Heavy Flavor in Small Collision Systems

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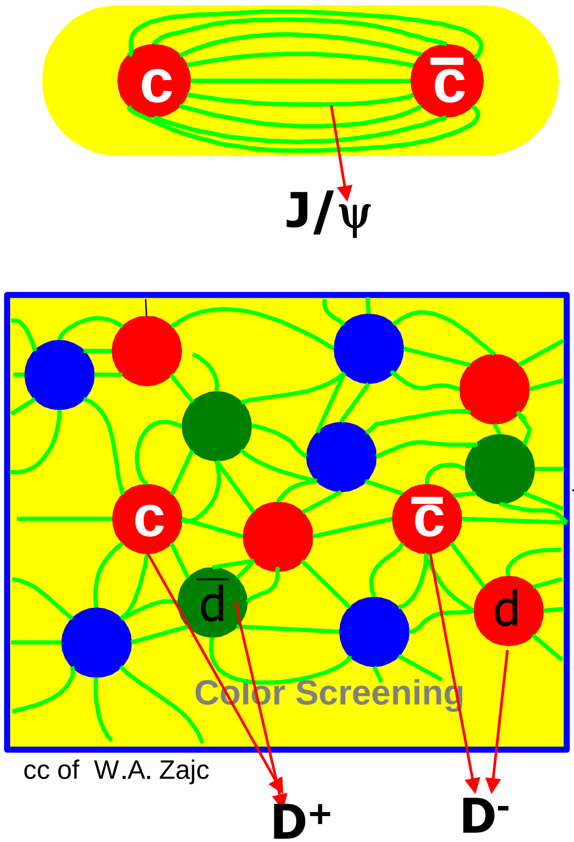
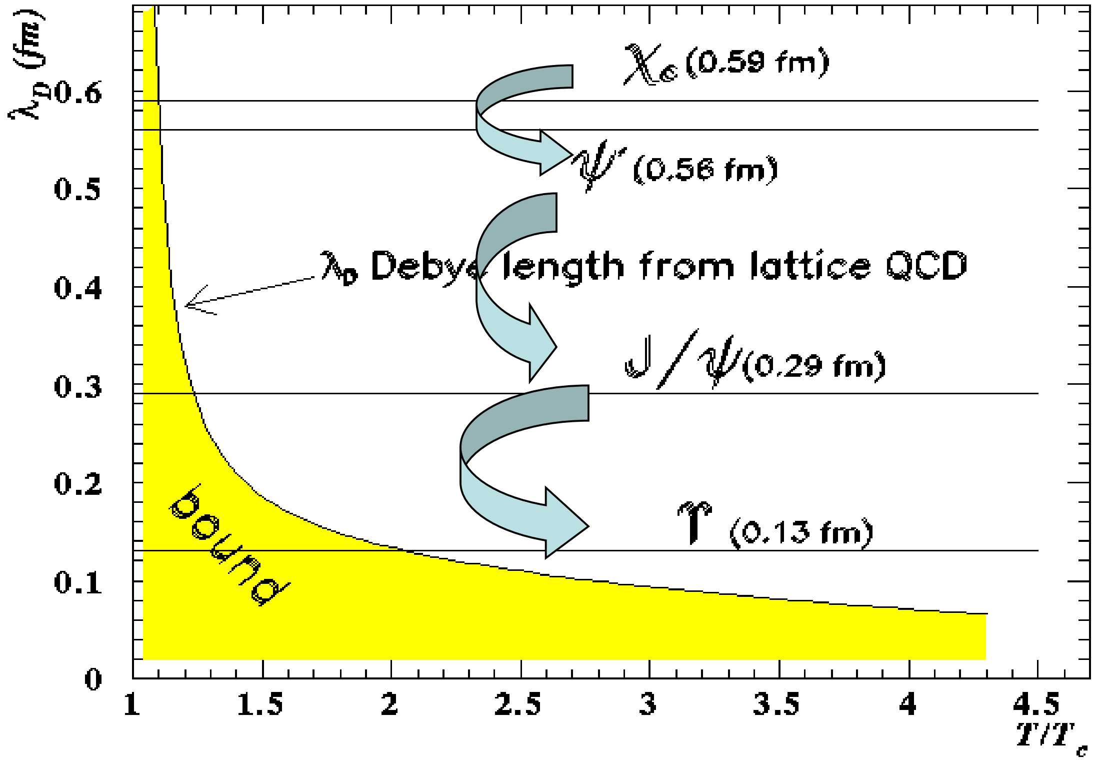
Quarkonia Suppression: "Smoking Gun" for QGP



cc of W.A. Zajc



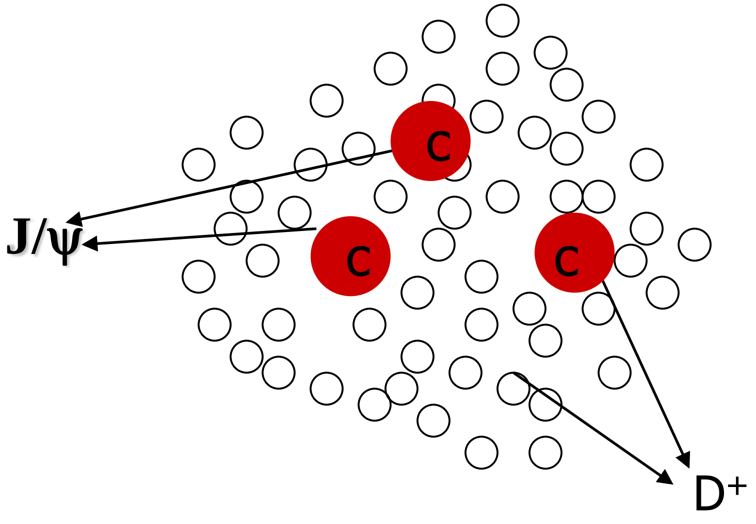
Sequential melting→a QGP thermometer

H. Satz, NPA 783 (2007) 249c.

The life of Quarkonia in the Medium can be Complicated

- Observed J/ψ is a mixture of prompt production+feeddown
  - direct J/ψ ≈ ~60% J/ψ(prompt) + ~30% χ_c + ~10% ψ(2s)
  - Non-prompt: B hadron feed down.
    - Important to disentangle different component

- Suppression and enhancement in the "cold" nuclear medium
  - Nuclear Absorption, nuclear PDF effects, initial state energy loss, Cronin effect and gluon saturation (CGC)
  - Study p+A collisions
    - QGP in small systems?



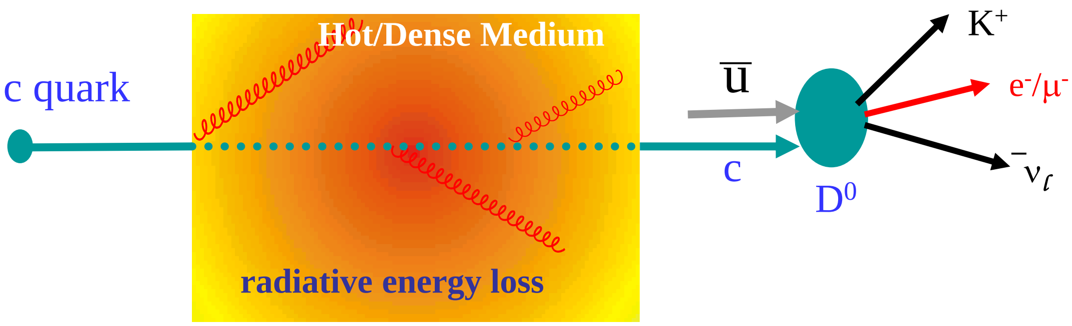
- Hot/dense medium effect
  - J/ψ, ϒ dissociation, i.e. suppression
  - Recombination, i.e. enhancement
  - Study different species, e.g. J/ψ, ϒ
  - Study at different energies, i.e. RHIC, LHC

Essential to understand Open Heavy Flavor Production

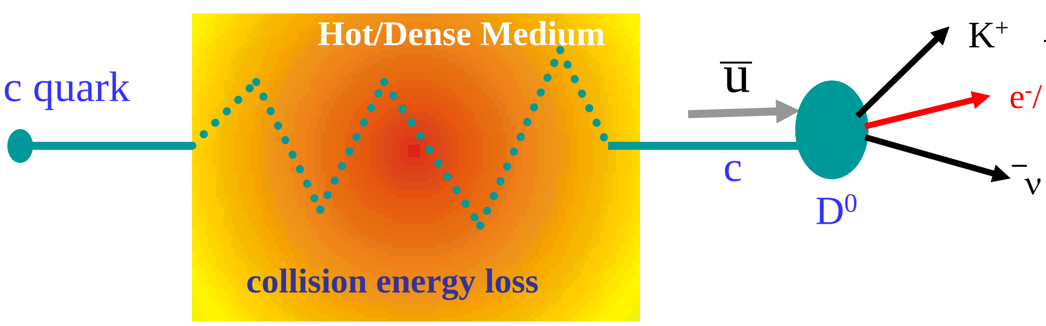
- A good reference to quarkonia production
  - Similar initial state effects
    - CGC, Shadowing, initial state energy loss, etc.
  - Large cross section (compared to J/ψ).
    - Accurate reference measurements.

- One of the most important probes for sQGP
  - Interactions between heavy quark and medium are quite different from the ones for light quarks
    - gluon radiation, collisional energy loss, collisional disassociation, etc

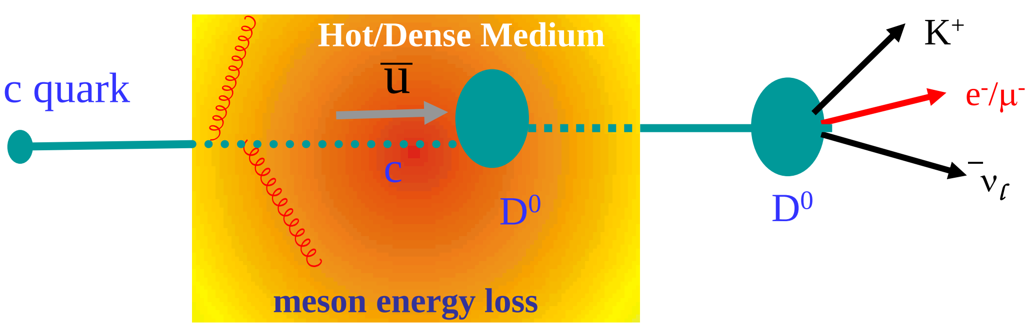
The Large Suppression of Non-photonic Electron Production was a Surprise



(Baier *et al*, Kharzeev *et al*, Djordjevic *et al*, Wiedemann *et al* .)

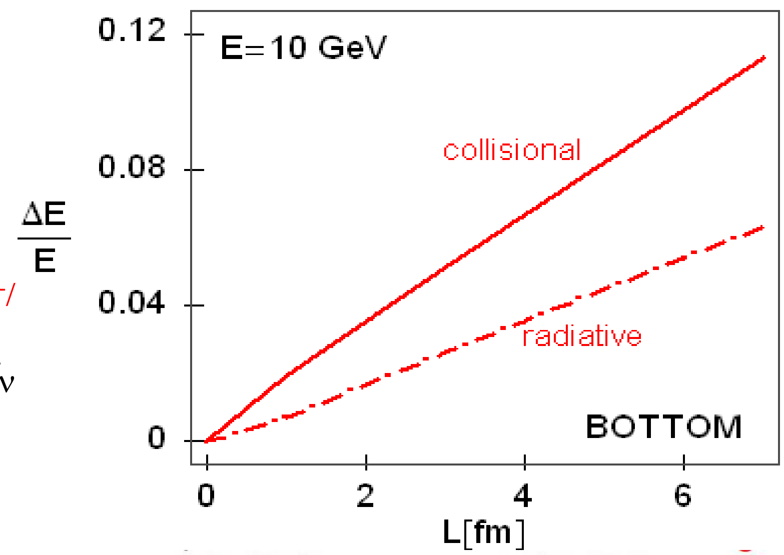


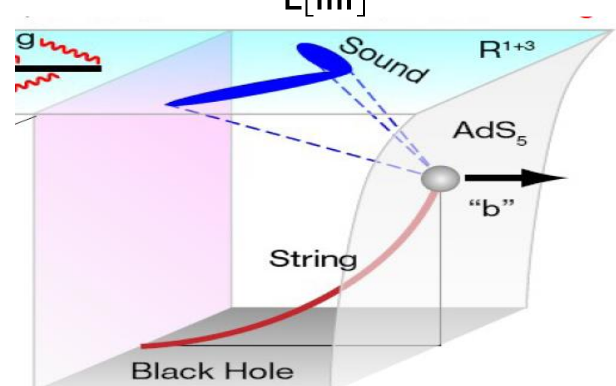
(Teaney *et al*, Rapp *et al*, Molnar *et al*, Gossiaux *et al*.)



Vitev, *et al*

"dead cone effect":
gluon radiation
suppressed at $\theta < m_Q/E_Q$





(Gubser *et al.*, Herzog *et al.*, Horowitz, Gyulassy *et al.*)

Essential to understand Open Heavy Flavor Production

- A good reference to quarkonia production
  - Similar initial state effects
    - CGC, Shadowing, initial state energy loss, etc.
  - Large cross section (compared to J/ψ).
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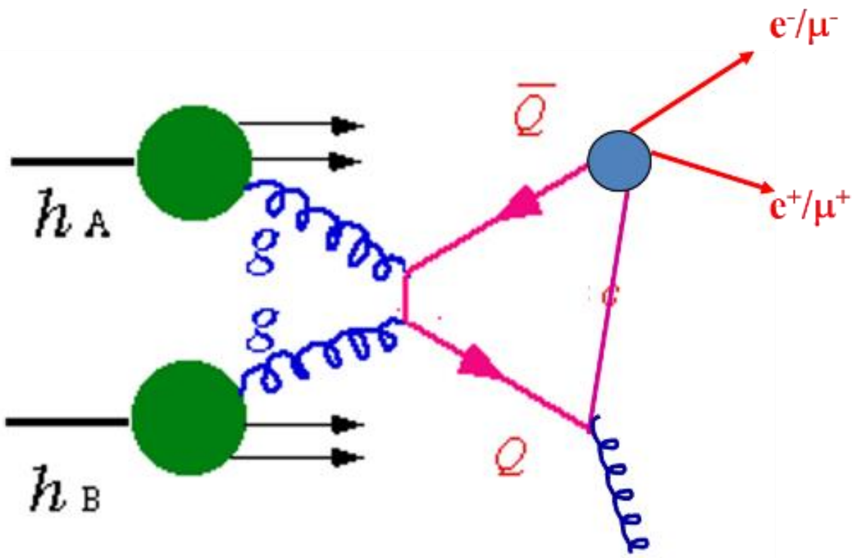
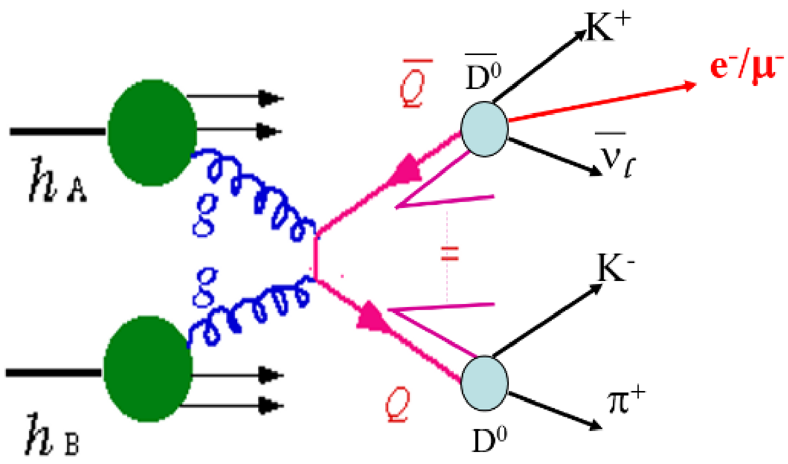
- One of the most important probes for sQGP
  - Interactions between heavy quark and medium are quite different from the ones for light quarks
    - gluon radiation, collisional energy loss, collisional disassociation, etc
  - allow further understanding of the medium properties.
  - A "**Gold Mine**" being fully explored.

How to study Heavy Quarks



Quarkonia

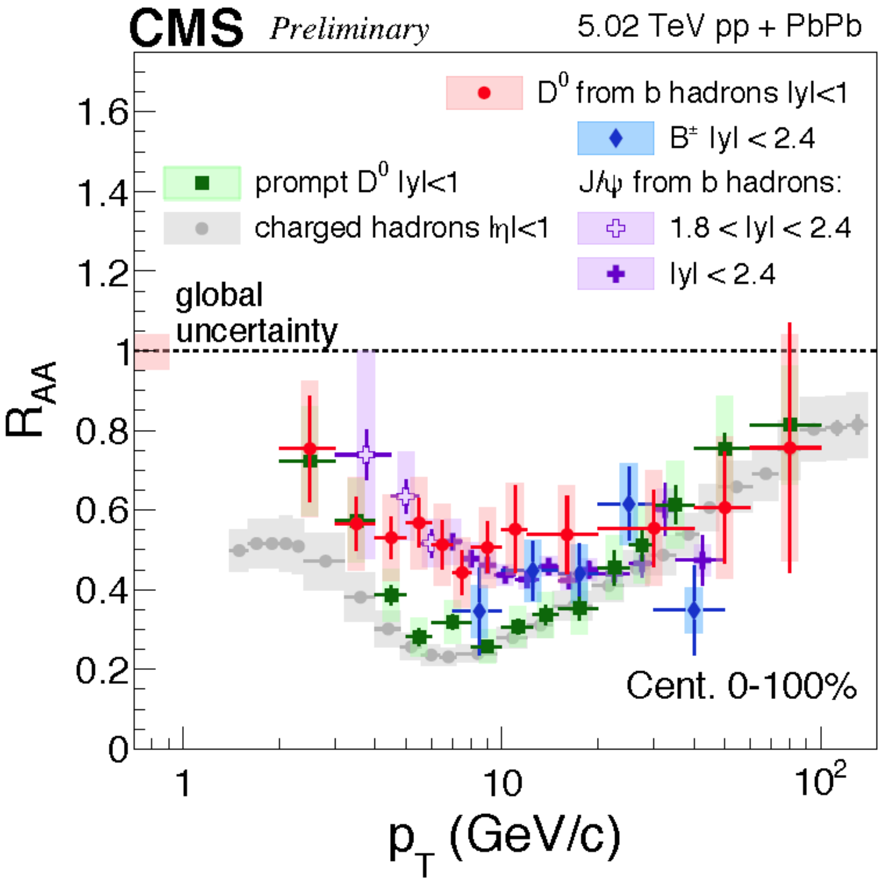


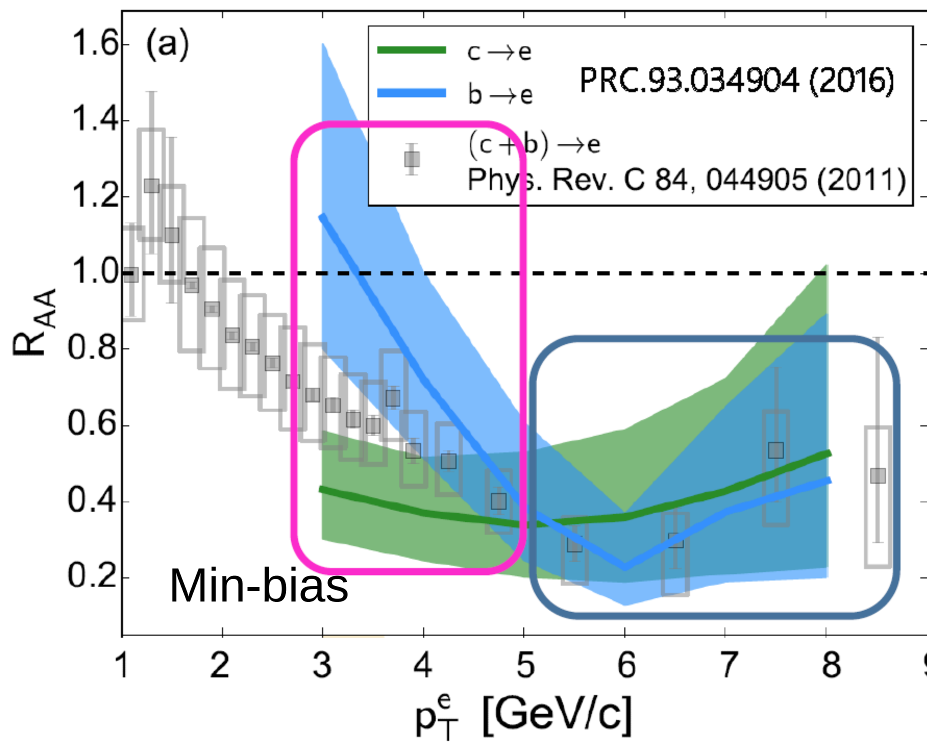
Open heavy flavor

- Heavy quark proxies:
  - Jet associated with the heavy quark
  - HF hadron via direct reconstruction
  - HF-decay, i.e. electrons, muons

- Production of each individual proxies, e.g. R_{AA} and V_2
- Correlation among proxies

Open HF production suppressed in large system

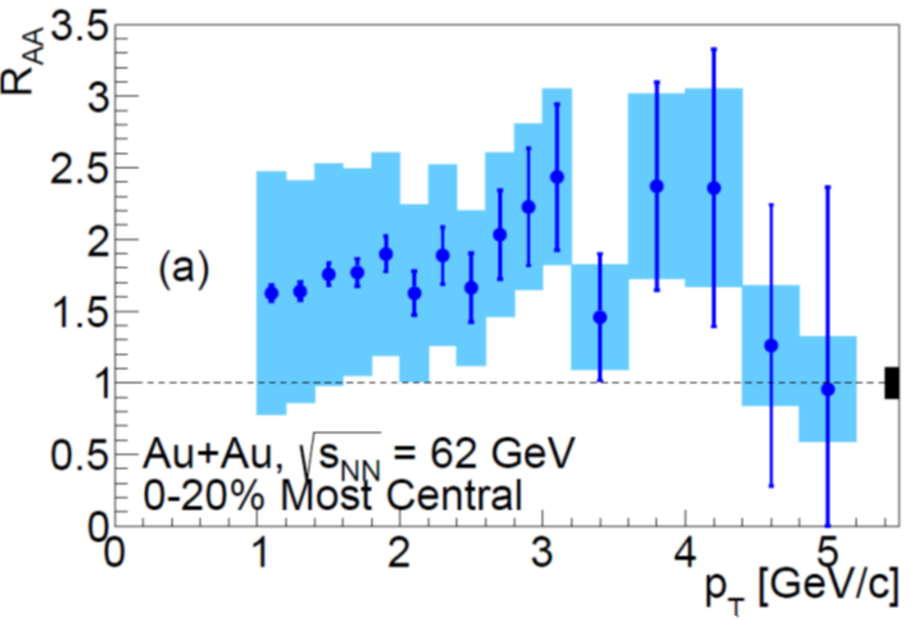


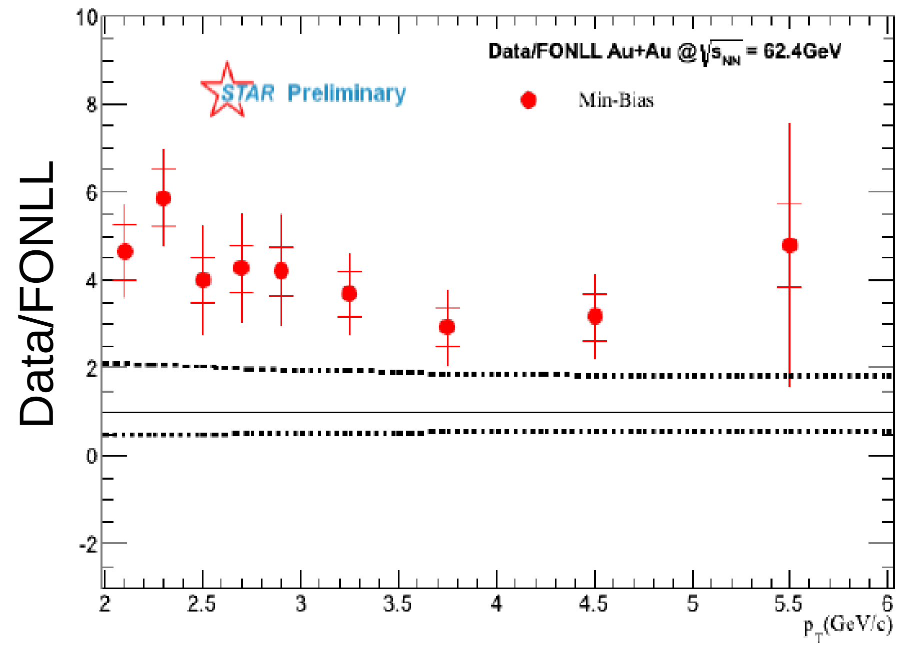


- ❑ Low pT
  - R_{AA} (bottom) > R_{AA} (charm) > R_{AA} (charged)
- ❑ High pT
  - R_{AA} (bottom) ≈ R_{AA} (charm) ≈ R_{AA} (charged)

CMS: HIN-16-016; PRL 119,152301(2017); arXiv:1708.04962; JHEP 04, 039(2017). PHENIX: PRC84,044905 (2011); PRC93,034904(2016);

HF→e Enhancement at 62.4 GeV





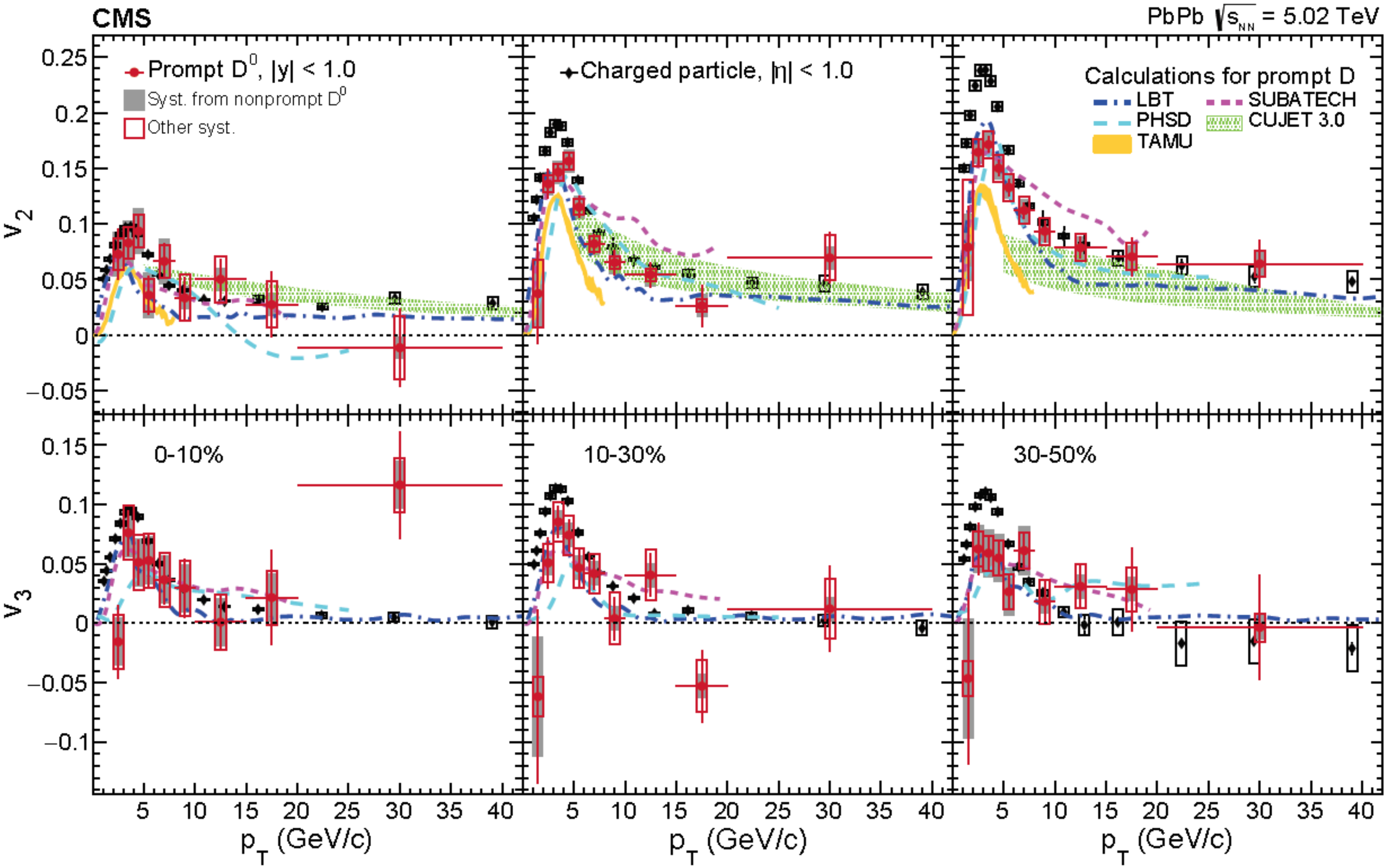
- ❑ Reference from ISR HF→e
  - well described by FONLL.
- ❑ Indication of "enhancement"

- ❑ 62.4 GeV pp well described by FONLL. NC A 65, 421 (1981).
- ❑ Indication of "enhancement"

Radial flow and/or CNM enhancement compensate suppression at lower energy?

PHENIX: PRC 91, 044907 (2015) *STAR:* NPA904,905, 665c(2013)

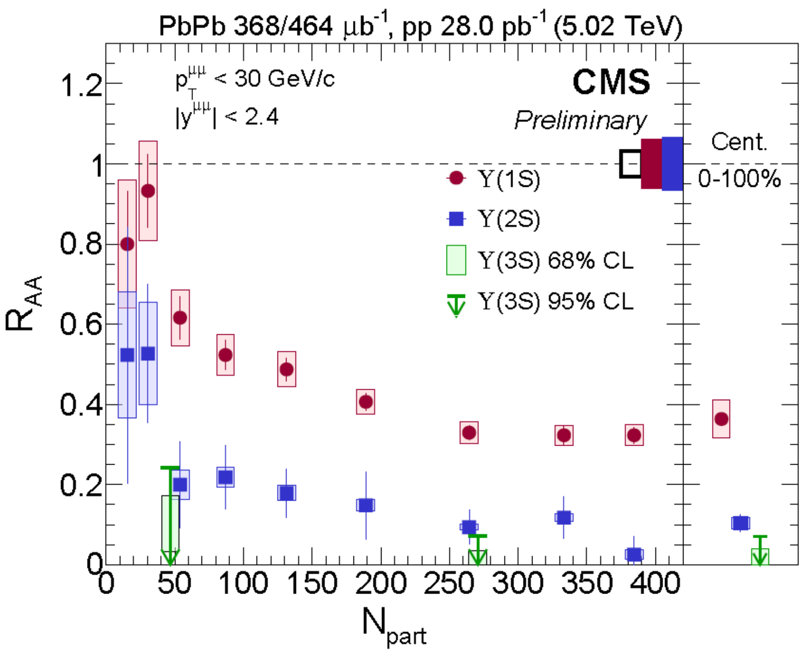
Large collectivity in large system

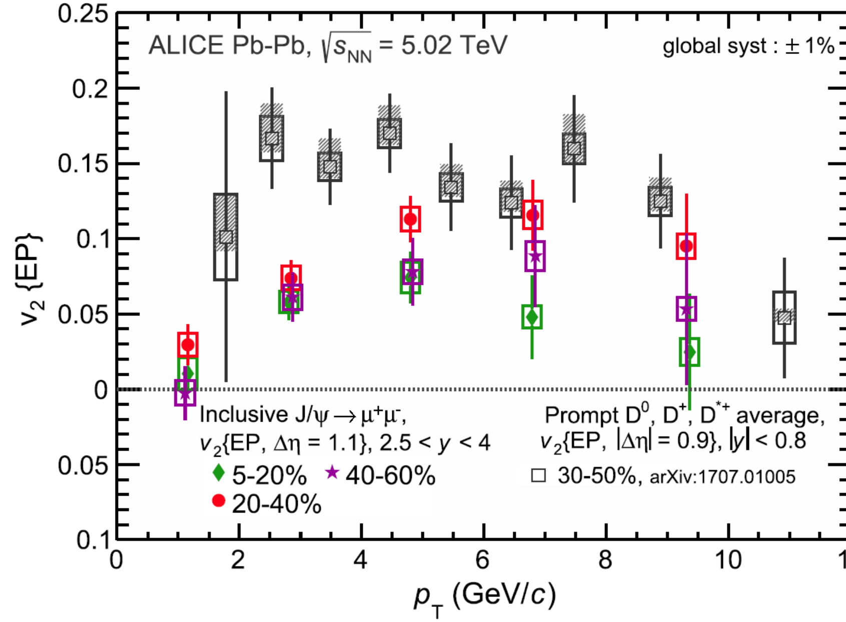


- Larger v2 in more periperial collisions
- v3 ≈ const.
- Mass ordering

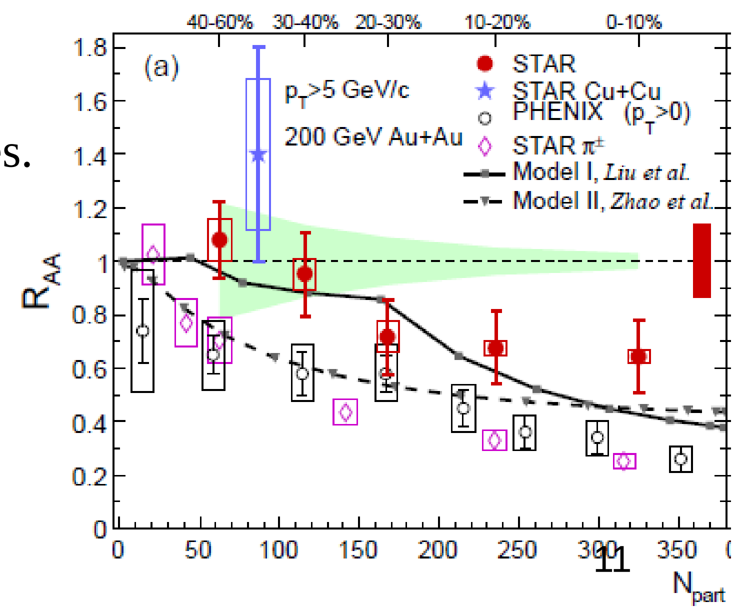
PRL120,202301(2018)

Quarkonia suppression and enhancement



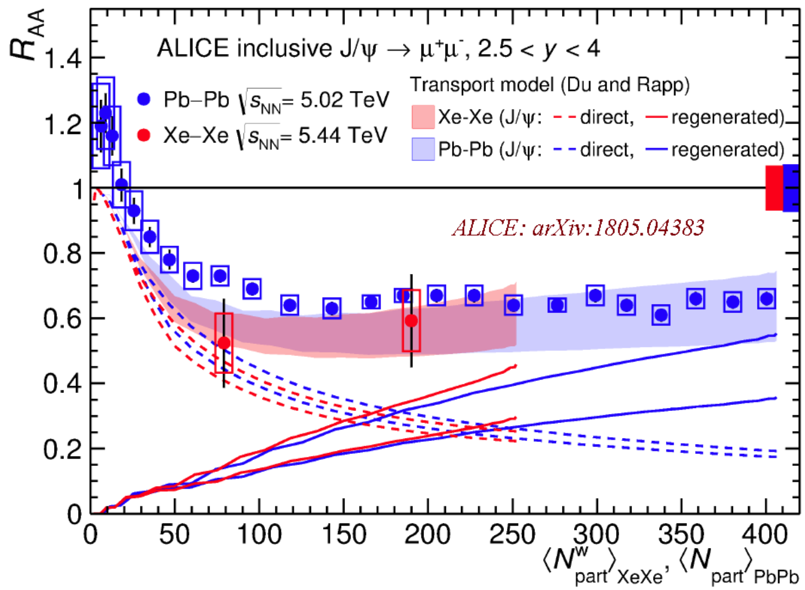


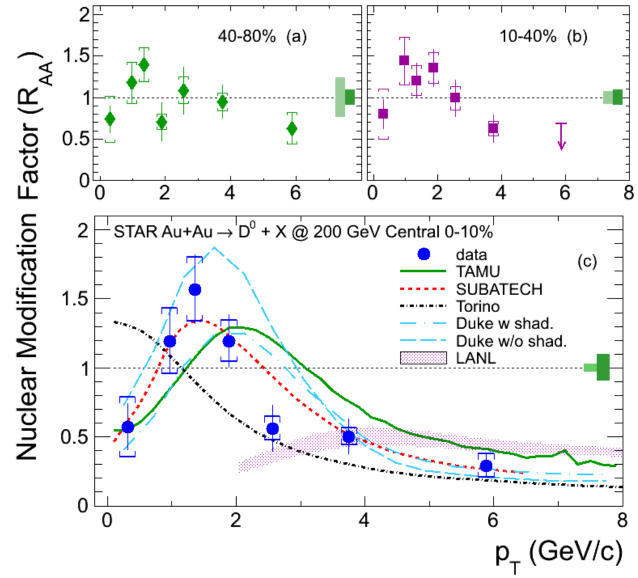
- High $p_{T:}$ more suppression in more central collisions
  - Binding energy ordering
- Less suppression at lower p_T & higher collision energies.
  - Large v2→Regeneration?
- Different dependence of R_{AA} on p_T at RHIC
  - High p_T less suppressed than low p_T
    - Cronin effect?
    - Longer formation time?
    - Less regeneration than at LHC?
    - Larger shadowing at LHC?

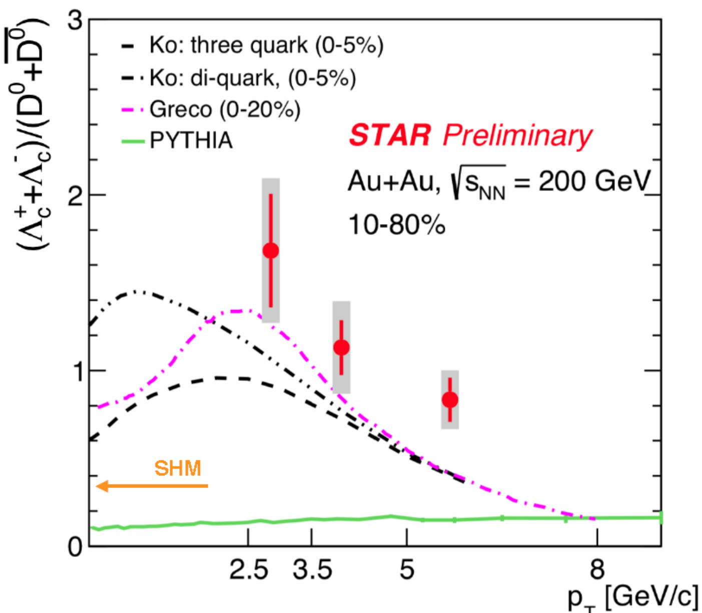


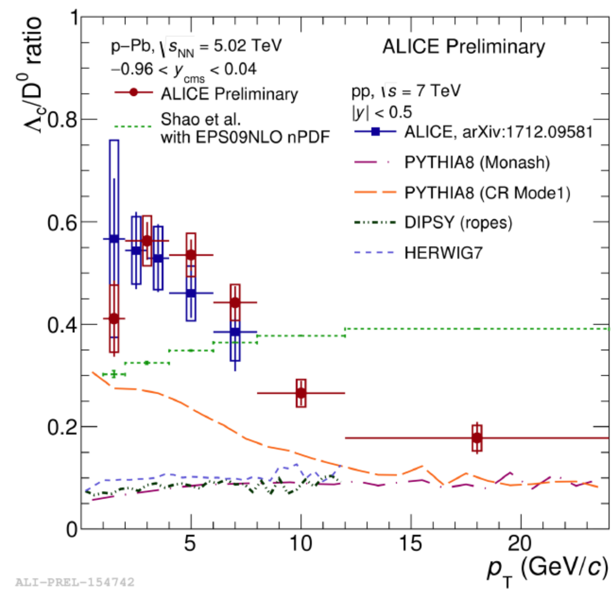
arXiv:1712.08959; arXiv:1805.04383; PLB 734 (2014) 314; PRC 84(2011)054912; PLB 722(2013)55-62; PRL119,242301(2017)

Hadronization from coalescence is essential









arXiv:1805.04383; PRL113, 142301(2014); arXiv:1712.09581; STAR@QM18

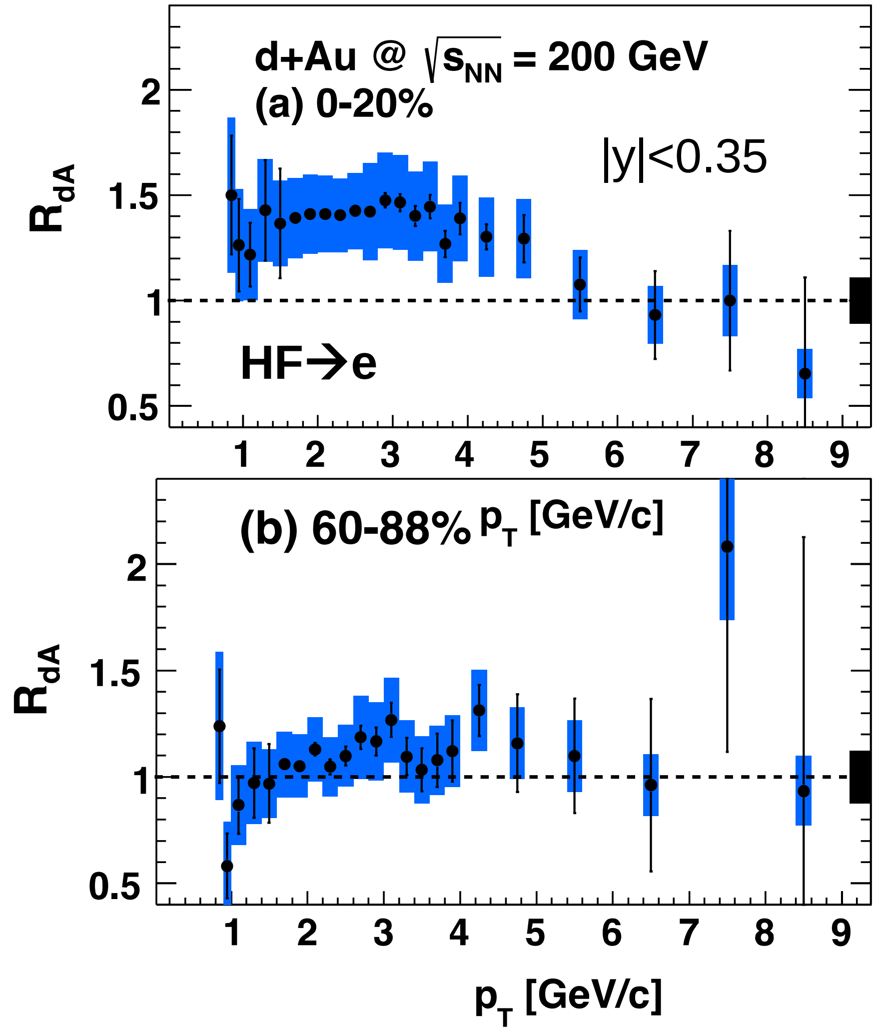
Mechanisms in large system is far from being settled

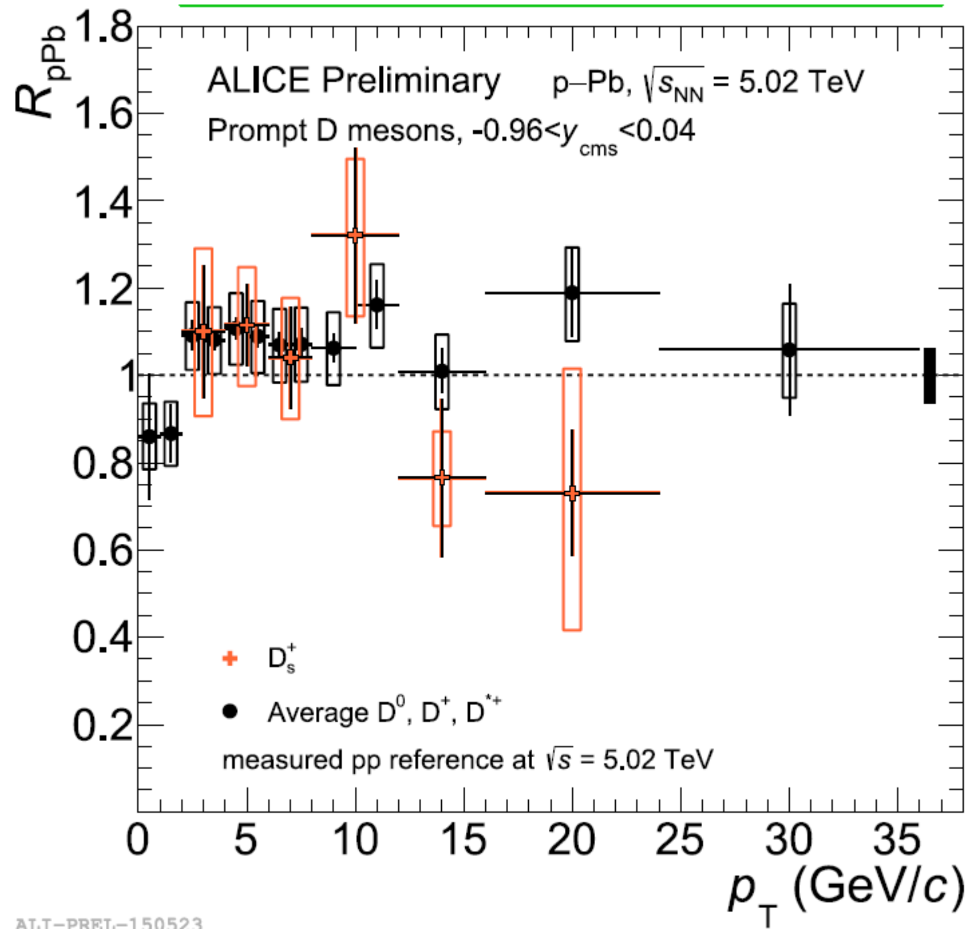
Models & Effective Theories

	elastic	Elastic + radiative	radiative	Other
Transport coeff based (LV,...)	TAMU POWLANG HTL Catania LV	Duke	ASW	ADS/CFT POWLANG lQCD *DABMOD (poster R. Katz)* *S. Li et al, arXiv:1803.01508*
Cross section (or $\|M\|^2$) based (Boltzmann,...)	AMPT MC@sHQ el URQMD PHSD Catania BM	Djordjevic et al MC@sHQ el + rad BAMPS CUJET3 Abir and Mustafa LBL-CCNU VNI/BMS *LIDO (DUKE; poster W. Ke)*	$SCET_{G,M}$	

Red: Transport models

Open HF: suppression & enhancement in small system

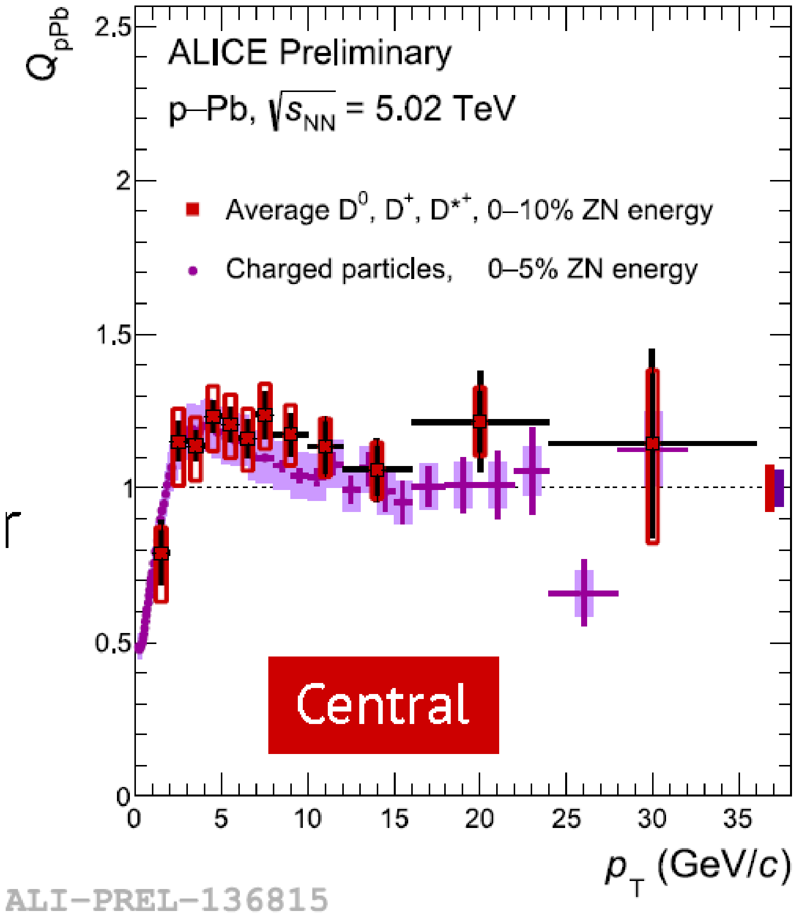


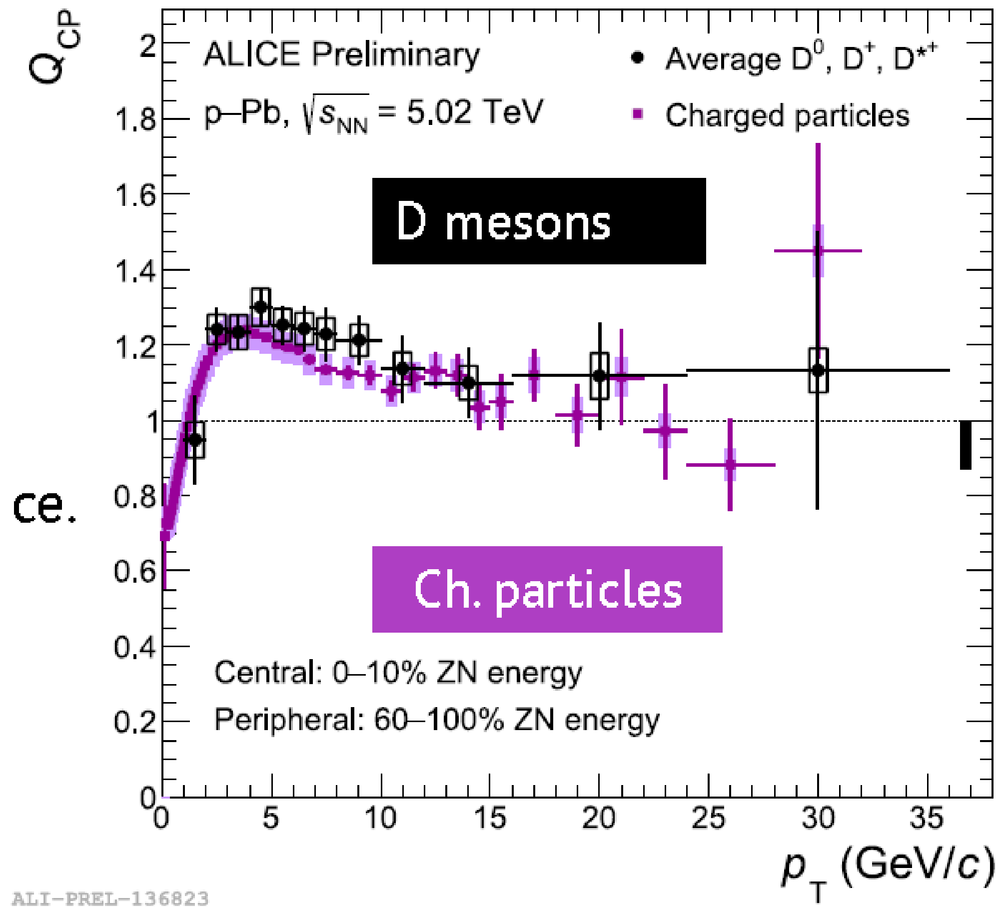


- ❑ Au-Au@200GeV (|y|<0.35)
  - $R_{dA} \approx 1.0$ in 60-88%
  - Large enhancement in 0-20%
- ❑ Pb-Pb@5.02TeV
  - R_{pPb} ~ 1.0 for min-bias

PHENIX: PRL109, 242301 (2012);
ALICE-PUBLIC-2017-008;

Open HF: suppression & enhancement in small system



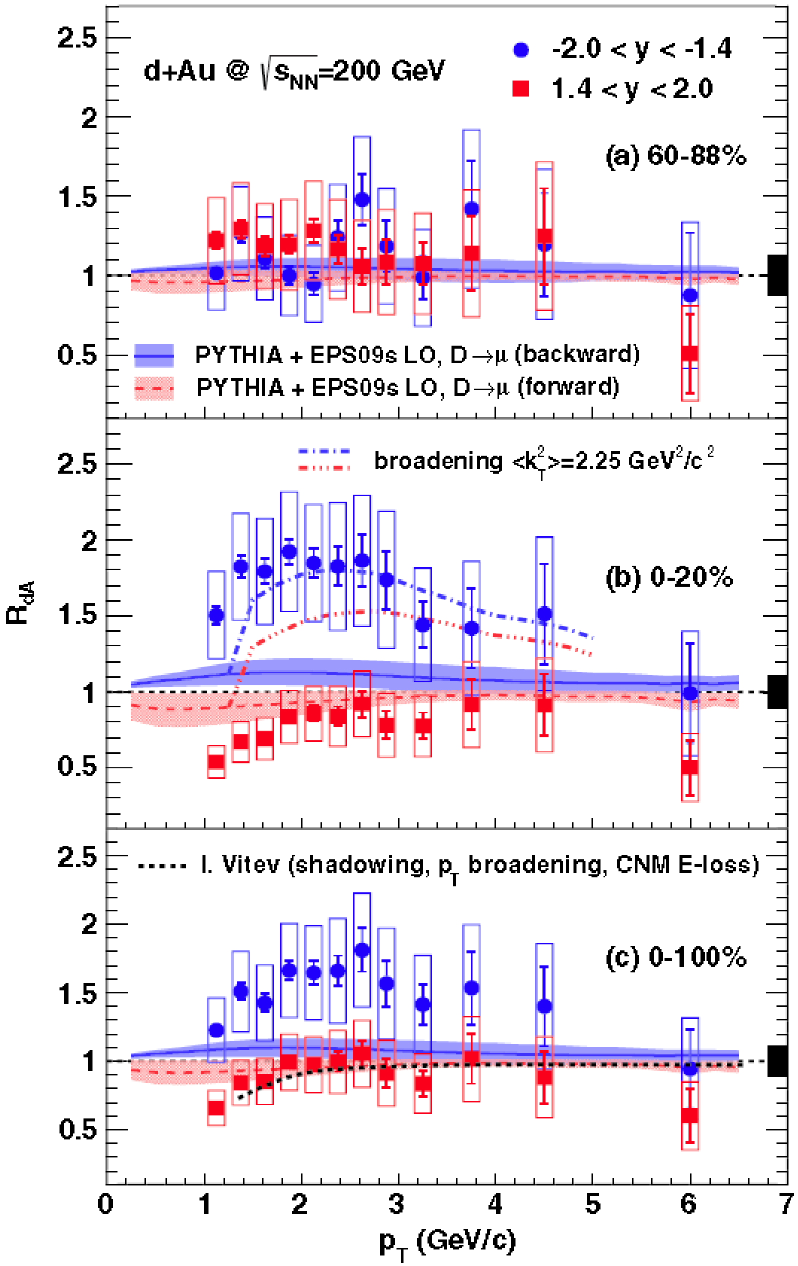


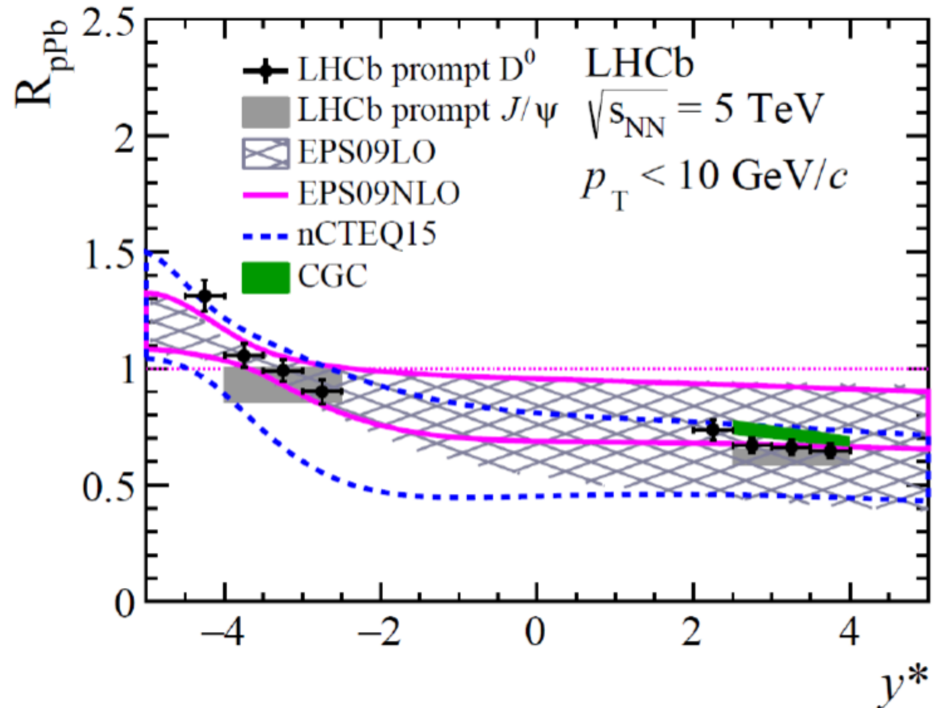
- ❑ Q_{pPb} ~ 1.0 for 60-100%
- ❑ Q_{pPb} > 1.0 in 3-10 GeV/c for 0-10%
- ❑ Qcp significantly above 1.0
- ❑ Similar trend as charged particle

- ❑ Due to CNM or remaining bias?
- ❑ May have large implication for theory

ALI-PREL-136815; PRC91,064905(2015)

Open HF: suppression & enhancement in small system

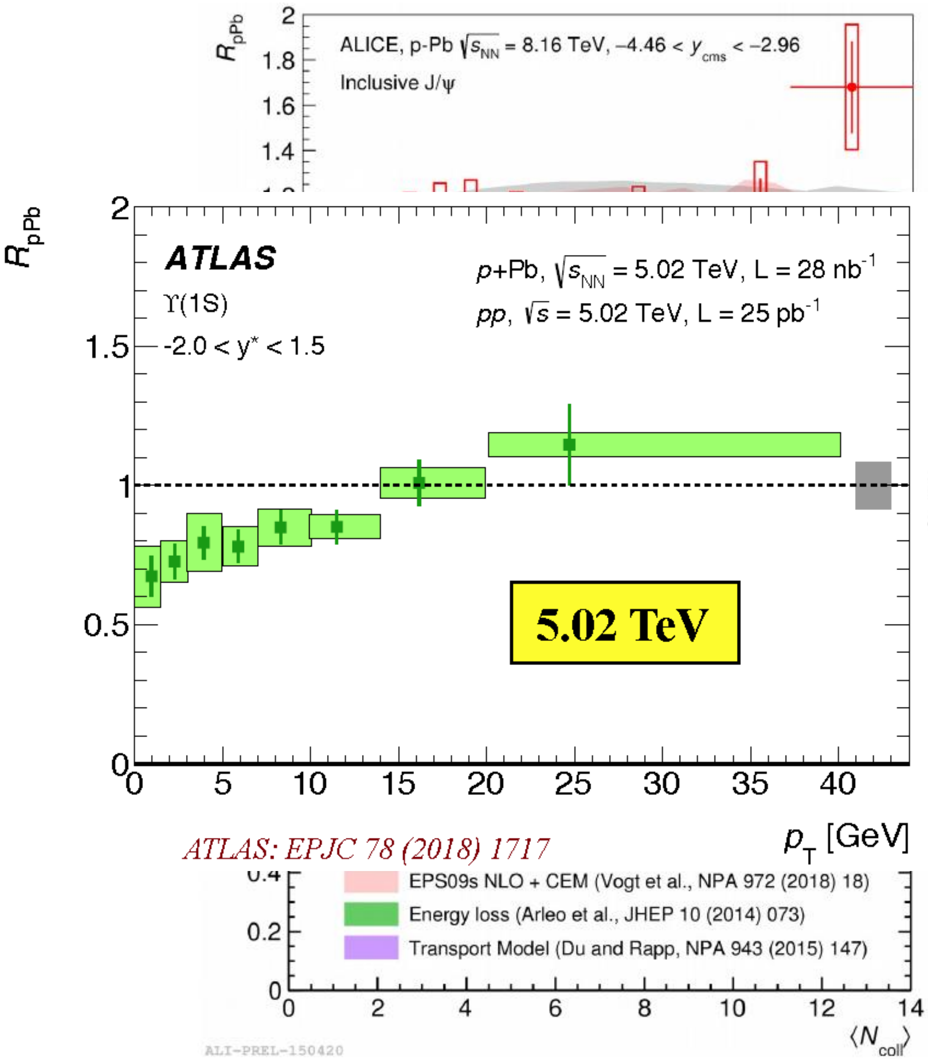


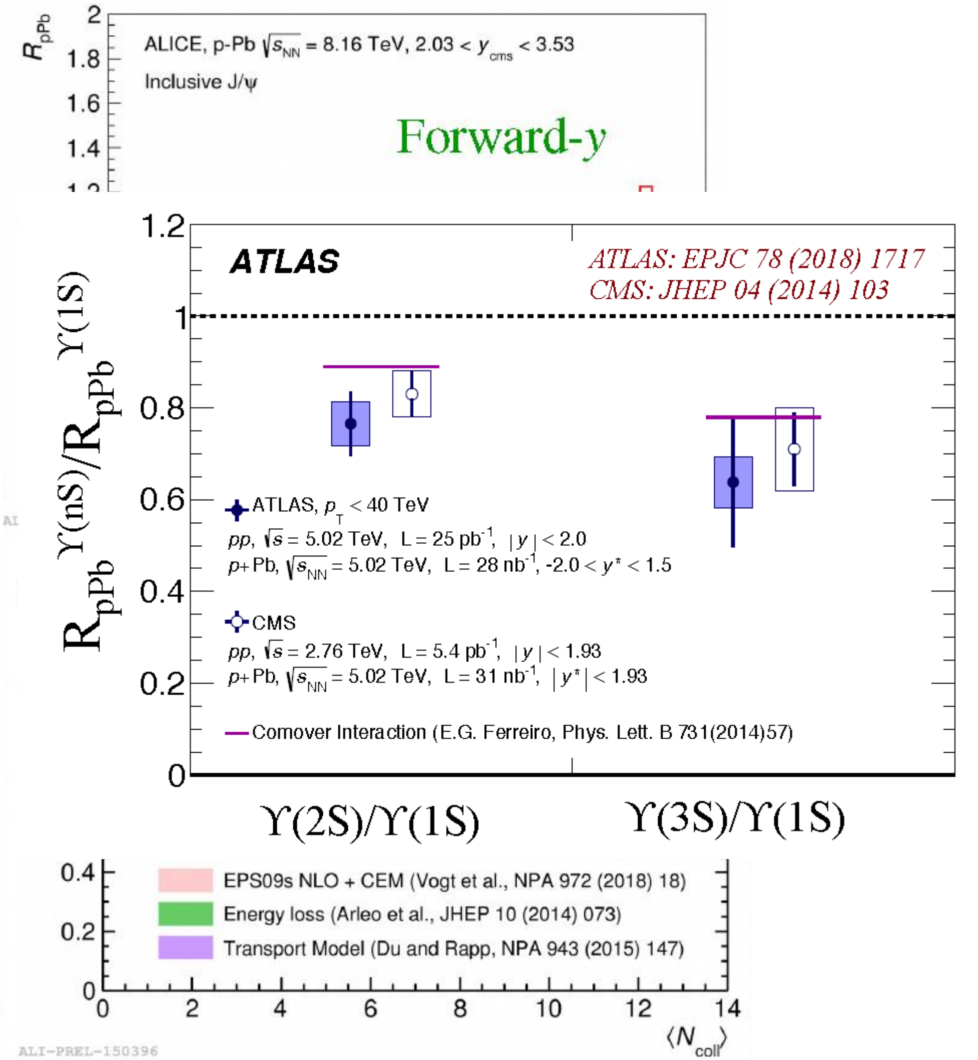


- Au-Au@200GeV in 0-20%
  - enhancement: -2.0<y<-1.4 (Au-going)
  - Suppression: 1.4 < y< 2.0 (d-going)
- Pb-Pb@ 5TeV
  - No as large enhancement
  - Data more precise then theory.

PHENIX: PRL 112, 252301(2014);
LHCb: JHEP 10, 090(2017)

Quarkonia: suppression&enhancement in small system



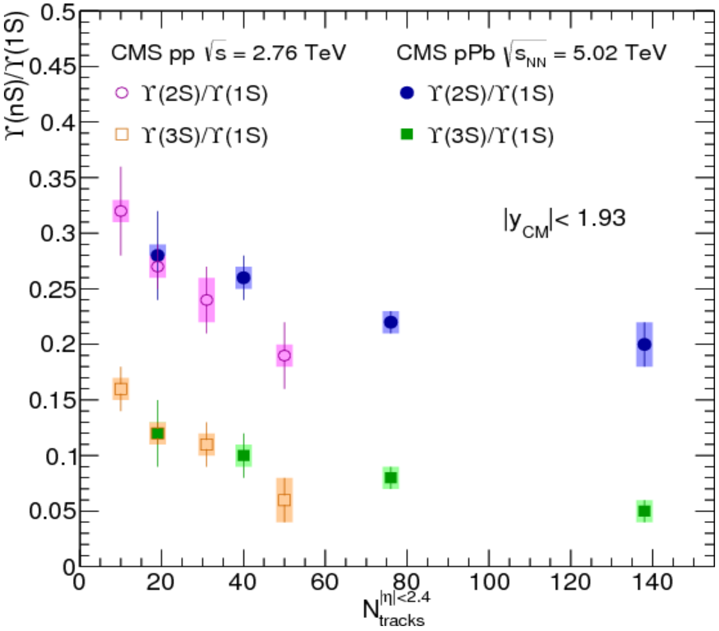


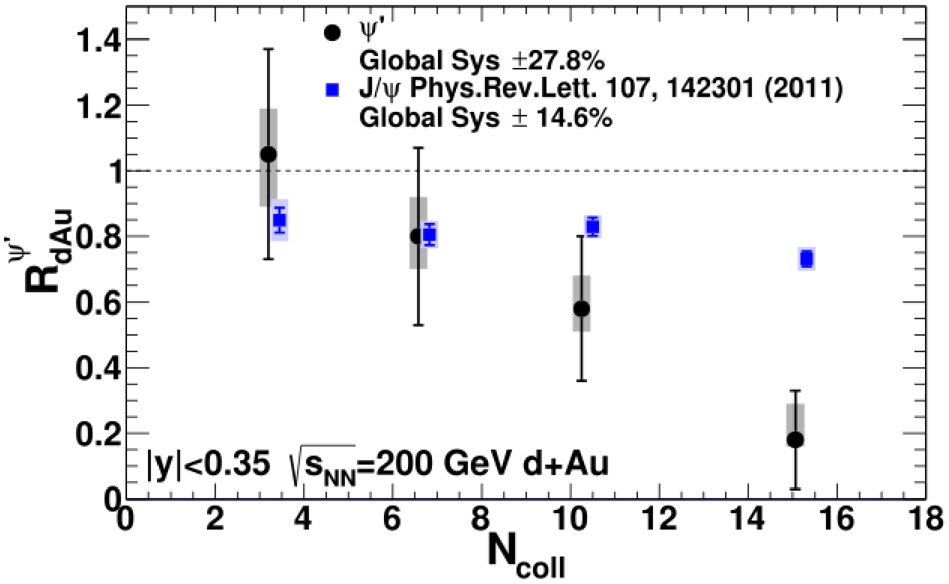
- ❑ Data ≈ model in R_{pPb} for min-bias
- ❑ Data ≠ model on Q_{pPb} vs. N_{coll}.

- ❑ Υ(1S) suppressed at low pT
- ❑ Υ(2S + 3S) more suppressed

ALICE: arXiv:1805.04381; ALI-PREL-150420

Final state effects indicated in pPb collisions

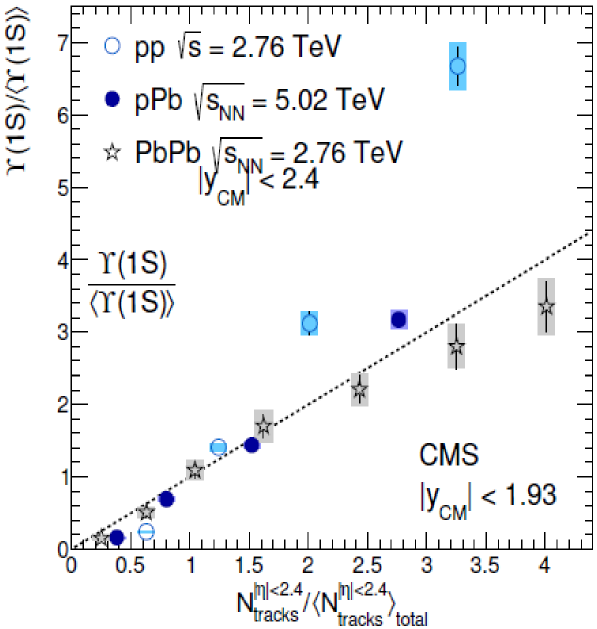


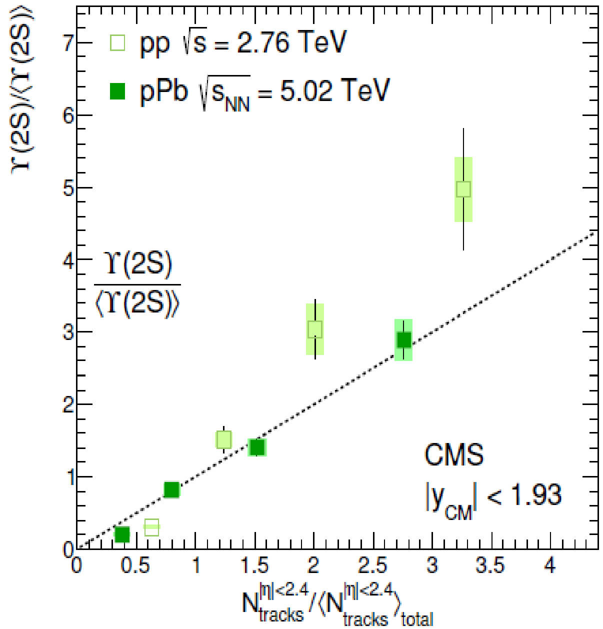


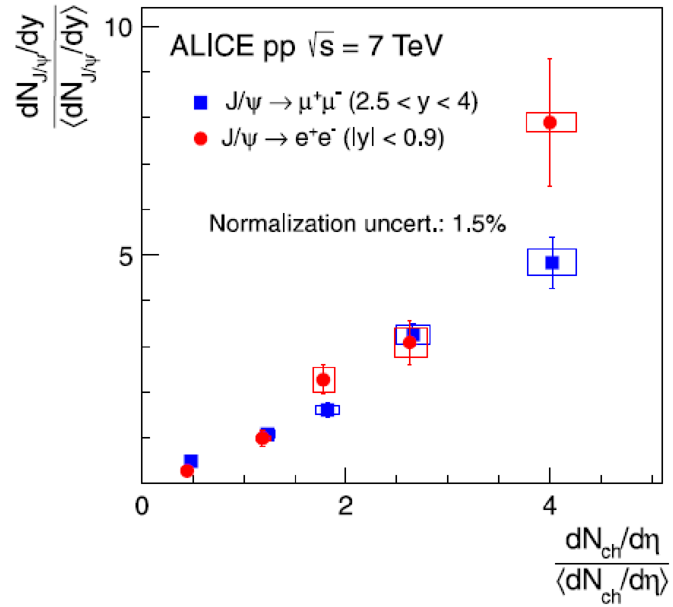
- ❑ $\Upsilon(ns)/\Upsilon(1s)$ decrease with increasing multiplicity in pPb collisions.
- ❑ Ψ(2s)/J/ψ decrease with Ncoll in dAu collisions
- ❑ More suppression of excited state with weaker binding energy indicate a final state effects in pA collisions.

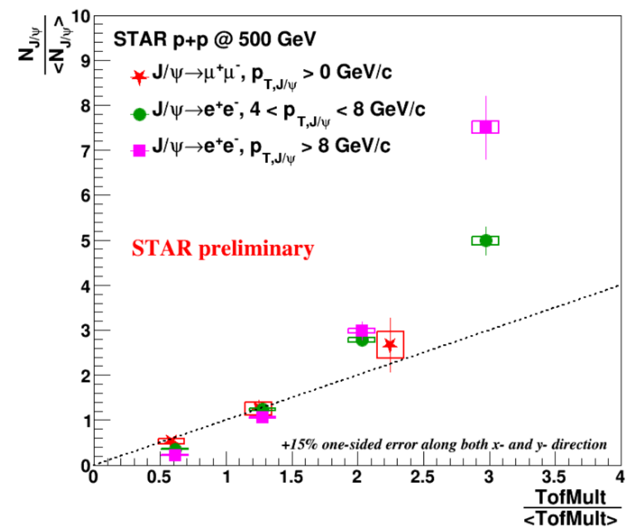
JHEP 04 (2014)103; PRL 107 (2011) 142301

Enhancement in high multiplicity p+p collisions





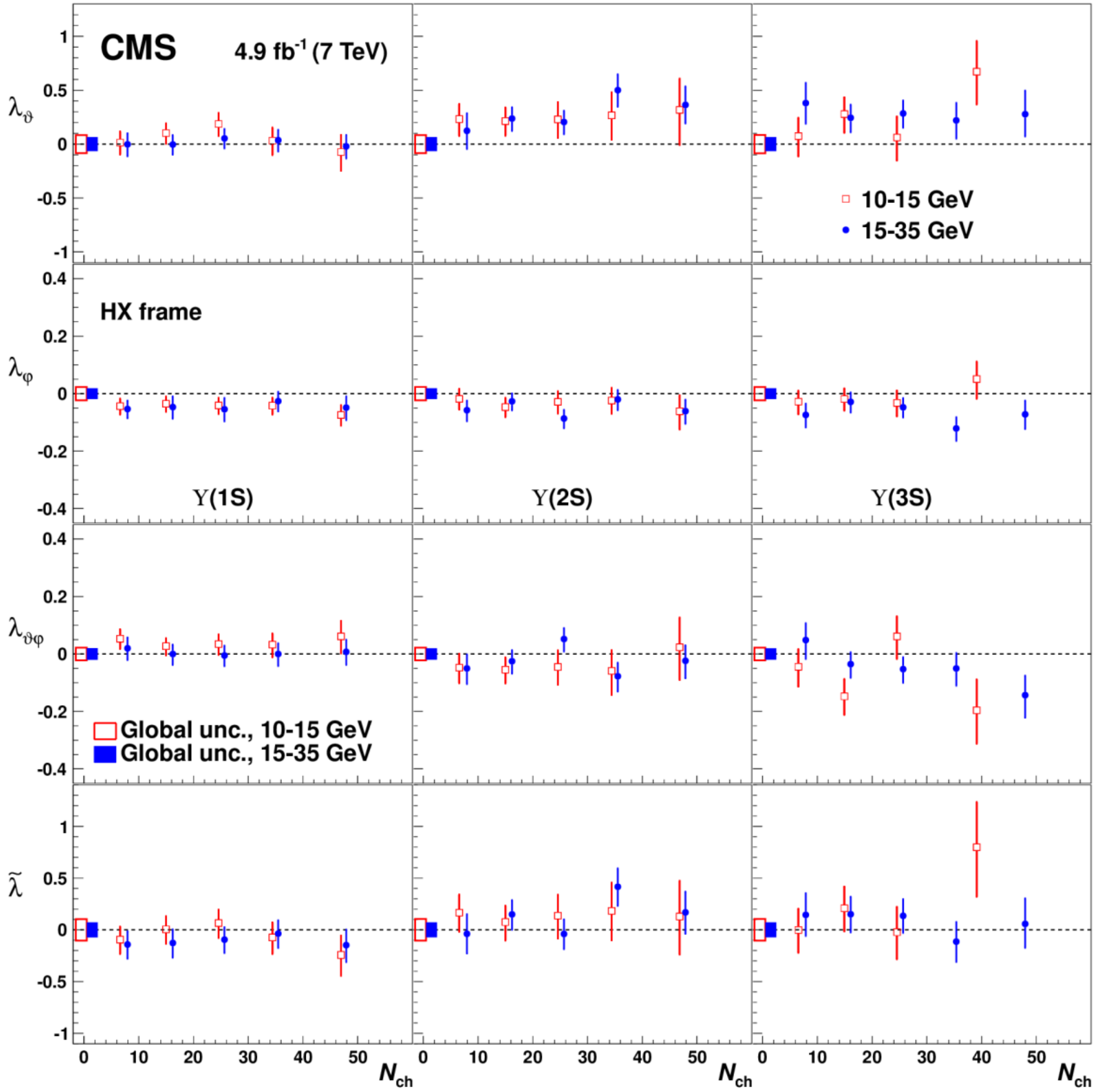




- ❑ Different trend in pp and HI collisions
  - Similar linear trend in pPb and PbPb
  - Faster rise in pp
- ❑ Similar trend in pp for J/ψ, D is also observed
  - at mid-rapidity and at RHIC
- ❑ Multi-parton interaction, CGC in pp collisions?
- ❑ How it affect heavy-ion collisions?

JHEP 04 (2014)103; PBL 712 (2012) 66; arXiv:1509.06440

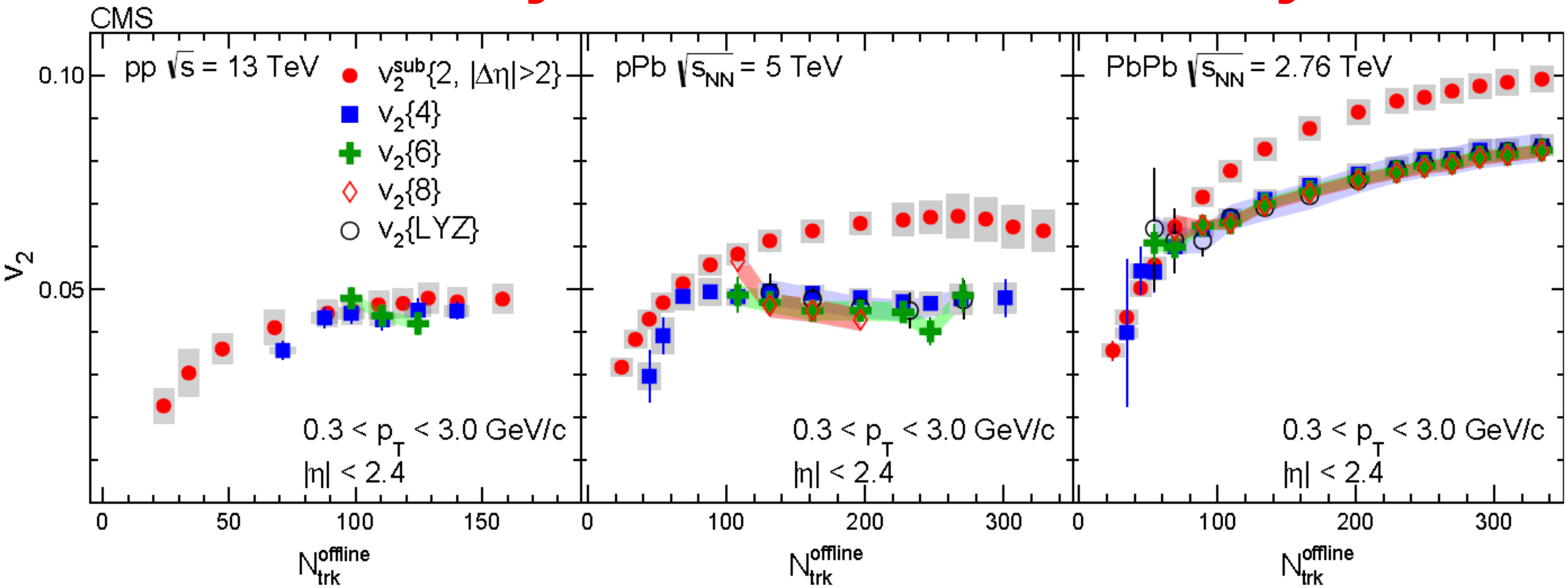
Upsilon polarization dependence on N_{ch}

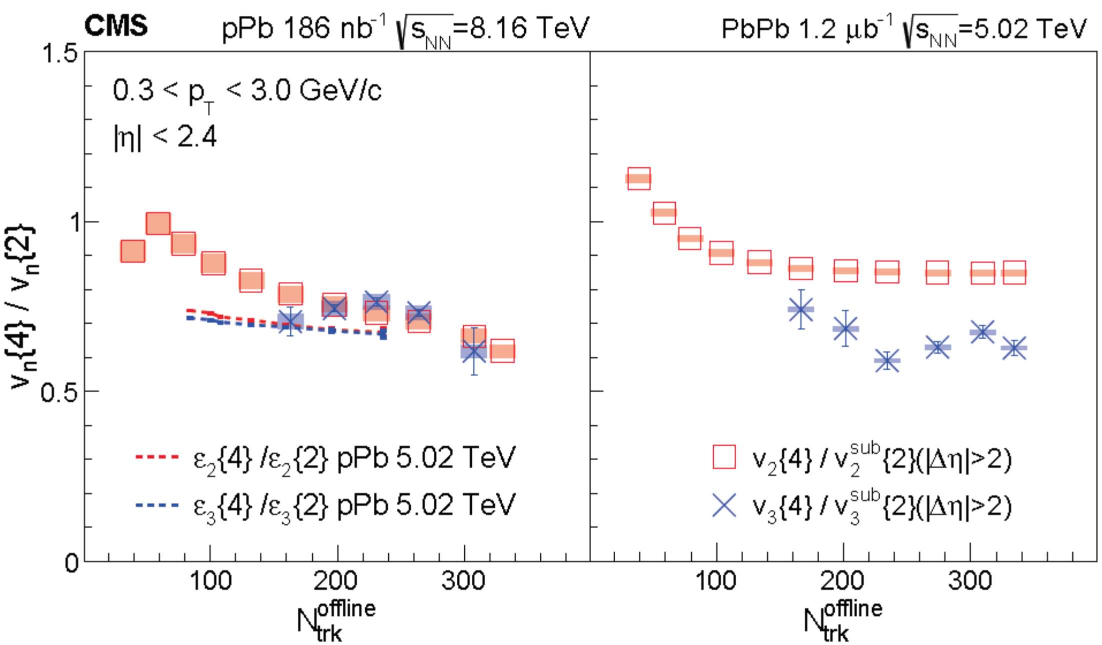


- Is the dependence on multiplicity due to a change of production mechanism.
- First step to probe if polarization depends on the hadronic environment created by collisions.
- Close to zero and no significant dependence on N_{ch} within uncertainties
- Indicating no strong changes of upsilon production mechanism between low and high multiplicity pp collisions

PLB761,31(2016)

Collectivity observed in small systems

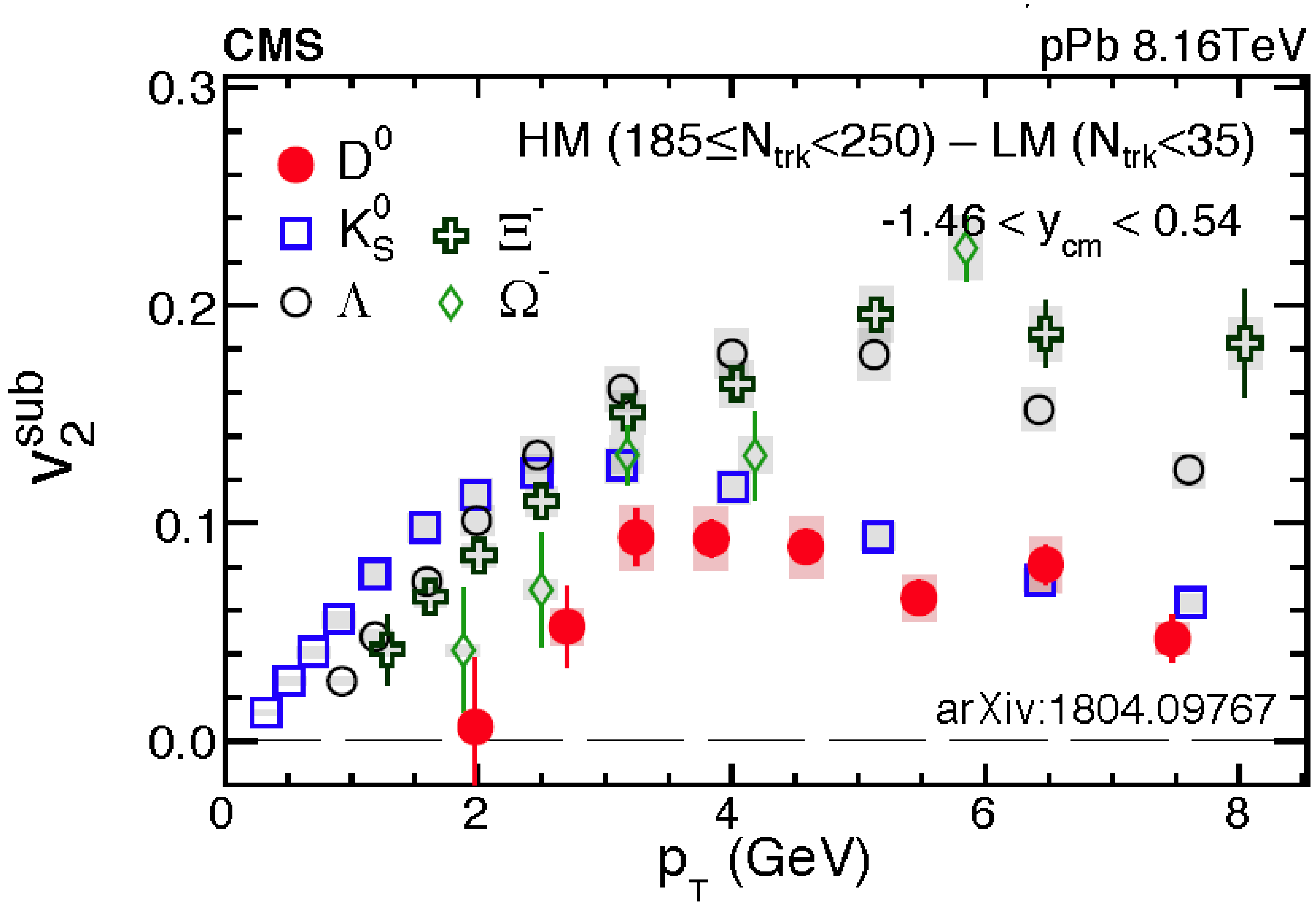




- pPb: $v_2\{4\}/v_2\{2\} \approx v_3\{4\}/v_3\{2\}$
- $v_3\{4\}/v_3\{2\}$(pPb) $\approx v_3\{4\}/v_3\{2\}$(PbPb)
  - Fluctuations-driven origin
- PbPb: $v_2\{4\}/v_2\{2\} > v_3\{4\}/v_3\{2\}$
  - Collision geometry + fluctuation

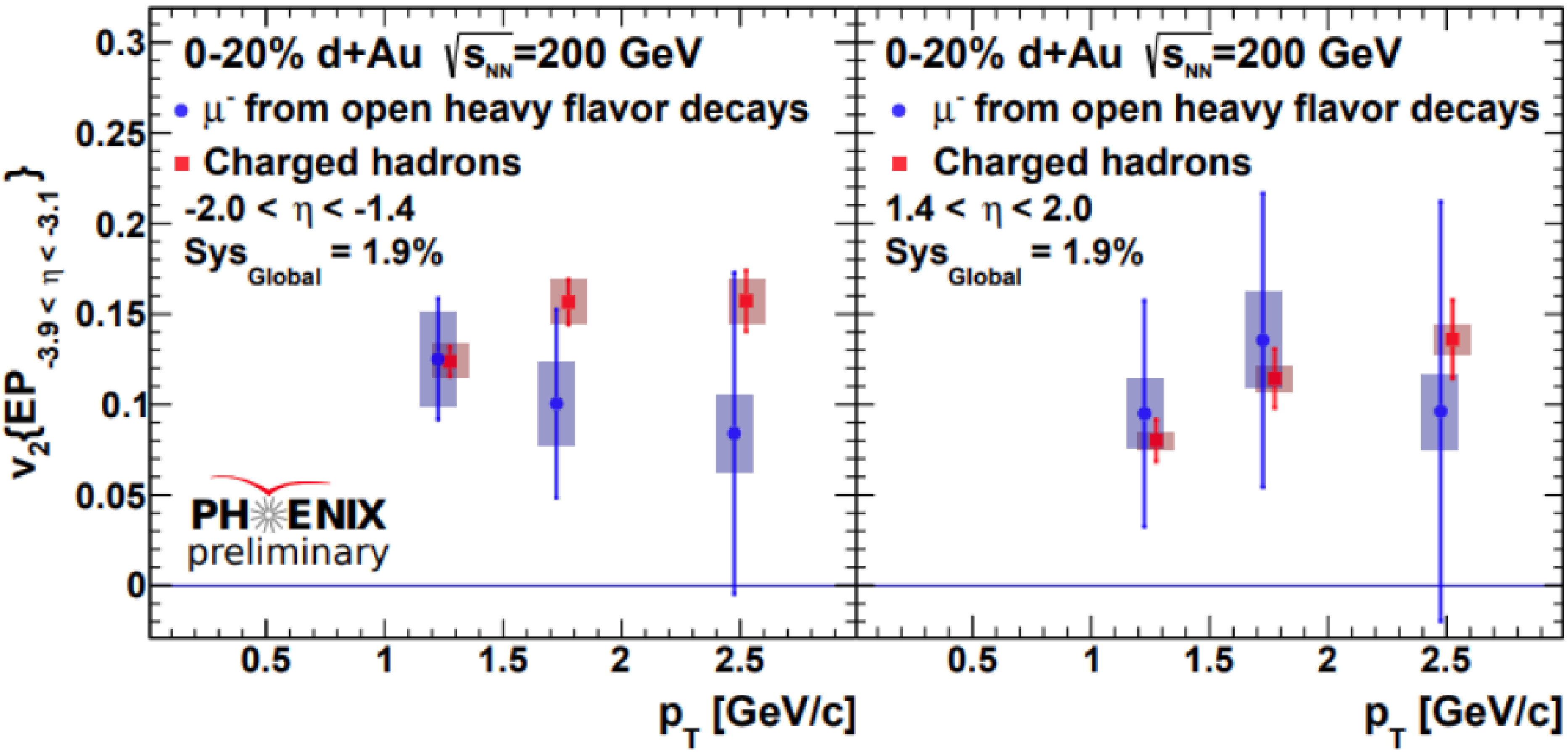
PLB765,93(2017); CMS-PAS-HIN-17-004

Significant D^0 v_2 in p-Pb at 8.16 TeV



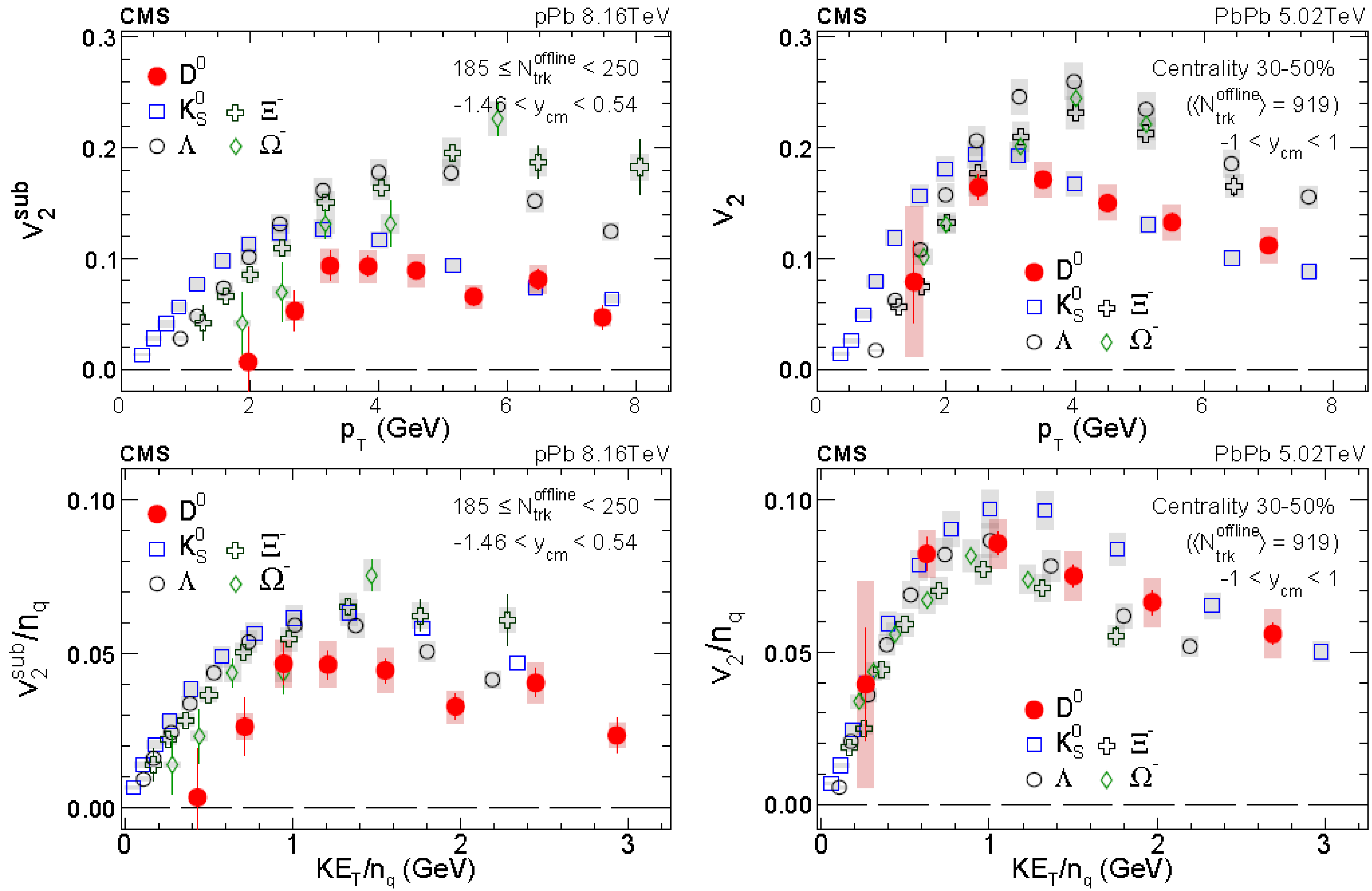
arXiv:1804.09767

Significant HF→e/μ v_2 in d-Au at 200 GeV



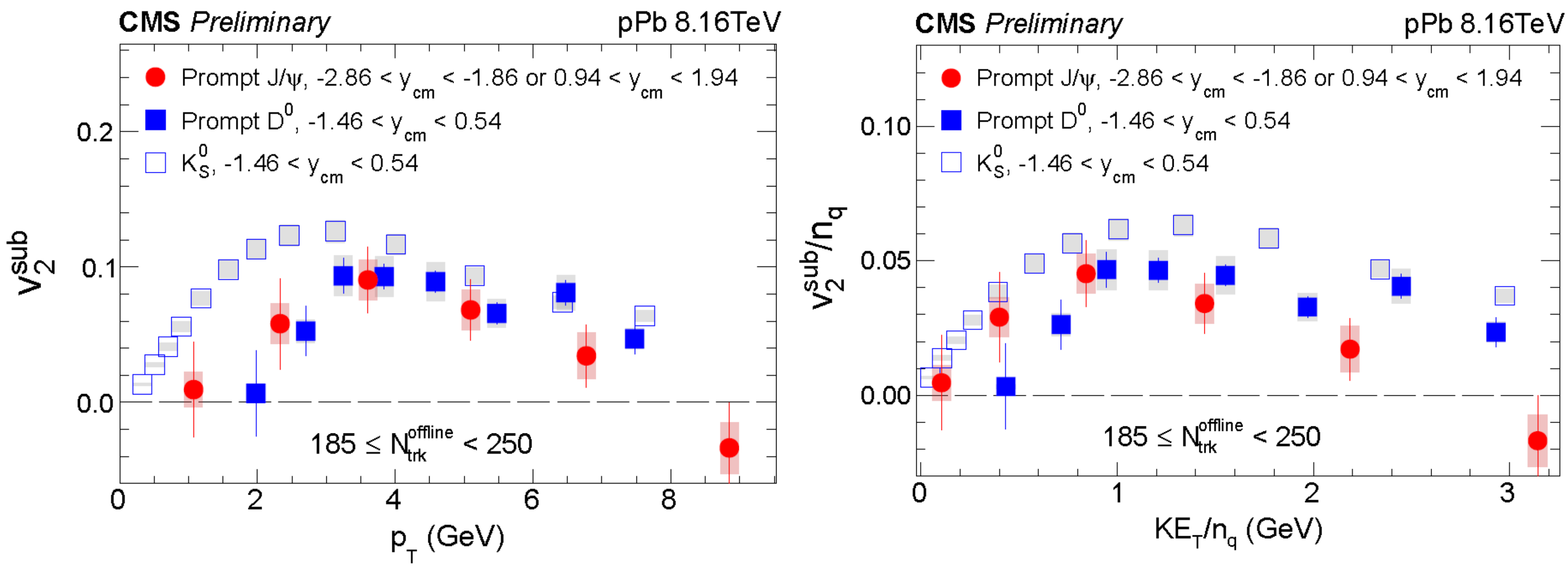
Significant HF→e/μ v_2 observed

NCQ scaling of D^0 v_2



arXiv:1804.09767

Significant J/ψ v_2 in p-Pb at 8.16 TeV



- ❑ $v_2(J/\psi) \approx v_2(D^0) < v_2(K_s^0)$
- ❑ Coalescence require consistent with similar velocity.
  - J/ψ: scaling $p_T(J/\psi)/2$
  - For D^0:
    - ○ $V_2[D^0@p_T(D^0)] \sim v_2[c@p_T(c)] + v_2[u@p_T(u)]$
      - ✓ $p_T(c) \sim p_T(D^0) \cdot m_c/(m_c + m_u) \sim p_T(D^0)/1.3$
      - ✓ $p_T(u) \sim p_T(D^0) \cdot m_u/(m_c + m_u) \sim p_T(D^0)/5.2$

CMS-HIN-18-010; Z.W Ling, D. Monlar, PRC68, 044901 (2003)

Summary & comments

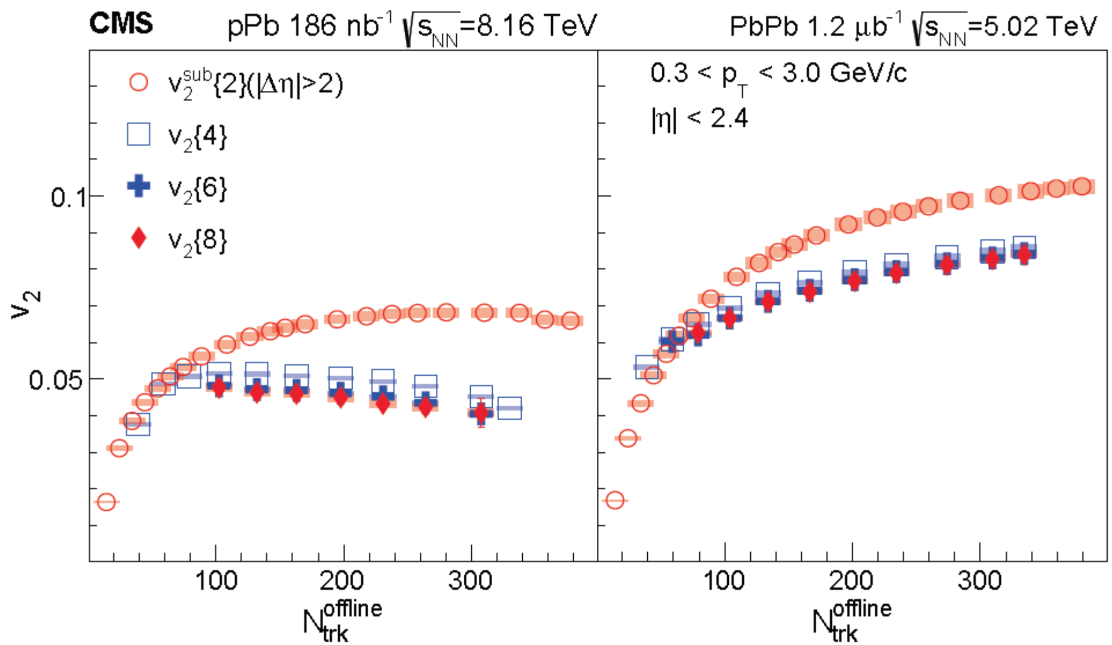
- ❑ large v_2 of D^0 and J/ψ observed in pPb collisions
  - Cautions about the meaning of NCQ scaling

- ❑ Keep in mind many significant "CNM" effects in the small systems with high multiplicities or in more central events
  - $R_{pA} \neq 1.0$
  - Production rate vs. event activity

- ❑ If a model can describe v_2 well, can it also describe all the observed CNM effects, e.g. R_{pA}
  - Are these effects closely connected?

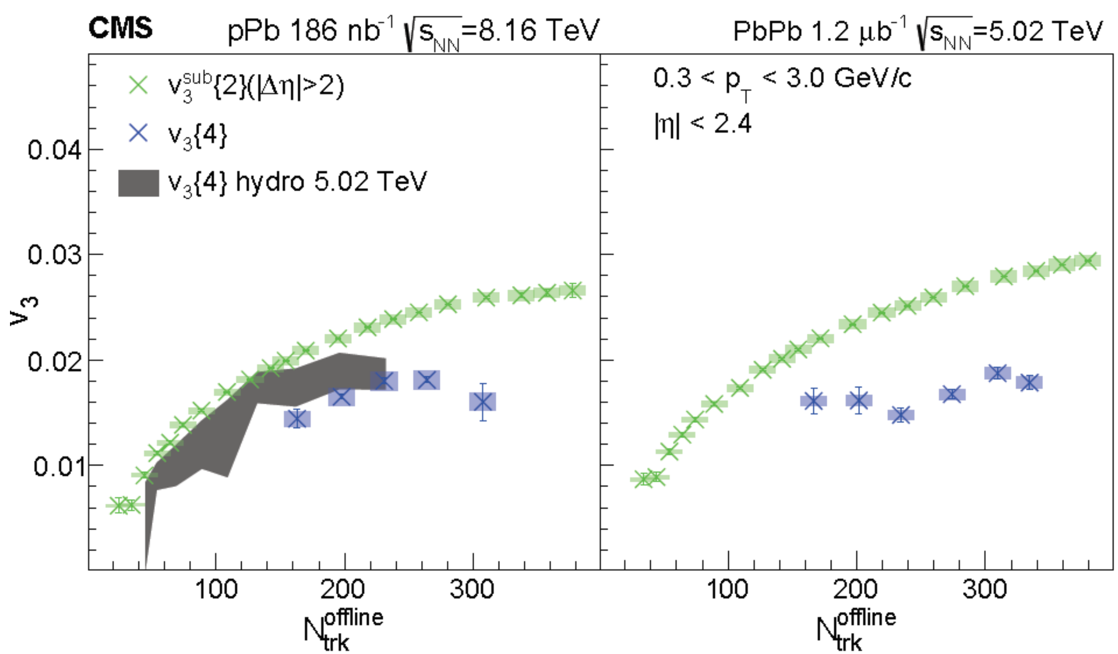
- ❑ More differential measurements **may be** needed to gain further insight

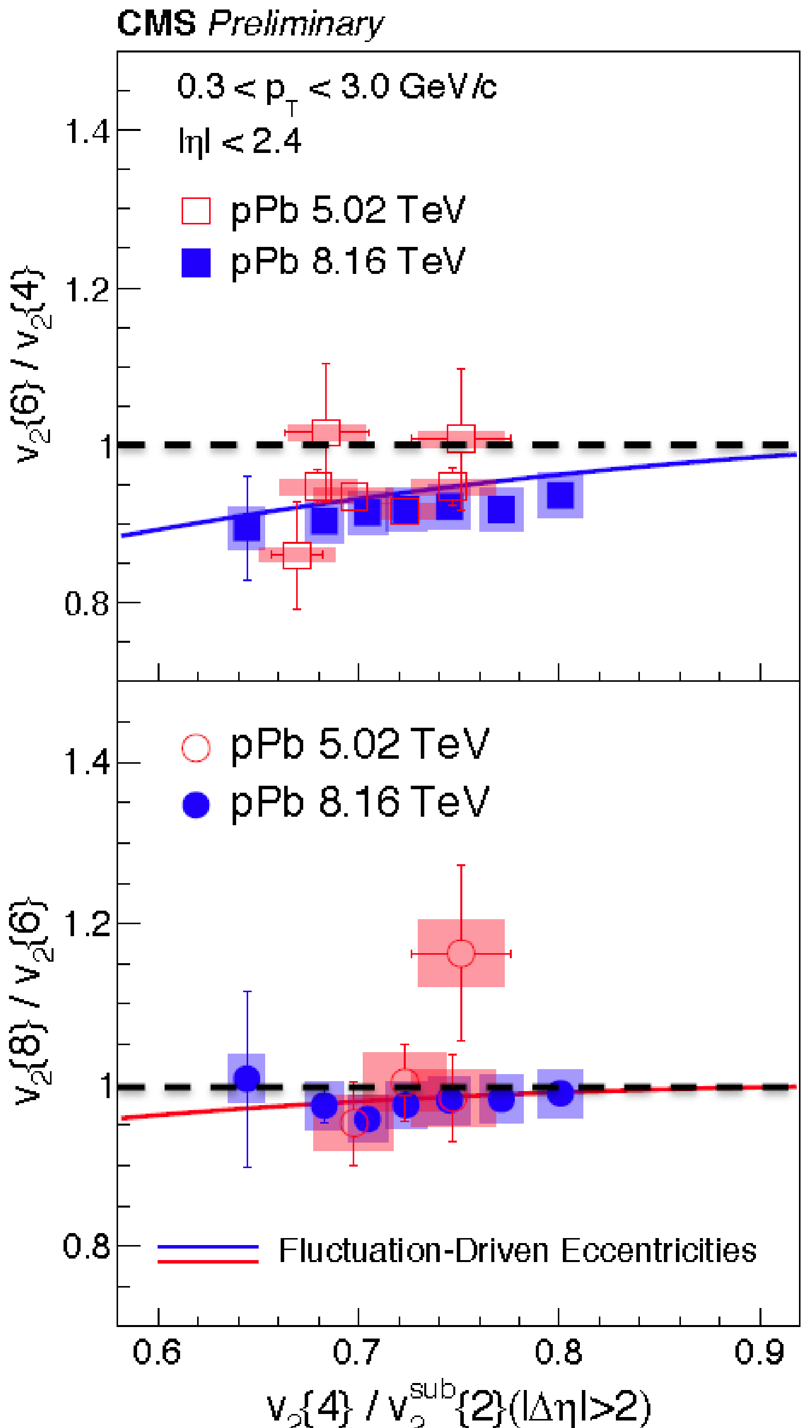
Backup



v2{2} > v2{4} >v2{6} ≥ v2{8}

Non-Gaussian eccentricity fluctuation





Power law function:

$$P(\varepsilon) = 2\alpha\varepsilon(1-\varepsilon^2)^{\alpha-1},$$

When $\alpha \gg 1$, with $\sigma^2 = 1/\alpha$, it become the Bessel-Gaussian function:

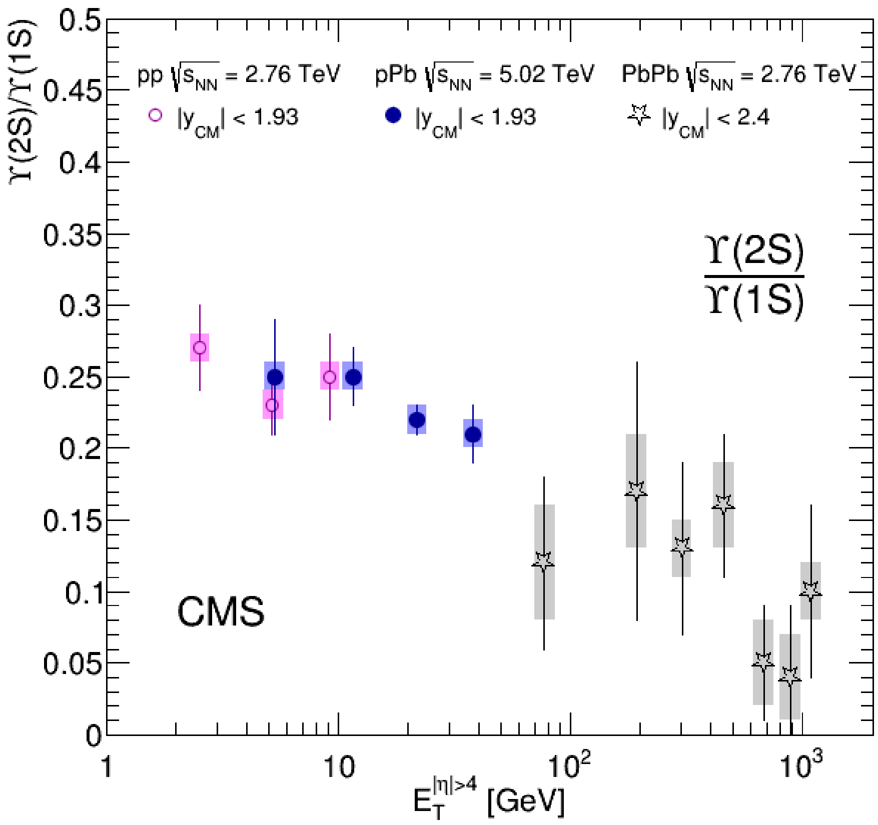
$$P(\varepsilon) = \frac{2\varepsilon}{\sigma^2} I_0\left(\frac{2\varepsilon\bar{\varepsilon}}{\sigma^2}\right) \exp\left(-\frac{\varepsilon^2+\bar{\varepsilon}^2}{\sigma^2}\right).$$

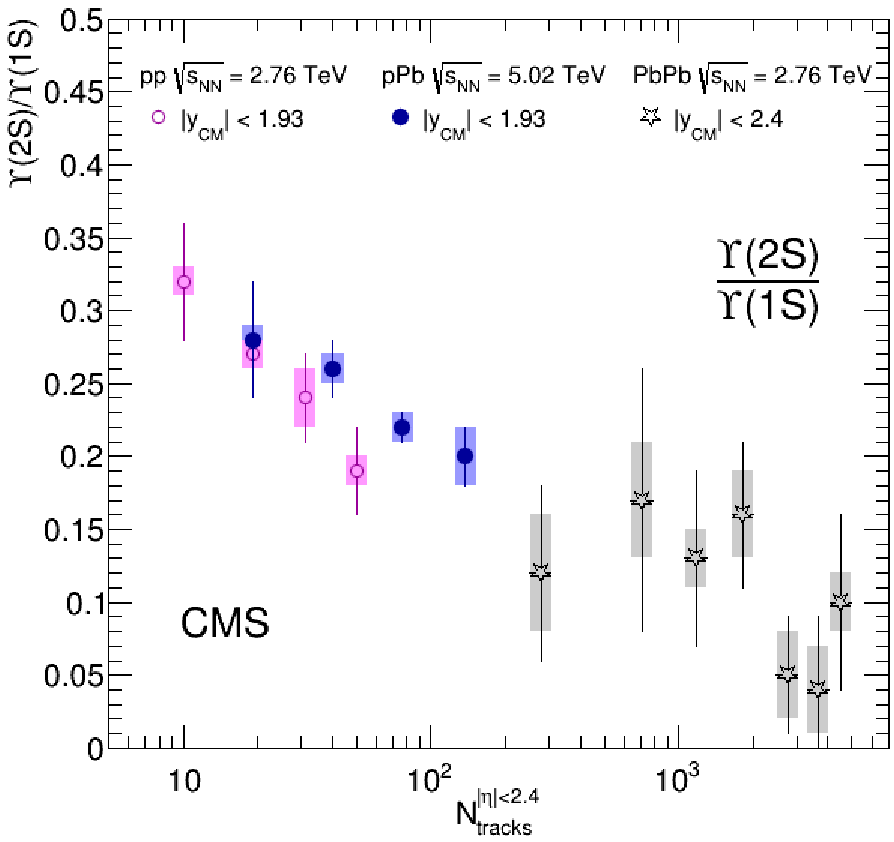
Fluctuation on top of Gaussian:

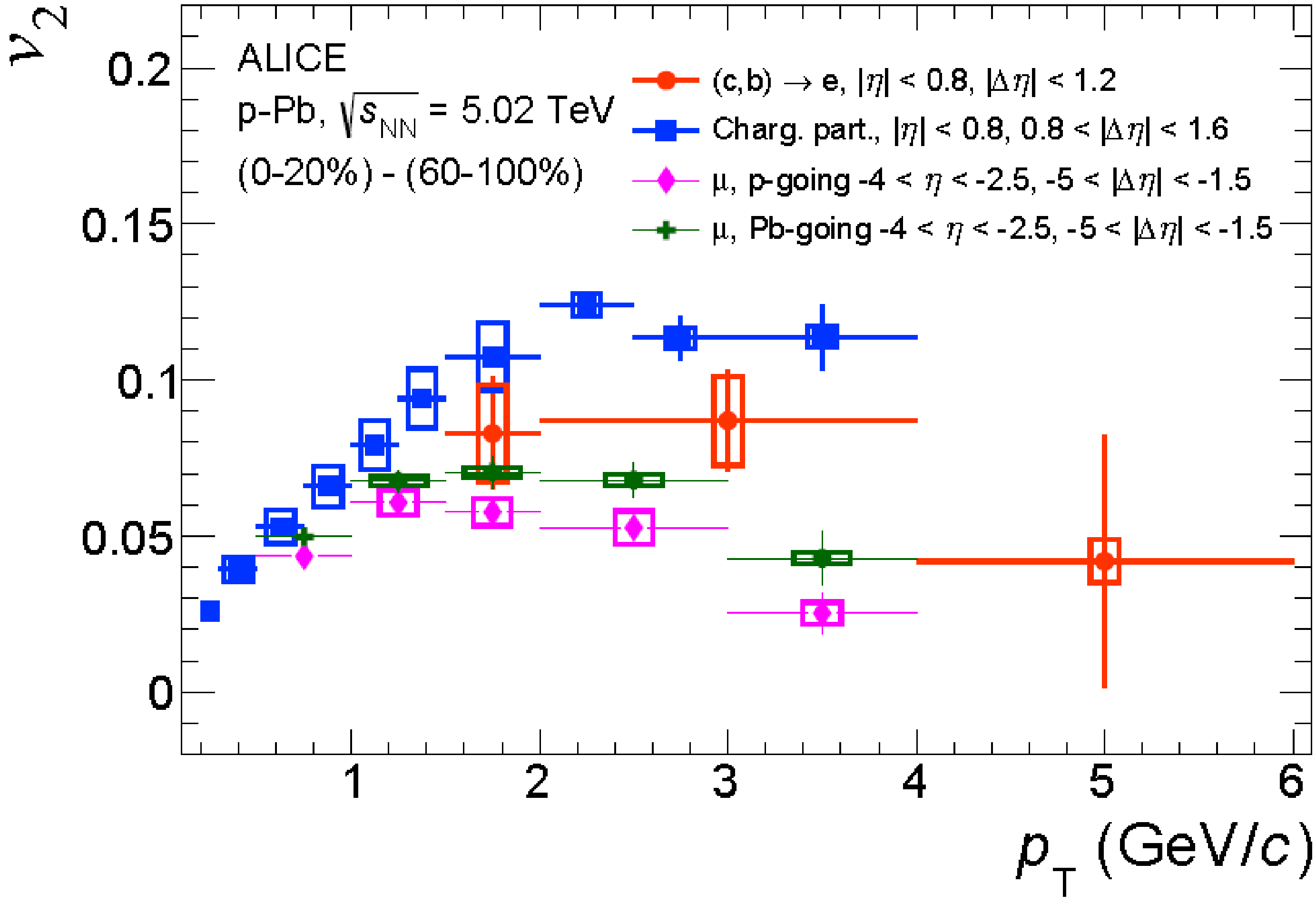
$$P(\varepsilon) = \frac{2\varepsilon}{\sigma^2} \exp\left(-\frac{\varepsilon^2}{\sigma^2}\right),$$

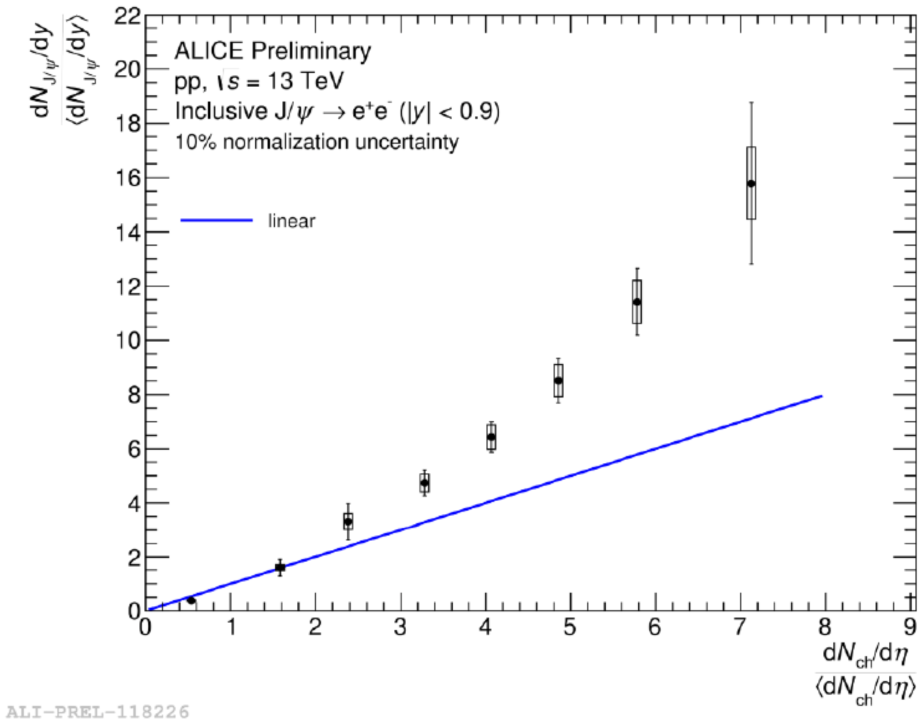
PRL 112, 082301 (2014)

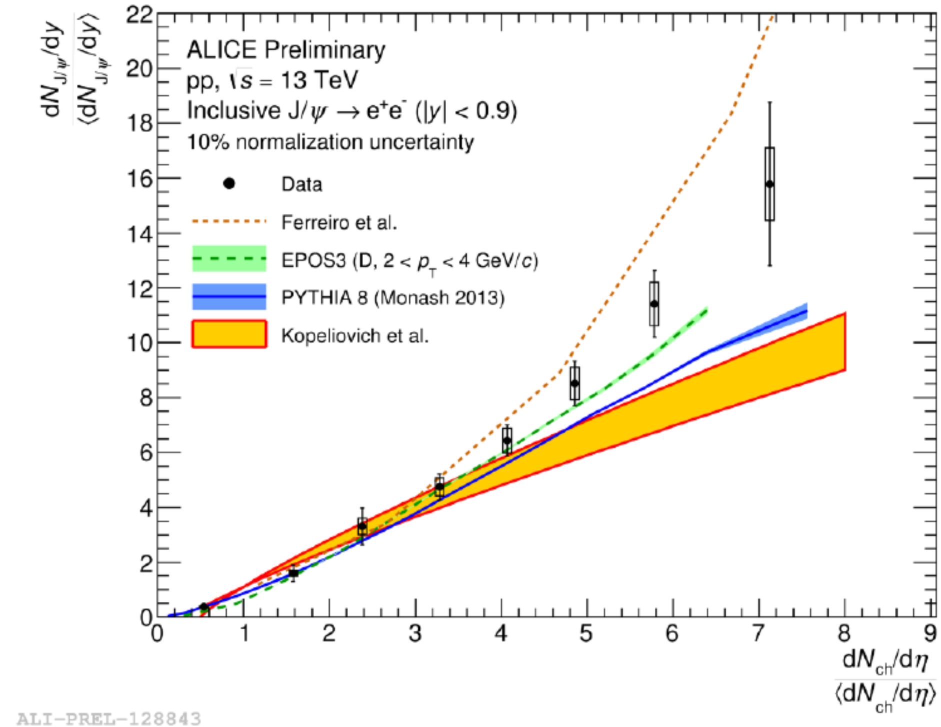
Upsilon vs. event activities

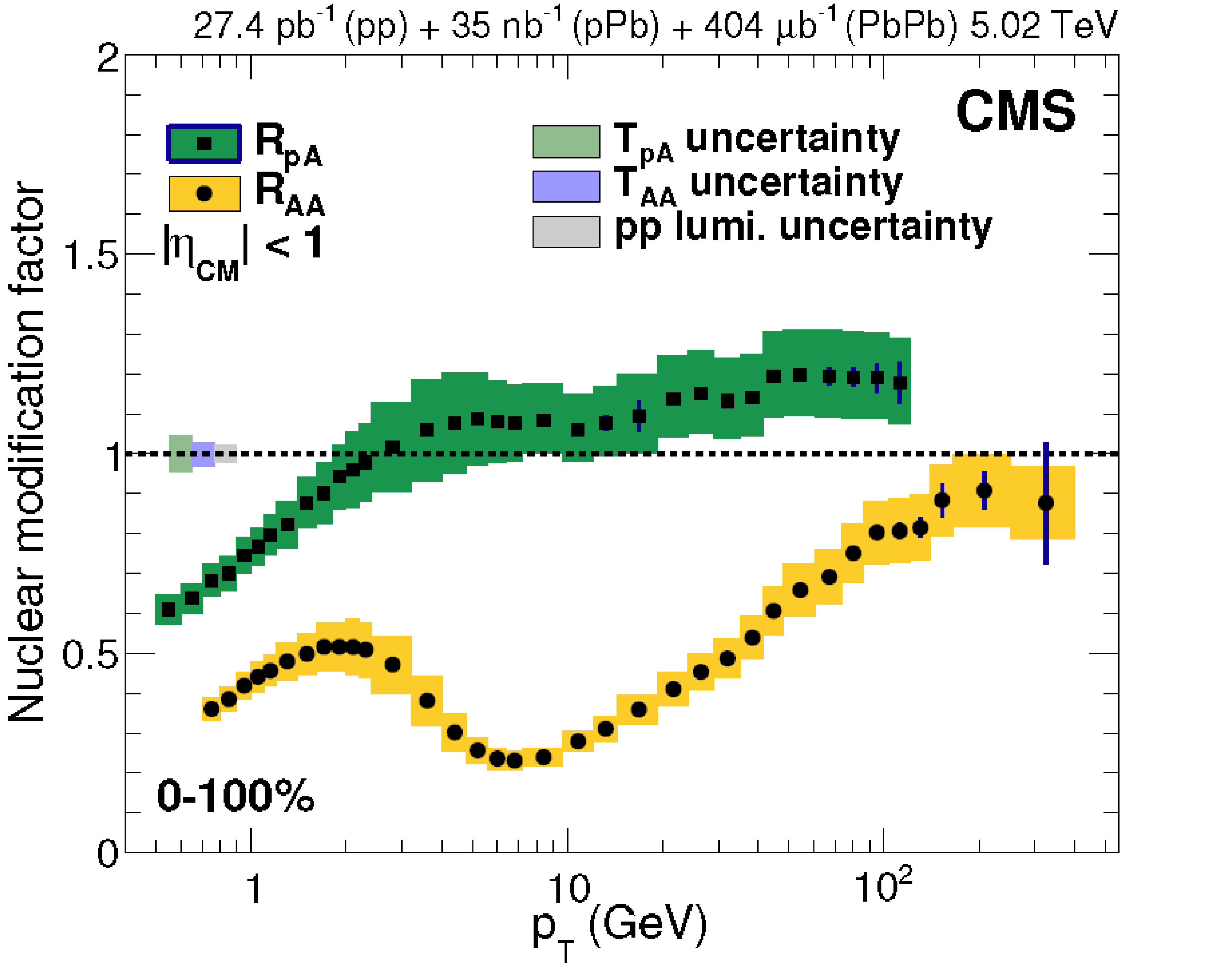





ALICE
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
(0-20%) - (60-100%)
(c,b) → e, |η| < 0.8, |Δη| < 1.2
Charg. part., |η| < 0.8, 0.8 < |Δη| < 1.6
μ, p-going -4 < η < -2.5, -5 < |Δη| < -1.5
μ, Pb-going -4 < η < -2.5, -5 < |Δη| < -1.5
v_2
0.2
0.15
0.1
0.05
0
1
2
3
4
5
6
p_T (GeV/c)

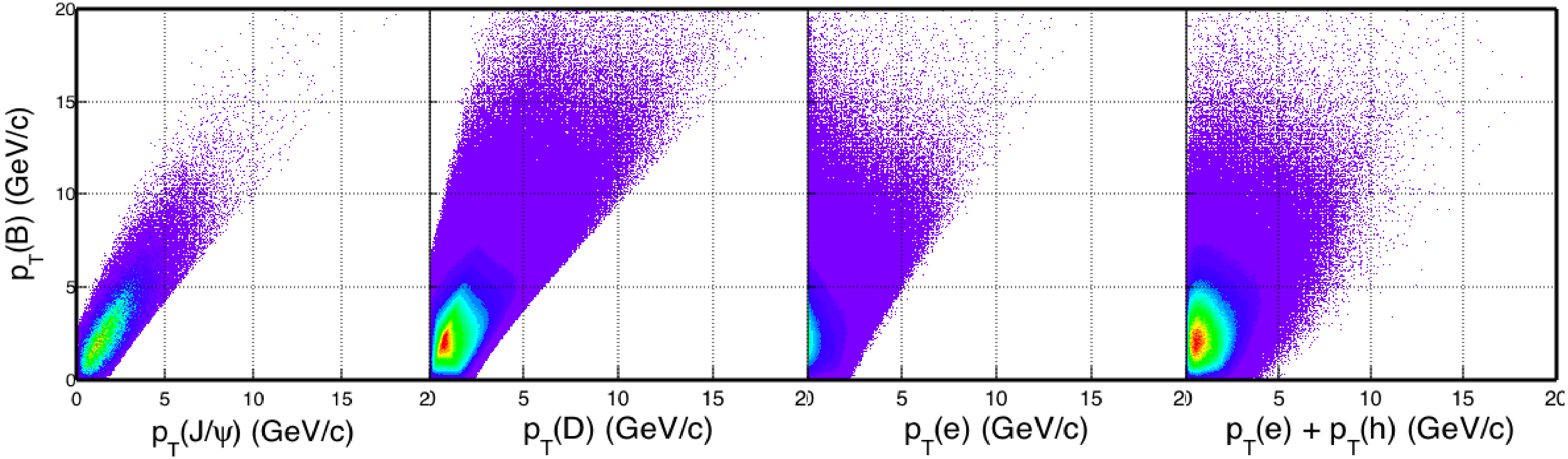

ALICE Preliminary
pp, √s = 13 TeV
Inclusive J/ψ → e+e- (|y| < 0.9)
10% normalization uncertainty
linear
dNJ/ψ/dy / ⟨dNJ/ψ/dy⟩
dNch/dη / ⟨dNch/dη⟩
ALI-PREL-118226


ALICE Preliminary
pp, √s = 13 TeV
Inclusive J/ψ → e+e- (|y| < 0.9)
10% normalization uncertainty
Data
Ferreiro et al.
EPOS3 (D, 2 < pT < 4 GeV/c)
PYTHIA 8 (Monash 2013)
Kopeliovich et al.
dNJ/ψ/dy / ⟨dNJ/ψ/dy⟩
dNch/dη / ⟨dNch/dη⟩
ALI-PREL-128843

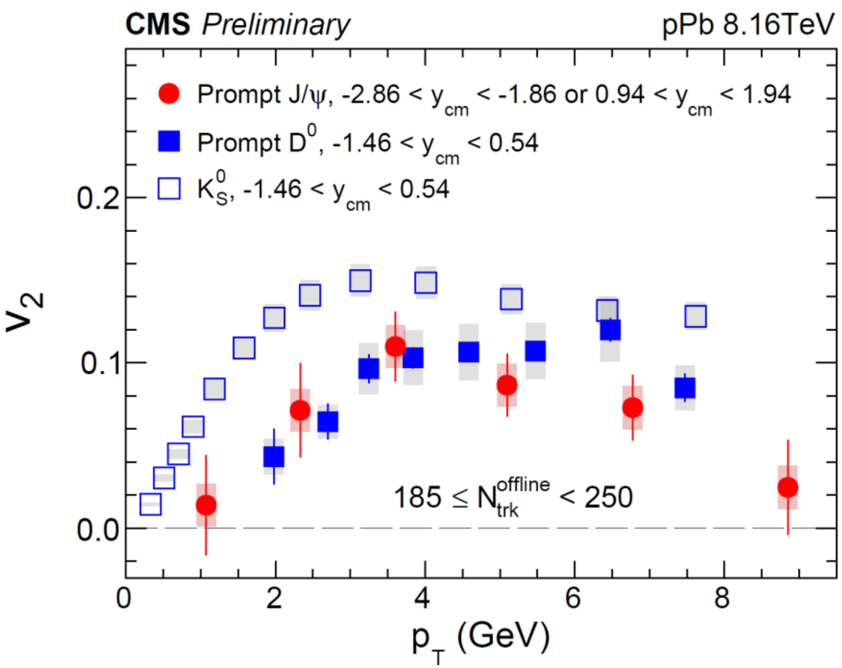


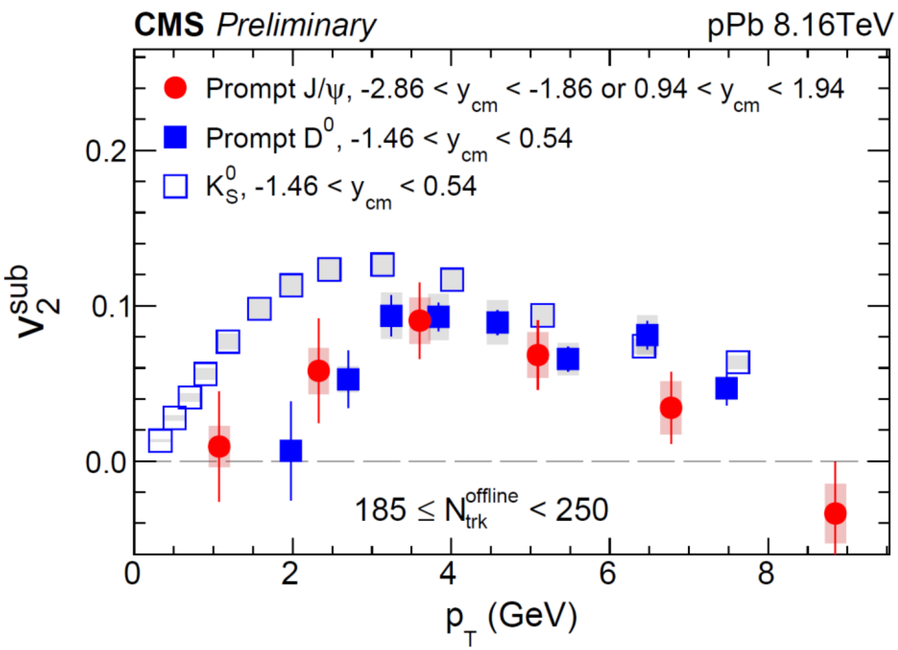
27.4 pb^{-1} (pp) + 35 nb^{-1} (pPb) + 404 μb^{-1} (PbPb) 5.02 TeV
CMS
R_{pA}
R_{AA}
$|\eta_{CM}| < 1$
T_{pA} uncertainty
T_{AA} uncertainty
pp lumi. uncertainty
0-100%
Nuclear modification factor
p_T (GeV)
0
0.5
1
1.5
2
1
10
10^2

Kinematical correlation between B-decay daughters and B meson



Significant D^0 v_2 in p-Pb at 8.16 TeV





Left: w/o subtracting low multiplity results.
Right: after submitting low multiplicity results

arXiv:1804.09767