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Recent results on quarkonia elliptic flow with ALICE

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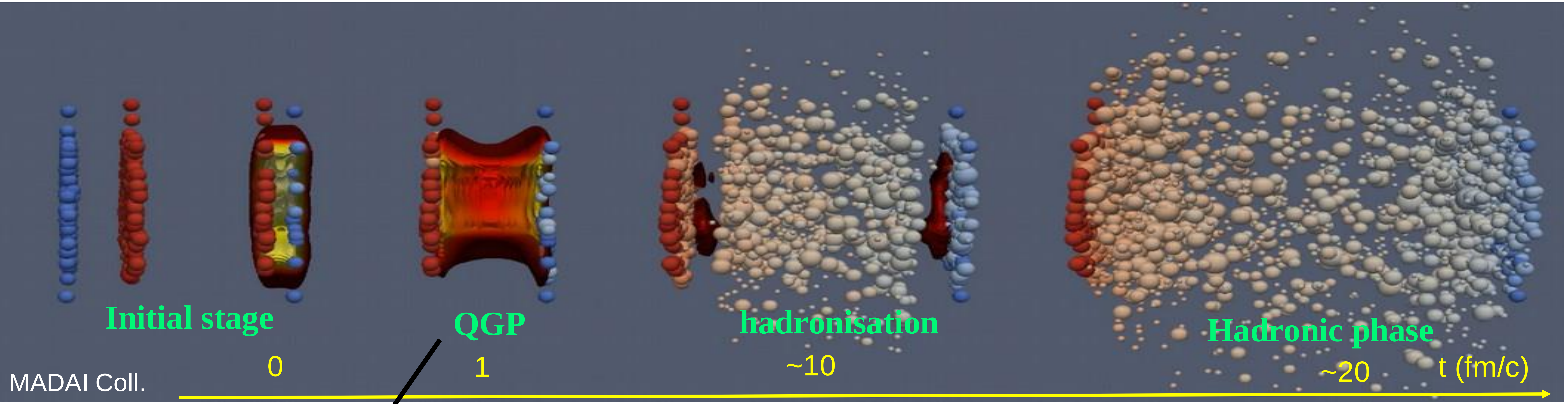
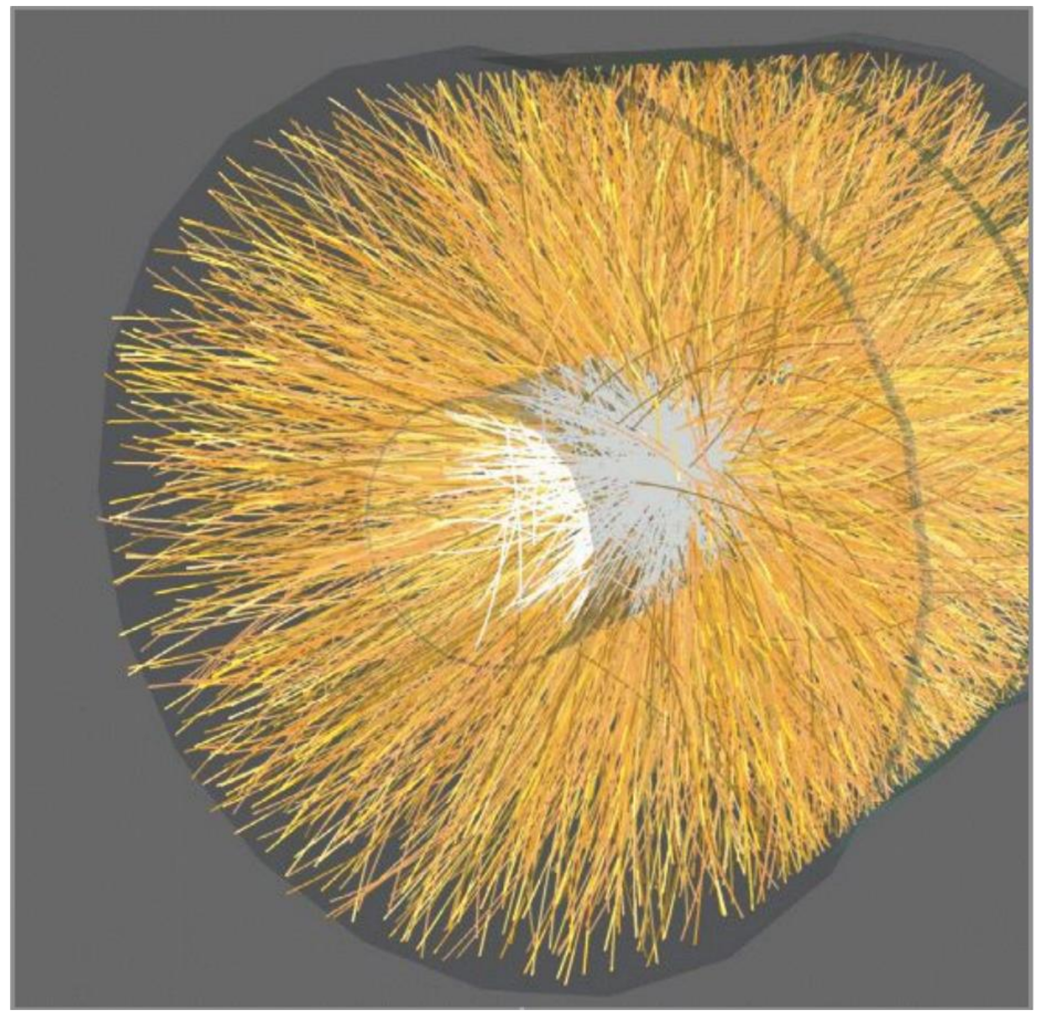
Evolution of a heavy ion collision





particles interact with detectors

deconfined strongly-interacting QCD matter with color degrees of freedom

Study the properties and evolution of **q**uark-**g**luon **p**lasma (**QGP**):

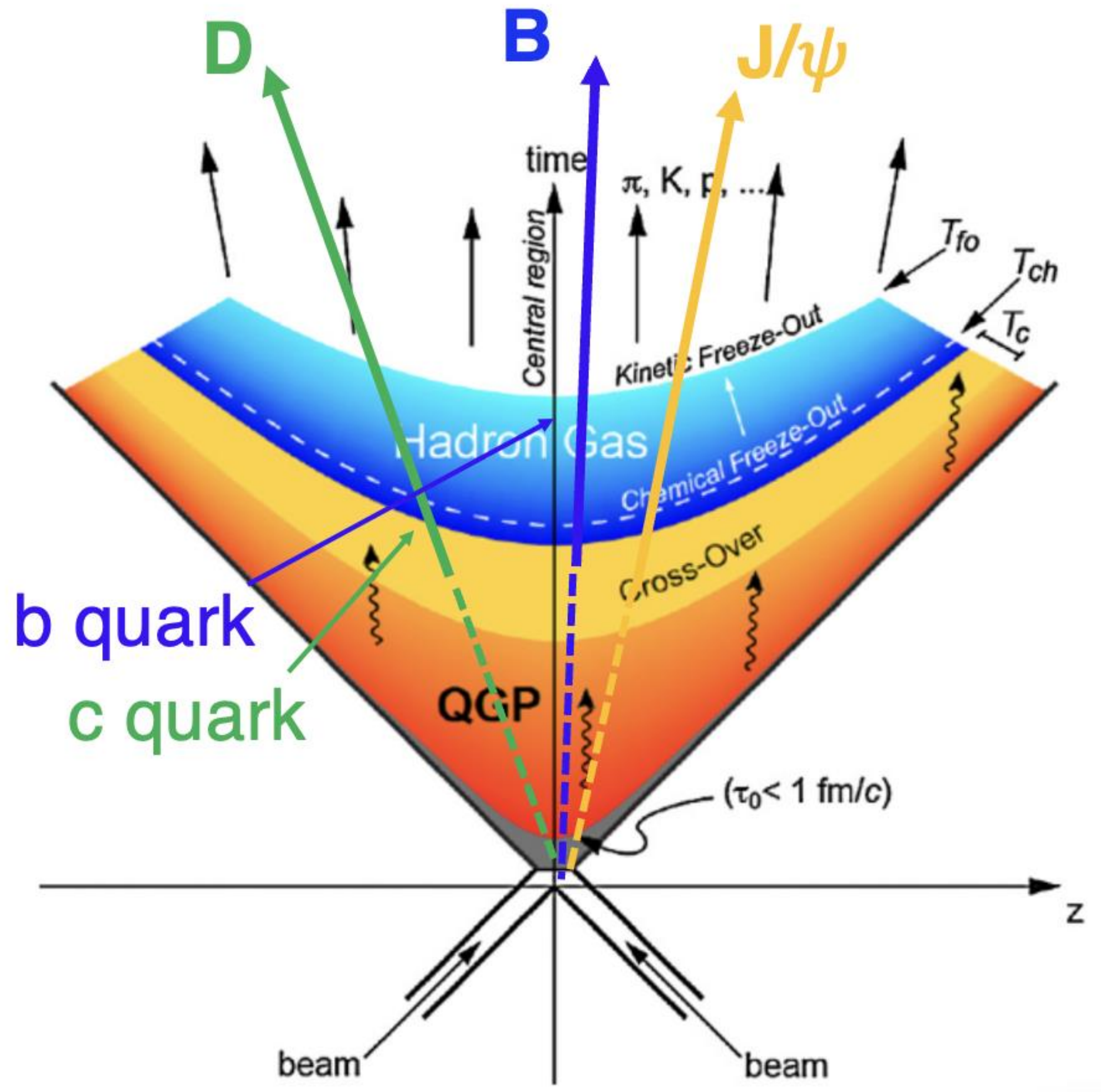
- ➢ Color deconfinement;
- ➢ Parton interactions;
- ➢ Expansion dynamics and hadronization;

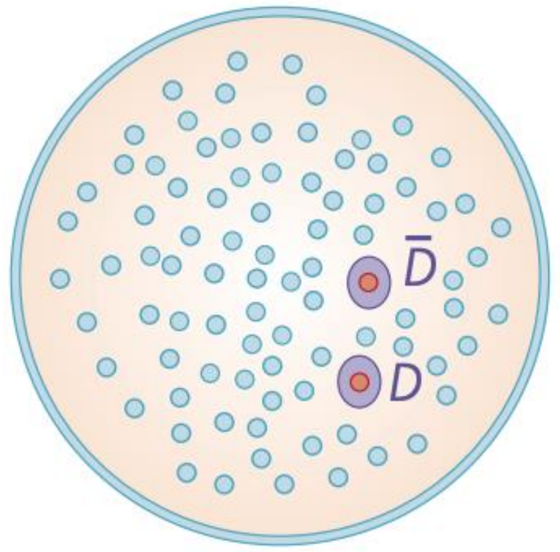
……

Why to study quarkonia?

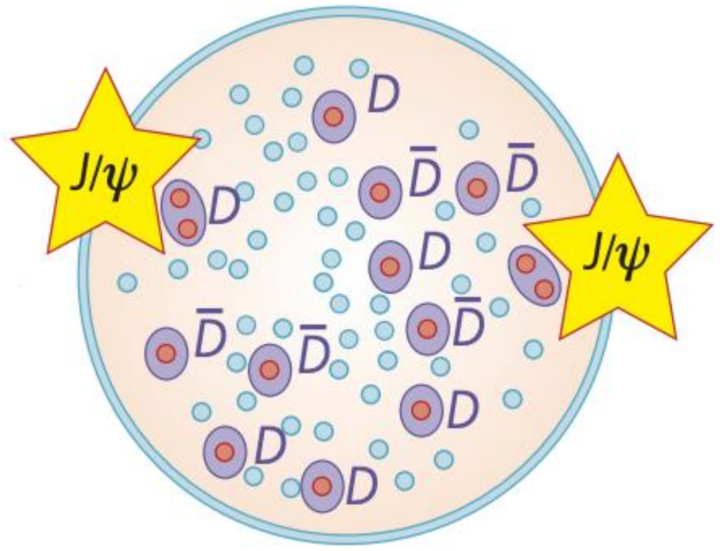
Quarkonia: bound state of 2 heavy quarks ($c\bar{c}$, $b\bar{b}$)

- ✓ Quarkonia produced in the initial hard partonic scattering with a large Q^2.
  → $c\bar{c}$ production can be computed via pQCD calculations;
  → evolution of the pair into the physical quarkonium state is non-perturbative;
- ✓ Experience the entire evolution of the medium;
- ✓ **Dissociated** while going through QGP due to Debye screening ($\lambda_D \propto \frac{1}{T}$).
  → suppression of quarkonia is a signature of QGP;
  - 📖 T. Matsui, H. Satz, PLB178(1986) 416
- ✓ **Regeneration**: the large abundance of large c and $\bar{c}$ quarks increases their probability to form charmonia, particularly at LHC energies;

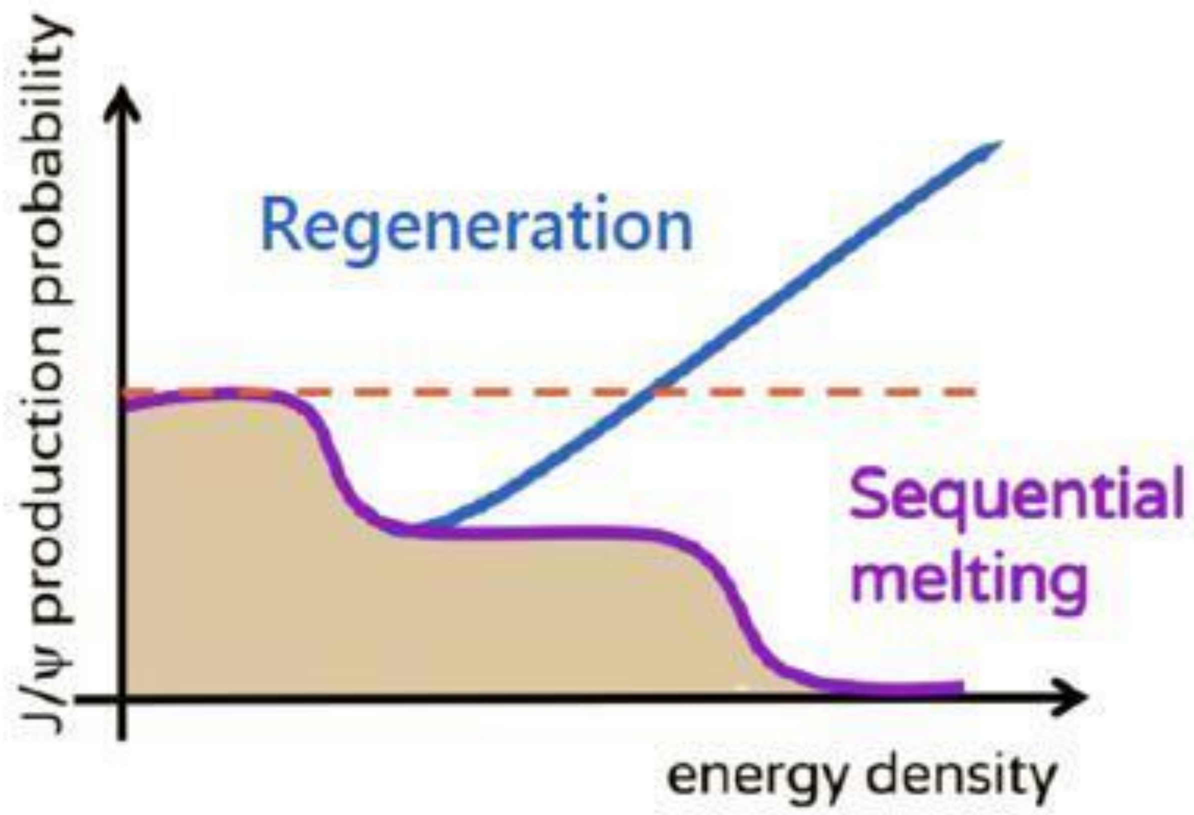




(RHIC)

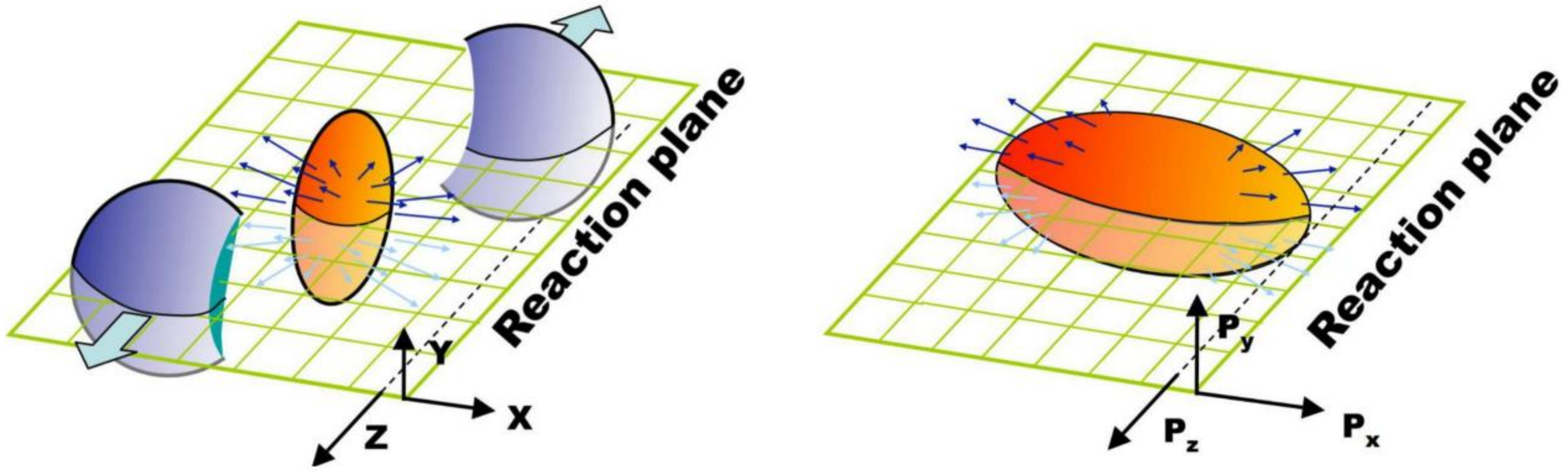


(LHC)



📖 Andronic et al, Nucl. Phys. A772: 167-199, 2006)
📖 R.Thews et al, Phys. Rev. C63(2001) 054905
📖 P.Braun-Munzinger, J. Stachel, Phys. Lett. B490 (2000) 196

Why elliptic flow?



- To probe early time:
  - The dense nuclear overlap is **ellipsoid** in non-central collisions at the beginning of HIC.
  - **Spatial** anisotropy → **momentum** anisotropy (Pressure gradients is largest in shortest direction);
  - Elliptic flow (v_2) is defined by the 2nd coefficient of Fourier expansion.

$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left\{1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]\right\}, \quad v_n = \langle\cos\left[n(\phi - \Psi_n)\right]\rangle$$

How to assess to elliptic flow?

- event plane method: reconstruct event plane
- two-particle correlations:

$$\frac{dN^{pairs}}{d\Delta\phi} \propto \left(1 + \sum_{n=1}^{\infty} 2v_n^2 \cos(n\Delta\phi)\right)$$

- multi-particle correlations (cumulants):

……

Quarkonia v_2: ideal probe

Quarkonia + **elliptic flow**

Quarkonia v_2:

Ideal probe to explore two factors:

- ✓ the initial spatial energy density in the nuclear collision region;
- ✓ the degree of thermalization of charm;

A Large Ion Collider Experiment (ALICE)

Run 2

Inner Tracking System (ITS):

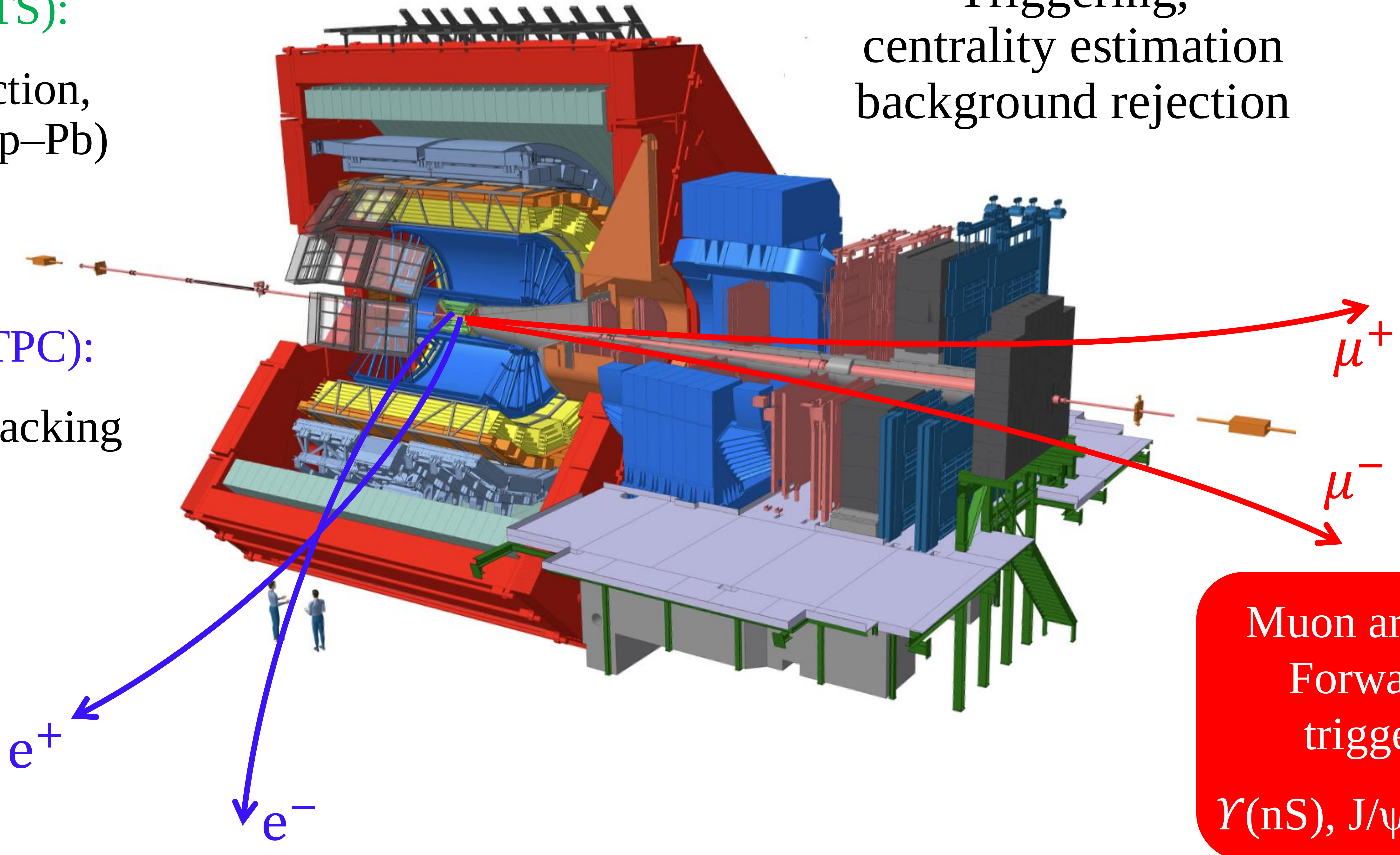
Tracking, vertex reconstruction, multiplicity estimation (pp, p–Pb)

Time Projection Chamber (TPC):

Vertex reconstruction, PID, tracking

V0 (A and C):

Triggering, centrality estimation background rejection



Muon arm ($2.5 < y < 4.0$): Forward tracking and triggering of muons

Υ(nS), J/ψ, ψ(nS)$\rightarrow \mu^+\mu^-$

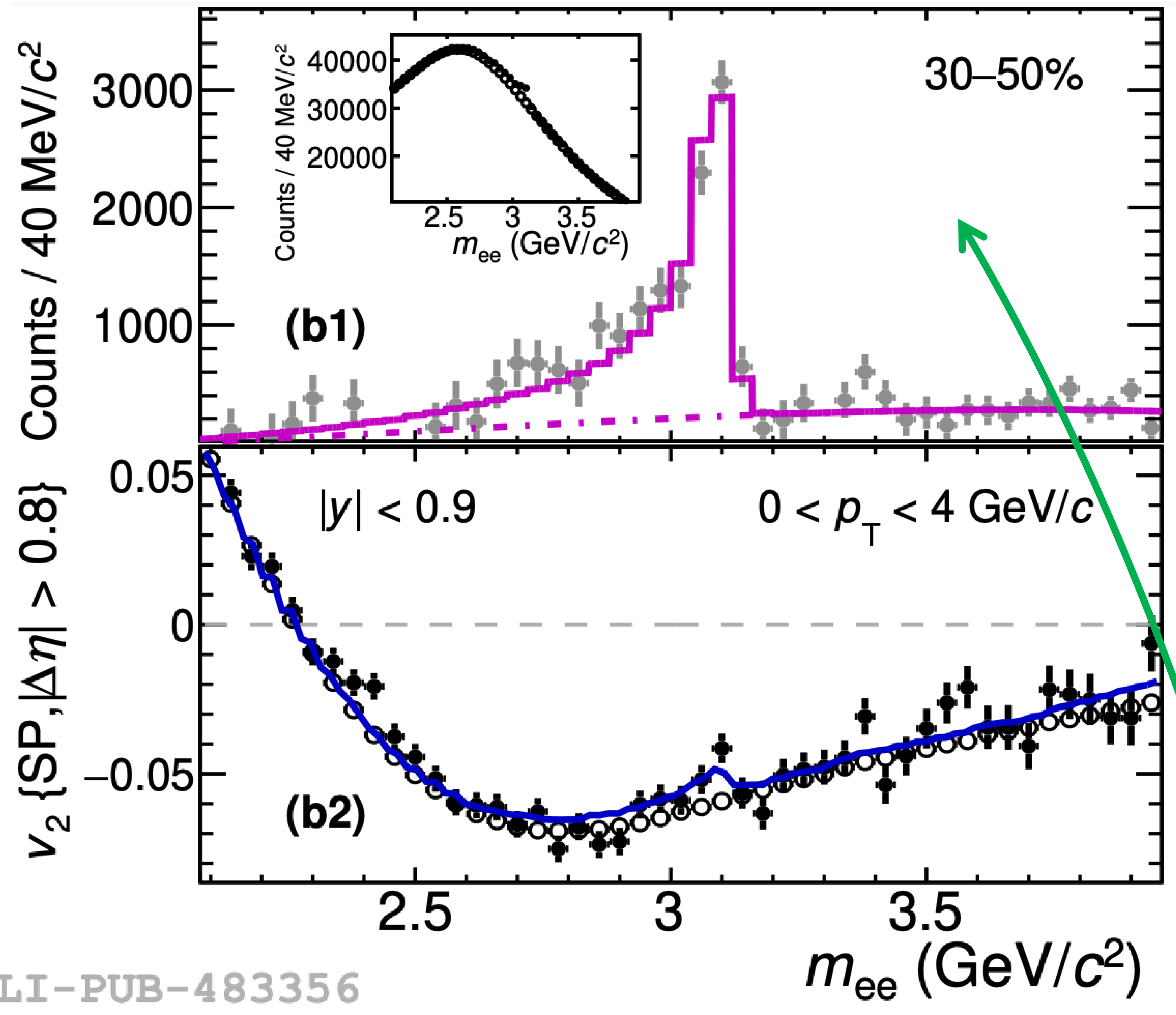
Central barrel ($|y| < 0.9$): J/ψ, ψ(nS) $\rightarrow e^+e^-$

Distinction between J/ψ prompt (produced at primary vertex) and non-prompt (b-hadron decays)

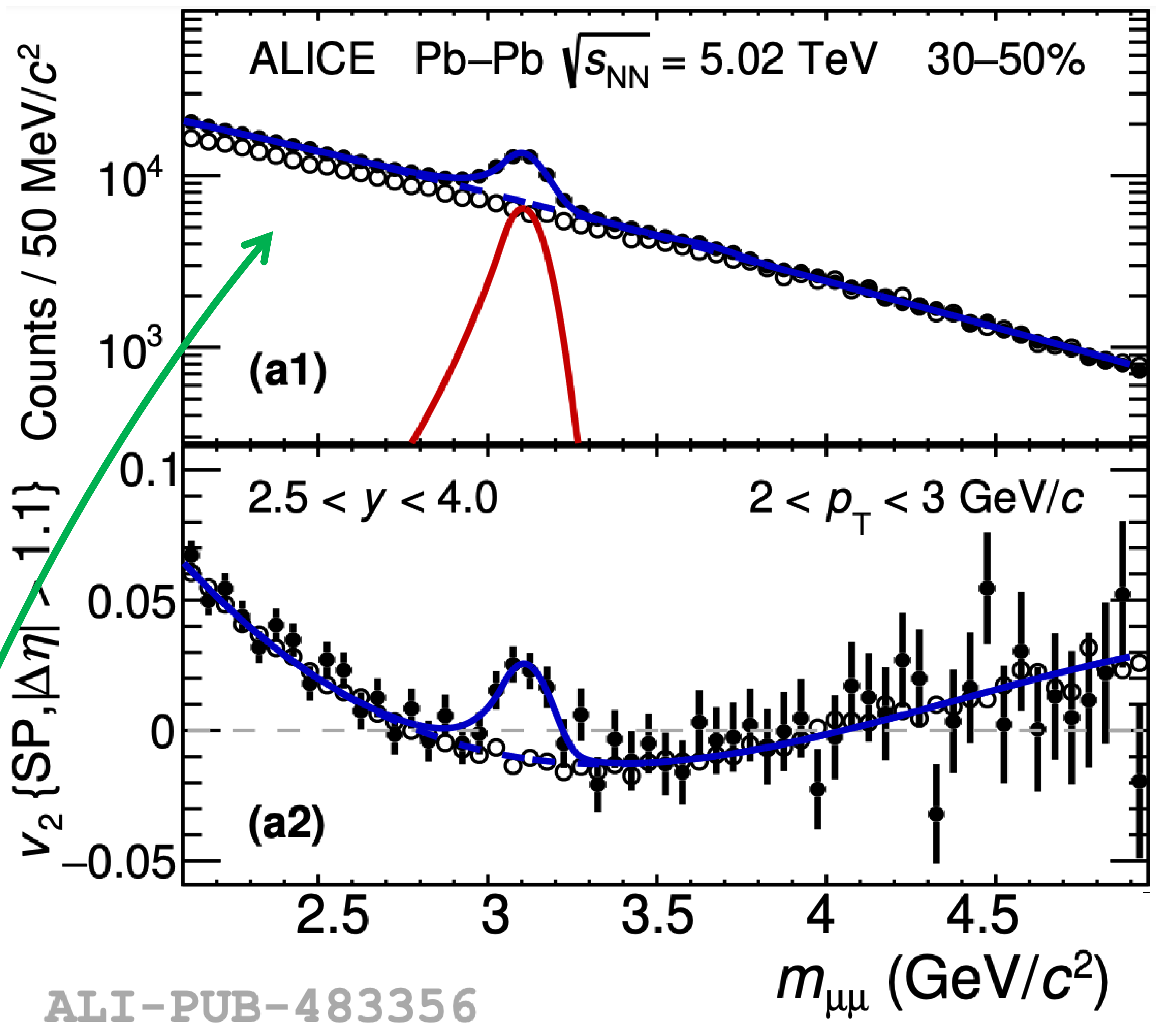
Int. J. Mod. Phys. A 29, No. 24 (2014) 1430044

J/ψ v_2 extraction

J/ψ→ e^+e^-



J/ψ→$\mu^+\mu^-$

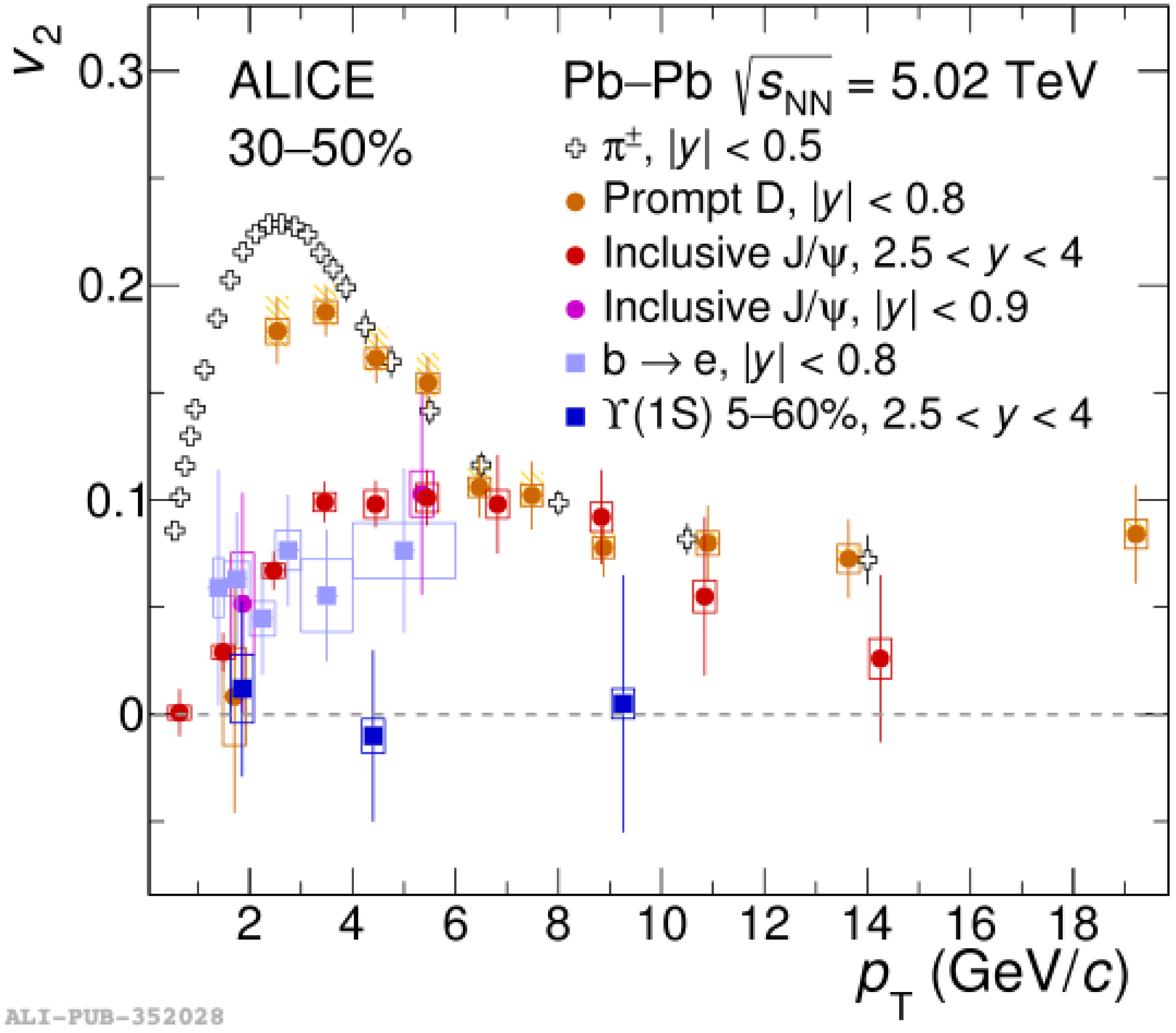


$$v_n(m_{\ell\ell}) = \alpha(m_{\ell\ell})\, v_n^{J/\psi} + [1-\alpha(m_{\ell\ell})]\, v_n^{bkg}(m_{\ell\ell})$$

📖 JHEP 10 (2020) 141

Elliptic flow in Pb–Pb collisions

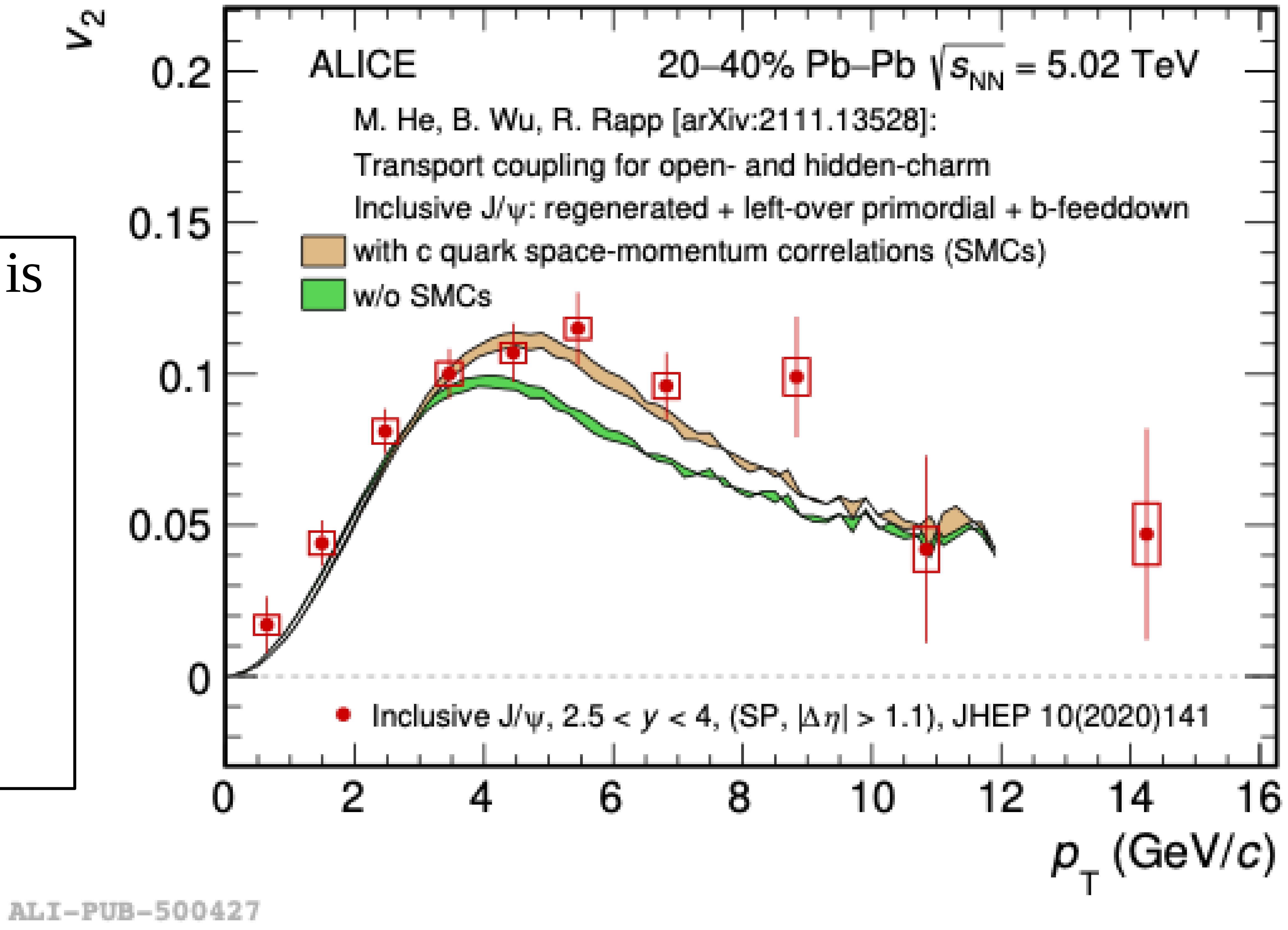
- J/ψ:
  - ✓ $p_T < 3$ GeV/c: $v_2(\Upsilon(1S)) \leq v_2(J/\psi) < v_2(D)$
    a mass ordering can be observed.
  - ✓ $3 < p_T < 6$ GeV/c: $v_2(J/\psi) < v_2(D) \sim v_2(\pi)$
    → charm quark thermalization?
  - ✓ $p_T > 6$ GeV/c: $v_2(J/\psi) \sim v_2(D) \sim v_2(\pi)$
    similar path-length dependence of the energy loss?
- $\Upsilon(1S)$: v_2 compatible with **zero**;



📖 JHEP 09(2018) 006
📖 PLB 813 (2021) 136054
📖 JHEP 10(2020)141
📖 PRL 126, 162001(2021)
📖 PRL 123, 192301(2019)

Elliptic flow in Pb–Pb collisions

- J/ψ v_2 described well by a recombination model which is based on:
  - ✓ charm quark transported through the QGP using Langevin;
  - ✓ space-momentum correlations of charm quarks in expanding fireball (equilibrium);



📖 Phys. Rev. Lett. **128**, 162301(2022)

📖 JHEP 10 (2020) 141

Elliptic flow in p–Pb collisions

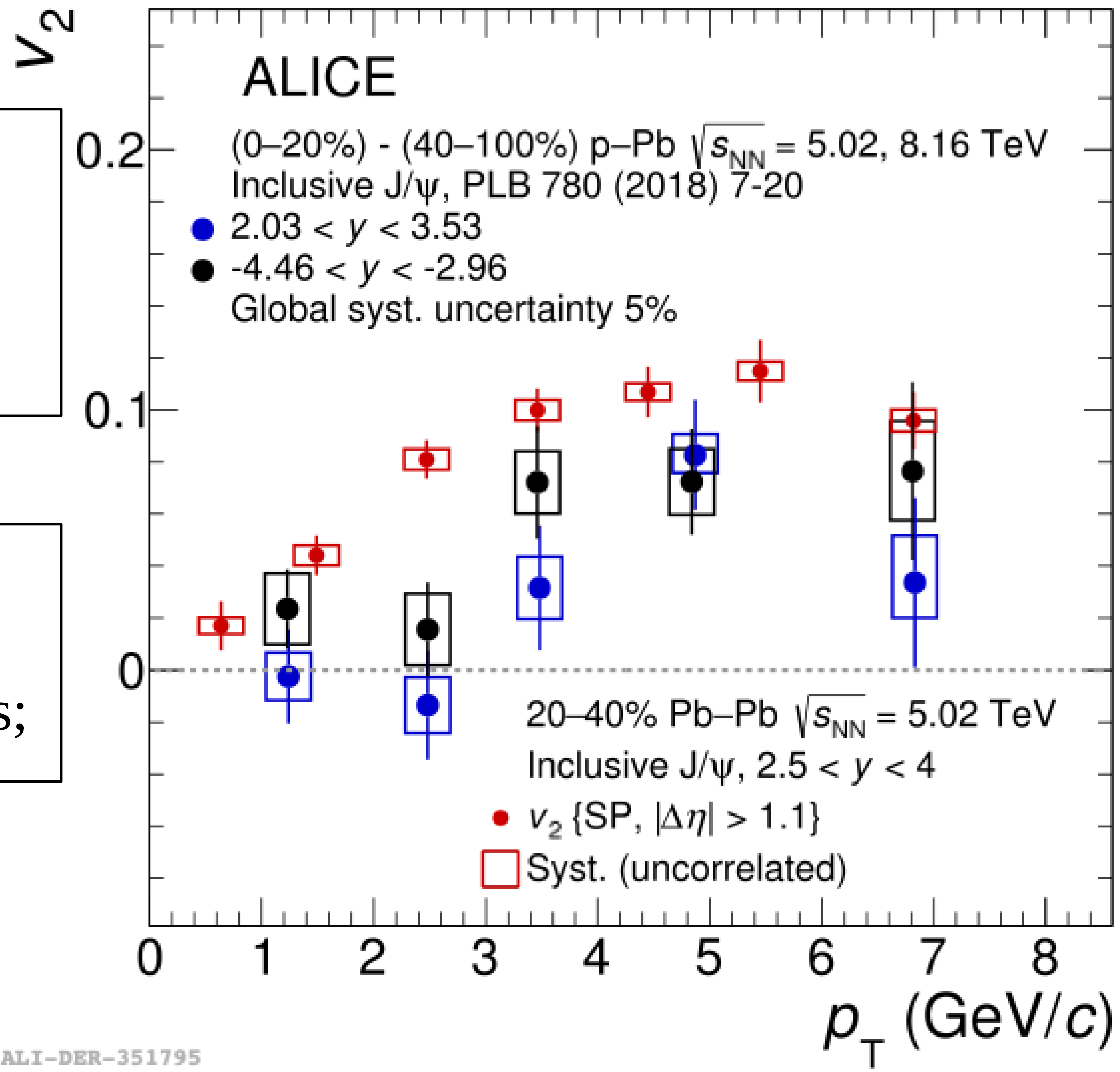
J/ψ v_2 are measured separately by:

p–Pb: two particle correlation (J/ψ-charged);

Pb–Pb: scalar product;

↓

- p_T < 3 GeV/c: consistent with zero;
- p_T > 3 GeV/c: J/ψ v_2 > 0 with similar amplitude as measured in semicentral Pb–Pb collisions;

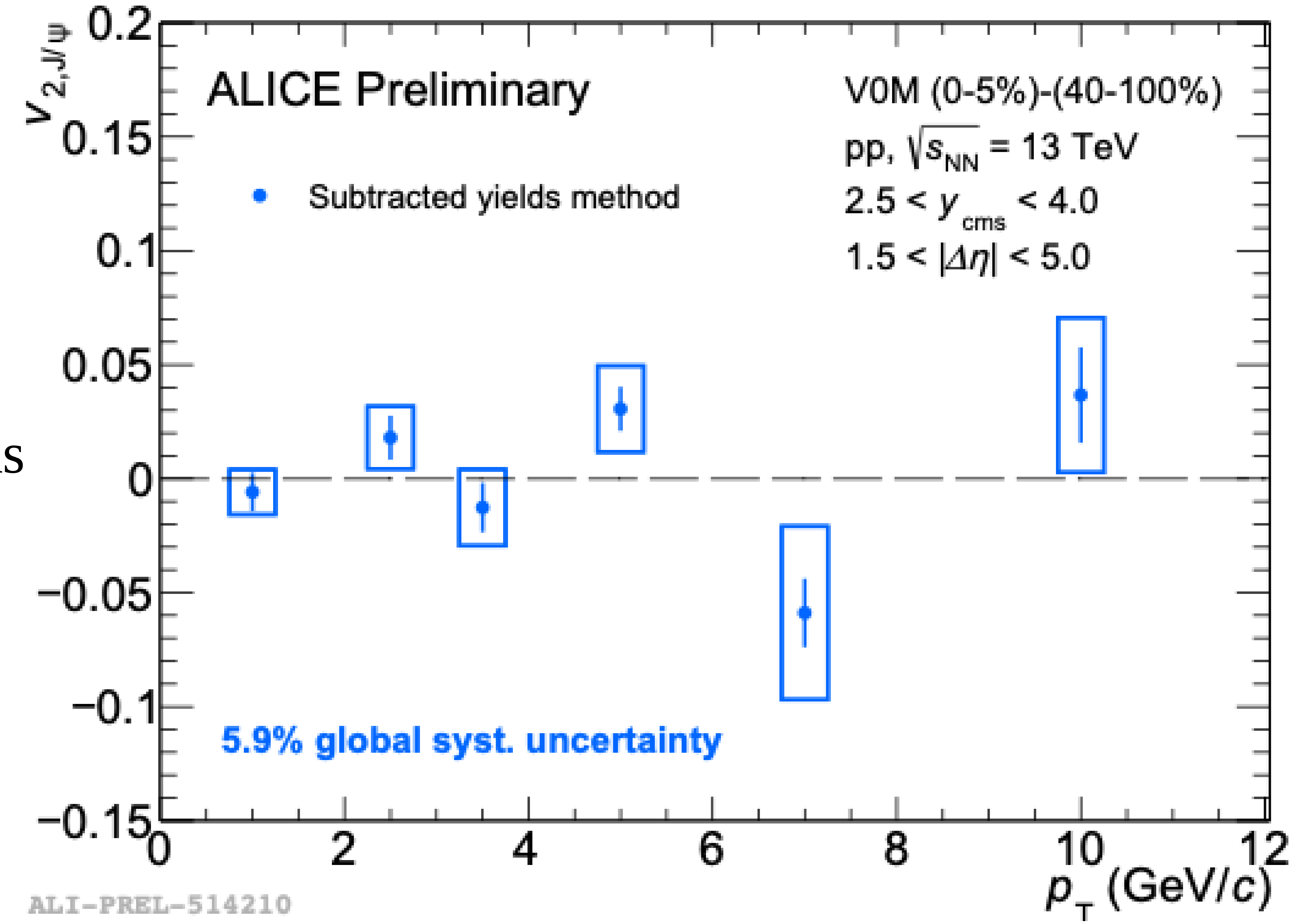


📖 Phys. Lett. B 780 (2018) 7-20

📖 JHEP 10 (2020) 141

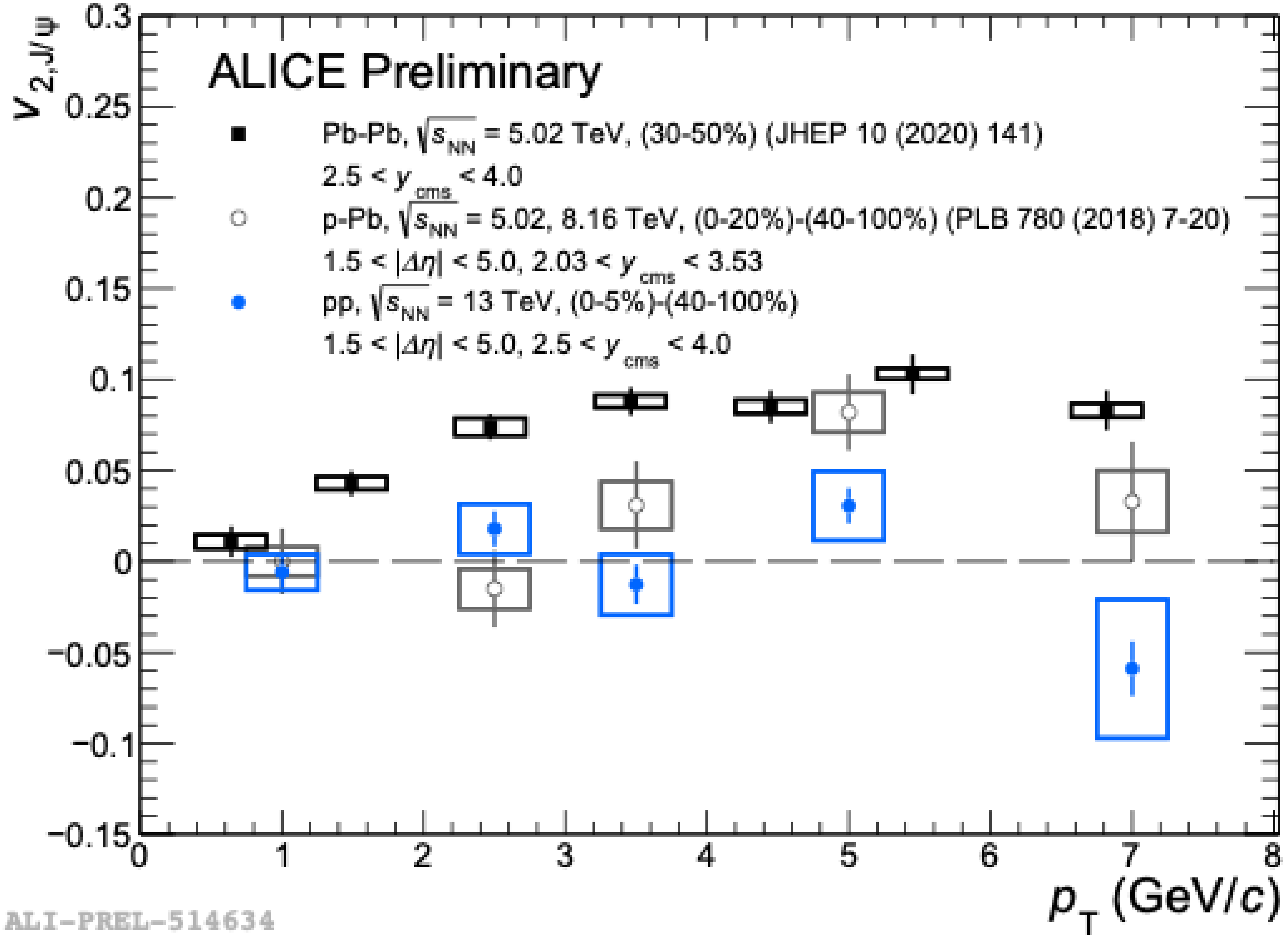
Elliptic flow in pp collisions

- No collective behavior observed for the J/ψ elliptic flow in high multiplicity pp collisions at the LHC, within uncertainties;
- First J/ψ elliptic flow measurement in pp collisions at LHC at forward rapidity;



Elliptic flow in Pb–Pb, p–Pb, pp collisions

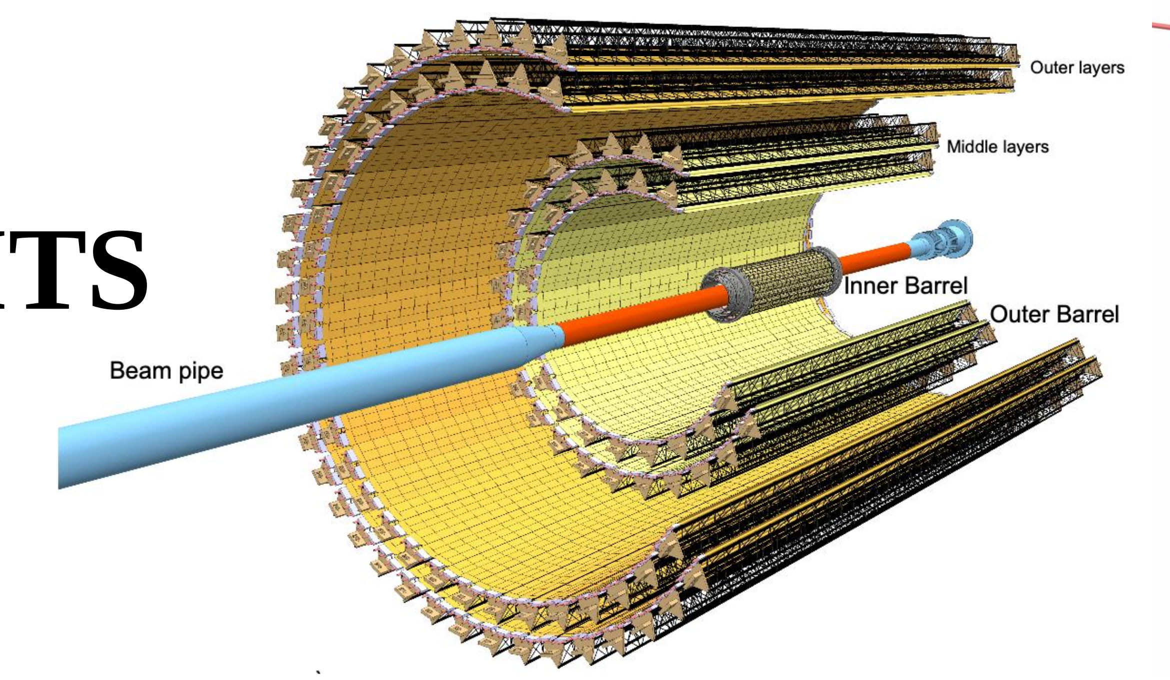
A clear hierarchy of J/ψ v_2 from **Pb–Pb**, p–Pb to high-multiplicity pp collisions can be observed.



A Large Ion Collider Experiment (ALICE)

Run 3: main upgrades of **ITS**, **TPC** and **MFT**

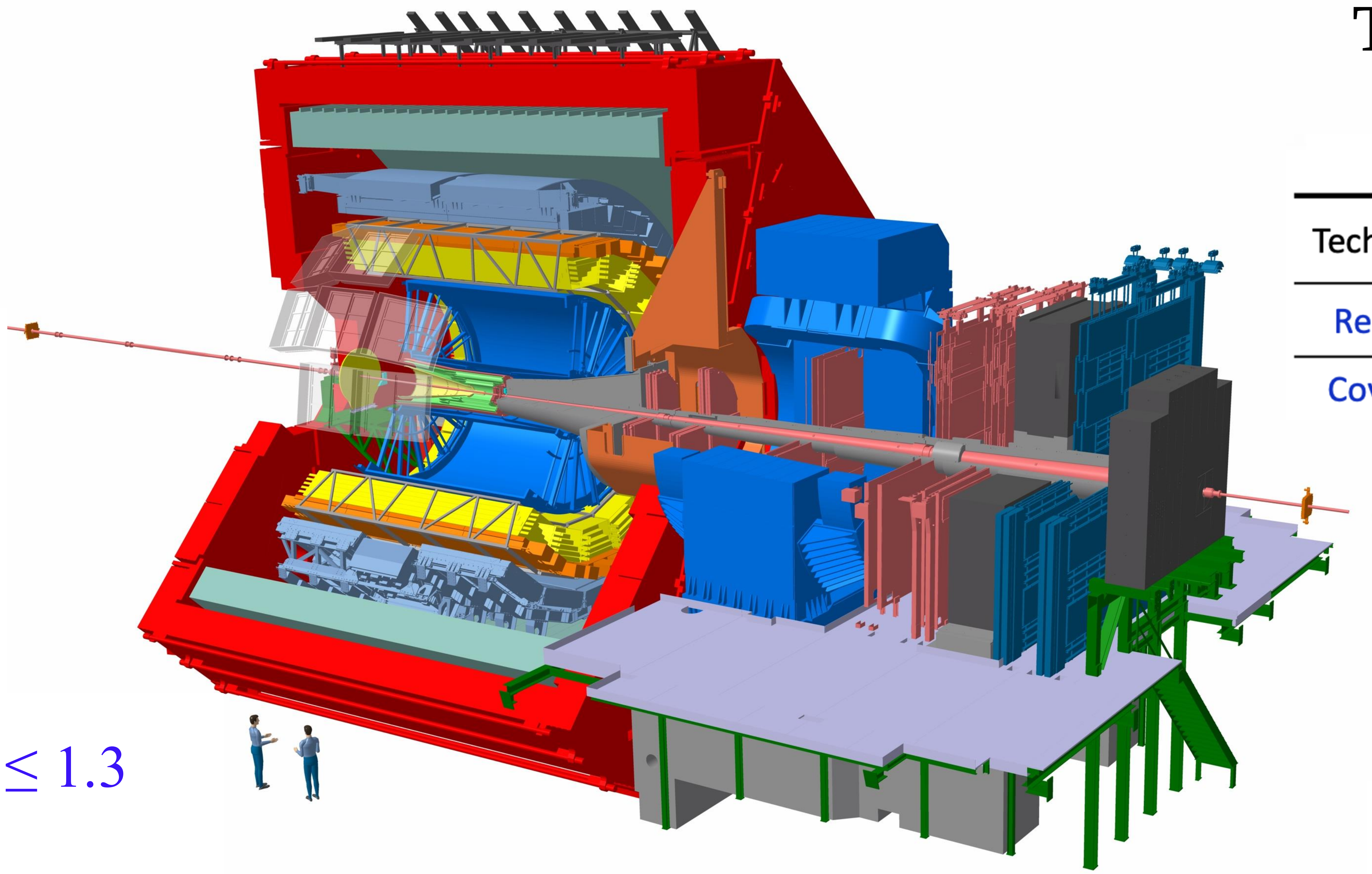
ITS



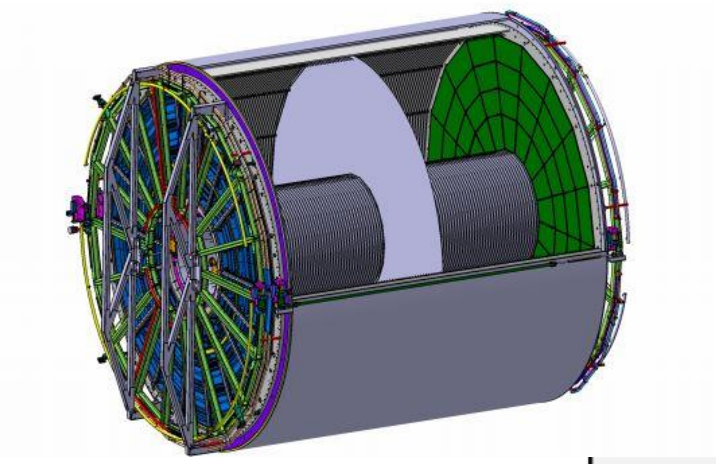
coverage: $|\eta| \leq 0.9 \rightarrow |\eta| \leq 1.3$

less material

Max rate: 1kHz →50 kHz

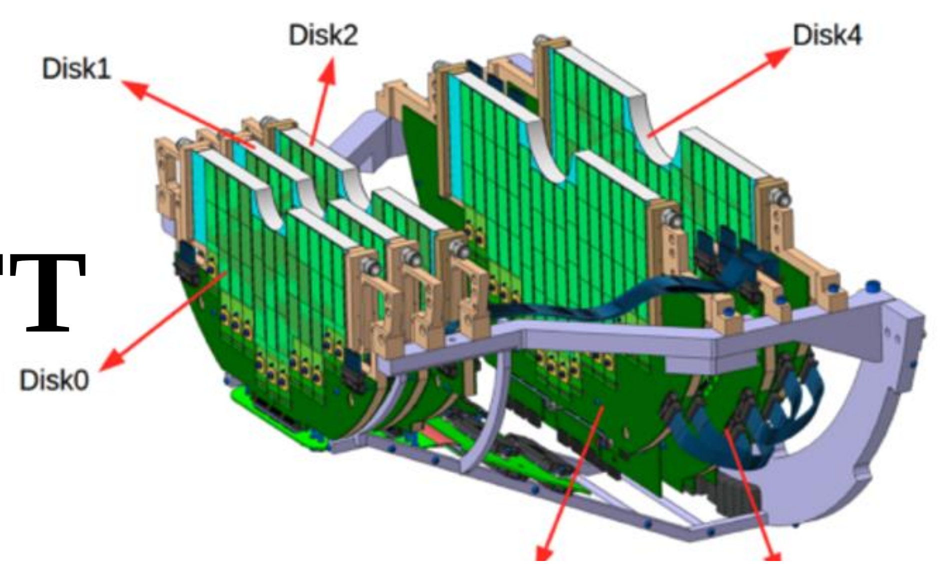


TPC



	Run 2	**Run 3**
Technology	MWPC (Multi wire proportional chamber)	**GEM**
Readout	few kHz	**50 kHz** (continuous readout)
Coverage	$\|\eta\| \leq 0.9$	

MFT



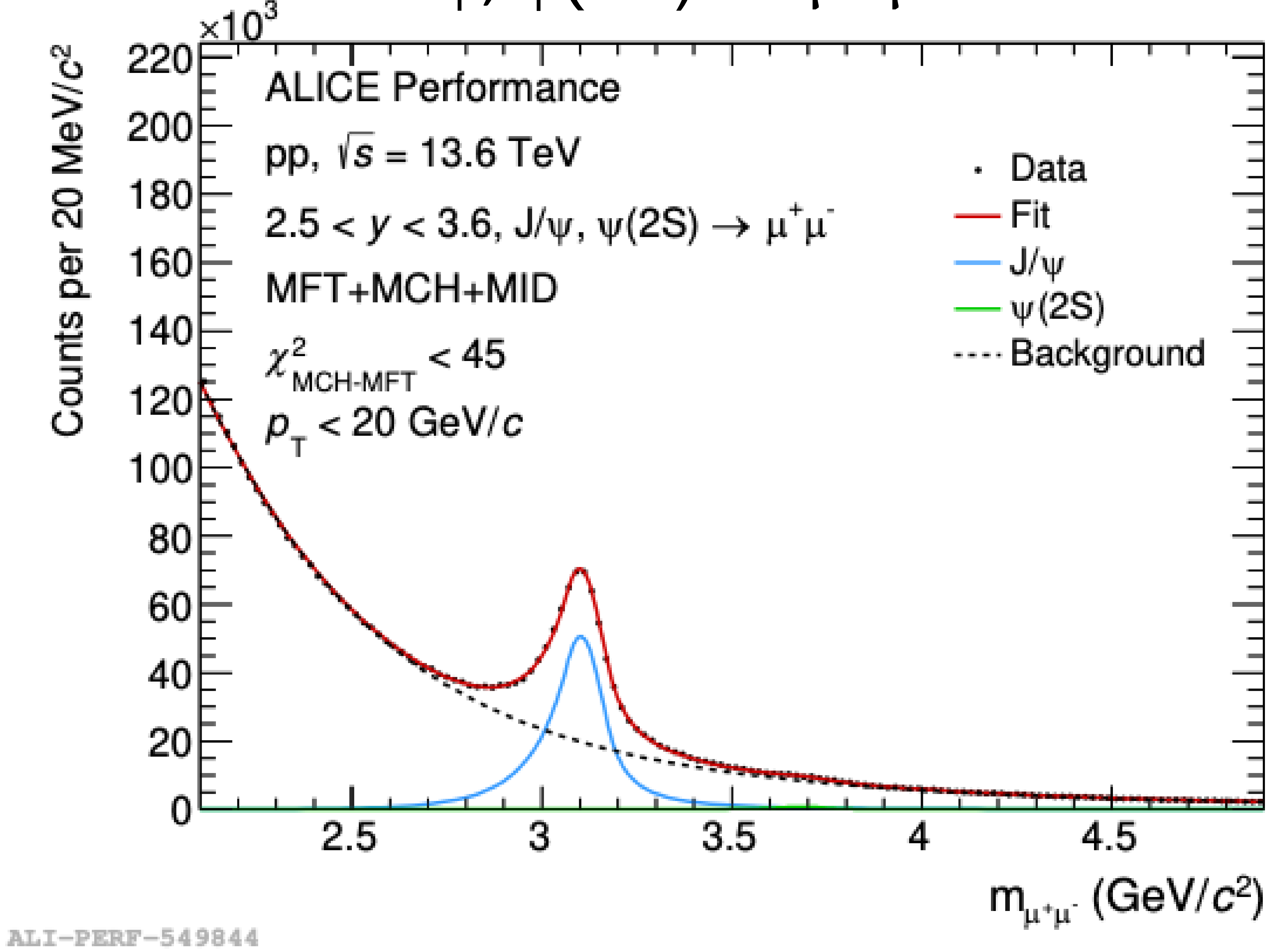
- Reconstruction of muon tracks together with existing Muon spectrometer.

Continuous readout → More statistics

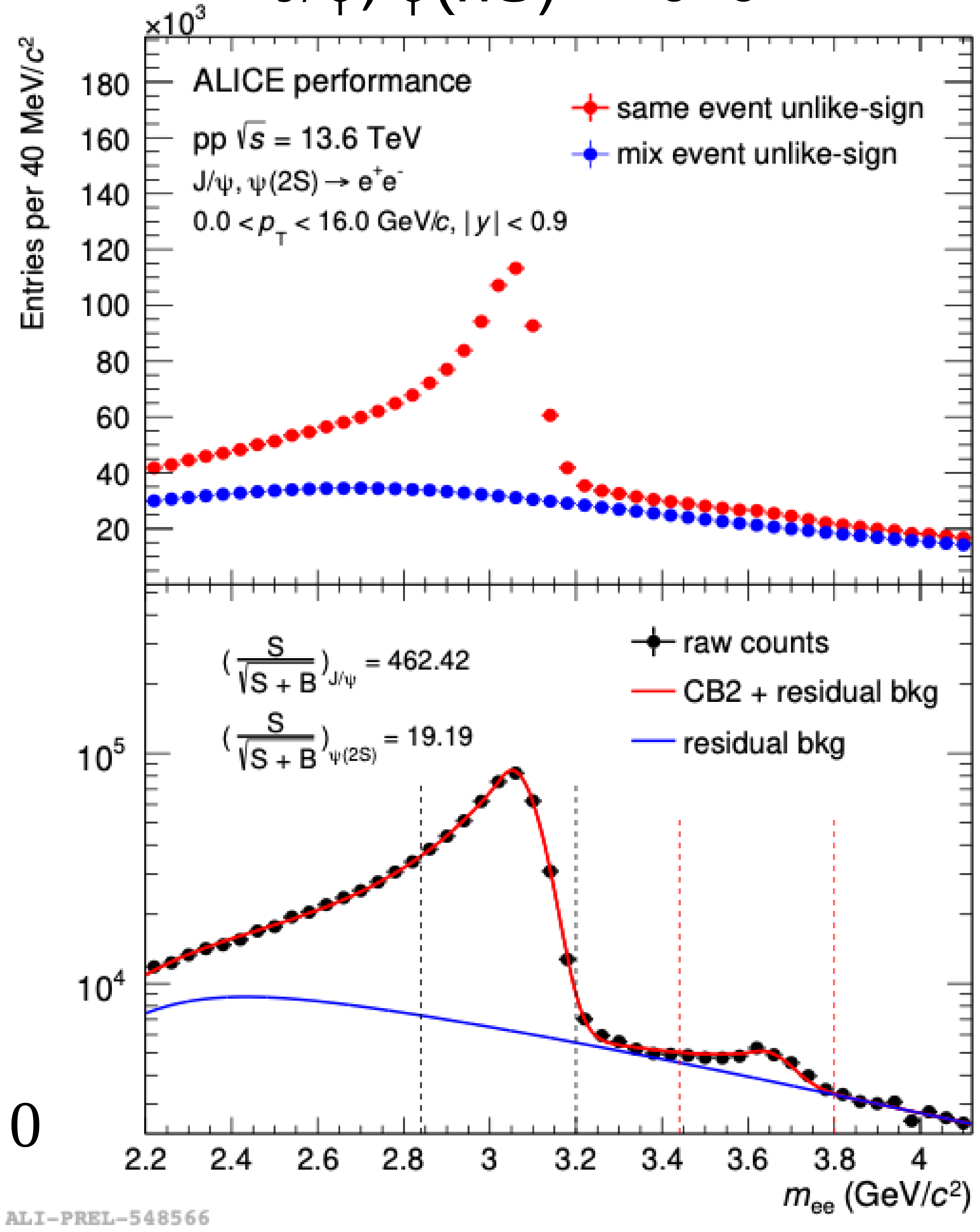
So far in Run 3 compared to Run 1 and 2 :
~ x 800 more pp, ~ x 30 more Pb−Pb min. bias collisions

Quarkonia reconstruction in ALICE

J/ψ, ψ(nS) → $\mu^+\mu^-$



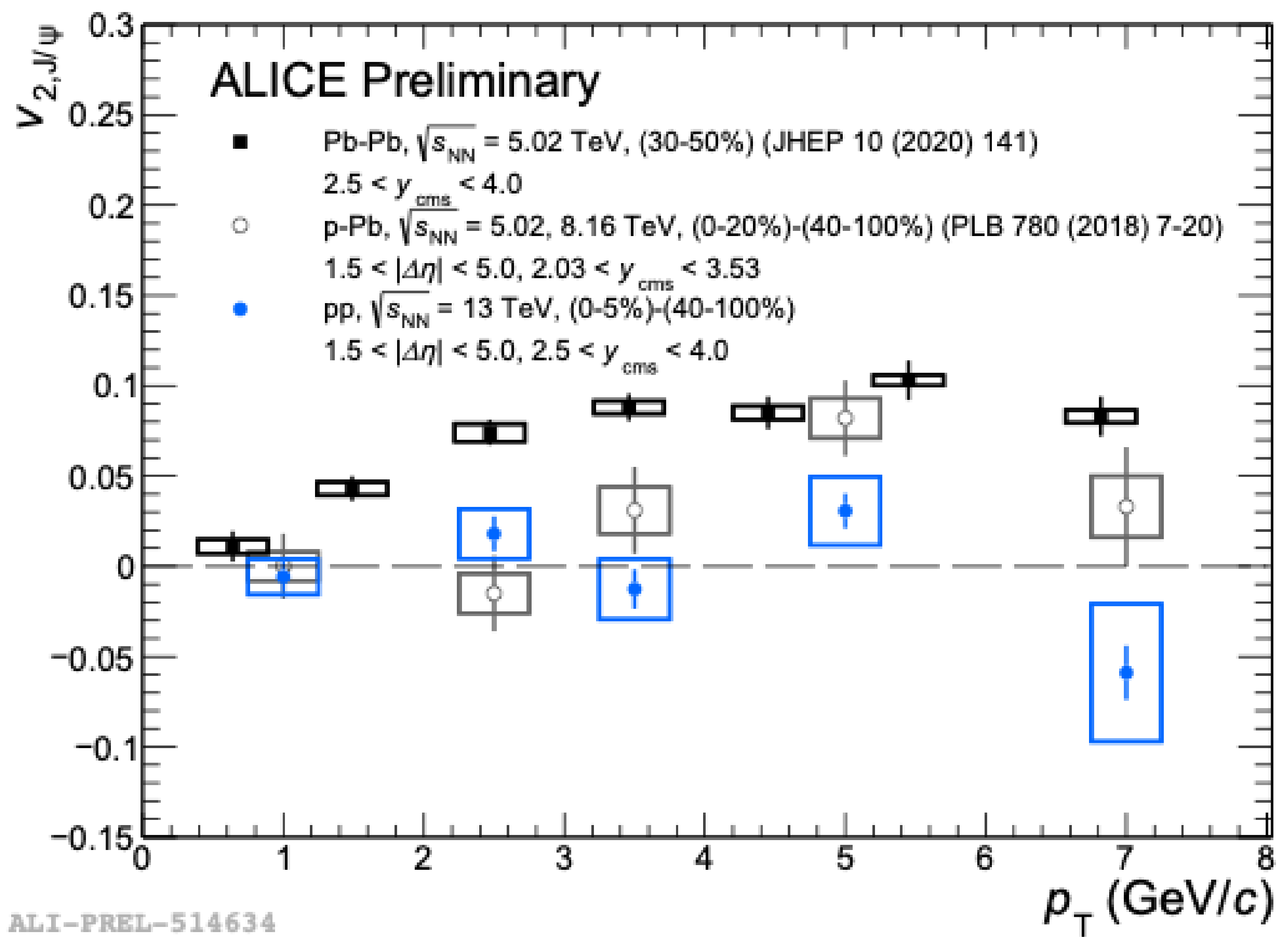
J/ψ, ψ(nS) → e^+e^-

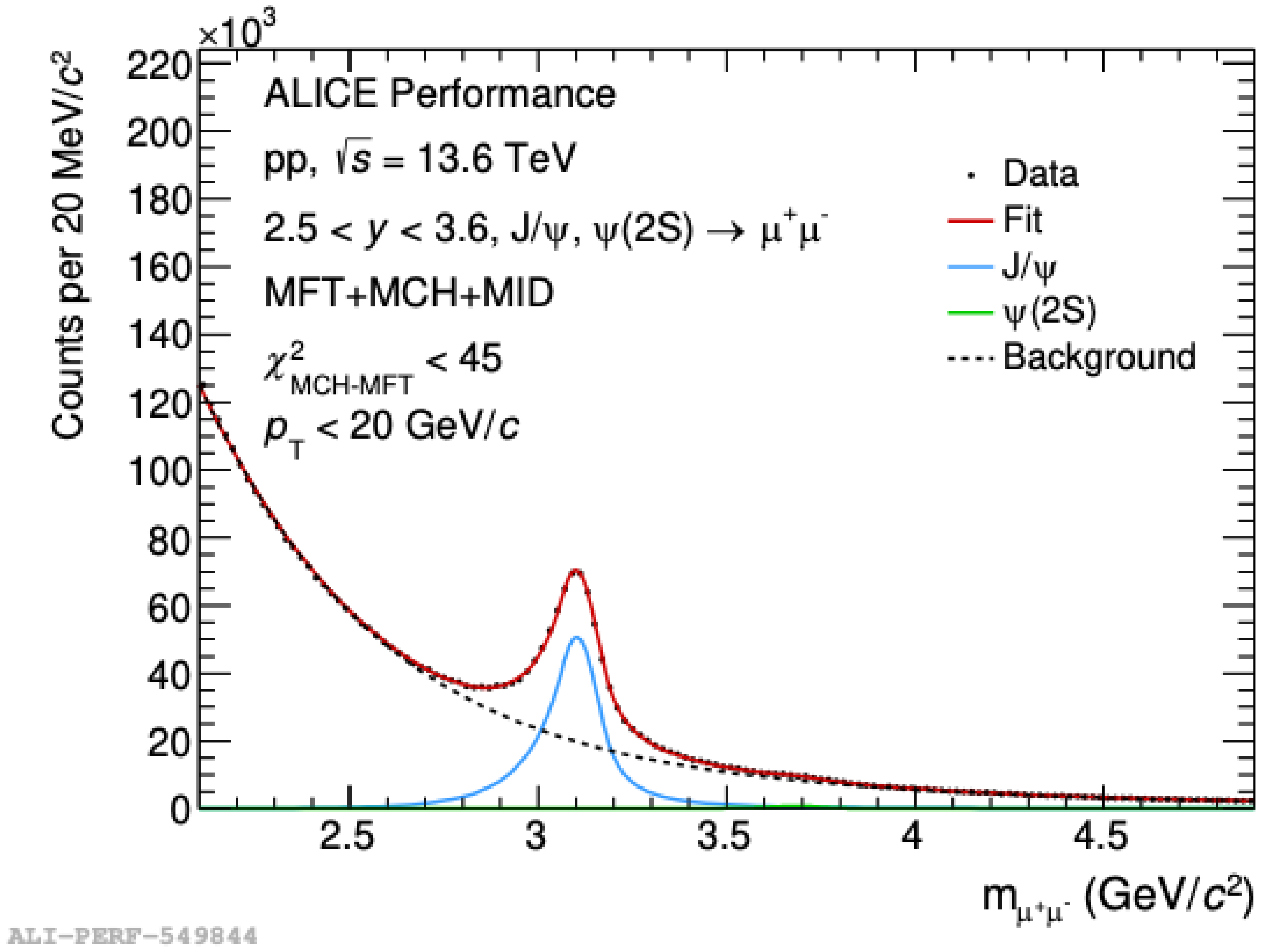


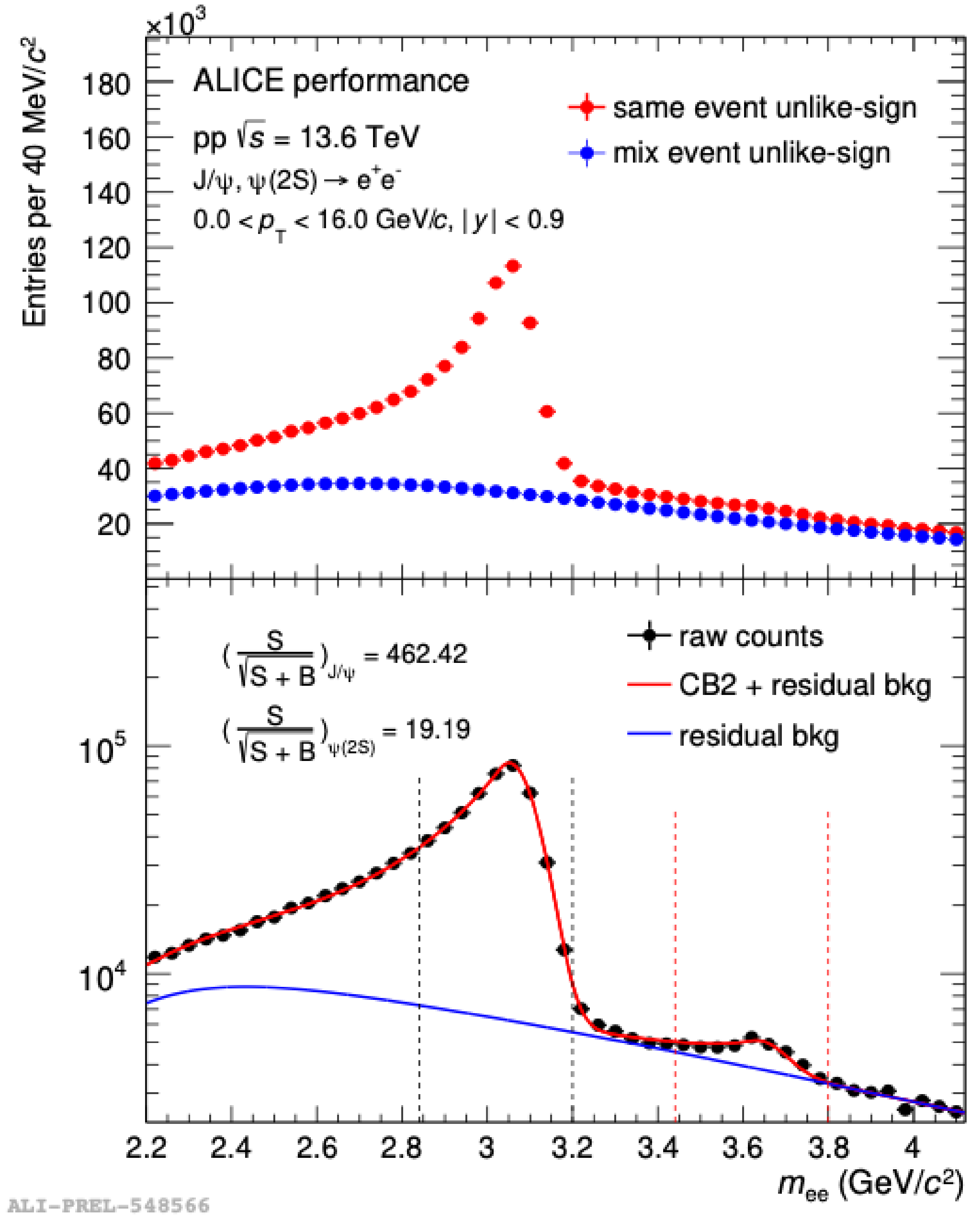
Quarkonia reconstructed at mid and forward rapidity down to $p_T = 0$

Summary

- A clear hierarchy of J/ψ elliptic flow from Pb–Pb, p–Pb to high-multiplicity pp is observed;
- Run 3 data taking ongoing with a huge boost in recorded luminosity – Stay tuned;
- More precise measurements will be possible in pp, and Pb–Pb in Run 3;
- J/ψ elliptic flow in pp collisions in ongoing...;





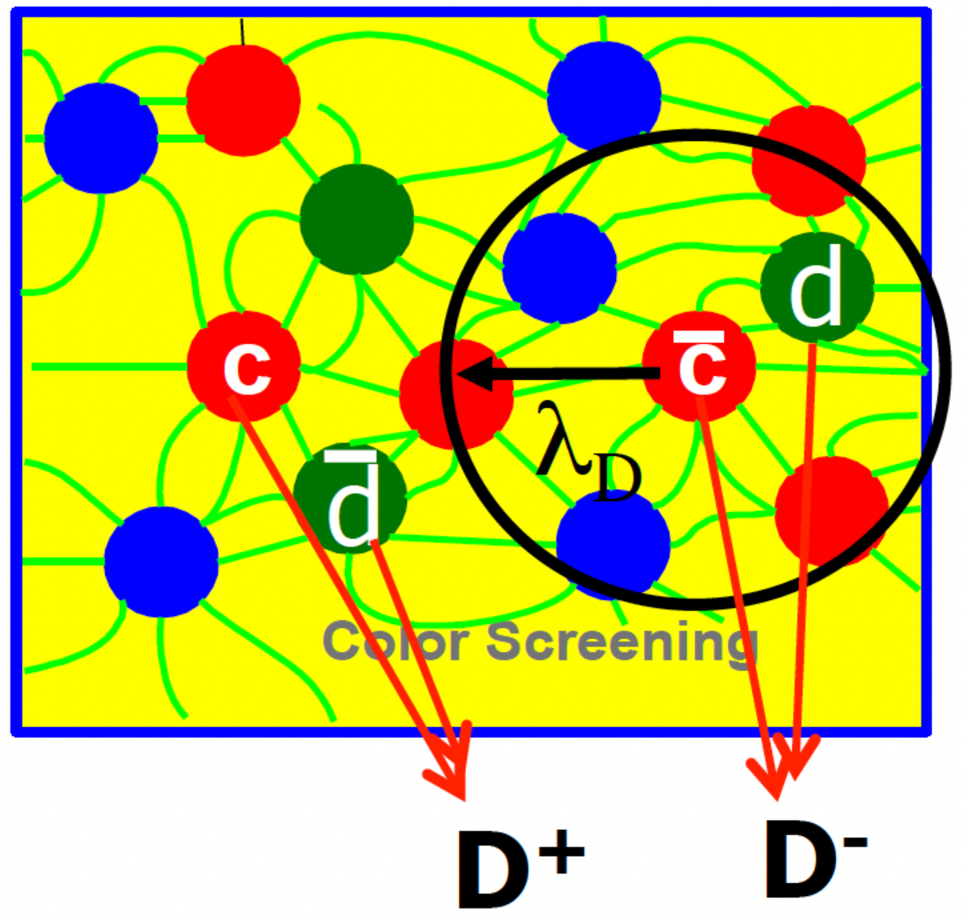


backup

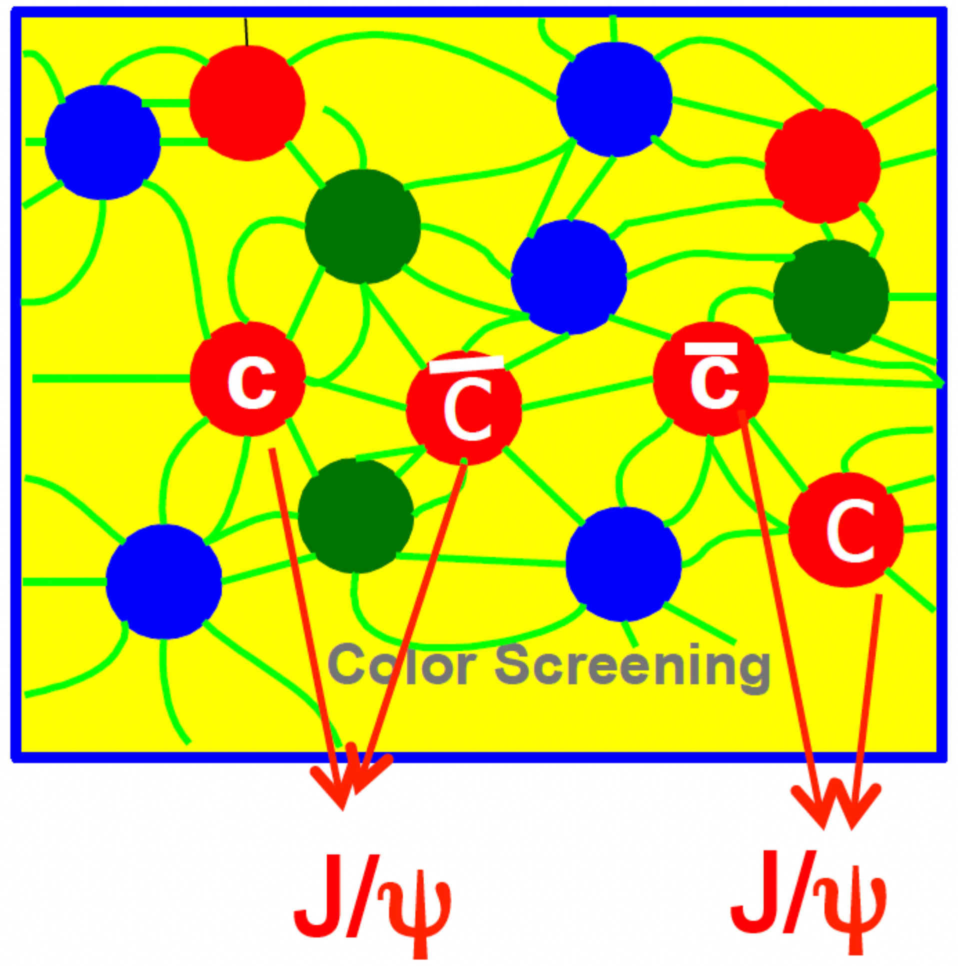
Hot nuclear matter effect (QGP)

- *Suppression due to color-screening*
- *Enhancement due to (re)generation*
- *Suppression due to b-quark energy loss*

QGP melting



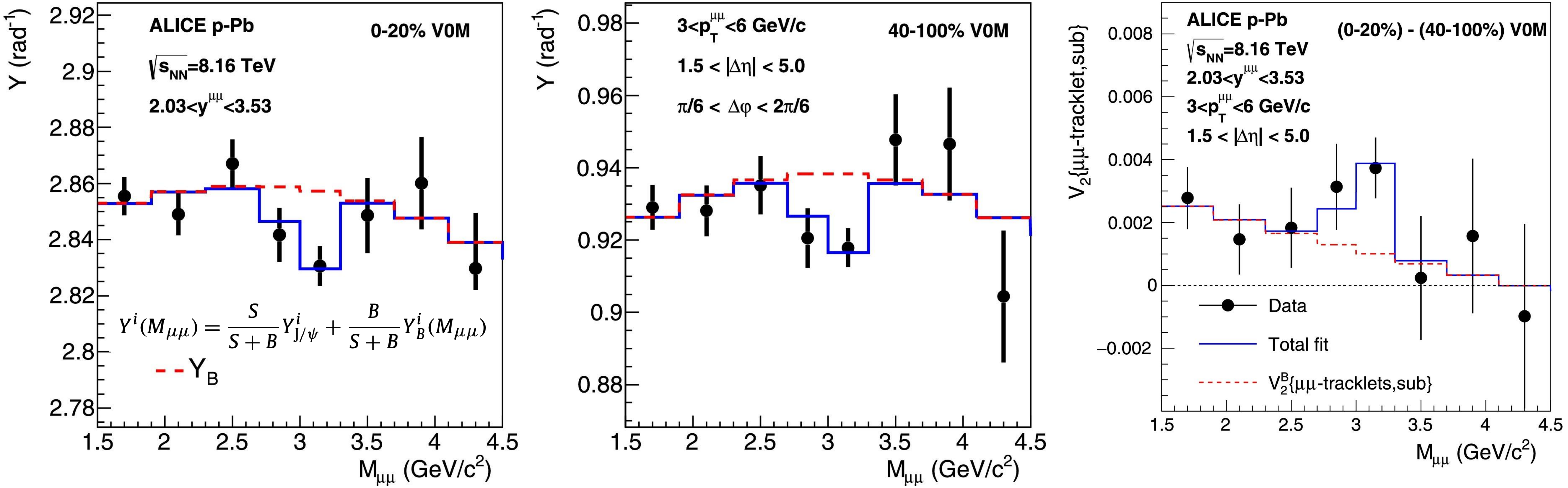
(Re)generation



ITS

	Run 2 (ITS 1)	Run 3 (ITS 2)
Technology	pixel, strip, drift	MAPS
# of layers	6	7
coverage	|η| ≤ 0.9	|η| ≤ 1.3
Material budget	1.14 % X_0	Innter: 0.36% X_0 Outer: 1.10% X_0
Spatial resolution	12 X 100 μm	5 X 5 μm
Max rate (Pb-Pb)	1 kHz	50 kHz

J/ψ v2 signal subtraction



1. $Y^i(\mathrm{M_{uu}}) = \frac{\mathrm{Sig}}{\mathrm{Sig{+}Bkg}} Y^i_{\mathrm{J}/\psi} + \frac{\mathrm{Bbk}}{\mathrm{Sig{+}Bkg}} Y^i_{\mathrm{B}}(\mathrm{M_{uu}})$ in central and peripheral, respectively

2. $a_0 + 2a_1\cos(\Delta\phi) + 2a_2\cos(2\Delta\phi)$

3. $\mathrm{V_2\{ee\text{-}h, sub\}\ (M_{uu})} = \frac{\mathrm{Sig}}{\mathrm{Sig{+}Bkg}} \mathrm{V_2}\{\mathrm{J}/\psi, \mathrm{sub}\} + \frac{\mathrm{Bbk}}{\mathrm{Sig{+}Bbkg}} \mathrm{V_2\{bkg\}(M_{uu})}$

📖 Phys. Lett. B 780 (2018) 7-20