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SINAP

Probing prompt charm quark dynamics via multiparticle azimuthal correlations in 5.02 TeV PbPb collisions

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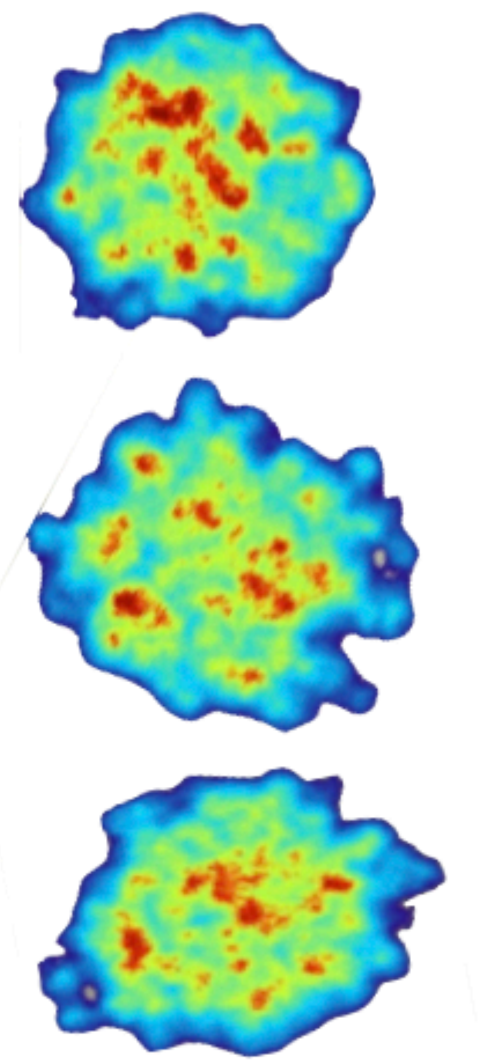
What is flow fluctuation?

Many collisions



⋮

Each with own evolution

$$\frac{dN}{d\phi} = N_a\left[1+2\sum_n \mathrm{v}_{n,a}\cos n\left(\phi-\Phi_{n,a}\right)\right]$$

$$\frac{dN}{d\phi} = N_b\left[1+2\sum_n \mathrm{v}_{n,b}\cos n\left(\phi-\Phi_{n,b}\right)\right]$$

$$\frac{dN}{d\phi} = N_c\left[1+2\sum_n \mathrm{v}_{n,c}\cos n\left(\phi-\Phi_{n,c}\right)\right]$$

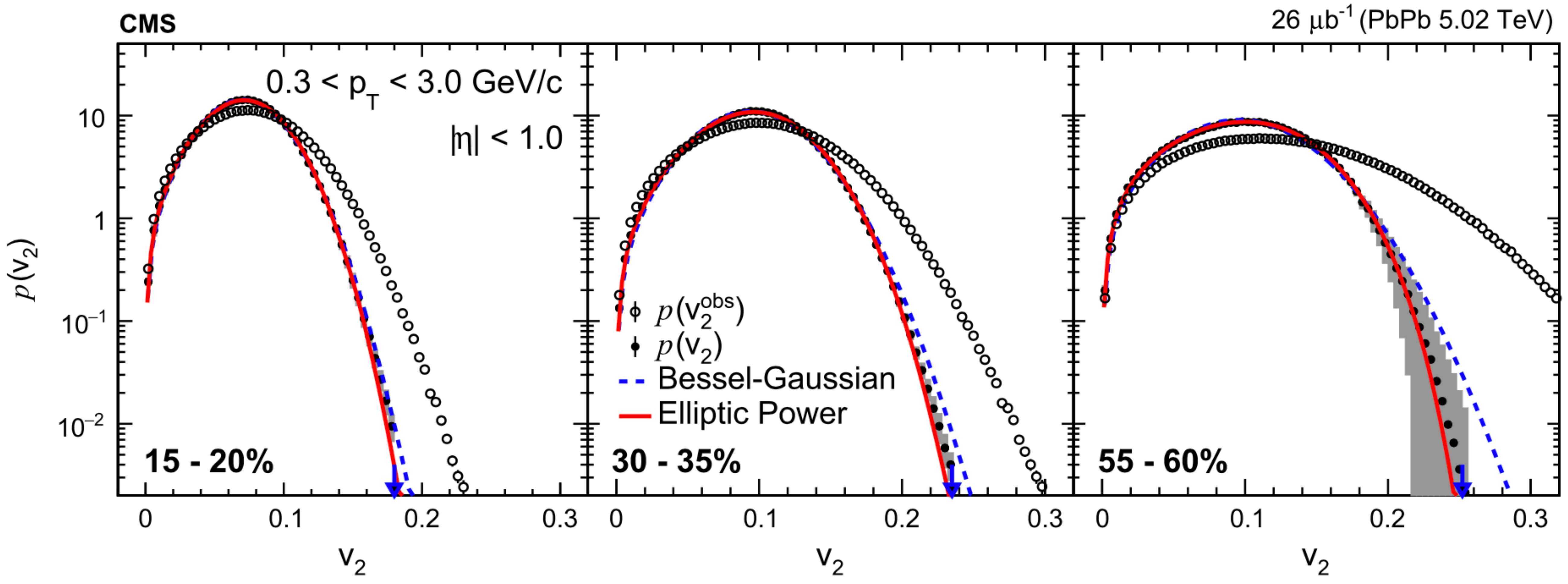
⋮

Event-by-event fluctuations

↓

$p(v_n)$

↓



PLB 789 (2019) 643–665

$$\langle v_n{}^k\rangle \neq \langle v_n\rangle^k$$

How to measure the flow fluctuation? $v_2\{4\}/v_2\{2\}$

flow(EP) | non-flow | flow fluctuation

$$v_2\{2\}^2 \sim \langle v \rangle^2 + \delta + \sigma_v^2$$

flow(EP) | flow fluctuation

$$v_2\{4\}^2 \sim \langle v \rangle^2 - \sigma_v^2$$

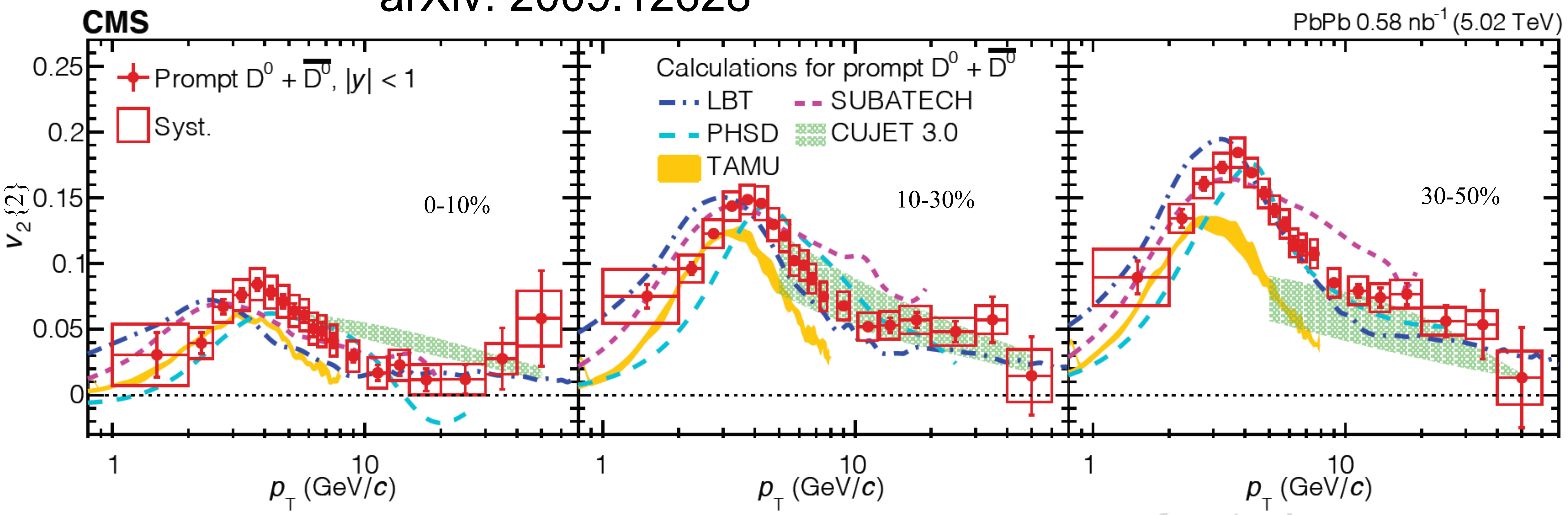
$v_2\{4\}/v_2\{2\}$: sensitive to flow fluctuations if non-flow is negligible.

Open question:

Event-by-event fluctuations of heavy quark flow have never been explored experimentally.

D^0 $v_2\{2\}$ has been measured

arXiv: 2009.12628



- v_2 from two-particle correlation (D^0 + 1 light-flavor particle) → strong charm flow
- Non-flow effect (δ) is negligible (suppressed with large eta gap requirement)

New measurement: $D^0\ v_2\{4\}$, which is compared to $D^0\ v_2\{2\}$ to probe the flow fluctuations.

First-time D^0 v_2 using four-particle cumulant (D^0 + 3 light-flavor particles)

Initial geometry Vs final state fluctuations

$v_2\{4\}/v_2\{2\}$ comparison between charm and charged particles.
$\Longrightarrow$ To disentangle the fluctuations from initial-state geometry and final state.

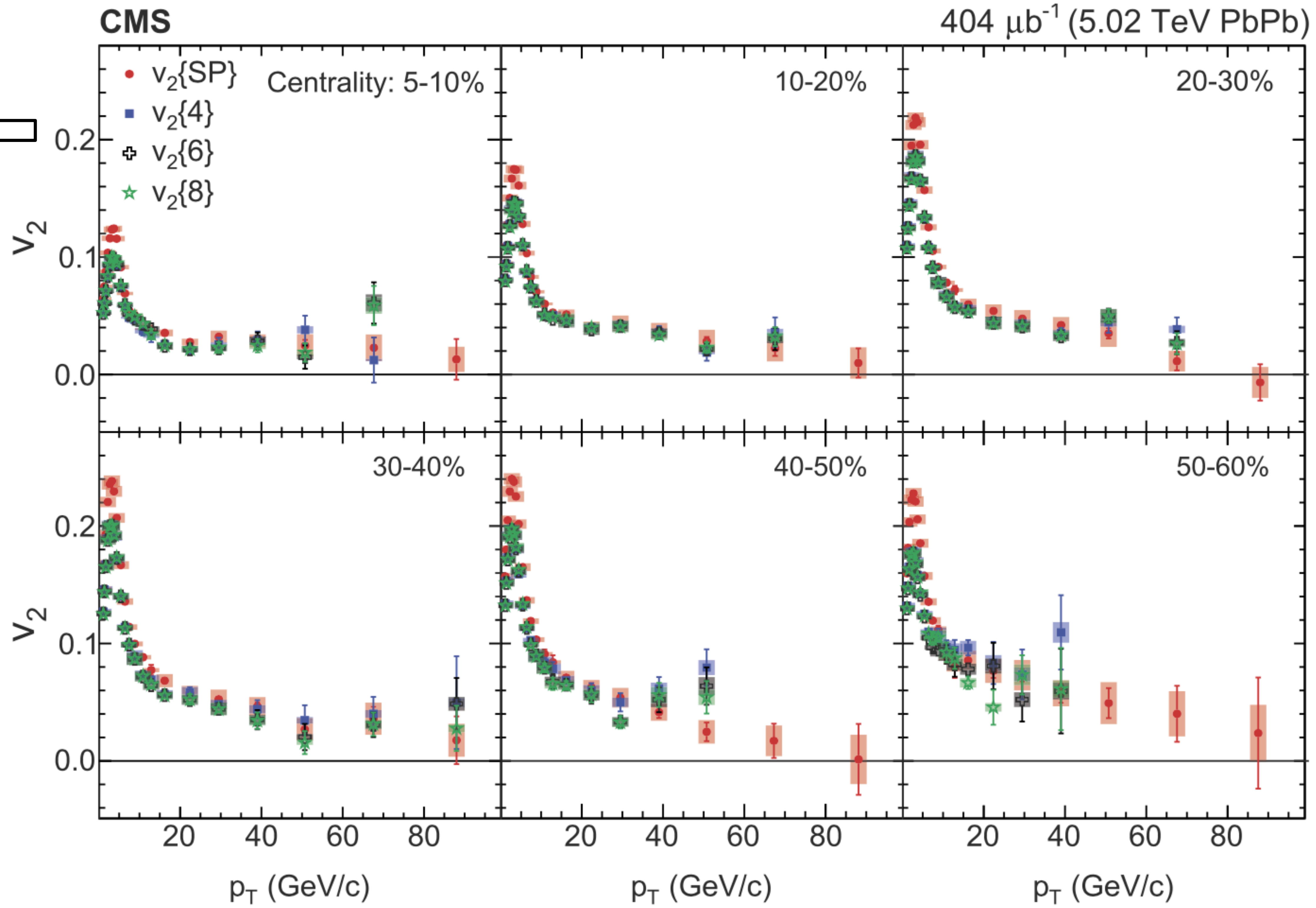
- Charged particle $v_2\{4\}$ and $v_2\{2\}$:

  1. In low p_T: $v_2\{4\} < v_2\{2\}$

  → Indicates that v_2 are strongly affected by the initial-state geometry fluctuations.

  2. In high p_T: $v_2\{4\}$ are similar to $v_2\{2\}$.

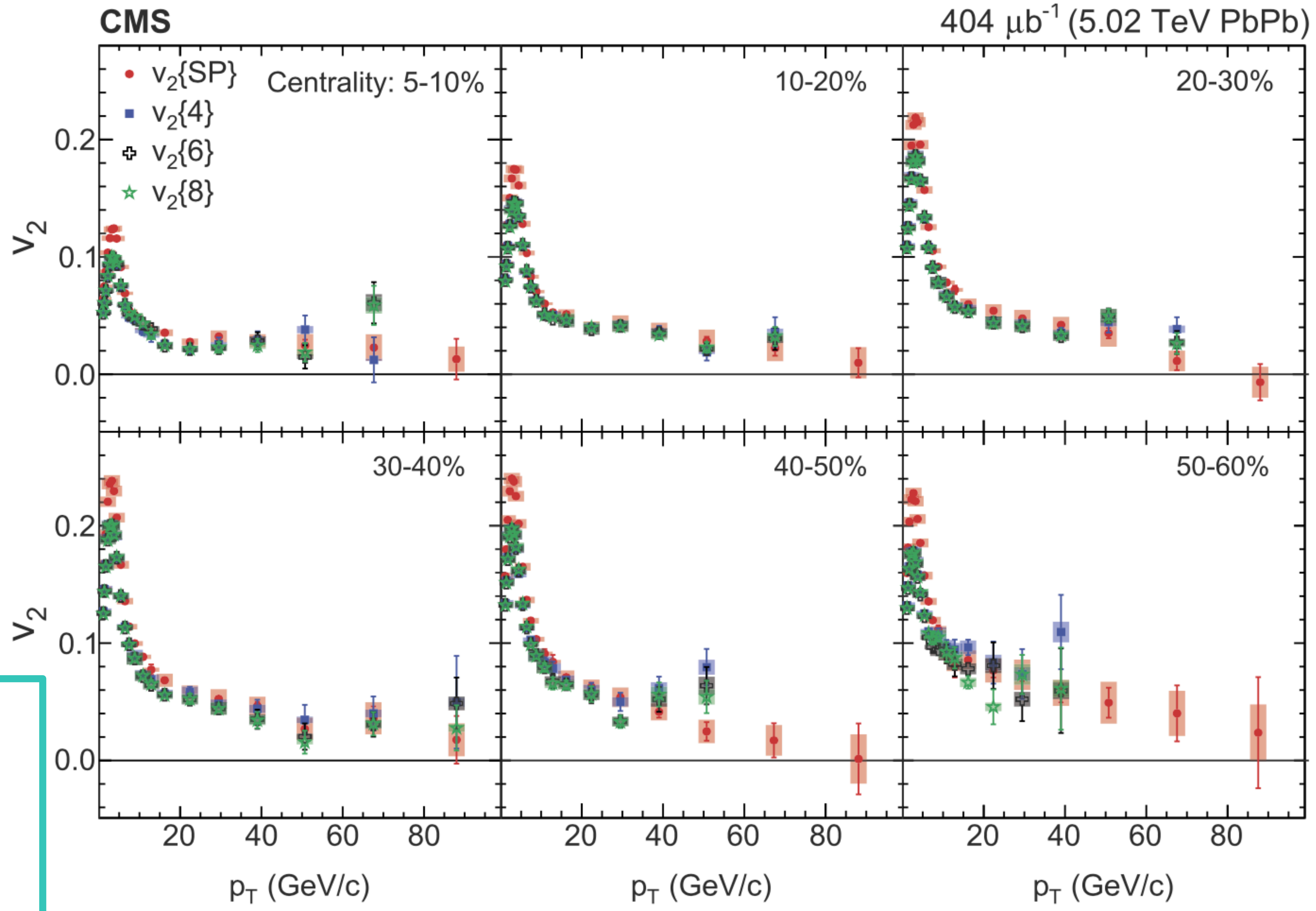
  Due to the contribution from energy loss fluctuations.



PLB 776 (2018) 195–216

Initial geometry Vs final state fluctuations

$v_2\{4\}/v_2\{2\}$ comparison between charm and charged particles.
⟹ To disentangle the fluctuations from initial-state geometry and final state.



PLB 776 (2018) 195–216

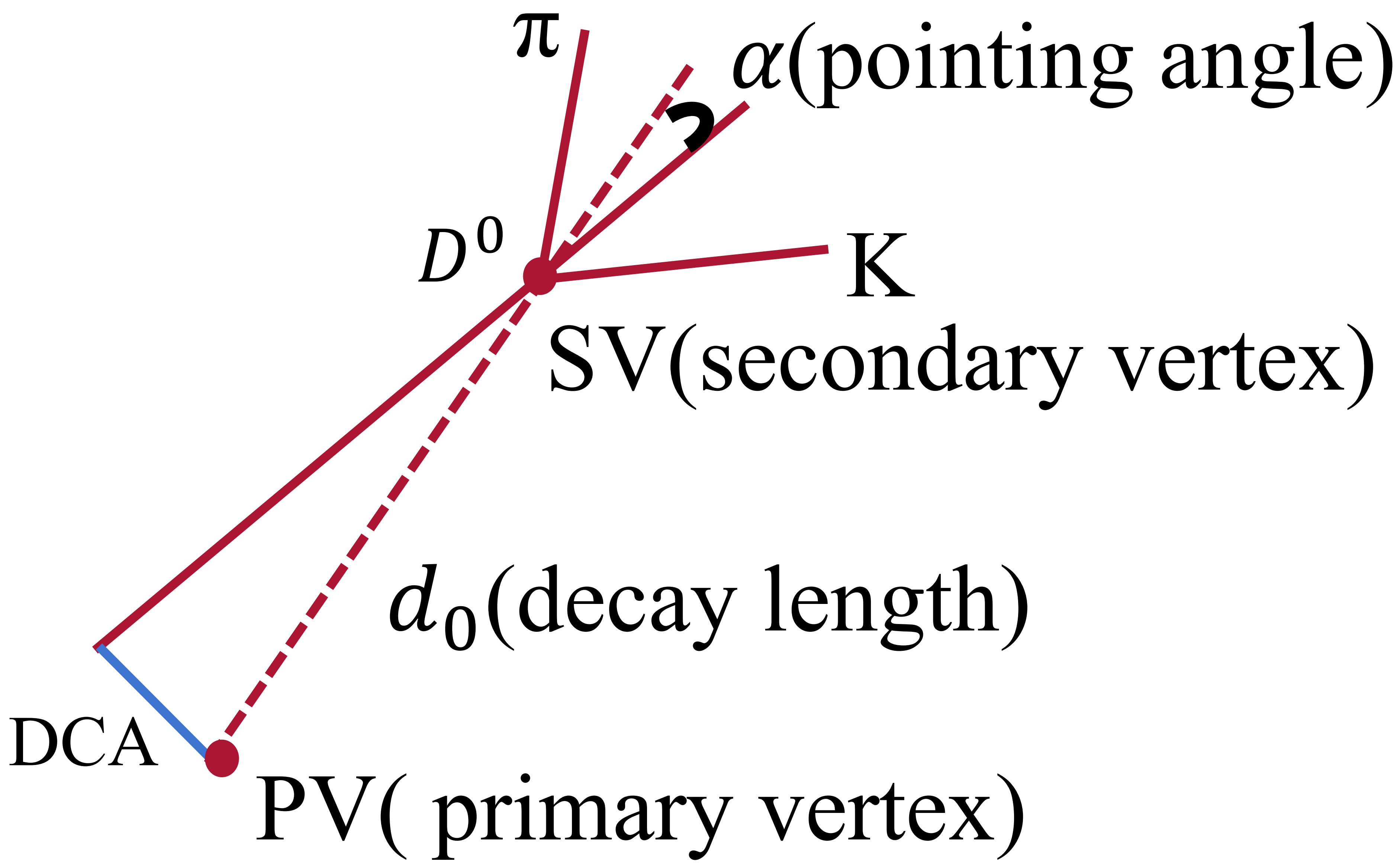
- What about D^0 $v_2\{4\}/v_2\{2\}$?

Experimental results strongly constrain charm energy loss model to probe the elastic scattering (low p_T) or gluon radiation (high p_T) in the QGP medium, for example, DAB-MOD model[1].

1.PRC 102, 024906 (2020)

Prompt D^0 reconstruction, optimization (2018 data)

Prompt D^0 meson reconstruction: $D^0 \rightarrow K^{-} + \pi^{+}$ (BR: 3.88 ± 0.05%)[1]



- ❑ D^0 reconstruction
  - ✓ Paring oppositely charged tracks (no PID)
  - ✓ Secondary vertex reconstruction

- ❑ Prompt D^0 candidate selection (MVA: BDT)
- ➢ D^0 variable: ($d_0/\sigma(d_0)$, α, SV probability)
- ➢ Tracks (Kπ): (DCA significance, $\sigma(p_T)$, Nhits.)

Similar to D^0 $v_2\{2\}$ measurement [2].

1.M. Tanabashi et al (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

2. arXiv: 2009.12628

Analysis technique: four-particle cumulants (I)

Differential flow: PRC 83, 044913(2011)

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2 * \langle\langle 2' \rangle\rangle \langle\langle 2 \rangle\rangle \quad (2)$$

$$v_n'\{4\}(D^0) = -\frac{d_n\{4\}(D^0)}{(-c_n\{4\})^{3/4}} \quad (1)$$

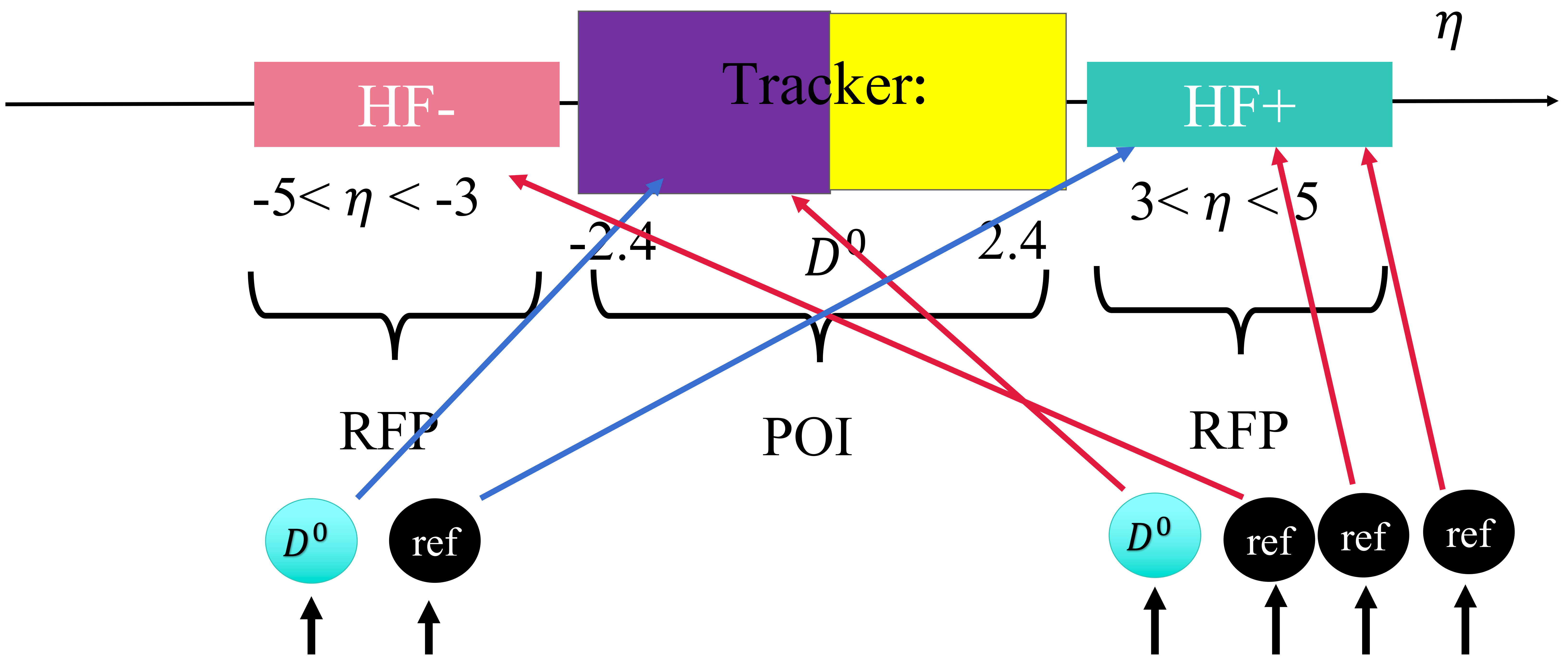
$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 * \langle\langle 2 \rangle\rangle^2 \quad (3)$$

$d_n\{4\}$: fourth-order differential cumulant.

$c_n\{4\}$: four-particle cumulant $\rightarrow$ reference flow.

Analysis technique: four-particle cumulants (II)

$d_n\{4\}(D^0)$: $d_n\{4\} = \langle\langle 4' \rangle\rangle - 2 * \langle\langle 2' \rangle\rangle \langle\langle 2 \rangle\rangle$

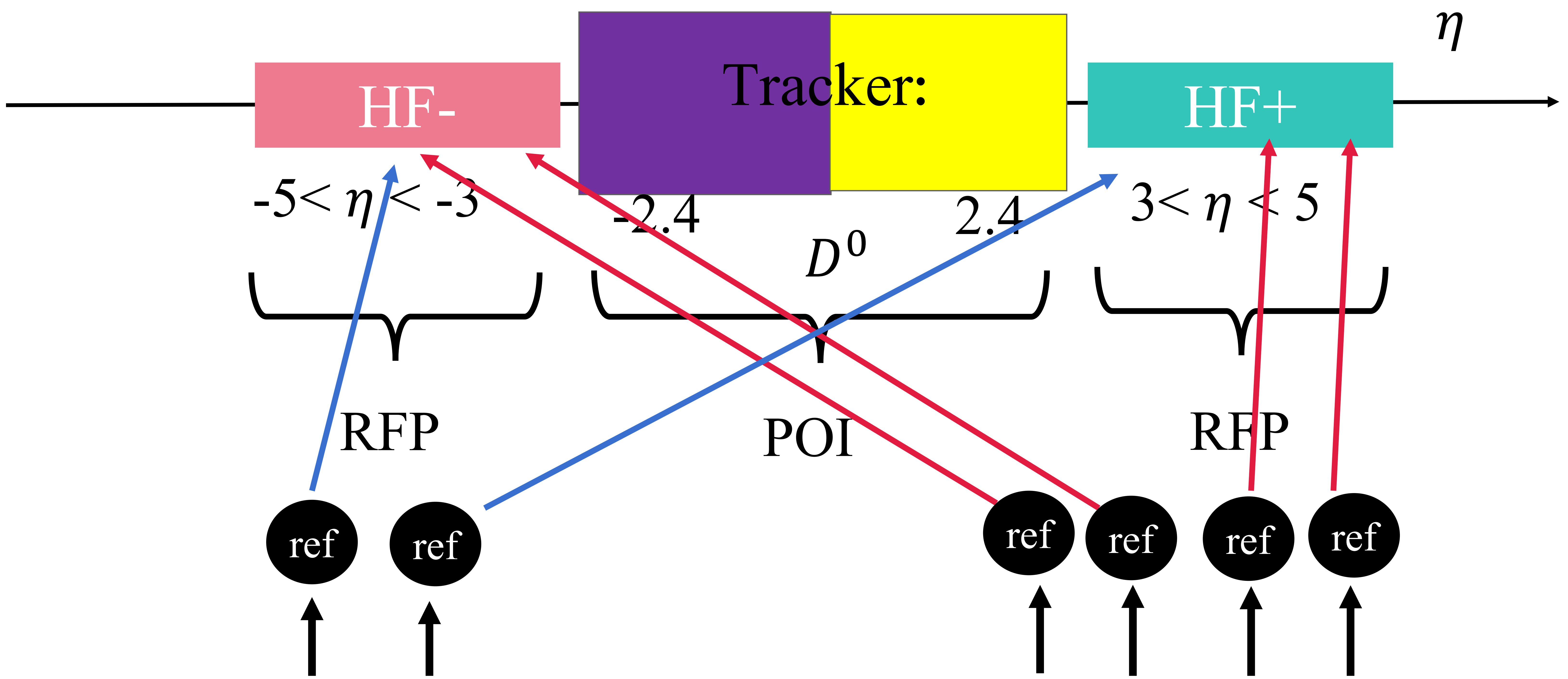


$$\langle 2' \rangle = \left\langle e^{in(\psi_1 - \phi_2)} \right\rangle \qquad \langle 4' \rangle = \left\langle e^{in(\psi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle$$

A consistent results are observed when reference particles chosen from Tracker.

Analysis technique: four-particle cumulants (III)

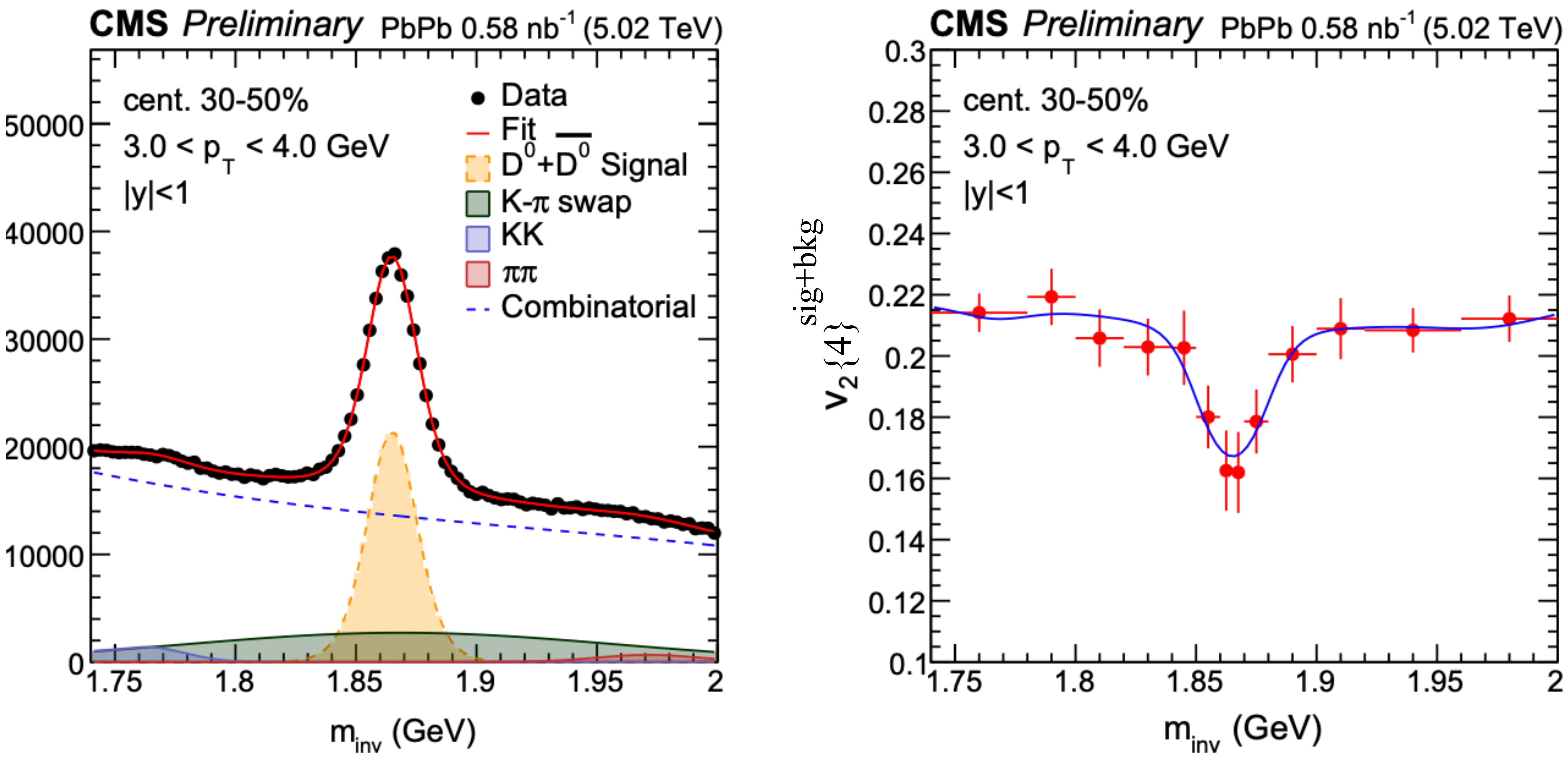
$c_n\{4\}$: $c_n\{4\} = \langle\langle 4\rangle\rangle - 2 * \langle\langle 2\rangle\rangle^2$



$$\langle 2\rangle = \left\langle e^{in(\phi_1-\phi_2)}\right\rangle \qquad \langle 4\rangle = \left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle$$

Signal D^0 $v_2\{4\}$ extraction

- ➢ Invariant mass fit.
  - ✓ $K^-\pi^+$ signal: double Gaussian.
  - ✓ Swapped $K^+\pi^-$: single Gaussian.
  - ✓ K^+K^-: Crystal Ball.
  - ✓ $\pi^+\pi^-$: Crystal Ball.
  - ✓ Combinatorial bkg.: 3rd polynomial.



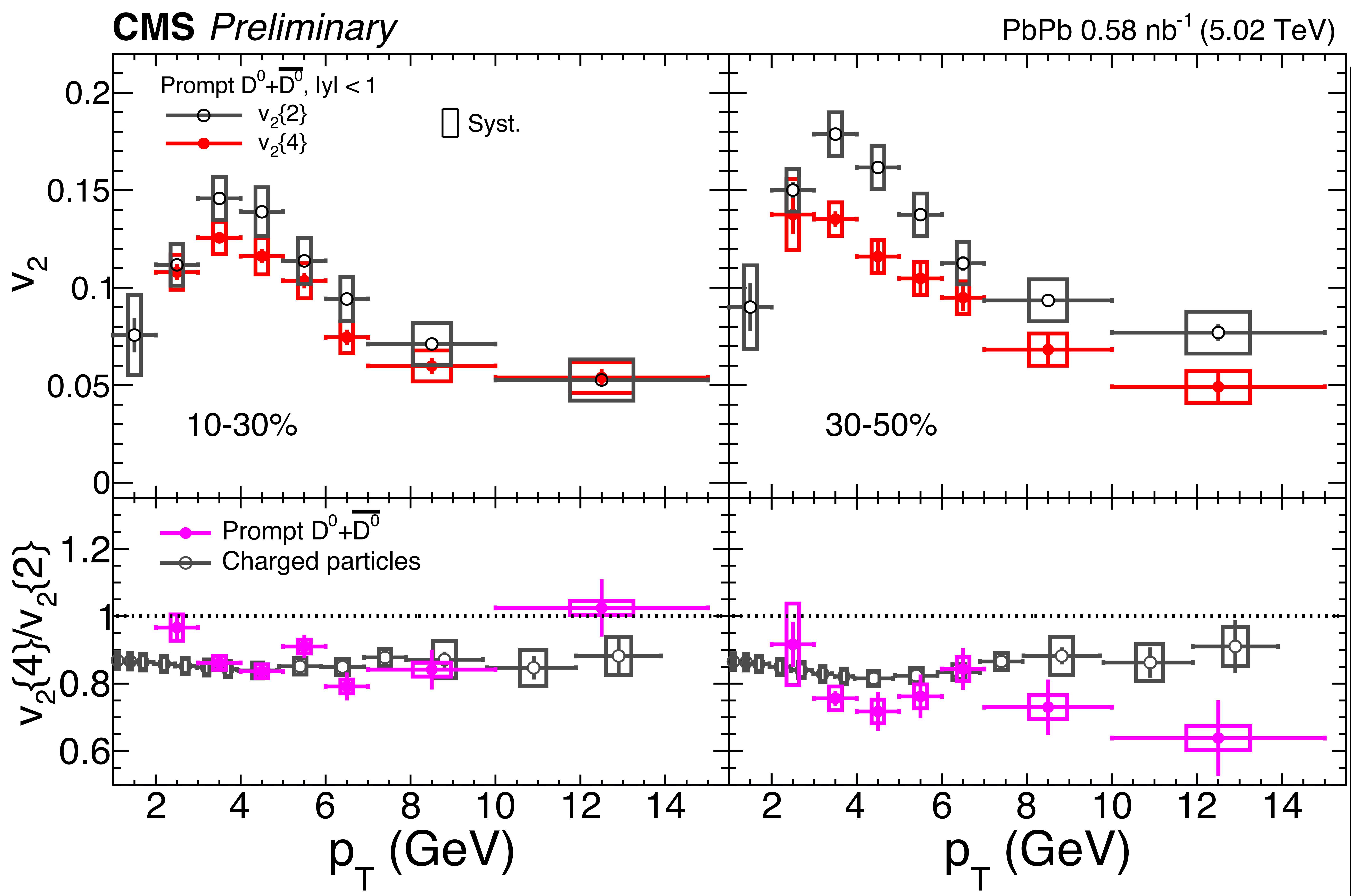
An example of the fits in 3.0 < p_T < 4.0GeV && 30-50%.

$$\alpha(m_{inv}) = \frac{\text{Signal}(m_{inv}) + \text{Swapped}(m_{inv}) + \text{KK}(m_{inv}) + \pi\pi(m_{inv})}{\text{Signal}(m_{inv}) + \text{Swapped}(m_{inv}) + \text{KK}(m_{inv}) + \pi\pi(m_{inv})\text{K}\pi + \text{Bkg}(m_{inv})}.$$

↓ $\alpha(m_{inv})$ is fixed.

$$v_2\{4\}^{sig+bkg}(m_{inv}) = v_2^{sig} \times \alpha(m_{inv}) + v_2^{bkg}(m_{inv})(1\text{-}\ \alpha(m_{inv}))$$

$D^0\ v_2\{4\}\ (p_T)$



Mid-rapidity region (|y|<1).

❑ First measurement $D^0\ v_2\{4\}$:

❖ $D^0\ v_2\{4\}(p_T)$: $v_2\{4\} < v_2\{2\}$

→ Initial-state fluctuations.

❖ $v_2\{4\}/v_2\{2\}\ (p_T)$:

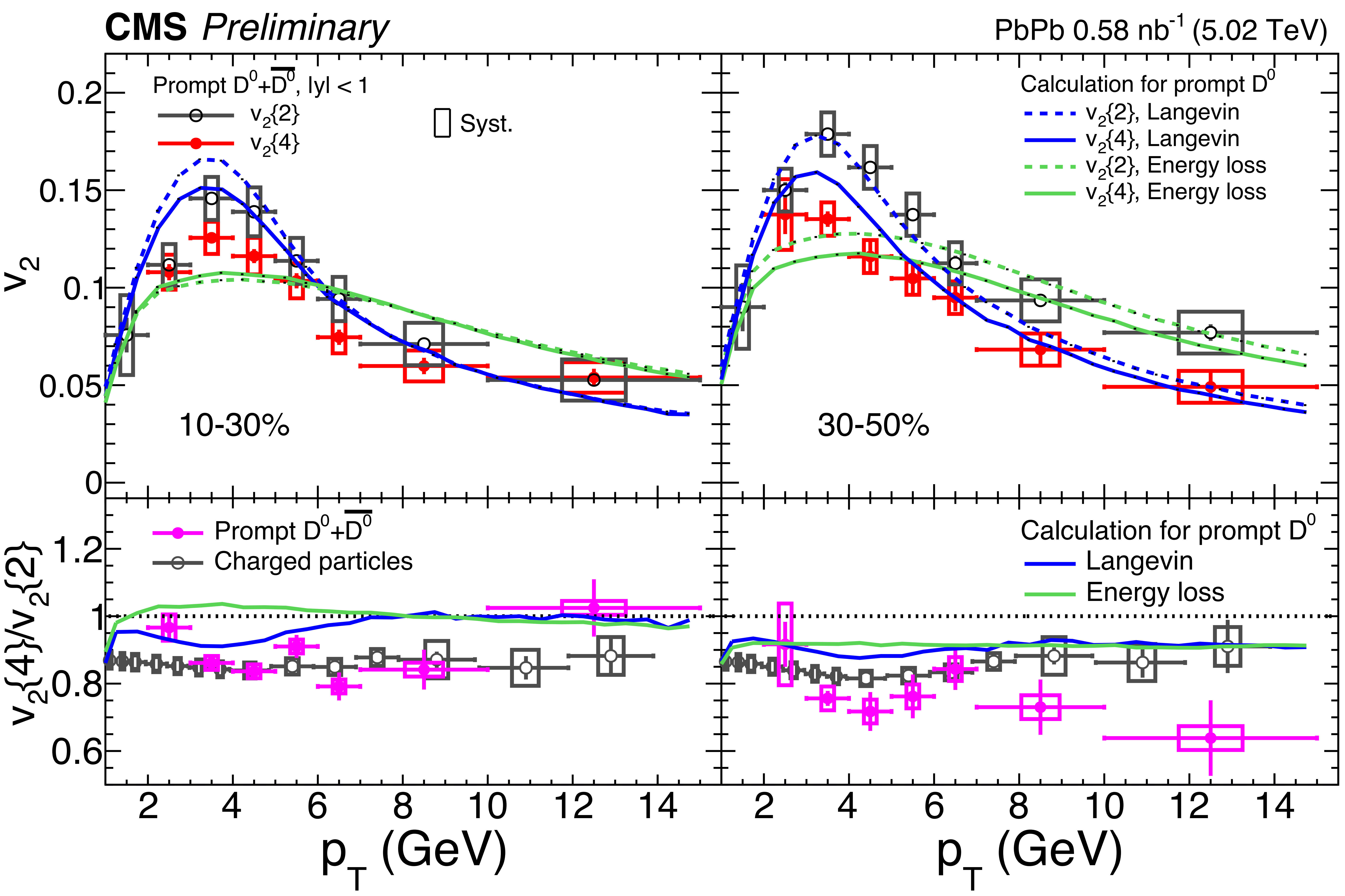
✓ 10-30%: More consistent with ones of charged particles.

→ Initial state fluctuations are dominant

✓ 30-50%: A hint of a splitting of $v_2\{4\}\ /v_2\{2\}$ between D^0 and charged particle in high p_T.

→ Indicates energy loss fluctuation effects become more significant.

$D^0\ v_2\{4\}\ (p_T)$



Mid-rapidity region (|y|<1).

Theoretical calculations:

- Capture the measurement trend, without reproducing them quantitatively.

$D^0\ v_2\{4\}$(cent.)

Mid-rapidity (|y|<1).

❑ $D^0 v_2\{4\}$(cent.)
Increasing and then declining.

→This trend can be explained by the initial collision geometry.

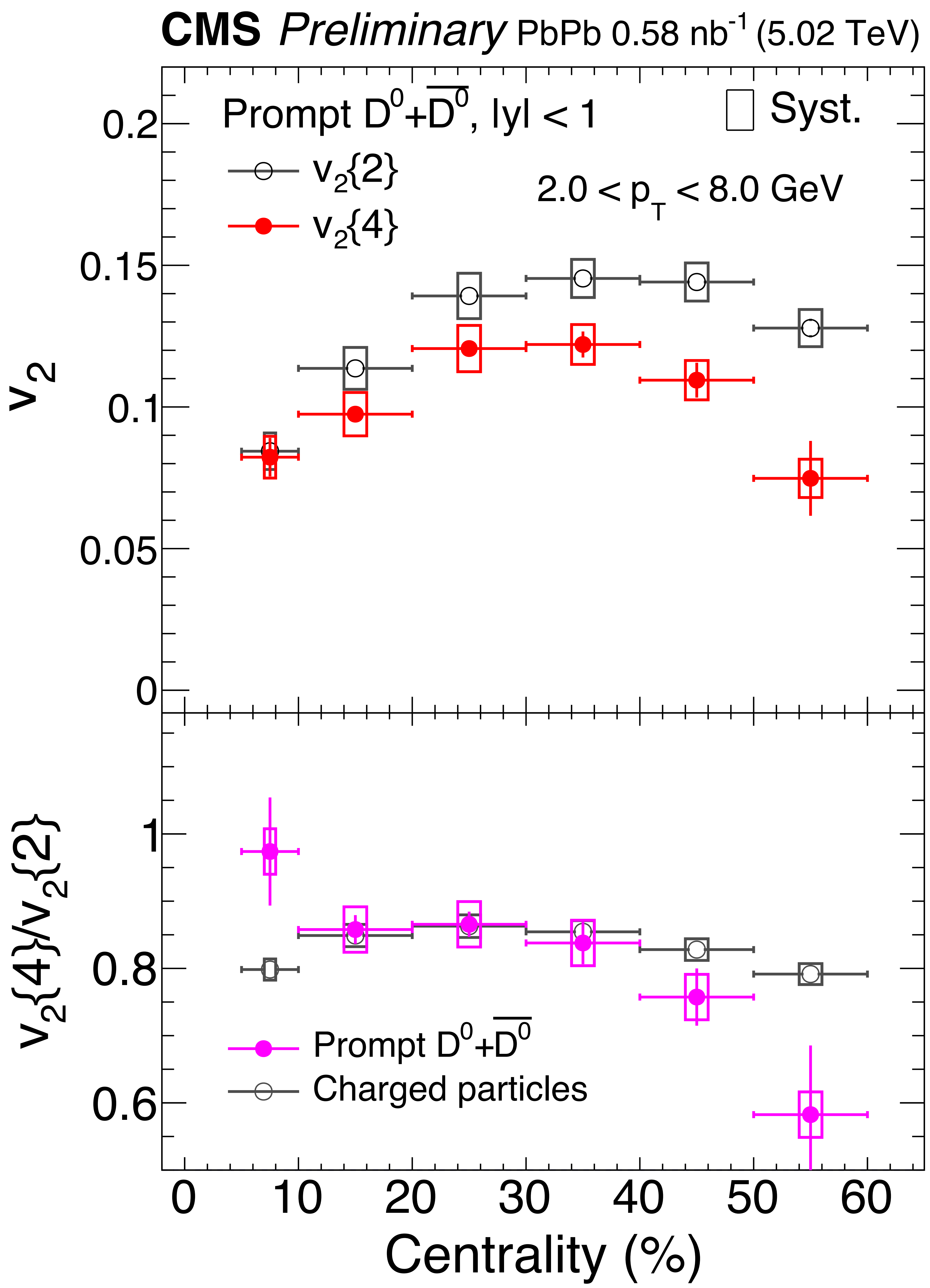
❑ $D^0\ v_2\{4\}/v_2\{2\}$(cent.)

✓ Mid central (10-40%): $D^0\ v_2\{4\}/v_2\{2\}$ are more consistent to charged particles.

→Initial state fluctuations are dominant

✓ More central and peripheral: a hint of a splitting between $D^0$and charged particles.

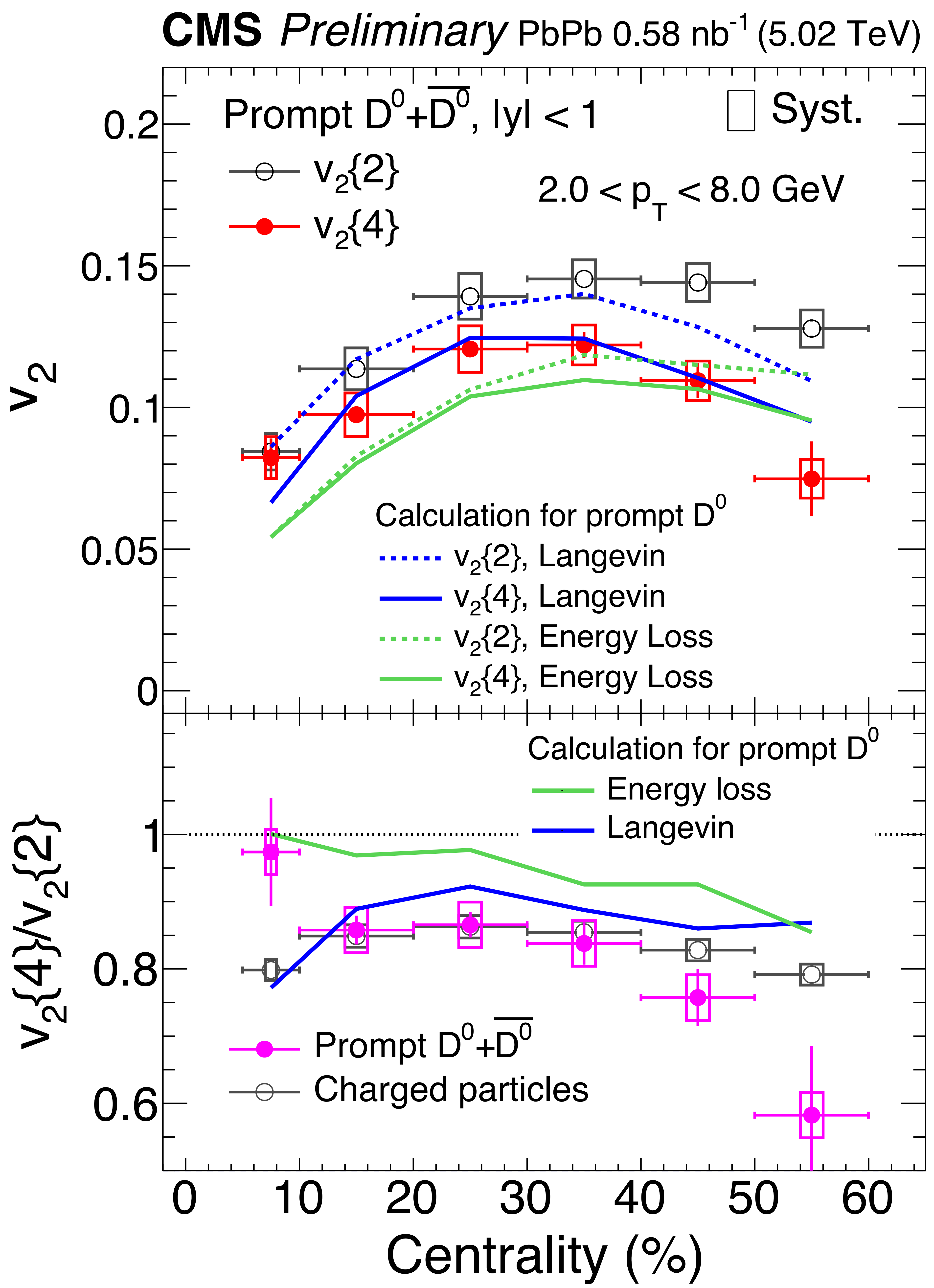
→ Indicates energy loss fluctuation effects become visible from D^0.



D^0 $v_2\{4\}$(cent.)

Mid-rapidity (|y|<1).

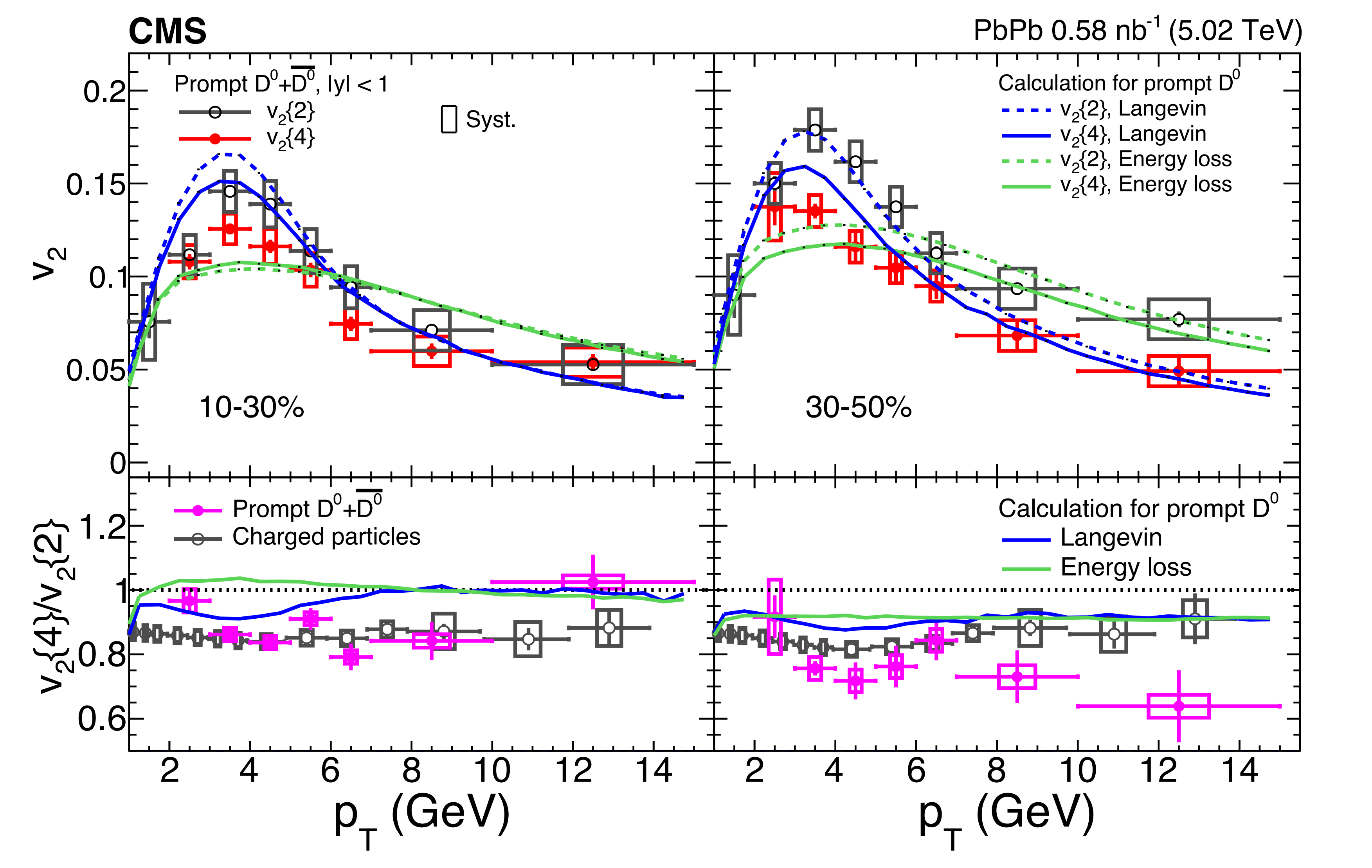
- ❑ Theoretical calculations: D^0 $v_2\{4\}/v_2\{2\}$(cent.)
  - ○ A better description of the experimental data (10-50%) is obtained using the Langevin dynamics.
  - ○ Still an improvement to make for 50-60%.

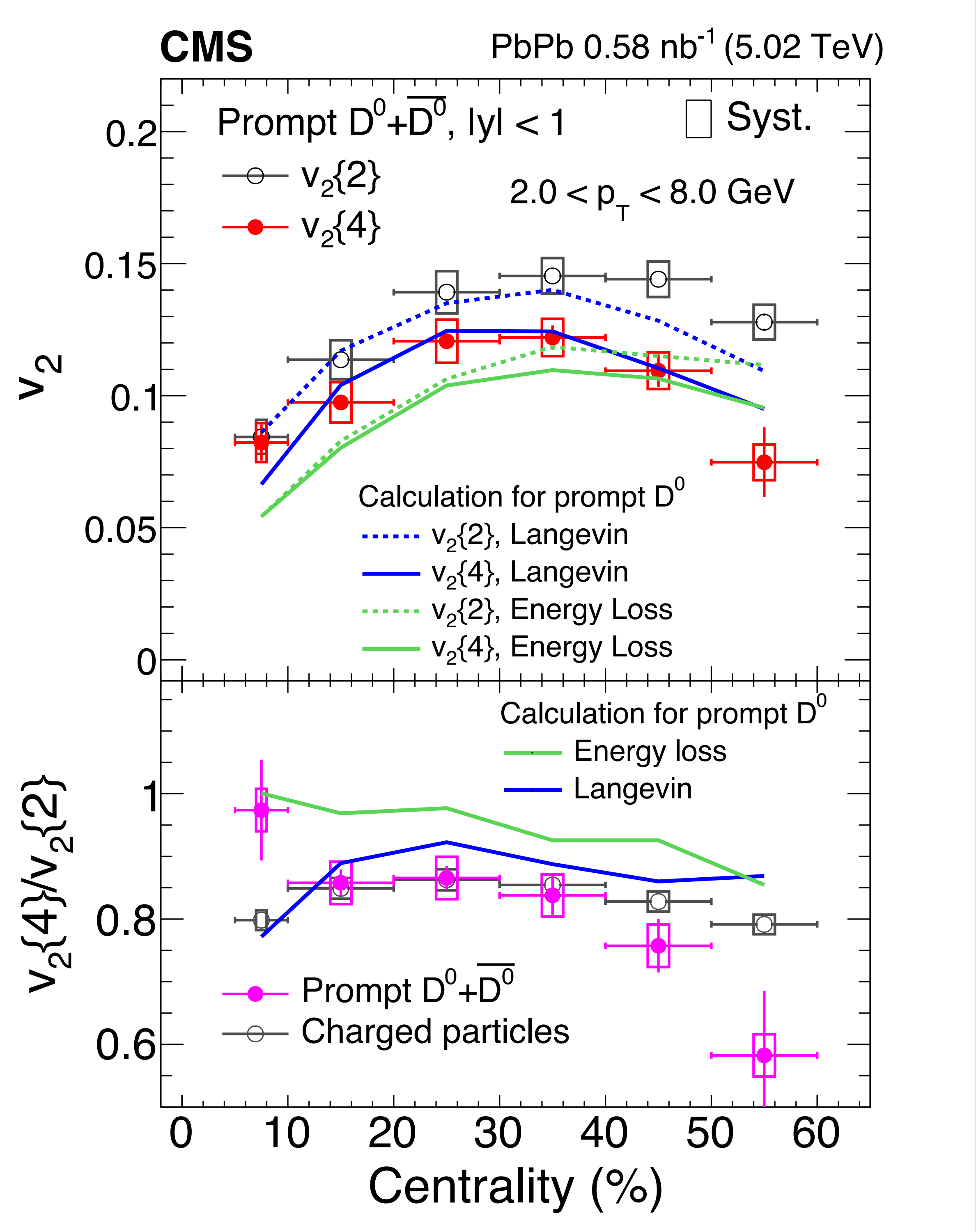


Summary:

- ❑ First measurement to probe charm flow fluctuation using 4-particle cumulant method.

- ❑ $v_2\{4\}/v_2\{2\}$:
  - ➢ Mid-central collision (10-40%): D^0 $v_2\{4\}/v_2\{2\}$ are consistent to charged particles.
    → Indicate that initial state fluctuations are dominant.
  - ➢ More central and peripheral collisions: a hint of a deviation between charm and charged particle is observed.
    →May indicate more significant contribution from energy loss fluctuations.





Thank you!

backup

Physics motivation: $v_2\{4\}/v_2\{2\}$ (fluctuation)

3. why uses four-particle correlation technique to measure harmonic flows.
$\Longrightarrow$ To judge the fluctuation from soft and hard components

$$\frac{v_2\{4\}(\text{hard})}{v_2\{2\}(\text{hard})} = \frac{v_2\{4\}}{v_2\{2\}}\left[1+\left(\frac{v_2\{2\}}{v_2\{4\}}\right)^4\left(\frac{\langle v_2^4\rangle}{\langle v_2^2\rangle^2} - \frac{\langle v_2^2 V_2 V_2^*(\text{hard})\rangle}{\langle v_2^2\rangle\langle V_2 V_2^*(\text{hard})\rangle}\right)\right]$$ [1]

Soft fluctuation: initial condition fluctuation

Hard fluctuation: energy loss fluctuation

Hard particle:

- High p_T charged particles.
- Heavy flavor particles over full p_T.

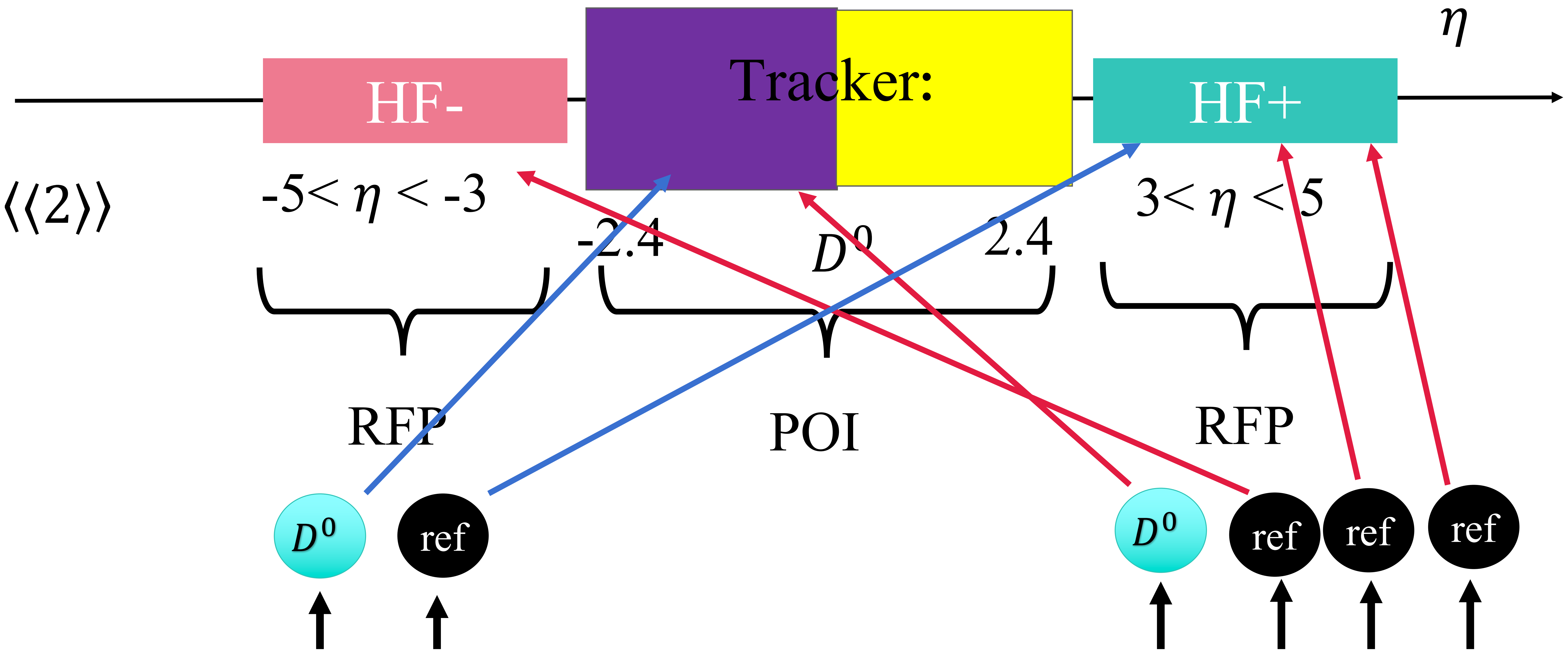
➢ Initial condition fluctuation dominated: $\frac{\langle v_2^2 V_2 V_2^*(\text{hard})\rangle}{\langle v_2^2\rangle\langle V_2 V_2^*(\text{hard})\rangle} \rightarrow \frac{\langle v_2^4\rangle}{\langle v_2^2\rangle^2}$ ⇩ $\frac{v_2\{4\}(\text{hard})}{v_2\{2\}(\text{hard})} \rightarrow \frac{v_2\{4\}}{v_2\{2\}}$

➢ Significant energy loss fluctuation: $\frac{\langle v_2^2 V_2 V_2^*(\text{hard})\rangle}{\langle v_2^2\rangle\langle V_2 V_2^*(\text{hard})\rangle} \neq \frac{\langle v_2^4\rangle}{\langle v_2^2\rangle^2}$ ⇩ $\frac{v_2\{4\}(\text{hard})}{v_2\{2\}(\text{hard})}$ ↓↑

1. arXiv:1906.10768v2

$d_n\{4\}$:

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2 * \langle\langle 2' \rangle\rangle \langle\langle 2 \rangle\rangle$$



$$\langle 2' \rangle = \langle e^{in(\psi_1 - \phi_2)} \rangle$$

$$\langle 4' \rangle = \langle e^{in(\psi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle$$

definition:

$$Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i}$$

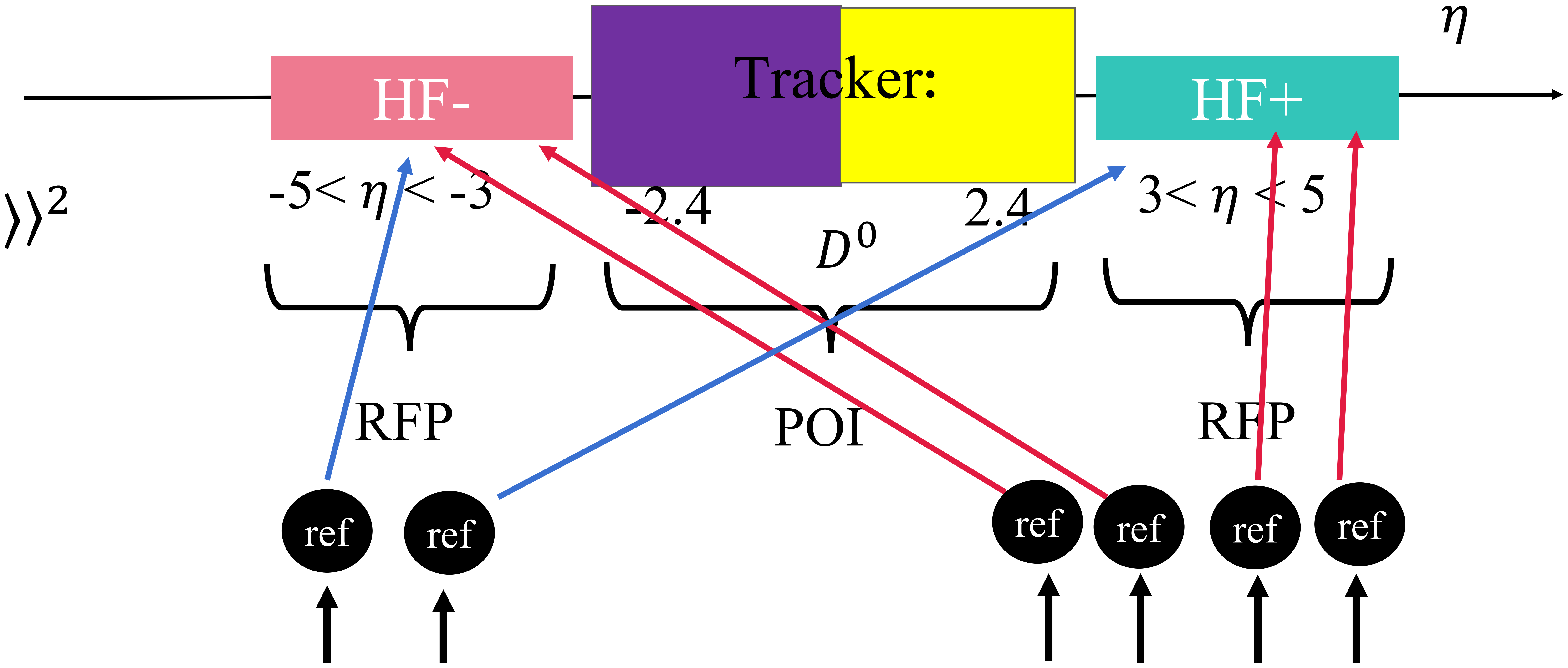
$$\langle 4' \rangle = \frac{Re[\, Q_n^{D^0} Q_n^{HF-} (Q_n^{HF+})^* (Q_n^{HF+})^*] - Q_n^{D^0} Q_n^{HF-} (Q_{2n}^{HF+})^*]}{M^{HF-}\, M^{HF+}\, (M^{HF+} - 1)} \quad \text{if: } D^0(\text{eta}<0) \qquad (4)$$

Note: weight $M^{HF-} = \sum (E_T)_i$ from HF- , $M^{HF+} = \sum (E_T)_i$ from HF+

Analysis technique: four-particle cumulants (III)

$c_n\{4\}$:

$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2 * \langle\langle 2\rangle\rangle^2$$



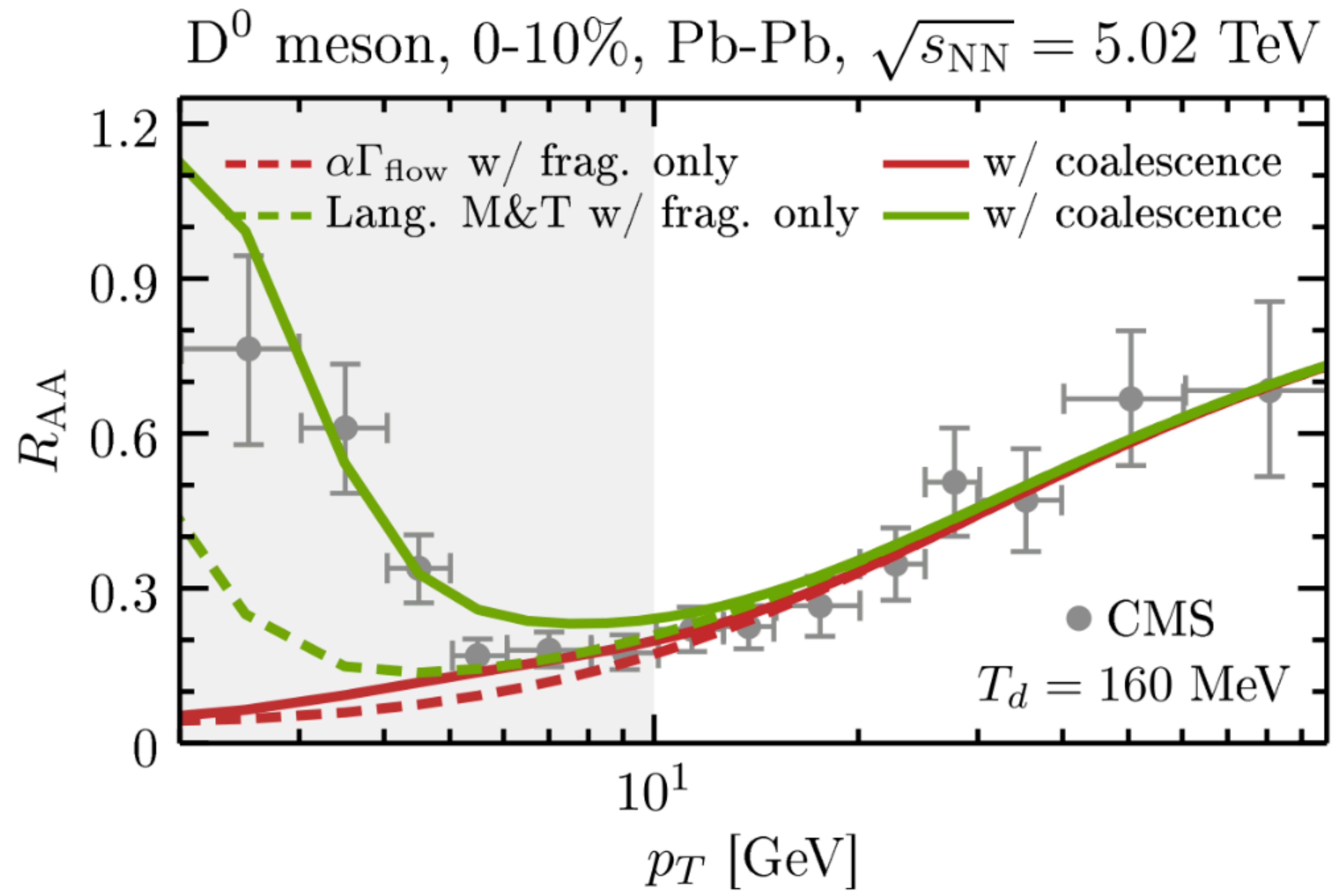
$$\langle 2\rangle = \left\langle e^{in(\phi_1-\phi_2)}\right\rangle \qquad \langle 4\rangle = \left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle$$

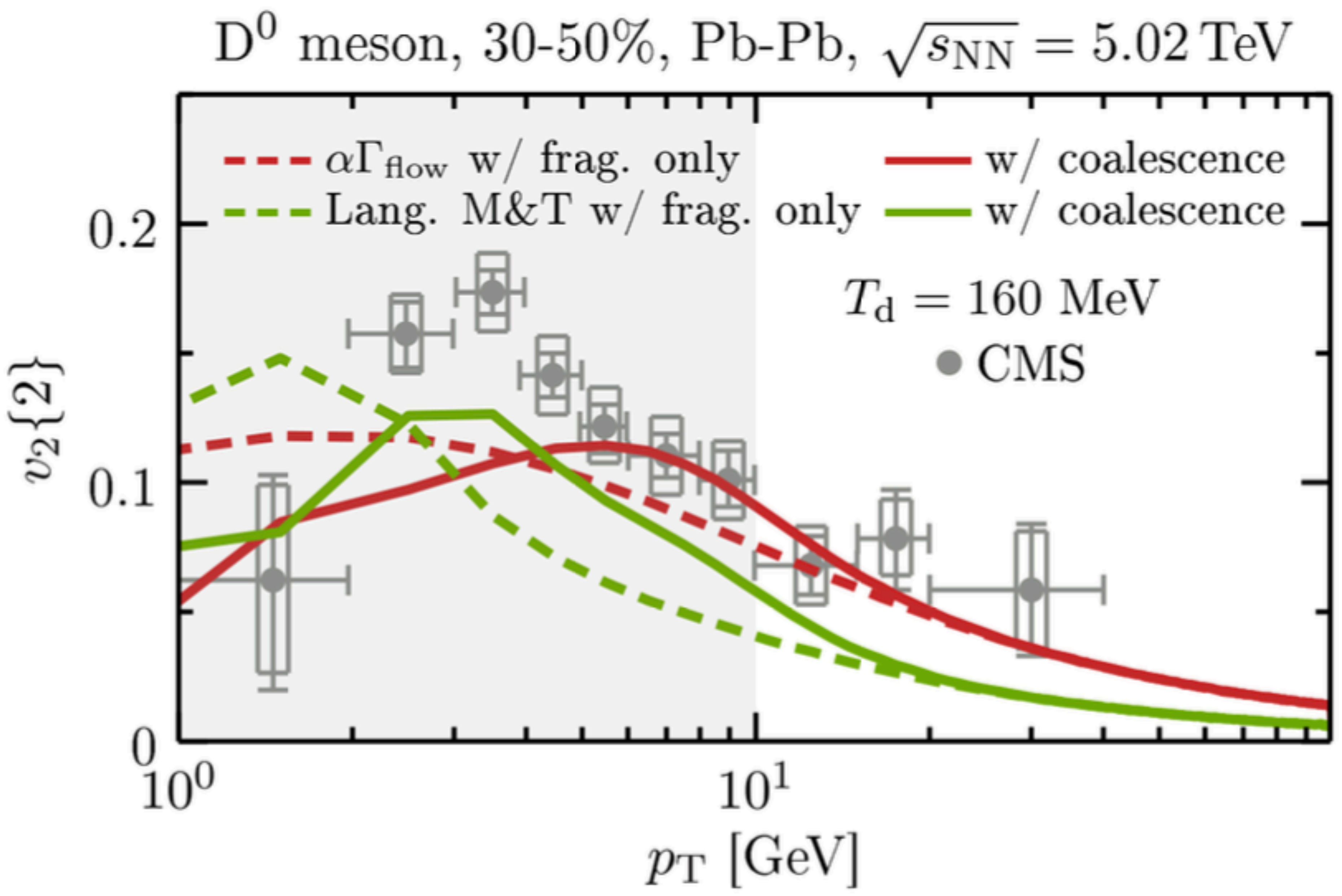
$$\langle 4\rangle = \frac{Re[\,Q_n^{HF-}Q_n^{HF-}(Q_n^{HF+})^*(Q_n^{HF+})^*\,]+Re[\,Q_{2n}^{HF-}(Q_{2n}^{HF+})^*\,]-Re[\,Q_{2n}^{HF-}(Q_n^{HF+})^*(Q_n^{HF+})^* + Q_n^{HF-}Q_n^{HF-}(Q_{2n}^{HF+})^*]}{M^{HF-} * (M^{HF-}-1) * M^{HF+}\,(M^{HF+}-1)} \quad (5)$$

Note: weight $M^{HF-} = \sum(E_T)_i$ from HF- , $M^{HF+} = \sum(E_T)_i$ from HF+

Langevin, Energy loss

HQs propagates the expanding the medium
- A straight line: energy loss.
- Brownian motion: Langevin dynamics





Loss energy can not describe the low pT Raa.