# Studying the Quark Gluon Plasma with heavy flavors

Gian Michele Innocenti
(CERN/MIT)

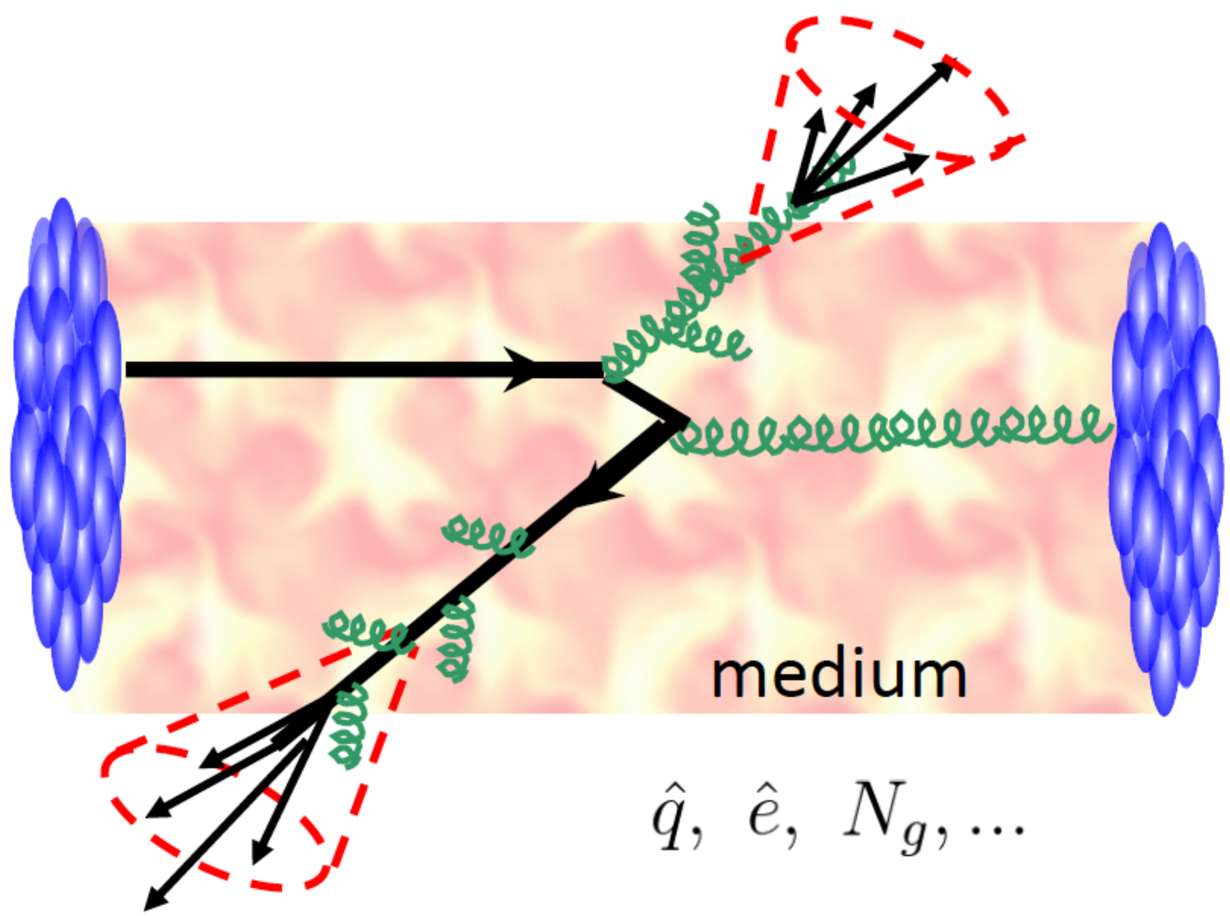
*Special thank to Prof. Byungsik Hong and Prof. Dongho Moon for providing me financial support for this trip and to my friend Dr. Hyunchul Kim for his precious help to organize it*

# Why hard probes and heavy flavors?

# Hard probes to study the QGP

High $p_T$ quarks and gluons created in hard parton-parton scatterings interact with the medium and lose energy via radiative and collisional process.

→The yields of high-$p_T$ particles created are reduced (**jet quenching**)




Magnitude of the suppression → average momentum lost by partons that is connected to the density of the QGP medium

$p_T$ dependence of the suppression → properties of the QGP and mechanisms of interactions

(and many others) ….

# Hard probes to study the QGP

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High $p_T$ Jets in Hadron-Hadron Collisions.

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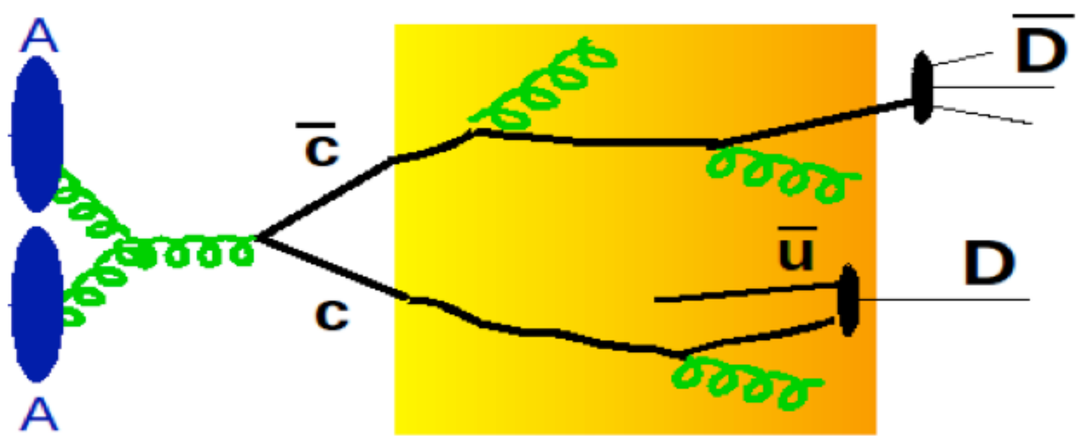
Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy $dE_T/dy$ in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-$p_T$ quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

# Heavy-flavors to study the energy loss




Heavy flavors (charm and beauty) have large masses

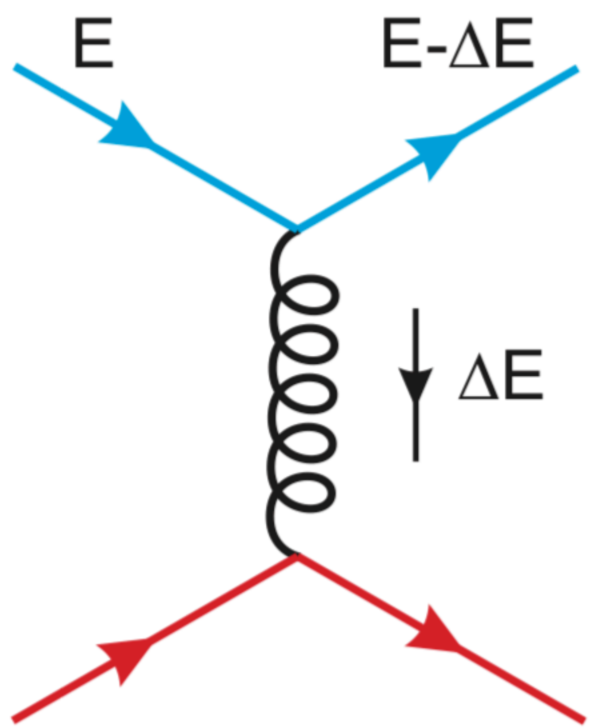
$m_c$~1.5 GeV, $m_b$~4.5 GeV

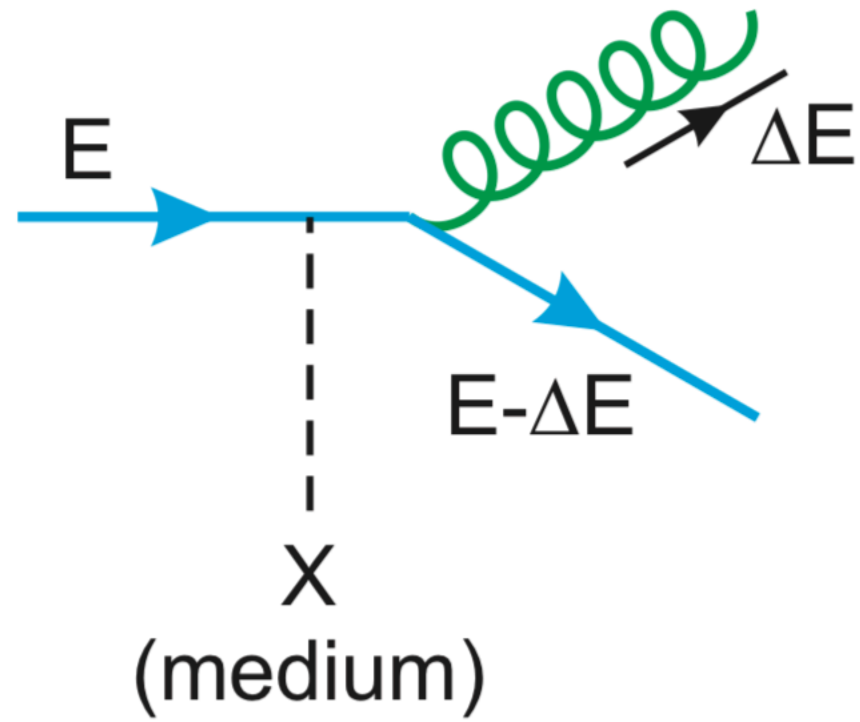
- Produced in hard partonic scatterings with large momentum transfer.
  For $Q^2 \geqq 4m^2_{c,b}$ , $\alpha_s <<1$ → a perturbative approach can be used.

$$\frac{d\sigma^{pp\rightarrow H_Q X}}{dp_t} = \sum_{i,j=q,\bar{q},g} f_i(x_i,\mu_F^2) \otimes f_j(x_j,\mu_F^2) \otimes \frac{d\sigma^{ij\rightarrow Q\bar{Q}}(x_i,x_j,\mu_F^2)}{d\hat{p}_t} \otimes D(z,\mu_F^2)$$

- formation time of heavy quark << formation time of QGP
- no thermal production $T_{QGP}$ ~ 150-180 MeV
- total amount of charm and beauty is conserved in the evolution of the medium

# Mechanisms of in-medium energy loss




**Elastic scatterings with the medium:**

$\langle E_{loss} \rangle \propto L * \ln(E_{in}) * C_R * f(T)$

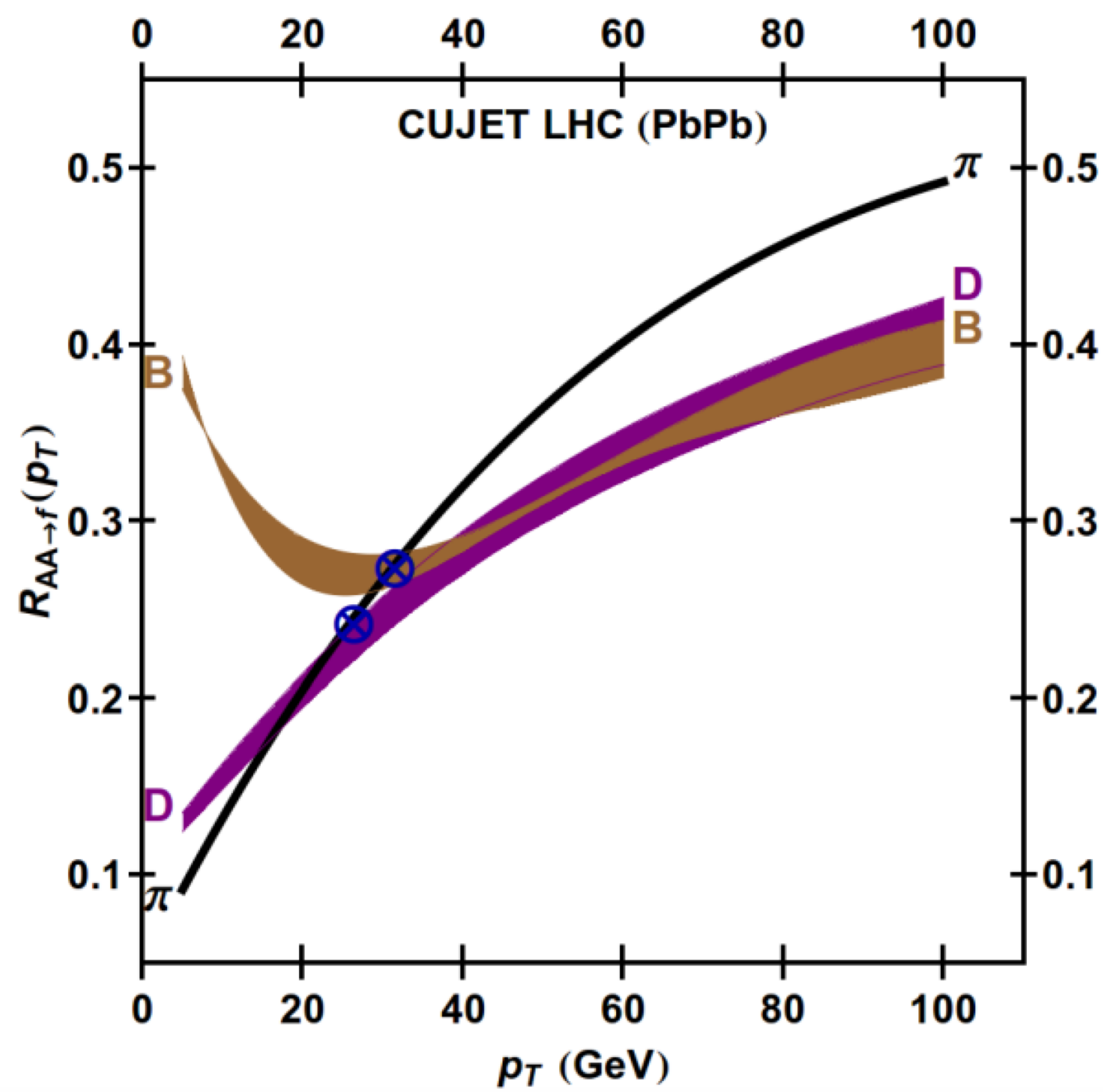
**Medium-induced gluon radiation:**

$\langle \Delta E \rangle \propto C_R\, q\, L^2$

# Flavor dependence of $E_{loss}$

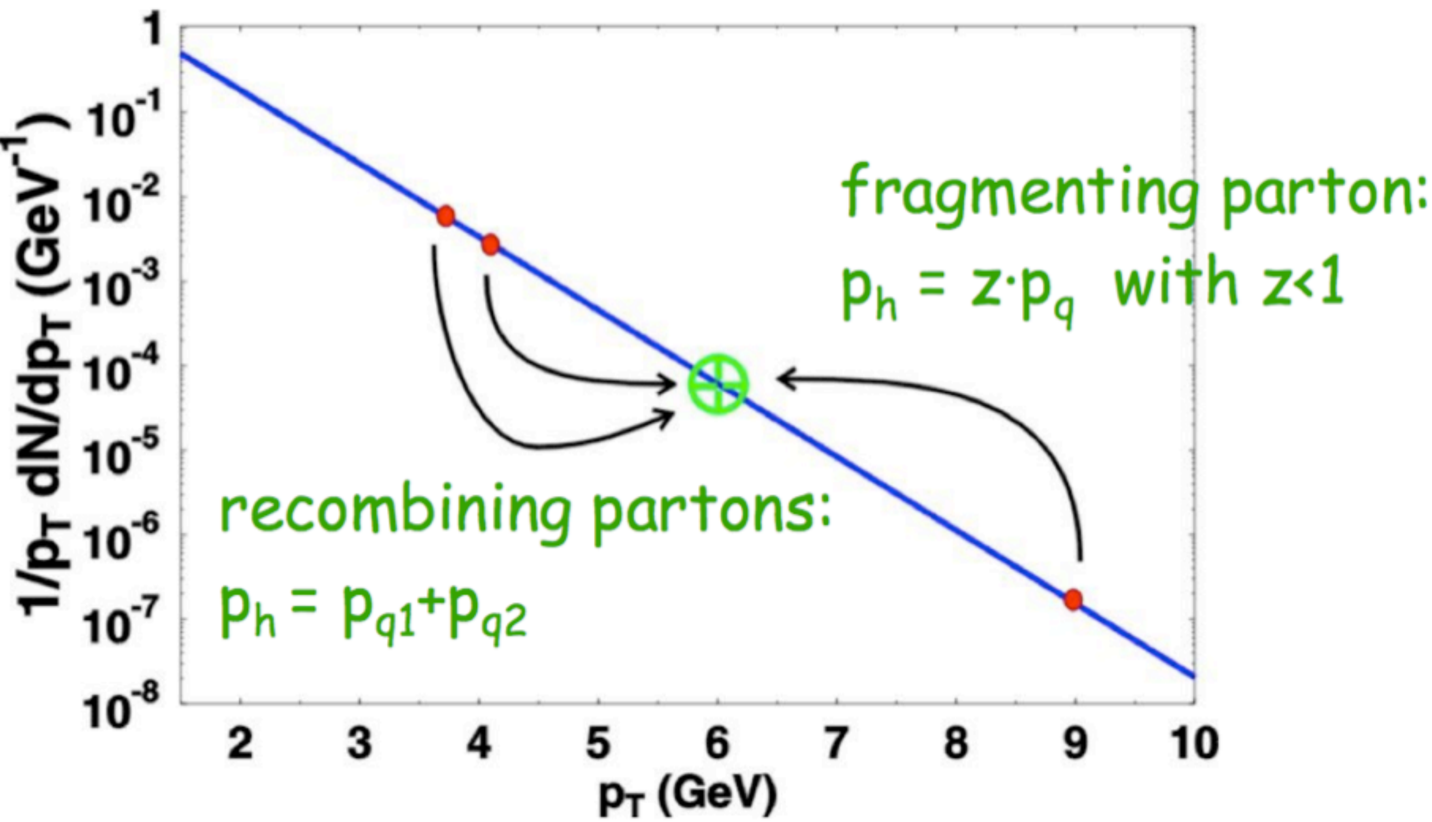
**Flavor-dependence of energy loss:**

- Larger for gluons than for quarks
  E.g. in BDMPS model [1] $\langle \Delta E \rangle \propto \alpha_s C_R q L$
- Dead cone effect: gluon radiation suppressed at small angles for massive quarks



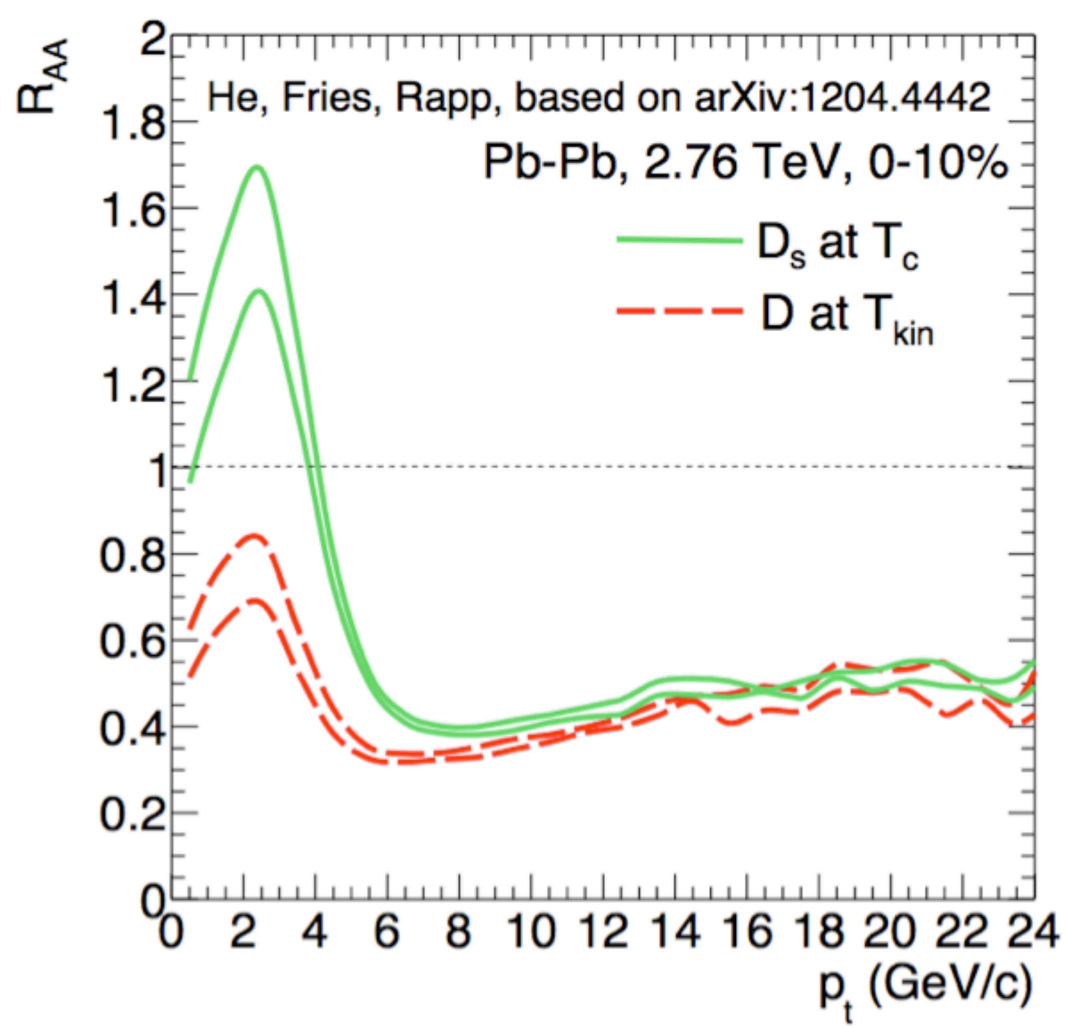

$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ → $R_{AA}^B > R_{AA}^D > R_{AA}^{light}$ (??)

# Heavy flavors as a probe for hadronisation

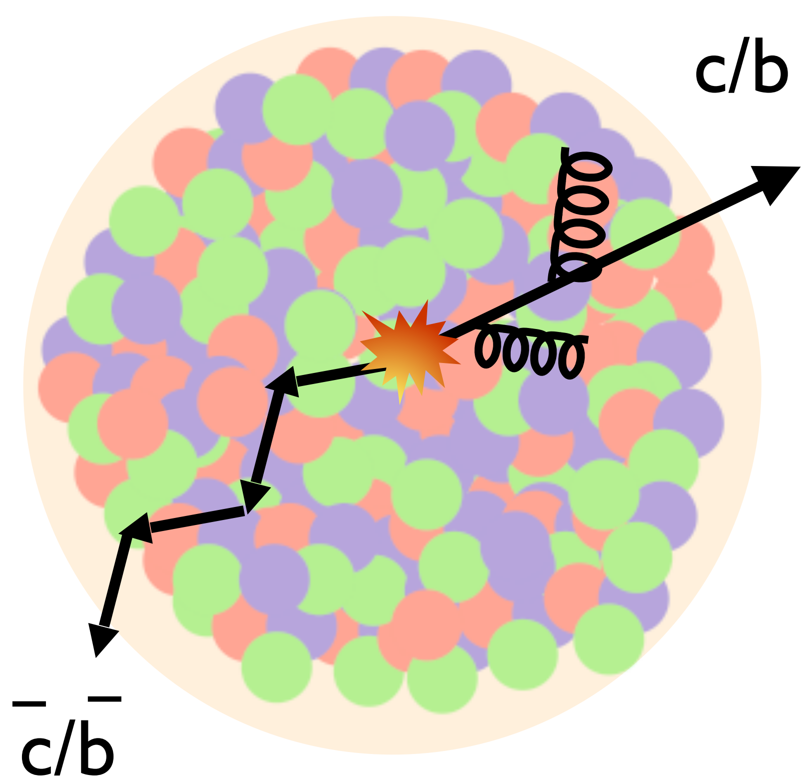



**Recombination*:*** low momentum quark hadronizes through a process of coalescence with a light quark of the medium.

→$D_s$/B enhancement and baryon/meson enhancement in central collisions

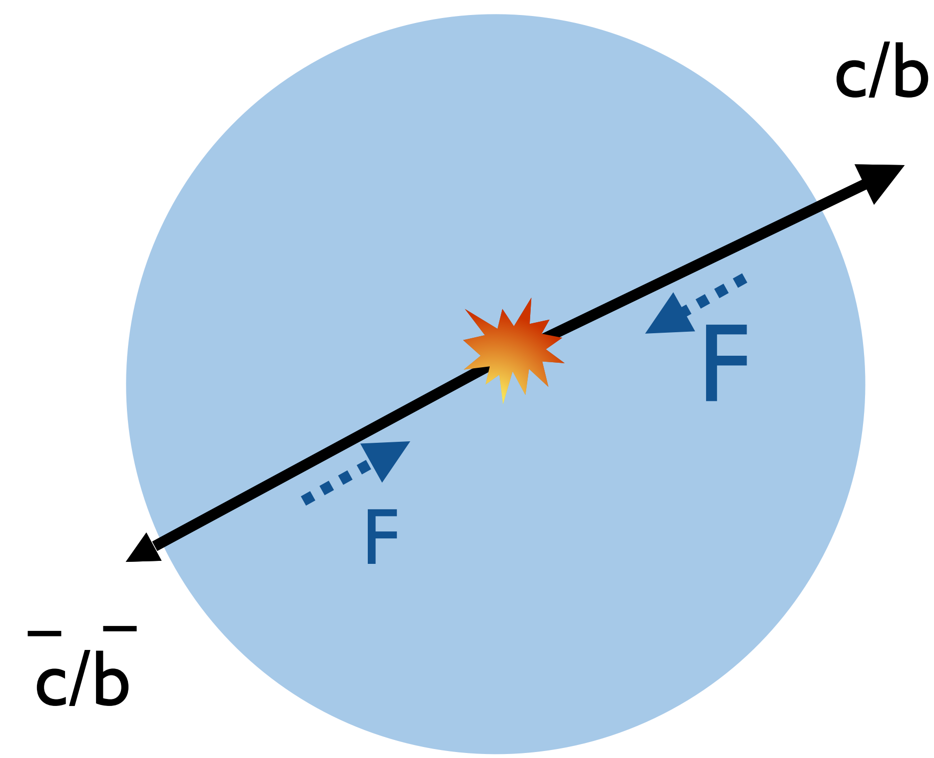


# Investigate the QGP degrees of freedom




pQCD system?

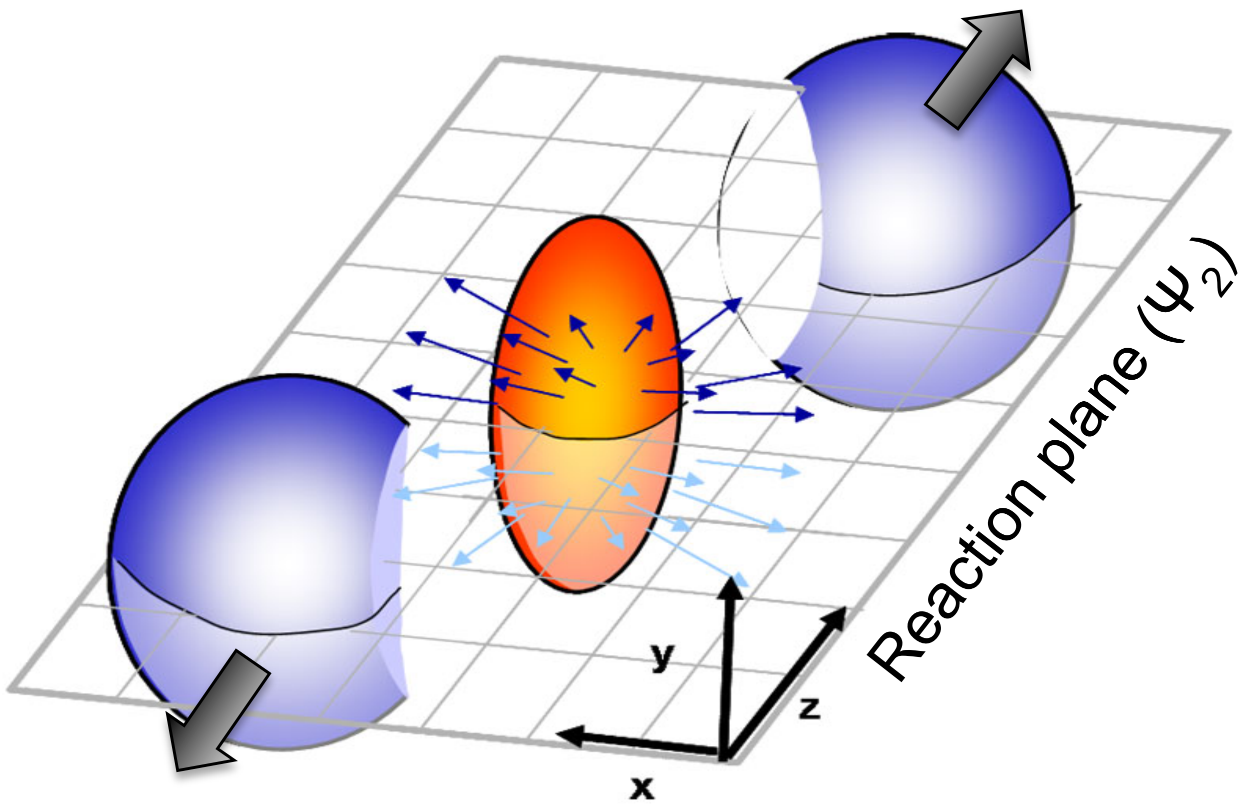
- collisional and radiative with quasi particles

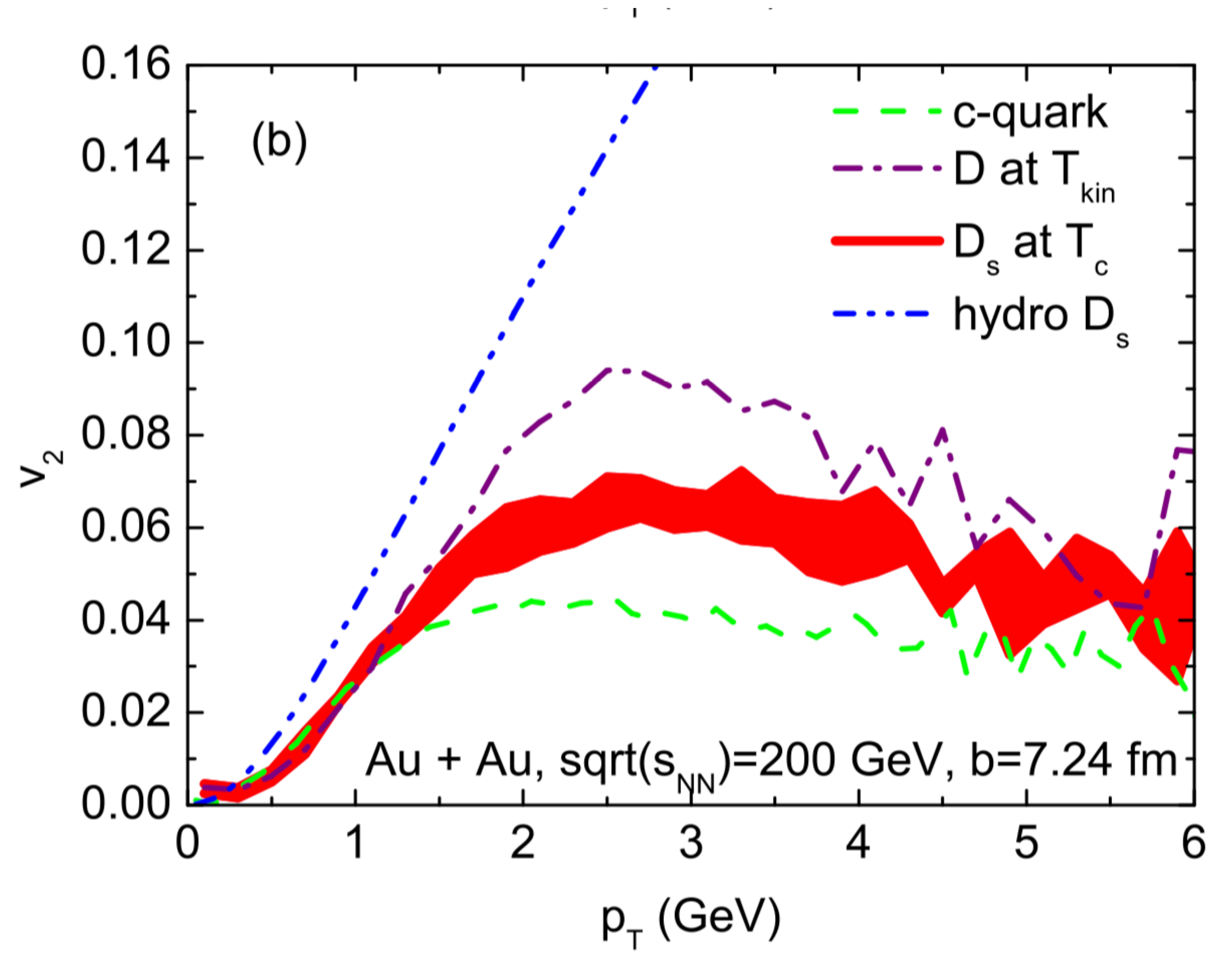



strongly-coupled medium?

- "drag" force in medium w/o quasi-particles

# heavy quarks to study medium collectivity



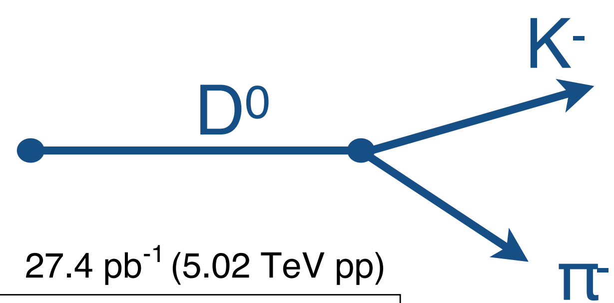

Non-complete thermalisation due to their mass
→ stronger constrain on $D_s$
→ strong constraints on the role of collisional and radiative processes

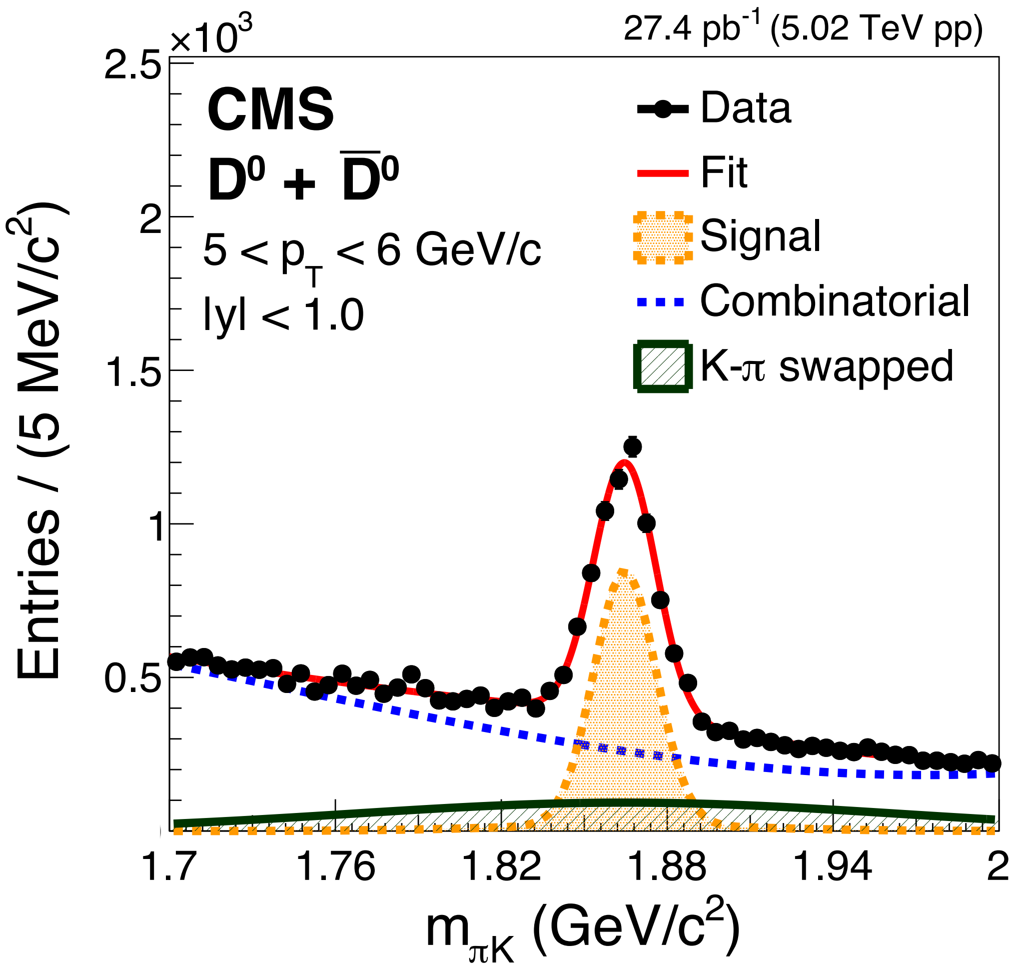
Constraints on the role of hadronic phase in "generating" the observed $v_n$ (e.g. via $D_s$ $v_2$ measurements)

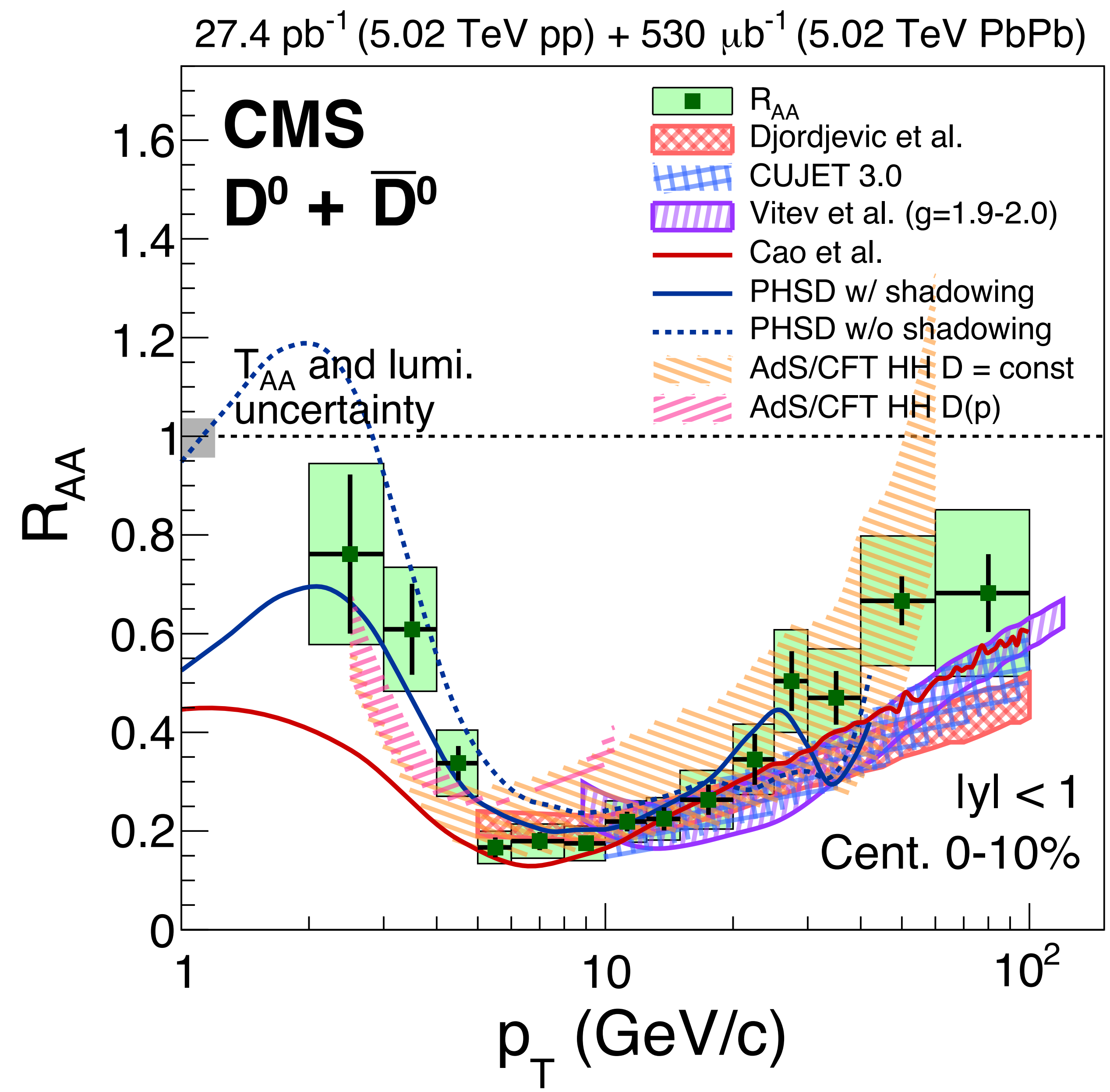
# heavy flavor energy loss

# Prompt $D^0$-meson $R_{AA}$ at 5.02 TeV

$D^0 \rightarrow K^- \pi^+$



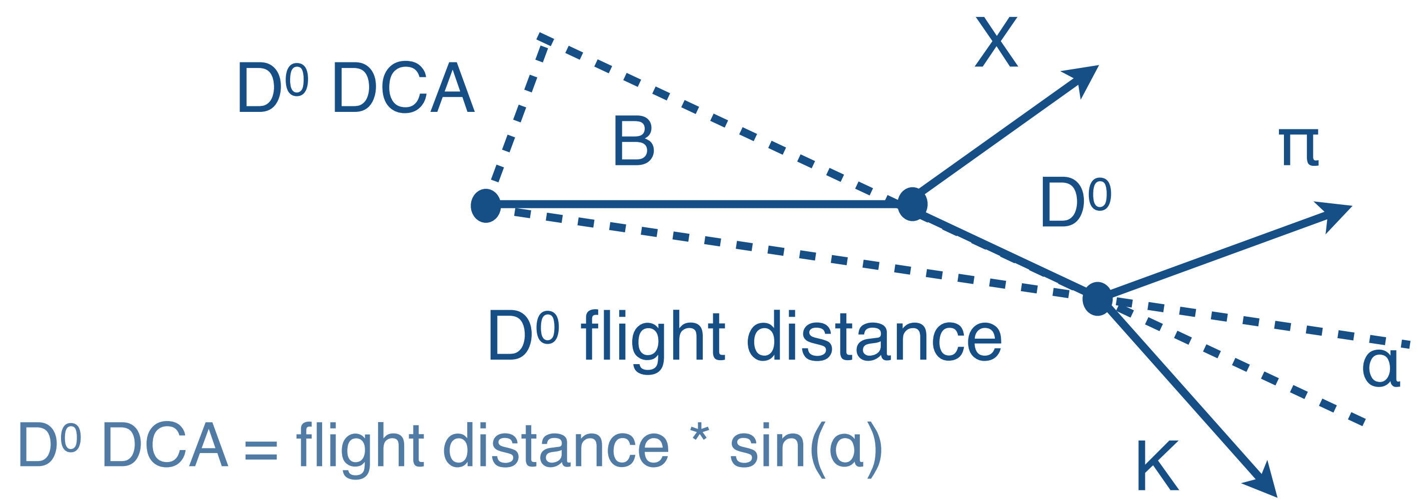

**No PID** → wide gaussian for candidates with swapped mass hypothesis

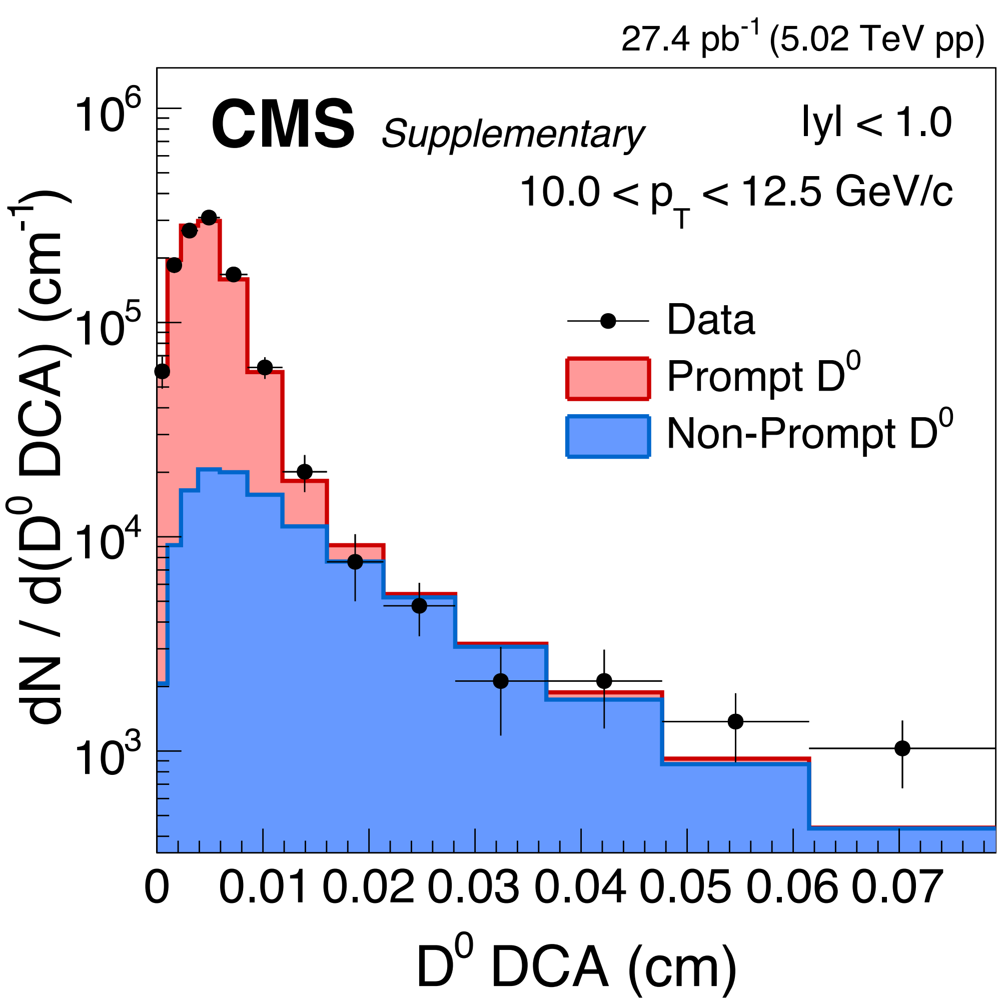

[1] arXiv:1703.00822
[2] Phys. Rev. C 92 (2015) 024918
[3] JHEP 02 (2016) 169
[4] Phys. Rev. D 91 (2015) 085019
[5] Phys. Rev. D 93 (2016) 074030
[6] Phys. Rev. C 93 (2016) 034906

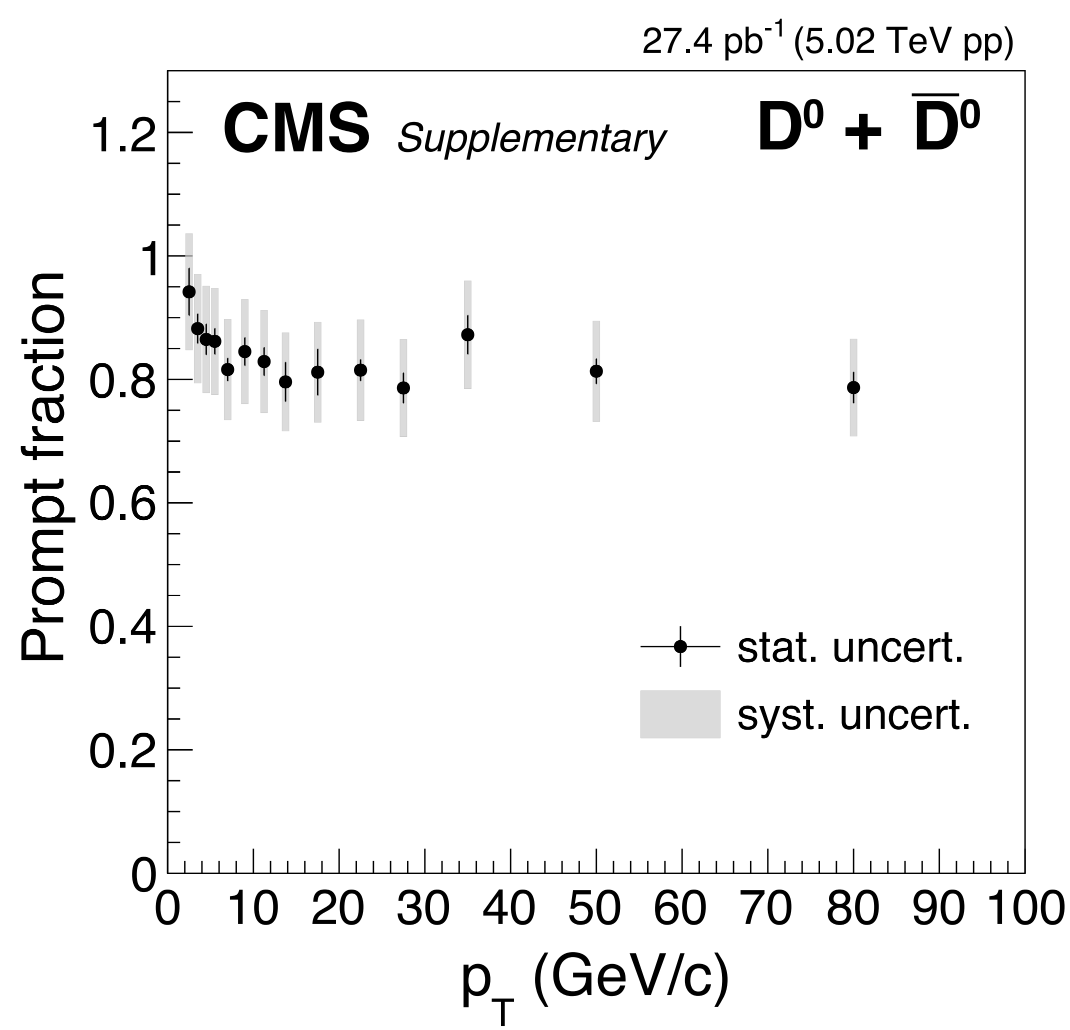

10.1016/j.physletb.2018.05.074

# Prompt $D^0$-meson $R_{AA}$ at 5.02 TeV

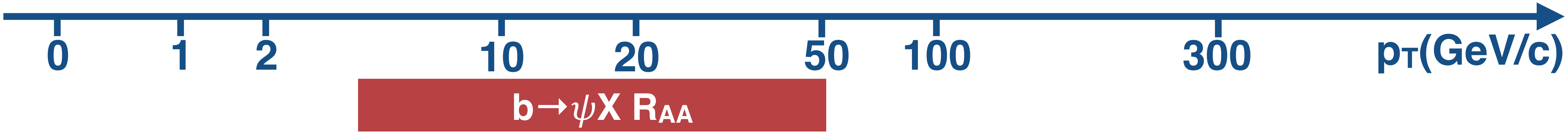
- Significant contribution of non-prompt $D^0$ from b hadron decays at LHC (**O(10%)**)
- **CMS separates prompt and non-prompt $D^0$ from DATA using $D^0$ DCA**

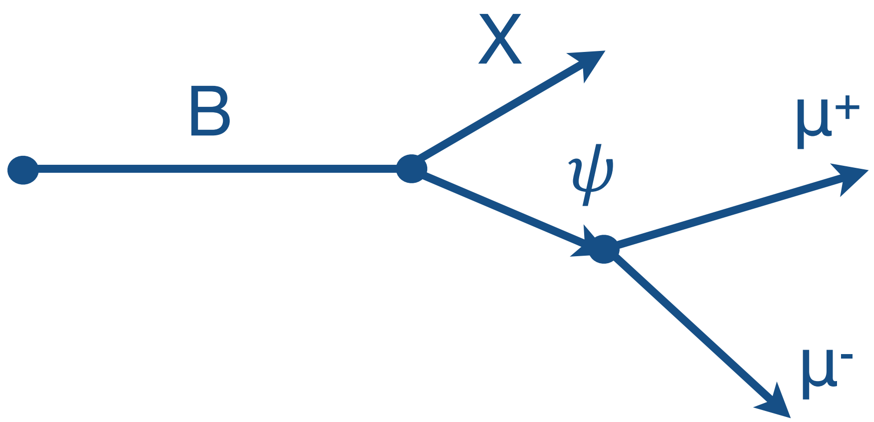


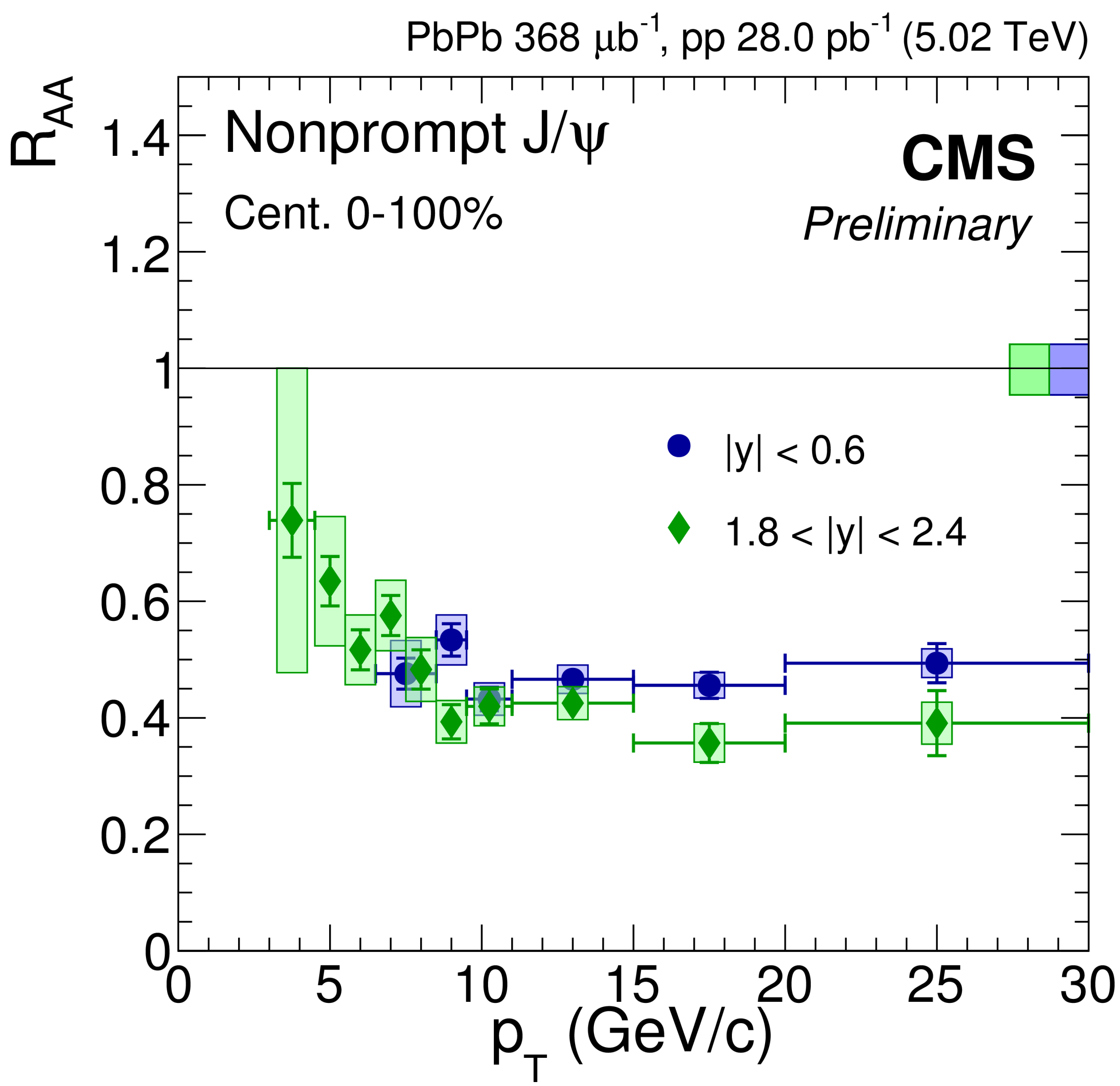



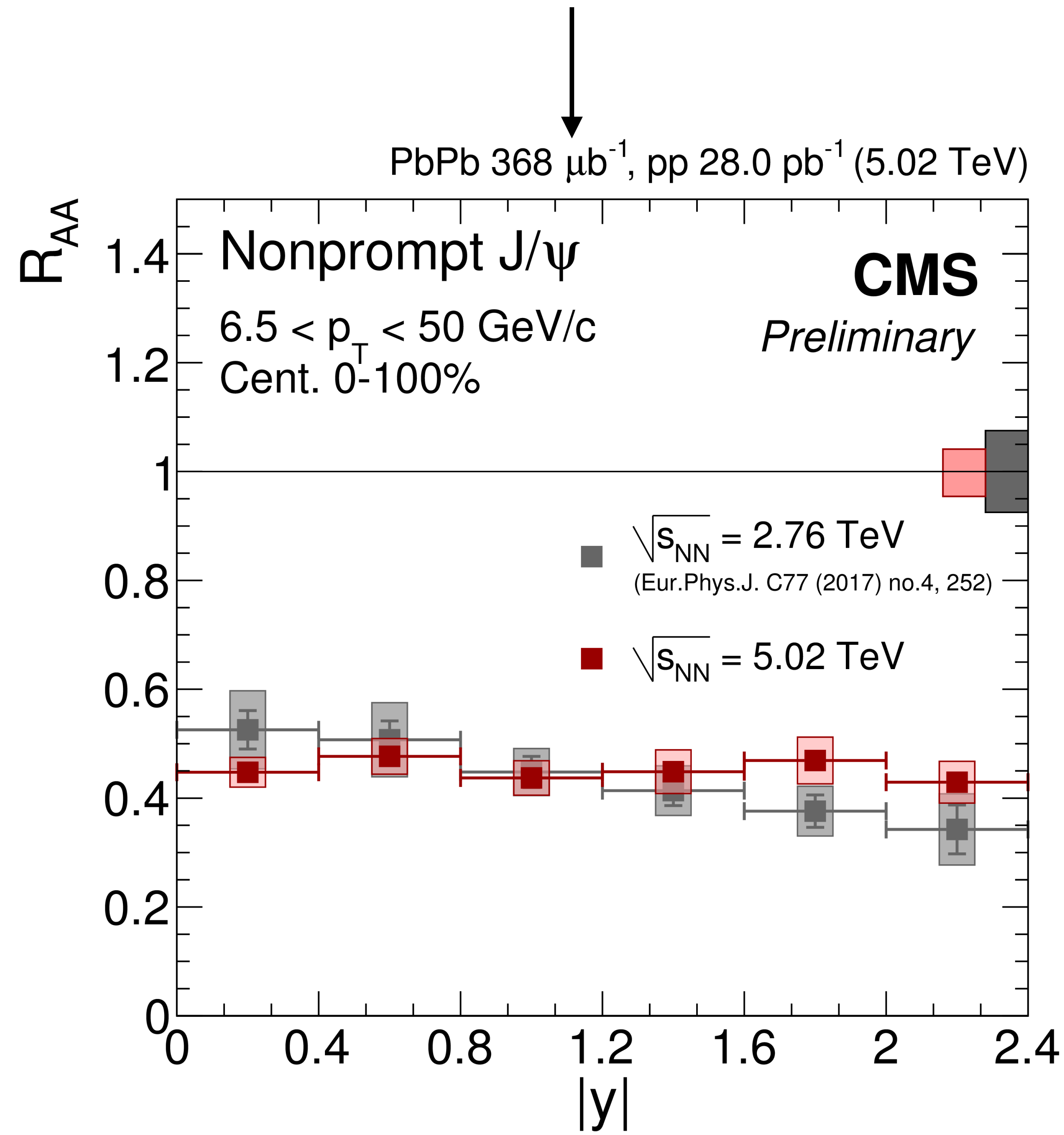
# $b \to \psi X$ $R_{AA}$ at 5.02 TeV



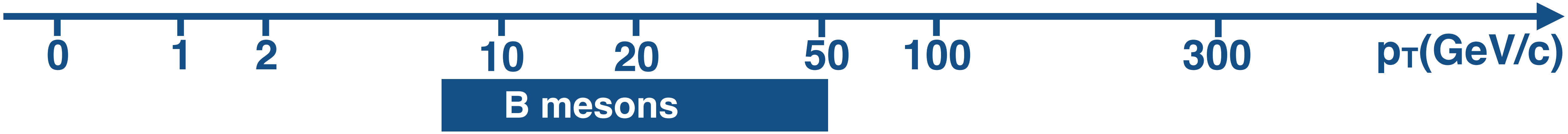




**measurement of the beauty suppression as function of rapidity!**

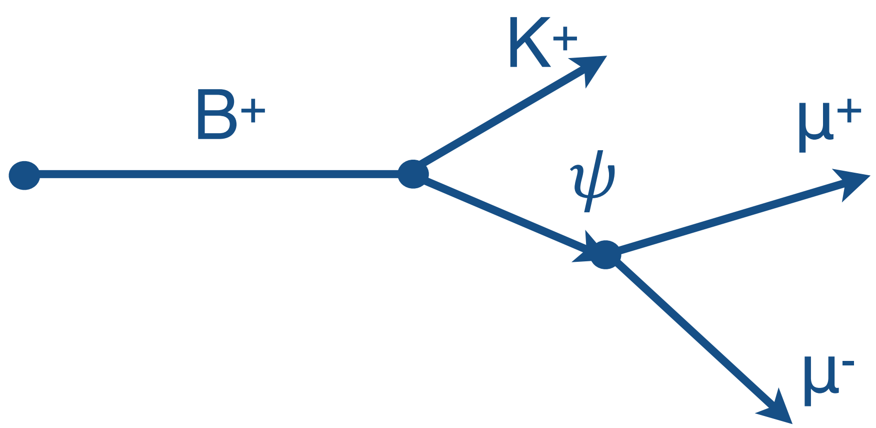


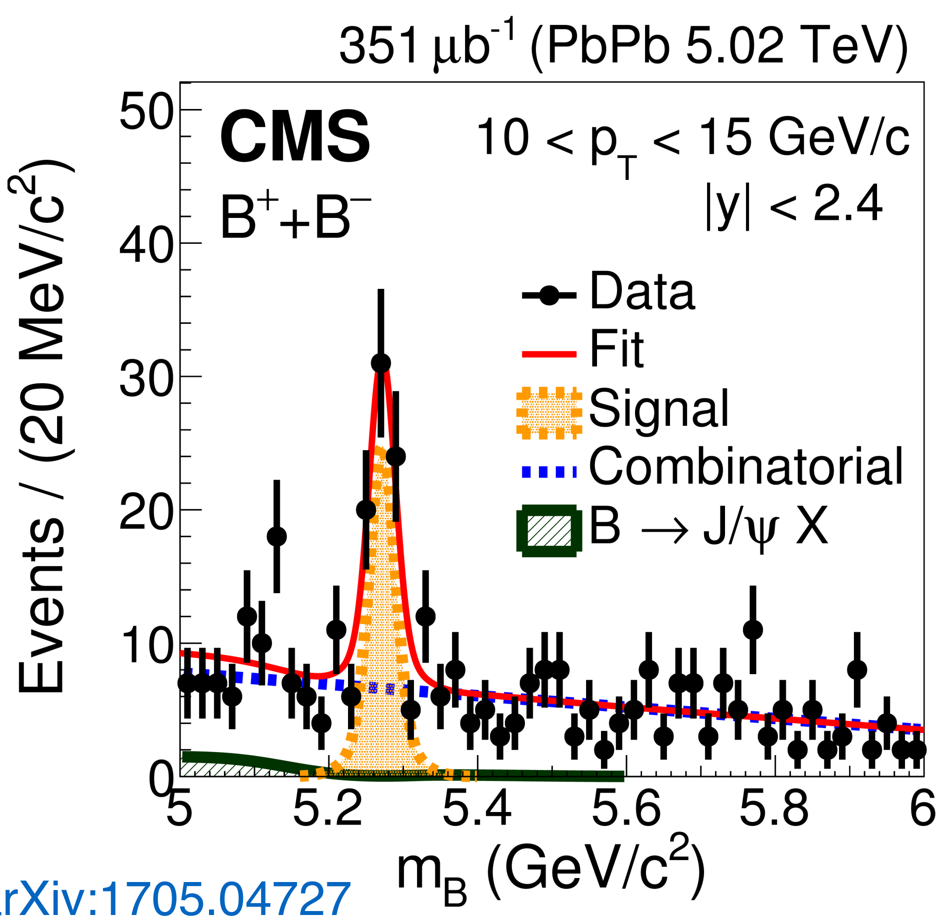



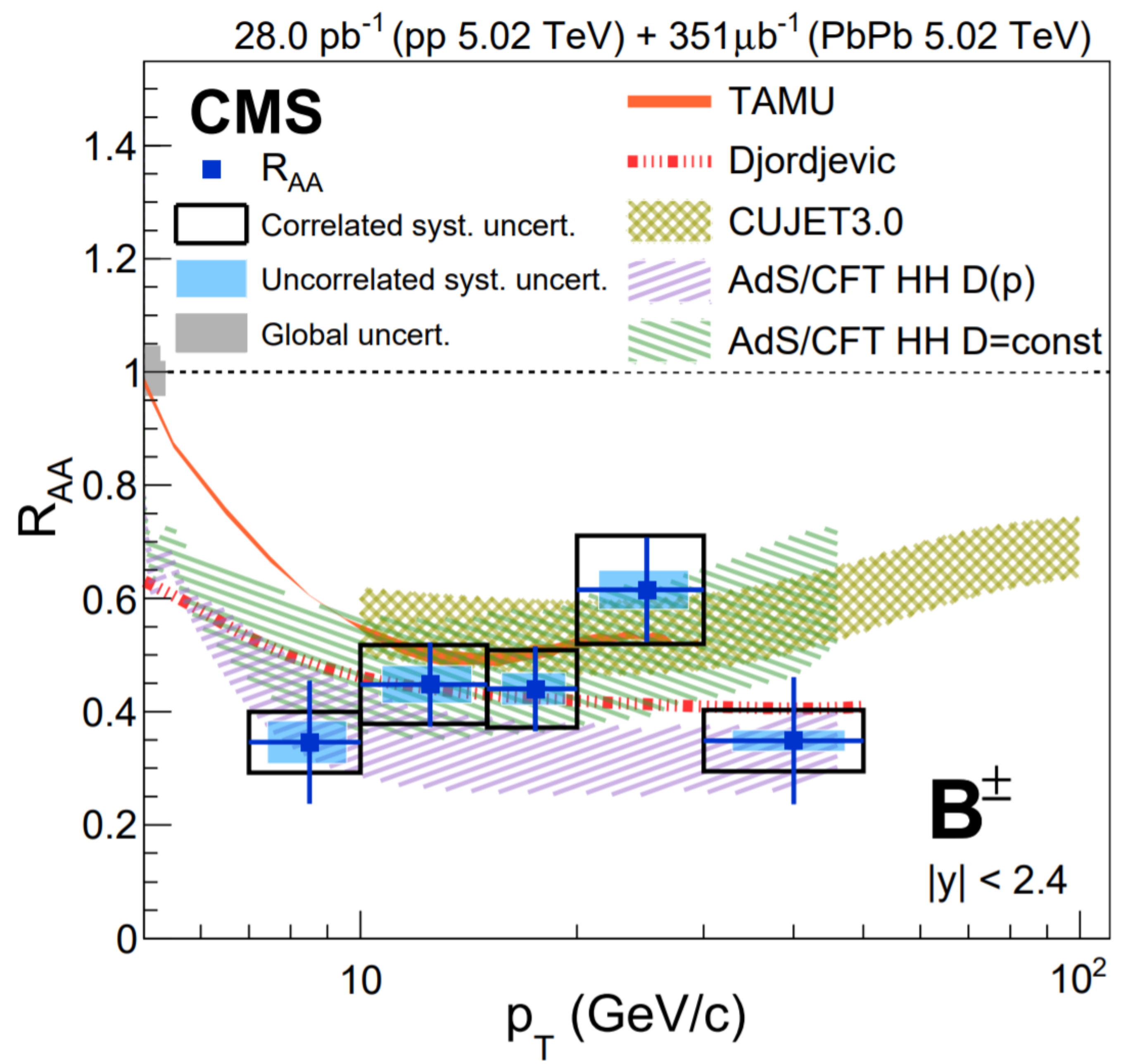
# $B^+$ meson $R_{AA}$ at 5.02 TeV




- Fully reconstructed $B^+$,$B_s$, $\Lambda_b$ in can isolate the possible effect of beauty recombination

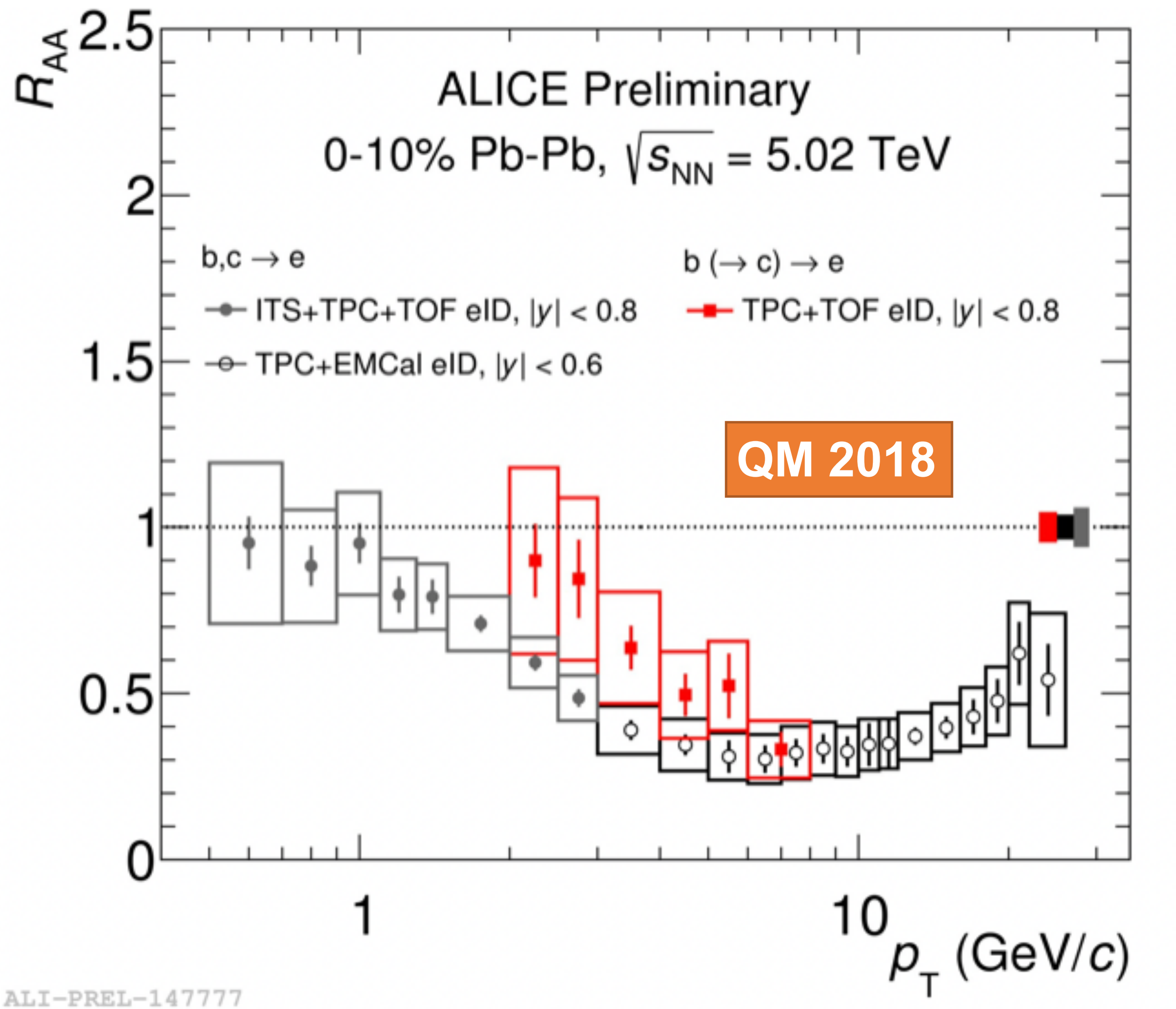


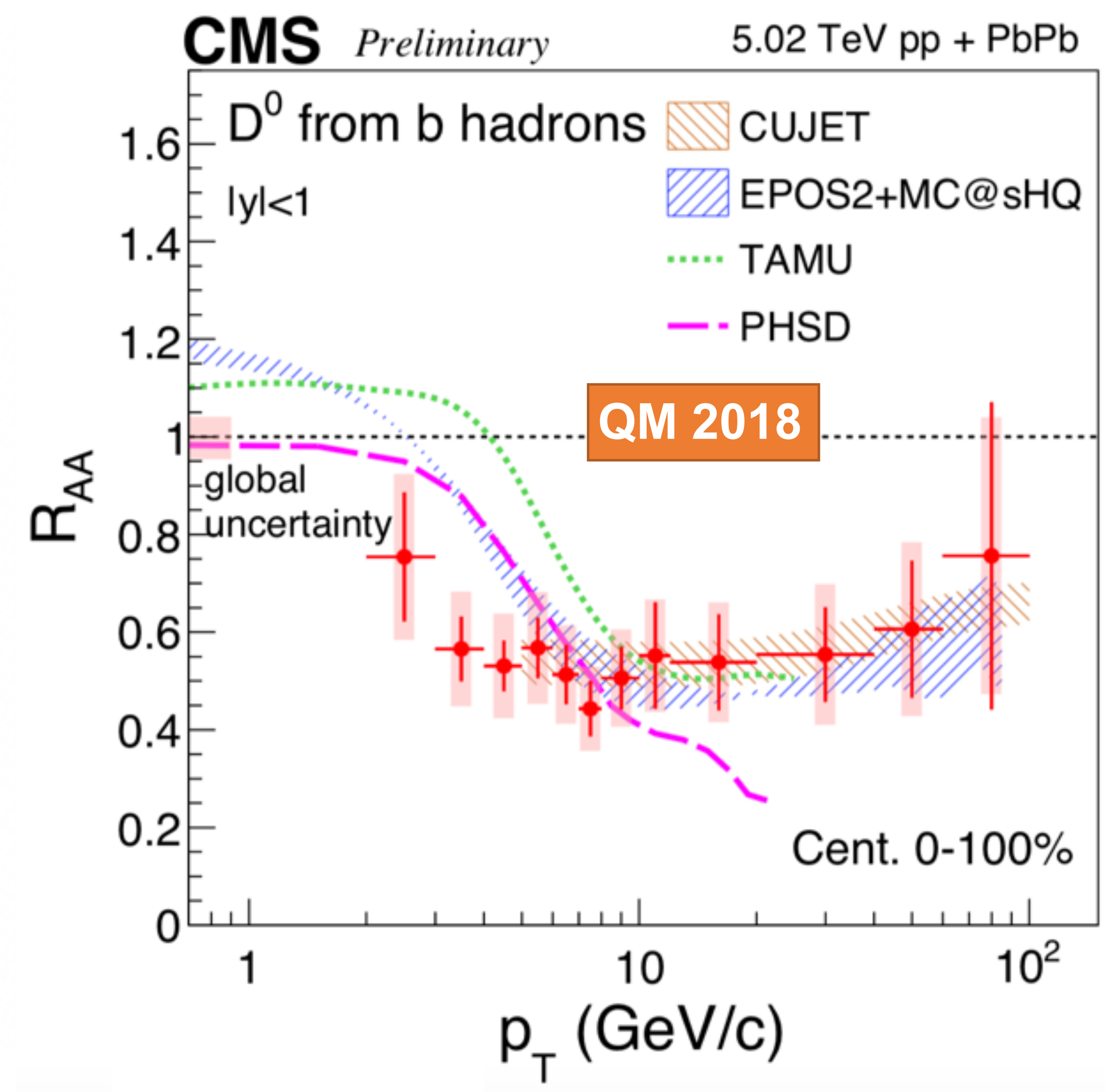




arXiv:1705.04727

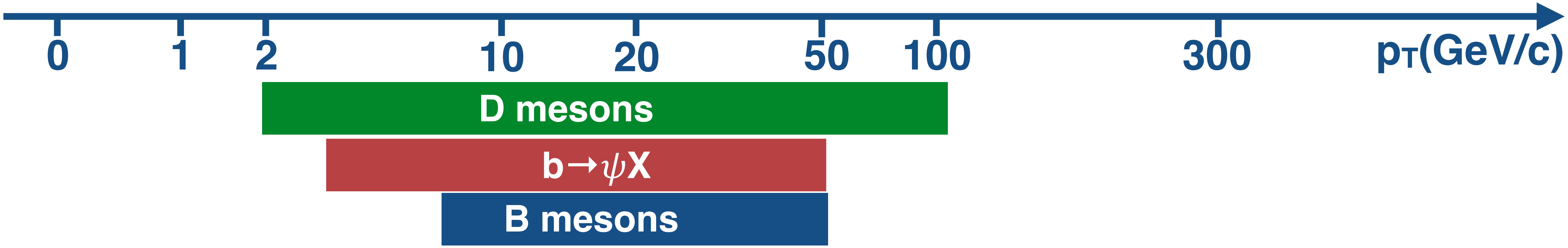
# $R_{AA}$ of b→DX and b,c→e

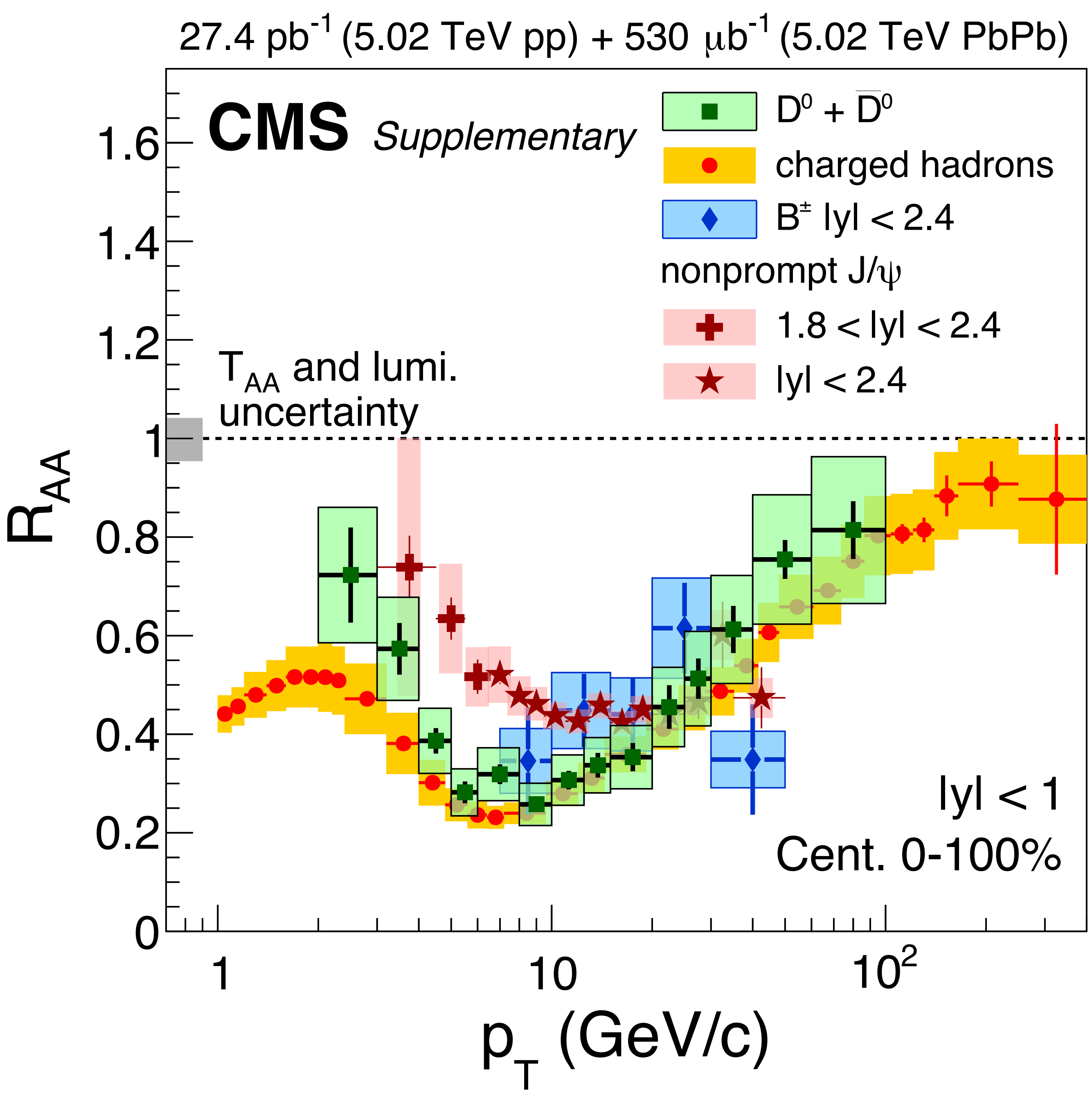



New measurements of beauty production via displaced D mesons and HF electrons
→ hint of a smaller suppression at low-intermediate $p_T$

# Flavor dependence of $E_{loss}$ at 5.02 TeV




**B+ meson**

**D0 meson**

**charged particle**

**non prompt J/ψ**

JHEP 04 (2017) 039

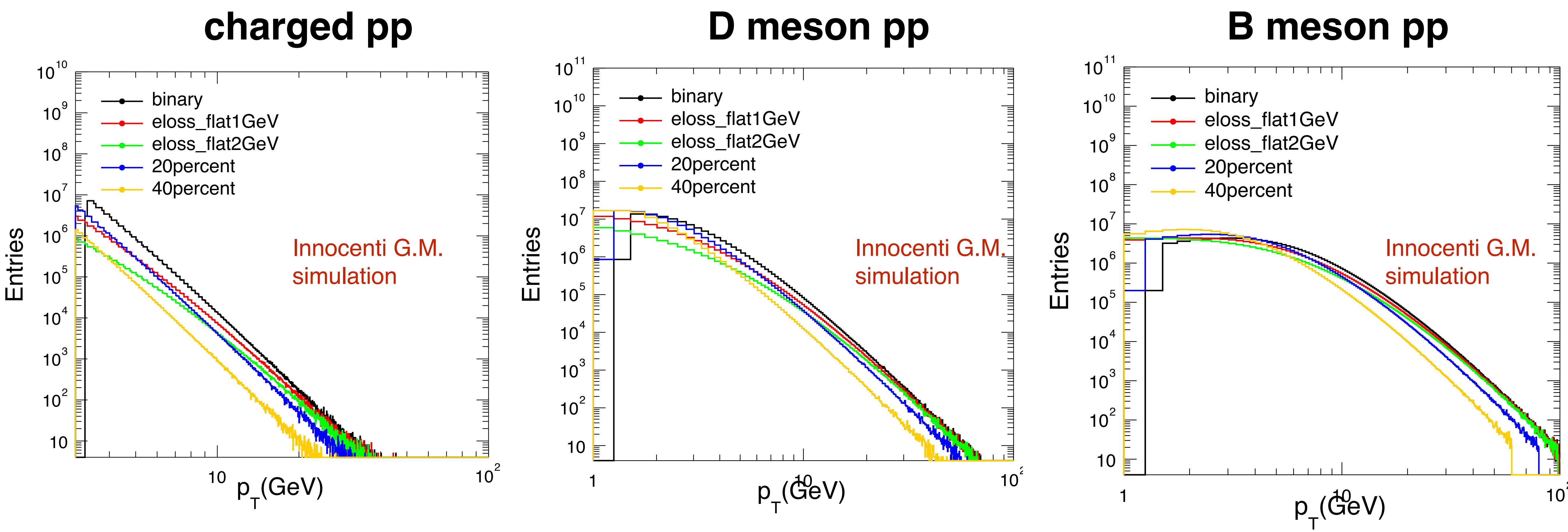
arXiv:1705.04727

CMS-PAS-HIN-16-025

arXiv: 1708.04962

# A little toy model to understand $R_{AA}$

- Considered a pp particle spectrum in pp collision
- Computed “quenched” spectrum assuming two scenarios:
  1. each particle loses a fraction of its initial $p_T$
  2. each particle loses a fixed amount of $p_T$ independently of its initial $p_T$




**1. Elastic scatterings with the medium:**

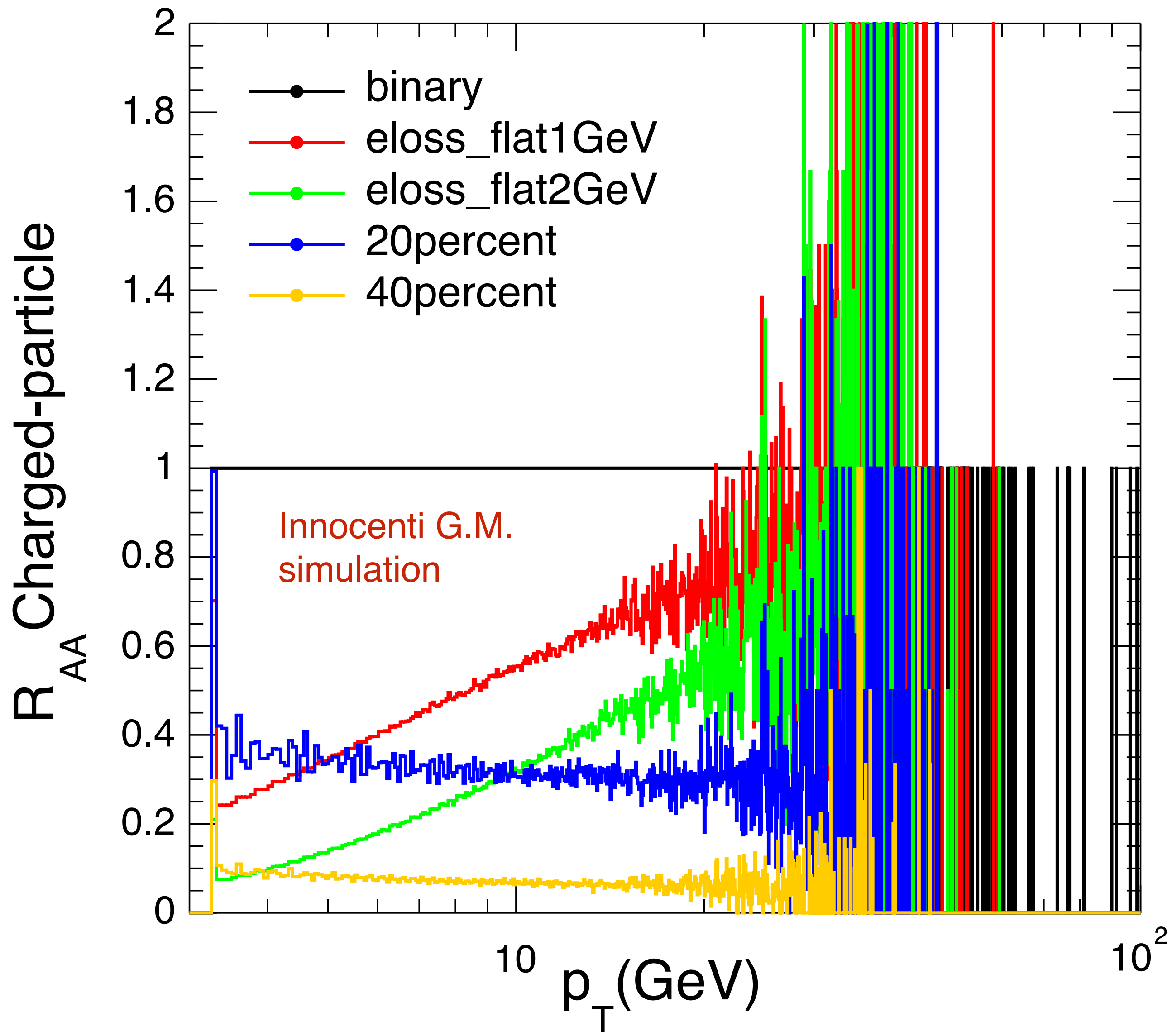
$<E_{loss}> \propto L^* \ln(E_{in}) * C_R * f(T)$

**2. Medium-induced gluon radiation:**

$<\Delta E> \propto C_R \, q \, L^2$

HANDLE WITH CARE! this toy model has no ambition of being a realistic model, but simply a way to get an intuitive understanding of the $R_{AA}$ shapes

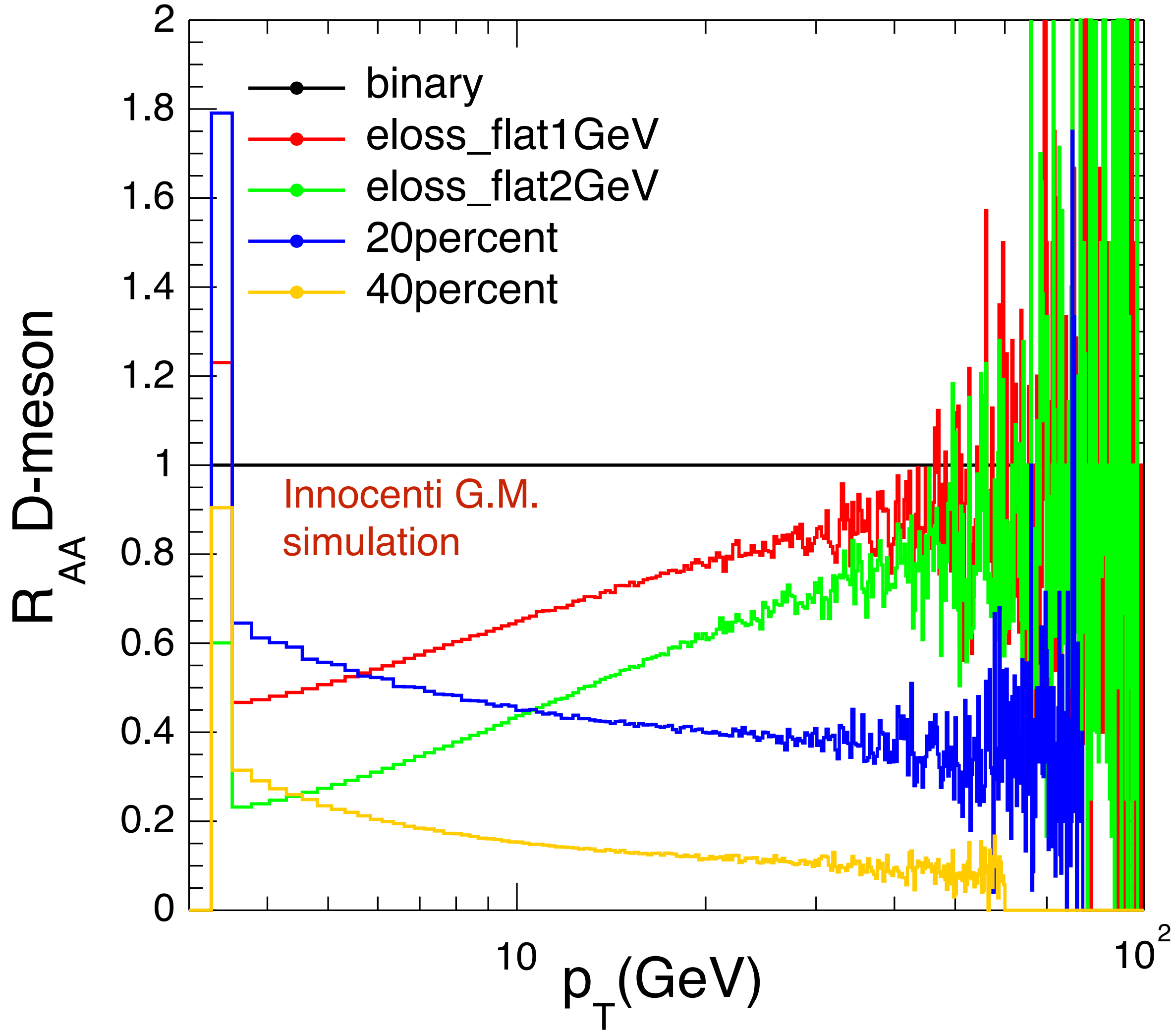
# "Toy-model" charged particle $R_{AA}$

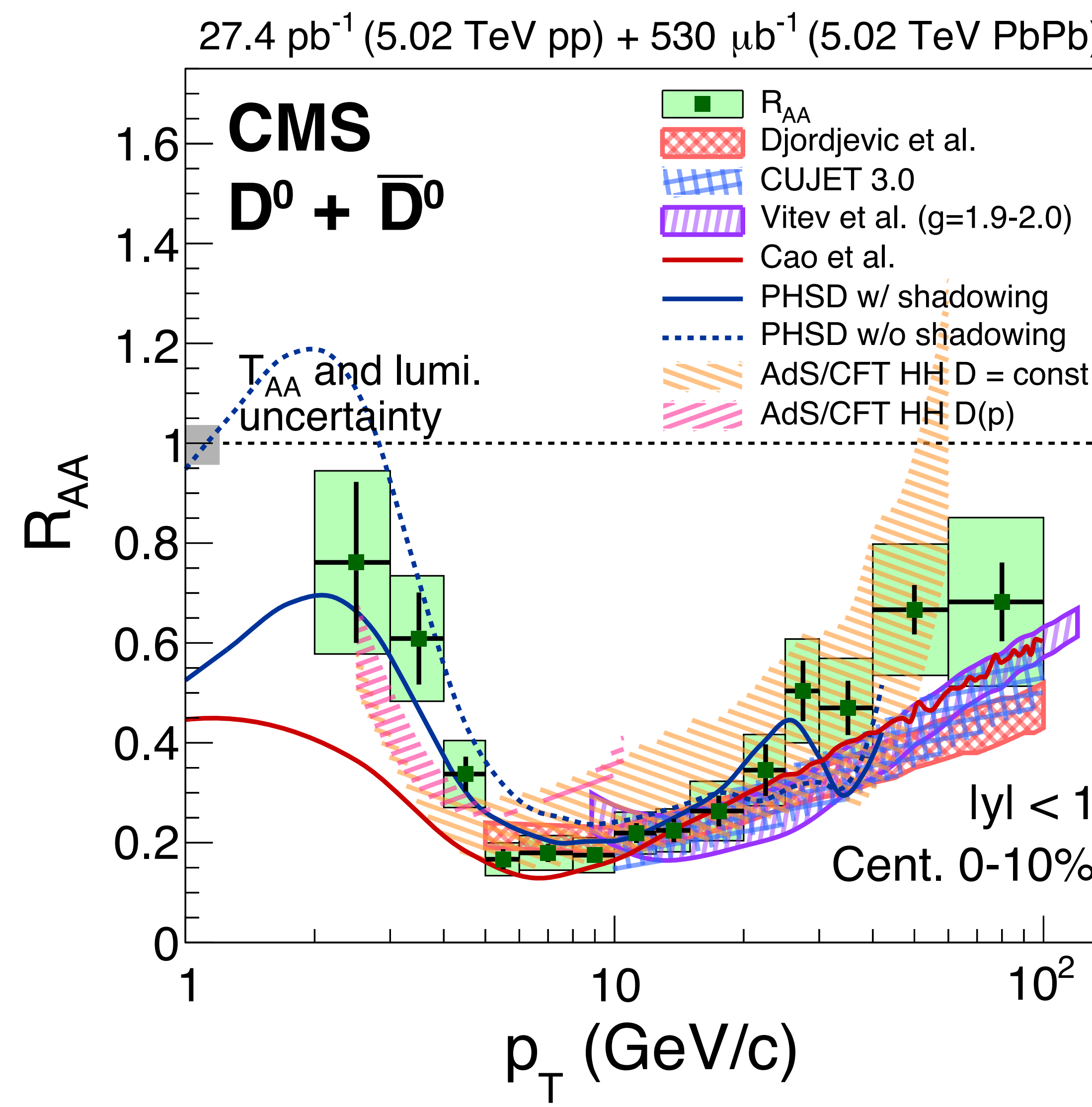



Scenario 1) energy loss proportional to $p_T$ (~collisional energy loss)
→ **the $R_{AA}$ is ~ flat as a function of $p_T$**

Scenario 2) energy loss independent from initial $p_T$ **(~radiative energy loss)**
→**$R_{AA}$ constantly increases**

# D meson $R_{AA}$



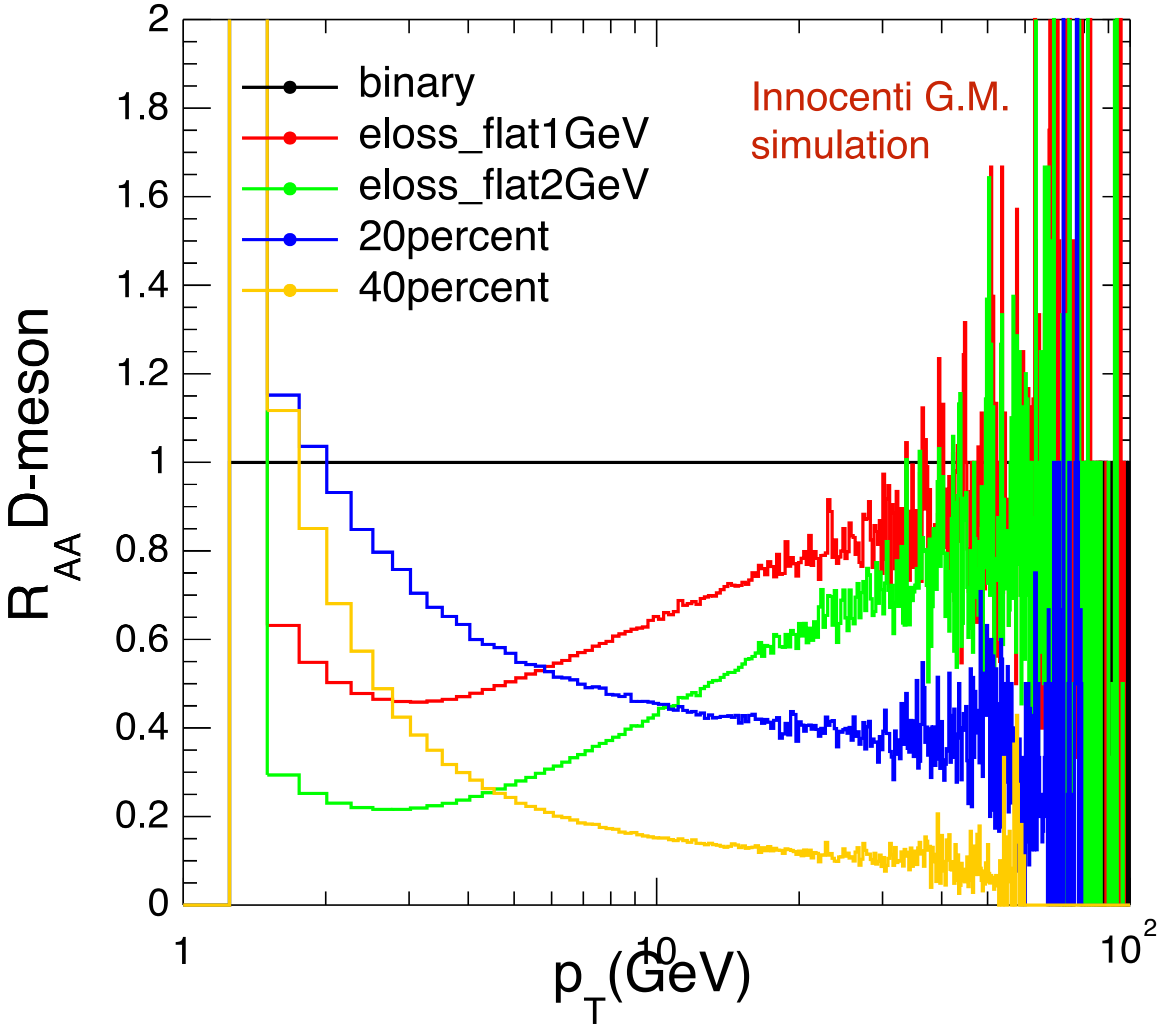



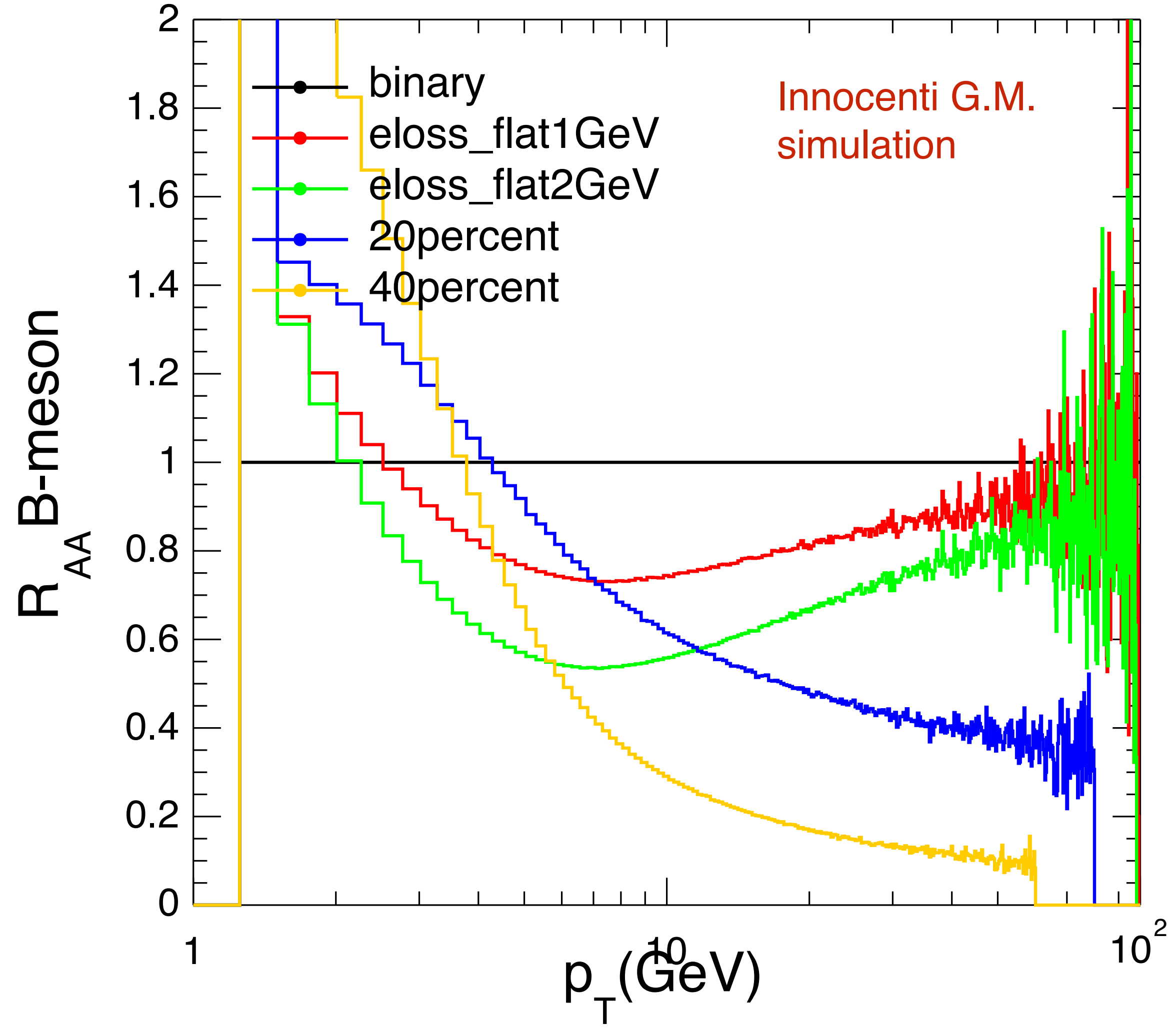

Scenario 1) energy loss proportional to $p_T$ (~collisional energy loss)
→**slight decrease as a function of $p_T$**

Scenario 2) energy loss independent from initial $p_T$ **(~radiative energy loss)**
**→ $R_{AA}$ increases as a function of $p_T$ as for charged particles**

# D vs B meson $R_{AA}$

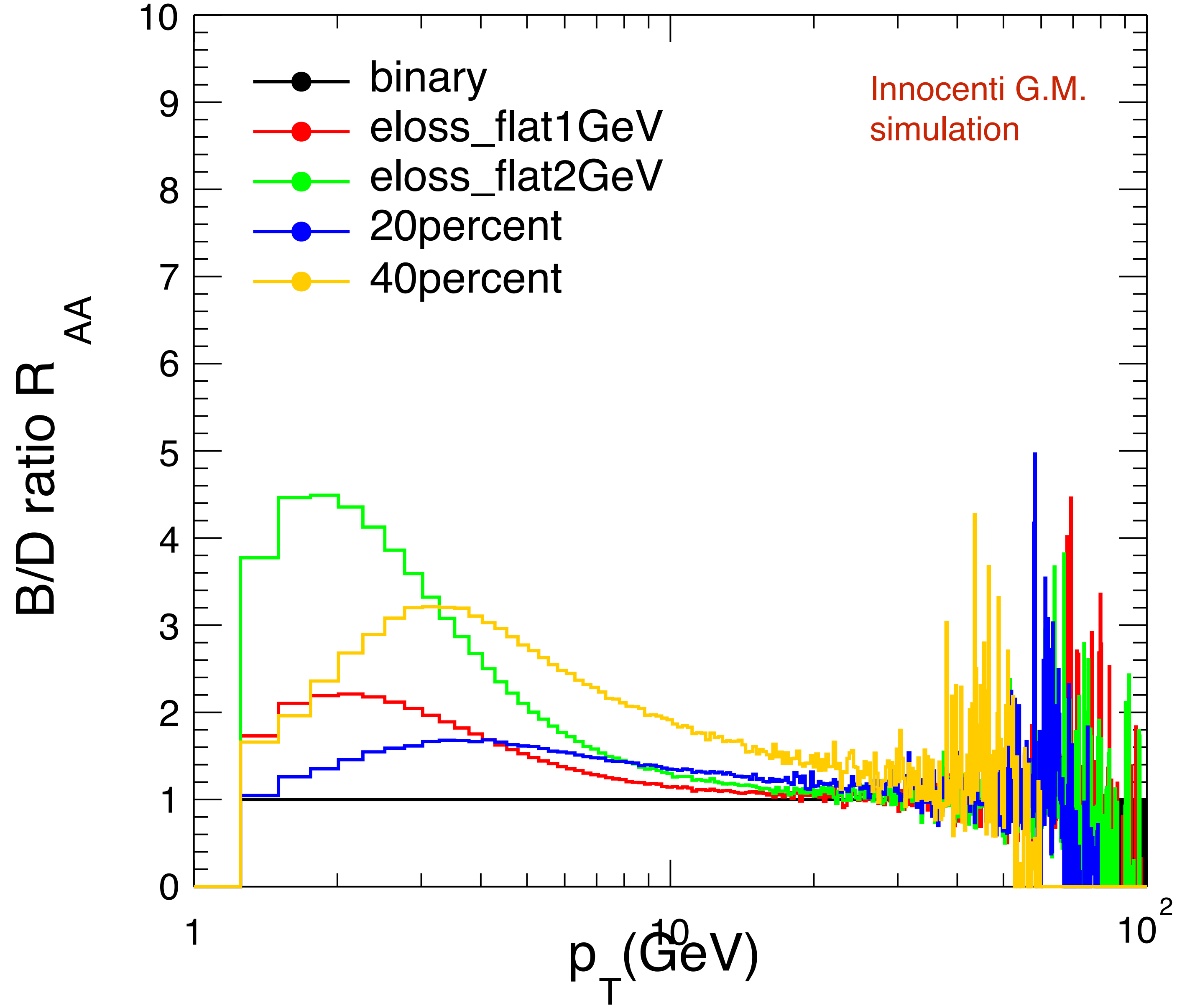
**BE CAREFUL: you can have different suppression even with the same energy loss**




I can reproduce a very similar shape of B vs D simply as a consequence of the different pT shape of B and D mesons. In particular because the beauty cross section gets smaller when $p_T$<4-5 GeV ($m_b$~4 GeV)

# Have we observed flavor dependence?




Big differences can be obtained as a simple consequence of the different initial pp spectra without any energy loss flavor dependence!

# New insights using heavy-flavor jets

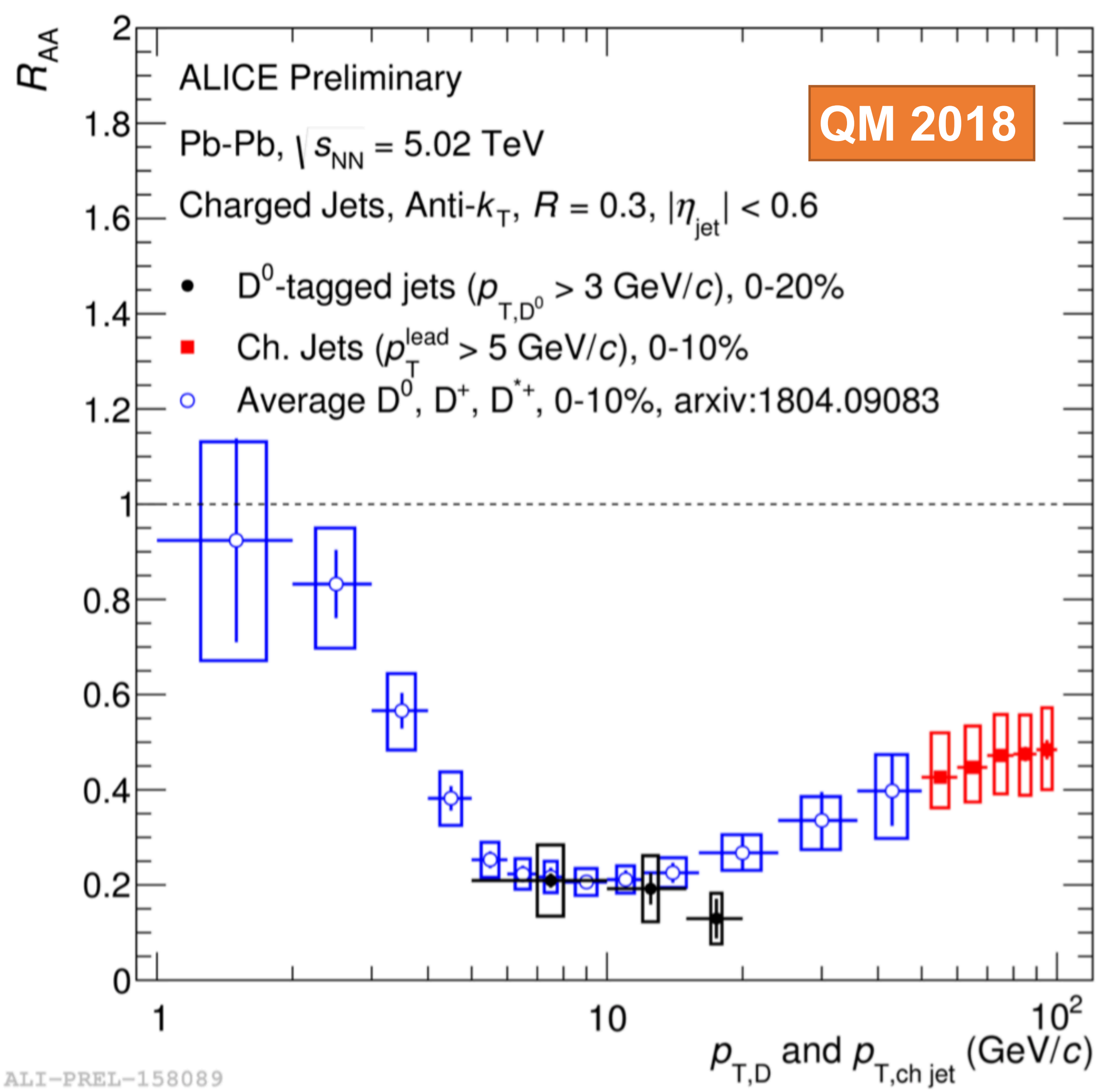
**Complementary to heavy flavor single-hadron measurements:**

- modification of the fragmentation function in heavy-ion collisions
- spacial redistribution of the lost energy
- heavy-flavor (~quark jets) vs light (~gluon-jets) jet studies

# $R_{AA}$ of $D^0$-tagged jets in PbPb

**Complementary to heavy flavor single-hadron measurements:**

- modification of the fragmentation function in heavy-ion collisions
- spacial redistribution of the lost energy
- heavy-flavor (~quark jets) vs light (~gluon-jets) jet studies

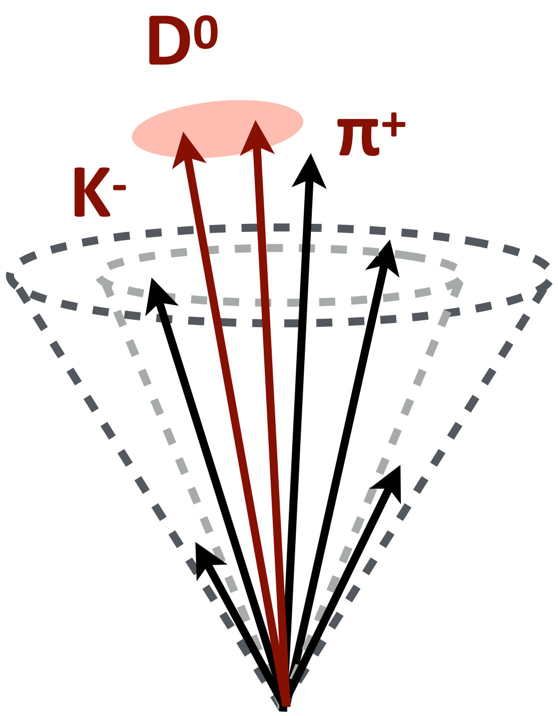



**First measurement of $D^0$-tagged jets in central PbPb collisions by ALICE:**

- **D-tagged jets down to 5 GeV!**
- similar suppression compared to light jets at low $p_T$ and ~ lower suppression at high $p_T$

# Radial shape of $D^0$-jet in pp and PbPb

Angular distribution of $D^0$ with respective to the jet axis $\frac{1}{N_{JD}}\frac{dN_{JD}}{dr}$



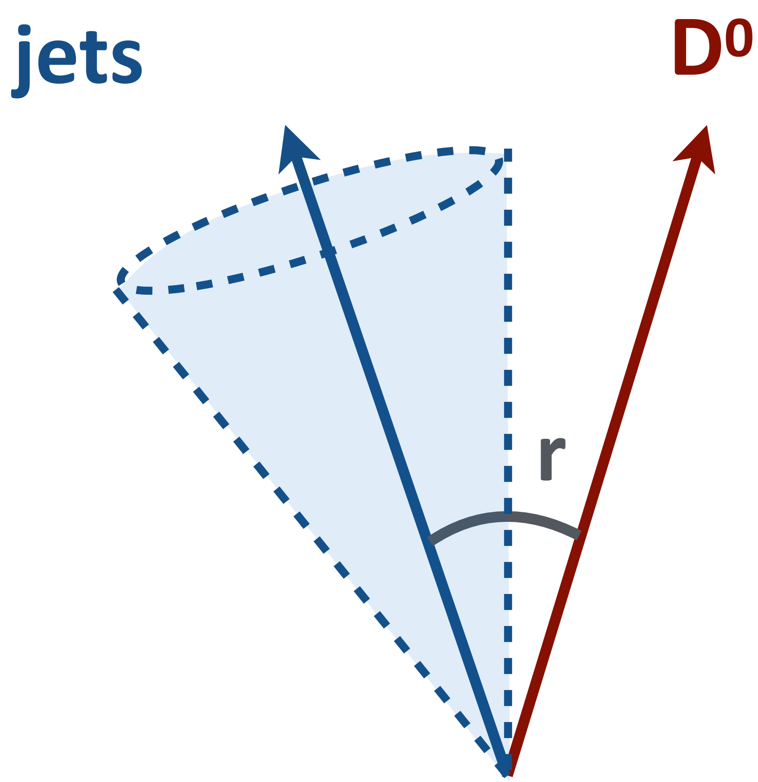

$$r = \sqrt{\Delta\phi^2_{JD} + \Delta\eta^2_{JD}}$$

relative η,Φ between D and jets

- **pp**: constraints on the mechanism of HF production (e.g. role of splitting)
- **PbPb**:
  - test of energy loss mechanisms
  - study the "response" of the medium in presence of a high momentum jet

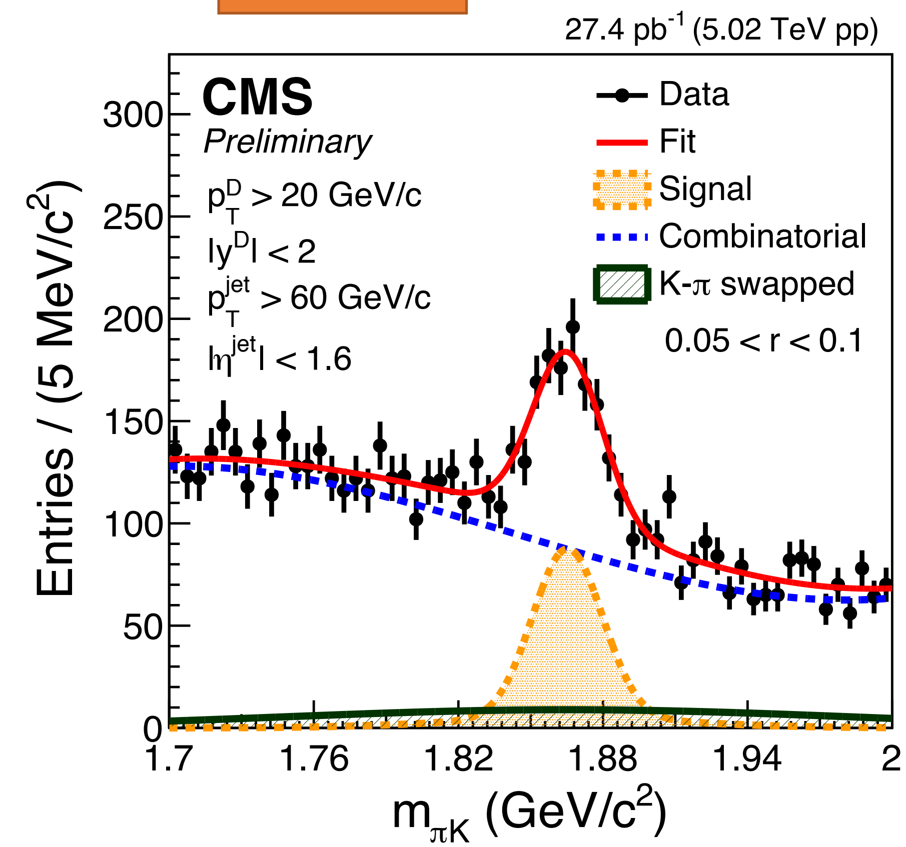
*CMS-PAS-HIN-18-007*

# Radial shape of D⁰-jet in pp and PbPb

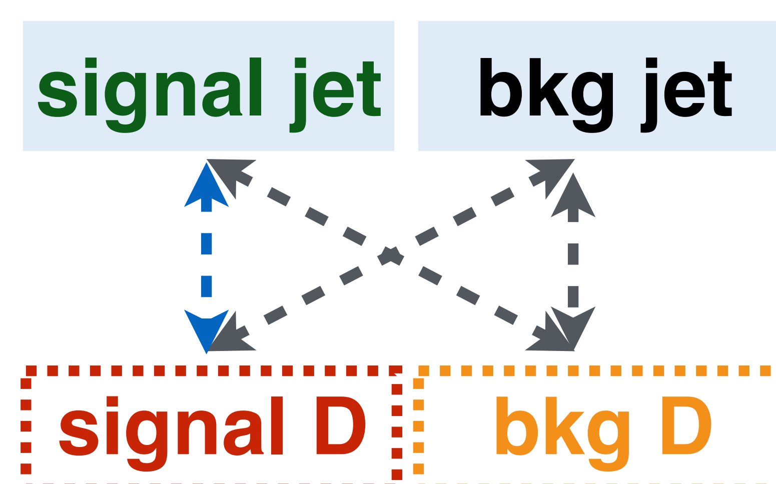



- Jet reconstruction
- D⁰ reconstruction and selection
- D⁰-jet pairs
- D⁰ yields extracted in bins of distance r
- background subtraction and corrections (removing the "uncorrelated" pairs)

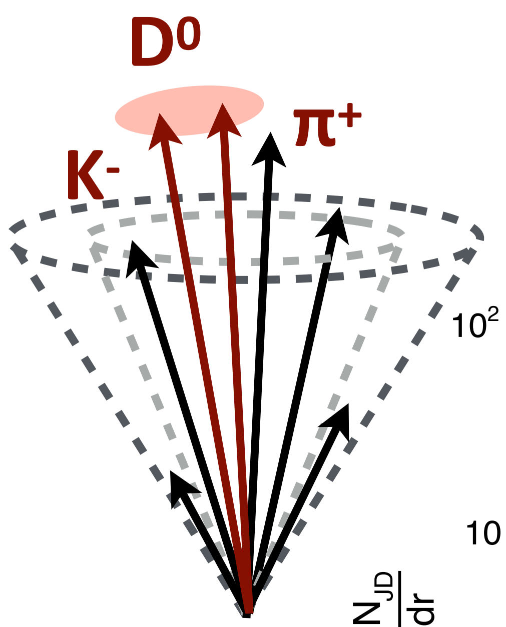
QM 2018

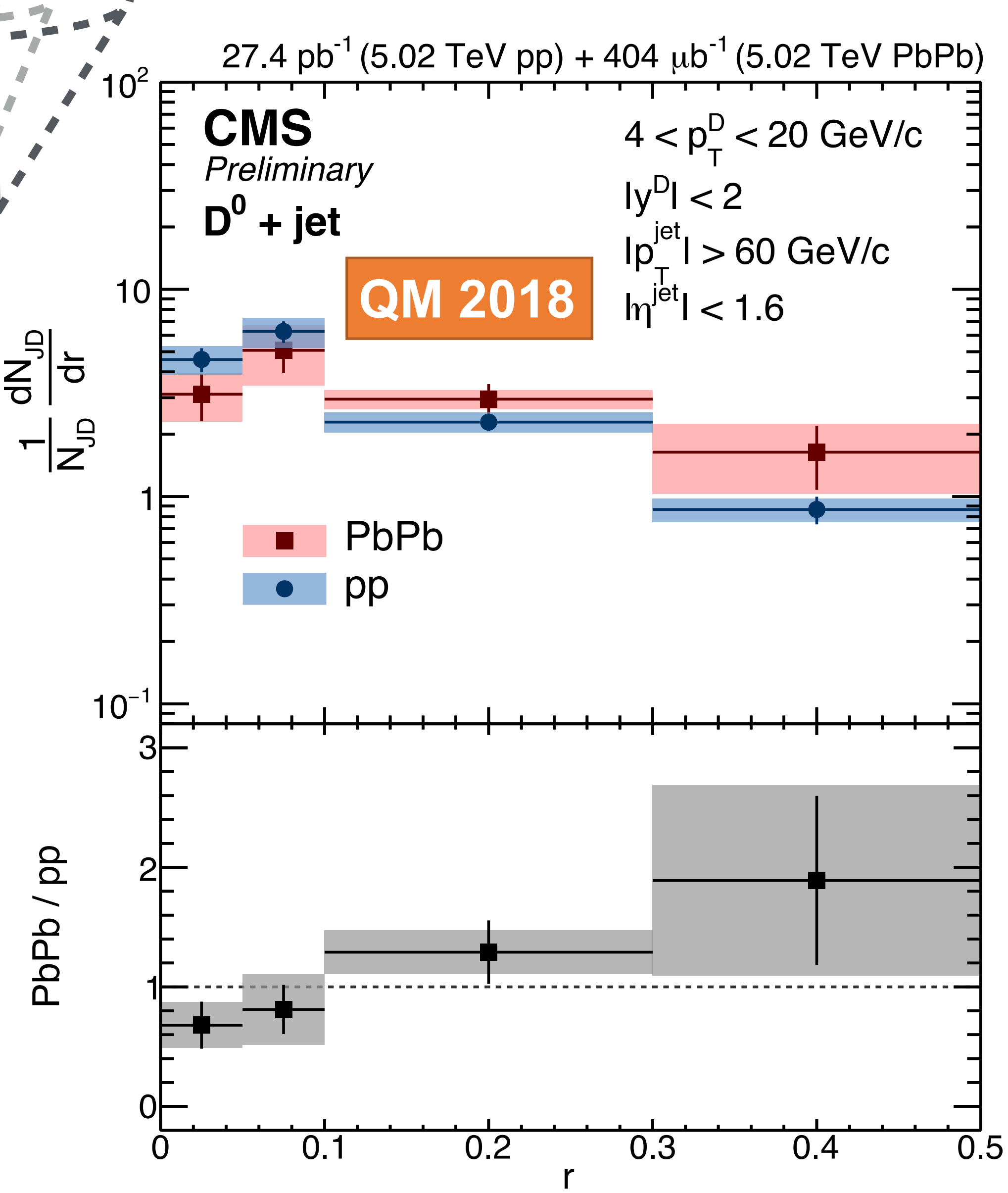



**background subtraction**



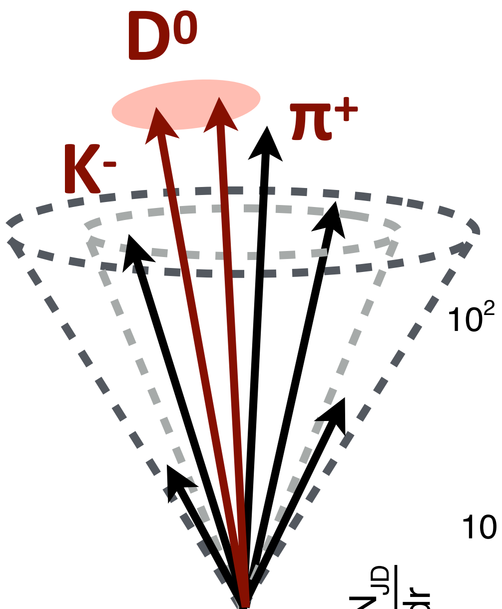
# Radial shape of D⁰-jet in pp and PbPb

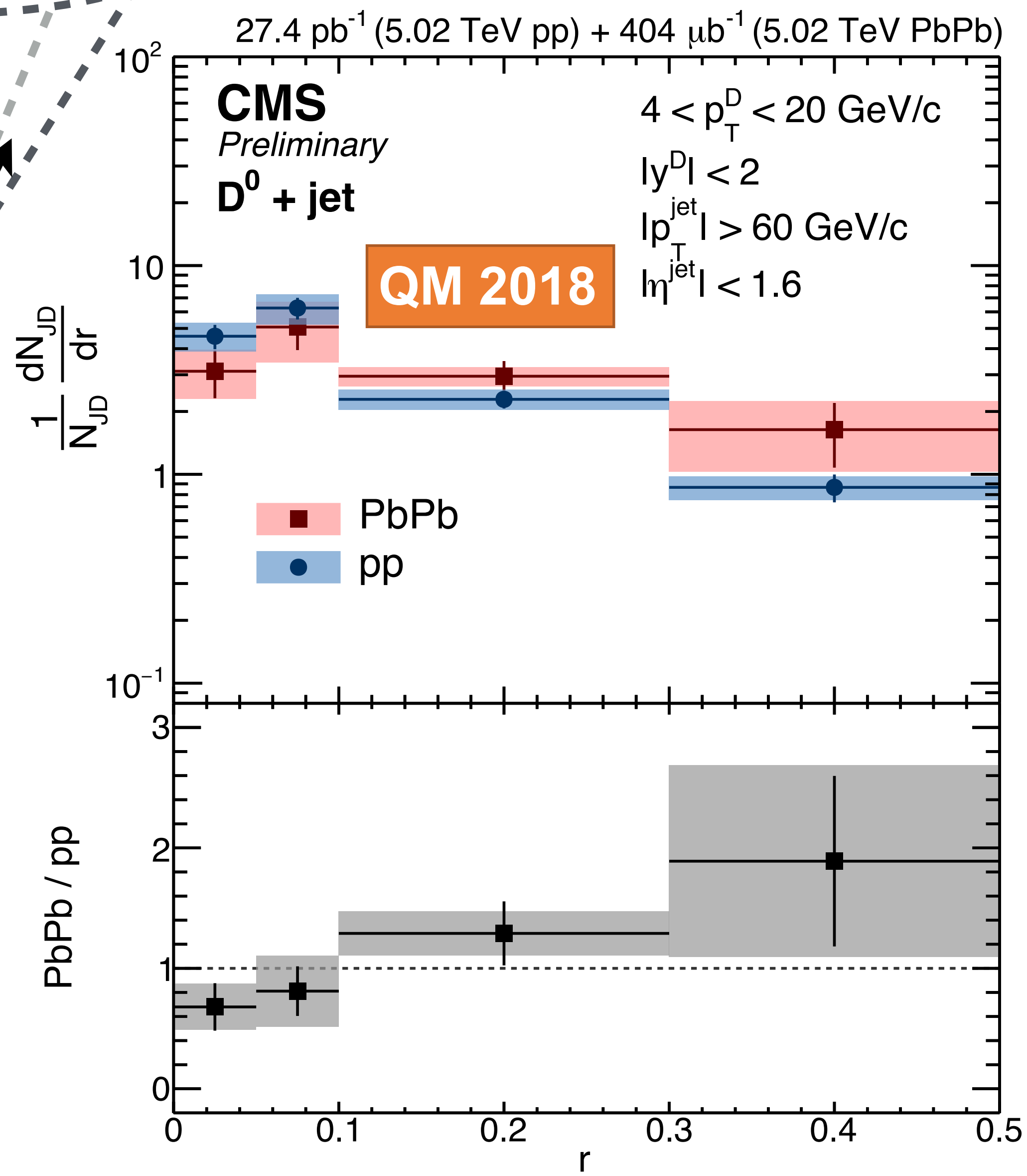


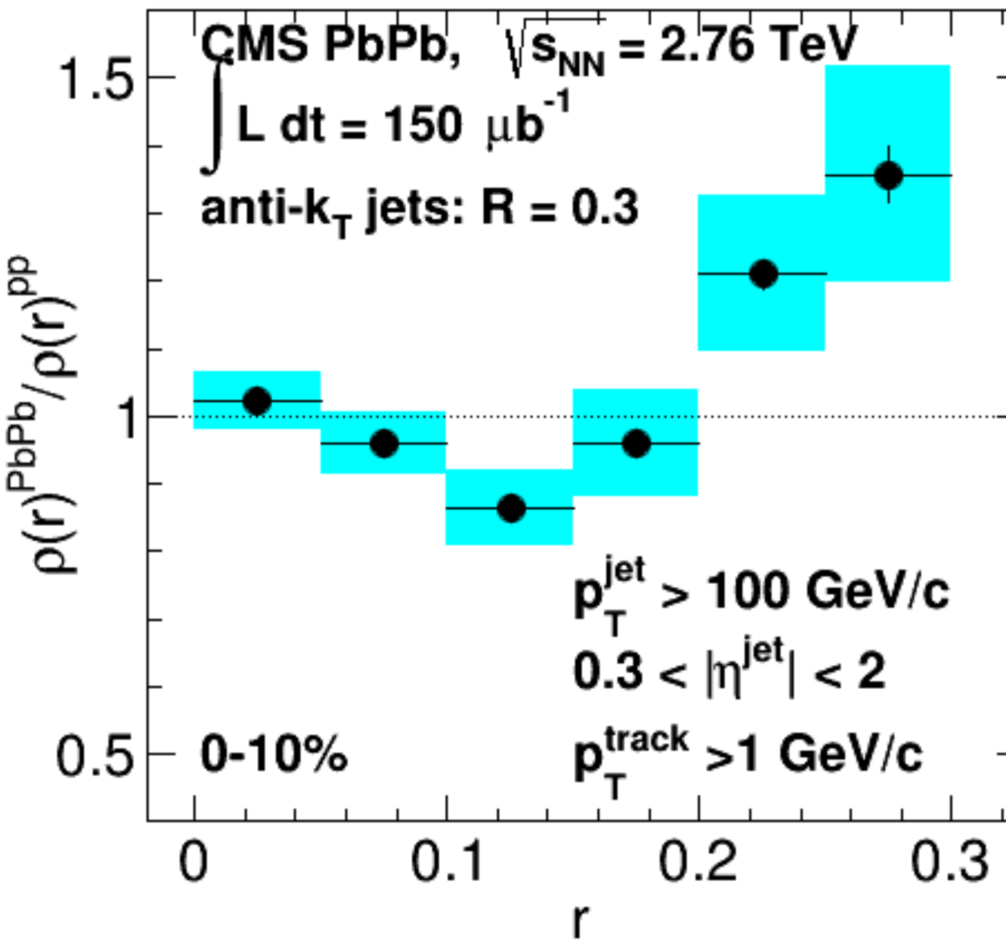



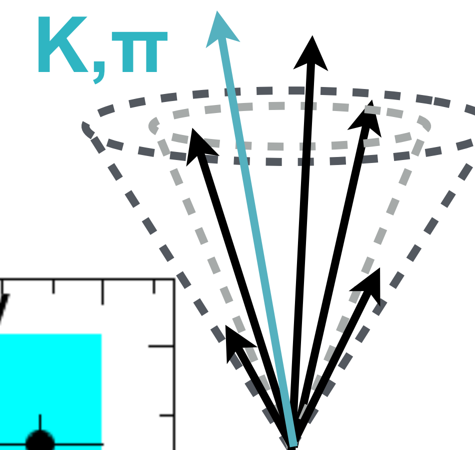

CMS-PAS-HIN-18-007

# Radial shape of $D^0$-jet in pp and PbPb



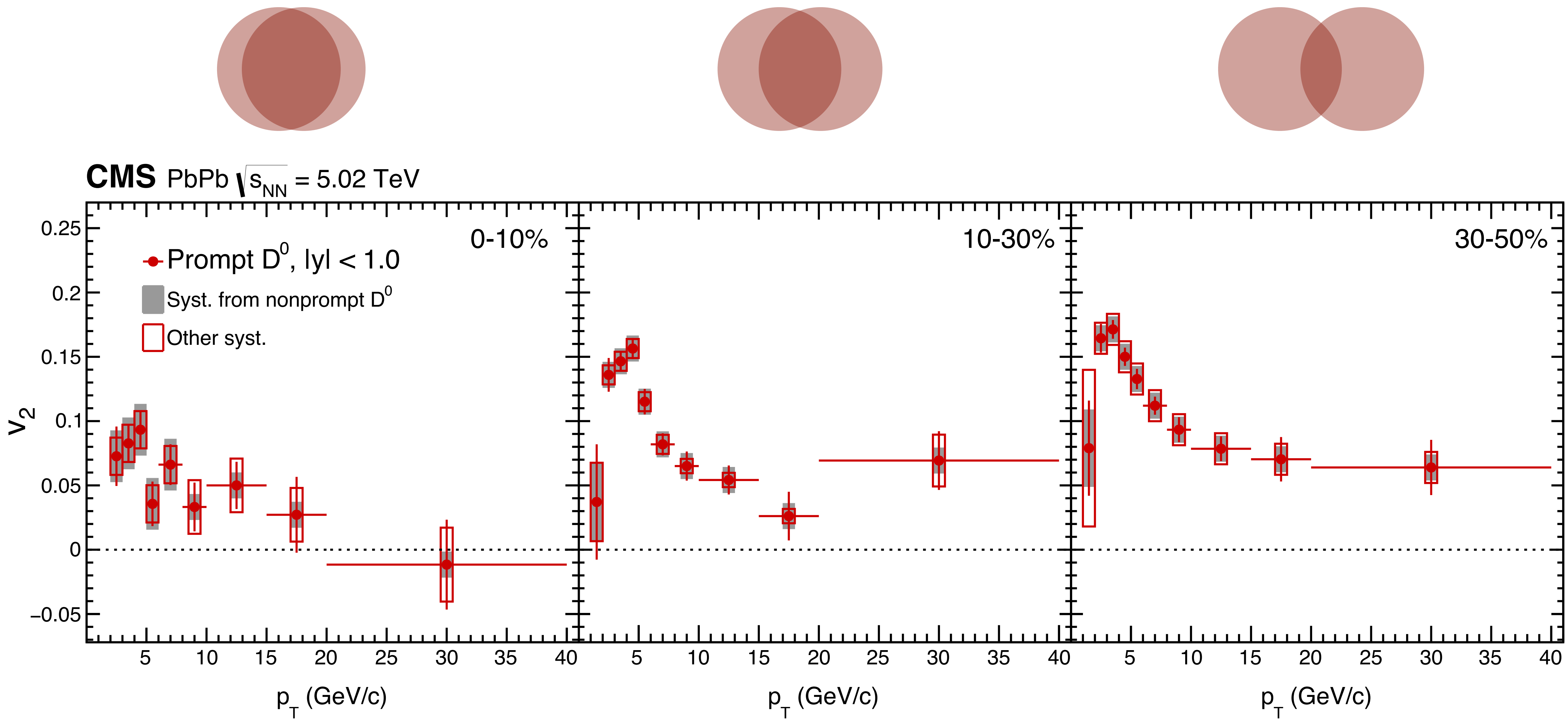




*CMS-PAS-HIN-18-007*

- For both **$D^0$-jet (left)** and correlation between **jets and light particles (right)** we observe an enhancement as large angles:
  → theoretical interpretation still not complete!
  → “medium response”? why is so similar for light and heavy particles?

# heavy flavor collectivity

# Prompt $D^0$ $v_2$ in PbPb at 5.02 TeV

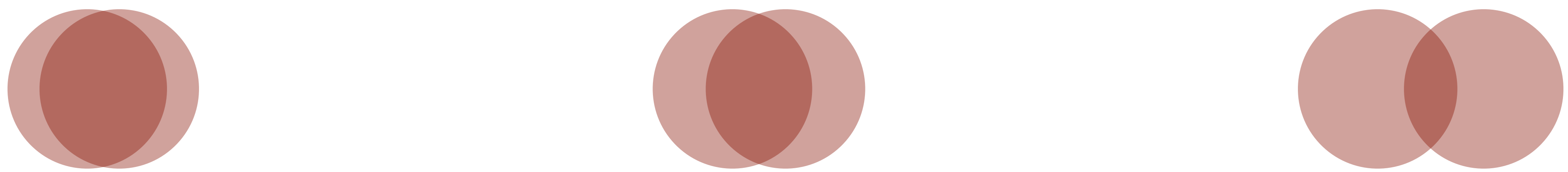


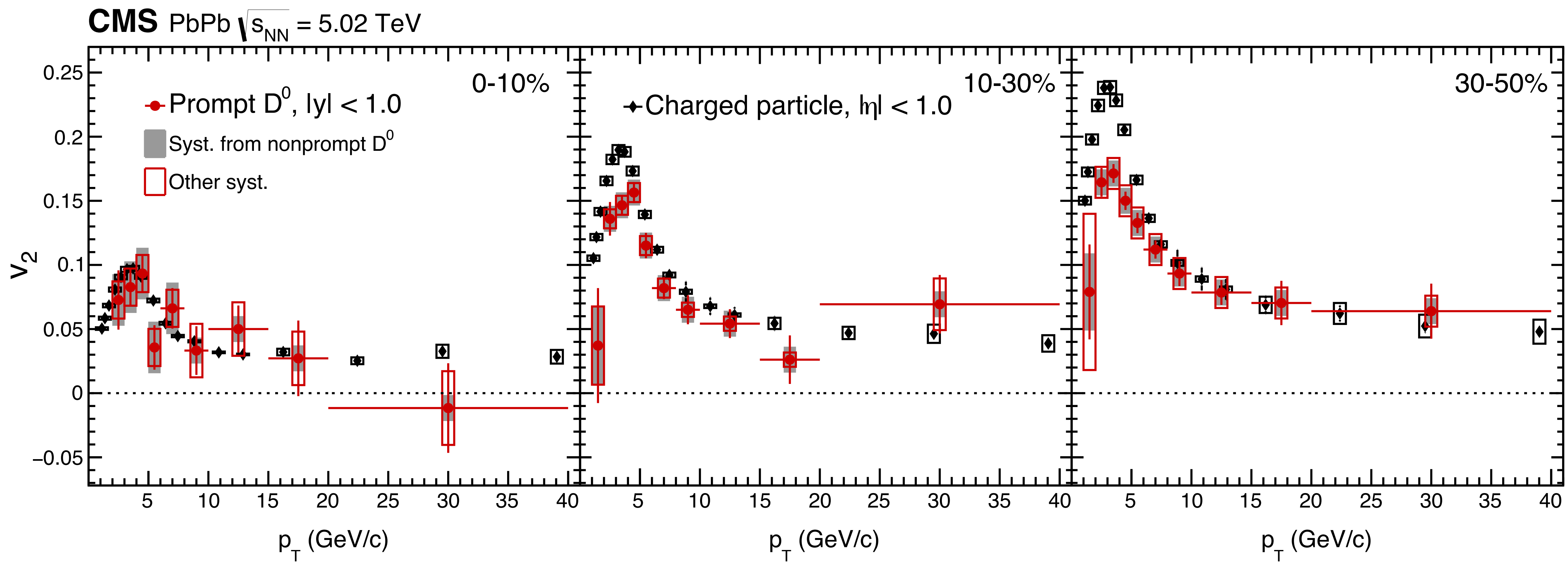

Positive prompt $D^0$ $v_2$ that increases with centrality at both low and high $p_T$

- Low $p_T$: charm quarks take part in the collective motion **(collisional)**
- High $p_T$: indicates path length dependence of energy loss **(radiative)**

arXiv: 1708.03497

# Prompt $D^0$ $v_2$ in PbPb at 5.02 TeV





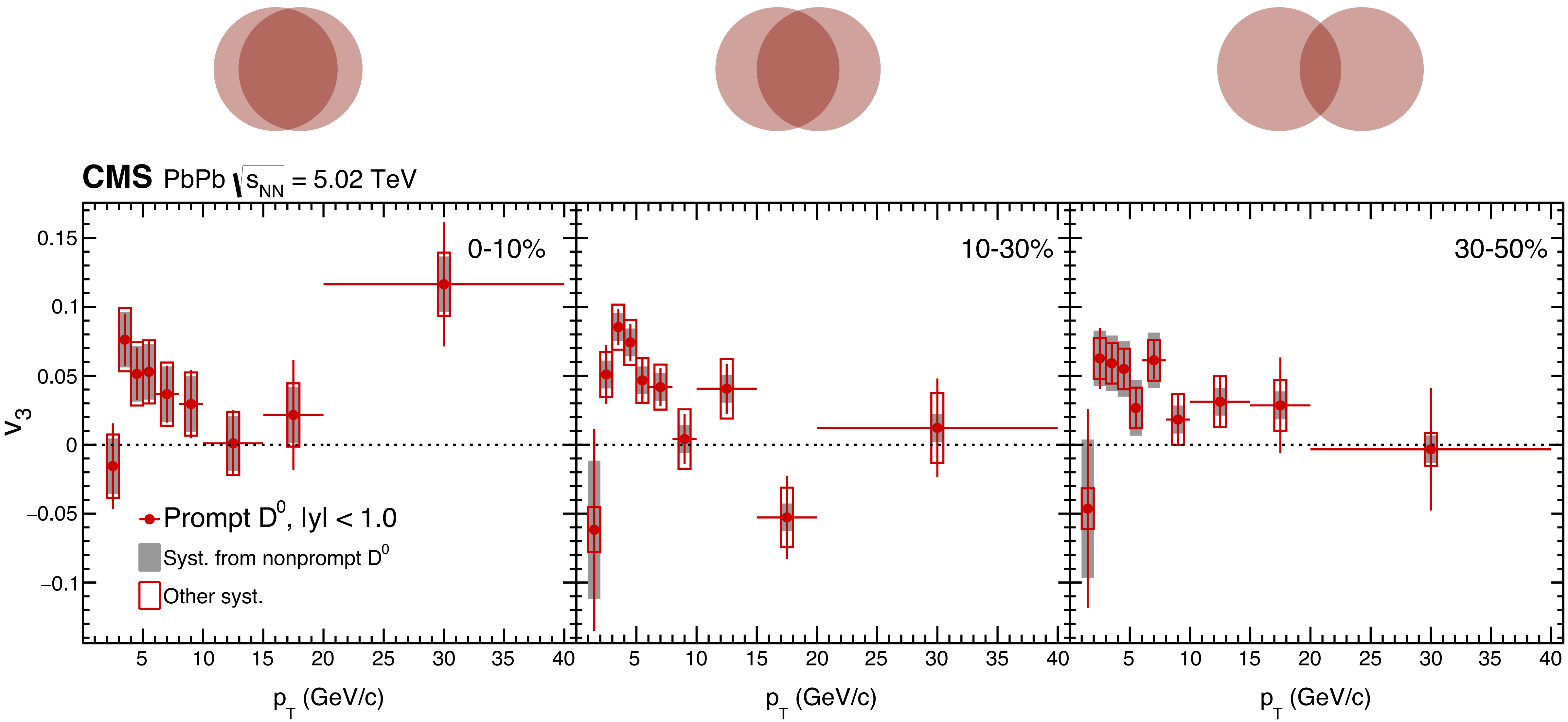

Low $p_T$: $v_2$ (prompt $D^0$) ≈ $v_2$ (charged particles) in central events

$v_2$ (prompt $D^0$) < $v_2$ (charged particles) in peripheral events

High $p_T$: $v_2$ (prompt $D^0$) ≈ $v_2$ (charged particles)

arXiv: 1708.03497

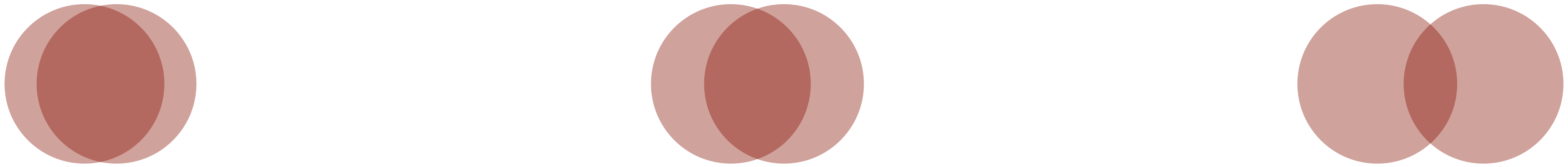
# Prompt $D^0$ $v_3$ in PbPb at 5.02 TeV

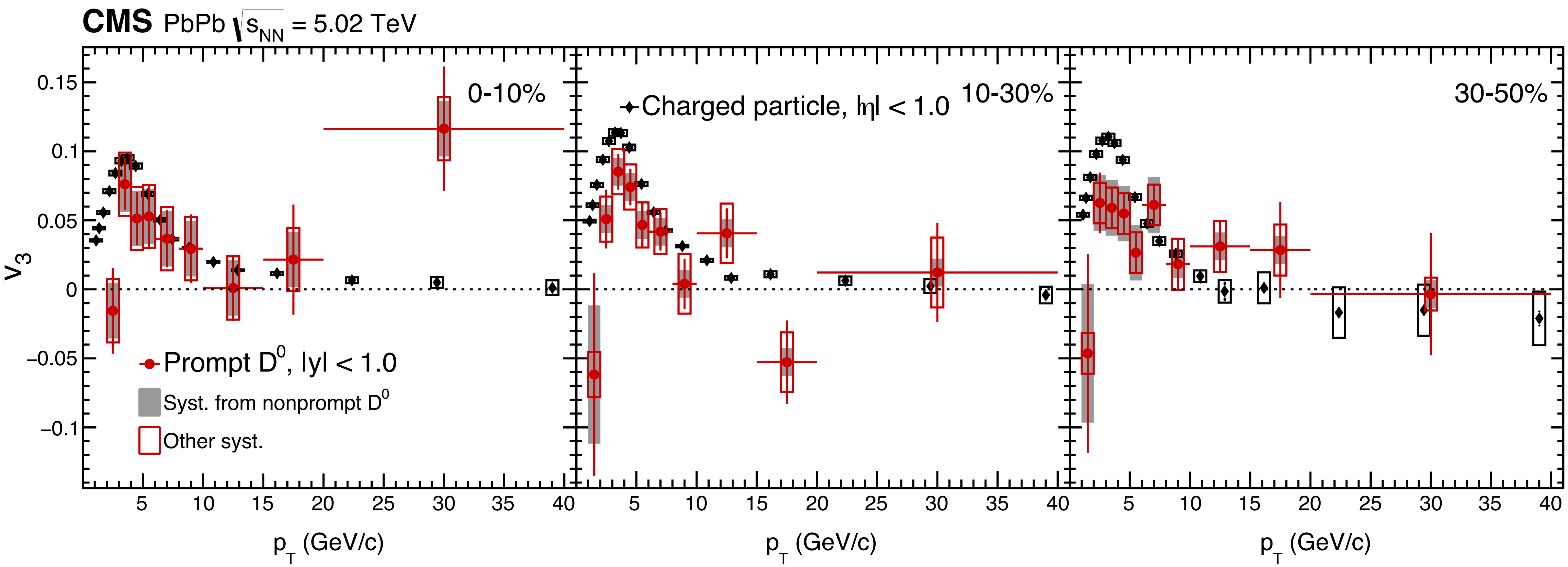



Low $p_T$: $v_3$ (prompt $D^0$) > 0;
High $p_T$: $v_3$ (prompt $D^0$) ≈ 0
Little centrality dependence

arXiv: 1708.03497

# Prompt $D^0$ $v_3$ in PbPb at 5.02 TeV

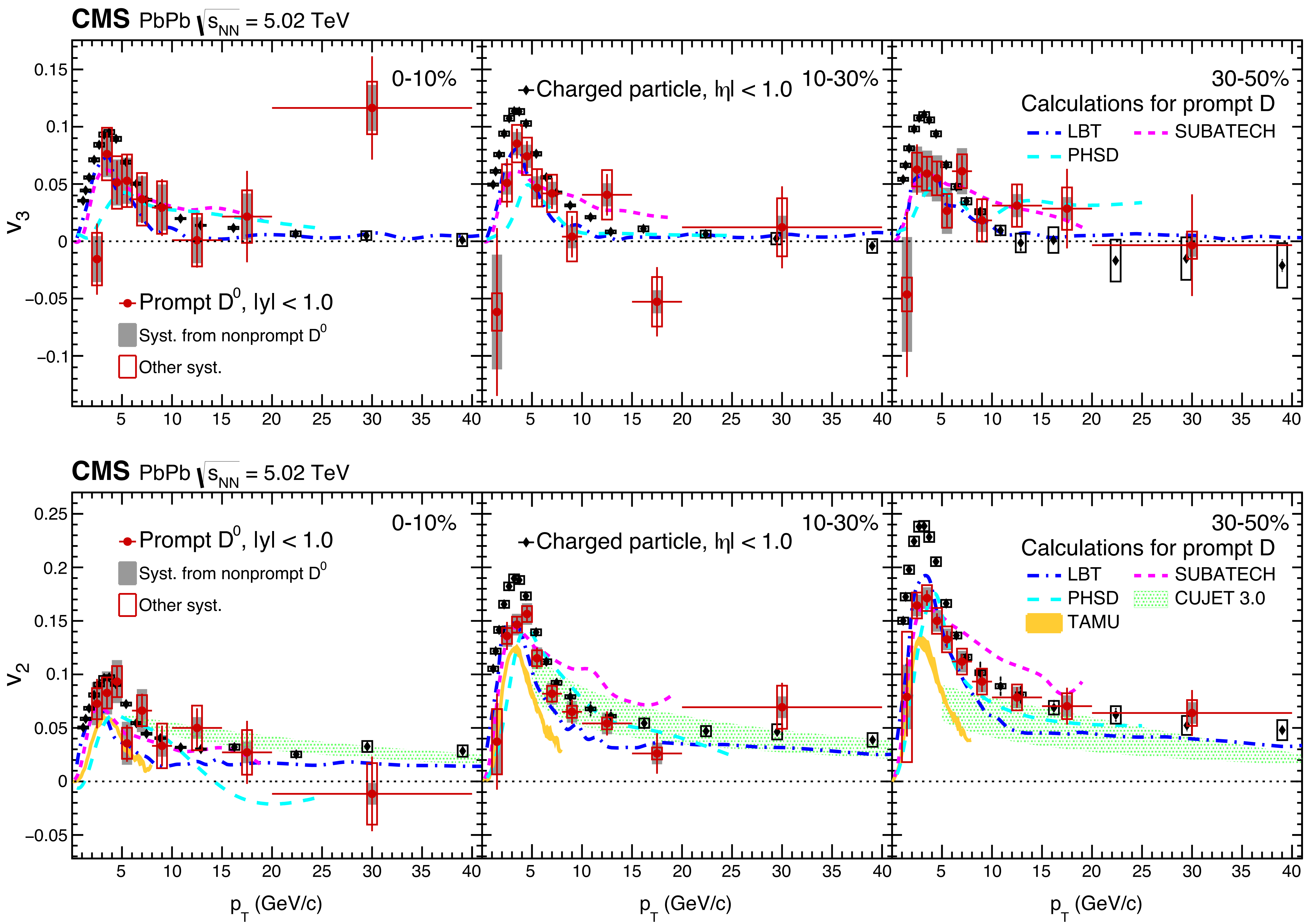





Low $p_T$: $v_3$ (prompt $D^0$) < $v_3$ (charged particles)
High $p_T$: $v_3$ (prompt $D^0$) ≈ $v_3$ (charged particles)
Both have little centrality dependence

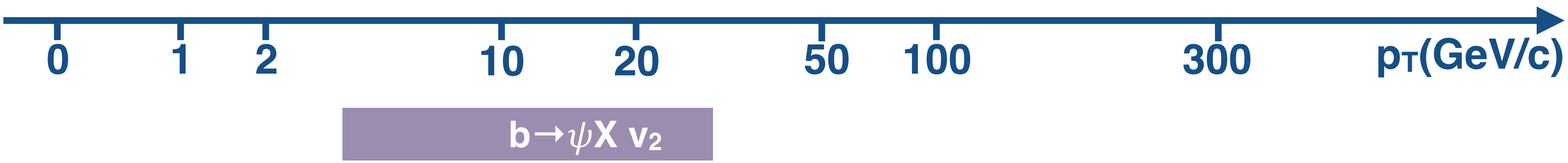
arXiv: 1708.03497

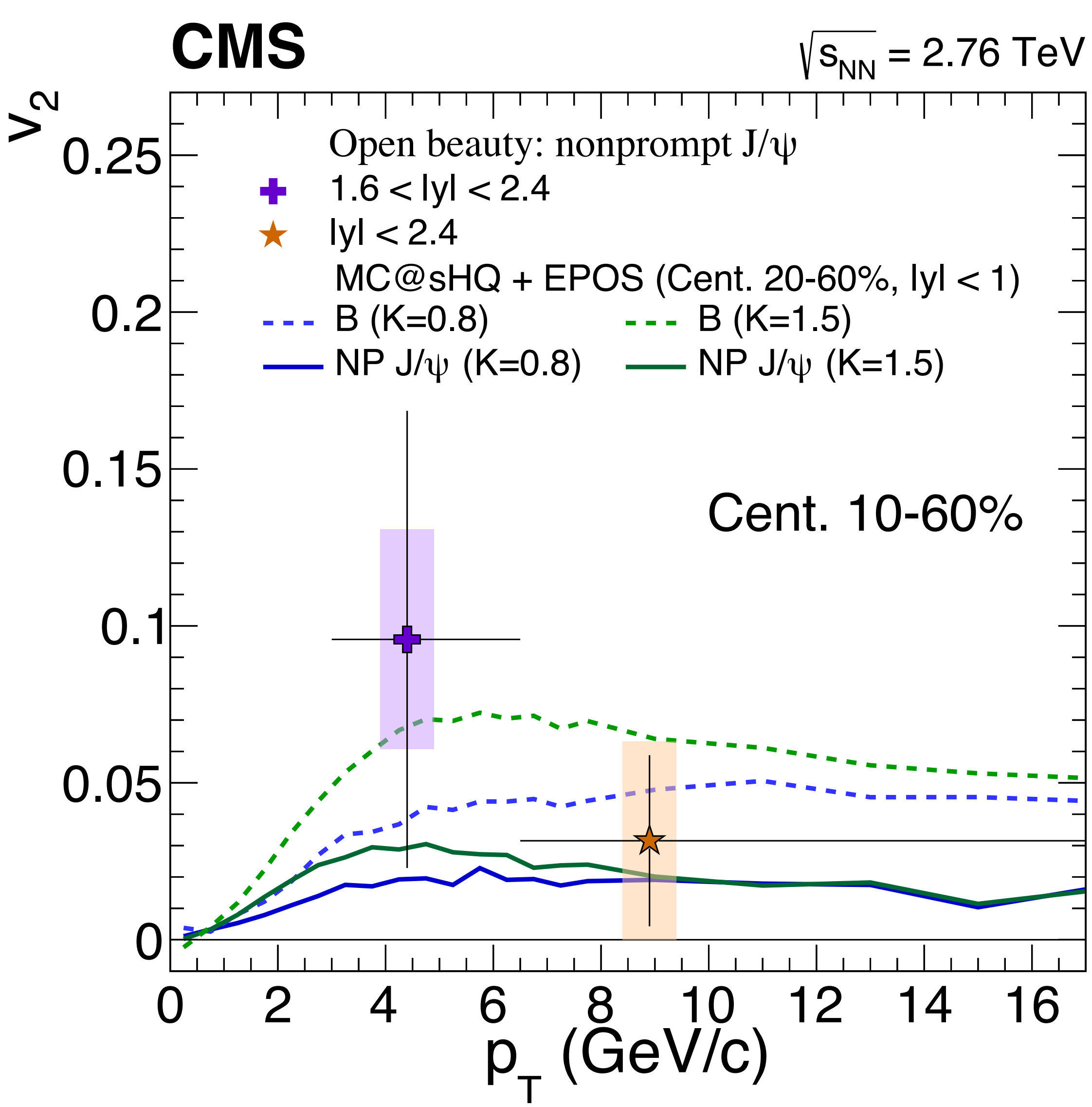
# Comparison to theoretical calculations

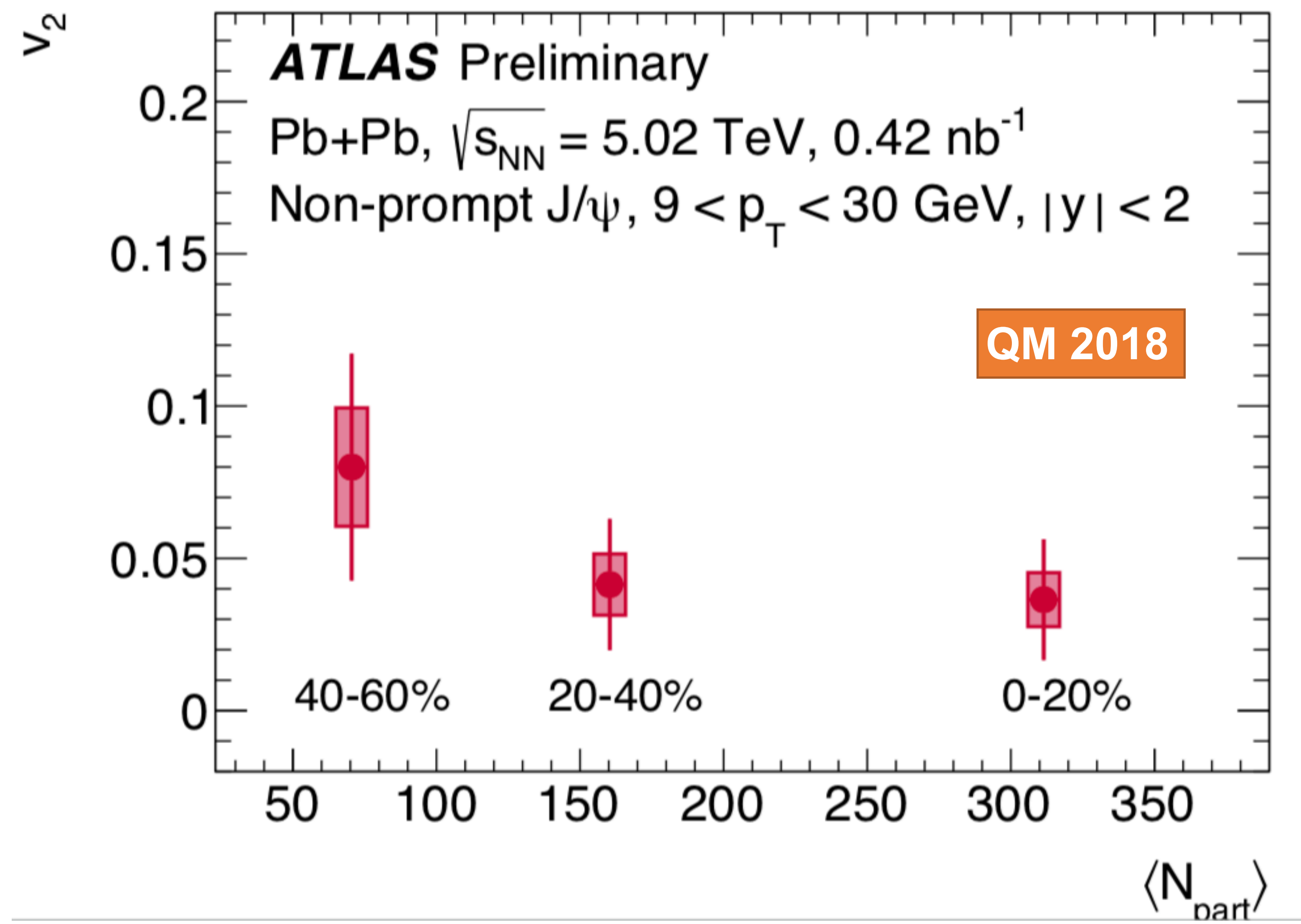



arXiv:

# b→ψX $v_2$ at 5.02 TeV



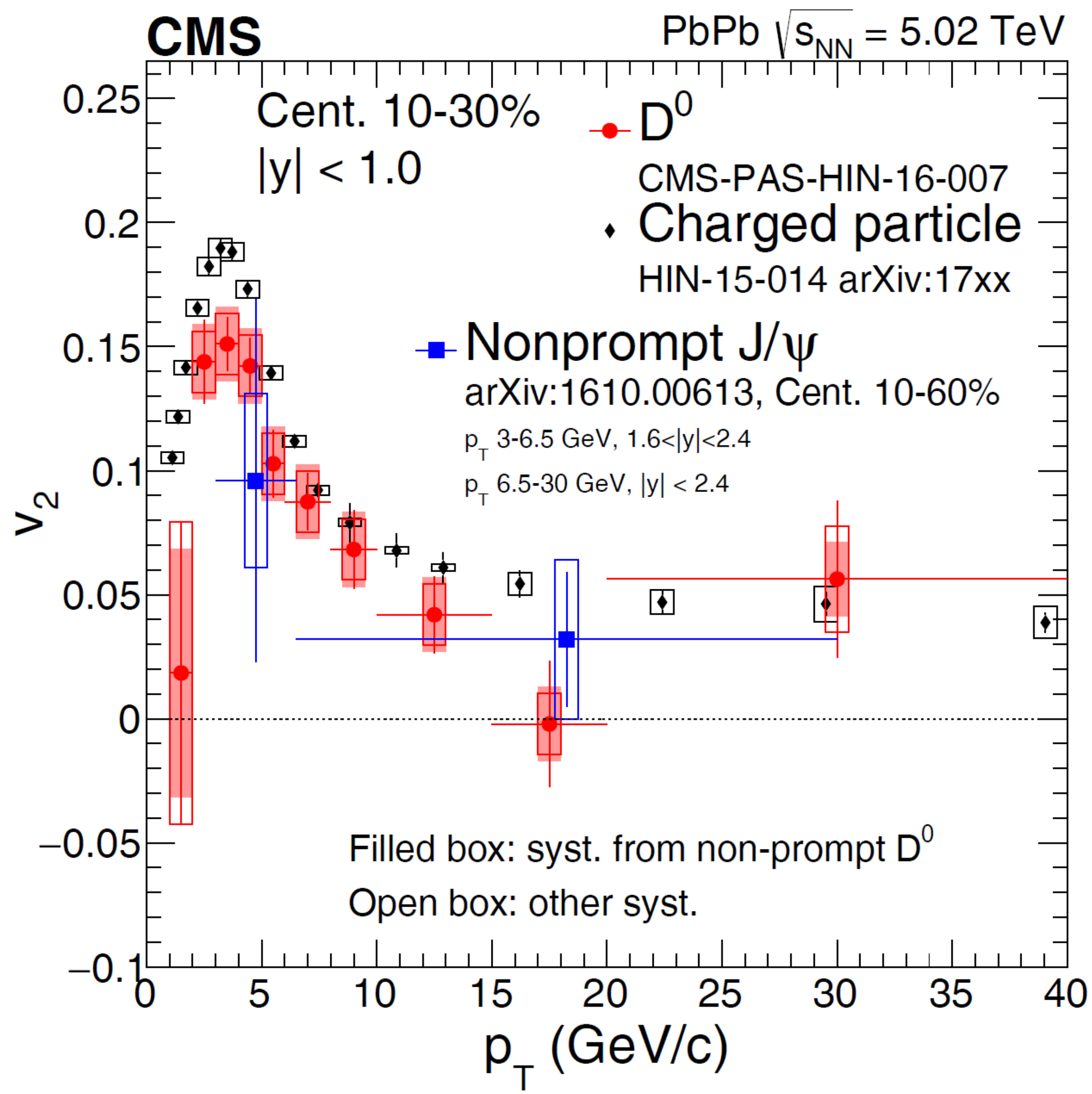




Current measurement $L_{int}$=150/μb, with ~70% statistical uncertainty at low $p_T$.

**~20% uncertainties expected in 2018** ($L_{int}$=1.5/nb)

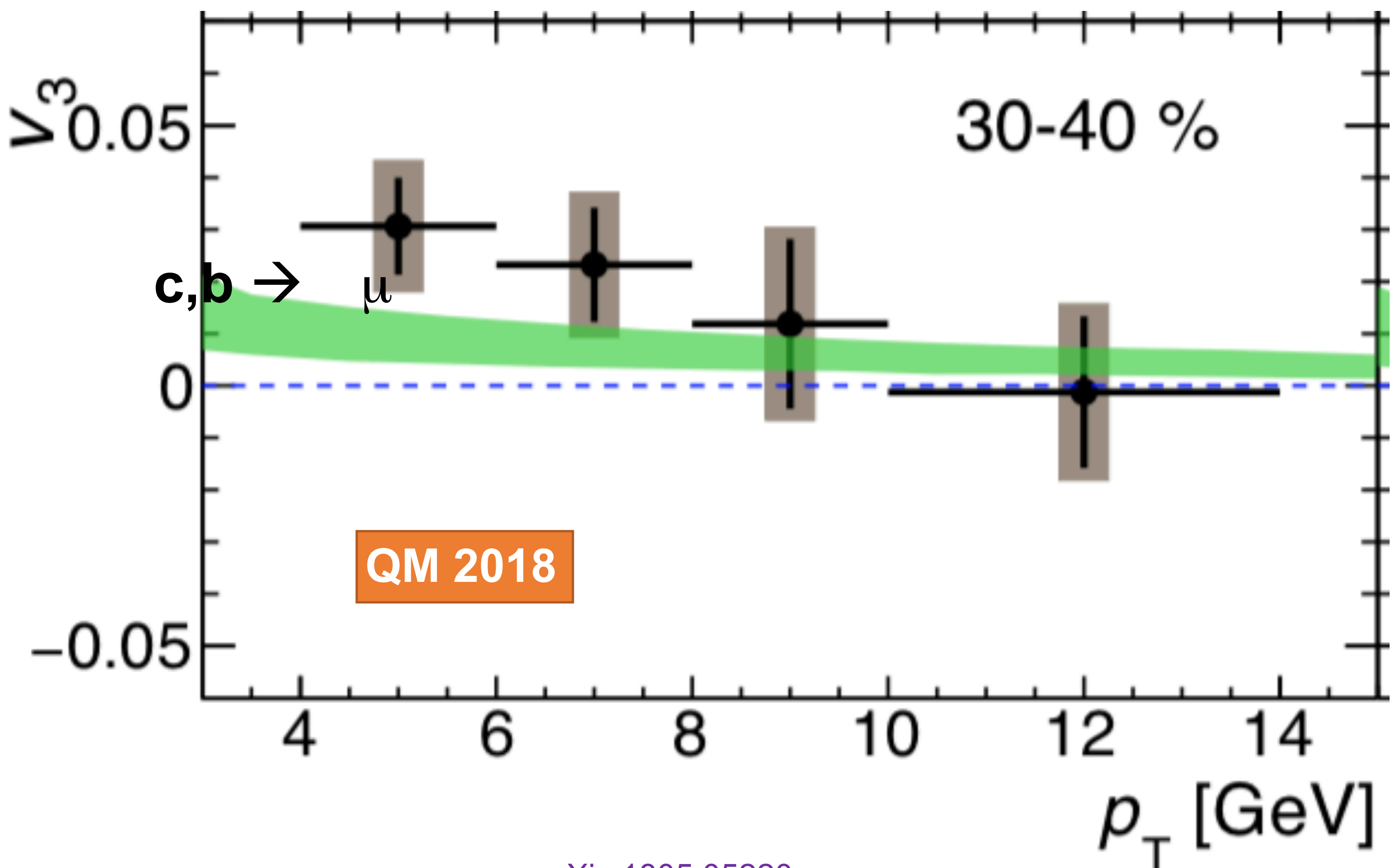
**~8% uncertainties expected with Run3!** ($L_{int}$=10/nb)

# $b \to \psi X$ $v_2$ at 5.02 TeV




**Similar flow for charm and beauty? Need more data!**

# $b \rightarrow \psi X$ $v_3$ at 5.02 TeV

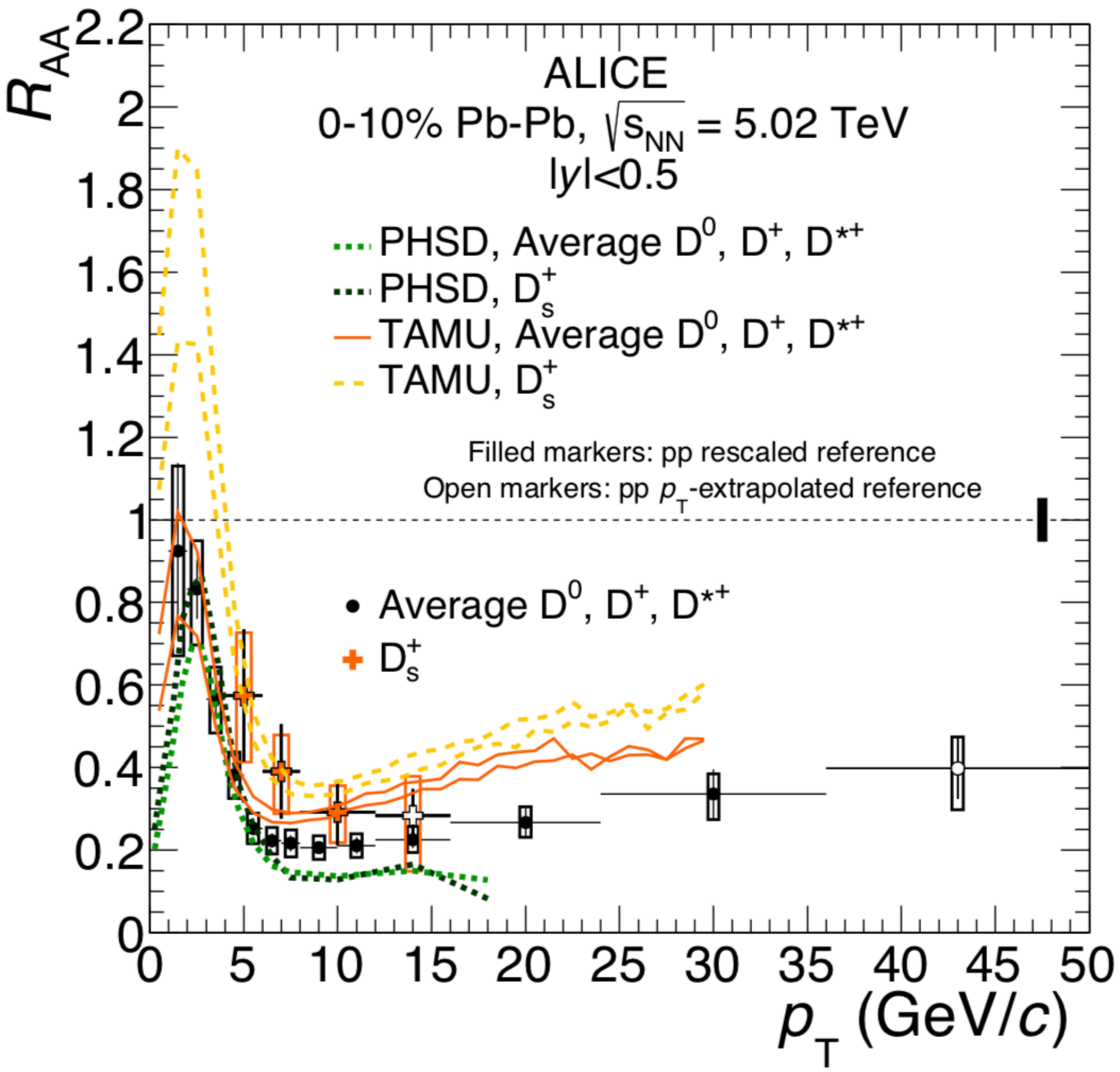


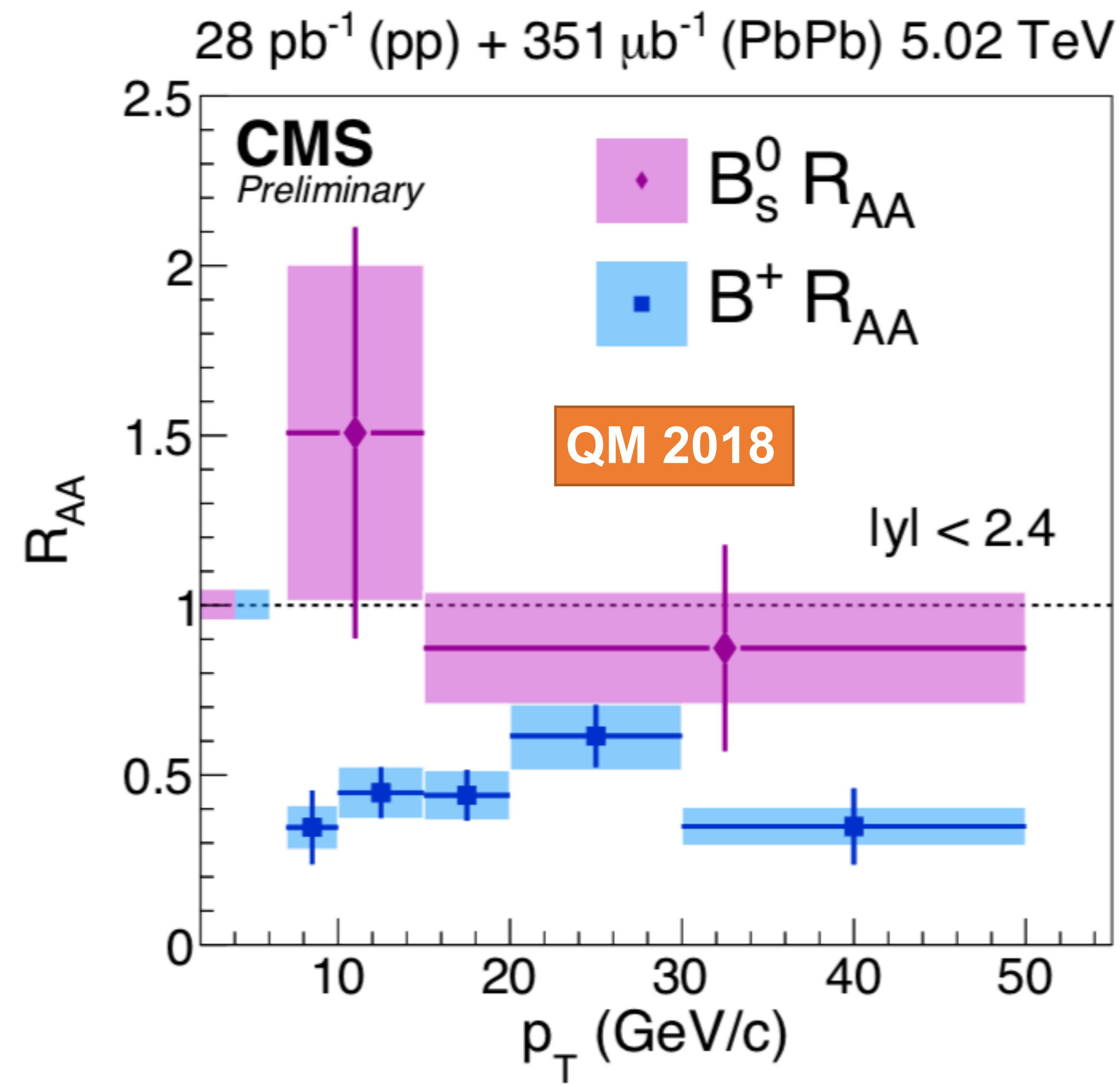

arXiv:1805.05220

Very impressive ATLAS result on the $v_3$ of HF muons.

→ Pretty significant non zero $v_3$ also for beauty!

# $D_s$ and $B_s$: insights into hadronization



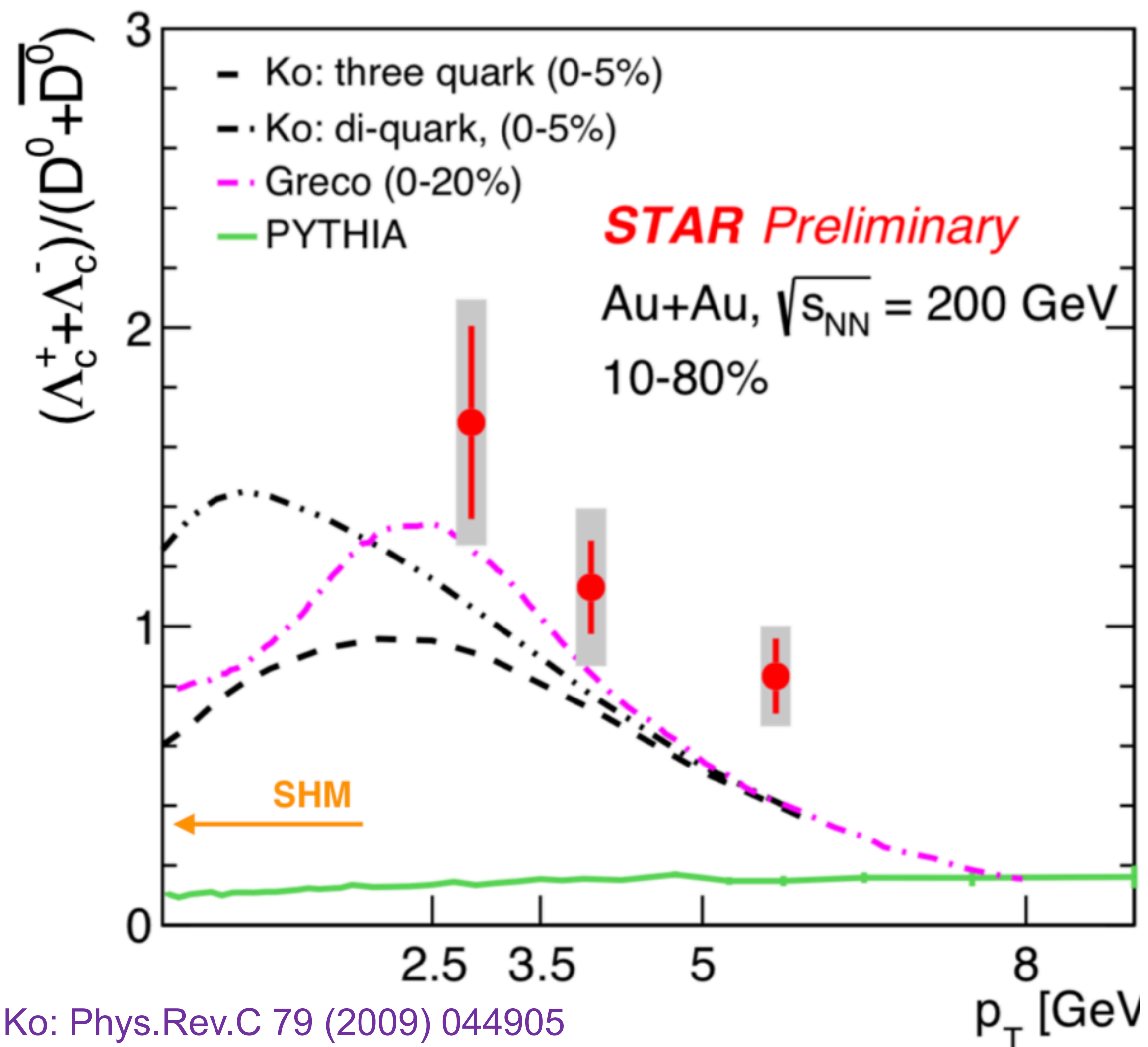



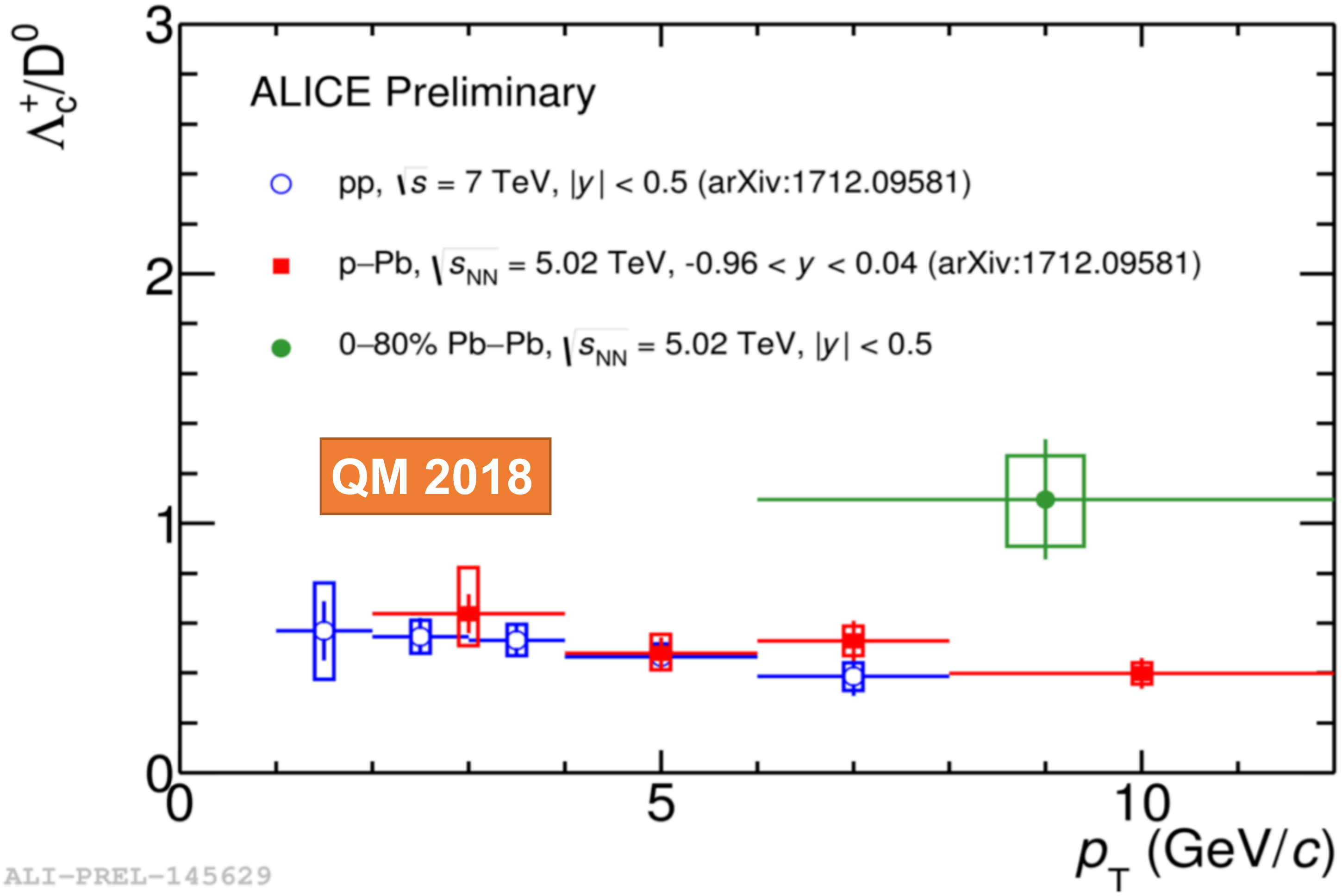

- Significant observation of $D_s/D$ enhancement in central PbPb

- First $B_s$ measurement in PbPb collisions
- hint of $B_s/B$ enhancement even if with very large uncertainties

→ consistent with the presence of charm recombination in the medium
→ one of the most striking indication of color reconnection in the QGP

# $\Lambda_c$: insights into hadronization



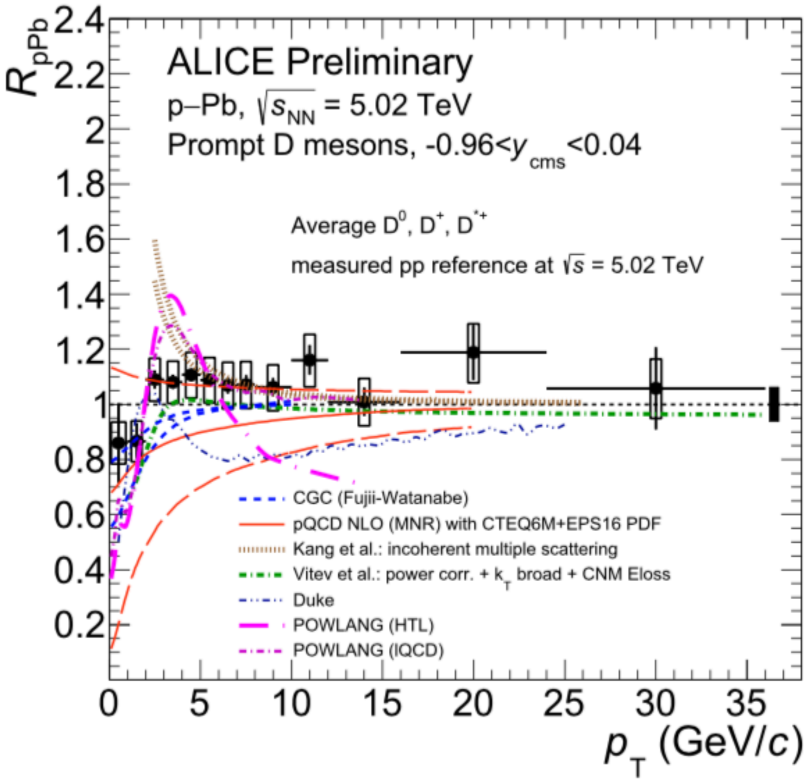

Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Rev.C 79 (2009) 044905

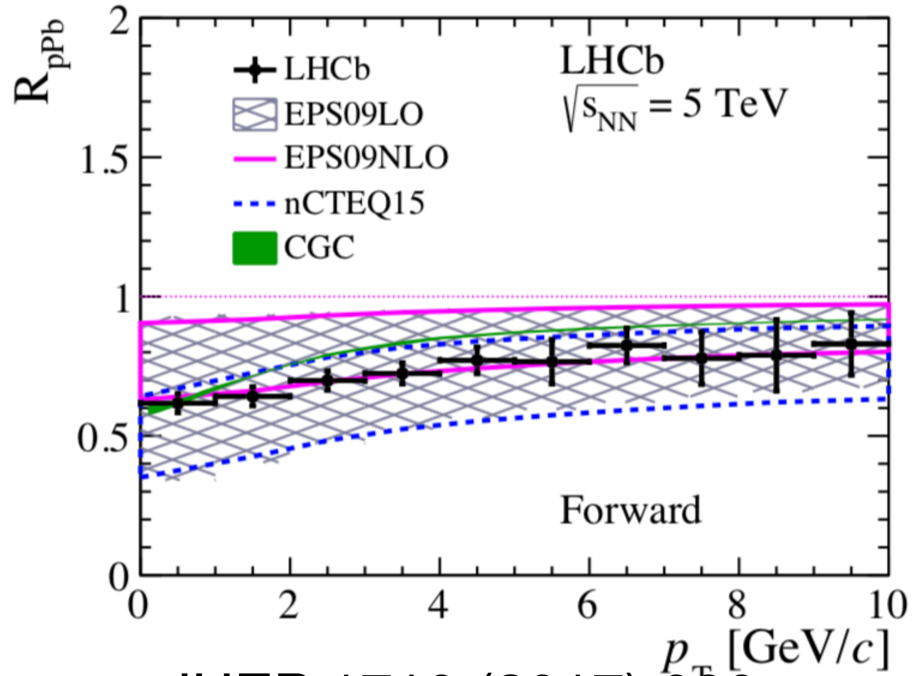
- $\Lambda_c$/D enhancement increases toward low $p_T$, increases from peripheral to central
- Similar $\Lambda_c$/D at RHIC and LHC (different $p_T$ ranges)

→ **Enhancement larger than models based on fragmentation + recombination**
Crucial measurement to extract **total cc cross section** !

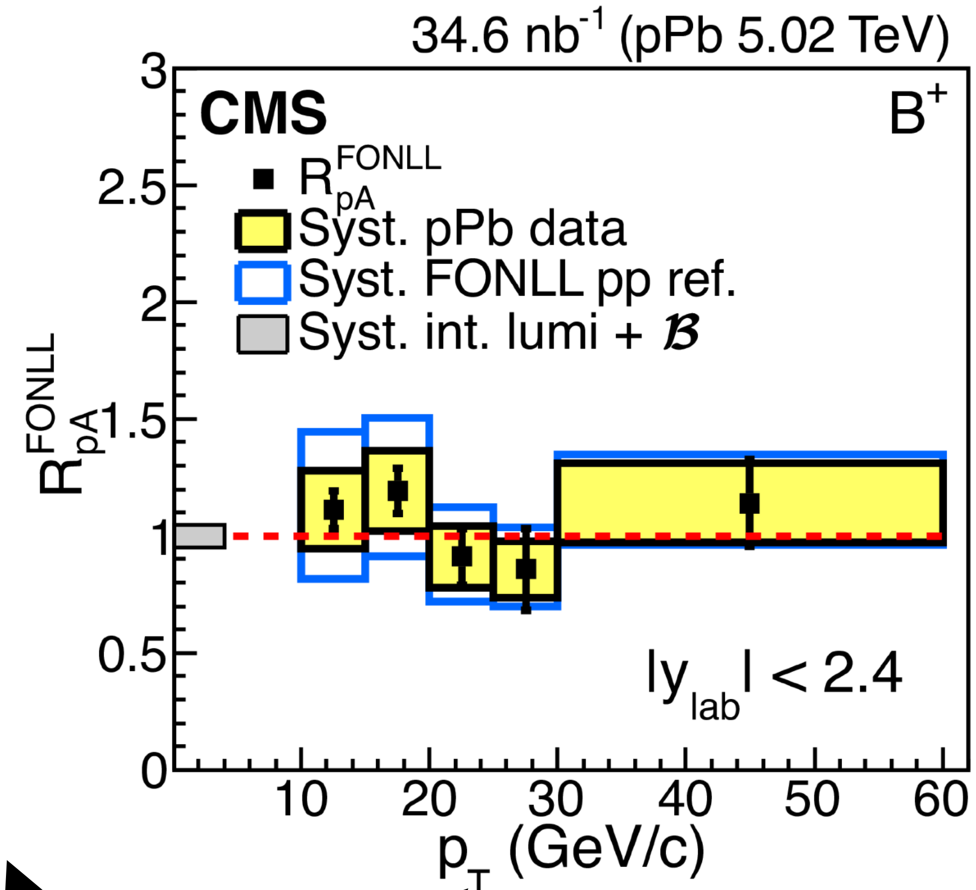
# heavy-flavour in small systems

# Heavy-flavours in pPb collisions




JHEP 1710 (2017) 090



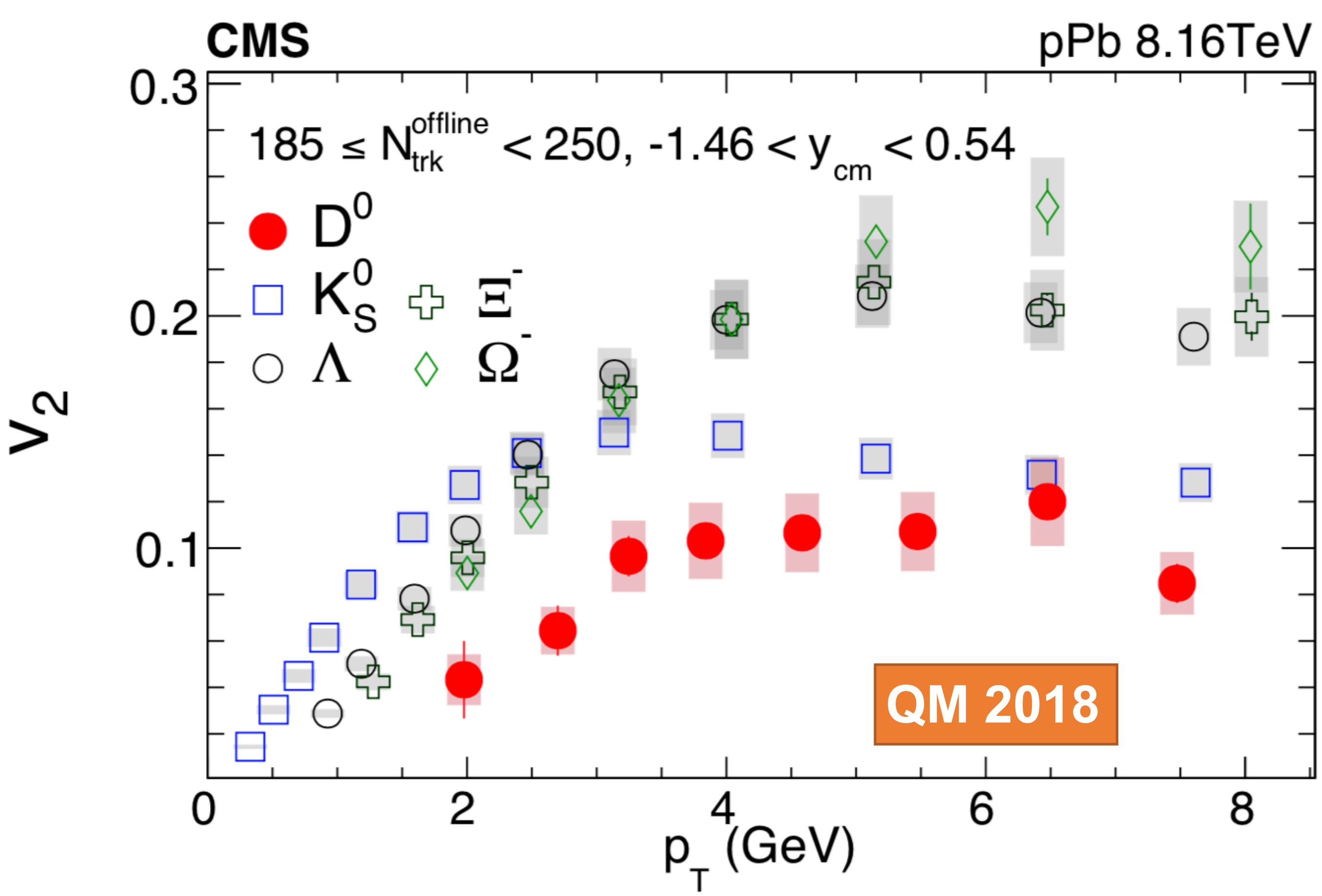

**D meson production:**

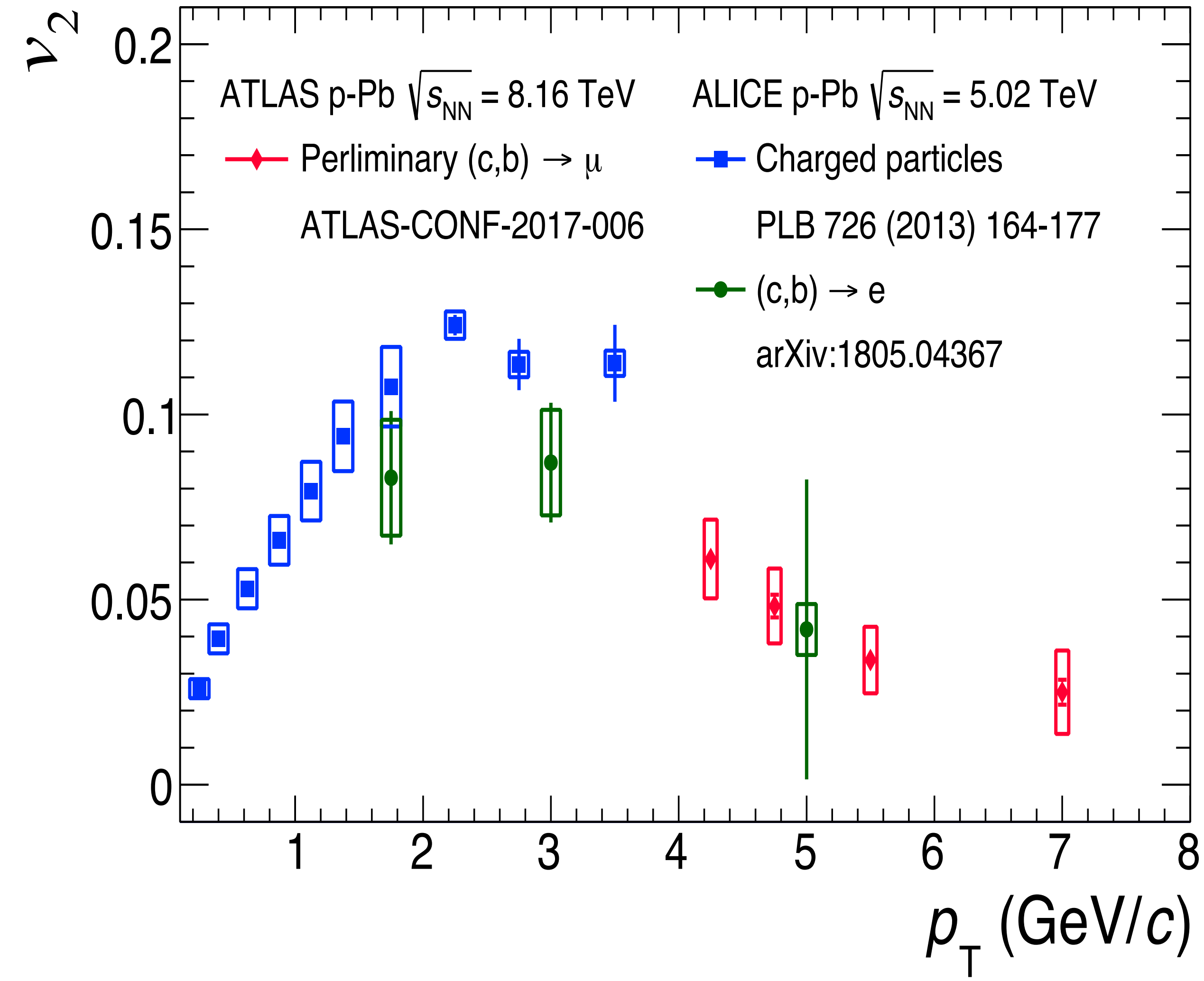
- first observation of significant modification due to shadowing
- binary scaling holds at high $p_T$

B production in pPb
→ compatible with predictions from FONLL scaled by A=208

PRL 116 (2016) 032301, JHEP 1710 (2017) 090

# HF collectivity in pPb collisions



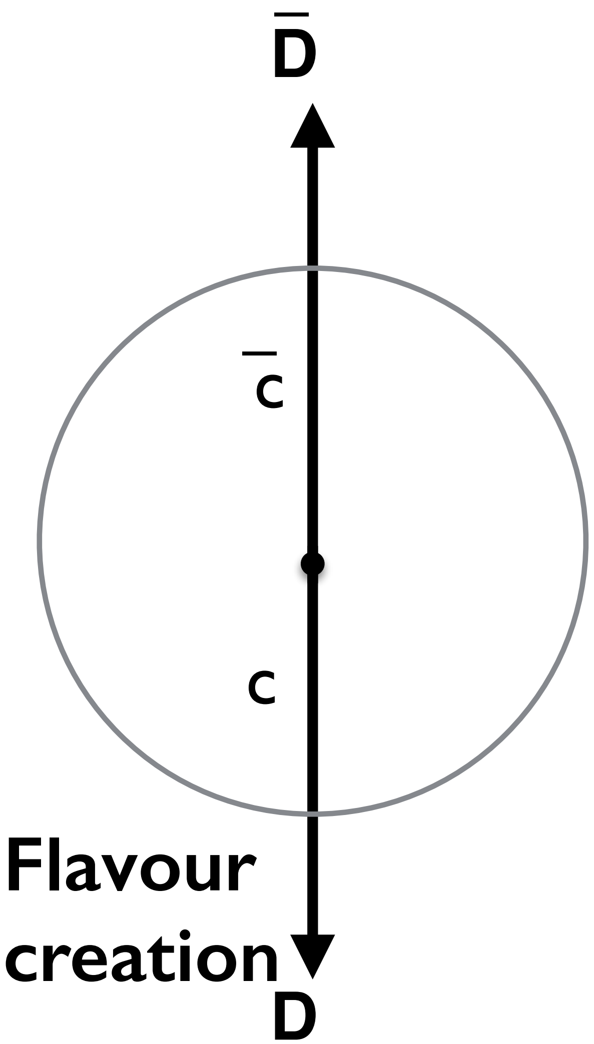



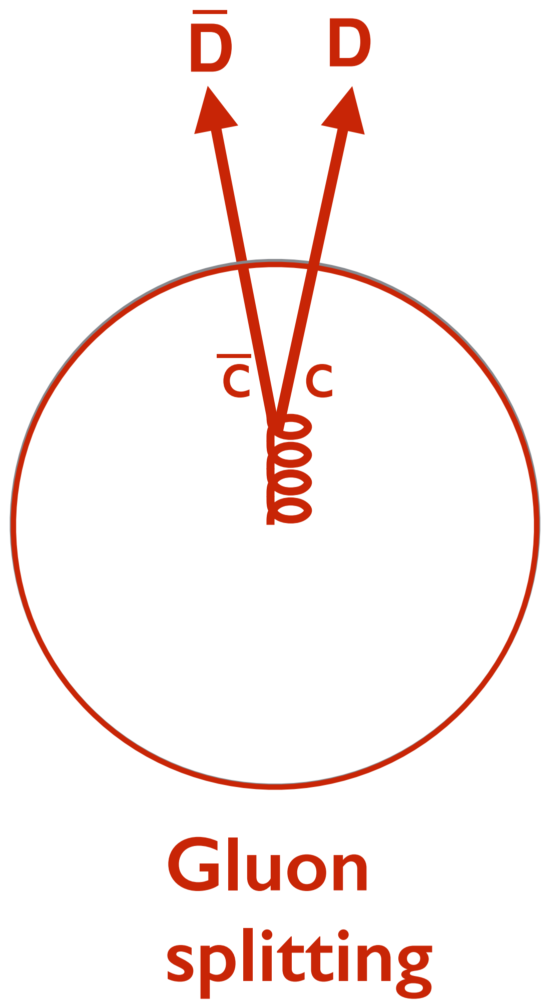

- **Positive $v_2$** for HF particles ($D^0$ , D* mesons, $e^{\pm}$ and $\mu^{\pm}$ from HF) from 2-particle correlations in **high-multiplicity p-Pb**
- $D^0$ $v_2$ persists up to high $p_T$, weaker than that of light flavors

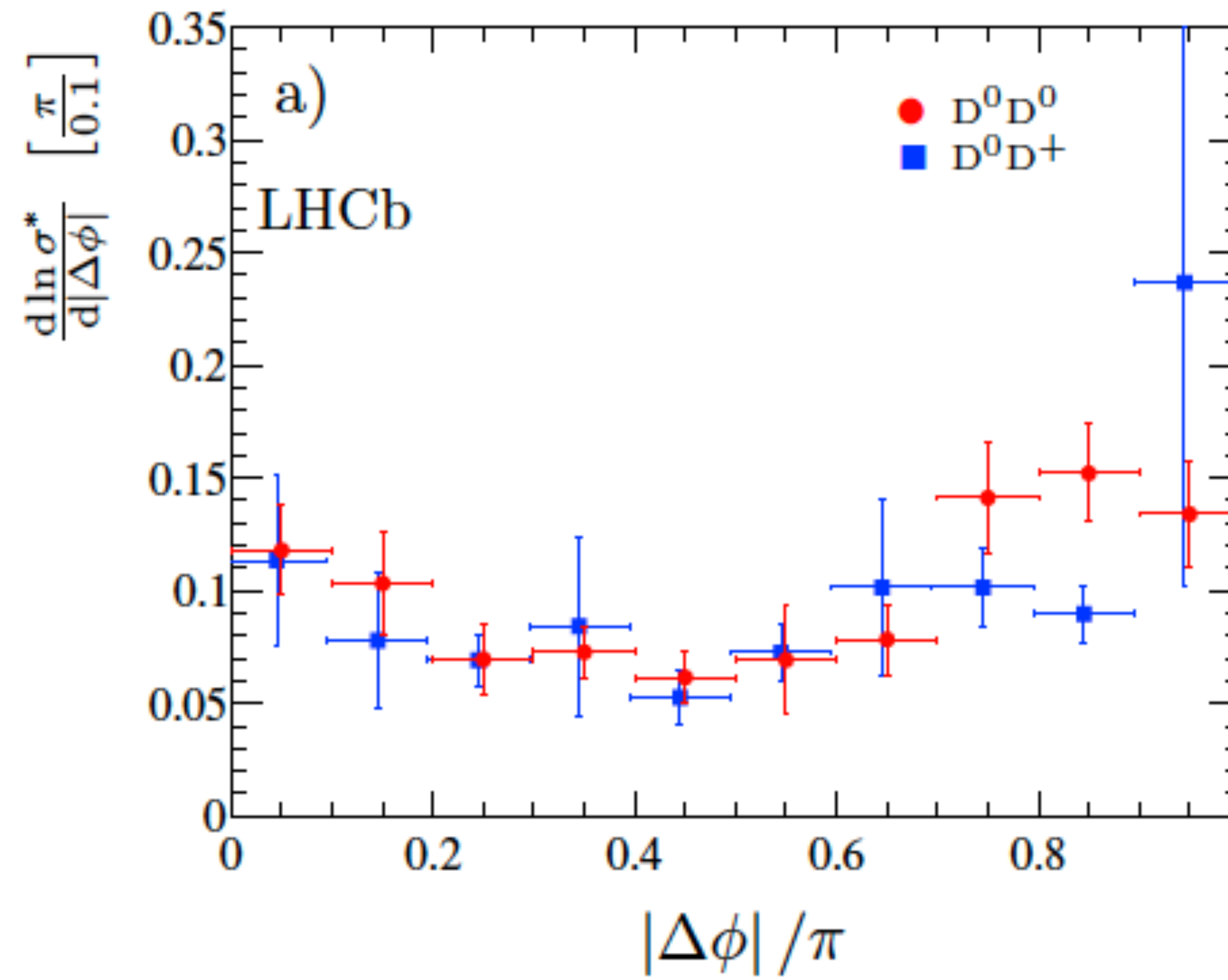
# Some ideas for future HF analysis

# Precise D-Dbar correlations in pp

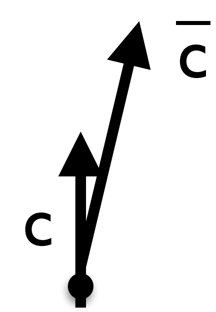
## D-hadrons and D-$\bar{D}$ correlations for studying pp production mechanisms



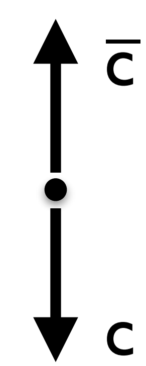




**Gluon splitting (GS) contribution** not well modelled by most of the pp calculations



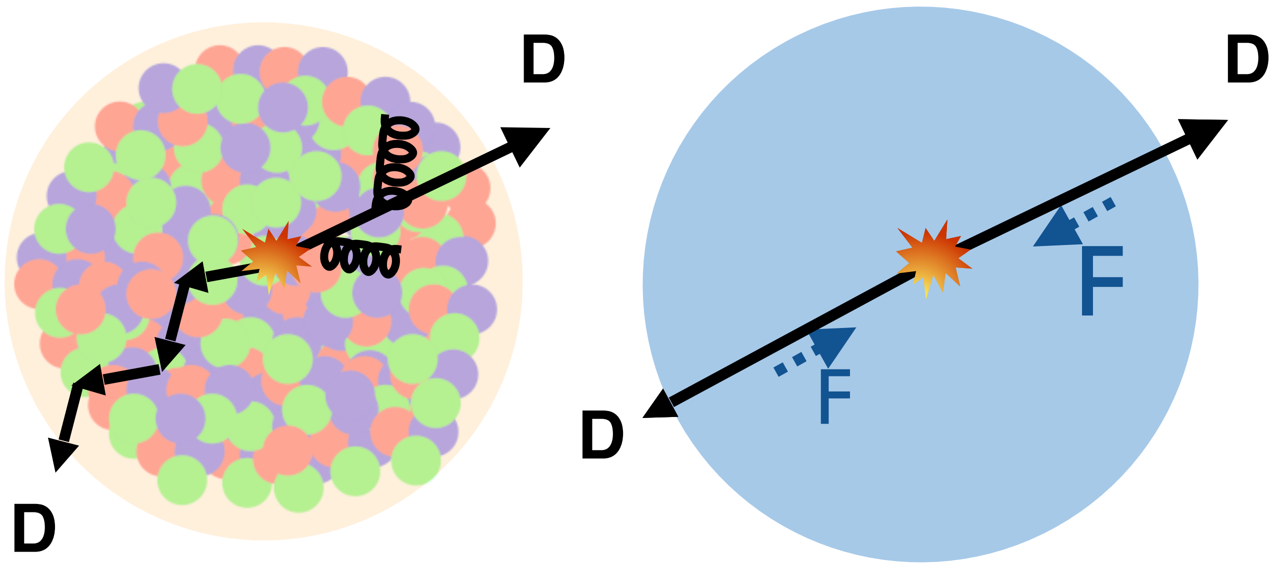

$\Delta\phi$(D-$\bar{D}$)




JHEP 1103:136,2011

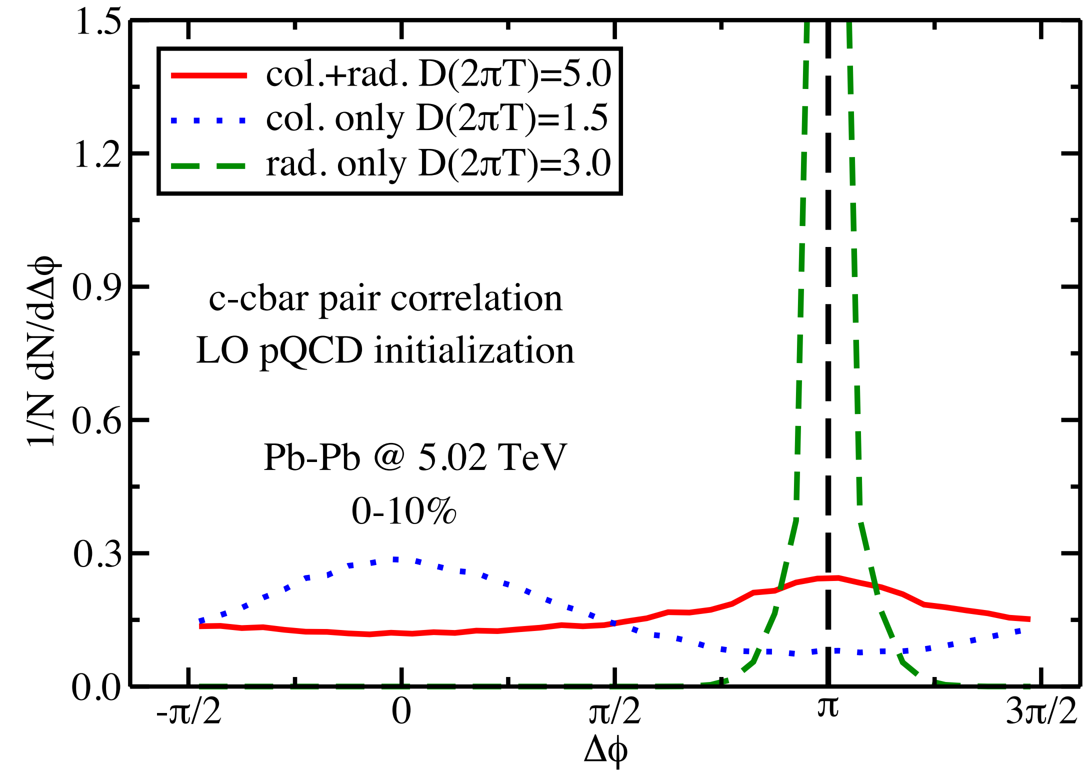
# HF correlations in PbPb

**In PbPb, to investigate the mechanisms of charm interaction with the medium**




pQCD QGP

strongly-coupled QGP




**Simplified example! quark level of a LO process! take with care!**

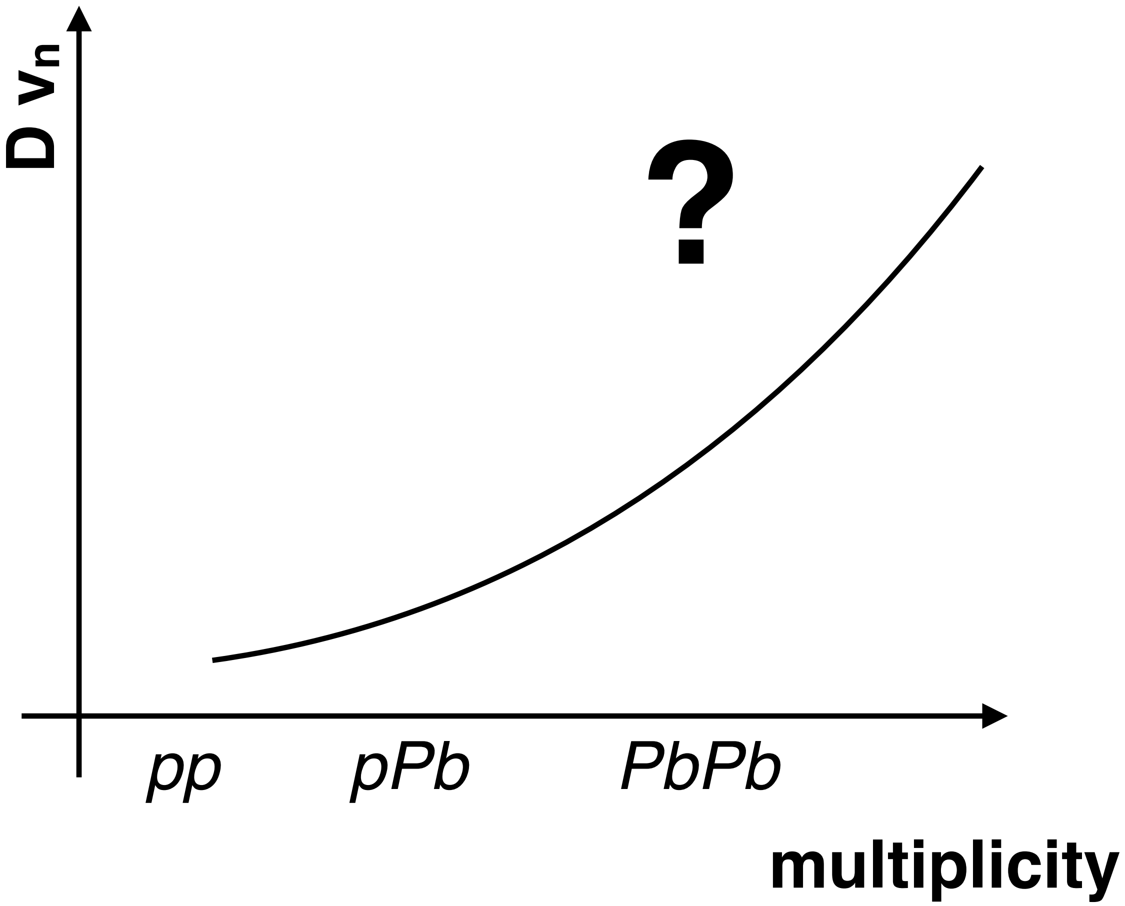
## D-Dbar $p_T$ asymmetry and $\Delta\varphi$:

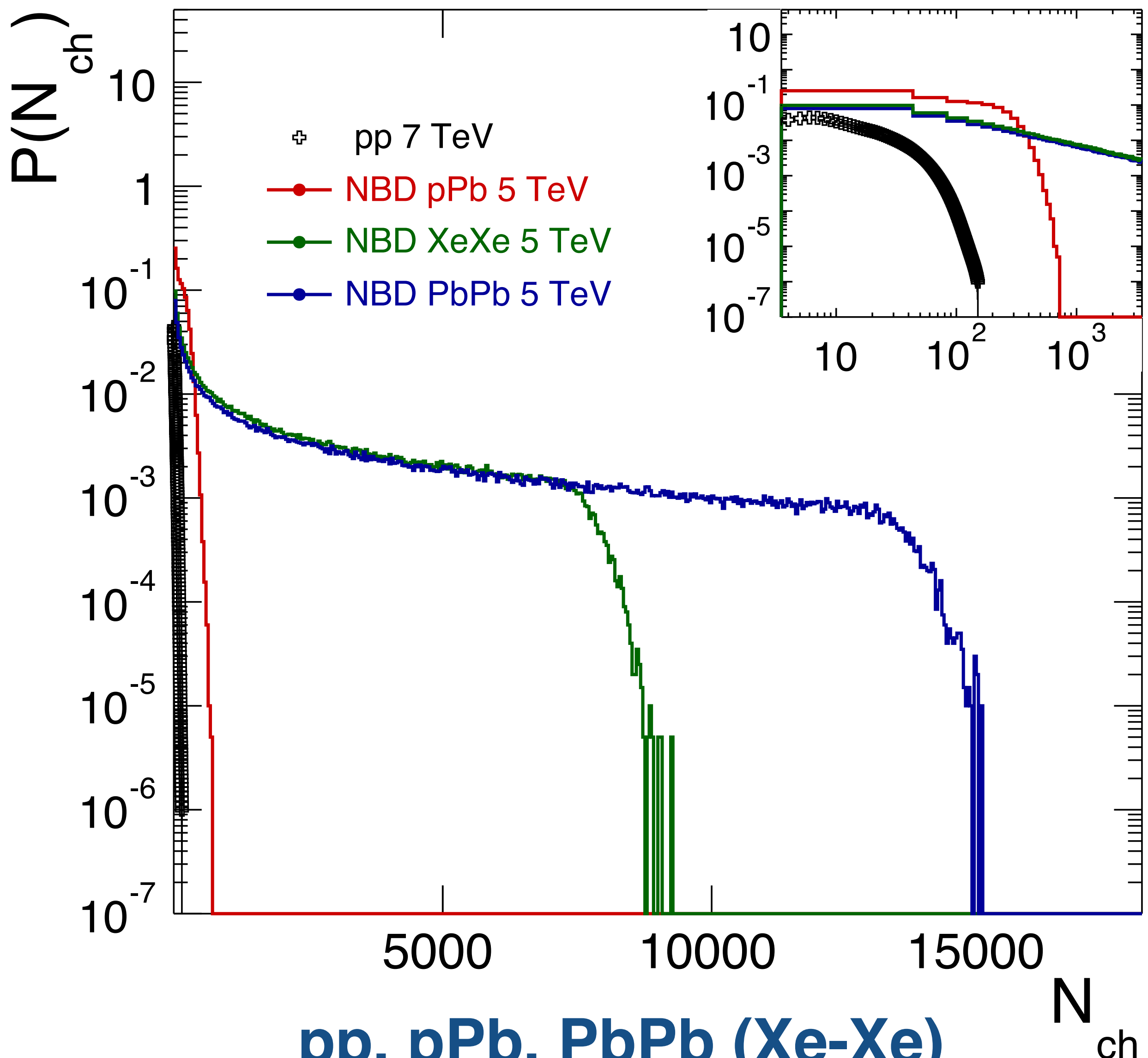
- pQCD vs strongly coupled QGP?
- path-dependence of energy loss
- collisional vs radiative?

→**2018 or Run3 luminosity is needed!**

# Small to large systems: flow

**Heavy-flavour studies can provide strong insights into the possible formation of a deconfined state in smaller systems**



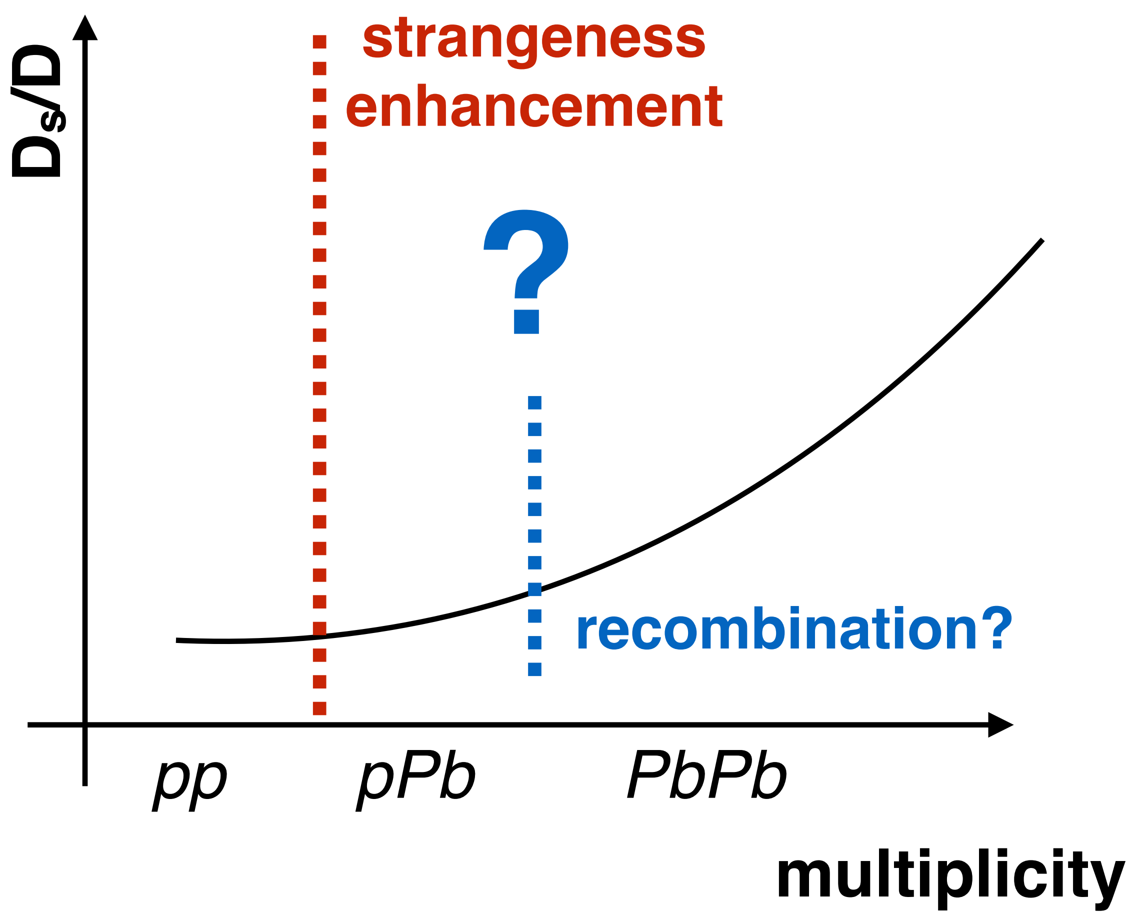



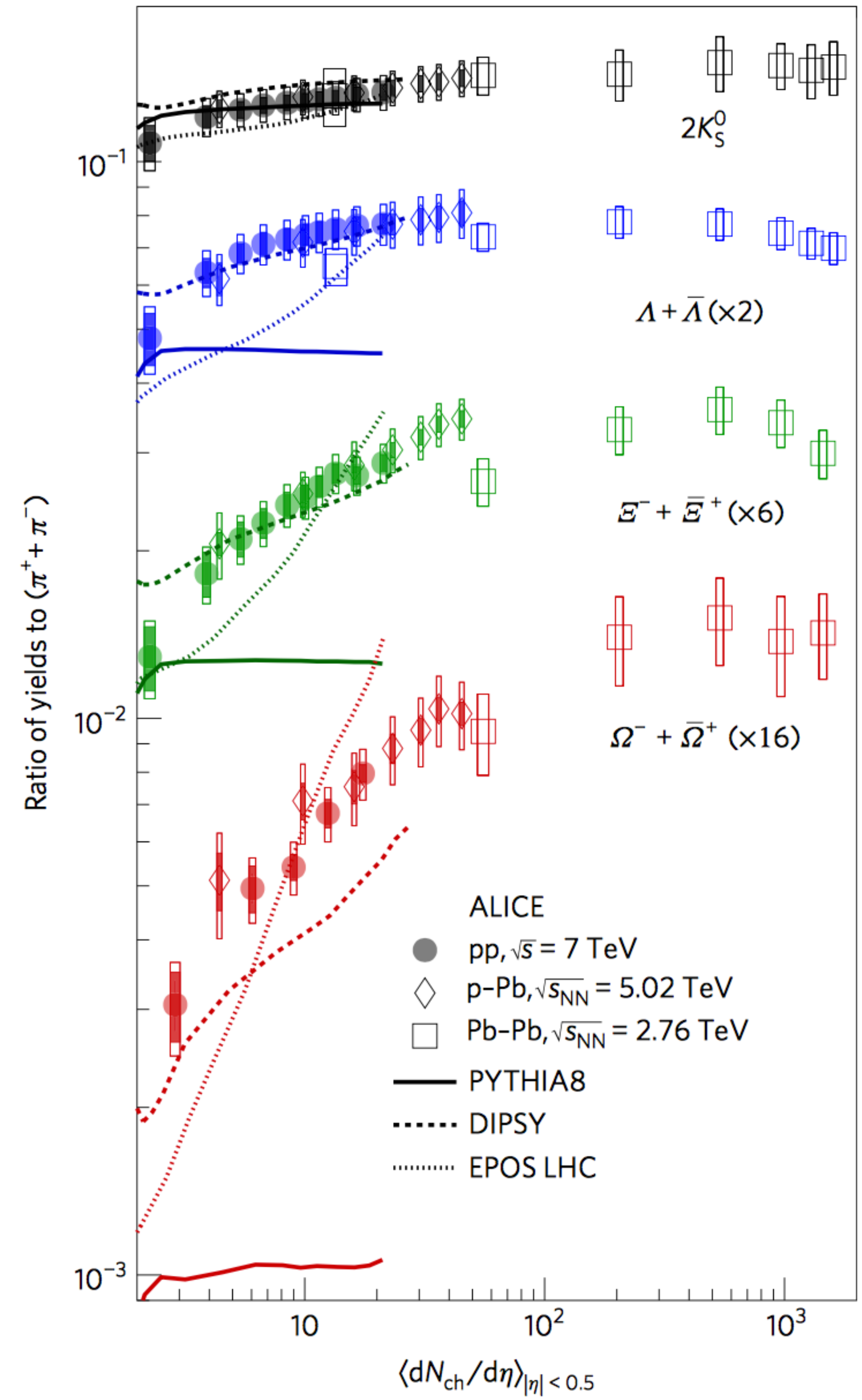

**pp, pPb, PbPb (Xe-Xe) show large overlap in track multiplicity**

**D $v_n$ as a function of multiplicity:**

- test of collectivity with heavier particles that acquire flow by interaction with expanding medium
- QGP in small system?

# Small to large systems: recombination



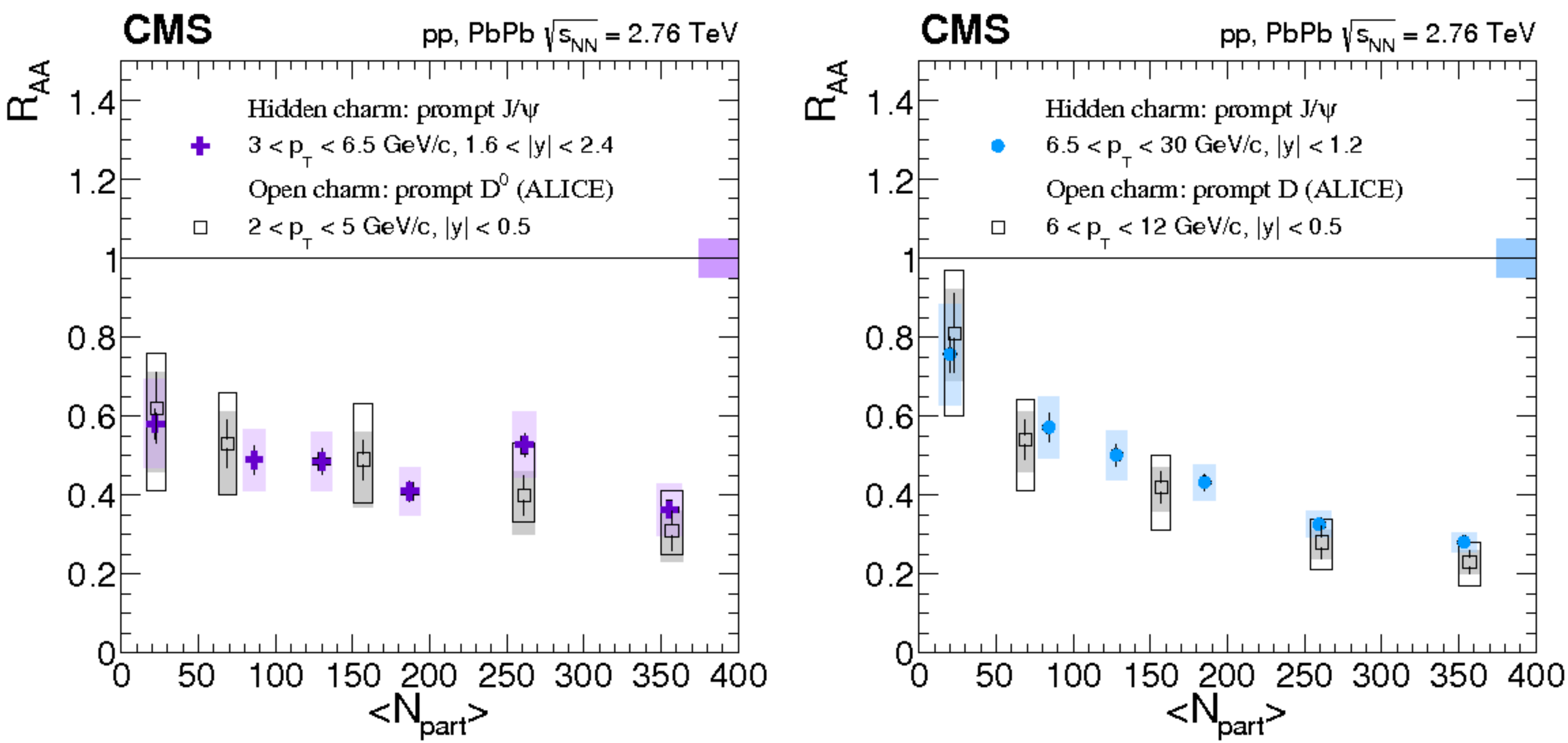




Nature Physics DOI: 10.1038/NPHYS4111

**Ds/D as a function of multiplicity to test charm recombination**

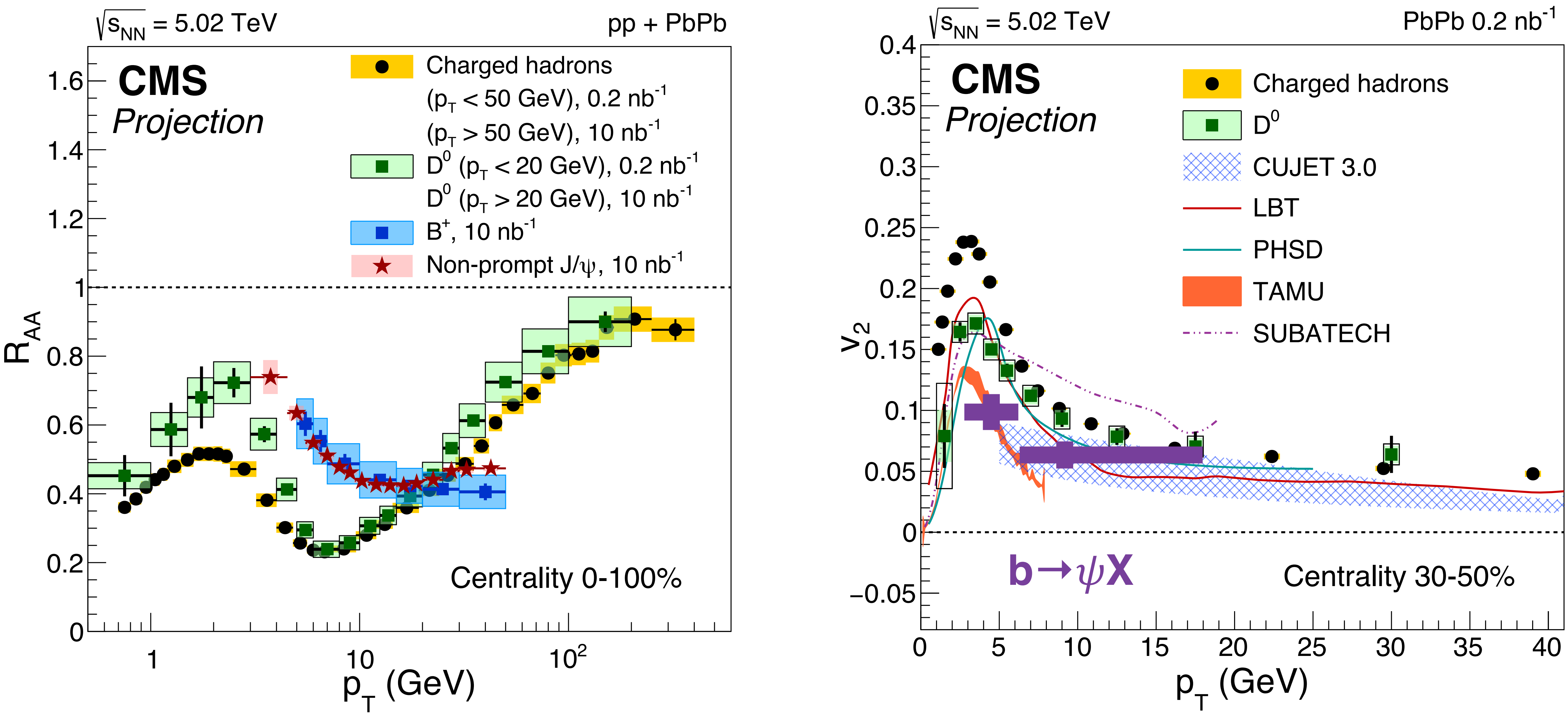
- strangeness enhancement observed by ALICE in high-multiplicity pp events.

# Aren't we too lucky?



# Projections for Run3 measurements

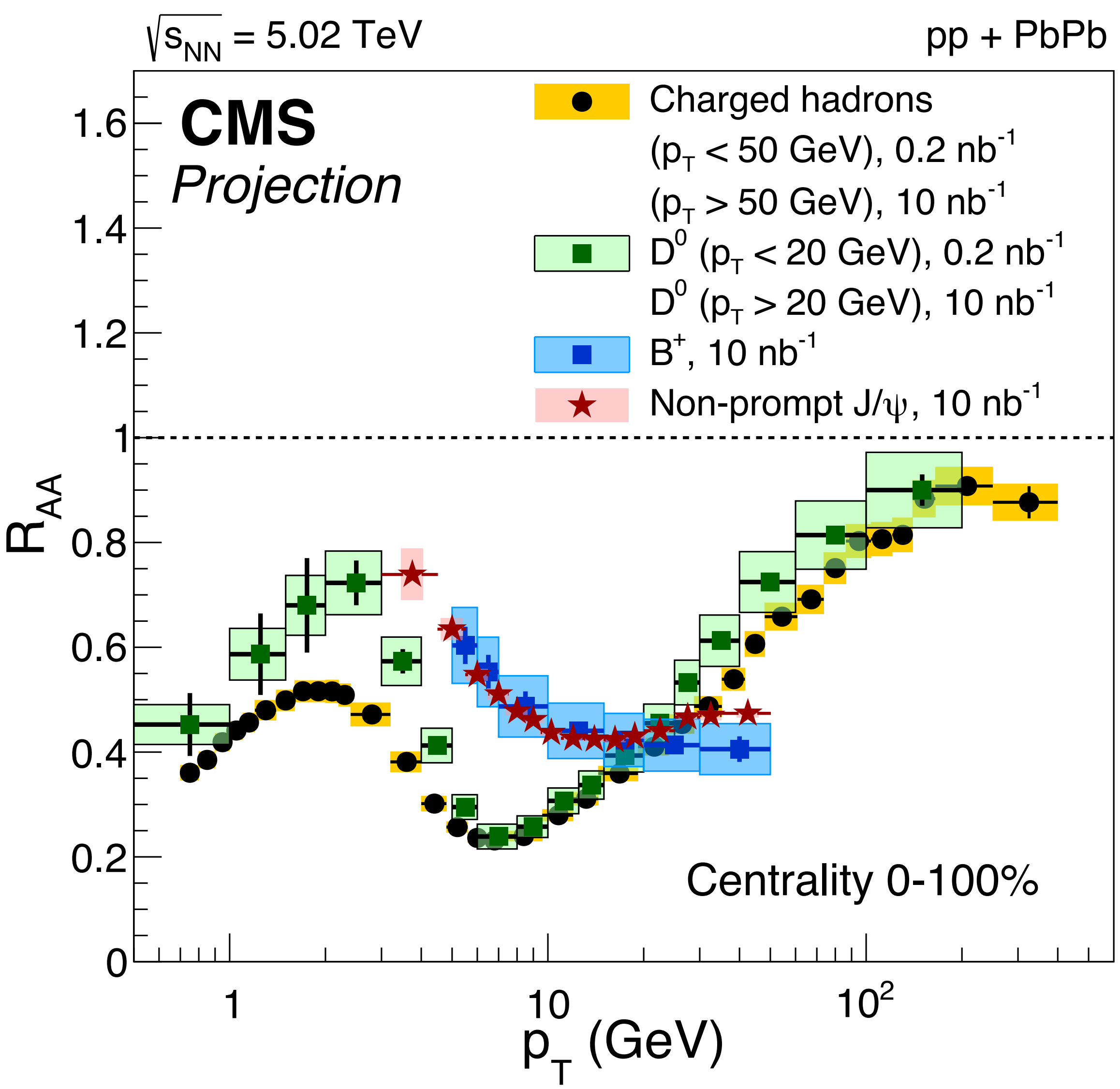
High-Luminosity LHC!

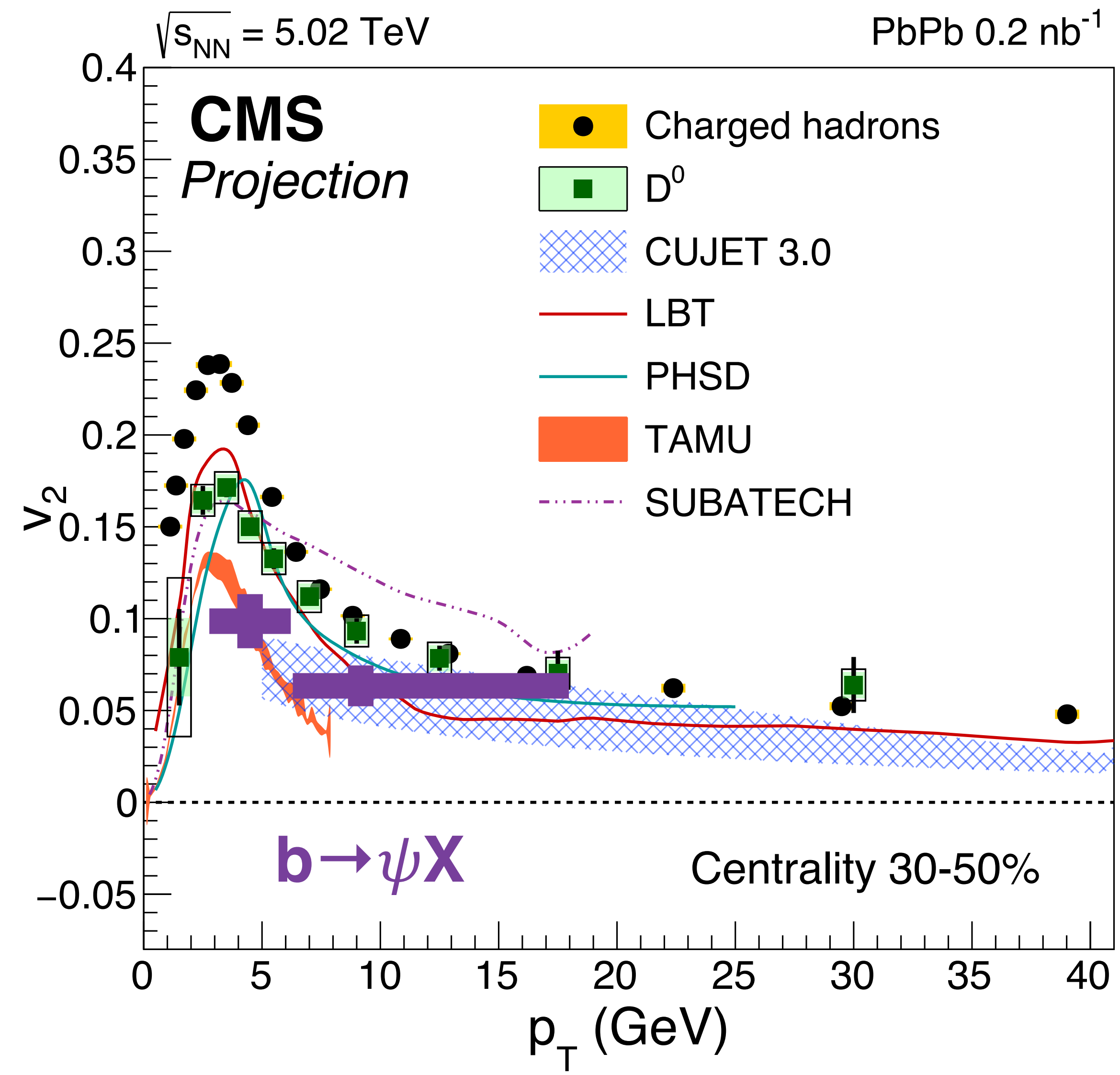



- With 10/nb, very high precision measurements of charged particle, D, B $R_{AA}$ and $v_n$!
- **$D_s$ / $B_s$ $R_{AA}$ and $v_n$ measurements to study recombination and the role of the hadronic phase for charm and beauty!**

# Projections for Run3 measurements

High-Luminosity LHC!

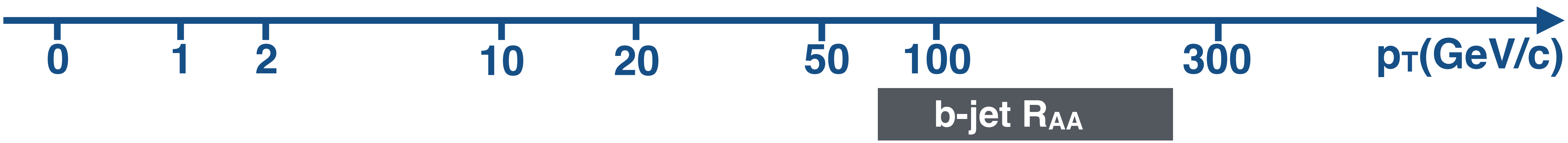


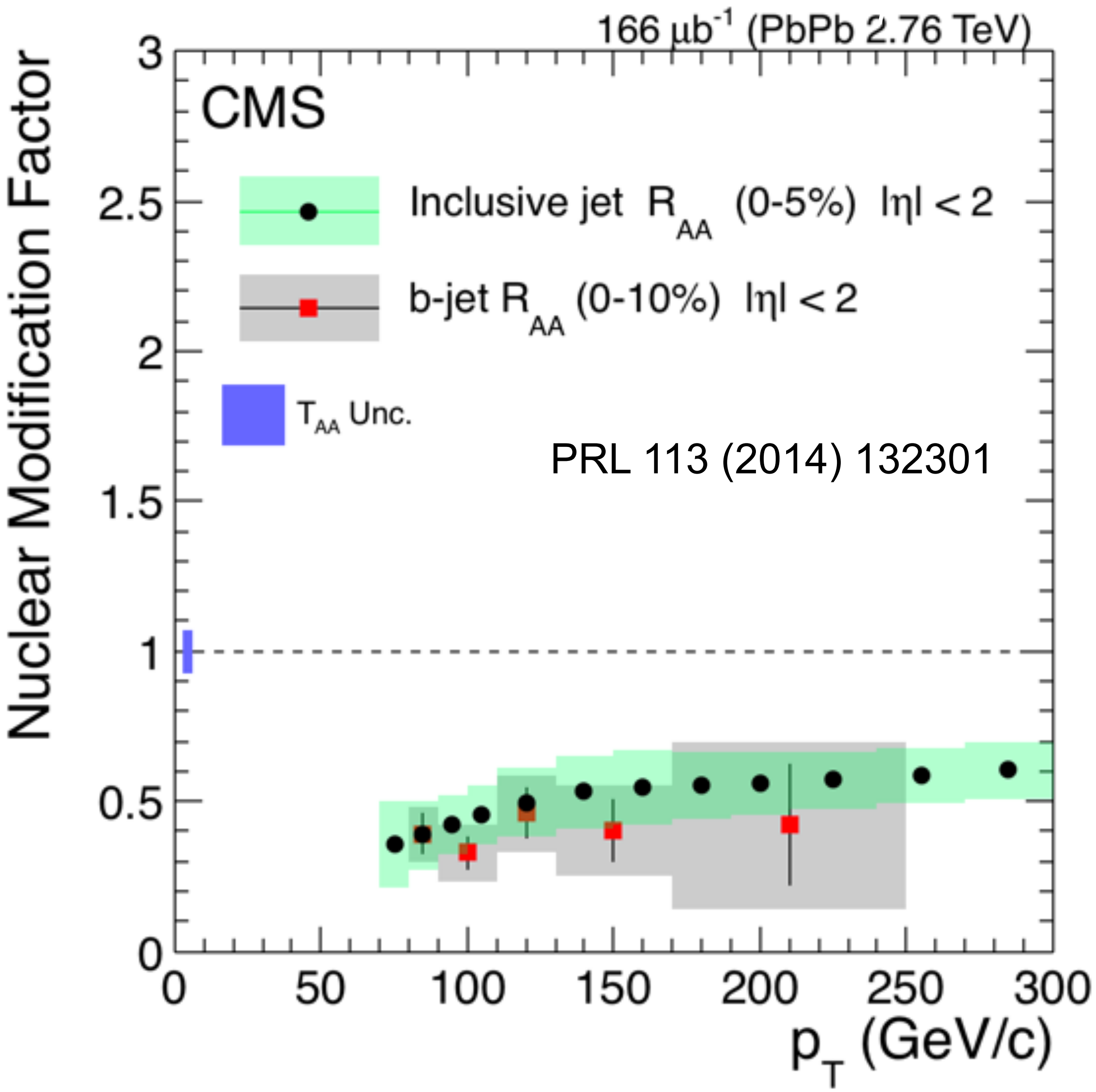




**Thank you for your attention!**

# BACKUP

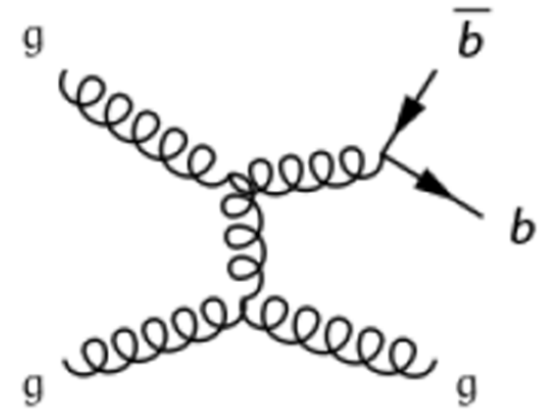
# b-jet $R_{AA}$ at 2.76 TeV

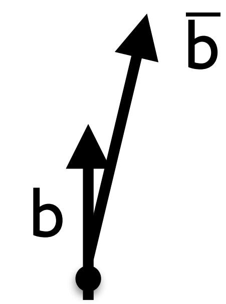



**b-jet $R_{AA}$**

**inclusive jet $R_{AA}$**

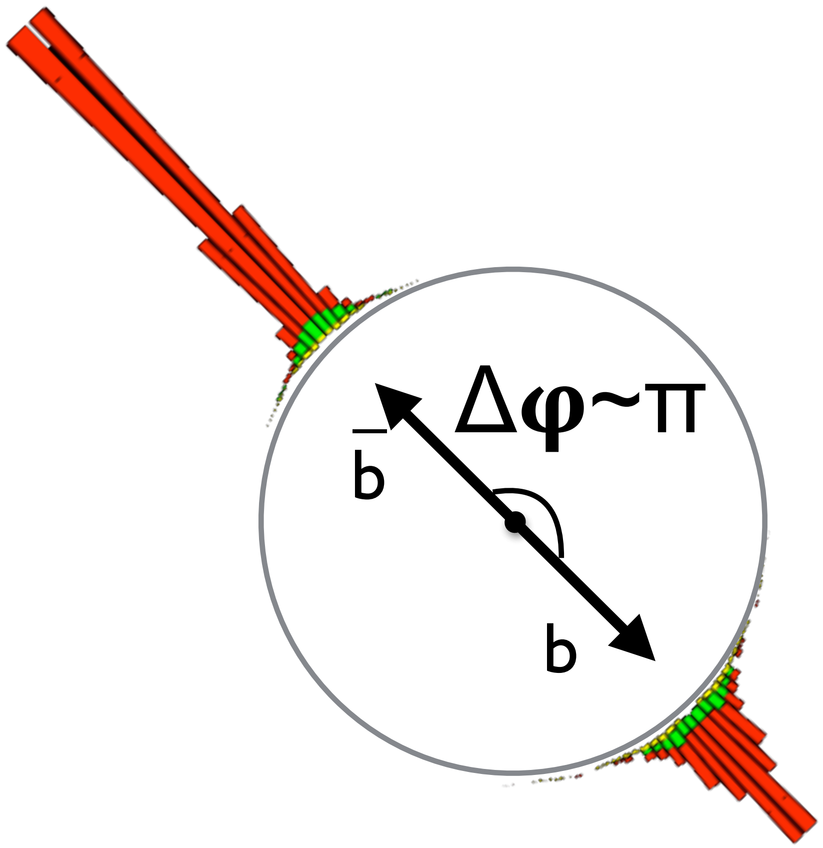



***Gluon splitting?***

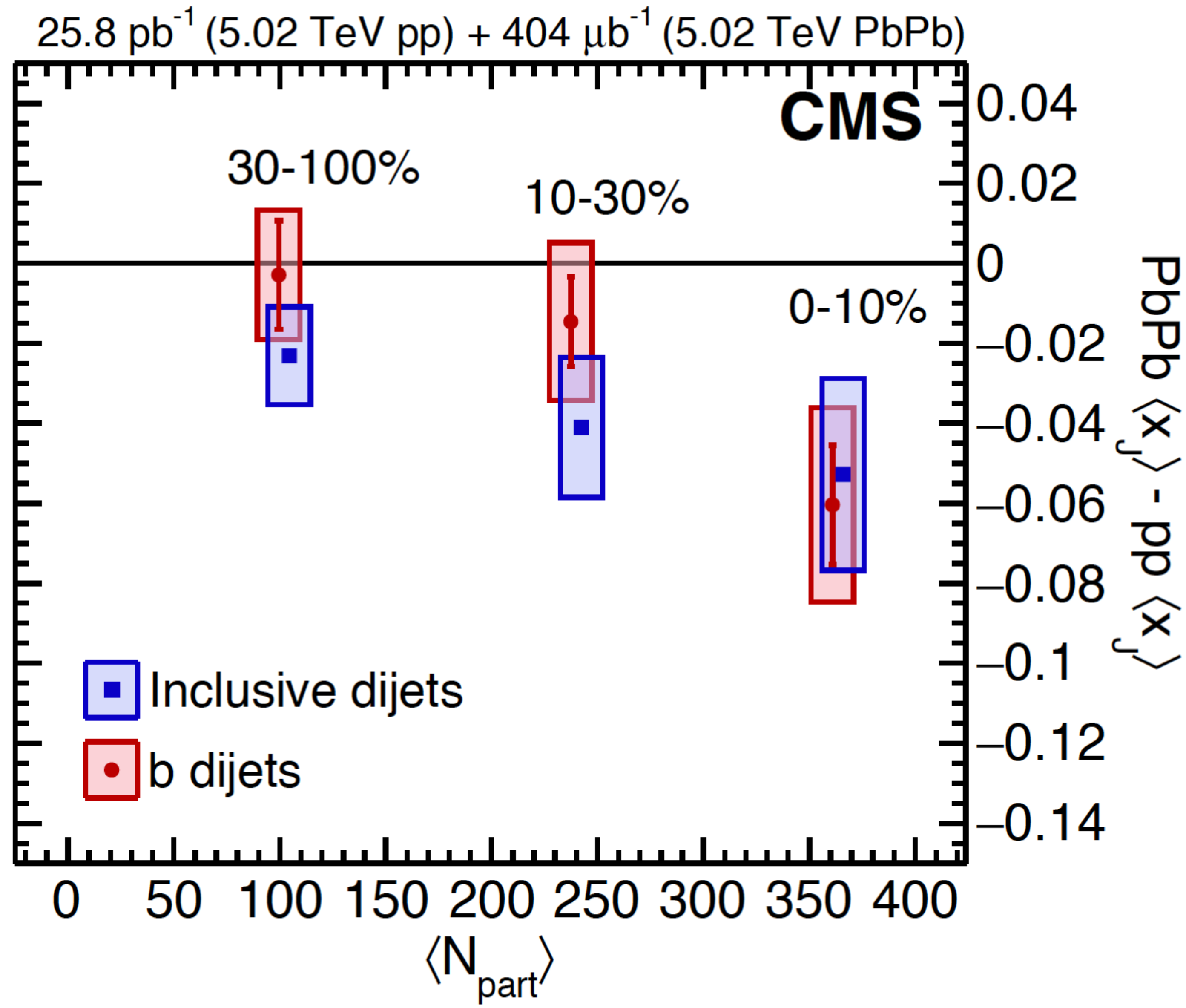
Same suppression for b-jets and inclusive jets at high $p_T$

# di-b-jet asymmetry at 5.02 TeV




**$p_T$ asymmetry of back-to-back b-jets:**

- dominated by LO production



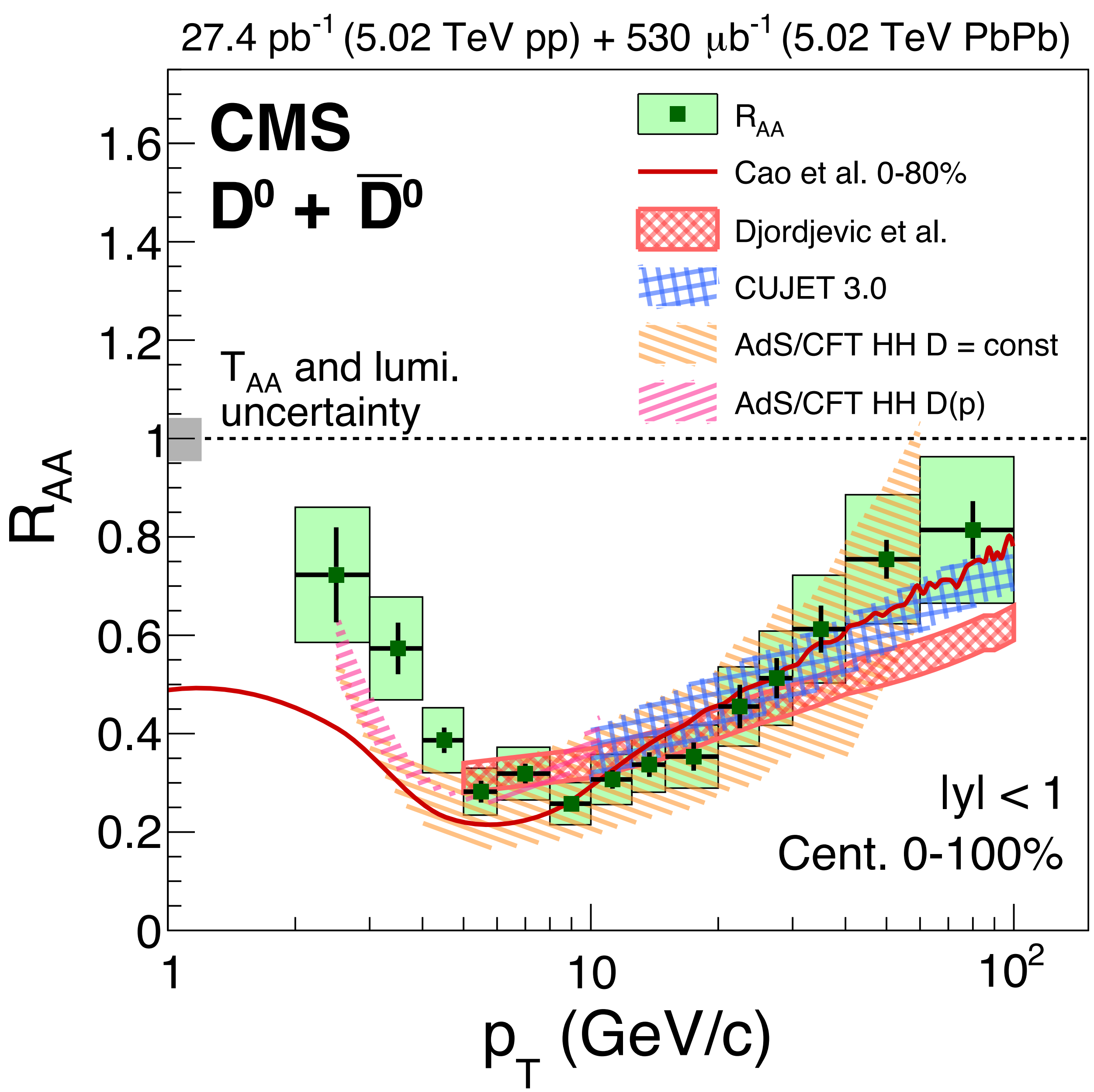

**"Shift" at low $x_J$ of b-jets was found to be compatible with the one of inclusive (light) jet**



**Final version! it will be on arXiv very soon!**

# Prompt $D^0$ $R_{AA}$ in PbPb at 5.02 TeV

**|y| < 1,** Centrality **0-100%**



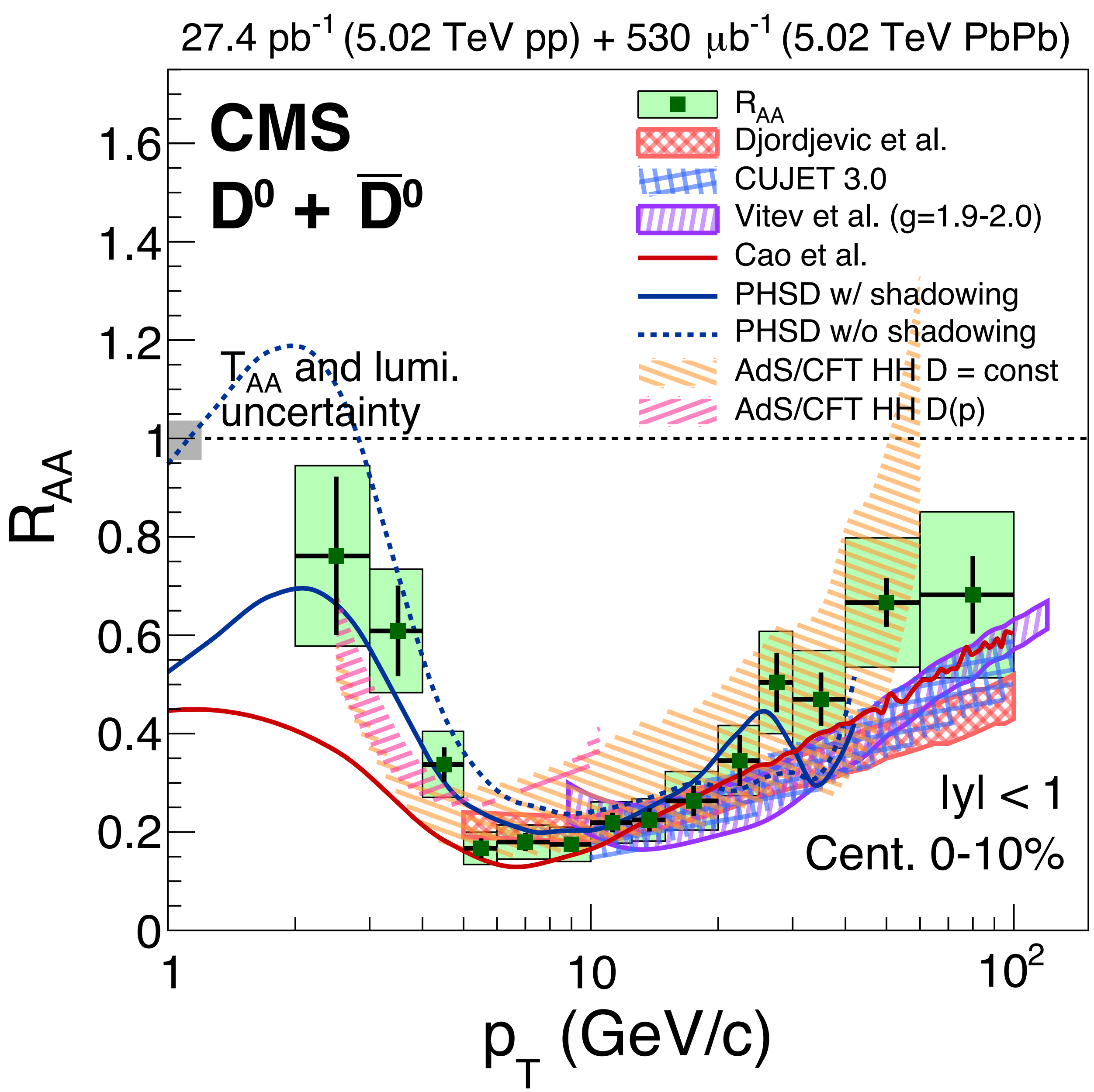

- Comparison with **theoretical predictions**
  - ➡ S. Cao et al. [1] *(Improved Langevin eq, Linearized Boltzmann)*
  - ➡ M. Djordjevic [2] *(pQCD calculations in a finite size optically thin dynamical QCD medium)*
  - ➡ CUJET3.0 [3] *(jet quenching model based on DGLV opacity expansion theory)*
  - ➡ AdS/CFT [4] *(a model based on the anti-de Sitter/conformal field theory)*


[1] arXiv:1703.00822
[2] Phys. Rev. C 92 (2015) 024918
[3] JHEP 02 (2016) 169
[4] Phys. Rev. D 91 (2015) 085019


arXiv: 1708.04962

# Prompt $D^0$ $R_{AA}$ in PbPb at 5.02 TeV

**|y| < 1,** Centrality **0-10%**




- Comparison with **theoretical predictions**
  - ➡ S. Cao et al. [1] *(Improved Langevin eq, Linearized Boltzmann)*
  - ➡ M. Djordjevic [2] *(pQCD calculations in a finite size optically thin dynamical QCD medium)*
  - ➡ CUJET3.0 [3] *(jet quenching model based on DGLV opacity expansion theory)*
  - ➡ AdS/CFT [4] *(a model based on the anti-de Sitter/conformal field theory)*
  - ➡ Vitev et al. [5] *(jet propagation in matter, soft-collinear effective theory with Glauber gluons (SCETG))*
  - ➡ PHSD [6] *(Parton-Hadron-String Dynamics transport approach)*


[1] arXiv:1703.00822
[2] Phys. Rev. C 92 (2015) 024918
[3] JHEP 02 (2016) 169
[4] Phys. Rev. D 91 (2015) 085019
[5] Phys. Rev. D 93 (2016) 074030
[6] Phys. Rev. C 93 (2016) 034906


arXiv: 1708.04962

# Azimuthal anisotropy

- The azimuthal anisotropy can be characterized by the Fourier coefficients $v_n$ in the azimuthal angle ($\phi$) distribution of the hadron yield

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)]\right),$$

  - ➡ Elliptic flow: $v_2$
  - ➡ Triangular flow: $v_3$

- Azimuthal anisotropy origins from
  - low $p_T$
    - ➡ collective motion in the thermalized medium
    - ➡ fluctuation ($v_3$)
  - high $p_T$
    - ➡ path length dependence of the energy loss

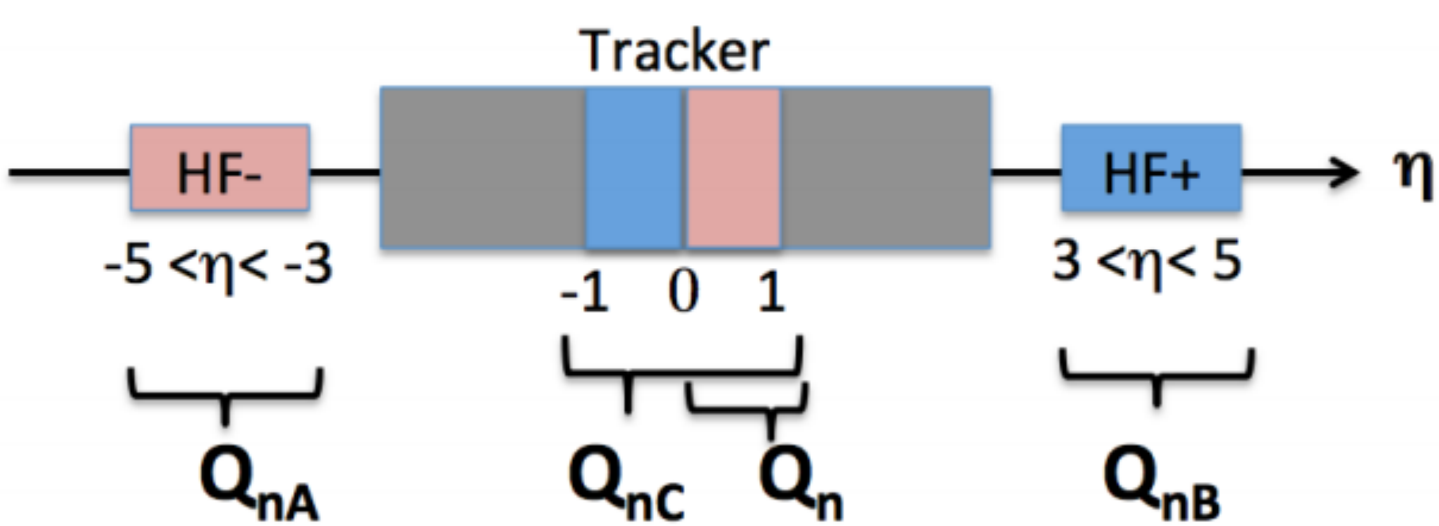
# Scalar product method

- $v_n$ coefficient can be expressed in terms of Q-vectors as

$$v_n\{\mathrm{SP}\} = \frac{\langle Q_{n,\mathrm{D}^0} Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}},$$

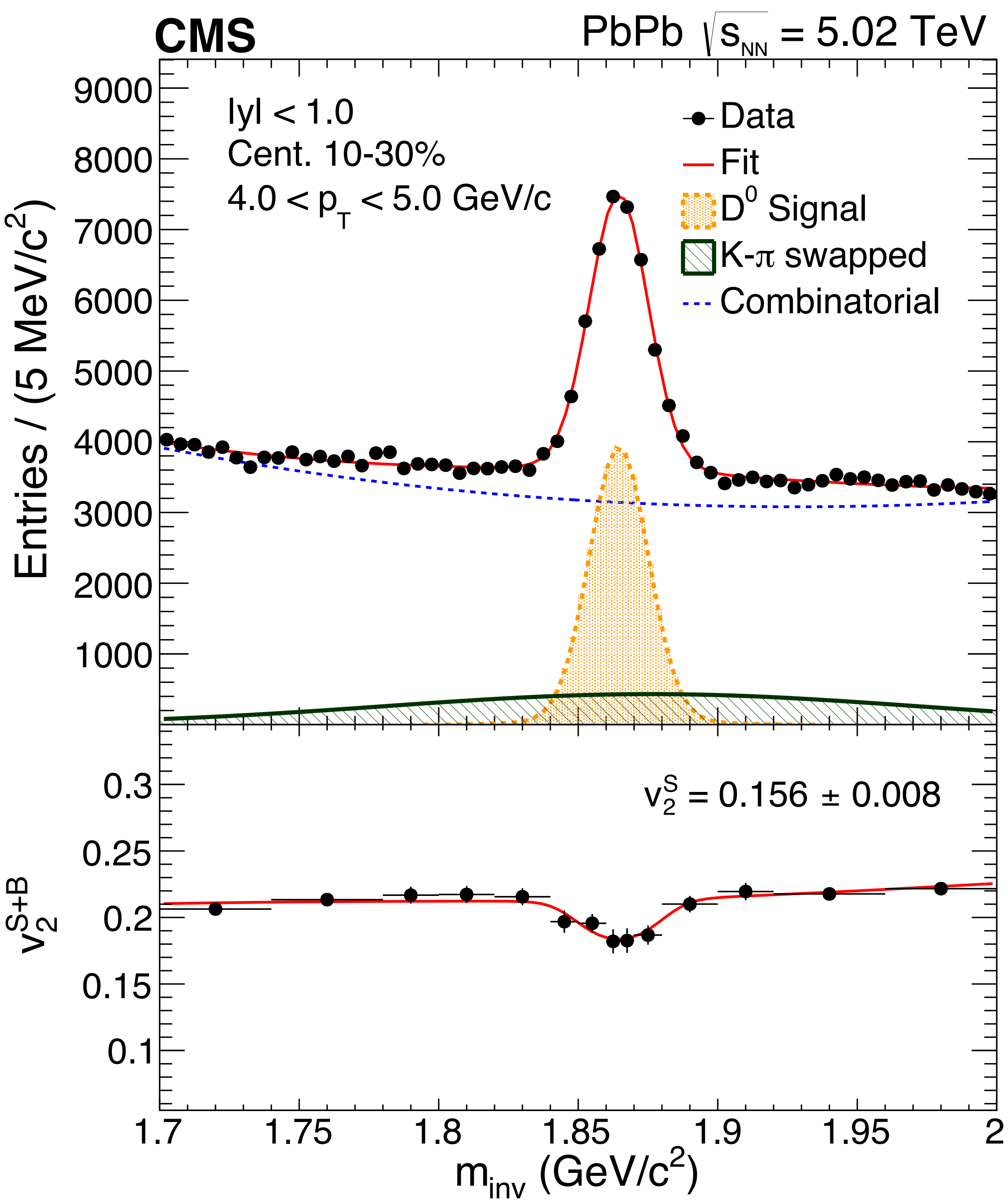
$$Q_n = \sum_{k=1}^{M} \omega_k e^{in\phi_k}$$

Scaling factor from 3 sub events




| | A | B | C |
|---|---|---|---|
| **sub evts** | HF- | HF+ | Tracker |
| **M** | towers | towers | tracks |
| $\omega_k$ | $E_T$ | $E_T$ | $p_T$ |

# Yield extraction




- Simultaneous fit on invariant mass distribution and $v_n$ vs mass

$$v_n^{S+B}(m_{\rm inv}) = \alpha(m_{\rm inv})v_n^S + [1-\alpha(m_{\rm inv})]v_n^B(m_{\rm inv}),$$

- $v_n^S$: $v_n$ of signal $D^0$
  - ➡ fit parameter
- other terms:
  - ➡ $v_n^{S+B}(m_{inv})$: $v_n$ of all $D^0$ candidates
  - ➡ $v_n^B(m_{inv})$: $v_n$ of combinatorial background, modeled by a linear function
  - ➡ $\alpha(m_{inv})$: signal fraction from invariant mass spectra fit

arXiv: 1708.03497

Table 11: Comparative overview of the models for heavy-quark energy loss or transport in the medium described in the previous sections.

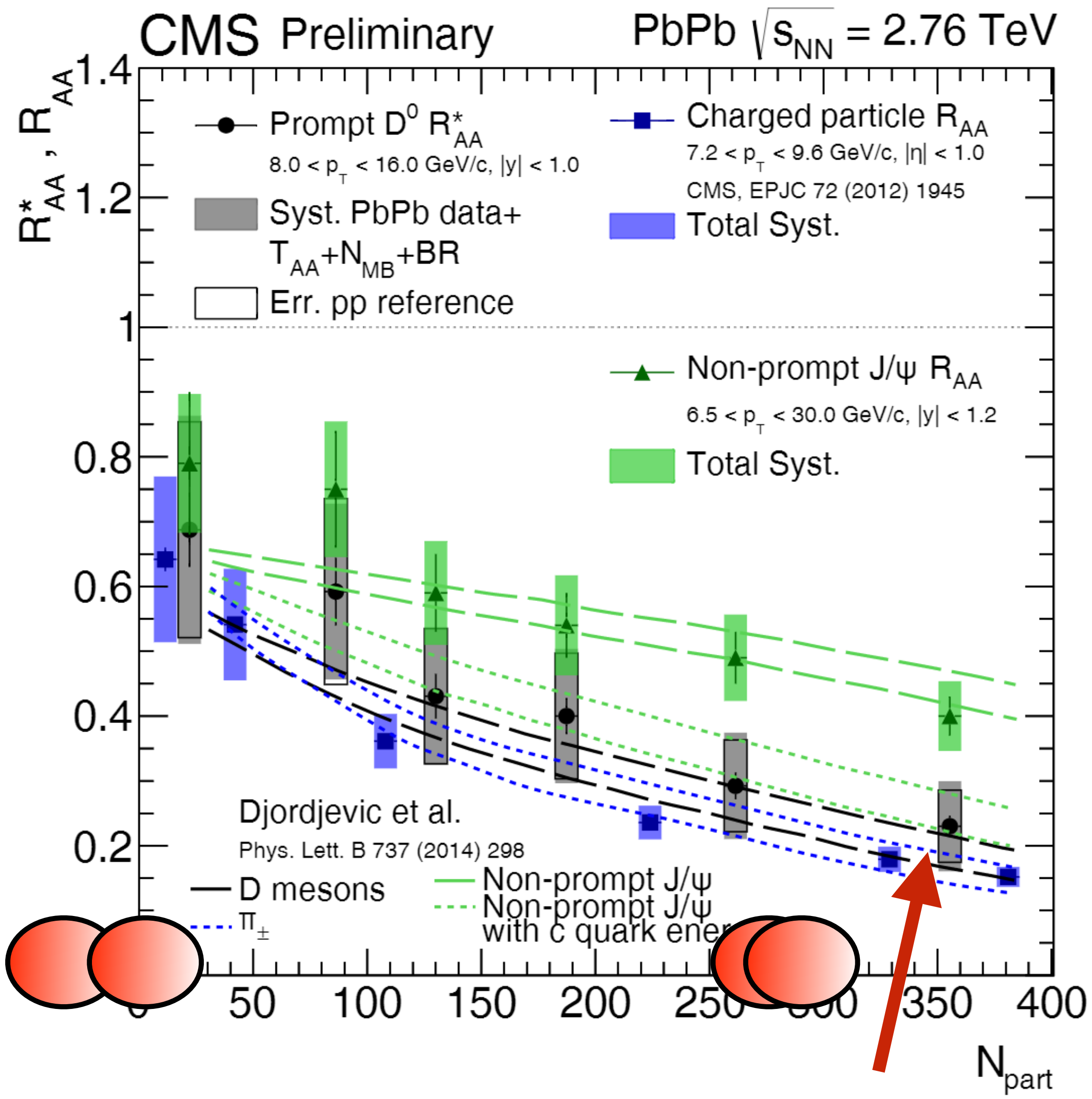
| *Model* | *Heavy-quark production* | *Medium modelling* | *Quark–medium interactions* | *Heavy-quark hadronisation* | *Tuning of medium-coupling (or density) parameter(s)* |
|---|---|---|---|---|---|
| **Djordjevic *et al.*** [511–515] | FONLL<br>no PDF shadowing | Glauber model<br>nuclear overlap<br>no fl. dyn. evolution | rad. + coll. energy loss<br>finite magnetic mass | fragmentation | Medium temperature<br>fixed separately<br>at RHIC and LHC |
| **WHDG** [459, 519] | FONLL<br>no PDF shadowing | Glauber model<br>nuclear overlap<br>no fl. dyn. evolution | rad. + coll. energy loss | fragmentation | RHIC<br>(then scaled with $dN_{ch}/d\eta$) |
| **Vitev et al.** [422, 460] | non-zero-mass VFNS<br>no PDF shadowing | Glauber model<br>nuclear overlap<br>ideal fl. dyn. 1+1d<br>Bjorken expansion | radiative energy loss<br>in-medium meson dissociation | fragmentation | RHIC<br>(then scaled with $dN_{ch}/d\eta$) |
| **AdS/CFT (HG)** [624, 625] | FONLL<br>no PDF shadowing | Glauber model<br>nuclear overlap<br>no fl. dyn. evolution | AdS/CFT drag | fragmentation | RHIC<br>(then scaled with $dN_{ch}/d\eta$) |
| **POWLANG** [507–509, 585, 586] | POWHEG (NLO)<br>EPS09 (NLO)<br>PDF shadowing | 2+1d expansion<br>with viscous<br>fl. dyn. evolution | transport with Langevin eq.<br>collisional energy loss | fragmentation<br>recombination | assume pQCD (or l-QCD<br>*U* potential) |
| **MC@$_s$HQ+EPOS2** [528–530] | FONLL<br>EPS09 (LO)<br>PDF shadowing | 3+1d expansion<br>(EPOS model) | transport with Boltzmann eq.<br>rad. + coll. energy loss | fragmentation<br>recombination | QGP transport coefficient<br>fixed at LHC, slightly<br>adapted for RHIC |
| **BAMPS** [537–540] | MC@NLO<br>no PDF shadowing | 3+1d expansion<br>parton cascade | transport with Boltzmann eq.<br>rad. + coll. energy loss | fragmentation | RHIC<br>(then scaled with $dN_{ch}/d\eta$) |
| **TAMU** [491, 565, 606] | FONLL<br>EPS09 (NLO)<br>PDF shadowing | 2+1d expansion<br>ideal fl. dyn. | transport with Langevin eq.<br>collisional energy loss<br>diffusion in hadronic phase | fragmentation<br>recombination | assume l-QCD<br>*U* potential |
| **UrQMD** [608–610] | PYTHIA<br>no PDF shadowing | 3+1d expansion<br>ideal fl. dyn. | transport with Langevin eq.<br>collisional energy loss | fragmentation<br>recombination | assume l-QCD<br>*U* potential |
| **Duke** [587, 628] | PYTHIA<br>EPS09 (LO)<br>PDF shadowing | 2+1d expansion<br>viscous fl. dyn. | transport with Langevin eq.<br>rad. + coll. energy loss | fragmentation<br>recombination | QGP transport coefficient<br>fixed at RHIC and LHC<br>(same value) |

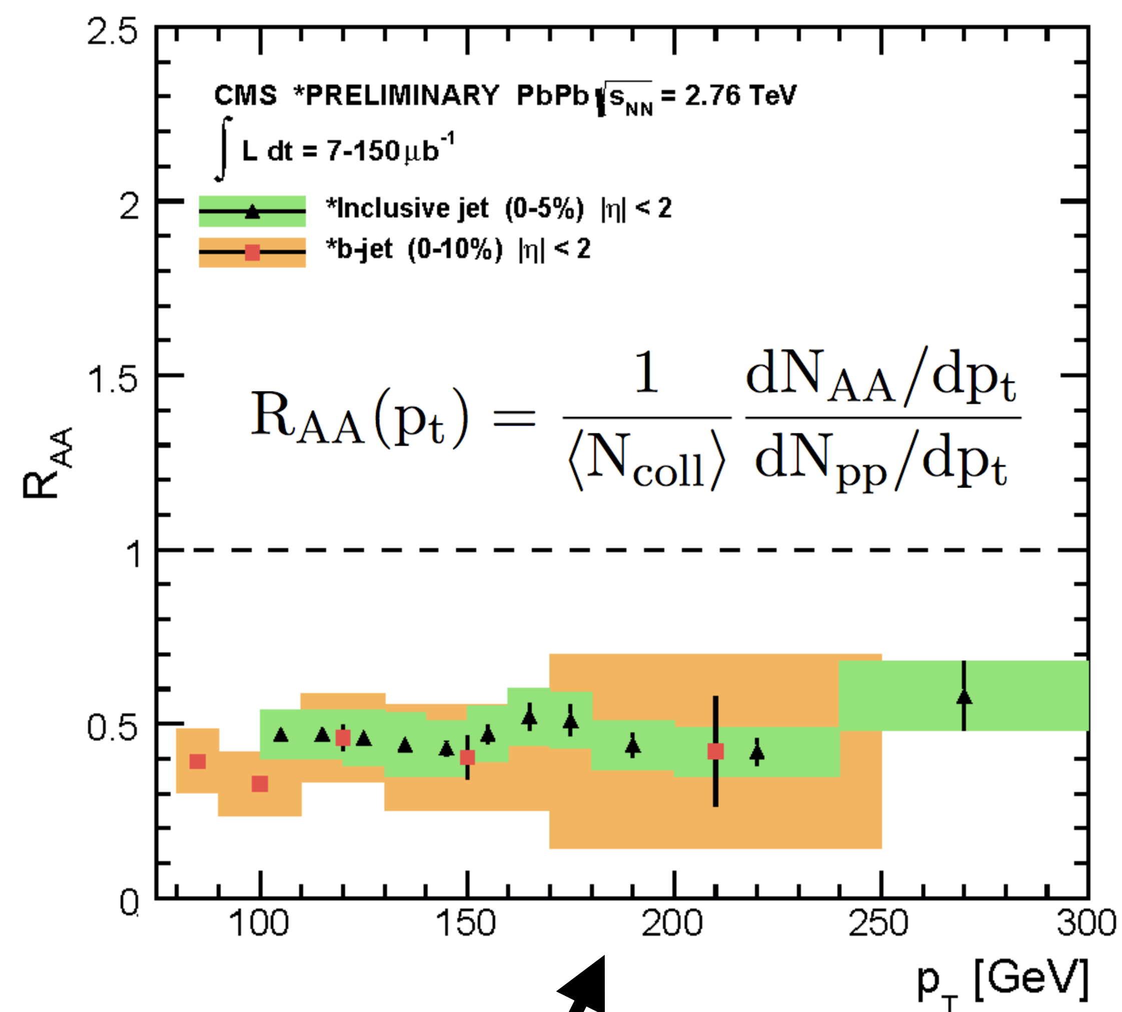
[1506.03981]

# Does the energy loss depend on parton flavour?

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

$R^{light\ particle}_{AA} < R^{D}_{AA} < R^{B}_{AA}$ ?



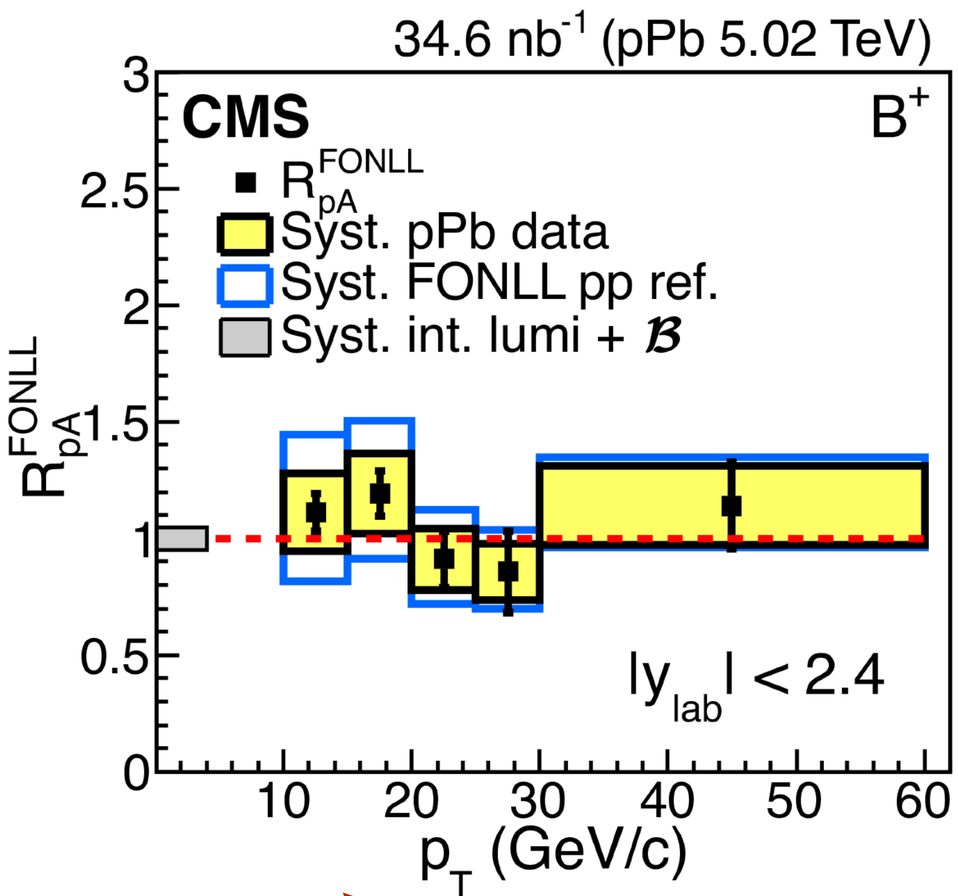



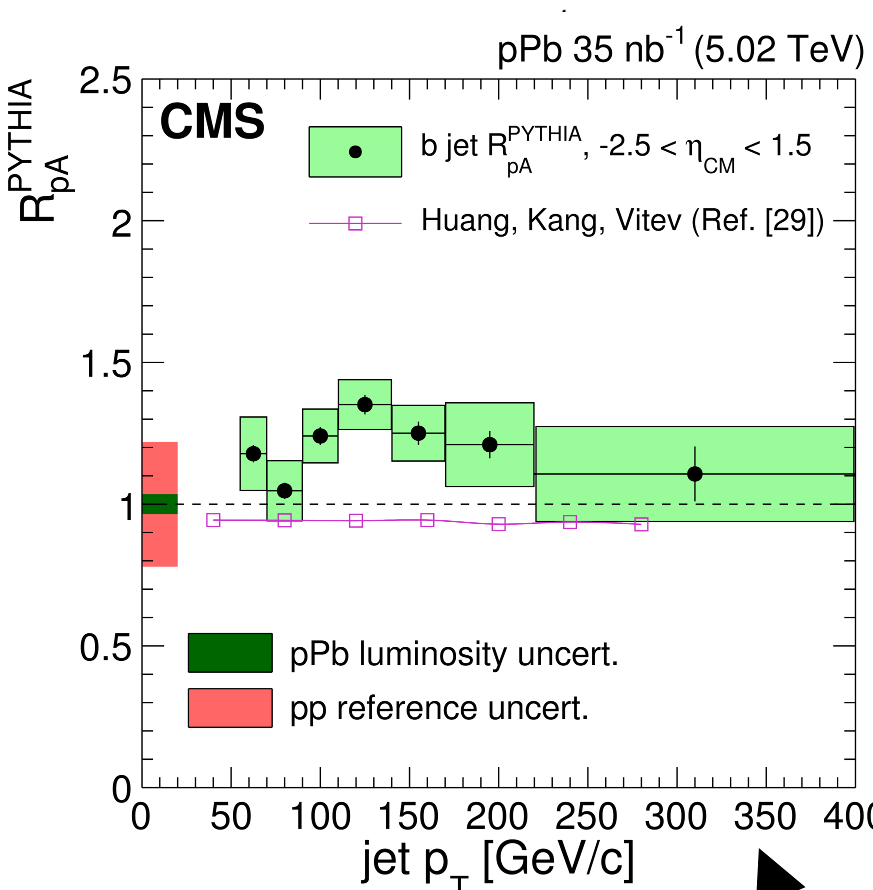

Same suppression observed for inclusive jets and b-tagged jets

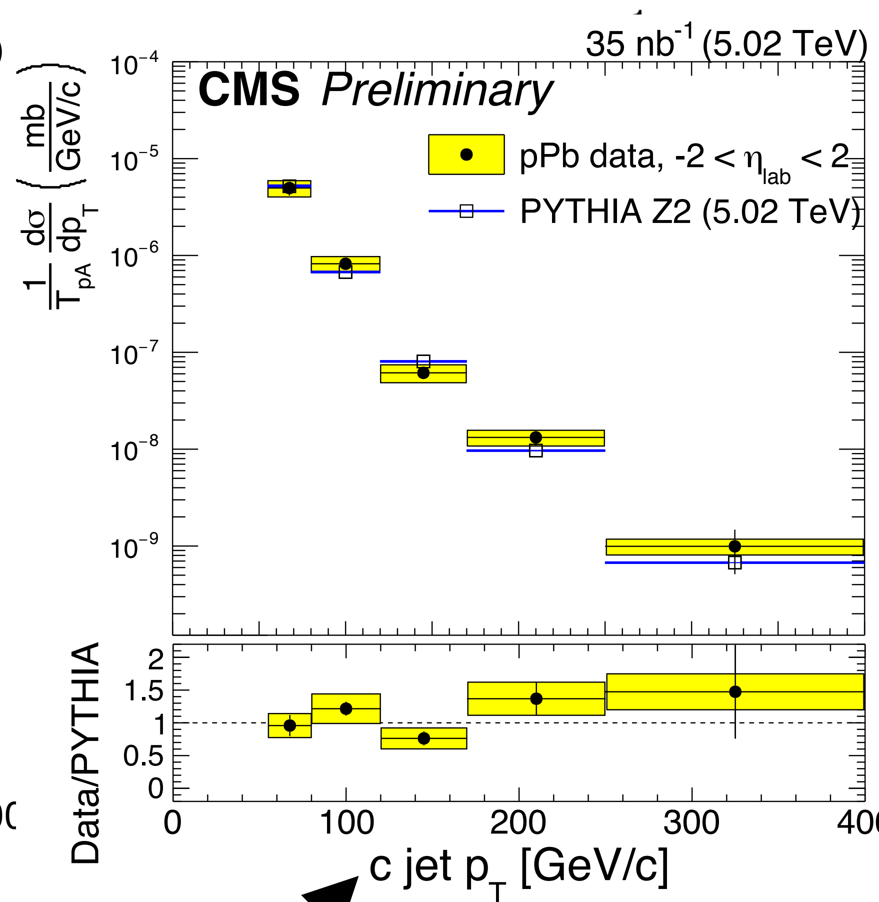
Hints of different suppression for D and non-prompt $J/\psi$ at low $p_T$!

CMS-HIN-15-005, PRL 113 (2014) 132301

# Heavy-Flavour production in pPb



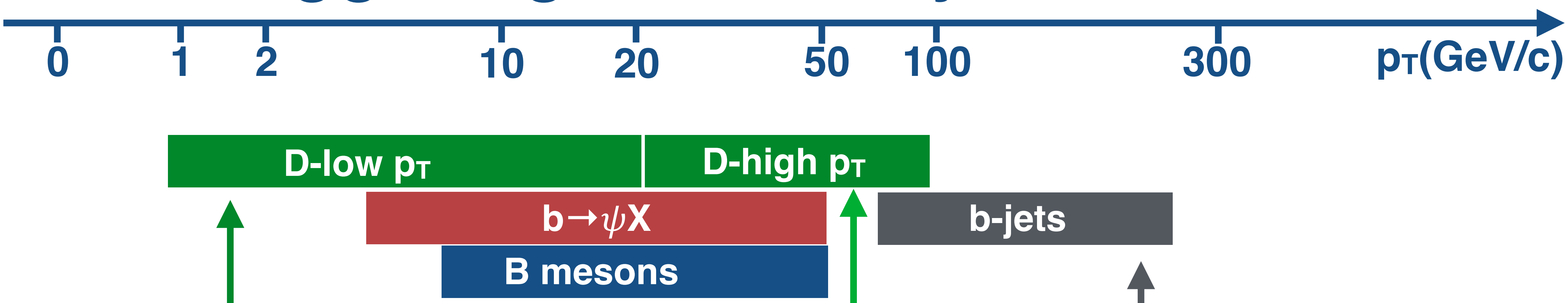

B$^{+}$ production in pPb
→ compatible with predictions
from FONLL scaled by A=208

tagged c and b-jet production
→ compatible with predictions
from PYTHIA scaled by A=208

**HF pPb production not significantly modified by cold nuclear matter effects (e.g. PDF modification in nuclei)**

PRL 116 (2016) 032301, CMS-HIN-15-012 ,PLB 754 (2016) 59

# Triggering as the key feature




**MB samples for low $p_T$ D:**

- ~300 M PbPb
- ~2.5 Billions pp
- ~2 Billions pPb

**L1 centrality triggers based on HF energy to increase semi-peripheral event statistics**

**HLT $D^0$ triggers for high pT $D^0$ (>20 GeV)**

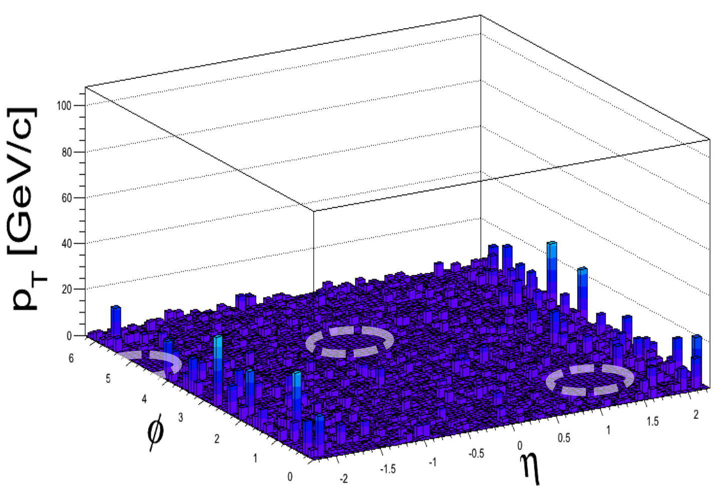
**HLT b-jet triggers**

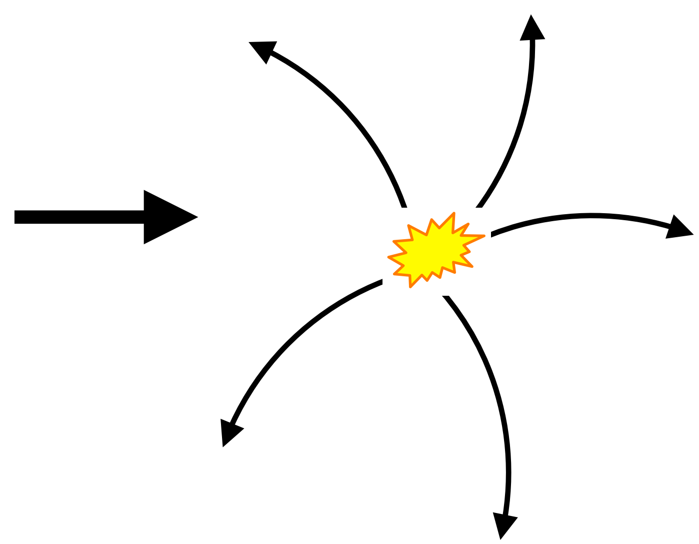
**Di-lepton triggers for B mesons and b→J/ψ**

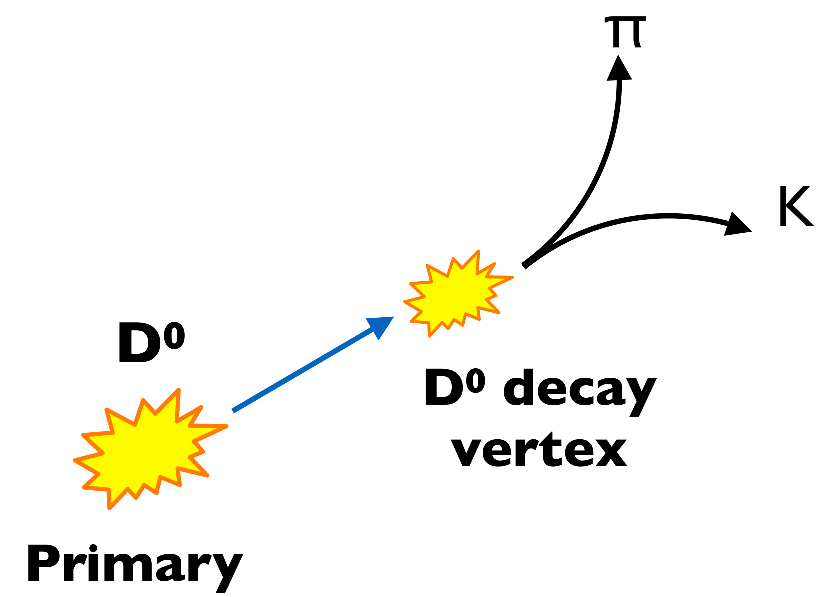
**Level-1 trigger**= first level of trigger of CMS, hardware-based (FPGA)
**High-Level-Trigger**= second trigger layer , software-based

# Focus on $D^0$ High-Level triggers

→**Collect full luminosity of high-$p_T$ $D^0$ mesons, not doable with MB trigger**






**Hardware jet triggers (Level-1)**

↓

**Problem of fake jets!**

L1 background subtraction

**Track reconstruction in software trigger system**

↓

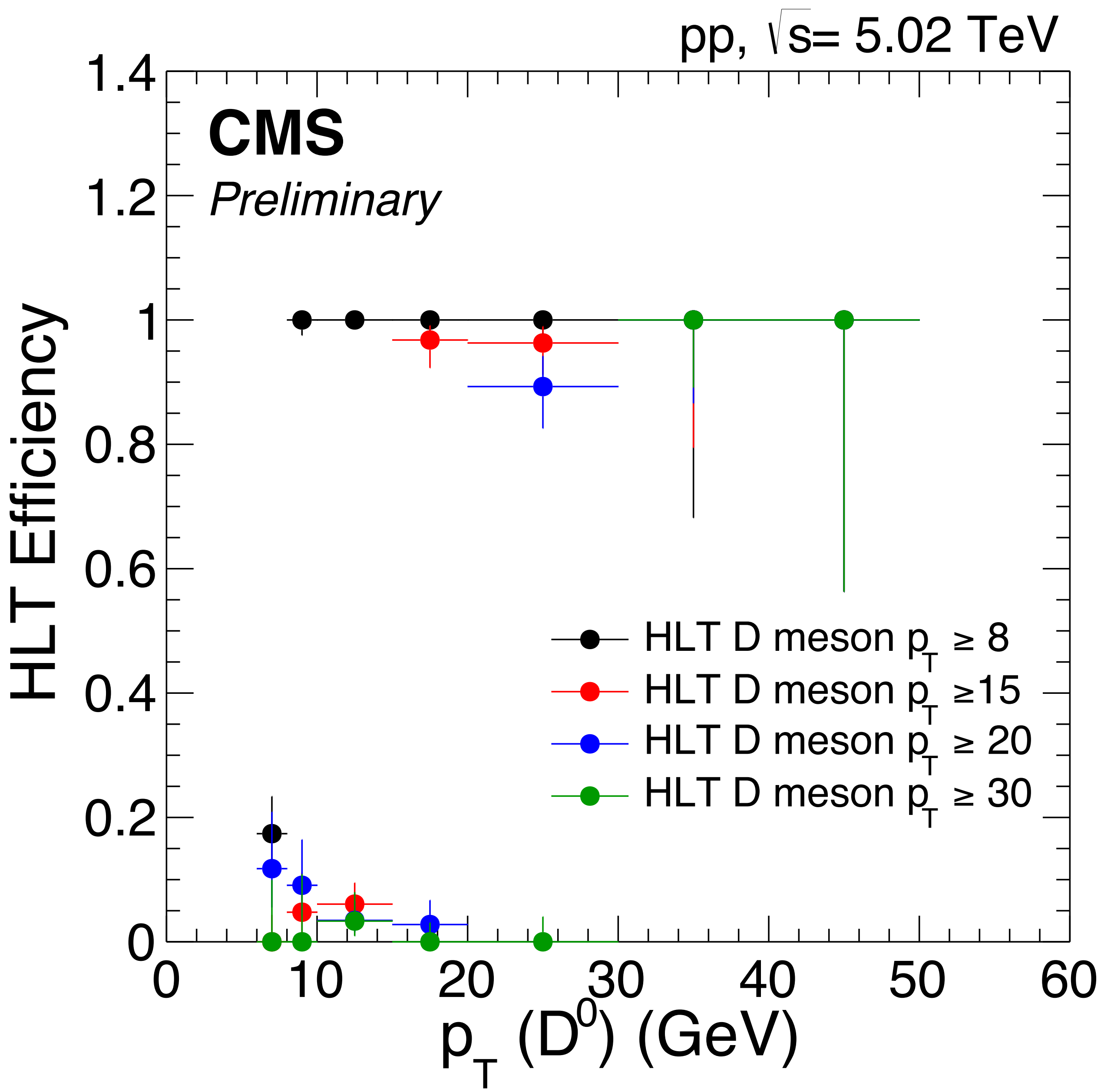
**Timing!**

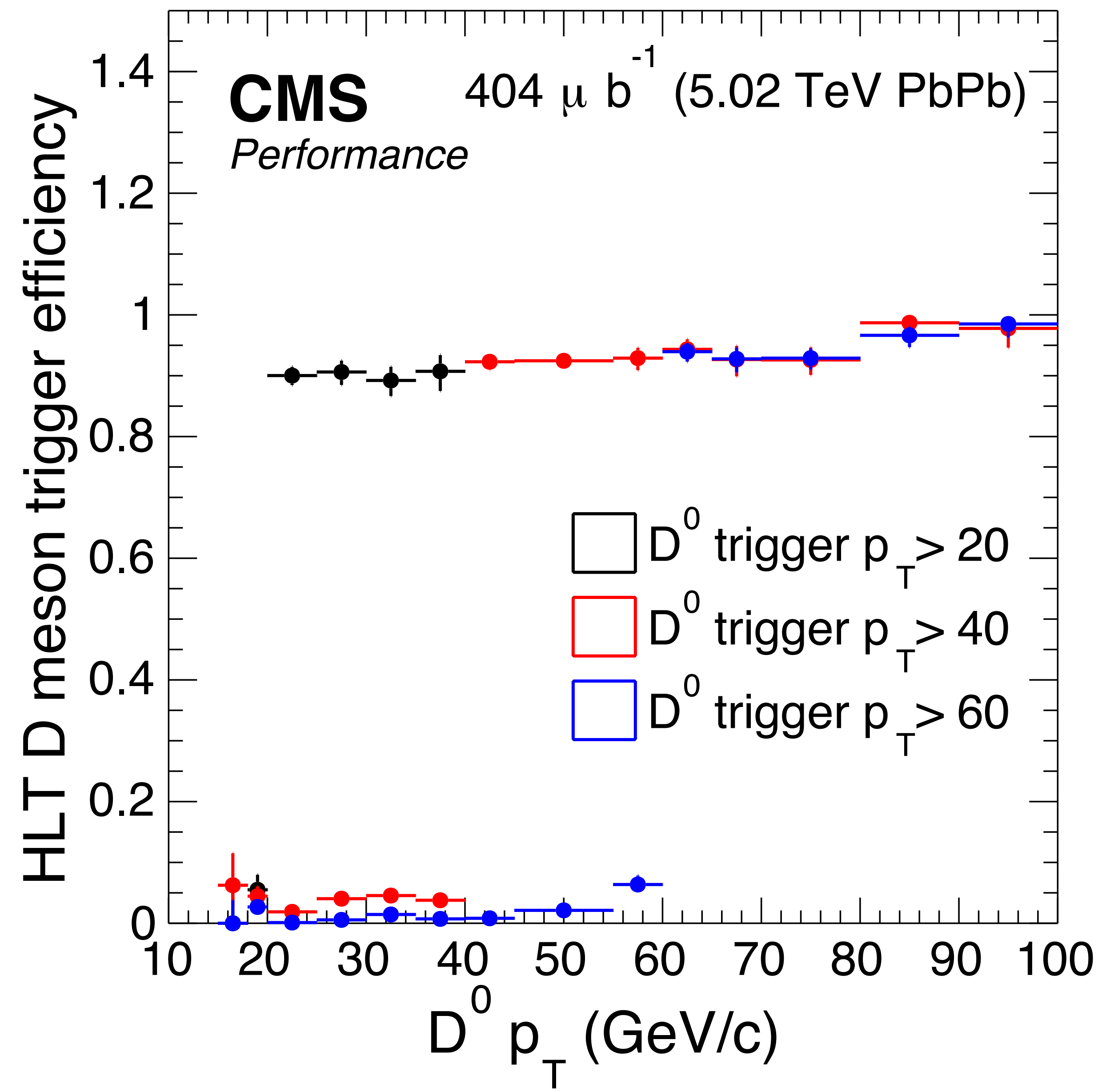
**$D^0$ meson reconstruction and selection**

↓

**HLT output rate!**

# Focus on D⁰ High-Level triggers




- factor x **800** (**30**) increased lumi in **pp** (**PbPb**) for $p_T > 60$ GeV compared to MB
- **entire $D^0 \rightarrow K^- \pi^+$ statistics collected for $p_T > 60$ GeV**

# D vs B $p_T$ shape in pp