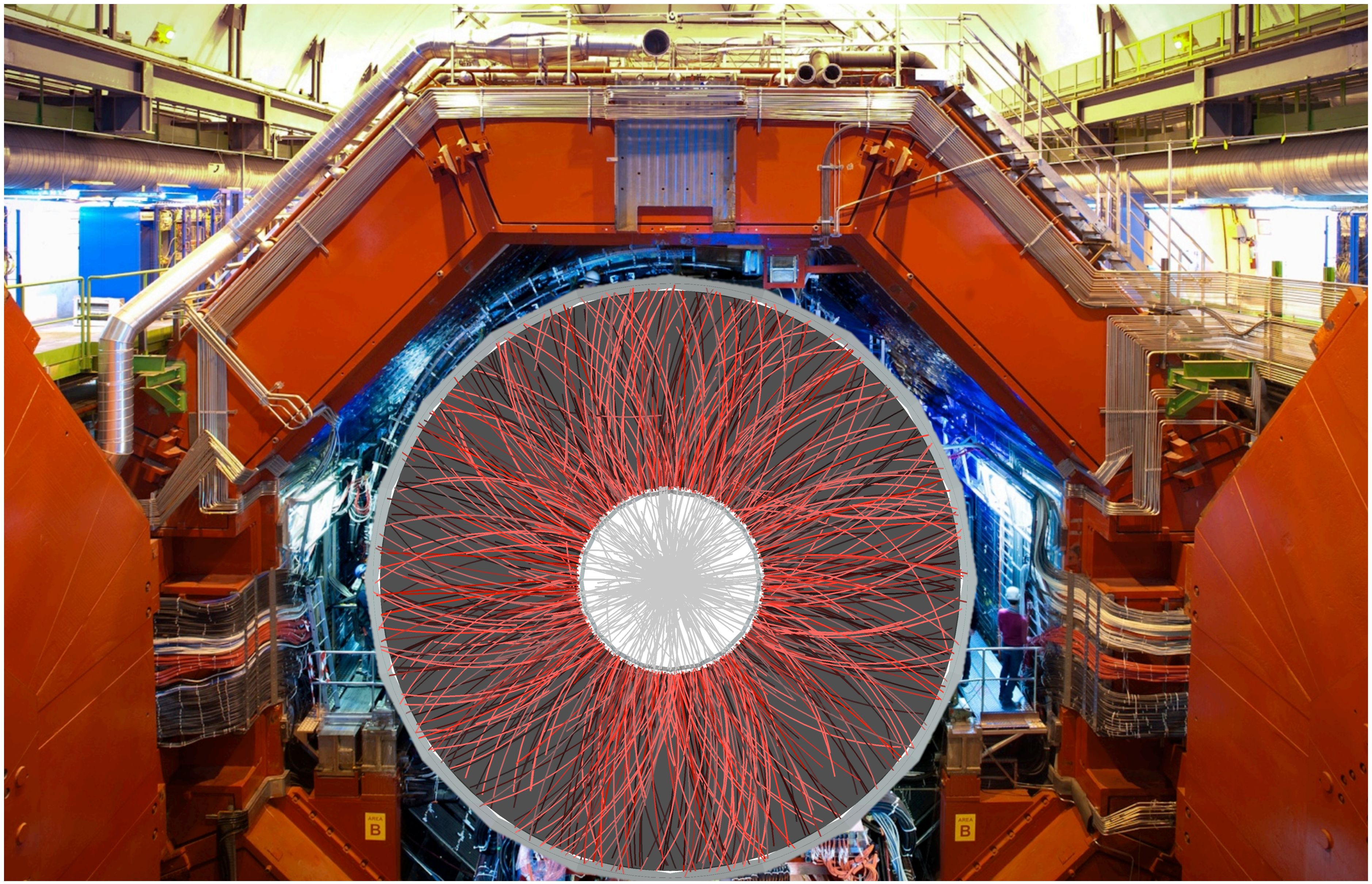
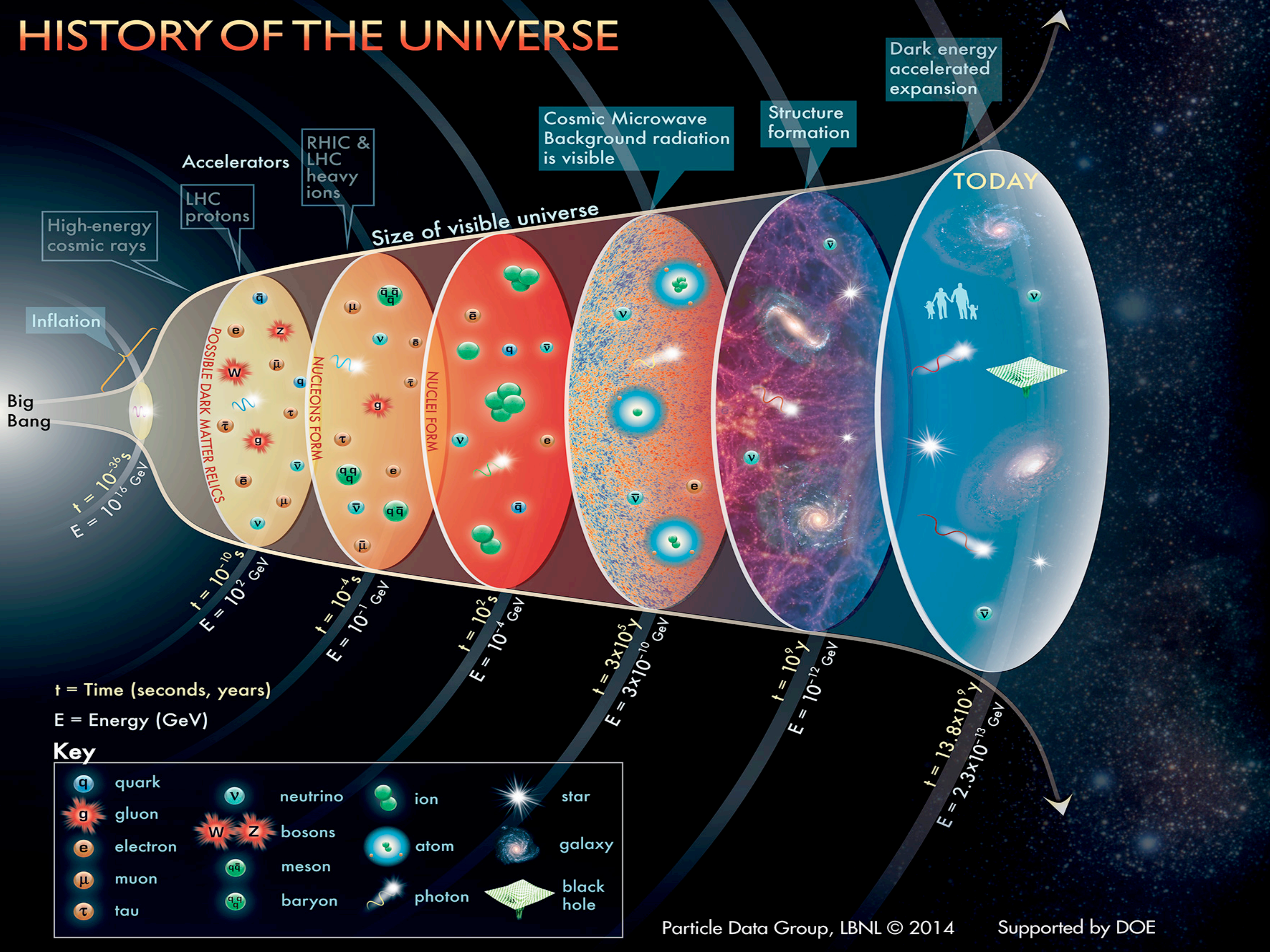
An Overview of Recent Results from ALICE at the LHC



- Introduction
- ALICE Experiment
- Pb–Pb collisions
  - Bulk properties
  - Hard probes
    - Open HF and jet
- Small systems
  - pp and p–Pb

Xiaoming Zhang, CERN

Seminar at IPHC, Feb 5, 2016, Strasbourg, France


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^{-36} s
E = 10^{16} GeV
t = 10^{-10} s
E = 10^{2} GeV
t = 10^{-4} s
E = 10^{-1} GeV
t = 10^{2} s
E = 10^{-4} GeV
t = $3x10^{5}$ y
E = $3x10^{-10}$ GeV
t = 10^{9} y
E = 10^{-12} GeV
t = $13.8x10^{9}$ y
E = $2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
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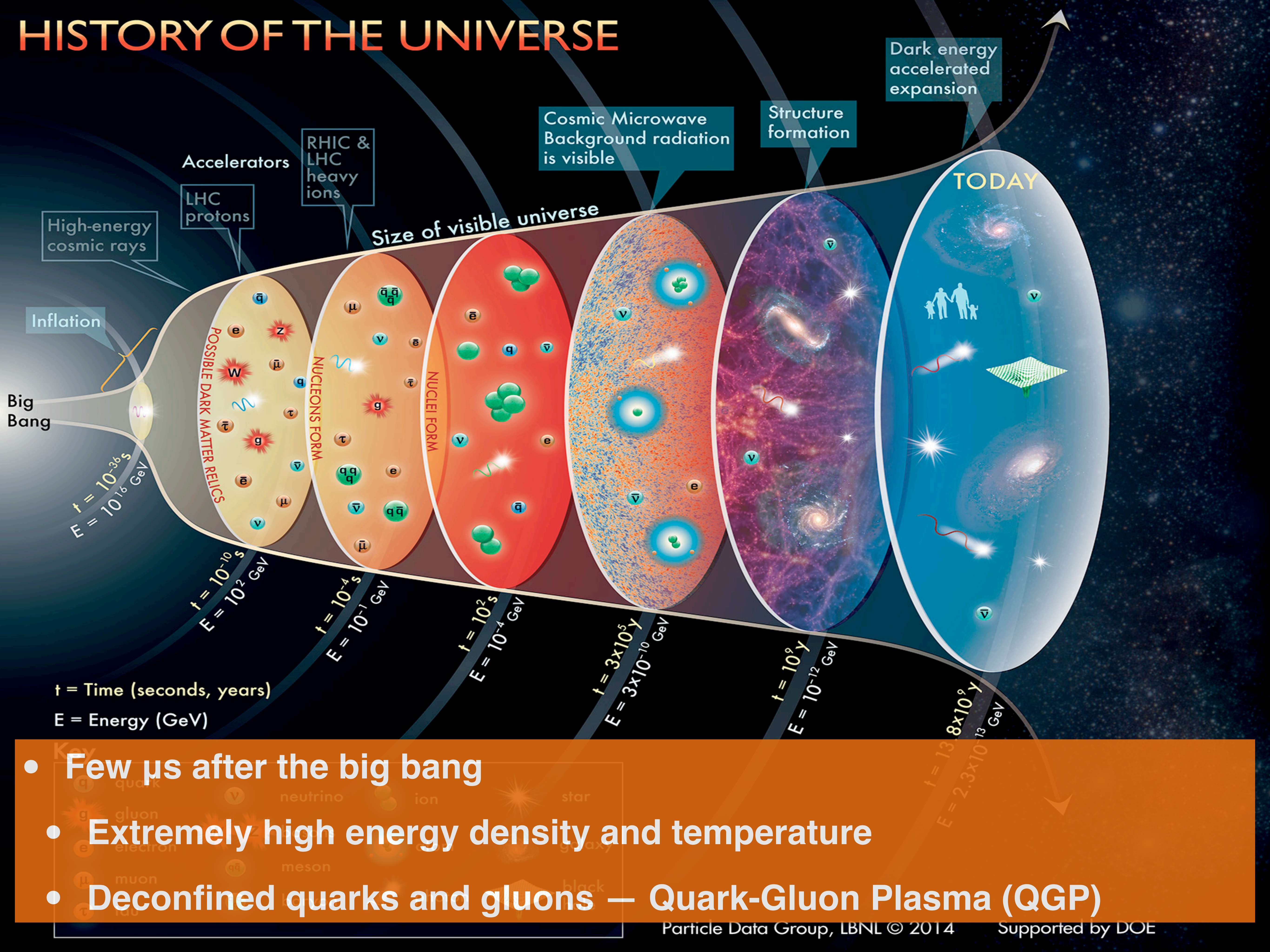
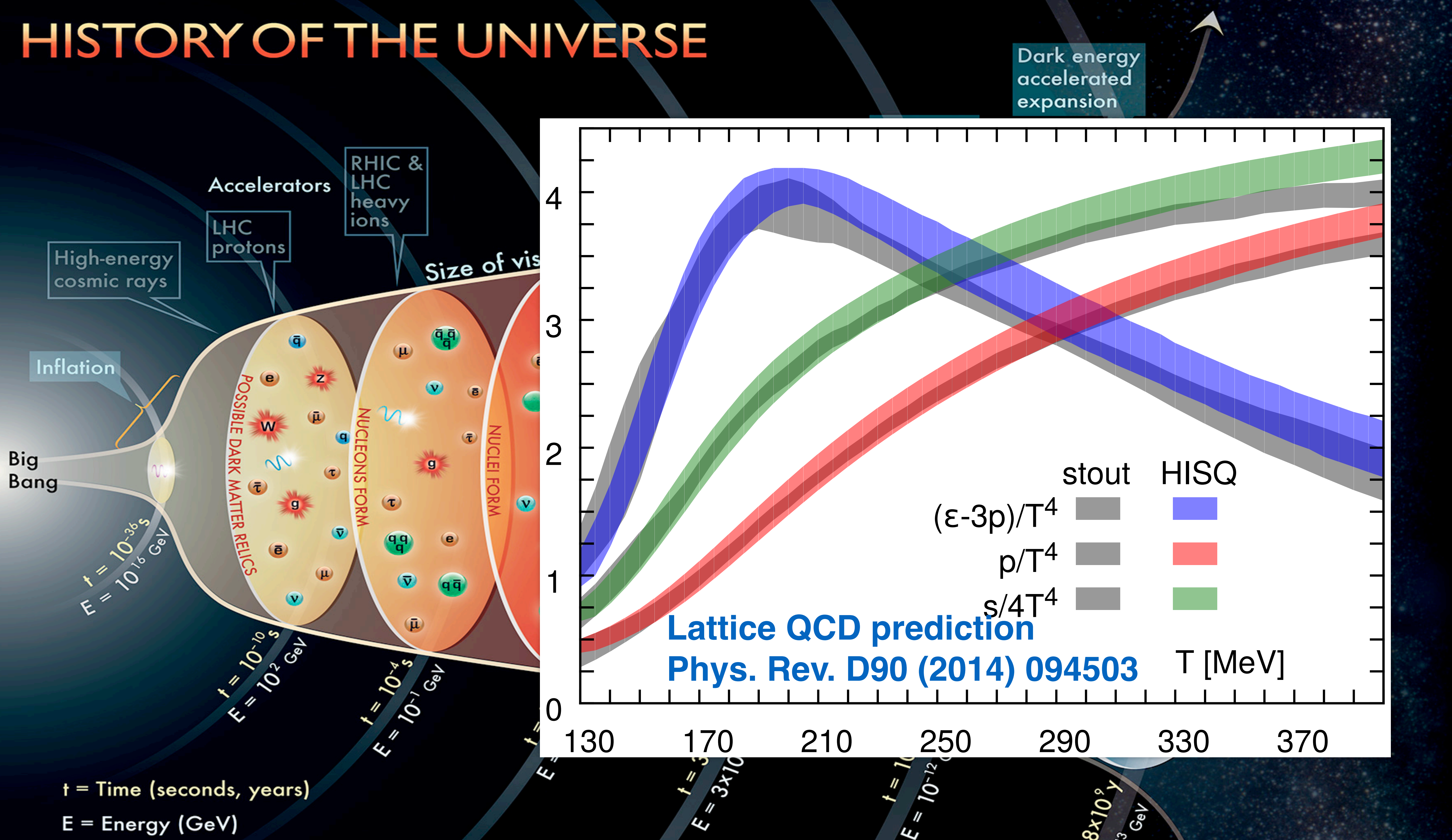


- **Few μs after the big bang**
  - **Extremely high energy density and temperature**
  - **Deconfined quarks and gluons — Quark-Gluon Plasma (QGP)**



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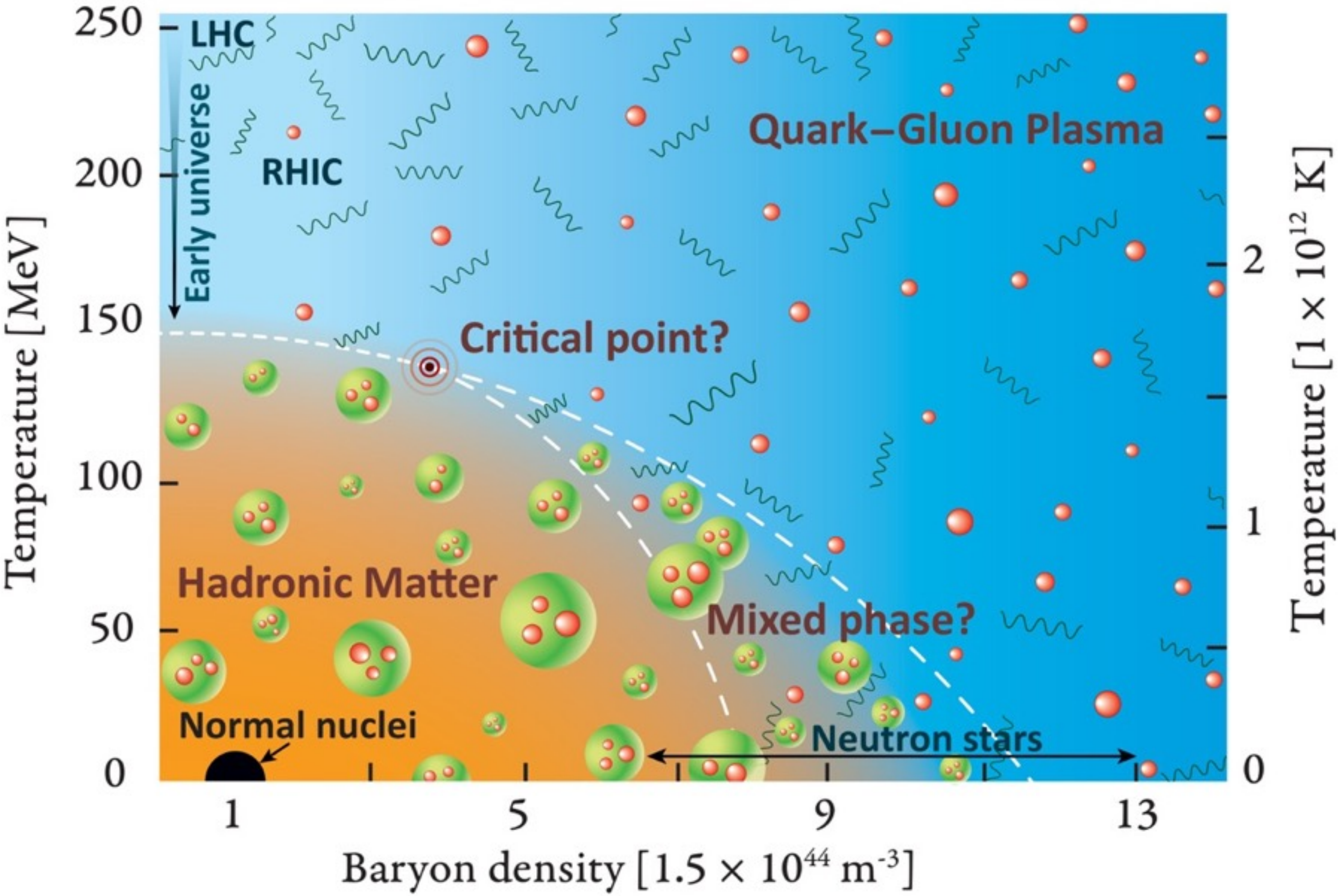
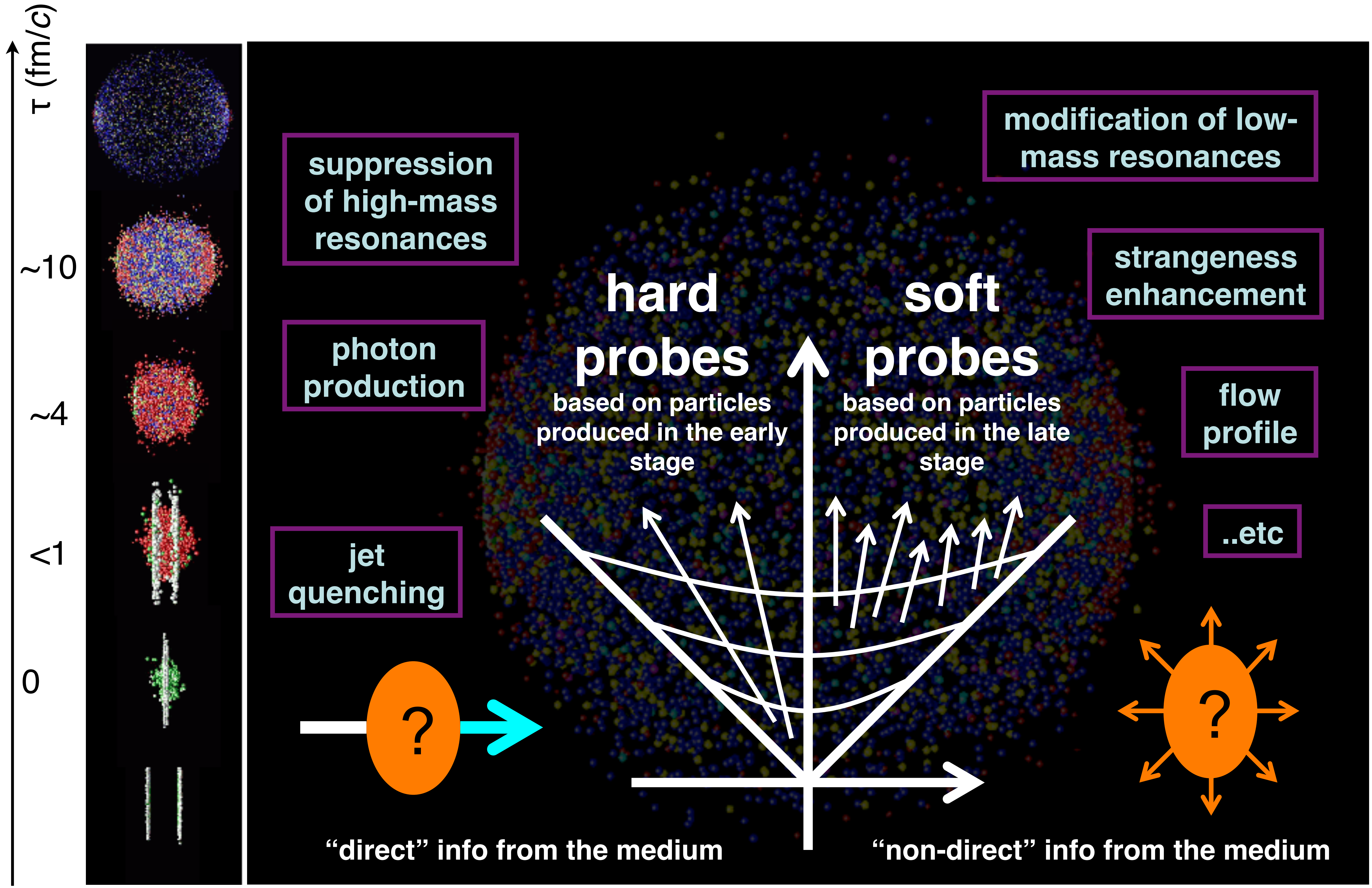
QCD Phase Diagram



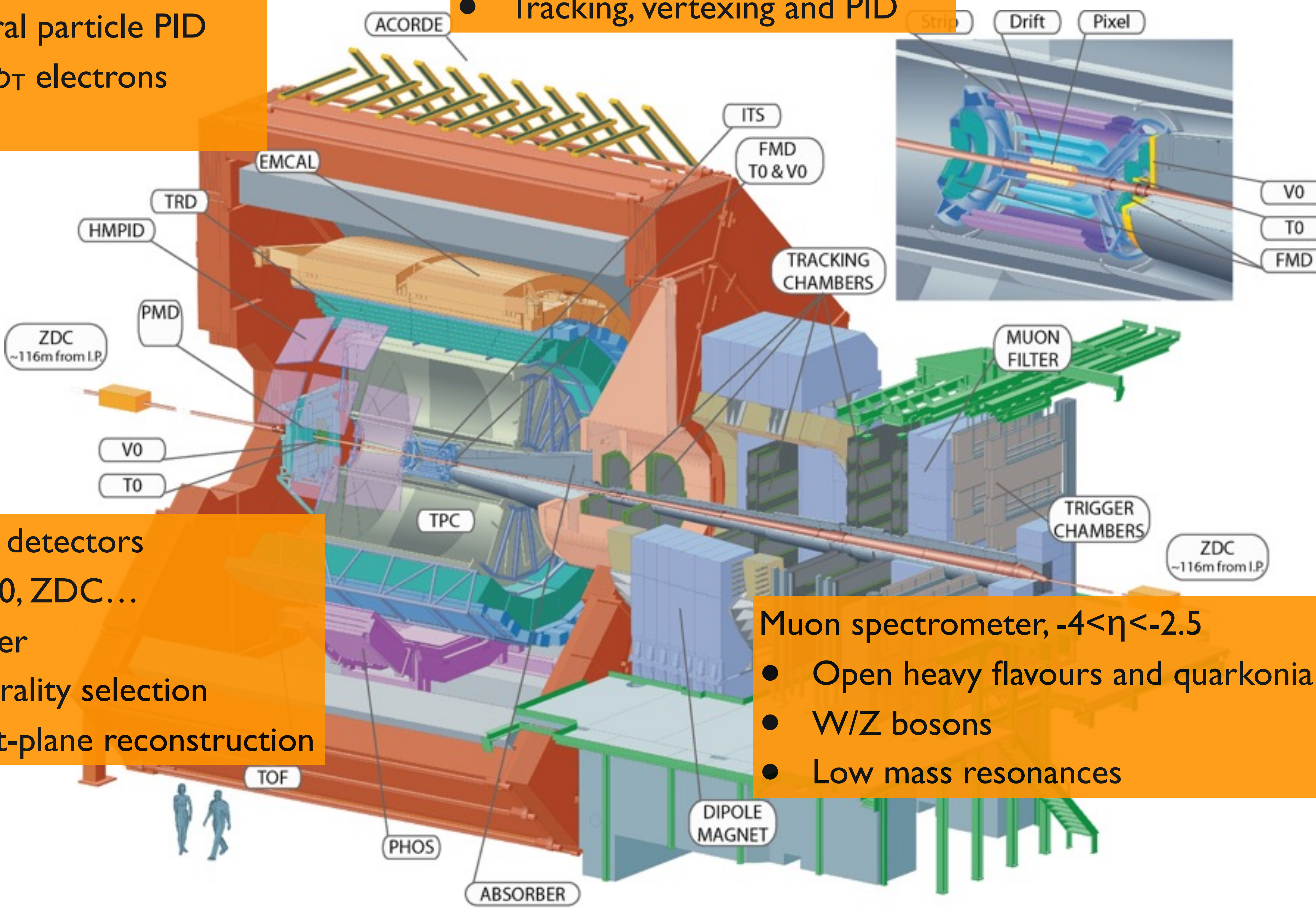
Heavy-ion Collisions



ALICE Experiment

EM calorimeters, |η|<0.7
- EMCal, DCal and PHOS
- Neutral particle PID
- High-p_T electrons
- Jets…

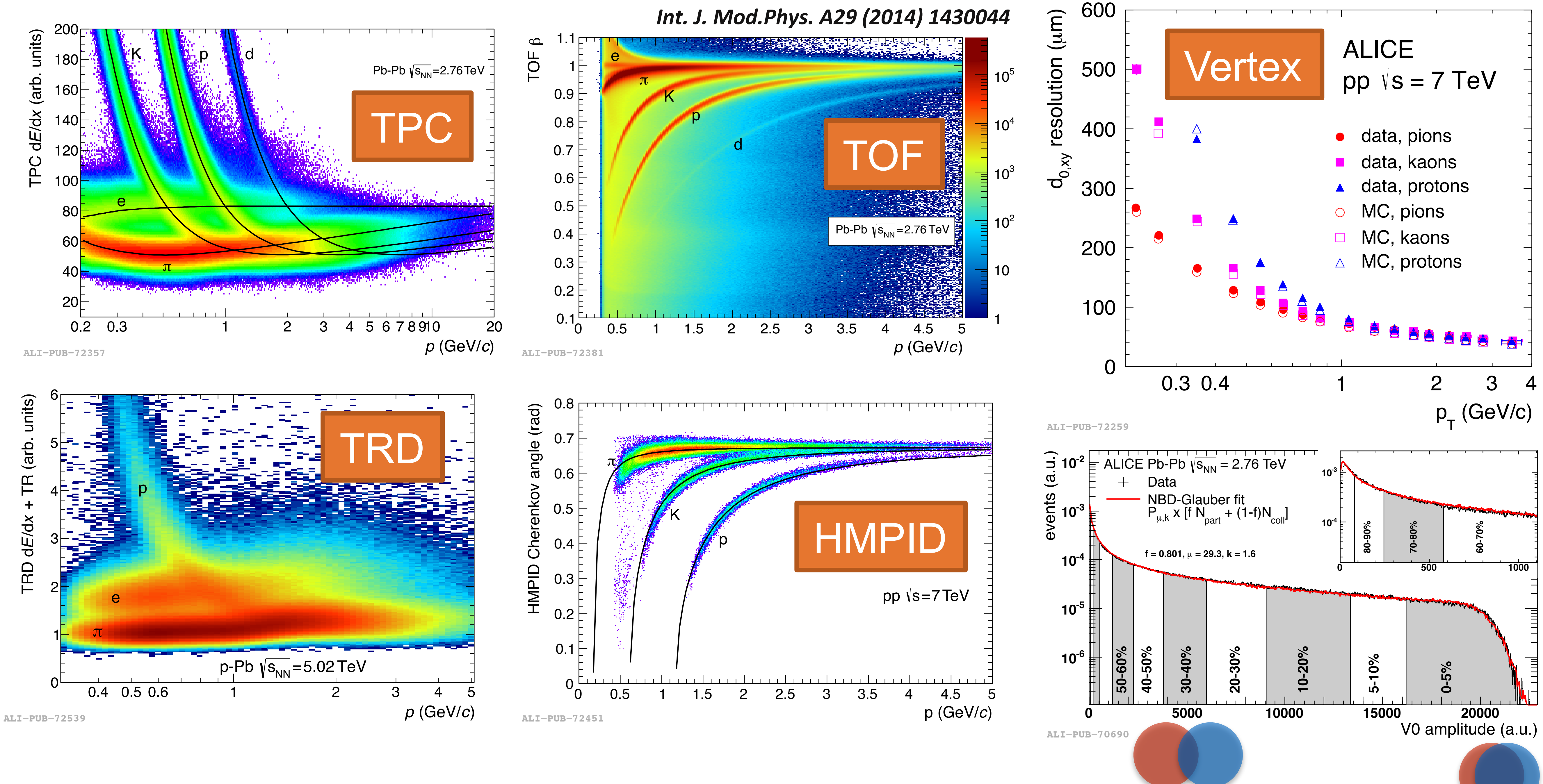
Center barrel, |η|<1
- Tracking, vertexing and PID



Forward detectors
- V0, T0, ZDC…
- Trigger
- Centrality selection
- Event-plane reconstruction

Muon spectrometer, -4<η<-2.5
- Open heavy flavours and quarkonia
- W/Z bosons
- Low mass resonances

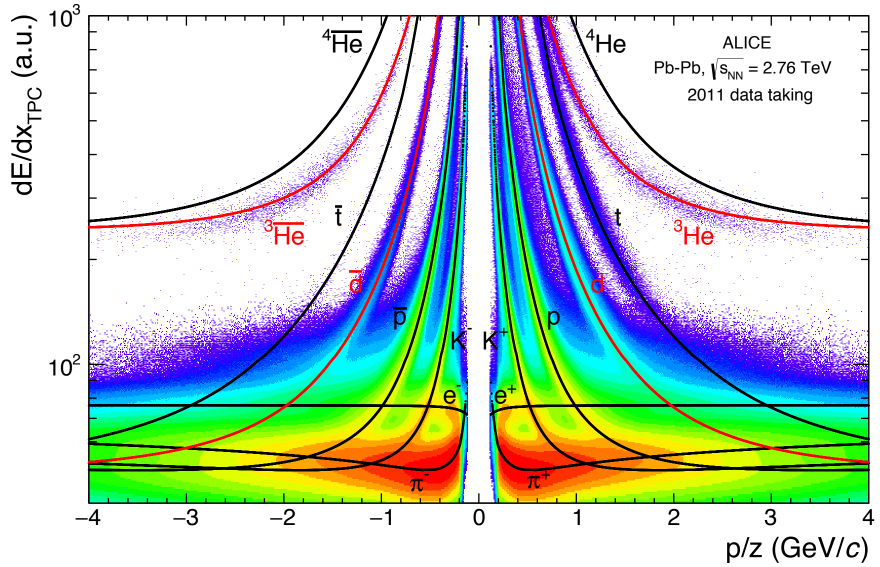
ALICE Performance



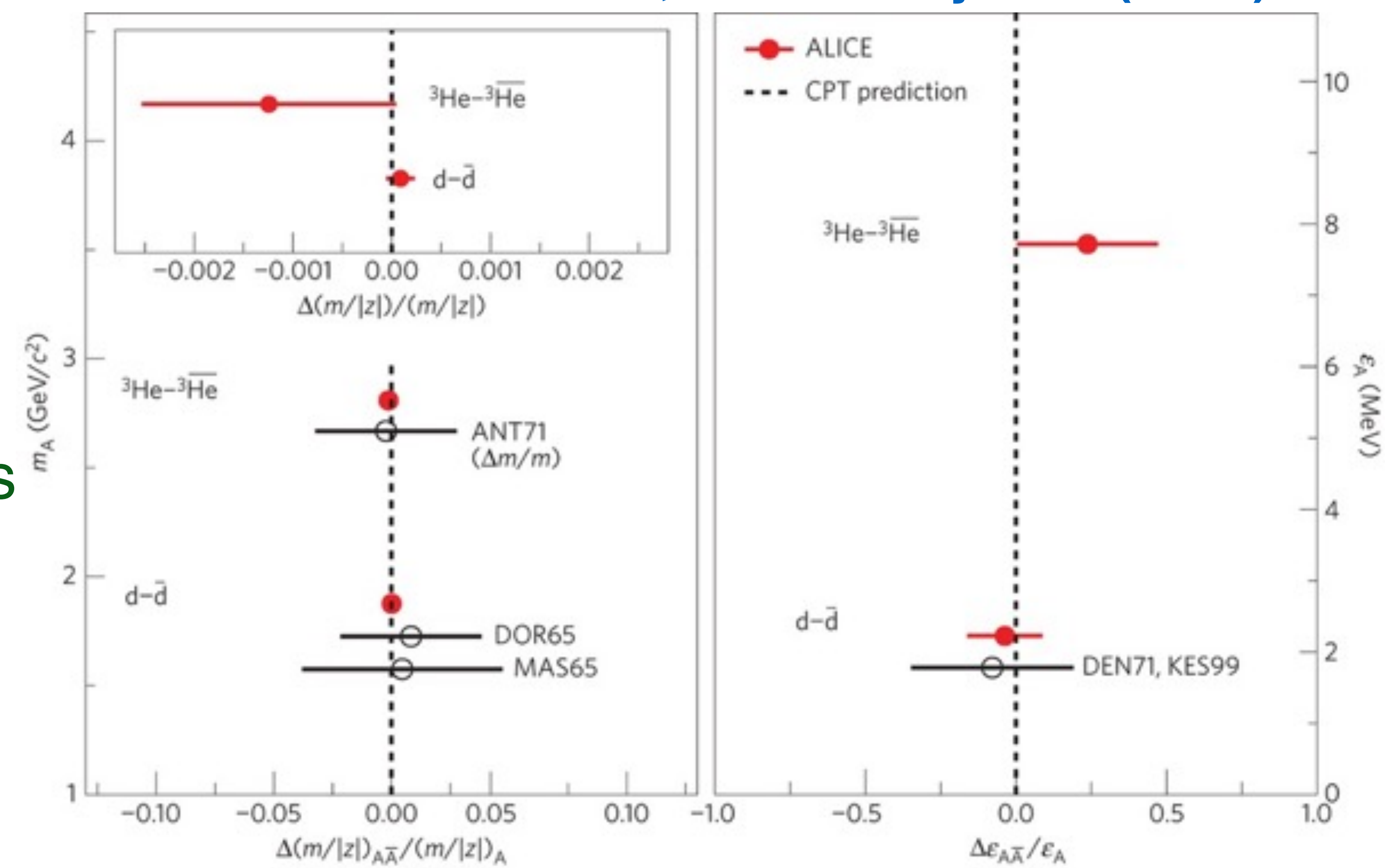
- Efficient low-momentum tracking — down to ~150 MeV/*c*
- Excellent particle identification (hadrons, leptons and photons) and jets
- Excellent vertex capability (HF, V^0, cascades, conversions)

Mass Difference of (Anti-)nuclei

- Test of CPT invariance of residual nuclear force by measuring mass difference in the nuclei sector (^{3}He and deuterons)



ALICE, Nature Phys. 11 (2015) 811



Mass difference

Binding-energy difference

- Improved by one to two orders of magnitude compared to earlier measurements
- First measurement of binding-energy for (anti-)^{3}He
- Confirms CPT invariance for light nuclei

$$\frac{\Delta\mu_{d\bar{d}}}{\mu_d} = [0.9 \pm 0.5(\text{stat.}) \pm 1.4(\text{syst.})] \times 10^{-4}$$

$$\frac{\Delta\mu_{^3\text{He}\overline{^3\text{He}}}}{\mu_{^3\text{He}}} = [-1.2 \pm 0.9(\text{stat.}) \pm 0.10(\text{syst.})] \times 10^{-3}$$

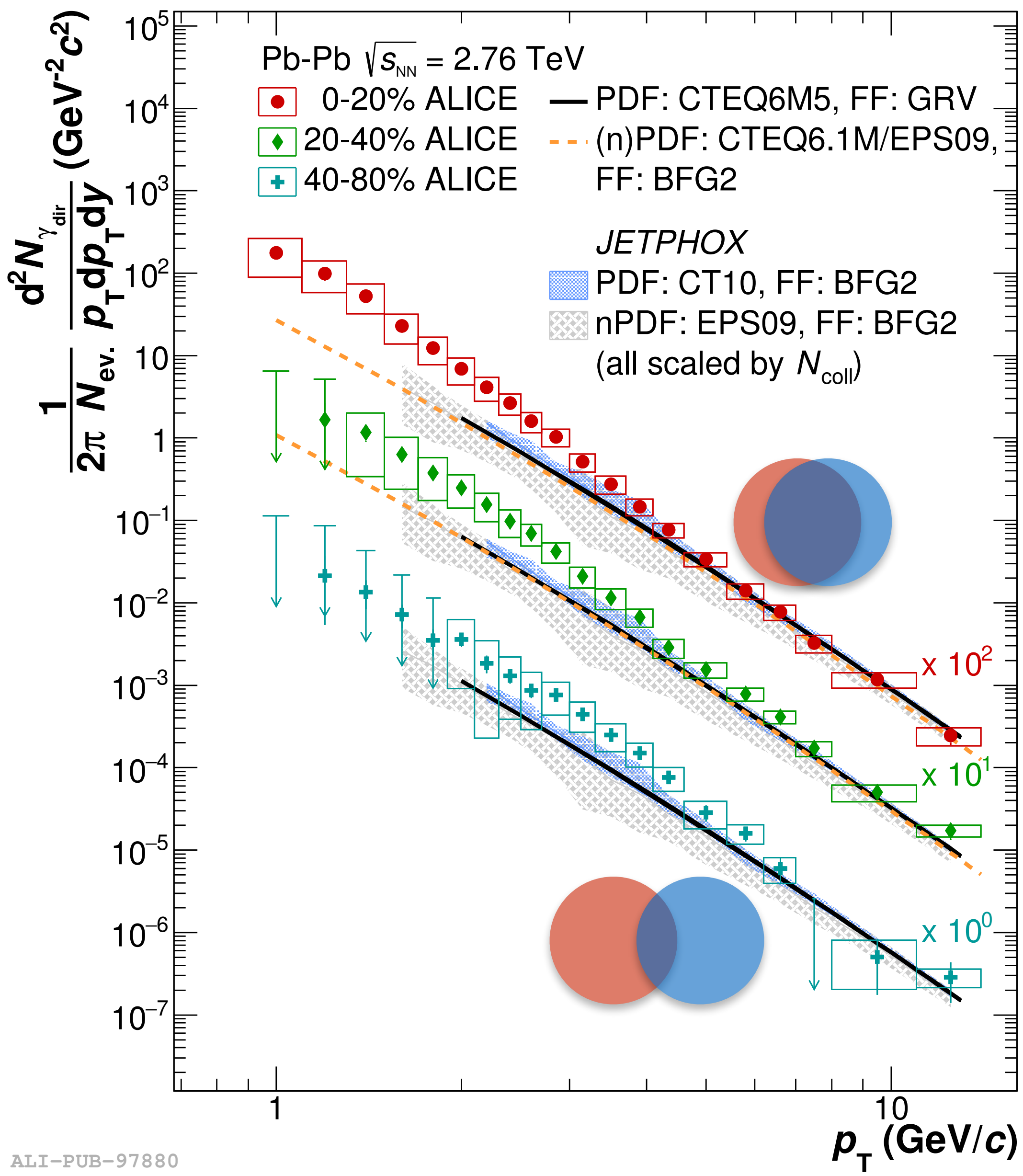
$$\Delta\varepsilon_{A\bar{A}} = Z\Delta m_{p\bar{p}} + (A-Z)\Delta m_{n\bar{n}} - \Delta m_{A\bar{A}}$$

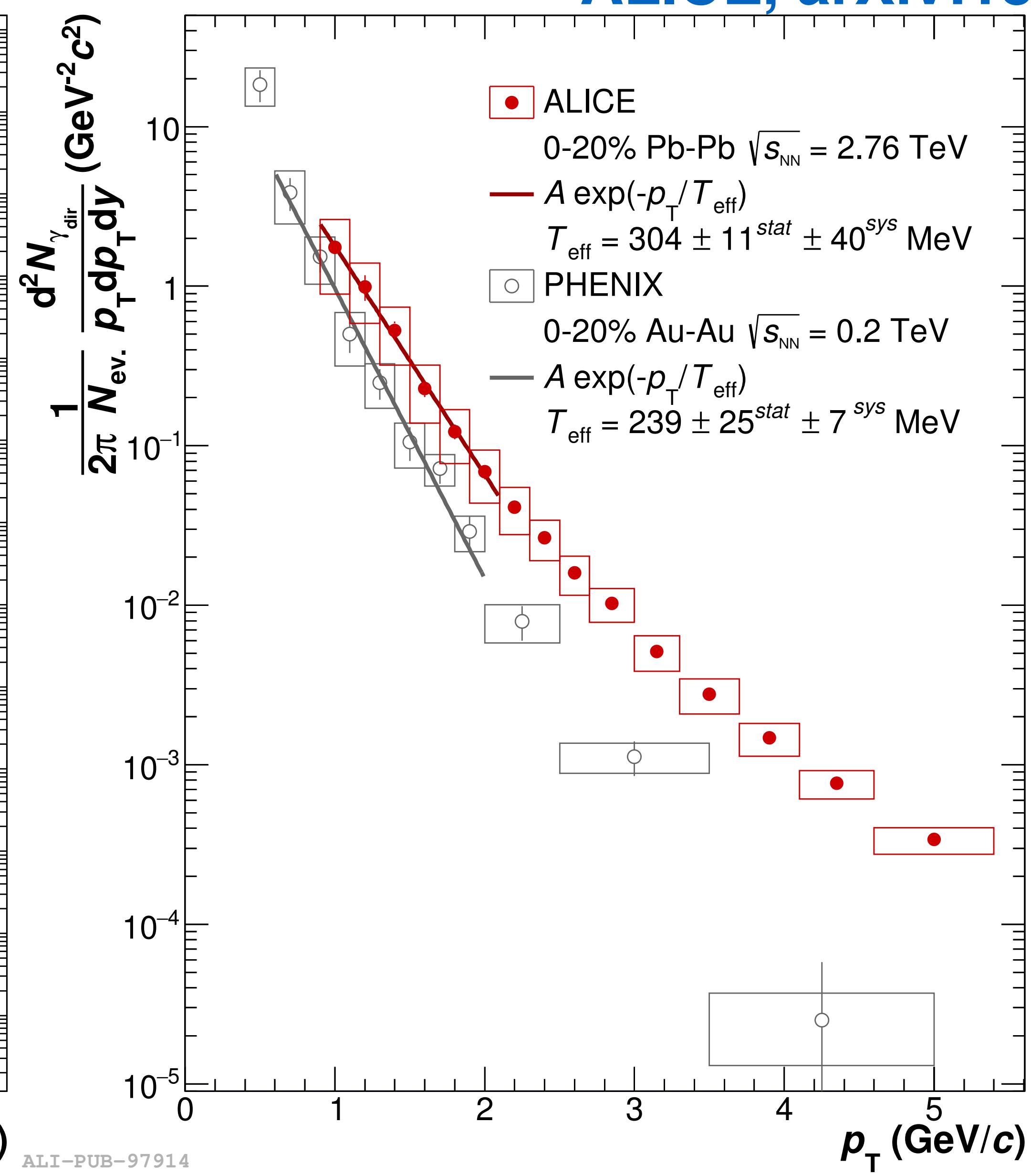
$$\frac{\Delta\varepsilon_{d\bar{d}}}{\varepsilon_d} = -0.04 \pm 0.05(\text{stat.}) \pm 0.12(\text{syst.})$$

$$\frac{\Delta\varepsilon_{^3\text{He}\overline{^3\text{He}}}}{\varepsilon_{^3\text{He}}} = 0.24 \pm 0.16(\text{stat.}) \pm 0.18(\text{syst.})$$

Direct Photons in Pb–Pb Collisions

ALICE, arXiv:1509.07324



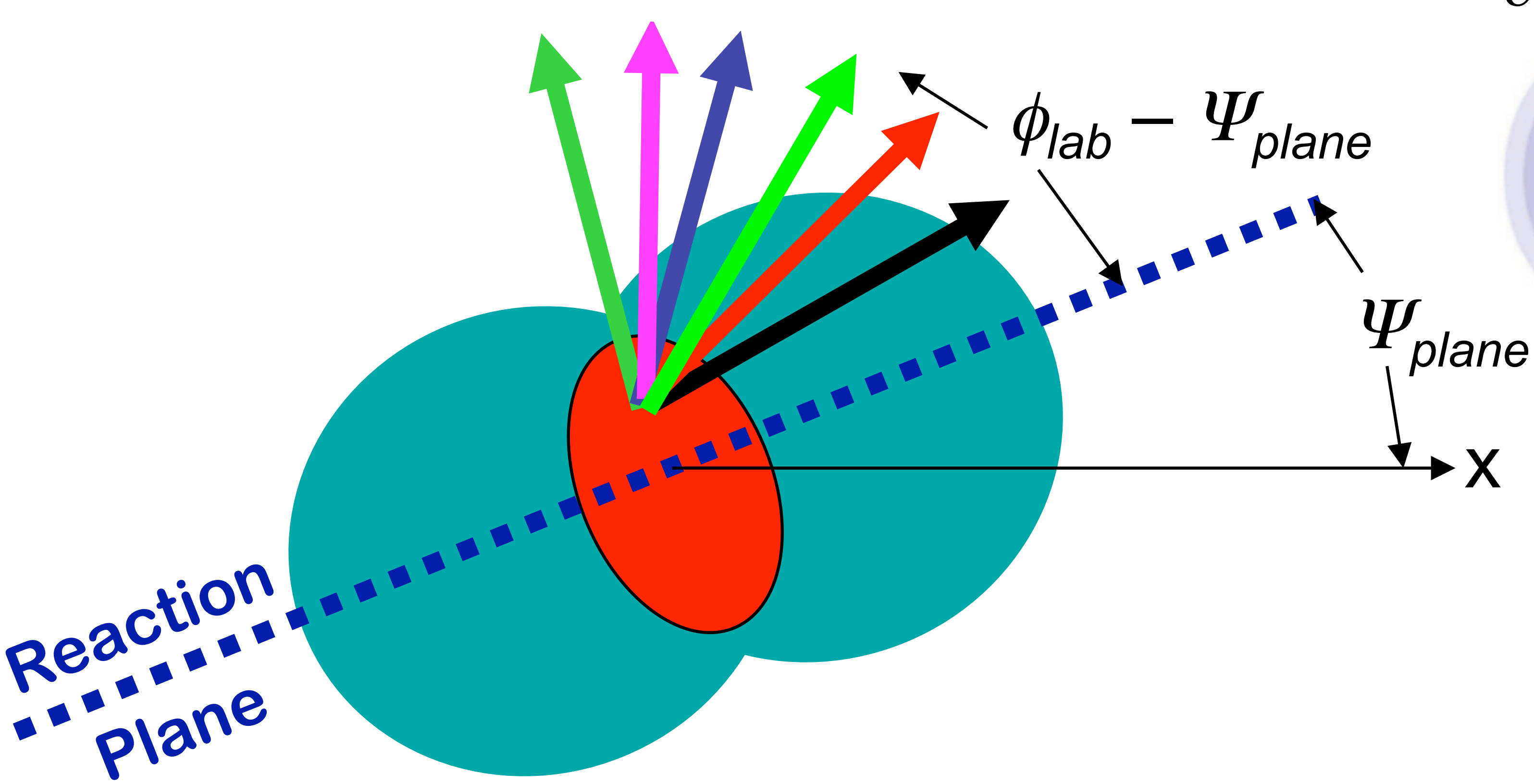


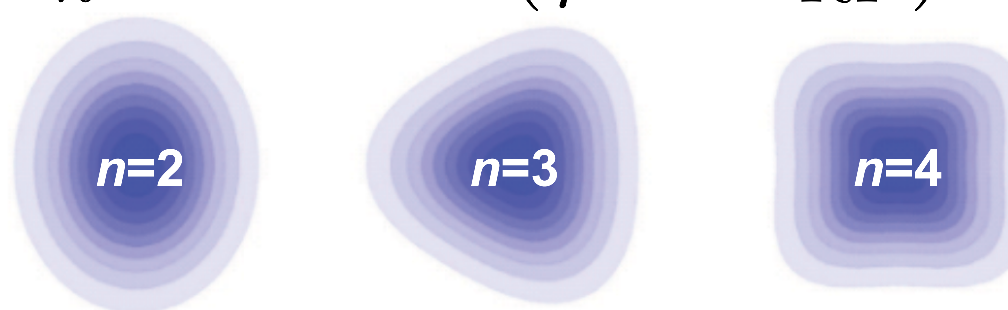
- Low-p_T: 2.6σ excess w. r. t. models in 0–20% central — thermal contribution
- T_{eff} = 304 ± 11(stat.) ± 40 (syst.) MeV in central collisions
  - 30% higher than at RHIC (Au–Au at $\sqrt{s_{NN}}$=200 GeV)

Azimuthal Anisotropy

- Quantify anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP}) — coefficients v_2, v_3, v_4… v_n
- Elliptic flow (v_2): spatial anisotropy to momentum anisotropy — large pressure gradients and more particles emitted in plane — hydrodynamics
- Higher order flow: bring additional constraints on the initial conditions, η/s, EoS, freeze-out conditions…

$$v_n = < \cos n(\varphi - \Psi_{\mathrm{RP}}) >$$





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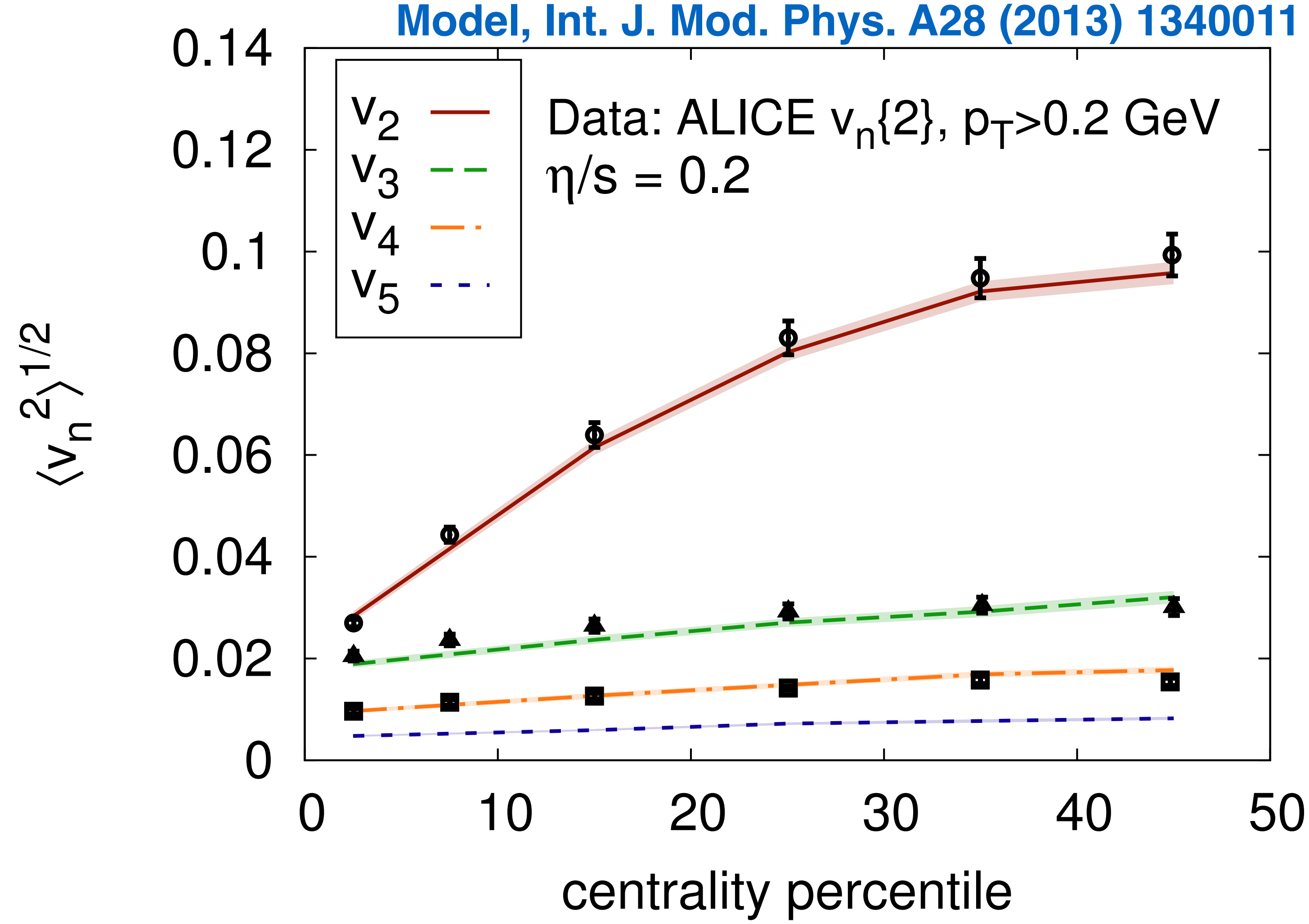
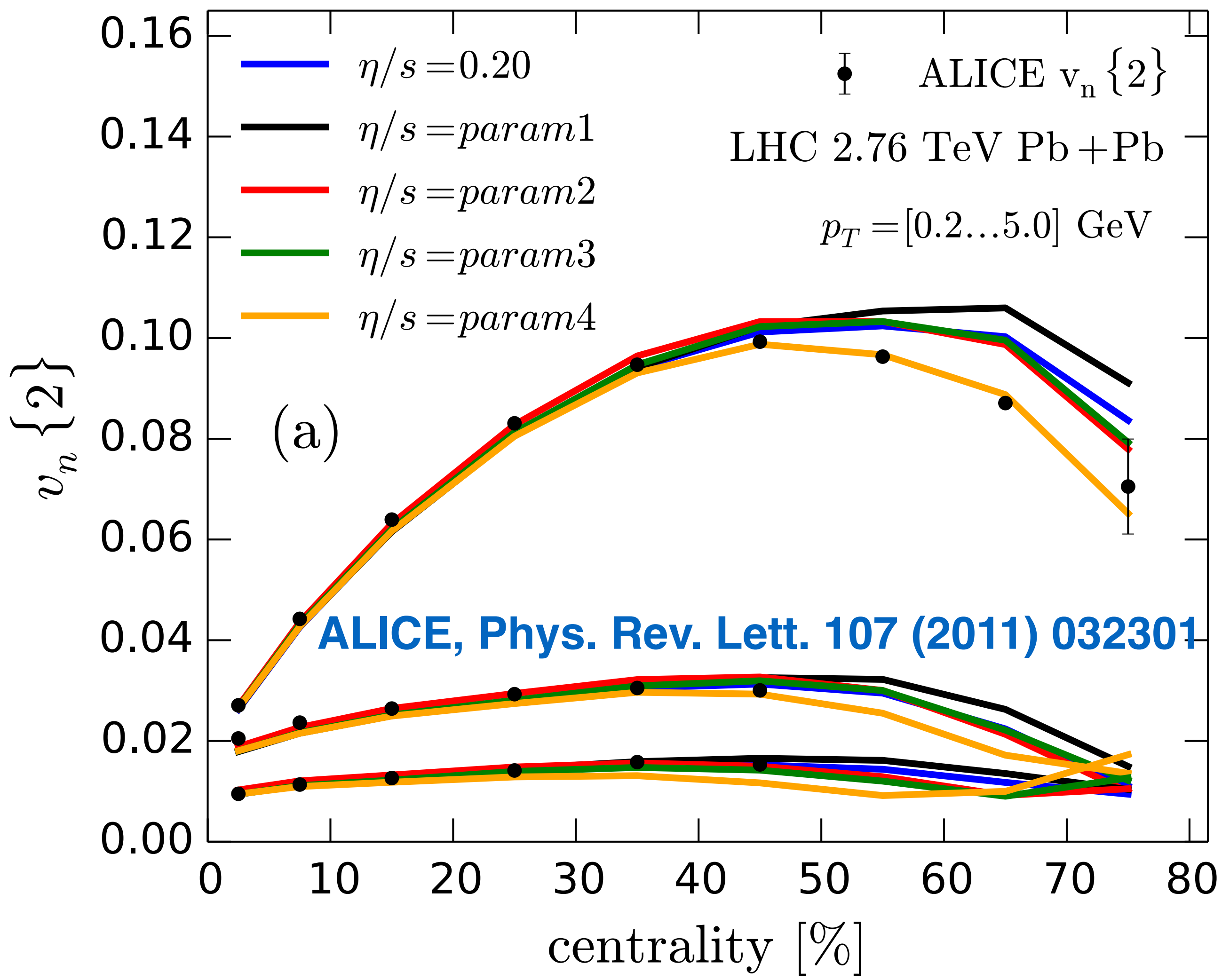
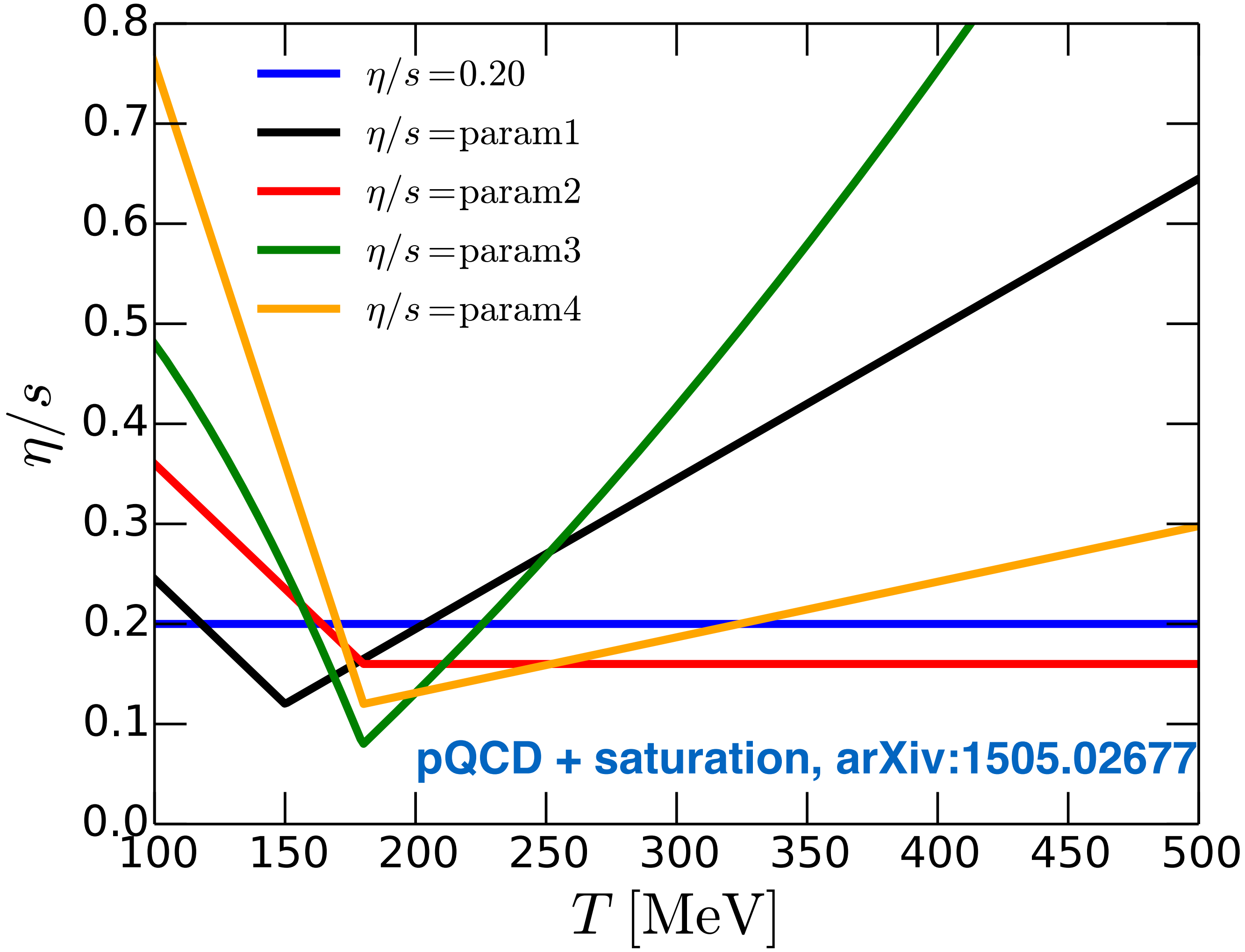
ALICE, Phys. Rev. Lett. 107 (2011) 032301
Model, Int. J. Mod. Phys. A28 (2013) 1340011

- ALICE has measured charged-particle anisotropic flow up to v_5
  - Constraints on $\eta/s = 0.2$
- It is necessary to look at more than v_n to extract $\eta/s(T)$



Flow Harmonics Correlations

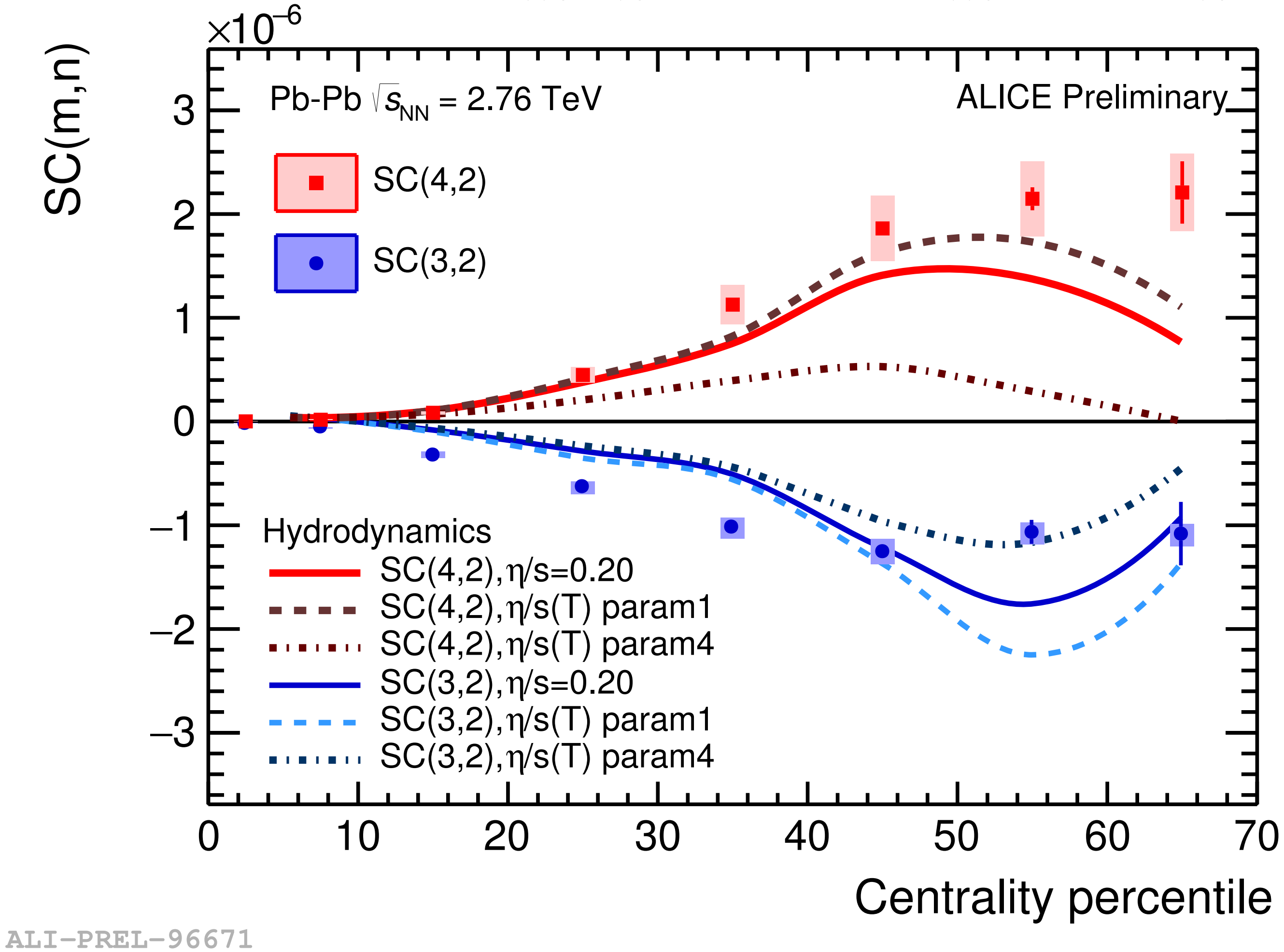


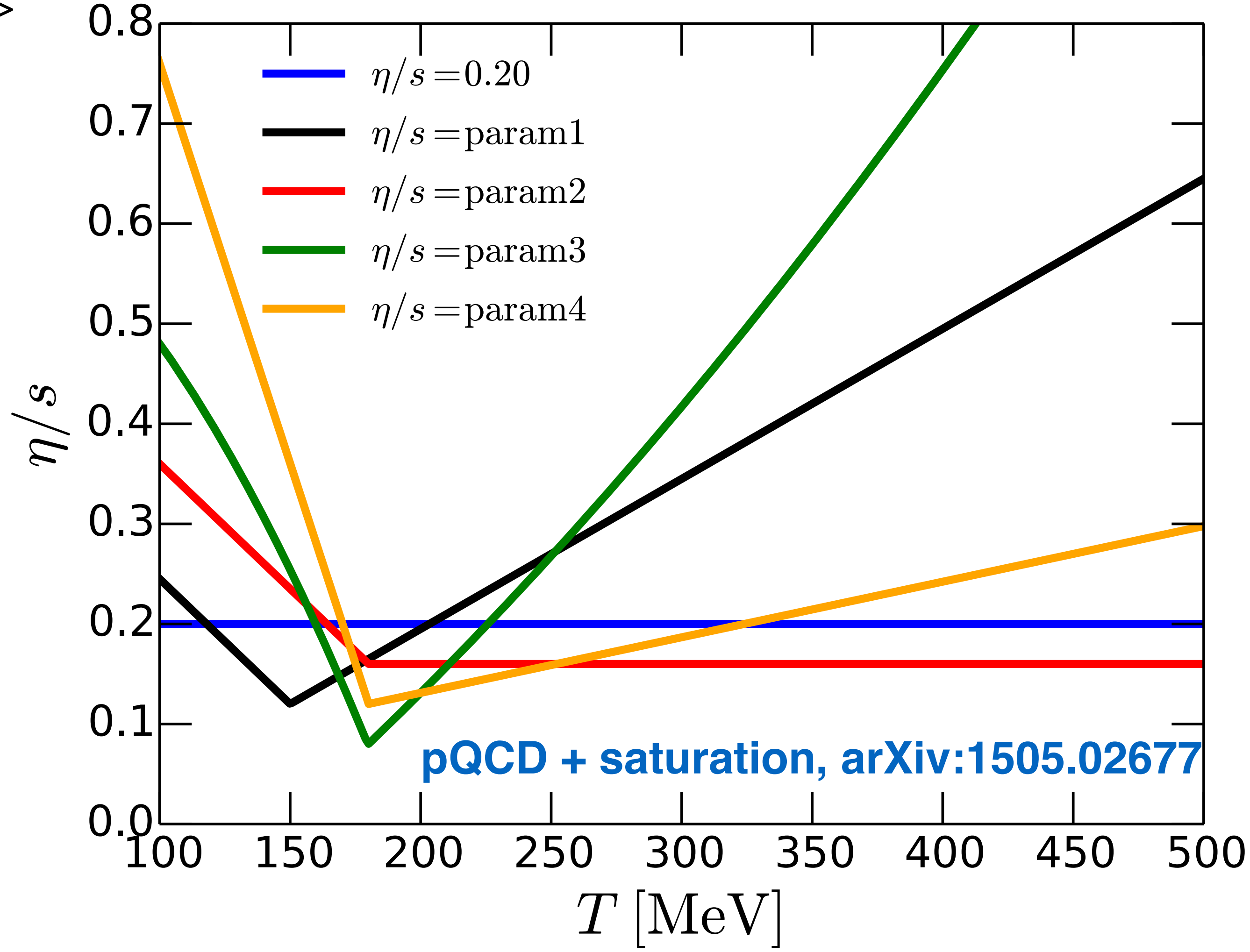


- It is necessary to look at more than v_n to extract $\eta/s(T)$
- Standard flow measurements are not very sensitive to $\eta/s(T)$
  - At least for central and semi-central collisions

Flow Harmonics Correlations

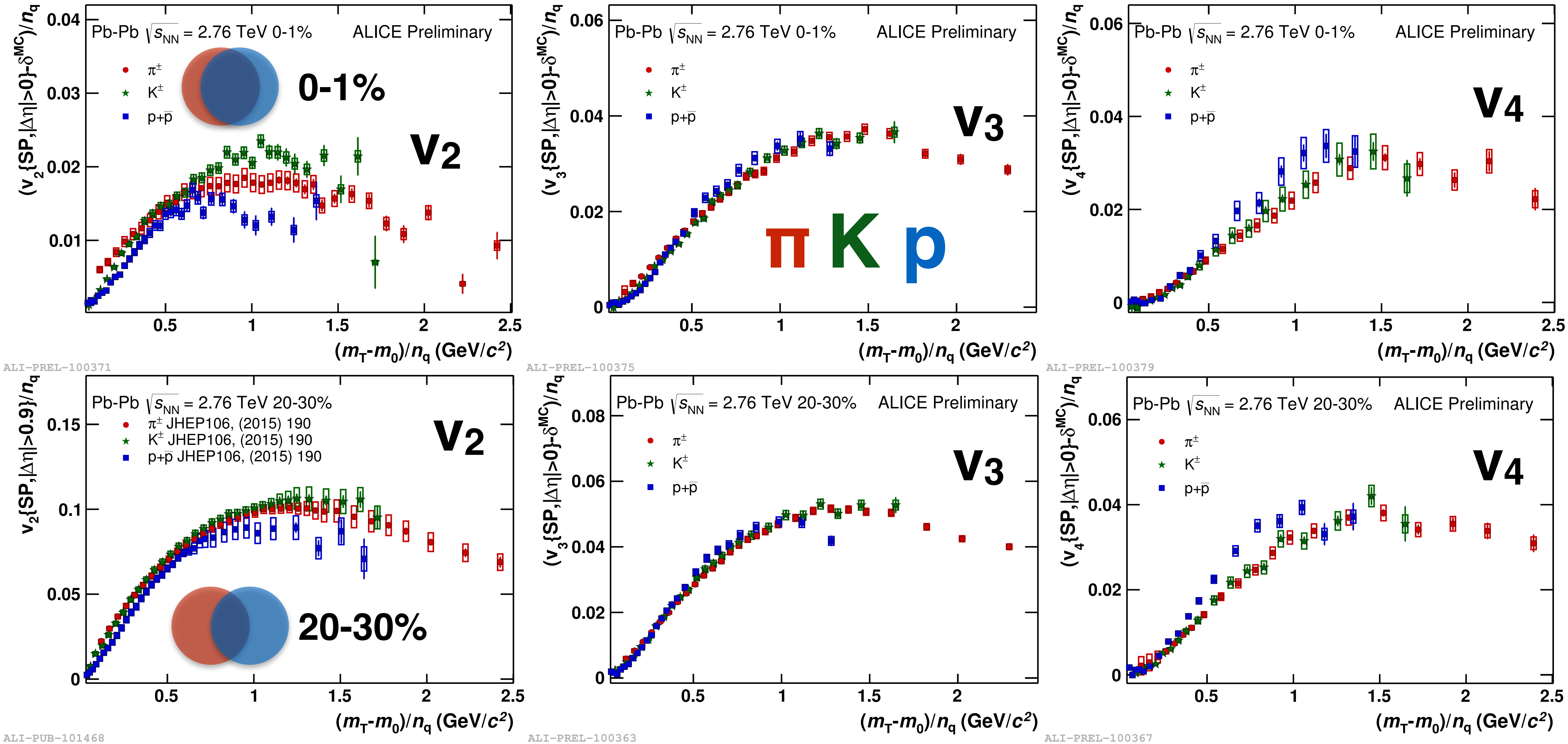
$$SC(m,n) = < v_m^2 v_n^2 > - < v_m^2 >< v_n^2 >$$





- New observable: Symmetric Cumulants (SC)
  - Insensitive to non-flow effects — due to multi-particle correlations
  - SC(3,2): sensitive to initial conditions
  - SC(4,2): sensitive to both initial conditions and η/s
  - Higher sensitivity to η/s and initial conditions than v_n alone

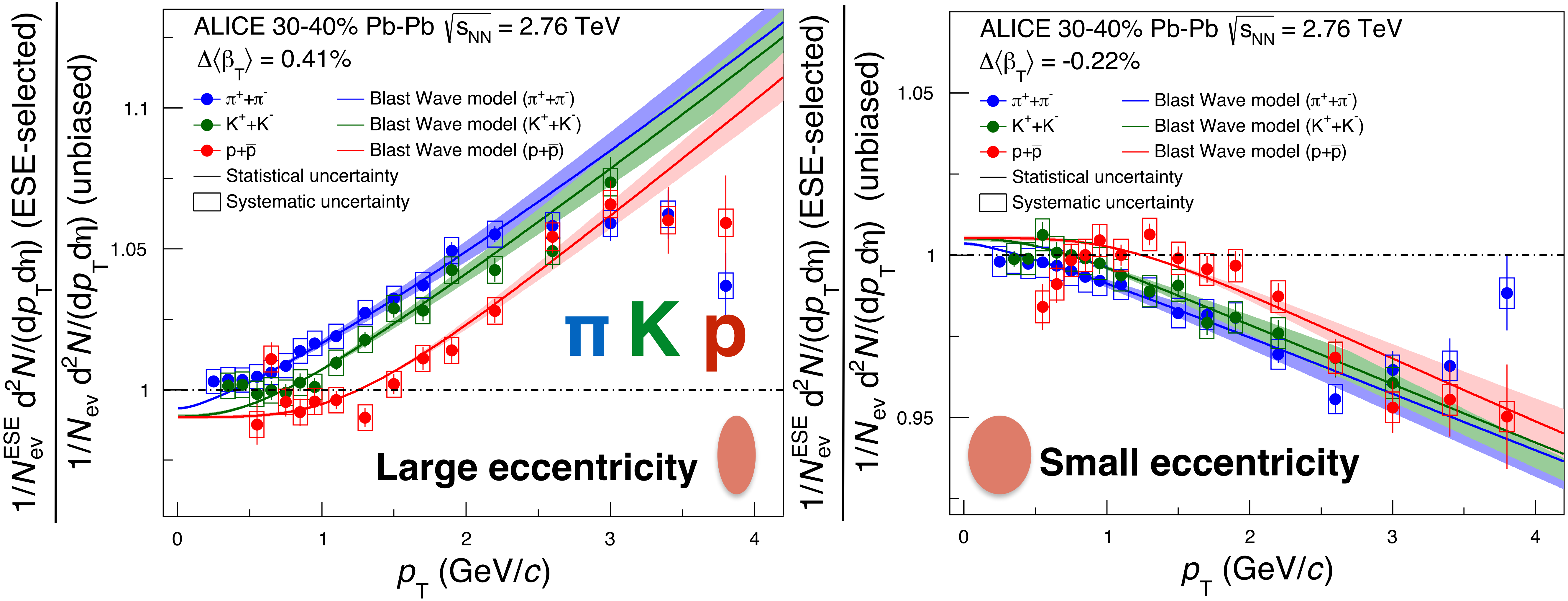
Identified Particle v_n: KE_T/n_q Scaling



- In very central collisions: $v_3 > v_4 > v_2$, geometry is not a dominated mechanism
- Scaling seems to hold better for higher order harmonics
- Additional constraint on medium expansion — radial flow, baryon/meson difference…

Event Shape Engineering

ALICE, arXiv:1507.06194



- Event eccentricity quantified by q_2: $<(q_2)^2> \approx 1 + <M\text{-}1><(v_2)^2>$
- Spectra are harder (softer) in events with larger (smaller) eccentricity
- Blast-wave study implies the correlations between elliptic flow and radial flow
- Increasing η/*s* decreases (increases) elliptic (radial) flow — further constraint on η/*s* in hydrodynamics models

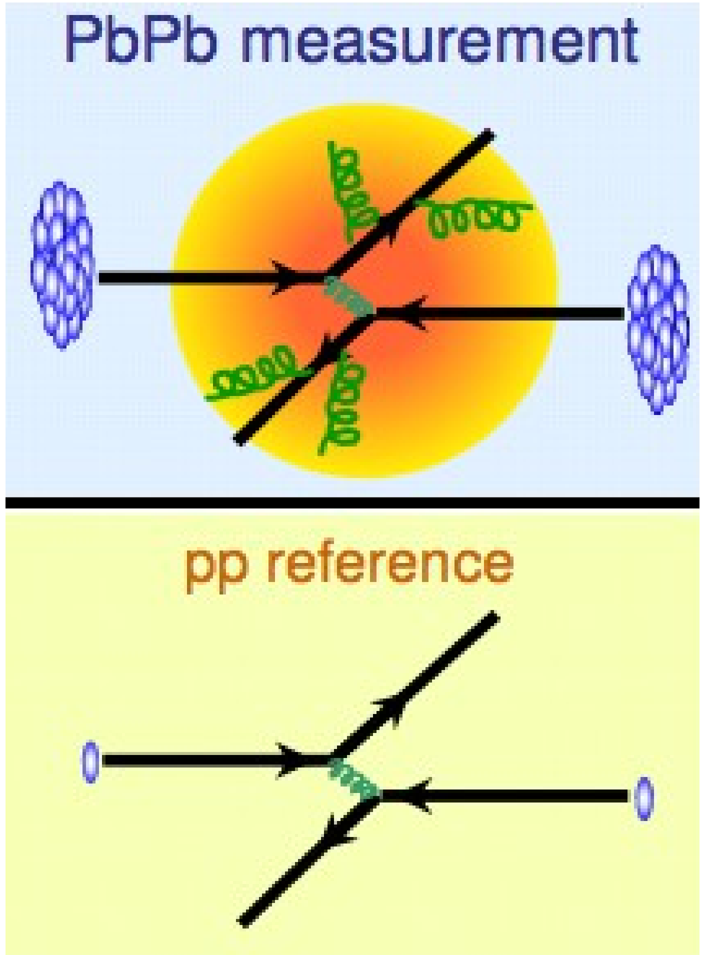
Hard Probes: Medium Tomography

- Hard probes (heavy-flavours, jets…)
  - Produced in the early stagy of heavy-ion collisions
    - Involve in the full evolution of the QCD medium and interact with particles in the medium and loss energy
  - Efficient probes for understanding the transport properties of the medium
- Nuclear modification factor, R_{AA}, quantifies in-medium energy loss

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

QCD medium

QCD vacuum



  - $R_{AA} = 1$, if there is no medium modification

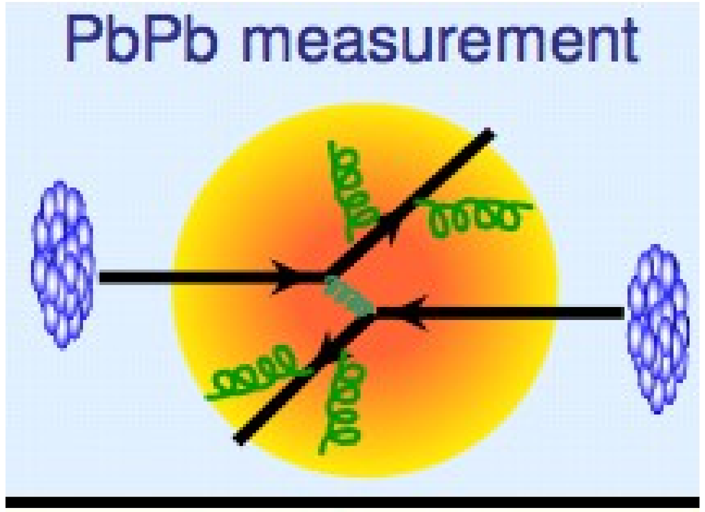
Heavy-Flavour in QCD Medium

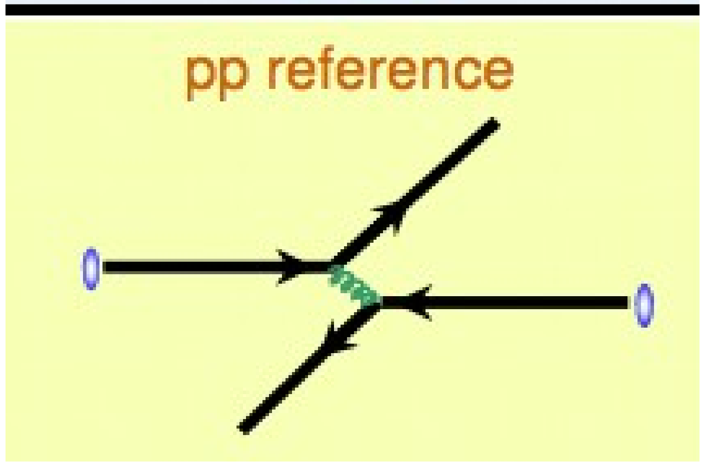
- Nuclear modification factor, R_{AA}, quantifies in-medium energy loss

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

QCD medium

QCD vacuum





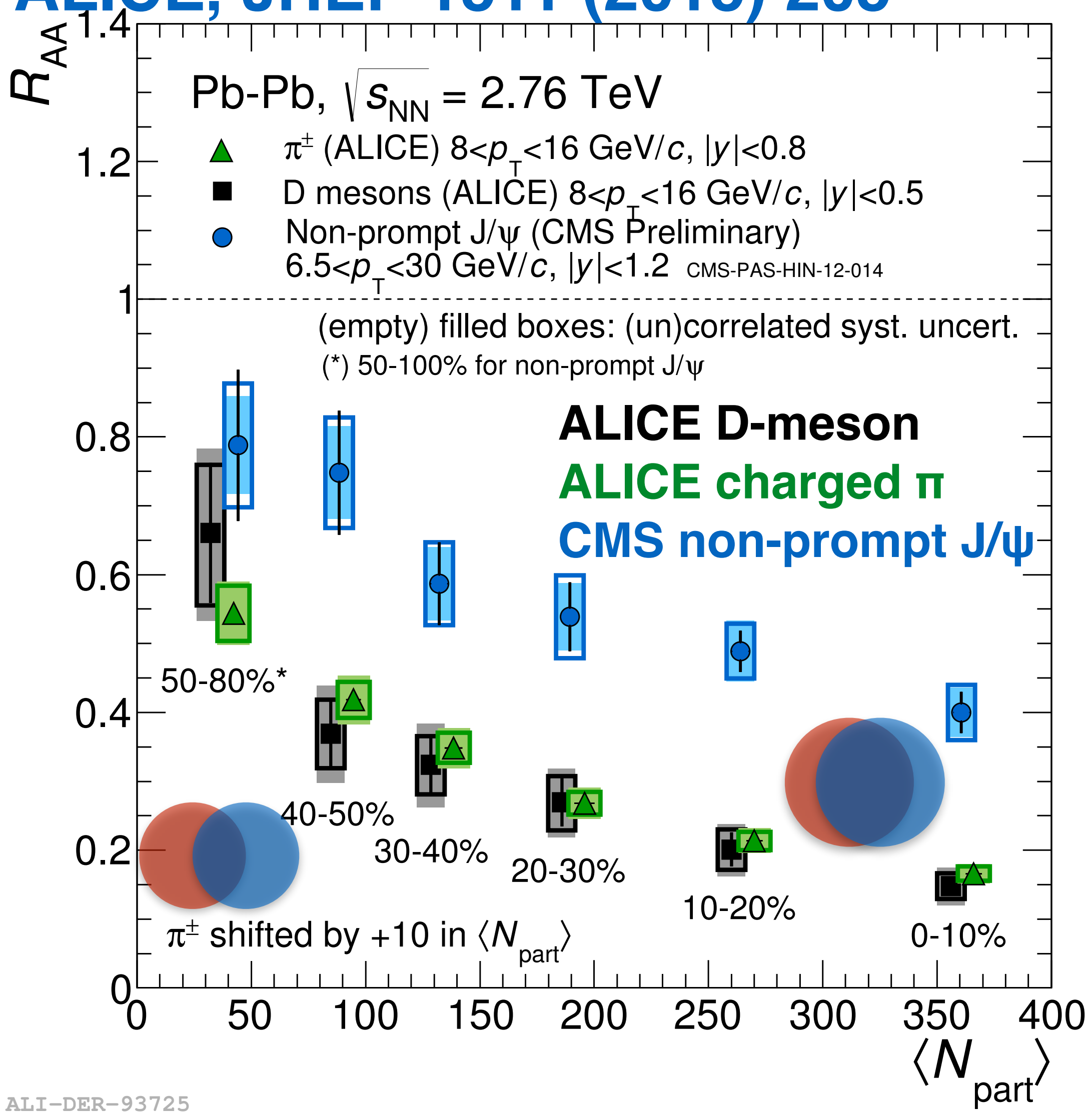
  - $R_{AA} = 1$, if there is no medium modification

$$\Delta E_{g} > \Delta E_{q \approx c} > \Delta E_{b} \rightarrow R^{h}_{AA} < R^{D}_{AA} < R^{B}_{AA} \text{ (?)}$$

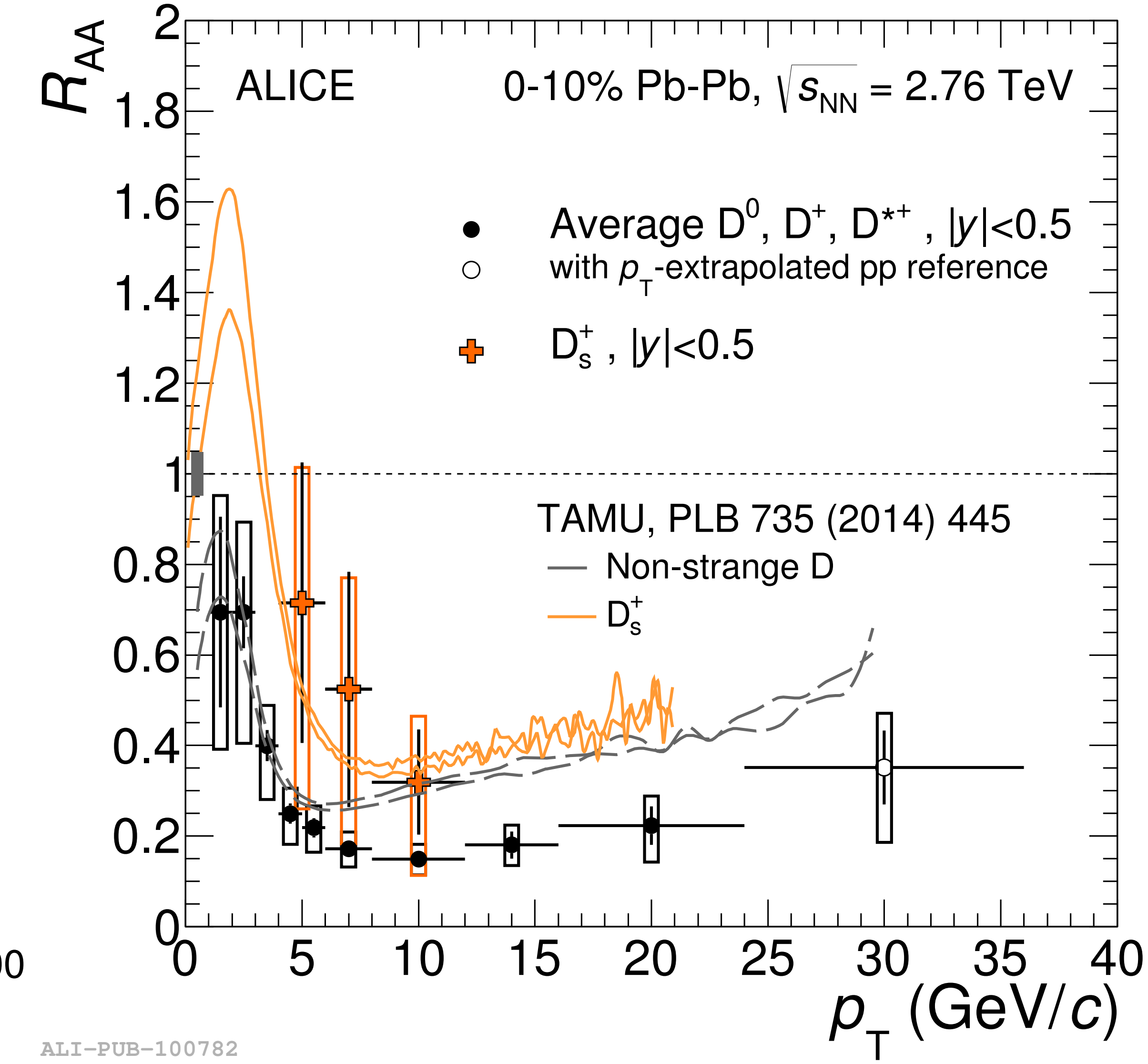
- Open heavy-flavours (HF)
  - R_{AA}: radiative energy loss vs. collisional energy loss
    - Mass and color charge dependence
  - Elliptic flow
    - Low-p_{T}: initial conditions and degree of thermalization of HF in QGP
    - High-p_{T}: path-length dependence of HF in-medium energy loss

R_{AA} of D mesons and Non-prompt J/ψ

ALICE, JHEP 1511 (2015) 205

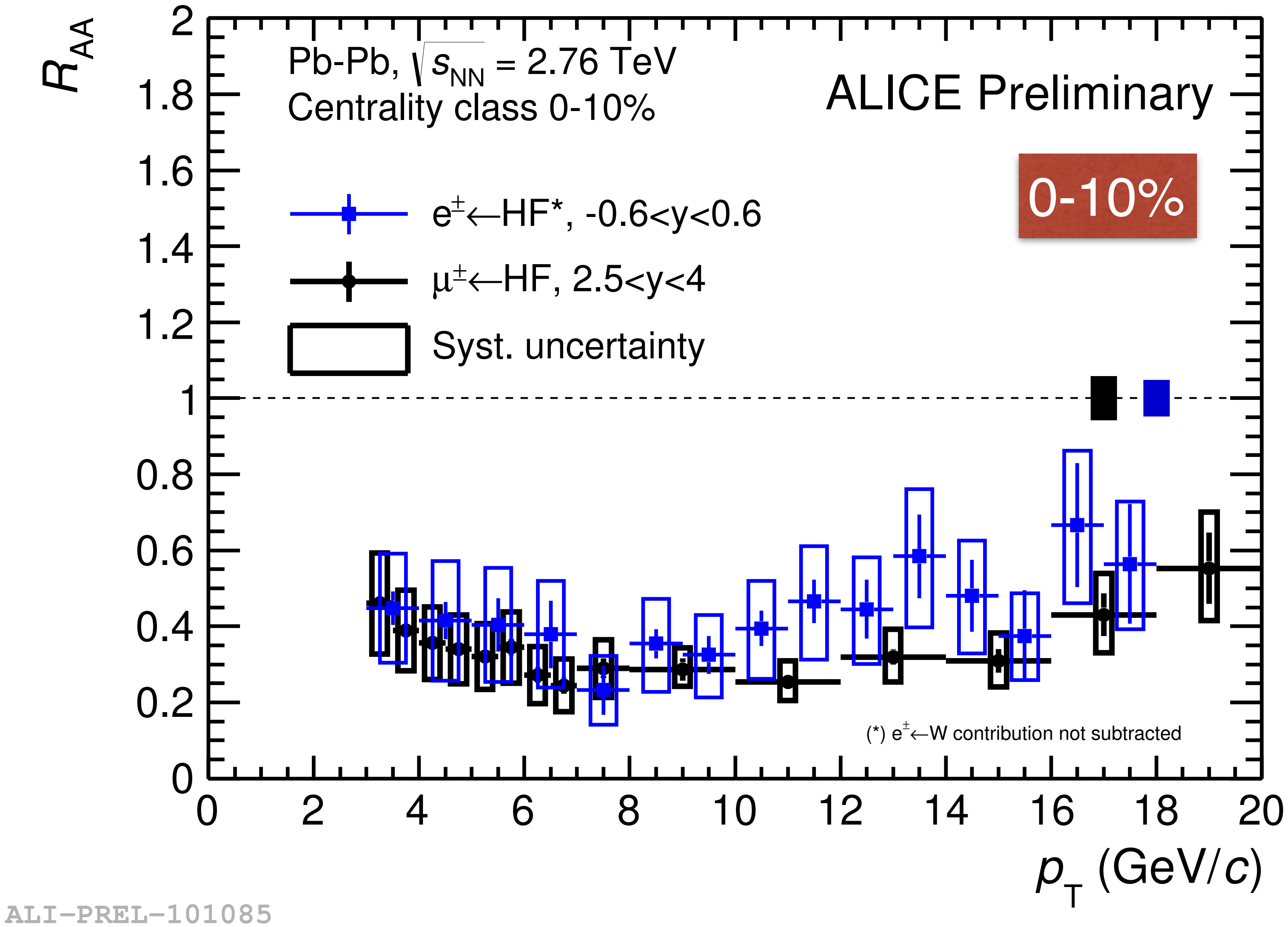


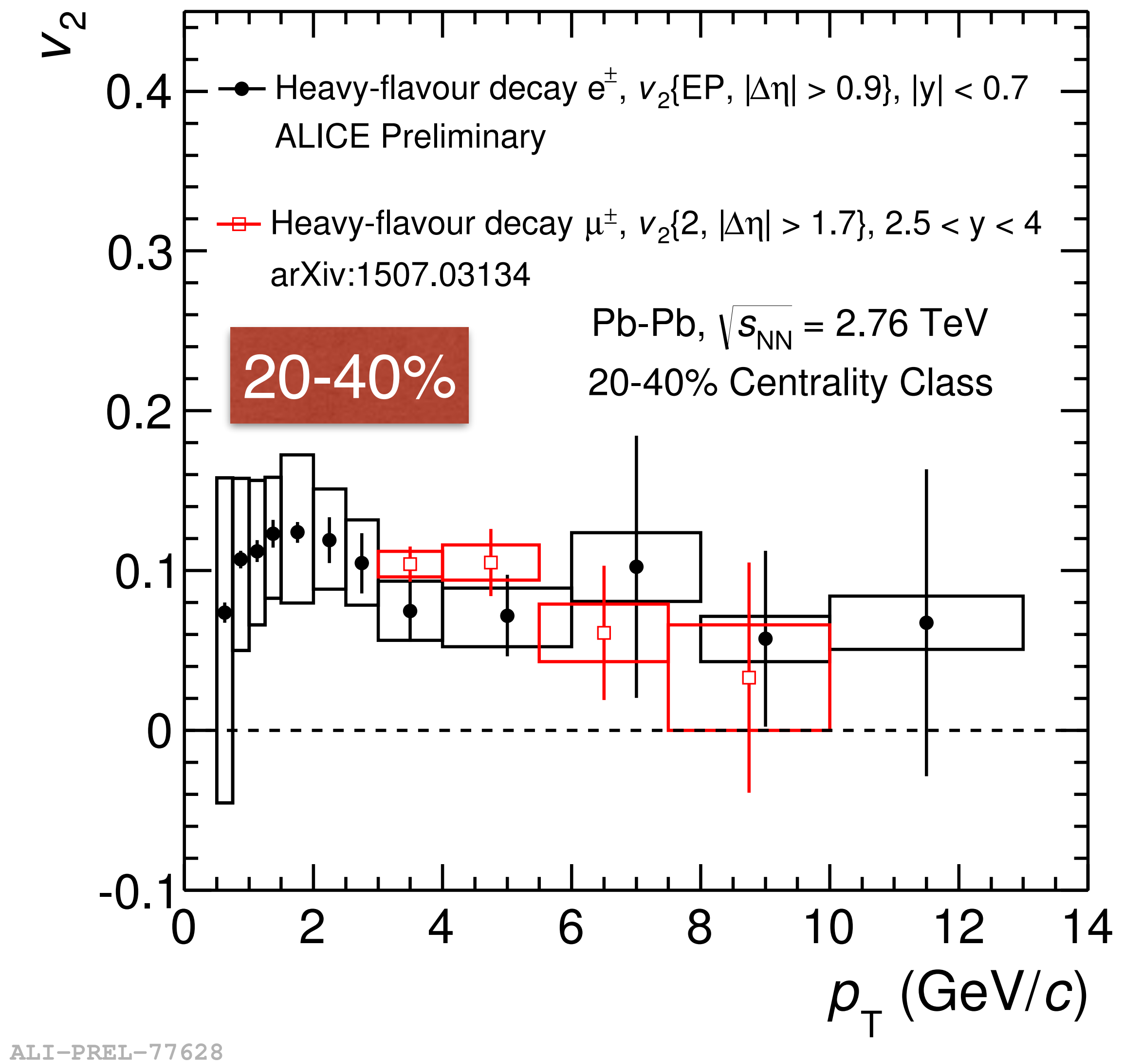
ALICE, arXiv:1509.06888, 1509.07287



- R_{AA}(D)<R_{AA}(J/ψ←B): $\Delta E_c > \Delta E_b$ — mass dependence of HF energy loss
- R_{AA}(D)≈R_{AA}(π): reproduced by more advanced models — different parton p_T distributions and fragmentation functions
- Hint of R_{AA}(D)<R_{AA}(D_s^+) at low p_T: if true — indicates charm hadronization through recombination in medium (due to strangeness enhancement)

Heavy-Flavour Decay Leptons

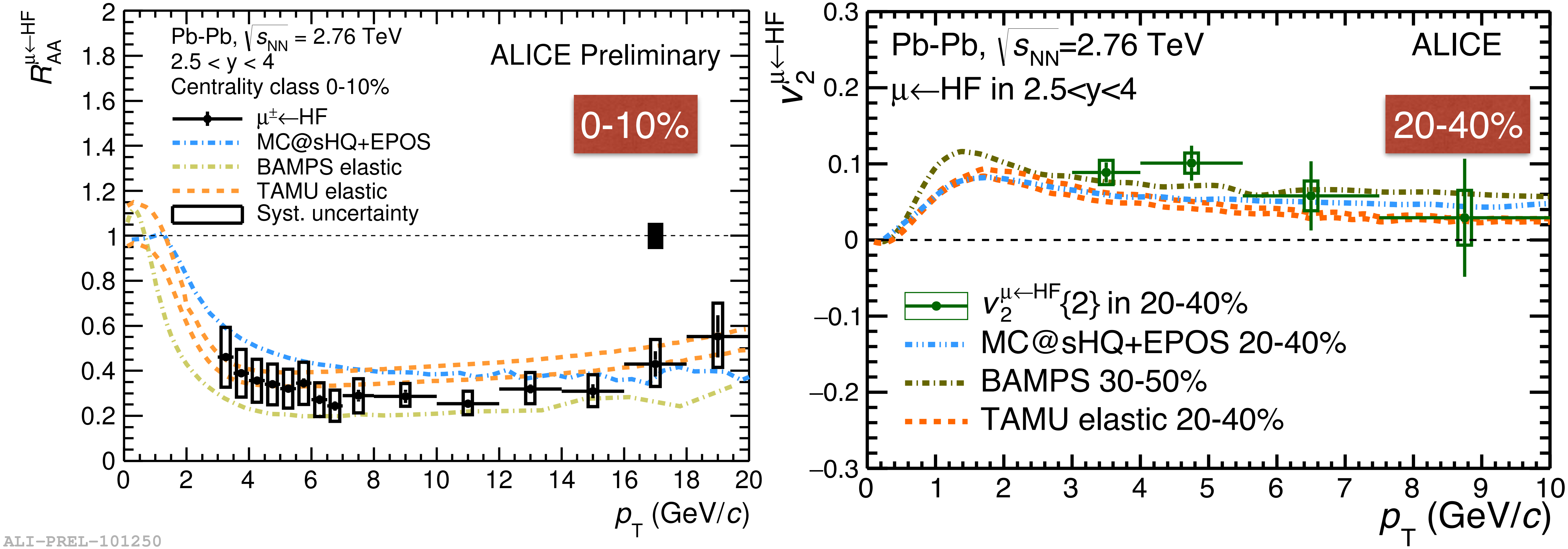




- Both R_{AA} and v_2 of heavy-flavour decay muons at forward rapidity (2.5<y<4) are compatible with heavy-flavour decay electrons at mid-rapidity (|y|<0.6 or <0.7)
- Large suppression of R_{AA} in central collisions — final-state effect
- Observed positive v_2 (3σ effect) — similar as for D mesons — confirms the significant interaction of heavy quarks with the medium

Heavy-Flavour Decay Muons: Model Predictions

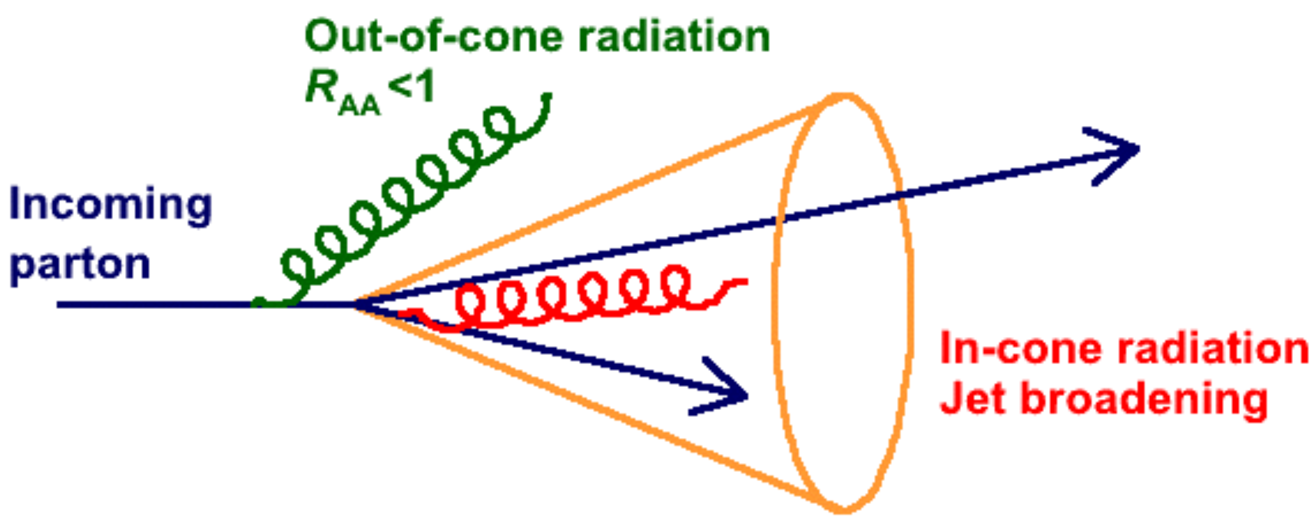
ALICE, Phys. Lett. B753 (2016) 41

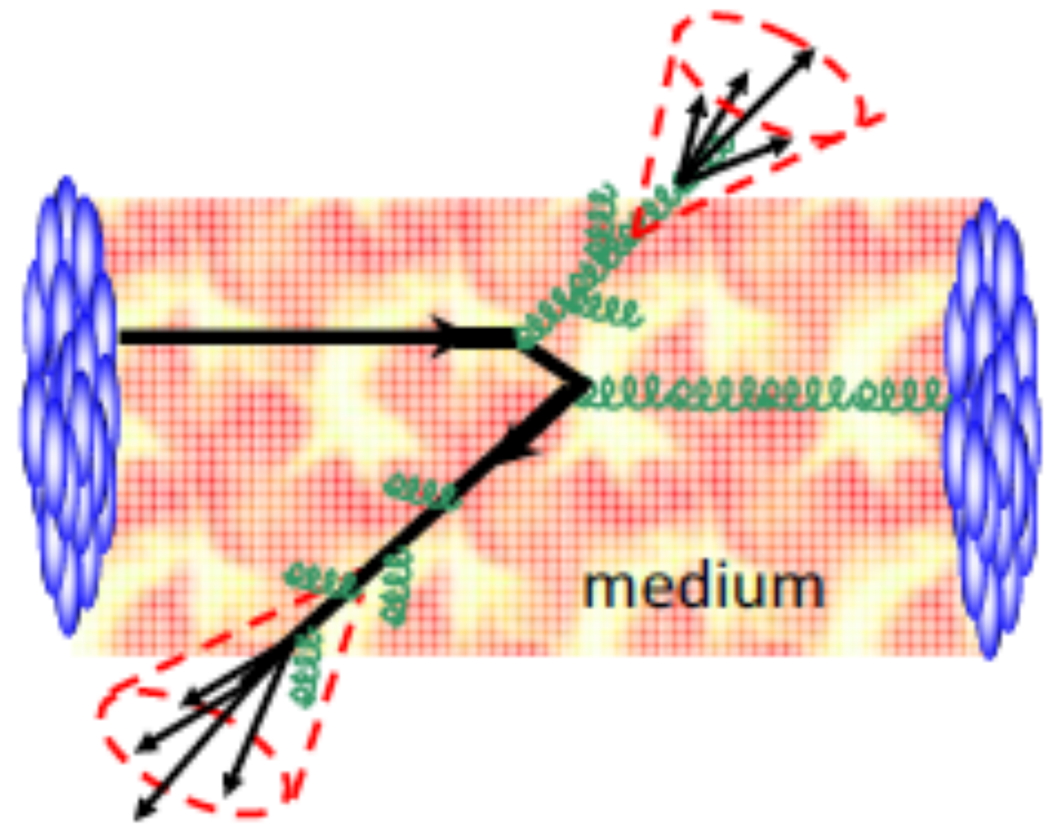


- The simultaneous description of R_{AA} and v_2 of heavy-flavour decay muons is challenging
  - Same picture for D-mesons and heavy-flavour decay electrons at mid-rapidity
  - R_{AA} and v_2 measurements together provide constraints for models

Jet Production in Heavy-Ion Collisions

- Jet: a spray of particles from hard parton fragmentation — get closer access to parton energy
- Hard partons produced before the QCD medium forms
- Interact with the hot and dense medium





- Out-of-cone radiation: energy loss in jet cone — $R_{AA} < 1$

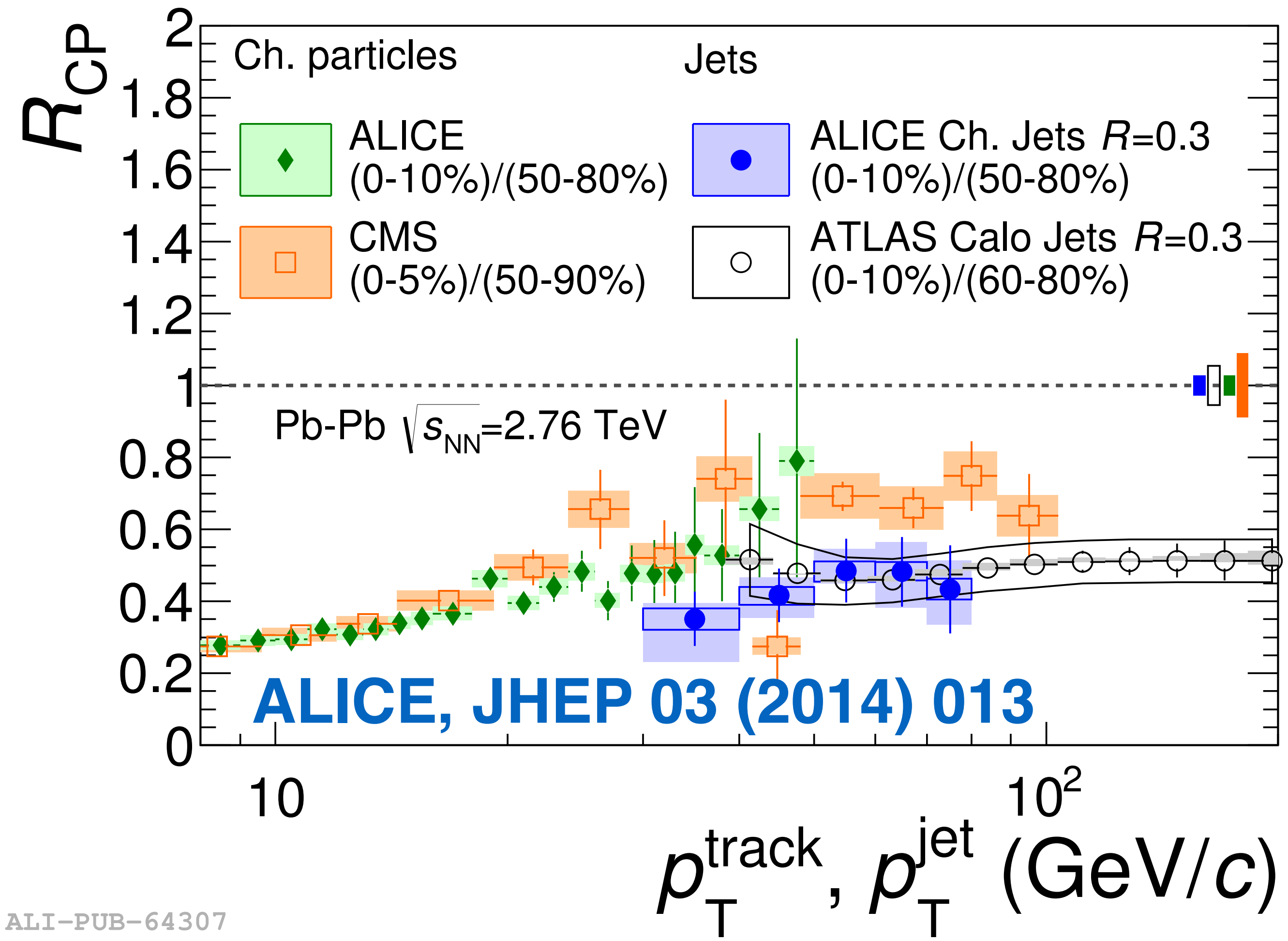
➡ Jet yield suppression, dijet or hadron–jet acoplanarity…

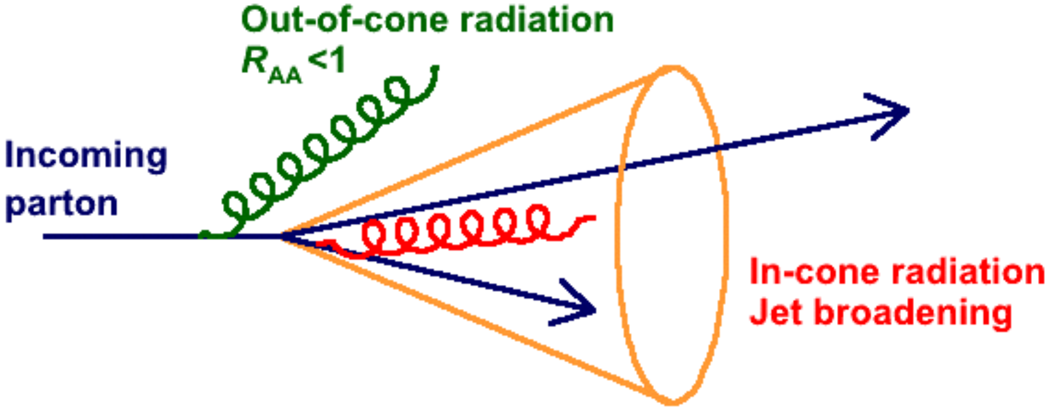
- In-cone radiation: medium modified fragmentation — $R_{AA} = 1$

➡ Jet shape broadening, modification of transverse energy profile…

Jet R_{AA} in Heavy-Ion Collisions

- Jet: a spray of particles from hard parton fragmentation — get closer access to parton energy





- ATLAS: calorimetric jets
- ALICE: charged-particle jets — more sensitive to the low-momentum fragments

- Agreement between ALICE and ATLAS

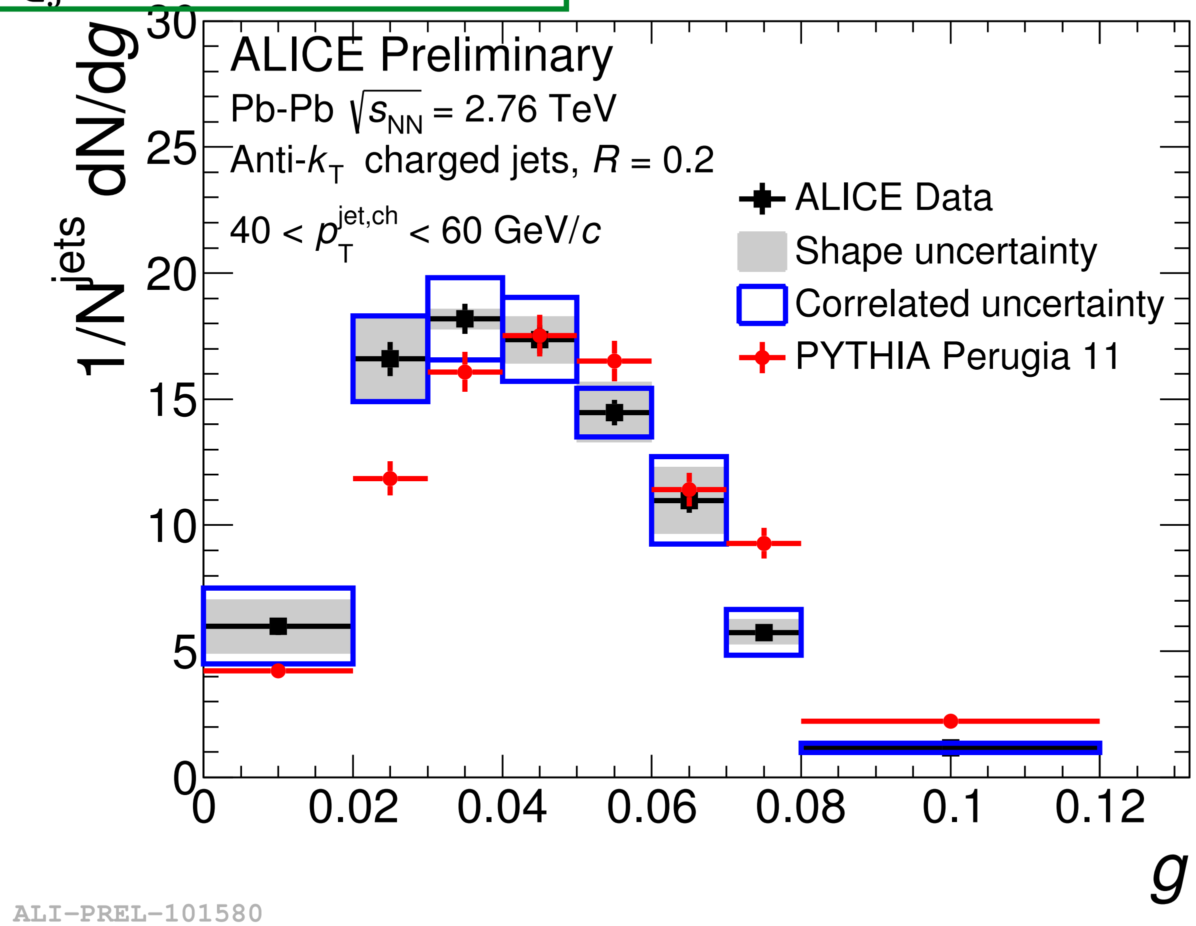
➡ Contribution of low momentum jet fragments to jet energy is small

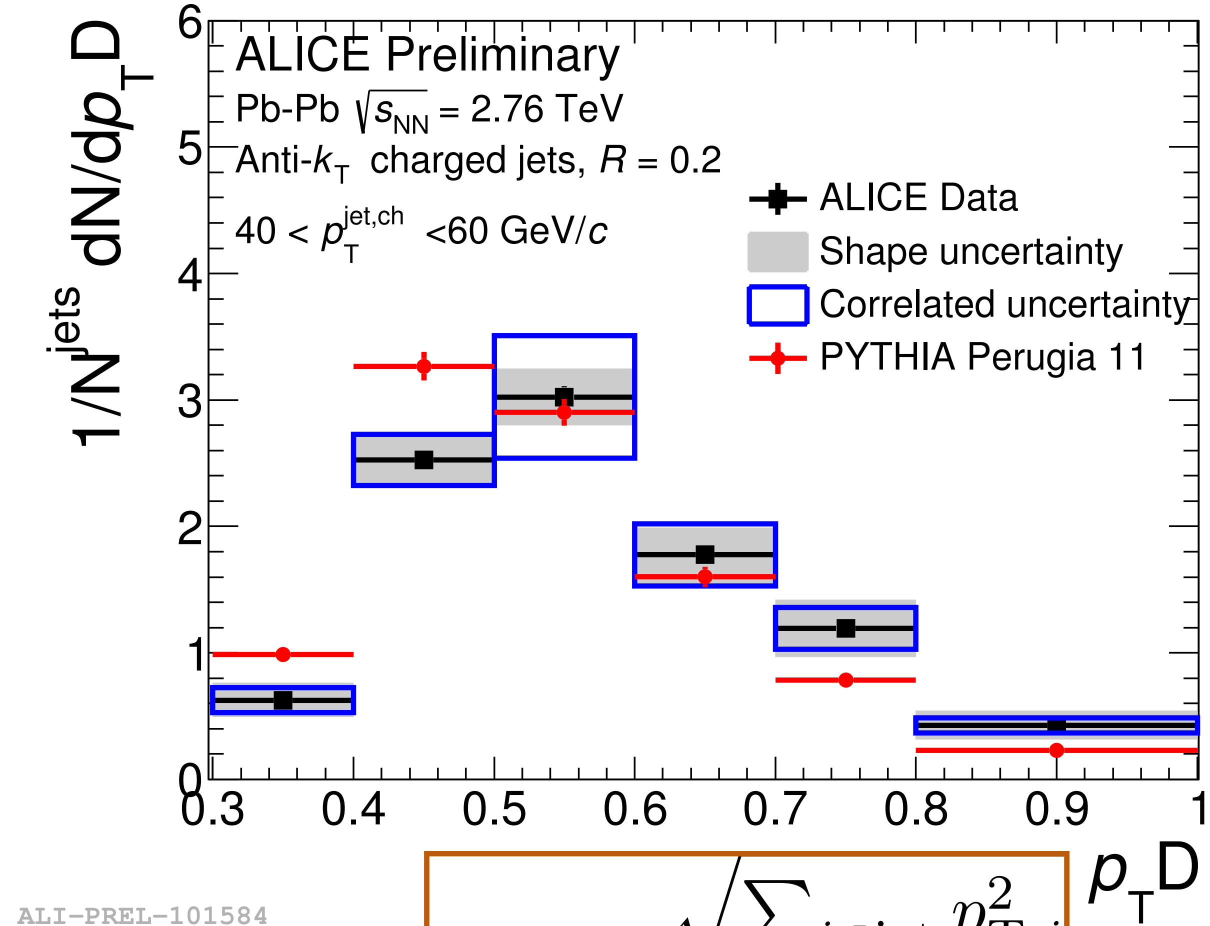
- R_{CP} of jets and single hadrons are compatible

➡ Indication that the momentum is redistributed to larger angles

Jet Shapes

$$g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \Delta R(i, \mathrm{jet})$$

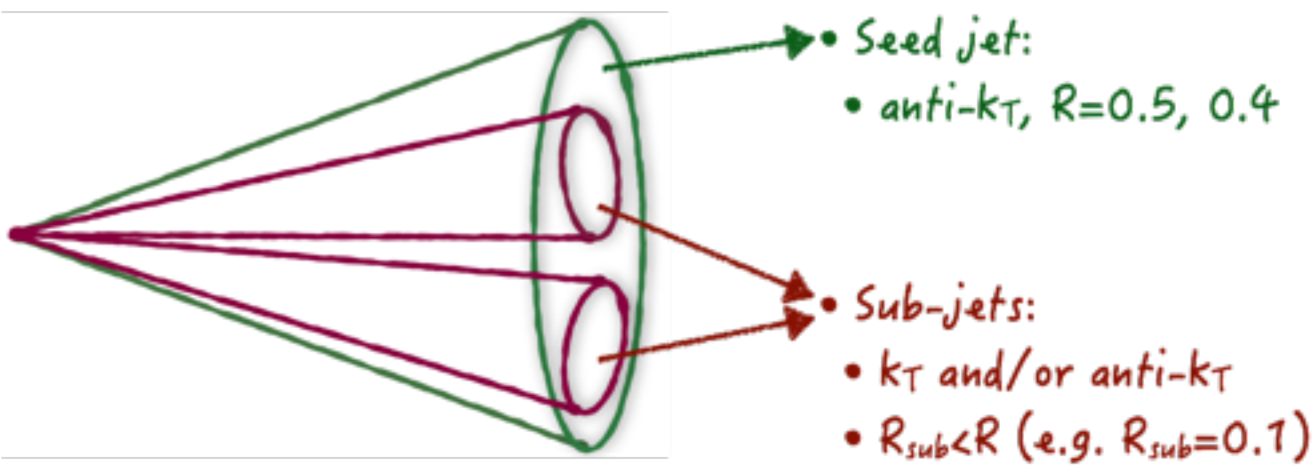




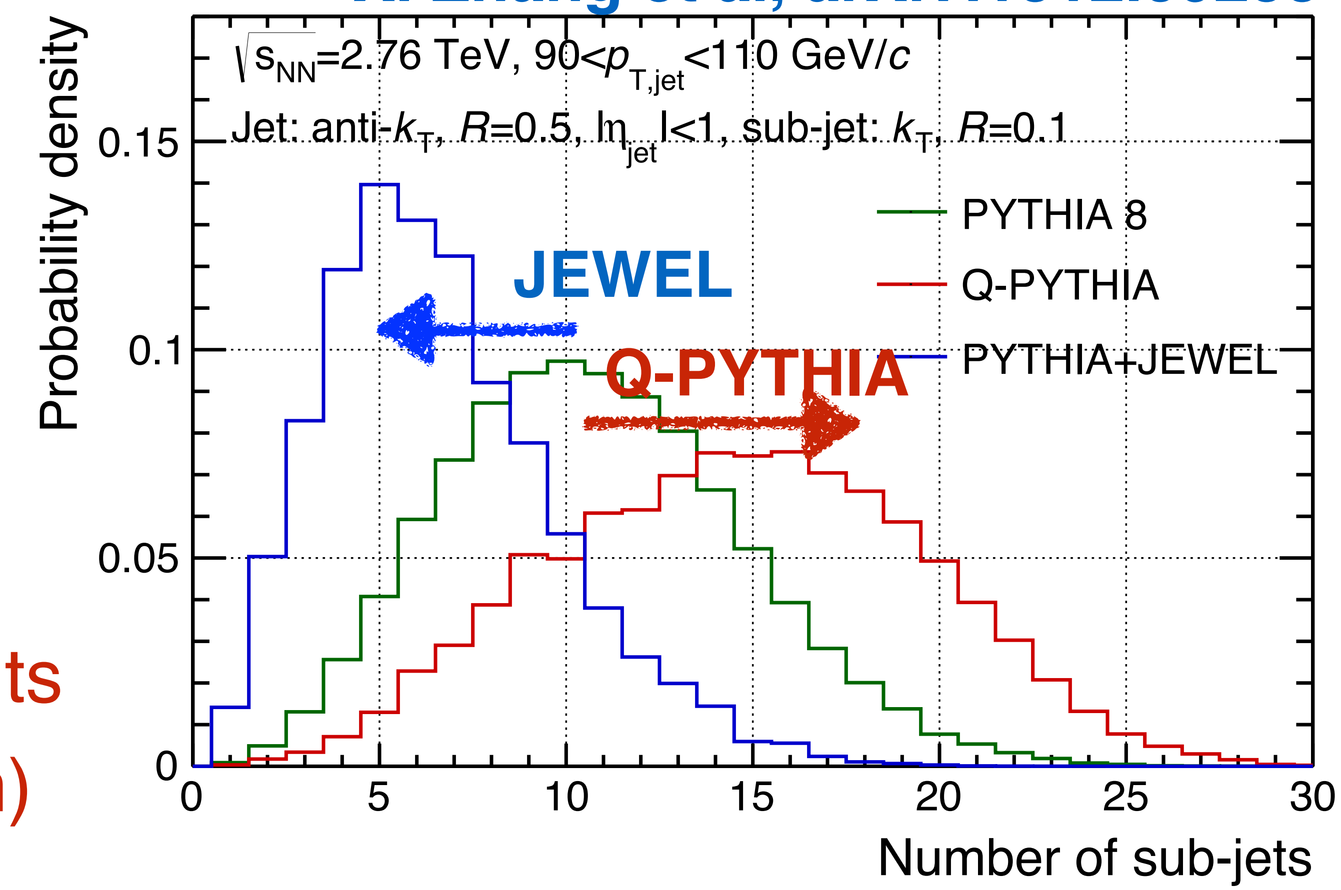
$$p_{\mathrm{T}} D = \frac{\sqrt{\sum_{i \in \mathrm{jet}} p_{\mathrm{T},i}^2}}{p_{\mathrm{T,jet}}}$$

- Radial momentum (g) — p_{T}-weighted width of jet
  - g shifted to lower values in Pb–Pb data relative to PYTHIA — indication of more collimated jet cores in data
- $p_{\mathrm{T}}D$ — dispersion of jet constituents
  - $p_{\mathrm{T}}D$ shifted to large values relative to PYTHIA — indication of few jet constituents and large dispersion

Sub-jet Structure: Proposed Observable



X. Zhang et al, arXiv:1512.09255



- Sub-jets: re-clustering the constituents in a jet (possibly a different algorithm)
- Smaller radius/area — reduces the background fluctuations and pile-up
- Opening the degree of freedom in jets — details of fragmentation with decreased dependence on hadronic DOFs, provides sensitivity to details of the parton radiation/shower
- Different multiplicity of sub-jets in the two models — sub-jet production is sensitive to quenching mechanisms

Sub-jet Structure: Proposed Observable

X. Zhang et al, arXiv:1512.09255

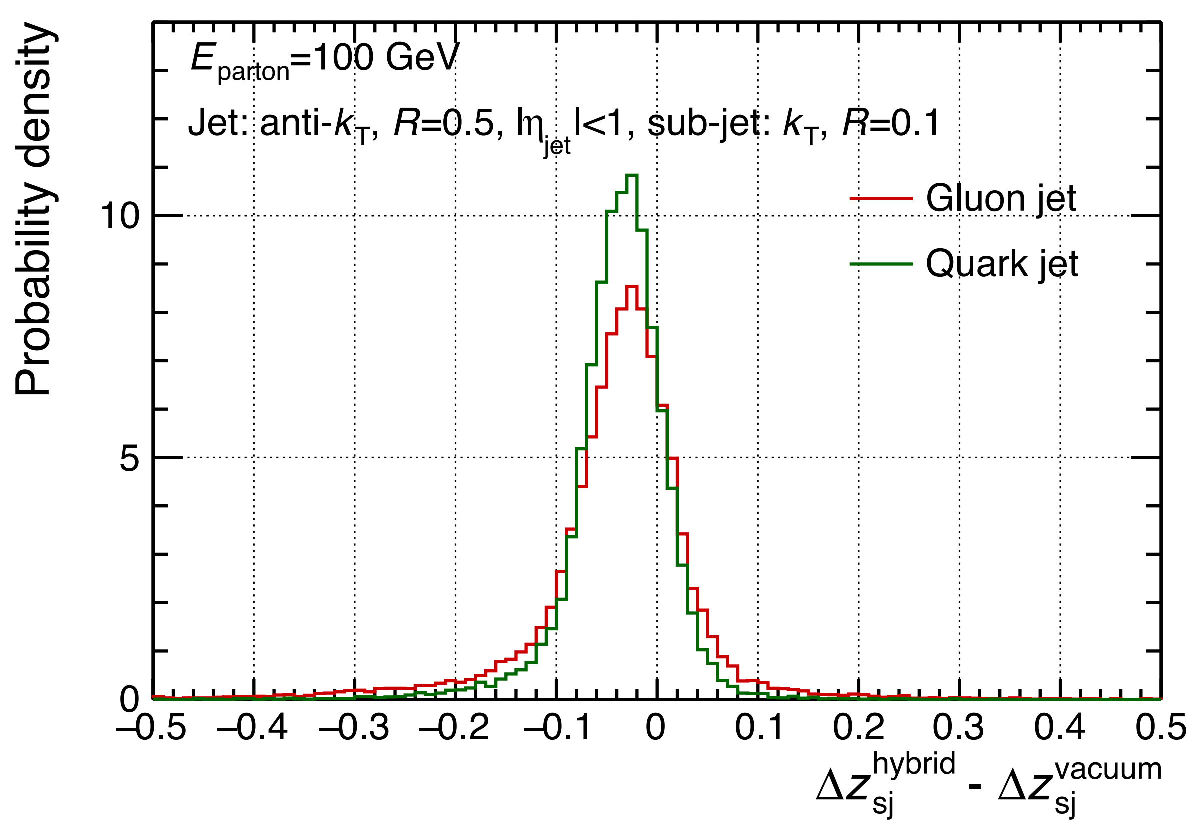
- The local background for the two sub-jets is (to a large extend) similar
  - use the p_T difference between the two leading sub-jets
- In the leading order (FastJet median background subtraction):

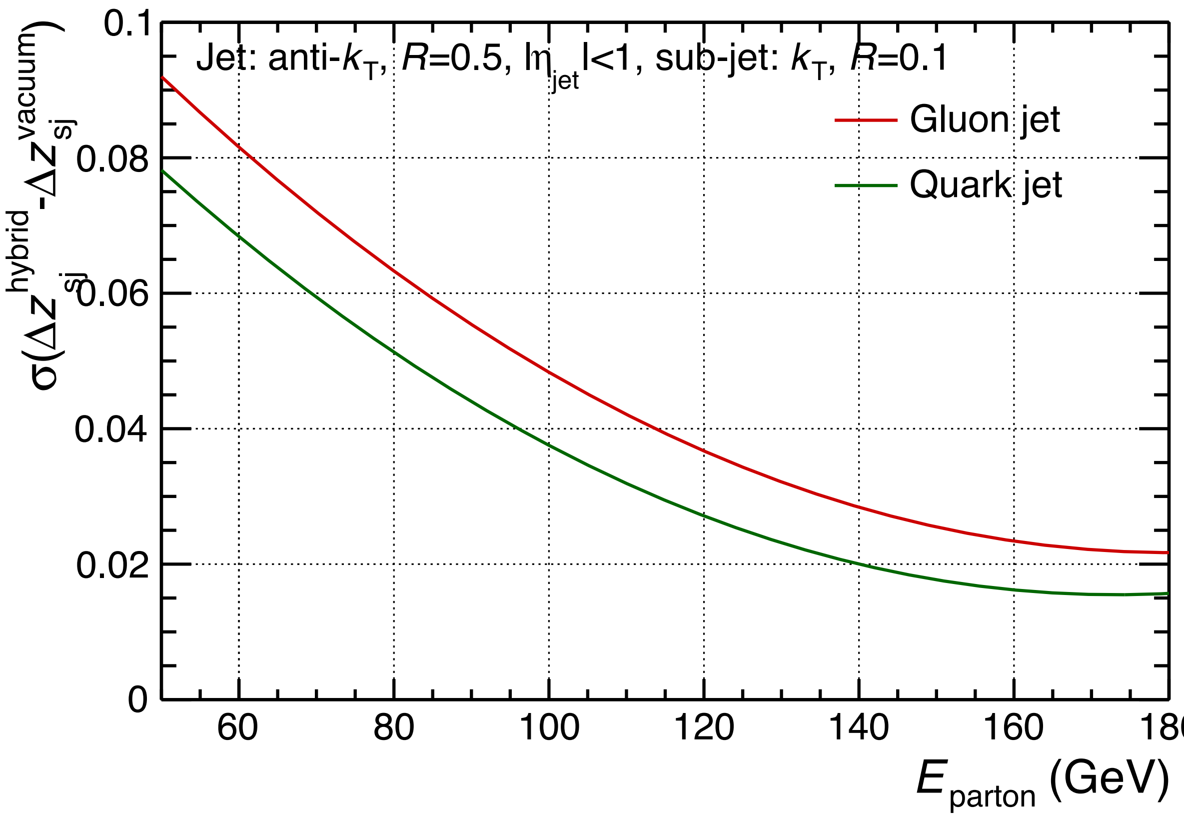
$$\Delta p_T^{sj12} = p_T^{sj1} - \rho^{BG} \times A^{sj1} \pm \delta^{BG}(A^{sj1}) - (p_T^{sj2} - \rho^{BG} \times A^{sj2} \pm \delta^{BG}(A^{sj2}))$$

Background terms cancel out for locally uniform background

Tests on a realistic LHC heavy-ion background show a promising behavior

$$\Delta_{\mathrm{sj}} = p_{\mathrm{T,subjet}}^{\mathrm{1st\ leading}} - p_{\mathrm{T,subjet}}^{\mathrm{2nd\ leading}}, \qquad \Delta z_{\mathrm{sj}} = \Delta_{\mathrm{sj}} / p_{\mathrm{T,jet}}$$

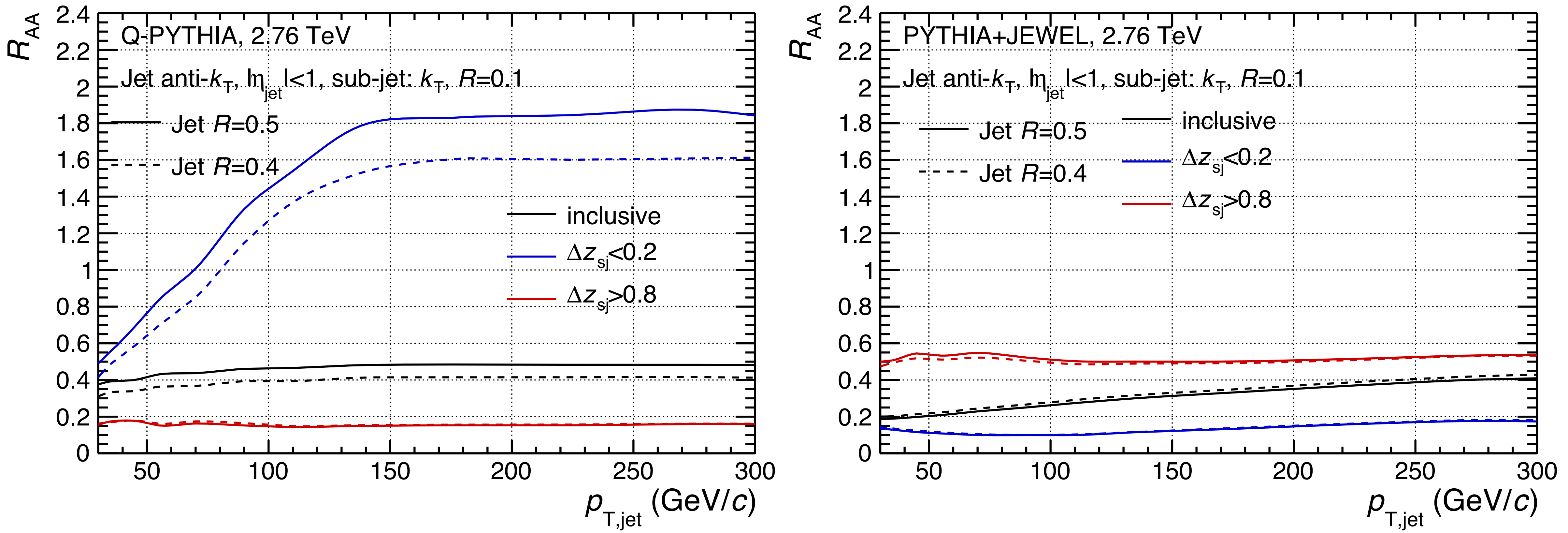




Sub-jet Structure: Proposed Observable

$$R_{\mathrm{AA}}(\Delta z_{\mathrm{sj}}) = \frac{\mathrm{d}\sigma_{\mathrm{medium}}/\mathrm{d}p_{\mathrm{T}}|_{\Delta z_{\mathrm{sj}}}}{\mathrm{d}\sigma_{\mathrm{vacuum}}/\mathrm{d}p_{\mathrm{T}}|_{\Delta z_{\mathrm{sj}}}}$$

X. Zhang et al, arXiv:1512.09255



- A jet by jet selection on Δz_{sj} carries little experimental difficulties (both in pp and AA)
- Differences for Δz_{sj} selected jets with respect to inclusive R_{AA}:
  - For large Δz_{sj}: R_{AA} suppressed in Q-PYTHIA but enhanced in JEWEL
    - The opposite behavior for small Δz_{sj}
- Small R-jet dependence only for Q-PYTHIA

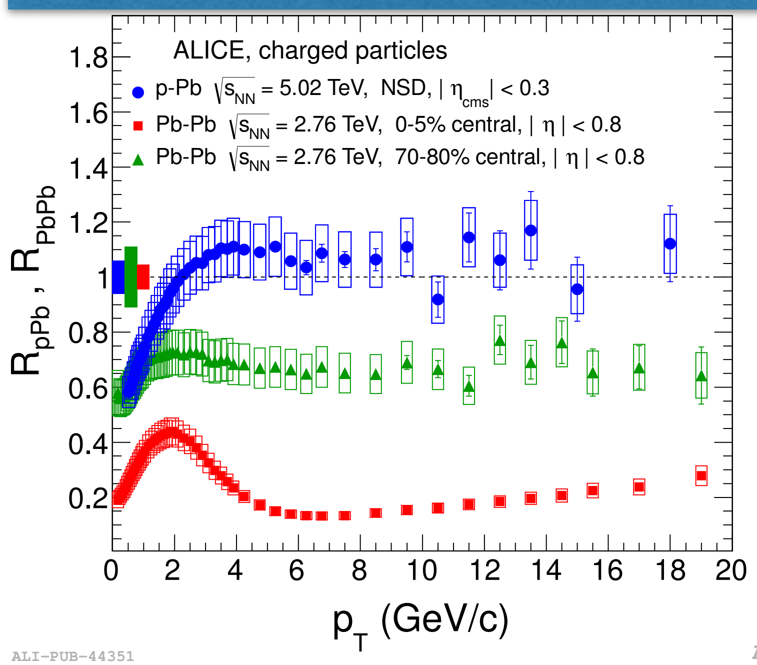
Note: These are shown as examples - different selections on sub-jet p_{T} difference possible - e.g. moments of the distributions etc

Small Systems

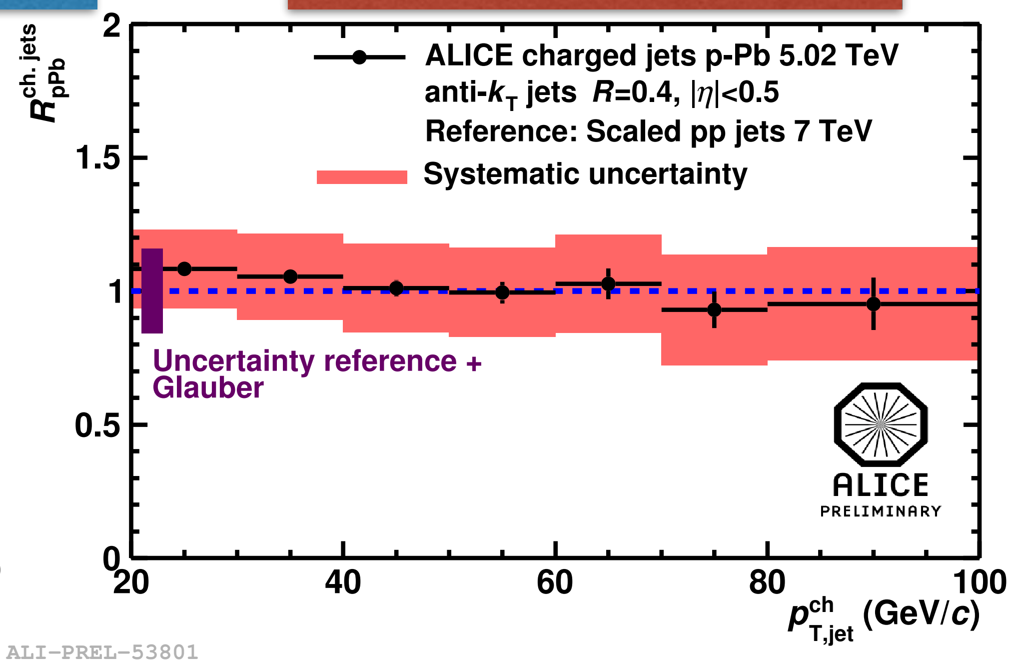
- Small systems
  - pp collisions: QCD vacuum, baseline for heavy-ion and p–Pb collisions
  - p–Pb collisions: quantify Cold Nuclear Matter (CNM) effects — nuclear modified PDF, k_T-broadening coherent energy loss of partons in nuclear medium…

ALICE, Phys. Rev. Lett. 110 (2013) 082302

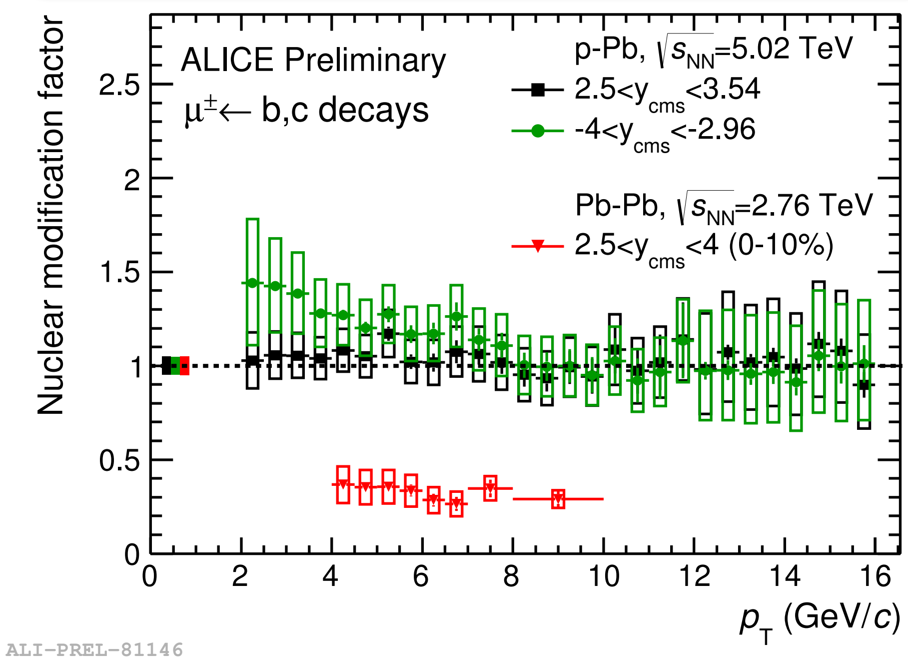
Charged particles $|\eta_{CMS}|<0.3$



Charged particle jets $|\eta|<0.5$

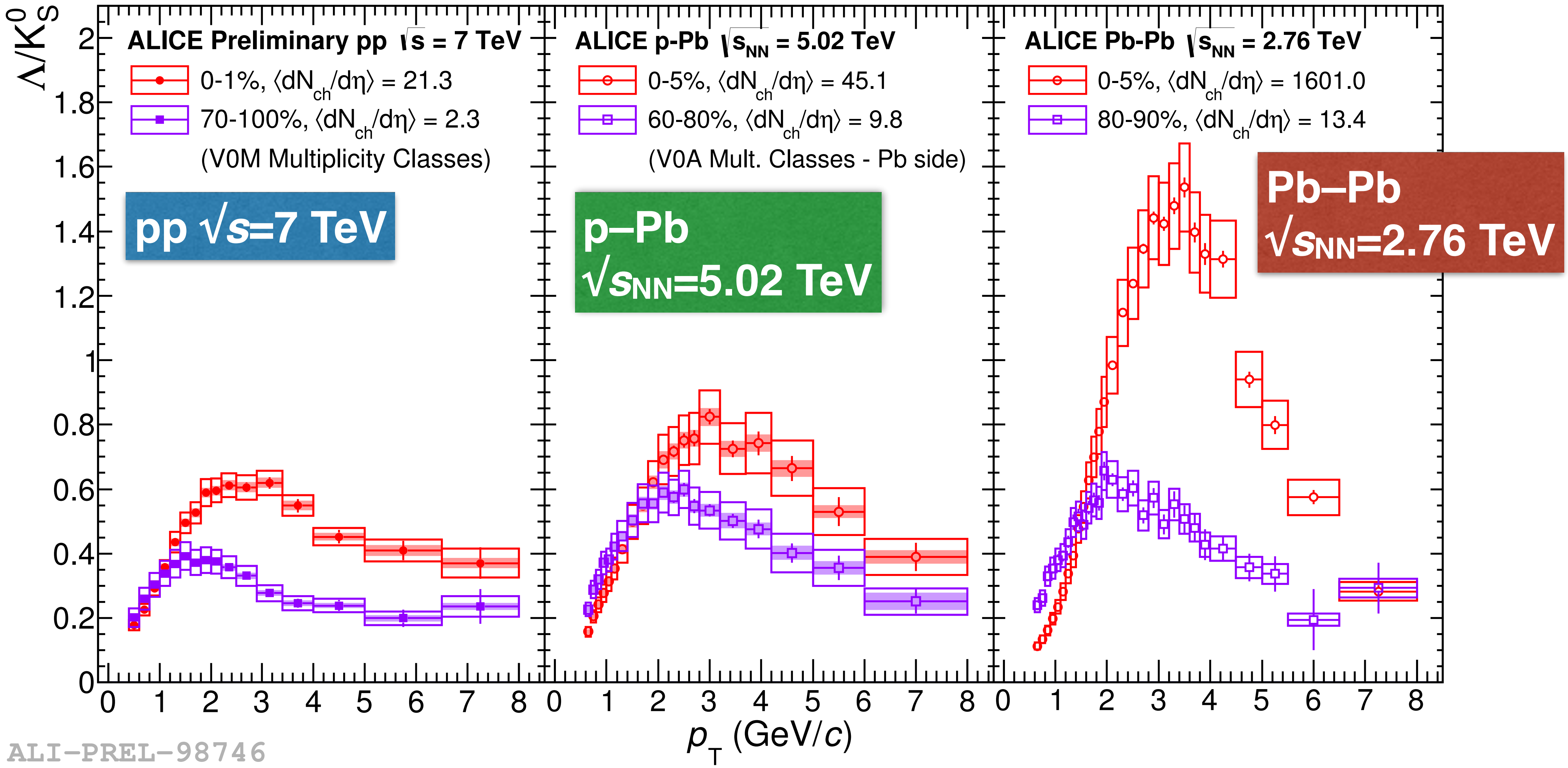


HF muons $2.5<y_{CMS}<3.54$, $-4<y_{CMS}<-2.96$



- R_{pPb} consistent with unity — strong suppression observed in central Pb–Pb collisions at mid-rapidity and forward rapidity is due to the hot medium

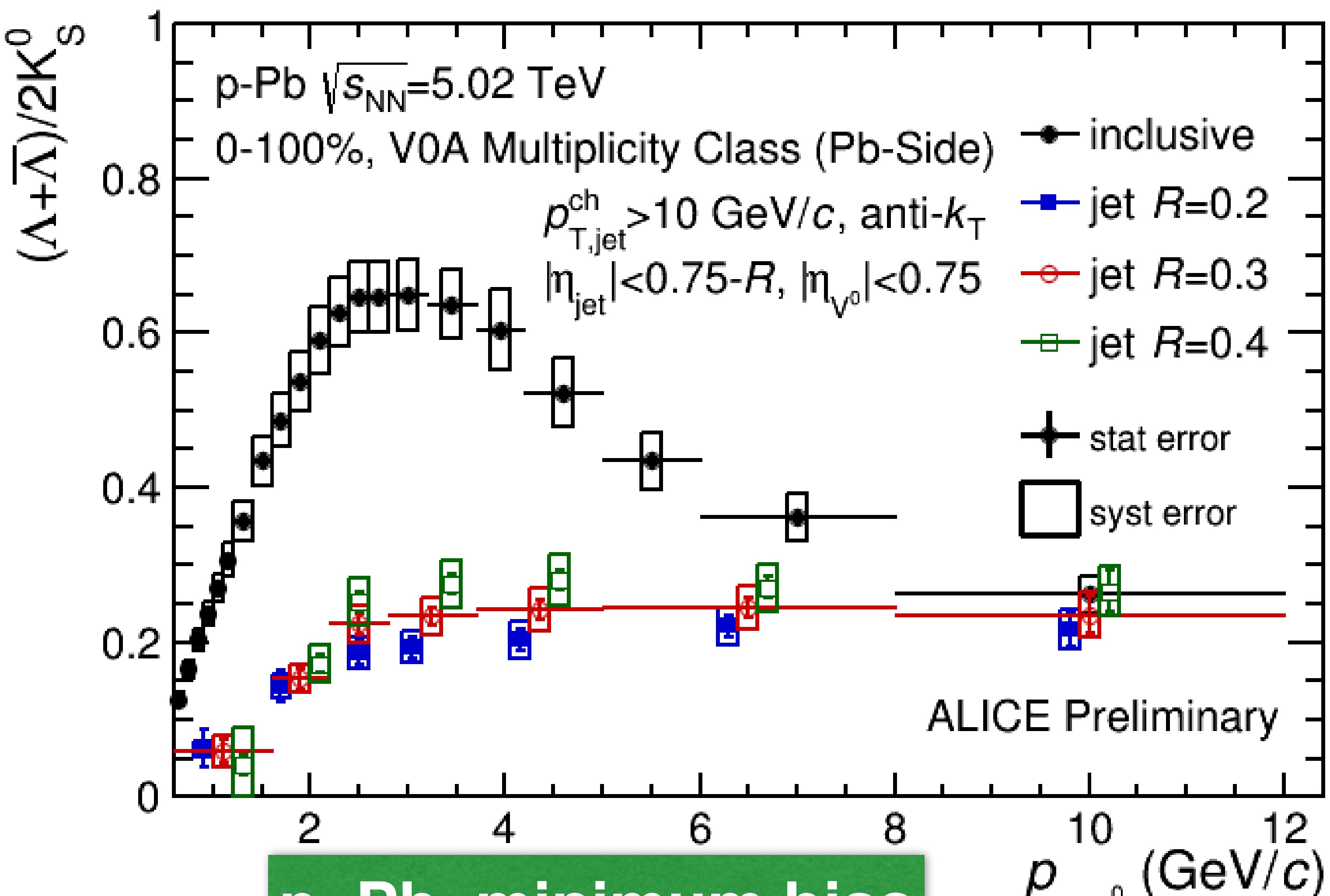
Λ/K_S^0 Ratio: Inclusive V^0s



- Increase of the ratio from low multiplicity (peripheral) to high multiplicity (central) collisions seen in pp, p–Pb, and Pb–Pb systems
- In Pb–Pb the enhancement at intermediate p_T can be explained by collective flow and/or quark recombination from QGP
- Same qualitative behavior seen in pp and p–Pb, but with smaller magnitude

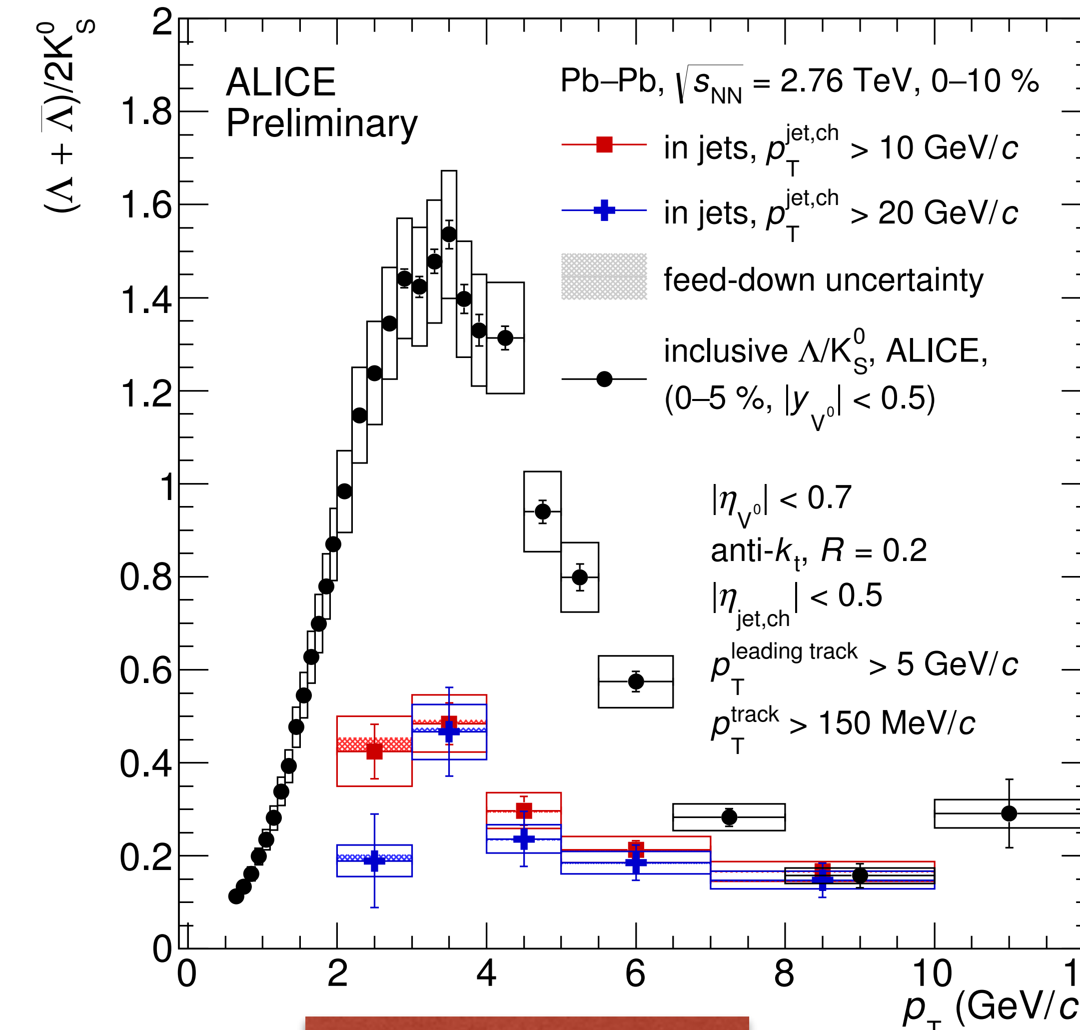
Λ/K_S^0 Ratio in Jets

- The enhanced ratio of Λ/K_S^0 at inter-median p_T of inclusive V^0s in p–Pb and Pb–Pb collisions relative to pp collisions is not present within the jet region
  - Baryon enhancement does not origin from modified jet fragmentation
  - Results independent on jet radii and disfavor the hard-soft recombination



ALI-PREL-80712

p–Pb, minimum bias

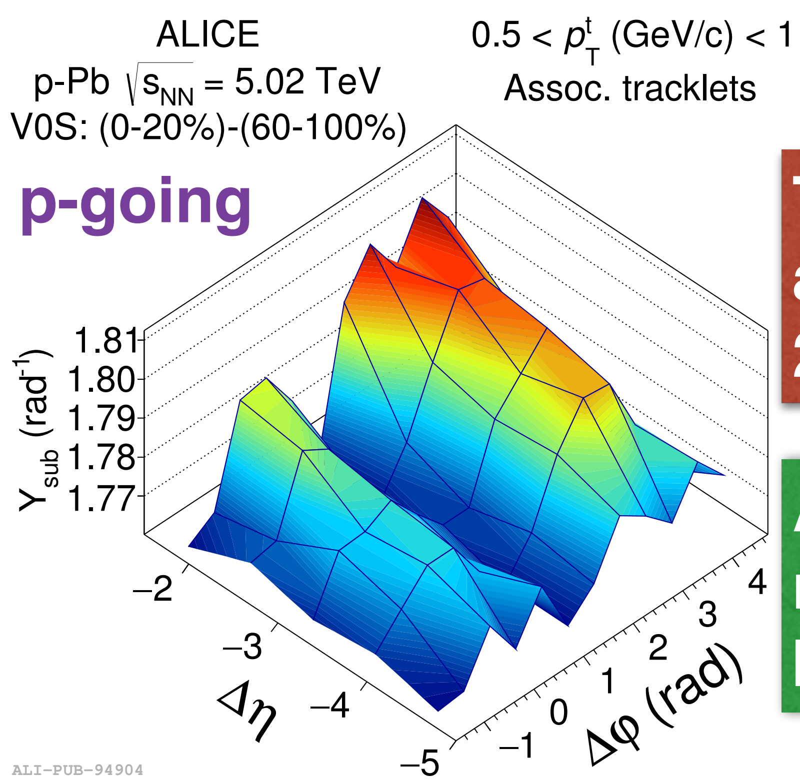


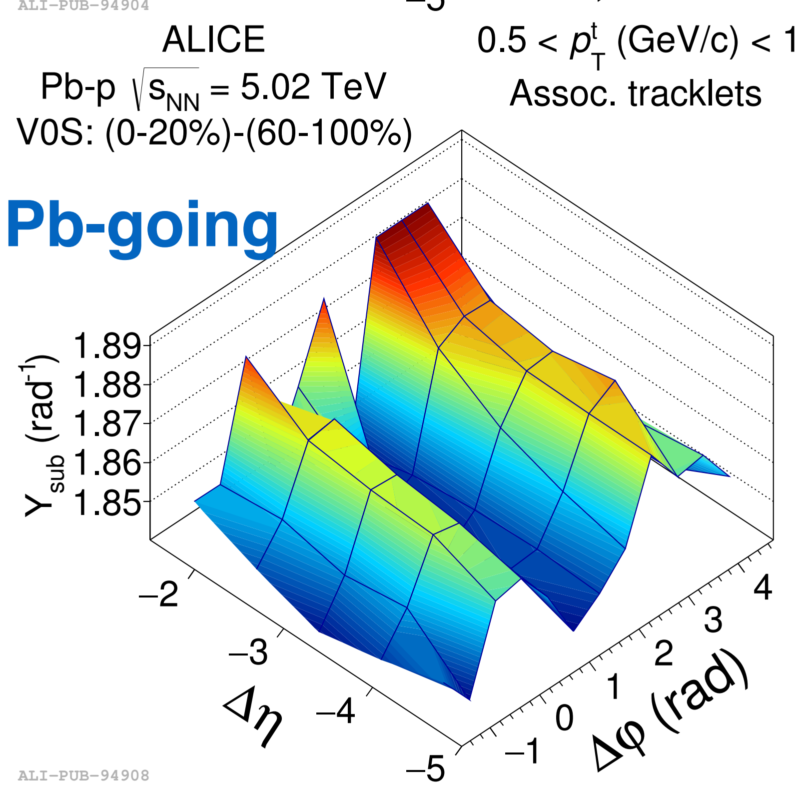
ALI-PREL-93799

Pb–Pb, 0-10%

Forward Muon Flow in p–Pb Collisions

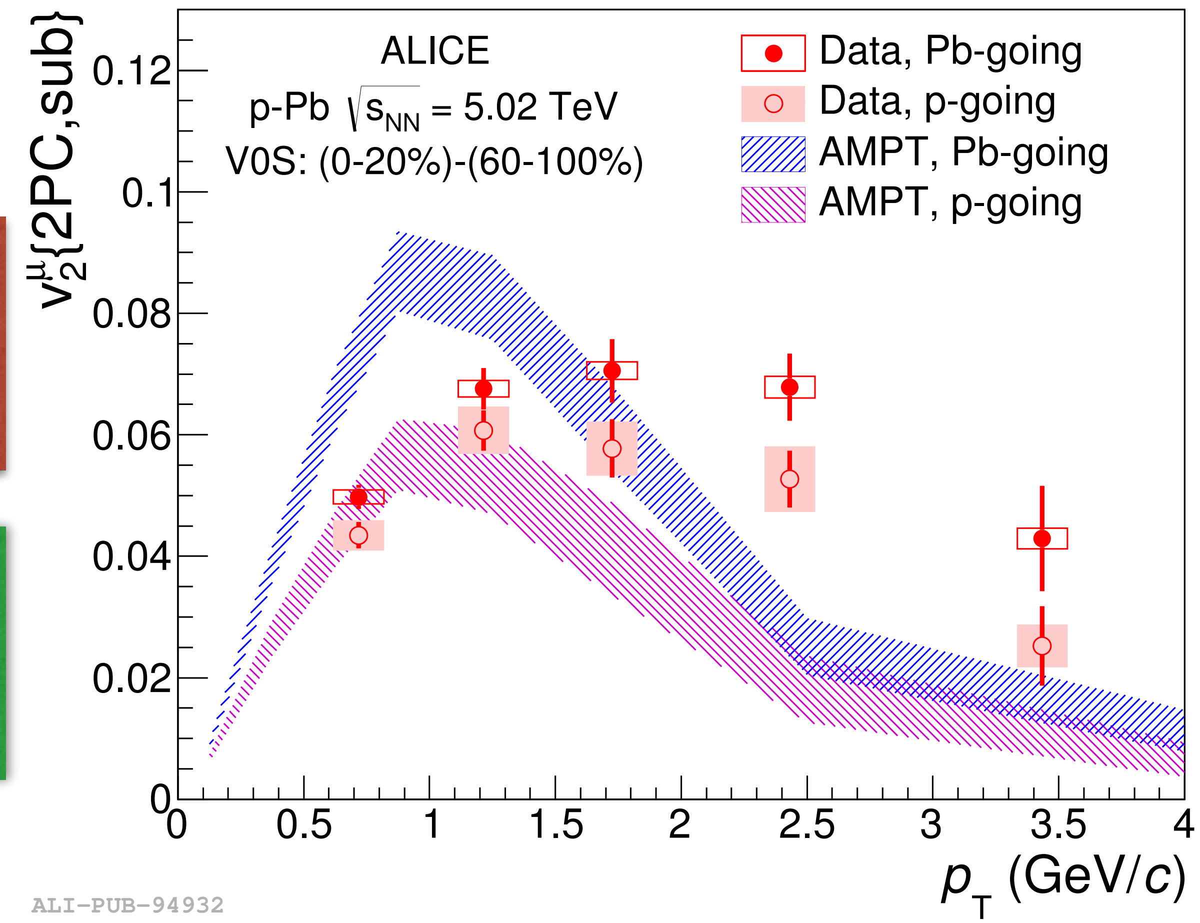
ALICE, Phys. Lett. B753 (2016) 126





Trigger particle: muon at forward rapidity 2.5<|η|<4

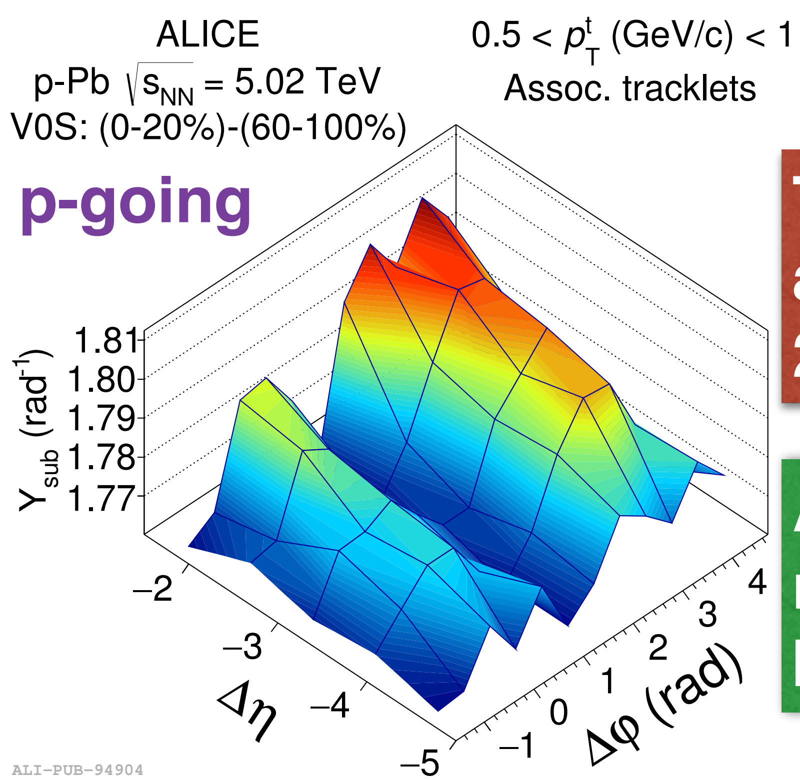
Associate particle: mid-rapidity tracklet |η|<1

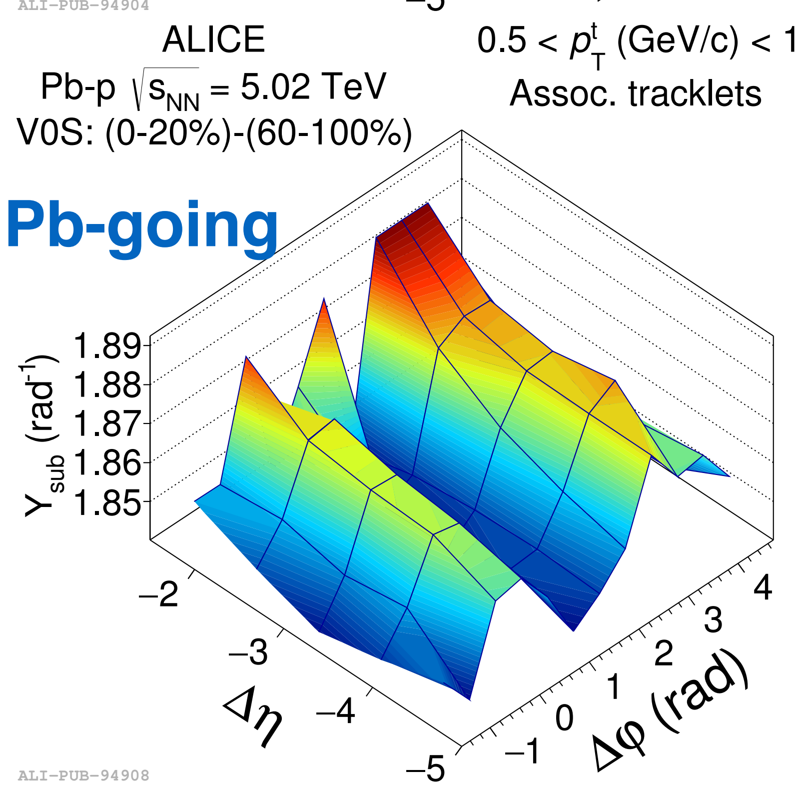


- Double ridge extends up to Δη ~ 5
- Inclusive muon v_2 on Pb-side is larger (~16%) than on p-side, qualitatively consistent with expectations from hydrodynamics (AMPT)

Forward Muon Flow in p–Pb Collisions

ALICE, Phys. Lett. B753 (2016) 126





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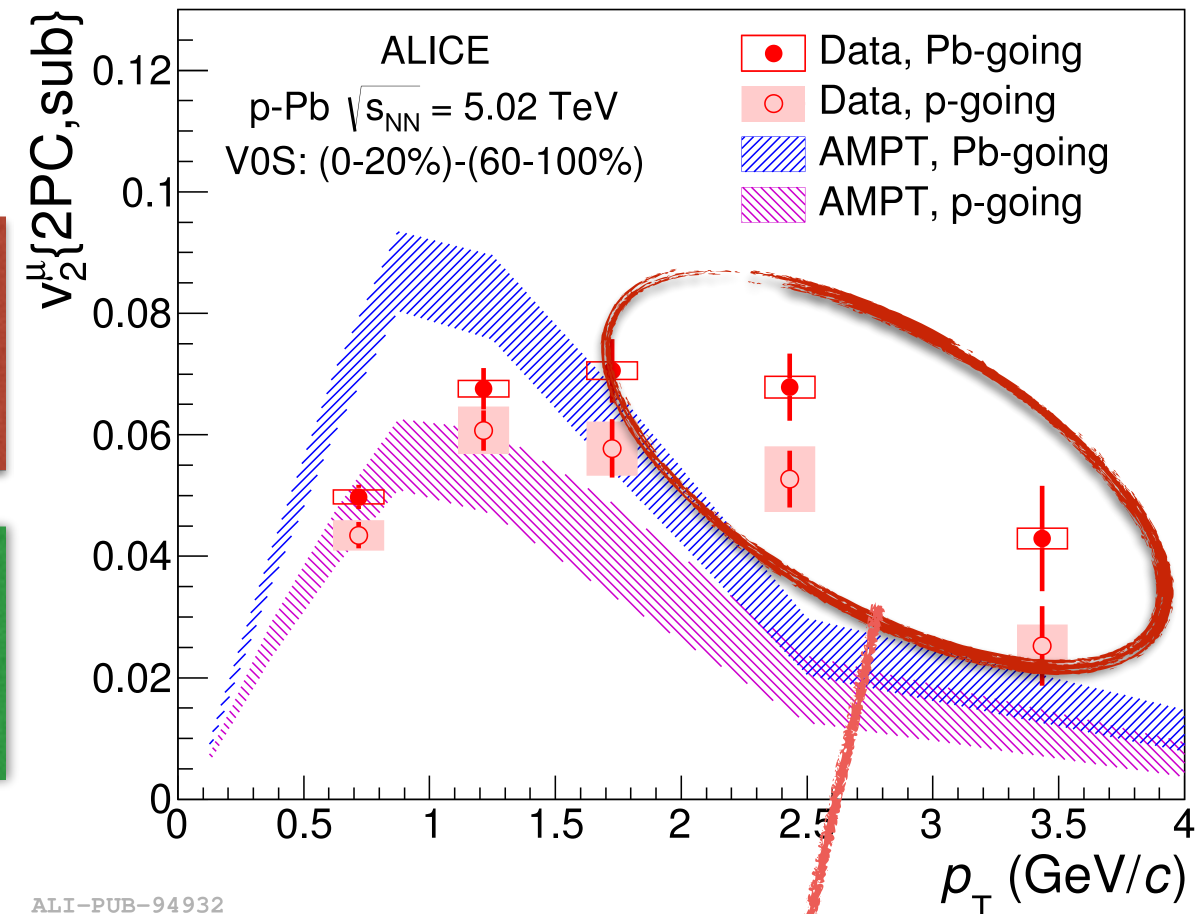
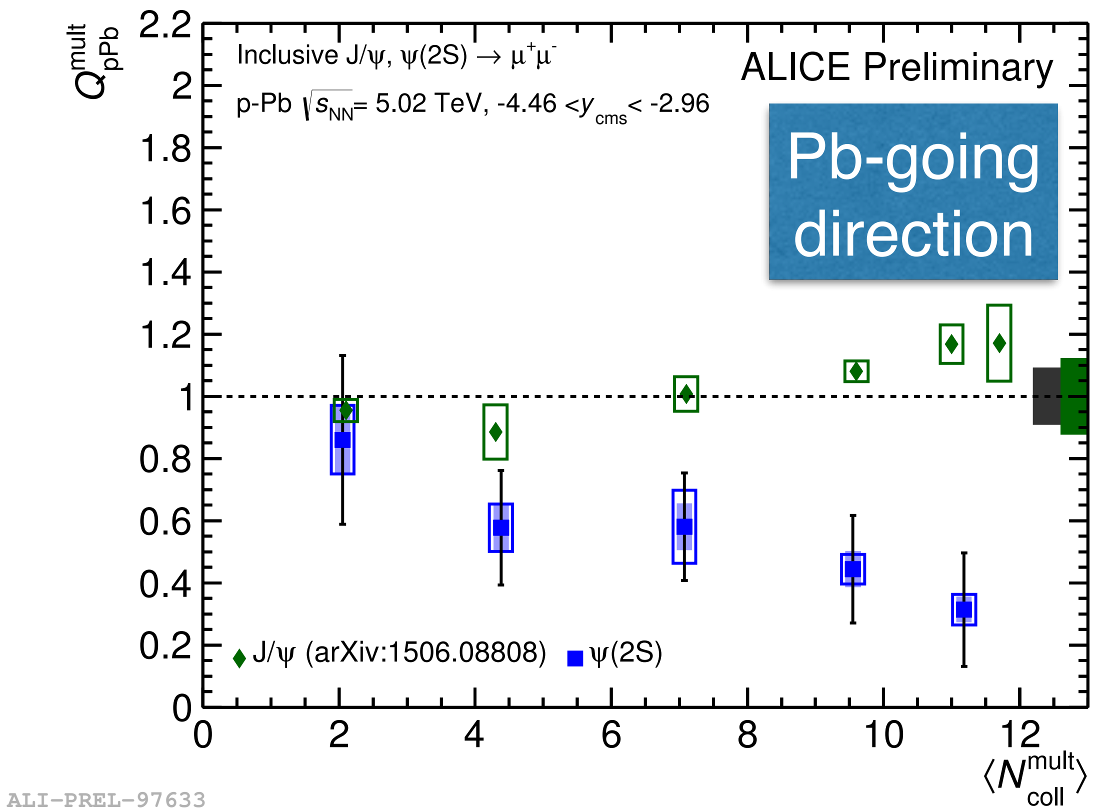
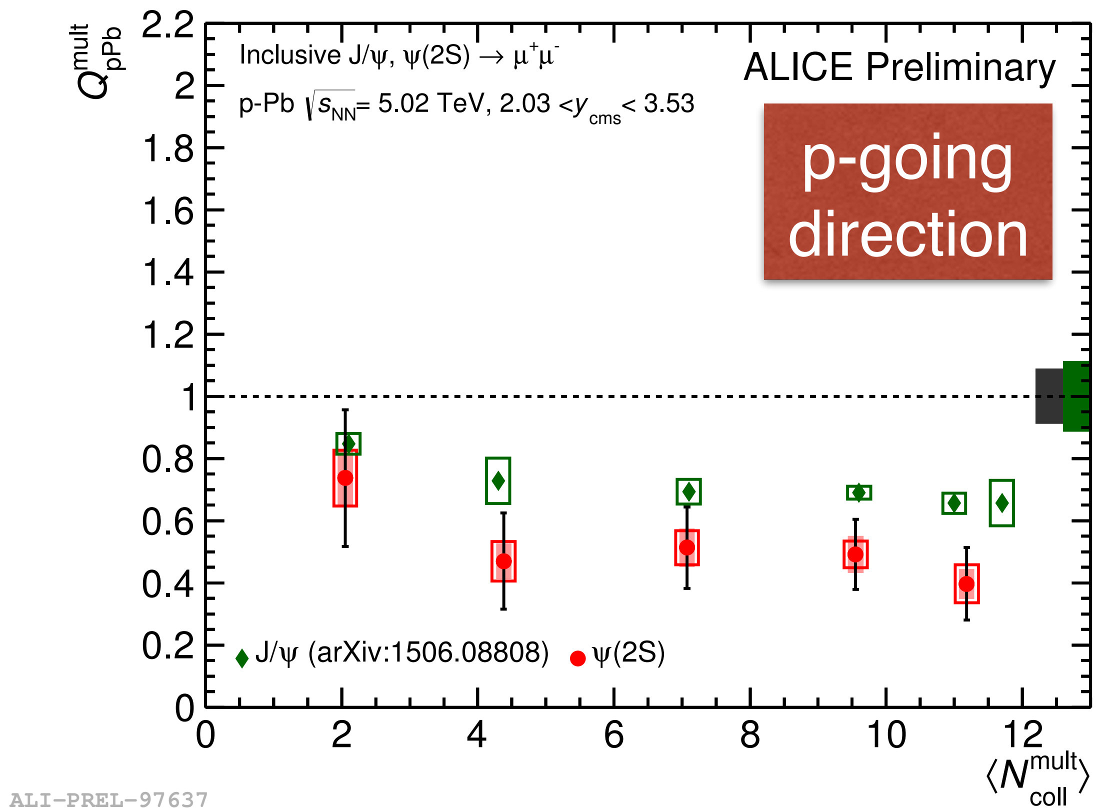


- Double ridge extends up to $\Delta\eta \sim 5$
- Inclusive muon v_2 on Pb-side is larger (~16%) than on p-side, qualitatively consistent with expectations from hydrodynamics (AMPT)
- p_T>2 GeV/c, dominated by (>60%) HF decay muons
  - Non-zero v_2 of HF muons as in Pb–Pb collisions (?)

Charmonia in p–Pb Collisions

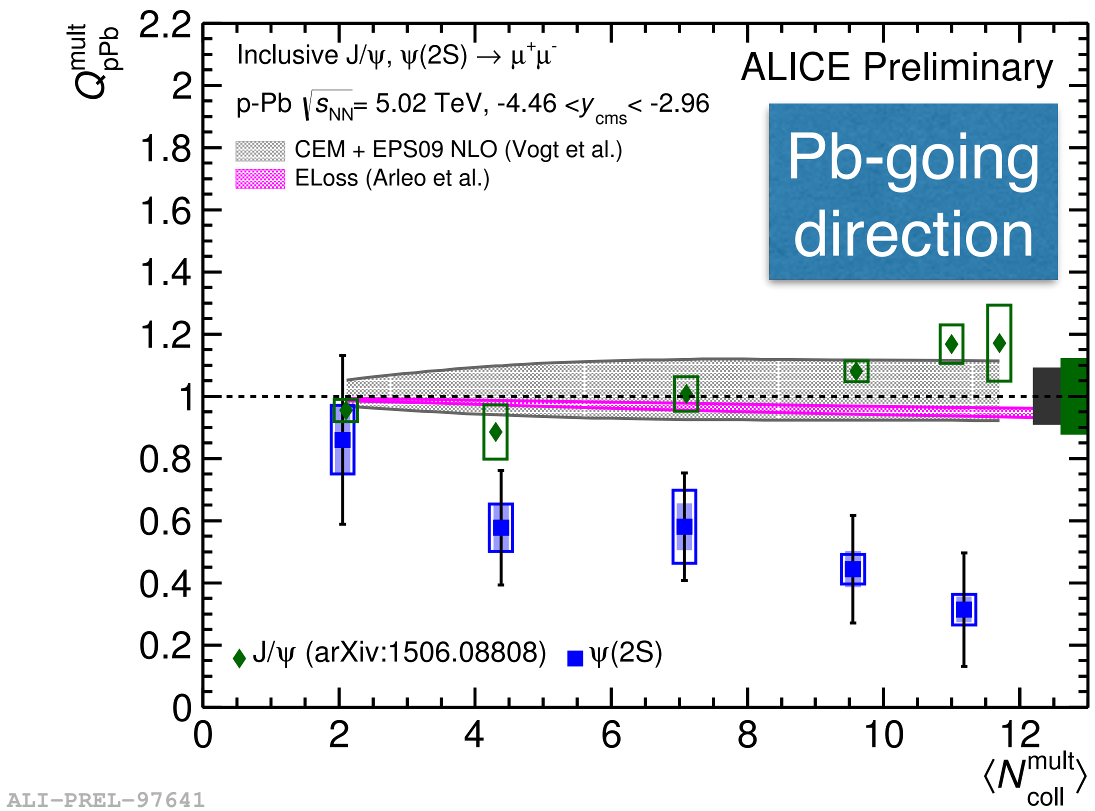
- J/ψ→μ⁺μ⁻ measured at forward/backward rapidities
- Pb-going direction: different trends for J/ψ and ψ(2*S*) — ψ(2*S*) suppressed
- p-going direction: Indication of smaller Q_{pPb} for ψ(2*S*) relative to J/ψ

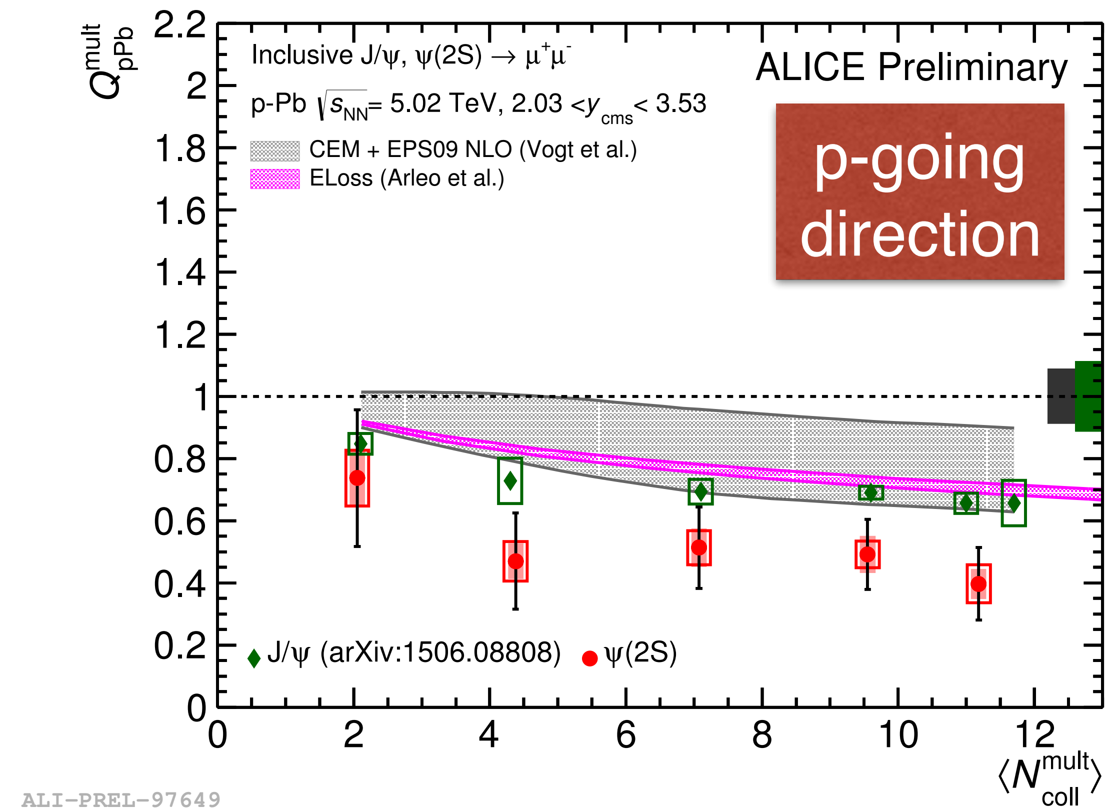




Charmonia in p–Pb Collisions

- $J/\psi \rightarrow \mu^+\mu^-$ measured at forward/backward rapidities
- Pb-going direction: different trends for J/ψ and $\psi(2S)$ — $\psi(2S)$ suppressed
- p-going direction: Indication of smaller Q_{pPb} for $\psi(2S)$ relative to J/ψ
- Models with only CNM effects (shadowing, *E* loss) do not describe $\psi(2S)$





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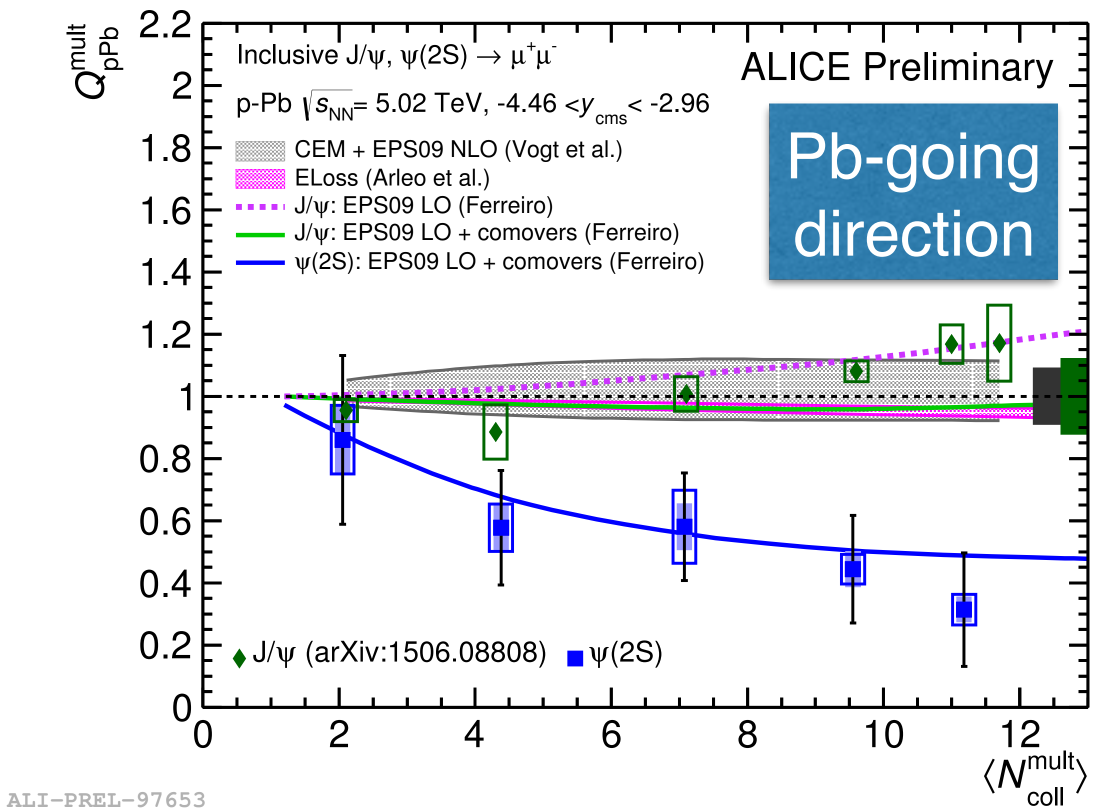
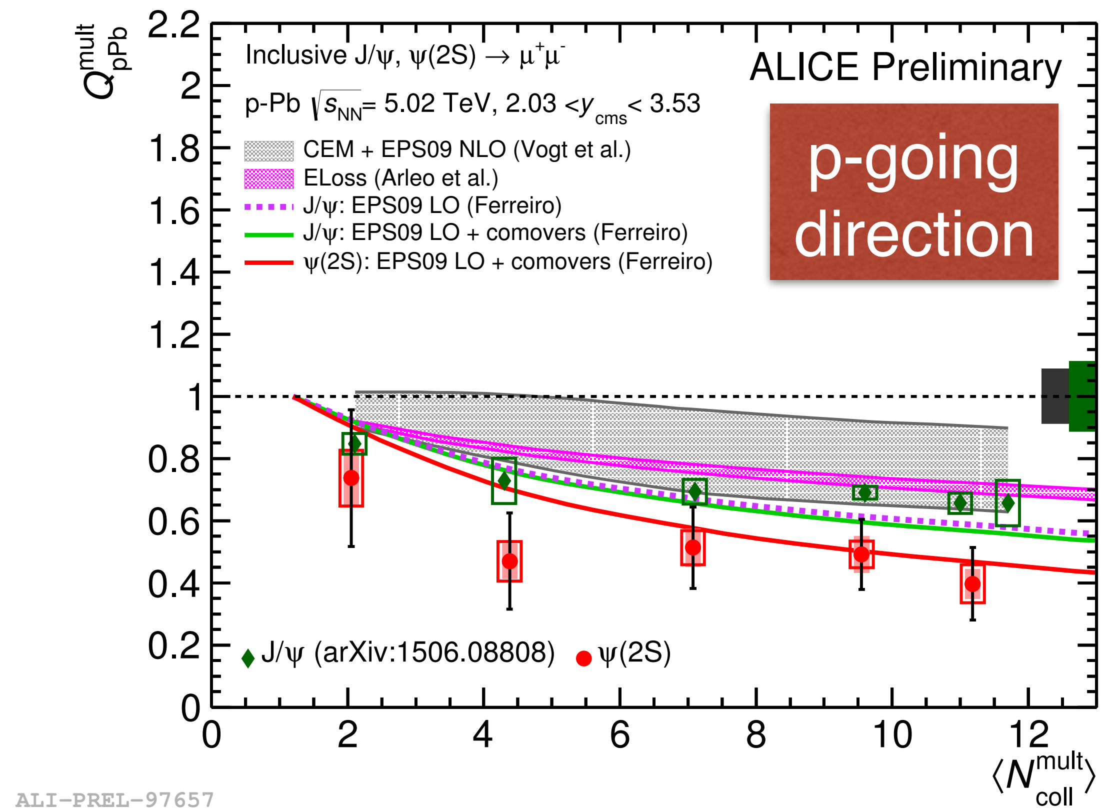
- Break-up due to interactions with hadronic resonance gas ("comovers") is a possible explanation for ψ(2*S*) suppression





Charmonia in p–Pb Collisions

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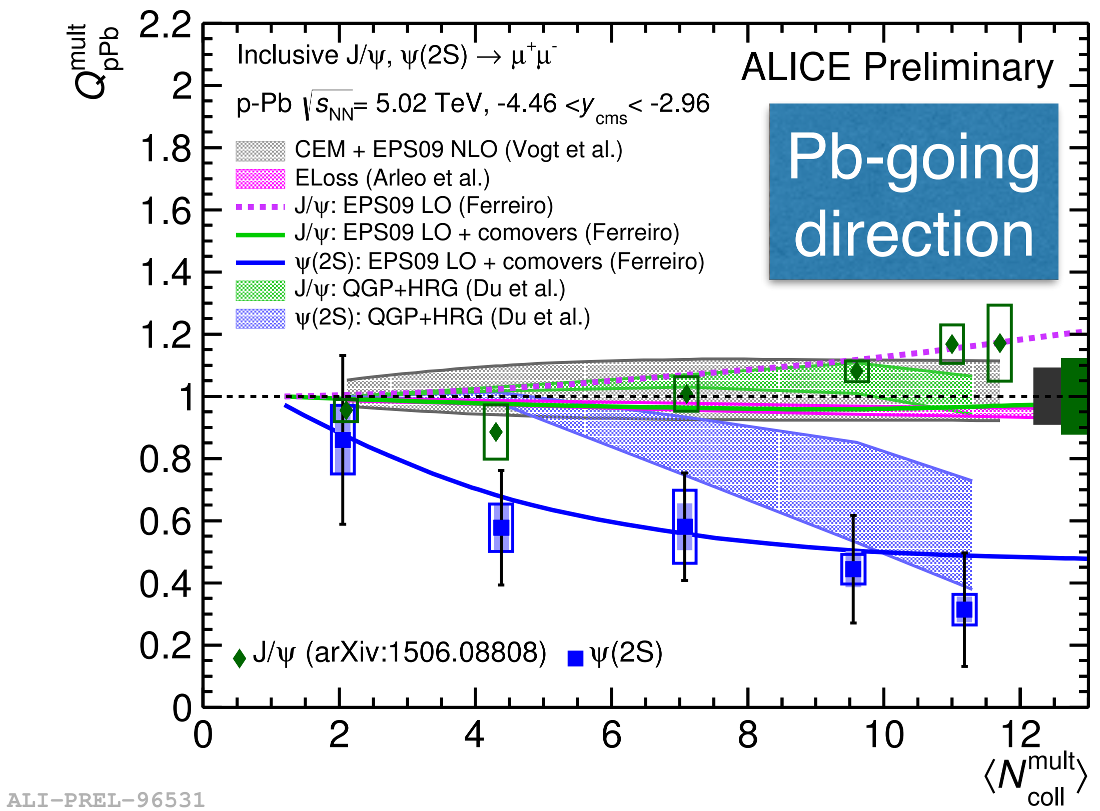
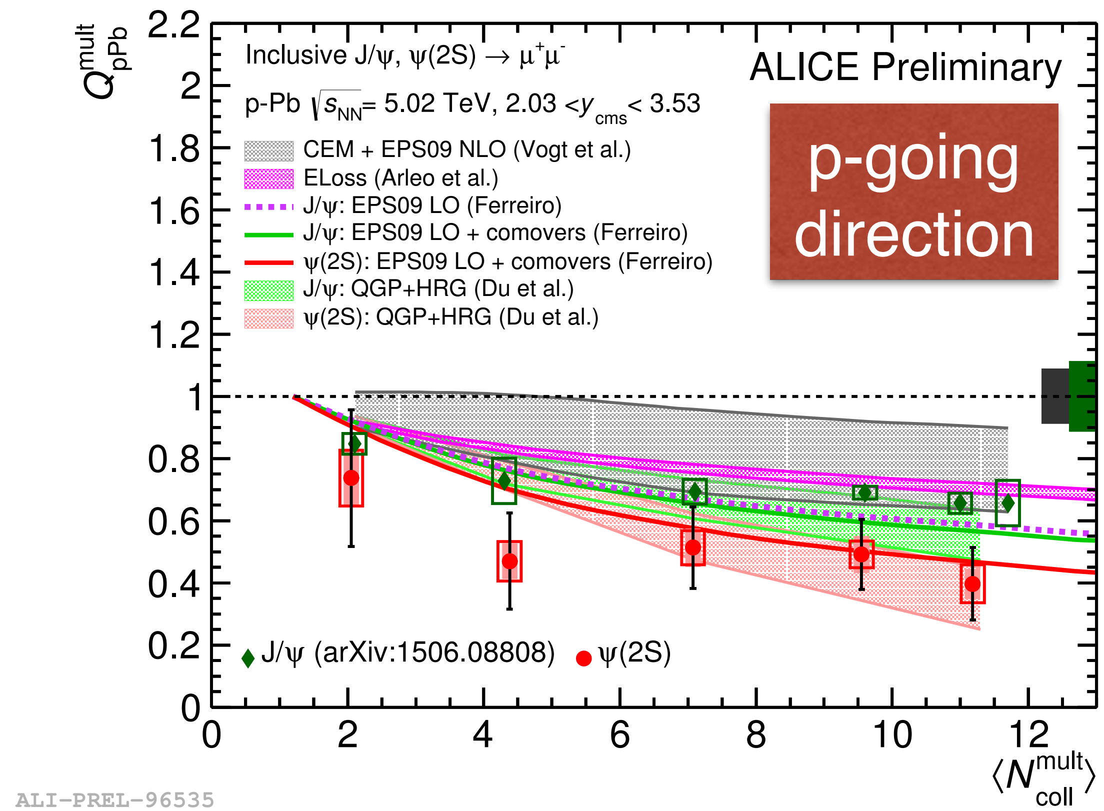
- Models with only CNM effects (shadowing, *E* loss) do not describe ψ(2*S*)
- Break-up due to interactions with hadronic resonance gas ("comovers") is a possible explanation for ψ(2*S*) suppression
- Models with QGP and Hadron Resonance Gas in fair agreement with data





Conclusion

- Pb–Pb Collisions
  - Confirm CTP invariance in light nuclei
  - Excess of low-p_T γ: $T_{eff} \approx 304$ MeV — 30% higher than at RHIC
  - v_m–v_n correlations, identified particle v_n and ESE— new constraints for bulk property
  - Open heavy flavours: mass dependence of parton in-medium energy loss, collective motion of heavy quarks at both mid- and forward rapidity
  - Jet shapes: jets are more collimated and more p_T dispersion in Pb–Pb collisions
  - New observable: sub-jet structure — sensitive to quenching details and robust against heavy-ion background
- Small systems
  - Strong suppression observed in central Pb–Pb collisions is due to the QCD medium
  - Λ/K_S^0 ratio in jets: disfavor the soft-hard recombination mechanism
  - Non-zero v_2 of heavy-flavour decay muons as in Pb–Pb collisions (?)
  - Initial-state effects not sufficient to describe ψ(2*S*) production

In Progress…

- Pb–Pb Collisions
  - Confirm CTP invariance in light nuclei
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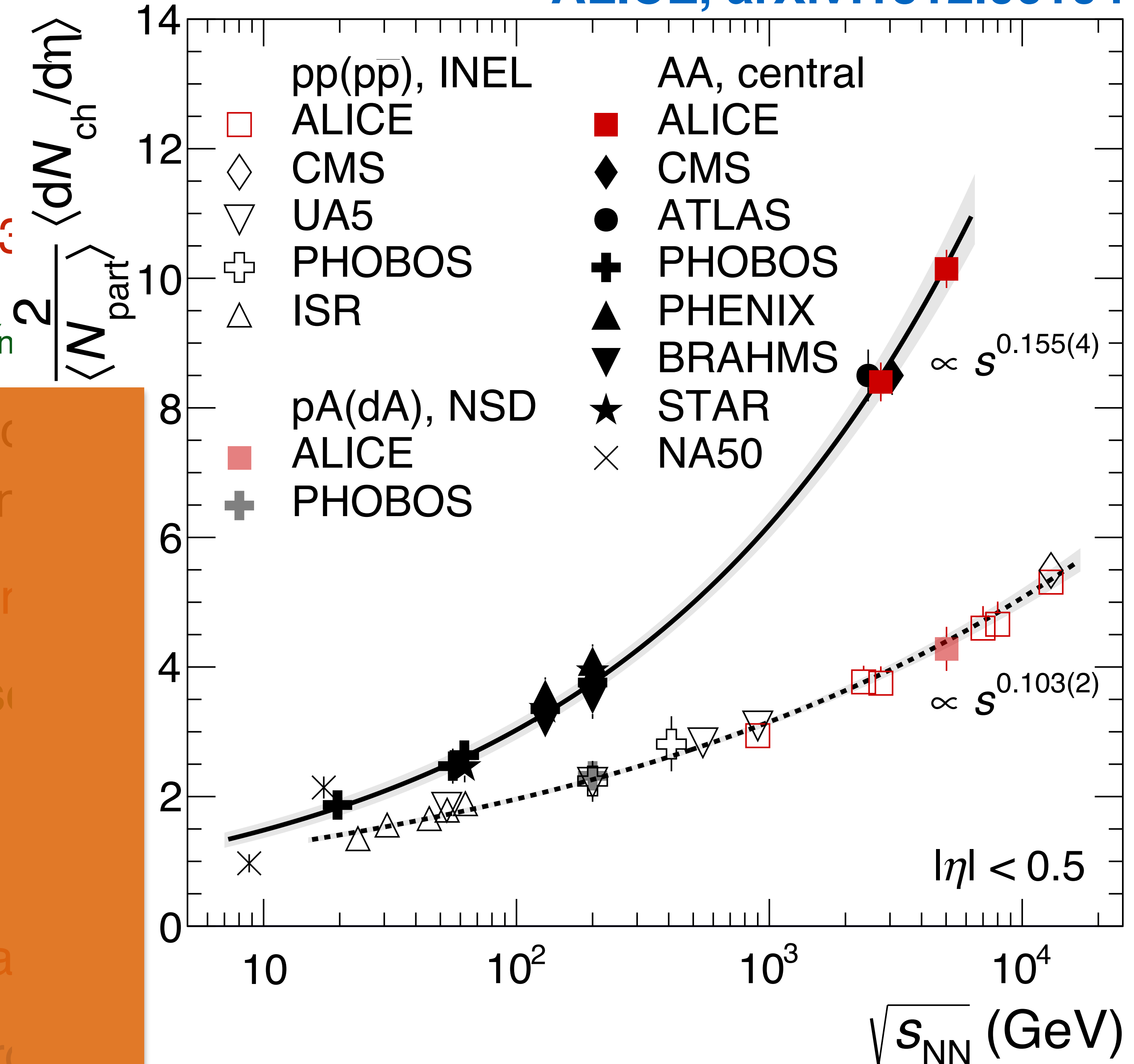
  - Non-zero v_2 of heavy-flavour decay muons as in Pb–Pb collisions (?)
  - Initial-state effects not sufficient to describe ψ(2S) production

- **LHC RUN-II**
  - **Pb–Pb at $\sqrt{s_{NN}}$=5.02 TeV**
  - **Higher collision energy and luminosity relative to RUN-I**
  - **Upgrade of EM calorimeter and tracker**
  - **Better conditions to access the deconfined matter**
  - **More precise measurements will come soon**

ALICE, arXiv:1512.06104



In Progress…

- Pb–Pb Collisions
  - Confirm CTP invariance in light nuclei
  - Excess of low-p_T γ: T_{eff} ≈ 304 MeV — 30% higher than at RHIC
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Thanks for your attention!

  - Strong suppression observed in central Pb–Pb collisions is due to the QCD medium
  - Λ/K_S^0 ratio in jets: disfavor the soft-hard recombination mechanism
  - Non-zero v_2 of heavy-flavour decay muons as in Pb–Pb collisions (?)
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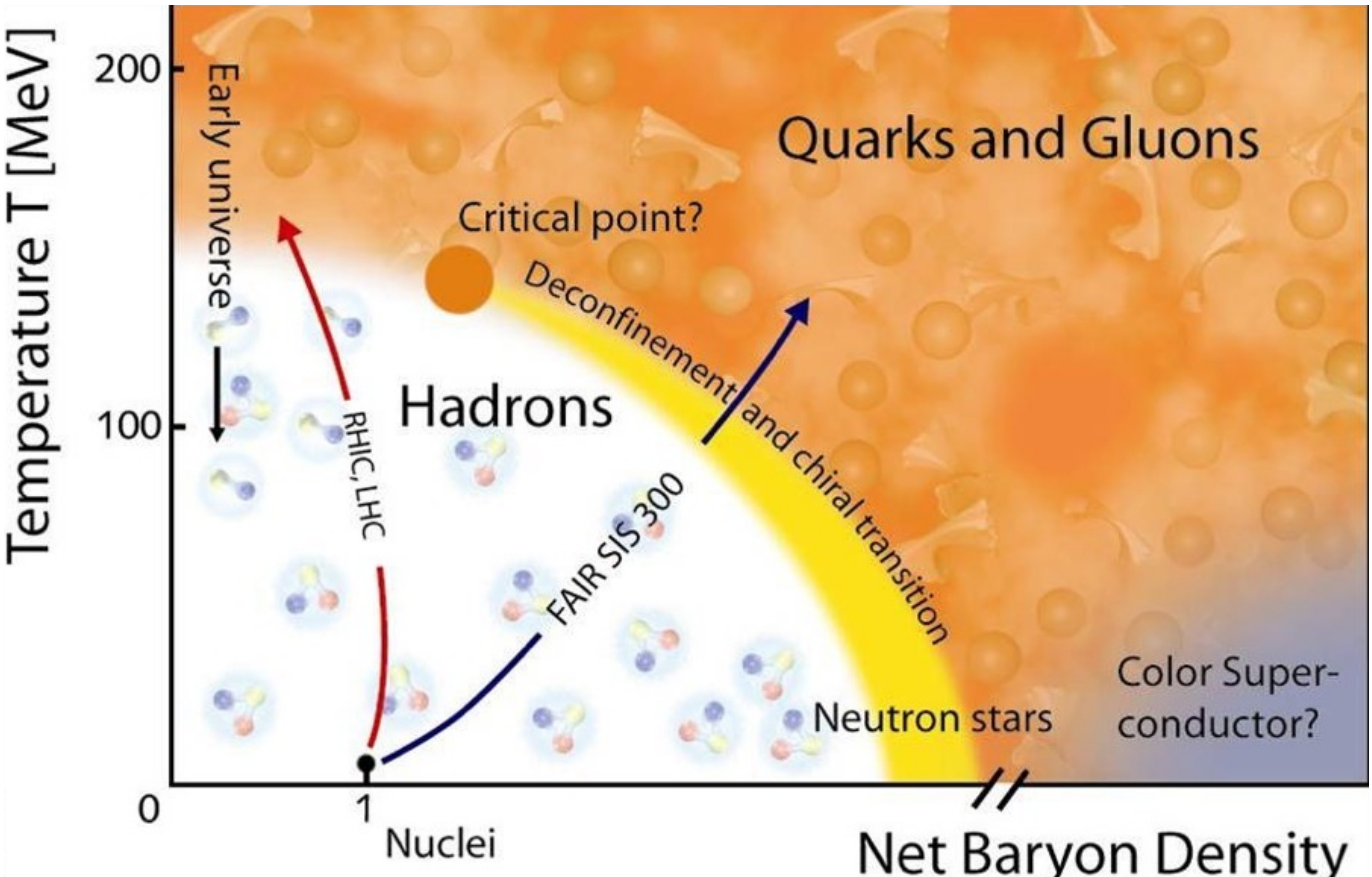
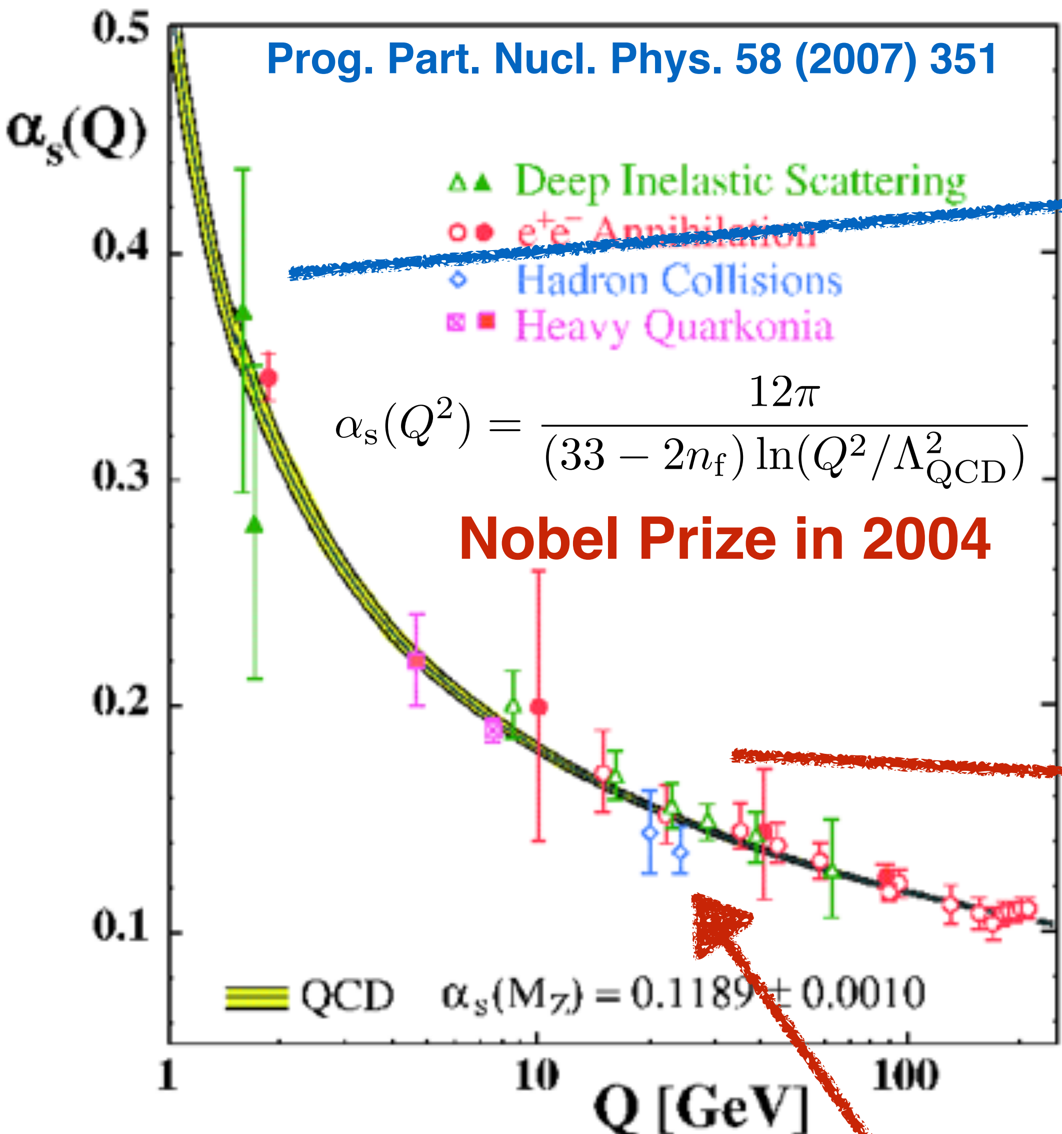
Backup

QCD Phase Diagram

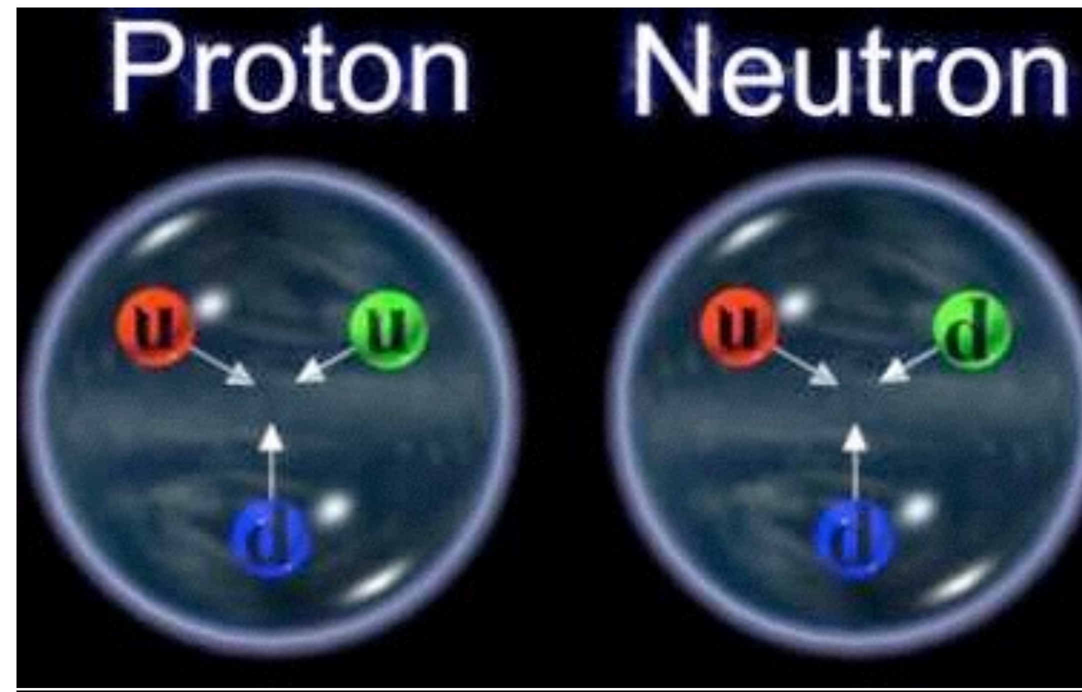


QCD Phase Transition

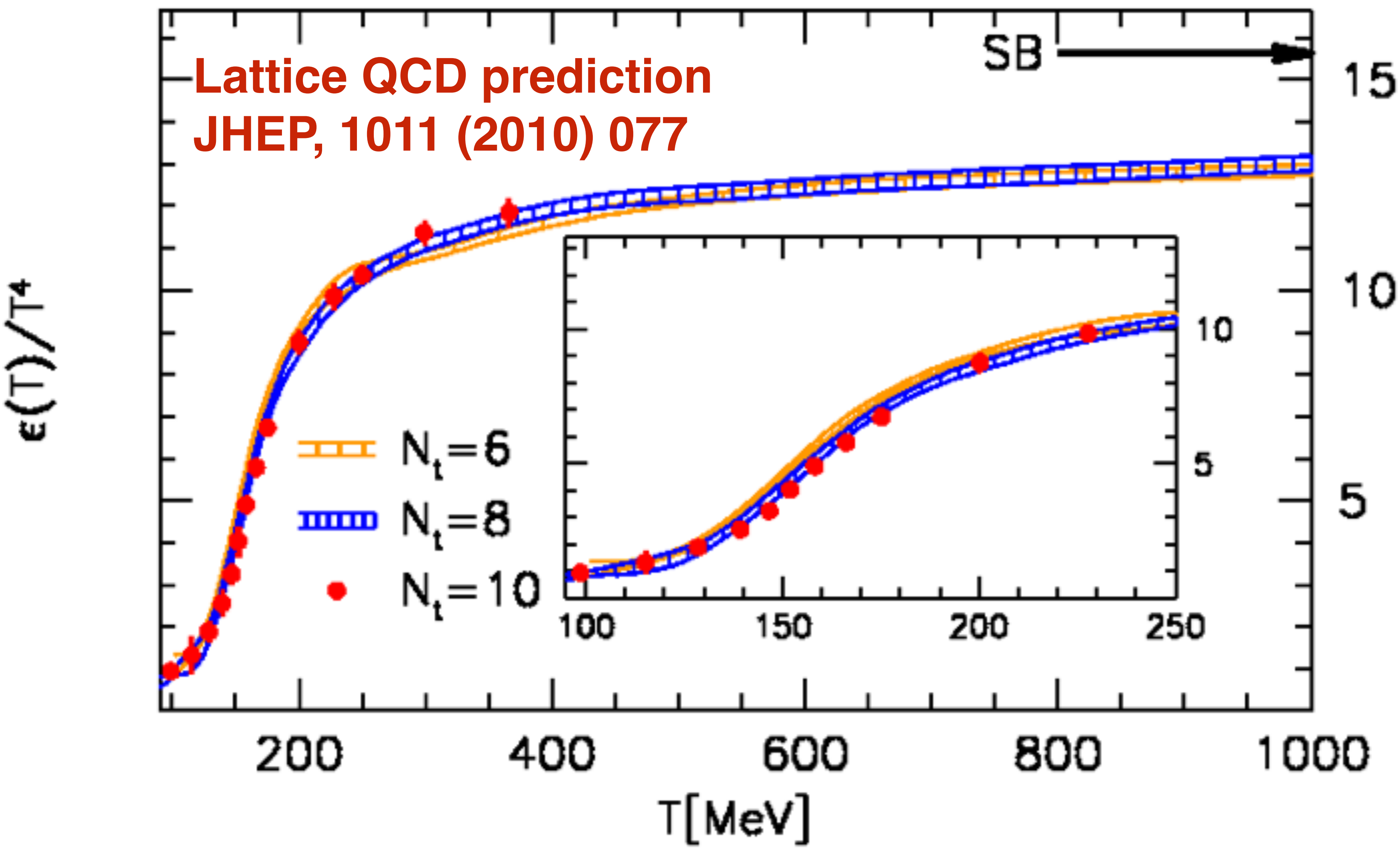
$$\mathcal{L} = \sum_q \overline{\psi}_{q,a}(i\gamma^\mu\partial_\mu\delta_{ab} - g_s\gamma^\mu t^C_{ab}\mathcal{A}^C_\mu - m_a\delta_{ab})\psi_{q,b} - \frac{1}{4}F^A_{\mu\nu}F^{A,\mu\nu}$$



Asymptotic freedom



QCD Phase Transition

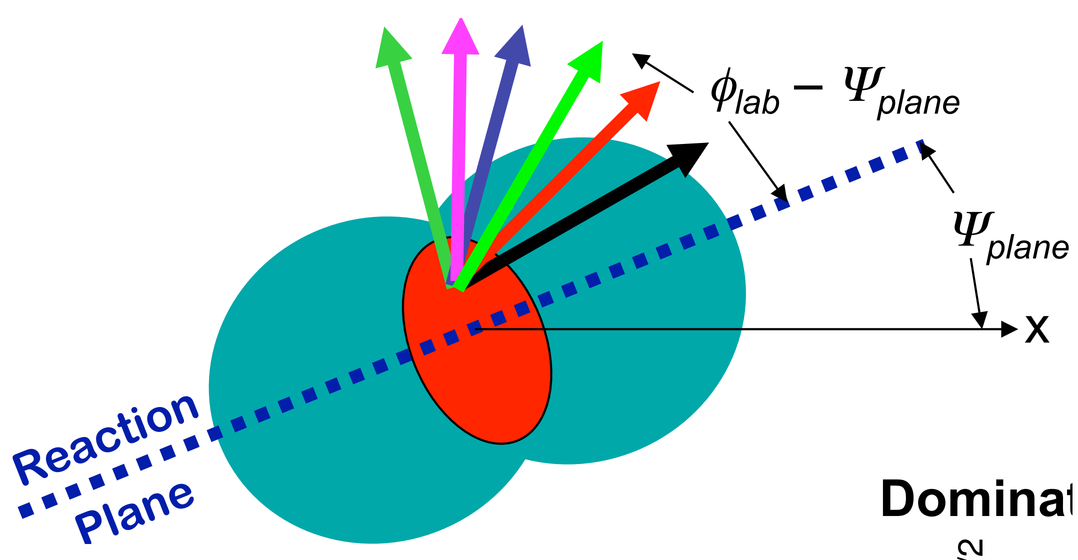


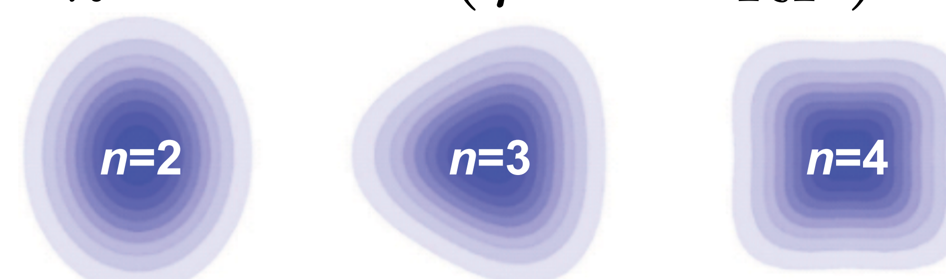
- Sharp increase of energy density around T_c = 170 MeV indicates a phase transition from hadronic matter to decomfined Quark Gluon Plasma (QGP)

Azimuthal Anisotropy

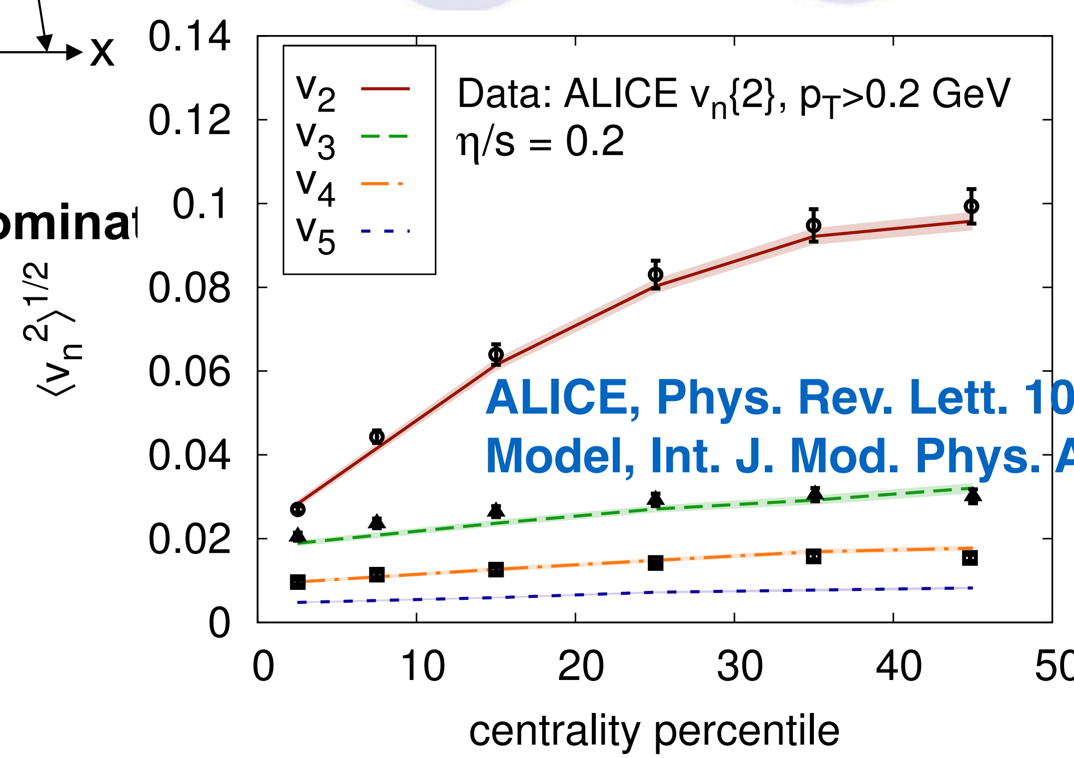
- Quantify anisotropy: Fourier decomposition of particle azimuthal distribution relative to reaction plane (Ψ_{RP}) — coefficients v_2, v_3, v_4… v_n
- Elliptic flow (v_2): spatial anisotropy to momentum anisotropy — large pressure gradients more particle emitted in plane — Hydrodynamic
- Higher order flow: with additional constraints on the initial conditions, η/s, EoS, freeze-out conditions…

$$v_n = < \cos(\varphi - \Psi_{RP}) >$$





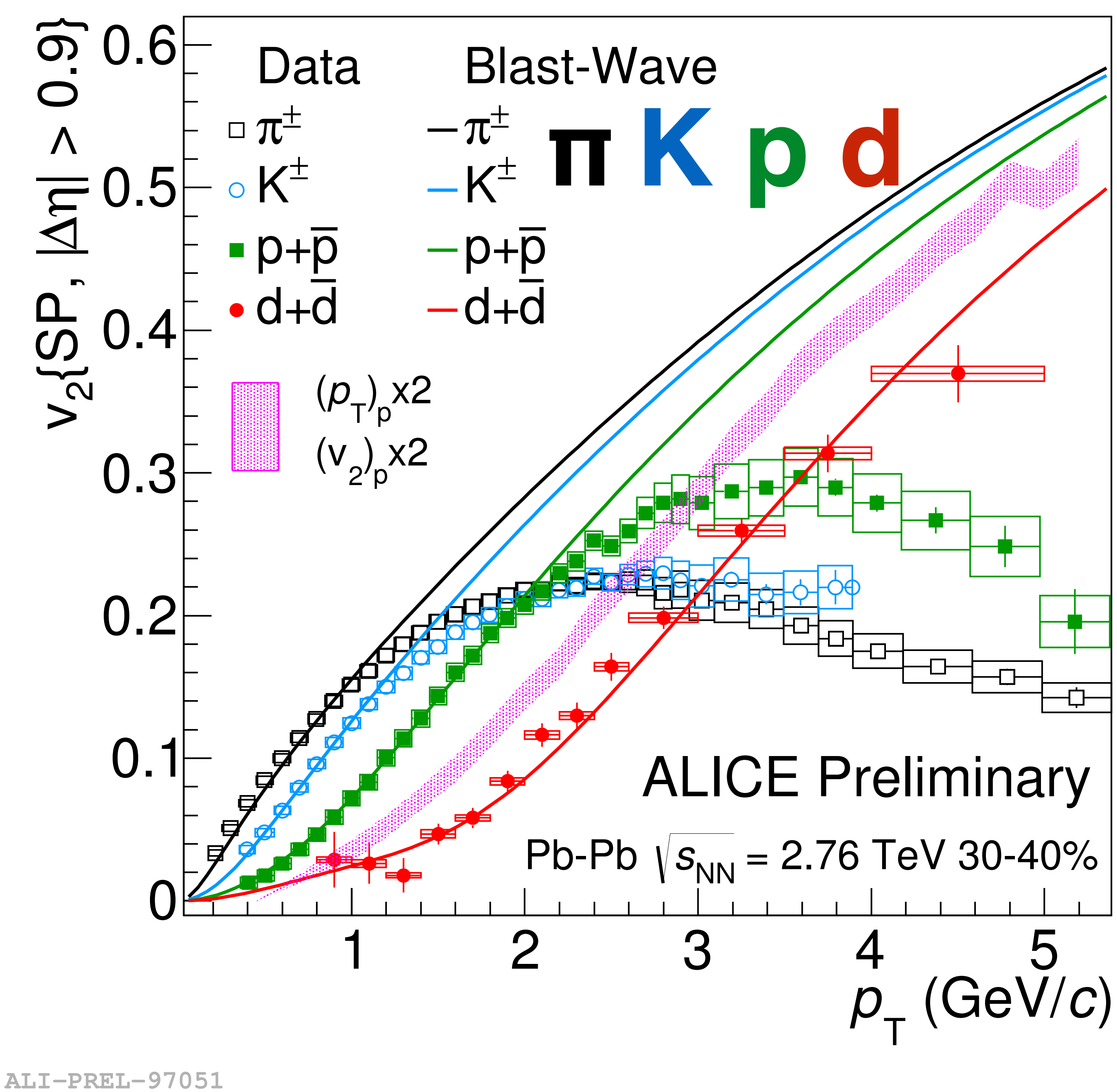
Dominat



ALICE, Phys. Rev. Lett. 107 (2011) 032301
Model, Int. J. Mod. Phys. A28 (2013) 1340011

- ALICE has measured charged particle anisotropic flow up to v5
    - Constraints on η/s = 0.2

Elliptic Flow of (Anti-)Deuterons



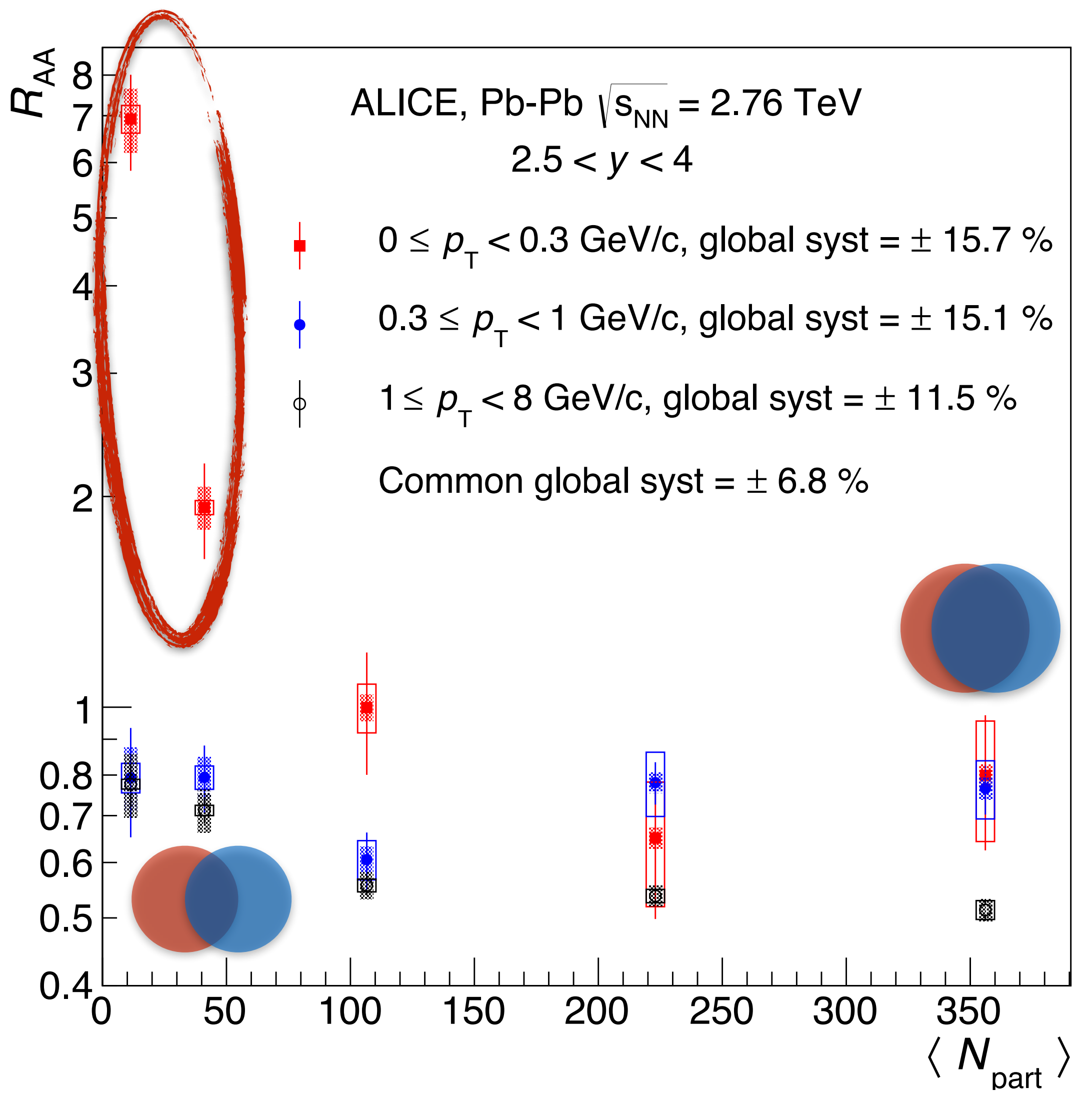
- Blast-Wave model: based on hydrodynamics
  - Predicts deuteron v_2 with parameters obtained by fitting measured π, K, p v_2 and p_T-spectra
- Simple coalescence model: compute the expected deuteron v_2 by using measured v_2 of protons
  - Reverse the n_q scaling:

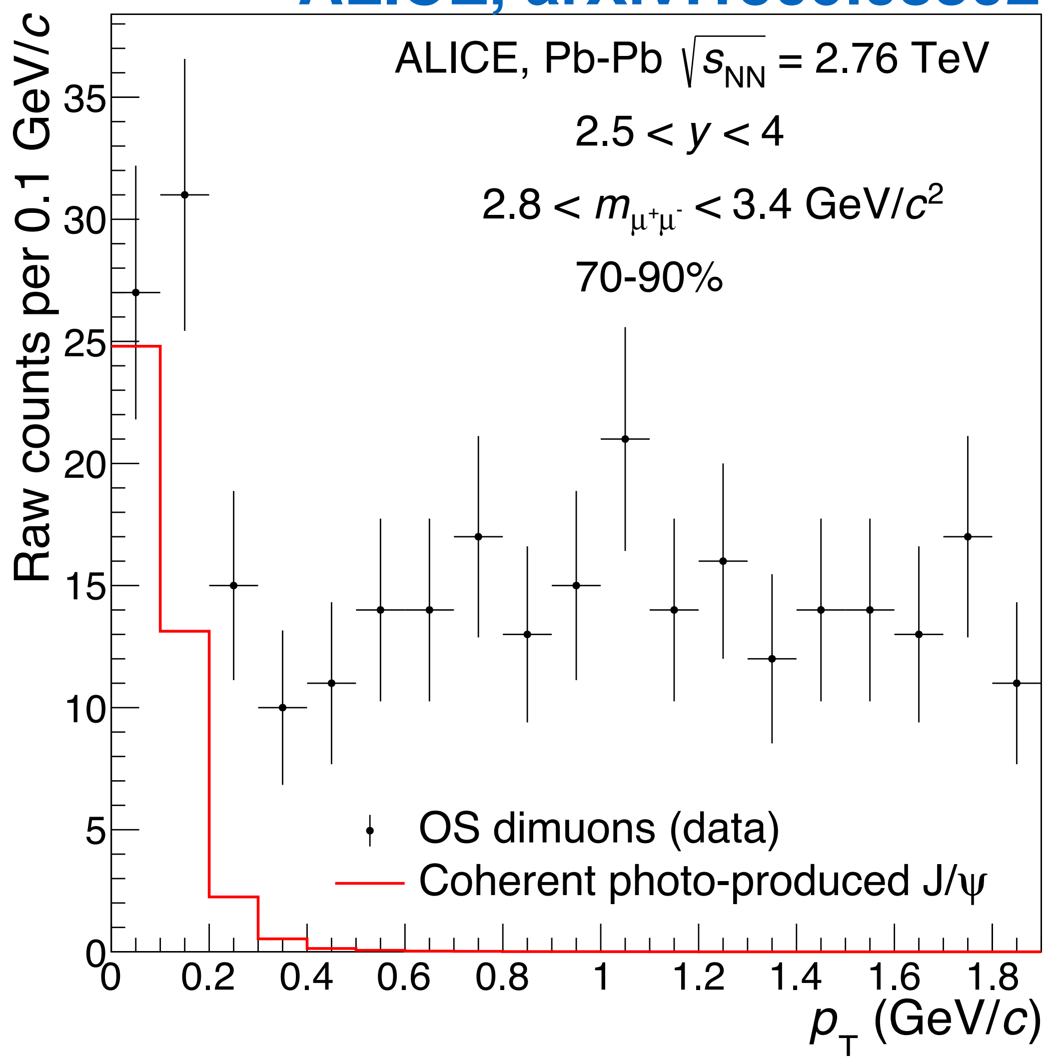
$$v_{2,d} = 2v_{2,p}(2p_T)$$

- Low-p_T (p_T<2 GeV/c): deuteron flow follows mass ordering — indicates a more pronounced radial flow in most central collisions
- Well described by Blast-Wave model, ~20% deviation from the simple coalescence estimation was observed

Excess of Low-p_T J/ψ

ALICE, arXiv:1509.08802





- Strong excess of very low p_T (0-0.3 GeV/c) J/ψ in peripheral collisions
  - R_{AA} ~ 7 (2) in 70-90% (50-70%) centrality class
- Hypothesis: coherent photo-production of J/ψ in Pb–Pb collisions
  - STARLIGHT calculation in ultra-peripheral collisions in good qualitative agreement