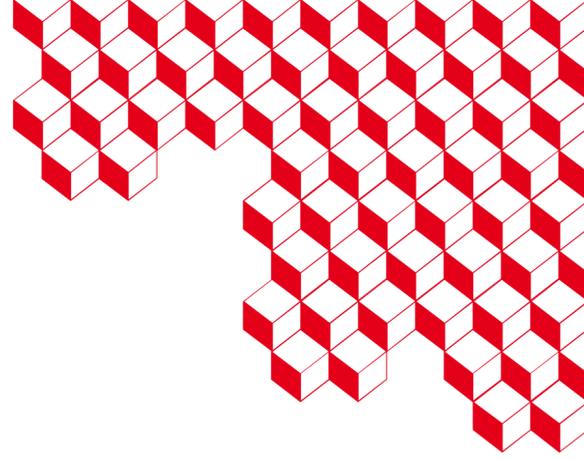


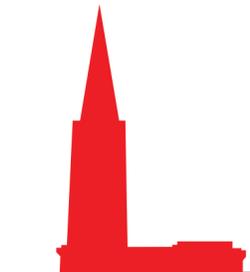


irfu



# Experimental summary

SQM 2024, Strasbourg



The 21<sup>st</sup> International Conference on Strangeness in Quark Matter  
3-7 June 2024, Strasbourg, France



*Javier Castillo Castellanos*

# Acknowledgment and disclaimer





# This is SQM, Strangeness in Quark Matter

So let's start with the famous strangeness enhancement



# The famous strangeness enhancement

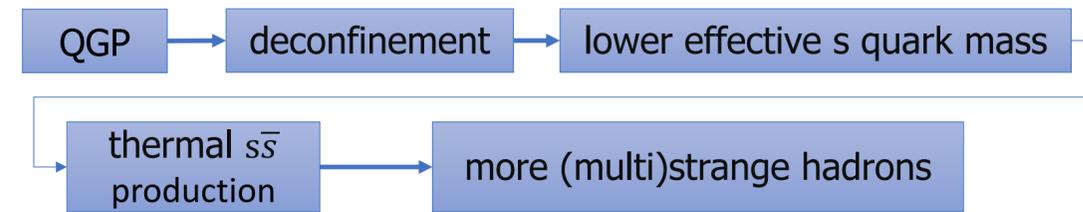
The original idea is simple

- Strangeness enhancement
- Stronger enhancement for larger s content

Observed at SPS, RHIC, LHC energies

## Strangeness enhancement phenomenon

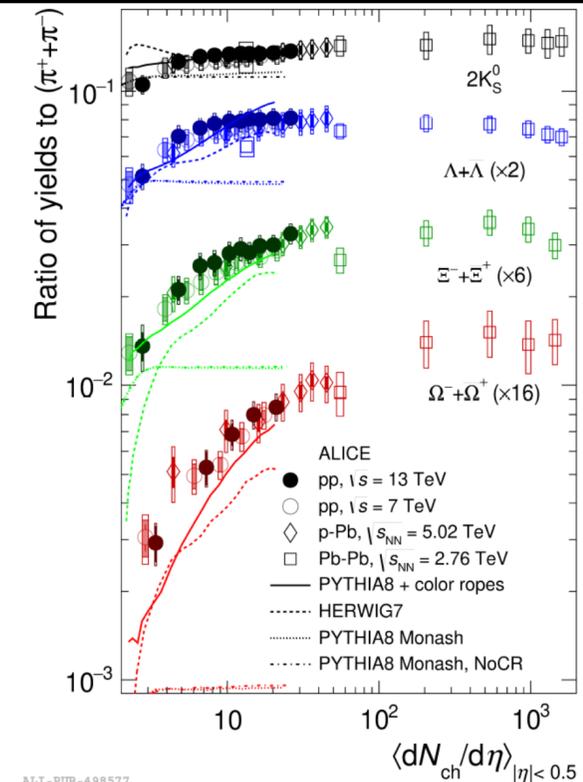
Strangeness originally proposed as a signature of QGP



Strangeness enhancement with particle multiplicity is **independent** of collision system and energy

interaction between **MPI** systems?

core-corona approach down to **pp** systems?



Roman Nepeivoda

SQM 2024 - Strasbourg

[Eur. Phys. J. C 80, 693 \(2020\)](#)

2

# The (in)famous strangeness enhancement

The original idea is simple

- Strangeness enhancement
- Stronger enhancement for larger s content

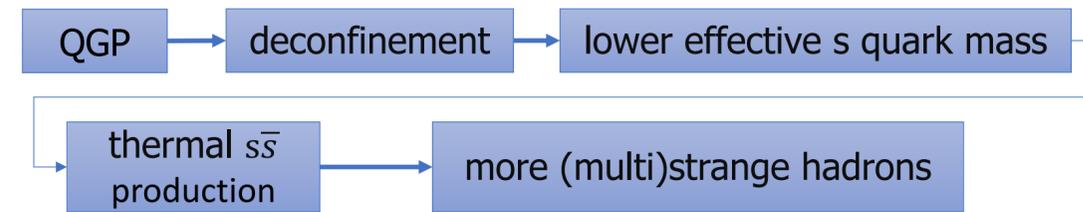
Observed at SPS, RHIC, LHC energies

But the interpretation still challenging

- Strange-to-non strange particle ratio increase with multiplicity
- Independently from collision system and energy

## Strangeness enhancement phenomenon

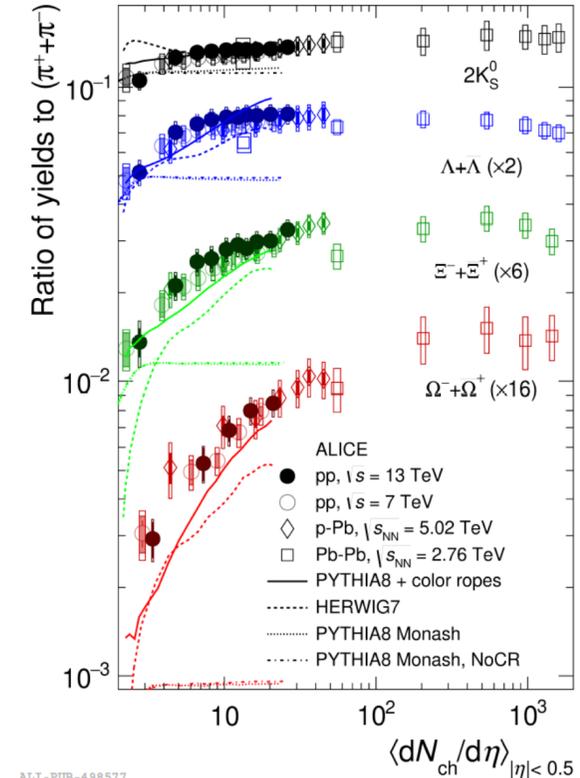
Strangeness originally proposed as a signature of QGP



Strangeness enhancement with particle multiplicity is **independent** of collision system and energy

interaction between **MPI** systems?

core-corona approach down to **pp** systems?



Roman Nepeivoda

SQM 2024 - Strasbourg

2

# The (in) famous strangeness enhancement

The original idea is simple

- Strangeness enhancement
- Stronger enhancement for larger s content

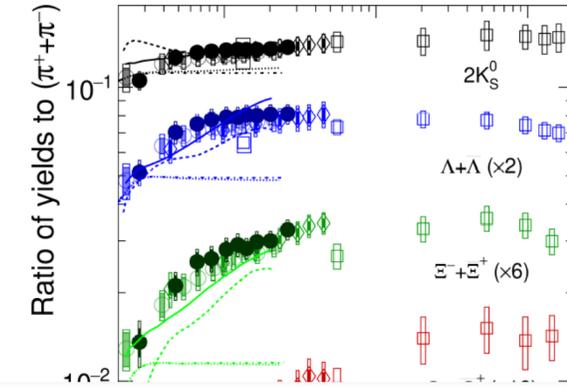
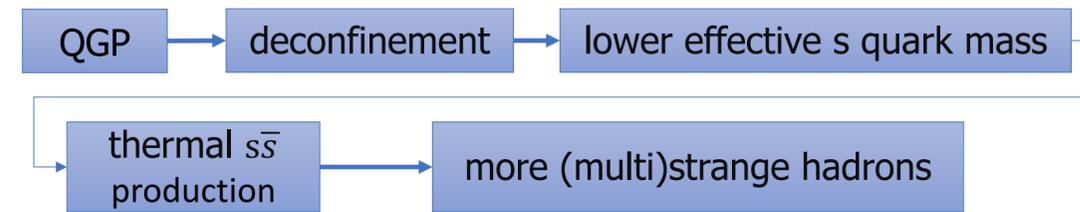
Observed at SPS, RHIC, LHC energies

But the interpretation still challenging

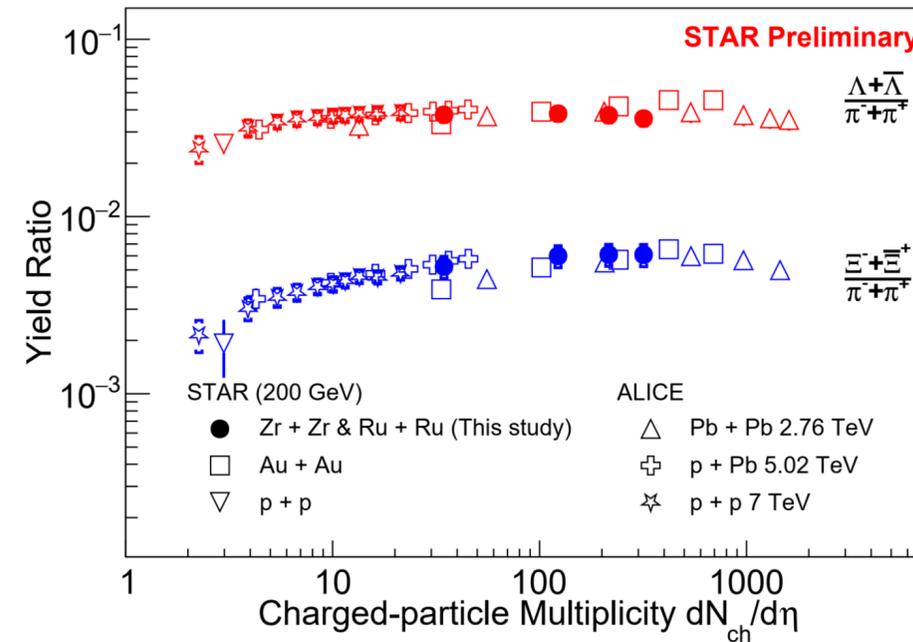
- Strange-to-non strange particle ratio increase with multiplicity
- Independently from collision system and energy

## Strangeness enhancement phenomenon

Strangeness originally proposed as a signature of QGP



## Hyperon production dependence on system size



- Hyperon-to-pion ratios follow the same trend as a function of  $dN_{ch}/d\eta$  for different collision systems
- Similar Hyperon production mechanism for systems with same multiplicity despite differences in collision energy or system

STAR:  
 PRL 98, 062301 (2007)  
 PRC 75, 064901 (2007)  
 PRC 79, 034909 (2009)

ALICE:  
 PLB 728, 216–227 (2014)  
 PLB 728, 25–38 (2014)  
 PLB 758, 389–401 (2016)  
 Nature Phys 13, 535–539 (2017)

# The (in) famous strangeness enhancement

The original idea is simple

- Strangeness enhancement
- Stronger enhancement for larger s content

Observed at SPS, RHIC, LHC energies

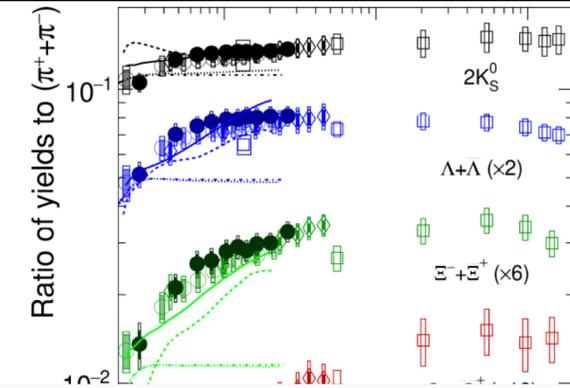
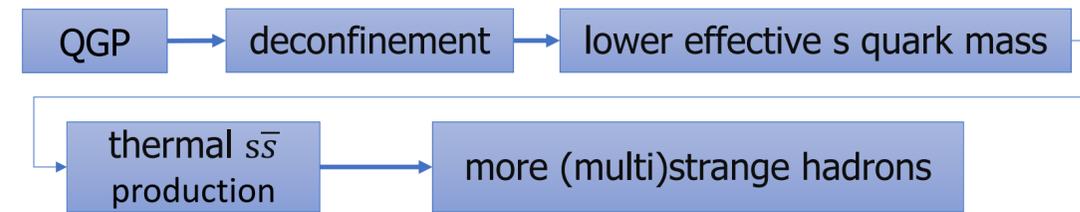
But the interpretation still challenging

- Strange-to-non strange particle ratio increase with multiplicity
- Independently from collision system and energy

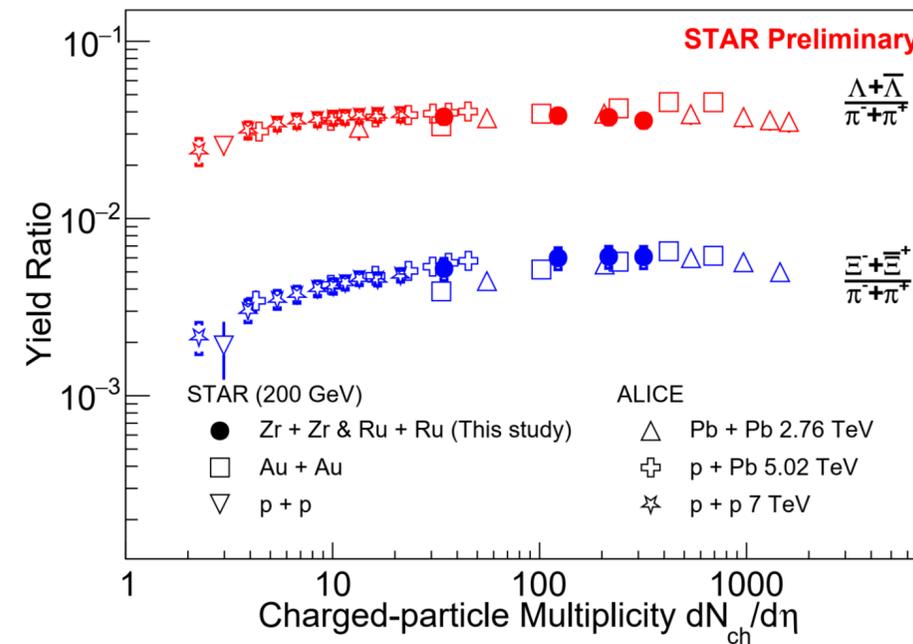
Has triggered a rich set of studies in small collision systems

## Strangeness enhancement phenomenon

Strangeness originally proposed as a signature of QGP



## Hyperon production dependence on system size



● Hyperon-to-pion ratios follow the same trend as a function of  $dN_{ch}/d\eta$  for different collision systems

● Similar Hyperon production mechanism for systems with same multiplicity despite differences in collision energy or system

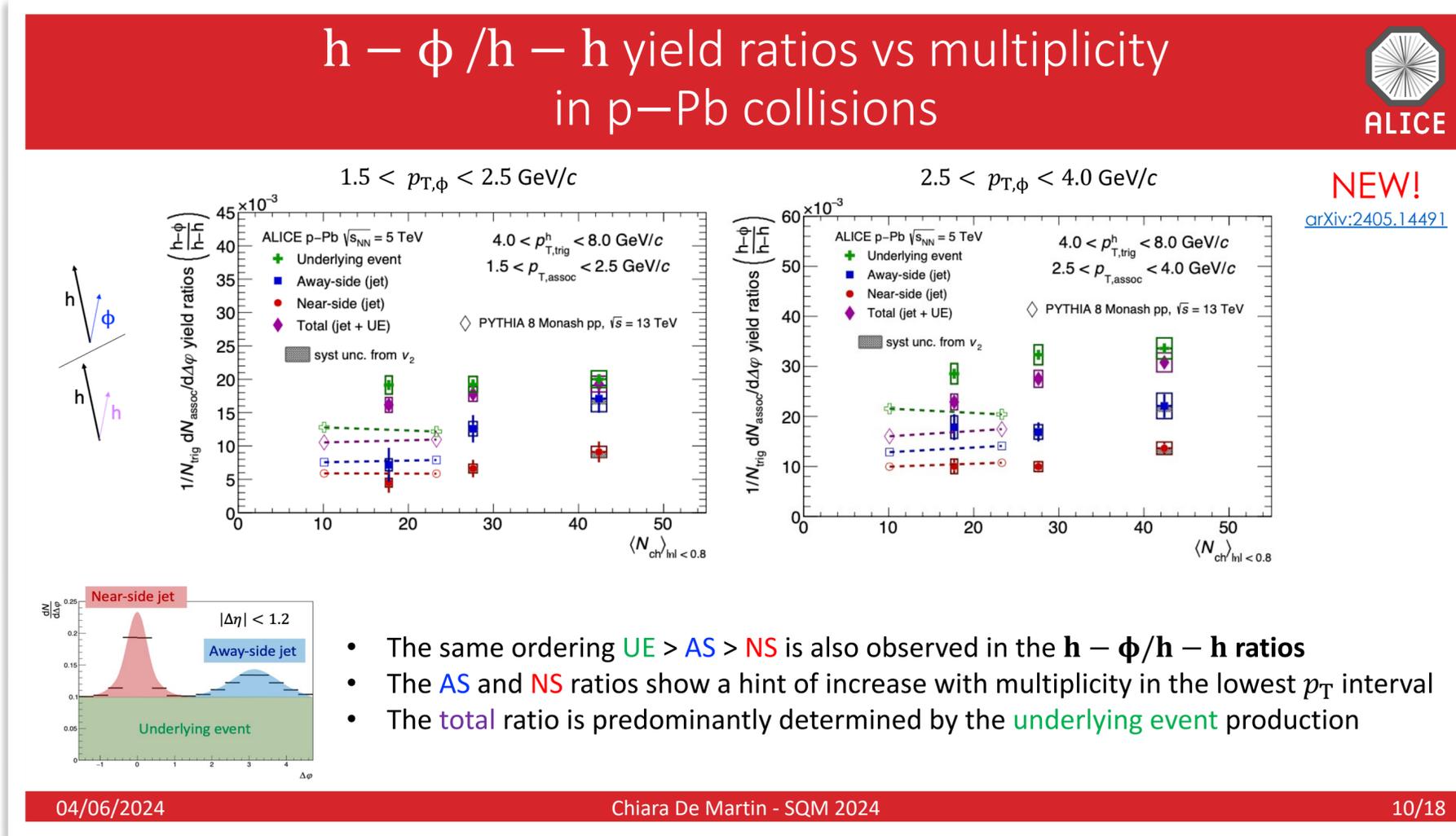
STAR:  
PRL 98, 062301 (2007)  
PRC 75, 064901 (2007)  
PRC 79, 034909 (2009)

ALICE:  
PLB 728, 216–227 (2014)  
PLB 728, 25–38 (2014)  
PLB 758, 389–401 (2016)  
Nature Phys 13, 535–539 (2017)

# Origin of strangeness enhancement in small systems

## Angular correlations in and out of jets

- The relative production of strange hadrons is larger in the underlying event than in hard scattering processes



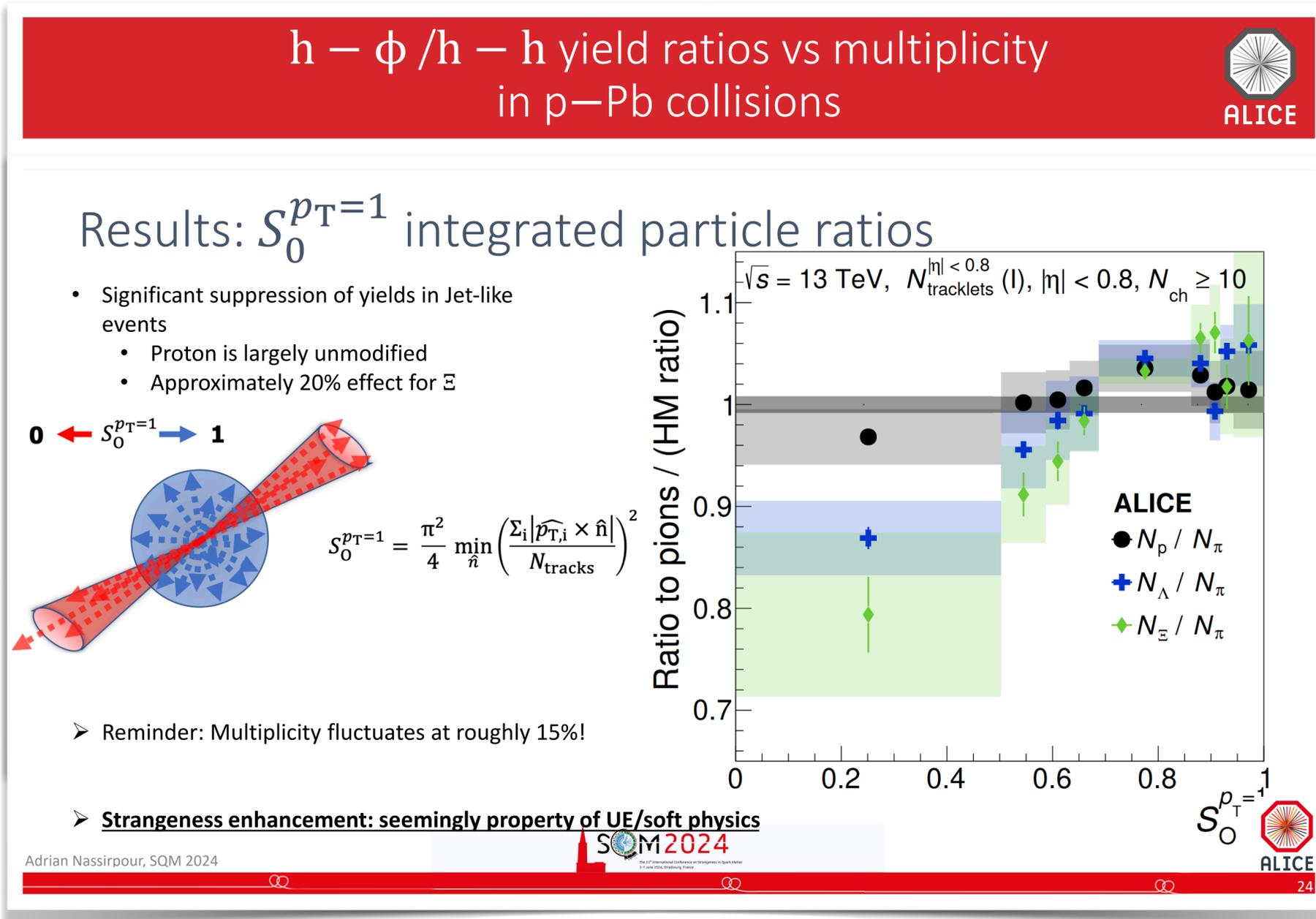
# Origin of strangeness enhancement in small systems

## Angular correlations in and out of jets

- The relative production of strange hadrons is larger in the underlying event than in hard scattering processes

## As a function of Spherocity

- Large Spherocity selects isotropic events driven by multiple softer collisions
- Strangeness enhancement: seemingly property of UE/soft physics



# Origin of strangeness enhancement in small systems

## Angular correlations in and out of jets

- The relative production of strange hadrons is larger in the underlying event than in hard scattering processes

## As a function of Spherocity

- Large Spherocity selects isotropic events driven by multiple softer collisions
- Strangeness enhancement: seemingly property of UE/soft physics

## As a function of $R_T, R_{T,min}, R_{T,max}$

- Activity (min, max) in the region transverse to the jet
- Enhancement with increasing  $R_{T,min}$ ?
  - Most sensitive to  $n_{MPI}$ ?

## $h - \phi / h - h$ yield ratios vs multiplicity in p-Pb collisions

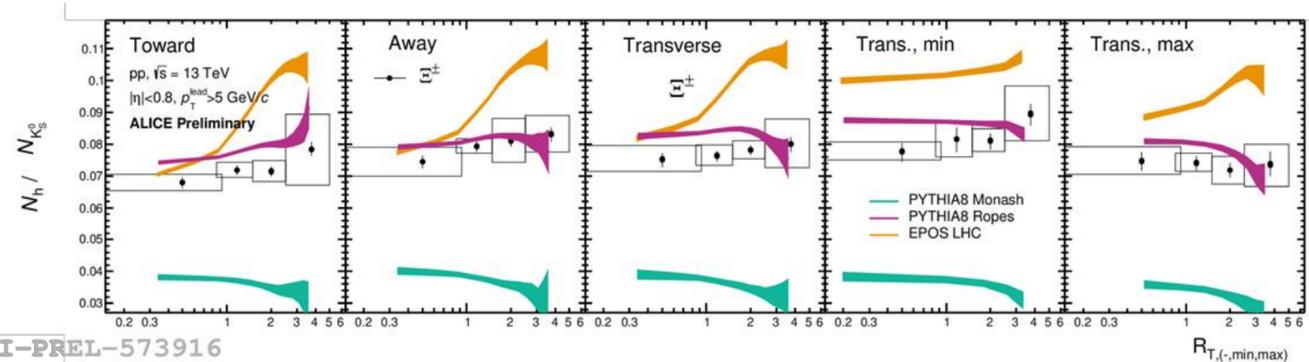


Results:  $S_0^{p_T=1}$  integrated particle ratios

- Significant suppression of yields in Jet-like

$$\sqrt{s} = 13 \text{ TeV}, N_{\text{tracklets}}^{|\eta| < 0.8} (l), |\eta| < 0.8, N_{\text{ch}} \geq 10$$

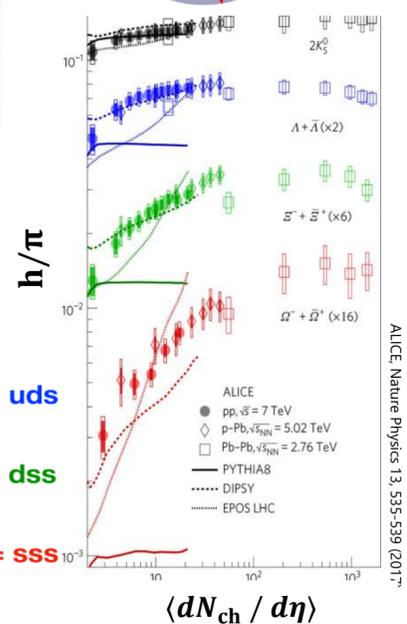
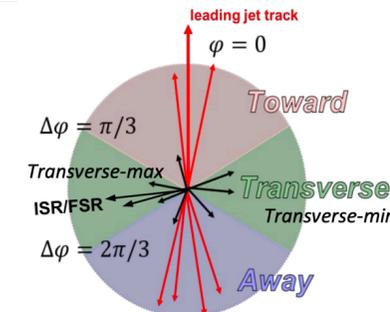
## Studying strangeness enhancement with $N_h / N_{K_S^0}$



ALI-PREL-573916

- $\Lambda$ : displays no apparent sensitivity on the  $R_T$  and region
- $\Xi$ : strangeness enhancement observed with increase in  $R_T$ 
  - the strongest effect is seen in the  $n_{MPI}$ -sensitive *transverse-min* whilst not evident in the ISR/FSR-sensitive *transverse-max*
- $\Xi$  has a weaker evolution than the  $\langle dN_{ch} / d\eta \rangle$  study, however more representative of the sheer increase in parton-parton activity

None of the models can describe the observed enhancement



ALICE Nature Physics 13, 535-539 (2017)

Oliver Matonoha (CTU)



27/31

# Origin of strangeness enhancement in small systems

## Angular correlations in and out of jets

- The relative production of strange hadrons is larger in the underlying event than in hard scattering processes

## As a function of Sphericity

- Large Sphericity selects isotropic events driven by multiple softer collisions
- Strangeness enhancement: seemingly property of UE/soft physics

## As a function of $R_T$ , $R_{T,min}$ , $R_{T,max}$

- Activity (min, max) in the region transverse to the jet
- Enhancement with increasing  $R_{T,min}$ ?
  - Most sensitive to  $n_{MPI}$

## Rather a baryon enhancement

- At least part of the enhancement seen in HM pp is due to a baryon-related effect
- Baryon-related effect well-reproduced by Pythia 8 QCD-CR Ropes

## $h - \phi / h - h$ yield ratios vs multiplicity in p-Pb collisions

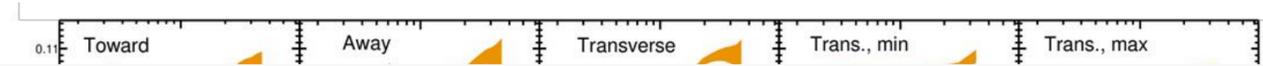


Results:  $S_0^{p_T=1}$  integrated particle ratios

- Significant suppression of yields in Jet-like
- $\sqrt{s} = 13 \text{ TeV}, N_{\text{tracklets}}^{|\eta| < 0.8} (l), |\eta| < 0.8, N_{\text{ch}} \geq 10$

## Studying strangeness enhancement with $N_h/N_{K_S^0}$

NEW!

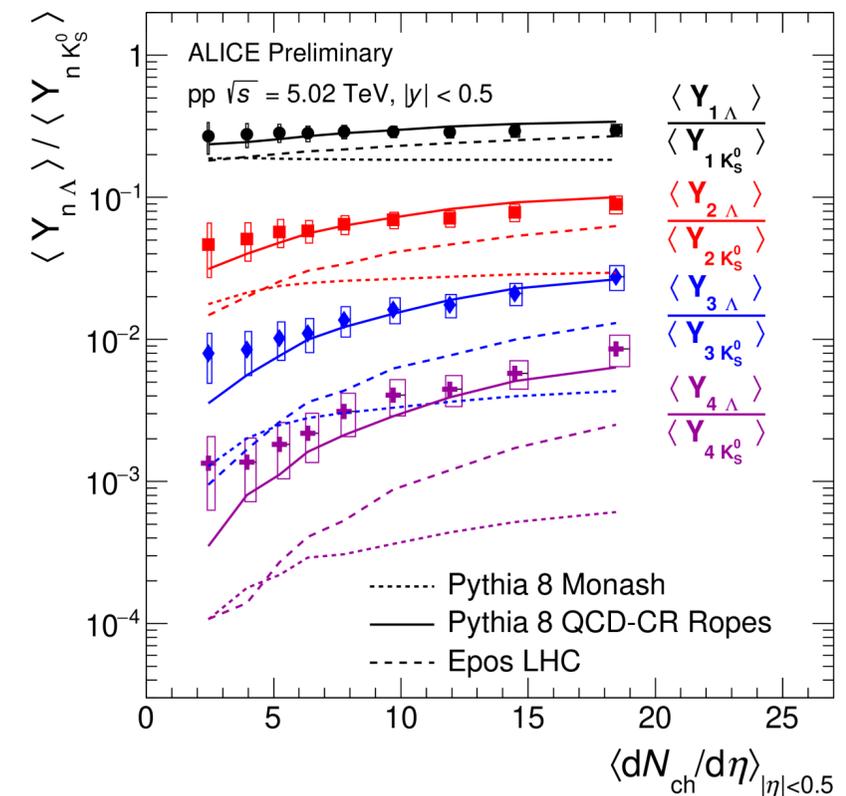


## Baryon/strangeness enhancement

NEW!

$$\langle Y_{k\text{-part}} \rangle = \sum_{n=k}^{\infty} \frac{n!}{k!(n-k)!} P(n)$$

- Important to **decouple strangeness-related** from **baryon-related** effects
- **Increase of  $^A/K_S^0$**  with multiplicity when looking at **multiple production**
- Possibly in all strange-hadron/ $\pi$  vs multiplicity plots we have a **strangeness-related** and a **contribution to the enhancement**
- **Baryon-related** effect **well-reproduced** by Pythia 8 QCD-CR Ropes



ALI-PREL-570749

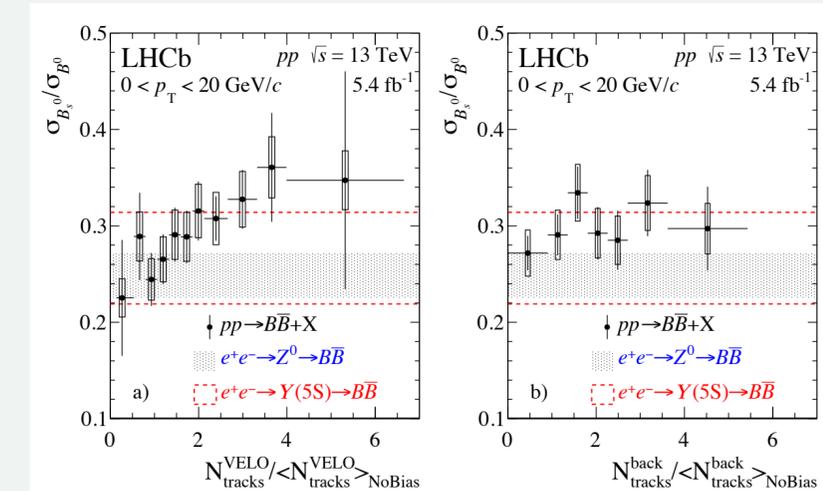
# The (in) famous strangeness enhancement

Also when hadronizing with heavy flavors?

- Strange-to-nonstrange B meson ratio increases with multiplicity (measured in the same eta region) in p-Pb

$B_s^0/B^0$  ratio with multiplicity  $pp$  collisions at  $\sqrt{s} = 13$  TeV *Phys. Rev. Lett.* 131 (2023) 061901

- Ratio enhancement observed with VELO tracks.
- No significant enhancement with backward tracks. This hints that the mechanism responsible for the increase in the ratio is related to the local particle density.
- Results coherent with  $e^+e^-$  measurements at low multiplicity.



Results quoted in normalised multiplicity

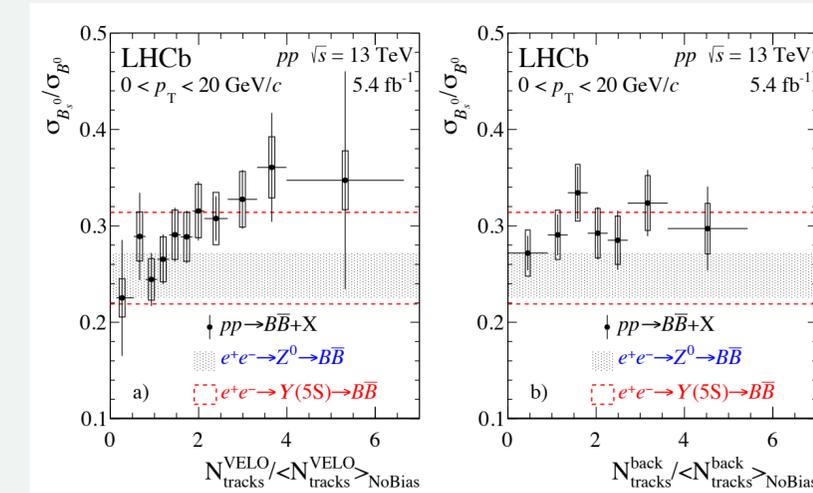
# The (in) famous strangeness enhancement

Also when hadronizing with heavy flavors?

- Strange-to-nonstrange B meson ratio increases with multiplicity (measured in the same eta region) in p-Pb
- Strange-to-nonstrange D meson ratio ... will come to that

$B_s^0/B^0$  ratio with multiplicity  $pp$  collisions at  $\sqrt{s} = 13$  TeV *Phys. Rev. Lett.* 131 (2023) 061901

- Ratio enhancement observed with VELO tracks.
- No significant enhancement with backward tracks. This hints that the mechanism responsible for the increase in the ratio is related to the local particle density.
- Results coherent with  $e^+e^-$  measurements at low multiplicity.



Results quoted in normalised multiplicity

# This is also SQM, sharm in Quark Matter

So let's now focus on charm (and beauty)  
hadronization



# Charm fragmentation function

## Factorisation approach

Open heavy-flavour hadron production cross section calculated by factorisation approach:

$$\frac{d\sigma^{H_c}}{dp_T}(p_T; \mu_F, \mu_R) = \text{PDF}(x_1, \mu_F) \otimes \text{PDF}(x_2, \mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(p_T; \mu_F, \mu_R) \otimes D_{c \rightarrow H_c}(z = p_{H_c}/p_c, \mu_F)$$

Parton distribution functions

Hard scattering cross section (pQCD)

Fragmentation functions (hadronisation)

Assumed **universal** across collision systems (ee, ..., AA)



SQM 2024, Antonio Palasciano



# Charm fragmentation function fraction

## Factorisation approach

Open heavy-flavour hadron production cross section calculated by factorisation approach:

$$\frac{d\sigma^{H_c}}{dp_T}(p_T; \mu_F, \mu_R) = \text{PDF}(x_1, \mu_F) \otimes \text{PDF}(x_2, \mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(p_T; \mu_F, \mu_R) \otimes D_{c \rightarrow H_c}(z = p_{H_c}/p_c, \mu_F)$$

Parton distribution functions
Hard scattering cross section (pQCD)
Fragmentation functions (hadronisation)

Assumed **universal** across collision systems (ee, ..., AA)

SOM 2024, Antonio Palasciano

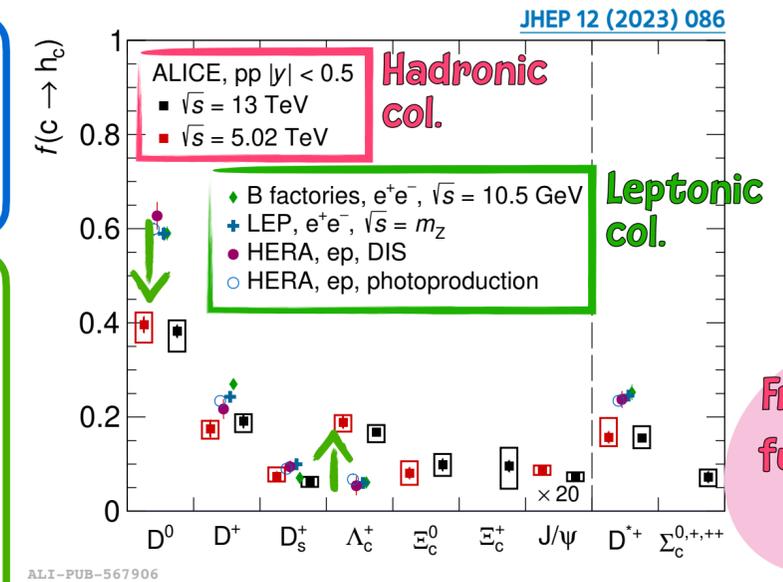
## Charm fragmentation fraction

### In different collisions energy

- ★ No energy dependence within the uncertainties

### Comparing to e<sup>+</sup>e<sup>-</sup> collisions

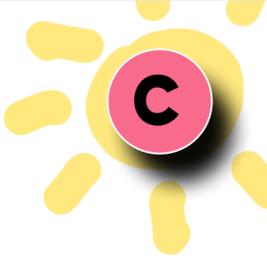
- ★ Significantly increased baryon production, decreased meson production
- ★ Indicate **different hadronization mechanism in hadronic collisions** with respect to leptonic collisions



JaeYoon CHO | jaeyoon.cho@cern.ch

34

SQM2024 | 2024.06.04



# Charm fragmentation function hadronization

## Factorisation approach

Open heavy-flavour hadron production cross section calculated by factorisation approach:

$$\frac{d\sigma^{H_c}}{dp_T}(p_T; \mu_F, \mu_R) = \text{PDF}(x_1, \mu_F) \otimes \text{PDF}(x_2, \mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(p_T; \mu_F, \mu_R) \otimes D_{c \rightarrow H_c}(z = p_{H_c}/p_c, \mu_F)$$

Parton distribution functions

Hard scattering cross section (pQCD)

Fragmentation functions (hadronisation)

Assumed **universal** across collision systems (ee, ..., AA)



Probability of charm quark to hadronize into a given charm hadron

- Charm mesons: reduced in hadronic collisions compared to ee
- Charm baryons: increased in hadronic collisions compared to ee
- But, no to little change for strange D meson
- No energy or hadronic collision system dependence

## Charm fragmentation fraction

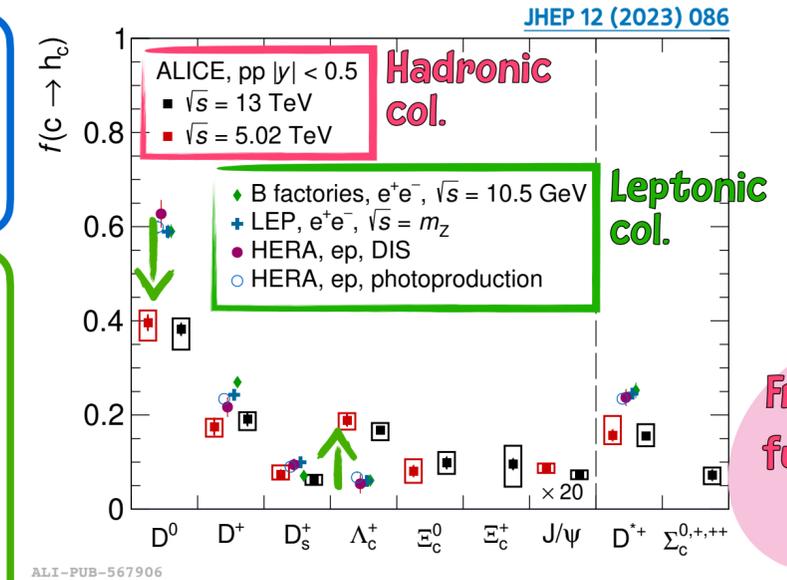
### In different collisions energy

★ No energy dependence within the uncertainties

### Comparing to e<sup>+</sup>e<sup>-</sup> collisions

★ Significantly increased baryon production, decreased meson production

★ Indicate **different hadronization mechanism in hadronic collisions** with respect to leptonic collisions



JaeYoon CHO | jaeyoon.cho@cern.ch

34

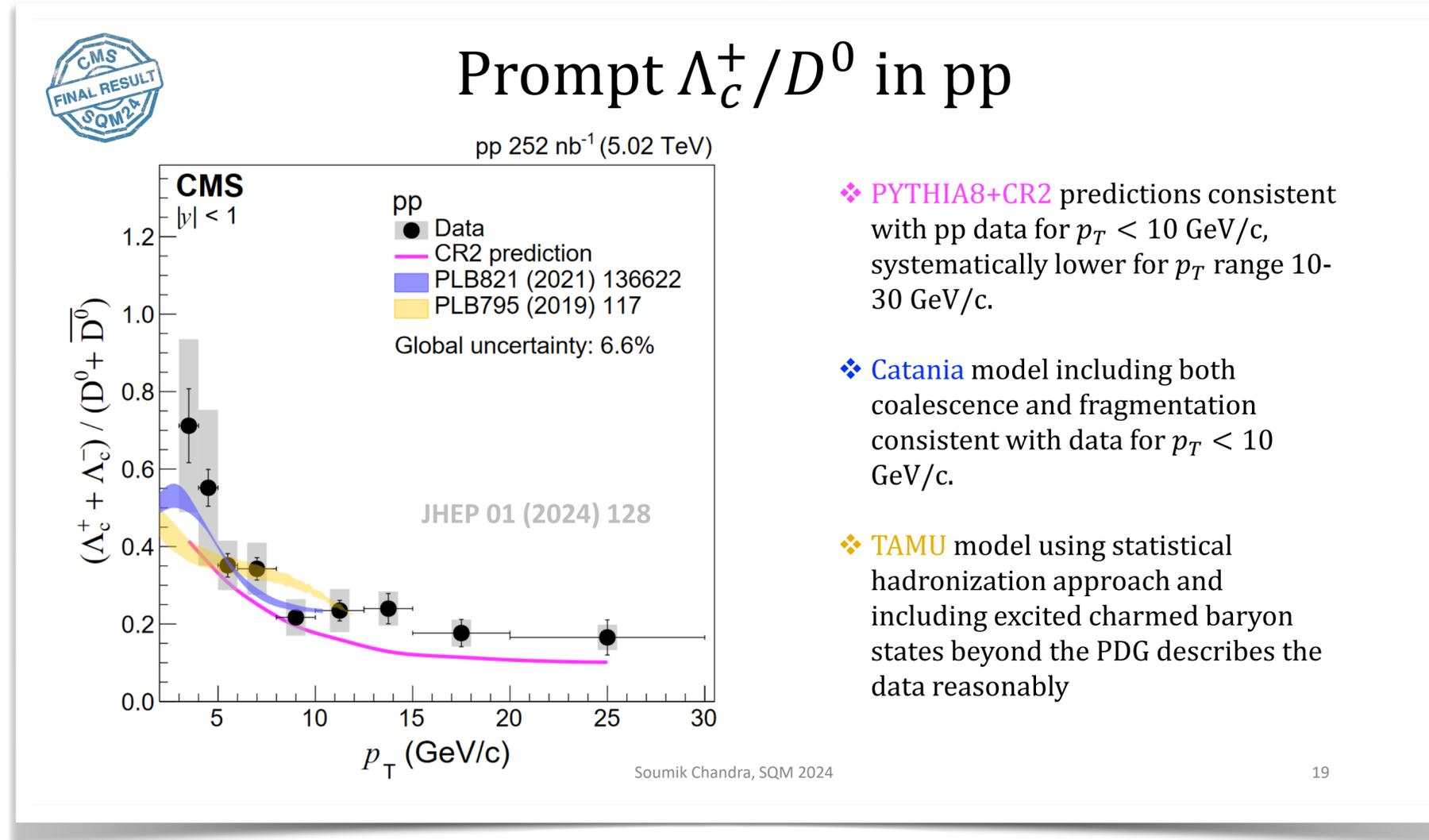
SQM2024 | 2024.06.04



# Charm fragmentation function fraction hadronization

## Charm baryon-to-meson ratio

- Charm baryon enhancement in pp collisions
  - Similar to enhancement in strange sector
  - Reminiscent of Pb–Pb
  - Reproduced by PYTHIA8 with color reconnection or by models including some sort of quark recombination



- ❖ **PYTHIA8+CR2** predictions consistent with pp data for  $p_T < 10$  GeV/c, systematically lower for  $p_T$  range 10-30 GeV/c.
- ❖ **Catania** model including both coalescence and fragmentation consistent with data for  $p_T < 10$  GeV/c.
- ❖ **TAMU** model using statistical hadronization approach and including excited charmed baryon states beyond the PDG describes the data reasonably

19

# Charm fragmentation function fraction hadronization

## Charm baryon-to-meson ratio

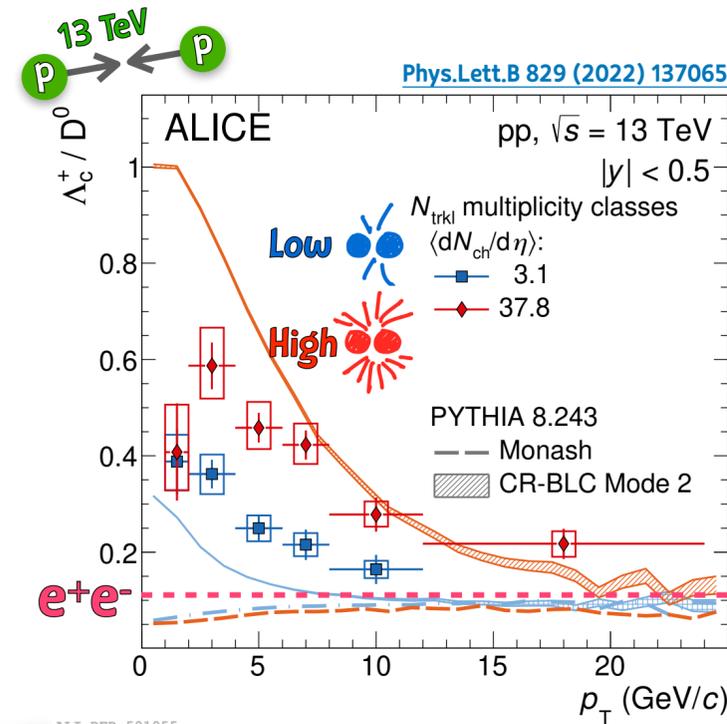
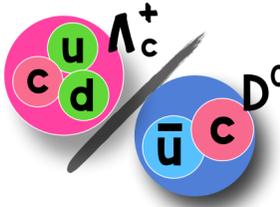
- Charm baryon enhancement in pp collisions
  - Similar to enhancement in strange sector
  - Reminiscent of Pb–Pb
  - Reproduced by PYTHIA8 with color reconnection or by models including some sort of quark recombination
- Enhancement increases with multiplicity



## Prompt $\Lambda_c^+ / D^0$ in pp

pp 252 nb<sup>-1</sup> (5.02 TeV)

### $\Lambda_c^+ / D^0$ vs. event multiplicity in pp collisions



#### Multiplicity dependence in baryon-to-meson ratio

- ★ Significant multiplicity dependence ( $5.3\sigma$ ) for  $p_T < 12$  GeV/c region going from lowest to highest multiplicity class
- ★ Even in lowest multiplicity class,  $\Lambda_c^+ / D^0$  is much higher than  $e^+e^-$  collisions

#### Model comparison

- ★ PYTHIA 8 Monash doesn't reproduce neither magnitude nor multiplicity dependence
- ★ PYTHIA 8 Mode 2 provides better description than Monash



JaeYoon CHO | jaeyoon.cho@cern.ch

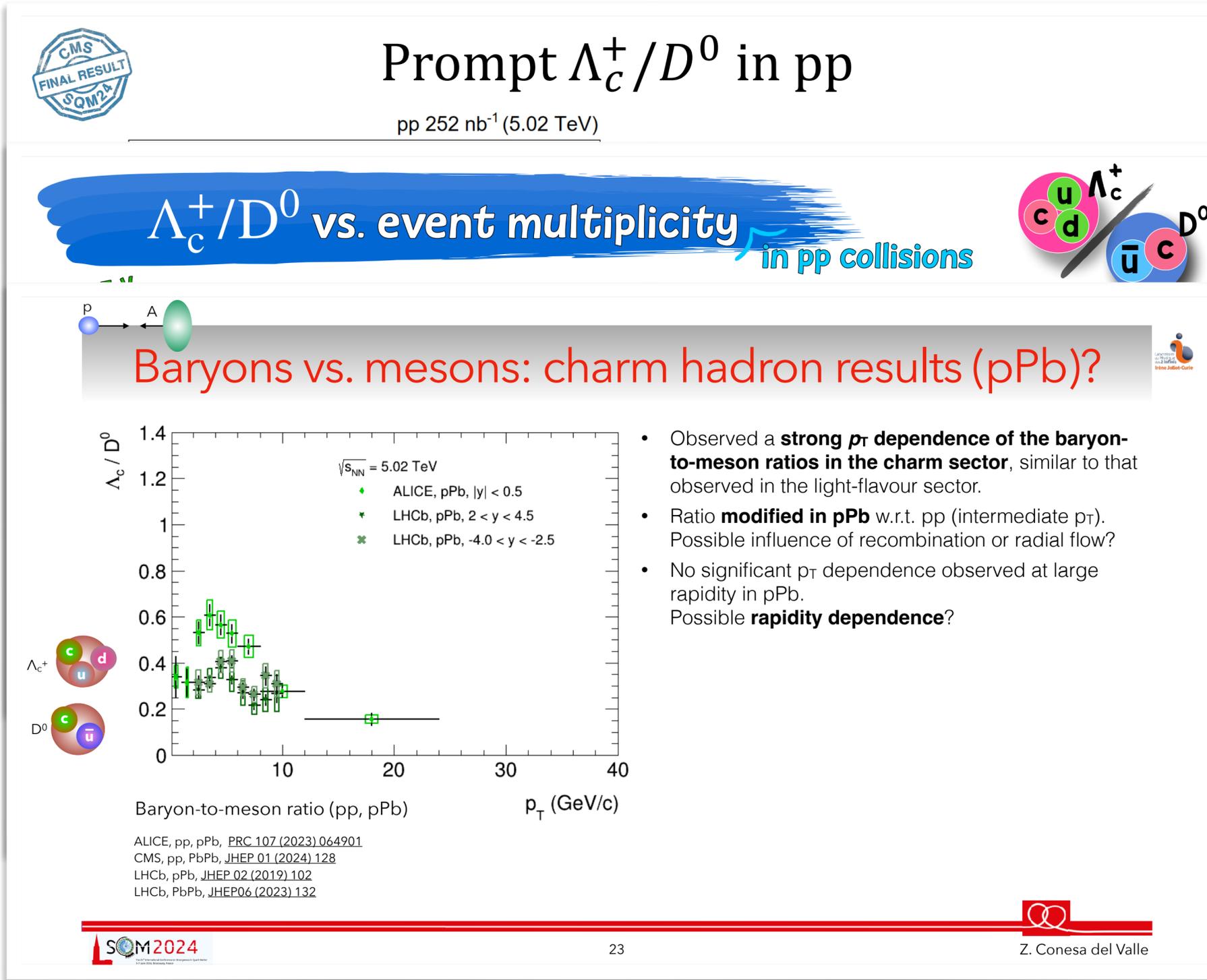
13

SQM2024 | 2024.06.04

# Charm fragmentation function fraction hadronization

## Charm baryon-to-meson ratio

- Charm baryon enhancement in pp collisions
  - Similar to enhancement in strange sector
  - Reminiscent of Pb–Pb
  - Reproduced by PYTHIA8 with color reconnection or by models including some sort of quark recombination
- Enhancement increases with multiplicity
- Enhancement is also there in p–Pb
- Rapidity dependence of enhancement in p–Pb?
  - No significant  $p_T$  dependence at forward rapidity



# Charm fragmentation function fraction hadronization

## Charm baryon-to-meson ratio

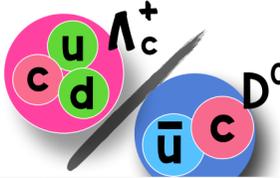
- Charm baryon enhancement in pp collisions
  - Similar to enhancement in strange sector
  - Reminiscent of Pb–Pb
  - Reproduced by PYTHIA8 with color reconnection or by models including some sort of quark recombination
- Enhancement increases with multiplicity
- Enhancement is also there in p–Pb
- Rapidity dependence of enhancement in p–Pb?
  - No significant  $p_T$  dependence at forward rapidity
- But no multiplicity dependence seen by CMS in p–Pb
  - Due to restricted  $p_T$  range?
  - Earlier coalescence?



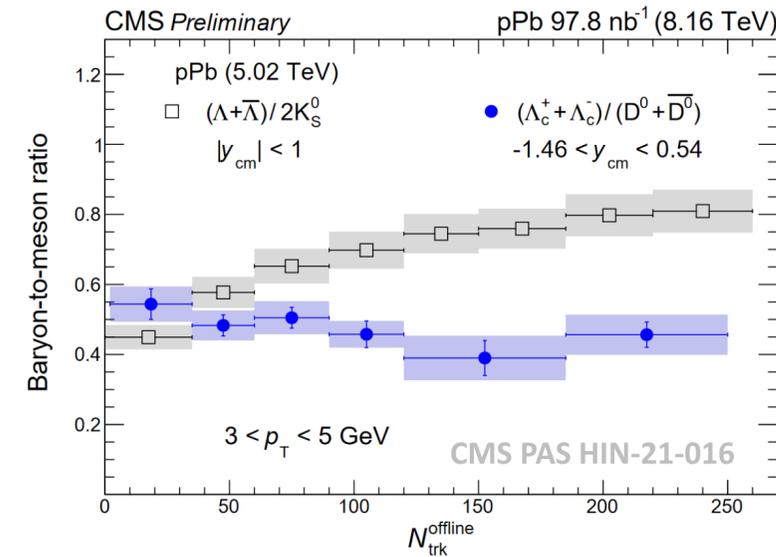
## Prompt $\Lambda_c^+ / D^0$ in pp

pp 252 nb<sup>-1</sup> (5.02 TeV)

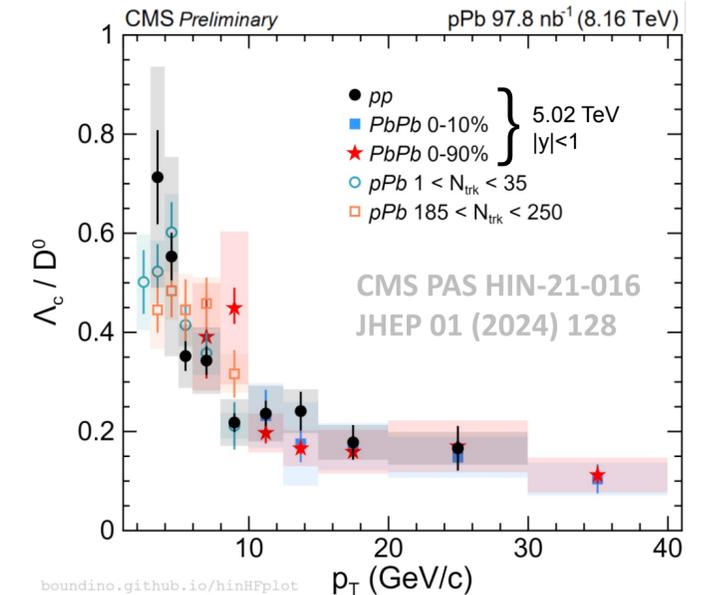
$\Lambda_c^+ / D^0$  vs. event multiplicity in pp collisions



## Prompt $\Lambda_c^+ / D^0$ ratio in pPb



- ❖ No significant multiplicity dependence
  - Differs from strange quark trend
- ❖ Coalescence process saturates early for charm quark with multiplicity



- ❖  $\Lambda_c^+ / D^0$  ratio decreases with increasing  $p_T$
- ❖ Consistent with pp and PbPb results

Soumik Chandra, SQM 2024

23

# Charm fragmentation function fraction hadronization

## Charm baryon-to-meson ratio

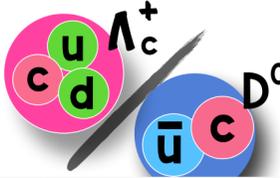
- Charm baryon enhancement in pp collisions
  - Similar to enhancement in strange sector
  - Reminiscent of Pb-Pb
  - Reproduced by PYTHIA8 with color reconnection or by models including some sort of quark recombination
- Enhancement increases with multiplicity
- Enhancement is also there in p-Pb
- Rapidity dependence of enhancement in p-Pb?
  - No significant p<sub>T</sub> dependence at forward rapidity
- But no multiplicity dependence seen by CMS in p-Pb
  - Due to restricted p<sub>T</sub> range?
  - Earlier coalescence?
- However, p<sub>T</sub>-integrated ratio does not depend on multiplicity or system size in hadronic collisions
  - Different p<sub>T</sub> redistribution for baryons and mesons rather than a multiplicity dependence in hadronization process itself?



## Prompt $\Lambda_c^+ / D^0$ in pp

pp 252 nb<sup>-1</sup> (5.02 TeV)

$\Lambda_c^+ / D^0$  vs. event multiplicity in pp collisions

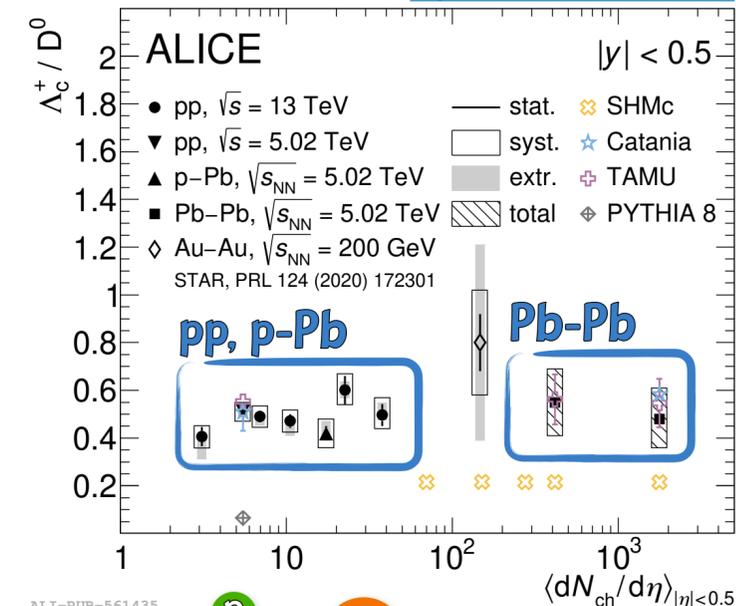


## Prompt $\Lambda_c^+ / D^0$ ratio in pPb

$\Lambda_c^+ / D^0$  in hadronic collisions

p<sub>T</sub> integrated

Phys.Lett.B 839 (2023) 137796



### Among hadronic collisions

★ NO multiplicity dependence in p<sub>T</sub> integrated  $\Lambda_c^+ / D^0$  ratios within the uncertainty

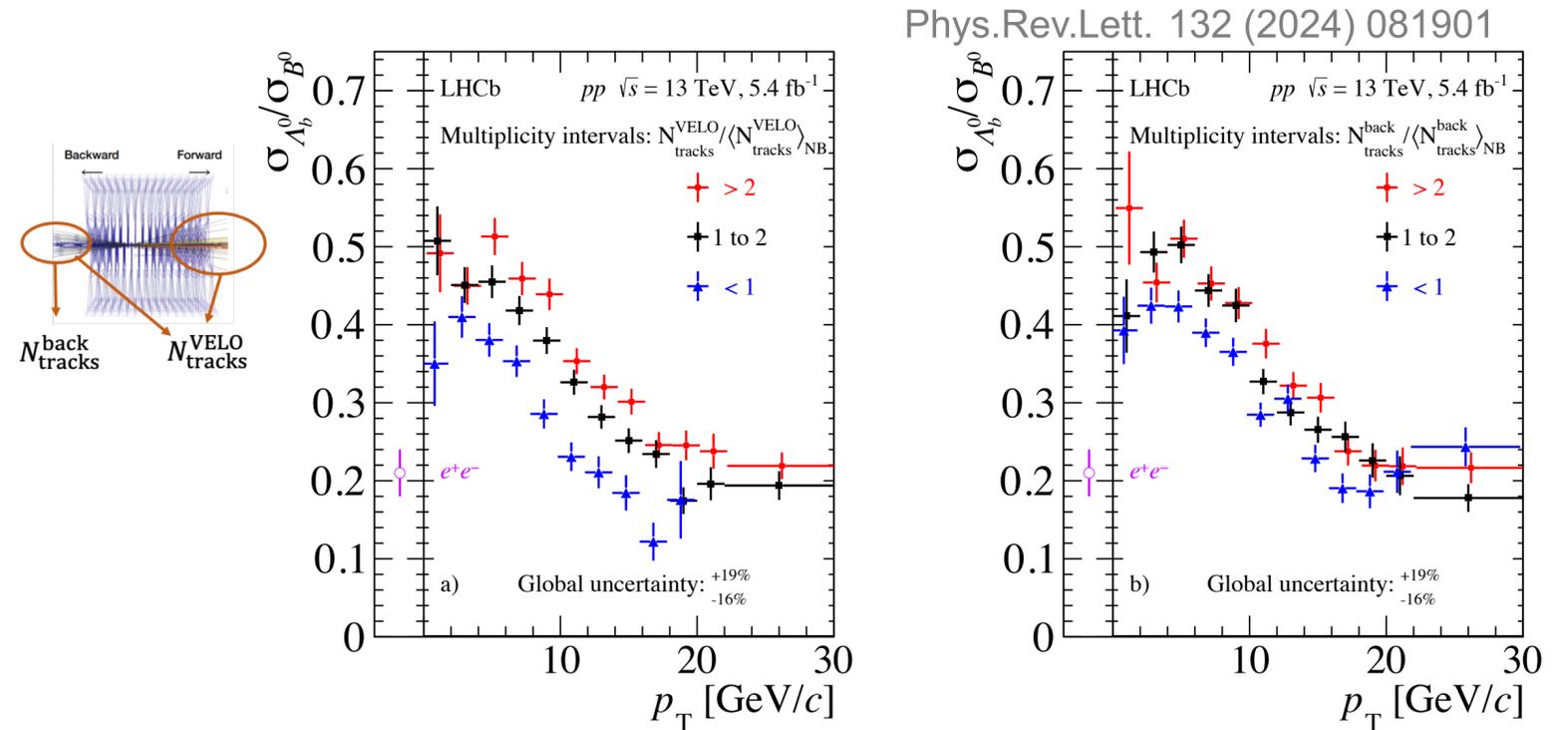


# Beauty fragmentation function fraction hadronization

## Beauty baryon-to-meson ratio

- Beauty baryon enhancement in pp collisions
  - Similar to enhancement in strange and charm sector
  - Statistical hadronisation model (SHM) with relativistic quark model (RQM) gives better description than with PDG data by considering  $\Lambda_b^0$  feed-down from excited baryons
  - EPOS4HQ reproduces the enhancement at low  $p_T$  by incorporating coalescence
- Enhancement increases with multiplicity
  - When multiplicity measured in the same eta region
  - Suggestive of coalescence induced by interactions with particles around b quarks (what does that exactly mean?)
- Would like to see beauty baryon-to-meson ratio in p-Pb, its multiplicity dependence and its comparison to charm baryon-to-meson ratio

## $\Lambda_b^0/B^0$ ratio versus $p_T$ in different multiplicity intervals



- $R_{\Lambda_b^0/B^0}$  shows a stronger dependence on normalised  $N_{\text{tracks}}^{\text{VELO}}$  (forward tracks dominant) than  $N_{\text{tracks}}^{\text{back}}$  (backward tracks only), which indicates that coalescence may be induced by interactions with particles around  $b$  quarks
- $R_{\Lambda_b^0/B^0}$  enhancement at low  $p_T$  observed
- Pronounced ordering of  $R_{\Lambda_b^0/B^0}$  with multiplicity at intermediate  $p_T$
- $R_{\Lambda_b^0/B^0}$  at high  $p_T \rightarrow e^+e^-$

# Charm with strangeness hadronization

Fragmentation fraction of charm to strange D meson is unmodified from ee to hadronic collisions

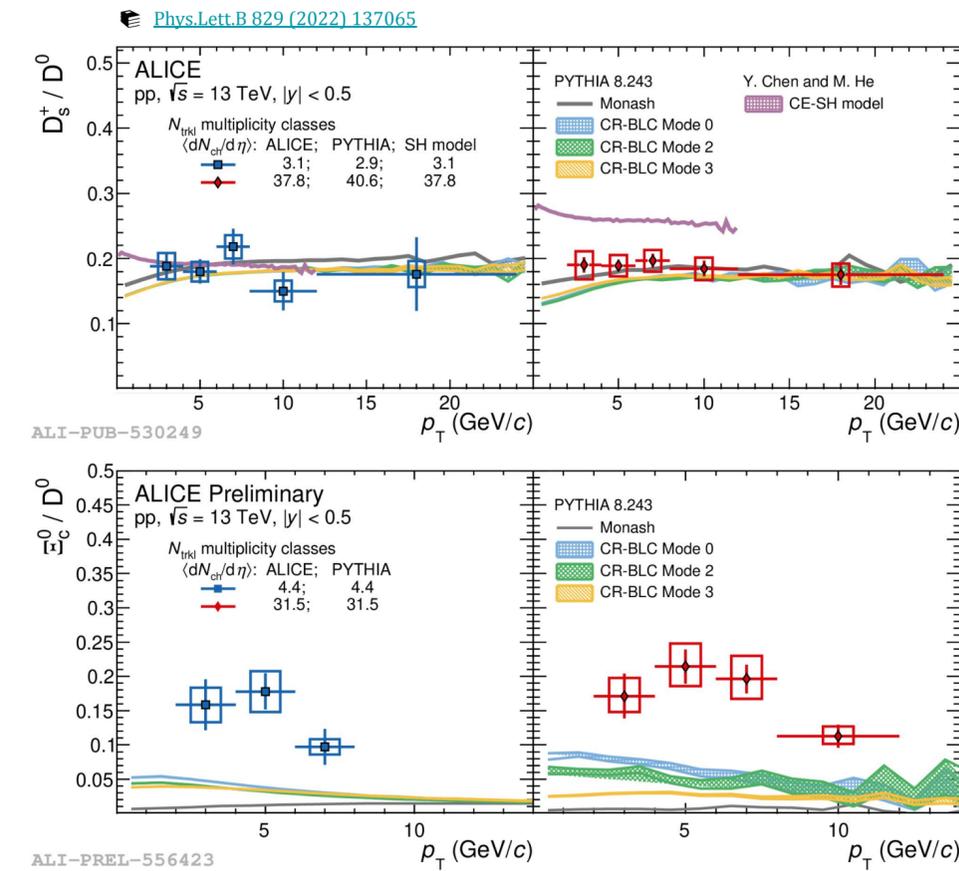
Strange-to-nonstrange D meson ratio

- No  $p_T$  dependence
- No multiplicity dependence
- Described by PYTHIA8 with or without CR
- Not described by CE-SH
- Compensation of reduction of meson hadronization probability by strangeness enhancement?

Xic baryon to D meson ratio

- Shows some  $p_T$  dependence
- Shows some multiplicity dependence
- Not described by PYTHIA8

## Strange charm hadrons vs. multiplicity



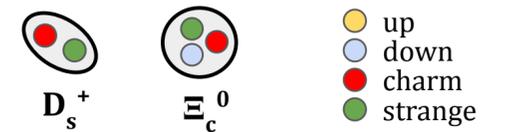
mfaggin@cern.ch

10/16



PYTHIA 8 (J. R. Christiansen, P. Z. Skands): [JHEP 08 \(2015\) 003](#)

CE-SH (J. Y. Chen, M. He): [Phys. Lett. B 815 \(2021\) 136144](#)



- $D_s^+/D^0$  ratio in pp collisions at midrapidity does not show any significant dependence vs.  $p_T$  and event multiplicity
- $D_s^+/D^0$  ratio described by PYTHIA 8 predictions at both low and high multiplicity
- $D_s^+/D^0$  ratio not described by canonical-ensemble statistical hadronization model (CE-SH) at high event multiplicity
- $\Xi_c^0/D^0$  ratio significantly underestimated by PYTHIA 8 predictions

# This is turning into SQM, small Quark Matter

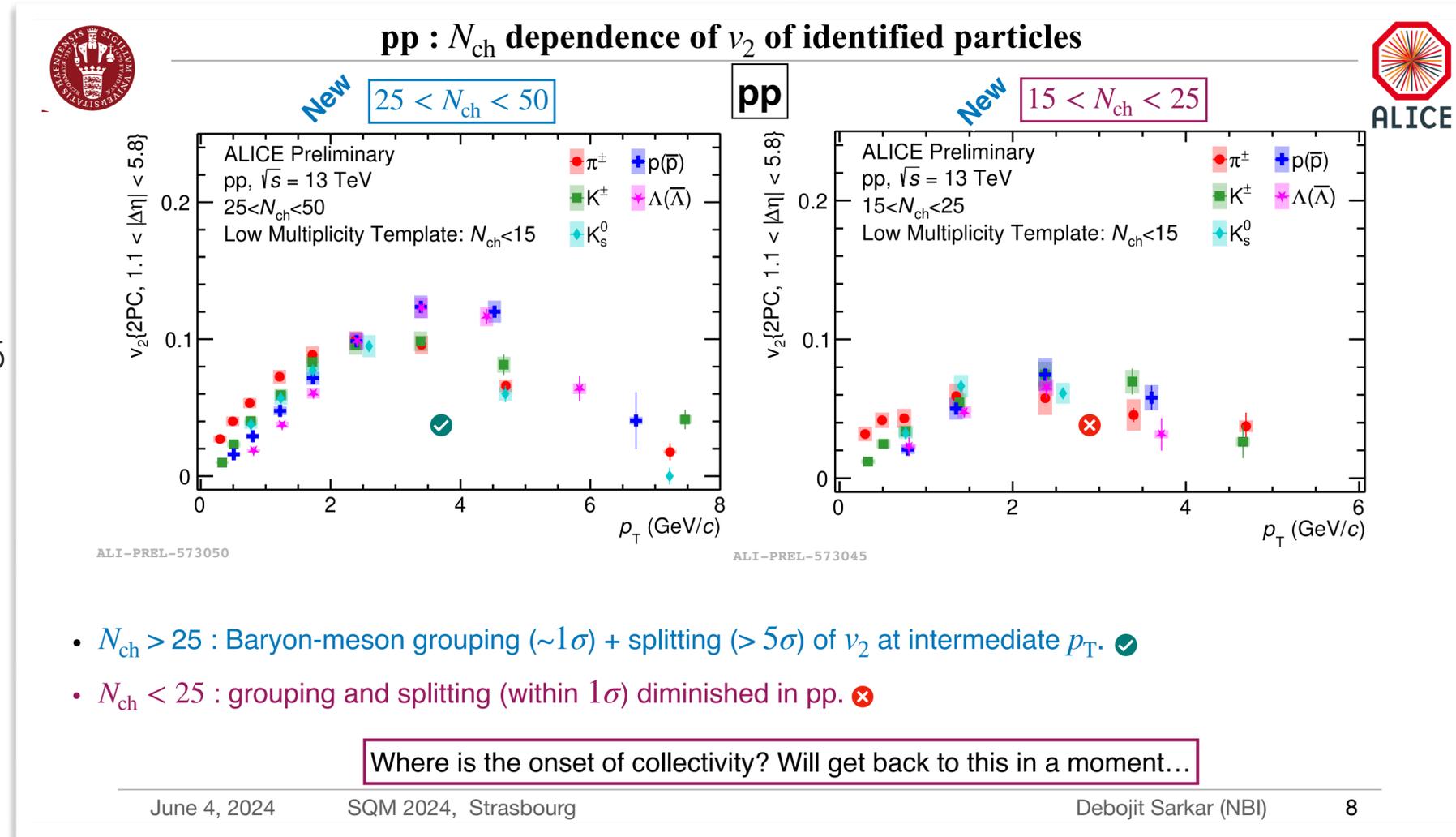
So let's look for the onset of collectivity in small systems



# Onset of collectivity in small systems

## Flow of identified particle in small systems

- Two particle correlations with large eta gap
- Baryon-meson grouping and splitting typically interpreted as sign of partonic collectivity
- Baryon-meson grouping and splitting breaks for  $N_{ch} < 25$ 
  - Both in pp and p-Pb
- Models need quark coalescence to reproduce grouping and splitting
  - Case in point: W. Zhao et al., PRL 125 (2020) 072301
- Onset of parton collectivity around  $N_{ch} \sim 25$ ?
  - What is baryon-meson grouping and splitting if not  $N_{CQ}$  scaling?
  - But  $N_{CQ}$  scaling only approximate even in Pb-Pb at LHC!



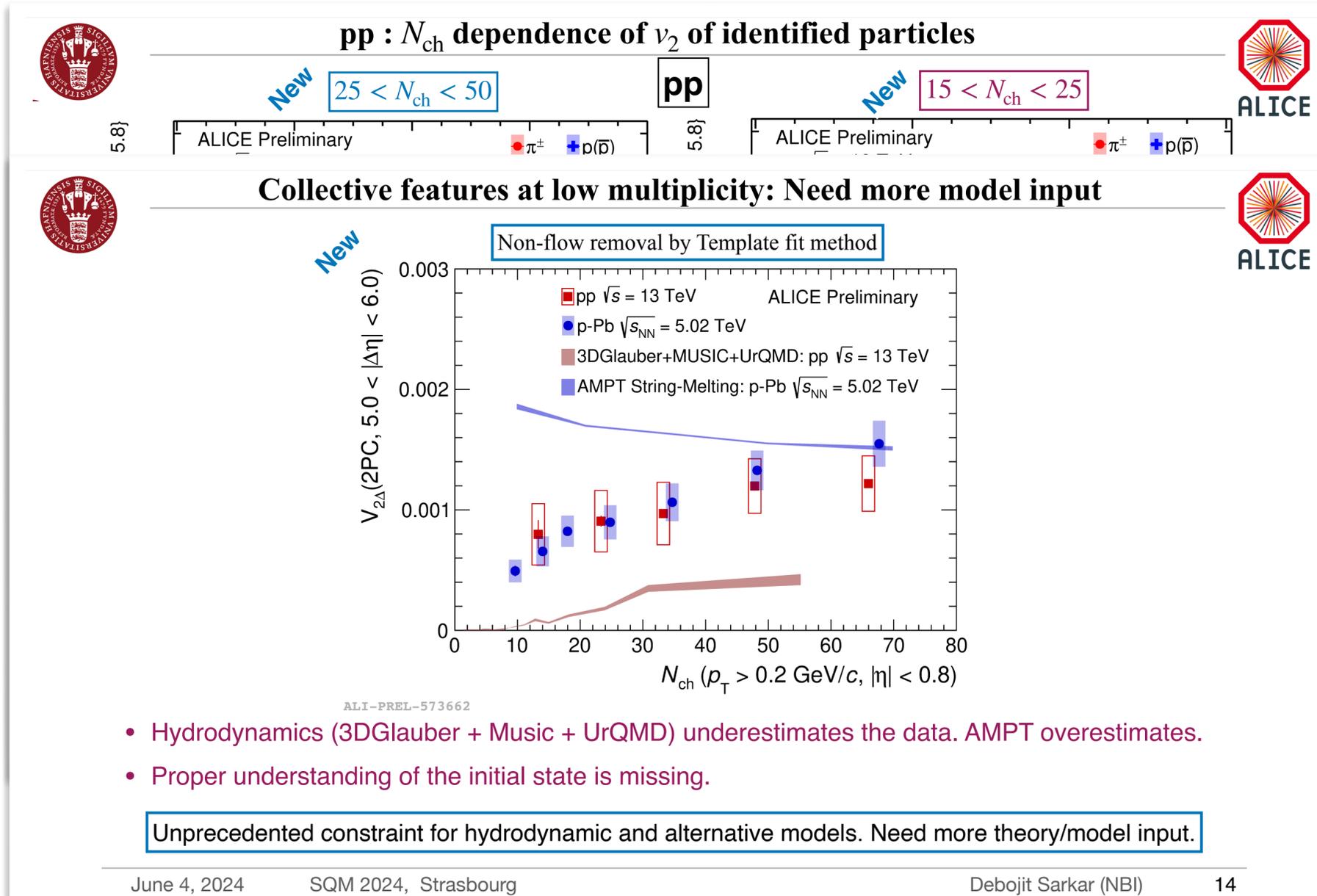
# Onset of collectivity in small systems

## Flow of identified particle in small systems

- Two particle correlations with large eta gap
- Baryon-meson grouping and splitting typically interpreted as sign of partonic collectivity
- Baryon-meson grouping and splitting breaks for  $N_{ch} < 25$ 
  - Both in pp and p-Pb
- Models need quark coalescence to reproduce grouping and splitting
  - Case in point: W. Zhao et al., PRL 125 (2020) 072301
- Onset of parton collectivity around  $N_{ch} \sim 25$ ?
  - What is baryon-meson grouping and splitting if not  $N_{cQ}$  scaling?
  - But  $N_{cQ}$  scaling only approximate even in Pb-Pb at LHC

## Ultra-long delta eta particle correlation

- Non-flow subtracted
- Ultra-long range particle correlation down to low multiplicity (about MB multiplicity)
- Available models fail to reproduce the data
- Further theoretical studies needed



# Onset of collectivity in small systems

## Flow of identified particle in small systems

- Two particle correlations with extra large eta gap
- Baryon-meson grouping and splitting typically interpreted as sign of partonic collectivity
- Baryon-meson grouping and splitting breaks for  $N_{ch} < 25$ 
  - Both in pp and p-Pb
- Models need quark coalescence to reproduce grouping and splitting
  - Case in point: W. Zhao et al., PRL 125 (2020) 072301
- Onset of parton collectivity around  $N_{ch} \sim 25$ ?
  - But  $N_{cQ}$  scaling only approximate even in Pb-Pb at LHC

## Ultra-long delta eta particle correlation

- Non-flow subtracted
- Ultra-long range particle correlation down to low multiplicity (about MB multiplicity)
- Available models fail to reproduce the data
- Further theoretical studies needed

## Collectivity in gamma-p collisions

- Lower  $v_2$  compared to p-Pb
  - Due to flow decorrelation and strong rapidity boost



**pp :  $N_{ch}$  dependence of  $v_2$  of identified particles**

**New**  $25 < N_{ch} < 50$  **pp** **New**  $15 < N_{ch} < 25$

ALICE Preliminary  $\pi^\pm$   $p(\bar{p})$





**Collective features at low multiplicity: Need more model input**

**New** Non-flow removal by Template fit method

ALICE Preliminary  $\pi^\pm$   $p(\bar{p})$   $\sqrt{s} = 13$  TeV



## New $\gamma$ +Pb theory comparisons

**Nonzero  $\gamma$ Pb  $v_2$**

comparison to 3D Glauber + MUSIC + UrQMD

Why is  $v_2(\gamma * Pb) < v_2(pPb)$   
Correlations performed in forward rapidity in  $\gamma$ Pb suppresses observed collectivity

$\rho^0$  VS.  $p$

[arXiv:2203.06094](https://arxiv.org/abs/2203.06094)

[arXiv:2101.10771](https://arxiv.org/abs/2101.10771)

# There is also SQM, suppression in Quark Matter

So let's briefly dive into quarkonium production

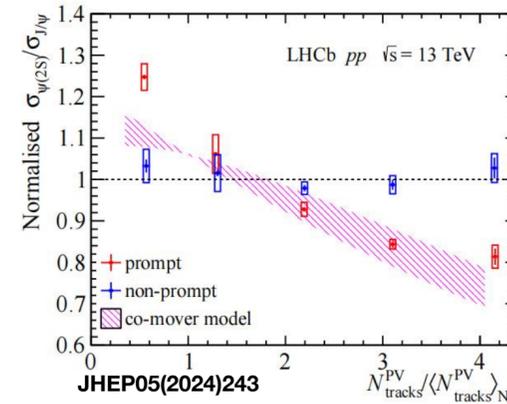


# psi(2S) suppression in high-multiplicity pp and p-Pb

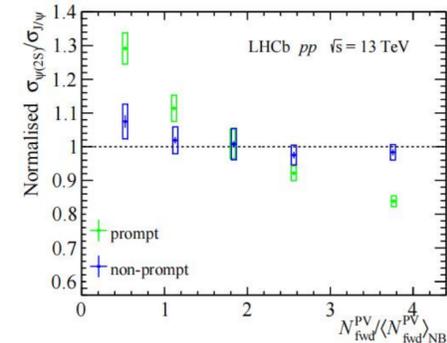
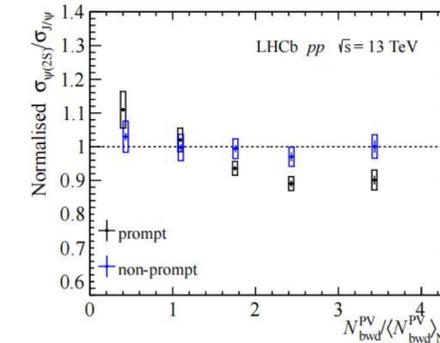
## Normalized psi(2S)-to-J/psi ratio

- psi(2S) suppression in pp collisions at high multiplicity
  - Suppression increases with multiplicity
  - No dependence with multiplicity in disconnected eta region
    - Bias due to counting of decay muons?
  - Stronger dependence at low p<sub>T</sub>
  - Little rapidity dependence (forward)
  - Comover model reproduces the measurements

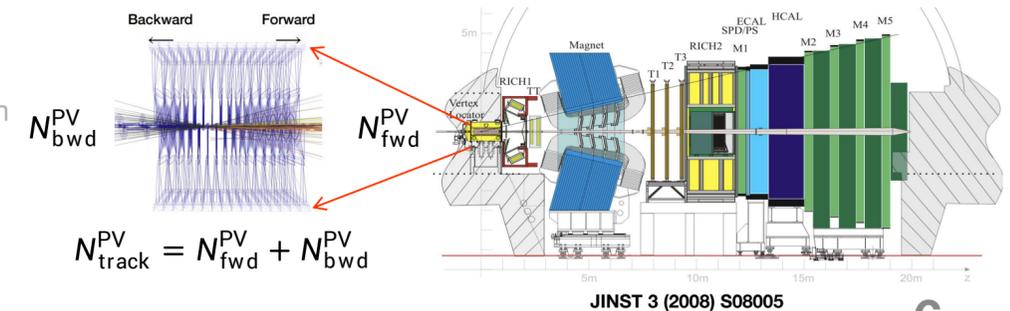
## ψ(2S)-to-J/ψ production ratio at √s = 13 TeV



$$\text{Normalised } \sigma_{\psi(2S),n} / \sigma_{J/\psi,n} = \frac{\sigma_{\psi(2S),n} / \sigma_{J/\psi,n}}{\sum_n \sigma_{\psi(2S),n} / \sum_n \sigma_{J/\psi,n}}$$



- Initial-state effects canceled
- Prompt ratio decrease with multiplicity, highly dependent on forward multiplicity, consistent with co-mover model [PLB749m 98(2015)]
- Non-prompt ratio independent of any multiplicity variables, consistent with co-mover model

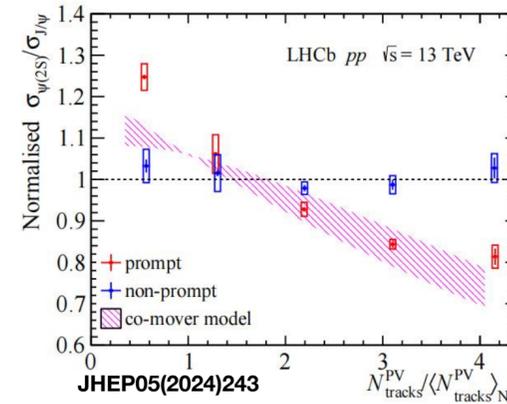


# psi(2S) suppression in high-multiplicity pp and p-Pb

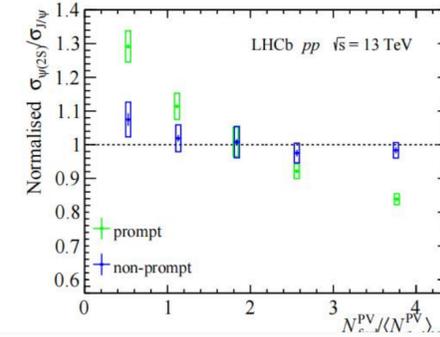
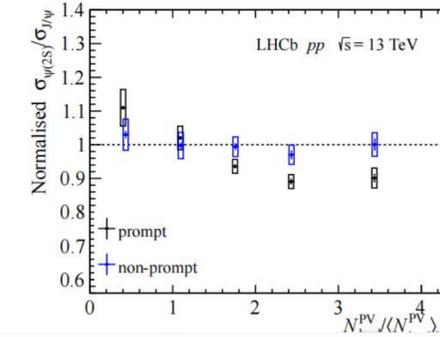
## Normalized psi(2S)-to-J/psi ratio

- psi(2S) suppression in pp collisions at high multiplicity
  - Suppression increases with multiplicity
  - No dependence with multiplicity in disconnected eta region
    - Bias due to counting of decay muons?
  - Stronger dependence at low p<sub>T</sub>
  - Little rapidity dependence (forward)
  - Comover model reproduces the measurements
- psi(2S) suppression in p-Pb collisions at high multiplicity
  - Suppression increases with multiplicity
  - Little rapidity dependence
  - Comover model reproduces the measurements

## ψ(2S)-to-J/ψ production ratio at √s = 13 TeV

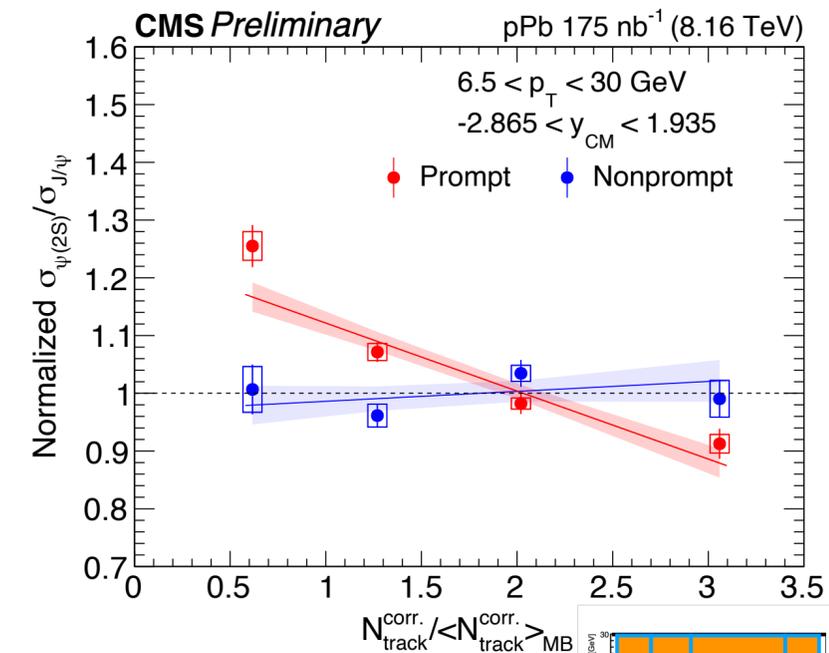
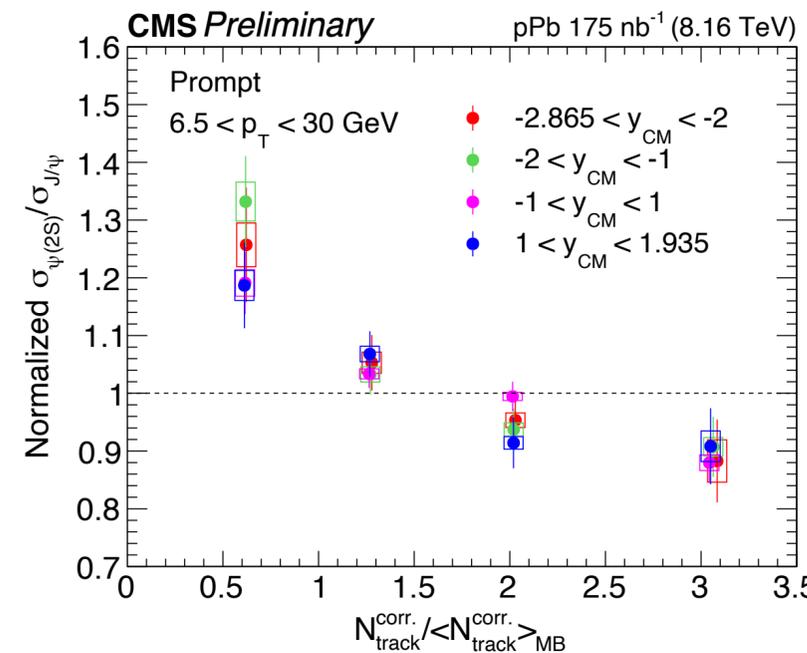


$$\text{Normalised } \sigma_{\psi(2S),n} / \sigma_{J/\psi,n} = \frac{\sigma_{\psi(2S),n} / \sigma_{J/\psi,n}}{\sum_n \sigma_{\psi(2S),n} / \sum_n \sigma_{J/\psi,n}}$$

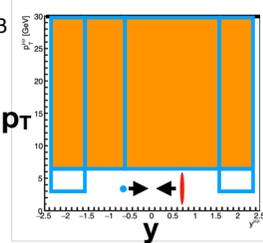


Initial state effects cancelled

## Summary of high-p<sub>T</sub> results



- $N_{trk}^{corr}$  dependence similar for all rapidities → combine
- 5.9σ deviation** from flat line for prompt
- Observation of multiplicity dependence of  $\sigma_{\psi(2S)}/\sigma_{J/\psi}$  in pPb**



# First measurement of Chic at LHC energies

## Chic production in p-Pb collisions

- Important missing piece to complete the picture

- Chic-to-J/psi double ratio is above unity

- No final state dissociation?

## Caution

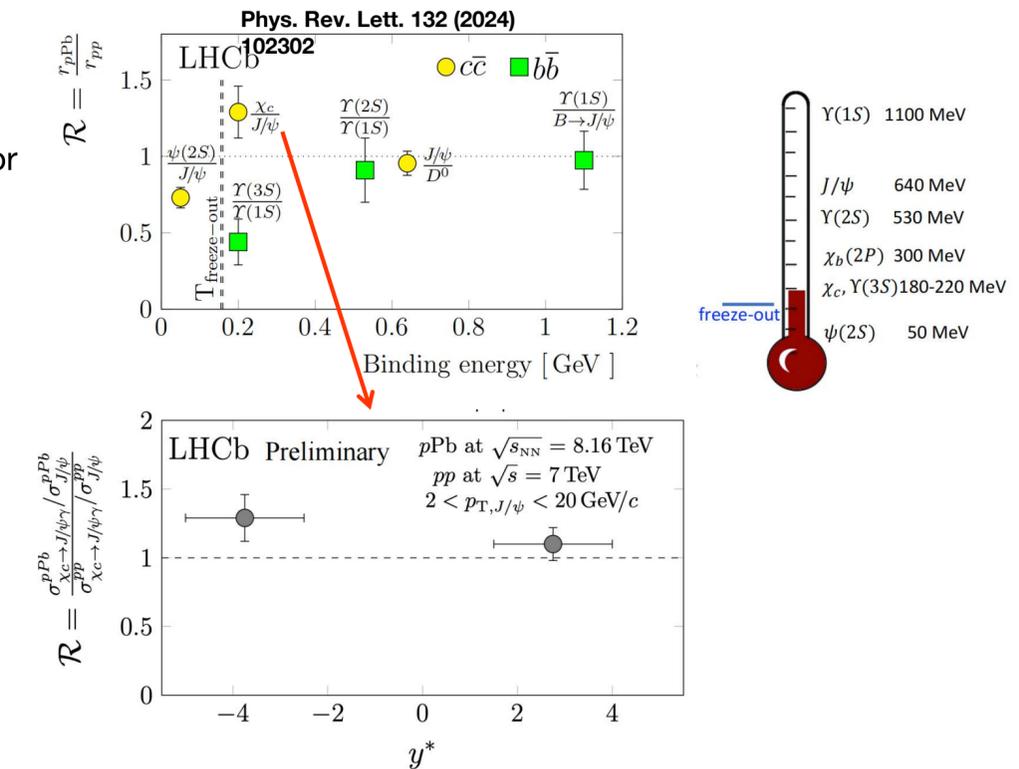
- The denominator may contain feed down from higher mass states, which in turn might be suppressed

- Since this is a double ratio plotted as a function of the binding energy of the numerator, the comparison between ratios with different denominators is not meaningful

- Thermometer picture is misleading

## $\chi_c$ -to- $J/\psi$ double ratio

- Initial-state effects canceled
- No dissociation due to final-state effects for  $\chi_c$  observed
- The medium temperature formed in pPb collisions **cannot** inhibit the formation of charmonium states with binding energy larger than 180 MeV
- Y(3S) dissociate, with similar size and binding energy, can due to its heavier and slower, more easily interact with co-mover



# Quarkonium regeneration

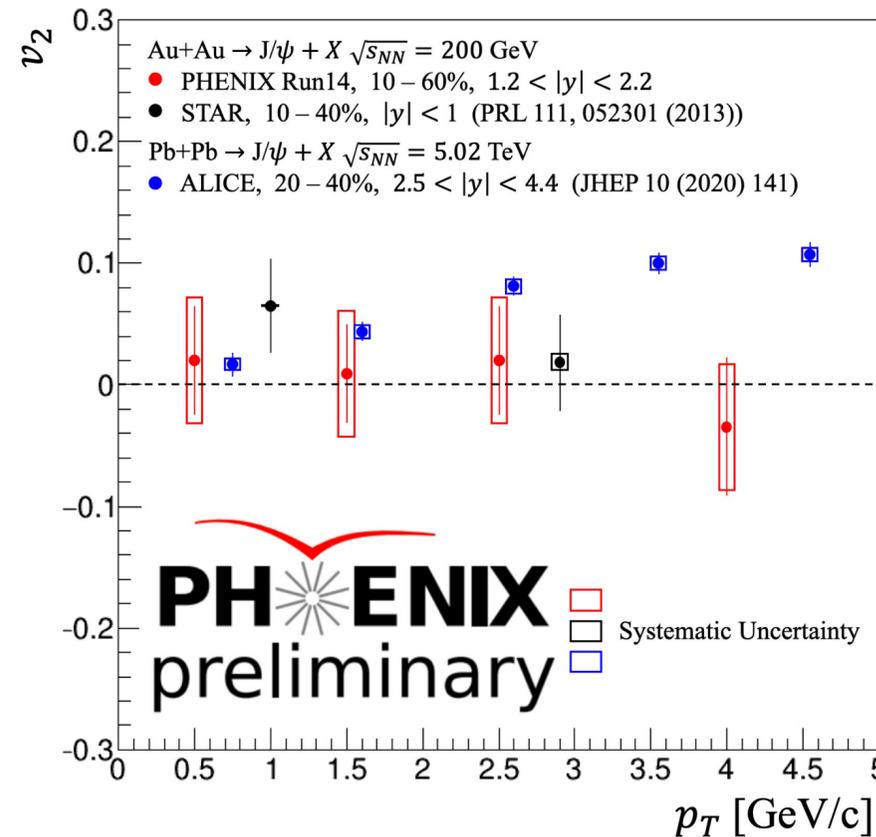
## J/psi v<sub>2</sub> at RHIC

- Compatible with zero
- Lower than non-zero J/psi v<sub>2</sub> at LHC
- Consistent with increase of regeneration contribution from RHIC to LHC energies

## J/psi R<sub>AA</sub> excitation function

- Constant below top RHIC energy
- Strong increase from top RHIC to LHC energies
- Consistent with increase of regeneration contribution from RHIC to LHC energies

## PHENIX J/ψ v<sub>2</sub> Measurement



- PHENIX J/ψ v<sub>2</sub> at forward rapidity is consistent with 0.
- Forward and mid-rapidity results at RHIC are consistent, but the uncertainties are large
- The ALICE nonzero result is different from our measurement.

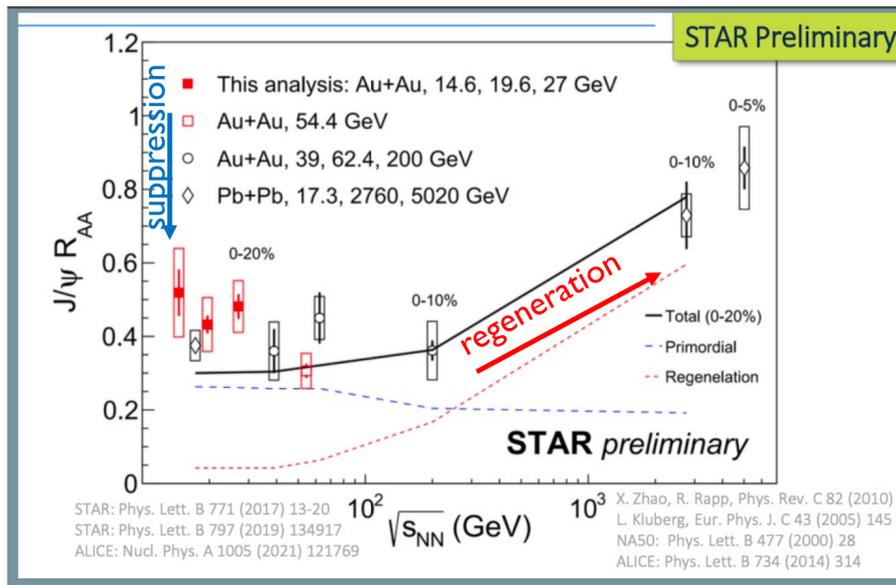


6/05/2024

SQM 2024, Luis Bichon III

PHENIX J/ψ Result

13



- Strong rise of the J/ψ R<sub>AA</sub> from RHIC to LHC energies → evidence for charmonium regeneration at LHC
- No significant energy dependence of J/ψ R<sub>AA</sub> below  $\sqrt{s_{NN}} = 200 \text{ GeV}$  at a given N<sub>part</sub>

# This sounds like SQM, speed of sound in Quark Matter

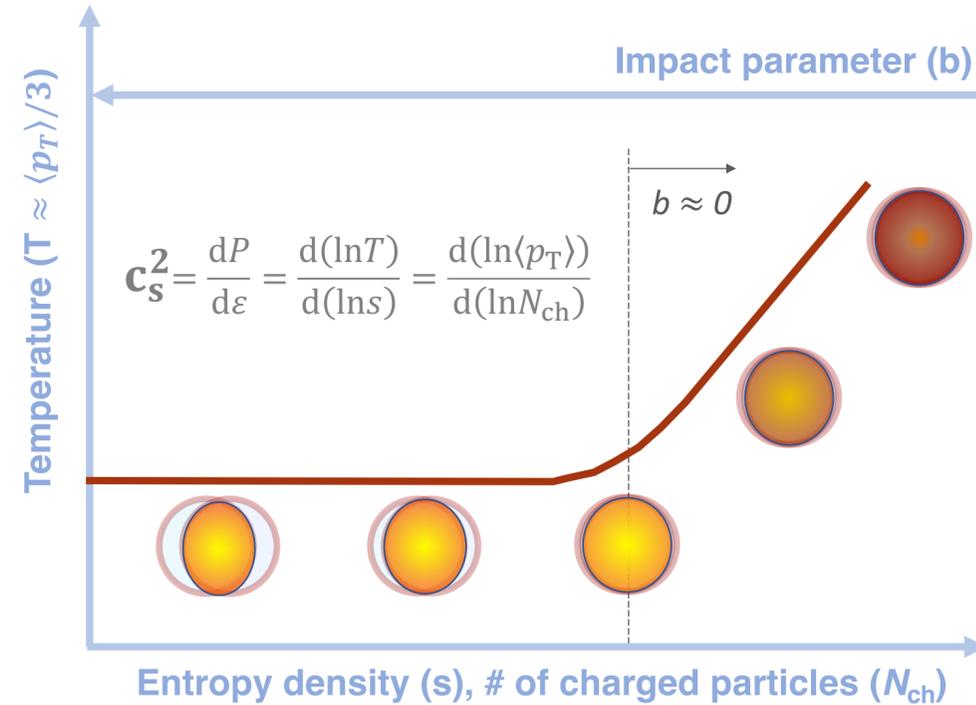


So let's study some basic thermodynamical properties of the QGP

# Speed of sound in the QGP

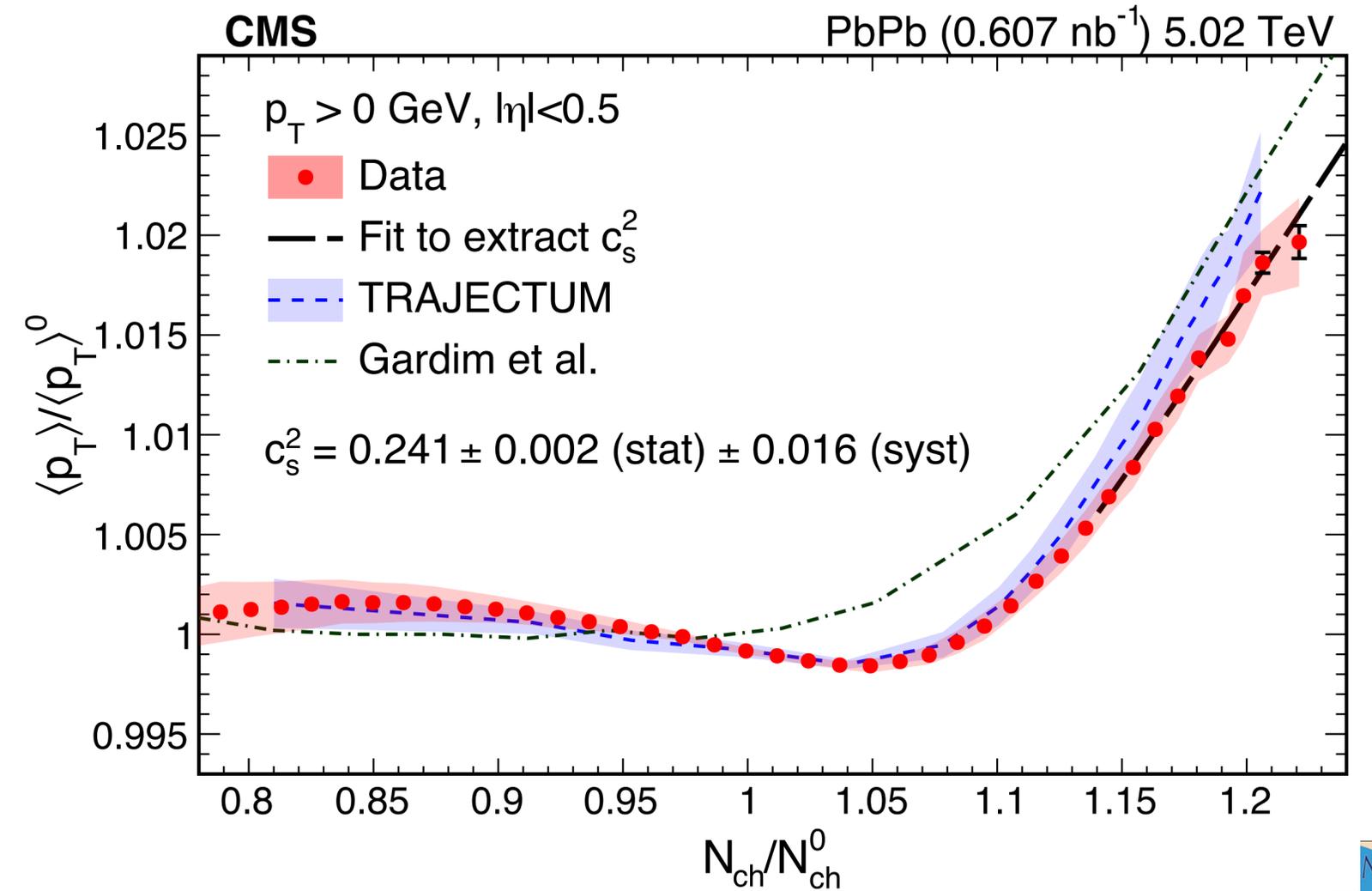
Measure speed of sound from  $\langle p_T \rangle$  and  $N_{ch}$

- Ultra-central collisions



F. G. Gardim, G. Giacalone, and J.-Y. Ollitrault,  
doi:10.1016/j.physletb.2020.135749, arXiv:1909.11609.

## Correlate average $p_T$ with multiplicity



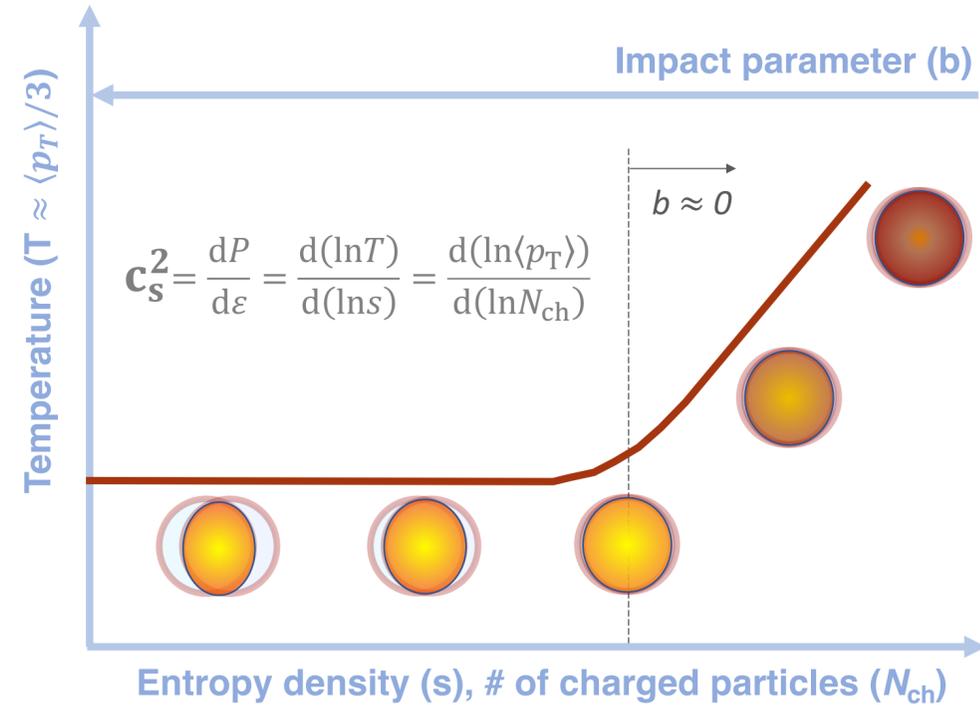
11



# Speed of sound in the QGP

Measure speed of sound from  $\langle p_T \rangle$  and  $N_{ch}$

- Ultra-central collisions

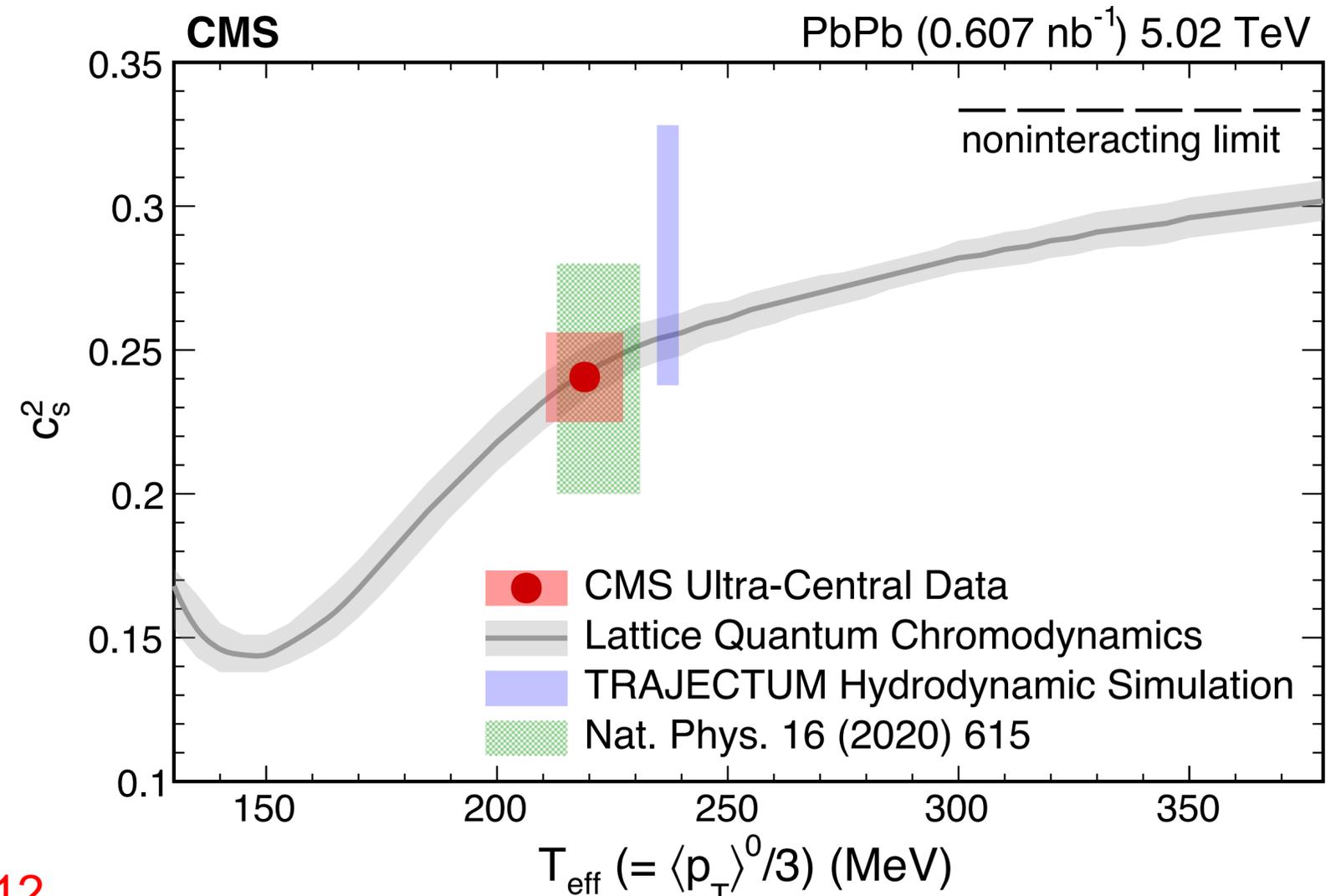


F. G. Gardim, G. Giacalone, and J.-Y. Ollitrault,  
doi:10.1016/j.physletb.2020.135749, arXiv:1909.11609.

- CMS measurement compatible with LQCD calculations

## Correlate average $p_T$ with multiplicity

## Starting to map $c_s^2$ versus temperature



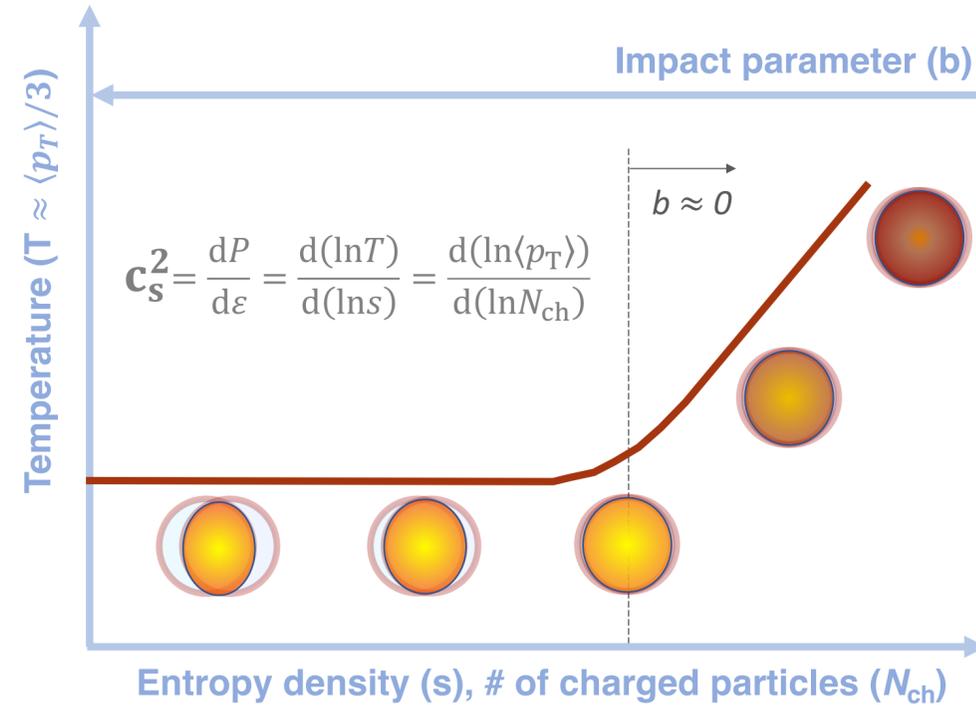
12



# Speed of sound in the QGP

Measure speed of sound from  $\langle p_T \rangle$  and  $N_{ch}$

- Ultra-central collisions



F. G. Gardim, G. Giacalone, and J.-Y. Ollitrault,  
doi:10.1016/j.physletb.2020.135749, arXiv:1909.11609.

- CMS measurement compatible with LQCD calculations
- But multiplicity estimator is key
  - Eta gap with particles used for  $\langle p_T \rangle$
  - $N_{ch}$  versus  $E_T$  based
- Important to carry out systematic studies

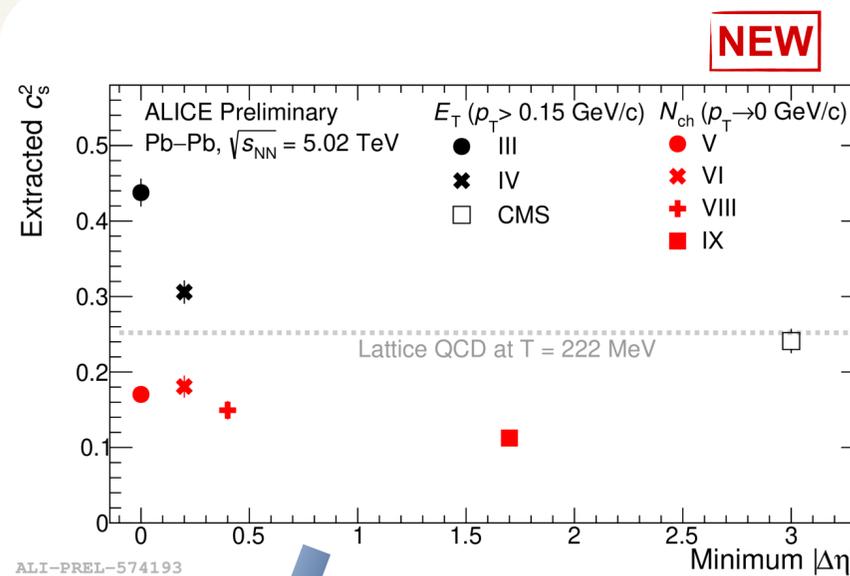
## Correlate average $p_T$ with multiplicity

## Starting to map $c_s^2$ versus temperature

0.35 **CMS** PbPb ( $0.607 \text{ nb}^{-1}$ ) 5.02 TeV



## Speed of sound as function of $\eta$ -gap



Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$	$\eta$ gap
$N_{ch}$ in TPC	I	$ \eta  \leq 0.8$	$ \eta  \leq 0.8$	0
	II	$0.5 \leq  \eta  \leq 0.8$	$ \eta  \leq 0.3$	0.3
$E_T$ in TPC	III	$ \eta  \leq 0.8$	$ \eta  \leq 0.8$	0
	IV	$0.5 \leq  \eta  \leq 0.8$	$ \eta  \leq 0.3$	0.3
$N_{tracklets}$ in SPD	V	$ \eta  \leq 0.8$	$ \eta  \leq 0.8$	0
	VI	$0.5 \leq  \eta  \leq 0.8$	$ \eta  \leq 0.3$	0.3
	VII	$0.3 <  \eta  \leq 0.6$	$ \eta  \leq 0.3$	0
	VIII	$0.7 \leq  \eta  \leq 1$	$ \eta  \leq 0.3$	0.4
$N_{ch}$ in V0	IX	$-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$	$ \eta  \leq 0.8$	1.7

Summary plot of extracted  $c_s^2$  with different centrality estimators and various  $\eta$  separations between particles used for  $\langle p_T \rangle$  and centrality

Emil Gorm Nielsen [NBI] | SQM2024

# There is search in SQM, search of the CEP in Quark Matter



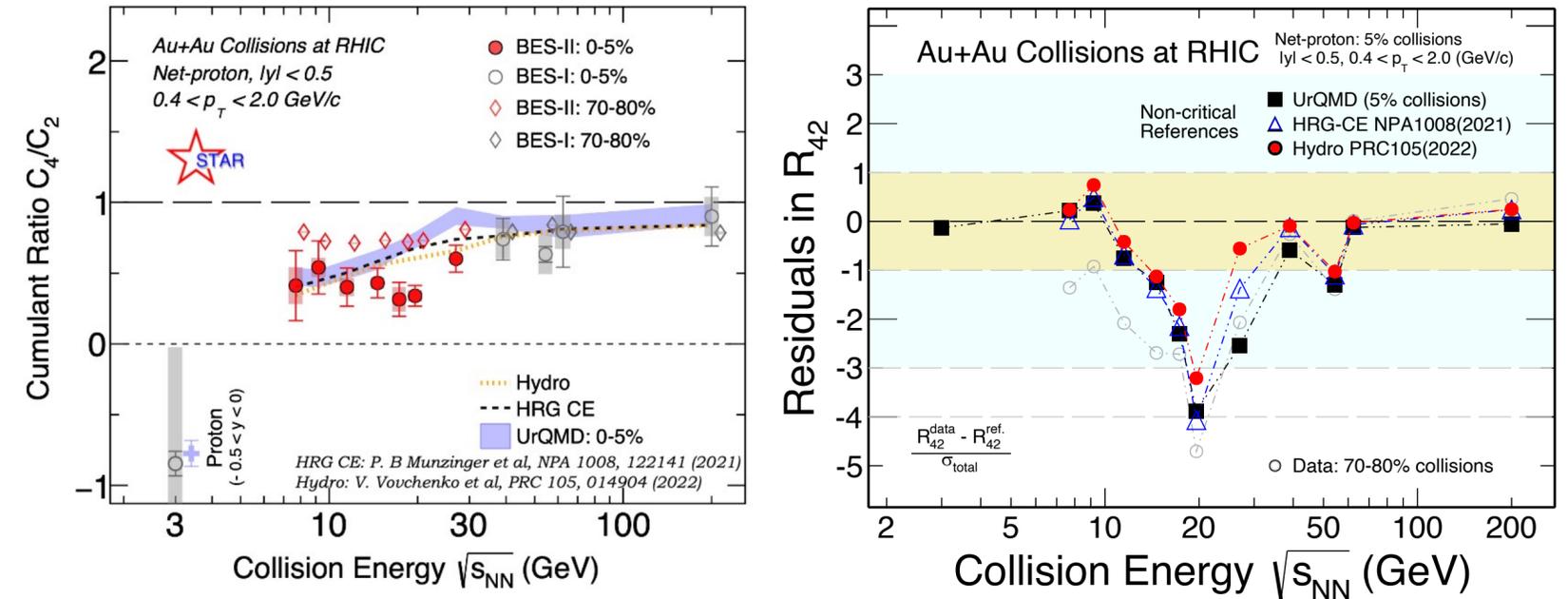
So let's continue with the search for the critical point

# Search for critical end point

## Net-proton cumulants

- More precise data from BES II
- Net-proton cumulant ratio  $C_4/C_2$  in 0–5% shows a minimum around 20 GeV compared to non-CP models (Hydro, HRG, UrQMD) and 70–80% data
- Non-critical models include baryon stopping but not its fluctuations
- Peripheral 70–80% also used as reference
- Maximum deviation:  $3.2\text{--}4.7\sigma$  at 20 GeV
- Overall deviation from 7.7–27 GeV:  $1.9\text{--}5.4\sigma$
- Interpretation of deviation is still under debate
- Further experimental input will come from STAR FXT

## Precision Measurement of Net-proton Cumulant on BES-II



Yifei Zhang, Thursday

# Search for critical end point

## Net-proton cumulants

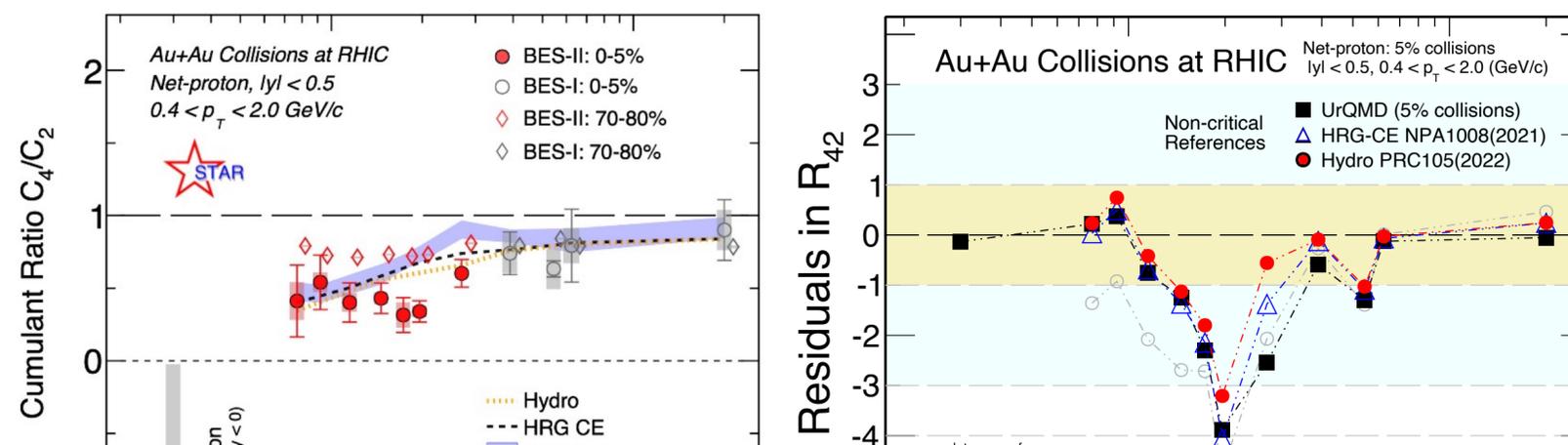
- More precise data from BES II
- Net-proton cumulant ratio  $C_4/C_2$  in 0–5% shows a minimum around 20 GeV compared to non-CP models (Hydro, HRG, UrQMD) and 70–80% data
- Non-critical models include baryon stopping but not its fluctuations
- Peripheral 70–80% also used as reference
- Maximum deviation:  $3.2\text{--}4.7\sigma$  at 20 GeV
- Overall deviation from 7.7–27 GeV:  $1.9\text{--}5.4\sigma$
- Interpretation of deviation is still under debate
- Further experimental input will come from STAR FXT

## Baryon–Strangeness correlation

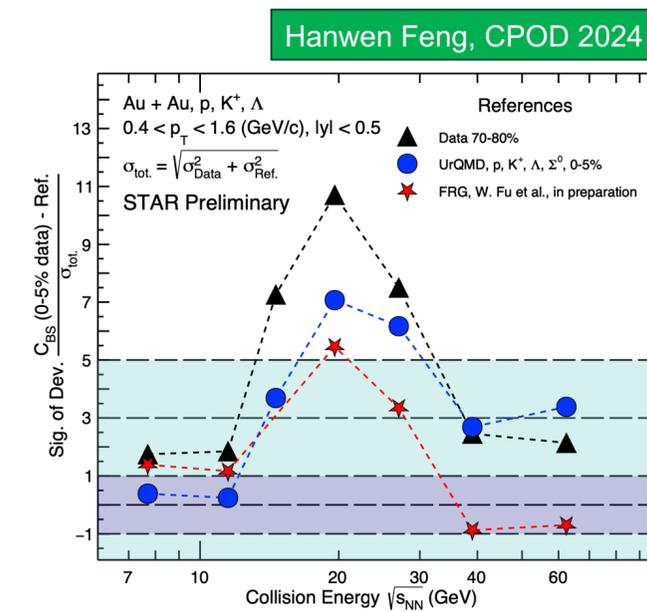
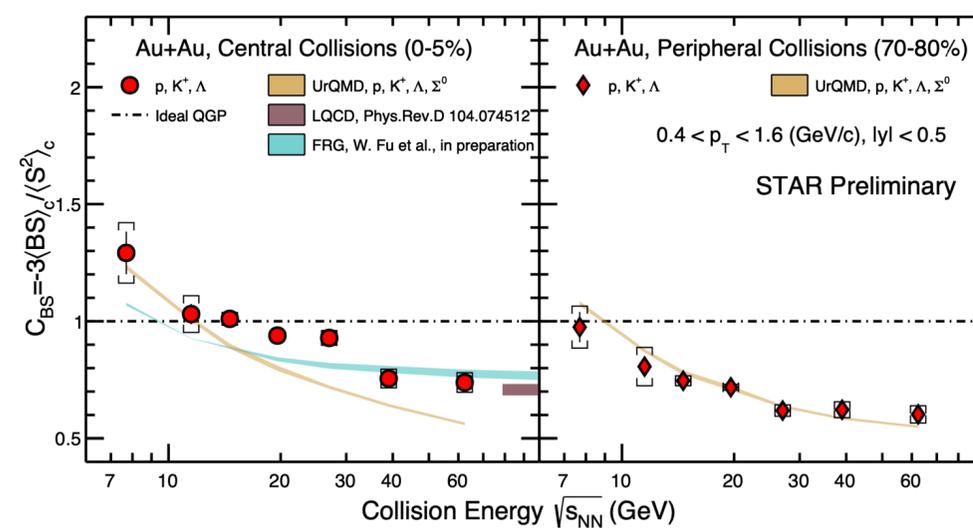
- Non-monotonic behavior around 20 GeV
- Not described by UrQMD
- But rather deconfinement sensitive?

But several caveats and homework discussed yesterday ...

## Precision Measurement of Net-proton Cumulant on BES-II



## Energy Dependence of $C_{BS}$ from STAR



- Central (0-5%): UrQMD qualitatively describes 7.7 and 11.5 GeV while underestimates other energies
- Peripheral (70-80%): qualitatively described by UrQMD
- At around 20 GeV, the deviation of central data reaches a maximum
- More investigation are needed on the deviation

Yu Zhang, SQM 2024, Strasbourg, France

# This could also be SQM, space Quark Matter

So let's finish with heavy ion physics for  
astrophysics



# From heavy ions to astrophysics

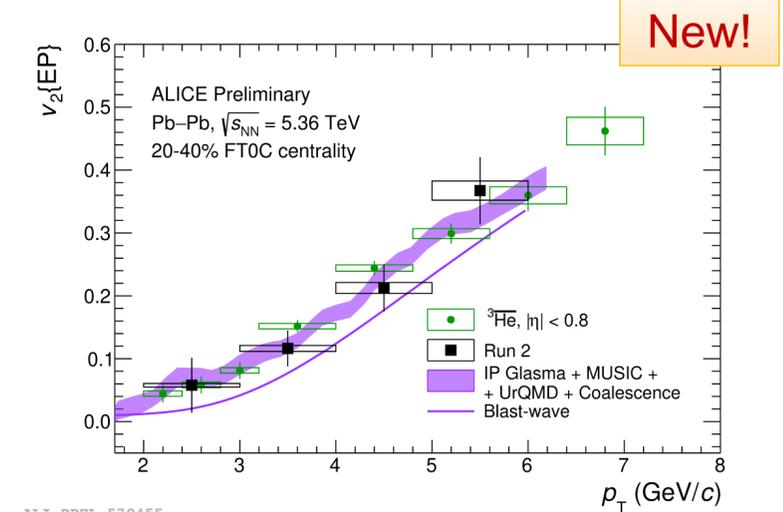
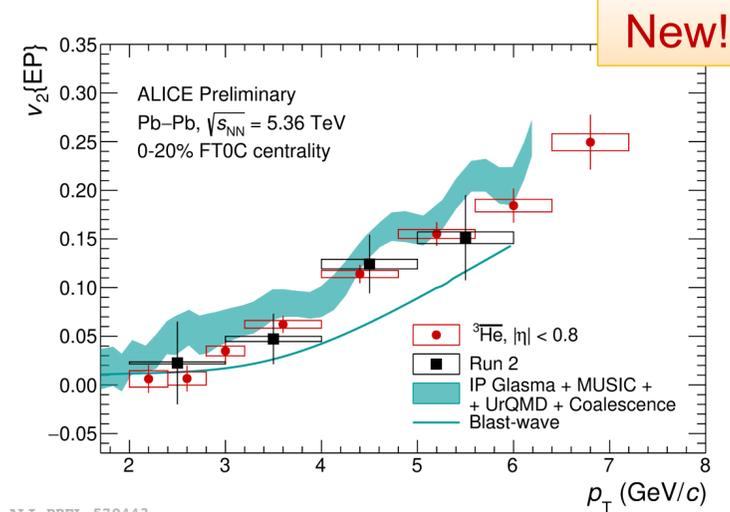
Heavy-ion collisions can provide important input for astrophysics, e.g.

- Cosmic ray fluxes of antinuclei for dark matter searches
- Particle interactions for neutron stars and equation of state

Rich light (anti)(hyper) nucleus programme

- Many new results showed (see C. Pinto summary)
- A glimpse of future results
  - High precision with ALICE

## Flow measurement in Run 3



- ▶ More precise flow measurement of  ${}^3\text{He}$  in Run 3
- ▶ Can we measure the flow of  ${}^3_{\Lambda}\text{H}$ ?

05/06/2024

Yuanzhe Wang || SQM 2024 || Strasbourg

23

# From heavy ions to astrophysics

Heavy-ion collisions can provide important input for astrophysics, e.g.

- Cosmic ray fluxes of antinuclei for dark matter searches
- Particle interactions for neutron stars and equation of state

Rich light (anti)(hyper) nucleus programme

- Many new results showed (see C. Pinto summary)
- A glimpse of future results
  - High precision with ALICE
  - LHCb as a new player

## Flow measurement in Run 3



## Observation of (Anti)hypertriton at LHCb

[CERN-LHCb-CONF-2023-002]

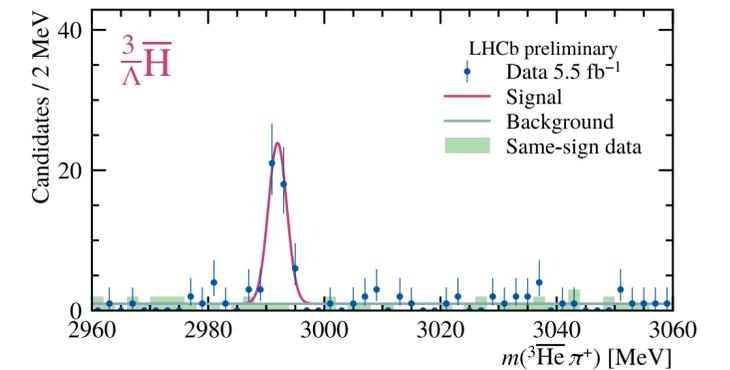
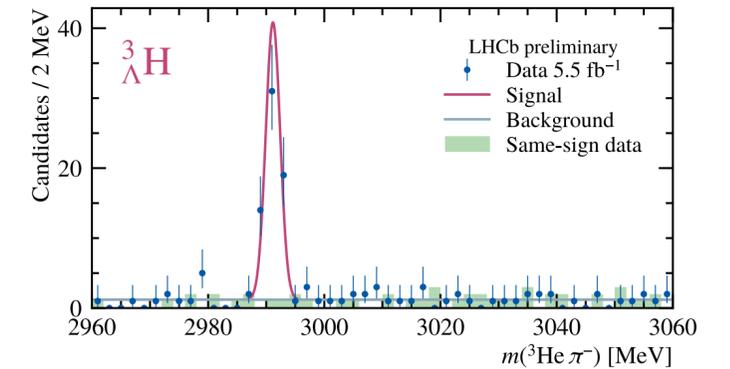
- **Preliminary fit results:**

- ▶  $N(\Lambda^3\text{H}) = 61 \pm 8$
- ▶  $N(\bar{\Lambda}^3\bar{\text{H}}) = 46 \pm 7$

- Statistical mass precision: 0.16 MeV

- **Under investigation:**

- ▶ Charge-sign dependent energy-loss corrections
- ▶ Tracking corrections for  $Z=2$
- ▶ Efficiency and acceptance corrections



# From heavy ions to astrophysics

Heavy-ion collisions can provide important input for astrophysics, e.g.

- Cosmic ray fluxes of antinuclei for dark matter searches
- Particle interactions for neutron stars and equation of state

Rich light (anti)(hyper) nucleus programme

- Many new results showed (see C Pinto summary)
- A glimpse of future results
  - High precision with ALICE
  - LHC as a new player

Comprehensive studies of two and three body hadron interactions using femtoscopy

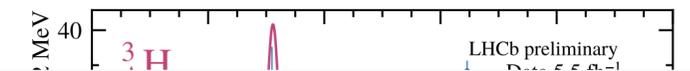
- Access to genuine three-body correlations
- First ever full three-body correlation function calculations
  - A. Kievsky, LS, et al., Phys.Rev.C 109 (2024) 3, 034006

## Flow measurement in Run 3

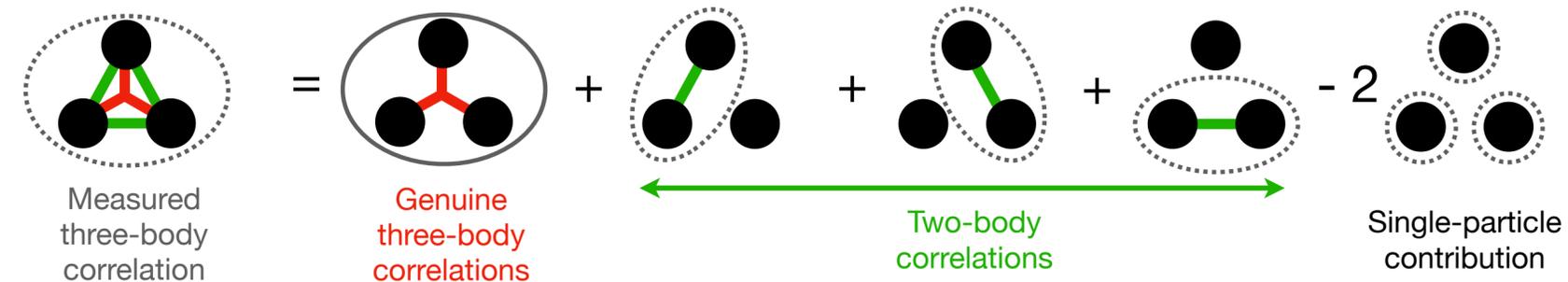


## Observation of (Anti)hypertriton at LHCb

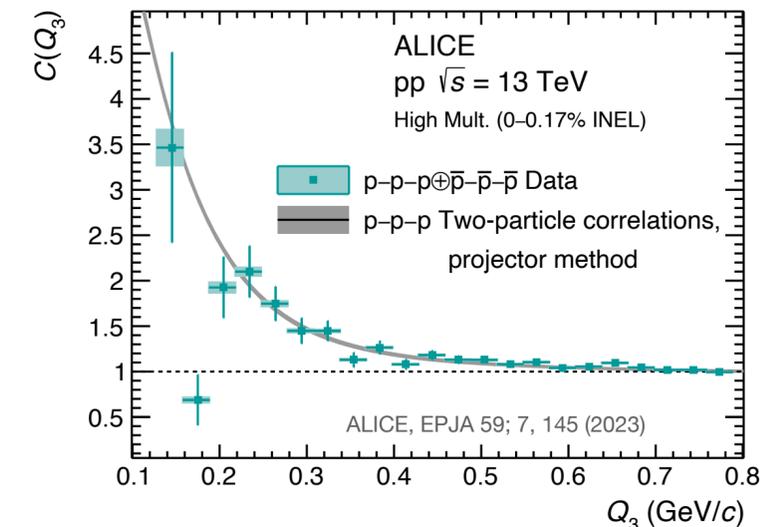
[CERN-LHCb-CONF-2023-002]



## p-p-p correlation function



- Cumulant method provides first hint of effects beyond two-body correlations  
R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)  
 Del Grande, LS et al. EPJC 82 (2022) 244
- A deviation of  $n\sigma = 6.7$  from lower-order contributions
- Theoretical predictions necessary to further understand the origin of the deviation further



[laura.serksnyte@tum.de](mailto:laura.serksnyte@tum.de)

13

# There is also a SQM, a “suite” to Quark Matter

So let's see what comes next



# A bright future at FAIR

## CBM at FAIR

### Outlook: Year 1 – 3 scenario as of September 2023

Year	Setup	Reaction	T <sub>Lab</sub> (A GeV)	Days on Target	Number of events	Remarks
0 (2028*)	ELEHAD	C+C, Ag+Ag, Au+Au	2,4,6,8,10, max	60		Commissioning
1	ELEHAD	Au+Au	2,4,6,8,10, max	30 (5 each)	2·10 <sup>10</sup> each	EB mBias
1	ELEHAD	C+C	2,4,6,8,10, max	18 (3 each)	4·10 <sup>10</sup> each	mBias
1	ELEHAD	p+Be	3,4,8,29	12 (3 each)	2·10 <sup>11</sup> each	mBias
2	MUON	Au+Au	2,4,6,8,10, max	30 (5 each)	2·10 <sup>11</sup> each	mBias
2	MUON	C+C	2,4,6,8,10, max	18 (3 each)	4·10 <sup>11</sup> each	mBias
2	MUON	p+Be	3,4,8,29	12 (3 each)	2·10 <sup>12</sup> each	mBias
3	HADR	Au+Au	2,4,6,8,10, max	12 (2 each)	4·10 <sup>11</sup> each	EB+ Selectors
3	HADR	C+C	2,4,6,8,10, max	6 (1 each)	8·10 <sup>11</sup> each	
3	HADES	Ag+Ag	2,4	28 (14 each)	10 <sup>10</sup> each	
3	ELEHAD	Ag+Ag	2,4	8 (4 each)	2·10 <sup>10</sup> each	mBias

#### Focus on beam energy scan:

- 60 days / year beam on target
- factor 100 more statistics w.r.t. STAR FXT

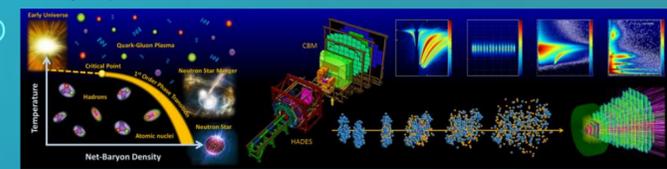
I. VASSILIEV SQM 2024 STRASBOURG

17




## PERSPECTIVES ON (MULTI-STRANGE) HYPERNUCLEI PHYSICS WITH THE CBM EXPERIMENT AT FAIR

Iouri Vassiliev, i.vassiliev@gsi.de, for the CBM Collaboration



[https://edms.cern.ch/ui/file/2893949/LATEST/FAIR\\*.mp4](https://edms.cern.ch/ui/file/2893949/LATEST/FAIR*.mp4)





The CBM Collaboration <https://www.cbm.gsi.de>

# A bright future at RHIC

## sPHENIX and STAR at RHIC

### Run Plan to Achieve Physics Goals

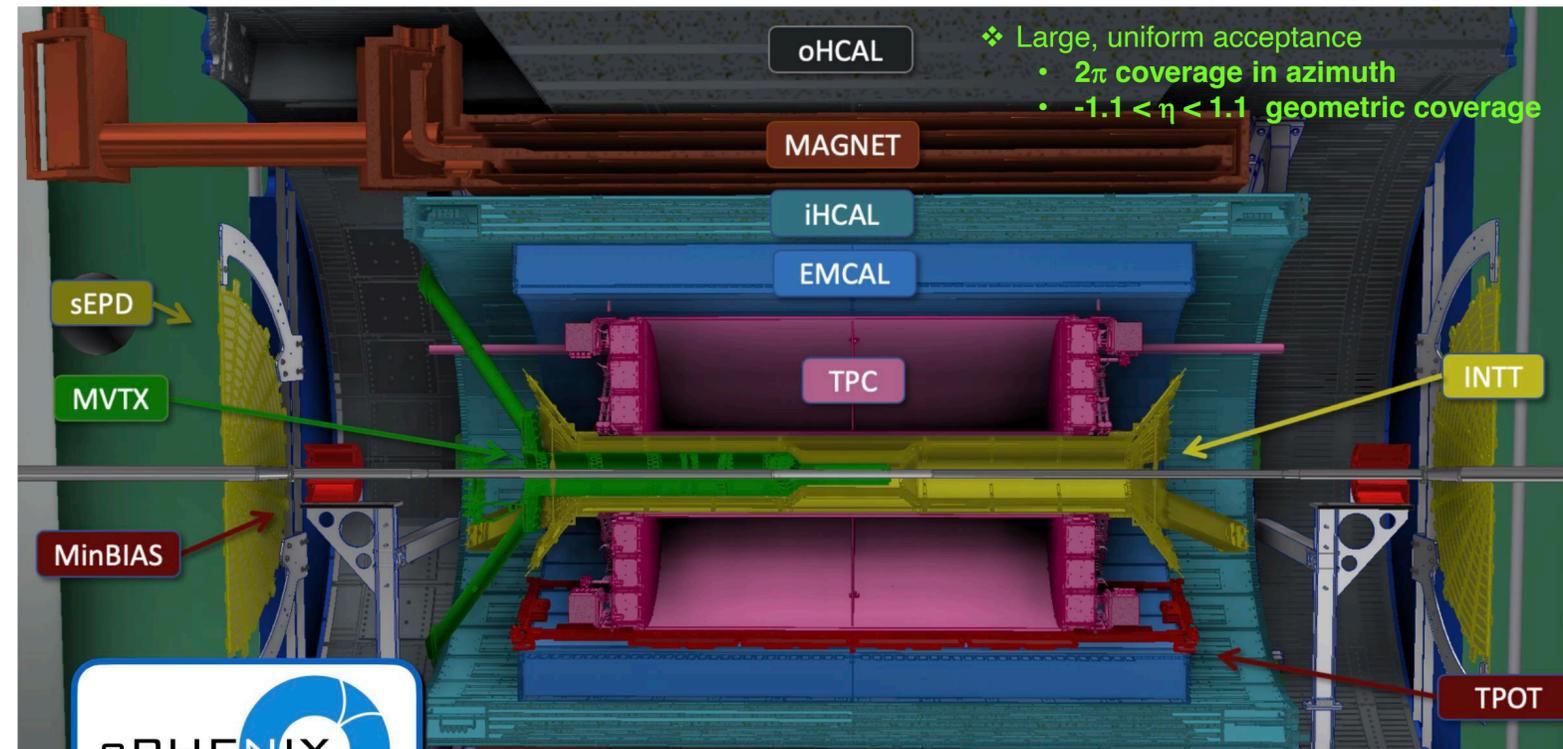


➤ **Run-2024:** transversely polarized  $p+p$  running, with a few options for short Au+Au running:

→ finish commissioning, ColdQCD  $p+p$  program, crucial reference data for AA program

➤ **Run-2025:** high-luminosity Au+Au running measurements of jets and heavy flavor observables with unprecedented statistical precision

Year	Cryo-weeks	Species	Goal
2023	11.5	Au+Au	Start of commissioning
2024	25	$p+p$ (at least 19 weeks) Au+Au	Finish commissioning, reference data & ColdQCD
2025	28	Au+Au	High-statistics jet and heavy-flavor QGP probes
2026	28	$p+Au$ , $p+p$ O+O, Ar+Ar	Small systems
2027	28	...	Additional unique sPHENIX opportunities!

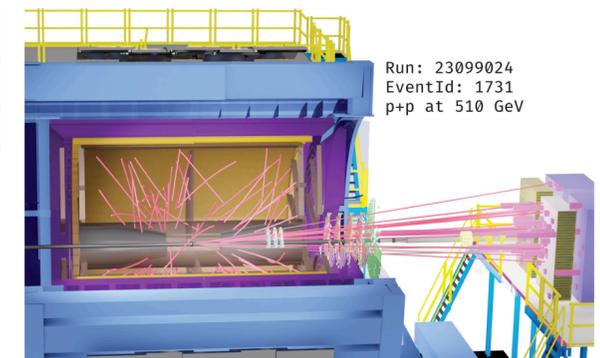


### Future physics opportunities



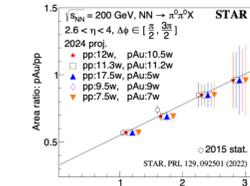
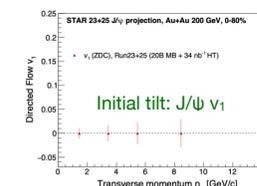
#### Projections as plans for 2023-2025

$\sqrt{s_{NN}}$ (GeV)	Species	Sampled Luminosity	Year
200	Au+Au&p+Au	AuAu 32.7 nb <sup>-1</sup> / pAu 0.69 pb <sup>-1</sup>	2023+2025
200	p+p	142 pb <sup>-1</sup>	2024



#### Hot QCD physics: Explore the microstructure of QGP

- What is the Nature of the 3D Initial State?
- What is the Temperature of QGP and the Temperature Dependence of Viscosity?
- What can Charmonium Tell Us About Deconfinement?
- What are the Electrical, Magnetic, and Chiral Properties of the Medium?
- What are the Underlying Mechanisms of Jet Quenching?
- What is the Nature of the Phase Transition Near  $\mu_B = 0$ ?
- What Can We Learn About the Strong Interaction?



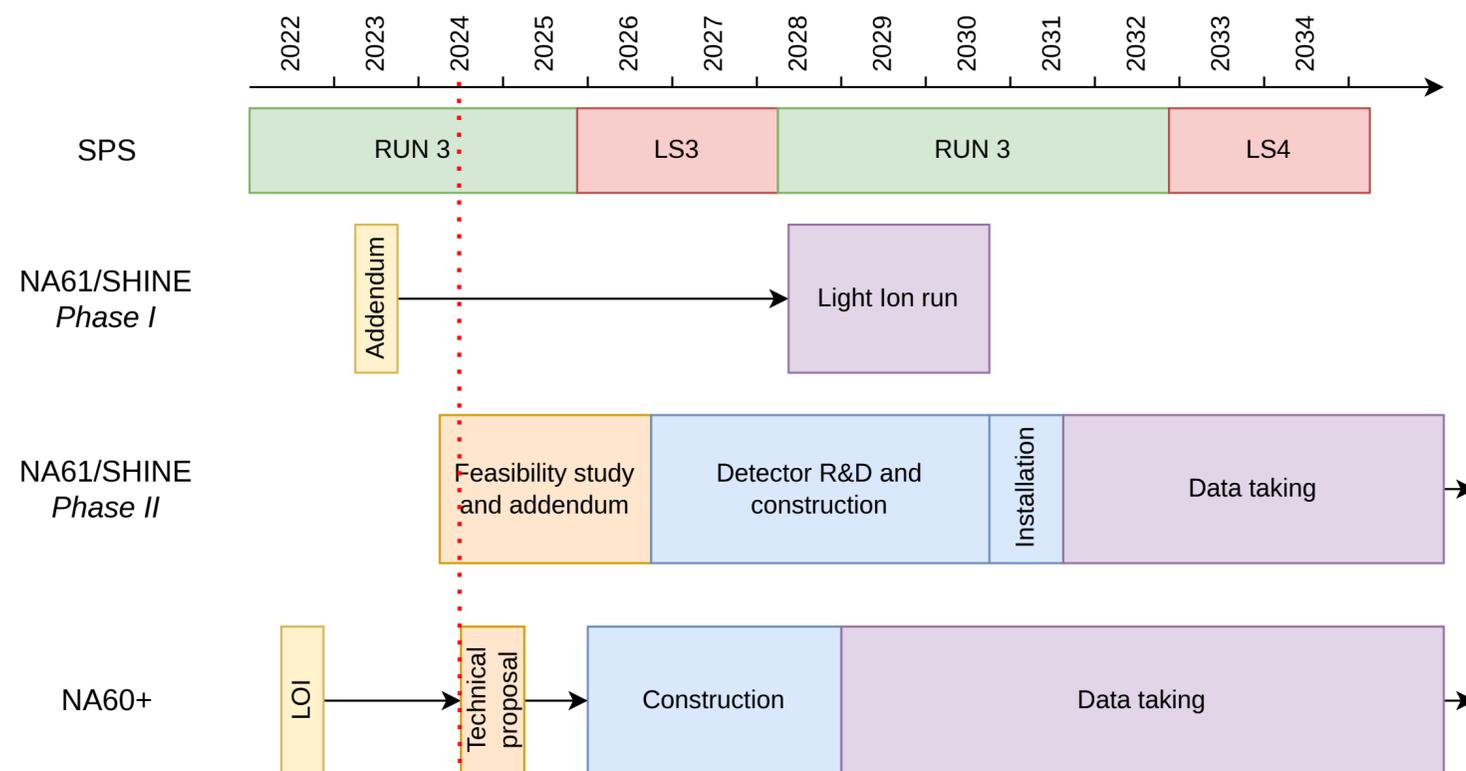
#### Cold QCD physics: Establish the validity and limits of factorization and universality to understanding of QCD

- Forward Transverse-Spin Asymmetries
- Sivers and Efremov-Teryaev-Qiu-Sterman Functions
- Transversely, Collins Function and Interference Fragmentation Function
- Ultra-Peripheral Collisions

# A bright future at SPS

## NA61/SHINE and NA60+ at the SPS

### NA61/SHINE and NA60+: timeline



Piotr Podlaski (University of Warsaw)

SPS upgrades and prospects

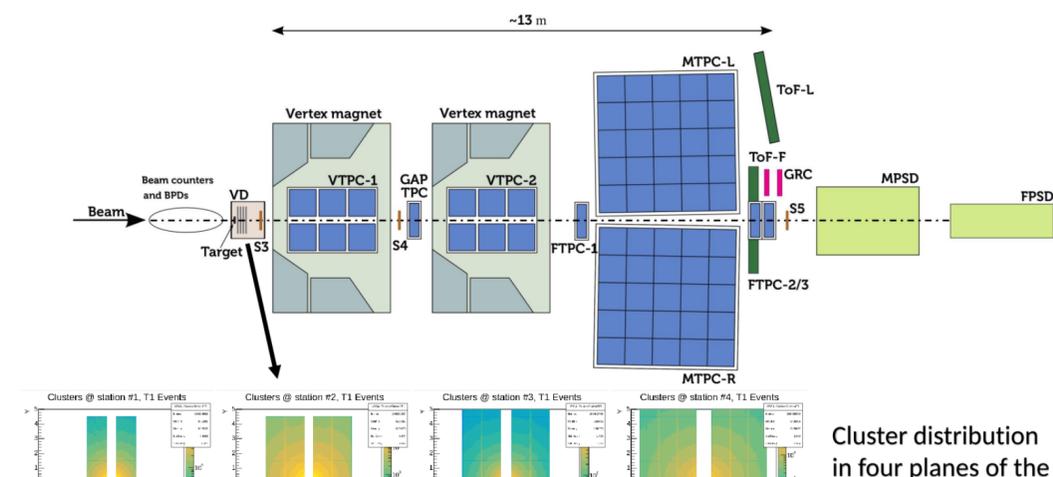
SQM 2024

29 / 37

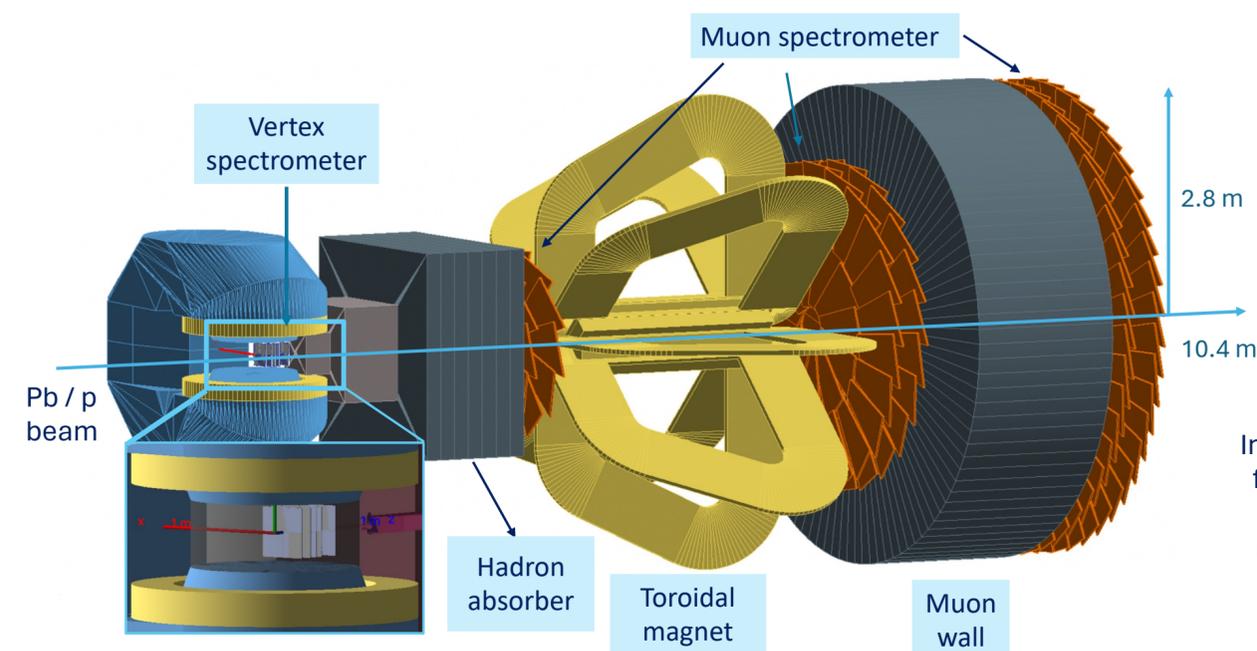
### Future Phase I: Detector



Significantly upgraded during LS2, the detector was successfully used in 2022 & 2033 data taking. No additional upgrades are needed for post-LS3 light-ion measurements



### NA60+ setup



Inspired by the former NA60 detector (2002-2004)

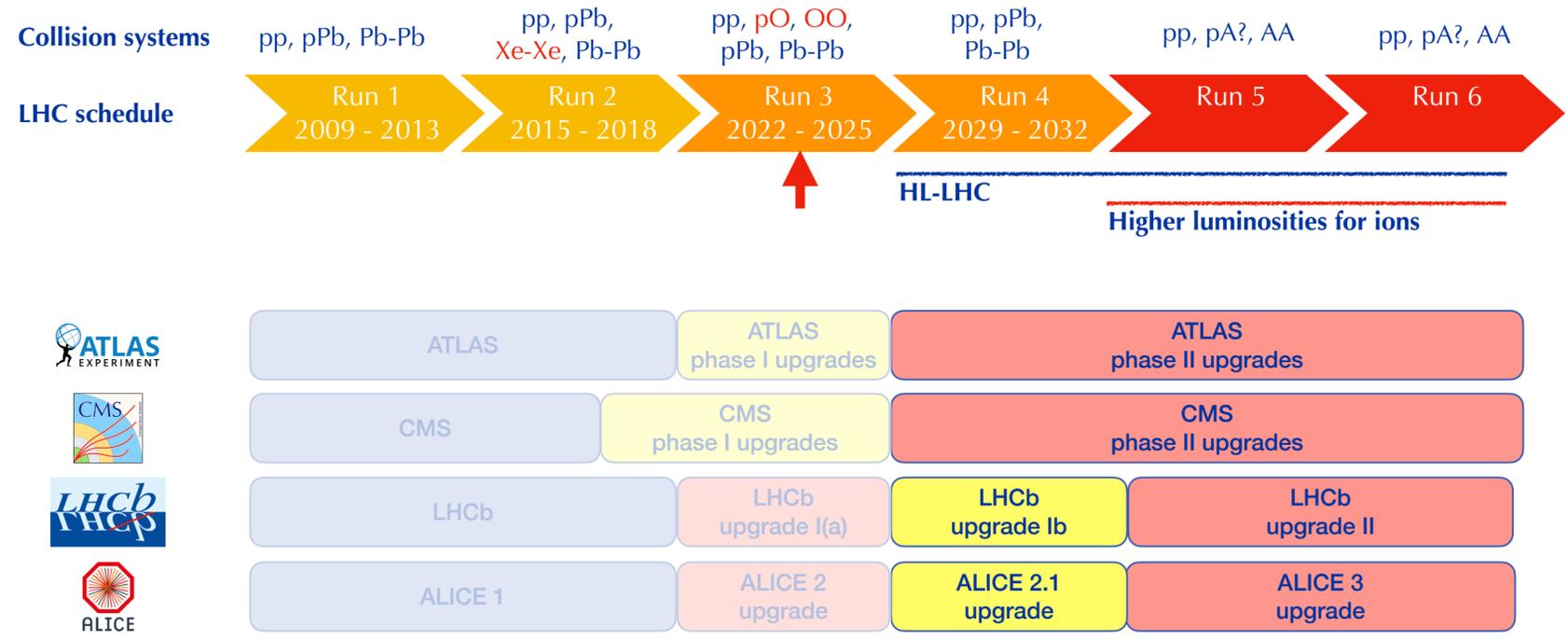
S. Siddhanta, SQM 2024, Strasbourg

5

# A bright future at LHC

ALICE, ATLAS, CMS, and LHCb upgrades at the LHC, not to forget SMOG 2

## LHC programme



### Upgraded experiments

**LS3**

**ATLAS phase II**  
ITk, HGTD, HL-ZDC, TDAQ, muon chambers

**CMS phase II**  
tracker, MTD, HL-ZDC, DAQ, trigger,  $\mu$  chambers

**LS4**

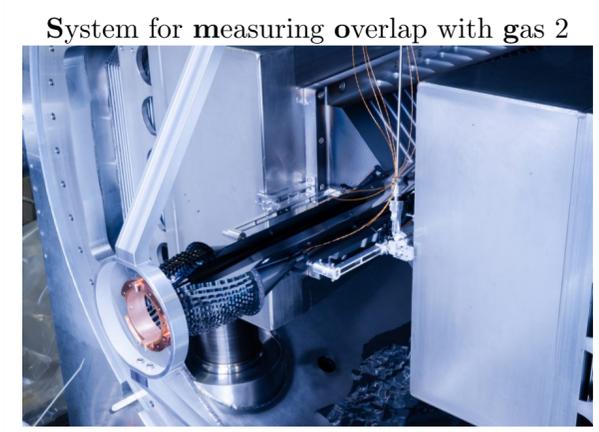
**LHCb phase IIb**  
VELO, RICH, TORCH, calo,  $\mu$  stations, UT, MT

**ALICE 2.1**  
FoCal, ITS3

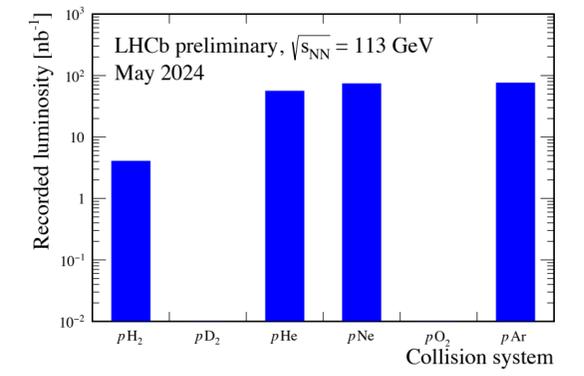
**ALICE 3**  
vertexing, tracking, TOF, RICH, ECal,  $\mu$ ID, FCT

Upgrades @ LHC | SQM, June 2024 | jkl

### The SMOG2 system



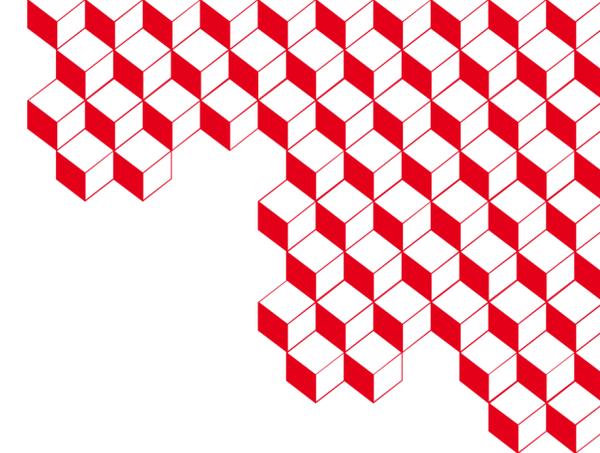
Concurrently collect collider and fixed-target data using a gas injection system



LHCb-FIGURE-2024-005

# Summary of summary?





Thank you for your attention!

**And have a safe trip back, but hold on a bit more**

**CEA SAACLAY**

91191 Gif-sur-Yvette Cedex

France

[javier.castillo@cea.fr](mailto:javier.castillo@cea.fr)

Tel. + 33 1 69 08 72 55