Heavy-ion experiments recent results

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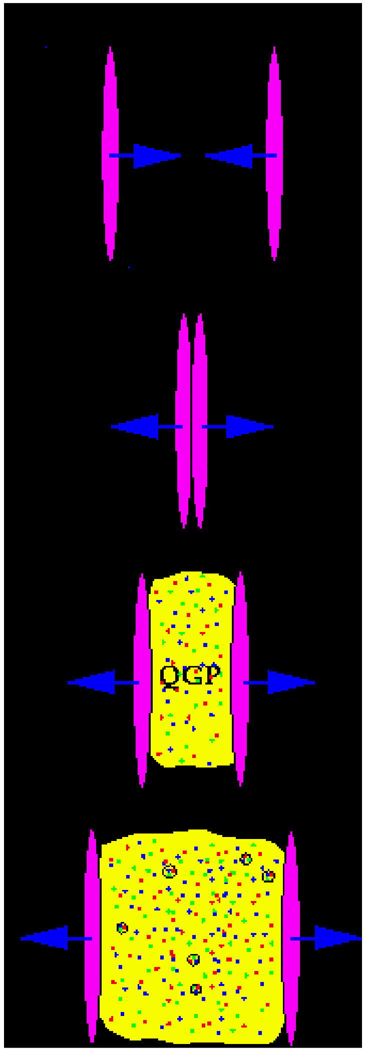
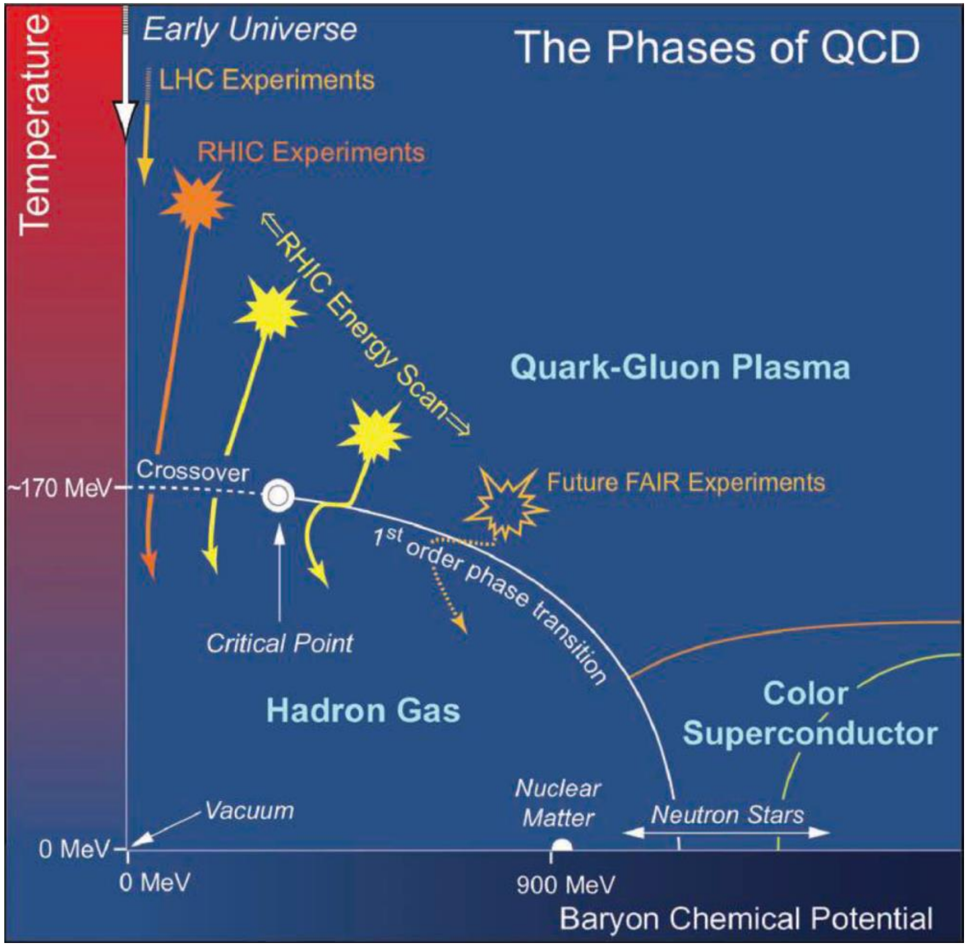
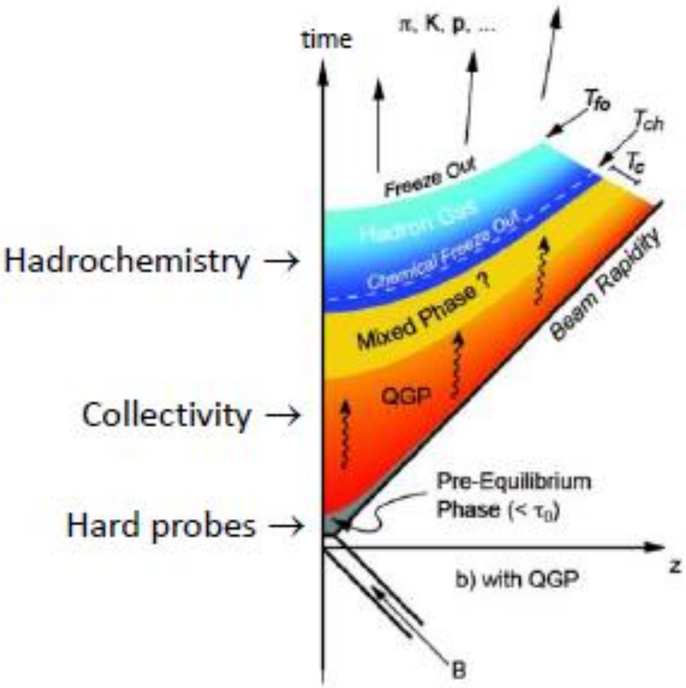
Heavy-ion collisions

- High-energy heavy-ion collisions: an effective way to concentrate a large amount of energy in a small volume
- This lead to the creation of a «fireball» of hot and dense QCD matter → under extreme conditions, phase transition to a deconfined QCD medium, according to QCD predictions.
- Experimental evidences for QGP already observed
- Current experimental campaigns (at RHIC and LHC) are aimed at a detailed study of the properties of the QCD medium in term of viscosity, opacity, transport properties etc.



Exploring the QCD phase diagram with heavy-ion beams at high energy

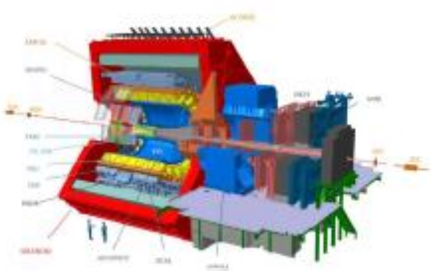


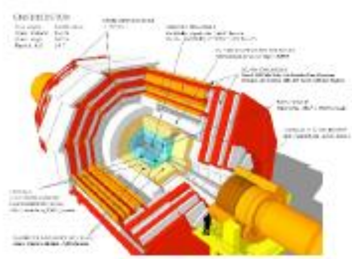


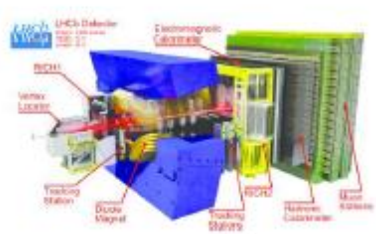
A selection of results on observables related to the different steps of the time evolution of the system is presented in this talk

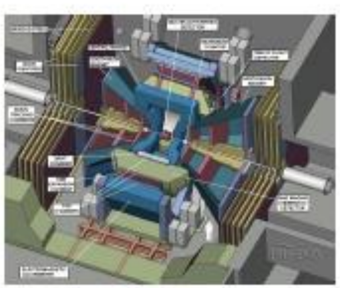
Heavy-ion paralle session: broad-scope talks by A. Ohlson and R. Snellings

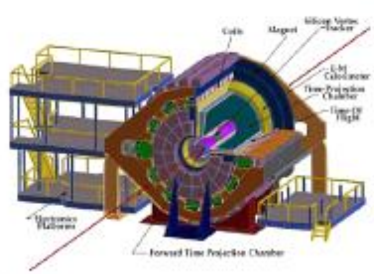
Exploring the QCD phase diagram with heavy-ion beams at high energy











LHC: ALICE, ATLAS, CMS and LHCb(*)

The collected data include:

→ Pb-Pb at $\sqrt{S_{NN}}$ = 2.76, 5.02 TeV

→ Xe-Xe at $\sqrt{S_{NN}}$ = 5.44 TeV

→ p-Pb at $\sqrt{S_{NN}}$ = 5.02, 8.16 TeV

→ p-p at different energies

(*) including fixed target mode

RHIC: PHENIX, STAR

The collected data include:

- At RHIC top energy

→ Cu-Cu, Cu-Au, Ru-Ru, Zr-Zr, Au-Au, U-U

→ p-p, p-Al, p-Au, d-Au, 3He-Au

- Energy scan

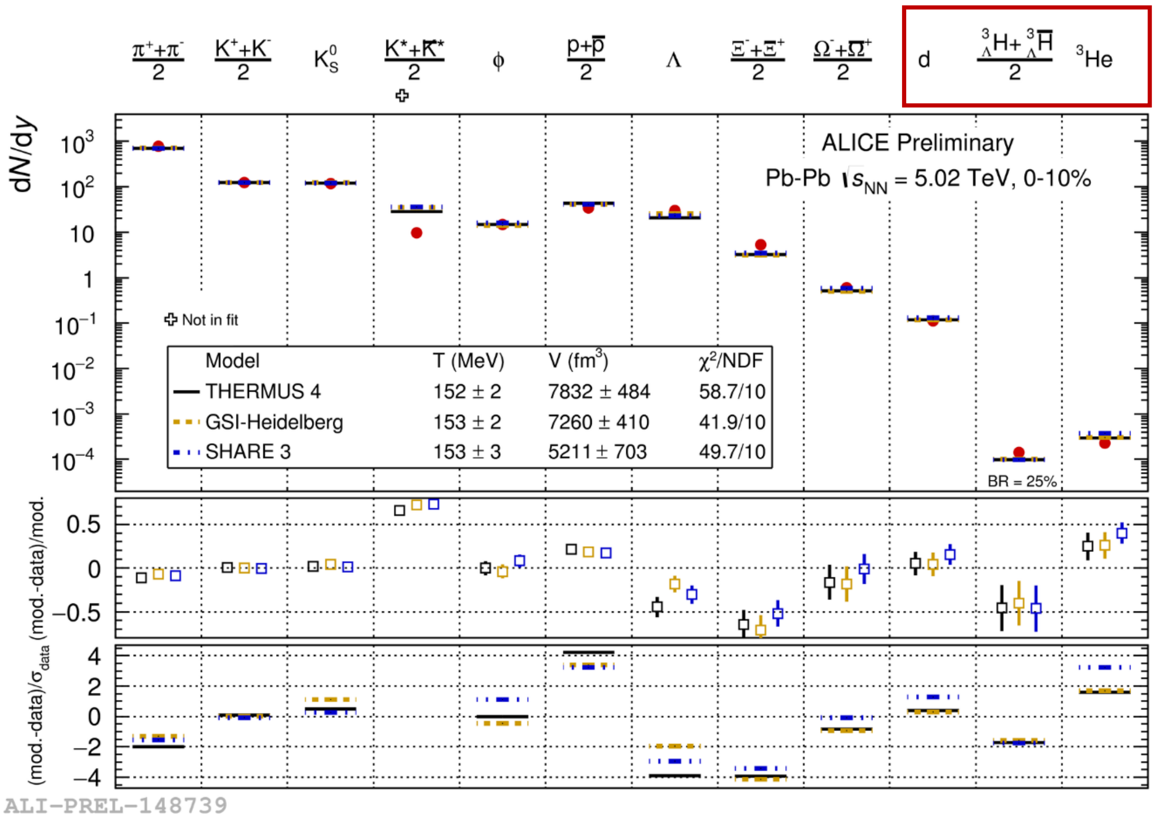
→ Au-Au for $\sqrt{S_{NN}}$ = 7.7 – 62 GeV

Heavy-ion parallel session: talk by L. Pappalardo on LHCb results

Identified hadron yields

«Hadron Chemistry»

(e.g.) Pb-Pb central collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared to thermal models



- Measured integrated yields of light-flavor hadrons, nuclei and hyper-nuclei
- Fairly well described by thermal models over 7 order of magnitude with single freeze-out temperature of about 153 MeV
- Some deviations (few σ) for short-lived resonances (K*), protons and multi-strange hadrons → role of rescattering?

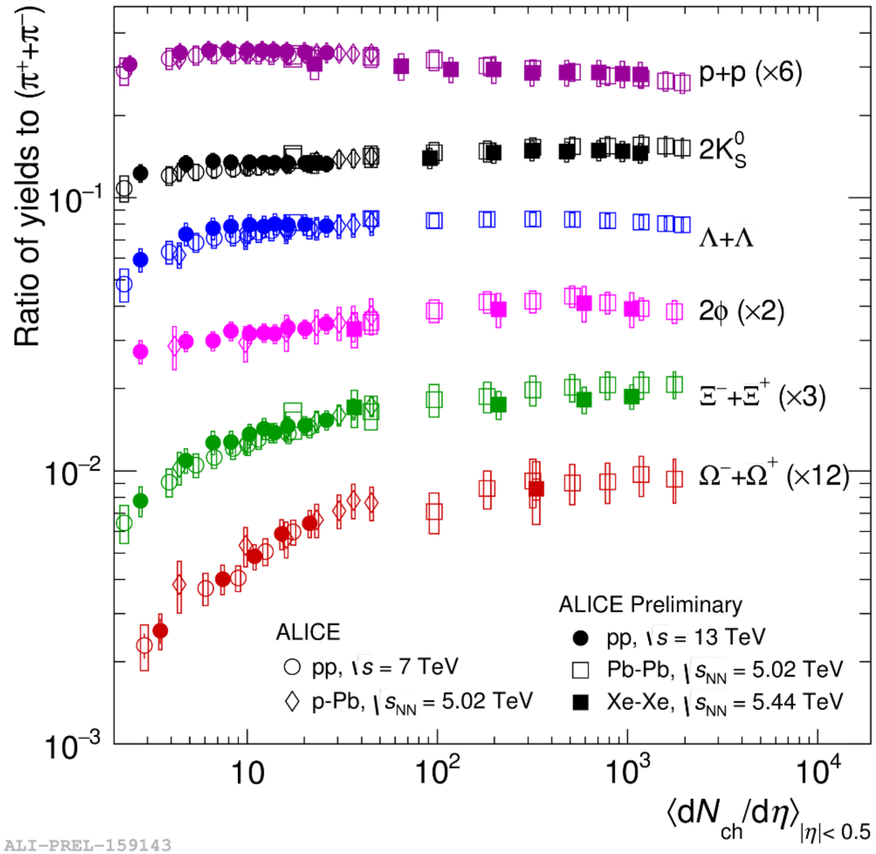
THERMUS: Wheaton *et al.*, *Comput. Phys. Commun.* **180** 84 (2009)
GSI-Heidelberg: Andronic *et al.*, *PLB* **673** 142 (2009)
SHARE: Petran *et al.*, *Comput. Phys. Commun.* **185** 2056 (2014)

Heavy-ion paralle session: related talks by A. Knospe, S. Piano and O.Ristea

Yields of strange hadrons vs. system size

Focus on strangeness:
production of strange and multi-strange hadrons in pp, p-Pb, Xe-Xe and Pb-Pb collisions

1982 (Rafelski, Muller): **Strangeness enhancement** relative to elementary collisions proposed as a signature for **QGP**.



- Measured yields normalized to pions
- Data for different collision system represented on the same plot as a function of charged particle multiplicity
- Smooth evolution of strange particle yields: hadron chemistry is driven by the multiplicity
  [ALICE, *Nat. Phys. 13, 535–539 (2017)*]
- Increase of strange-particle production for small systems, saturation around thermal-model values for large systems.
- Hierarchy: larger increase for particles with larger strange-quark content

Ongoing efforts to explain behavior with models
- Lund string, color ropes (PYTHIA, DIPSY)
- core-corona (EPOS-LHC)
- thermal-statistical (canonical suppression)

[V. Vislavicius, A. Kalweit, aXiv:1610.03001]

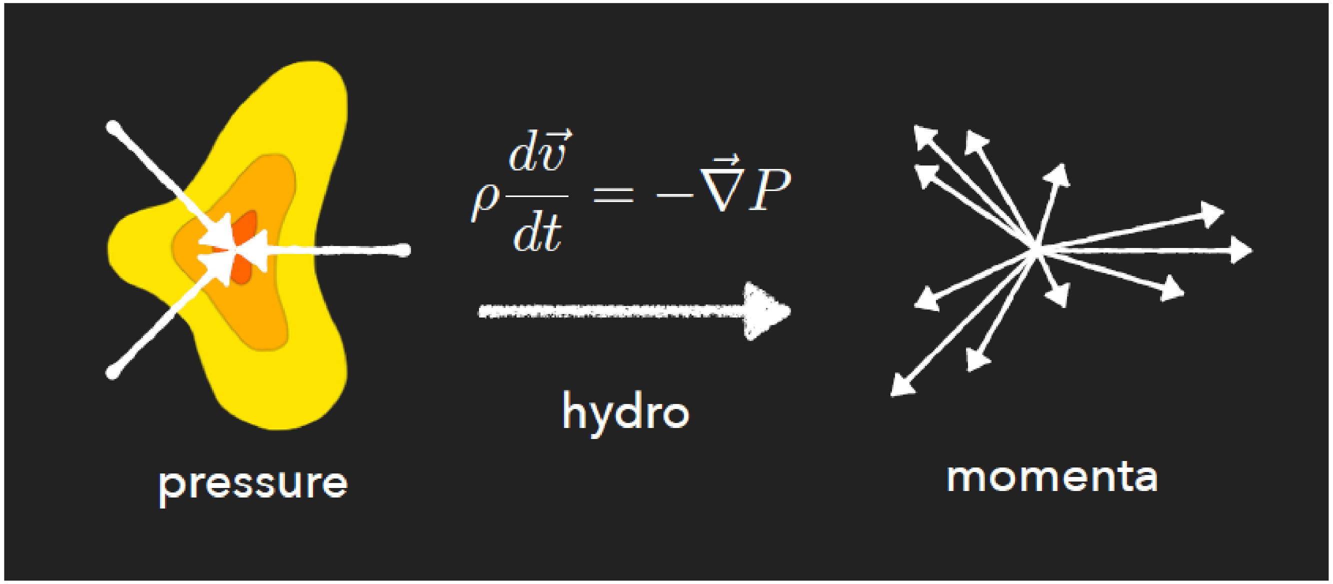
Need new framework, currently no known unique solution (T. Sjostrand, QM2018)

Anisotropic Flow

- Azimuthal anysotropy of emitted particles ⟸ pressure gradient ⟸ initial space anisotropy of the overlap region
- Quantified by Fourier decomposition of particle azimuthal distribution relative to the reaction plane

$$\frac{dN}{d\varphi} = \frac{N}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)\right]$$

- Sensitive to hydrodinamic properties of the expanding medium

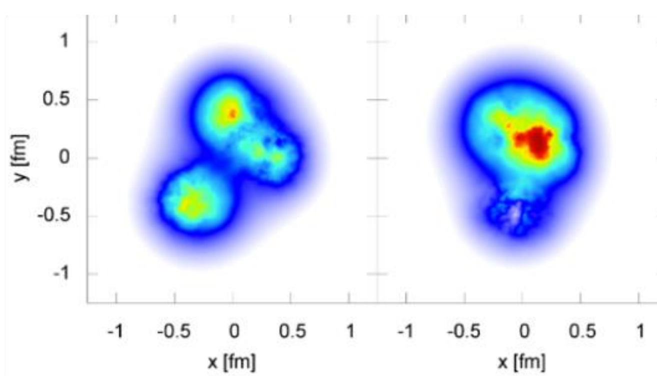


Anisotropic Flow

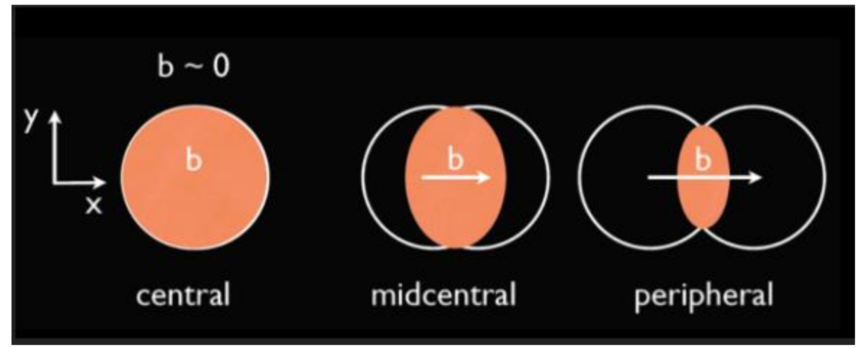
Spatial anisotropy of the initial system are due to:

Event by event fluctuations

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117, 052301 (2016)



Geometry of the collisions

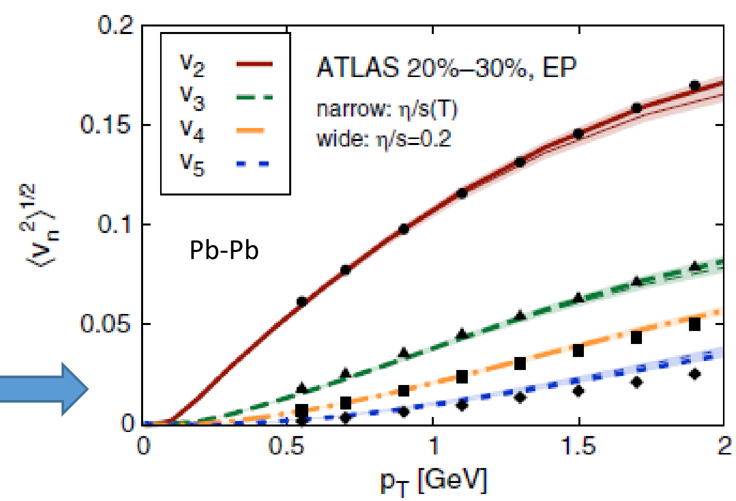


Main message from heavy-ion (e.g. Au-Au, Pb-Pb) collisions studies at RHIC and LHC

- ✓ Values of flow coefficients are large
- ✓ Data reproduced by hydro calculation with low shear viscosity-to-entropy ratio (η/s), close to theoretical lower bound: $1/4\pi$

Hydro models reproduce v_n by meands of an almost «perfect» fluid with $\eta/s \approx 0.2$

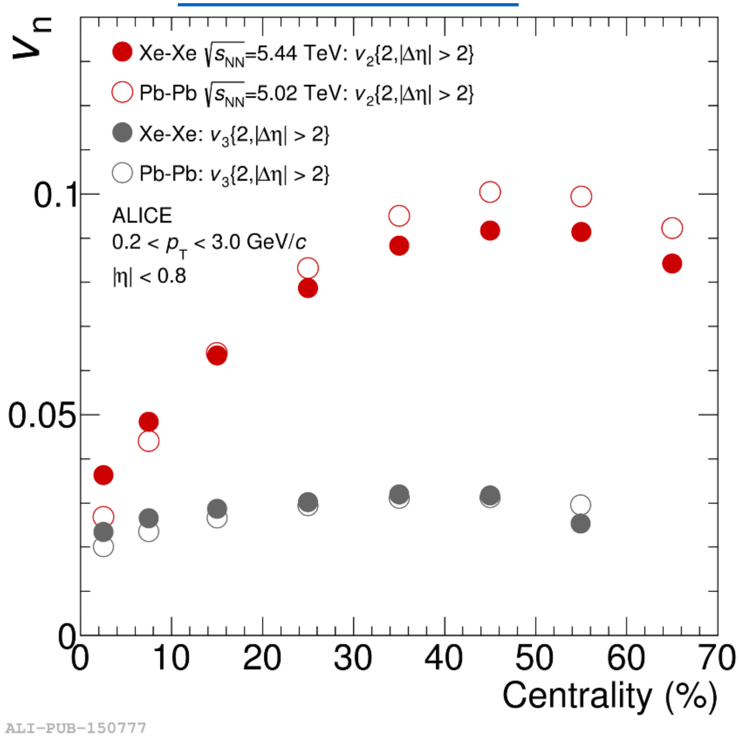
Gale, Jeon, Schenke, Tribedy, Venugopalan; PRL 110, 012302 (2013)



Anisotropic Flow in Xe-Xe

Recent results in heavy-ion collisions from RUN II at the LHC: Xe-Xe

[arXiv:1805.01832](https://arxiv.org/abs/1805.01832)



Comparison Xe-Xe to Pb-Pb:

- Centrality dependence of average v_n very similar, driven by centrality, not volume or multiplicity
- Some difference for central collisions, reproduced by models (fluctuations, Xe deformation)

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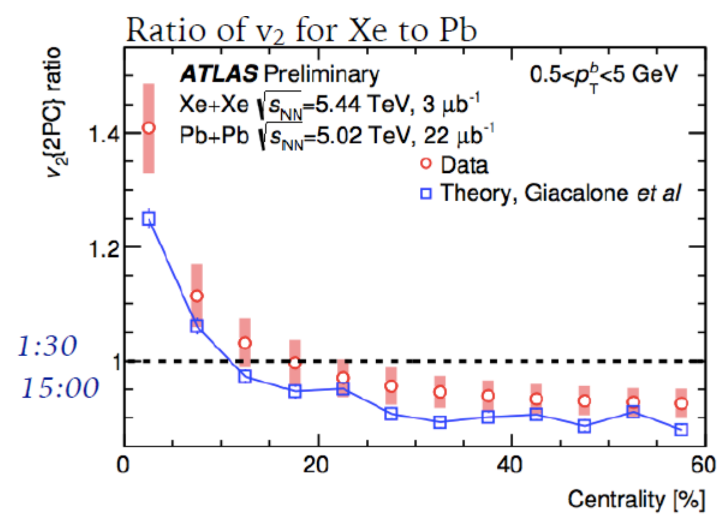
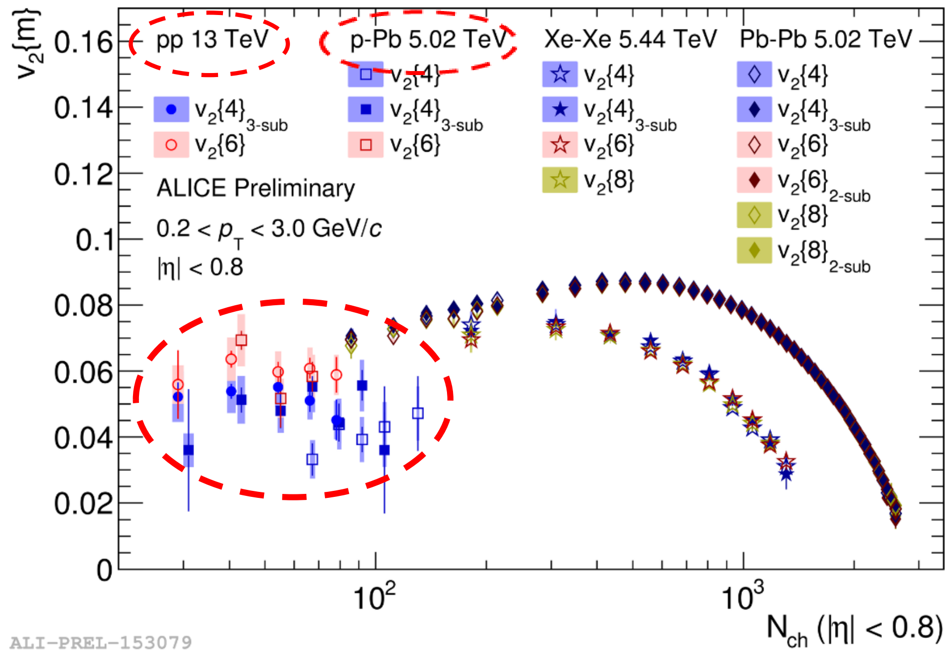
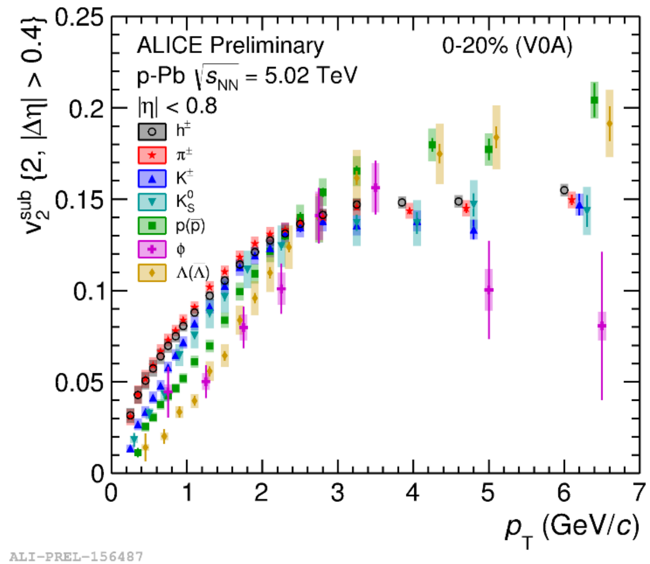


Anisotropic Flow in small systems





Small systems: growing evidence for flow

- Detailed measurements of v_2 as a function of the charged particle density performed by different experiments
- Non-flow contributions not easy to estimate in small systems; to minimise the effect, multi-particle cumulants are used

→ $v_2 \neq 0$ observed in pp and p-Pb

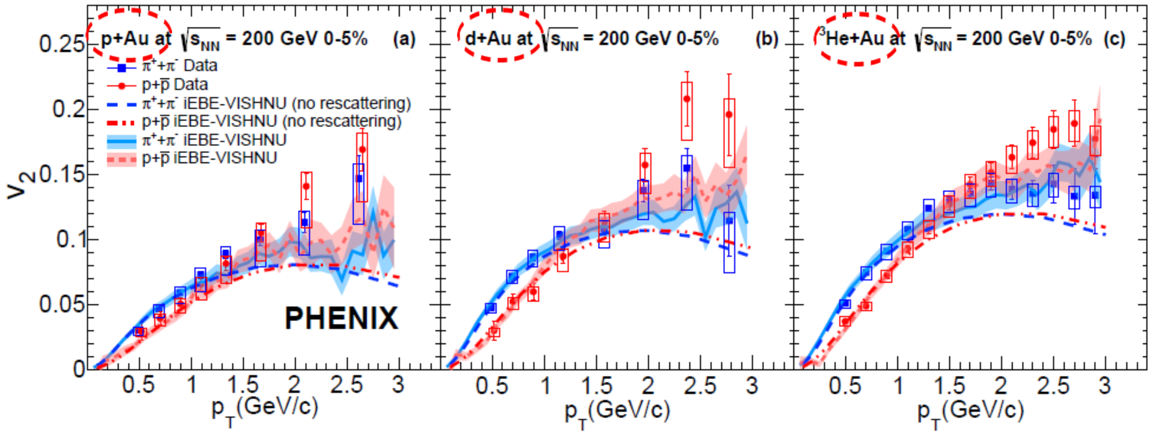
→ v_2 for identified particles: mass ordering similar to Pb-Pb

Anisotropic Flow in small systems

RHIC and LHC data: comparison to hydro models

Can hydro develop in so small systems?

arXiv:1710.09736, accepted by Phys. Rev. C

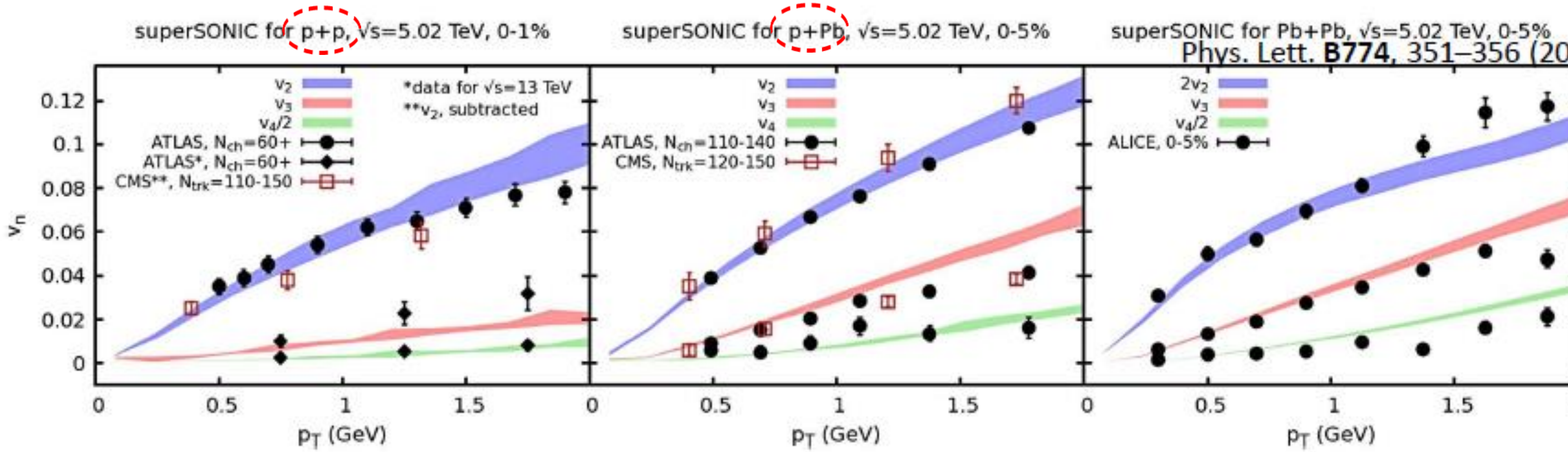


Naïve expectation: need “large enough” and “live long enough” medium to reach thermal equilibrium and apply hydro (several interactions needed)

- ~~$R > \lambda$~~
- ~~$\tau > \lambda/v$~~

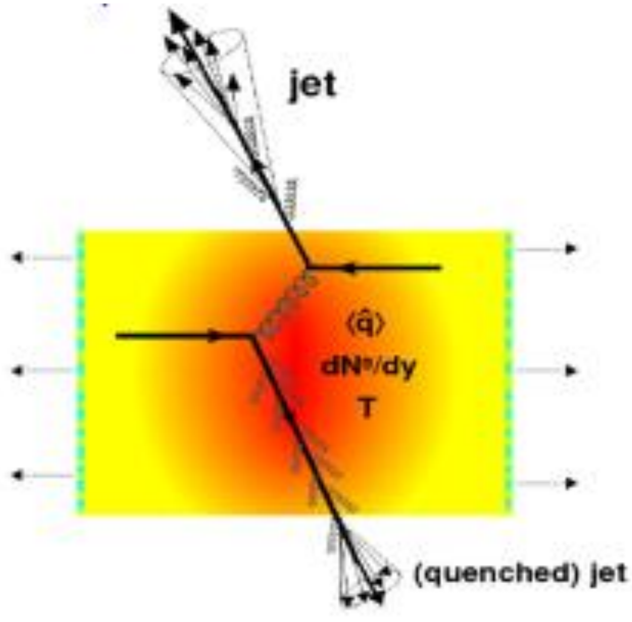
Too restrictive: hydro can be applied far from thermalization!

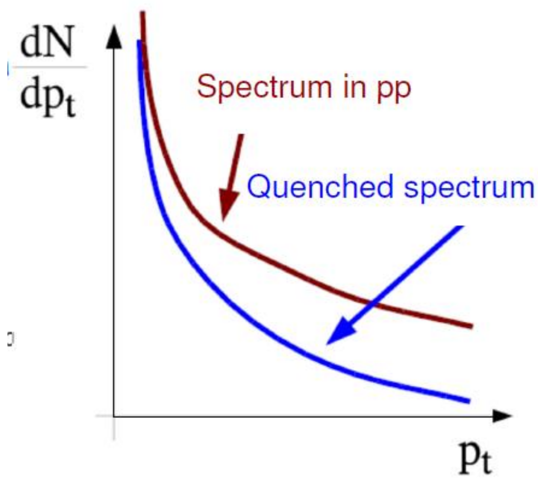
W. Li, arXiv: 1704.03576



Phys. Lett. **B774**, 351–356 (2017)

High-p_T hadrons and Jets





Parton energy loss:

a parton passing through the QCD medium undergoes energy loss which results in the suppression of high-p_T hadron yields, *via*

- *Collisional energy loss with partons in the medium*
- *Radiation of gluons (gluonstralhung)*
- *Dead-cone effect expectation:* $\Delta E_{light\ quarks} > \Delta E_{heavy\ quarks}$

Experimental observable:

Nuclear Modification Factor R_{AA}

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

QCD medium

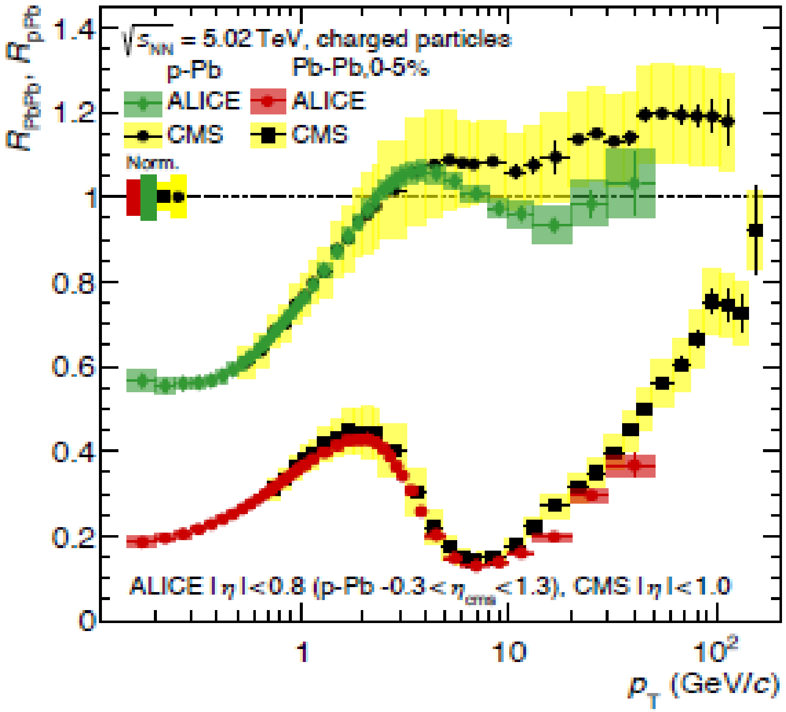
QCD vacuum

Binary scaling

Note: R_{AA} depends on energy loss but also on other parameters, such as the slope of the p_T distribution

High-p_t hadrons R_{AA}

arXiv:1802.09145



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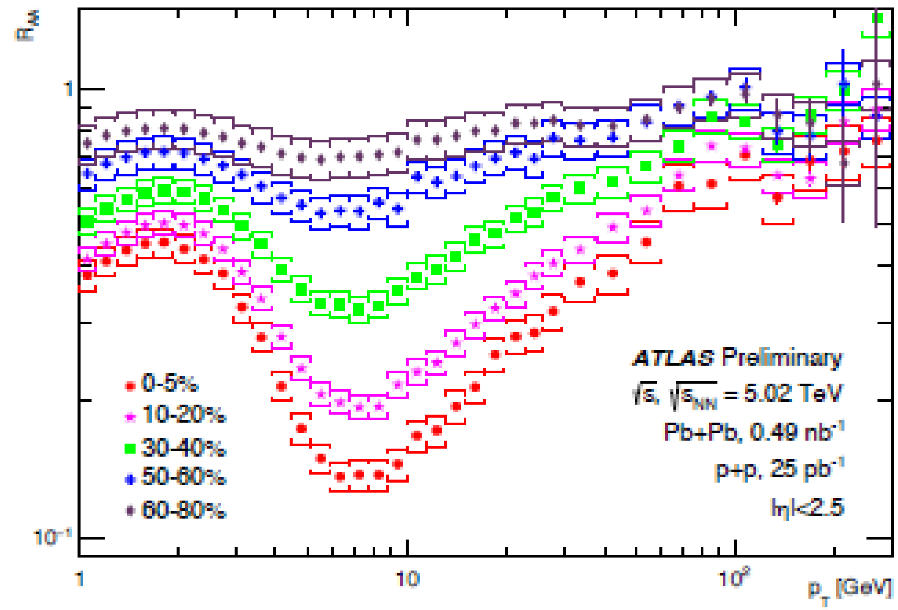


- Strong suppression in central Pb-Pb collisions, R_{AA} re-approaching unity at large p_T
- Negligible suppression in peripheral Pb-Pb
- No indication for relevant final state suppression in p-Pb

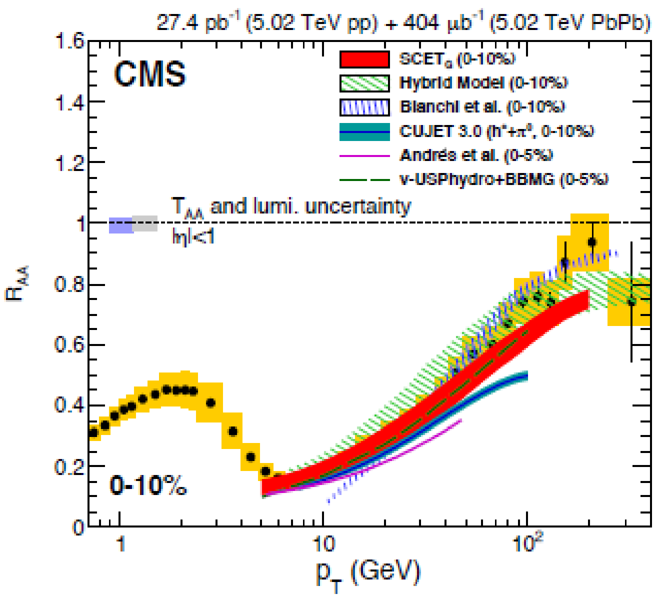
More quantitative infos on energy loss (transport coefficient $\hat{q}$) can be inferred by data:

$\Delta E_{rad} \sim \alpha_S \, C_R \, \hat{q} \, L^2$ $\Longrightarrow$ $\hat{q} \approx 1.2 - 1.9 \;\; GeV^2/fm$ at RHIC and LHC, rispectively

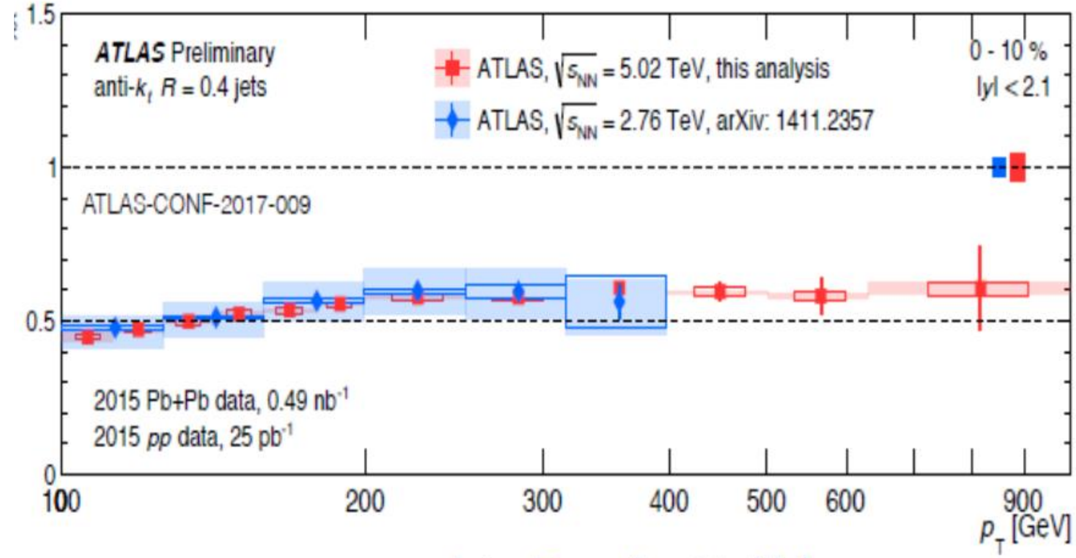
(JET coll., Phys. Rev. C 90 014909)

High-p_t: hadrons vs. jets

Charged particle R_{AA}



Jet R_{AA}



Jets: $R_{AA} < 1$ out to high p_T

p_T-dependence:

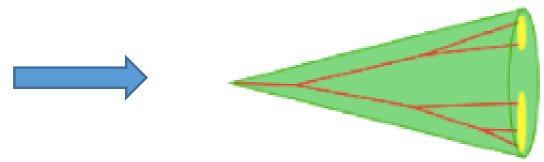
Single particles: consistent with expected constant (log E) dependence

Jets: suggest increase of ΔE vs E

Tentative interpretation: in jets, multiple partons lose energy; more partons in high-E jets ⇒ more E-loss

Jet shape studies

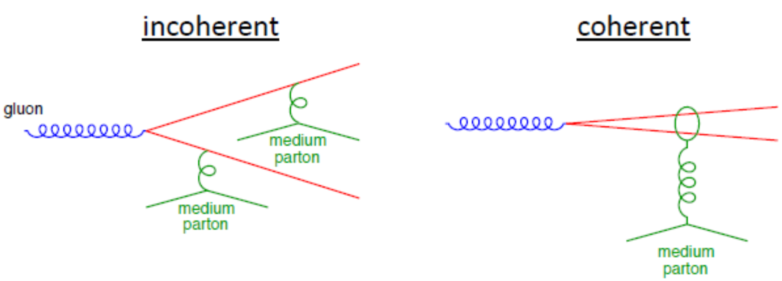
- Jet shape modifications may arise from the interaction with the deconfined medium created heavy-ion collisions.
- Jets are multi-parton states; do the partons loose energy independently?
- Declustering: by removing the soft wide-angle radiation inside a jet (soft drop), a pair of "subjets" can be selected.

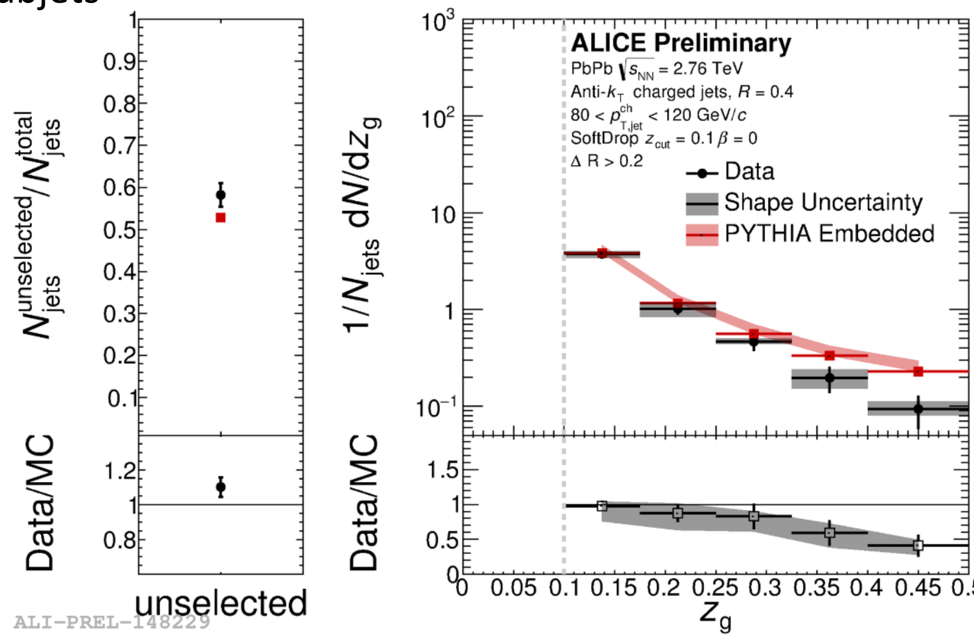


- Key observable: momentum ratio of these subjets (splitting function)

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

- Sensitive to coherence of energy loss





- Suppression of large-z_g events (symmetric splittings) observed
- Consistent with independent energy loss of large angle splittings

Open heavy flavors

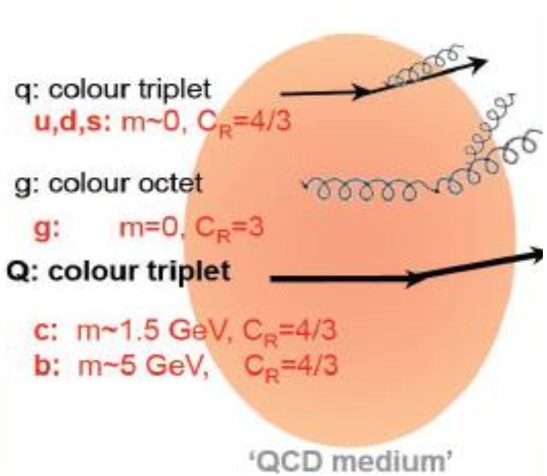
Specific features of heavy quarks relevant to heavy-ion studies

- **Large mass** ($m_c \approx 1.5$ GeV, $m_b \approx 5$ GeV) → **produced in hard processes at the initial stage of the collision** with short formation time, much smaller than QGP lifetime
- **Flavor conserved** by strong interaction + **production** of HF **in QGP** is **subdominant** → interaction with **QGP do not change flavor identity**

→

HF are hardly distroyed/created by the medium and **are transported through the full system evolution**

Tool for understanding the **general properties of parton energy loss** in a deconfined medium since this is expected to depend (also) on the quark mass (dead cone effect)



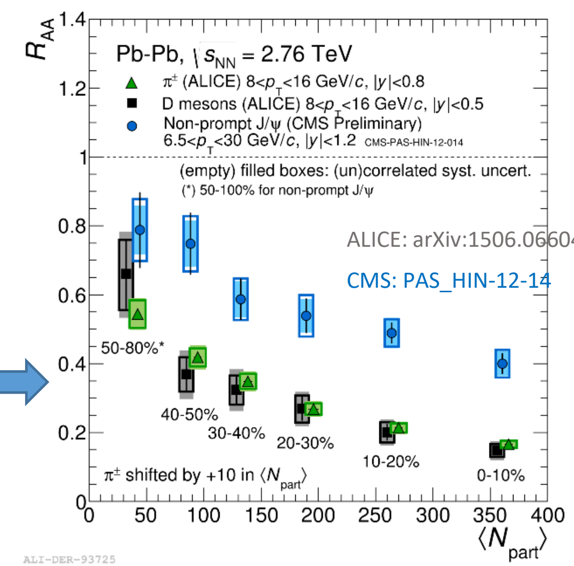
Heavy-ion paralle session: talk by A. Festanti

$$\Delta E_{quark} < \Delta E_{gluon}$$
$$\Delta E_b < \Delta E_c < \Delta E_{light\ q}$$

which should imply

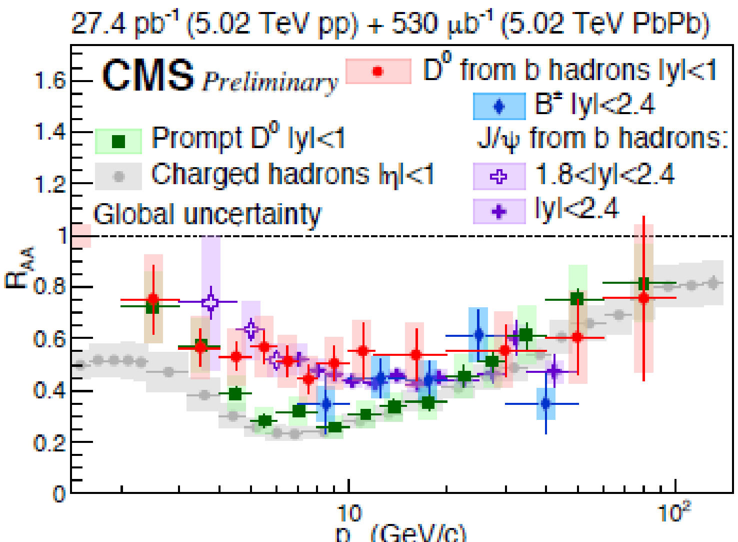
$$R_{AA}^{\ B} > R_{AA}^{\ D} > R_{AA}^{\ \pi}$$

RUN-I: first indication of mass dependence of energy loss



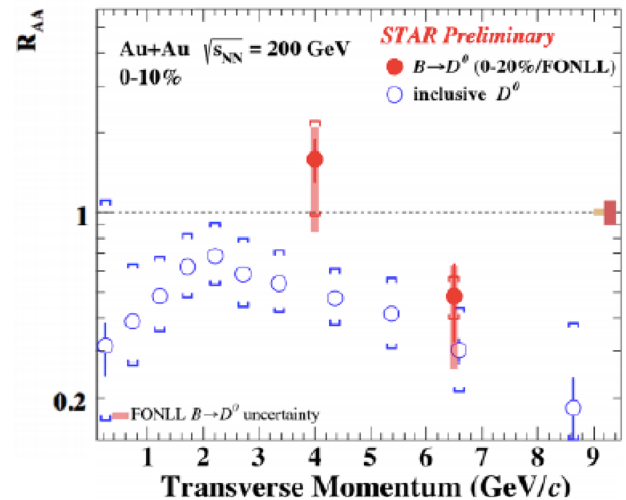
Heavy Flavors: energy loss

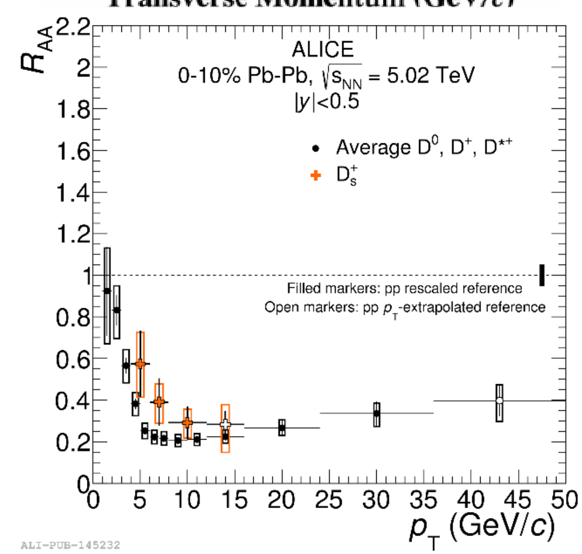
Hierarchy and flavor dependence → recent results at RHIC and LHC



CMS-HIN-16-001; arXiv:1708.04962

STAR: D⁰ from B mesons





arXiv:1804.09083

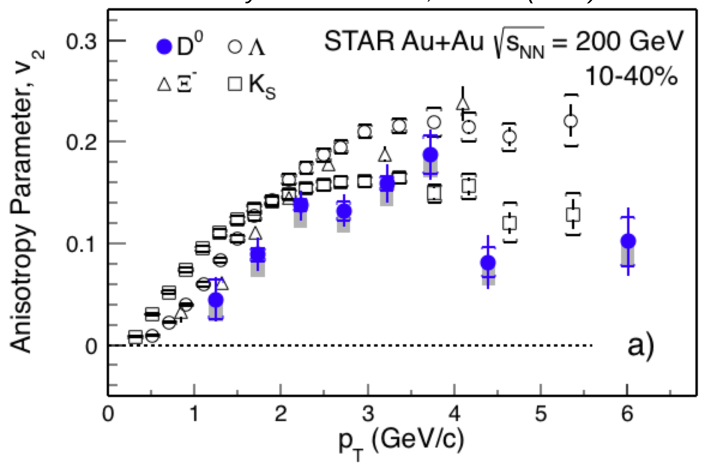
- B mesons and J/ψ from beauty hadrons show nuclear modification factors larger than those of D mesons and charged hadrons

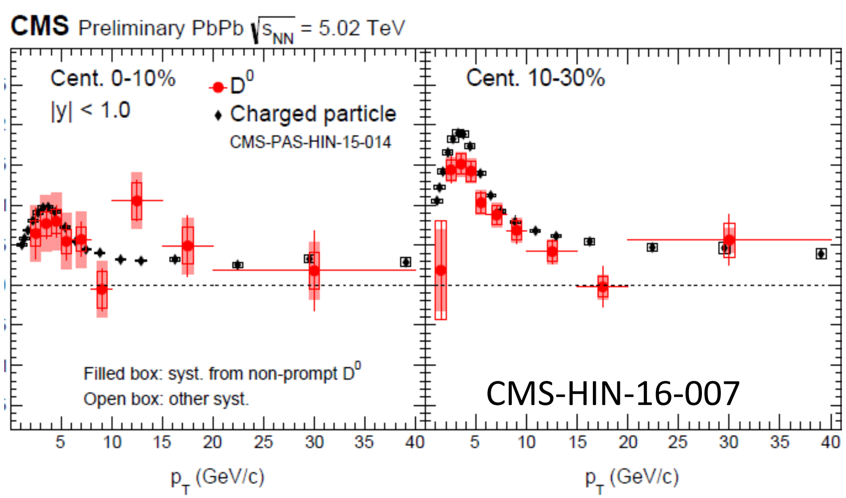
- Hint of smaller D_s suppression: Strangeness enhancement ?

Heavy Flavors: elliptic flow

Charm does flow...

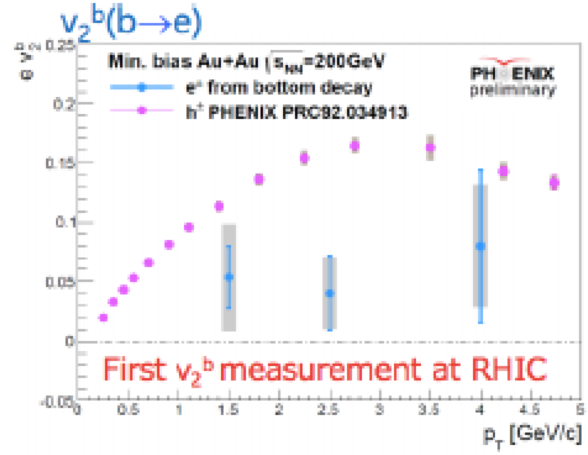
Phys Rev. Lett. 118, 212301 (2017)





Charm v_2 similar to charged particles suggests that charm approaches thermal equilibrium with the medium

... and Beauty is being explored!



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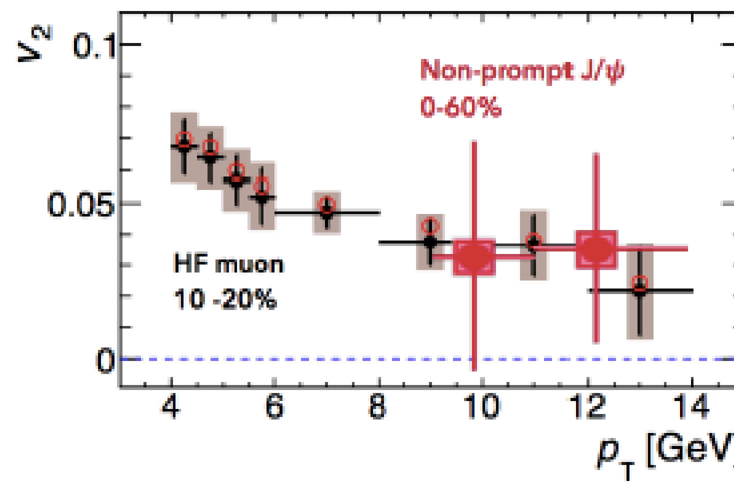
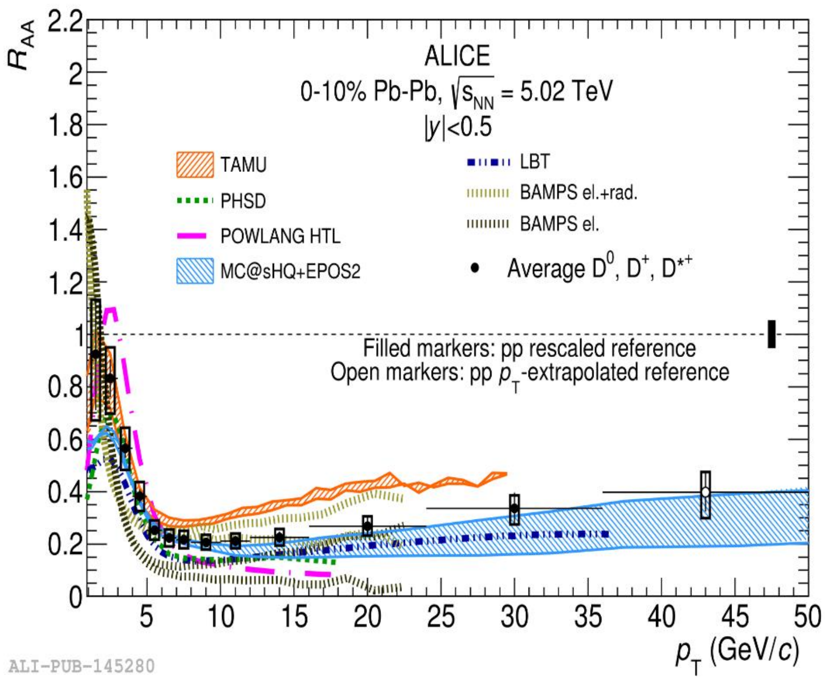
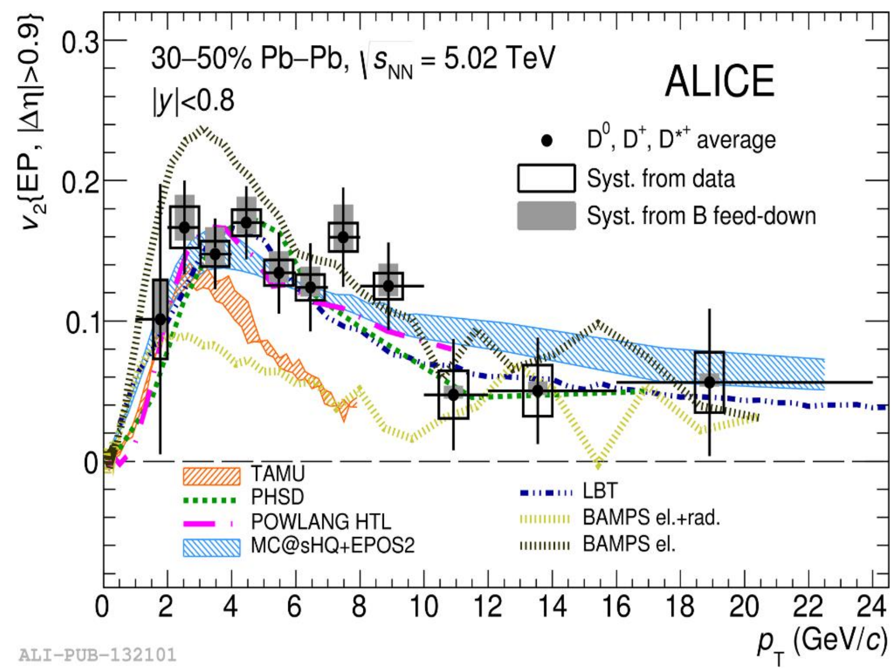


Heavy Flavors: energy loss *and* flow

- Large collision systems (e.g. Pb-Pb): the simultaneous measurement of R_{AA} and v_2 allows to constrain models describing the QGP transport properties.

arXiv:1804.09083





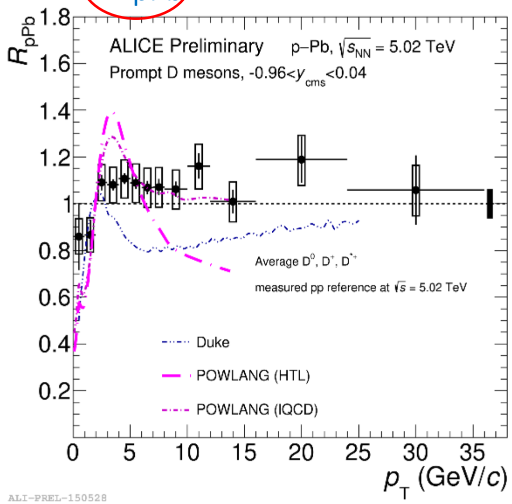
$$R_{AA} = \frac{(dN/dp_T)_{AA}}{\langle N_{coll}\rangle (dN/dp_T)_{pp}}$$

$$\frac{dN(p_T,\varphi)}{d\varphi} \propto 1 + 2v_1\cos(\varphi-\psi_1) + 2v_2\cos(2[\varphi-\psi_2]) + \dots$$

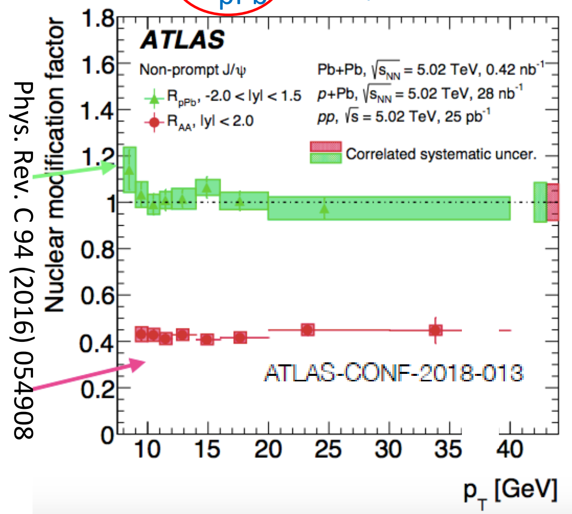
Heavy Flavors: energy loss *and* flow

Small systems (e.g. p-Pb): HF behavior similar to charged particles

R_{pPb} → D mesons



R_{pPb} → J/ψ from B



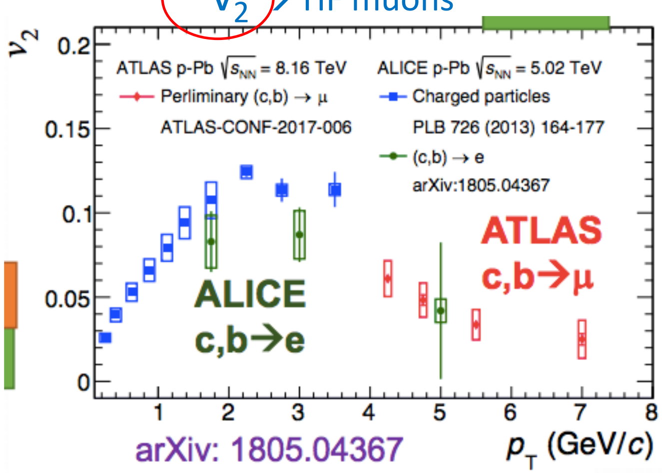
R_{pPb} ≈1 → modest energy loss in cold matter

v_2 ≠ 0 → anisotropic emission, flow

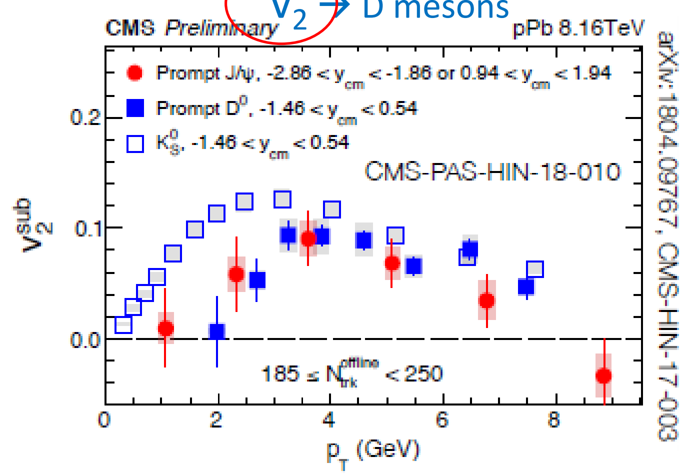
Flow without energy loss?

Only few (elastic) scatterings to generate v_2, energy loss can be small

v_2 → HF muons



v_2 → D mesons



Quarkonia: suppression and (re)-generation

- Early idea by Matsui and Satz: J/ψ suppression by (color) Debye screening in QGP

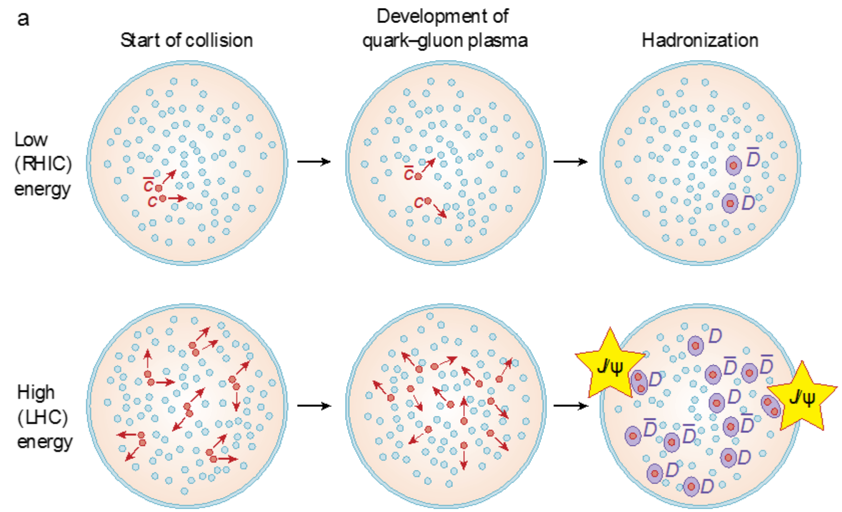
- Differences in the binding energies of the quarkonium states lead to a sequential melting of the states with increasing temperature
  (Digal,Petrecki,Satz PRD 64(2001) 0940150)
  → thermometer of the initial QGP temperature

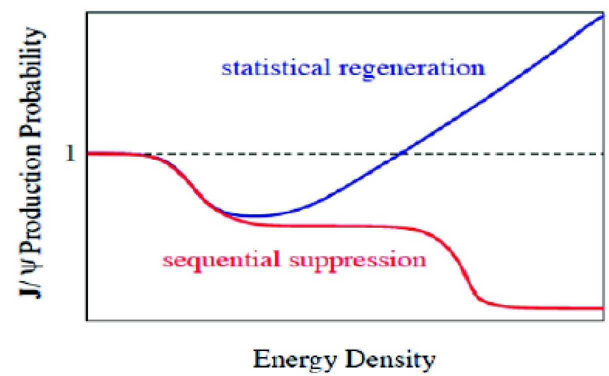
- Increasing the energy of the collision the $c\bar{c}$ pair multiplicity increases and may led to charmonium production via recombination

In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.2	~10	~60

Charmonoum production **may be enhanced via (re)combination of cc pairs** at hadronization (statistical approach) or during QGP stage (kinetic recombination approach)

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





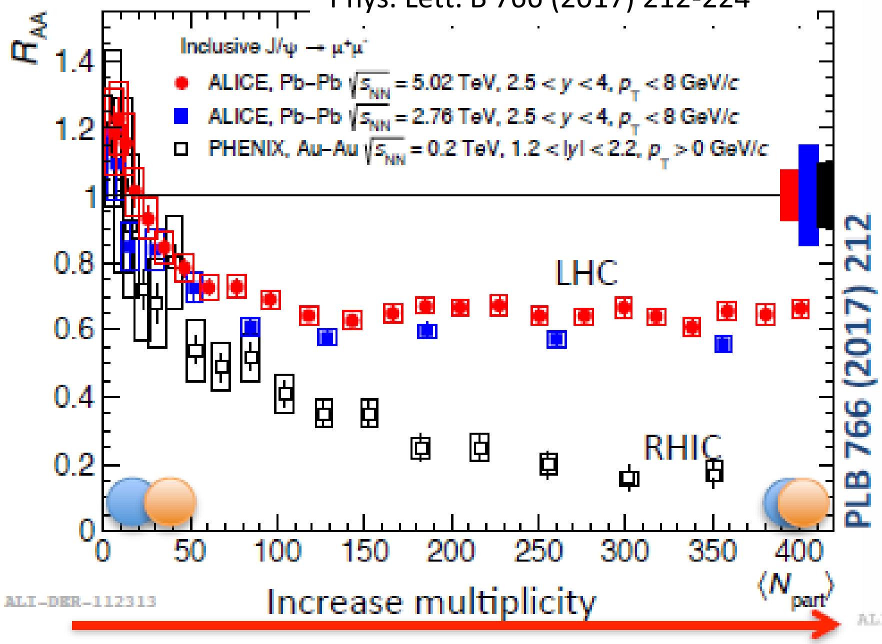
Heavy-ion parallel session: talks by
E. Ferreiro, G. Fronzé, E. Boulova-Thacker

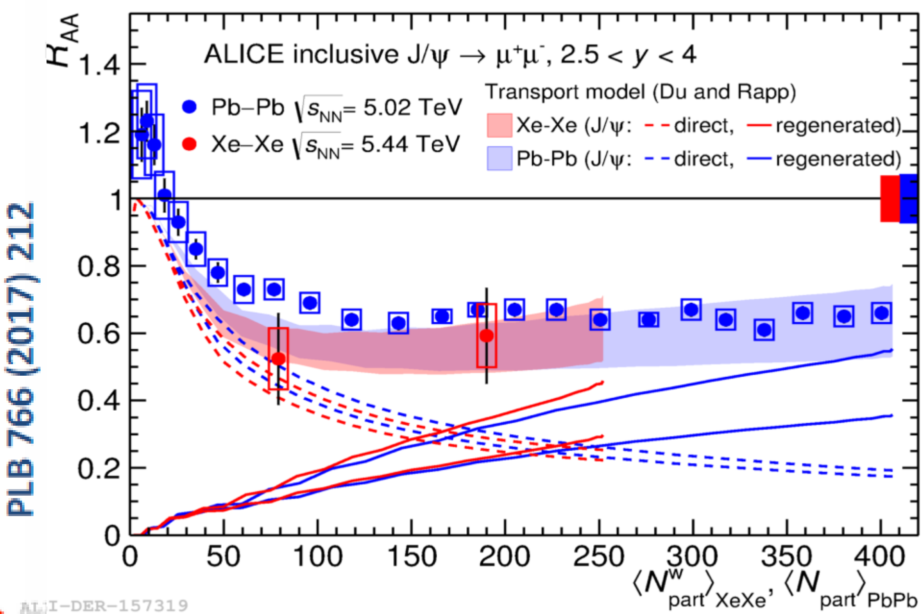
J/ψ suppression: RHIC vs. LHC

«moderate» p_T:

Results on inlcusive J/ψ: centrality dependence of the nuclear modification factor R_{AA}

Phys. Lett. B 766 (2017) 212-224





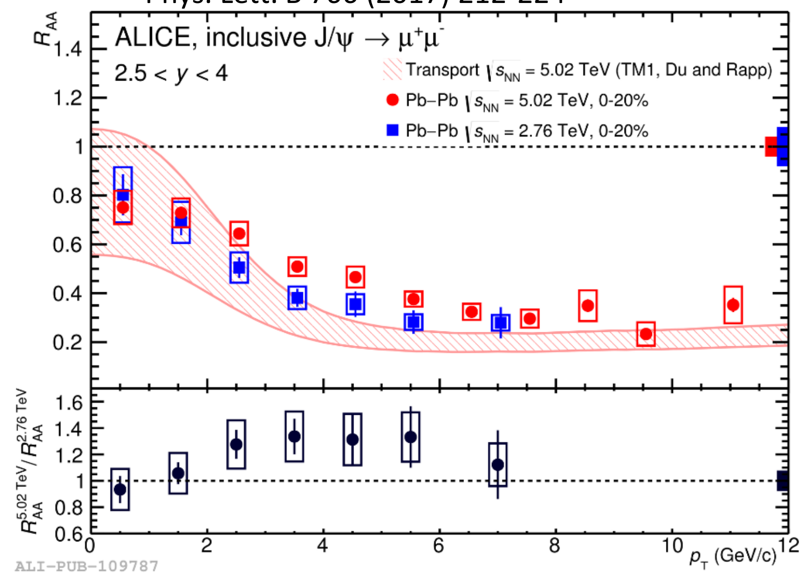
- Large suppression observed at RHIC, increasing with centrality
- Much smaller suppression at LHC, with different behavior as a function of centrality.

→ **Consistent with regeneration scenario**

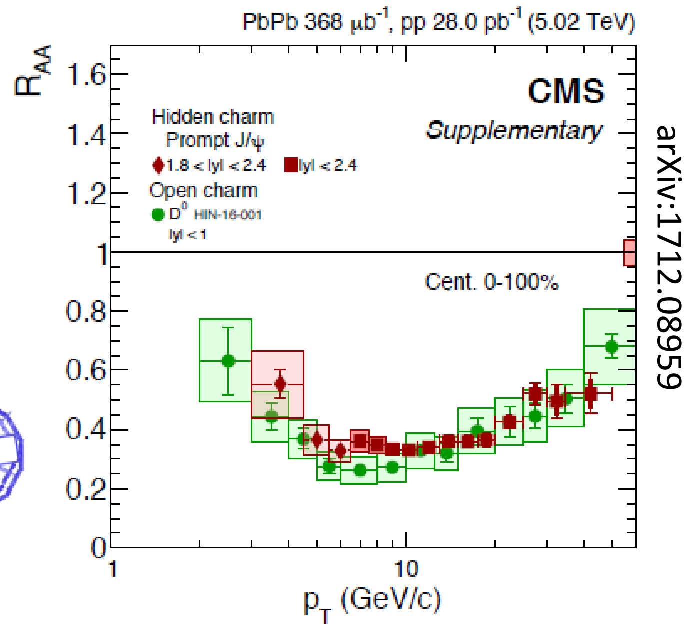
More on J/ψ

- Regeneration mechanism relevant at low p_T, as predicted by models
- At p_T larger than about 5 GeV/c, J/ψ suppression similar at RHIC and LHC

Phys. Lett. B 766 (2017) 212-224



PbPb: prompt J/ψ suppression



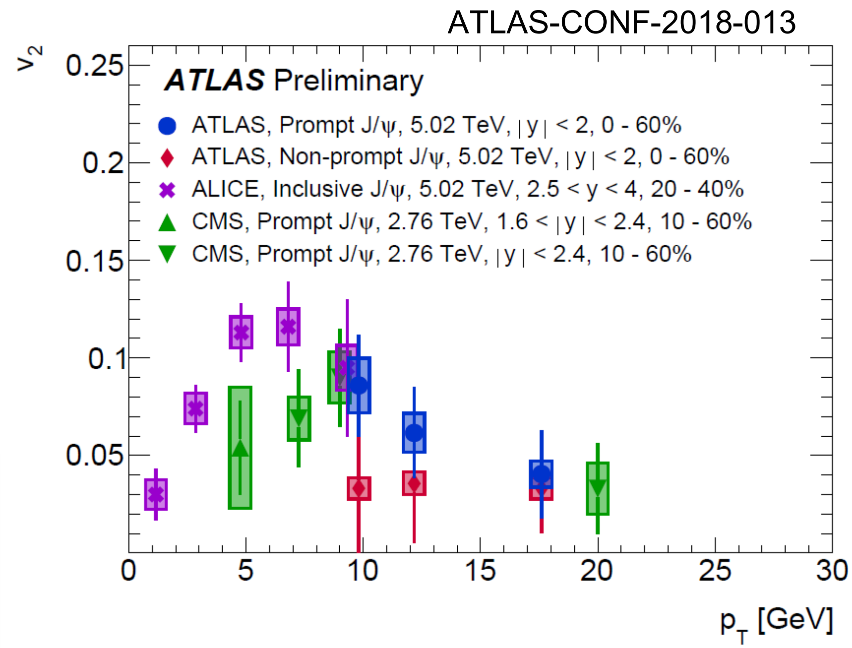
J/ψ suppression similar to D^0 suppression
Jet quenching for charmonia?

Study of the suppression of «prompt» J/ψ at larger p_T: the nuclear modification factor is very close to the one measured for D-mesons.

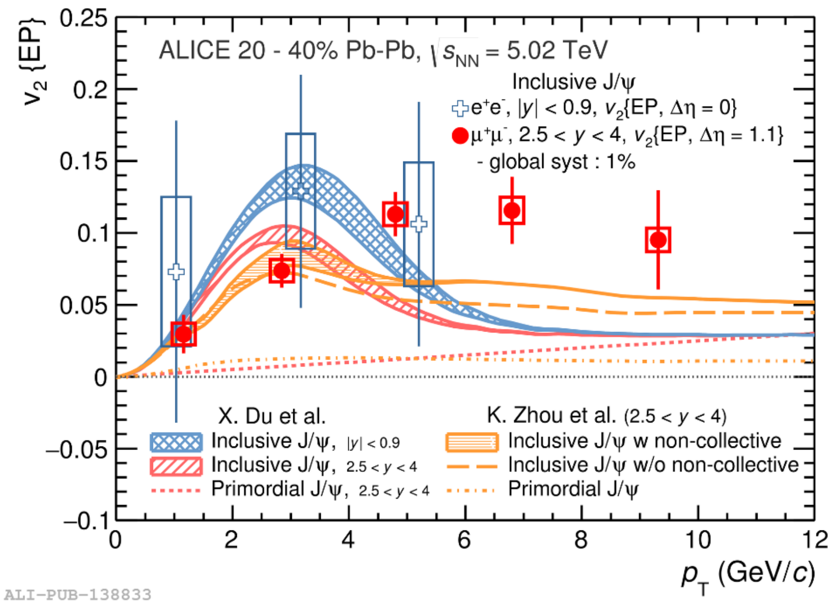
J/ψ flow

- Pb-Pb collisions at LHC: $v_2 \neq 0$ measured by different experiments

ATLAS-CONF-2018-013



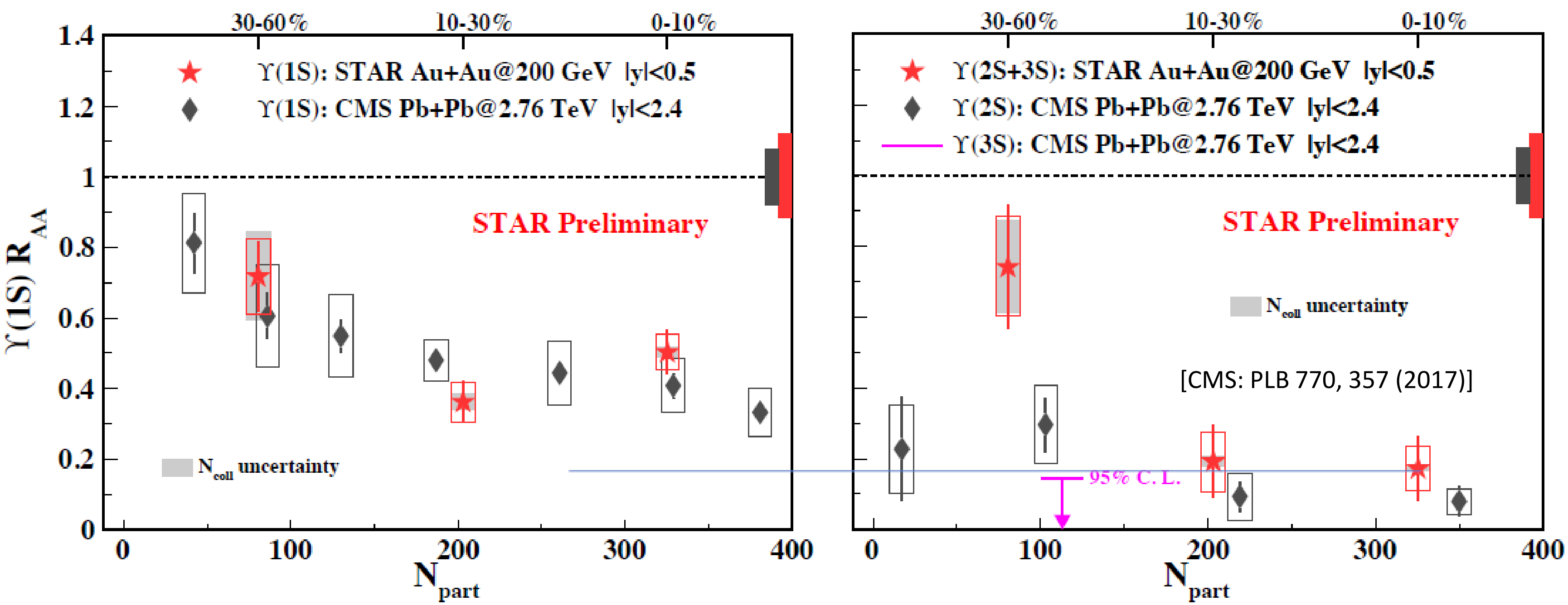
ALICE, PRL 119 (2017) 242301



Zhou et al., PRC89(2014) 054911
Du et al., NPA943 (2015) 147

- Magnitude of v_2 reproduced at low p_T by models including J/ψ regeneration, but underestimated at larger transverse momenta.

Bottomonia



- RHIC and LHC results for the Υ family:
  - Hierarchy of suppression, reflecting the different binding energies
  - No sudden turn-on
  - Similar R_{AA} for Υ(1S) at RHIC and LHC, could be due to:
    - Different temperatures of the medium due to the different beam energy
    - Larger regeneration at LHC
    - Different Cold Nuclear Matter effects
  - Not in contraddiction with models, e.g. ➡

TAMU, X. Du et al PRC 96, 054901

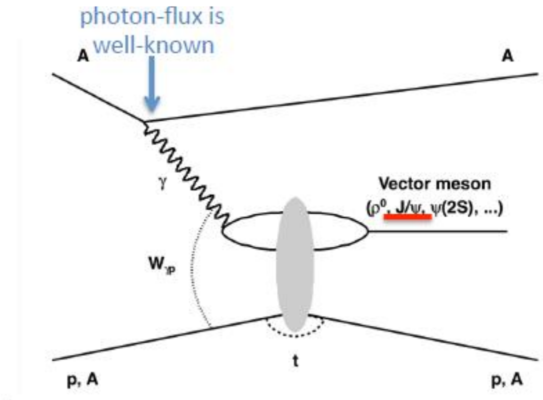
	Υ(1S)	Υ(2S)	Υ(3S)
T_{disso}(MeV)	500	240	190

B. Krouppa, et al PRD 97, 016017

	Υ(1S)	Υ(2S)	Υ(3S)
T_{disso}(MeV)	600	230	170

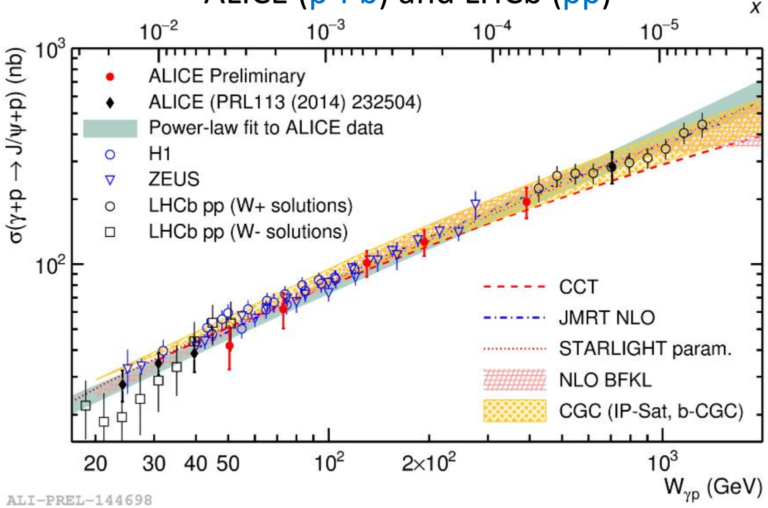
Ultra-Peripheral Collisions

High-energy heavy-ion beams as a photon emitter



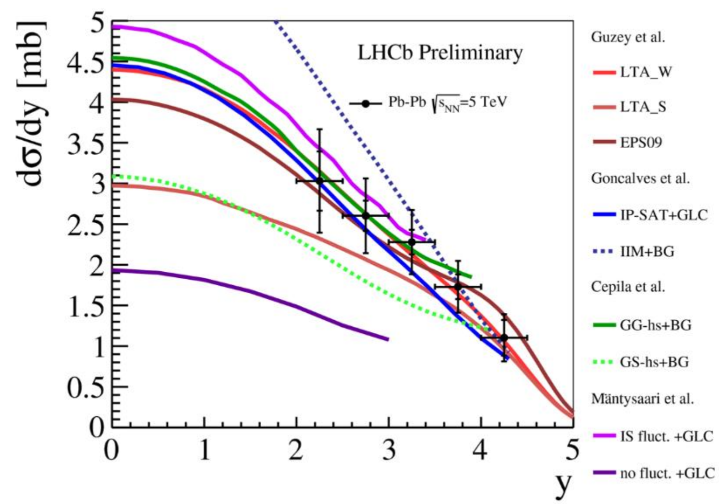
- UPC: collisions with *b>R1+R2* → hadronic interaction suppressed
- E.M. field of a Pb nucleus → beam of quasi-real energetic photons
- The number of photons is proportional to Z^2
- Study γ–A and γ-p interaction → vector meson production → J/ψ
- Clean identification → «a lepton pair in an (almost) empty detector»
- Separation coherent/incoherent (p_T – based)
- Access to gluon distribution functions at low-x ($10^{-5}<x<10^{-2}$)

ALICE (p-Pb) and LHCb (pp)



for LHCb measurements in **pp** **at 13 TeV** see LHCb-CONF-2016-007

Pb-Pb : LHCB-CONF-2018-003



Summary and outlook

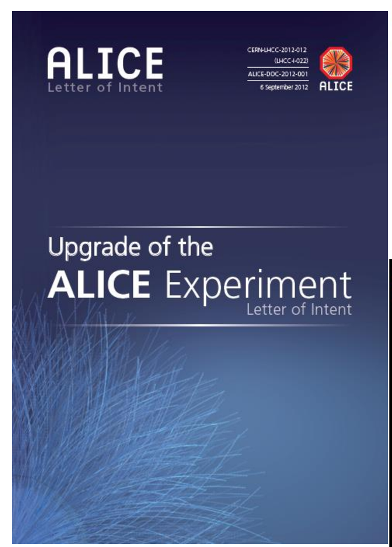
High-energy heavy-ion experiments:

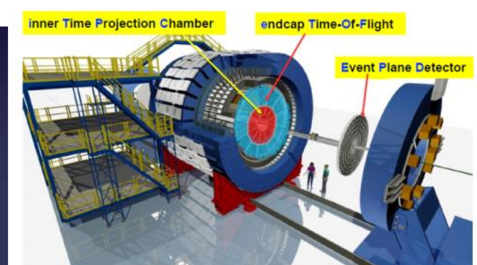
- impressive amount of new data (only a part can fit in this talk)
- clarifying the parton nature of QGP through:
  - → different probes
  - → study of small systems

More to come:

- Enhanced LHC luminosity in RUN III
- Beam Energy Scan phase II at RHIC
- Detector upgrades
- New facilities and experiments (FAIR - NICA)

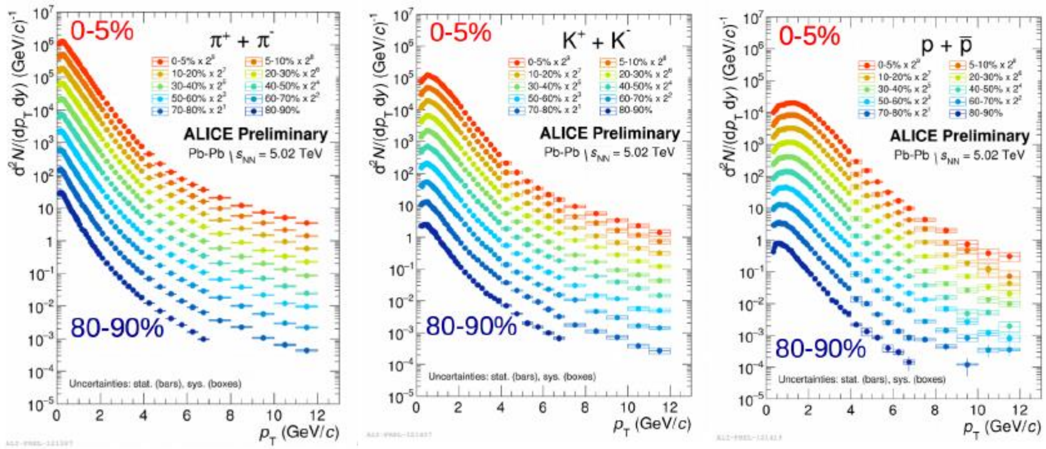
Parallel sessions:
Talk on ALICE upgrades by I. Ravasenga
Talk on physics with CBM exp. At FAIR by M. Zyzak a.
Talks on NICA project and h.i. accellerators by A. Sidorin
(instrumentation) and B. Sharkov





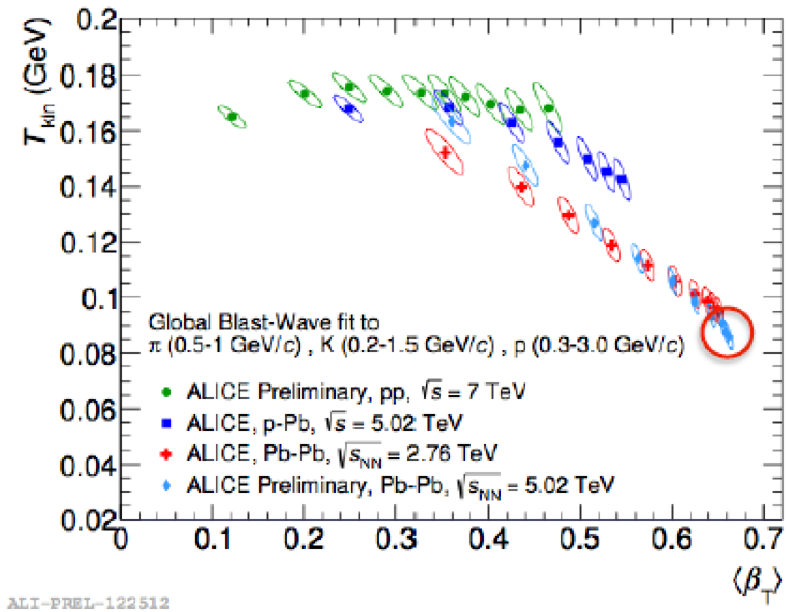
Additional Slides

Radial flow



- p_T spectra become harder for central collisions

"Blast-Wave" fits to hadron spectra

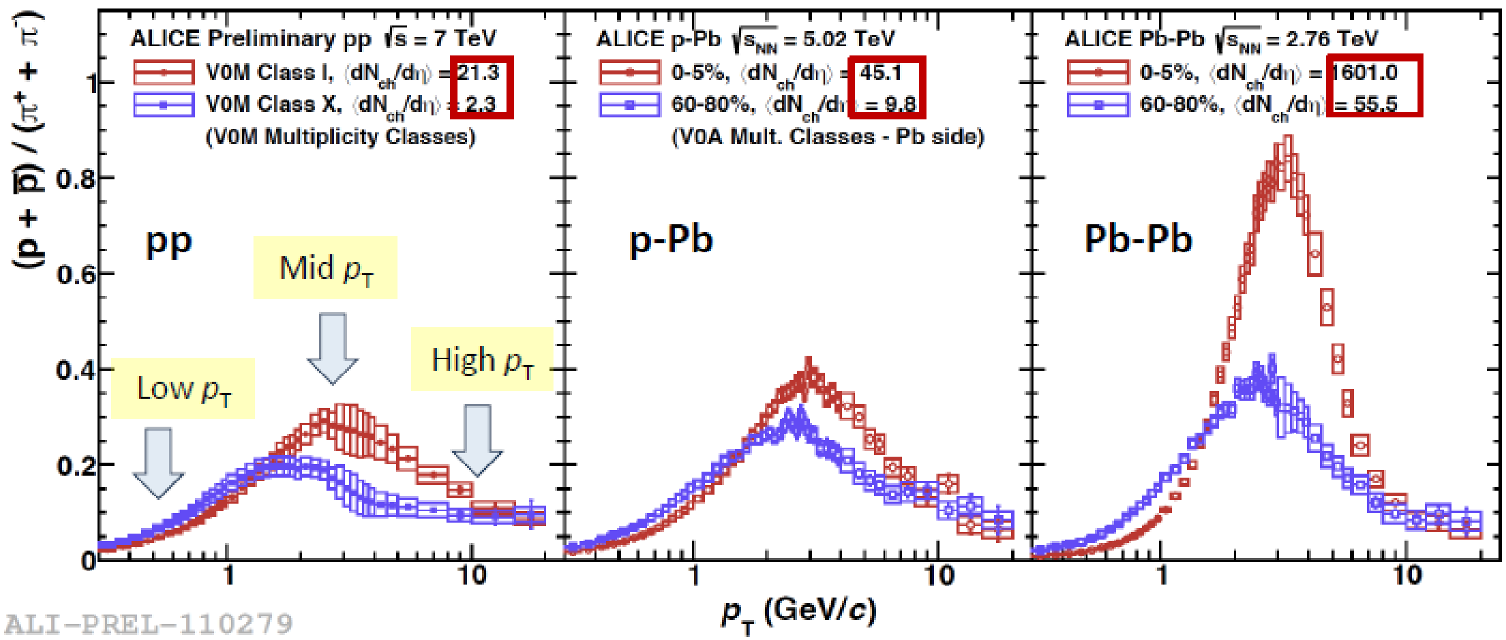


- model of radial expansion
  mass dependence → kinetic parameters
  - T_{kin}: kinetic freeze-out temperature
  - β_T: radial flow velocity
- Run 2 (5.02 TeV)
  - ~ 2/3 c (largest β_T ever observed)

Baryon to meson ratio

- Consequence of radial flow: protons are pushed to a higher momentum

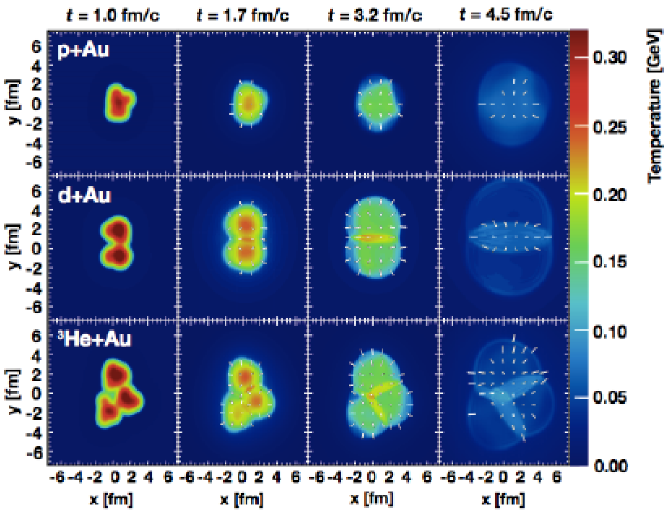
p/π ratio as a function of p_T in pp, p-Pb and Pb-Pb



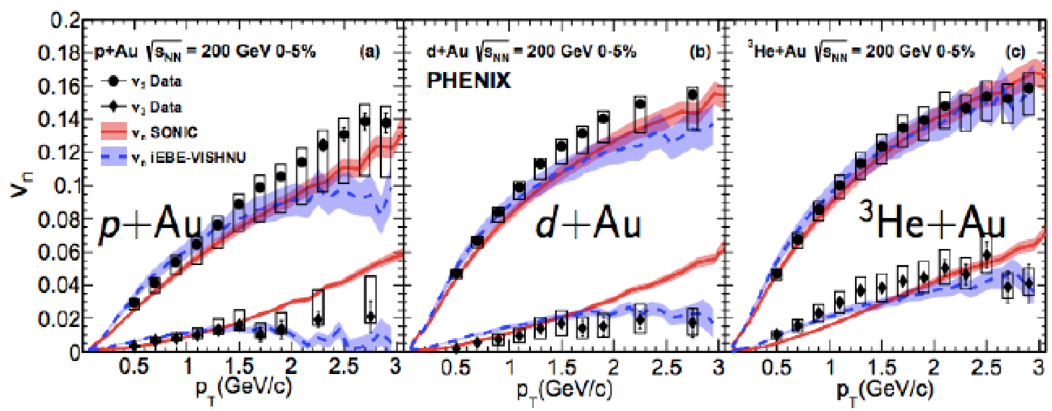
Comparison of high to low multiplicity events in pp and p-Pb, the same trend is seen in Pb-Pb

Checking geometry; $v_2 + v_3$

Elegant idea: vary geometry by changing shape of colliding nuclei



PHENIX, arXiv:1805.02973

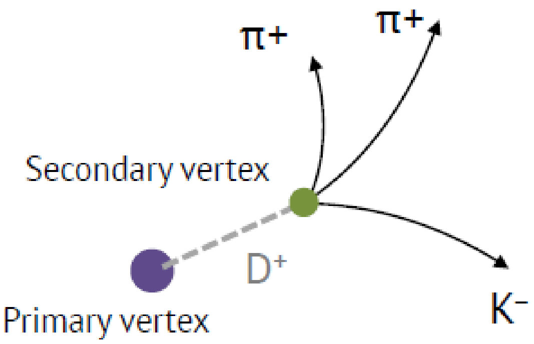


On top of this: fluctuations, orientation

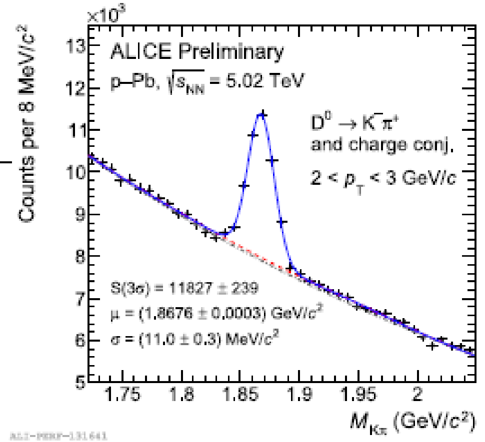
5

D meson reconstruction

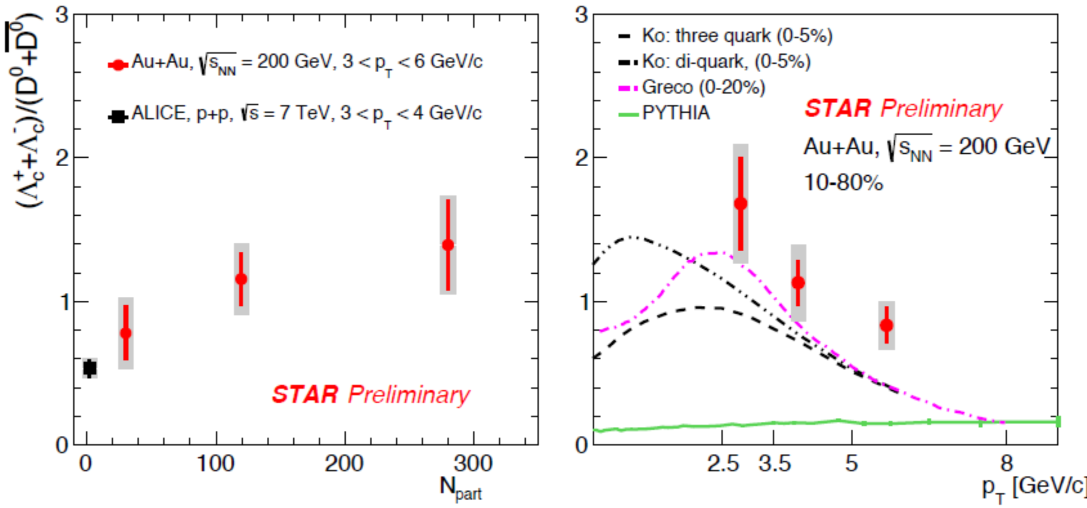
- Fully reconstructed in hadronic decays
- Topological selection of secondary vertexes and invariant mass analysis
- Analysis with detailed study of combinatorial-background inv. mass shape and without vertex reconstruction for D^0 (best results for $p_T < 1$ GeV/c)

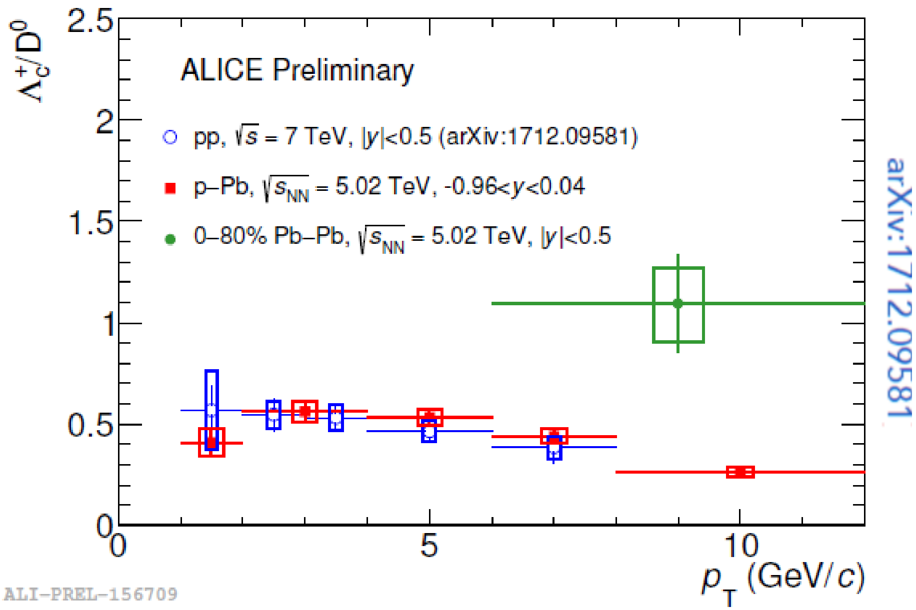


	Mass (GeV/c^2)	$c\tau$ (μm)	Decay	BR (%)
D^0	1.865	123	$K^- \pi^+$	3.93
D^+	1.870	312	$K^- \pi^+ \pi^+$	9.46
D^{*+}	2.010	-	$D^0 (K^- \pi^+) \pi^+$	67.7 x 3.93
D_s^+	1.968	150	$\Phi(K^- K^+) \pi^+$	2.27



Charmed baryons

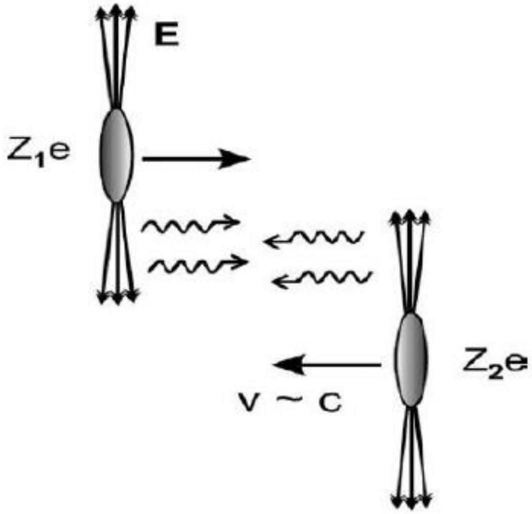


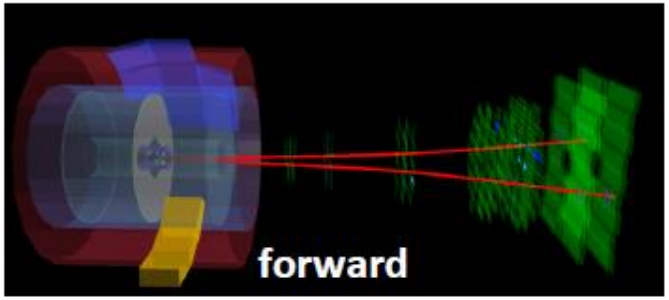


Λ_c production enhanced in heavy-ion collisions w.r.t. pp

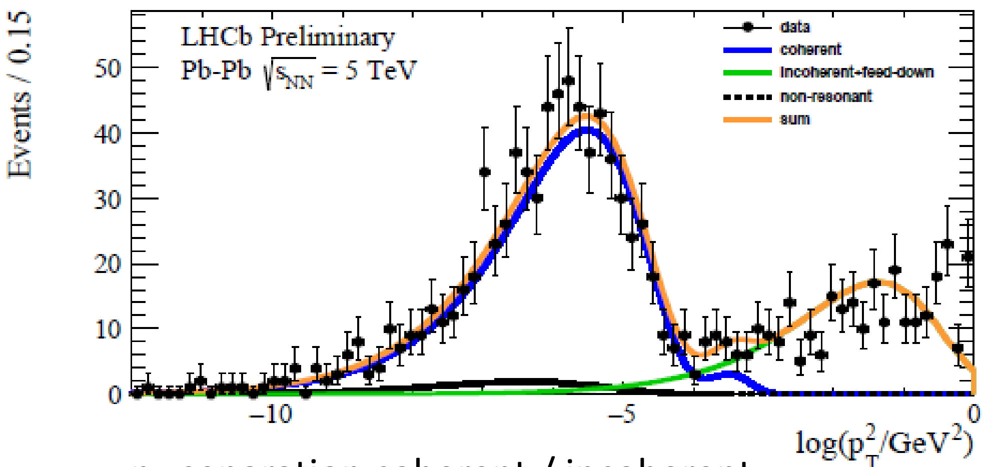
Ultra-Peripheral Collisions

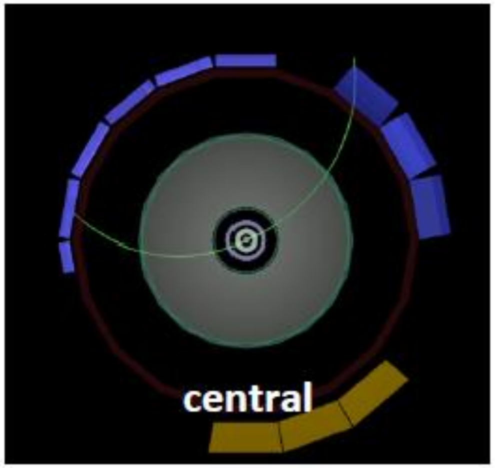
Experimental aspects





LHCB-CONF-2018-003





p_T-separation coherent / incoherent