Heavy-flavour results from CMS and prospects for future measurements

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Heavy Flavour Workshop in High Energy Collisions
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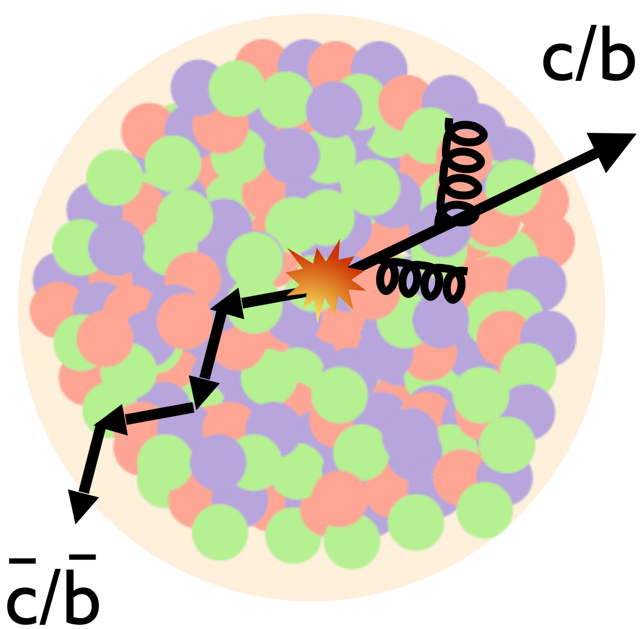
Lawrence Berkeley National Laboratory

*** focus on PbPb observable! CMS pp and pPb HF results in the backup!**

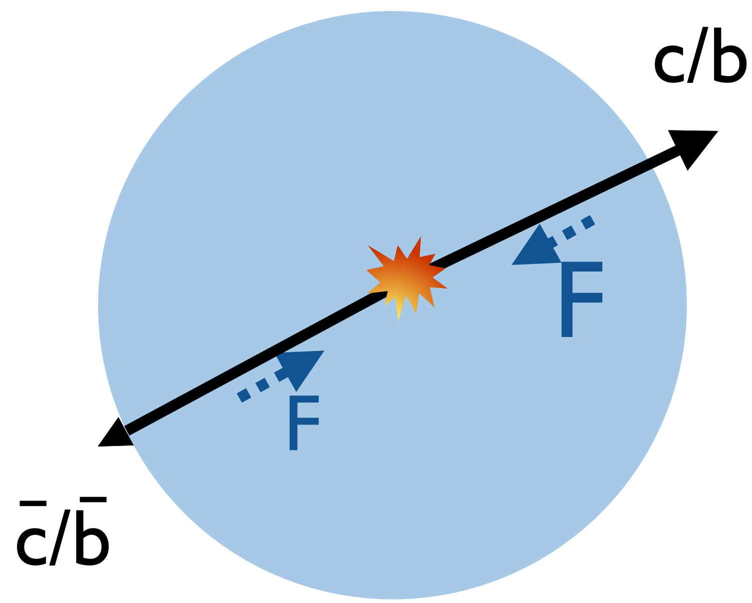
Heavy-flavours in CMS

Energy loss and collectivity using both charm and beauty probes

Jet quenching and flavour dependence

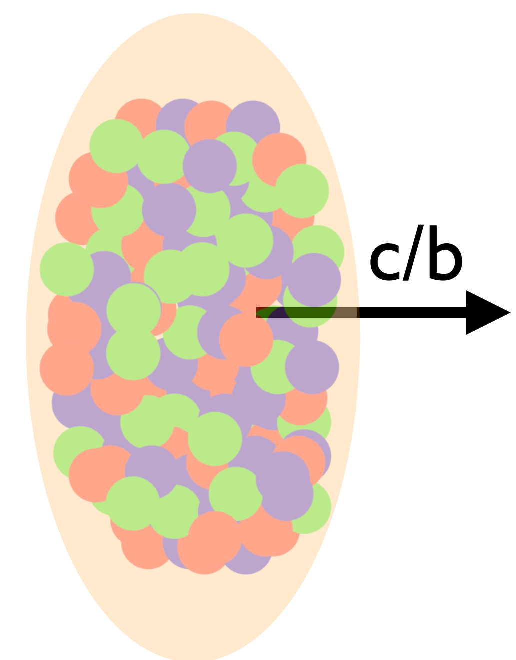


pQCD system?
- collisional and radiative with quasi particles



strongly-coupled medium?
- “drag” force in medium w/o quasi-particles

Degree of collectivity of heavy-particles



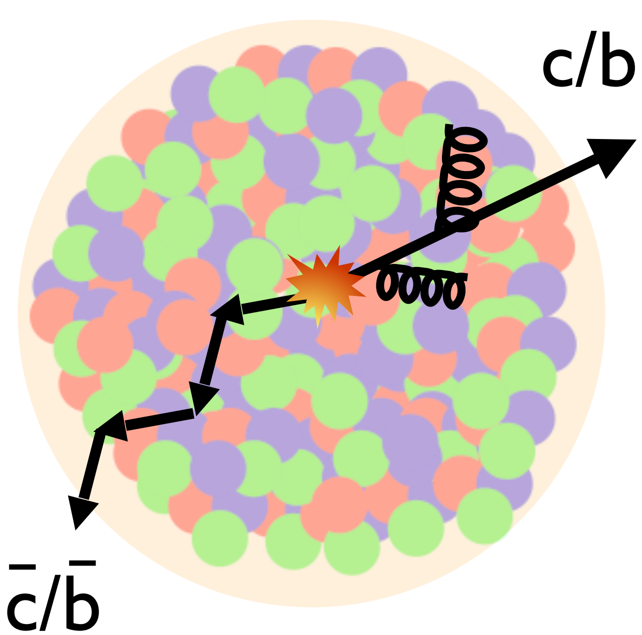
- thermalisation?
- collisional vs radiative?
- charm transport coefficient D_s

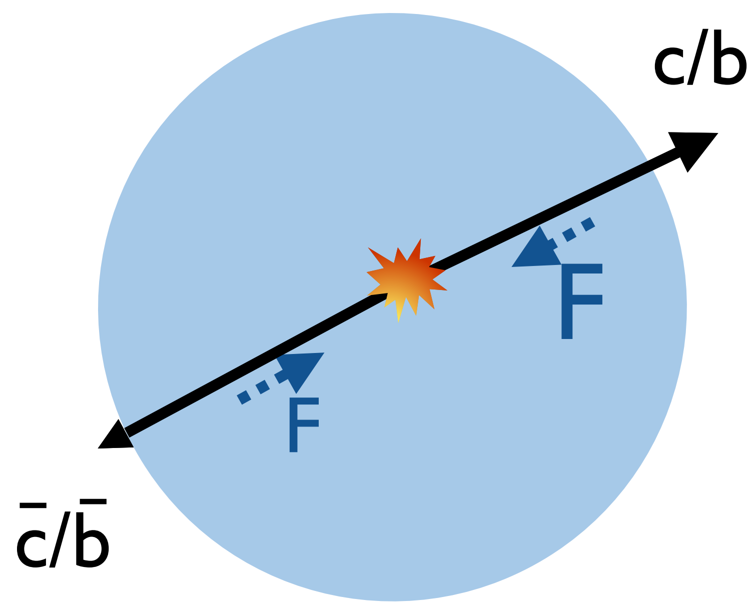
Heavy-flavours in CMS

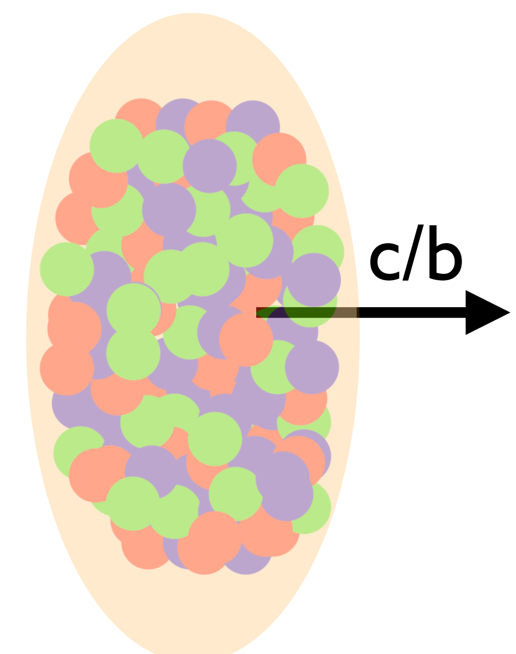
Energy loss and collectivity using both charm and beauty probes

Jet quenching and flavour dependence

Degree of collectivity of heavy-particles







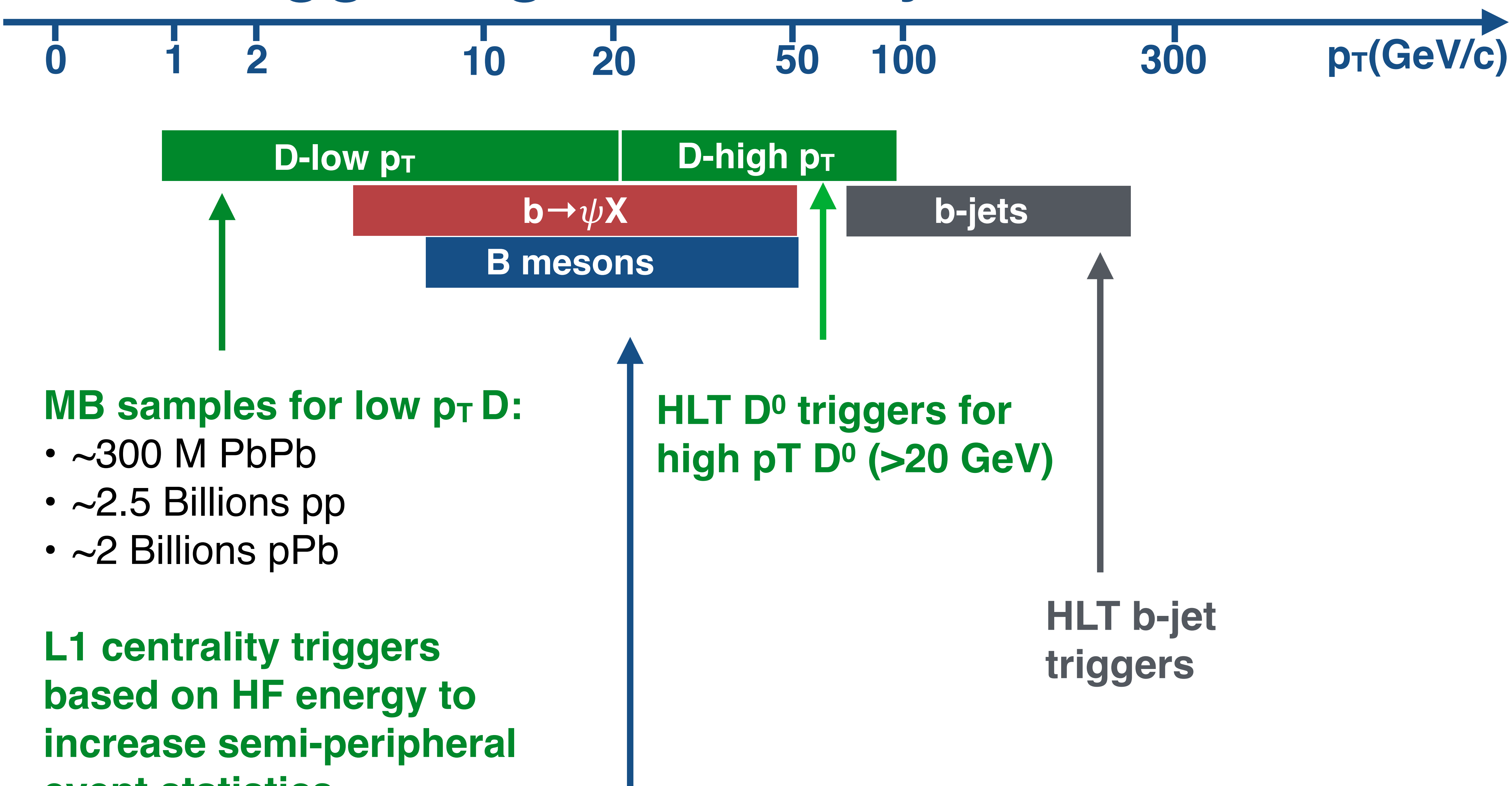
pQCD system?
- collisional and radiative with quasi particles

strongly-coupled medium?
- “drag” force in medium w/o quasi-particles

- thermalisation?
- collisional vs radiative?
- charm transport coefficient D_s

BUT energy loss and transport coefficient are not our goal!
We need to connect this to more fundamental properties (e.g η/s)!

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)

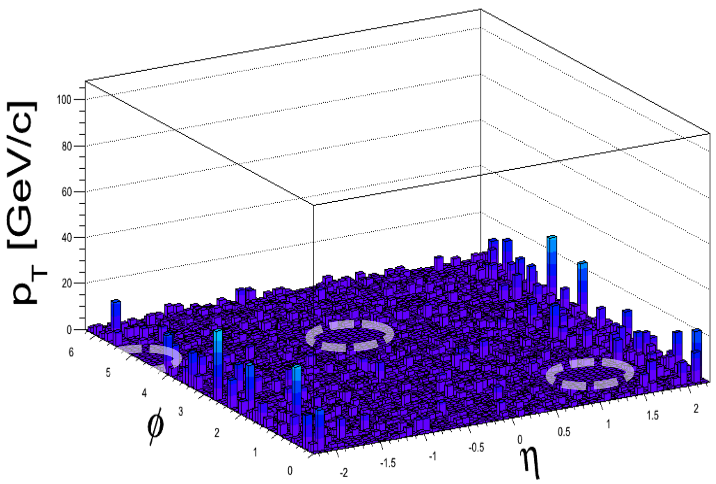
HLT b-jet triggers

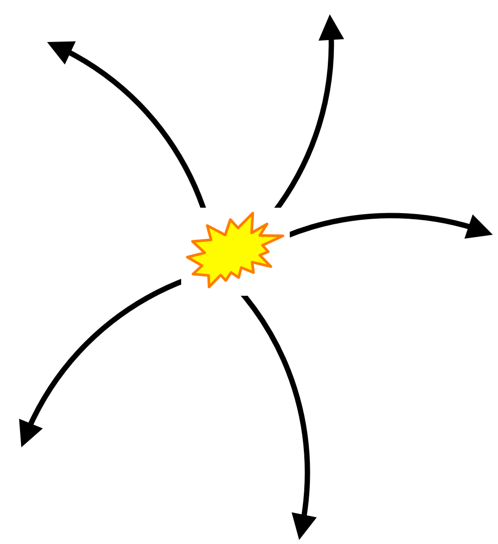
Di-lepton triggers for B mesons and b→J/ψ

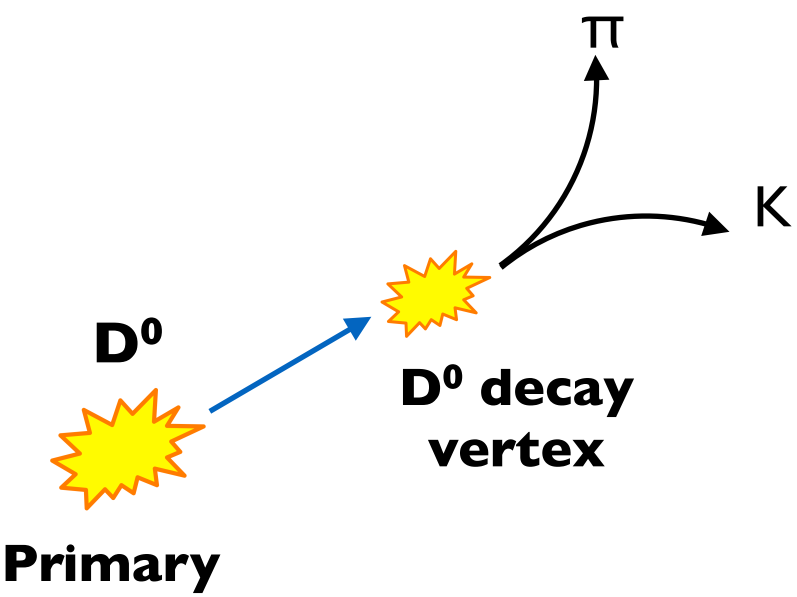
Level-1 trigger= first level of trigger of CMS, hardware-based (FPGA)
High-Level-Trigger= second trigger layer , software-based

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

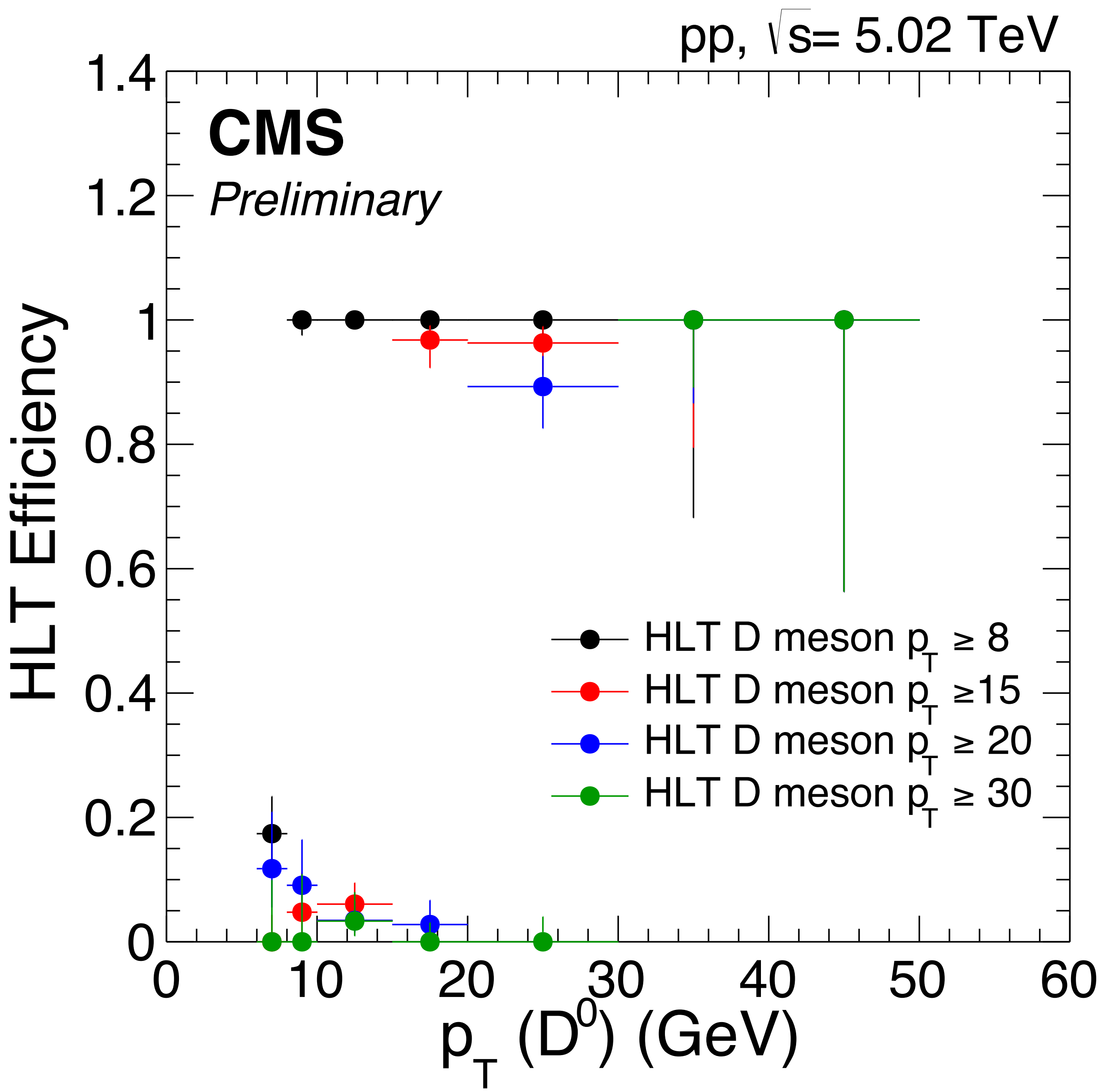
Track reconstruction in software trigger system

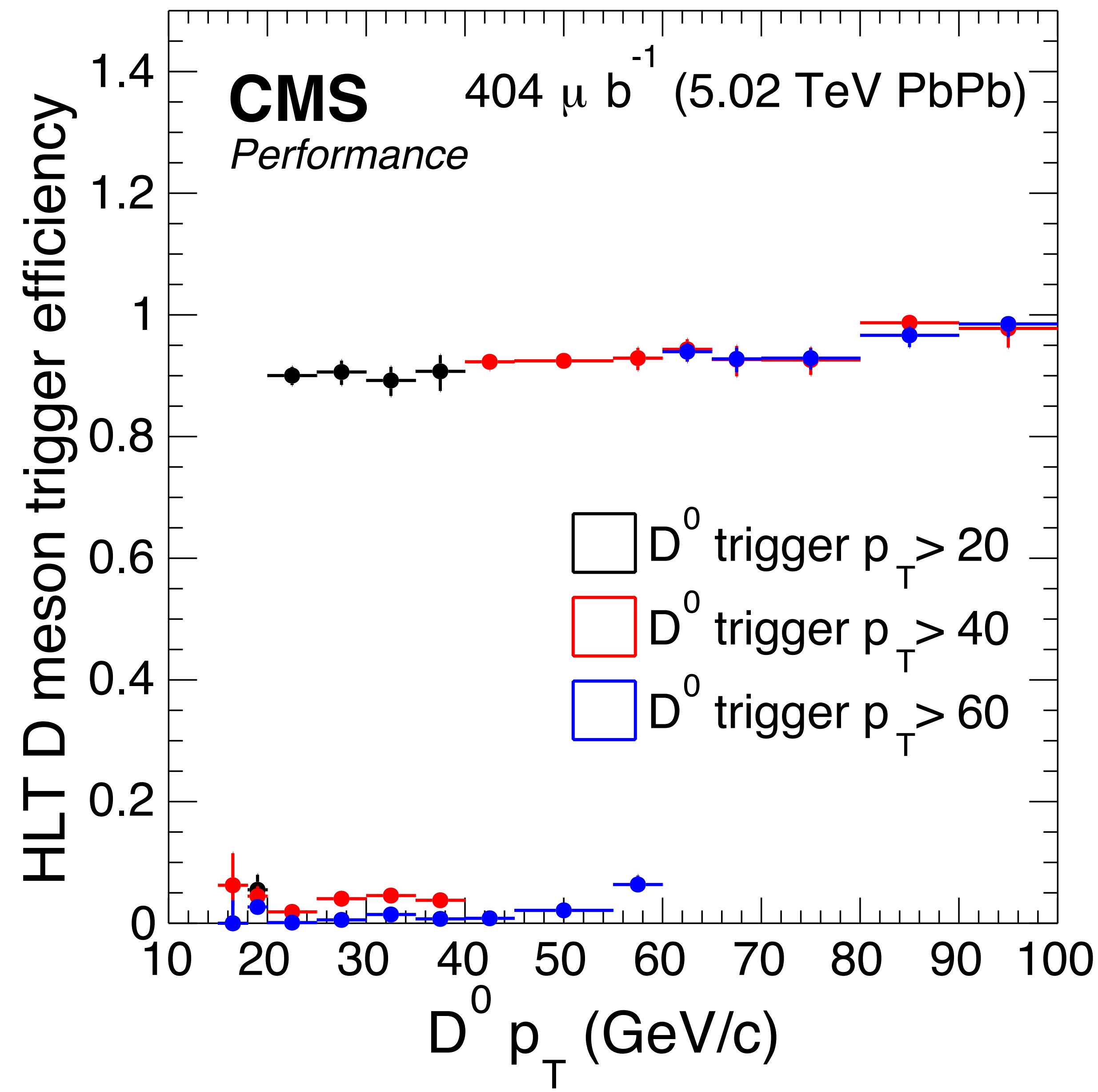
Timing!

D^0 meson reconstruction and selection

HLT output rate!

Focus on D^0 High-Level triggers



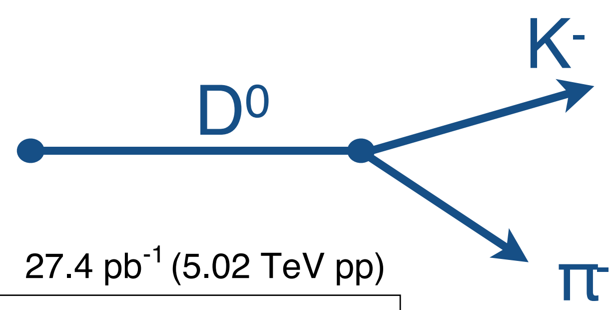


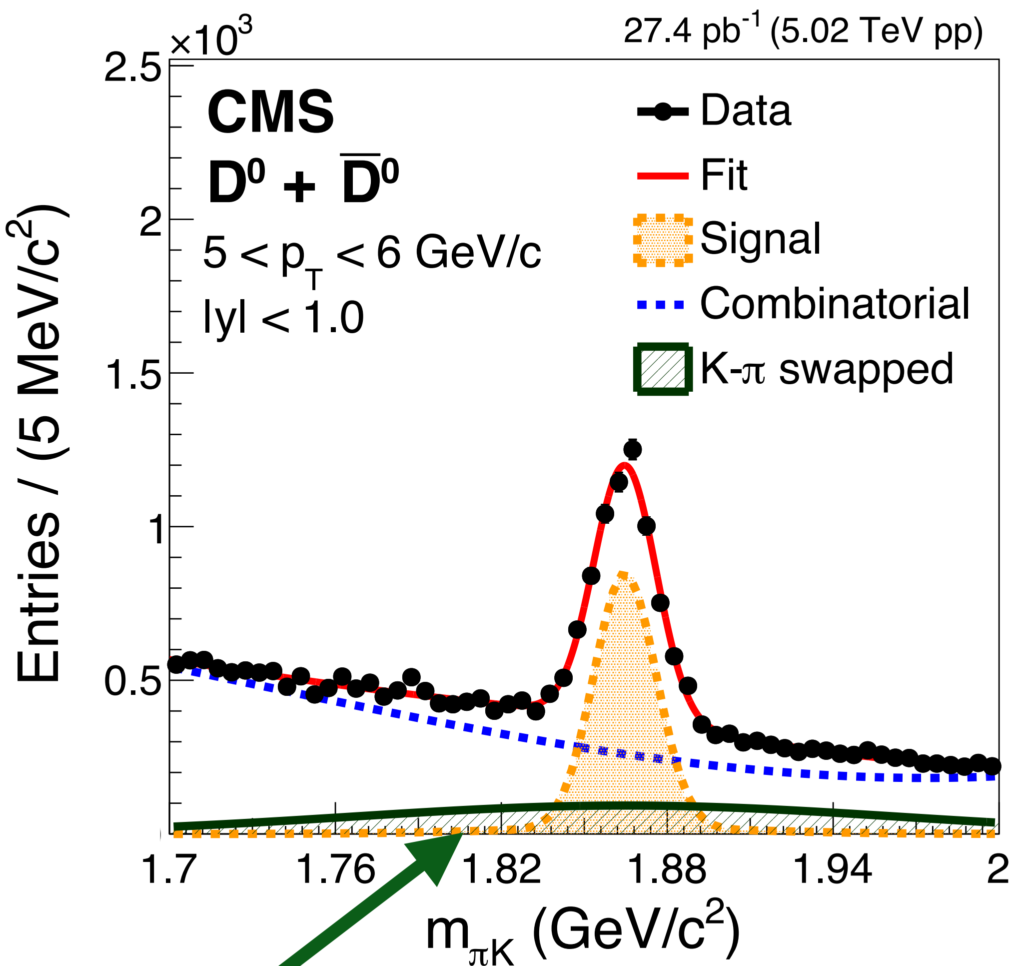
- factor x **800** (**30**) increased lumi in **pp** (**PbPb**) for p_T > 60 GeV compared to MB
- **entire $D^0 \rightarrow K^- \pi^+$ statistics collected for p_T > 60 GeV**

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

D mesons

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



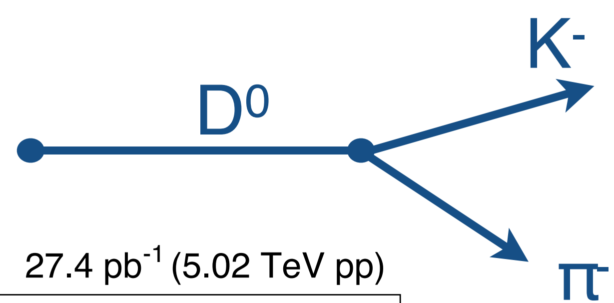


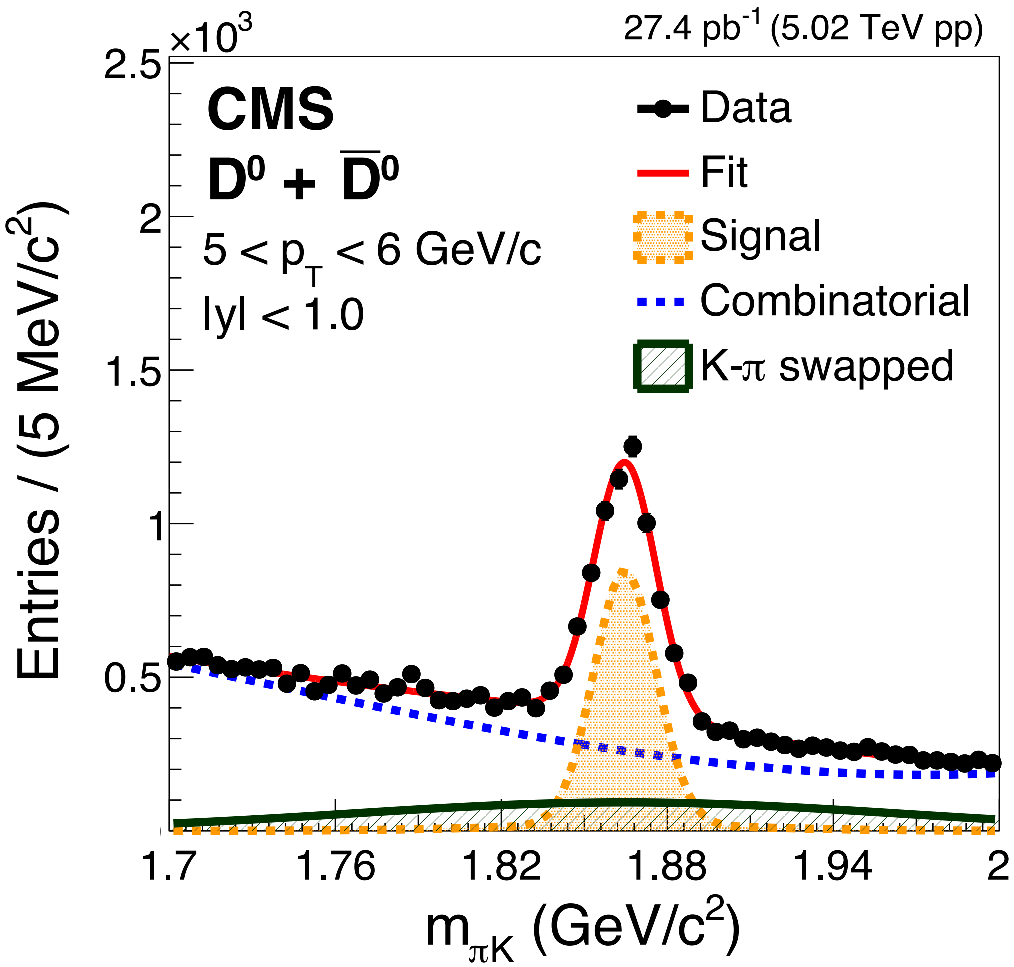
No PID → wide gaussian for candidates with swapped mass hypothesis

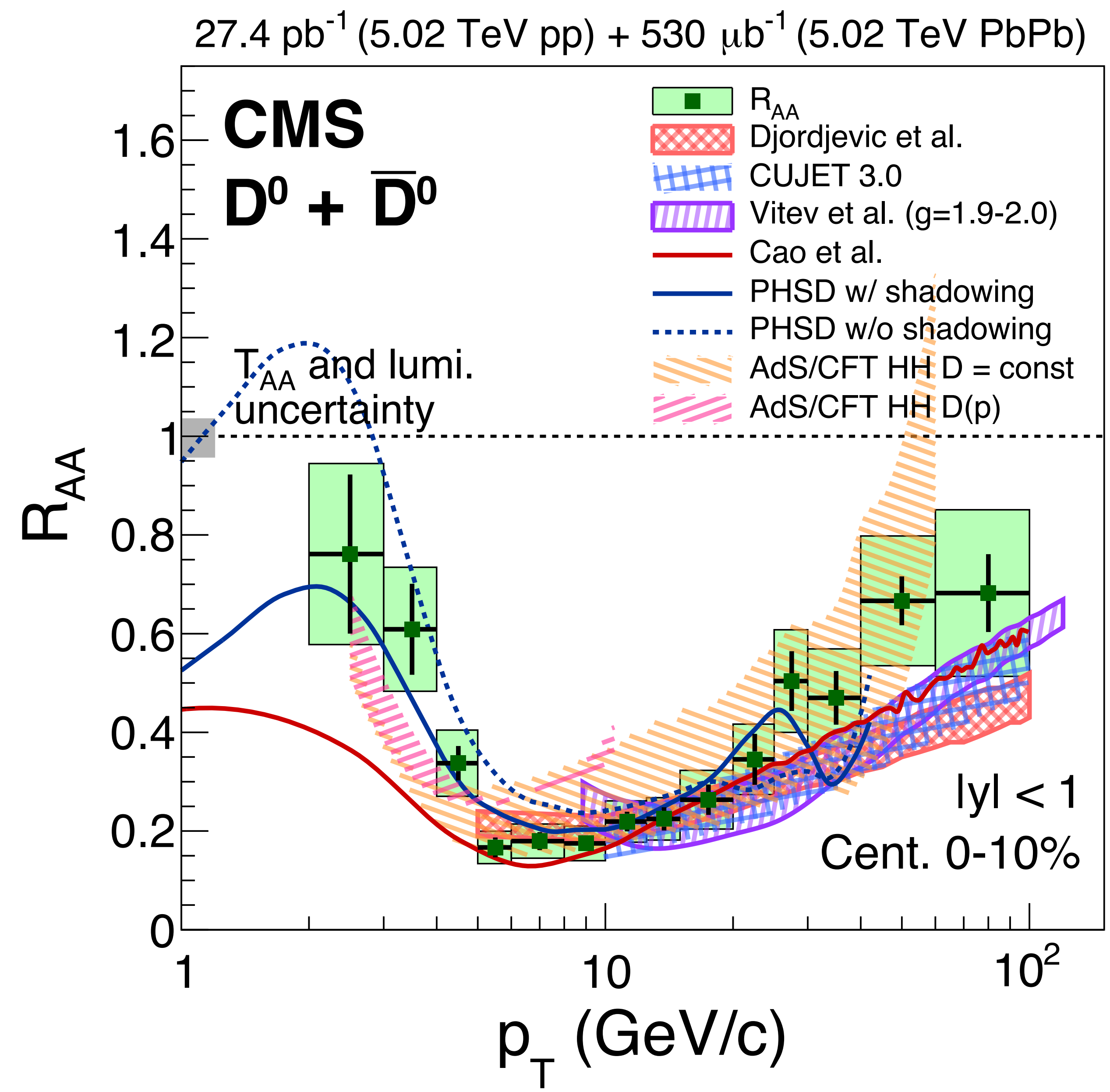
arXiv: 1708.04962

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

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





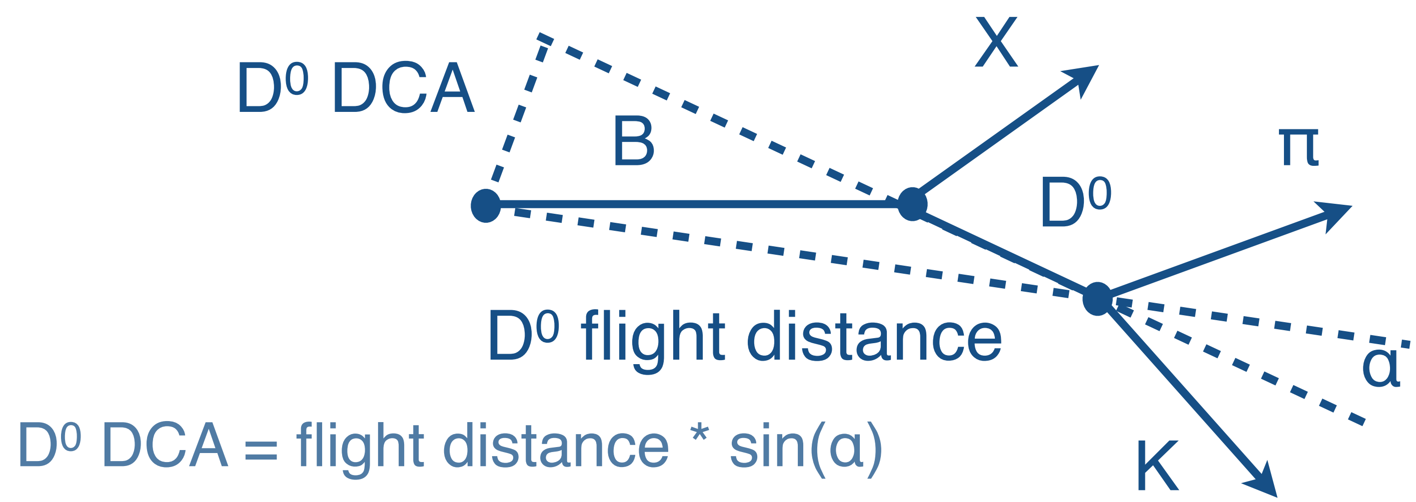


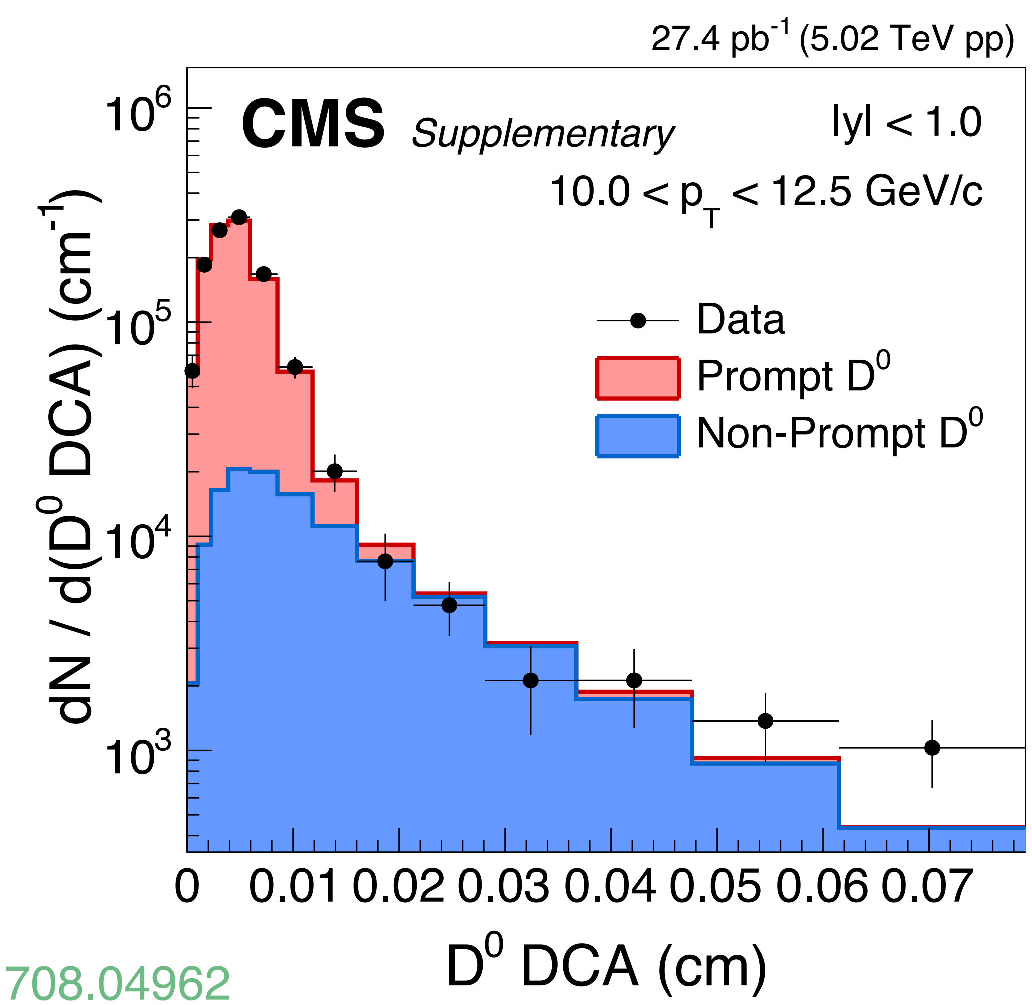
No PID → wide gaussian for candidates with swapped mass hypothesis

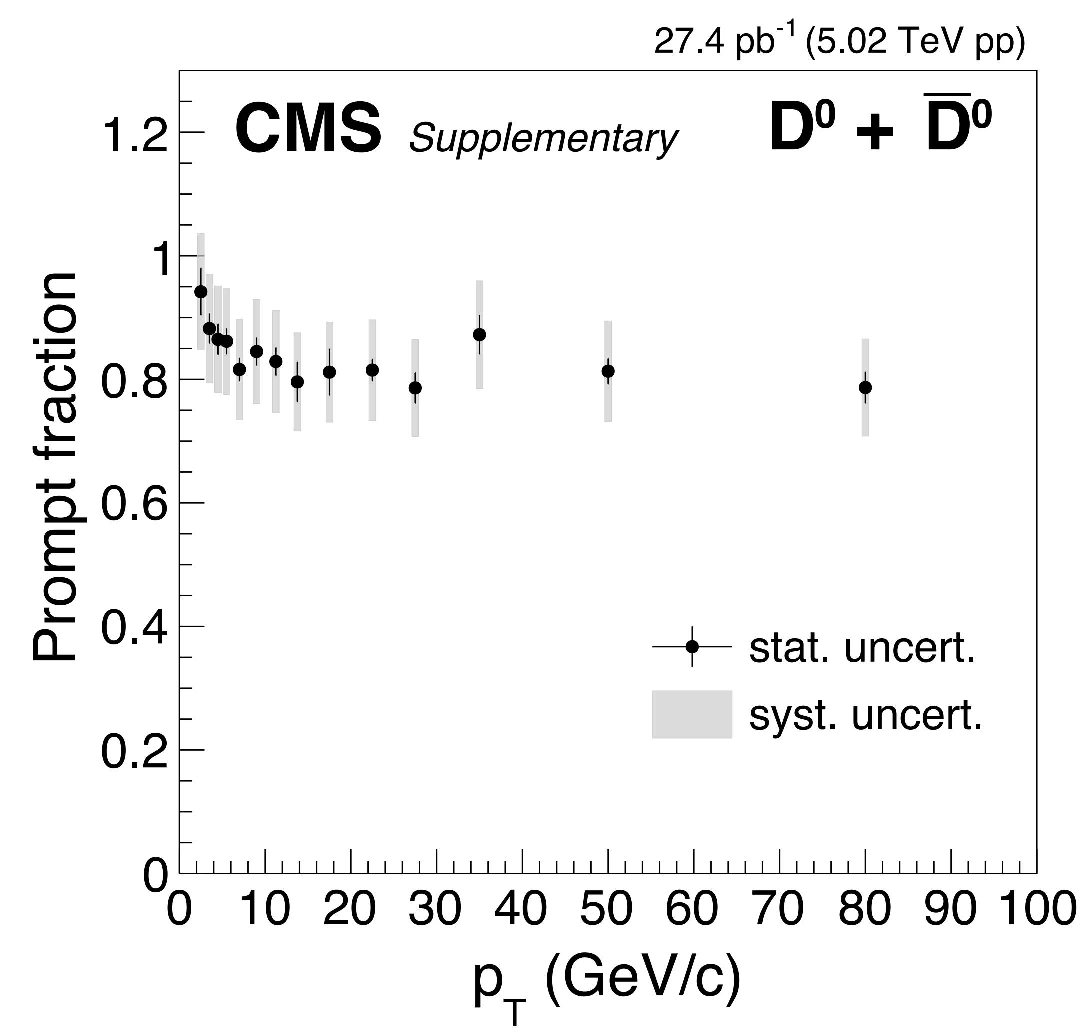
[1] arXiv:1703.00822
[2] Phys. Rev. C 92 (2015) 024918
[3] JHEP 02 (2016) 169
[4] Phys. Rev. D 91 (2015) 085019
[5] Phys. Rev. D 93 (2016) 074030
[6] Phys. Rev. C 93 (2016) 034906

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

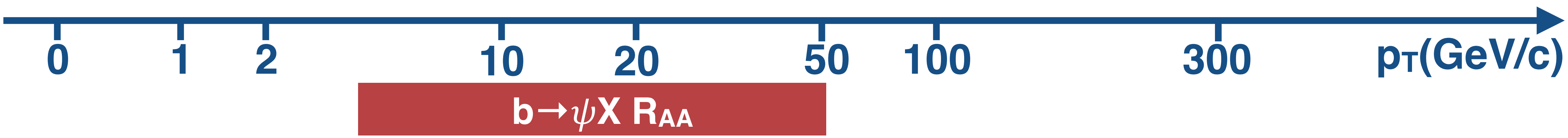
- Significant contribution of non-prompt D^0 from b hadron decays at LHC (**O(10%)**)
- **CMS separates prompt and non-prompt D^0 from DATA using D^0 DCA**

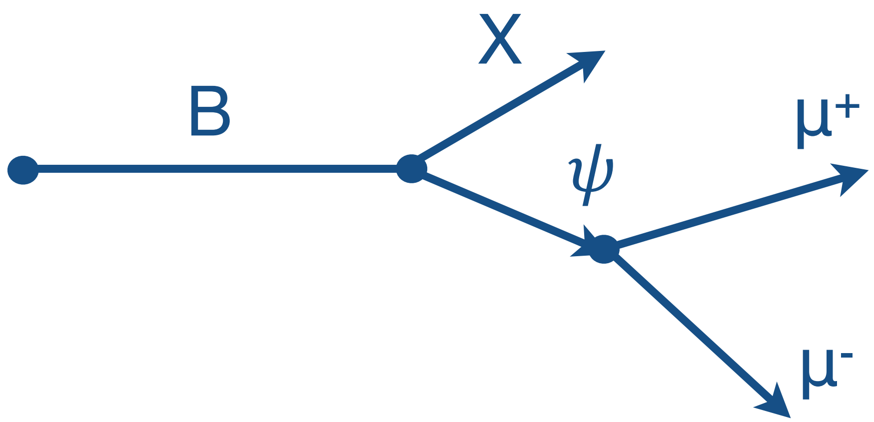




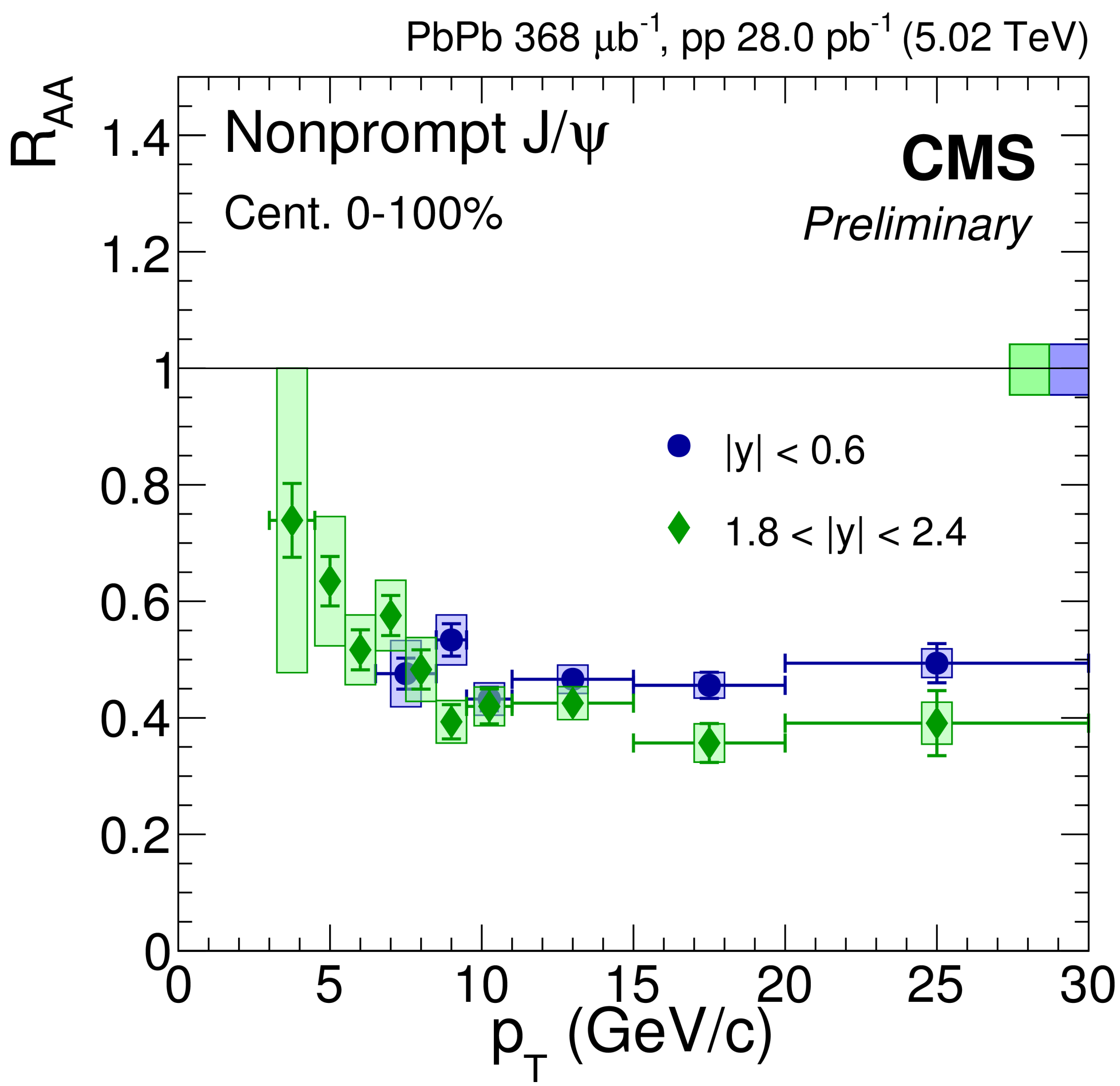


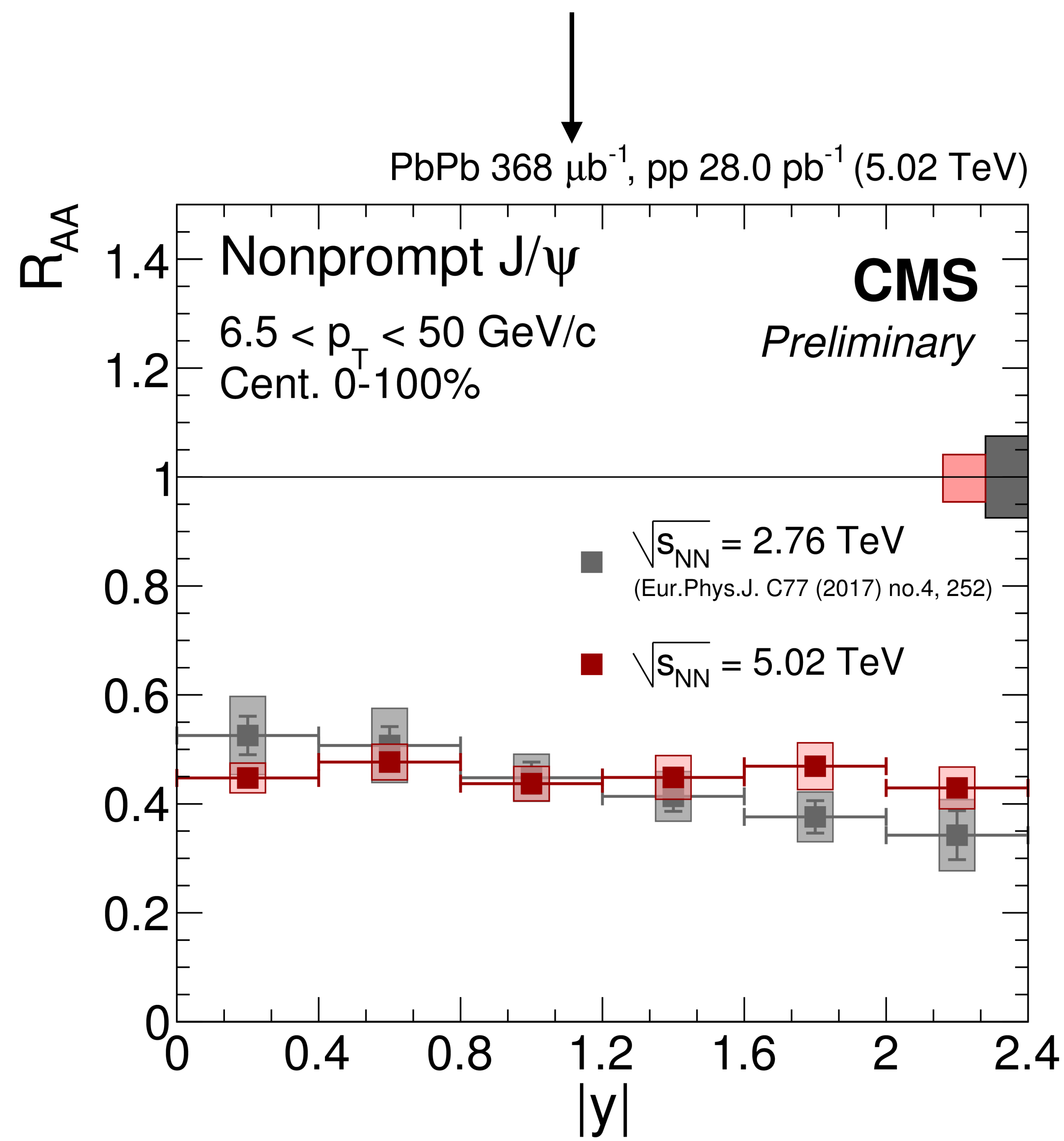
$b \to \psi X$ R_{AA} at 5.02 TeV



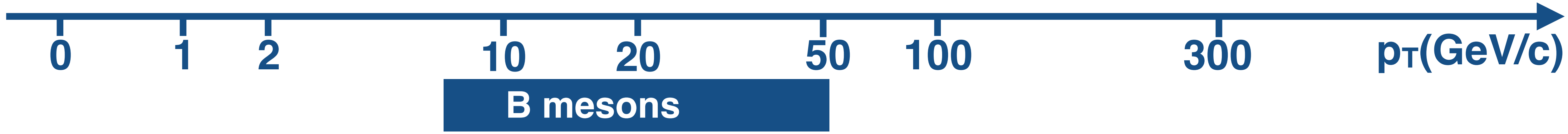


measurement of the beauty suppression as function of rapidity!

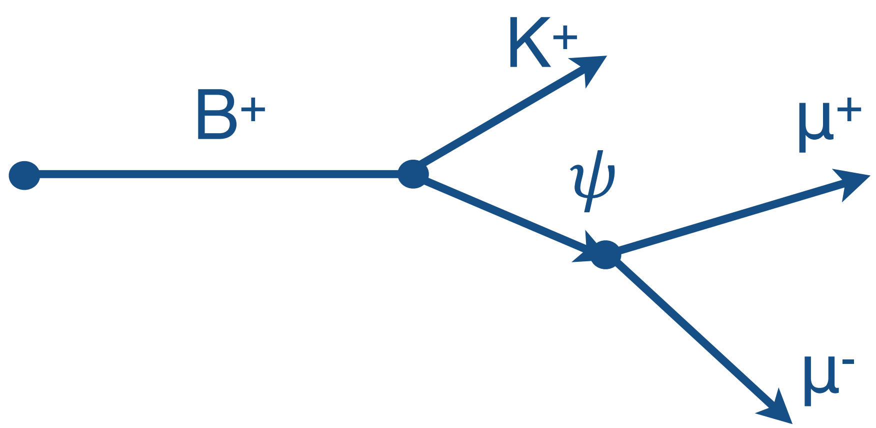


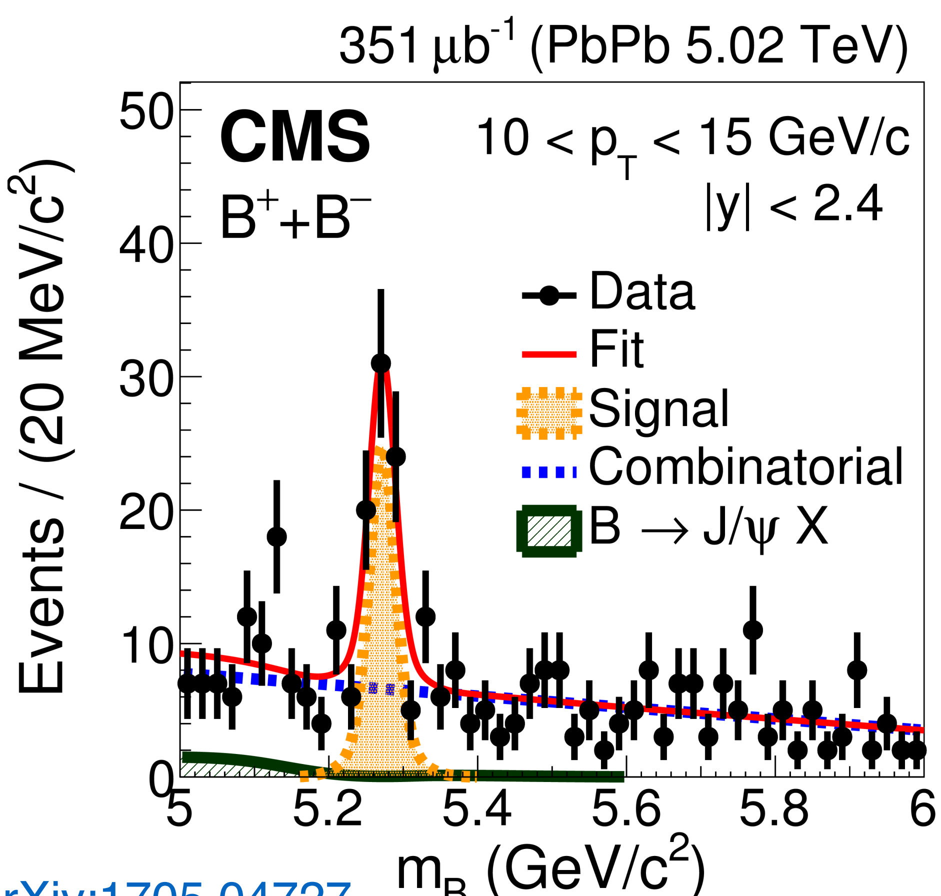


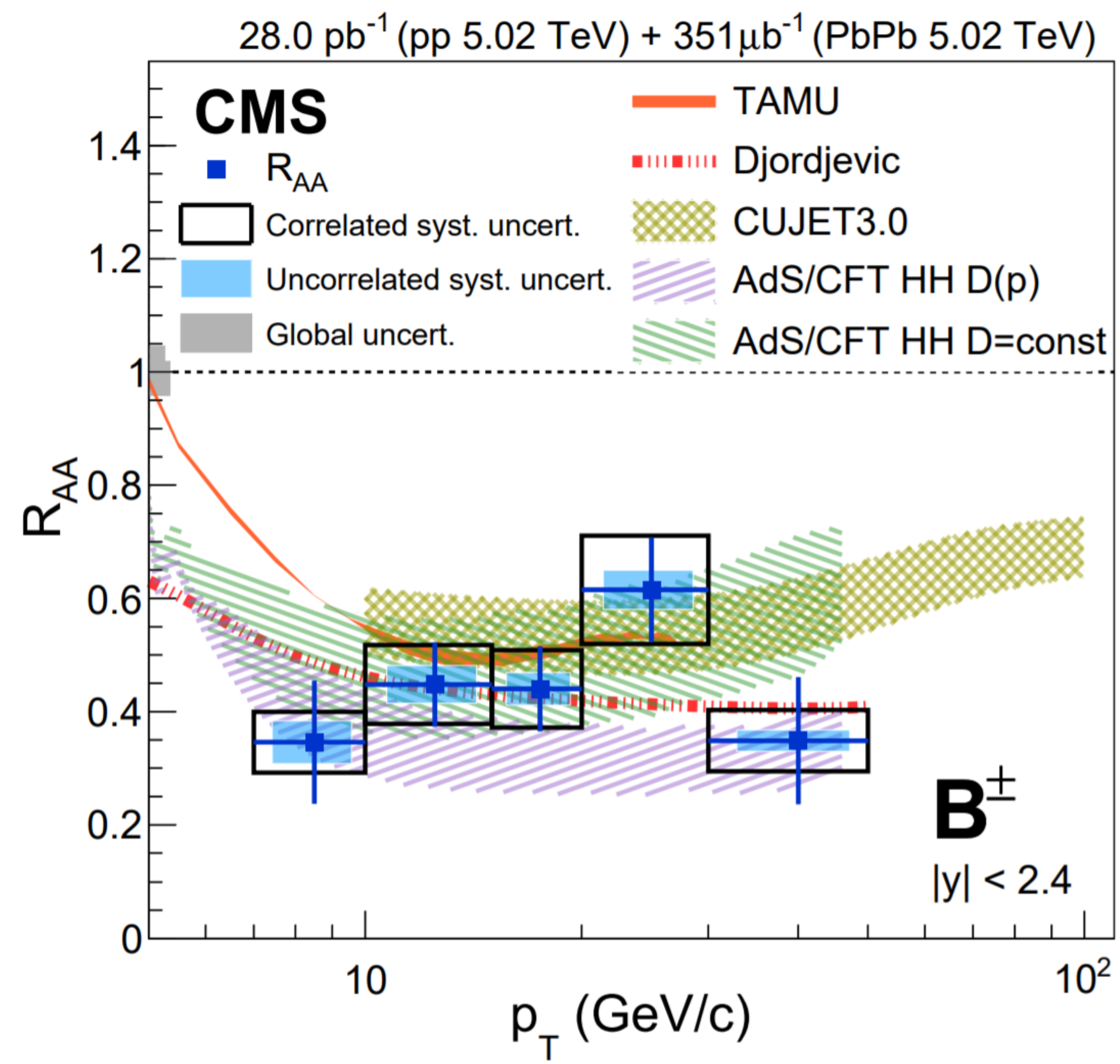
B^+ meson R_{AA} at 5.02 TeV



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

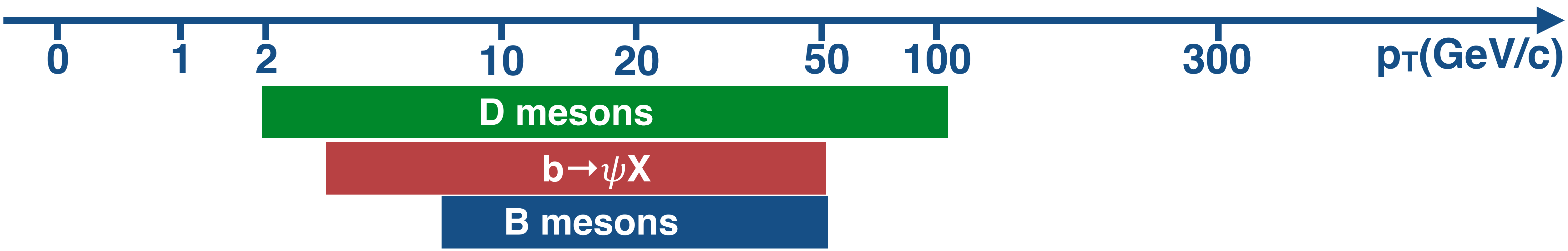


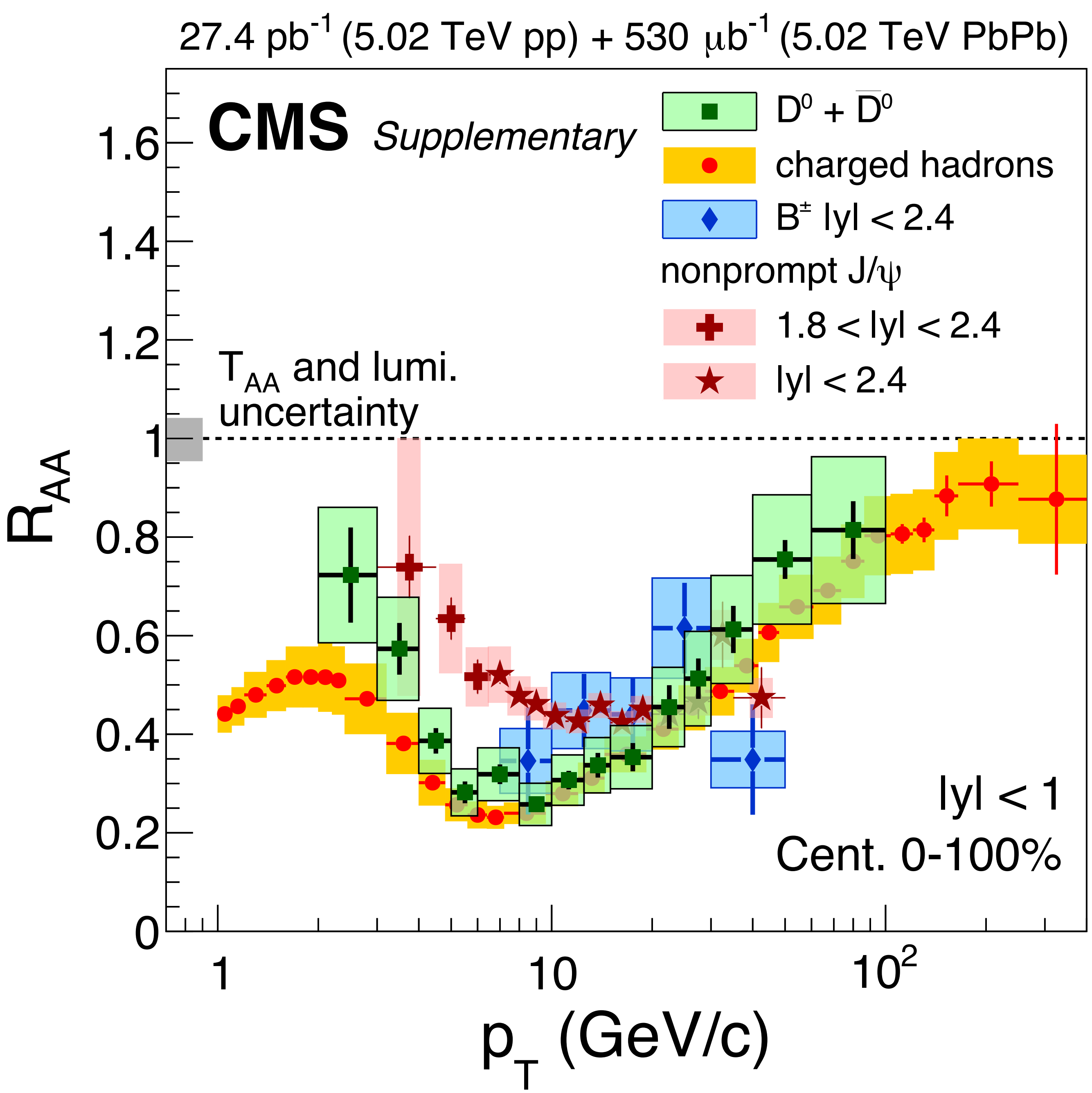




arXiv:1705.04727

Flavour dependence of E_{loss} at 5.02 TeV





B+ meson

D0 meson

charged particle

non prompt J/ψ

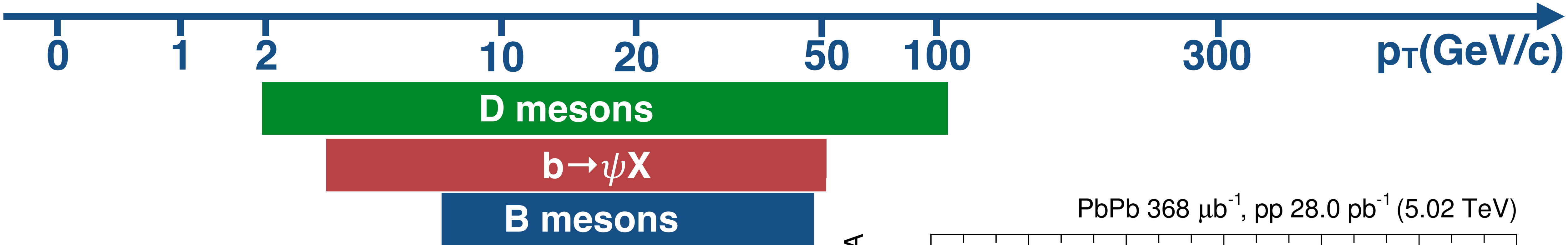
JHEP 04 (2017) 039

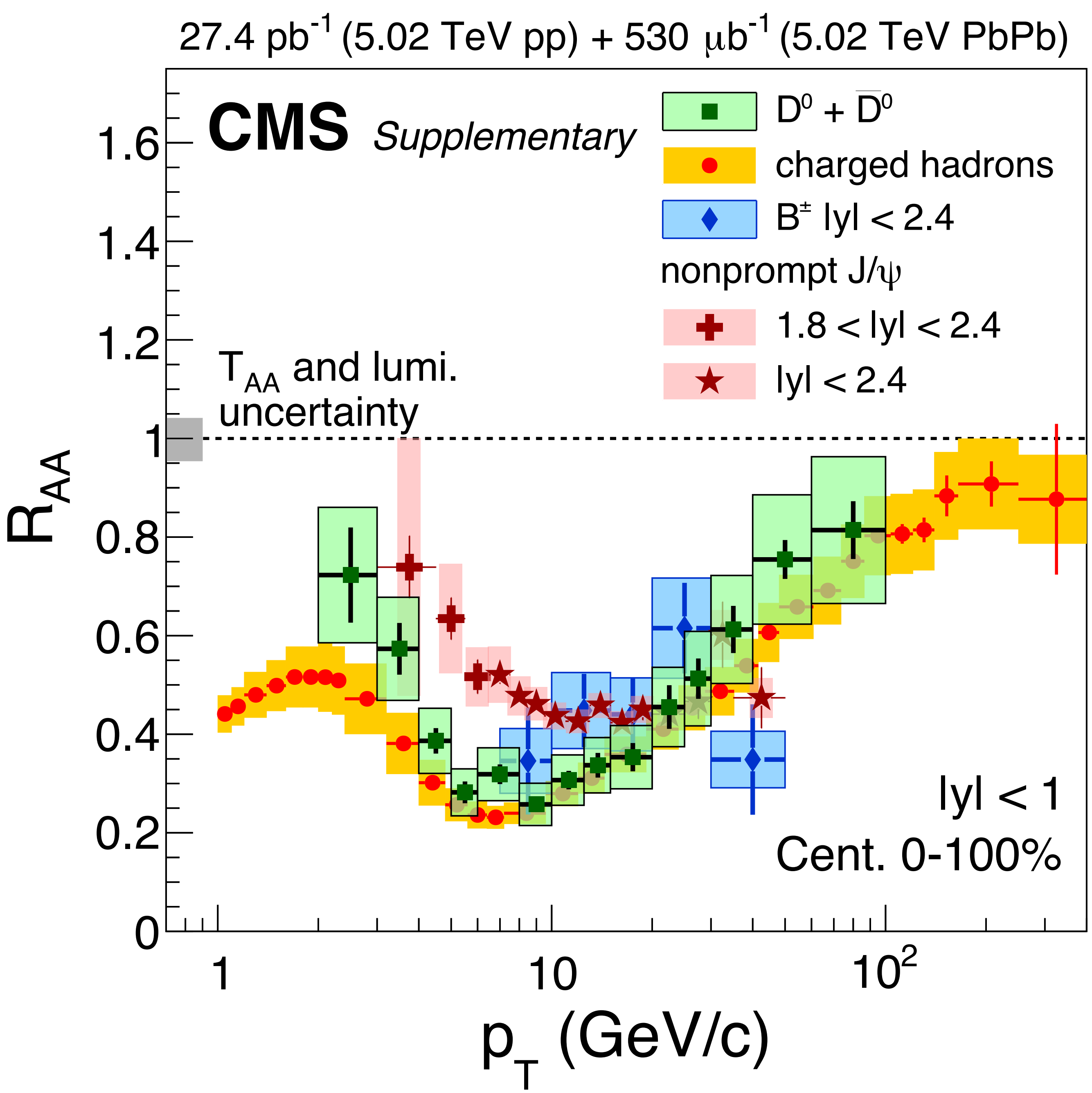
arXiv:1705.04727

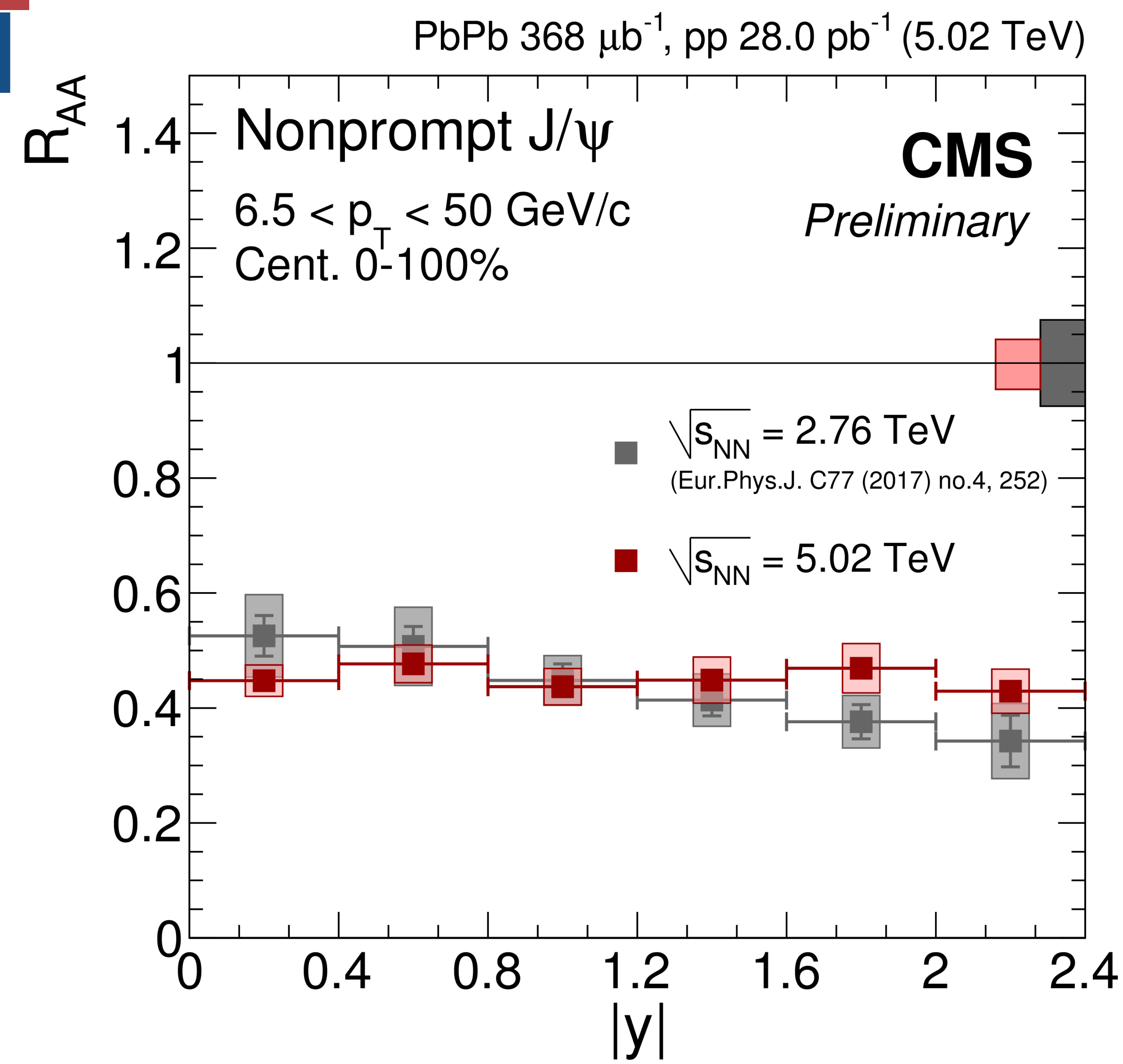
CMS-PAS-HIN-16-025

arXiv: 1708.04962

Flavour dependence of E_{loss} at 5.02 TeV

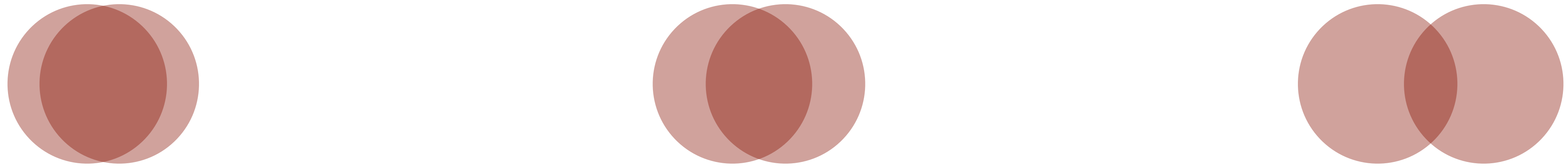


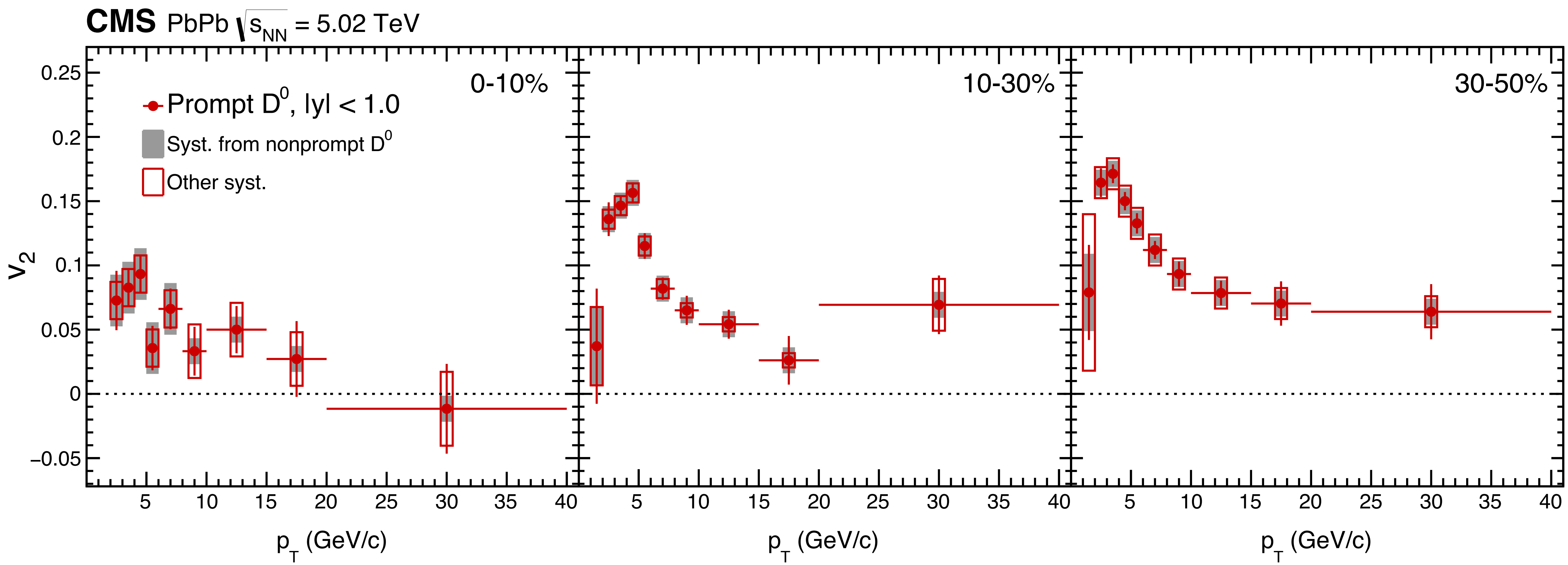




- **No strong dependence of beauty R_{AA} vs rapidity**

Prompt D^0 v_2 in PbPb at 5.02 TeV



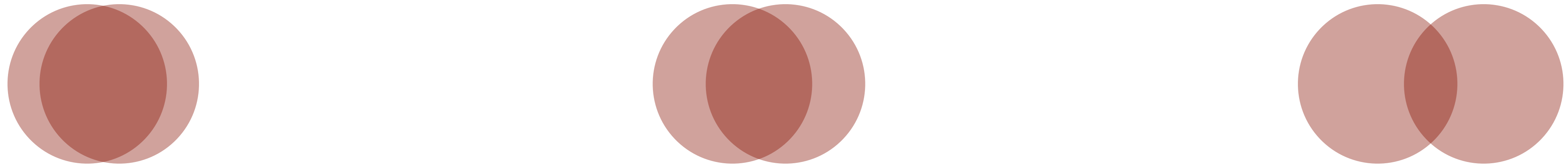


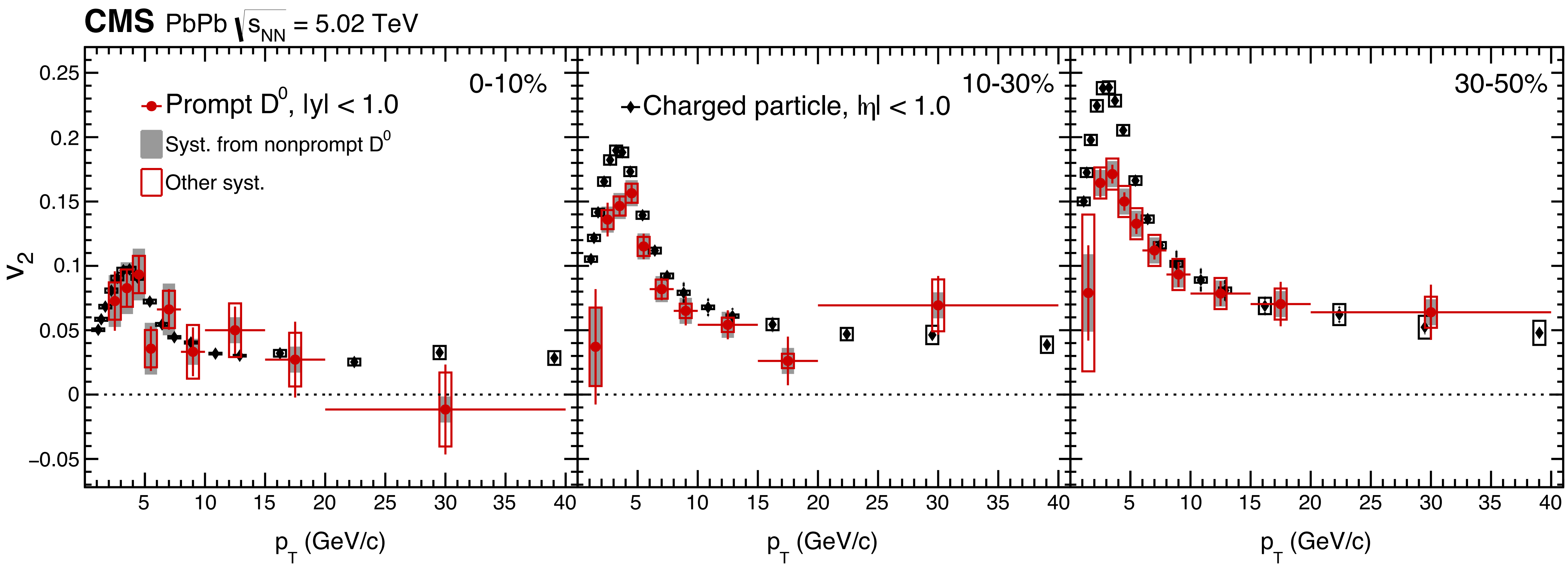
Positive prompt D^0 v_2 that increases with centrality at both low and high p_T

- 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





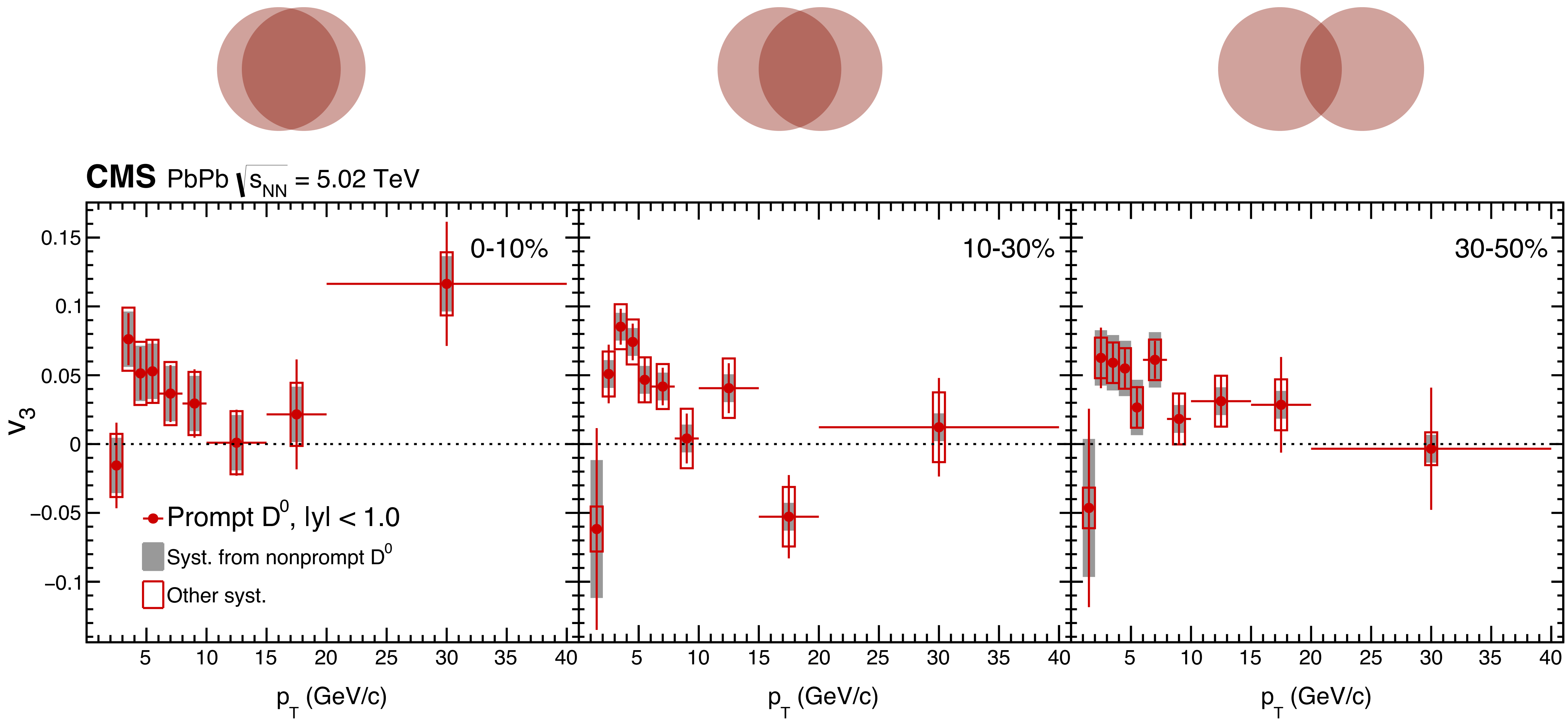
Low p_T: v_2 (prompt D^0) ≈ v_2 (charged particles) in central events

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

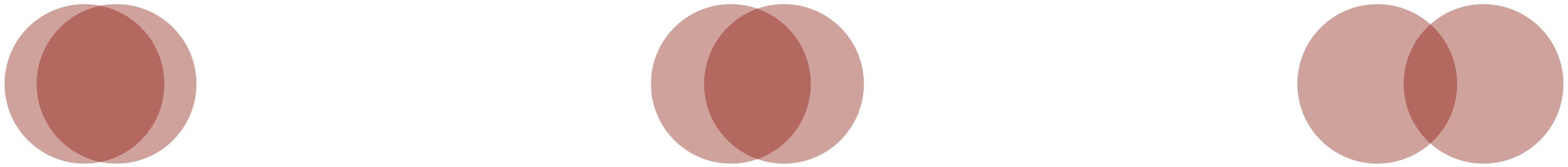
Prompt D^0 v_3 in PbPb at 5.02 TeV

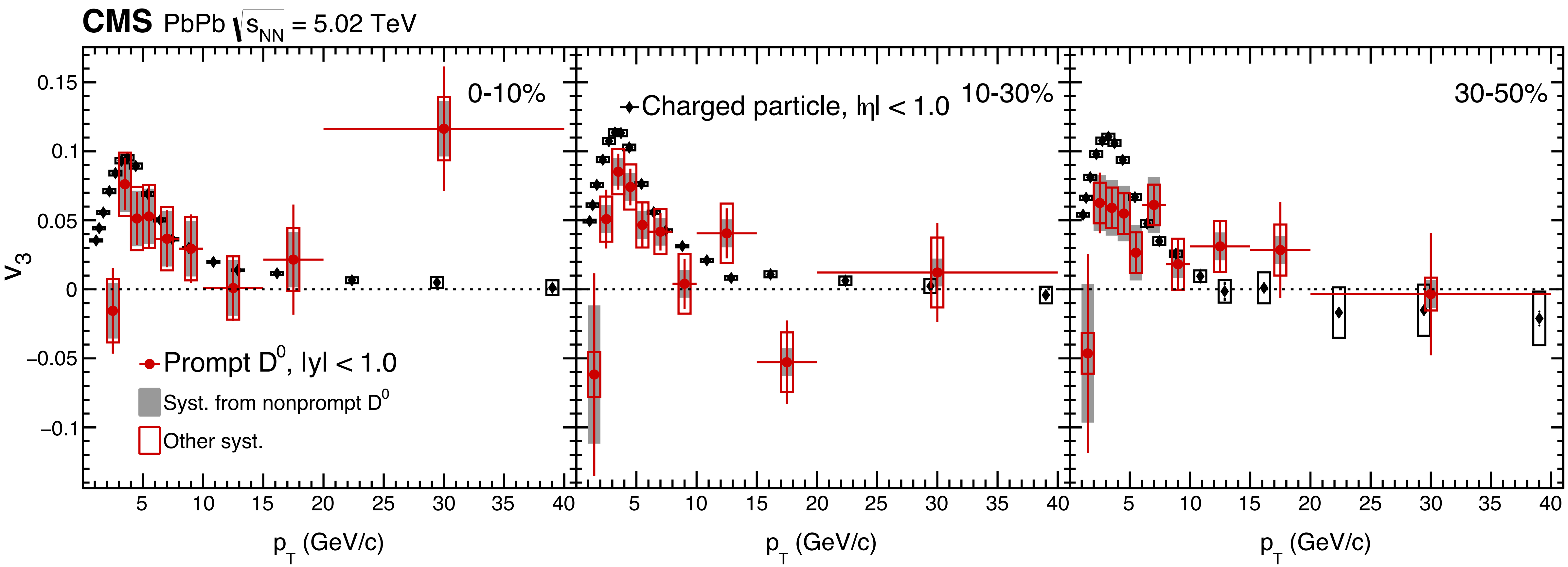


Low p_T: v_3 (prompt D^0) > 0;
High p_T: v_3 (prompt D^0) ≈ 0
Little centrality dependence

arXiv: 1708.03497

Prompt D^0 v_3 in PbPb at 5.02 TeV

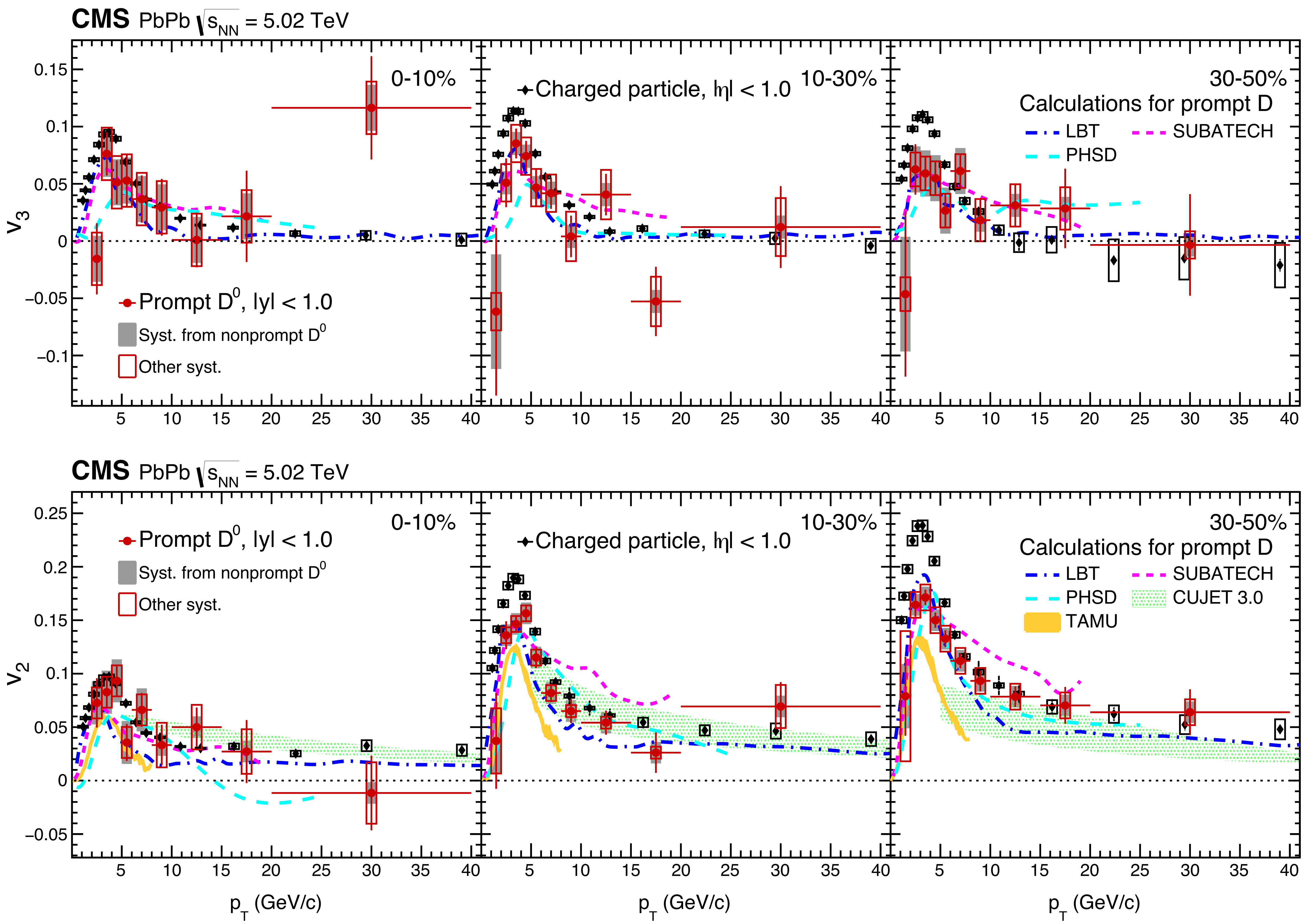




Low p_T: v_3 (prompt D^0) < v_3 (charged particles)
High p_T: v_3 (prompt D^0) ≈ v_3 (charged particles)
Both have little centrality dependence

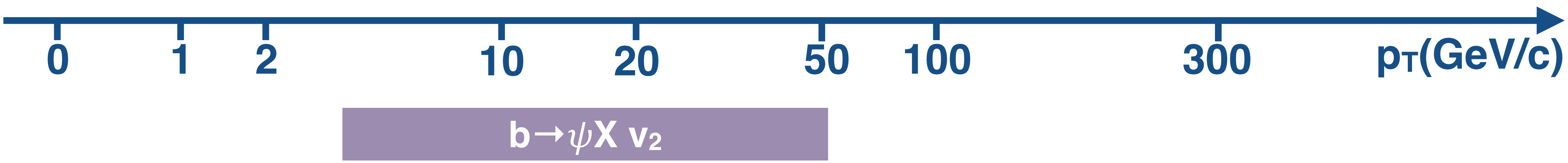
arXiv: 1708.03497

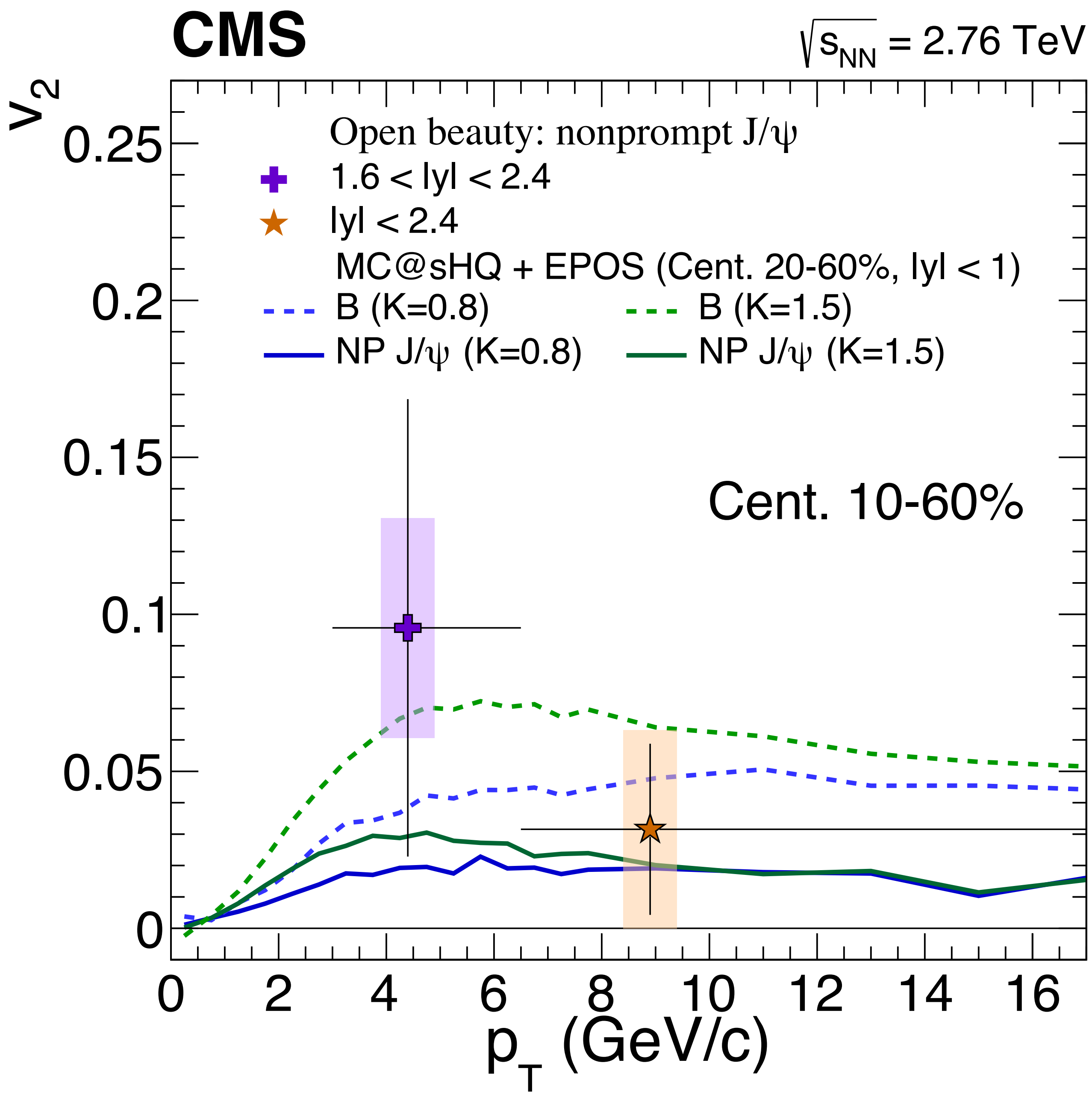
Comparison to theoretical calculations



arXiv:

First look at b→ψX v_2 at 5.02 TeV



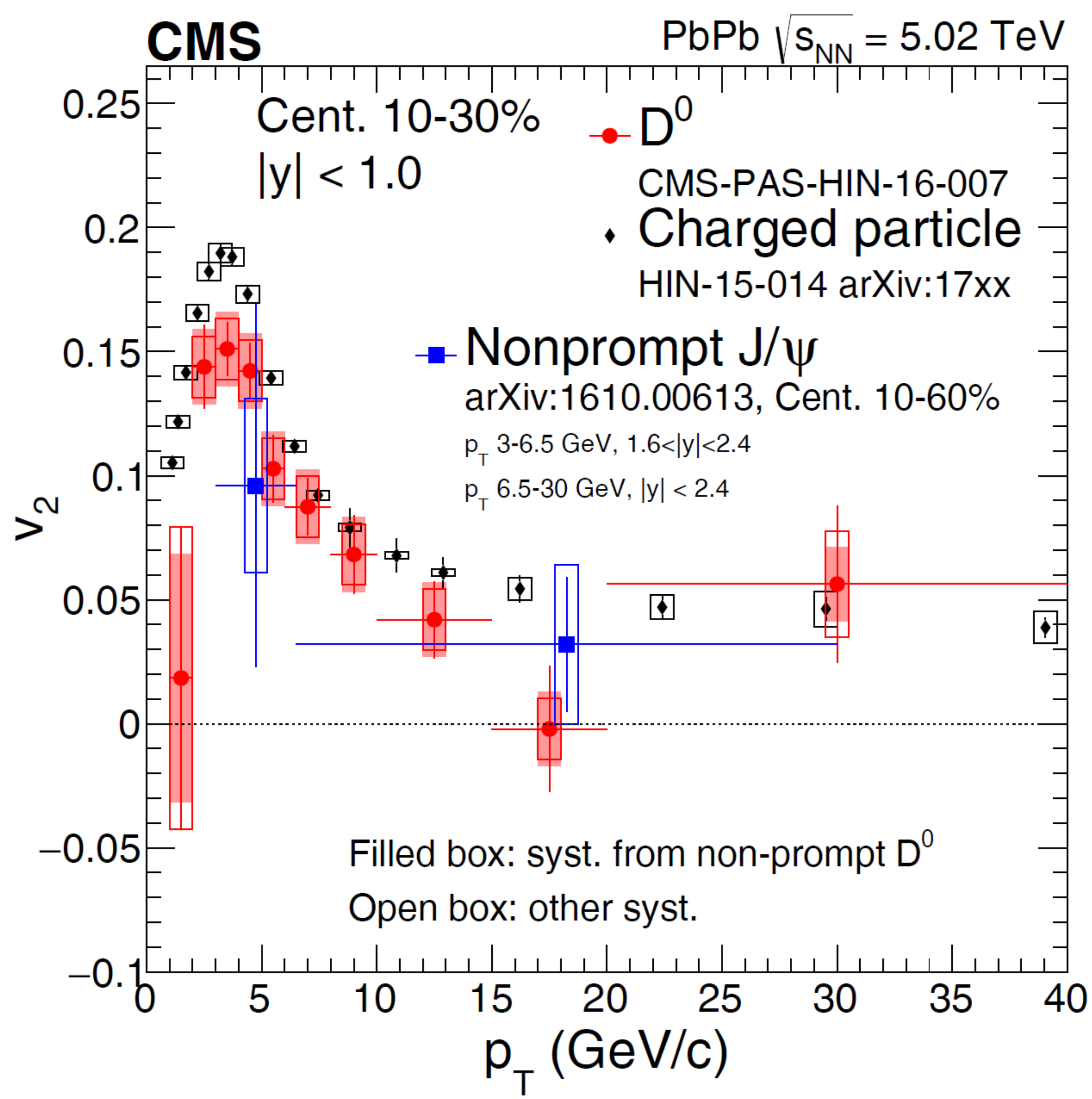


Current measurement L_{int}=150/µb, with ~70% statistical uncertainty at low p_T.

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

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

First look at $b \to \psi X$ v_2 at 5.02 TeV



Similar flow for charm and beauty? Need more data!

Open questions

Energy loss
- pQCD vs strongly-coupled?
- collisional vs radiative?
- *flavour dependence*: first indications at low p_T

proton-proton:
- LO vs NLO mechanism: gluon splitting

Hadronisation
- still missing a quantitative estimation of recombination
- recombination in pp/pPb?

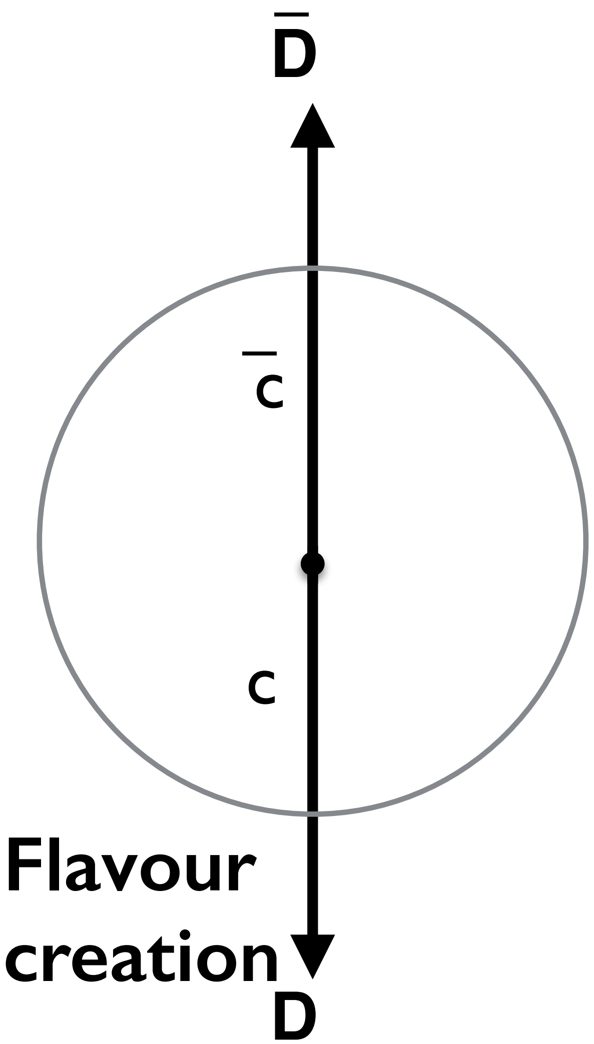
Collectivity:
- is charm hydro/ thermalised?
- does beauty flow?

Small systems:
- flow in high-milt pp or pPb?
- any indication of QGP from heavy-flavour observables?

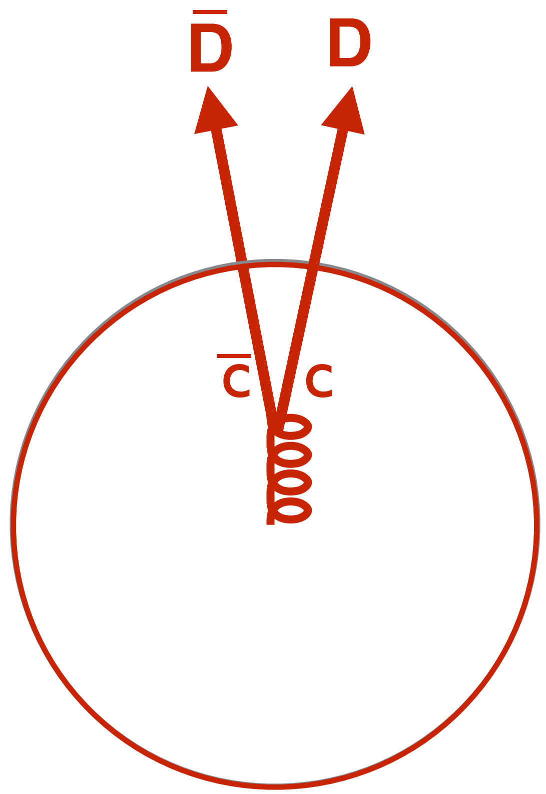
Some ideas for future CMS HF analysis

HF correlations in pp

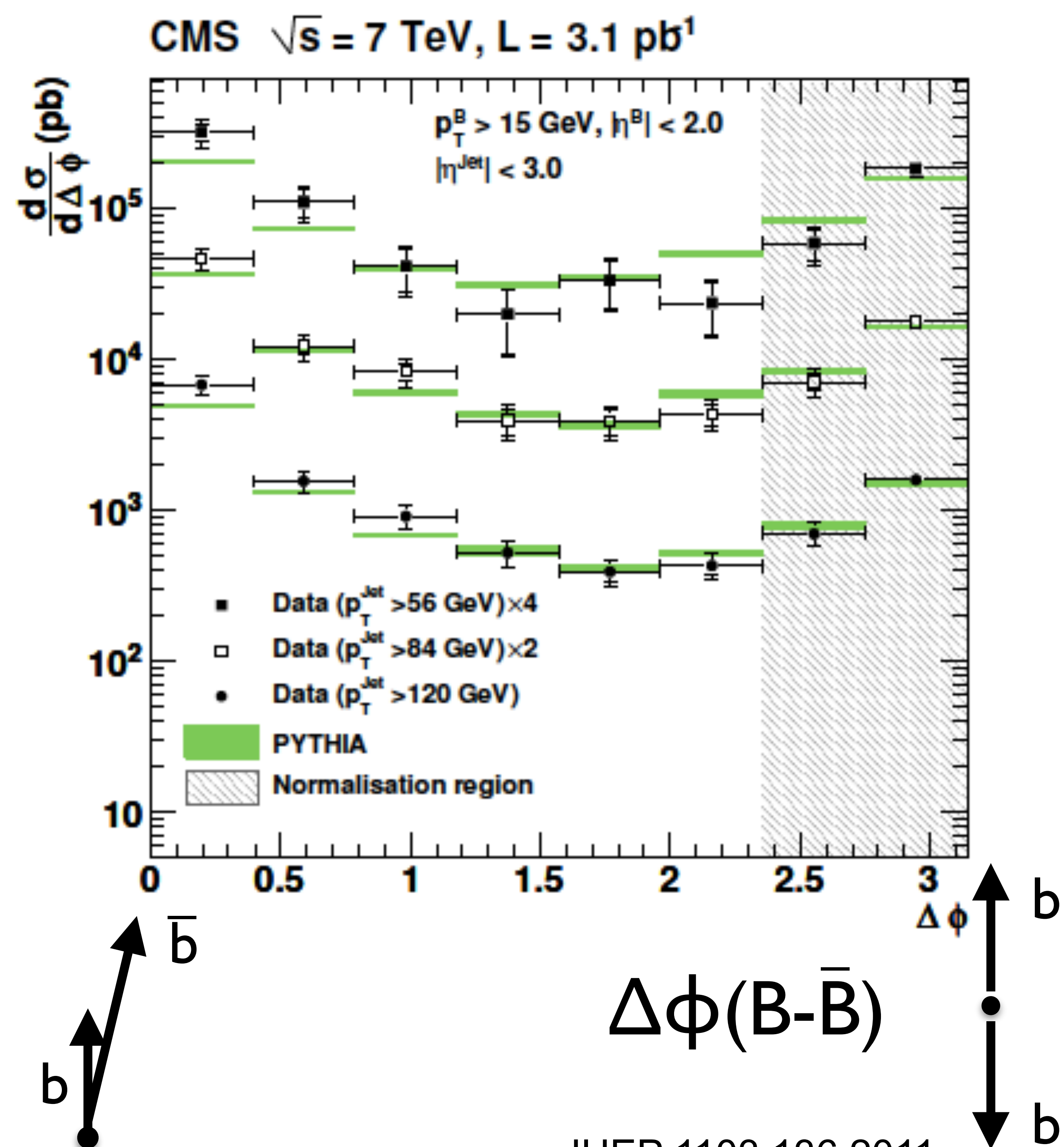
D-hadrons and D-$\bar{D}$ correlations for studying pp production mechanisms



Flavour creation



Gluon splitting



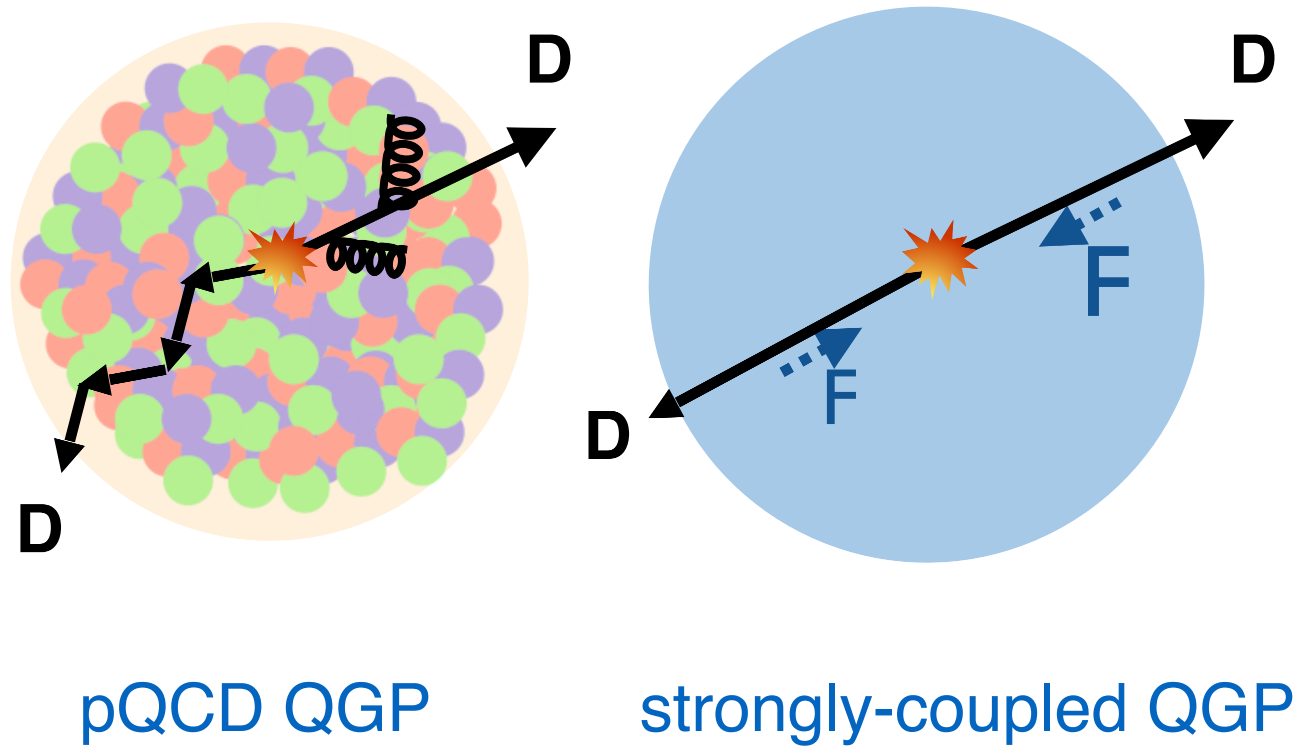
JHEP 1103:136,2011

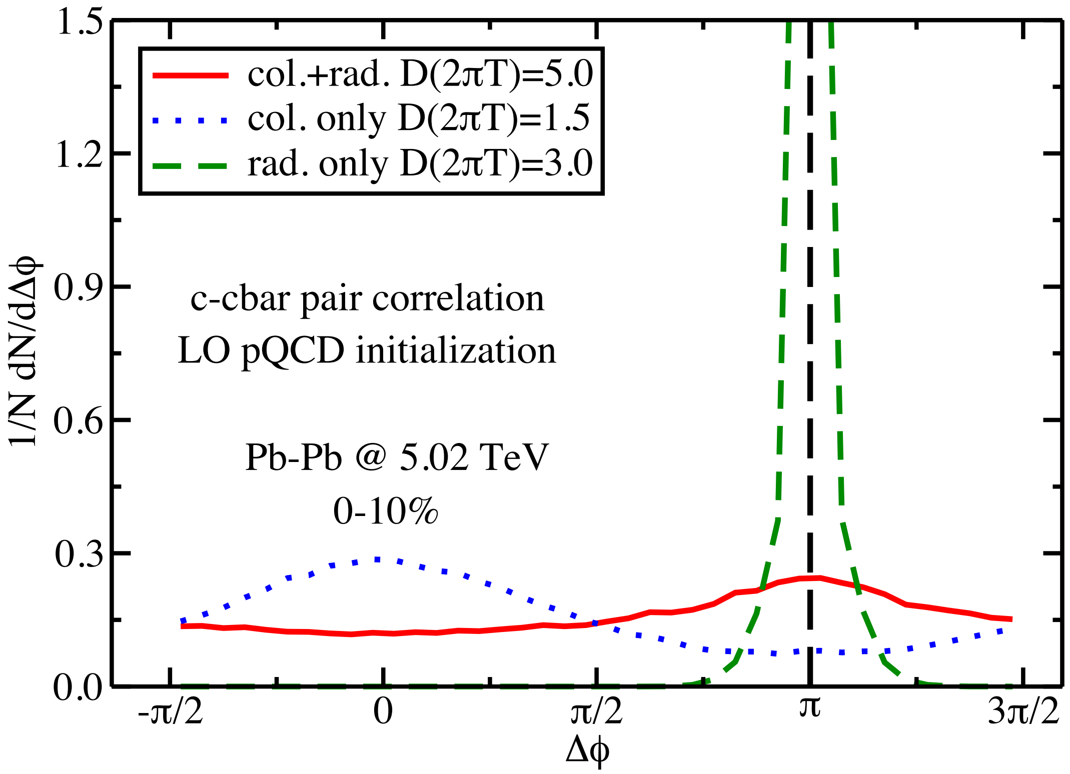
Gluon splitting (GS) contribution not well modelled by most of the pp calculations

→**Probably doable with upcoming high-luminosity 2017 pp run!**

HF correlations in PbPb

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





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

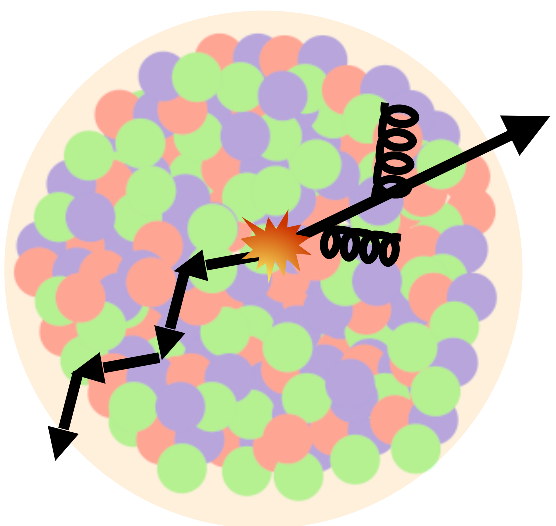
D-Dbar p_T asymmetry and $\Delta\varphi$:

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

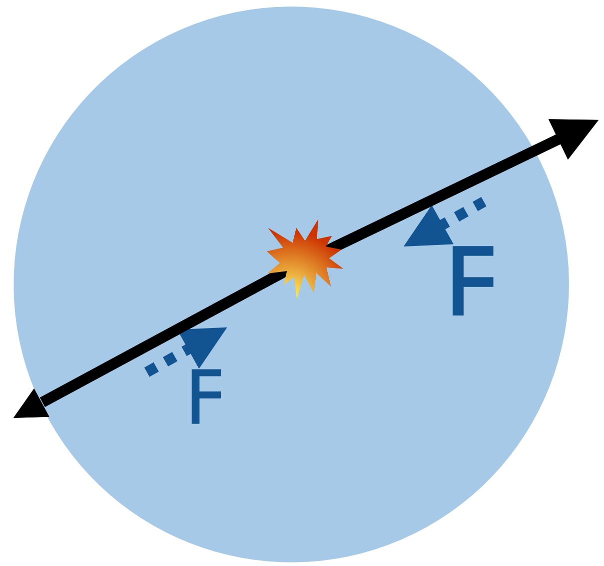
→2018 or Run3 luminosity is needed!

HF correlations in PbPb

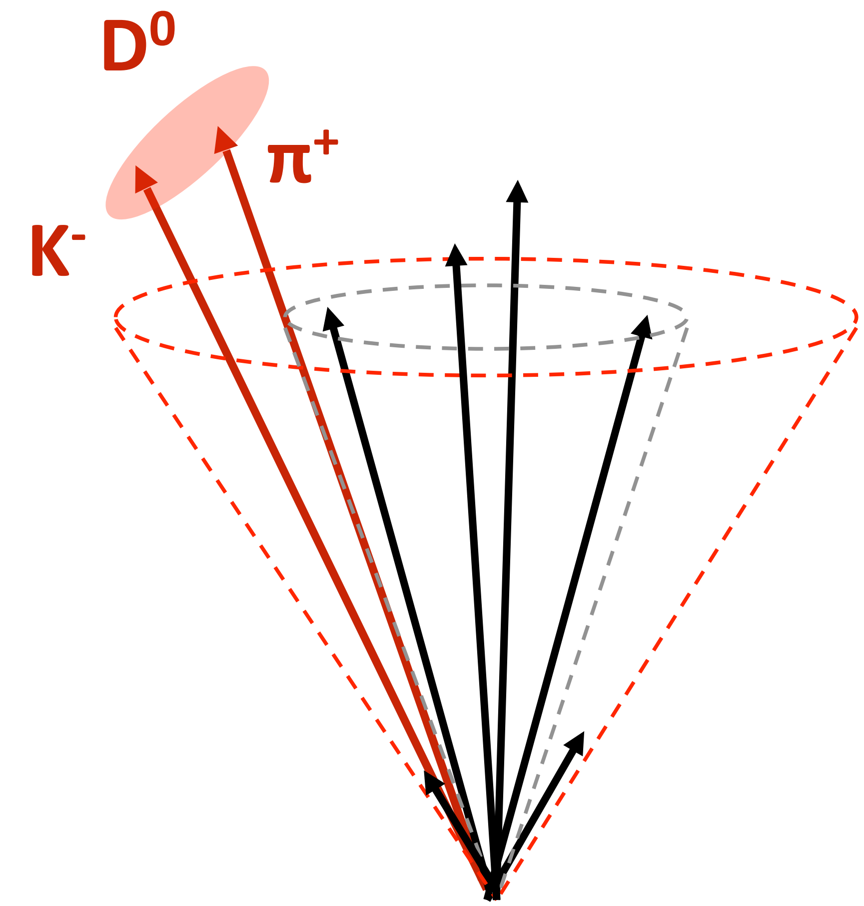
In PbPb, to investigate the mechanisms of charm interaction with the medium



pQCD QGP



strongly-coupled QGP



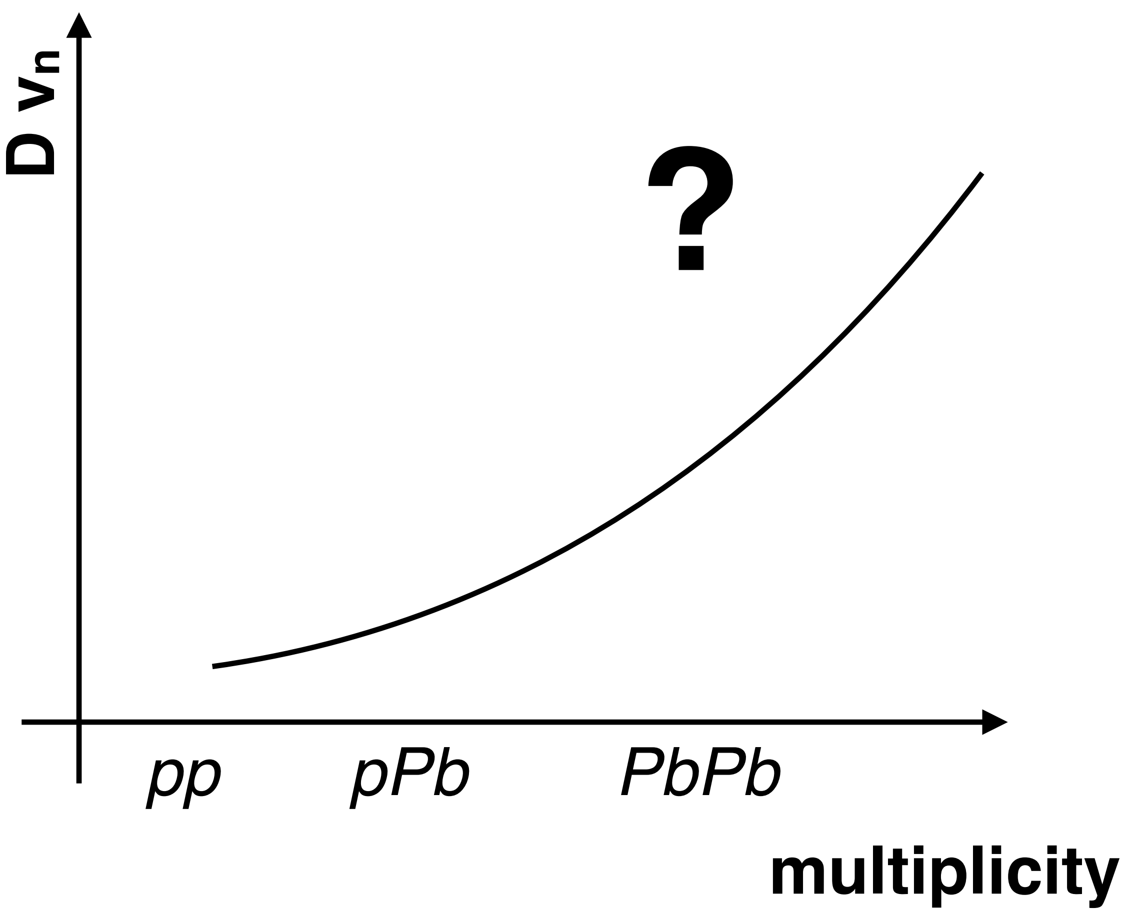
D-jet correlations

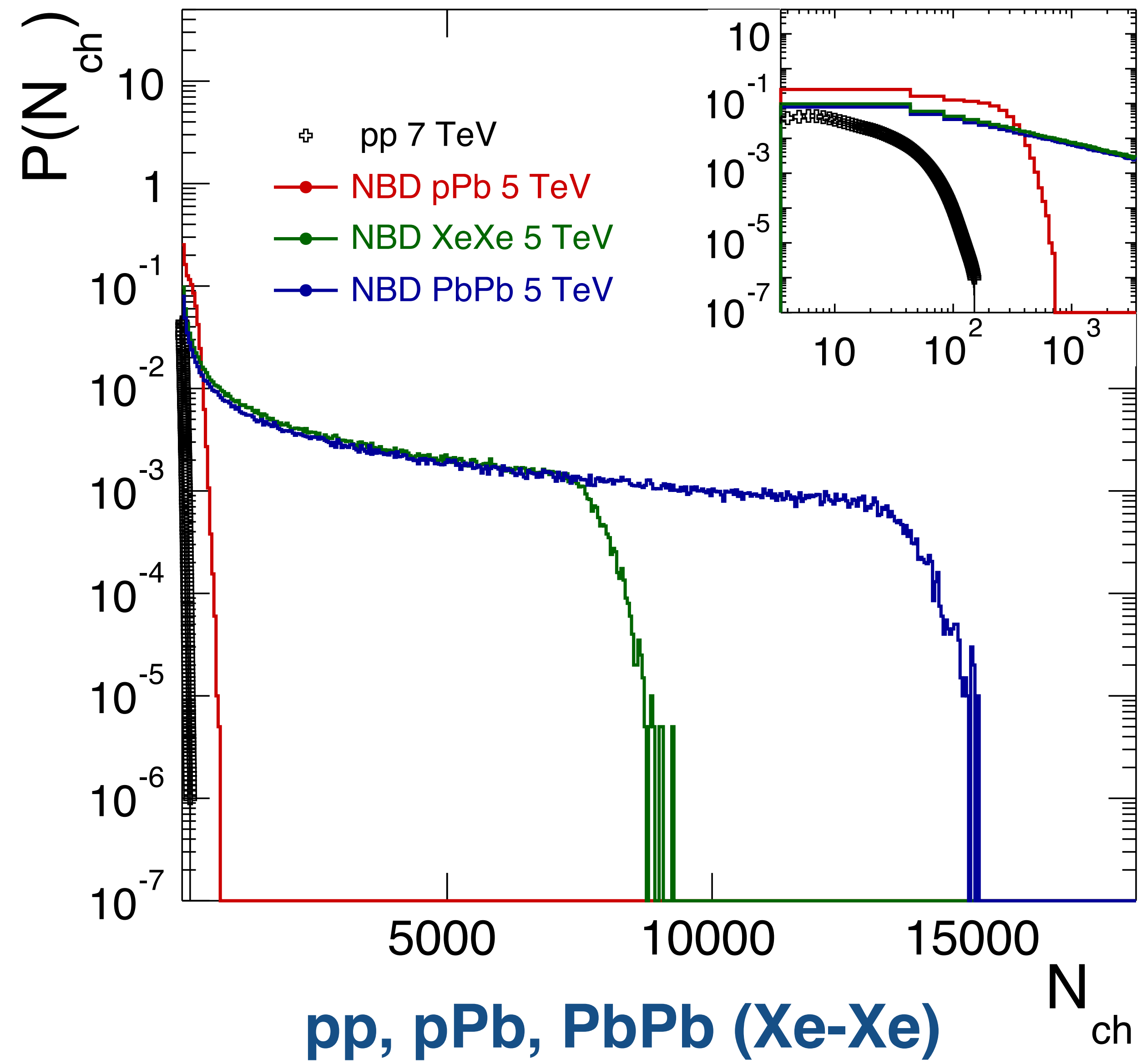
- charm fragmentation in the medium
- Energy loss for charm from LO and NLO processes

→**Less statistics needed since it does not require the presence of two fully reconstructed D mesons**

Small to large systems: flow

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





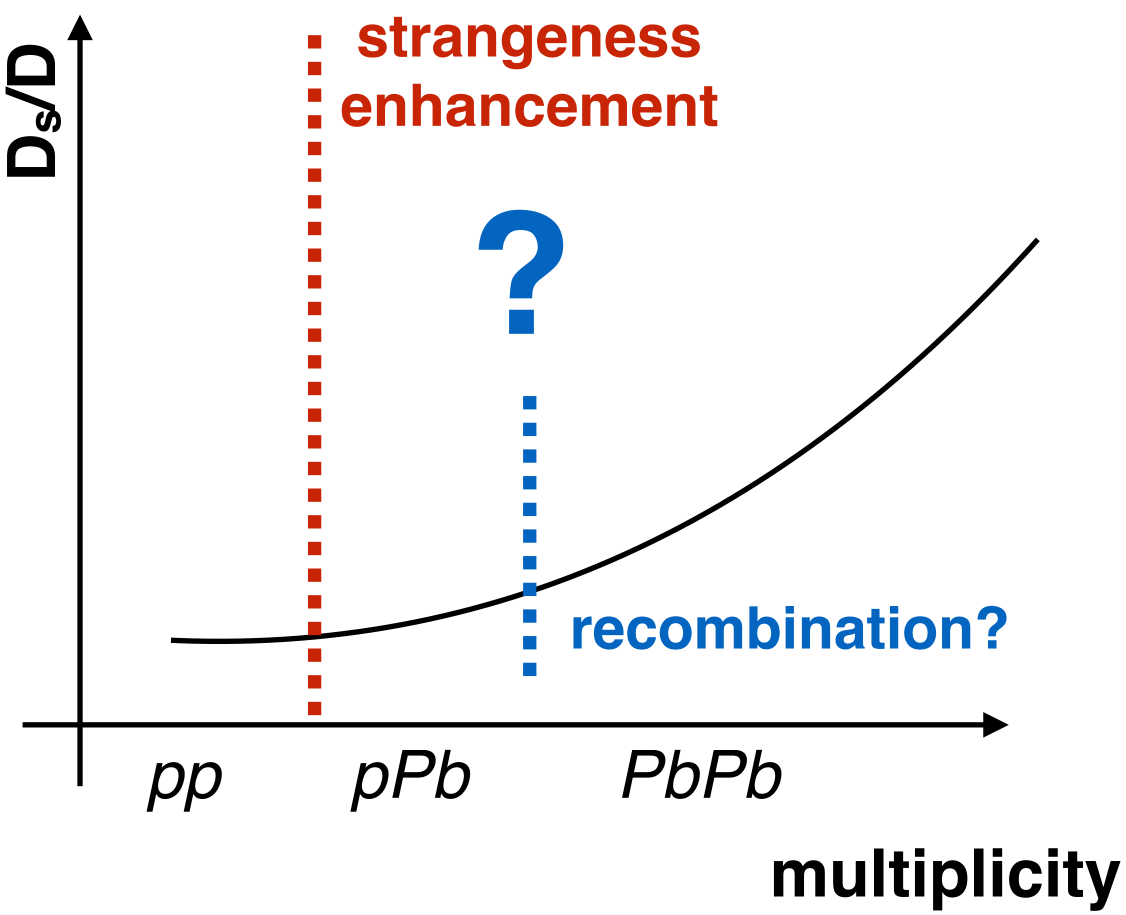
D v_n as a function of multiplicity:

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

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

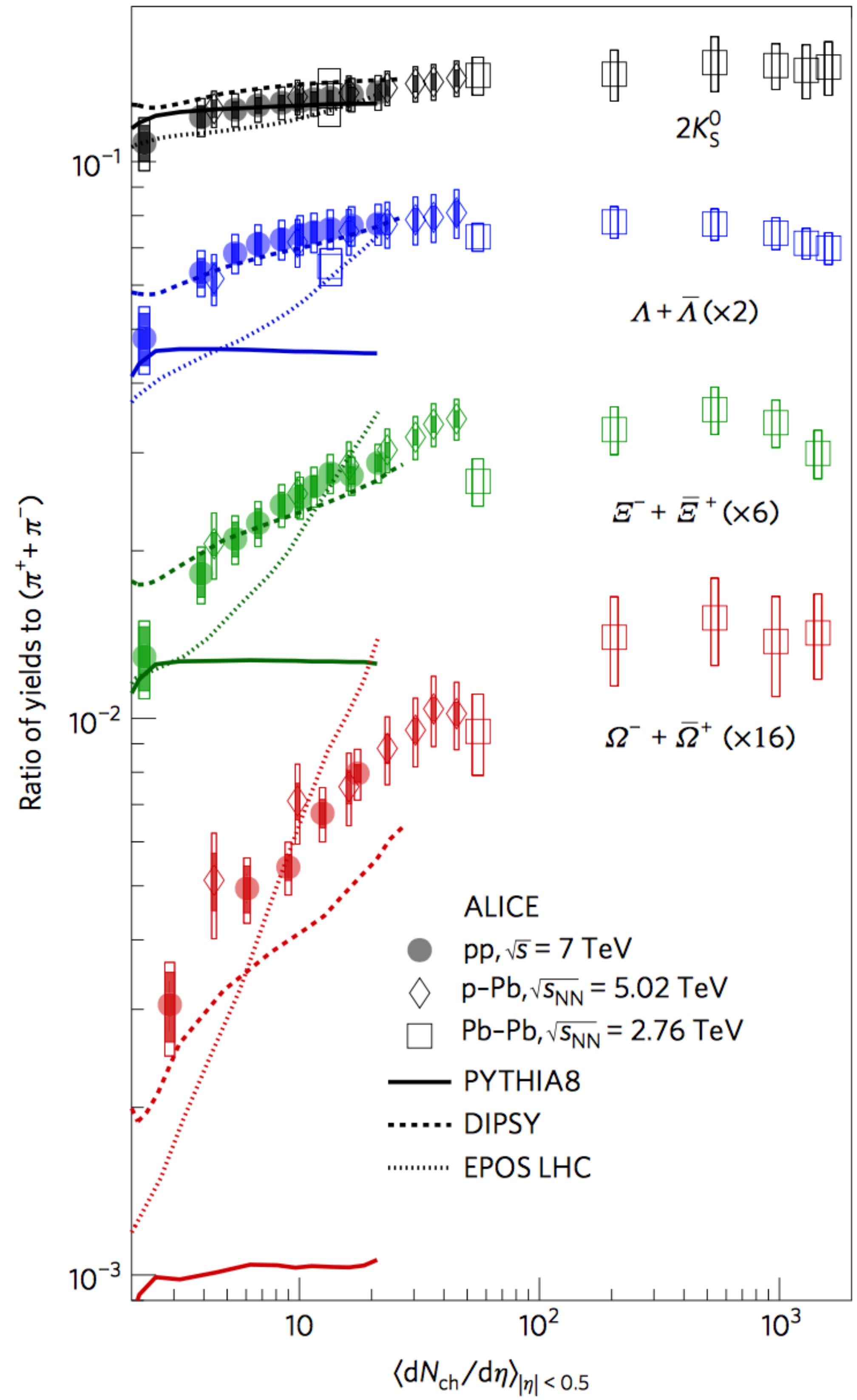
Very large samples of high-multiplicity events collected with L1-HLT high multiplicity triggers in 2017 pp data at 13 TeV

Small to large systems: recombination



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

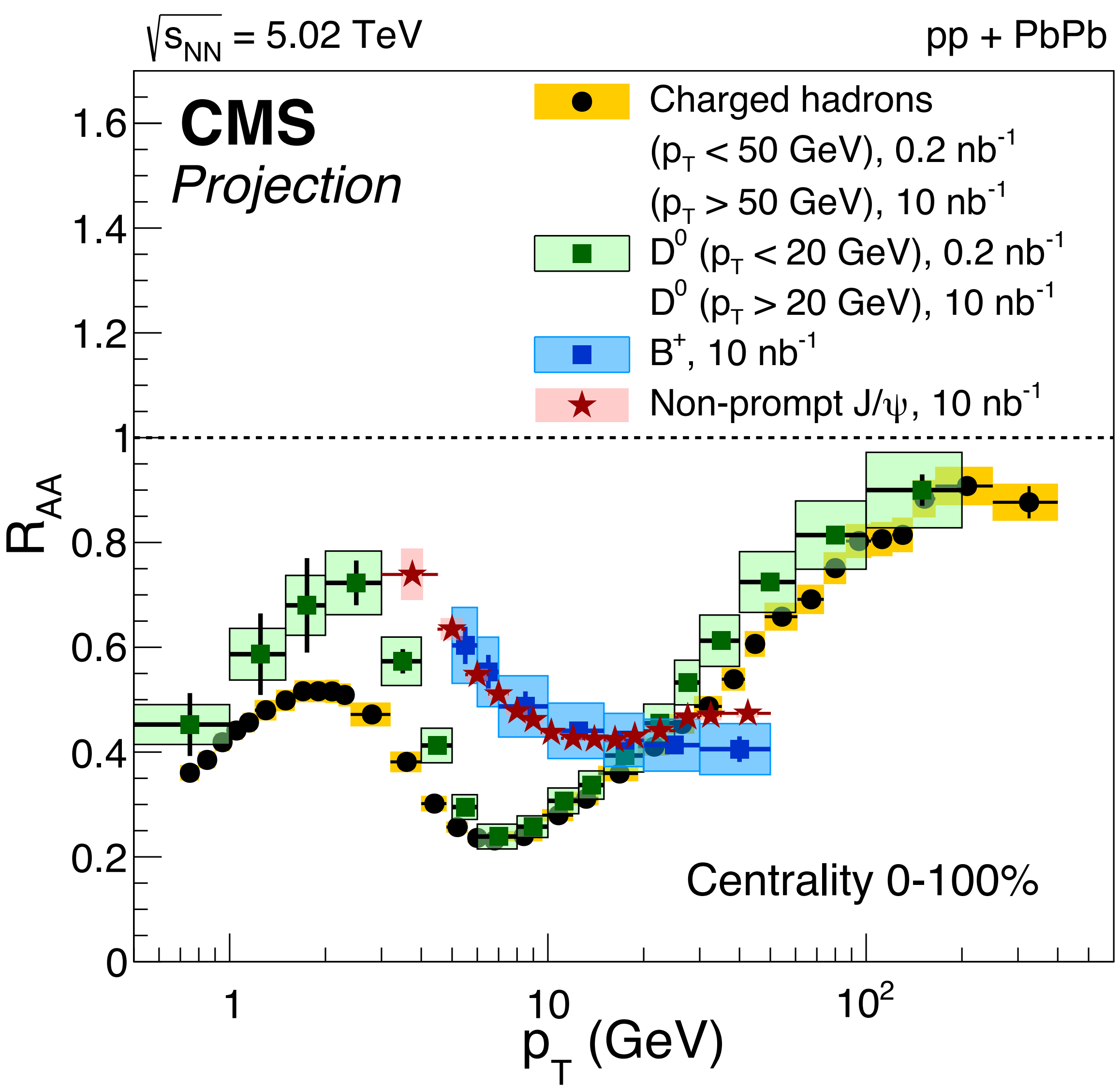
- strangeness enhancement observed by ALICE in high-multiplicity pp events.

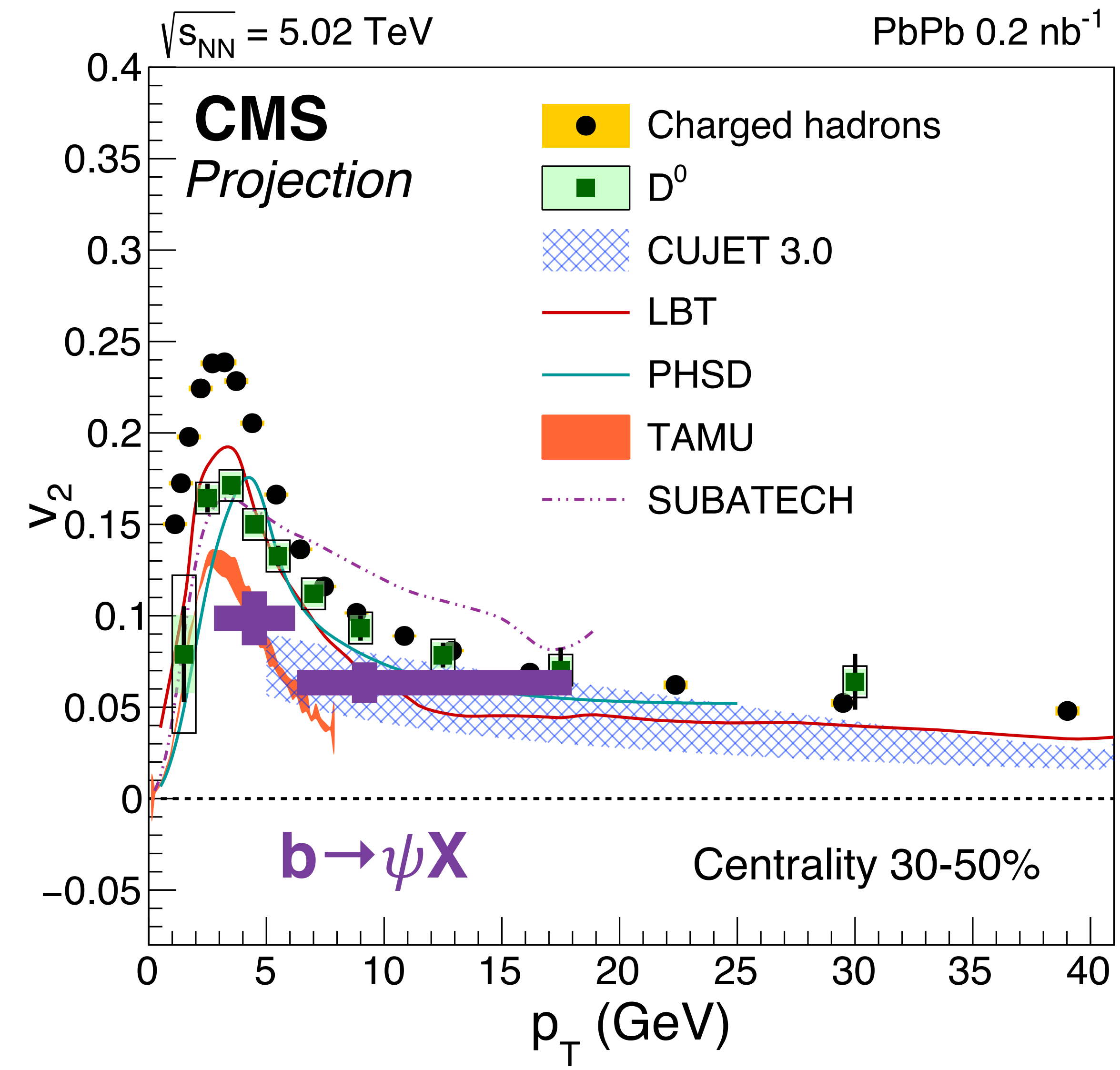


Nature Physics DOI: 10.1038/NPHYS4111

Projections for Run3 measurements

High-Luminosity LHC!

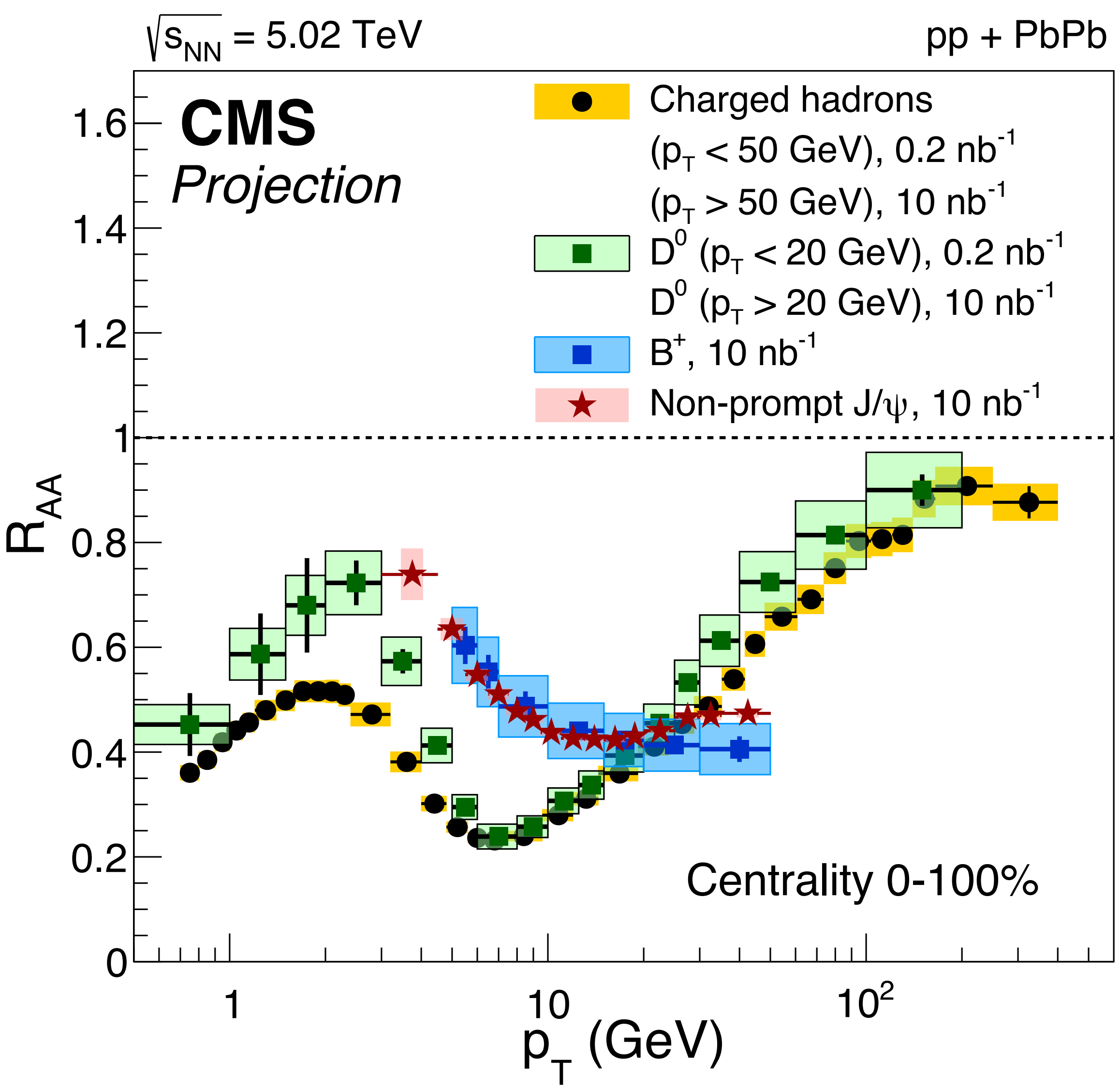


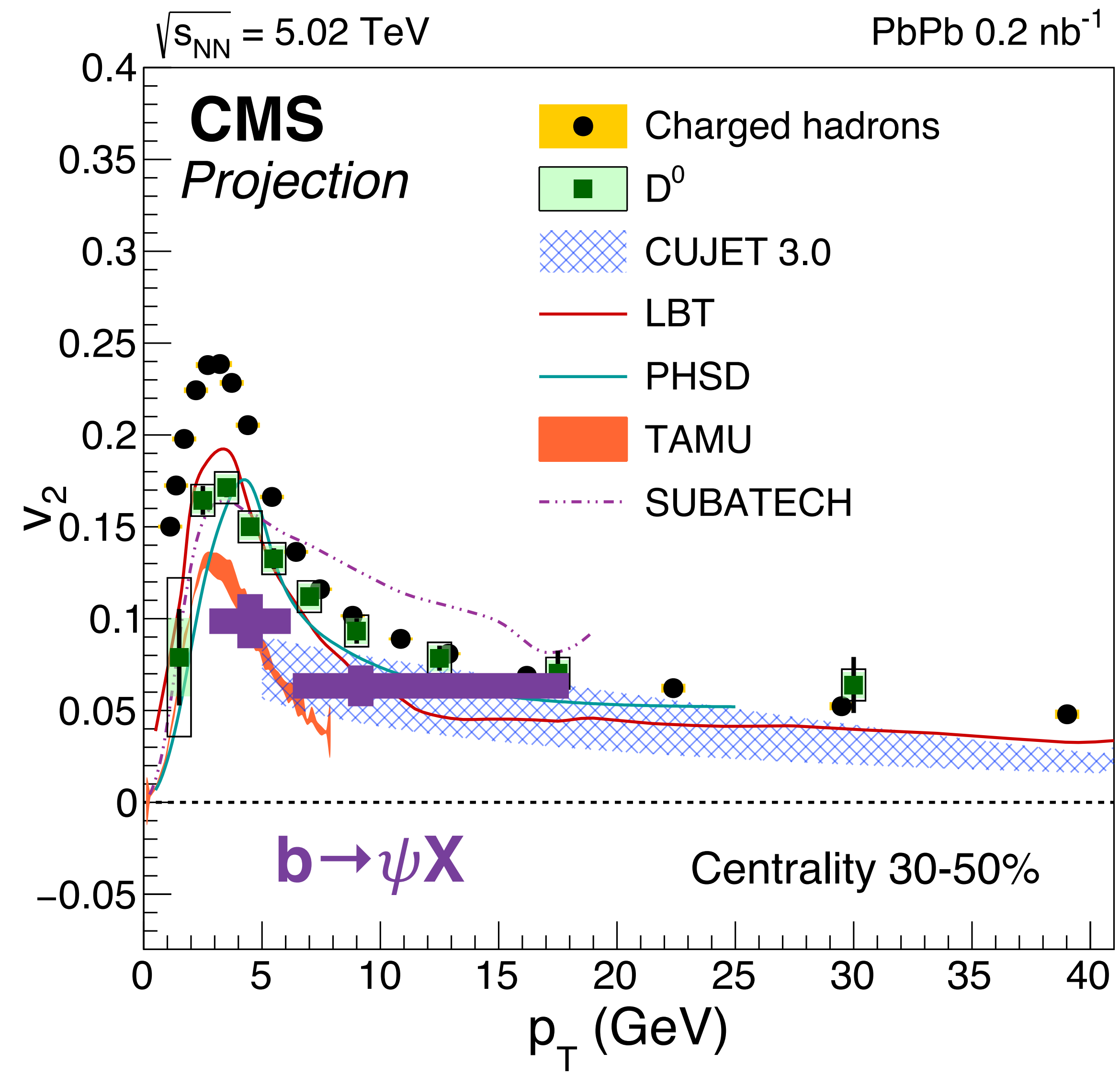


- With 10/nb, very high precision measurements of charged particle, D, B R_{AA} and v_n!
- **D_s / B_s R_{AA} and v_n measurements to study recombination and the role of the hadronic phase for charm and beauty!**

Projections for Run3 measurements

High-Luminosity LHC!

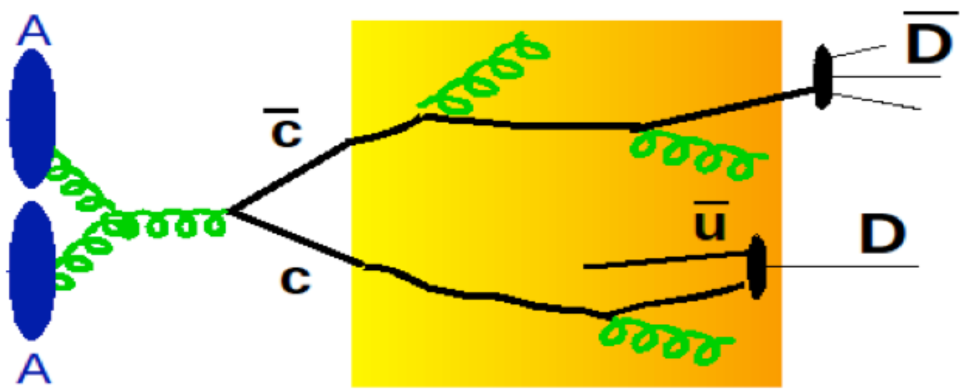




Thank you for your attention!

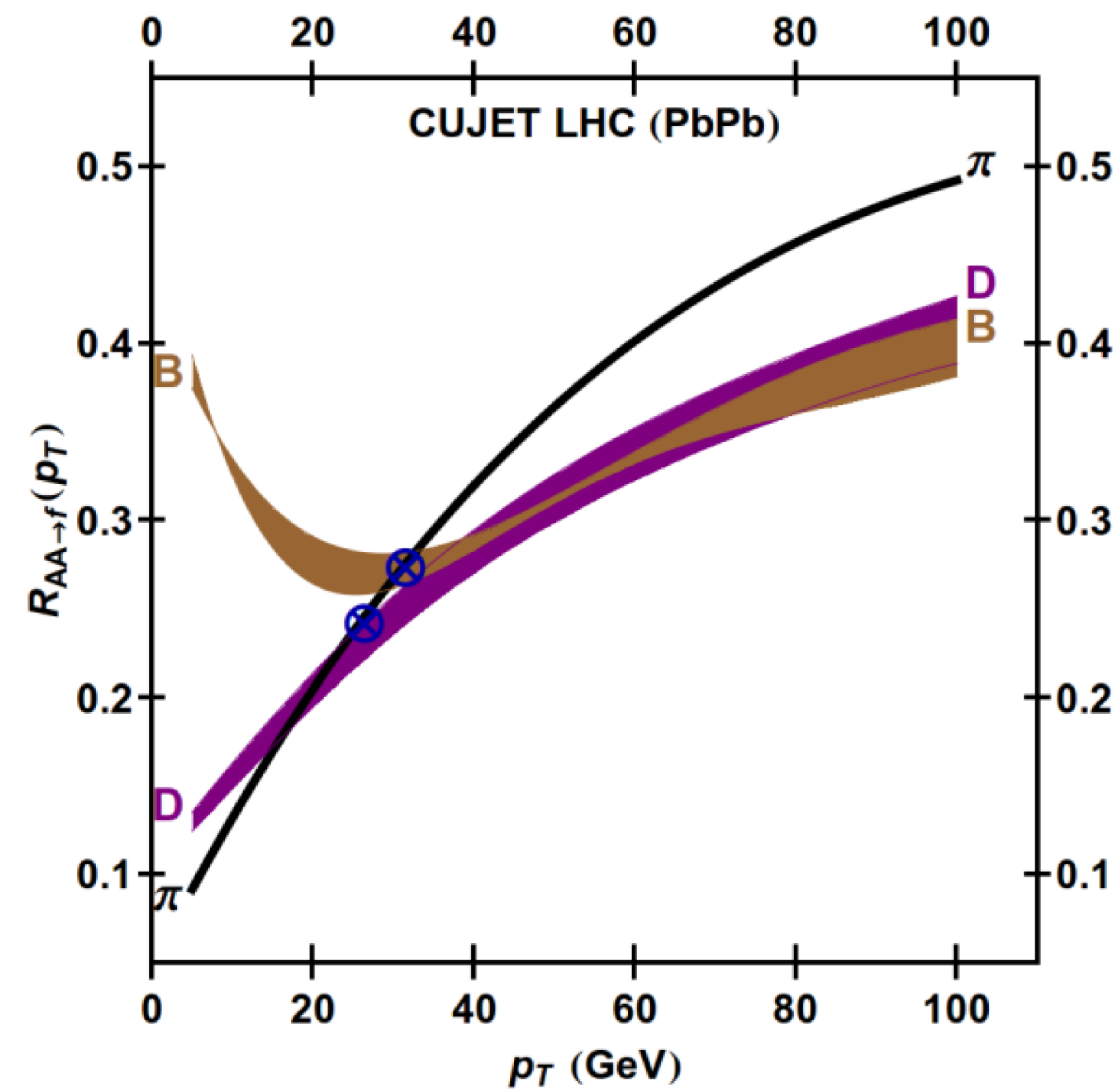
BACKUP

In-medium energy loss



produced early in the collision, they strongly interact with the deconfined medium

→ In-medium energy loss as a consequence of radiative and collisional processes.



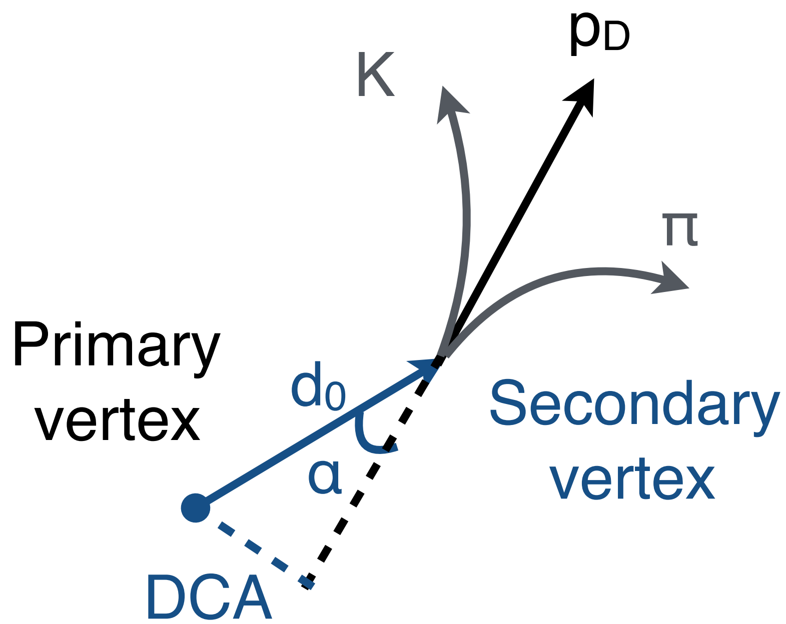
Flavour-dependence of radiative energy loss:

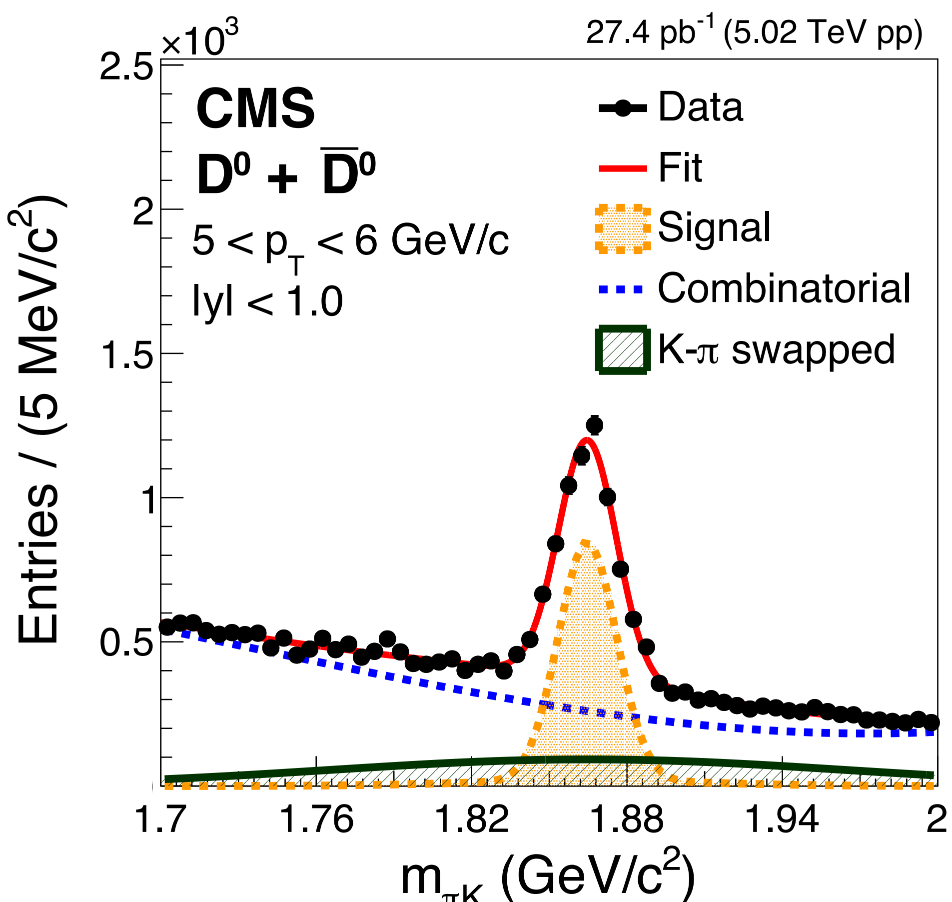
- Larger for gluons than for quarks
  E.g. in BDMPS model [1] $\langle\Delta E\rangle \propto \alpha_s C_R \hat{q} L^2$
- Dead cone effect: gluon radiation suppressed at small angles for massive quarks

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

D^0 reconstruction and selection

- Primary vertex reconstruction *several tracks*
- D^0 candidates (vertex) reconstruction *pairing two tracks + kinematic fitter*
- D^0 candidates selection (TMVA) *decay topology*
  - ➡ Pointing angle (α) *< ~0.12*
  - ➡ 3D decay length (d_0) normalized by its error *> ~4*
  - ➡ Secondary vertex probability *> ~0.1*
  - ➡ Distance of Closest Approach (DCA) *< ~0.008 cm*
- Raw yields extraction *Invariant mass*





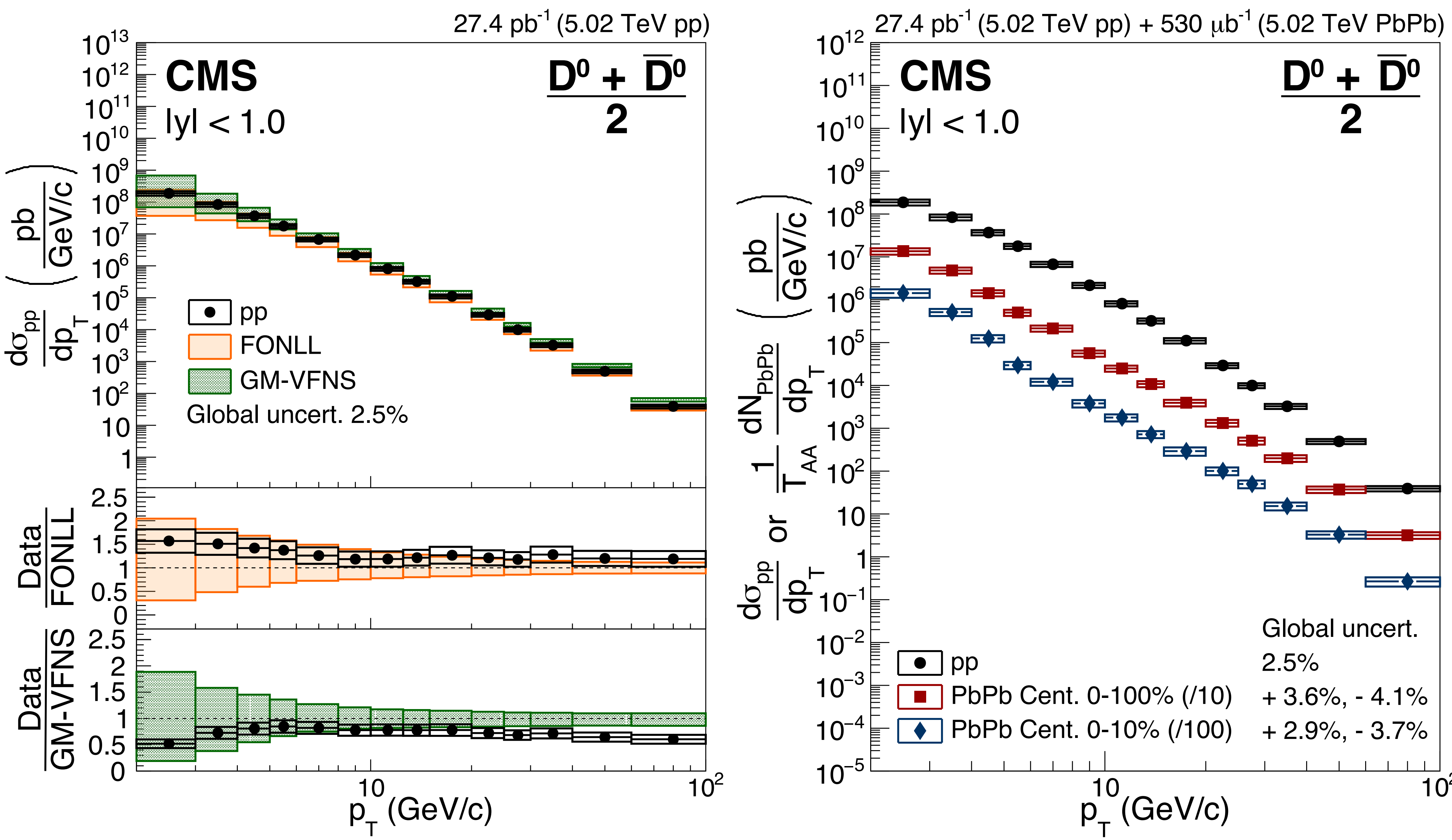
arXiv: 1708.04962

Mass distributions fitted by

- Double gaussian (Signal)
- 3rd order polynomial (Combinatorial)
- Single gaussian (K-π swapped)
  - No PID: Candidates with wrong mass assignment

D^0 pp cross-section at 5.02 TeV

- p_T range covers from ***2 to 100 GeV/c*** (wide p_T range!)
- Compared with the FONLL [1] and GM-VFNS [2] predictions



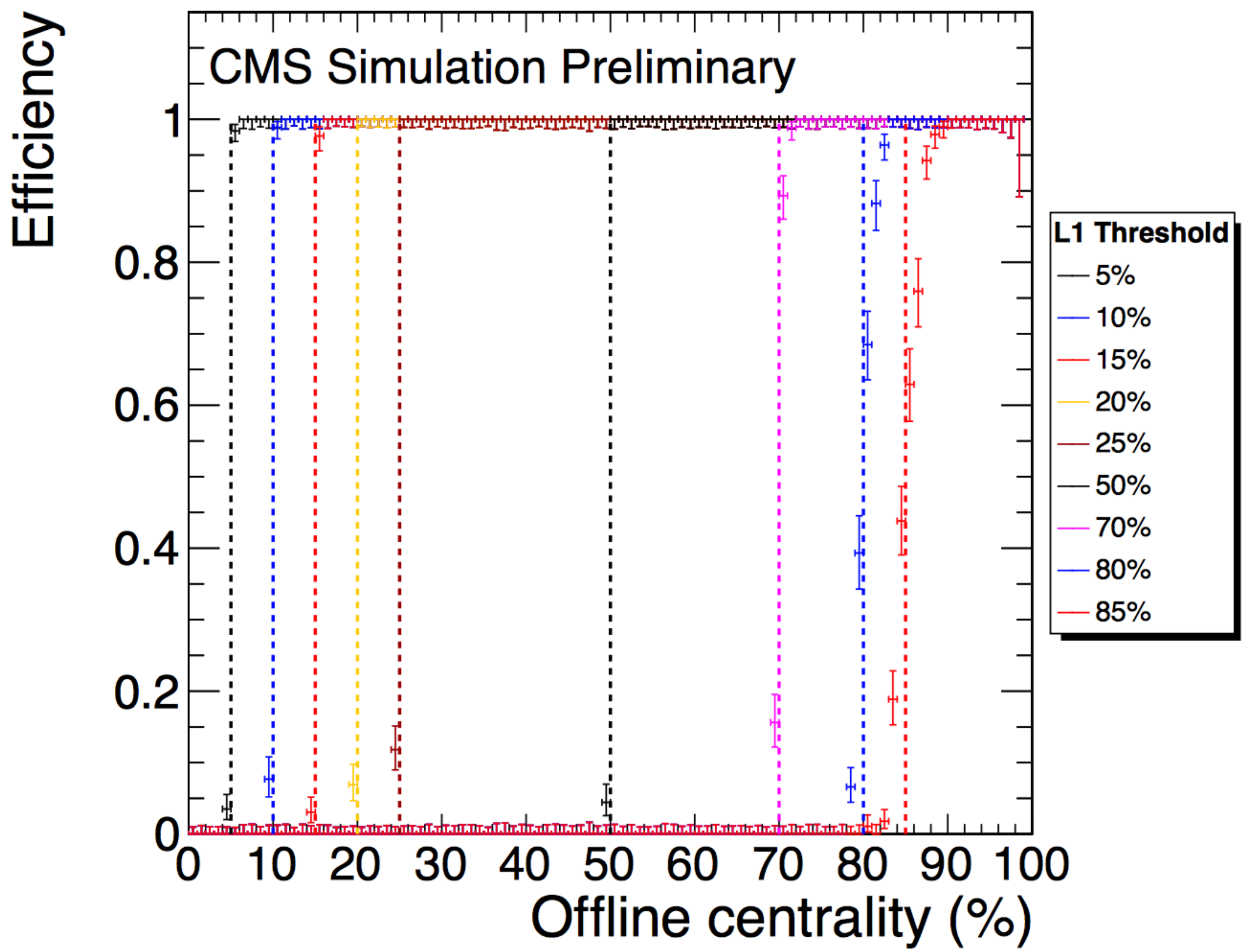
arXiv: 1708.04962

[1] JHEP 05 (1998) 007
[2] Eur. Phys. J. C 72 (2012) 2082

Focus on Level-1 centrality triggers

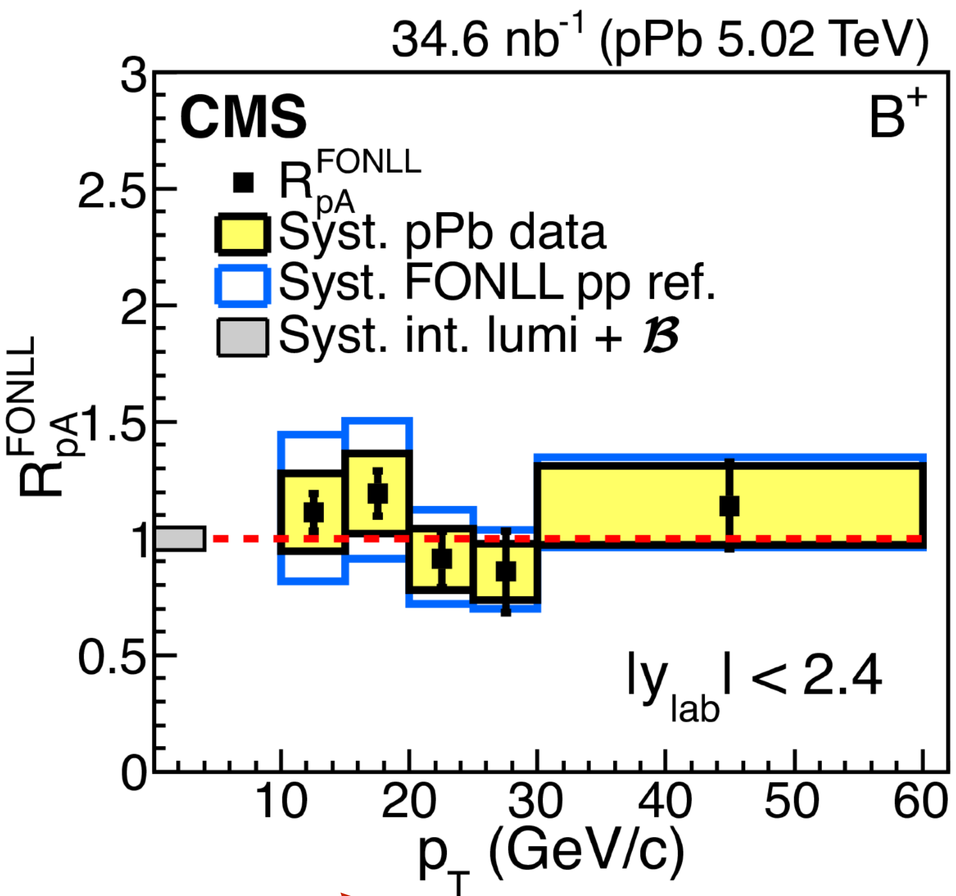
Goal: increase the rate of 30-50 and 50-100% PbPb events for HF v_n measurement

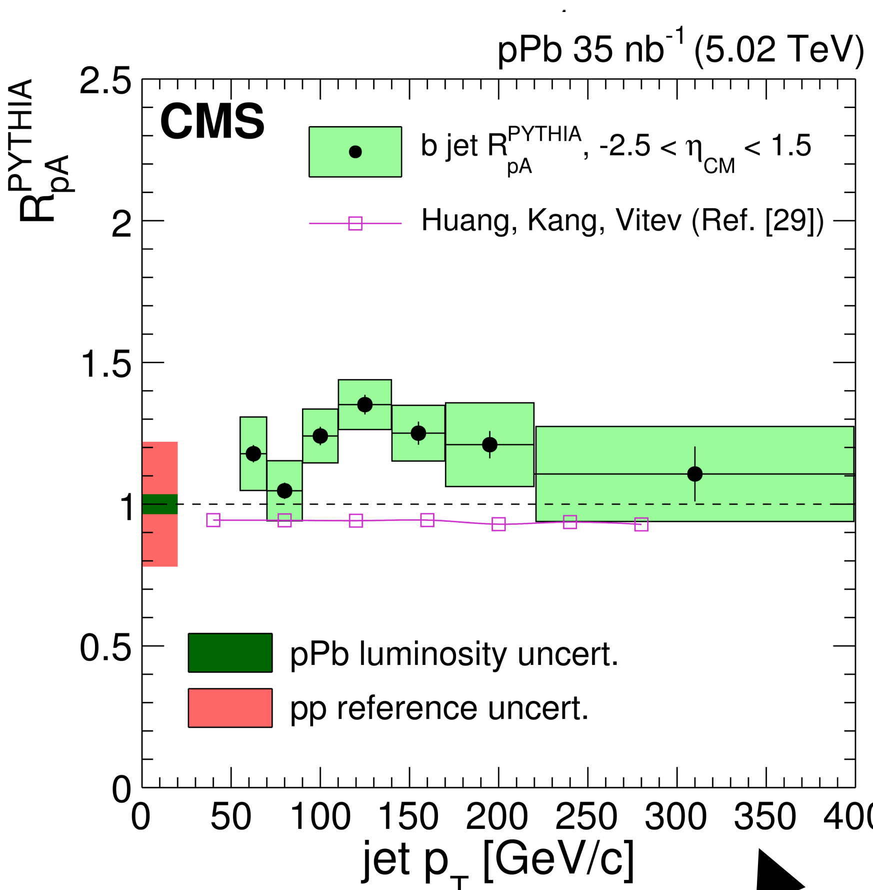
Hadronic forward calorimeter (HF) energies at L1 $\propto$ **centrality** → Offline calibrations centrality vs L1 HF energy → Level-1 centrality selection

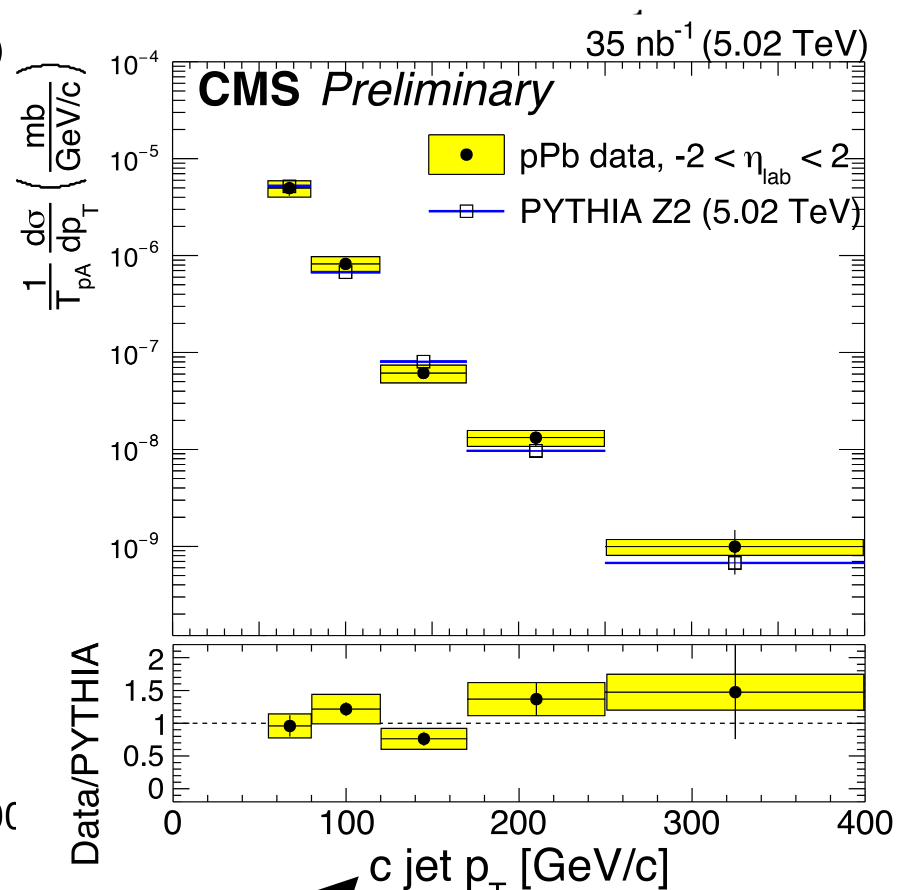


~80 M PbPb events in the centrality 30-50% during the 2015 PbPb run

Heavy-flavours in pPb collisions







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

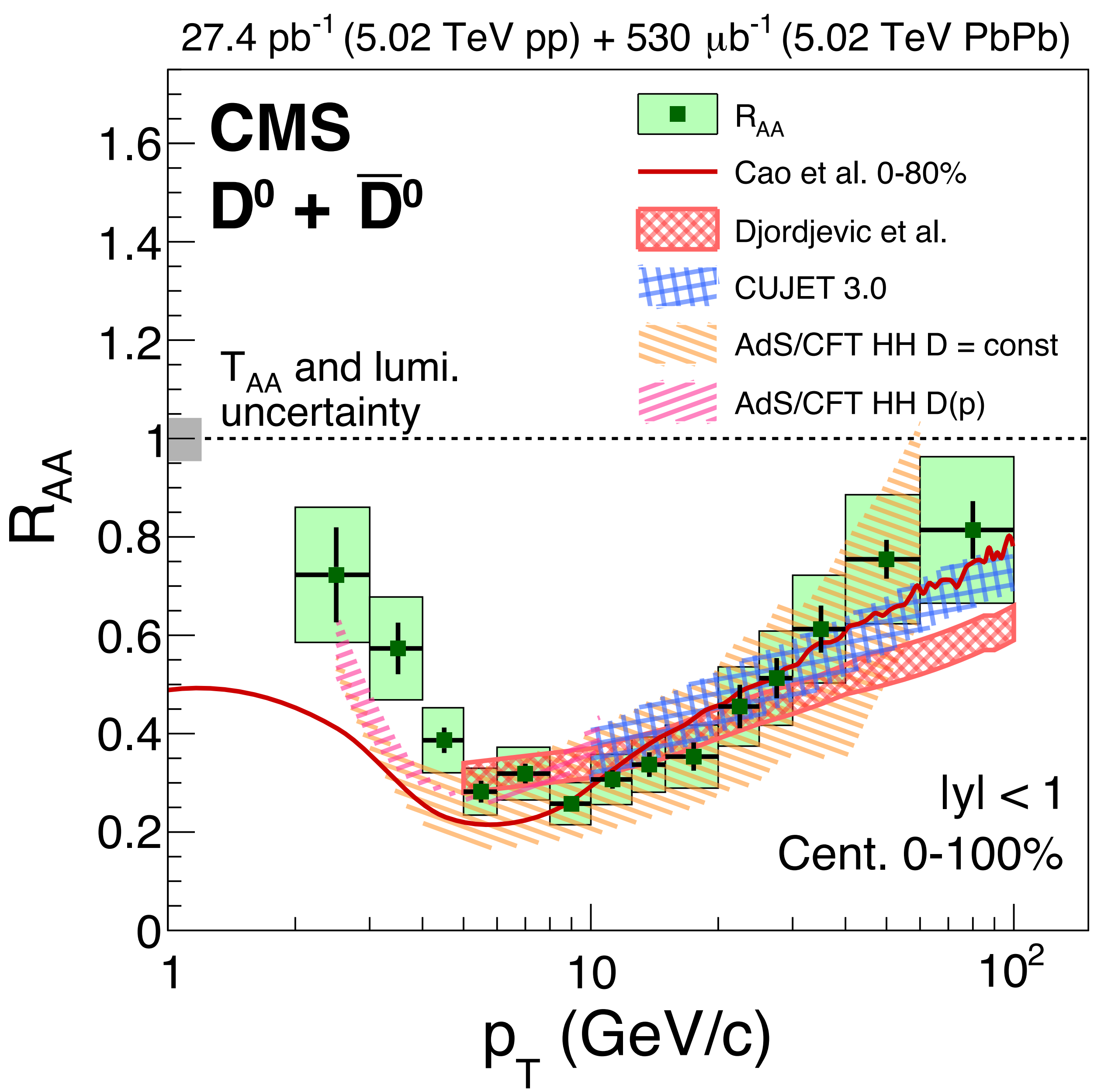
tagged c and b-jet production
→ compatible with predictions
from PYTHIA scaled by A=208

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

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

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



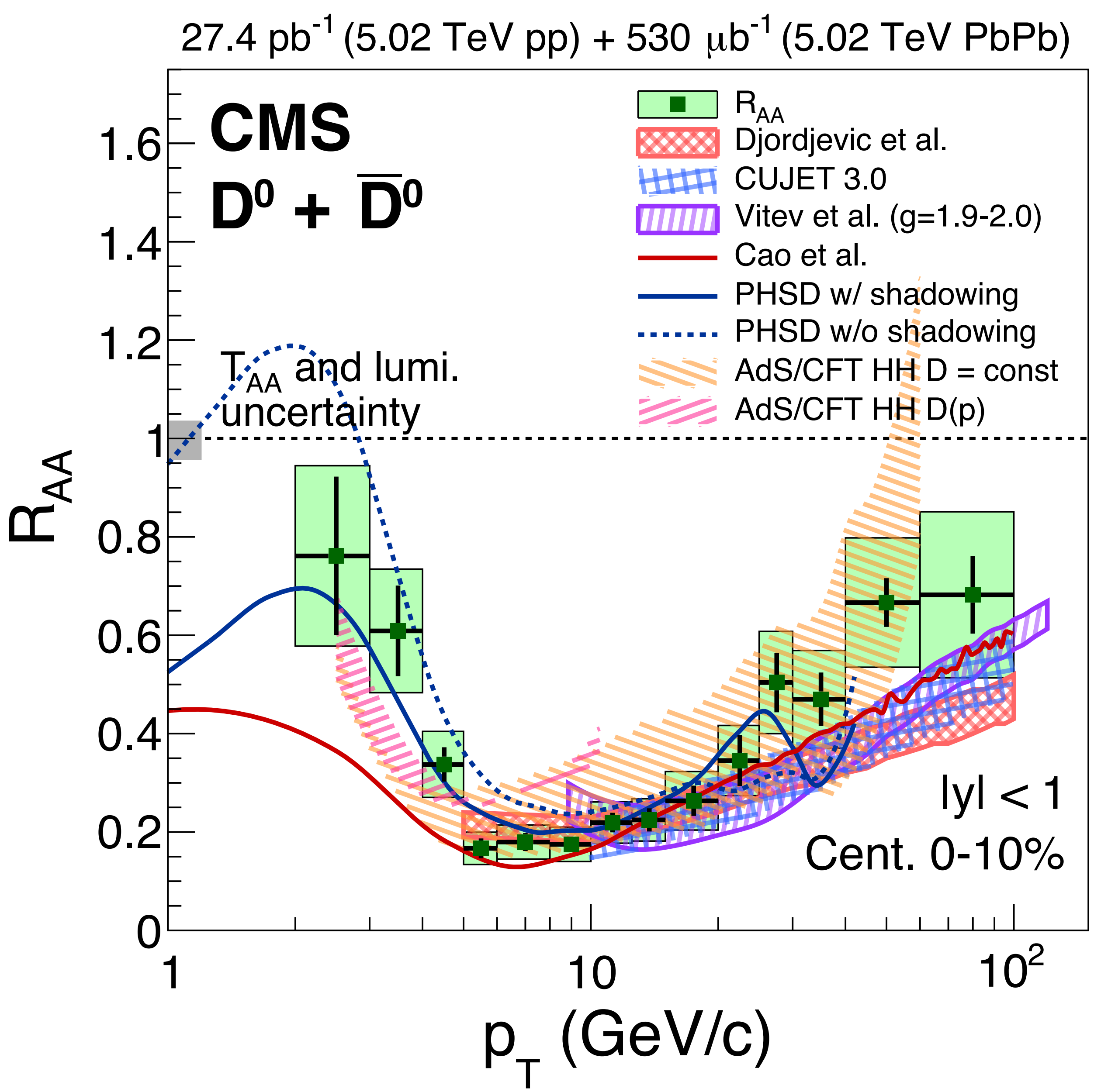
- Comparison with **theoretical predictions**
  - ➡ S. Cao et al. [1] *(Improved Langevin eq, Linearized Boltzmann)*
  - ➡ M. Djordjevic [2] *(pQCD calculations in a finite size optically thin dynamical QCD medium)*
  - ➡ CUJET3.0 [3] *(jet quenching model based on DGLV opacity expansion theory)*
  -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



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  - ➡ 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 (ϕ) 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

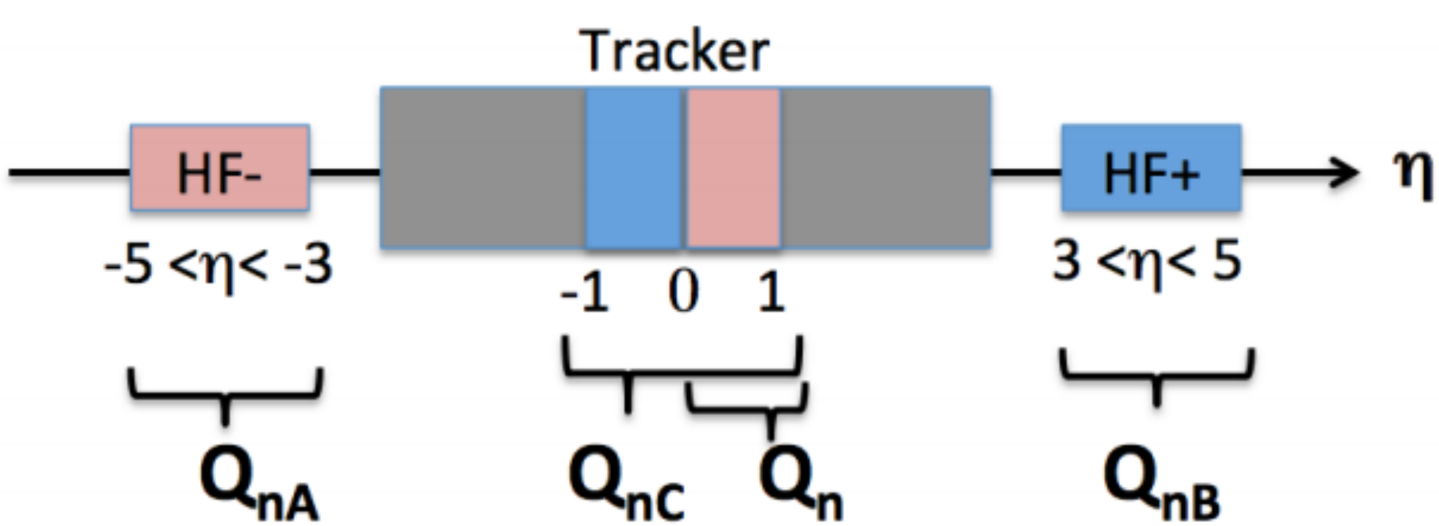
✦ Azimuthal anisotropy origins from
- low p_T
  ➡ collective motion in the thermalized medium
  ➡ fluctuation (v_3)
- high p_T
  ➡ path length dependence of the energy loss

Scalar product method

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

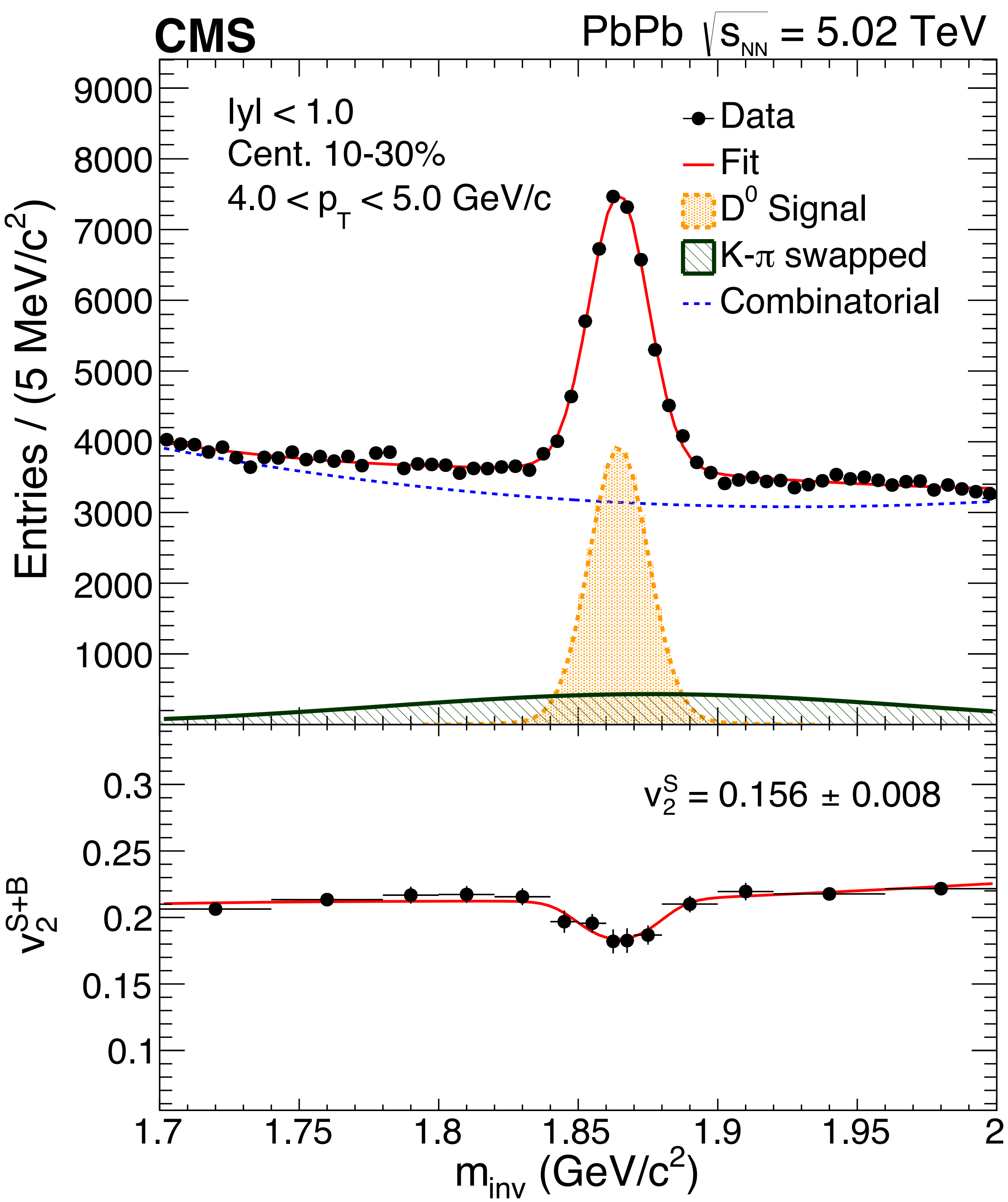
$$v_n\{\mathrm{SP}\} = \frac{\left\langle Q_{n,\mathrm{D}^0} Q_{nA}^{*} \right\rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^{*}\rangle \langle Q_{nA} Q_{nC}^{*}\rangle}{\langle Q_{nB} Q_{nC}^{*}\rangle}}},\qquad Q_n = \sum_{k=1}^{M} \omega_k e^{in\phi_k}$$

Scaling factor from 3 sub events



	A	B	C
sub evts	HF-	HF+	Tracker
M	towers	towers	tracks
ω_k	E_T	E_T	p_T

Yield extraction



- Simultaneous fit on invariant mass distribution and v_n vs mass

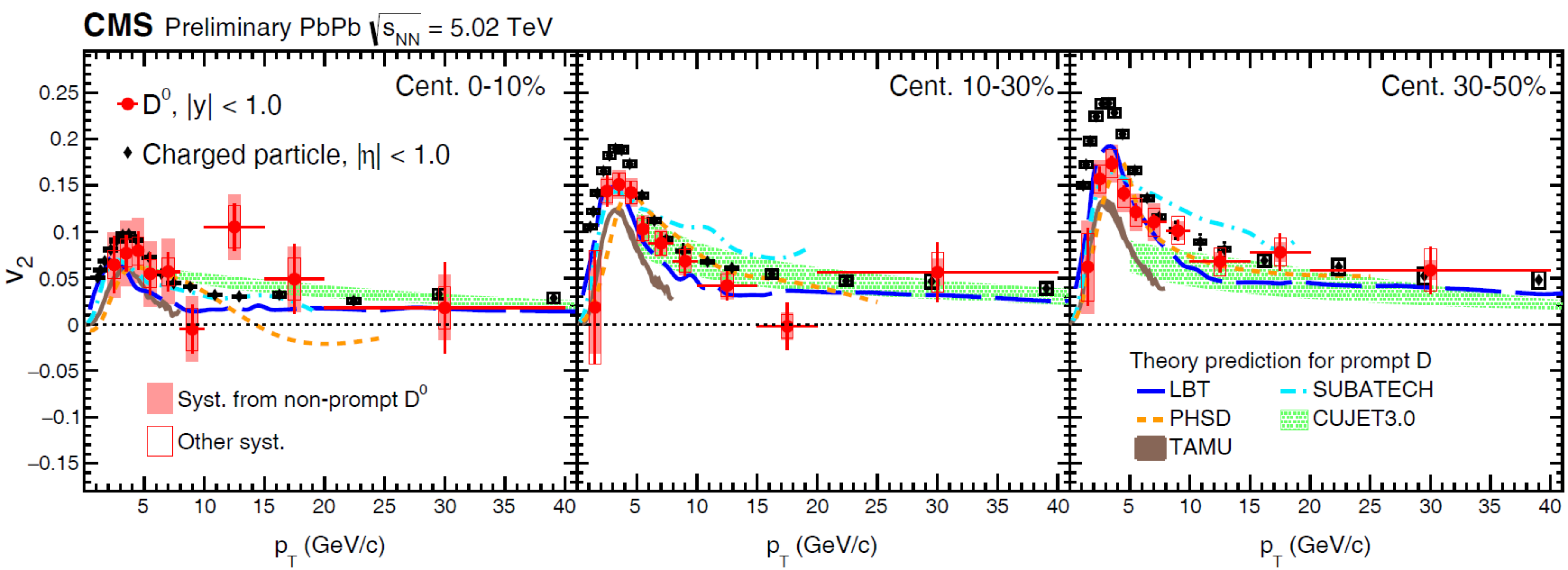
$$v_n^{S+B}(m_{\mathrm{inv}}) = \alpha(m_{\mathrm{inv}})v_n^S + [1 - \alpha(m_{\mathrm{inv}})]v_n^B(m_{\mathrm{inv}}),$$

- 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

D elliptic flow

New CMS measurement of v_2 and v_3 in PbPb collisions at 5.02 TeV in different collision centralities

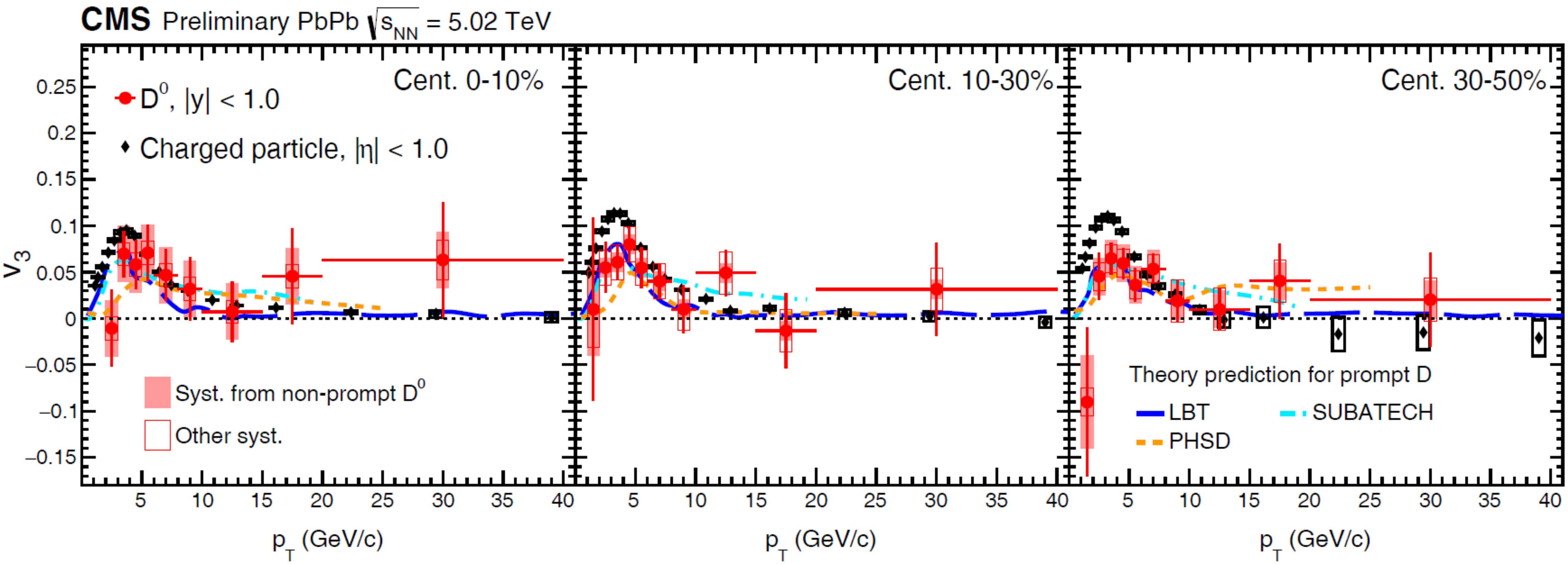


Significant confirmation of $v_2>0$ for D^0 at 5.02 TeV:

v_2 of D mesons larger than v_2 of charged particles

v_2(0-10%)< v_2(10-30%) ~ v_2(30-50%)

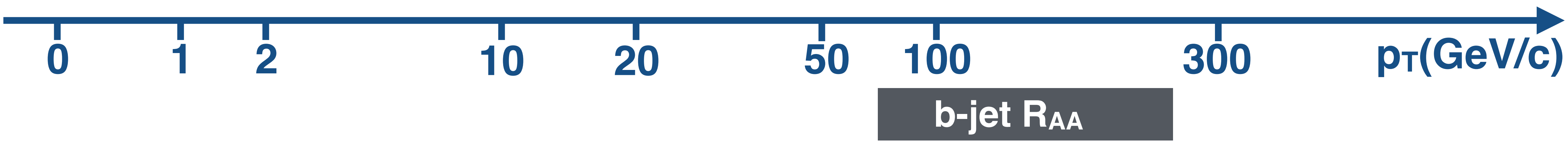
D triangular flow

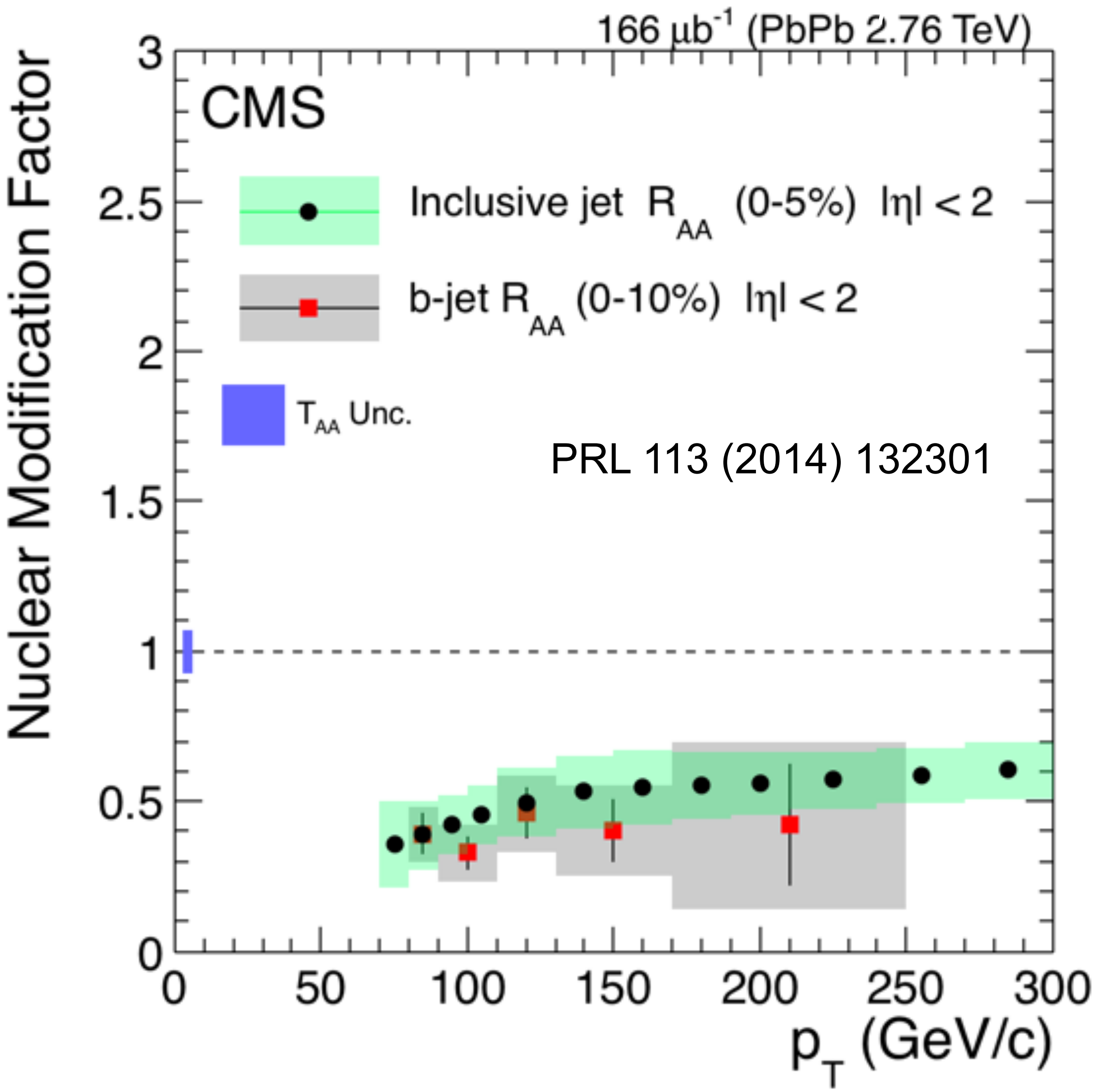


First observation of $v_3 > 0$ for charm!

v_3 for charged particle larger that D^0 v_3 although not fully significative given current uncertainties

b-jet R_{AA} at 2.76 TeV





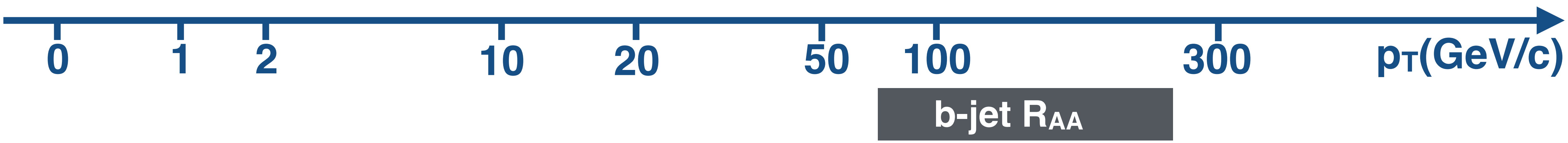
b-jet R_{AA}

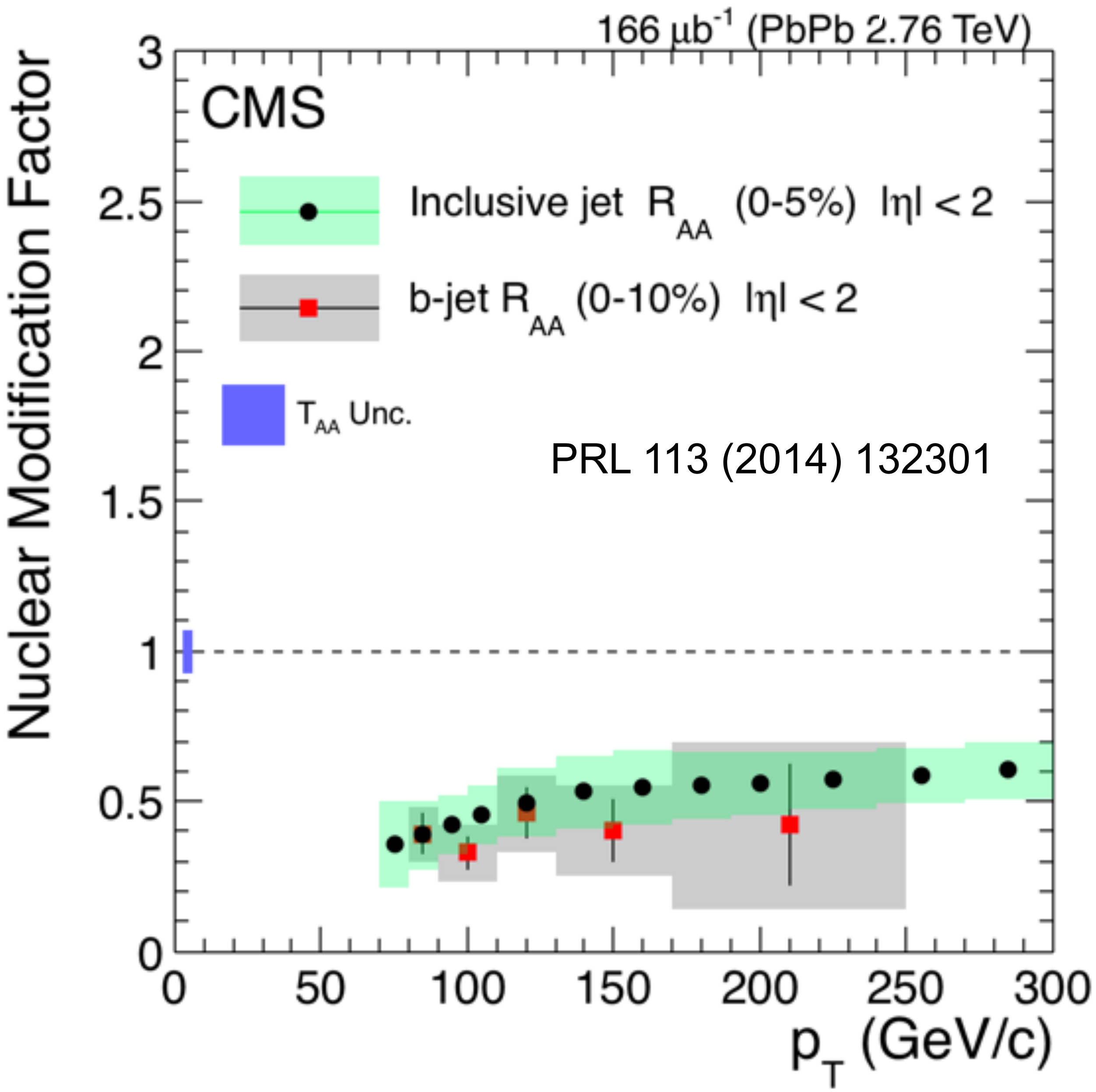
inclusive jet R_{AA}

Same suppression for b-jets and inclusive jets!

PRL 113 (2014) 132301

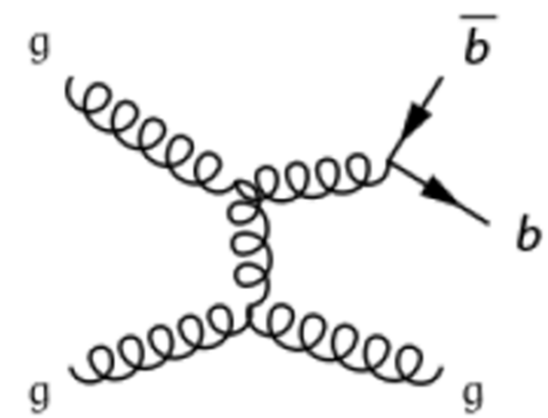
b-jet R_{AA} at 2.76 TeV

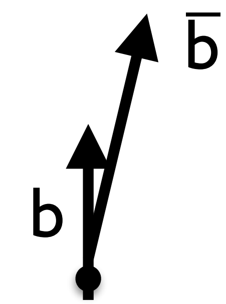




b-jet R_{AA}

inclusive jet R_{AA}



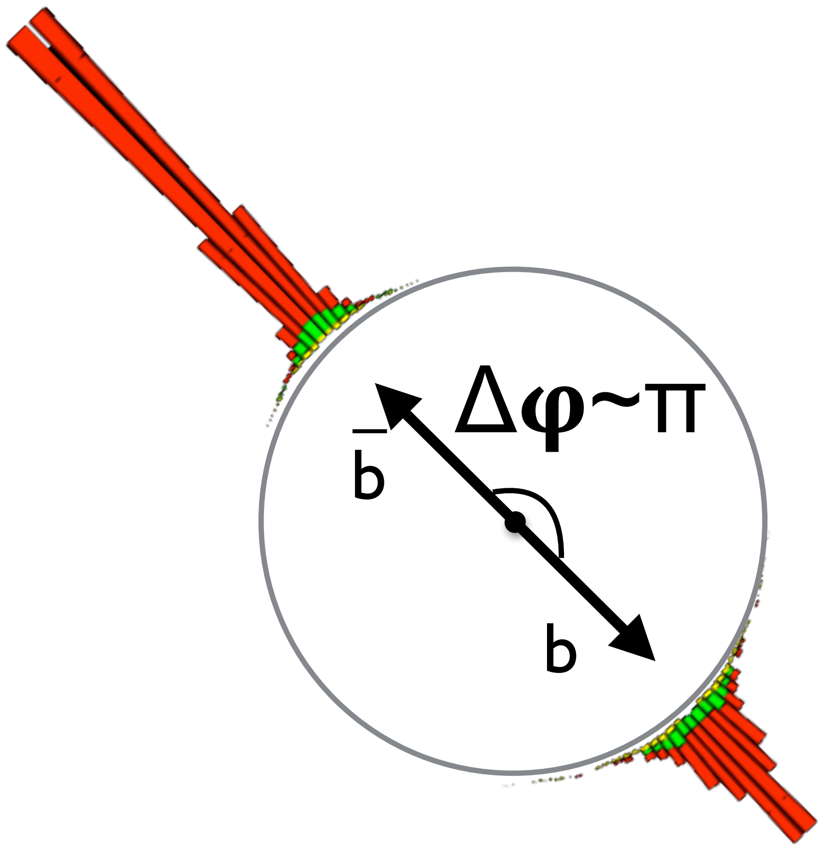


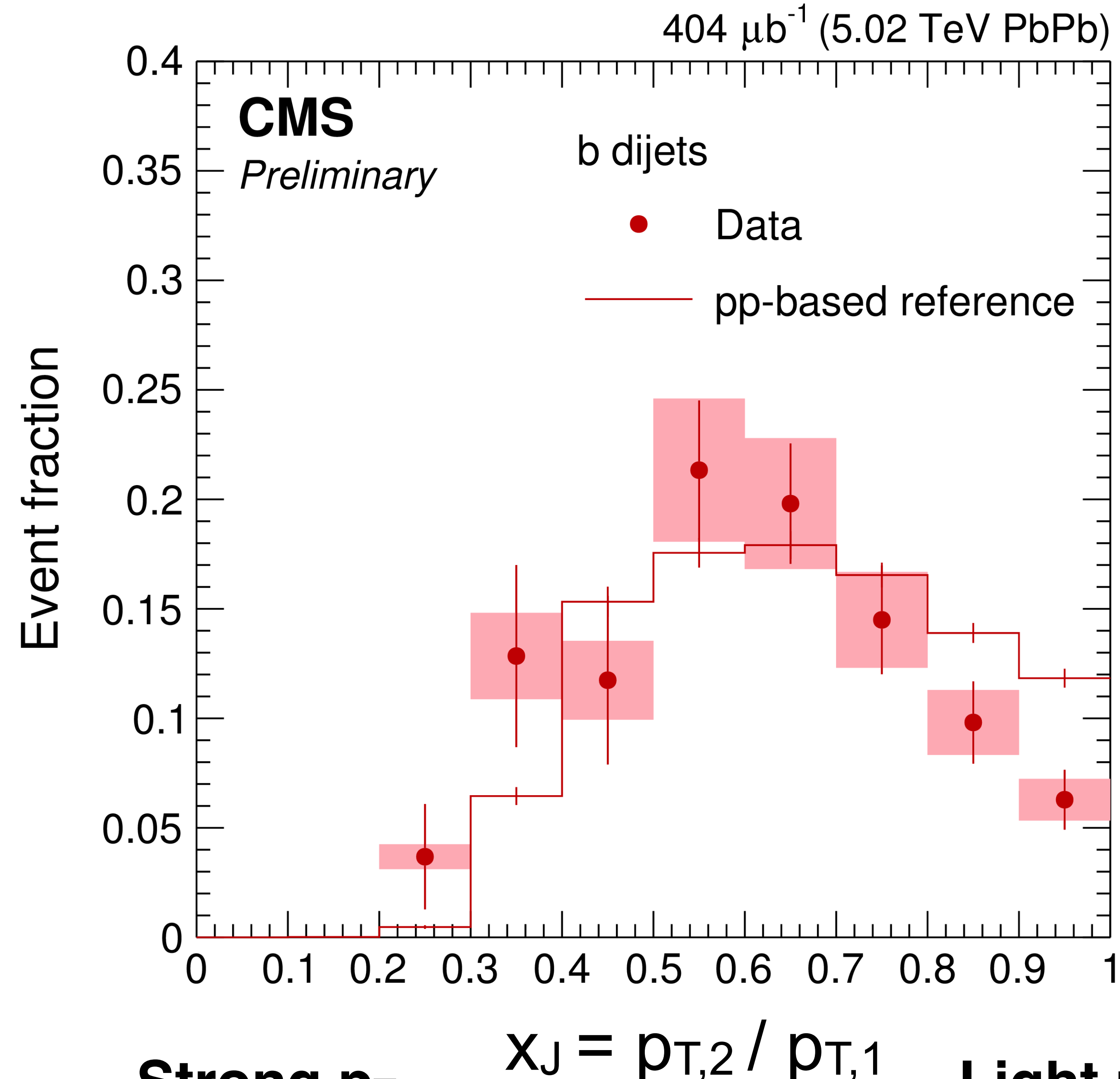
Gluon splitting?

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

PRL 113 (2014) 132301

di-b-jet asymmetry at 5.02 TeV





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

- dominated by LO production

Strong p_T imbalance

Light p_T imbalance

PbPb more imbalanced!

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

CMS-HIN-16-005

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

[1506.03981]