Strange, charm, and bottom hadrons flow in pPb and PbPb with CMS

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On behalf of the CMS collaboration

Indian Institute Of Technology Madras

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Outline

Collective Phenomena:

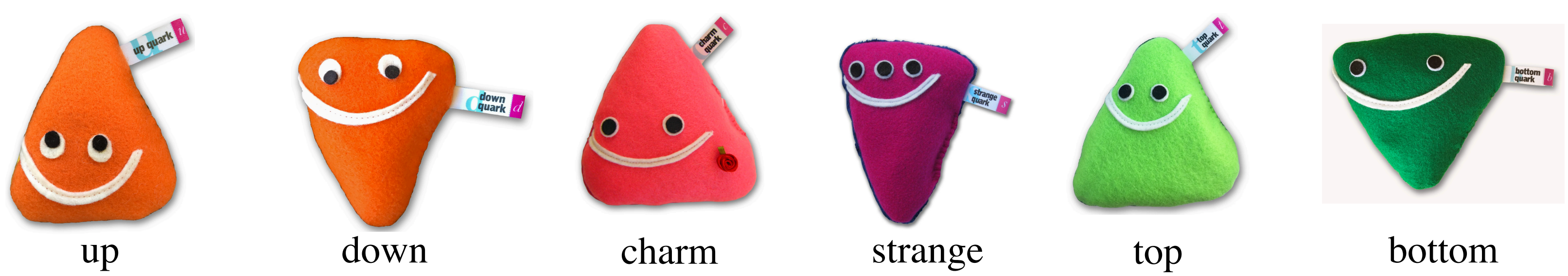
In large system (A-A collisions):

- What are the properties of the medium created?
- How partons interact with the medium?

In small system (p-p and p-A collisions):

- Do we observe similar effect in small system as in large system?

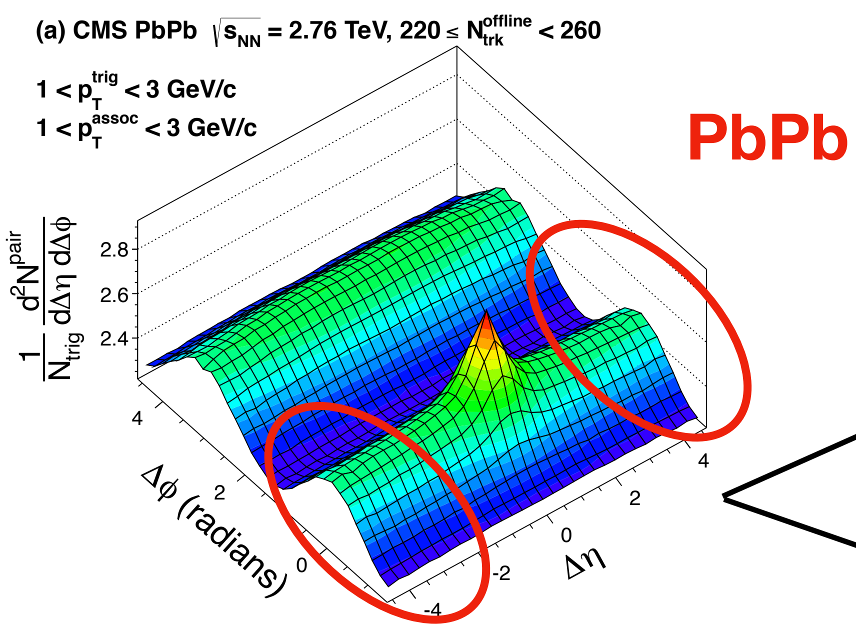
Flavor in CMS:



- **Light Flavor:** up, down, strange and multi-strange hadron
- **Heavy Flavor:** charm, bottom, top

Introduction:Two Particle Correlation

Long range(|Δη| > 2), near side(Δϕ≃0) angular correlation



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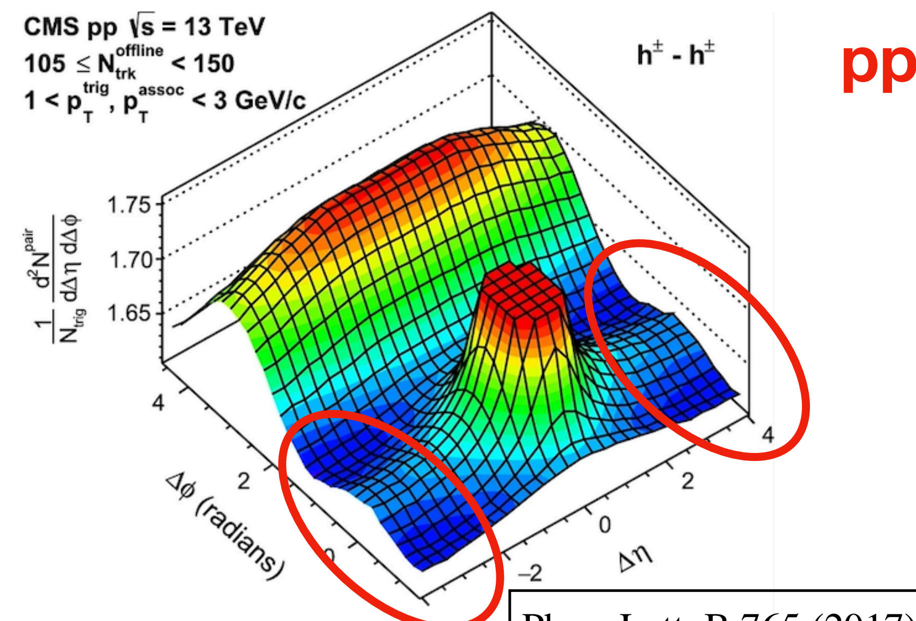
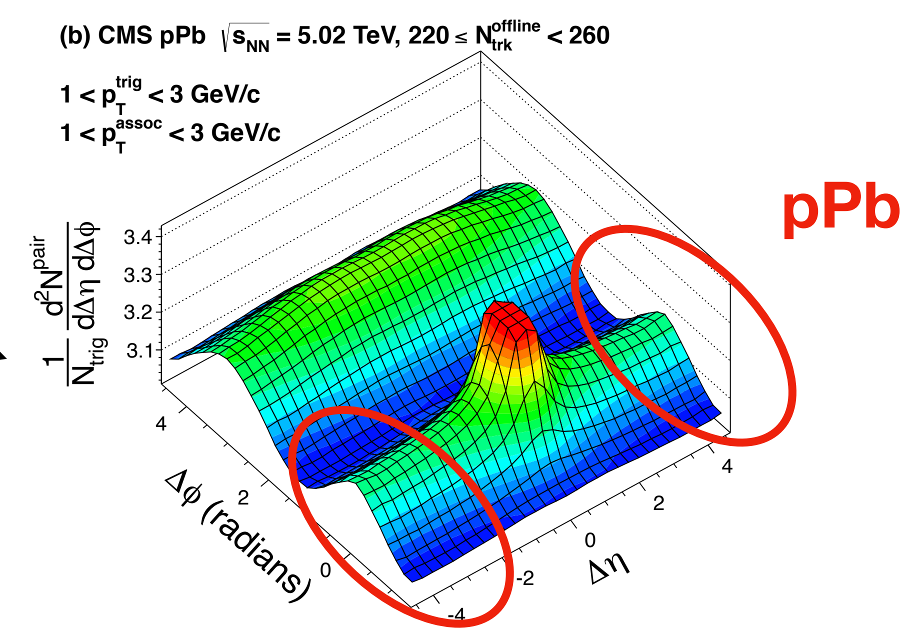
Similar ridge observed in pp and pPb also

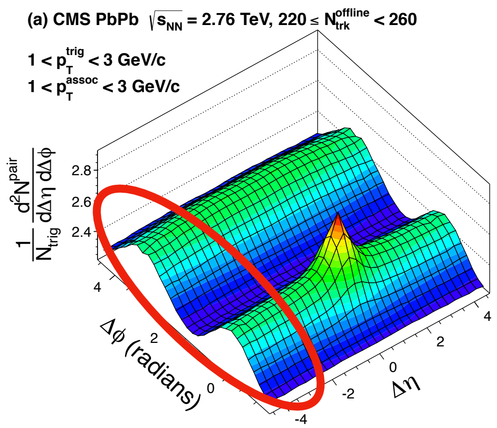


Phys. Lett. B 765 (2017) 193



Phys. Rev. Lett. 120, 092301 (2018)

Nature of the ridge



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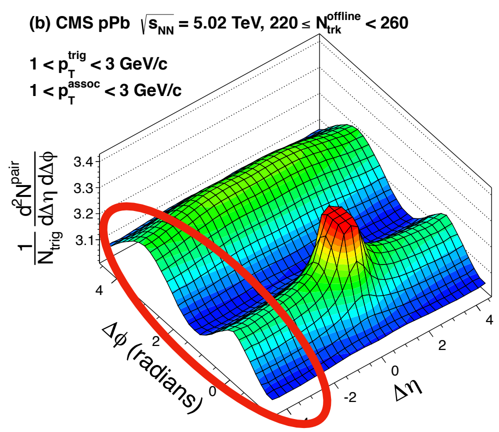

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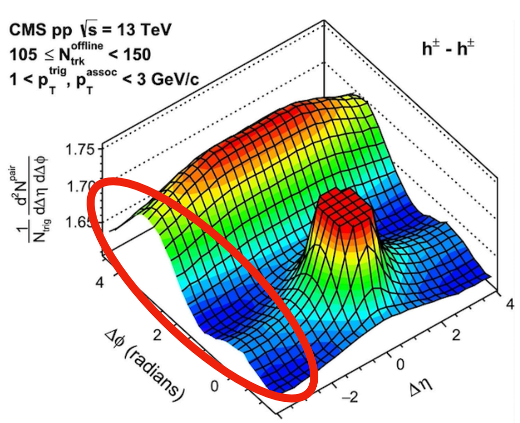

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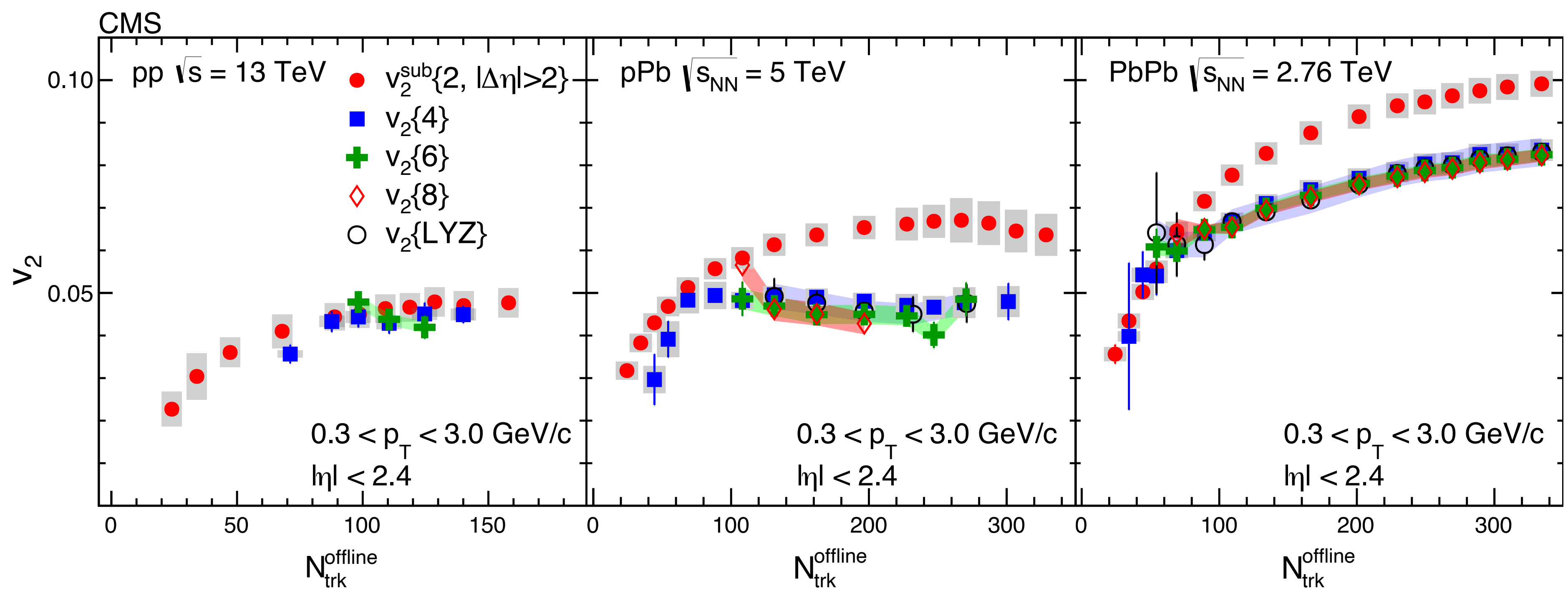

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pp ⟶ $v_2\{2\} \simeq v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\}$

pPb and PbPb ⟶ $v_2\{2\} \geq v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\}$

Collective behavior !

Collective nature:

- Multi particle correlation
- Similar pattern for all the system

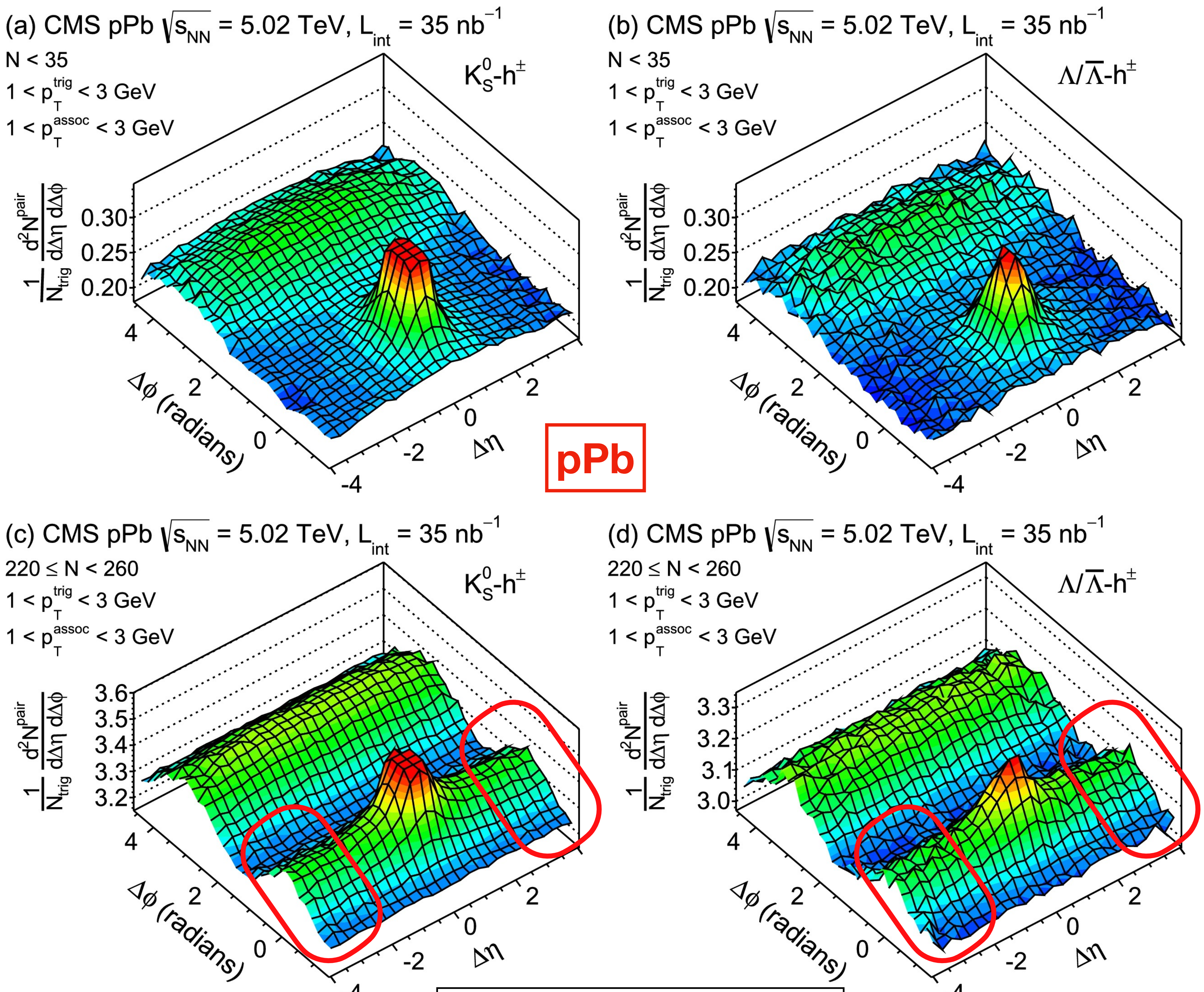
✦ Is this a sign of hydro in small system?

✦ Is it collectivity in small system?

Ridge in strange hadron

Low multiplicity →

High multiplicity →



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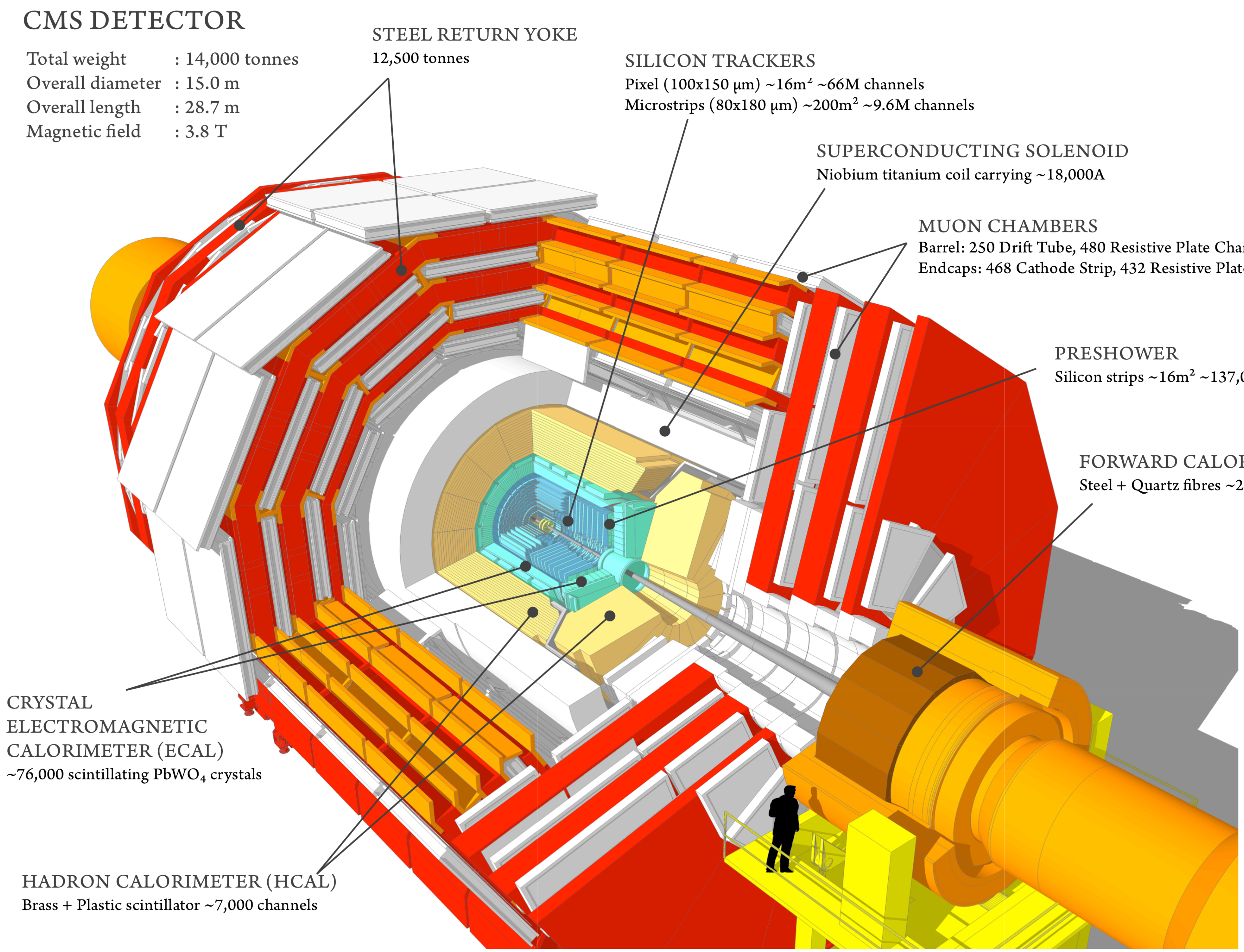
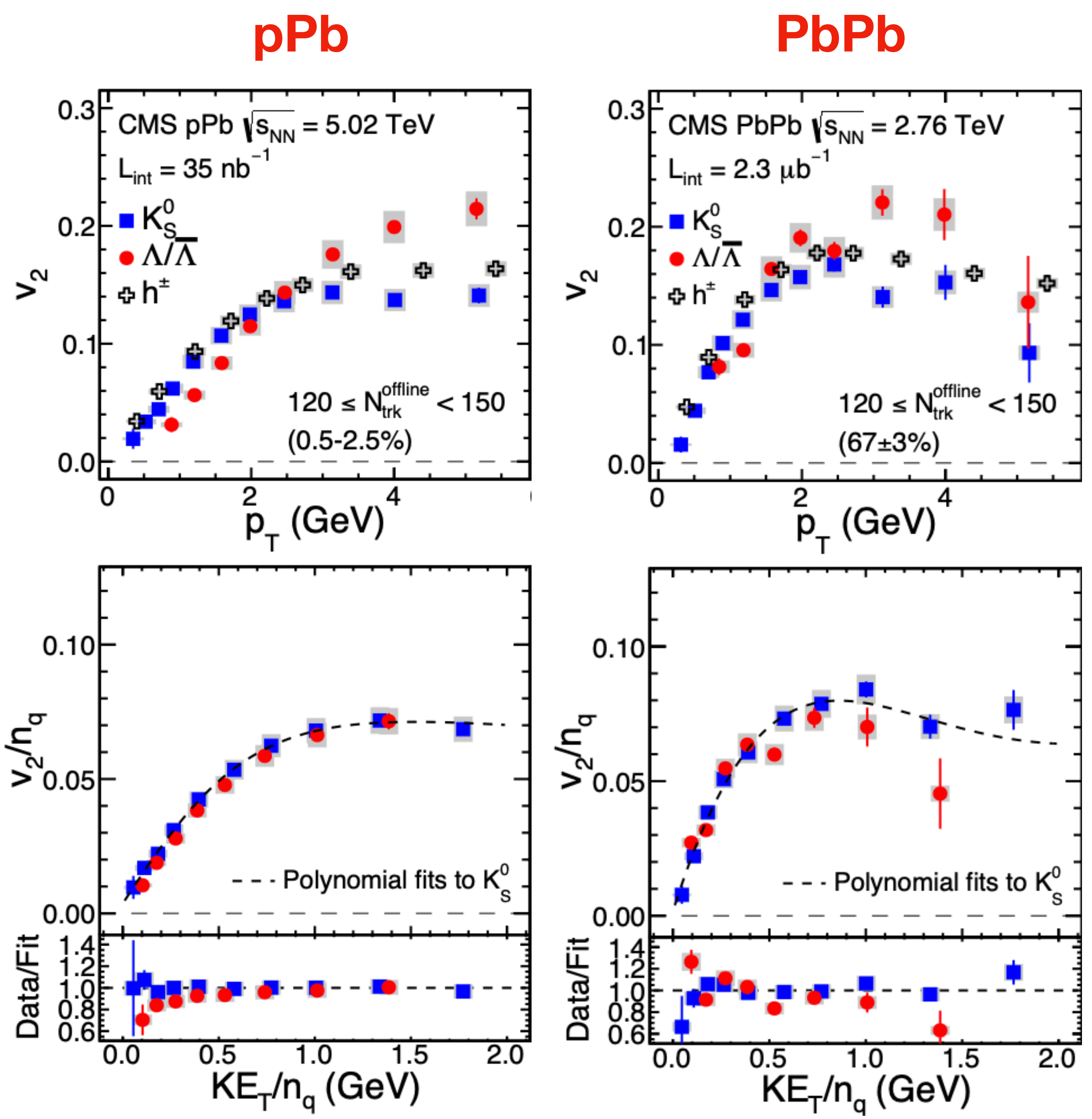
CMS Detector



Strange hadron v_2

p_T dependence v_2 of k_S^0, Λ from long range correlation

- Significant p_T dependent v_2 in both pPb and PbPb
- Follow mass ordering at low p_T (Radial flow)
- Number of constituent quark scaling:
  - Strange hadrons following universal trend in pPb
  - Violation in PbPb up to 25% compared to pPb in higher KE_T/n_q



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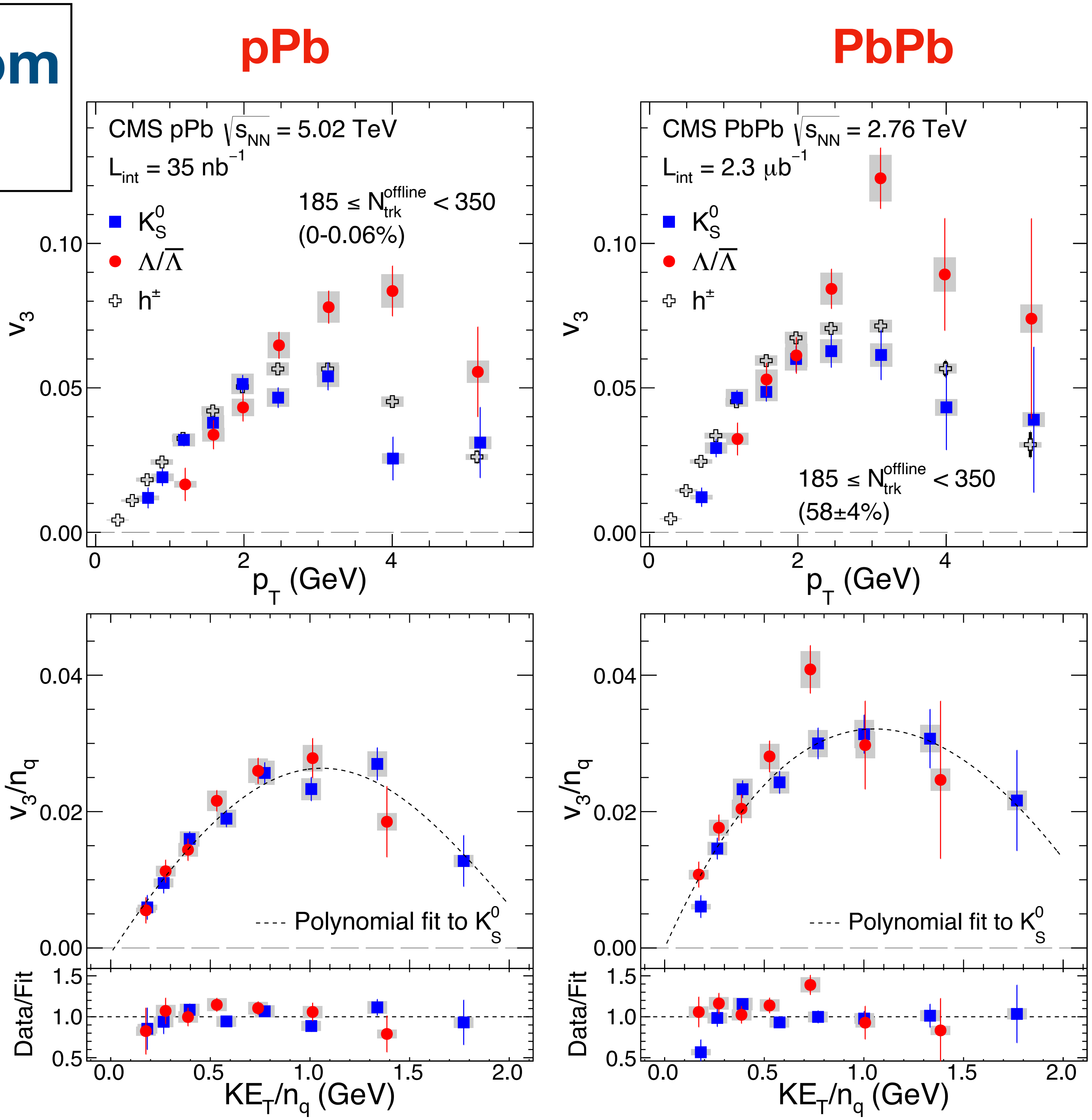
Strange hadron v_3

p_T dependence v_3 of k_S^0, Λ from long range correlation

- Significant p_T dependent v_3 in both pPb and PbPb
- Positive v_3 signifies geometry driven fluctuation
- Both pPb and PbPb showing similar behavior for strange hadron.
  - Similar origin?



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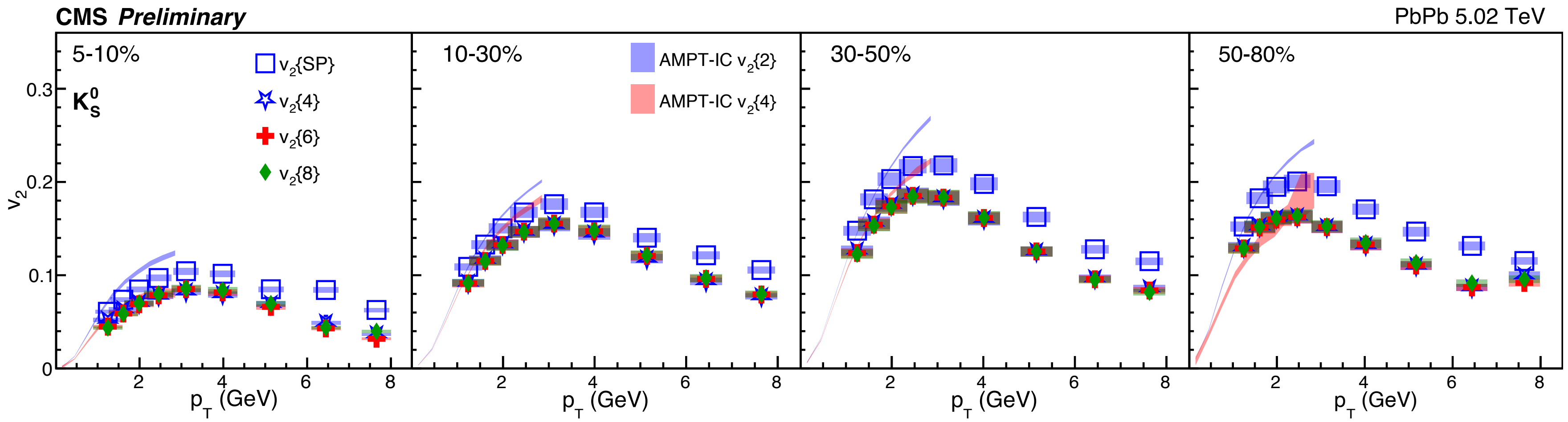
Strange hadron v_2

p_T dependence v_2 of k_S^0 from multi-particle correlation

PbPb

- $v_2\{SP\} > v_2\{4,6,8\}$
- $v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\}$

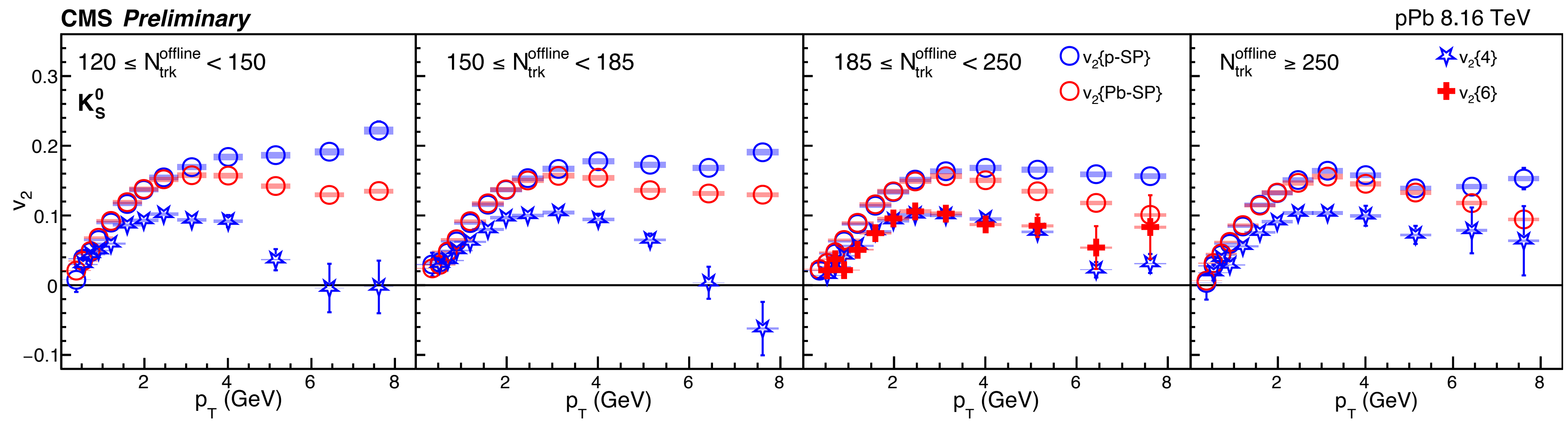
$v_2\{SP\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$



pPb

- $v_2\{SP\} > v_2\{4,6,8\}$
- $v_2\{4\} \simeq v_2\{6\}$

$v_2\{p\text{-}SP\}$, $v_2\{Pb\text{-}SP\}$, $v_2\{4\}$, $v_2\{6\}$

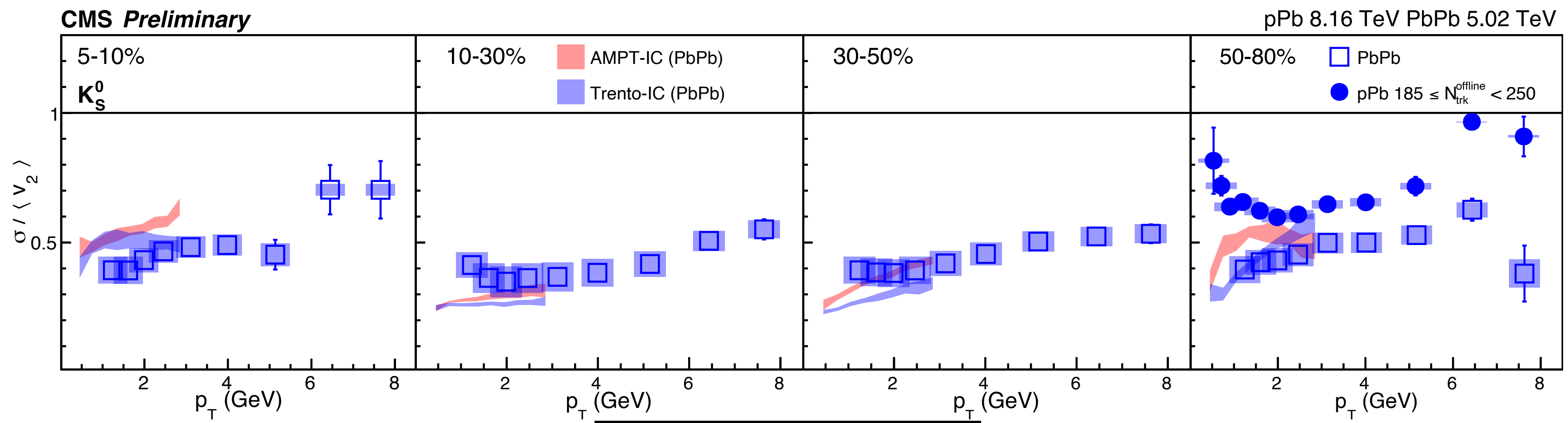


$$\frac{\sigma}{\langle v_2 \rangle} = \sqrt{\frac{v_2\{sp\} - v_2\{4\}}{v_2\{sp\} + v_2\{4\}}}$$

AMPT-IC

Trento-IC

- $\frac{\sigma}{\langle v_2 \rangle}$ (pPb > PbPb)



CMS-PAS-HIN-19-004

Strange hadron v_2

p_T dependence v_2 of Λ from multi-particle correlation

PbPb

- $v_2\{SP\} > v_2\{4,6,8\}$
- $v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\}$

$v_2\{SP\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$

pPb

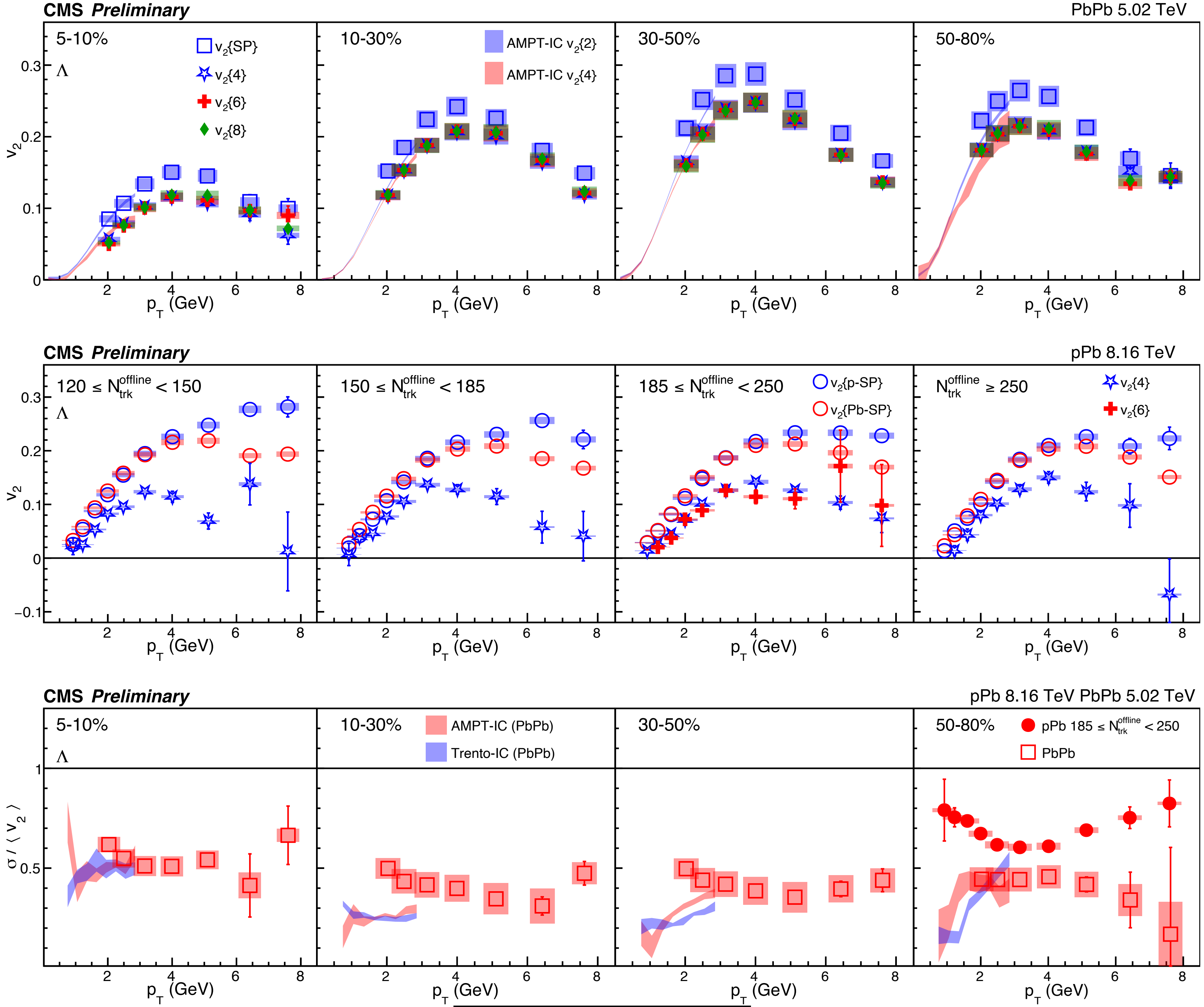
- $v_2\{SP\} > v_2\{4,6,8\}$
- $v_2\{4\} \simeq v_2\{6\}$

$v_2\{p\text{-}SP\}$, $v_2\{Pb\text{-}SP\}$, $v_2\{4\}$, $v_2\{6\}$

$$\frac{\sigma}{\langle v_2 \rangle} = \sqrt{\frac{v_2\{sp\} - v_2\{4\}}{v_2\{sp\} + v_2\{4\}}}$$

AMPT-IC, Trento-IC

- $\frac{\sigma}{\langle v_2 \rangle}$ (pPb > PbPb)



CMS-PAS-HIN-19-004

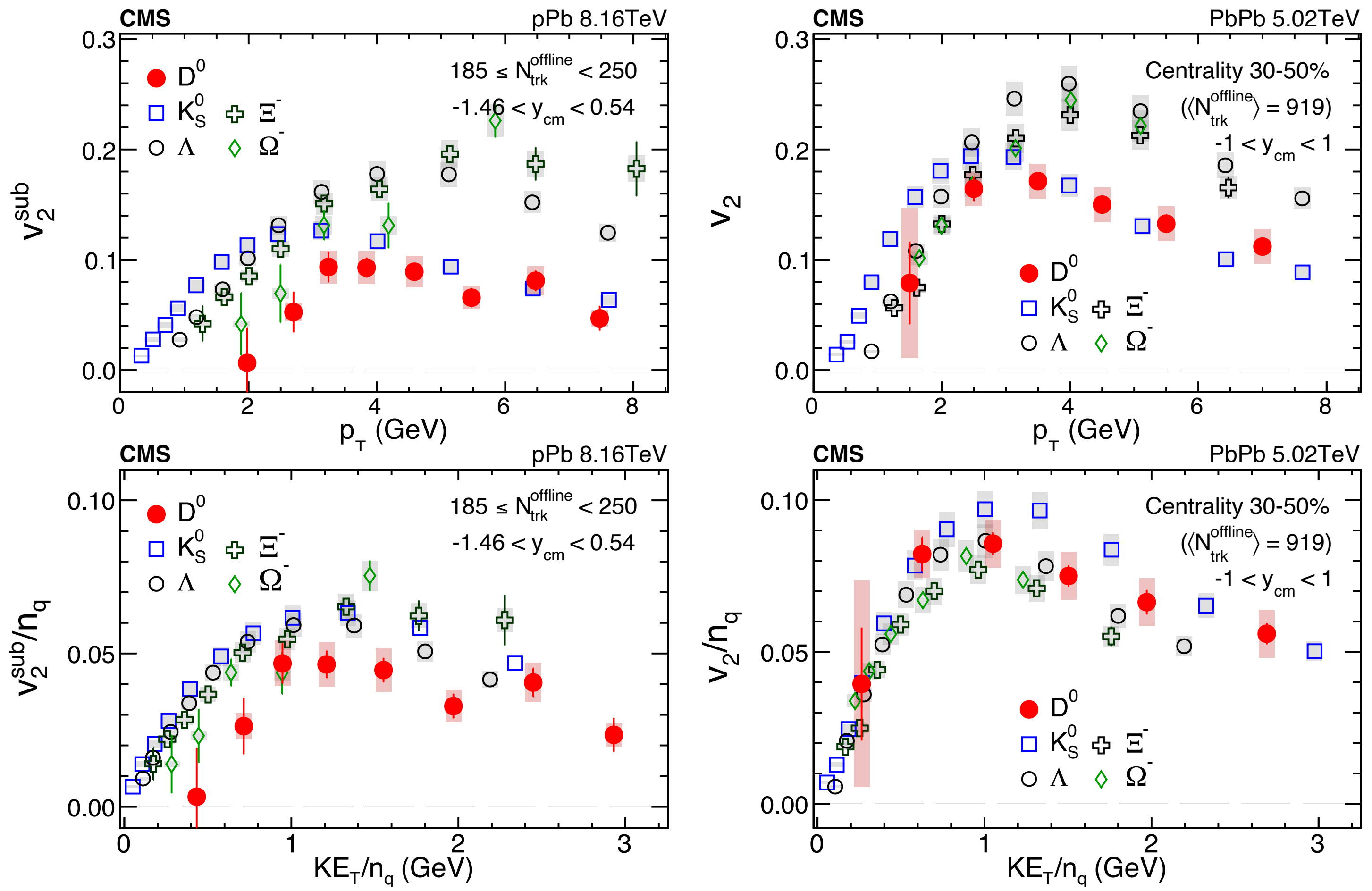
Charm hadron v_2

p_T dependence v_2 of prompt D^0

- Heavy quarks are produced in the early stage of collisions
  - Experience the full evolution of the produced medium
- Clear trend of rising and declining with p_T
- Clear mass ordering at $p_T < 2$ GeV in pPb
  - Indicating significant collective behavior of charm quark in small system
- v_2^{sub}/n_q of D^0 in $KE_T/n_q < 1.5$ GeV, is smaller than strange hadron in pPb
  - Weaker collectivity of charm quark in pPb
- In PbPb, following universal trend in $KE_T/n_q < 1.0$ GeV
  - Strong collectivity in PbPb

pPb

PbPb

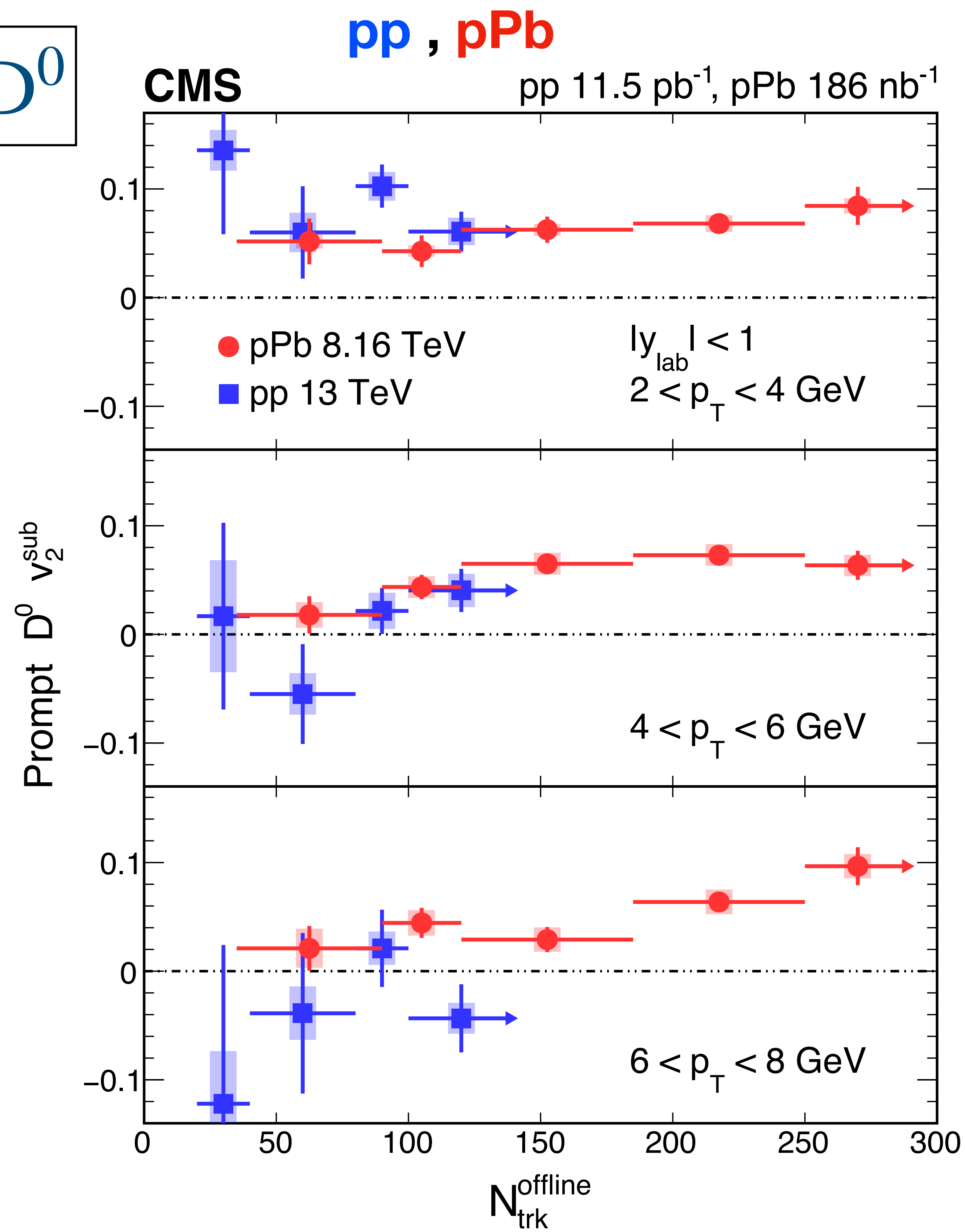


Phys. Rev. Lett. 121, 082301 (2018)

Charm hadron v_2

Multiplicity dependence v_2 of prompt D^0

- Significant positive v_2 down to $N_{trk} \approx 50$ for $2 < p_T < 4$ GeV in pPb
- Compatible magnitude of v_2 between pp and pPb for region with similar multiplicity in $2 < p_T < 4$ GeV
- v_2 signal tend to diminish in pPb as multiplicity decrease for $p_T > 6$ GeV

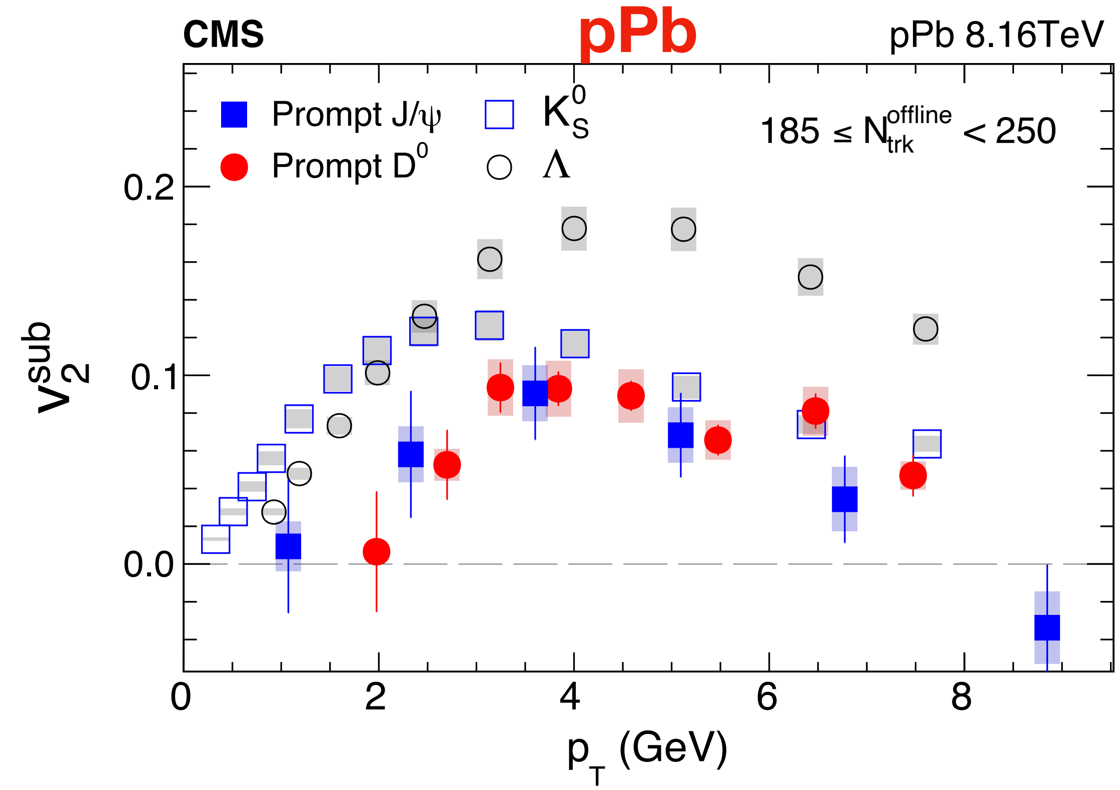


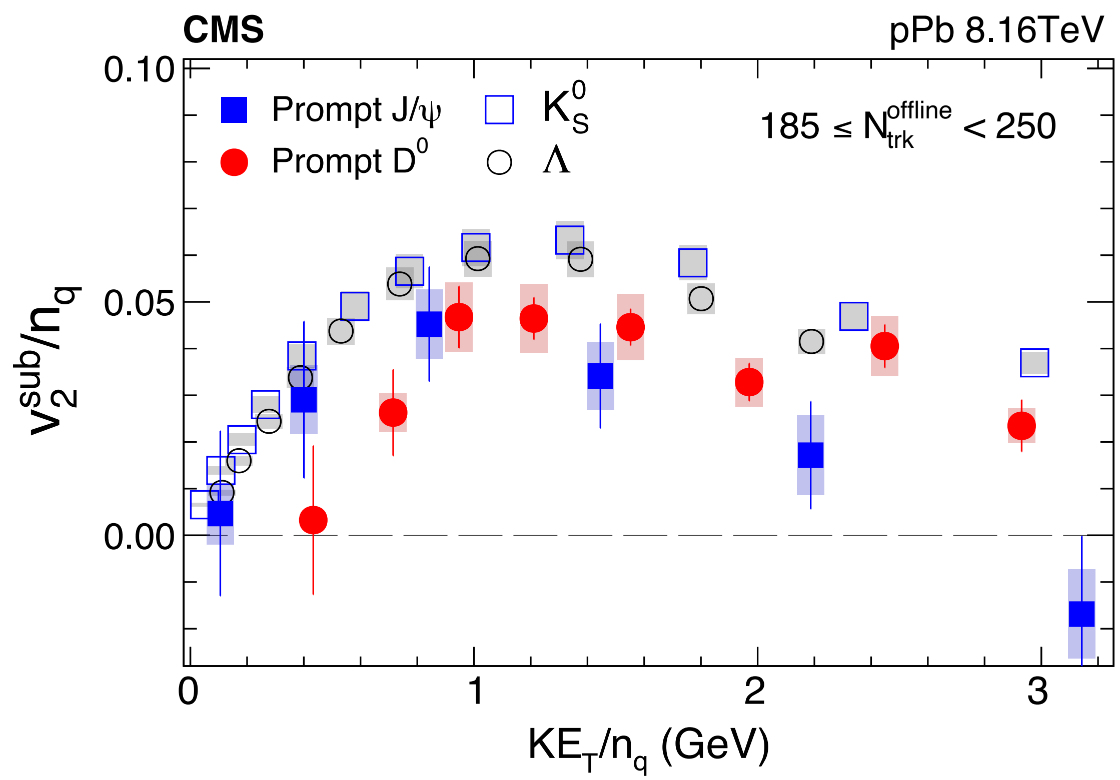
Phys. Lett. B 813 (2021) 136036

Charm hadron v_2

Adding prompt J/ψ

- Heavy quarks are produced in the early stage of collisions
  - Experience the full evolution of the produced medium
- Positive v_2 value in $2 < p_T < 8$ GeV
- $v_2(D^0)$ and $v_2(J/\psi)$ smaller than strange hadron in entire p_T range
  - $v_2(c) < v_2(u, d, s)$
  - Flavor hierarchy
- $v_2^{sub}/n_q(J/\psi) < v_2^{sub}/n_q(D^0)$, for $KE_T/n_q >$ 1.0 GeV
  - $D^0(c,\bar{u})$, $J/\psi(c,\bar{c})$





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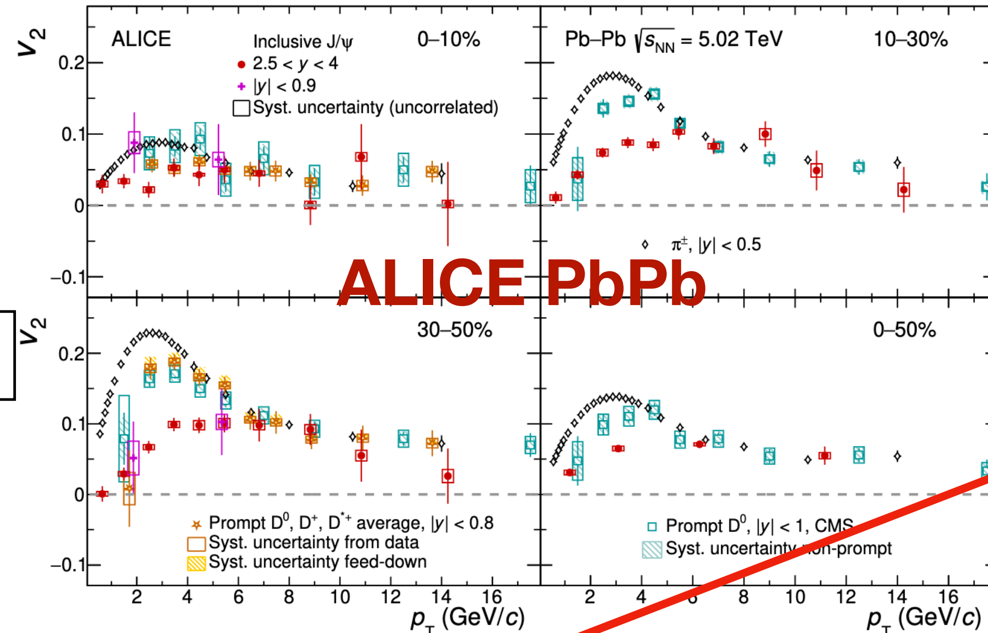
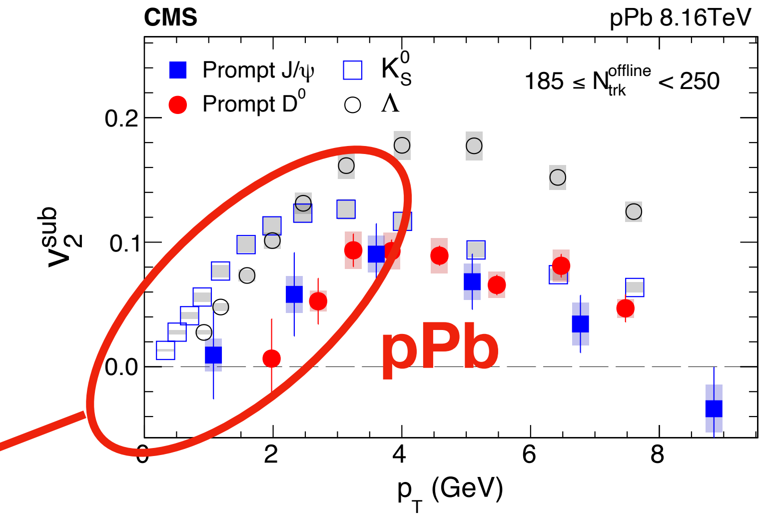
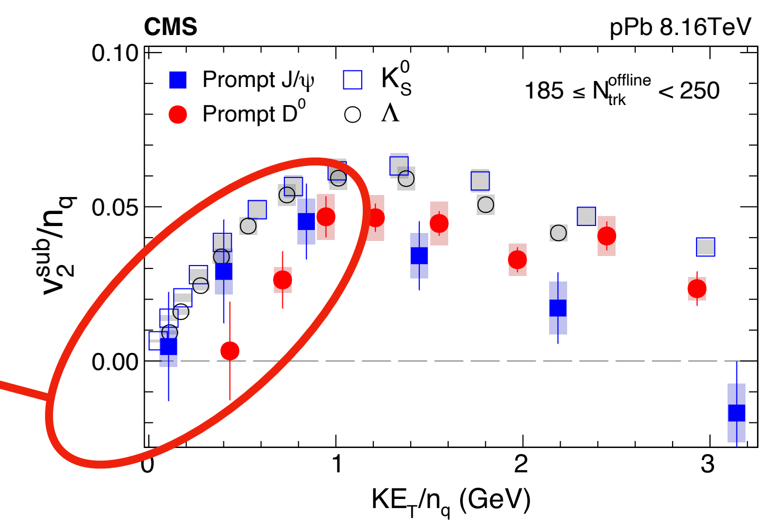
Charm hadron v_2

Adding prompt J/ψ

JHEP10(2020)141







Surprisingly!

- v_2^{sub}/n_q of J/**ψ** in KE_T/n_q< 1.0 GeV, is greater than v_2^{sub}/n_q of D^0 in pPb

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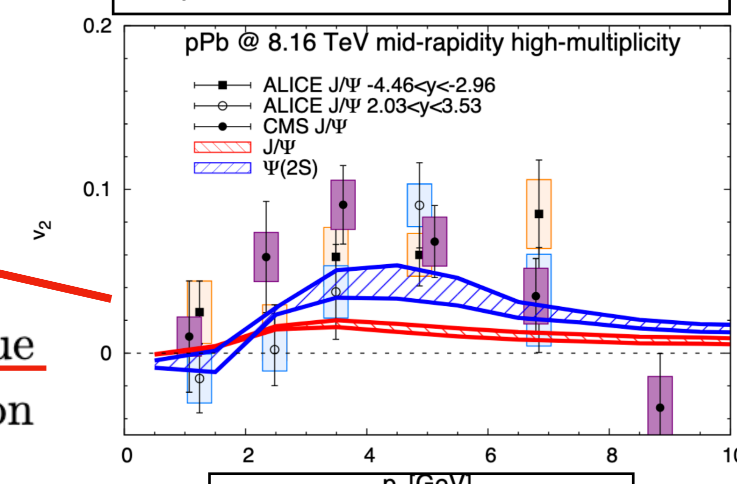
- From hydrodynamic model calculation, v_2 of J/**ψ** should come below D^0



✦ Final state interaction alone can not explain this.

LHC data. We are therefore forced to conclude that this signal must be in large part due to initial-state (or pre-equilibrium) effects not included in our approach. This situation

JHEP03(2019)015

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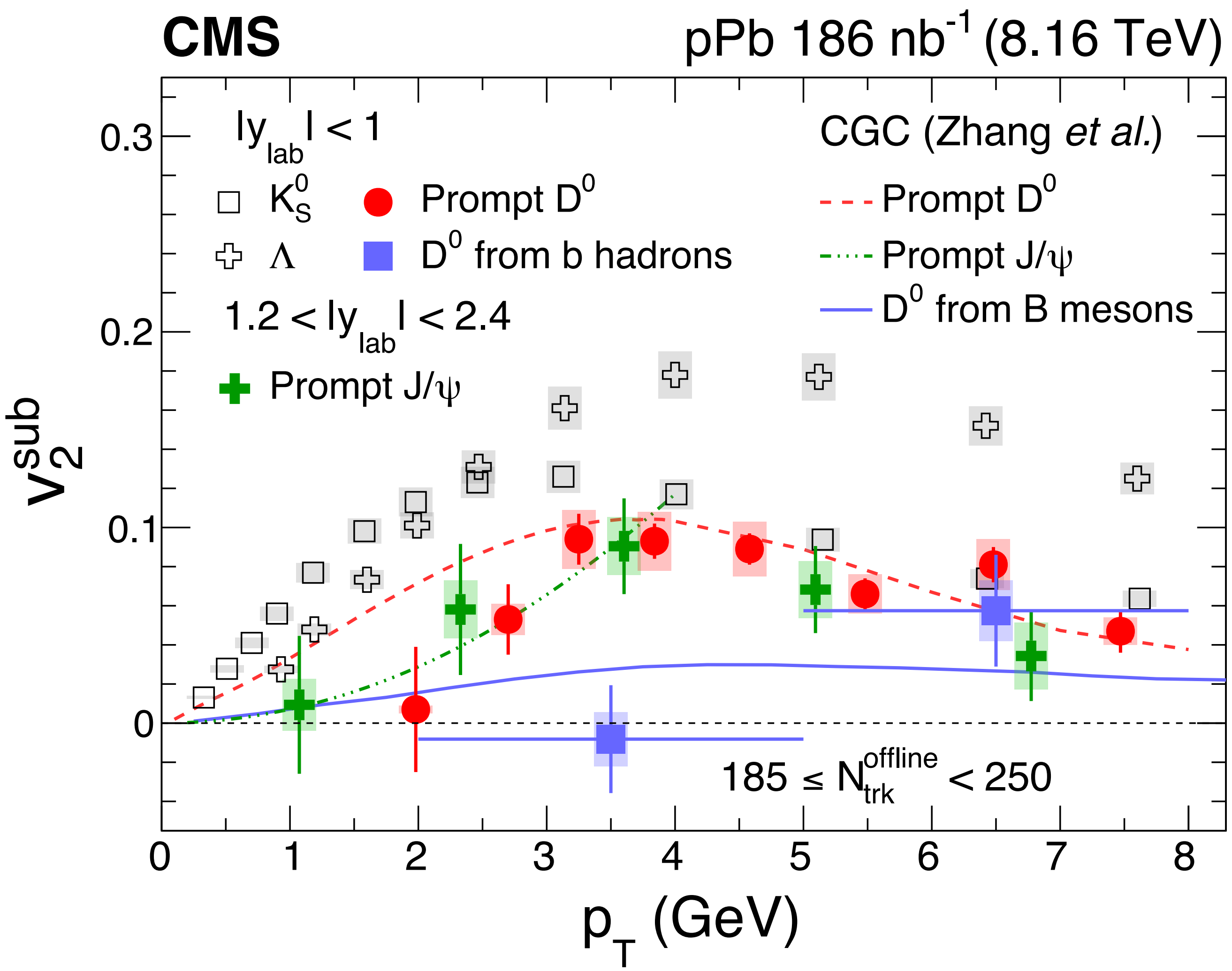
Prediction from CGC model

- Prediction of J/ψ v_2 from CGC model
  - Correlations between partons originated from the projectile proton and dense gluons inside the target nucleus
- Qualitative agreement between data and theory for J/ψ
  - Suggesting that initial-state effects may play an important role in the generation of collectivity for these particles in pPb collisions

pPb



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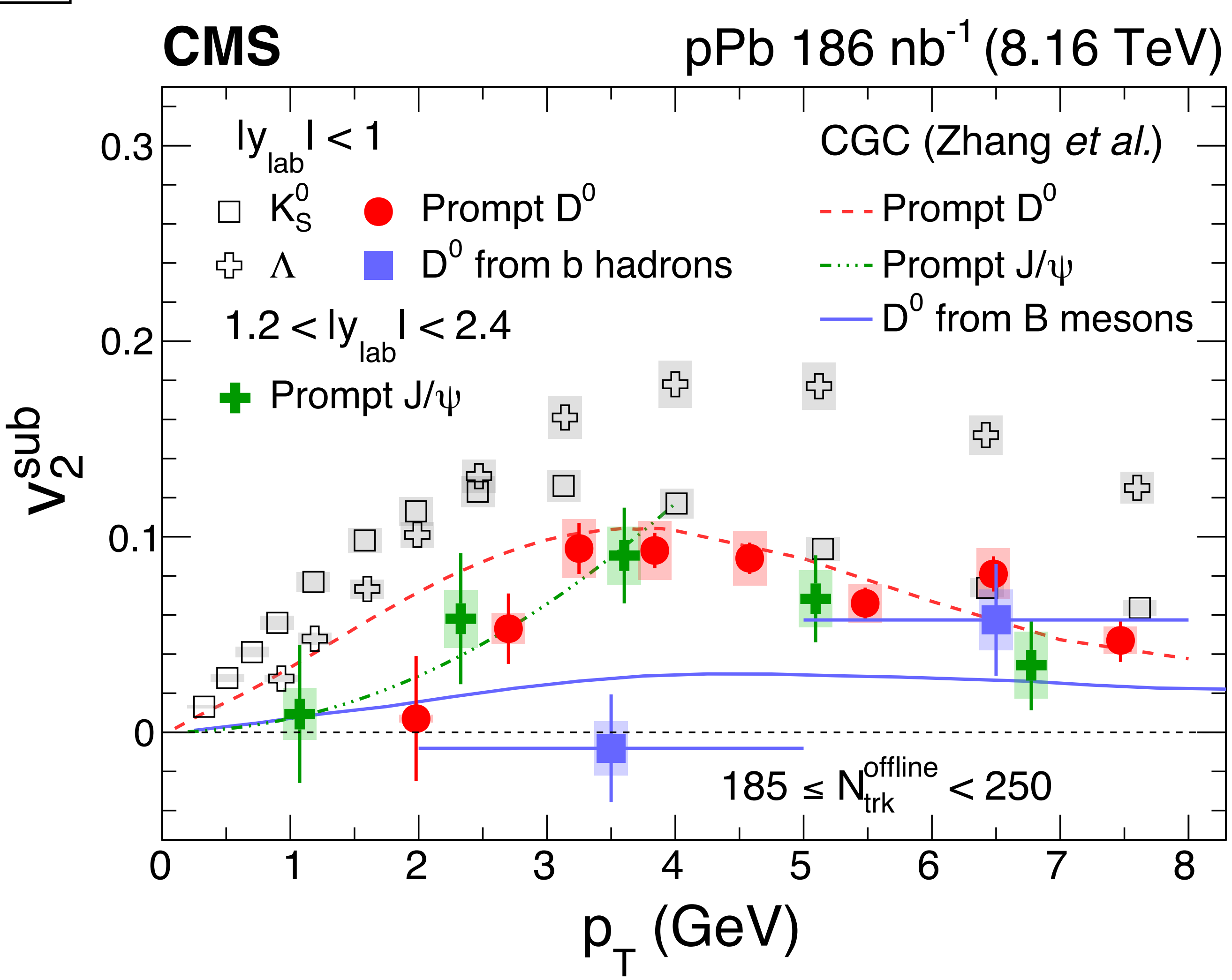
Bottom hadron v_2

p_T dependence v_2 of non prompt D^0

- Non-prompt D^0 originate primarily from B hadron
  - Contain 50% of B transverse momenta based on MC simulations using PYTHIA 8.209 and tune CUETP8M1
- Have a larger distance of closest approach
- v_2 of non-prompt D^0 consistent with zero in low p_T, while in high p_T, hint of a positive v_2
- v_2(prompt D_0) > v_2(non-prompt D_0) in 2< p_T < 5 GeV
- Indication of Flavor hierarchy of collectivity signal
  - Heavier quark tend to develop a weaker collective v_2 signal

pPb



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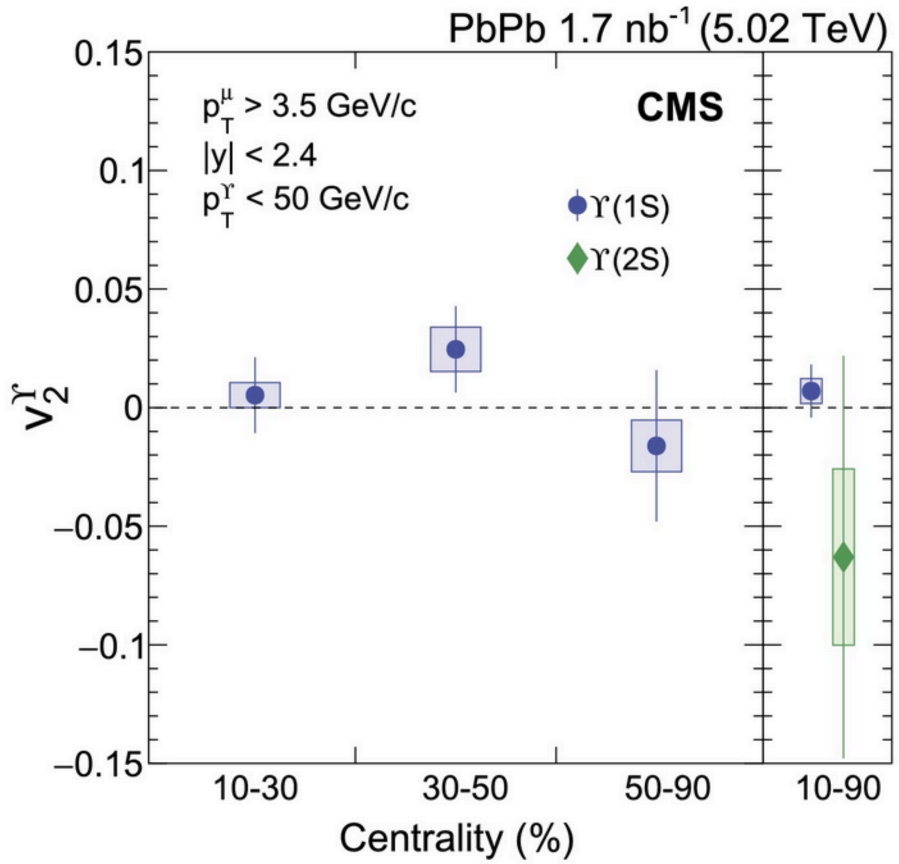
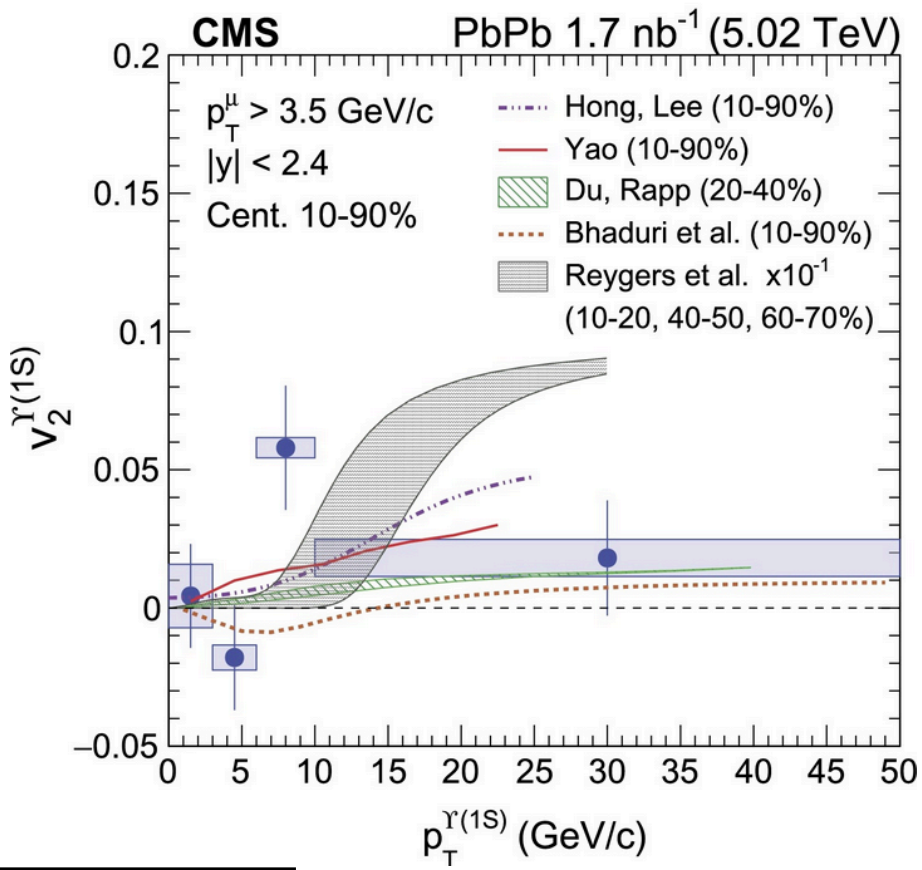
Bottom hadron v_2

Centrality and p_T dependence v_2 of $\Upsilon(1S)$ and $\Upsilon(2S)$





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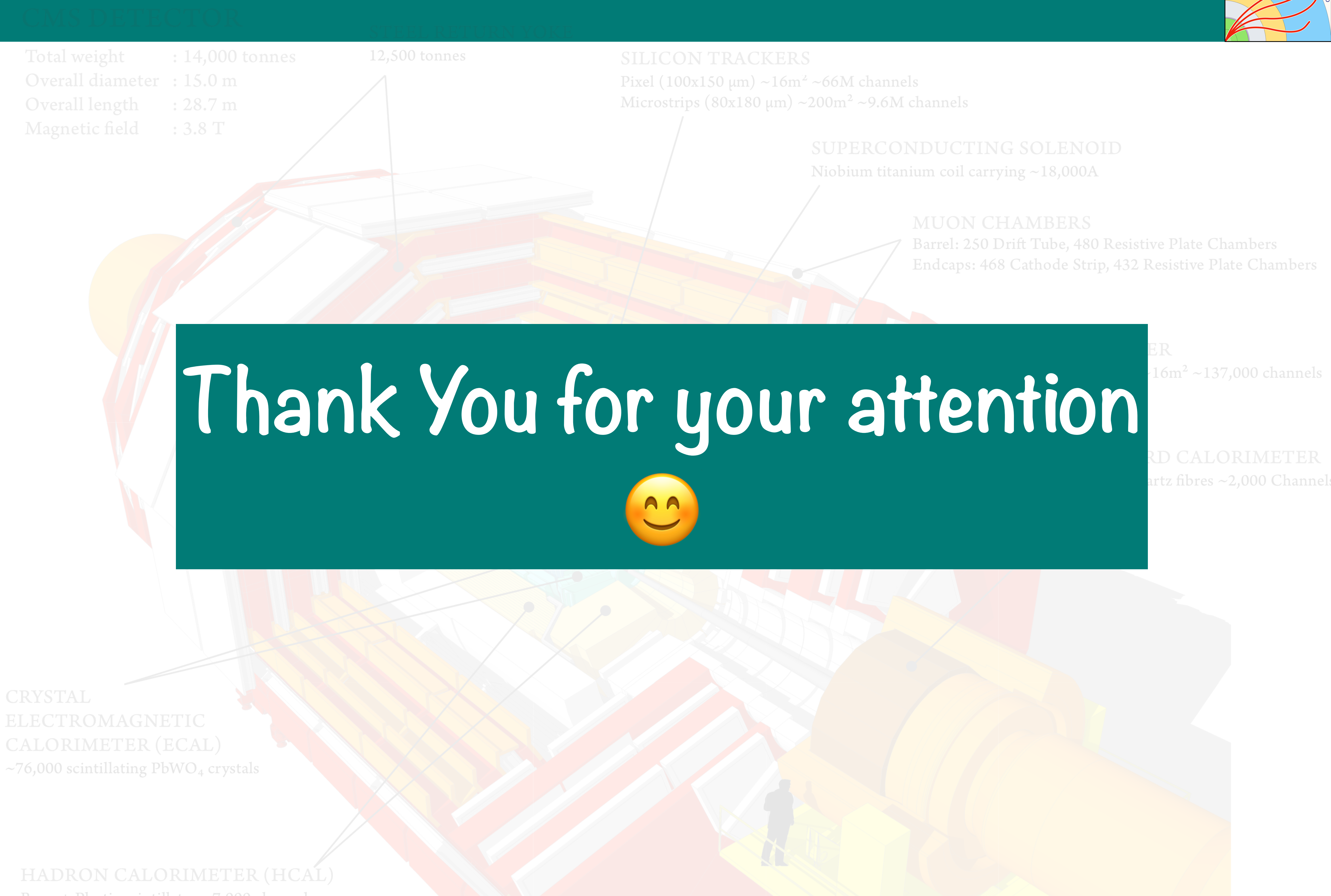
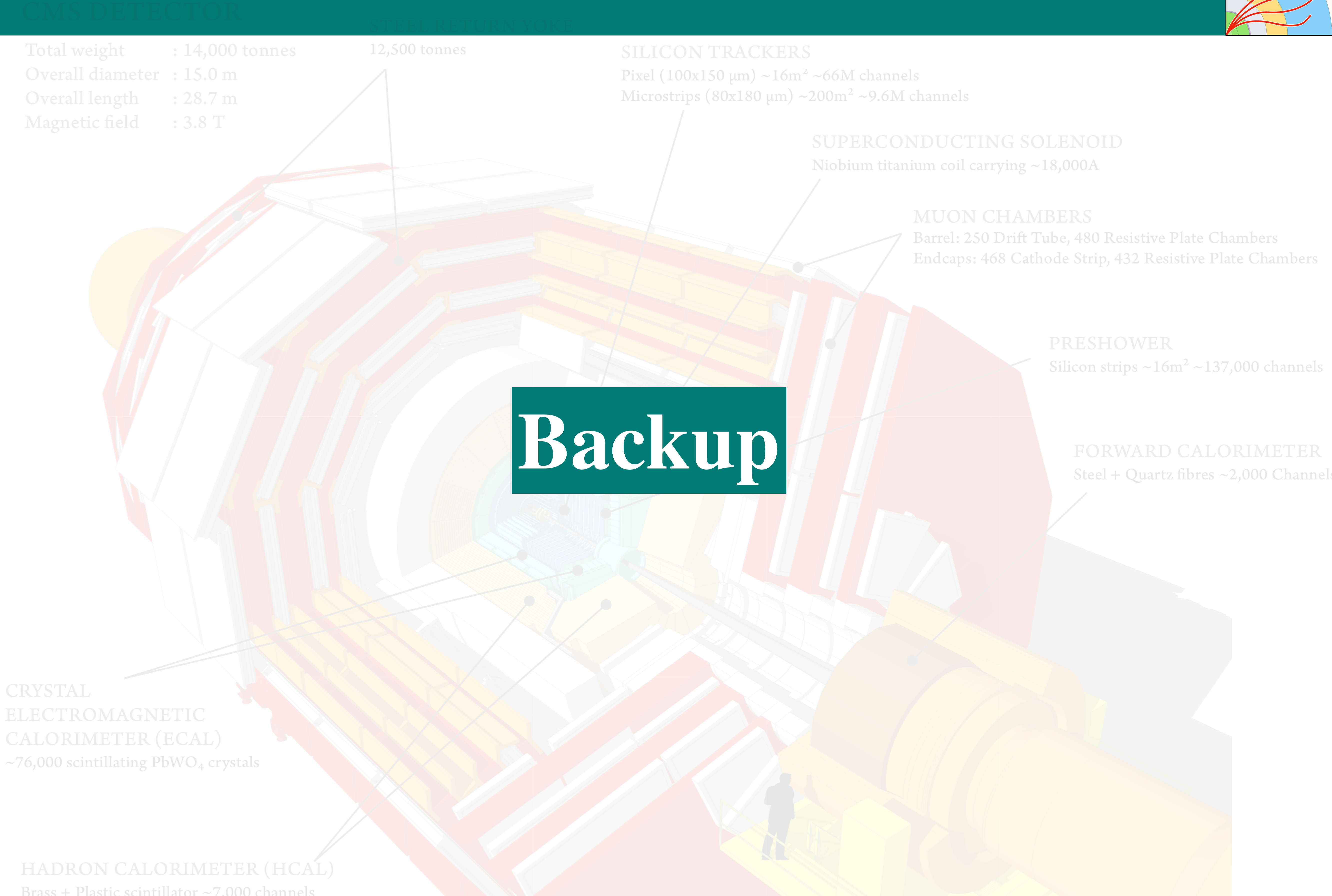
- v_2 of $\Upsilon(1S)$ and $\Upsilon(2S)$ consistent with zero within the statistical uncertainties

Summary

- Significant p_T dependent v_2 and v_3 observed for the strange hadrons in pPb and PbPb
- Strange hadron flow fluctuation is larger in pPb than PbPb
- D^0 and J/ψ v_2 is smaller than strange hadron in entire p_T range
- Evidence of weaker collectivity of charm quark in pPb than PbPb
- Multiplicity dependence v_2 measured for D^0 meson in pPb
- Qualitative agreement from CGC model for J/ψ
- Non-prompt D^0 v_2 consistent with zero in low p_T, while in high p_T , hint of a positive v_2
- v_2 of $\Upsilon(1S)$ and $\Upsilon(2S)$ consistent with zero within the statistical uncertainties

Thank You for your attention 😊

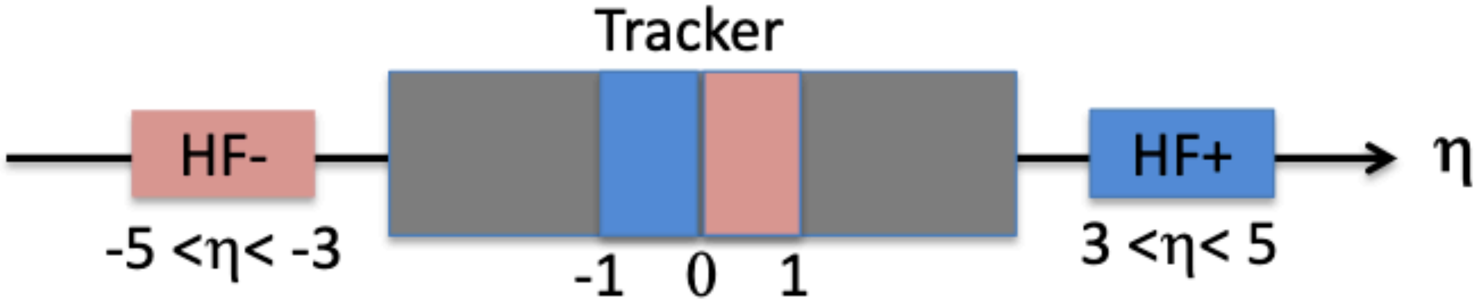



CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

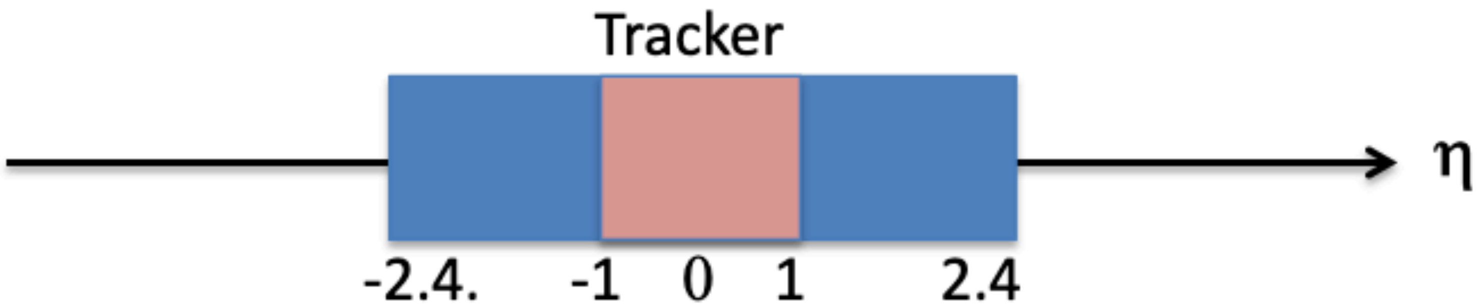
Backup

Strange hadron v_2 Signal extraction

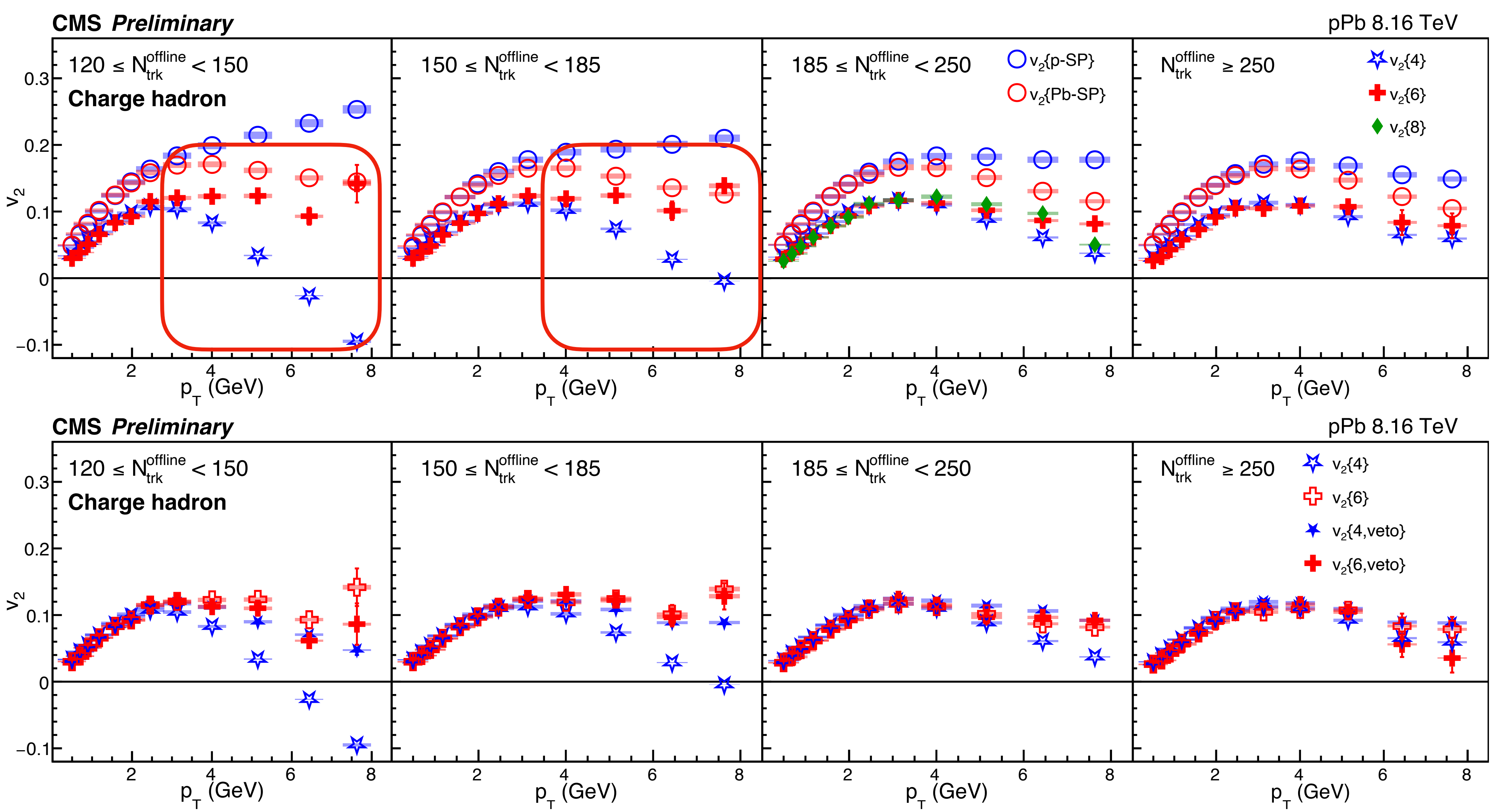
- Scalar-product $v_2\{SP\}$
  - POI wrt HF ($\Delta\eta>3$)

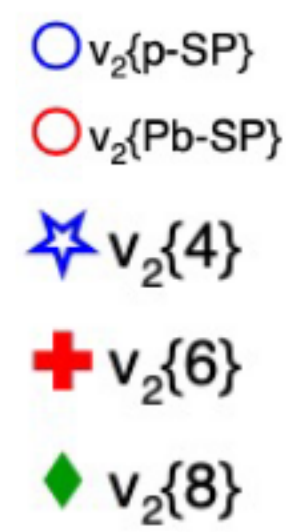


- Multiparticle cumulant $v_2\{4,6,8\}$
  - Q-cumulant



Jet related non-flow in pPb





- $v_2\{4\} < v_2\{6\}$!! Large jet related non-flow at low N_{trk}

- To remove non-flow, veto jet method used
  - CMS anti-kt PF hets with bkg subtraction
  - Reject events with at least one jet $p_T > 20$ GeV

Strange hadron v_2 Signal extraction

V_2 Signal extraction:

- Two particle correlation technique

$$\frac{1}{N_{\mathrm{trig}}}\frac{dN^{\mathrm{pair}}}{d\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left\{1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$

- v_2 extracted from charge reference particle($0.3 < p_T < 3.0$ GeV)

$$v_n\{2, |\Delta\eta| > 2\}(p_T) = \frac{V_{n\Delta}(p_T, p_T^{\mathrm{ref}})}{\sqrt{V_{n\Delta}(p_T^{\mathrm{ref}}, p_T^{\mathrm{ref}})}}, n = 2, 3$$

$$v_n^{\mathrm{signal}} = \frac{v_n^{\mathrm{obs}} - (1 - f_{\mathrm{sig}})v_n^{\mathrm{bkg}}}{f_{\mathrm{sig}}}$$

- f_{sig} is the signal fraction extracted from mass fit
- For back-to-back jet correction

$$V_{n\Delta}^{\mathrm{sub}} = V_{n\Delta} - V_{n\Delta}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35) \times \frac{N_{\mathrm{assoc}}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35)}{N_{\mathrm{assoc}}} \times \frac{Y_{\mathrm{jet}}}{Y_{\mathrm{jet}}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35)},$$

D^0 v_2 Signal extraction

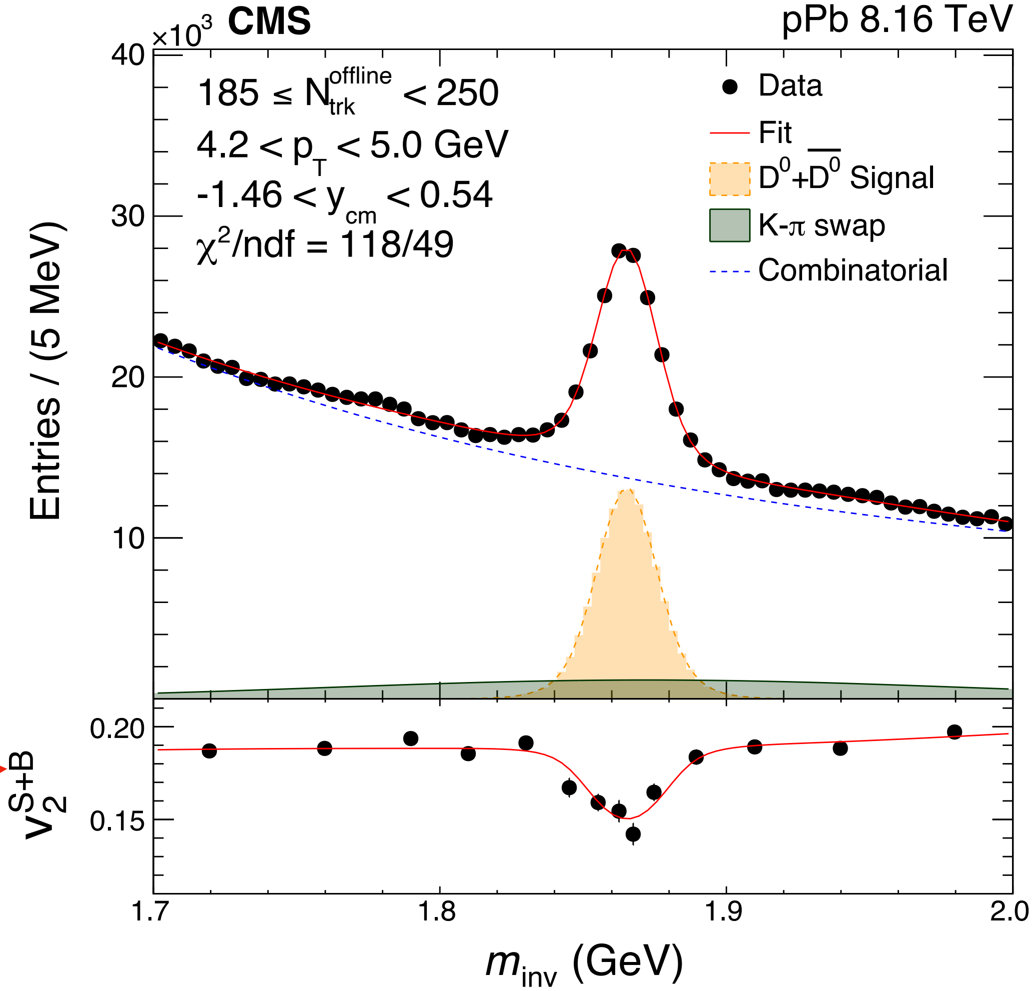
D^0 v_2 Signal extraction:

- Two particle correlation technique

$$\frac{1}{N_{D^0}}\frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi}\left(1+\sum_{n=1}^{3} 2V_{n\Delta}\cos(n\Delta\phi)\right)$$

- v_2 extracted from charge reference particle($0.3 < p_T < 3.0$ GeV)
  - Assuming $V_{n\Delta}$ to be the product of single-particle anisotropies

$$v_n(D^0) = V_{n\Delta}(D^0,\text{ref})/\sqrt{V_{n\Delta}(\text{ref},\text{ref})}.$$



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- Fit the v_2^{s+b} vs. mass to extract v_2^s

$$v_2^{S+B}(m_{\text{inv}}) = \alpha(m_{\text{inv}})v_2^S + [1-\alpha(m_{\text{inv}})]v_2^B(m_{\text{inv}}),$$

where

$$\alpha(m_{\text{inv}}) = \frac{S(m_{\text{inv}}) + SW(m_{\text{inv}})}{S(m_{\text{inv}}) + SW(m_{\text{inv}}) + B(m_{\text{inv}})}.$$

- For back-to-back jet correction

$$V_{n\Delta}^{\text{sub}} = V_{n\Delta} - V_{n\Delta}(N_{\text{trk}}^{\text{offline}} < 35) \times \frac{N_{\text{assoc}}(N_{\text{trk}}^{\text{offline}} < 35)}{N_{\text{assoc}}} \times \frac{Y_{\text{jet}}}{Y_{\text{jet}}(N_{\text{trk}}^{\text{offline}} < 35)},$$