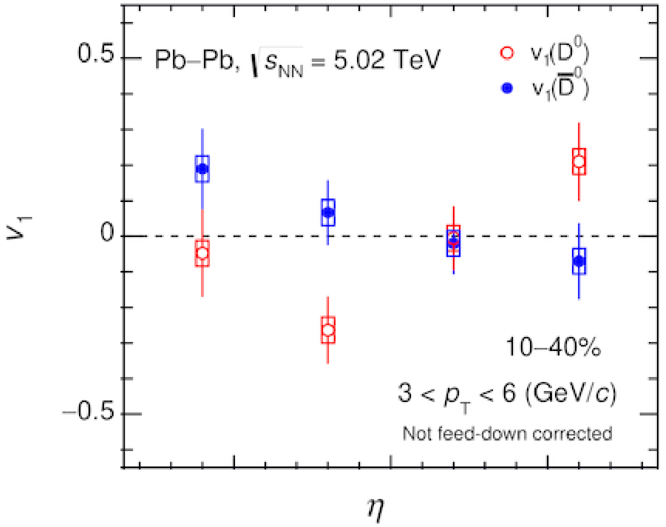


Charm should gain significant directed flow if it has enough interactions with the tilted medium



STAR: PRL123, 162301 (2019).

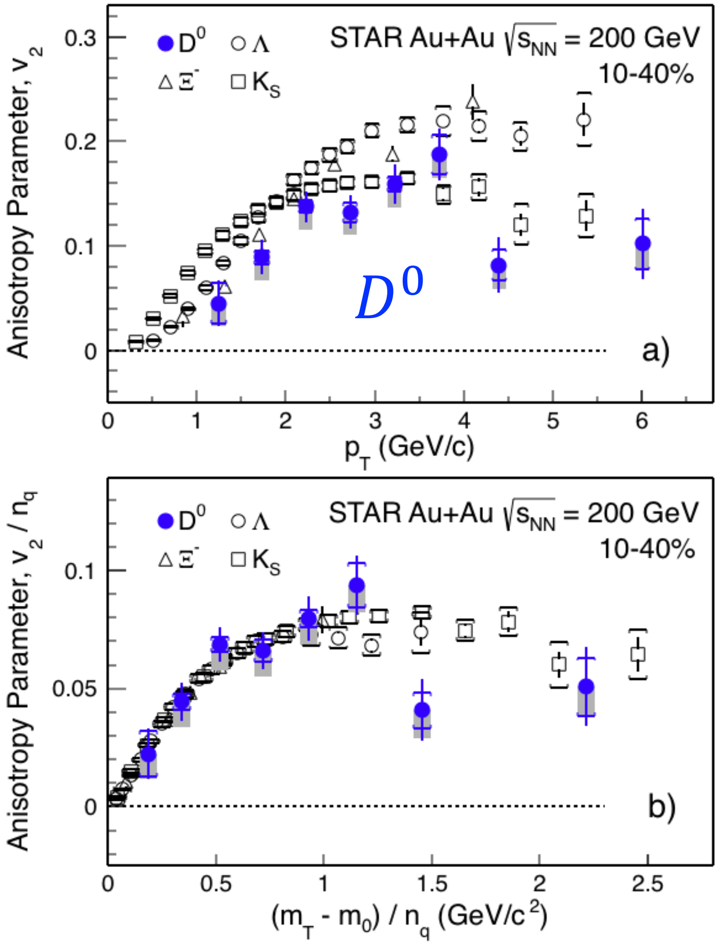
ALICE, PRL125, 022301 (2020)

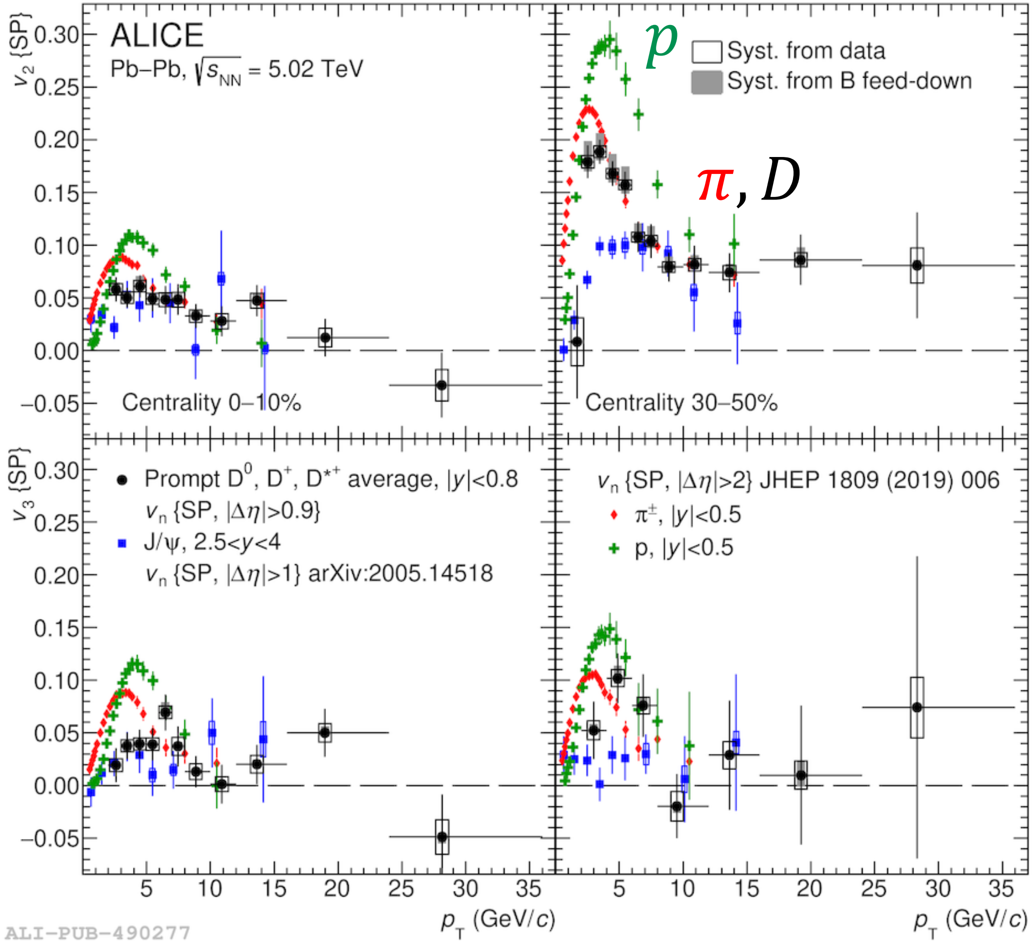


- Huge v_1 slop of D-meson is observed
- Need much more statistics to prob early electromagnetic field

Elliptic/Triangular Flow of D-meson

STAR, PRL 118, 212301 (2017)





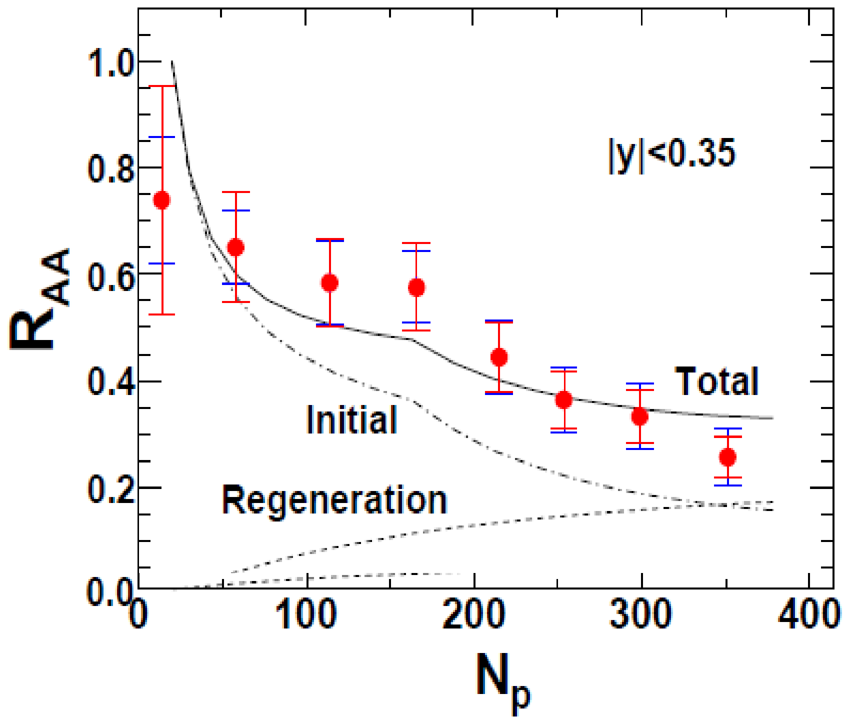
QUESTION: Why large flow at high p_T?

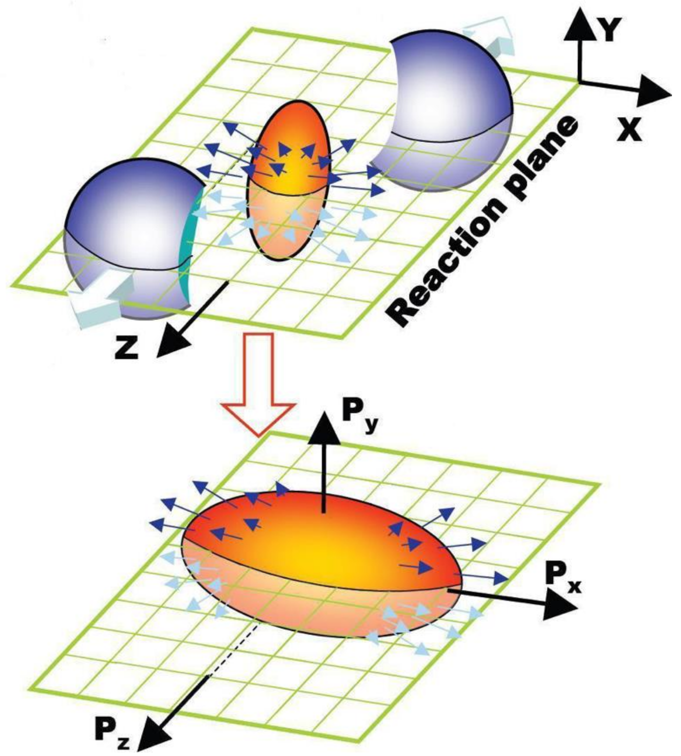
ALICE, PLB813, 136054 (2021)

Significant v_2 and v_3 observed for D^0-meson

- Mass ordering at low p_T – hydrodynamics behavior
- Follow mesons' flow at intermediated p_T – quark coalescence

Test J/ψ Regeneration with Elliptic Flow





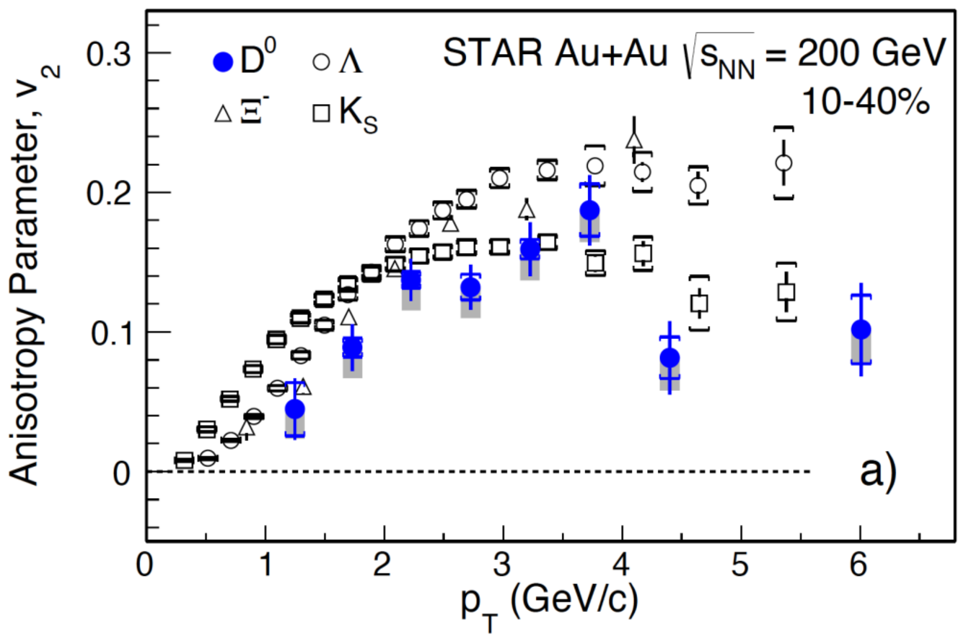
Theory predicts comparable contribution of color screening and regeneration in central collisions at RHIC

May study via azimuthal anisotropy (elliptic flow)

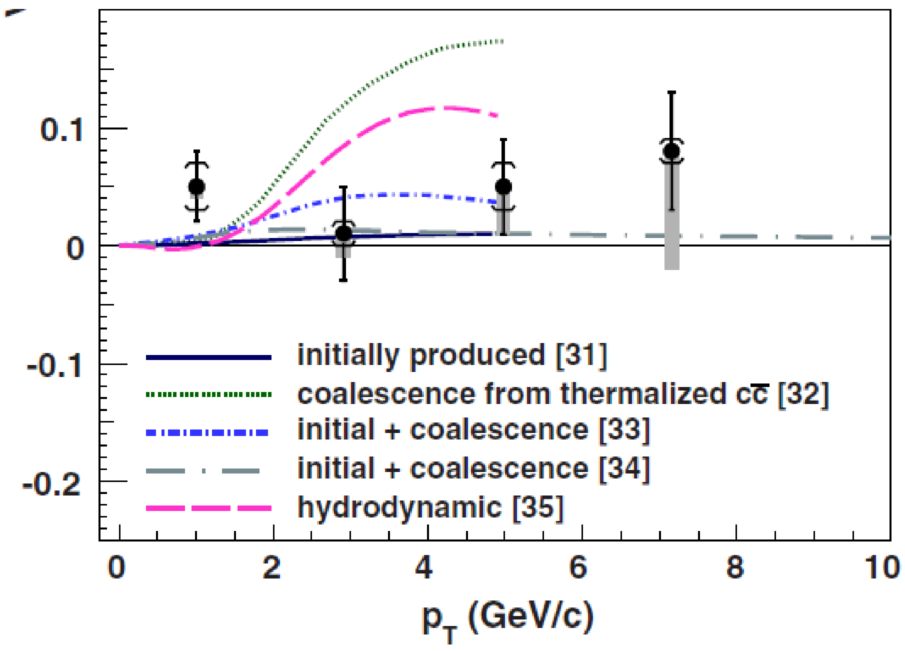
If charm quark have elliptic flow, regenerated J/ψ should inherit it

Elliptic Flow J/ψ Mesons at RHIC

STAR, PRL118, 212301 (2017)



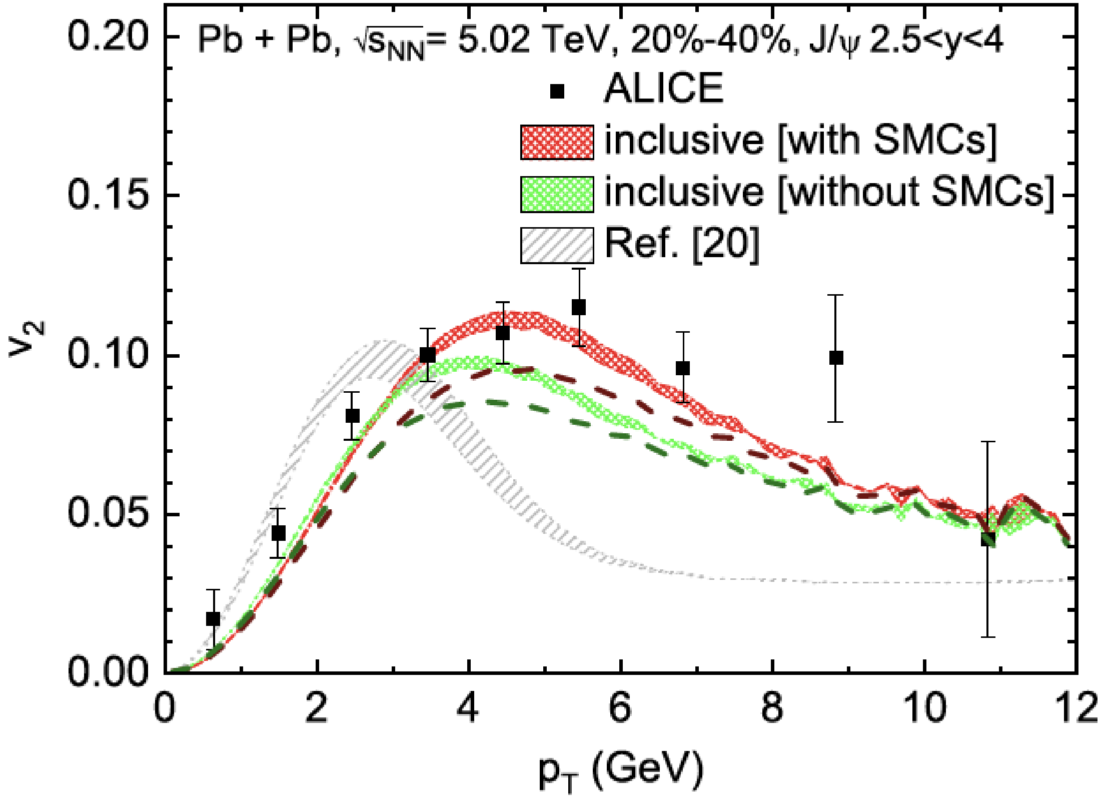
STAR, PRL 111, 052301 (2013)



Significant elliptic flow for D mesons → thermalization of charm quark

At p_T>2 GeV/c, J/ψ elliptic flow consistent with 0
→ Disfavor the case of dominantly produced by thermalized charm quarks coalescence

J/ψ Elliptic Flow at LHC

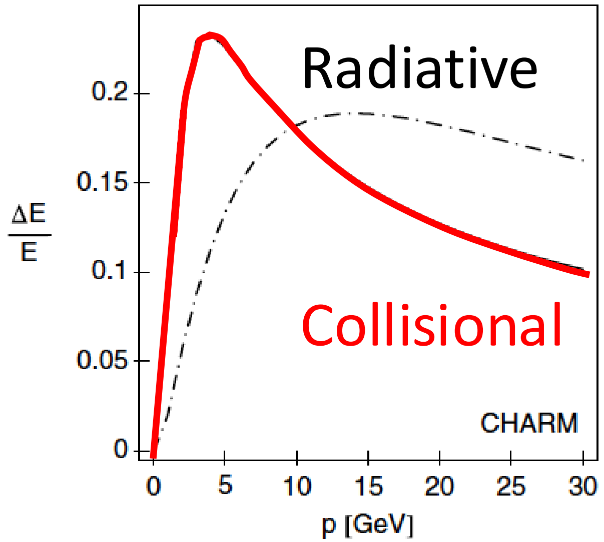


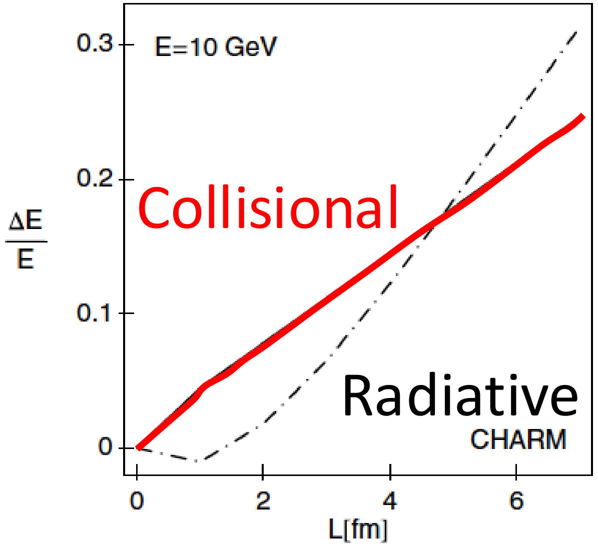
ALICE, JHEP10, 141 (2021)

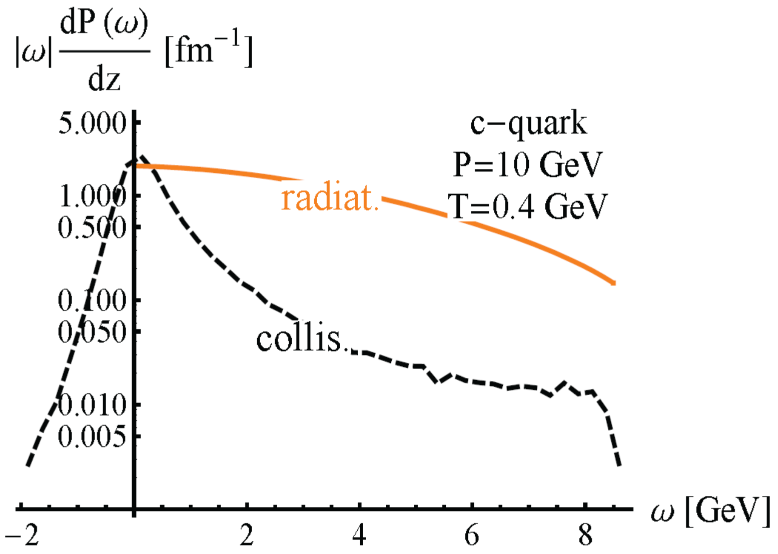
Transport model:
X. Du and R. Rapp, NPA943, 147 (2015)
M. He, B. Wu and R. Rapp, PRL128, 162301 (2022)

- Significant J/ψ v_2 observed at forward-rapidity (via dimuon trigger)
- Primordial only can not explain the large v_2 → (Re)generation
- The role of jet fragmentation at high p_T?

Elastic vs. Inelastic Collisions in QGP







M. Djordjevic, PRC74, 064907 (2006)

Elastic collision:

- Dominant at low-p_T
- Proportional to L
- Not aways energy "loss"
- Responsible for heavy quark collectivity

Inelastic collision:

- More important at high-p_T
- Proportional to L^2
- Main contributor of energy loss (jet quenching)

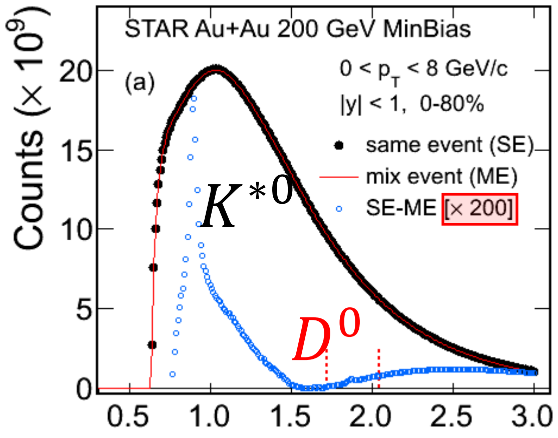
Both have much less effect on bottom than charm

D^0 Signal with Topological Cuts

2010+2011

820M events

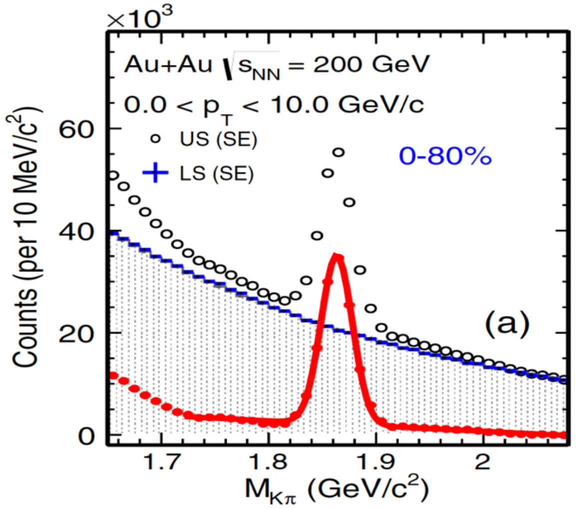
w/o HFT



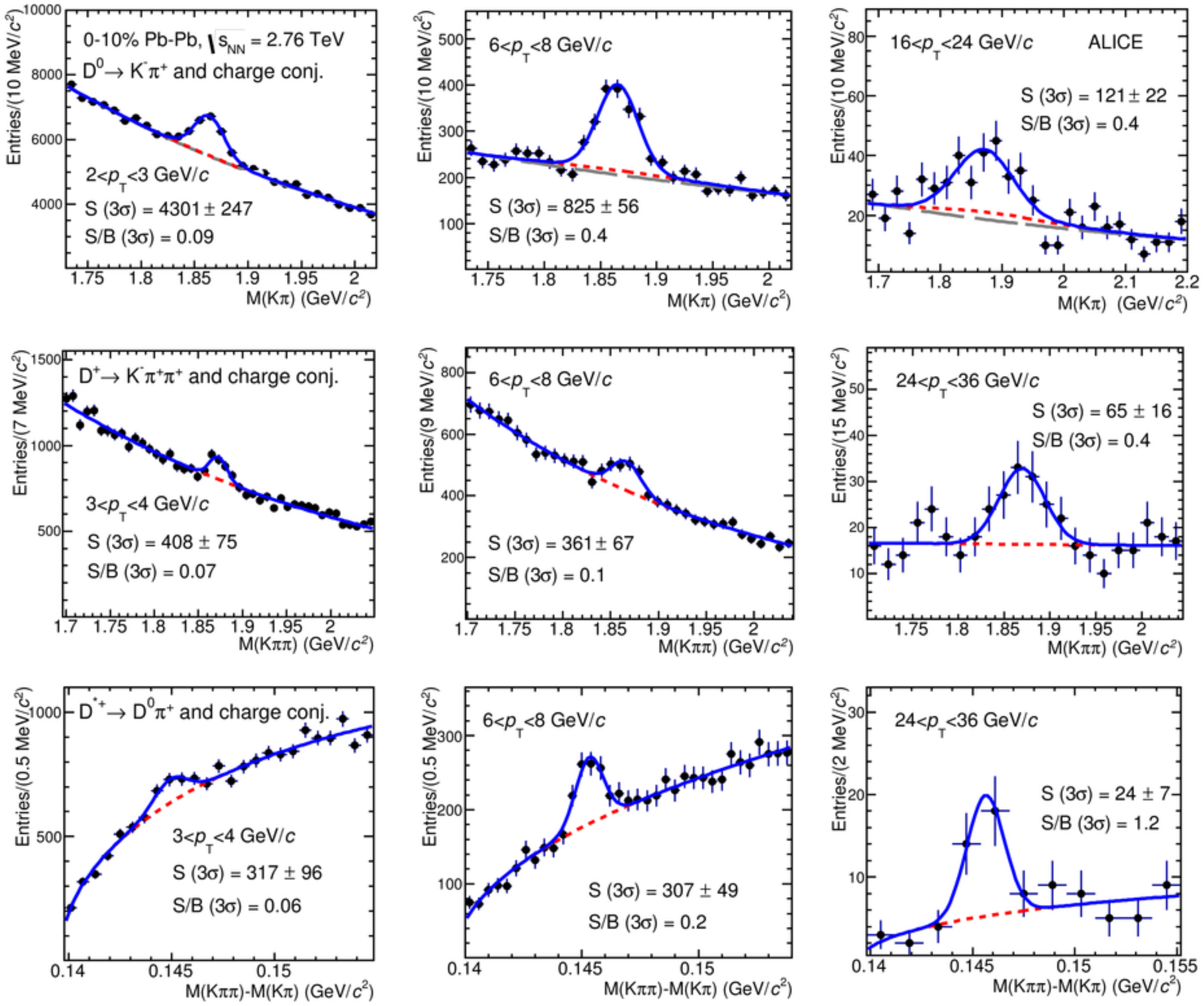
2014

900M events

w/ HFT



S/B improved by O(10^4)



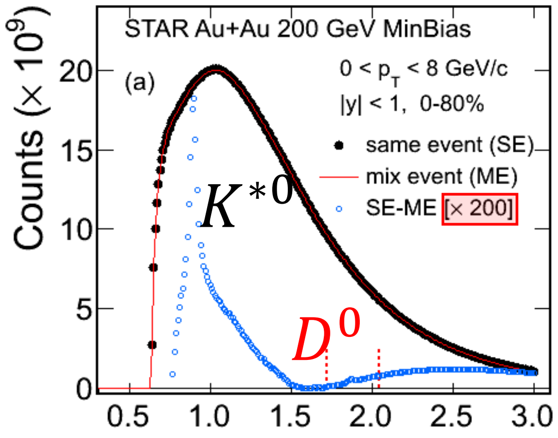
ALICE, JHEP03, 081 (2016)

D^0 Signal with Topological Cuts

2010+2011

820M events

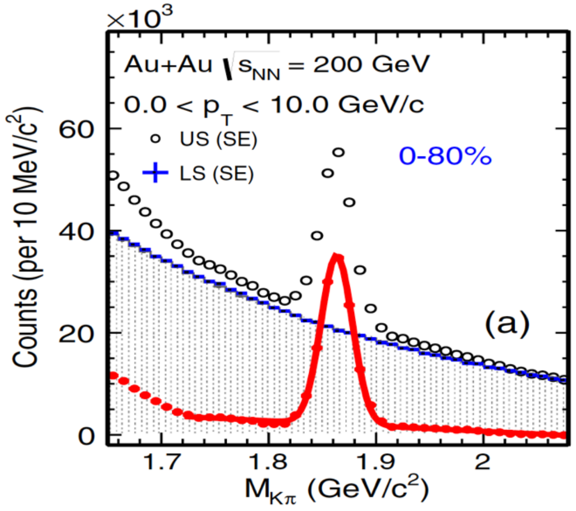
w/o HFT



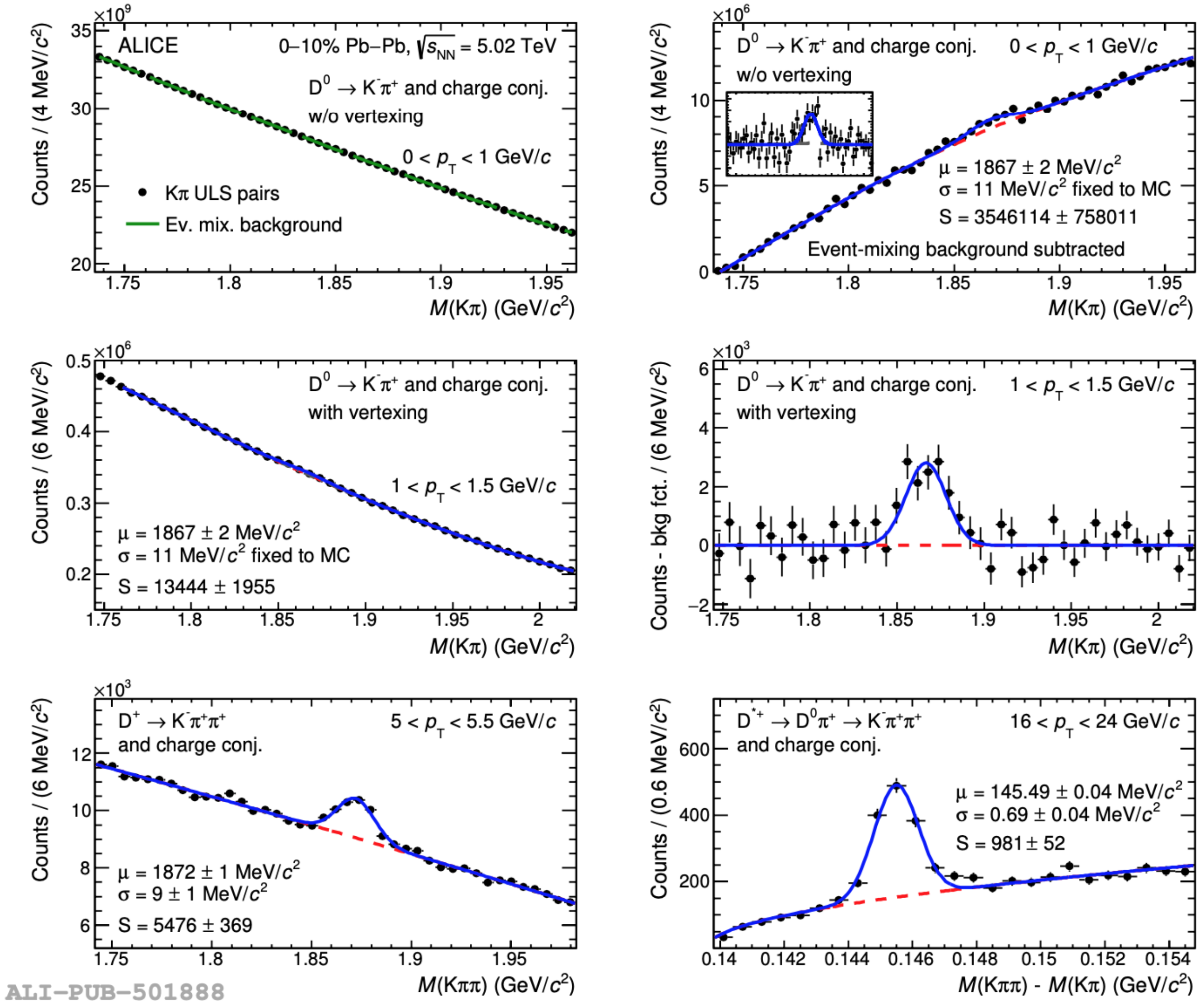
2014

900M events

w/ HFT

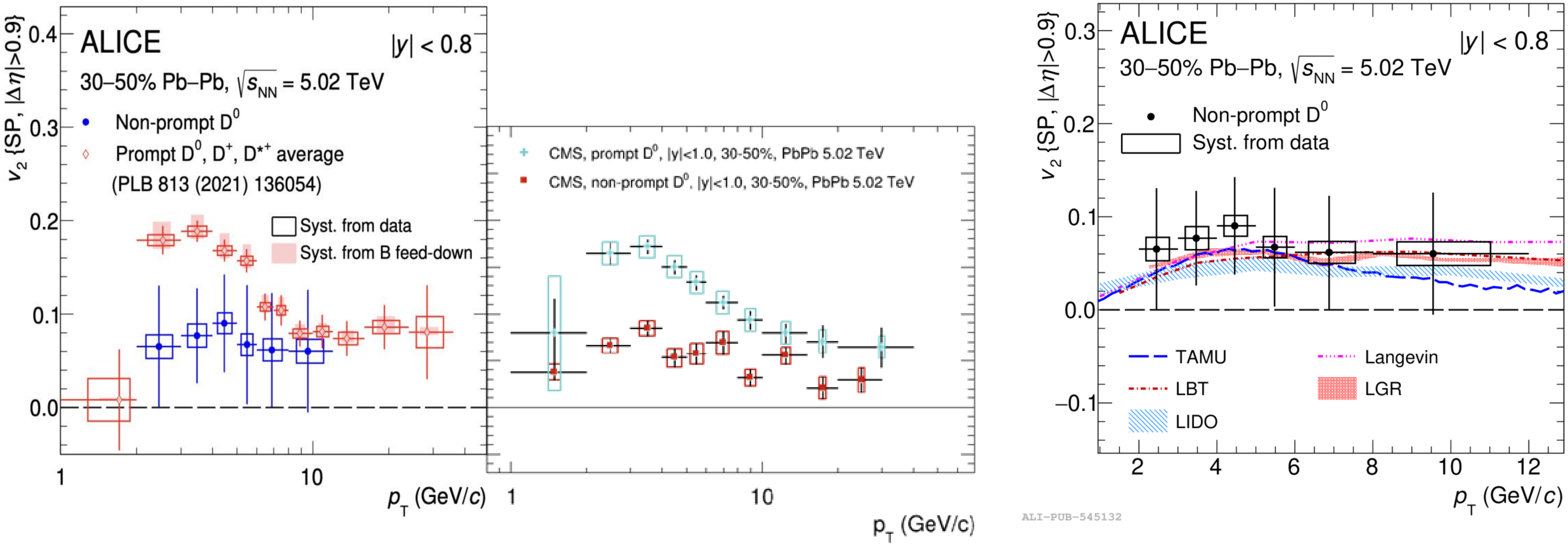


S/B improved by O(10^4)



ALICE, JHEP01, 174 (2022)

Collectivity of Bottom



- Significant flow of D from B decay
- Much smaller than prompt D
- Different degree of thermalization of charm and bottom