D^0 meson R_{AA} in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and elliptic flow in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV with CMS

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on behalf of the CMS Collaboration

Massachusetts Institute of Technology

Quark Matter 2018

05/15/2018

Heavy quarks as hard probes to study QGP

- Heavy quarks: $m_q \sim$ O(GeV)

➡ Creation in the early hard scattering process. Calculable in pQCD.

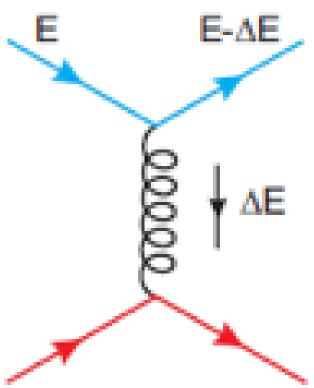
➡ Long thermal relaxation time

- Significant fraction of energy loss when propagating through QGP

➡ Probe QGP by studying the energy loss mechanism

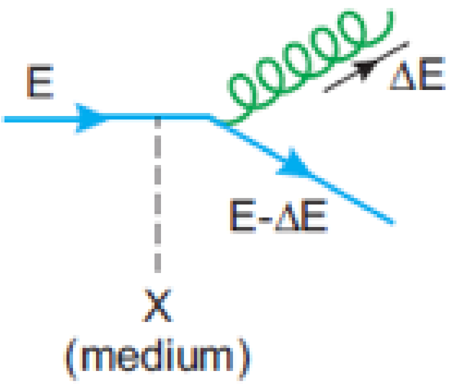
Energy loss mechanism of heavy quarks

pQCD: Collisional



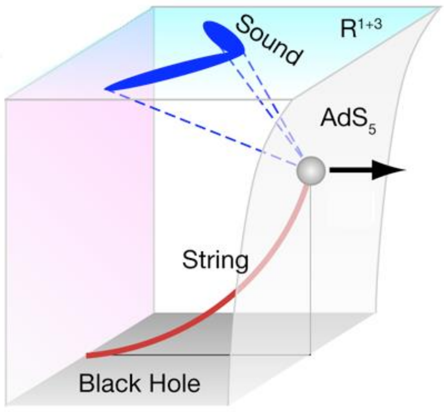
$$-\frac{dE}{dx} = \kappa_{coll} T^2$$

Radiative



$$-\frac{dE}{dx} = \kappa_{rad} T^3 x$$

AdS/CFT: Drag Force



$$-\frac{dE}{dx} = \frac{4}{\pi} E_{in} \frac{x^2}{x_{stop}^2} \frac{1}{\sqrt{x^2 - x_{stop}^2}}$$

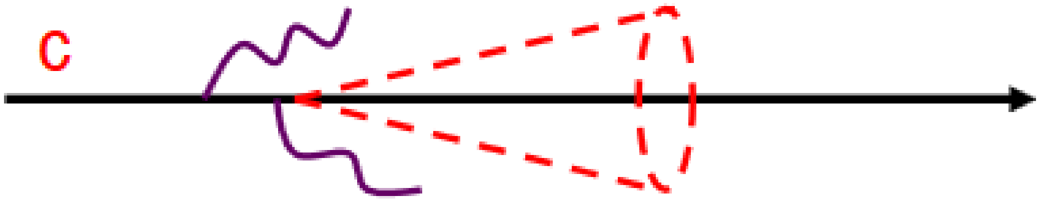
Nuclear Modification Factor in Heavy Ion Collisions

- **p_T spectrum and R_{AA}**

➡ Test the calculations of perturbative QCD in pp collisions
➡ Understand the QGP medium effects on heavy flavor quarks

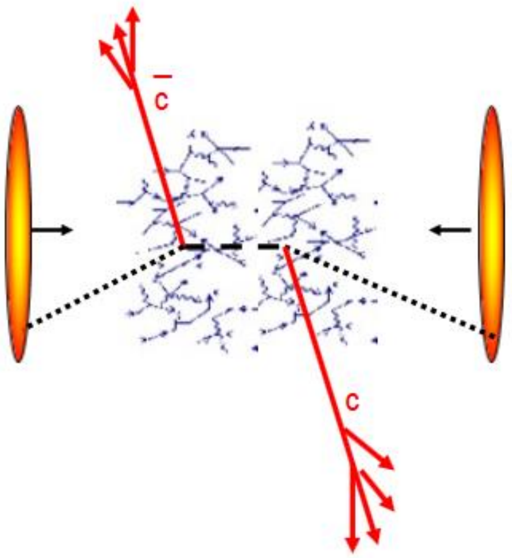
- **Relevant physics**

➡ Flavor dependence of energy loss
➡ Dead cone effect [1]



- **Predictions**

➡ R_{AA} of different flavor hadrons reveals the difference in energy loss of partons



[1] Phys. Lett. B 519 (2001) 199

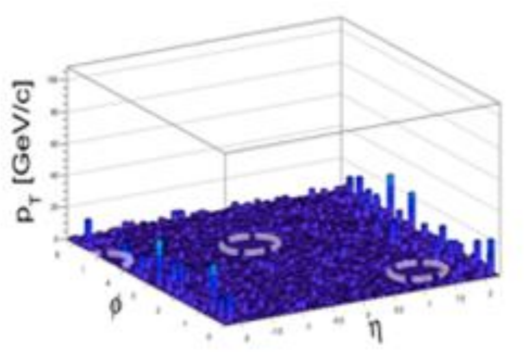
The CMS Trigger and Data Sets

Data sets

- LHC Run II 2015 pp and PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV and 2016 pPb data at $\sqrt{s_{NN}}$ = 8.16 TeV
- Minimum bias sample for $p_T < 20$ GeV/c and triggered samples for $p_T > 20$ GeV/c
- Dedicated HLT D meson filters to enhance the statistics of very high p_T D mesons
- High multiplicity trigger to select high multiplicity pPb events comparable to peripheral PbPb

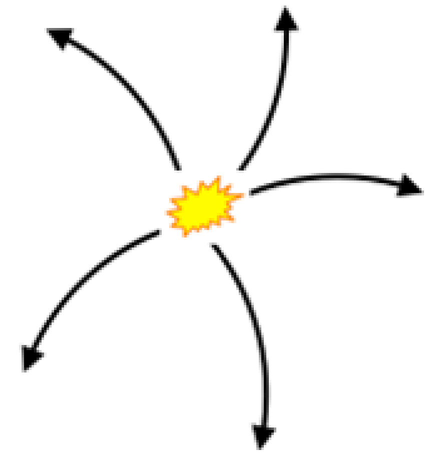
Triggering system

Hardware Level 1 Jet Trigger Selections



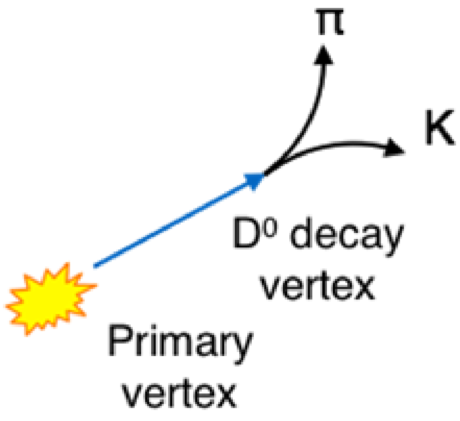
Level 1 (L1) jet algorithm with online background subtraction

Track Selections in Software Triggers



Track seed p_T cut applied:
$p_T > 2$ GeV/c for pp/pPb
$p_T > 8$ GeV/c for PbPb

D^0 Selections



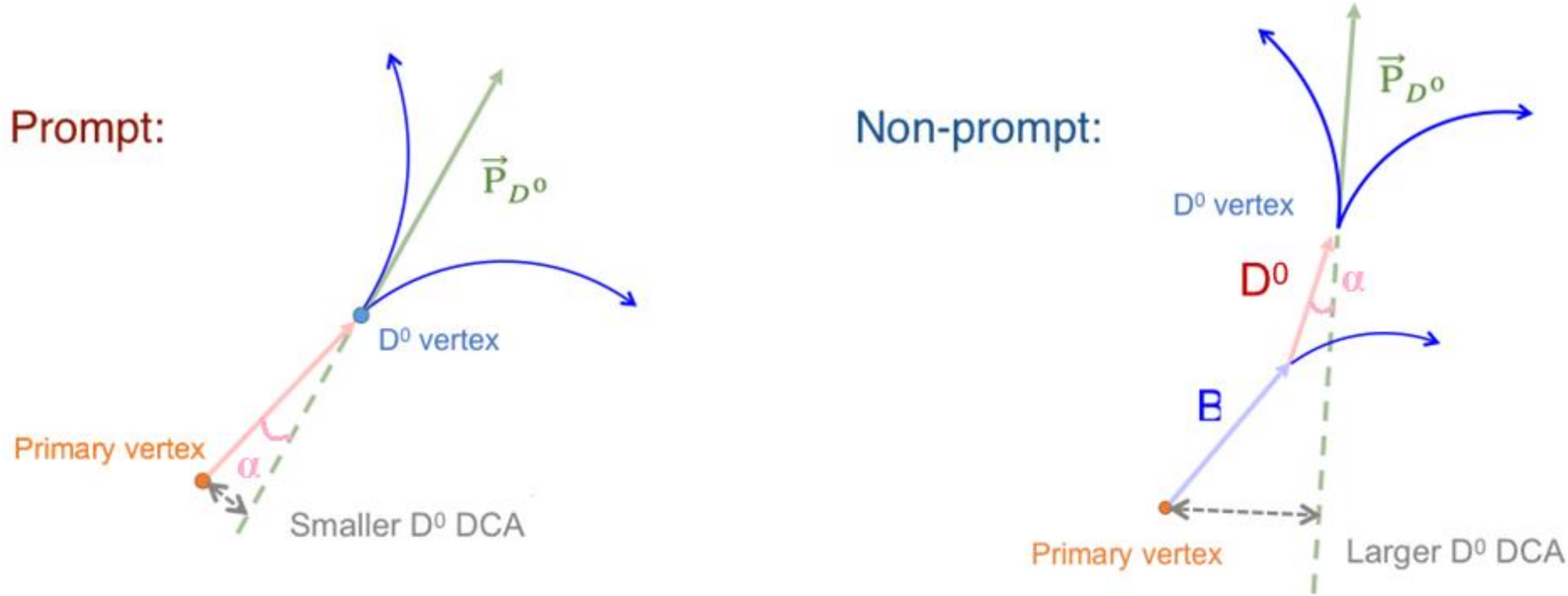
D^0 online reconstruction
Loose selections based on D^0 vertex displacement

D^0 Reconstruction and Selections

- Primary vertex reconstruction **several tracks**
- D0 candidates (vertex) reconstruction **pairing two tracks + kinematic fitter**
- D0 candidates selection (TMVA Rectangular Cuts) **decay topology**

➡ Pointing angle (α) **< ~0.12**
➡ 3D decay length (d0) significance **> ~4**
➡ Secondary vertex probability **> ~0.1**
➡ Distance of Closest Approach (DCA) **< ~0.008 cm**

$\boldsymbol{D^0 \rightarrow K^-\pi^+}$ **channel**
$f(c \rightarrow D^0) \sim 50\%$
Branching Ratio = 3.93%
$c\tau \simeq 120\ \mu m$



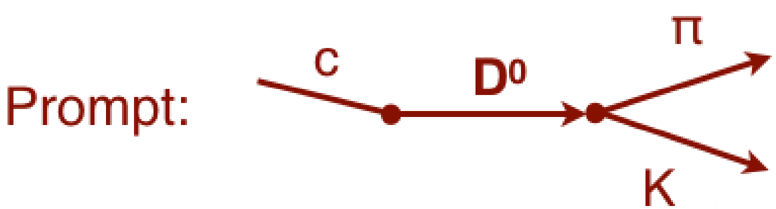
Extraction of Prompt Faction from Data

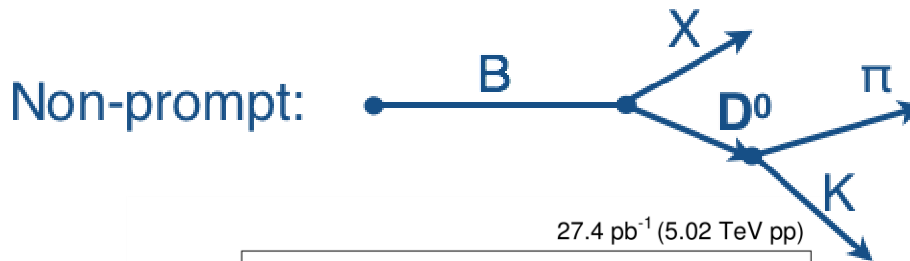
- **Data-driven way to extract the prompt fraction of D^0**

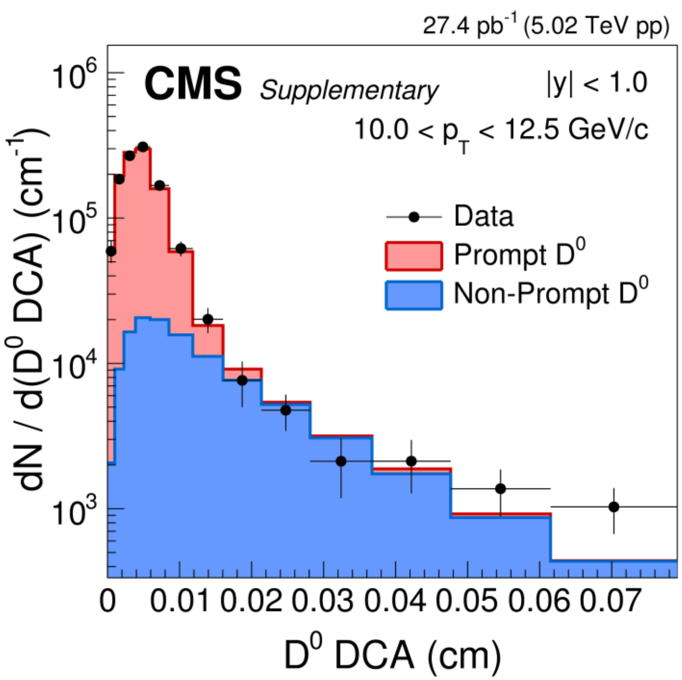
➡ Fit the DCA of the data with prompt and non-prompt D^0 DCA Monte Carlo templates

➡ Correct the to full D^0 spectrum with the prompt fractions in pp and PbPb

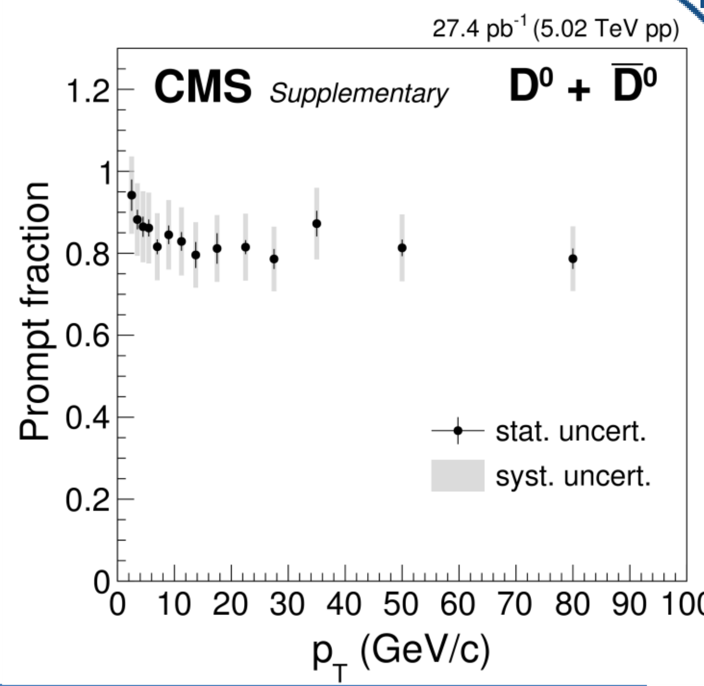
- Non-prompt D^0 study: Wei Xie's poster (OHF-34) and Ta-wei Wang's parallel talk







CMS HIN-16-001
arxiv: 1708.04962
Submitted to PLB

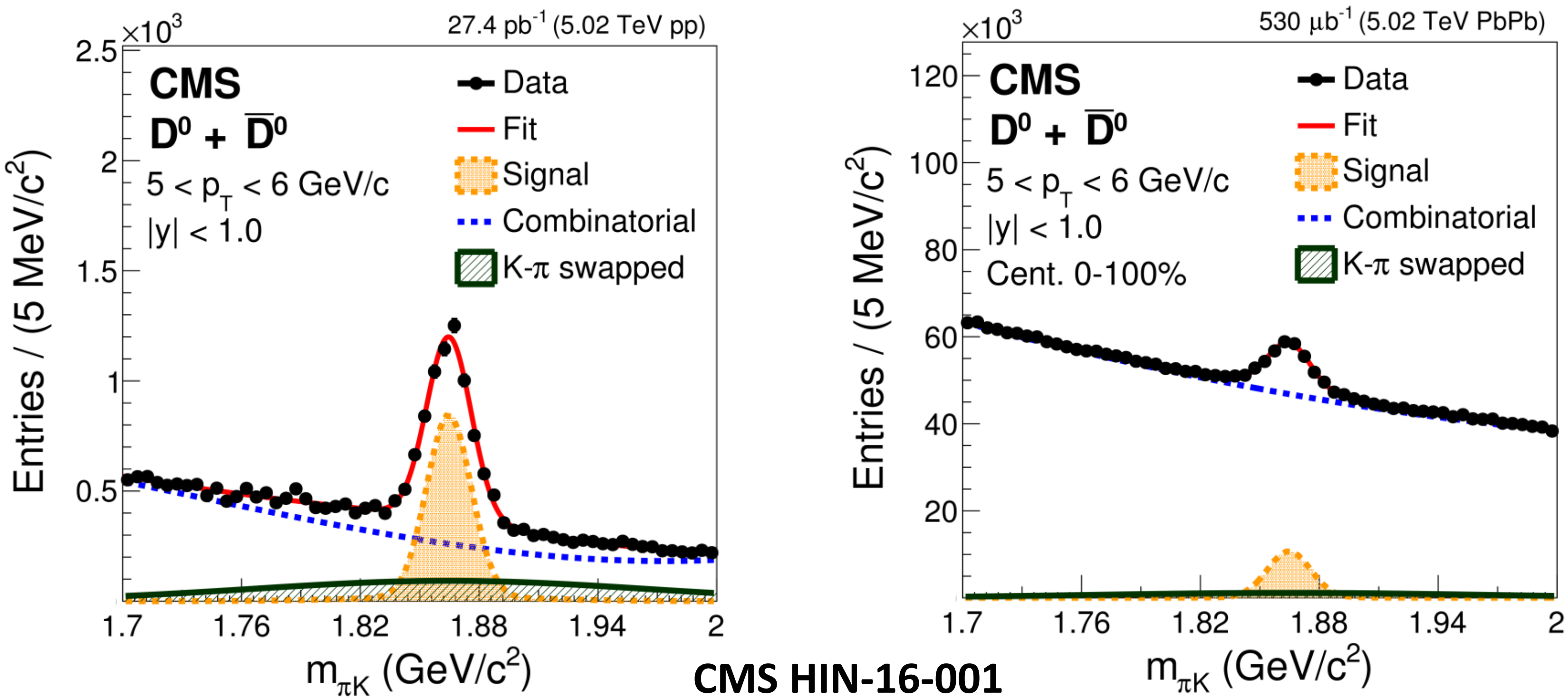


D^0 Invariant Mass Extraction

D^0 invariant mass distributions are fitted by

- Double Gaussian (Signal)
- 3rd order polynomial (Combinatorial)
- Single Gaussian (K-π swapped: candidates with wrong mass assignment)

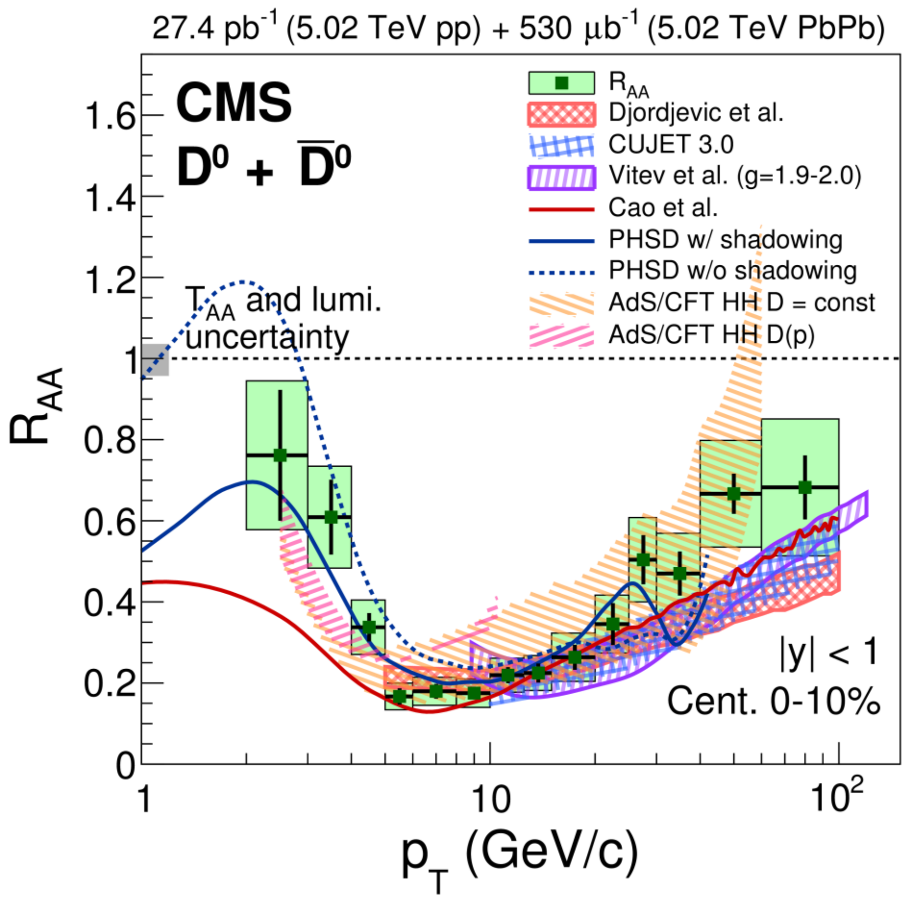
➡ Not using PID



CMS HIN-16-001
arxiv: 1708.04962
Submitted to PLB

D^0 R_{AA} and Comparison with Model Calculations

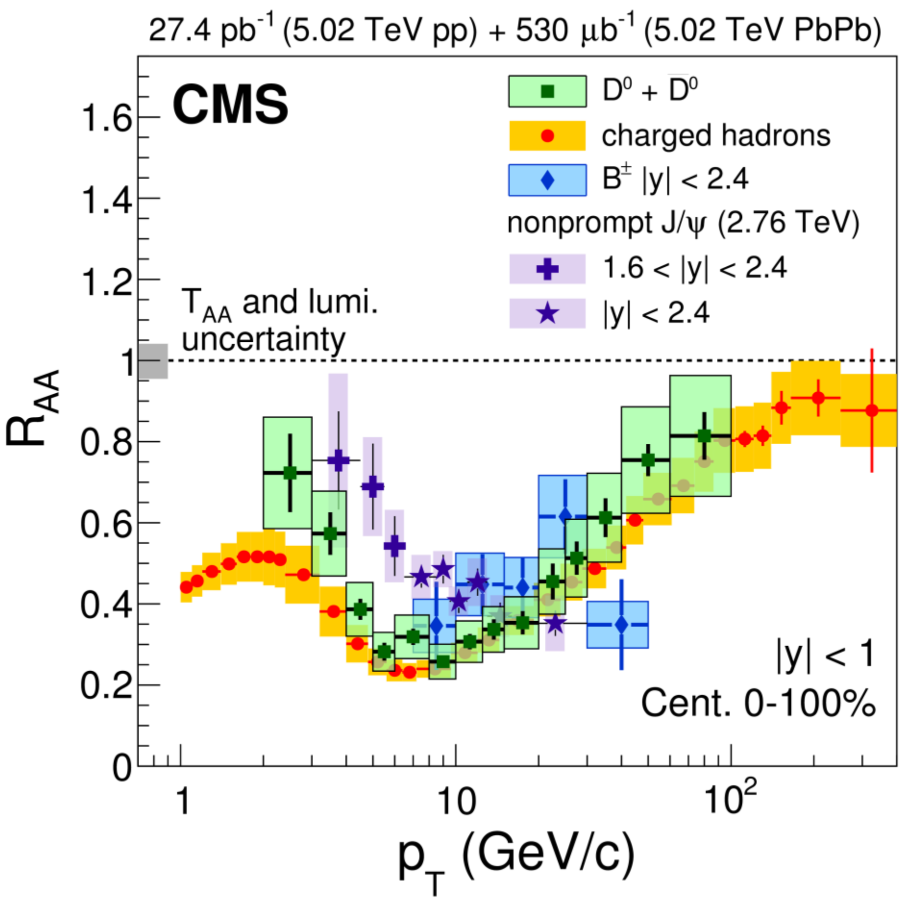
- Charm quarks lose a significant fraction of energy in the QGP medium
- R_{AA} minimal near $p_T \sim 10$ GeV/c and then increases
- At high p_T, both pQCD and AdS/CFT predictions reasonably agree with our R_{AA} results
- At low p_T, PHSD with shadowing describes our data better



CMS HIN-16-001
arxiv: 1708.04962
Submitted to PLB

Comparison of D^0, Charged Particles, Non-prompt J/ψ, and B Meson R_{AA}

- At low p_T, smaller suppression of D^0 and non-prompt J/ψ than charged particles
- At high p_T, the D^0 R_{AA} is similar to charged particles R_{AA}
- The non-prompt J/ψ R_{AA} is higher than the D^0 R_{AA} for almost all p_T



CMS HIN-16-001
arxiv: 1708.04962
Submitted to PLB

D^0 v_2 in pPb Collisions at 8.16 TeV

- **Fourier series describing the azimuthal anisotropy of particle spectrum**

$$\frac{dN}{d\phi} \propto 1 + \sum 2v_n(p_T,\eta)cos[n(\phi-\psi_n)]$$

- **D^0 elliptic flow v_2 in high multiplicity pPb events**

➡ Shed light on how much the heavy flavor quarks are coupled to a possibly hydrodynamic medium at a significantly reduced size

➡ Provide hints of the parton-medium interaction as an evidence of QGP in small systems

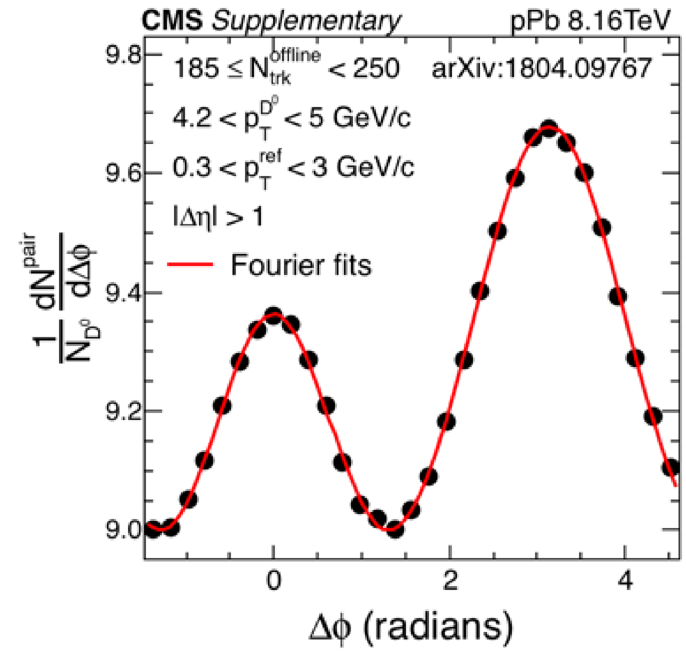
- **Two-particle correlation method to extract v_2**

➡ Correlate D^0 and charged hadrons ($\Delta\eta$ gap = 1)

➡ Perform Fourier fits the two particle correlation distribution for D^0 to extract $V_{2\Delta}(p_T^{D^0}, p_T^{assoc})$

➡ Obtain D^0 $v_2(p_T)$ can be obtain by

$$v_2^{D^0}(p_T) = \frac{V_{2\Delta}(p_T^{D^0}, p_T^{assoc})}{\sqrt{V_{2\Delta}(p_T^{assoc}, p_T^{assoc})}}$$



arXiv: 1804.09767

Extraction for D^0 v_2 Signal in pPb Analysis

- **Data sample**

➡ High multiplicity data sample for our v_2 analysis

- **v_2^S extraction from invariant mass distribution**

➡ Simultaneous fit on m_{inv} distribution and v_2 vs mass

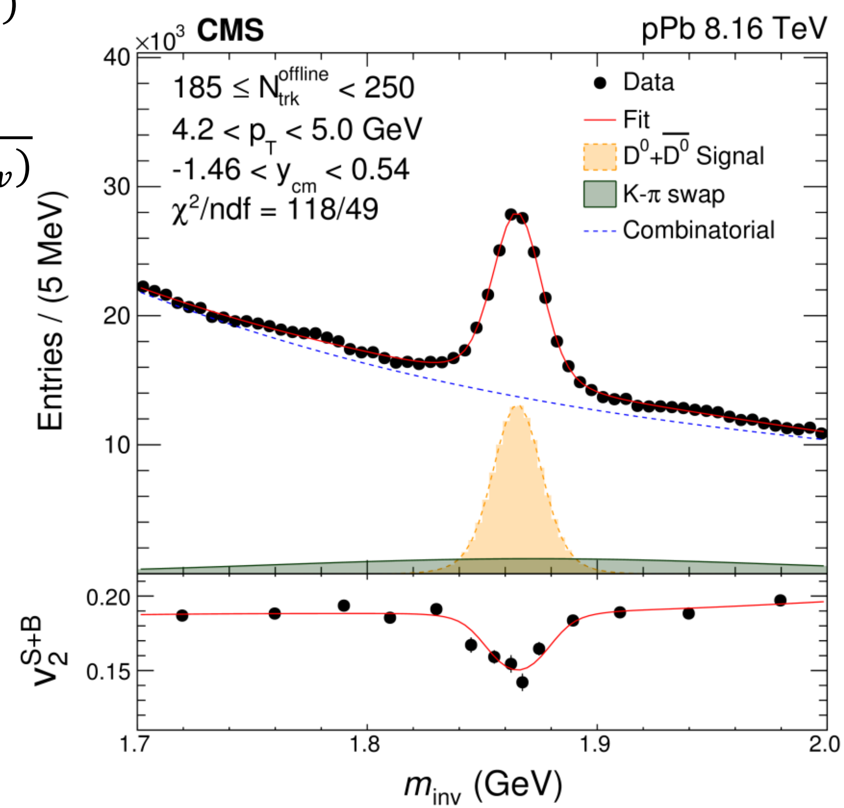
➡ Determine the signal components v_2^S

$$v_2^{S+B}(m_{inv}) = \alpha(m_{inv})v_2^S(m_{inv}) + [1 - \alpha(m_{inv})]v_2^B(m_{inv})$$

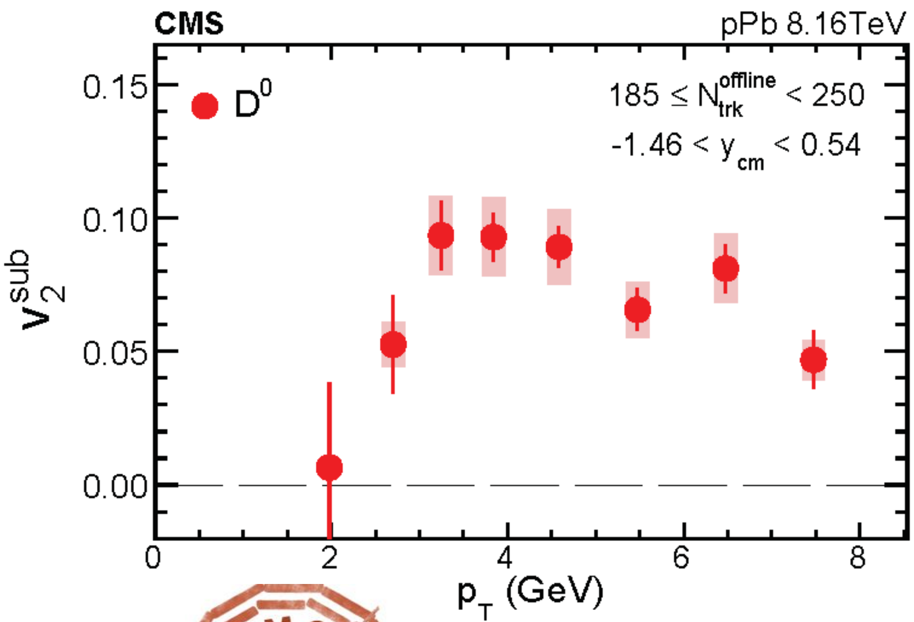
$$\alpha(m_{inv}) = \frac{Signal(m_{inv}) + Swapped(m_{inv})}{Signal(m_{inv}) + Swapped(m_{inv}) + Bkgd(m_{inv})}$$

arXiv: 1804.09767

Simultaneous Fits



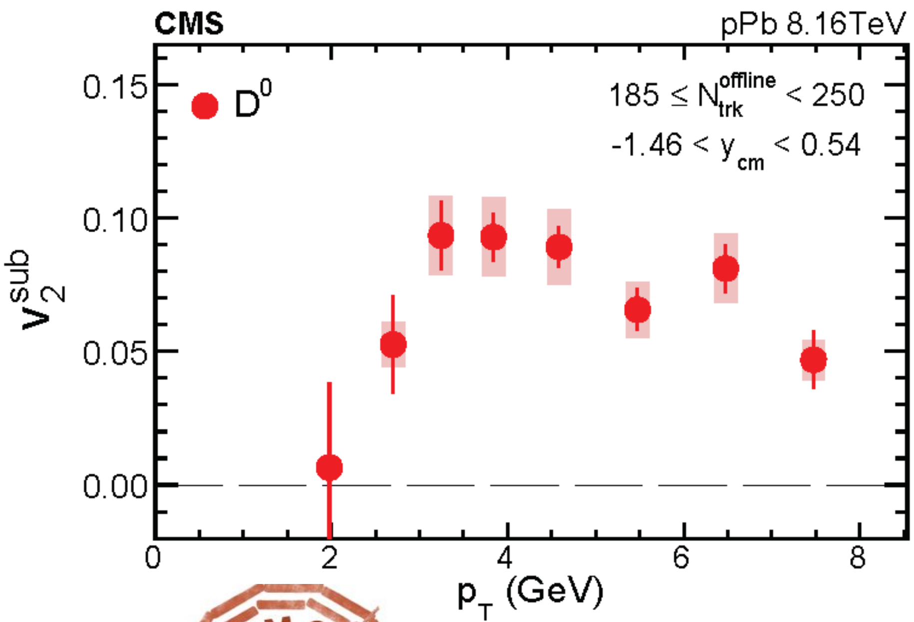
D^0 meson v_2 vs p_T pPb Collisions

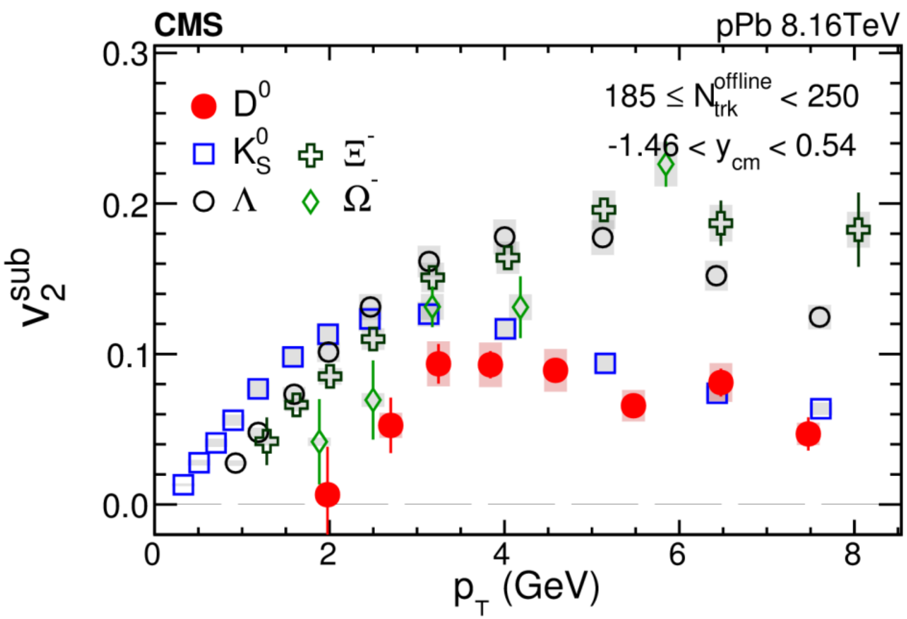


arXiv: 1804.09767

- First measurement of D^0 v_2 in pPb collisions
- D^0 v_2^{sub} in pPb is obtained by subtracting the $V_{2\Delta}$ in low multiplicity from high multiplicity events to reduce the non-flow contributions
- Significant D^0 v_2 have been observed in high multiplicity pPb collisions

D^0 Meson and Light Hadrons v_2 vs p_T

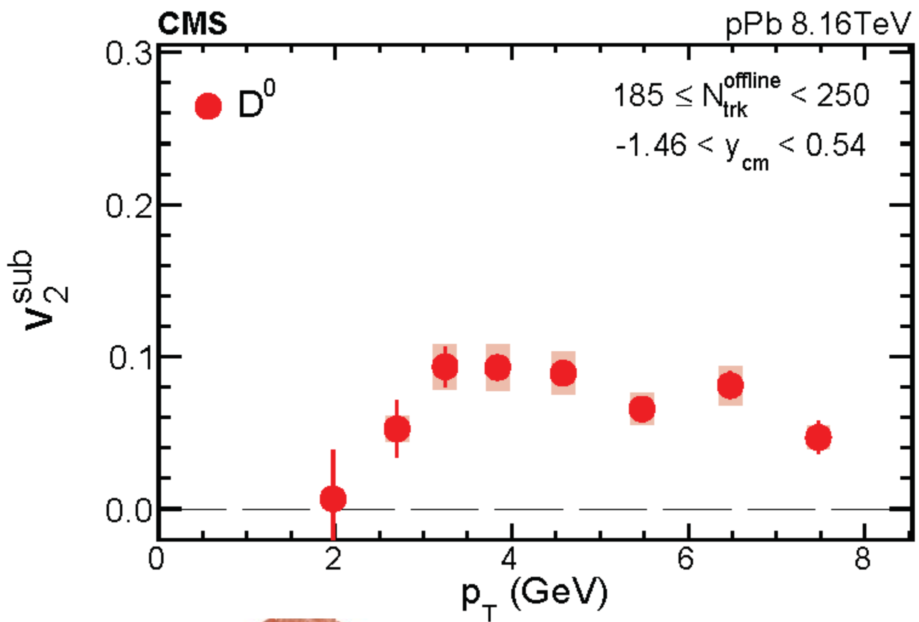


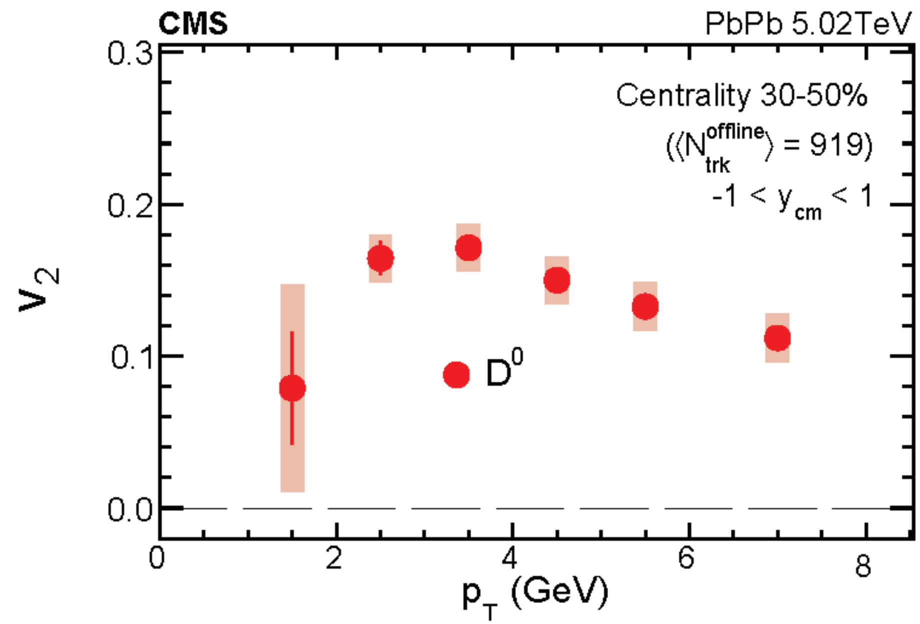


arXiv: 1804.09767

- $v_2^{D^0} < v_2^{light\ hadrons}$
- Charm quarks does not couple to the system as strongly as the light flavor quarks

D^0 Meson v_2 vs p_T and PbPb Collisions



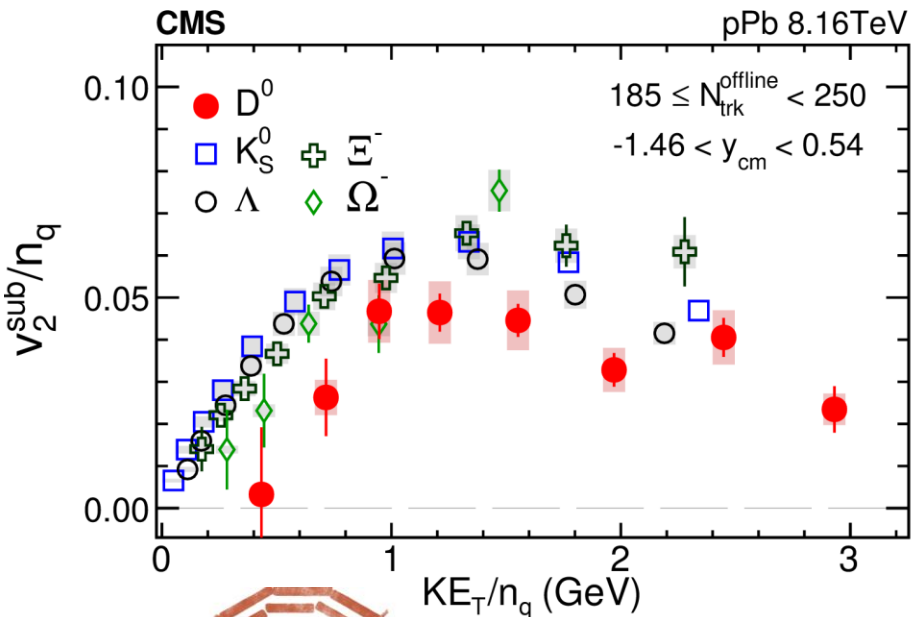


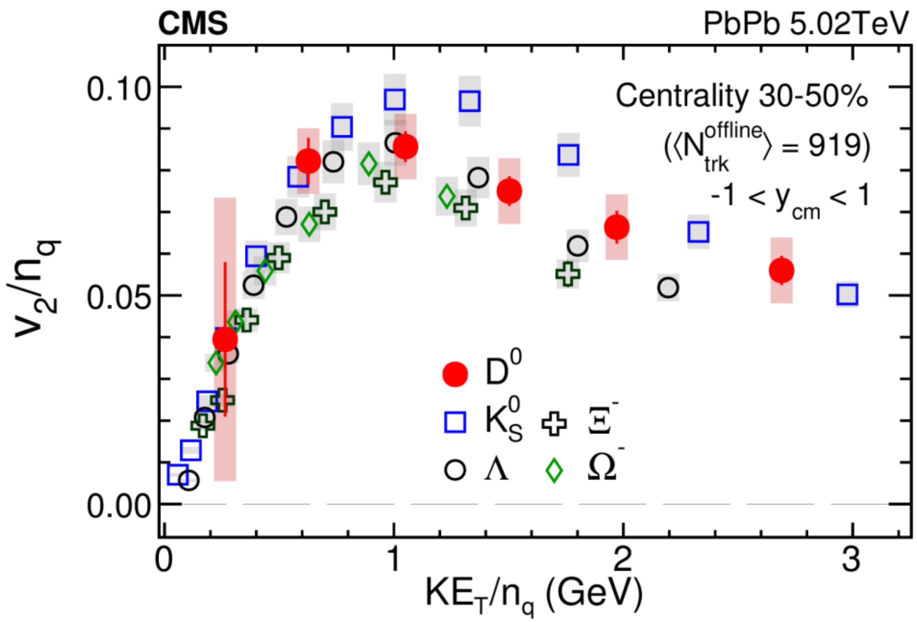
CMS NEW RESULT QM18

arXiv: 1804.09767

- $D^0 \; v_2^{pPb} < v_2^{PbPb}$ for a given p_T
- Charm quarks flow in the QGP medium created in PbPb collisions

D^0 Meson v_2/n_q vs KE_T/n_q pPb and PbPb Collisions





CMS NEW RESULT QM18

arXiv: 1804.09767

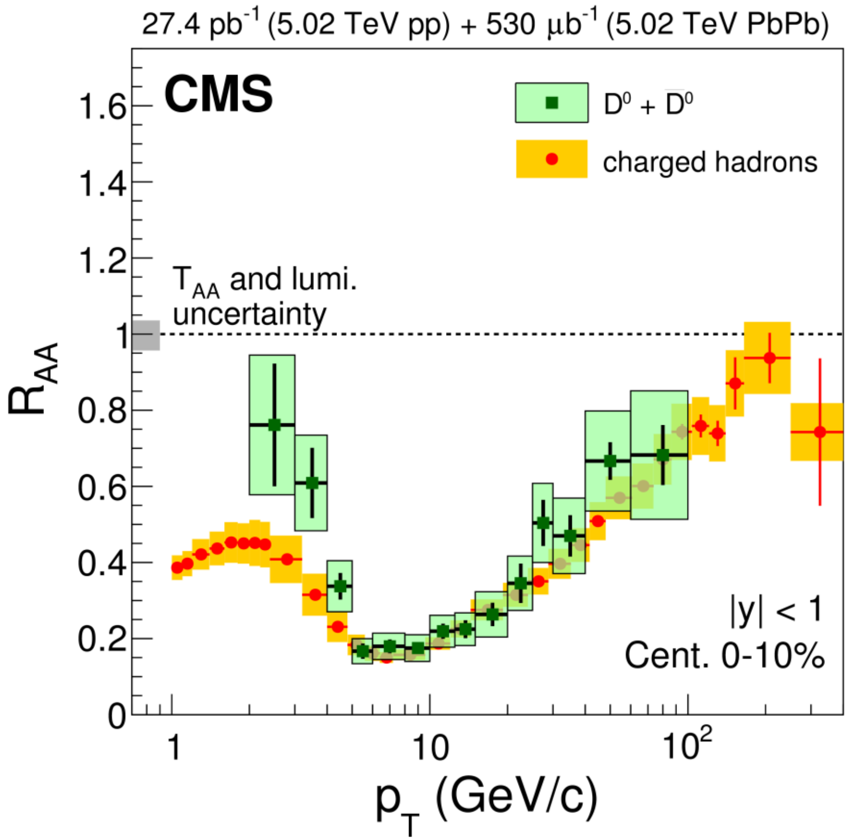
- Number of constituent quarks (NCQ) scaling is motivated by quark coalescence model
- Similar behavior of D^0 v_2 to light hadrons scaled by NCQ in PbPb
- D^0 demonstrate significantly lower v_2/n_q vs KE_T/n_q compared to light hadrons in pPb

Summary and Outlook

- **D^0 R_{AA} at 5.02 TeV PbPb from $D^0 \rightarrow K^-\pi^+$**

➡ Strong suppression of D^0 R_{AA} is observed

➡ D^0 R_{AA} is similar to charge hadrons R_{AA} at high p_T and higher at low p_T

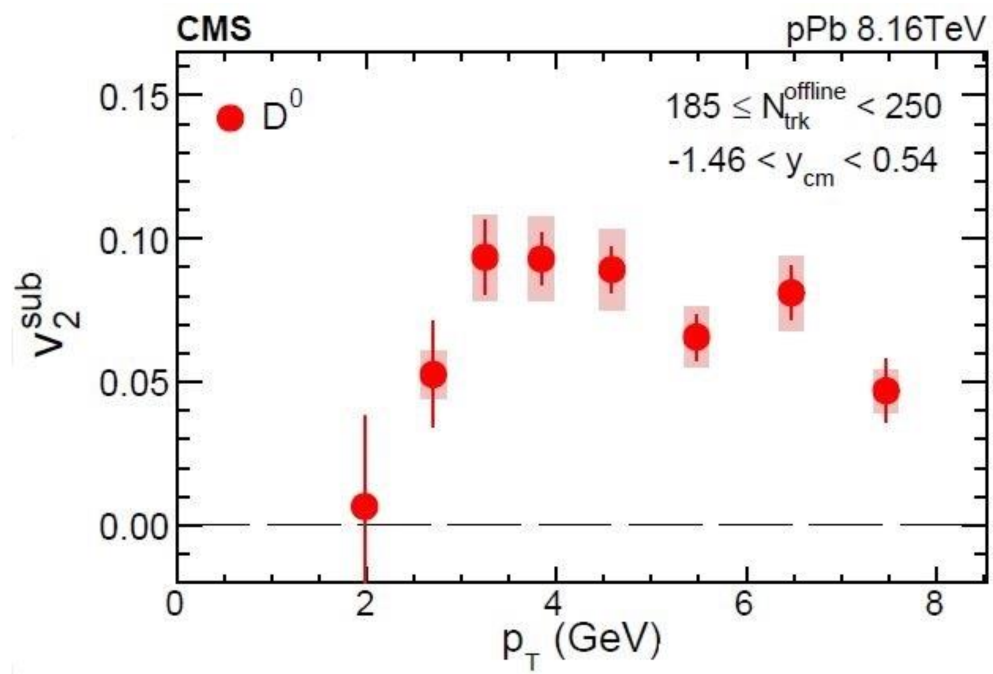


- **D^0 v_2 at 8.16 TeV pPb from $D^0 \rightarrow K^-\pi^+$**

➡ First measurement of D^0 v_2 in pPb

➡ Observation of D^0 v_2 in high multiplicity pPb collisions

➡ D^0 v_2 in pPb is smaller than strange hadrons



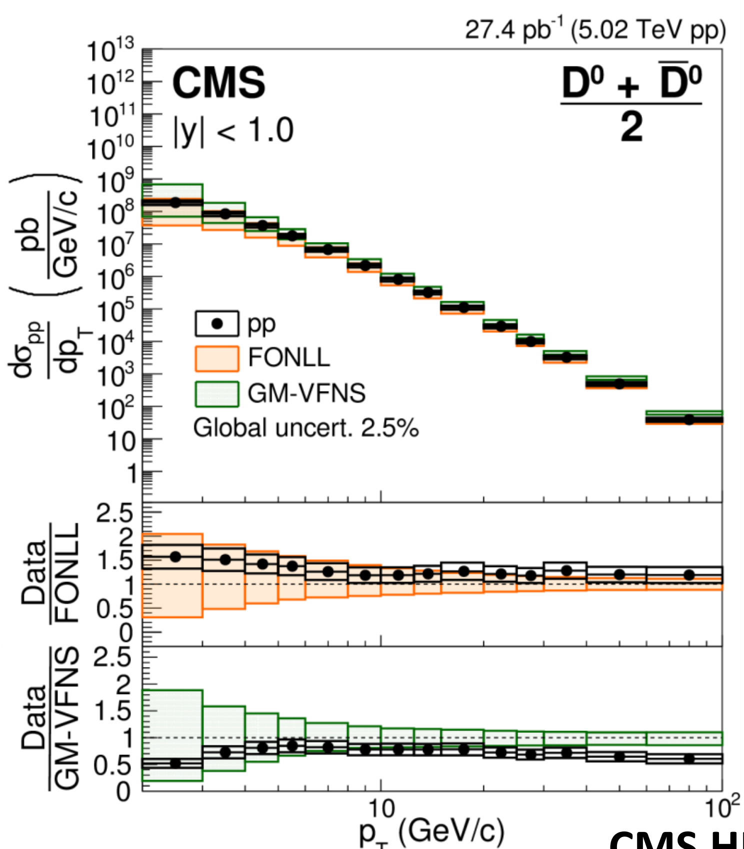
Thank You

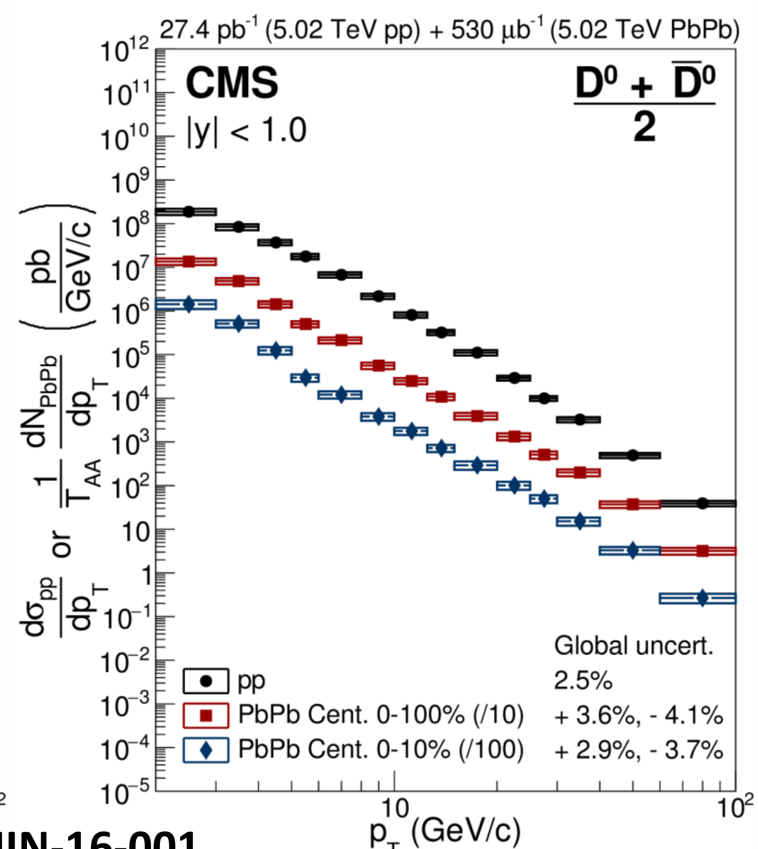
This MIT group's work was supported by US DOE-NP

Back up

Results – D^0 Differential Cross-section vs p_T in pp and PbPb Collisions

- p_T range from 2 to 100 GeV/c
- Overall consistent with FONLL [2]
- At high p_T, GM-VFNS [3] calculations overpredicts the data



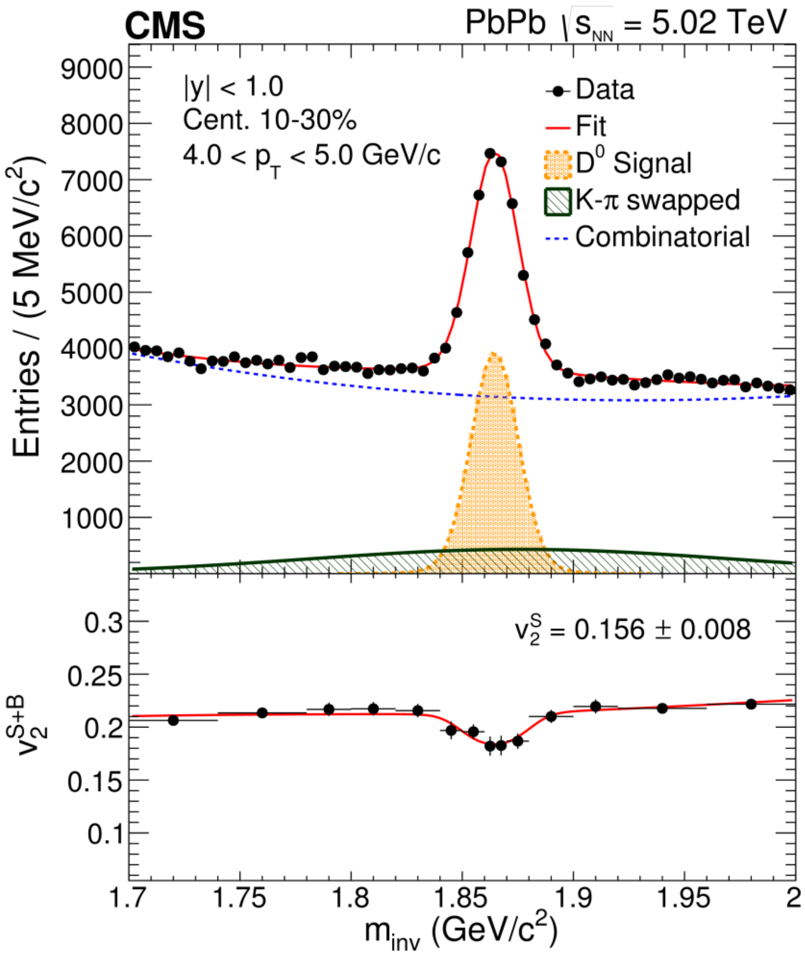


[2] JHEP 05 (1998) 007
[3] Phys. J. C 72 (2012) 2082

CMS HIN-16-001
arxiv: 1708.04962
Submitted to PLB

Plots for Flow Extractions in PbPb from the Invariant Mass Fits

- Yield extraction of v_2 is similar to the yield extract of R_{AA}
- Determination of v_2^{S+B} from the invariant mass distribution



- **Methodology**

➡ Simultaneous fit on invariant mass distribution and v_n vs mass

➡ Determine the fraction of the signal and background components

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

- **Parameters**

➡ v_n^{S+B}: v_n for all D^0 candidates in the signal region

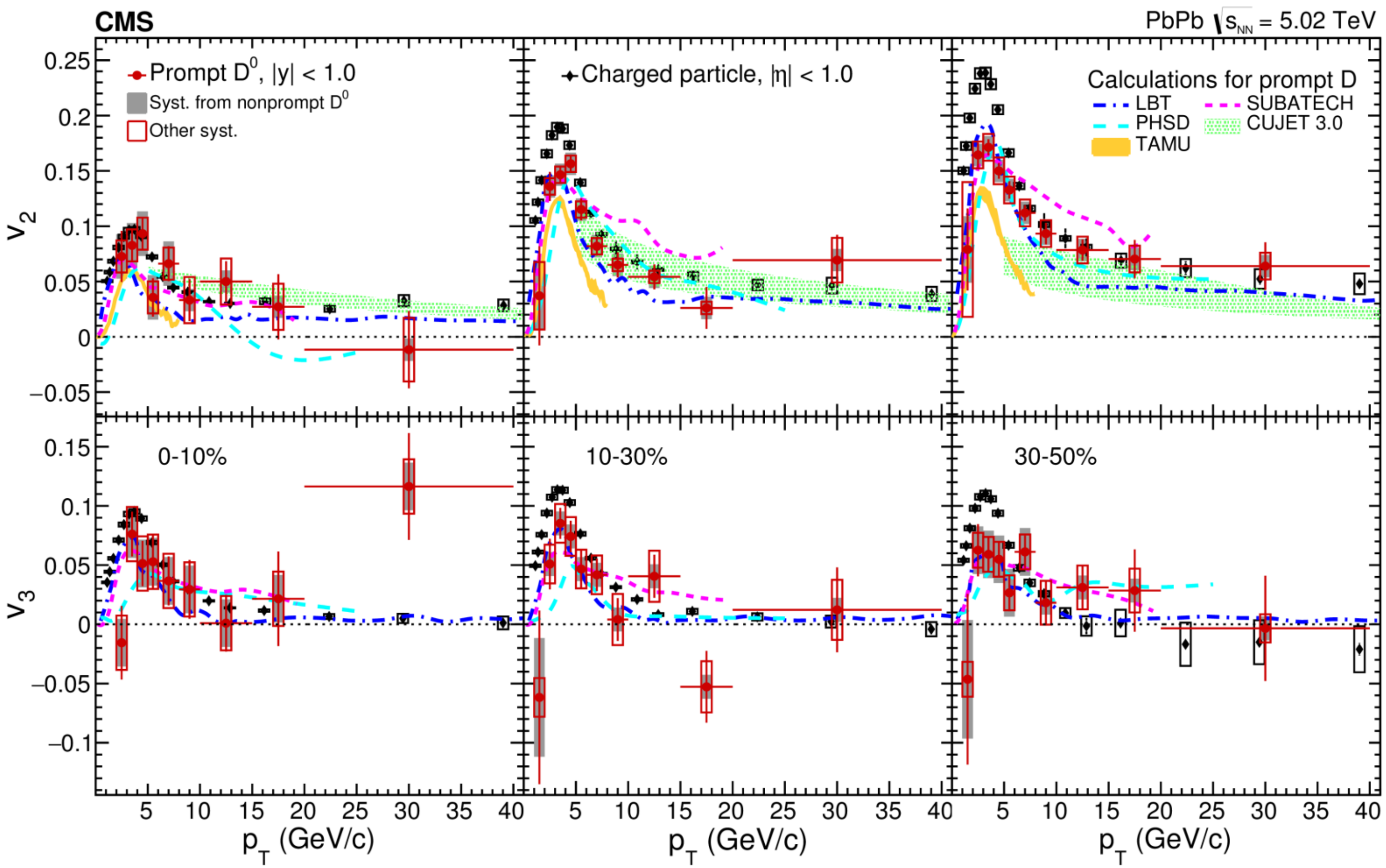
➡ v_n^S: v_n for all D^0 signals (after background subtraction, modeled by double Gaussian function)

➡ v_n^B: v_n for all D^0 combinatorial background (modeled by linear function)

➡ α: fraction of the signal component from the fits on the invariant mass distribution

CMS HIN-16-007 arxiv: 1708.03497 Accepted by PRL

D^0 meson v_2 and v_3 in PbPb Collisions and Comparison with Theoretical Models



CMS HIN-16-007

arxiv: 1708.03497

Accepted by PRL

- D^0 v_2 and v_3 are observed in PbPb collisions
- Indication of charm quarks flow in the QGP medium
- Challenge to theoretical models: must simultaneously describe R_{AA} and v_n

High Level Trigger in pPb v_2 Analysis

- **High Multiplicity Trigger**

➡ Dedicated trigger on high multiplicity events

➡ Multiplicity of pp and pPb are comparable to peripheral PbPb events

Algorithm

- Online selection of events with multiplicity > 120

➡ Multiplicity threshold 120 and 150 seeded with L1 Minimum-Bias triggers

➡ Multiplicity threshold 185, 250, 280 seeded with the tower count with barrel ECAL and HCAL

- Multiplicity threshold selection at HLT

➡ $p_T > 0.4$ GeV/c

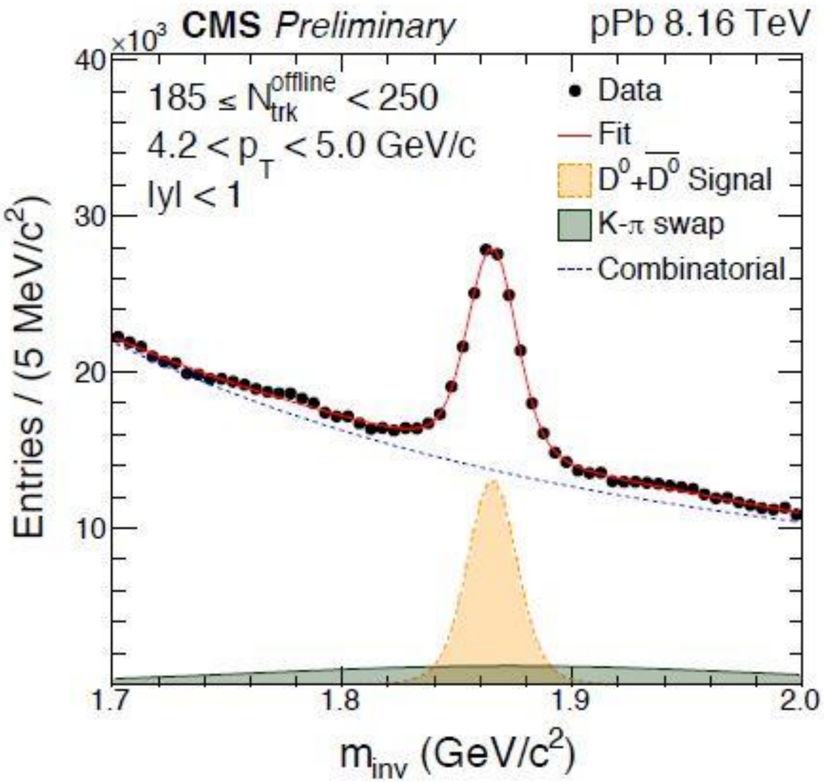
➡ $|\eta| < 2.4$

➡ $MinSepZ_{pixel} < 0.12$ m

➡ $MinSepZ_{full} < 0.15$ m

CMS HIN-16-007
arxiv: 1708.03497
Accepted by PRL

Invariant Mass Plot



- Conclusion: we are able to obtain D^0 signal in the high multiplicity pPb data and study D^0 v_2

Azimuthal Anisotropy in Heavy Ion Collisions

- **Fourier series describing the azimuthal anisotropy of particle spectrum**

$$F(p_T,\eta,\phi) = 1 + \sum 2v_n(p_T,\eta)cos[n(\phi-\psi_n)]$$

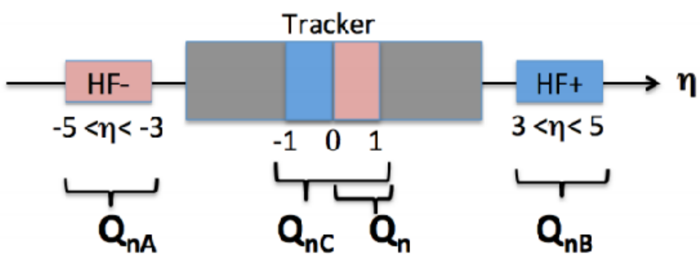
- Event plane ψ_n is determined by the HF calorimeter $3 < |\eta| < 5$ and the tracker $|\eta| < 0.75$
- Q vector: $Q_n = \sum_M \omega_k e^{-in\phi}$
- Measure Fourier harmonics v_n with two-particle correlations method (η gap = 1.0)
- The scalar product method (η gap = 1.5) as a cross-check

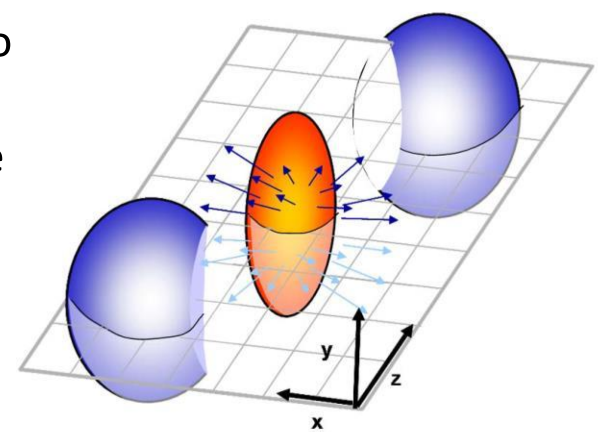
$$v_n\{SP\} = \frac{\langle Q_{n,D^0} Q_{nA}{}^{*}\rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}{}^{*}\rangle\langle Q_{nA} Q_{nC}{}^{*}\rangle}{\langle Q_{nB} Q_{nC}{}^{*}\rangle}}}$$

- ***D^0 v_2* in high multiplicity pPb events**

➡ Shed light on how much the heavy flavor quarks are coupled to a possibly hydrodynamic medium at a significantly reduced size

➡ Provide hints of the parton-medium interaction as an evidence of QGP in small systems





D^0 v_2 Cuts in pPb

- **Track quality selections**

➡ High purity track

➡ $\frac{\Delta p}{p} < 0.1$

➡ nHits > 11 for pixel + strip trackers

- **Topological cuts**

p_T (GeV/c)	$d_0/\sigma(d_0)$	α	Vertex Probability
1.5 – 2.4	> 3.50	< 0.15	> 0.15
2.4 – 3	> 3.50	< 0.15	> 0.13
3 – 3.5	> 3.50	< 0.12	> 0.12
3.5 – 4.2	> 3.50	< 0.10	> 0.11
4.2 – 5.0	> 3.50	< 0.09	> 0.10
5.0 – 6.0	> 3.50	< 0.08	> 0.09
6.0 – 7.0	> 3.50	< 0.07	> 0.08
7.0 – 8.0	> 3.50	< 0.06	> 0.08

Low Multiplicity Subtraction Technique

- **Low multiplicity subtraction**

$$V_{n\Delta}^{sub} = V_{n\Delta}(N_{trk}^{offline} > 185) - V_{n\Delta}(N_{trk}^{offline} < 35)\frac{N_{assoc}(N_{trk}^{offline} < 35)}{N_{assoc}}\frac{Y_{jet}}{Y_{jet}(N_{trk}^{offline} < 35)}$$

Y_{jet}: The near-side jet yield defined as integral or near-side jet peak in the short range ($|\Delta\eta| < 1$) Projected In the 1-D $\Delta\phi$ distribution.