Highlights from the Hard Probes 2016 conference

EMMI-NQM Seminar

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Physics motivation

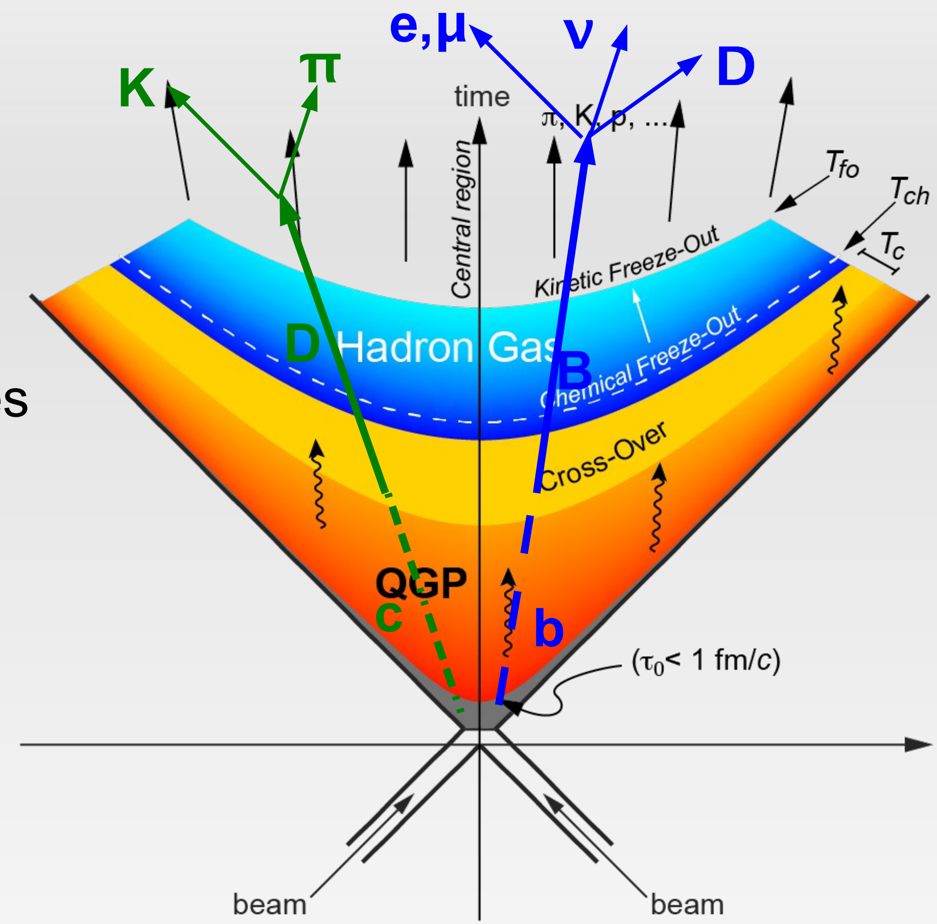
→ Hard probes are produced in hard scattering processes (large Q^2) in the early stage of the collision

→ They experience the full evolution of the system → sensitive probes of the properties of the hot and dense QCD matter (QGP)

→ **Energy loss** mechanisms

→ **Collective expansion**

→ **Hadronization** mechanisms

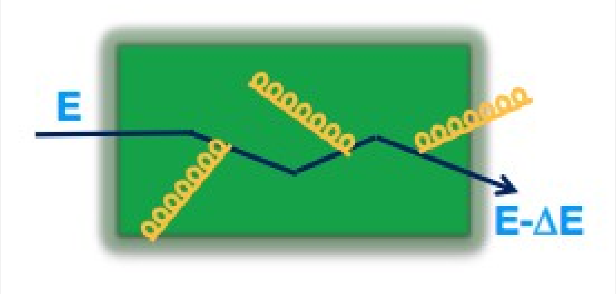


→ **Need reference measurements in pp and p-Pb collisions**
→ **Perturbative QCD** describes the **cross sections** measured in pp collisions.

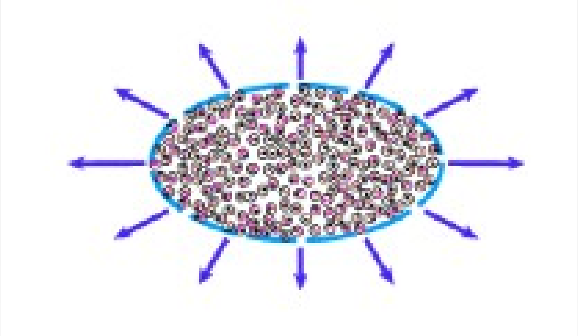
Hot and dense medium effects: Pb-Pb collisions

Interaction with the QCD medium constituents

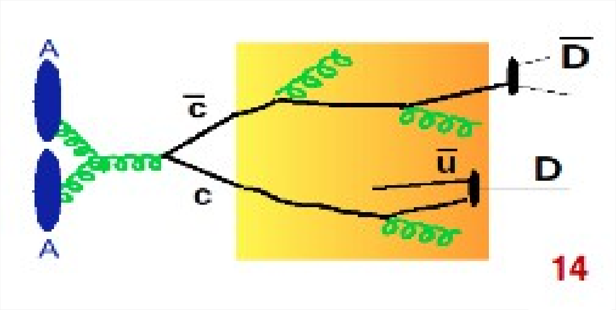
→ **Energy loss:**
- Elastic collisions (collisional energy loss)
- Gluon radiation (radiative energy loss)



→ **Momentum gain** due to the "push" from medium collective expansion:
- Thermalization in the medium?



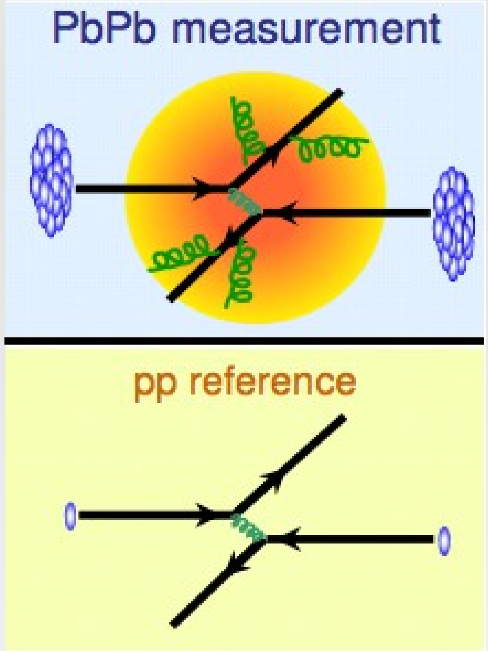
→ **In-medium hadronization:**
- Hadronization via coalescence in the medium vs fragmentation in the vacuum?



Goal: extract medium properties with hard probes observables

Study in-medium energy loss

- Production of hard probes (heavy quarks, jets...) in A-A collisions is expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)



- **Observable**: nuclear modification factor

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle d\sigma_{pp}/dp_T} \sim \frac{QCD\ \text{medium}}{QCD\ \text{vacuum}}$$

- If no nuclear effects are present → R_{AA} = 1 (binary scaling)
- In-medium parton energy loss via **radiative** (gluon emission) and **collisional** processes depending on:
  → color charge
  → quark mass (dead cone effect)
  → path length and medium density

⇨ $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

Need to compare R_{AA}^{π}, R_{AA}^{D}, R_{AA}^{B}

? → $R_{AA} \neq 1$

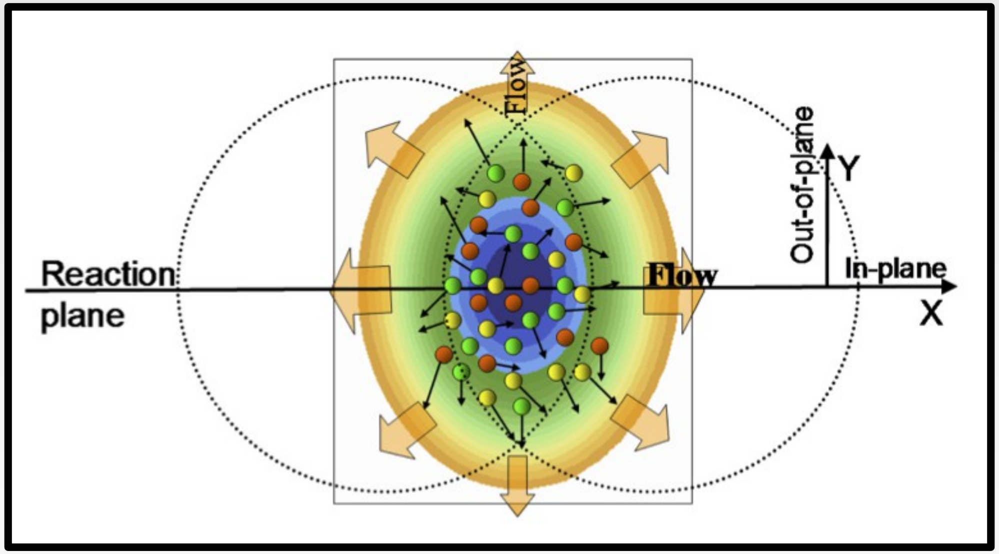
Dokshitzer and Kharzeev, PLB 519 (2001) 199
Wicks, Gyulassy, J.Phys. G35 (2008) 054001

Collectivity: azimuthal anisotropy

– Re-scatterings among produced particles convert the initial **geometrical anisotropy** into an observable **momentum anisotropy**

– In addition, path-length dependent energy loss induces an asymmetry in momentum space

– **Observable**: **elliptic flow v_2 =** 2nd Fourier coefficient of the particle azimuthal distribution



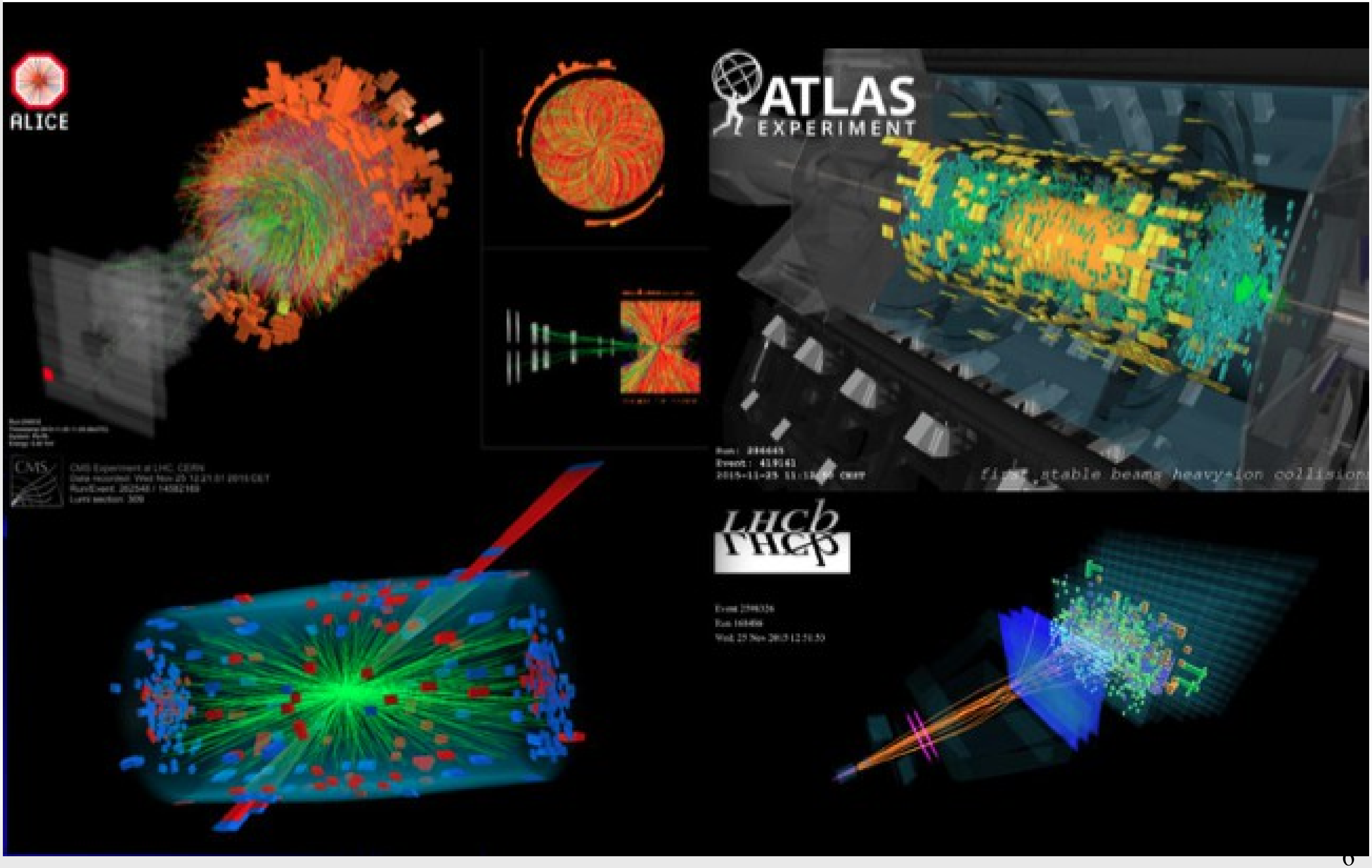
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

v_2 measurements probe:

– **Low/intermediate p_T:** collective motion, degree of thermalization and hadronization mechanism (recombination)

– **High p_T:** path-length dependence energy loss

Results from the main LHC experiments



Highlights from the conference

Spectra

- Charged particle R_{AA} at 5 TeV
- Jet R_{AA} at 2.76 TeV
- Collectivity in small systems

nPDFs

- Dijet pseudo-rapidity at 5 TeV

Jet structure

- Splitting function at 5 TeV
- Jet-track correlation at 2.76 TeV

Boson-jet

- Gamma-jet at 5 TeV
- Z-jet at 5 TeV

Heavy flavour

- D meson R_{AA} at 5 TeV
- B meson R_{AA} at 5 TeV
- Di-b-jet at 5 TeV
- Non-prompt J/psi at 2.76 TeV
- Heavy flavour decay leptons

Flow: path lenght dependence

- D meson v_n at 5 TeV
- High p_T v_n at 5 TeV

Quarkonia

- Charmonium at 5 TeV
- Bottomonium at 5 TeV

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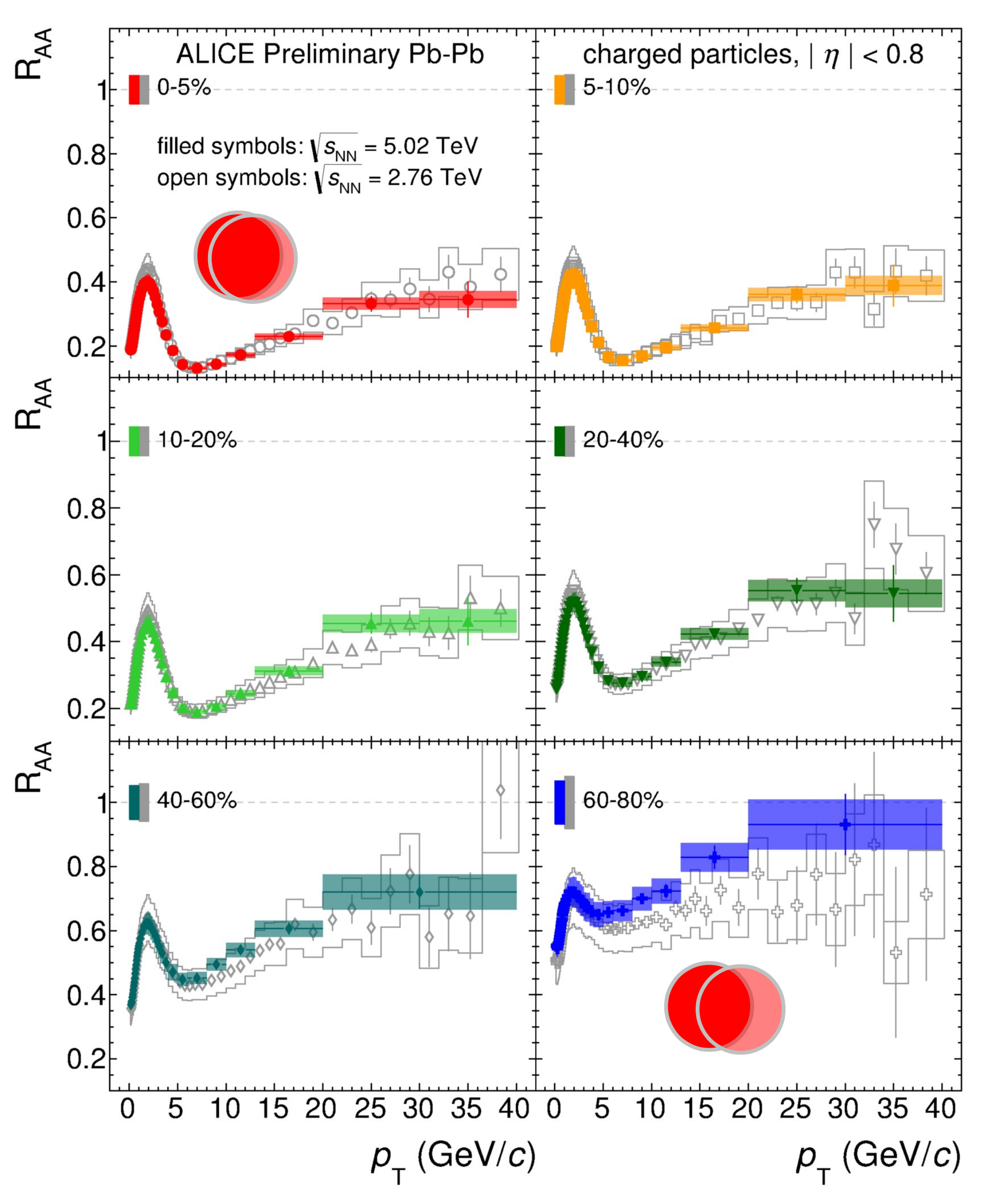
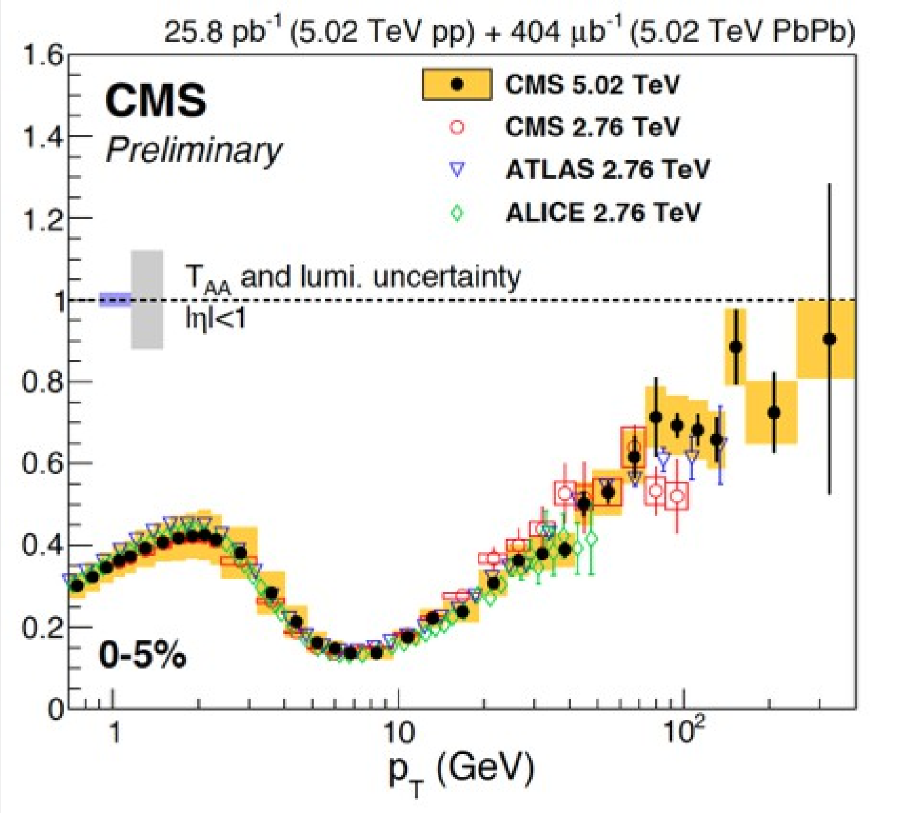
Light flavour

Higher and higher p_T....

Do quenching effects sustain at very high p_T?
Suppression, path lenght and inner structure modification

Charged hadron suppression

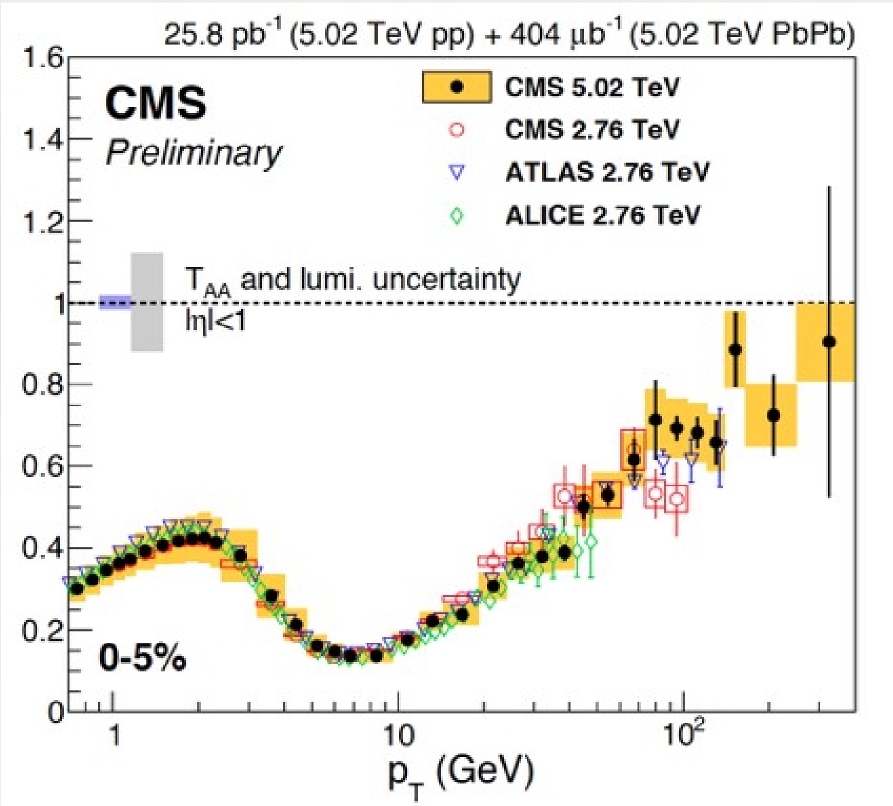


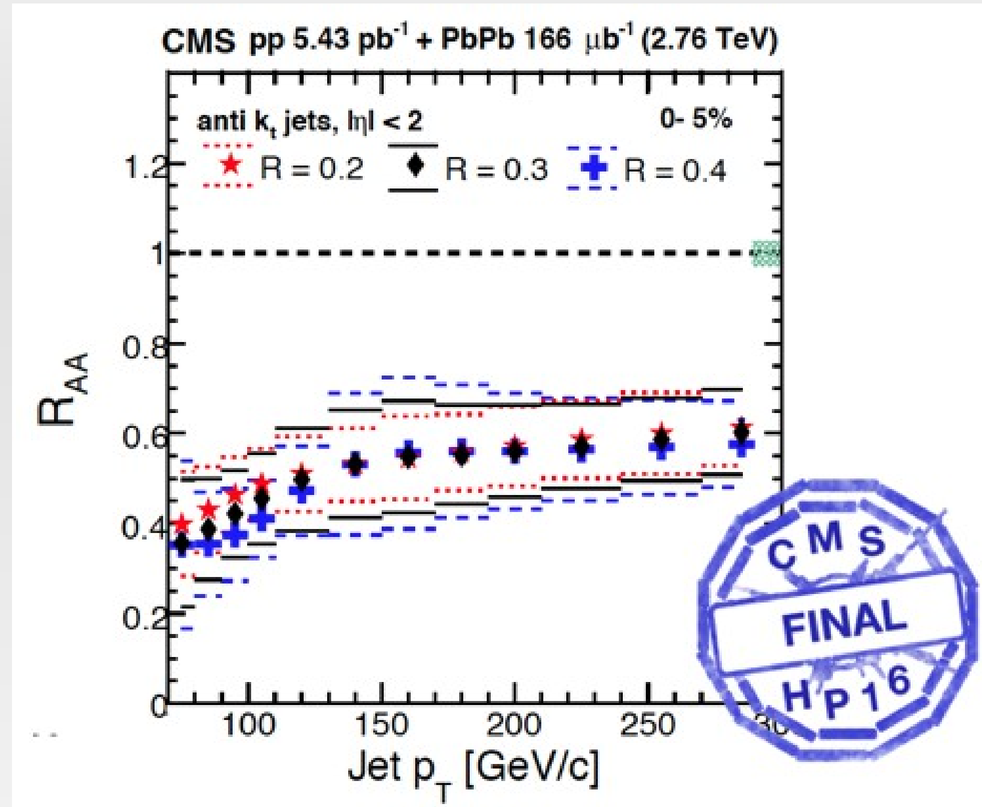


– **Energy loss at high p_T:**
Rising trend as a function of p_T up to 400 GeV/c
→ approaching 1

– **Center of mass energy dependence**
Slightly larger E_{loss} → higher p_T and density

Charged hadron vs jet

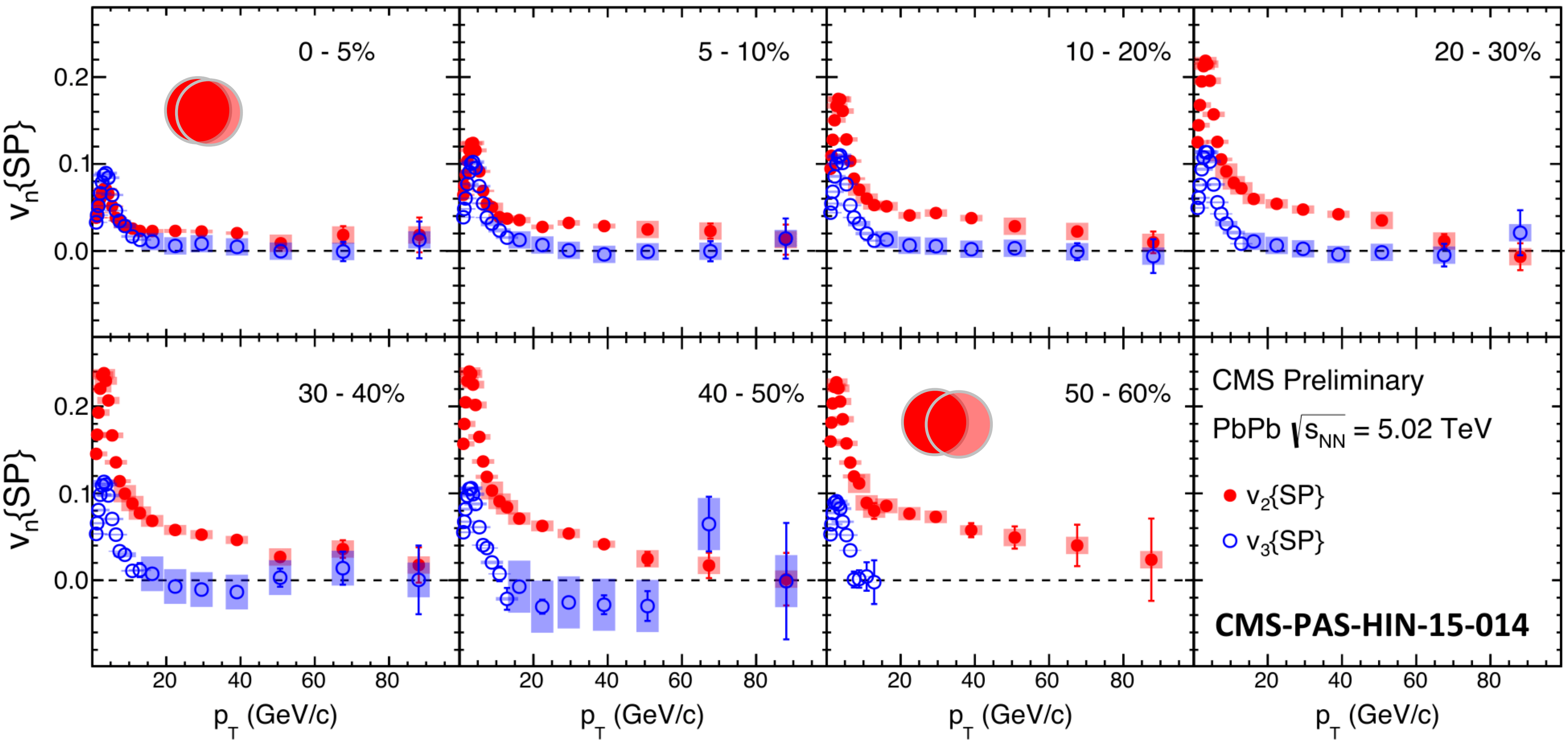




– Charged hadron at high p_T → hard fragmenting high p_T jets

- Center of mass energy is different but changes are expected to be small
- High p_T hadrons are less suppressed than jets

v_2{SP} and v_3{SP} up to high p_T

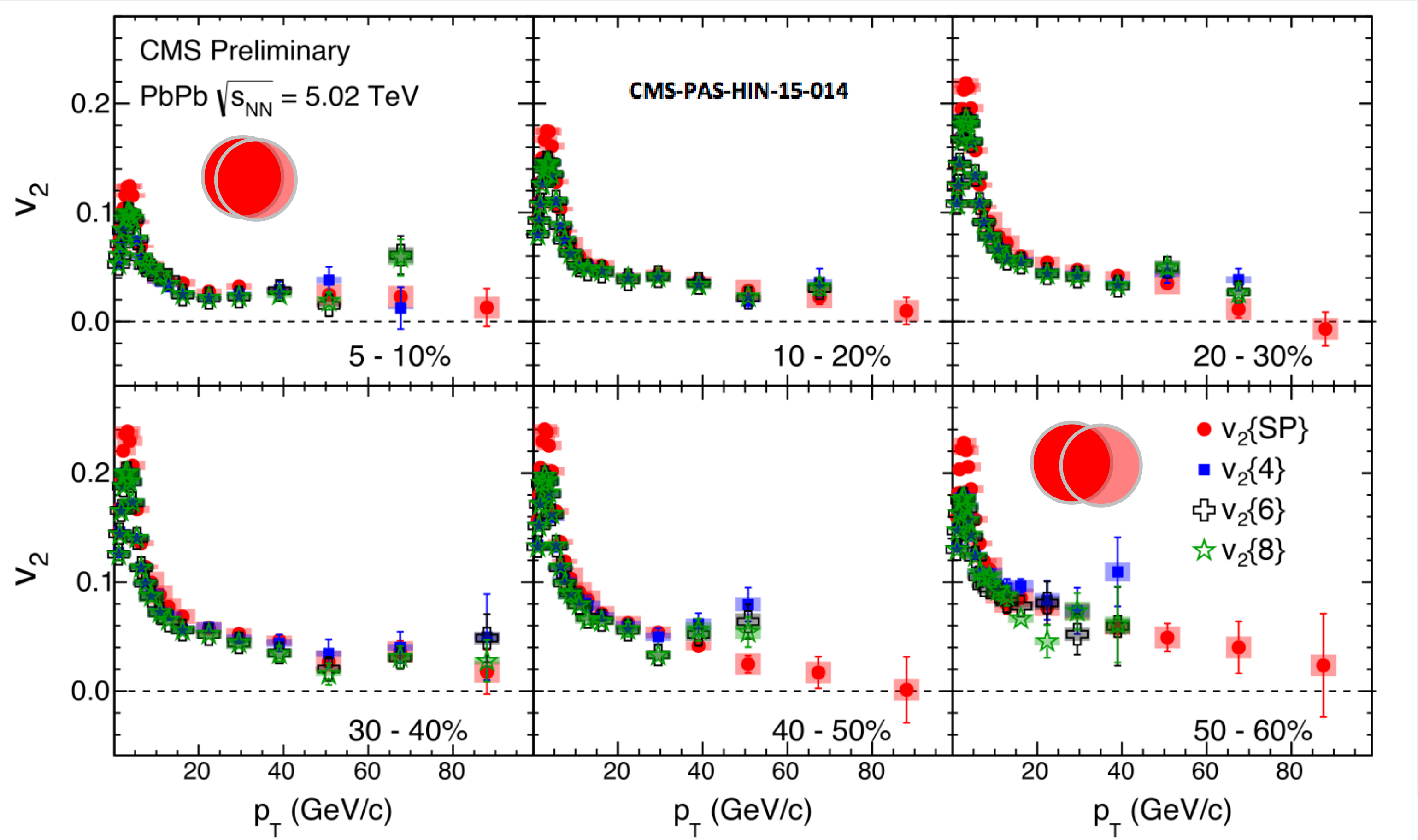


→ FIRST TIME measured v_2 and v_3 up to 100 GeV/c

→ v_2 remains positive at very high p_T, v_3 consistent with 0 for p_T > 30 GeV/c

→ Little centrality dependence of v_3 w.r.t v_2

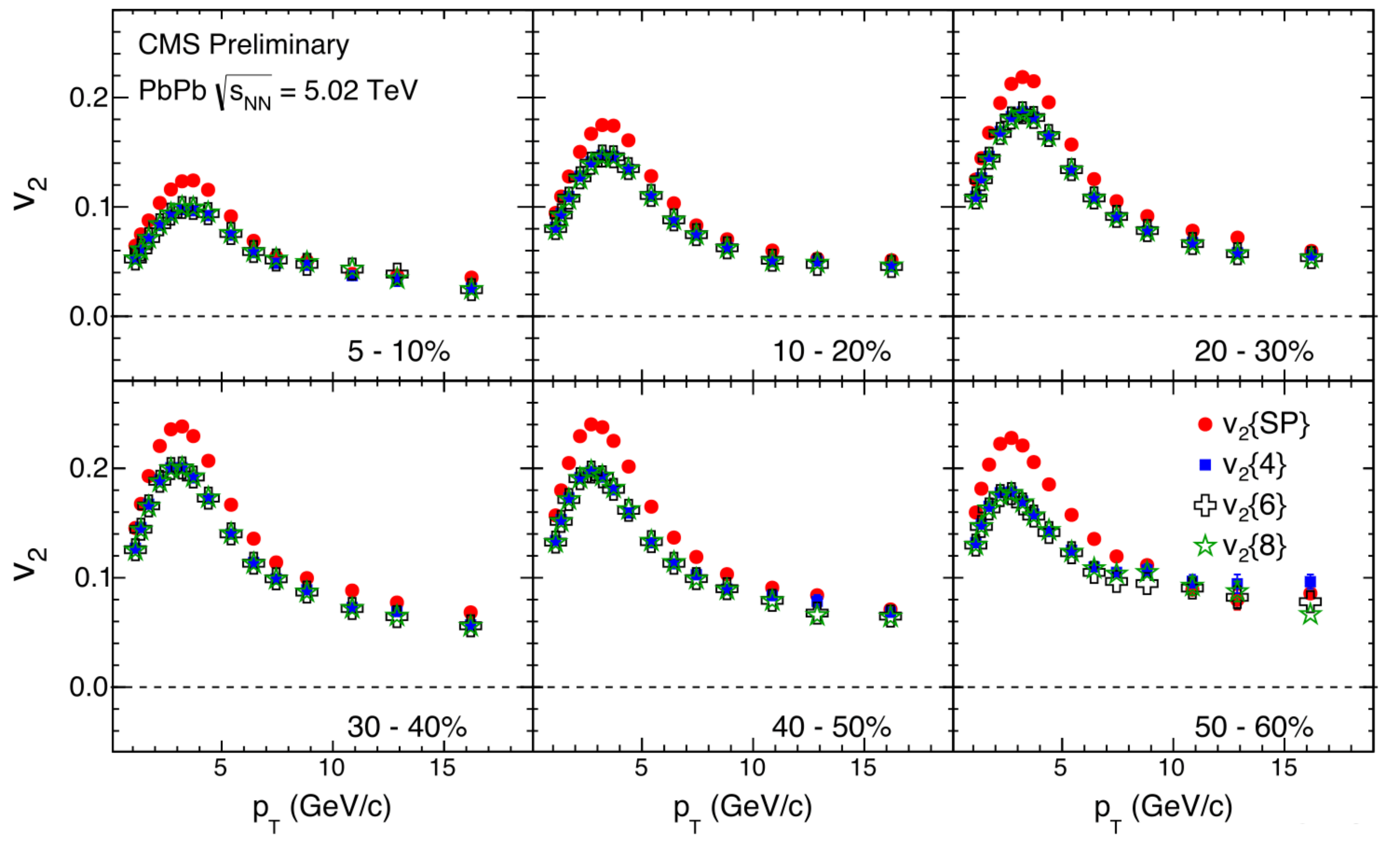
Multi-particle cumulants



– FIRST TIME measured $v_2\{4,6,8\}$ up to p_T = 80 GeV/c

– Multi-particle seems to converge with $v_2\{SP\}$ at high p_T
- Multi-particle nature at high p_T → initial geometry effect

Multi-particle cumulants



– Low p_T: $v_2\{SP\} > v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$

– Expected in hydrodynamics

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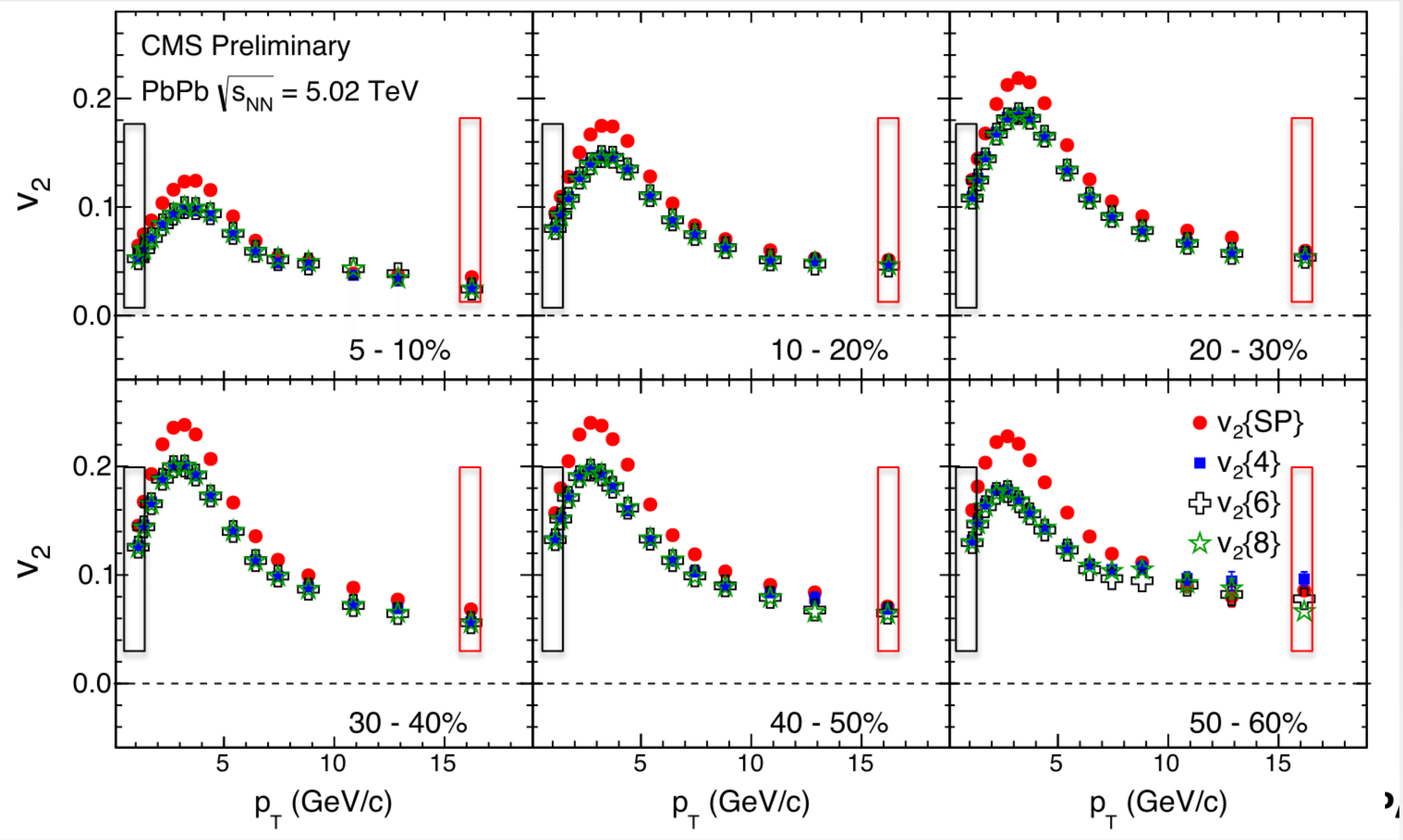
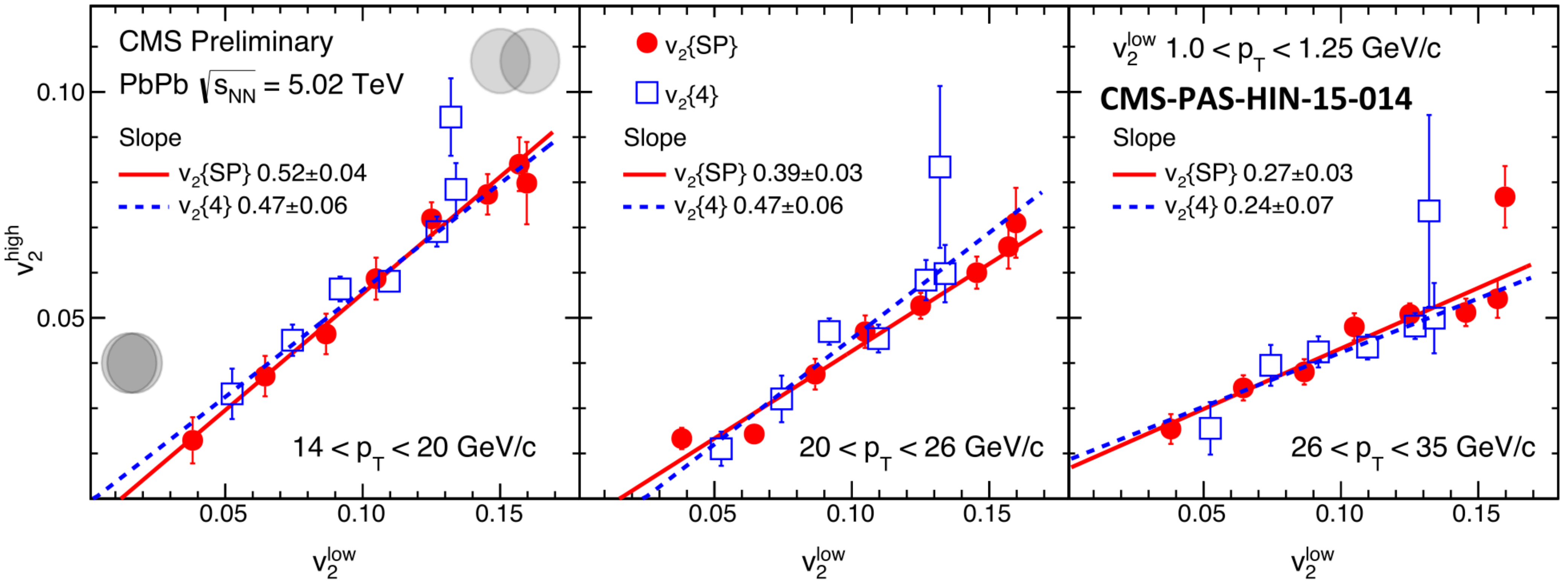


– Low p_T: $v_2\{SP\} > v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$

– Expected in hydrodynamics

v_2\{high\} vs v_2\{low\}

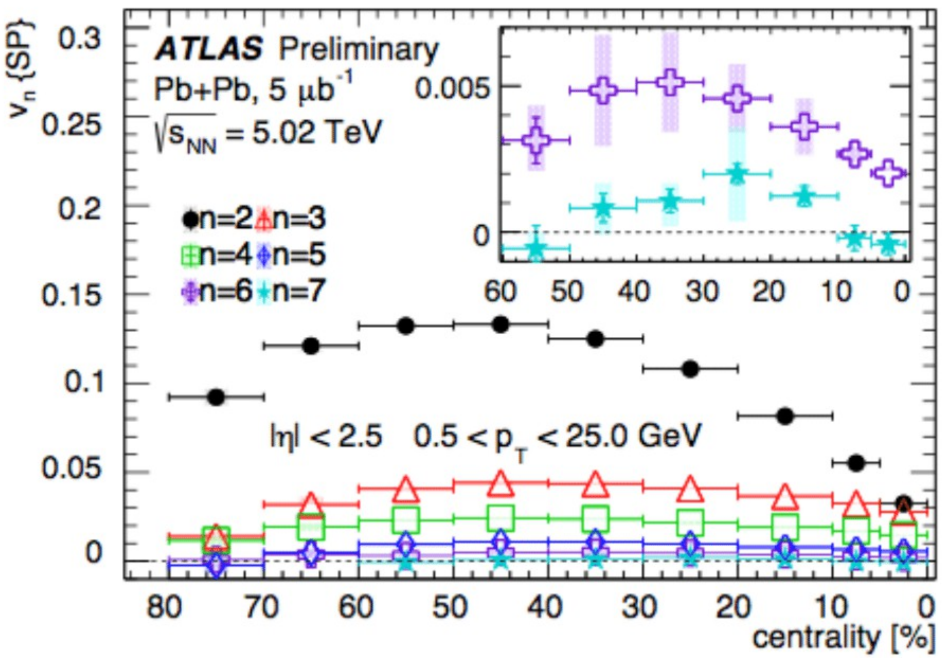


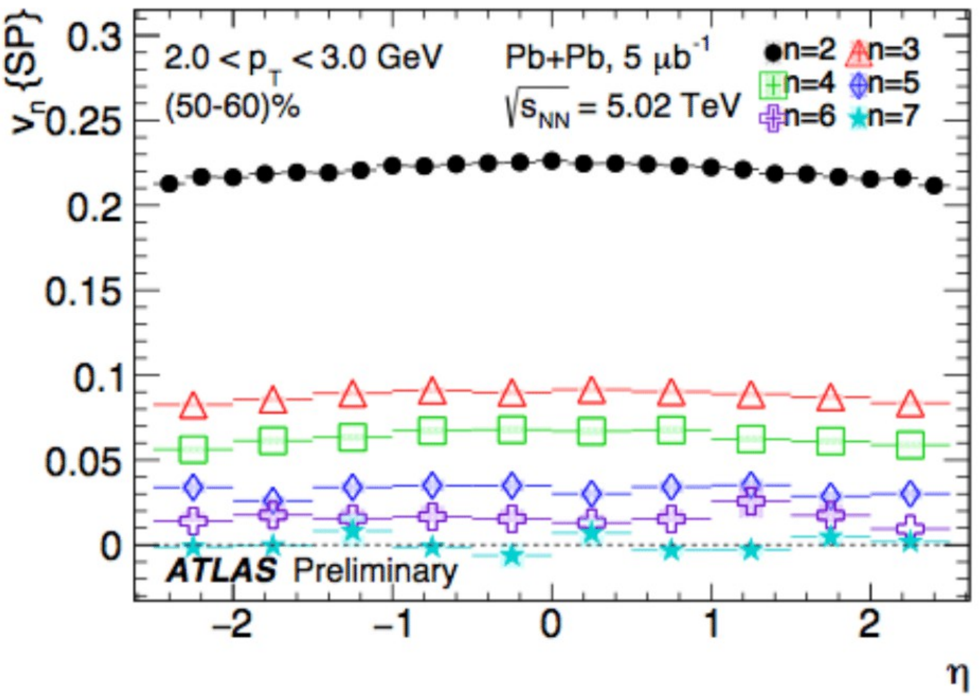
– High p_T v_2 strongly correlated with low p_T v_2
→ Slope decrease while increasing p_T

– Clear demonstration that **soft and hard v_2** probe the same **initial geometry**

– Not so easy: one both varies the geometry and the medium properties
→ Use Event Shape Engineering!

Flow harmonics in Pb-Pb at 5.02 TeV

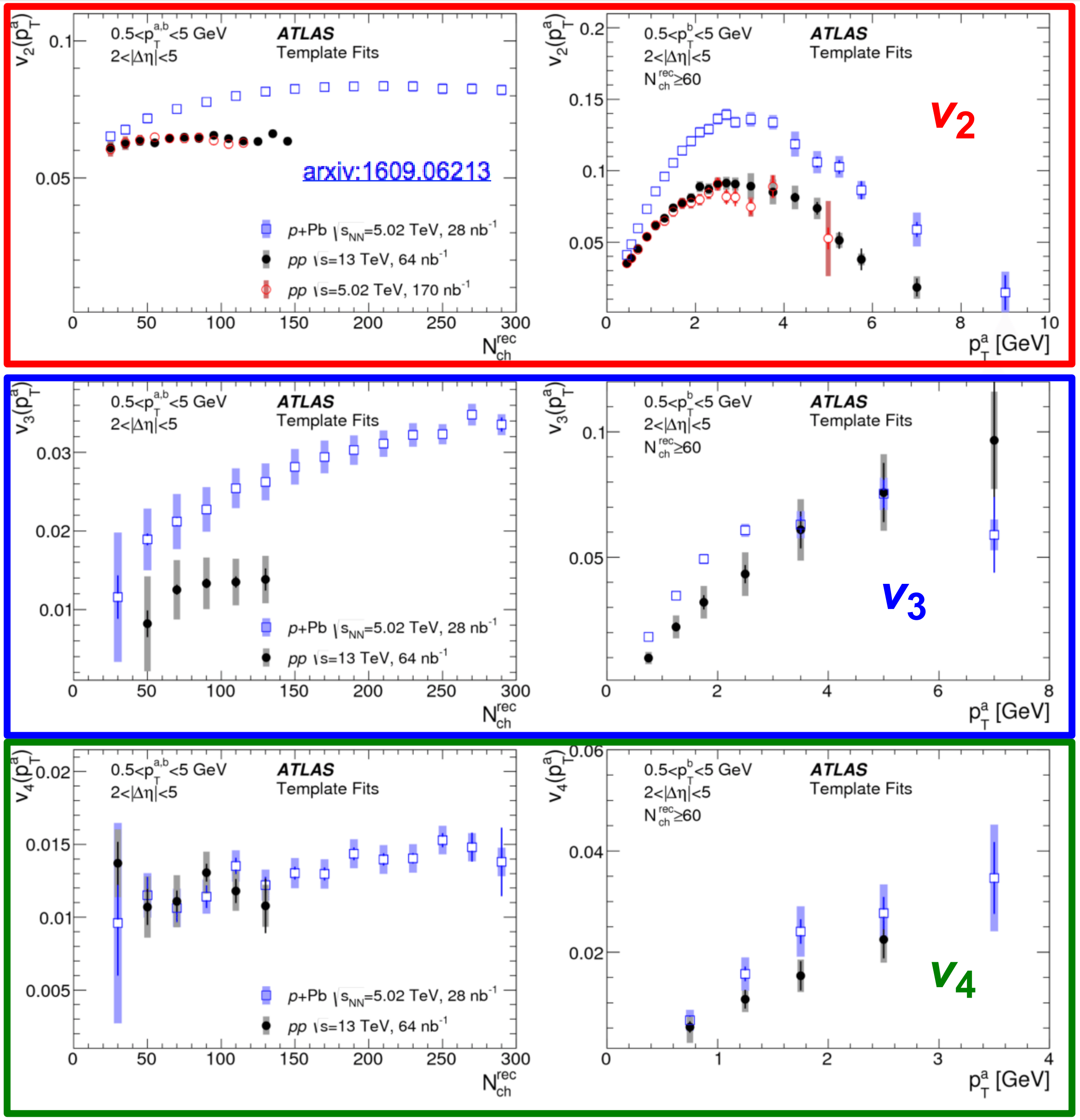




– Flow harmonics v_n measured up to n = 7

→ First measurements of v_7 in 0-60% centrality
→ kinematic range: 0.5 < p_T < 25 GeV/c, $|\eta|$ < 2.5
→ very weak pseudo-rapidity dependence

Ridge in pp and p-Pb systems



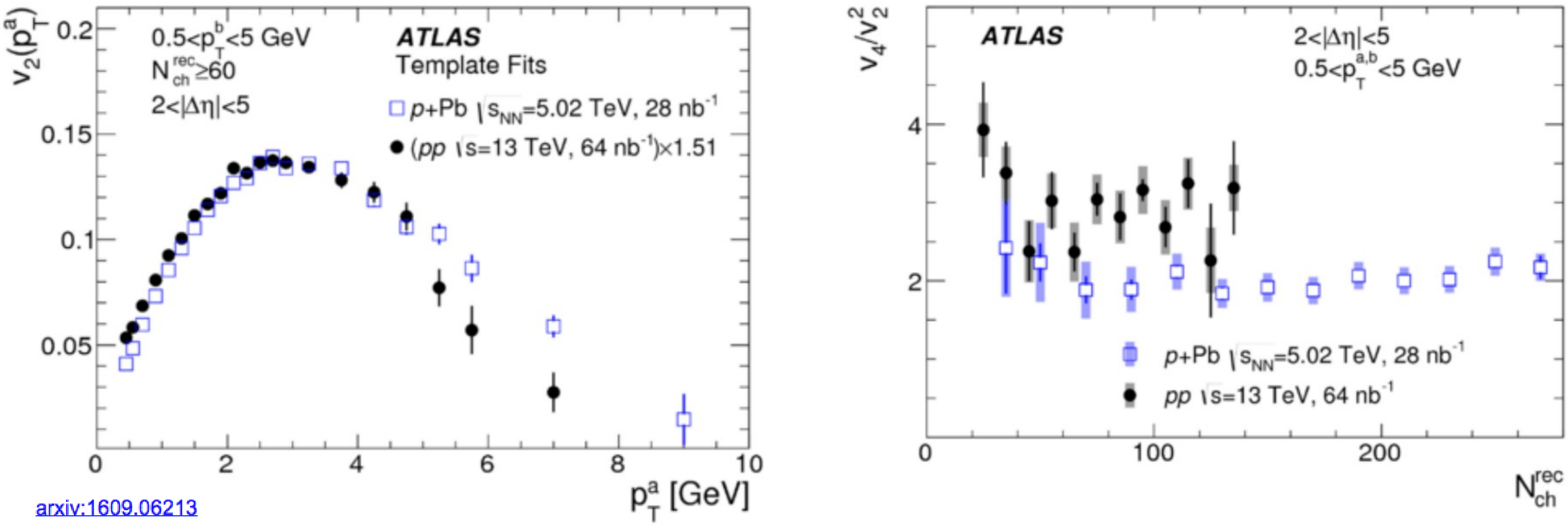
– In pp collisions v_2 is flat as a function of N_{ch} and non-zero even for low value of N_{ch}

– Agreement in all fourier coefficients between 5 and 13 TeV in pp collisions

– v_2 and v_3 are larger in p-Pb collisions (w.r.t. pp) and rise monotonically

– v_4 tend to be consistent within uncertainties between the two collision systems

Ridge in pp and p-Pb systems



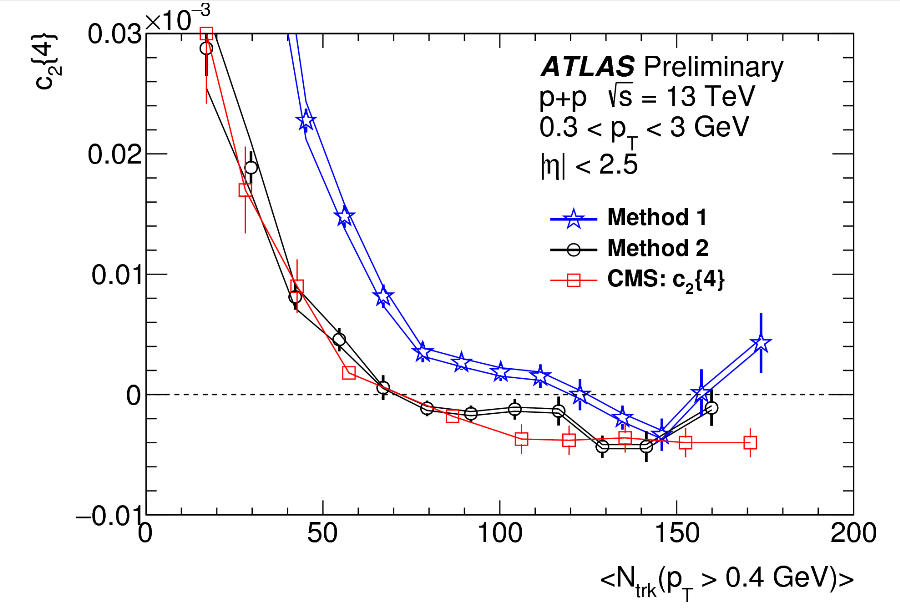
arxiv:1609.06213

– Shape of p_T-dependence of v_2 is consistent between **p-Pb** and **pp** (scaled by 1.51)

– v_4/v_2^2 ratio is flat in N_{ch} in both systems
→ Hint of a **common origin** of the ridge in the two systems?

Multi-particle cumulants in pp

Cumulants are extracted for reference particles (N_{trk}^{ref}): $0.3 < p_T < 3$ GeV/c using two methods:
Method 1: fixed N_{trk}^{ref} multiplicity (avoids multiplicity fluctuations)
Method 2: events are selected using N_{trk} ($p_T > 0.4$ GeV/c)



– Weak energy dependence to cumulants, however systemtically higher $c_2\{4\}$ measured at 13 TeV at low N_{trk}, at higher N_{trk} the trend is reversed.

– **Method 1**: positive cumulants, therefore no collective effects
– **Method 2**: negative cumulants over a broad range of N_{trk}

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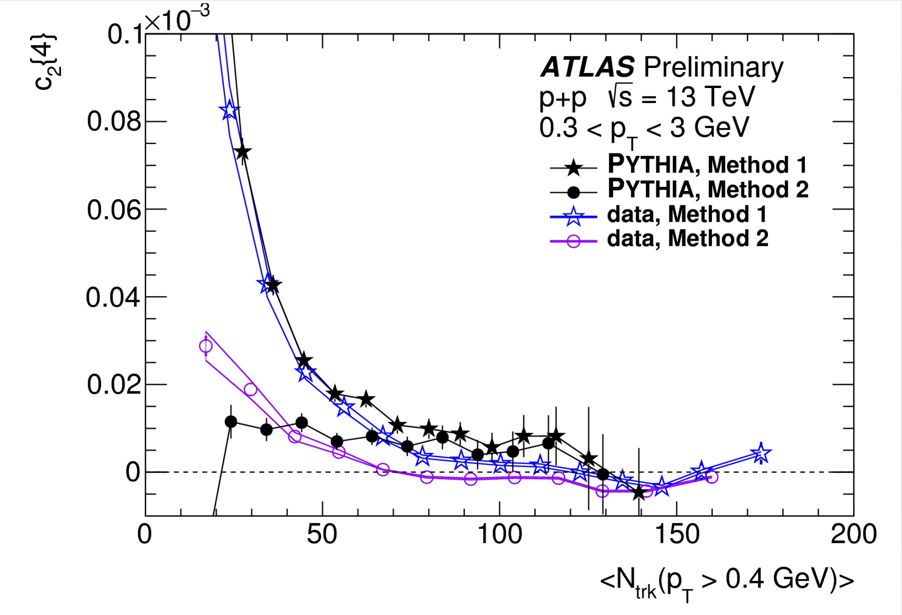

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– **Method 1**: positive cumulants, therefore no collective effects
– **Method 2**: negative cumulants over a broad range of N_{trk}
– **PYTHIA**: confirm a negative contribution of fluctuation in method 2

– **Conclusion**: $c_2\{4\}$ in pp is sensitive to the choice of event class
→ Mult. fluctuation and non flow could give a negative contribution to $c_2\{4\}$
→ Premature to conclude on collectivity w/o quantify influence of these effects

Heavy flavour

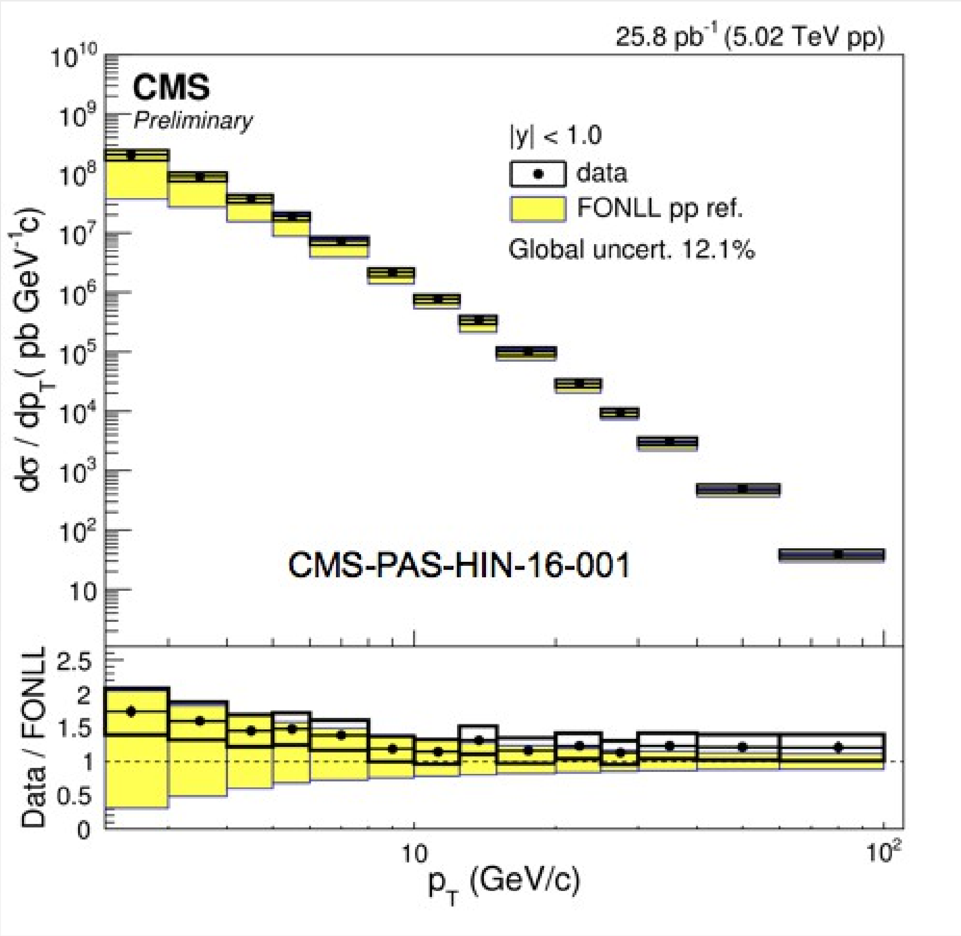
Can we see the dead cone effect?

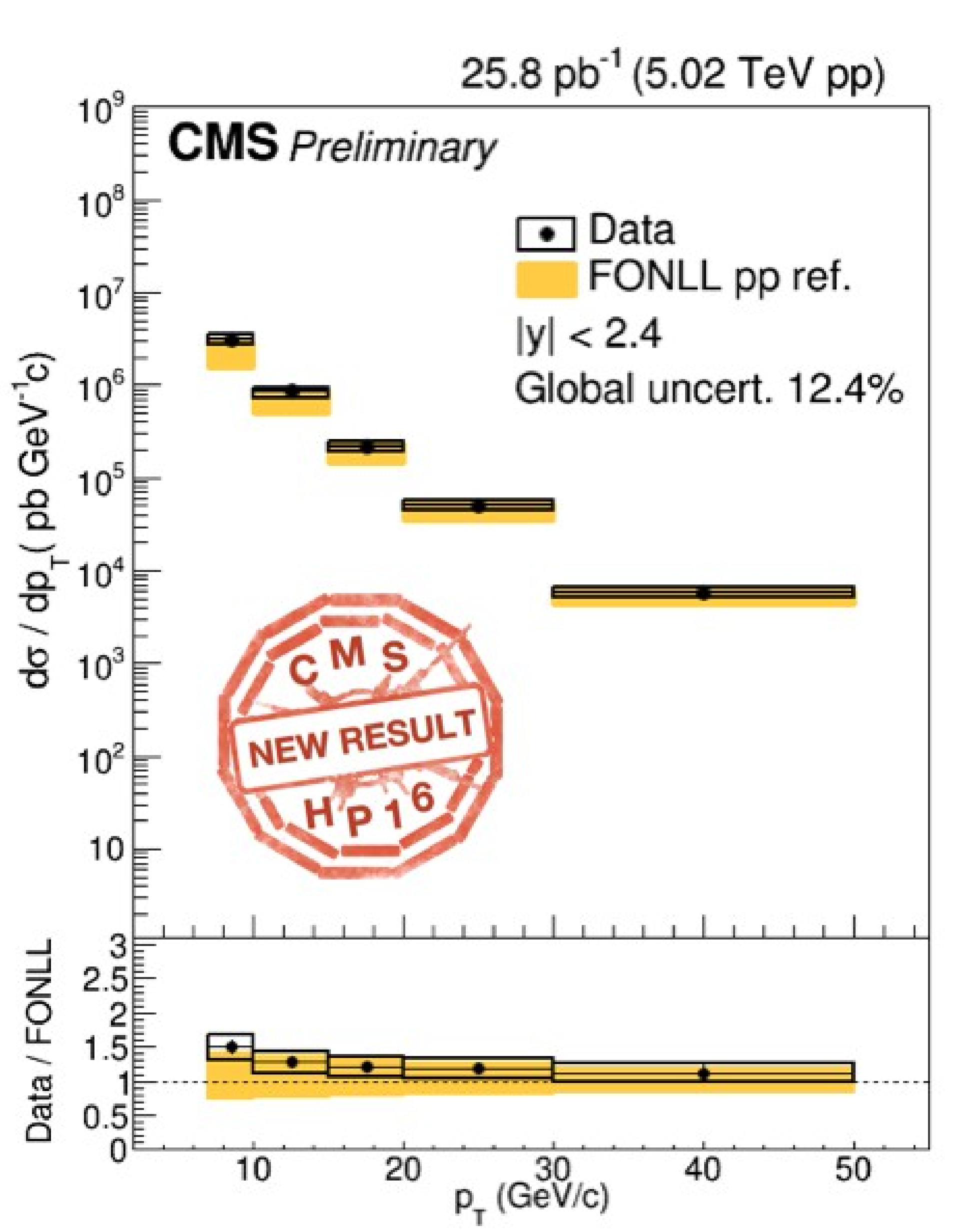
As p_T gets larger → effect gets smaller
Low-p_T contribution from other effects e.g. radial flow

Coalescence

Is D meson v_2 enhanced?
D_s measurements

D and B cross sections at LHC in pp collisions



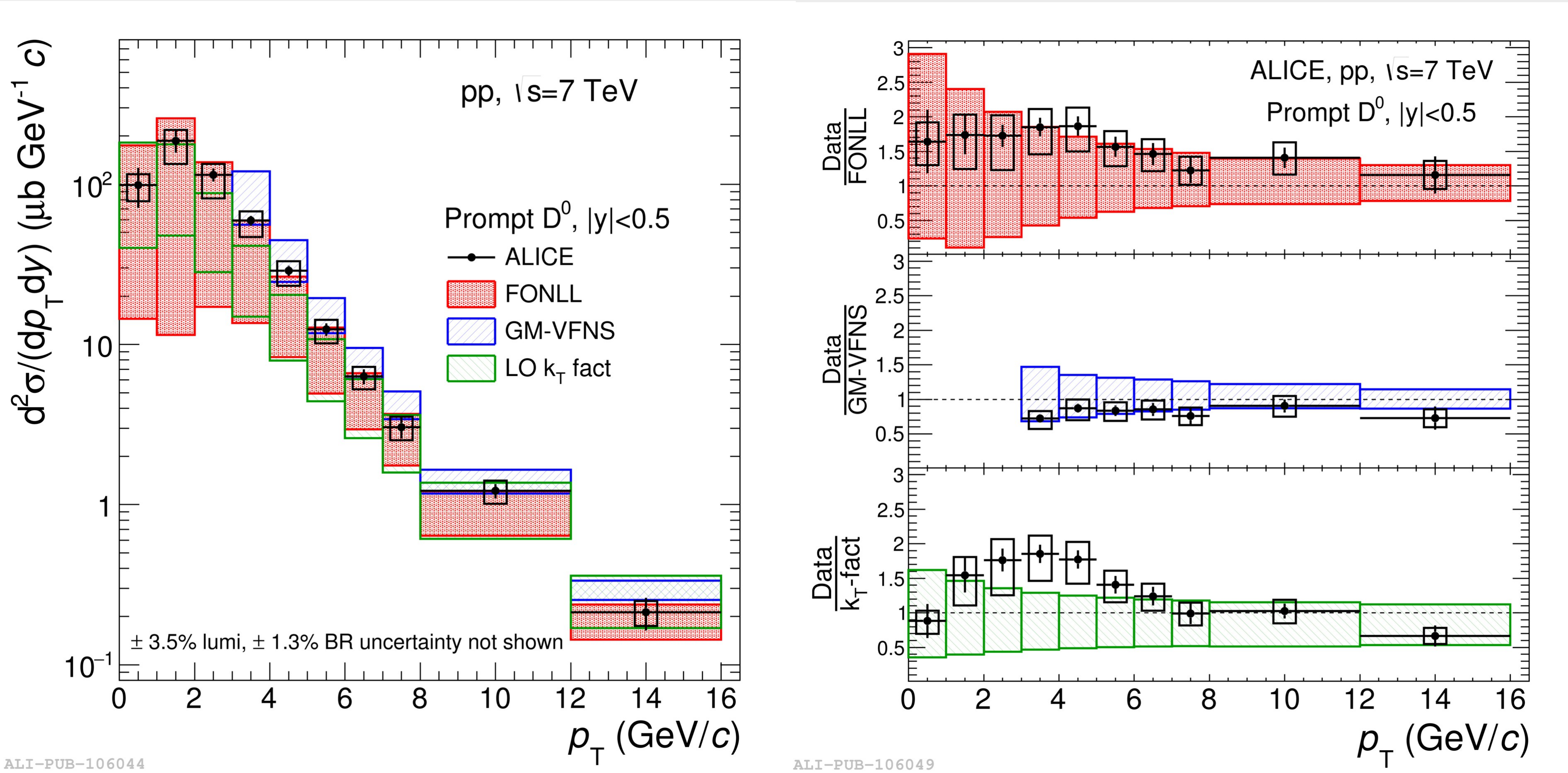


HF production cross section well described by NLO calculations:

→ D meson on upper edge of FONLL calculation

→ B meson consisten with central vaues of FONLL

D and B cross sections at LHC in pp collisions

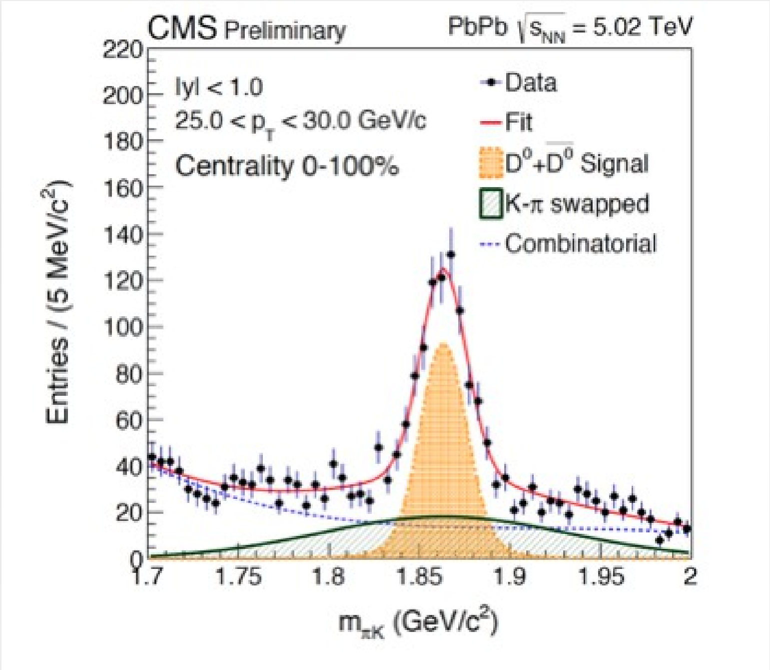


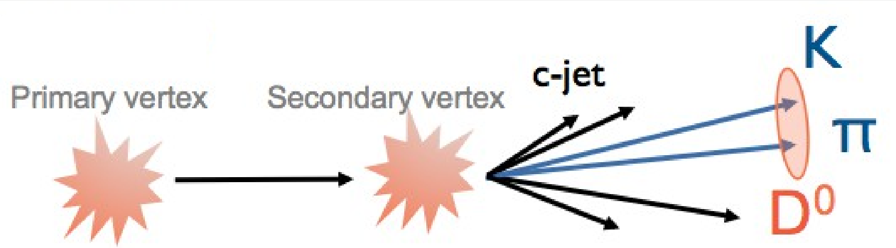
ALICE experiment:

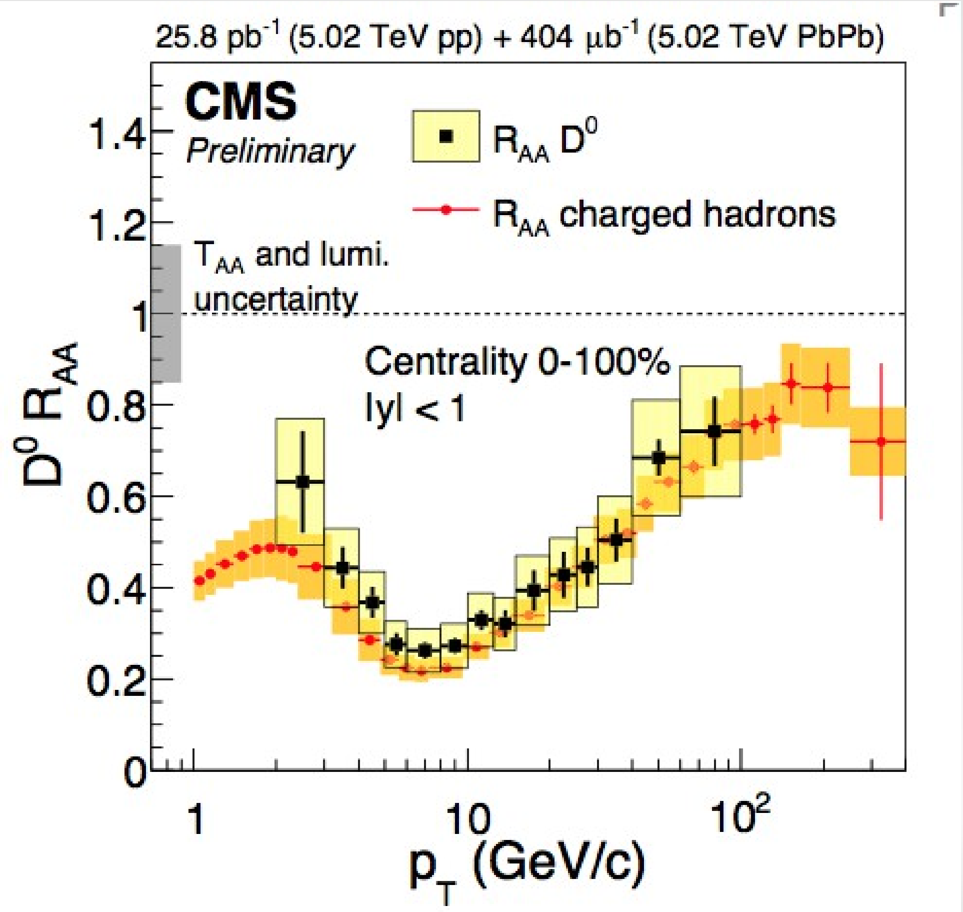
D meson measurements down to $\boldsymbol{p_T}$ **= 0 GeV/*c*** in both pp and p-Pb collisions!

Analysis based on PID only w/o reconstruction of decay vertex topologies

D meson nuclear modification factor





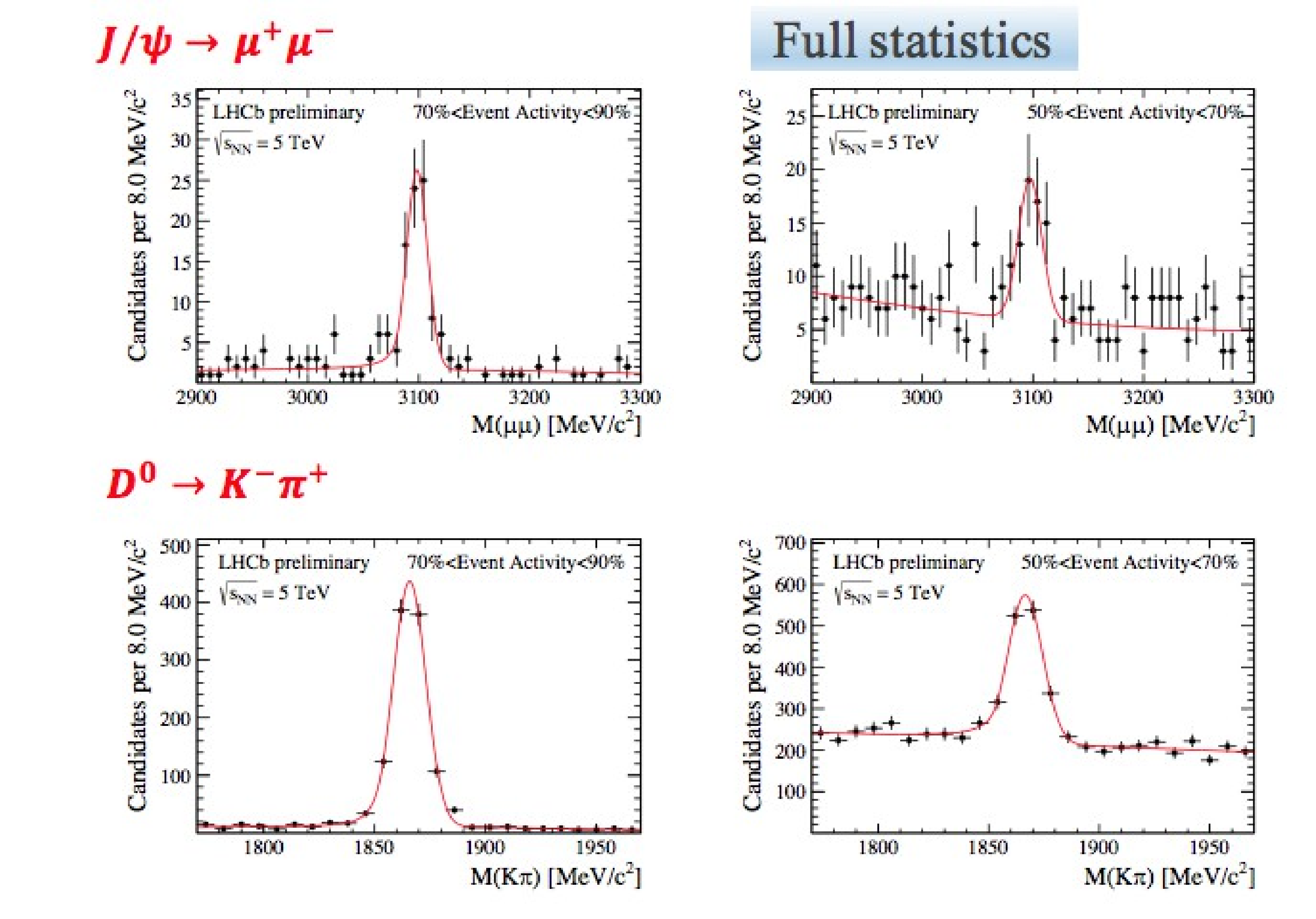


New D meson R_{AA} from 2 GeV/c to 100 GeV/c at the centre of mass energy of 5.02 TeV
→ similar suppresion as observed at 2.76 TeV

→ same level of suppression as for charged hadrons

J/ψ and D⁰ signal in Pb-Pb with LHCb

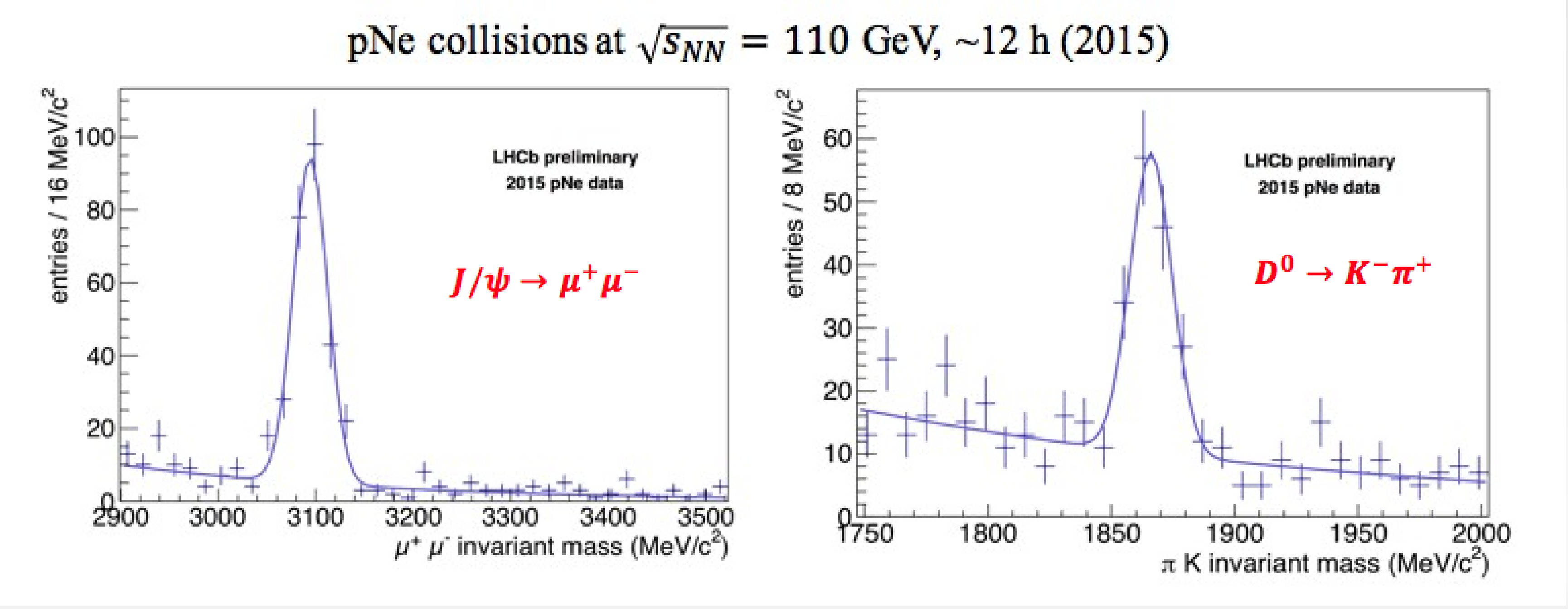
– LHCb can contribute to heavy-ion studies in a unique kinematic range



J/ψ and D^0 signal with LHCb: fixed target

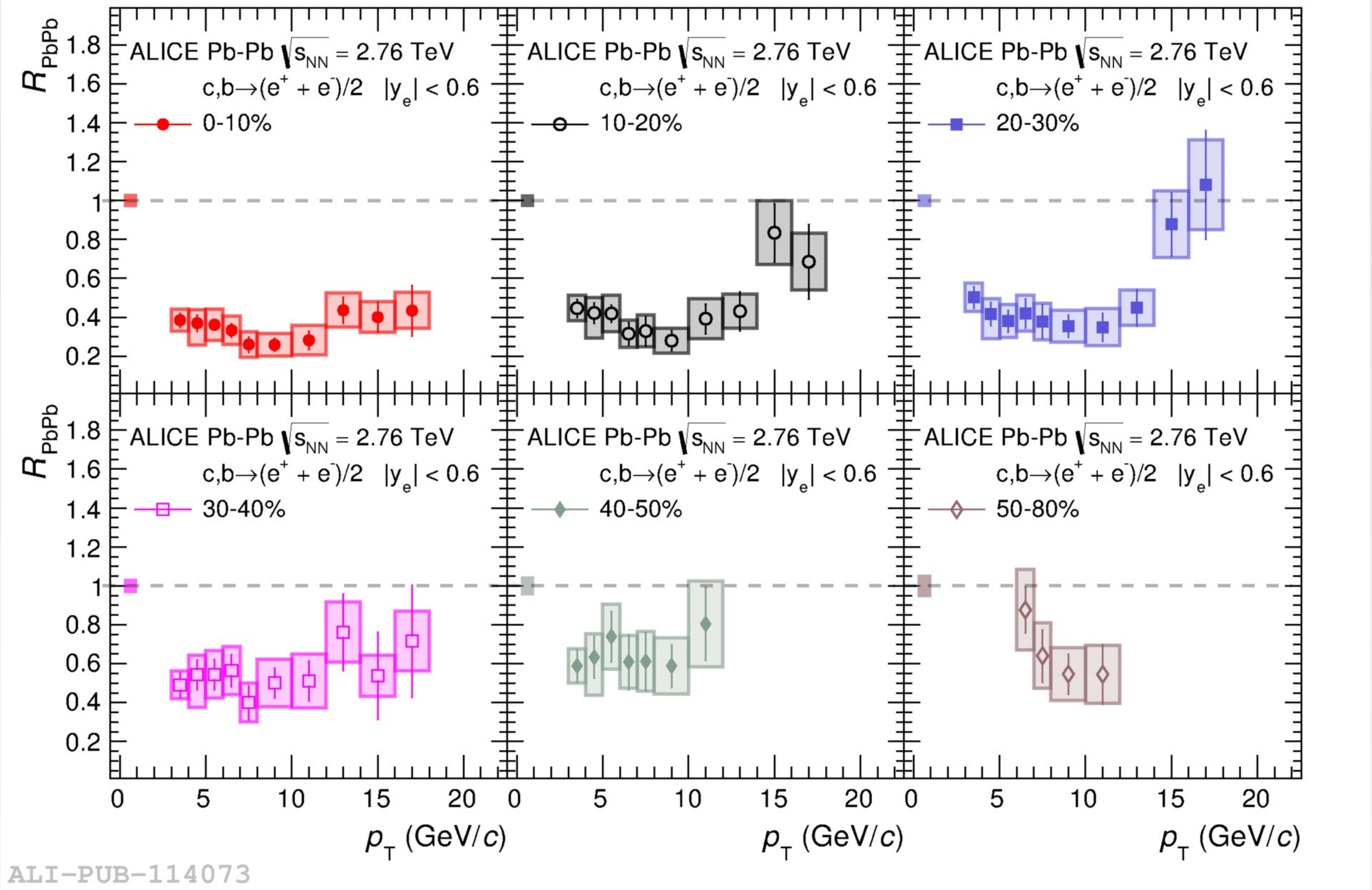
LHCb is unique to explore fixed targed physics
→ will provide measurements in many different environment

- SMOG data collected
  - pHe at $\sqrt{s_{NN}} = 110$ GeV
  - pNe at $\sqrt{s_{NN}} = 87$ GeV, 110GeV
  - pAr at $\sqrt{s_{NN}} = 69$ GeV, 110 GeV
  - PbNe at $\sqrt{s_{NN}} = 54$ GeV
  - PbAr at $\sqrt{s_{NN}} = 69$ GeV



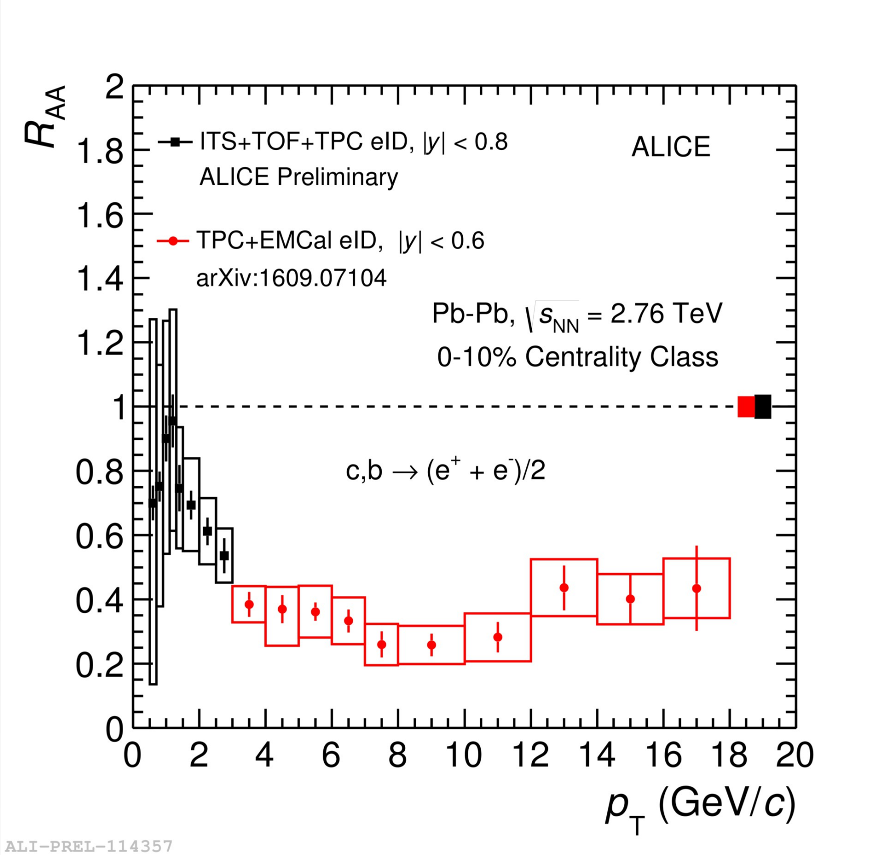
Heavy-flavour decay electron nuclear modification factor

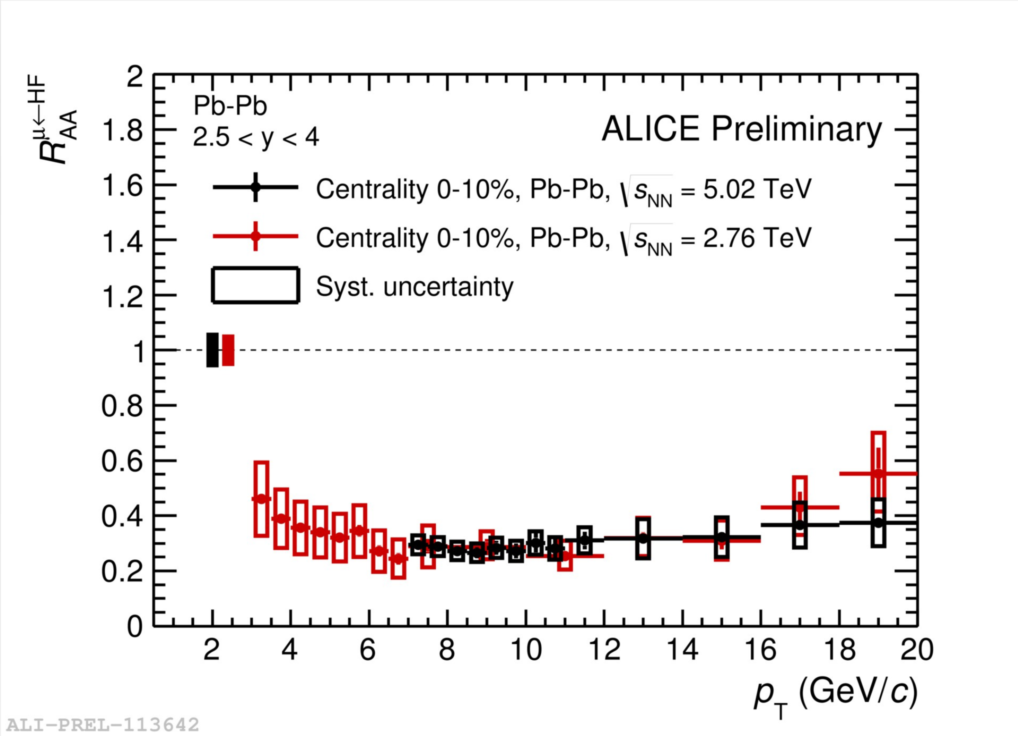
arXiv:1609.07104



New high p_T R_{AA} measurements in several Pb-Pb centrality classes show stronger suppression in the 10% most central collisions respect to semi-central collisions. Stronger energy loss in central collisions due to the increase of medium density

Heavy-flavour decay leptons nuclear modification factor





New R_{AA} measurements in 0-10% central Pb-Pb collisions are extented down to p_T = 0.5 GeV/*c*

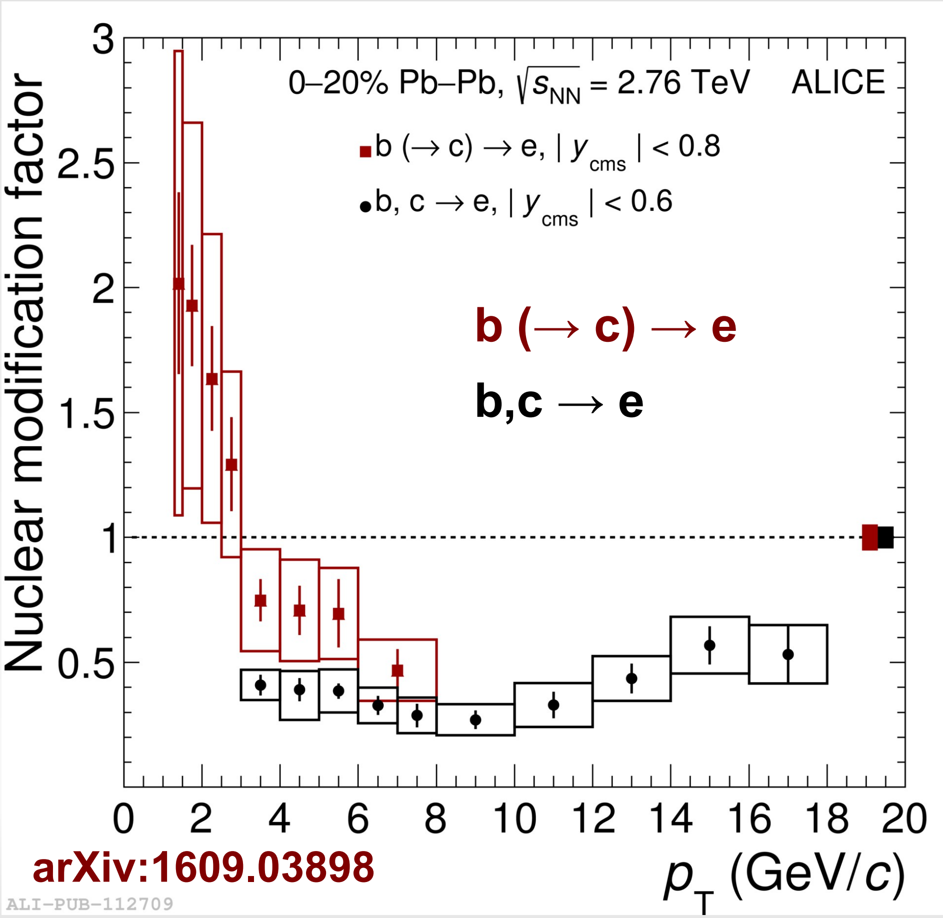
→ **low-p_T** measurements **crucial** in all systems to **test binary scaling** of total $c\bar{c}$ cross section

→ Suppression compatible with the one observed in the muon decay channel

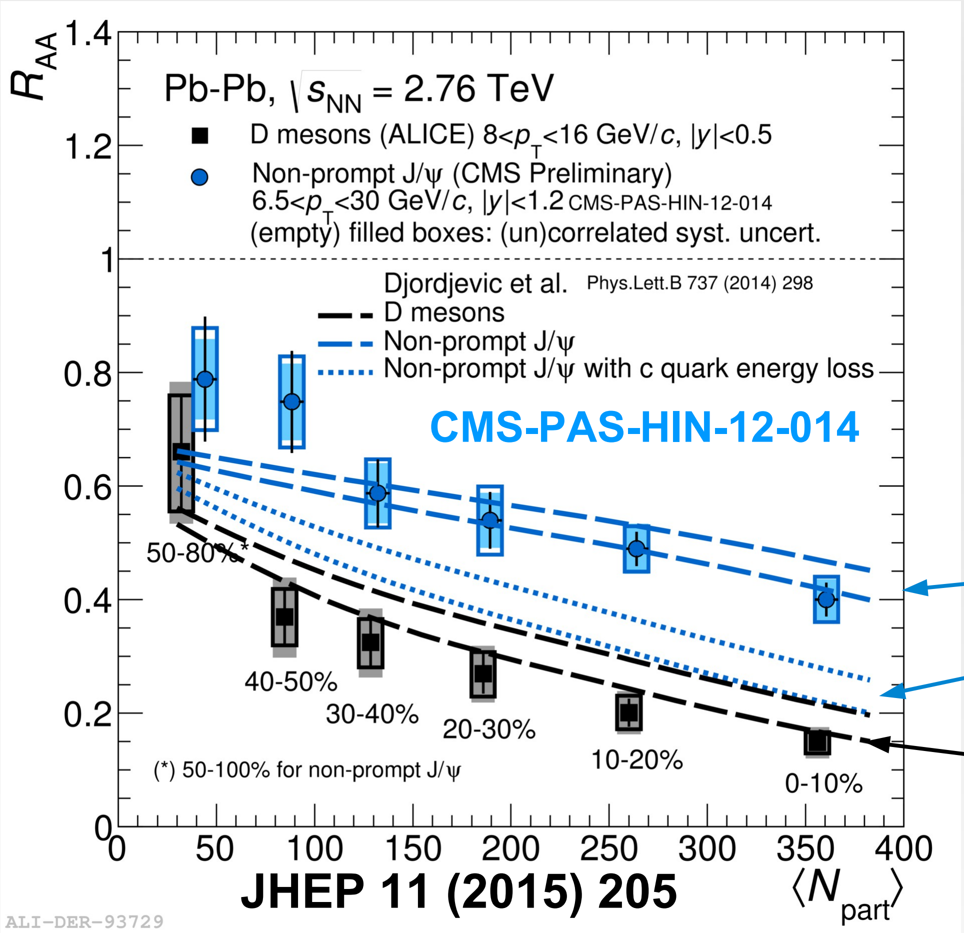
→ Heavy-flavour decay muon R_{AA} at 5.02 TeV consistent with that at 2.76 TeV

Beauty-decay electron R_{AA}

– Analysis based on the electron impact parameter distribution.
– First R_{AA} measurement of beauty-decay electron:
→ $R_{AA} < 1$ for $p_T > 3$ GeV/c
→ consistent with the picture of **mass-dependent radiative and collisional energy loss**



D-meson and J/ψ ← B R_{AA} vs centrality



– Similar <p_T> (~10 GeV/c) for D and B mesons (J/ψ ← B) from CMS

– **Indication of R_{AA}(D) < R_{AA}(J/ψ ← B)** in central events at high p_T

✔ **Djordjevic**: non-prompt J/ψ R_{AA} considering for energy loss

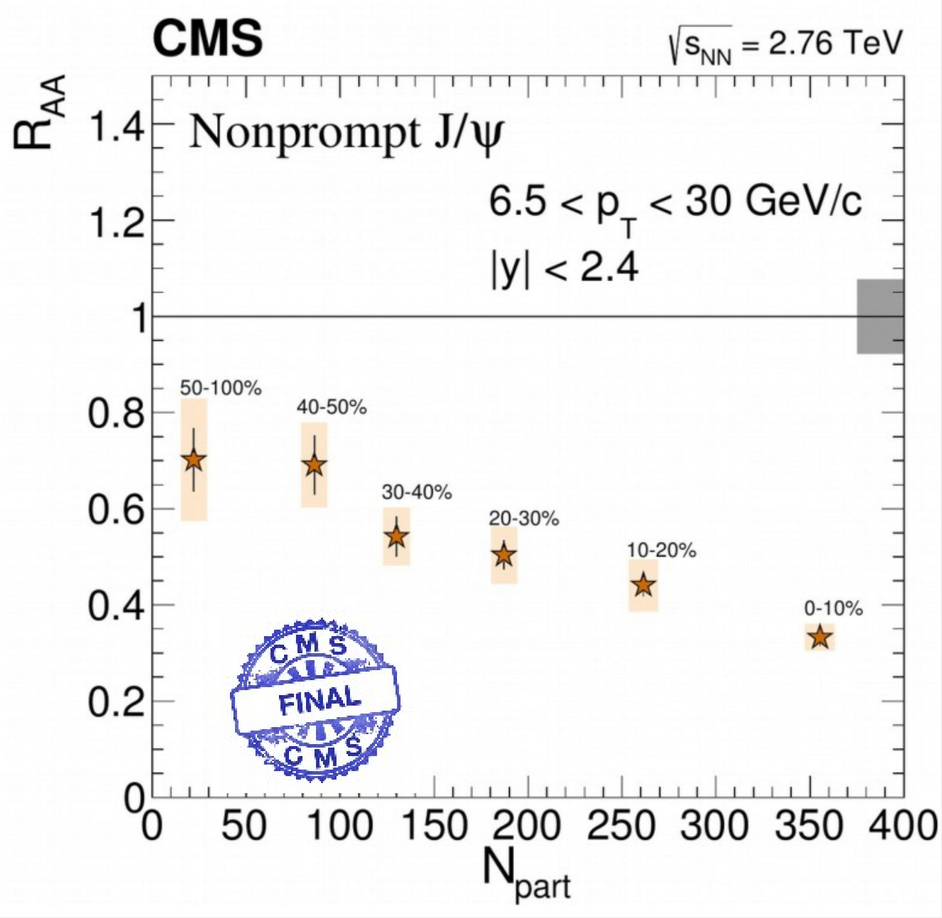
– b quark mass
– c quark mass

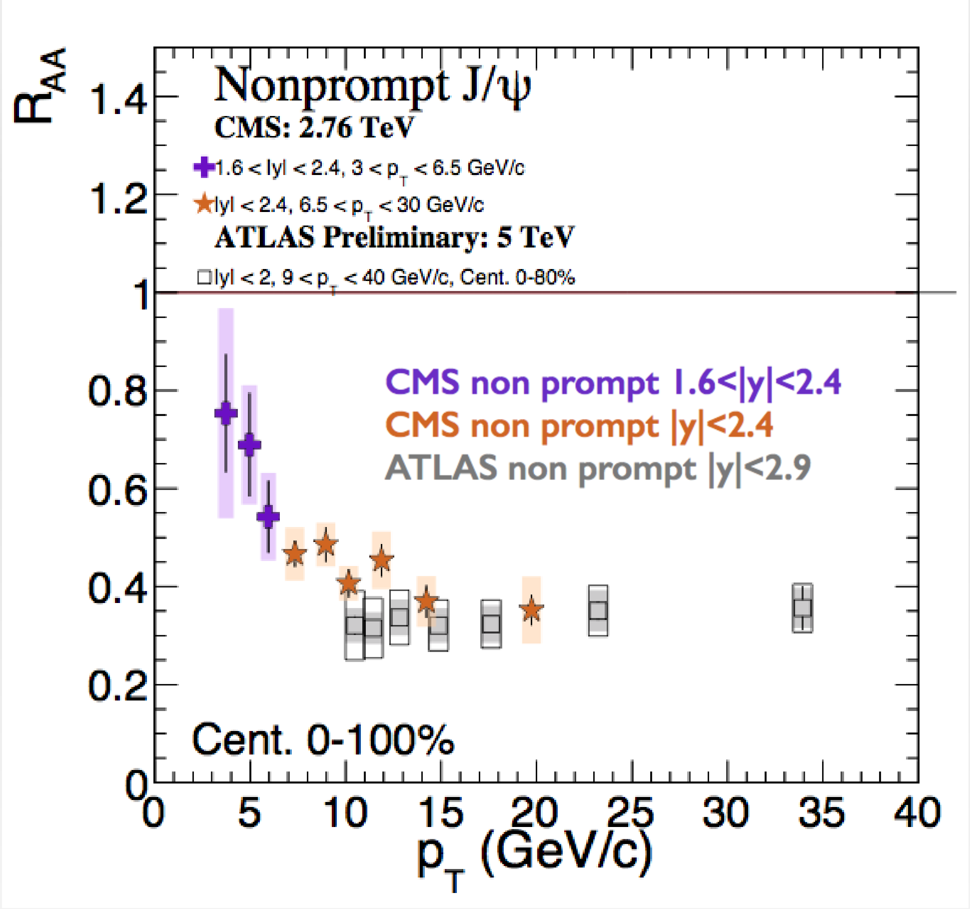
Testing the mass dependence

✔ **Djordjevic**: D-meson R_{AA}
PRL 737 (2014) 298

– **pQCD model including mass-dependent radiative and collisional energy loss predicts a difference between the D-meson and non-prompt J/ψ R_{AA} similar to that observed**

J/ψ ← B R_{AA} vs centrality and pT



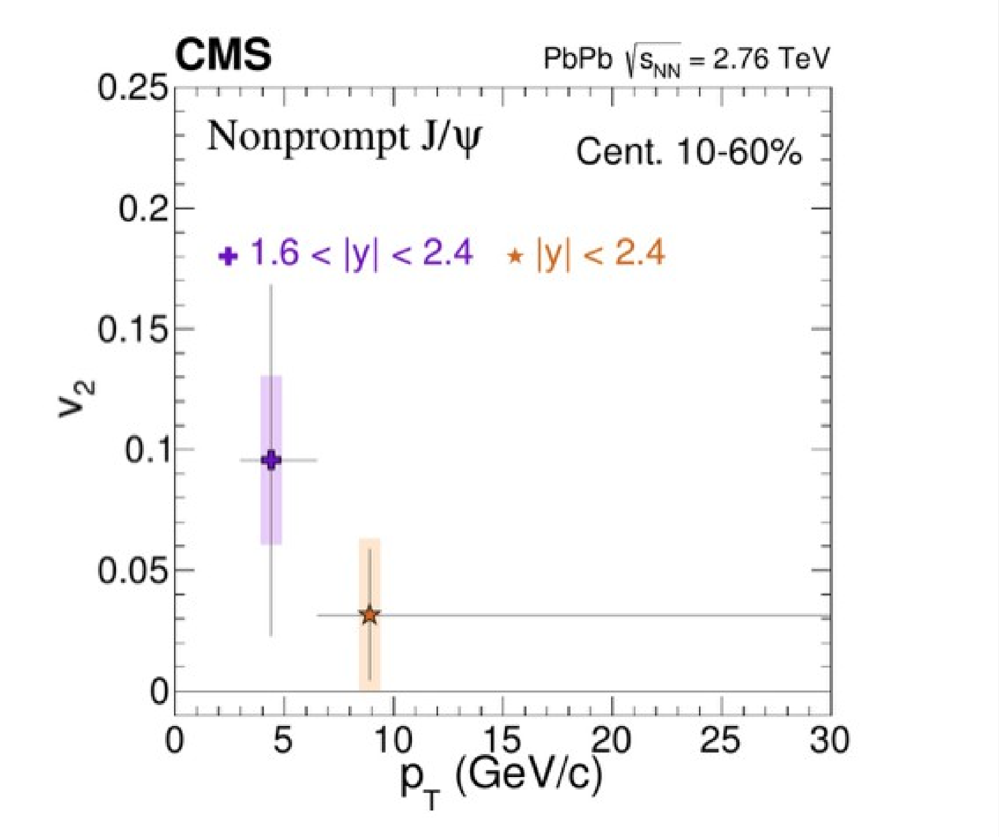


Strong suppression observed for non-prompt J/ψ in Pb-Pb collisions
Clear suppression as a function of centrality and p_T

2.76 TeV and 5.02 TeV (ATLAS) results well consistent within the uncertainties

Elliptic flow of J/ψ ← B

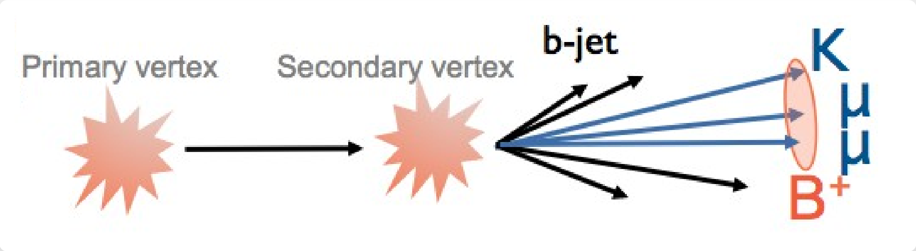
New measurement of v_2 of non-prompt J/ψ in Pb-Pb collisions at 2.76 TeV

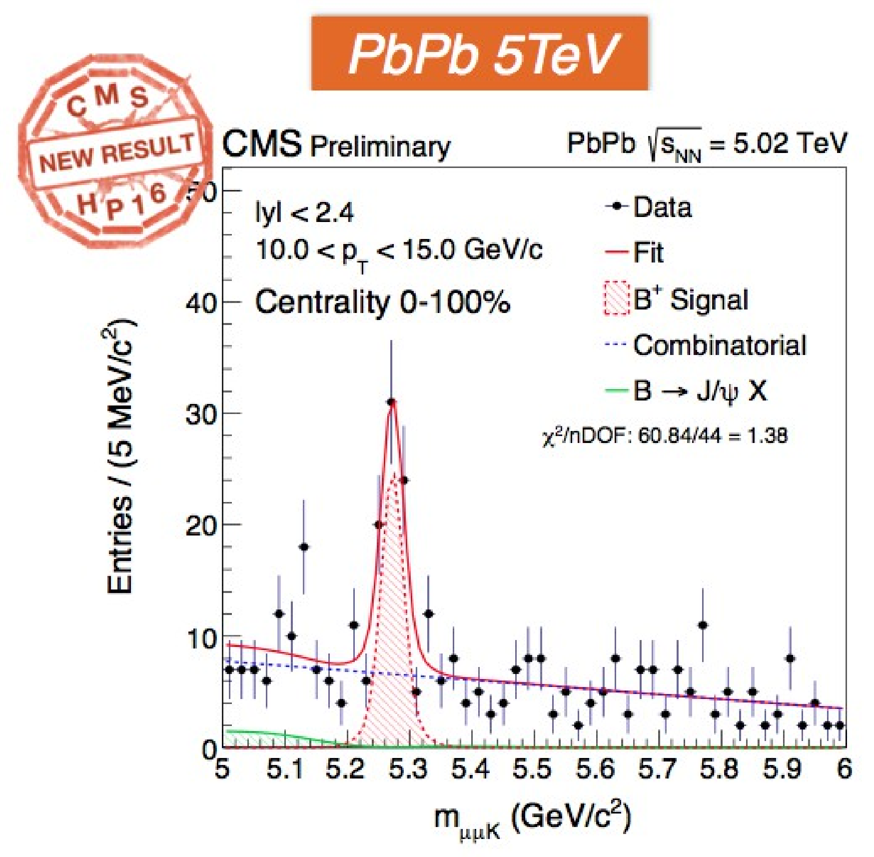


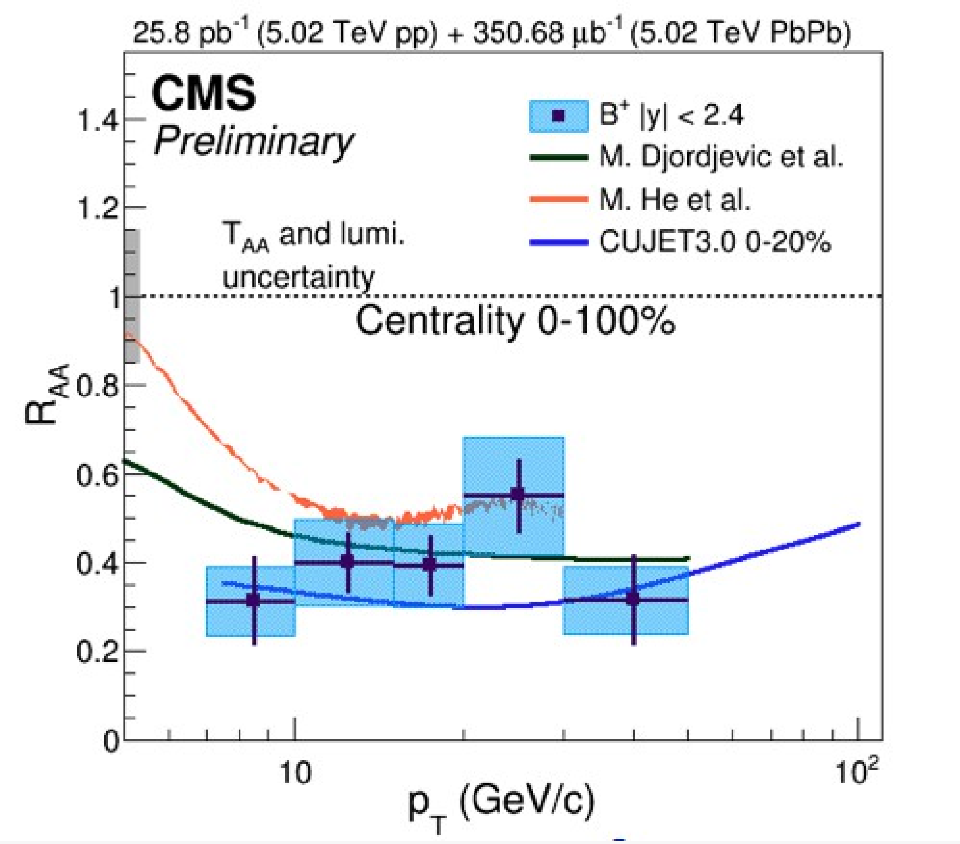
→ Central value of v_2 of non-prompt J/ψ compatible within 2σ with 0
→ Looking to see the new measurement with Run 2 data with larger statistics

B^+ meson R_{AA}

FIRST EVER measurement of fully reconstructed B^+ meson in Pb-Pb collisions



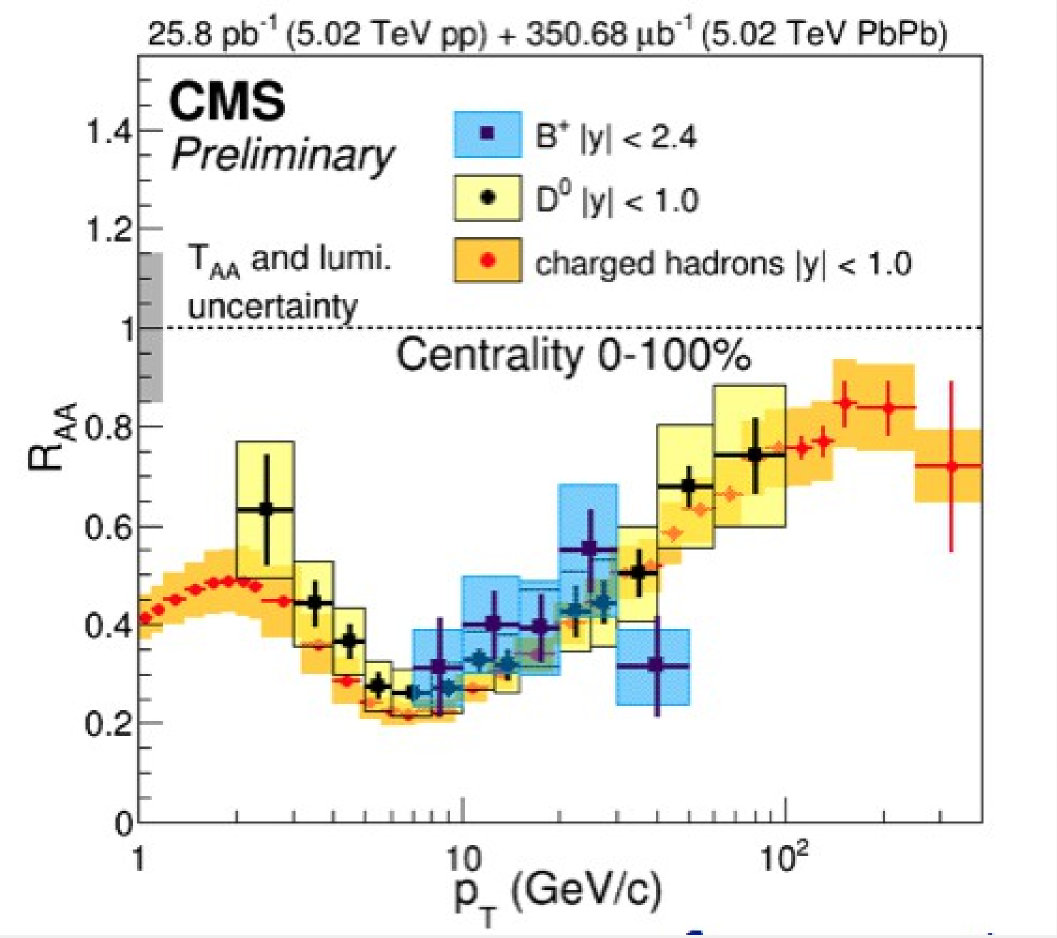




Strong suppression of B^+ mesons (p_T between 7-50 GeV/c)

Flavour dependence of E_{loss} at 5.02 TeV

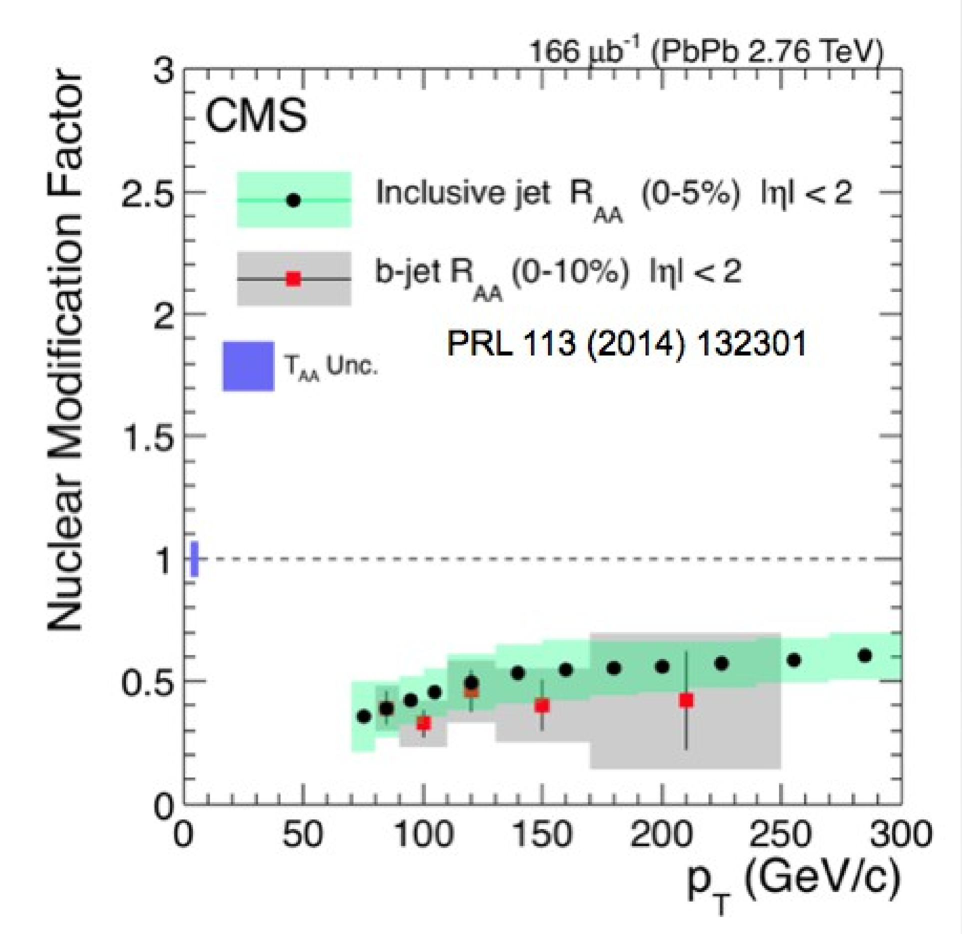
R_{AA} of B, D and charged hadrons fully compatible within the uncertainties in the available p_T range (REMEMBER: p_T^B > 7 GeV/c)



Does it mean that there is no flavour dependence?
Not necessarily!!!

→ $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
→ different shape of the parton p_T spectra
→ different parton fragmentation functions

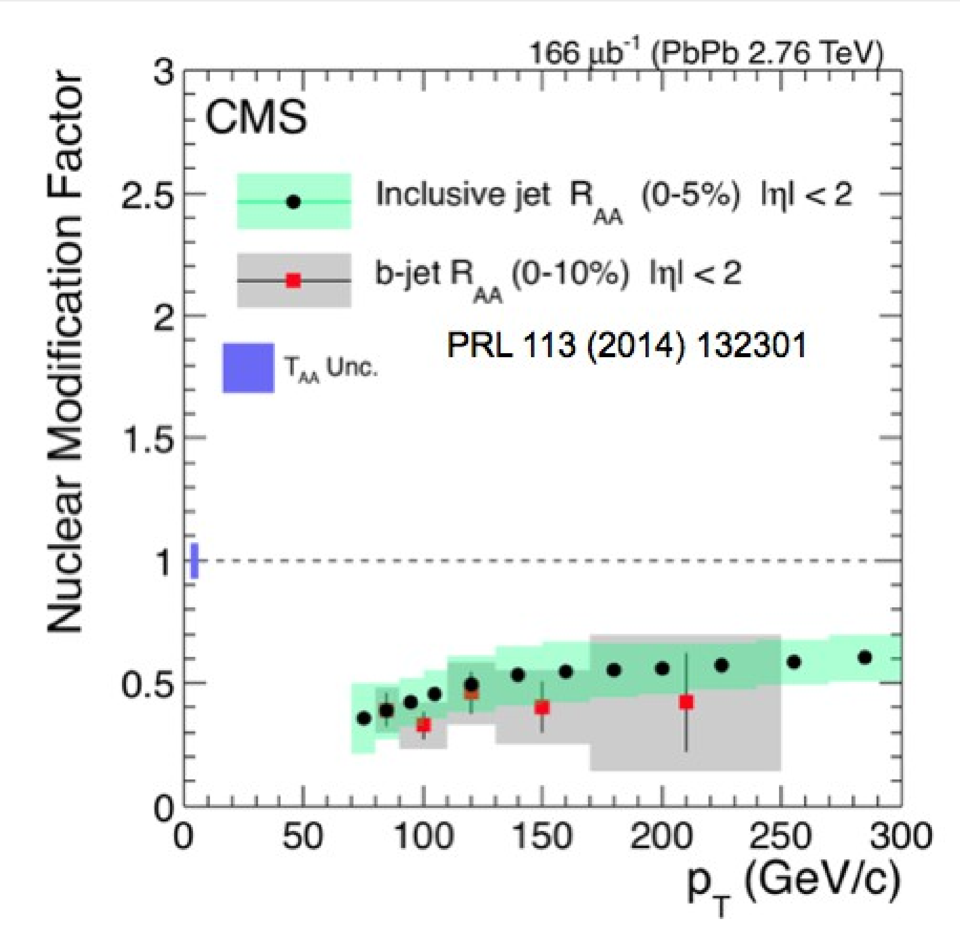
Flavour dependence at high p_T

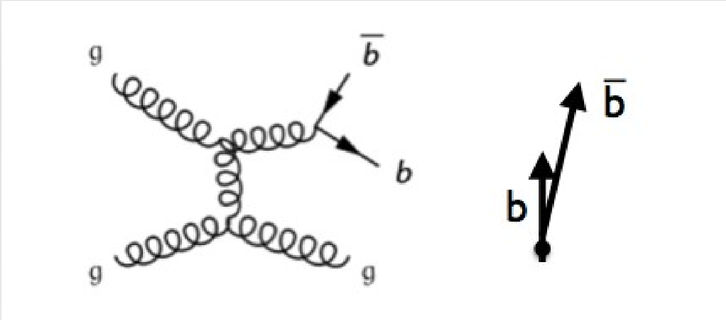


Same suppression for b-jets and inclusive jets at high p_T

→ mass difference negligible at high p_T

Flavour dependence at high pT





NLO process:
gluon splitting about 20%,
dominat at small opening angles

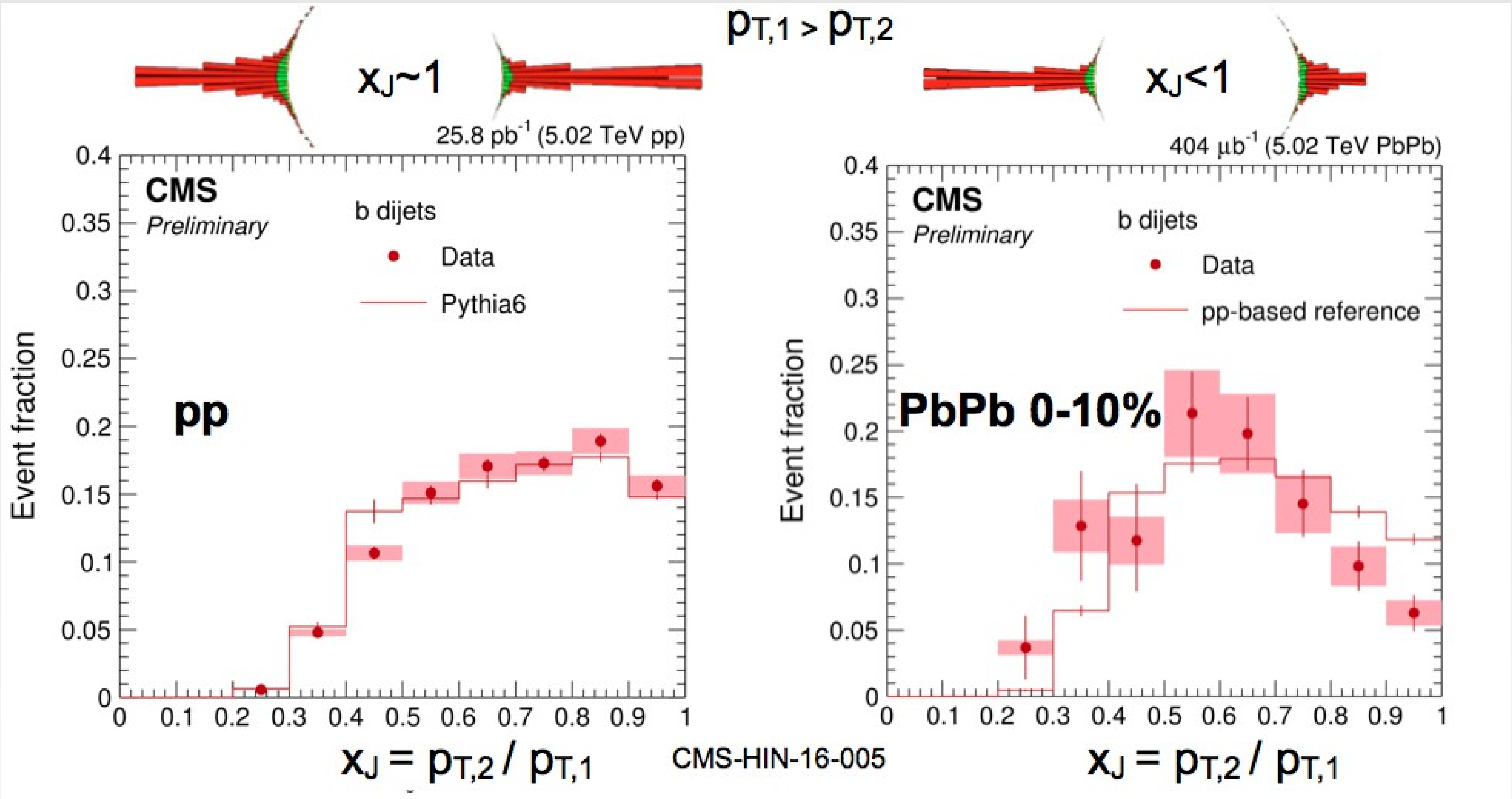
Same suppression for b-jets and inclusive jets at high p_T

→ mass difference negligible at high p_T

→ Contribution of gluon splitting processes? In GSP case, we are not measuring the b-quark E_{loss} but to some fact gluon E_{loss}

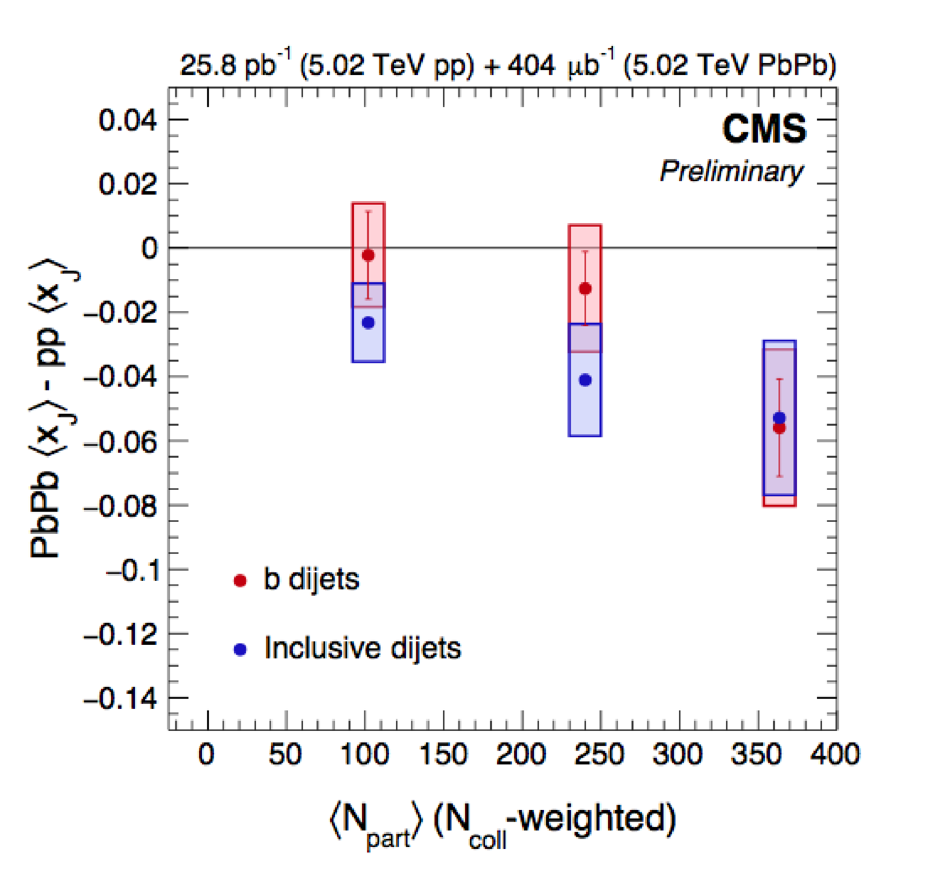
Di-b-jet measurements in Pb-Pb at 5.02 TeV

In back-to-back events $b\bar{b}$ production via gluon splitting is negligible



x_J distribution of di-b-jets significantly modified in central Pb-Pb collisions

Di-b-jet measurements in Pb-Pb at 5.02 TeV



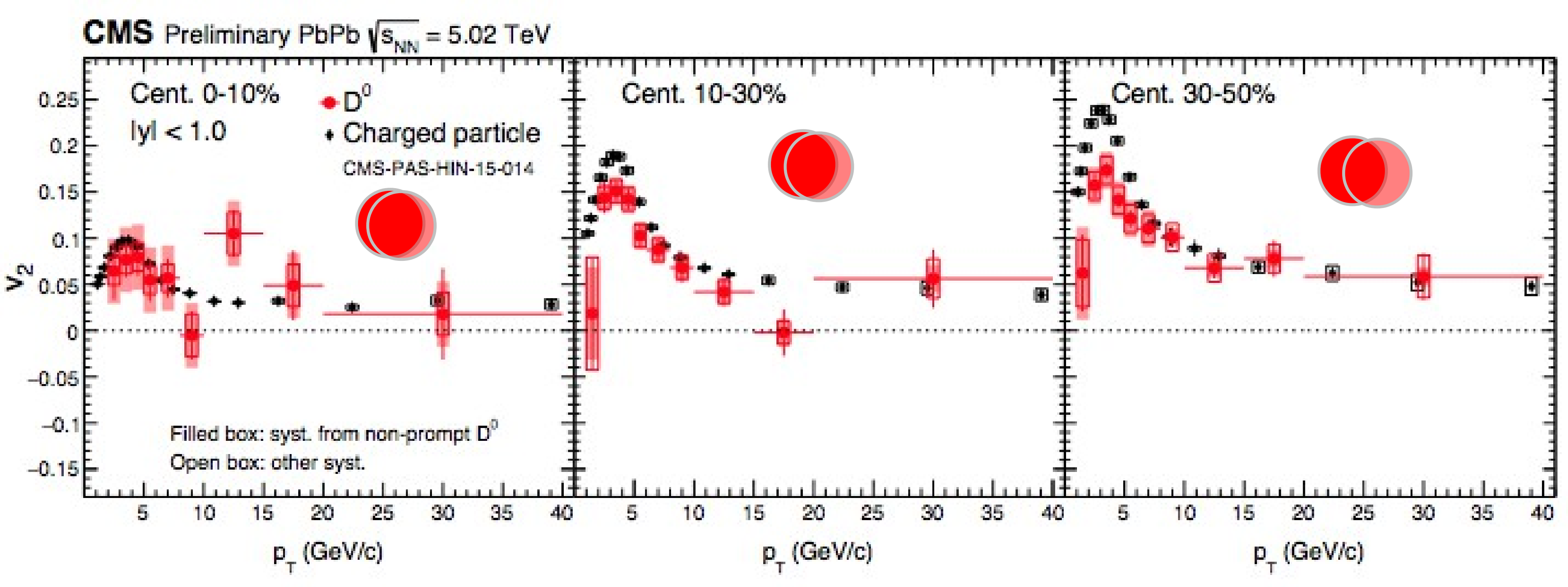
$x_J = p_{T,2} / p_{T,1}$

→ Inclusive dijet and b dijet imbalance are within uncertainty

→ Same average asymmetry observed for inclusive jets

There is no significant difference in the suppression of inclusive and b-jets even after excluding the contribution of gluon splitting processes

D-meson elliptic flow



– v_2 > 0 at low and high p_T in peripheral events

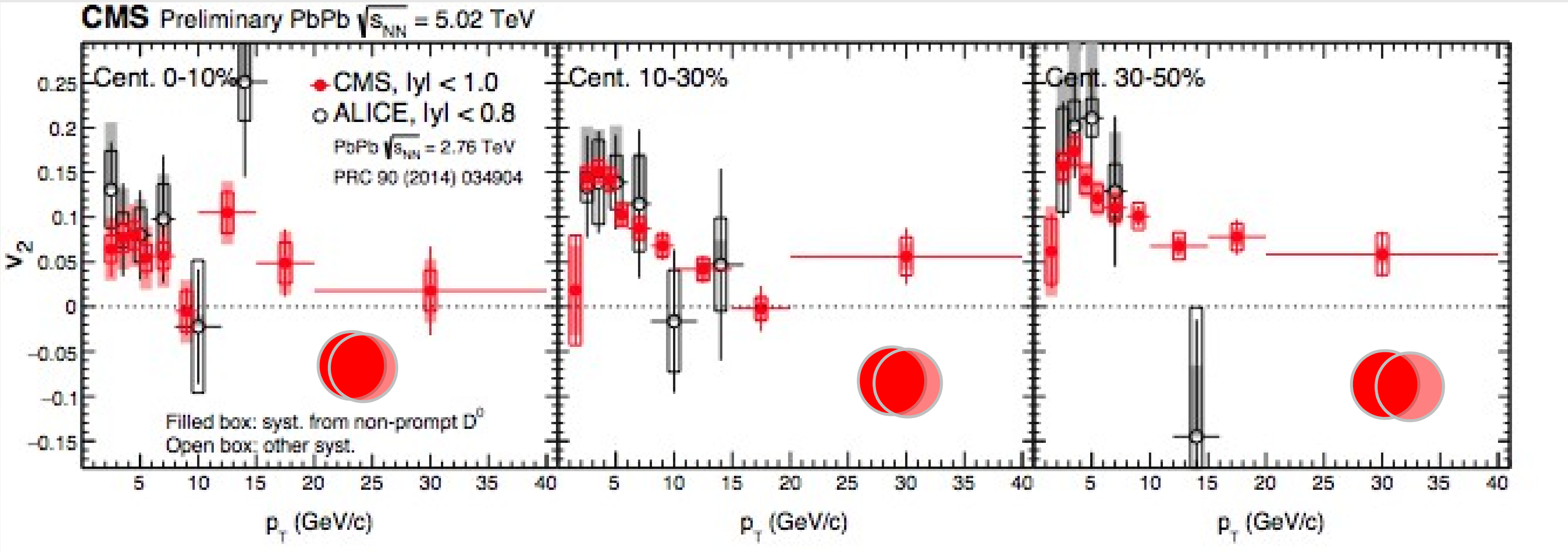
– In 0-10% → consistent with v_2 of charged hadrons

– In 10-30% and 30-50%

→ Low p_T: v_2 (promt D^0) < v_2(charged hadrons)

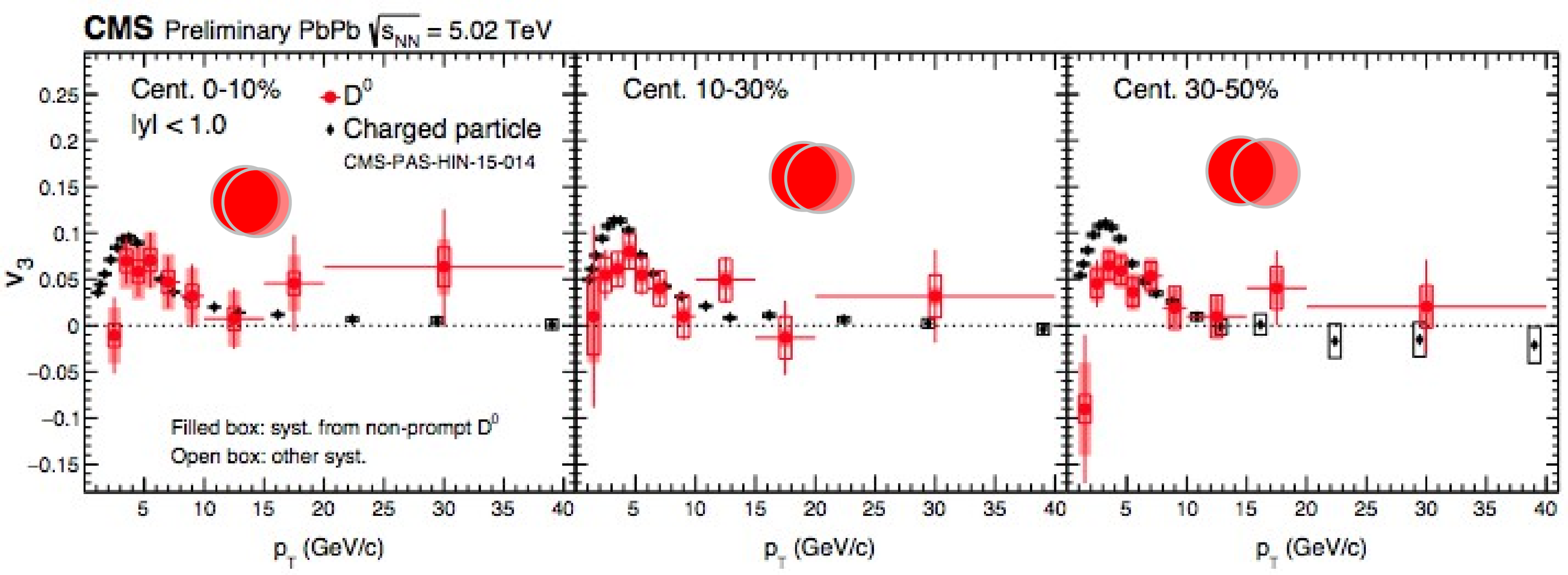
→ High p_T: v_2 (promt D^0) ~ v_2(charged hadrons)

D-meson elliptic flow at different collision energies



CMS preliminary results at 5.02 TeV are consistent with ALICE results at 2.76 TeV within uncertainties

D-meson triangular flow



– FIRST observation of triangular flow for charm!

– p_T dependence

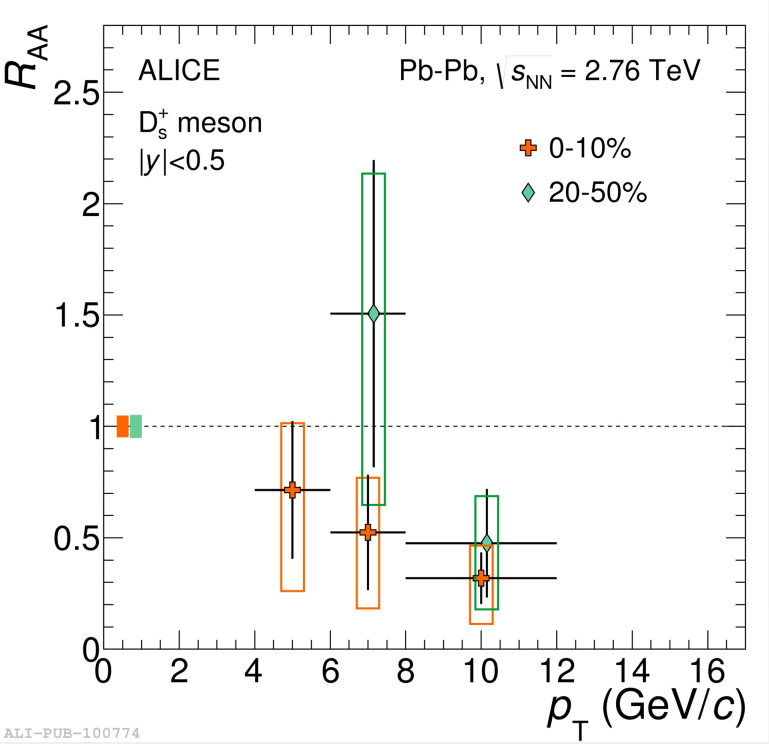
→ Low p_T: v_3 (prompt D^0) > 0;

→ High p_T: v_3 (prompt D^0) ~ 0

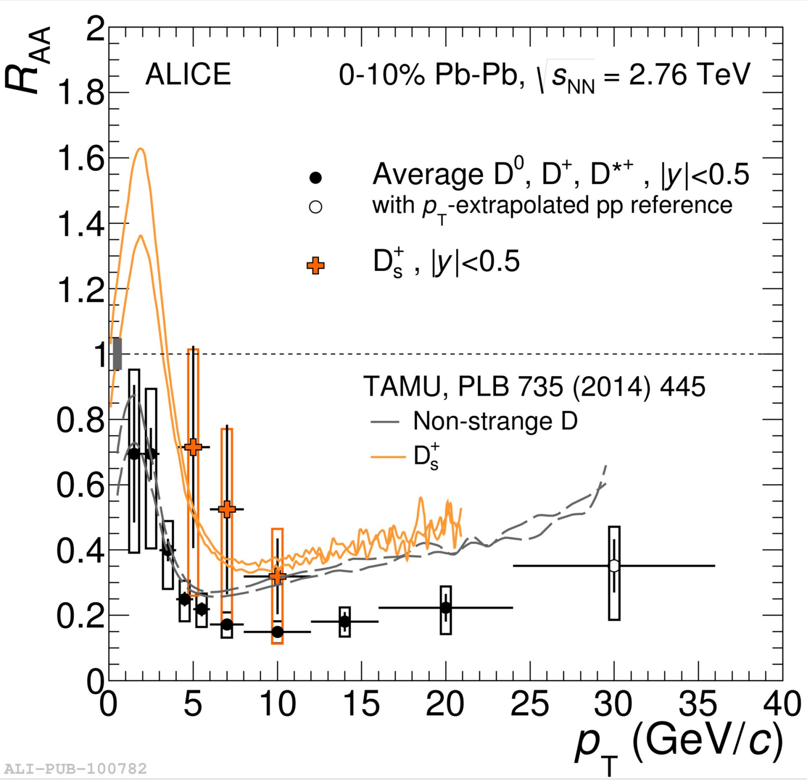
– Little centrality dependence as for charged hadrons

D_s^+ as a probe of charm recombination

- Measurement of D_s^+ production in Pb-Pb collisions
- **Expectation**: due to enhanced strangeness abundance → enhancement of the **strange** over **non-strange** D-meson yield at intermediate p_T if charm hadronizes via recombination in the medium



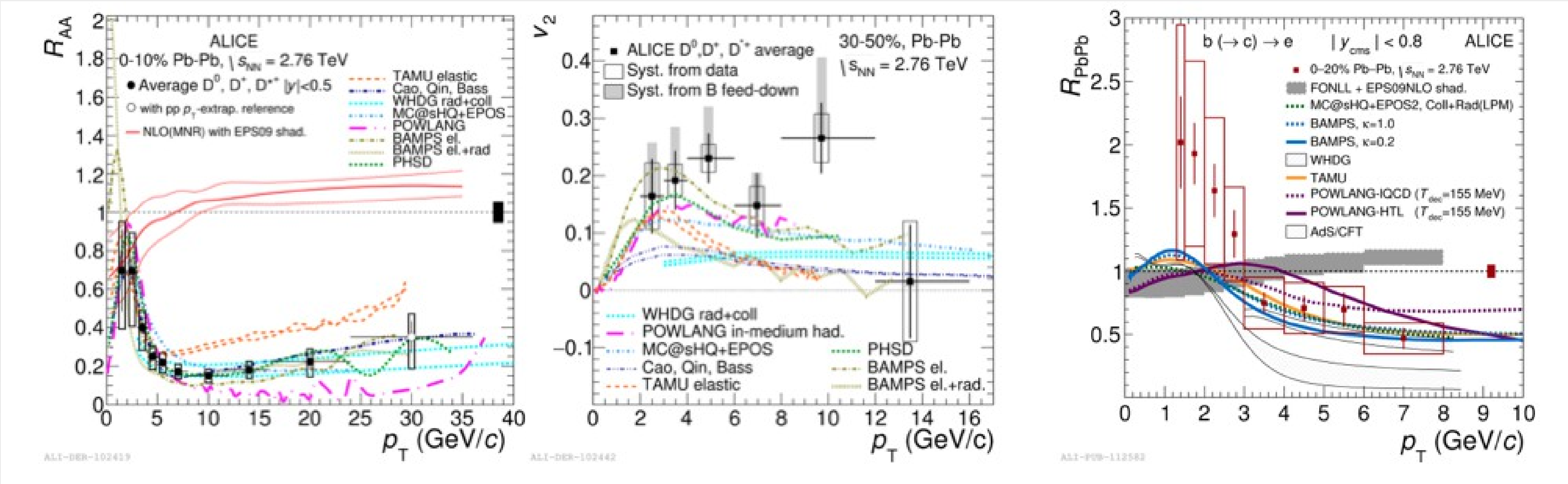
JHEP 03 (2016) 082



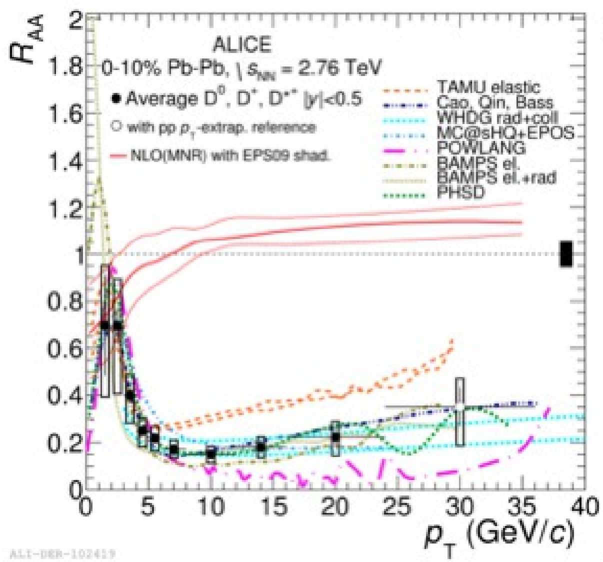
- Strong D_s^+ **suppression** in **central collisions** (similar to other D-meson) for $8 < p_T < 12$ GeV/c
- Hint of less suppression for $p_T < 8$ GeV/c

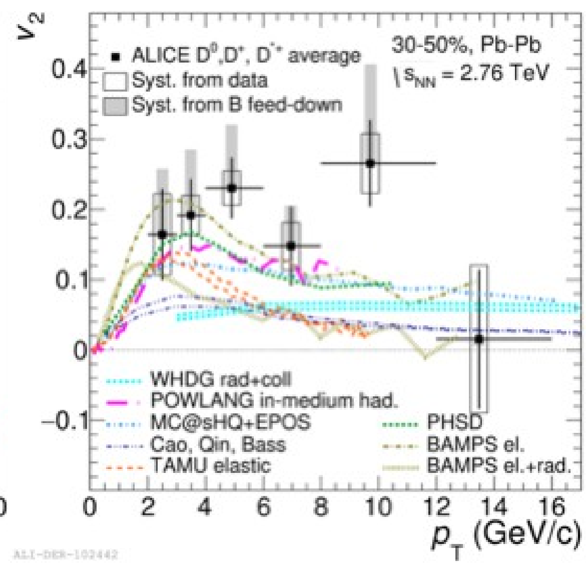
TAMU: PRL 110 (2013) 112301
Andronic et al. PLB 659 (2008) 149
Kuznetsova, Rafelski EPJ C51 (2007) 113

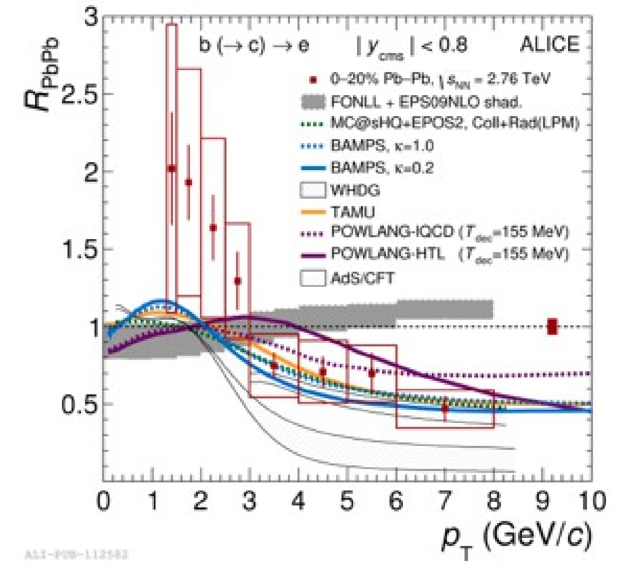
The final picture

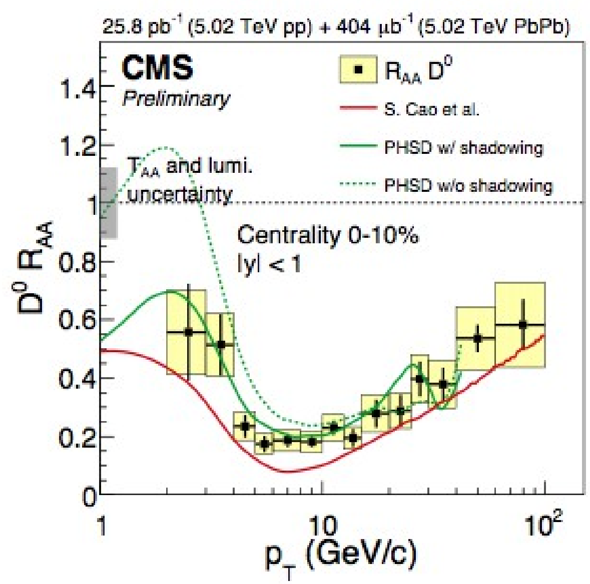


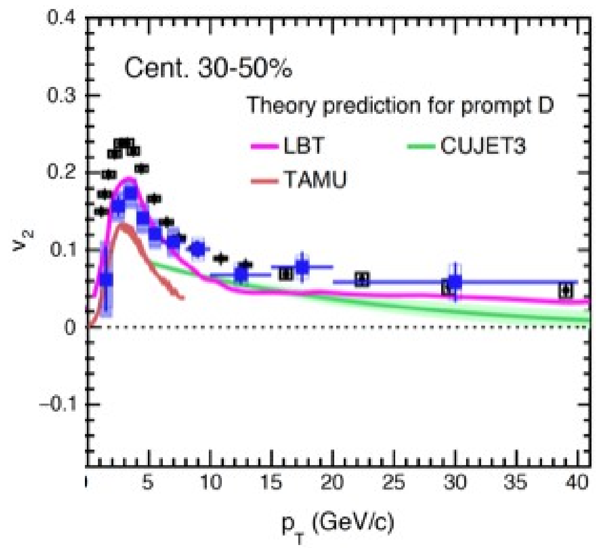
The final picture

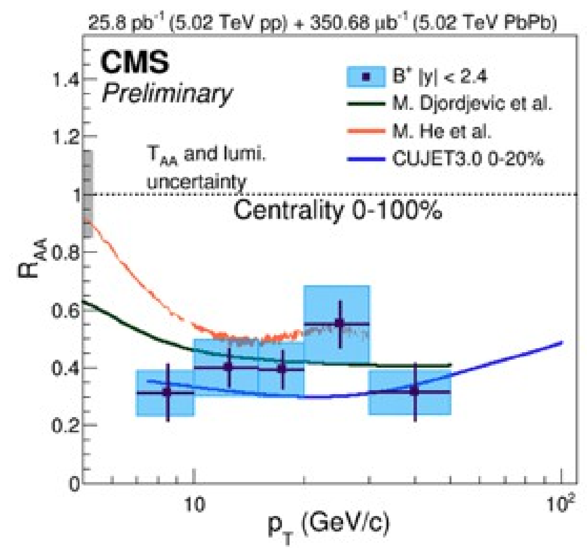












Conclusion

→ Demonstration that soft and hard v_2 probe the same initial geometry

→ Additional studies on collectivity in small systems carried out by ATLAS
– Premature to conclude on collectivity in pp collisions

→ Strong **suppression** of particle yields in Pb-Pb collisions → **final-state effect**

→ Strong suppression of **B mesons** and similar to **D mesons** and **charged hadrons**
– Described by theoretical models implementing **mass-dependent** energy loss

→ A **non-zero elliptic flow** of heavy flavours was measured in **semi-central** collisions at both 2.76 and 5.02 TeV

→ First ever measured v_3 of **D mesons**

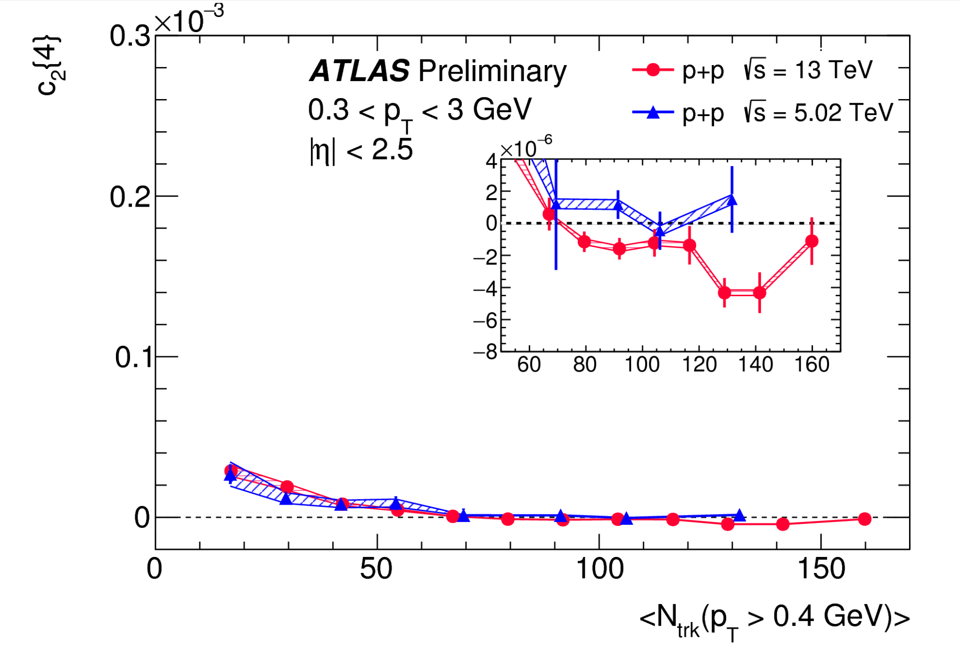
→ Suggests collective motion of low-p_T heavy quarks (mainly charm)

→ Comparison of **different observables** (R_{AA}, v_2) at different collision energies with theory provide additional constrain the **energy-loss and hadronization models**

BACKUP

Multi-particle cumulants in pp

Cumulants are extracted for reference particles (N_{trk}^{ref}): $0.3 < p_T < 3$ GeV/c using two methods:
Method 1: fixed N_{trk}^{ref} multiplicity (avoids multiplicity fluctuations)
Method 2: events are selected using N_{trk} ($p_T > 0.4$ GeV/c)

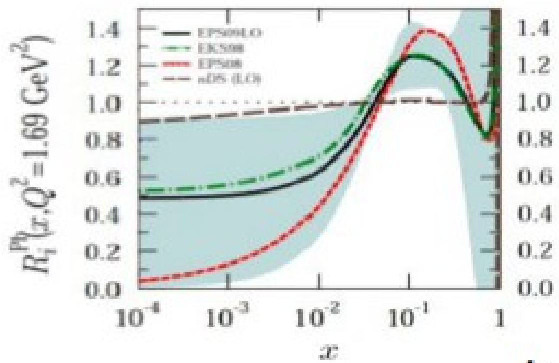


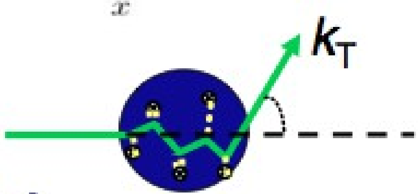
– Weak energy dependence to cumulants, however systemtically higher c2{4} measured at 13 TeV at low Ntrk, at higher Ntrk the trend is reversed.

Physics motivation

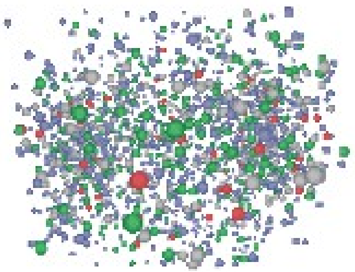
Cold nuclear matter effects: p-Pb collisions

- GOAL: assess the role of **cold nuclear matter** (CNM) **effects**
  - ⇨ **Initial-state** effects:
    - ✓ ***Nuclear modification of the PDFs***
      → ***shadowing*** *at low Bjorken-x is the dominant effect at LHC energies*
    - ✓ ***Initial-state energy loss***
    - ✓ ***k_T broadening***
      → *due to multiple collisions of the parton before the hard scattering*





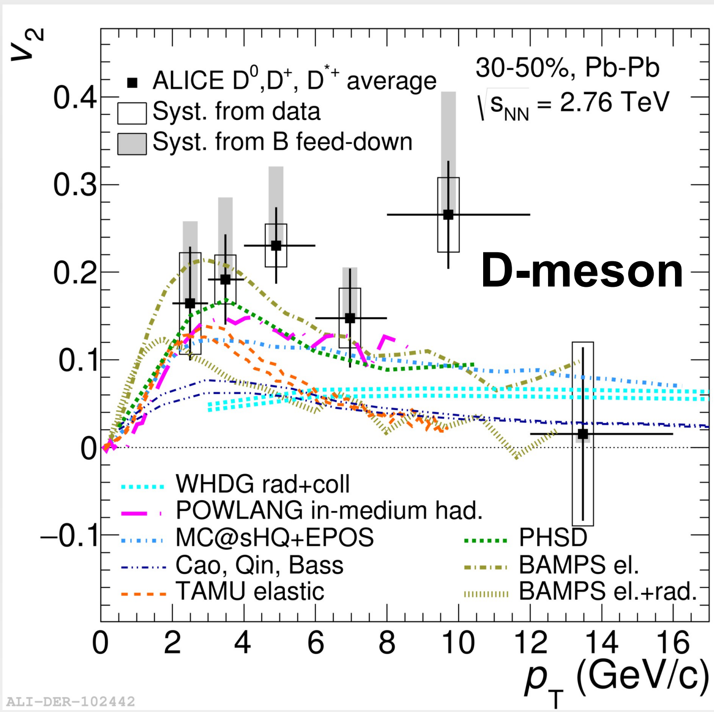
  - ⇨ **Final-state** effects
    - ✓ ***Final-state energy loss***
    - ✓ ***Interactions with the particles produced in the collision***
      → *collective expansion?*
      → *Mini QGP?*

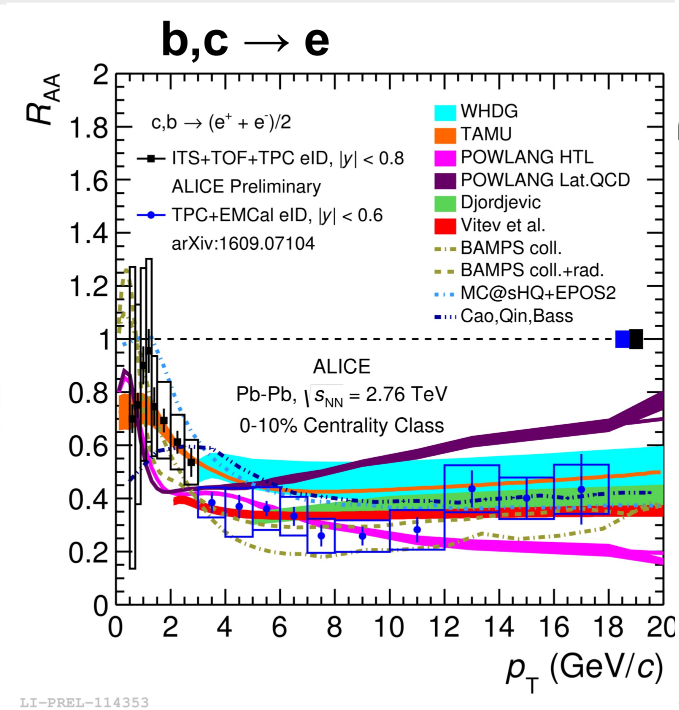


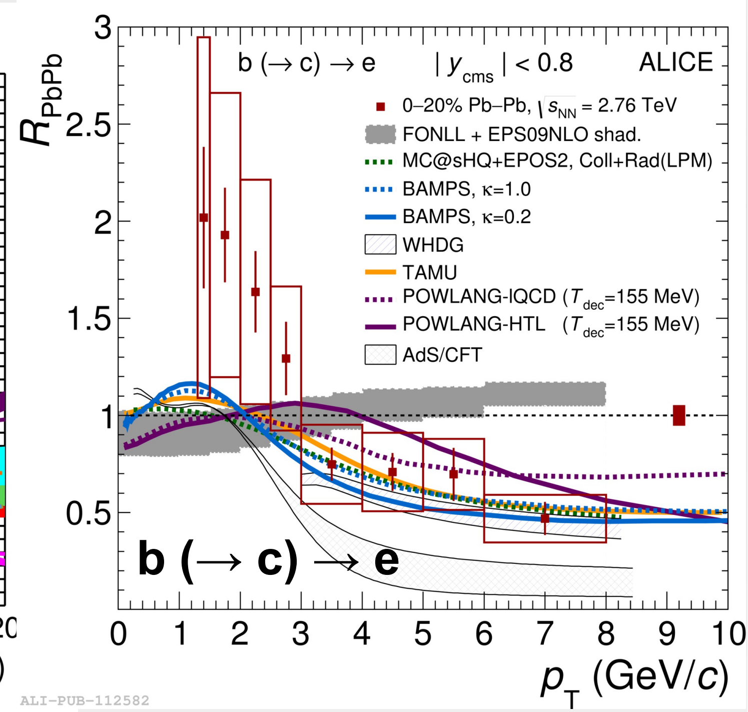
- Crucial for interpretation of Pb-Pb results

9

Model predictions: R_{AA} and v_2





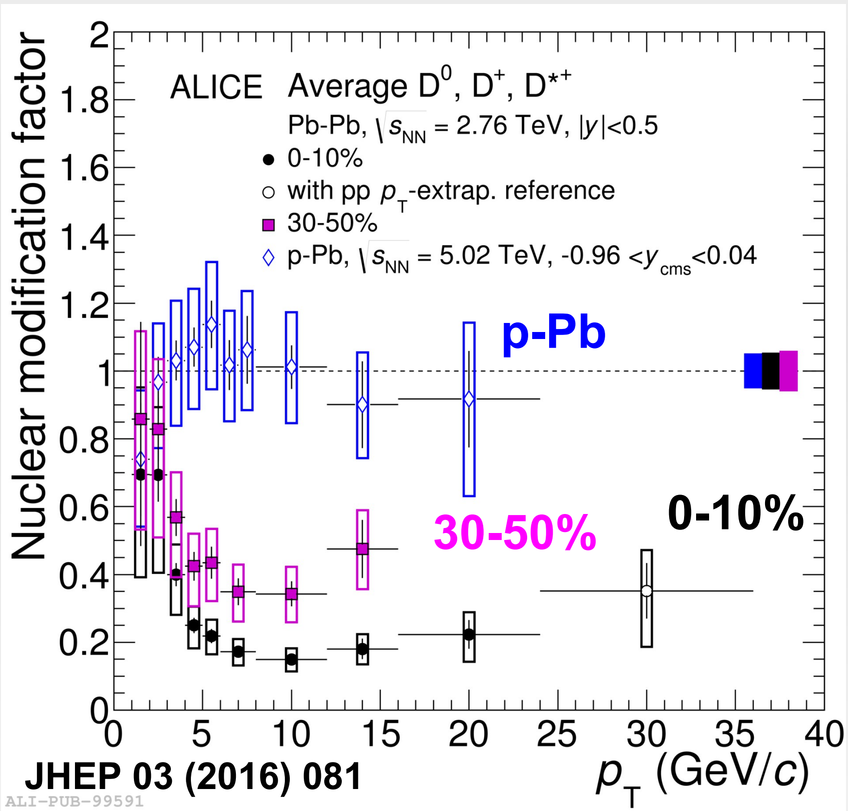


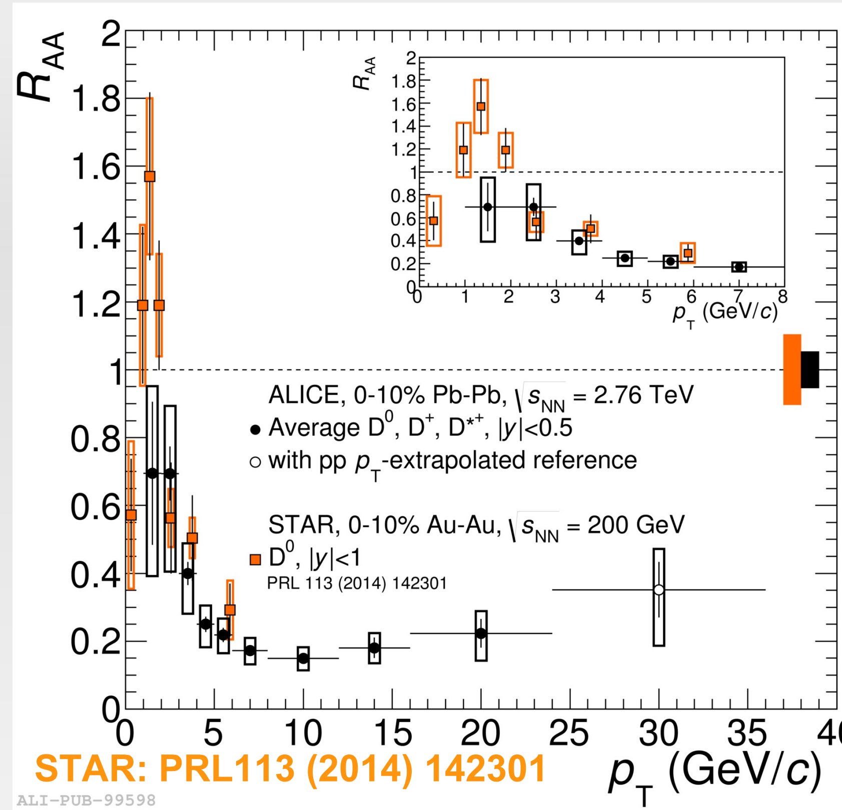
– v_2 and R_{AA} measurements for different heavy-flavour decay channels together start to provide constraints for models.

→ Both collisional and radiative energy loss mechanisms and an expanding medium seem to be needed to describe v_2 and R_{AA} for most of the model.

→ Role of recombination of heavy quark in the medium seems to help in describing v_2

D-meson nuclear modification factor





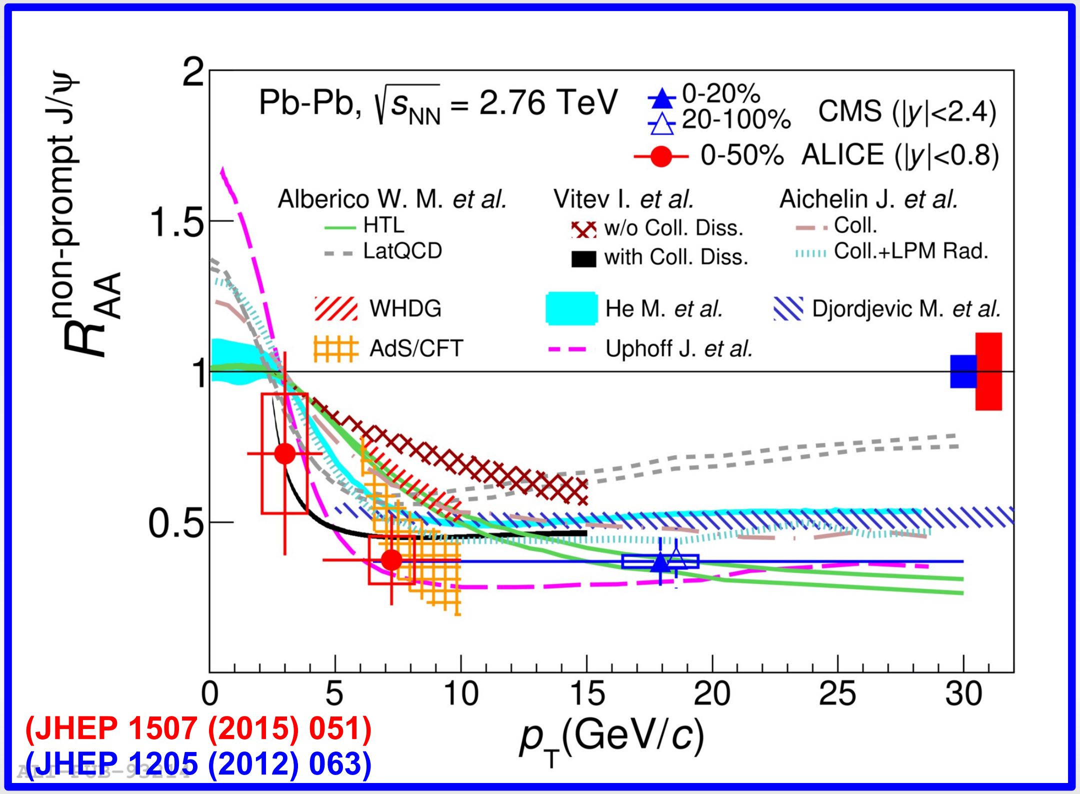
- R_{pPb} **consistent with unity (PRL 113 (2014) 232301)** → no strong modification of D-meson spectra in p-Pb collisions relative to pp collisions
- **Large suppression** of D-mesons at high p_T in **Pb-Pb** collisions → larger suppression in the 10% most central collisions → **final-state effect** due to charm quark in-medium energy loss
- **D-meson R_{AA}** compatible within uncertainties with **D^0 R_{AA}** by **STAR** for p_T > 2 GeV/*c*
  → low-p_T measurements crucial in all systems to test binary scaling of total $c\bar{c}$ cross section

R_{AA} of beauty decay electrons and J/ψ ← B

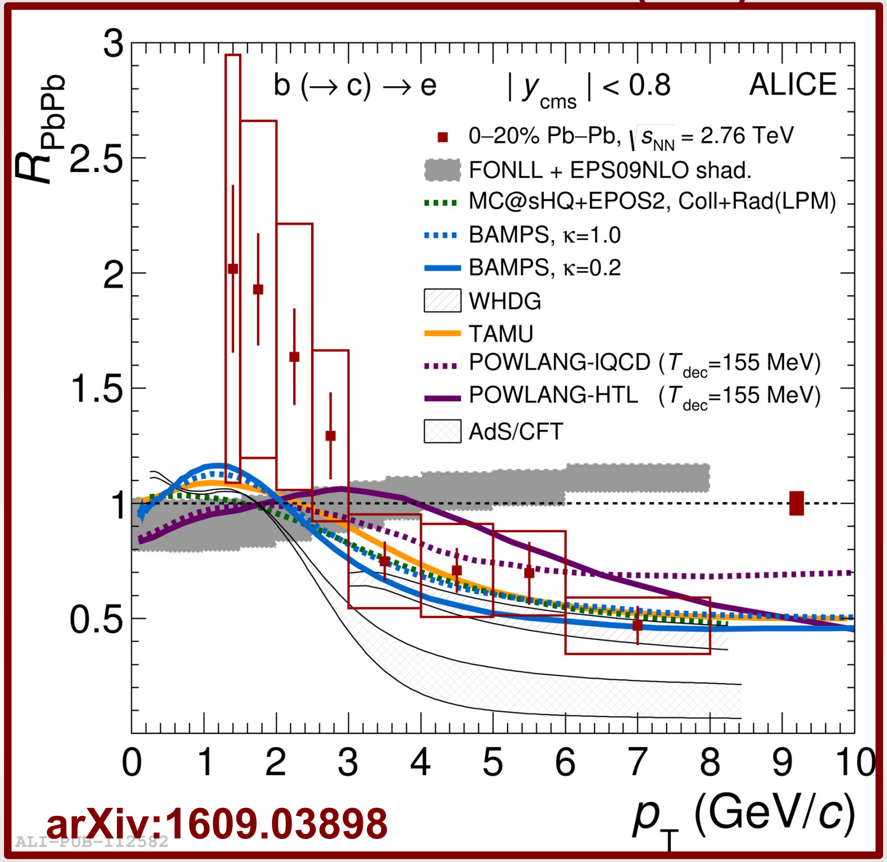
– **Indication of suppression R_{AA}(J/Ψ ← B)** in central events at high p_T

– **R_{AA} measurement of beauty:**
→ Hint for R_{AA} < 1 for beauty-decay electrons in p_T > 3 GeV/c

– models including in-medium energy loss can describe qualitatively the measured suppression

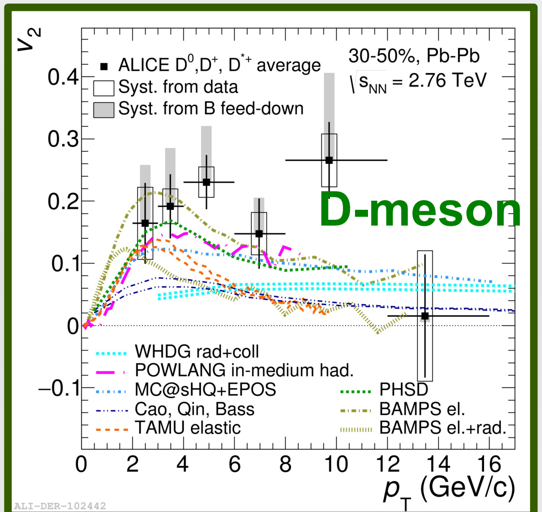


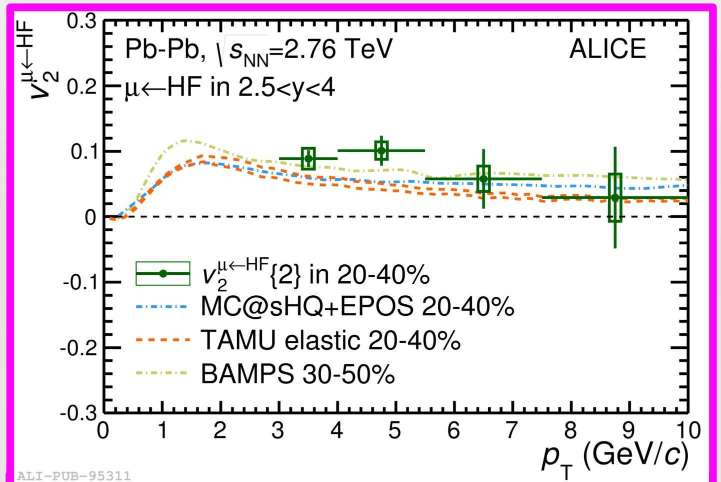
b (→ c) → e

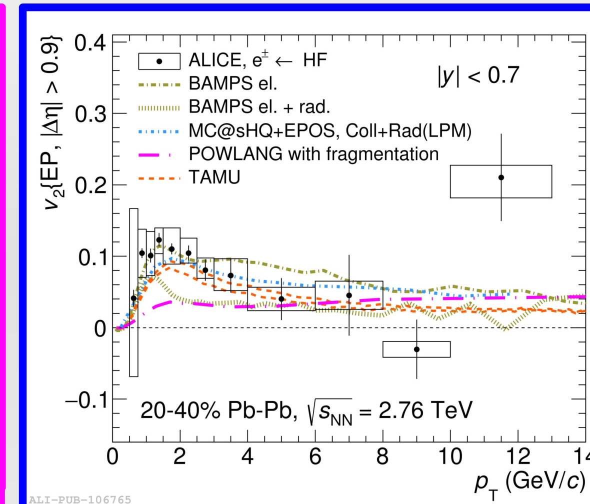


Model predictions: R_{AA} and v_2

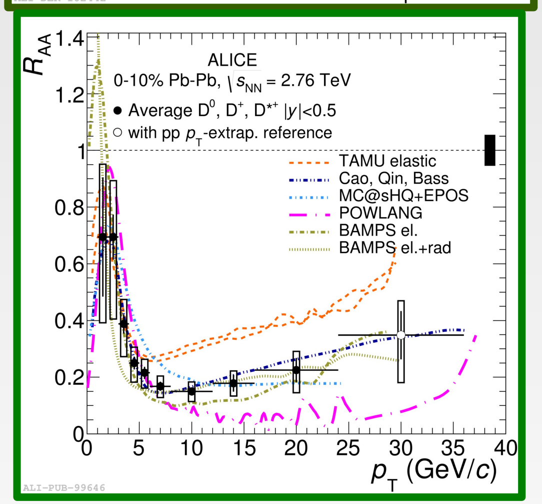
v_2

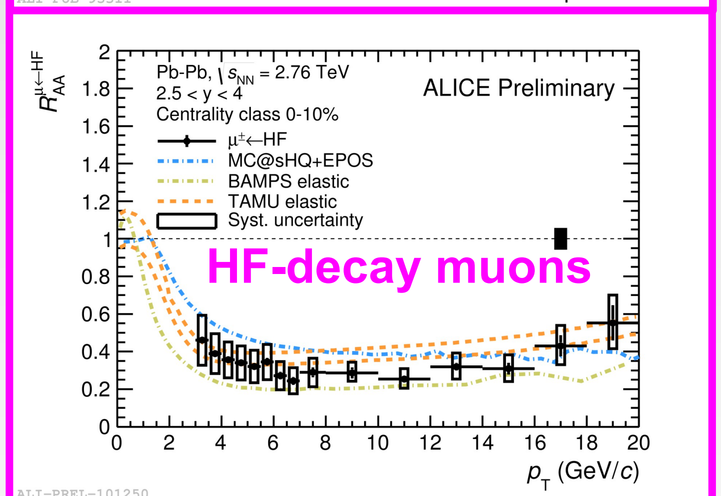


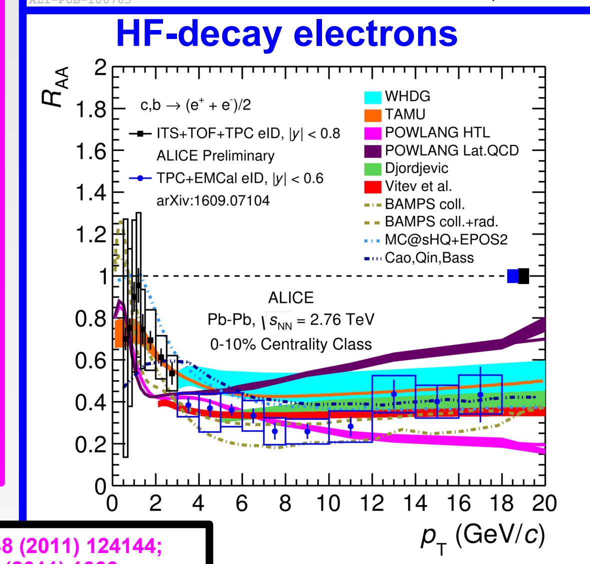




R_{AA}



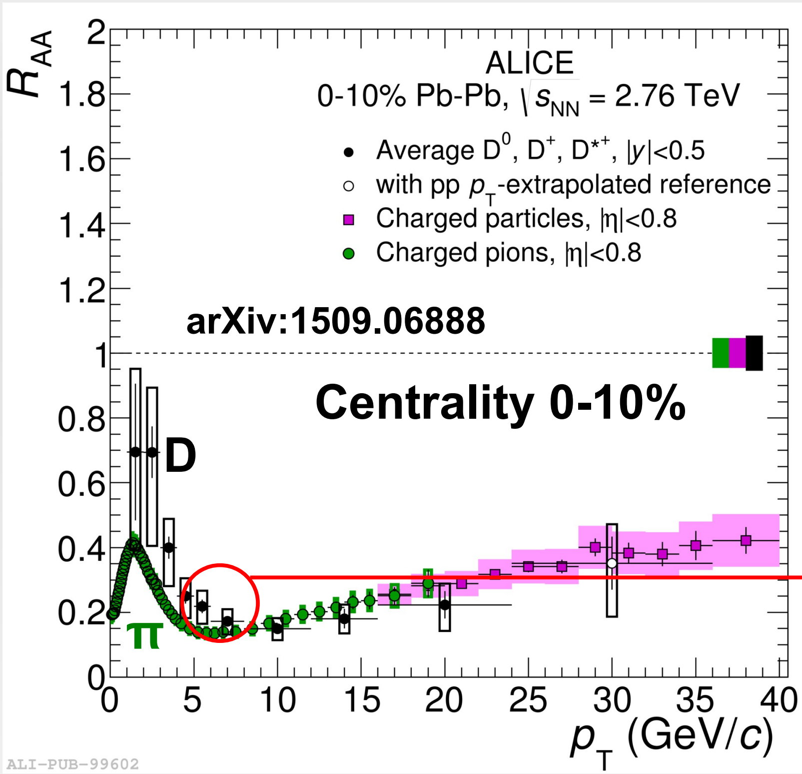


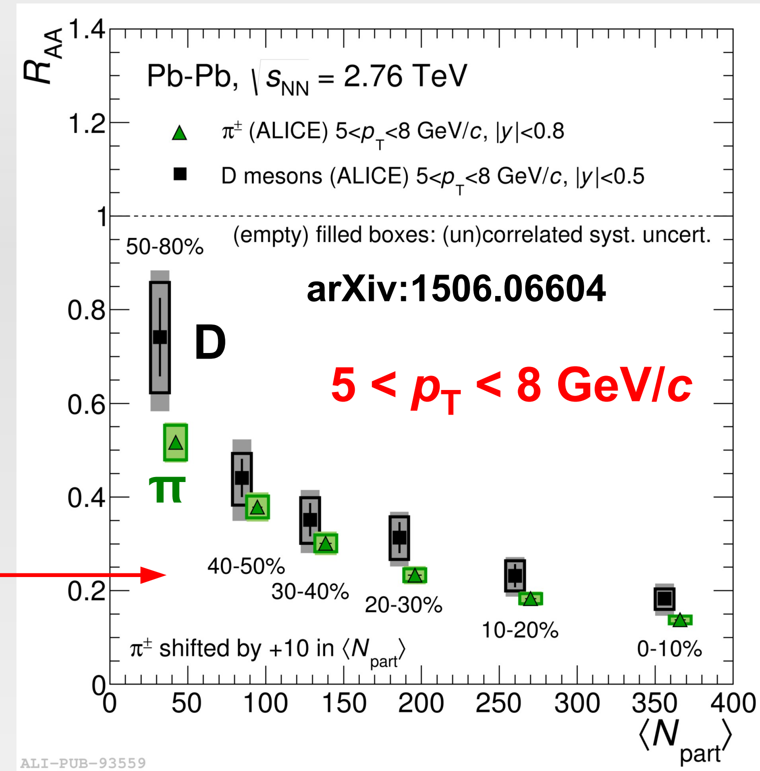


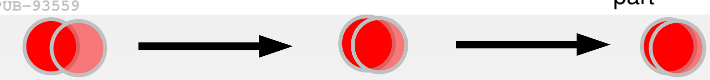
– v_2 and R_{AA} measurements together start to provide constraints for models

– POWLANG: JPG 38 (2011) 124144; Eur. Phys.J. C71 (2011) 1666;
– TAMU: arXiv:1401.3817;
– MC@HQ+EPOS: PRC 89 (2014) 014905;
– WHDG: Nucl. Phys. A 872 (2011) 256;
– BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph];
– UrQMD: arXiv:1211.6912[hep-ph]; J.Phys. Conf. Ser. 426 (2013) 012032; –
Cao,Quin, Bass: PRC 88 (2013);
– Vitev:: PRC 80 (2009) 054902;
– Djordjevic: PRL 737 (2014) 298

D-meson and pion R_{AA}

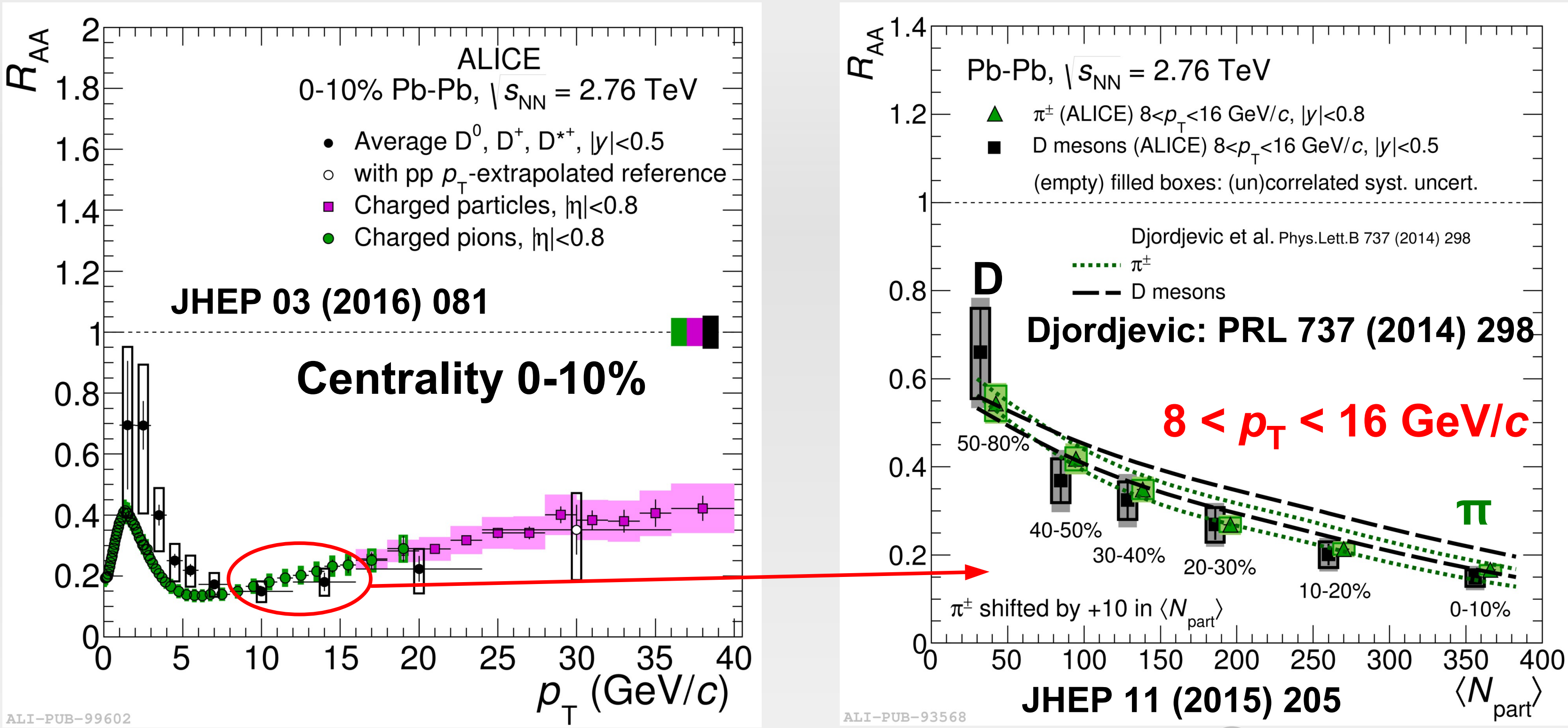






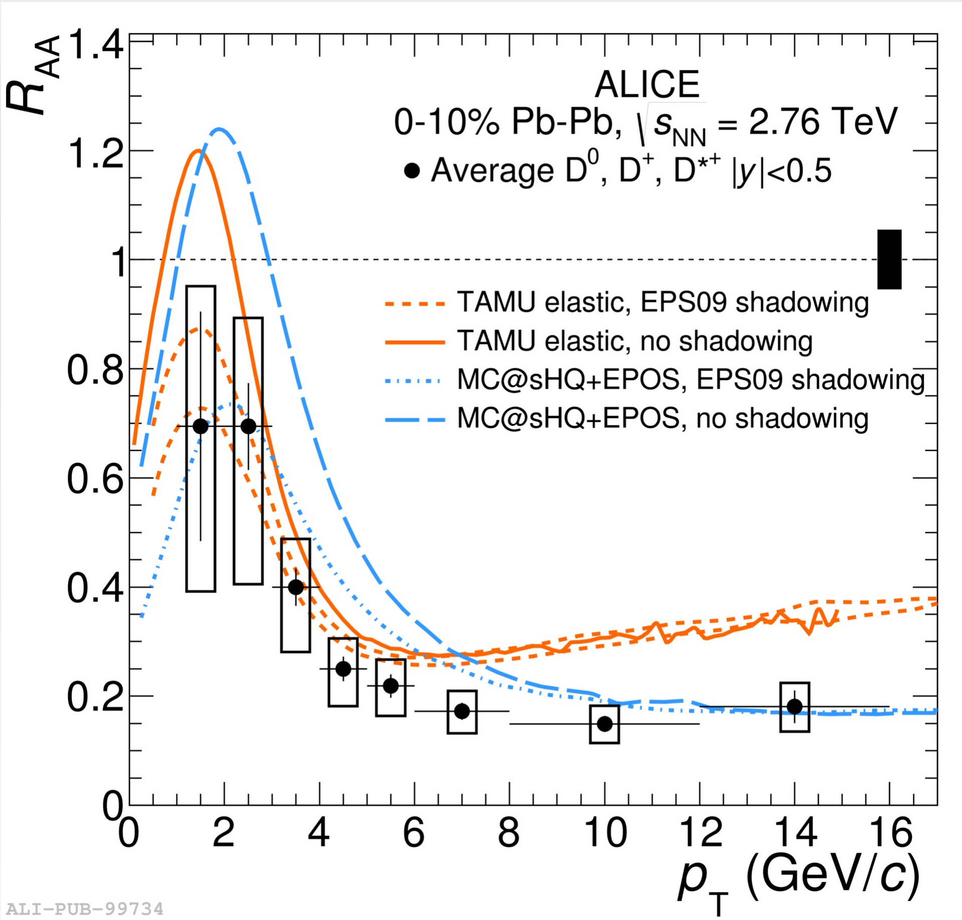
- Expected hierarchy in the energy loss:
  $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$?→ $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$
- D meson and π R_{AA} as a function of p_T and N_{part} are compatible within uncertainties

D-meson and pion nuclear modification factor



- Expected hierarchy in the energy loss:
  $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$?→ $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$
- D-meson and π R_{AA} as a function of p_T and <N_{part}> are compatible within uncertainties
- Consistency between R_{AA}(D) and R_{AA}(π) described by models taking into account:
  - → $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$
  - → different shape of the parton p_T spectra
  - → different parton fragmentation functions

D-meson and pion R_{AA}



Centrality 0-10%

arXiv:1509.06888

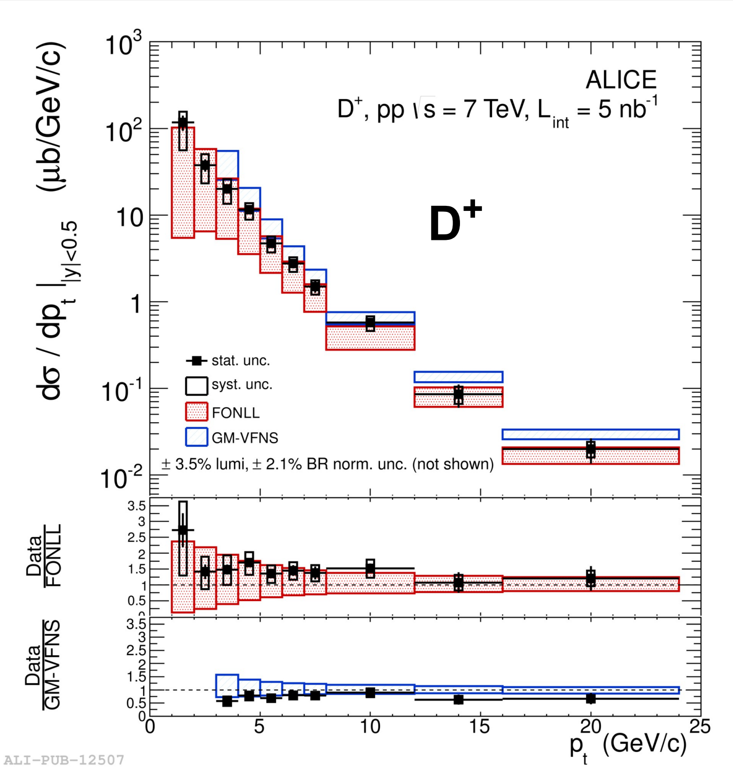
MC@sHQ+EPOS2: PRC 89 (2014) 014905

TAMU: PLB 735 (2014) 445

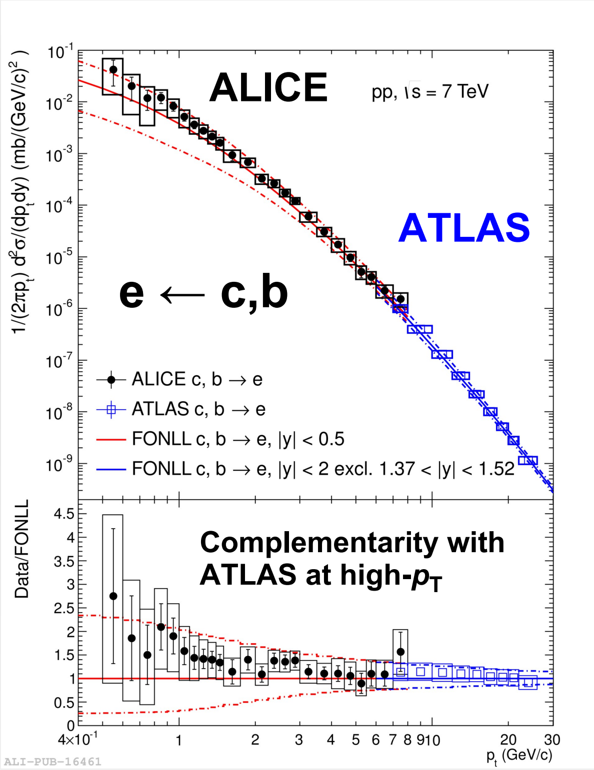
→ low-p_T measurements better described by model including nuclear shadowing (EPS09)

→ low-p_T measurements crucial in all systems to test binary scaling of total $c\bar{c}$ cross section

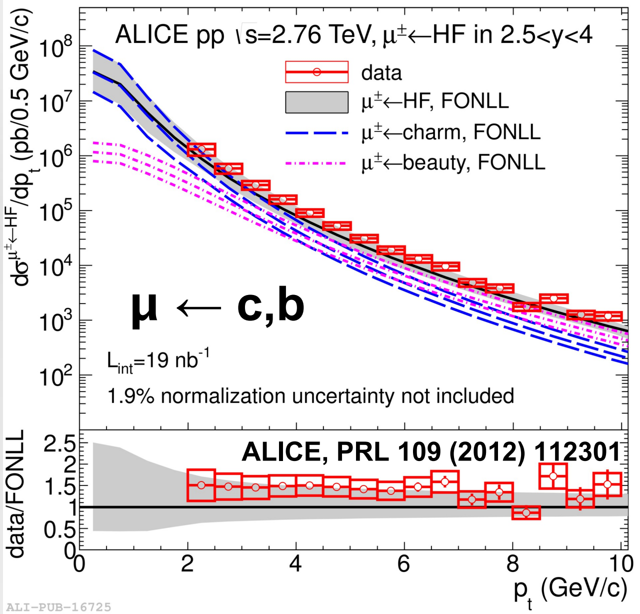
p_T-differential cross section

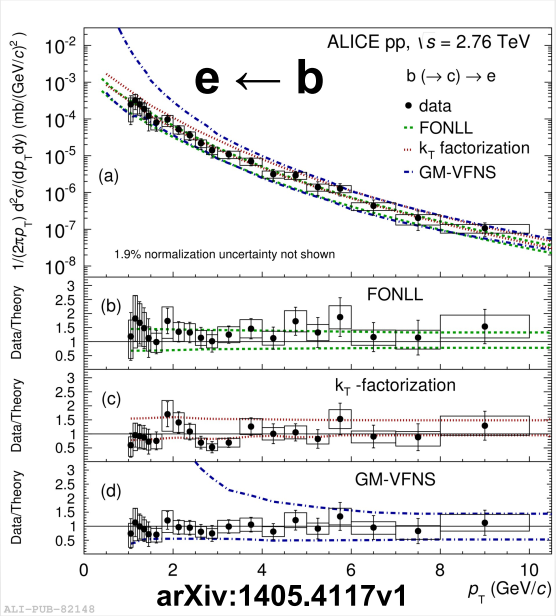


ALICE, JHEP 1201 (2012)



(ATLAS) PLB 707 (2012) 438
(ALICE) Phys. Rev. D86 (2012) 112007





arXiv:1405.4117v1

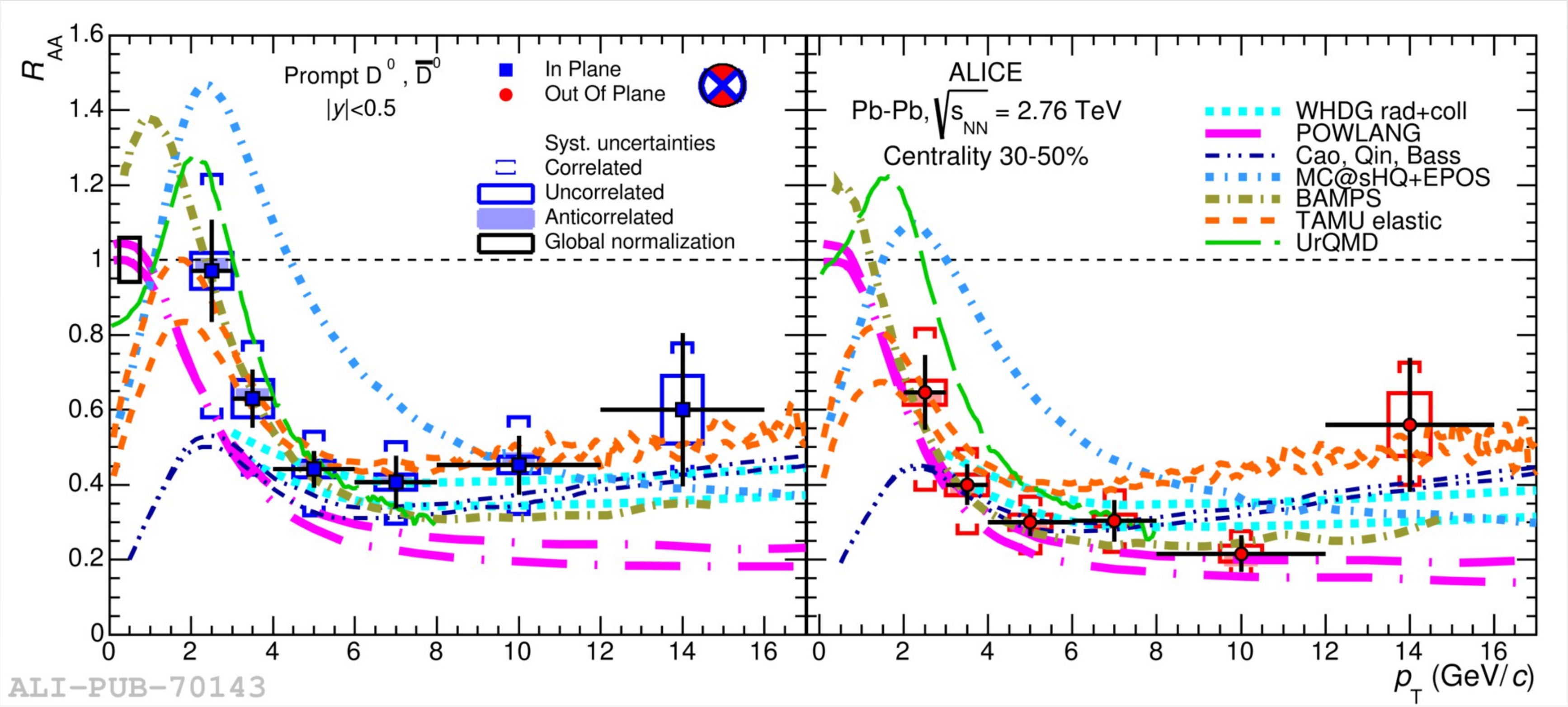
FONLL: JHEP 9805 (1998) 007
GM-VFNS: PRL 96 (2006) 012001
k_T Fact: PRD 62 (2000) 071502

Heavy-flavour p_T-differential cross sections well described by pQCD calculations at both energies (7 and 2.76 TeV)

Model predictions: D meson R_{AA} and v_2

– POWLANG: JPG 38 (2011) 124144; Eur. Phys.J. C71 (2011) 1666; – TAMU: arXiv:1401.3817;
– MC@HQ+EPOS: PRC 89 (2014) 014905; – WHDG: Nucl. Phys. A 872 (2011) 256;
– BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph]; – UrQMD: arXiv:1211.6912[hep-ph];
J.Phys. Conf. Ser. 426 (2013) 012032; – Cao,Quin, Bass: PRC 88 (2013);

In-plane **Out-of-plane**



arXiv: 1405.2001; PRL 111, 102301 (2013)

R_{AA} measured in-plane and out-of-plane, sensitive to
– path length dependence of parton energy loss at high p_T
– collectivity at low p_T