Collectivity of Heavy Flavor Hadrons in pp and pPb Collisions at LHC Energy

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On behalf of CMS experiment

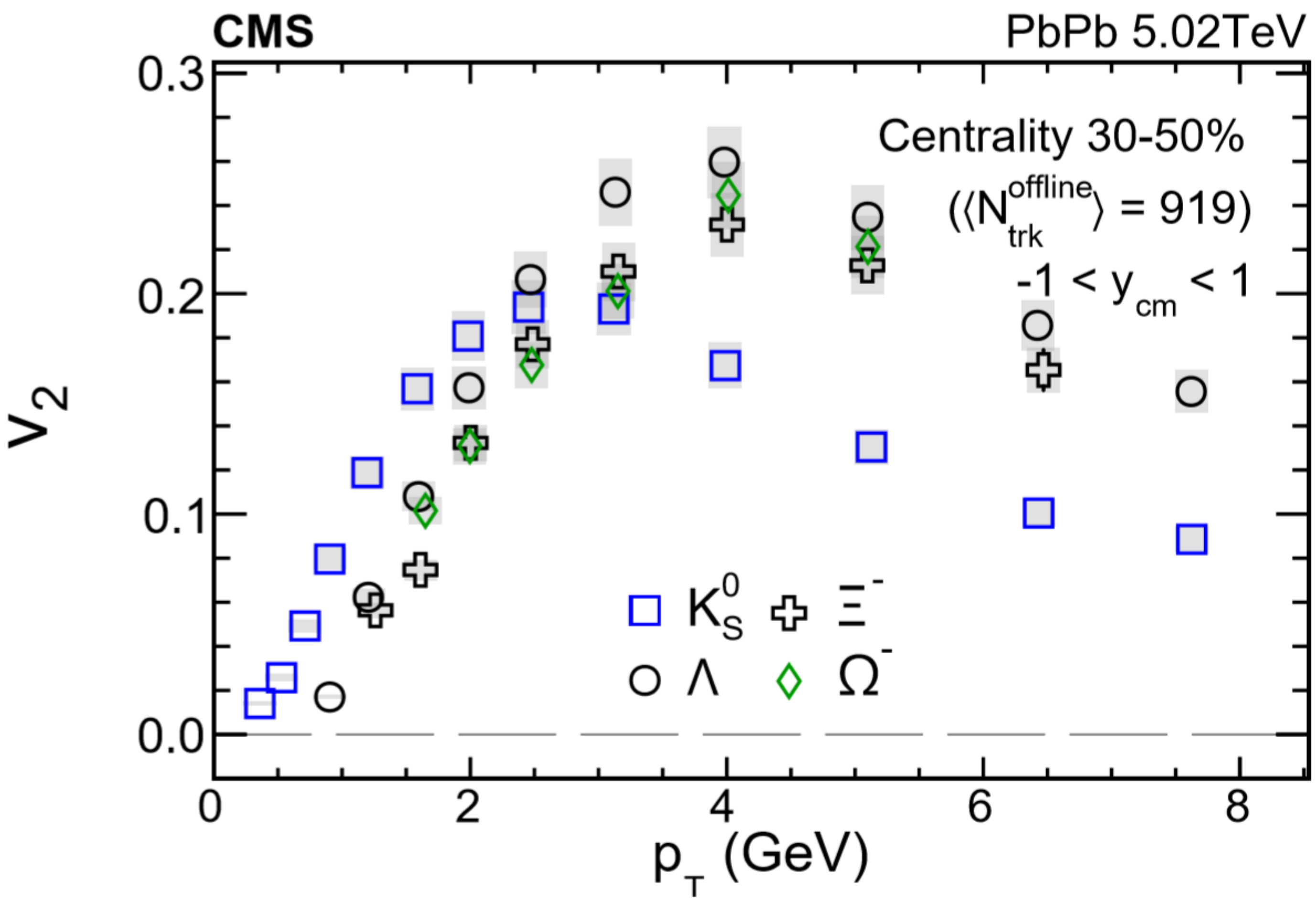
Rice University

March 2nd, 2020

Winter Workshop on Nuclear Dynamics, 2020

Collectivity of light quarks in large systems

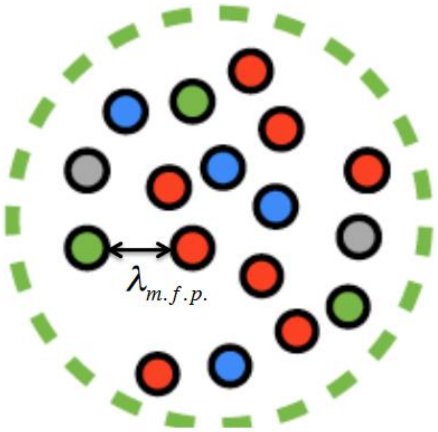
- Positive v_2 of light flavor hadrons
- Mass order shows common velocity



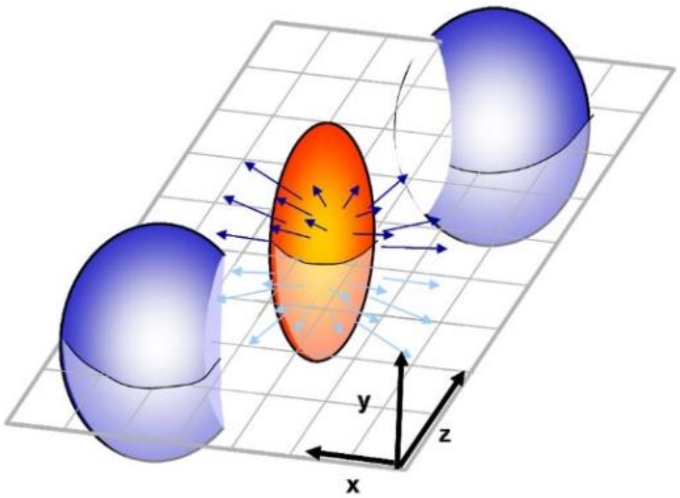
PRL 121, 082301 (2018)

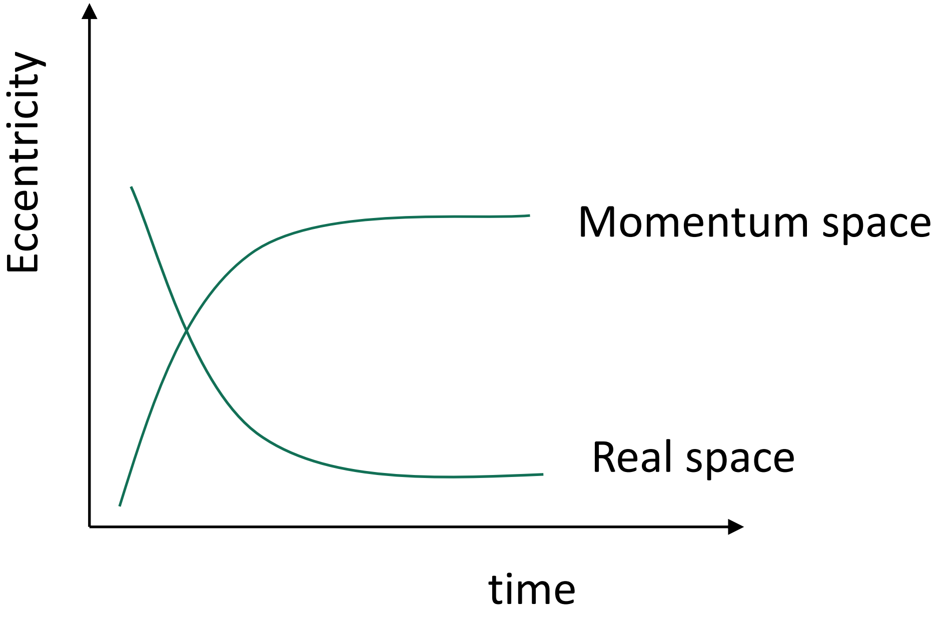
Origin of the collectivity

- Hydrodynamics
  - Initial geometric eccentricity hydrodynamically propagate to final states
  - Applies when system size >> mean free path



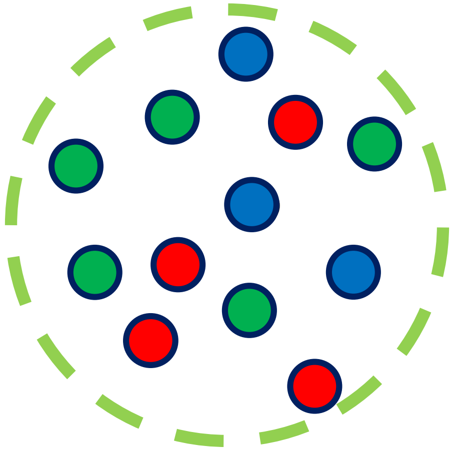
Large nuclei





Origin of the collectivity

Collectivity of light quarks in large systems



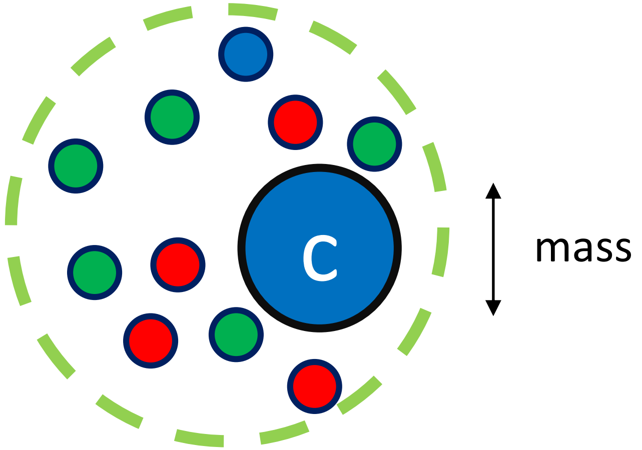
Light quarks in large system

$\lambda_{m.f.p.} \sim 1/(n\sigma)$

$\sigma \sim 1/m_q^2$

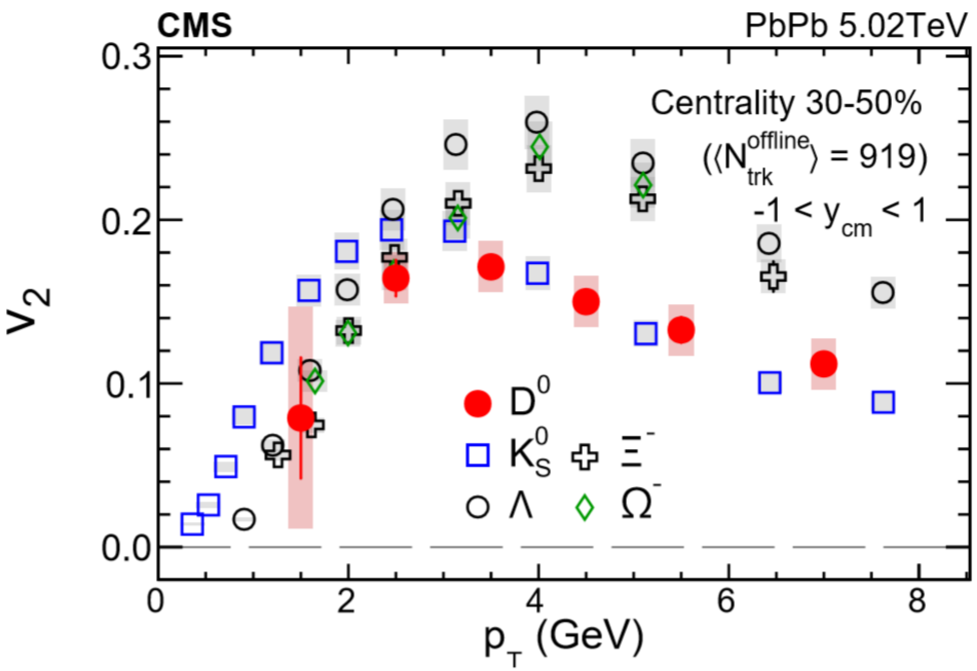
Increase the mean free path

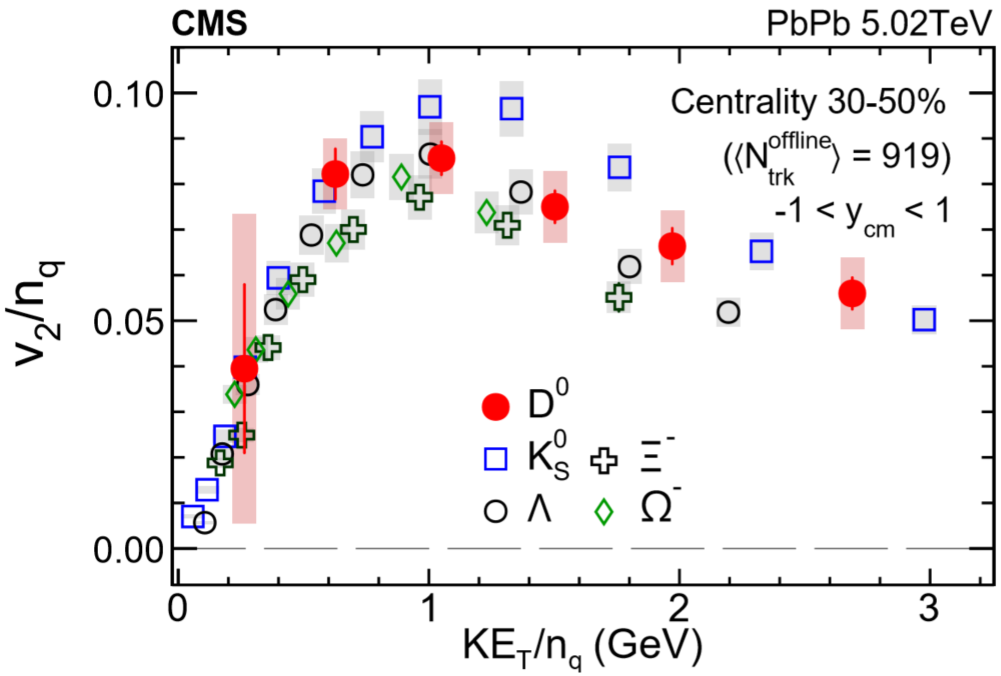
Collectivity of heavy quarks in large systems



Heavy quarks in large system

Collectivity of heavy quarks in large systems



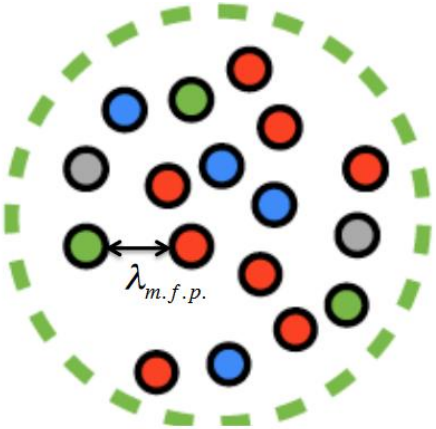


PRL 120, 202301 (2018)
PRL 121, 082301 (2018)

- Mass order at low p_T , similar to light-flavor hadrons
- At moderate p_T , prompt D^0 v_2 is comparable with that of light-flavor hadrons

Origin of the collectivity

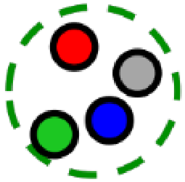
Collectivity of light quarks in large systems



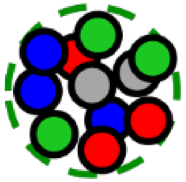
Large nuclei

Decrease the size of systems

Collectivity of light quarks in small systems



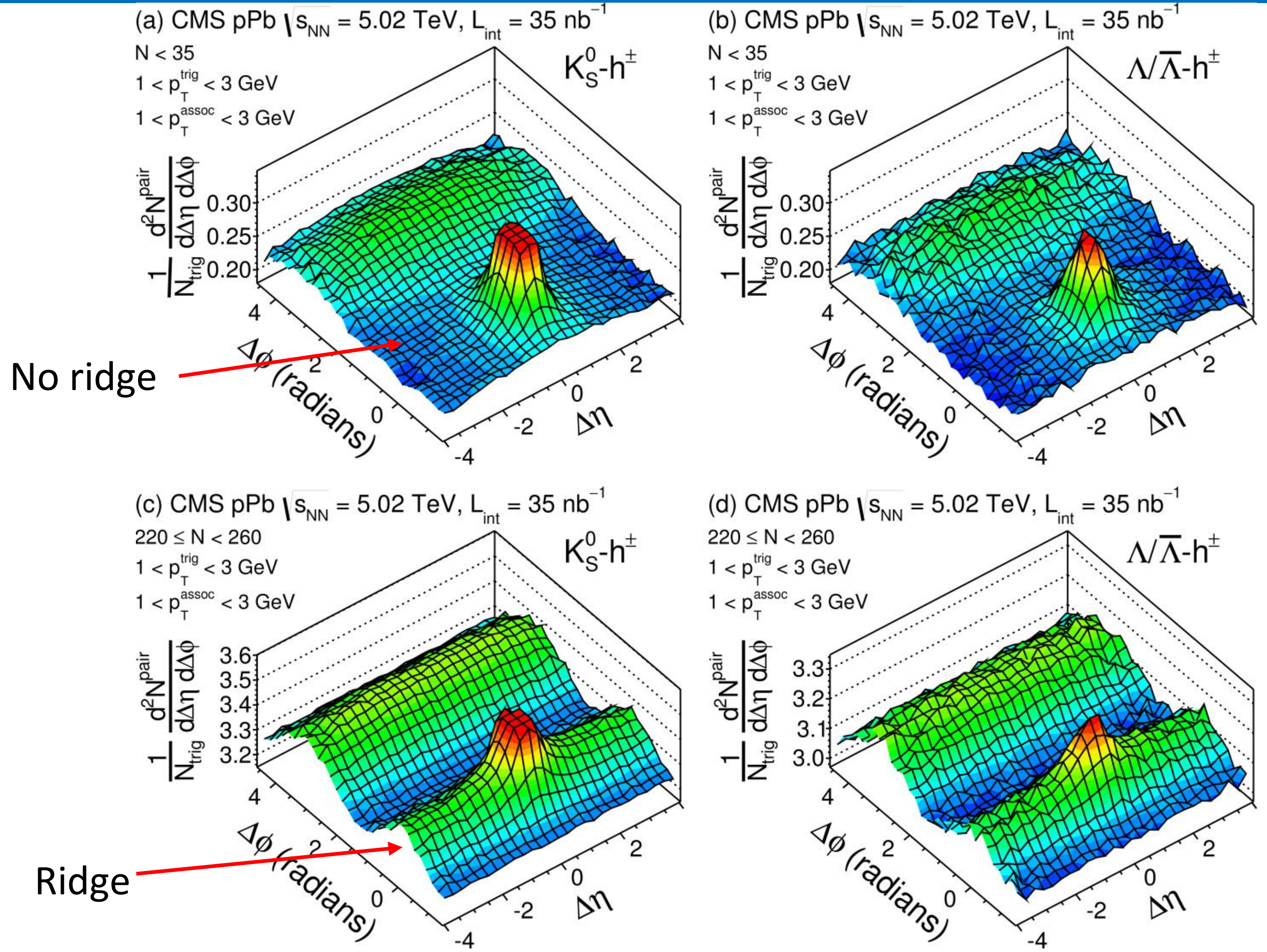
Small nucleon, low temperature (energy density)



Small nucleon, high T

Collectivity of light quarks in small systems

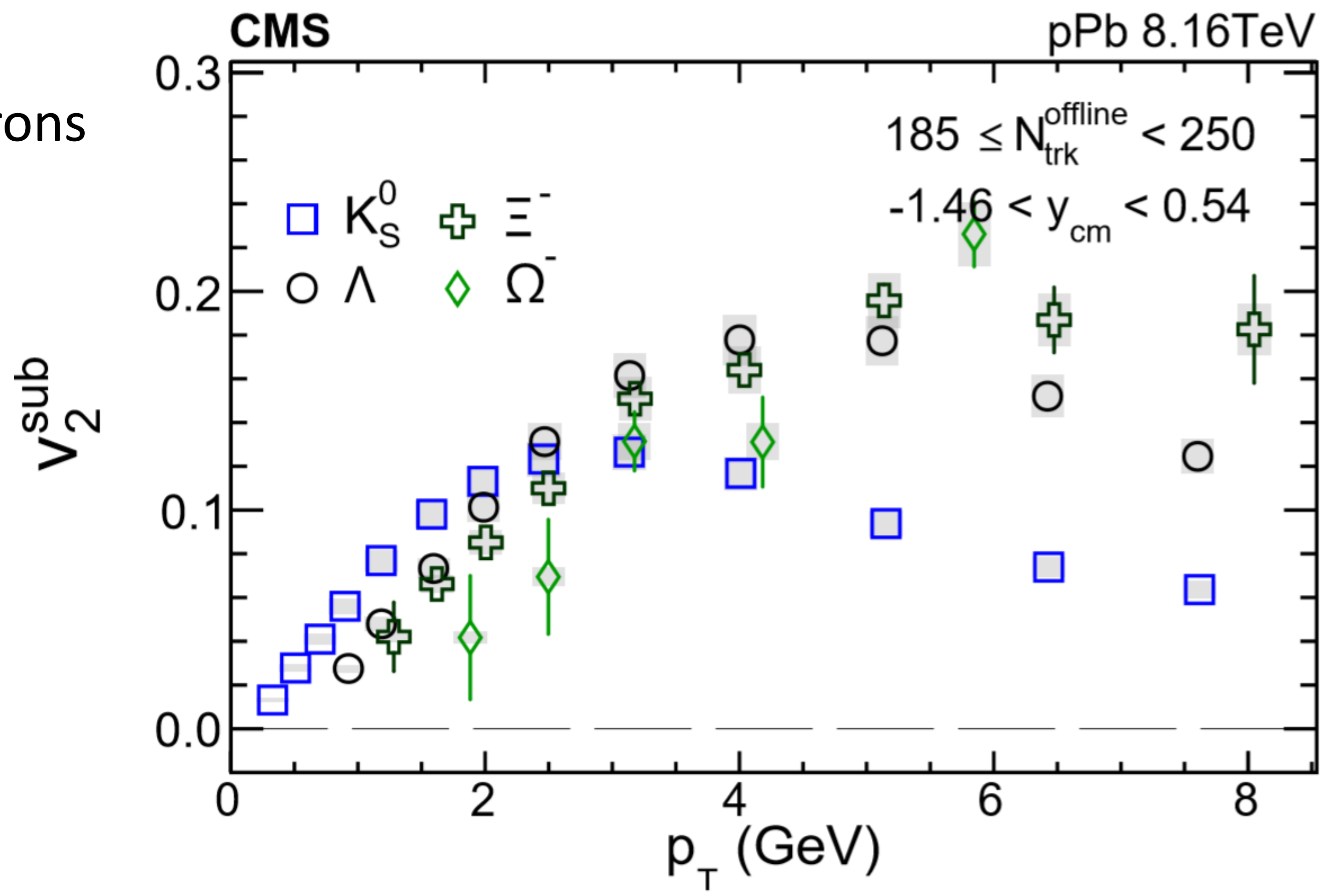
- Ridges in the high multiplicity events



PLB 742 (2015) 200

Collectivity of light quarks in small systems

- Positive v_2 of light flavor hadrons
- Mass order shows common velocity
- Similar observations to large systems



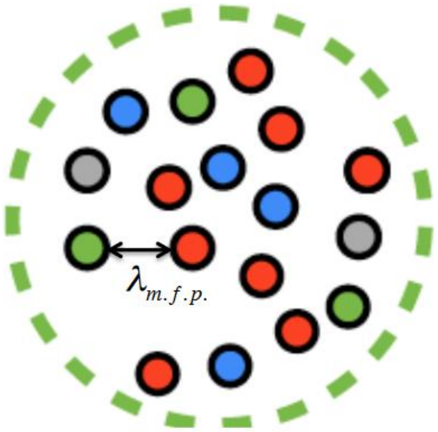
PRL 121, 082301 (2018)

Origin of the collectivity in small systems

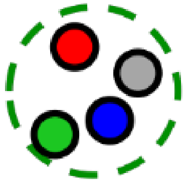
- Theoretical interpretations
  - Final-state interactions
  - Initial-state interactions
  - Hybrid of the above

Origin of the collectivity in small systems

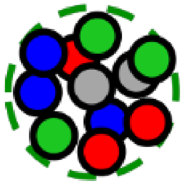
- Final state interactions – Hydrodynamics
  - Initial geometric eccentricity, and color filed fluctuations, hydrodynamically propagate to final states
  - Applies when system size >> mean free path



Large nuclei

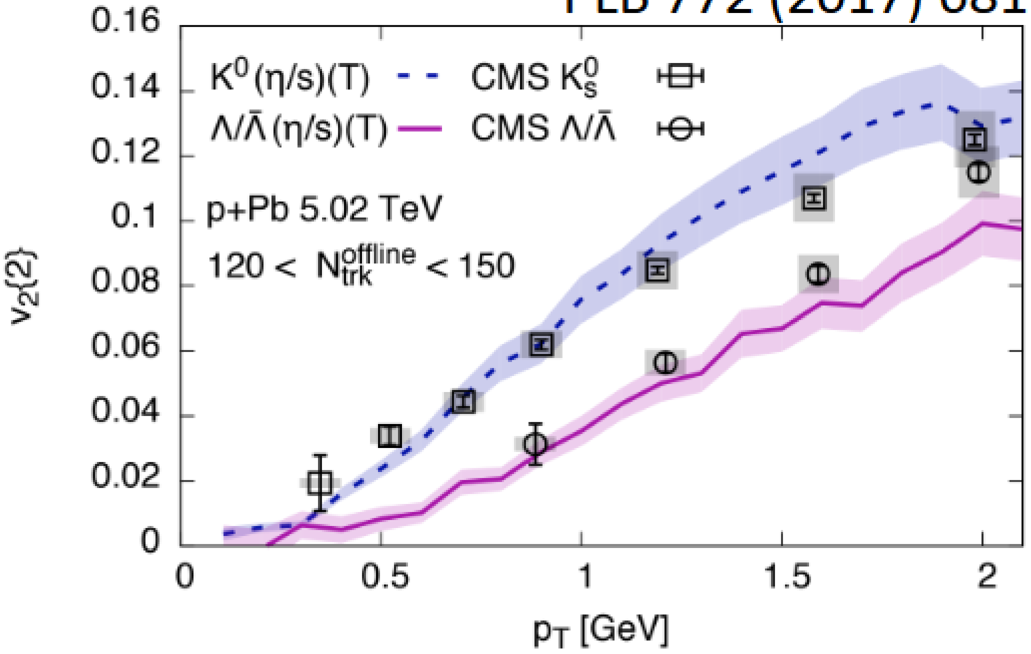


Small nucleon, low temperature (energy density)



Small nucleon, high T

PLB 772 (2017) 681

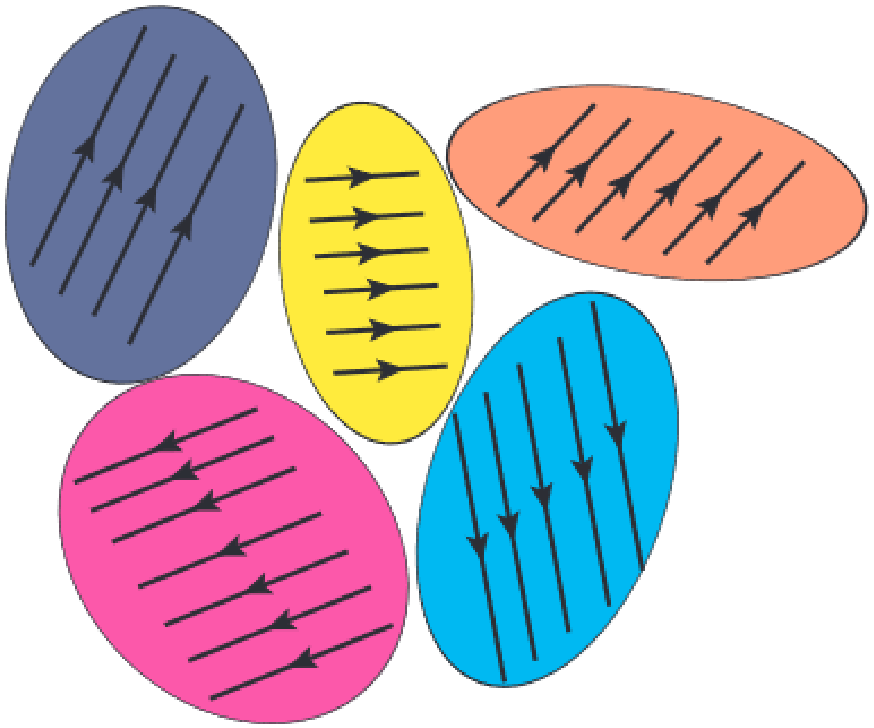


Hydrodynamics evolution of IP Glasma initial states

Origin of the collectivity in small systems

- Initial state interactions – Color Glass Condensate
- Before collisions, non-zero color electric fields exits
- Non-geometry-related
- Non-hydrodynamical evolution

Lappi, Schenke, Schlichting, Venugopalan
JHEP 01 (2016) 061



Origin of the collectivity

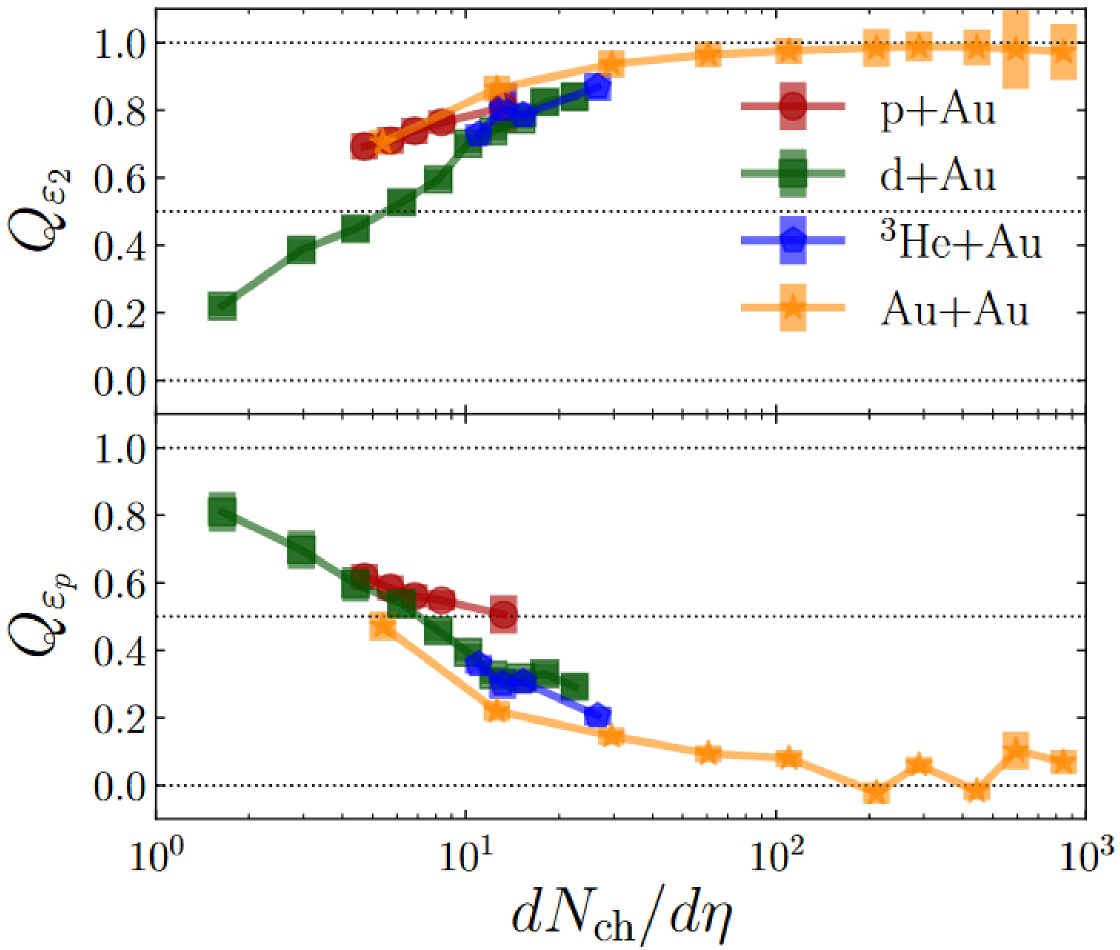
Hybrid model

- $dN_{ch}/d\eta$ > 100, Geometry driven
- $dN_{ch}/d\eta$ <10, Initial momentum anisotropy driven

$$Q_{\varepsilon_2} = \frac{\mathrm{Re}\langle \vec{\mathscr{E}}_2 \cdot \vec{V}_2^* \rangle}{\sqrt{\langle |\vec{\mathscr{E}}_2|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$

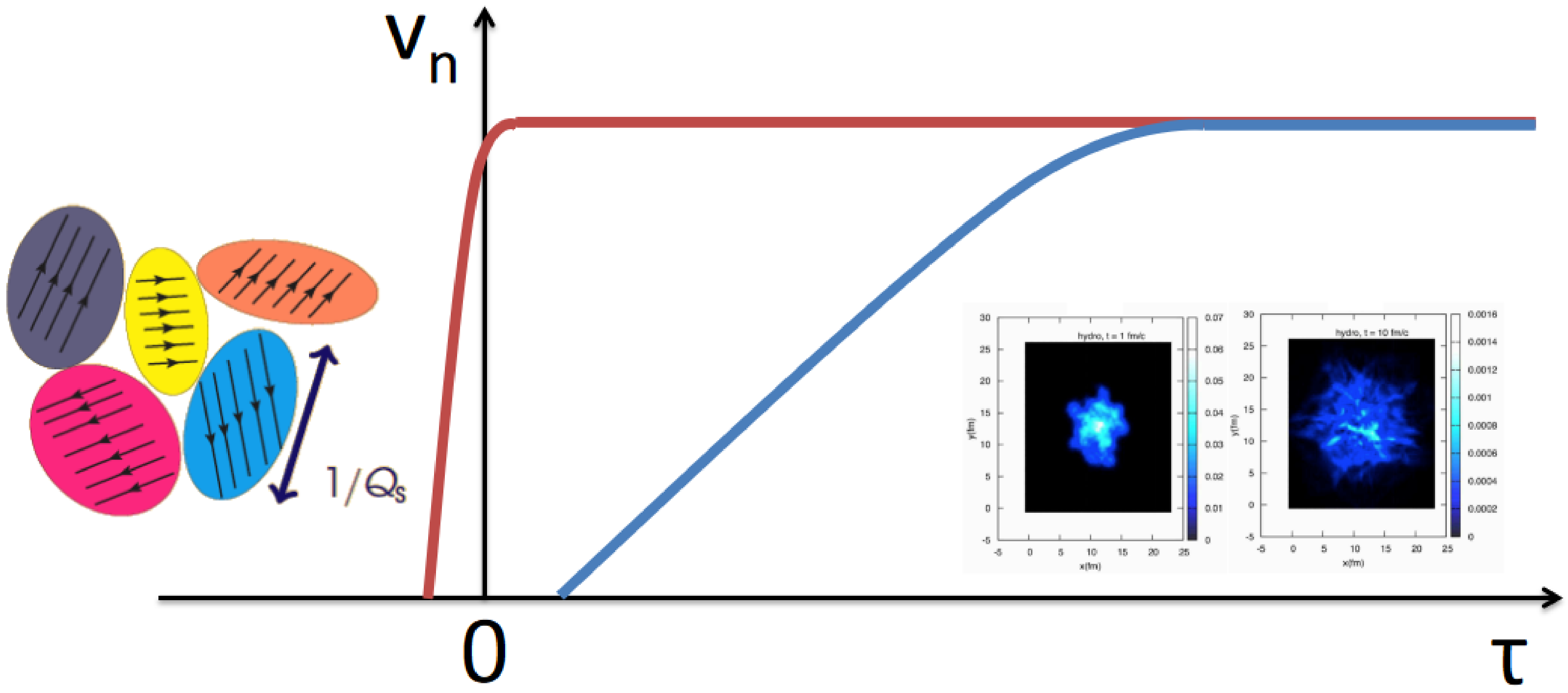
$$Q_{\varepsilon_p} = \frac{\mathrm{Re}\langle \vec{\mathscr{E}}_p \cdot \vec{V}_2^* \rangle}{\sqrt{\langle |\vec{\mathscr{E}}_p|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$

B.Schenke, arXiv:1908.06212

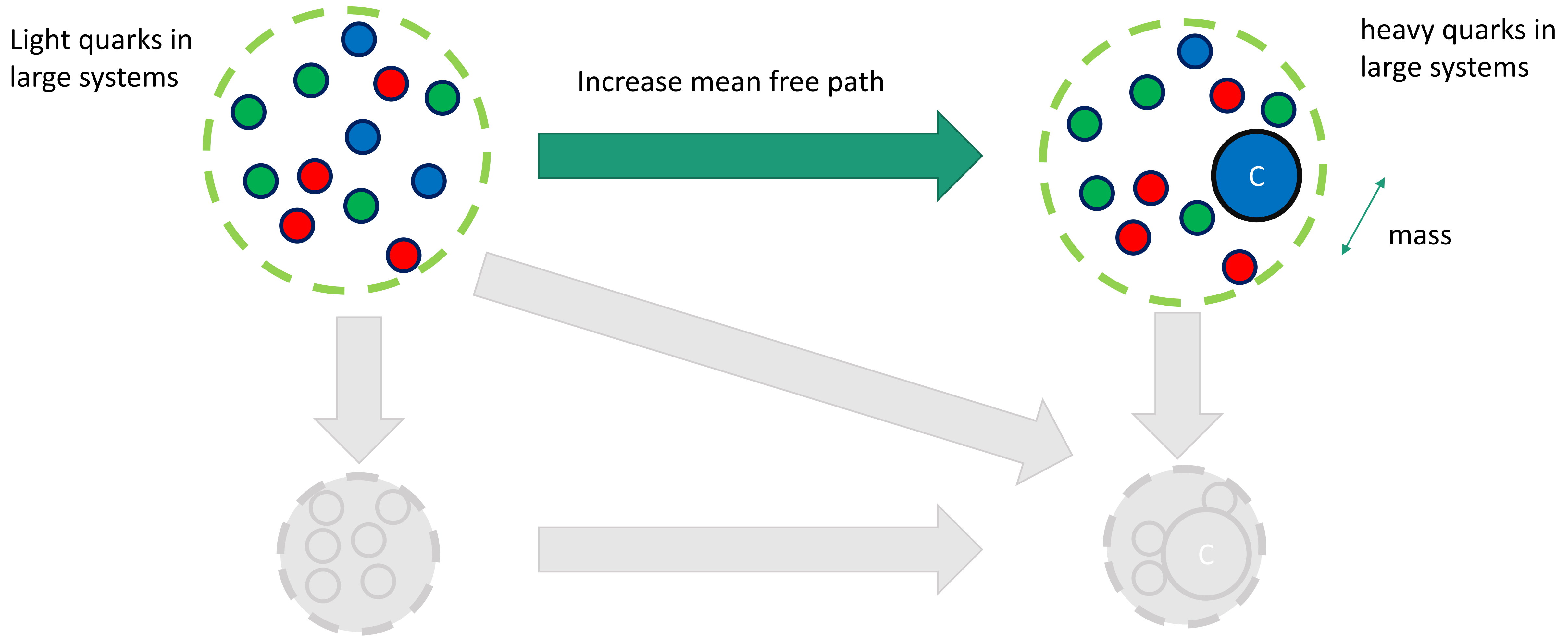


Origin of the collectivity

Initial-state dynamics vs **Final-state interaction**



Origin of the collectivity



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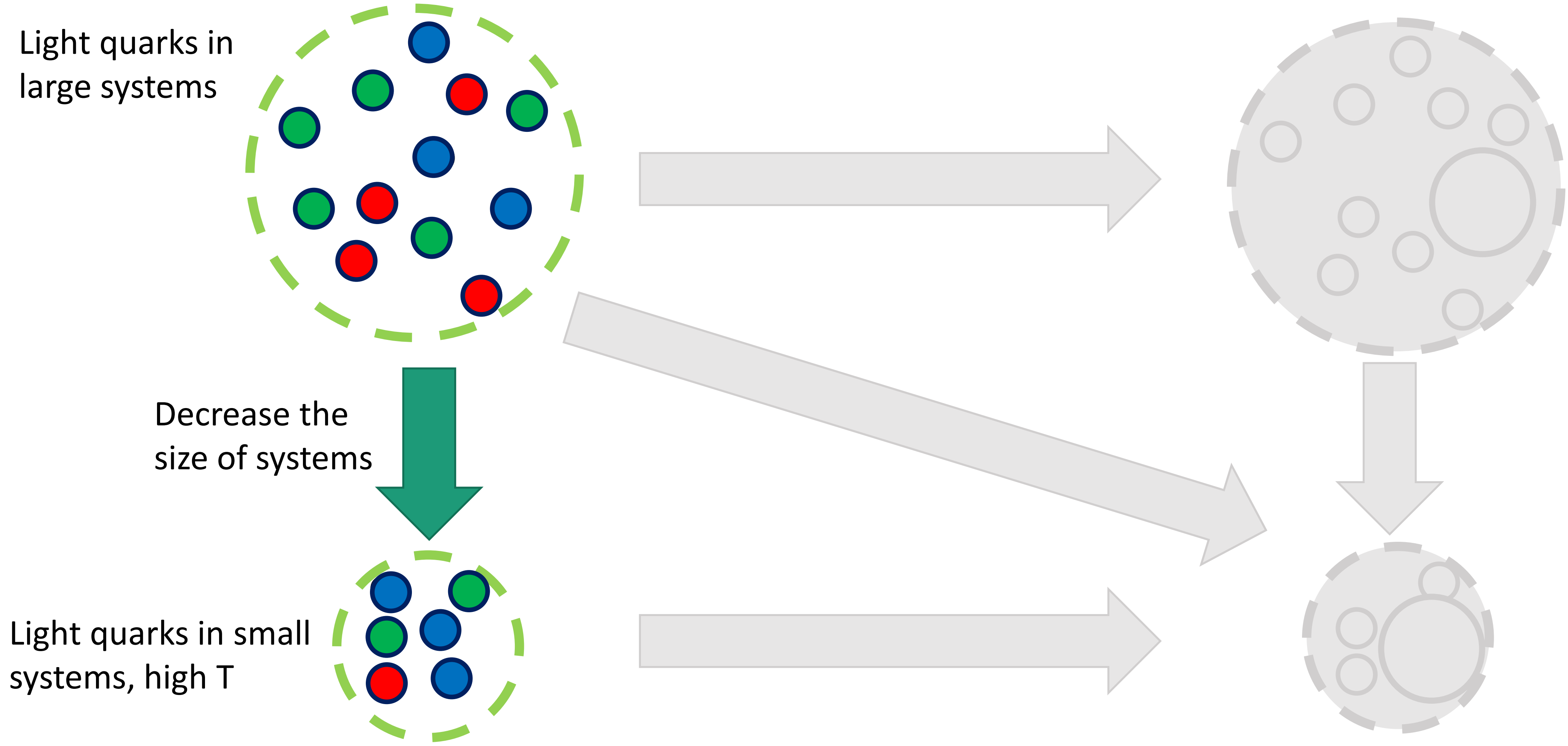

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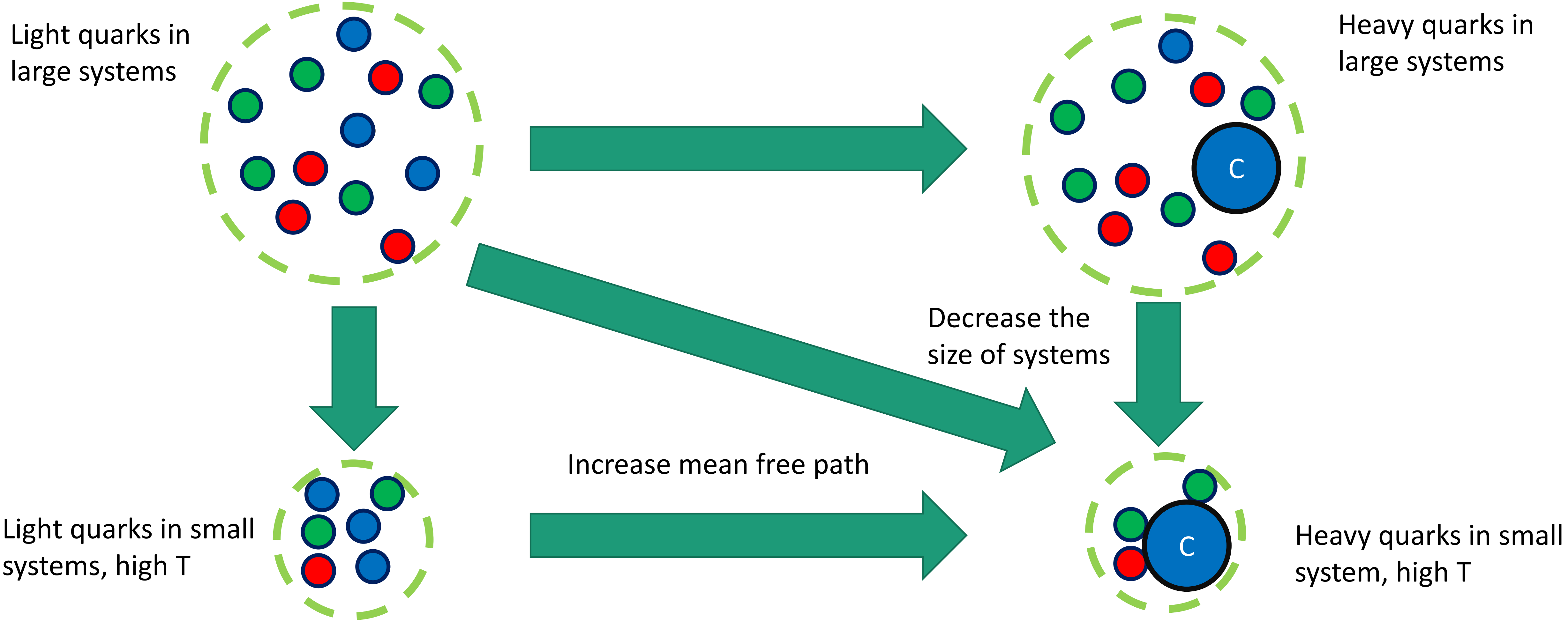
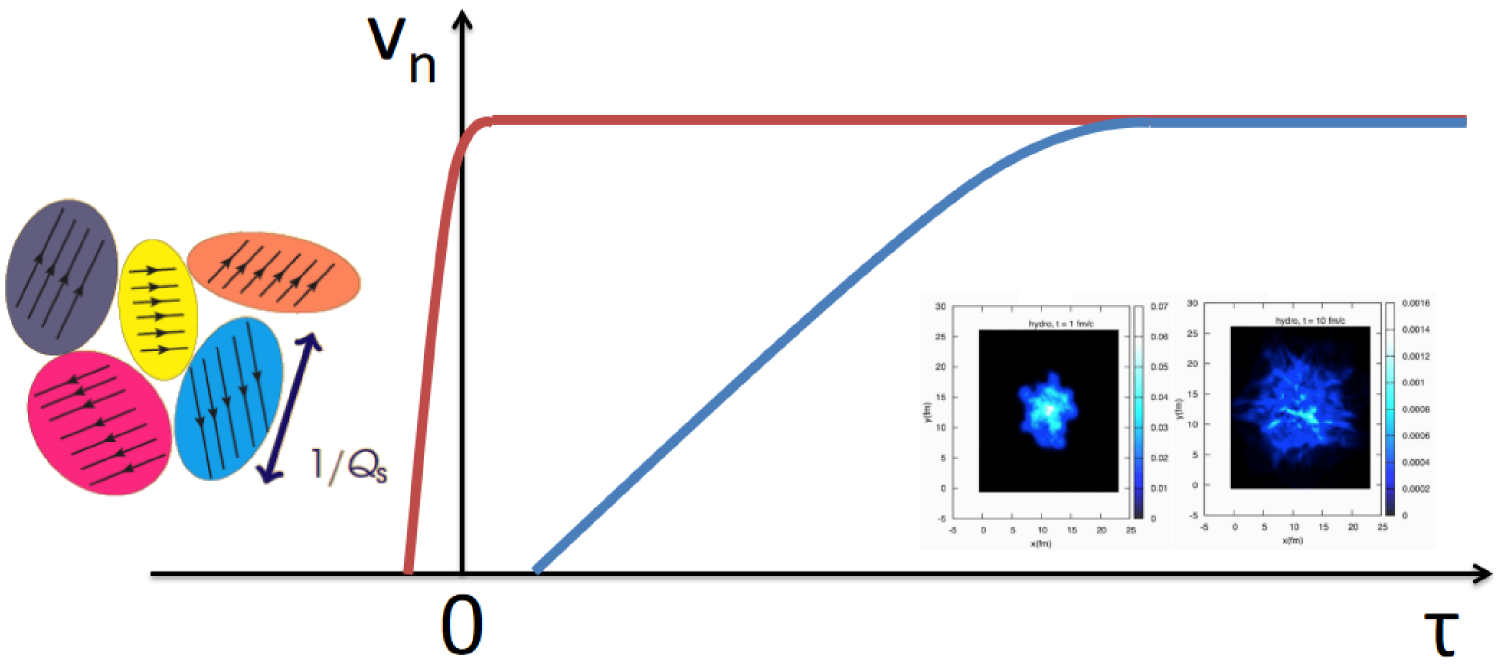


Heavy Flavor Probes

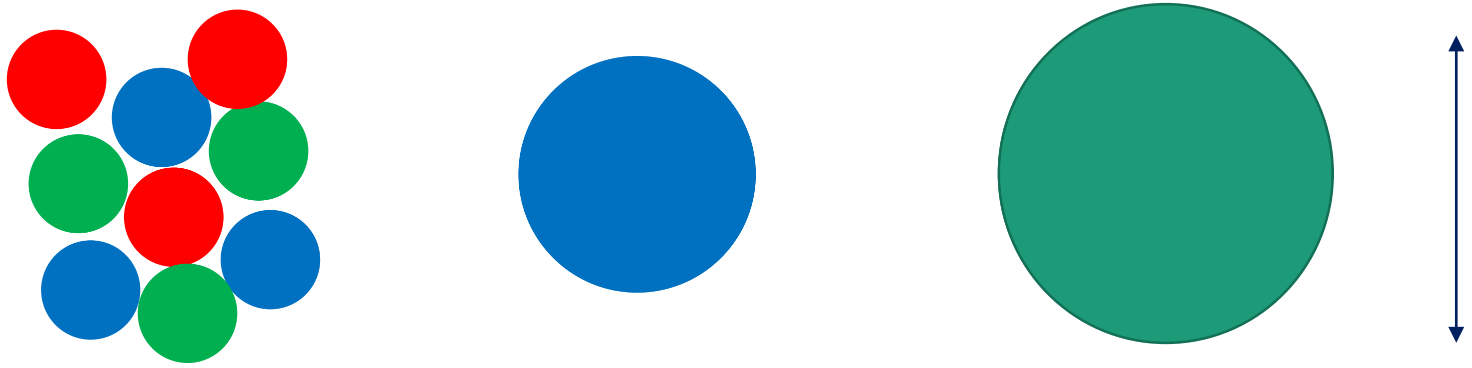
- Created at the initial stage via hard processes
- Experience the entire evolution of the system

Initial-state dynamics vs **Final-state interaction**

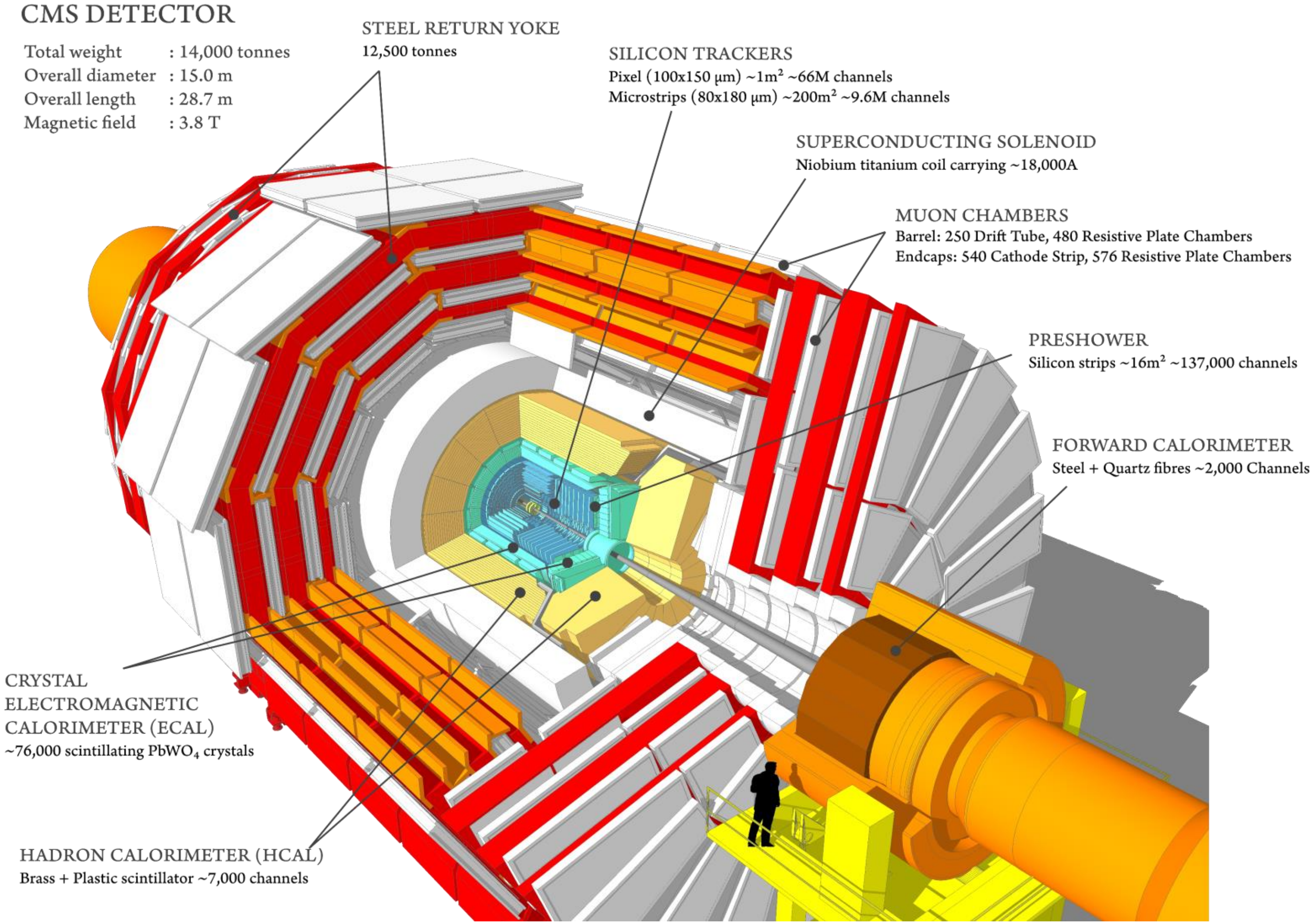


Heavy Flavor Probes

- Hard to thermalize due to large masses
  - hydrodynamics calculation suggests a small value of v_2 (JHEP 03,(2019)015)
  - A large v_2 expected by CGC (PRL 122, 172302 (2019))

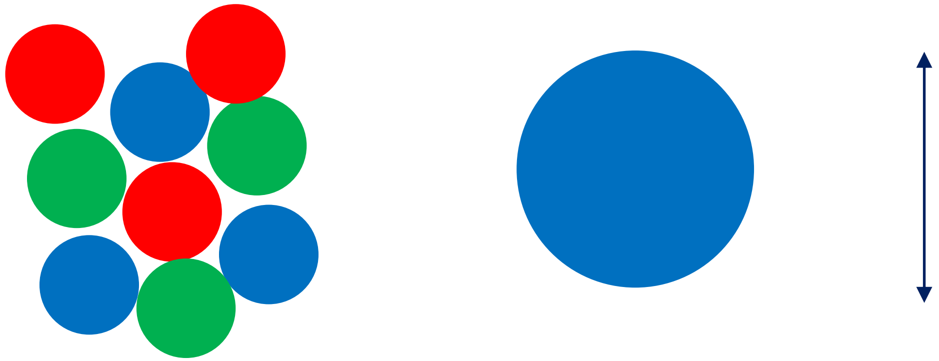


CMS Experiment



- Tracker, $|\eta|<2.5$
- Muon system, $|\eta|<2.4$

Prompt D^0 in pPb Collisions



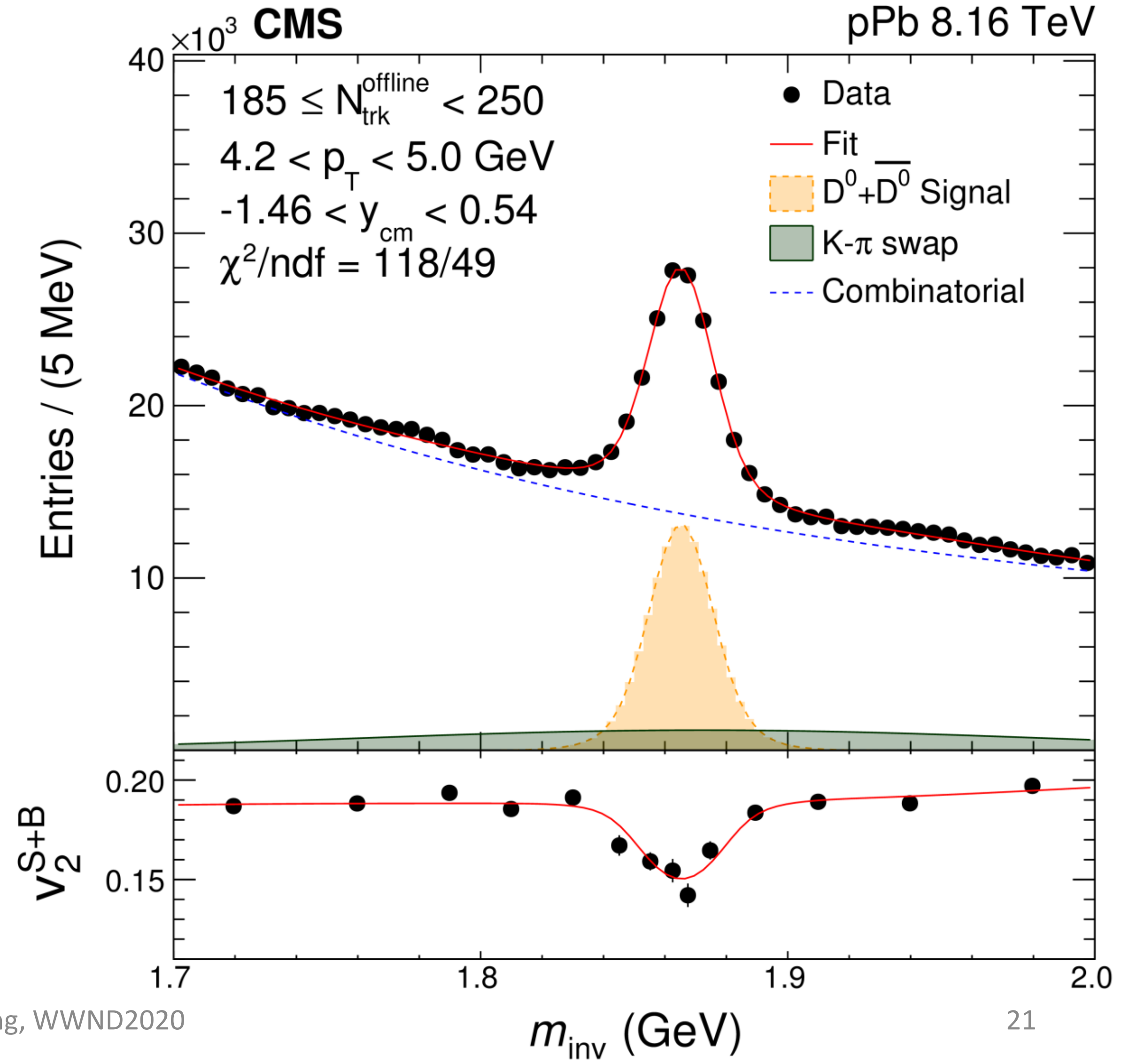
Mass

uds, ~1-10^2MeV

c ~ 1 GeV

Prompt D^0 in pPb Collisions

- D^0 ($c\bar{u}$) reconstruction



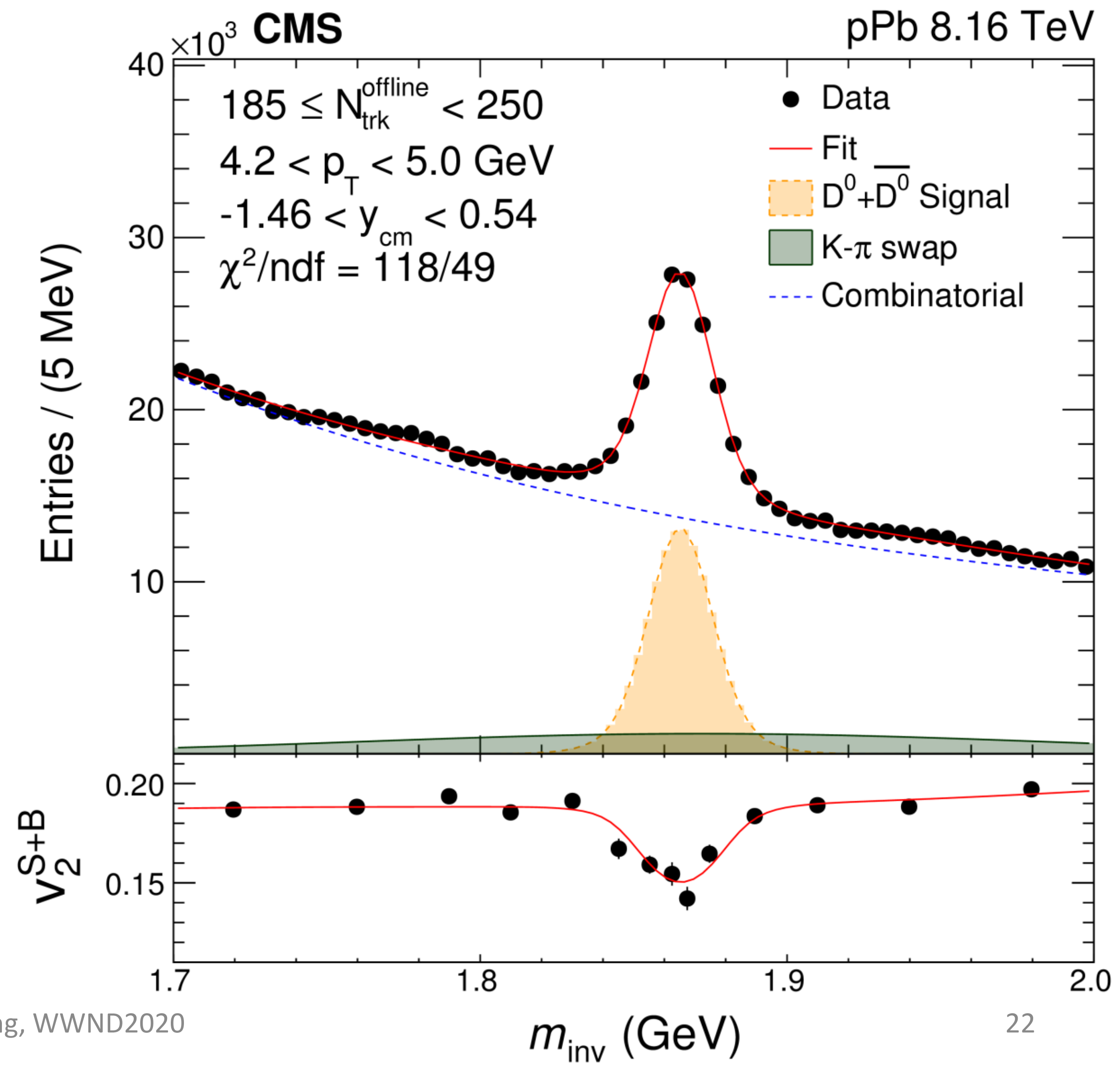
PRL 121, 082301 (2018)

Prompt D^0 in pPb Collisions

- D^0 reconstruction
- Two particle correlation techniques

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

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



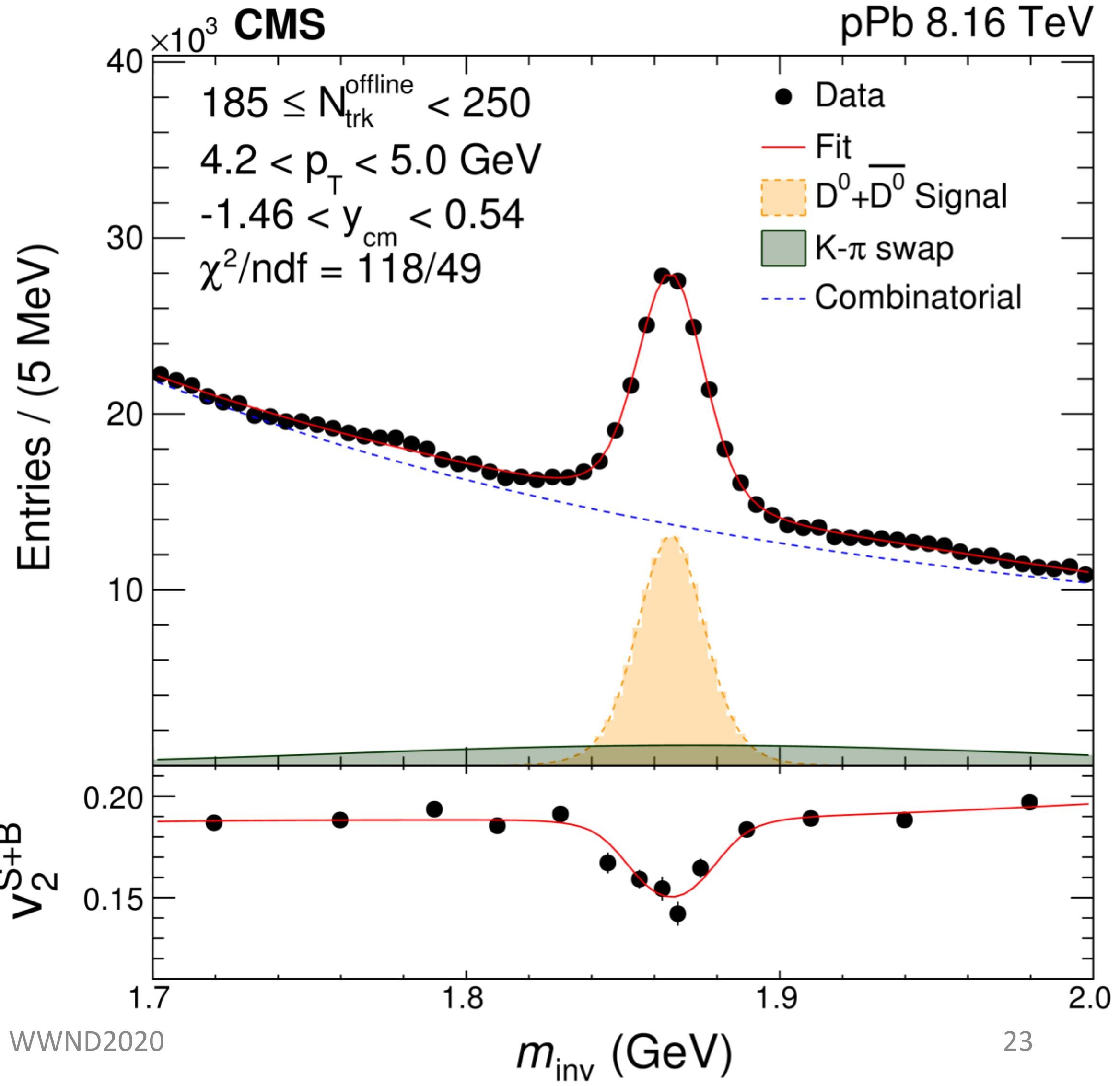
PRL 121, 082301 (2018)

Prompt D^0 in pPb Collisions

- D^0 reconstruction
- Two particle correlation techniques

- Signal extraction

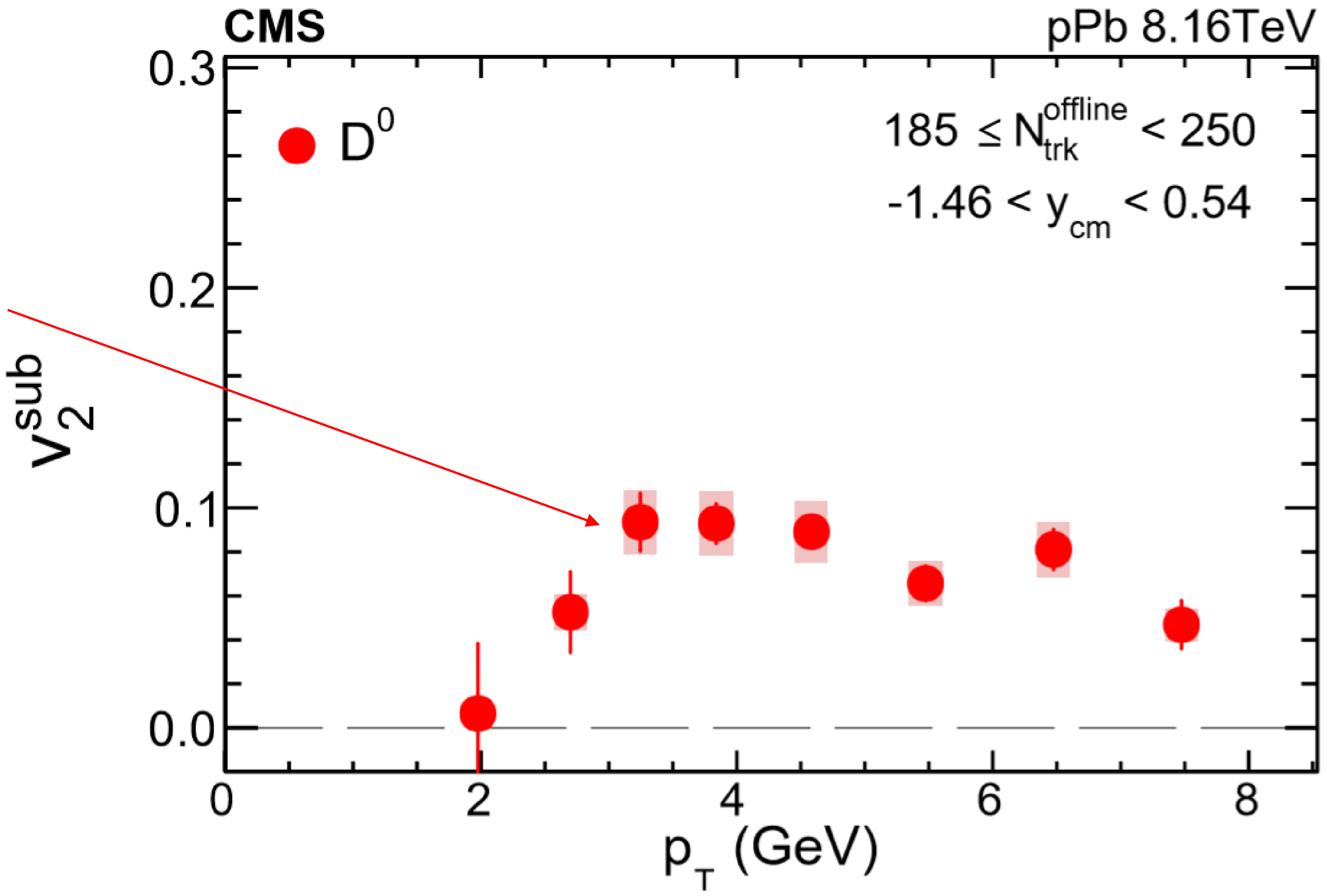
$$v_2^{S+B}(m_{\text{inv}}) = \alpha(m_{\text{inv}})v_2^S + [1-\alpha(m_{\text{inv}})]v_2^B(m_{\text{inv}})$$



PRL 121, 082301 (2018)

Prompt D^0 in pPb Collisions

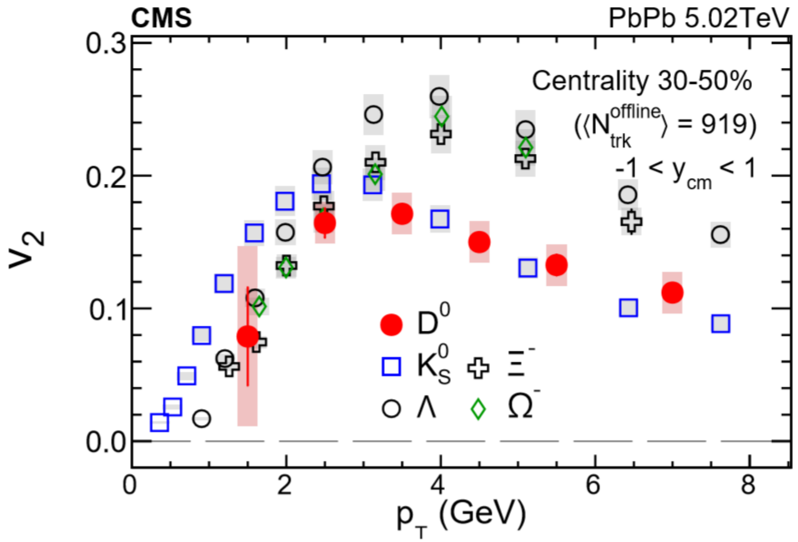
Positive v_2 signal in pPb



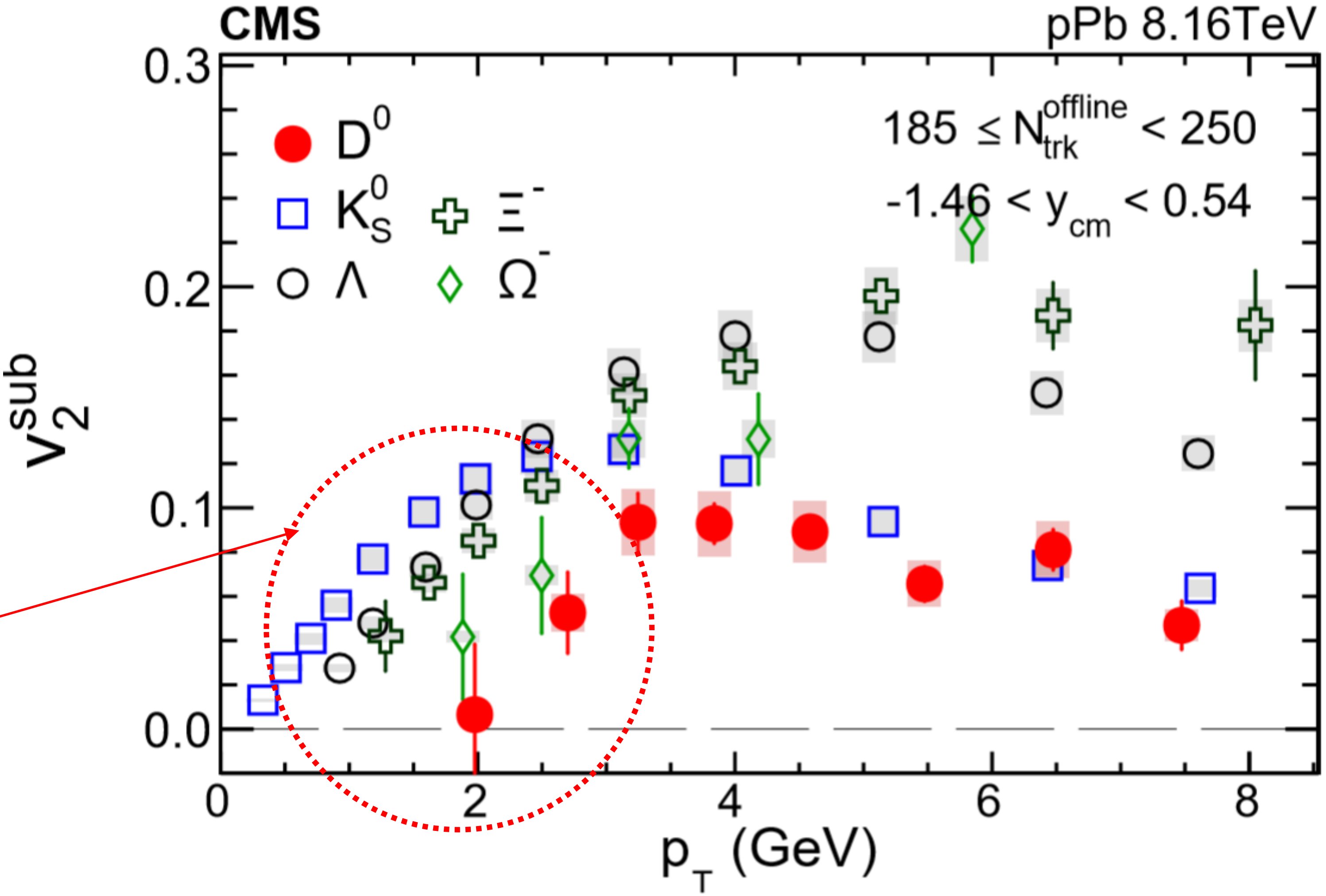
PRL 121, 082301 (2018)

Prompt D^0 in pPb Collisions

PRL 120, 202301 (2018)



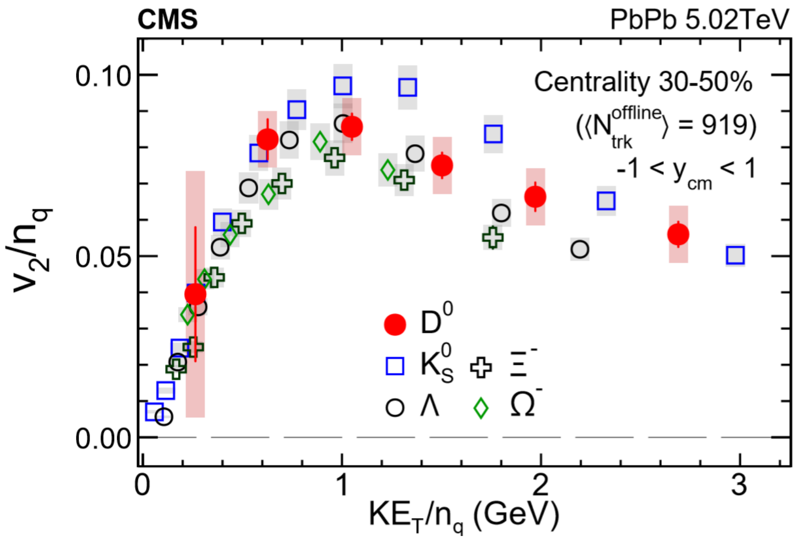
- Mass order at low p_T -- common flow veclocity
- Similar to PbPb

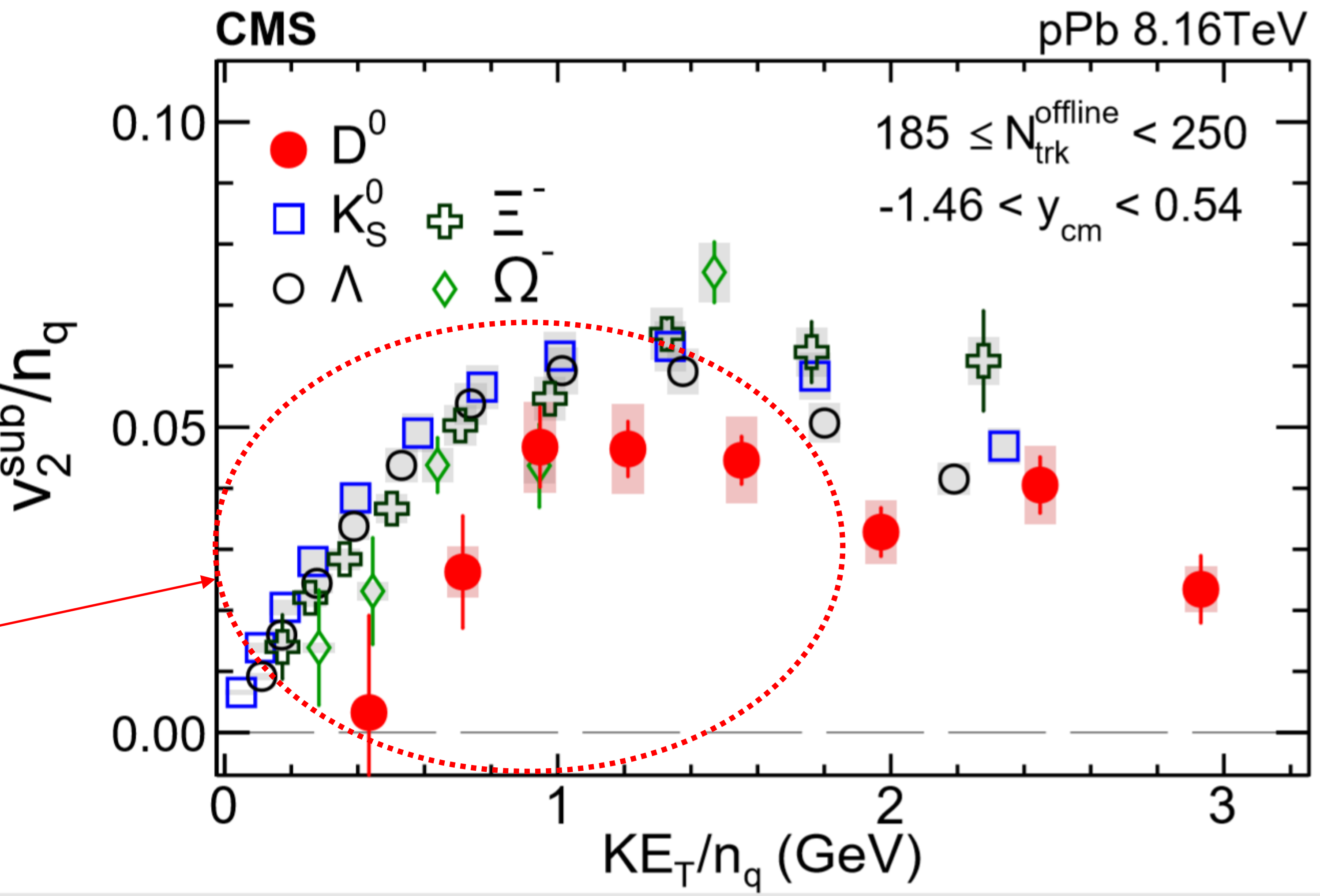


PRL 121, 082301 (2018)

Prompt D^0 in pPb Collisions

PRL 120, 202301 (2018)





PRL 121, 082301 (2018)

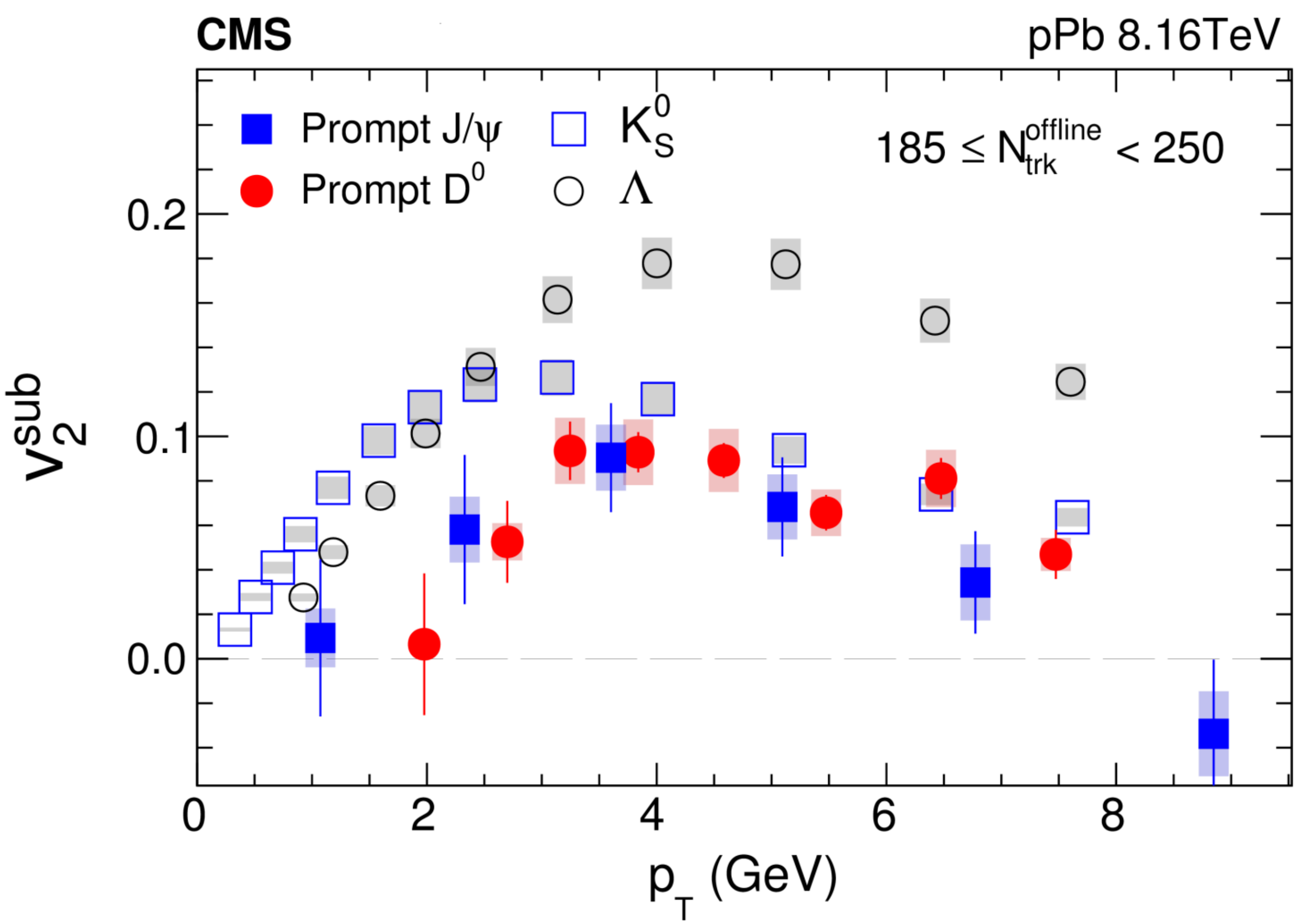
- Slightly weaker than light hadrons
- Different from PbPb

Prompt J/ψ in pPb Collisions

- Collectivity from $\bar{u}$ in D^0 ($c\bar{u}$)?
- Study the flow of prompt J/ψ ($c\bar{c}$)

Prompt J/ψ in pPb Collisions

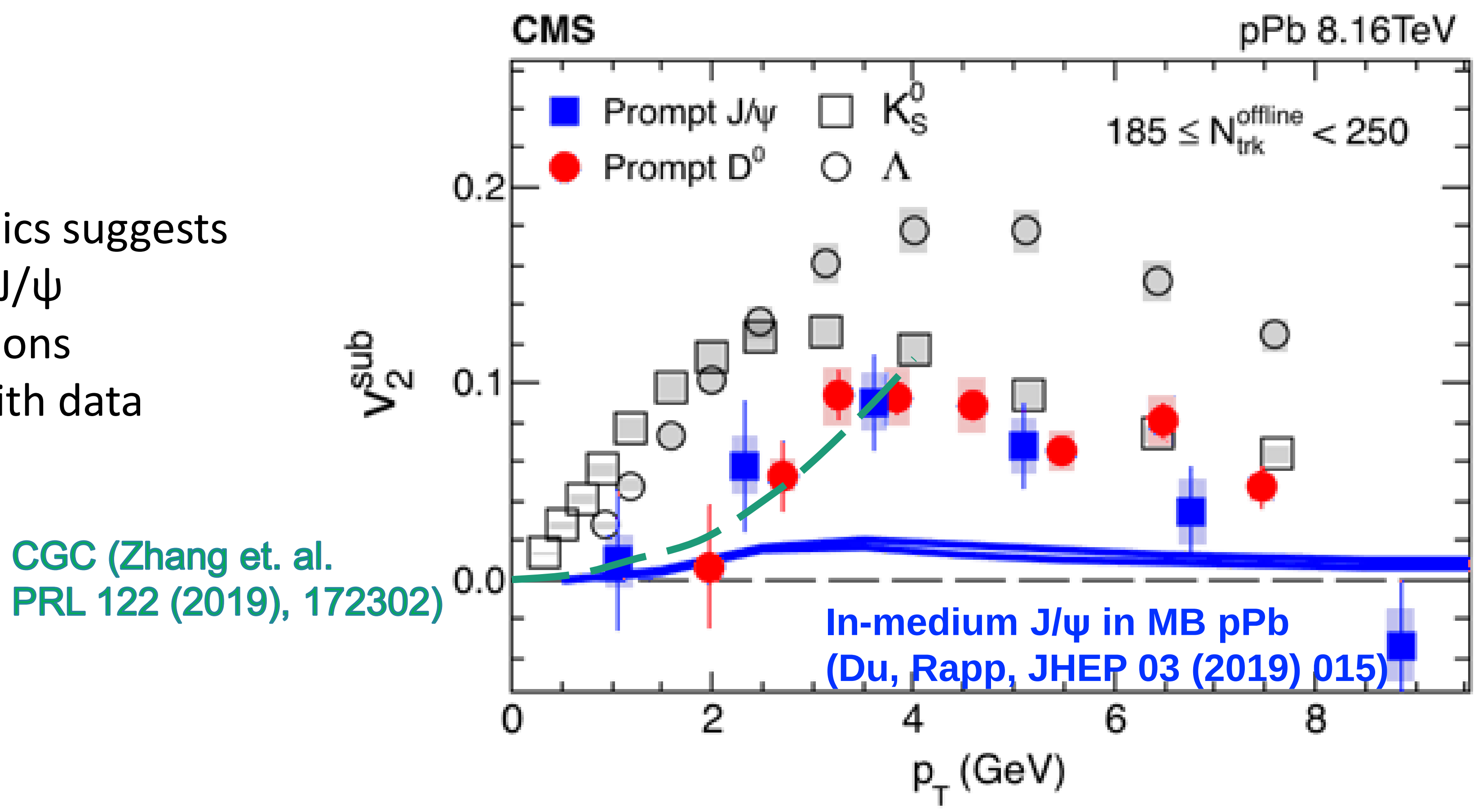
Collectivity from $\bar{u}$ in D^0 ($c\bar{u}$)? Study the flow of prompt J/ψ ($c\bar{c}$)



PRL 121, 082301 (2018)
PLB 791 (2019) 172

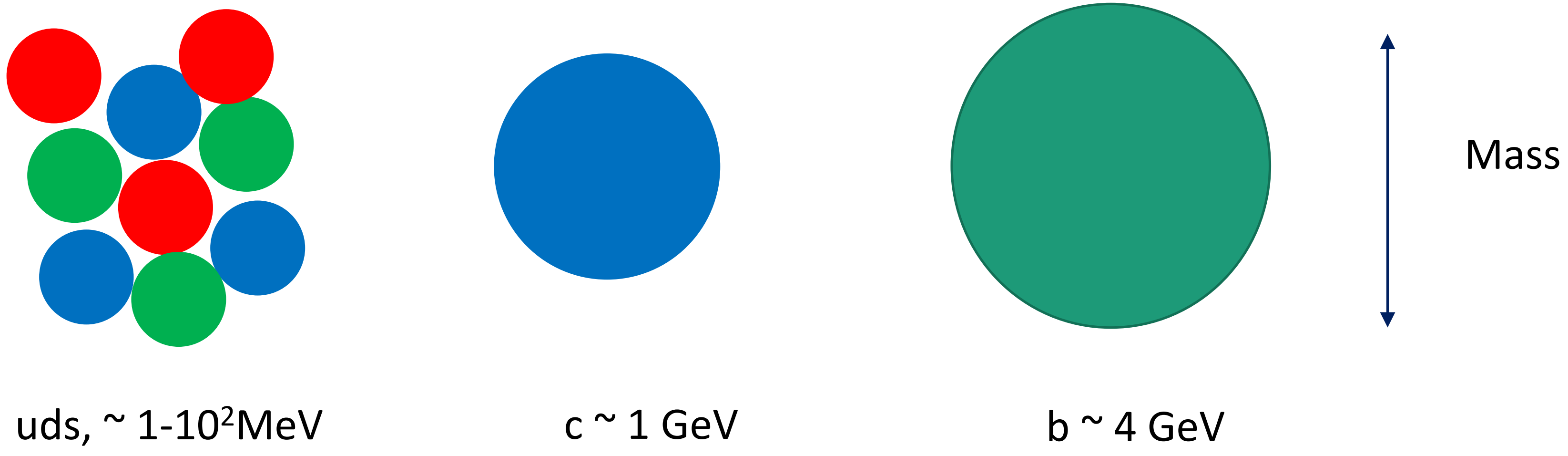
Prompt J/ψ in pPb Collisions

- Hydrodynamics suggests a small v_2 of J/ψ
- CGC calculations consistent with data



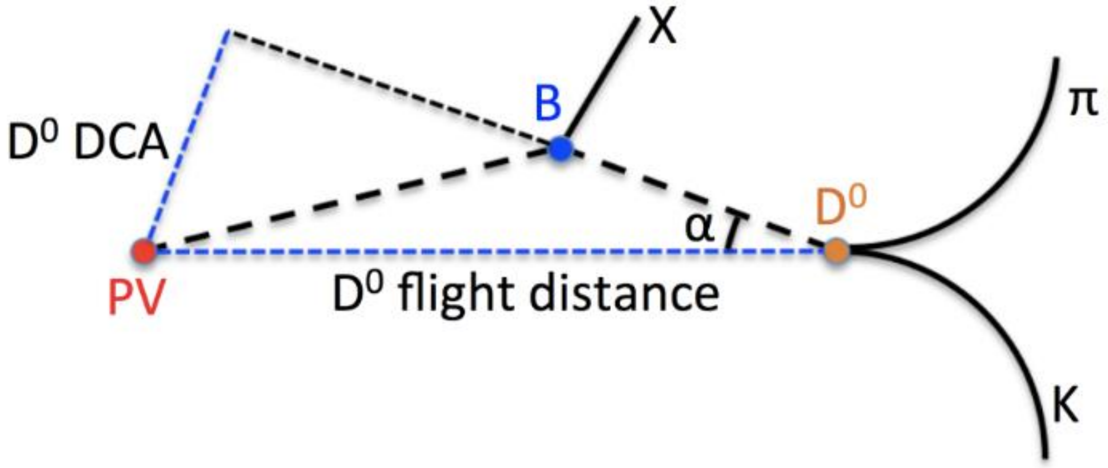
PRL 121, 082301 (2018)
PLB 791 (2019) 172

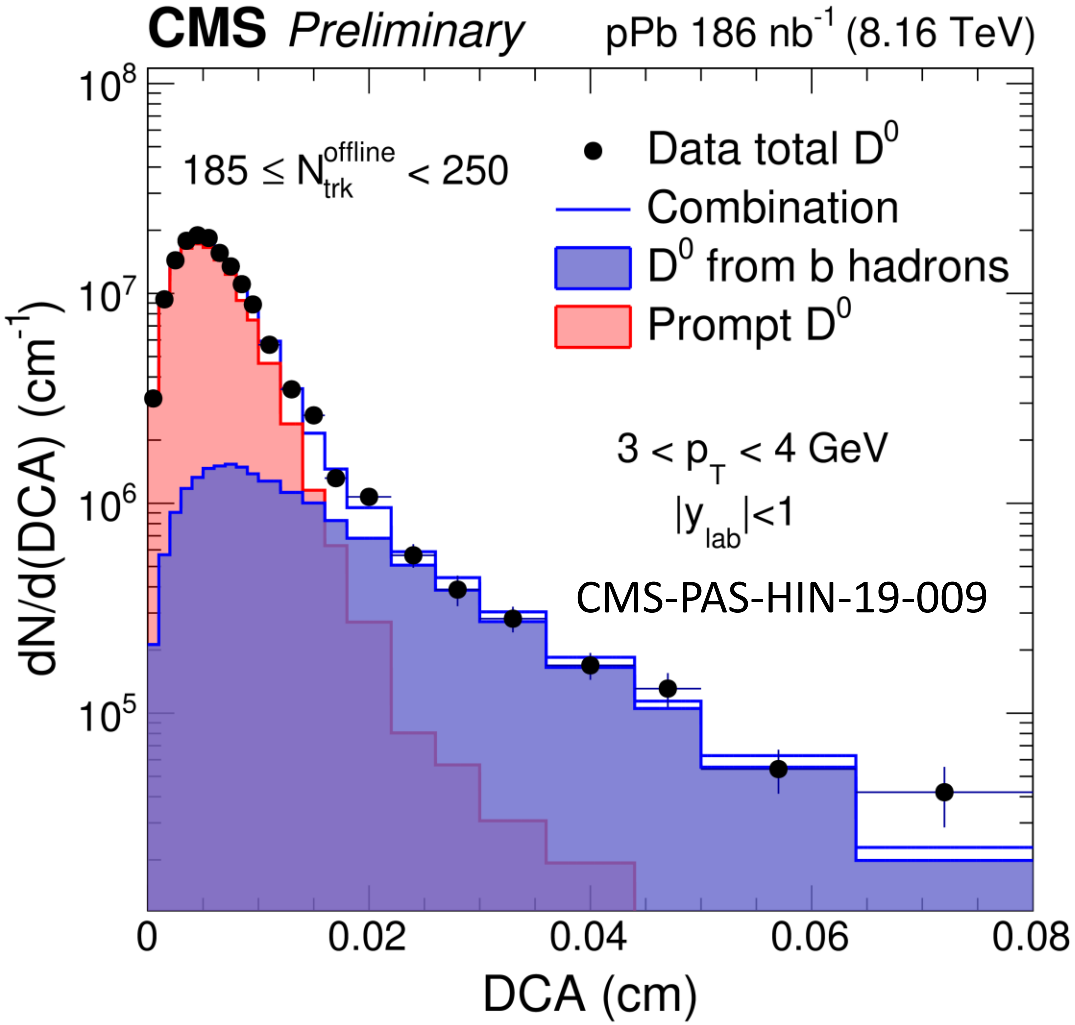
Nonprompt D^0 in pPb Collisions



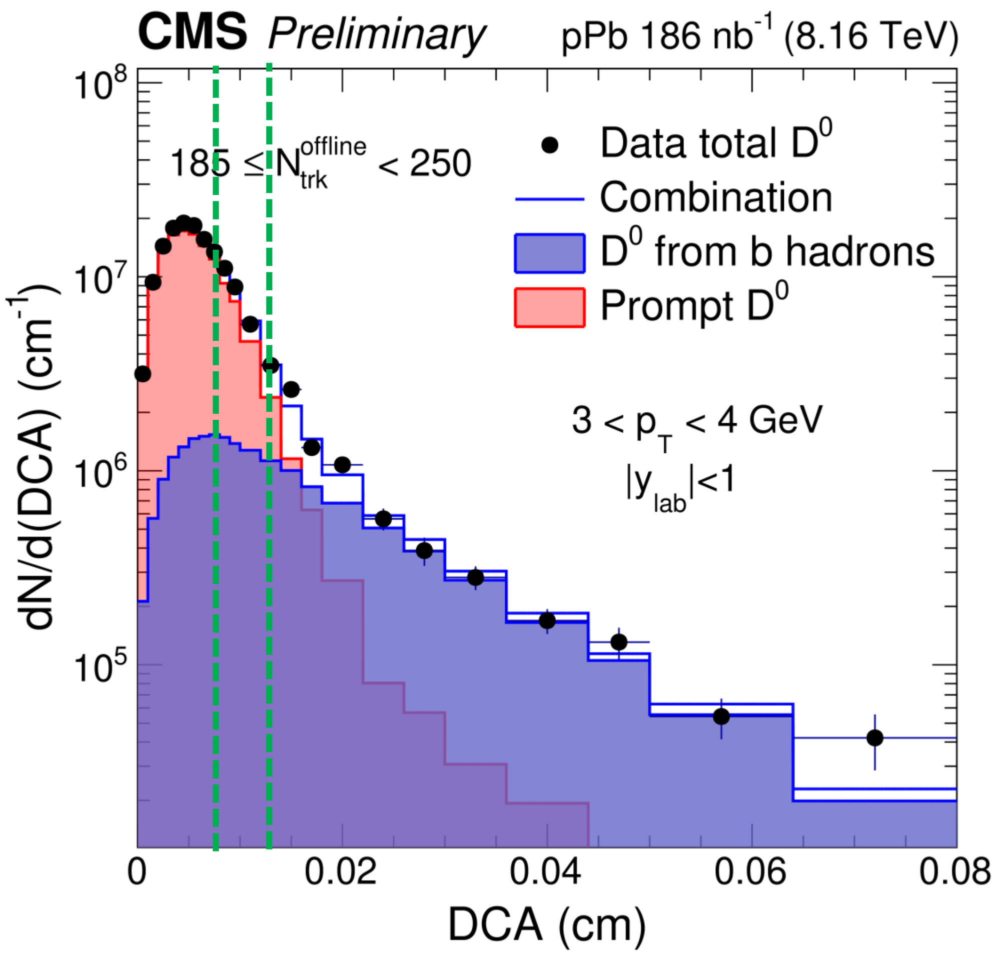
Nonprompt D^0 in pPb Collisions

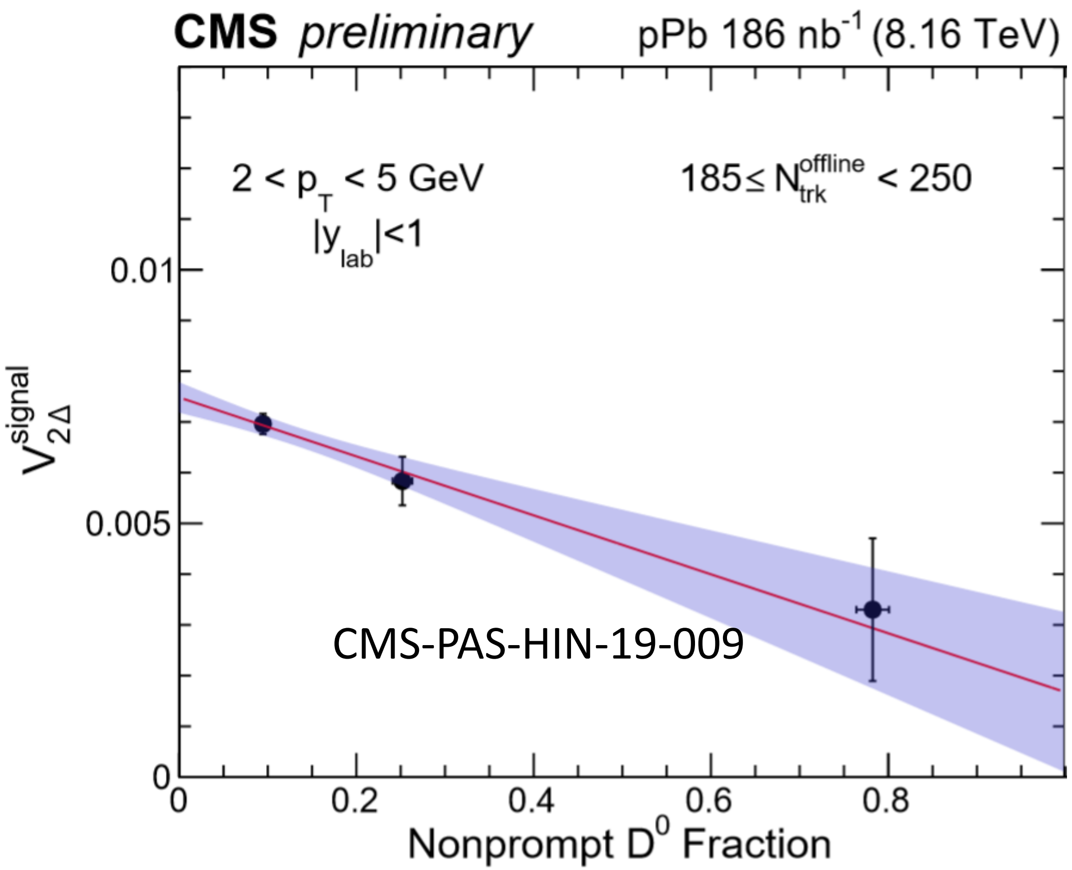
- Nonprompt D^0 originates form b hadron
- Distinguish prompt and nonprompt D^0 by DCA distribution



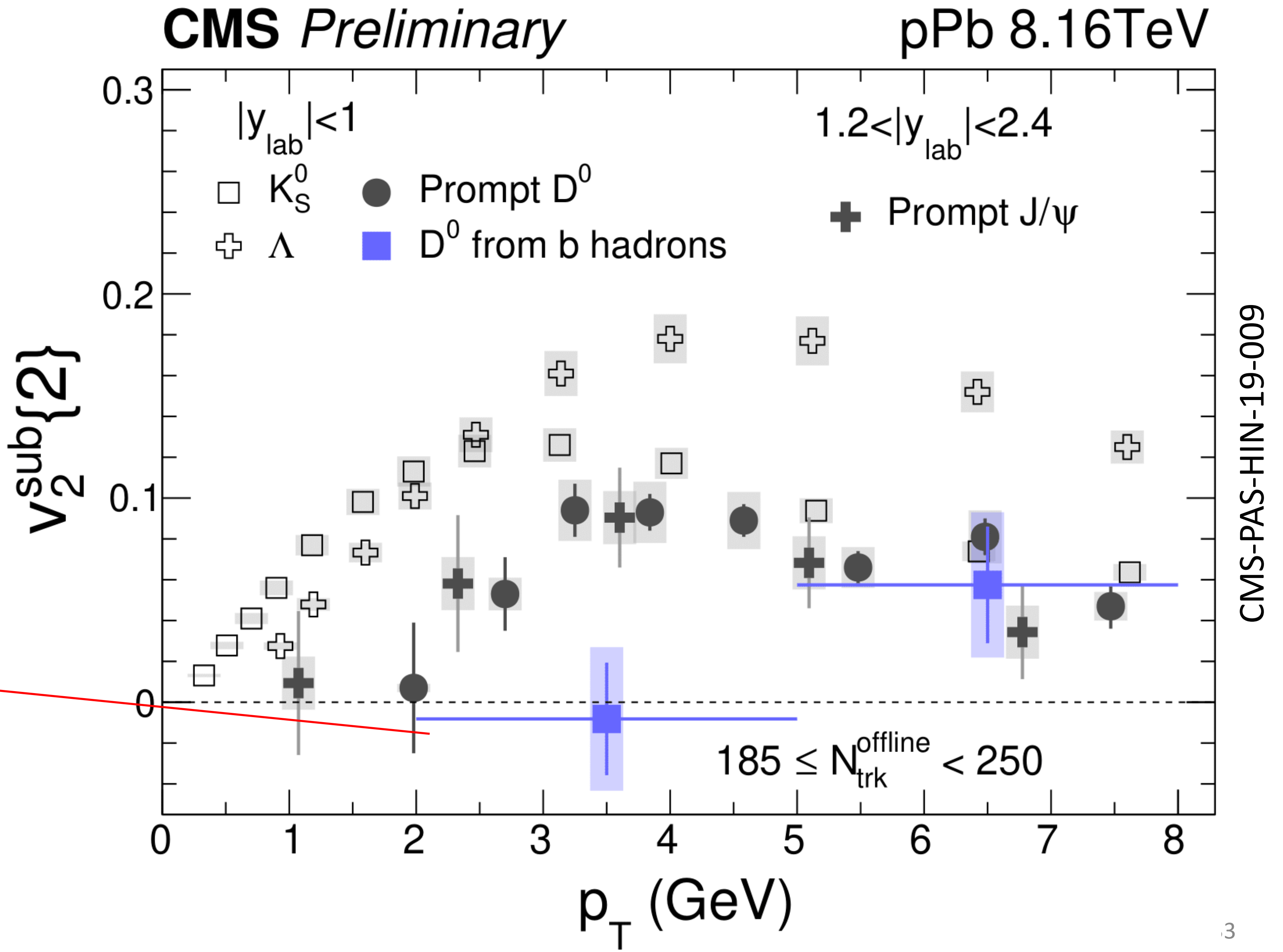


Nonprompt D^0 in pPb Collisions



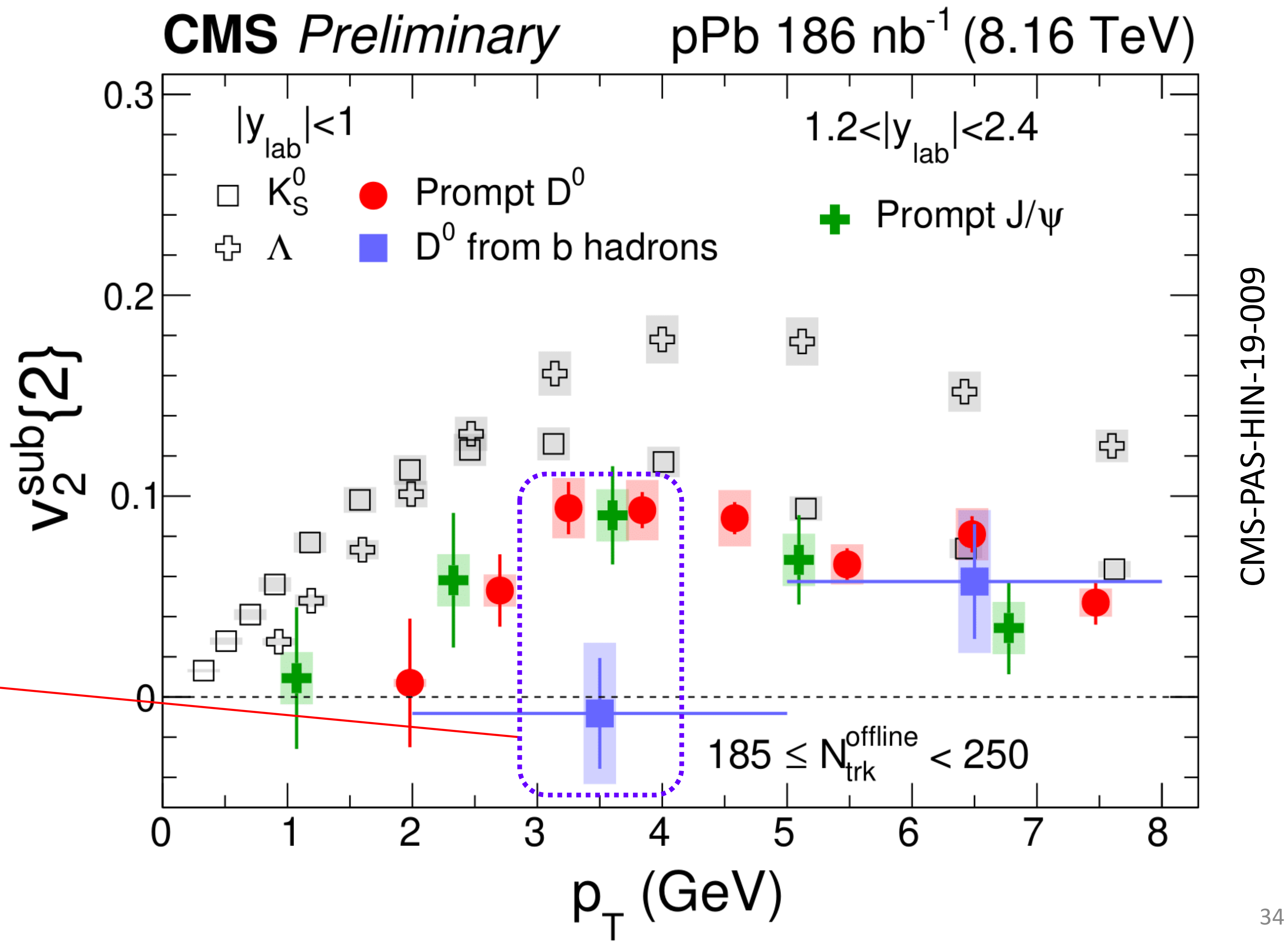


Nonprompt D^0 in pPb Collisions



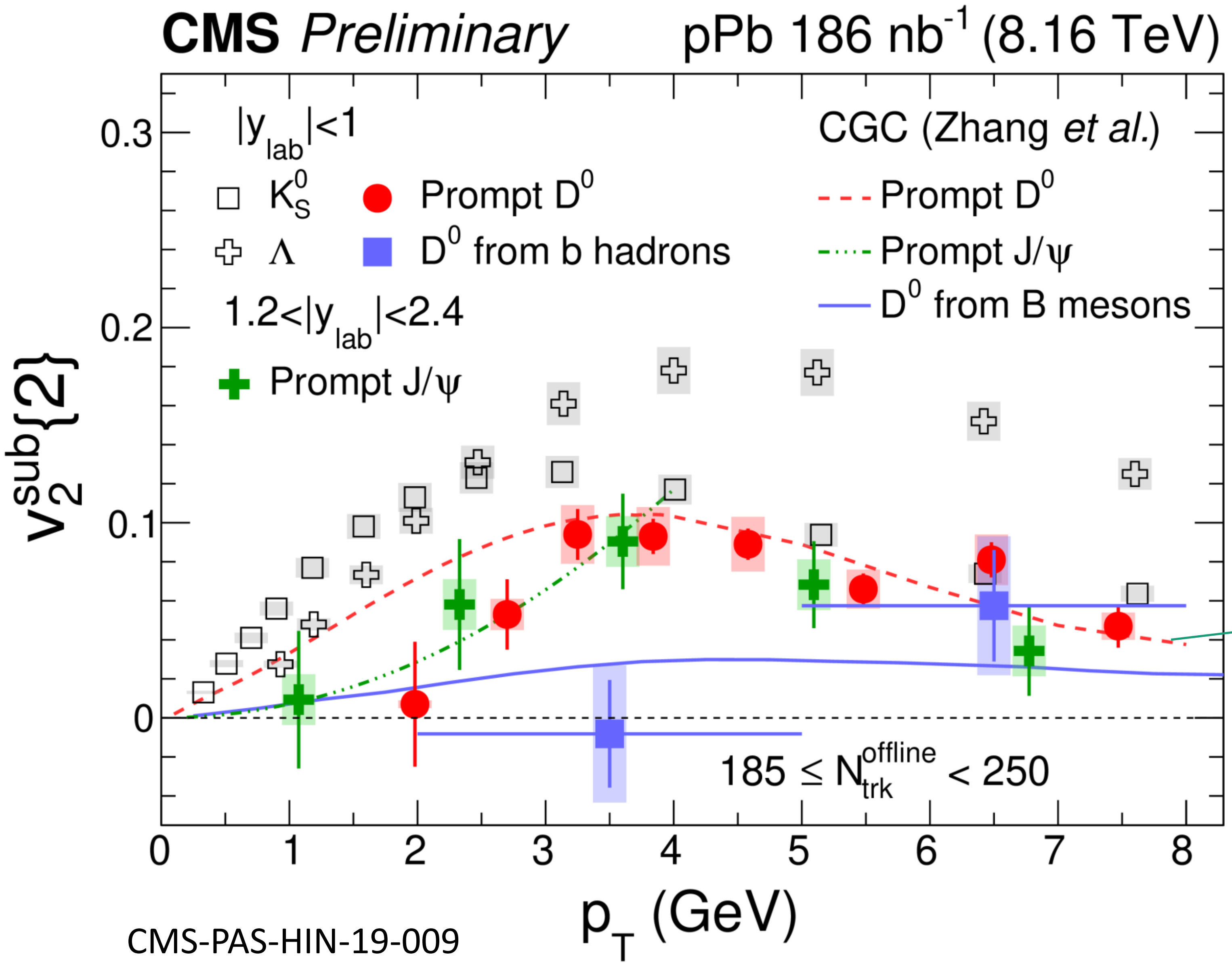
v_2 of nonprompt D^0 consistent with zero

Nonprompt D^0 in pPb Collisions



Indication of flavor hierarchy

Nonprompt D^0 in pPb Collisions



Consistency between CGC and data

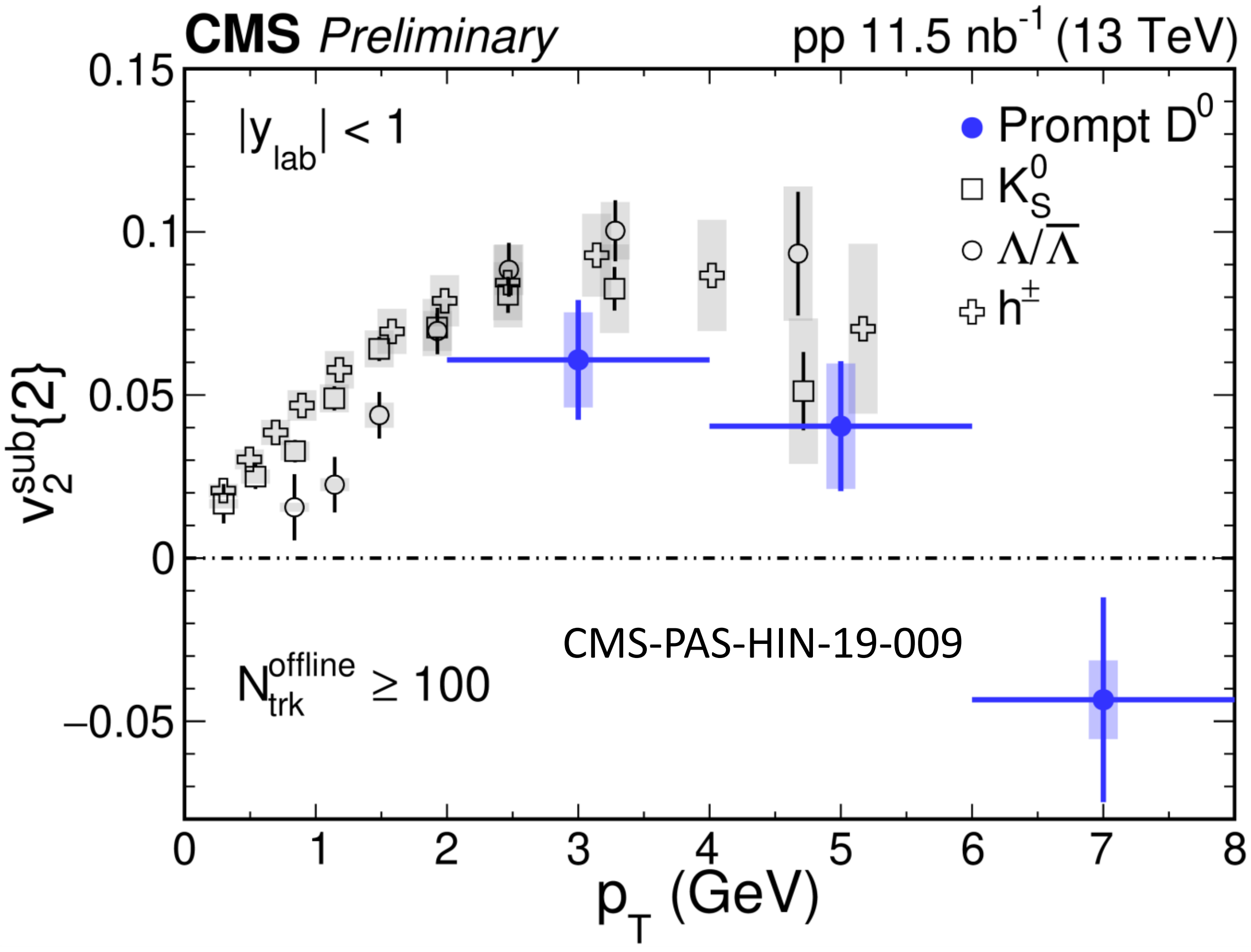
CMS-PAS-HIN-19-009

Prompt D^0 in pp Collisions

A smaller system

Prompt D^0 in pp Collisions

- Indication of positive v_2 signal at p_T from 2 – 4 GeV
- v_2 of Prompt D^0 comparable with that of light hadrons within uncertainties



Prompt D^0 in pp Collisions

- Indication of positive v_2 signal at p_T from 2 – 4 GeV
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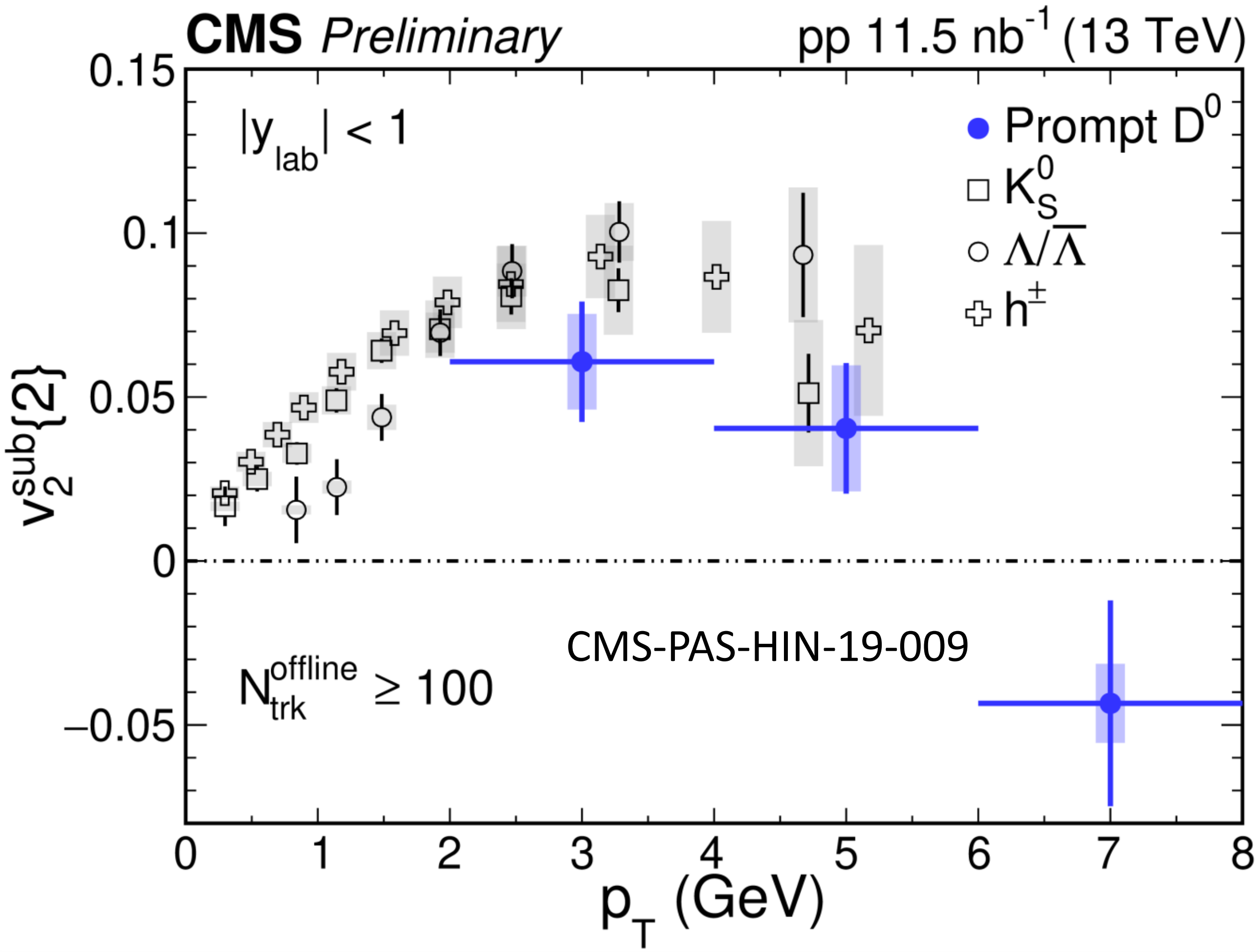


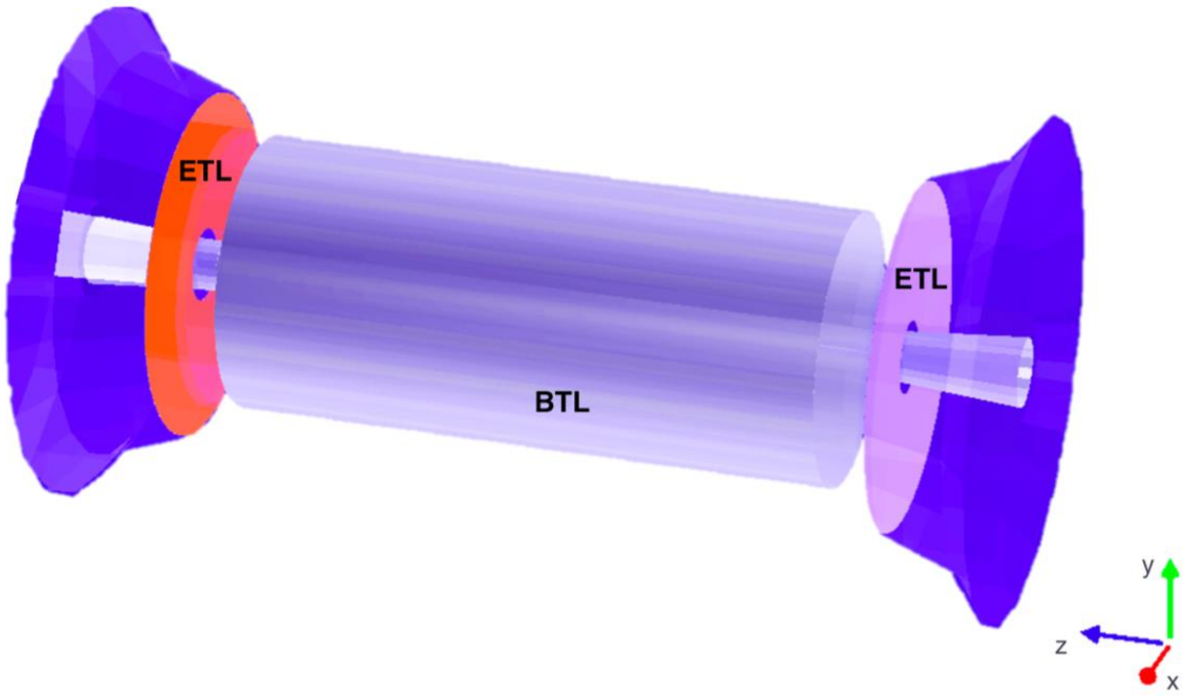
Future opportunities at HL-LHC

LHC Run2	LS2	LHC Run3	LS3	HL-LHC Run4	……
2015-2018	2019-2020	2021-2024	2025-2026	2027-2030	

CMS Phase-2 upgrade

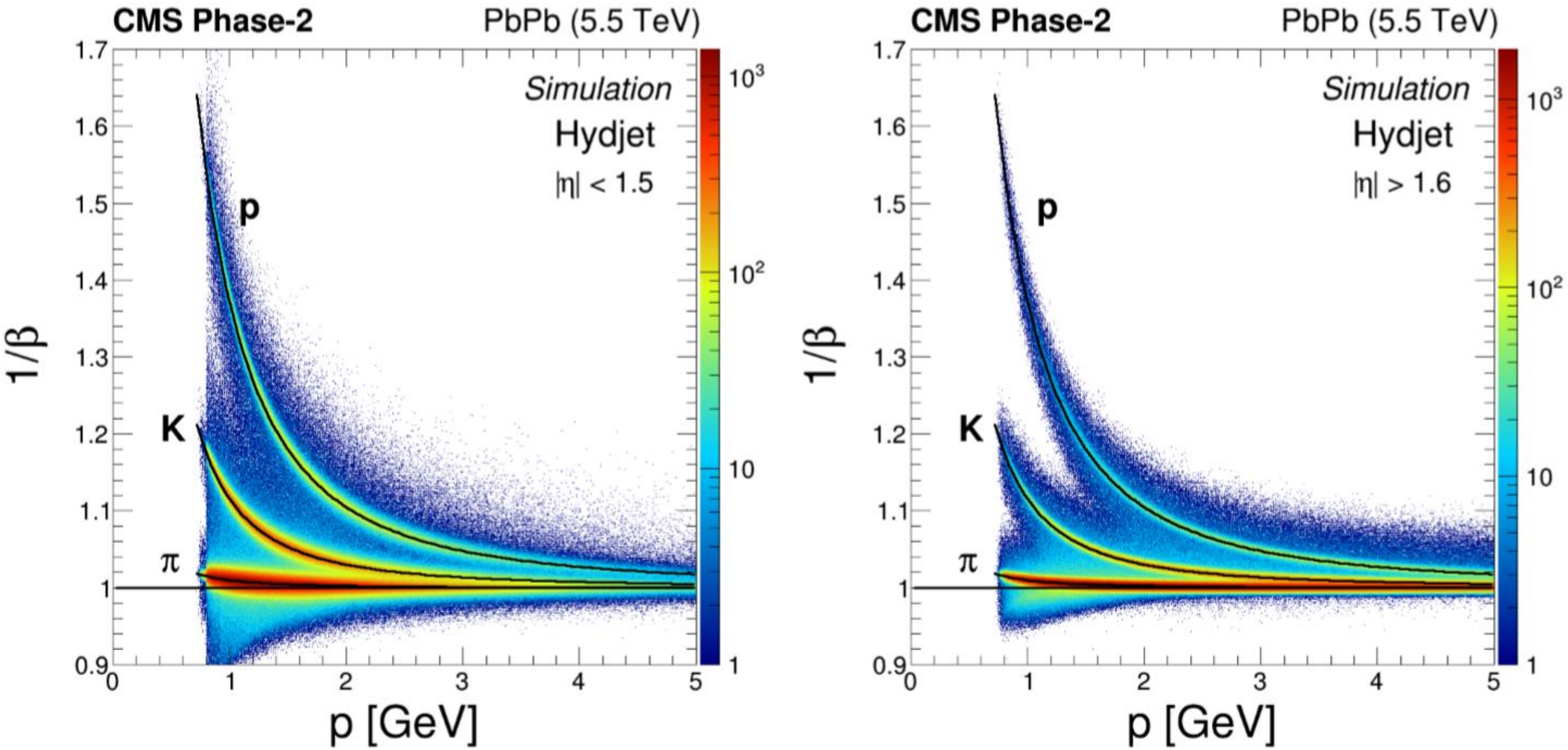
Future opportunities at HL-LHC

- A new Mip Timing Detector
  - High timing precision σ_T~30 ps
  - Large acceptance $|\eta|<3.0$



Future opportunities at HL-LHC

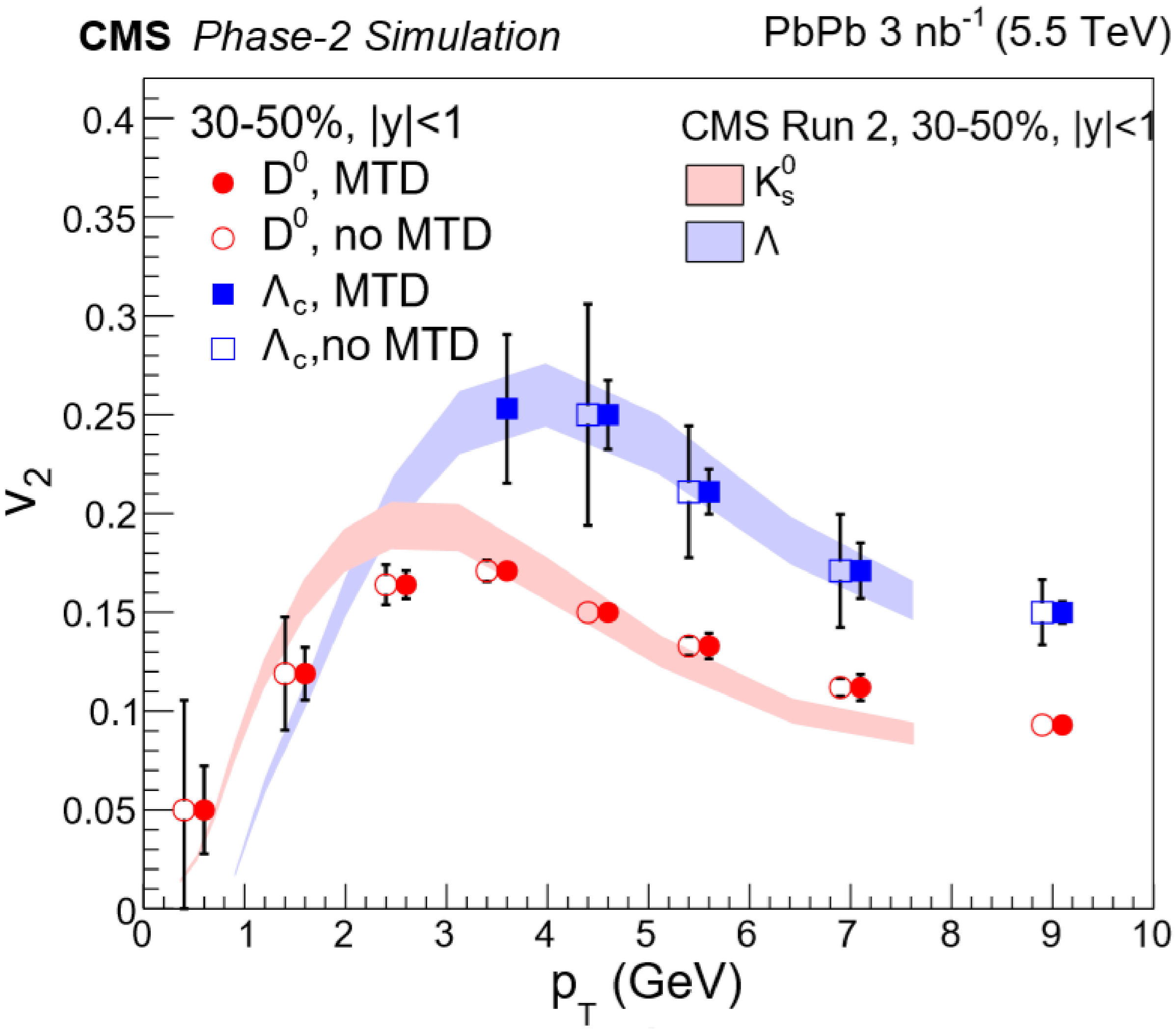
- Kaon ID up to 3 GeV
- Proton ID up to 5 GeV



CERN-LHCC-2019-003

Future opportunities at HL-LHC

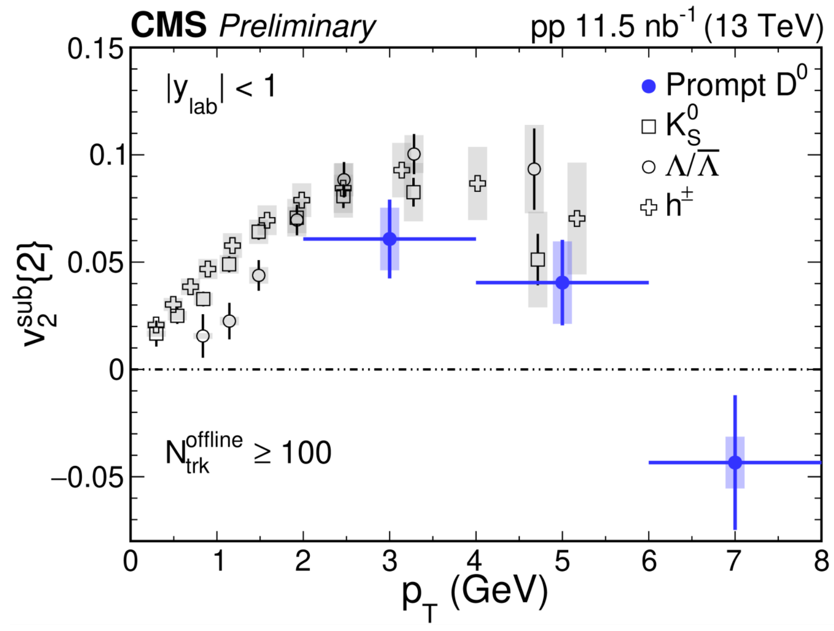
- Precise measurements on v_2 with PID
  - v_2 ratio of Λ_c to D^0
  - v_2 of D^0 down to zero p_T

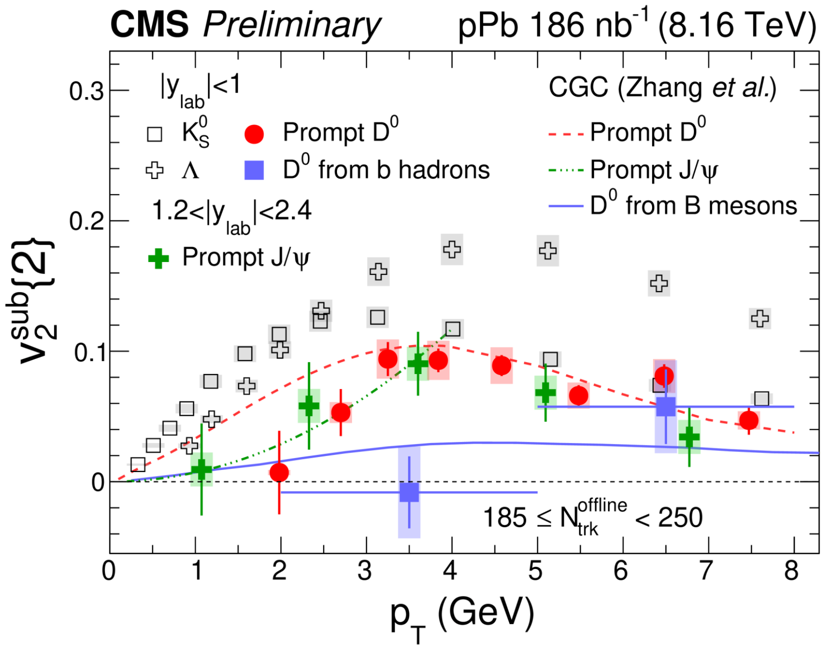


CERN-LHCC-2019-003

Summary

- Strong evidences of positive v_2 of charm quark in pPb collisions
- Little v_2 of nonprompt D^0 (compatible with zero) shows bottom quarks does not involve in collective phenomena strongly
- Indication of positive v_2 of D^0 in pp collisions





Ackownledgement

U.S. DEPARTMENT OF ENERGY

Office of Science

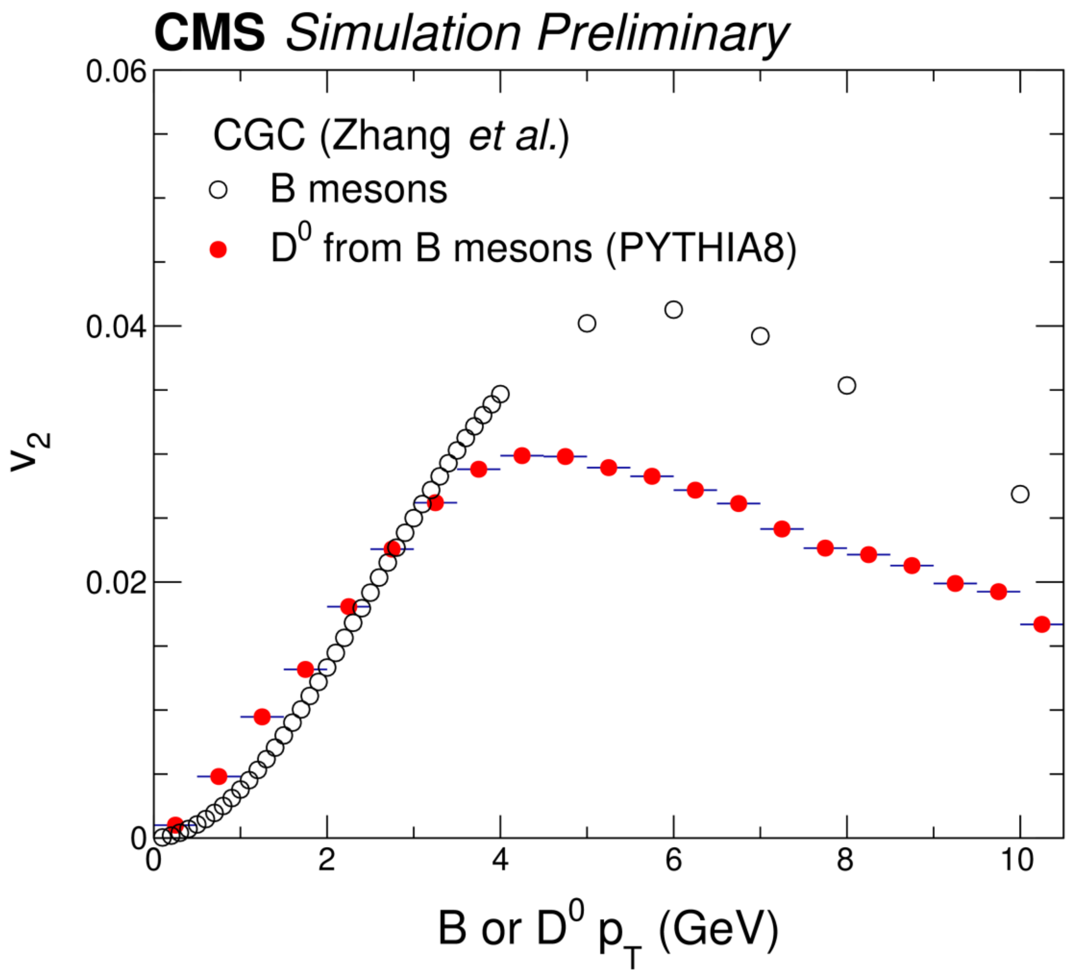
Alfred P. Sloan FOUNDATION

THE Welch FOUNDATION

Backup nonflow

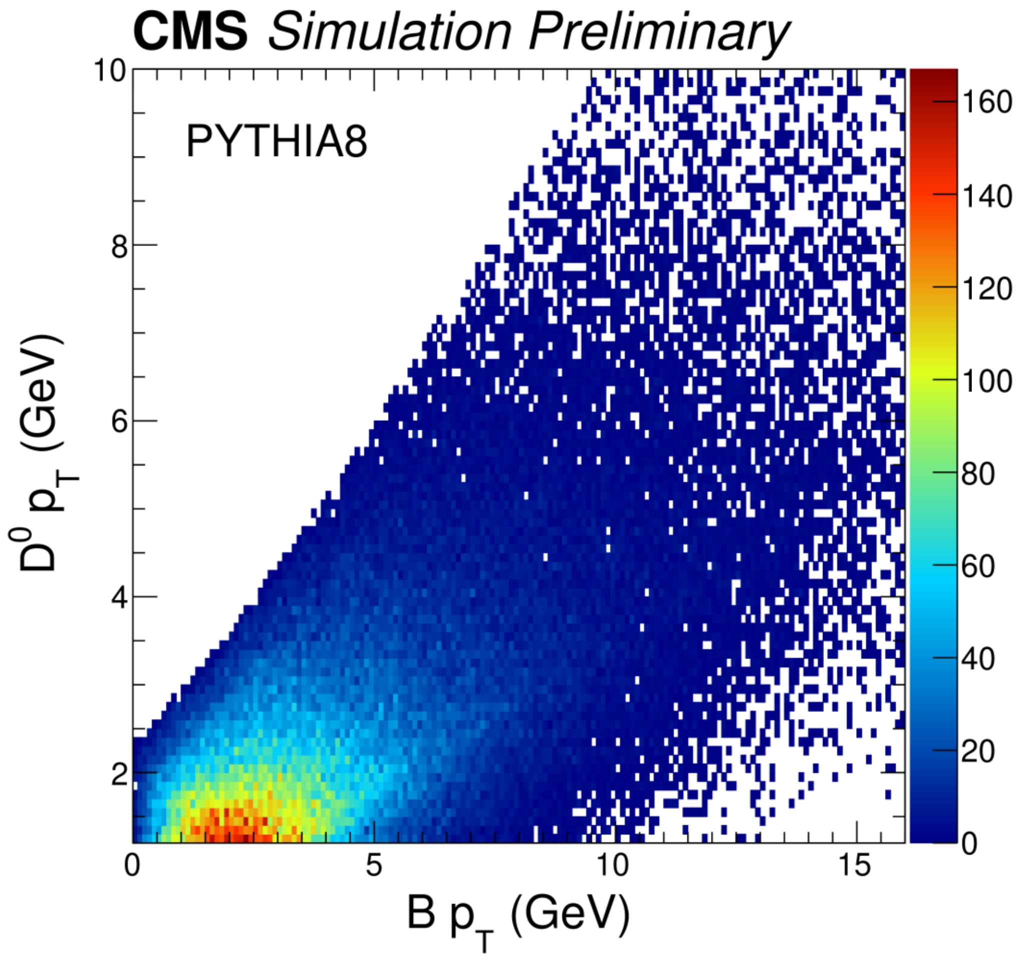
$$V_{n\Delta}^{\mathrm{sub}} = V_{n\Delta} - V_{n\Delta}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35) \times \frac{N_{\mathrm{assoc}}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35)}{N_{\mathrm{assoc}}} \times \frac{Y_{\mathrm{jet}}}{Y_{\mathrm{jet}}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35)},$$

Backup

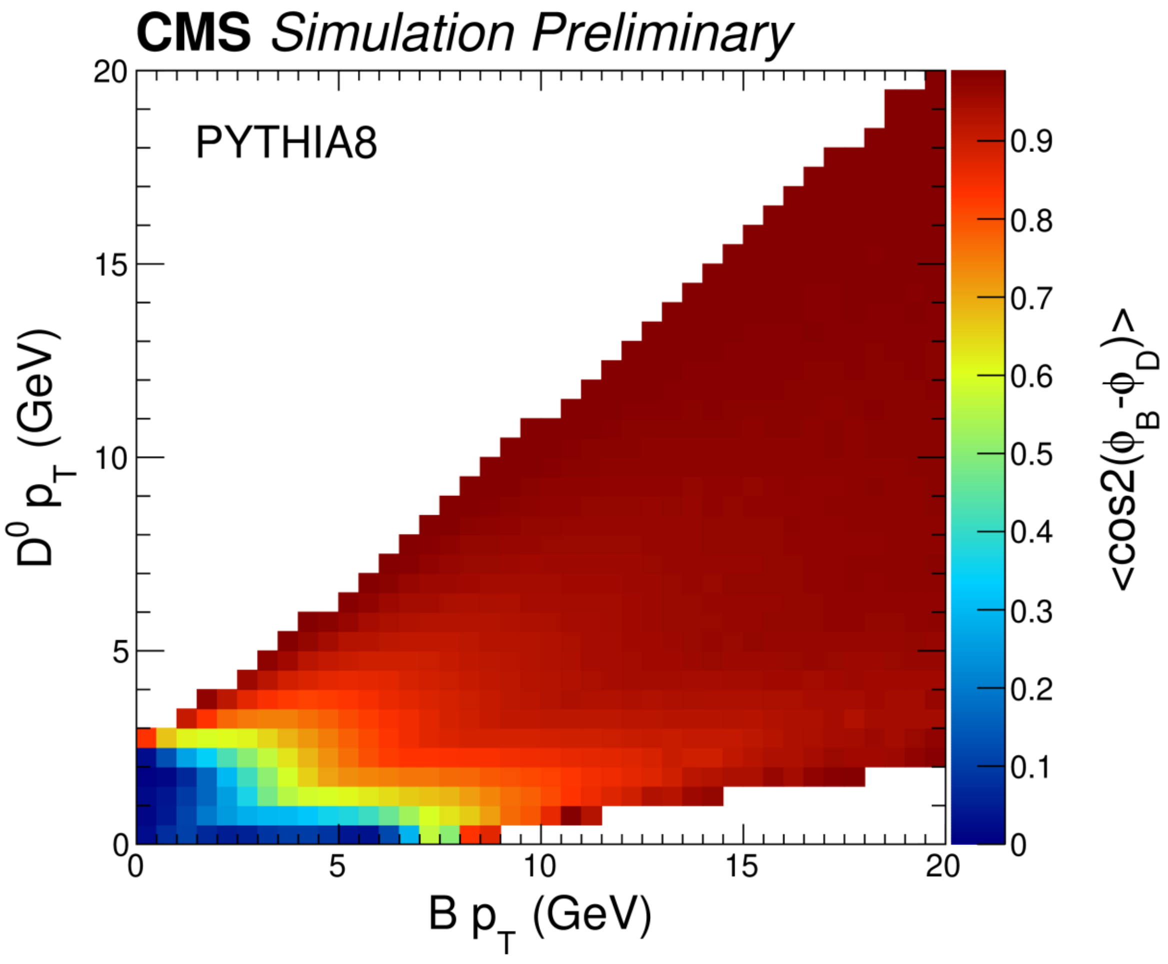

CMS Simulation Preliminary
CGC (Zhang et al.)
B mesons
D0 from B meson (PYTHIA8)
v2
B or D0 pT (GeV)
0.06
0.04
0.02
0
0
2
4
6
8
10

Backup

Backup

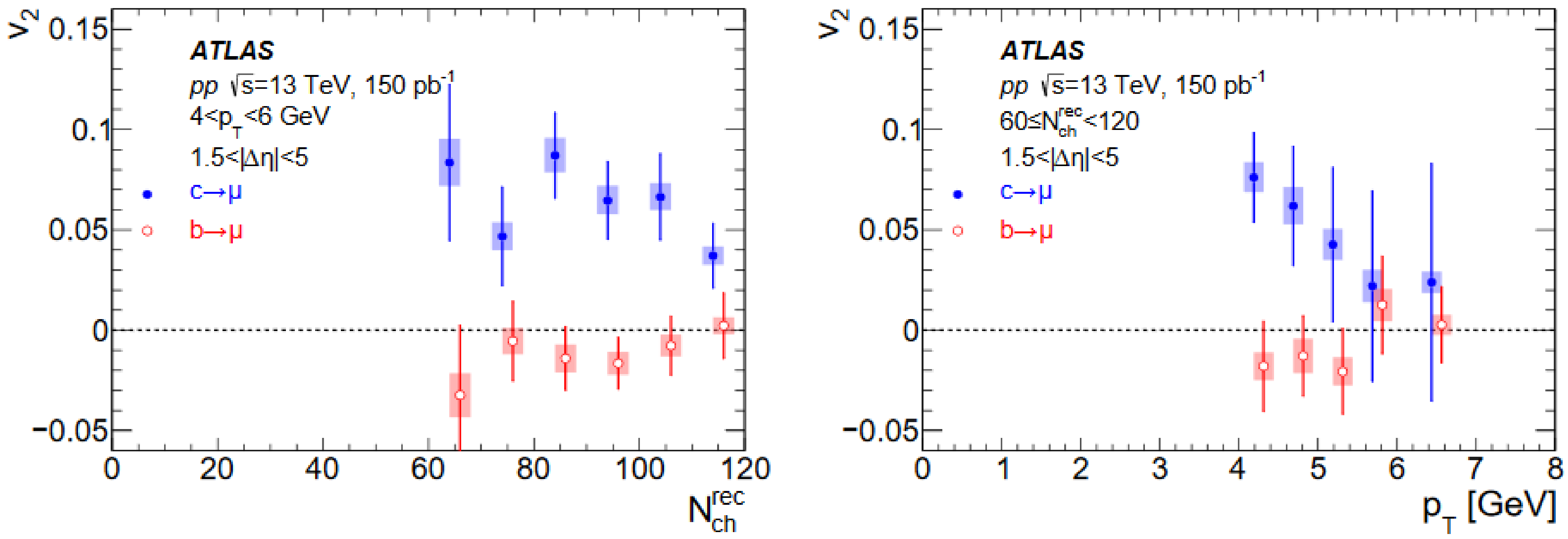


CMS Simulation Preliminary
PYTHIA8
D0 pT (GeV)
B pT (GeV)
0
5
10
15
2
4
6
8
10
20
40
60
80
100
120
140
160



CMS Simulation Preliminary
PYTHIA8
D0 pT (GeV)
B pT (GeV)
<cos2(φB -φD)>
0
5
10
15
20
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Backup

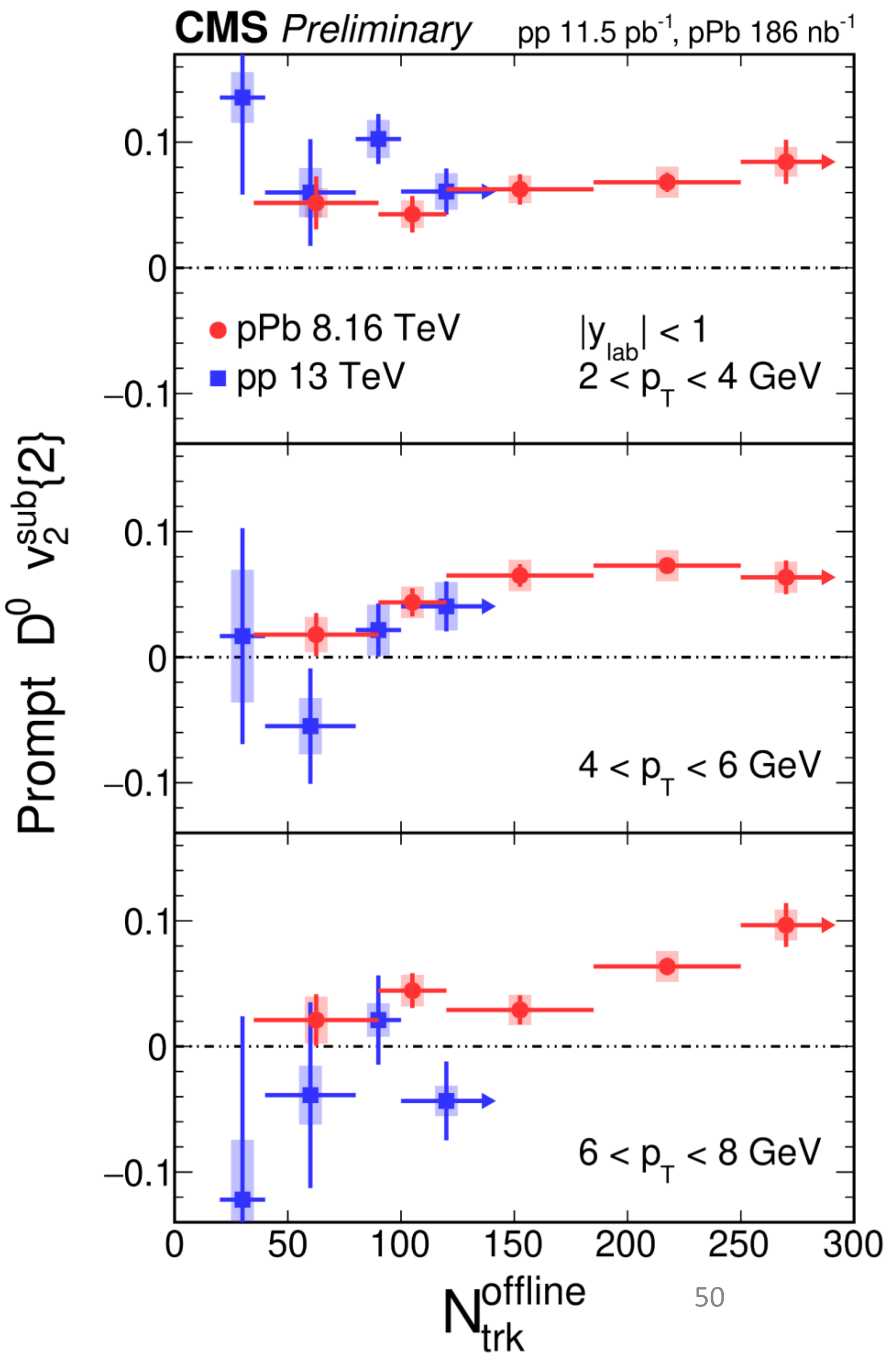


ATLAS
pp √s=13 TeV, 150 pb^-1
4<p_T<6 GeV
1.5<|Δη|<5
c→μ
b→μ
v_2
0.15
0.1
0.05
0
−0.05
0
20
40
60
80
100
120
N_ch^rec
ATLAS
pp √s=13 TeV, 150 pb^-1
60≤N_ch^rec<120
1.5<|Δη|<5
c→μ
b→μ
v_2
0
1
2
3
4
5
6
7
8
p_T [GeV]

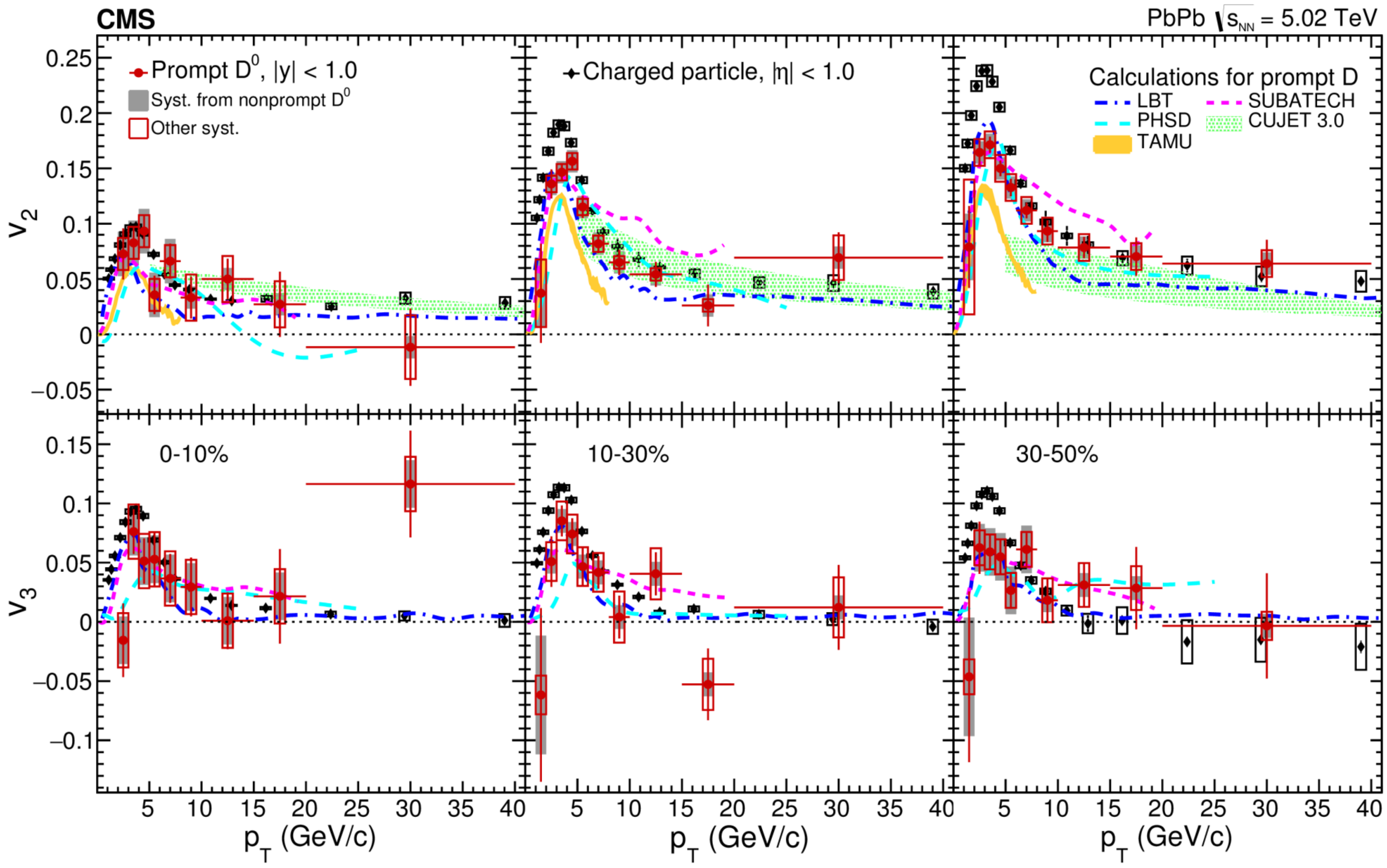
Backup System size and Collecitivity

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

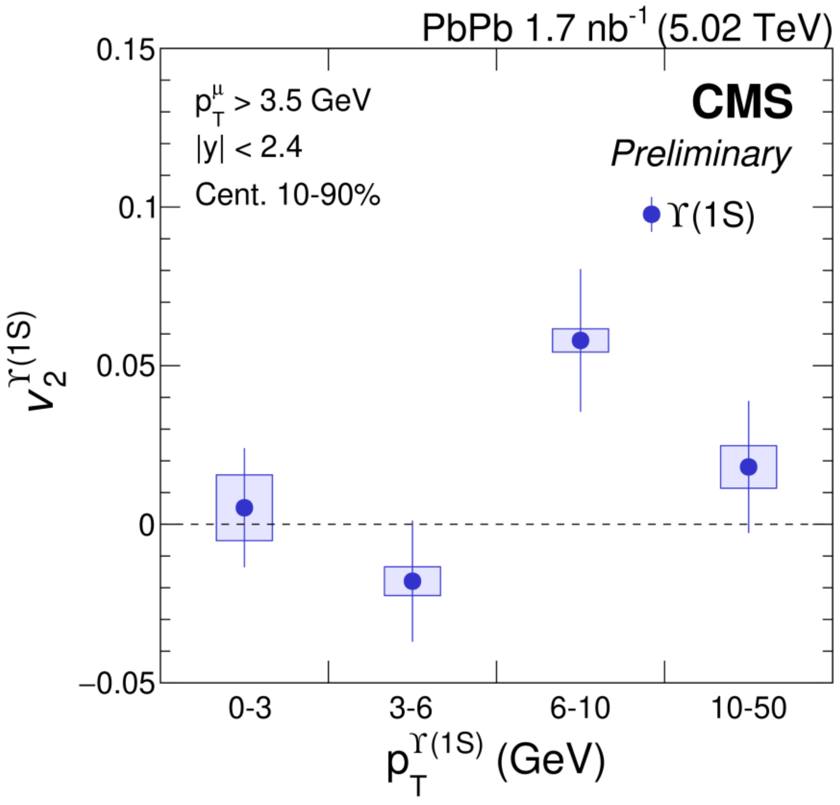
CMS-PAS-HIN-19-009



Backup

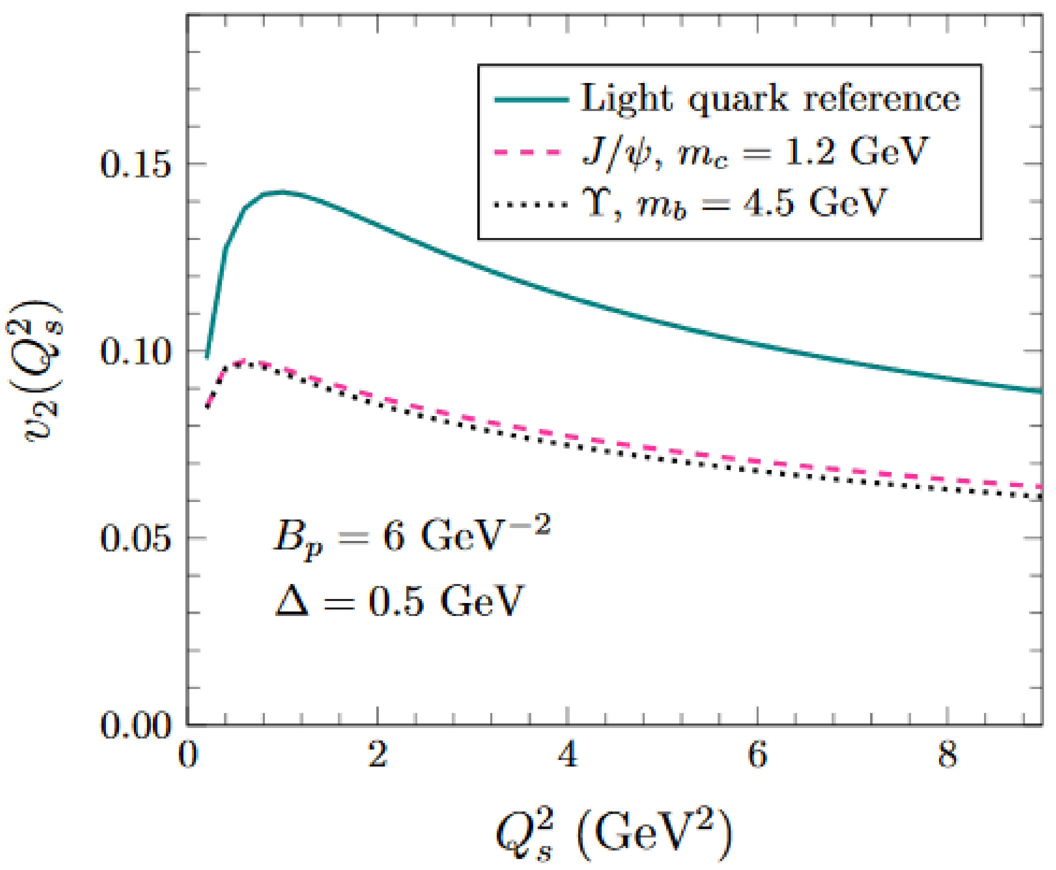

CMS
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
Prompt D^0, |y| < 1.0
Syst. from nonprompt D^0
Other syst.
Charged particle, |η| < 1.0
Calculations for prompt D
LBT
SUBATECH
PHSD
CUJET 3.0
TAMU
v_2
v_3
0-10%
10-30%
30-50%
p_T (GeV/c)

Backup



PbPb 1.7 nb^{-1} (5.02 TeV)
p_T^{μ} > 3.5 GeV
|y| < 2.4
Cent. 10-90%
CMS
Preliminary
Υ(1S)
$v_2^{\Upsilon(1S)}$
0.15
0.1
0.05
0
−0.05
0-3
3-6
6-10
10-50
$p_T^{\Upsilon(1S)}$ (GeV)

Backup



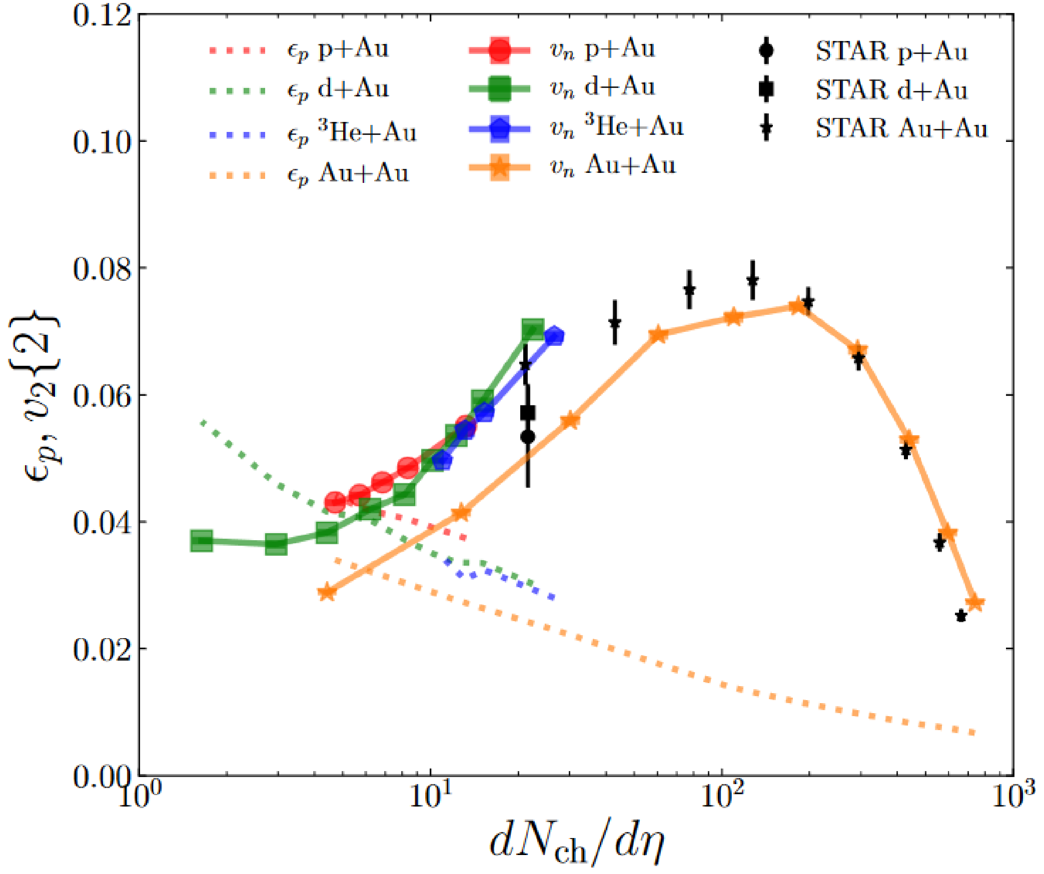
Light quark reference
J/ψ, $m_c = 1.2$ GeV
Υ, $m_b = 4.5$ GeV
$B_p = 6$ GeV^{-2}
$\Delta = 0.5$ GeV
$v_2(Q_s^2)$
0.15
0.10
0.05
0.00
0
2
4
6
8
Q_s^2 (GeV^2)

Origin of the collectivity

Model: B.Schenke, arXiv:1908.06212
Experimental Data: PRL,122, 172301 (2019)

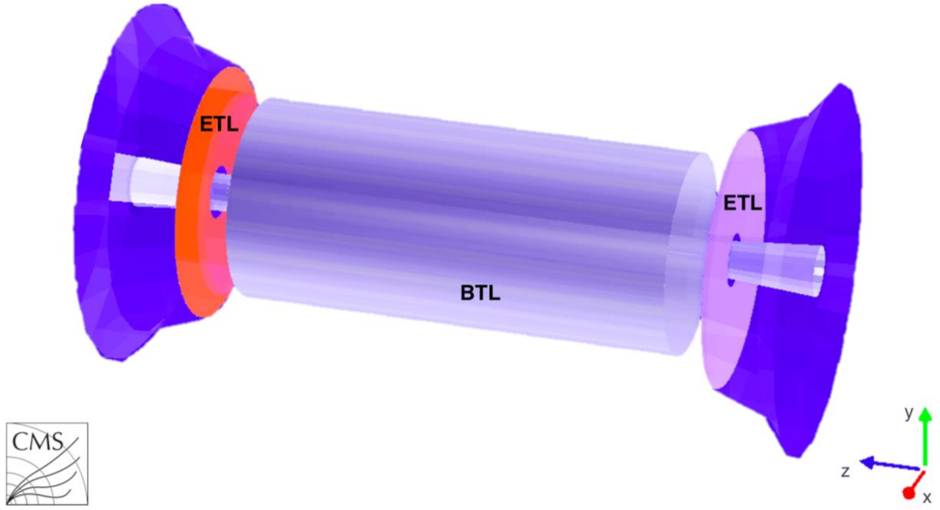
Hybrid model

- Initial momentum anisotropy decrease over $\mathrm{d}N_{ch}/\mathrm{d}\eta$
- Opposite to v_2, final state anisotropy



Backup

- One barrel section (BTL) and two end-cap disks (ETL).
- Coverage for tracks: p > 0.7 GeV at $|\eta| < 3.0$, and time resolution: ~30 ps
- Installation planned for HL-LHC: 2022 for BTL and 2024 for ETL



Backup

Experiment	η coverage	L at $\eta = 0$ (m)	σ_T (ps)	L/σ_T ($\times 100$)
CMS	$\lvert\eta\rvert < 3.0$	1.16	30	3.9
ALICE	$\lvert\eta\rvert < 0.9$	3.7	56	6.6
STAR	$\lvert\eta\rvert < 0.9$	2.2	80	2.2

CERN-LHCC-2019-003

Backup, BTL

- 72 trays covering a surface of ~38 m^2
- Material budget: < 0.4 X_0
- Rapidity coverage: $|\eta| < 1.5$
- Timing resolution: ~ 30 ps
- L(Y)SO:Ce crystal bars as scintillator:
    - Excellent radiation tolerance, high signal and fast response time.
- Silicon Photomultipliers as detectors
    - Compact, fast and insensitive to magnetic fields

Backup, ETL

- 2 disks covering a surface of ~14 m^2
- Material budget: < 0.2 X_0
- Rapidity coverage: $1.6 < |\eta| < 3.0$
- x10 higher radiation level than BTL
- Timing resolution: ~ 30-50 ps
- Ultra fast silicon detectors
  - Low gain avalanche diodes optimized for timing