Experimental constraints from LHC on the Quark-Gluon Plasma

(including recent results from ALICE)

Jan Fiete Grosse-Oetringhaus, CERN
for the ALICE collaboration

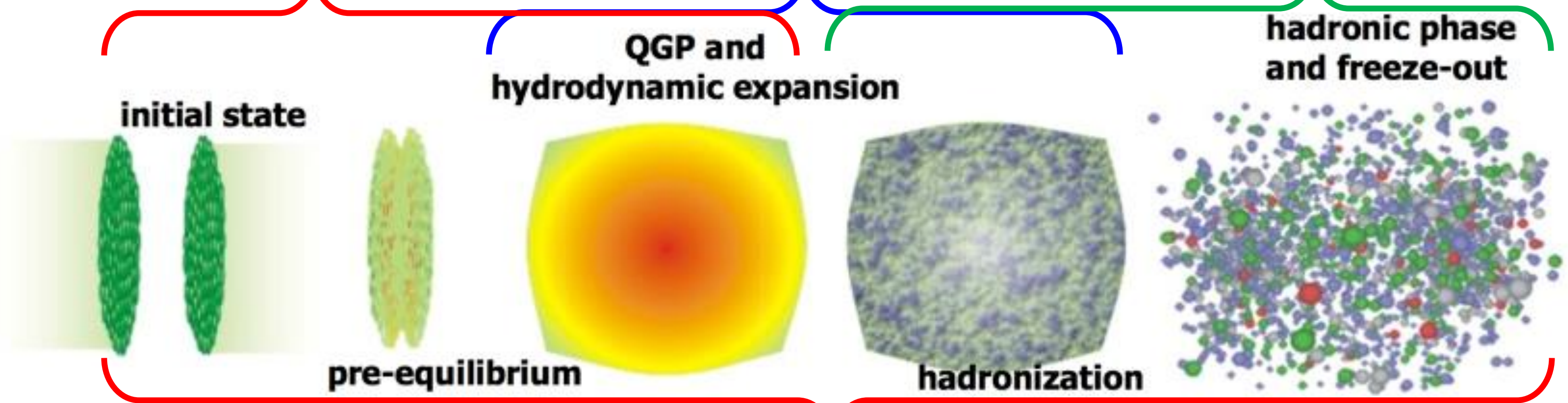
57th International Winter Meeting on Nuclear Physics
January 2019

Outline

Collective flow & hydrodynamics

Parton-medium interactions

Particle yields & hadronization



Surprises in small systems

measurement

Results & Lessons learnt

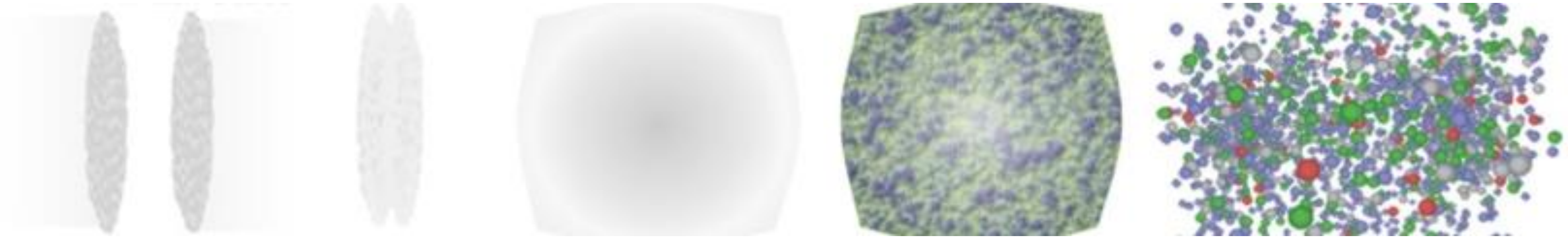
LHC Run 1 and 2 (2010–18)

projection

Prospects

LHC Run 3 and 4 (2021–29)

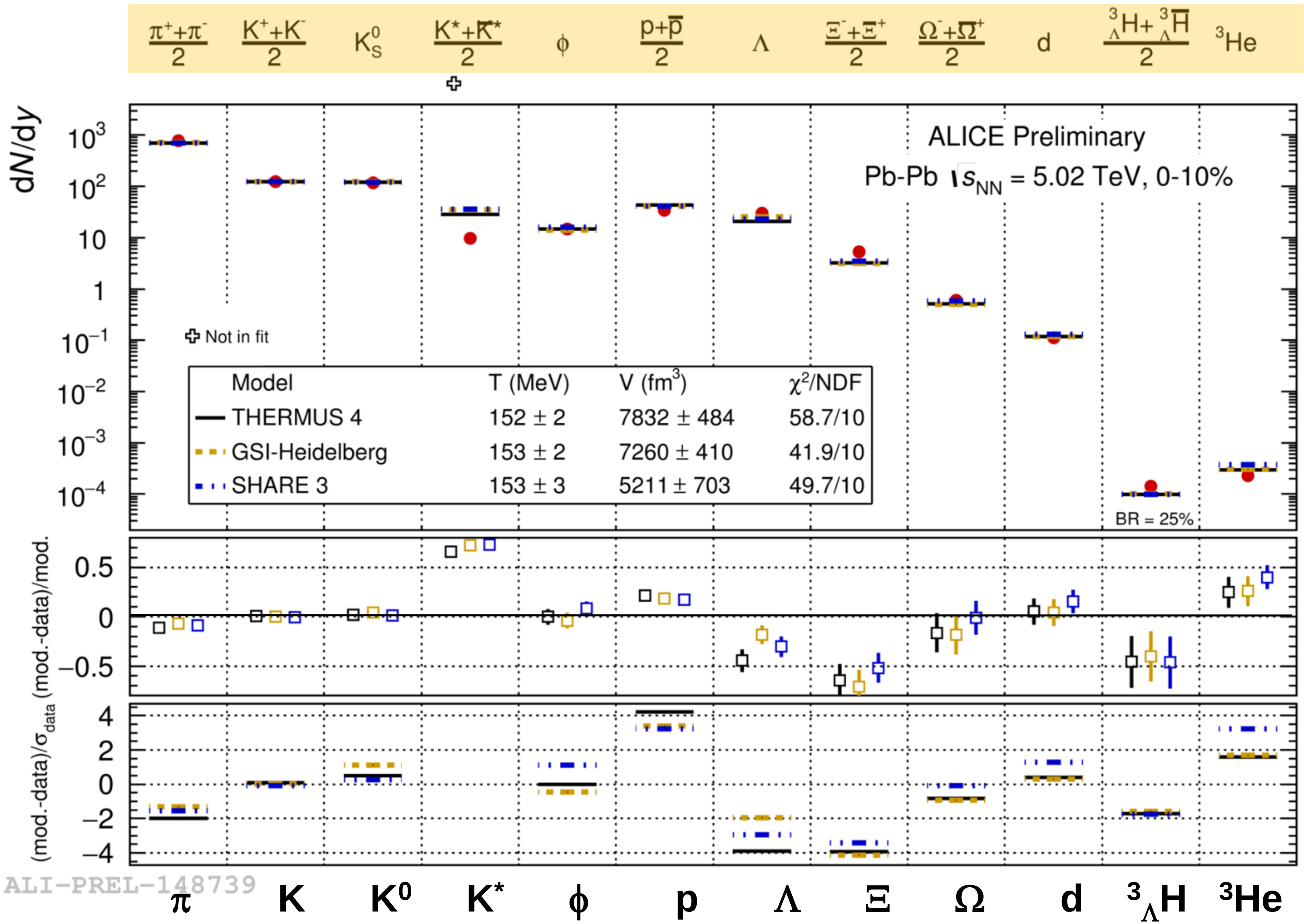
Particle Production and Hadronization



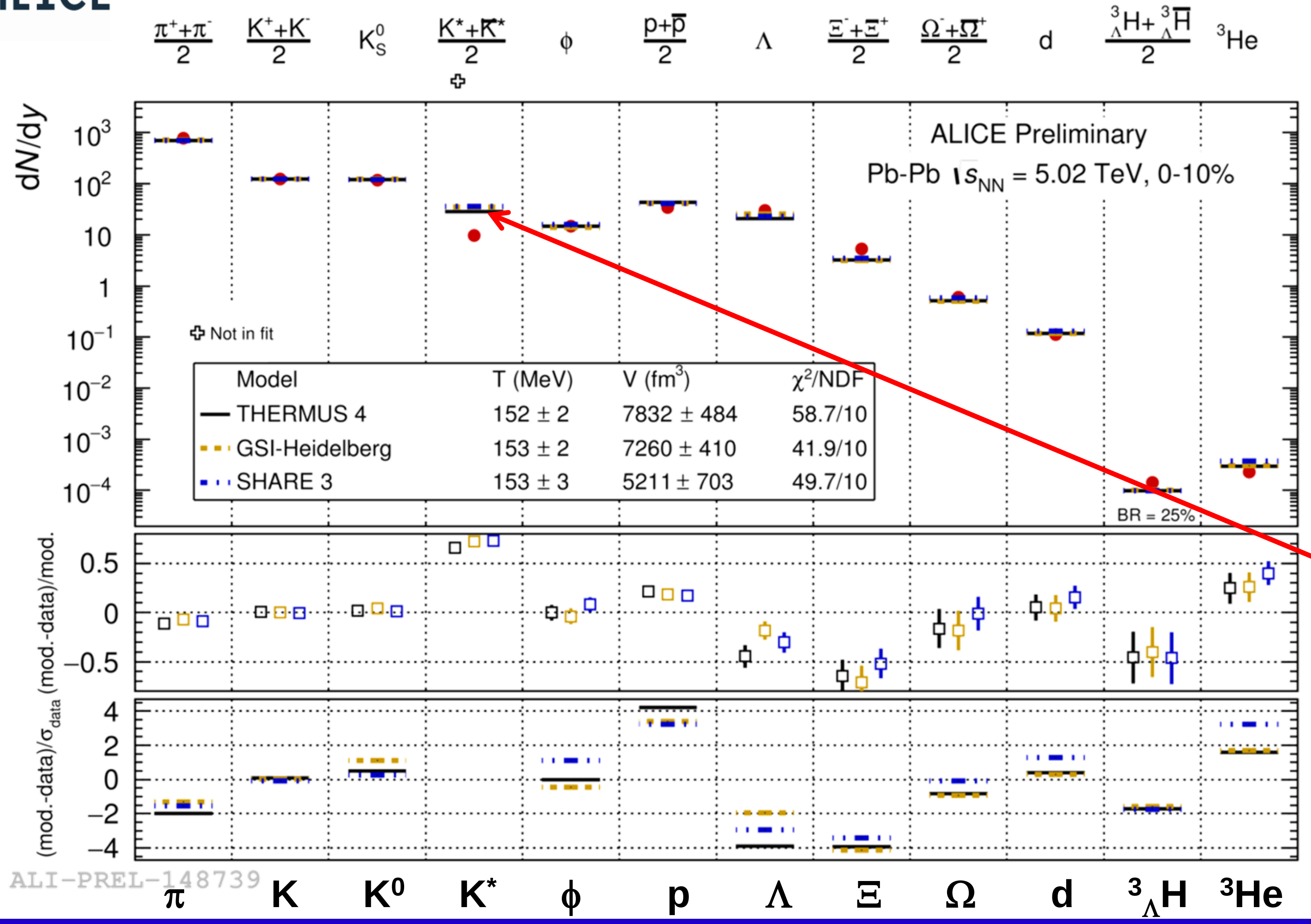
Particle Yields in Pb-Pb 5 TeV

12 different particles

7 orders of magnitude



Particle Yields in Pb-Pb 5 TeV



Fit with statistical (thermal) model

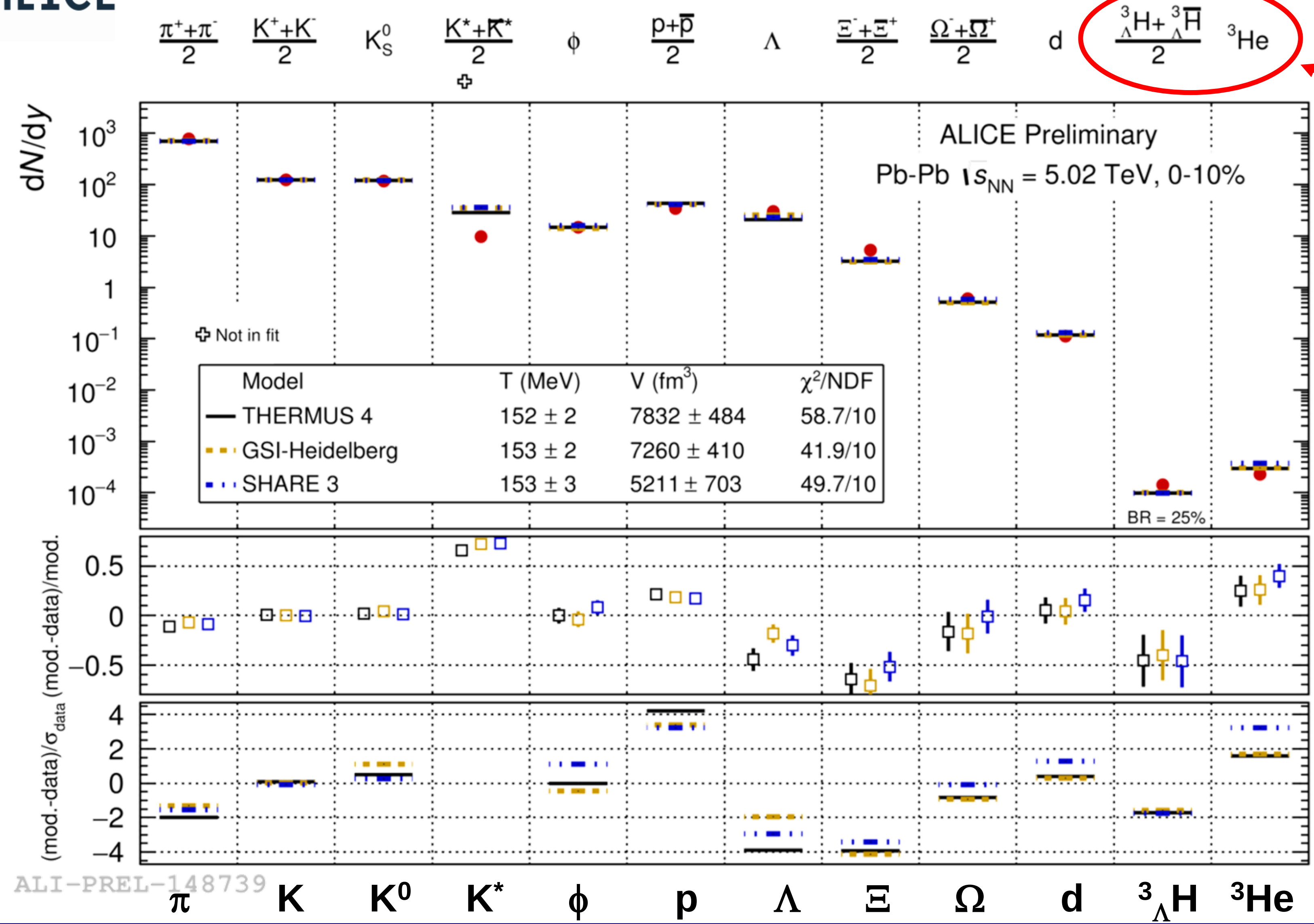
- Relativistic ideal quantum gas of hadrons
- 3 parameters: V, T, μ_B
- At LHC, μ_B ~ 1 MeV, fixed by antip/p ratio

T = 153 MeV
(3 MeV lower than at 2.76 TeV due to proton yield)

K* yields too low
→ final-state rescattering

Particle yields well described by equilibrium thermal models over 7 orders of magnitude

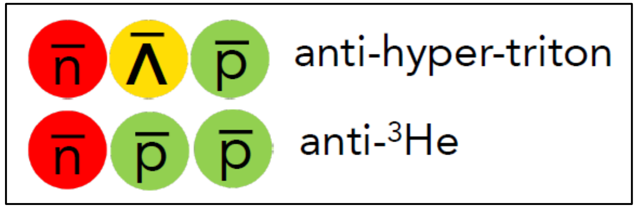
Particle Yields in Pb-Pb 5 TeV



Nuclei!

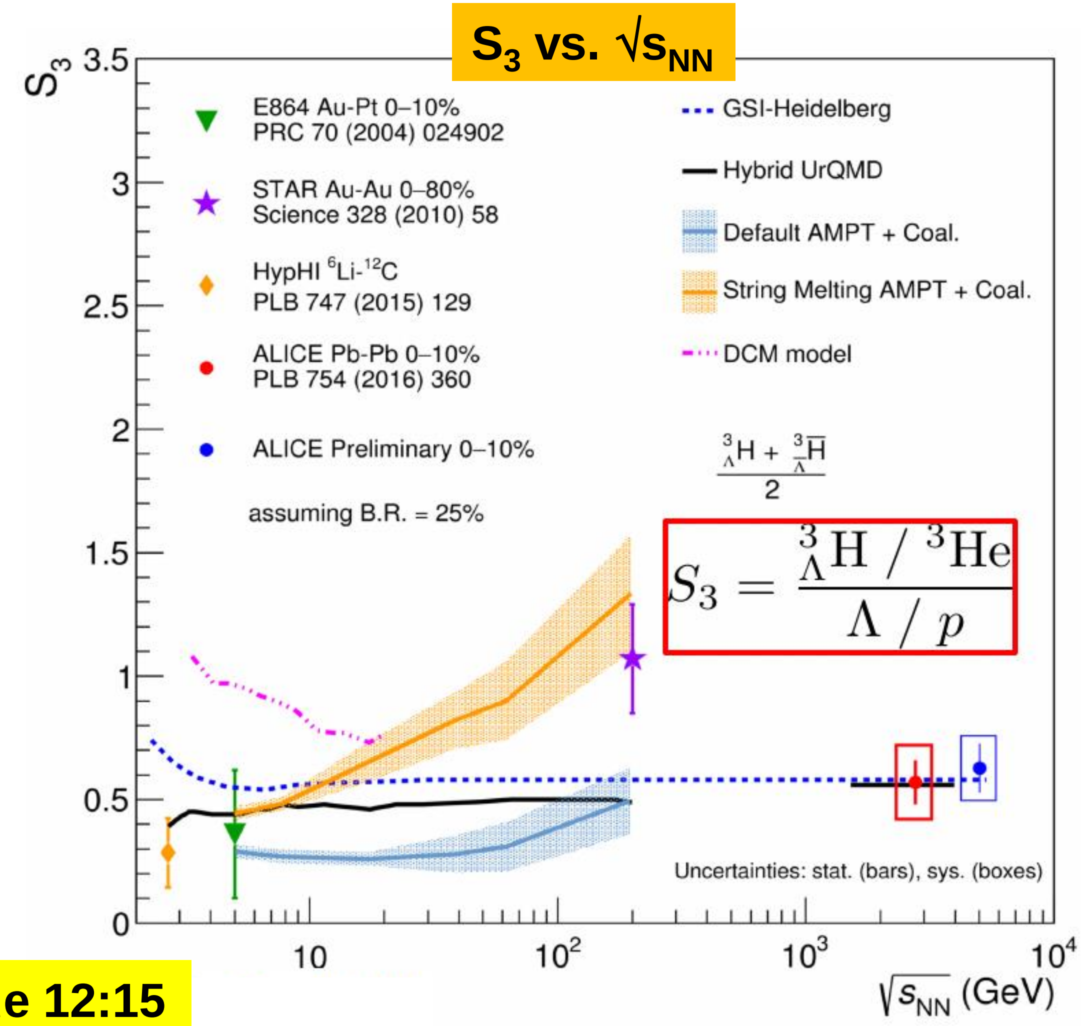
Particle yields well described by equilibrium thermal models over 7 orders of magnitude

Nuclei: Production Mechanism



- Heavy and fragile objects in agreement with thermal model at chemical freeze out
  - Binding energy d ~ 2.3 MeV, ^{3}He ~ 7.7 MeV
  - Chemical freeze-out ~ 153 MeV
- Open puzzle: Apparently no re-scattering of anti-nuclei in hadronic phase despite large dissociation cross-section
- Simple coalescence after kinetic freeze-out does not describe the data

$$E_i \frac{d^3 N_i}{(dp_i)^3} = B_A \left(E_p \frac{d^3 N_p}{(dp_p)^3} \right)^A$$



Francesca Bellini, Tue 12:15

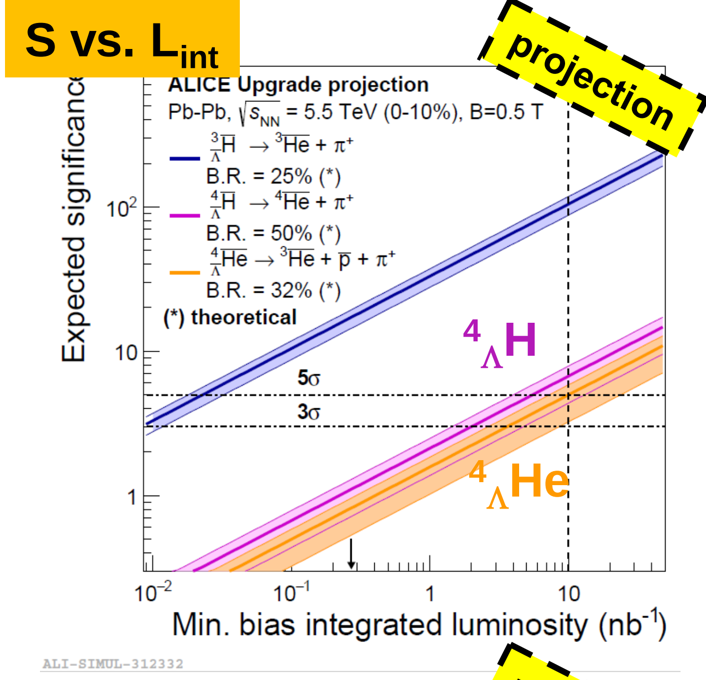
Nuclei : Next Decade

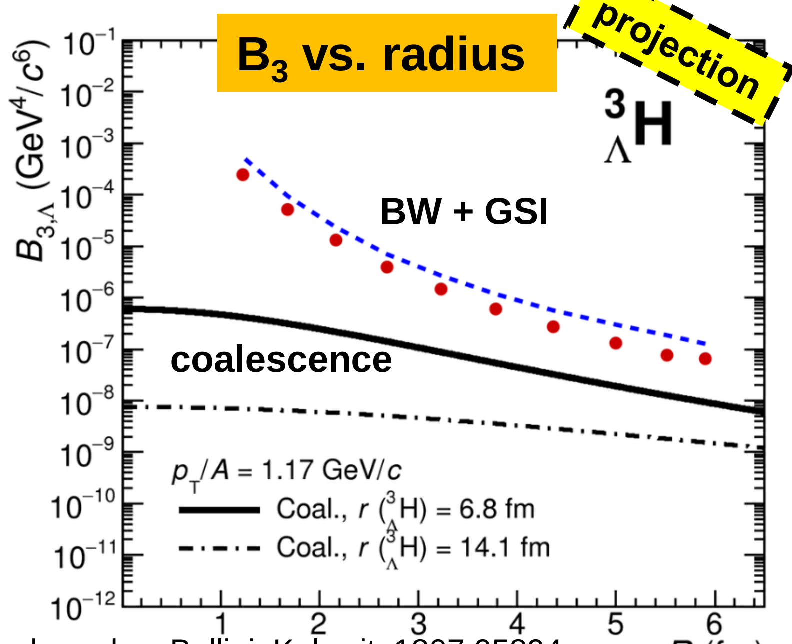
- Precision era for (anti-)(hyper-)nuclei production
  - Abundant d, ^{3}He, $^{3}_{\Lambda}$H; > 1000 ^{4}He
  - Significance above 5σ for $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He
  - v_2 for loosely-bound objects (e.g. hypertriton)

- Production mechanism
  - Coalescence vs. thermal model

- Astrophysical background in dark matter searches use anti-d and anti-^{3}He data (AMS)

Francesca Bellini, Tue 12:15





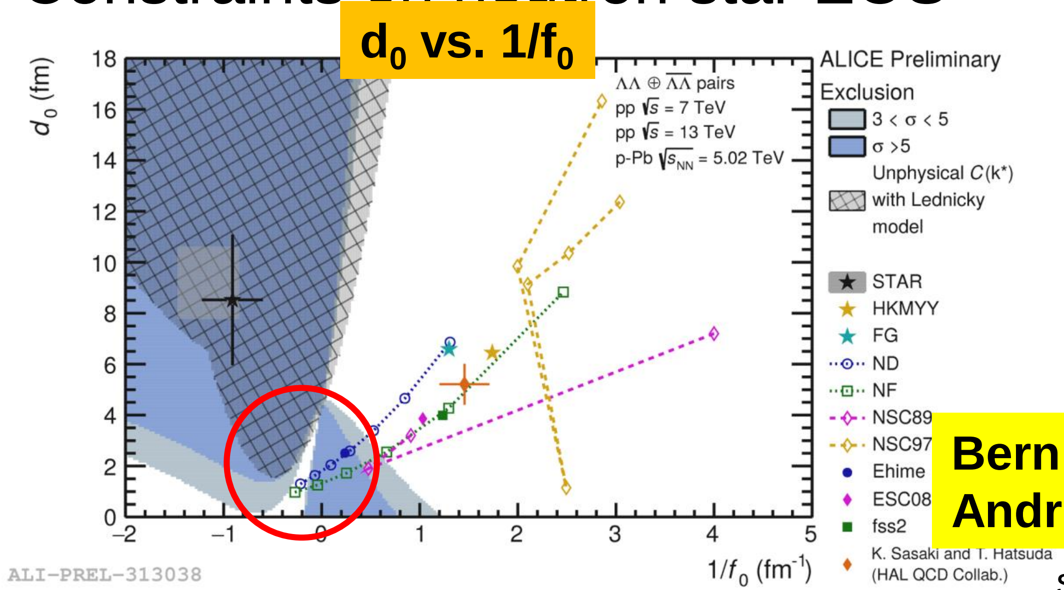
based on Bellini, Kalweit, 1807.05894

Hyperon-Nucleon Potentials

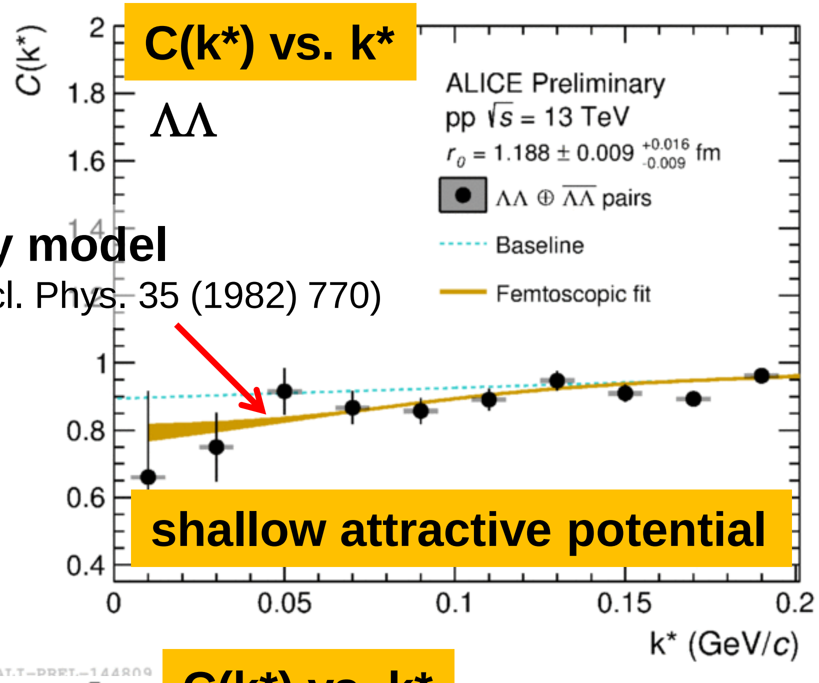
- Femtoscopy of ΛΛ and pΞ pairs
  - Assume emission source (Gaussian) → constrain interaction potential
- H-dibaryon binding energy tightly constrained

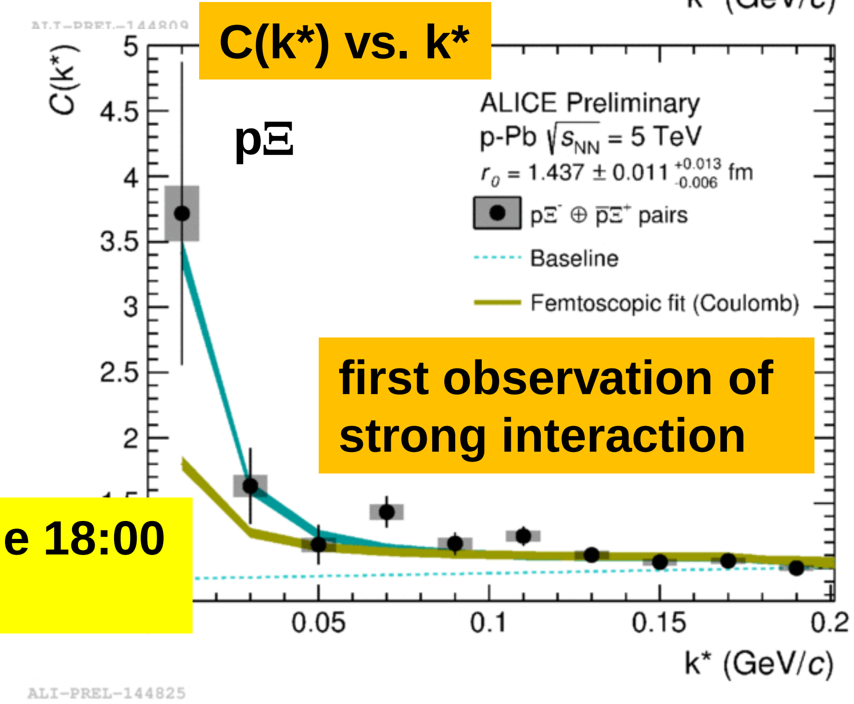
$$B_{\Lambda\Lambda} = 3.4\,^{+1.4}_{-2.5}\,(\mathrm{stat})\,^{+0.7}_{-0.2}\,(\mathrm{syst})\ \mathrm{MeV}$$

- Constraints on neutron star EOS



Lednicky model
(Sov. J. Nucl. Phys. 35 (1982) 770)

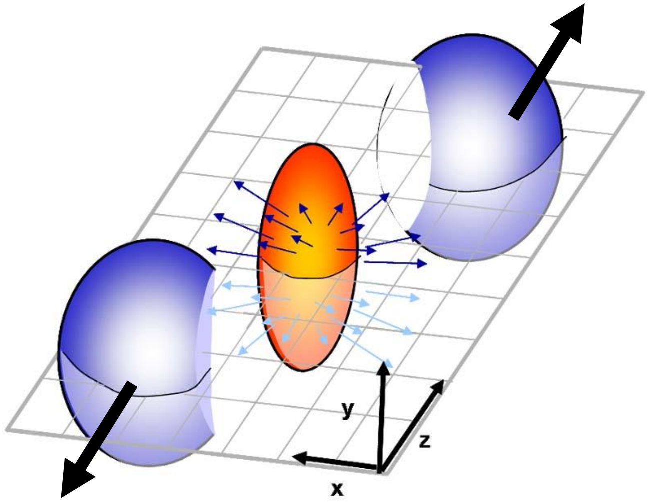


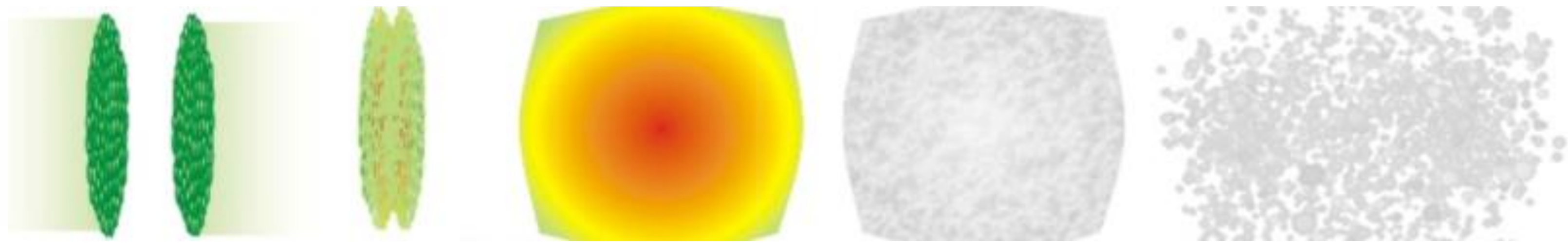


Bernhard Hohlweger, Tue 18:00
Andreas Mathis, Poster

see also arXiv:1805.12455

Collective Flow



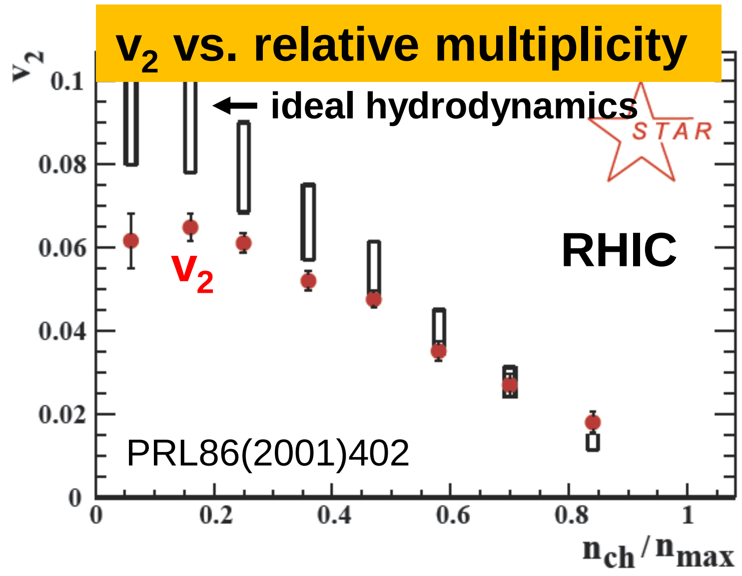


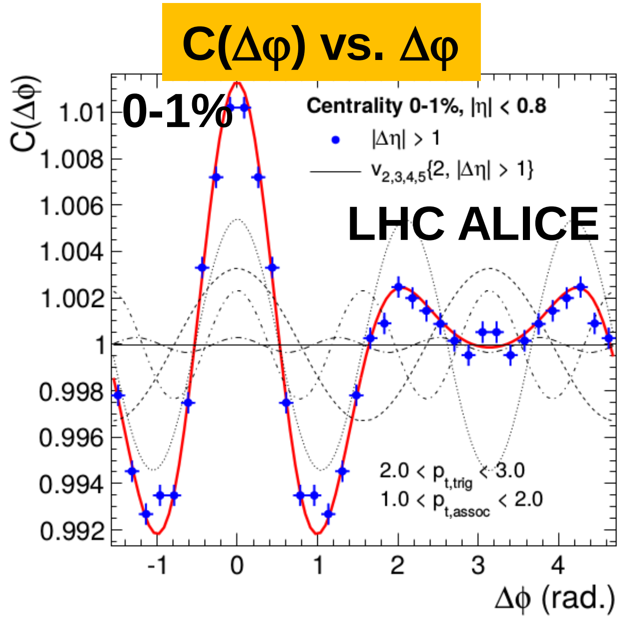
Collective Flow

- Key observable in heavy-ion collisions

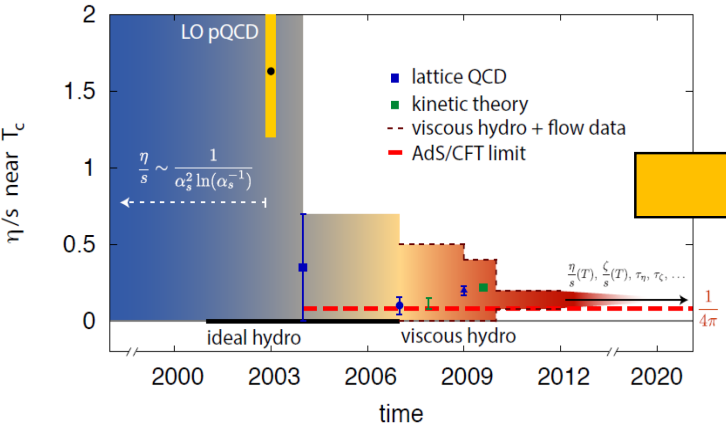
$$\frac{dN}{d\varphi} = A\left(1 + \sum_n 2v_n \cos n(\varphi - \Psi_n)\right)$$

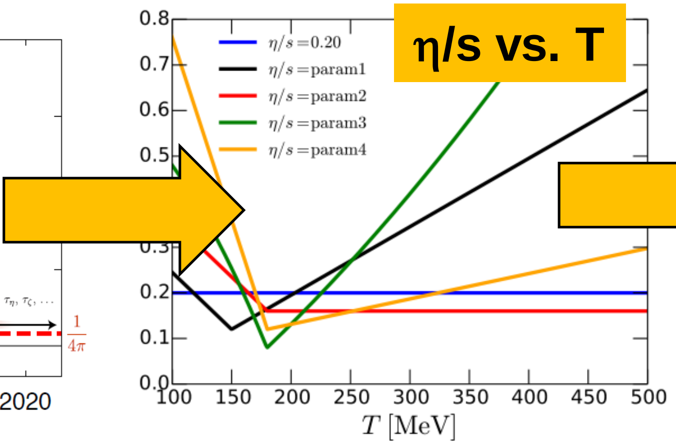
- Elliptic flow v_2 established (perfect) fluid paradigm
- Triangular flow v_3 established participating nucleon picture
- Precision and wealth of flow measurement constrain initial conditions and medium transport coefficients (η/s, ζ/s, …)

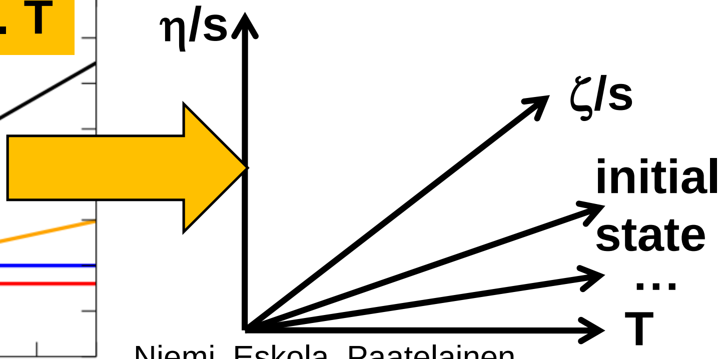




PRL107, 032301 (2011)



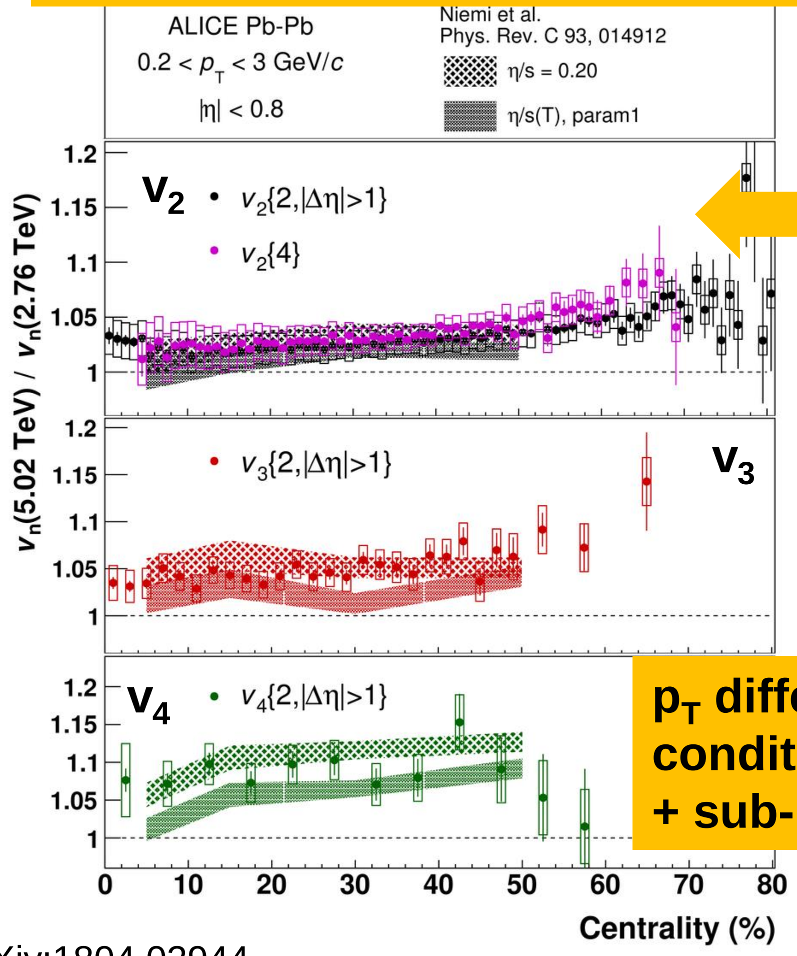




Niemi, Eskola, Paatelainen, PRC93,024907(2016)

High-Precision Measurements

v_n 5 / 2.76 TeV ratio vs. centrality

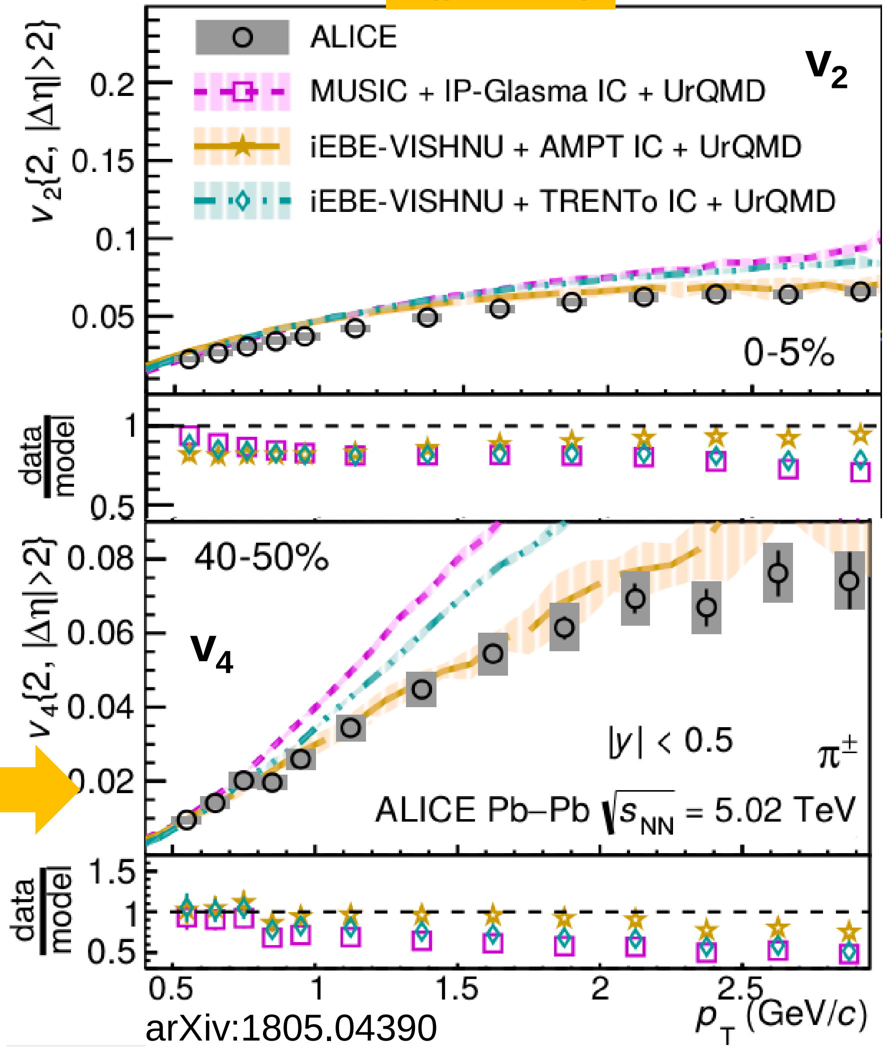


arXiv:1804.02944

v_n ratios constrain medium properties: η/s, ζ/s

p_T differential v_n constrains initial conditions and medium properties + sub-nucleon sensitivity

v_n vs. p_T



arXiv:1805.04390

High-Precision Correlations of Correlations

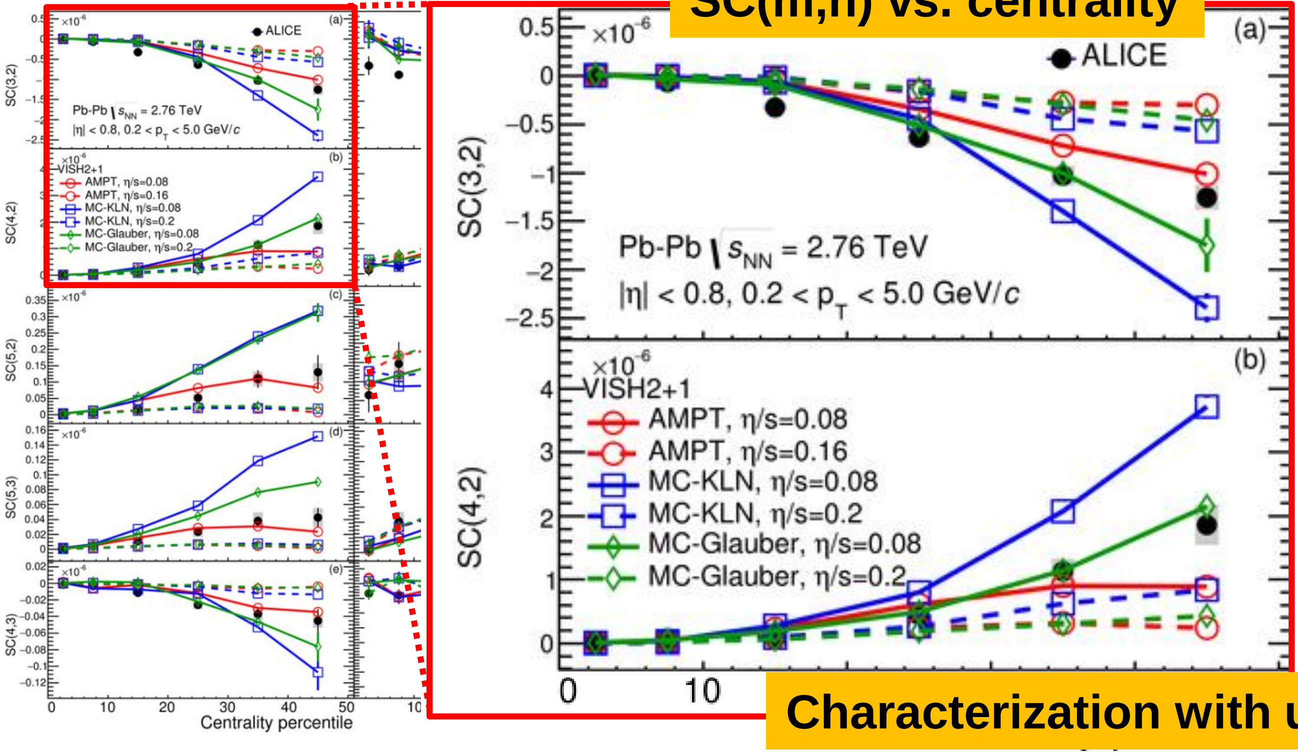
Symmetric cumulants

$$SC(m,n) \equiv \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle_c = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

How are v_n and v_m correlated?

SC(m,n) vs. centrality

PRC97 (2018) 024906

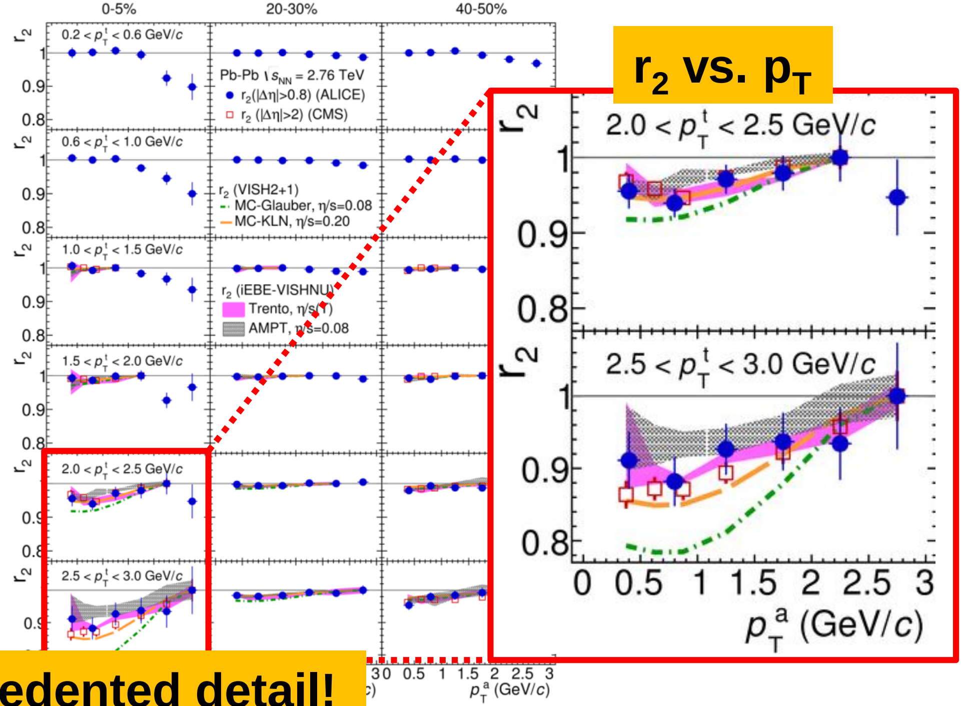


Factorization ratios

$$r_n = \frac{\langle v_n(p_T^a)\, v_n(p_T^t) \cos[n(\Psi_n(p_T^a) - \Psi_n(p_T^t))]\rangle}{\sqrt{\langle v_n(p_T^a)^2\rangle \langle v_n(p_T^t)^2\rangle}}$$

Do v_n factorize in p_T?

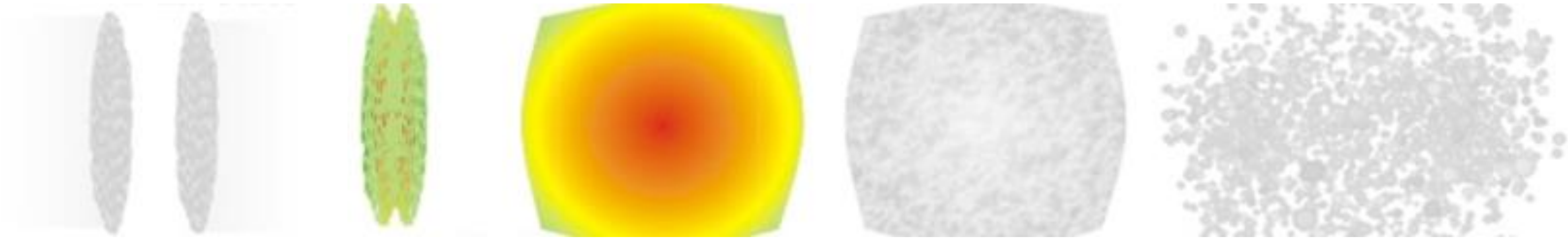
r_2 vs. p_T



JHEP 09 (2017) 032

Characterization with unprecedented detail!

Parity Violation in the Strong Interaction

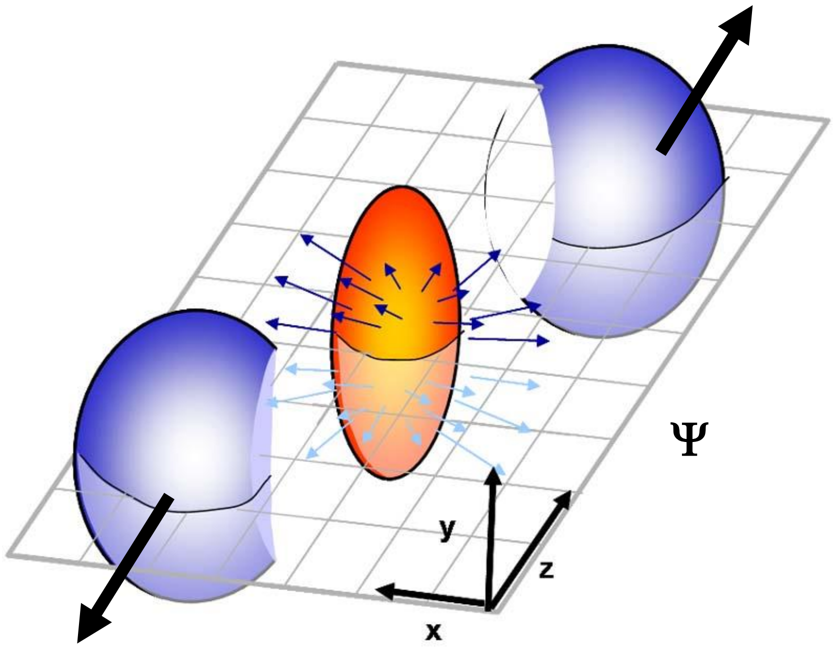


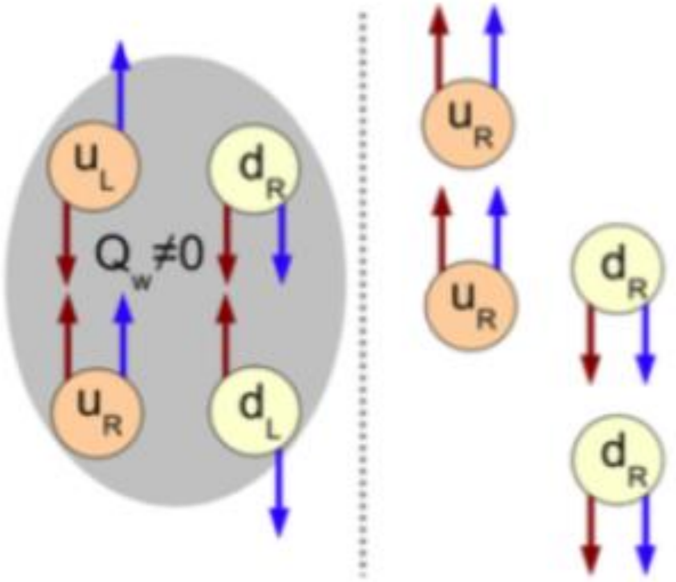
Chiral Magnetic Effect

- Spectator charge causes large magnetic field (~10^{18} Gauss)
  - Aligns spins
- Domains with non-zero topological charge → chirality flip
- Leads to charge separation
- Experimental correlator

$$\gamma_{112} = \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \qquad \alpha, \beta = \pm$$

  - Same sign = signal
  - Opposite sign = control





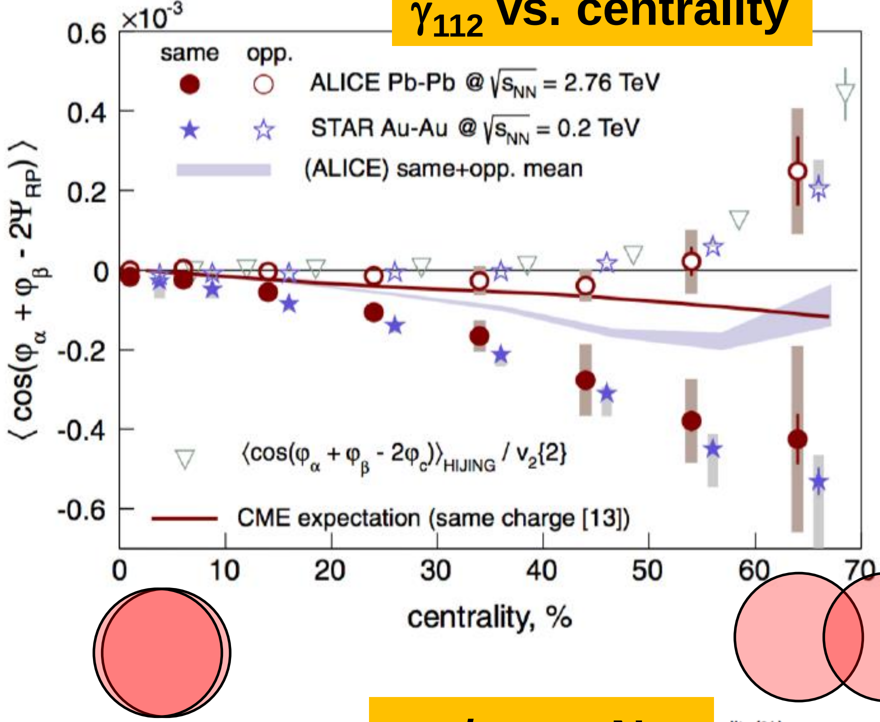
Earlier Results

- Signal observed increasing with increasing centrality

- Magnitude similar at 0.2 TeV (STAR) and 2.76 TeV (ALICE)
- Magnitude similar in Pb-Pb and p-Pb

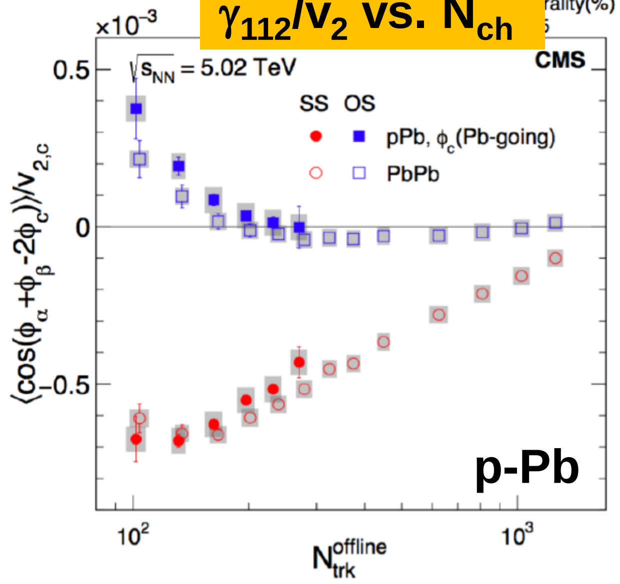
- Issue: Large backgrounds due to local charge conservation (resonance decays, momentum conservation, parton fragmentation)

γ_{112} vs. centrality



PRL110 (2013), 012301

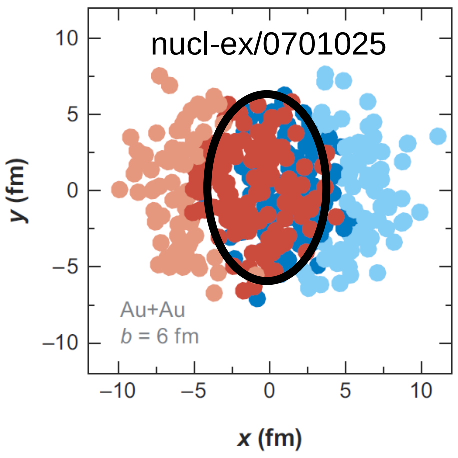
γ_{112}/v_2 vs. N_{ch}

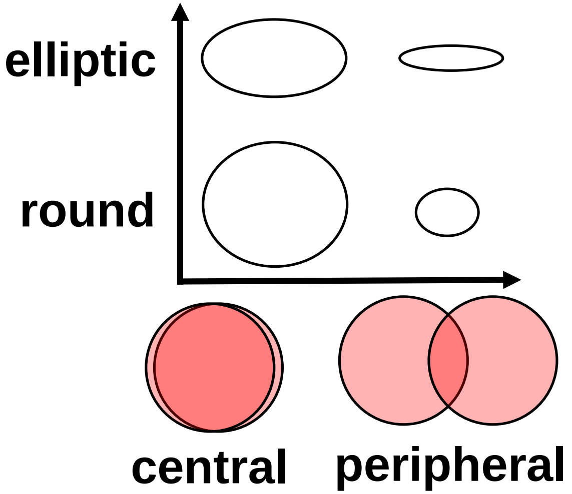


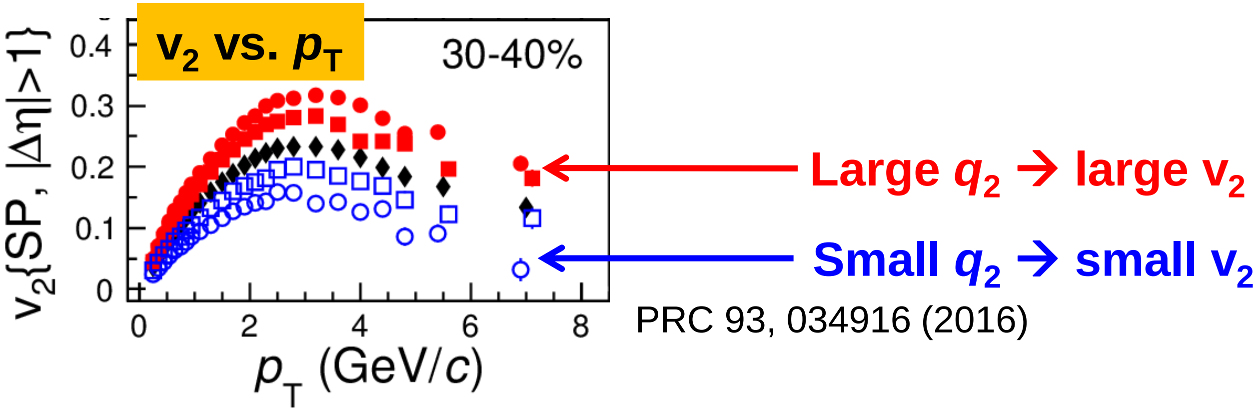
PRL118 (2017), 122301

Event Shape Engineering

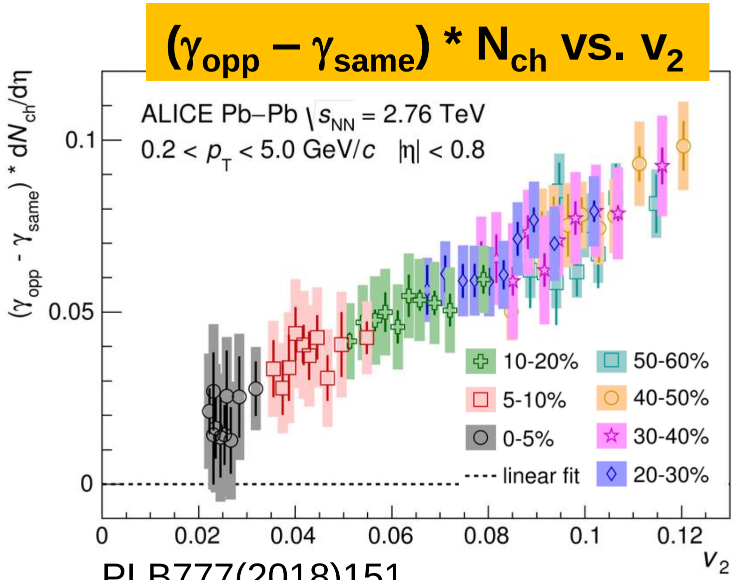
- Large event-by-event variation of v_n
- Final-state v_2 correlated with initial-state eccentricities ε_2 (hydro with small η/s)
- At fixed centrality, split events by event-by-event v_2 (q vector)
  [Schukraft, Timmins, Voloshin (PLB719 (2013) 394)]







PRC 93, 034916 (2016)

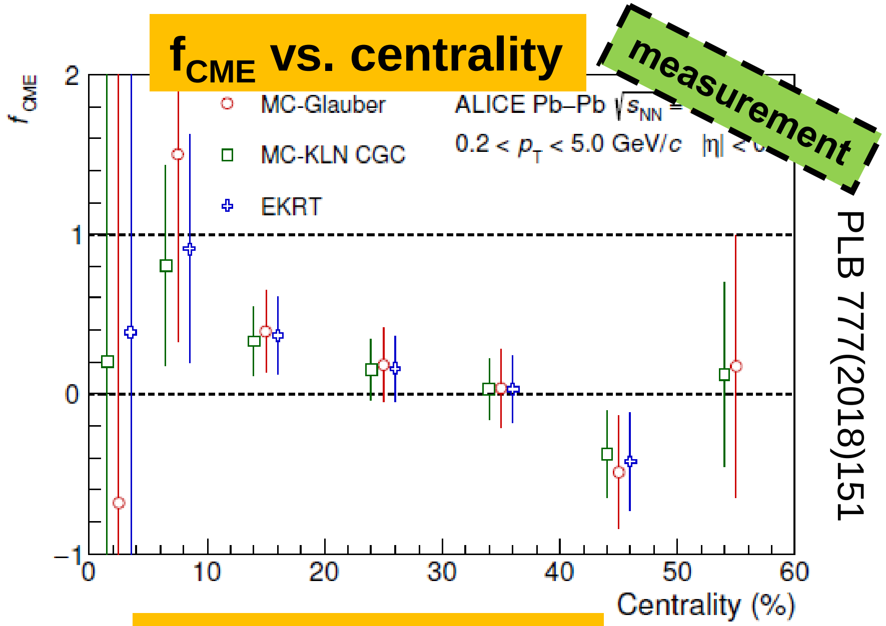


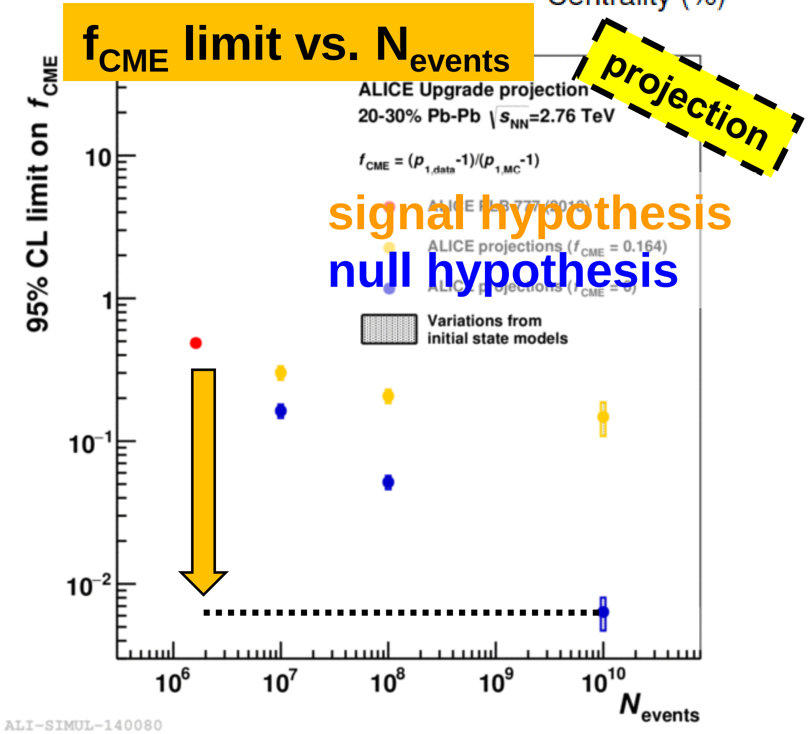
PLB777(2018)151

- CME backgrounds proportional to v_2
  - Possibility to constrain background

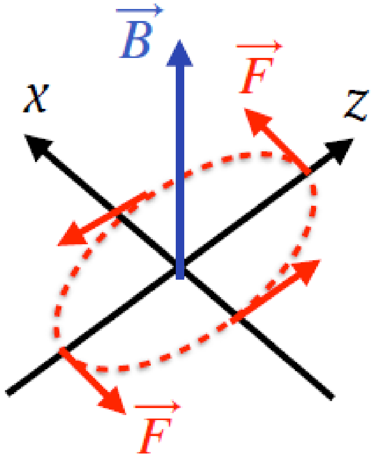
Now & Future

- Event shape engineering, modelling of magnetic field + initial state models allows limit on CME
- f_{CME} = maximal signal contribution in correlator
  - Limit set on signal 7-33% at 95% C.L. [PLB 777(2018)151, PRC 97(2018)044912]
- Sub-percent precision in Run 3 and 4
- Interesting opportunity: Isobar run at RHIC
  - Test Z^2 magnetic field dependence with Zirconium and Rubidium





D-meson Directed Flow



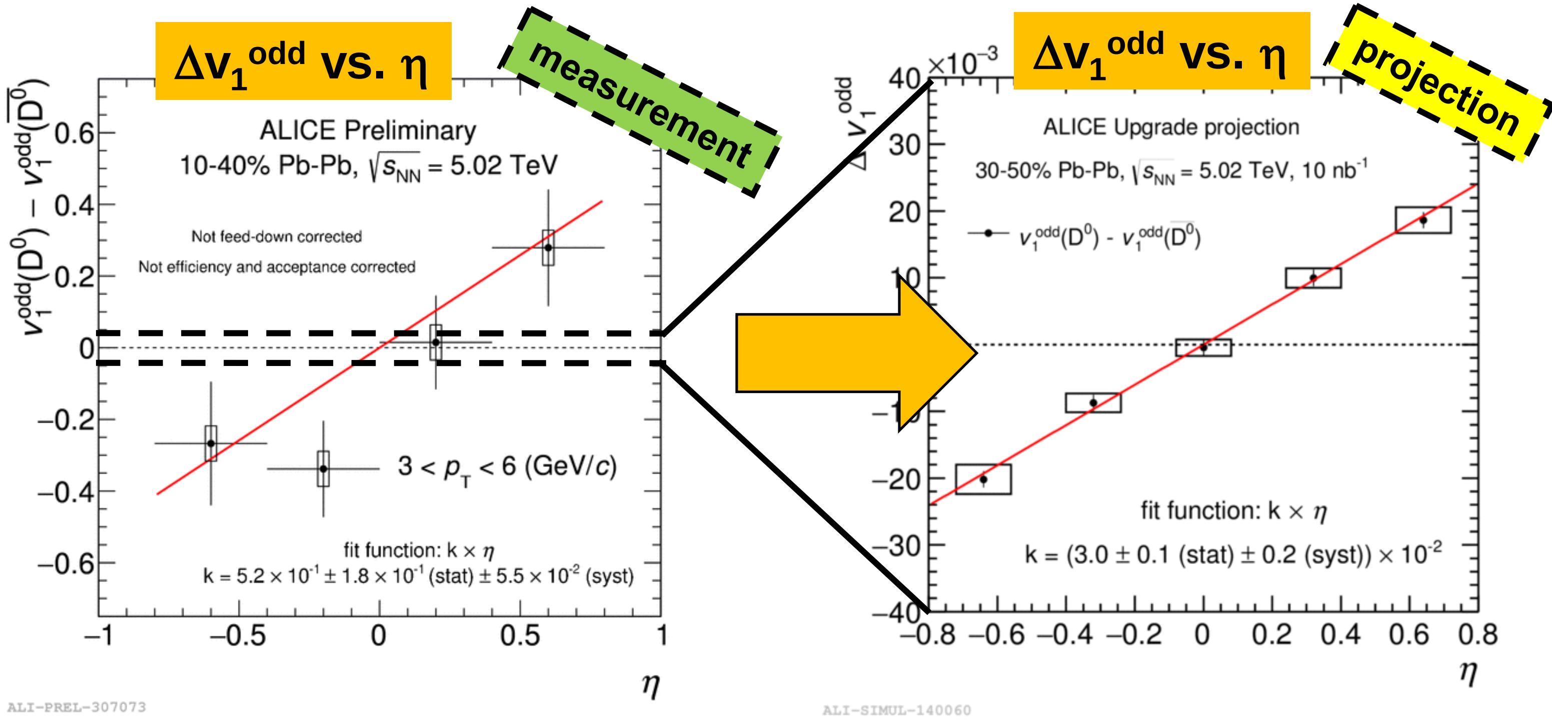
- Passing nuclei → strong magnetic field → C-odd directed flow v_1
- Electric field → same effect with opposite direction
- Measured for hadrons and D mesons
  - Earlier formation time of D mesons → sensitivity to stronger magnetic field

Theory expects that B field dominates, but opposite slope measured (with limited significance)

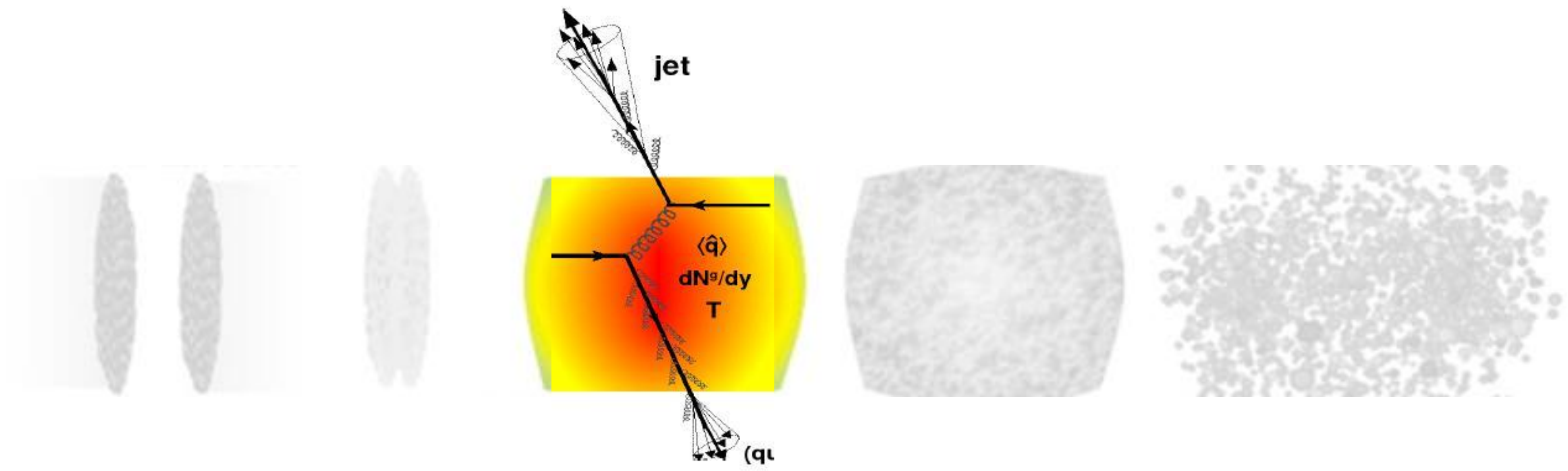
Signal factor 10 larger

Run 3 and 4 will tell

Prediction from S. Das et al.
PLB 768 (2017) 260 (see backup)



Parton-Medium Interactions



Energy Loss

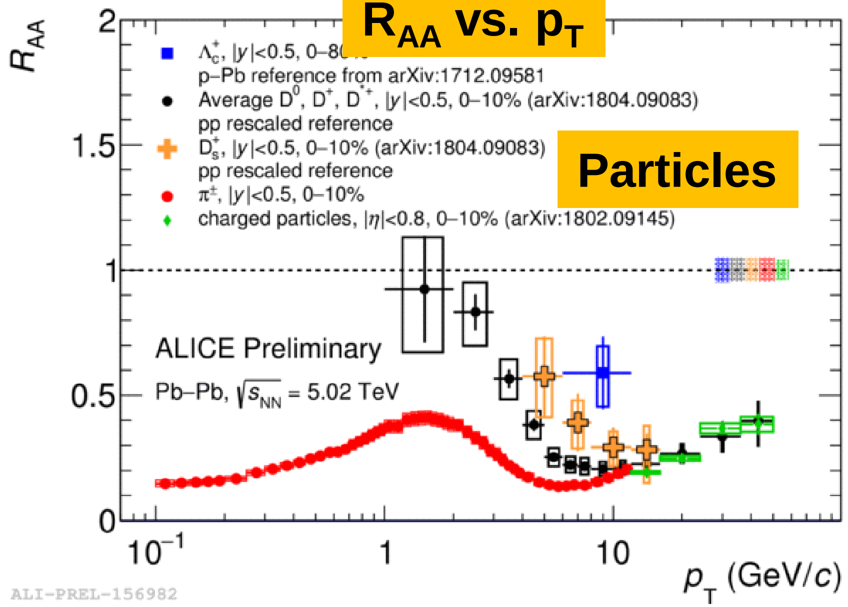
- HI collision = superposition of nucleon-nucleon collisions with incoherent fragmentation?

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

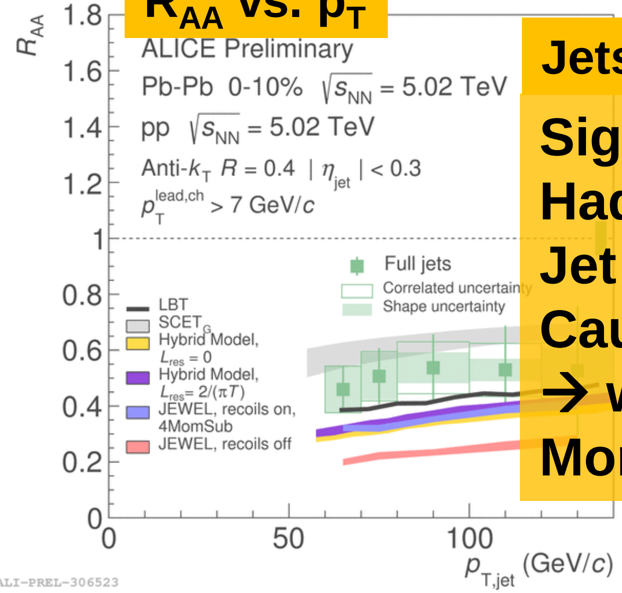
R_{AA} = 1 → no modification

R_{AA} != 1 → medium effects

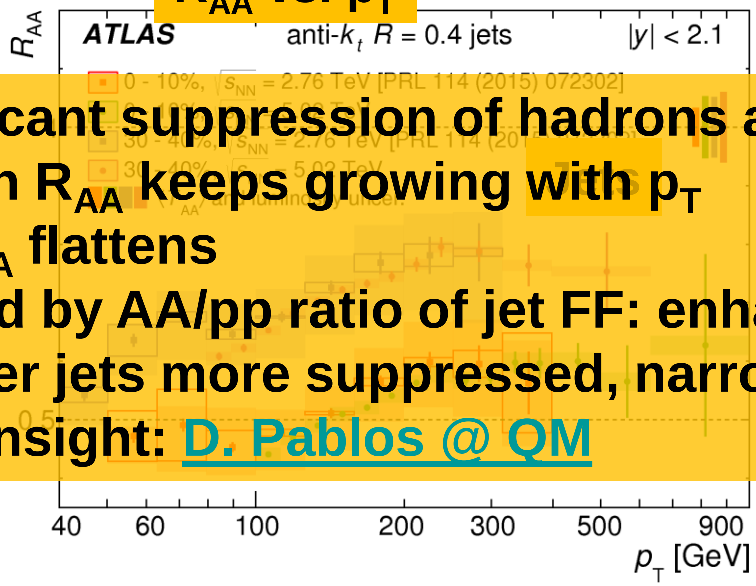
R_{AA} vs. p_T **Particles**



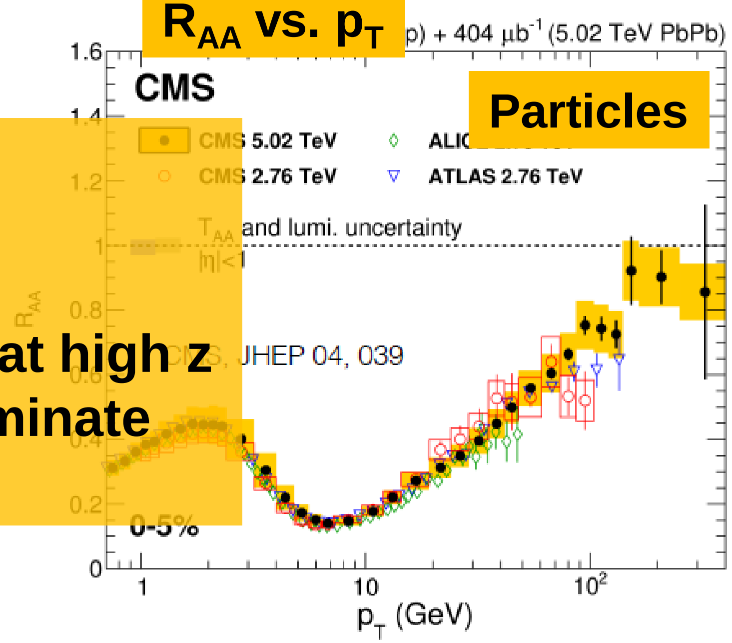
R_{AA} vs. p_T **Jets**



R_{AA} vs. p_T



R_{AA} vs. p_T **Particles**

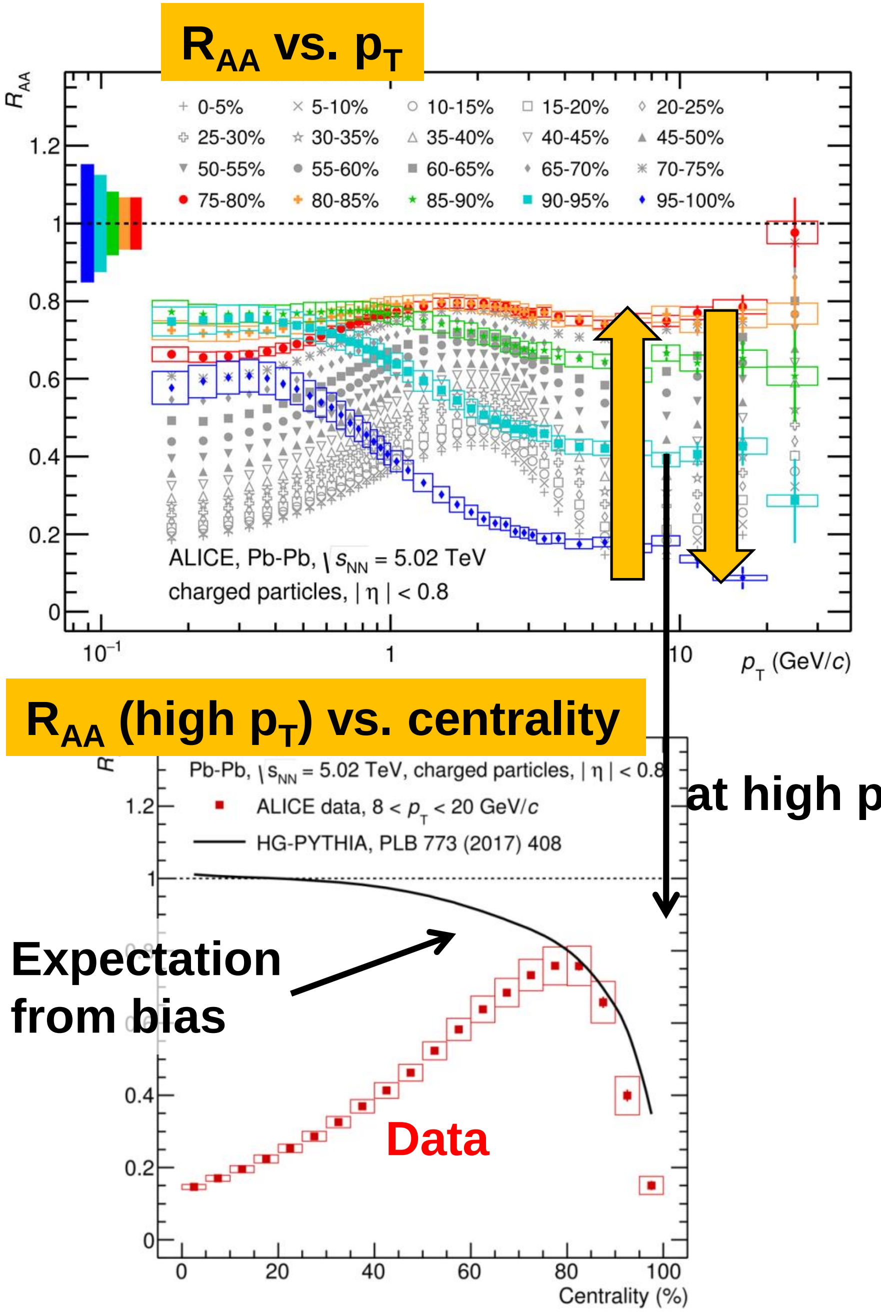


Significant suppression of hadrons and jets
Hadron R_{AA} keeps growing with p_T
Jet R_{AA} flattens
Caused by AA/pp ratio of jet FF: enhancement at high z
→ wider jets more suppressed, narrow jets dominate
More insight: [D. Pablos @ QM]

Solved Puzzle: Peripheral R_{AA}

- R_{AA} ~ 0.8 in peripheral Pb-Pb collisions
  - N_{part} ~ 5-10, like in p-Pb and there R_{pA} ~ 1
- Shown to be caused by biases
  - Event selection
  - Nucleon-nucleon impact parameter: in peripheral Pb-Pb collisions, the average NN impact parameter is larger than in pp
- Above 80% reproduced by simple superposition model HG-PYTHIA (Loizides, Morsch, Phys.Lett. B773 (2017) 408-411)

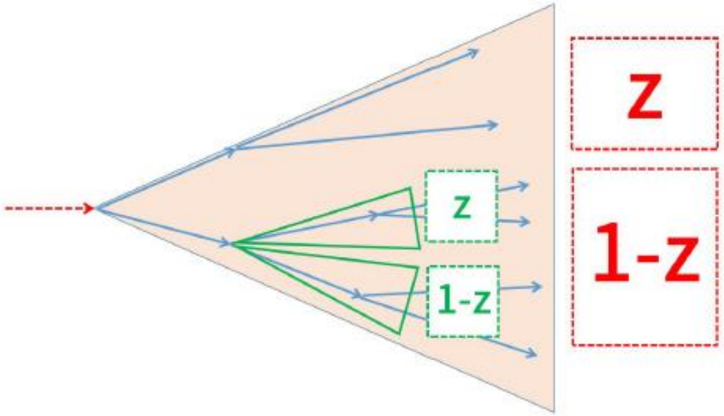
No need to involve energy loss in peripheral collisions



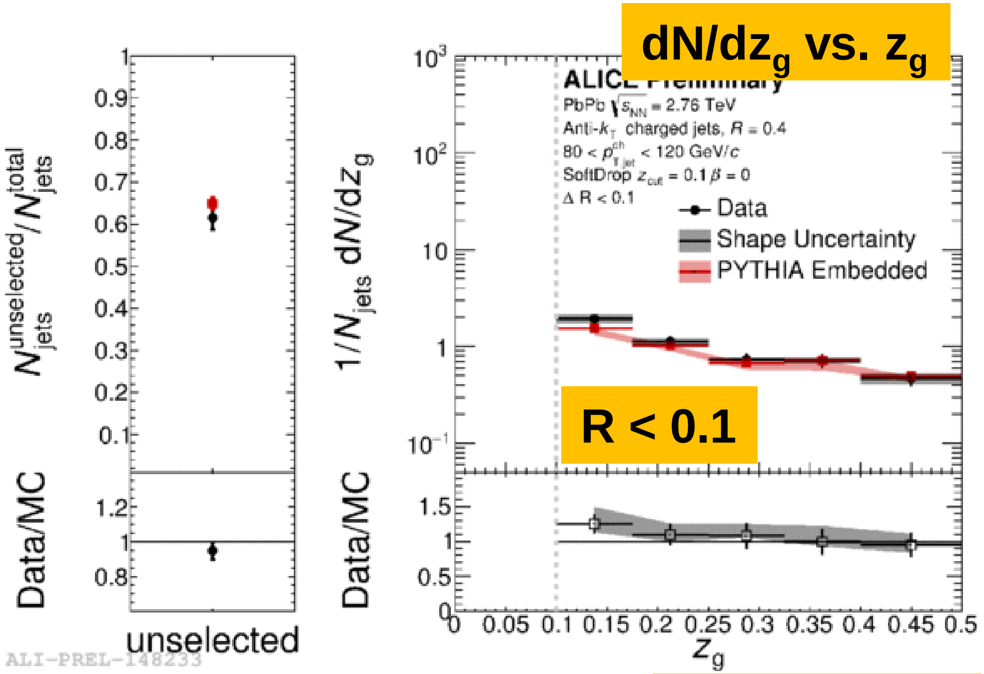
arXiv:1805.05212

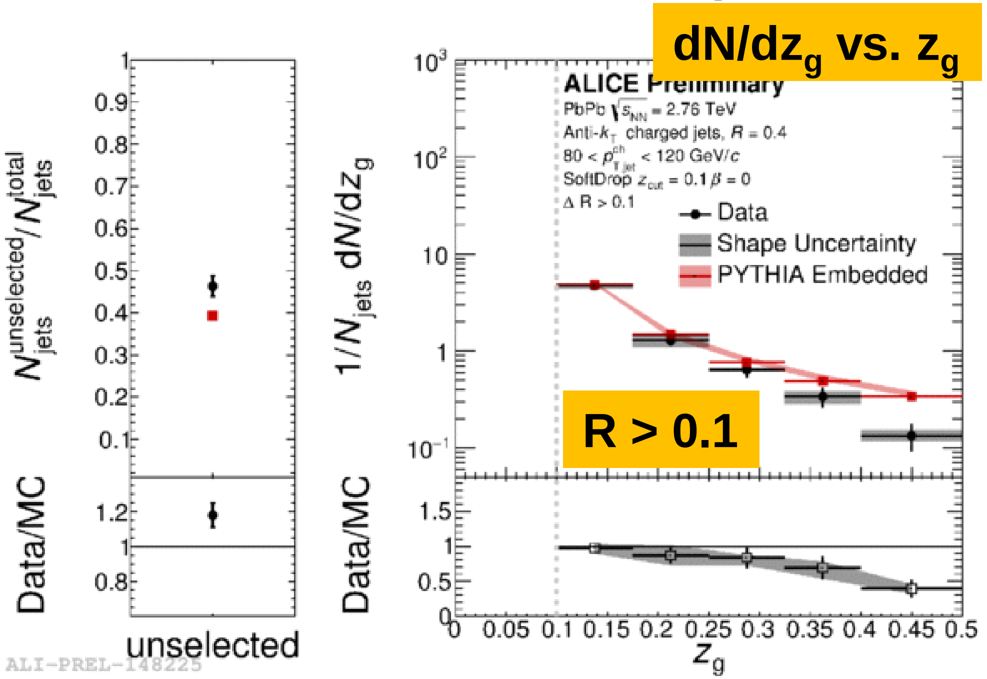
Jet Substructure

- Characterize and understand parton-medium interactions by exploring splitting phase space



- First splitting at small angles
  - Pb-Pb jets ~ vacuum reference
- First splitting at large angles
  - Overall suppression, steeper z_g distribution

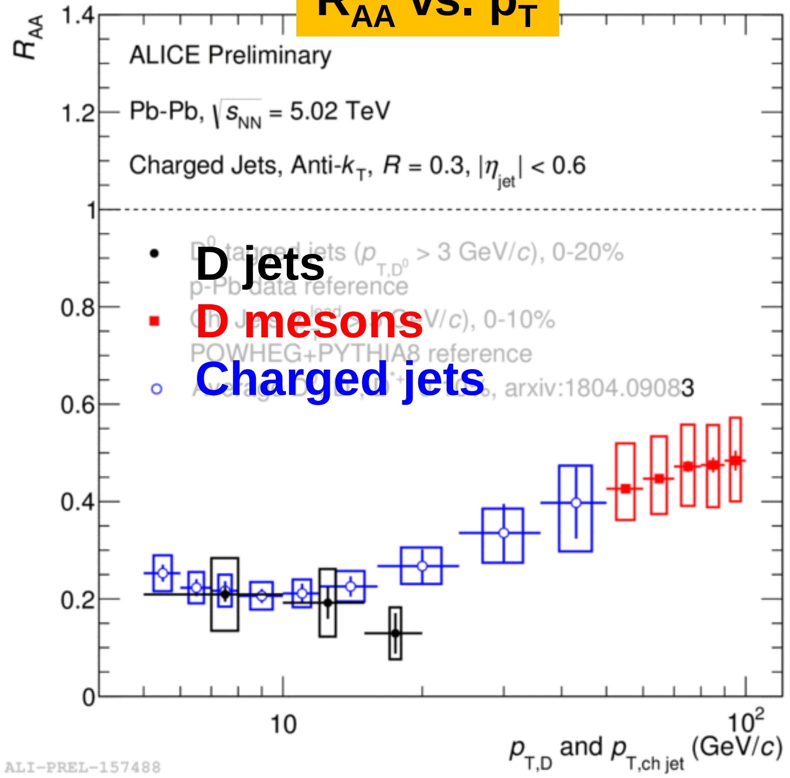




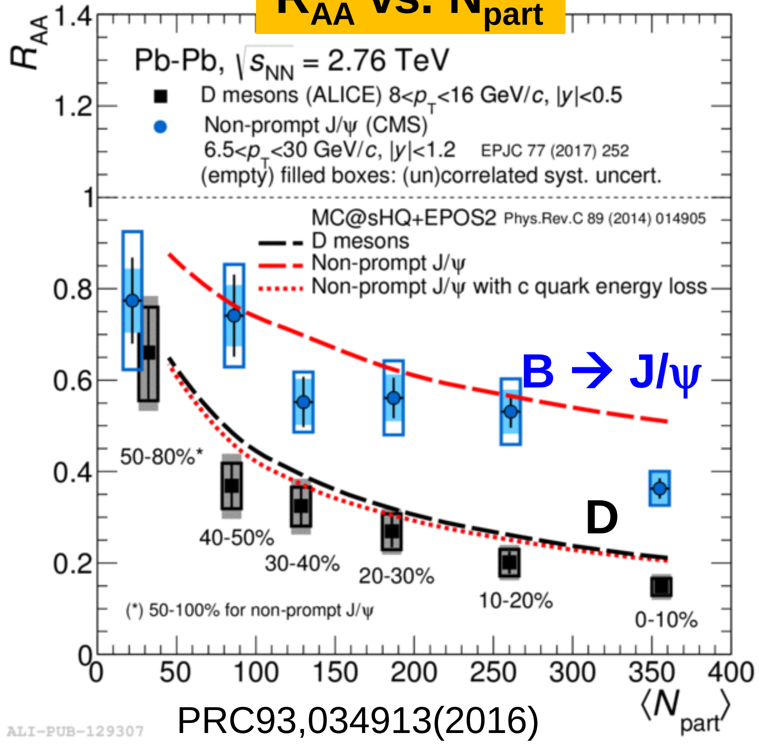
Energy Loss and Heavy Quarks

- Significant energy loss
  - Consistent picture of charged jets, D jets and D mesons
- Quark-mass dependent energy loss involving b ⇨ $R_{AA}^{\pi} \approx R_{AA}^{D} < R_{AA}^{B}$

R_{AA} vs. p_T



R_{AA} vs. N_{part}

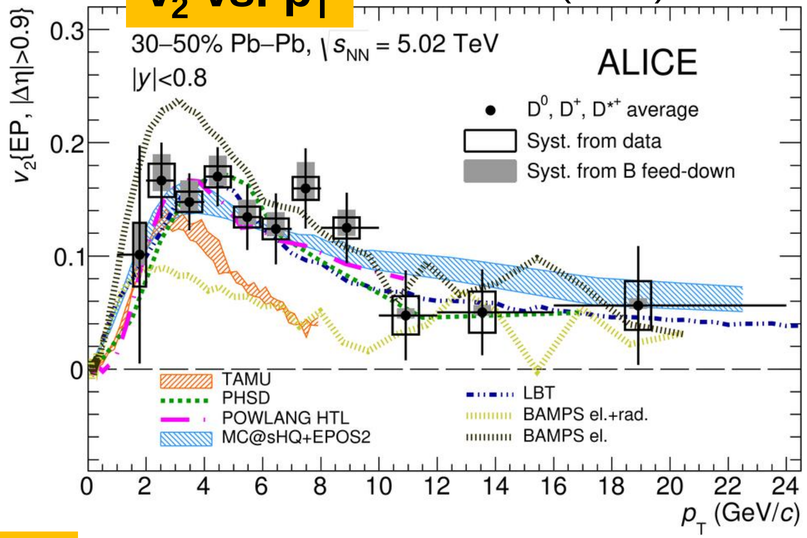


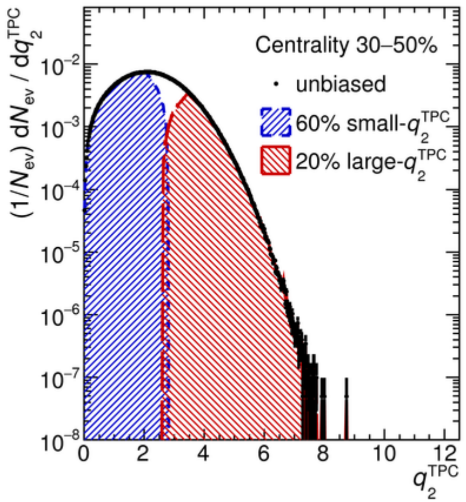
PRC93,034913(2016)

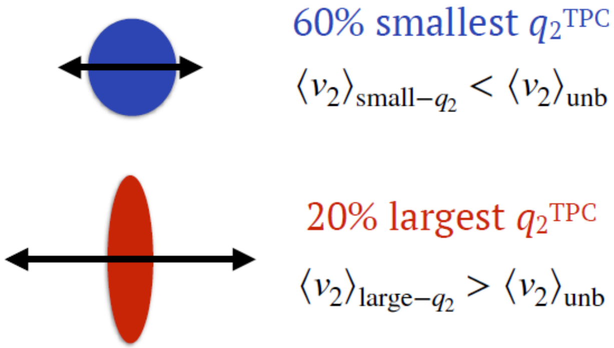
Heavy Quark-Medium Interactions

- Charm $v_2 > 0$ → charm quarks flow with medium
  - Constrains quark diffusion coefficient $2\pi TD_s \sim 1.5\text{-}7$ at T_c preferred
- Event shape engineering
  - At fixed impact parameter, select shape of collision region
- Heavy flavour v_2 "follows" shape fluctuations q_2

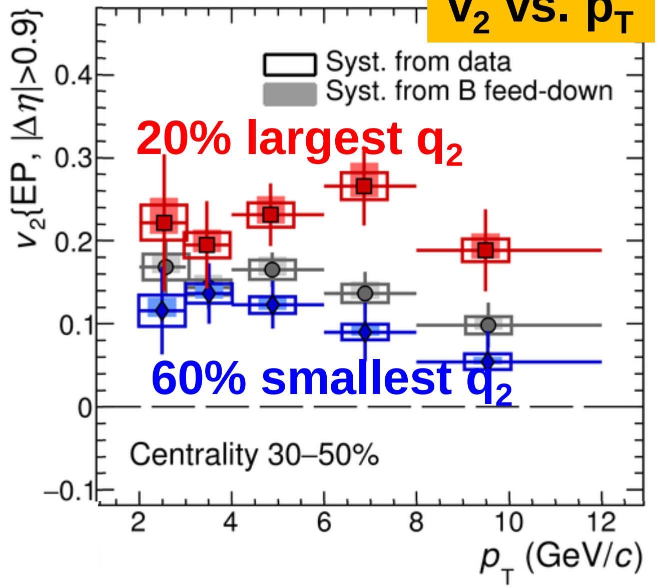
v_2 vs. p_T PRL120(2018)102301



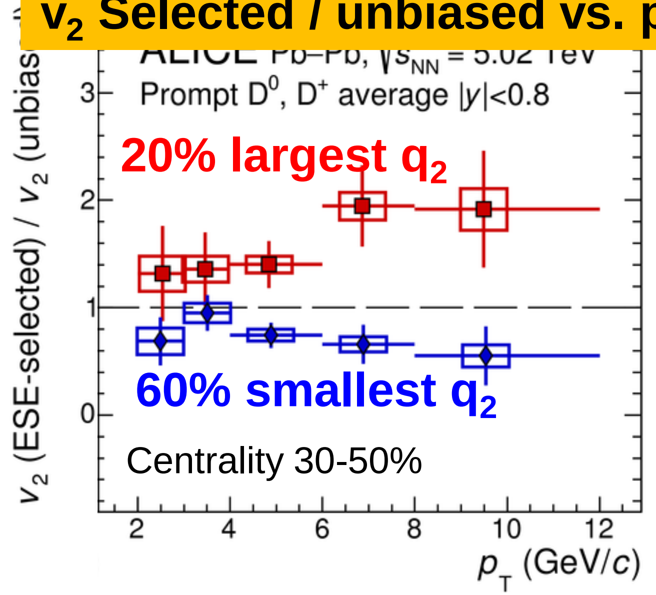




v_2 vs. p_T



v_2 Selected / unbiased vs. p_T

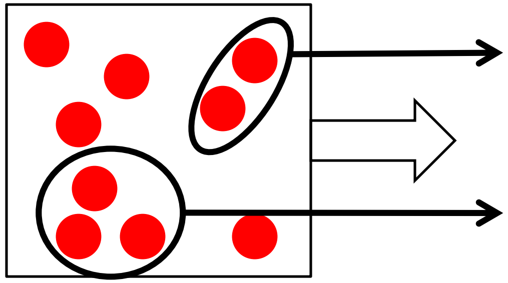


arXiv:1809.09371

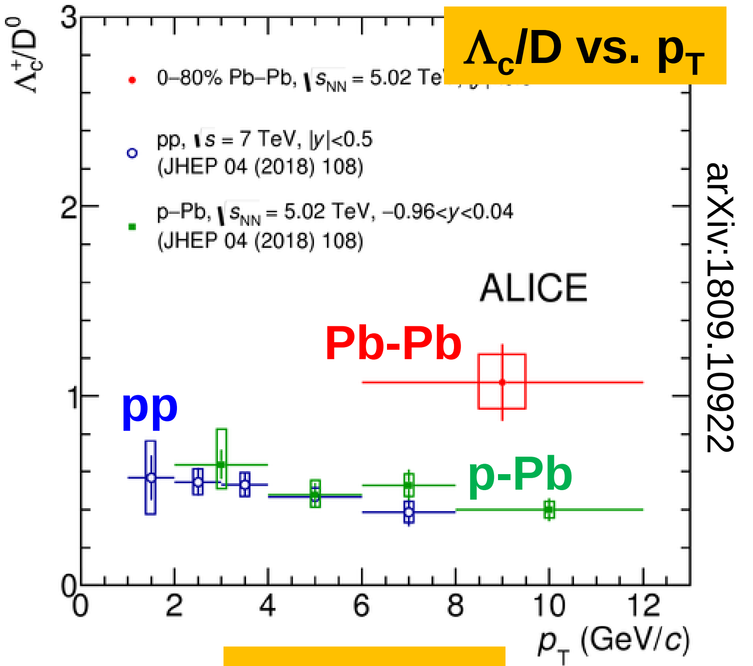
Λ_c

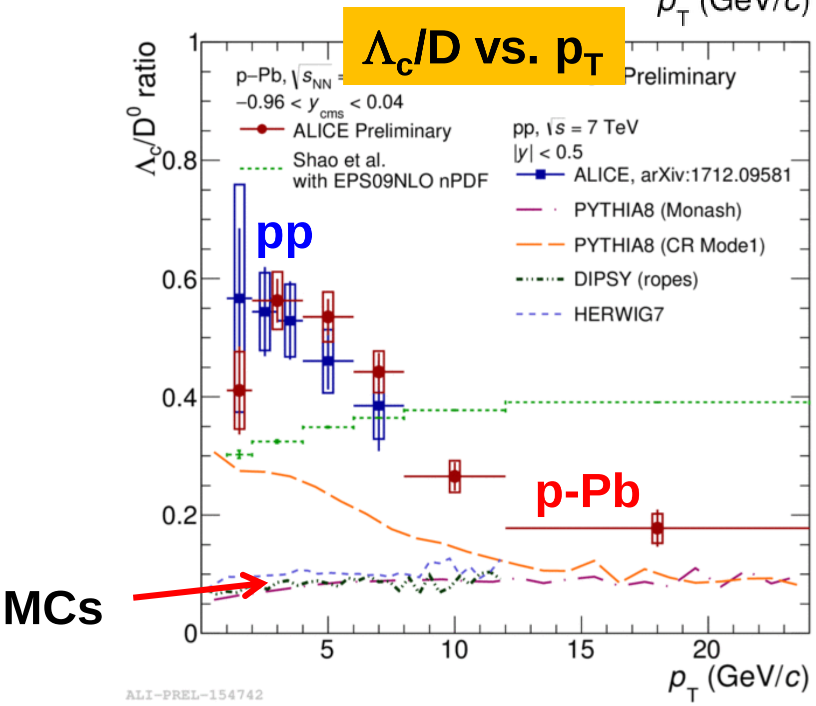
- Does charm recombine from the QGP?
  - Baryon/meson ratios D_s/D, Λ_c/D, Λ_b/B
  - Very challenging: e.g. Λ_c cτ ~ 60 μm

- First measurement at LHC
- Validation of recombination and coalescence models



  - PbPb > pp → coalescence contribution
  - pp: larger than in LEP-tuned common MCs → impact on total charm cross-section

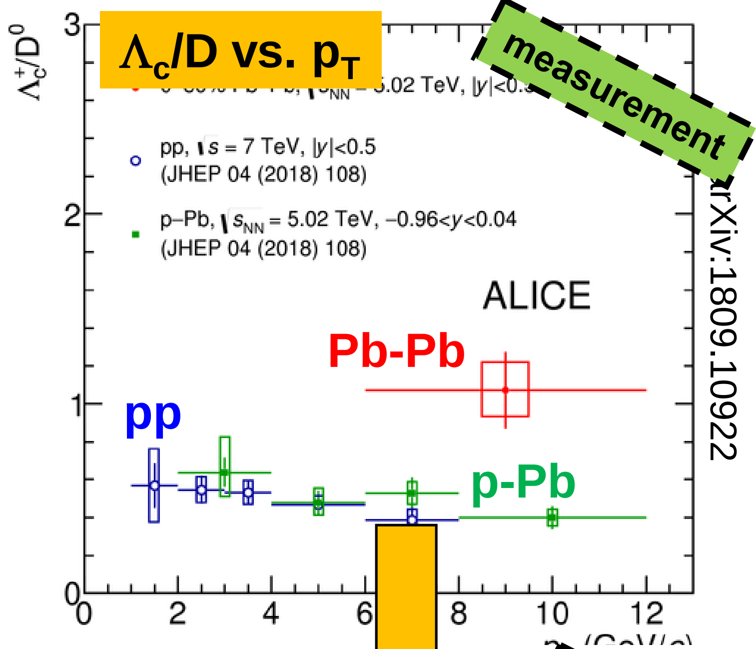


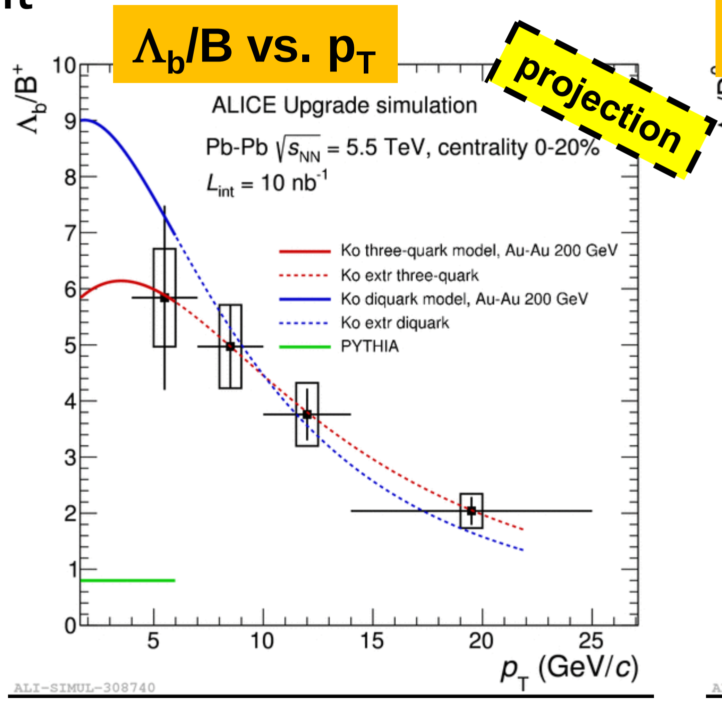


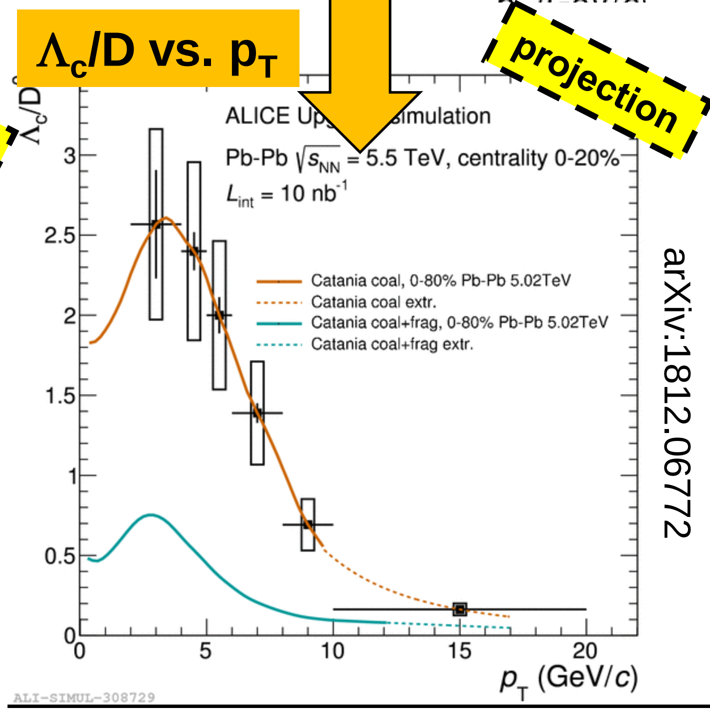
Λ_c

- Does charm recombine from the QGP?
  - Baryon/meson ratios D_s/D, Λ_c/D, Λ_b/B
  - Very challenging: e.g. Λ_c $c\tau$ ~ 60 μm

- High statistics and detailed insight expected in Run 3 and 4

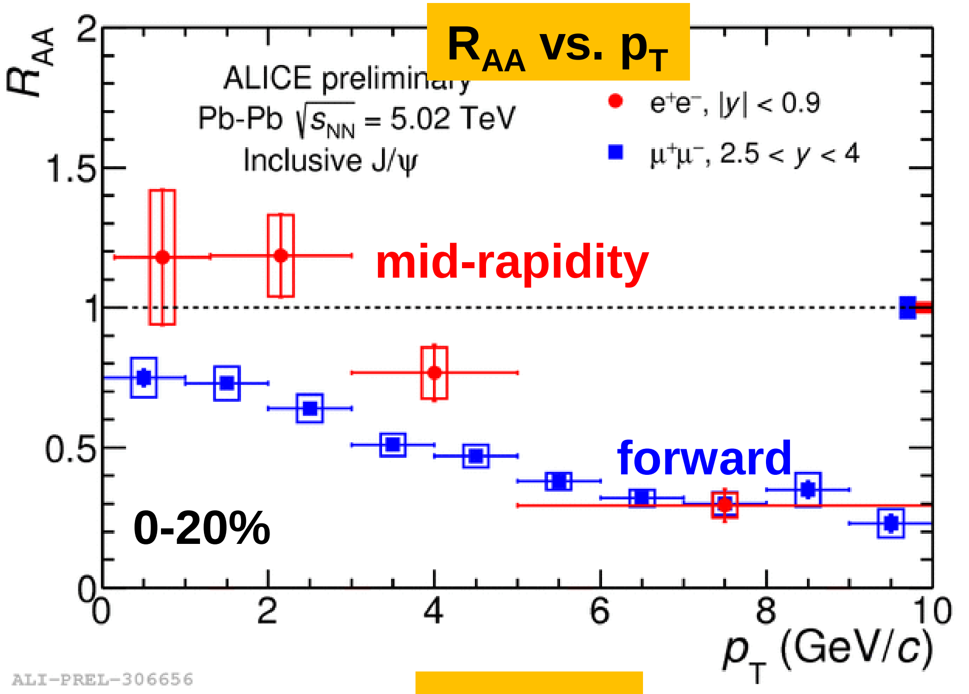


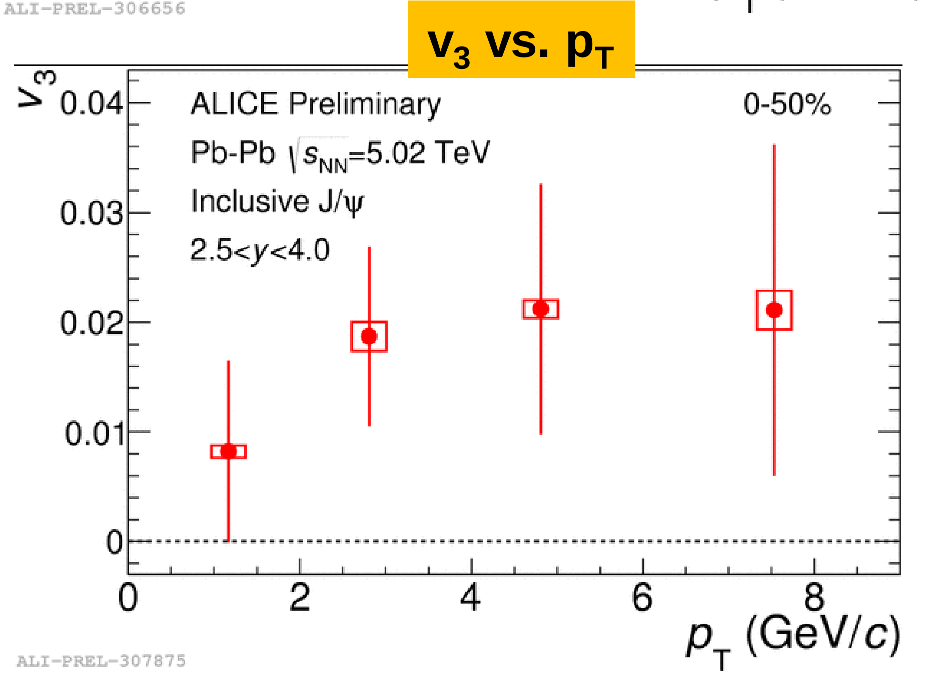


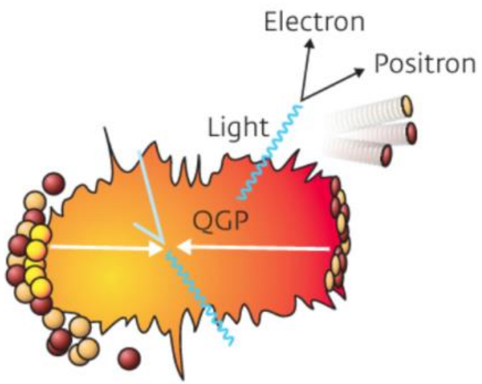


J/ψ

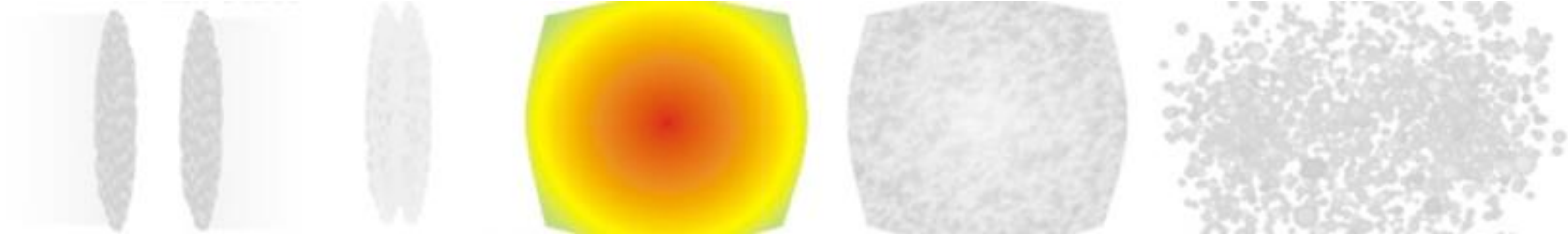
- Regeneration at play
  - Midrapidity less suppressed than forward
  - Less suppressed at low p_T
- Sizable J/ψ v_2 (see backup)
- First evidence for $v_3 > 0$ (3.7σ)
- Underlines importance of regeneration component
  - Finite value at high p_T value puzzling







Thermal Radiation

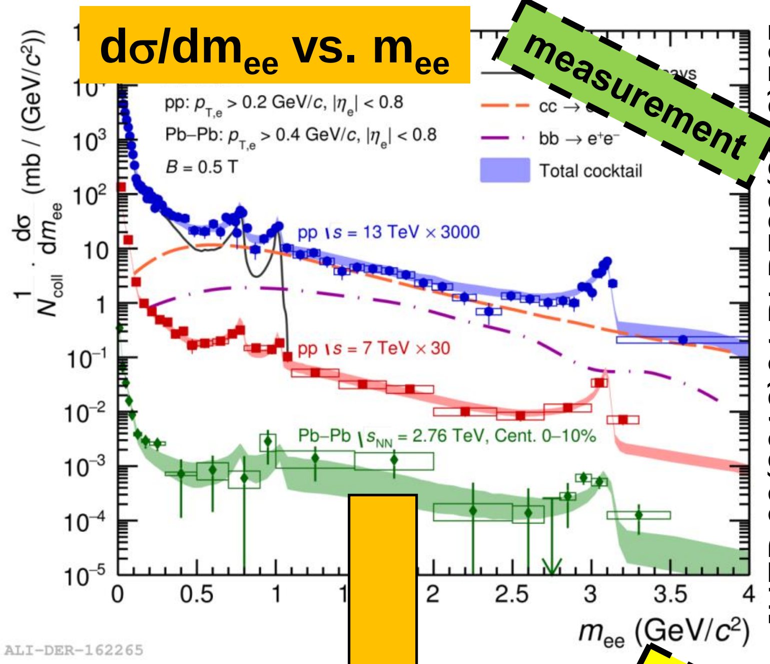


Thermal Radiation

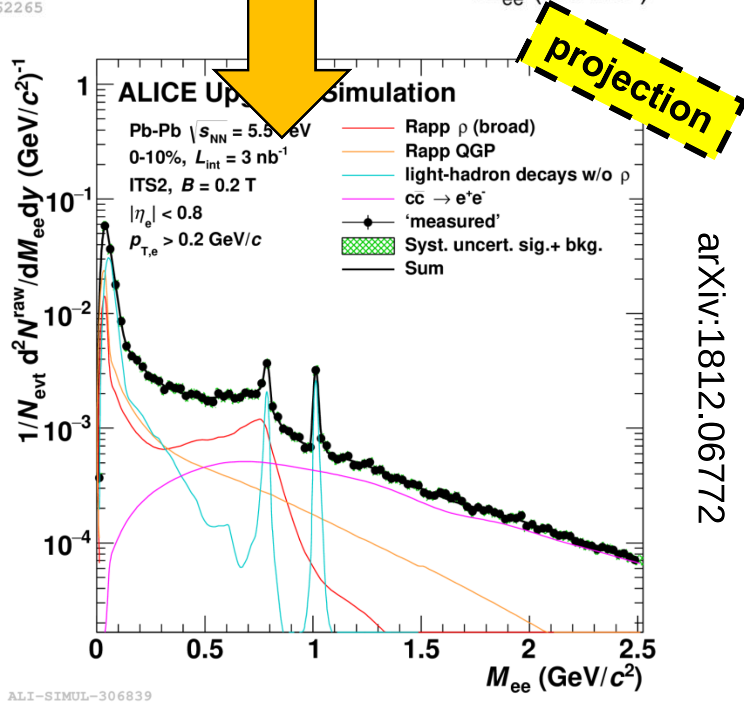
(at vanishing μ_B)

- Access space-time evolution of medium
- Change of ρ spectral function connected to chiral symmetry restoration
- Results in pp at 7 and 13 TeV and Pb-Pb at 2.76 TeV
  - Data consistent with cocktail expectation
  - Charm and beauty cross sections in pp major background
- Not yet sensitive to quantify the presence of an enhancement in Pb-Pb

- Run 3 and 4
  - Temperature (→ 20% uncertainty)
  - v_2 of thermal photons (1% abs. uncertainty on v_2)

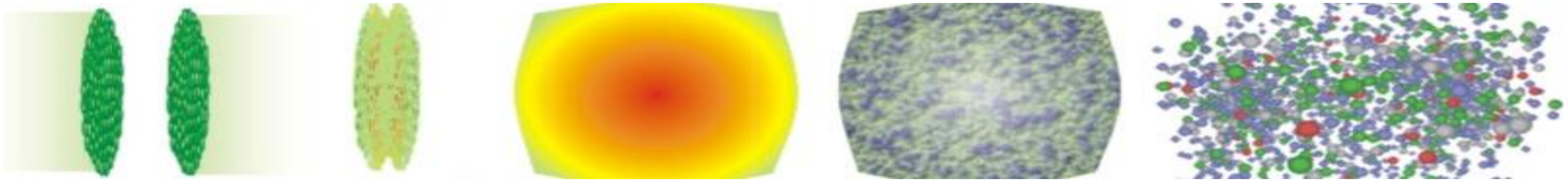


JHEP 09(2018)64,PLB788(2019)505, arXiv:1807.00923



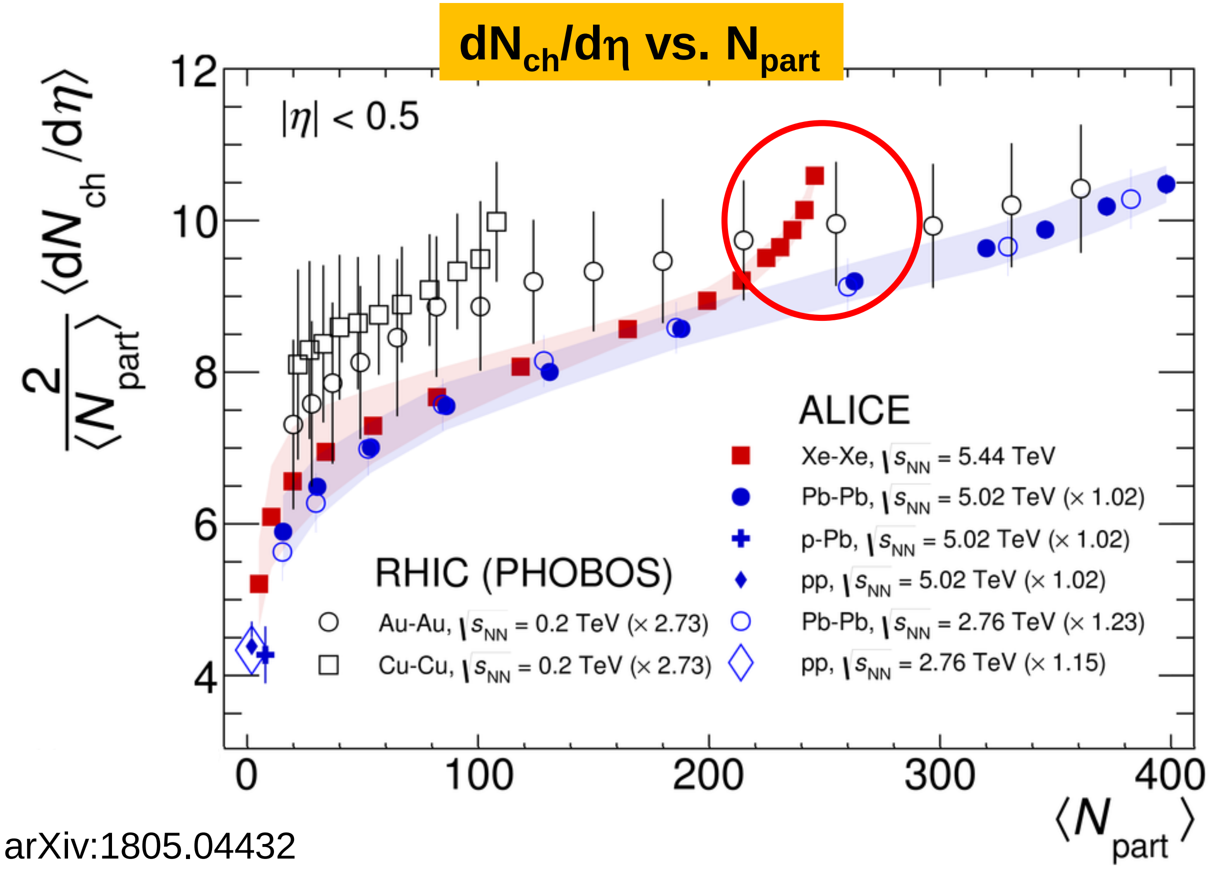
arXiv:1812.06772

Xe-Xe

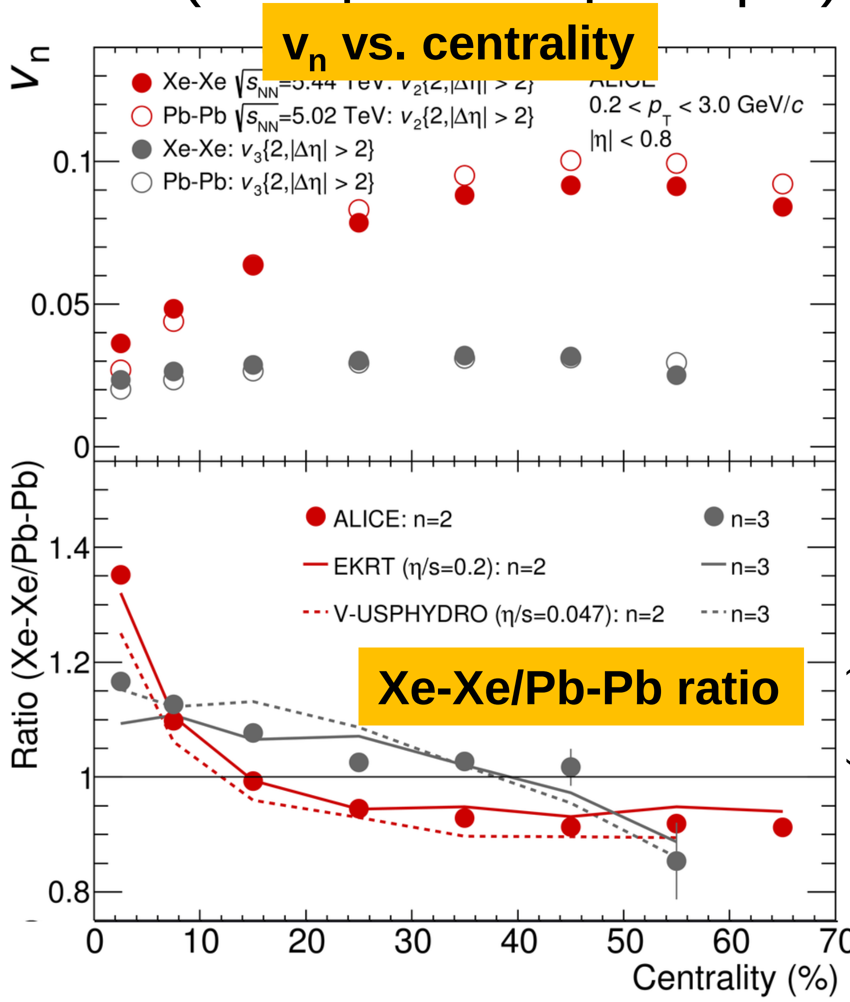


Xe-Xe

- LHC provided a few hours of Xe-Xe collisions in 2018 (as a proof-of-principle)
  - Resulted in a number of publications



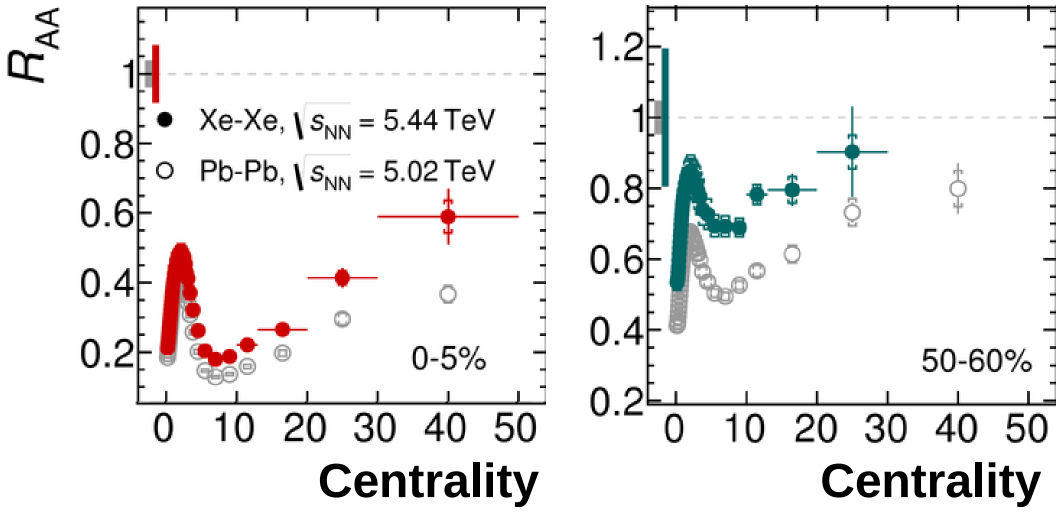
arXiv:1805.04432

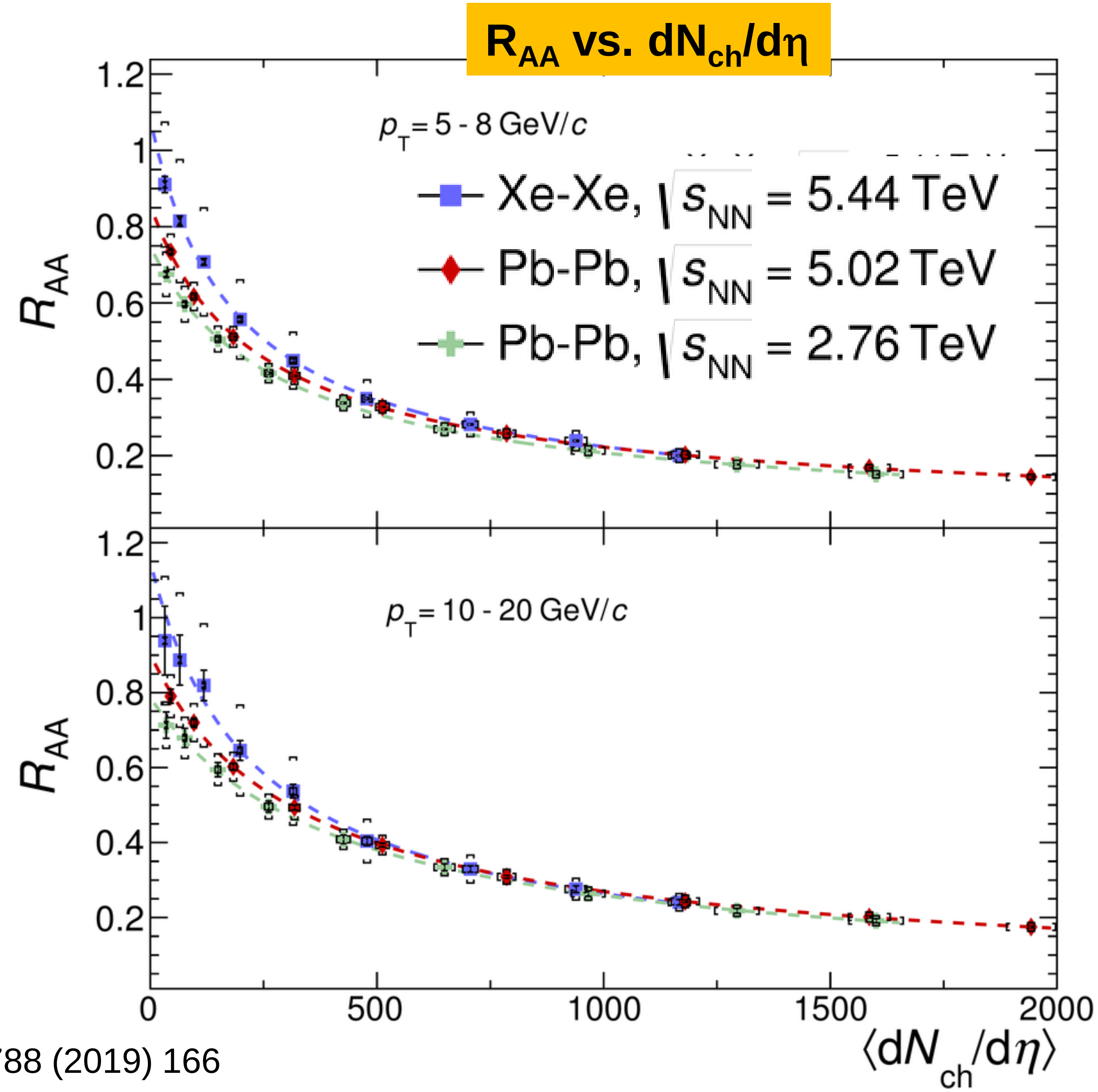


PLB784(2018)82

Xe-Xe (2)

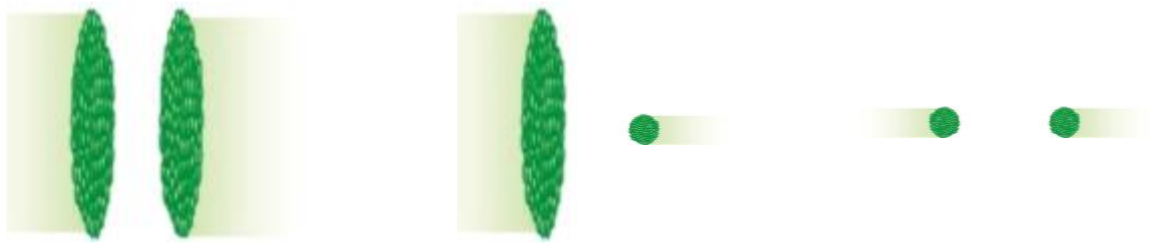
- R_{AA} suppression Pb-Pb vs. Xe-Xe
  - weaker at same centrality
  - identical at same dN/dη or N_{part} for central events
  - deviations above 30% centrality but within uncertainties



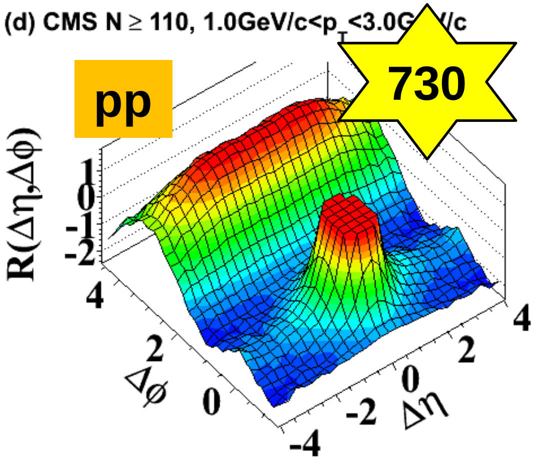


PLB788 (2019) 166

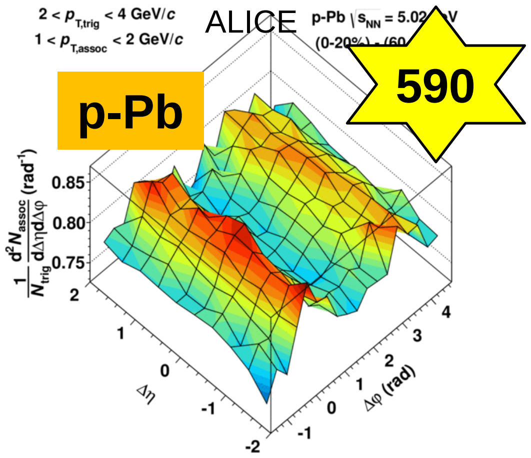
Discoveries in Small Systems
&
Paradigm Shifts



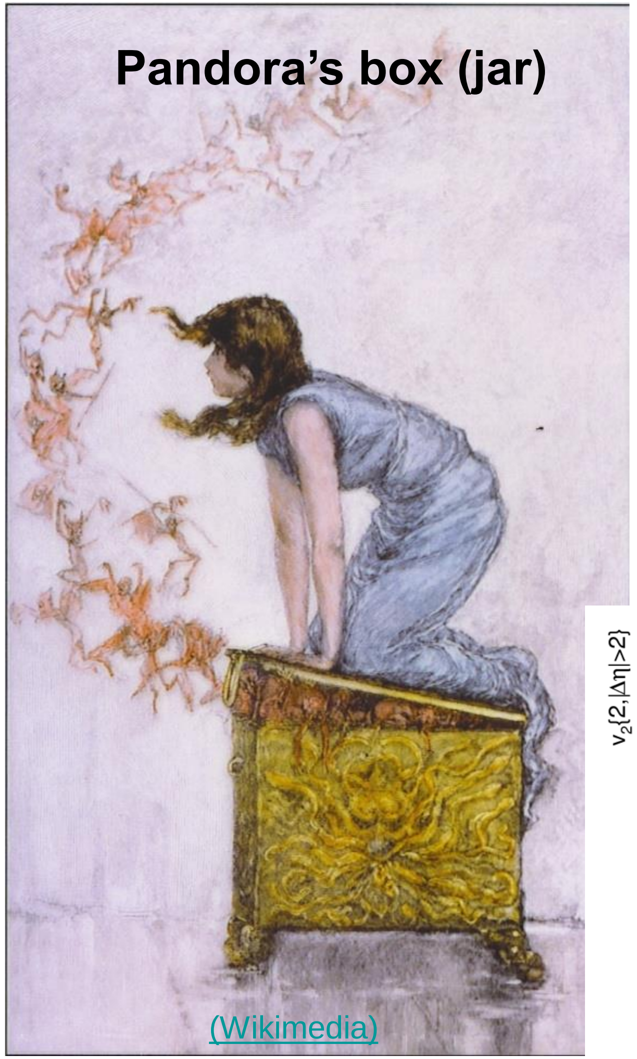
Small Systems



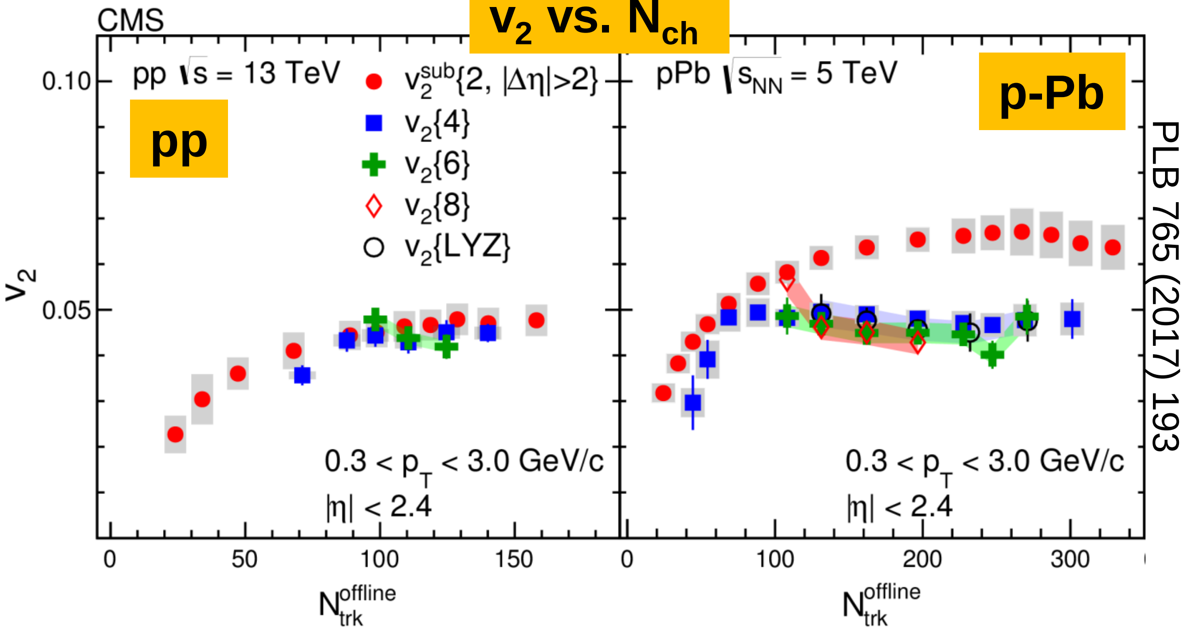
JHEP09(2010)091



PLB719 (2013) 29



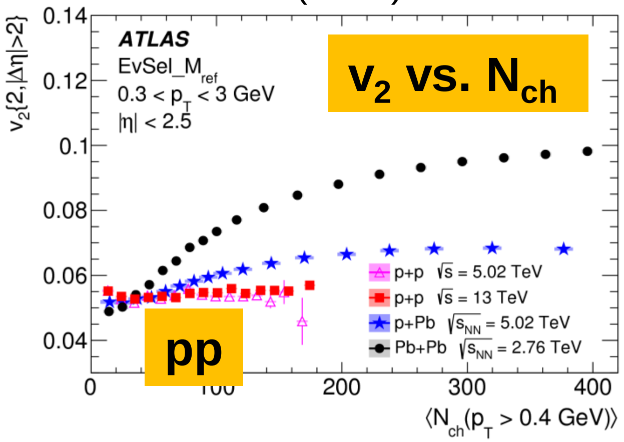
(Wikimedia)

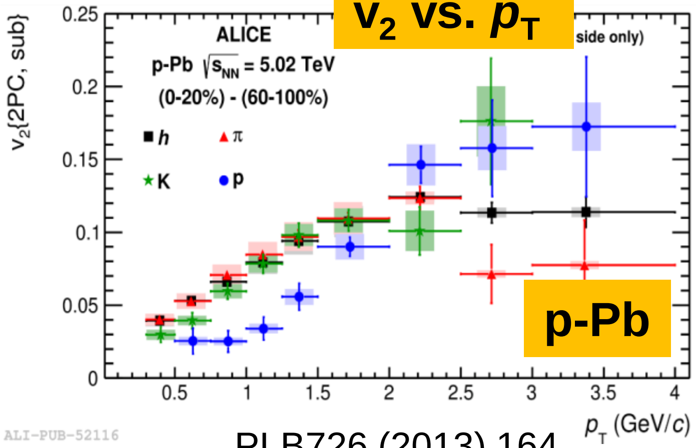


PLB 765 (2017) 193

Collective phenomena in pp and p-Pb collisions have caused a paradigm shift

EPJC 77 (2017) 428



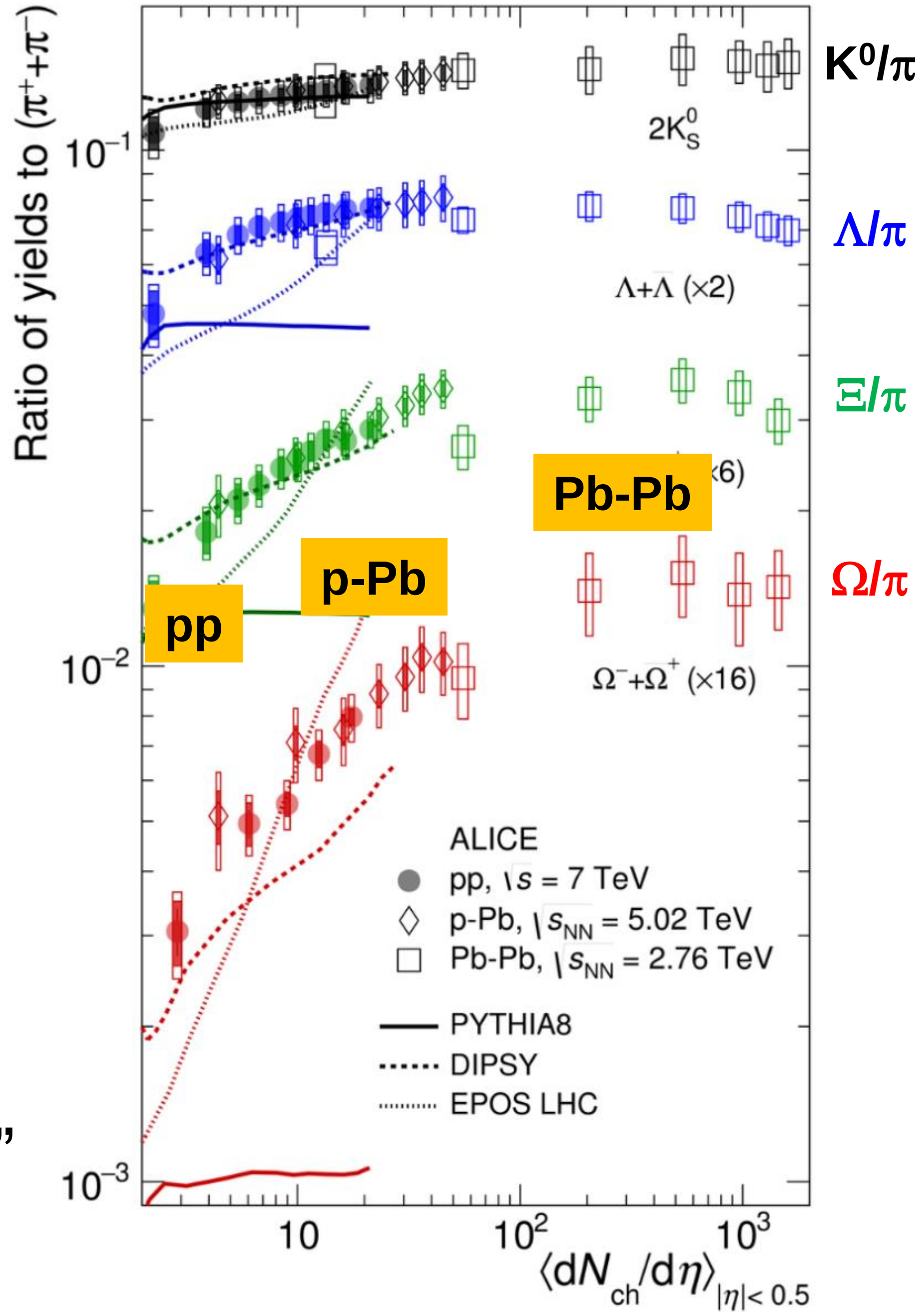


PLB726 (2013) 164

Strangeness Production

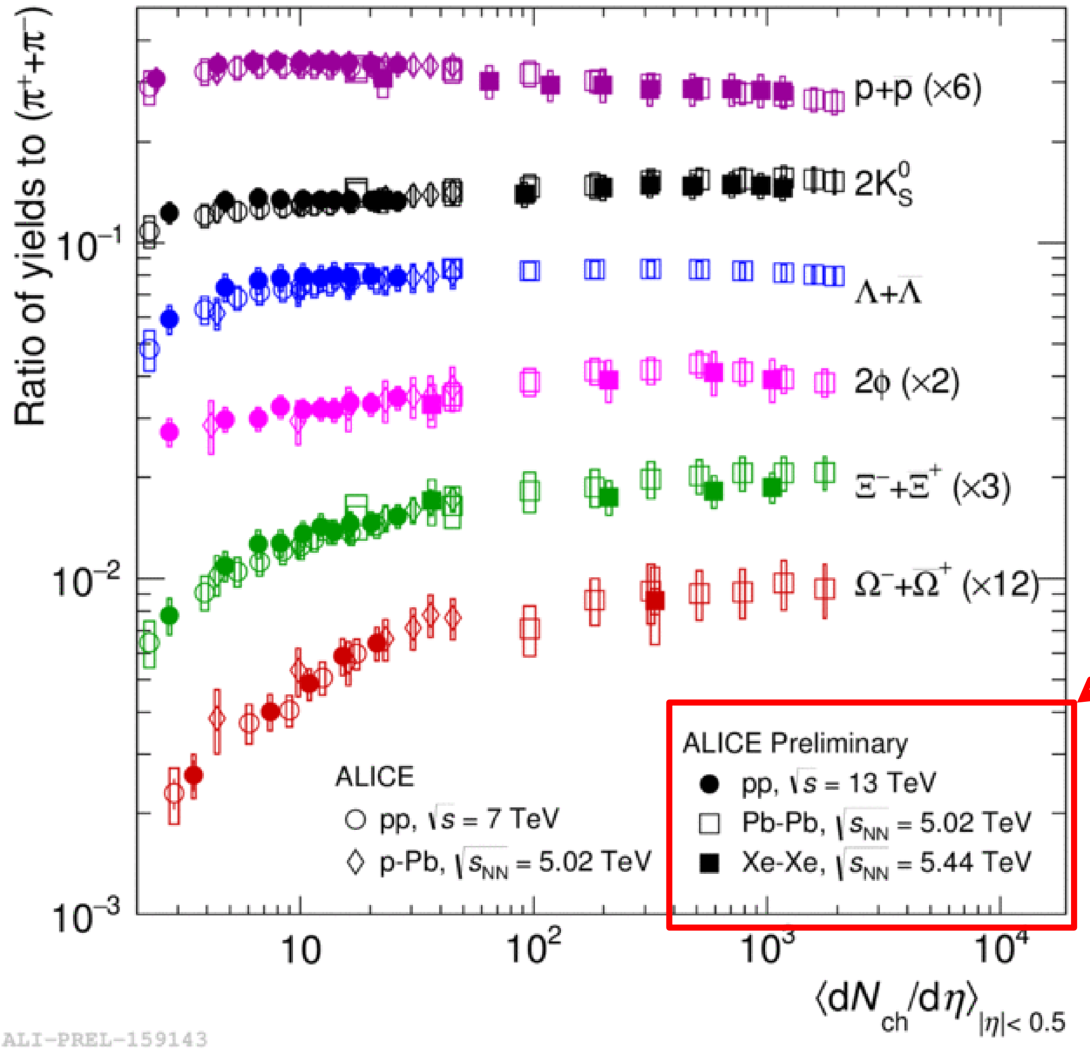
- Strange baryon production increases with increasing multiplicity
  - K^0, Λ, Ξ, Ω
  - Smooth across system (pp, p-Pb, Pb-Pb)
  - Multiplicity only relevant variable here?
    - Need more overlap for final answer

- Traditional MC codes fail to reproduce trend
- Tjorben Sjostrand (QM '18): "need new framework for baryon production"



Nature Phys.13(2017)535

Strangeness Production (2)

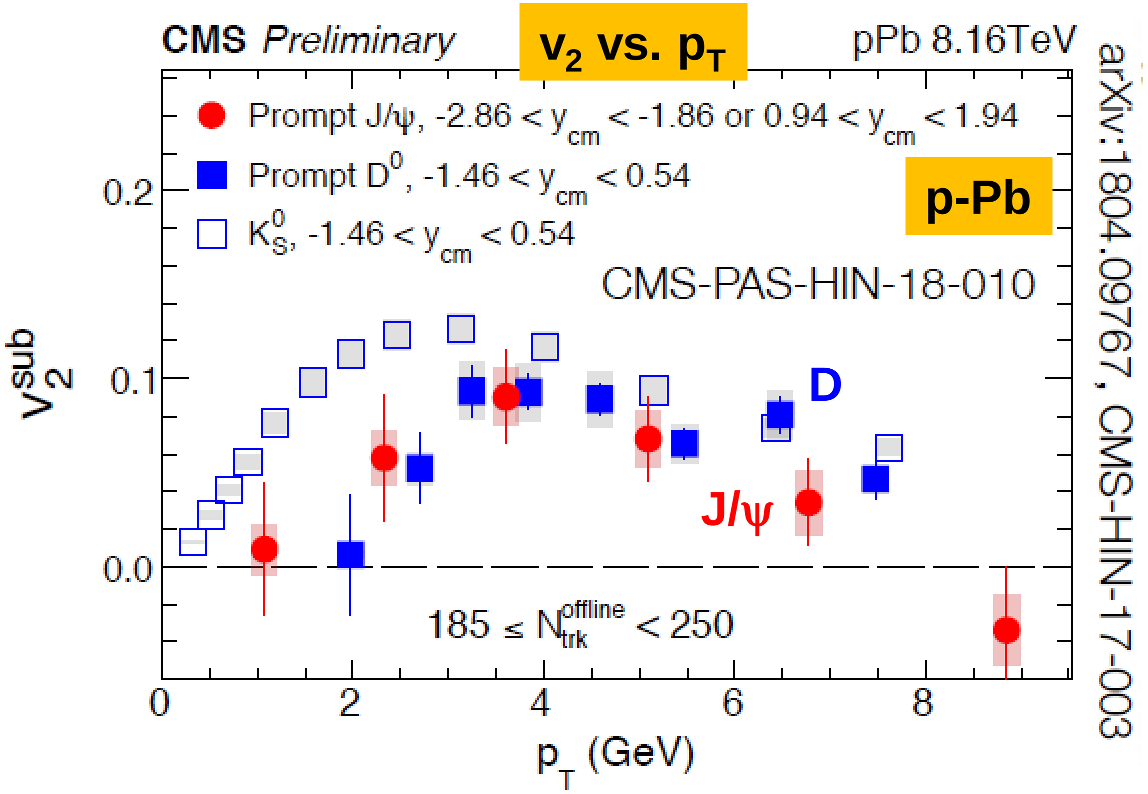


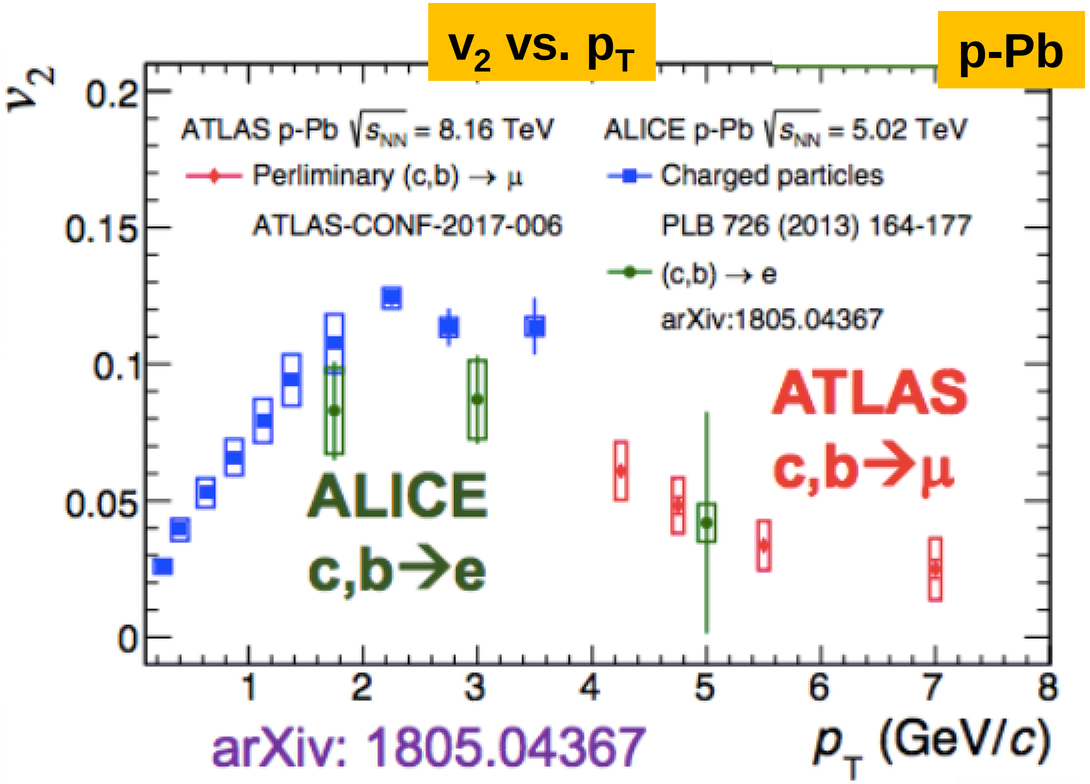
NEW:
pp @ 13 TeV
Pb-Pb @ 5 TeV
Xe-Xe @ 5.44 TeV

Consistent picture of smooth enhancement vs. $dN_{ch}/d\eta$

Charm & Beauty

Can similar effects be observed for heavy quarks?



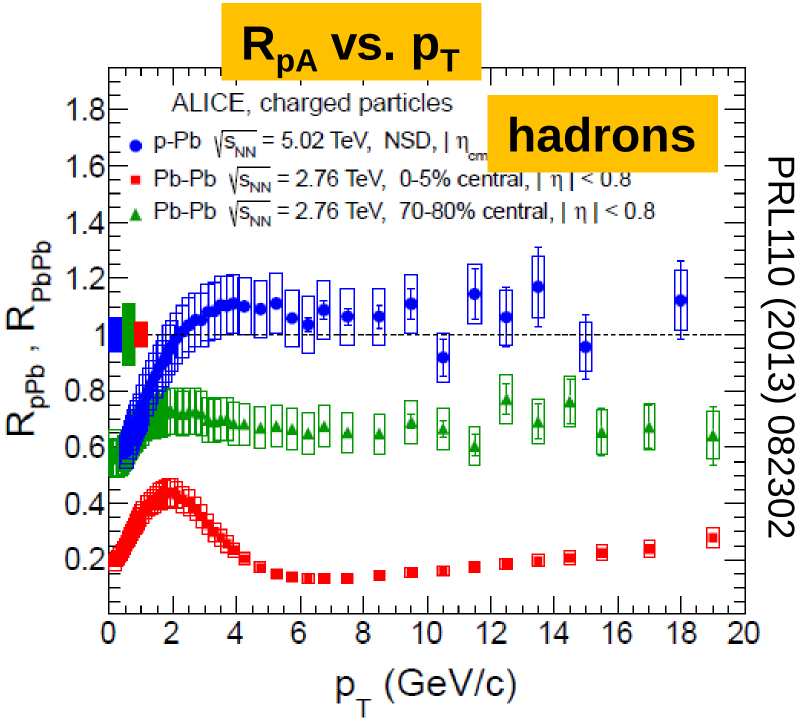


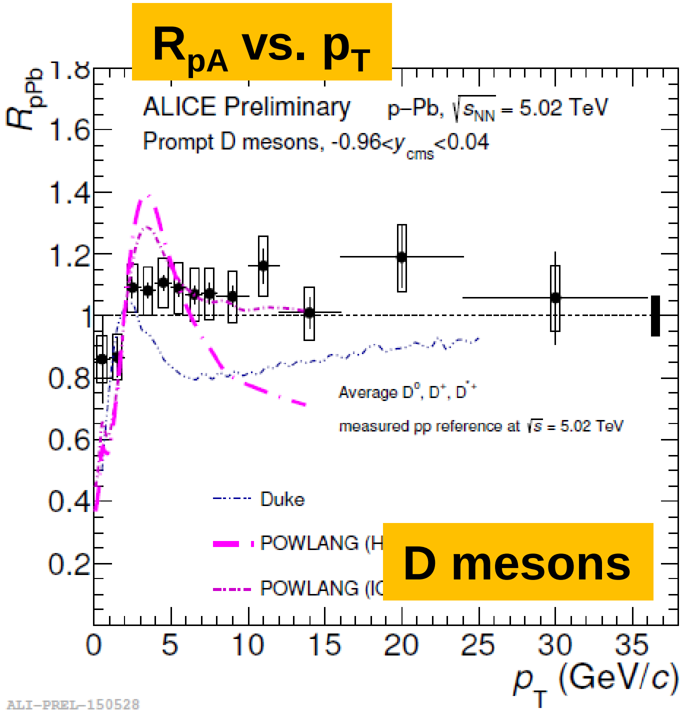
- **Signal observed for D, J/ψ, leptons from HF decays**
- **Heavy quarks participate in the collective effects observed**

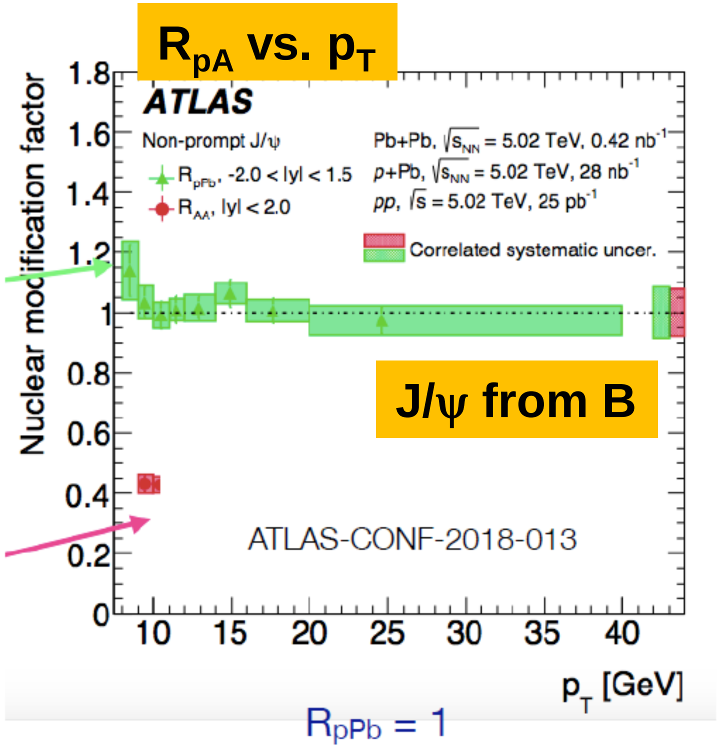
Energy Loss

What is the role of final-state interactions?

- If v_n are caused by final-state interactions, partons should loose energy





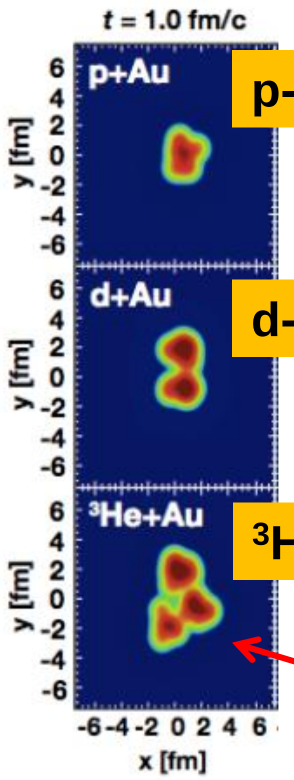


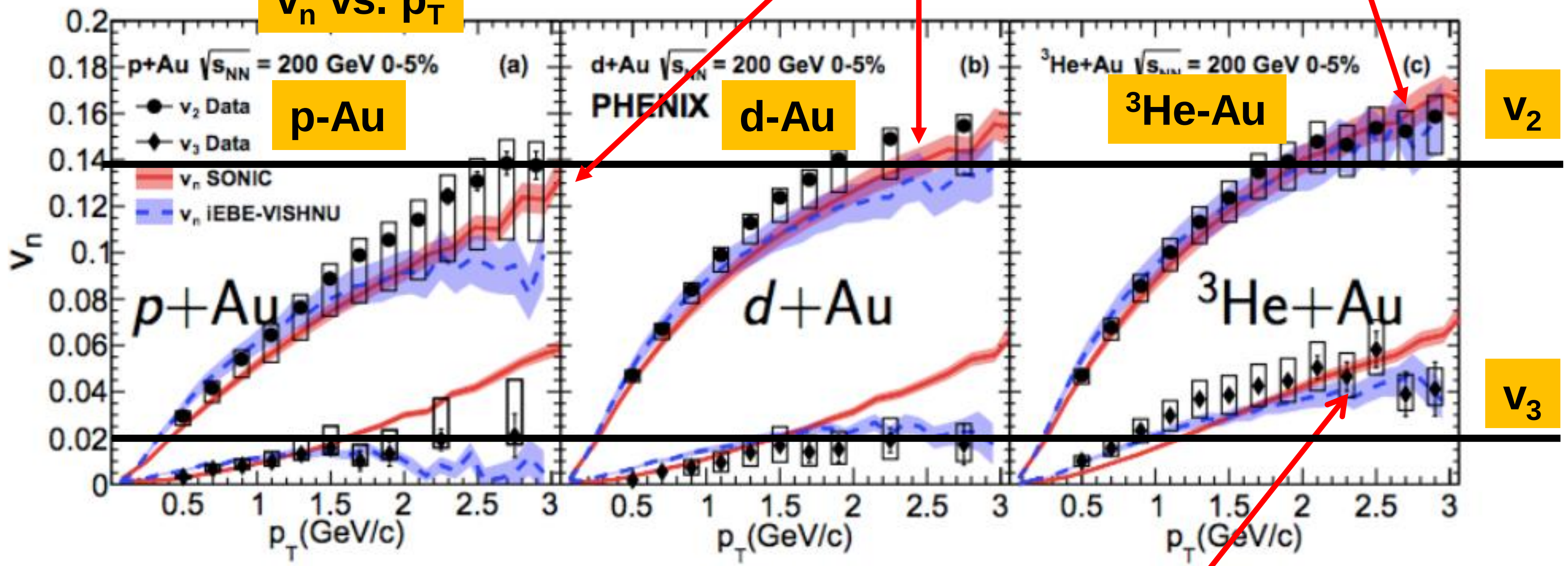
No significant signal observed in R_{pA} for hadrons, D and B

Initial or final state effect?

What is the relation to the shape of the initial state?

RHIC geometry scan





Prediction by hydrodynamic models

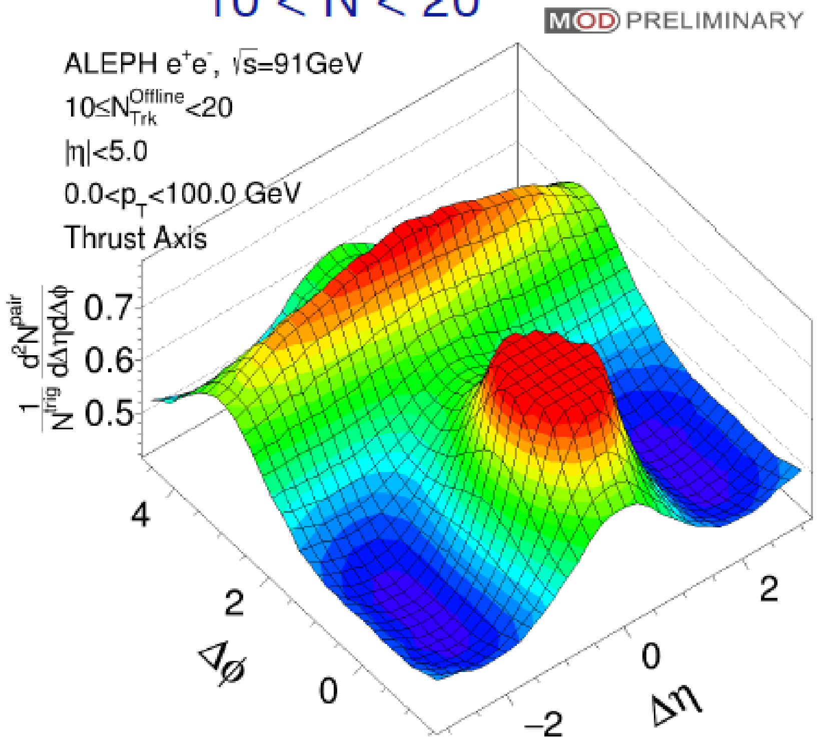
Triangular initial state → large v_3

arXiv:1805.02973

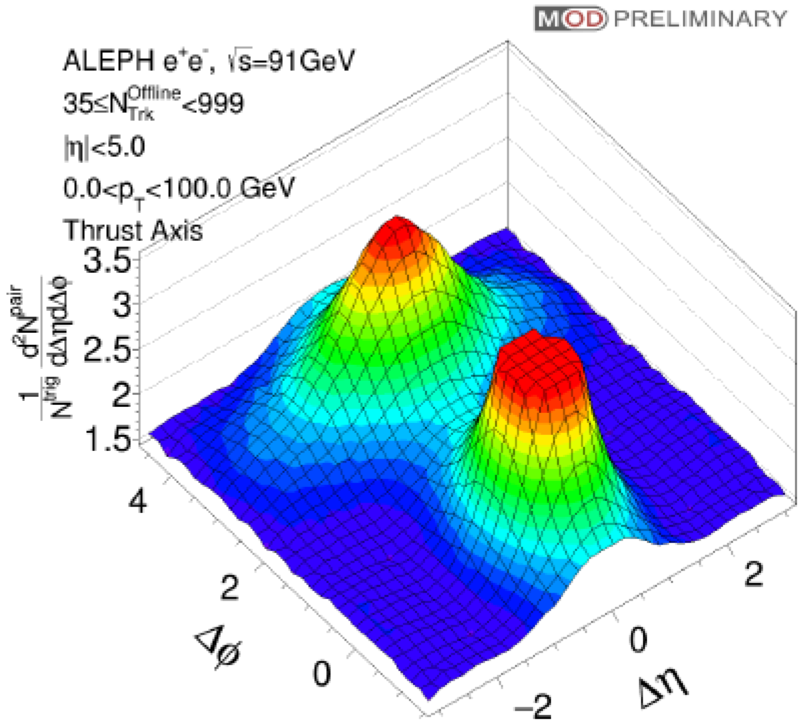
e^+e^- (archived ALEPH data)

Can we observe the same structures in e^+e^- collisions?

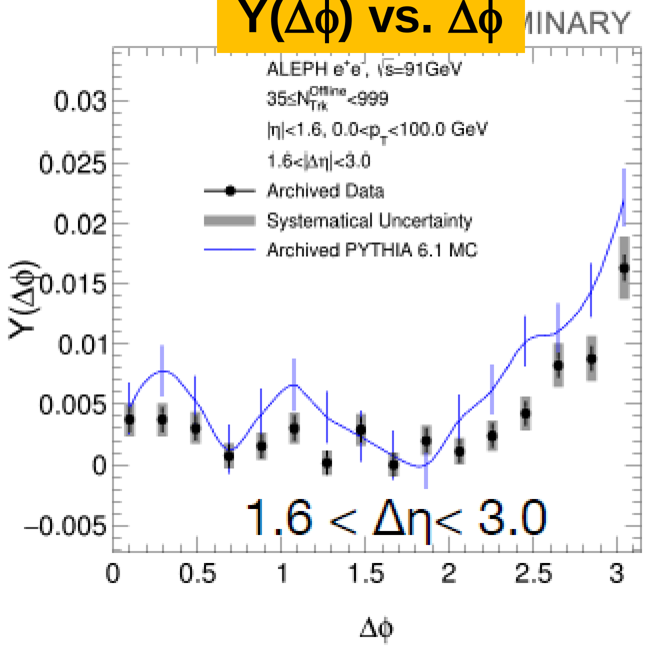
10 < N < 20



N ≥ 35



Y(Δϕ) vs. Δϕ

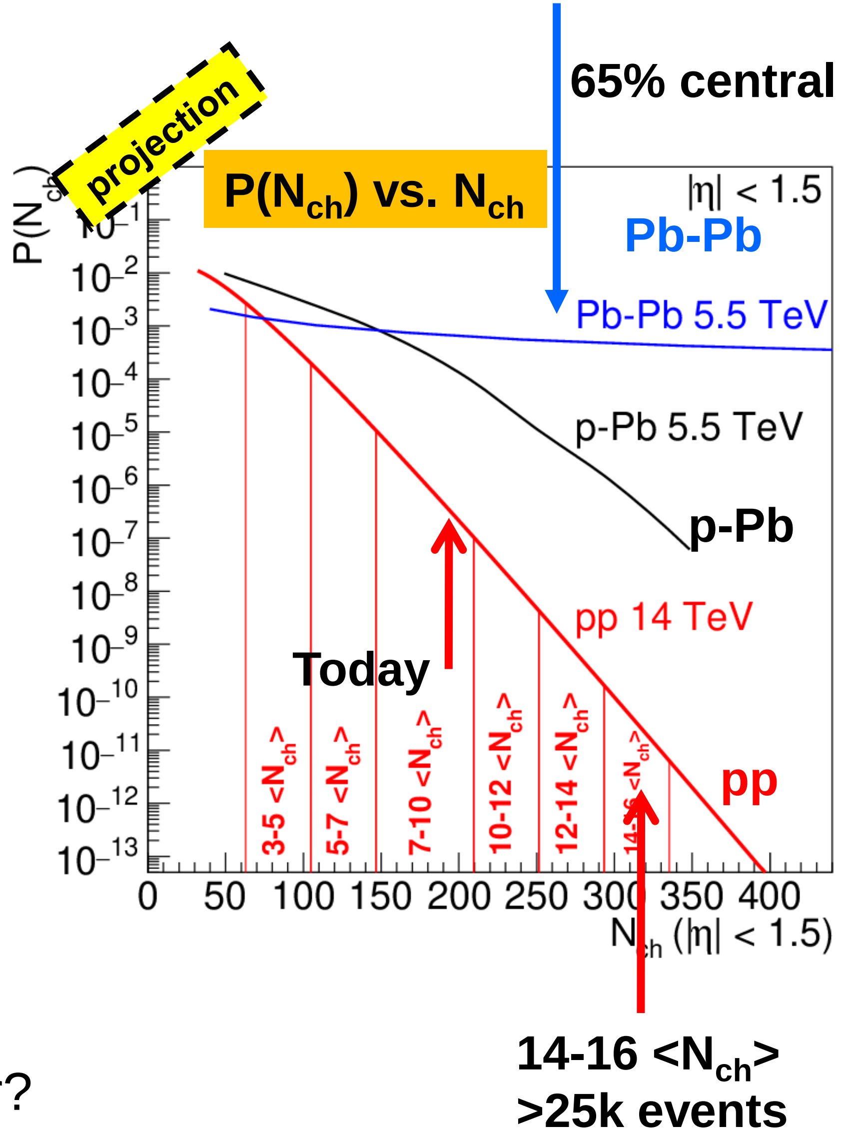


No collective effects found in ee collisions!

Yen-Jie Lee, Quark Matter 2018

Understanding Small Systems

- Observations challenge two paradigms at once
  - For how small systems does the “HI SM” remain valid?
  - Can the standard tools for pp physics remain standard?
- Run 3 can reach extremely rare (10^{-11}) pp events
  - 200 pb^{-1} | Sampling 10^{13} events
- Significant overlap between pp and PbPb
  - In multiplicity up to ~65% centrality
- If pp behaves as HI, we can see “standard” HI physics
  - Including jet quenching if effects driven by final state
  - If not, we can see the differences
- In addition: MB sample for low-multiplicity limit
  - What is smallest droplet of matter showing collective behavior?

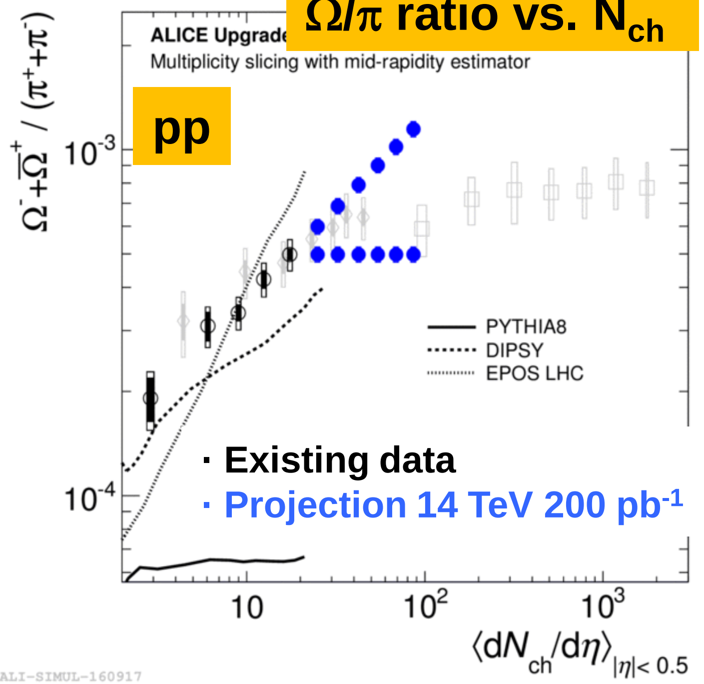


Future Opportunities

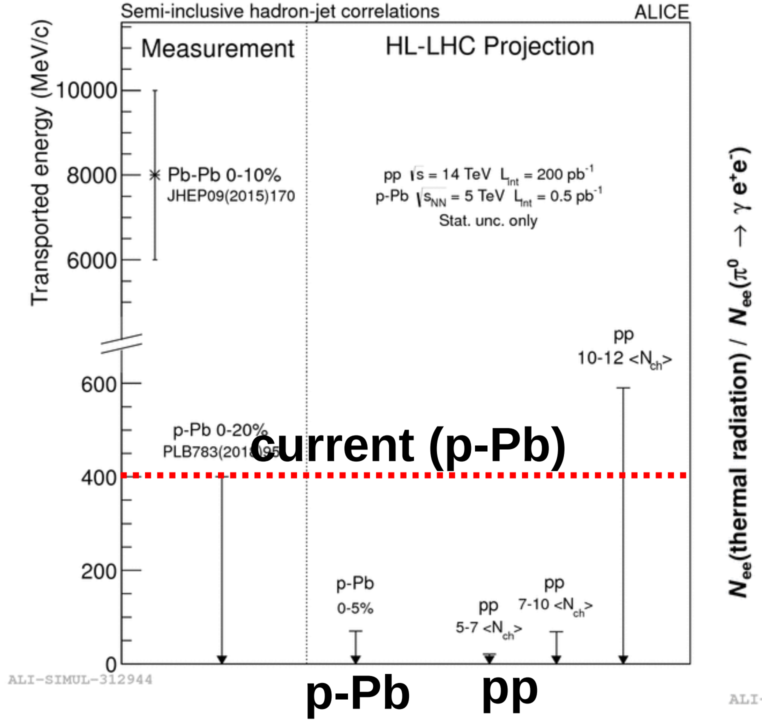
projection

- Strangeness enhancement. Thermal limit in pp?
- Precise D and J/ψ v_2 in p-Pb
  - and in pp?
- Measure energy loss or put stringent limit
  - h-jet, jet-γ, jet-Z correlations
- Sign of thermal radiation?

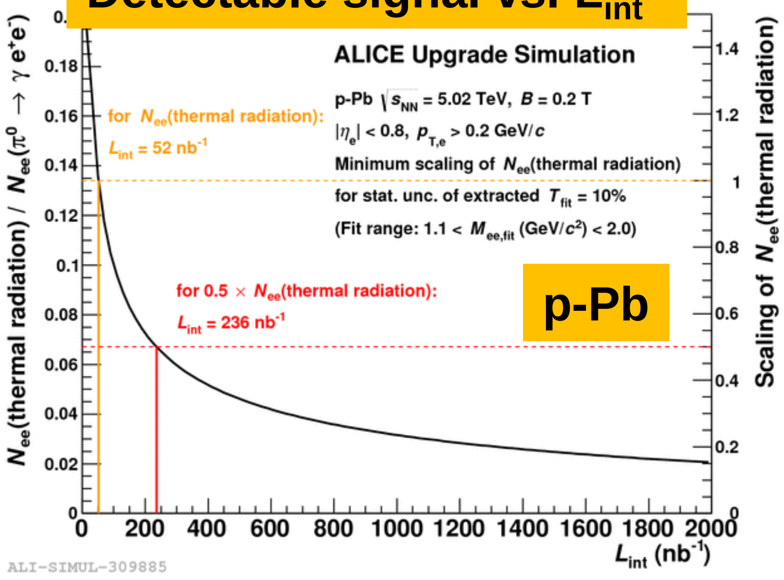
Ω/π ratio vs. N_{ch}



Limit on (medium-induced) transferred energy

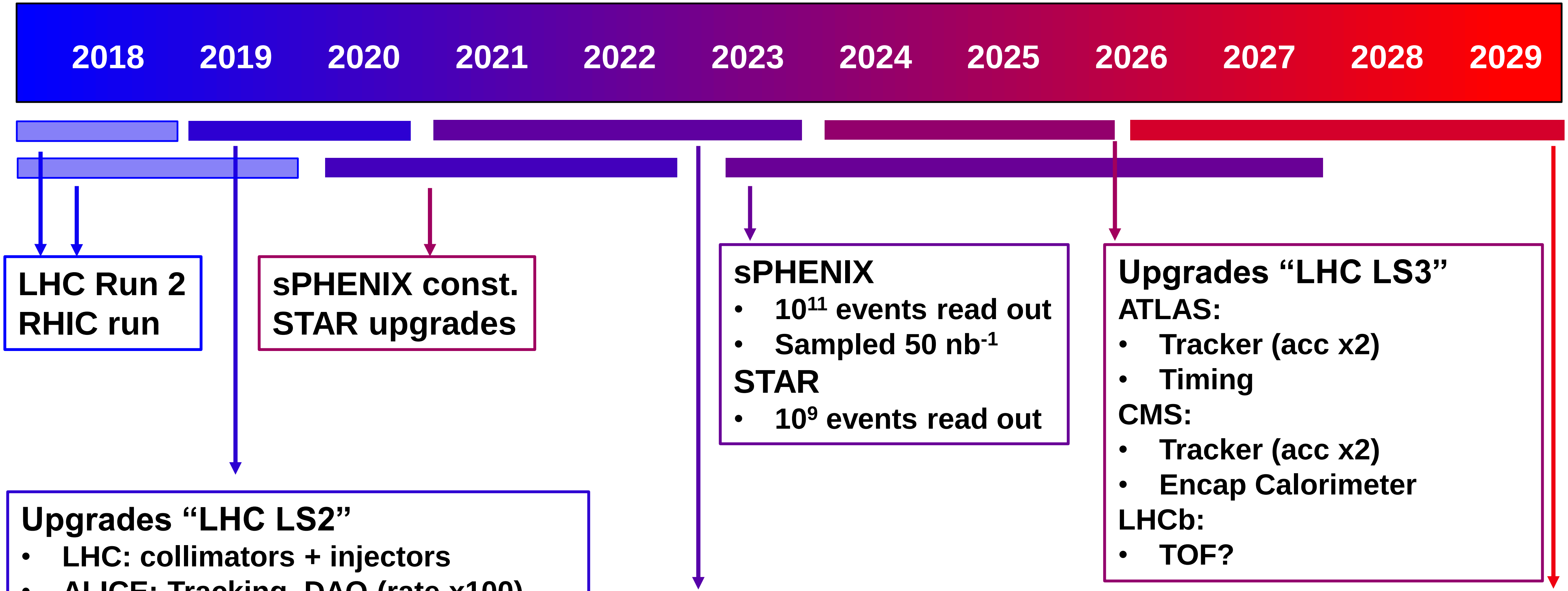


Detectable signal vs. L_{int}



The Next Decade

Timeline



LHC Run 2
RHIC run

sPHENIX const.
STAR upgrades

sPHENIX
- **10^{11} events read out**
- **Sampled 50 nb^{-1}**

STAR
- **10^{9} events read out**

Upgrades "LHC LS3"
ATLAS:
- **Tracker (acc x2)**
- **Timing**

CMS:
- **Tracker (acc x2)**
- **Encap Calorimeter**

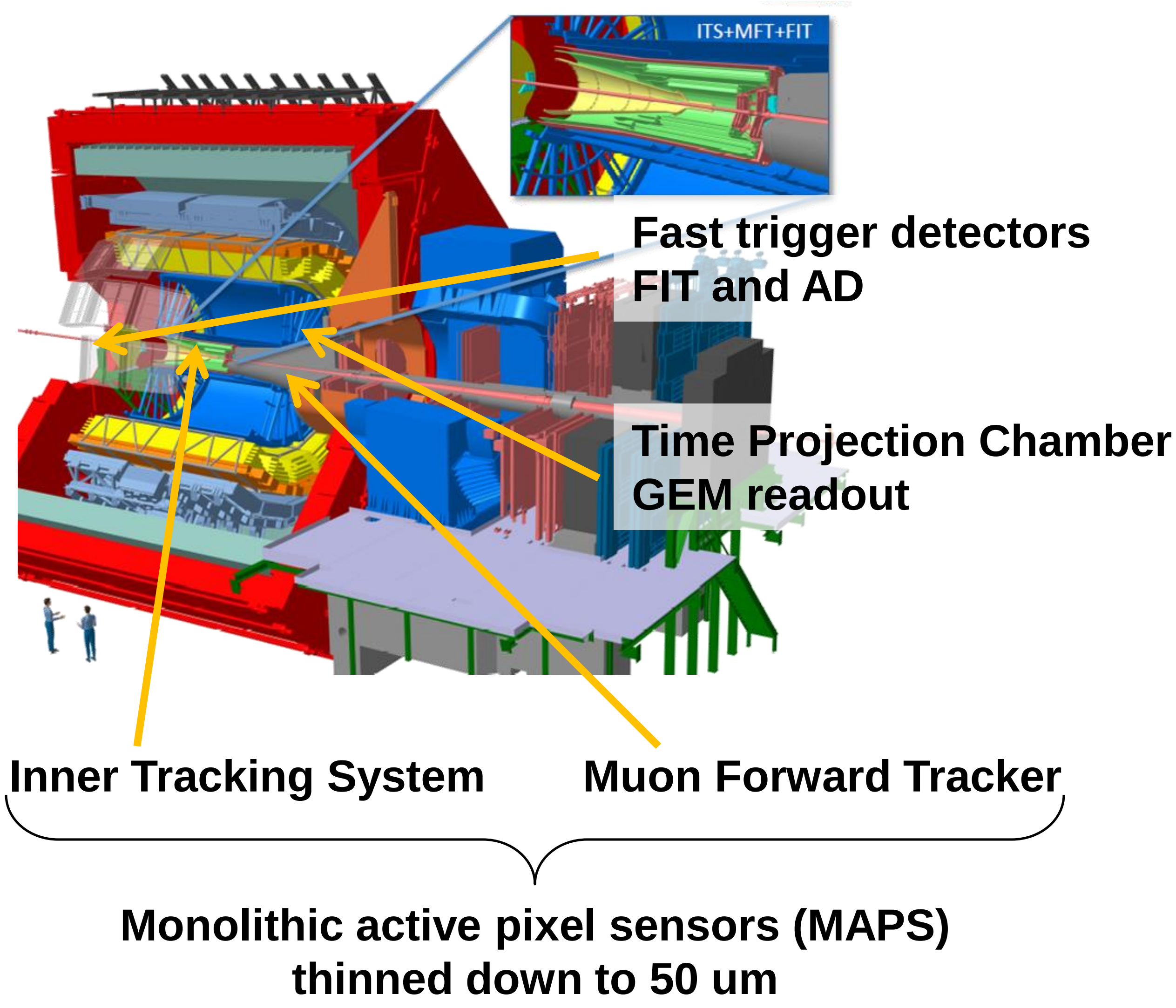
LHCb:
- **TOF?**

Upgrades "LHC LS2"
- **LHC: collimators + injectors**
- **ALICE: Tracking, DAQ (rate x100)**
- **ATLAS: Fast tracker trigger (rate x2)**
- **CMS: pixel detector (rate x2)**
- **LHCb: VELO, tracker, DAQ (rate x10)**

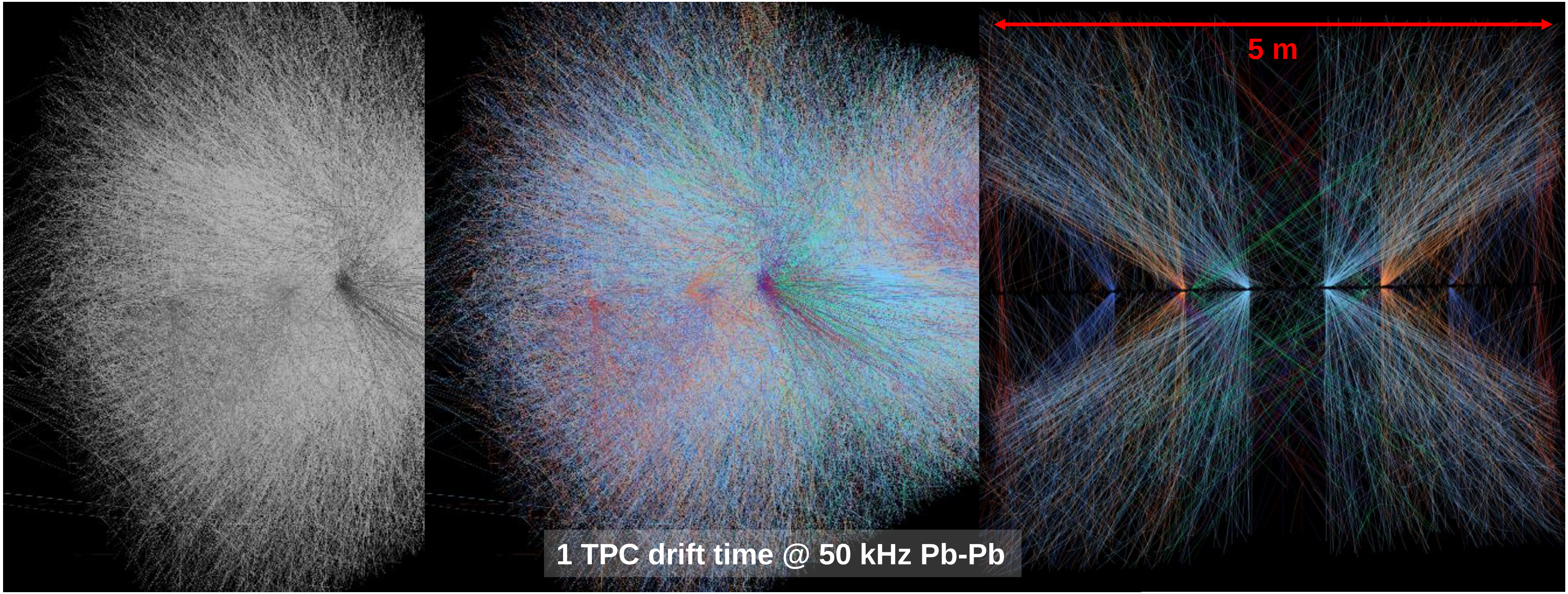
LHC Run 3 + 4 (numbers for Pb-Pb)
- **$L = 6 \cdot 10^{27}\ cm^{-2}s^{-1}$ ~ 50 kHz rate**
- **13 nb^{-1} (ALICE, CMS, ATLAS) | 2 nb^{-1} (LHCb)**

Ongoing ALICE Upgrade (data taking from 2021)

- Significant upgrade, including
  - Data rate x100 [MBx100 | L_{int}x10]
  - Impact parameter resolution x3
- Collision spacing < TPC drift time
  - No notion of event during data taking
- Continuous data-taking
  - 50 kHz Pb-Pb
  - Offline reconstruction determines which track belongs where
  - Online reduction 3.4 TB/s → 0.1 GB/s
  - 10 nb^{-1} = 10^{11} Pb-Pb events in 2021-29
- Focus on “untriggerable” signals with tiny signal over background



Time Projection Chamber at 50 kHz



Space charge limit → rate limit !

Dariusz Miskowiec, Thu 17:20

Summary

- Legacy of results from first 8 years of heavy-ion collisions at the LHC
  - Participant picture, medium properties, energy loss in 100-1000 GeV regime, quarkonia regeneration
  - Paradigm shift of understanding of small collision systems

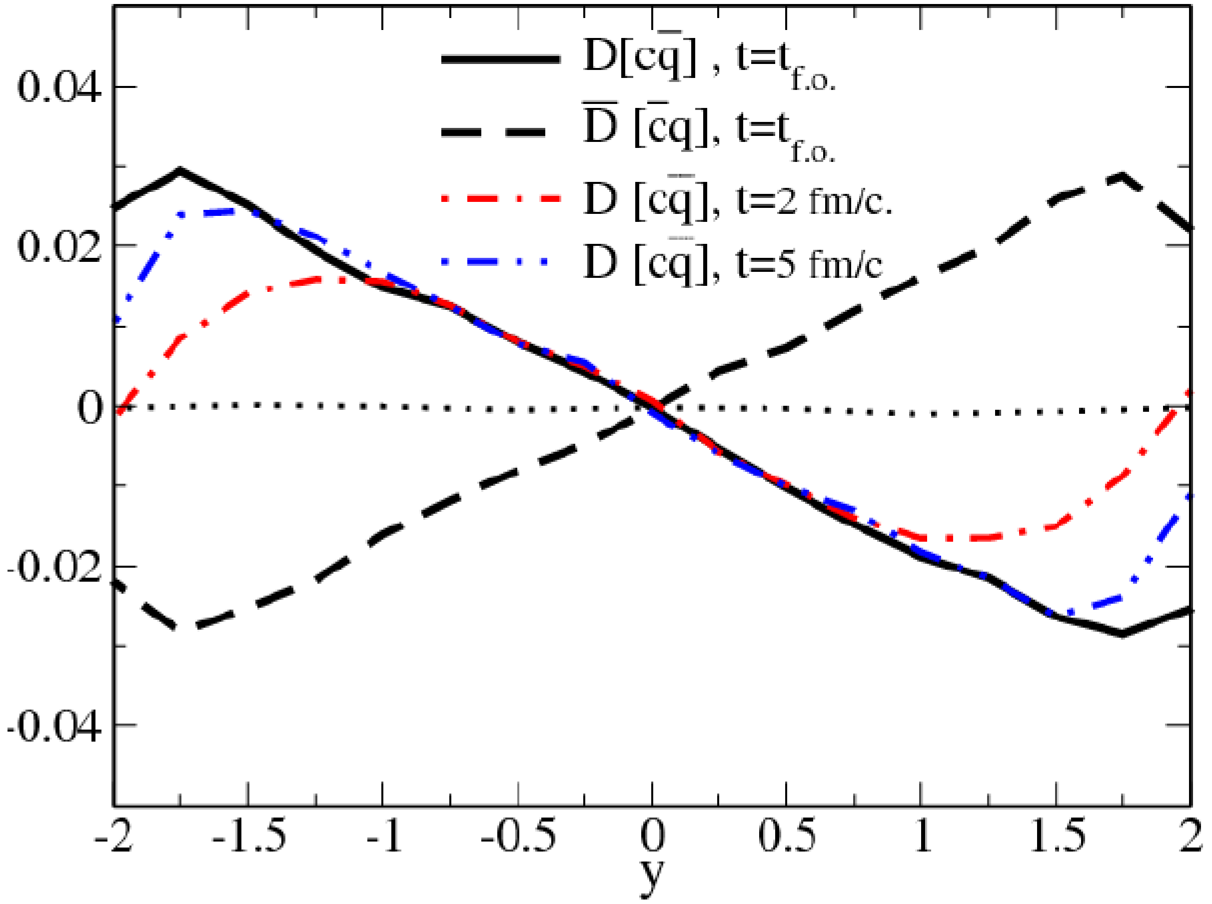
- Next decade (LHC run 3 and 4) expects up to 100x larger data sample
  - Macroscopic long-wavelength QGP properties
  - Microscopic parton dynamics underlying the QGP properties
  - Investigate unified picture of particle production from small to large systems

Opportunities detailed in community document: arXiv:1812.06772

Thank you for your attention!

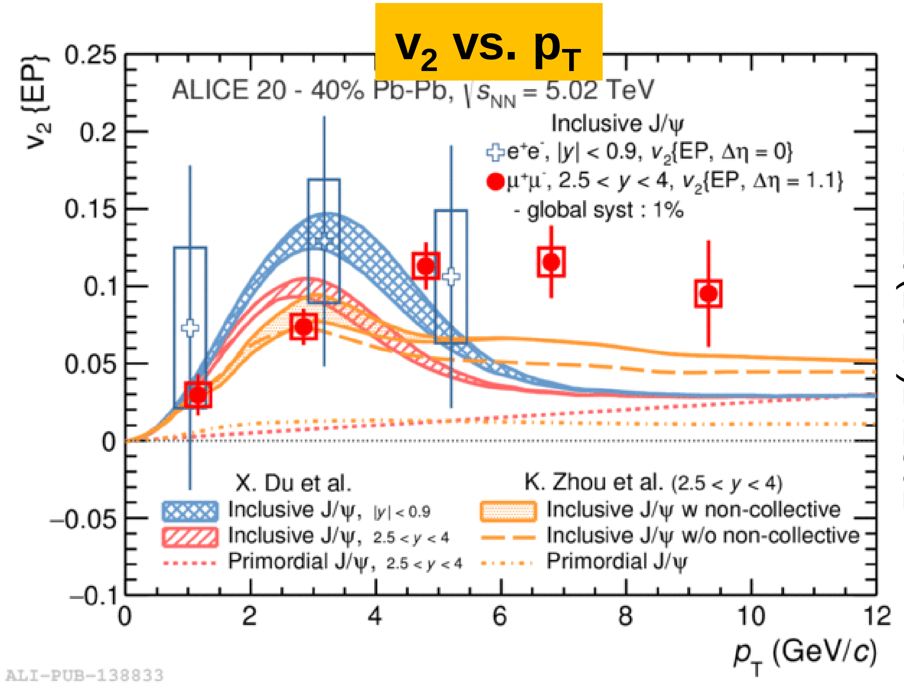
Backup

D Directed Flow



predicted strength from S. Das et al., PLB 768 (2017) 260

J/ψ v_2



PRL119(2017)242301