Probing the Quark-Gluon Plasma with Heavy Flavor

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Outline

- Introduction
  - The strong interaction and the quark-gluon plasma
  - High-energy heavy-ion collisions
- Open heavy-flavor production
  - pp : pQCD benchmark and reference
  - p-A : Cold nuclear matter effects
  - A-A : Hot nuclear matter effects
- Quarkonia ($Q\bar{Q}$ bound state)
  - The J/Ψ puzzle: dissociation and regeneration
  - ϒ states and the “sequential melting”

Elecromagnetism vs. strong force

- **Quantum-electrodynamics (QED):**
  - Abelian U(1) gauge theory
  - Generator ~ photon

interaction

massive field (e)

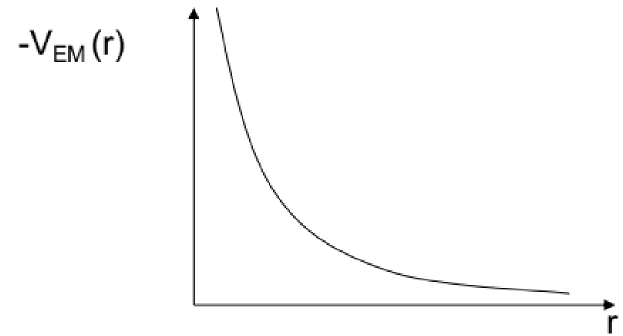
$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$D_{\mu} \equiv \partial_{\mu} + ieA_{\mu}$$

$$F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$$

gauge field (photon)

Effective potential $V_{EM}(r) \sim -\alpha/r$



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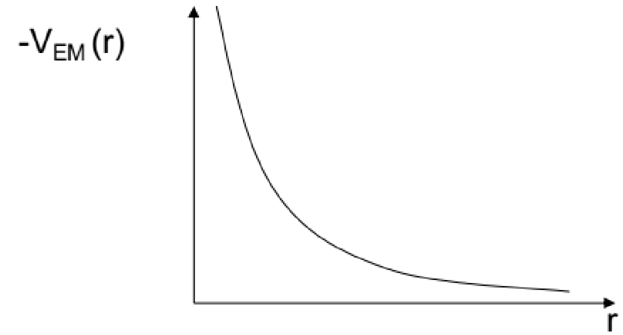

- **Quantum-chromodynamics (QCD):**
  - Non-abelian SU(3) gauge theory
  - 8 independent generators ~ 8 gluons
  - **gluon: color charge, self-interaction**

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i\left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij}\right)\psi_j - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu}$$

$$G^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g f^{abc}\mathcal{A}^b_\mu \mathcal{A}^c_\nu\,,$$

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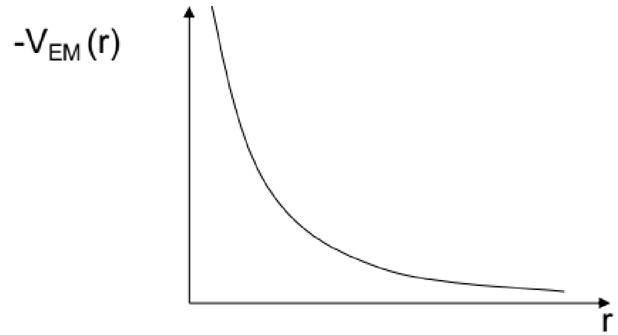

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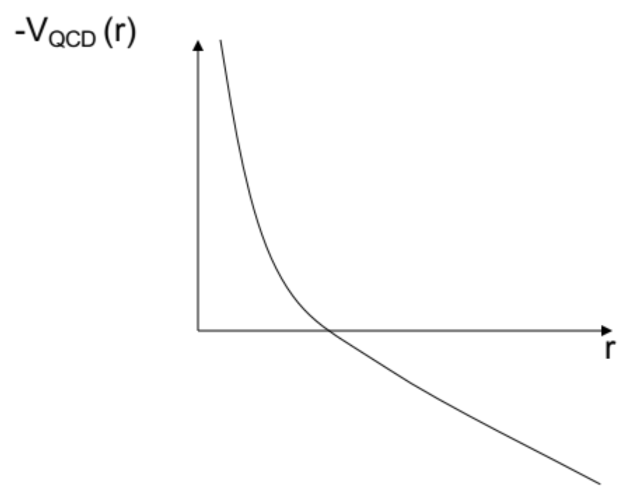
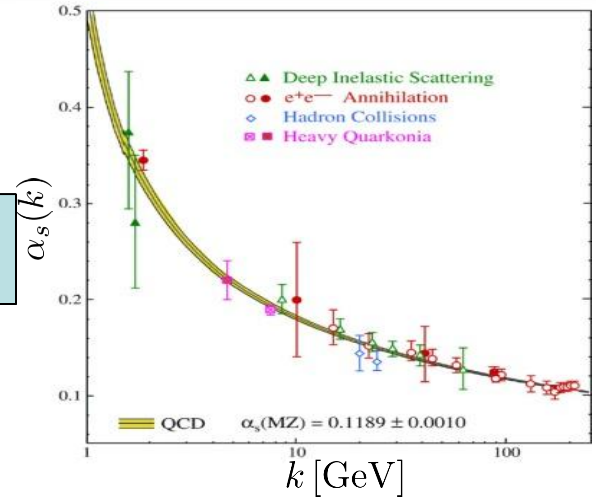


The dual nature of the strong force

- **Running coupling constant**

$$\alpha_s(k^2) \stackrel{\text{def}}{=} \frac{g_s^2(k^2)}{4\pi} \approx \frac{1}{\beta_0 \ln\left(\frac{k^2}{\Lambda^2}\right)},$$

k: momentum transfer
Λ~200 MeV: QCD scale parameter



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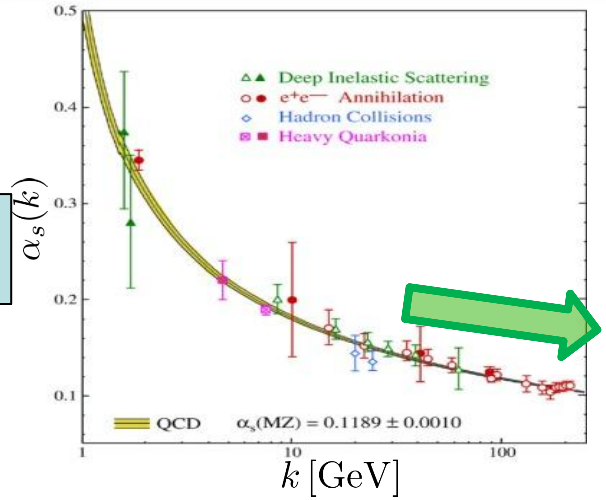
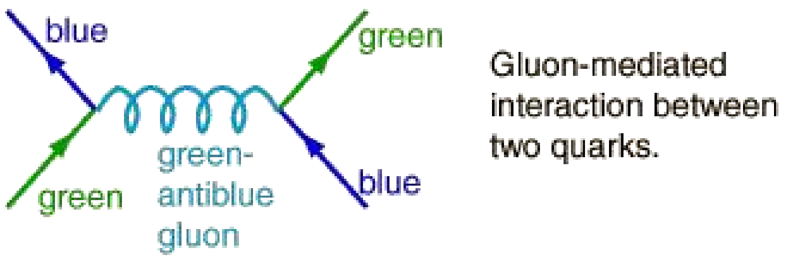


- **Asymtotic freedom** $k \gg \Lambda$
  - "Hard" partons interact
  - Perturbative calculations applicable



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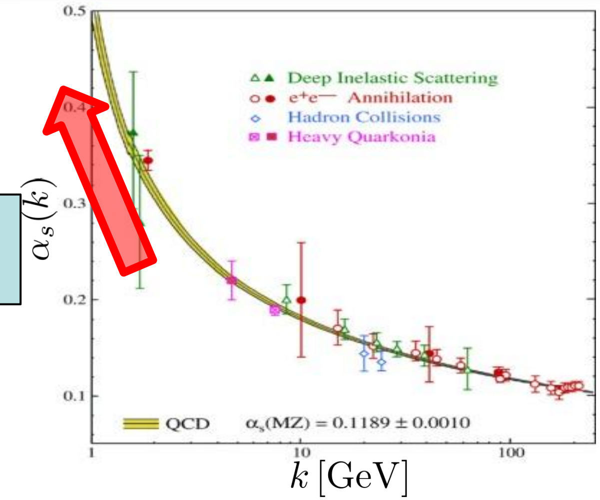

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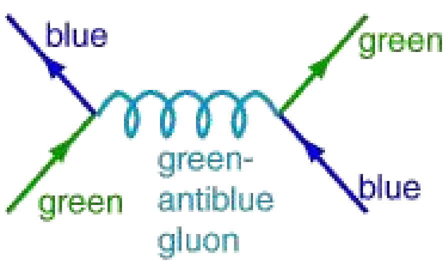
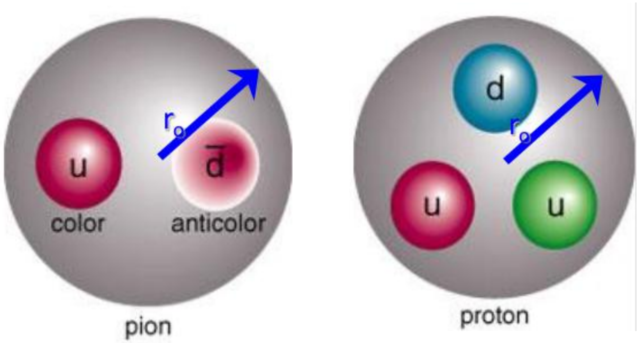


Gluon-mediated interaction between two quarks.

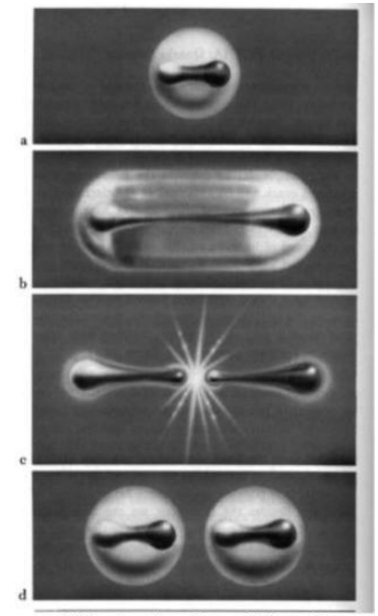
- **Quark confinement** $k \lesssim \Lambda$
  - meson ($q\bar{q}$), baryon (qqq)
  - **Not accessible analytically**
  - Lattice QCD
  - Effective models: bag, string, hydro...



Fragmentation and jets

Quarks escaping from each other

- Linear potential, "string": $U \sim \sigma r$ ($\sigma \sim 1$ GeV/fm)
- Accumulating energy → creates new $q\bar{q}$ pair



[illustration from Fritzsch]

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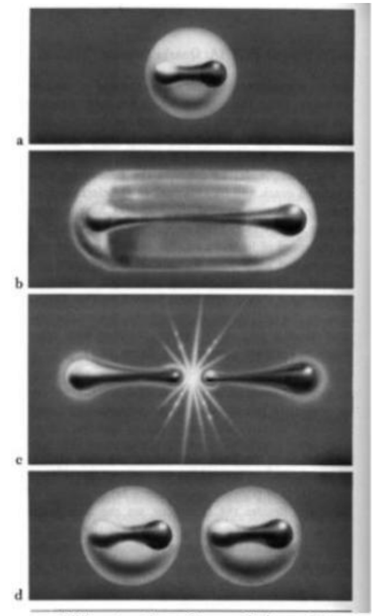
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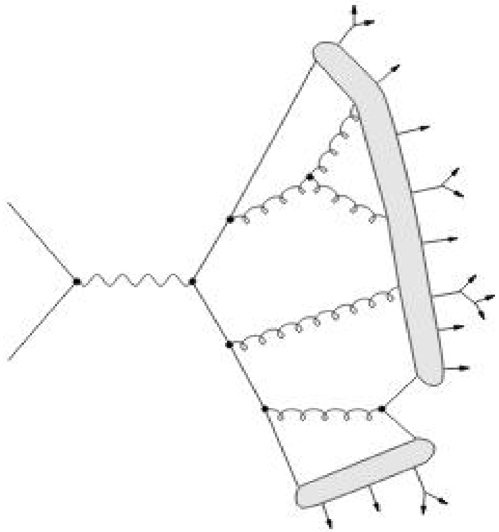
- QCD parton ↔ collimated spray of hadrons



Fragmentation and jets

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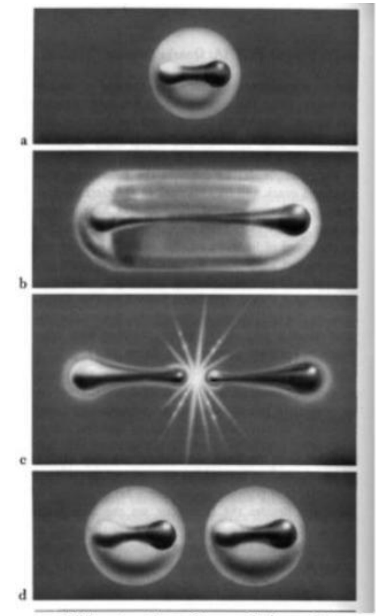

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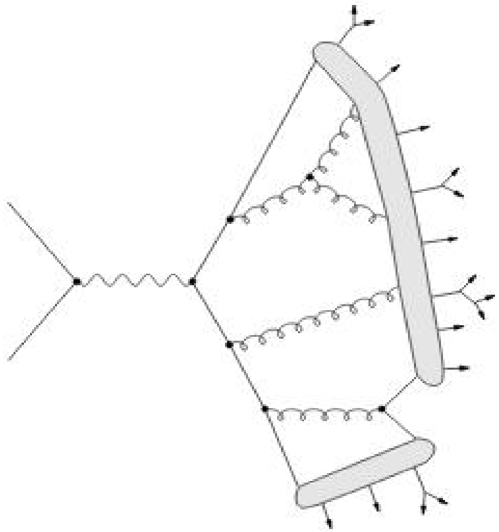
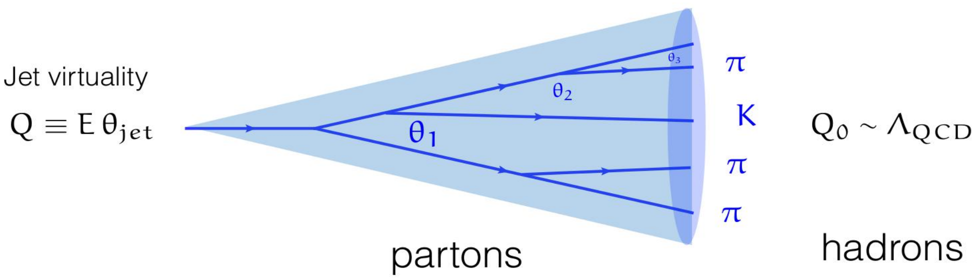




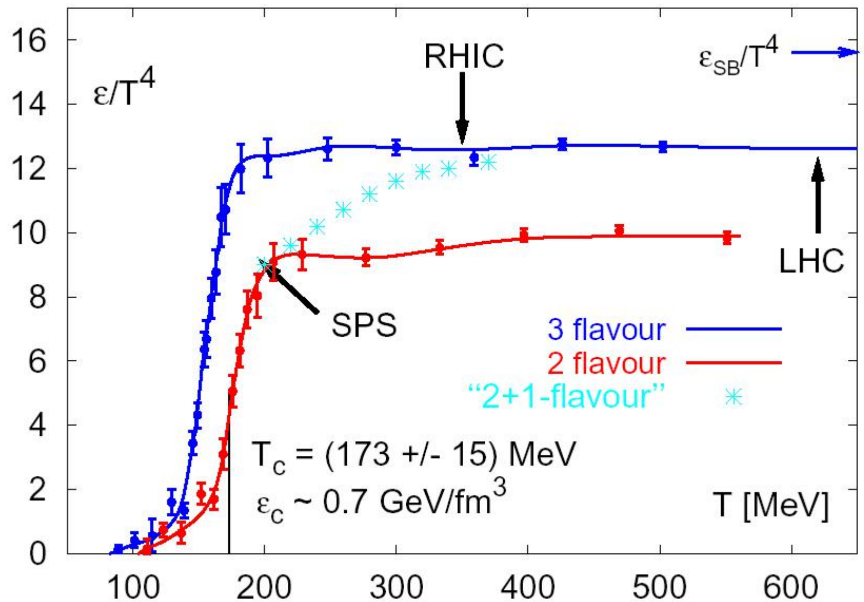
Jet: ~arbitrary definition,

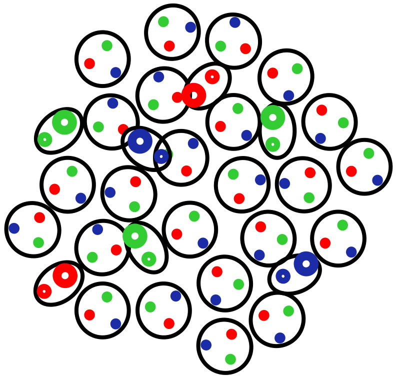
"experiment-theory interface"

Hot, dense nuclear matter: new phase?

- Lattice QCD calculations: hadronic material cannot exist over a certain temperature, energy density

T_c~170 MeV~1.5x10^{12} K $\varepsilon_c \sim 1$ GeV/fm^3





- Phase transition

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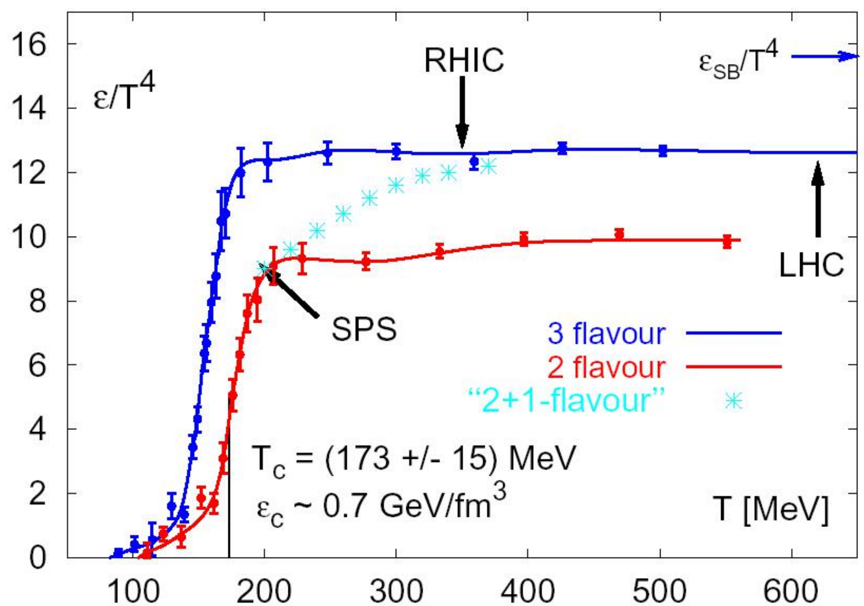
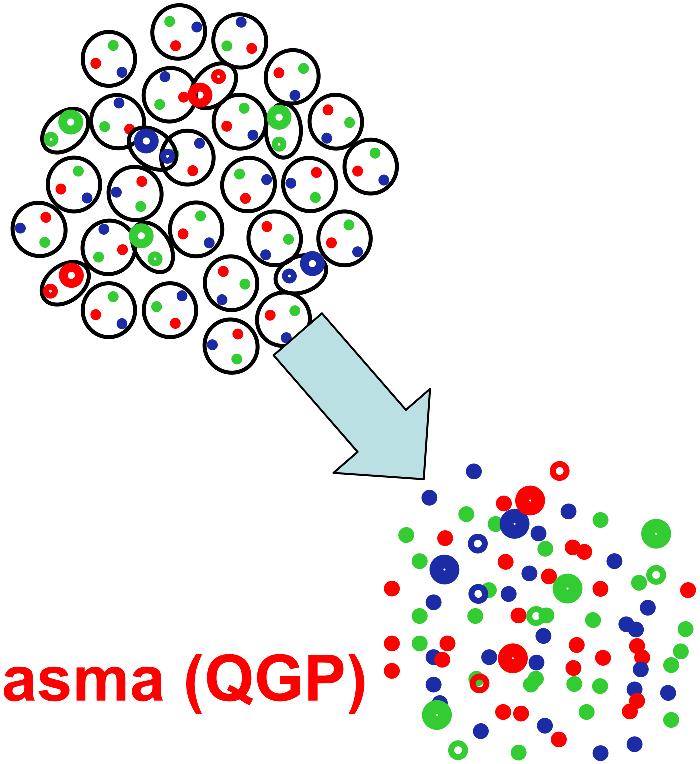
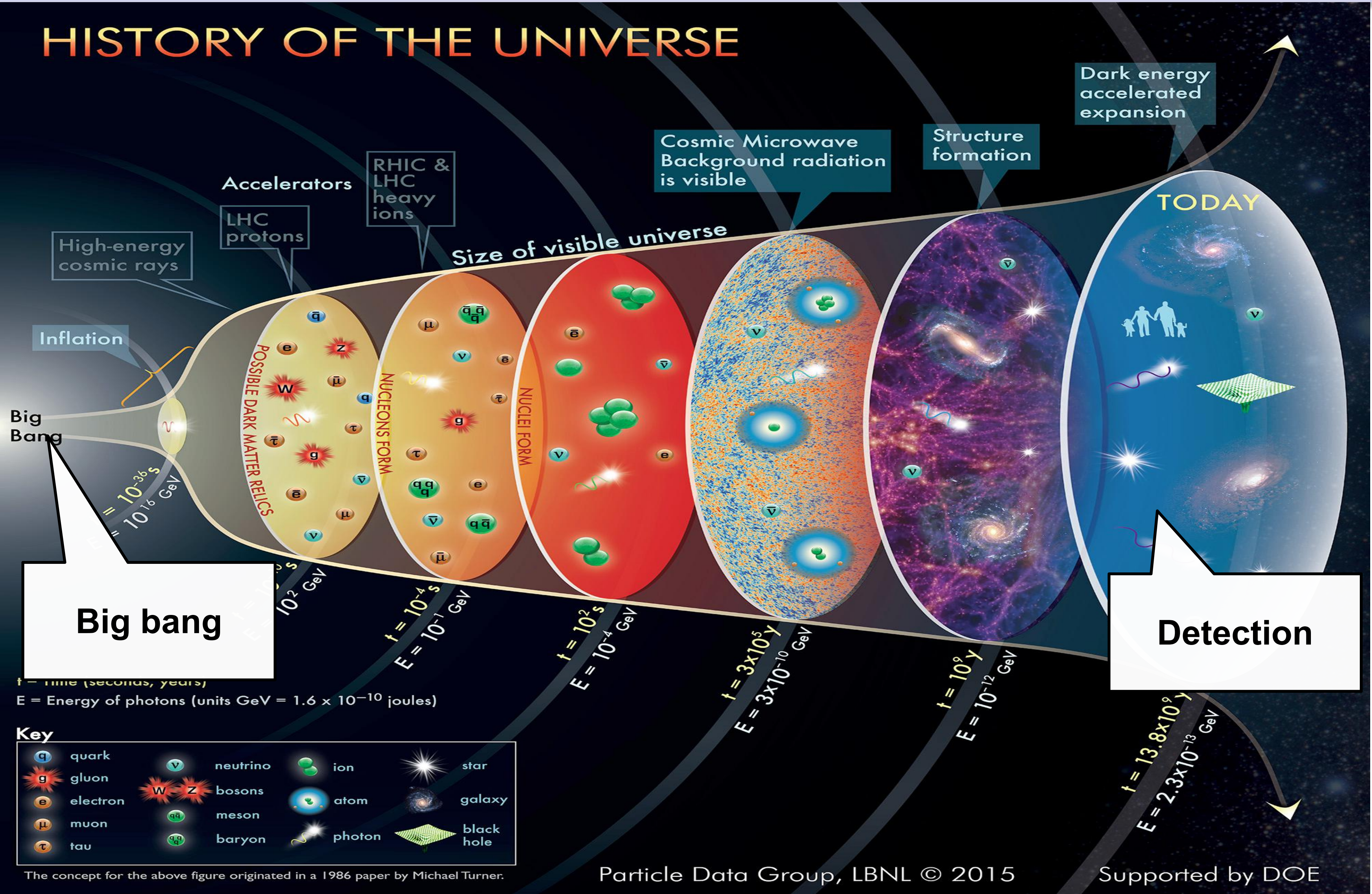


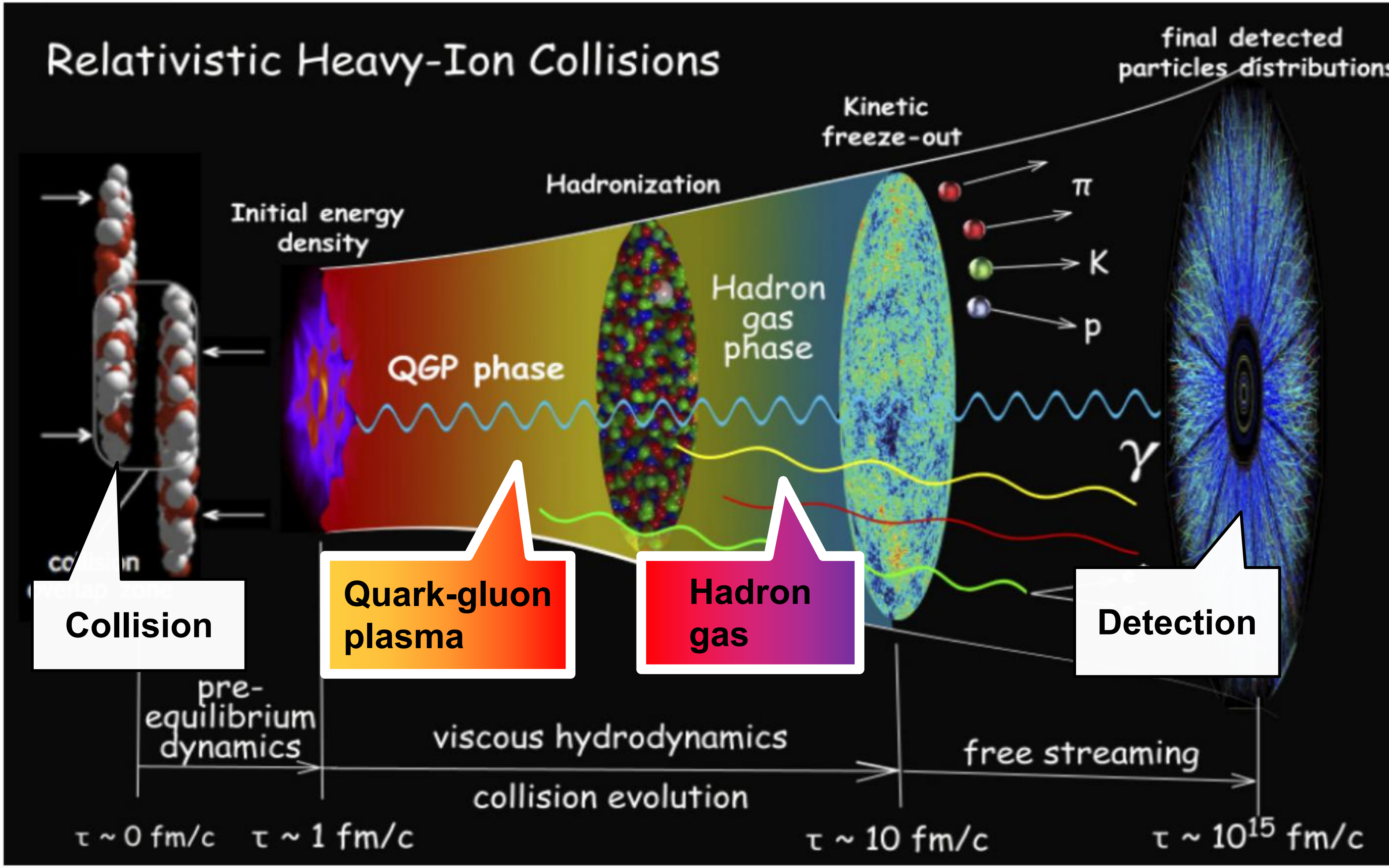


- Phase transition → **Quark-gluon plasma (QGP)**
  - **Does it exist?**
  - **What are its properties?**

It all started with a big bang...

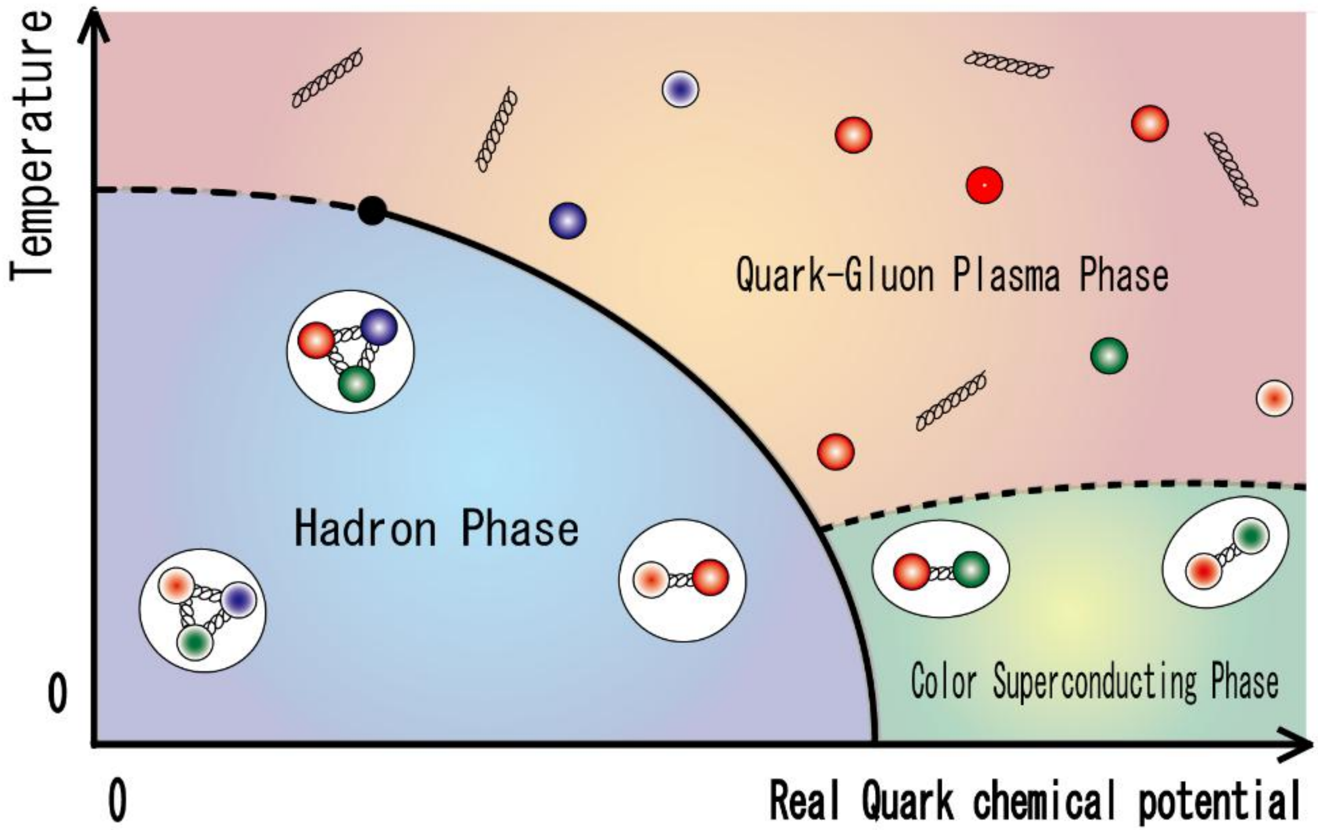


“Little bangs” in high-energy collisions



Courtesy of Paul Sorensen and Chun Shen

The phase diagram of QCD



- Goal: establish the QCD phase diagram

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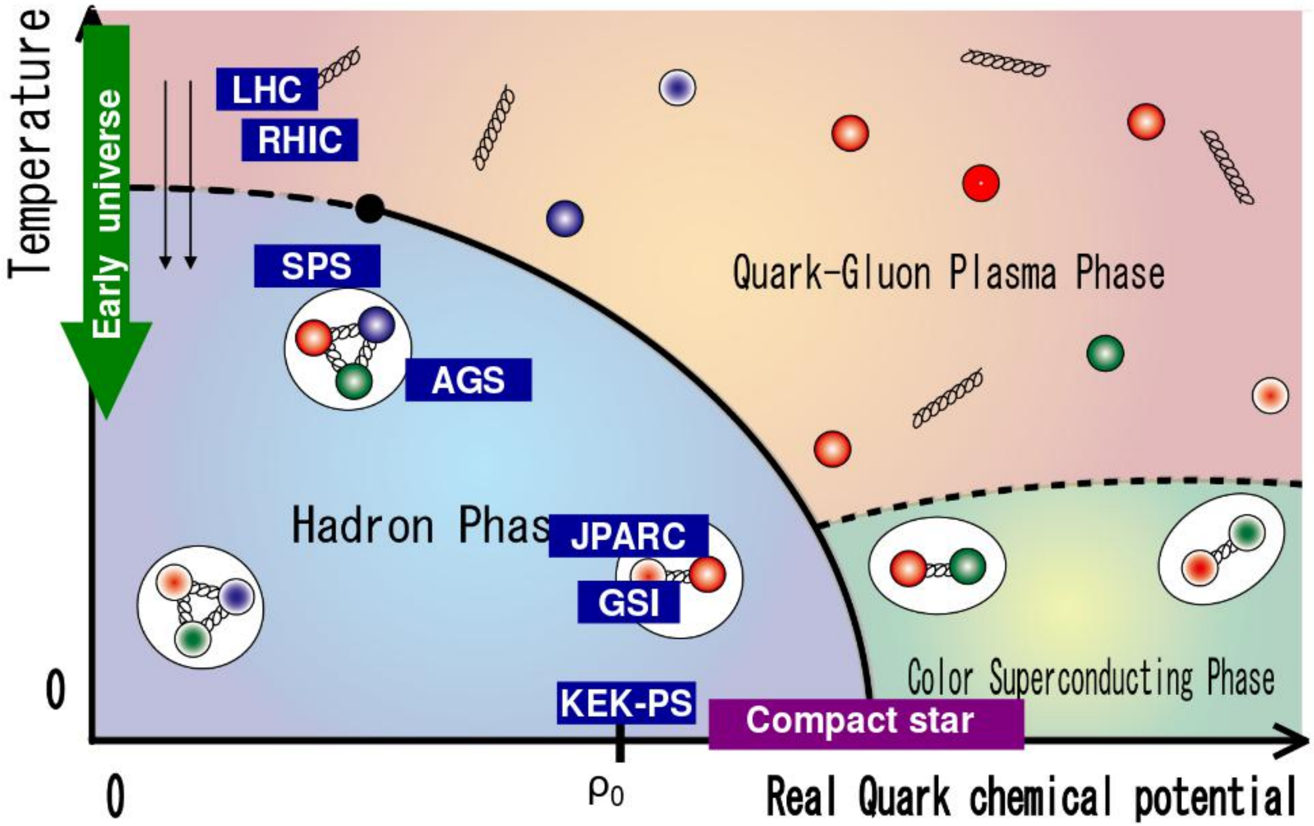


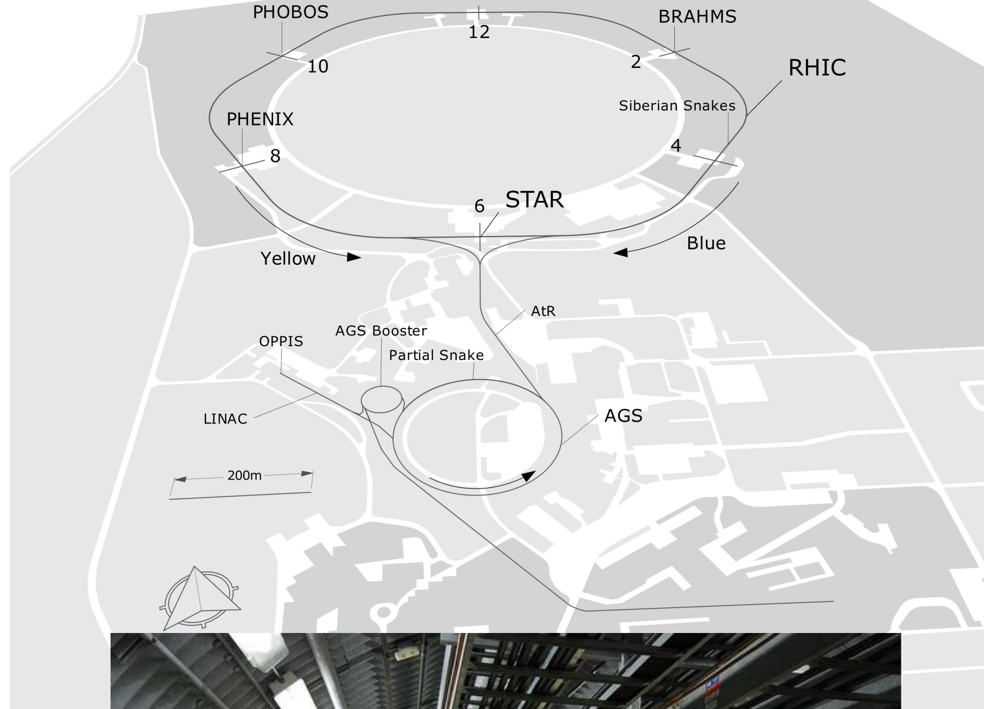
- Goal: establish the QCD phase diagram
  - **Understand the quark-gluon plasma**
  - Do we see the phase transition? Which order is it?
  - Is there a critical point?

Experimental tools and basic concepts

- Accelerators and experiments: RHIC, LHC
- The hard and the soft regimes

RHIC relativistic heavy-ion collider

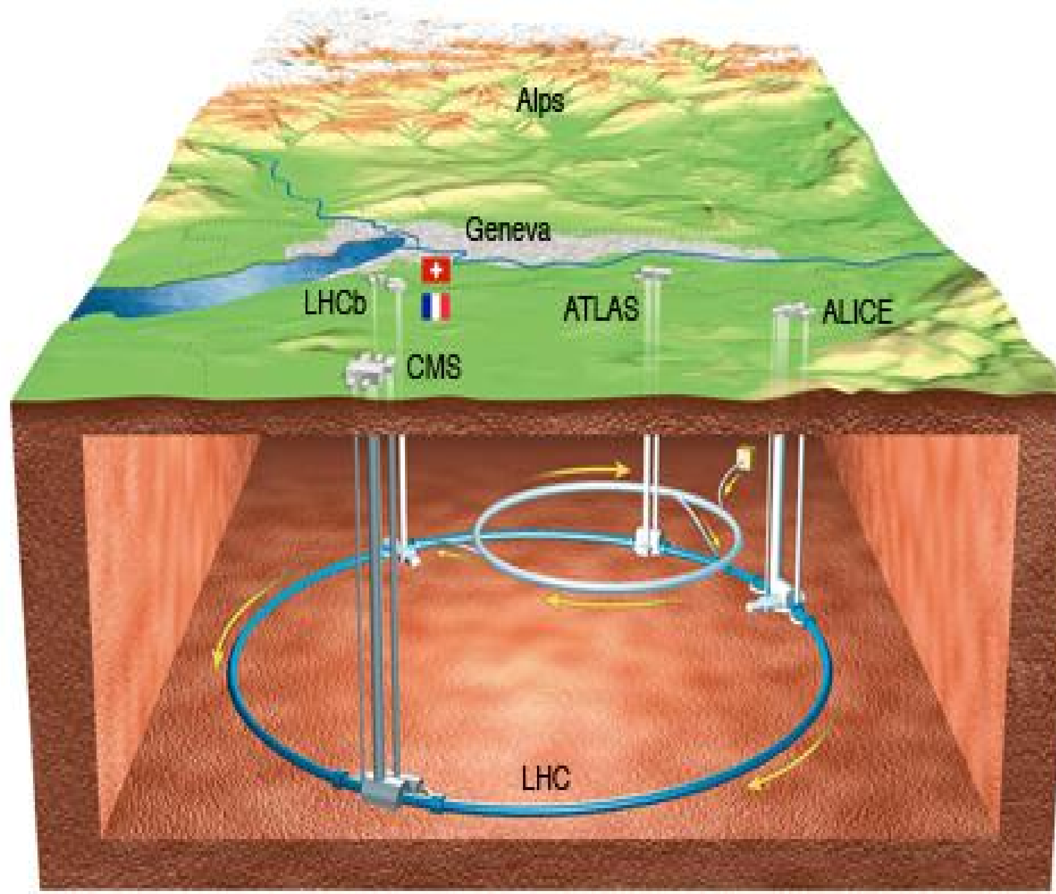
BNL (NY, USA)



- Two synchrotron rings 3,6 km long
- Extremely versatile
  - Au, Cu, U, d, ^{3}He, p
  - polarized protons (→ spin physics)
  - Asymmetric setups
- Broad energy range
  - **p+p:** **$\sqrt{s}$ = 62 - 500 GeV**
  - **Au+Au:** **$\sqrt{s_{NN}}$ = 5.5 - 200 GeV** (fix target: 2.7 GeV)
- Experiments: STAR, sPHENIX, (PHOBOS, BRAHMS)

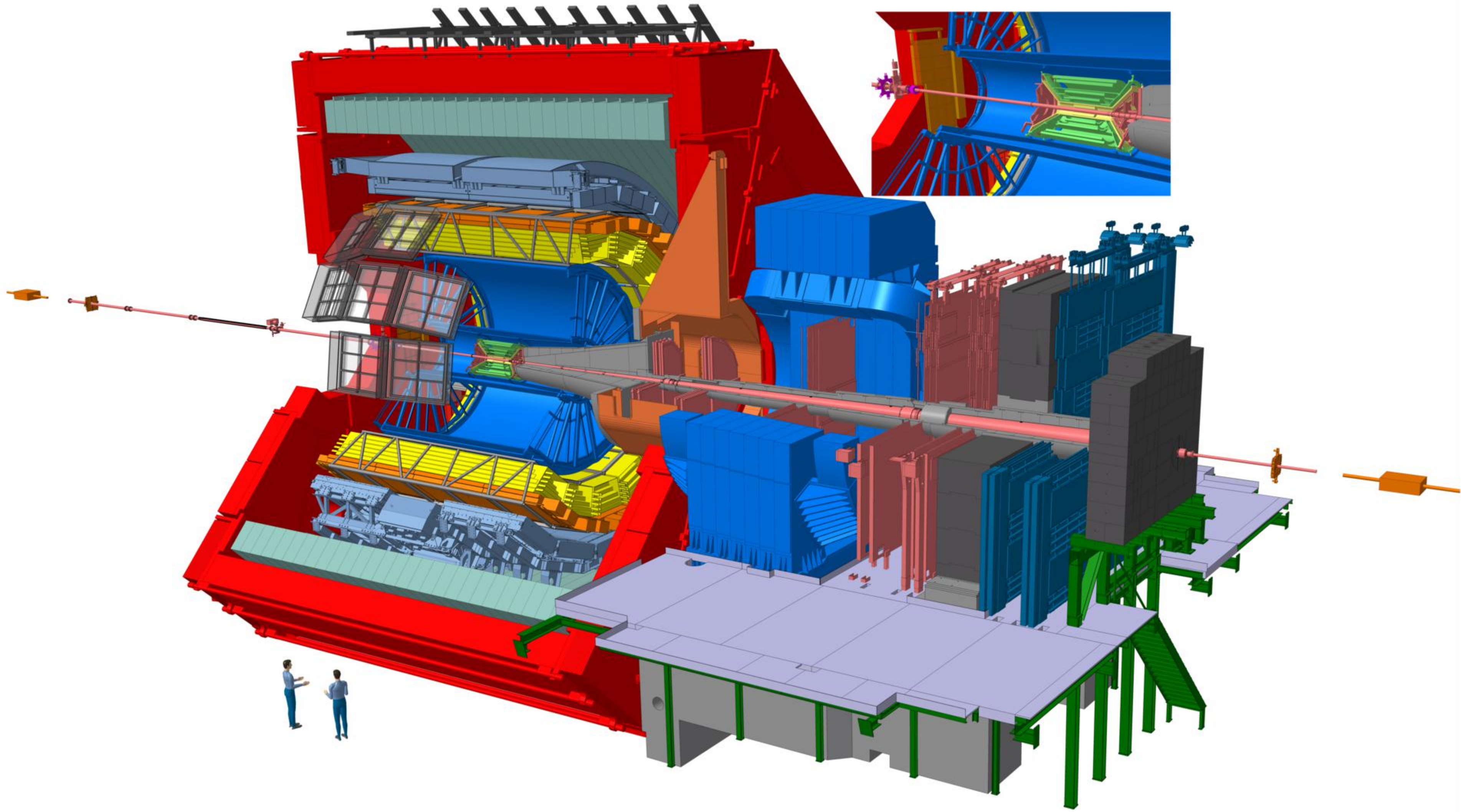
LHC: The Large Hadron Collider

- CERN: European Nuclear Research Centre
- 22 member countries collaborate



- LHC: 27 km long ring
  - Acceleration with electromagnetic field (close to the speed of light)
  - Magnetic field keeps particl on curved track
- Highest energies
  - **pp: $\sqrt{s}$=13.6 TeV**
  - **Pb-Pb: $\sqrt{s_{NN}}$=5.02 TeV**
  - p-Pb, Xe-Xe

ALICE (example detector system)



A dedicated heavy-ion experiment at the LHC, excellent PID

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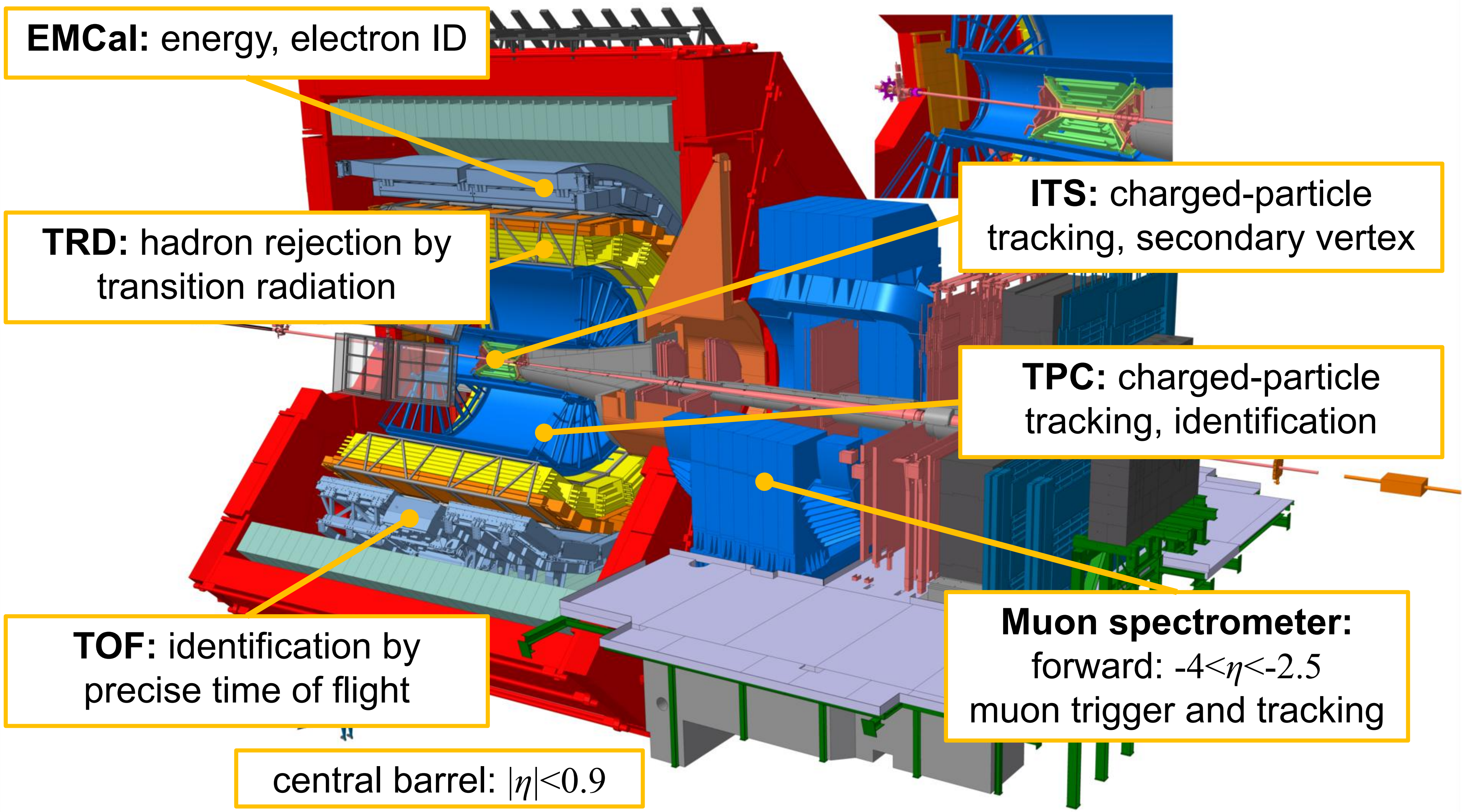

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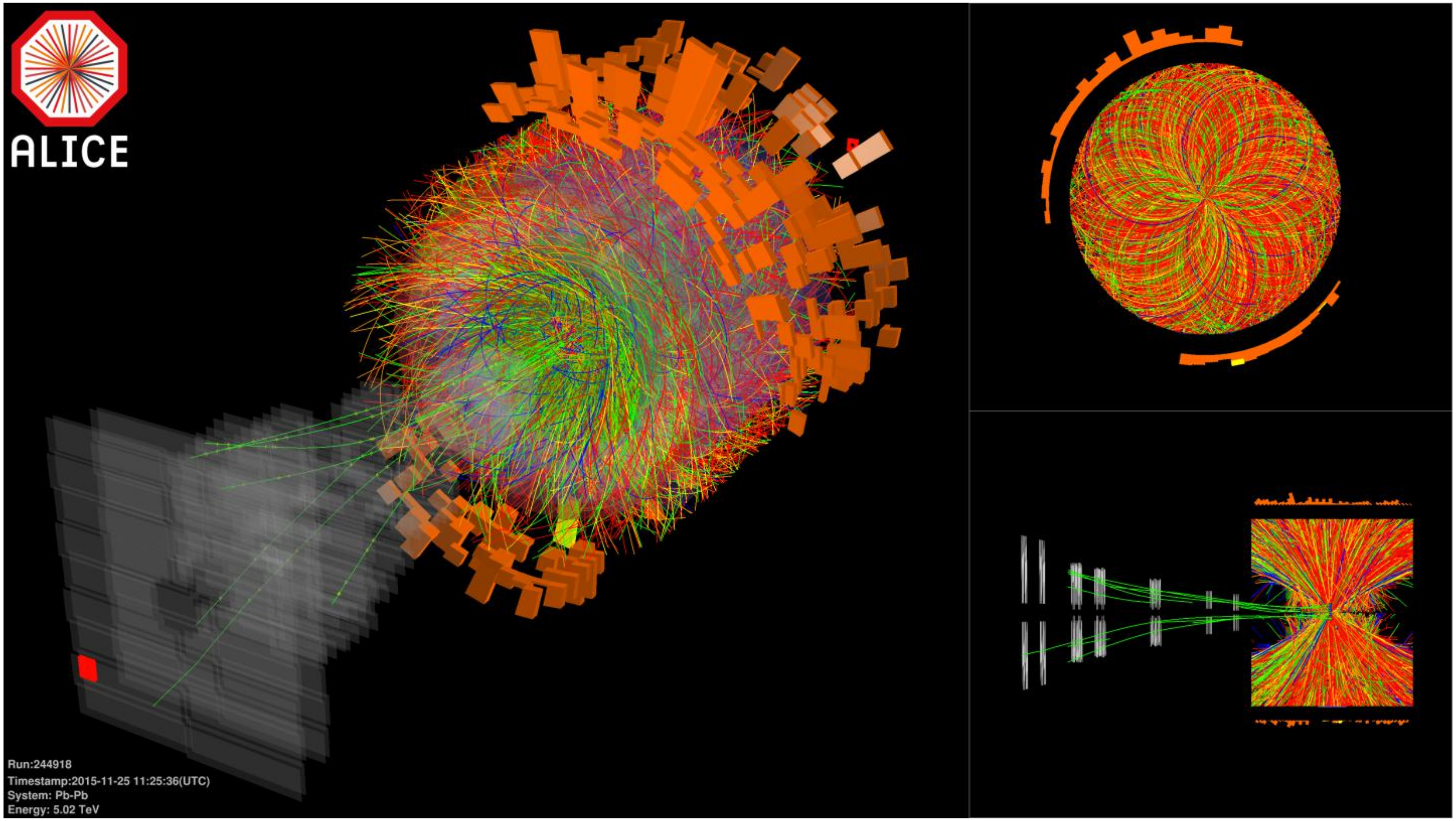
Reconstructed heavy-ion collision



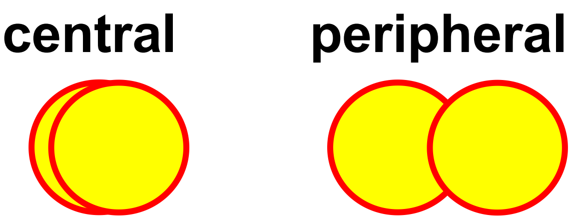
- Up to 600 million events per second
- Signals of up to thousands of particles to be identified, processed
- 2-4 GB data every second

Basic concepts

- Collision energy per nucleon (c.m.s.): $\sqrt{s_{NN}}$
- Centrality

$$c(b) \cong \frac{\pi b^2}{\sigma_{\rm inel}}$$

σ_{inel}: total inelastic cross section
$b<b_{max}$: impact paraméter



- Kinematic variables

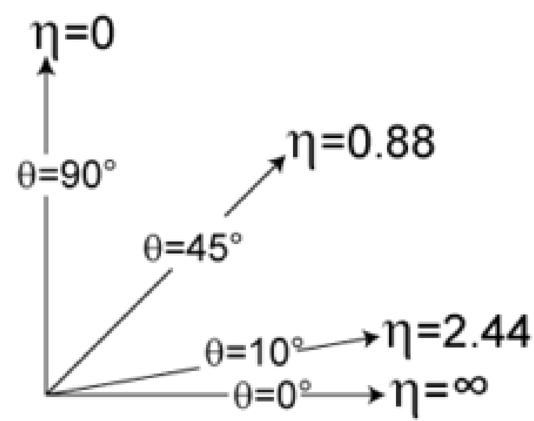
perpendicular to the (x,y) plane - "physics":

- **Transverse momentum**: $p_T = \sqrt{(p_x^2 + p_y^2)}$
- **Azimutal angle:** φ

Boosted in beam direction (z):

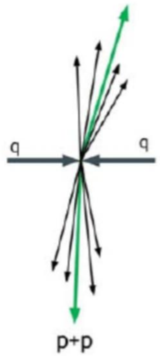
- Rapidity: $y = 0.5 \log \frac{E+p_z}{E-p_z}$
- **Pseudo-rapidity** (η=y if m=0):

$$\eta = 0.5 \log \frac{p+p_z}{p-p_z} = -\ln \tan \frac{\theta}{2}$$



Colliding systems

- **pp:** the QCD vacuum
  - Reference for heavy-ion collisions
  - Perturbative QCD benchmark



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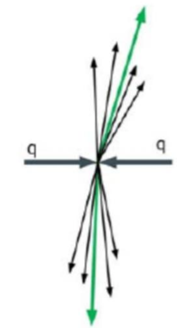
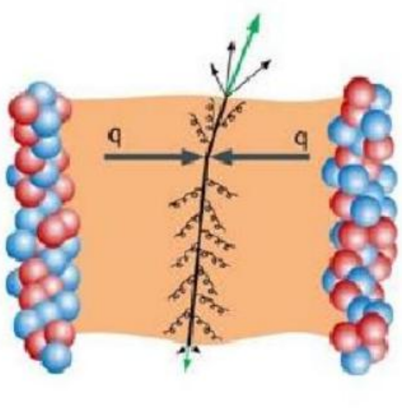


p+p

- **A-A**: "Hot" (+cold) nuclear matter effects
  ("hot": sQGP, but hadronic matter also present)
  - Energy loss in the hot nuclear matter
  - Collective behavior



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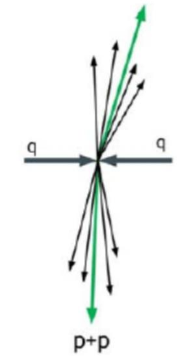
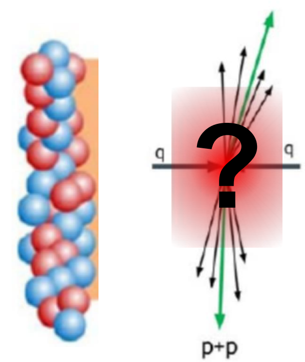


- **p(d)-A**: "cold" nuclear matter effects
  ("cold": mostly or exclusively hadronic)
  - Modification of nPDF, eg. shadowing
  - Effect of the initial state
  - Energy loss in the cold nuclear matter (CNM)



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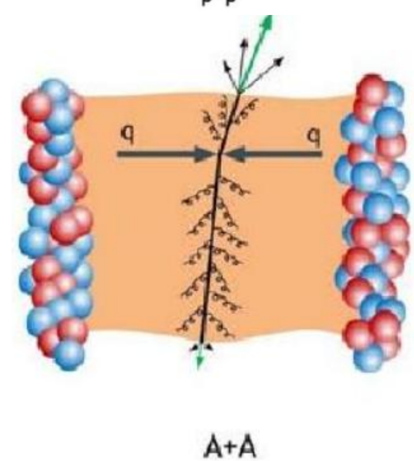
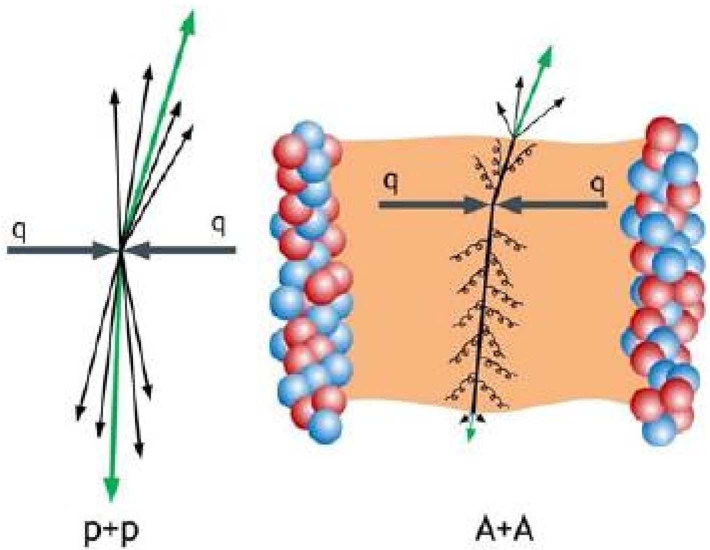


Probes

- **"Hard" processes**
  - few, high-momentum particles
  - early production in well-known pQCD processes
  - high permeability
  - **Tomography of the sQGP, modification in the medium**



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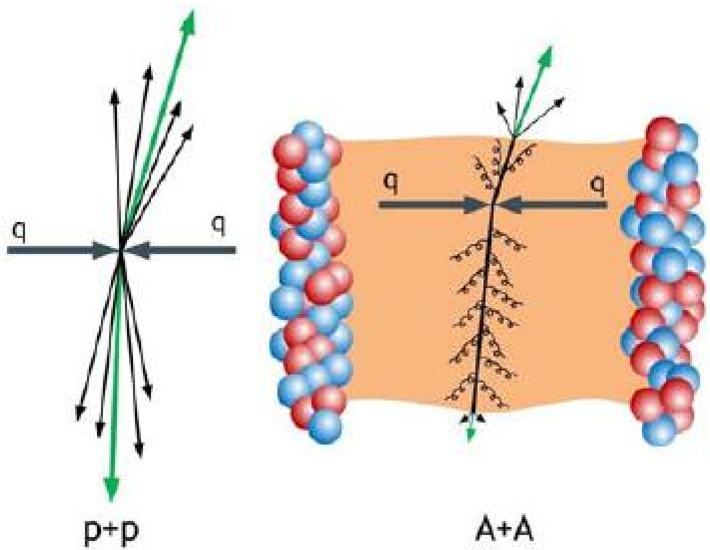

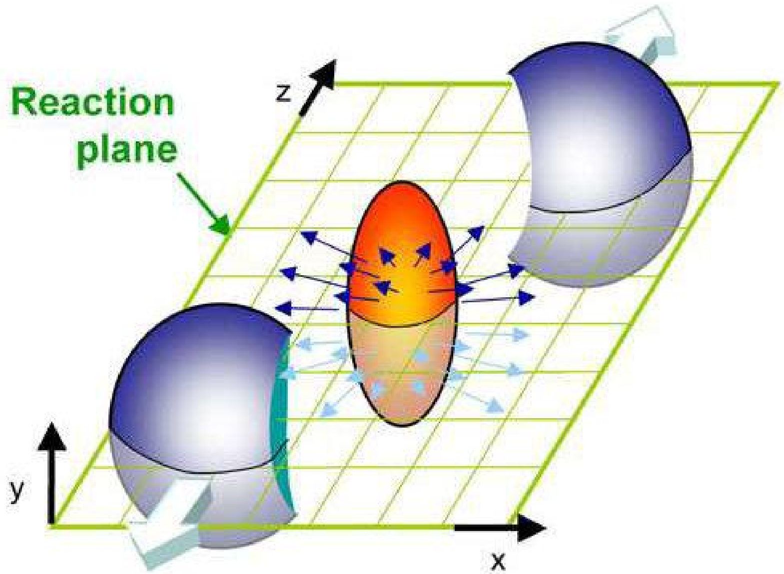

- **"Soft" processes**
  - Many, low-momentum particles
  - From the later stages
  - **Thermal behavior**
  - **Collective dynamics (“flow”)**

Nuclear modification

- Comparing yield in A+A to p-p collisions
- $R_{AA} = 1$: no nuclear effect
- $R_{AA} < 1$: momentum loss in the medium

Yield in heavy-ion collisions

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

Number of binary nucleon-nucleon collisions in heavy-ion reactions

Yield in p-p collisions

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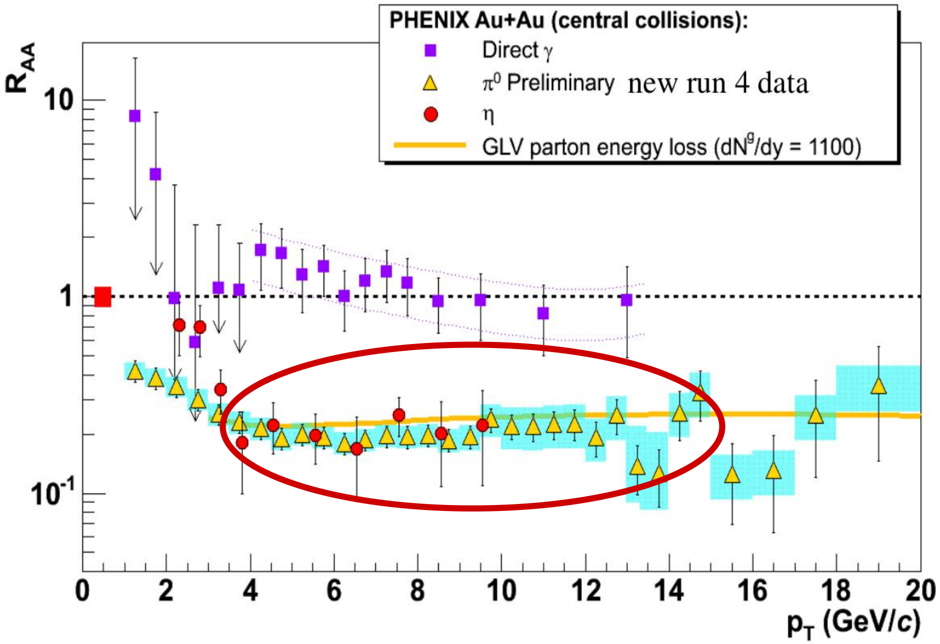

BNL RHIC R_{AA} results NPA 757 (2005)

Gyulassy-Lévai-Vitev model NPB 571 (2000)

- Approximately identical suppression of all light hadrons (R_{AA}^{h}~0.2)

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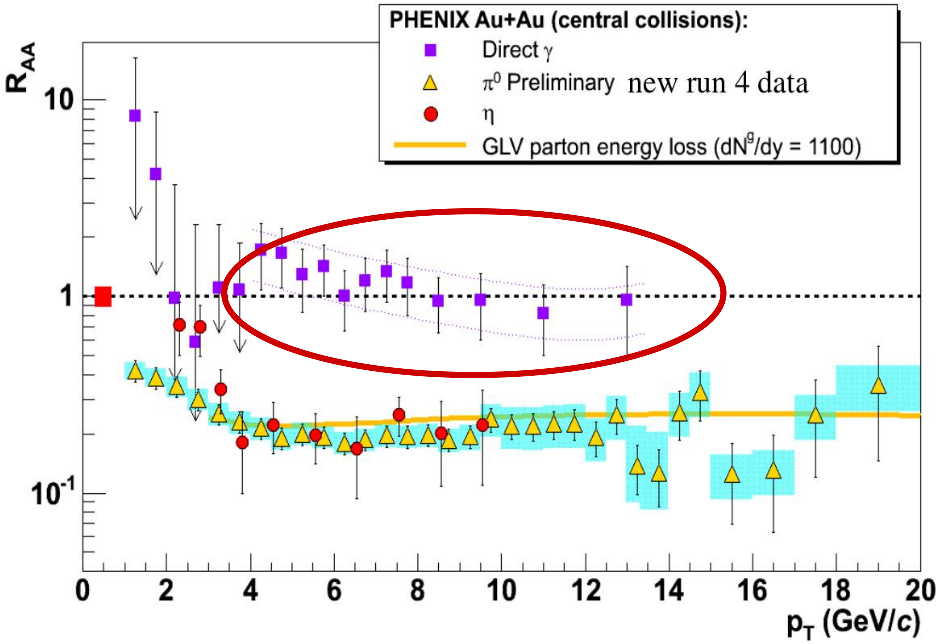
Yield in heavy-ion collisions

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

Number of binary nucleon-nucleon collisions in heavy-ion reactions

Yield in p-p collisions



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Gyulassy-Lévai-Vitev model **NPB 571 (2000)**

- Approximately identical suppression of all light hadrons ($R_{AA}{}^{h} \sim 0.2$)
- No quenching of photon production ($R_{AA}{}^{\gamma} \sim 1$)
  - The medium is transparent for the EM radiation

Nuclear modification

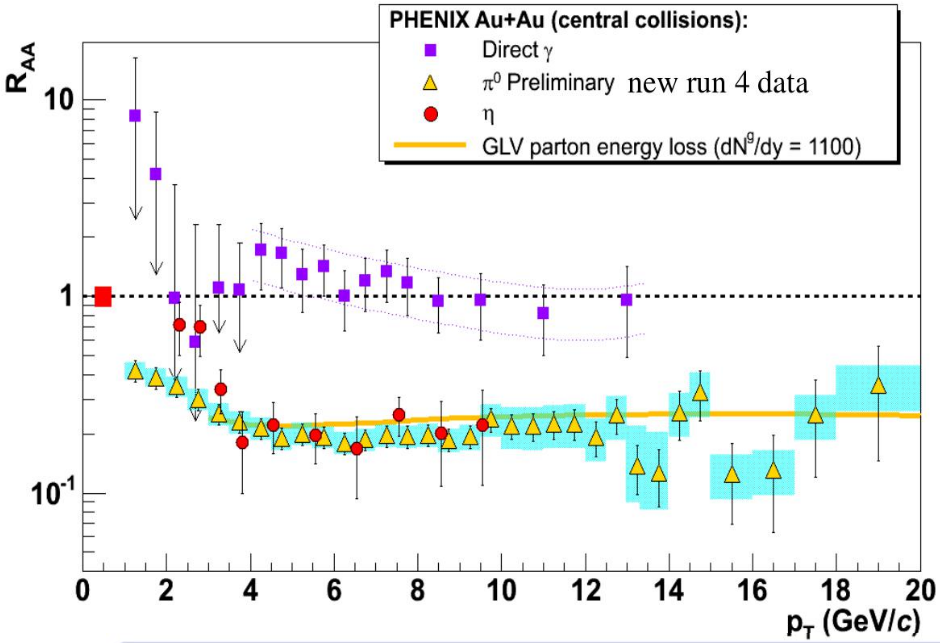
- Comparing yield in A+A to p-p collisions
- R_{AA} = 1 : no nuclear effect
- R_{AA} < 1 : momentum loss in the medium

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

Yield in heavy-ion collisions

Number of binary nucleon-nucleon collisions in heavy-ion reactions

Yield in p-p collisions



BNL RHIC R_{AA} results NPA 757 (2005)

Gyulassy-Lévai-Vitev model NPB 571 (2000)

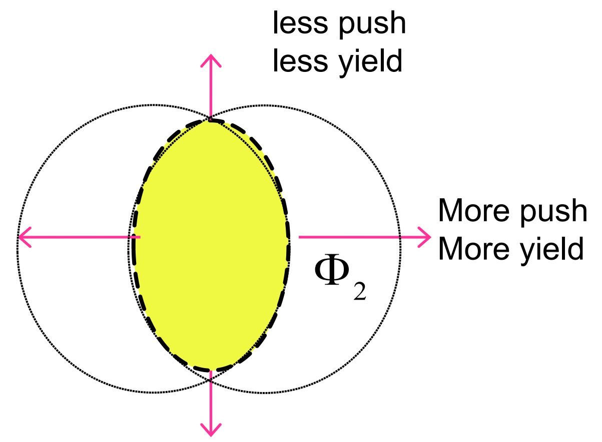
- Approximately identical suppression of all light hadrons ($R_{AA}{}^{h}$~0.2)
- No quenching of photon production ($R_{AA}{}^{\gamma}$ ~ 1)
  - The medium is transparent for the EM radiation

First convincing evidence of the strongly interacting QGP

Azimuthal anisotropy

- Momentum-distribution is cyclic ("elliptic flow")

$$\frac{dN}{d\phi} \approx 2v_2 \cos(\phi - \Phi_1)$$



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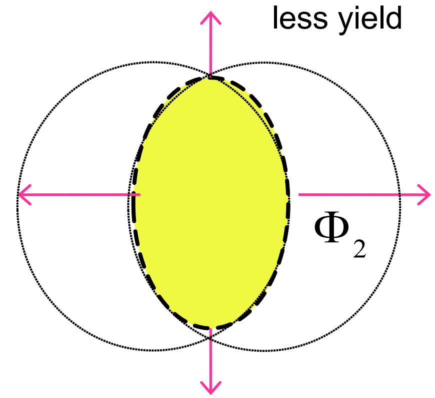
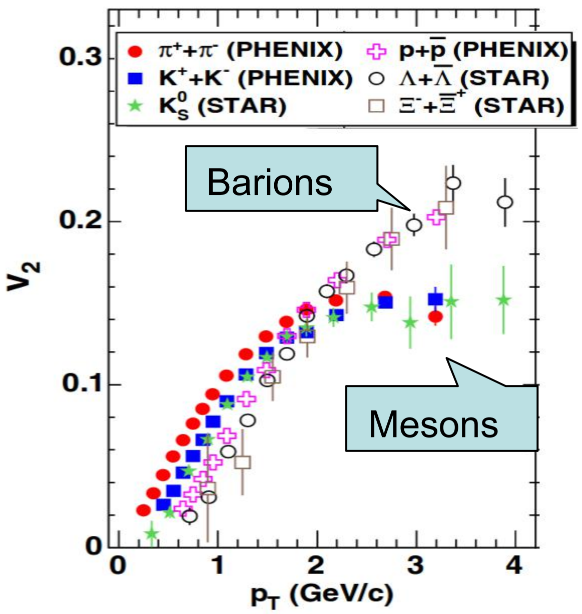


- Very strong collectivity!
  => Strongly coupled QGP
  - Good description by hydrodinamical models
  - Very low viscosity
    => "Perfect" fluid

  Asimptotic freedom?



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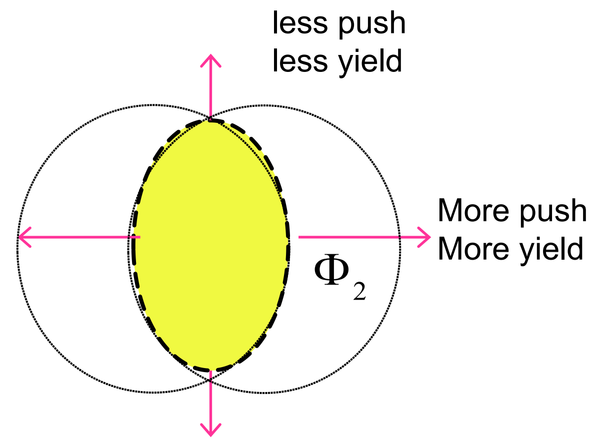

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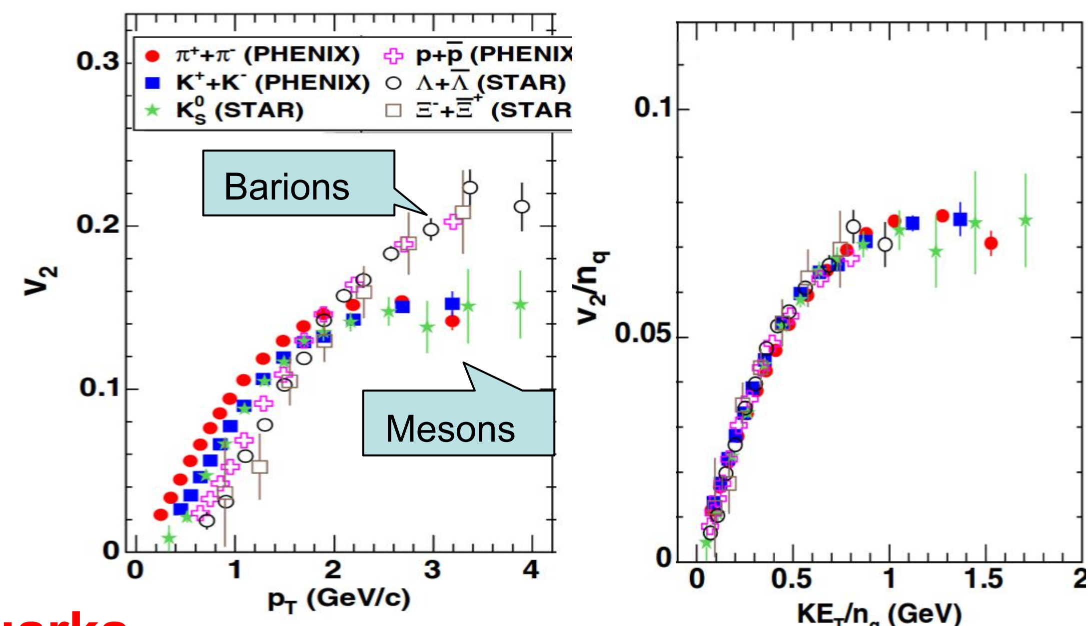


- Scaling with the number of Constituent quarks
  => Degrees of freedom: quarks
  - *Note: Scaling not perfect on LHC energies*

Open heavy flavor

- Motivation
- Detection
- System size, energy, rapidity dependence

Heavy-flavour (HF) probes

- Heavy quarks are produced early

$$\tau_{c,b} \sim \frac{1}{2} m_{c,b} \sim 0.1 \text{ fm} \ll \tau_{QGP} \sim 5\text{-}10 \text{ fm}$$

Rapp, Hees, ISBN:978-981-4293-28-0

- Heavy quarks are (almost) conserved

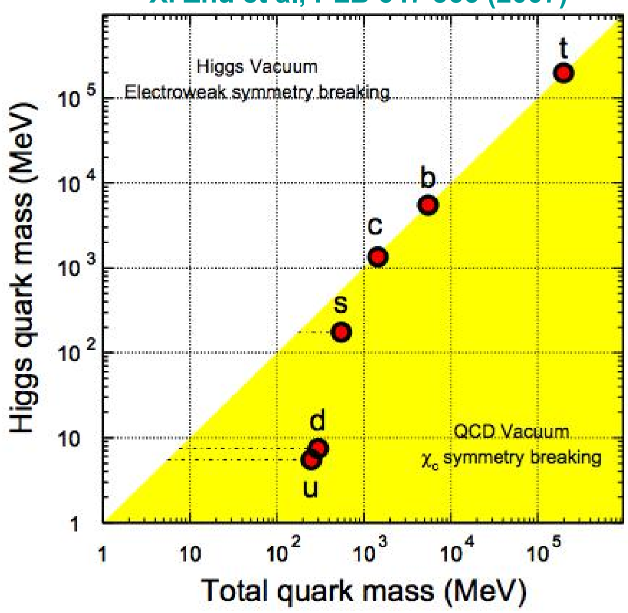
$$m \gg \Lambda_{QCD} \; (m_c \sim 1.5 \text{ GeV}, m_b \sim 5 \text{ GeV})$$

  - No flavour changing
  - Negligible thermal production

→ Very little production or destruction in the sQGP

Collins, Soper, Sterman, NPB 263 (1986) 37.

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



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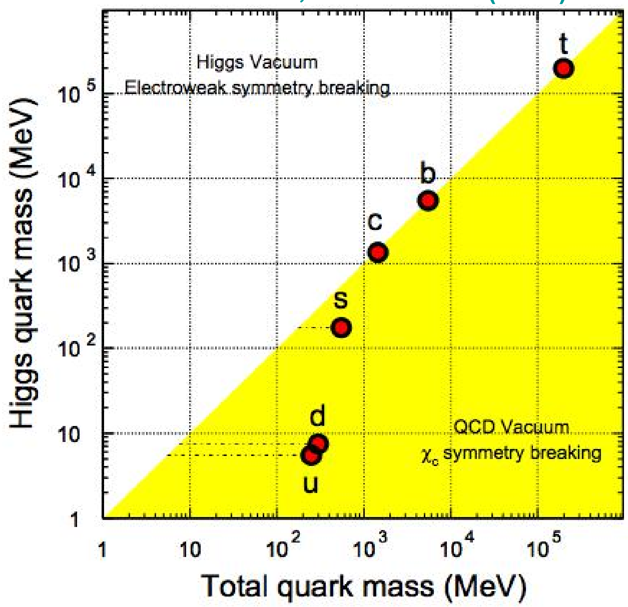
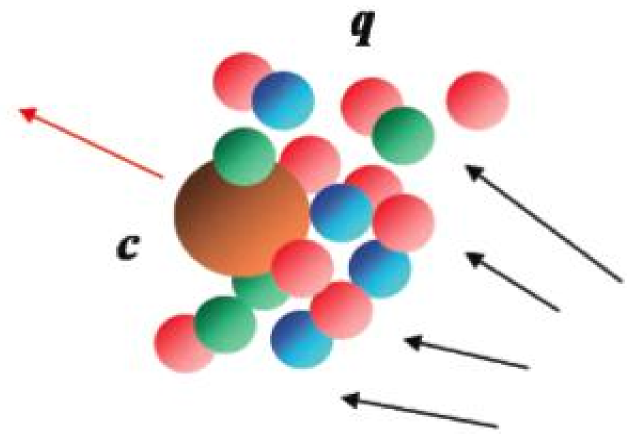


- Transport through the whole system
  - **Heavy quark kinematics in the sQGP**
  - Access to **transport properties** of the system
  - ...exits the medium also at **low momenta**
  - **Hadronization** (fragmentation, coalescence)
  - **Heavy vs. light? Charm vs. bottom?**



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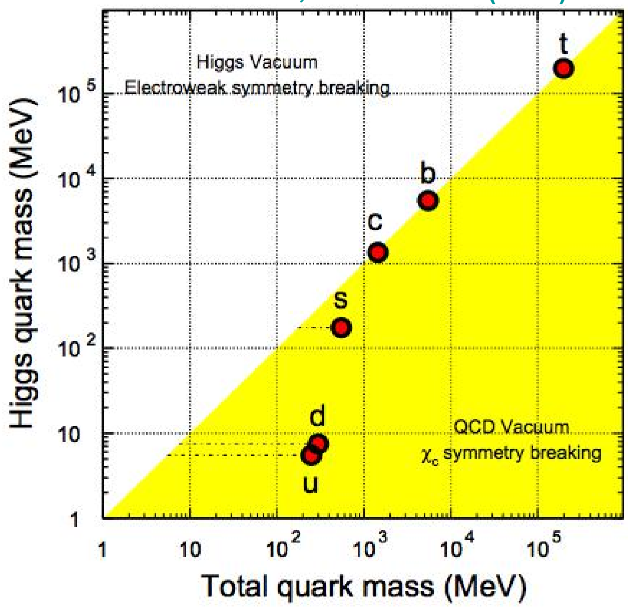

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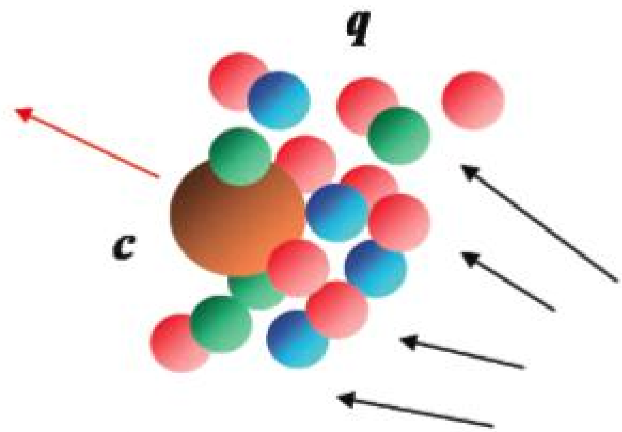


Penetrating probes down to low momenta!

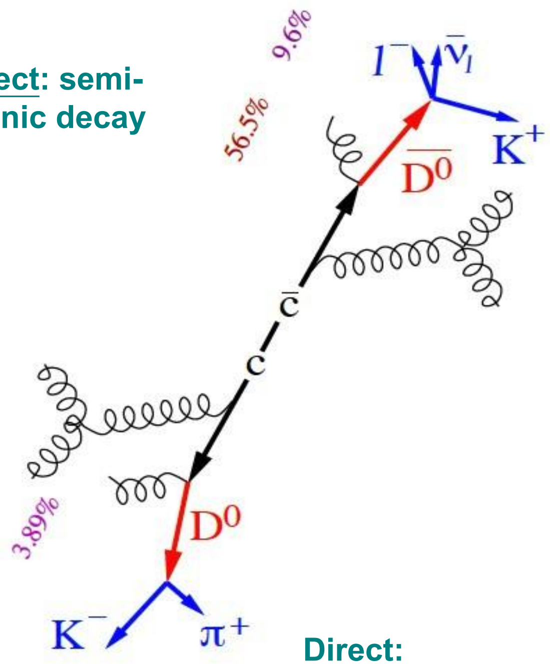
Experimental access to HF

- Quark confinement: only indirect detection of c and b
- Heavy quarks hadronize into HF mesons (D, B)

- Identification:

reconstruction from decay products

Indirect: semi-leptonic decay



Direct: hadronic channels

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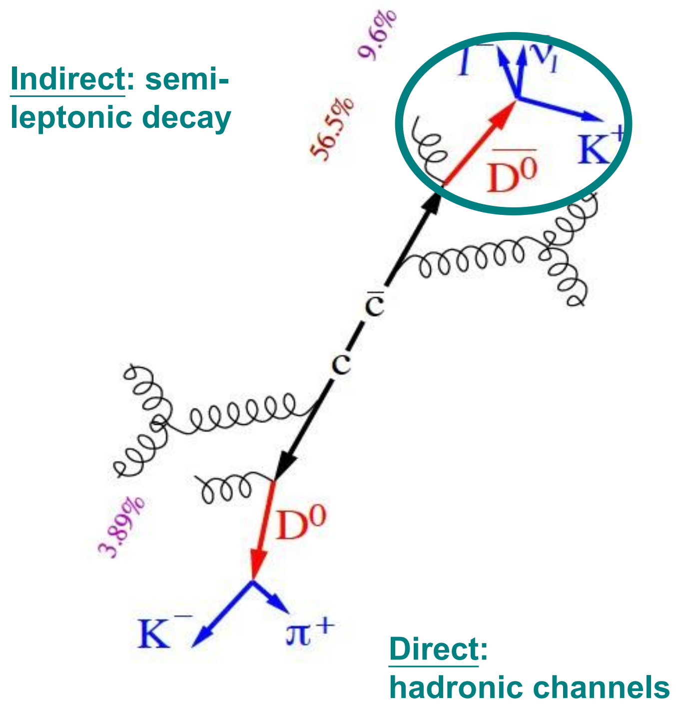

Semileptonic decays

- c,b → μ
- c,b → e

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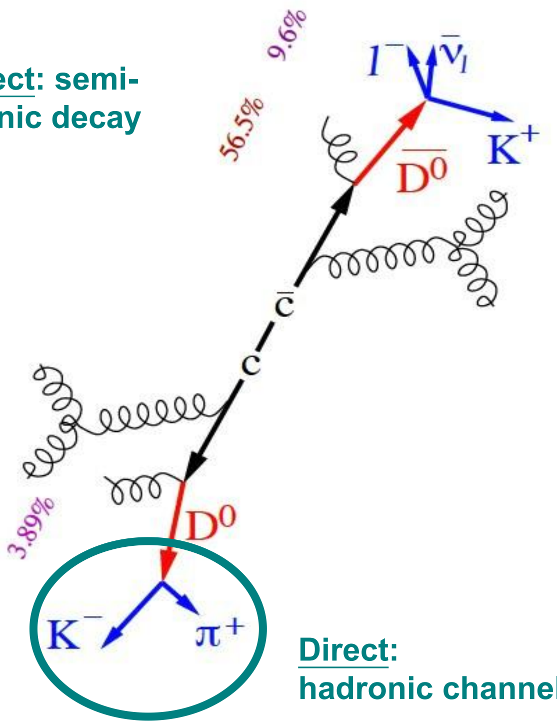

Direct: hadronic channels

Hadronic decay channels

- $D^0 \rightarrow K^- \pi^+$
- $D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+)\pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D_S^+ \rightarrow \Phi(\rightarrow K^+ K^-)\pi^+$
- $\Lambda_c^+ \rightarrow p K^- \pi^+$
- $\Lambda_c^+ \rightarrow pK^0_S(\rightarrow \pi^+\pi^-)$
- $\Xi_c^0 \rightarrow \Xi^- \pi^+$
- $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$
- $\Sigma_c^{0,++} \rightarrow \Lambda^+_c \pi^{+,-}$
- $\Omega_c^0 \rightarrow \Omega^- \pi^+$

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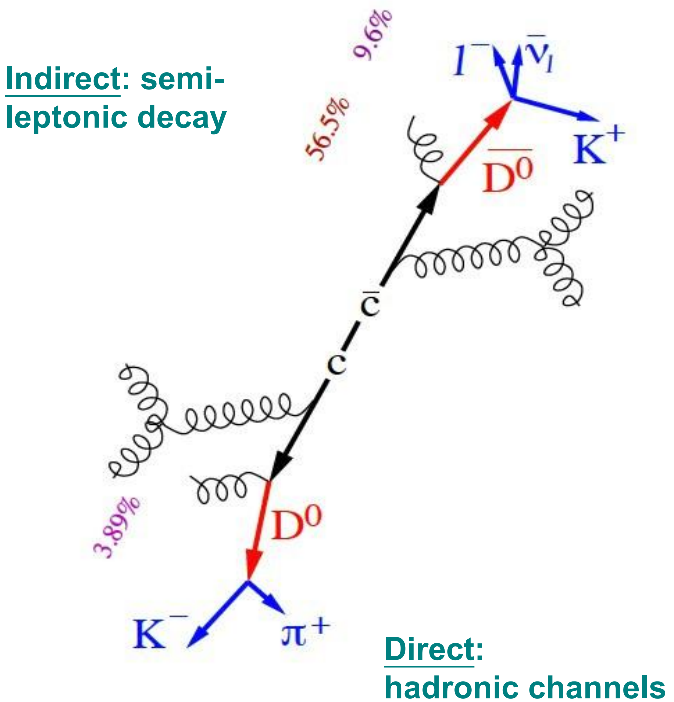
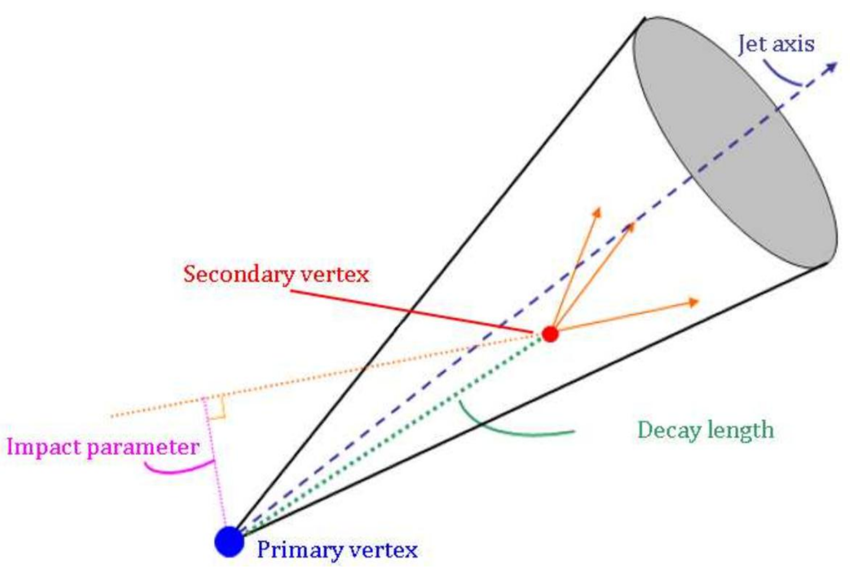
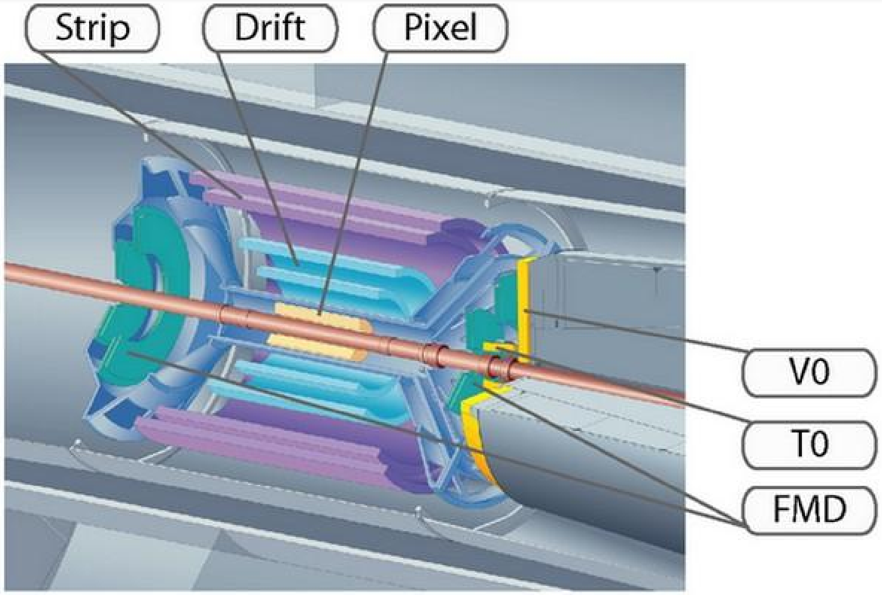


finding the location of the weak decay
(reconstructing the secondary vertex)



Finding the secondary vertex - ITS



- Semiconducting technology

Lifetime of heavy flavor: $c\tau(D) \sim 100\text{-}300\ \mu m$
$c\tau(B) \sim 400\text{-}500\ \mu m$

Secondary vertex resolution: $<100\ \mu m$

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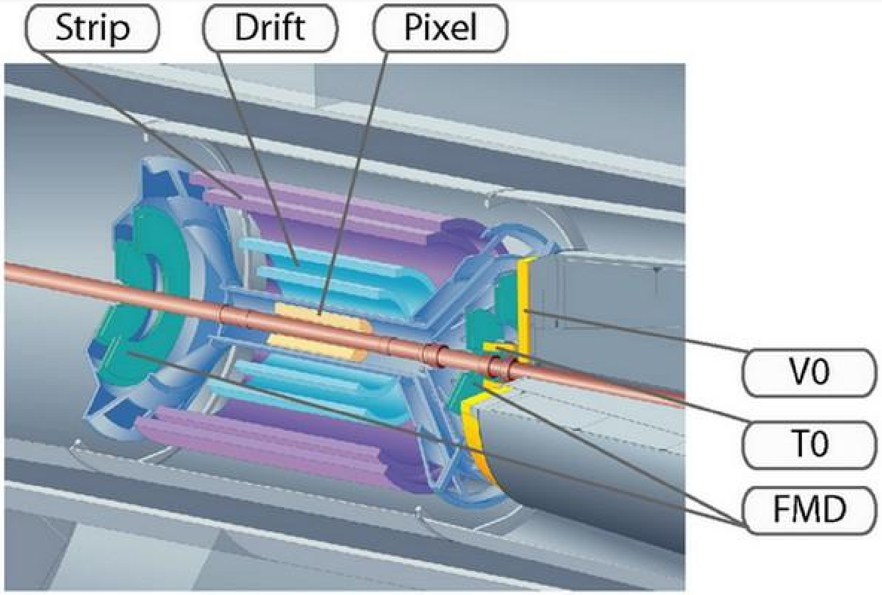

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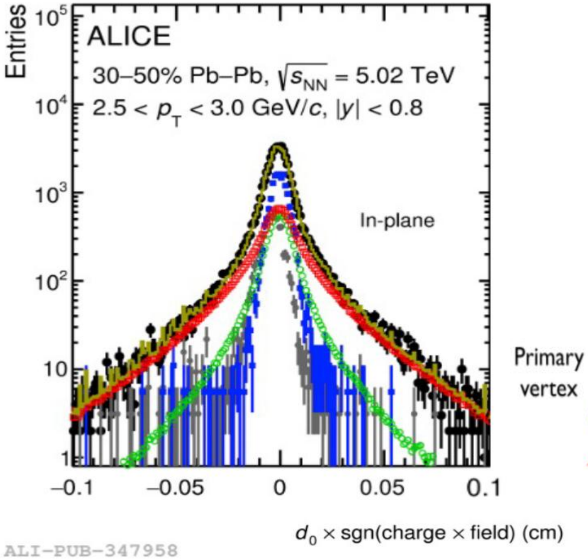
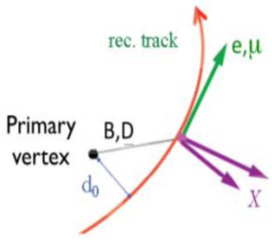
- **Distance of Closest Approach (e)**





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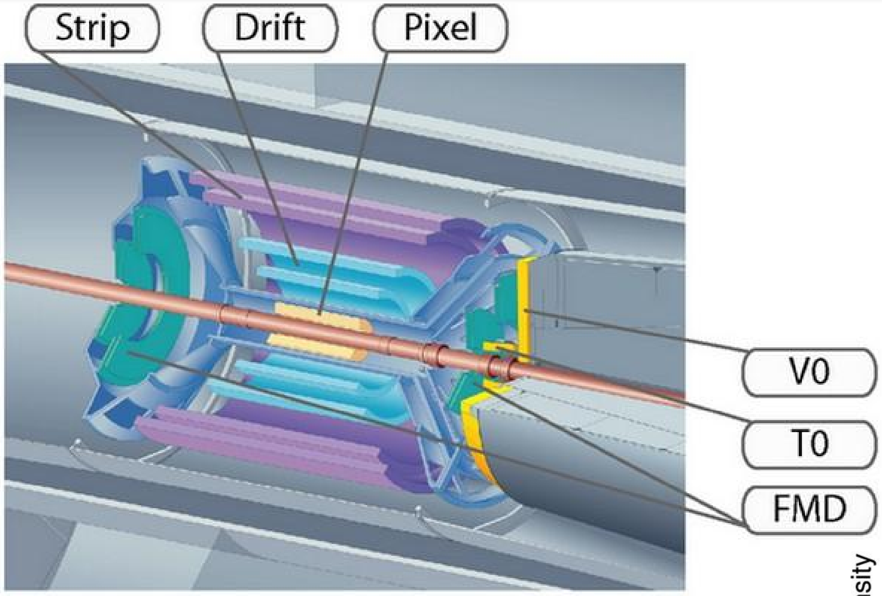


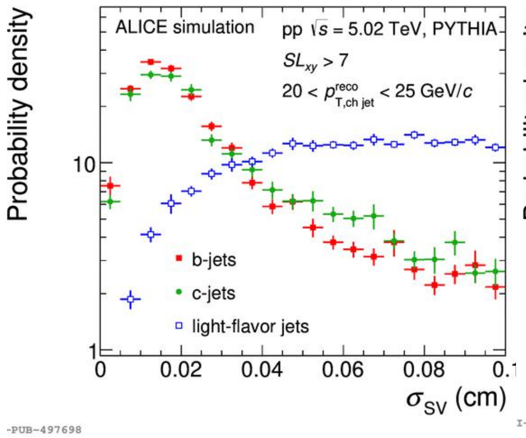
- Semiconducting technology

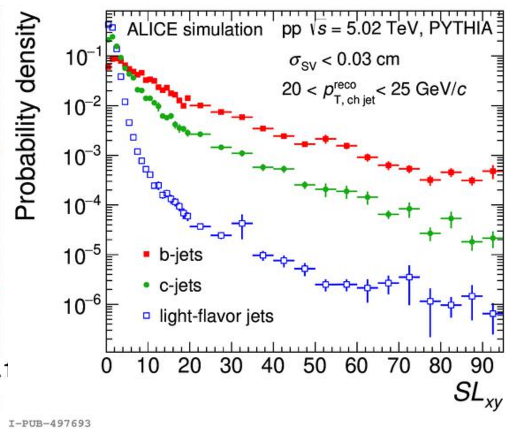
Lifetime of heavy flavor: cτ(D) ~ 100-300 μm
cτ(B) ~ 400-500 μm

Secondary vertex resolution: <100 μm

- **Secondary vertices (jets)**

dispersion **displacement**





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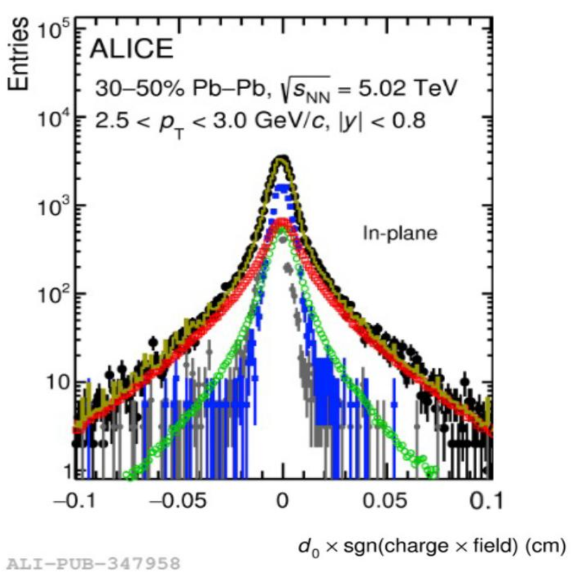
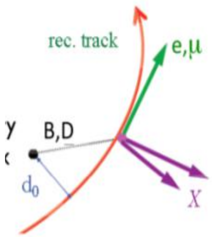
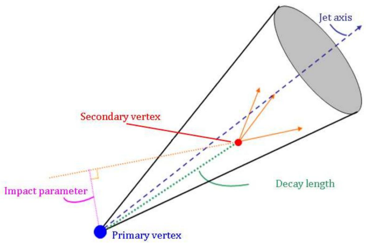
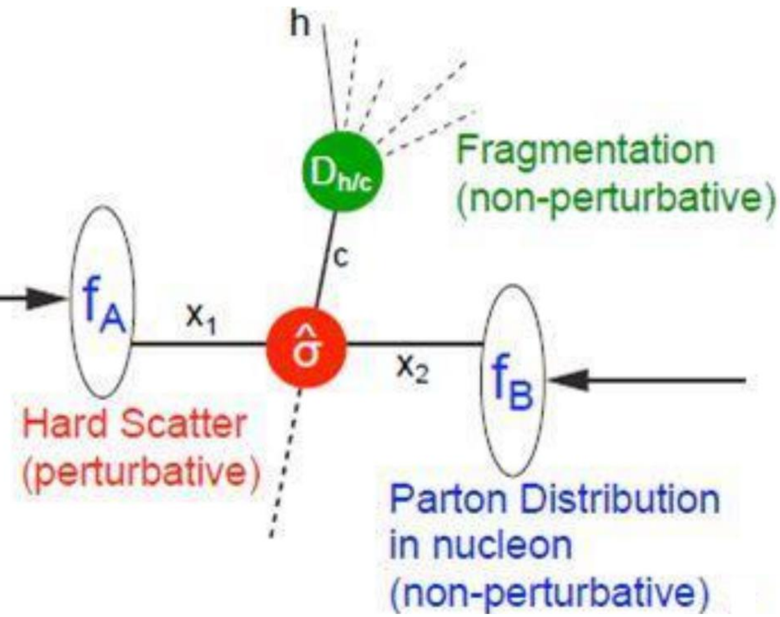






Heavy quarks in p+p collisions

- Test of pQCD models
  - Heavy quarks: $m_{c,b} >> \Lambda_{QCD}$
    → Perturbative even at low momenta
  - Factorization:
    - Parton distribution function (PDF)
    - Hard scattering
    - Fragmentation



Feynman-*x*:
$x_1 = p^A_{||} / p^A_{||,max}$

Q: momentum transfer

$$\sigma_{hh\to H} = f_a(x_1,Q^2)\otimes f_b(x_2,Q^2)\otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to H}(z_q,Q^2)$$

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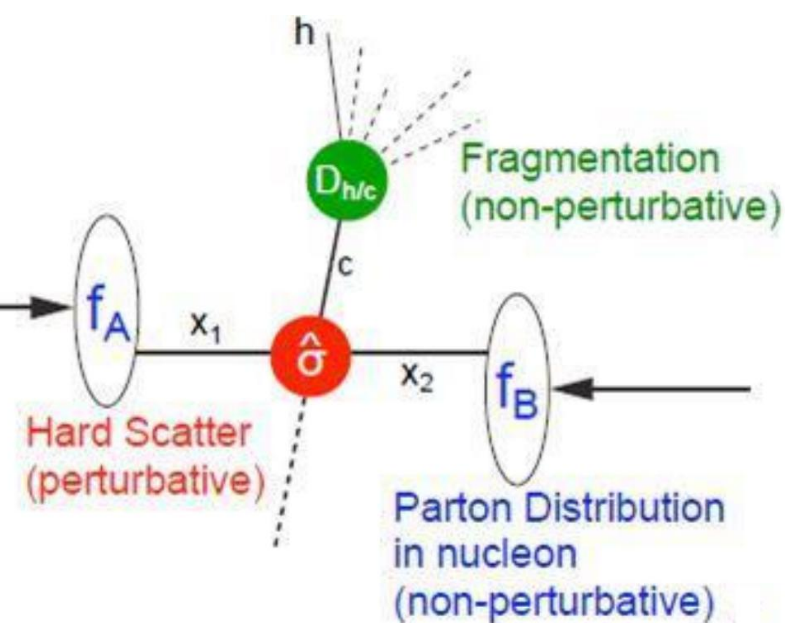

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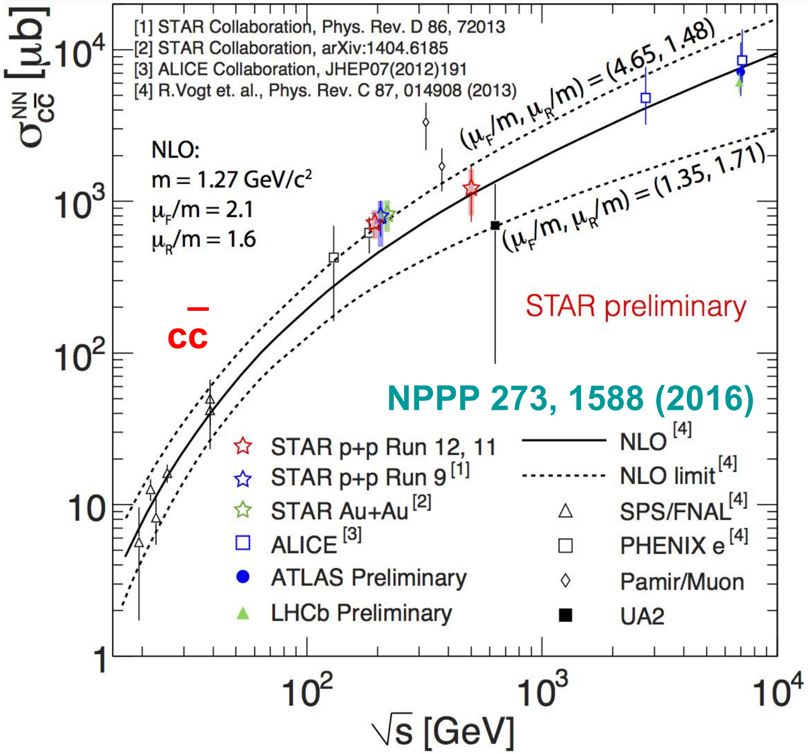
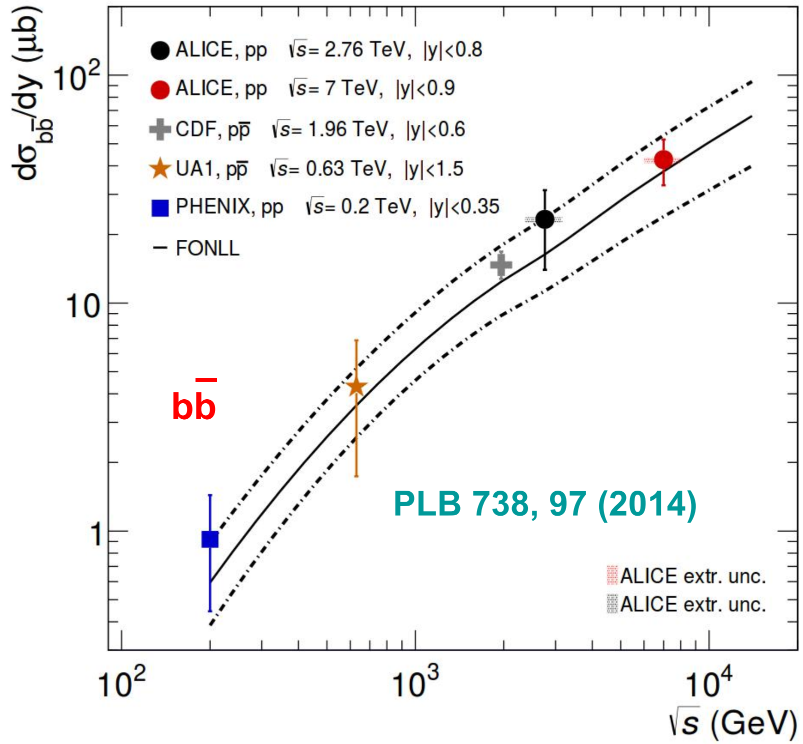
- Reference for the evaluation of p-A and A-A collisions (eg. for computing R_{pA}, R_{AA})

Total pp→q$\bar{q}$X cross-section





Cross-sections at different beam energies:

Primary test of models describing heavy-quark production

- pQCD description of data works, but uncertainties are large

LHC 7 TeV charm pair production cross section from D⁰ measurements

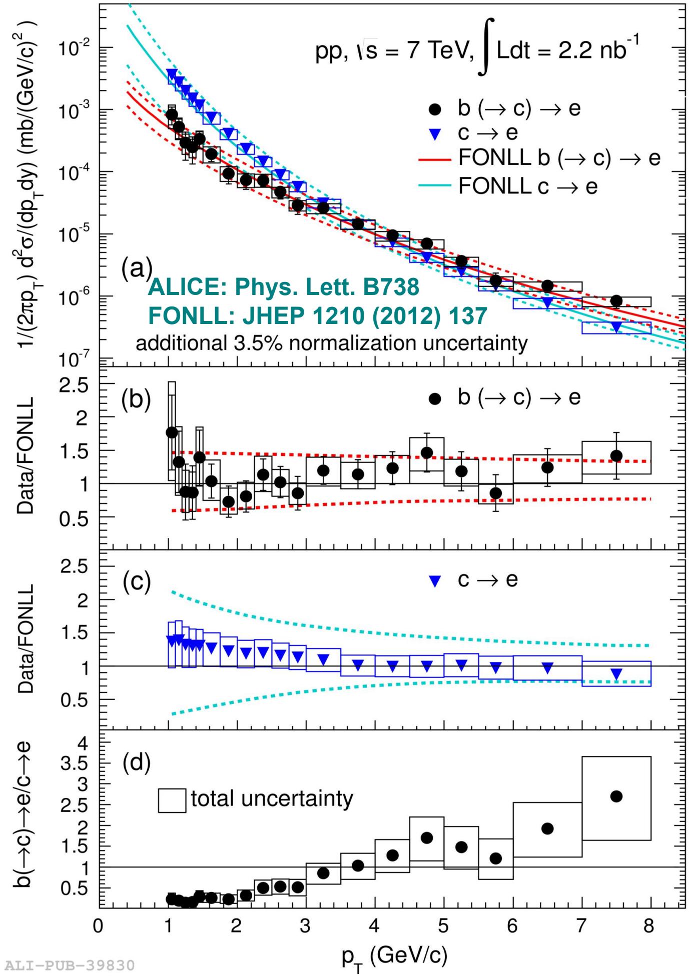
arXiv:1702.00766.pdf

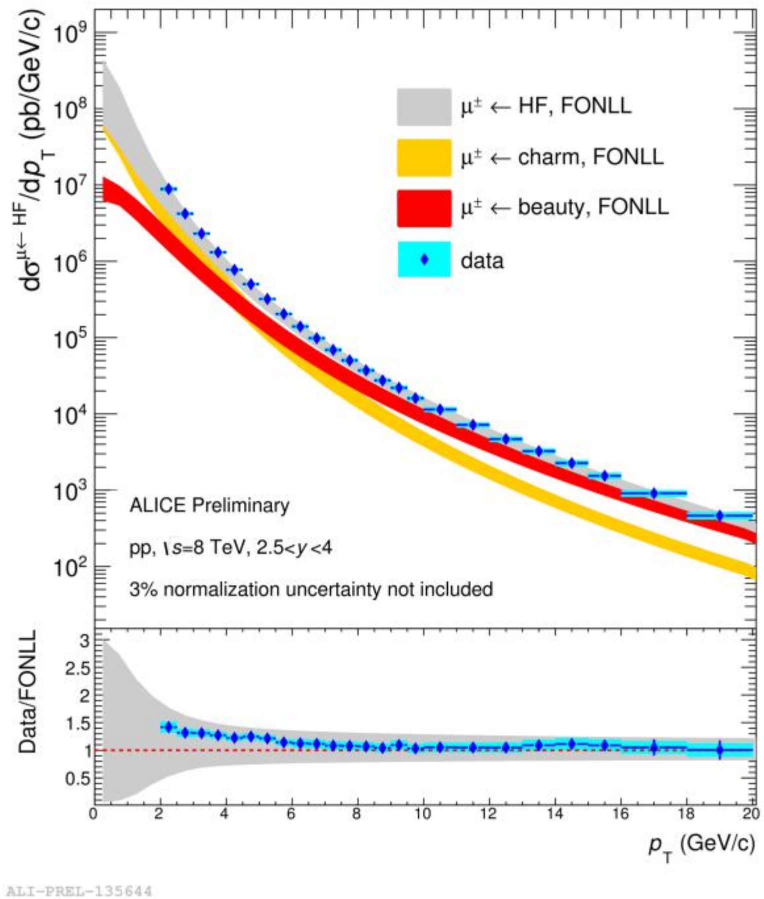
$$\sigma_{c\bar{c}}(\sqrt{s} = 7\ \mathrm{TeV}) = 8.08^{+2.55}_{-1.04}\ \mathrm{mb}$$

LHC 7 TeV beauty pair production cross-section from semi-leptonic decay electrons

$$\sigma_{b\bar{b}}(\sqrt{s} = 7\ \mathrm{TeV}) = 383 \pm 120\ \mu\mathrm{b}$$

Leptons from heavy quarks



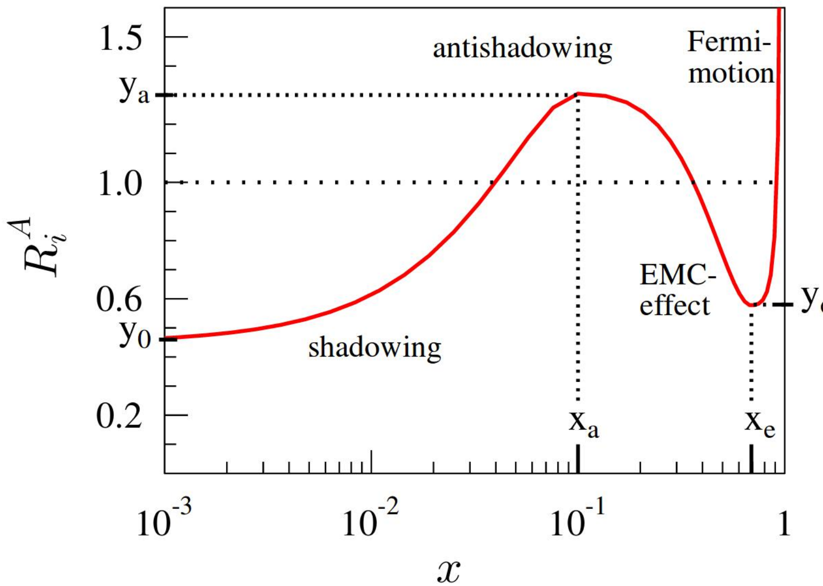


- Contributions of **beauty** and **charm** can be statistically separated
- Perturbative models give a good description for mid-rapidity **electrons** as well as **muons** at 2.5<y<4

Heavy flavor in p+A collisions

- Cold nuclear matter effects
  - nPDF modification (shadowing)
  - Gluon-saturation
  - Multiple scatterings (k_T-broadening)
  - Attenuation in the CNM

Eskola et al., JHEP 0904, 065 (2009)



$$f_i^A(x, Q^2) \equiv R_i^A(x, Q^2)\, f_i^{\mathrm{CTEQ6.1M}}(x, Q^2)$$

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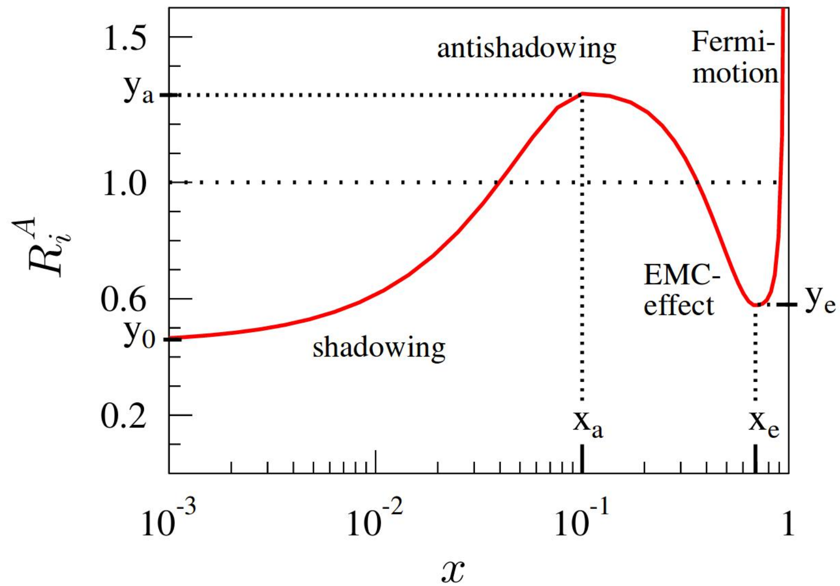
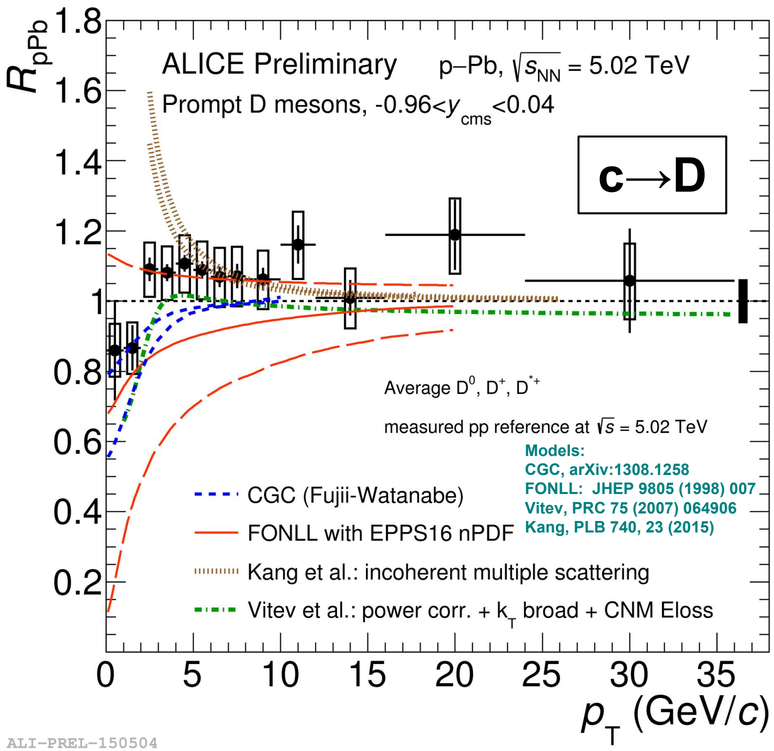


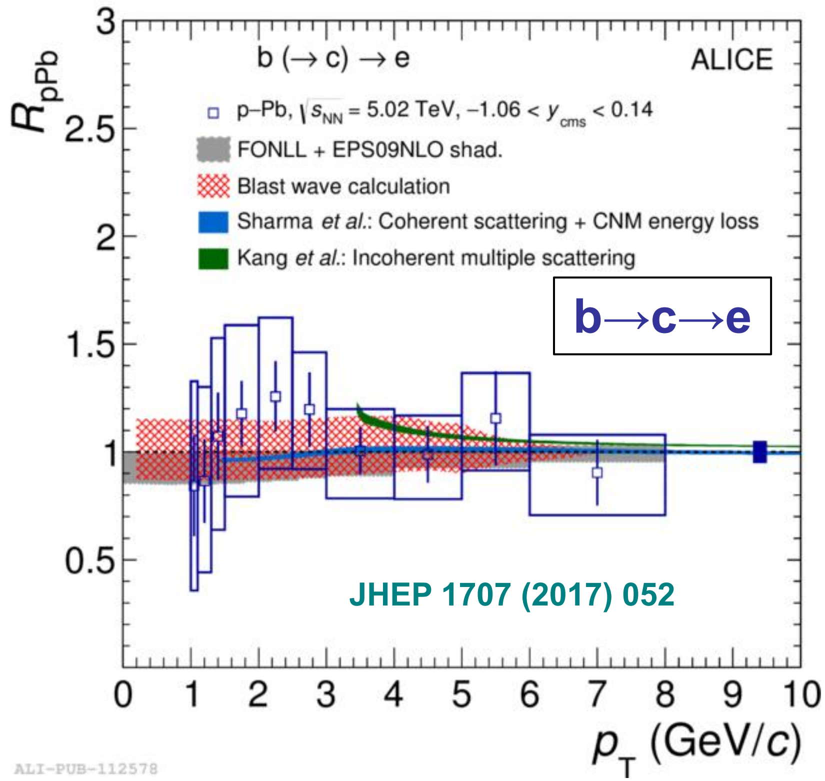
- Nuclear modification (R_{pA})
- Reference for hot nuclear matter effects

$$f_i^A(x, Q^2) \equiv R_i^A(x, Q^2) f_i^{\mathrm{CTEQ6.1M}}(x, Q^2)$$

Note: Hot nuclear matter may also be created in high-energy p+A collisions

p-Pb charm (→D) and beauty (→e)





- Nuclear modification is weak in p-Pb collisions at 5 TeV
  - Both **charm** and **beauty** are consistent with unity
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  - More precise measurements are needed

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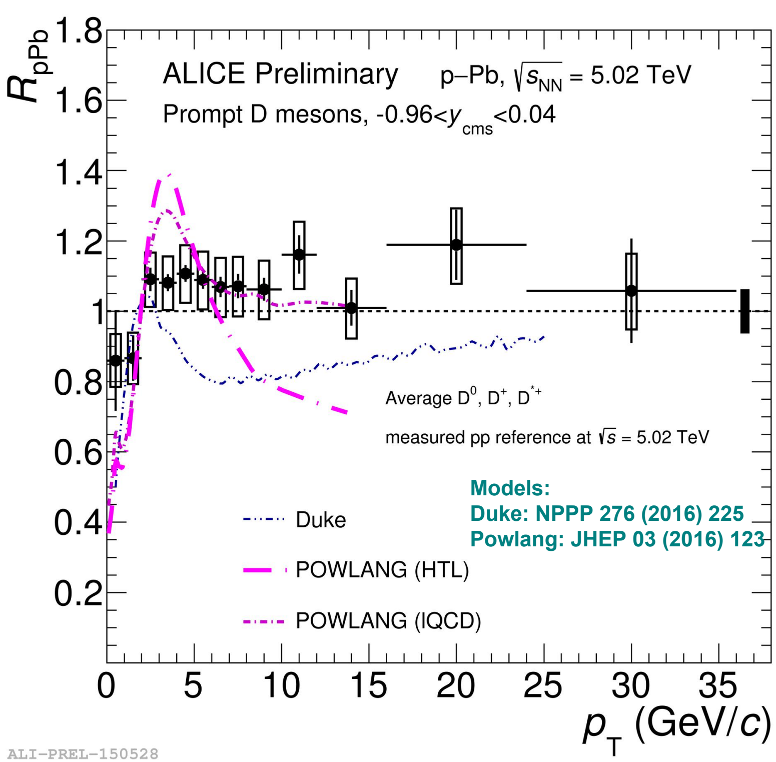

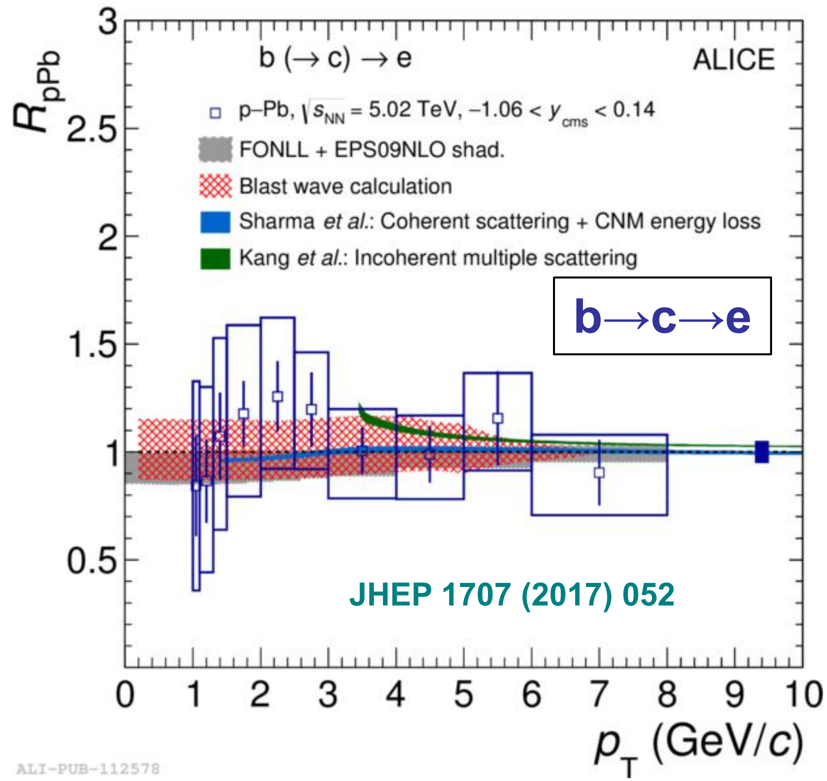

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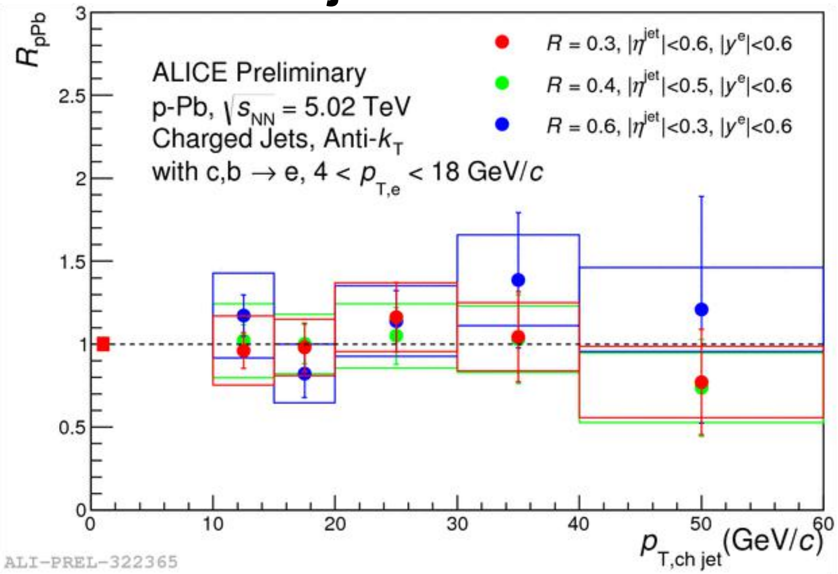
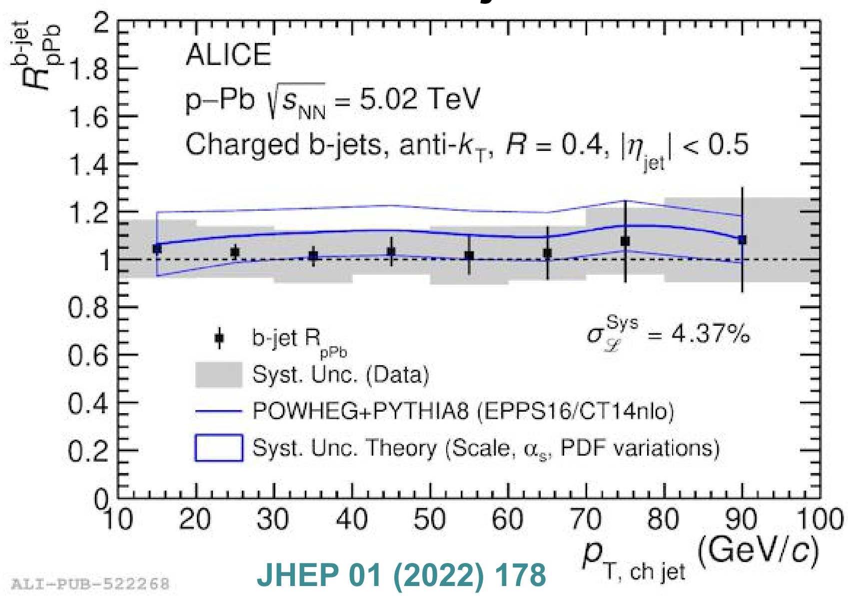
  - Both **charm** and **beauty** are consistent with unity
- Models with CNM effects describe the trends
  - More precise measurements are needed
- **Production of QGP in pA collisions cannot be excluded but disfavored**

Heavy flavor jets in p-Pb

jets with HFE



b-jets



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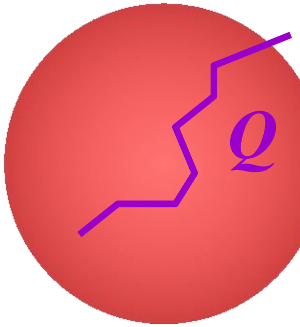
- Heavy-flavor jets measured down to p_T = 10 GeV/c
- No visible mid-rapidity modification of HFE-jets or b-jets
  - In accordance with model expectations
- **Currently no proof for heavy-flavor jet modification in p-A**
- **More detailed measurements expected soon**

Heavy flavor in A+A collisions

- Parton transport in the medium:
  - "Brownian motion"



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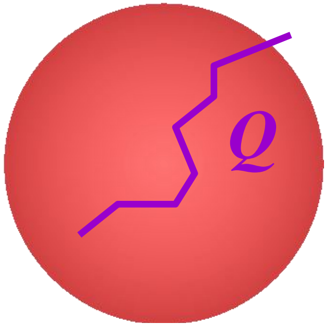
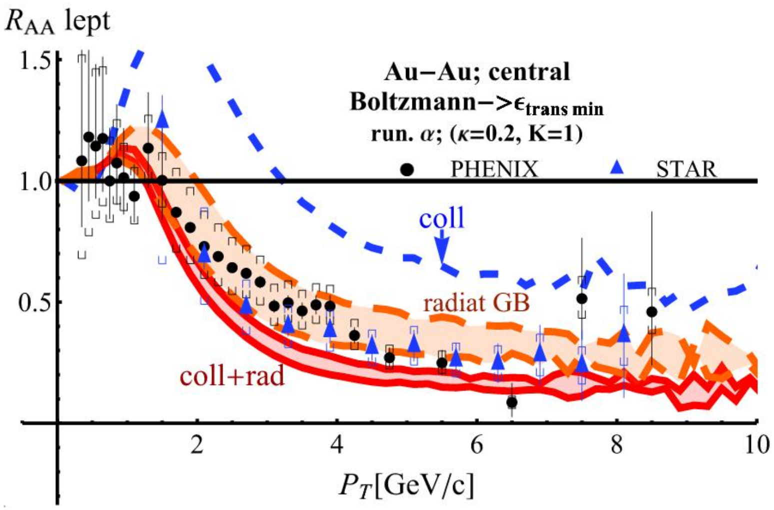


- Energy loss → R_{AA}
  - Radiational and collisional
  - Expectation: mass-ordering?

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$$
$$\rightarrow ?$$
$$R_{AA}^{h} < R_{AA}^{D} < R_{AA}^{B}$$



Gossiaux et al., J.Phys. G37 (2010) 094019

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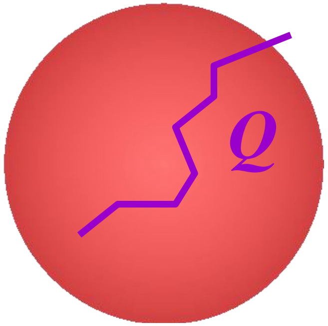

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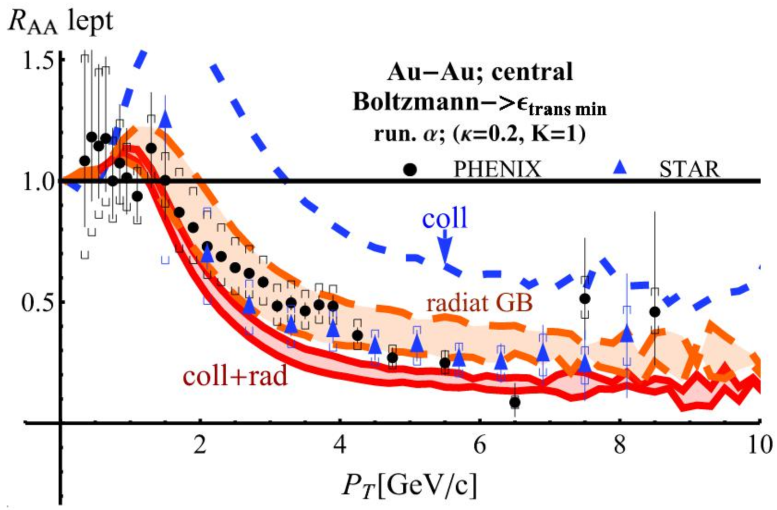
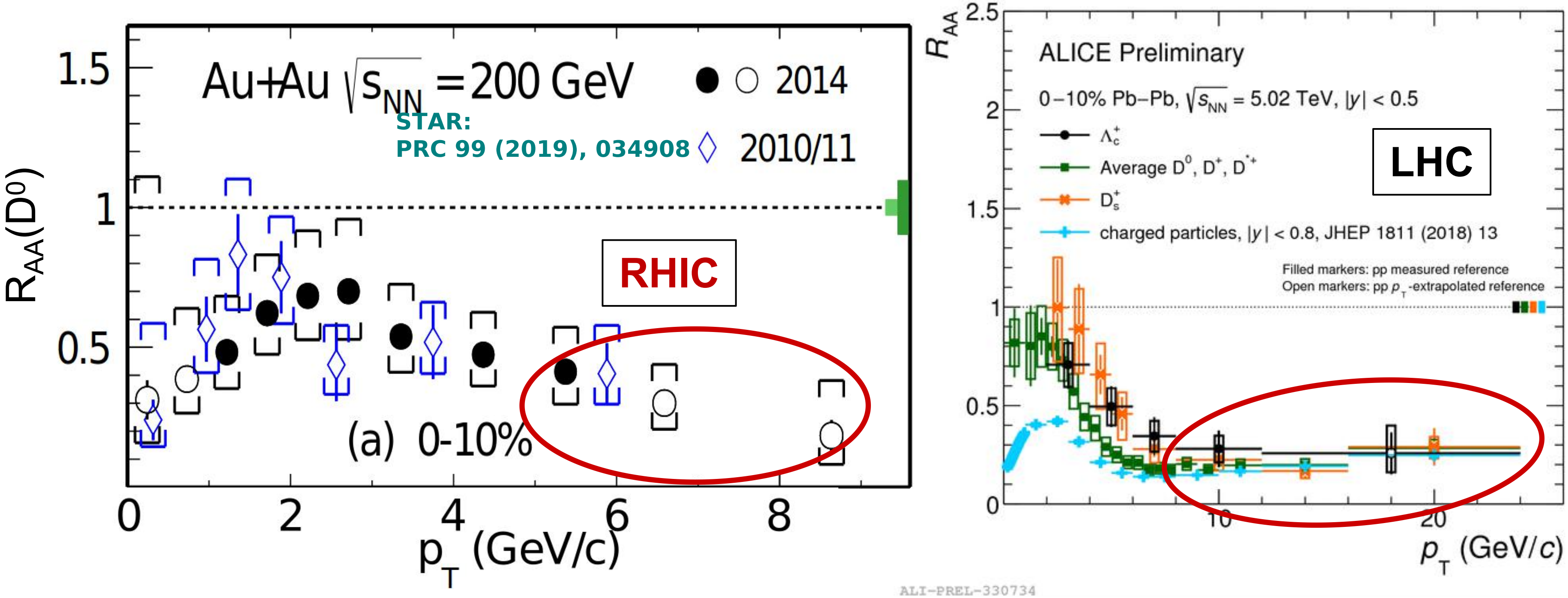


Gossiaux et al., J.Phys. G37 (2010) 094019

- Collective dynamics → v_2
  - Coalescence of heavy and light quarks?
  - Thermalization of heavy flavor?

D mesons in A+A collisions: R_{AA}



- **High momenta**: nuclear modification is similar to that of light hadrons (~5x suppression at p_T~5 GeV/*c*)
  - Expectation: ΔE(g) > ΔE(u,d,s) > ΔE(c) → R_{AA}(π,K,p) < R_{AA}(D)

    → **suggests strong interaction with the medium**

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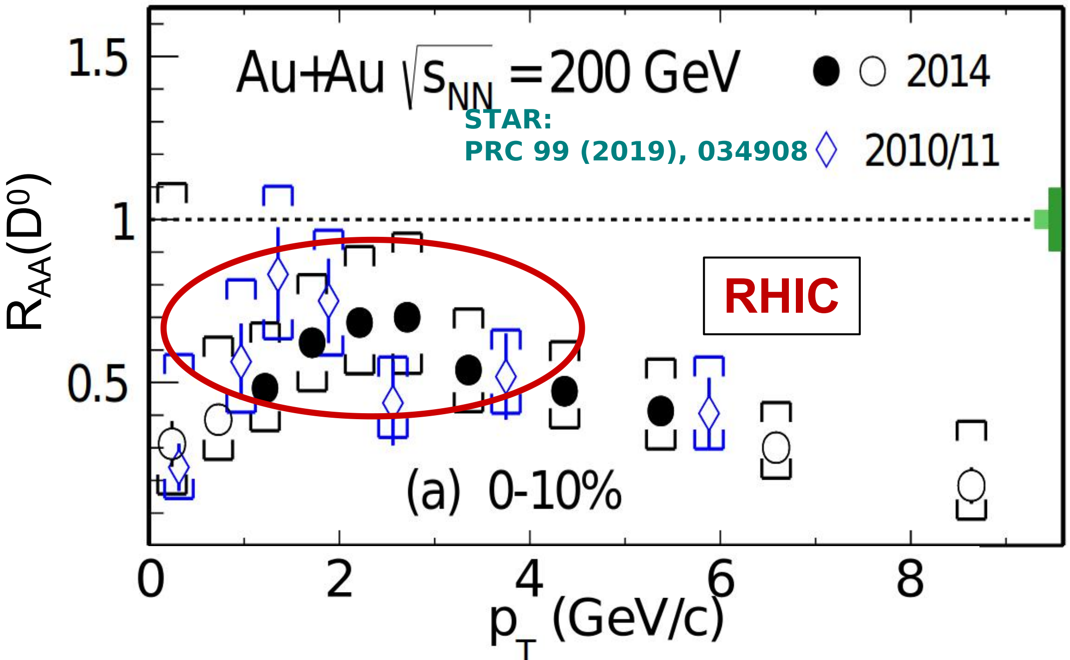

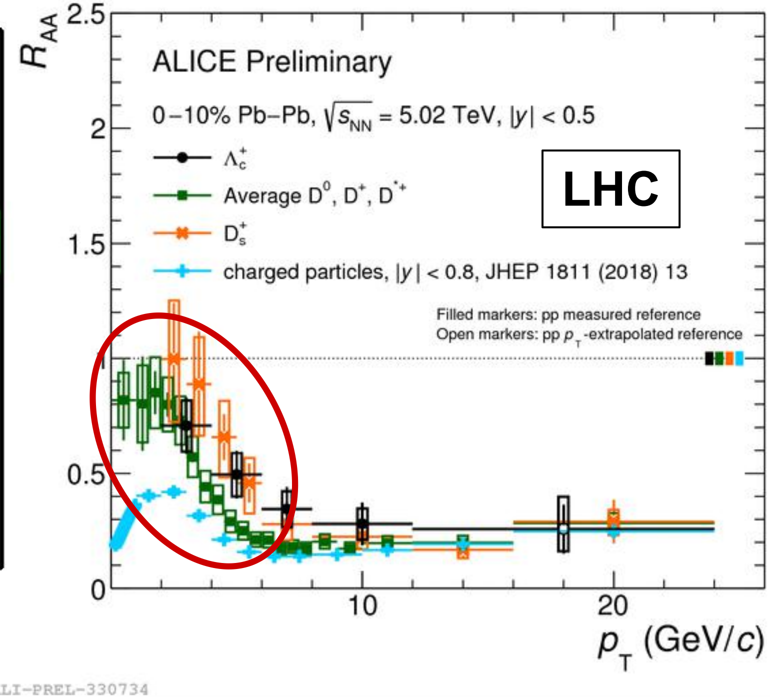

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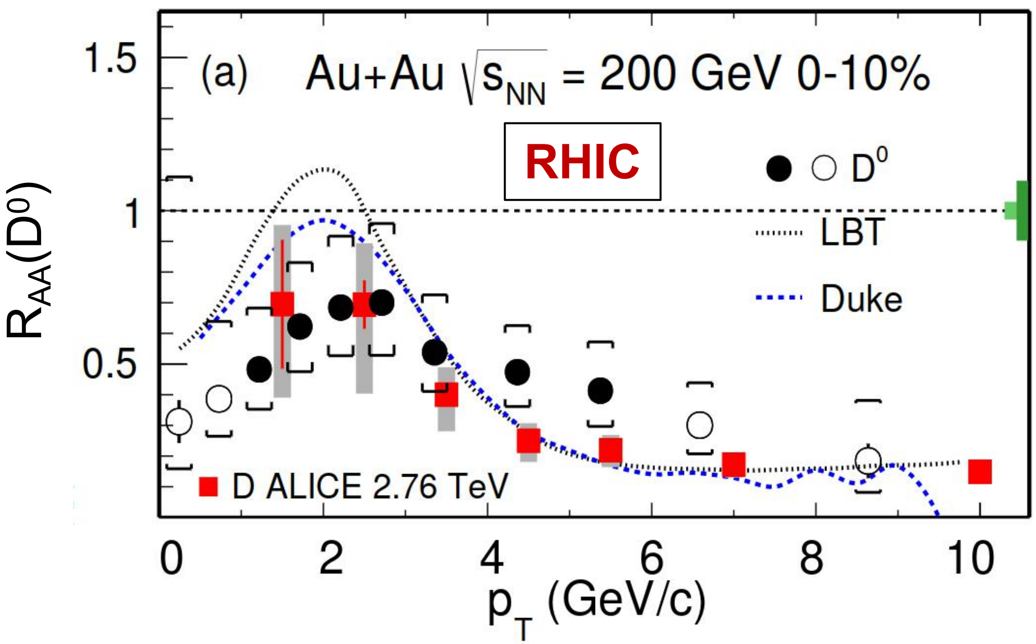
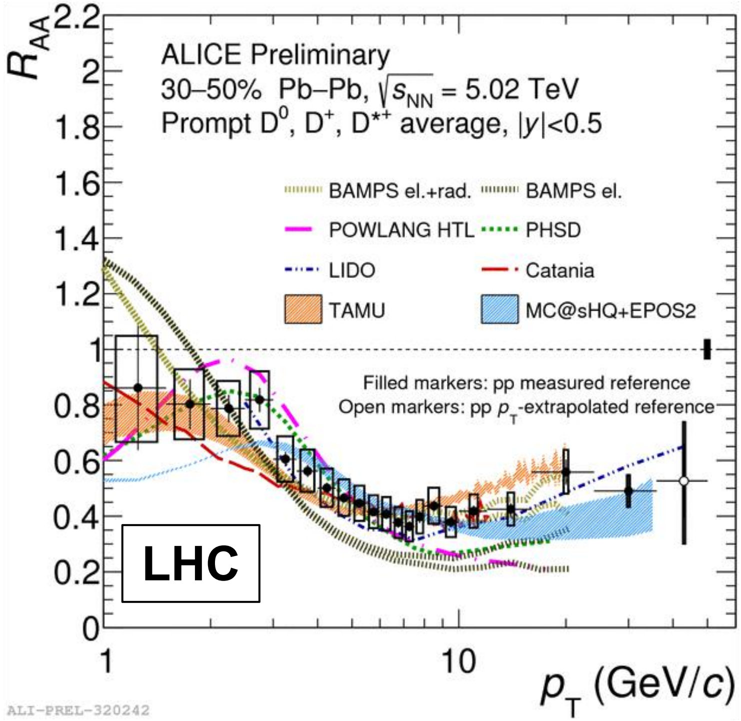
    → **suggests strong interaction with the medium**
- **Low momenta**: significantly less suppression than light flavor

  from RHIC 200 GeV to LHC 5.02 TeV

  → **coalescence of charm and light flavor?** ("stick-together")

D mesons in A+A collisions: R_{AA}

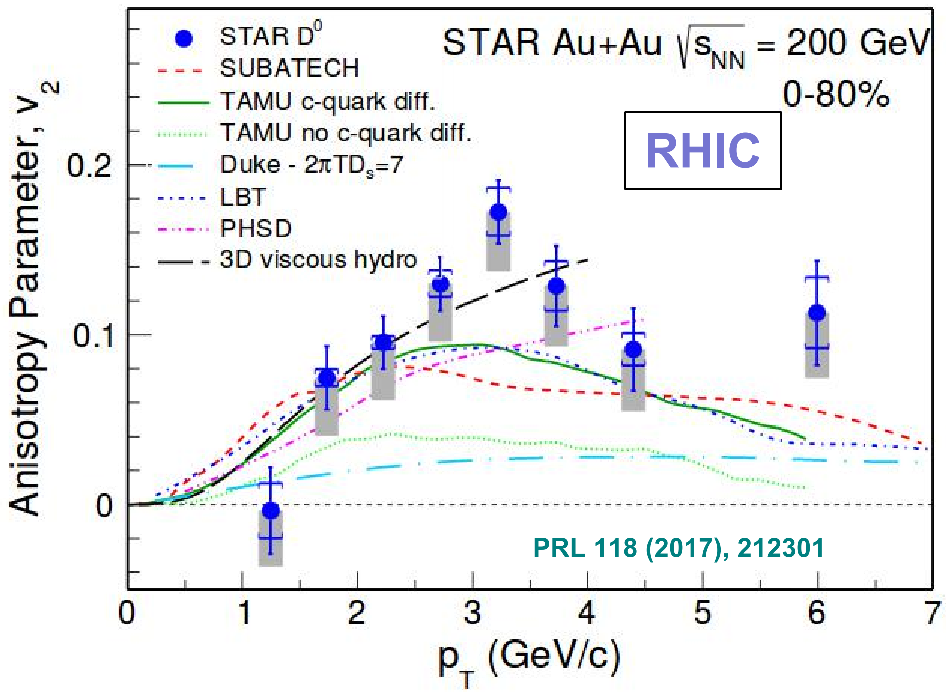


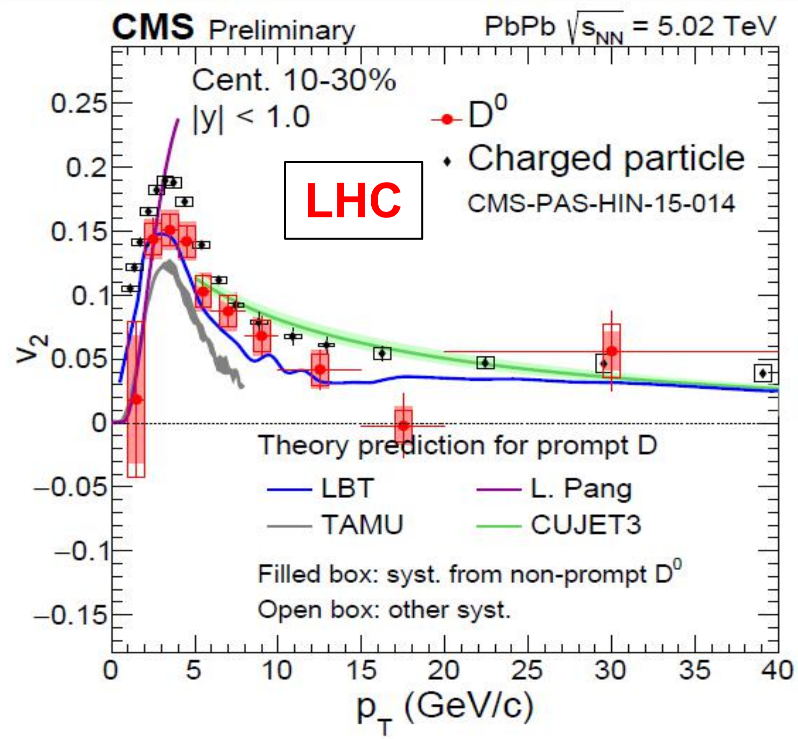


- Several models with different components describe results well
  - Production of heavy quark: FONLL or NLO pQCD calculations
  - Energy loss via radiation or collisions
  - Evolution of nuclear matter: hydrodynamical? Glauber?
  - Model of fragmentation

R_{AA} alone is not restrictive enough for strong conclusions

D mesons in A+A collisions: v_2





- A sizeable azimuthal anizotropy

  → **heavy flavor participates in collectivity**
- Models that include the recombination of charm with the flowing light flavor perform better

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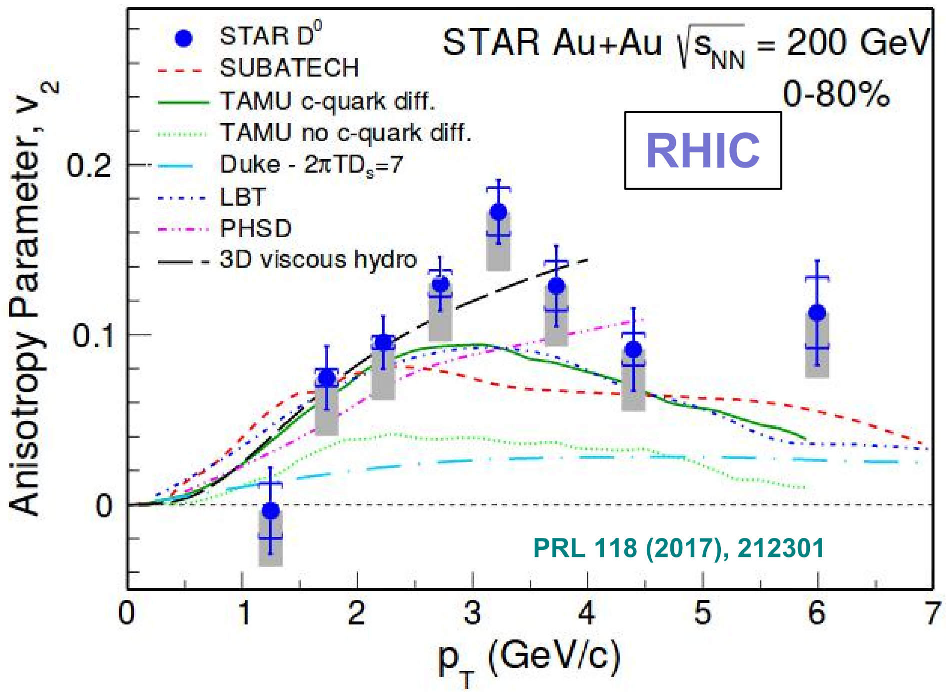

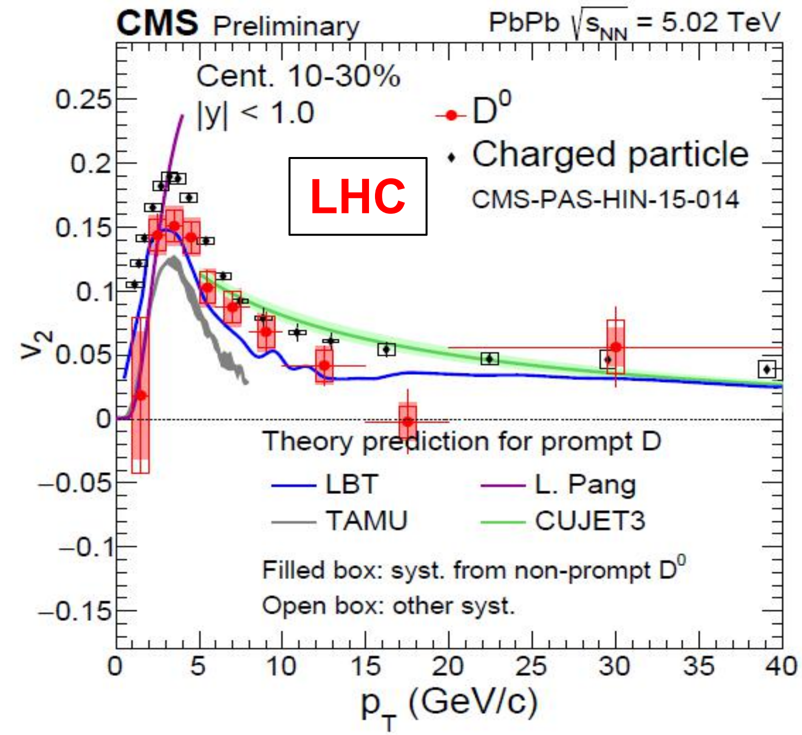

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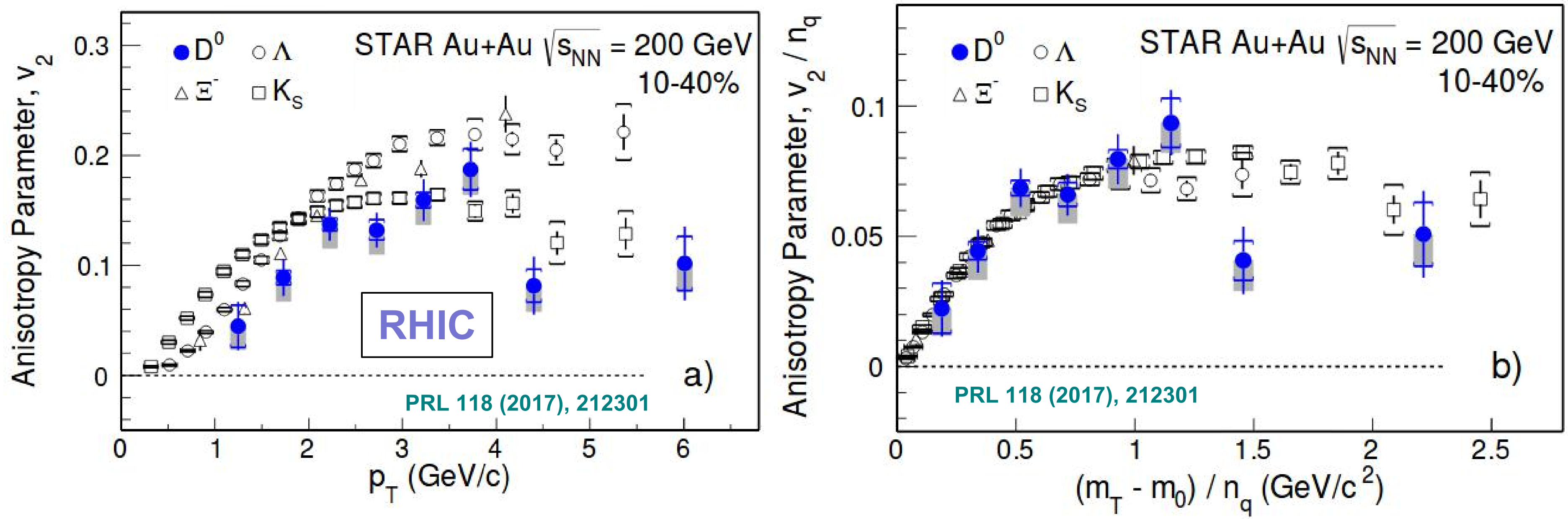
Simultaneous description of R_{AA} and v_2: challenge for models

D mesons in A+A collisions: v_2

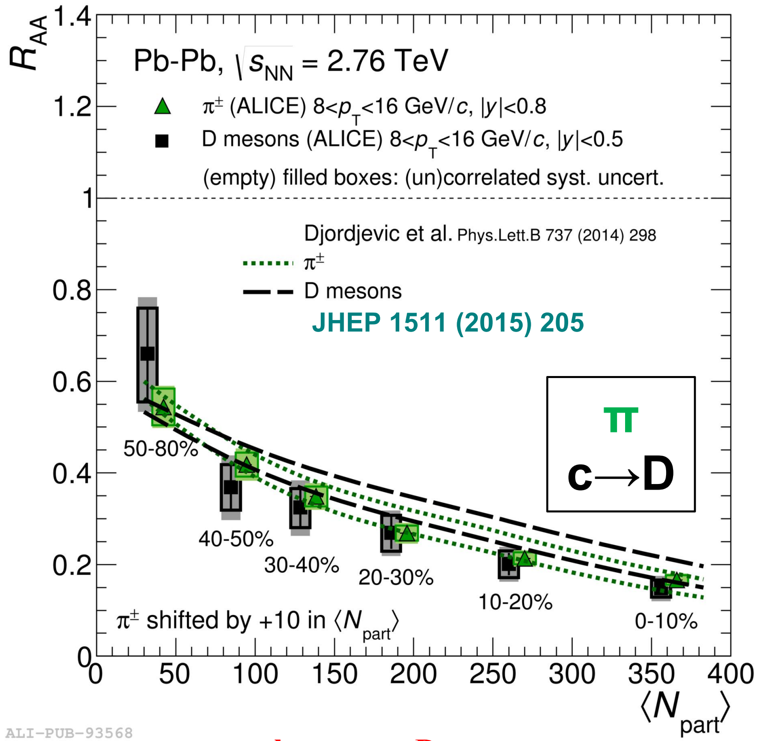


RHIC 200 GeV Au+Au

- Mass-ordering
- **Quark number scaling**

→ **local thermal equilibrium of heavy quarks!**

Suppression of high-momentum D, B

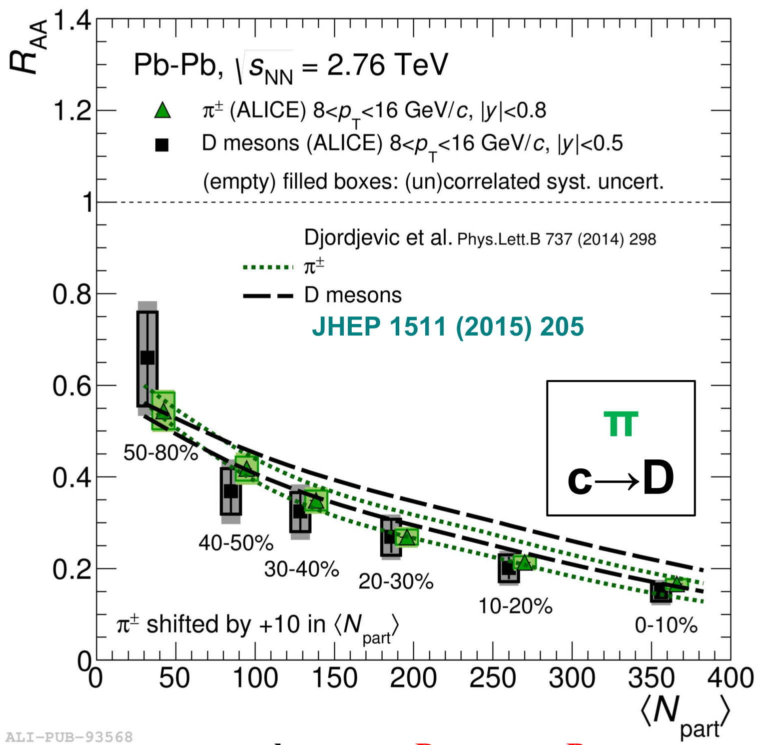


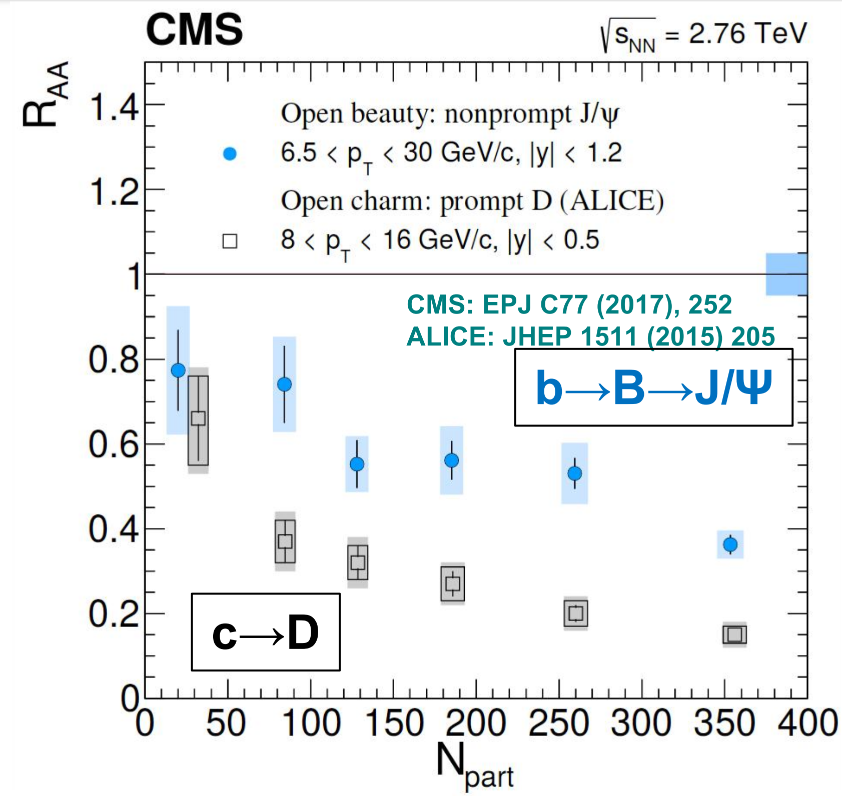
$R_{AA}^{h} = R_{AA}^{D}$

- Similar suppression of **D mesons** and **pions** at high p_T

  Model: different fragmentation compensates mass-ordered diffusion

Suppression of high-momentum D, B





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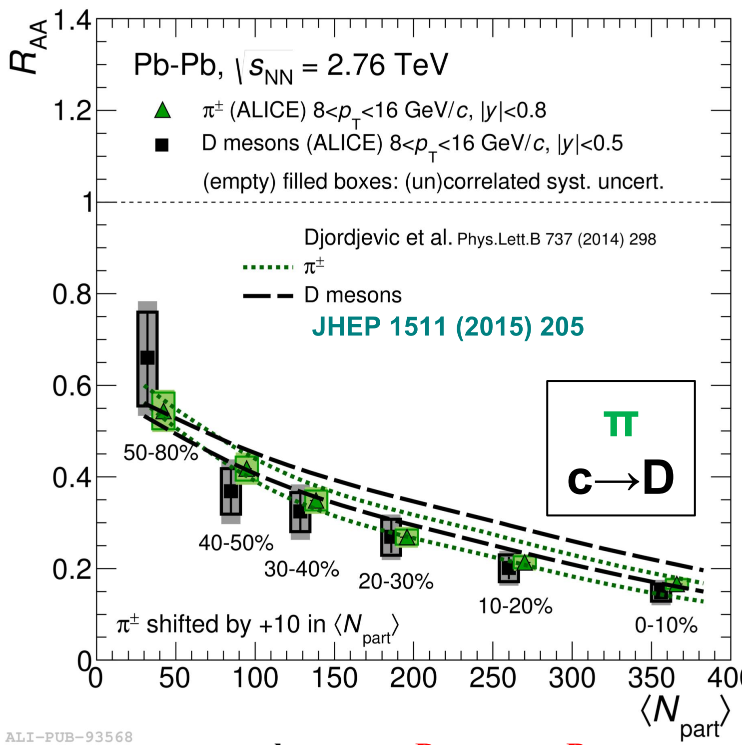

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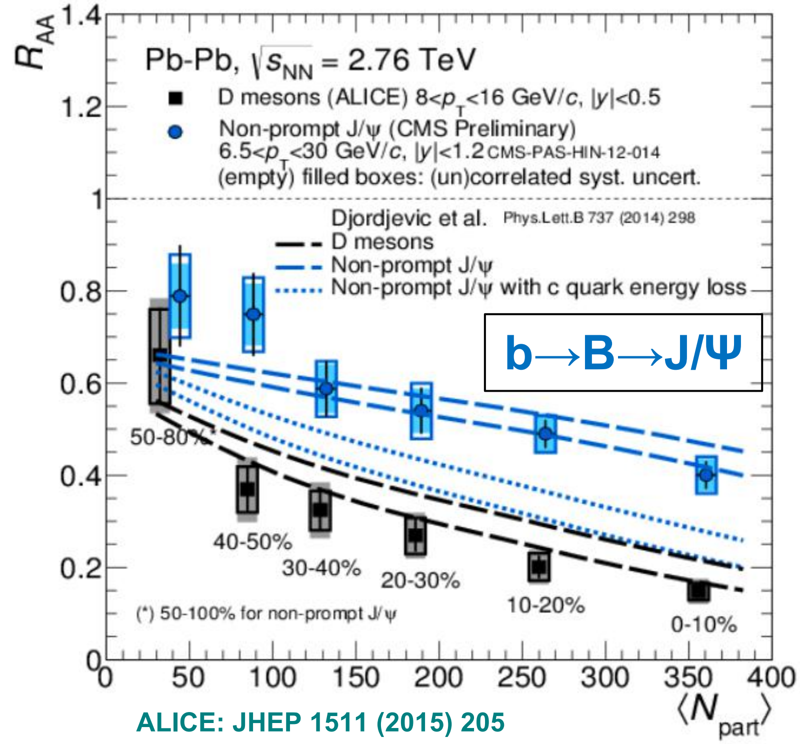

ALICE: JHEP 1511 (2015) 205
CMS: EPJ C77 (2017), 252
Model: Djordjevic, PLB 737 (2014) 298

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  Model: different fragmentation compensates mass-ordered diffusion
- Weaker "Non-prompt" **B→J/ψ** suppression at high p_T
  Model: **c** and **b** are in similar kinematical range, mass-ordering visible

Jets with heavy quarks: D(c), b

- Expectation: $\Delta E(g) > \Delta E(uds) > \Delta E(c) > \Delta E(b)$ → R_{AA}(h-jets) < R_{AA}(b-jet)
- Effect of color charge? Contribution of gluon-splitting?

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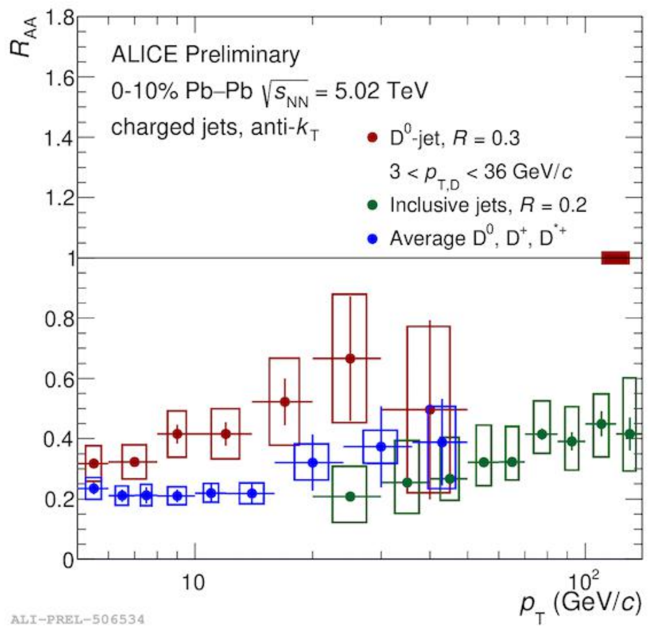
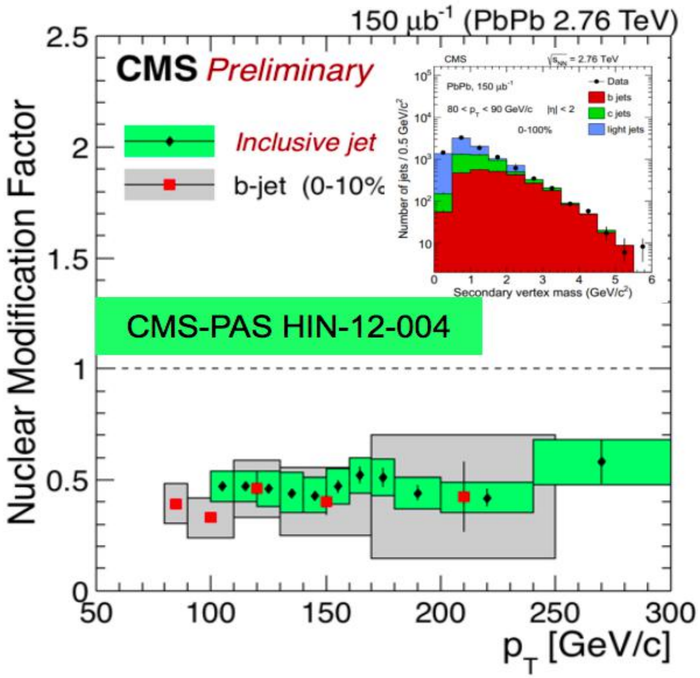


R_{AA}(D-jet) < R_{AA}(charged)



R_{AA}(b-jet) ~ R_{AA}(h-jets)

- **D-jets mid-p_T:** hint of weaker suppression than inclusive jets
- **b-jets, very high p_T**: similar modification of **light jets** and **b-jets**

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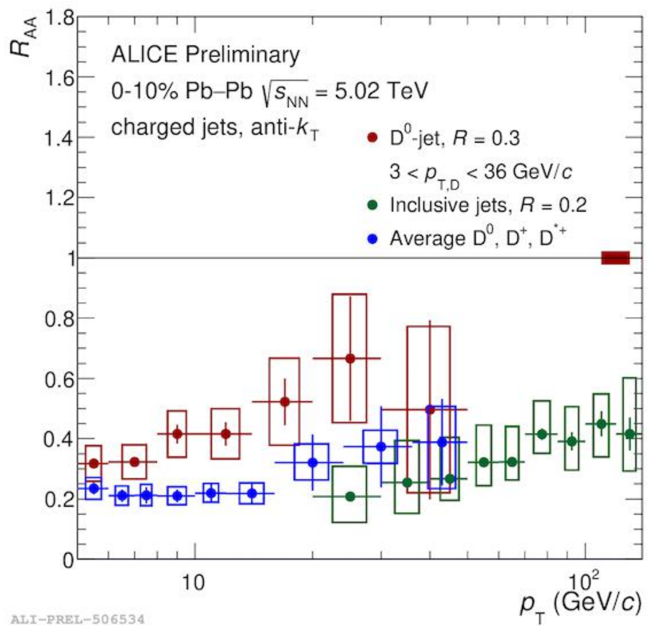

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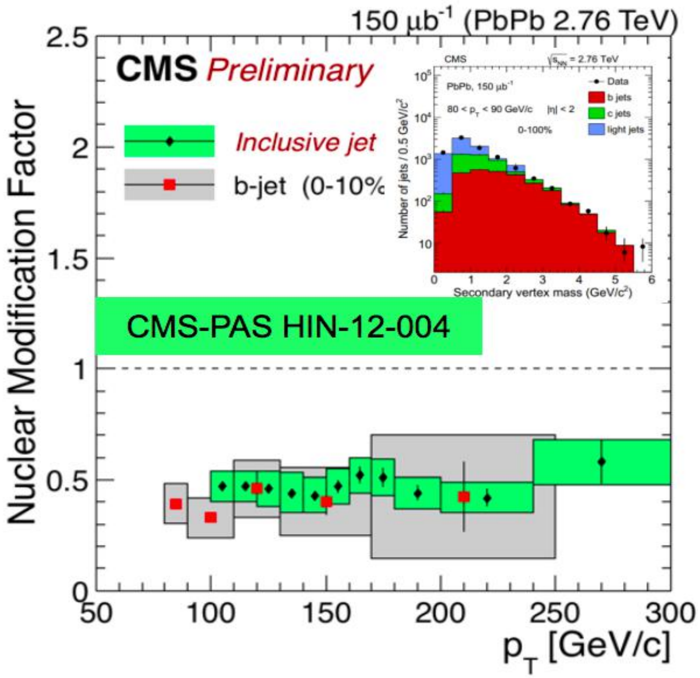

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Precise measurements required at low p_T

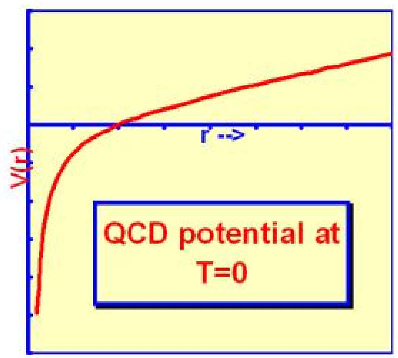
Quarkonia in the QGP

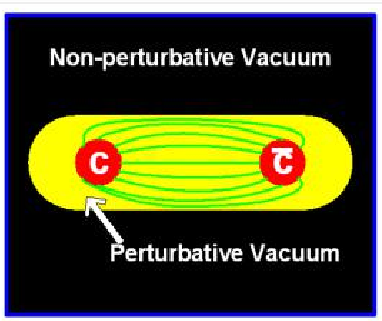
- Dissociation of quarkonia and the "J/Ψ puzzle"
- Temperature of the QGP

Quarkonia in the QGP

- Quarkonium: bound state of a quark-antiquark pair
  - Charmonium $(c\bar{c})$: J/Ψ, Ψ', χ_c
  - Bottomonium $(b\bar{b})$: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_B

$$V = -\frac{\alpha_s(r)}{r}$$





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- Debye-screening

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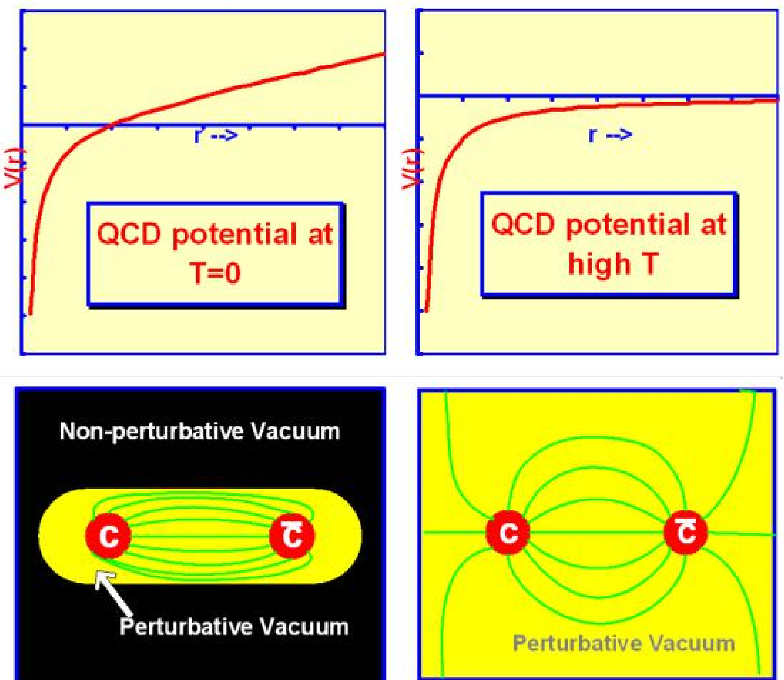

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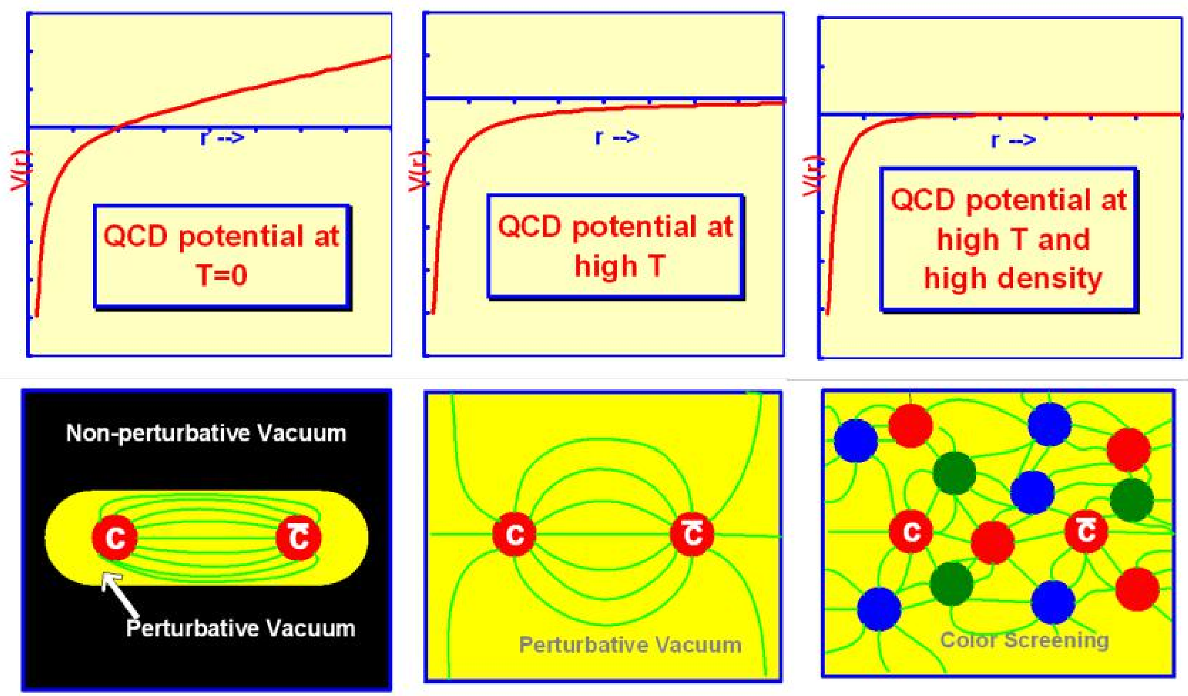
- Debye-screening → dissociation in the QGP

T. Matsui, H. Satz, Phys.Lett. B178, 416 (1986)

Debye-screening

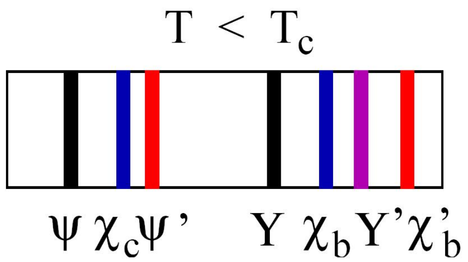
$$V = -\frac{\alpha_s(r)}{r}\exp\left(\frac{-r}{r_D}\right)$$

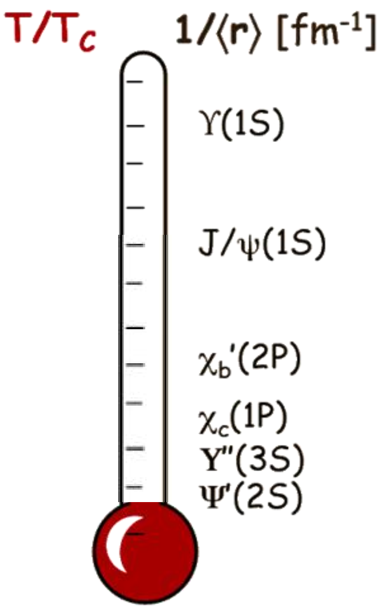
$$r_D \propto \frac{1}{\sqrt[3]{n}}$$



The quarkonium-thermometer

- Sequential dissociation:
  The “melting” temperature of individual quarkonium states depend on the bounding energy





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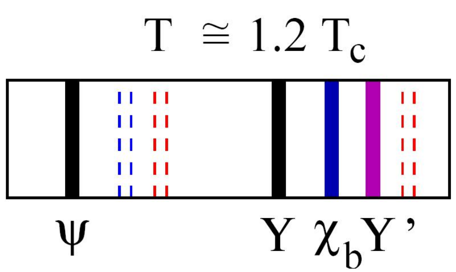

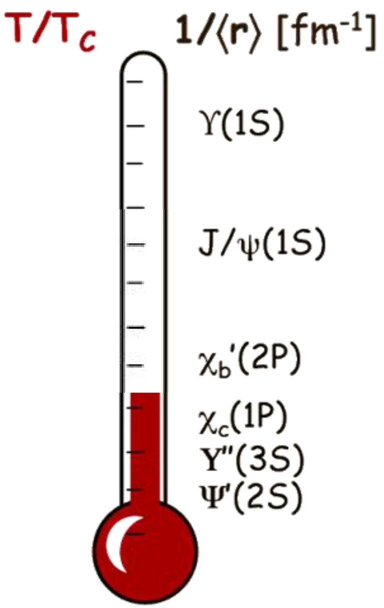

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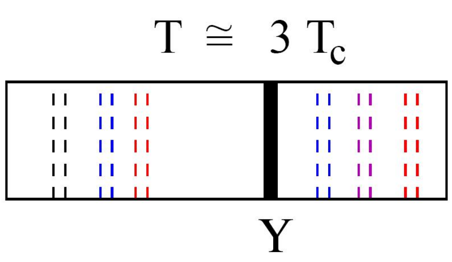

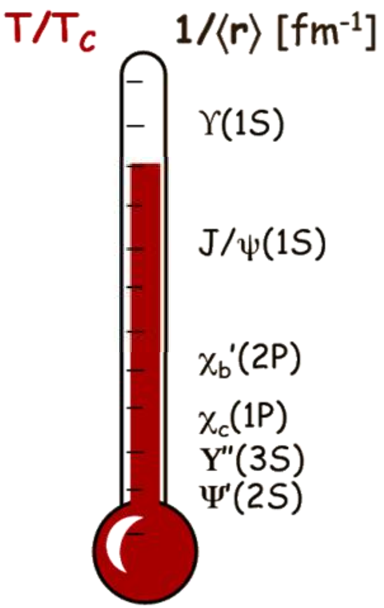

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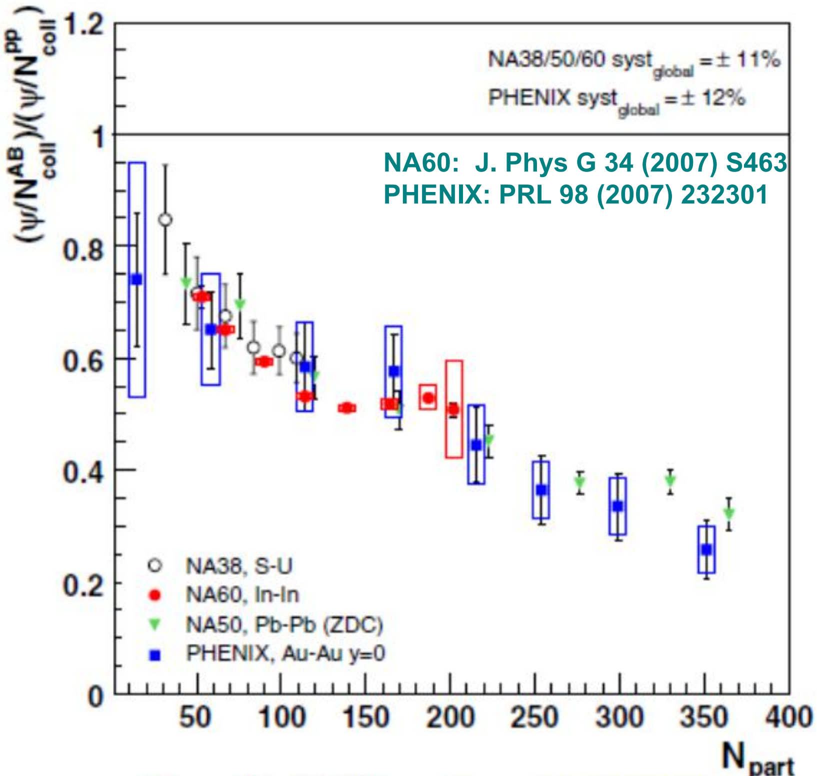
"The J/ψ-puzzle"



R_{AA} @ SPS = R_{AA} @ RHIC

- Strong suppression already at SPS energies! ($\sqrt{s_{NN}}$=17-22 GeV)
- **Suppression at RHIC 200 GeV** collisionss is **~identical to SPS**

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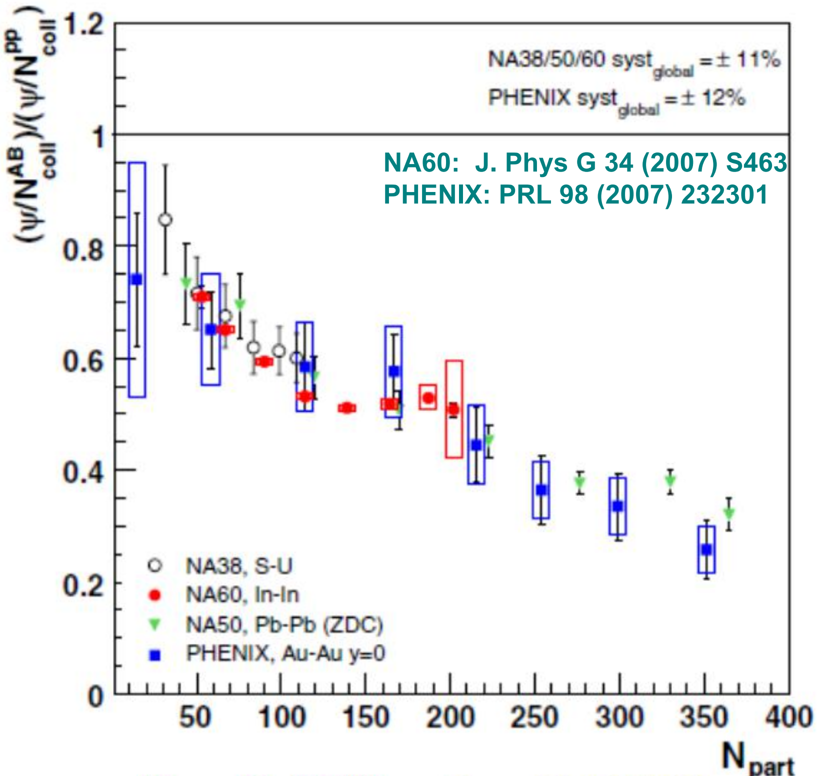

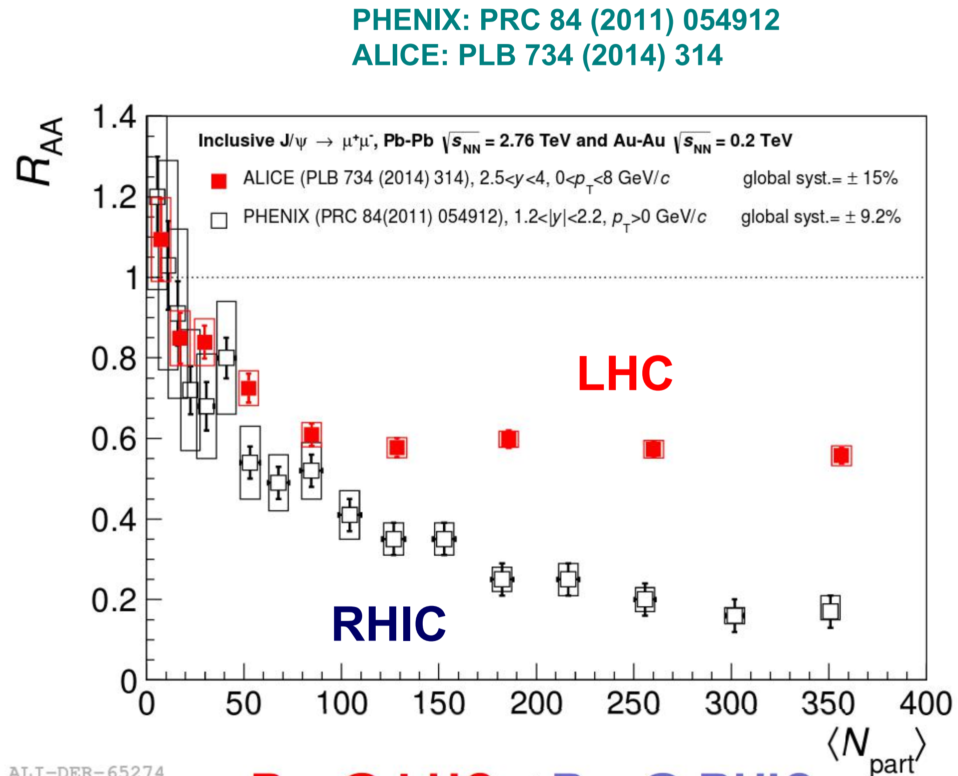

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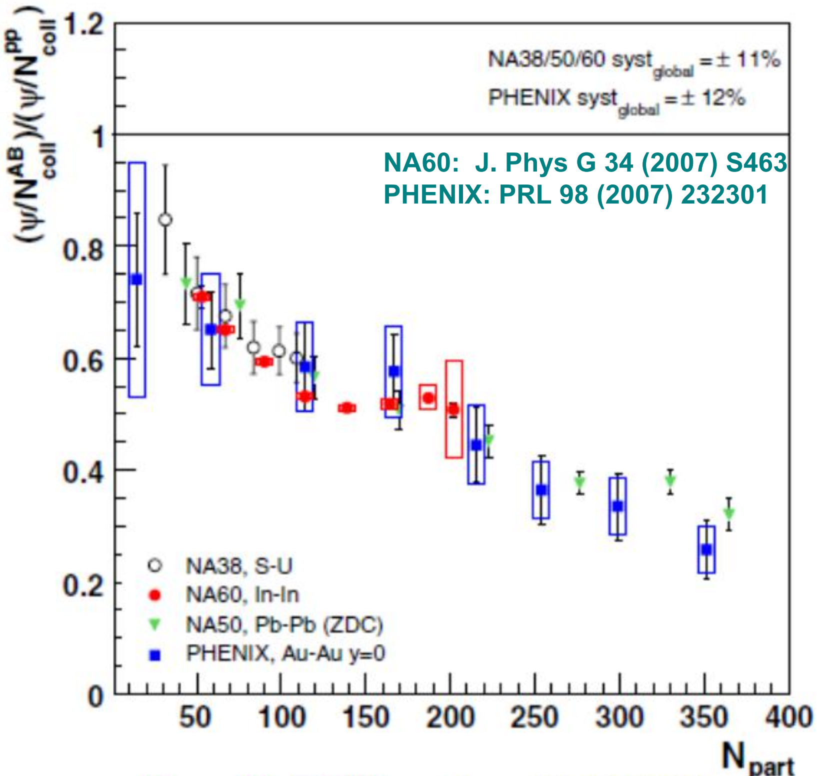
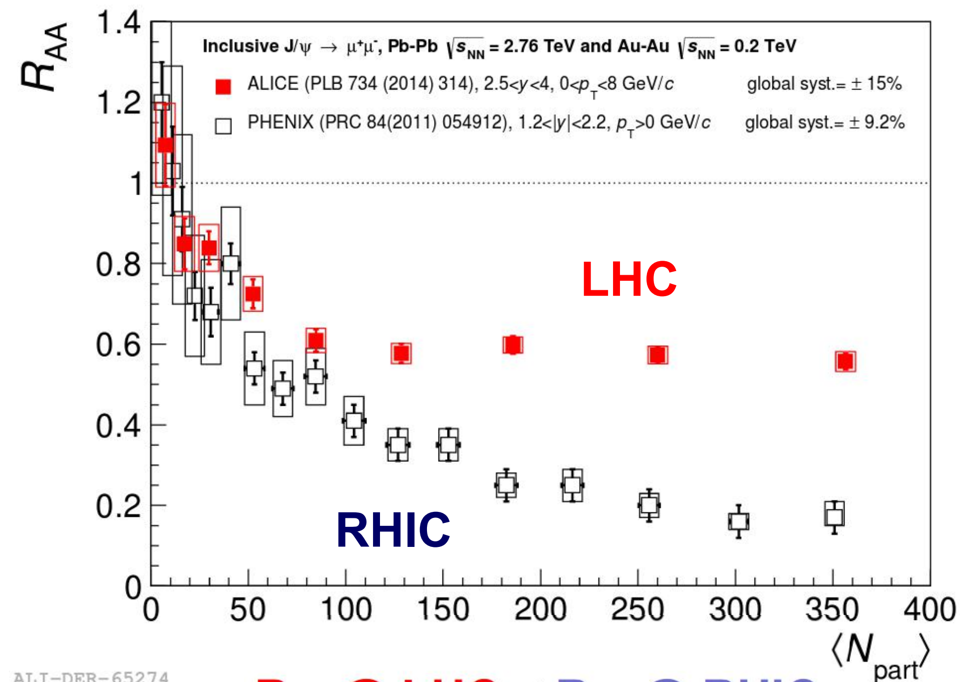


R_{AA}@ SPS = R_{AA}@ RHIC

PHENIX: PRC 84 (2011) 054912
ALICE: PLB 734 (2014) 314



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How is it possible ???

Life is not so simple...

- **Cold nuclear matter effects**
  - Nuclear shadowing (modification of the PDF in the nucleus)
  - Initial state energy loss
  - Co-mover absorption
- **Effects of the hot medium**
  - Quarkonium dissociation
  - Coalescence of uncorrelated cc and bb pairs
- **Chain decays (feed-down)**
  - c_c, ψ', B → J/ψ
  - c_b, ϒ(2S), ϒ(2S) → ϒ(1S) …

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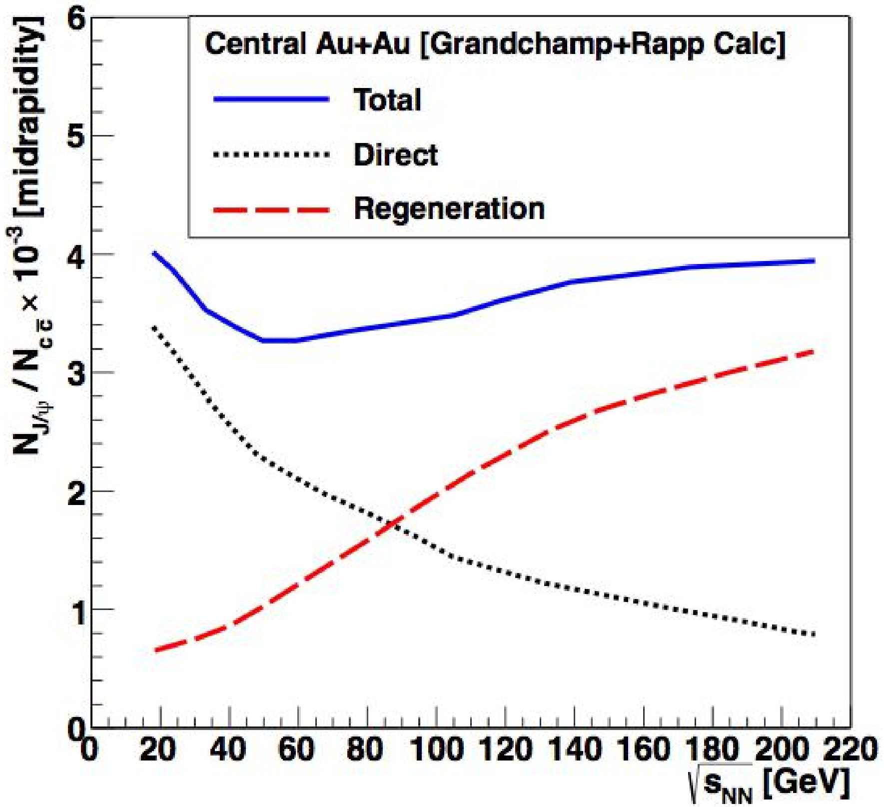
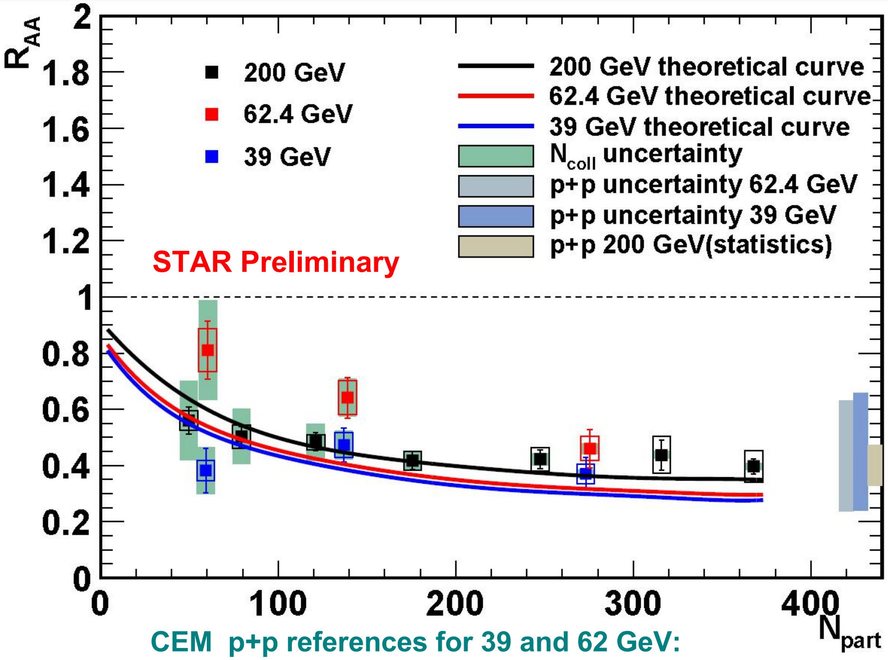
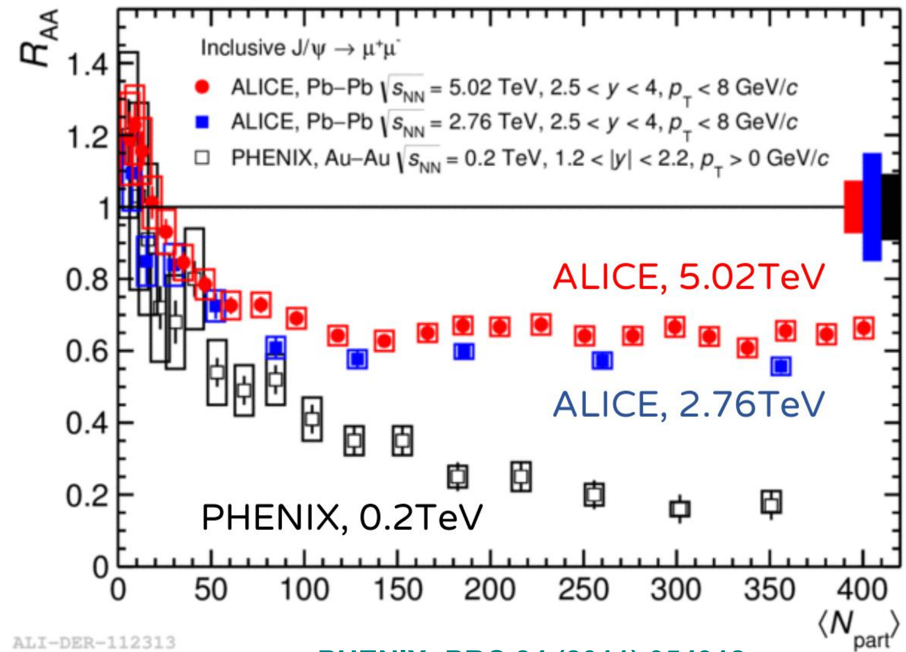


Dissociation and regeneration compete

$R_{AA}^{J/\Psi}$ versus beam energy



CEM p+p references for 39 and 62 GeV:
Nelson, Vogt et al., PRC87, 014908 (2013)
Theory: Zhao, Rapp, PRC82, 064905 (2010)



PHENIX: PRC 84 (2011) 054912
ALICE: PLB 734 (2014) 314

- **RHIC 200**, **62.4** és **39** GeV Au+Au collisions: similar modification
  Note: p+p reference from CEM calculations with large uncertainty

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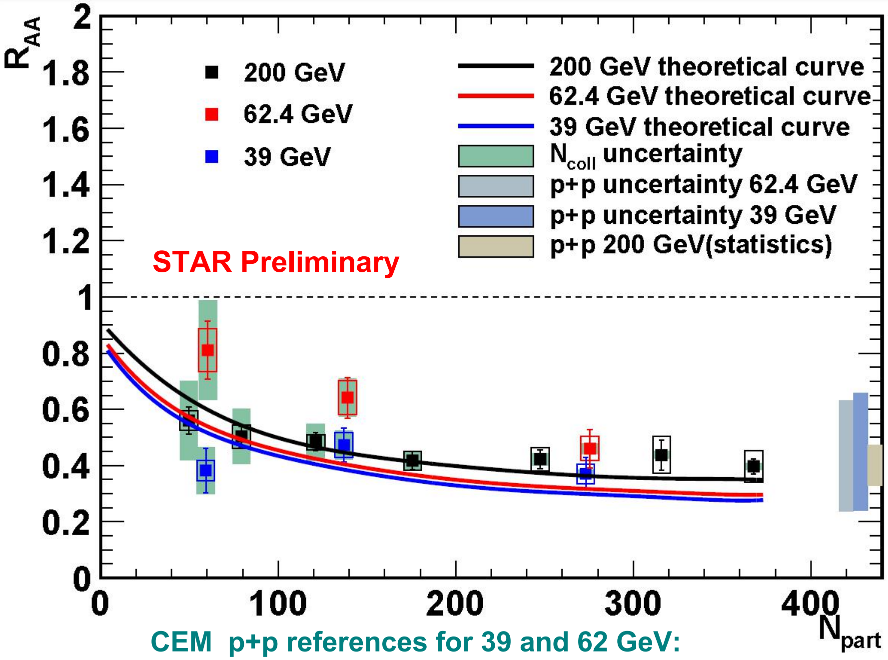
$R_{AA}^{J/\Psi}$ versus beam energy



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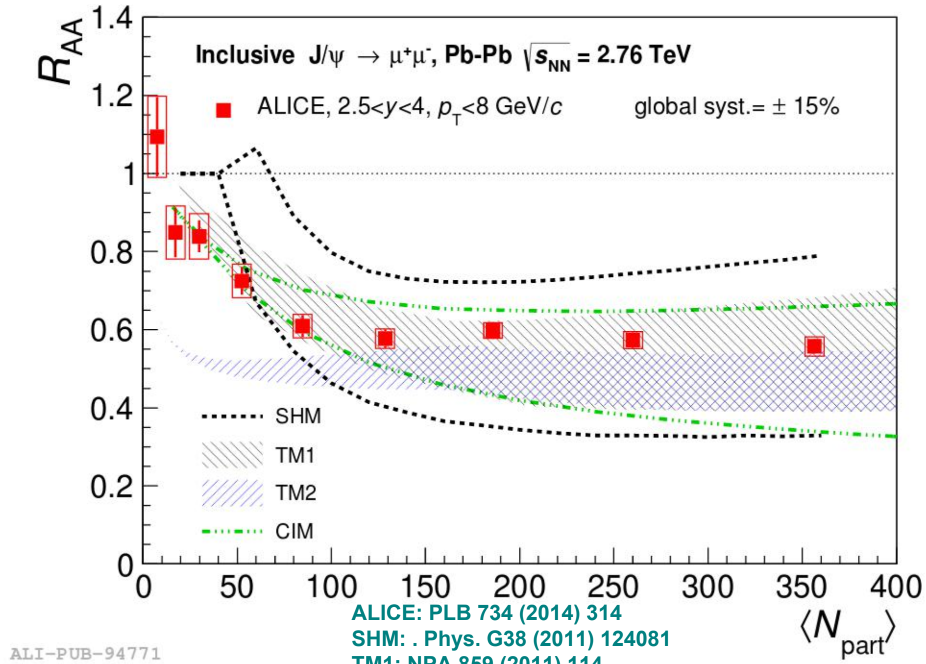
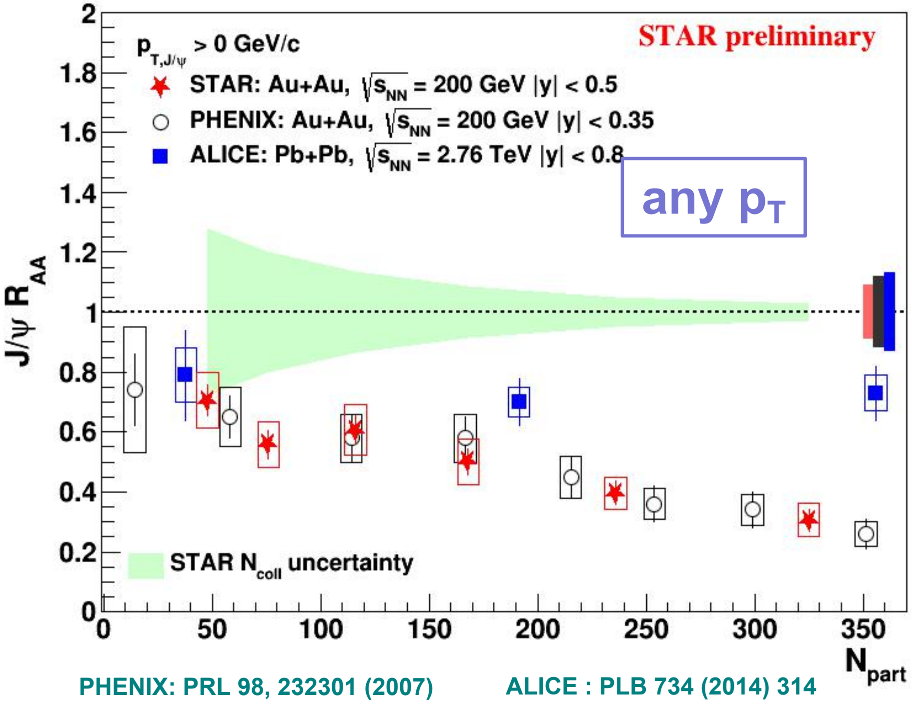


ALICE: PLB 734 (2014) 314
SHM: . Phys. G38 (2011) 124081
TM1: NPA 859 (2011) 114
TM2: PRC 89 (2014) 054911
CIM: PLB 731 (2014) 57

- **RHIC 200**, **62.4** és **39** GeV Au+Au collisions: similar modification
  Note: p+p reference from CEM calculations with large uncertainty
  - **Dissociation ~ Regeneration**
- **LHC 2.76 TeV, 5 TeV** central Pb+Pb: way weaker modification
  - **Dissociation < Regeneration**

Regeneration compensates, then overcomes dissociation

$R_{AA}^{J/\Psi}$: low and high momenta



PHENIX: PRL 98, 232301 (2007)
STAR: SQM 2016
ALICE : PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063

- p_T>0 central: stronger suppression at RHIC than at the LHC

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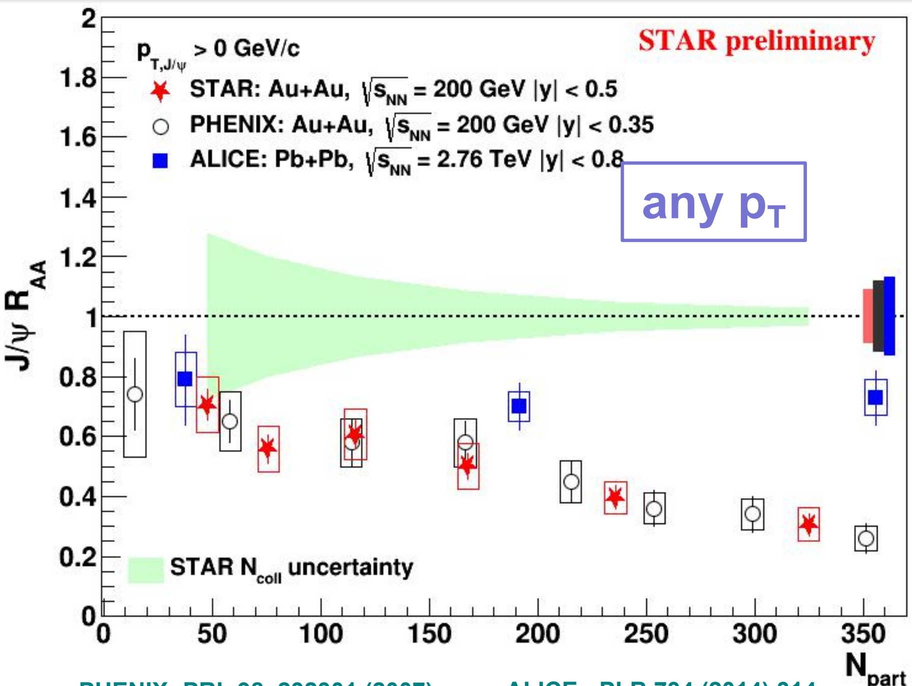

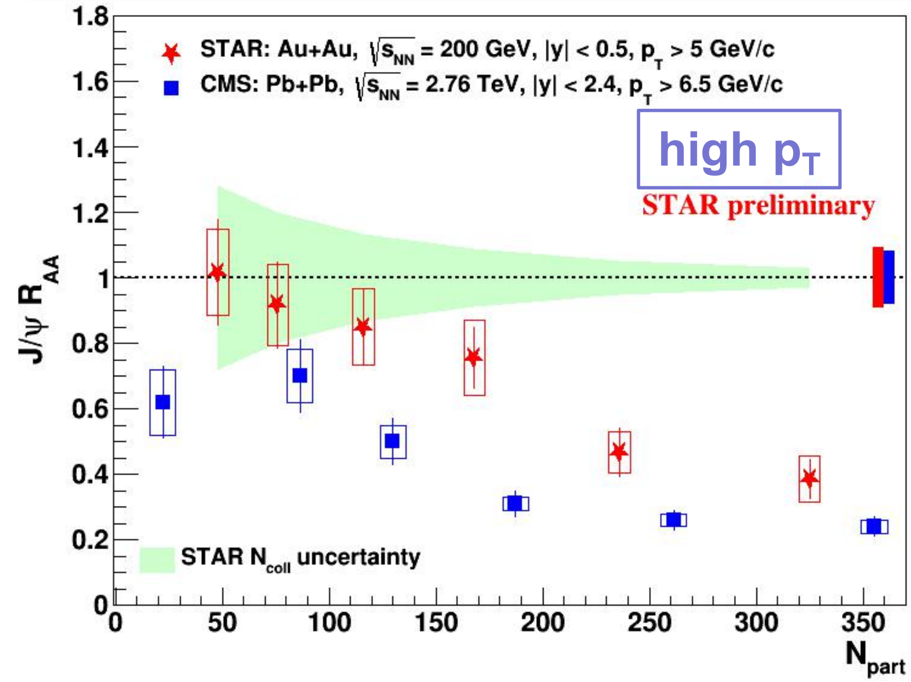

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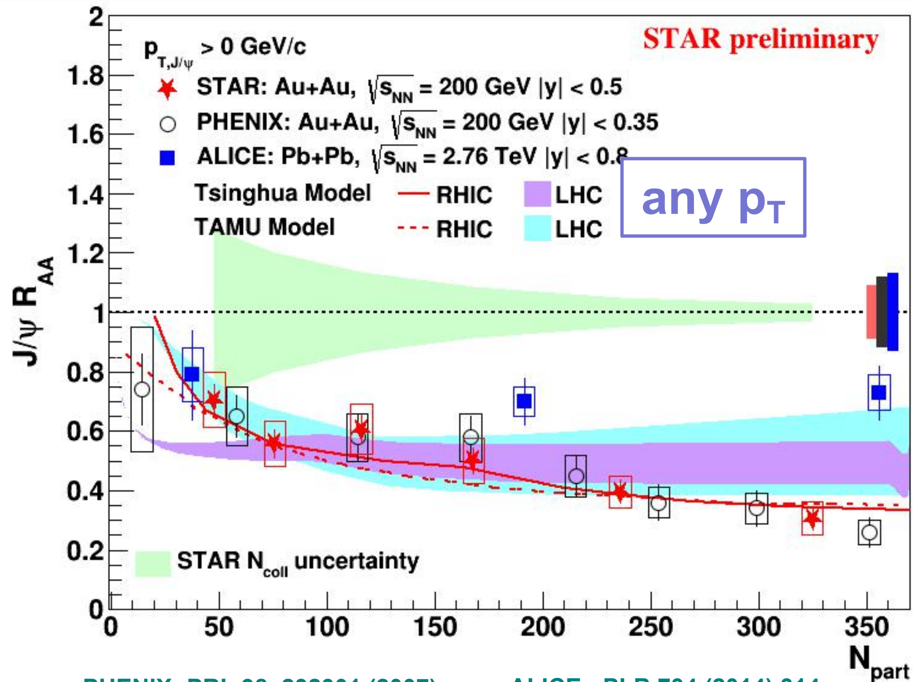

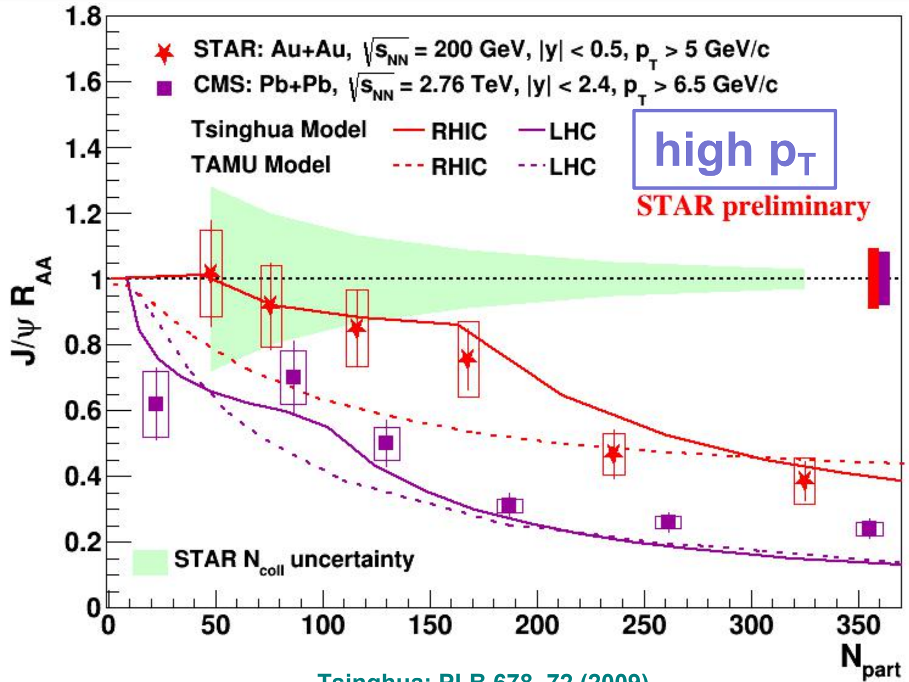

PHENIX: PRL 98, 232301 (2007)
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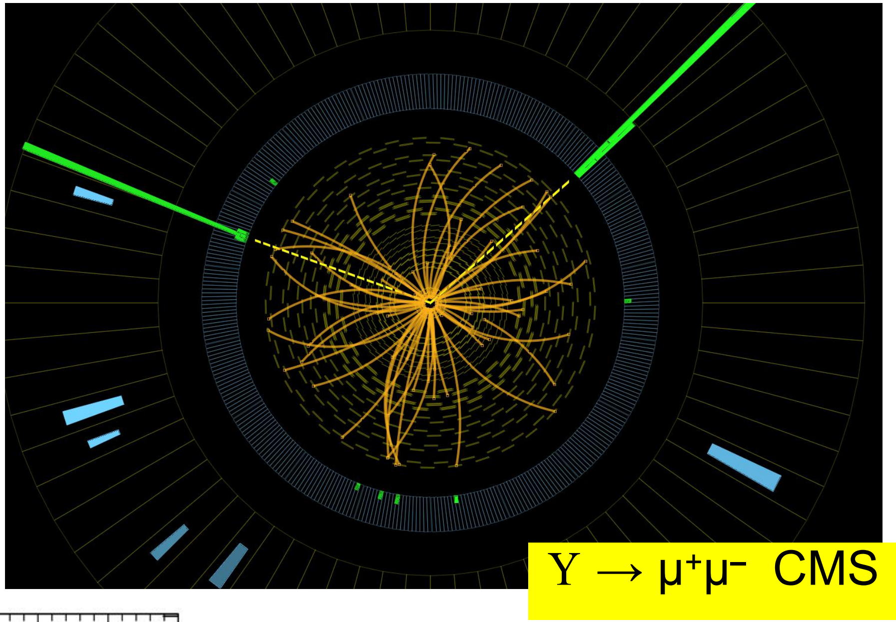
Tsinghua: PLB 678, 72 (2009)
TAMU: PRC 83, 014914 (2011)

- p_T>0 central: stronger suppression at RHIC than at the LHC
- High p_T, any centrality: stronger suppression at LHC
  - Models include: **dissociation, CNM, regeneration, feed-down**

High-p_T J/Ψ suppression is the effect of the sQGP

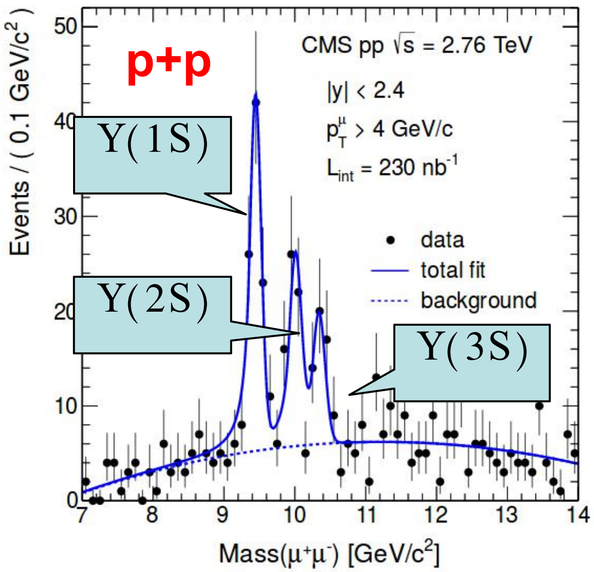
Upsilon mesons

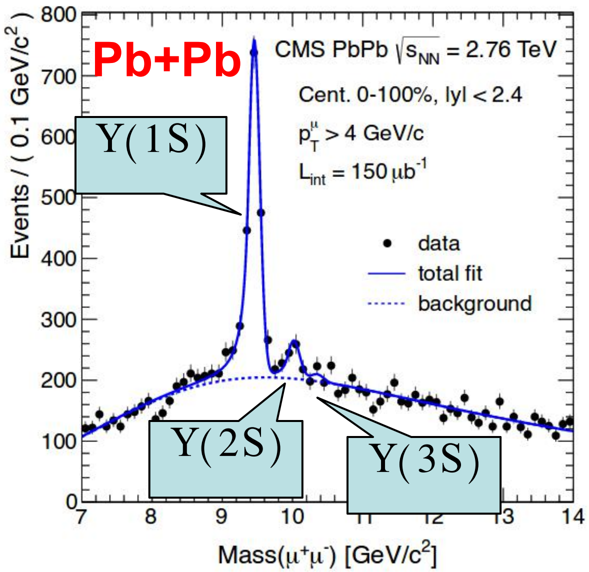
- Bottomonium:
  - Way less production than charm
  - Negligible regeneration
  - Weaker CNM effects



Reconstructed invariant mass

$$m^2 = E^2 - \mathbf{p}^2 = (E_1 + E_2)^2 - (\mathbf{p_1} + \mathbf{p_2})^2$$

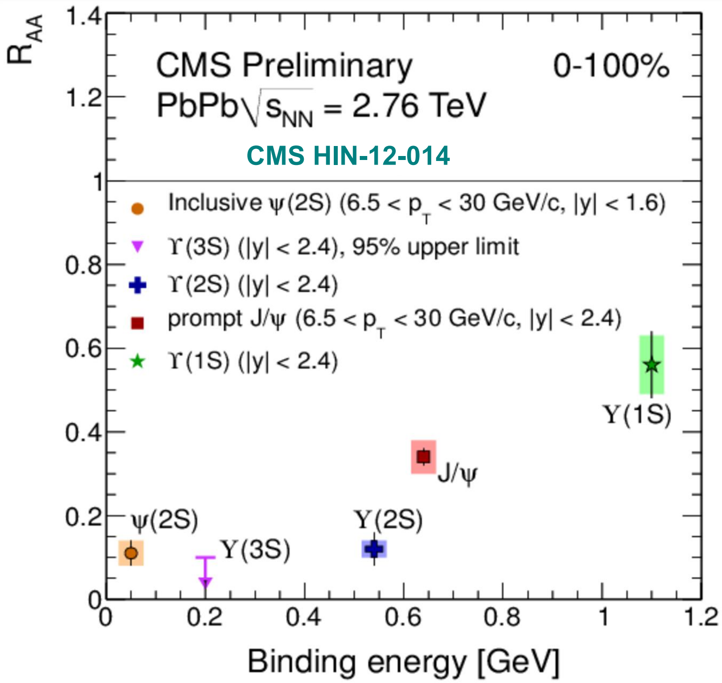


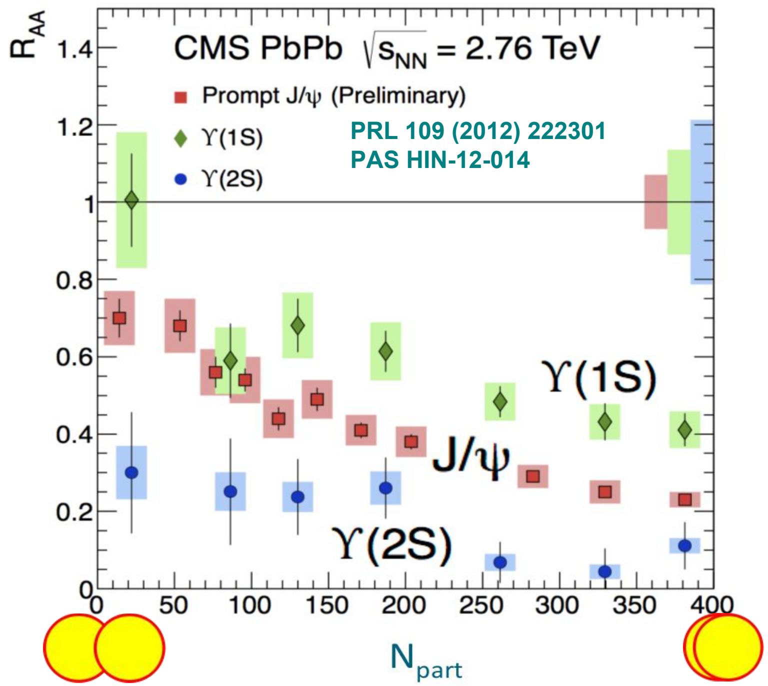


Computing the yield (p+p and Pb+Pb)

- Determine background
- Calculate peak area
- Normalize with the number of collisions

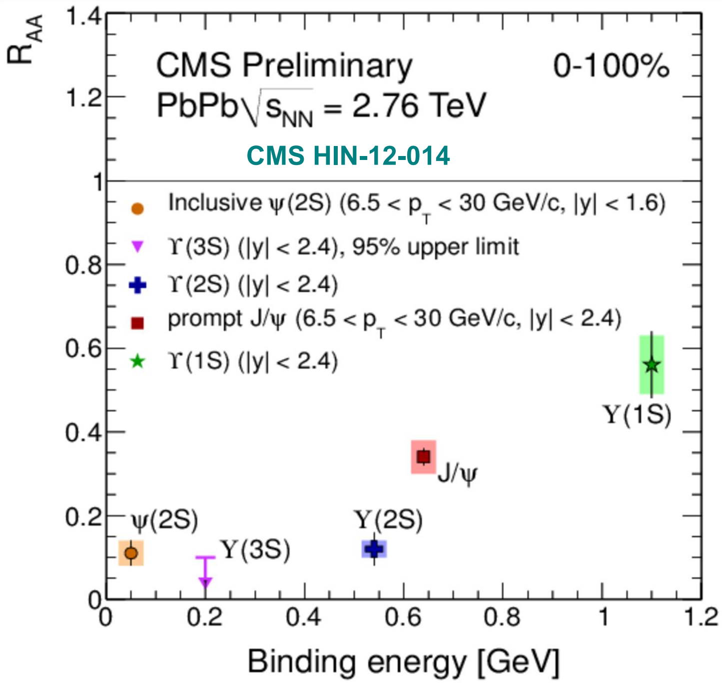
R_{AA} and temperature (LHC)

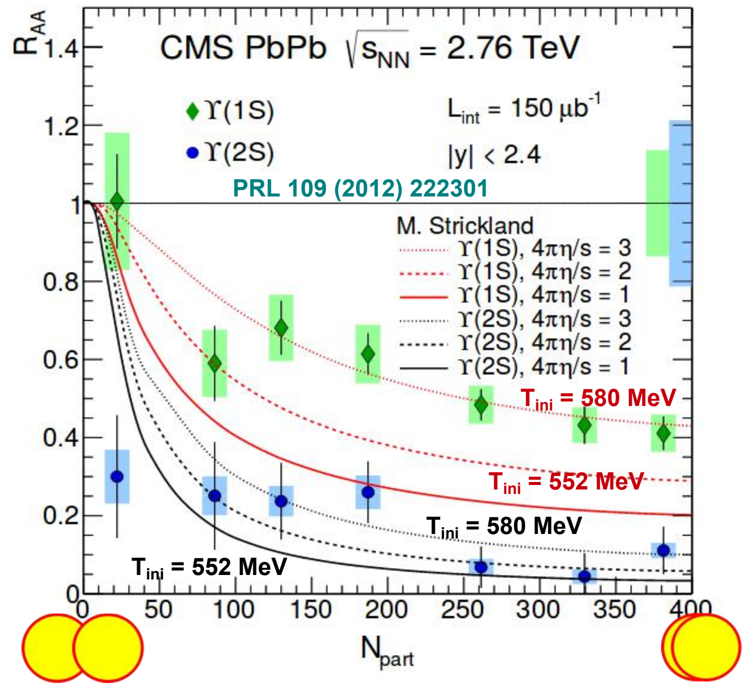




- Lower binding energy
  → stronger nuclear modification
- Central collisions
  → stronger nuclear modification

R_{AA} and temperature (LHC)





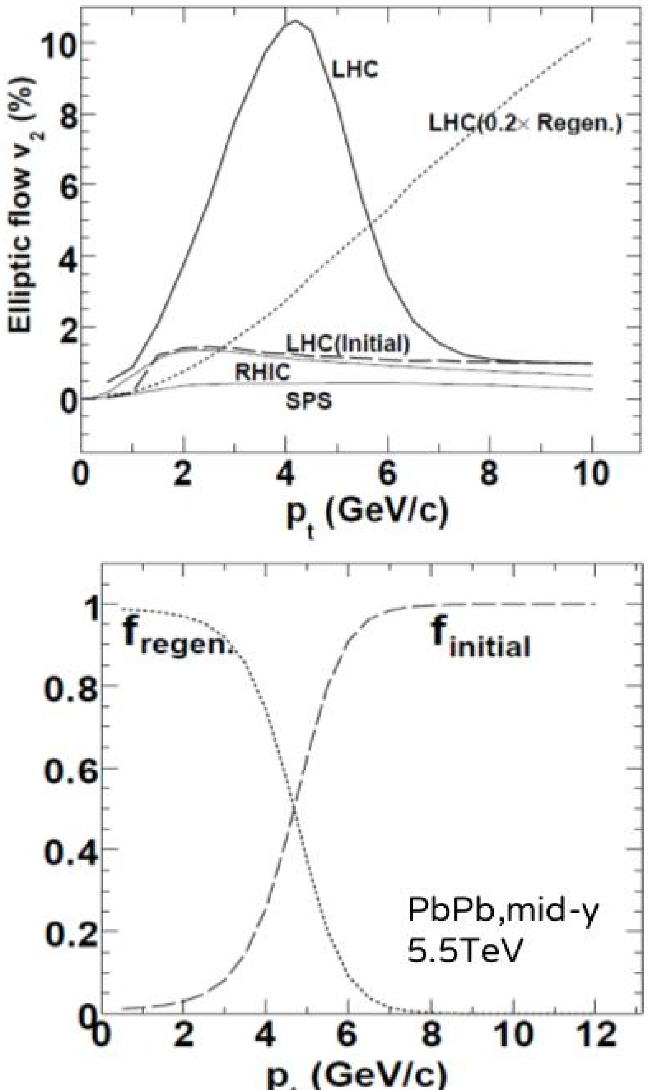
- Lower binding energy
  → stronger nuclear modification

- Central collisions
  → stronger nuclear modification

- **Initial temperature of the QGP** from model calculations:
  - **RHIC** $\sqrt{s_{NN}}$=**200 GeV** Au+Au: **T_{ini} ~300 - 440 MeV**
  - **LHC $\sqrt{s_{NN}}$=2.76 TeV** Pb+Pb: **T_{ini} ~500 - 610 MeV**
  - **LHC** $\sqrt{s_{NN}}$=**5.02 TeV** Pb+Pb: **T_{ini} ~600 - 700 MeV**

NPA 879 (2012), 25
Eur.Phys.J A48 (2012) 72
PLB 697 (2011) 32
Universe 2 (2016), 16

Collective dynamics and J/ψ



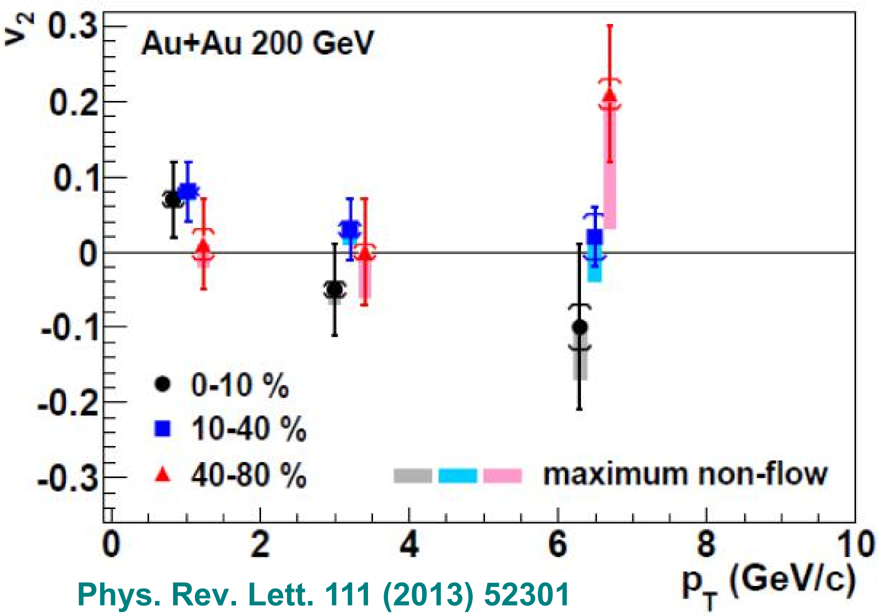
N. Xu et al, NPA834(2010) 317c

Expectation based on model calculations:

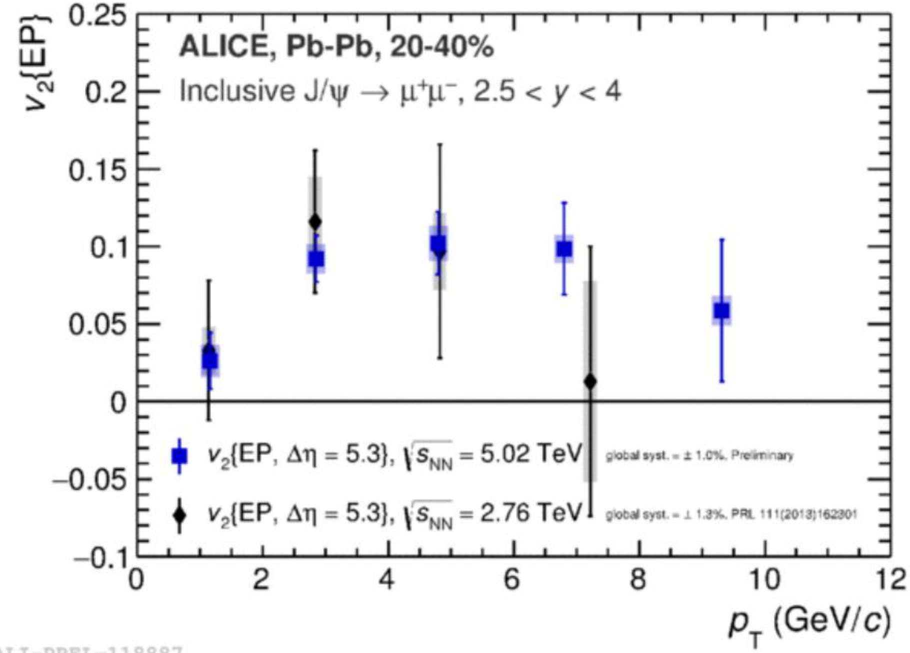
- J/ψ produced in pQCD processes does not take part in collectivity
- J/ψ produced via thermalized regeneration will flow together with other hadrons

→ J/ψ v_2 is expected to be much smaller at RHIC than at LHC energies

Collective dynamics and J/ψ

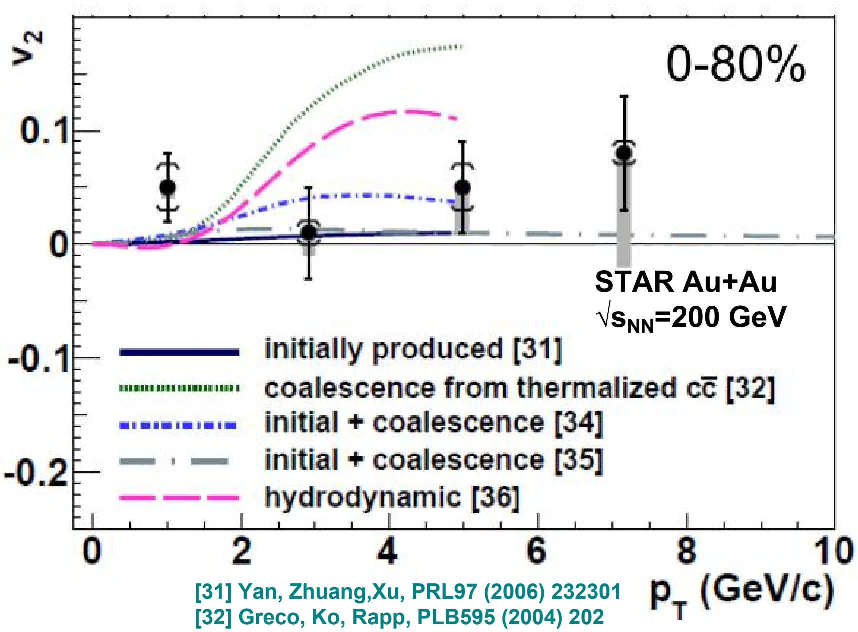


Phys. Rev. Lett. 111 (2013) 52301

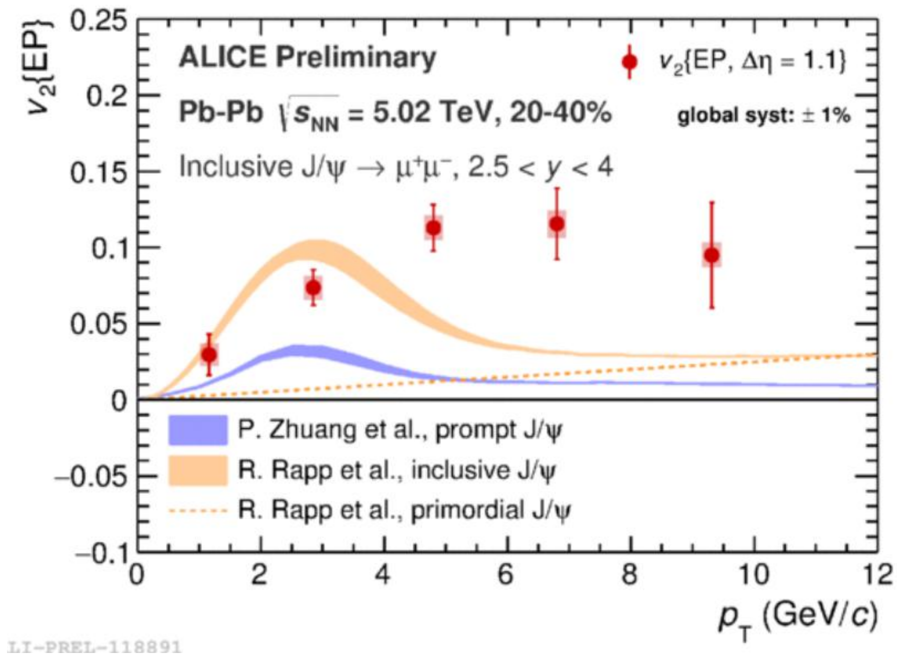


- RHIC 200 GeV: p_T>2 GeV/c J/ψ does not exhibit elliptic flow (v_2)
  - Contrary to open heavy-flavor!
- LHC 2.76 TeV and 5 TeV: sizeable elliptic flow

Collective dynamics and J/ψ



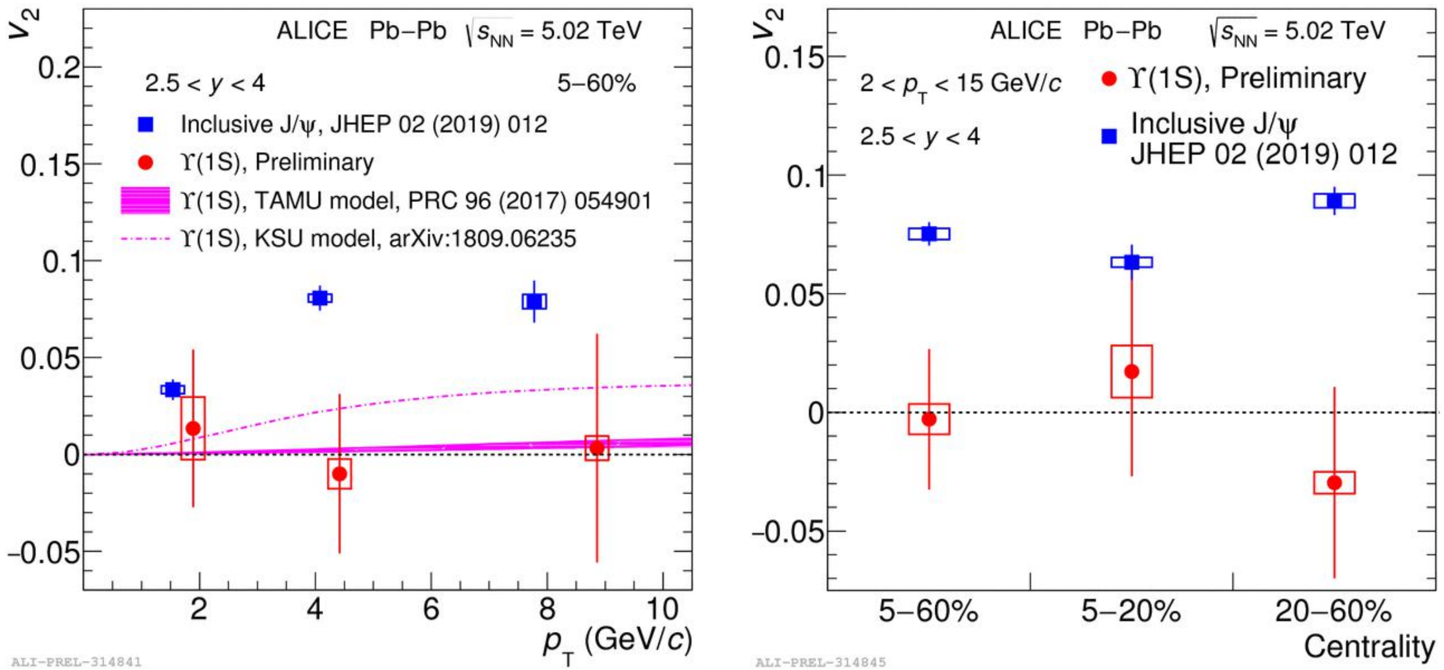
[31] Yan, Zhuang,Xu, PRL97 (2006) 232301
[32] Greco, Ko, Rapp, PLB595 (2004) 202
[34] Zhao, Rapp, PLB 655 (2007) 126
[35] Liu,Xu,Zhuang, NPA834 (2010) 317c
[36] Heinz, Chen (2012)



- RHIC 200 GeV: p_T>2 GeV/c J/ψ does not exhibit elliptic flow (v_2)
  - Contrary to open heavy-flavor!
- LHC 2.76 TeV and 5 TeV: sizeable elliptic flow
  - *Note: only qualitative match with models*

Thermalized cc̄ coalescence becomes dominant at LHC

Anisotropy of bottomonium: Υ(1S)



- v_2 consistent with 0 : **Only hadron at the LHC**
  - Early production, decouples from medium
  - Later recombination is not strong (#b<<#c)

Summary and Outlook

- Open heavy flavor production
- Quarkonia in the QGP
- The future of heavy-flavor physics

Summary - open heavy flavor

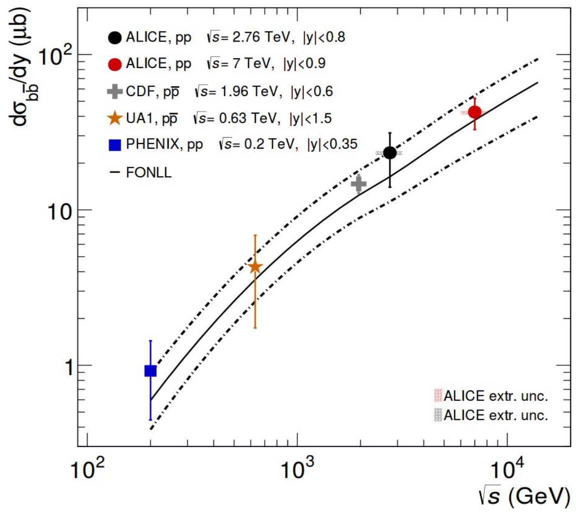
- **pp collisions:** serve as pQCD model tests. Production cross-sections vs. p_T of c and b quarks are well described by models
- **p(d)-A collisions**: CNM effects are weak at mid-rapidity at LHC energies. No proof for modification of particle yields or jets.
- **A-A collisions**: **Tomography of the QGP.** Penetrating probe down to low p_T. Understanding energy loss and collective behavior.
  - **Low p_T**: relative enhancement in nuclear modification (R_{AA}) compared to light flavor, and a strong collectivity (v_2).
    - Coalescence of charm and the flowing medium
    - Local thermal equilibrium of D-mesons with the medium?
  - **Mid-p_T** : charm: D meson R_{AA}
beauty: non-prompt J/Ψ
    - $R_{AA}^{\pi} \sim R_{AA}^{D}$ (consistent with the $\Delta E_{u,d,s} > \Delta E_c$ expectations)
    - $R_{AA}^{D} < R_{AA}^{B}$ (agrees the $\Delta E_c > \Delta E_b$ expectations)
  - **Very high p_T** - jets containing b-quarks
    - $R_{AA}^{\text{inclusive jet}} \sim R_{AA}^{\text{b-jet}}$ (needs explanation!)

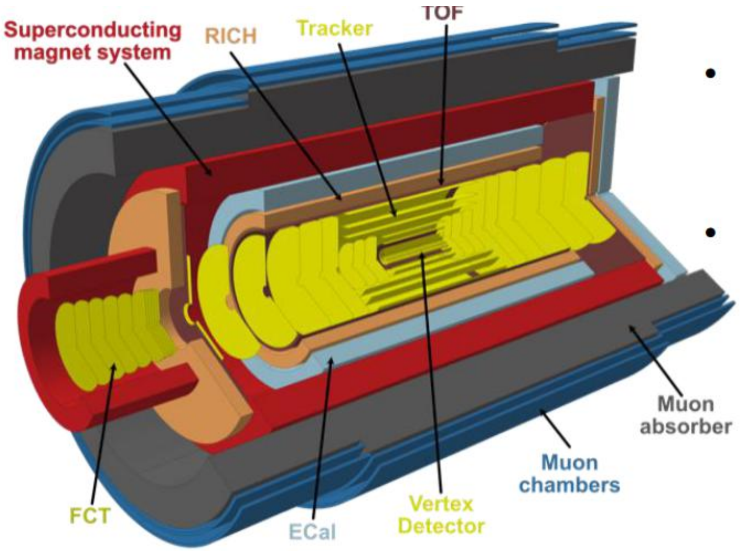
Summary - quarkonia

- **The J/Ψ puzzle** - Dissociation and regeneration
  - R_{AA}(39 GeV) ~ R_{AA}(200 GeV) < R_{AA}(2.75 TeV)
    - ➢ At RHIC energies, regeneration compensates for dissociation
    - ➢ At LHC energies, regeneration overcomes dissociation
  - v_2(200 GeV) is very low
    v_2(2.75 TeV) is similar to that of D mesons
    - ➢ Early, direct pQCD J/Ψ production dominates at RHIC energies
    - ➢ Regeneration in the flowing medium dominates at LHC energies
- **"Clean probes"** - Bottomonium and high-momentum J/Ψ
  - R_{AA}(200 GeV) > R_{AA}(2.75 TeV) - according to original expectations
  - No significant v_2 of $\Upsilon(1S)$
  - Less regeneration, CNM effect than in the low-momentum J/Ψ case
- **Sequential dissociation, sQGP-thermometer**
  - Weakly bound quarkonium states experience stronger suppression:
    $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{J/\Psi} < R_{AA}^{\Upsilon(1S)}$
  - T_{ini} @ LHC ~ 500-700 MeV; T_{ini} @ RHIC ~ 300-450 MeV,

Outlook

- The RHIC Era (2000-)
  - Finding the QGP
  - Understanding its basic properties
  - Precision light quark measurements
  - **First heavy-flavor measurements**
- The RHIC-II/early LHC era (2010-)
  - Higher energies
  - More luminosity, more precision
  - **Precision charm & first beauty measurements**
- The LHC Run-3 era (2022-)
  - Upgraded facilities, detectors
  - x100 luminosity at LHC
  - **Detailed beauty & charm baryon sector**
- Future detectors: ALICE3 (~2030)
  - Full/mostly silicon-based detector
  - **A heavy-flavor factory for multi-differential measurements**





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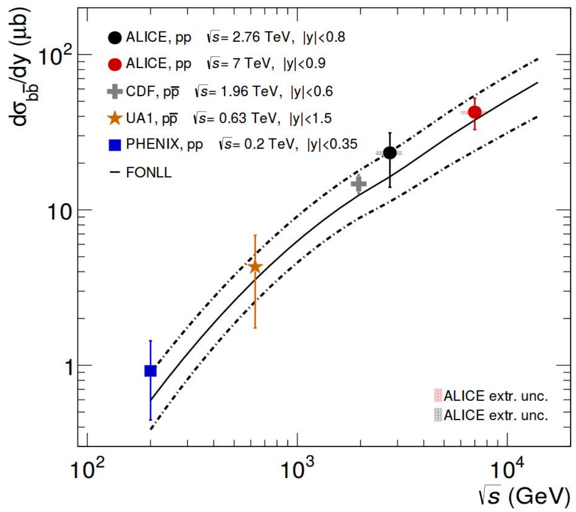
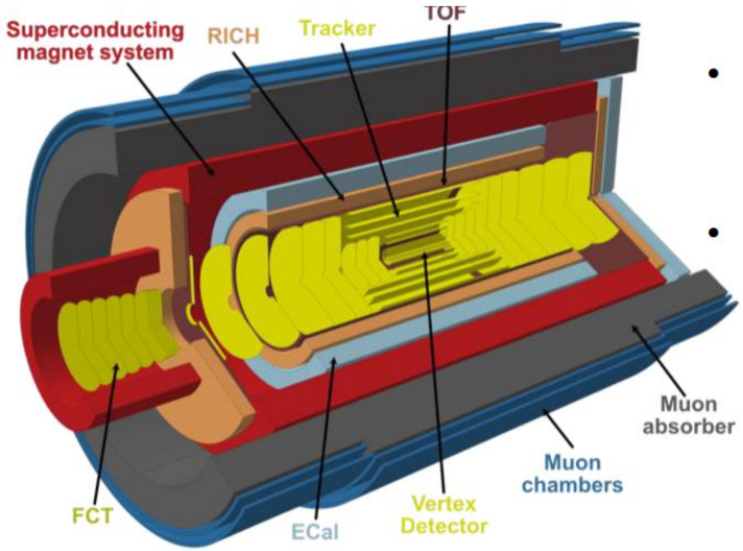




Era of the heavy quarks

The ALICE-Budapest group

Analysis group

Wigner RCP Hadron Physics

http://hadronphysics.wigner.hu

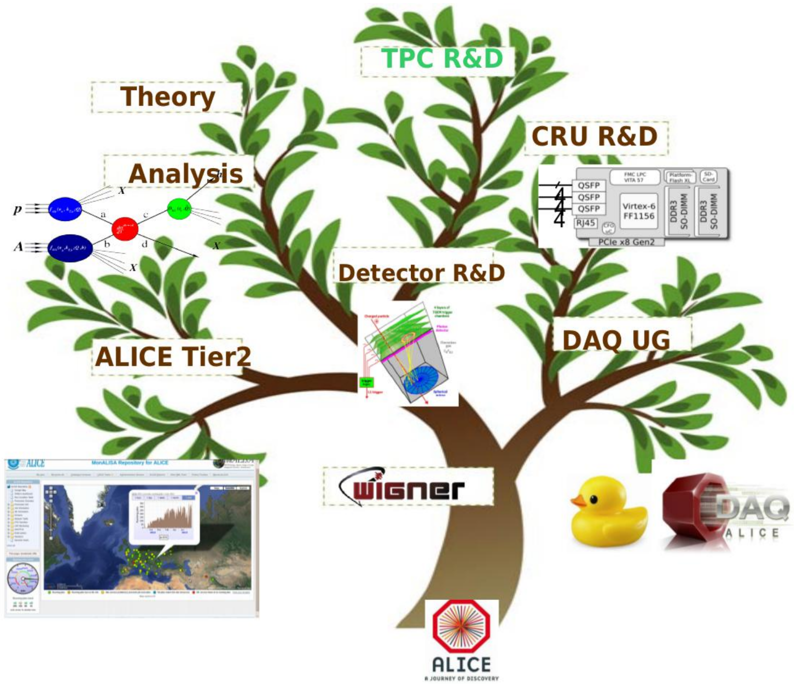
Experiment & phenomenology

- Heavy-flavor: jet substructure, correlations, meson and baryon fragmentation
- Small systems: semi-soft region of QCD, droplets of QGP, underlying event
- High-p_T spectra of light-flavor hadrons

People

- Róbert Vértesi
- Varga-Kőfaragó Mónika
- Aditya Nath Mishra
- Gyula Bencédi
- László Gyulai
- Zoltán Varga
- Zsófia Jólesz
- Endre Futó
- Anikó Horváth
- Szende Sándor

http://alice.kfki.hu



G.G. Barnaföldi: Wigner ALICE Group

contacts:

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Péter Lévai

Róbert Vértesi

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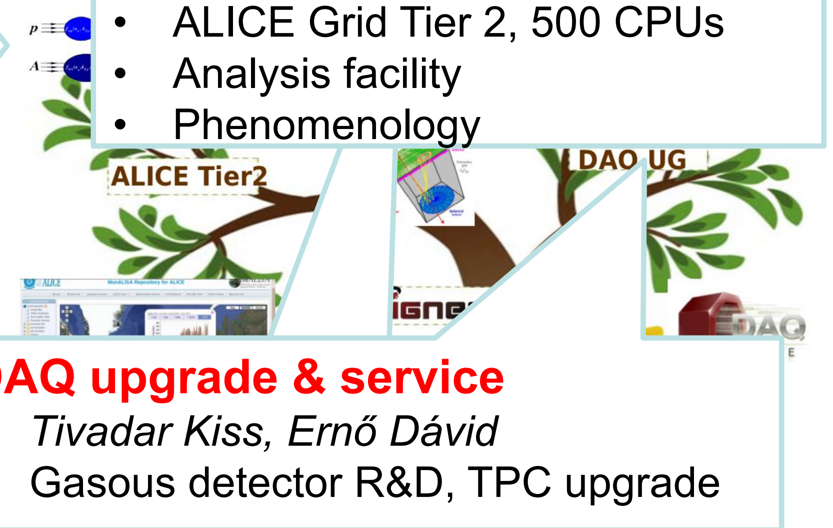
- Szende Sándor

Theory & Computing

Gergely Gábor Barnaföldi, Péter Lévai, Gábor Bíró, A.N. Mishra, Zs. Jólesz, L. Gyulai

- ALICE Grid Tier 2, 500 CPUs
- Analysis facility
- Phenomenology



DAQ upgrade & service

Tivadar Kiss, Ernő Dávid

- Gasous detector R&D, TPC upgrade

Detector R & D

Dezső Varga, László Boldizsár, Gergő Hamar, Ádám Gera, Róbert Vértesi

- Gasous detectors:
  TPC upgrade, ALICE3 MID

Thank you!

Róbert Vértesi

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Wigner Research Centre for Physics

Hadron physics research group

http://hadronphysics.wigner.hu

ALICE-Budapest group

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