Elliptic Flow of D Mesons in Pb-Pb Collisions

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Journal Club on heavy-ion collisions

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ALICE papers discussed

- *D meson elliptic flow in non-central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV*

  PRL 111, 102301 (2013)

  - elliptic flow v_2 of D^0, D^+, D^{*+} in 30-50% centrality

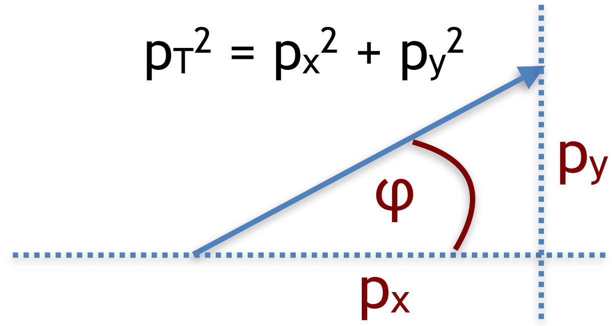
- *Azimuthal anisotropy of D meson production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV*

  submitted to Phys. Rev. C, 2014

  - v_2 of D^0, D^+, D^{*+} in 3 centrality classes in 0-50%
  - 3 different methods to determine v_2
  - R_{AA} with respect to event plane

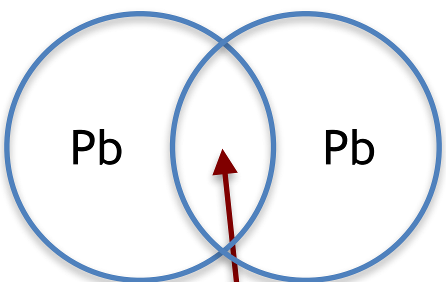
What is Azimuthal Anisotropy?

coordinate basis
in momentum space:
(p_T, y, φ)



transverse plane

transverse plane



asymmetric
overlap region

ultrarelativistic heavy-ion collisions:

collision geometry **not** symmetric in φ

—> initial spatial **azimuthal anisotropy**

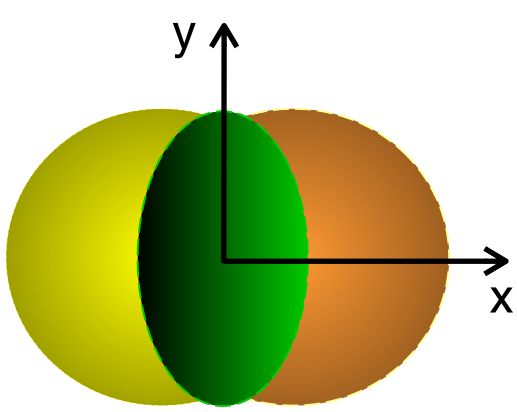
—> particle production dN/dφ can be anisotropic

depending on the effect of the
quark gluon plasma (QGP)

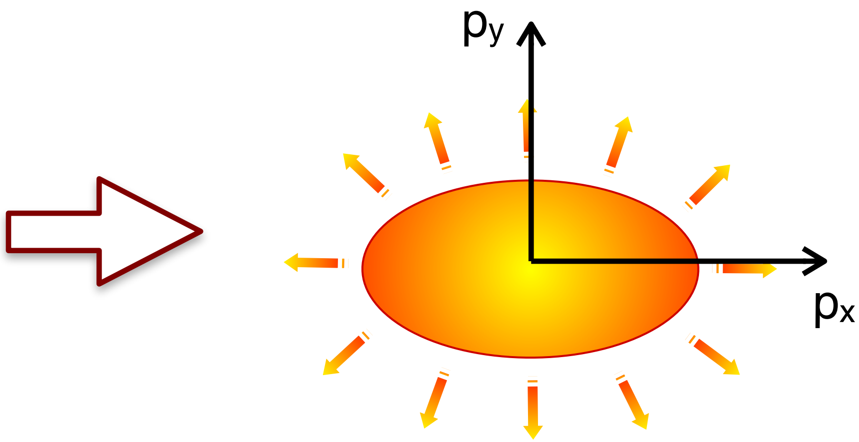
What is Flow?

- thermalized QGP can be described by hydrodynamis
- Euler equation: collective dynamics driven by pressure gradients
- expansion of the fireball
- flow is affected by azimuthal anisotropy
  —> different pressure gradients in different directions

initial spatial anisotropy



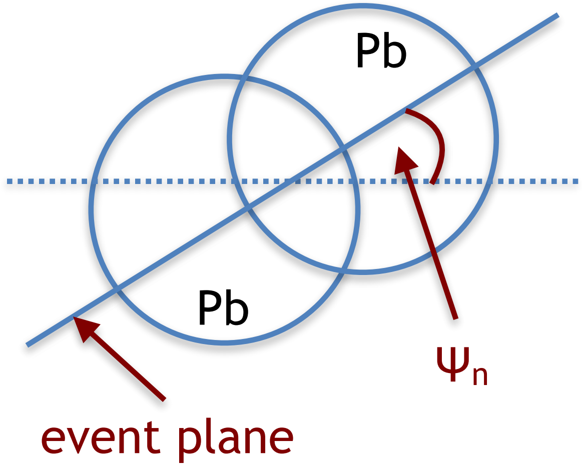
momentum-space anisotropy



Characterizing Anisotropy

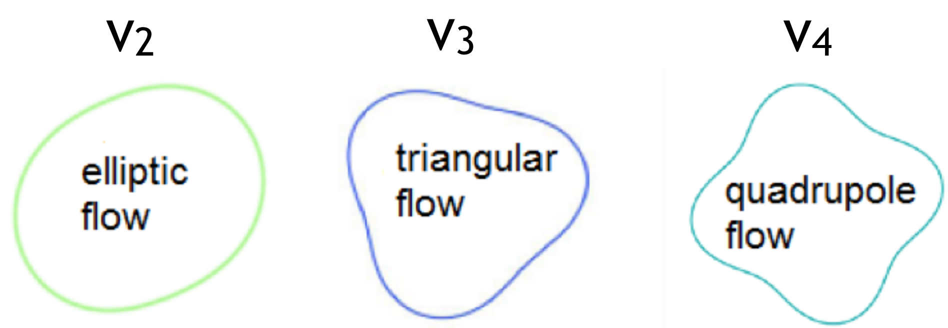
dN/dφ - 2π-periodic function in φ
—> expand in Fourier series

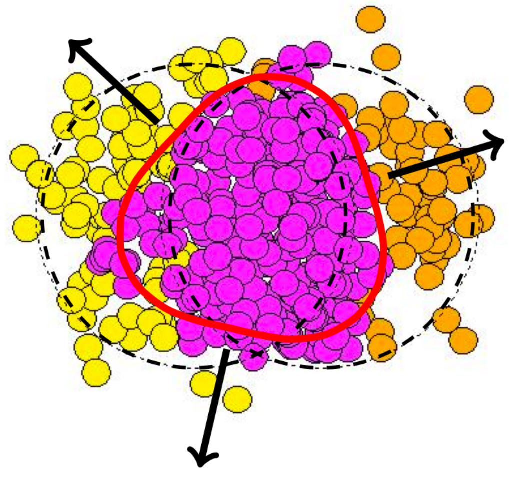
$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left[1 + 2\sum_{n=0}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]\right]$$



Fourier coefficients:

$$v_n = \int_0^{2\pi} \frac{dN}{d\phi} \cos\left[n\left(\phi - \Psi_n\right)\right] d\phi = \langle \cos\left[n(\phi - \Psi_n)\right] \rangle$$

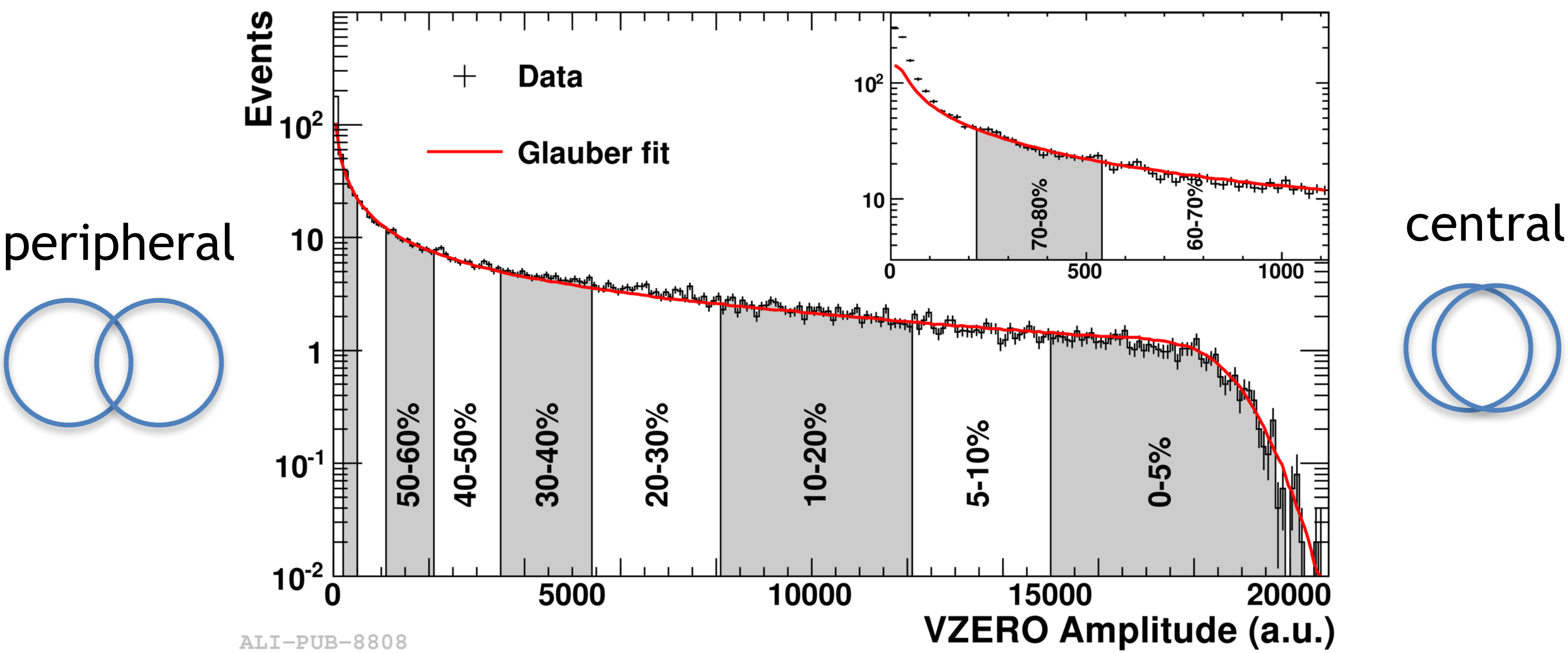




shape of participant zone (overlap of the nuclei)

Centrality Classes

- more central collision —> higher multiplicity
- take amplitude in VZERO detectors (scintillators) as a measure for multiplicity
- cluster into percentiles = centrality classes



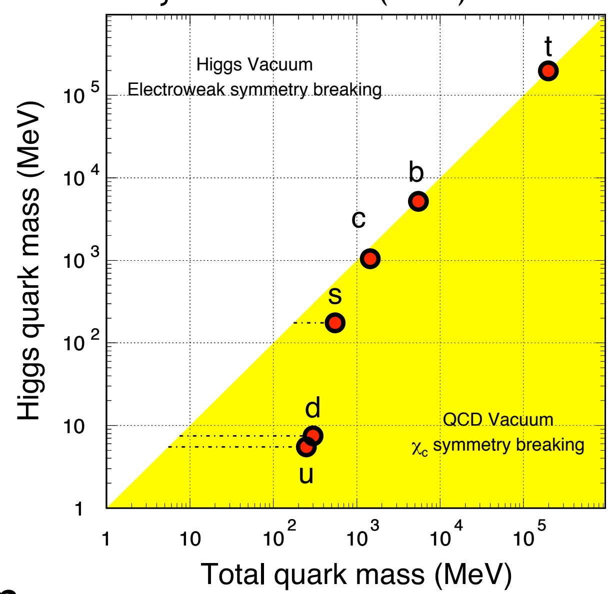
Outline

- Introduction
  - heavy quarks in the QGP
  - interest in measuring charm flow
- Analysis
  - reconstruction of D mesons in ALICE
  - ALICE detector
  - determination of v2
- Results
- Conclusion

Heavy Quarks in the QGP

- heavy quarks: charm ~1.5 GeV, bottom ~4.5 GeV, [top ~173 GeV]
- m_c, m_b >> Λ_{QCD}
  heavy quarks produced in early pQCD stage
- masses generated mainly by Higgs field
  —> remain heavy when chiral symmetry is restored
- m_c, m_b >> T_{QCD}
  —> no thermal production in medium
- no annihilation
- total charm/beauty is conserved in the medium
- heavy quark experiences full evolution of the system

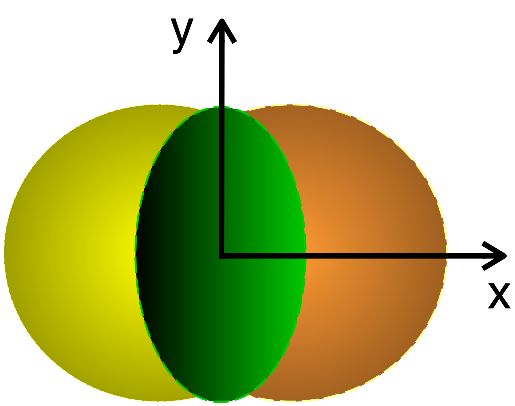
Phys. Lett. B 647 (2007) 366-370

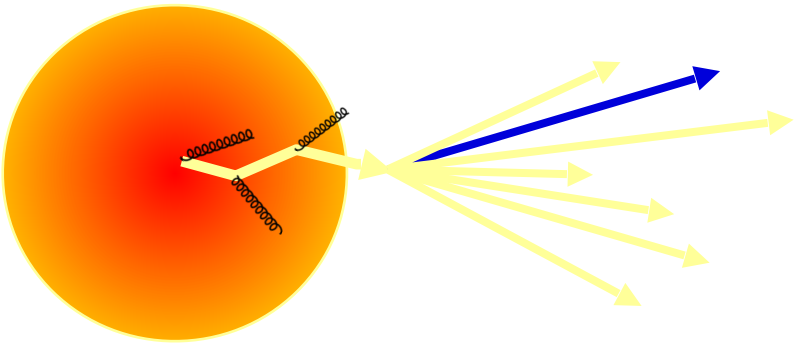


heavy quark = unique probe of QGP medium properties

Charm v_2

- two contributing mechanisms:
  - collective expansion (low p_T)
  - path-length dependence of in-medium energy loss (high p_T)
- does charm participate in the collective expansion?
- how does charm interact in the QGP?
- strong interplay between experiment and theory





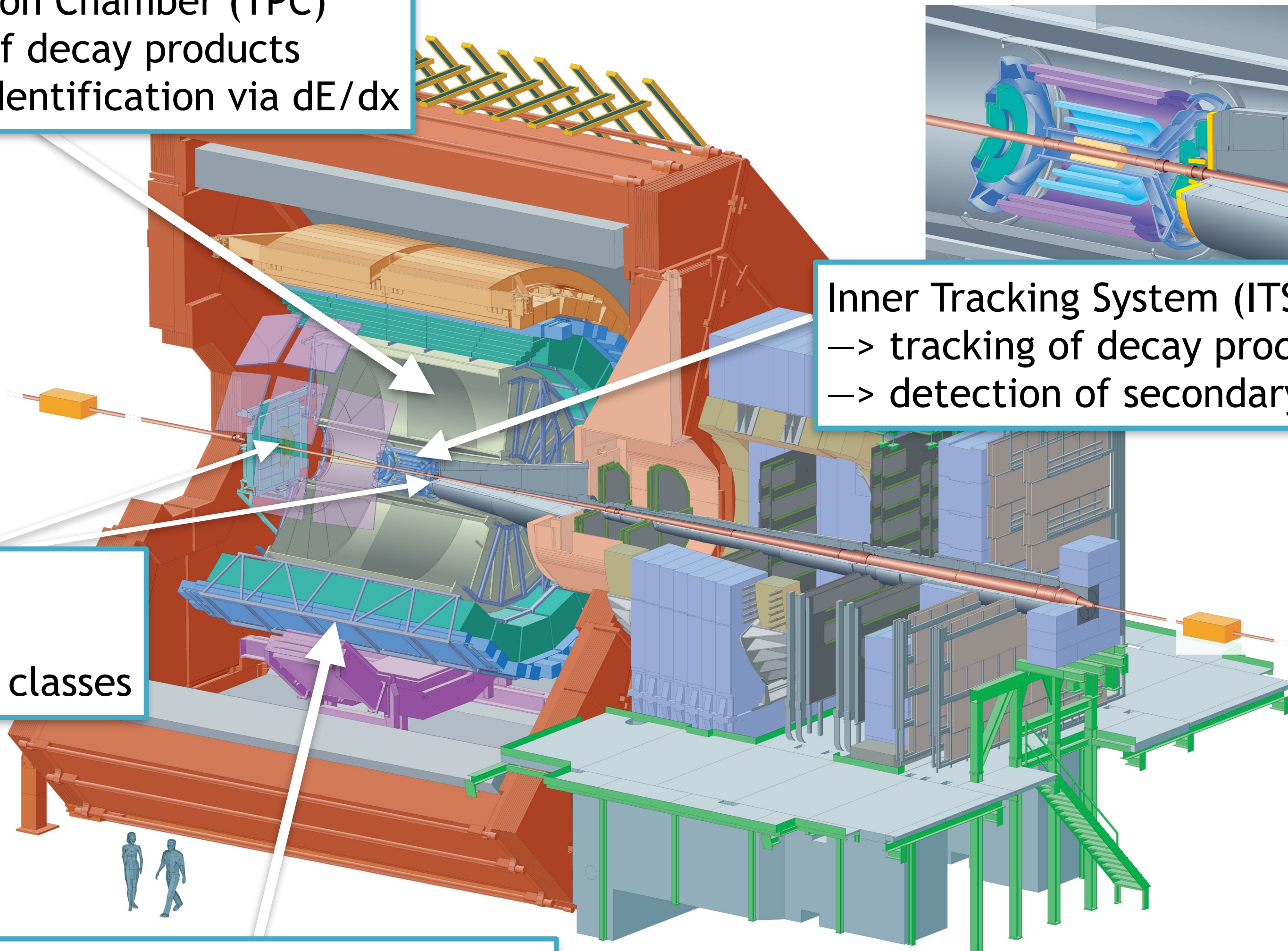
Reconstruction of D Mesons in ALICE

meson	M (GeV/c^2)	$c\tau$ (μm)	decay channel	BR (%)
D^0 ($c\overline{u}$)	1865	123	$K^-\pi^+$	3.9
D^+ ($c\overline{d}$)	1870	312	$K^-\pi^+\pi^+$	9.1
D^{*+} ($c\overline{d}$)	2010	$\Gamma = 83.3$ keV	$D^0(K^-\pi^+)\pi^+$	67.7
D_s^+ ($c\overline{s}$)	1969	150	$\phi(K^-K^+)\pi^+$	5.5

+ anti-particles

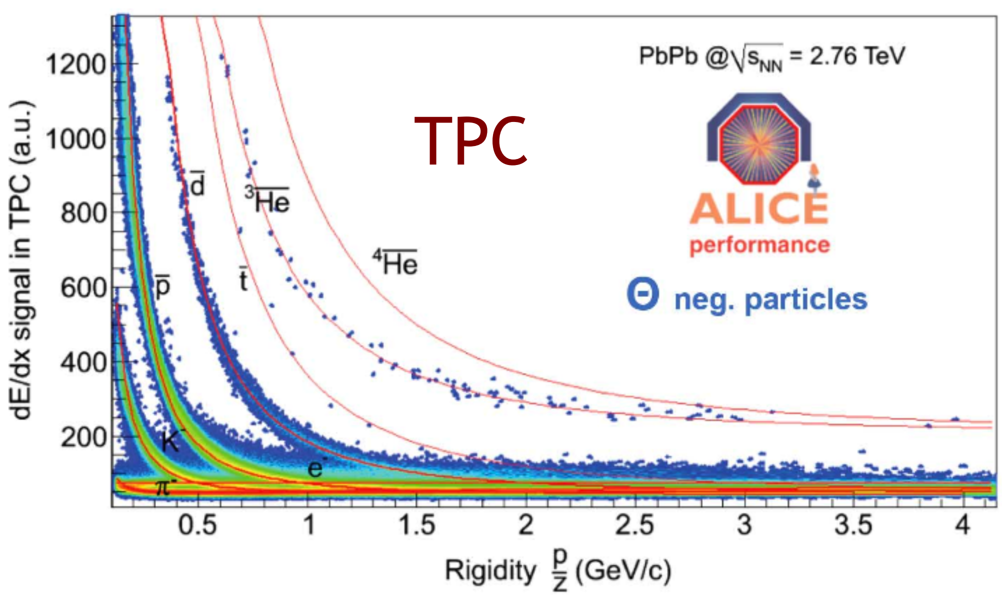
- D mesons decay before they can be detected
- invariant mass analysis in selected decay channels
- downside: large combinatorial background
  - need excellent particle identification (PID)
  - expoloit topology of secondary decay vertex

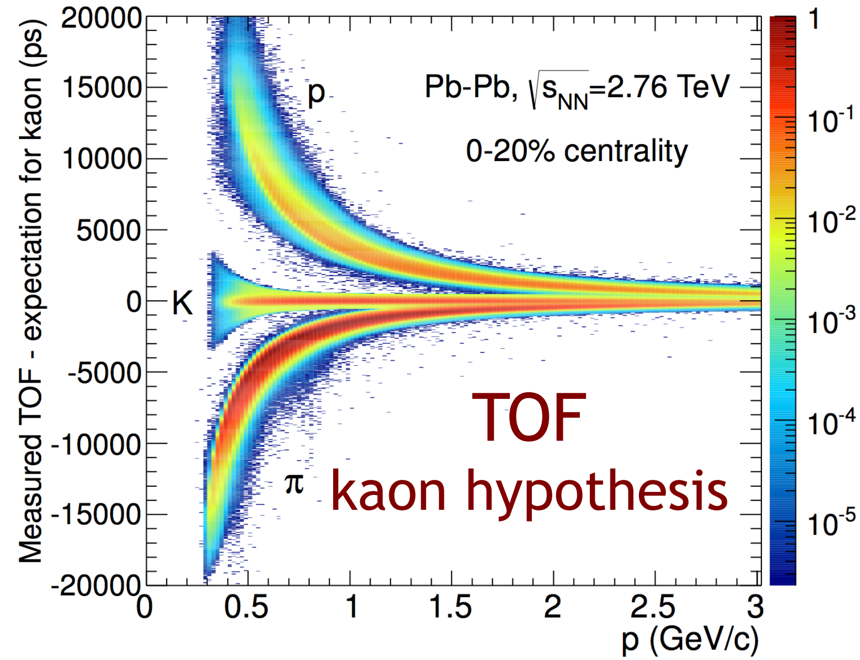
ALICE Detector



Particle Identification

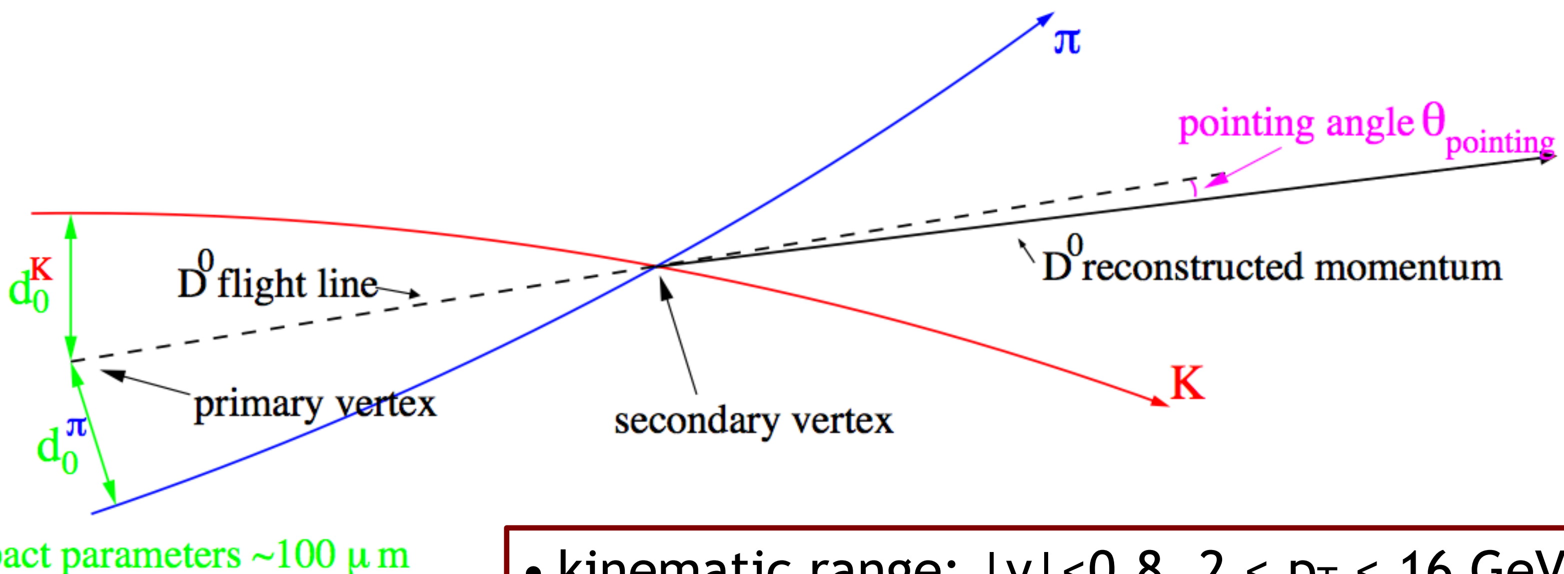
- specific energy loss dE/dx in TPC gas
- velocity β via time of flight in TOF
- require measured signal to be within 3σ of the expected signal for each species (K, π)





Topological Selection for D^0

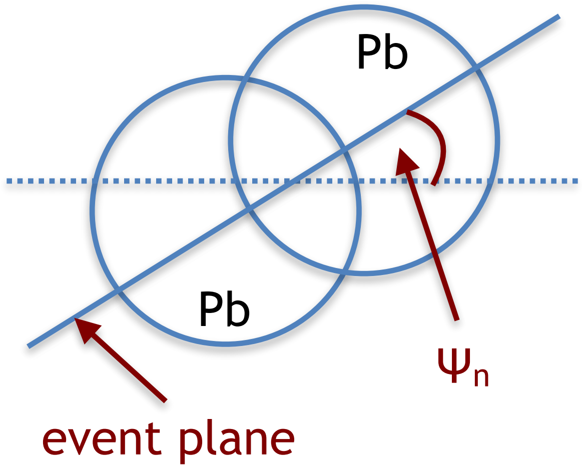
- decay vertex displaced from primary vertex by a few 100 μm
- most effective topological cuts:
  - pointing angle: $\cos(\theta_{pointing}) > 0.95$
  - product of impact parameters: $d_0^K \times d_0^\pi < -(200\ \mu m)^2$



- kinematic range: $|y|<0.8$, $2 < p_T < 16$ GeV/c
- topological approach limited at ultra-low p_T

Reconstruction of the Event Plane

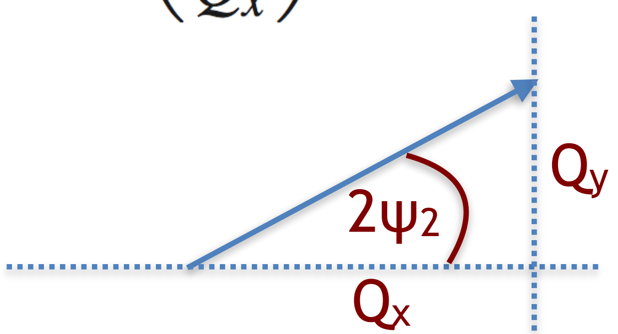
$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left[1 + 2\sum_{n=0}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]\right]$$



- reconstruct event plane angle ψ_2 from the distribution of charged particles
- select 'good' TPC tracks from event
- exclude candidates for D mesons to remove auto-correlations

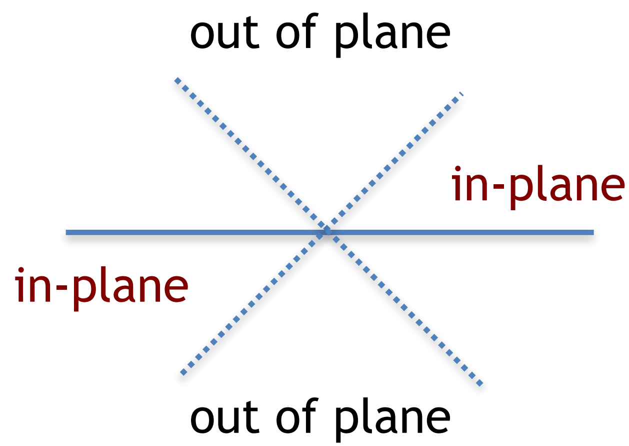
$$\vec{Q} = \begin{pmatrix} \sum_{i=1}^{N} w_i \cos 2\varphi_i \\ \sum_{i=1}^{N} w_i \sin 2\varphi_i \end{pmatrix} \qquad \psi_2 = \frac{1}{2}\tan^{-1}\left(\frac{Q_y}{Q_x}\right)$$

- N - multiplicity of the event
- φ_i - azimuthal angle of particle i
- w_i - weight to correct for azimuthal non-uniformity in TPC



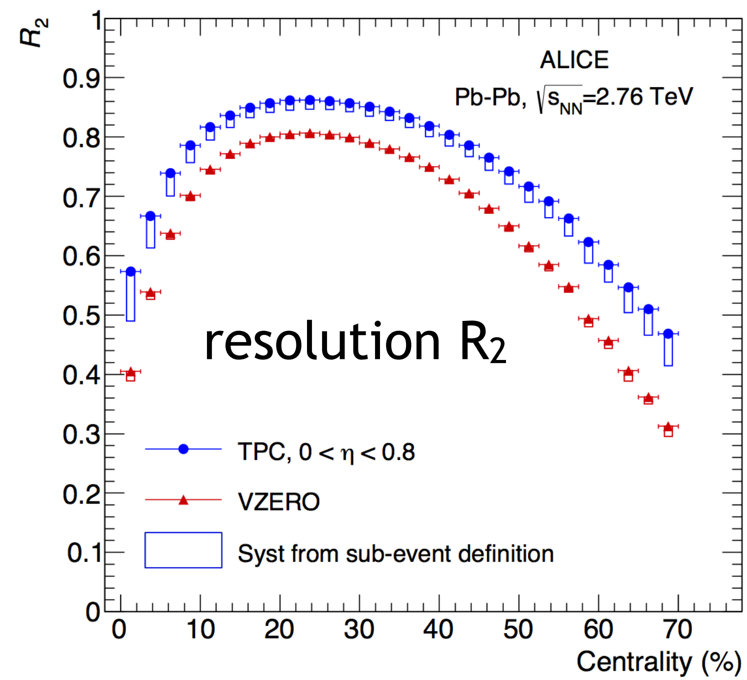
Event Plane Method

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left[1 + 2\sum_{n=0}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]\right]$$

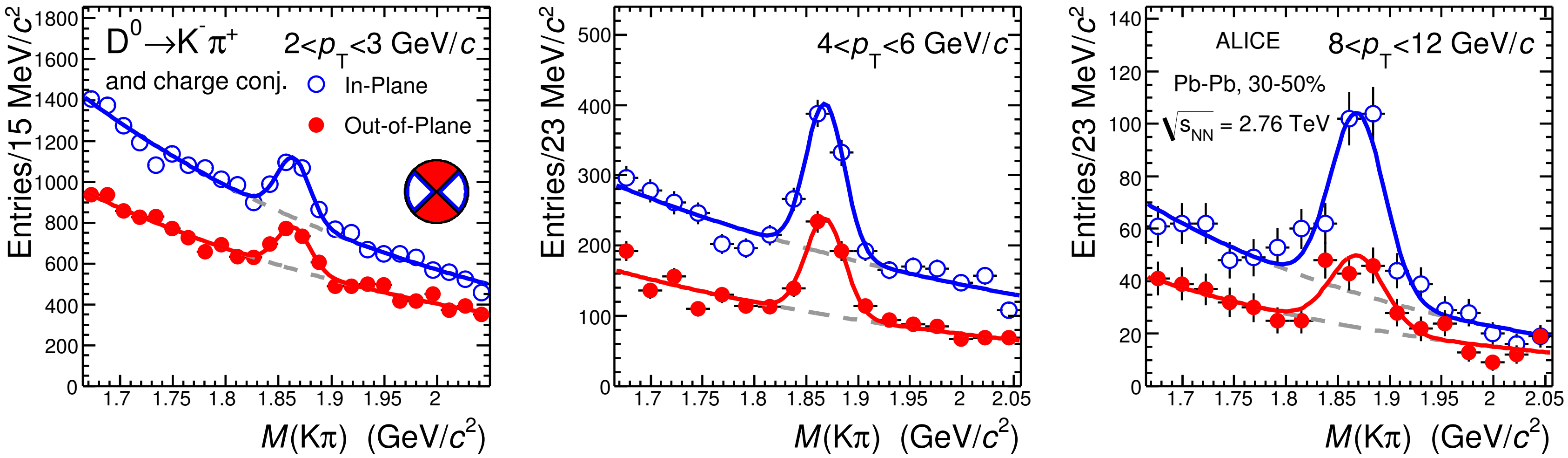


- divide φ into 4 quartiles
- 2 categories: in plane, out of plane
- integrate dN/dφ to get the yields $N_{\text{in-plane}}$ and $N_{\text{out-of-plane}}$
- v_2 can be determined as:

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$



Invariant Mass Distributions



- invariant mass of daughter particles (e.g. Kπ for D^0)
- fitted by second order polynomial (for the background) plus Gaussian (for the signal)
- extract $N_{\text{in-plane}}$ and $N_{\text{out-of-plane}}$ as the integral of the Gaussian
- higher yield in-plane than out-of-plane
- —> non-negative v_2

$$v_2 = \frac{1}{R_2} \frac{\pi}{4} \frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

Feed-Down from B

$B \longrightarrow D + X$

- contribution of D mesons from B decays ~10-20%
- feed-down enhanced by topological selection
- want to give result for prompt D only
- $m_b > m_c \longrightarrow v_2^{feed\text{-}down} \leq v_2^{prompt}$
- most conservative assumption:
  $v_2^{feed\text{-}down} = v_2^{prompt} \longrightarrow v_2^{prompt} = v_2^{all}$
- use as an upper limit for systematic uncertainties:
- use $v_2^{feed\text{-}down} = 0 \longrightarrow v_2^{prompt} = v_2^{all} / f_{prompt}$

Relevant Systematic Uncertainties

Particle	D^0			D^+			D^{*+}		
v_2 analysis	$v_2\{EP\}$	$v_2\{SP\}$	$v_2\{2\}$	$v_2\{EP\}$	$v_2\{SP\}$	$v_2\{2\}$	$v_2\{EP\}$	$v_2\{SP\}$	$v_2\{2\}$
M and v_2 fit stability	9%	10%	8%	25%	8%	17%	30%	14%	11%
2 or 3 sub-ev. R_2	2.3%	–	–	2.3%	–	–	2.3%	–	–
R_2 centrality dependence	2%	–	–	2%	–	–	2%	–	–
Centrality selection	–	10%	10%	–	10%	10%	–	10%	10%
Total (excl. B feed-down)	9%	14%	13%	25%	13%	20%	30%	17%	15%
B feed-down		$^{+48}_{-0}\%$			$^{+26}_{-0}\%$			$^{+26}_{-0}\%$	

$4 < p_T < 6$ GeV/c, 30-50%

- signal extraction
  - vary fit range, functional form, binning…
  - bin counting instead of integral
  - fix fit parameters
- feed-down from B
  - as described on previous slide

Results

- *D meson elliptic flow in non-central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV*
  PRL 111, 102301 (2013)
  - elliptic flow v_2 of D^0, D^+, D^{*+} in 30-50% centrality

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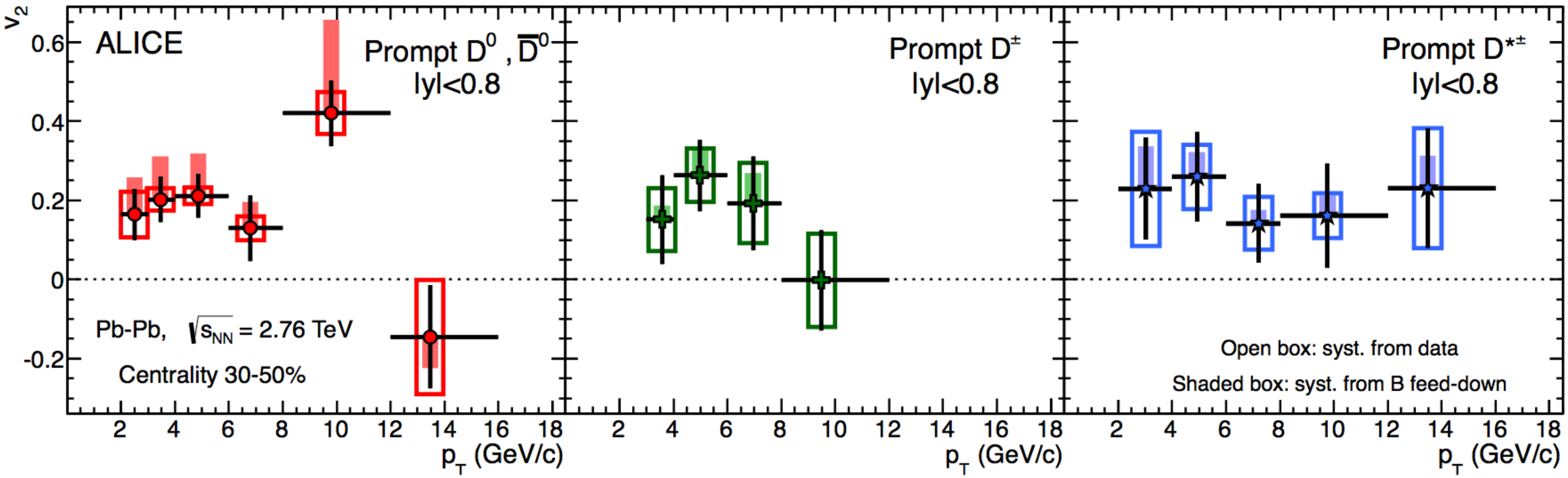
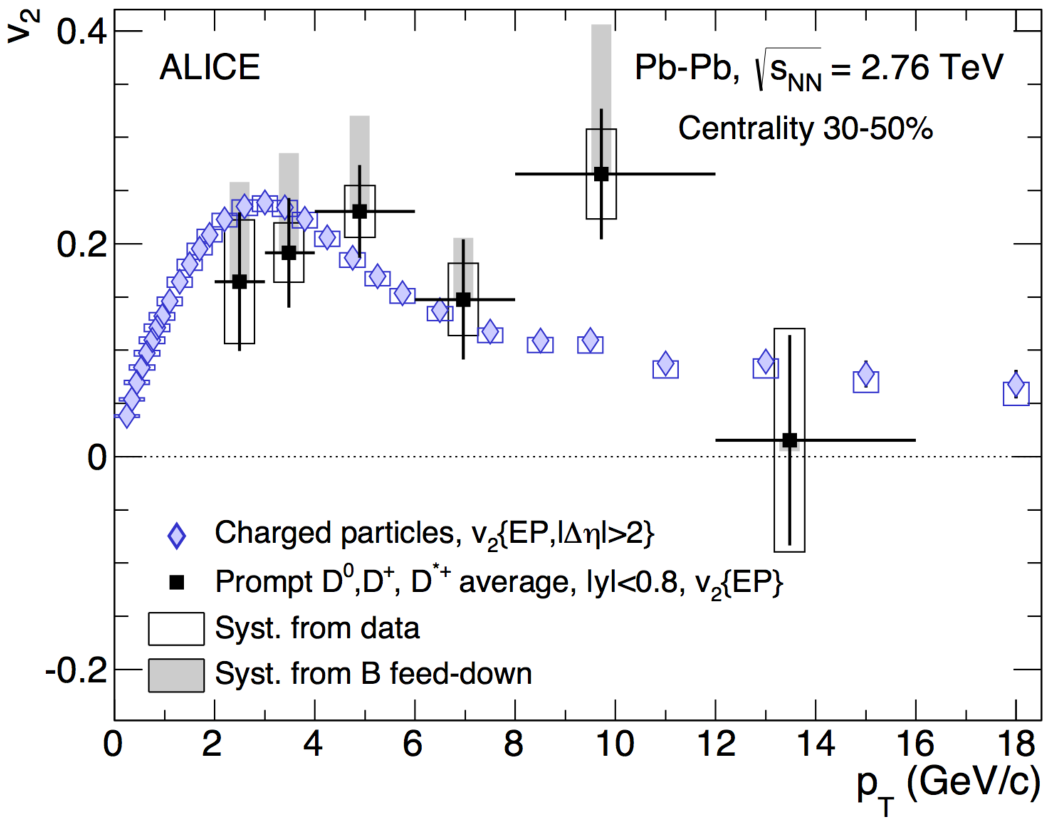
D meson v_2 in 30-50% centrality



- first measurement of D meson v_2 in ALICE!
- non-zero v_2 for all species
- v_2 of different species consistent within uncertainties

Average D meson v_2 in 30-50%



- average computed using statistical significance as weights
- full propagation of systematic uncertainties

- v_2 of D mesons comparable to light flavor
- v_2 in $2<p_T<6$ GeV/c: $0.204 \pm 0.030\ (\text{stat}) \pm 0.020\ (\text{syst})\ ^{+0.092}_{-0}$
- larger than 0 with 5.7σ !

Results

- *D meson elliptic flow in non-central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV*
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    - elliptic flow v_2 of D^0, D^+, D^{*+} in 30-50% centrality

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    - 3 different methods to determine v_2
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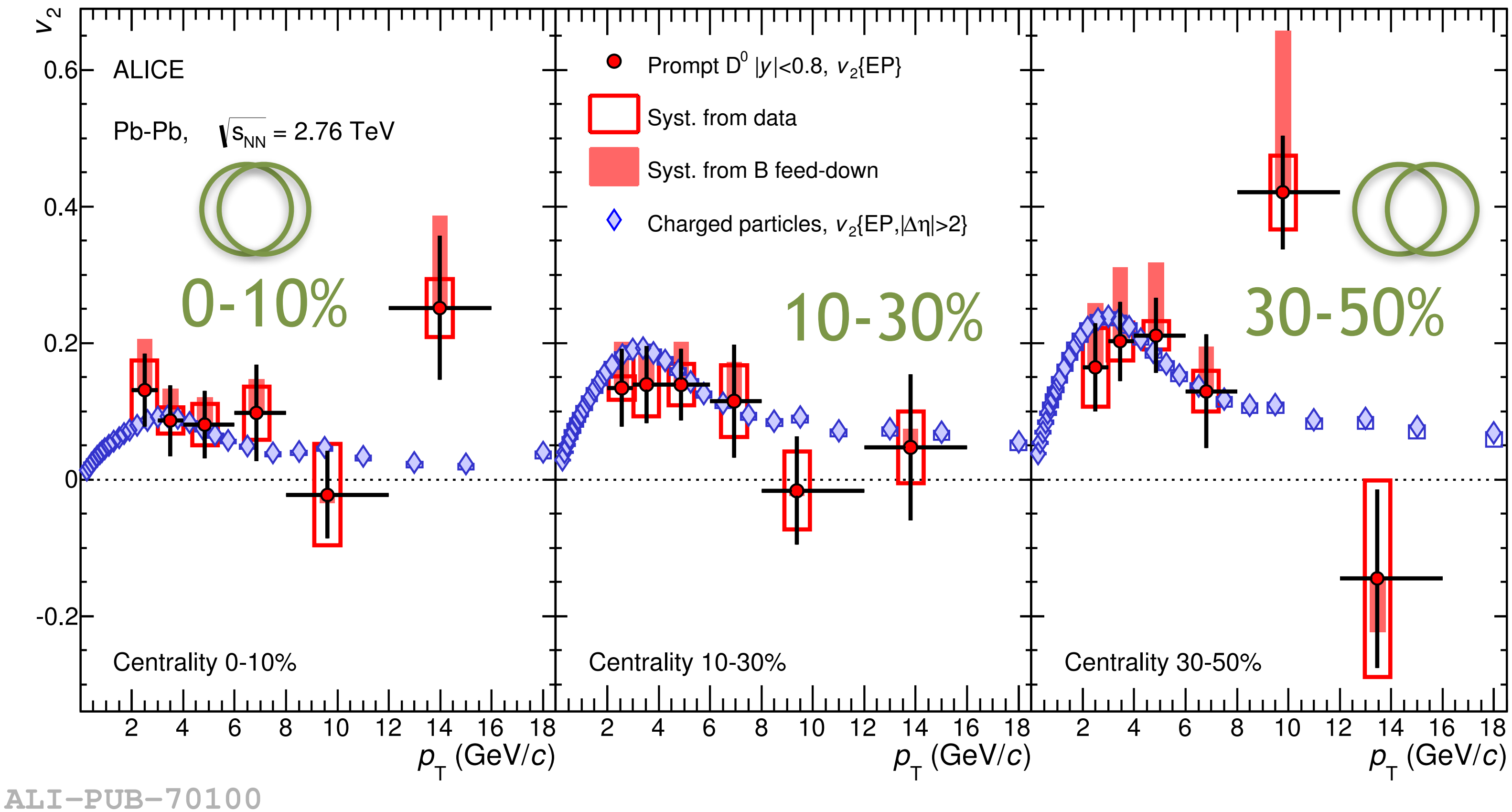
D_0 Elliptic Flow vs. centrality



- indication for increase of v_2 vs. mid-central collisions
- comparable to charged particles in all centrality bins

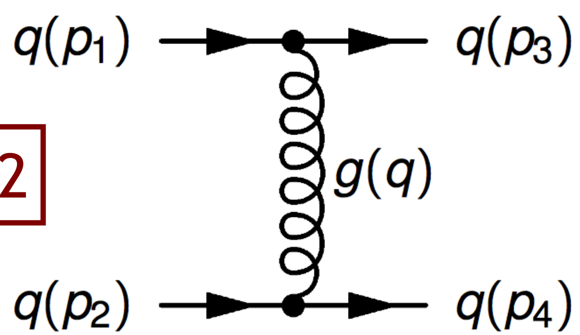
Modelling Flow

- e.g. BAMPS model:

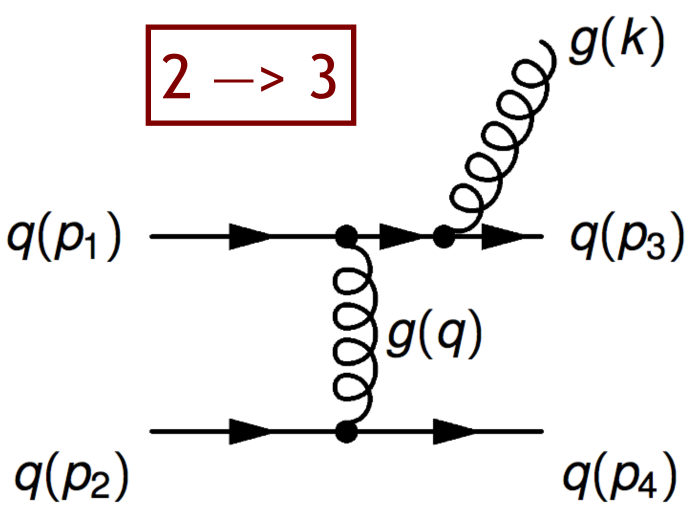
O. Fochler, J. Uphoff, Z. Xu and C. Greiner
Phys. Rev. C 84 (2011) 024908

- Boltzmann approach to multi-parton scattering
- microscopic partonic transport model
- implemented processes:
  - elastic collisions
  - gluon radiation

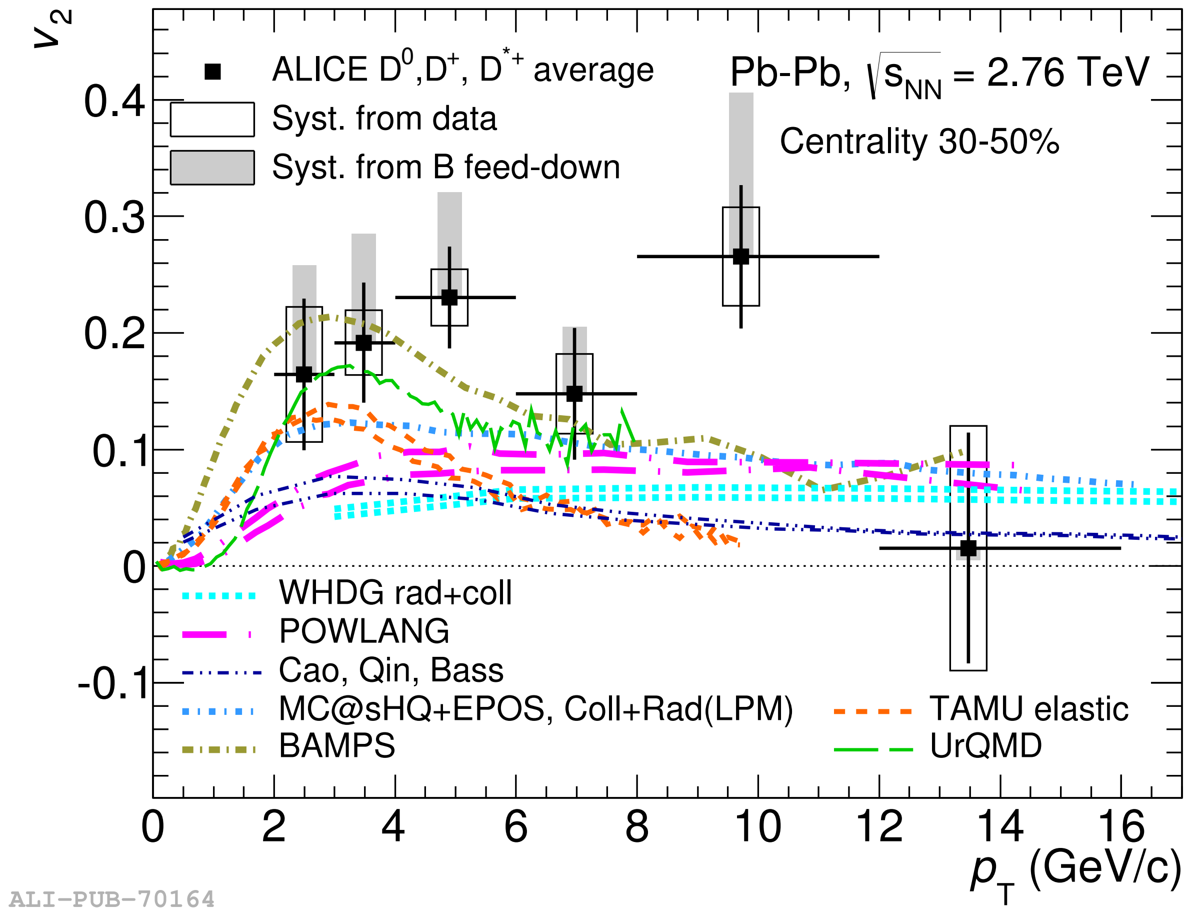
2 —> 2



2 —> 3



Comparison with Models



- many different models exist that predict v_2
- with better precision (Run 2) models will be constrained further

Take Home Messages

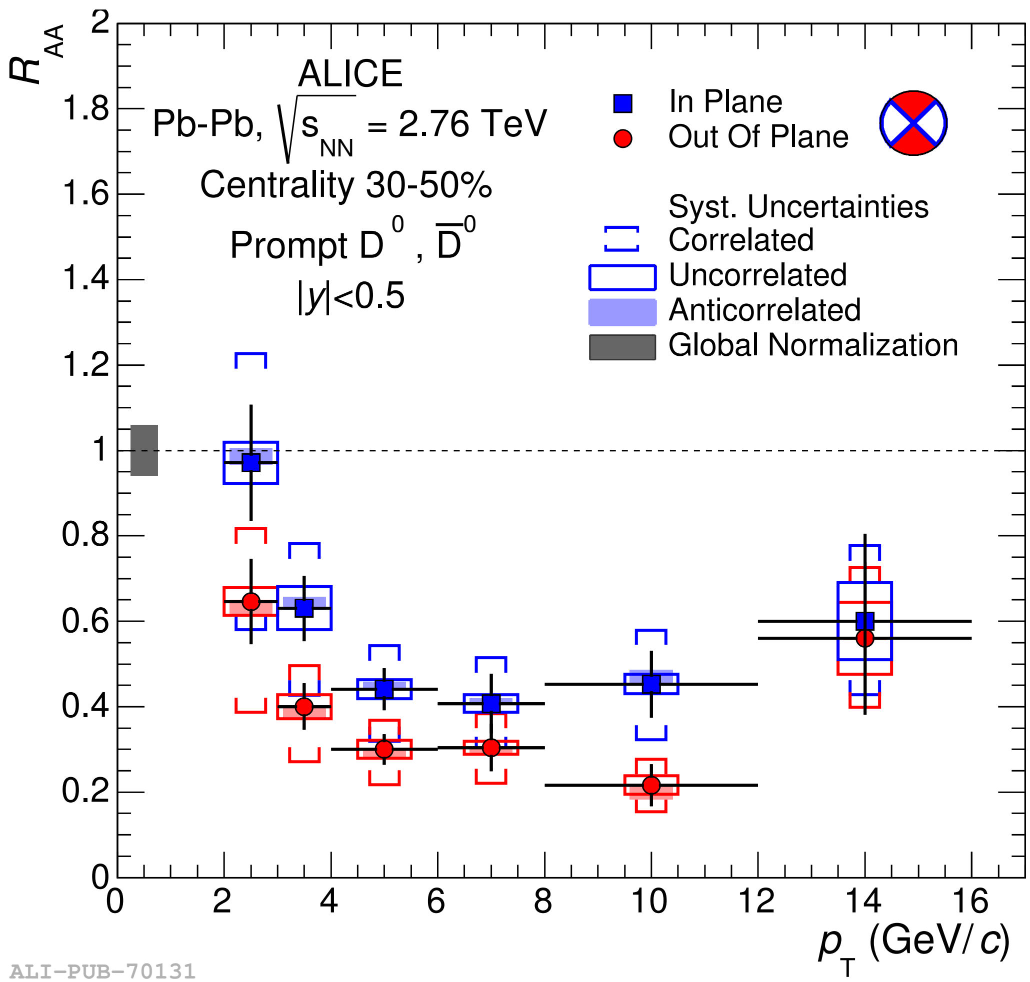
- D mesons reconstructed via invariant mass analysis using topological selection and particle identification
- D meson elliptic flow v_2 measured for the first time in ALICE
- in $2 < p_T < 6$ GeV/c:
  - $v_2 = 0.204 \pm 0.030\,(\text{stat}) \pm 0.020\,(\text{syst})\,^{+0.092}_{-0}$
  - $v_2 > 0$ with 5.7σ significance
- elliptic flow of D mesons and charged particles consistent within uncertainties
- indication for an increase of v_2 from central to mid-central collisions

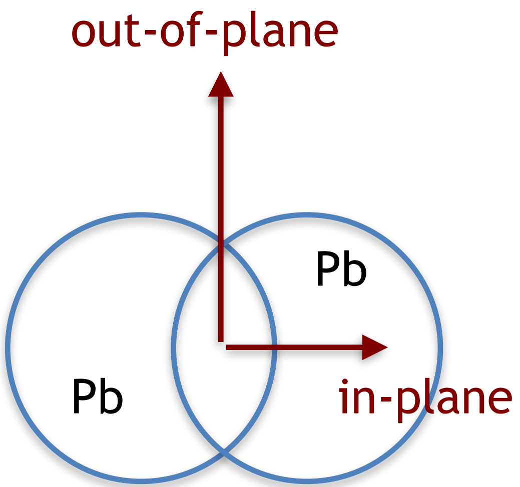
→ **evidence for collective flow of charm quarks**

- no model describes all data yet —> challenge for theory!

Backup

R_{AA} in plane and out of plane





- stronger suppression in out-of-plane direction where the path length is larger

Elliptic Flow with Different Methods