

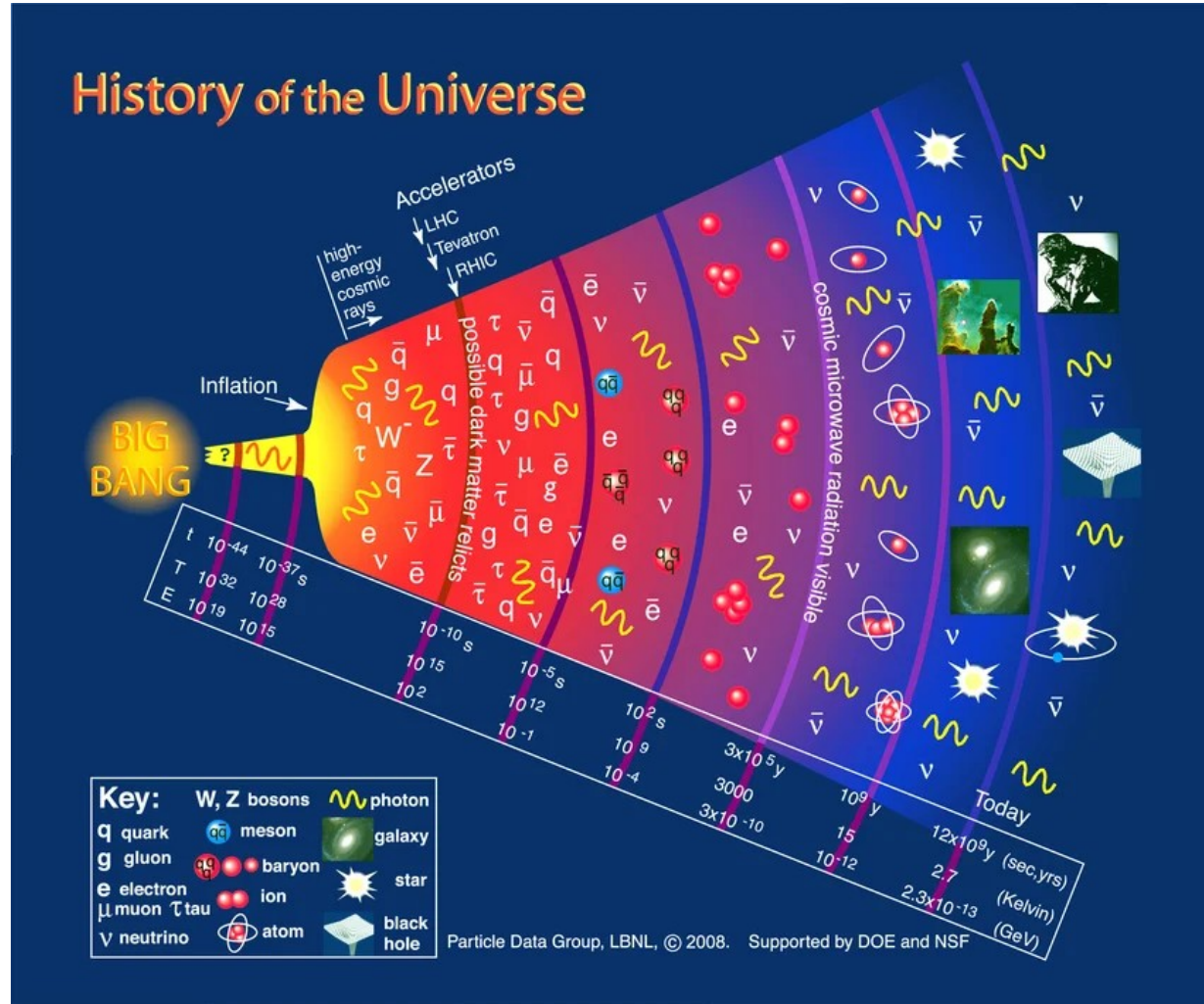
Heavy quarks production in relativistic nuclear collisions: past, present and future

Ionut-Cristian Arsene
University of Oslo, Norway



- Motivation for studying heavy quarks in high energy heavy-ion collisions
- How to measure open heavy flavour and quarkonium hadrons
- Past and current measurements
- ALICE upgrade plans: FoCal and ALICE3

What are we made of and how did it happen ?



Physicist's theory on what the Universe is made of



Standard Model of Elementary Particles

three generations of matter
(fermions)

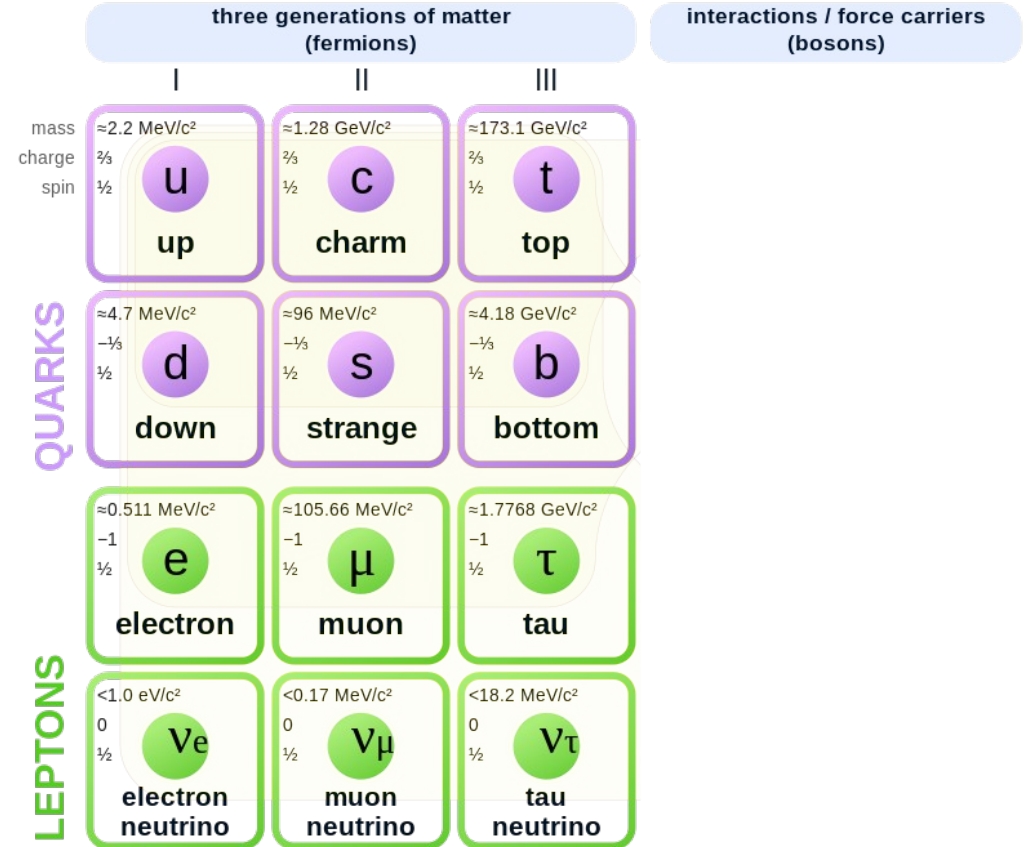
interactions / force carriers
(bosons)

Physicist's theory on what the Universe is made of



- Elementary fermions:
6 quarks and 6 leptons

Standard Model of Elementary Particles

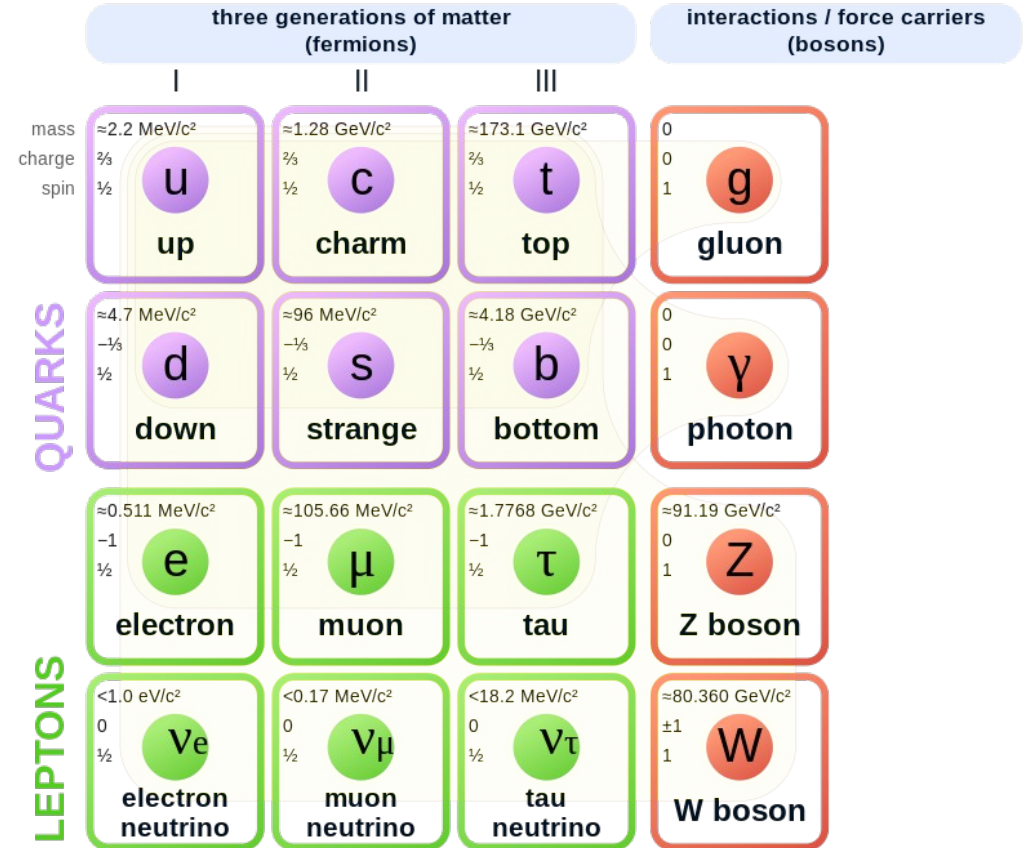


Physicist's theory on what the Universe is made of



- Elementary fermions:
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- Gauge bosons: photon (electromagnetic), W and Z (electro-weak) and gluons (strong force)

Standard Model of Elementary Particles

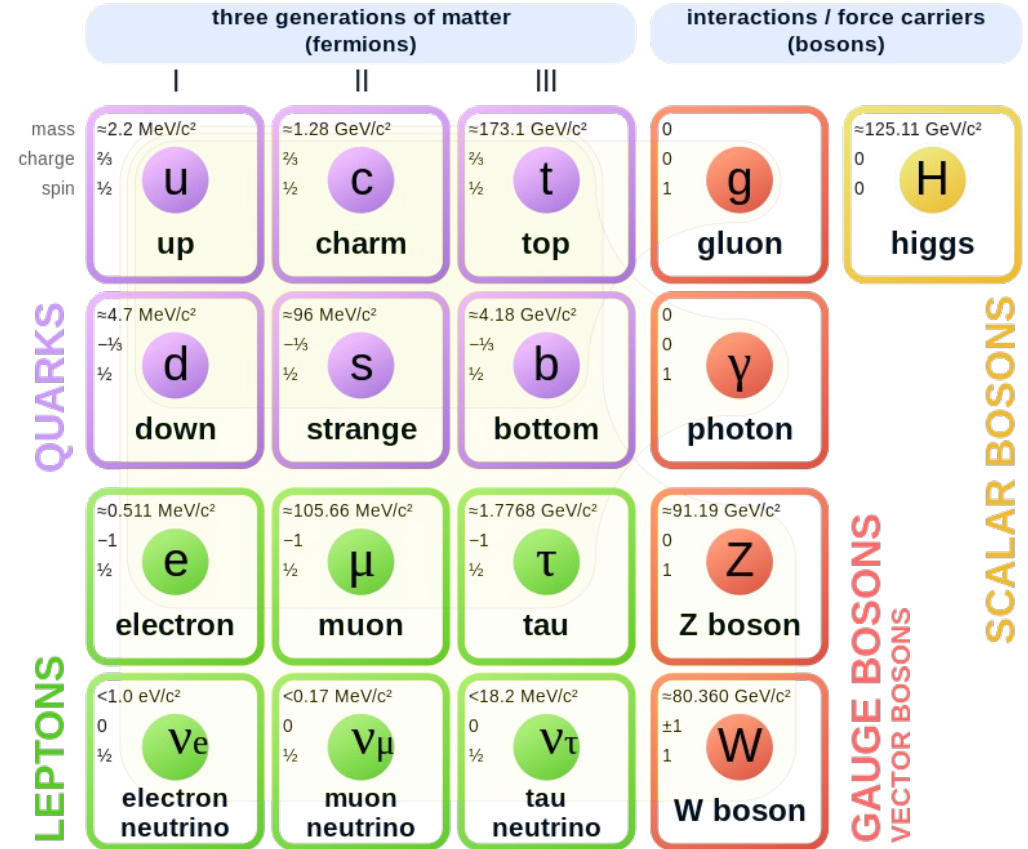


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- Scalar boson: Higgs boson

Standard Model of Elementary Particles



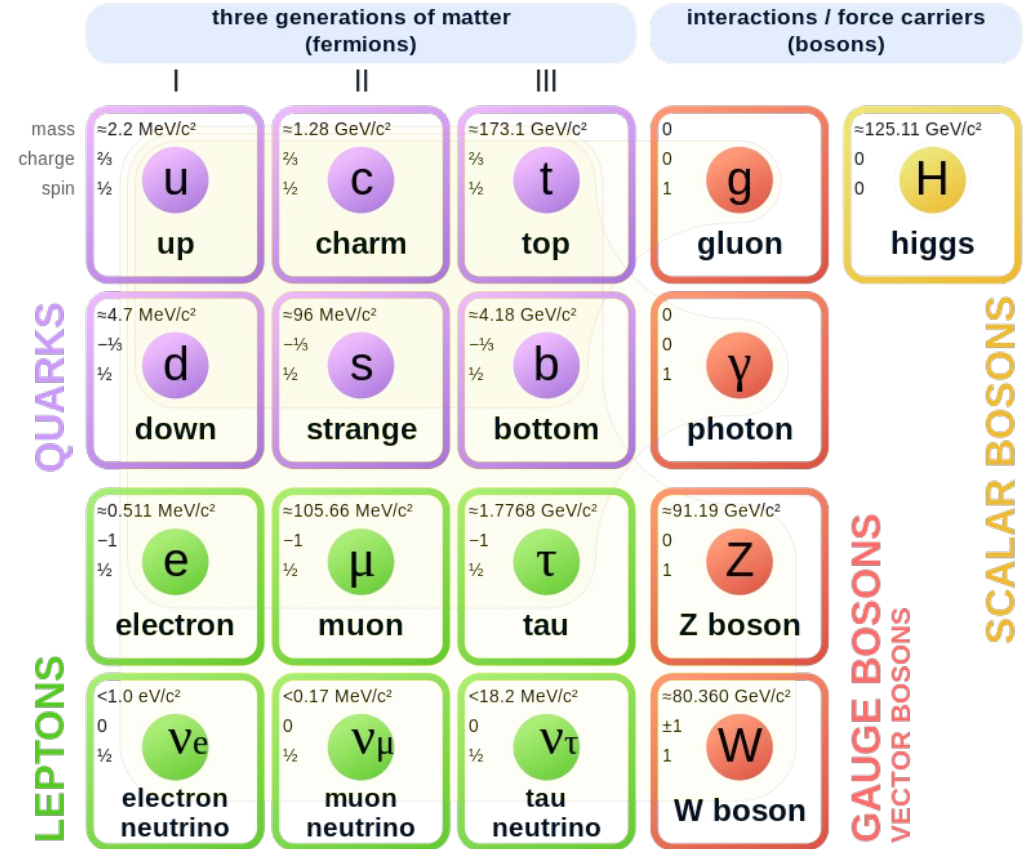
Physicist's theory on what the Universe is made of



- Elementary fermions:
6 quarks and 6 leptons
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- Scalar boson: Higgs boson
- Extensions of the Standard Model attempt explaining experimental results incompatible with SM, e.g. dark matter and neutrino oscillations

But, is this enough ?

Standard Model of Elementary Particles



The puzzle about visible matter



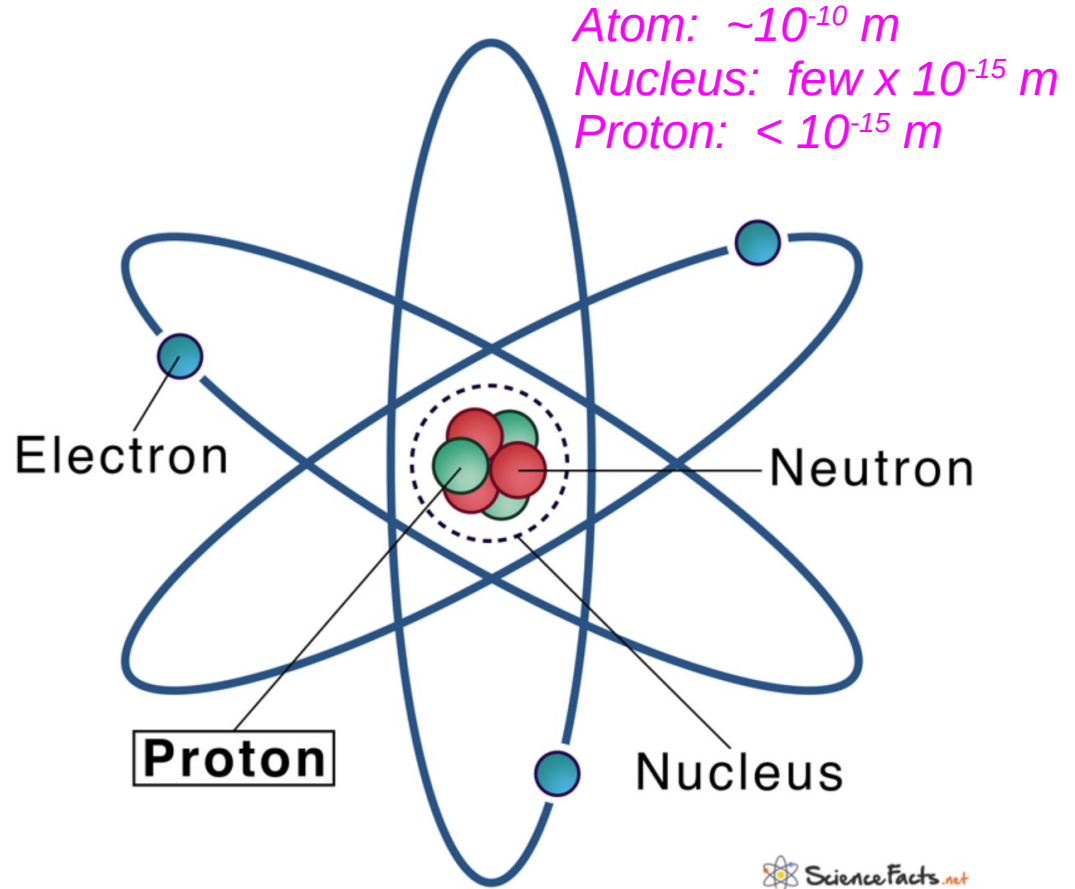
Mass of an atom: # nucleons x 1 GeV

Ionization energy: few eV

- Binding / mass $\approx 10^{-9}$

Nucleus binding energy: few MeV / nucleon

- Binding / mass $\approx 10^{-2}$



The puzzle about visible matter



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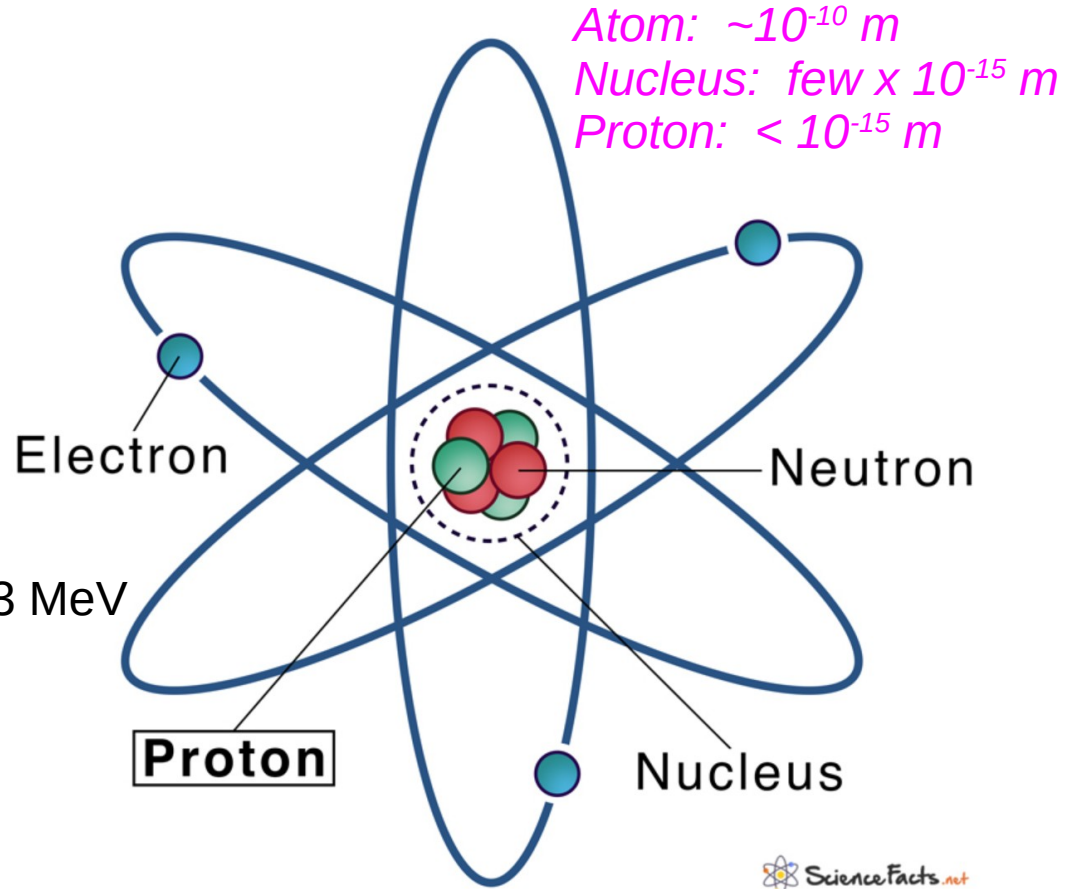
- Binding / mass $\approx 10^{-9}$

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Nucleus at quark level

- Mass of constituent quarks ≈ 3 quarks x 3 MeV
- Observed mass (1 nucleon) ~ 1 GeV
- Binding / mass ≈ 100 !!!



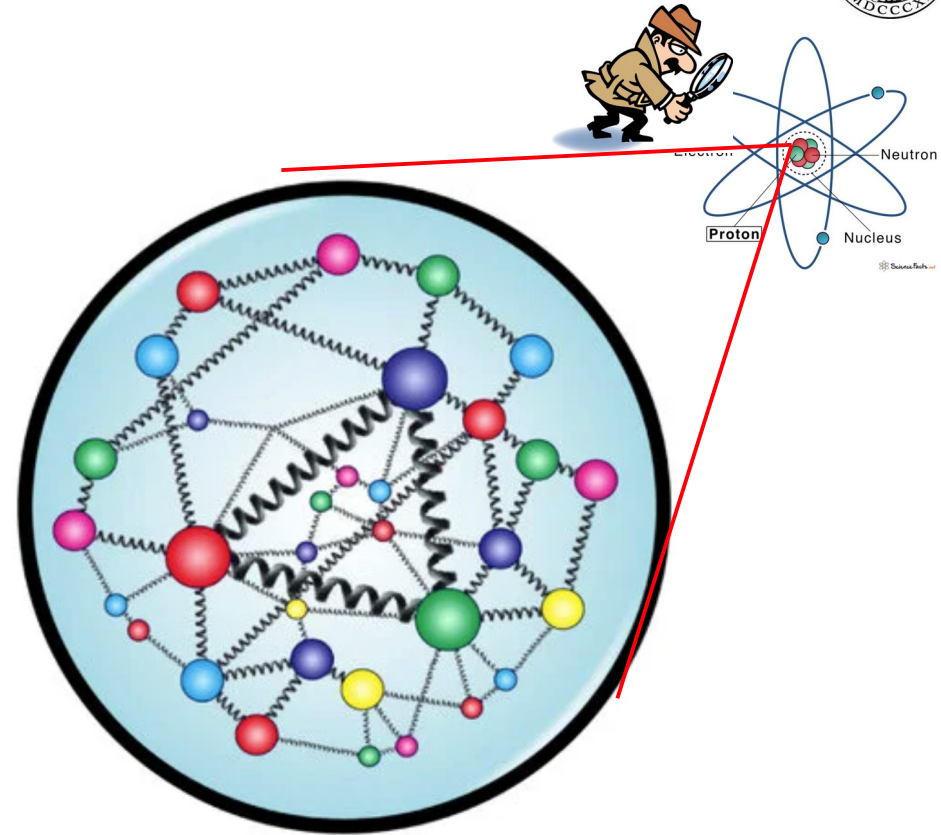
Subatomic world is very strongly bound and we do not know much about it !!!

Studying the nuclear matter: imaging



Nuclear imaging

- Requires a suitable microscope
- Typical instrument: electron – ion collider
- Aim: map the structure of nucleons in terms of
 - x : momentum fraction of the quark or gluon
 - b_T : transverse position
 - k_T : transverse momentum

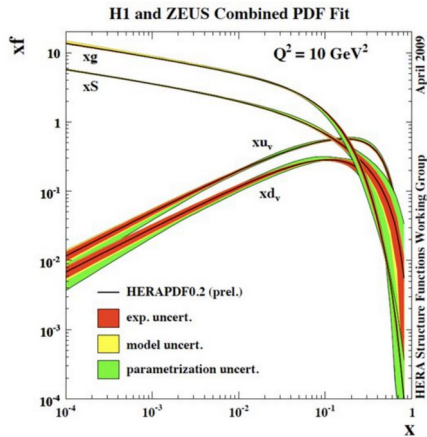
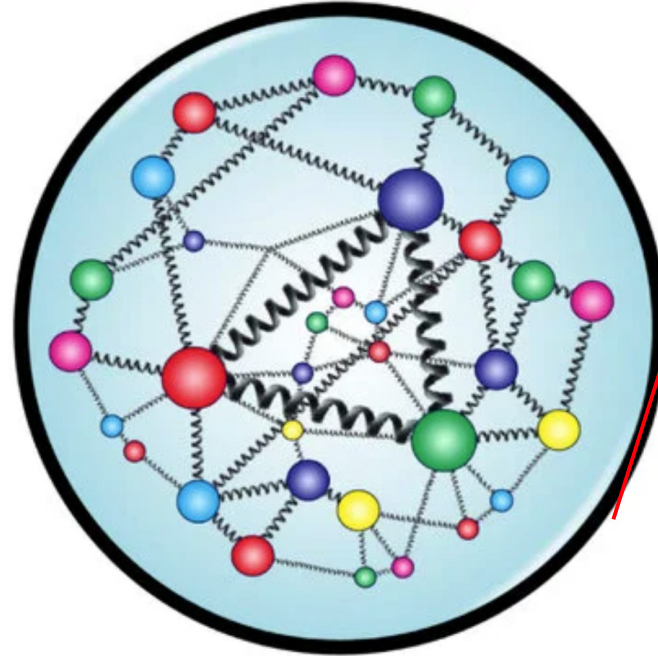
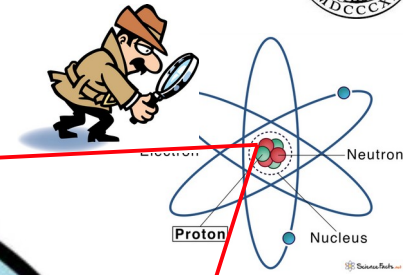


Studying the nuclear matter: imaging

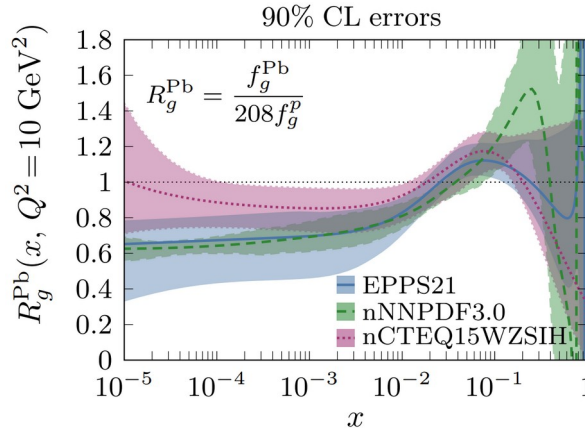


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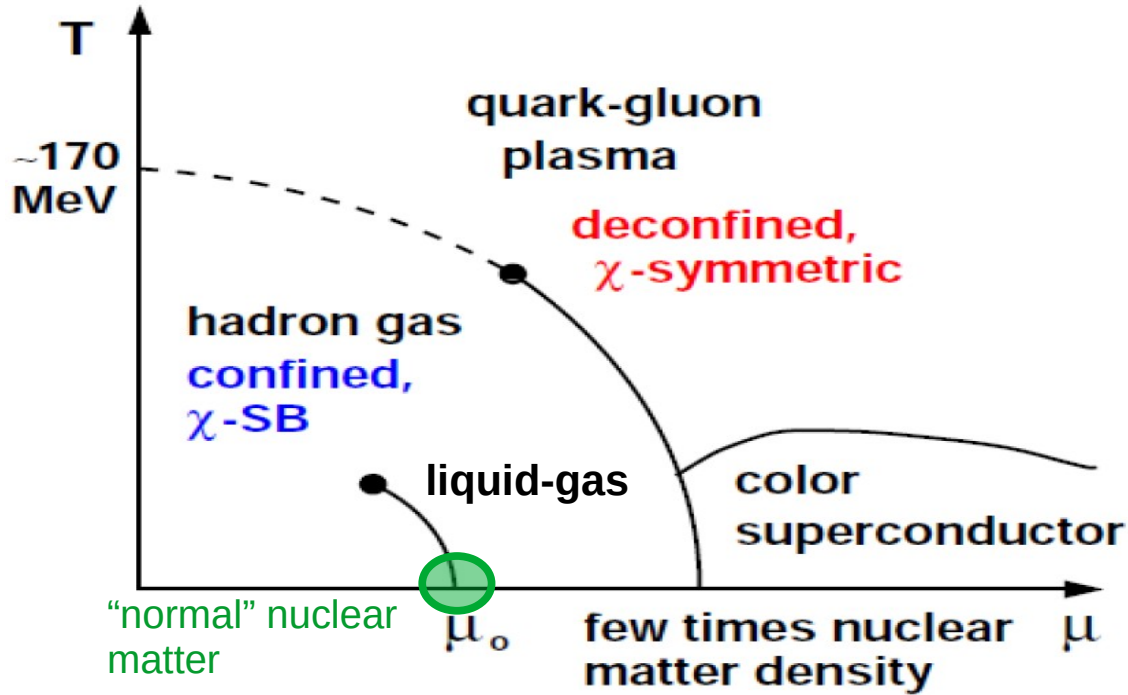
free nucleon



nucleon in a nucleus

Nucleons are full of gluons and sea quarks

Studying the nuclear matter: phase diagram

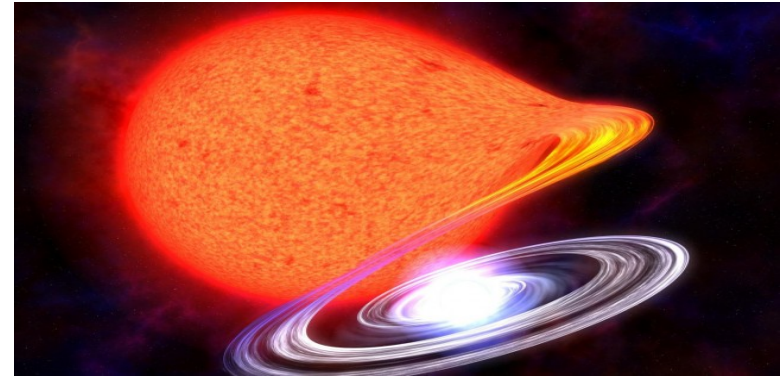
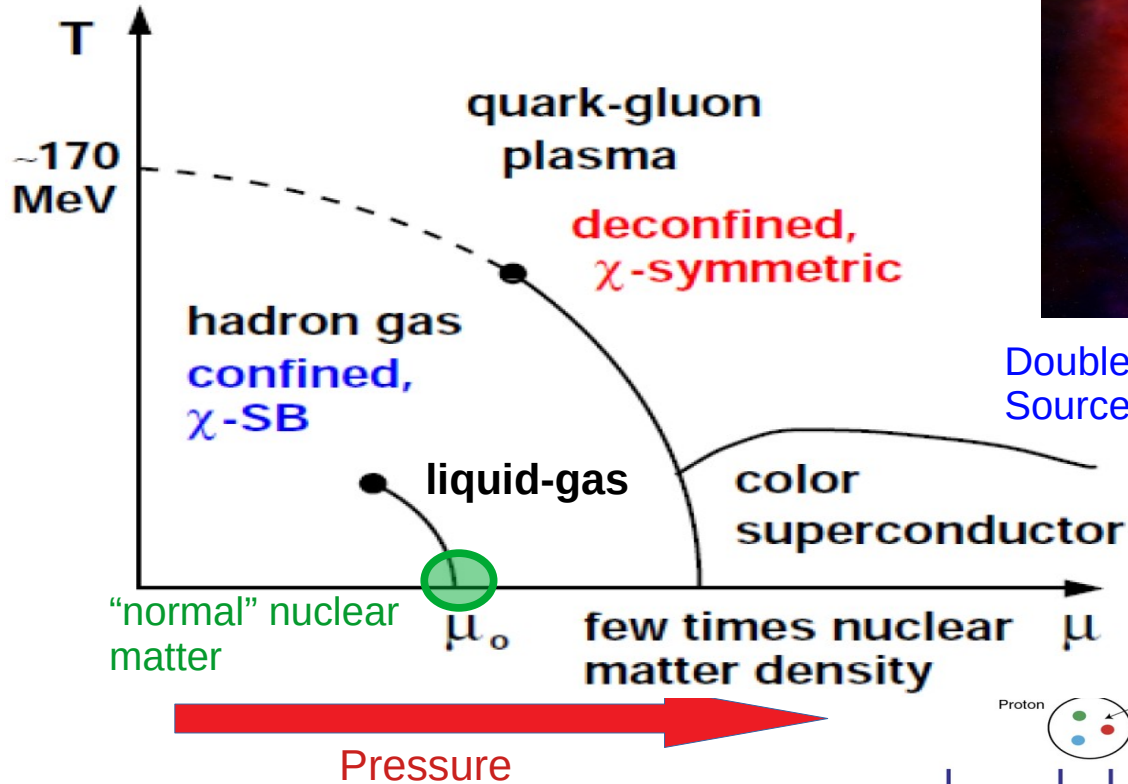


μ : baryo-chemical potential
(amount of energy required to create a nucleon)

$\mu_0 (T = 0) \sim 938$ MeV

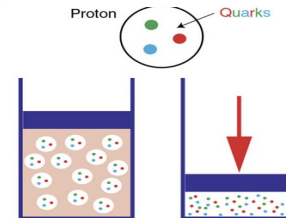
Study nuclear matter properties under different conditions

Studying the nuclear matter: phase diagram

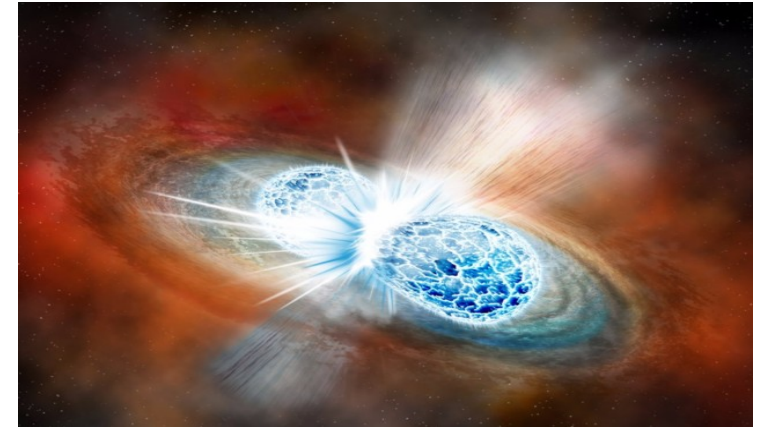
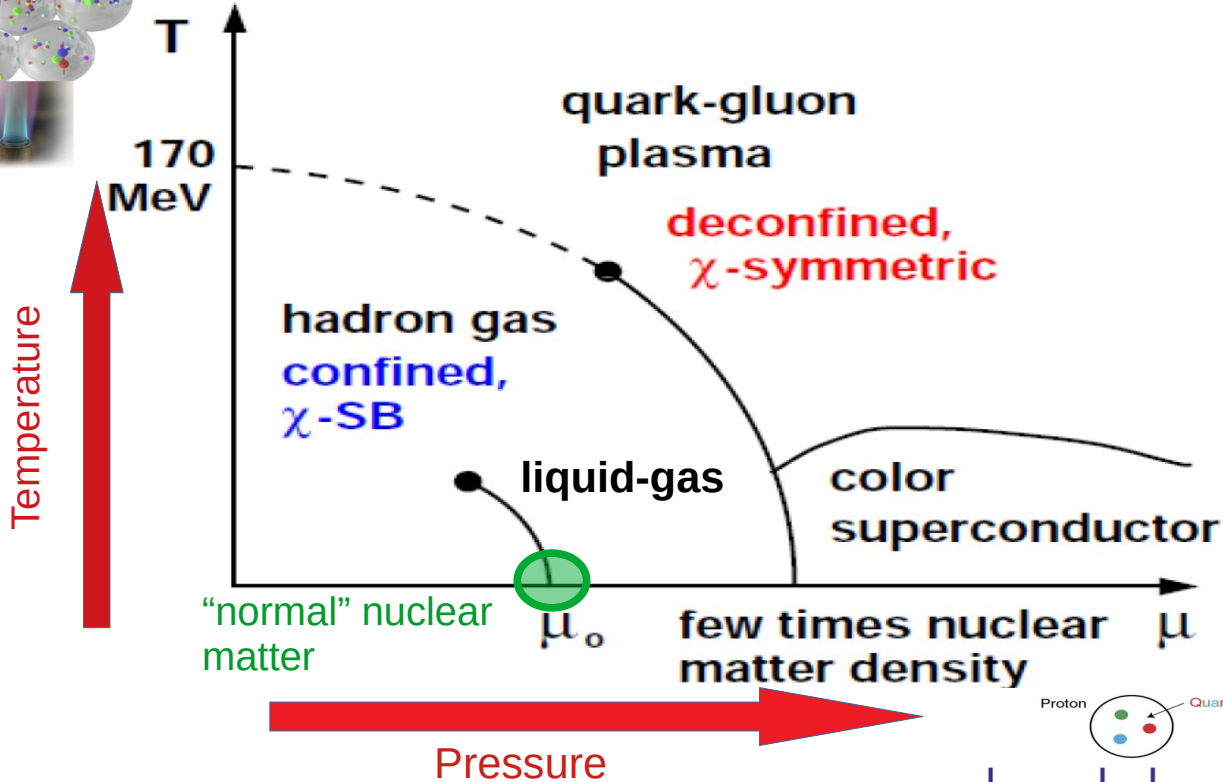
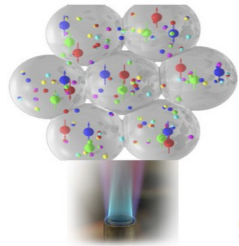


Double star system with one neutron star
Source: astronomie.nl

Neutron stars may contain nuclear matter in color superconductor phases

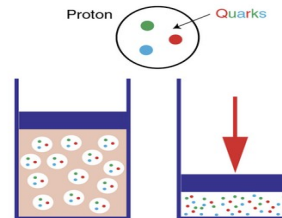


Studying the nuclear matter: phase diagram

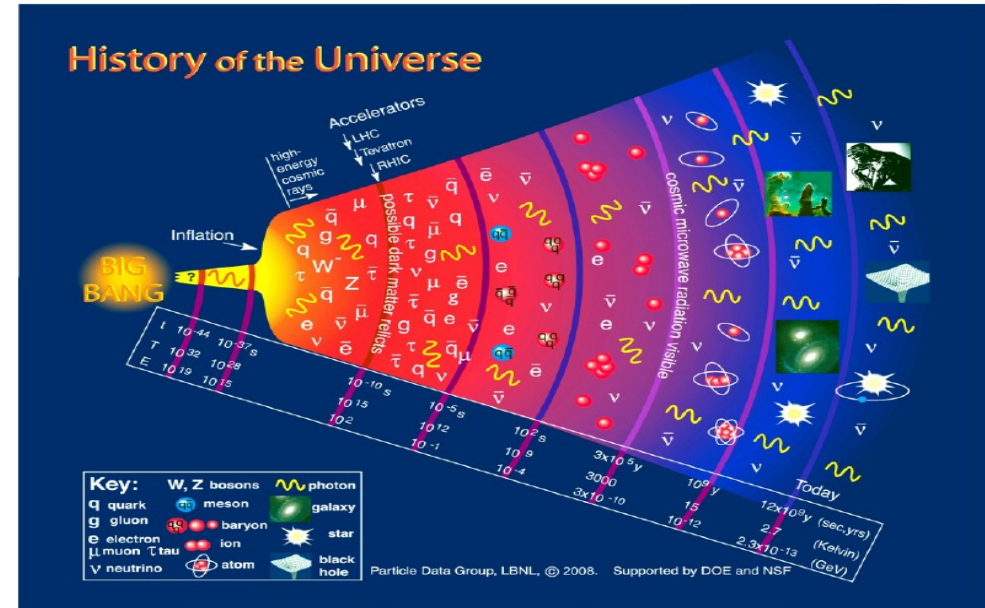
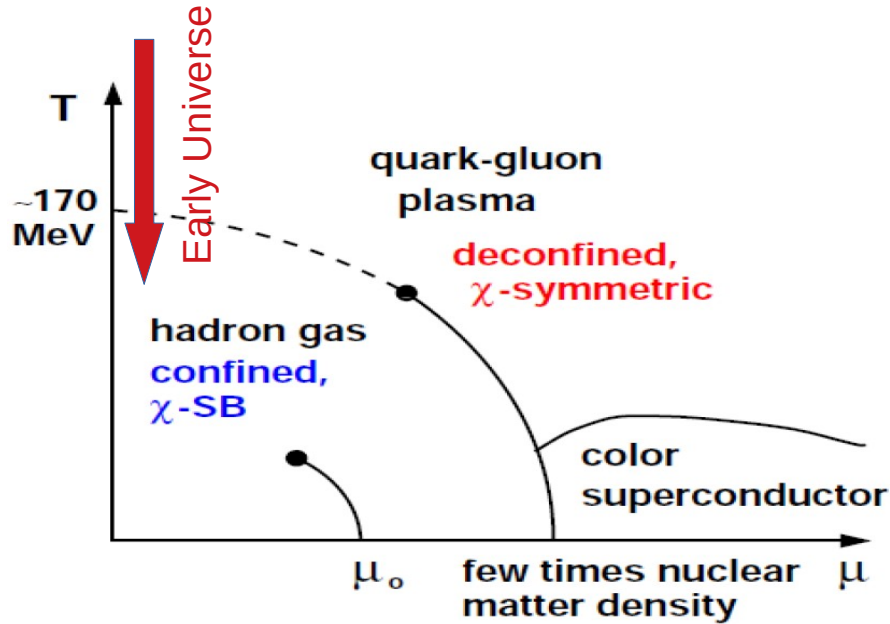


Neutron star merger
Source: NASA

Increasing both pressure and temperature, more phases appear, including **QGP**

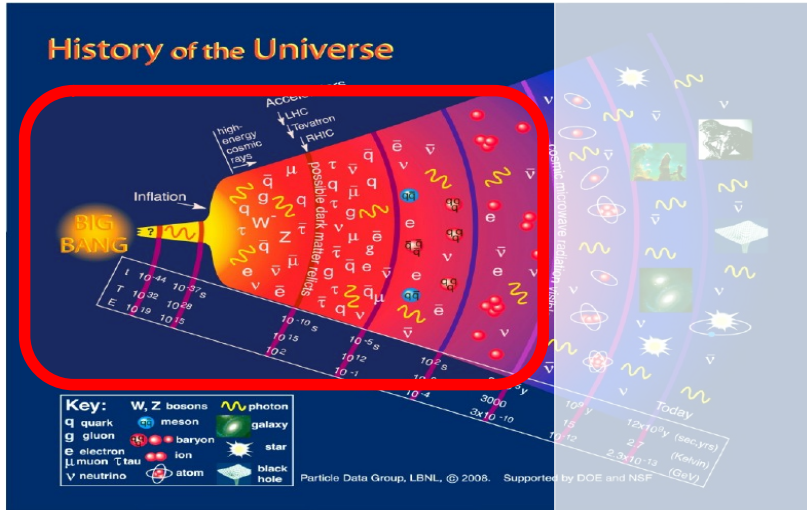


QGP in the Early Universe



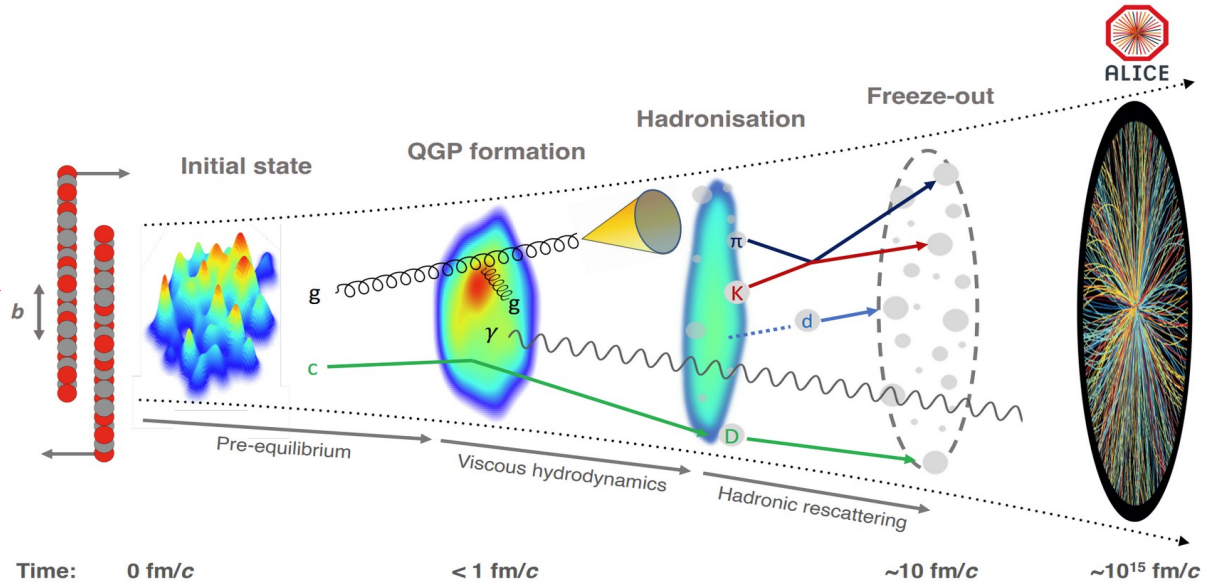
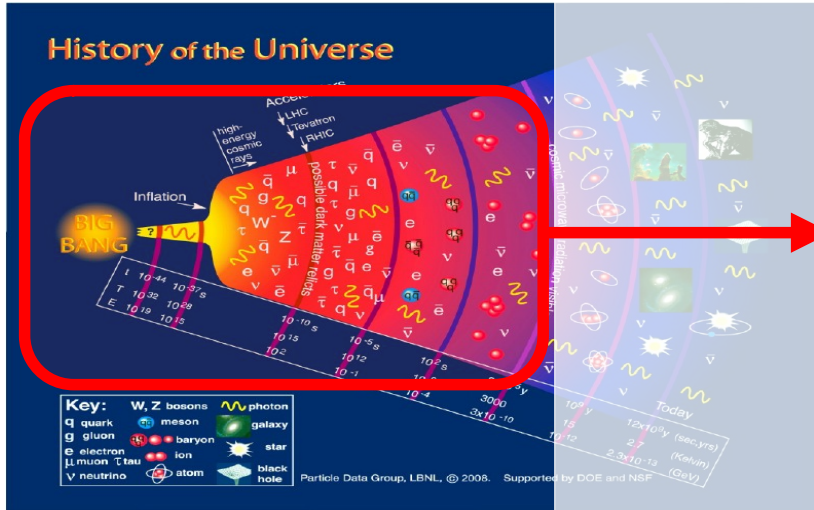
- For the first $O(10\mu\text{s})$, it is hypothesised that the Universe existed in a deconfined, hot, dense and low μ_B state
- ... then followed by cooling and transition to a hadron gas phase which then led to the creation of bound nuclei, atoms, ...

QGP in the lab: nuclear collisions



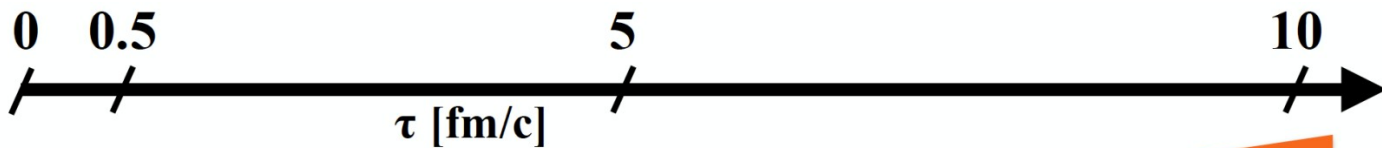
- Ultra-relativistic heavy-ion collisions produce very high energy density in the collision volume, $\sim 100x$ cold nuclear matter density
 - partly recreate the Big-Bang

QGP in the lab: nuclear collisions

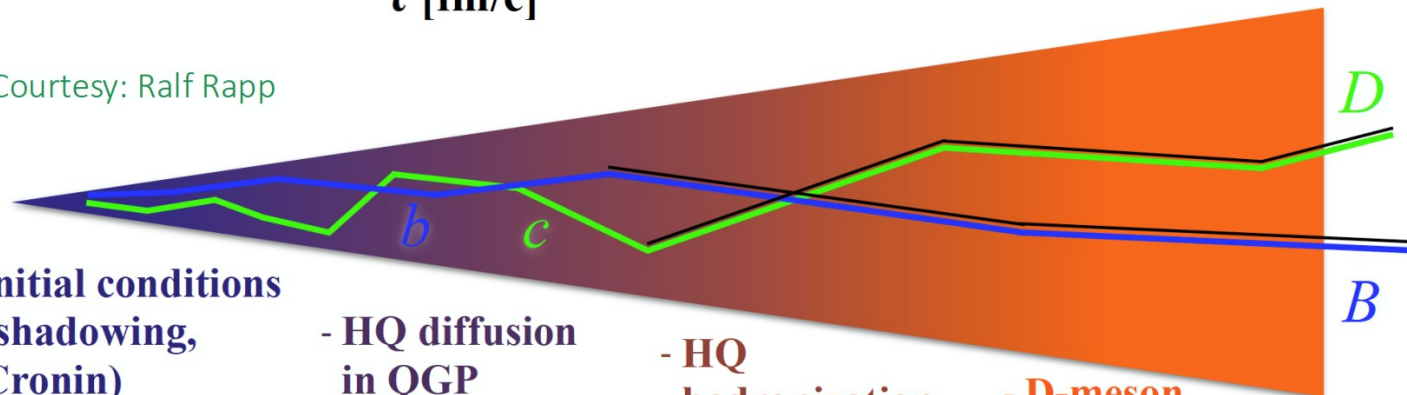


- Ultra-relativistic heavy-ion collisions produce very high energy density in the collision volume, $\sim 100x$ cold nuclear matter density
 - partly recreate the Big-Bang
- Main goal of high energy collisions field is the study of the QGP phase, but
- All stages of the nuclear collision need to be understood simultaneously...

Heavy quarks and heavy-ion collisions



Courtesy: Ralf Rapp



Heavy quark number is conserved during the evolution

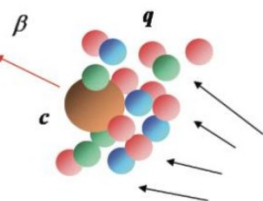
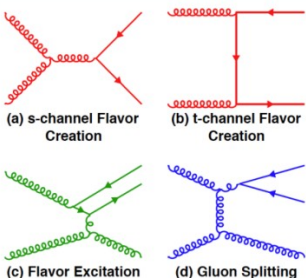
The modification of their initial kinematics contain information about the medium at the different collision stages

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

- HQ diffusion in QGP

- HQ hadronization

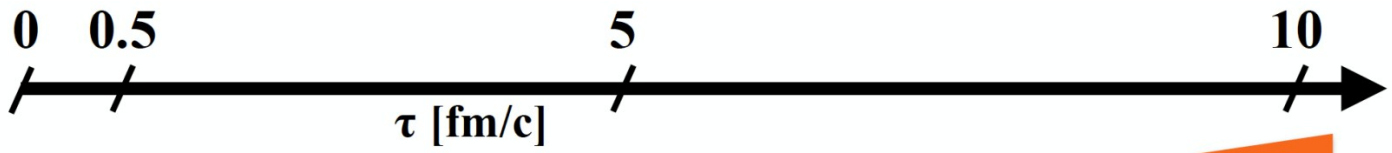
- D-meson diffusion at hadronic phase



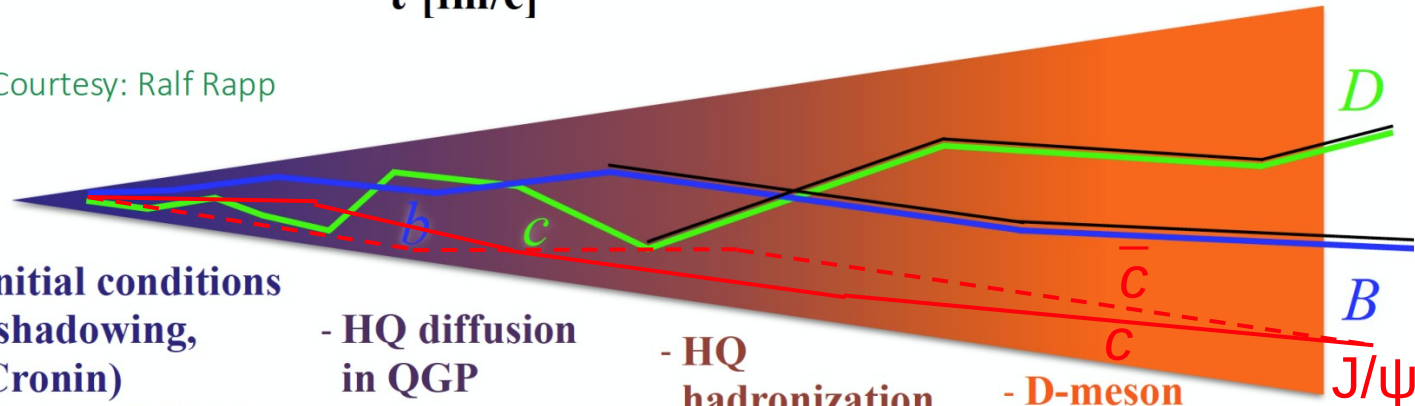
Fragmentation
+
Coalescence?

Experimentally we measure bound hadrons containing heavy quarks:
Open heavy flavour

Heavy quarks and heavy-ion collisions



Courtesy: Ralf Rapp



Heavy quark number is conserved during the evolution

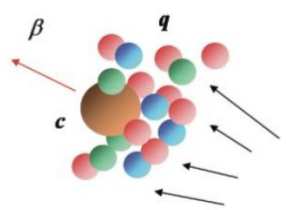
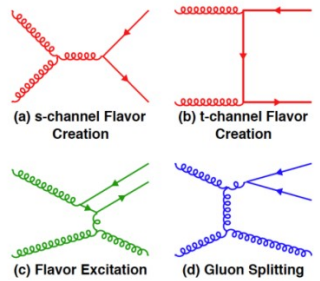
The modification of their initial kinematics contain information about the medium at the different collision stages

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

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- HQ hadronization

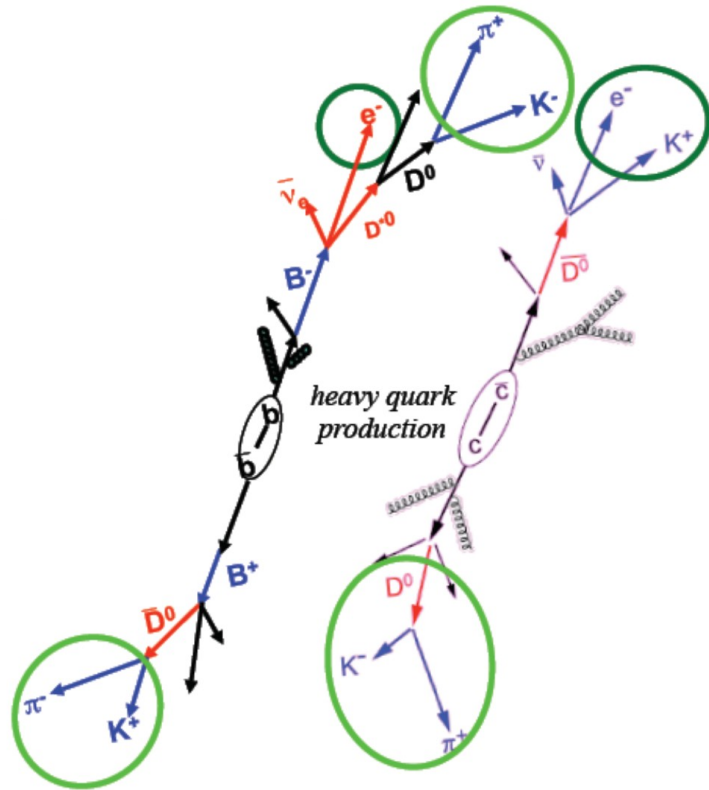
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Fragmentation + Coalescence?

Experimentally we measure bound hadrons containing heavy quarks: Open heavy flavour and quarkonia

Experimental observables: open heavy flavour hadrons



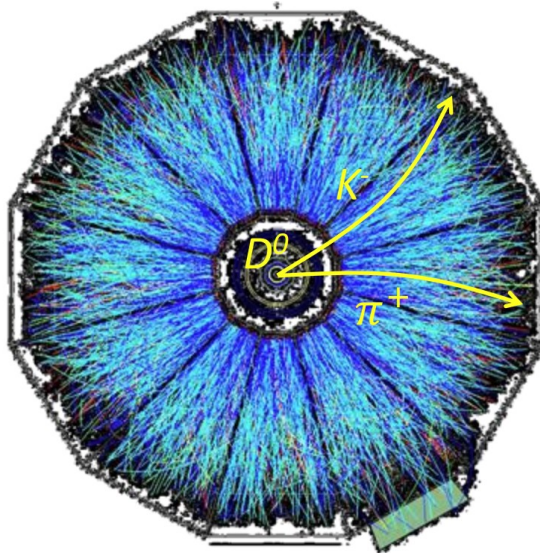
$\tau_D \sim 100 \mu\text{m}$
 $\tau_B \sim 500 \mu\text{m}$

- Leptons from semi-leptonic decays (**HFL**)
- **Partial reconstruction of hadronic decays**, e.g. reconstruct D meson from a B meson decay
- **Full reconstruction of HF hadrons**
- **HF tagged jets**
- **Challenges**
 - Backgrounds
 - Connection with the kinematics of the original quark kinematics
 - Separation of charm and beauty
- **Experimental performance requirements**
 - Vertexing (weak decay vertex reconstruction)
 - Tracking (momentum resolution)
 - Excellent particle ID (especially for leptons)

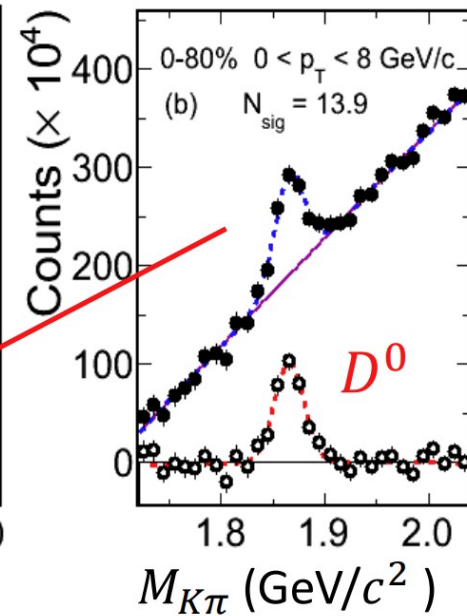
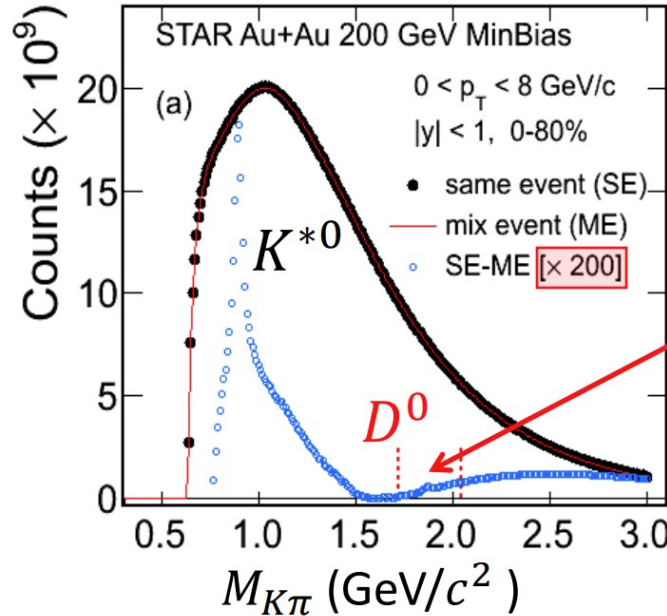
D^0 meson reconstruction, e.g. at RHIC or LHC



STAR, PRL113 (2014) 142301



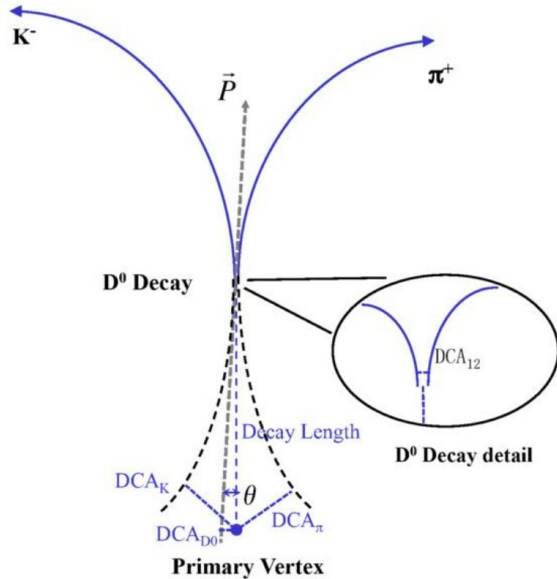
“Golden” channel:
 $D^0 \rightarrow K^-\pi^+$
B.R. $\sim 4\%$



Pair all kaon and pion candidates in the same event

- Leads to huge combinatorial background, i.e. thousands of combinatorial pairs per event, **but it can be done**

D⁰ meson reconstruction, e.g. at RHIC or LHC

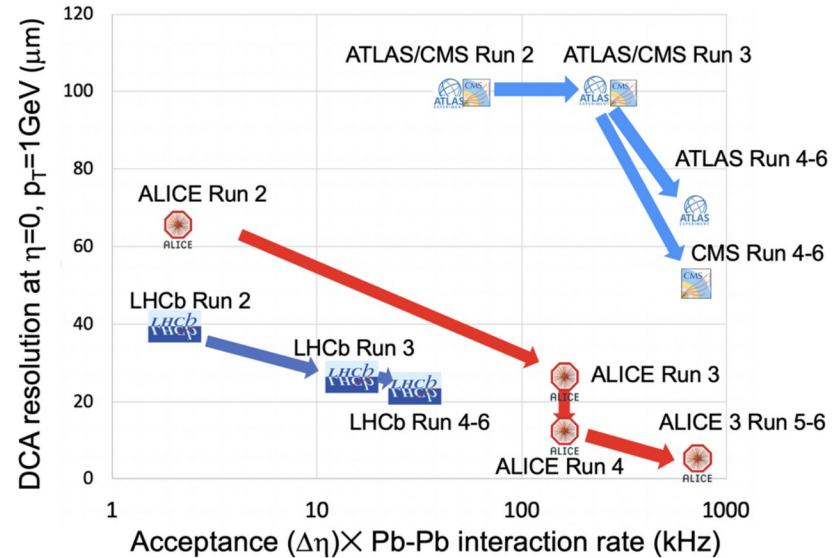


$$\tau_D \sim 100 \mu\text{m}$$

$$\tau_B \sim 500 \mu\text{m}$$

What else can be done ?

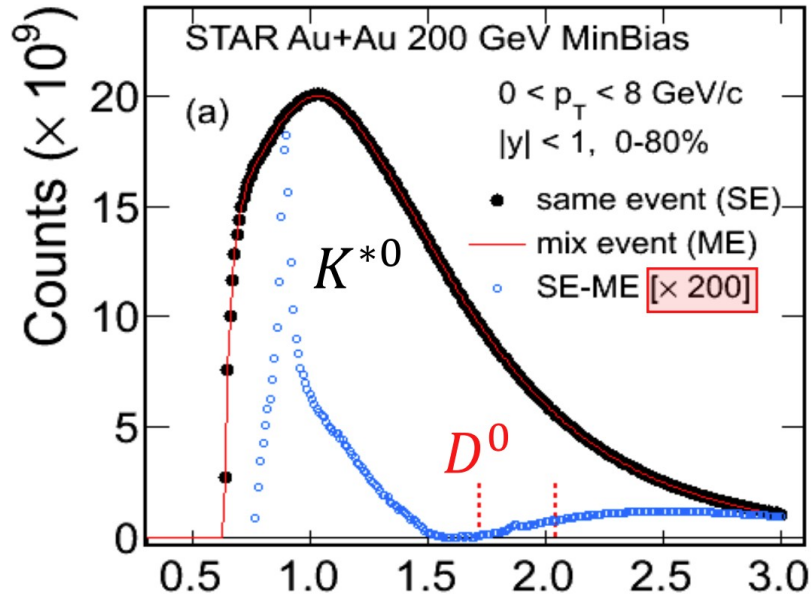
- Exploit the long proper lifetime of HF hadrons: state-of-the-art detectors can reach resolutions in the order of 10 μm



D⁰ signal with vertexing selection

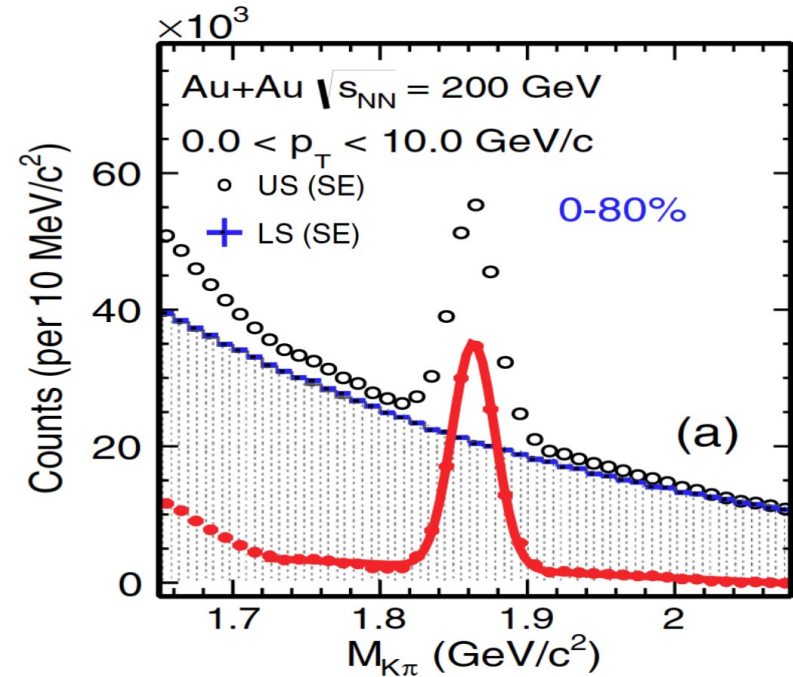


(Without vertexing)



STAR, PRL113 (2014) 142301

(With vertexing)



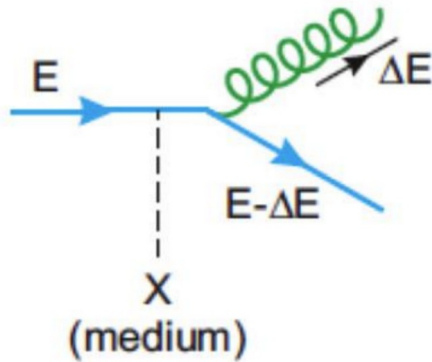
STAR, PRC99 (2019) 034908

S/B improvement of $O(10^4)$!!!

Heavy quarks as a probe: energy loss in the QGP



Radiative energy loss
Inelastic scatterings



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

- Energy lost via radiation induced by interactions with scattering centers in the hot and dense medium

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

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda} \quad \text{Transport coefficient of the medium} \\ \text{(connected to the energy density of the system)}$$

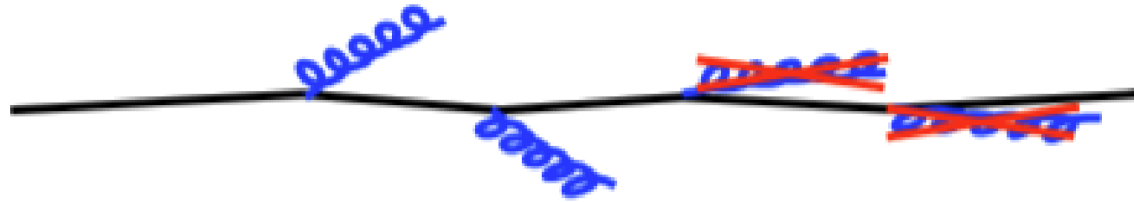
C_R Casimir coupling factor
4/3 for quark-gluon
3 for gluon-gluon

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

“Dead-cone” effect



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

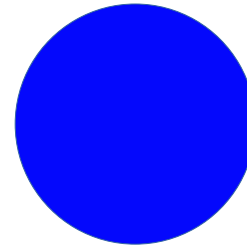
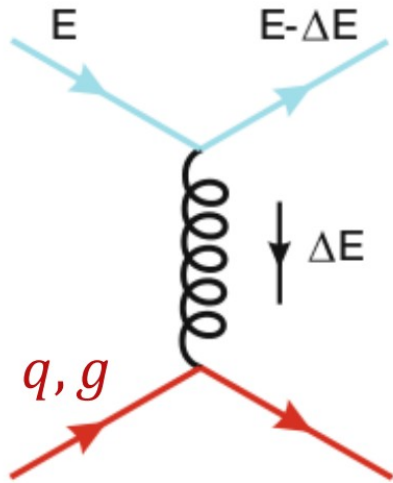


$$\langle \Delta E \rangle = \frac{\langle \Delta E \rangle_0}{(\theta^2 + \theta_0^2)} \quad \theta_0 = \frac{1}{\gamma} = \frac{m_q}{E}$$

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

- Gluon radiation in vacuum (and in medium) is suppressed for small angles due to kinematical constraints
- Smaller energy loss for heavy quarks

Elastic collisions in the QGP



$$\langle \Delta E \rangle = \frac{4k}{(k+1)^2} \quad k = \frac{M}{m} \gg 1$$

Elastic collisions in classical mechanics:

- High-energy object: lose small energy per collision
- Low-energy object: “Brownian” motion

Elastic scatterings
Collisional energy “loss”

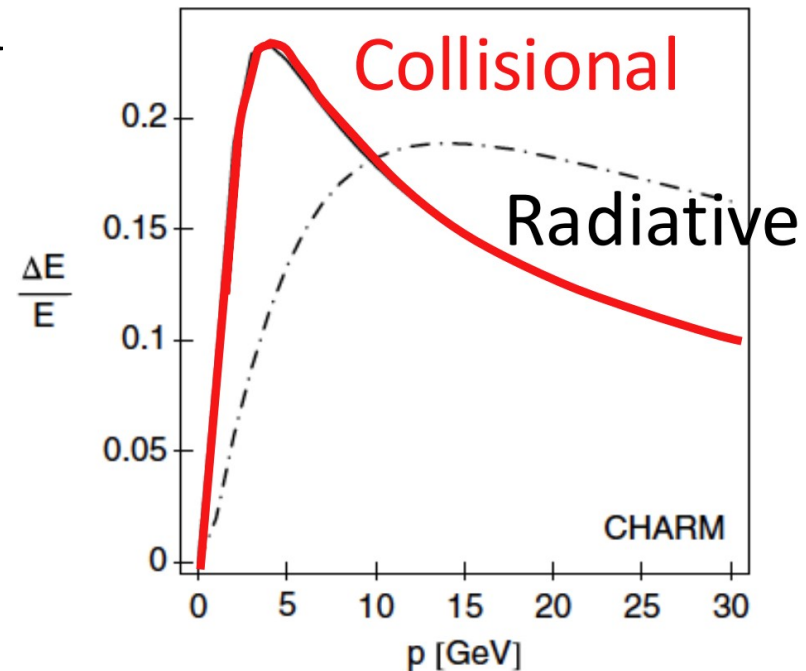
For heavy-quarks:

- Large relaxation time, comparable to the QGP lifetime (keeps memory of initial kinematics)

So, what are we probing with the heavy quarks ?

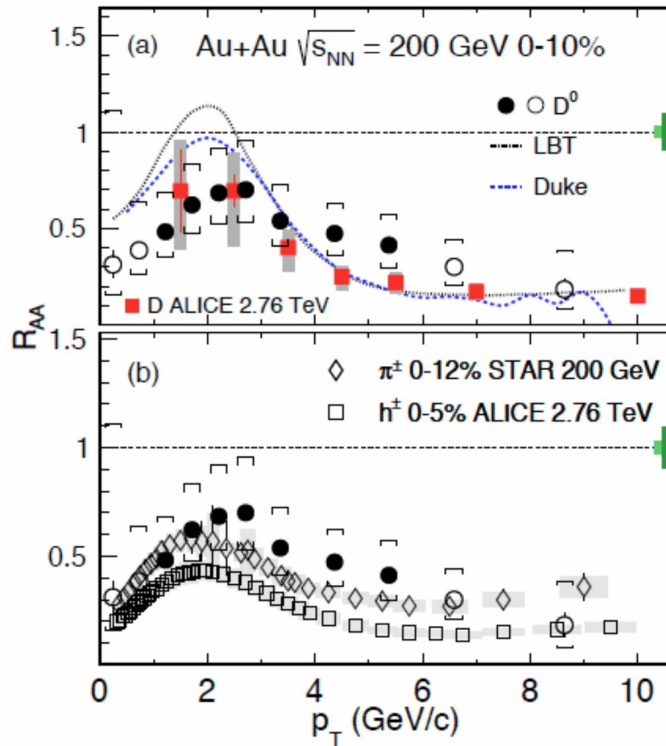
- Since they interact with the QGP, HQ are sensitive to
 - Bulk and microscopic properties of the medium
 - Mechanisms of the HQ interaction with medium
- Low- p_T
 - Thermalization (equilibration)
 - Diffusion coefficient
- High- p_T
 - Energy loss
 - Transport coefficient

M.Djordjevic, PRC74 (2006) 064907



D⁰ nuclear suppression at RHIC

STAR, PRC99 (2019) 034908



$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y^{AA}}{Y^{pp}}$$

N_{coll} - # binary collisions

Y^{AA} - yield in AA

Y^{pp} - yield in pp

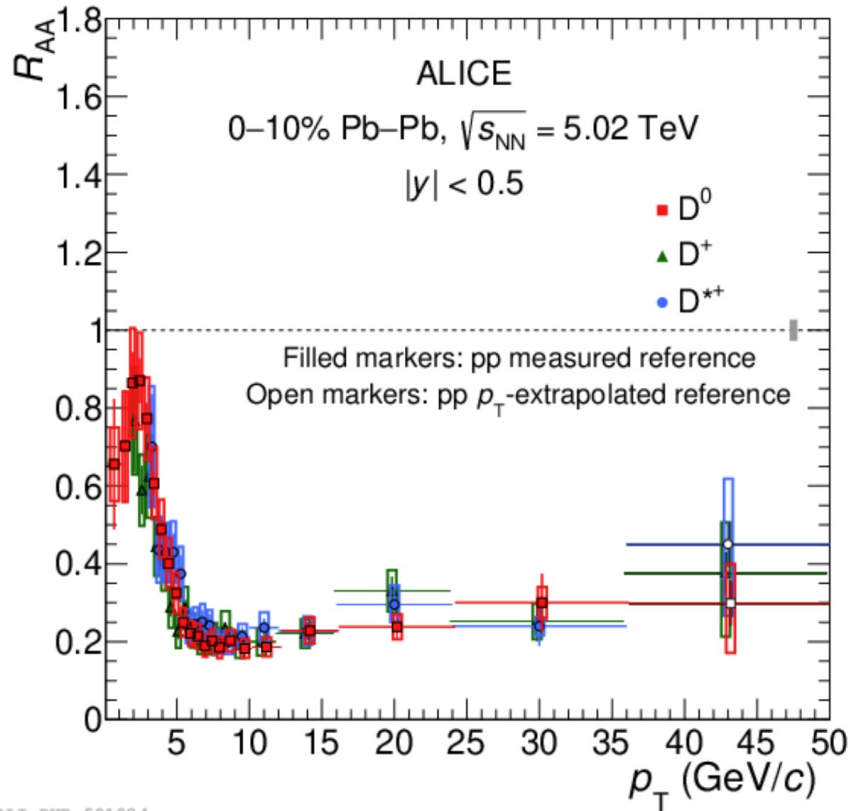
If no nuclear effects, then $R_{AA} = 1$

- Significant suppression of D⁰ yield at high p_T in Au+Au collisions
- Trends are qualitatively well described by pQCD calculations

D-mesons suppression at the LHC



ALICE, JHEP01 (2022) 174

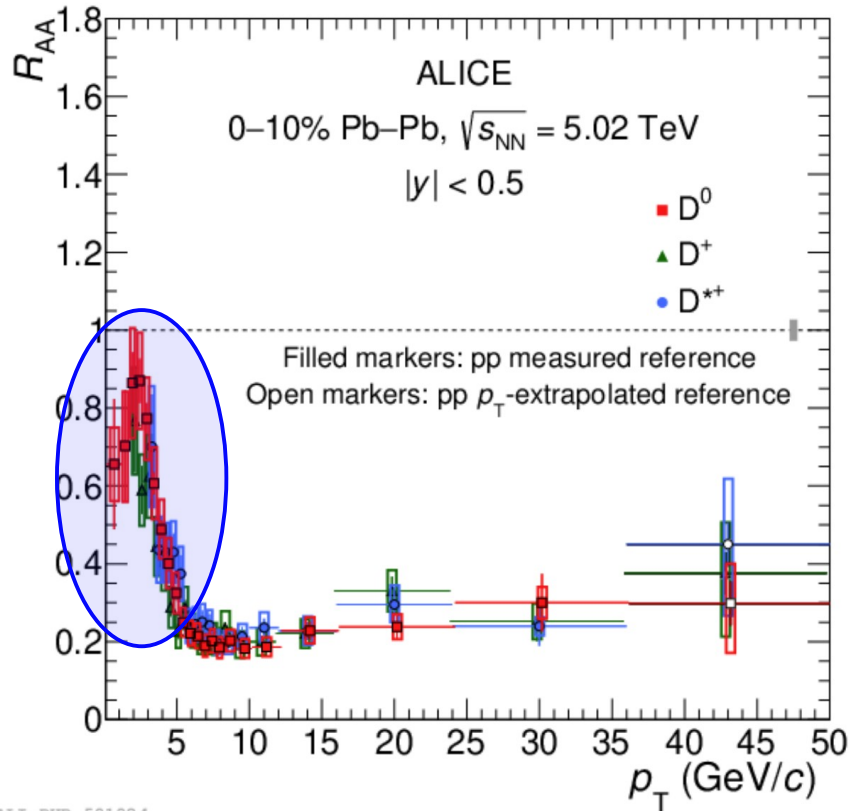


- Rather similar suppression pattern for the most abundant D mesons: D^0 , D^+ and D^{*+}
- Integrated R_{AA} less than 1:
 - Possible additional cold nuclear matter and hadronization effects

D-mesons suppression at the LHC



ALICE, JHEP01 (2022) 174

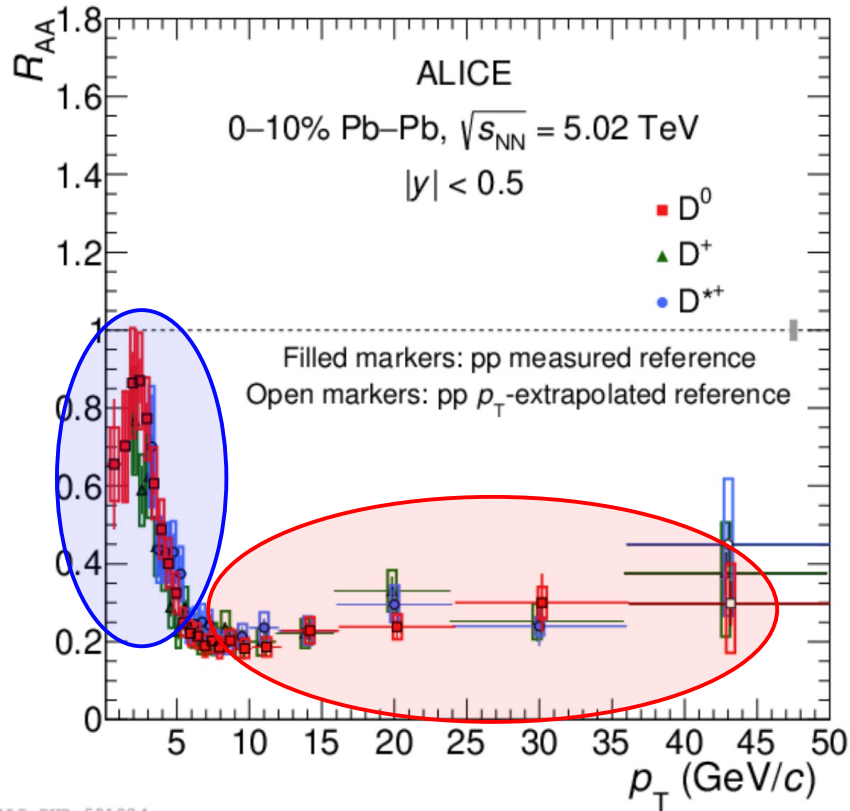


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ALICE, JHEP01 (2022) 174

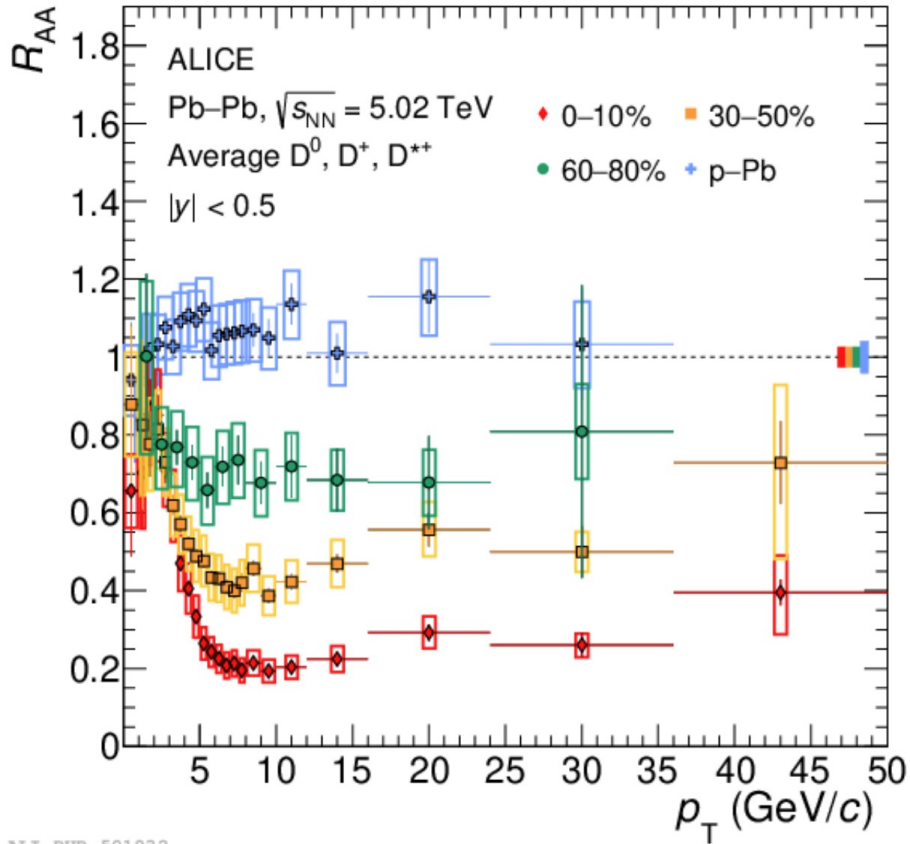


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- Integrated R_{AA} less than 1:
 - Possible additional cold nuclear matter and hadronization effects
- Low- p_T : R_{AA} close to 1 due to charm-quark conservation
- High- p_T : strong suppression (compatible with energy loss)

D-mesons suppression at the LHC

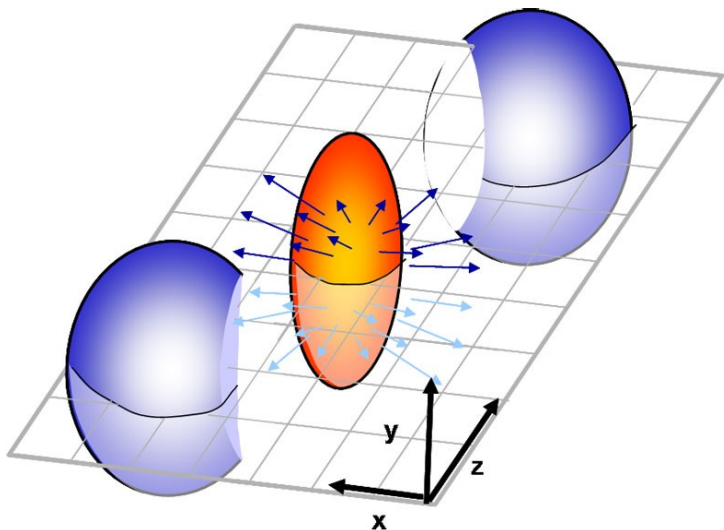


ALICE, JHEP01 (2022) 174



- Strong centrality dependence
- Compatible to unity in p-Pb collisions

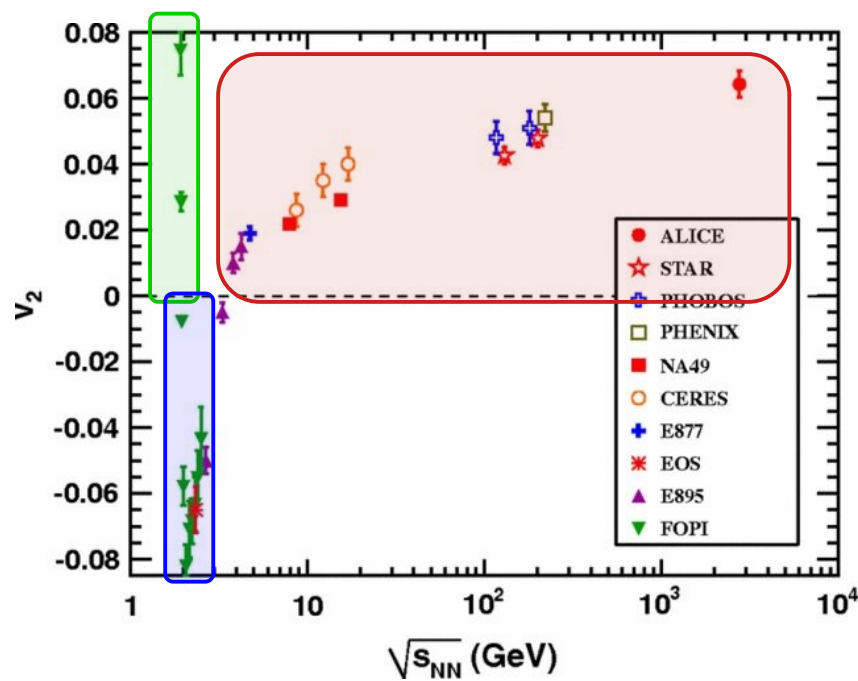
Azimuthal anisotropy



Fourier decomposition of azimuthal yield densities:

$$\frac{dN}{d\phi} \simeq 1 + 2 \sum_n v_n \cos[n(\phi - \Psi_n)]$$

- Azimuthal anisotropy is a very good measure of the collision dynamics
- Sensitive to bulk properties of the medium

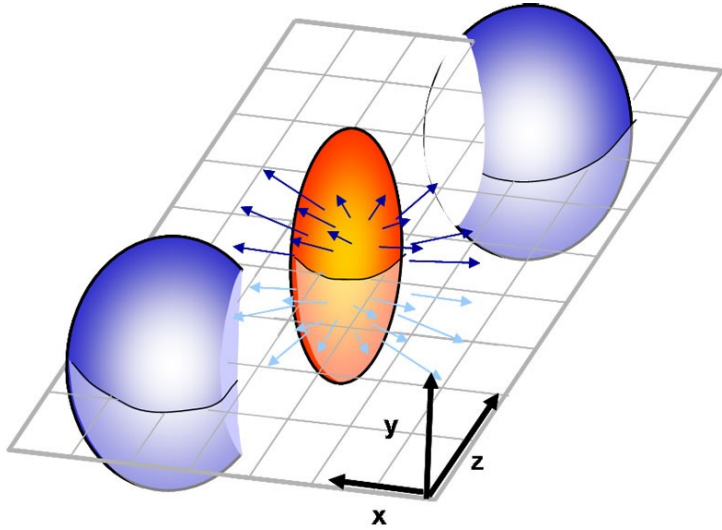


$\sqrt{s_{NN}} < 2$ GeV: angular momentum conservation

$2 < \sqrt{s_{NN}} < 4$ GeV: squeeze-out

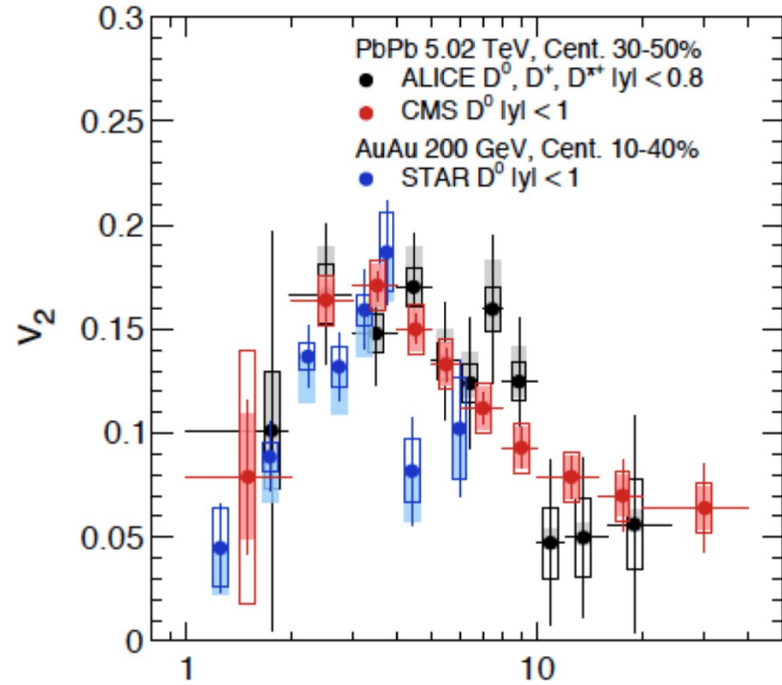
$\sqrt{s_{NN}} > 4$ GeV: hydro flow

Elliptic flow (v_2) of D mesons



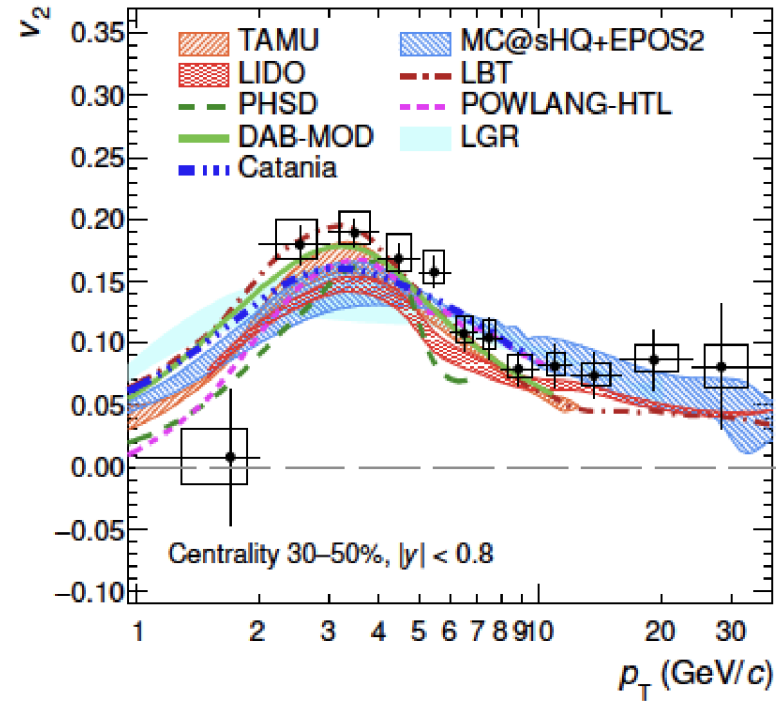
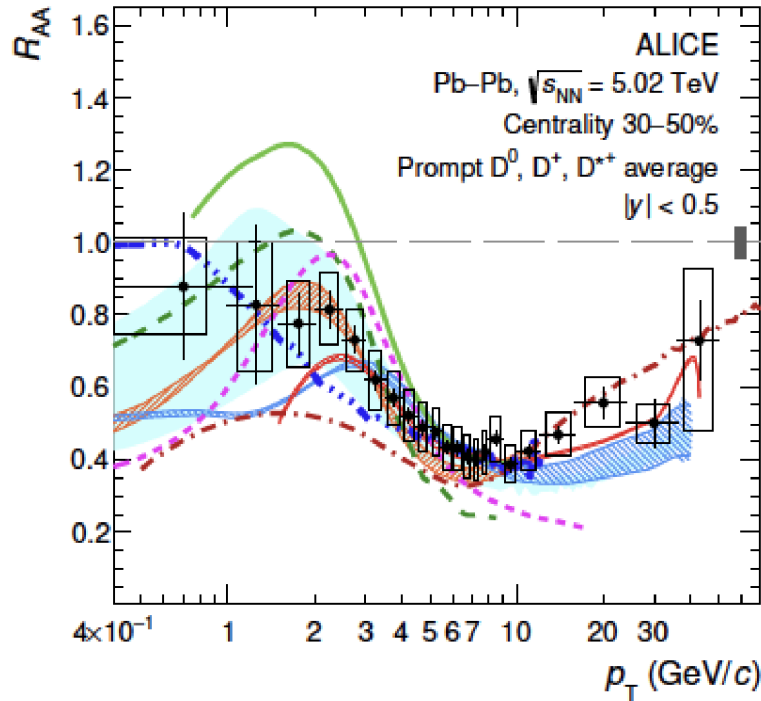
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STAR, PRL118 (2017) 212301



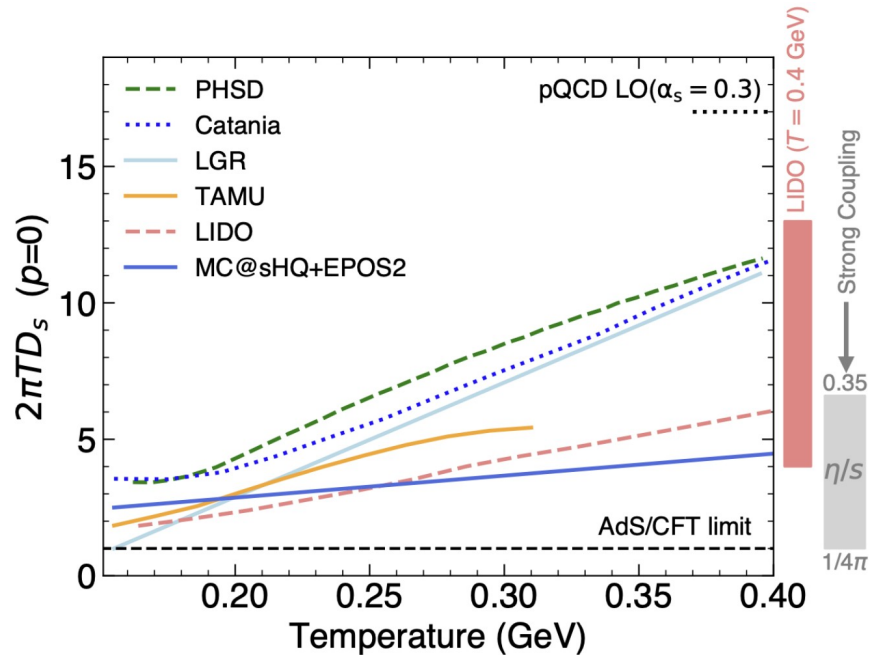
- Strong charm hadrons elliptic flow observed at both RHIC and the LHC
- No significant energy dependence, similar as for the light particle species

Comparison to model calculations



- Good qualitative description of both R_{AA} and v_2 for many different calculations
 - All implement charm quark diffusion in the medium and quark coalescence at hadronization time
 - Data provides constraints for the spatial diffusion coefficient

Charm quark diffusion coefficient, D_s



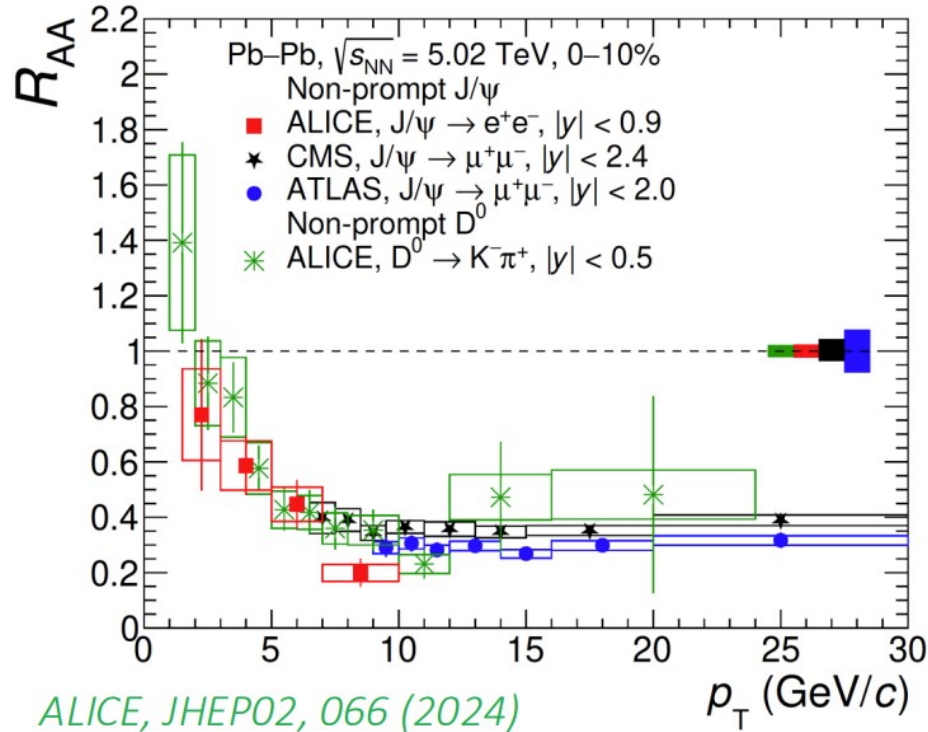
$$D_s \propto \frac{T}{m_Q \gamma}$$

$$\tau_Q = \frac{m_Q}{T} D_s \quad \text{charm quark relaxation time}$$

- Small D_s : fast relaxation time (more flow)
- Large D_s : slow relaxation (less flow)

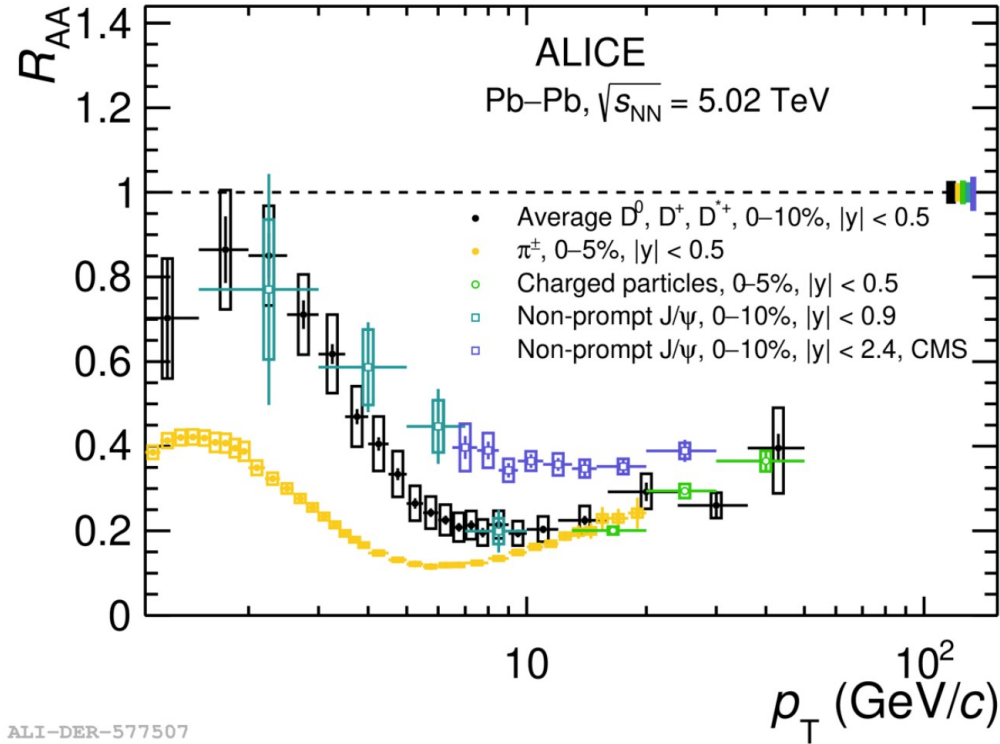
- Large differences between models in extracting the temperature dependence of D_s
- Relaxation time values: $3 < \tau_{\text{relax}} < 9$ fm/c
 - Overall less than the QGP lifetime, but large theoretical uncertainty

Beauty quark nuclear suppression



- Best measured using non-prompt J/ ψ and D^0
- High- p_T : strong suppression
- Low- p_T : R_{AA} goes up to nearly 1 (quark number conservation again)

Beauty quark nuclear suppression

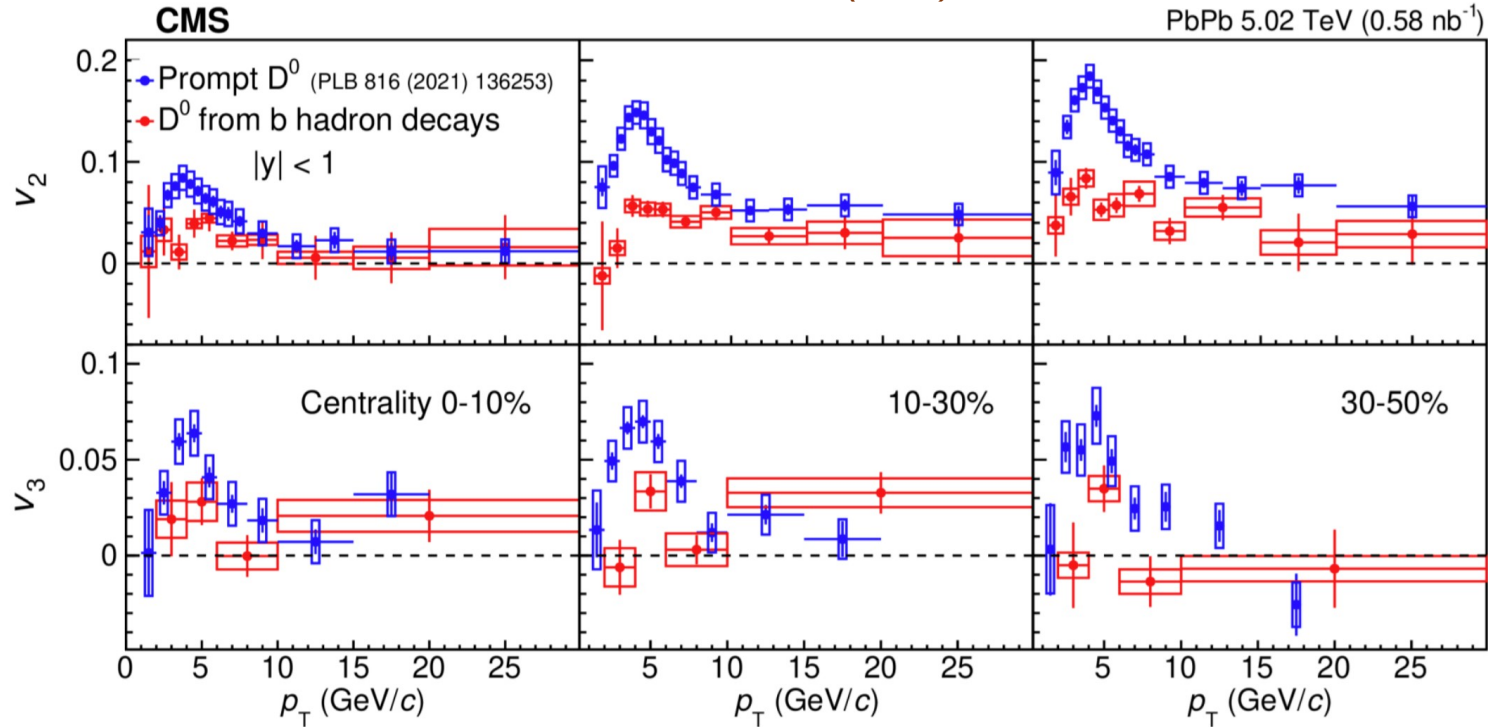


- Mass hierarchy of R_{AA} up to about 10 GeV/c: $R_{AA}(B) > R_{AA}(D) > R_{AA}$ (light)
- Compatible to expectations of energy loss hierarchy!!
- High- p_T : species independent $R_{AA} \rightarrow$ common underlying mechanism

Azimuthal anisotropy for beauty



CMS, PLB850 (2024) 138389



- Flow of D mesons from B decays smaller than for prompt D, but its significant
- Partial thermalization for beauty quarks?
- Hadronization effects ?

Charmonium production: the beginning



Experimental Observation of a Heavy Particle J/ψ

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCarriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Y. Y. Lee

Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J , with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + Be \rightarrow e^+ + e^- + X$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to study the behavior of timelike photons in $p + p \rightarrow e^+ + e^- + X$ reactions¹ and to search for new particles which decay into e^+e^- and $\mu^+\mu^-$ pairs.

We use a slow extracted beam from the Brookhaven National Laboratory's alternating-gradient synchrotron. The beam intensity varies from 10^{10} to 2×10^{12} p /pulse. The beam is guided onto an extended target, normally nine pieces of 70-ml Be, to enable us to reject the pair accidentals by requiring the two tracks to come from the same origin. The beam intensity is monitored with a secondary emission counter, calibrated

daily with a thin Al foil. The beam spot size is 3×6 mm², and is monitored with closed-circuit television. Figure 1(a) shows the simplified side view of one arm of the spectrometer. The two arms are placed at 14.6° with respect to the incident beam; bending ($M1, M2$) is done vertically to decouple the angle (θ) and the momentum (p) of the particle.

The Cherenkov counter C_0 is filled with one atmosphere and C_1 with 0.8 atmosphere of H_2 . The counters C_2 and C_3 are decoupled by magnets $M1$ and $M2$. This enables us to reject knock-on electrons from C_0 . Extensive and repeated calibra-

approximately 10^{-24} cm².

The most striking feature of J is the possibility that it may be one of the theoretically suggested charmed particles² or a^+a^- or $Z_0^+Z_0^-$, etc. In order to study the real nature of J , measurements are now underway on the various decay modes, e.g., an e^+e^- mode would imply that J is weakly interacting in nature.

It is also important to note the absence of an e^+e^- continuum, which contradicts the predictions of parton models.³

We wish to thank Dr. R. R. Rau and the alternating-gradient synchrotron staff who have done an outstanding job in setting up and maintaining this experiment. We thank especially Dr. F. Eppling, B. M. Bailey, and the staff of the Laboratory for Nuclear Science for their help and encouragement. We thank also Ms. I. Schultz, Ms. H. Feind, N. Feind, D. Osborne, G. Krey, J. Donahue, and

E. D. Weiner for help and assistance. We thank also M. Deutsch, V. F. Weisskopf, T. T. Wu, S. Drell, and S. Glashow for many interesting conversations.

¹Accepted without review under policy announced in Editorial of 20 July 1964 [Phys. Rev. Lett. **23**, 79 (1964)].

²The first work on $p + p \rightarrow \mu^+ \mu^- + X$ was done by L. M. Lederman *et al.*, Phys. Rev. Lett. **25**, 1523 (1970).

³S. L. Glashow, private communication.

⁴D. Lee, Phys. Rev. Lett. **26**, 801 (1971).

⁵S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967), and **27**, 1688 (1971), and Phys. Rev. D **5**, 1412, 1962 (1972).

⁶After completion of this paper, we learned of a similar result from SPEAR. B. Richter and W. Panofsky, private communication; J.-E. Augustin *et al.*, following Letter Phys. Rev. Lett. **25**, 1464 (1974).

⁷S. D. Drell and T. M. Yan, Phys. Rev. Lett. **25**, 316 (1970). An improved version of the theory is not in contradiction with the data.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Luth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinozsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeck, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

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(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^- , and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^- , and possibly $\mu^+\mu^-$ in the Stanford Linear Accelerator Center (SLAC)—Lawrence Berkeley Laboratory magnetic detector¹ at the SLAC electron-positron storage ring SPEAR. The resonance has the parameters

$$E = 3.105 \pm 0.003 \text{ GeV,}$$

$$\Gamma = 1.3 \text{ MeV}$$

(full width at half-maximum), where the uncertainty in the energy of the resonance reflects the

uncertainty in the absolute energy calibration of the storage ring. [We suggest naming this structure $\psi(3105)$.] The cross section for hadron production at the peak of the resonance is > 2300 nb, an enhancement of about 100 times the cross section outside the resonance. The large mass, large cross section, and narrow width of this structure are entirely unexpected.

Our attention was first drawn to the possibility of structure in the $e^+e^- \rightarrow$ hadron cross section during a scan of the cross section carried out in 200-MeV steps. A 30% (6 nb) enhancement was

- 1964: Charm quarks predicted by Bjorken and Glashow
- 1974: The “november revolution”
- J/ψ discovery in p-A (BNL) and e^+e^- (SLAC) collisions



Burton Richter and Samuel Ting, 1976

- Late 1970: J/ψ hadro-production in pp collisions at CERN ISR

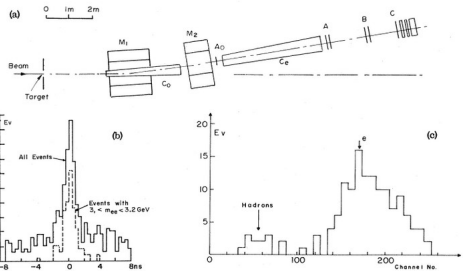


FIG. 1. (a) Simplified side view of one of the spectrometer arms. (b) Time-of-flight spectrum of e^+e^- pairs and of those events with $3.0 < m < 3.2$ GeV. (c) Pulse-height spectrum of e^+e^- (same for e^-) of the e^+e^- pair.

Brookhaven:
PRL33 (1974) 1404

Stanford:
PRL33 (1974) 1406

The initial argument



PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986

BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui

Center for Theoretical Physics
Laboratory for Nuclear Science
Massachusetts Institute of Technology
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and

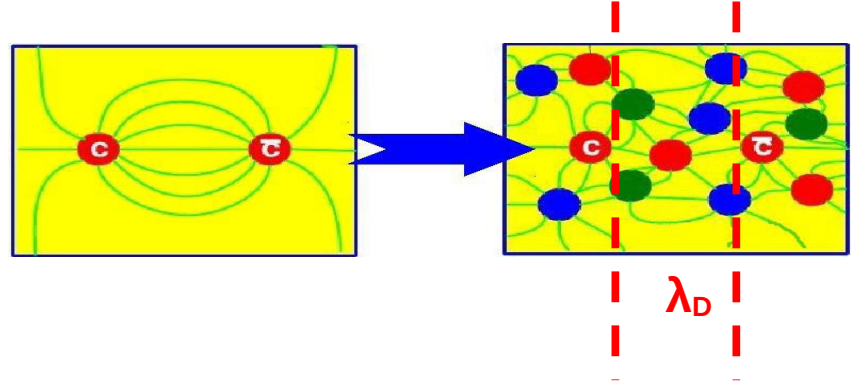
H. Satz

Fakultät für Physik
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and
Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined.

We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.



Vacuum potential (Cornell):

$$V_{total} = (-q) \frac{q}{4\pi r} + kr$$

In-medium potential (Yukawa-like):

$$V_{medium}(r) = \frac{q}{4\pi} \frac{e^{-r/\lambda_D}}{r}$$

Debye screening length:

$$\lambda_D \approx \frac{1}{T}$$

The initial argument



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If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined.

We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

($m_c = 1.25$ GeV, $m_b = 4.65$ GeV, $\sqrt{\sigma} = 0.445$ GeV, $\alpha = \pi/12$)

Binding energy ranges from 50 MeV to 1 GeV

The initial argument



PHYS. LETT. B, in press

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BNL-38344

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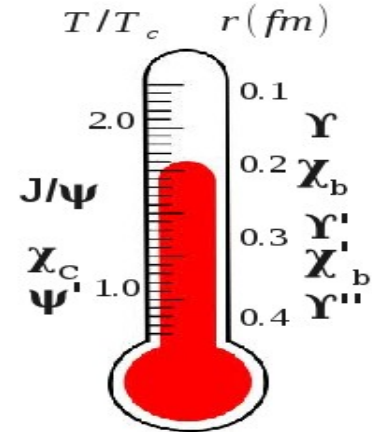
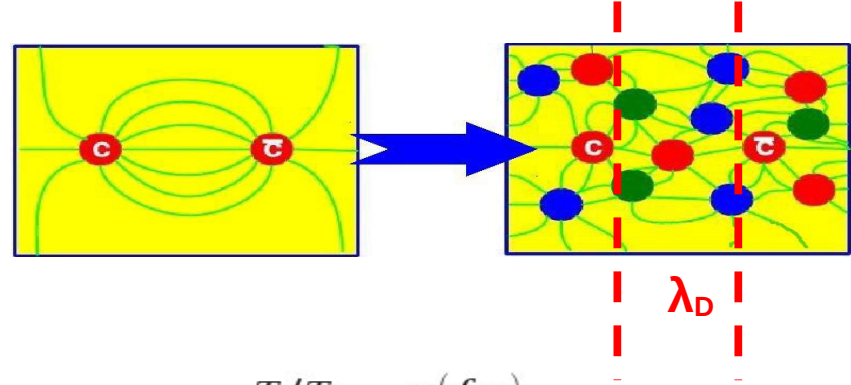
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ABSTRACT

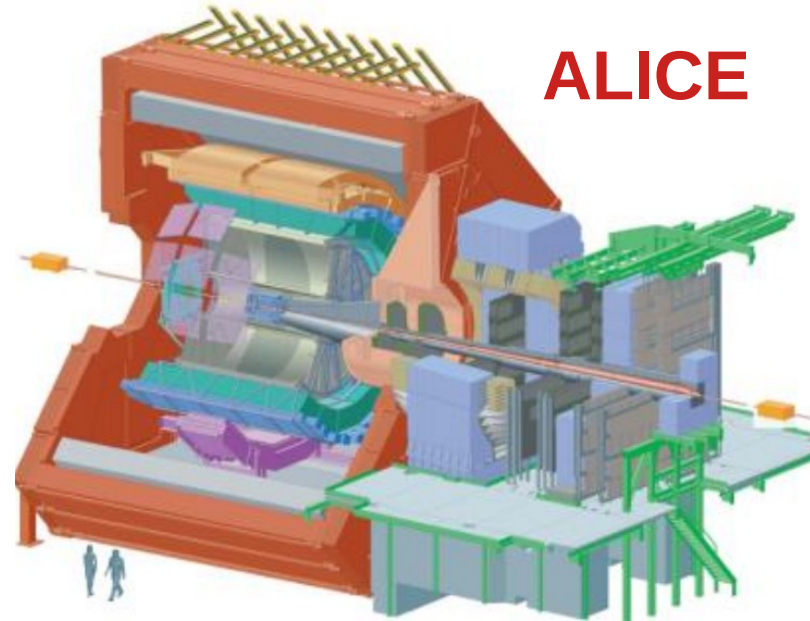
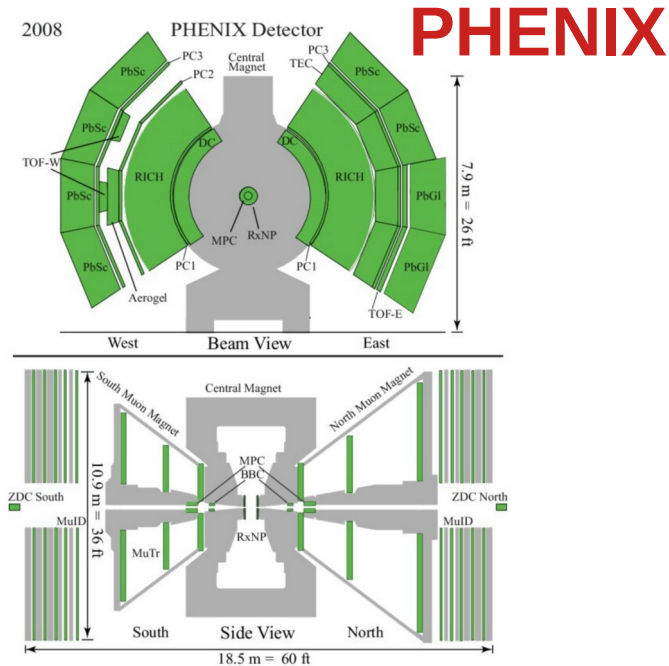
If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined.

We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.



Quarkonium states are melted if $r > \lambda_D$
Quarkonia is a thermometer of the medium
and a probe of QGP formation !

Quarkonium measurements in heavy-ion collisions



- Due to large backgrounds, measurements are mostly limited to the ψ and Y families
- Decay channels exploited: e^+e^- and $\mu^+\mu^-$
- Experimental methods
 - Dimuons: spectrometers placed behind hadron absorbers
 - Dielectrons: tracking+PID, calorimeters, transition radiation

The initial observation



THE PRODUCTION OF J/Ψ IN 200 GeV/NUCLEON OXYGEN-URANIUM INTERACTIONS

NA38 Collaboration

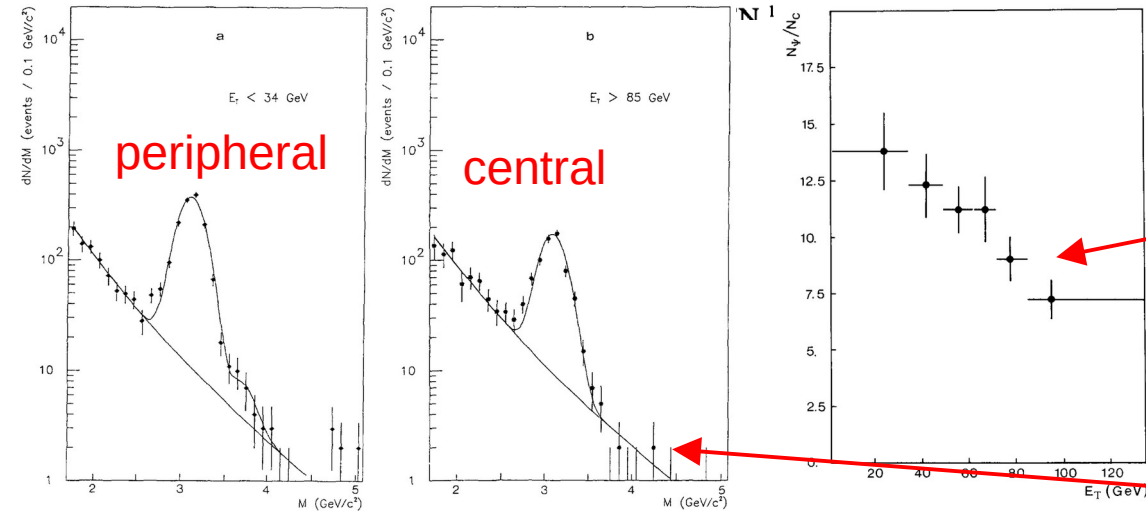


Fig. 5. Mass spectrum and fit of the signal muon pairs in two different E_T bins: $E_T < 34$ GeV (a) and $E_T > 85$ GeV (b).

Fig. 6. The evolution of $S = N_{J/\psi} / N_c$ as a function of E_T .

- O-U collisions at $\sqrt{s_{NN}} \sim 20$ GeV
- $N_{J/\psi} / N_c$ decreases by a factor 2 from peripheral to central collisions
- Relative suppression wrt number of continuum dimuon pairs (Drell-Yan)
- Hint of $\psi(2S)$ suppression

PLB220 (1989) 471

Z.Phys. 38 (1988) 117

IPNO-DRE 92 - 01

Comparison of J/ψ -Suppression in Photon, Hadron and Nucleus-Nucleus Collisions :Where is the Quark-Gluon Plasma?

C. Gerschel^a and J. Hüfner^b

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^b Institut für Theoretical Physik, Universität Heidelberg, Germany

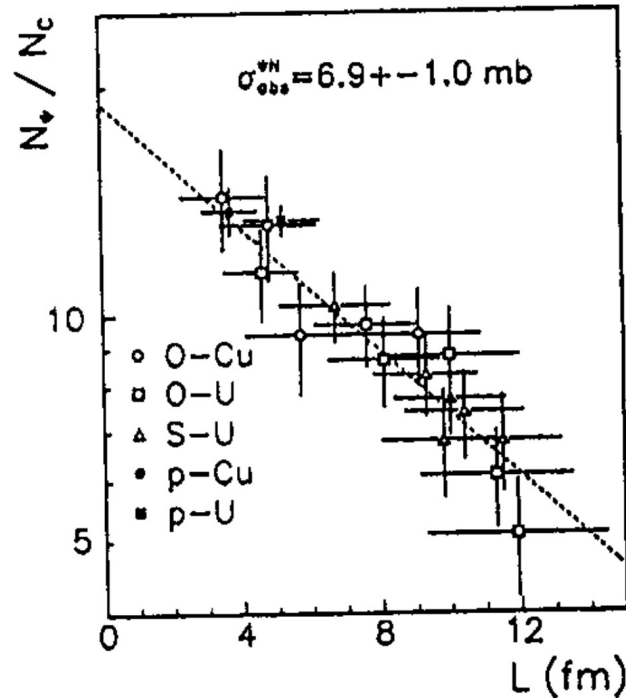


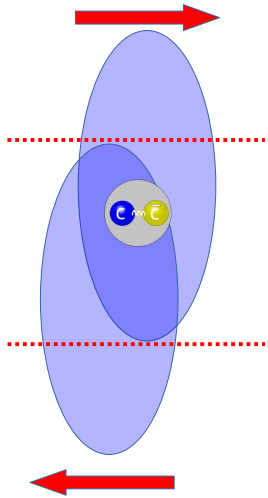
Fig.3 : E_T -dependence of J/ψ -suppression in NA38 data plotted as a function of L .

- J/ψ “suppression” in A-A and p-A depend on the average path length in cold nuclear matter
 - Dissociation in “cold” nuclear matter
 - Nuclear absorption: $\sigma_{abs} \sim 7 \text{ mb}$
- **O – U system not hot/large enough for QGP formation !**

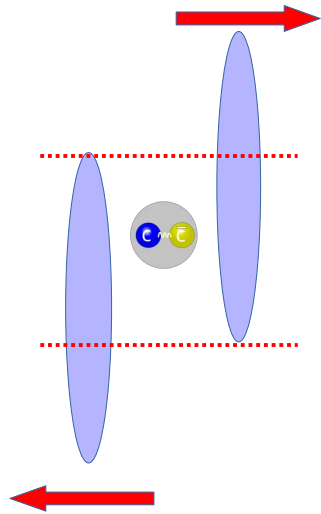
Non-QGP effects



SPS



LHC



Crossing time: $\tau = L/(\beta_z \gamma)$

After being produced, charmonia can be broken-up in the interaction with the nuclear remnants

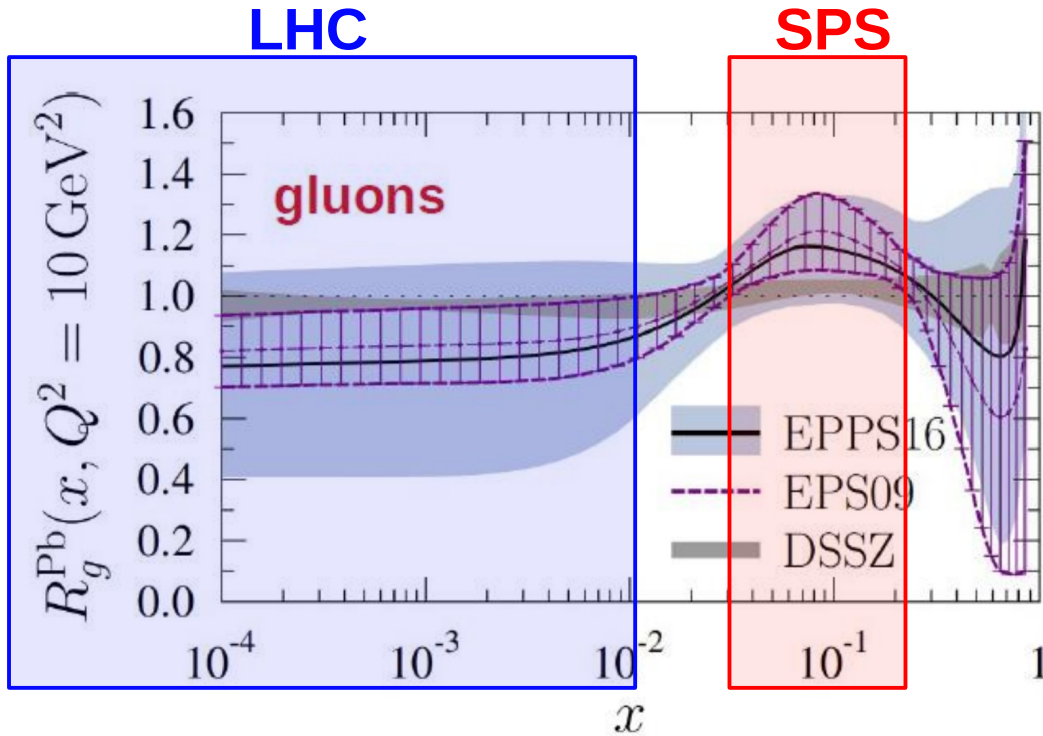
SPS:

Break-up in nuclear matter, $\tau \sim 0.5$ fm/c

LHC

Very short crossing time, negligible break-up, $\tau < \sim 10^{-2}$ fm/c

Initial state effects: nuclear PDFs



Charmonium production rate affected by the modification of parton PDFs in the nucleus

SPS:

moderate anti-shadowing, $x \sim 10^{-1}$ ($y=0$)

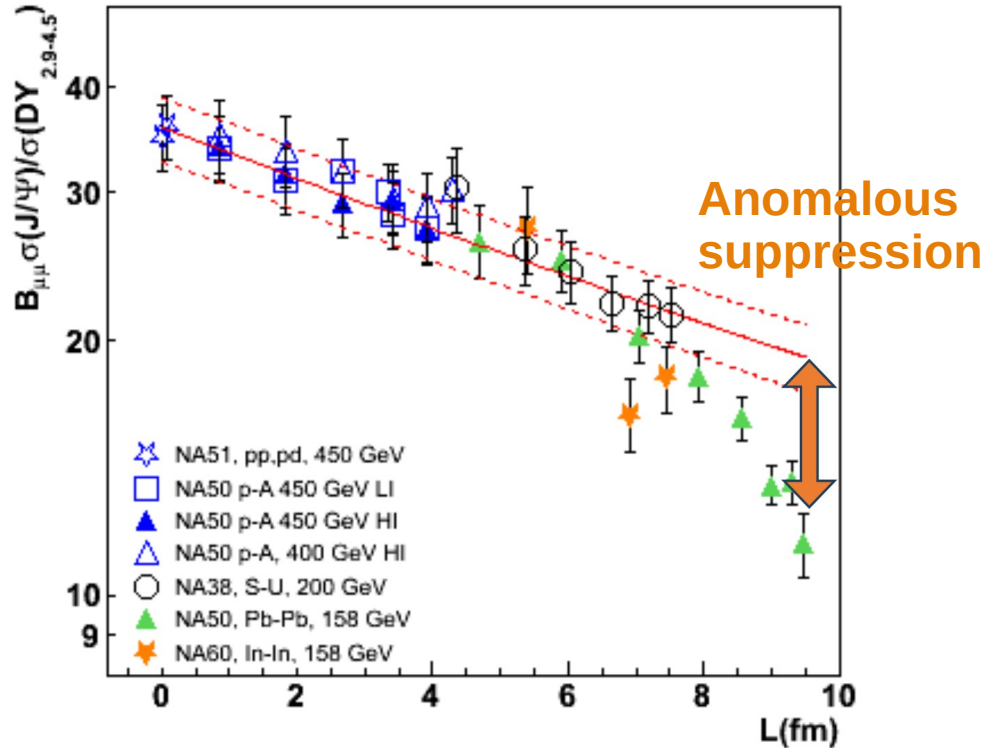
LHC:

shadowing, $x < 10^{-2}$ ($|y| < 3$)

Finally, the “anomalous” J/ψ suppression: Pb-Pb at the SPS



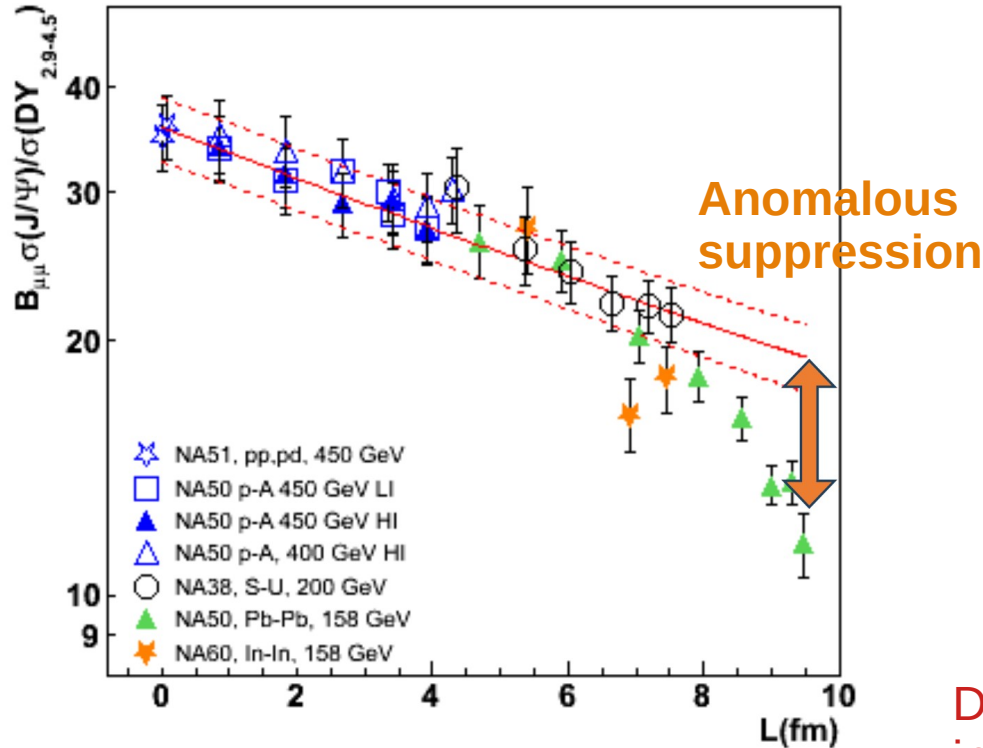
NA50, PLB410 (1997) 337



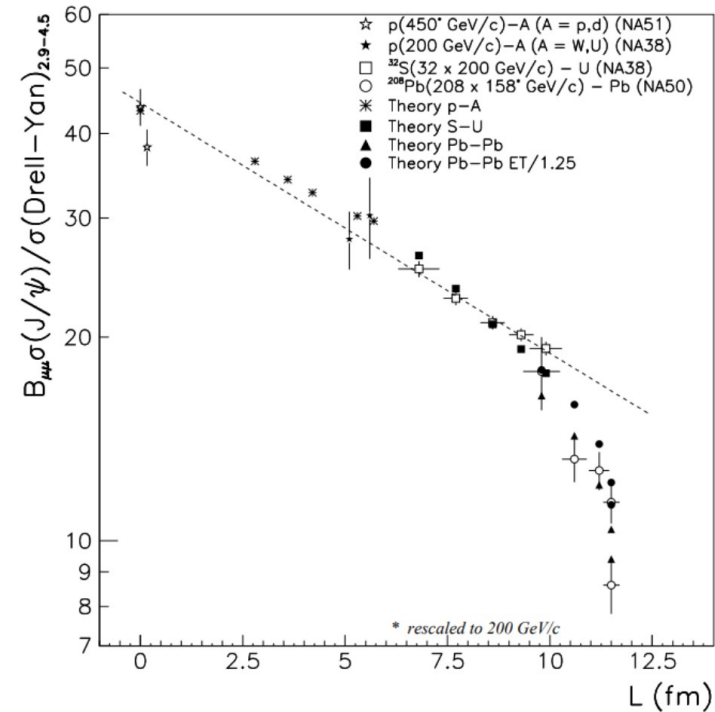
Central Pb-Pb collisions indicate suppression beyond the expectations from nuclear break-up

However ...

NA50, PLB410 (1997) 337



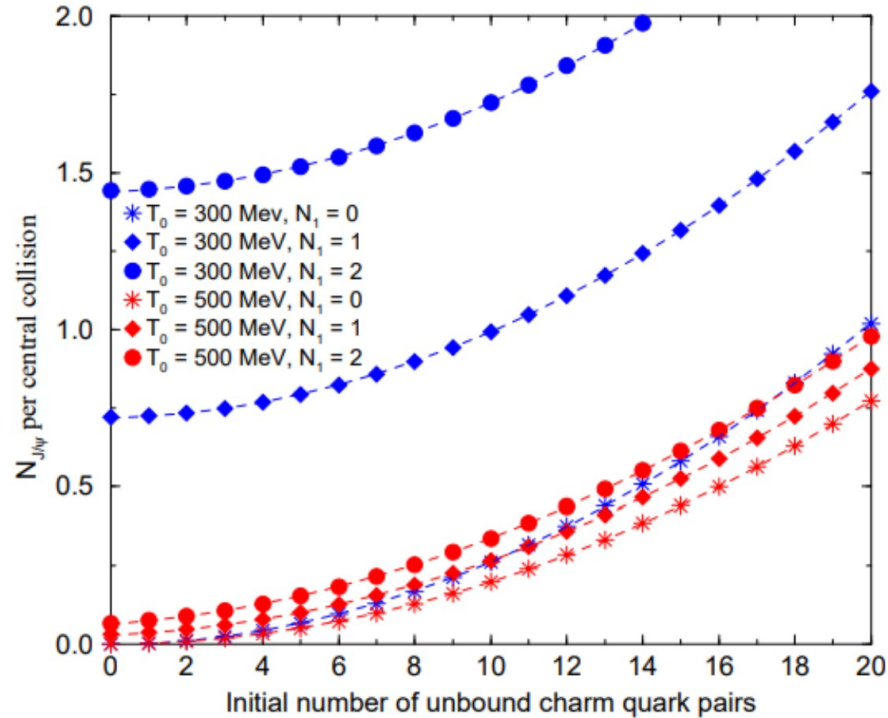
Central Pb-Pb collisions indicate suppression beyond the expectations from nuclear break-up



Data could be explained also by means not involving suppression in the QGP:

- Final state interaction with co-moving hadrons
- Melting of $\psi(2S)$ and χ_c states

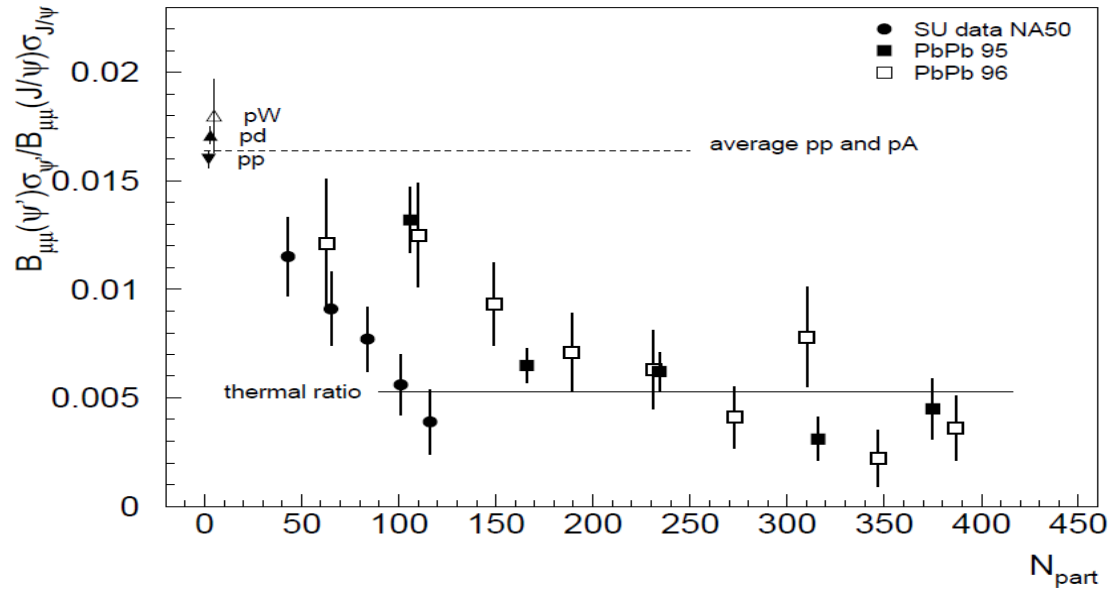
RHIC and LHC era: the J/ψ enhancement



Thews et al.

- Prediction of strong J/ψ enhancement due to
 - Many charm quark pairs per event produced at RHIC and LHC
 - **Recombination of the initial unbound charm quarks into charmonium**

RHIC and LHC era: the J/ψ enhancement



$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V \left(\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm} \right) + g_c^2 V \left(\sum_i n_{\psi_i}^{therm} \right) + \dots$$

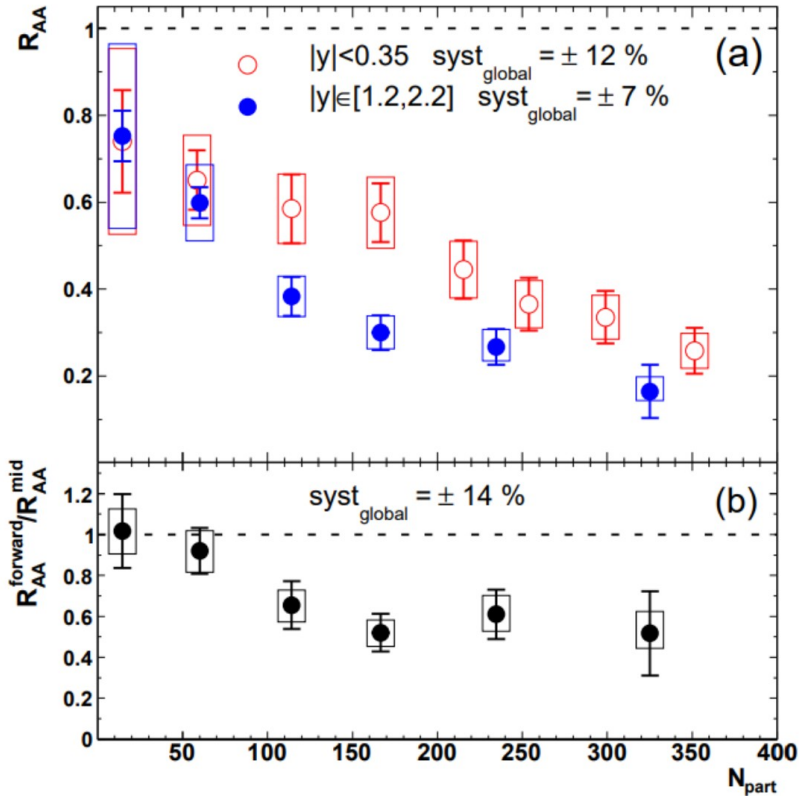
P. Braun-Munzinger and J. Stachel

- J/ψ yields are not thermal !
- Ratio of $\psi(2S)$ / J/ψ converges to the expected thermal ratio
- **Direct production of charm quarks followed by statistical hadronization at freeze-out**

RHIC: the J/ψ nuclear suppression



PHENIX, PRL 98 (2007) 232002

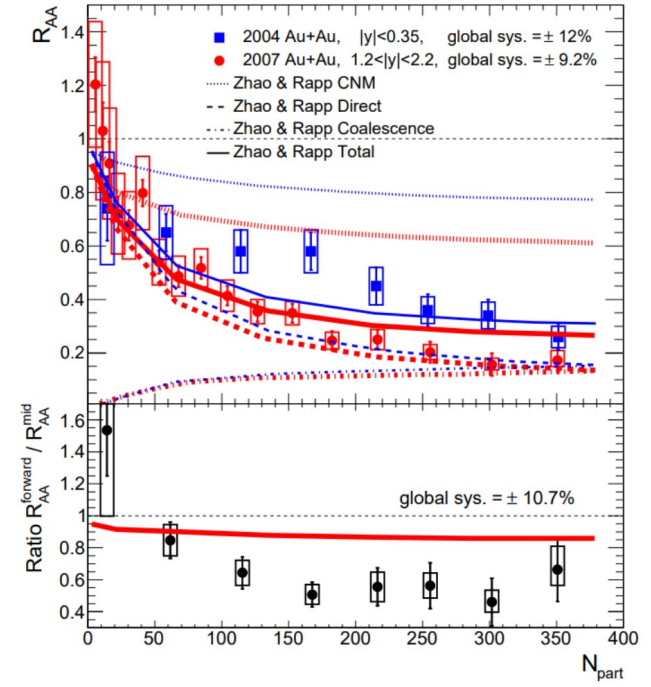
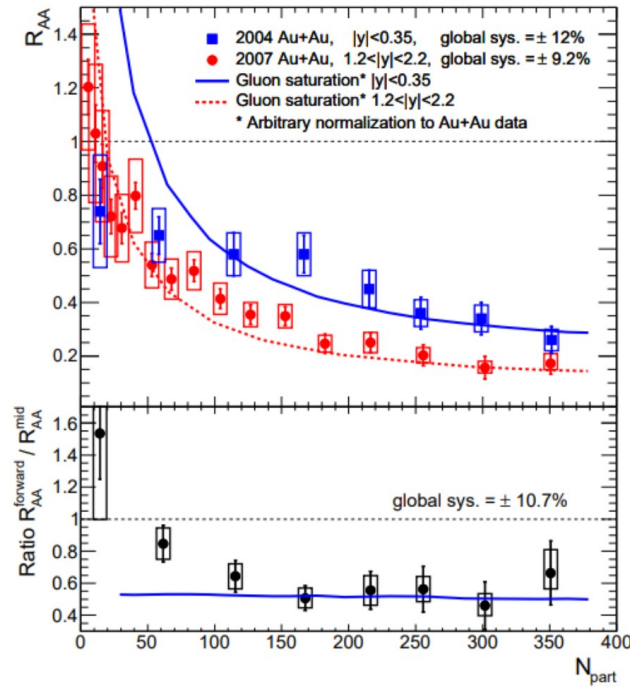
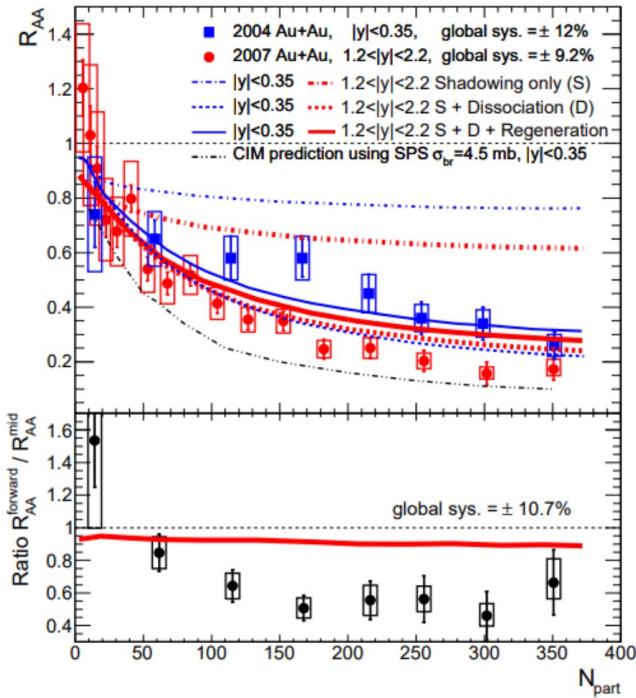


- Nuclear suppression measurements at RHIC done using the nuclear modification factor R_{AA}
- Measurement done both at mid- and forward rapidity
- Counter-intuitive results
 - Expectation: higher energy density at mid-y leads to stronger suppression
 - Can regeneration explain the observations?

RHIC: the J/ψ nuclear suppression



PHENIX, PRC 84, 054912



Comover interaction

Gluon saturation

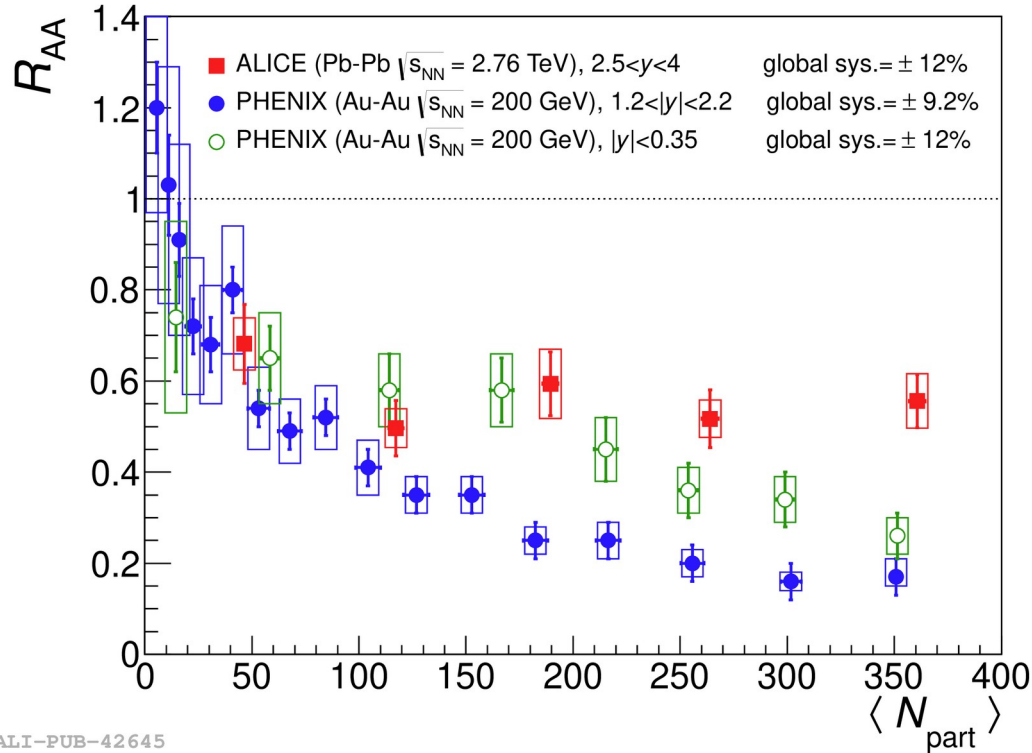
QGP/Hadron gas transport

- Explaining the data requires a combination of cold and hot matter effects
- Difficult task for phenomenology !

J/ψ suppression at the LHC



ALICE, PRL 109 (2012) 072301

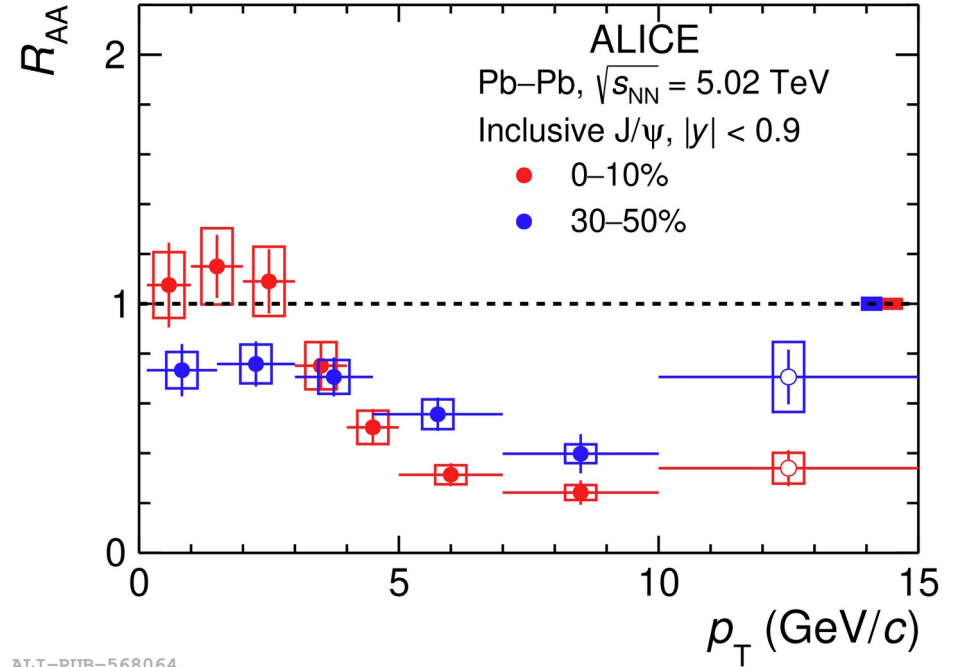
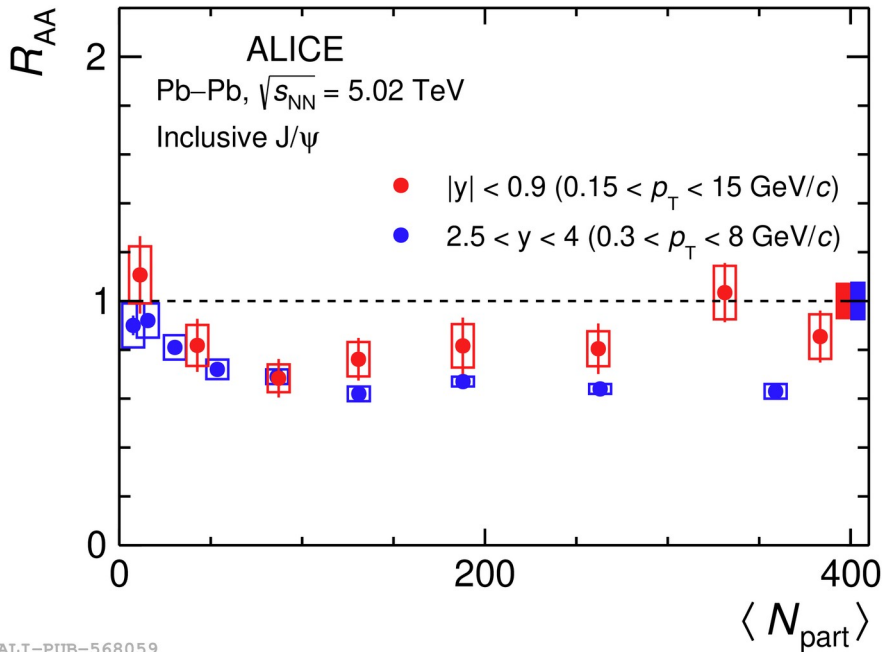


- RHIC to LHC: factor > 10 in energy increase
- R_{AA} larger by factor 2 at LHC in central Pb-Pb!
- Regeneration effects at play ?

J/ψ suppression at the LHC at mid-rapidity



ALICE, PLB 849 (2024) 138451

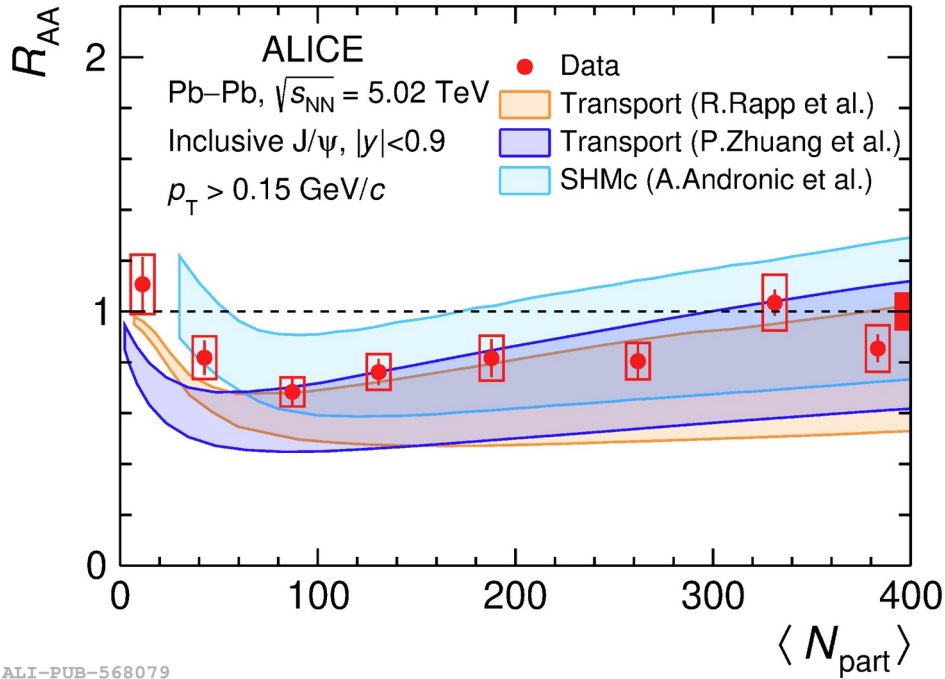


- R_{AA} larger at mid-y
 - Integrated R_{AA} is larger towards central collisions
 - p_T -differential R_{AA} is larger at low- p_T
- Expected if regeneration plays a dominant role due to higher charm density

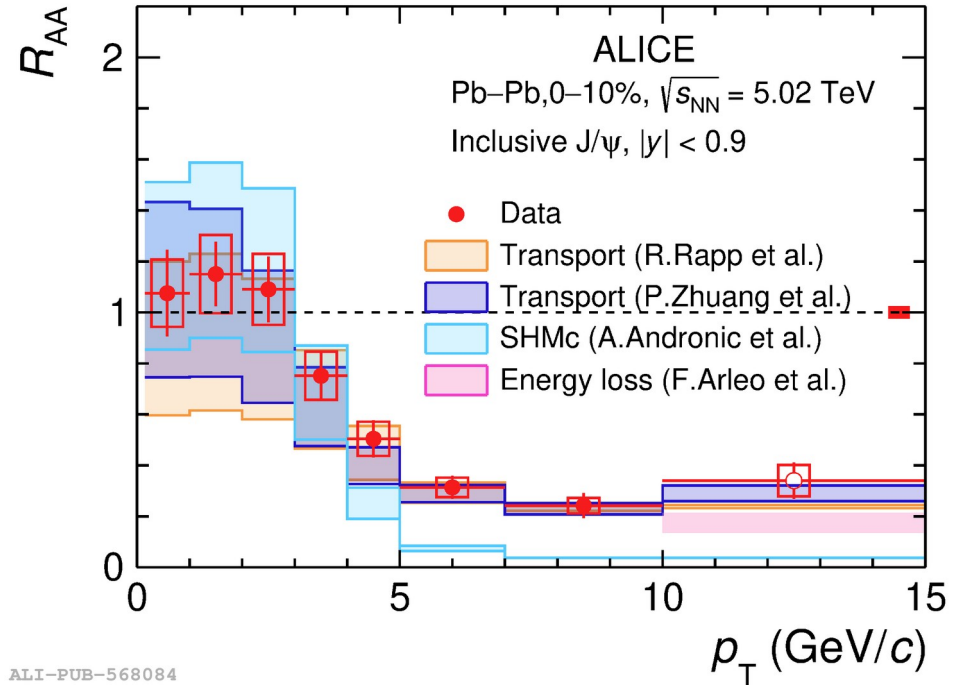
Data / model comparisons



ALICE, PLB 849 (2024) 138451



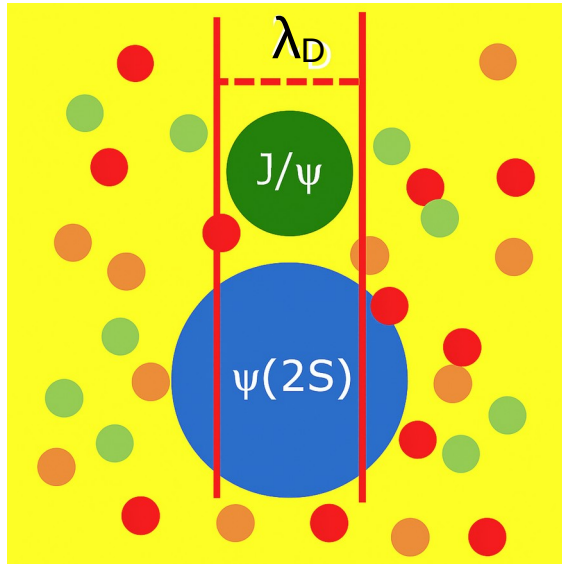
ALI-PUB-568079



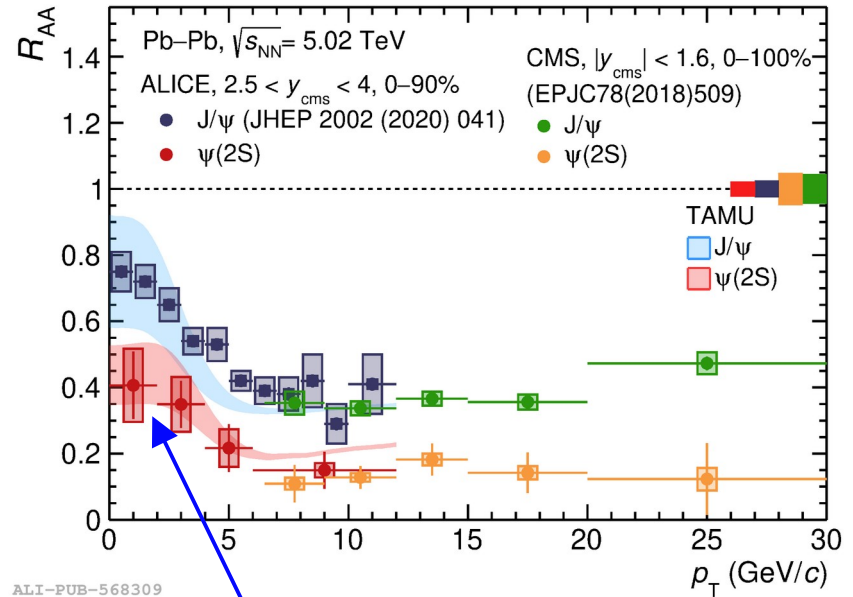
ALI-PUB-568084

- Both transport and SHM approaches describe data well
 - All implement J/ψ regeneration
- Main source of model uncertainty is the total open-charm cross-section and its shadowing in Pb-Pb collisions

Production of excited charmonia at the LHC: $\psi(2S)$



ALICE, PRL 132 (2024) 042301



ALI-PUB-568309

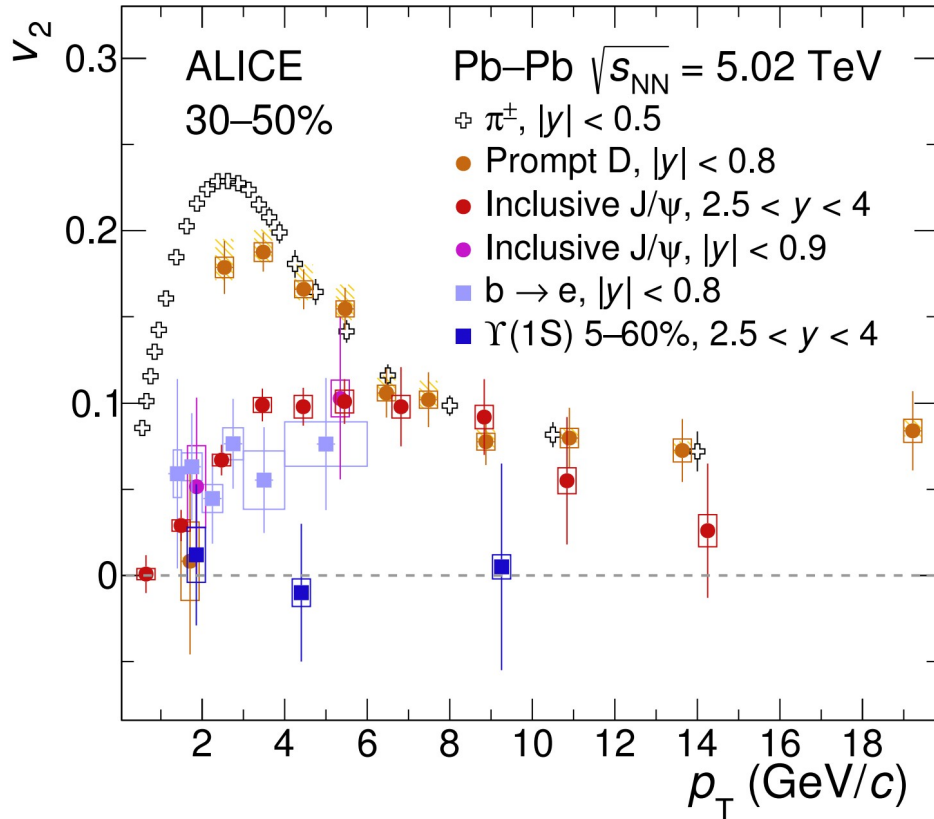
Indication of an increase of the R_{AA} towards low p_T

- Much lower binding energy: ~ 60 MeV
- Stronger dissociation effects (already seen at SPS)
- Recombination effects could be important also for $\psi(2S)$, especially when the system is more diluted, at later times

Anisotropic flow of light and charm hadrons



ALICE, JHEP 10 (2020) 141

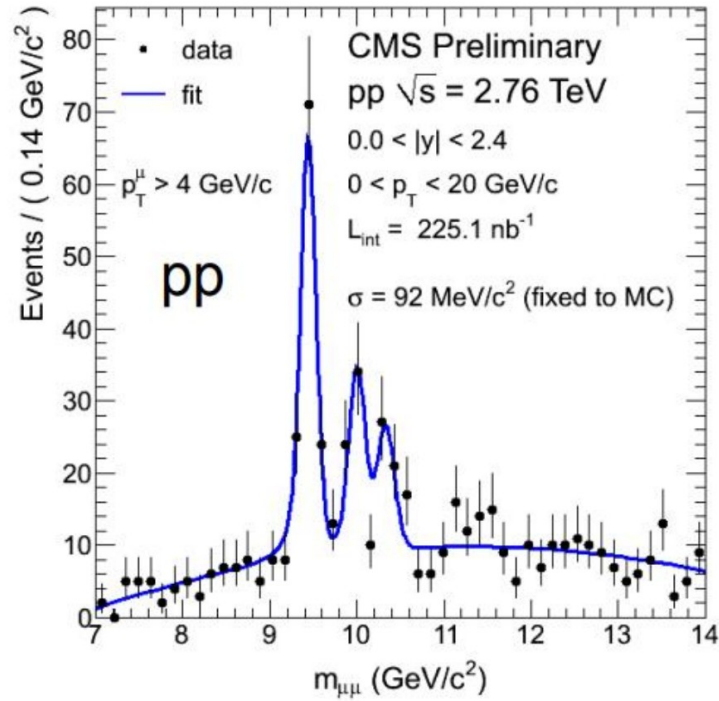


- J/ ψ flows as well !
 - Unambiguous probe of charm quark flow
- Hierarchy of anisotropy:
 $v_2(\pi) > v_2(D) > v_2(J/\psi) > v_2(b \rightarrow e) > v_2(Y)$

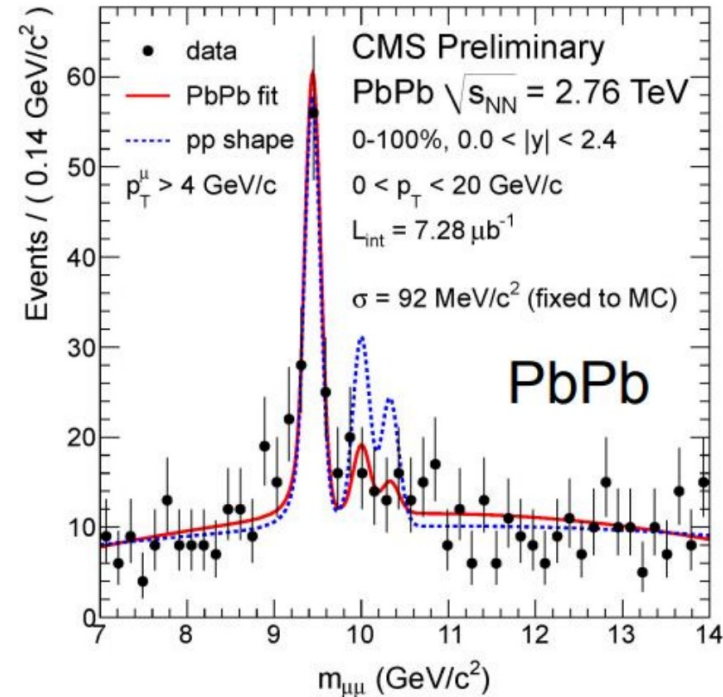
What about bottomonium ?



CMS, *J.Phys.G38(2011) 124071, PRL107 (2011) 052302*



$$\Upsilon(2S + 3S)/\Upsilon(1S) \Big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$



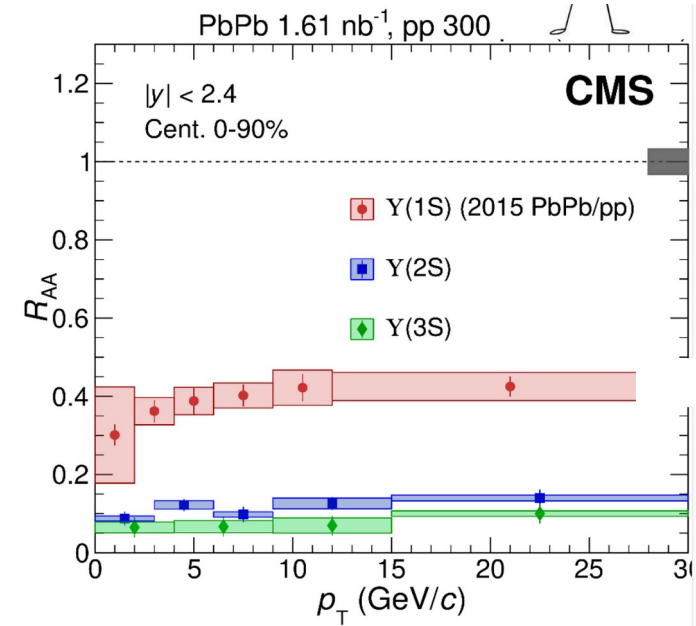
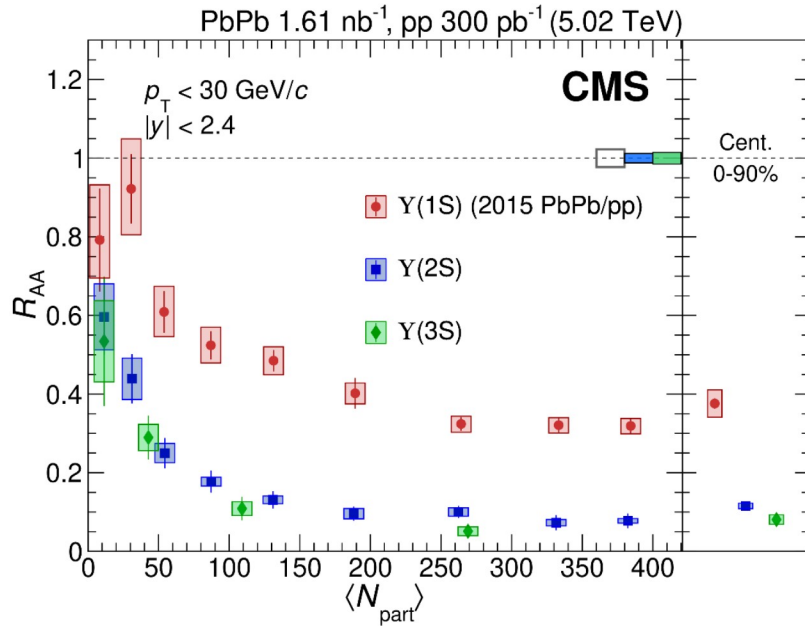
$$\Upsilon(2S + 3S)/\Upsilon(1S) \Big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

First evidence for sequential suppression in the bottomonium sector

Bottomonium differential measurements



CMS, *J.Phys.G*38(2011) 124071, *PRL*107 (2011) 052302



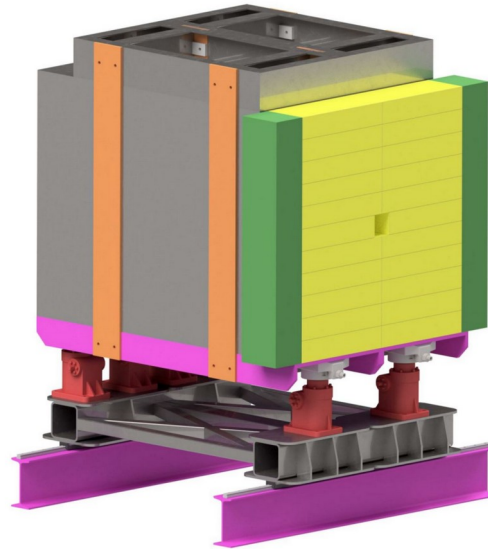
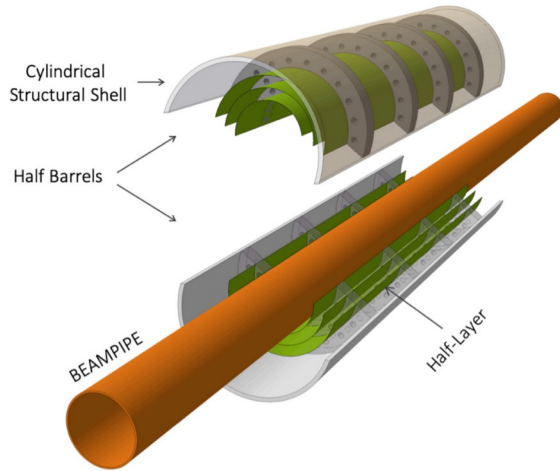
- Hierarchy of suppression for the 1S, 2S and 3S states

$$Y(1S) > Y(2S) > Y(3S)$$

The next 20 years



ALICE upgrades timeline: ITS3 and FoCal

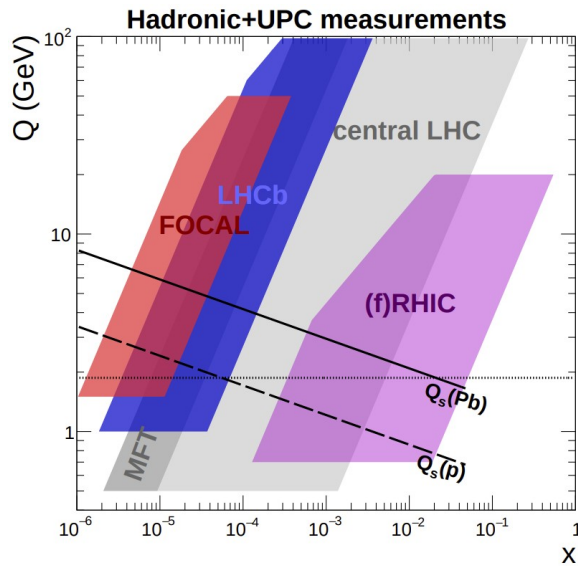
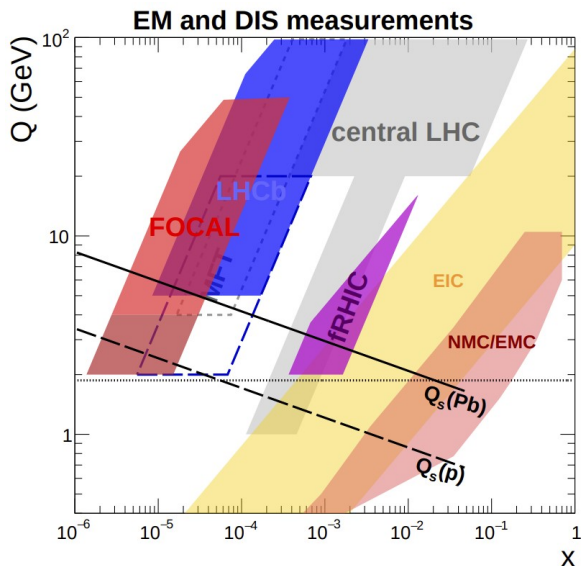


- TDRs approved in 2024
- To be installed during LS3
- Moving towards production phase

ITS3 TDR: [CERN-LHCC-2024-003](#)

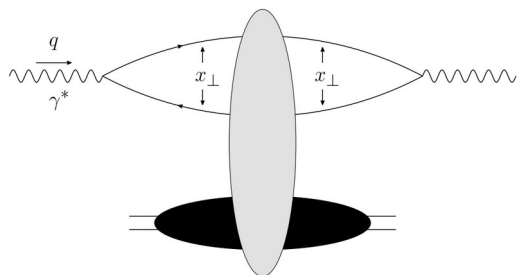
FoCal TDR: [CERN-LHCC-2024-004](#)

Nuclear imaging with FoCal



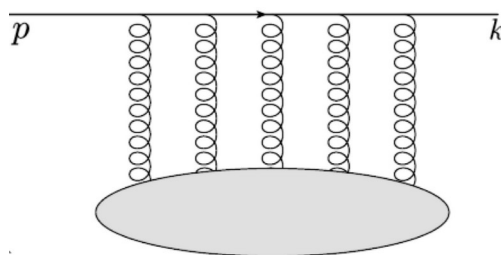
- Expand sensitivity to gluon distributions into previously unexplored regions
- Multiple experimental observables
 - Prompt γ
 - γ – hadron correlations
 - Photoproduction in UPCs
 - Jets
 - Hadroproduction of neutral mesons, quarkonia, Z^0
- Complementarity with the EIC
 - Multiple processes in e-A and forward p-A are theoretically described using the same scattering amplitudes
 - Test universality of the description of gluon distributions in hadrons

(e+A DIS)



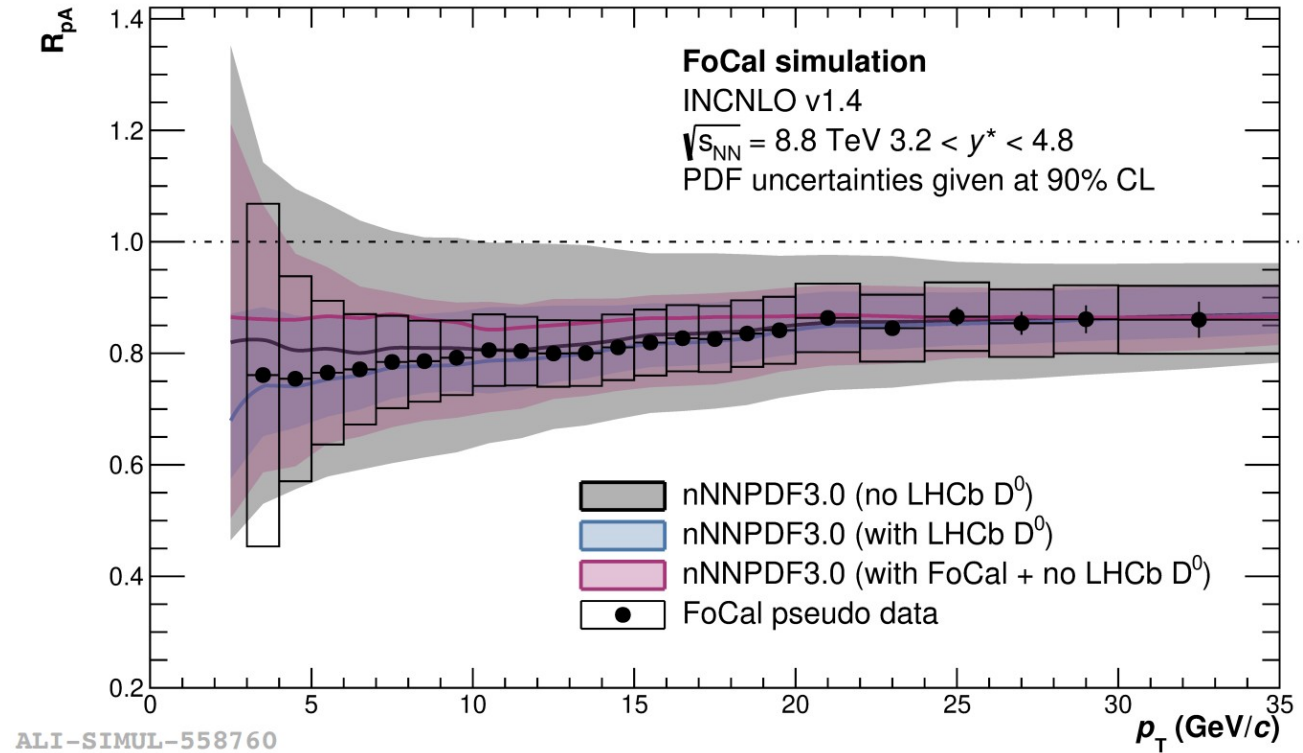
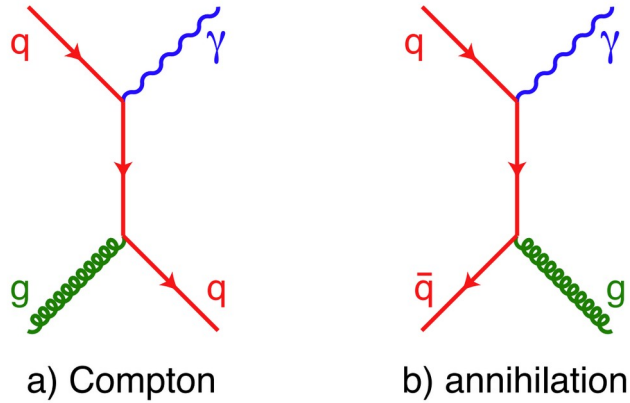
Gribov, JETP 30 (1970) 709

(Forward p+A)



Kopeliovich, Phys.Rev.C 59 (1999) 1609

Constraining PDFs with isolated photons



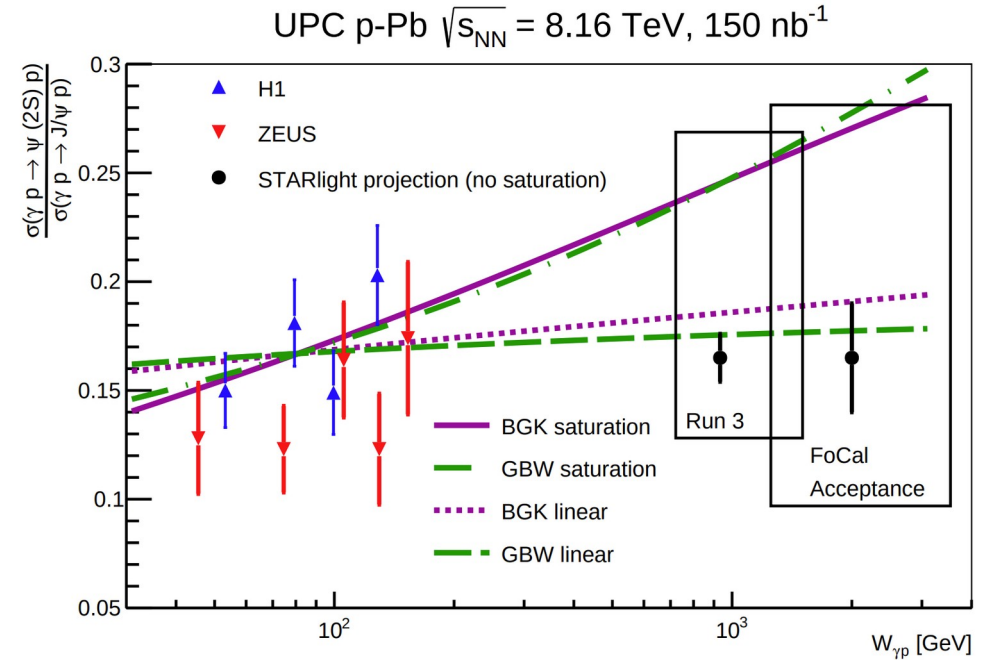
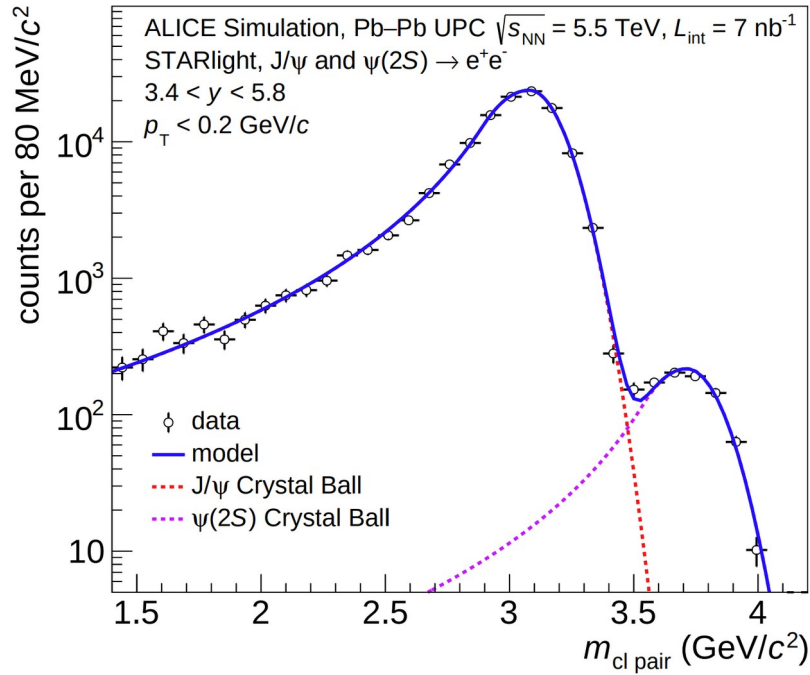
Isolated photons

- Advantage: no final state fragmentation
- Strong constraints to nuclear PDFs
- Complementarity to LHCb measurements using D^0 s

Coherent charmonia photoproduction in UPC (p-A and A-A)



Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107



Quarkonia production in ultra-peripheral collisions

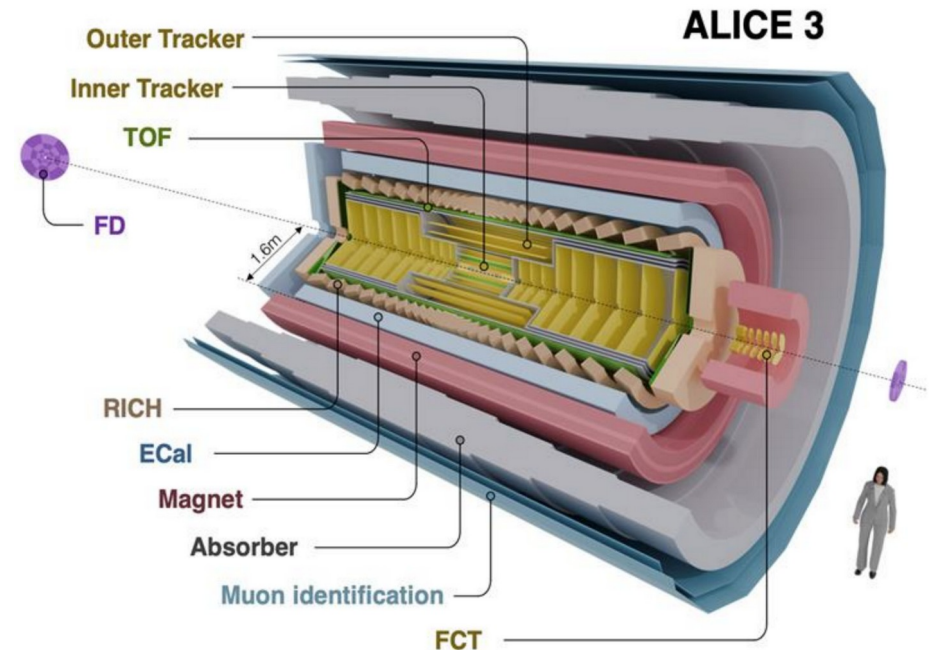
- Extending coverage in $W_{\gamma p}$ up to 2 TeV
- Large lever arm for discriminating linear vs saturation scenarios

ALICE upgrades timeline: ALICE3

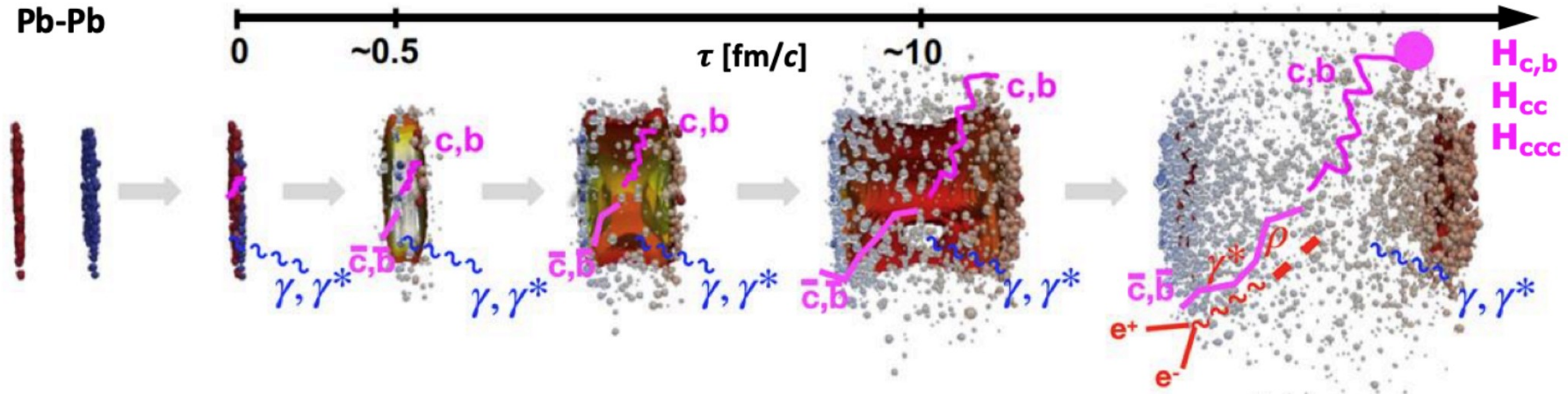


ALICE3 Loi: [CERN-LHCC-2022-009](#)
Scoping document: [CERN-LHCC-2025-002](#)

- Scoping document review completed in 2025
- Installation foreseen during LS4
- Ongoing R&D phase



ALICE 3 physics goals



Early stages: temperature, chiral symmetry restoration

- Dilepton and photon production

Heavy flavour diffusion and thermalization in QGP

- Precise beauty flow at low p_T , $D\bar{D}$ correlations

Hadronization in heavy-ion collisions

- Multi-charm production
- Excited quarkonium states: dissociation and regeneration

Fluctuations of conserved charges

- Hadron correlations and fluctuations

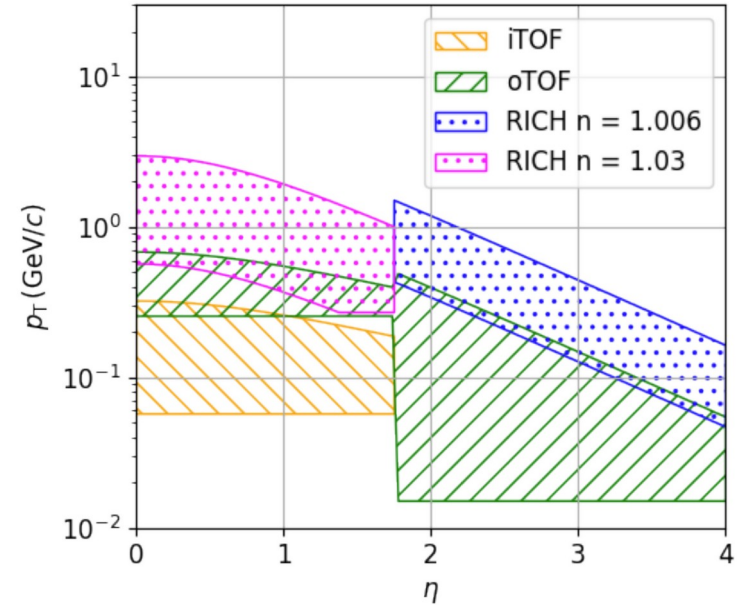
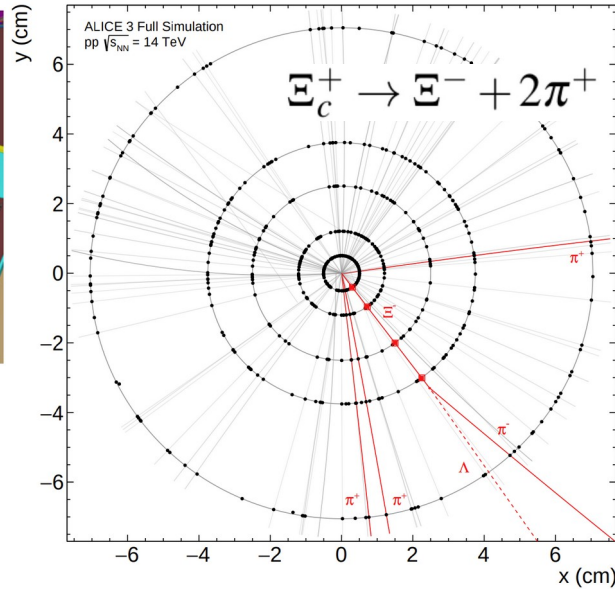
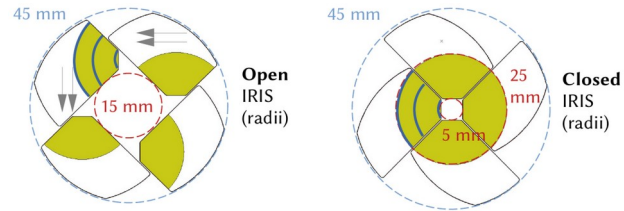
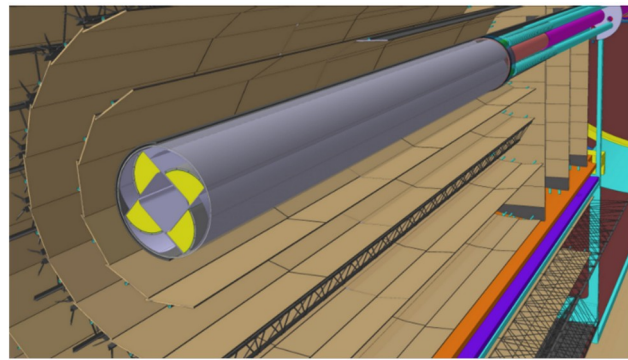
Nature of exotic hadrons

- DD femtoscopy, production yields

Beyond QGP physics

- Ultra-soft photon production (Low's theorem)
- Search for ALPs in ultra-peripheral Pb-Pb
- Search for super-nuclei (c-deuterium, c-tritium)

ALICE3 performance: tracking and PID



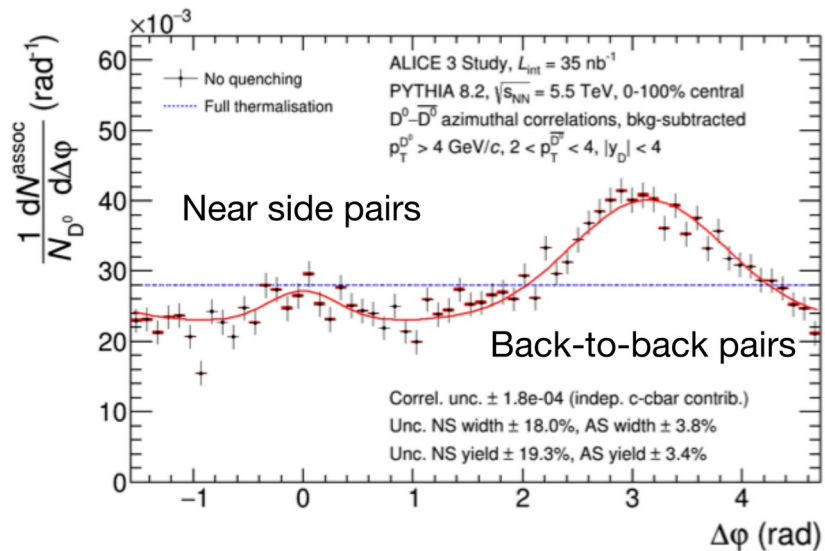
Silicon-based tracking detectors

- State-of-the-art inner tracker (IT) with a spatial resolution of 3-4 μm for precise vertexing
- Outer tracker for momentum measurement

Particle identification

- Time-of-Flight detector
- Cerenkov detectors (RICH)
- Muon tracker

Heavy quark transport

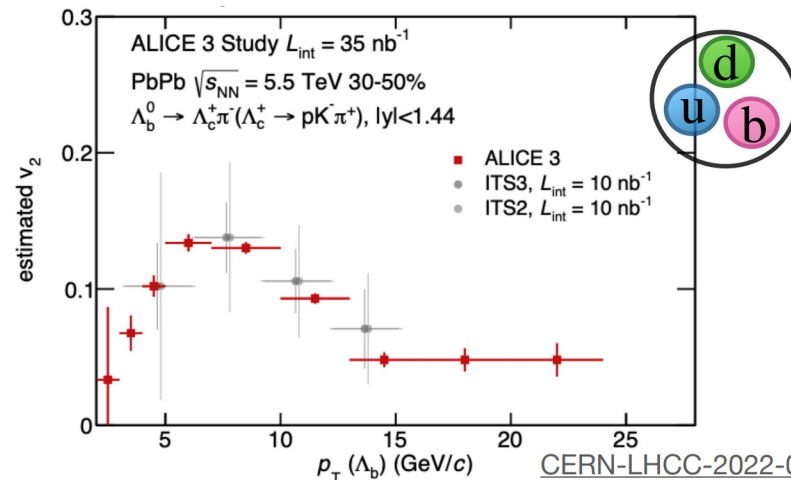
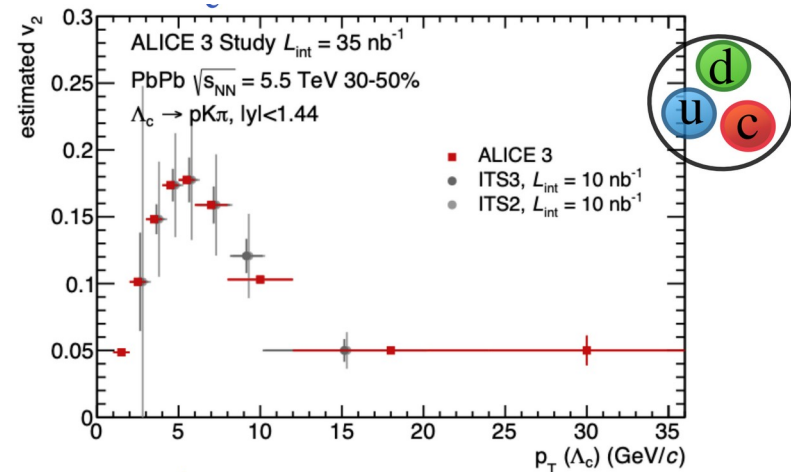


Angular decorrelation of heavy-flavour hadrons

- Direct measurement of momentum broadening in QGP via $D\bar{D}$ correlations

Differential production measurements (flow and R_{AA})

- Heavy-quark transport properties in QGP
- Probe degree of beauty thermalization



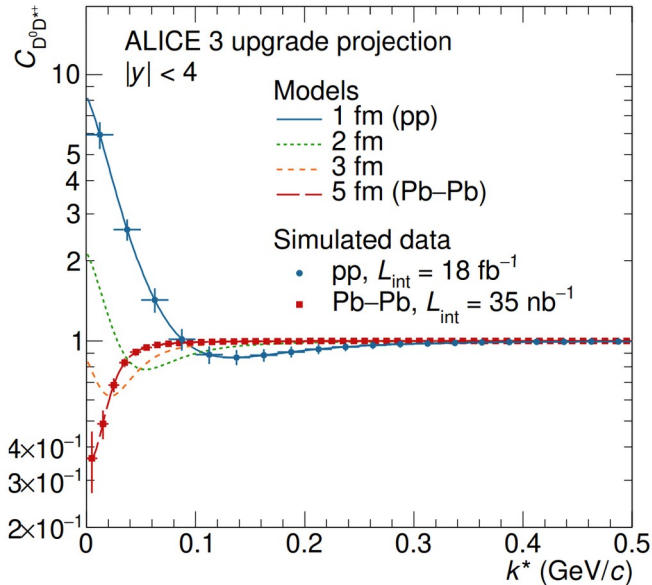
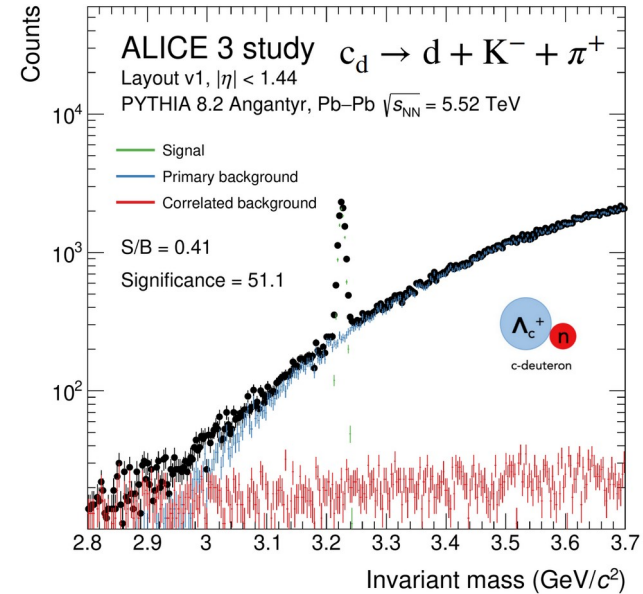
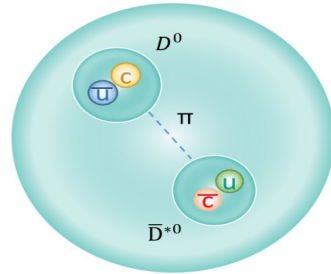
Exotic bound states



Tetraquark (4q)



$D^0 - \bar{D}^{*0}$ molecule



High mass charm-nuclei

- Sensitivity to c-deuteron and c-tritium
- Search for anti-(hyper)nuclei with $A > 5$

Search for DD bound states using femtoscopy

- Unique tests of long range strong interactions
- Nature of exotic states

Many of the questions still to be answered...

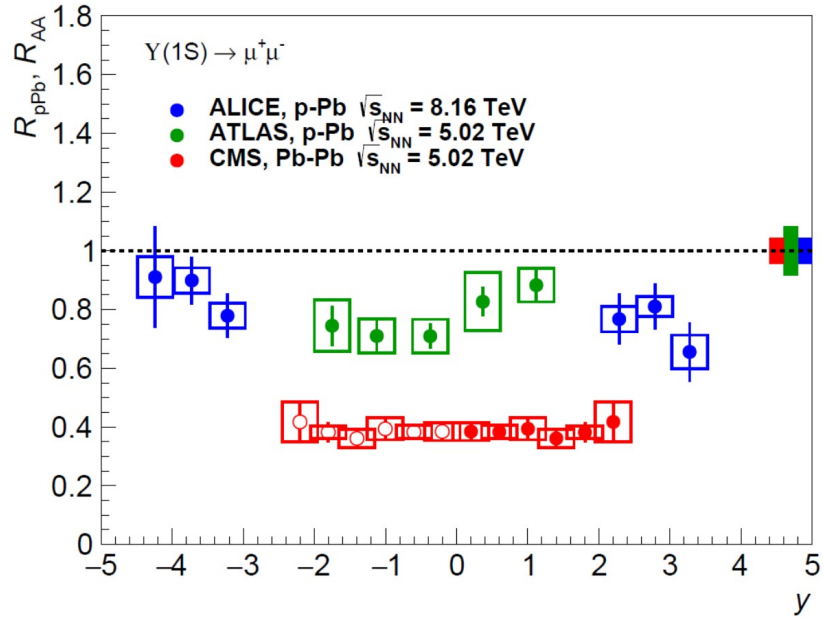


- Heavy quarks offer valuable information on the macro- and microscopic properties of the QGP
- Charm quarks
 - experience significant energy loss
 - thermalize to a very high degree within the plasma
 - Additional effects such as CNM and hadronization play an important role in the interpretation of the data
- Quarkonium production
 - statistical hadronization vs transport models vs open quantum systems
- What is the impact of cold nuclear matter effects
 - Are measurements in p-Pb a good handle to constrain CNMs ?
- Hadronization of heavy quarks plays a big role in the interpretation of the data
 - Better handle needed on baryon and higher mass meson production

Backup

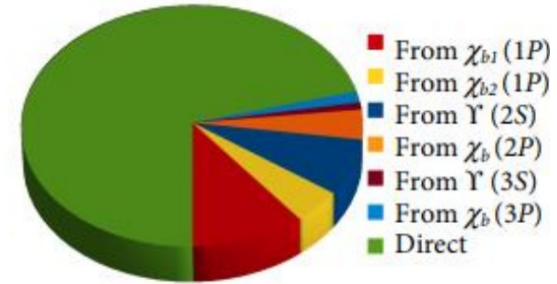


Is $\Upsilon(1S)$ really suppressed ?

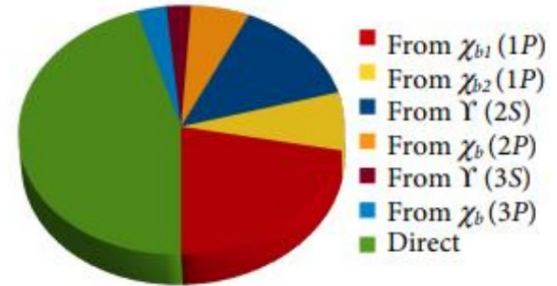


$\Upsilon(1S)$ suppression in p-Pb

- Non-negligible CNM effects on $\Upsilon(1S)$: gluon shadowing
- Feed-down contribution of 30-55% from higher mass, less bound bottomonia



(a) Low P_T $\Upsilon(1S)$

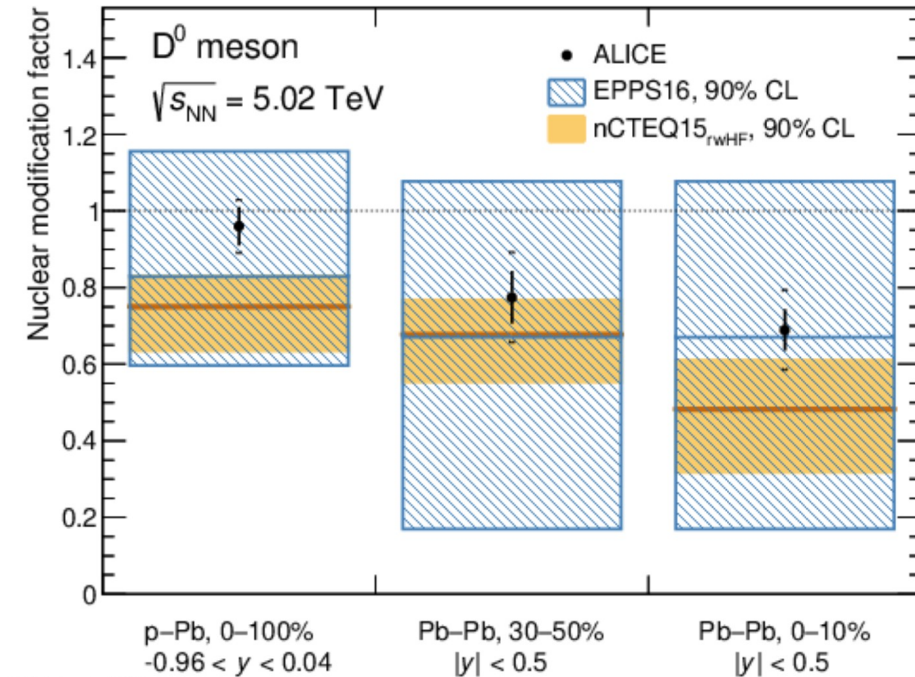


(d) High P_T $\Upsilon(1S)$

Cold nuclear matter effects for D mesons



ALICE, PLB839 (2023) 137796



ALI-PUB-501940

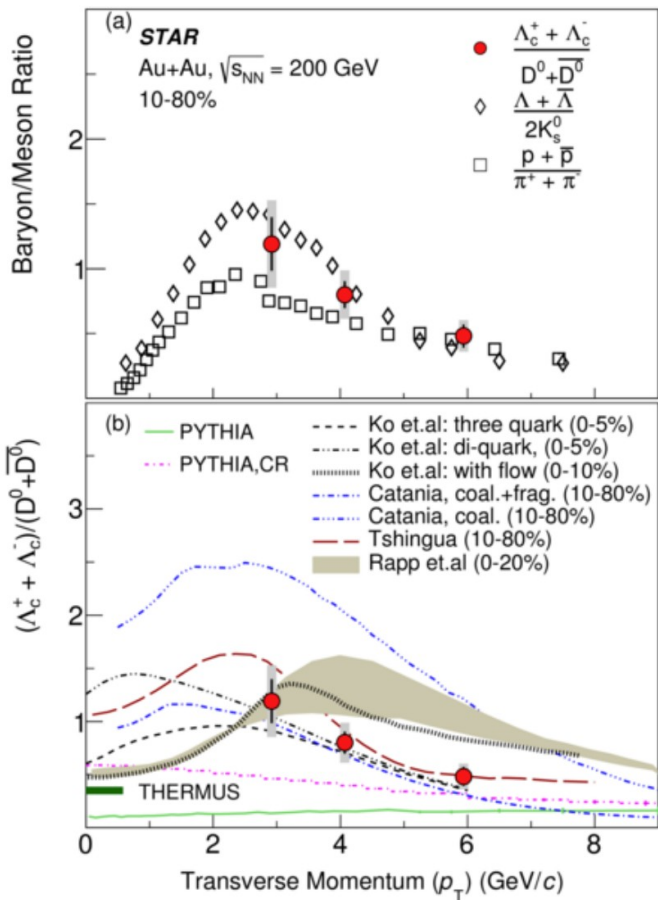
p_T -integrated D^0 meson R_{AA}

- About 30% observed suppression in central Pb-Pb
- Consistent with calculations based on nuclear gluon PDFs
 - But large uncertainties

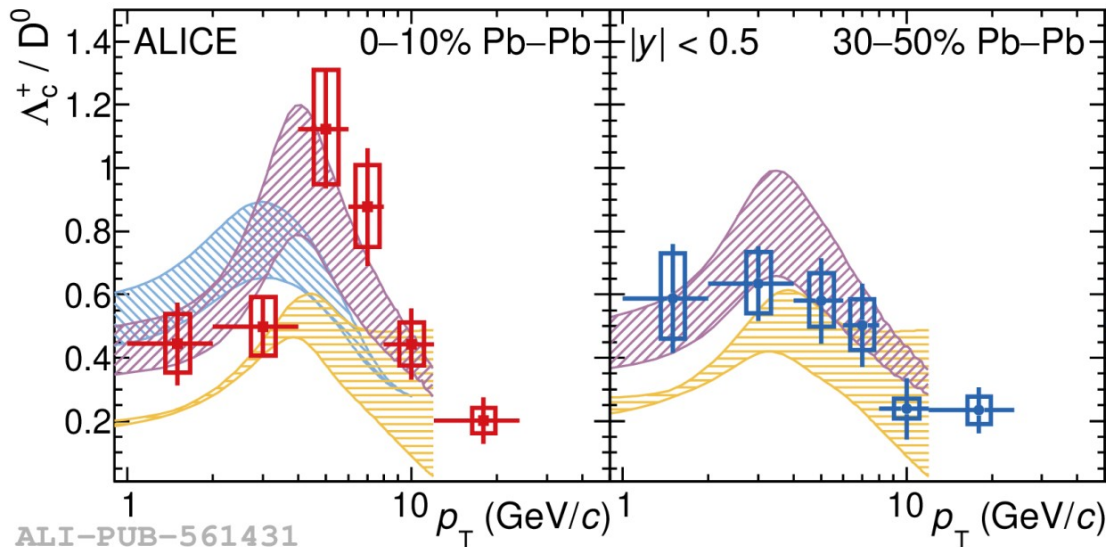
Charmed baryon/meson ratios



STAR, PRL124 (2020) 172301



ALICE, PLB839 (2023) 137796

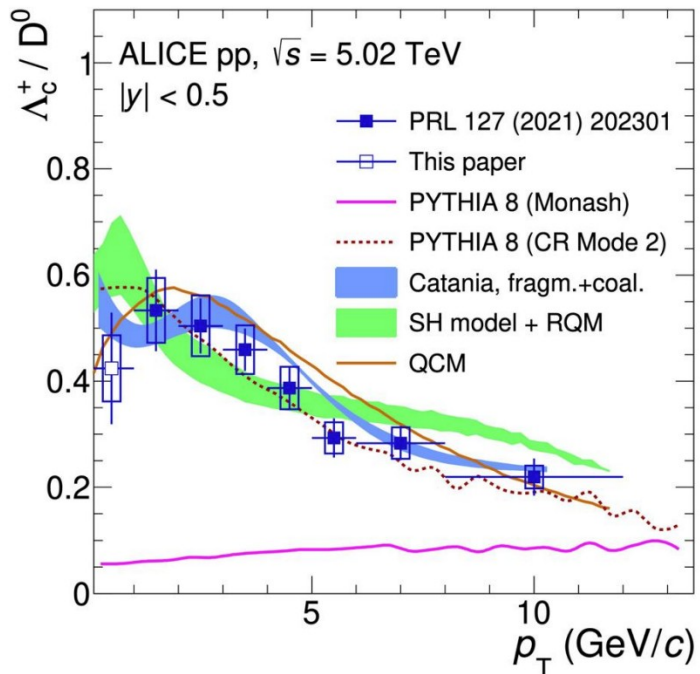


- Charmed baryon/meson ratio similar to light hadrons
- Significantly higher than usual PYTHIA
- Possibly features also centrality dependence

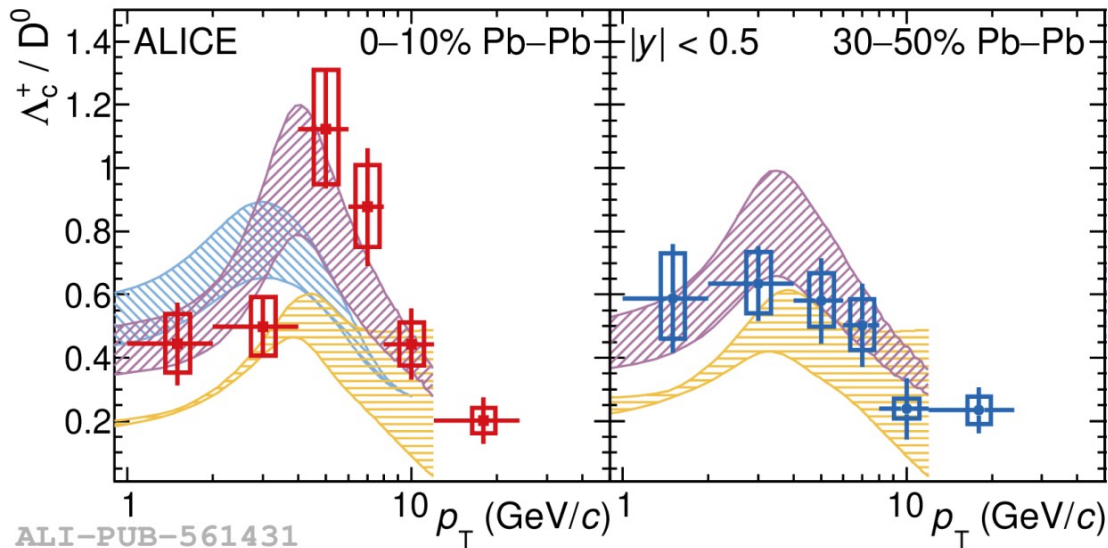
Charmed baryon/meson ratios



ALICE, PRC107 (2023) 064901



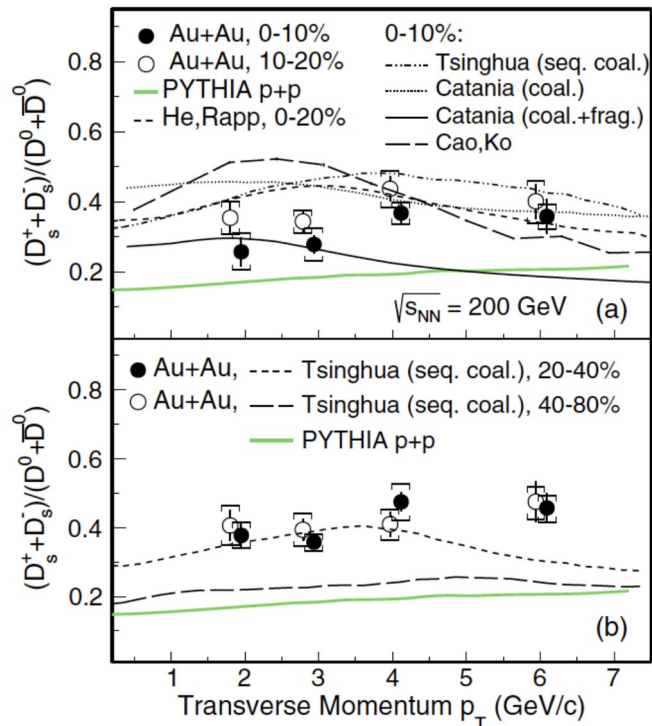
ALICE, PLB839 (2023) 137796



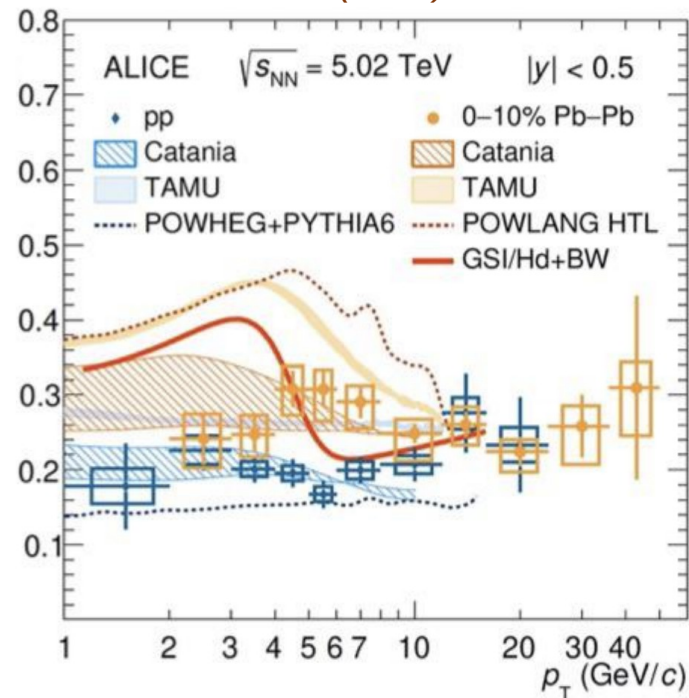
- Charmed baryon/meson ratio similar to light hadrons
- Significantly higher than usual PYTHIA
- Possibly features also centrality dependence
- Semi-central ratio in agreement with pp ratio

D_s / D^0 ratio

STAR, PRL127 (2021) 092301



ALICE, PLB827 (2022) 136986

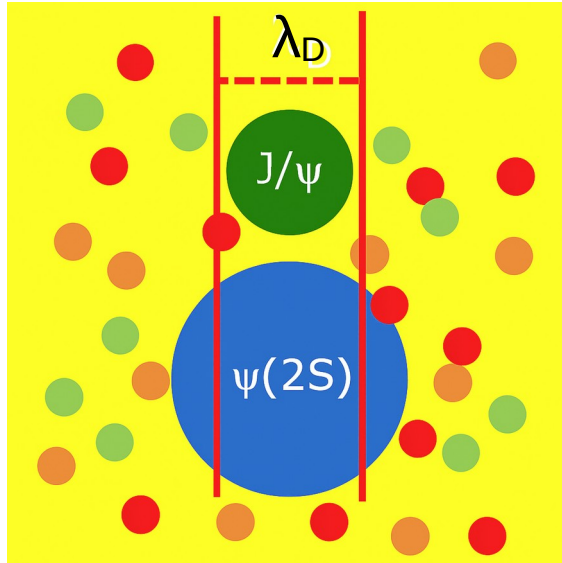


- D_s / D^0 ratio is larger in AA than in pp
 - Strangeness enhancement in the QGP + coalescence
- Together with the modifications of the baryon/meson ratio, this highlights the need for higher precision understanding of the most abundant charm hadron species

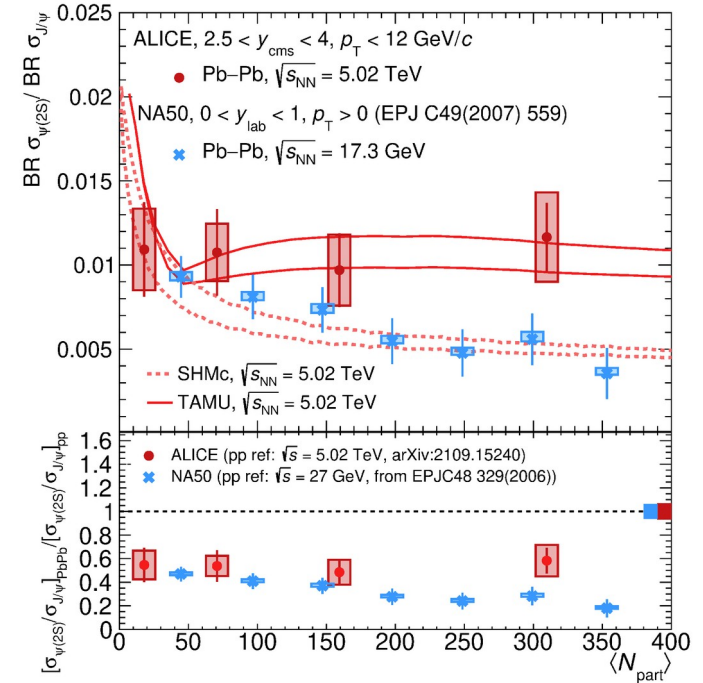
Production of excited charmonia at the LHC: $\psi(2S)$



ALICE, PRL 132 (2024) 042301



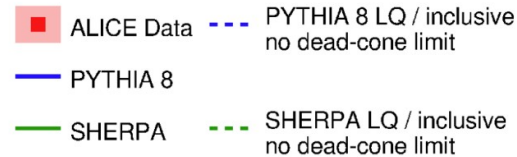
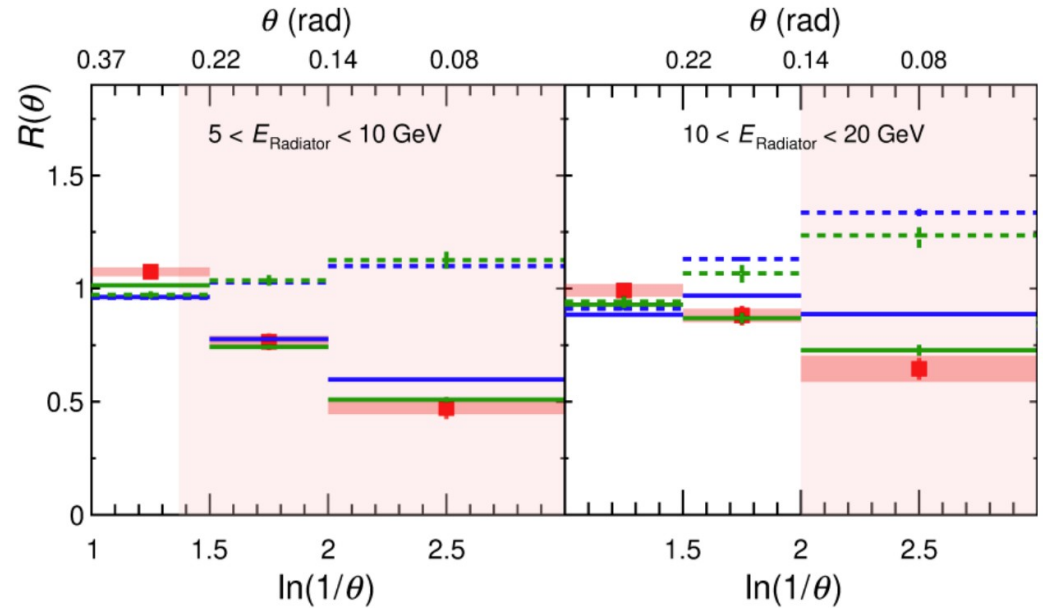
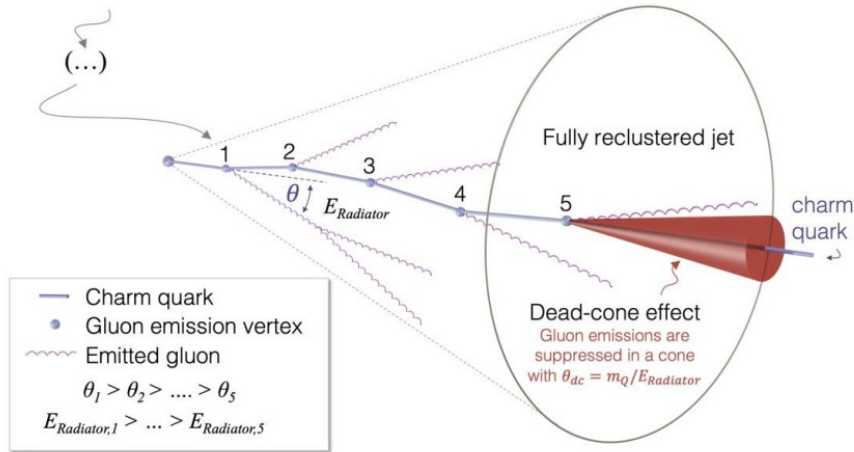
- Much lower binding energy: ~ 60 MeV
- Stronger dissociation effects (already seen at SPS)
- Recombination effects could be important also for $\psi(2S)$, especially when the system is more diluted, at later times



ALI-PUB-568299

First indication of $\psi(2S)$ / J/ψ ratio deviating from thermal expectation

Observation of the “Dead-cone” effect



First observation of the dead-cone effect in jets containing a D-meson

ALICE, Nature 605 (2022) 440