Prompt D^0 v_n harmonics in PbPb at 5.02 TeV with CMS

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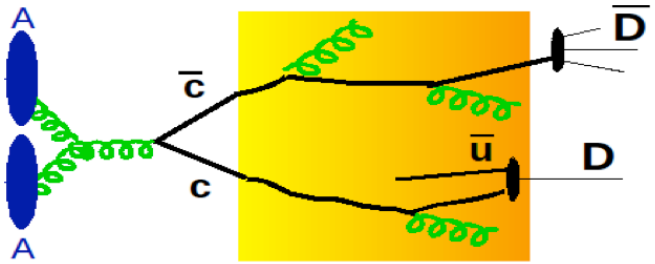
Motivation

- Heavy quarks are primarily produced at the early stages of the collisions

→Experience the full evolution of the medium

→Good probes of the medium



- At low p_T, to what extent heavy quarks flow with the medium is a good measure of the interaction strength.
  - Information on the degree of medium thermalization

- At high p_T, v_n harmonics are sensitive to the path length dependence of the heavy quark energy loss
  - Complementary to R_{AA}

Dataset and trigger

- 2015 PbPb run at 5.02 TeV

- Large minbias and centrality triggered PbPb sample
  - 0-100%: 170M events
  - 30-100%: 270M events

→ Measurement of D^0 v_2 and v_3 in PbPb at 5.02 TeV

- Centrality classes 0-10%, 10-30% and 30-50%
- Wide p_T range (1-40 GeV)
- CMS PAS HIN-16-007

Analysis workflow

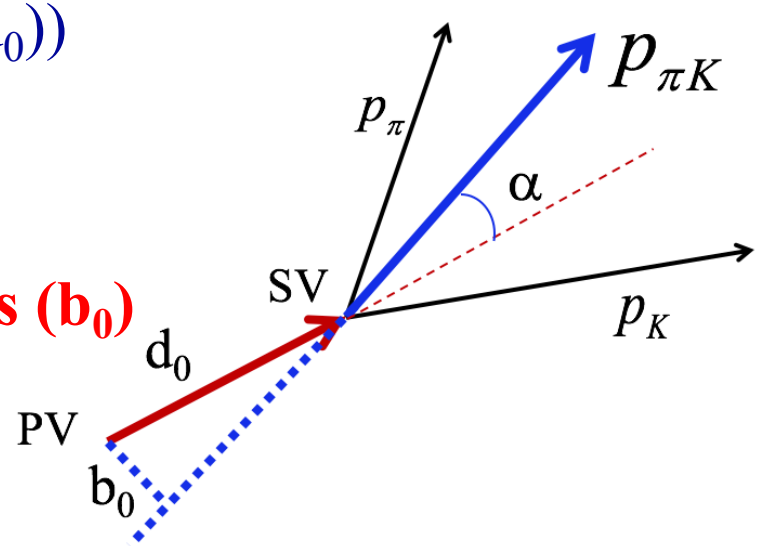
- D^0 reconstruction
  - Candidates with two tracks
  - Topological selections
- Extract D^0 v_n in data
  - Scalar product method
  - Fit on mass spectra and v_n vs mass
- Evaluate the effect from non-prompt D^0
  - Prompt D^0 fraction from impact parameter fit

D^0 Reconstruction

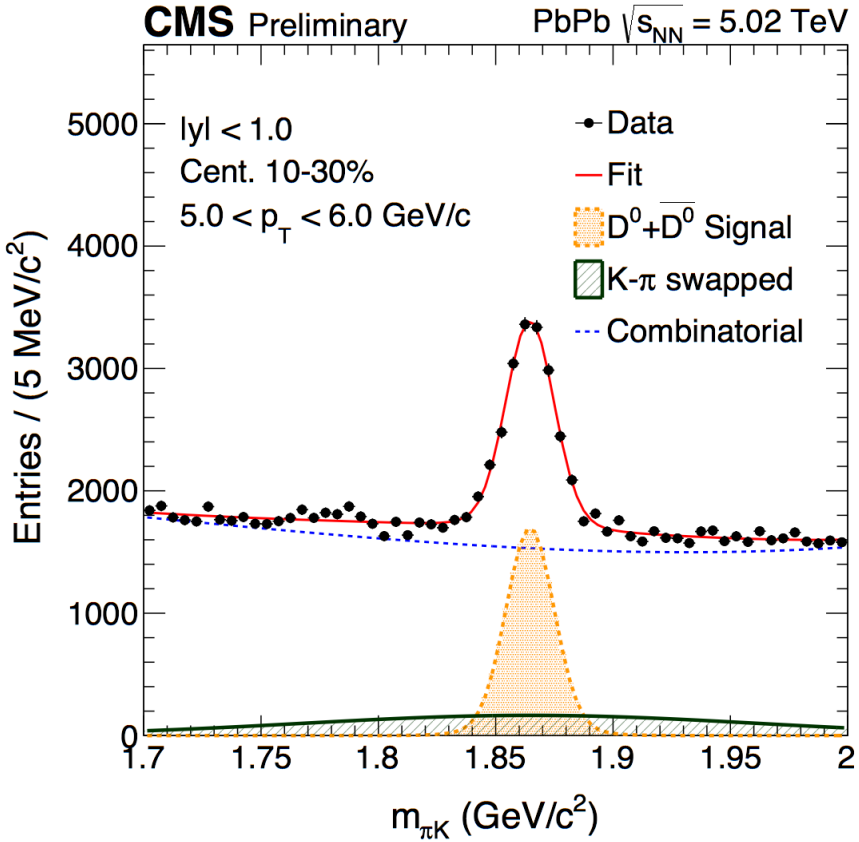
- **$D^0 \rightarrow K\pi$, BR = 3.88±0.05%, $c\tau(D^0)$ = 122.9 μm**

- **D^0 candidates**
  - Pairing oppositely charged tracks
  - Secondary vertex reconstruction

- **Topological selections** :
  - 3D decay length significance ($d_0/\sigma(d_0)$)
  - Pointing angle α
  - Secondary vertex probability
  - **Impact parameter of D^0 candidates (b_0)**
    - **b_0 < 80 μm (0.008 cm)**



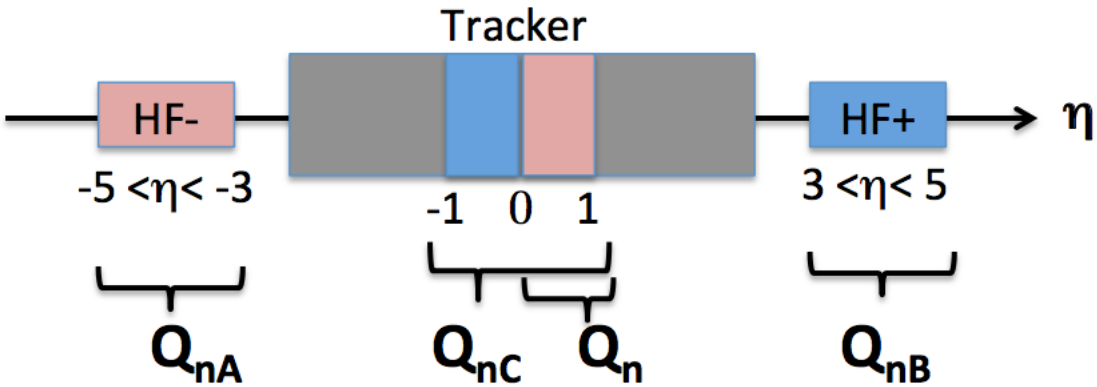
Invariant mass spectra fit



Invariant mass fitted with:

- **3rd order polynomial for combinatorial background**
- **Double gaussian for signal**
- **Single gaussian for k-π swapped candidates**
  - **No PID. Candidates with wrong mass assignment on tracks**

Scalar Product Method



$$Q_n = \sum_j w_j e^{in\phi_j}$$

Sum over tracks (tracker), or towers (HF)
***w_j*: tower E_T for HF, track p_T for tracker**

$$v_n\{SP\} = \frac{\langle Q_n \cdot Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} \cdot Q_{nB}^* \rangle \langle Q_{nA} \cdot Q_{nC}^* \rangle}{\langle Q_{nB} \cdot Q_{nC}^* \rangle}}}$$

Scaling factor from 3 sub events

- Large η gap applied (|Δη|>3.0)
- $v_n\{SP\}$, non-ambiguous measure of $\sqrt{\langle v_n^2 \rangle}$

Luzum, Ollitrault PRC87 (2013), 044907

Extract v_n of D^0

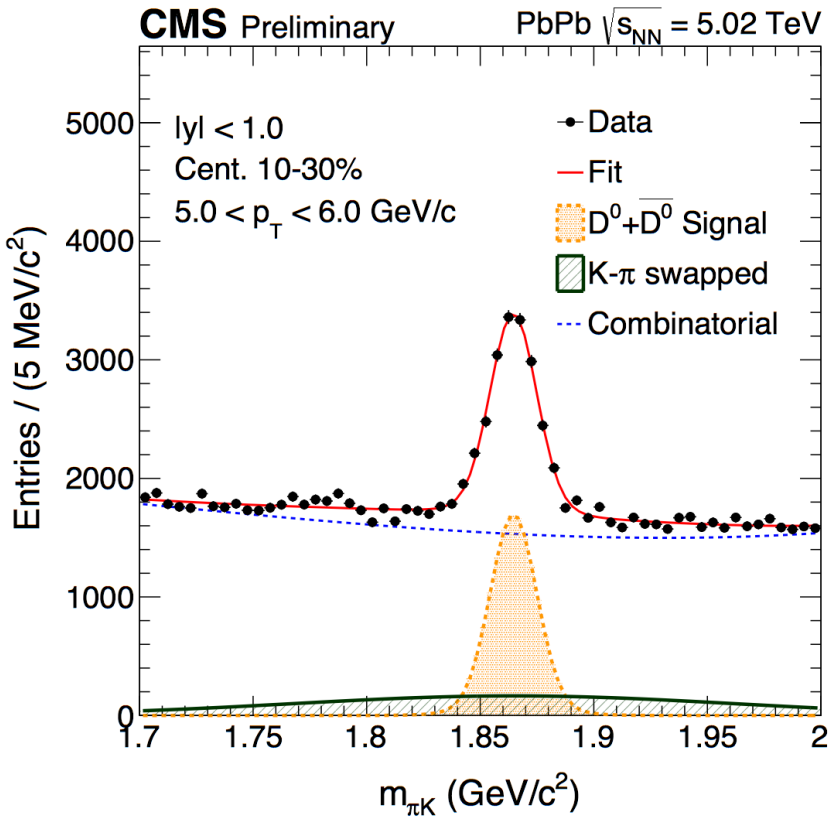
$$v_n^{Sig+Bkg}(m_{inv}) = \alpha(m_{inv})v_n^{sig} + (1-\alpha(m_{inv}))v_n^{Bkg}(m_{inv})$$

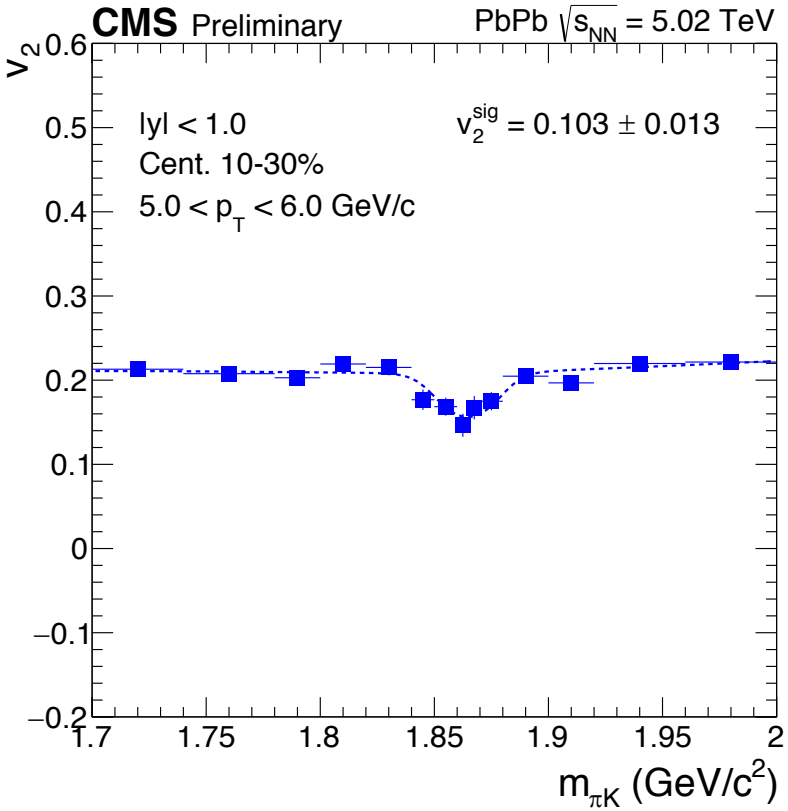
$$\alpha(m_{inv}) = (Signal(m_{inv}) + Swapped(m_{inv}))/(Signal(m_{inv}) + Swapped(m_{inv}) + Bkg(m_{inv}))$$

- $\alpha(m_{inv})$ is the signal fraction from mass spectrum fit
- v_n^{S+B} is v_n of D^0 candidates in each mass bin.
- v_n^{Sig} is the v_n of D^0, a fit parameter
- v_n^{Bkg} is v_n of combinatorial background candidates and modeled by a linear function of mass

Extract v_n of D^0

- Simultaneous fit on invariant mass distribution and v_n vs mass is performed



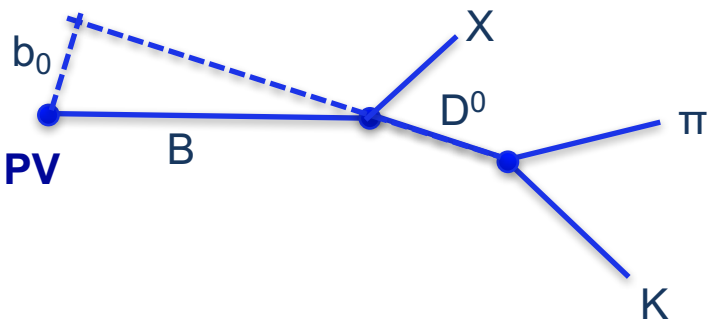


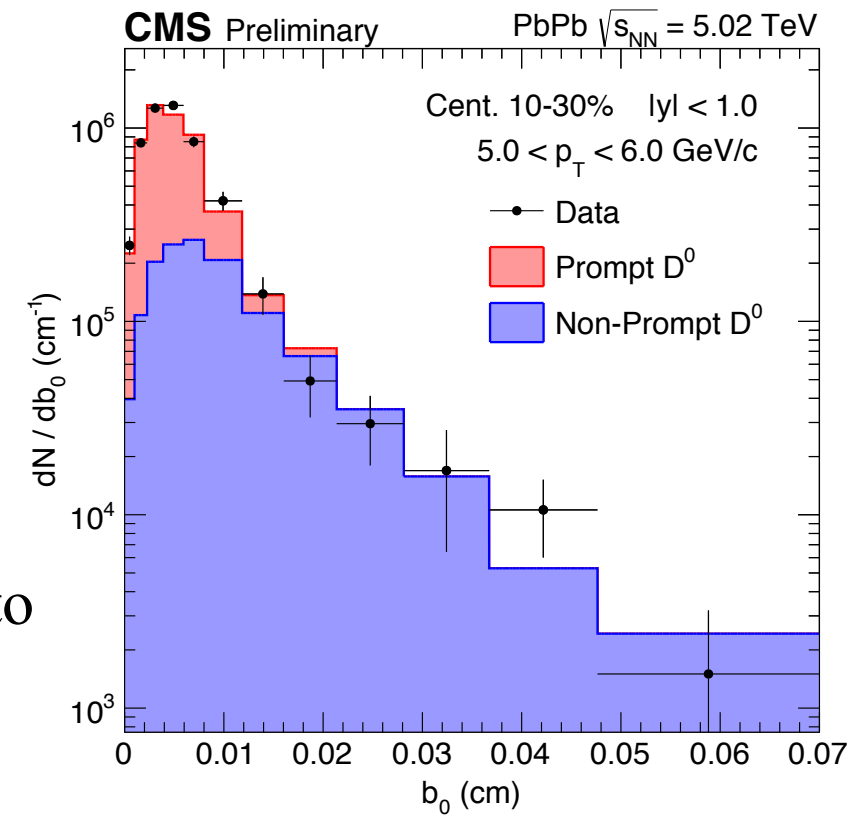
Systematic uncertainty from non-prompt D^0

- D^0 in data is a mixture of prompt and non-prompt D^0

$$v_n^{sig} = f_{prompt}\, v_n^{prompt} + (1-f_{prompt})\, v_n^{non\text{-}prompt}$$

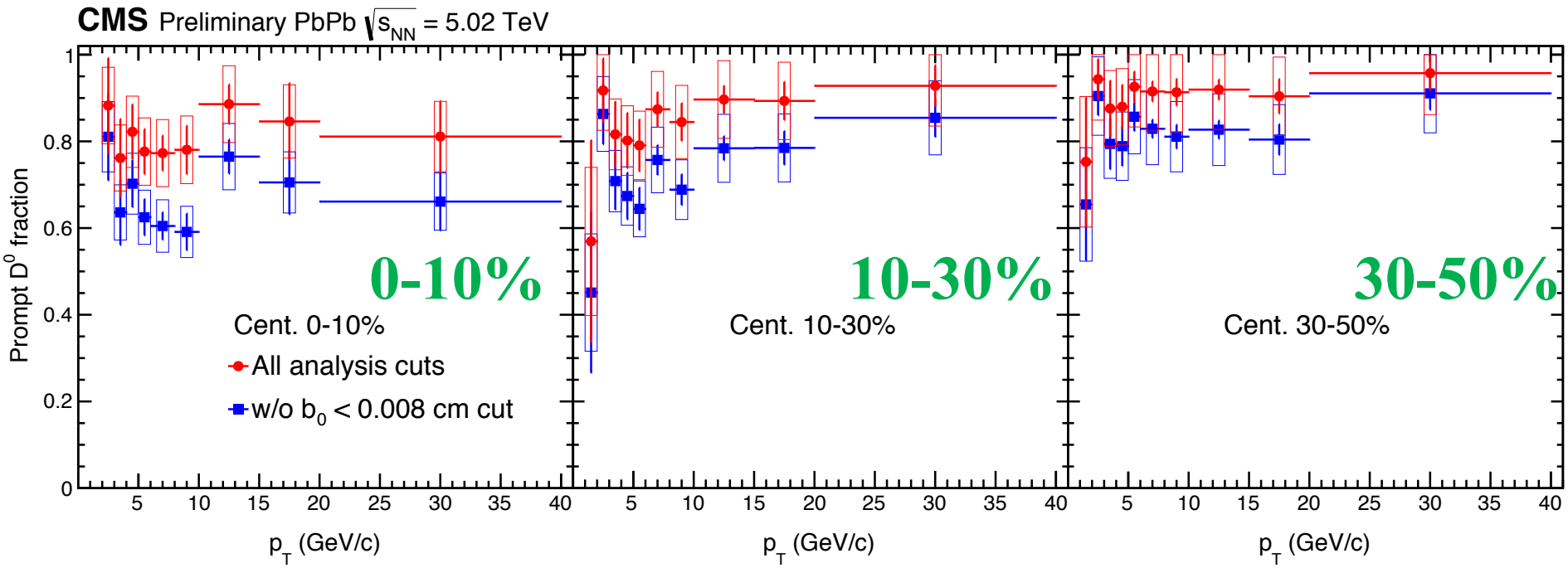
- To evaluate the effect from non-prompt D^0, prompt D^0 fraction is needed





- Different b_0 distributions of prompt D^0 and non-prompt D^0
- Template fit on b_0 distributions to evaluate prompt D^0 fraction
  - Fit in whole b_0 region

Prompt D^0 fraction with impact parameter fit



- The prompt D^0 fraction is around 75-95% after all analysis cuts
- The impact parameter cut suppress the non-prompt D^0 by around 50%

Systematic uncertainty from non-prompt D^0

- Systematic uncertainties from non-prompt D^0 are evaluated in a data driven method based on:
  - v_n of D^0 with all analysis cut and w/o b_0 cut
  - Fractions of prompt D^0 with all analysis cut and w/o b_0 cut

All analysis cut: $v_{n,1}^{sig} = f_{p,1}\, v_n^{p} + (1-f_{p,1})\, v_n^{np}$

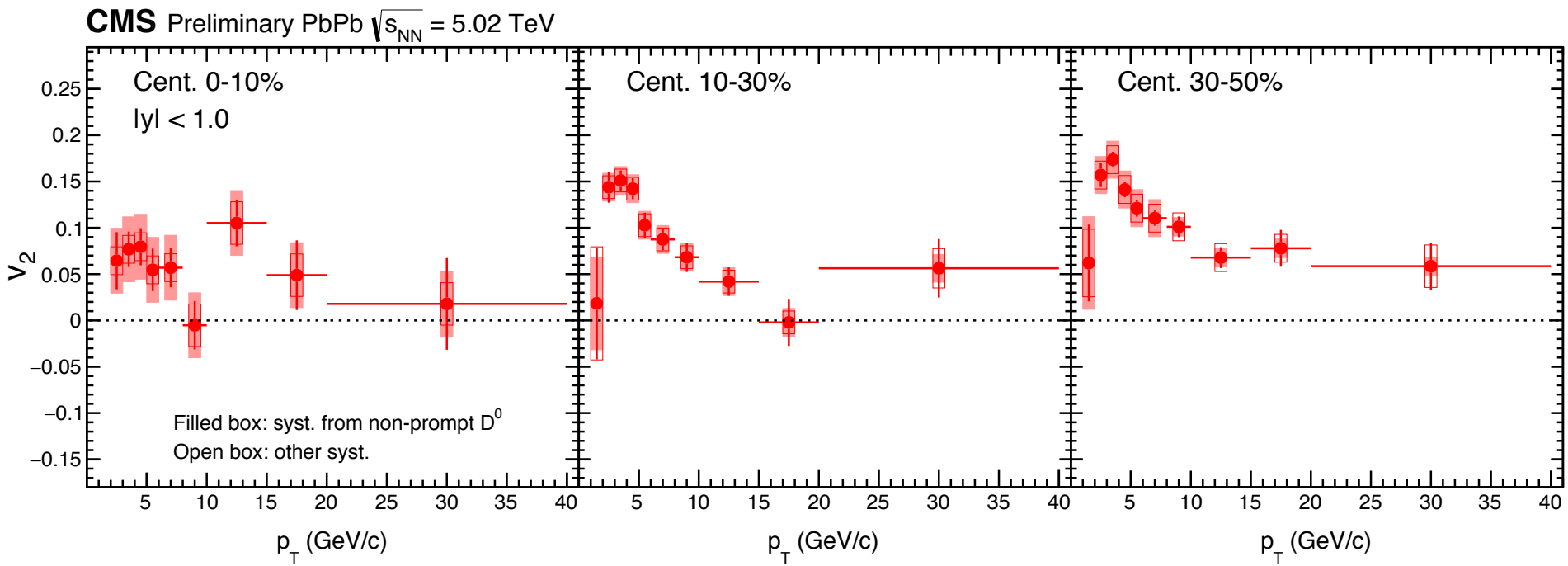
Without b_0 cut: $v_{n,2}^{sig} = f_{p,2}\, v_n^{p} + (1-f_{p,2})\, v_n^{np}$

$$v_n^{p} = v_{n,1}^{sig} + \frac{1-f_{p,1}}{f_{p,1}-f_{p,2}}\left(v_{n,1}^{sig} - v_{n,2}^{sig}\right)$$

D^0 v_n with all analysis cuts as central value

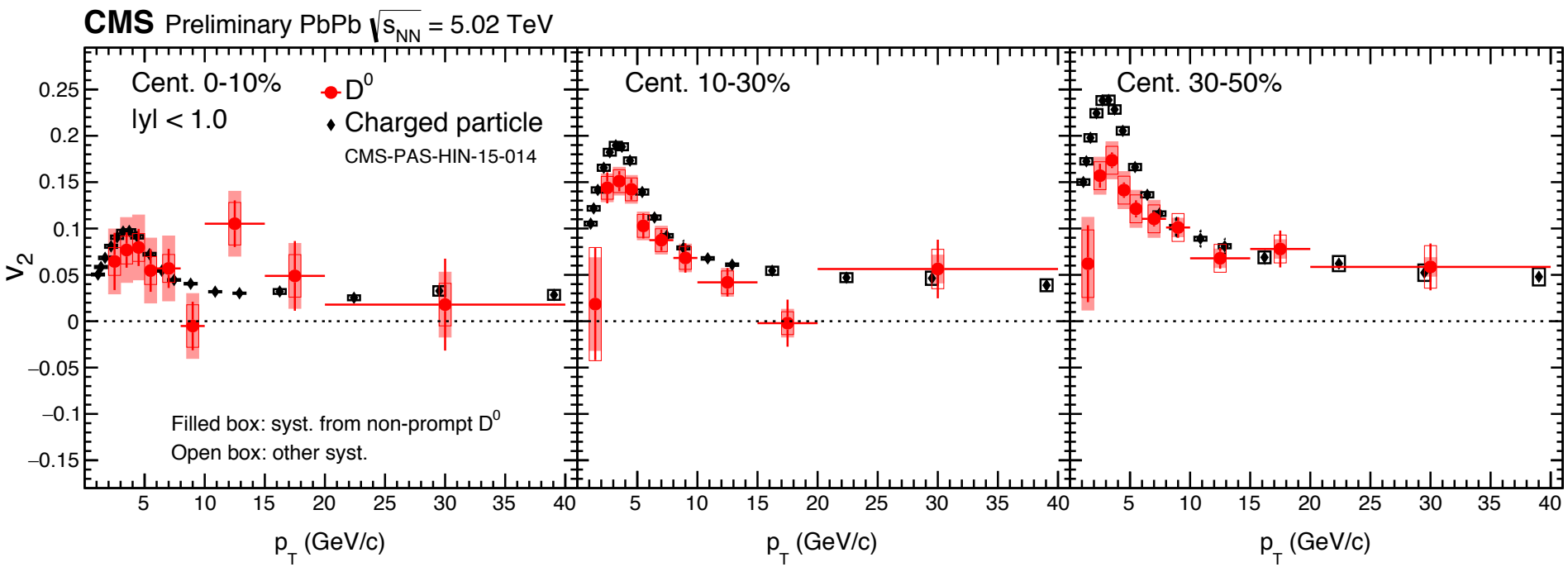
As systematics from non-prompt D^0

Prompt D^0 v_2 results



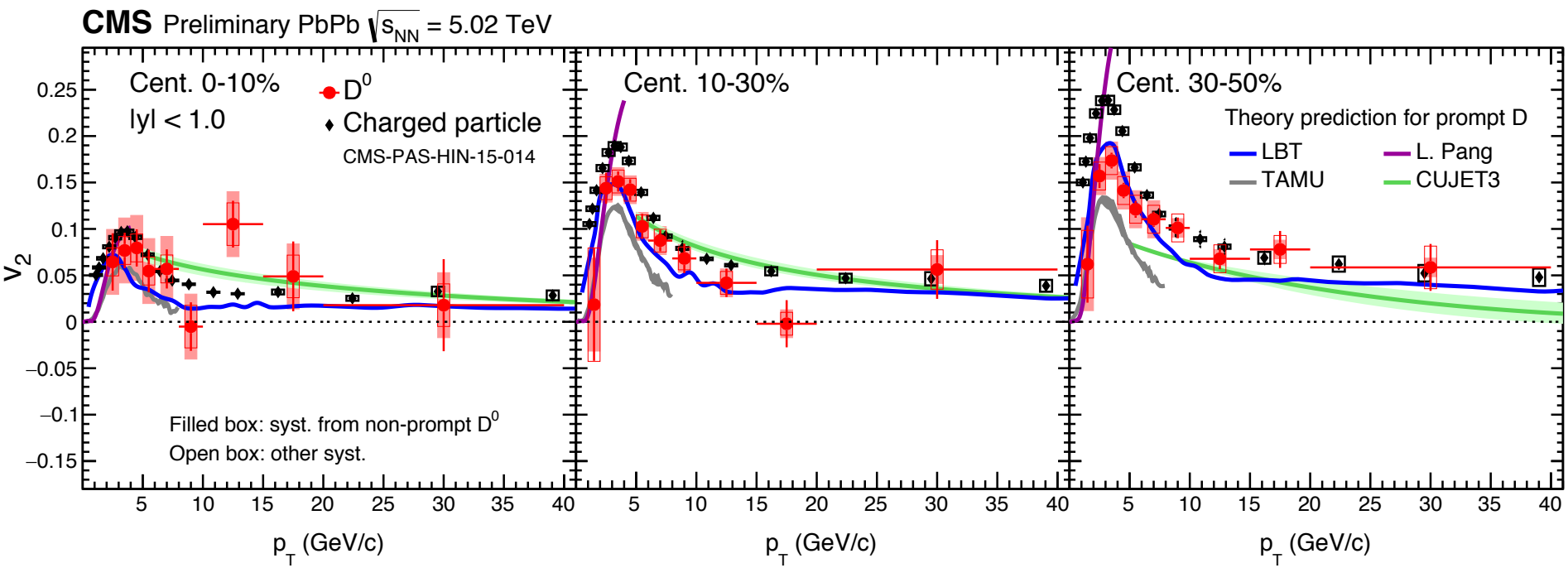
- **Positive prompt D^0 v_2 observed in studied p_T range**
  - Low p_T: charm quarks take part in the collective motion of the system
  - High p_T: indicates path length dependence of energy loss
- **Peaks around 3 GeV, then decrease vs p_T**
- **Low p_T: v_2 (0-10%) < v_2 (10-30%) ≈ v_2 (30-50%)**

Prompt D^0 v_2 compared with v_2 of charged particle



- In 0-10%, consistent with v_2 of charged particles
- In 10-30% and 30-50%
  - Low p_T: v_2 (prompt D^0) < v_2 (charged particle)
  - High p_T: v_2 (prompt D^0) ≈ v_2 (charged particle)
- Similar shape
- At low p_T, smaller centrality dependence in 10-50% than charged particle v_2

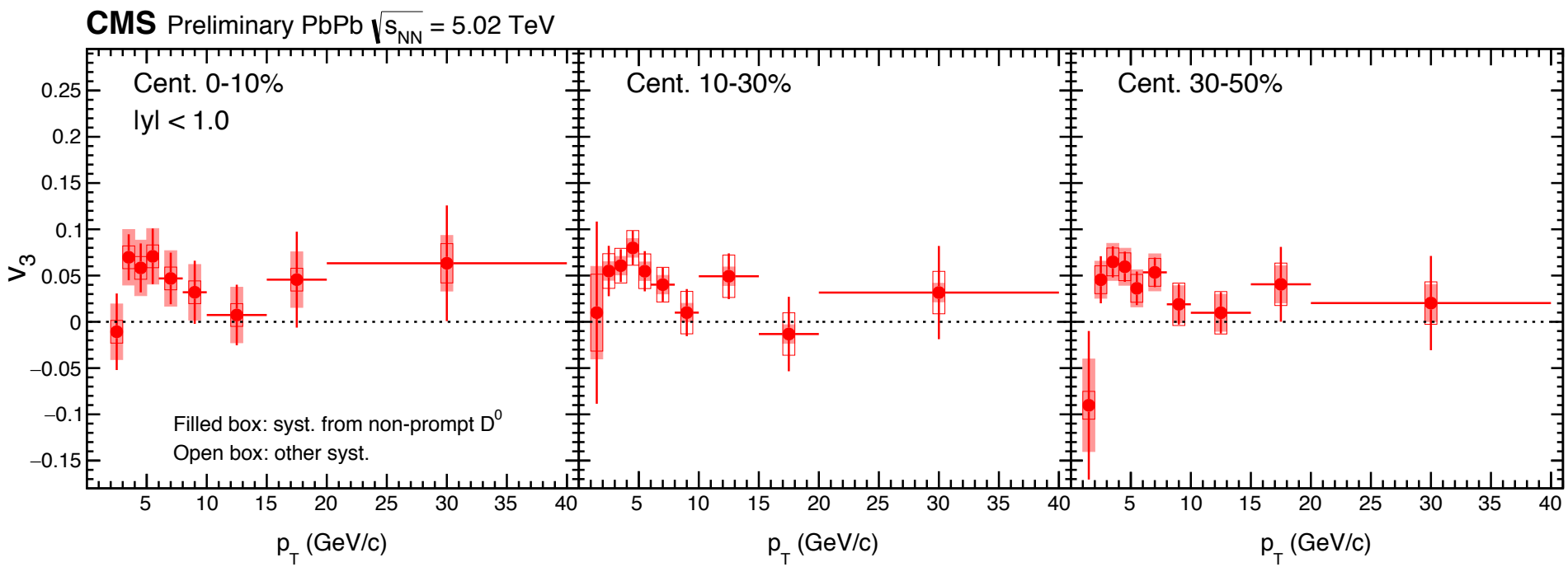
Prompt D^0 v_2 compared with model calculations



- **LBT:** linearized Boltzmann transport model for jet propagation in QGP
- **TAMU:** non-perturbative transport model with thermodynamic T-matrix approach
- **CUJET3:** jet quenching model based on DGLV
- **L. Pang**: second order viscosity hydrodynamic model

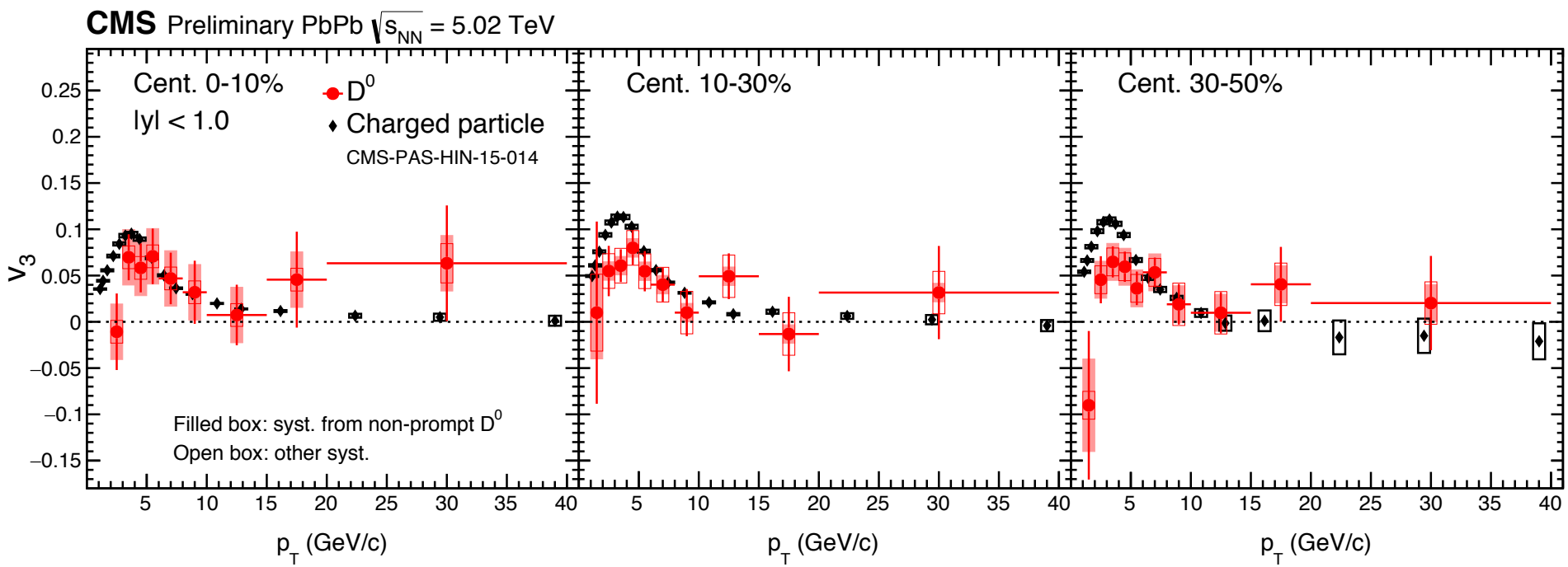
LBT: Cao, Luo, Qin, Wang PRC 94 014909 (2016)
TAMU: He, Fries, Rapp PLB 735 (2014) 445
CUJET3: Xu, Liao, Gyulassy JHEP 1602 (2016) 169
L. Pang: Pang, Hatta, Wang, Xiao PRD 91, 074027 (2015)

Prompt D^0 v_3 results



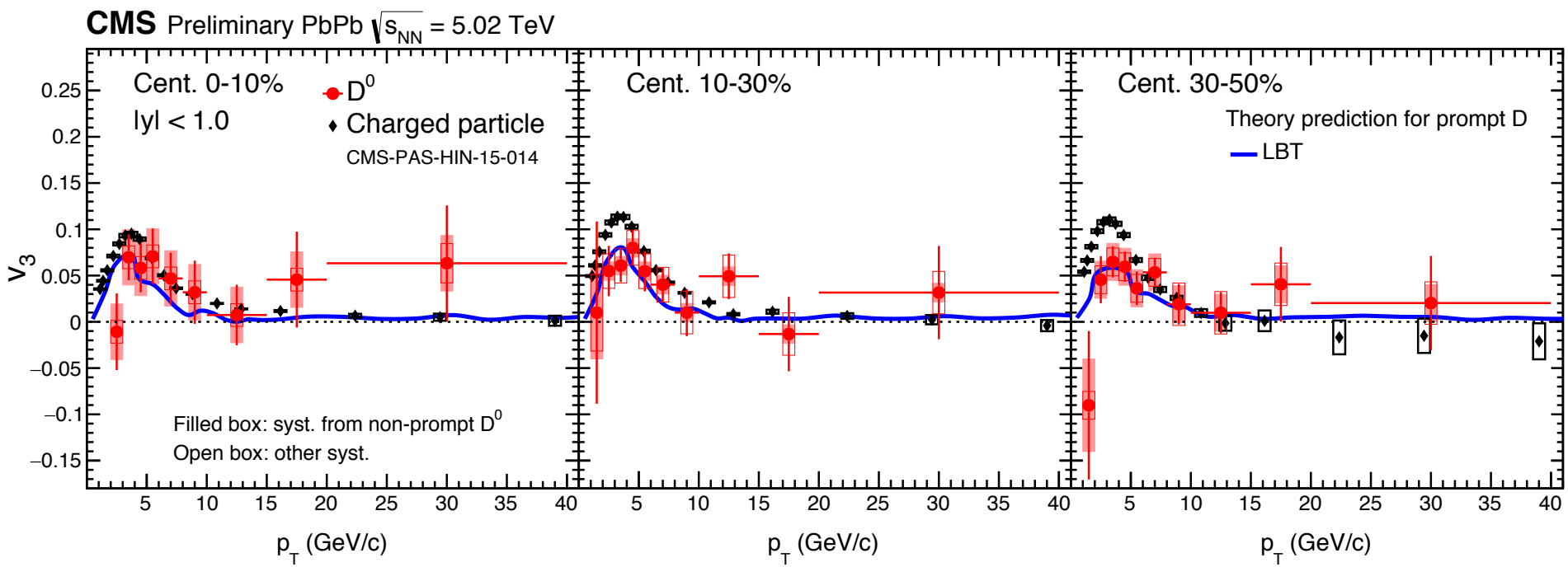
- ❑ **First measurement of D^0 v_3**
- ❑ **p_T dependence**
  - ❖ **Low p_T: v_3 (prompt D^0) > 0; High p_T: v_3 (prompt D^0) ≈ 0**
  - ❖ **Peaks around 3 GeV, then decrease vs p_T**
- ❑ **Little centrality dependence**

Prompt D^0 v_3 compared with v_3 of charged particle



- In 0-10%, consistent with v_3 of charged particles
- In 10-30% and 30-50%
  - Low p_T: v_3 (prompt D^0) < v_3 (charged particle)
  - High p_T: v_3 (prompt D^0) ≈ v_3 (charged particle)
- Similar shape
- Both have little centrality dependence

Prompt D^0 v_3 compared with model calculations

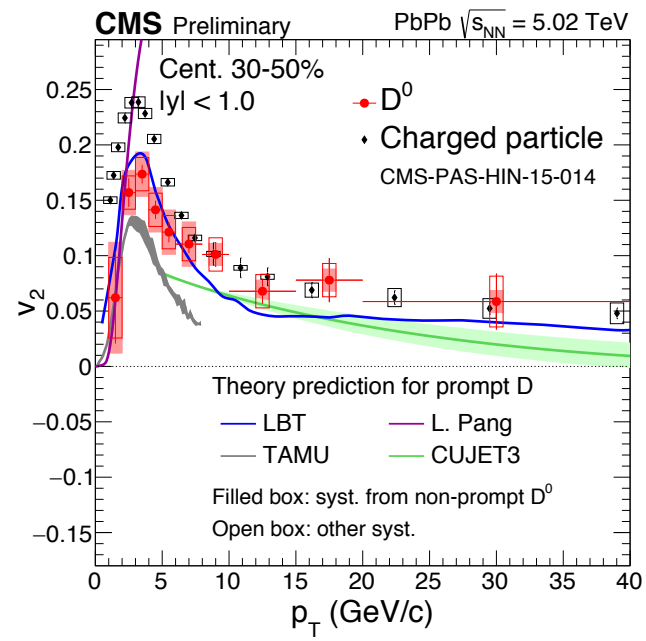


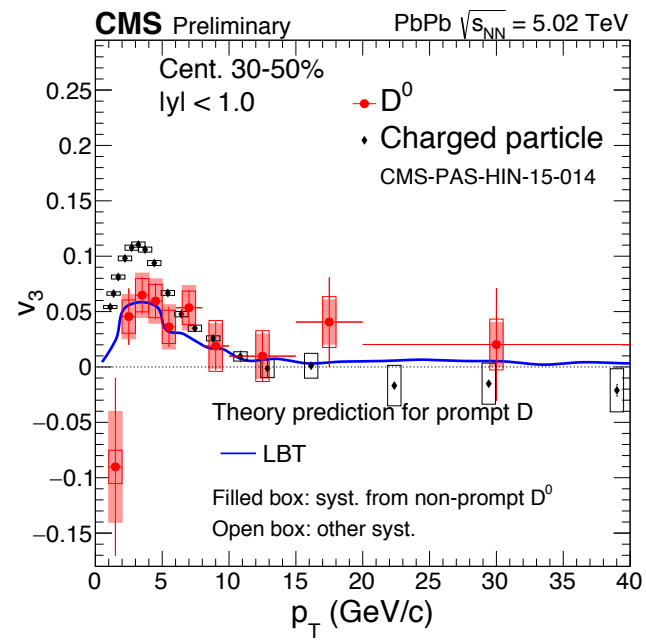
- **LBT:** linearized Boltzmann transport model for jet propagation in QGP

LBT: Cao, Luo, Qin, Wang PRC 94 014909 (2016)

Summary

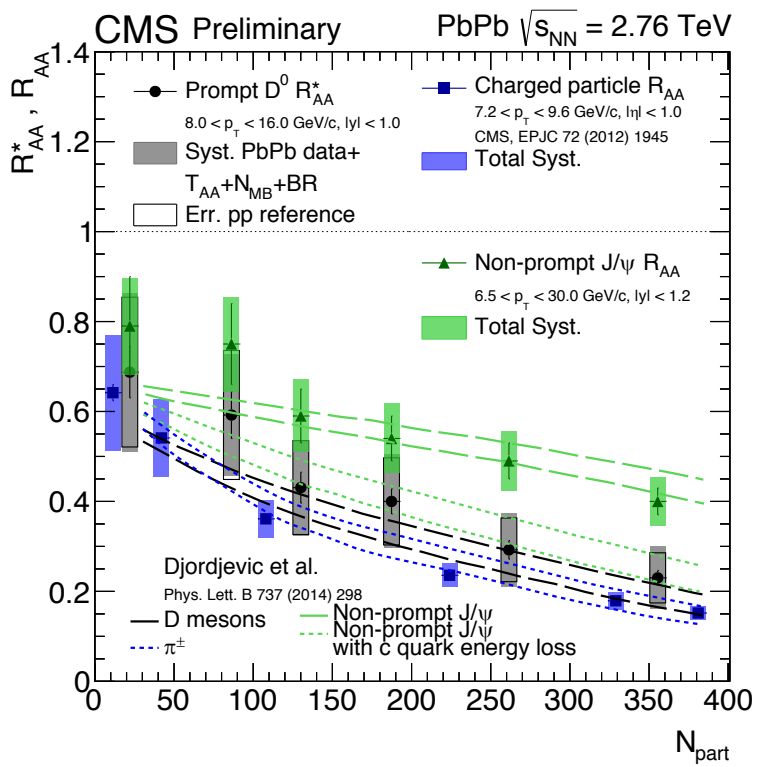
- **Prompt D^0 v_2 and v_3 is measured for centrality 0-10%, 10-30% and 30-50%**
  - First measurement of D^0 v_3
  - Positive v_2 in both low and high p_T ranges
  - Positive v_3 in low p_T range
- **The prompt D^0 v_2 and v_3 is compared with these of charged particle**
  - Low p_T: v_n (prompt D^0) < v_n (charged particle)
  - High p_T: v_n (prompt D^0) ≈ v_n (charged particle)
- **The results provide important input for theoretical studies**

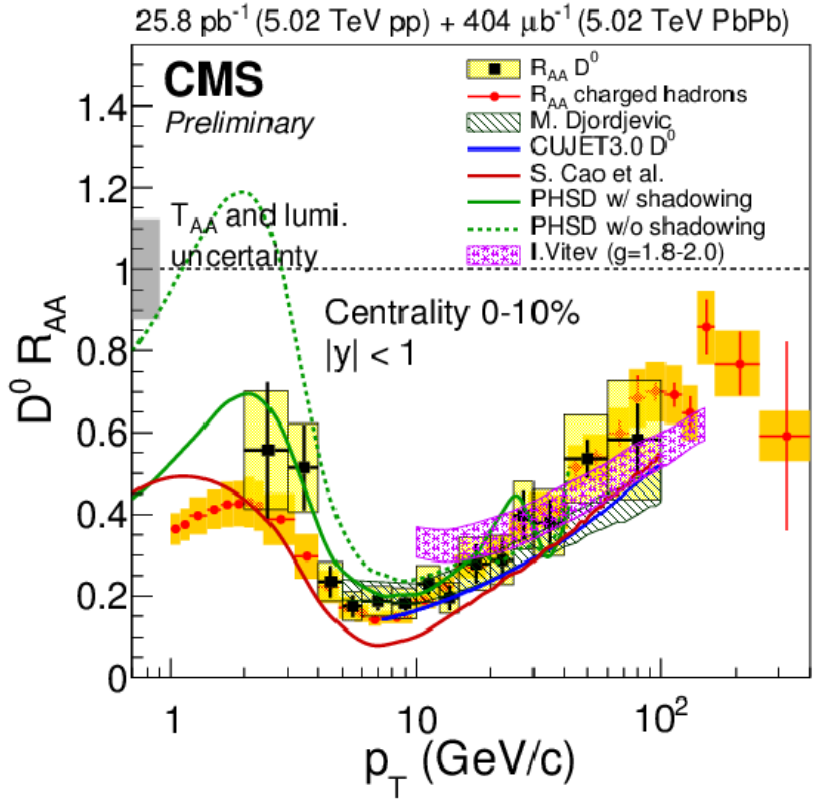




Backup

Previous D meson measurements with CMS





- CMS has measured R_{AA} of prompt D^0 in PbPb both at 2.76 TeV and 5.02 TeV
- D^0 flow and R_{AA} can be used simultaneously to constrain models

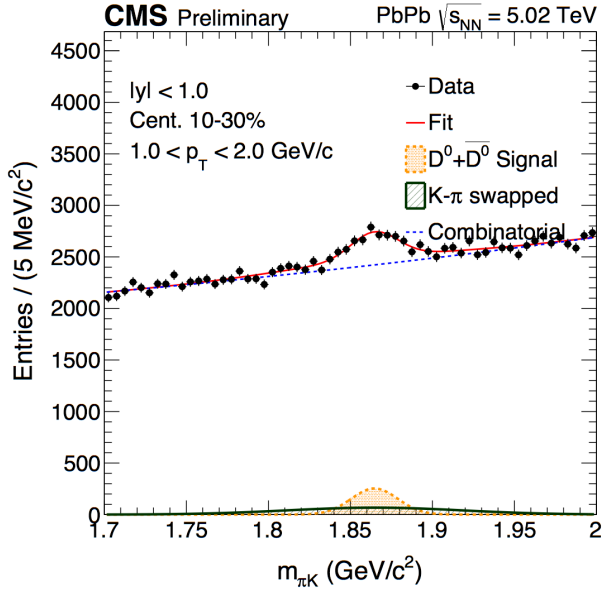
See J. Wang's talk on D^0 R_{AA}, 24 Sep. 14:40

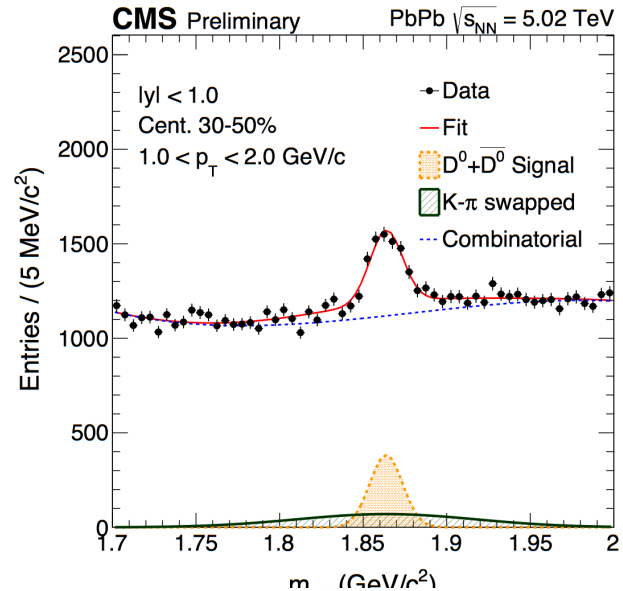
CMS PAS HIN-15-005
CMS PAS HIN-16-001

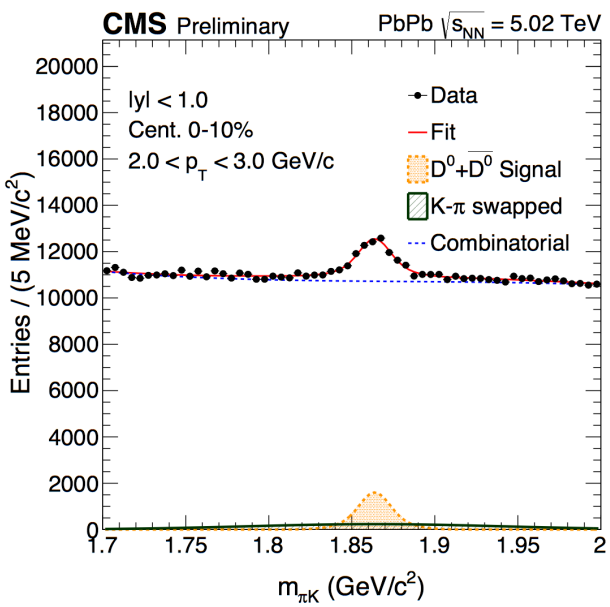
More mass spectra fit

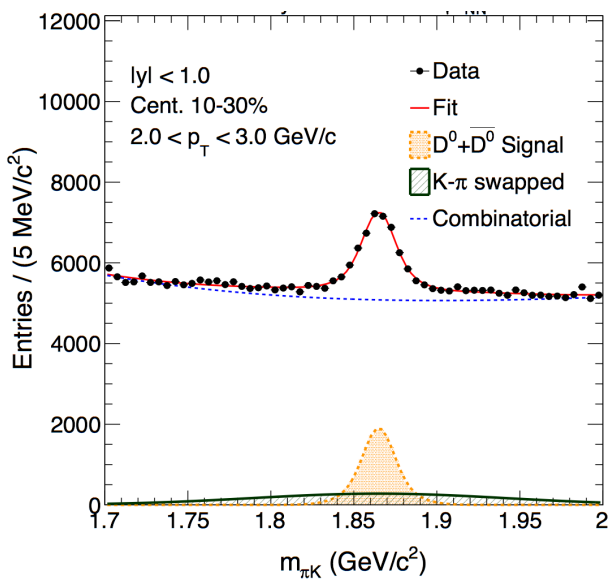
Top: p_T 1-2 GeV for centrality 10-30% and 30-50%

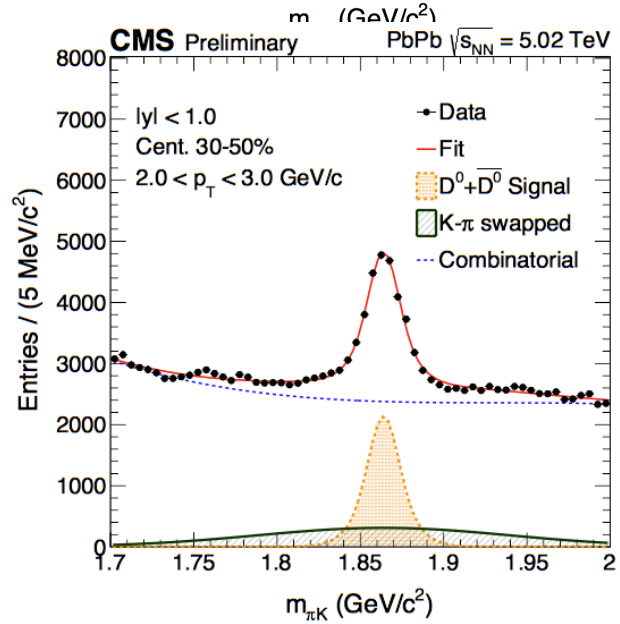
Bottom: p_T 2-3 GeV for centrality 0-10%, 10-30% and 30-50%



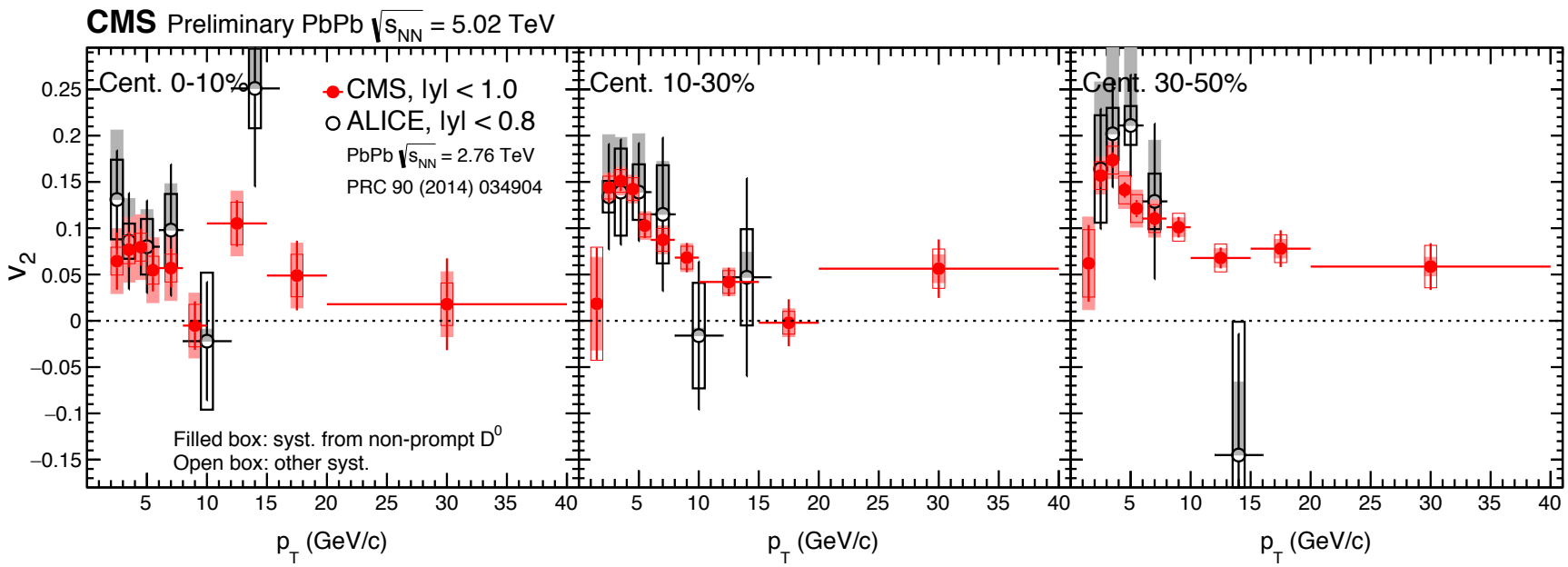


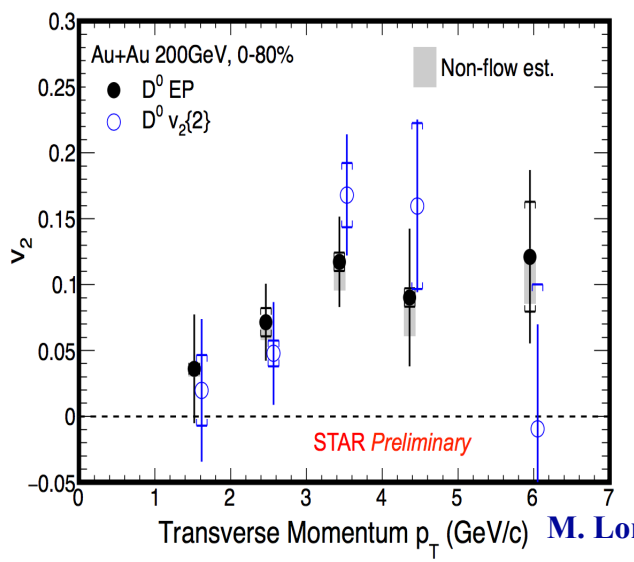






D^0 v_2 compared with ALICE and STAR results



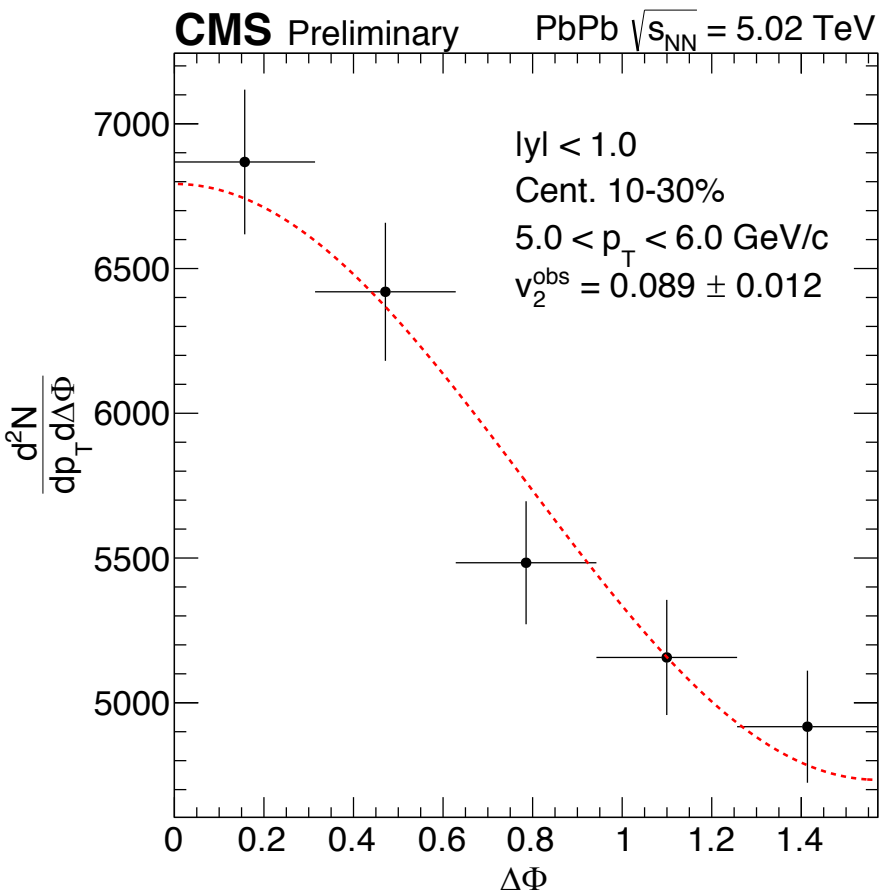


CMS preliminary results are consistent with ALICE results within uncertainties

M. Lomnitz, QM 2015 talk

PRC 90, 034904 (2014)

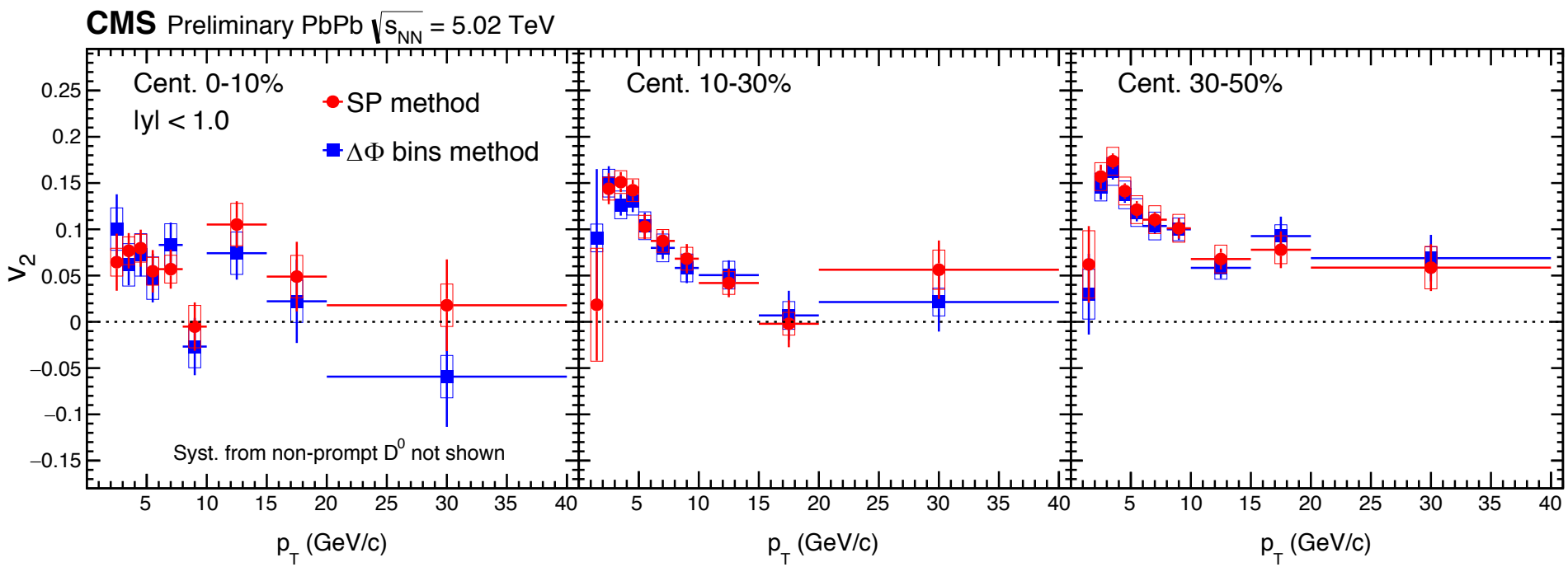
Δϕ Bins Method



- D^0 v_n can also be measured by fitting $d^2N/(dp_T d\Delta\phi)$ with: $N_0(1+2v_n^{obs}\cos(n\Delta\phi))$
  - Δϕ between D^0 candidates and event planes
  - Large η gap applied ($|\Delta\eta|>3.0$)
- v_n^{obs} corrected by event plane resolution: $v_n^{sig} = v_n^{obs}/R_n$
- Measuring ambiguous value between average v_n and RMS of v_n

Luzum, Ollitrault PRC87 (2013), 044907

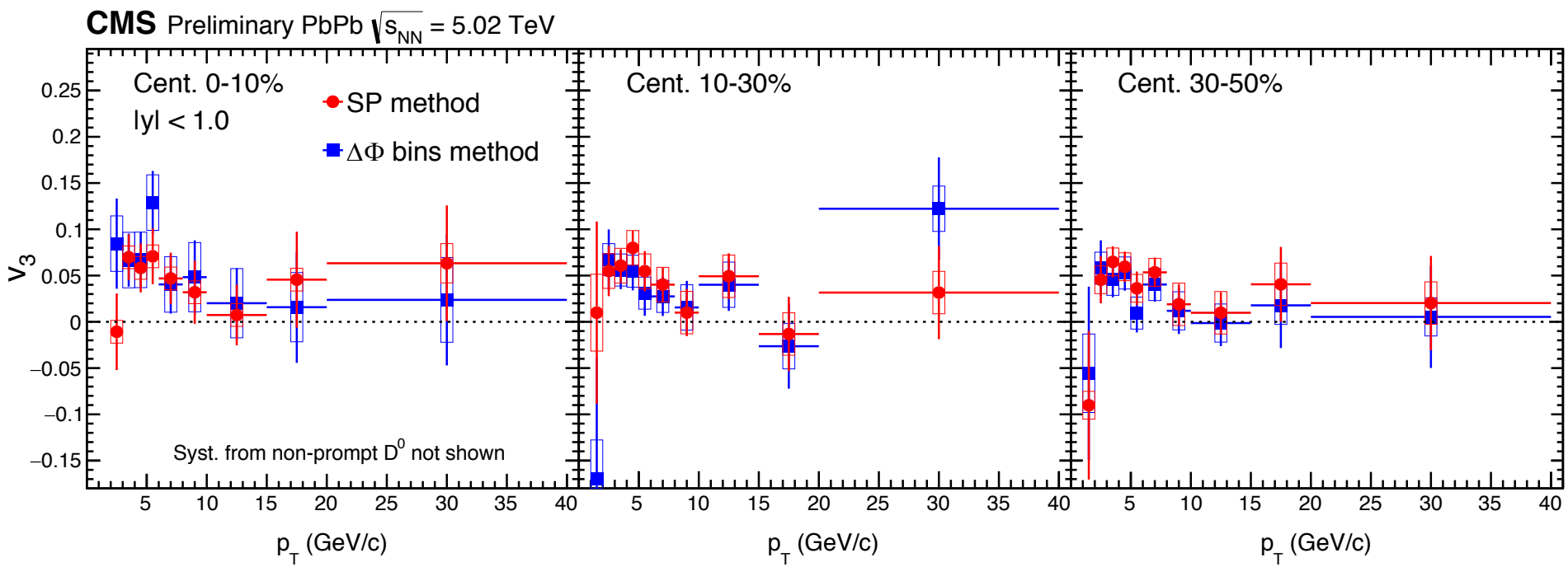
D^0 v_2 from SP and $\Delta\phi$ bins method



Results from SP method and $\Delta\phi$ bins method are consistent within uncertainties

- Small differences are expected

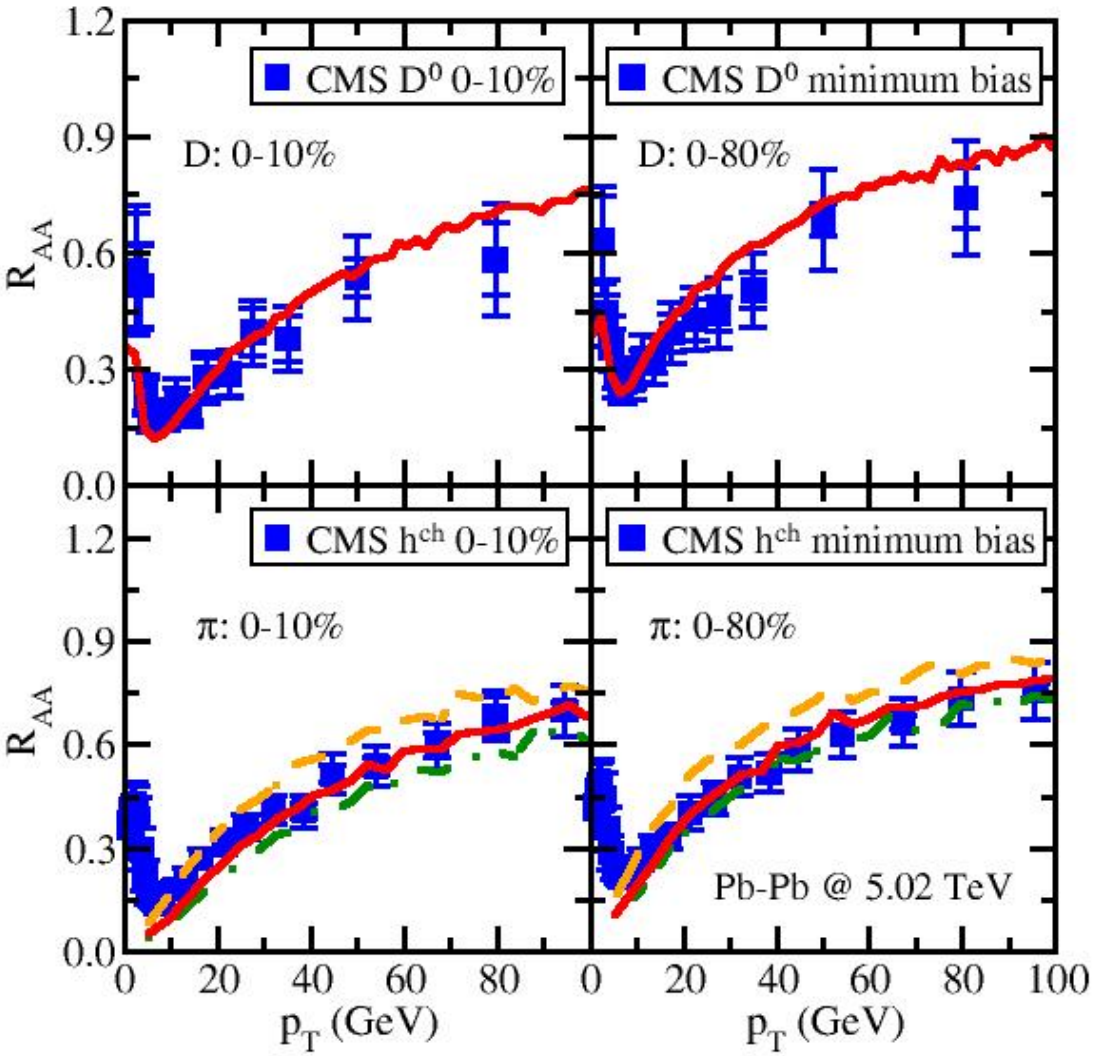
D^0 v_3 from SP and $\Delta\phi$ bins method



Results from SP method and $\Delta\phi$ bins method are consistent within uncertainties

- Small differences are expected

Prompt D^0 R_{AA} compared with LBT model



S. Cao SQM 2016 talk
G. Qin SQM 2016 talk

CMS PAS HIN-16-001

CMS PAS HIN-15-015

LBT: Cao, Luo, Qin, Wang PRC 94 014909 (2016)