Experimental summary

SQM 2024, Strasbourg

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

Javier Castillo Castellanos

Acknowledgment and disclaimer

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This is SQM, Strangeness in Quark Matter

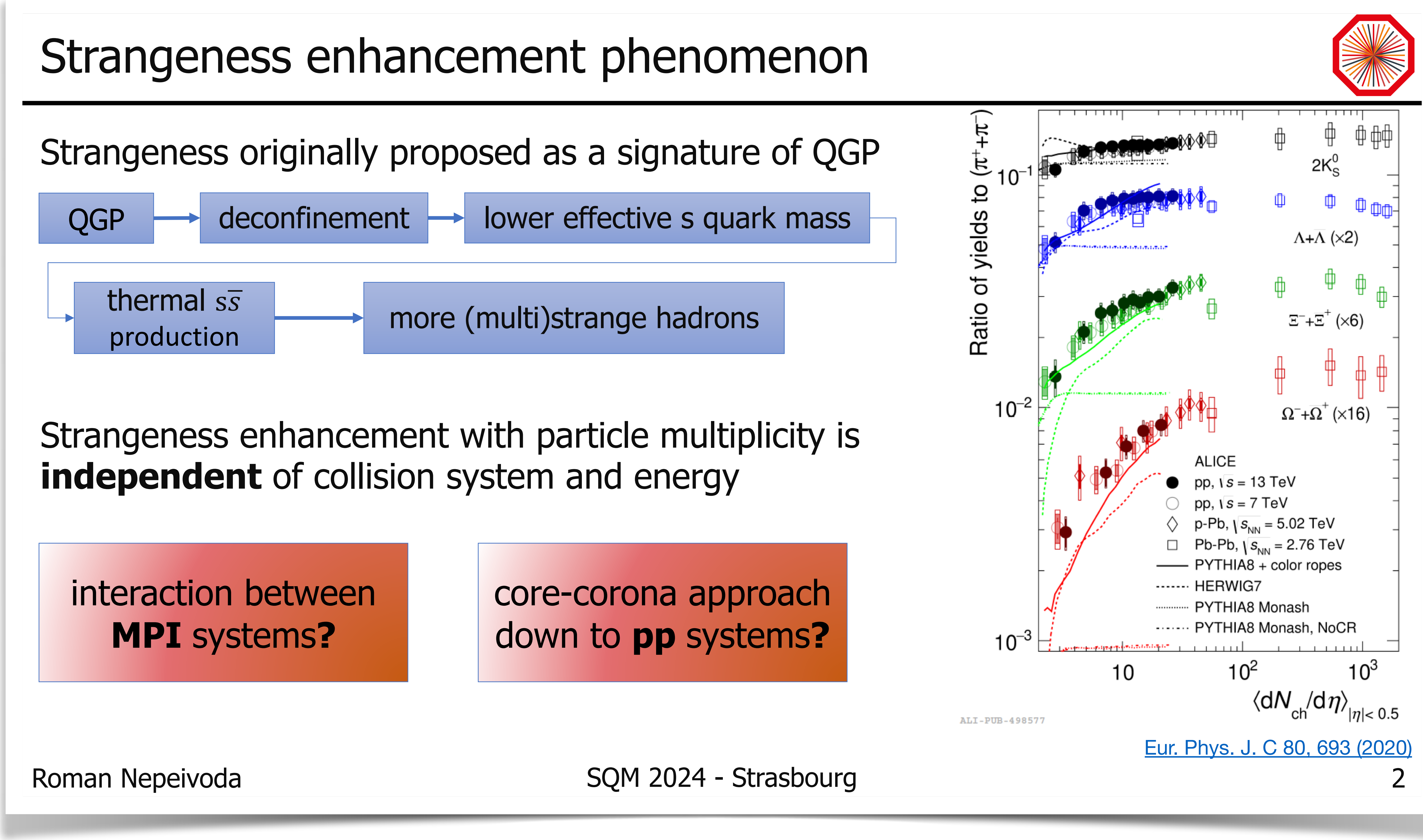
So let's start with the famous strangeness enhancement

The famous strangeness enhancement

The original idea is simple

- Strangeness enhancement
- Stronger enhancement for larger s content

Observed at SPS, RHIC, LHC energies



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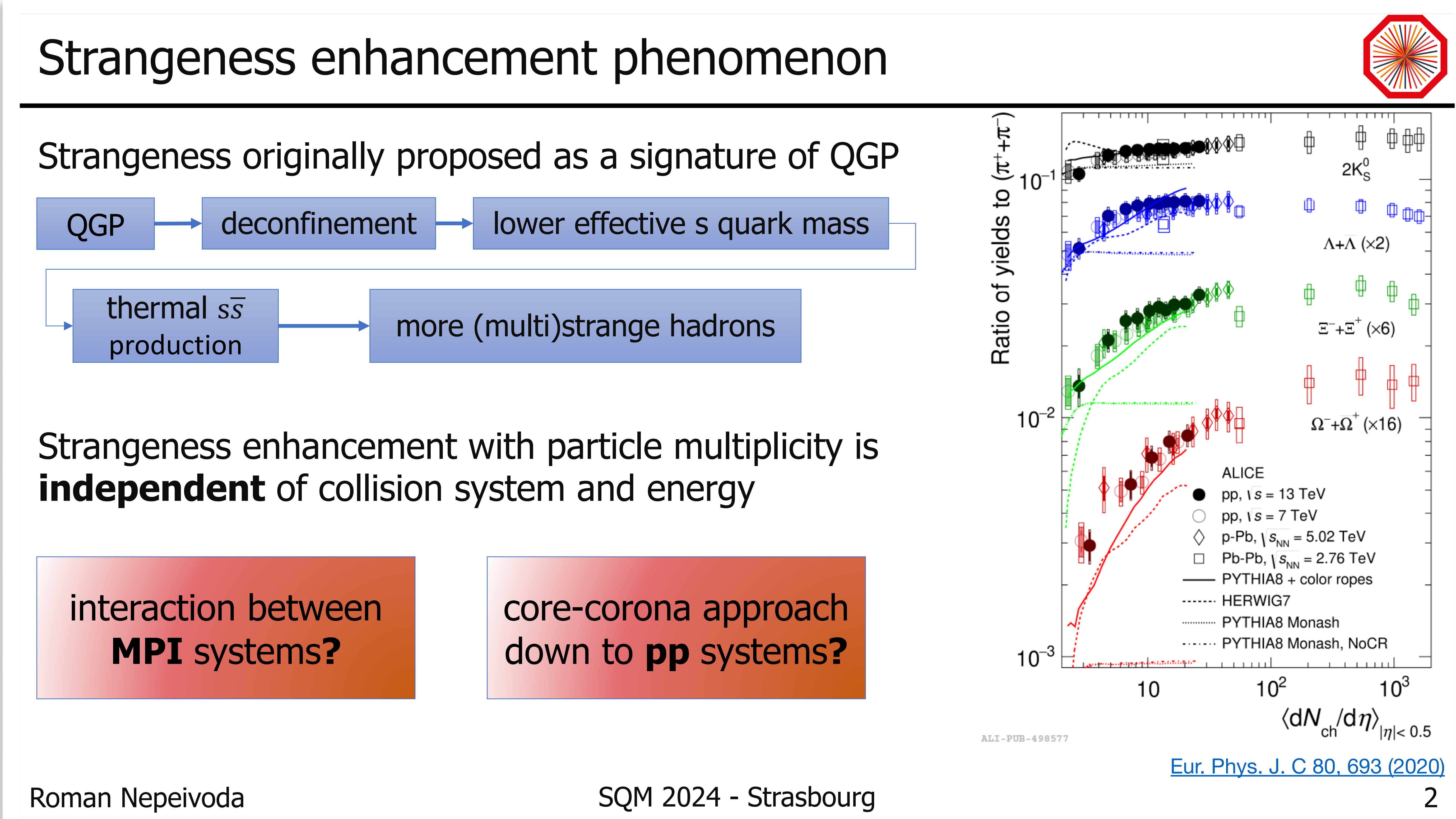
- Strange-to-non strange particle ratio increase with multiplicity
- Independently from collision system and energy



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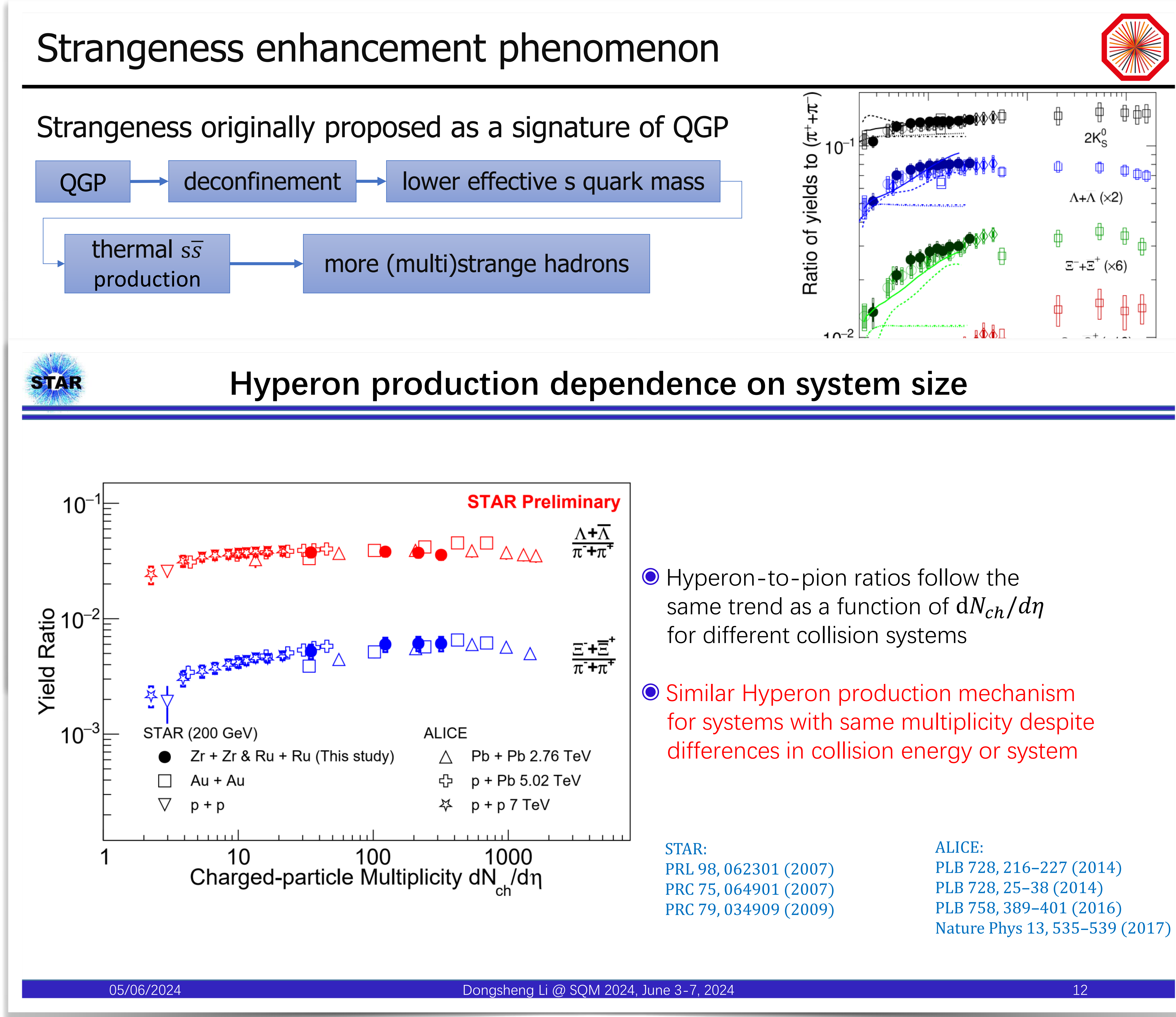

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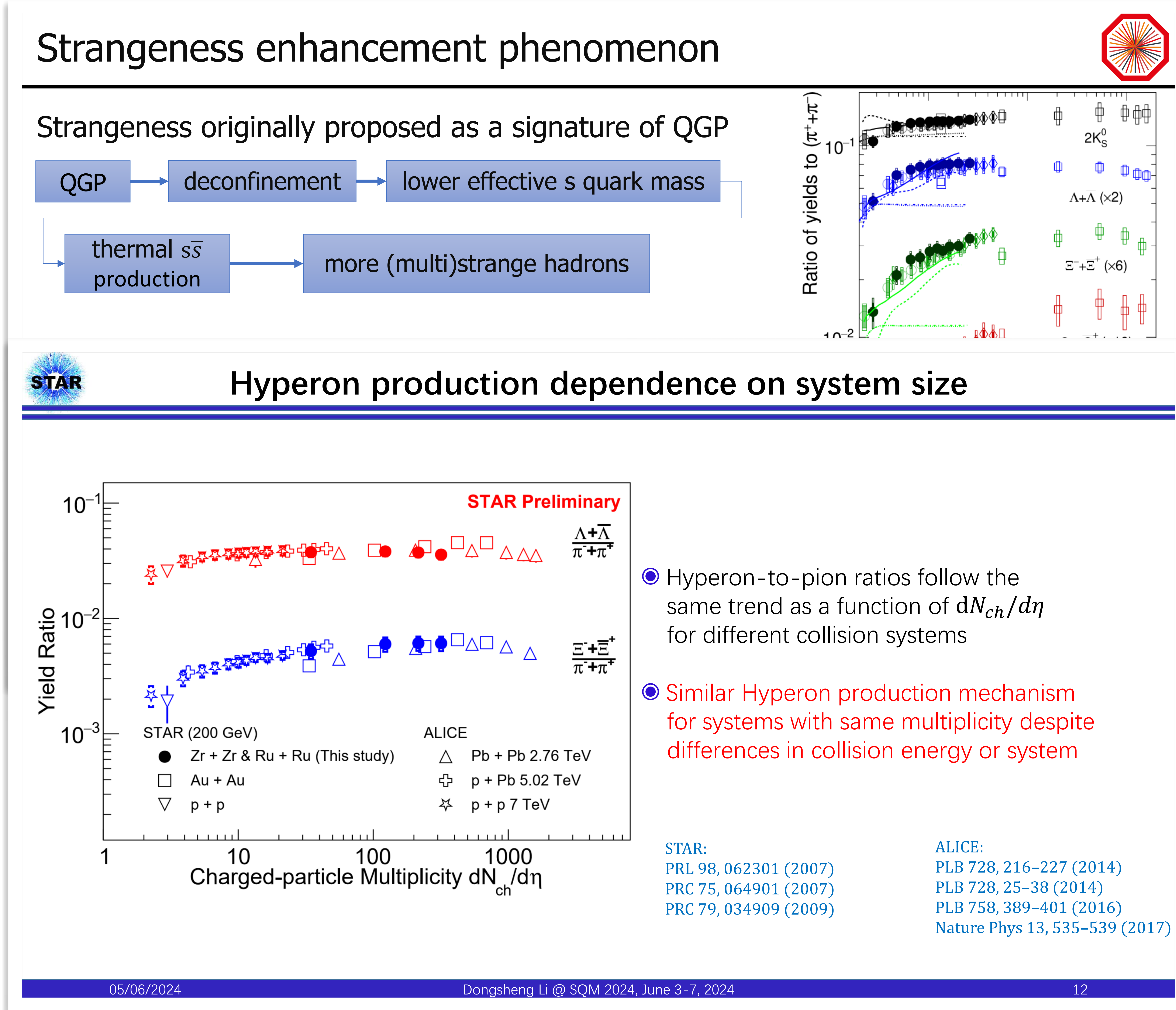
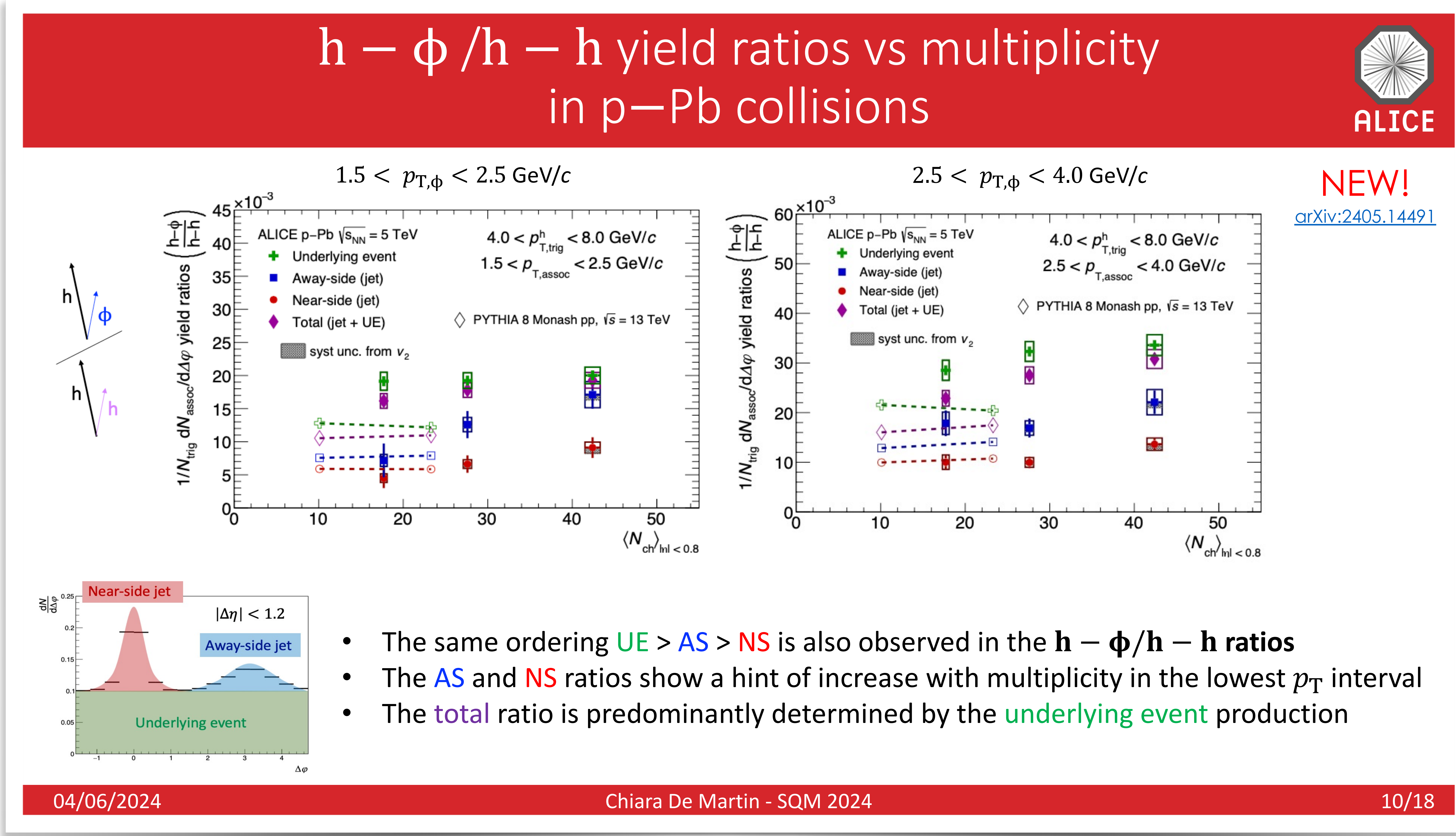
Has triggered a rich set of studies in small collision systems



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



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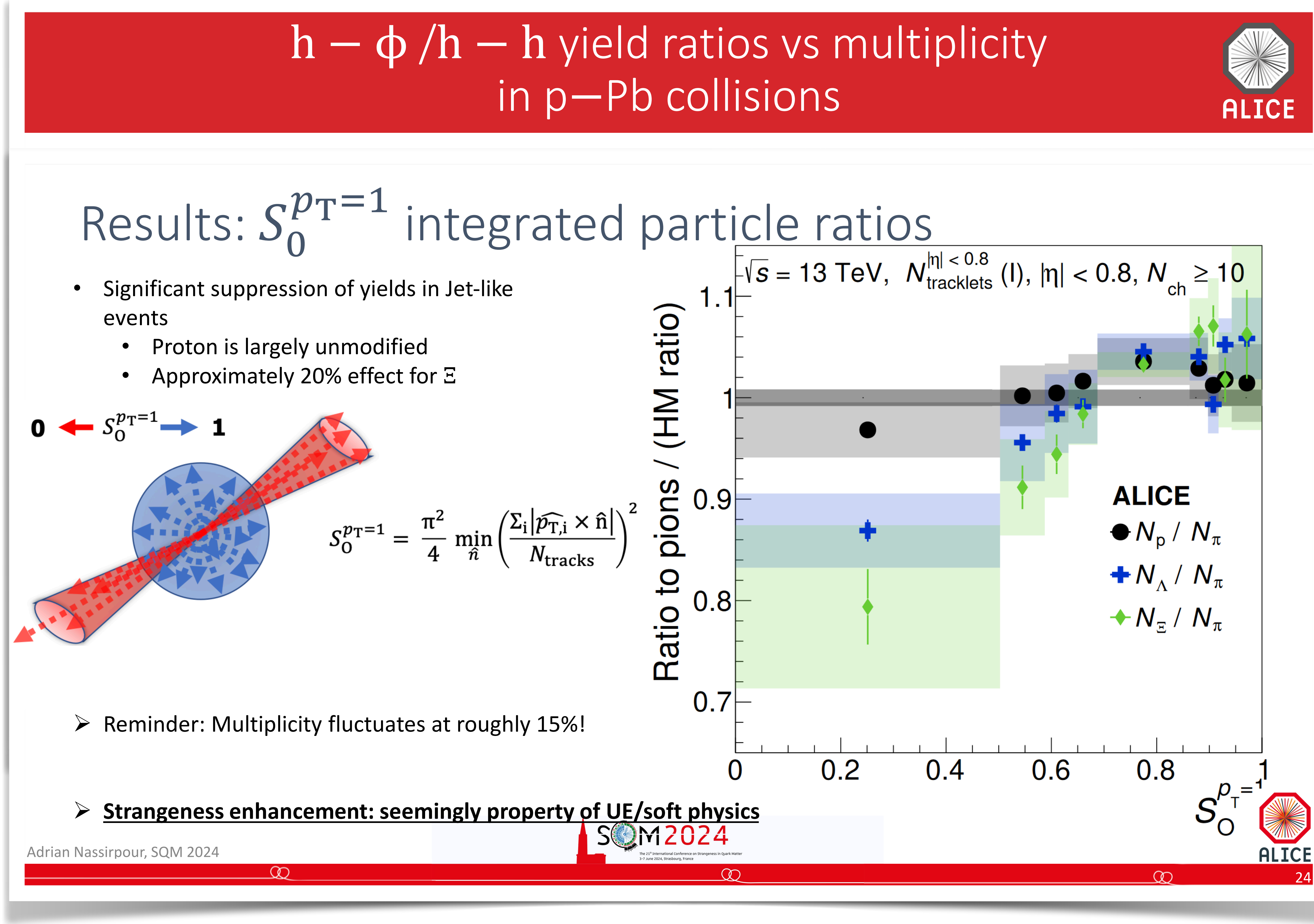
As a function of Spherocity

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



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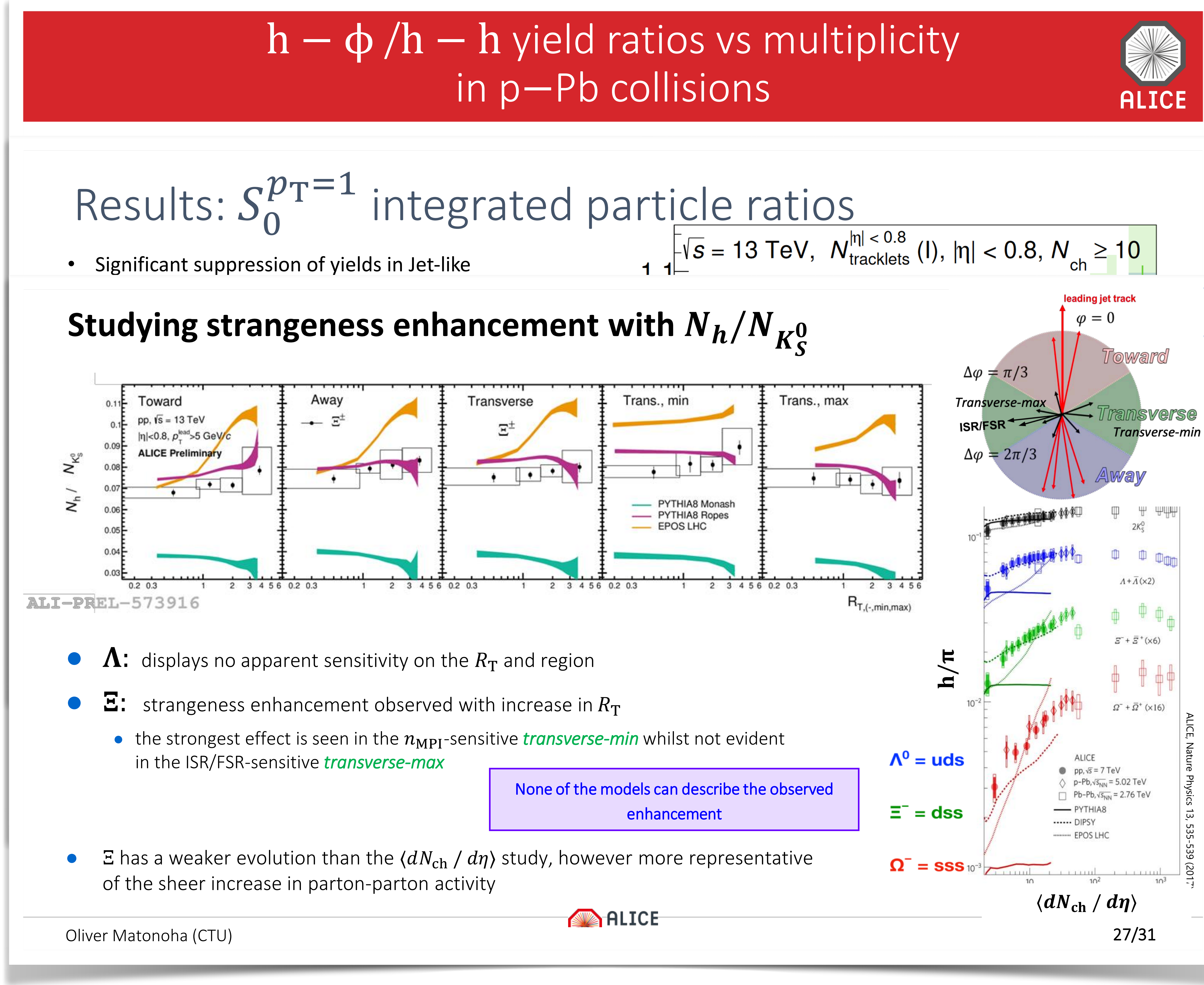
As a function of R_T, $R_{T,min}$, $R_{T,max}$

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



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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

ALICE

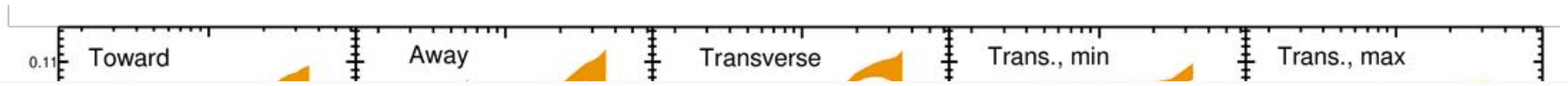
Results: $S_0^{p_T=1}$ integrated particle ratios

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

- Significant suppression of yields in Jet-like

Studying strangeness enhancement with $N_h/N_{K^0_S}$

NEW!

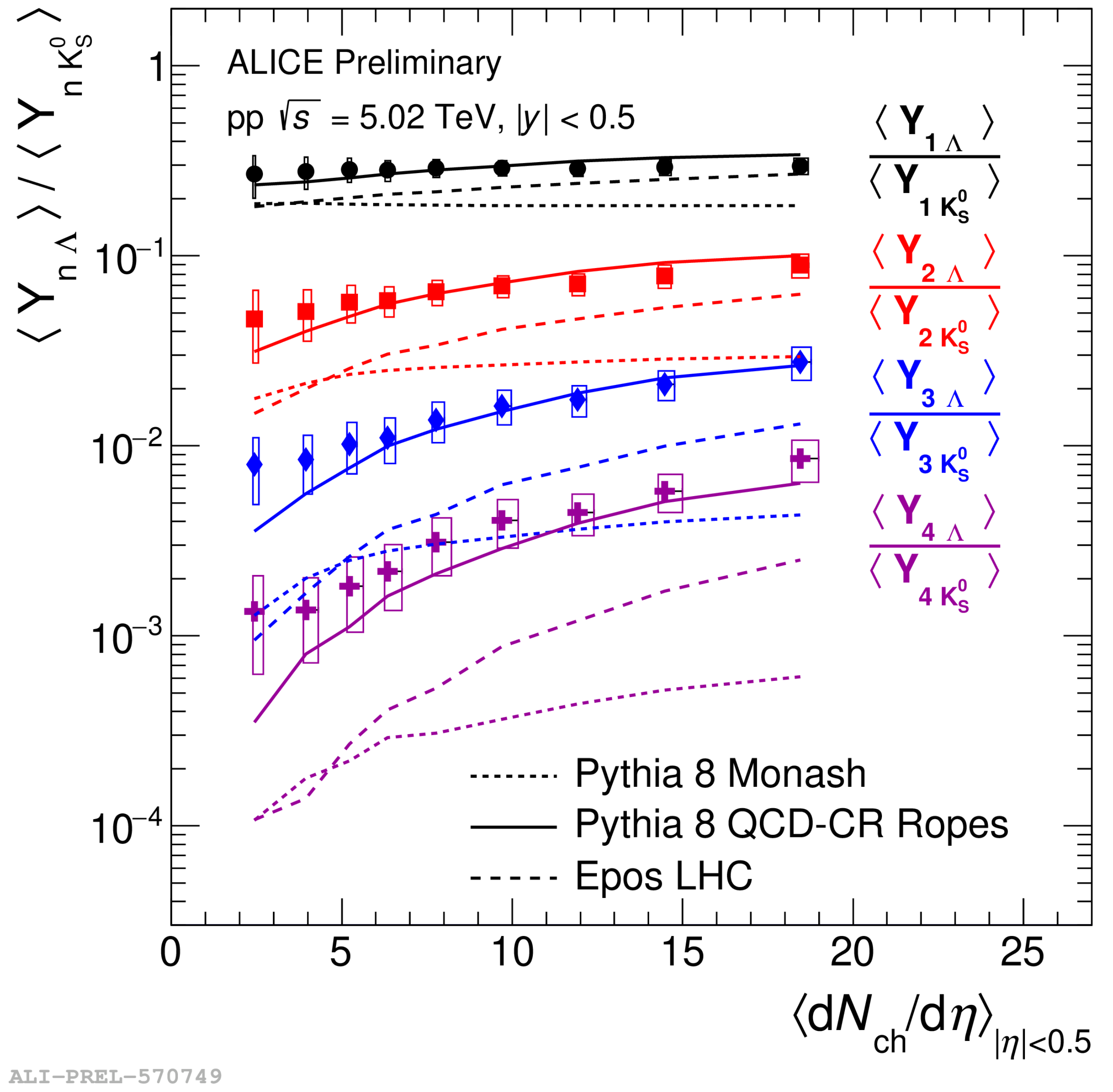


Baryon/strangeness enhancement

NEW!

$$< Y_{k-\text{part}} > = \sum_{n=k}^{\infty} \frac{n!}{k!\,(n-k)!} P(n)$$

- Important to **decouple strangeness-related** from **baryon-related** effects
- **Increase of** $^{\Lambda}/_{K^0_S}$ with multiplicity when looking at **multiple production**
- Possibly in all strange-hadron/π 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

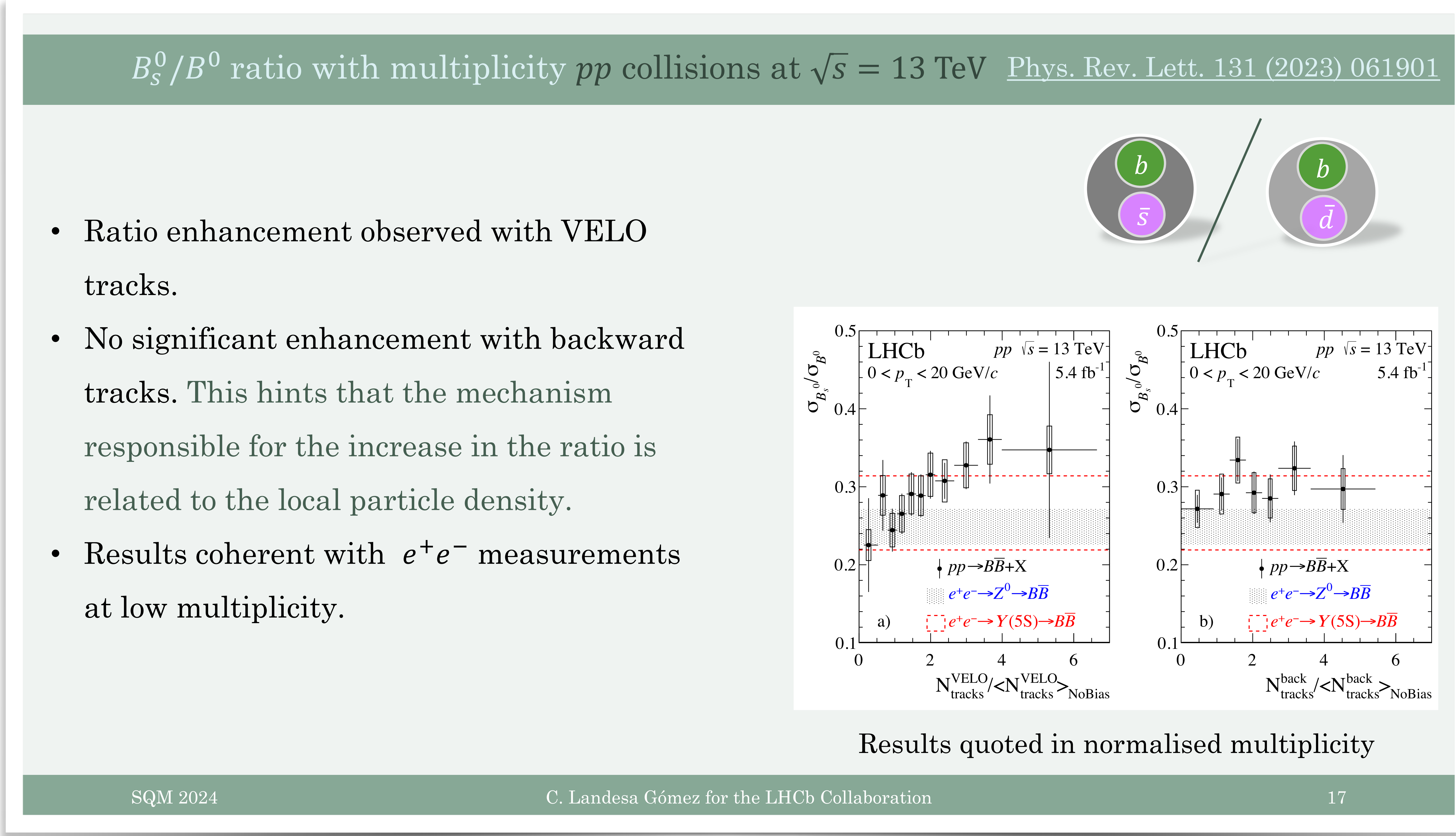


Roman Nepeivoda SQM 2024 - Strasbourg 11

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



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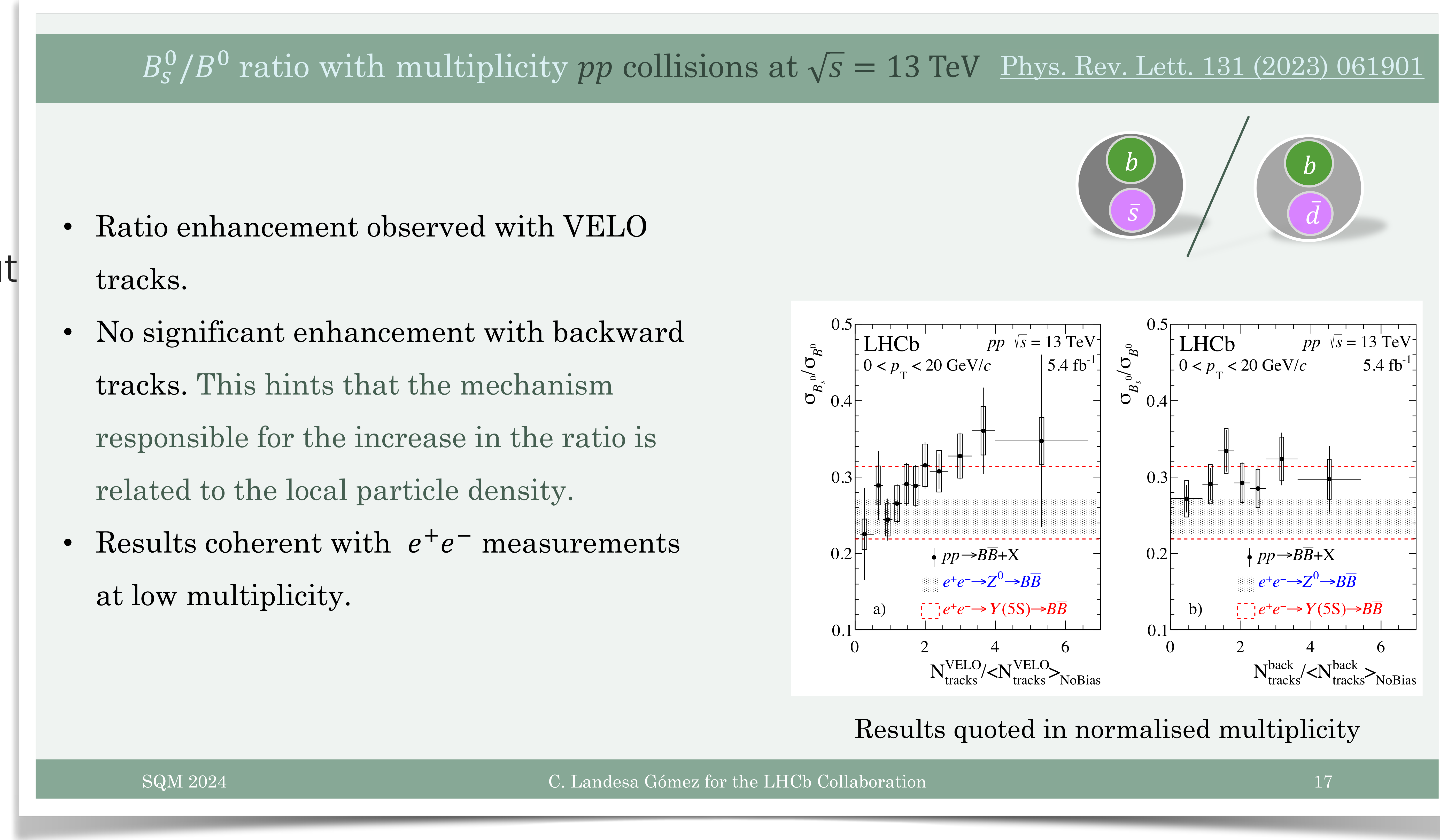
Also when hadronizing with heavy flavors?

- 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



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:

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

Parton distribution functions

Hard scattering cross section (pQCD)

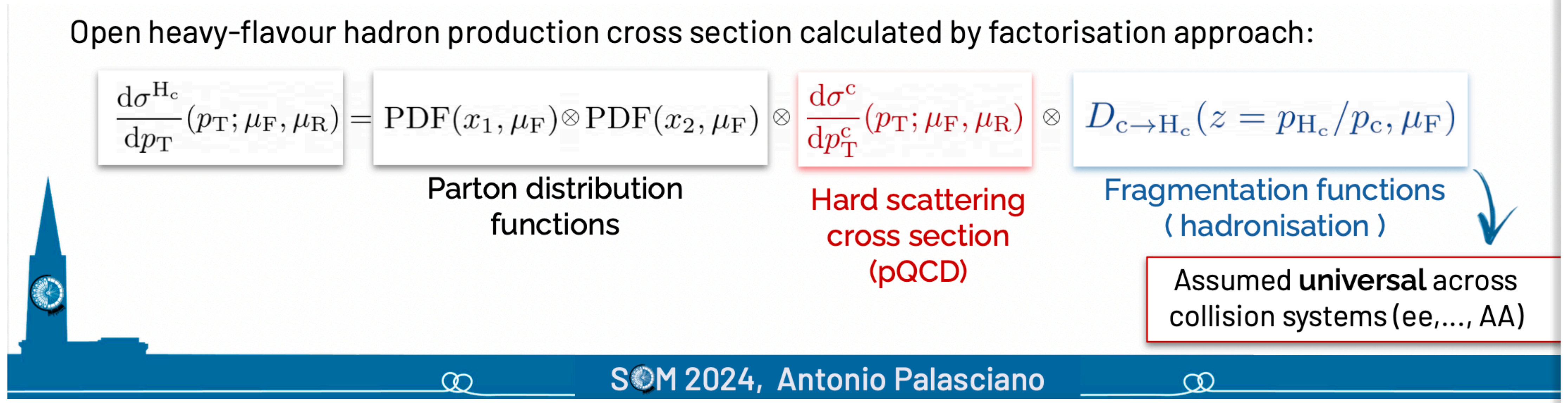
Fragmentation functions (hadronisation)

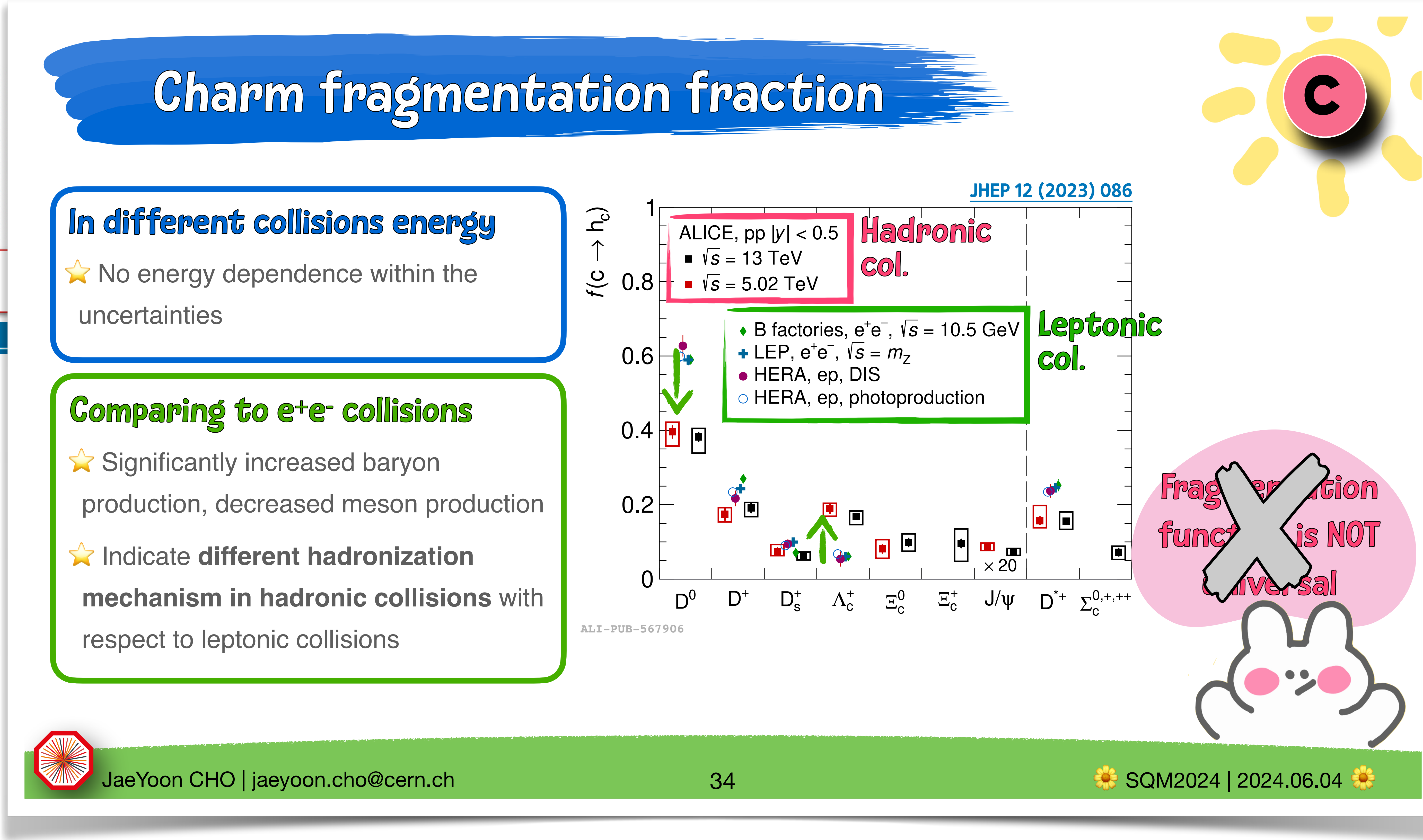
Assumed **universal** across collision systems (ee,..., AA)

SQM 2024, Antonio Palasciano

Charm ~~fragmentation function~~ fraction

Factorisation approach





Charm ~~fragmentation function fraction~~ hadronization

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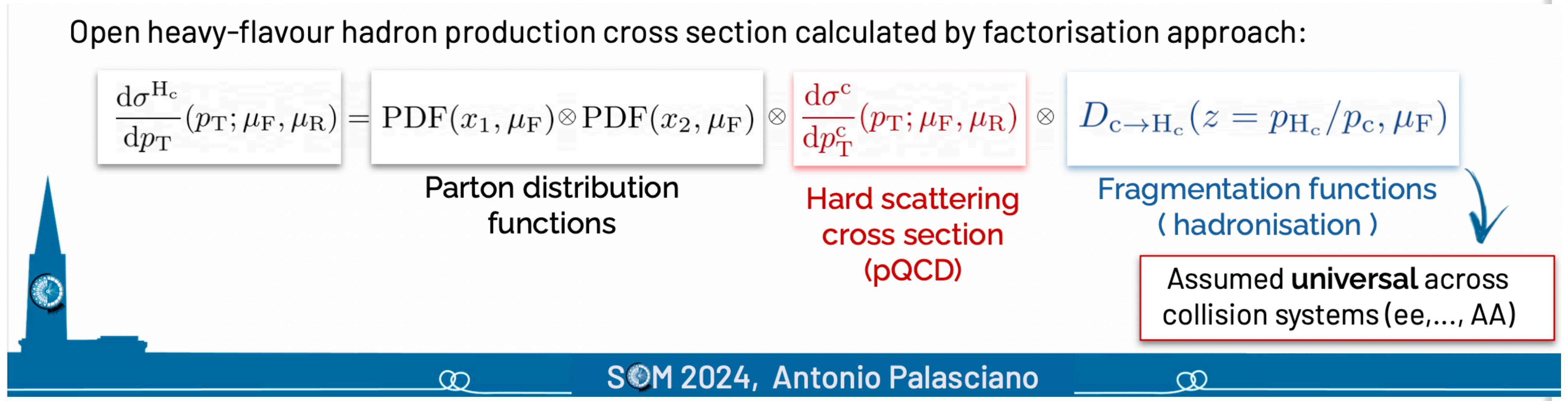
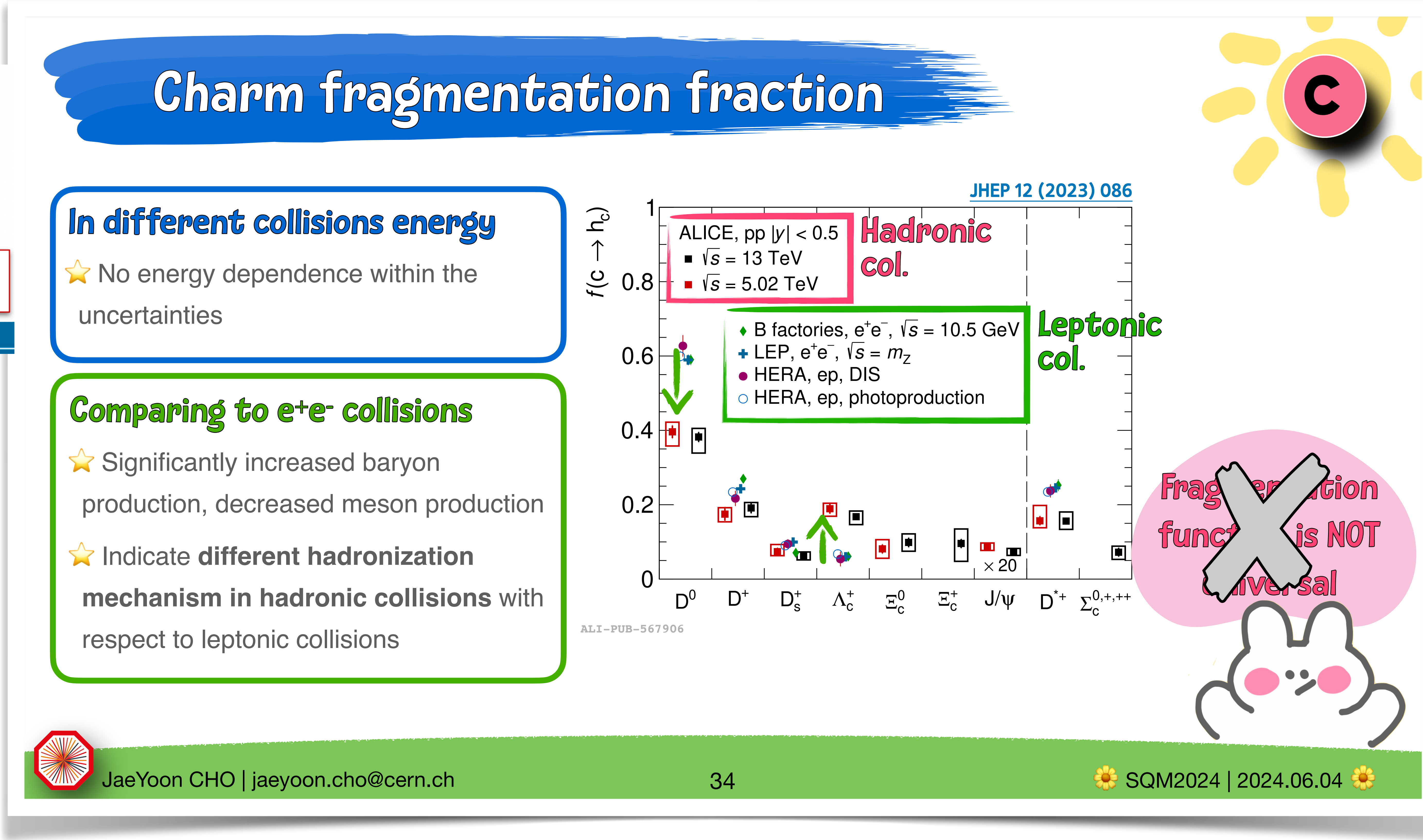


Probability of charm quark to hadronize into a given charm hadron

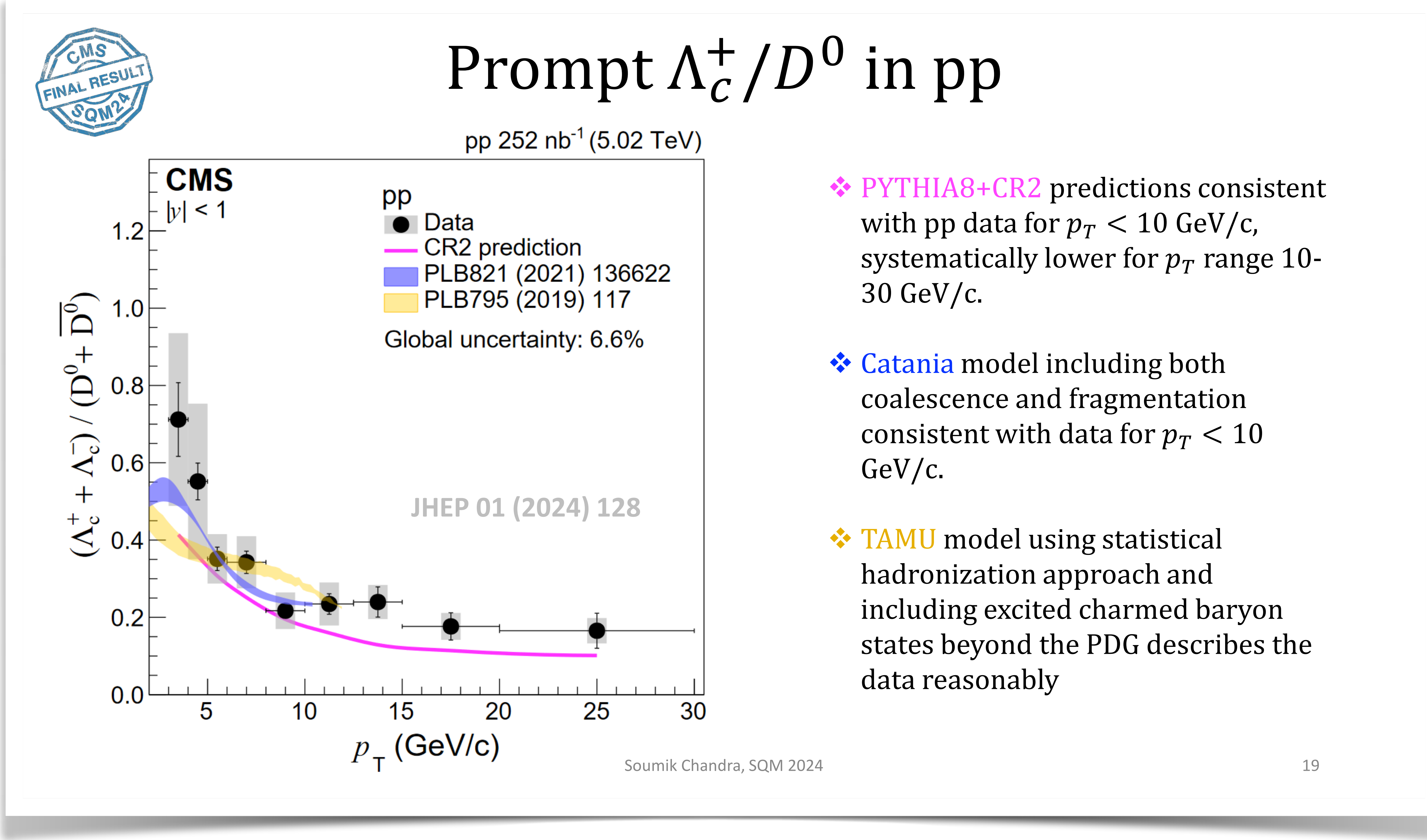
- Charm mesons: reduced in hadronic collisions compared to ee
- Charm baryons: increased in hadronic collisions compared to ee
- But, no to little change for strange D meson
- No energy or hadronic collision system dependence



Charm ~~fragmentation~~ ~~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



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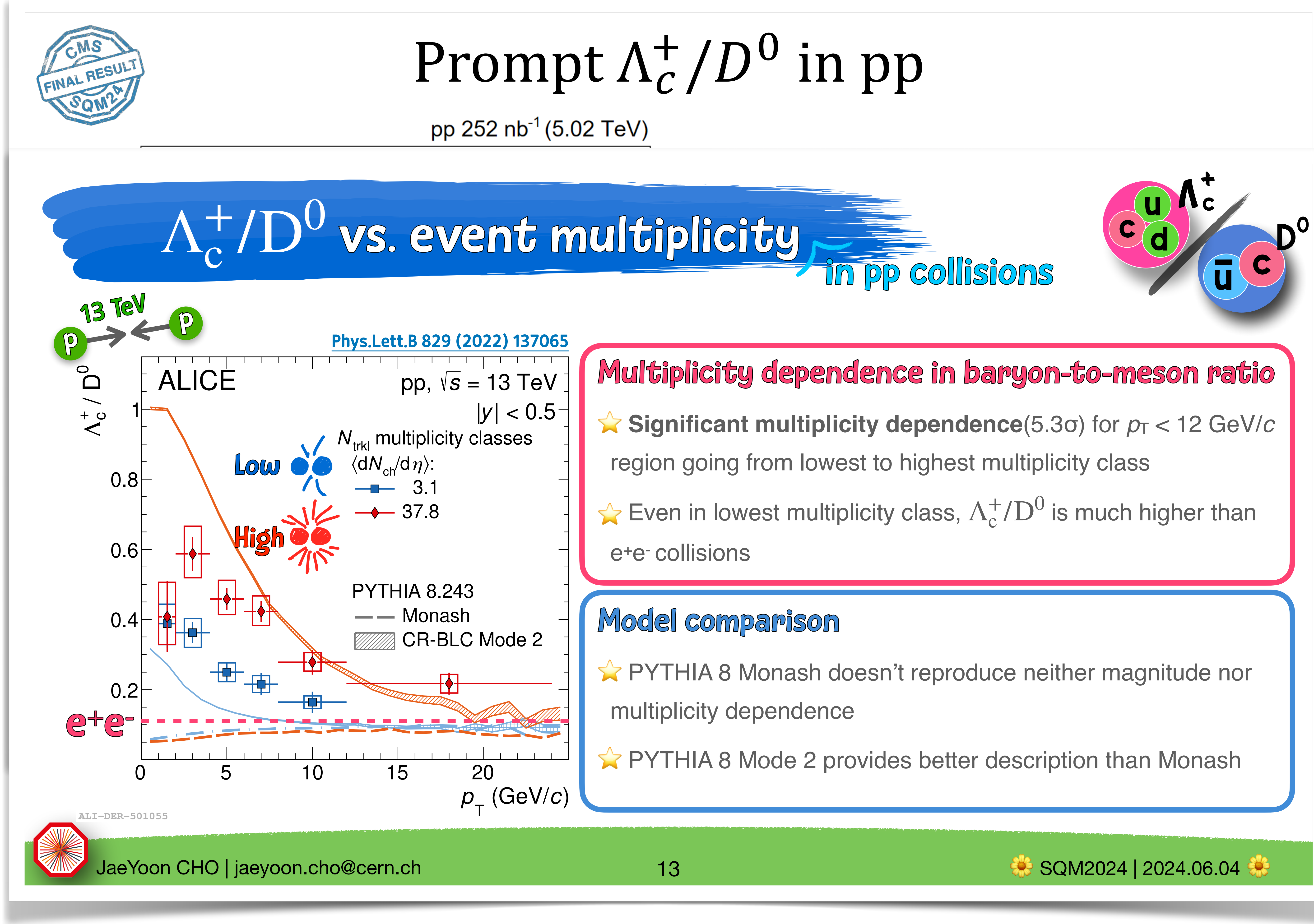

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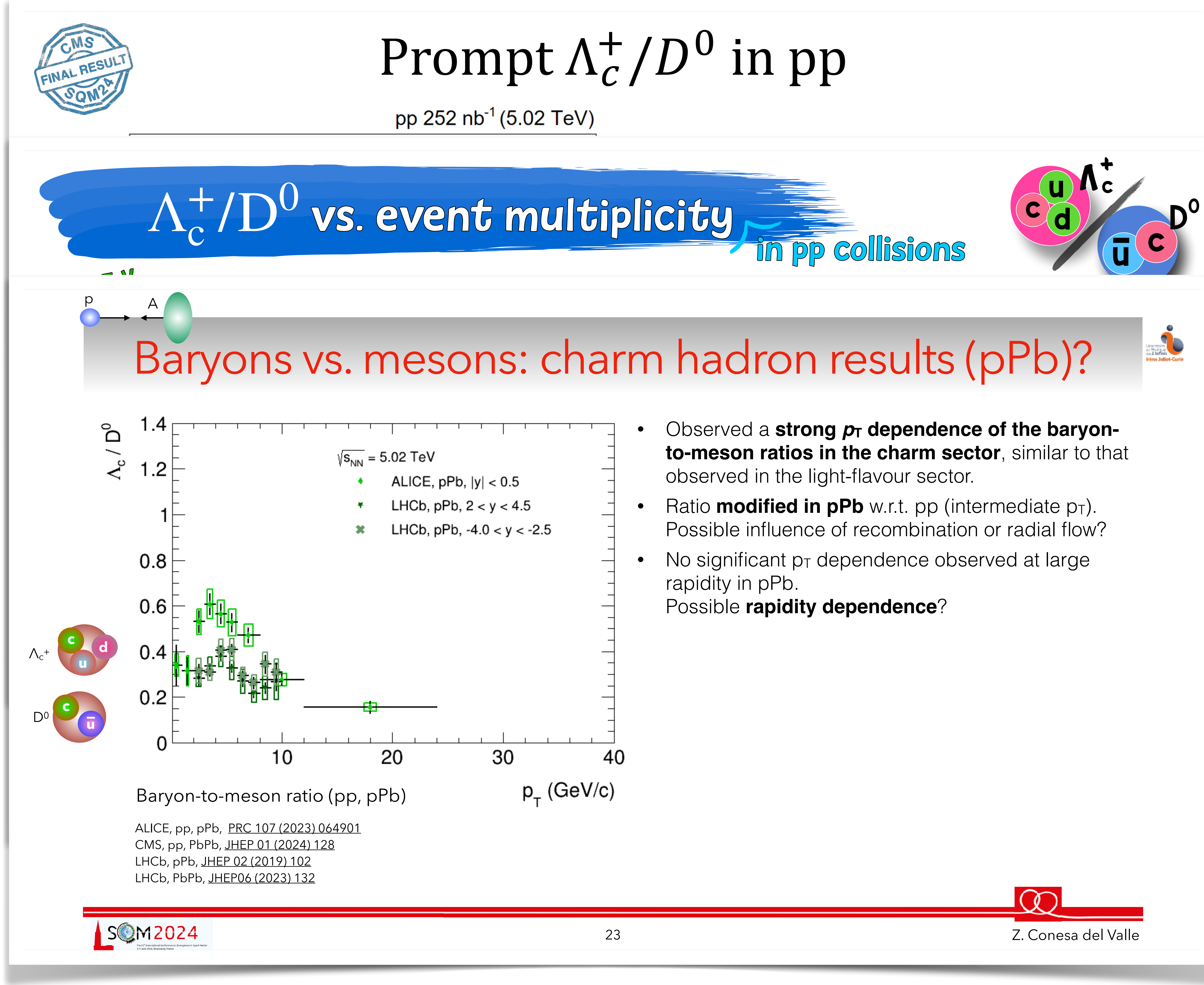
- Rapidity dependence of enhancement in p–Pb?
  - No significant p_T dependence at forward rapidity



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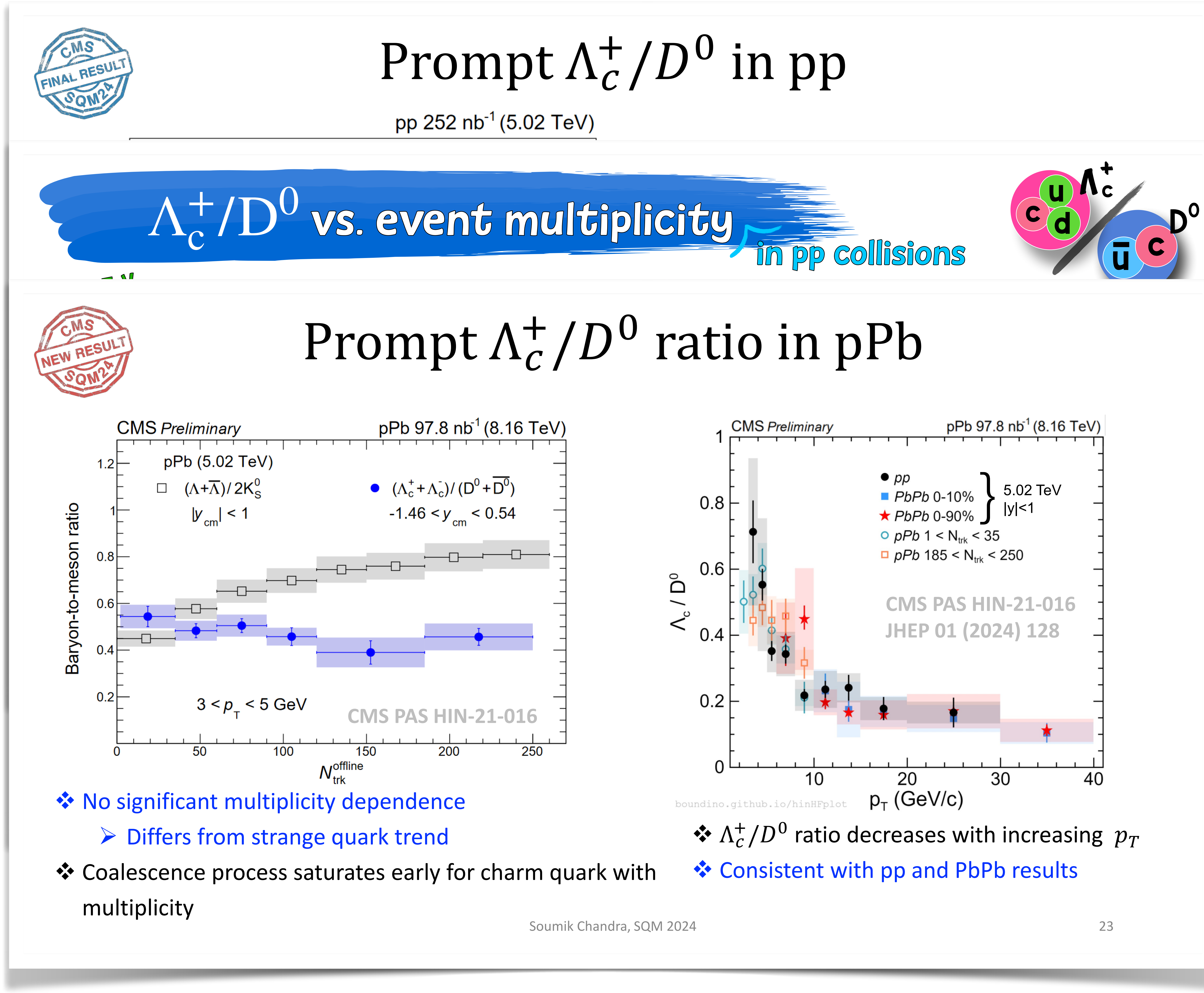
- But no multiplicity dependence seen by CMS in p–Pb
  - Due to restricted p_T range?
  - Earlier coalescence?



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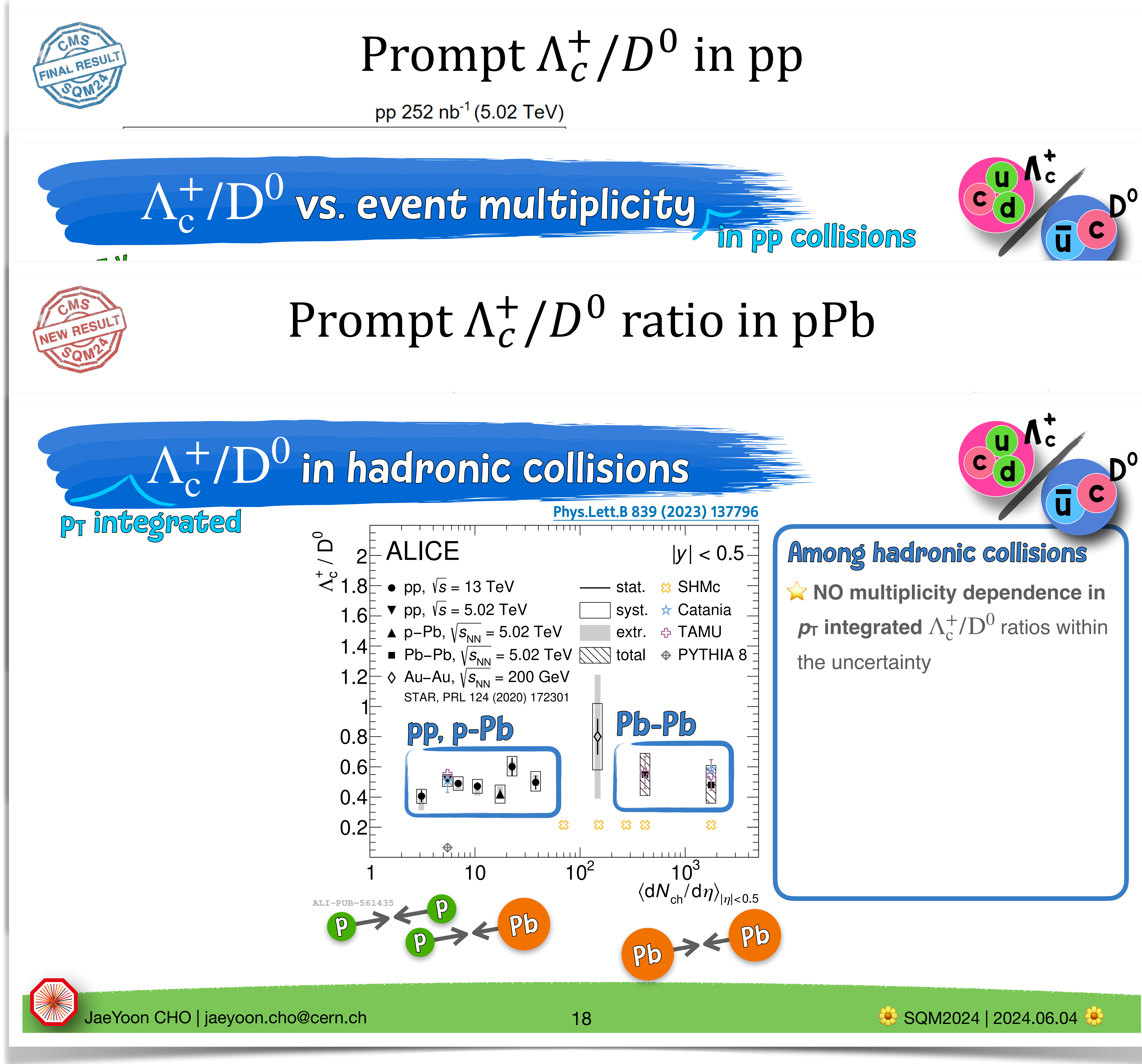
  - Earlier coalescence?
- However, p_T-integrated ratio does not depend on multiplicity or system size in hadronic collisions
  - Different p_T redistribution for baryons and mesons rather than a multiplicity dependence in hadronization process itself?



Beauty ~~fragmentation function fraction~~ hadronization

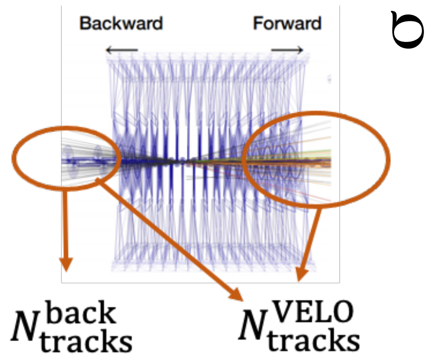
Beauty baryon-to-meson ratio

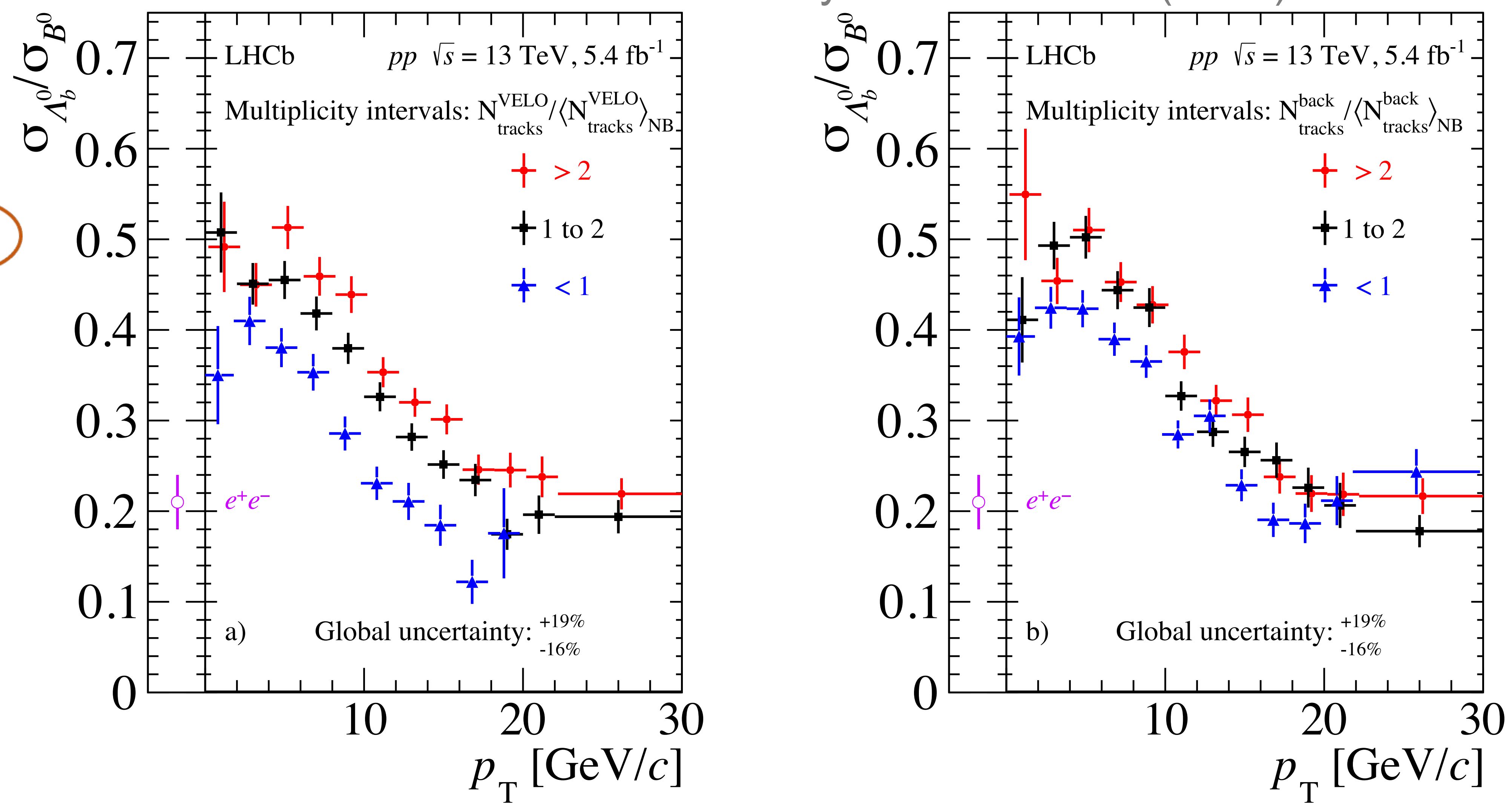
- Beauty baryon enhancement in pp collisions
  - Similar to enhancement in strange and charm sector
  - Statistical hadronisation model (SHM) with relativistic quark model (RQM) gives better description than with PDG data by considering Λ^0_b feed-down from excited baryons
  - EPOS4HQ reproduces the 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

Λ^0_b/B^0 ratio versus p_T in different multiplicity intervals

Phys.Rev.Lett. 132 (2024) 081901





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

7 / 17

Charm with strangeness hadronization

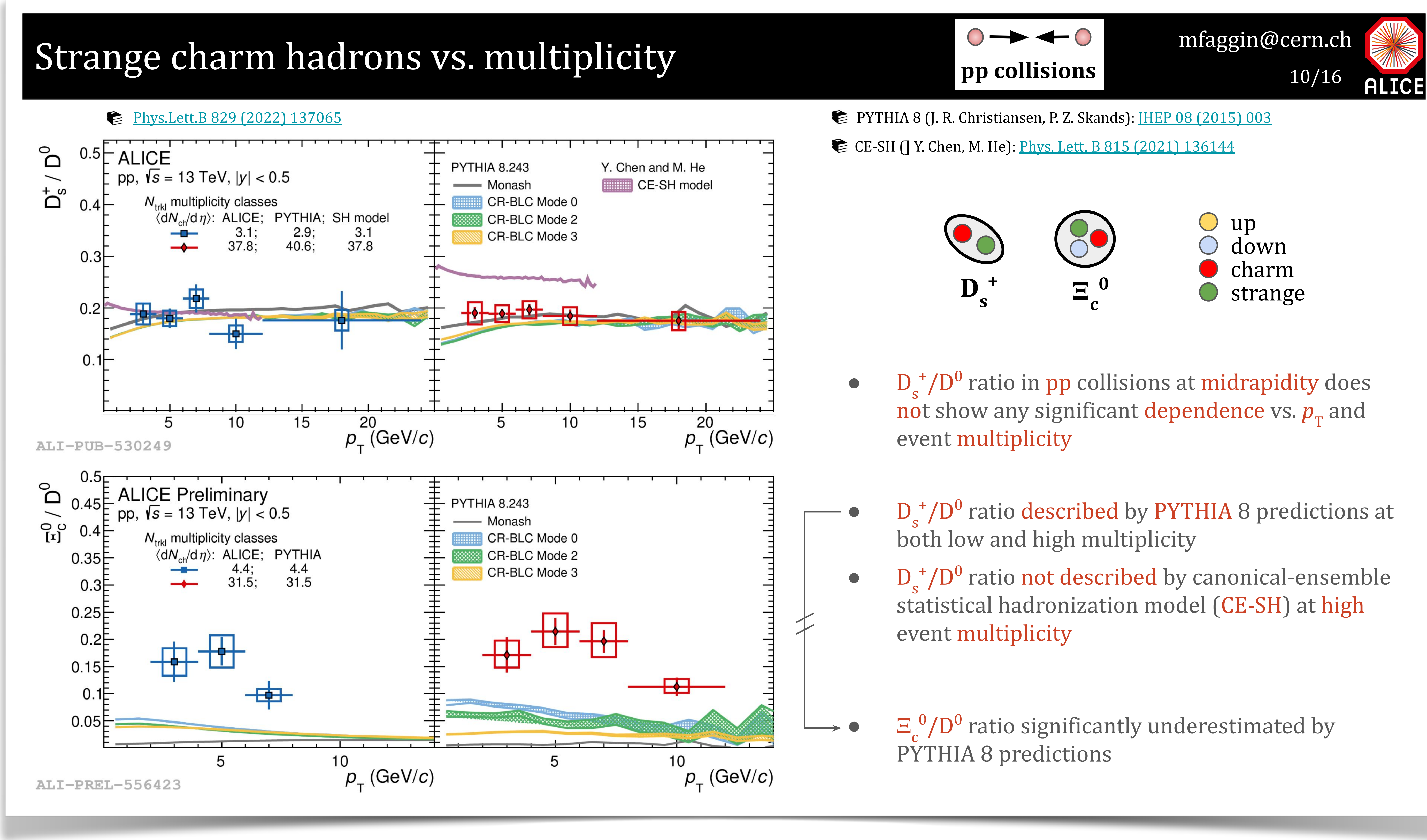
Fragmentation fraction of charm to strange D meson is unmodified from ee to hadronic collisions

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 pT dependence
- Shows some multiplicity dependence
- Not described by PYTHIA8



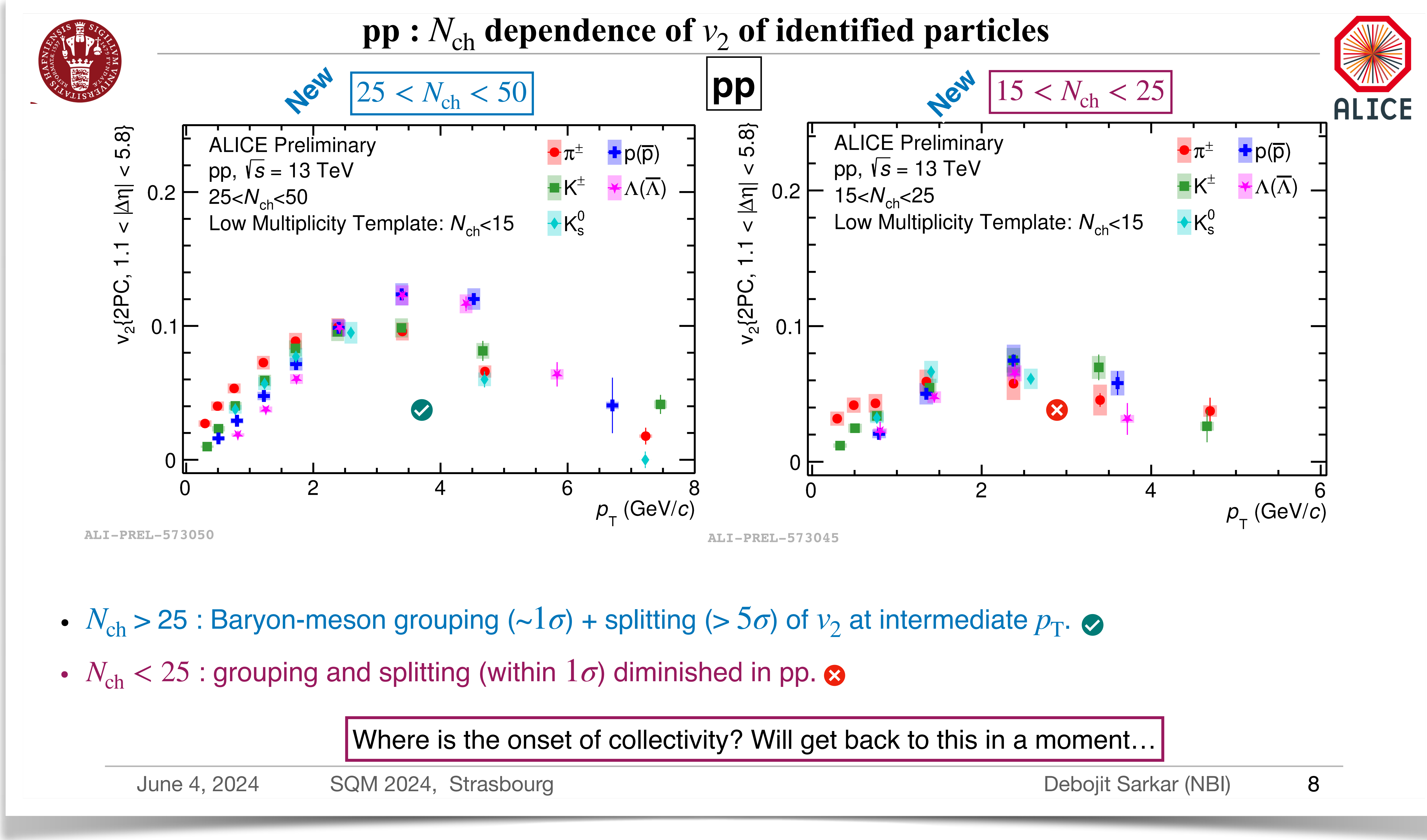
This is turning into SQM, small Quark Matter

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} ~ 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!



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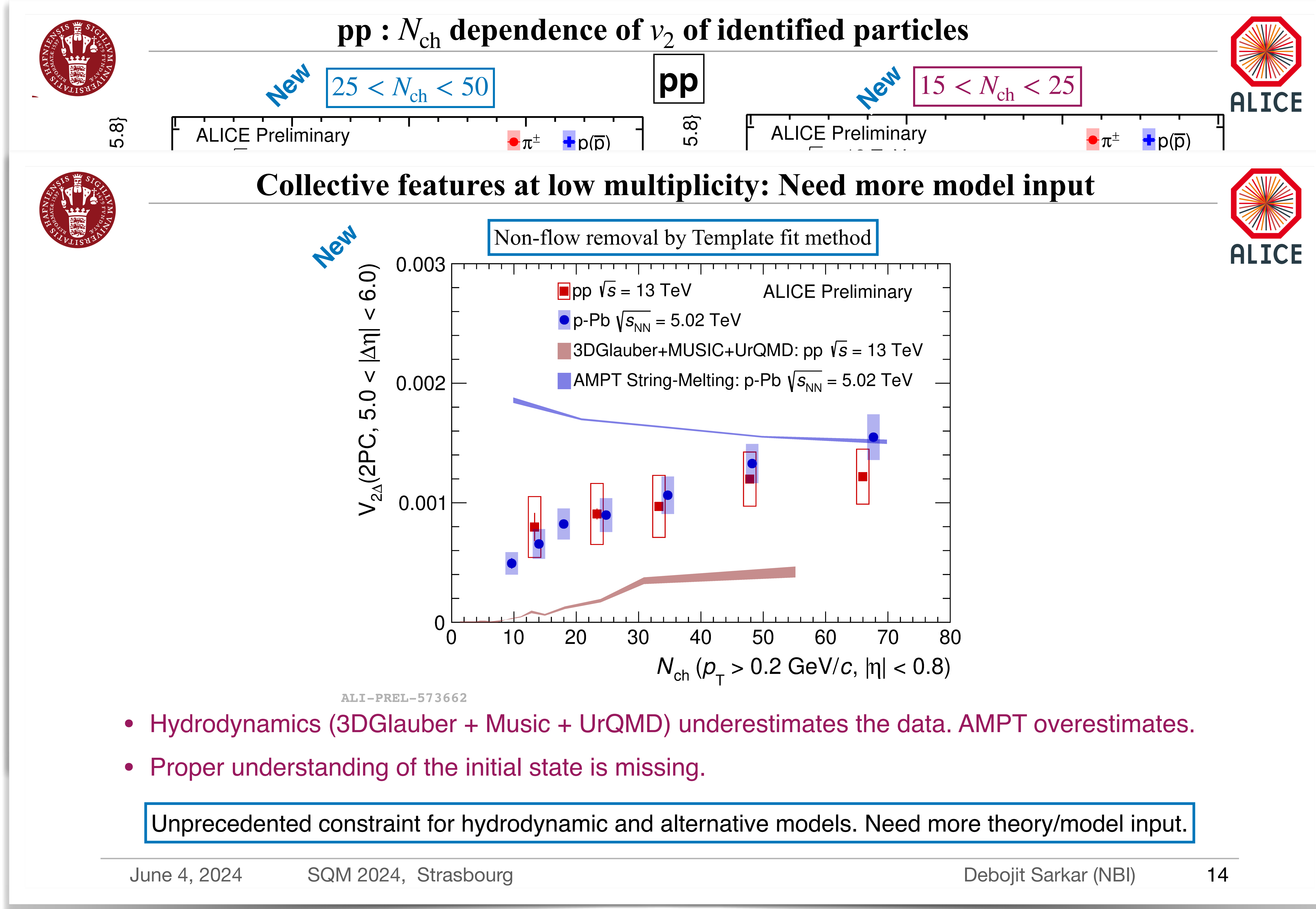
Ultra-long delta eta particle correlation

- 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



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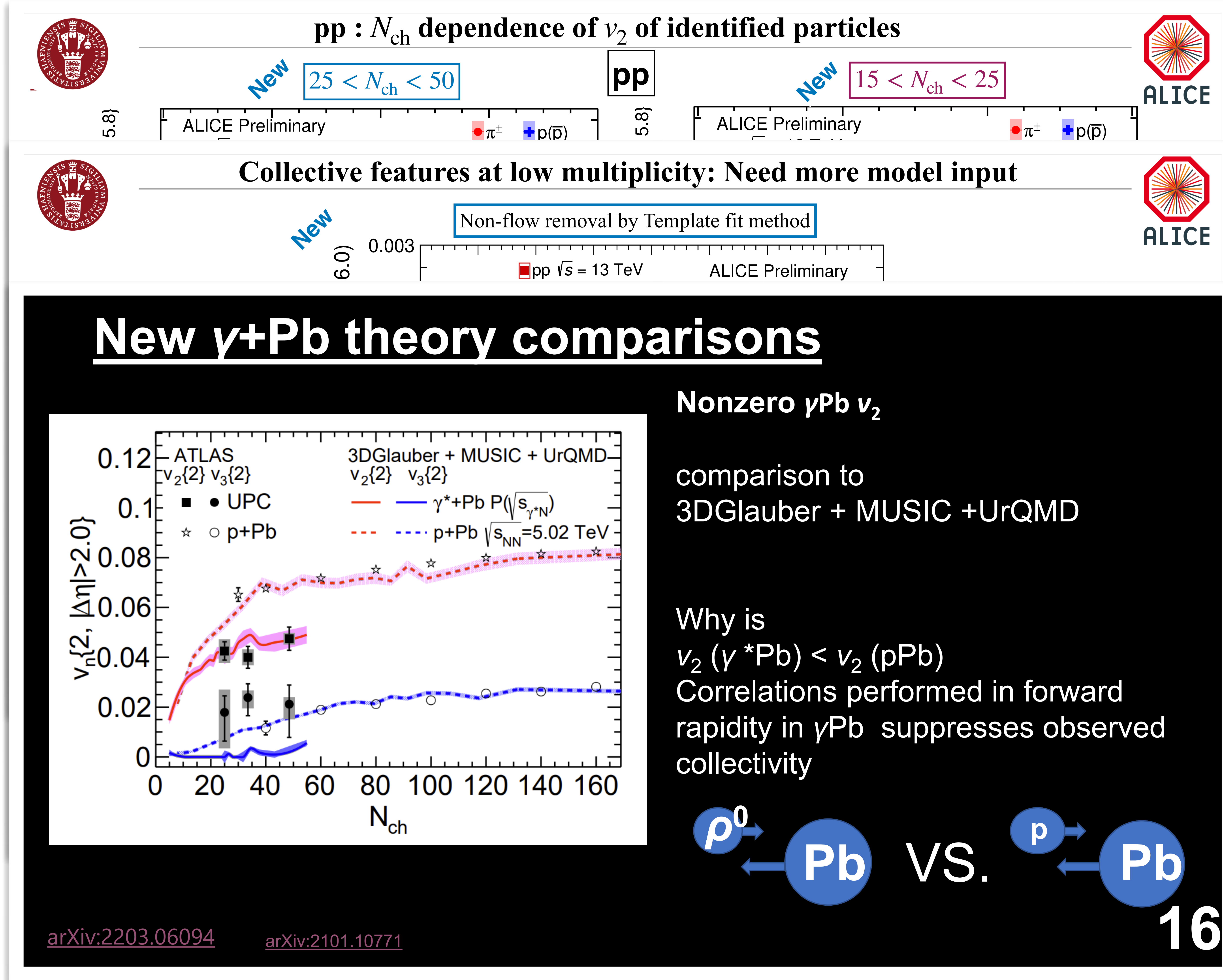
Collectivity in gamma–p collisions

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



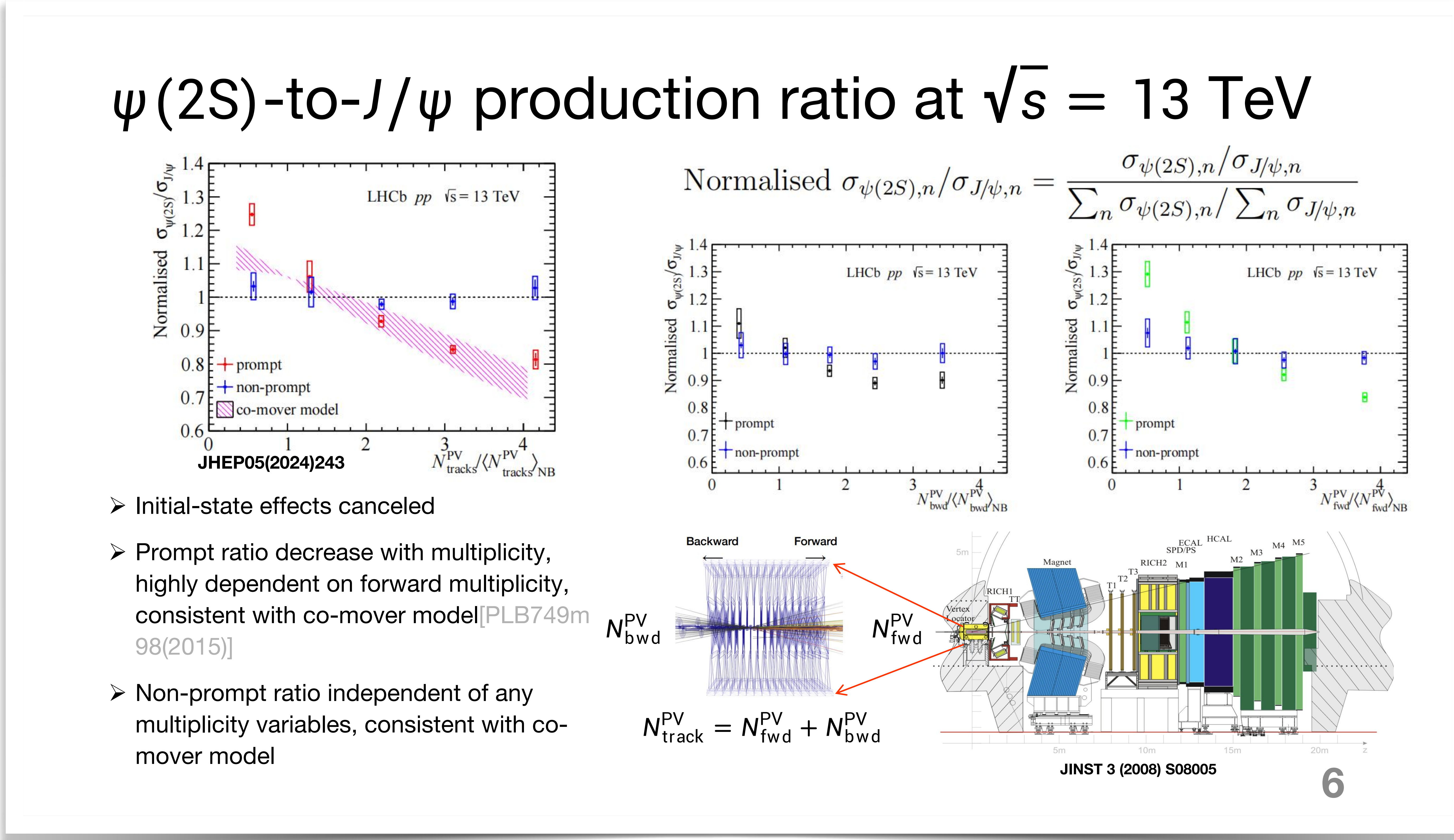
There is also SQM, suppression in Quark Matter

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_T
  - Little rapidity dependence (forward)
  - Comover model reproduces the measurements



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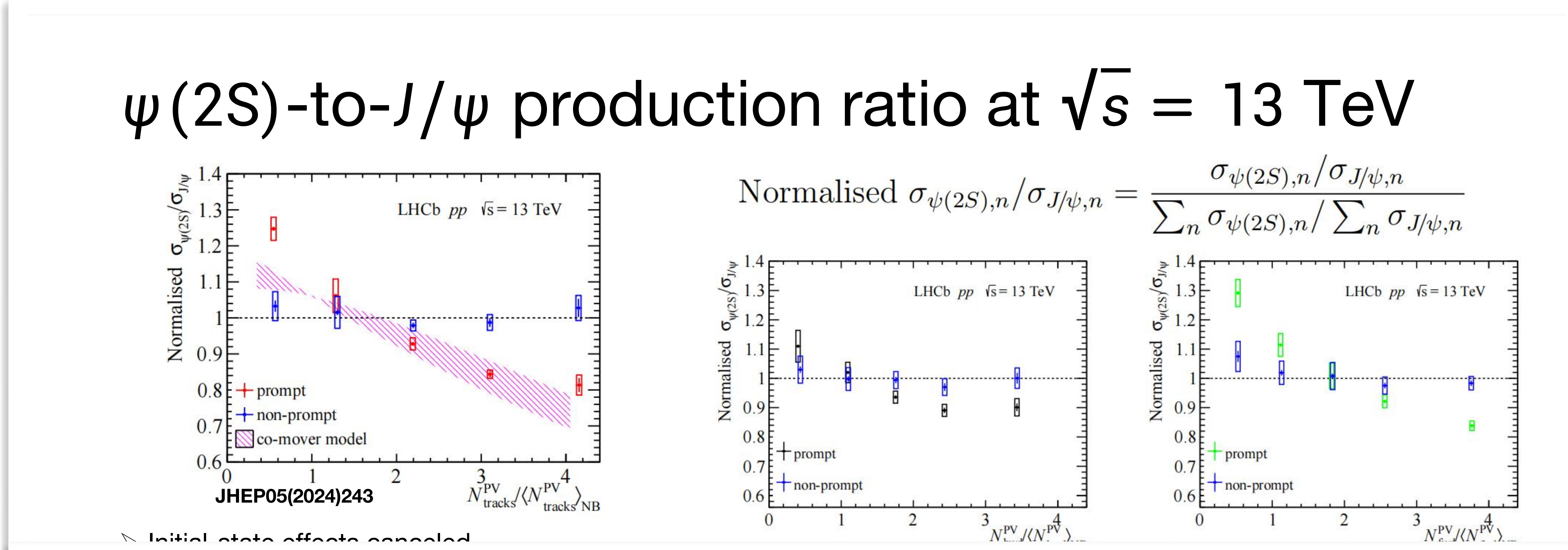
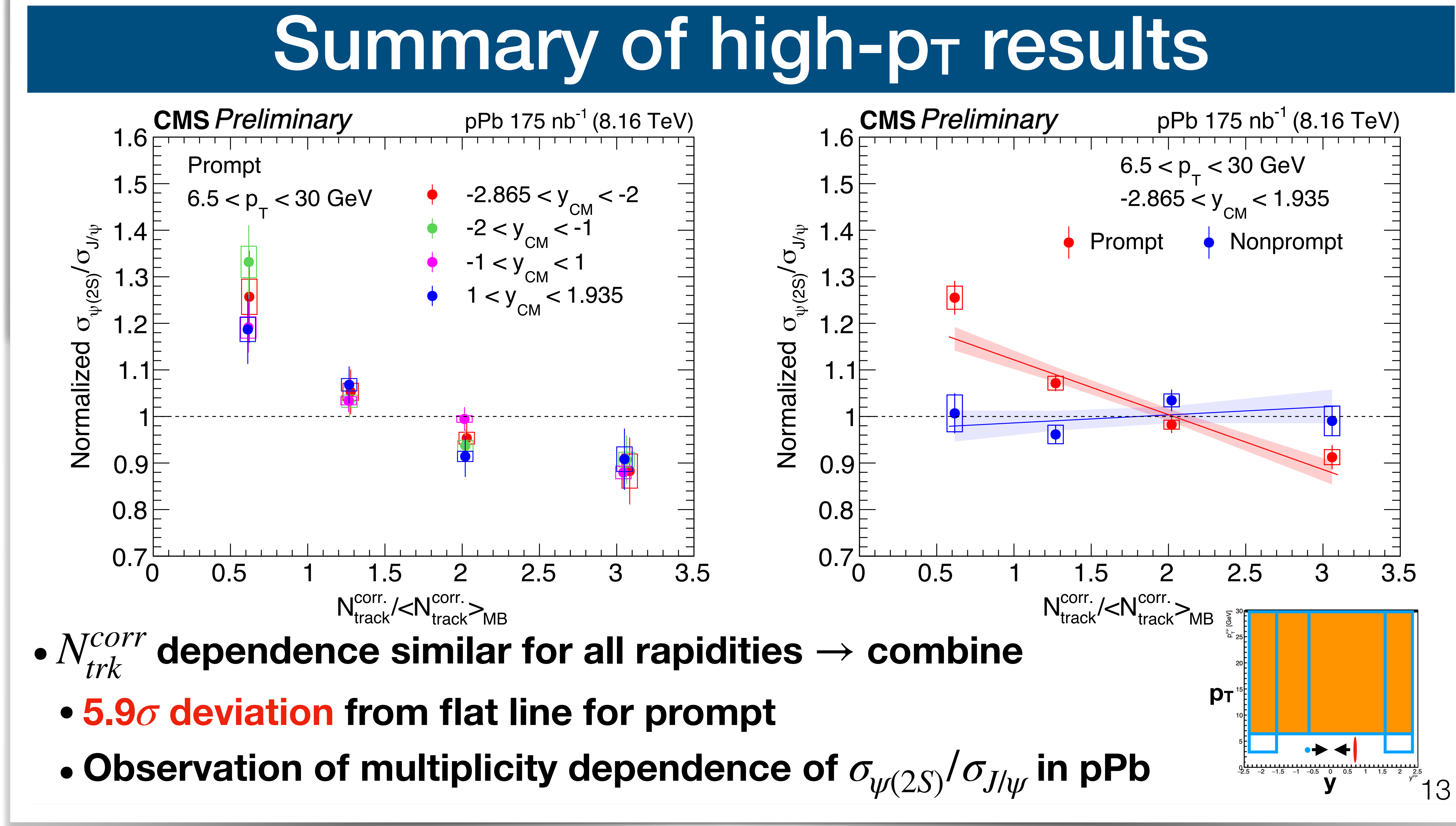




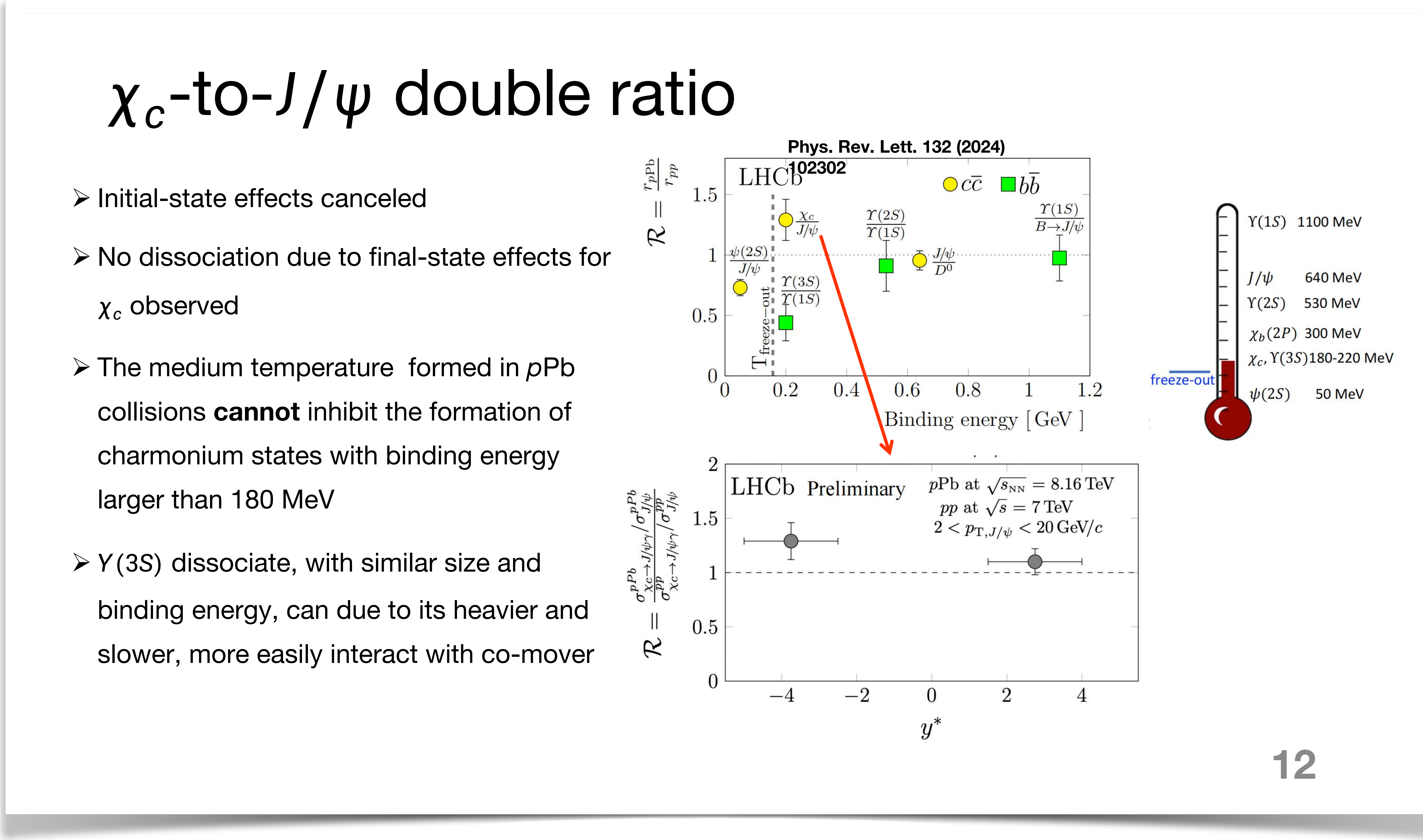
First measurement of Chic at LHC energies

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



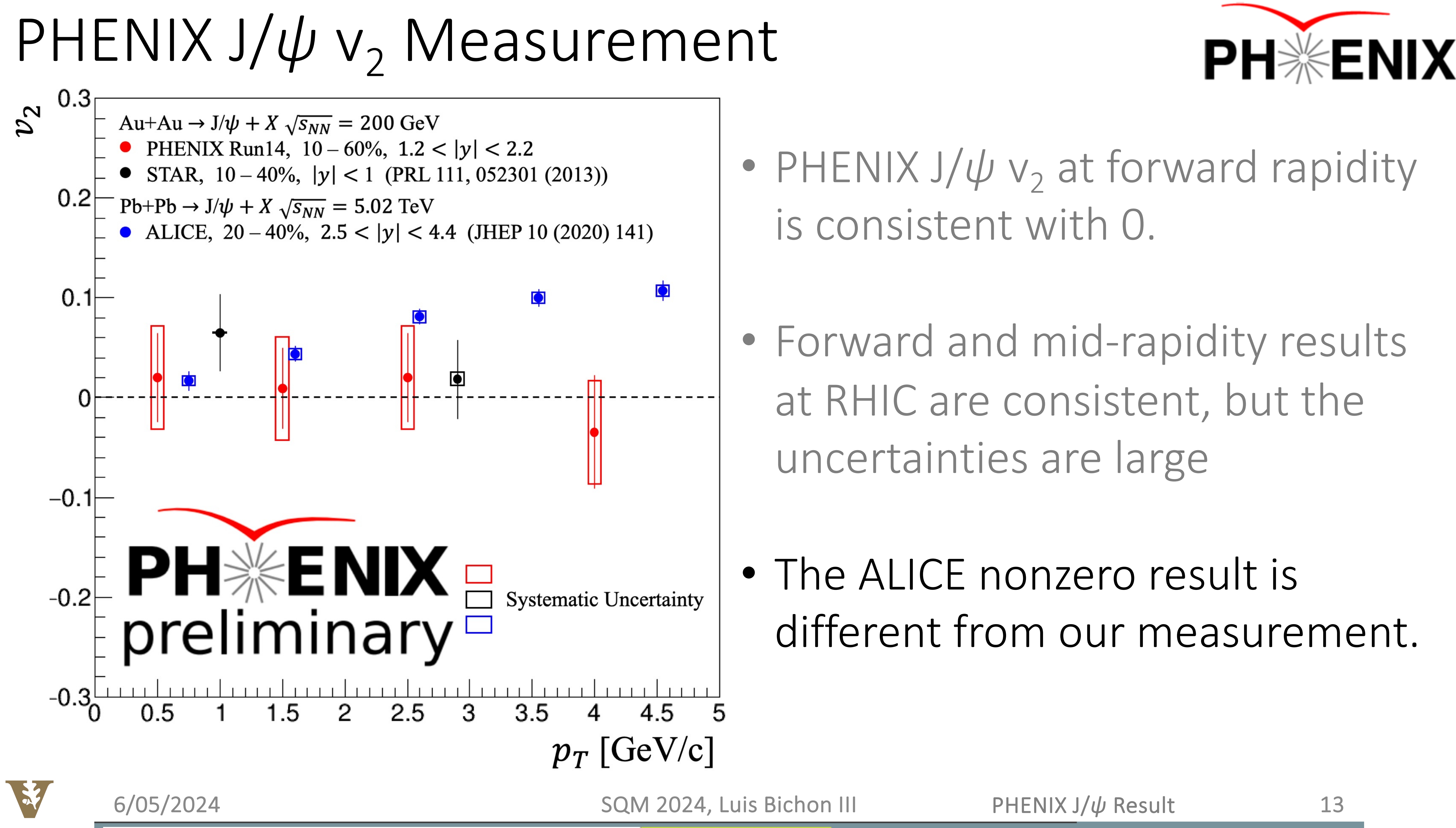
Quarkonium regeneration

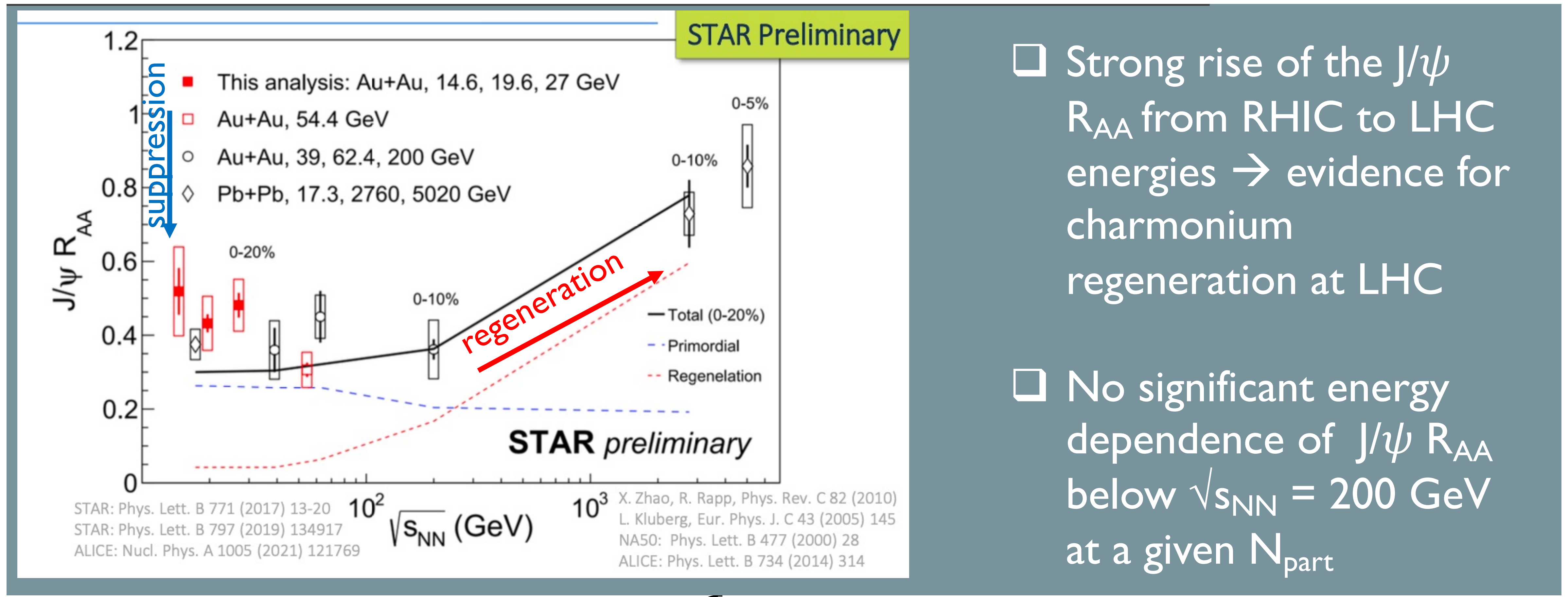
J/psi v_2 at RHIC

- Compatible with zero
- Lower than non-zero J/psi v_2 at LHC
- Consistent with increase of regeneration contribution from RHIC to LHC energies

J/psi R_{AA} 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





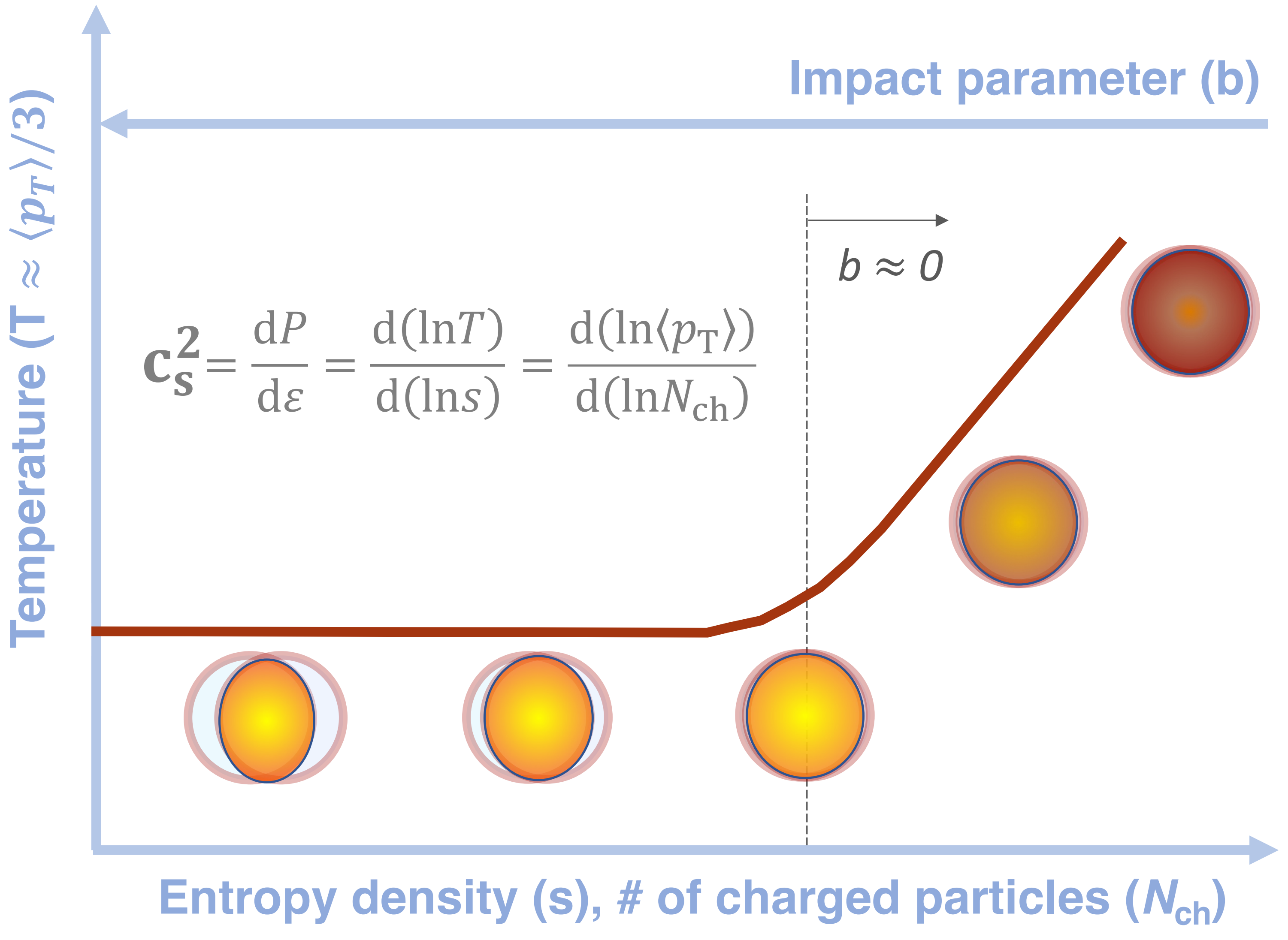
This sounds like SQM, speed of sound in Quark Matter

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

Speed of sound in the QGP

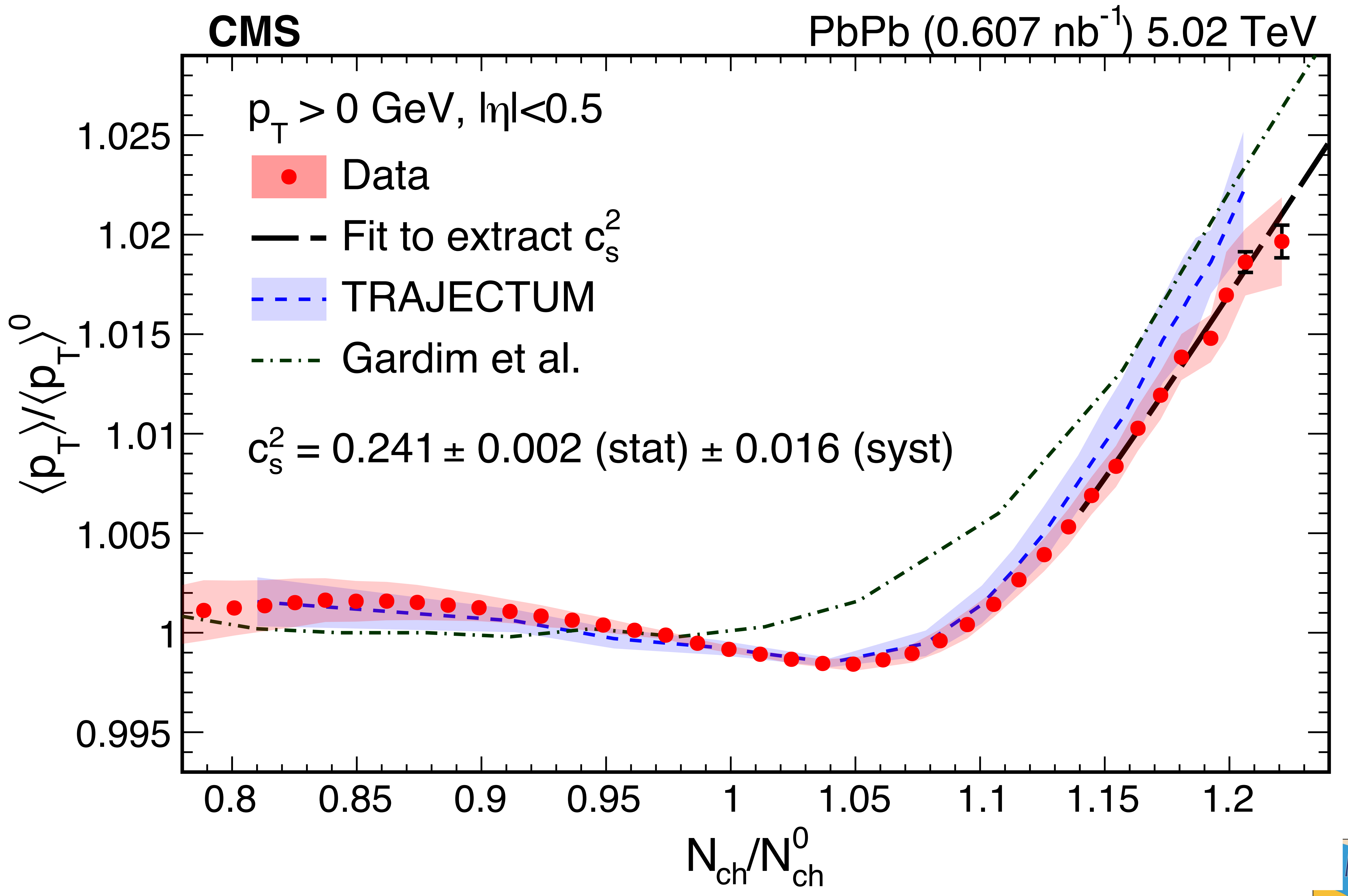
Measure speed of sound from ⟨p_T⟩ and N_{ch}

- 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



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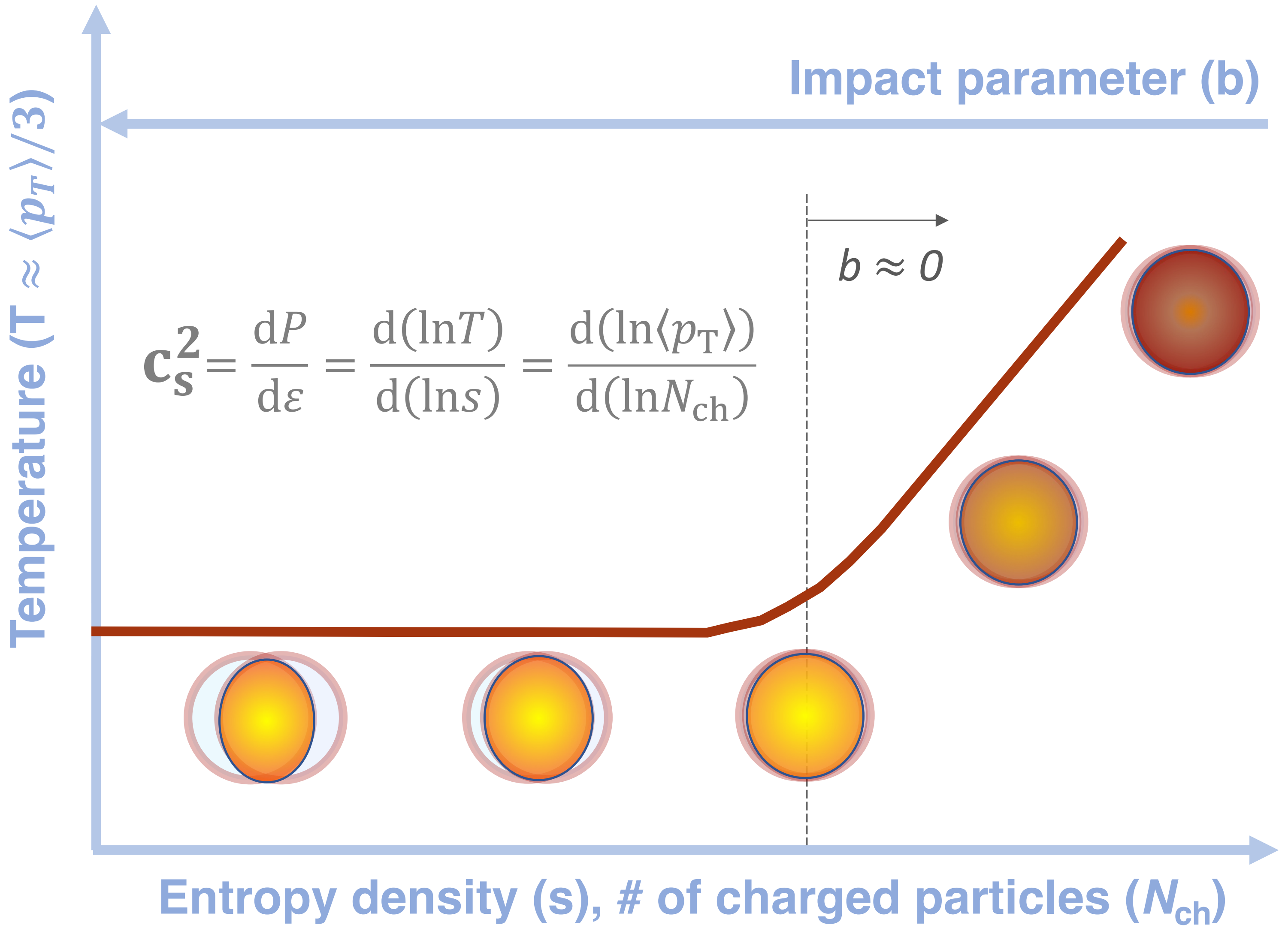

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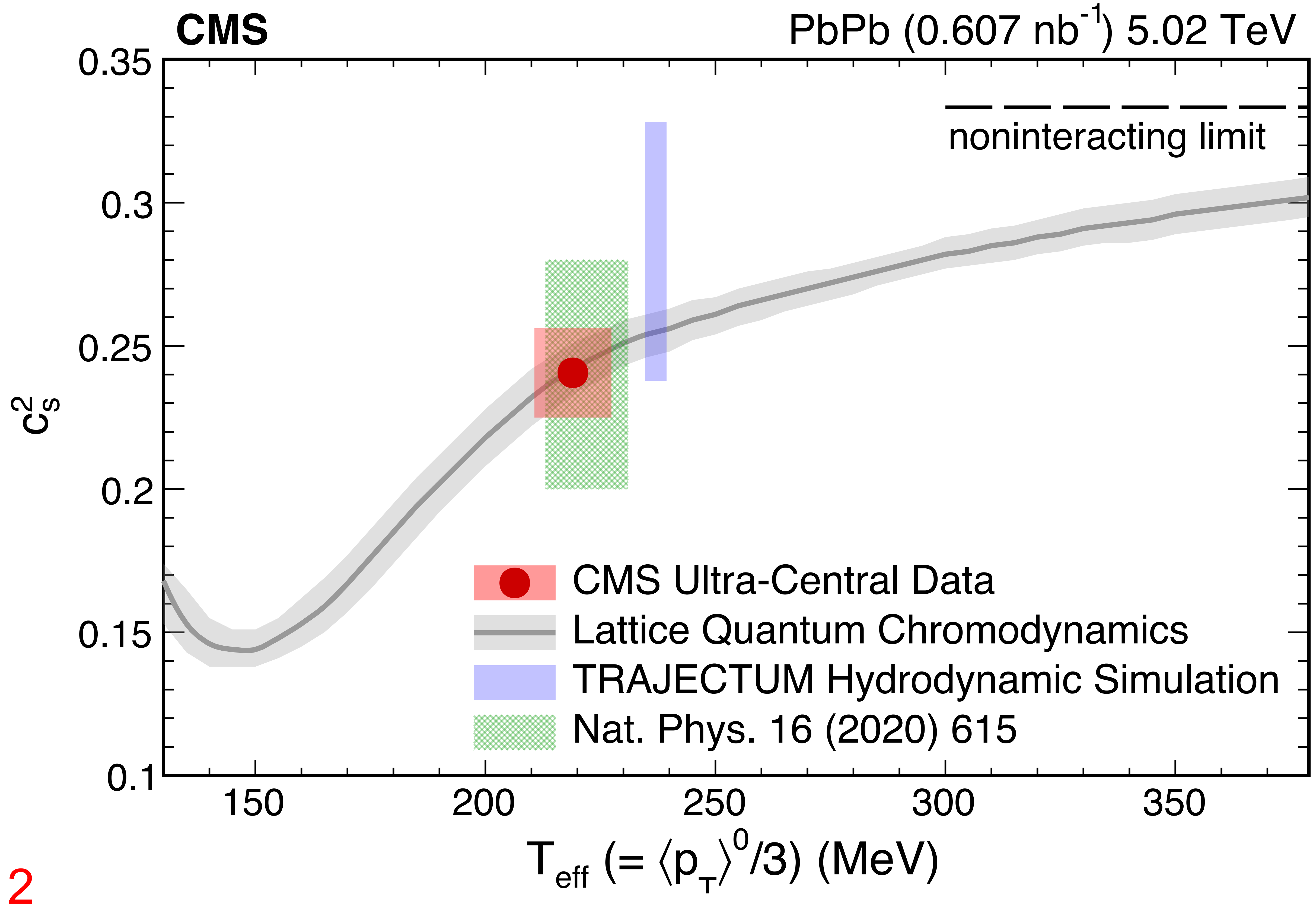
- CMS measurement compatible with LQCD calculations

Correlate average p_T with multiplicity

Starting to map c_s^2 versus temperature



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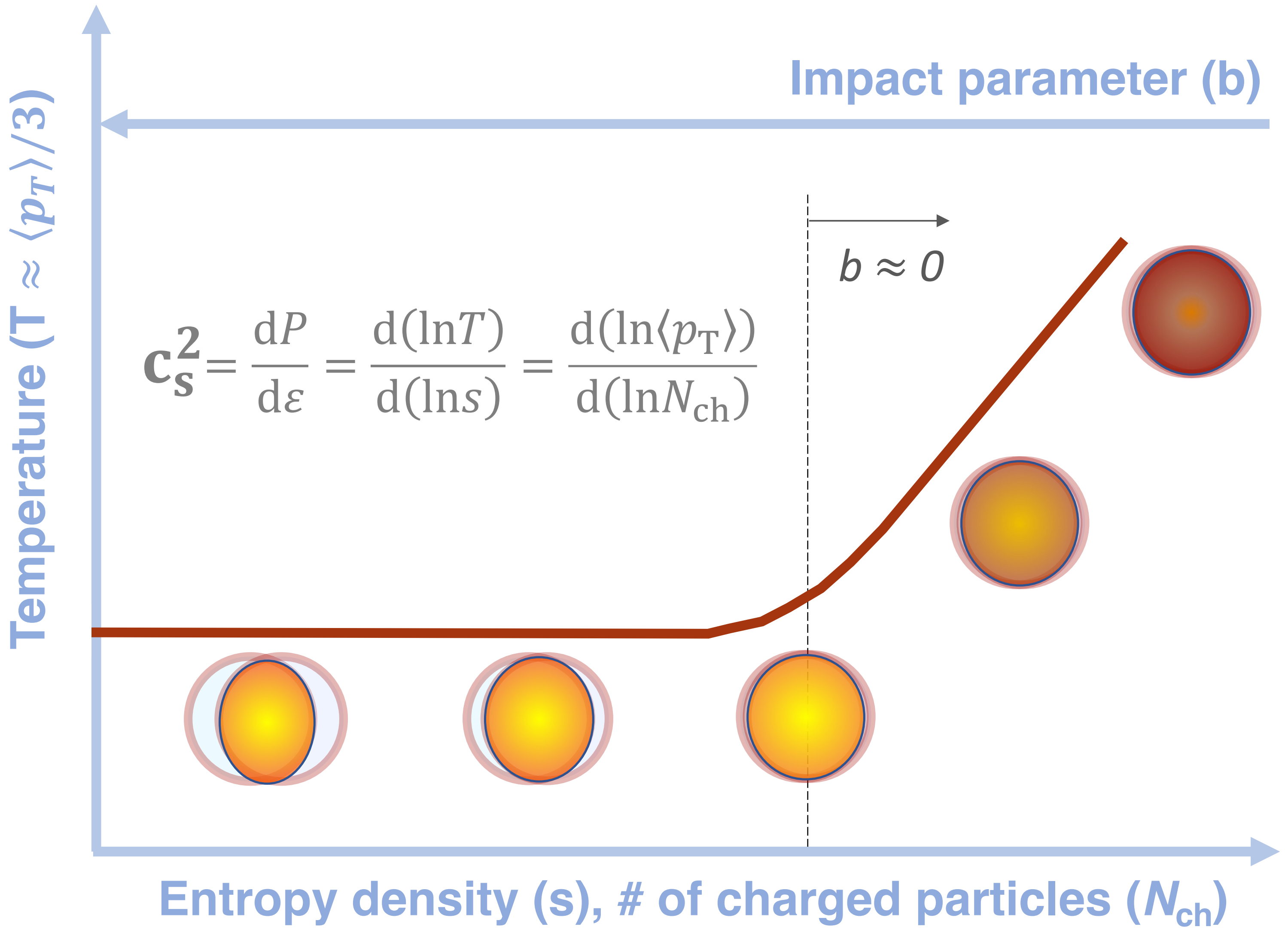
- Ultra-central collisions



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

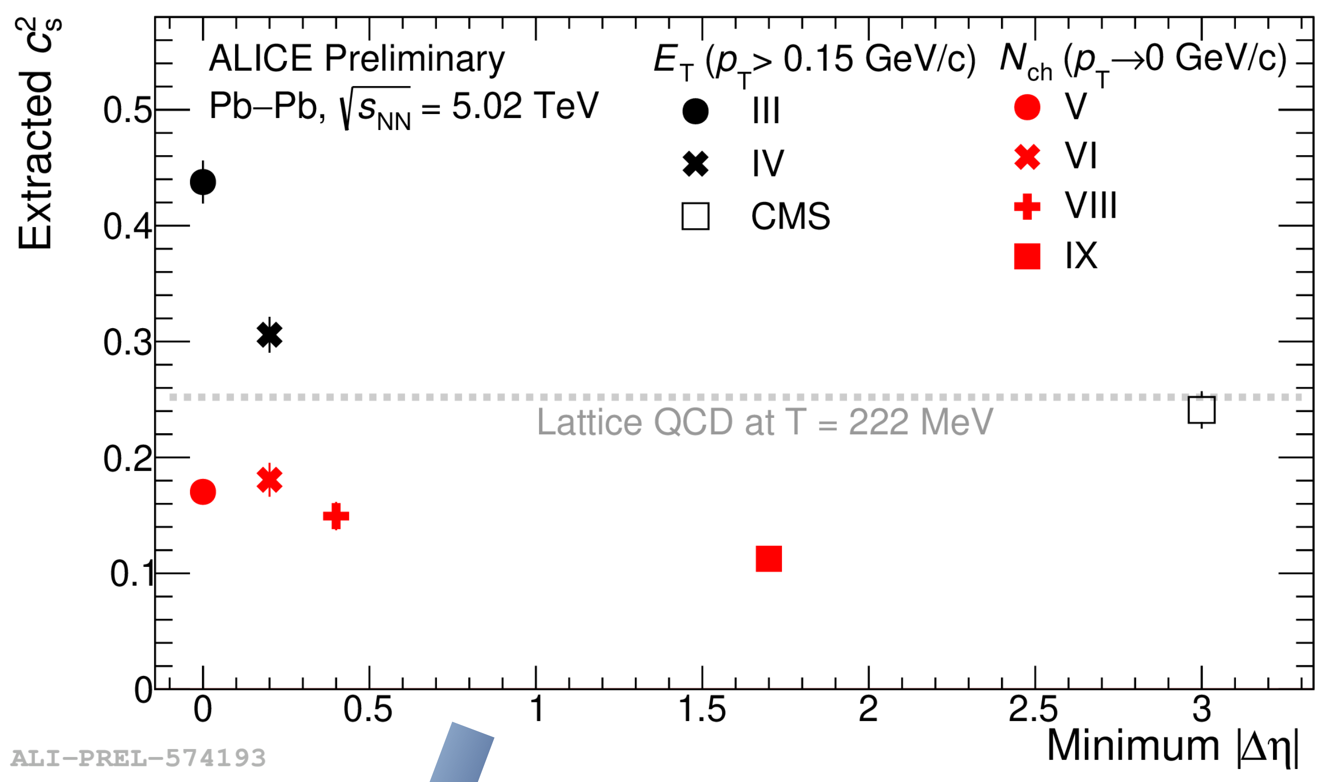
CMS PbPb (0.607 nb^{-1}) 5.02 TeV

0.35

ALICE

Speed of sound as function of η-gap

NEW



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

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

Emil Gorm Nielsen [NBI] | SQM2024 9

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

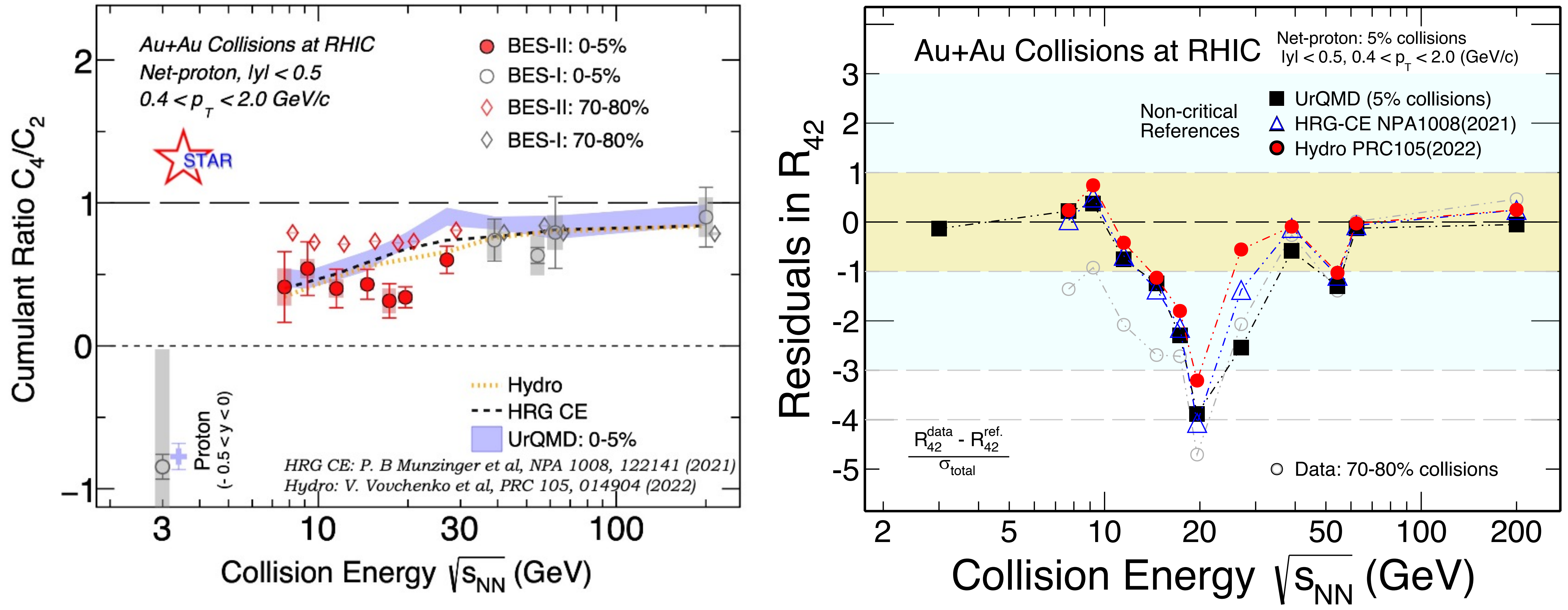
So let's continue with the search for the critical point

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: 3.2–4.7σ at 20 GeV
  - Overall deviation from 7.7–27 GeV: 1.9–5.4σ
- 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, Thurday

Search for critical end point

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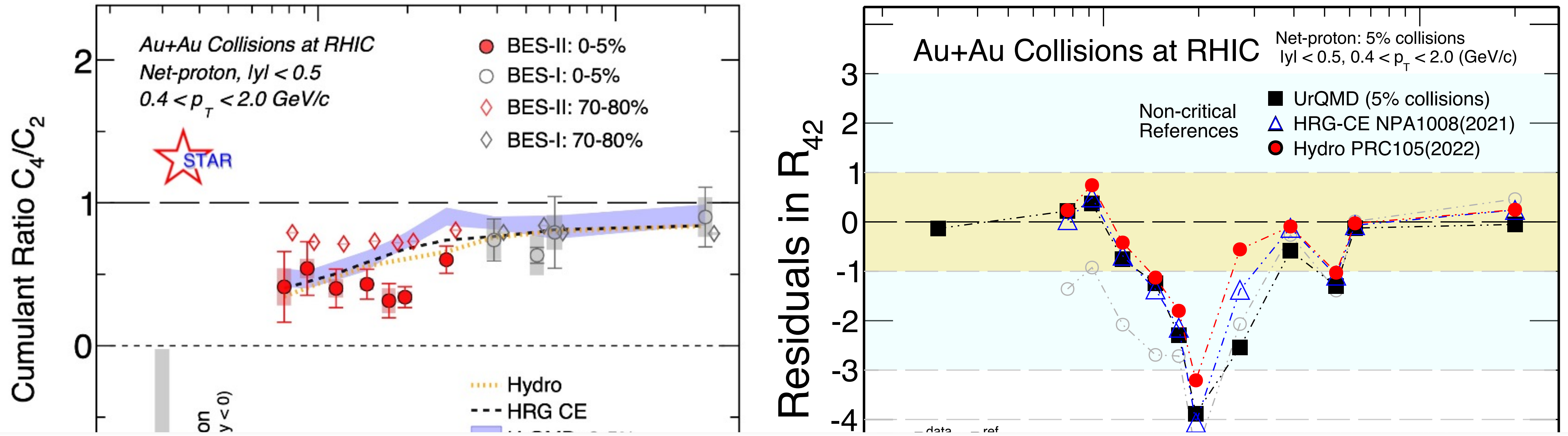
Baryon–Strangeness correlation

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

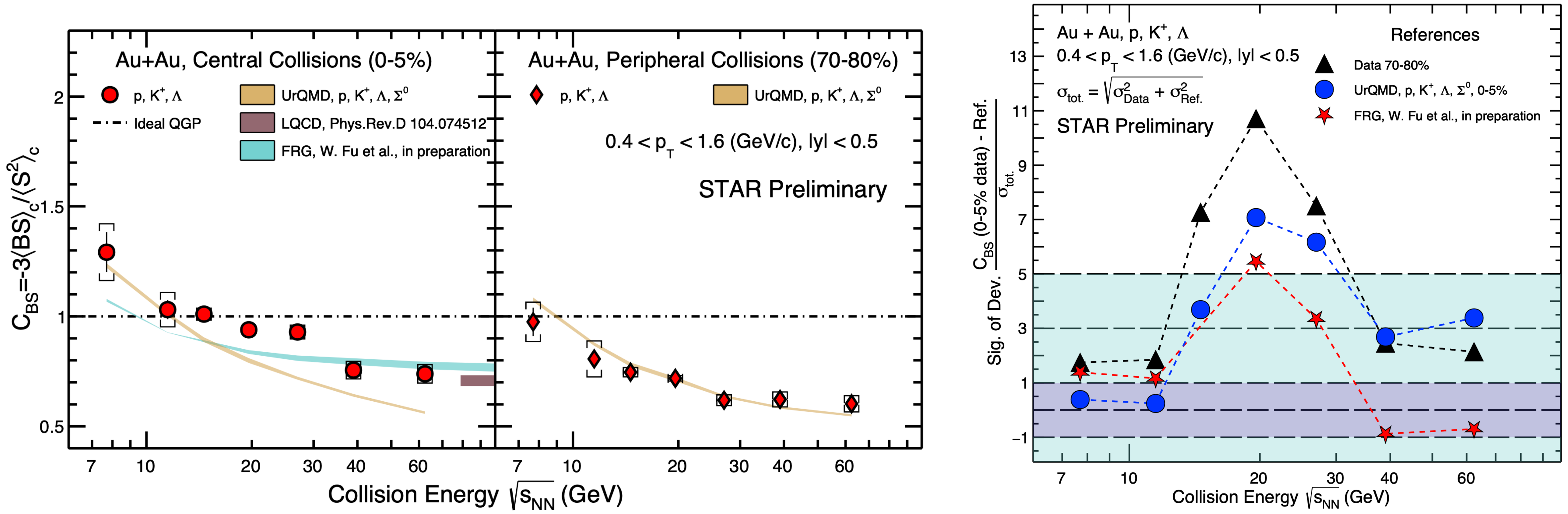
But several caveats and homework discussed yesterday …

Precision Measurement of Net-proton Cumulant on BES-II



Energy Dependence of C_{BS} from STAR

Hanwen Feng, CPOD 2024



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

Yu Zhang, SQM 2024, Strasbourg, France **14**

This could also be SQM, space Quark Matter

So let's finish with heavy ion physics for astrophysics

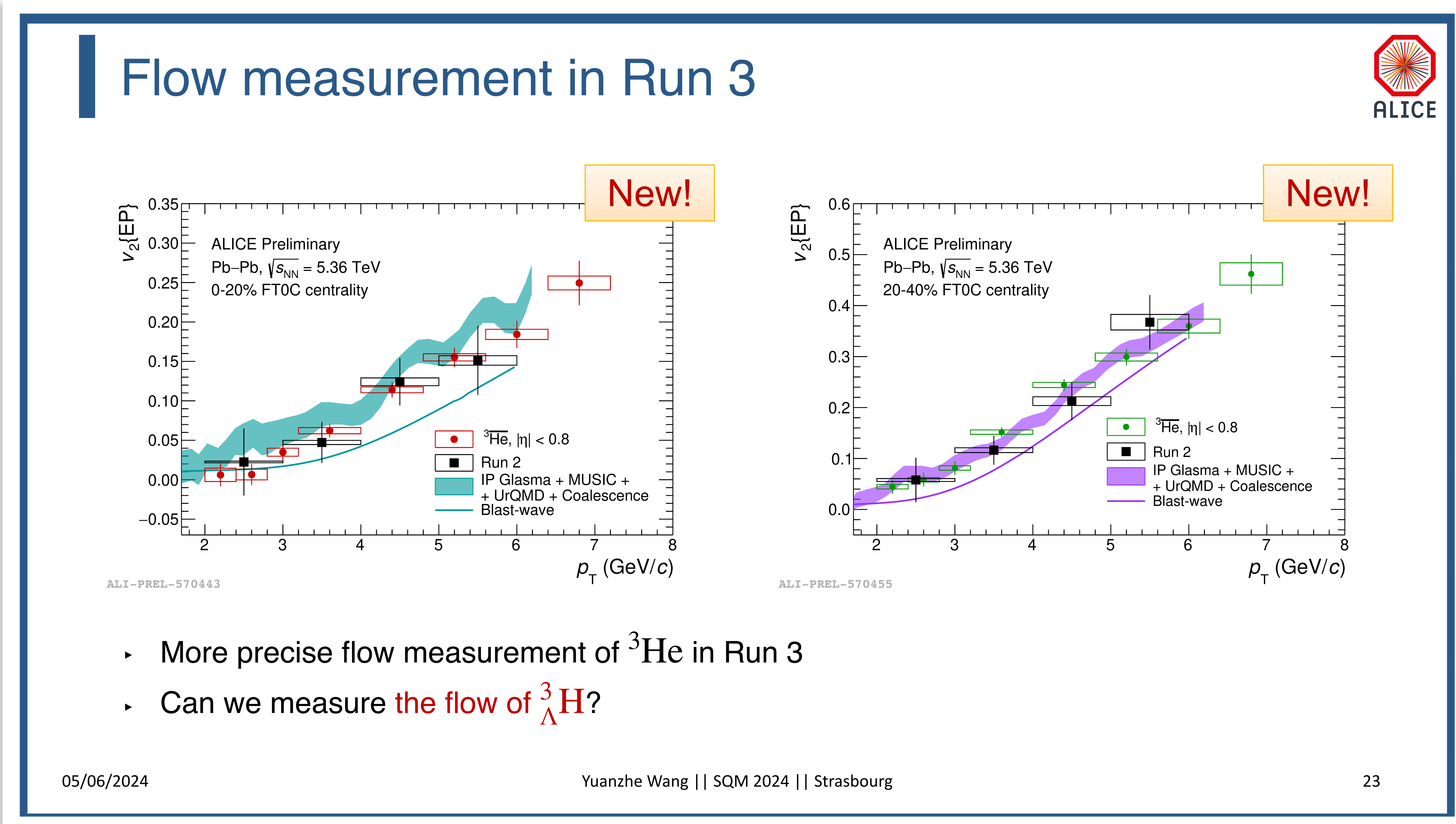
From heavy ions to astrophysics

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



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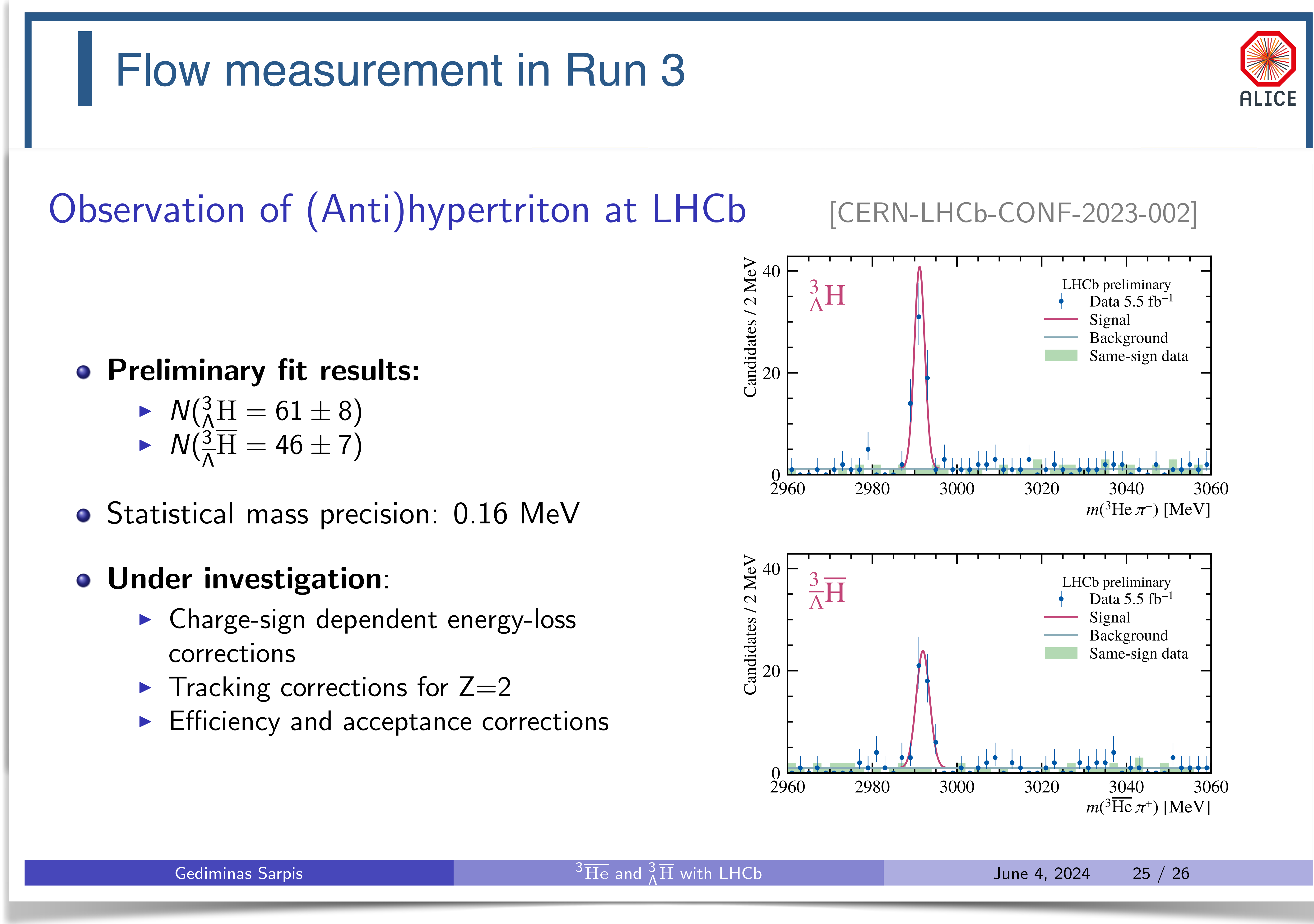

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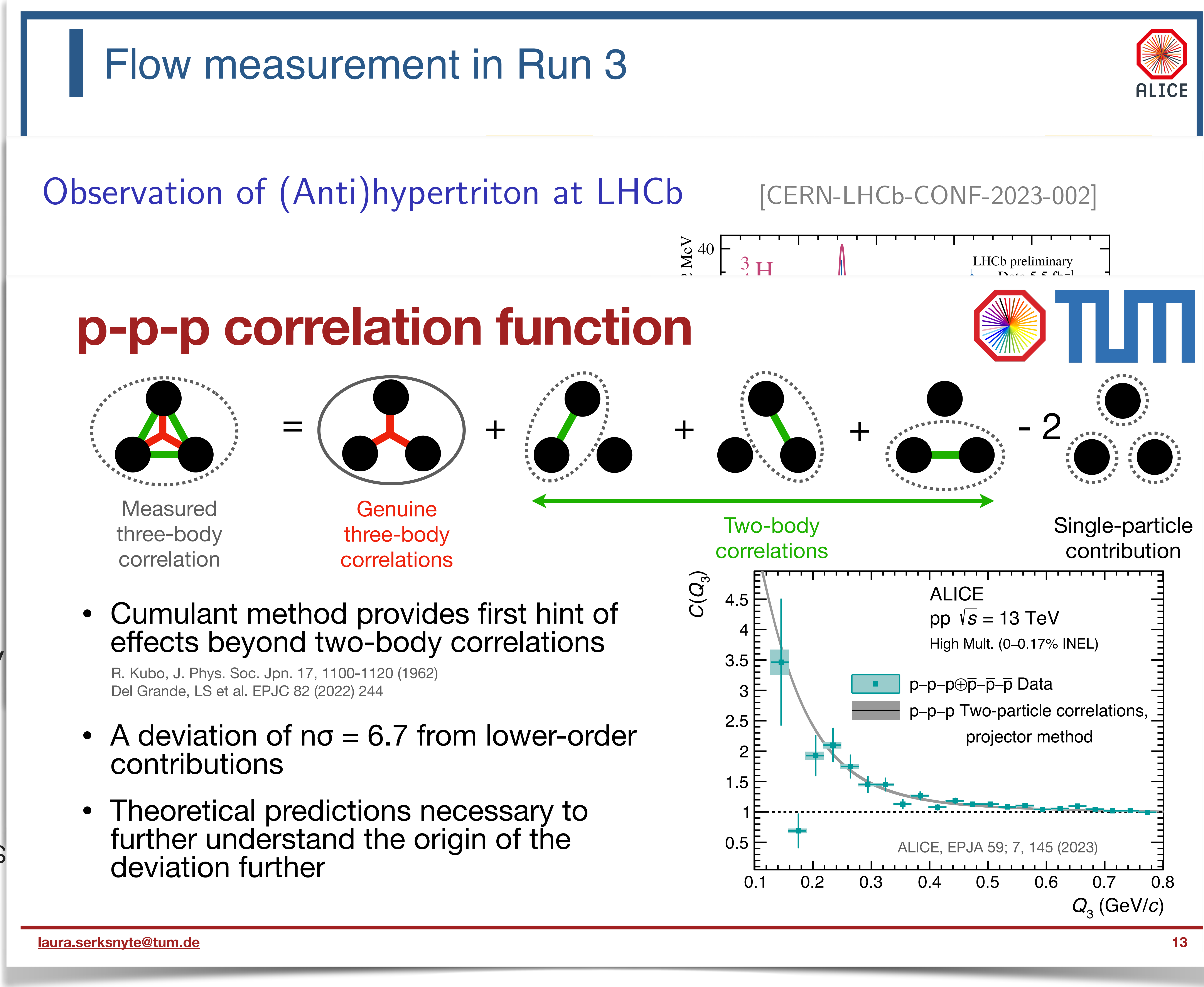
- A glimpse of future results
  - High precision with ALICE
  - LHC as a new player

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



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

So let’s see what comes next

A bright future at FAIR

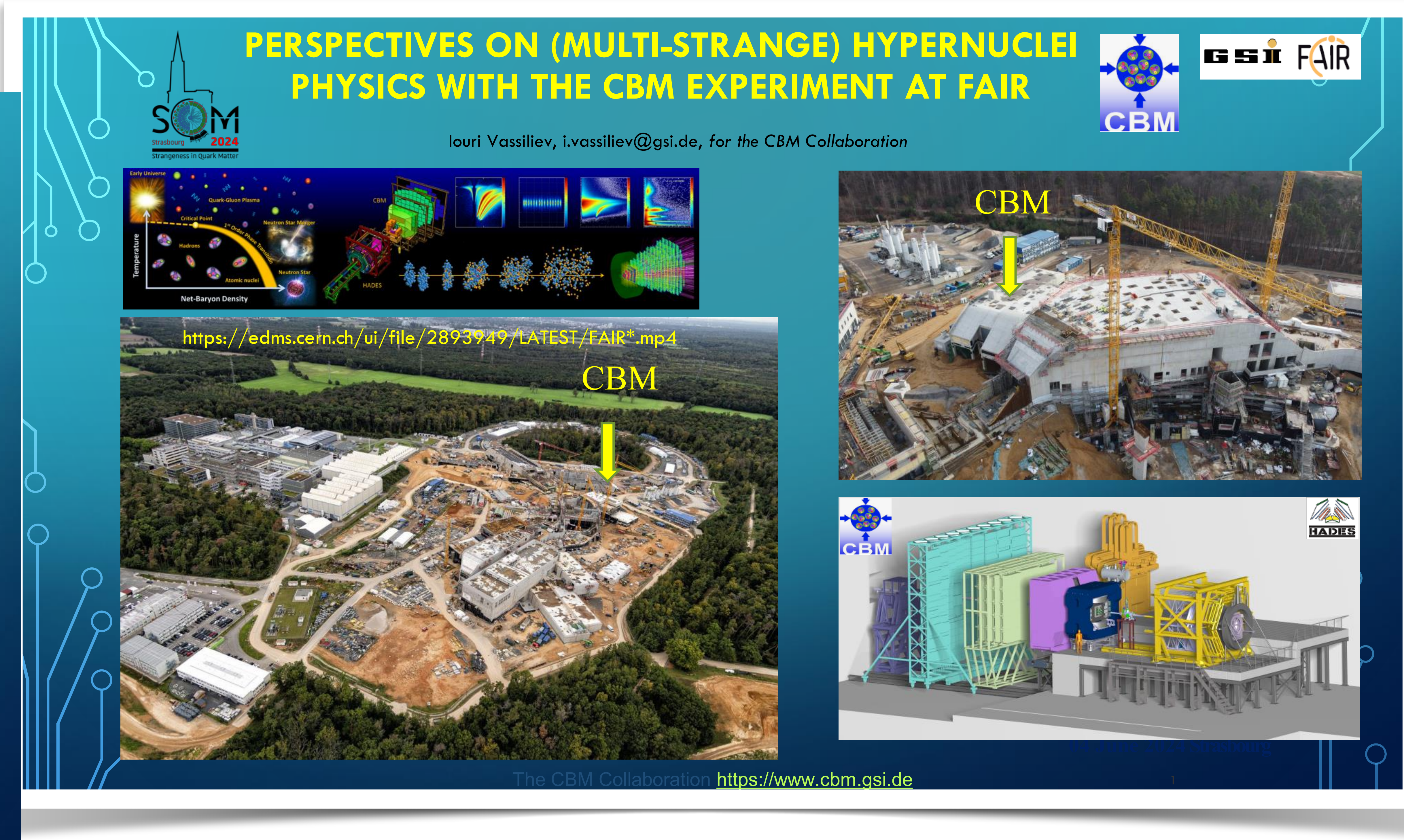
CBM at FAIR

Outlook: Year 1 – 3 scenario as of September 2023

Year	Setup	Reaction	T_{Lab} (AGeV)	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)	$2 \cdot 10^{10}$ each	EB mBias
1	ELEHAD	C+C	2,4,6,8,10, max	18 (3 each)	$4 \cdot 10^{10}$ each	mBias
1	ELEHAD	p+Be	3,4,8,29	12 (3 each)	$2 \cdot 10^{11}$ each	mBias
2	MUON	Au+Au	2,4,6,8,10, max	30 (5 each)	$2 \cdot 10^{11}$ each	mBias
2	MUON	C+C	2,4,6,8,10, max	18 (3 each)	$4 \cdot 10^{11}$ each	mBias
2	MUON	p+Be	3,4,8,29	12 (3 each)	$2 \cdot 10^{12}$ each	mBias
3	HADR	Au+Au	2,4,6,8,10, max	12 (2 each)	$4 \cdot 10^{11}$ each	EB+ Selectors
3	HADR	C+C	2,4,6,8,10, max	6 (1 each)	$8 \cdot 10^{11}$ each	
3	HADES	Ag+Ag	2,4	28 (14 each)	10^{10} each	
3	ELEHAD	Ag+Ag	2,4	8 (4 each)	$2 \cdot 10^{10}$ 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



A bright future at RHIC

sPHENIX and STAR at RHIC

Run Plan to Achieve Physics Goals

sPHENIX

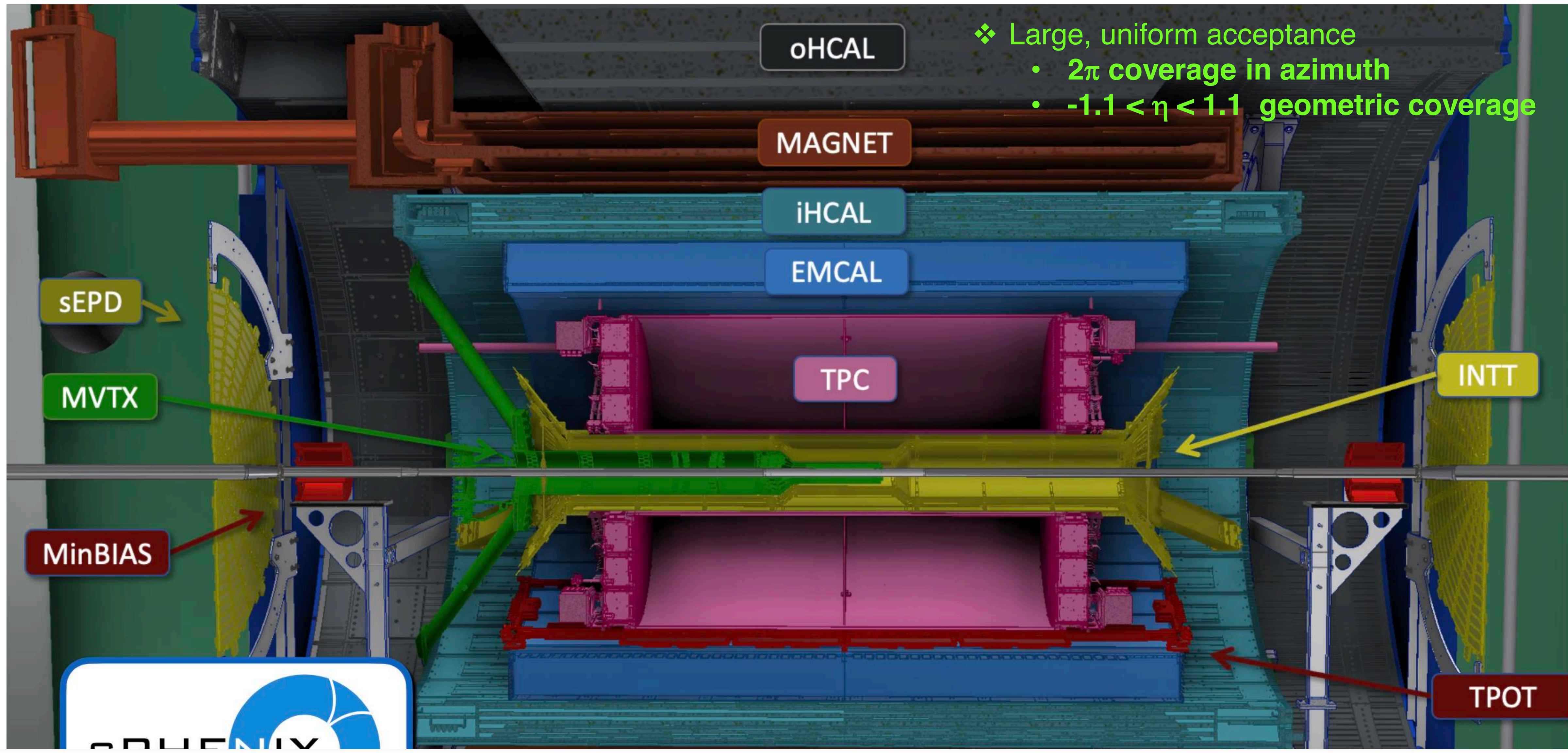
- Run-2024: transversely polarized *p+p* running, with a few options for short Au+Au running:

  → 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!

Rachid Nouicer SQM 2024 5

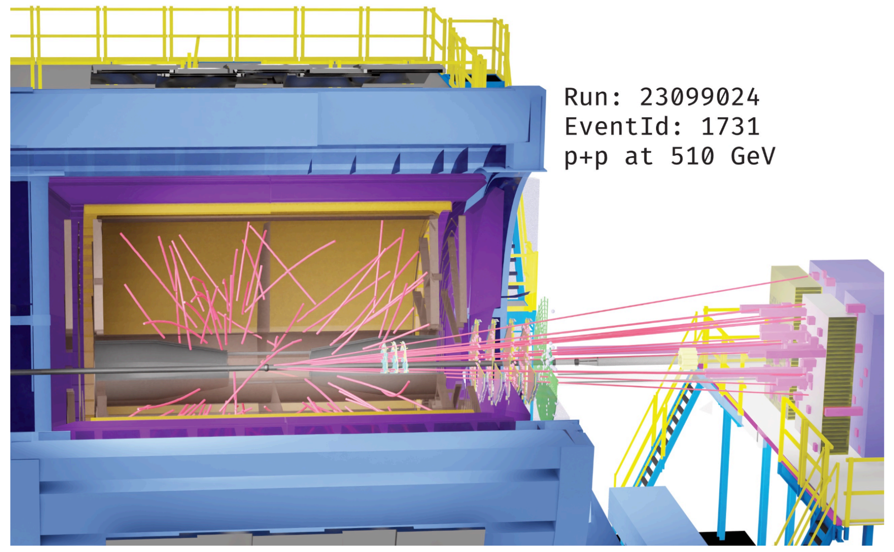


Future physics opportunities

STAR

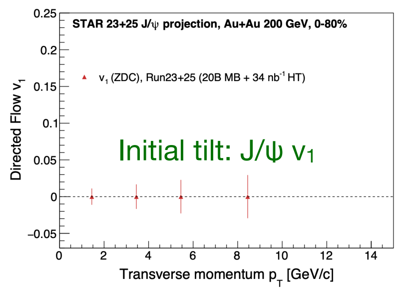
Projections as plans for 2023-2025

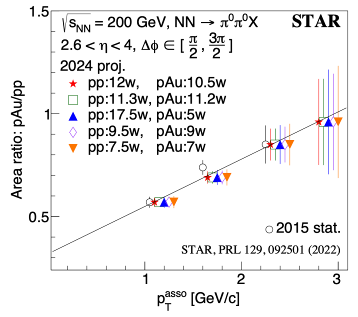
√SNN (GeV)	Species	Sampled Luminosity	Year
200	Au+Au&p+Au	AuAu 32.7 nb^{-1} / pAu 0.69 pb^{-1}	2023+2025
200	p+p	142 pb^{-1}	2024



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?





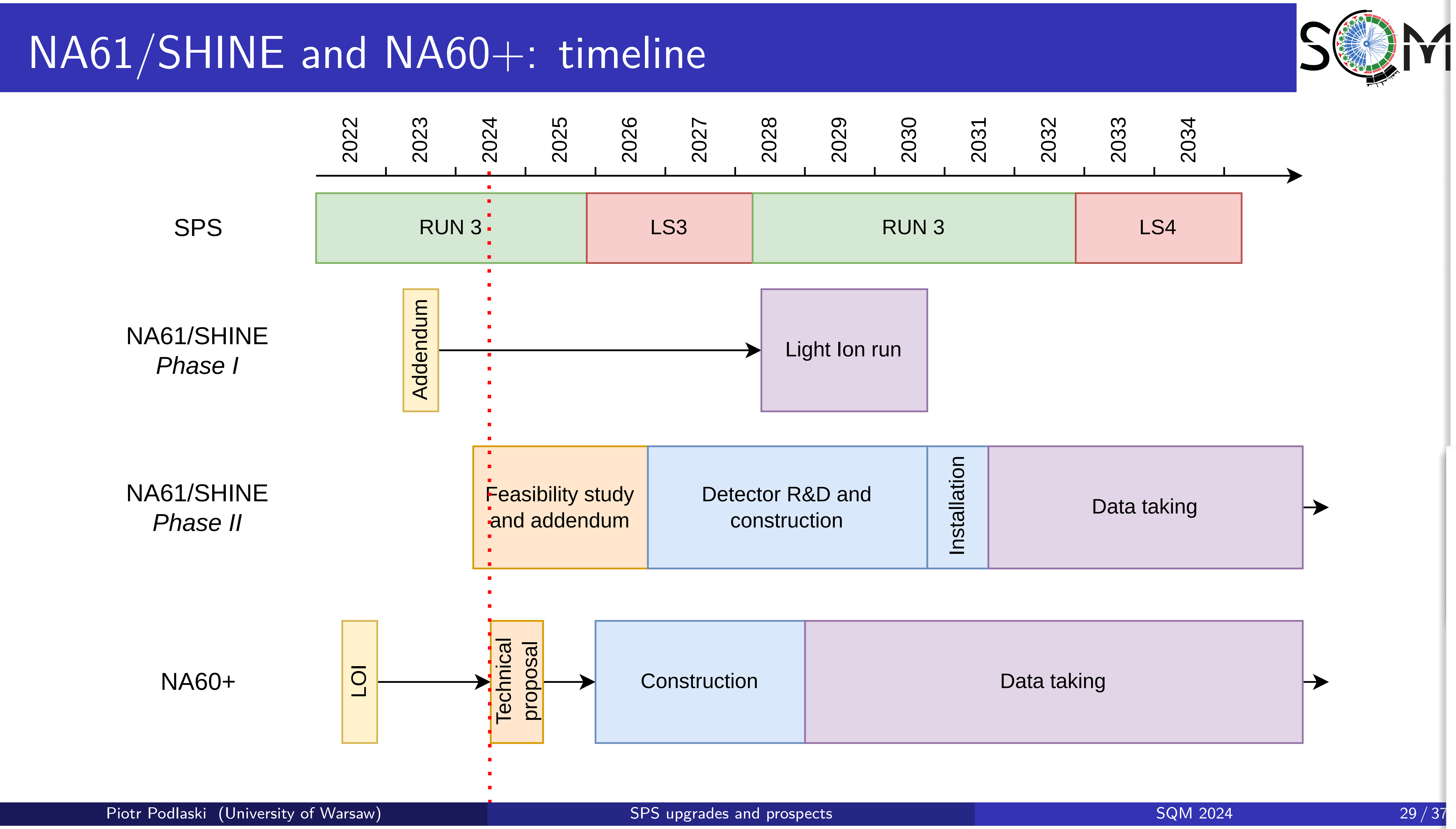
Cold QCD physics: Establish the validity and limits of factorization and universality to understanding of QCD

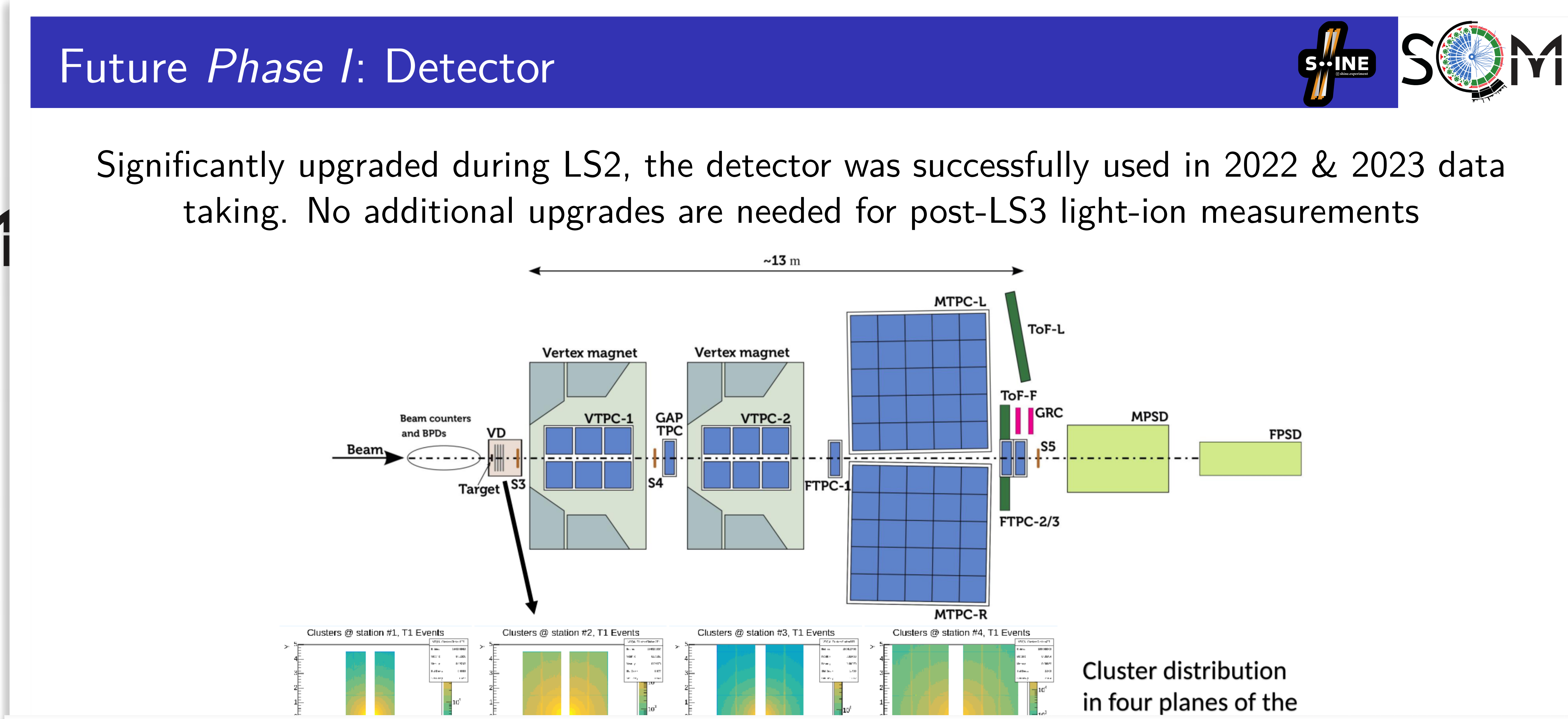
- Forward Transverse-Spin Asymmetries
- Sivers and Efremov-Teryaev-Qiu-Sterman Functions
- Transversely, Collins Function and Interference Fragmentation Function
- Ultra-Peripheral Collisions

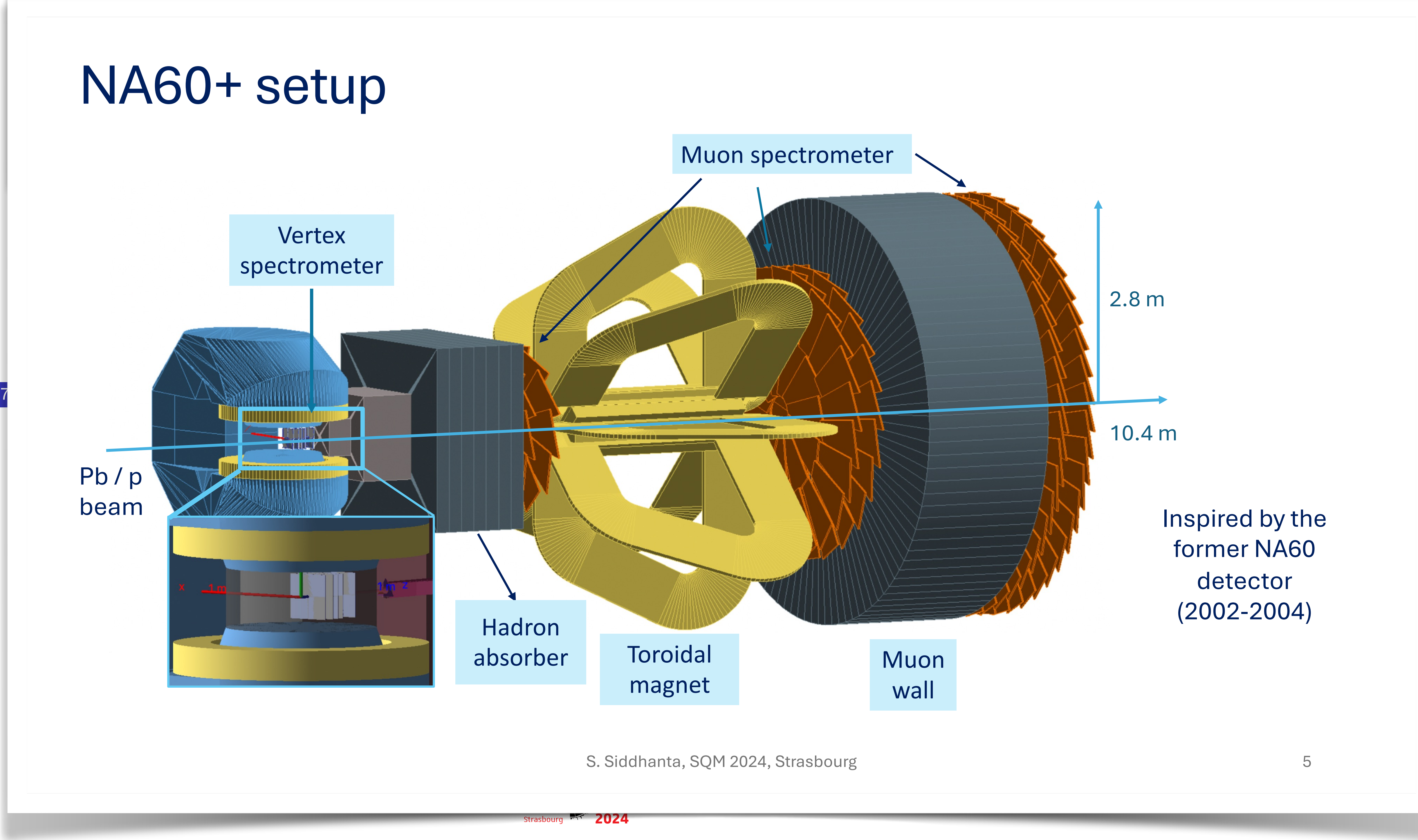
2024/06/03 Qian Yang @ SQM 2024, Jun. 3rd - Jun. 7th 2024 30

A bright future at SPS

NA61/SHINE and NA60+ at the SPS

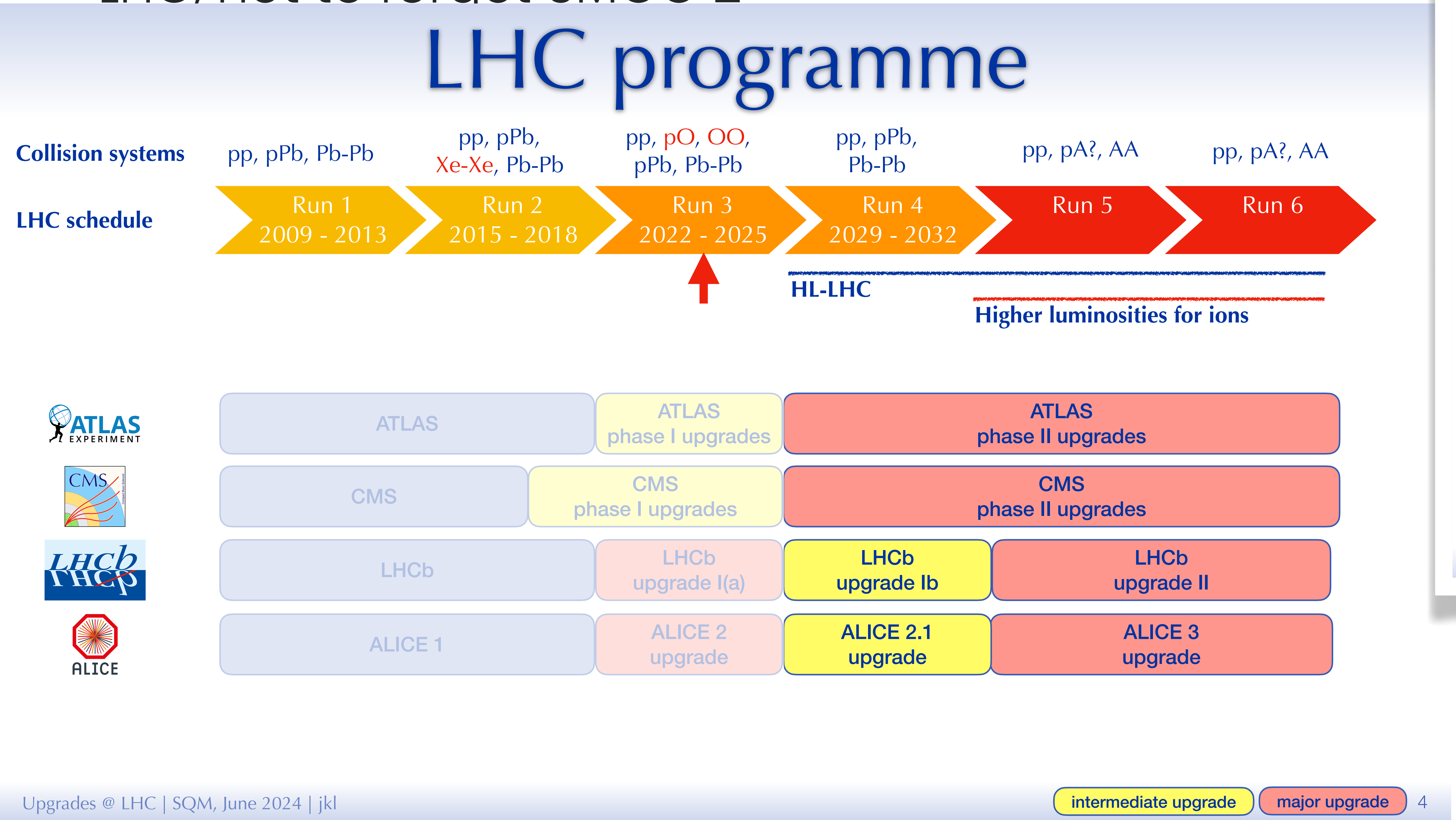


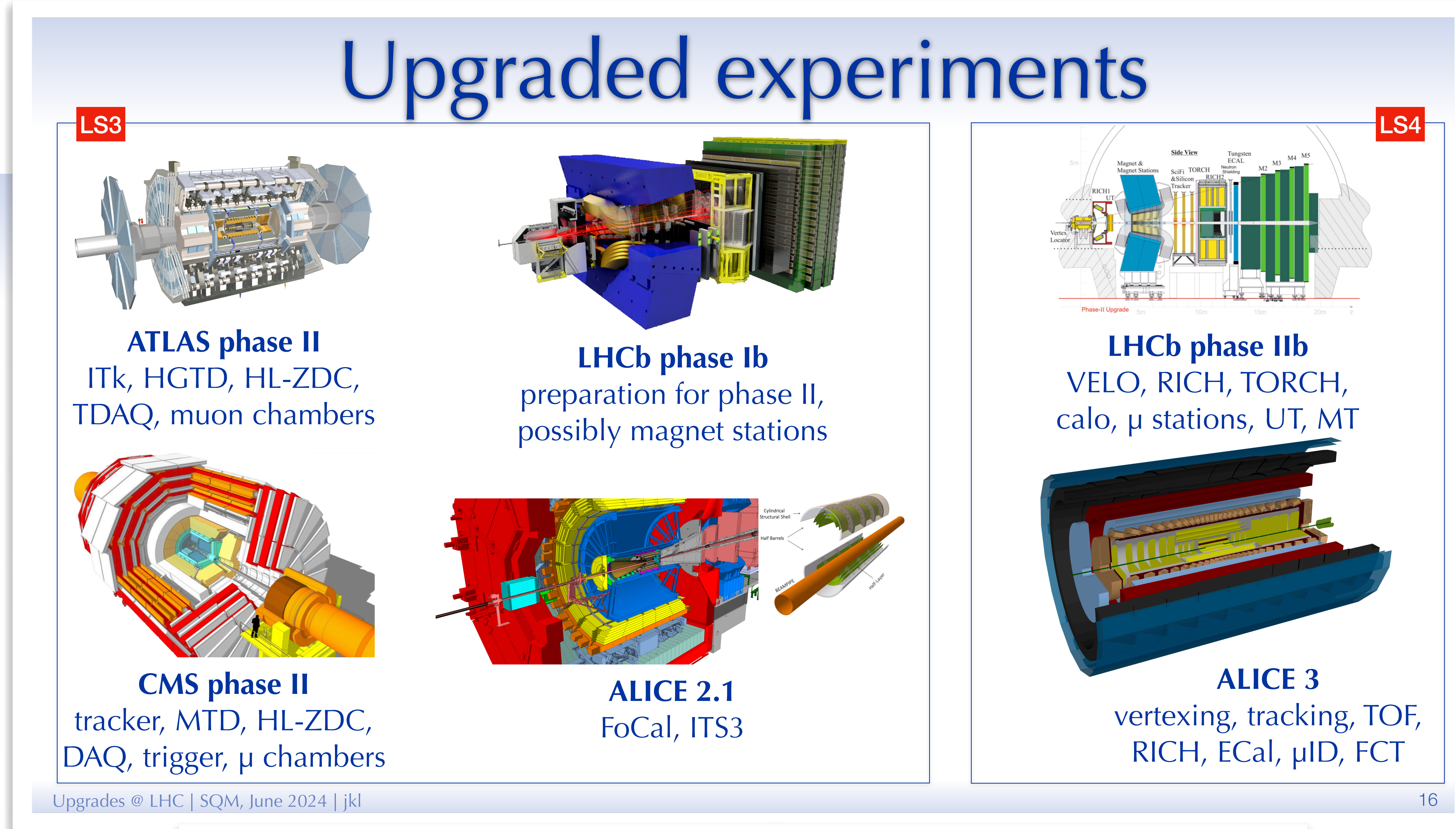


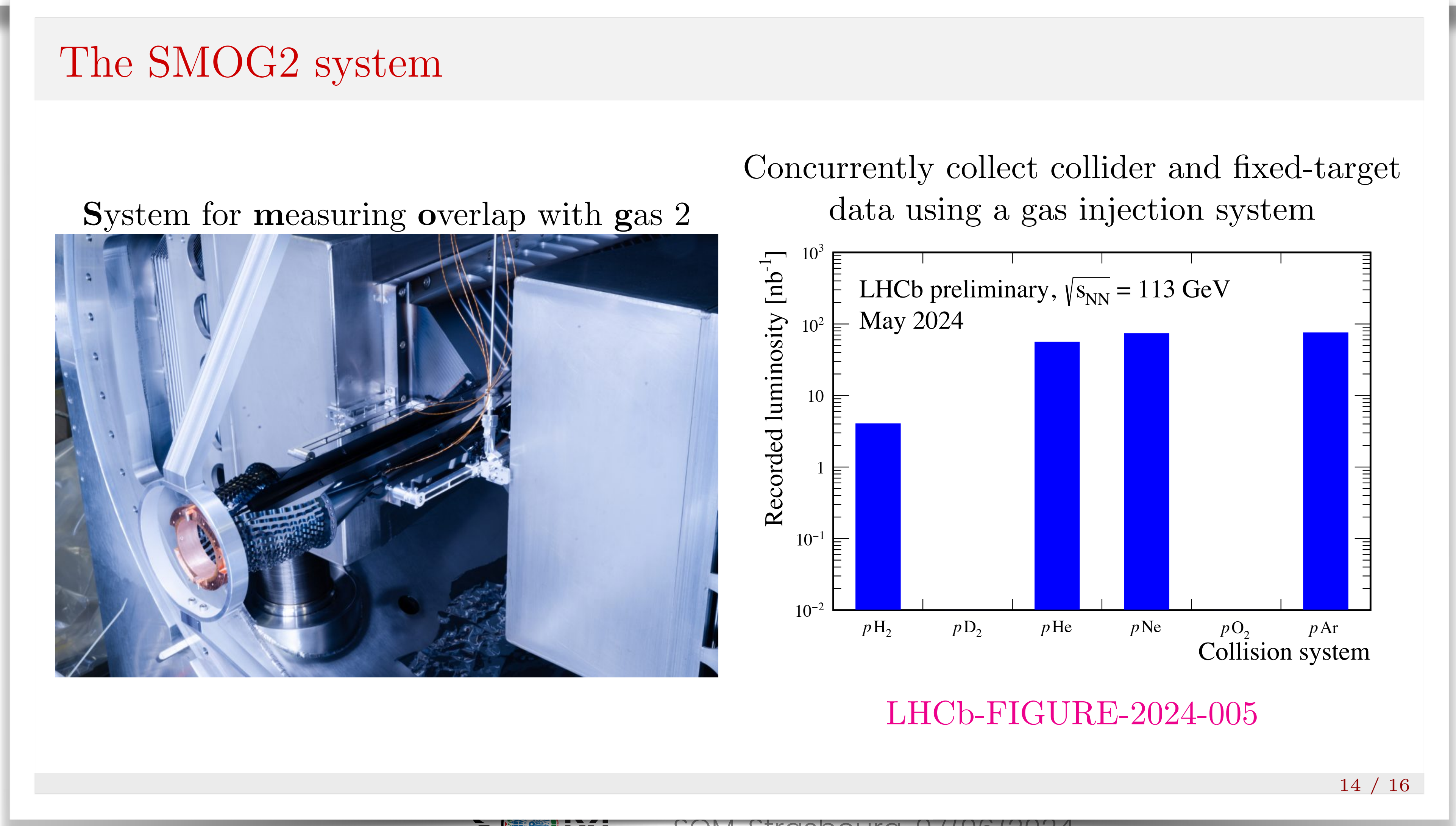


A bright future at LHC

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







Summary of summary?

Thank you for your attention!

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

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