Overview of ALICE results

Biased selection: new & most interesting

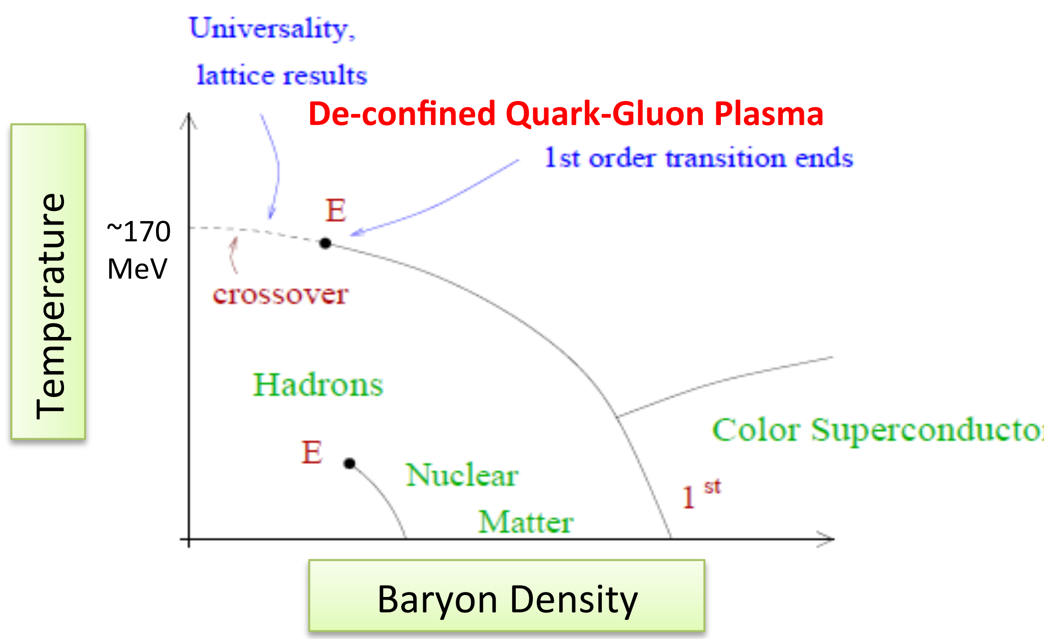
Mateusz Płoskoń

ALICE Collaboration

Hot QCD in laboratory
=> Heavy-ion collisions at the LHC

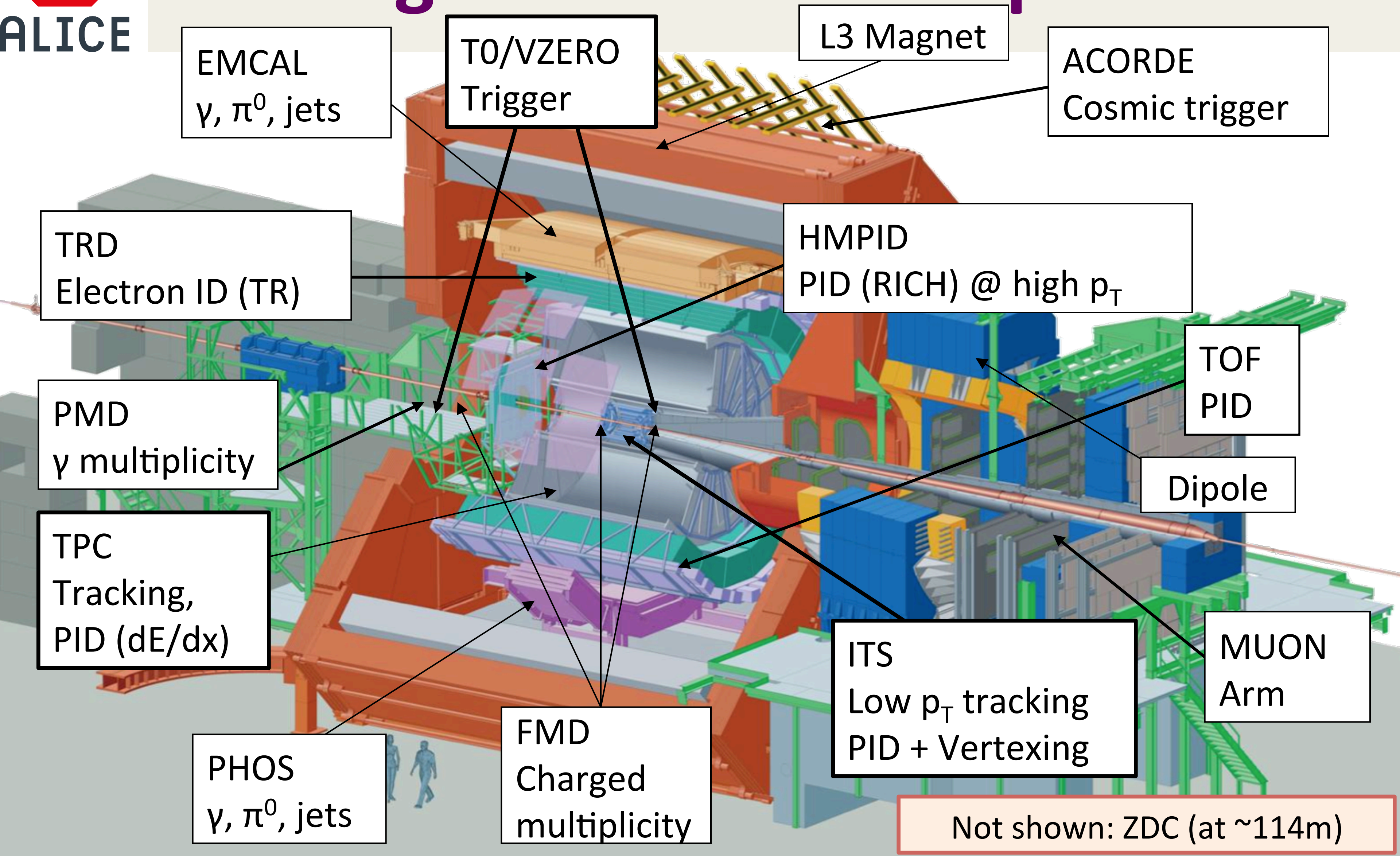
- QCD (lattice) predicts a phase transition from hadronic matter to a deconfined phase at high temperatures
- QGP at μ~0 similar to early Universe (~few first μs)
- First signals of QGP from SPS and RHIC
- LHC: detailed studies of QGP exploiting wealth and abundance of [hard] probes (heavy-quarks, jets, quarkonia…)

QCD phase diagram



<u>LHC – a new era of high-precision measurements</u>

A Large Ion Collider Experiment



Outline

Systems:

- Proton-proton
- p-Pb
- Pb-Pb

- Outline of this talk:
  - Selected subjects from soft and hard probes
  - Focus on p-Pb and signatures of collective effects
  - Summary

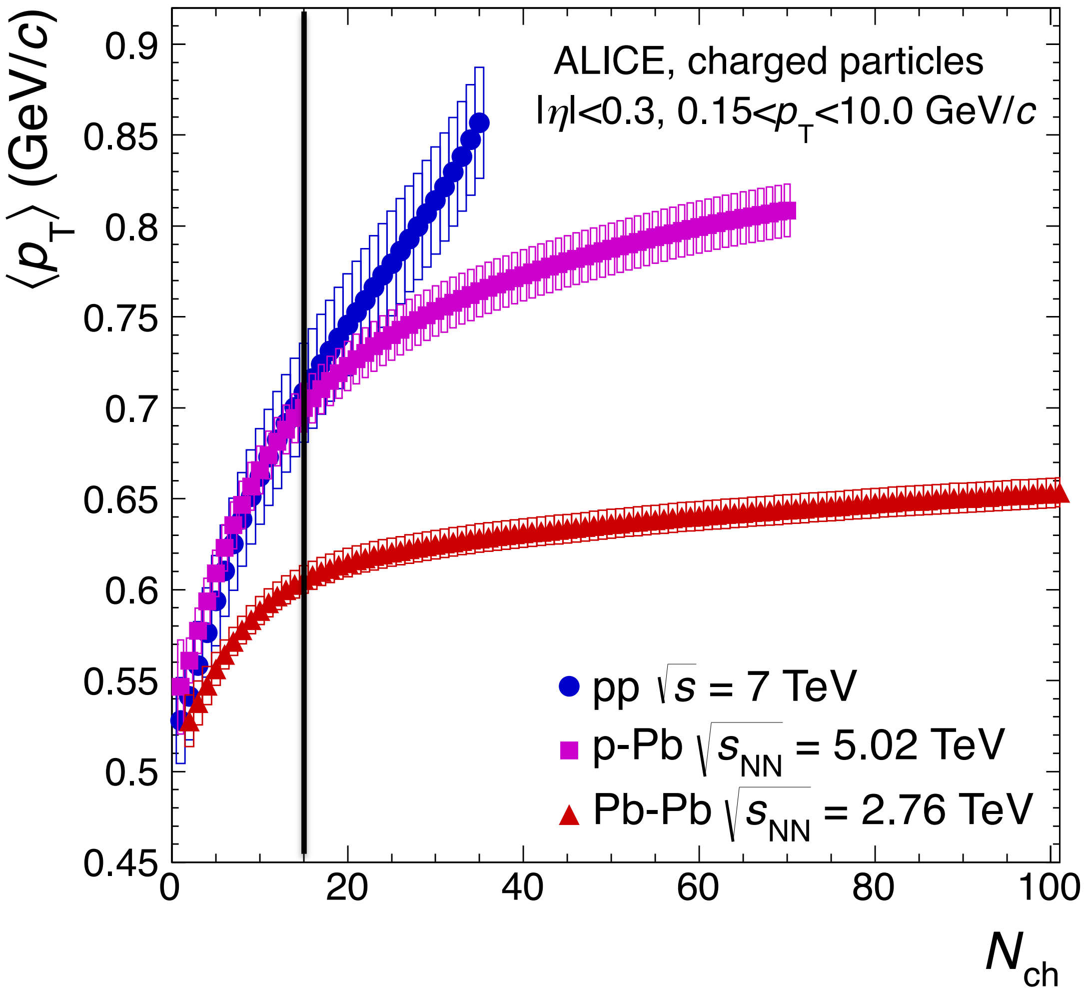
Properties & Tools

- Global event / system properties:
  - Inclusive spectra; Identified particles; mean p_T; "Blast-wave" fits (T, collective velocity)
- Collective effects
  - Correlations, flow coefficients, v_2, v_3 (propagation / energy dissipation)
- Heavy-flavour – energy loss and thermalization
  - Production vs. multiplicity; suppression and v_2
- Quarkonia – QGP vs. Cold Nuclear Matter
  - Production vs. multiplicity; suppression in Pb-Pb; v_2; suppression/enhancement in pA
- Jets
  - R_{AA} – inclusive production in pp and AA; jet structure; test of N_{binary} scaling in min. bias pPb

GLOBAL EVENT PROPERTIES

Global event properties: mean p_T vs. multiplicity

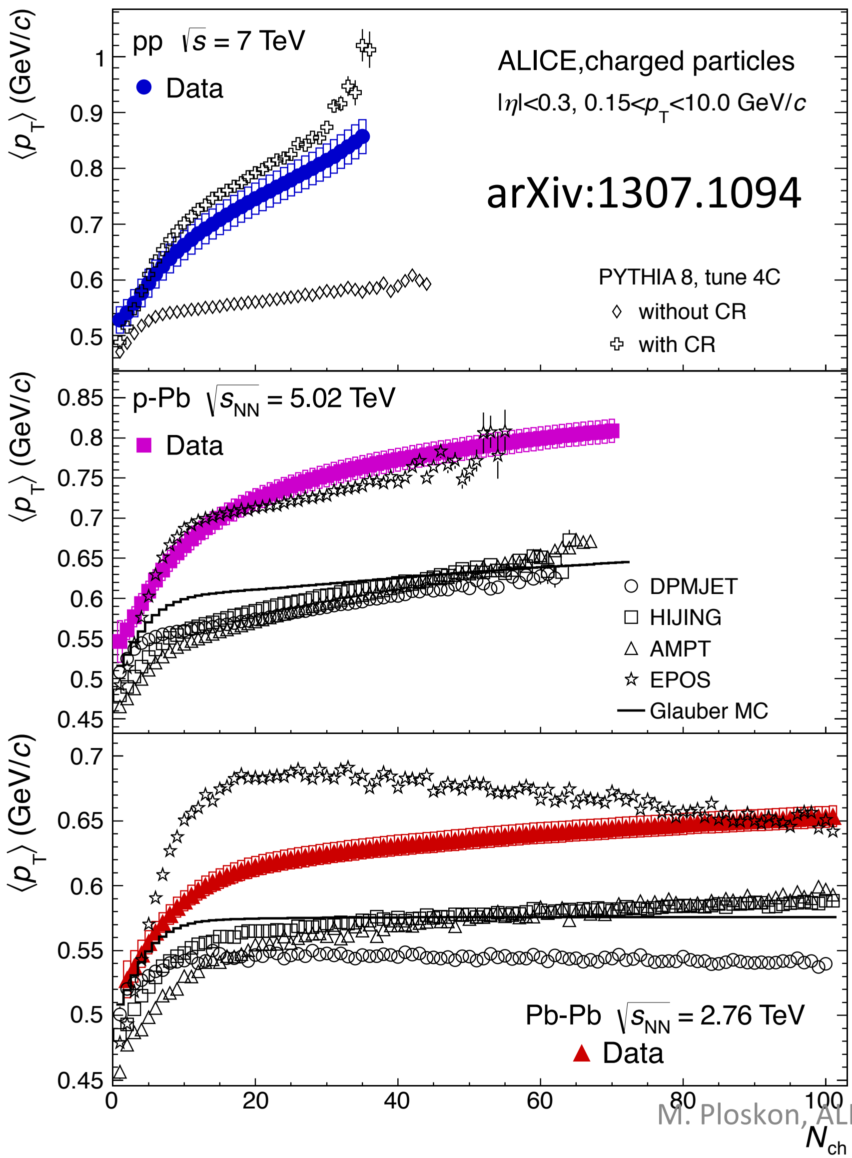
arXiv:1307.1094



Proton-proton and pPb follow the same trend up to **Nch~15**; however: this is **90% of pp x-section and 50% of pPb x-section** (different biases)

pp and pPb – much stronger increase than in PbPb

Global event properties: mean p_T vs. multiplicity



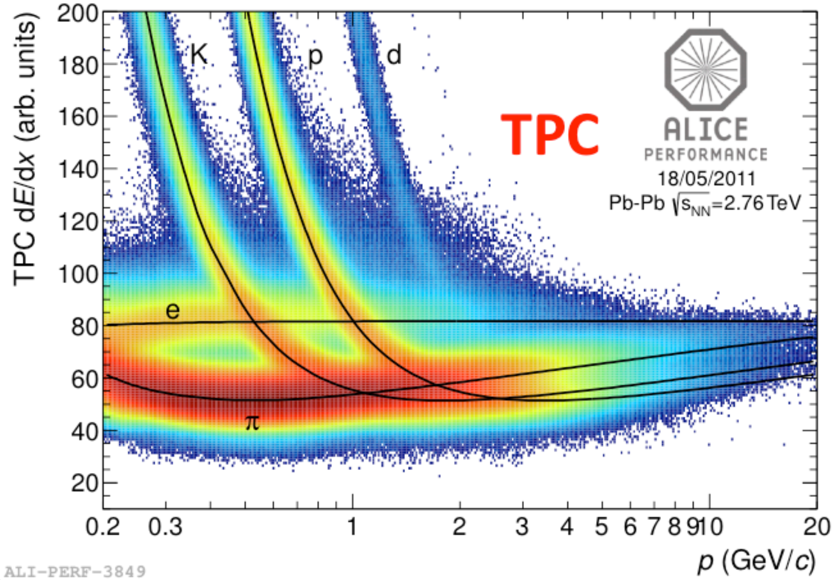
- Proton-proton: PYTHIA - strong increase with Nch attributed to **Color Reconnections** between hadronizing strings - a collective final state effect

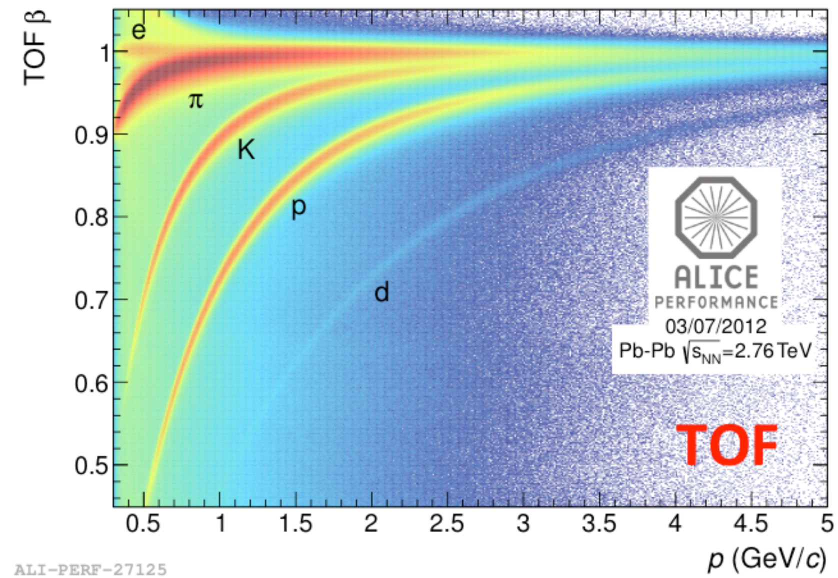
- pPb:
  - Glauber MC (incoherent p-N's) using measured <pT> in pp does not work
  - Coherent effects via strings from different p-N?
  - EPOS includes collective effects.

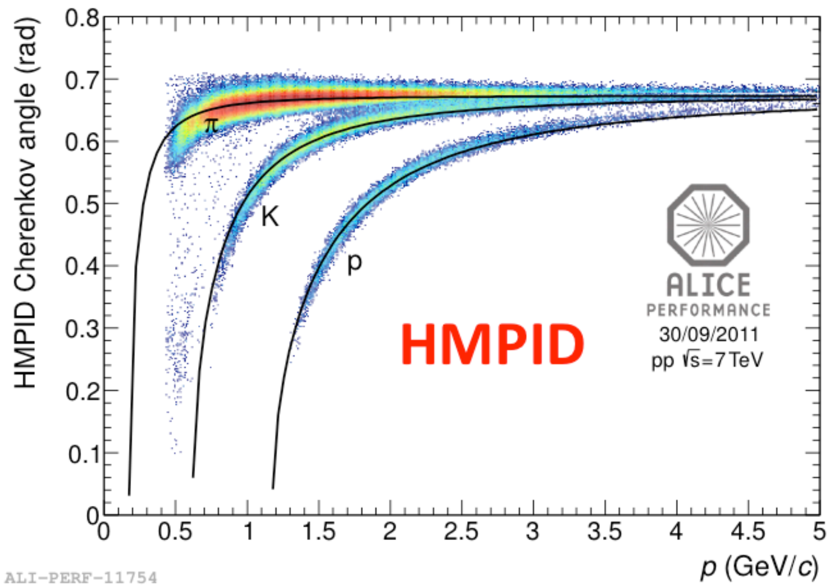
- Pb-Pb: DPMJet gets trend right. EPOS has different shape for very peripheral collisions.

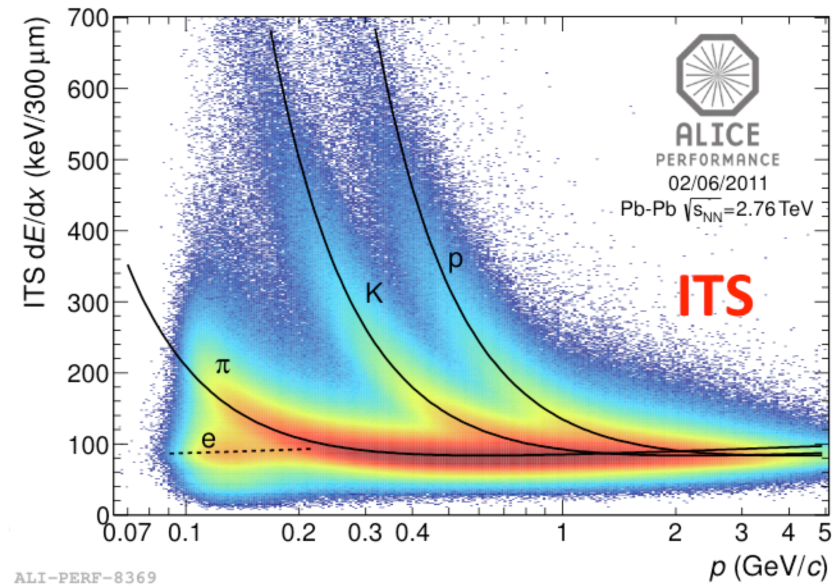
IDENTIFIED PARTICLE PRODUCTION

ALICE: Particle identification



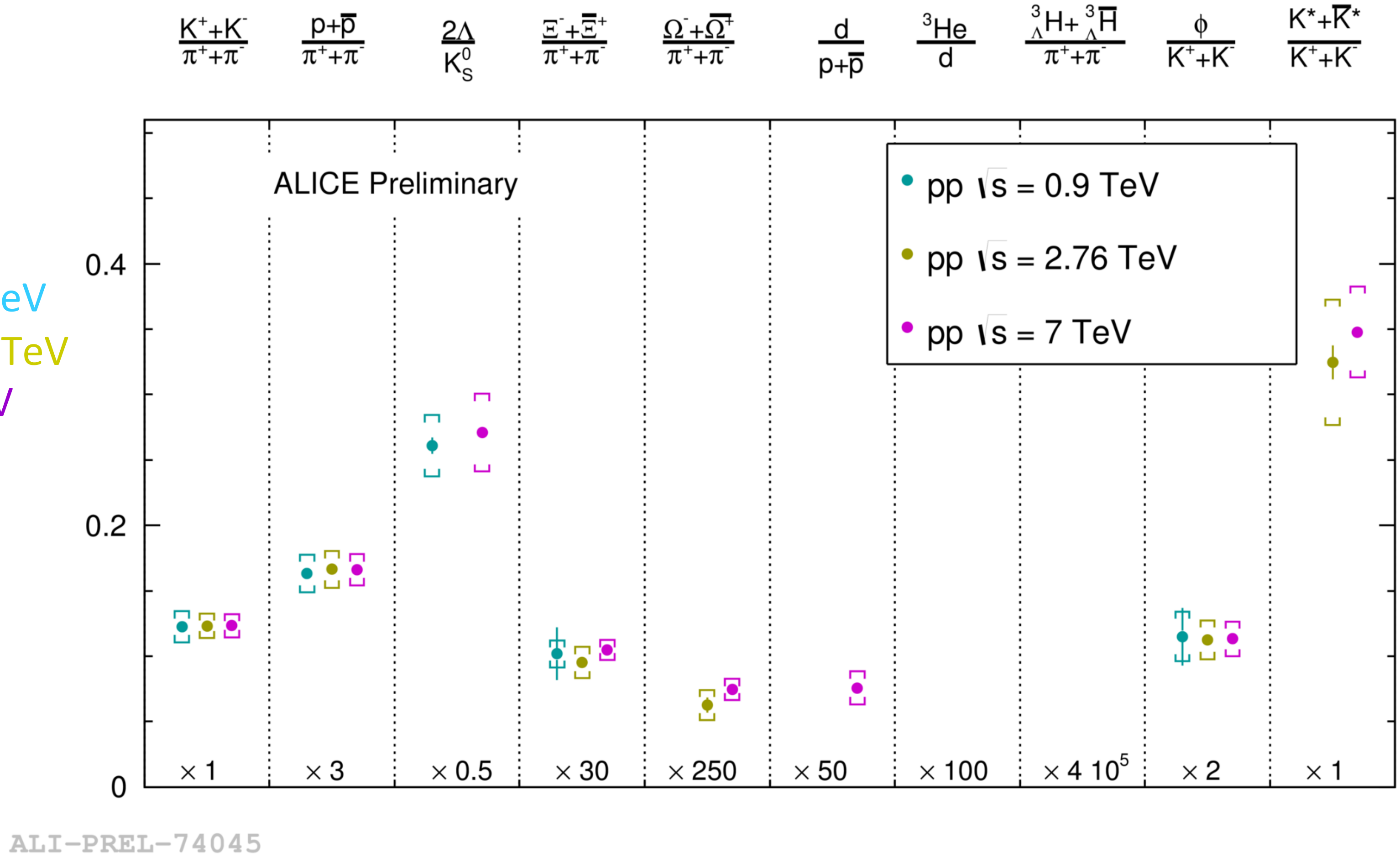






π K K^* K^0 p ϕ Λ Ξ Ω d ^{3}He ^{3}H

pp
0.9 TeV
2.76 TeV
7 TeV



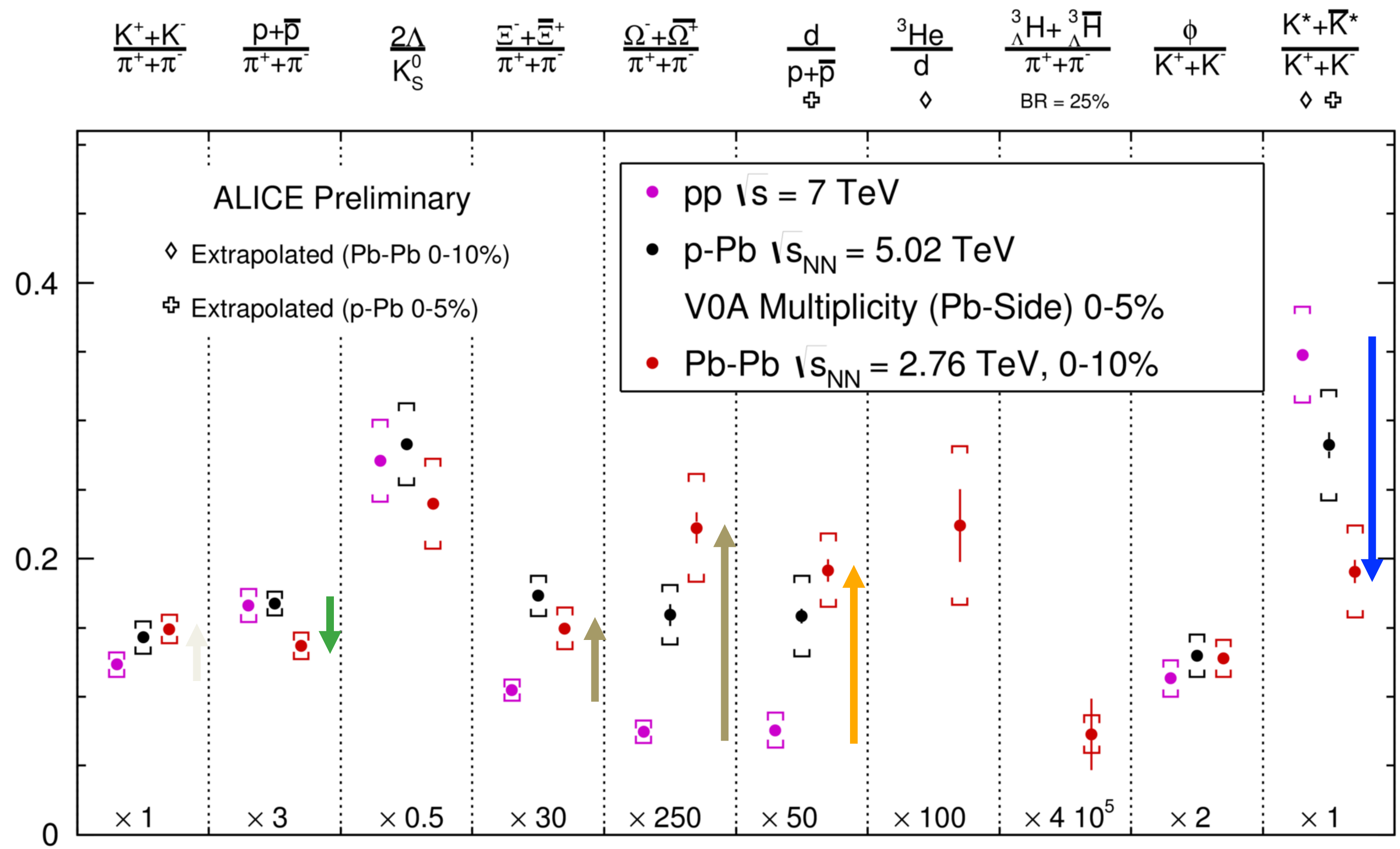
pp: no significant energy dependence

π K K^* K^0 p ϕ Λ Ξ Ω d ^{3}He ^{3}H

pp

p-Pb

Pb-Pb



ALI-PREL-74423

Strangeness enhancement

Deuteron enhancement

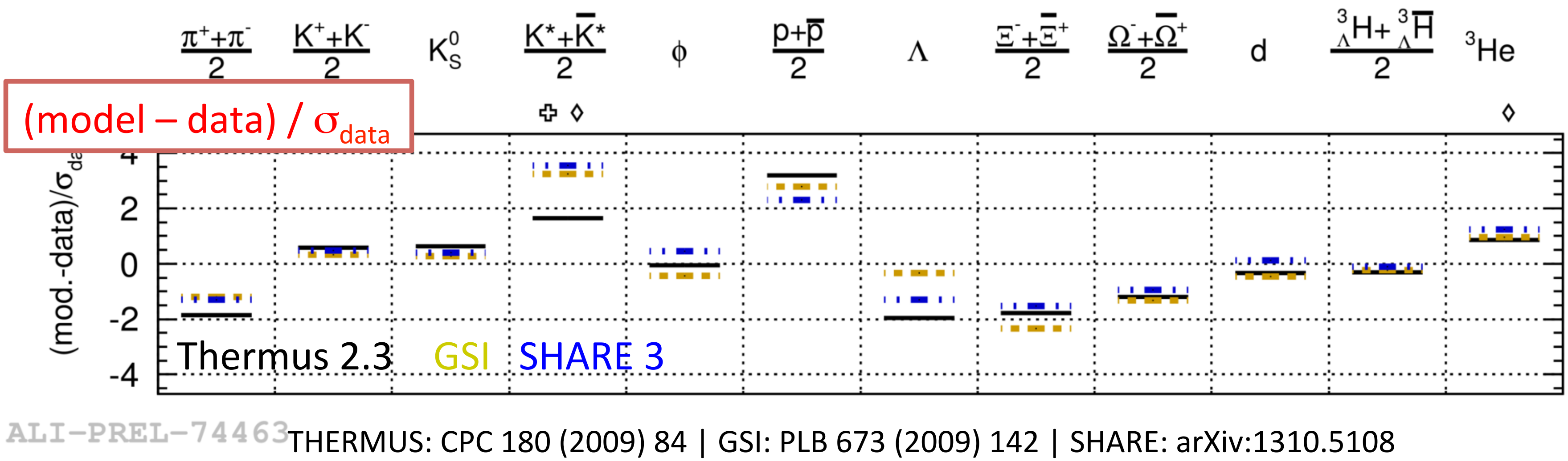
K* Suppression

p ?

Poster on hadronic resonances by Enrico Fragiacomo

Thermal fits in Pb-Pb

- Equilibrium models yields **T = 156-157 MeV**
  - But with χ^2/ndf of about 2



THERMUS: CPC 180 (2009) 84 | GSI: PLB 673 (2009) 142 | SHARE: arXiv:1310.5108

- Fits without the proton (and K*)
  - similar T, V but χ^2/ndf drops from about 2 to about 1

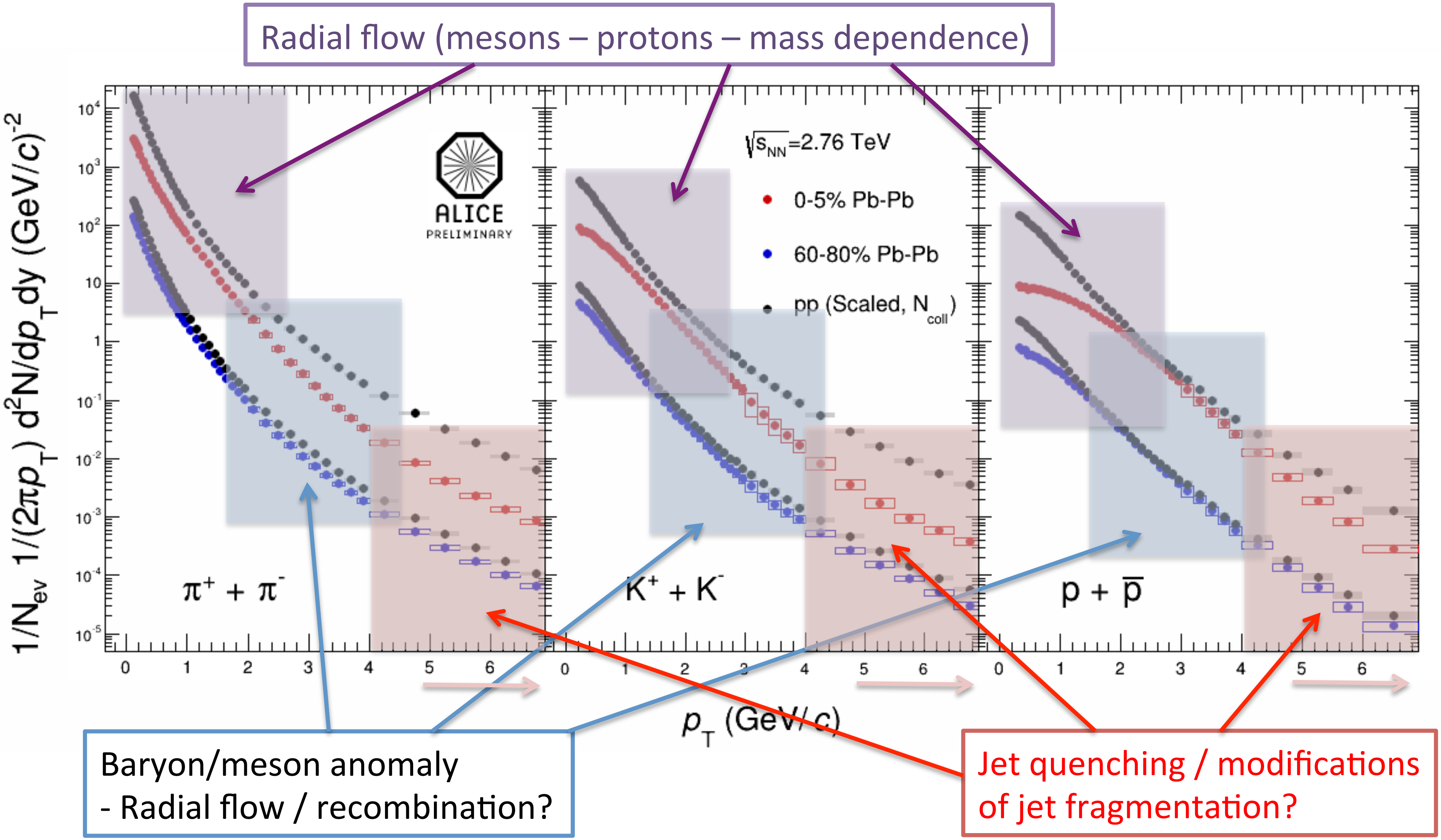
→ proton anomaly?

Poster on hadronic resonances by Enrico Fragiacomo

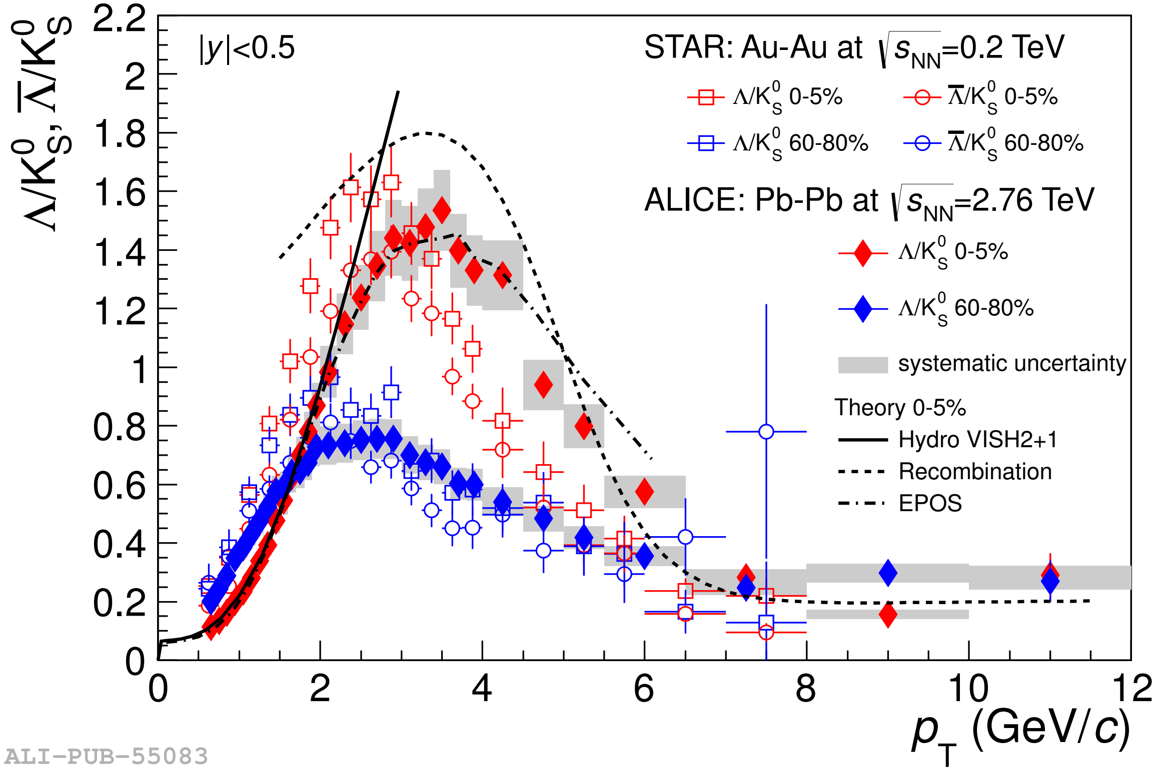
Physics origin?

- Non equilibrium thermal model
- Baryon annihilation
- Freeze-out temperature hierarchy
- Incomplete hadron spectrum

Pion/Kaon/Proton p_T spectra in pp and Pb-Pb



Baryon/meson "anomaly"

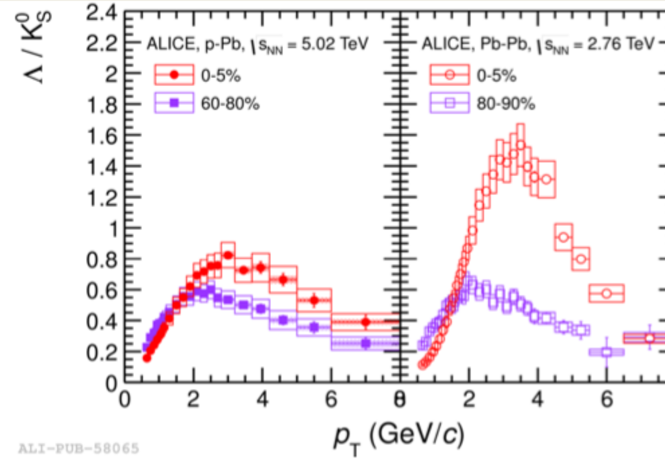


- Integrated ratio independent of centrality (L/K^0_s ~ 0.25)
- Intermediate p_T: Λ/K^0_s ratio enhanced in central Pb-Pb
  - consistent with radial flow
- High-p_T: ratio consistent with vacuum-like fragmentation.

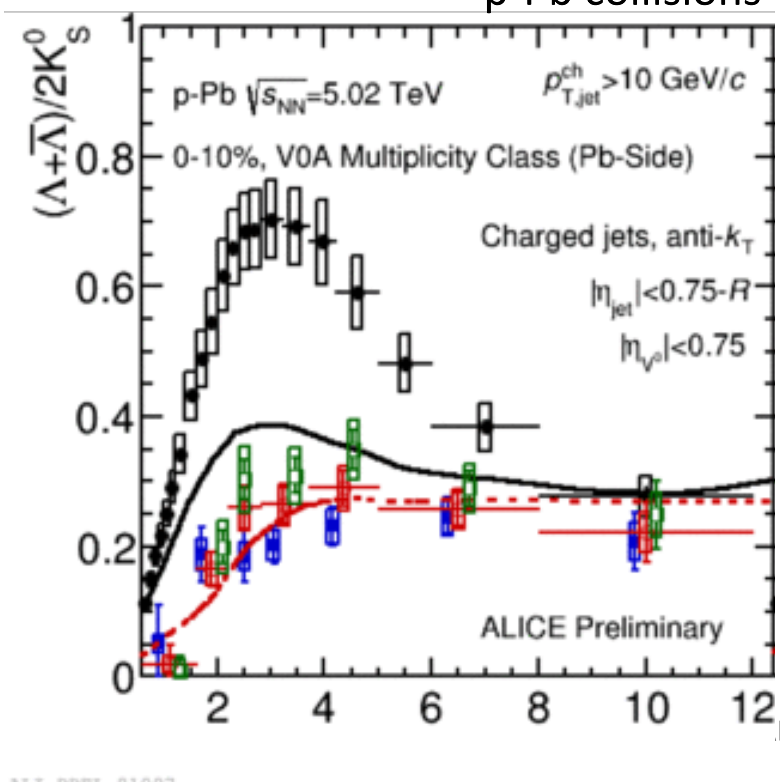
Λ/K^0 in jets and underlying event

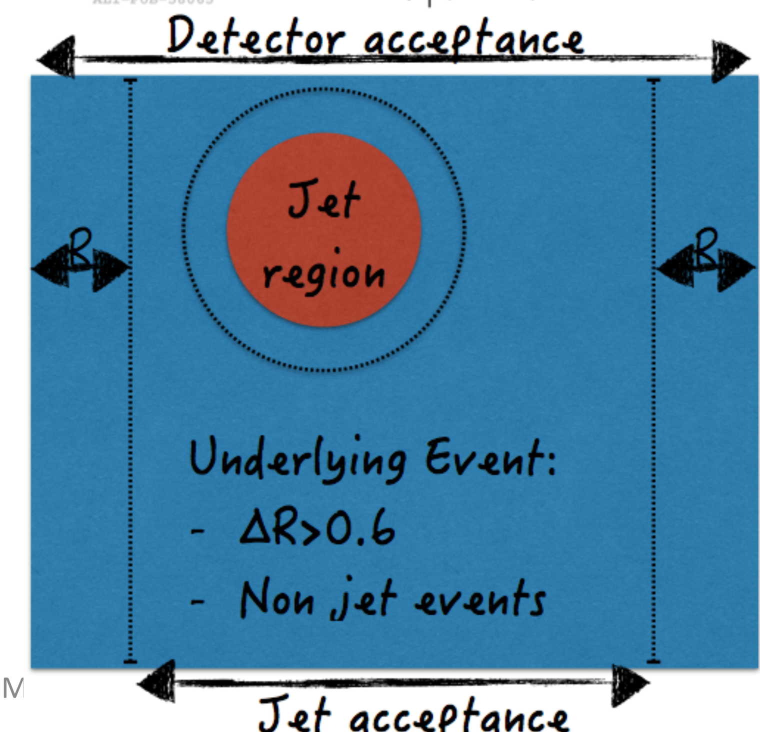
Λ/K in jets and UE separately consistent with vacuum

Baryon/meson enhancement is not associated to jets

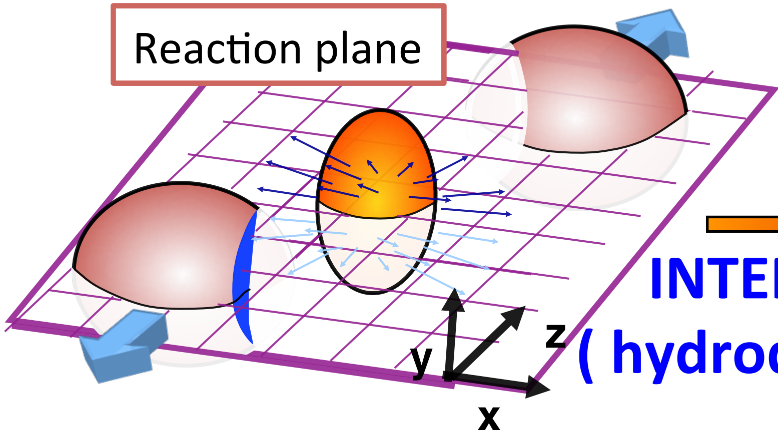


p-Pb collisions

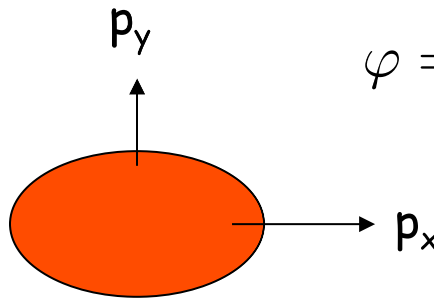




Collective Flow of QCD Matter



INTERATIONS
(hydrodynamics?)



$$\varphi = \arctan \frac{p_y}{px}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial spatial anisotropy

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Final momentum anisotropy

Reaction plane defined by "soft" (low p_T) particles

$$\Delta\varphi = \varphi - \varphi^{Reaction\ \ Plane}$$

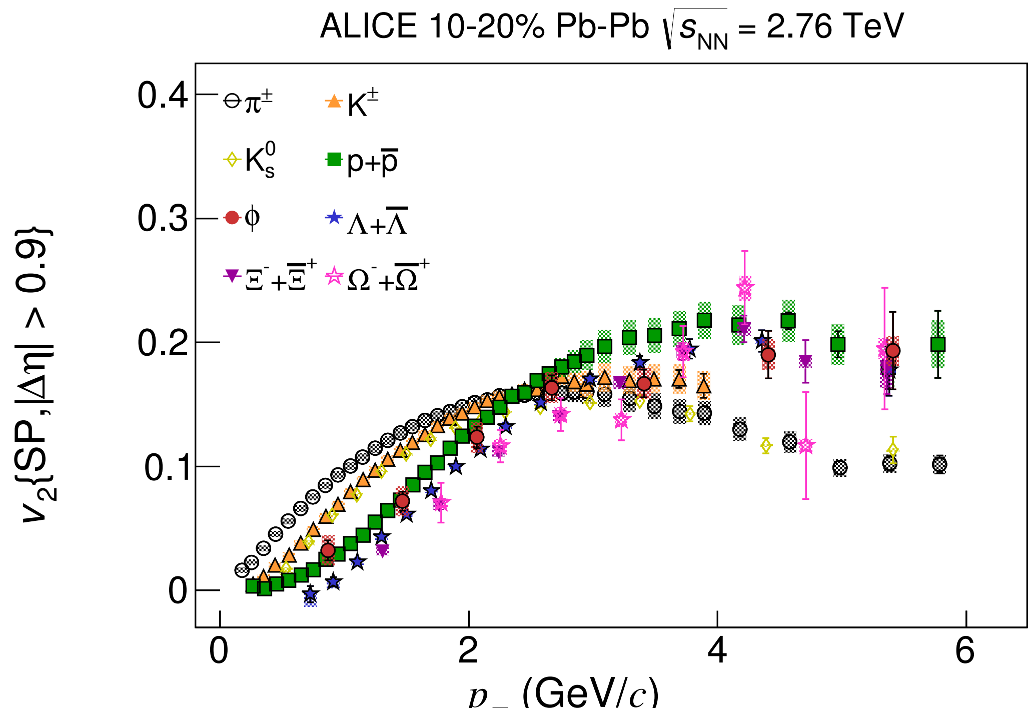
Elliptic flow

$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_2 \cos(2\Delta\varphi)$$

v_2 of identified particles

arXiv: 1405.4632

- Mass ordering for multi-strange baryons
  - Described by hydrodynamical model(s)



- v_2/n_q scaling at the LHC less obvious (within ~20%)

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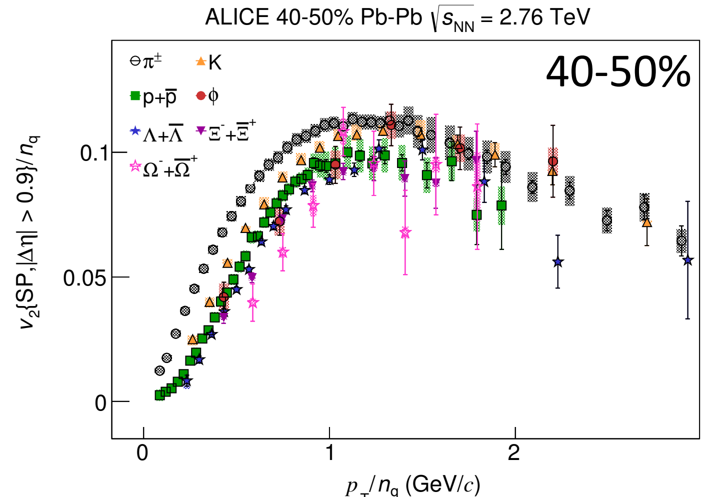

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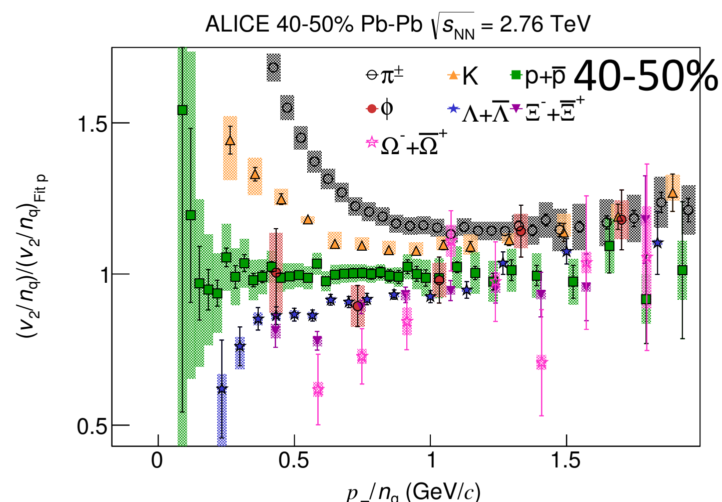


ALI-PUB-82776

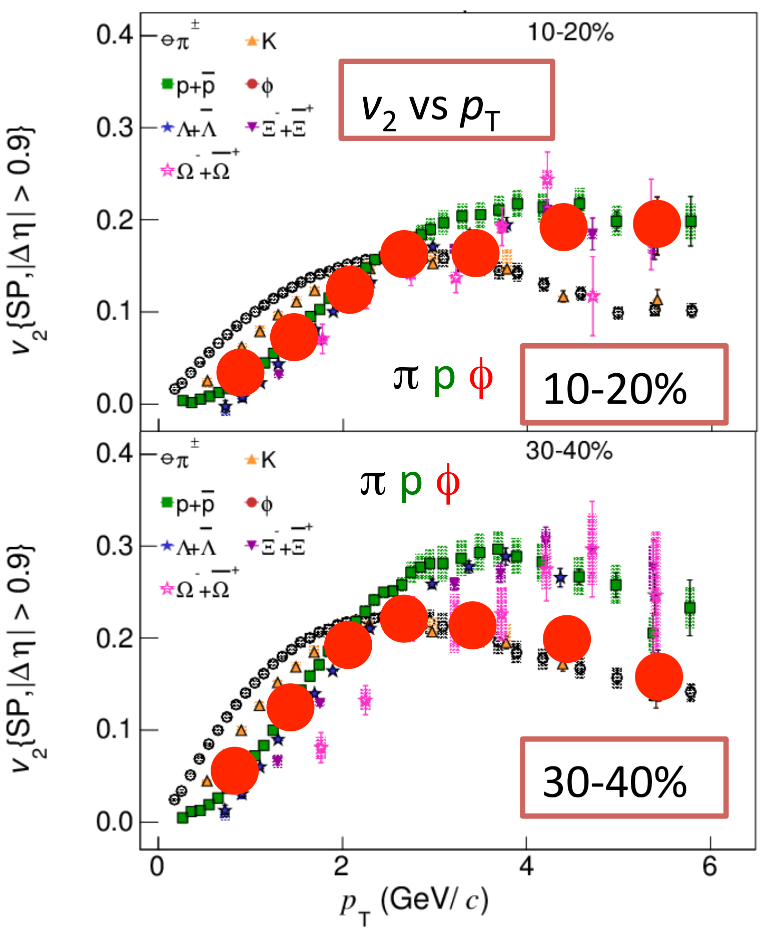
Not shown: v_2 and $v_3(p_T)$ – mass ordering reproduced by hydrodynamic calculations with very small viscosity to entropy ratio: η/s ~ 0.2

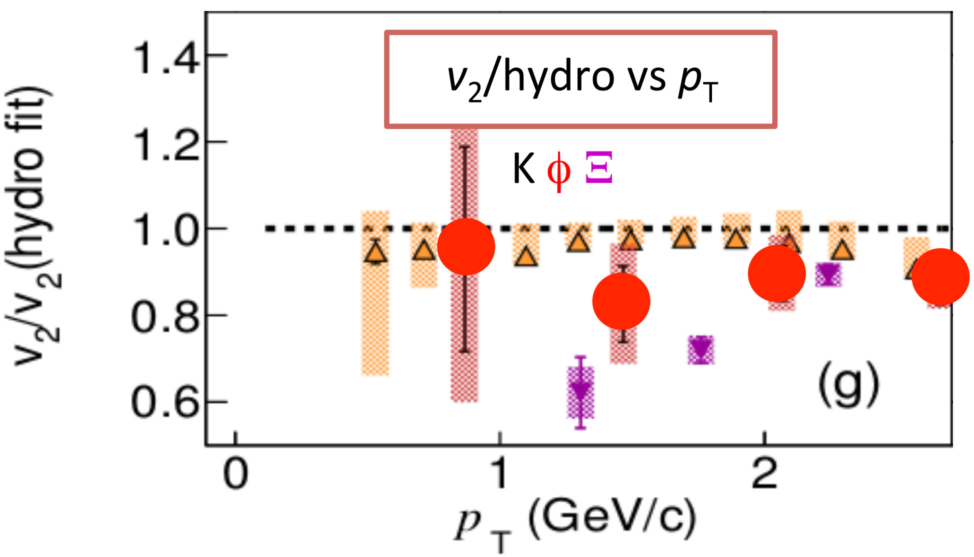
Flow and particle mass…
Focus on the ϕ meson

arXiv: 1405.4632

- Pb-Pb: Hydrodynamics + hadronic scattering model struggles with v_2

- v_2 at low p_T follows mass ordering
- v_2 at high p_T close to p in central and close to π in mid-central





Flow and particle mass… Focus on the ϕ meson

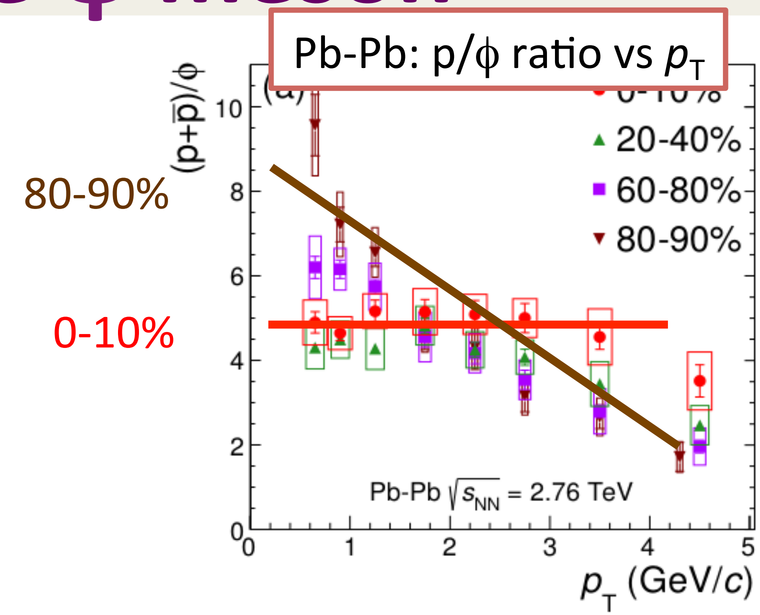
arXiv: 1404.0495

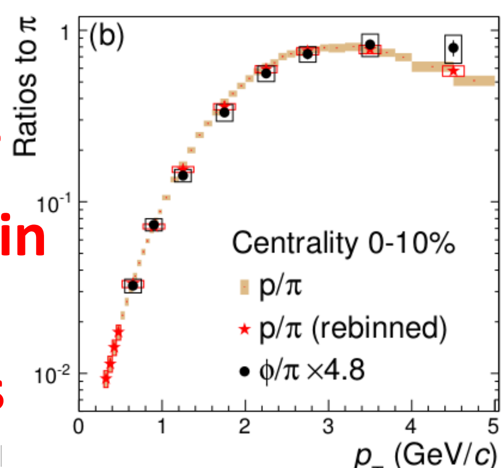
- Pb-Pb: Hydrodynamics + hadronic rescattering model struggles with v_2

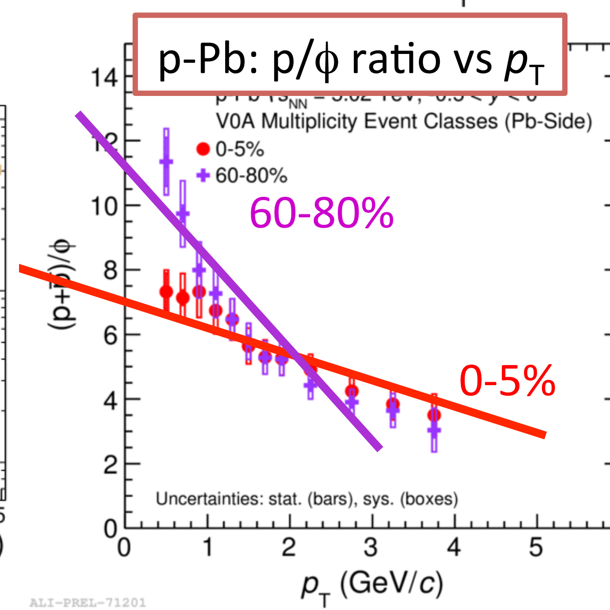
- v_2 at low p_T follows mass ordering
- v_2 at high p_T close to p in central and close to π in mid-central

- **In central collisions p and ϕ p_T spectra: similar shape up to ~4 GeV/*c***
  - **As expected from radial flow**
  - **Similar in p-Pb?**

- **Mass (and not number of constituent quarks) is main driver of v_2 and spectra in central Pb-Pb collisions**

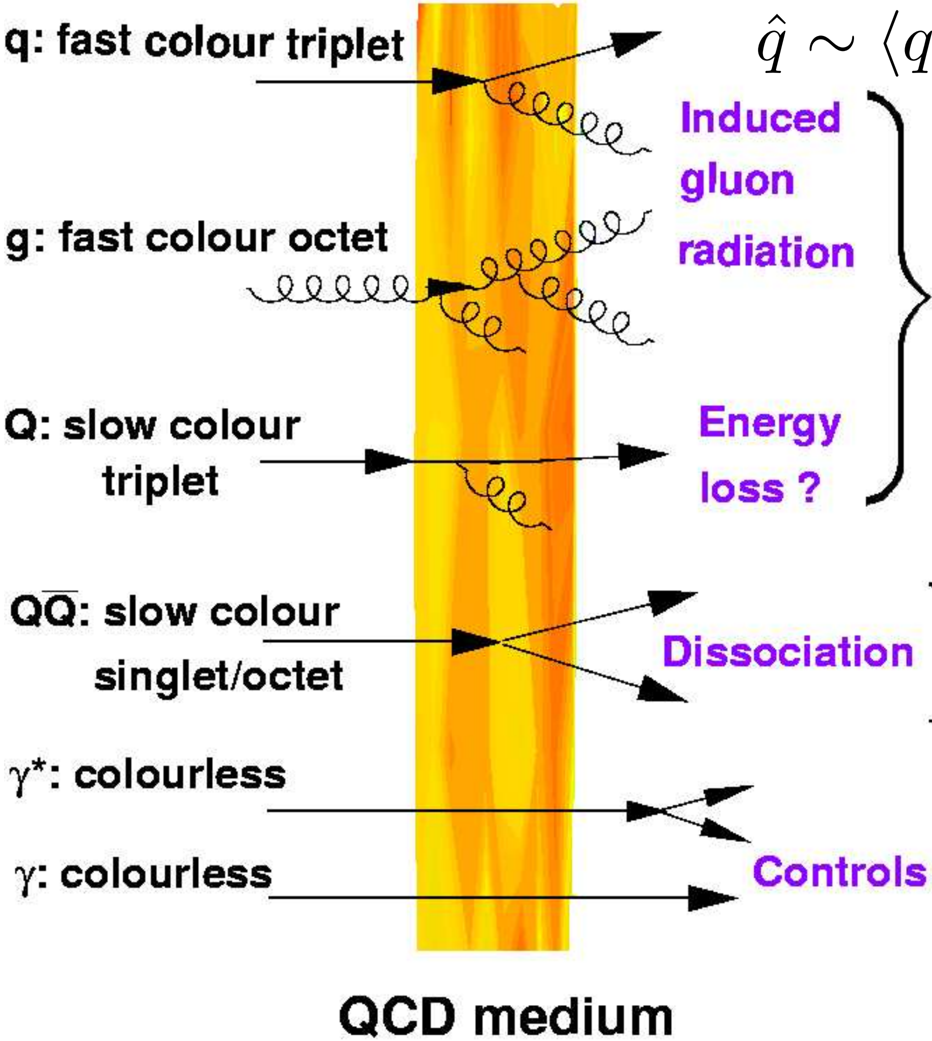






“Hard probes” of the medium

$$\hat{q} \sim \langle q_T^2 \rangle / \lambda = \langle q_T^2 \rangle / (\rho\sigma)$$



<$\hat{q}$> Transport coeff.

$\frac{dN_g}{dy}$ Initial gluon density

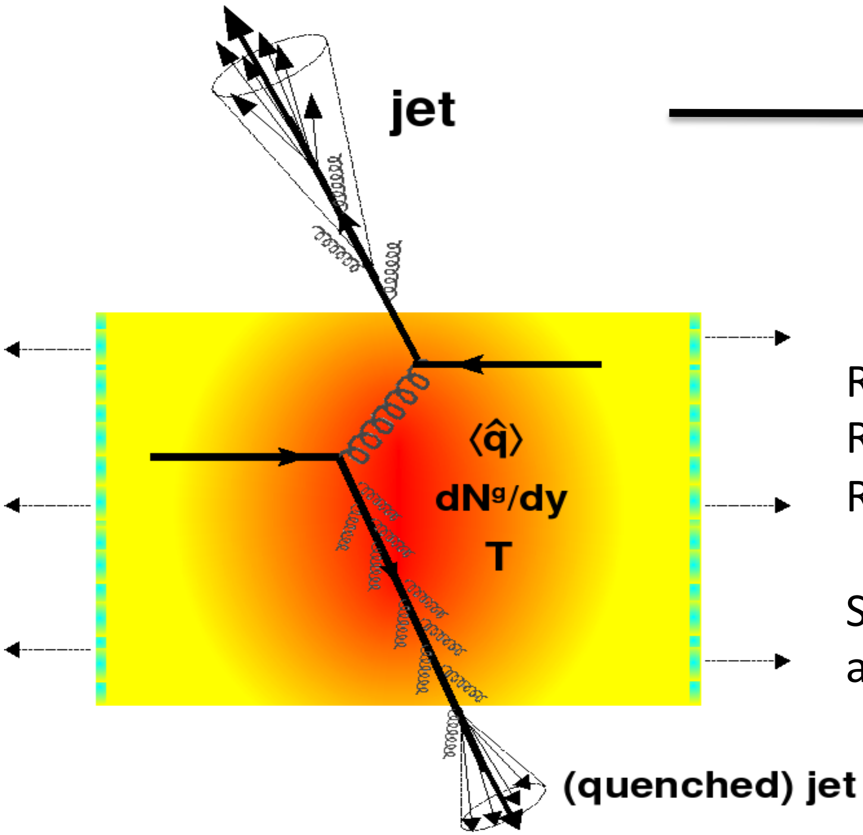
T_c, ε_c Critical temperature and energy density

Figure: d'Enterria arXiv:0902.2011

Quantifying nuclear effects: R_{AB}

$$R = \frac{\text{“QCD medium”}}{\text{“QCD vacuum”}}$$

$$\frac{\text{Yields measured in AA (or pA) per binary N-N collision}}{\text{Yields measured in pp collisions}}$$



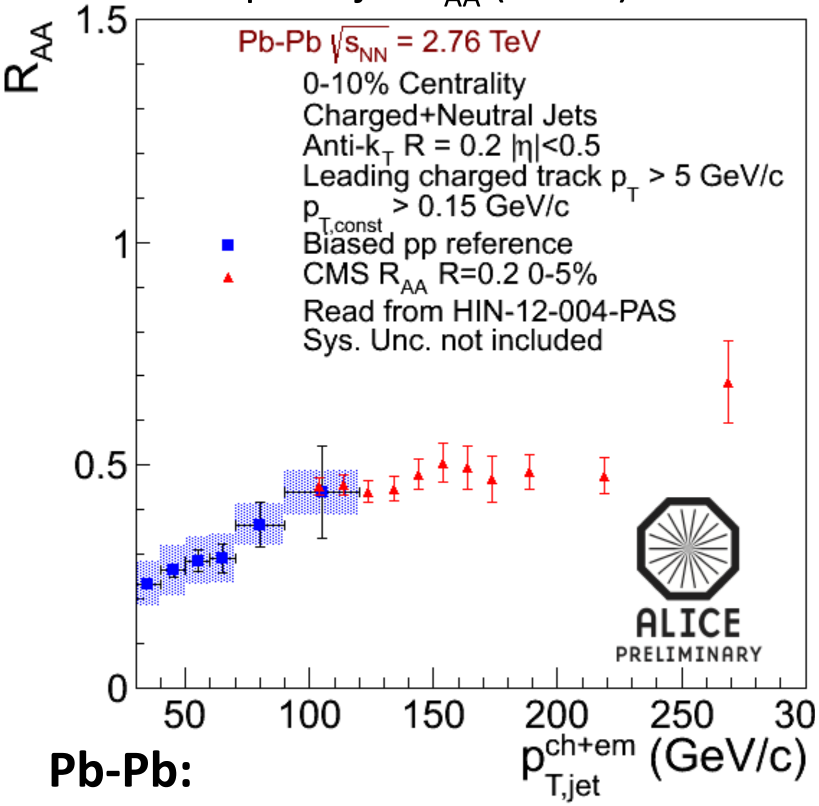
R > 1 – enhanced particle production
R = 1 – no nuclear effects
R < 1 – suppression

Sometimes useful to take the “vacuum” reference as yields in peripheral events – defined as R_{CP}

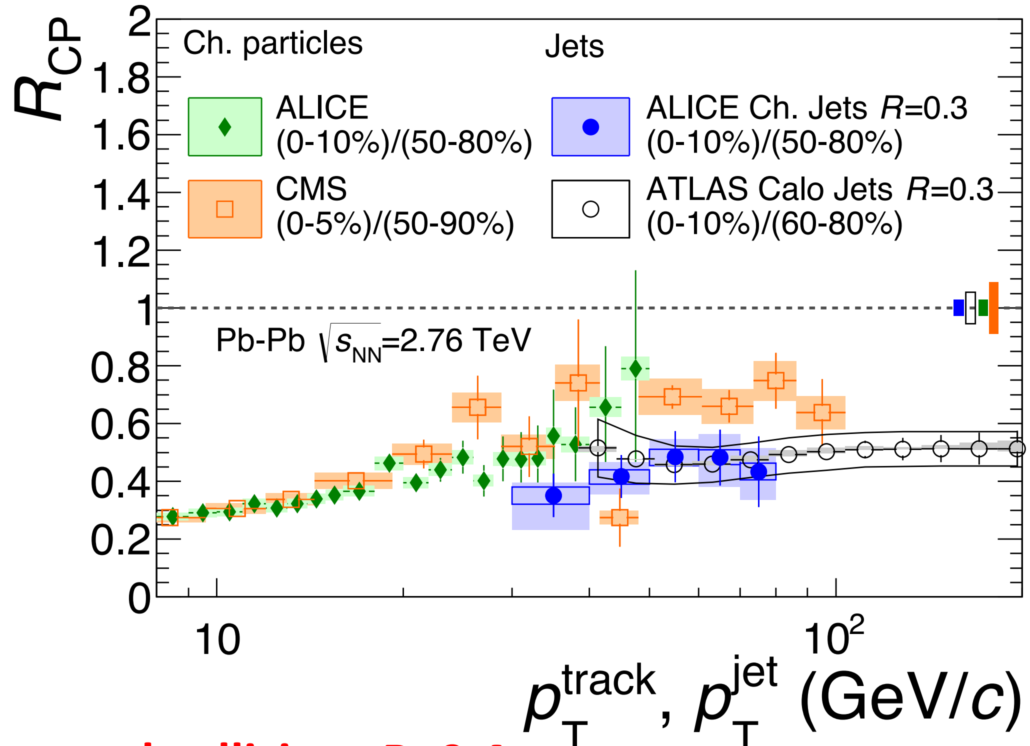
Jet quenching: Jet R_{AA}

arXiv: 1311.0633

Complete jet R_{AA} (R=0.2)



R_{CP} of charged particle jets (R=0.2)
- with respect to 50-80% centrality class



Pb-Pb:

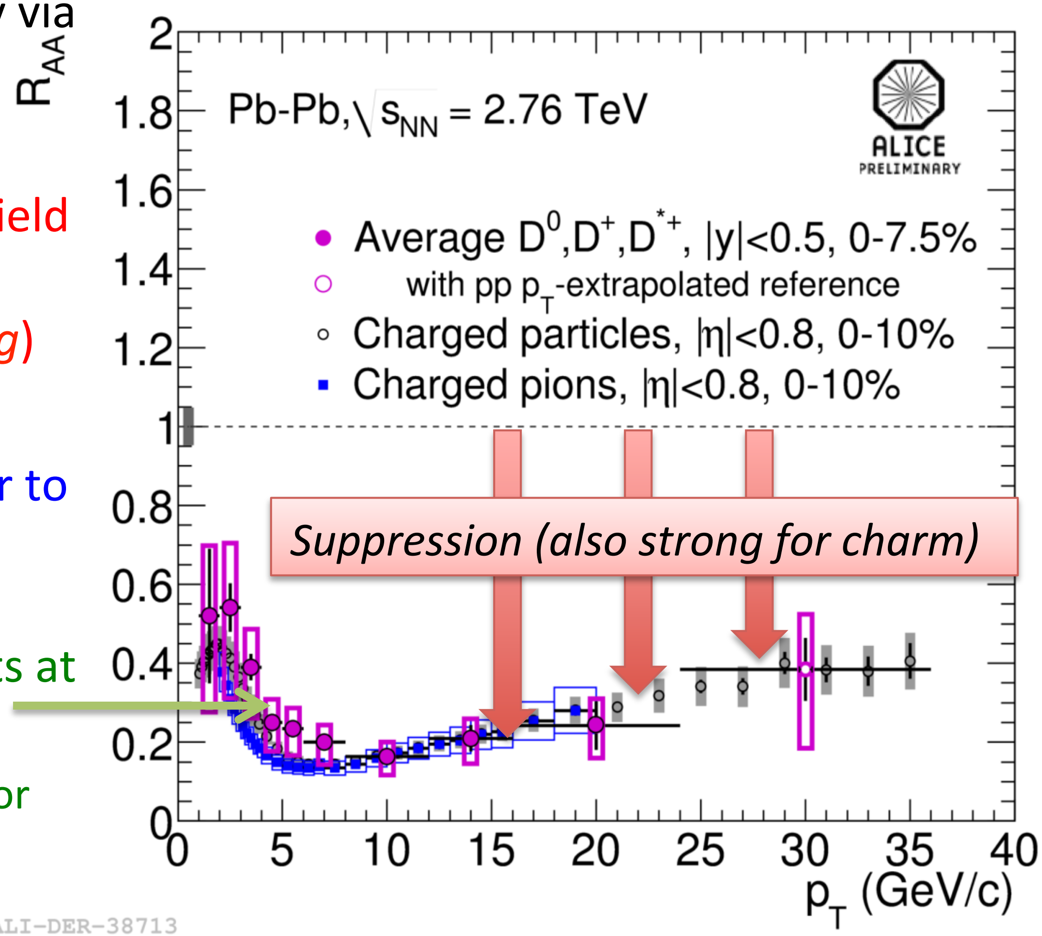
- **R_{AA}: Strong suppression in most central collisions R~0.4**
- **R_{CP}(50-80%): Similar suppression for jet radii R=0.2 (shown) and R=0.3**
- **Moderate p_T dependence (plateau at R_{AA}=0.4? similar to hadron R_{AA})**

QGP properties…

Charm suppression ⇔ Jet quenching

Studies for colour charge and mass dependence of parton energy loss

- D-mesons measured at mid-rapidity via hadronic decays
- R_{AA} - suppression pattern (ratio of yield in Pb-Pb to yield in proton-proton) shows a strong deficit (*jet quenching*)
- Quenching: charm at high-pT similar to light flavor
- Possible hint of colour charge effects at low-p_T (below 10 GeV/c)
  - => need better precision (outlook for next years and upgraded detector)



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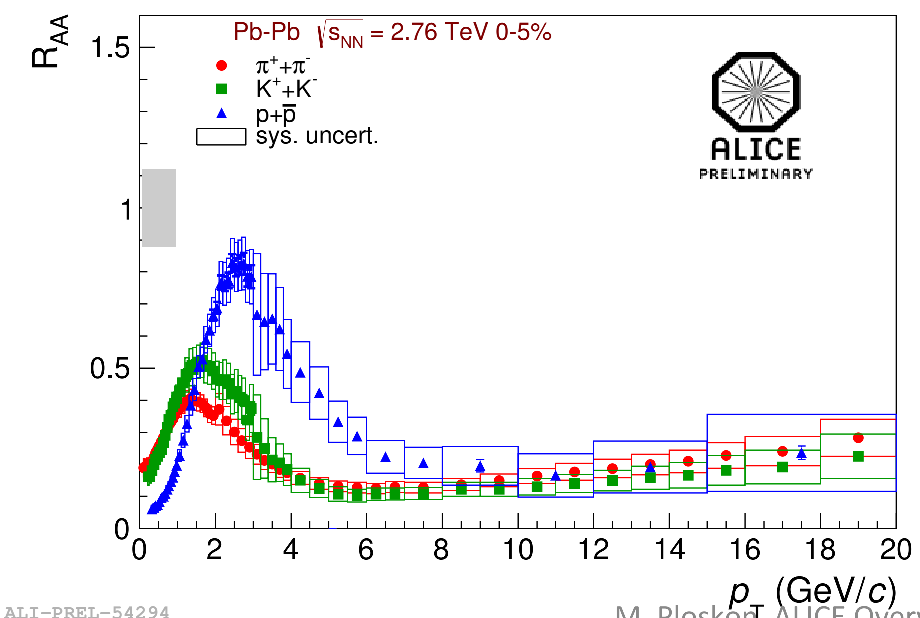
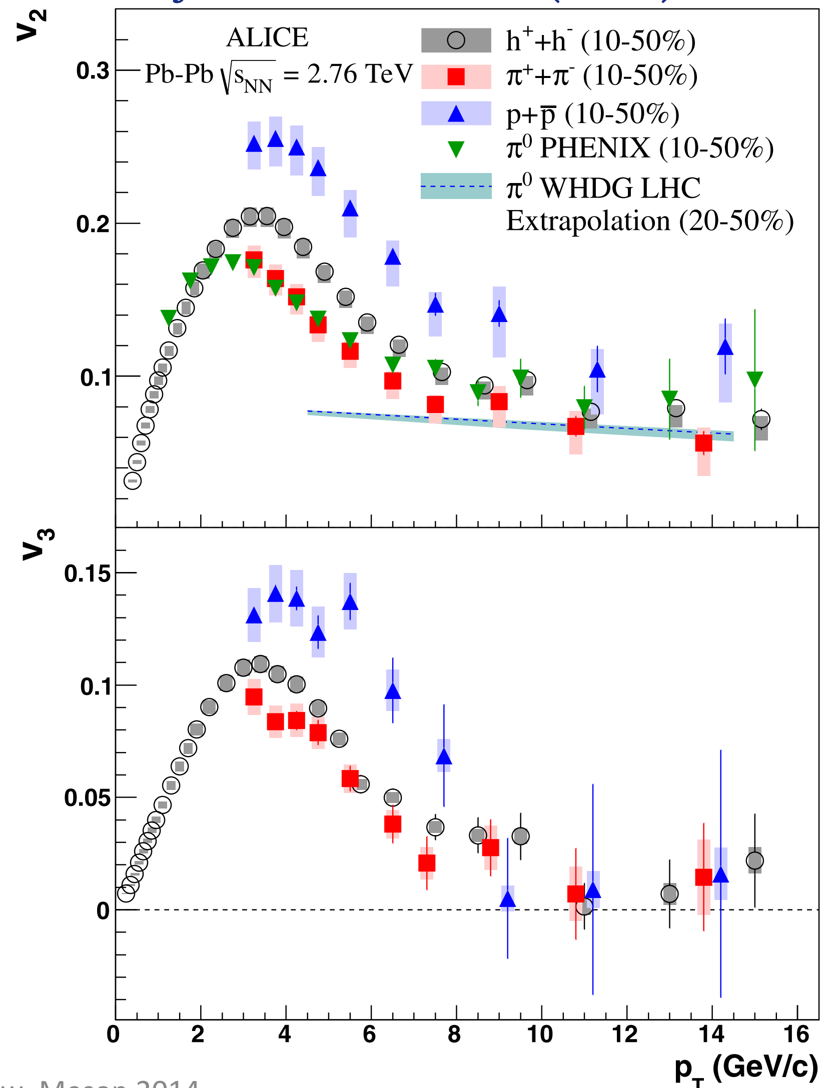
v_2 at high-p_T and R_{AA}

Physics Letters B 719 (2013) 18–28

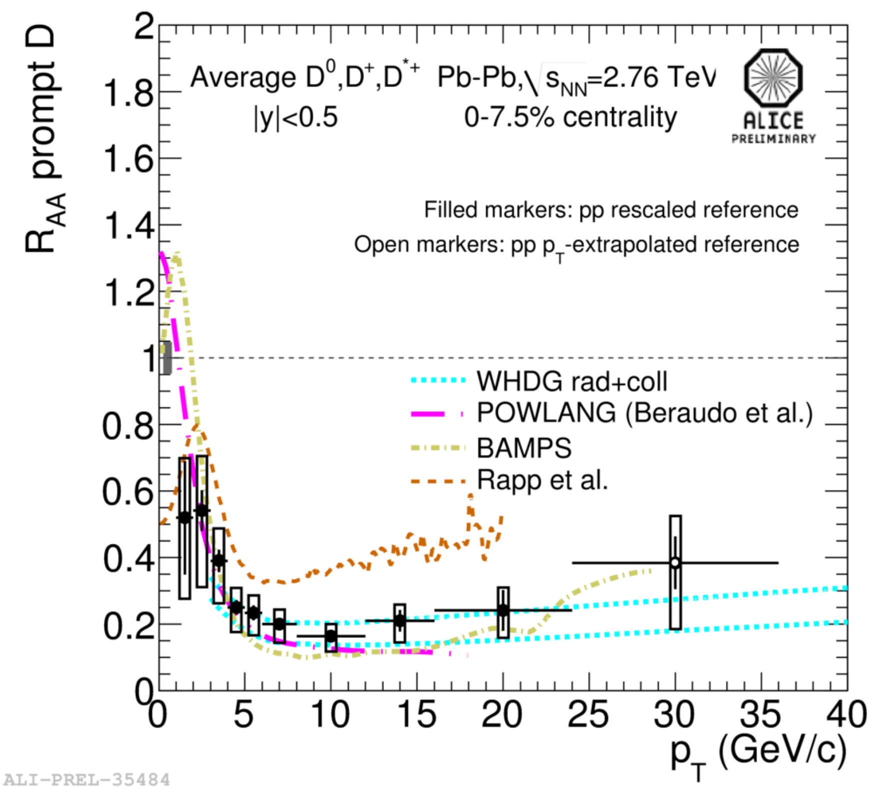
Jet quenching and non-zero v_2 are closely related – signature of the physical properties of QGP:

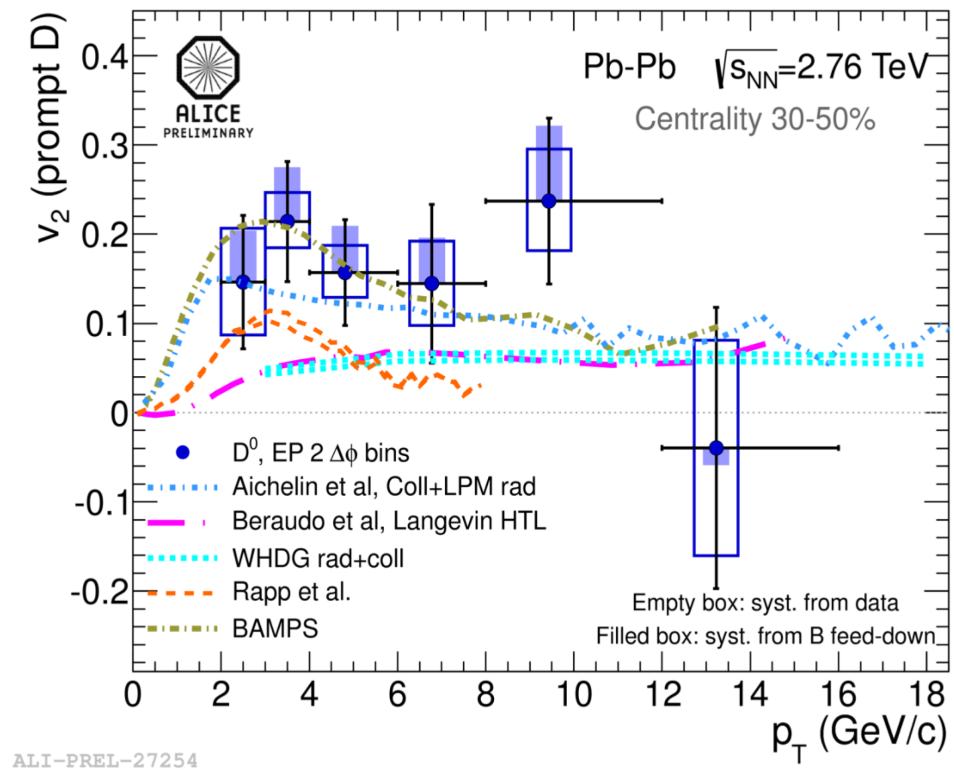
- QGP is opaque to colored probes
- In-medium energy-loss depends on the path length





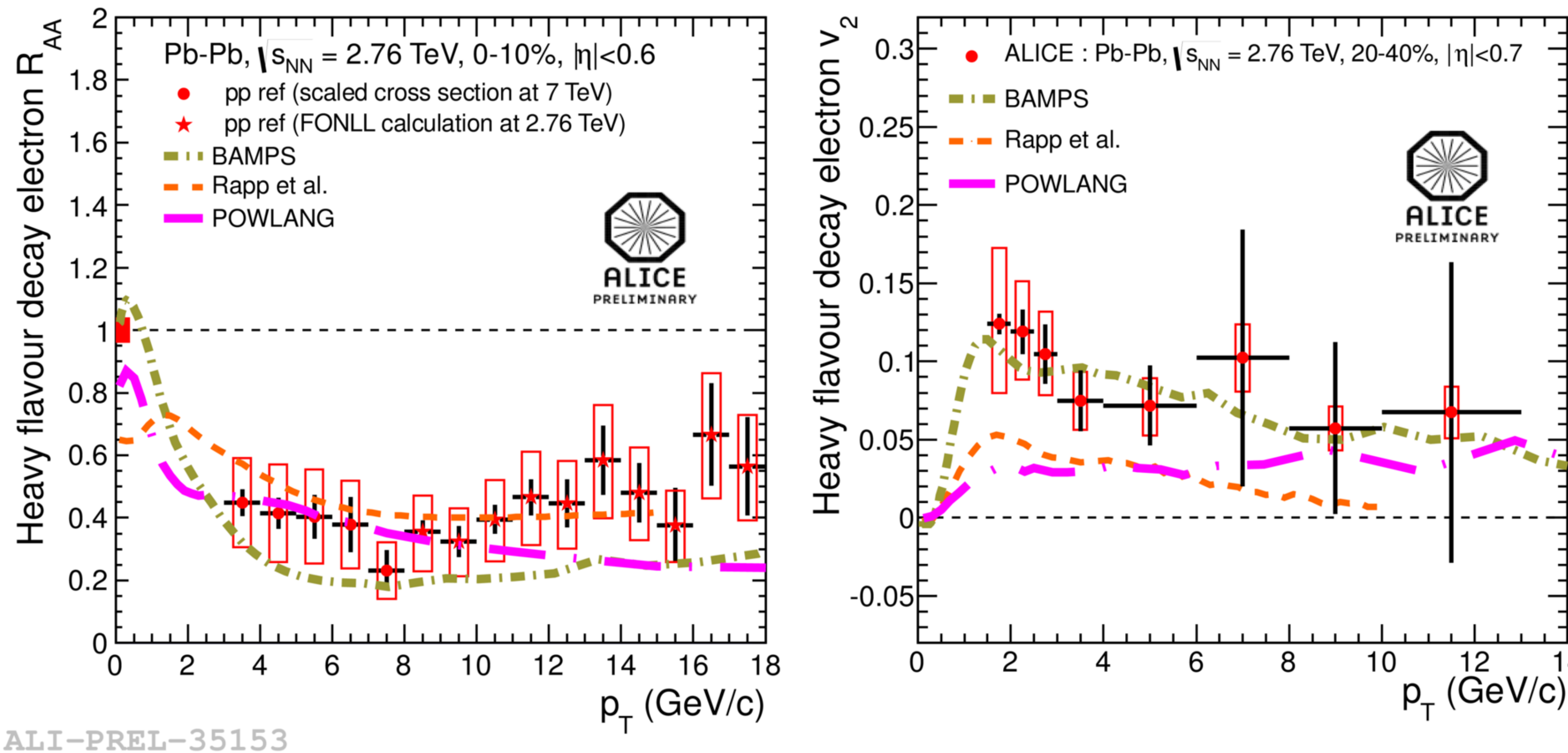
Challenge for theory – consistent description of charm production and its v_2





- **The simultaneous description of D meson R_{AA} and v_2 is a challenge to theoretical models**

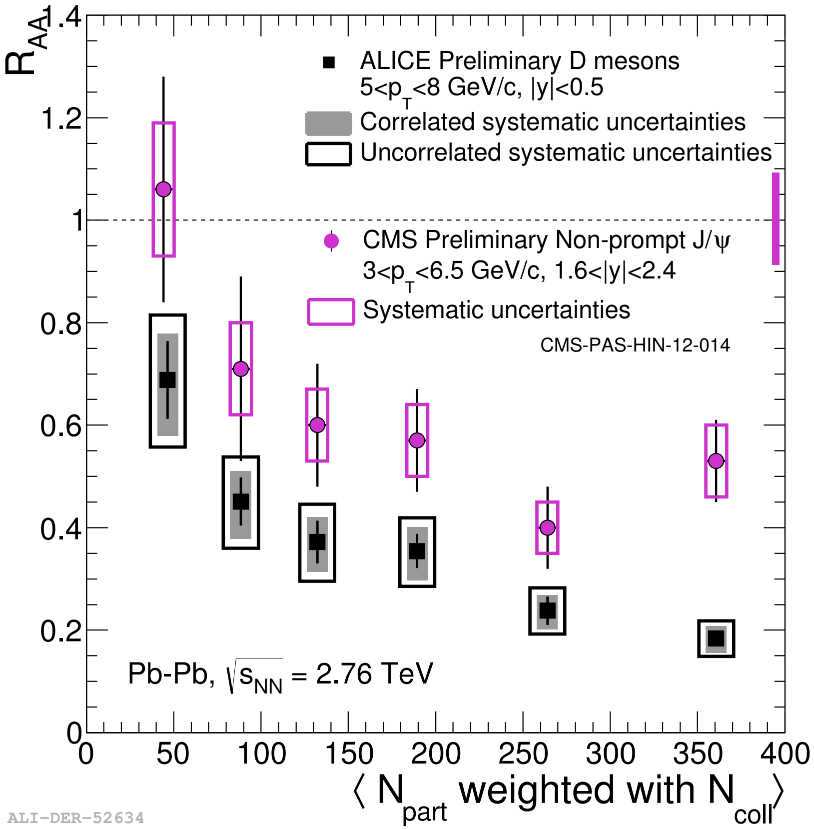
Challenge for theory – consistent description of HFE and its v_2



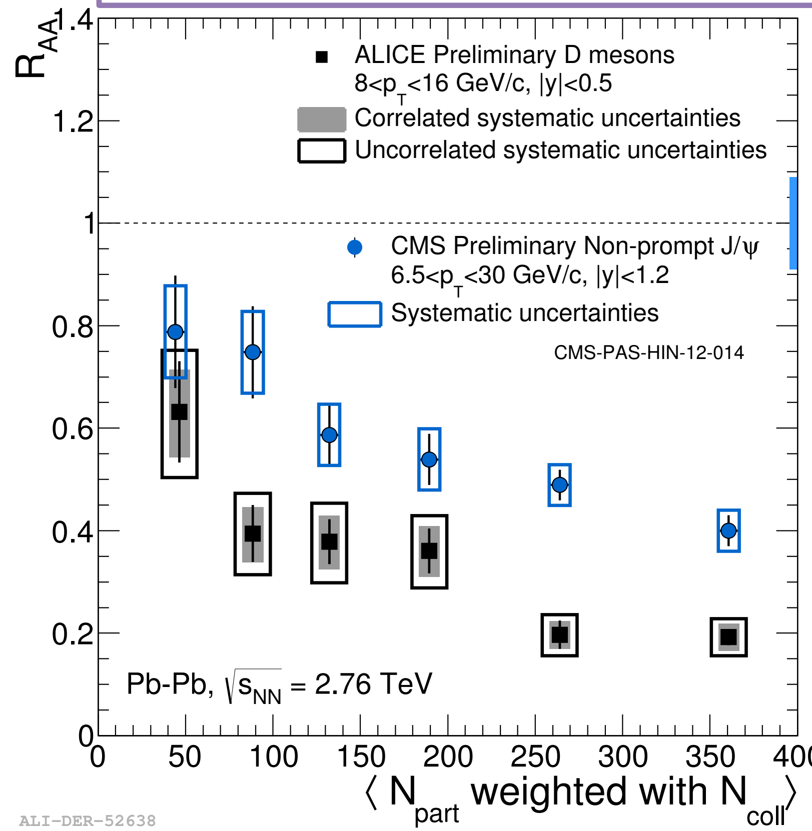
- **The simultaneous description of heavy flavor decay electrons R_{AA} and v_2 is a challenge to theoretical models**
- **Not shown: J/ψ: v_2 > 0 at LHC; R_{AA} LHC > R_{AA} RHIC for most central events**

D vs. B mesons R_{AA} vs. centrality

D's 5-8 GeV/c – NP J/ψ 3-6.5 GeV/c



D's 8-16 GeV/c – NP J/ψ 6.5-30 GeV/c

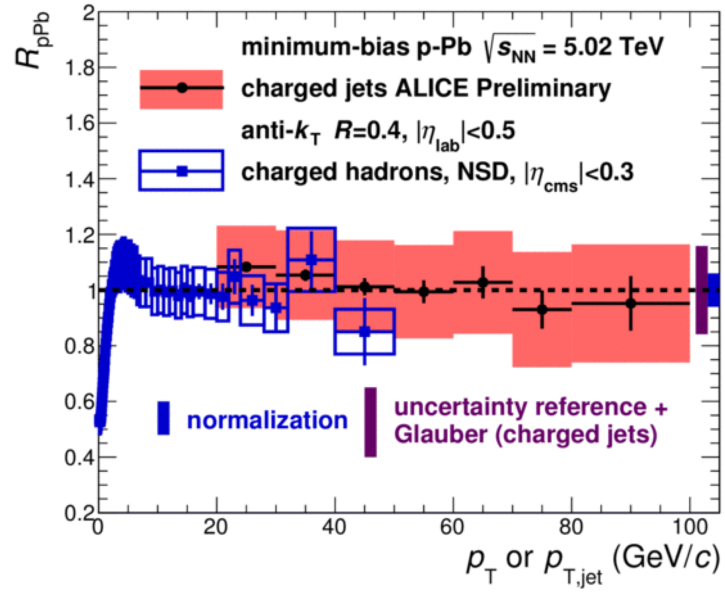


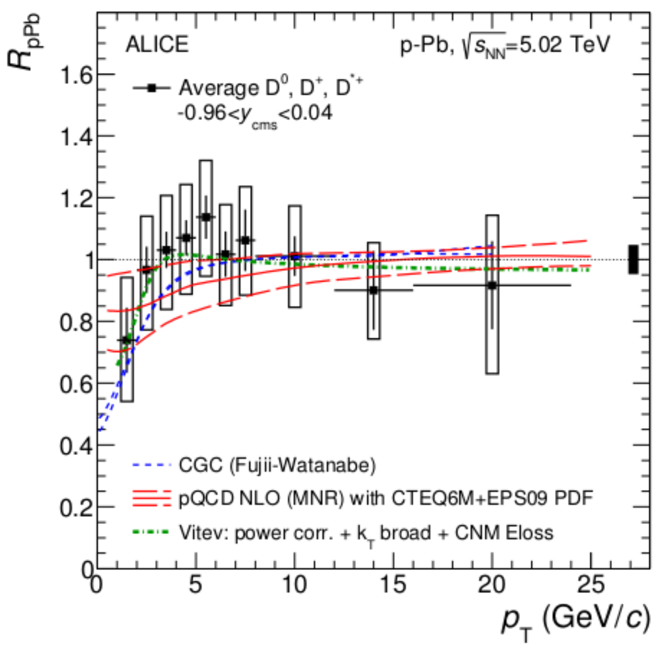
- p_T ranges: similar kinematics for D and B mesons (measured via non-prompt J/ψ)
  - simulations of decay kinematics used, i.e. in 8-16 GeV/c, in J/ψ p_T range 6.5-30 GeV/c

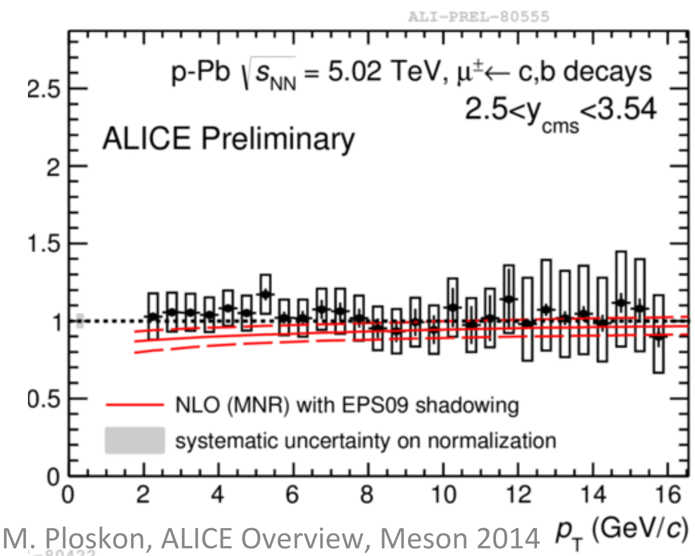
Indication for larger suppression of charm than beauty

No nuclear effects at high-p_T in pA

- R_{pPb} at high p_T consistent with unity:
  - for charged particles above 10 GeV/*c*
  - for charged jets up to 100 GeV/*c*
  - for D^0, D^+, D^{*+} mesons (mid rapidity)
  - for b → e decays (mid rapidity)
  - for c, b → μ decays (forward)
  - for W → μ







=> Binary scaling is preserved, no evidence of initial state effects

Jet quenching in Pb-Pb collisions is a final state effect (parton energy loss)

QUARKONIA

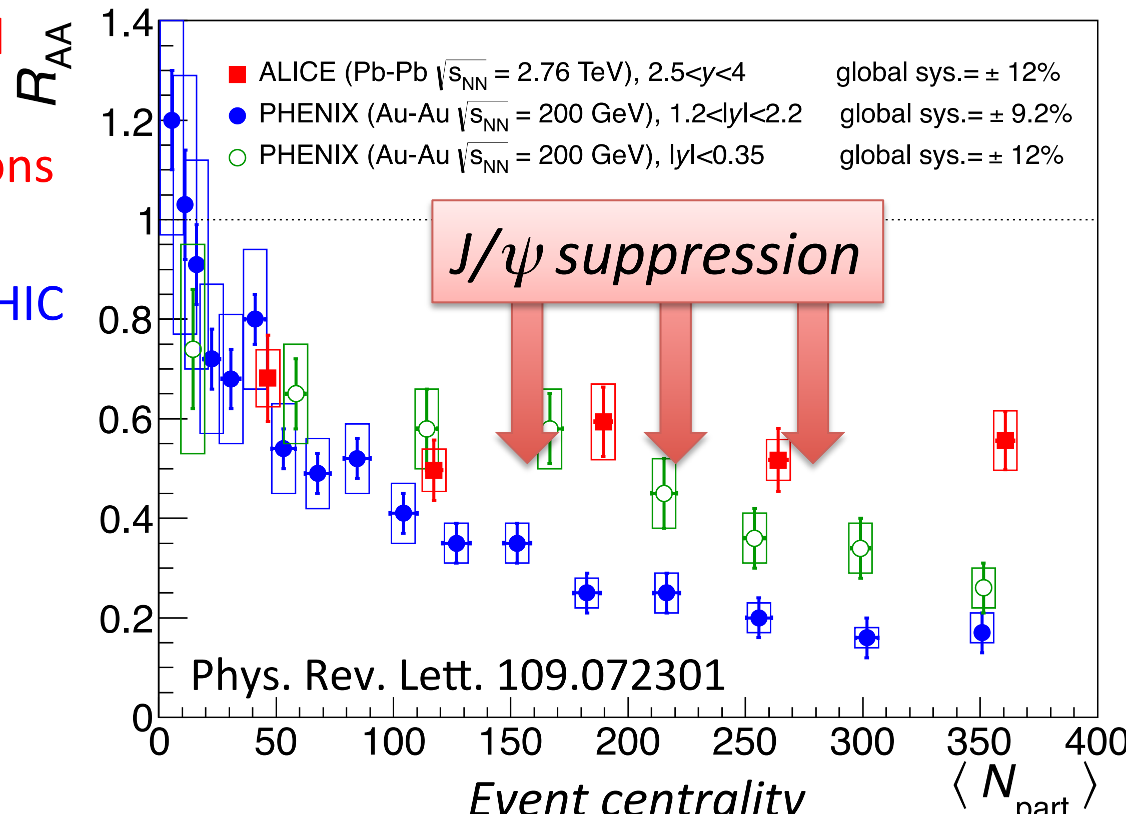
QGP Properties with J/ψ measurements

J/ψ measured with forward muon arm

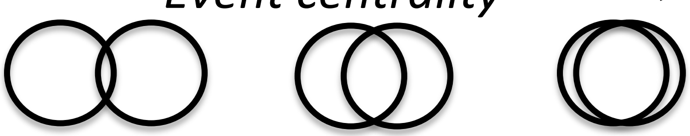
$J/\psi \rightarrow \mu^+\mu^-$

- Inclusive J/ψ yield lost in central Pb-Pb collisions as compared to equivalent number of pp collisions
  - Quarkonia "melts" within QGP
- LHC: Less suppression than at RHIC and flat centrality dependence
- => in-medium ccbar recombination?

- Important: better knowledge of initial state effects crucial – cold nuclear matter / shadowing / saturation



Event centrality



QGP Properties with J/ψ measurements

arXiv: 1311.0214

J/ψ measured with forward muon arm

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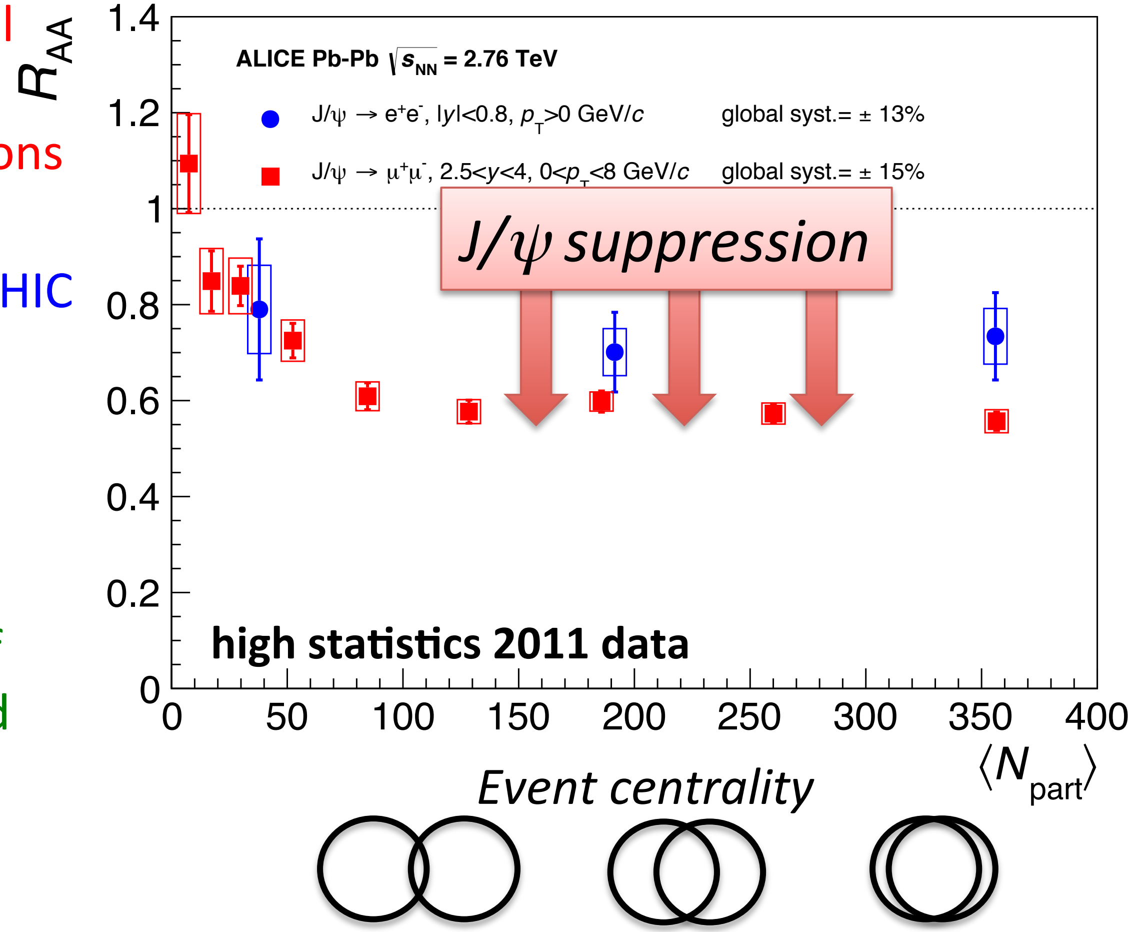
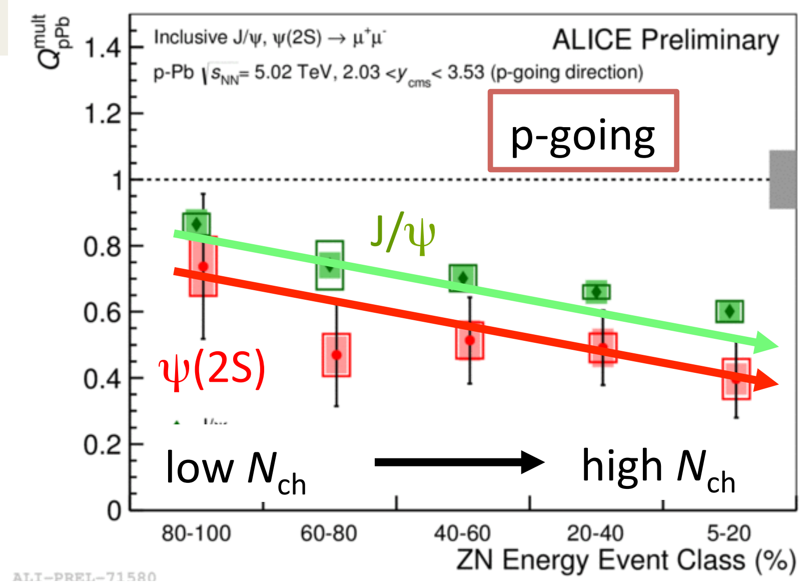
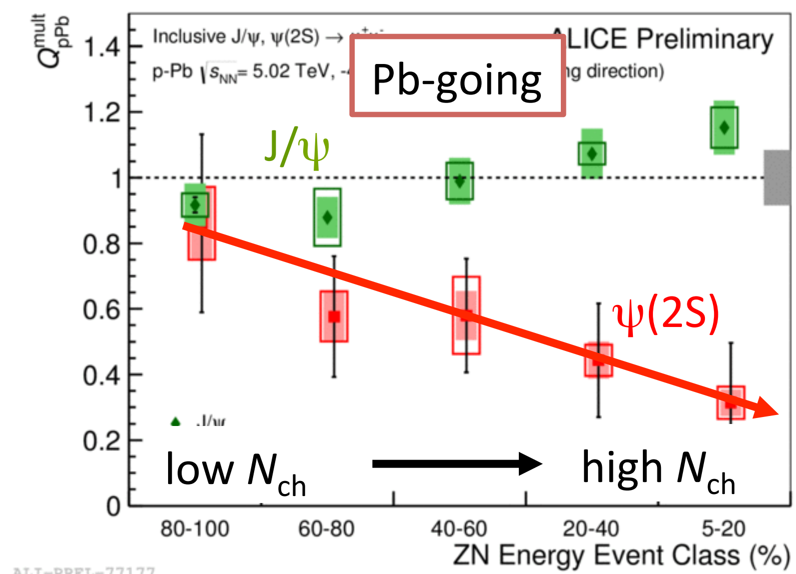


p-A: Charmonia

- Q_{pA} is an experimental proxy for R_{pA}
- J/ψ → μμ: Multiplicity dependent suppression in p-going direction
  - Independent of p_T
  - Shadowing region; <x> ~ 10^{-4}
- No suppression in Pb-going direction
  - Anti-shadowing region; <x> ~ 10^{-2}
- ψ(2S) → μμ: Multiplicity dependent suppression in both directions
- J/ψ consistent with shadowing
- ψ(2S) additional effects at play
  → Final state interactions?

Q_{pA} vs event class





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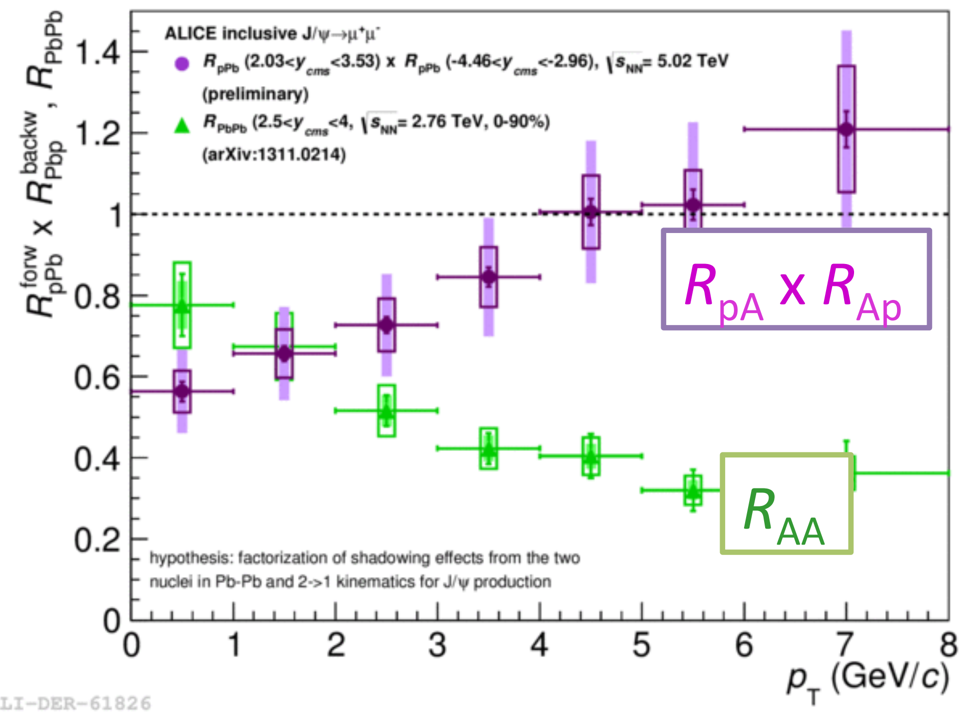
  - Shadowing region; <x> ~ 10^{-4}
- No suppression in Pb-going direction
  - Anti-shadowing region; <x> ~ 10^{-2}

$R_{p\text{-}Pb}$ x $R_{Pb\text{-}p}$: proxy for cold nuclear matter effects in Pb-Pb
Caveat: sqrt(s_{NN}), kinematics

Pb-Pb: stronger suppression at high pT
→ not an initial state effect

Increase of R_{PbPb} at low p_T suggests contribution from (re)combination

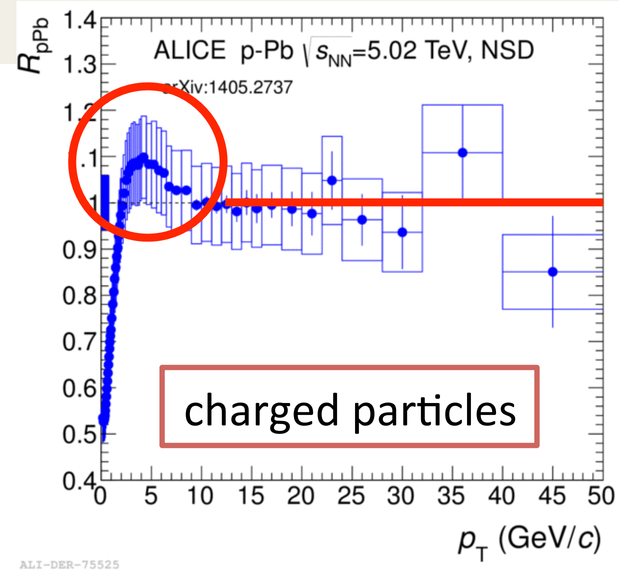
J/ψ R_{AA}/R_{pA} vs. p_T

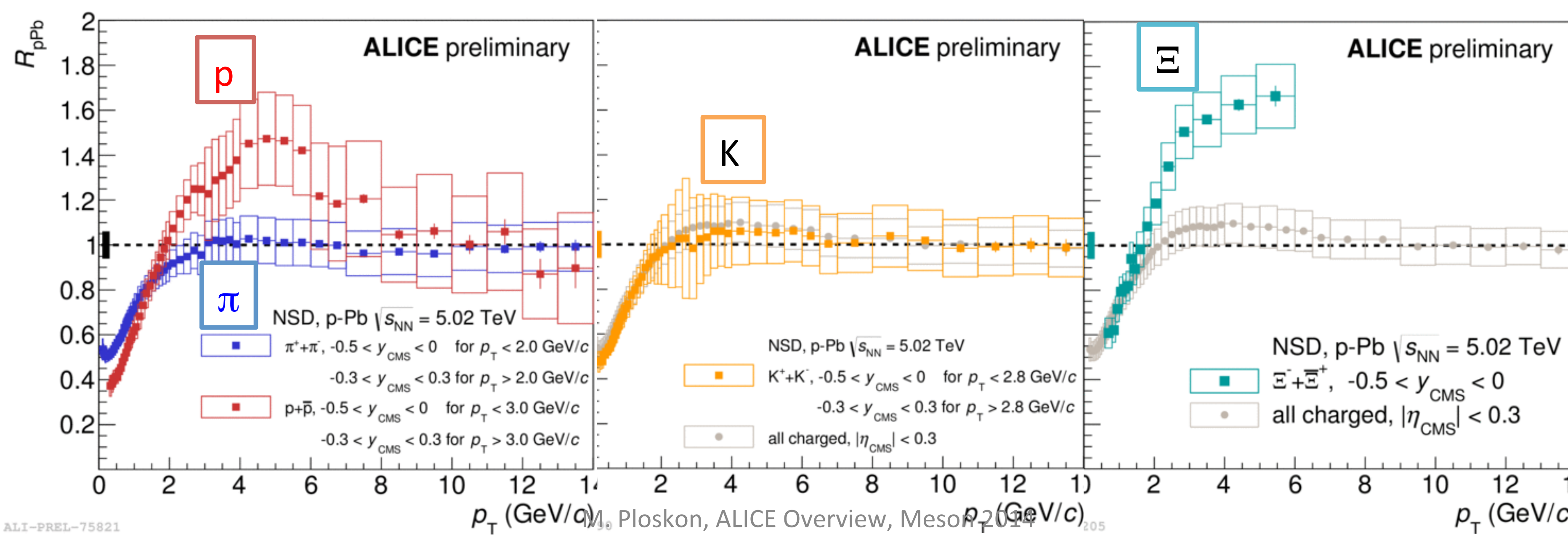


PROTON-LEAD COLLISIONS:
COLLECTIVE EFFECTS IN SMALL SYSTEMS?

Identified particle R_{pA}

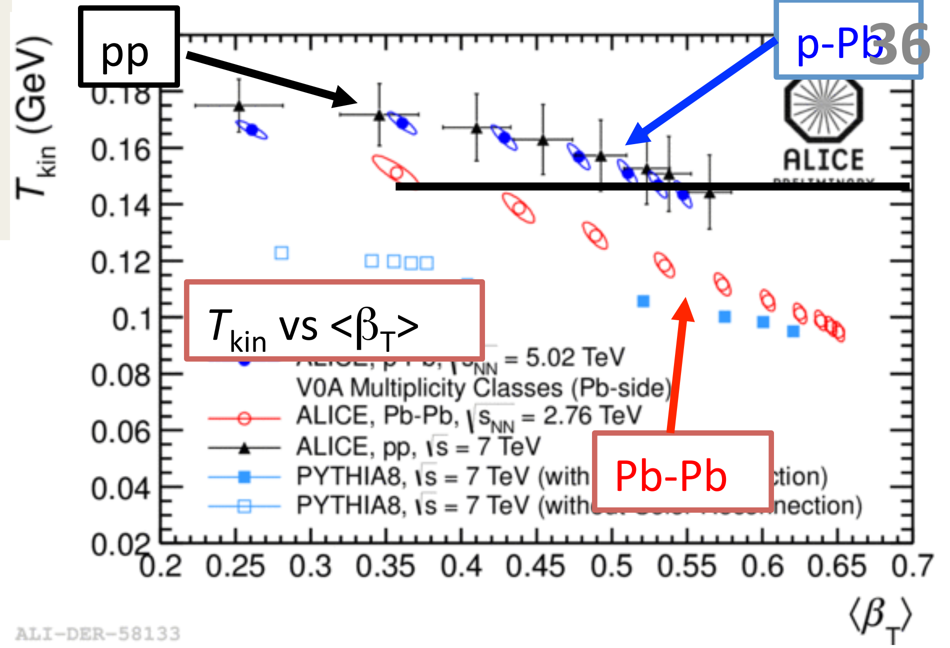
- "Cronin peak" around 3-4 GeV/*c*
- Shows dependence on particle type (mass)
  - No peak for π, K
  - Rather pronounced for p, Ξ
  - Weak for ϕ

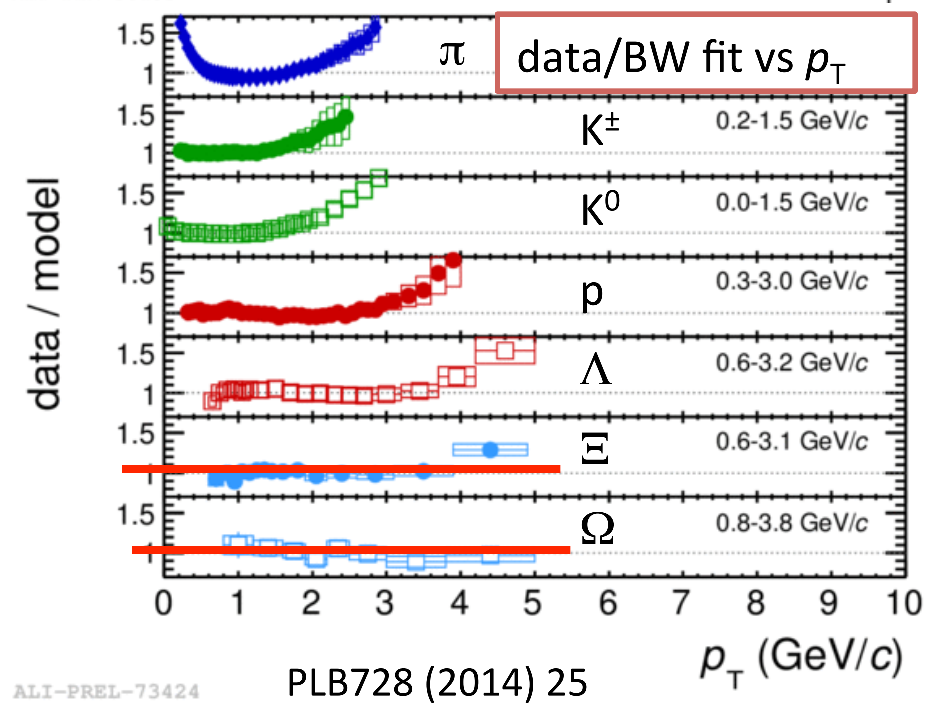




Radial Flow

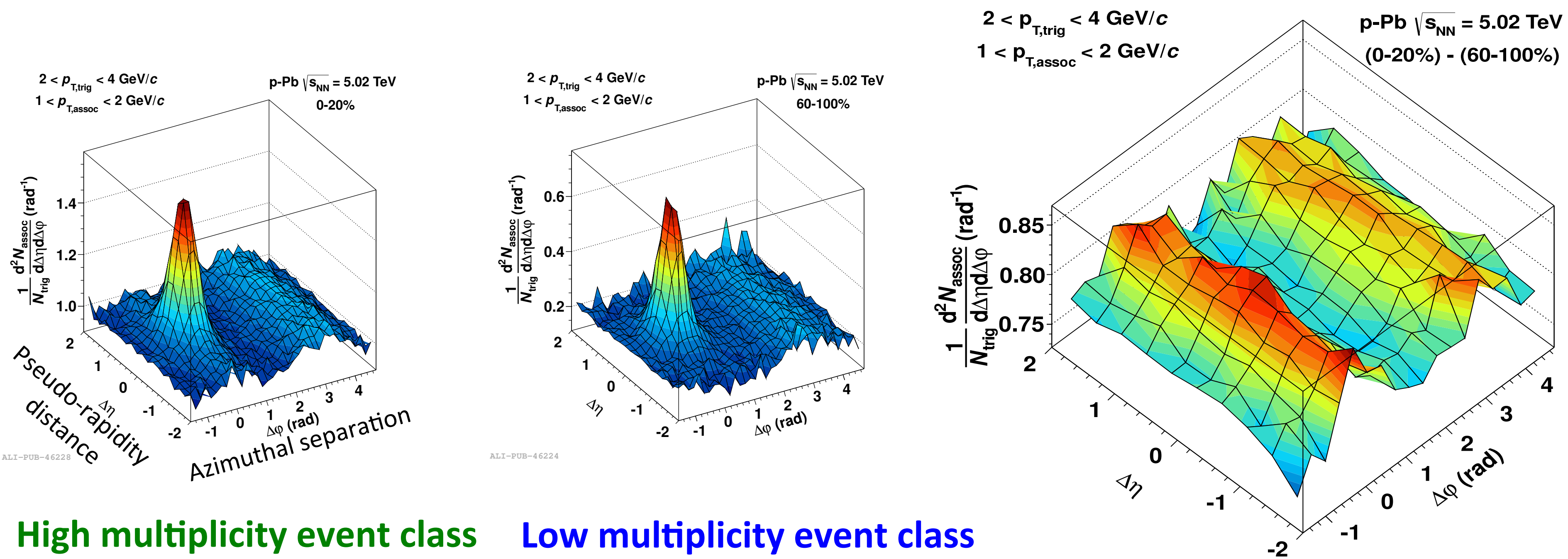
- Blast-wave fits - a proxy for hydrodynamic modeling
  - Coherent fit for π, K, p, K^0, Λ, Ξ, Ω
- At same N_{ch}, $<\beta_T>$ larger in p-Pb than in Pb-Pb
  - Larger density gradient
- However $<\beta_T>$ similarly large in pp and p-Pb (at same N_{ch})





Two-particle correlations in p-Pb

The method: from the high-multiplicity yield subtract the jet yield in low-multiplicity events (no ridge)



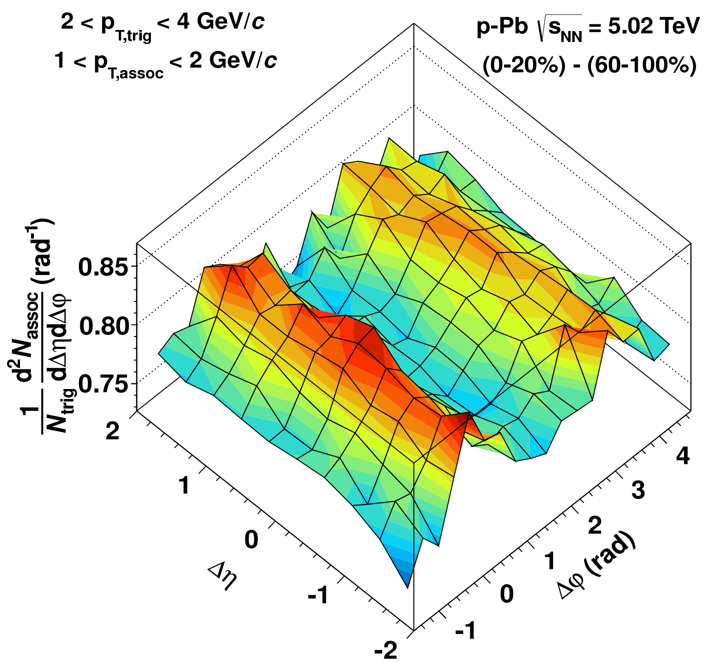
High multiplicity event class
$\langle dN_{ch}/d\eta \rangle \sim 35$

Low multiplicity event class
$\langle dN_{ch}/d\eta \rangle \sim 7$

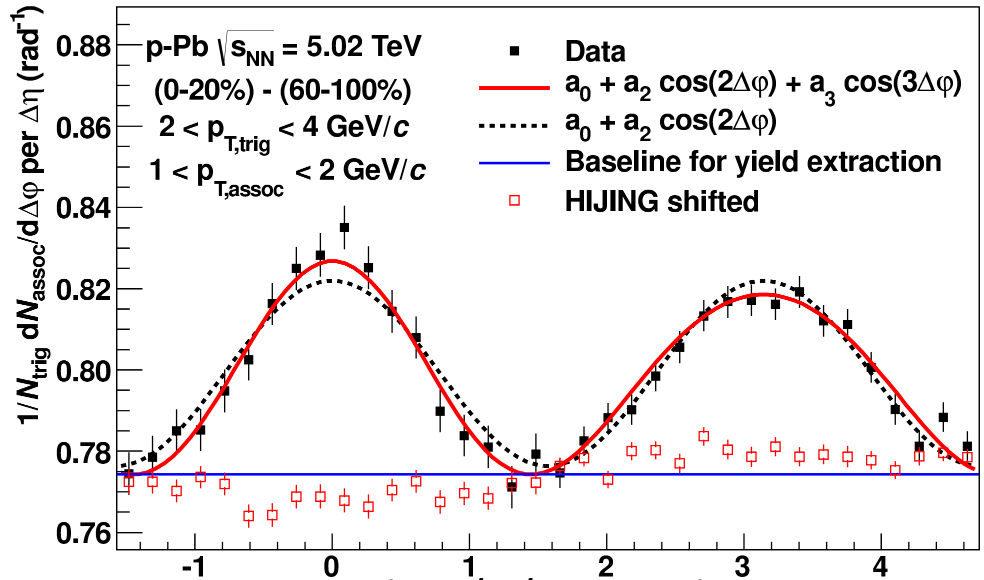
Remaining correlation: two twin long range structures

Analysis in multiplicity classes defined by the total charge in VZERO detector (away from the central region)

Twin ridge structure in p-Pb



Remaining correlation described by finite amplitudes of Fourier terms



Azimuthal separation

Further investigations reveal:

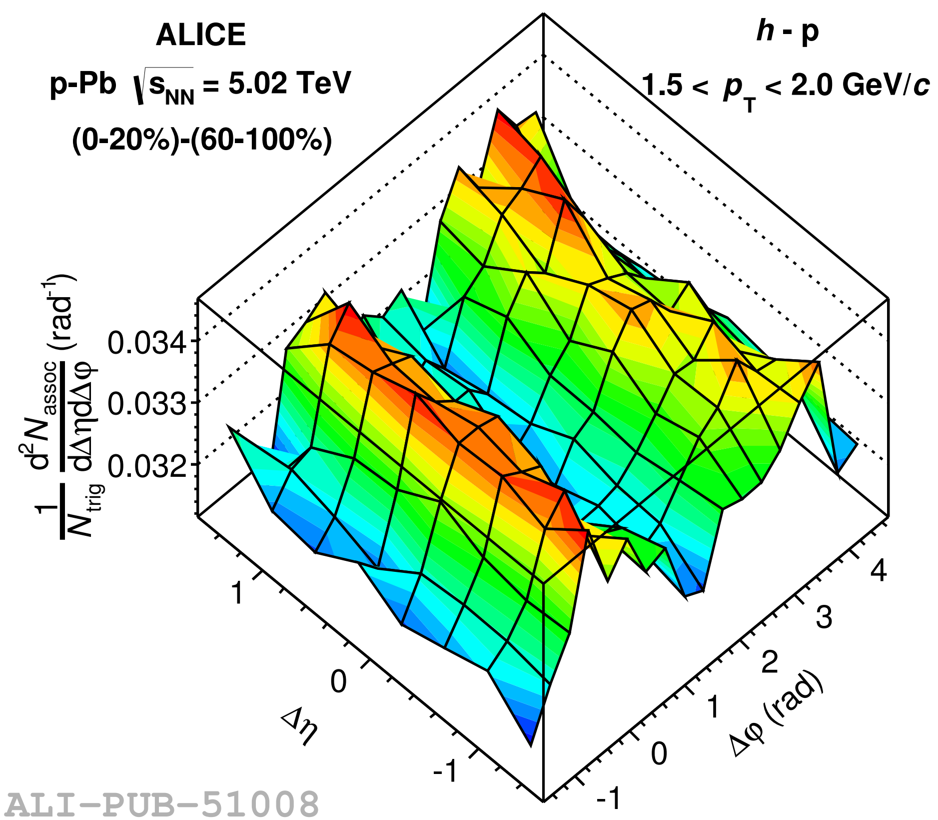
- **the full modulation is (1) di-jets and (2) the double-ridge structure – nothing more**
- **Same yield near and away side for all classes of p_T and multiplicity suggest a common underlying process**

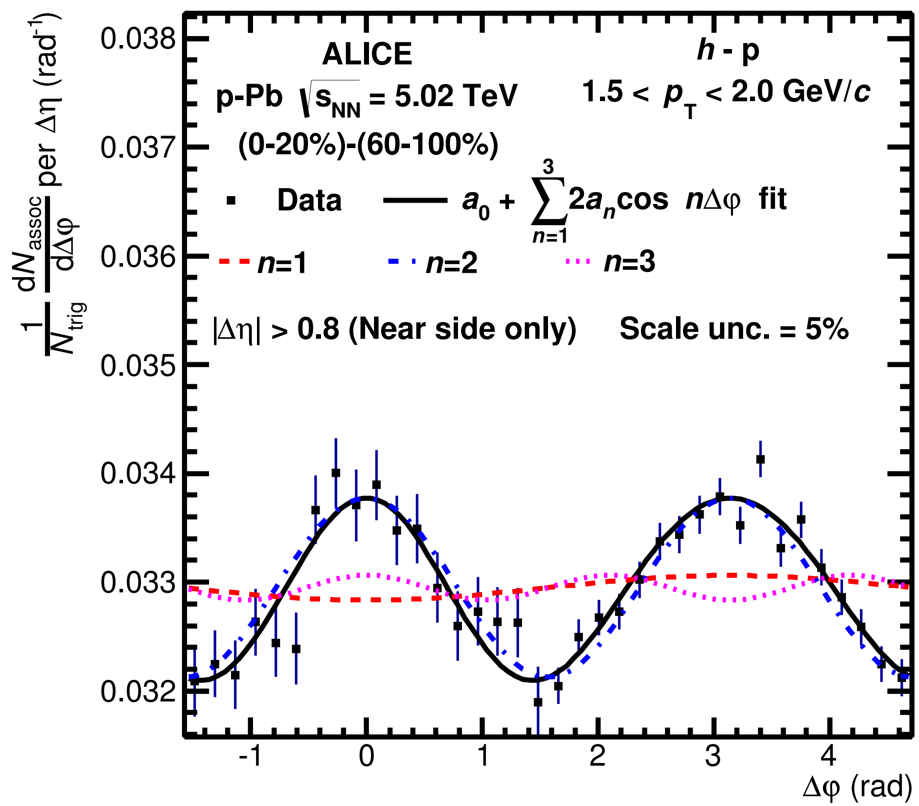
Similar observations in Pb-Pb are ascribed to collective effects!

Number of explanations put forward raging from hydrodynamic flow to CGC formalisms

Twin ridge structure in p-Pb with identified particles

Shown here: hadron-proton correlation (high-low mult. percentile subtracted)

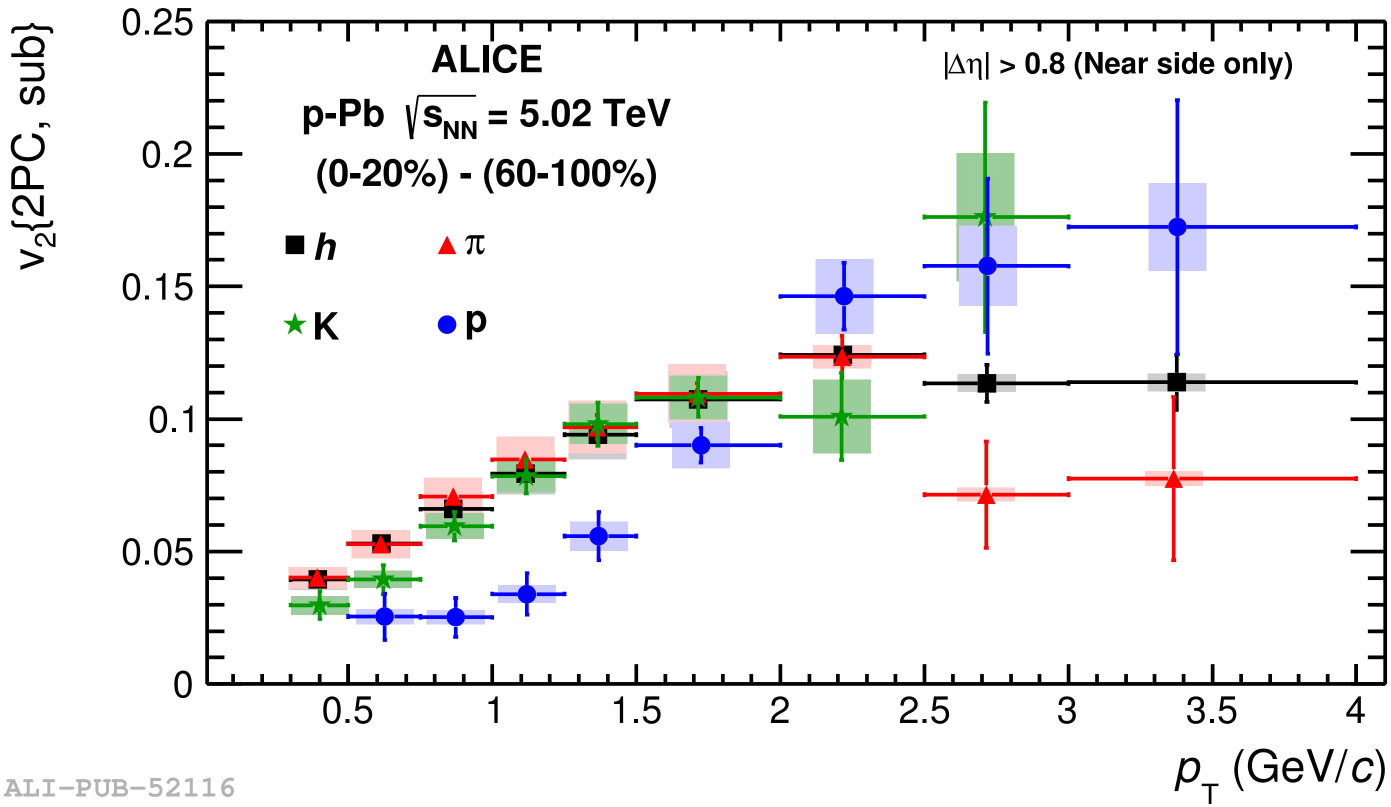




Jet peak excluded: Δη < 0.8

v_2 coefficient in p-Pb

PLB719 (2013) 29
PLB726 (2013) 164

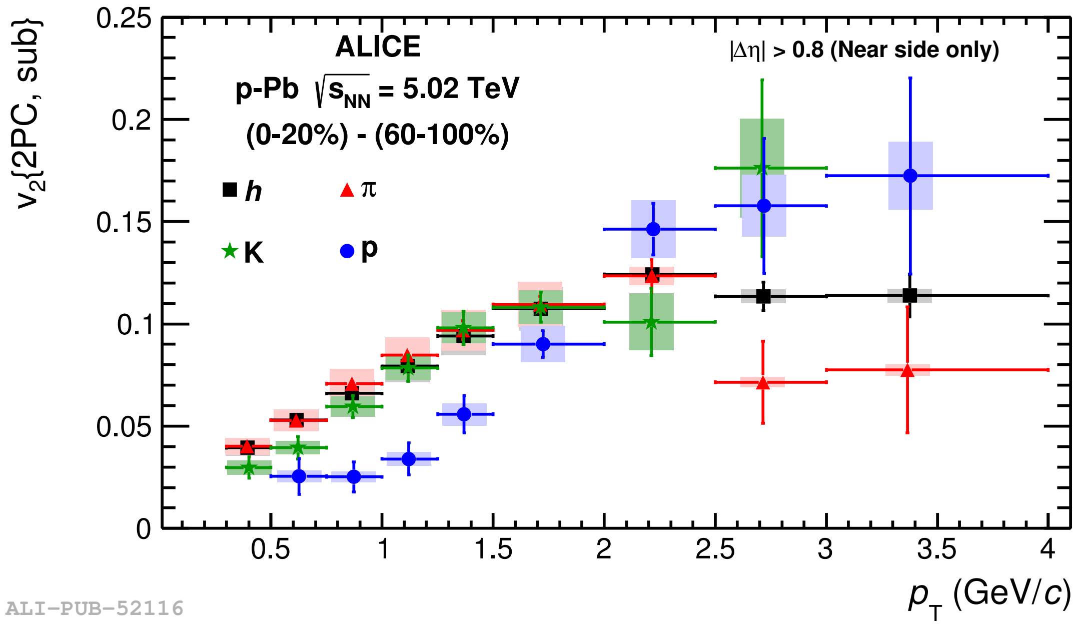


Mesons (pions and kaons) following the same trend (<2.5 GeV/c)

Intersection with protons ~2 GeV/c

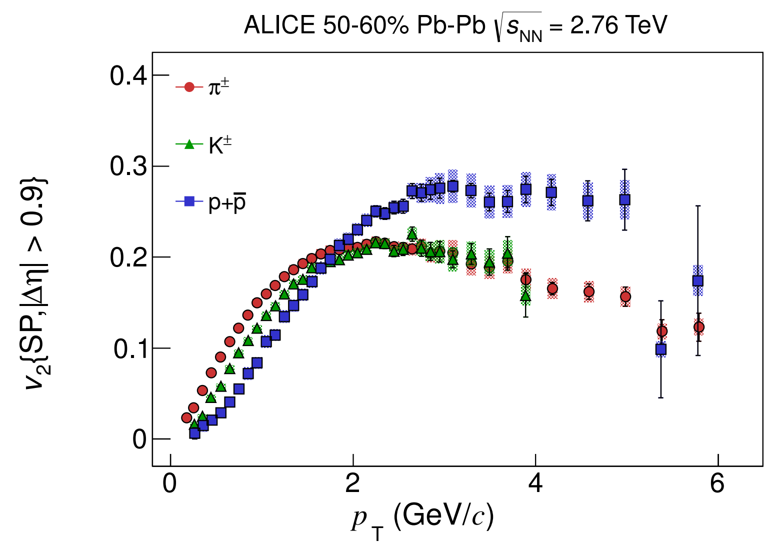
Comparison of v_2 in Pb-Pb and p-Pb

High-multiplicity p-Pb collisions



ALI-PUB-52116

50-60% Pb-Pb

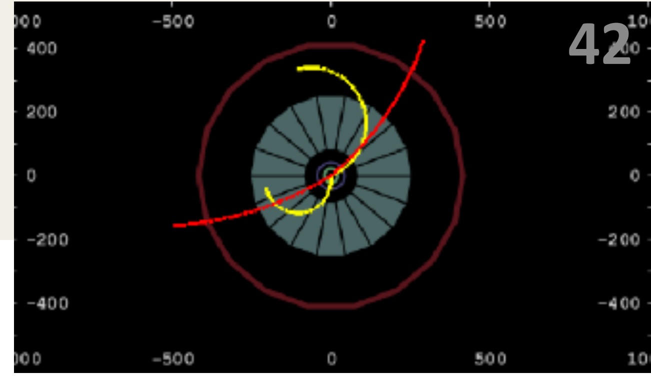


I-PUB-83874

Similar features in p-Pb and Pb-Pb: mass ordering at low-p_T in Pb-Pb ascribed to hydrodynamics

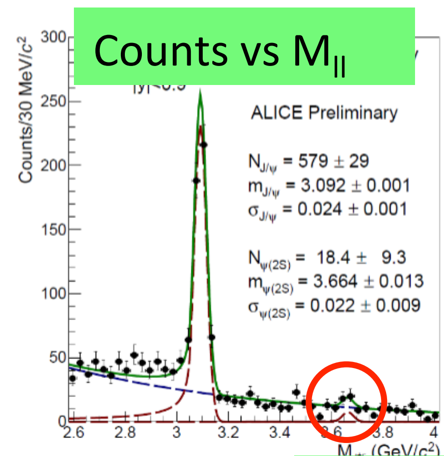
- Not shown: more signatures for collectivity from cumulant analysis

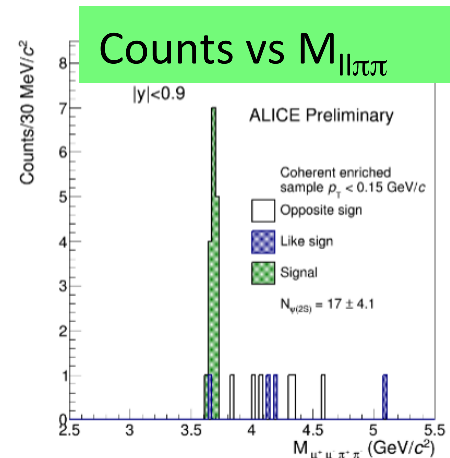
More from ALICE! Ultra-Peripheral Collisions

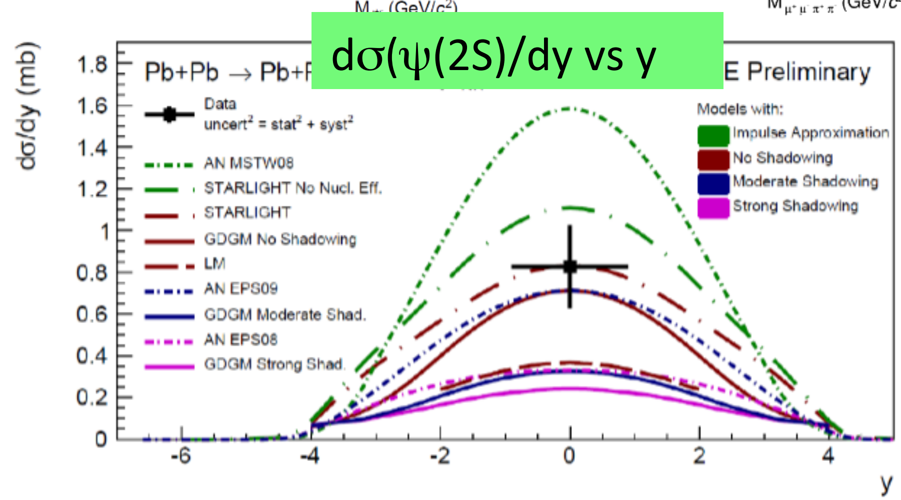


- Coherent J/ψ photo-production
  (PLB718 (2013) 1273, EPJC 73 (2013) 2617)
- **First measurement of exclusive ρ^0**
- First measurement of ψ(2S) photoproduction in a nuclear target
  - ψ(2S) → l^+l^-
  - ψ(2S) → l^+l^- + $\pi^+\pi^-$
- Strong model constraints
  - Strong shadowing disfavored
  - No nuclear effects disfavored

Talk by Christoph Mayer

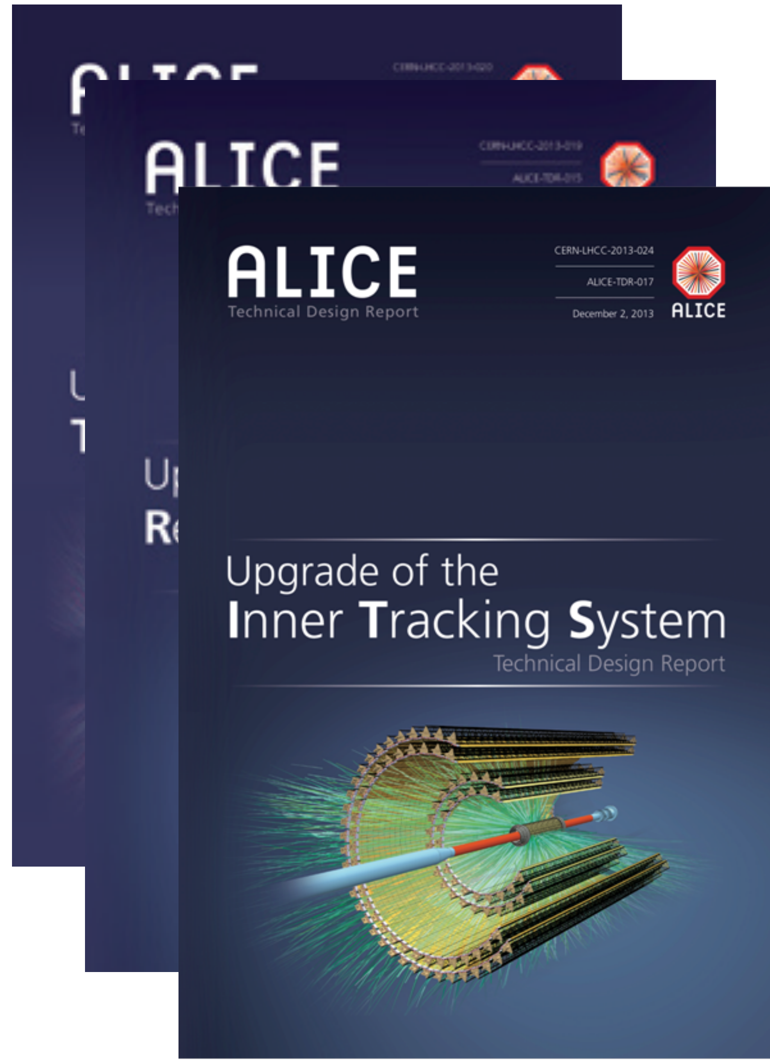






Run II and Upgrade

- Run II in 2015 – 2017
  - Updated detectors, readout, trigger
  - LHC energy up to 13 TeV for pp (~5.1 TeV for Pb-Pb)
  - Factor 2-3 to 10 increase in pp, p-Pb and Pb-Pb depending on channel
- ALICE underway for physics in the 2020s
  - New ITS and new TPC readout
  - Increase data-taking rate by factor 100! (→ 50kHz Pb-Pb continuous)
  - Heavy flavor, quarkonia, low-mass dileptons, jets …



Summary

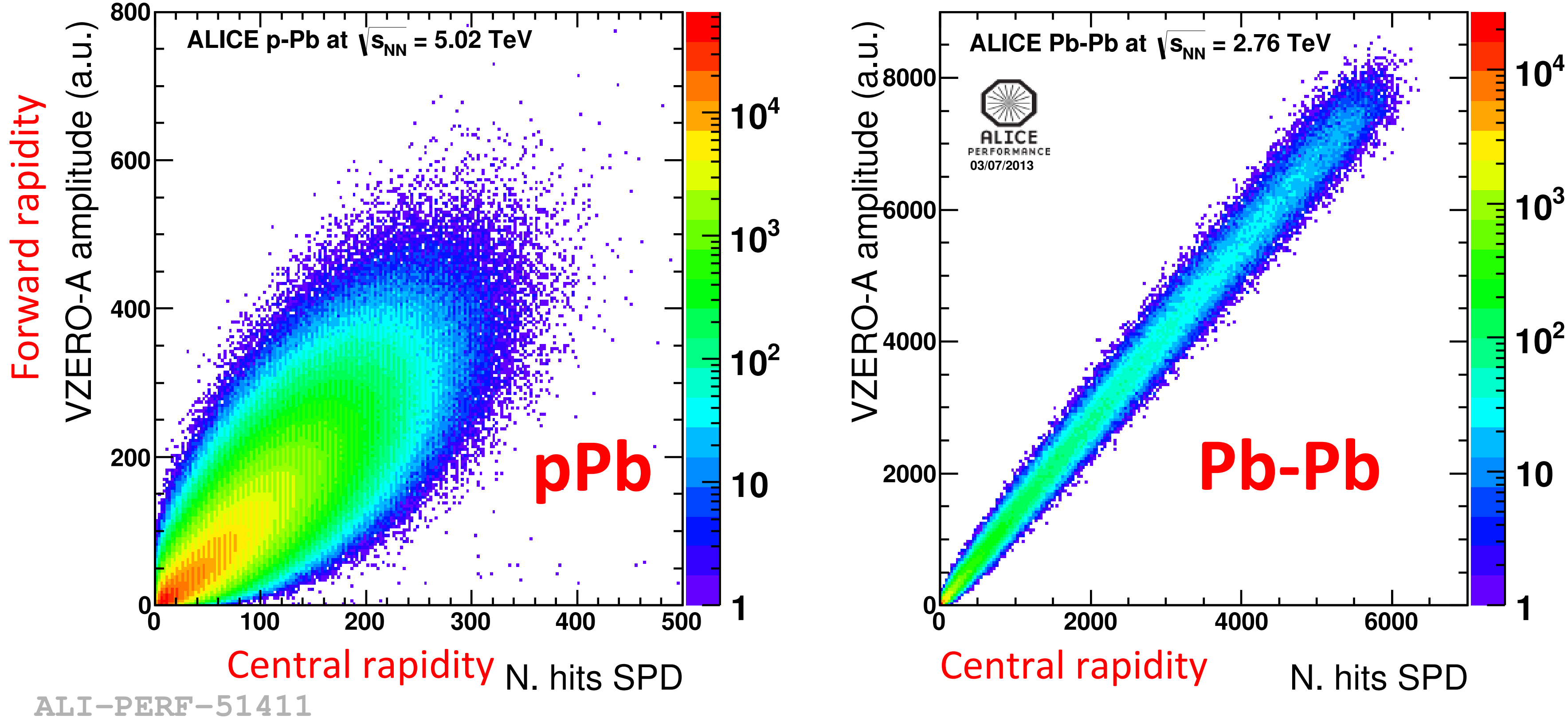
- QGP is opaque to colored probes $R_{AA} < 1$; signatures of different energy loss for charm and bottom quarks
- Collective flow measured for identified particles in Pb-Pb collisions; features consistent with hydrodynamical nature of QGP (RHIC: even at lowest $\sqrt{s_{NN}}$)
- Measurements of v_2 and R_{AA} – complementary observables – discriminating input to theory
- Minimum bias collisions of p-Pb confirm jet quenching in Pb-Pb is a final state effect
- However, finite v_2 and other signatures of collective effects are found in most violent p-Pb collisions resembling findings from Pb-Pb collisions (!)
- Intriguing suppression patterns for ψ(2S) in p-Pb collisions – signature of final state interactions?
- Wealth of results – interesting learning curve ahead!

EXTRA SLIDES

Broad view outline

- Heavy-ion collisions at LHC energies
  - Extract physical properties of the hot de-confined QCD matter: $T \gg T_c$ at $\mu_b = 0$
  - Must have: sensitivity of observables to QGP effects
- pA collisions: cold nuclear matter
  - Understanding of initial state of AA collisions
  - Must test: sensitivity of observables to QGP effects
- proton-proton collisions:
  - Vacuum reference; p-QCD jet cross-section
  - Single NN ≠ single parton-parton interaction
  - Is this the best reference for all observables?

Intermezzo: p-Pb multiplicity

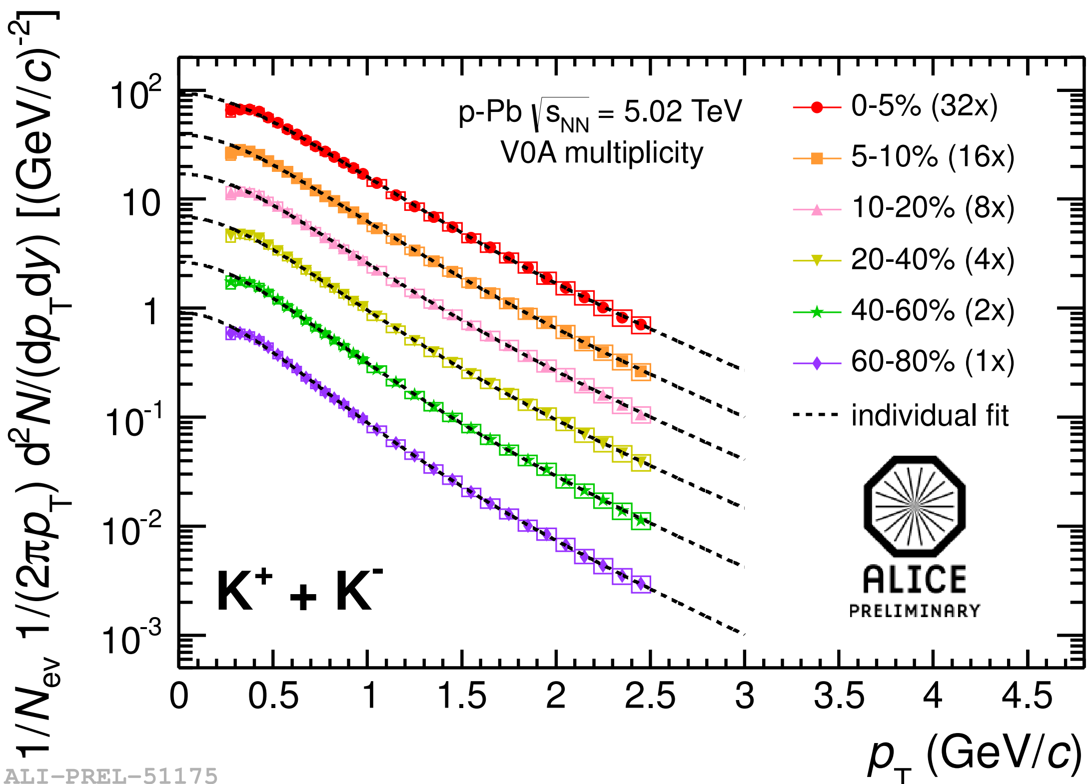


Much broader correlation between different multiplictiy (event class) estimators

$\Rightarrow$ expect different sensitivity (bias) to event geometry (Glauber! – Ncoll scaling)

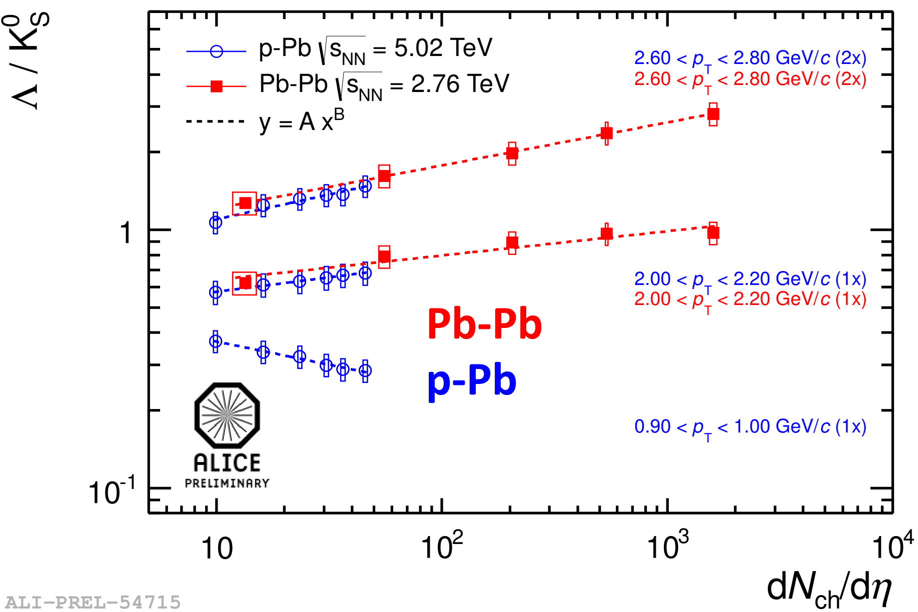
Identified particles in p-Pb

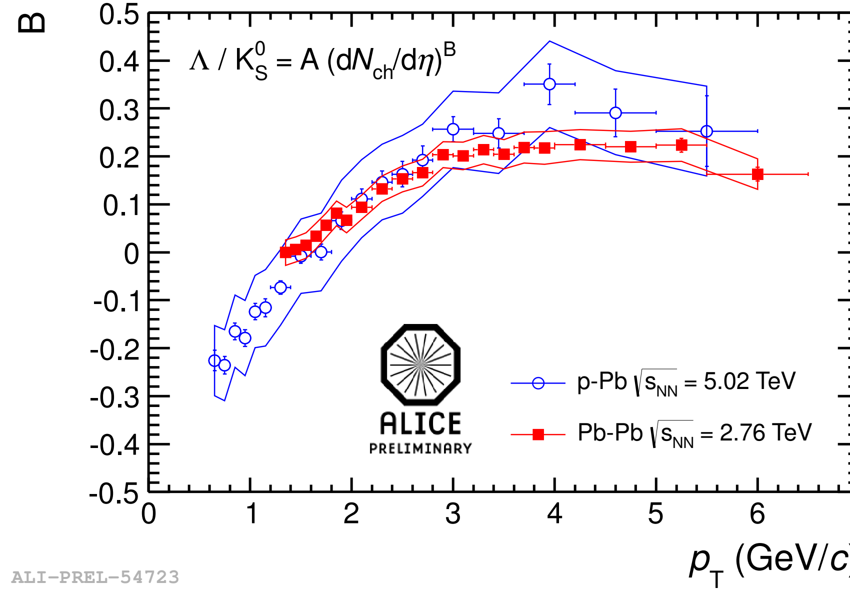
- Yields of pions, charged kaons, protons (TPC+TOF) and K0s, Lambda's (inv. mass)
- Binned in percentiles of multiplicity of VZERO-A detector
- Fitted with blast-wave
- Not shown: studied <pT> (mass ordering present)
- and ratios of particles (dependence on dN/dh similar in pp, pPb and PbPb)



Identified particles in p-Pb

Lambda/Kaon ratio vs. charged particle multiplicity density $R = A(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)^{\mathrm{B}}$





- Baryon to meson ratio:
  - **similar trend of p/pion ratio in p-Pb as in Pb-Pb per $dN_{ch}/d\eta$**
  - follows a **power-law with a same exponent $B(p_T)$** in two systems (although in p-Pb much smaller than in Pb-Pb case) - similar case for proton/pion ratio

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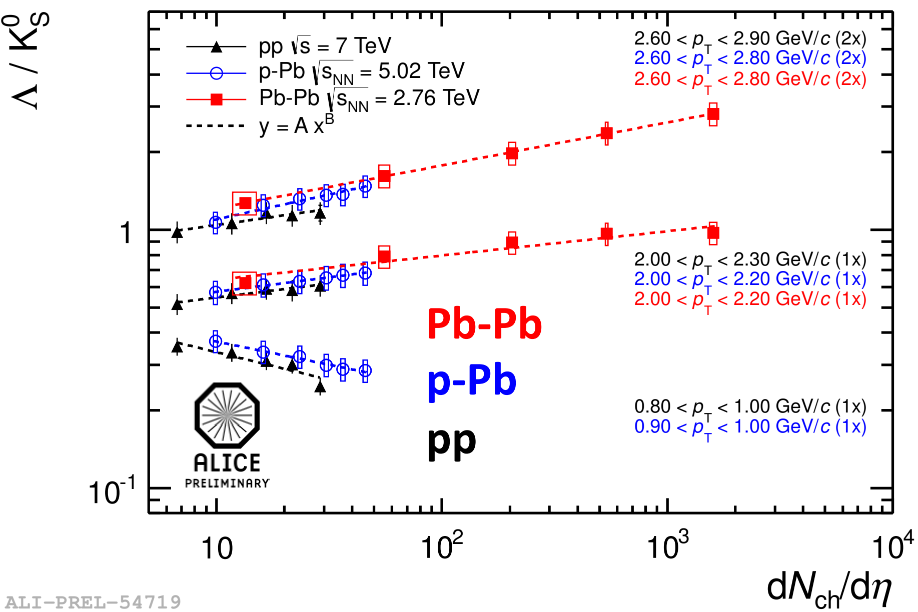

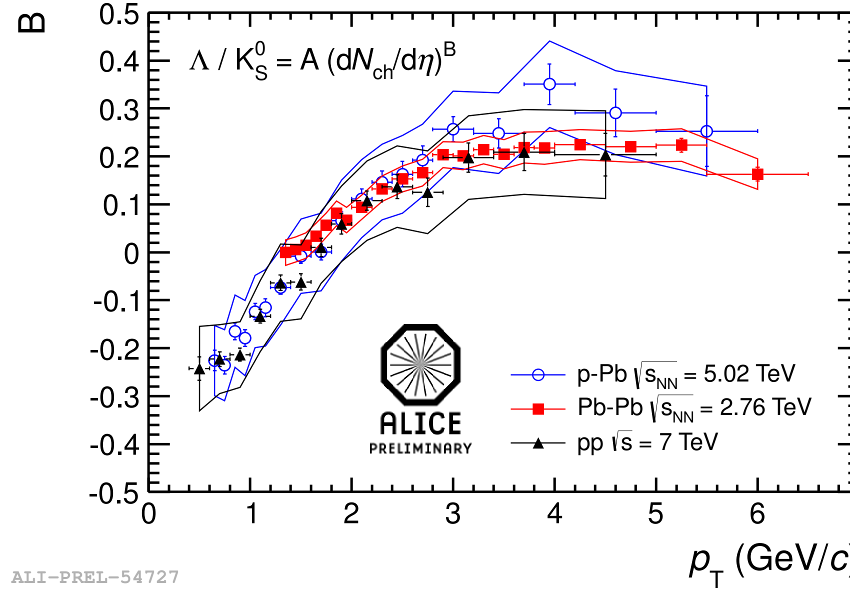

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  - follows a **power-law with a same exponent $B(p_T)$** in two systems (although in p-Pb much smaller than in Pb-Pb case) - similar case for proton/pion ratio
  - **Same trend in proton-proton collisions**

Results from p-Pb

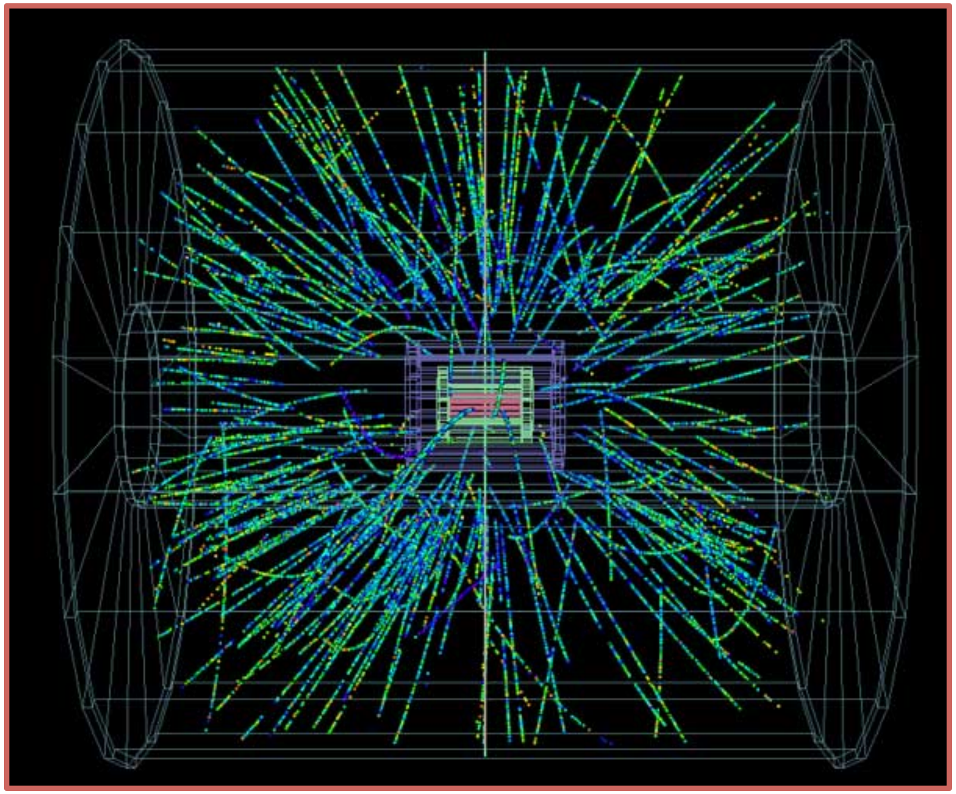
p-A: Address cold nuclear effects and calibrate findings related to hot QGP

Valuable reference measurements for high-p_T physics

New unexpected effects…

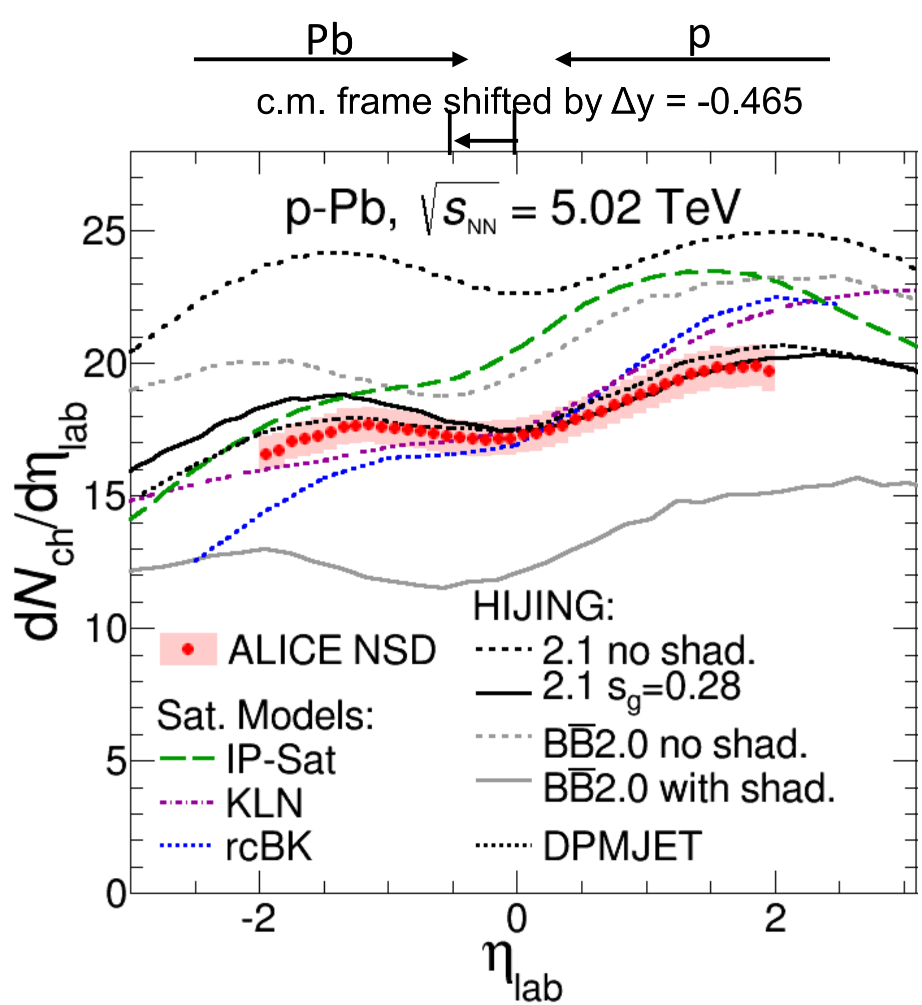
$\sqrt{s_{NN}}$=5.02 TeV

A p-Pb collision at ALICE side-view



"Calibration" measurement – $dN_{ch}/d\eta$

ALICE: arXiv: 1210.3615



Basic measurement allows to discriminate between models

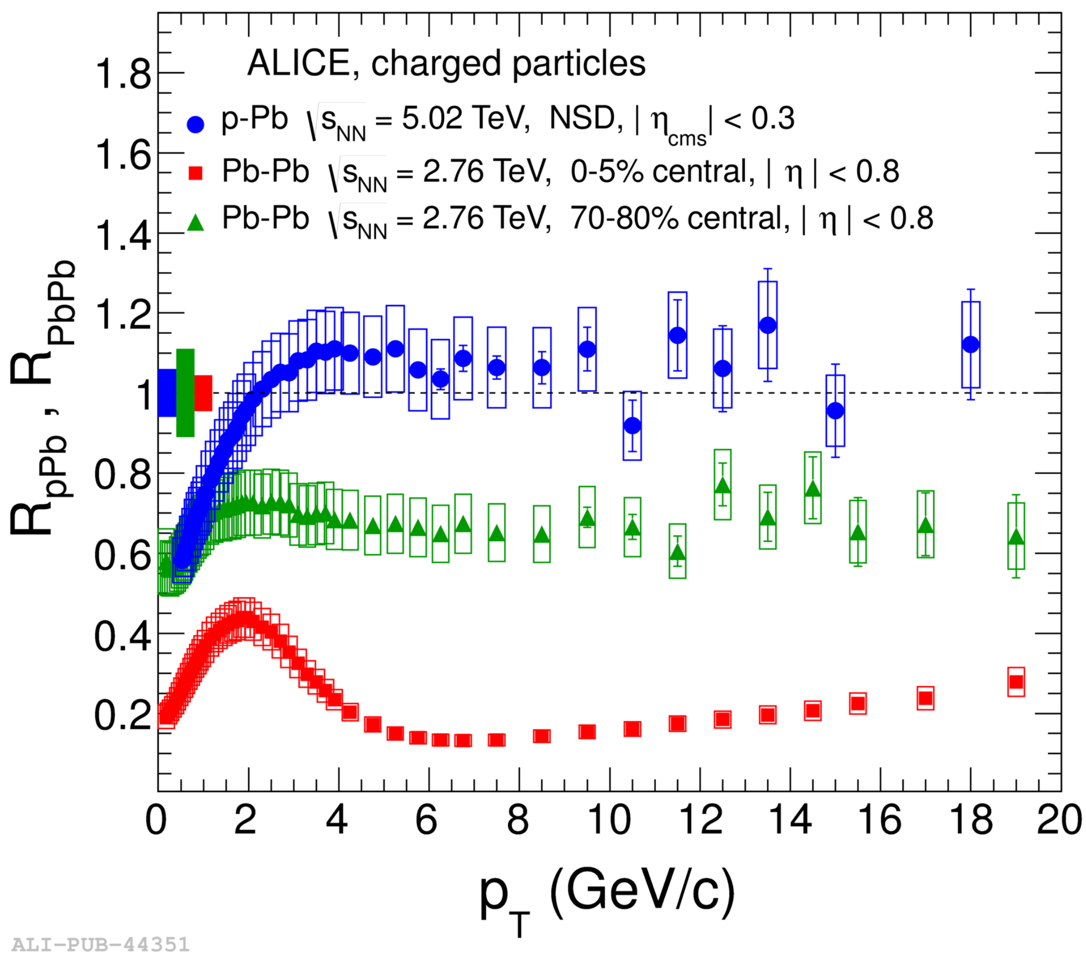
Data favors models that incorporate shadowing

Saturation models predict much steeper η-dependence not seen in the data

Cold nuclear matter effects vs. jet quenching in Pb-Pb…

Ratio = particle yield in p-Pb per single N-N collision / particle yield in proton-proton

ALICE: arXiv: 1210.4520



Compatible with unity above 2-3 GeV/c

=> Binary scaling is preserved, no evidence of initial state effects

Jet quenching in Pb-Pb collisions is a final state effect (parton energy loss)

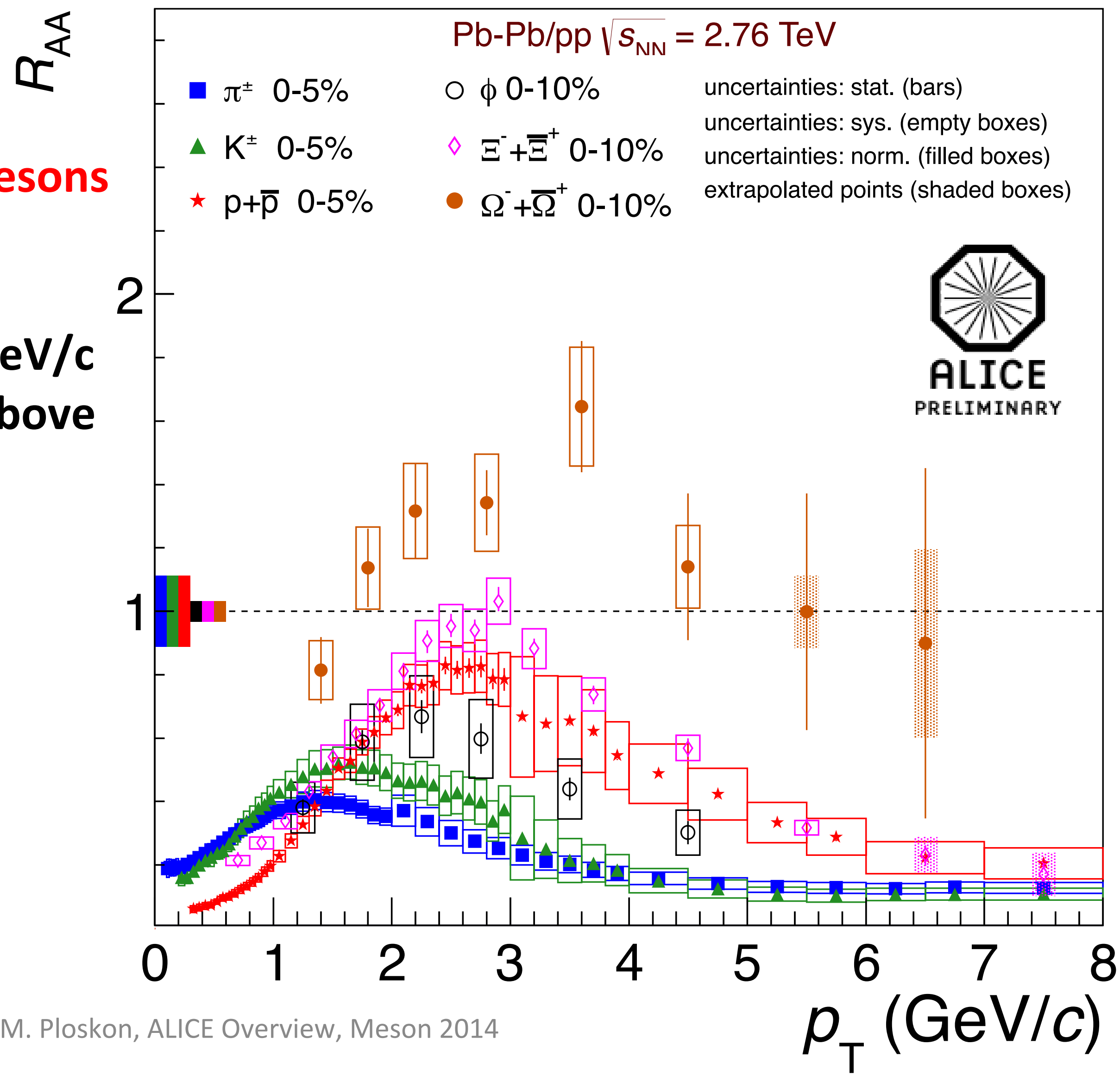
News from R_{AA} of identified particles

Same R_{AA} for π, K, p at high-p_T within uncertainties AND D-mesons

ϕ in 0-10%:
- **Similar to proton below 2 GeV/c**
- **Between pion and proton above 2 GeV/c**

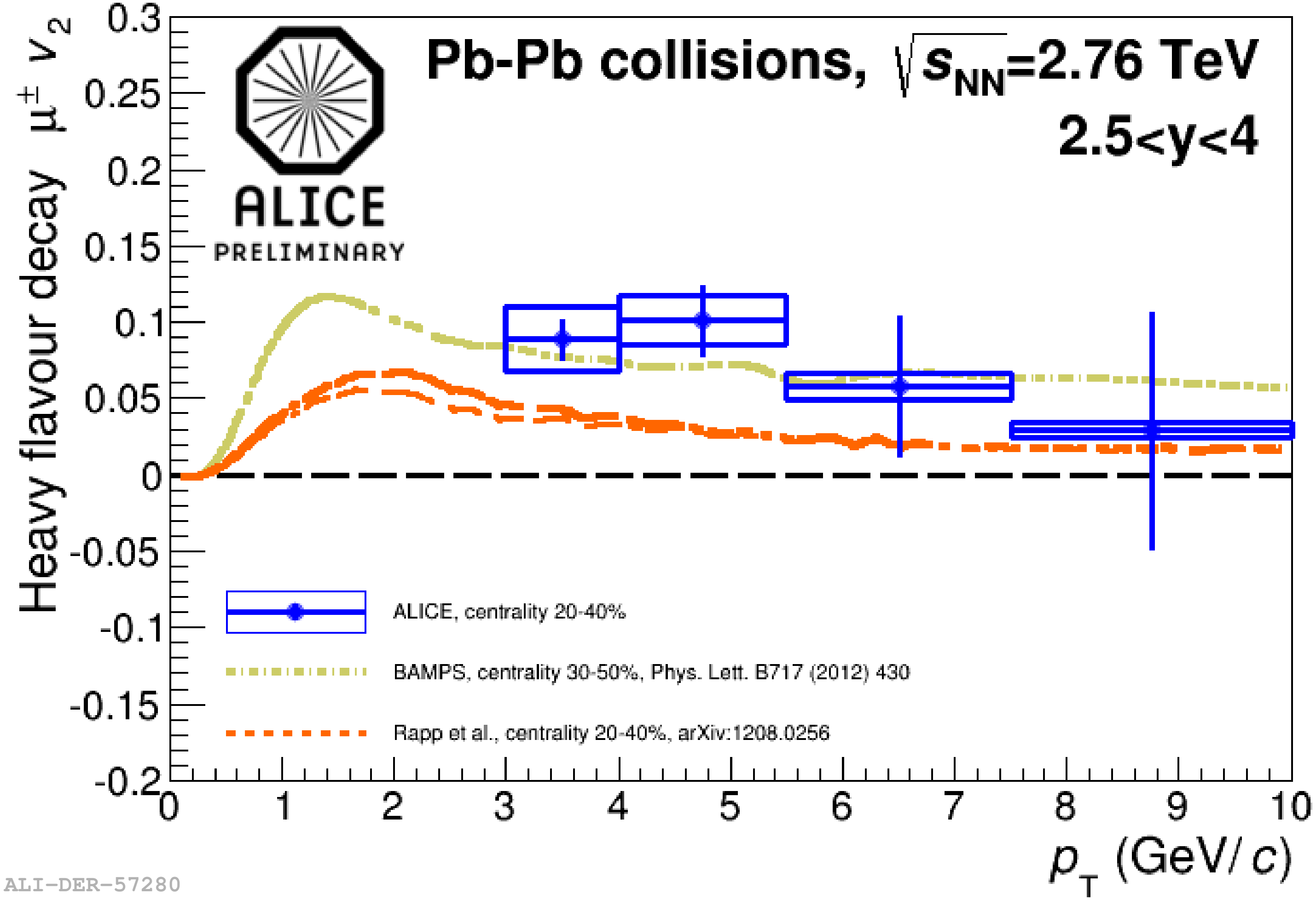
Ξ R_{AA} compatible with protons

Ω – large R_{AA} consistent with enhancement in HI collisions; however, largely due to the suppression in pp



Flow of heavy-flavor muons

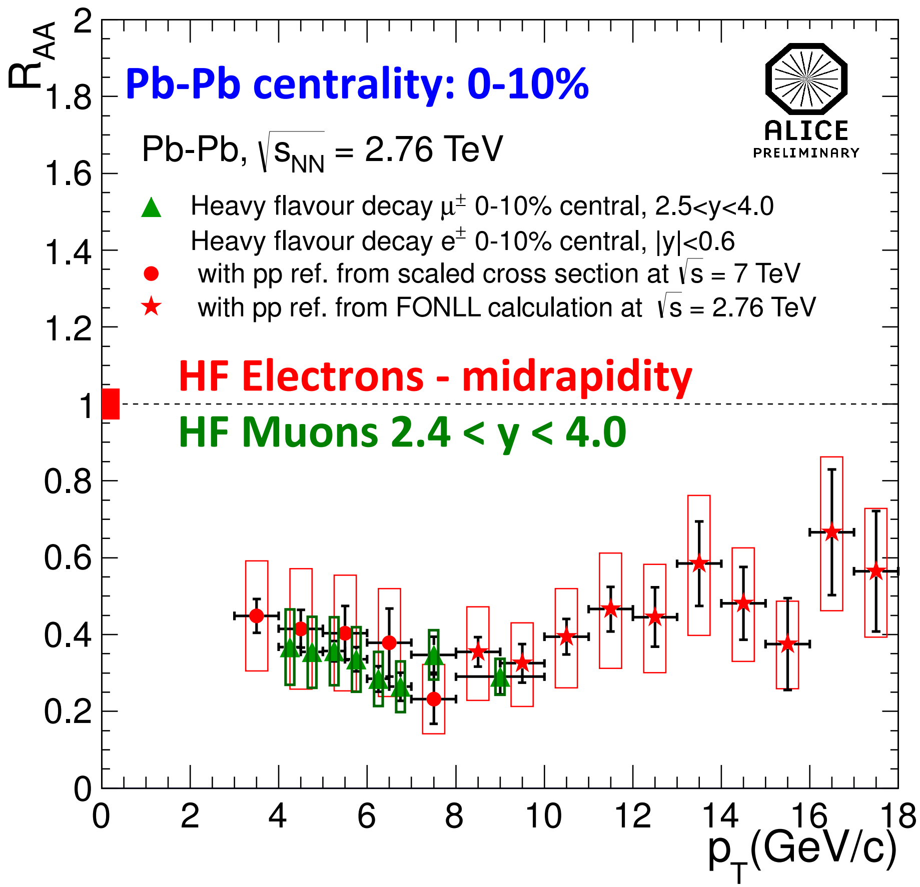
NEW

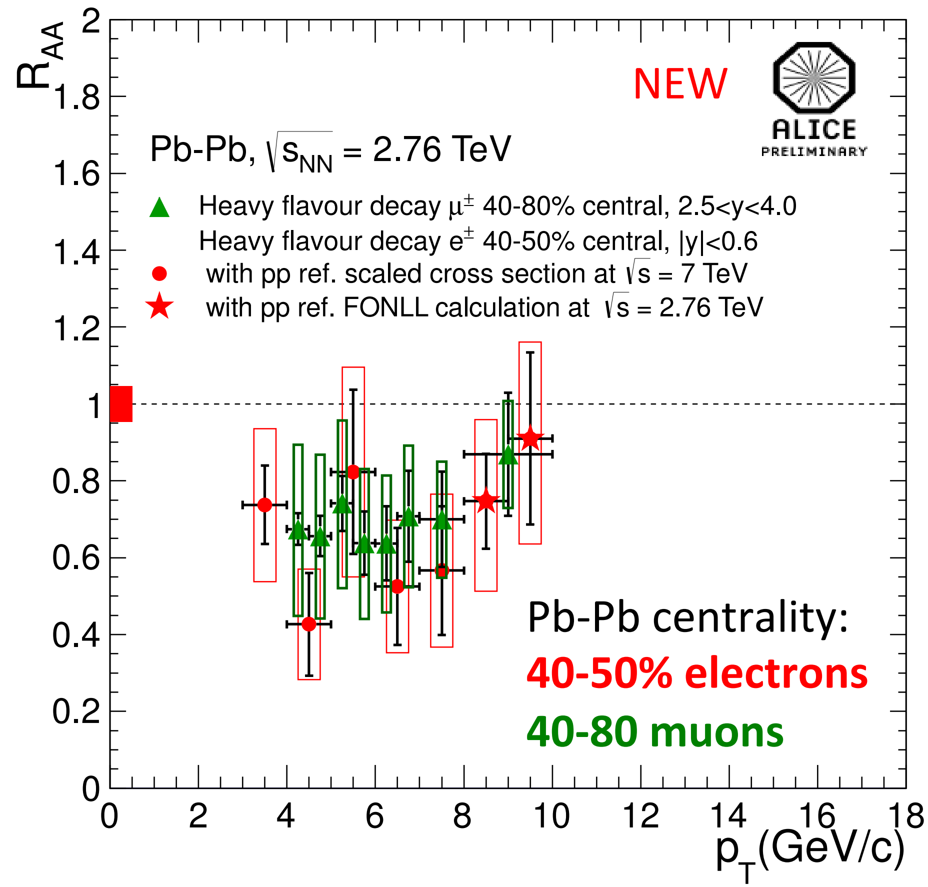


20-40%: v_2 of HFM similar as for HF-electrons in central rapidity

Heavy-flavor electrons

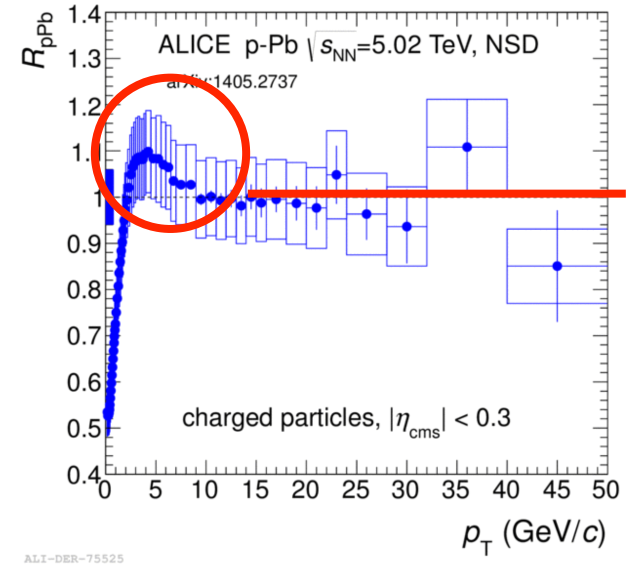
- Pb-Pb: Heavy-flavor electrons at **|η|<0.7** and heavy-flavor muons at **2.4<|η|<5**
  - **Similar suppression pattern (centrality dependence) for muons and electrons**

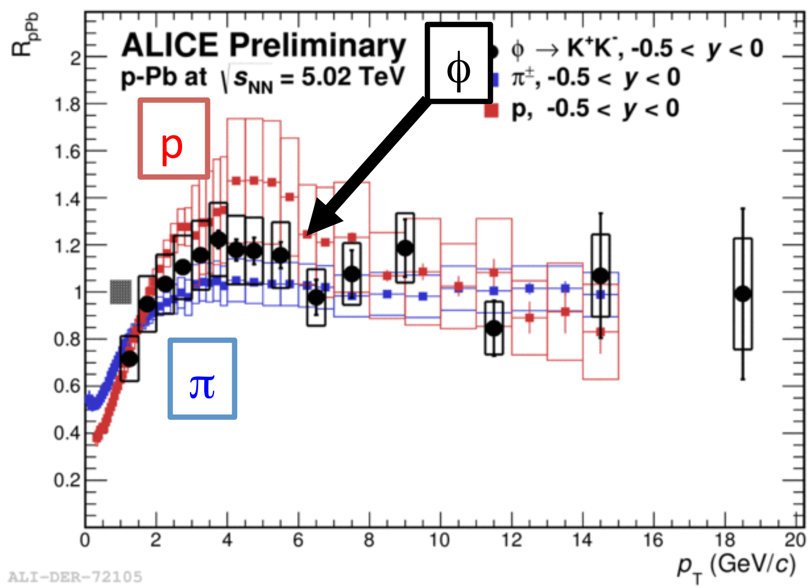




Identified R_{pA} – phi meson

- "Cronin peak" around 3-4 GeV/*c*
- Shows dependence on particle type
  - No peak for π, K
  - Rather pronounced for p, Ξ
  - Weak for ϕ





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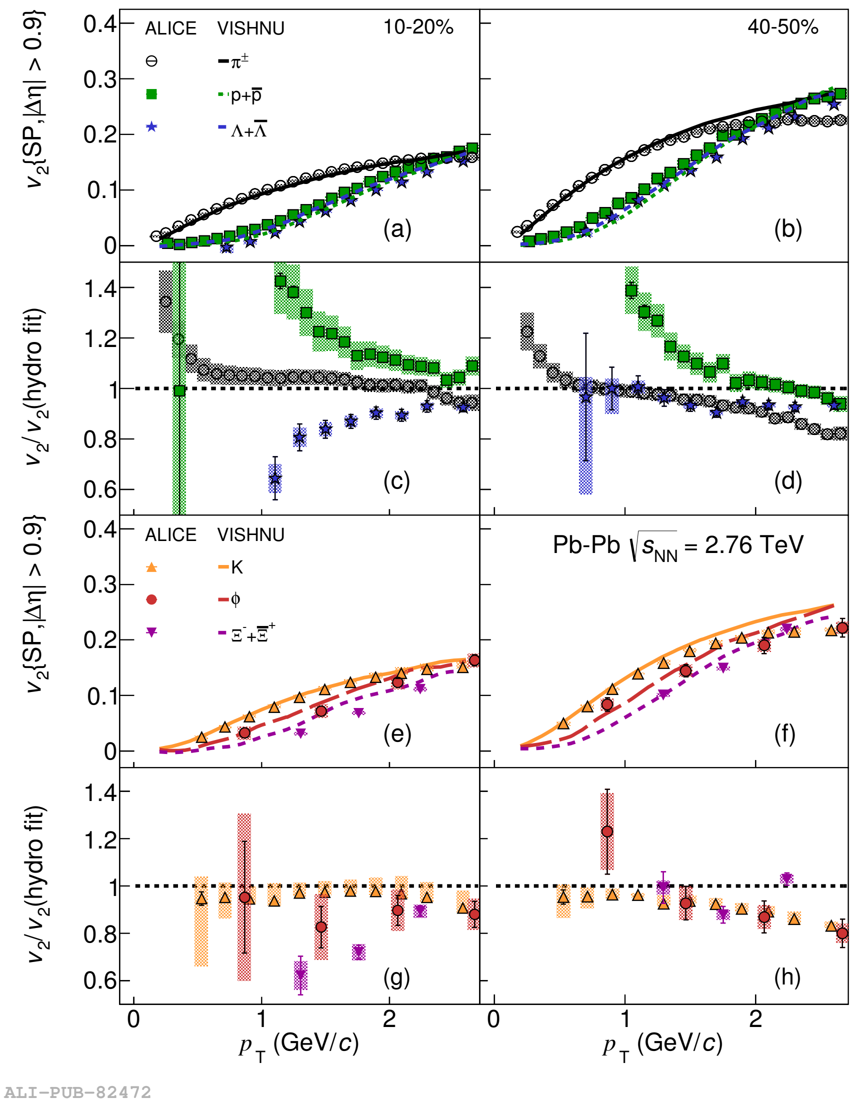
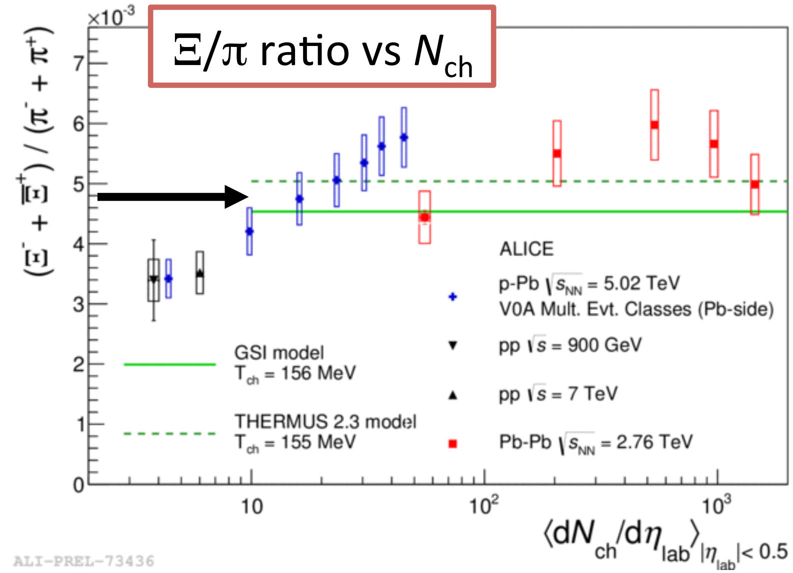
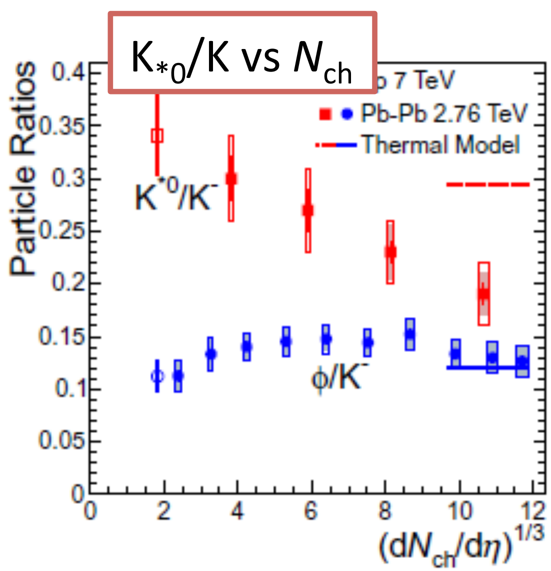
v_2 and VISHNU



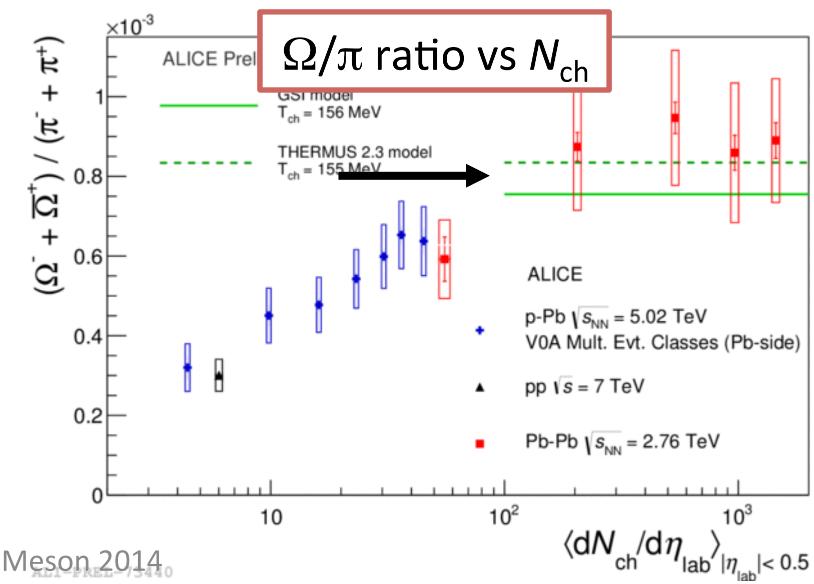
Strangeness in p-Pb and Pb-Pb

- Multi-strange baryons
  - p-Pb bridges pp and Pb-Pb smoothly
  - Ξ/π reach thermal model in p-Pb (so does the Λ/π)
  - Ω/π below thermal model
- K* suppression → rescattering?





arXiv:1404.0495



QGP Properties with J/ψ measurements

arXiv: 1311.0214

J/ψ measured with forward muon arm

J/ψ—>$\mu^+\mu^-$

- Inclusive J/ψ yield lost in central Pb-Pb collisions as compared to equivalent number of pp collisions
  - Quarkonia "melts" within QGP
- LHC: Less suppression than at RHIC and flat centrality dependence
- => in-medium ccbar recombination?
- Important: better knowledge of initial state effects crucial – cold nuclear matter / shadowing / saturation