New insights on heavy flavor dynamics with CMS detector

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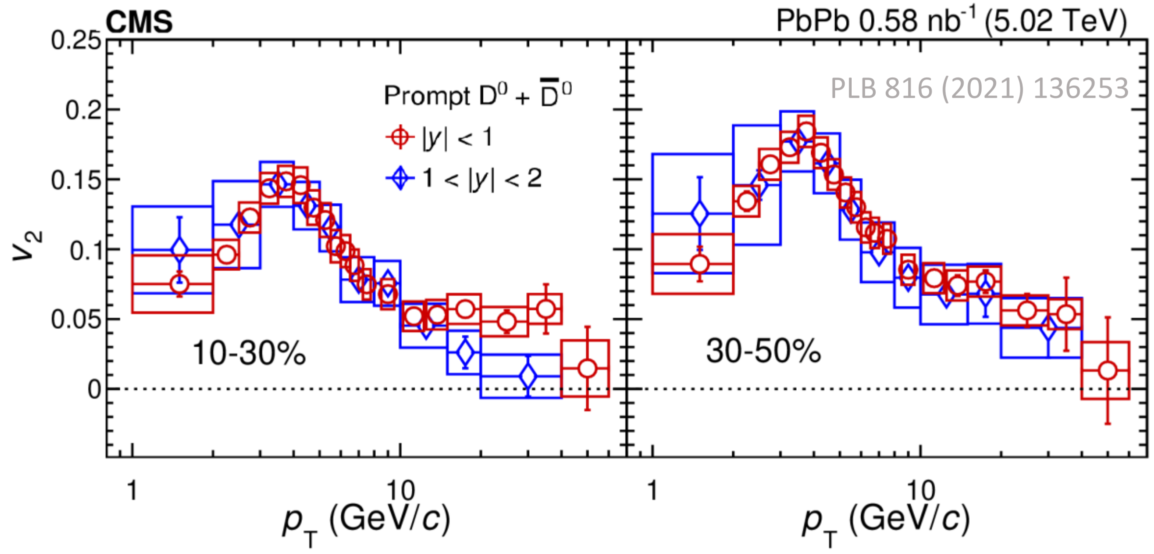
June 2, 2022

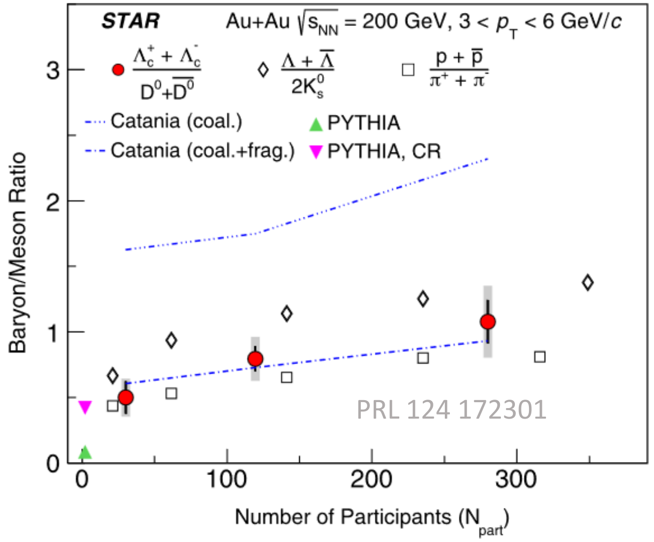
Outline

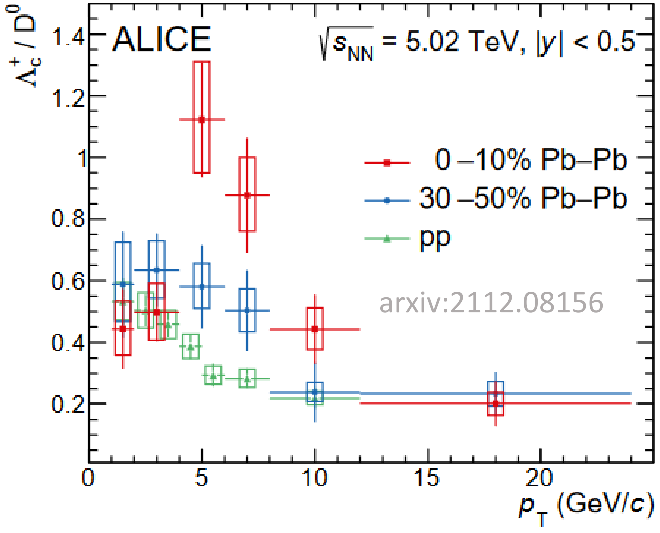
- Open heavy flavor in small systems
  - QGP creation in small systems?
- Open heavy flavor in large systems
  - The details of heavy flavor dynamics within QGP
- Future opportunities
  - CMS-MTD

Observations in large systems

- QGP fluid in nucleus-nucleus collisions
  - Collective motions – elliptic flow (v_2) and ridges
  - Coalescence process – baryon enhancement
  - …

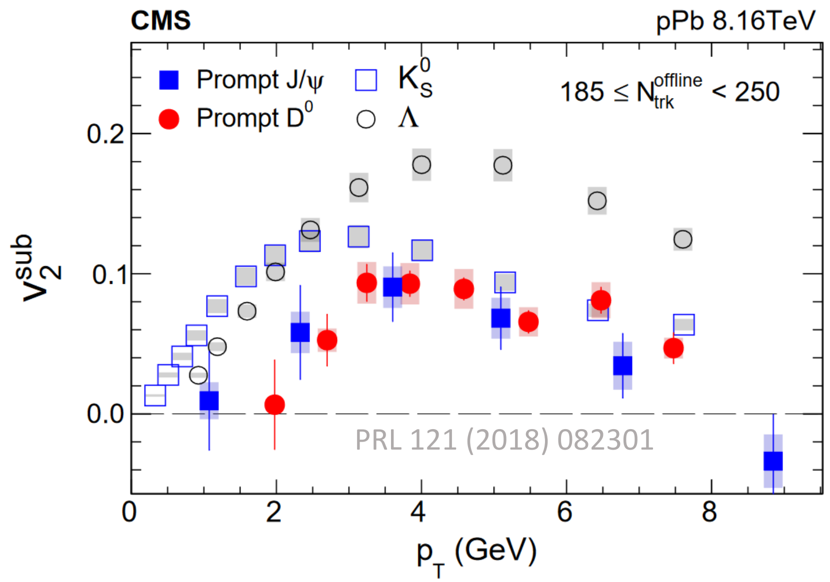


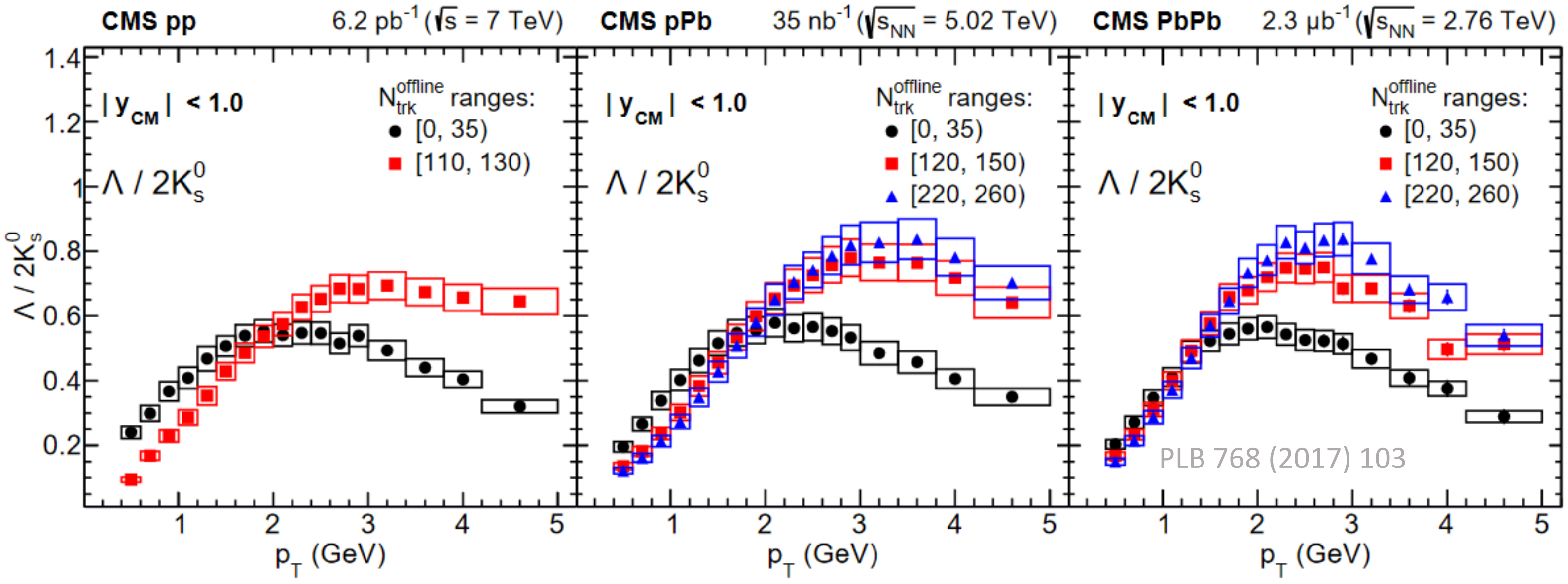




Observations in small systems

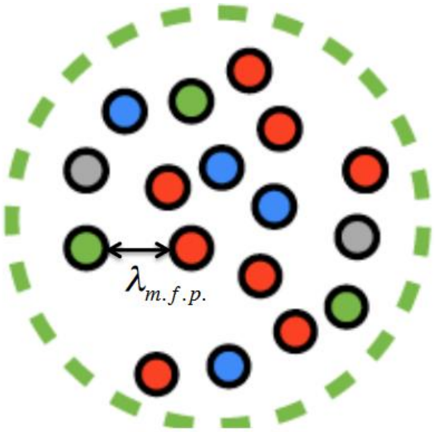
- Not expected at the beginning
  - Large and positive elliptic flow
  - Baryon enhancement
  - …



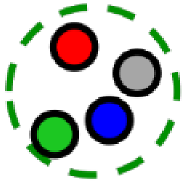


Creation of tiny QGP?

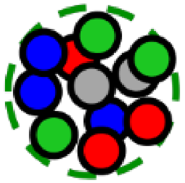
- A small QGP droplet created – in-medium and final state effects
- Alternative explanations for collectivity:
  - Correlations established prior to collisions – initial state effects



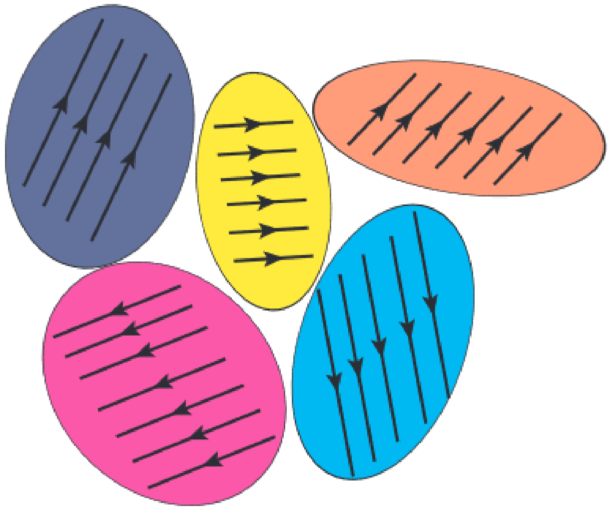
Large nuclei



Small nucleon, low temperature (low energy density)

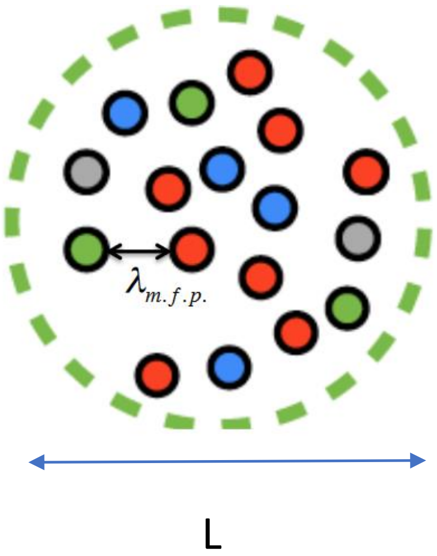


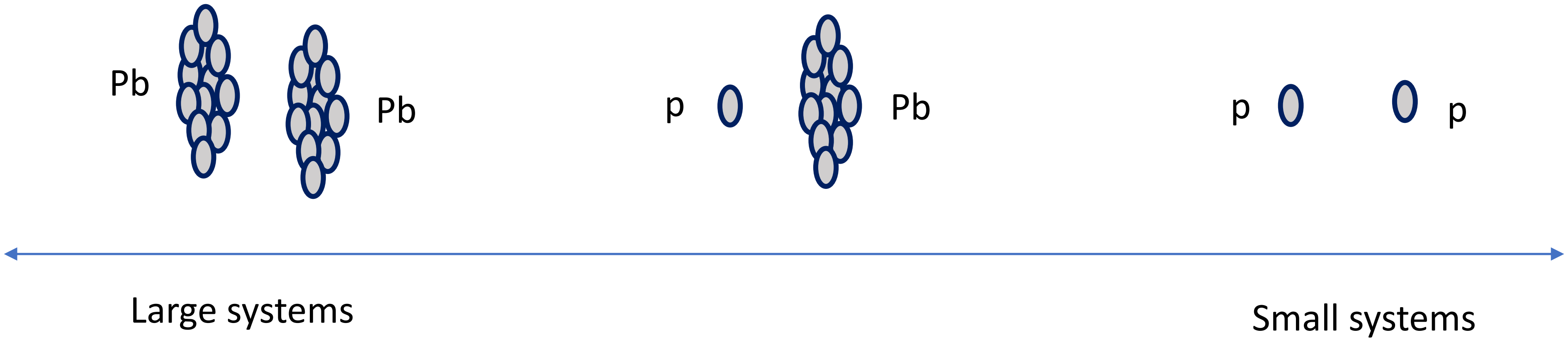
Small nucleon, high density



Explore the small system deeply

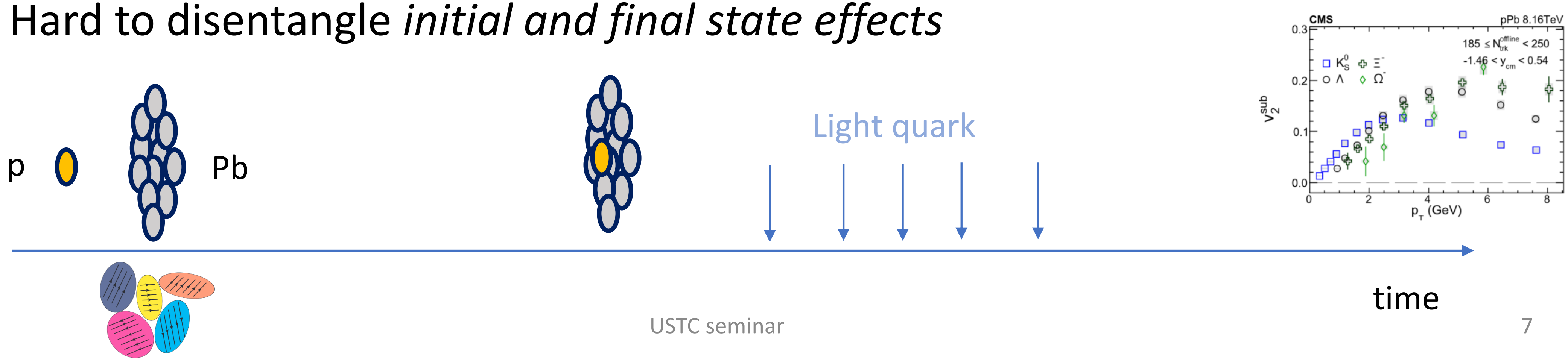
- If there are any in-medium effects
  - $\lambda_{m.f.p.}$<< L
  - to test medium effects
    - Increase $\lambda_{m.f.p.}$
    - decrease L





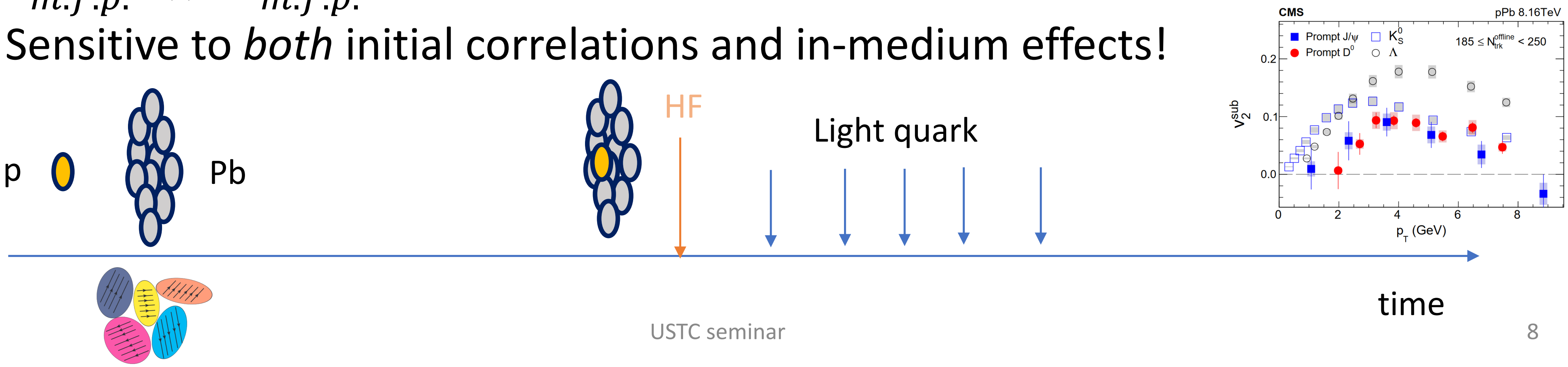
Explore the small system deeply

- We need probes sensitive to
  - Initial correlations
  - Relative system size – $\lambda_{m.f.p.}/L$
- Light flavor particles (q)
  - Can be created anytime – lose the sensitivity to initial correlations
  - $\lambda_{m.f.p.}{}^{q}$ may be always *small compared to system size*
  - Hard to disentangle *initial and final state effects*



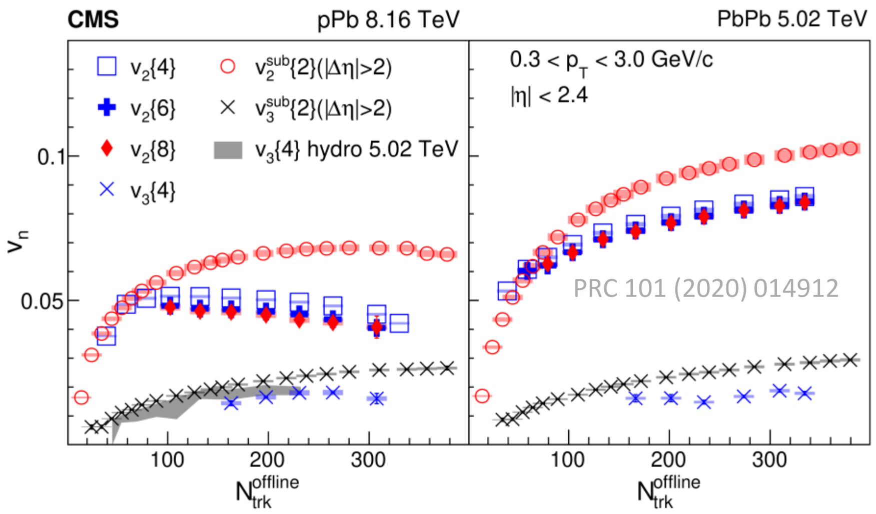
Explore the small system deeply

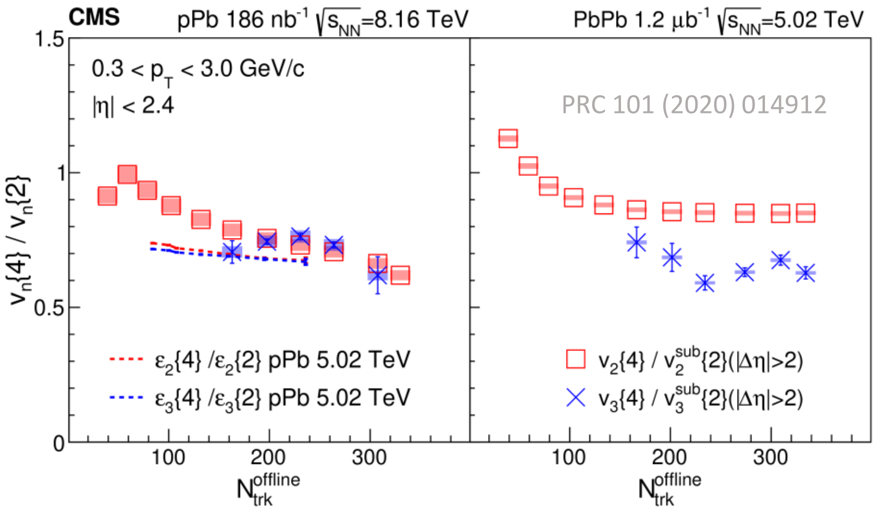
- We need probes sensitive to
  - Initial correlations
  - Relative system size – $\lambda_{m.f.p.}/L$
- Heavy flavor quarks (HF or Q)
  - Mostly created *in initial stages*
  - Evolve in the *entire evolution* of the system
  - $\lambda_{m.f.p.}{}^{Q} \gg \lambda_{m.f.p.}{}^{q}$
  - Sensitive to *both* initial correlations and in-medium effects!



Observables we are interested in

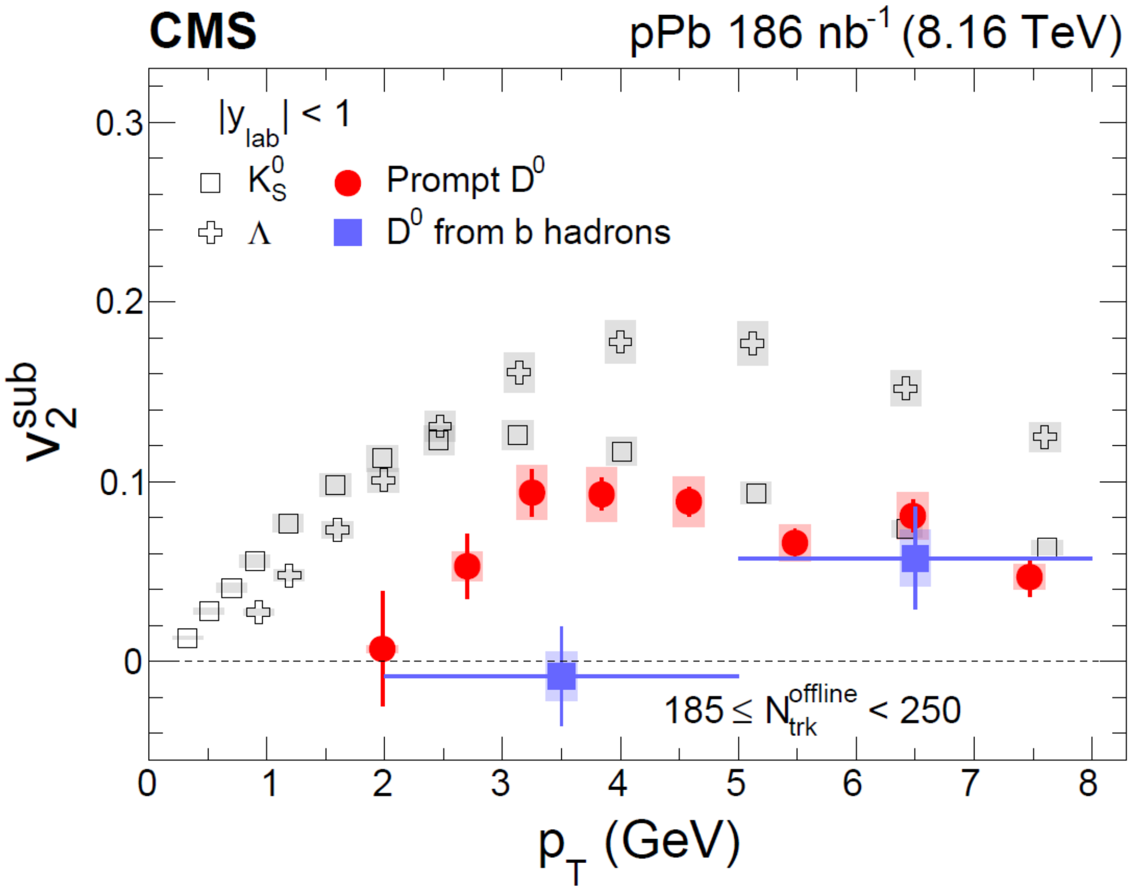
- HF flavor v_2
  - Open charm/bottom quarks, charmonia and bottomonia
- v_2 signal and its dependence on multiplicity (relative system size)
- Collisions geometry and dynamics, *v_2 driven by eccentricity?*





Open HF collectivity in pPb

- Fist time in pPb collisions – vanishing v_2 for b hadrons via non-prompt D^0
- Indication of flavor hierarchy between charm and bottom hadrons at low p_T



PLB 813 (2021) 136036

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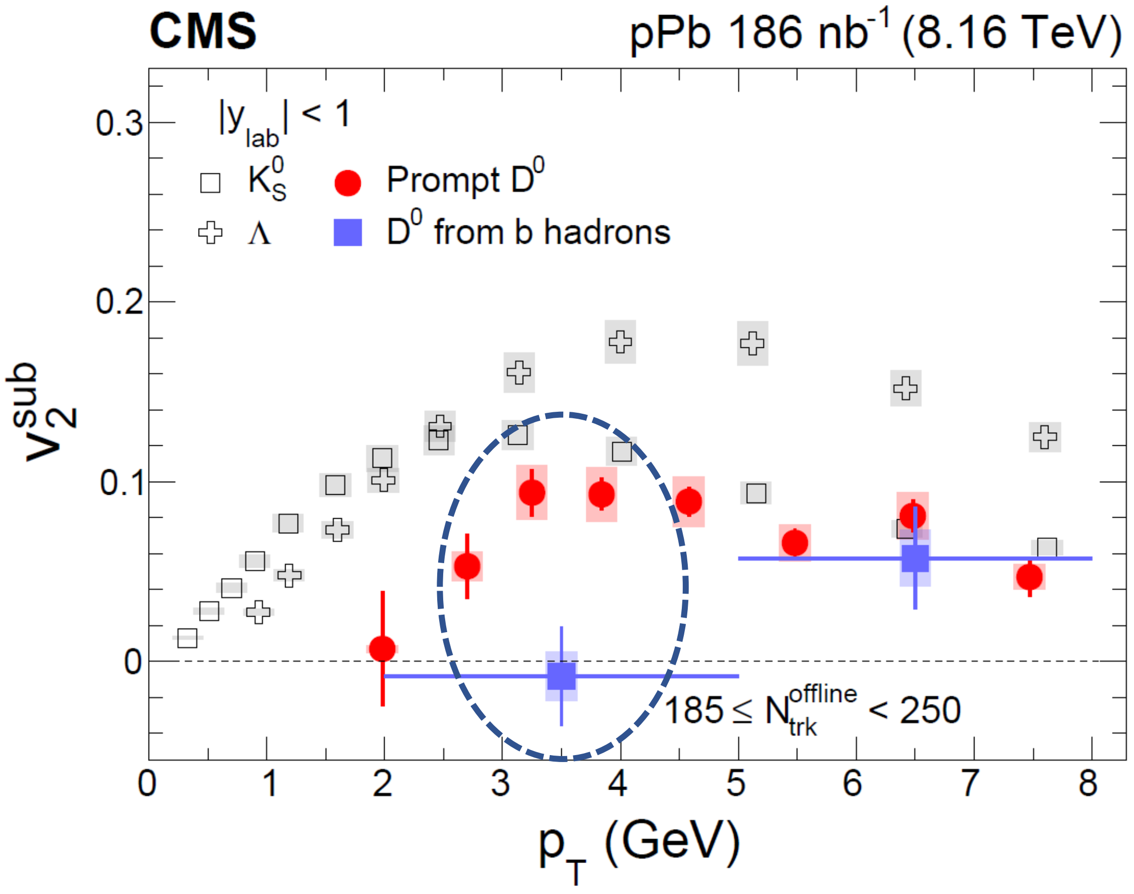

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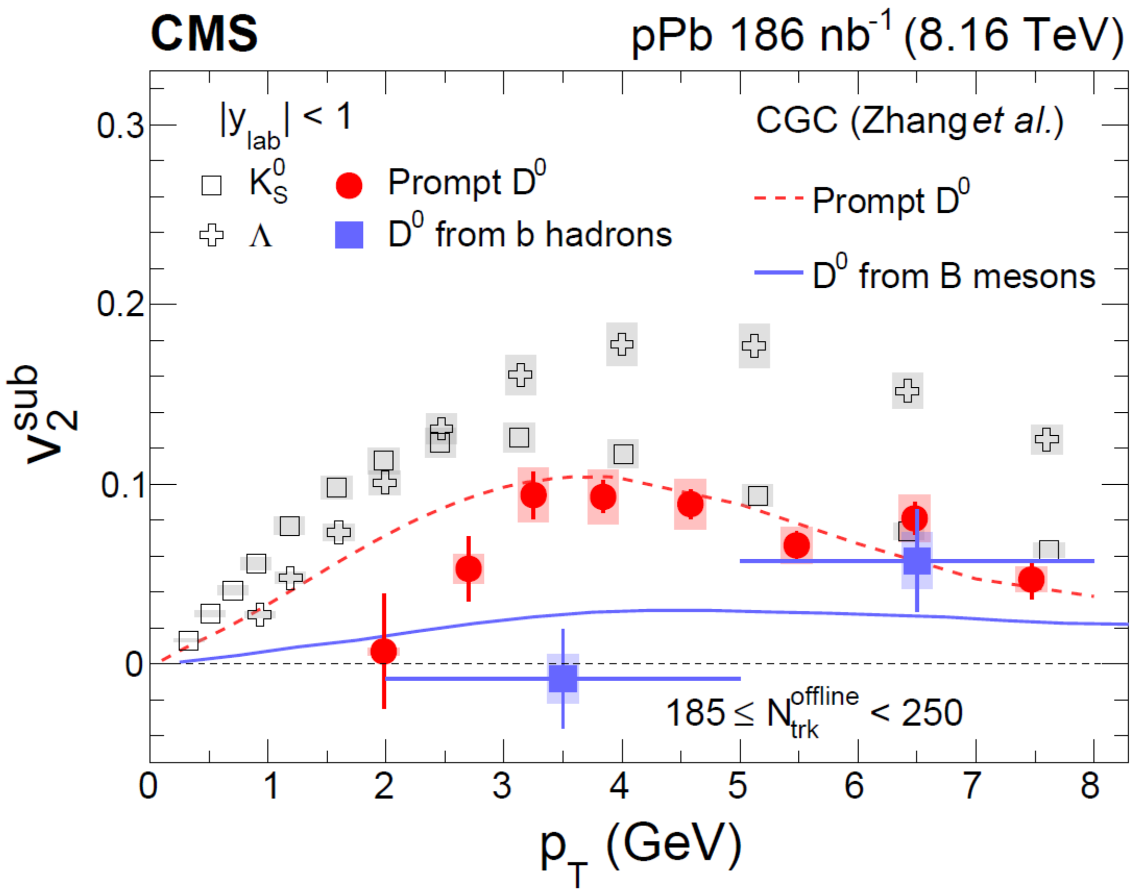
Open HF collectivity in pPb

- Comparisons with CGC calculations – show consistency within large uncertainties

- Precision measurements in the future – HL-LHC with CMS MTD



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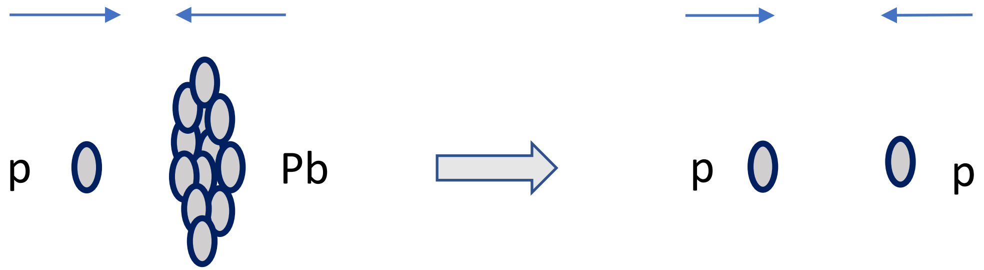
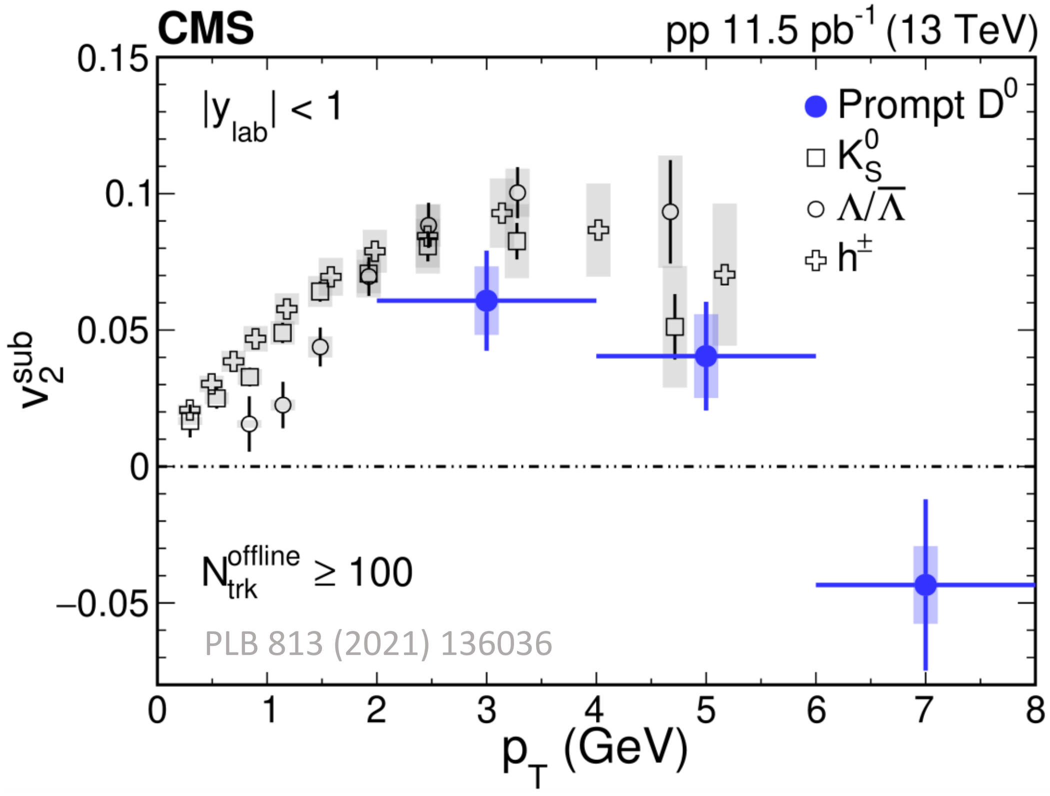
Collectivity in even smaller system

- First measurement of prompt D^0 v_2 in high multiplicity pp collisions
- Indication of positive v_2 signal at $2 < p_T < 4$ GeV
- v_2 of prompt D^0 comparable with that of light hadrons

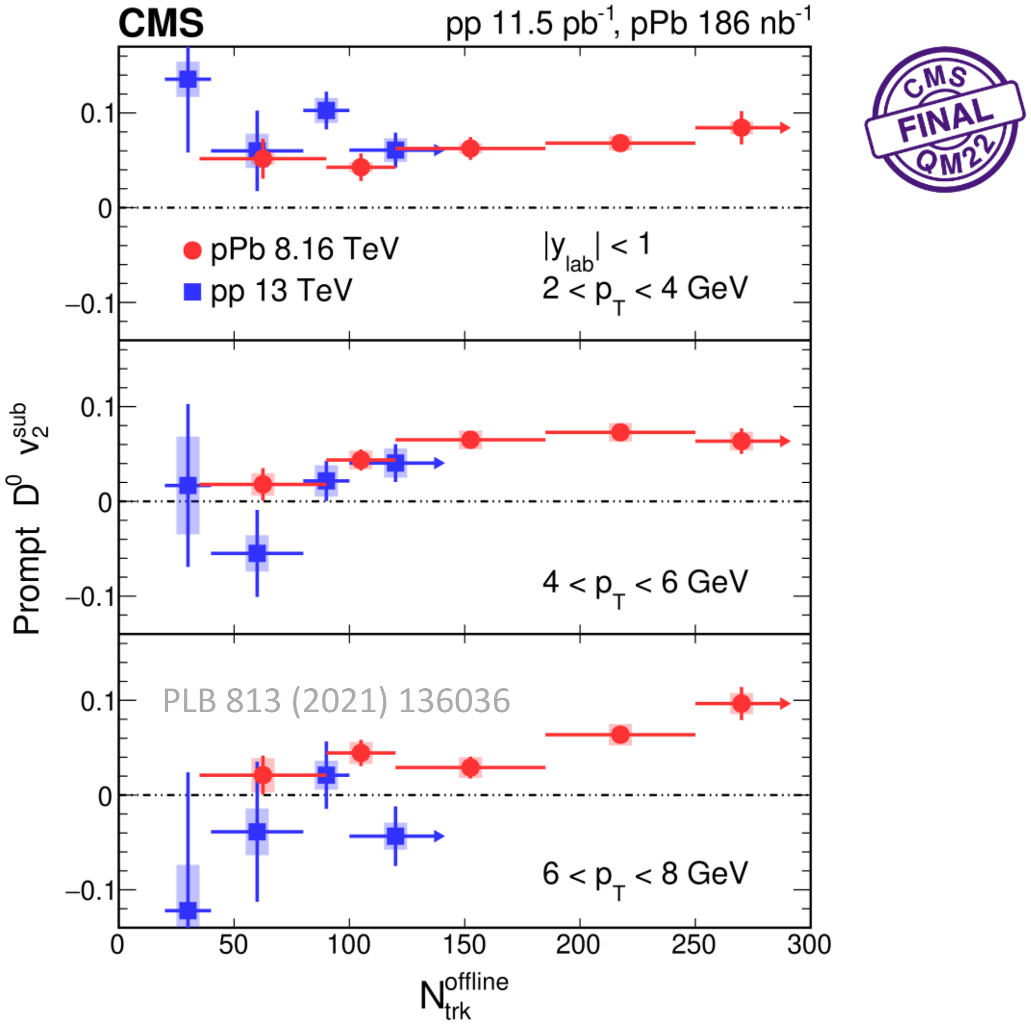




Multiplicity is defined in the same way as in pPb

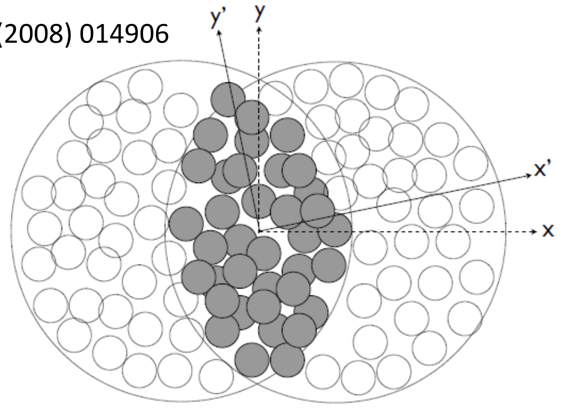
System size dependence

- Positive v_2 is observed in high multiplicity events
- Non-zero v_2 of prompt D^0 mesons diminish towards low-multiplicity regimes
- v_2 of prompt D^0 in pp collisions comparable to that in pPb collisions with similar multiplicity under large uncertainty



HF dynamics in large systems

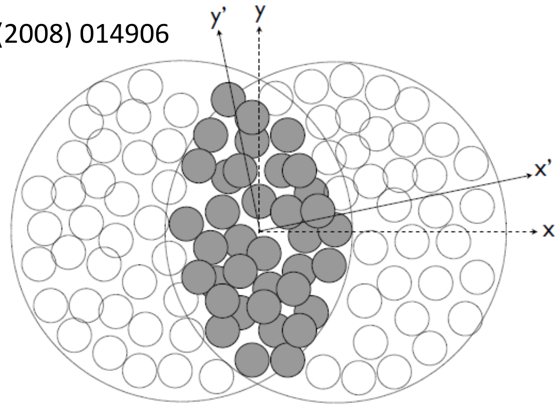
PRC 77 (2008) 014906

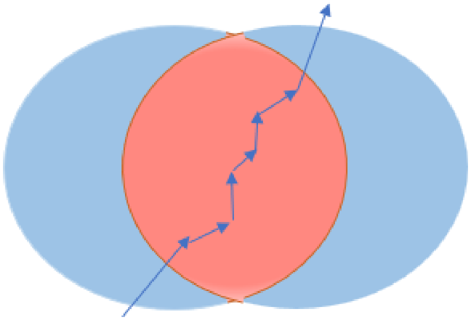


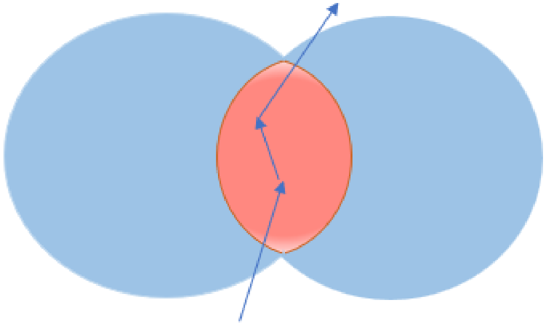
- Insights from **LARGE** systems – fluctuations of elliptic flow
  - $v_2 = k\,\epsilon_2$ where ϵ_2 is the eccentricity of the collision geometry
  - *Event-by-event* fluctuations of ϵ_2 lead to fluctuations of v_2
  - k can also fluctuate *event-by-event* if the system is *small*
  - Multi-particle correlation sensitive to fluctuations
    - $v_2\{4\}^2 \approx {v_2}^2 - \sigma^2$, $v_2\{2\}^2 \approx {v_2}^2 + \sigma^2$

Origin of v_2 fluctuations

PRC 77 (2008) 014906



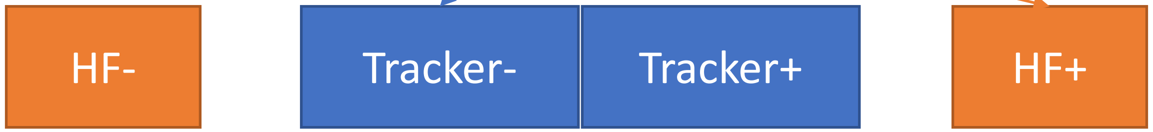




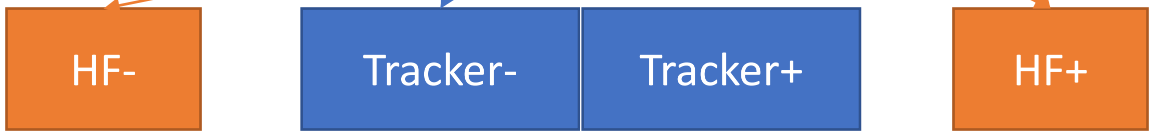
- Insights from **LARGE** systems – fluctuations of elliptic flow
  - If fluctuations only from ϵ_2, $\dfrac{v_2\{4\}(pT)}{v_2\{2\}(pT)} = \dfrac{v_2\{4\}}{v_2\{2\}} = \dfrac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}}$
  - If k can fluctuate, $\dfrac{v_2\{4\}(pT)}{v_2\{2\}(pT)} = \dfrac{v_2\{4\}}{v_2\{2\}} + \ \delta(pT)$
  - Full equation for v_2 fluctuations, see PRC 95 (2017) 044901
  - Initial ϵ_2 fluctuations vs. final state (in-medium) k fluctuations?

v_2 via multi-particle correlations

- ***First time*** **to measure charm** $\mathbf{v_2}$ **using** ***multiple particle correlator***
- Correlator
  - $\langle\langle 2' \rangle\rangle = \langle\langle e^{i2(\varphi(D^0)_1 - \varphi^{ref}{}_2)} \rangle\rangle$



  - $\langle\langle 4' \rangle\rangle = \langle\langle e^{i2(\varphi(D^0)_1 + \varphi^{ref}{}_2 - \varphi^{ref}{}_3 - \varphi^{ref}{}_4)} \rangle\rangle$

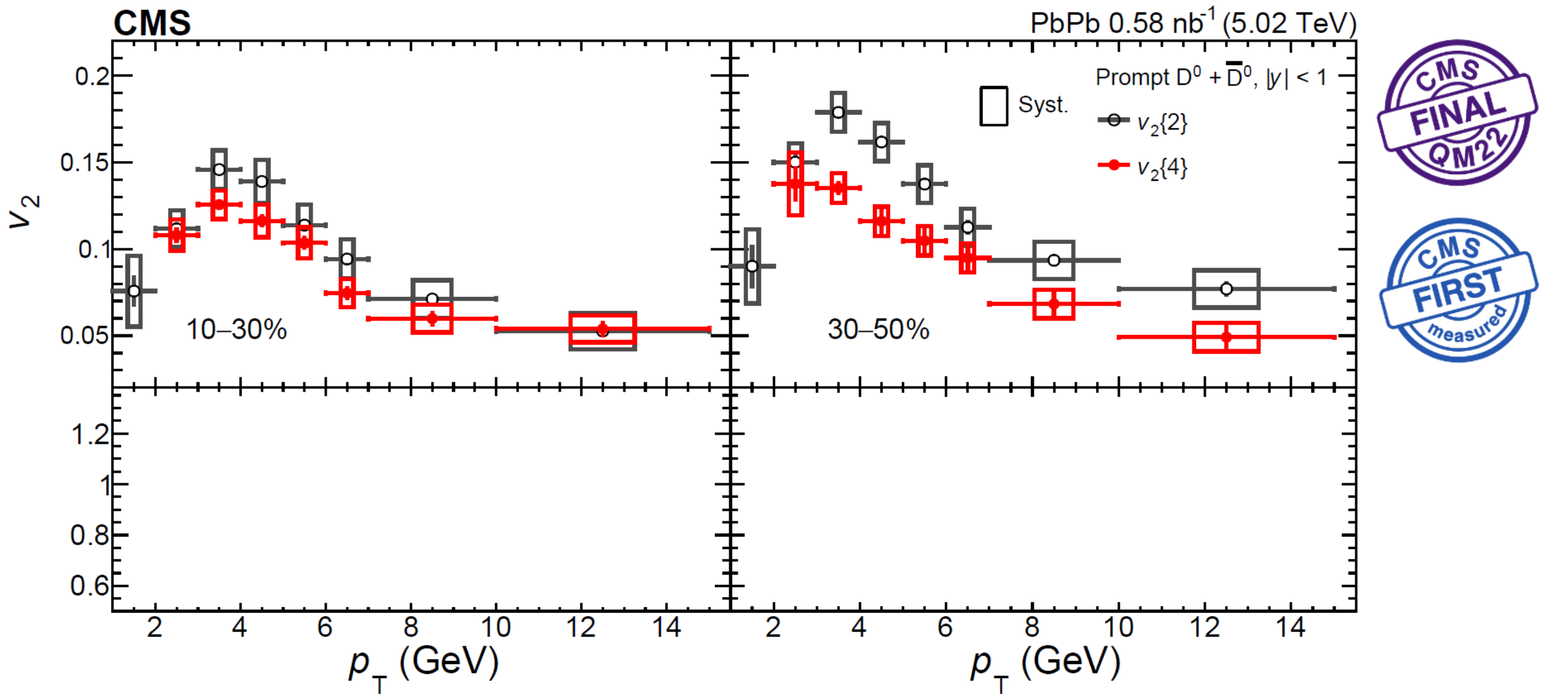


- $v_2\{4\}$ and $v_2\{2\}$ can be calculated from these correlator
- More info in PRC 83 (2011) 044913

Fluctuations of v_2

- Expected ordering between $v_2\{2\}$ and $v_2\{4\}$,$v_2\{4\} < v_2\{2\}$

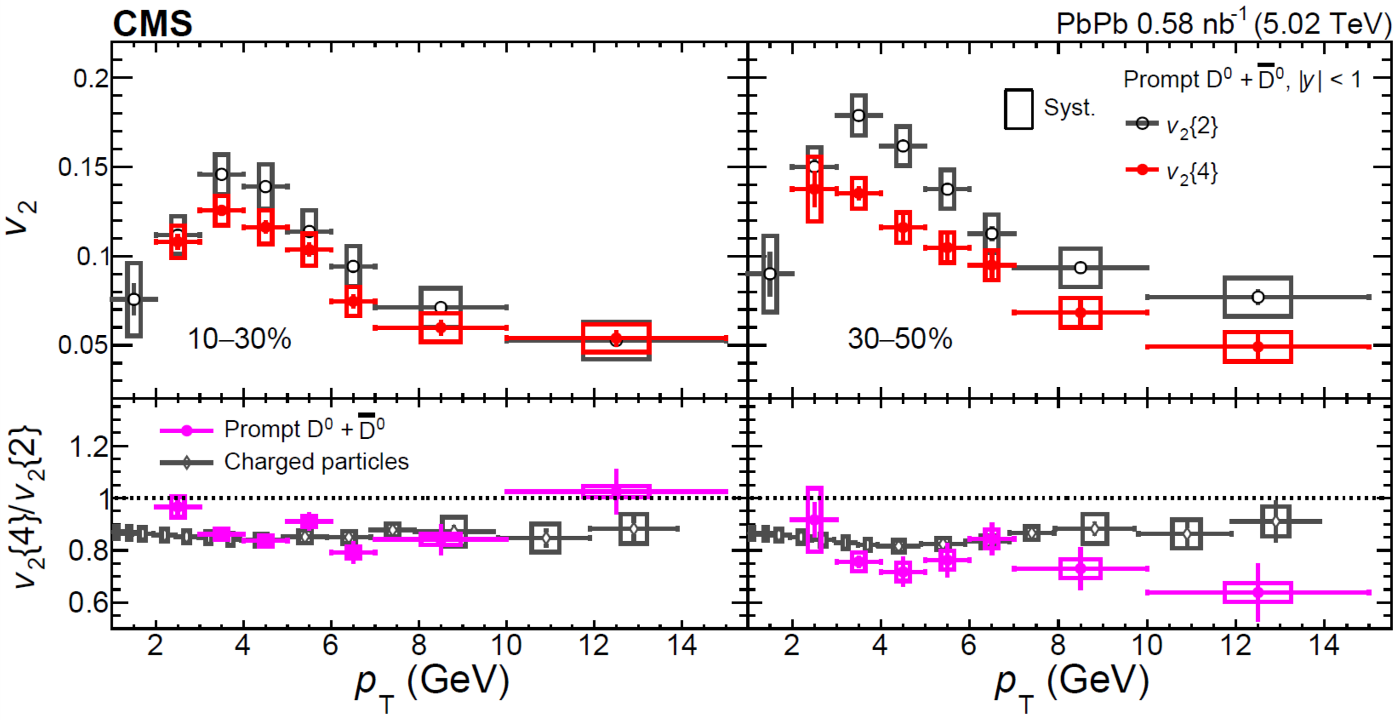
arxiv:2112.12236



Fluctuations of v_2

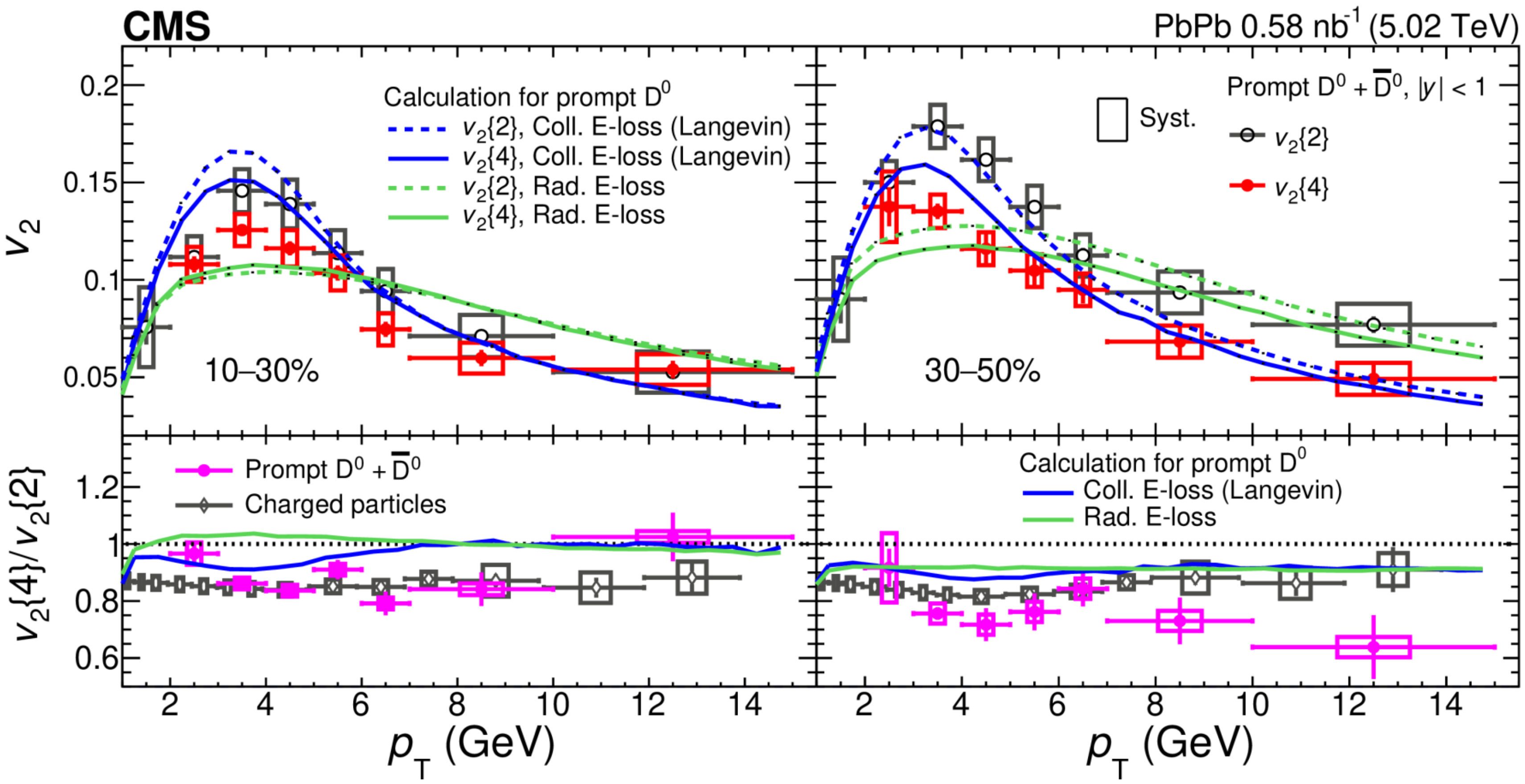
- The fluctuations of D^0 is comparable with charged particles – fluctuations are from ϵ_2 dominately

arxiv:2112.12236



Fluctuations of v_2

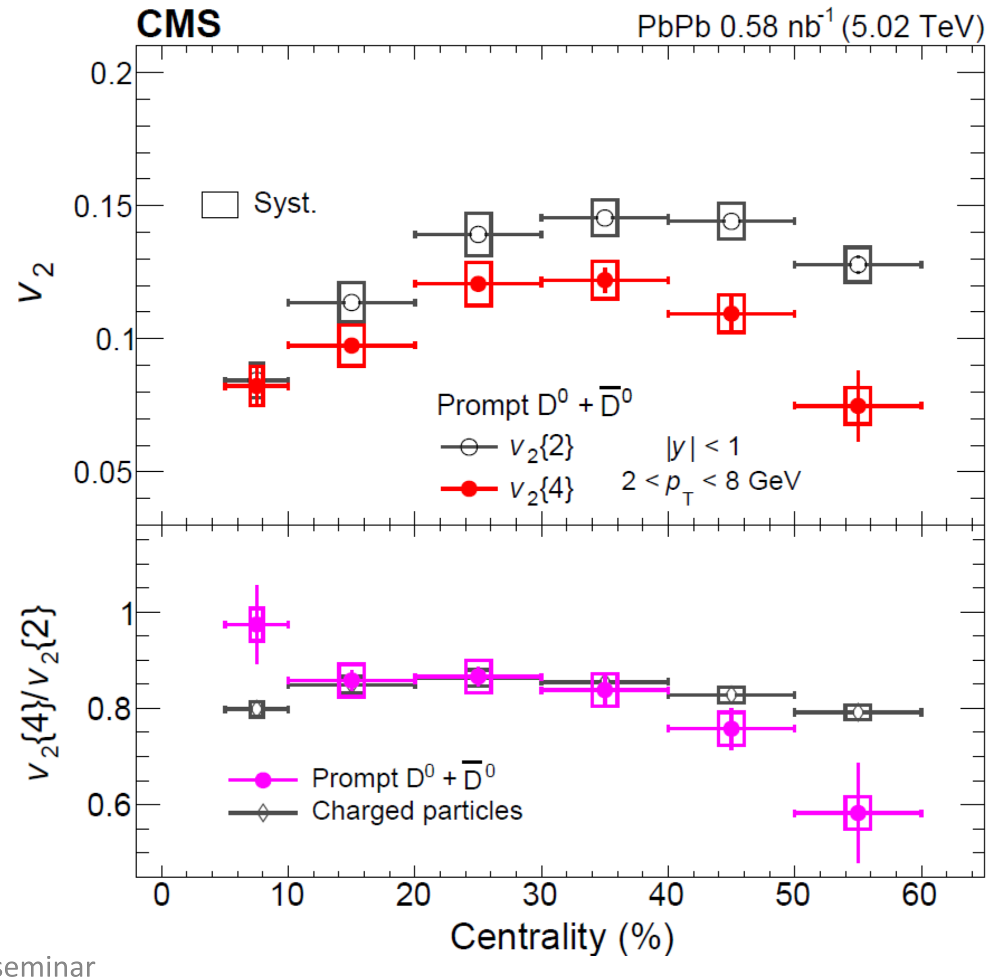
- Model capture the trend but not quantitatively
- Strong constraints on model descriptions



Fluctuations across different system size

arxiv:2112.12236

- $v_2\{4\}/v_2\{2\}$ for charm sectors are almost the same across different centrality classes – similar findings of charged particles – fluctuations almost from initial geometry



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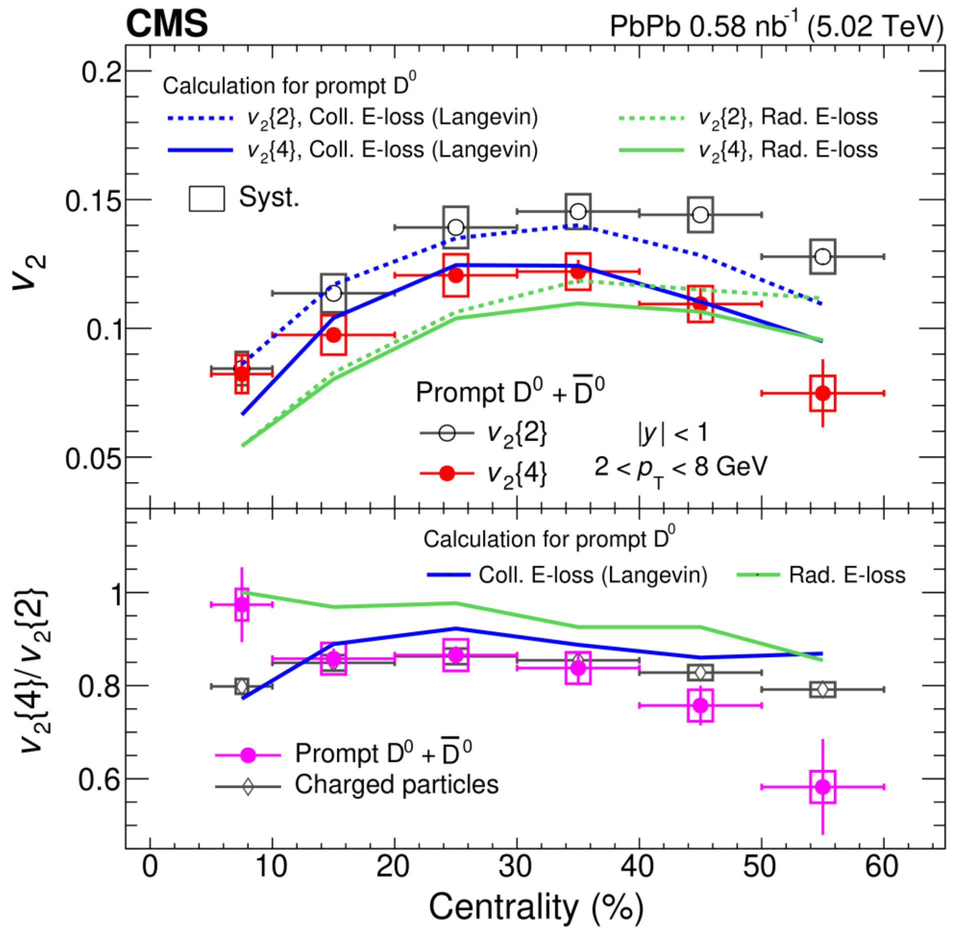
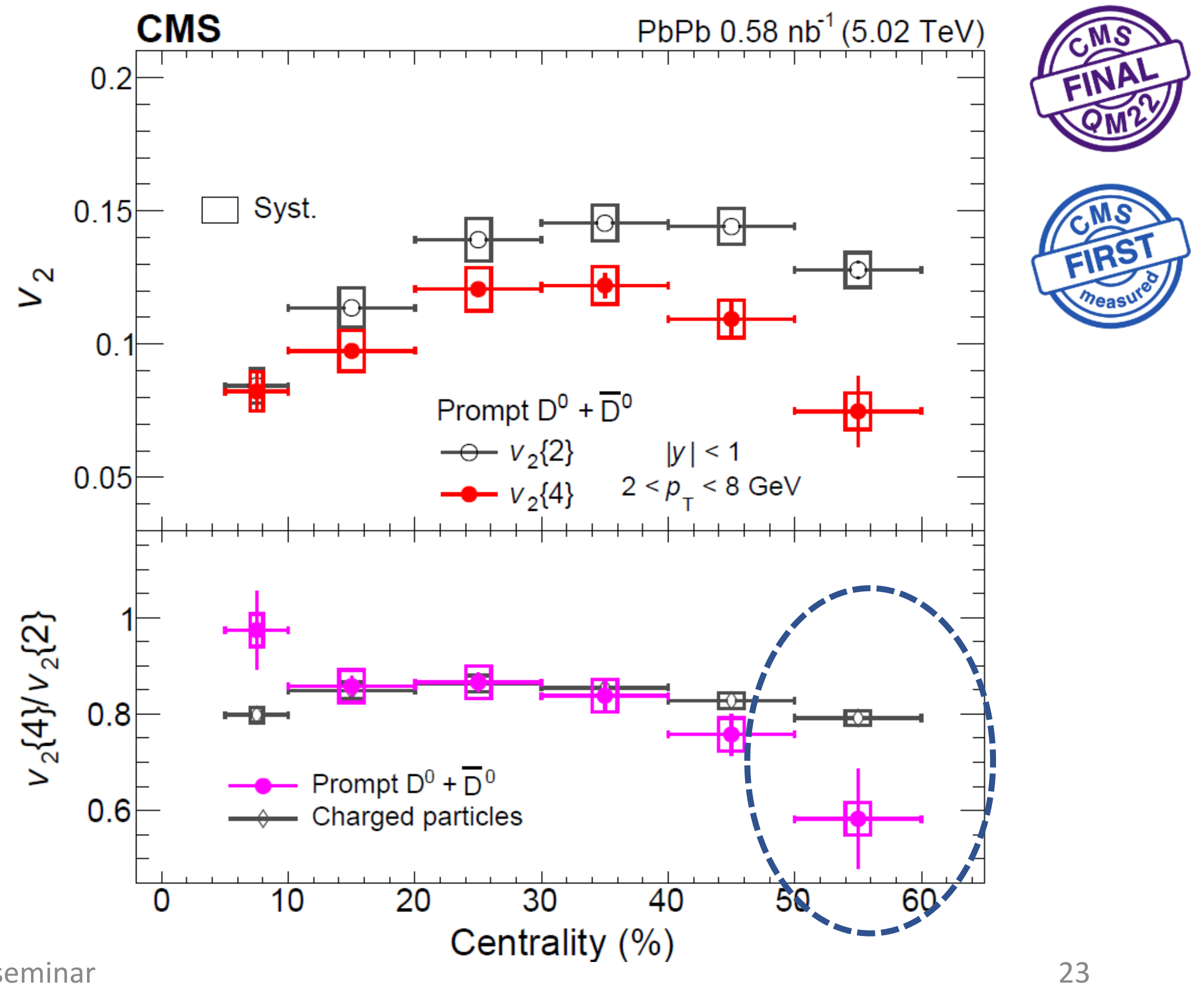


Fluctuations towards *smaller* systems

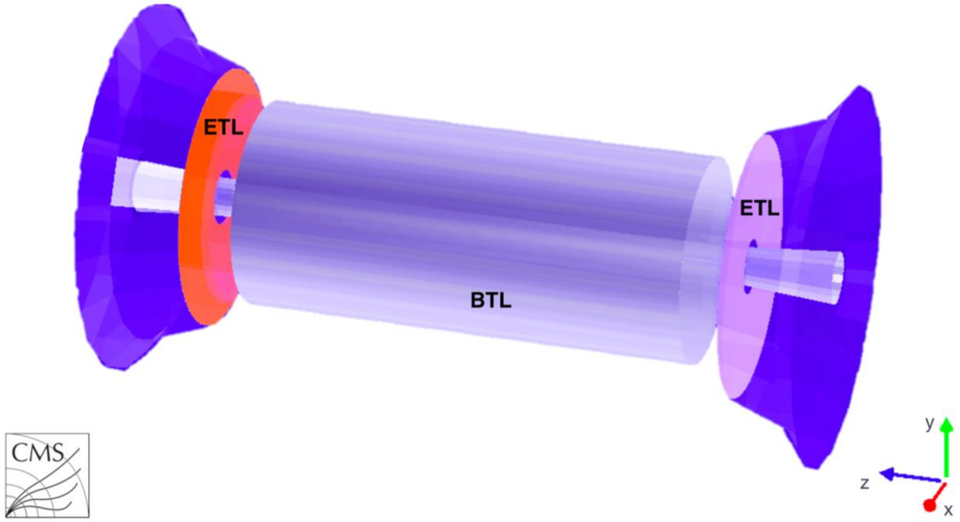
arxiv:2112.12236

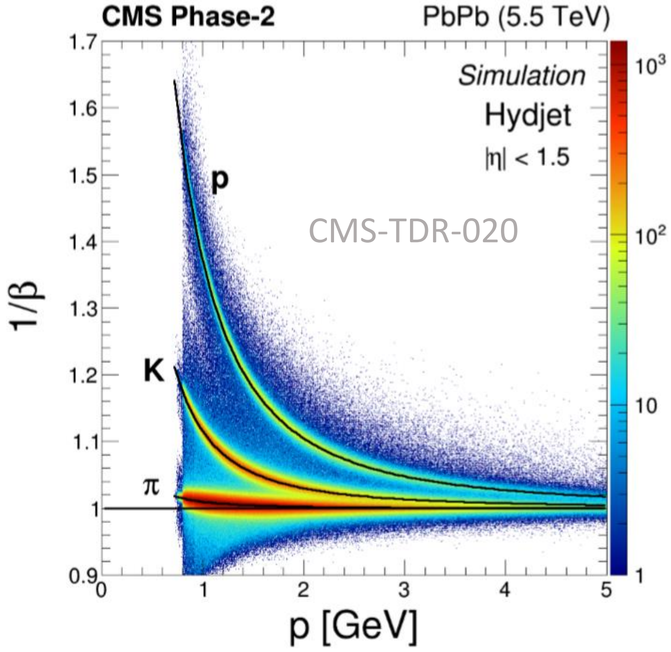
- Indication of splitting between charged particles and charm sectors – hint of fluctuations on energy loss towards *smaller* system
- Possible findings in pPb and pp collisions if medium effects are dominant?

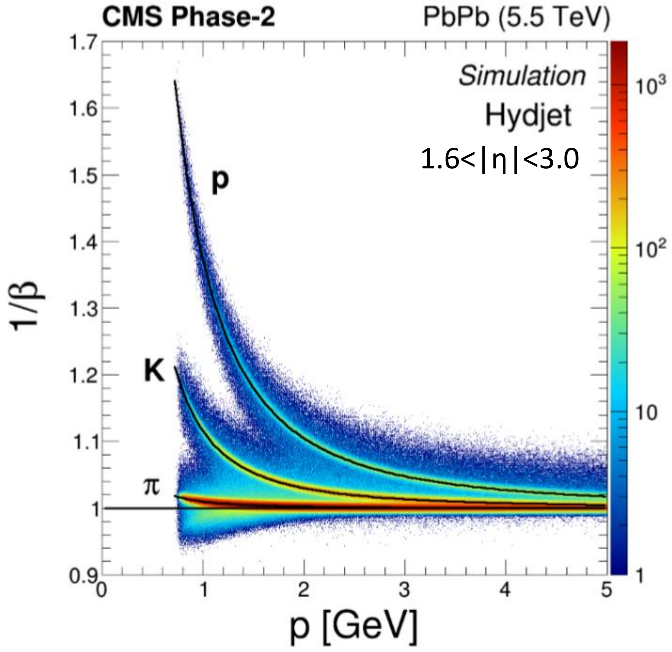


Opportunities at HL-LHC

- A new timing detector with timing resolution ~30ps
  - PID for Kaon up to 2.5 GeV
  - PID for proton up to 5 GeV



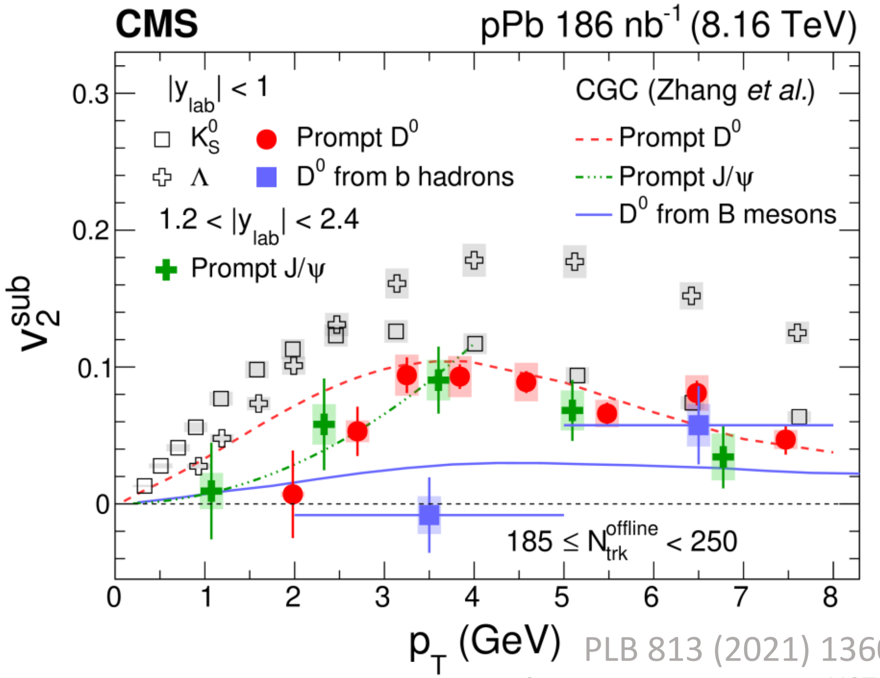




Opportunities at HL-LHC

- Uncertainties significantly reduced, from Run 2 to Run 4
  - A factor of 3 increase on luminosity, 186 nb^{-1} => 0.6 pb^{-1}
  - Better signal discriminating power, no PID => good PID
  - CMS talk by Andre Govinda Stahl Leiton , 7 Apr 2022, 15:20

CMS-DP-2021-037



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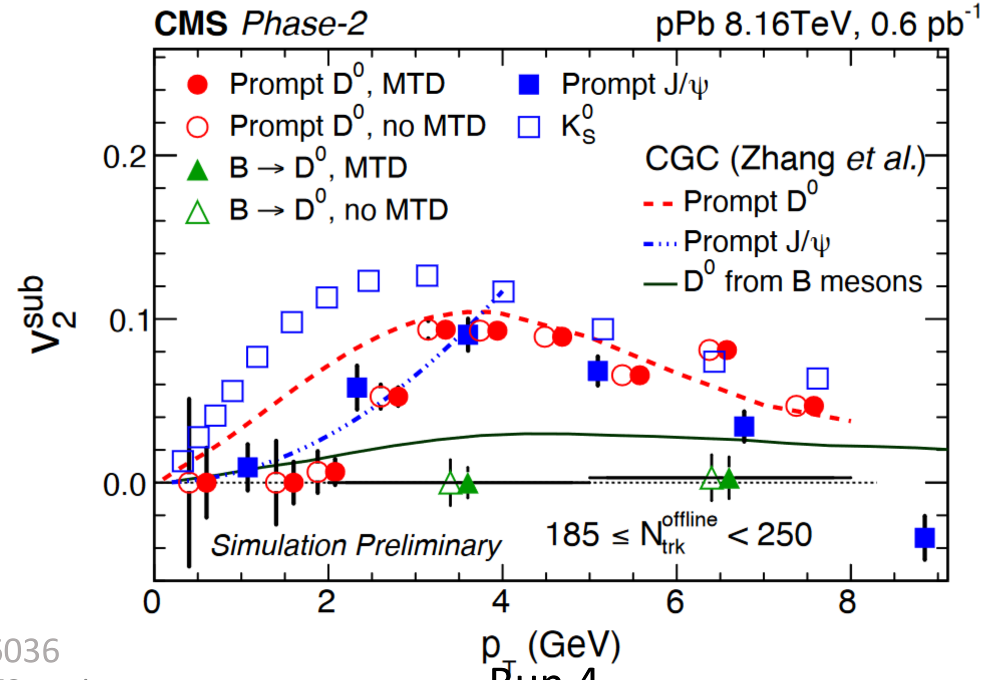
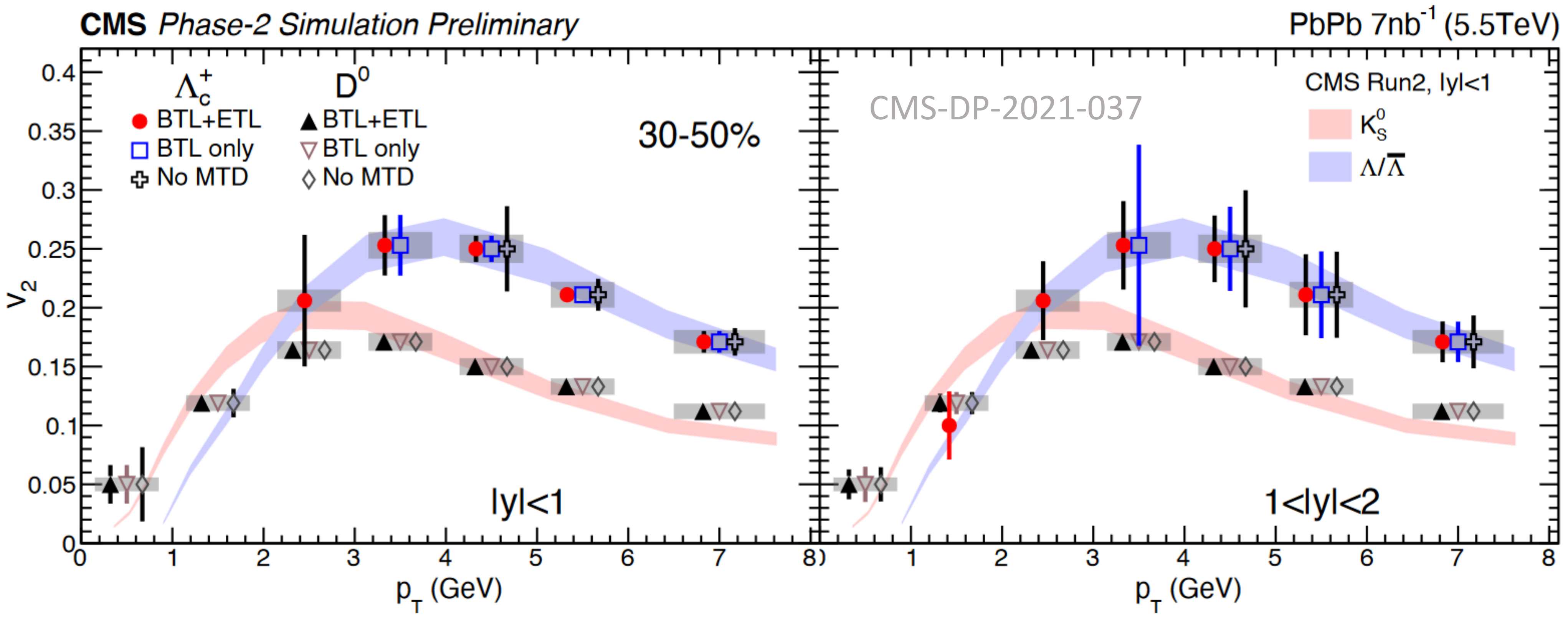
Run 2



Run 4

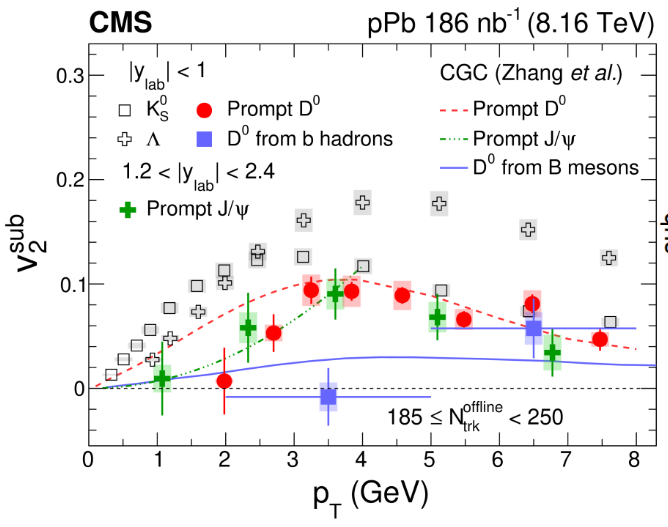
Opportunities at HL-LHC

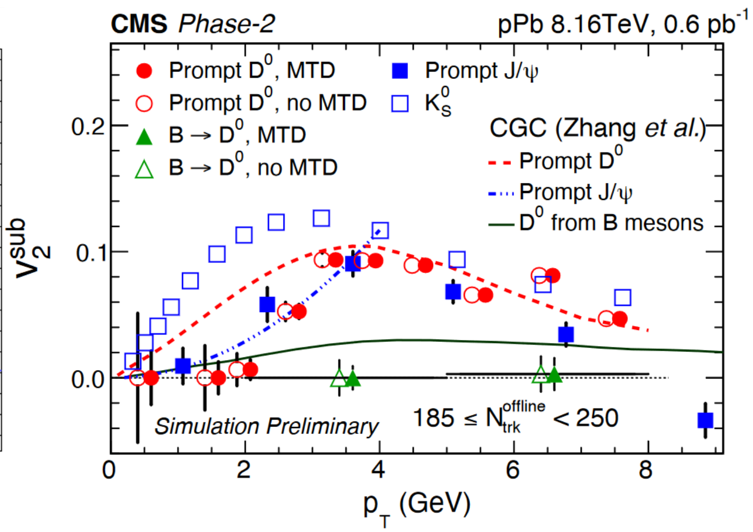
- Coalescence effects for HF?

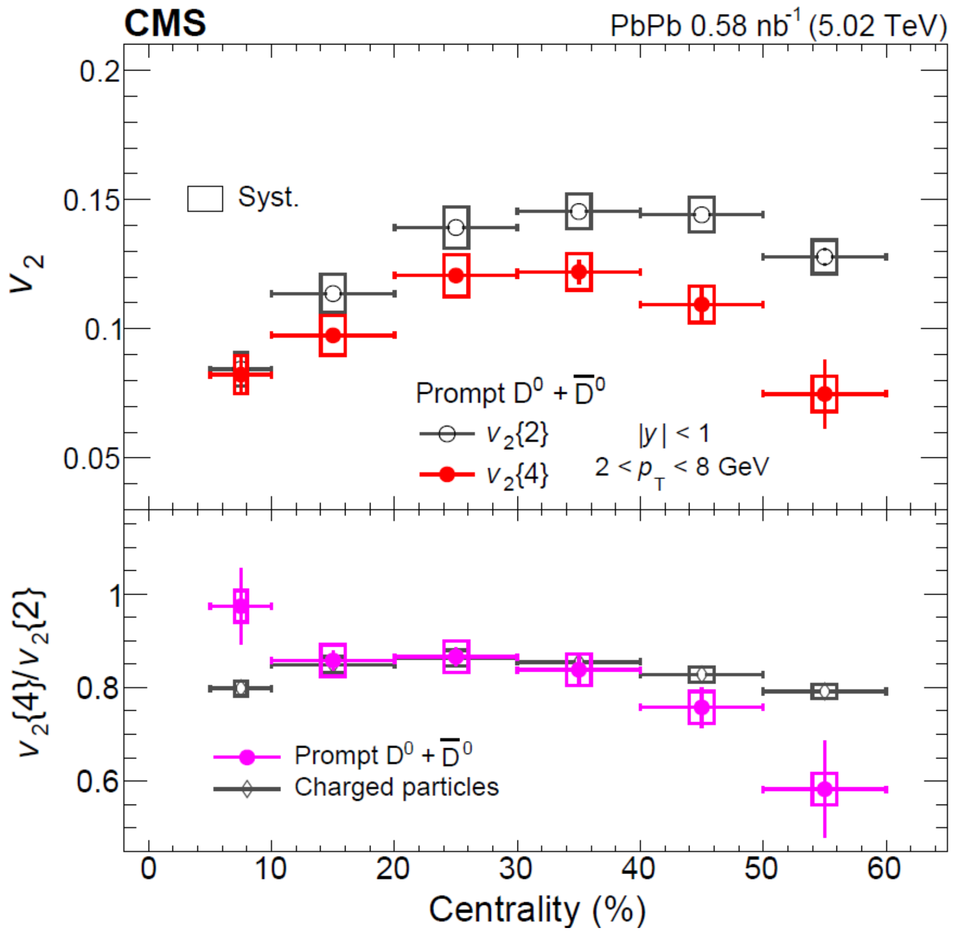


Summary and outlook

- Evident charm collectivity in pPb collisions and indications of charm flow in pp collisions
- Elliptic flow signal diminishes towards lower event activity
- Hint of energy loss fluctuations in peripheral PbPb collisions
- Future opportunities with CMS-MTD



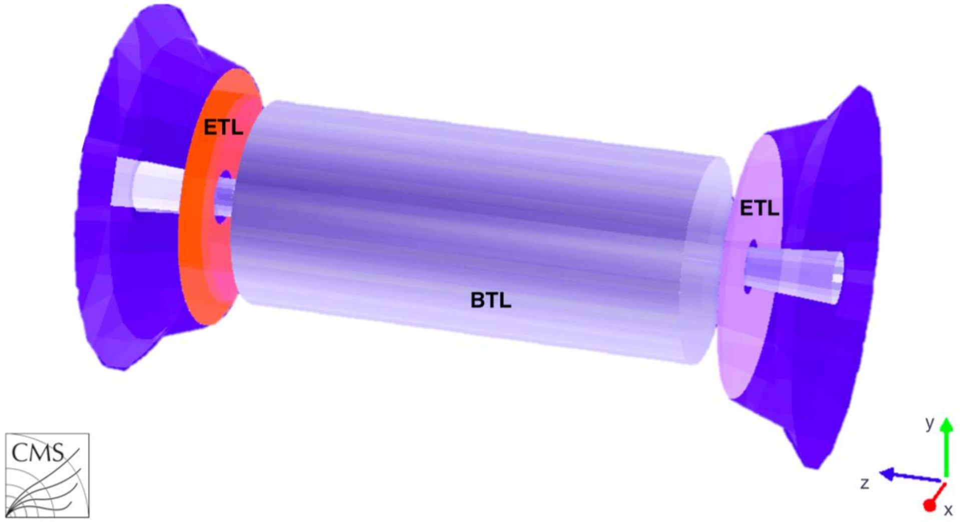


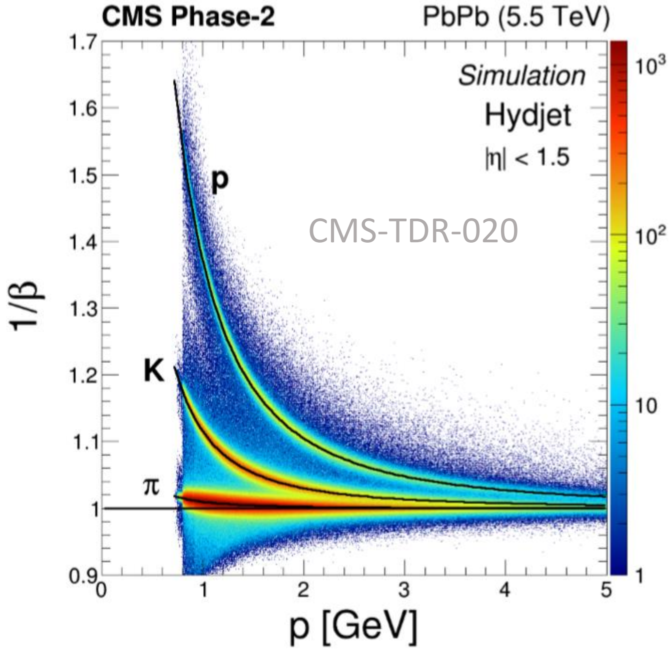


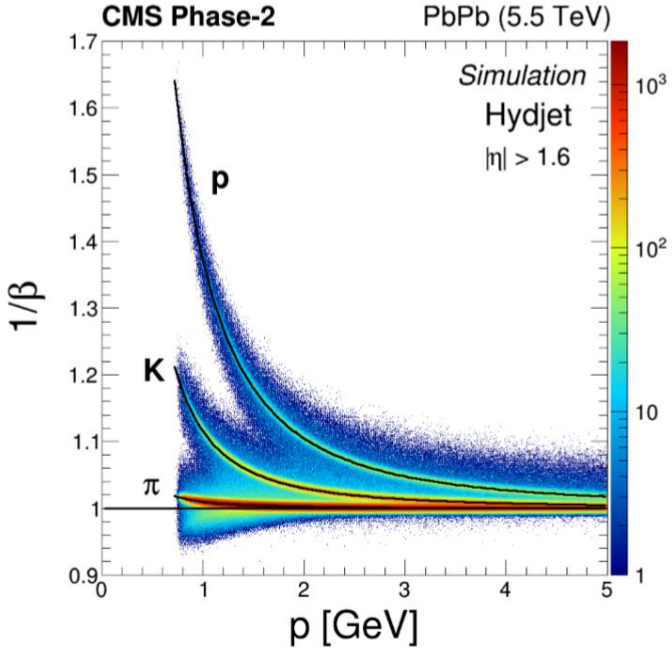
Backup

Opportunities at HL-LHC

- A new timing detector with timing resolution 30ps
  - Barrel Timing Layer: scintillating crystals and SiPM device
  - Endcap Timing Layer: Low Gain Avalanche Detector

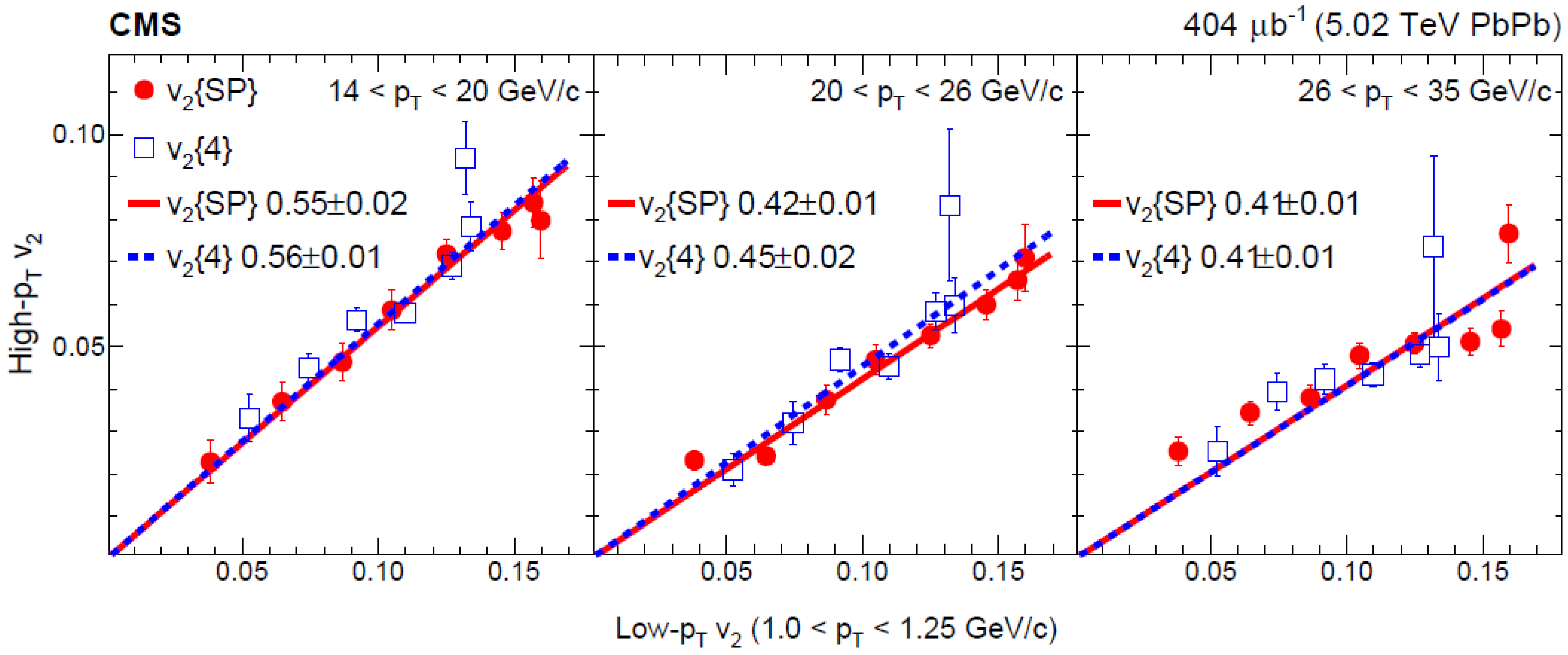






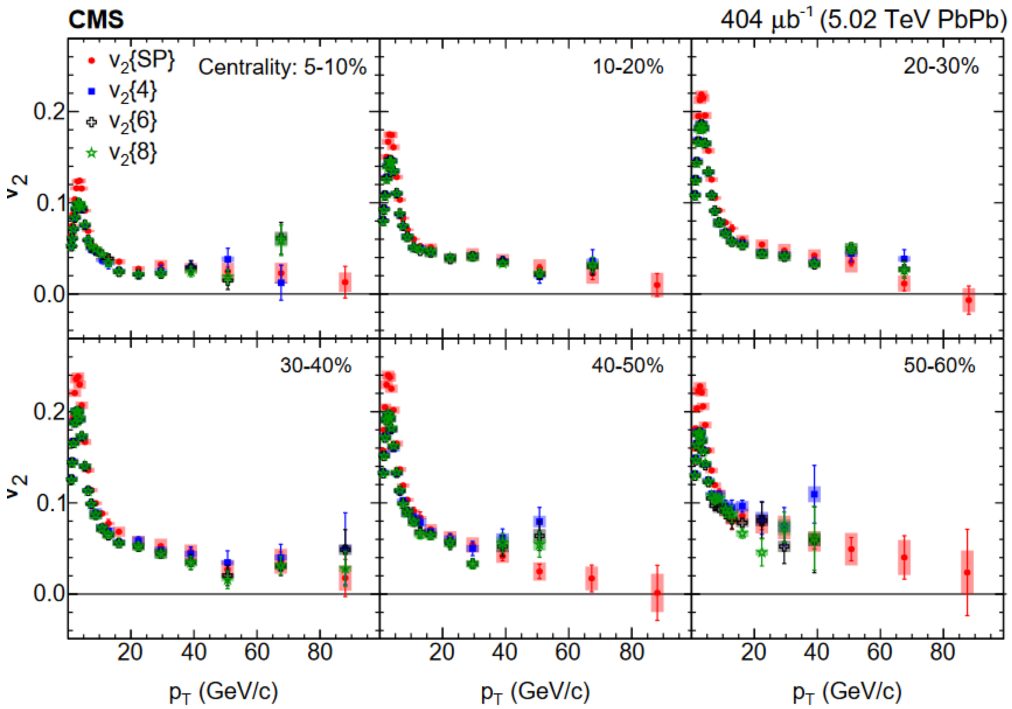
Charge particles

- Linear dependence
- Hard to tell differences between 2- and 4-particle correlations



Charge particles

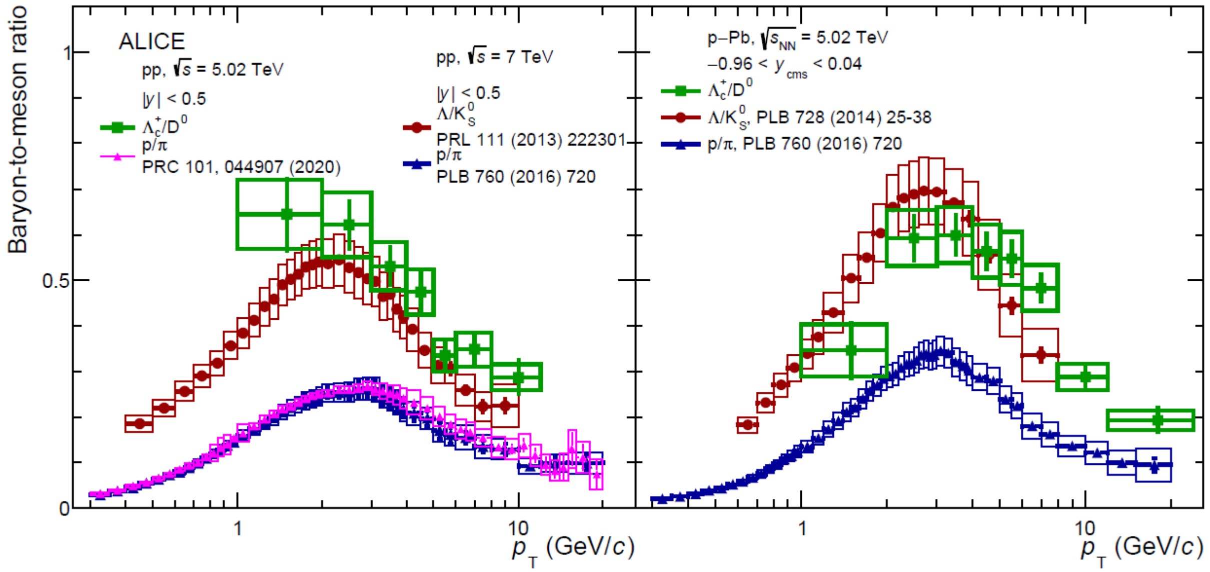
- Smaller differences between 2- and multi-particle correlations towards high p_T, limited to statistical uncertainties



Future opportunities via HF productions

- If there are any in-medium effects
  - Hadronization and its dependence on multiplicity – possible baryon enhancement for high multiplicity events?

PRL 127 (2021) 202301



arxiv:2111.11948