Heavy-Ion Physics at the LHC

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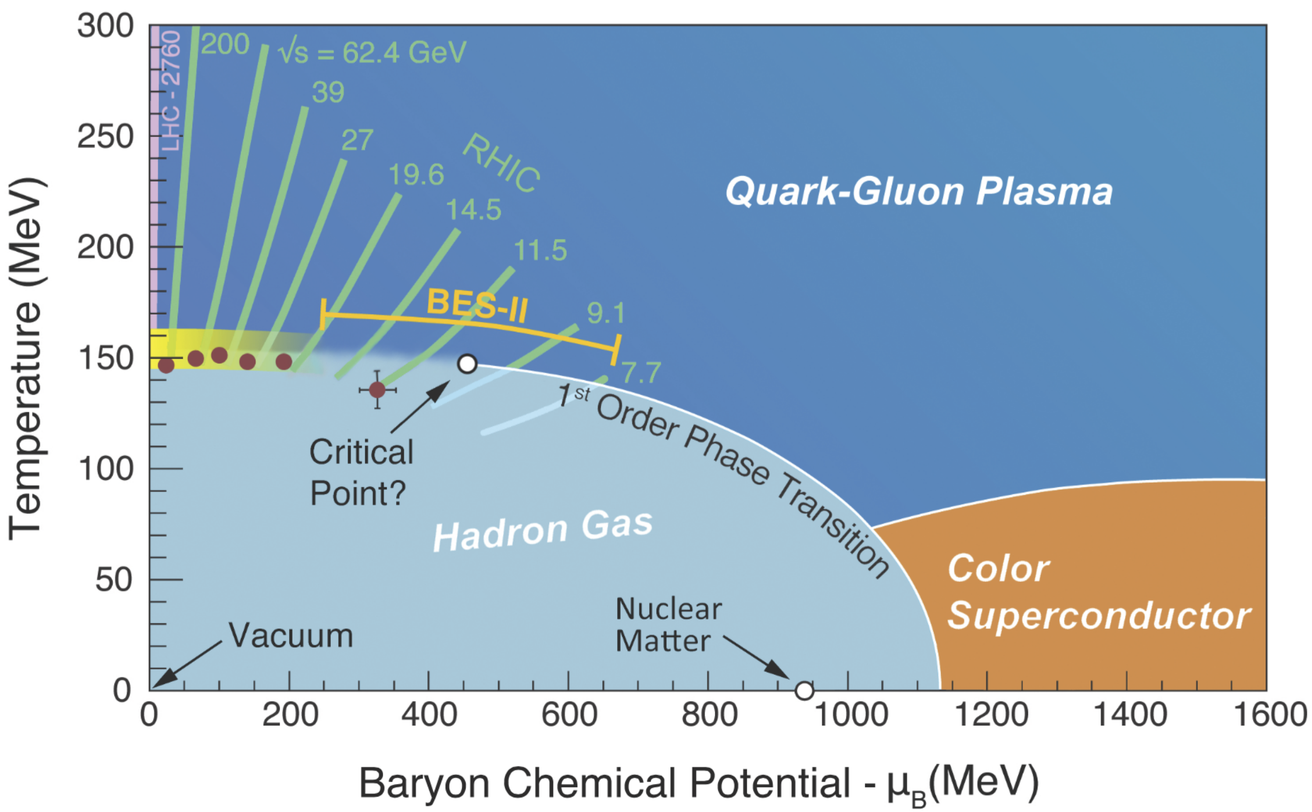
University of Oslo

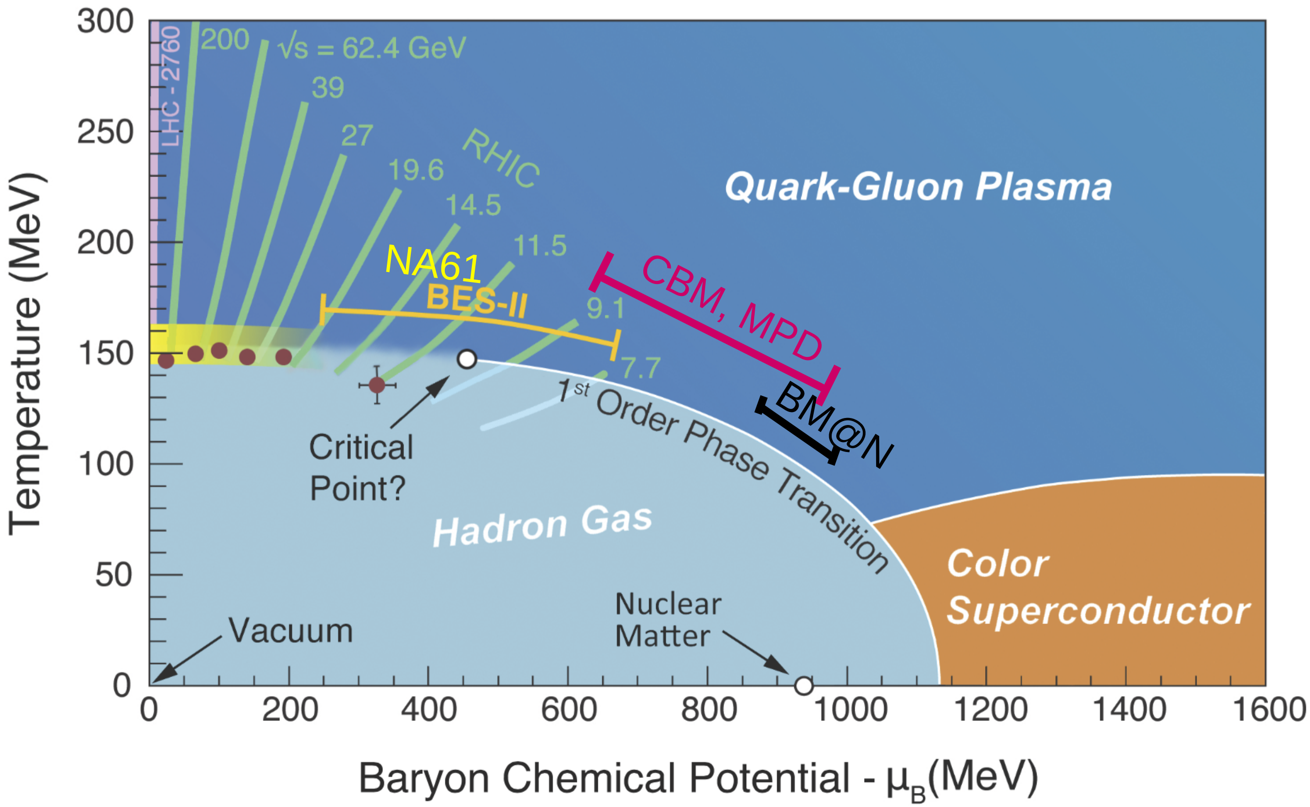
IV International Conference on Particle Physics and Astrophysics, Moscow 22-26 October 2018

Why relativistic heavy-ion collisions ?



- QCD studies at low *Q*, finite temperature *T* and baryon chemical potential μ_B
- Deconfinement (+ chiral symmetry restoration): hadron gas → Quark-Gluon Plasma
  - Smooth cross-over at small μ_B
  - Critical temperature from Lattice QCD: T_c ~ 156 MeV

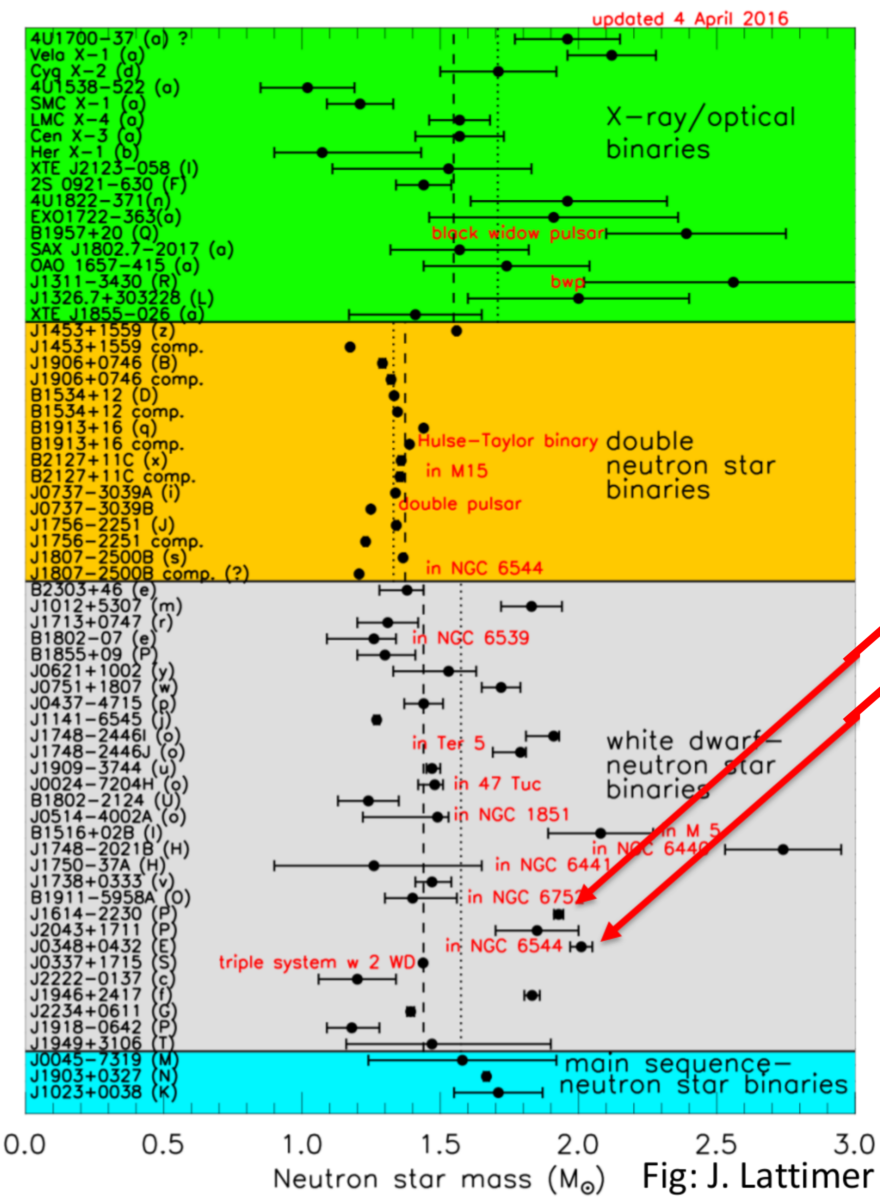
Why relativistic heavy-ion collisions ?



- Critical point and first order phase transition at large μ_B:
  - main physics target for several collaborations (STAR-BES, NA61, CBM, MPD)
- Color superconducting phases (low T, very high μ_B): neutron stars

Astrophysics and heavy-ion collisions

J.M.Lattimer, arXiv:1305.3510

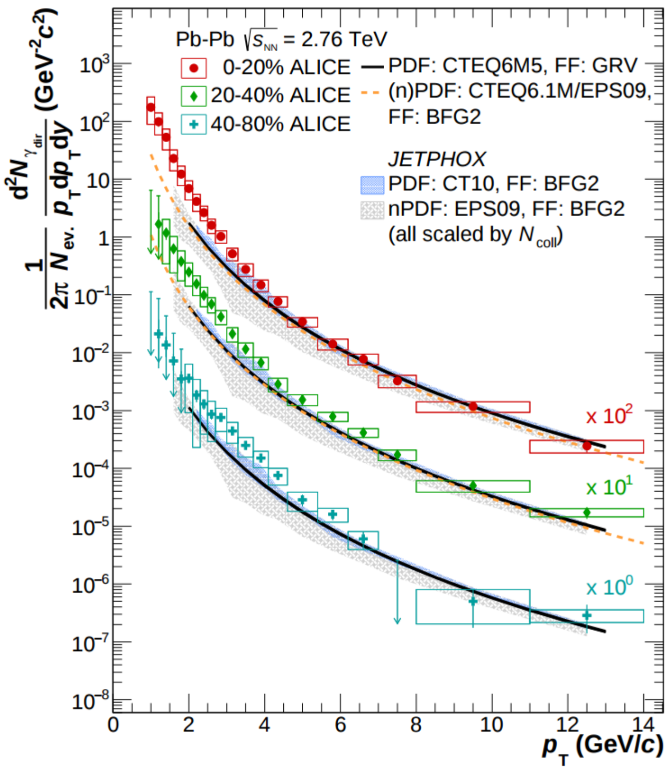


- Neutron stars mass controlled by the equation of state (EoS) of nuclear matter
  - "Canonical" mass: 1.4 M_{sun}
  - How can the outliers exist ?
    - Stiffer EoS at larger nuclear densities (hyperon matter? QGP cores ?)
- Neutron star mergers
  - EoS an important parameter

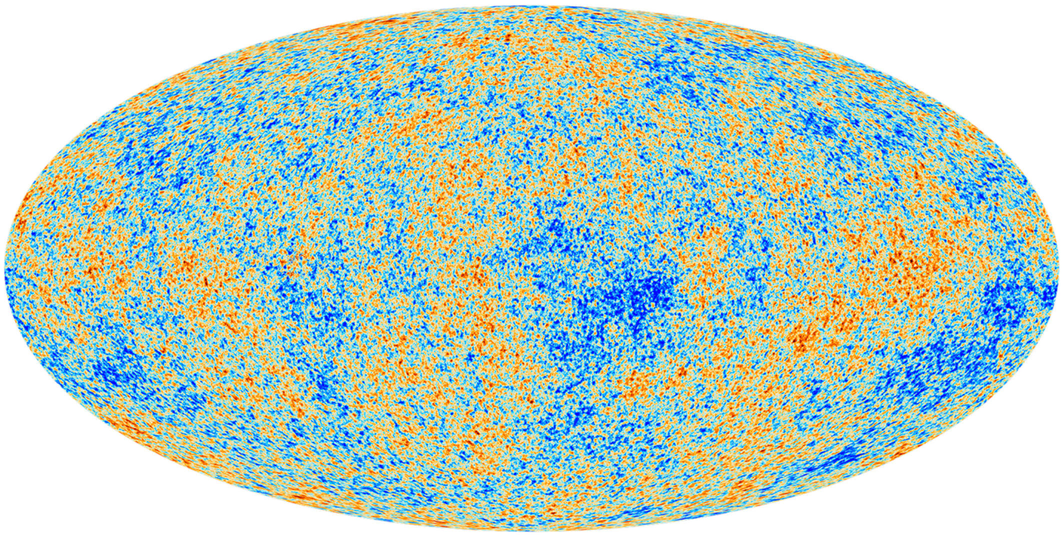
Cosmology and relativistic heavy-ion collisions

ALICE Collaboration, PLB754 (2016) 235

Direct photon production



Cosmic microwave background seen by Planck



T_{CMB}=2.7 K (~2x10^{-4} eV)

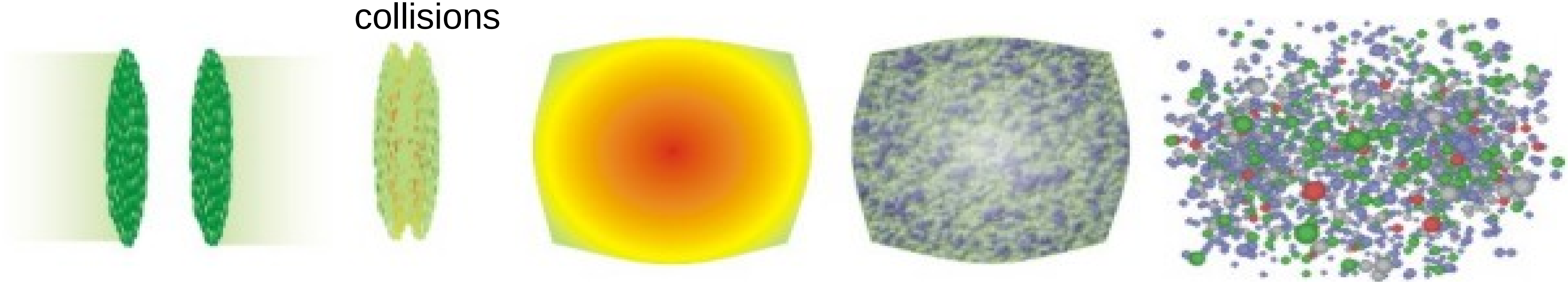
T_{QGP}= 3500000000000 K (3x10^8 eV)

- Access early Universe conditions (10^{-5} s):
  - QGP temperature in Pb-Pb collisions from direct photon measurements:

    T ~ 300 MeV

“Standard Model” of high-energy nuclear collisions

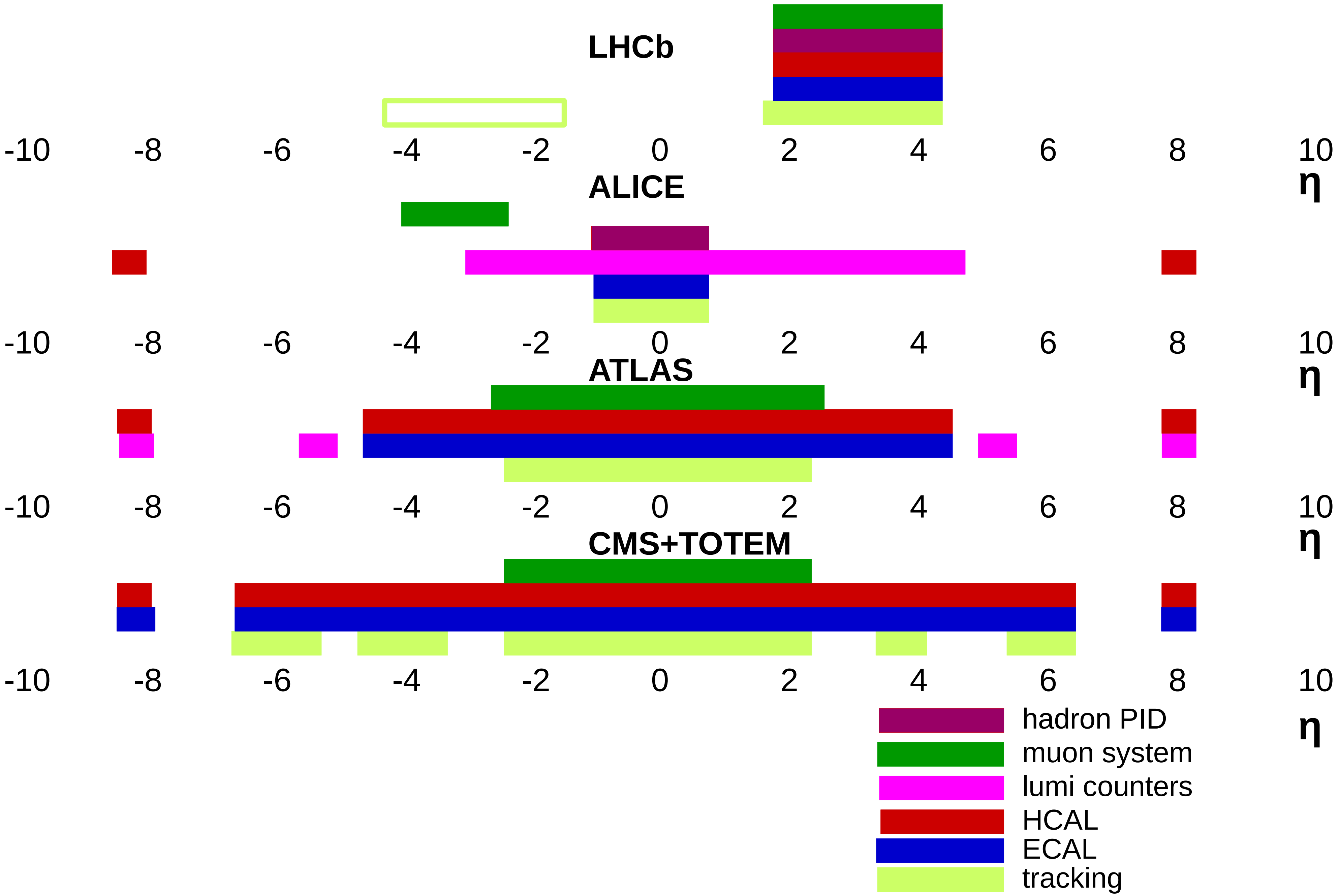
Initial state	Hard partonic collisions	QGP	Chemical freeze-out	Kinetic freeze-out	



0	10^{-26}-10^{-24}	10^{-24}-10^{-23}	~10^{-23}	10^{-23}-10^{-22}	**t (s)**
0	0.01-1	1-10	~10	10-100	**(fm/c)**
Modified gluon PDF (saturation, shadowing), Fermi motion, ...	Gluon and quark-pair creation	Deconfined nuclear matter expanding hydrodynamically	Inelastic collisions cease; hadronization	Elastic collisions cease; free streaming particles	

- We measure only at the latest stages but we want to understand the hard partonic and the QGP stages... extremely challenging!

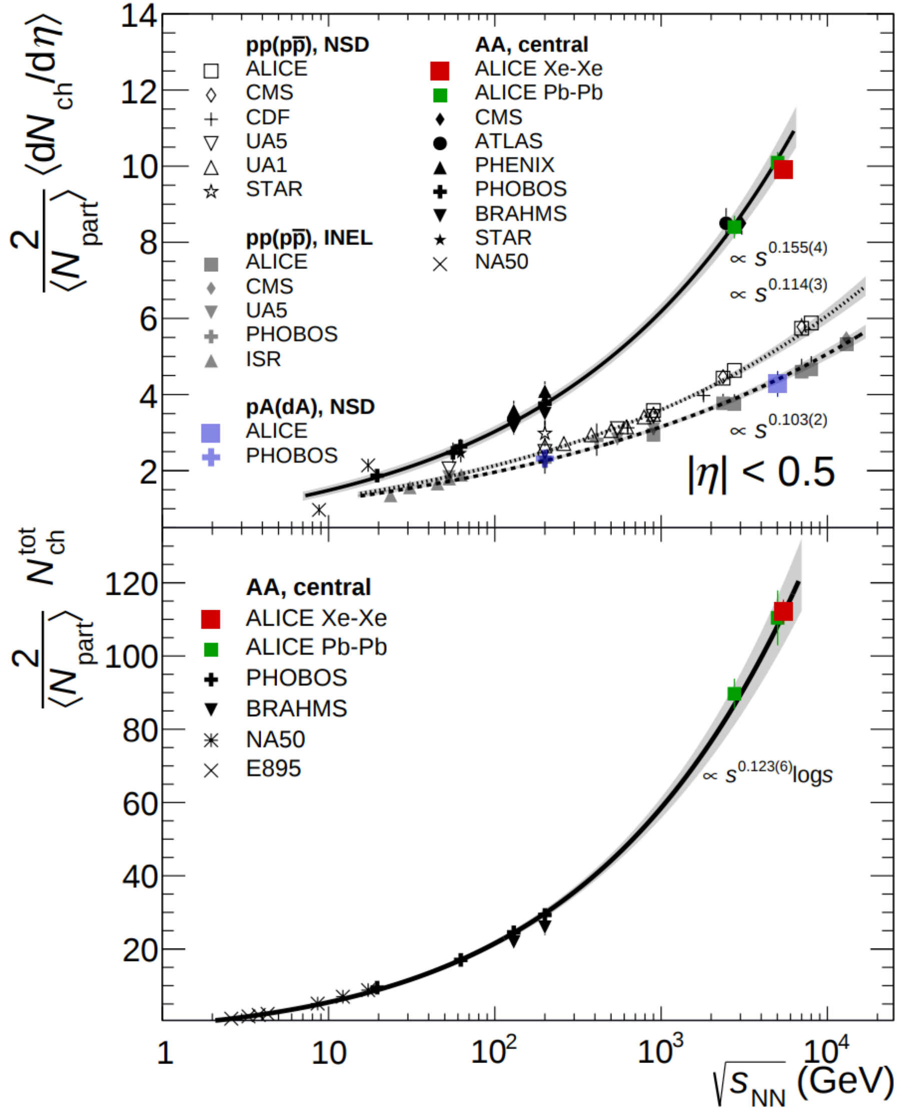
LHC experiments

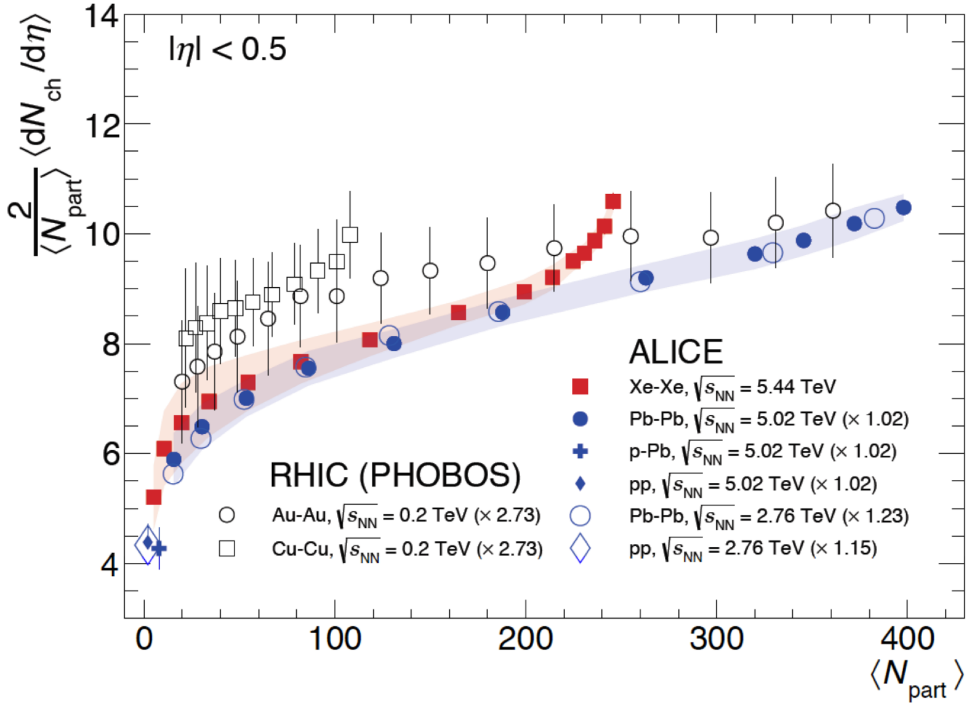


Bulk (soft) observables

Charged particle production

ALICE, arxiv:1805.04432



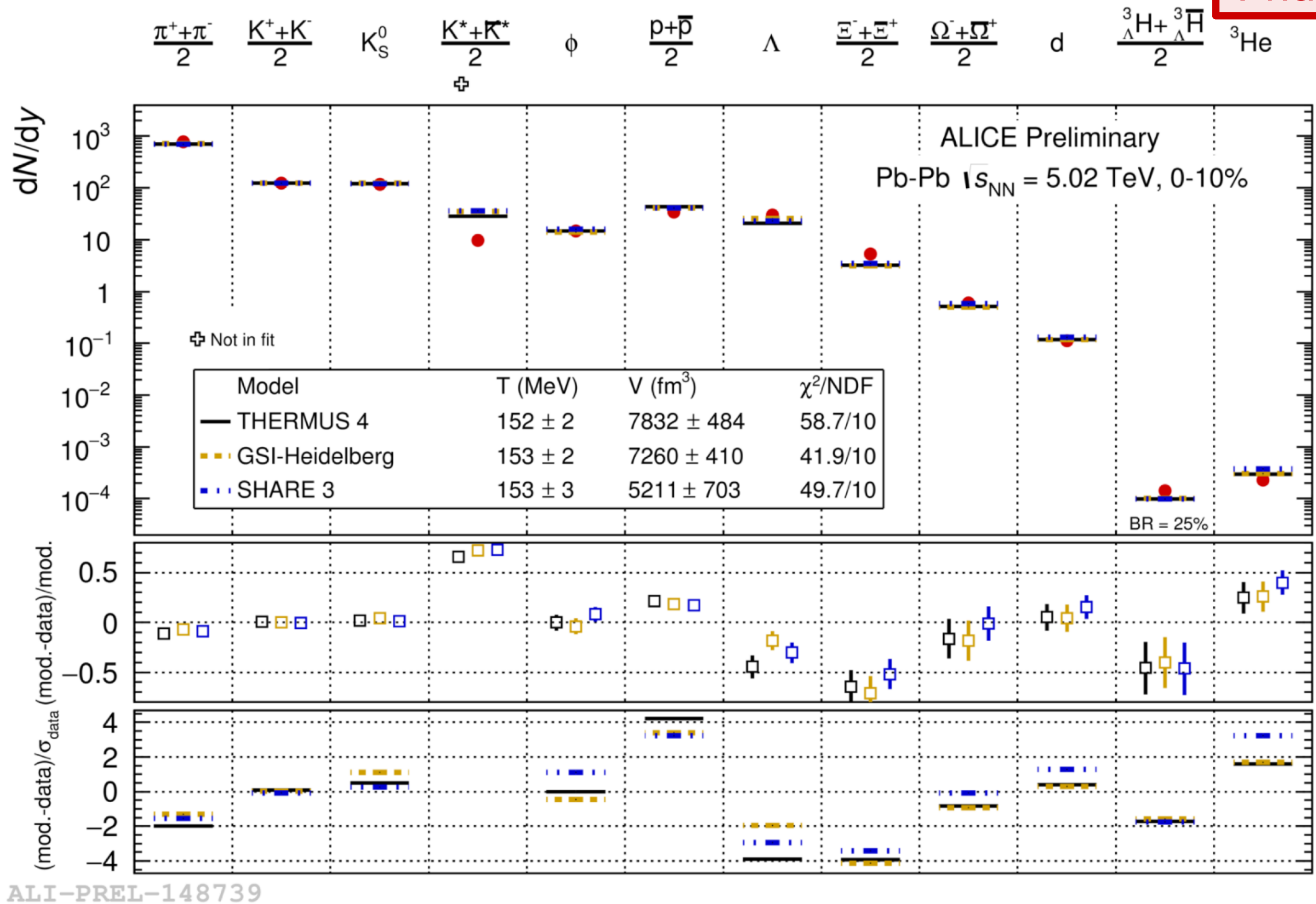


- Charged multiplicity per participant pair grows from peripheral towards central collisions
  - Larger number of binary collisions → more entropy production

- Power law increase of produced multiplicity per participant pair with collision energy
  - Stronger increase in AA than in pp collisions!

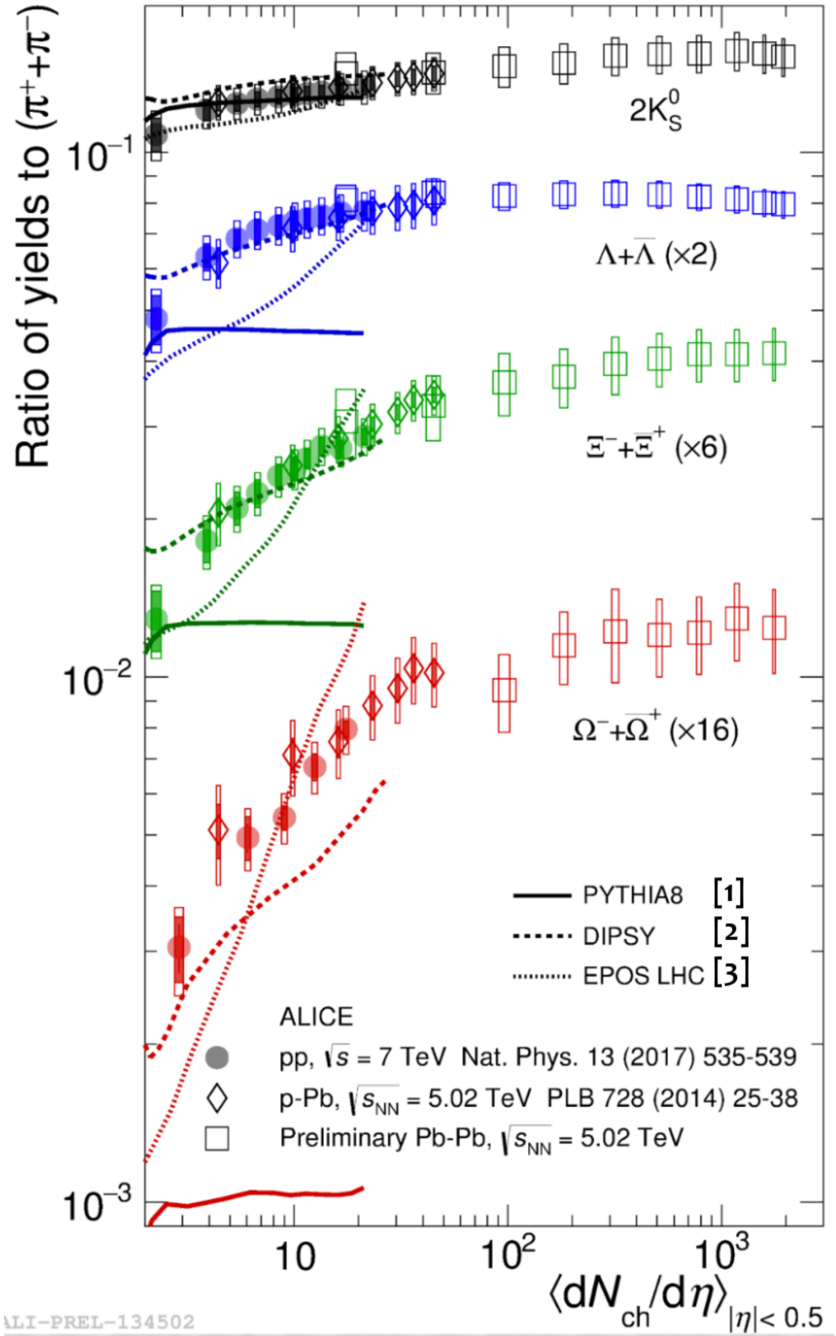
Identified particle production

Talk by Victor Riabov
Friday 10:00



- Screenshot of the fireball at the chemical freeze-out
- Particle yields described by thermodynamics over 7 orders of magnitude with just 3 parameters: volume, temperature and μ_B
- Chemical freeze-out temperature: ~153 +/- 2 MeV (similar to Lattice QCD calculations)

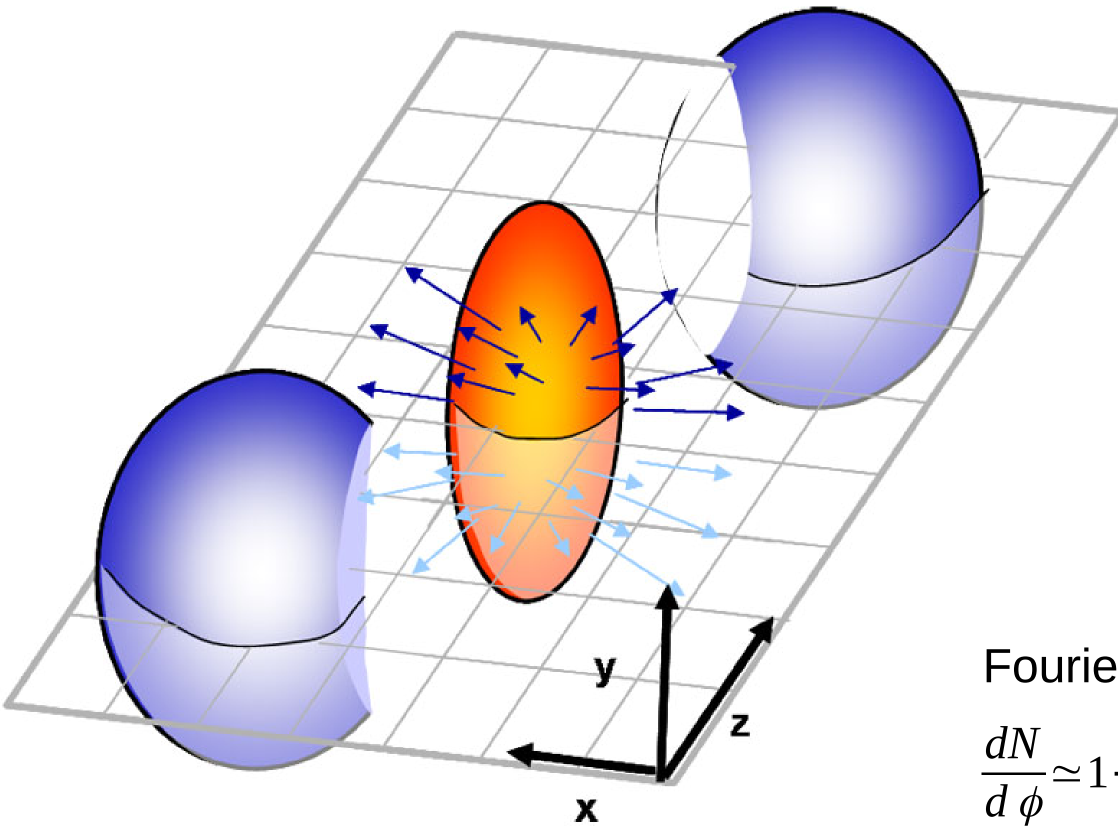
Strangeness production



Talk by Victor Riabov
Friday 10:00

- Characteristic of QGP formation
  - Rafelski and Mueller 1982
- Universal dependence of strangeness production as a function of event multiplicity independent on collision system (pp, p-Pb and Pb-Pb collisions)
- Strangeness enhancement saturation in central Pb-Pb collisions (grand-canonical regime)

Anisotropic flow



Talk by Arkadiy
Thursday 17:10

Fourier decomposition:

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

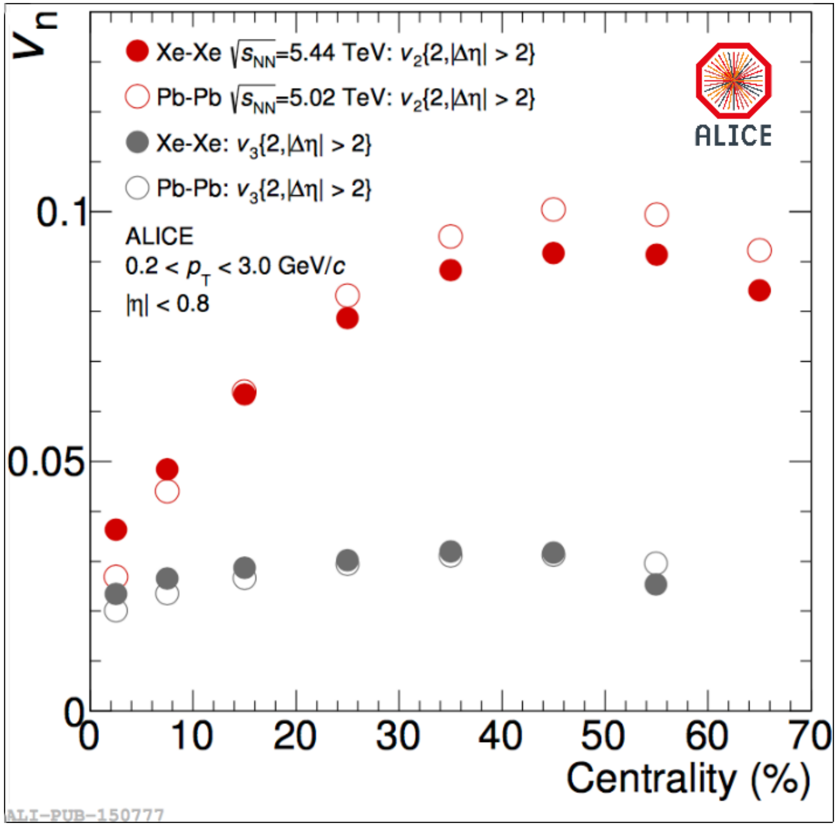
- Initial geometry of the collision is non-uniform (almond shaped)
- Large initial energy density gradients
- Multiple rescatterings in the system

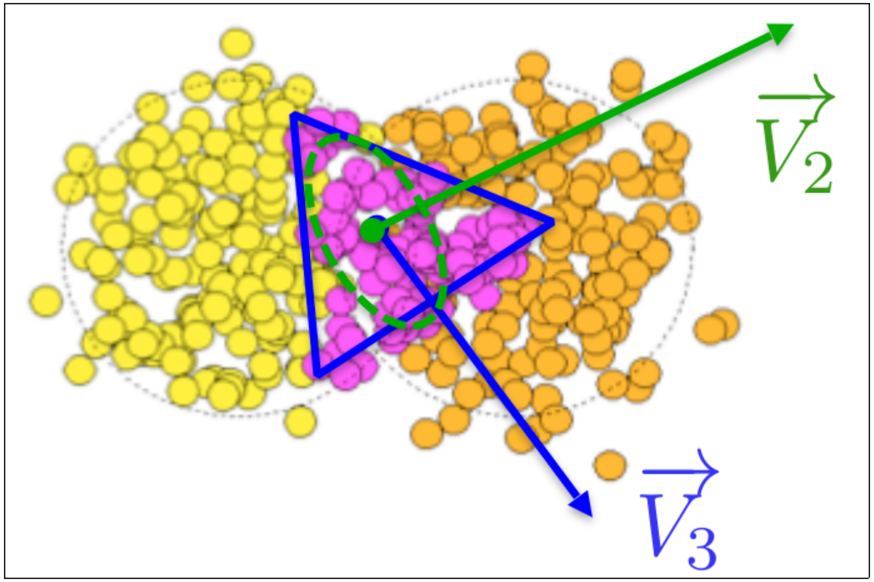
→ Anisotropic flow

- Sensitive to initial state and key QGP properties like the equation of state, viscosity, transport coefficients

Elliptic (v2) and triangular (v3) flow

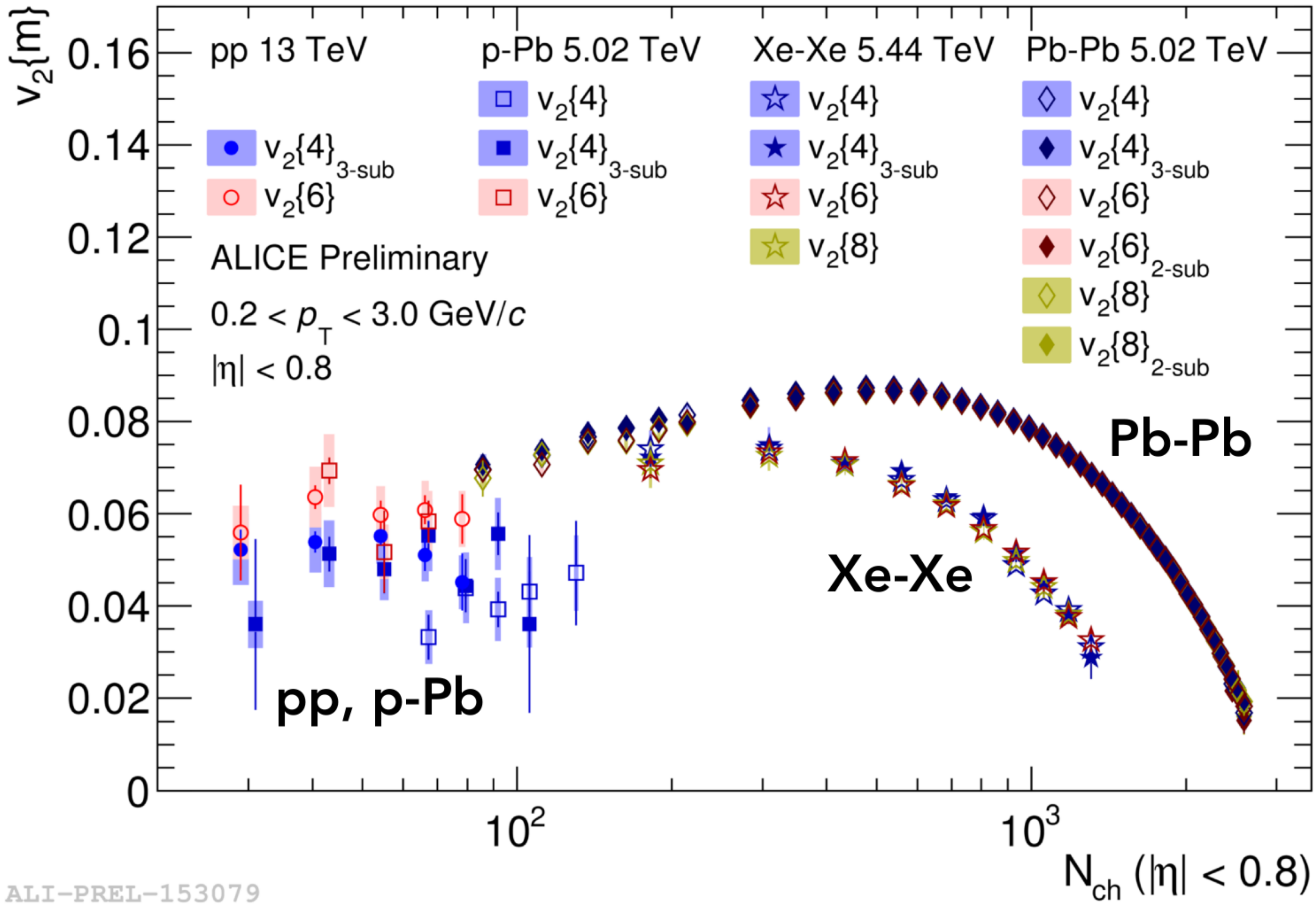
ALICE, arxiv:1805.01832





- 2^{nd} harmonic: dominant; exhibits a maximum at mid-central collisions
- 3^{rd} harmonic: less sensitive on centrality → mainly related to initial state energy density fluctuations

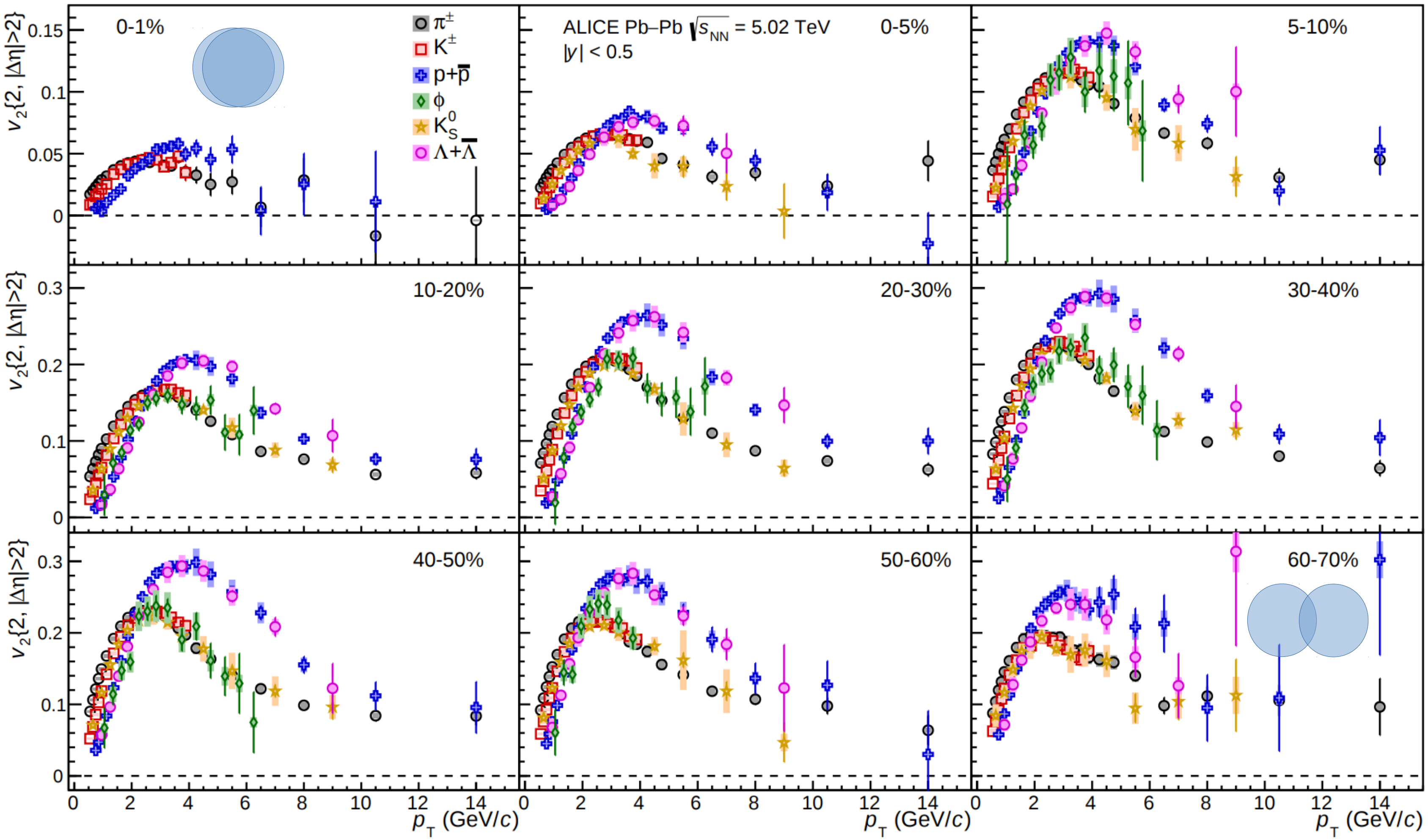
v_2 measurements vs multiplicity



- Elliptic flow (v_2) measurements available for all colliding systems
  - Challenge to understand results in small systems → collective effects in small systems?

Identified particles v_2

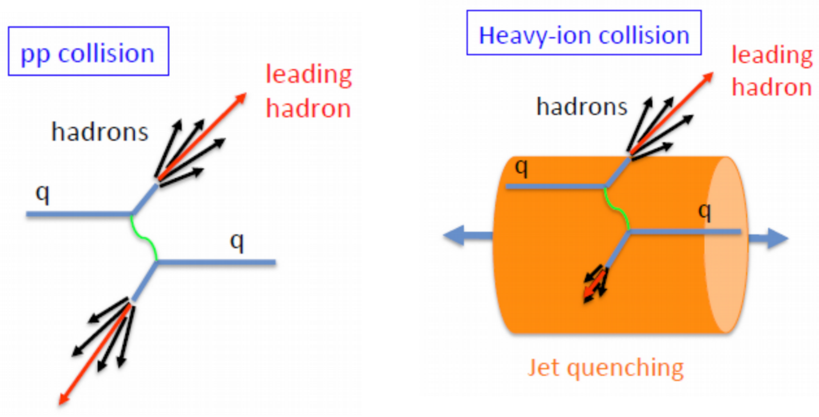
ALICE, arXiv:1805.04390

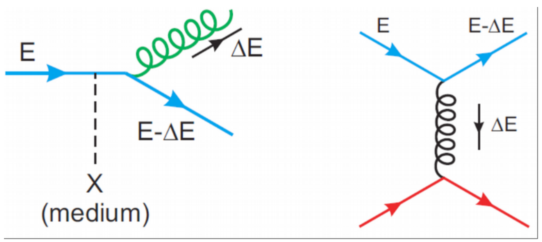


- Low-p_T : mass ordering $v_2(\pi)>v_2(K)>v_2(p,\varphi,\Lambda)$ → strong collective radial flow
- High-p_T: splitting in meson and baryon branches → hadronization via quark coalescence

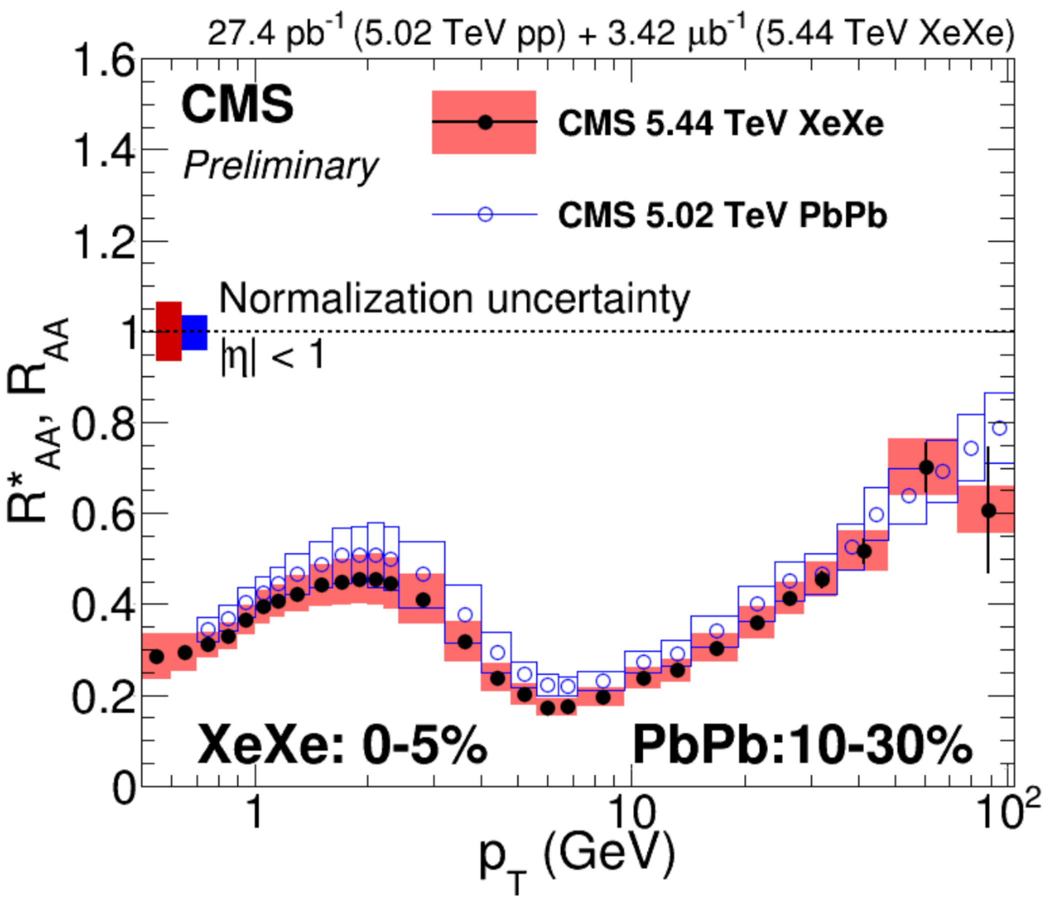
Hard and electro-magnetic probes

High-p_T hadron suppression





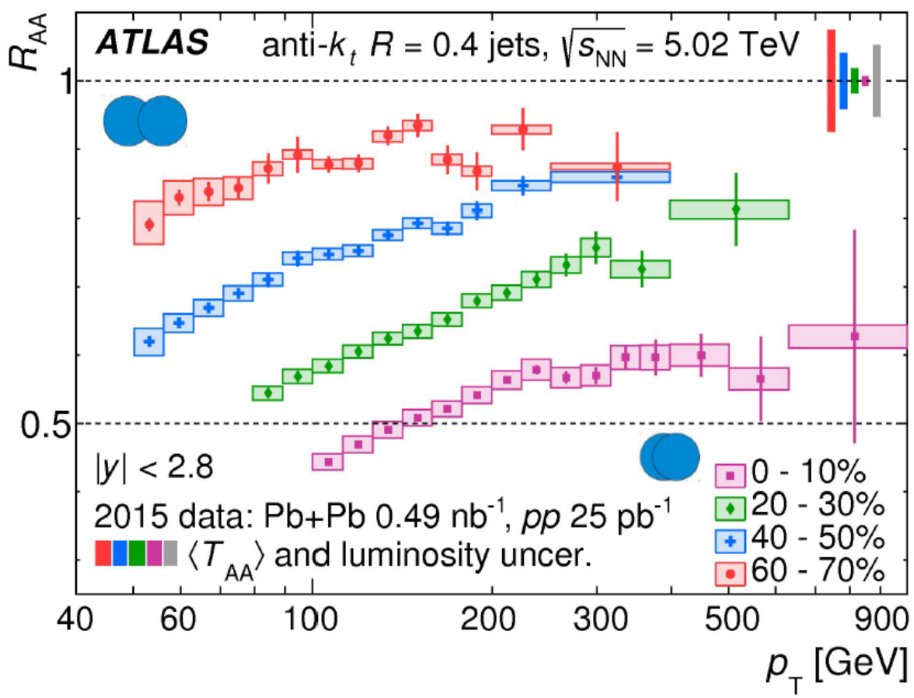
$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y_{AA}}{Y_{pp}}$$

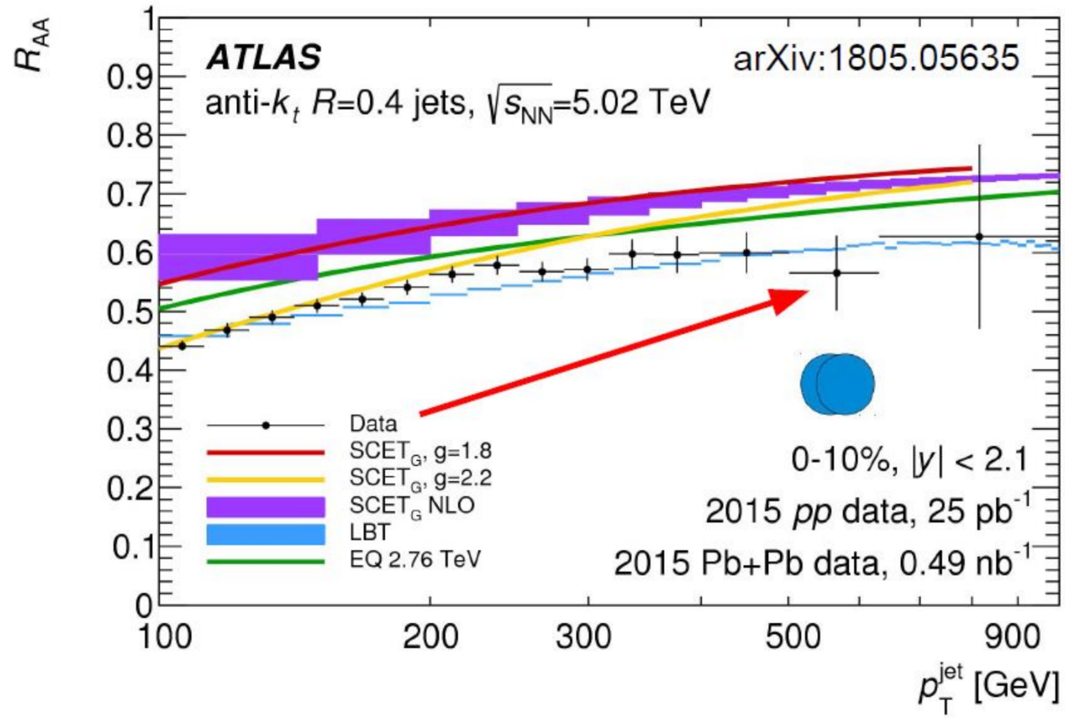


- High-p_T hadrons are suppressed even at 100 GeV/c
- Strong energy loss in the QGP medium
- Important measurement for the extraction of transport properties: $\hat{q}$

Jet suppression in nuclear collisions

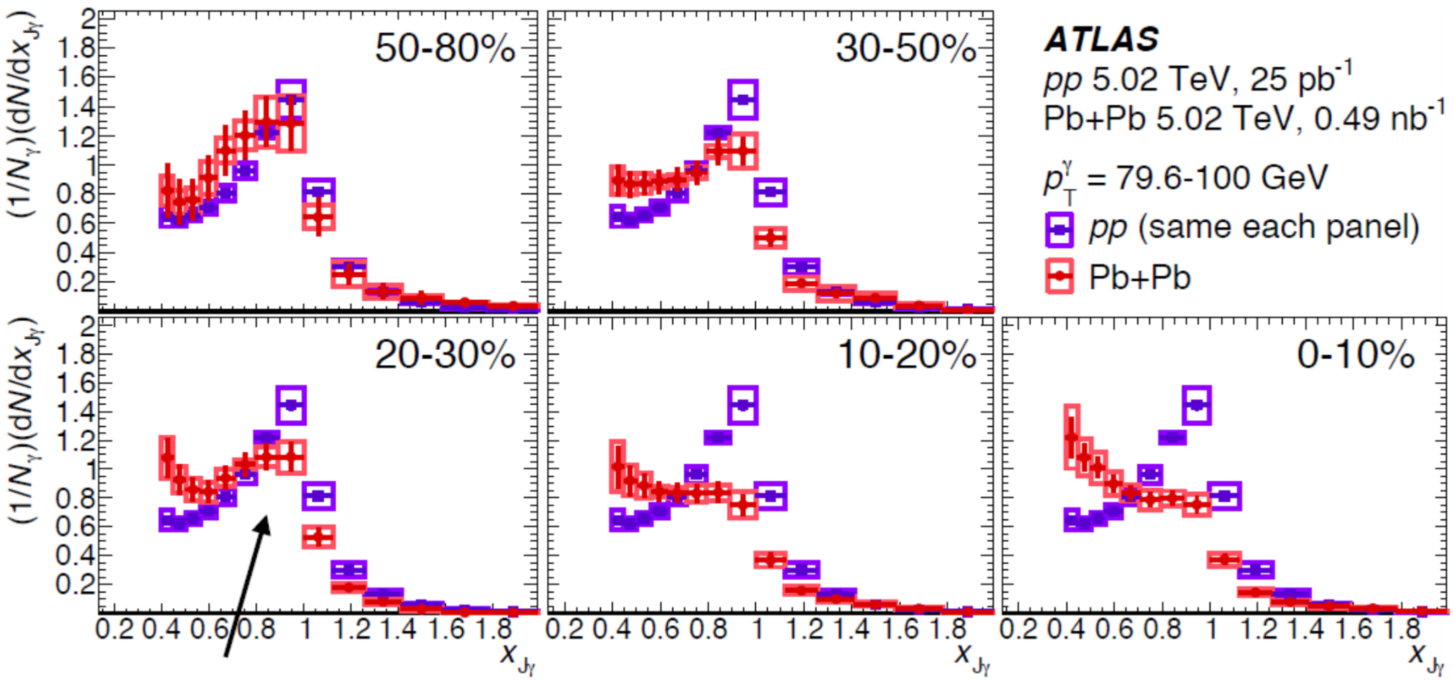
ATLAS, arXiv:1805.05635



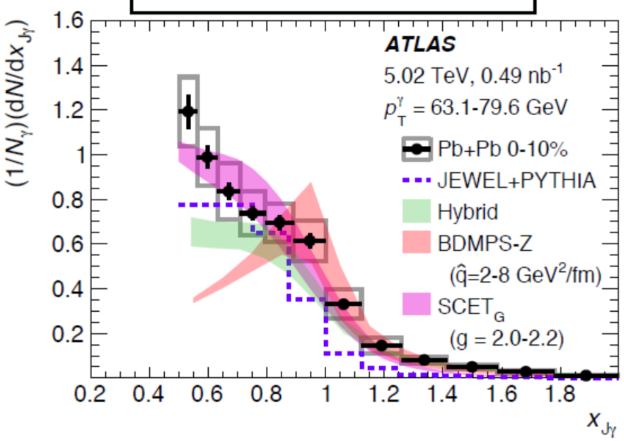


- Strong centrality dependence → quenching grows with the energy density of the medium
- Jets still suppressed even at ~1 TeV

Photon tagged jets



0-10% Pb+Pb



$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$ (for $\Delta\phi > 7\pi/8$)

- Photon-tagging: well calibrated initial energy
- Direct measure of energy loss ΔE of the recoil jet
- Energy imbalance grows towards central collisions

Flavour dependence of energy loss

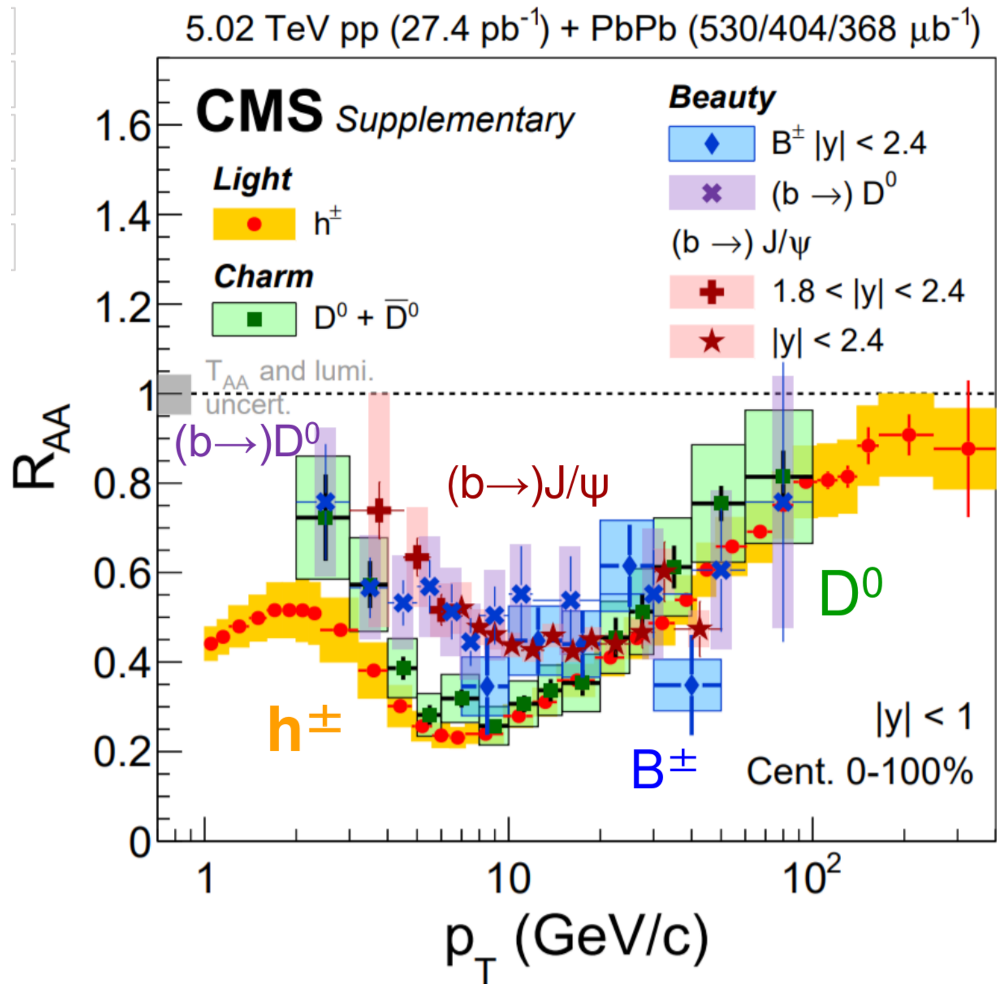
D⁰ PLB 782 (2018) 474

J/ψ EPJC 77 (2017) 269

b→D⁰ CMS-PAS-HIN-18-010

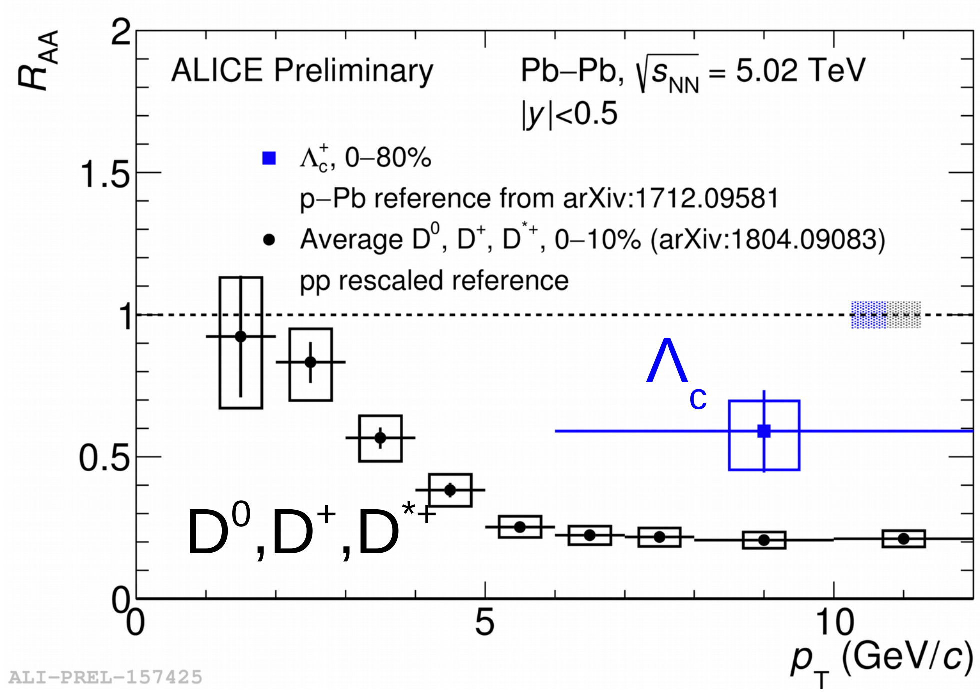
h± JHEP 04 (2017) 039

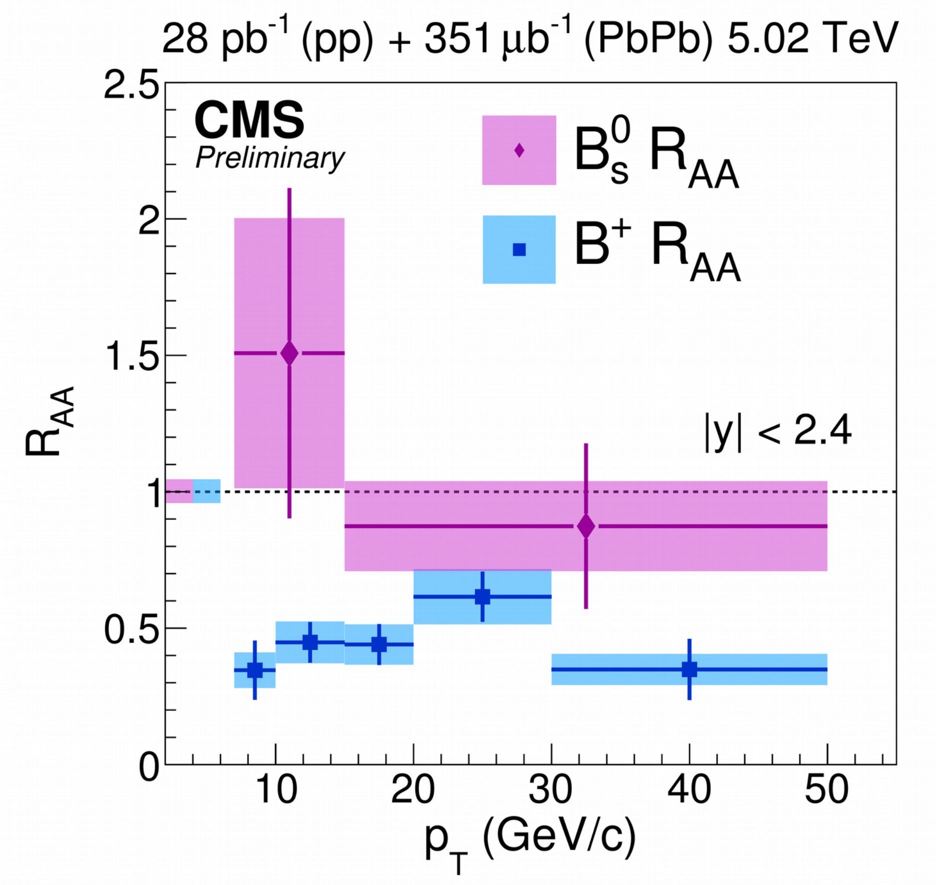
B± PRL 119 (2017) 152301



- Low p_T: mass hierarchy
  $R_{AA}(b) < R_{AA}(c) < R_{AA}(u,d,s)$
- High p_T: flavor independence of energy loss

Heavy strange mesons



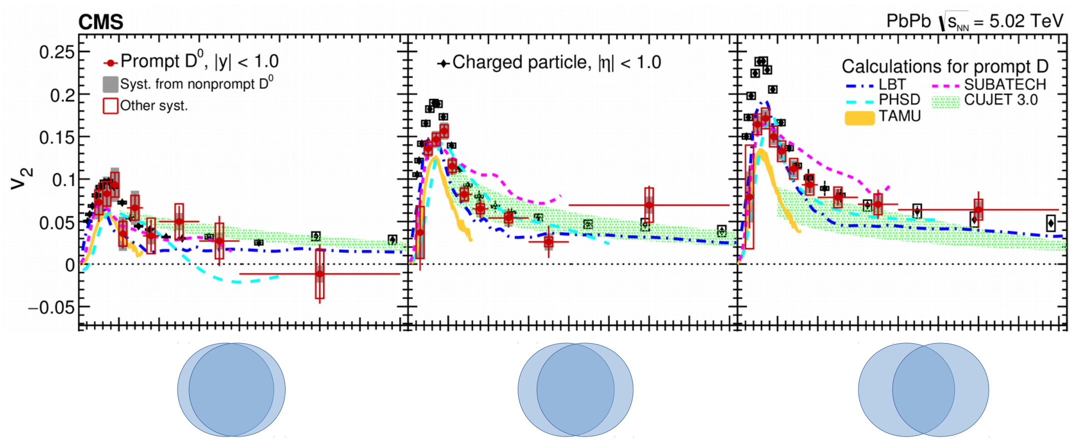


- First Λ_c measurement in Pb-Pb!
- Charmed baryons less suppressed than mesons

- First B_s^0 measurement in Pb-Pb!
- Hint of enhancement of B_s^0 wrt B^+

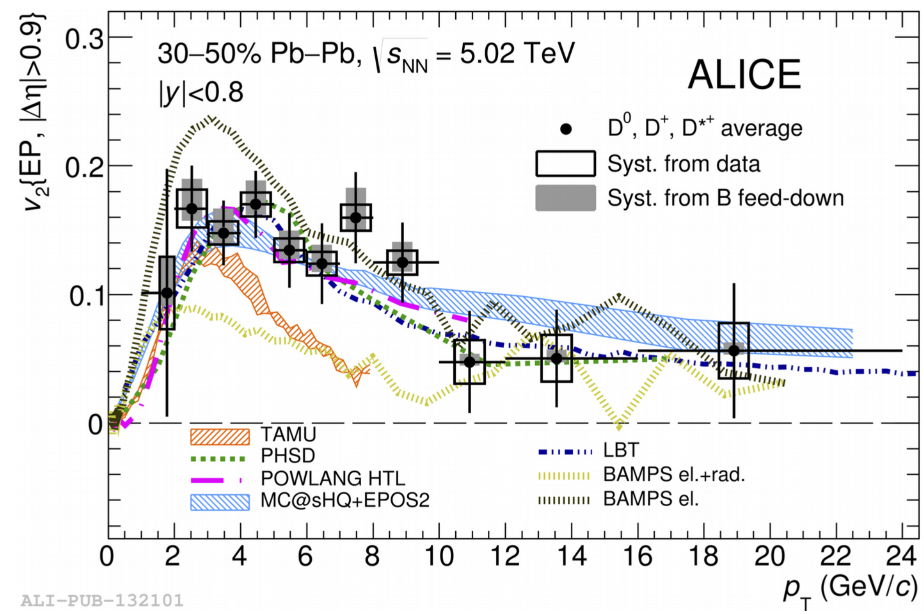
Elliptic flow of D mesons

CMS, PRL 120(2018)202301



0-10% 10-30% 30-50%

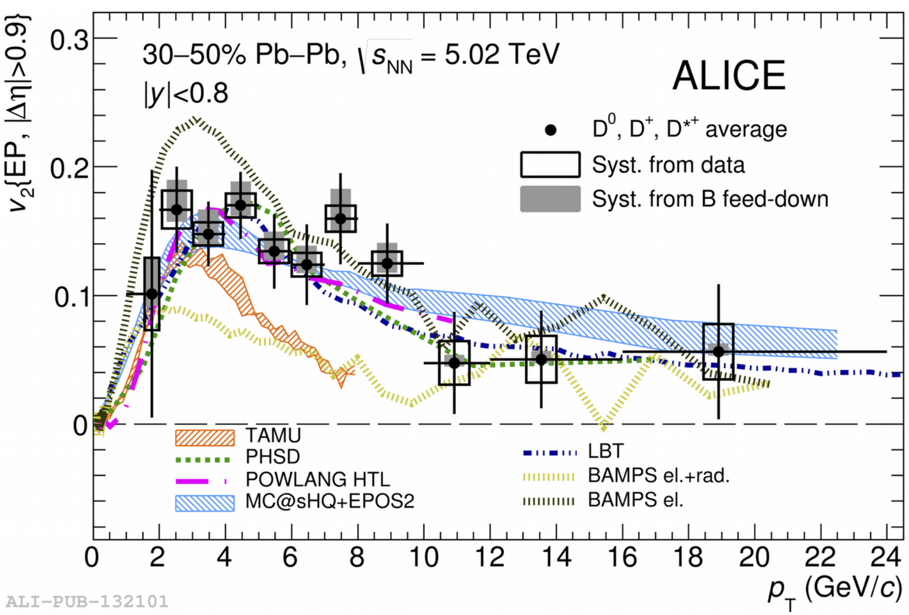
ALICE PRL 120 (2018) 102301

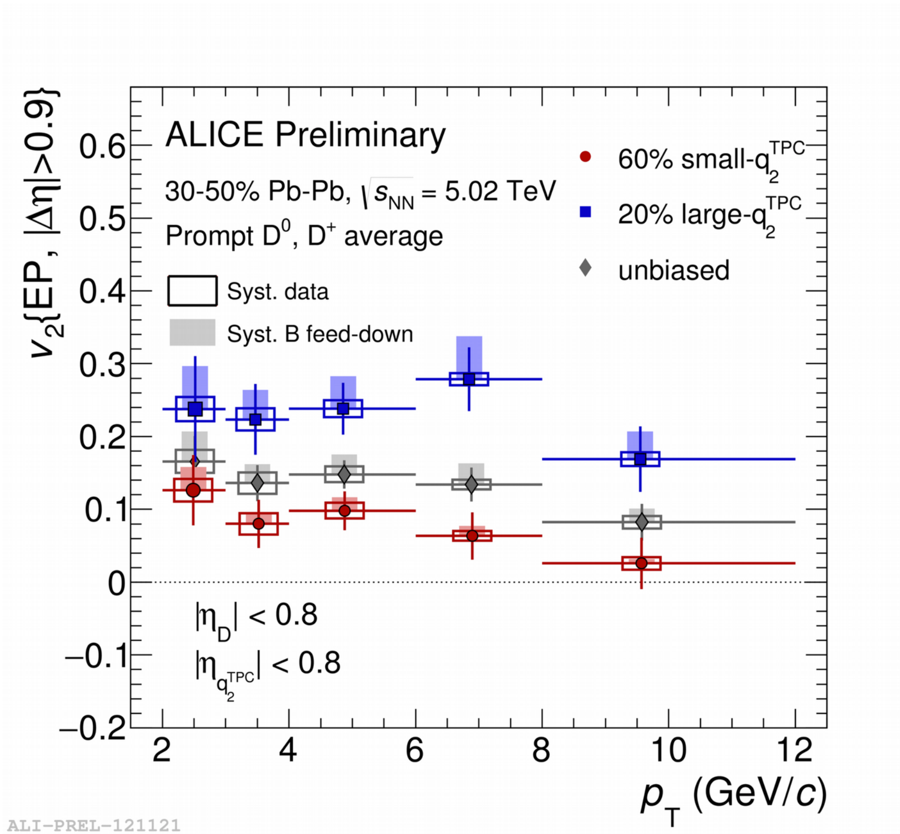


- Significant elliptic flow v_2 of charm at the LHC
- Stronger in semi-central collisions
- Does charm take part in the collective motion ?

Event shape engineering and D-meson elliptic flow

ALICE PRL 120 (2018) 102301

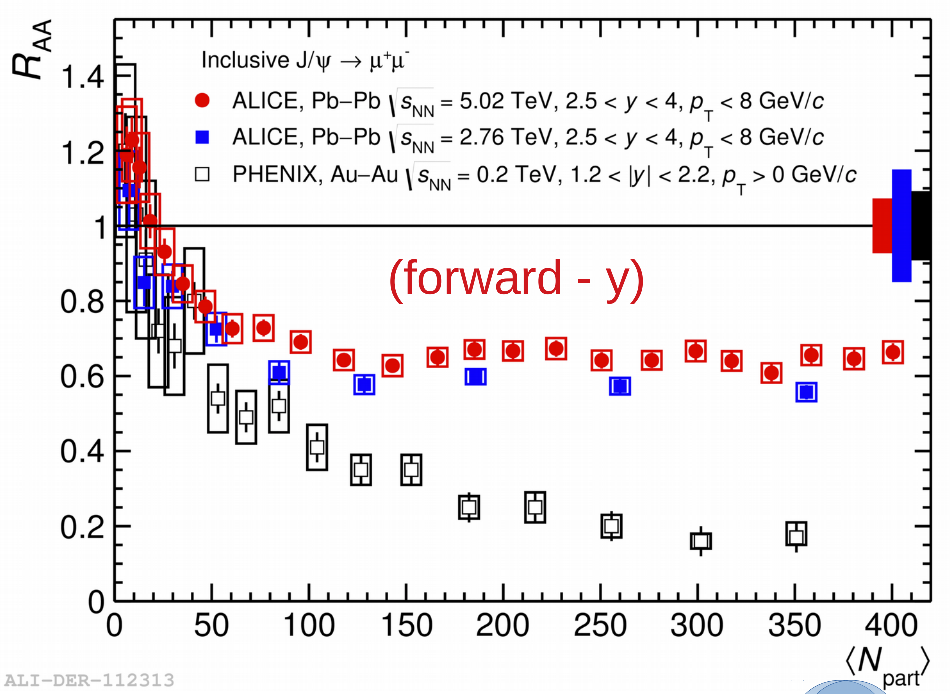


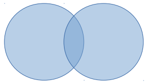


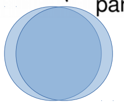
- Event shape engineering technique
- D-meson elliptic flow correlated with the overall hydrodynamic flow of the bulk charged particles

J/ψ suppression

ALICE, PLB 734 (2014) 314
ALICE, PLB 766 (2017) 212
PHENIX, PRC 84 (2011) 054912



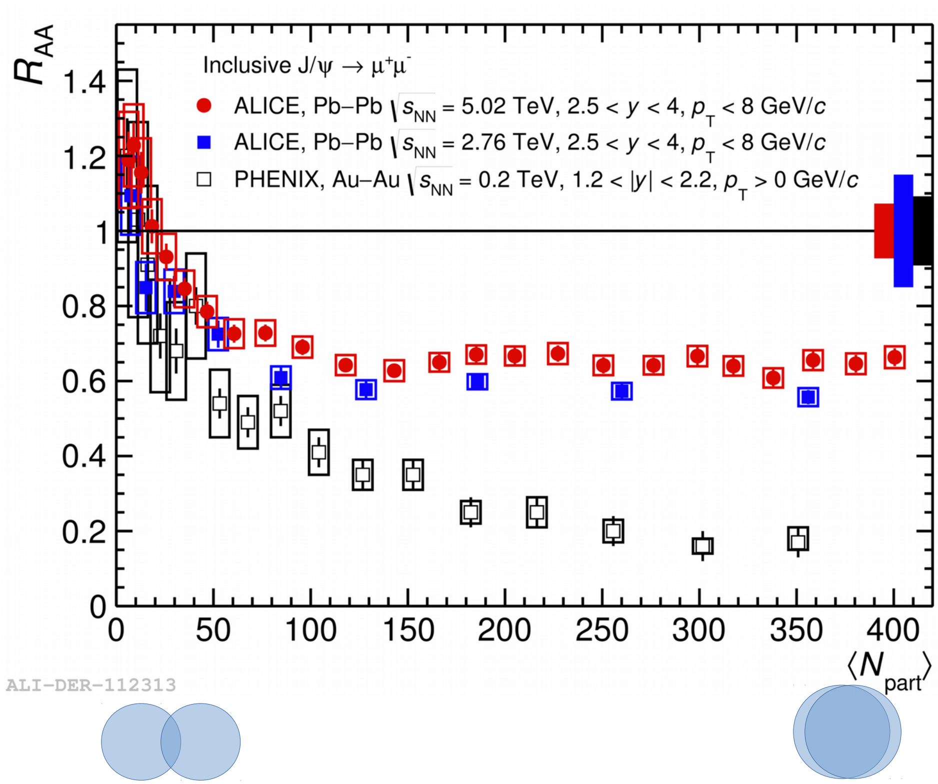


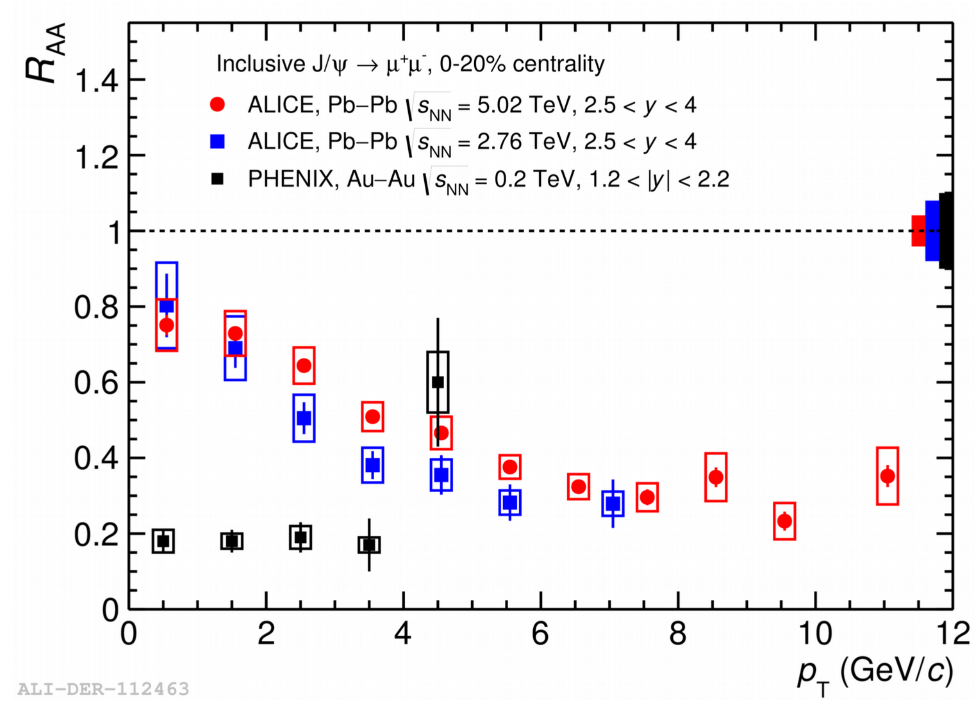


- Striking observation in central collisions: J/ψ less suppressed at LHC wrt RHIC

J/ψ suppression

ALICE, PLB 734 (2014) 314
ALICE, PLB 766 (2017) 212
PHENIX, PRC 84 (2011) 054912



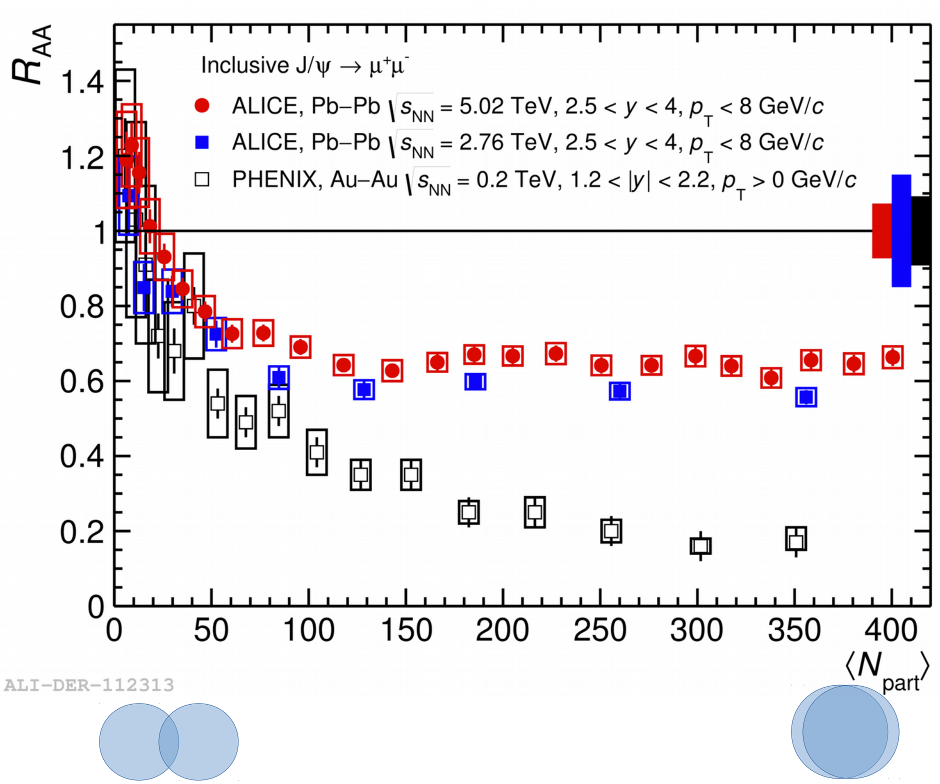


- Striking observation in central collisions: J/ψ less suppressed at LHC wrt RHIC
- Low-p_T: less suppression at LHC wrt RHIC
  - New mechanism of charmonium production → in-medium $c\bar{c}$ recombination

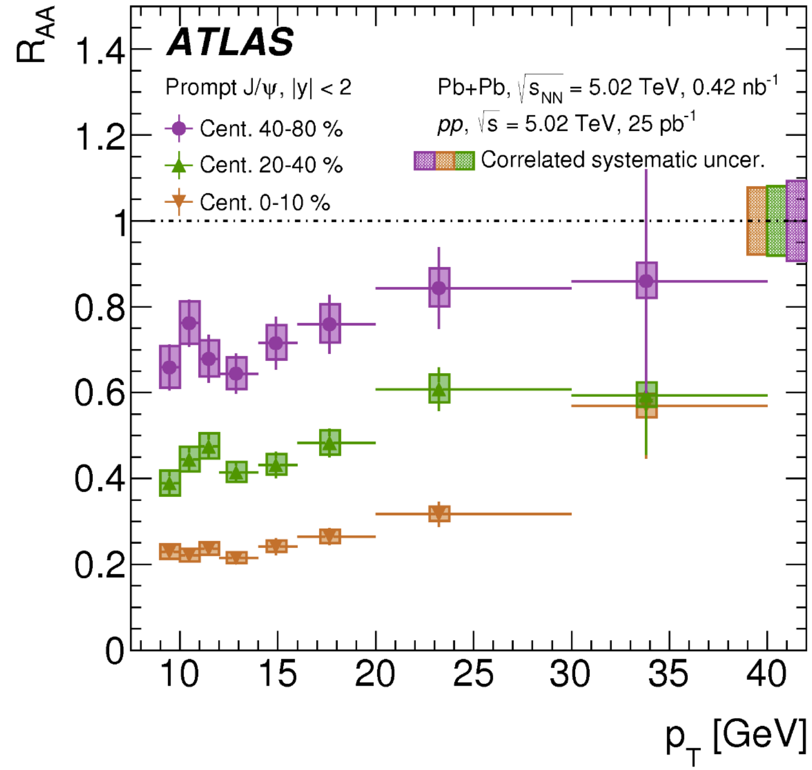
J/ψ suppression

ALICE, PLB 734 (2014) 314
ALICE, PLB 766 (2017) 212
PHENIX, PRC 84 (2011) 054912

Talk by Jakub Kremer
Thursday 16:30



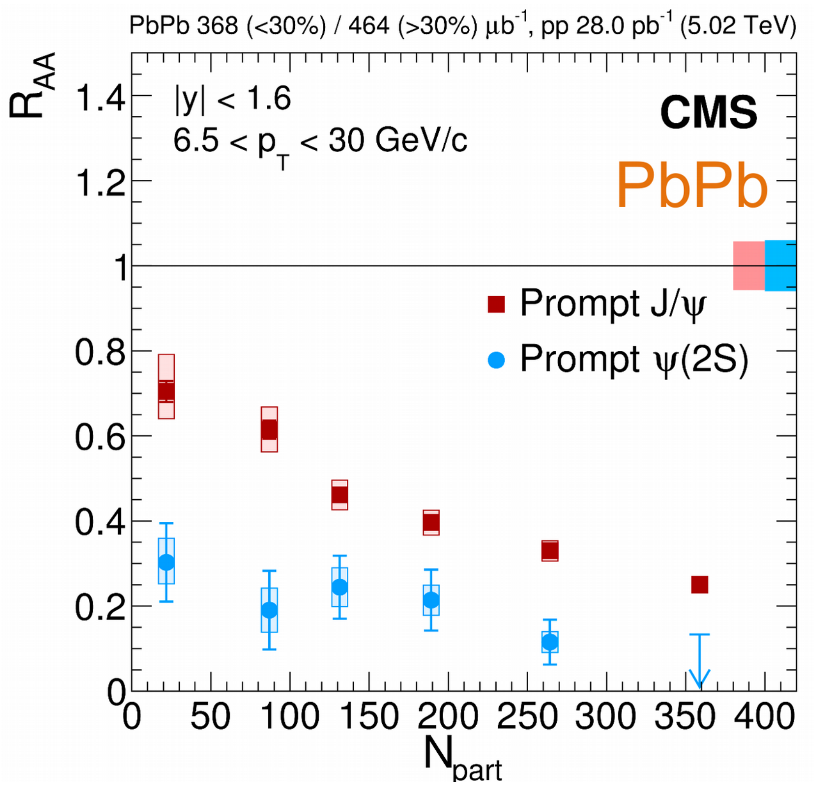
ATLAS, arXiv:1805.04077

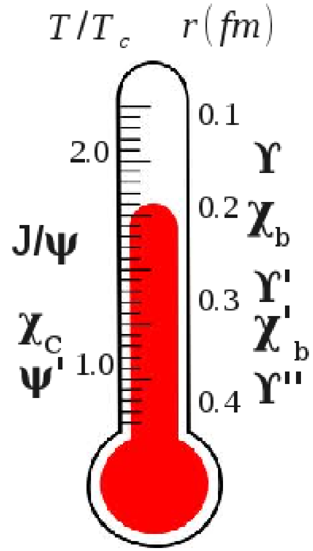


- Striking observation in central collisions: J/ψ less suppressed at LHC wrt RHIC
- Low-p_T: less suppression at LHC wrt RHIC
  - New mechanism of charmonium production → in-medium $c\bar{c}$ recombination
- High-p_T: strong centrality dependent J/ψ suppression

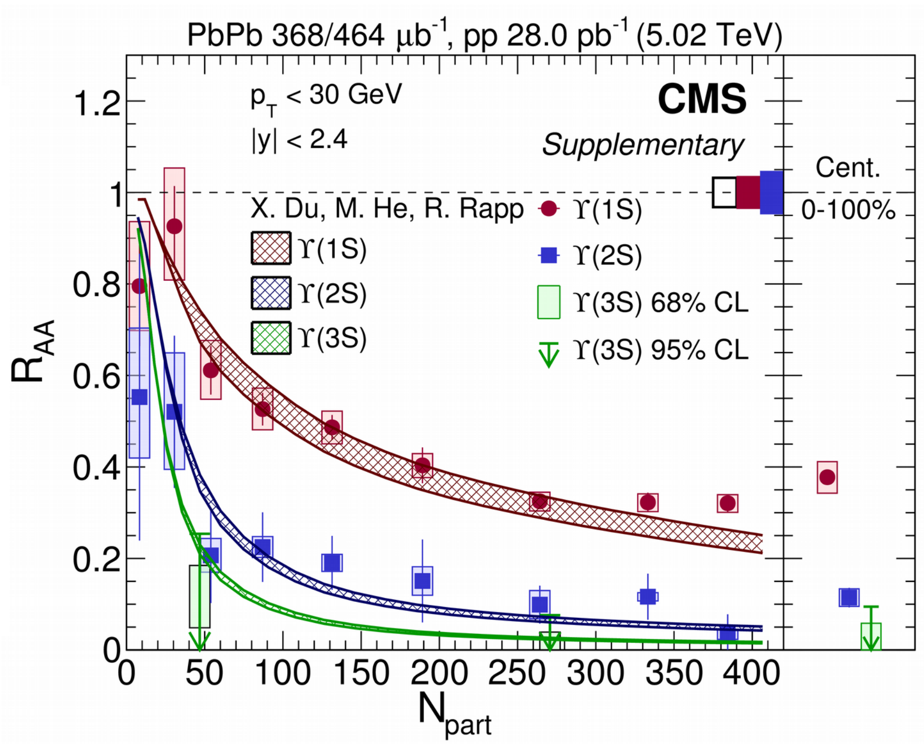
Binding energy dependence of quarkonium suppression

CMS, arxiv:1712.08959





CMS, arxiv:1805.09215

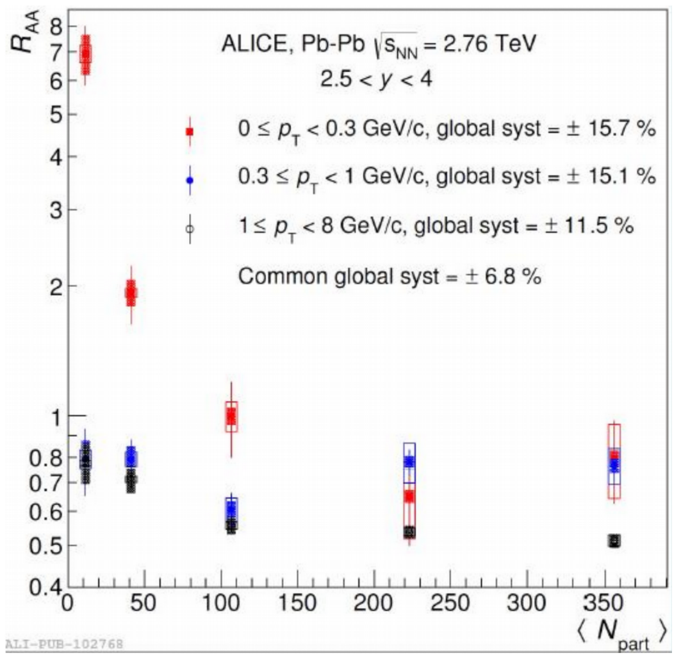


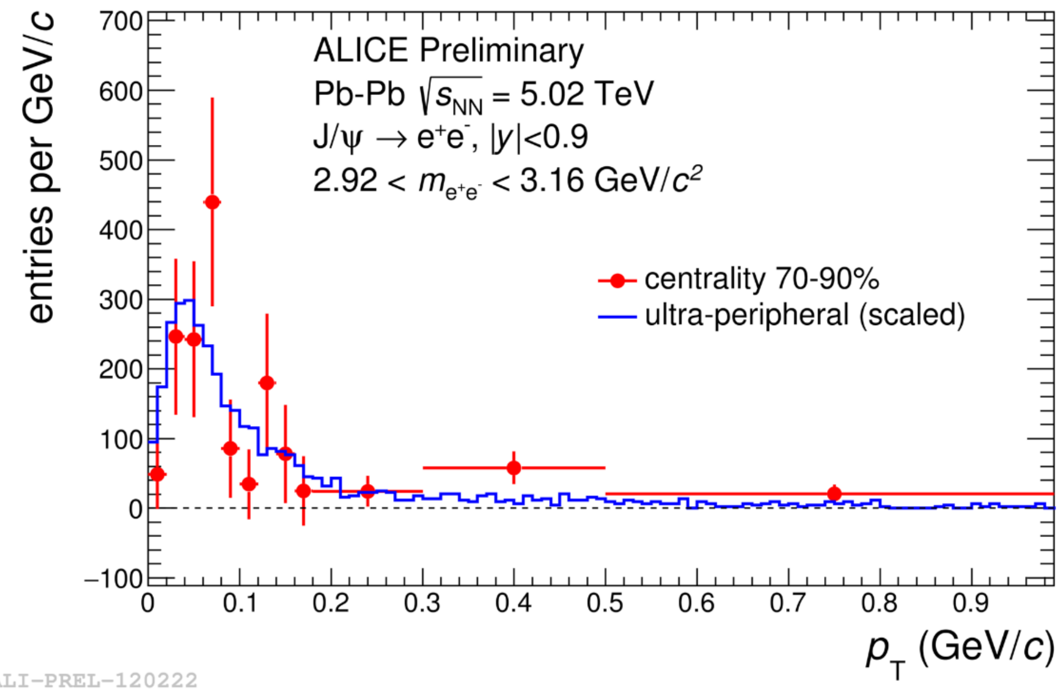
- Bottomonia and high-p_T charmonia
- Increasing suppression towards more central collisions
- Sequential suppression:
  - $R_{AA}\{\Upsilon(1S)\} > R_{AA}\{\Upsilon(2S)\} > R_{AA}\{\Upsilon(3S)\}$
  - $R_{AA}\{J/\psi\} > R_{AA}\{\psi(2S)\}$ (*NB:* Only at high p_T)
- Transport model calculations in agreement with data

J/ψ photo-production in Pb-Pb collisions with b<2R

Talk by Roman Lavicka
Thursday 10:20

ALICE, PRL116 (2016)222301





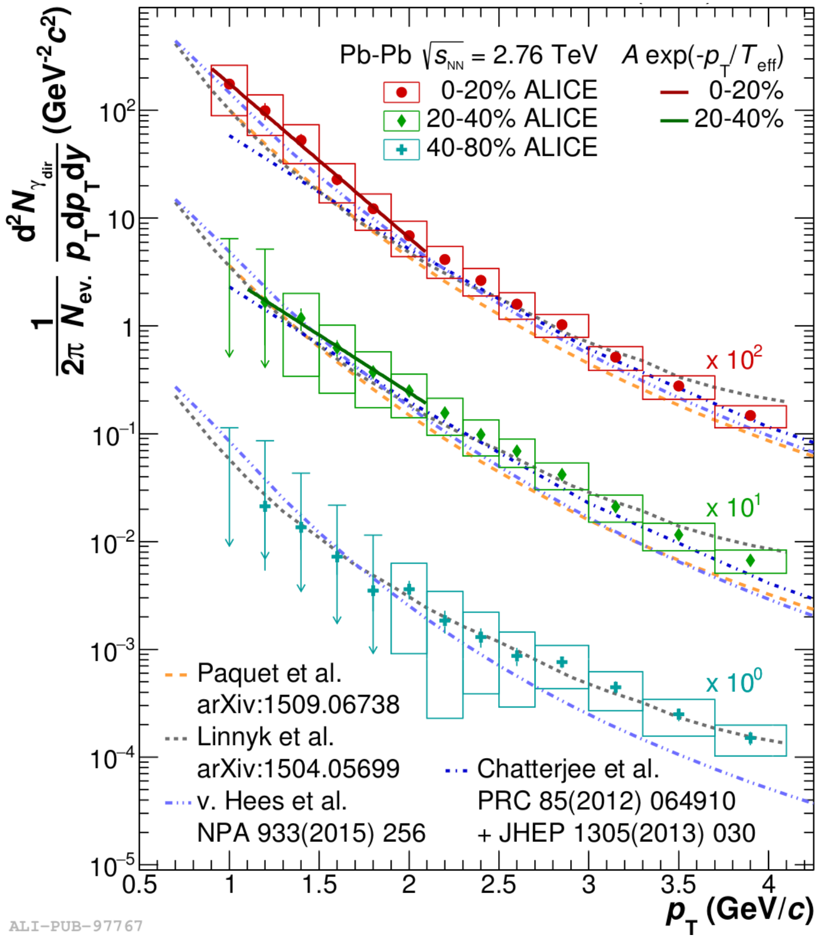
- J/ψ excess observed at very low-p_T in peripheral Pb-Pb collisions
  - Likely origin: coherent photo-production

- Challenge for theoretical models
  - Sensitivity to nuclear gluon PDFs
  - Probe of QGP ?

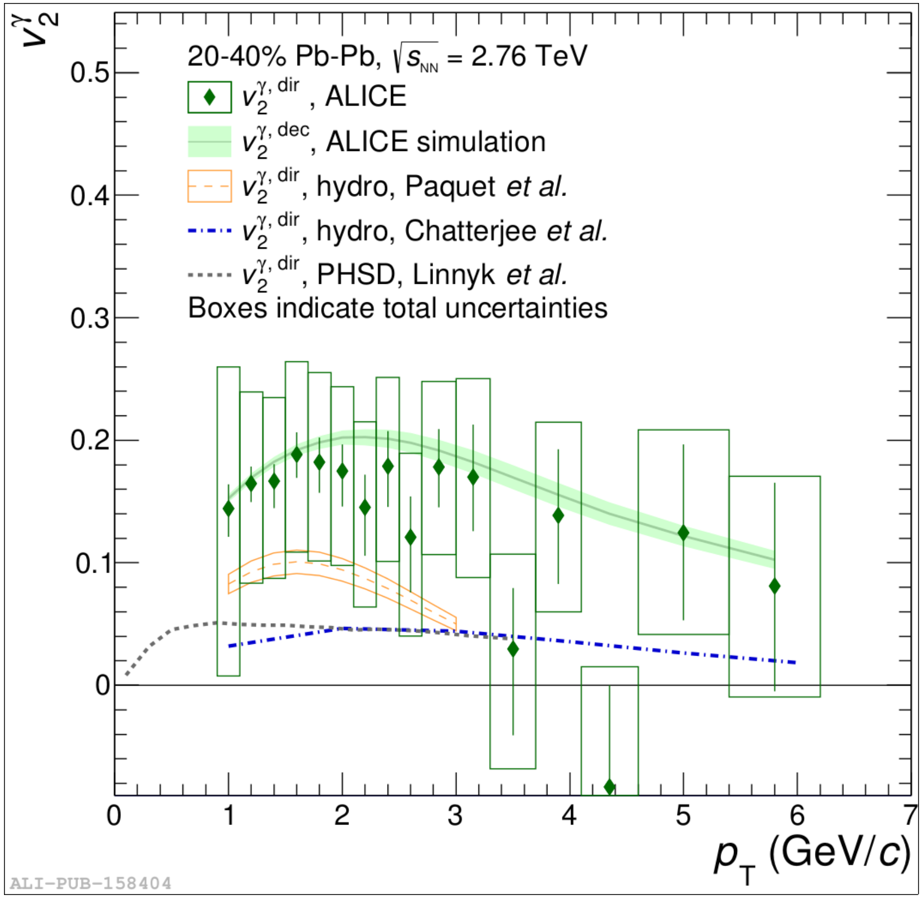
Direct photons

Talk by Dimitri Peresounko
Thursday 10:35

ALICE, PLB 754 (2016) 23-248



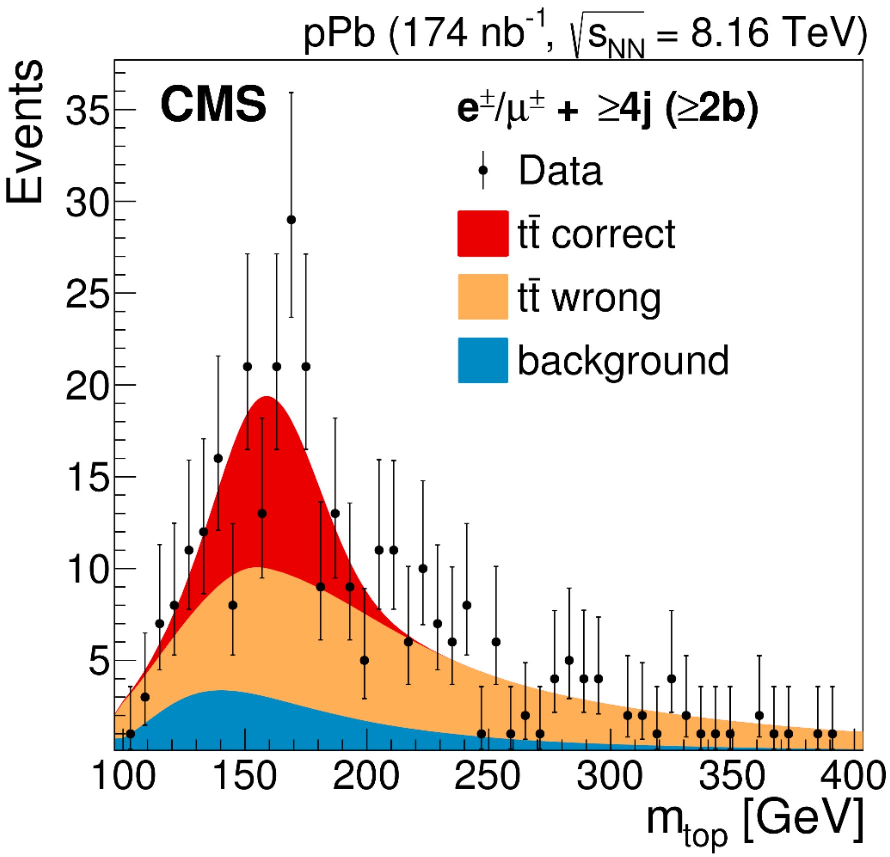
ALICE, arXiv:1805.04403

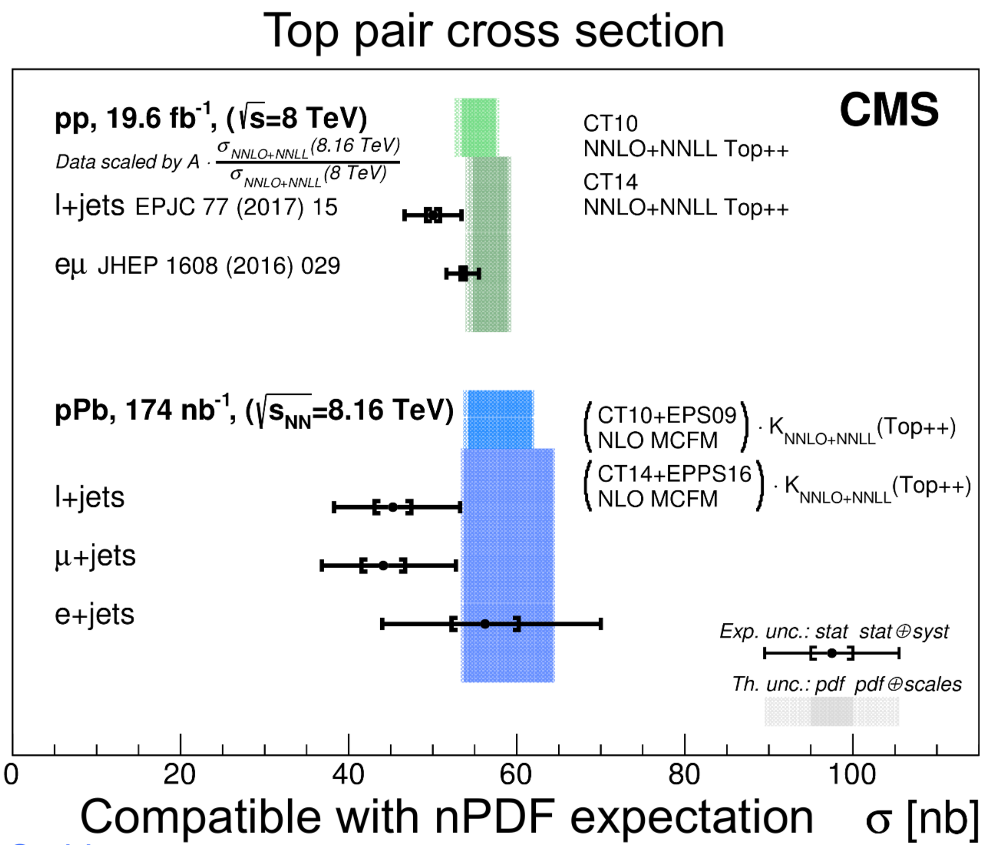


- Direct photons sensitive to the entire history of the collision
- Strong measured elliptic not described by models: puzzle!

Top-quark production in p-Pb collisions

CMS, PRL 119 (2017) 242001



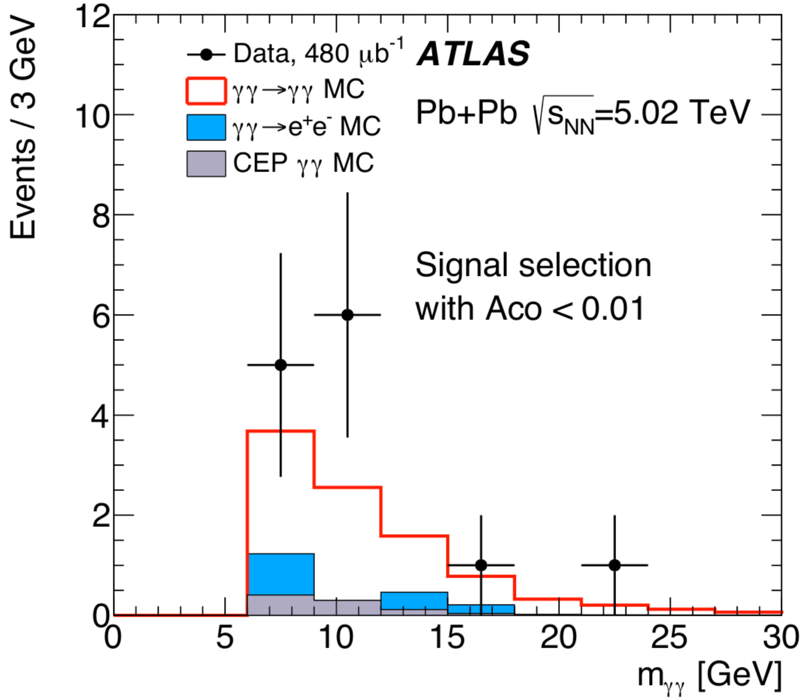


Compatible with nPDF expectation

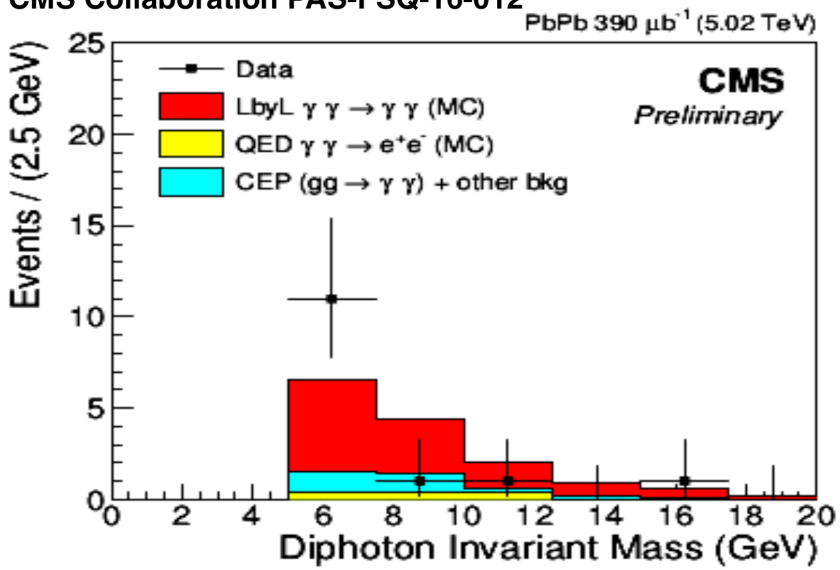
- First observation of the top quark in nuclear collisions

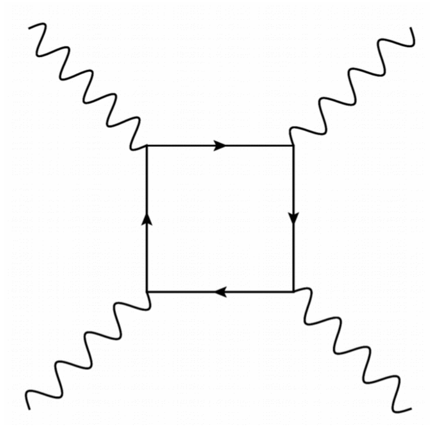
Light-by-light scattering

ATLAS, Nature Physics 13 (2017) 9, 852-858



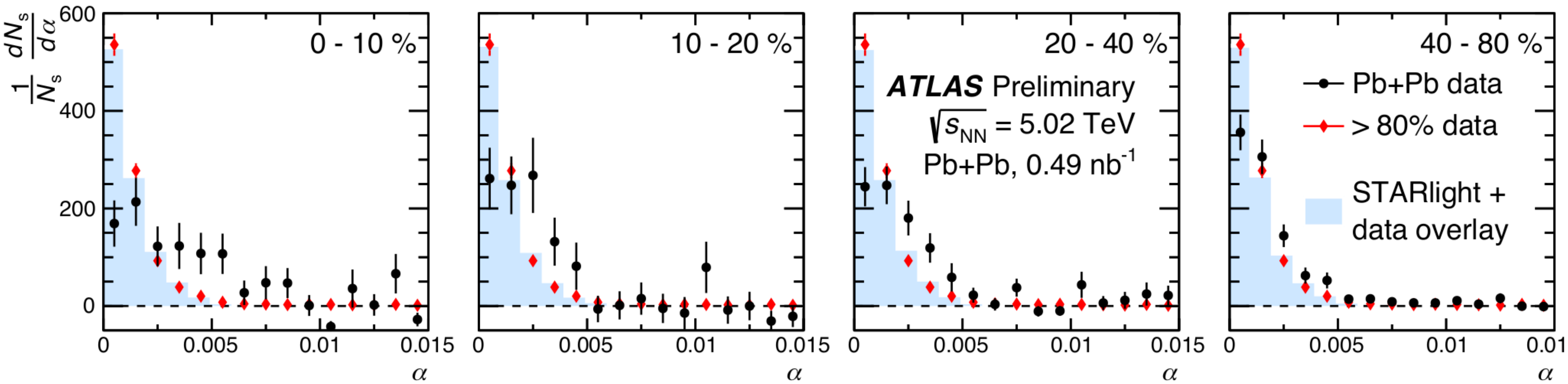
CMS Collaboration PAS-FSQ-16-012





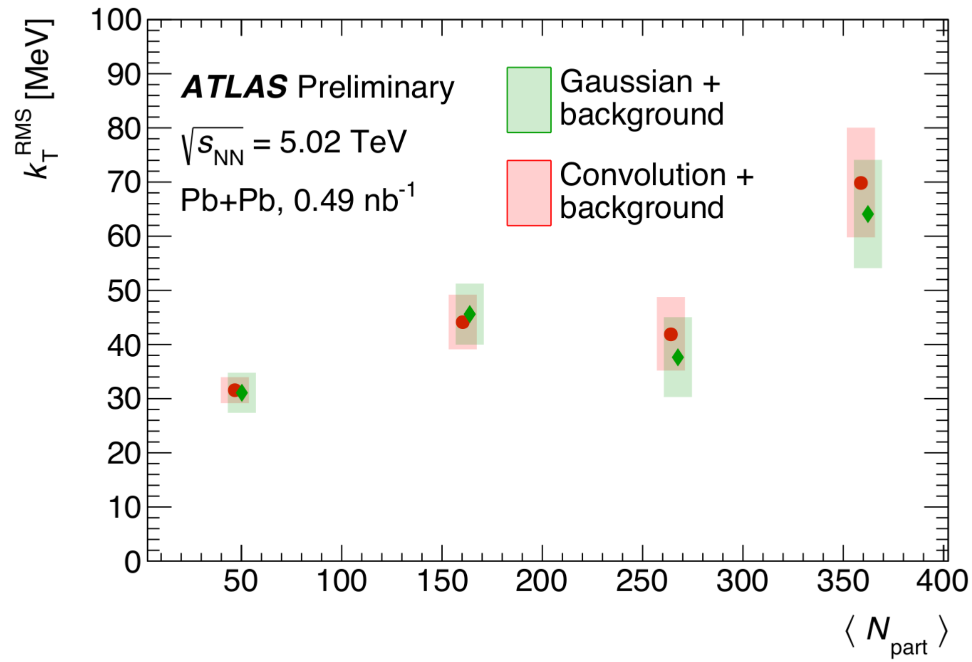
- Forbidden by classical electro-dynamics
- Natural consequence of QED
- First direct observation of this process
- >4 σ significance
- Cross-section consistent with Standard Model

Photo-produced di-muons in Pb-Pb collisions



$$a = 1 - \frac{|\varphi^{+} - \varphi^{-}|}{\pi}$$

- $\mu^{+}\mu^{-}$ pairs balanced in energy and small acoplanarity
- Origin from photo-nuclear interactions
- Acoplanarity broadens towards central collisions
- Muons scatter off electric charges in the plasma



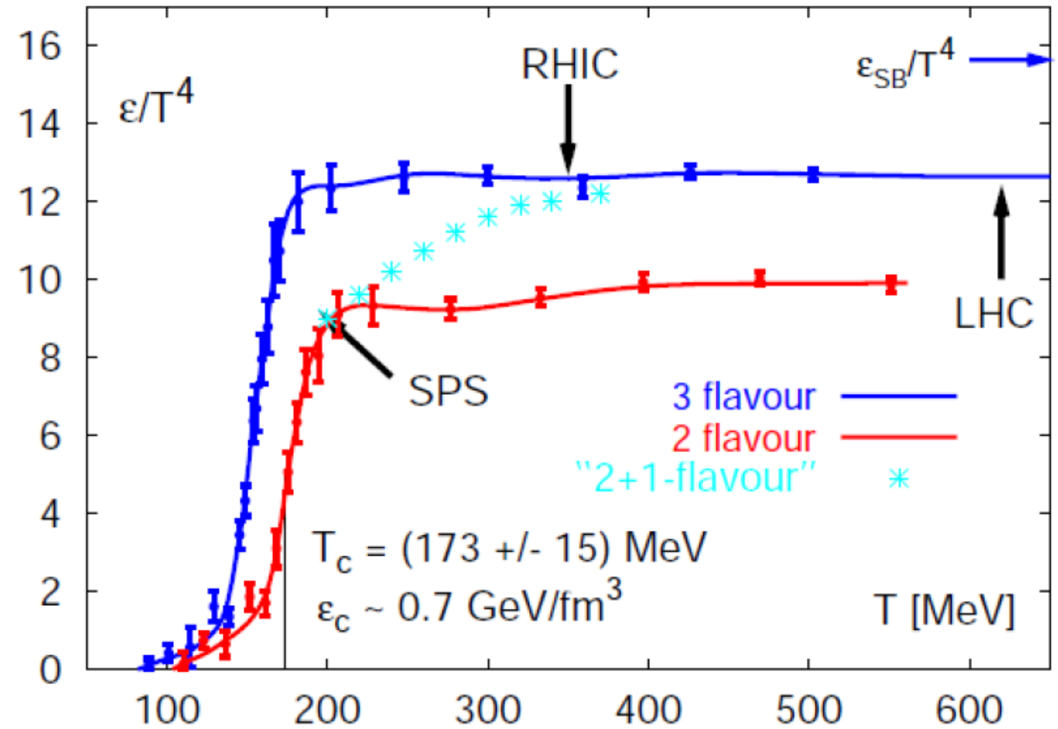
Summary

- A wealth of results from heavy-ion physics at the LHC
- Many first time observations of various processes in heavy-ion collisions
- LHC prepares for a new Pb-Pb run (november 2018) bringing a boost in statistics

- LHC talks in the parallel sessions:
  - **Jakub Kremer**, Quarkonia and open heavy flavour with ATLAS (thursday 16:30)
  - **Piotr Janus**, Electroweak bosons with ATLAS (thursday 16:50)
  - **Arkadiy Taranenko**, Anisotropic flow from LHC to SIS (thursday 17:10)
  - **Victor Riabov**, Light flavors with ALICE (friday 10:00)
  - **Roman Lavicka**, J/ψ photo-production in UPC with ALICE (friday 10:20)
  - **Dimitri Peresounko**, Direct photons with ALICE (friday 10:35)

Backup

Relativistic heavy-ion collisions



F. Karsch, hep-lat/0106019

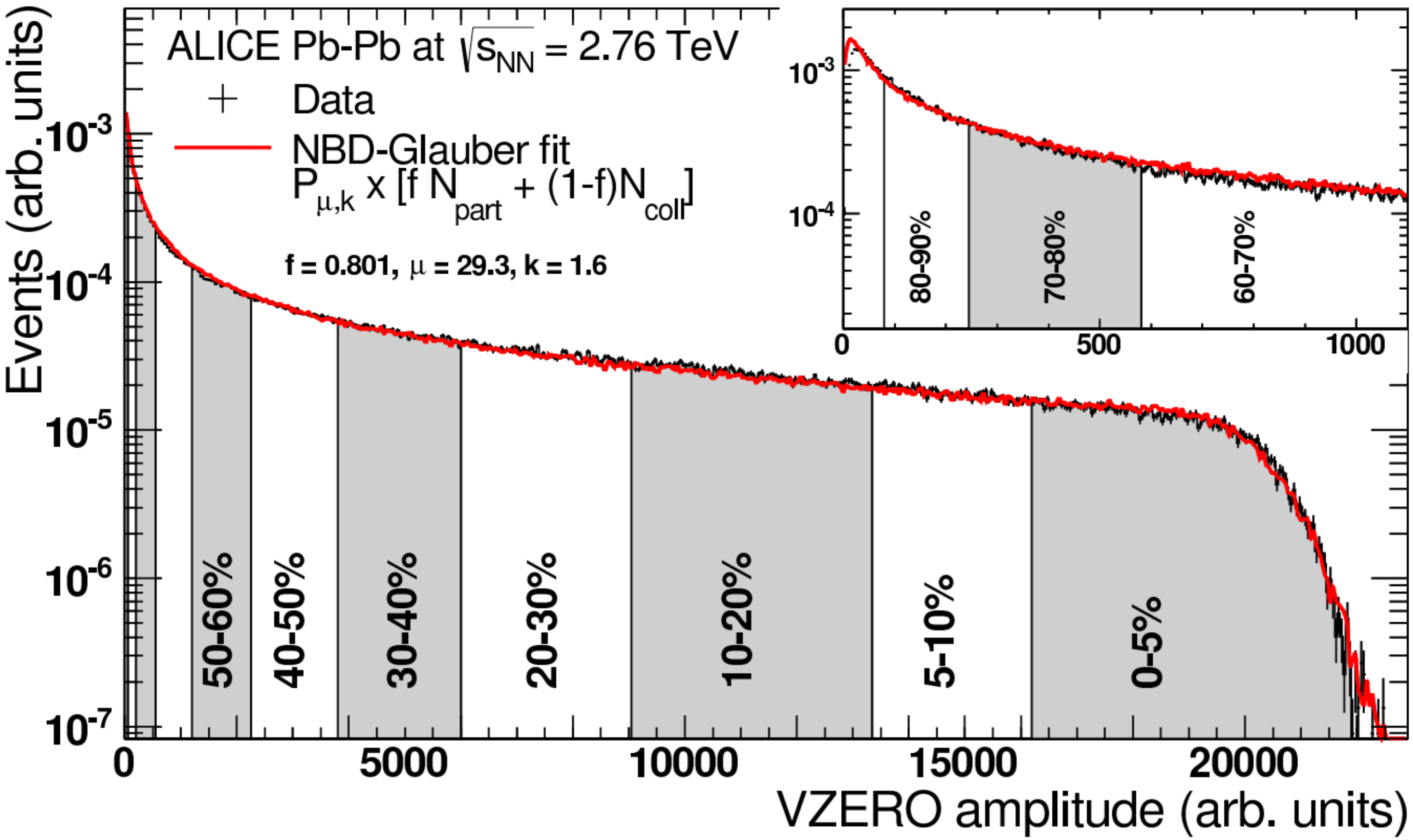
- QCD studies (low-Q, finite T and μ)
  - Phase diagram of nuclear matter:
    - deconfinement phase transition
    - Lattice QCD calculations conclude transition is cross-over type

      (*Y.Aoki et al., Nature 443 (2006) 675*)
    - "Critical" temperature: $T_C \approx 155\text{-}160$ MeV

(*A.Bazavov et al., arXiv:1111.1710, S.Borsanyi et al., arXiv:1005.3508*)

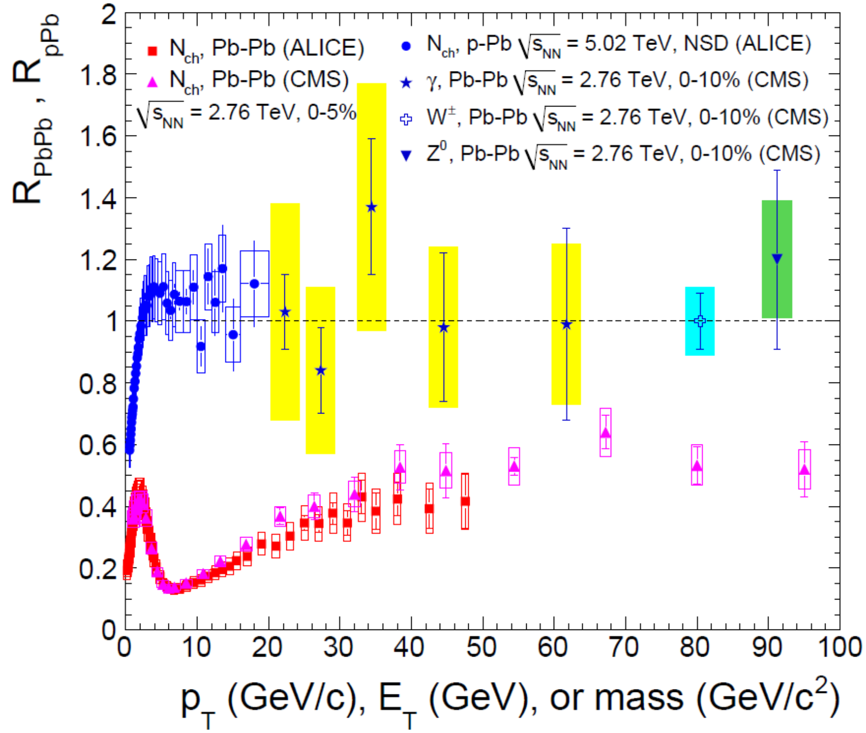
Collision centrality

ALICE Collaboration, PRC88 (2013) 4, 044909



- Centrality determination in ALICE, using the charged particle measurement at forward rapidity (VZERO)
- Multiplicity distribution fitted well by an optical Glauber model which allows the determination of <N_{part}> and <N_{coll}> for each centrality interval

The nuclear modification factor



N_{ch} p-Pb: *ALICE PRL110(2013)082302*

N_{ch} Pb-Pb: *ALICE, Phys.Lett.B720 (2013)52*

N_{ch} Pb-Pb: *CMS, EPJC (2012) 72*

γ: *CMS, PLB 710 (2012) 256*

$W^{\pm}$, *CMS, PLB715 (2012) 66*

Z^0, *CMS, PRL106 (2011) 212301*

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

N_{coll}: the number of binary nucleon-nucleon collisions

Y_{AA}: yield in AA collisions

Y_{pp}: yield in pp collisions

- Superposition of NN collisions → $R_{AA} = 1$
- Suppression → $R_{AA} < 1$
- Enhancement → $R_{AA} > 1$

- Weakly interacting particles are not affected by the QGP
  - Photons, $W^{\pm}$ and Z^0 bosons R_{AA} are compatible with 1