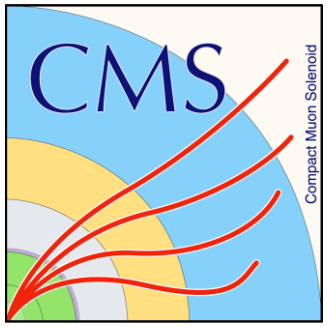
Production and Collective Flow of Open Heavy Flavor in PbPb Collisions with CMS

Yen-Jie Lee (MIT)

For the CMS collaboration



SQM 2017

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10-15 July, 2017

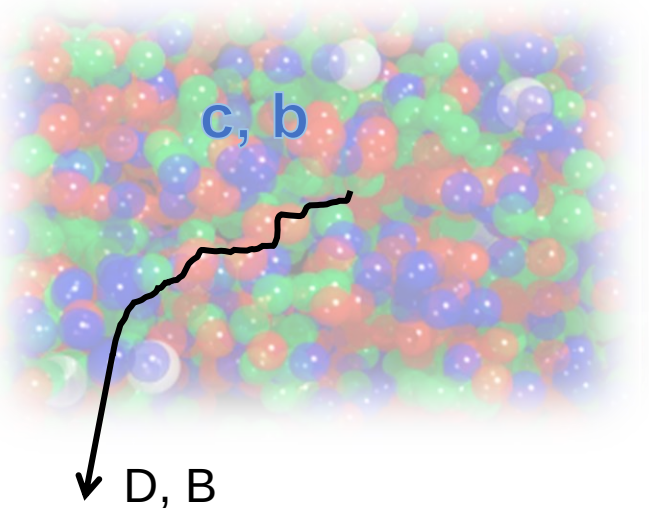
Supported by the US DoE Early Career Research Award Program

Introduction

Heavy quarks are ideal probes for the QGP

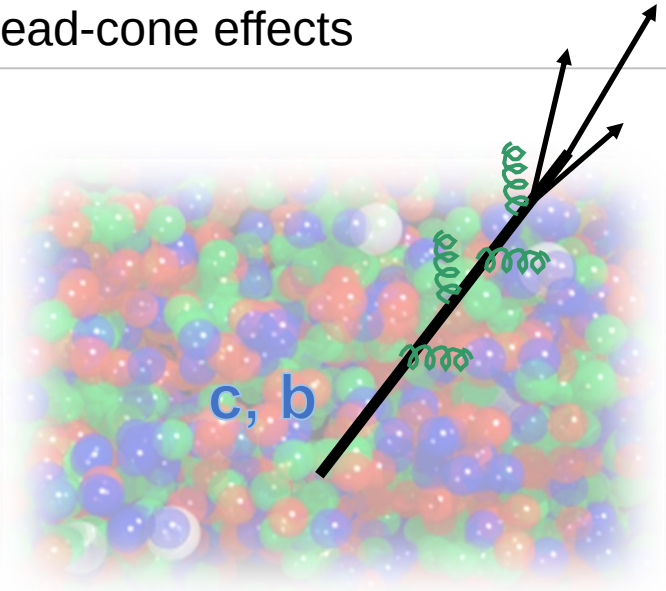
- Mostly produced early in time, p_T spectra could be calculated with pQCD
- Could be traced (though heavy flavor mesons)

Picture of pQCD based models



At intermediate to high p_T:

- Test our understanding of jet quenching
- Smaller energy loss than gluons (color charge)
- Smaller radiative energy loss than light quarks due to dead-cone effects



At low transverse momentum:

- "Kicked around" by quasi-particles in the QGP
- Probe the temperature and density of the medium

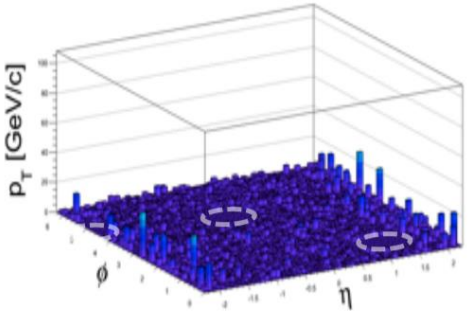
Picture of AdS/CFT based models

Heavy quarks experience **drag force** from the QGP

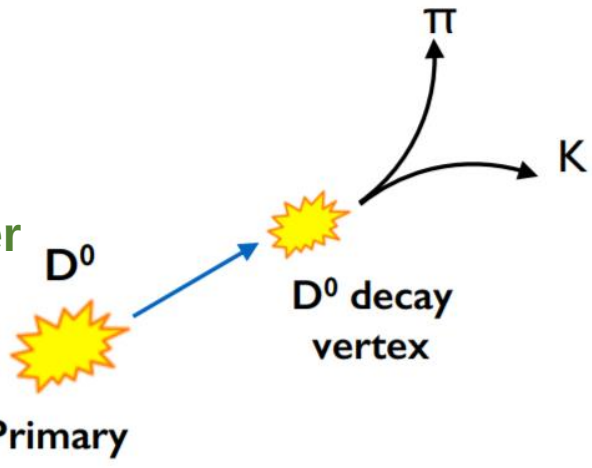
New measurements of Heavy flavor R_{AA} and v_n from CMS

2015 pp and PbPb data at 5.02 TeV

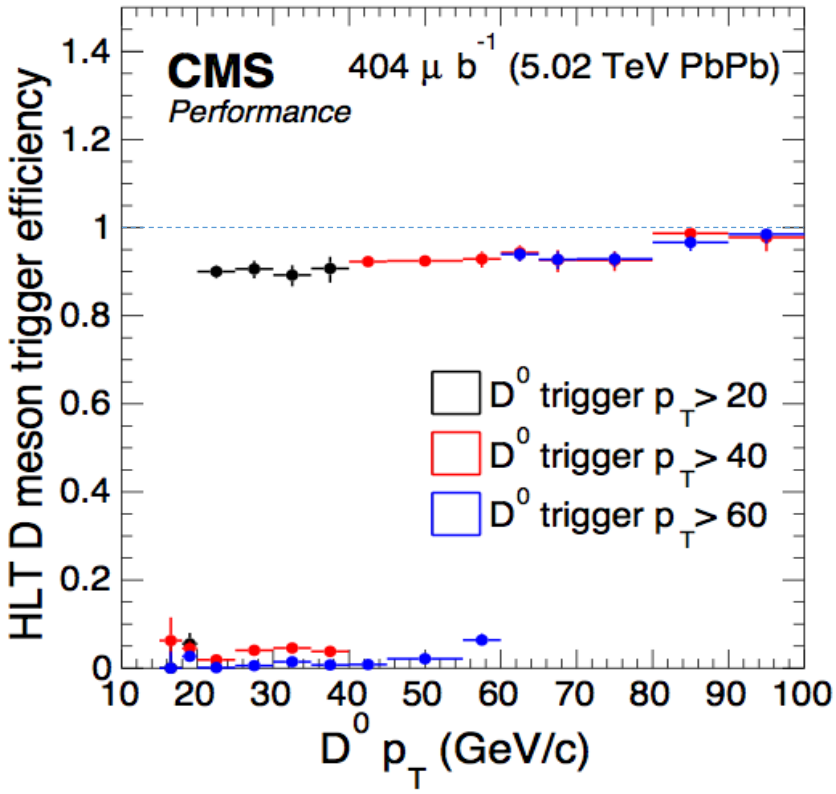
- **Non-prompt J/ψ and B meson:**
  - Dimuon trigger which sample the full delivered luminosity by LHC
- **Low p_T D^0:** MB and event centrality triggered events
  - pp: 2B MB events
  - PbPb: 170M 0-100% and 270M 30-100% events analyzed
- **High p_T D^0:** dedicated D^0 triggers for both PbPb and pp
  - Compared to minimum bias triggers, the high p_T D^0 statistics are increased by a factor of 800 (30) in pp (PbPb) collisions



(1) Hardware level jet trigger
(Level 1 filter)

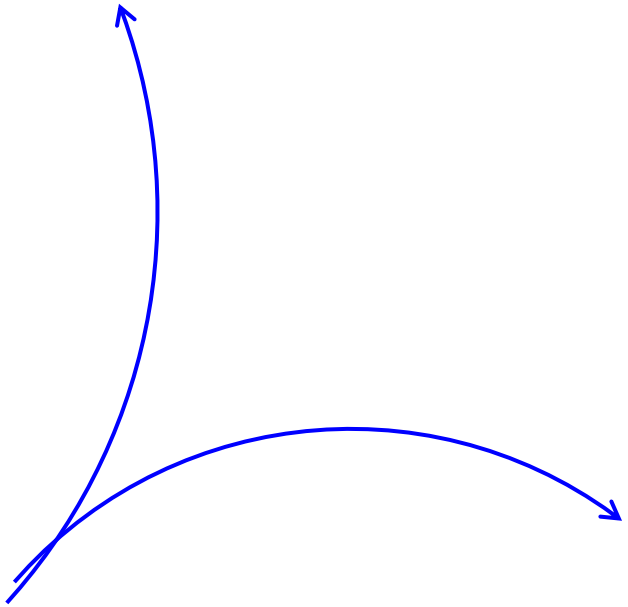


(2) Online D^0 to Kπ analysis in the high level trigger computing farm (HLT filter)



D^0 identification in CMS

- No K-π identification for charged tracks used
- D^0 from pairs of oppositely charged tracks with both Kπ and πK mass assumptions (2 D^0 candidates per pair)



Primary vertex

D^0 identification in CMS

- No K-π identification for charged tracks used
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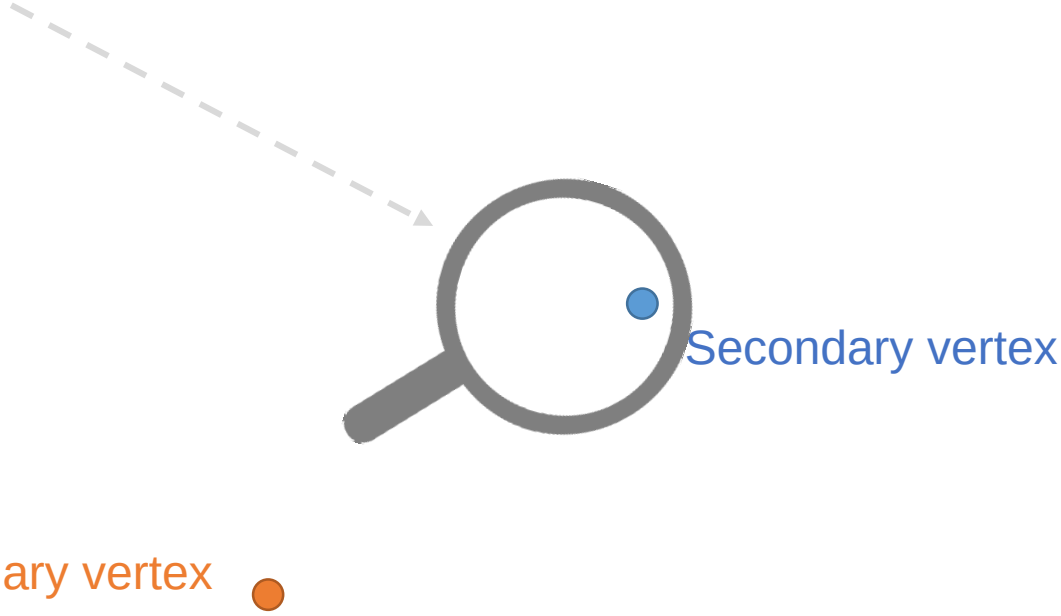
- Secondary vertex reconstruction (SV)
- D^0 identification:
  - Secondary vertex quality



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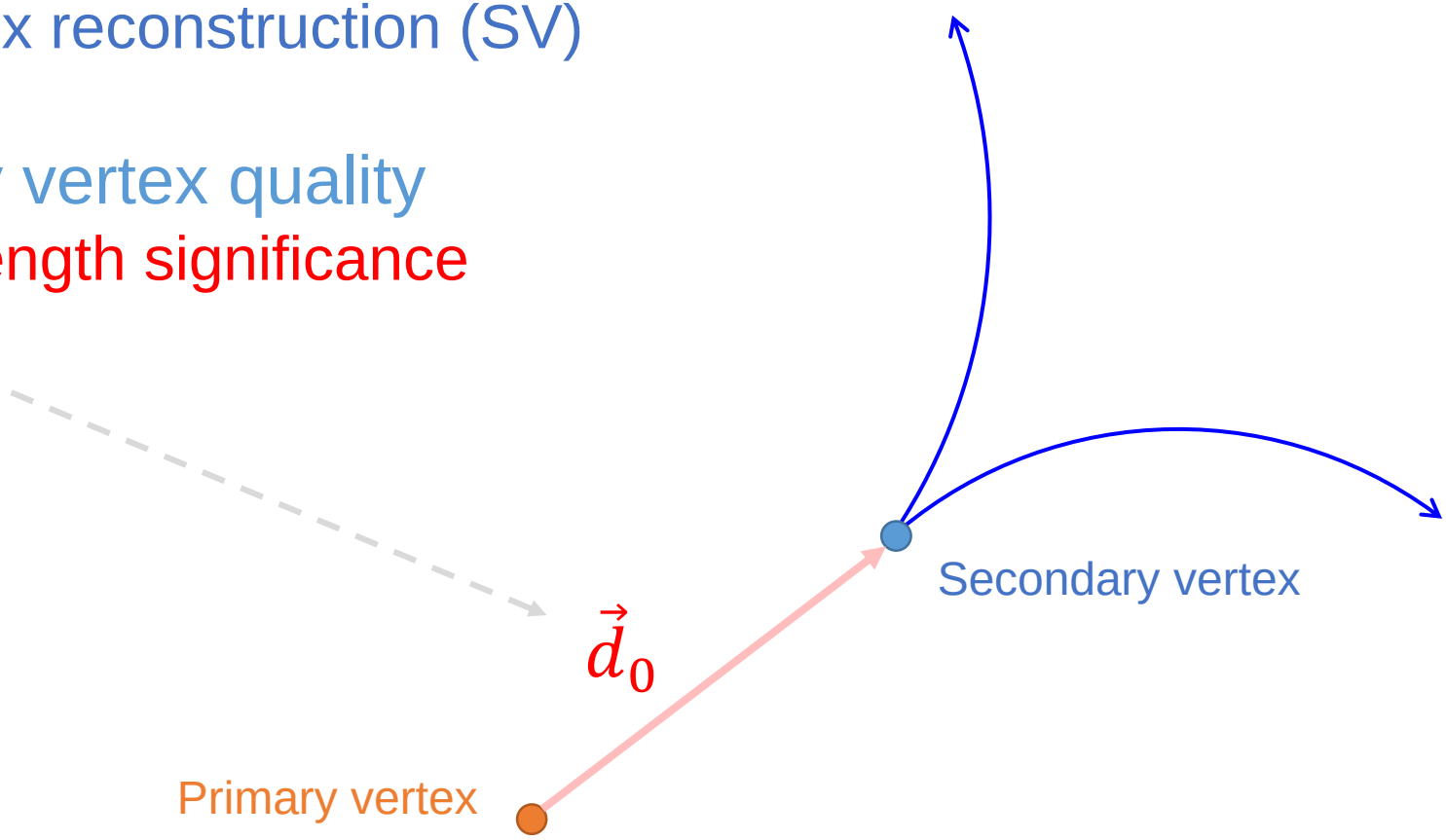
  - 3D decay length significance ($d_0/\sigma(d_0)$)



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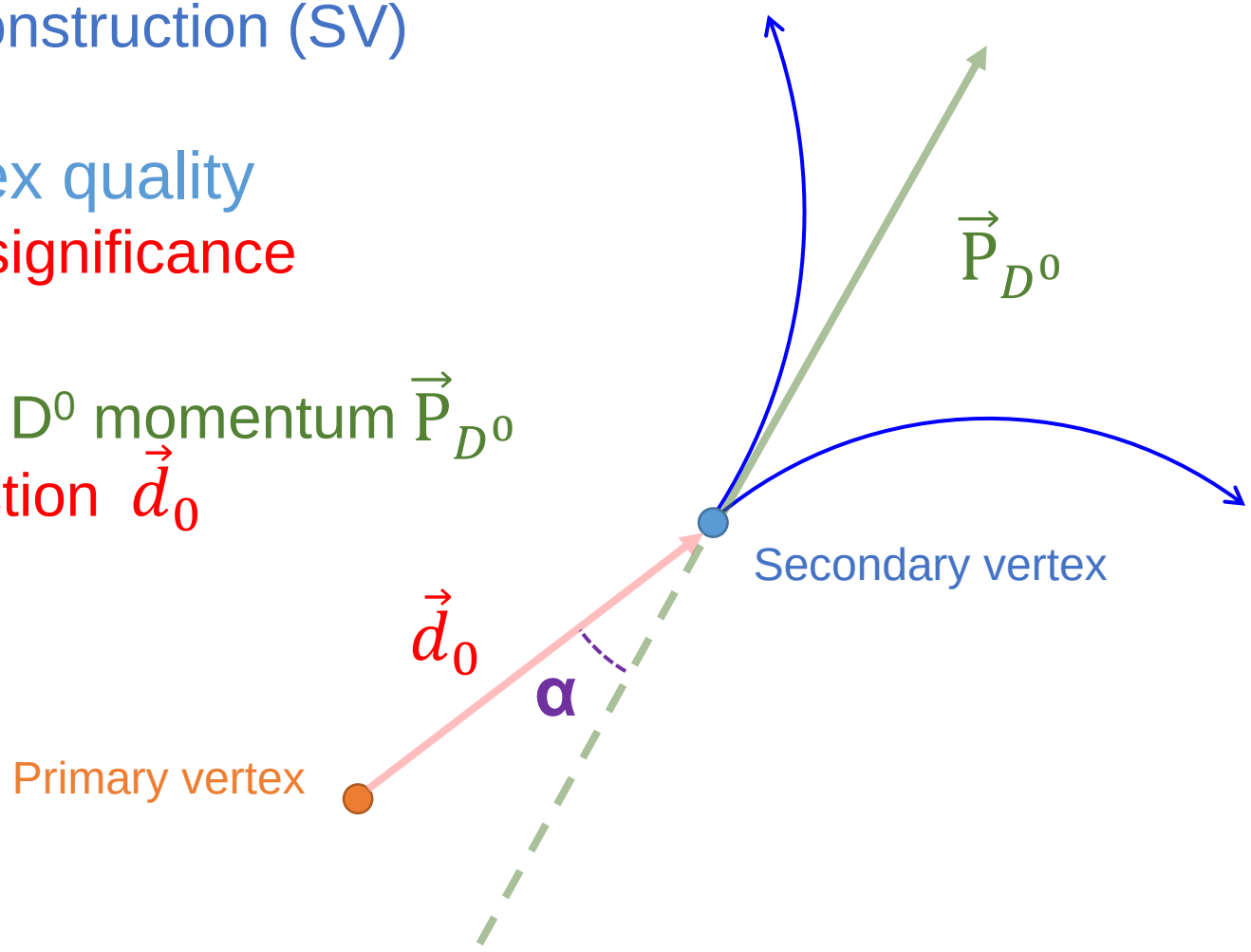
  - Angle **α** between D^0 momentum $\vec{P}_{D^0}$ and D^0 flight direction $\vec{d}_0$



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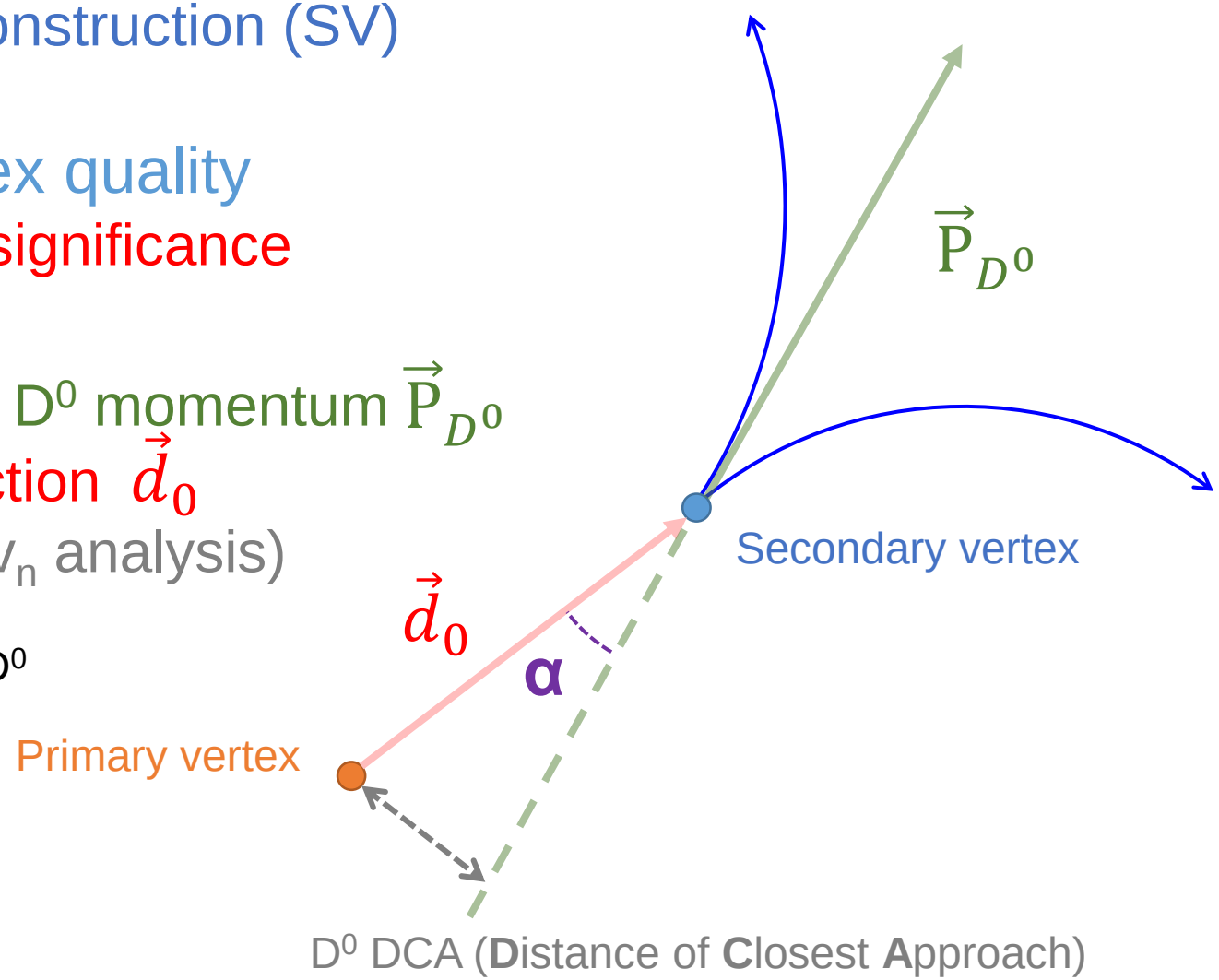
  - 3D decay length significance ($d_0/\sigma(d_0)$)
  - Angle **α** between D^0 momentum $\vec{P}_{D^0}$ and D^0 flight direction $\vec{d}_0$
  - D^0 DCA (used in v_n analysis)
    DCA < 0.008 cm
    Suppress non-prompt D^0

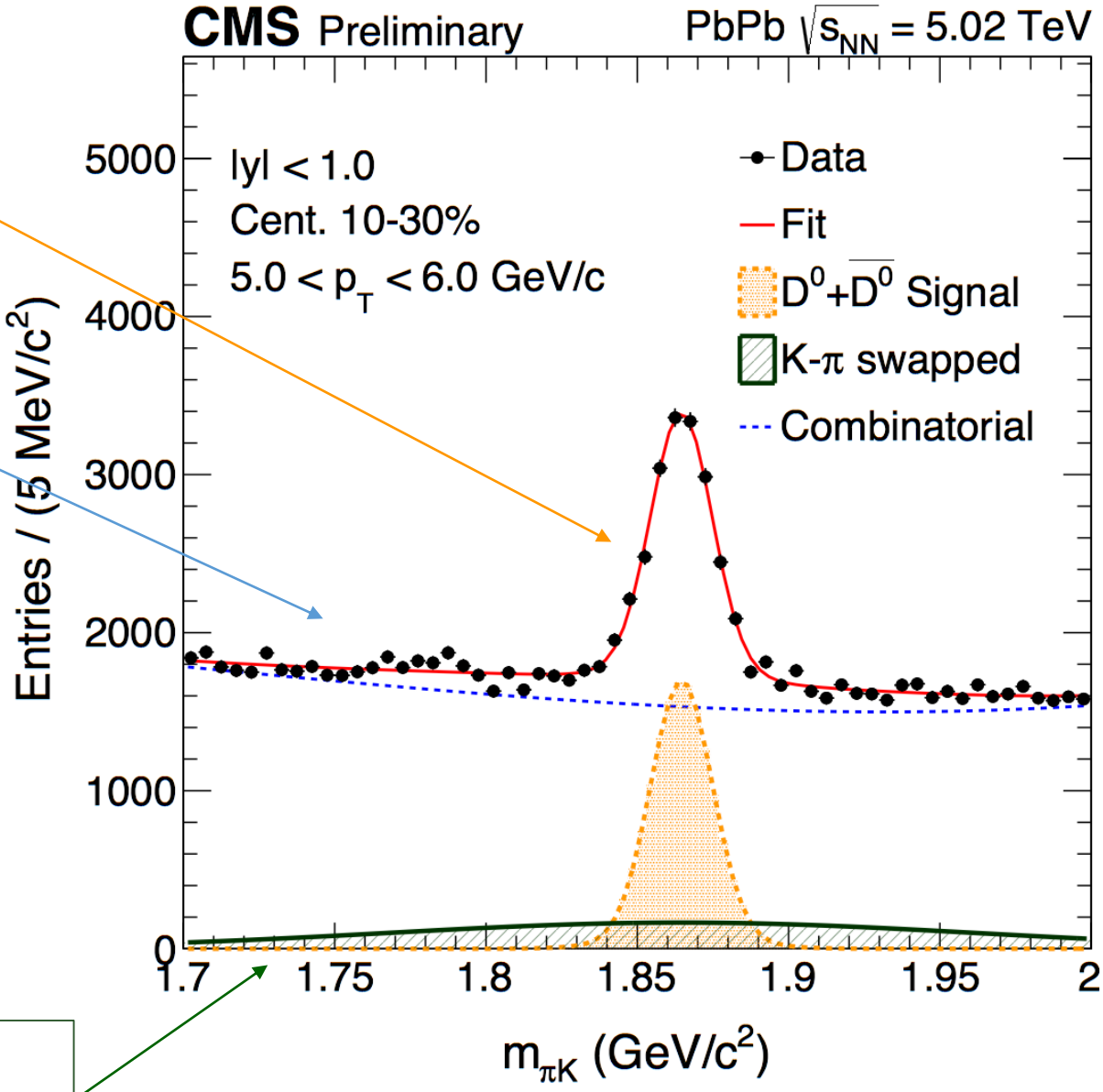


D^0 Signal Extraction

Double Gaussian for
$D^0 \rightarrow K\pi$ signal

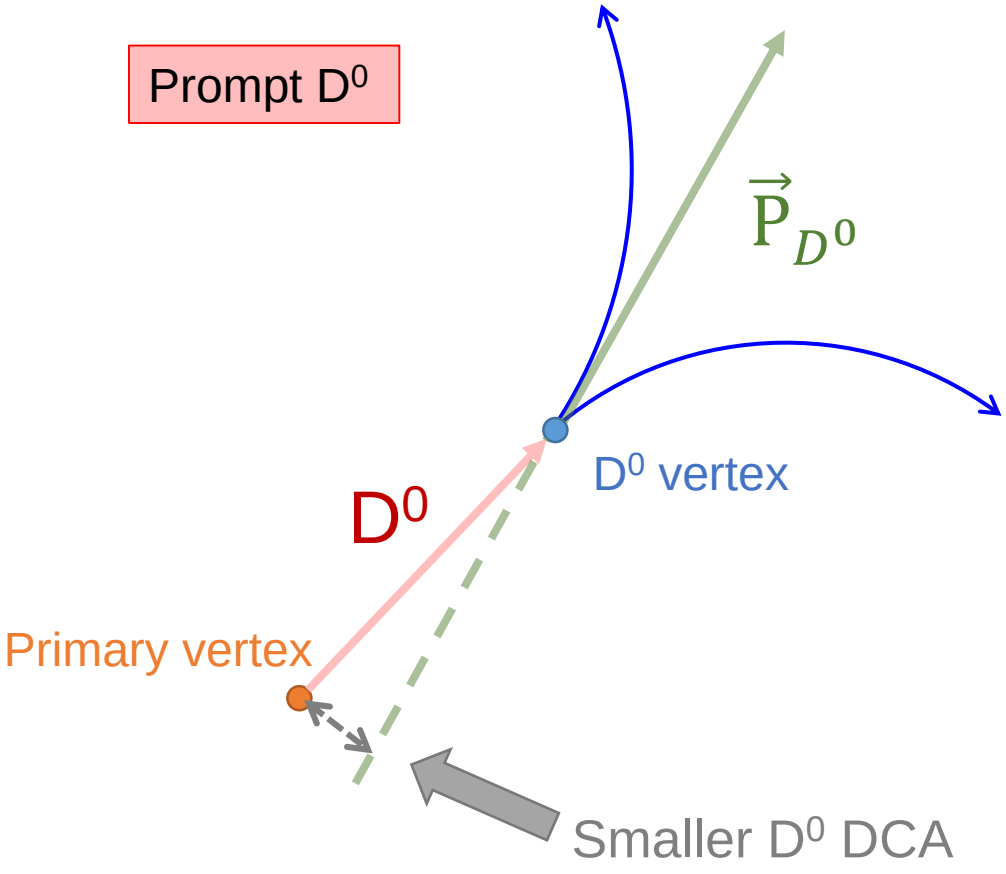
3rd order polynomial for
Combinatorial background

Gaussian shape for
Swapped mass hypothesis
(Wrong K-π mass assignment)



Extraction of Prompt D^0 with DATA

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



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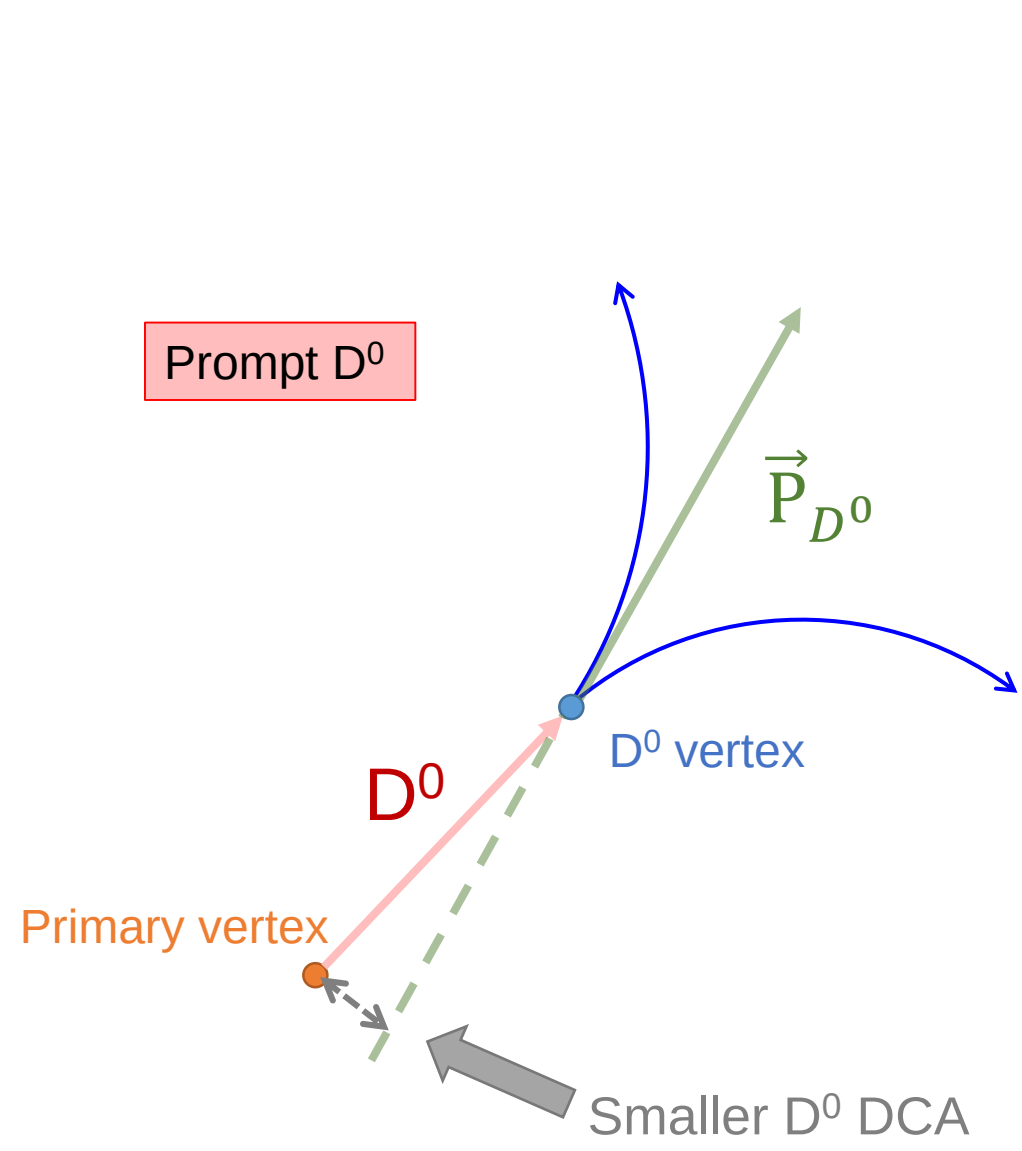
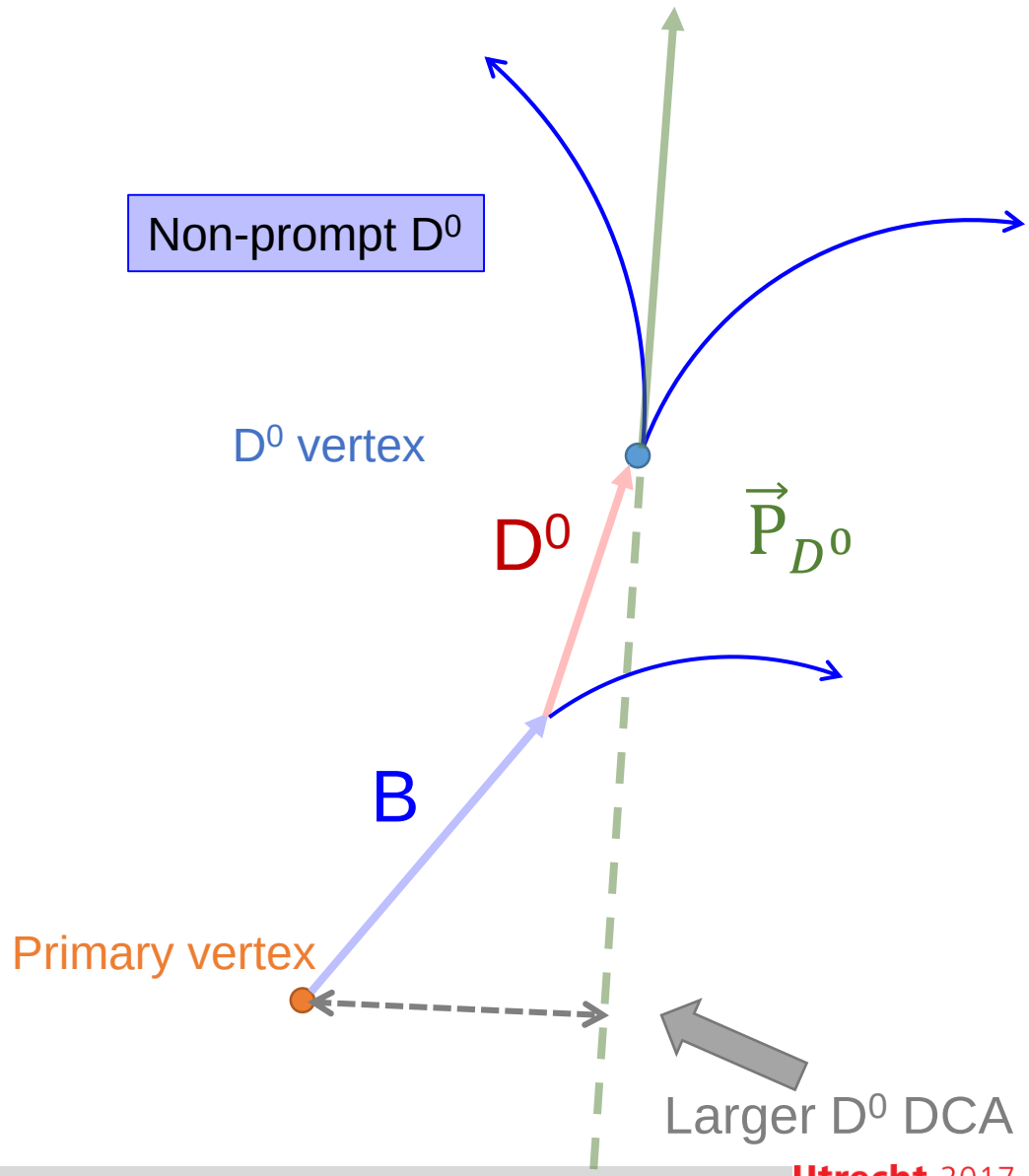
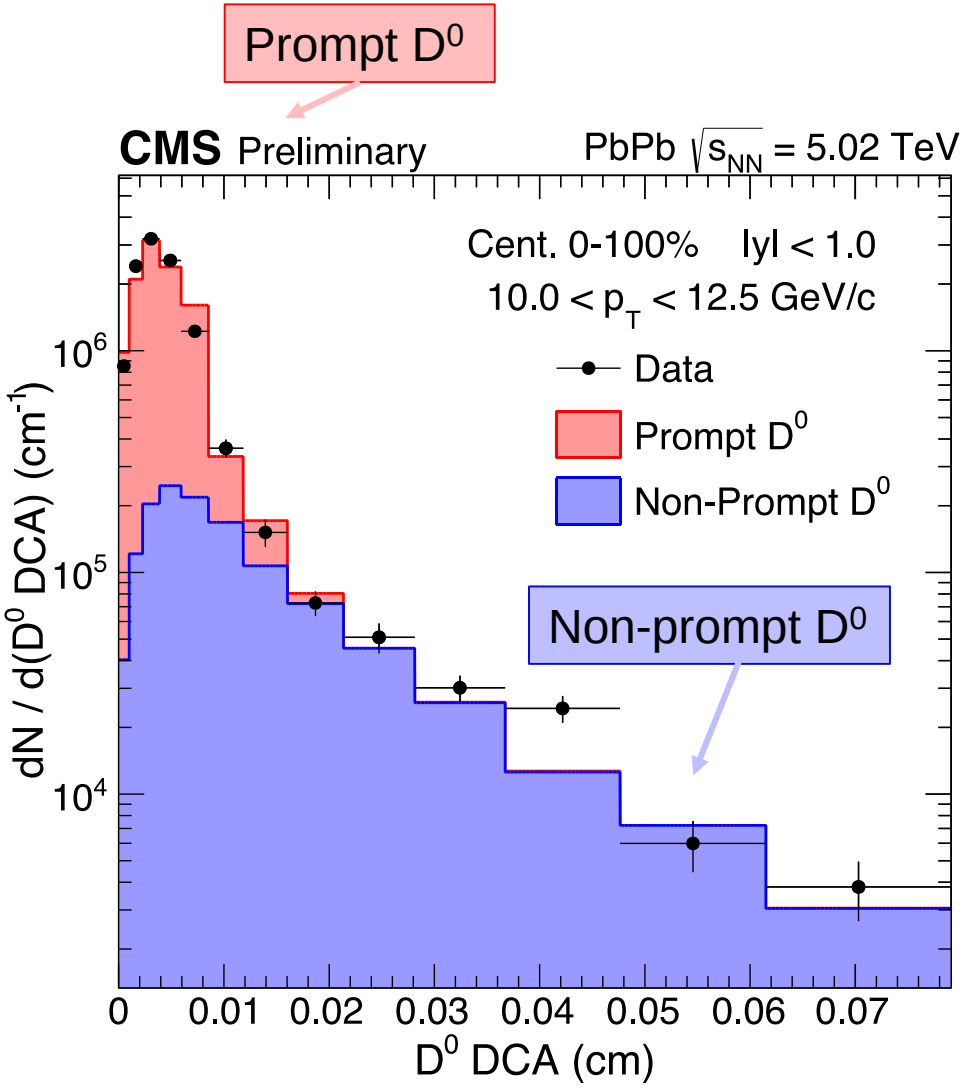


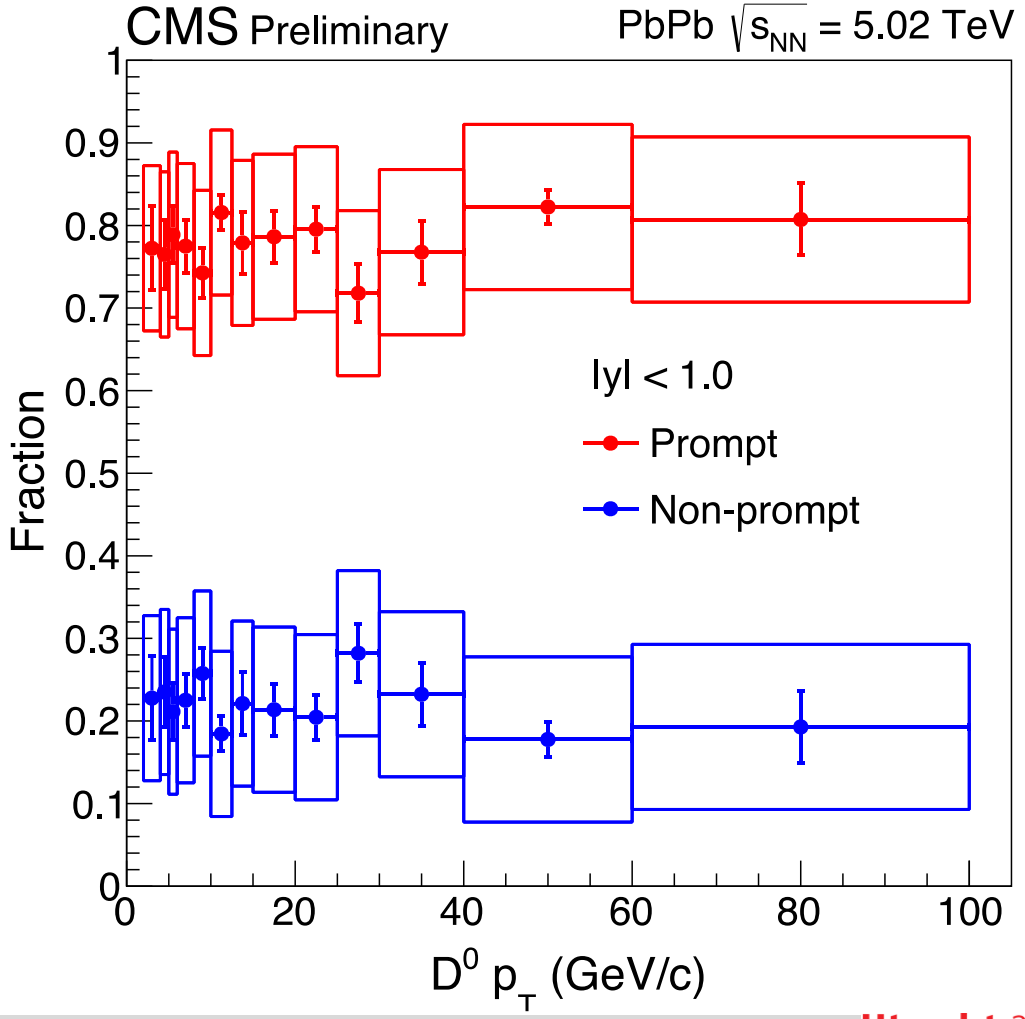


Extraction of Prompt D^0 with DATA

- Significant contribution of non-prompt D^0 from b hadron decays at LHC (**O(10%)**)
- CMS separates prompt and non-prompt D^0 with **D^0 DCA**
- Prompt fraction extraction from a MC template fit

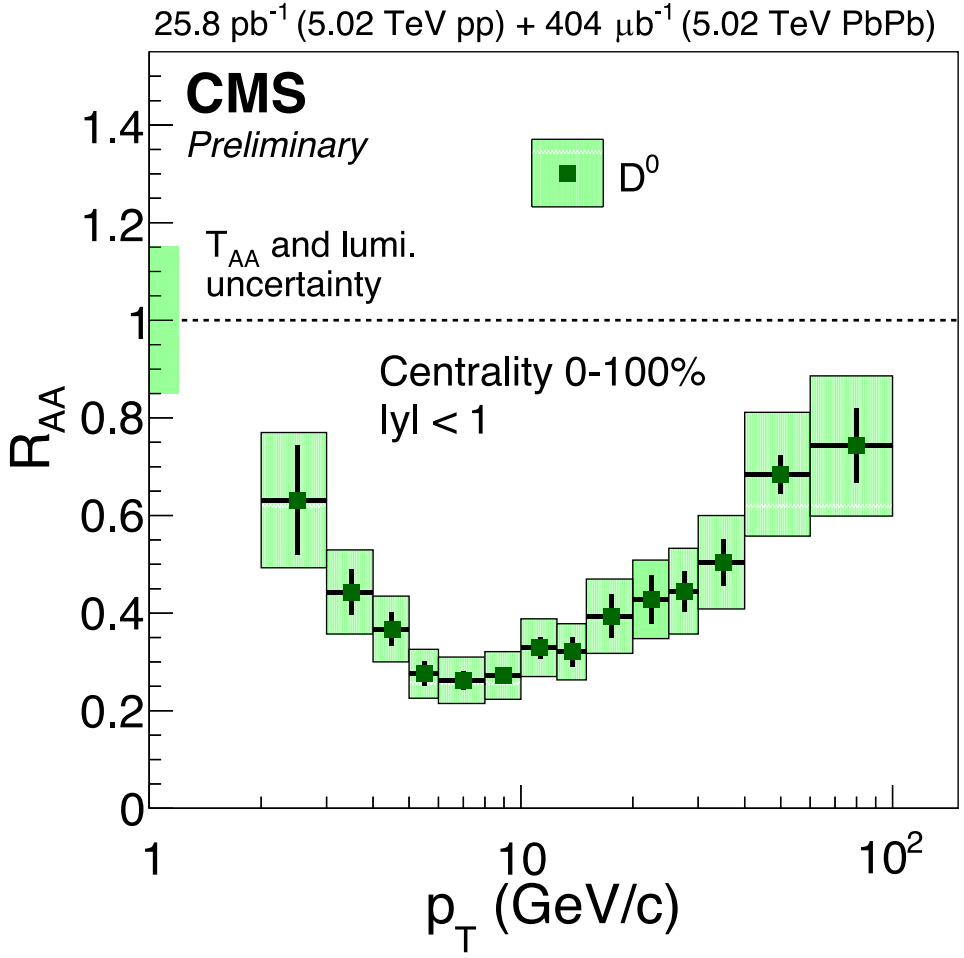


PbPb 0-100%

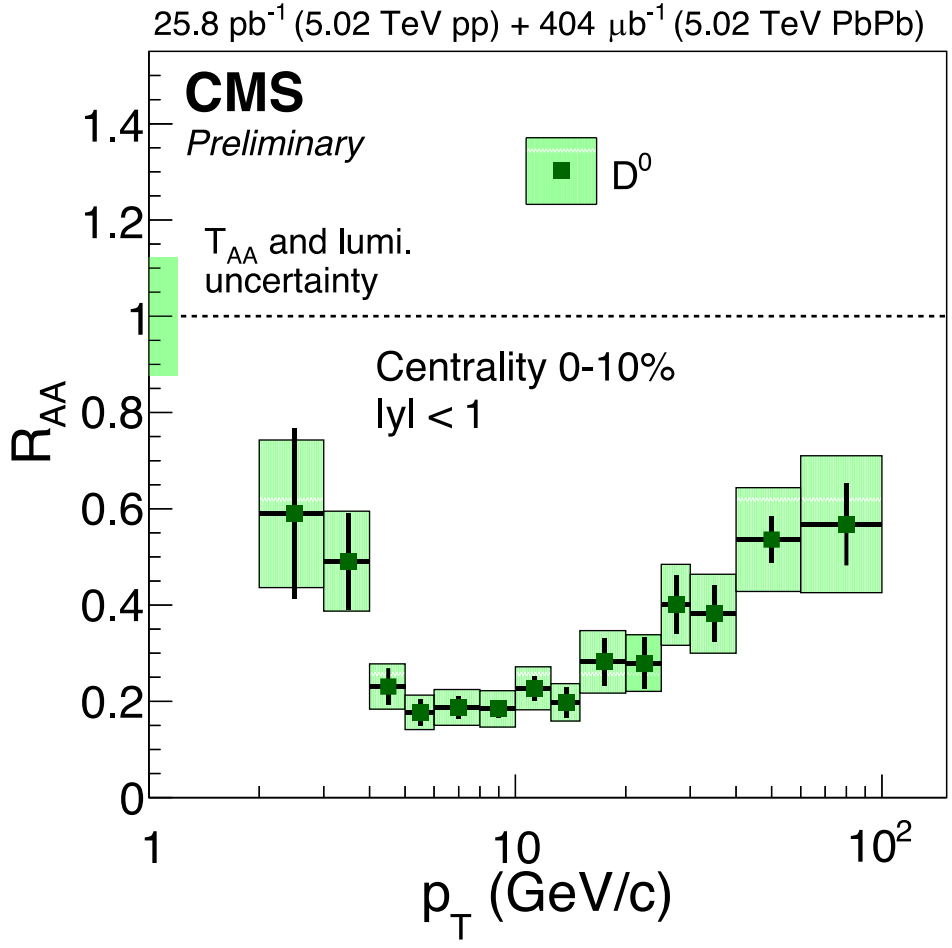


Prompt D^0 R_{AA} in PbPb at 5.02 TeV

PbPb 0-100%



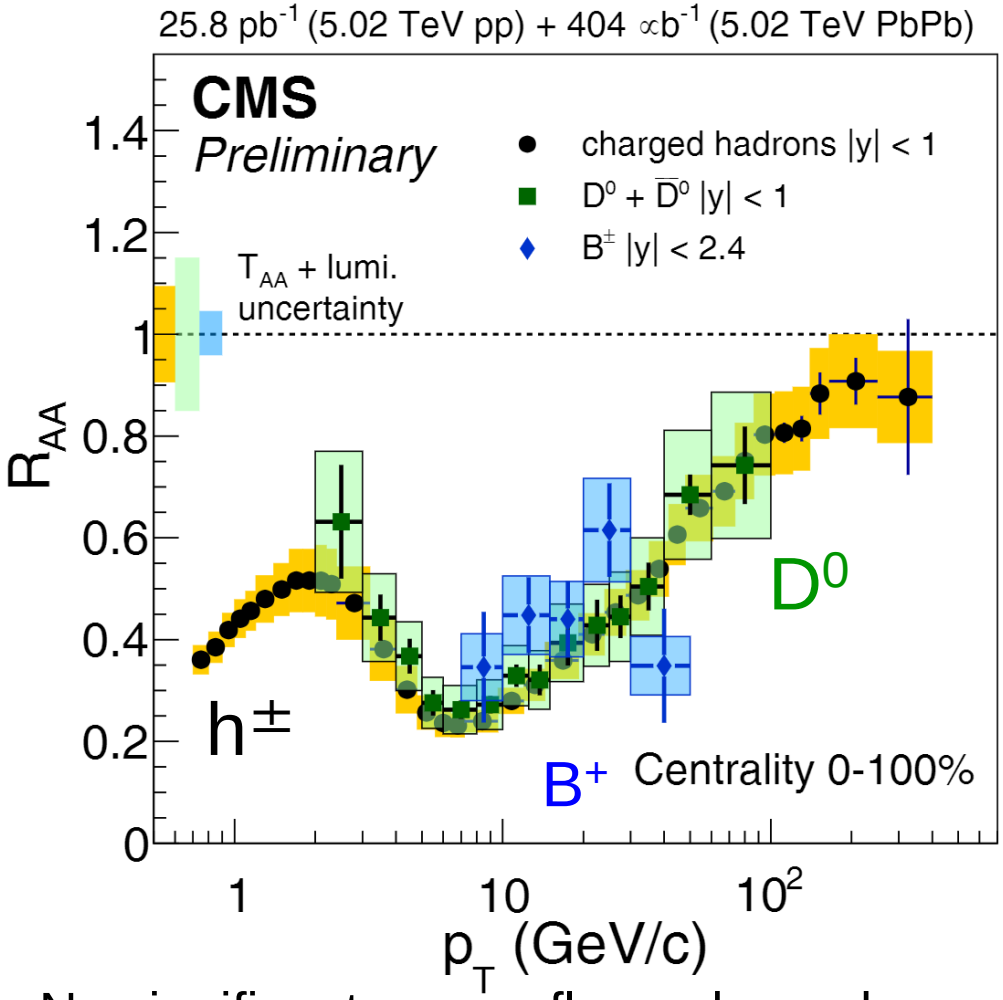
PbPb 0-10%



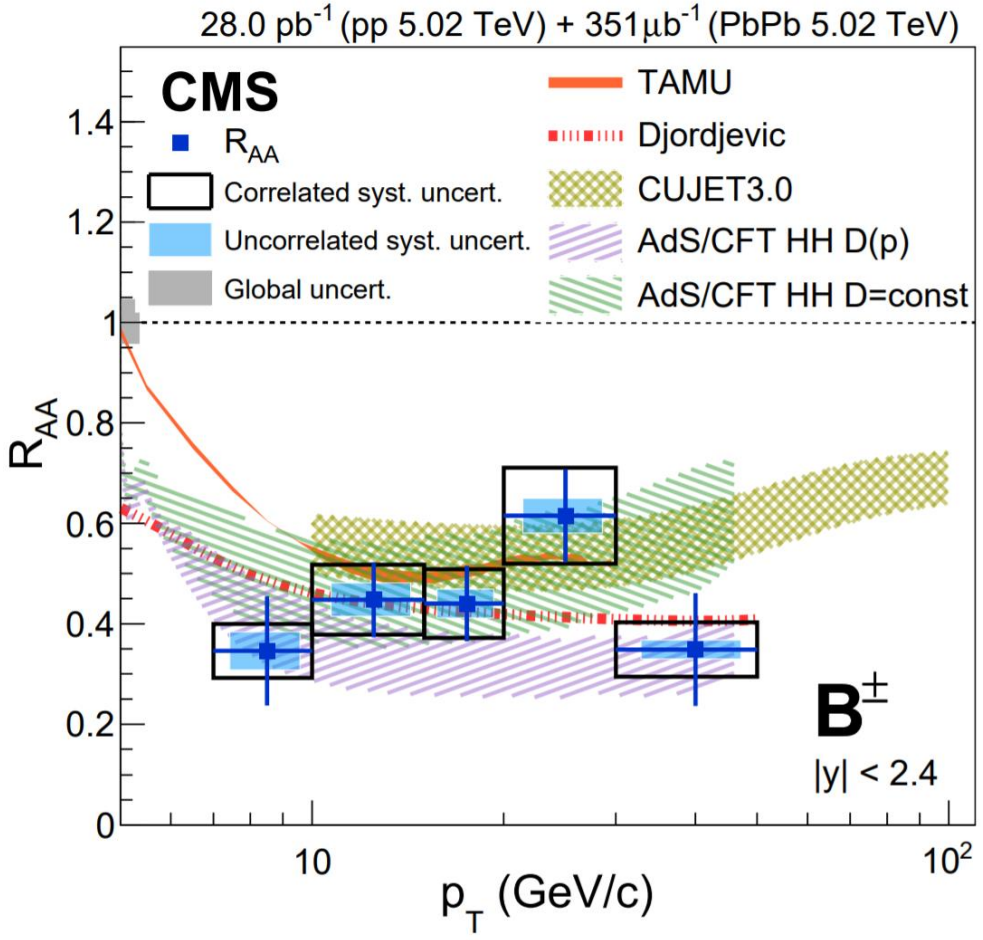
- Strongest suppression around p_T = 5-8 GeV
- 0-10%: Similar suppression compared to ALICE 2.76 TeV result

D^0, B^+ and $h^\pm$ R_{AA} in PbPb at 5.02 TeV

PbPb 5.02 TeV



B^+ R_{AA} vs. theory NEW!



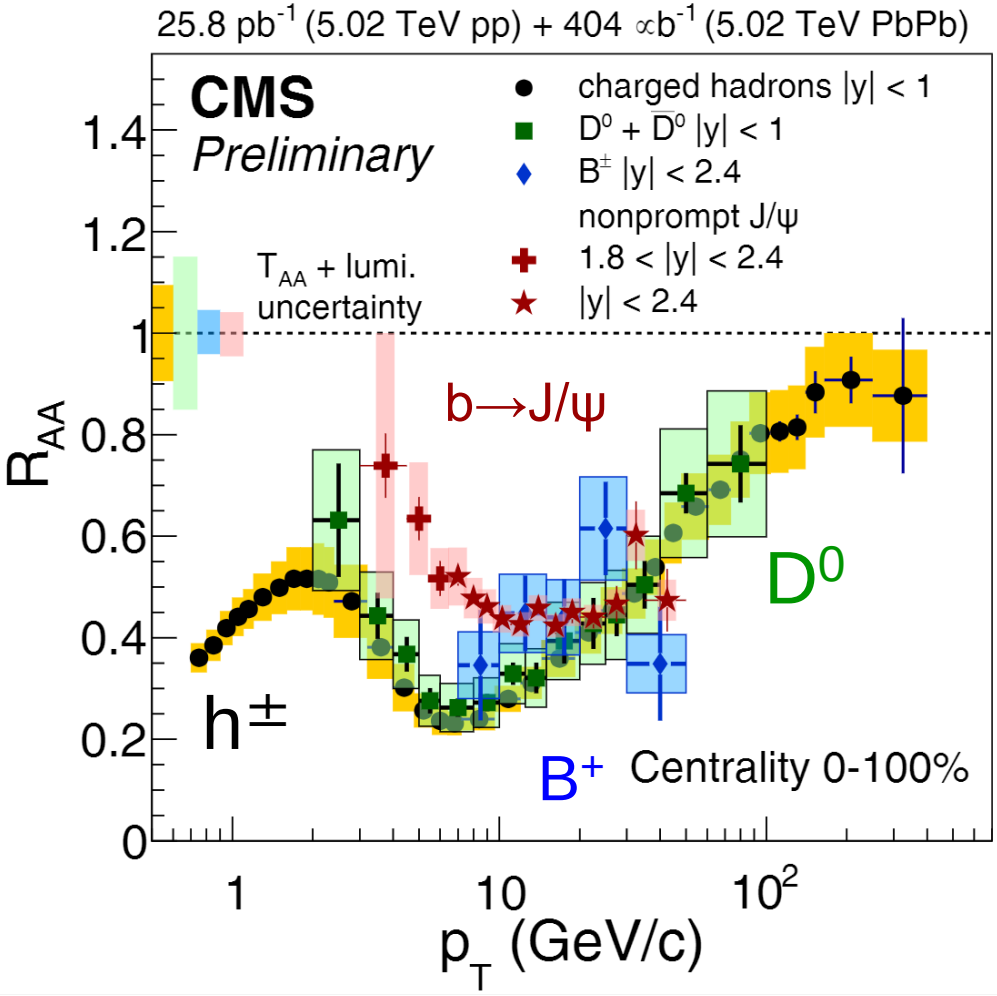
- No significant meson flavor dependence of R_{AA} at high p_T with the current accuracy

- New B^+ R_{AA} data: could constrain the coupling strength between b-quark and the medium in the theoretical models

Charged particle R_{AA} JHEP 04 (2017) 039
B meson R_{AA} arXiv:1705.04727 **submitted to PRL**

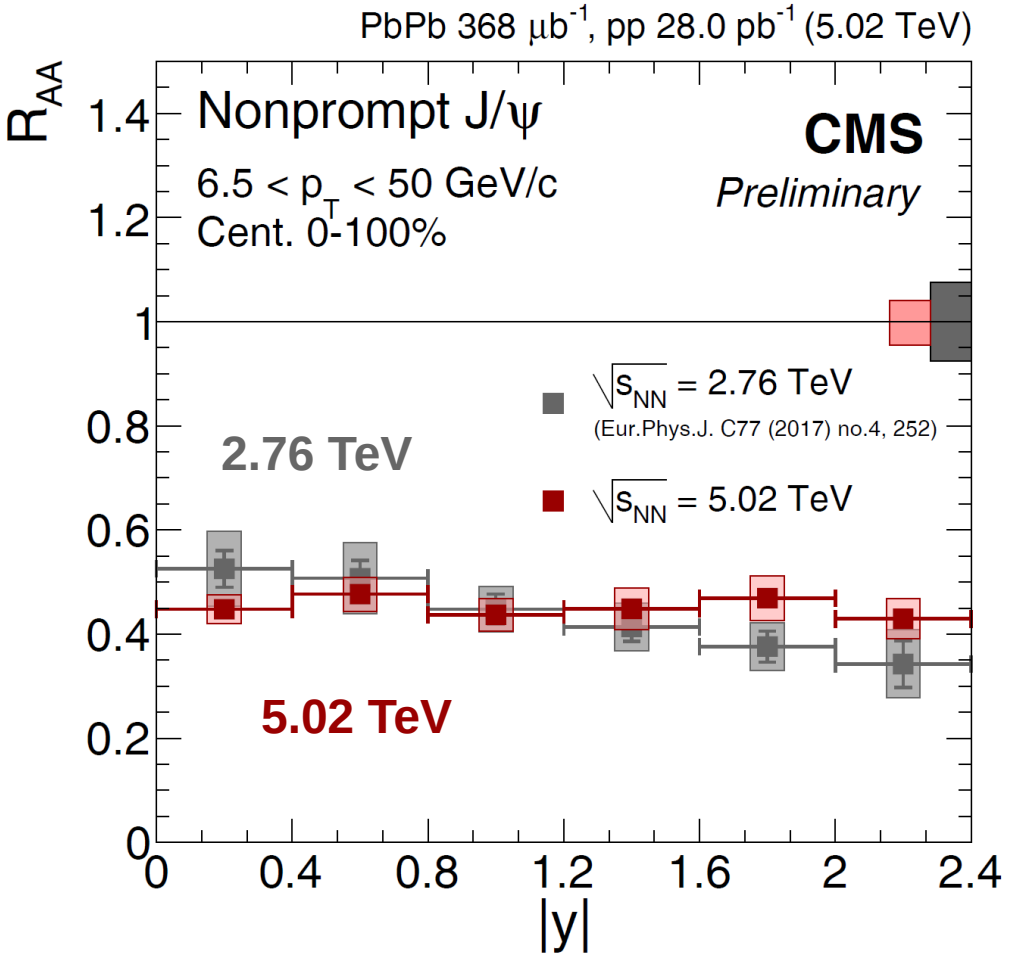
D^0, B^+ , b→J/ψ and $h^\pm$ R_{AA} in PbPb at 5.02 TeV

PbPb 5.02 TeV NEW!



- **New b→J/ψ R_{AA}** results at **5.02 TeV!**
- Significant meson flavor dependence at low p_T

b→J/ψ NEW!

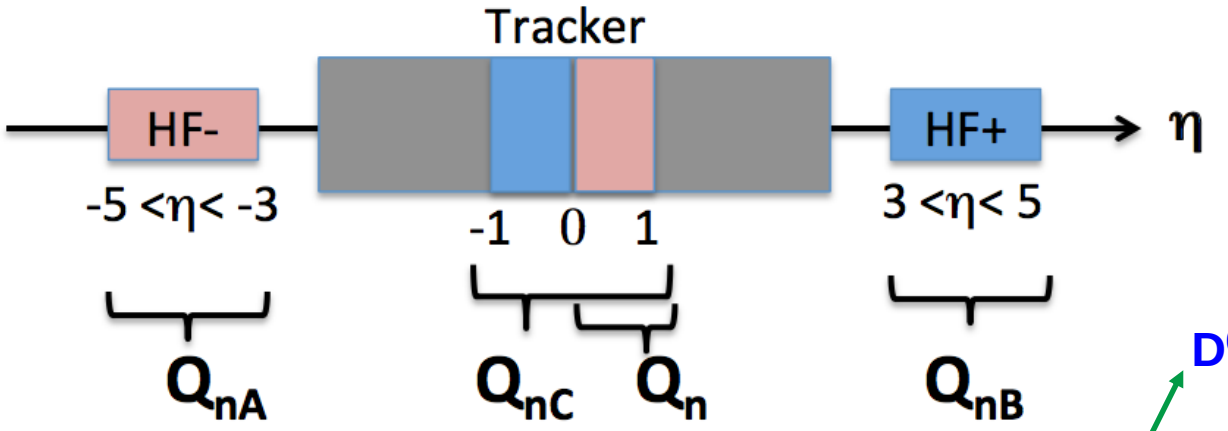


- **b→J/ψ R_{AA}** from 2.76 and **5.02** TeV are compatible to each other.
- No significant |y| dependence at 5.02 TeV

Charged particle R_{AA} JHEP 04 (2017) 039
B meson R_{AA} arXiv:1705.04727 **submitted to PRL**

b→J/ψ R_{AA} CMS-PAS-HIN-16-025

D^0 Azimuthal Anisotropy: Scalar Product Method



$$Q_n = \sum_j w_j e^{inf_j}$$

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

D^0 candidate

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

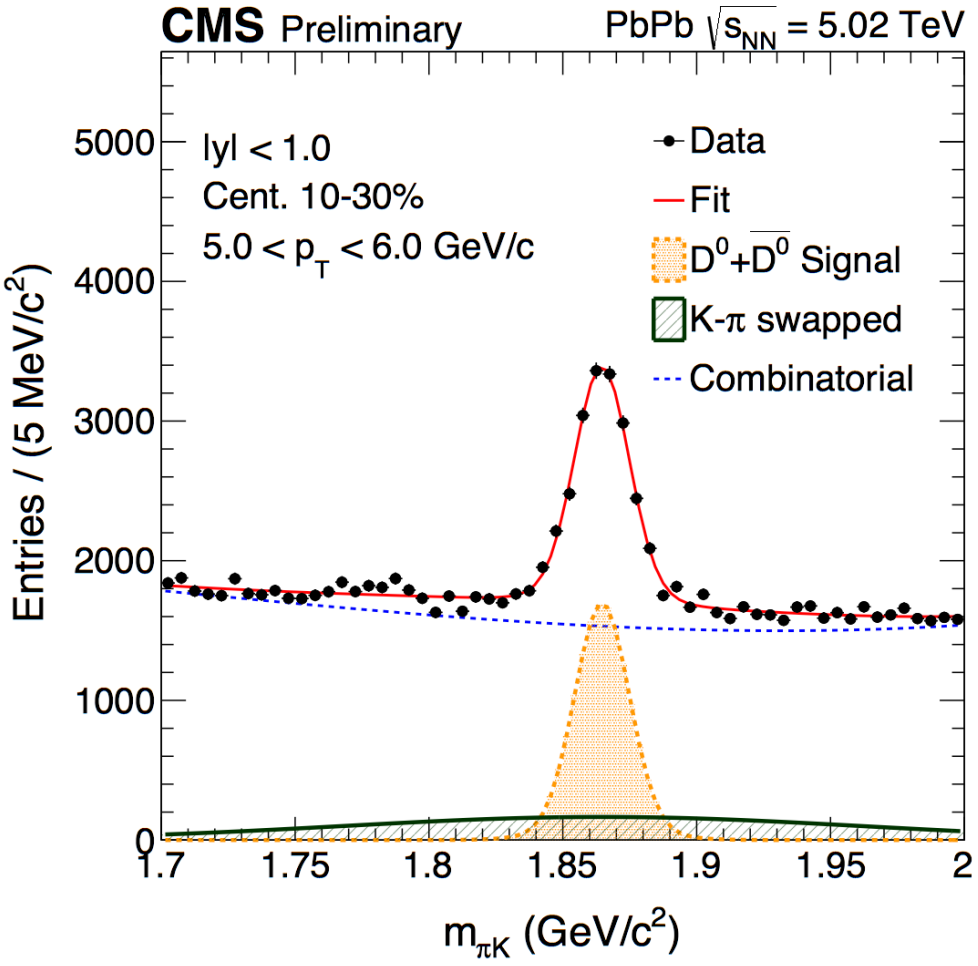
Scaling factor from 3 sub events

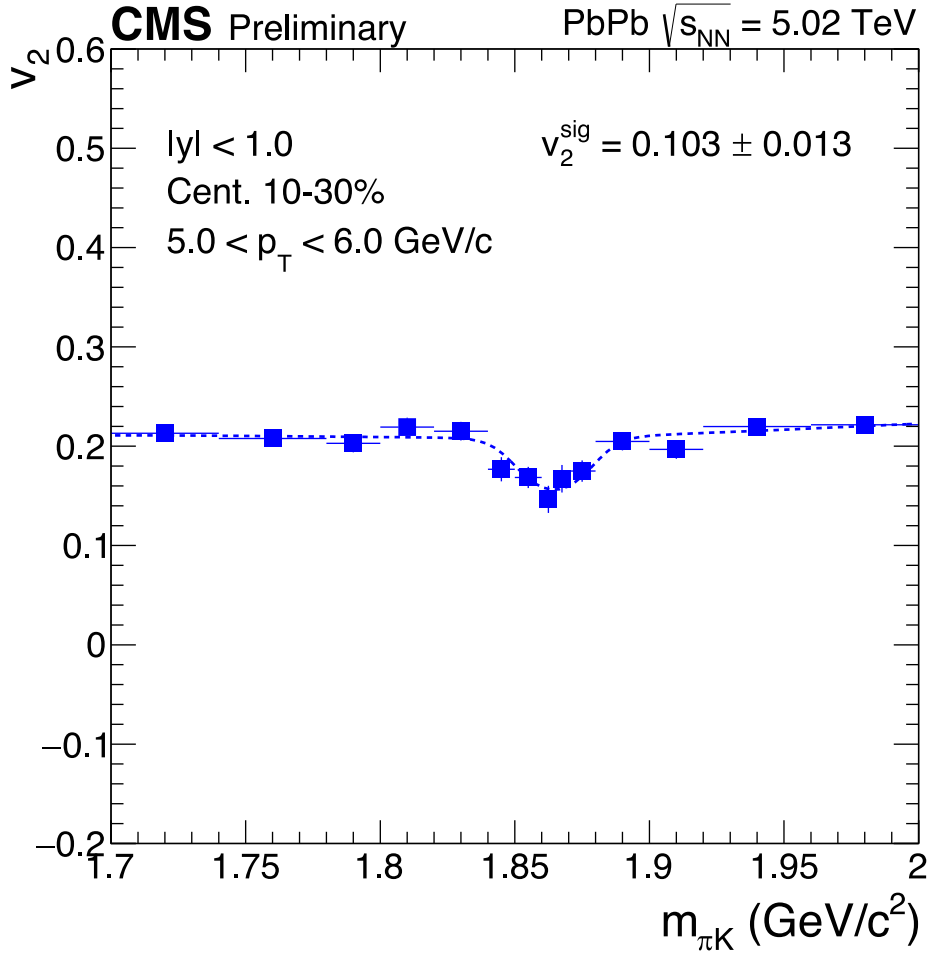
- Large η gap applied (|Δη|>3.0)
- $v_n\{SP\}$, non-ambiguous measure of $\sqrt{\langle v_n^2 \rangle}$

Luzum, Ollitrault PRC87 (2013), 044907

Extract v_n of D^0

D^0 candidate v_n are first measured as a function of candidate mass



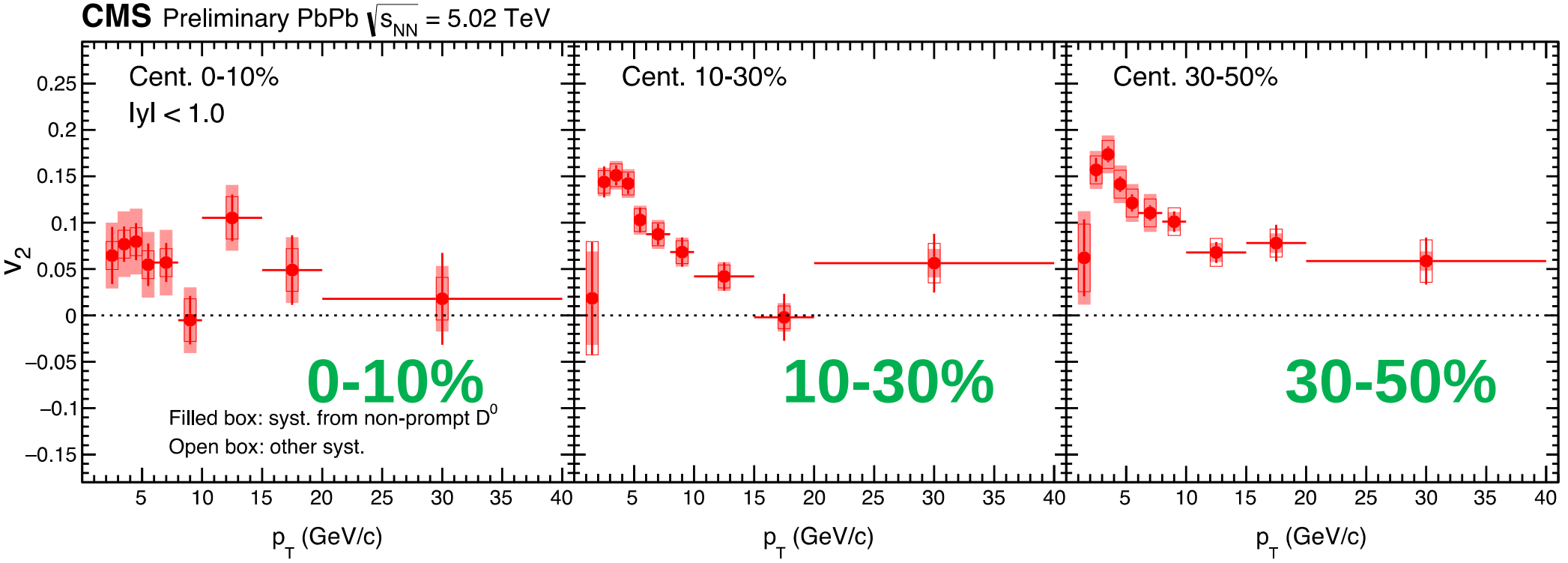


D^0 v_n extracted with a simultaneous fit on D^0 mass spectra and v_n (v_2 or v_3) vs. mass:

$\alpha(m_{inv})$: D^0 signal fraction

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

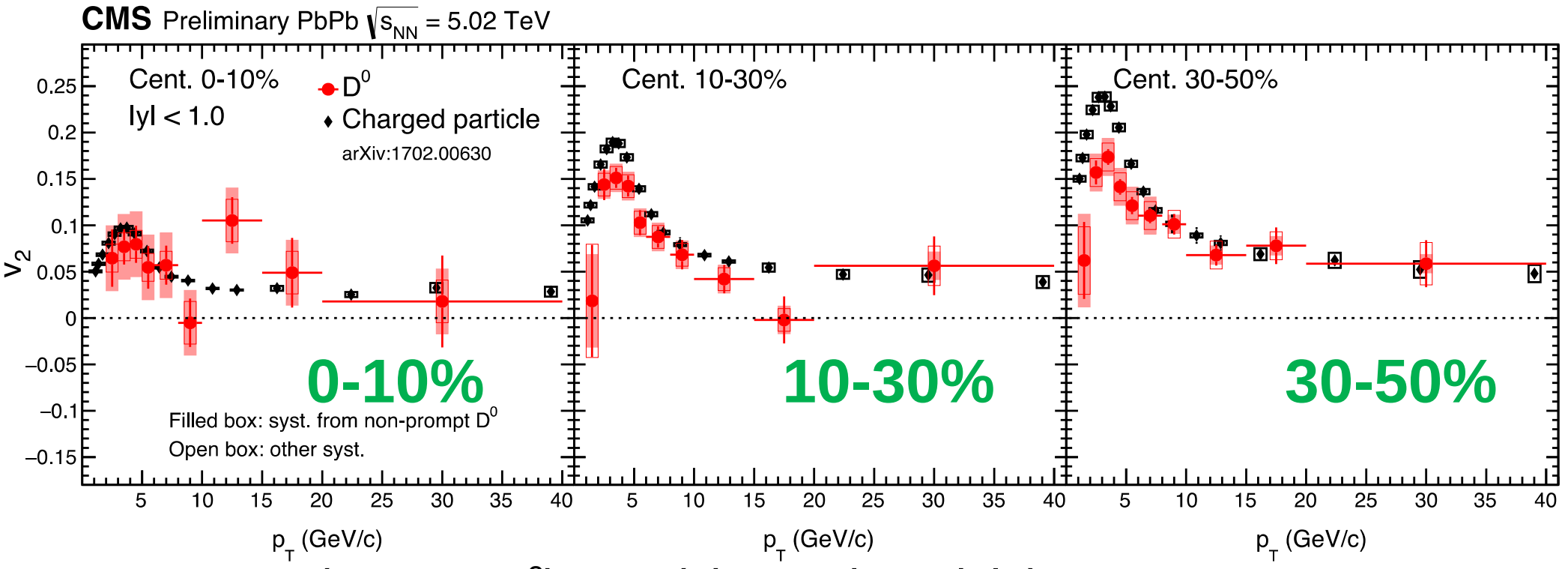
Prompt D^0 v_2 in PbPb at 5.02 TeV



- Positive prompt D^0 v_2 observed in p_T range studied
  - Low p_T: charm quark collective motion
  - High p_T: path length dependence of energy loss
- In 30-50%, D^0 v_2 peaks around 3 GeV, then decrease vs p_T

CMS PAS HIN-16-007

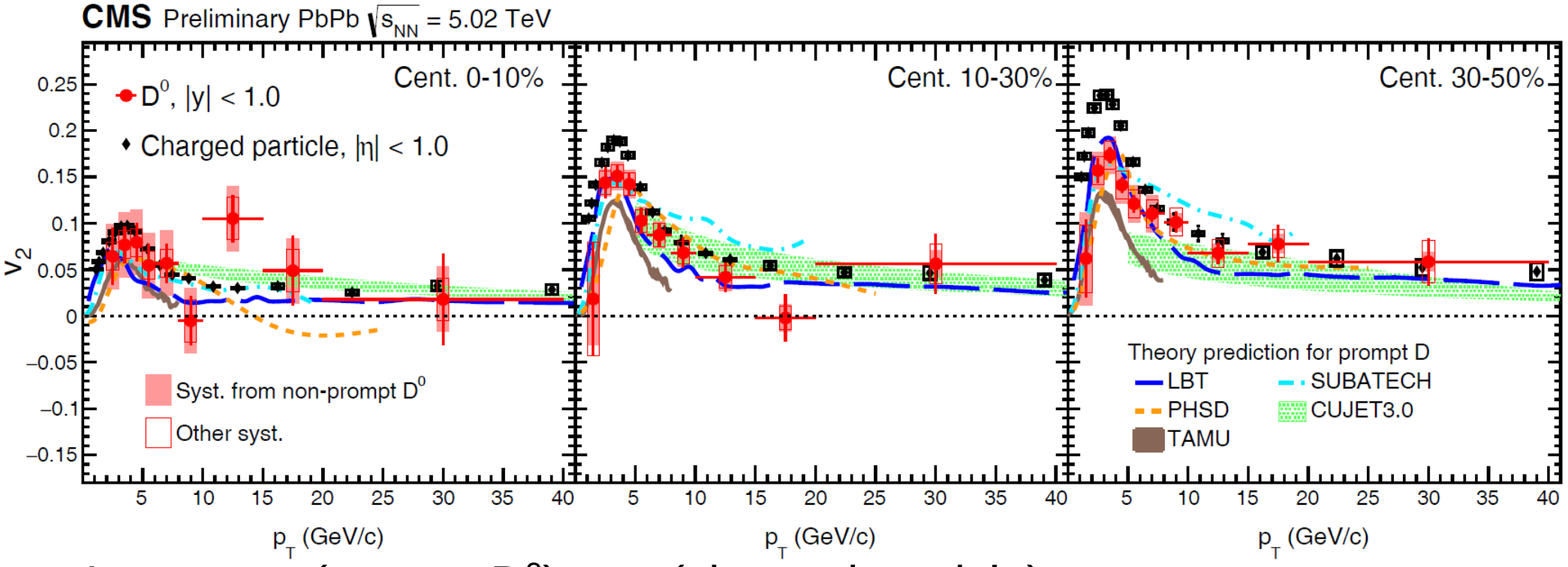
Prompt D^0 v_2 vs. Charged Particle v_2



- Low p_T: v_2 (prompt D^0) < v_2 (charged particle)
  - Indication of weaker centrality dependence than charged particles
- High p_T: v_2 (prompt D^0) ≈ v_2 (charged particle)
  - A consistent picture of ΔE (charm) ≈ ΔE (light quark) at high p_T from R_{AA} and v_2 analyses
- Similar p_T dependence

CMS PAS HIN-16-007

Prompt D^0 v_2 vs. Theoretical Models



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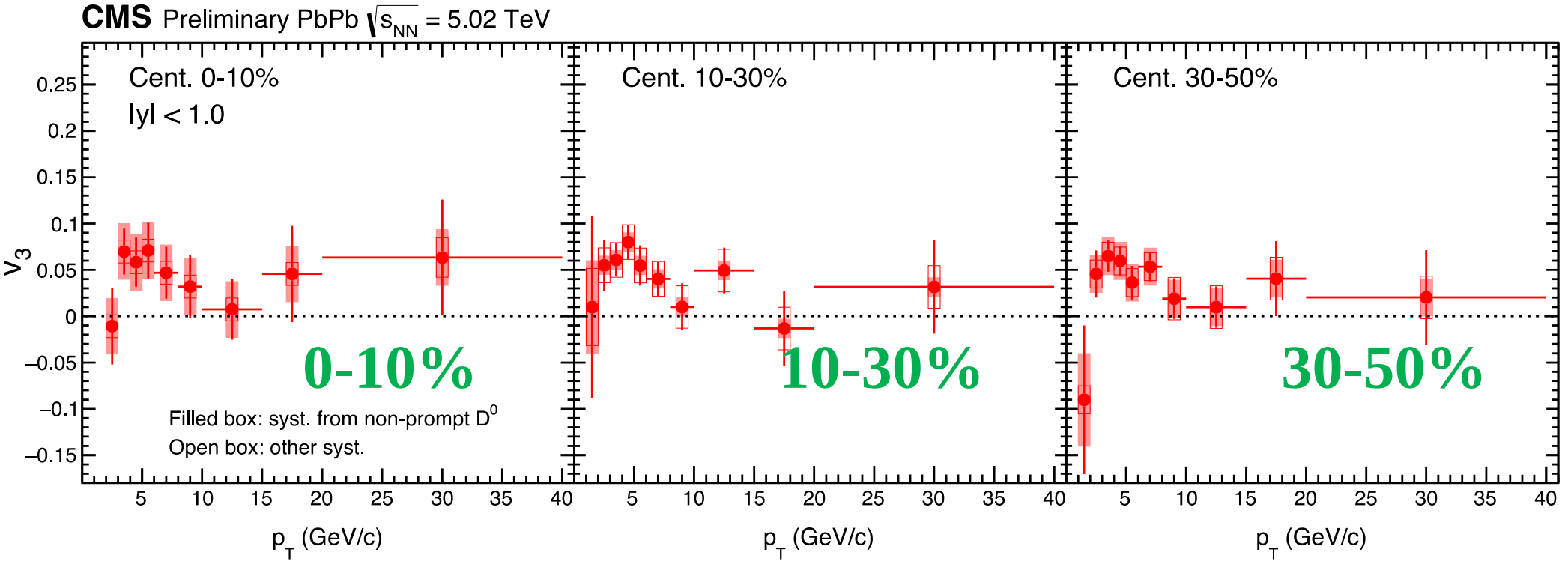
CMS PAS HIN-16-007

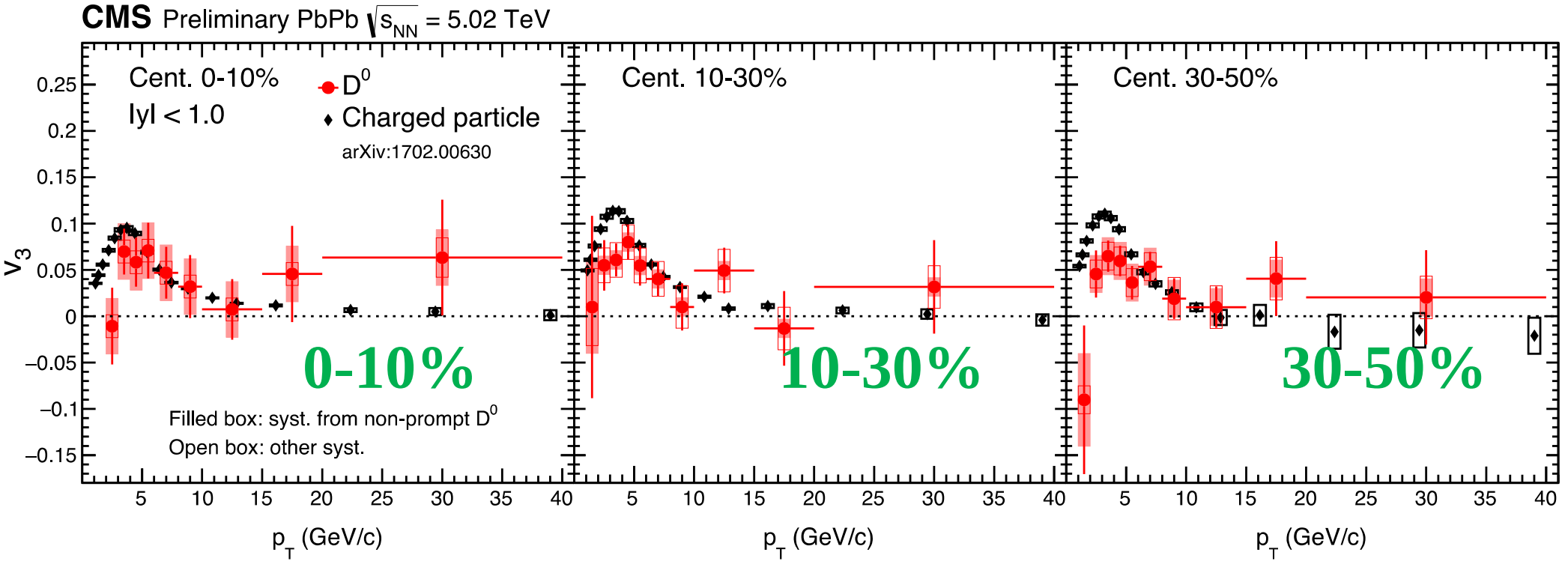
Prompt D^0 v_3 in PbPb at 5.02 TeV



- First measurement of D^0 v_3
- Low p_T: v_3 (prompt D^0) > 0; High p_T: v_3 (prompt D^0) ≈ 0
- v_3 Peaks around 3-5 GeV, then decrease vs. p_T
- Little centrality dependence

CMS PAS HIN-16-007

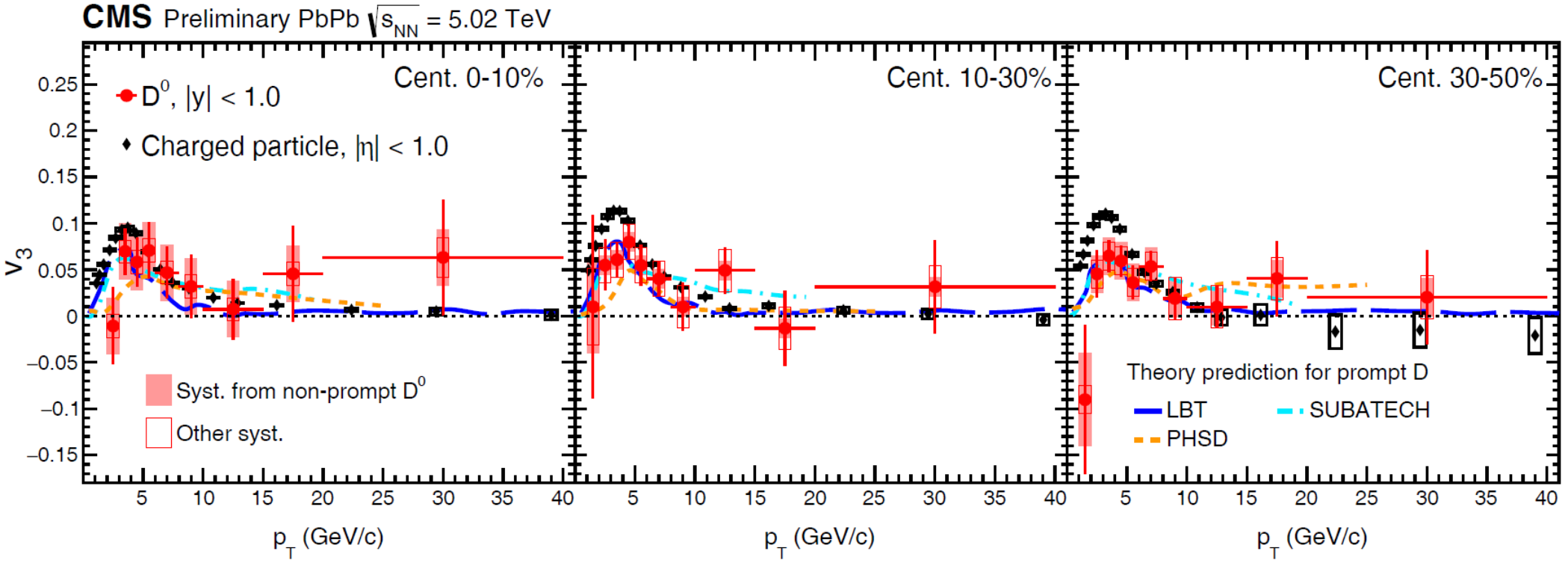
Prompt D^0 v_3 vs. Charged Particle v_3



- 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 p_T dependence
- Both have little centrality dependence

CMS PAS HIN-16-007

Prompt D^0 v_3 vs. Theoretical Models



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- Both have little centrality dependence

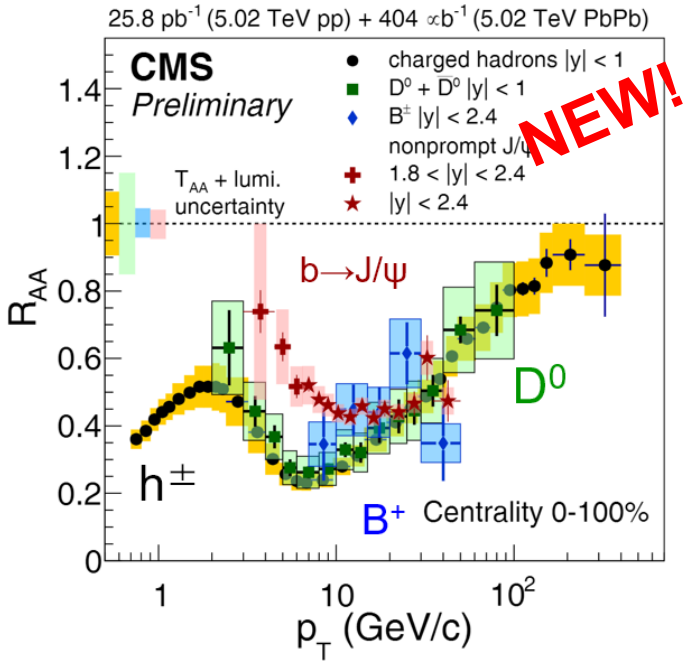
CMS PAS HIN-16-007

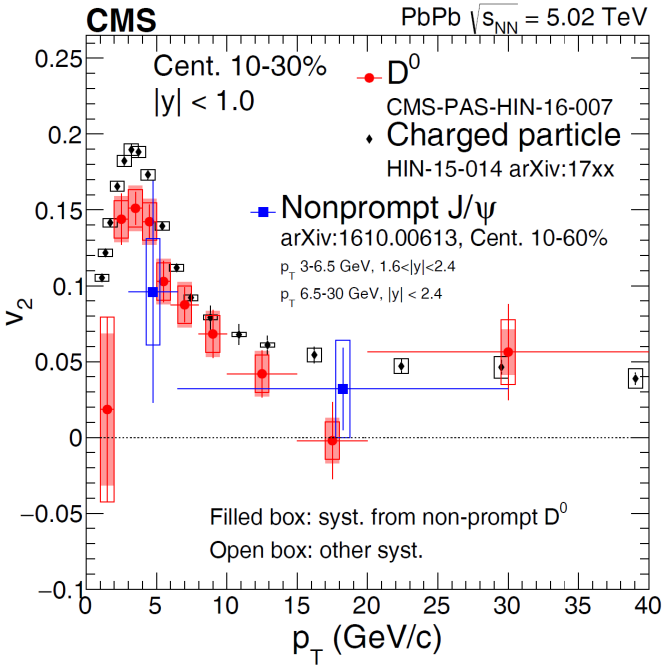
Summary & Outlook

- **D^0, B^+ and b→J/ψ R_{AA} in PbPb at 5.02 TeV**
  - First fully reconstructed B^+ analysis
  - b→J/ψ R_{AA} **(NEW)**: no significant |y| dependence
  - Strong suppression of D^0, B^+ and b→J/ψ, similar to $h^\pm$ at high p_T
  - Significant flavor dependence of R_{AA} at low p_T

- **D^0 v_2 and v_3 are measured for 3 centrality classes in PbPb at 5.02 TeV**
  - Weaker centrality dependence of D^0 v_2 than $h^\pm$ v_2
  - First measurement of D^0 v_3
  - Data consistent with models with charm flow: Light flavor azimuthal anisotropy could "transfer" to heavy flavor particles efficiently

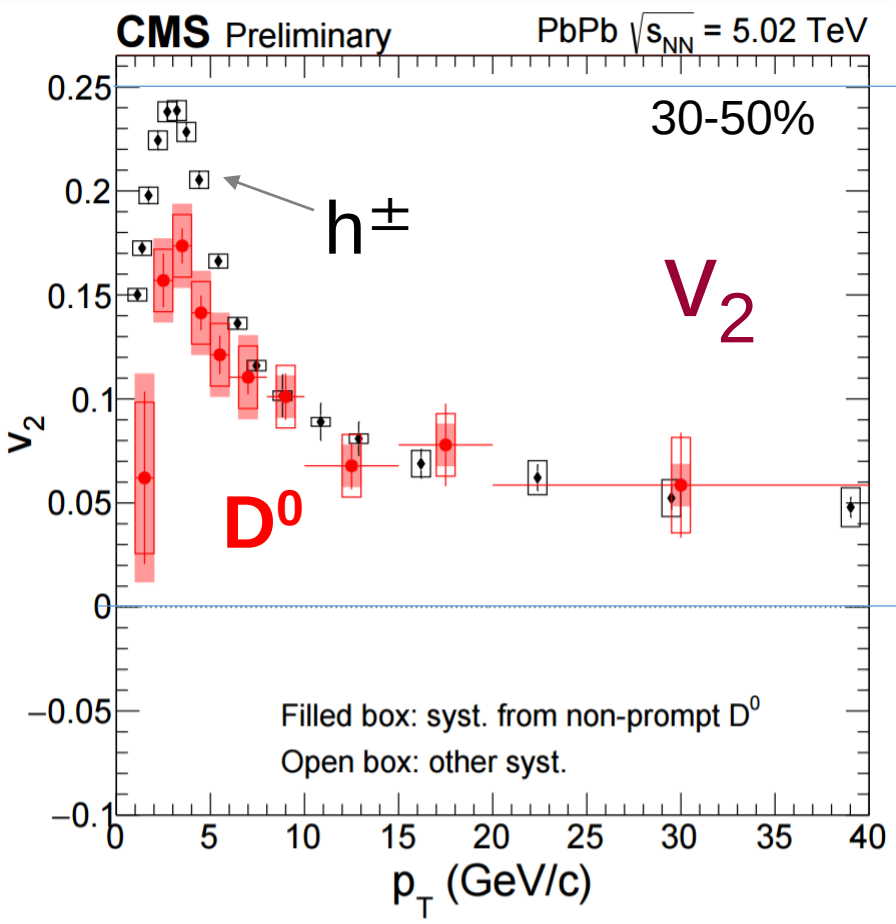
- **Provide important inputs for theory models**
  - Many more results from 5 TeV data in the pipeline
  - Expect high precision results with 2018 and Run III data … stay tuned!

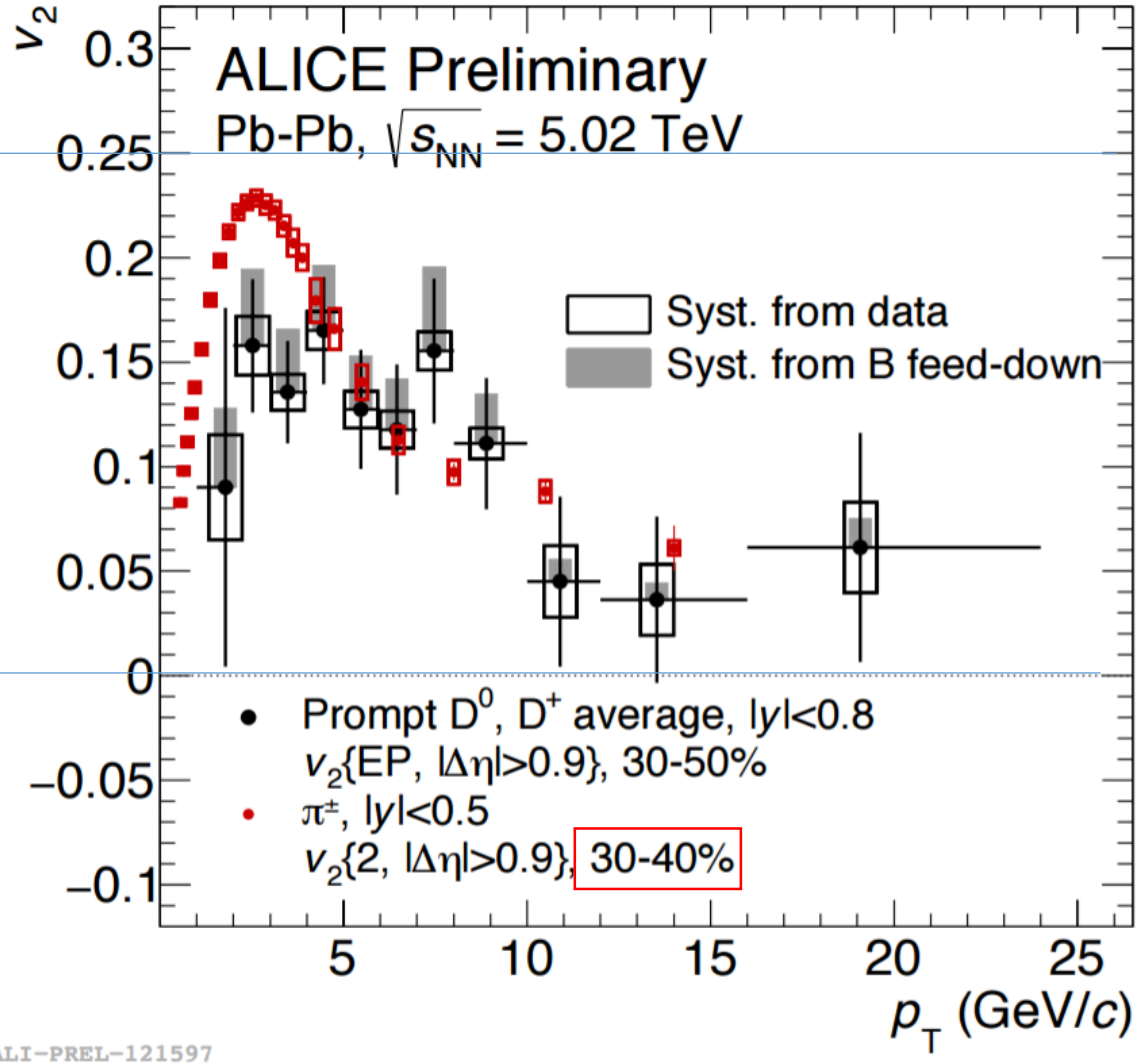




- Backup slides

The Life of Charm Quark in the Soup



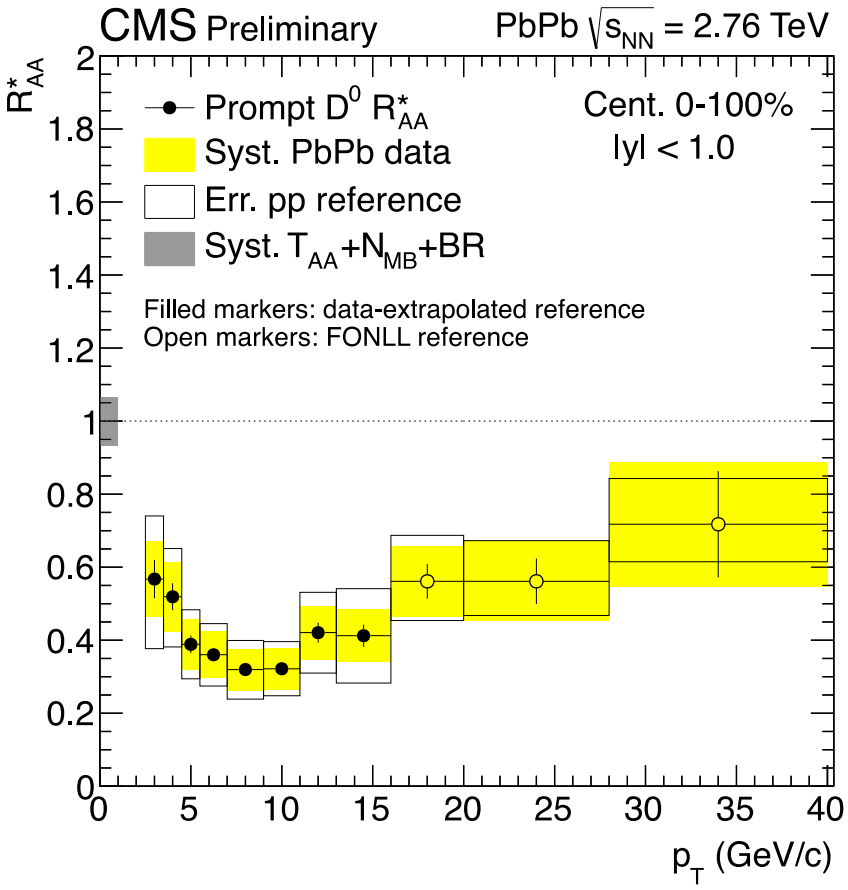


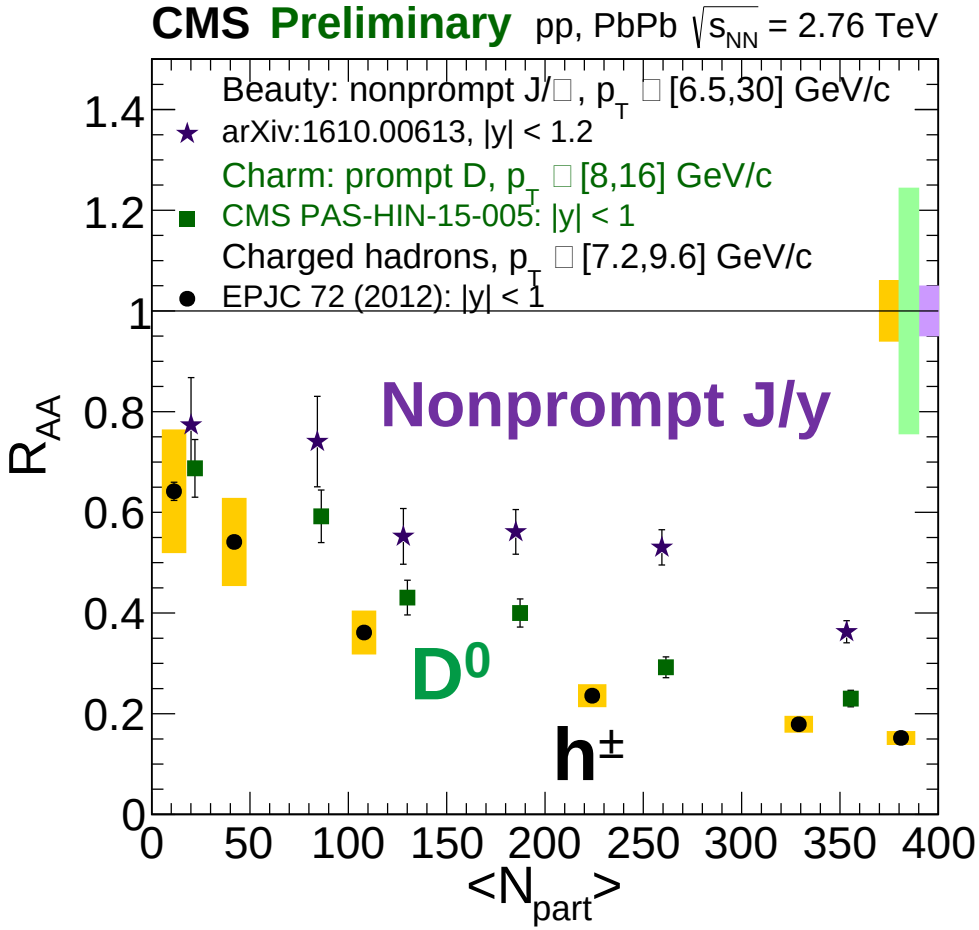
- At low p_T: **D^0 v_2** signal is significantly lower than that of charged particles
- At high p_T: **D^0 v_2 ≈ charged particle v_2**

  Same parton energy loss picture from high p_T D^0 R_{AA} and v_2 measurements

CMS-PAS-HIN-16-007

D meson measurement with CMS in Run-I



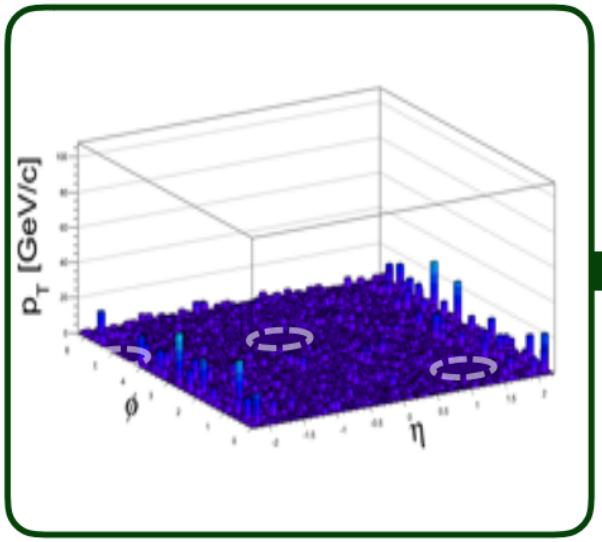


- Run I data: 30M MB PbPb events at 2.76 TeV
- D^0 R_{AA} both as functions of p_T and centrality
  - pp reference: data-extrapolated and FONLL
- Hint of flavor dependent R_{AA}

CMS PAS HIN-15-005

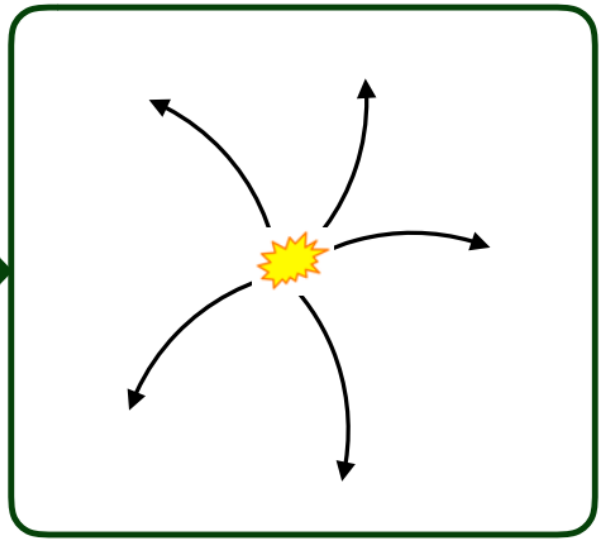
Online D^0 triggers

Hardware L1 jet triggers selection



- Level-1 (L1) jet algorithm with online background subtraction

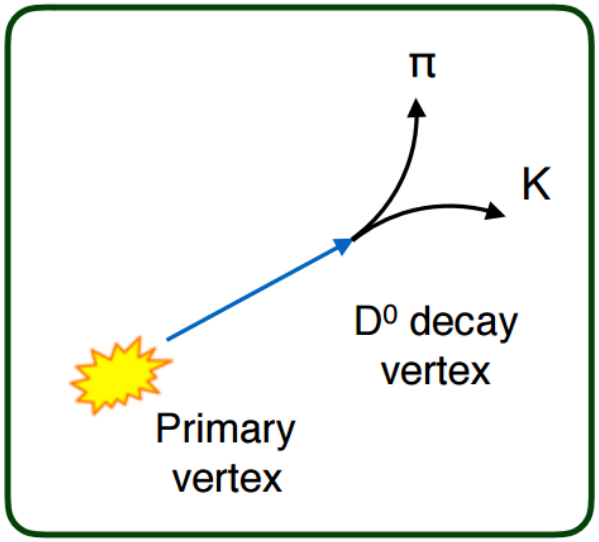
Track selection in software triggers



Track seed p_T cut applied:

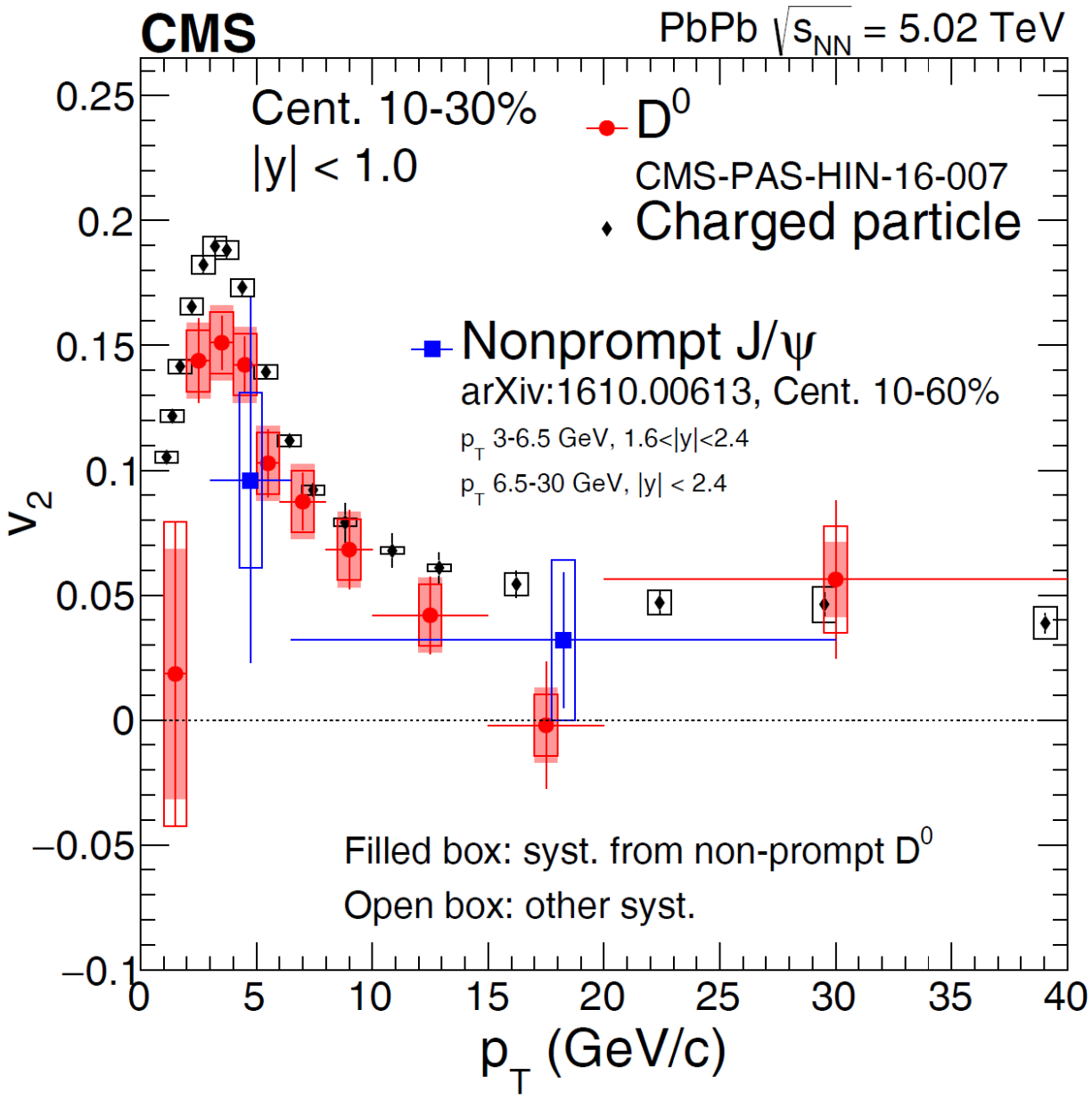
- $p_T > 2$ GeV for pp
- $p_T > 8$ GeV for PbPb

D^0 selection

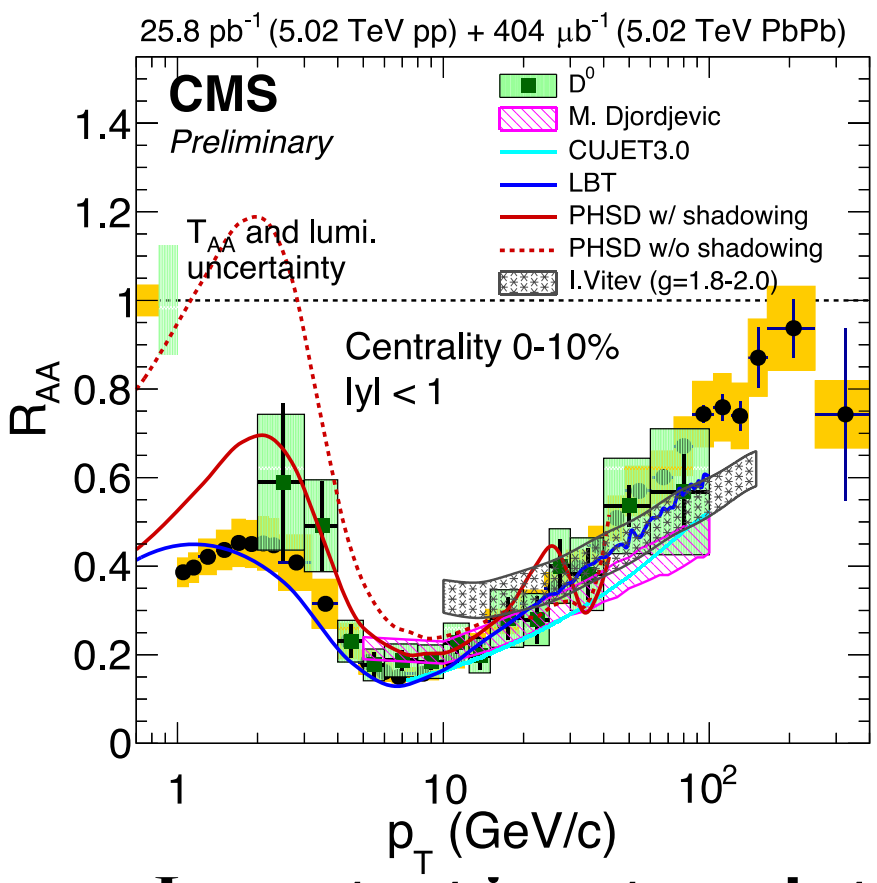


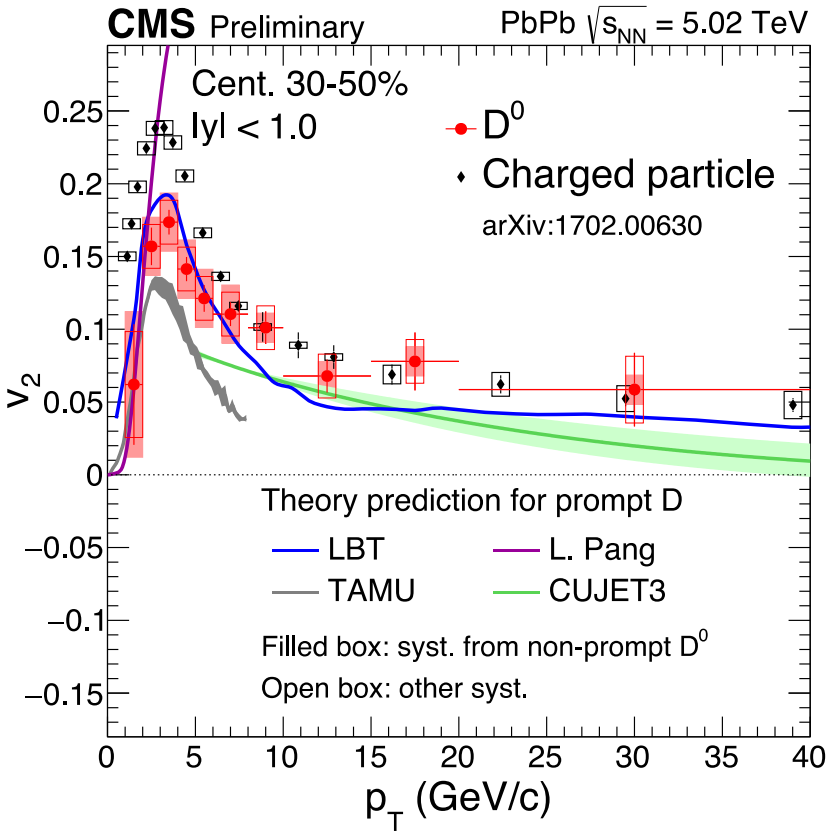
- D^0 online reconstruction
- loose selection based on D^0 vertex displacement

Comparison between D0 and non-prompt J/ψ



Comparison with model calculations



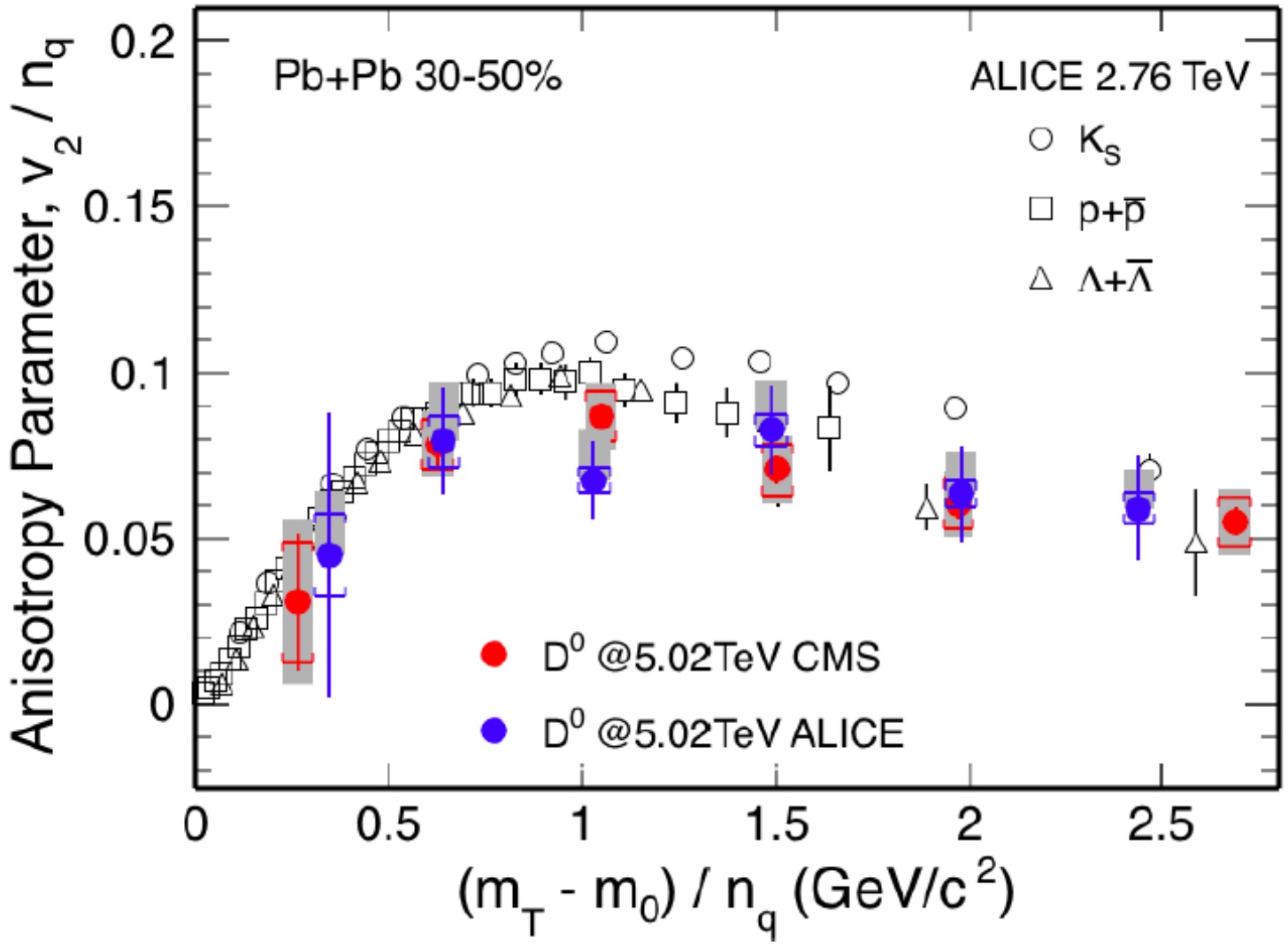


Important inputs and strong constraints on theory:

- **Theoretical calculations need to describe D^0 R_{AA} and v_n results simultaneously in a wide kinematic range**
- **Good progress has been made recently**

M. Djordjevic: PRC 92, 024918 (2015)
PHSD: PRC 93, 034906 (2016)
I. Vitev: PRD 93, 074030 (2015)
CUJET3: JHEP 1602 (2016) 169
LBT: PRC 94 014909 (2016)
TAMU: PLB 735 (2014) 445
L. Pang: PRD 91, 074027 (2015)

D^0 v_2 compared to light hadrons



D^0 v_2 seems to fall on the trend of light flavor

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