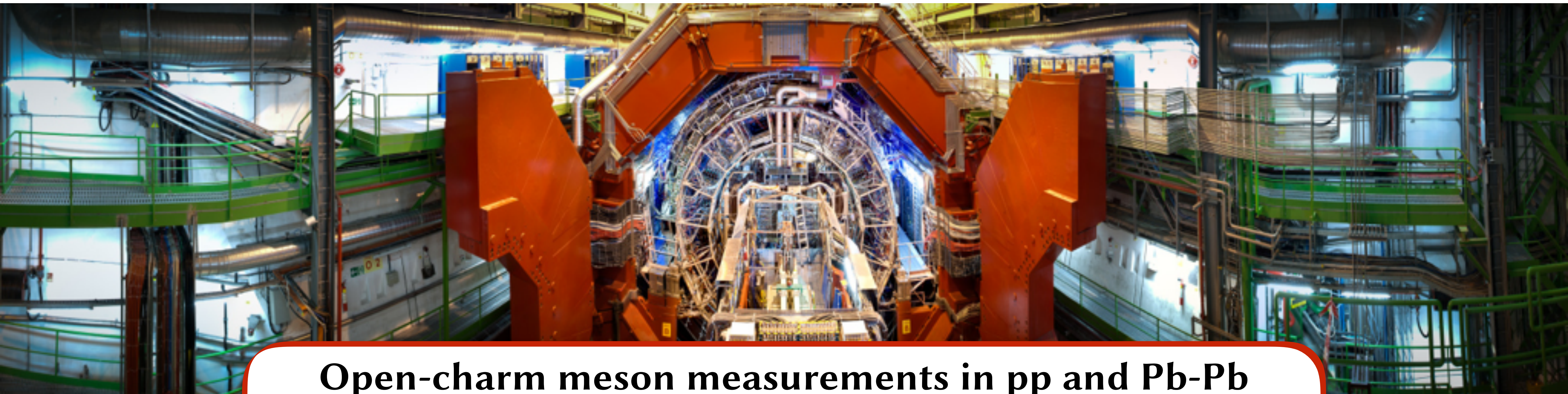

Open-charm meson measurements in pp and Pb-Pb collisions at central rapidity with ALICE

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Hot Quarks 2016

September 12-17

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Outline

- Introduction
- Overview of ALICE recent results:
  - pp collisions
  - Pb-Pb collisions
- Comparison with models
- Conclusion

Heavy-quark specificities

madai-public.cs.unc.edu

Charm ~ 1.3 GeV/c^2
Beauty ~ 4.2 GeV/c^2

Why are heavy quarks interesting?

Heavy quarks are interesting *probes* offering insights into the strong interaction

a./ Produced in hard scattering processes: sensitive test of pQCD (large quark masses)

b./ Short formation time: heavy quarks are produced before the QGP formation

$\Delta t_c < 1/(2m_c) \sim 0.1$ fm/c $<$ $\tau_{QGP} \sim 0.3$ - 1 fm/c at LHC

c./ Negligible annihilation rate: heavy quarks experience the *whole* collision history

d./ Interact with the medium constituents: via elastic (collisions) and/or inelastic (radiations) processes?

e./ Hadronize: via fragmentation and/or coalescence processes?

Heavy-flavour hadrons

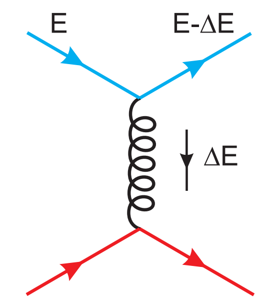
Front door to access the medium properties affecting heavy quarks: **D**, **B**, J/Ψ, Ψ(2S), ϒ(1S, 2S, 3S), Λ_c ...

Heavy quark interactions with the medium

Medium properties are accessible by understanding the *interactions* of heavy quarks with the medium constituents.

Heavy quark energy loss:

1./ Elastic processes (*collisional*): scatterings with other partons, *dominate at low p_T ($p_Q < 10\ m_Q$)*



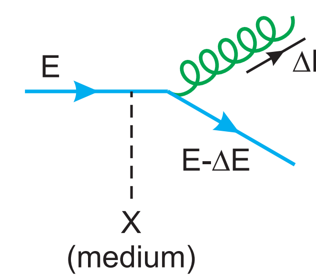
2./ Inelastic processes (*radiative*): gluon radiations, *dominate at high p_T ($p_Q > 10\ m_Q$)*

- Colour-charge dependence Baier, Dokshitzer, Mueller, Peigné, Schiff: Nucl. Phys. B483 (1997) 291-320

  Casimir factor: $C_R = 3$ for gluons; 4/3 for quarks

- Mass dependence: *dead-cone effect* Dokshitzer, Kharzeev: Phys. Lett. B519 (2001) 199-206

  Energy distribution of radiated gluons is suppressed by an angle-dependent factor



\+ Other processes: in-medium hadron formation and dissociation Adil, Vitev: Phys. Lett. B649 (2007) 139-146

$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b) \xrightarrow{?} R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

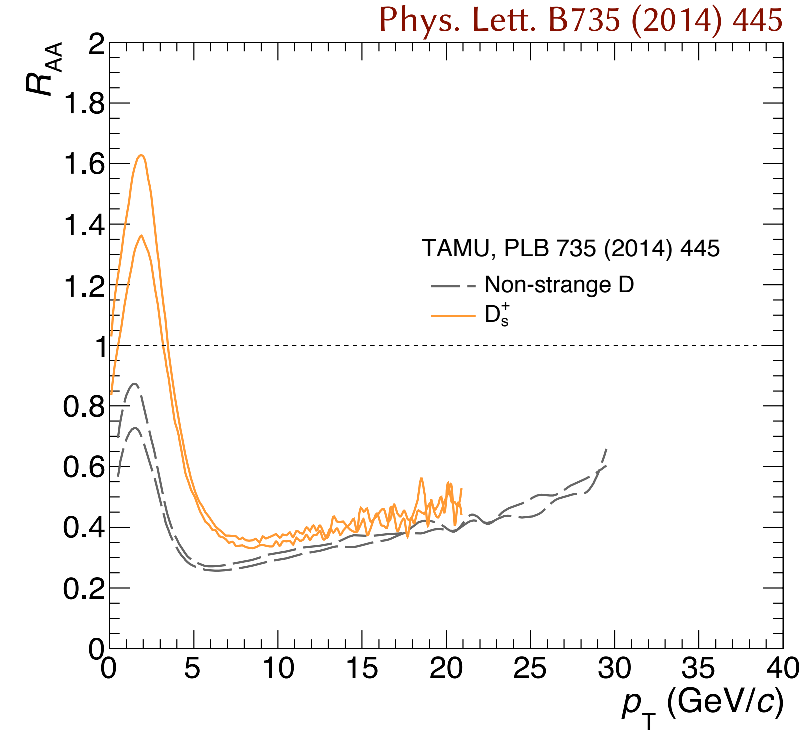
The reduction of parton energy leads to a reduction of the average momentum of the produced parton, quantified by the ***nuclear modification factor:***

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA}\rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

Heavy quark interactions with the medium

Medium properties are accessible by understanding the *interactions* of heavy quarks with the medium constituents.

Phys. Lett. B735 (2014) 445



Hadronization:

1./ Fragmentation: in the vacuum, *dominates at high p_T*

2./ Recombination: for quarks close in the phase space, *may dominate at low p_T*

If charm quarks recombine in the QGP, the relative fraction of strange vs. non-strange D mesons might increase at low p_T

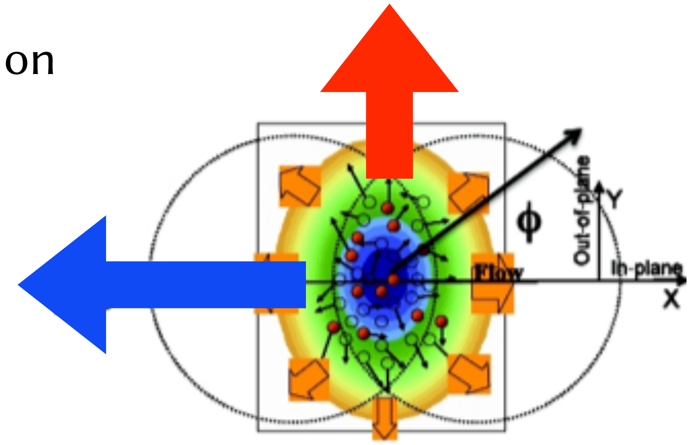
$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

$R_{AA}(D^+, D^0, D^{*+}) < R_{AA}(D_s^+)$?

Azimuthal anisotropy: initial spatial anisotropy ⟶ anisotropic momentum distribution

$$\frac{dN}{d\varphi} = \frac{N}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + ...\right)$$

v_2 : the elliptic flow



Collective expansion: of a hydrodynamical medium, *sensitivity at low p_T*

All particles *in a same region* might be pushed apart all together

Ollitrault: Phys. Rev. D46 (1992) 229

D-meson studies with ALICE

A Large Ion Collider Experiment: designed for the QCD study

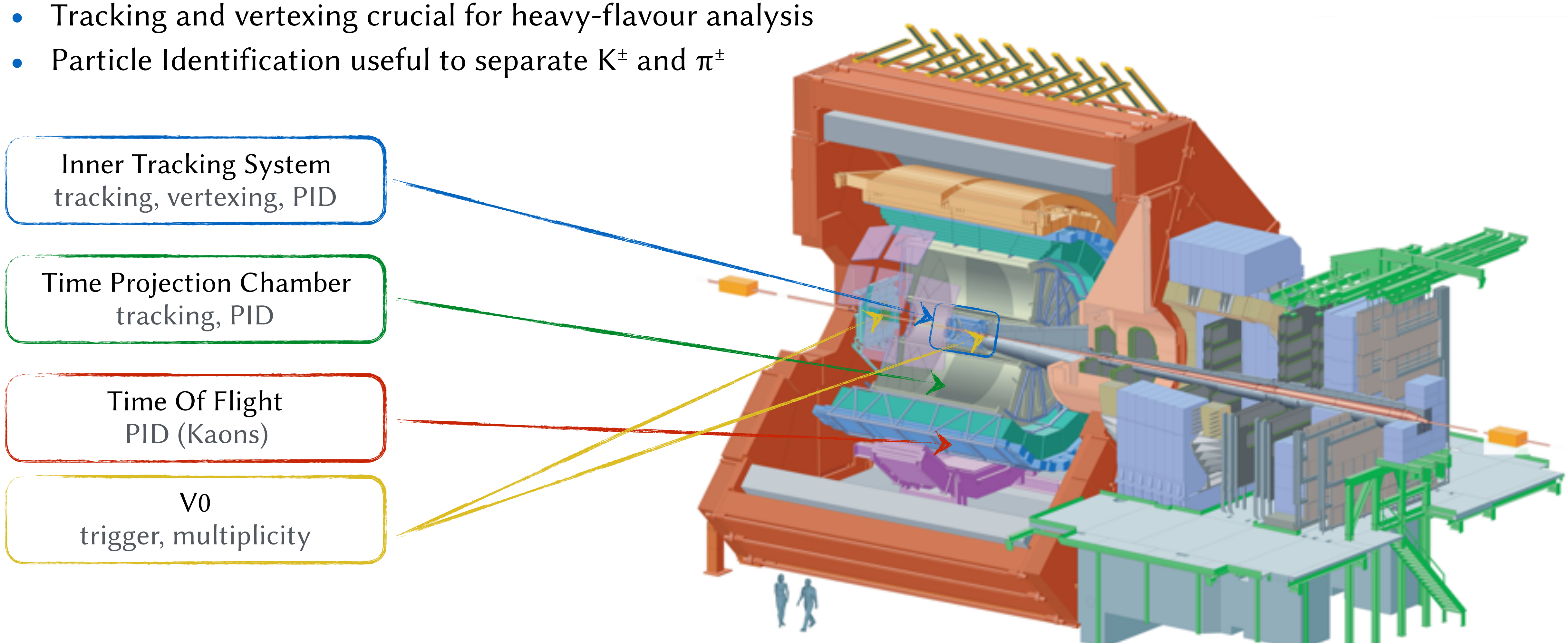
Optimised to work in high-track density environment, reach low p_T (~100 MeV/c) measurements with good PID capabilities

Open-charm hadrons studied in ALICE:

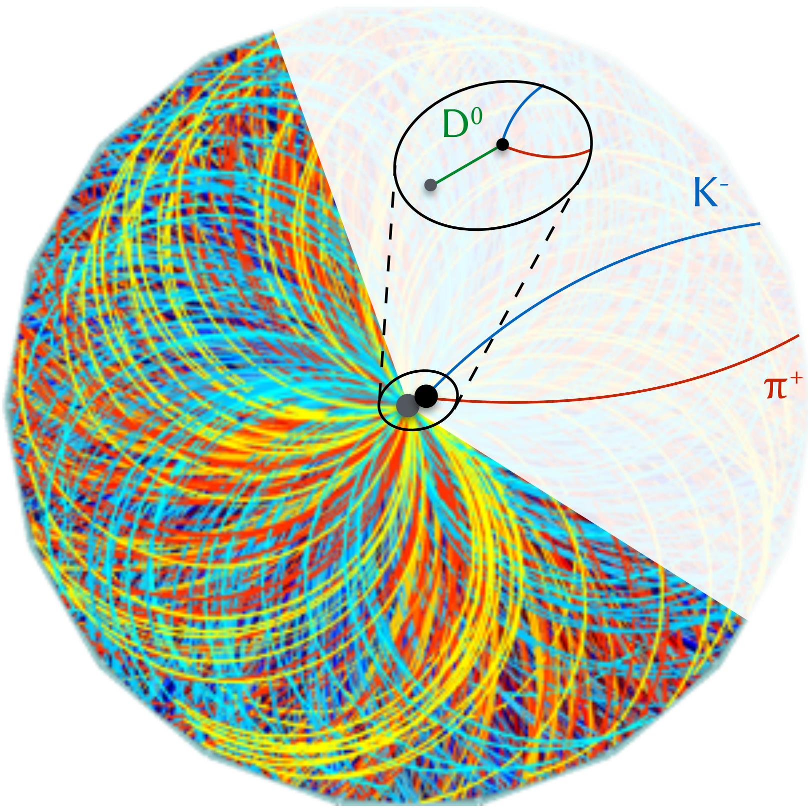
- Decay electrons: D, Λ_c^+, B $\longrightarrow$ e + X in $|\eta| < 0.9$
- Decay muons: D, Λ_c^+, B $\longrightarrow$ μ + X in $-4 < \eta < -2.5$
- Hadronic ($\pi^\pm$, $K^\pm$) channels in $|\eta| < 0.9$

Hadronic *full* reconstruction of D mesons: invariant mass analysis in $|\eta| < 0.9$

- Tracking and vertexing crucial for heavy-flavour analysis
- Particle Identification useful to separate $K^\pm$ and $\pi^\pm$



D-meson hadronic full reconstruction

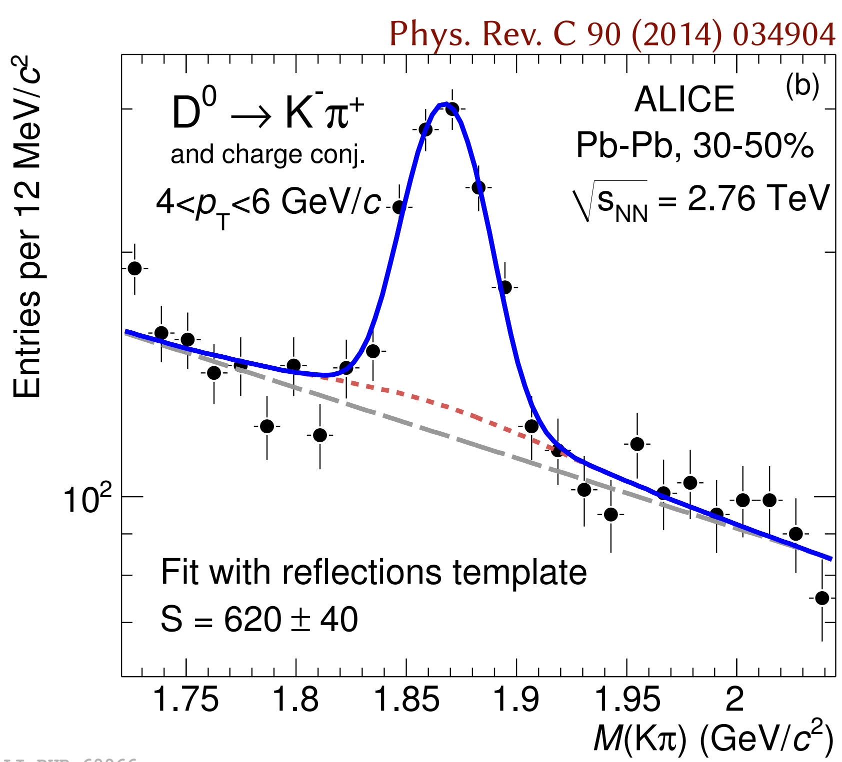


Exploit the D-meson displacement up to few hundred micrometers

	Decay	$c\tau$	Mass
✔	$D^0 \longrightarrow K^-\pi^+$	$c\tau \sim 123$ μm	1864.8 MeV/c^2
✔	$D^+ \longrightarrow K^-\pi^+\pi^+$	$c\tau \sim 312$ μm	1869.6 MeV/c^2
✔	$D_s^+ \longrightarrow \phi(1020)\pi^+ \longrightarrow K^+K^-\pi^+$	$c\tau \sim 150$ μm	1968.3 MeV/c^2
✔	$D^{*+} \longrightarrow D^0\pi^+$	$c\tau \sim 2$ fm	2010.3 MeV/c^2
✘	$\Lambda_c^+ \longrightarrow pK^-\pi^+, pK^0_S$	$c\tau \sim 60$ μm	2286.5 MeV/c^2

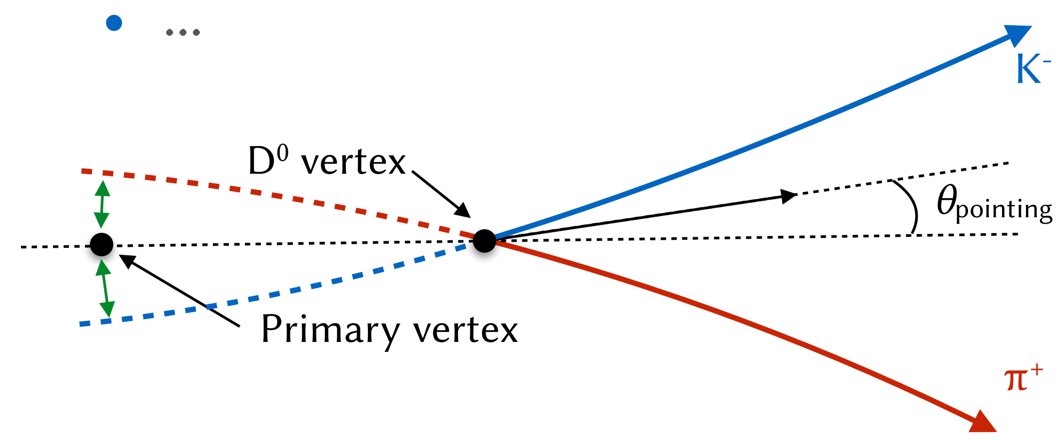
Invariant mass analysis in $|\eta| < 0.9$ mainly based on

- Secondary vertex reconstruction & topological criteria
- Particle identification



Typical topological selections have to be optimised per p_T-bin

- D-meson pointing angle: $\cos(\theta_{pointing})$
- D-meson decay length: L_{xy}
- Impact parameter of daughters: d_0
- ...



pp collisions

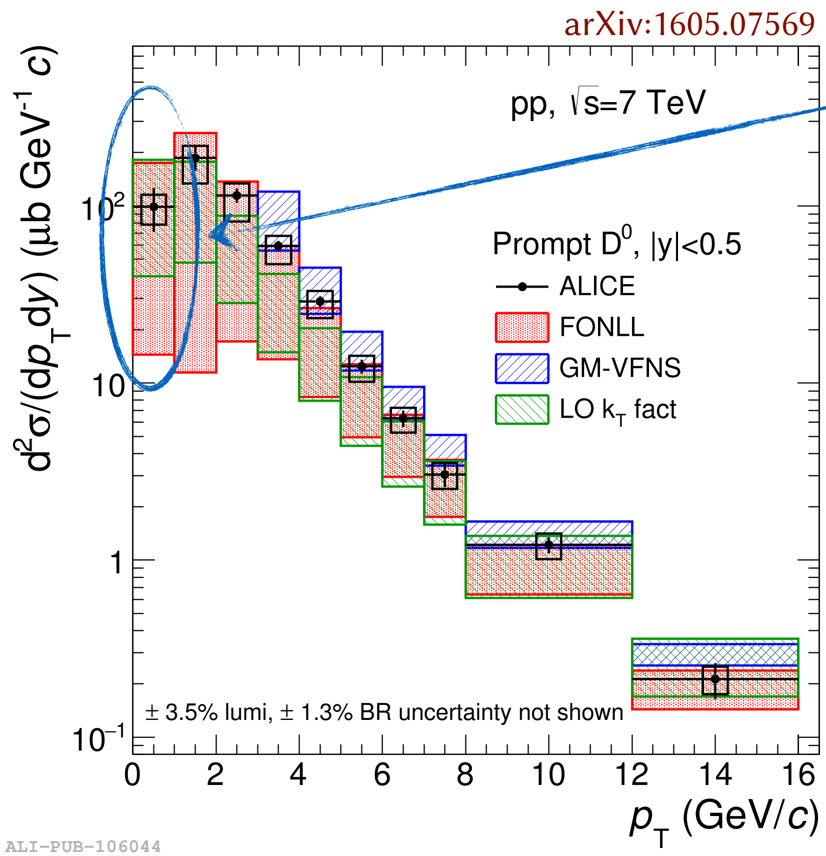
D^0 production cross-section down to $p_T = 0$ GeV/c and total inclusive charm cross-section

arXiv:1605.07569

D^+ and D^{*+} production cross-section at 8 TeV and comparison with 7 TeV results

preliminary results

D mesons in pp collisions for testing the pQCD (7 TeV)

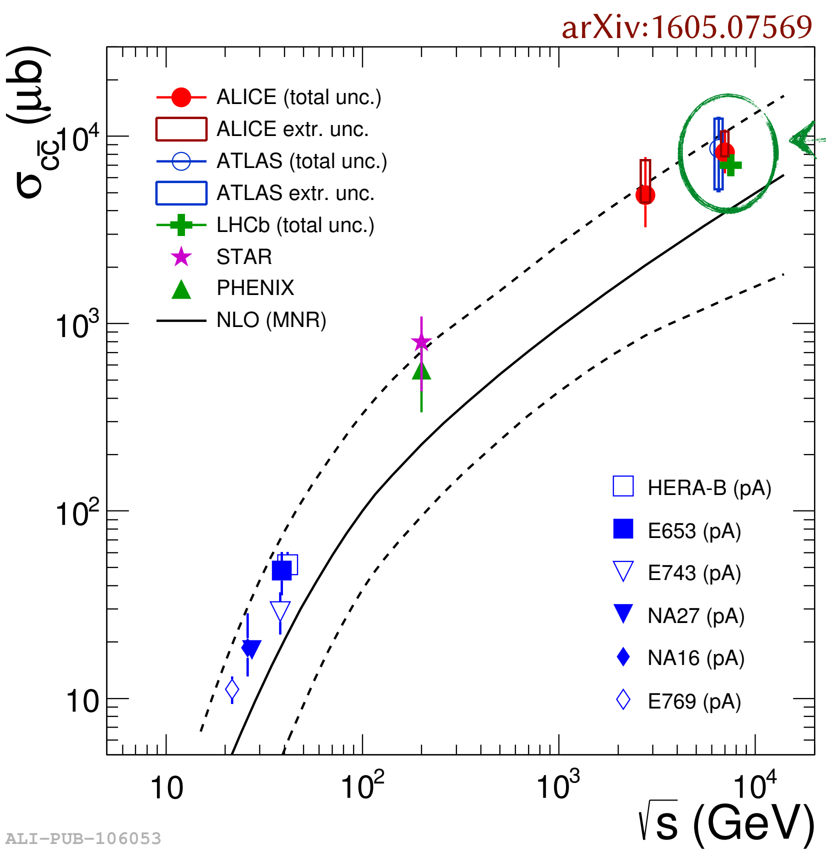


New analysis method allows to reach D^0 at low p_T, *down to 0 GeV/c*

- no selection on secondary vertex, only combinatorics
- estimation and subtraction of the background

pQCD calculations (FONLL, GM-VFNS, k_T factorisation) are compatible within uncertainties with all D-meson species

FONLL: JHEP 10 (2012) 137
GM-VFNS: Eur. Phys. J. C72 (2012) 2082
k_T factorisation: Phys. Rev. D87 (2013) 094022

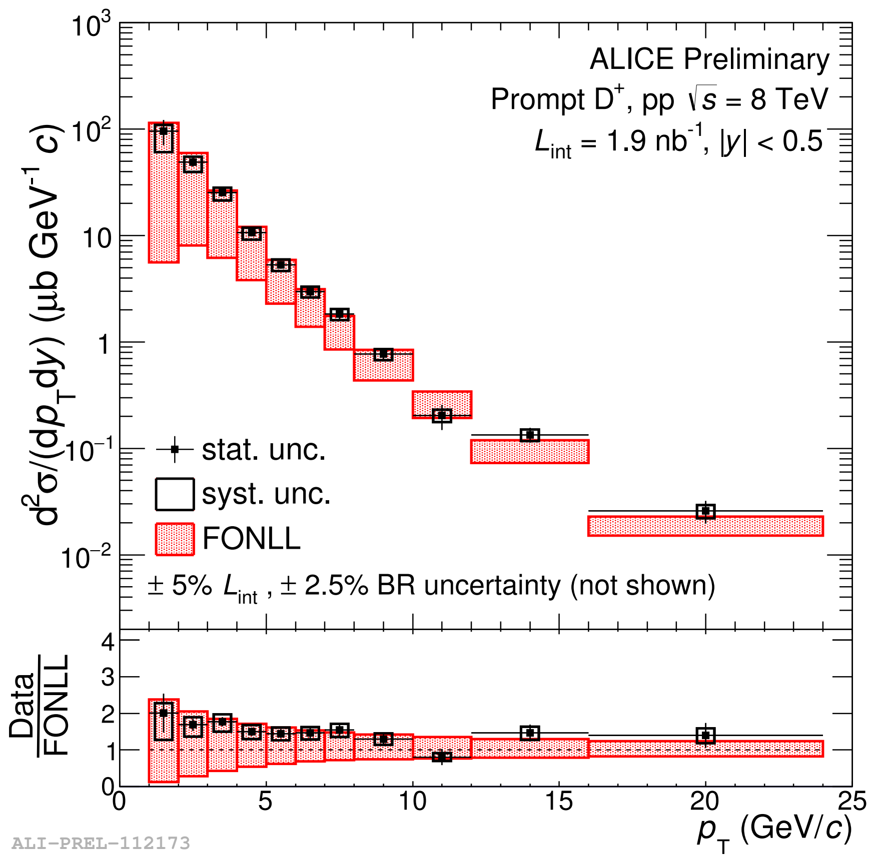


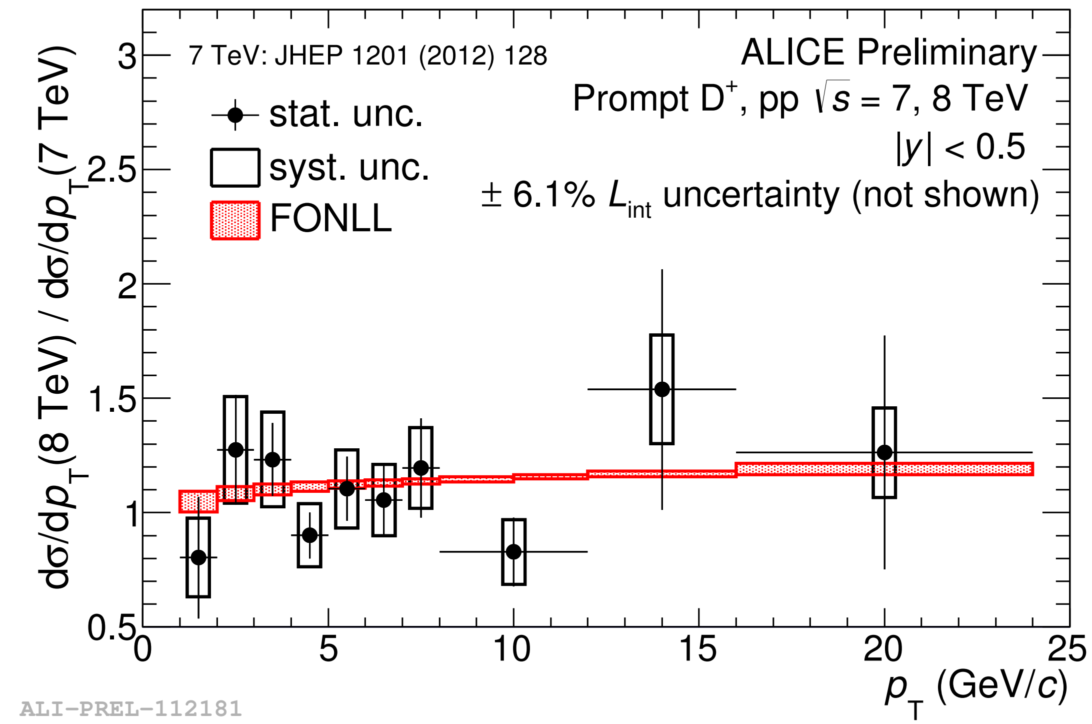
Updated total charm cross-section

QCD predictions at NLO in agreement within large uncertainties over a wide $\sqrt{s}$ range

NLO MNR: Nucl. Phys. B373 (1992) 295-345

D mesons in pp collisions for testing the pQCD (8 TeV)





Production cross sections of D^+ and D^{*+} in pp collisions at $\sqrt{s}$ = 8 TeV have been measured by ALICE (preliminary results)

- D^+ and D^{*+} cross sections slightly higher at 8 TeV than at 7 TeV, as expected
- FONLL describes reasonably well the data, within uncertainties
  - → as already noticed at lower energies, data sit at the upper edge of FONLL calculations

FONLL: JHEP 10 (2012) 137

pp collisions are the reference for p-Pb and Pb-Pb collisions

Pb-Pb collisions

D-meson nuclear modification factor as a function of centrality

JHEP 11 (2015) 205

D-meson nuclear modification factor in 0-10% and 30-50%

JHEP 03 (2016) 081

First measurement of D_s^+ nuclear modification factor

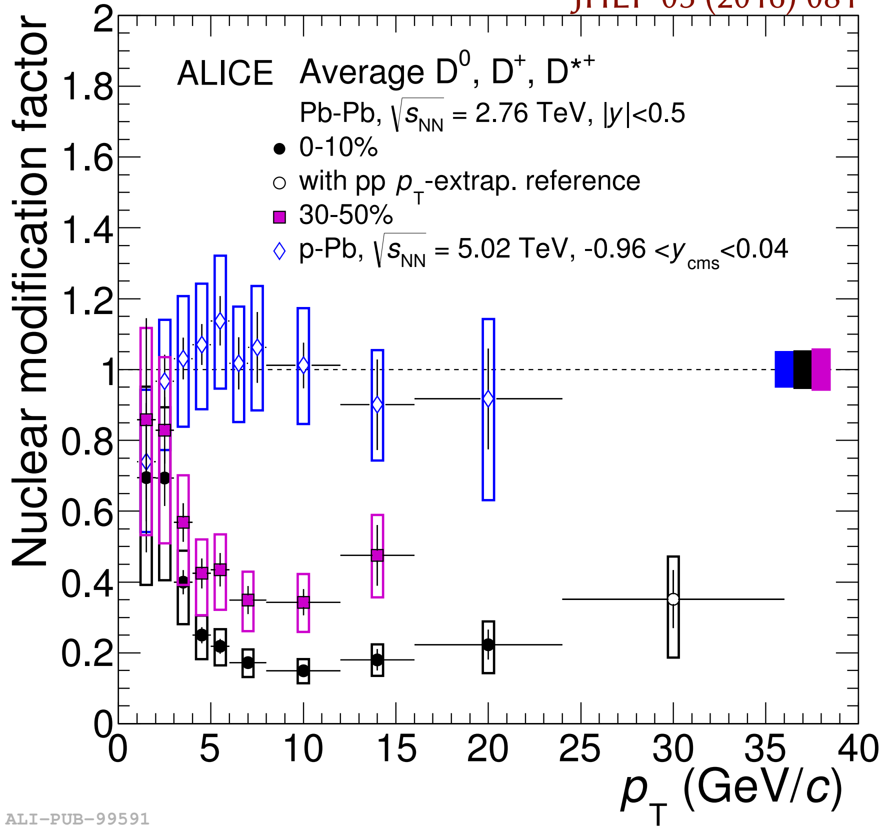
JHEP 03 (2016) 082

D-meson elliptic flow

Phys. Rev. C 90 (2014) 034904

D-meson suppression as a function of centrality

JHEP 03 (2016) 081



- Large *suppression* of D mesons (D$^+$, D^0, D^{*+}) in **Pb-Pb** collisions
- Stronger suppression for **central Pb-Pb collisions**, up to a factor of 5-6, than for **semi-central collisions**, up to a factor 3.

- No significant suppression in MB **p-Pb collisions** for p_T > 2 GeV/c

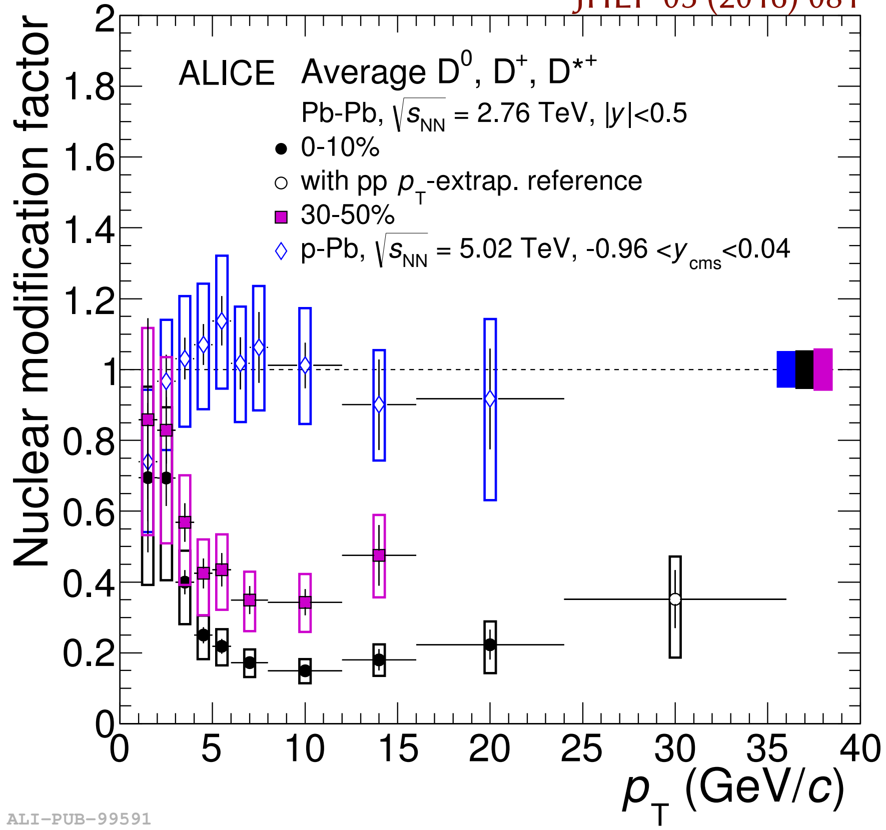
  Phys. Rev. Lett.113 (2014) 232301

Interpretation:

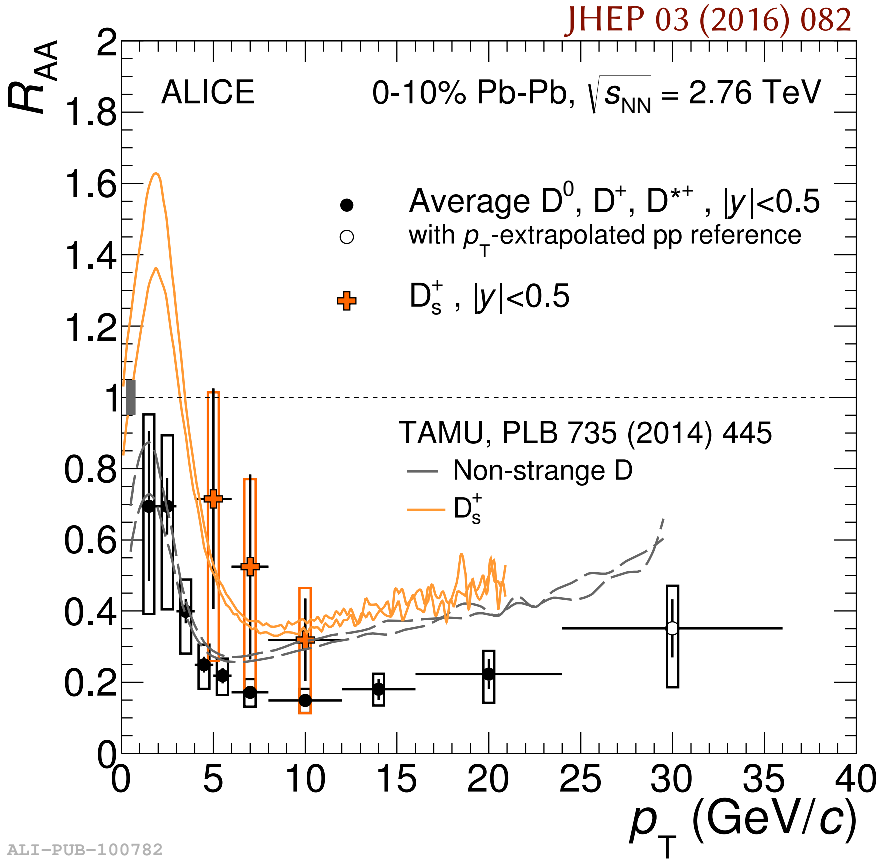
- suppression observed in Pb-Pb cannot be caused by Cold Nuclear Matter effects
- stronger energy loss in central collisions due to the increase of medium density, size and lifetime

D-meson suppression as a function of centrality

JHEP 03 (2016) 081



JHEP 03 (2016) 082



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0-10% **30-50%**

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Interpretation:

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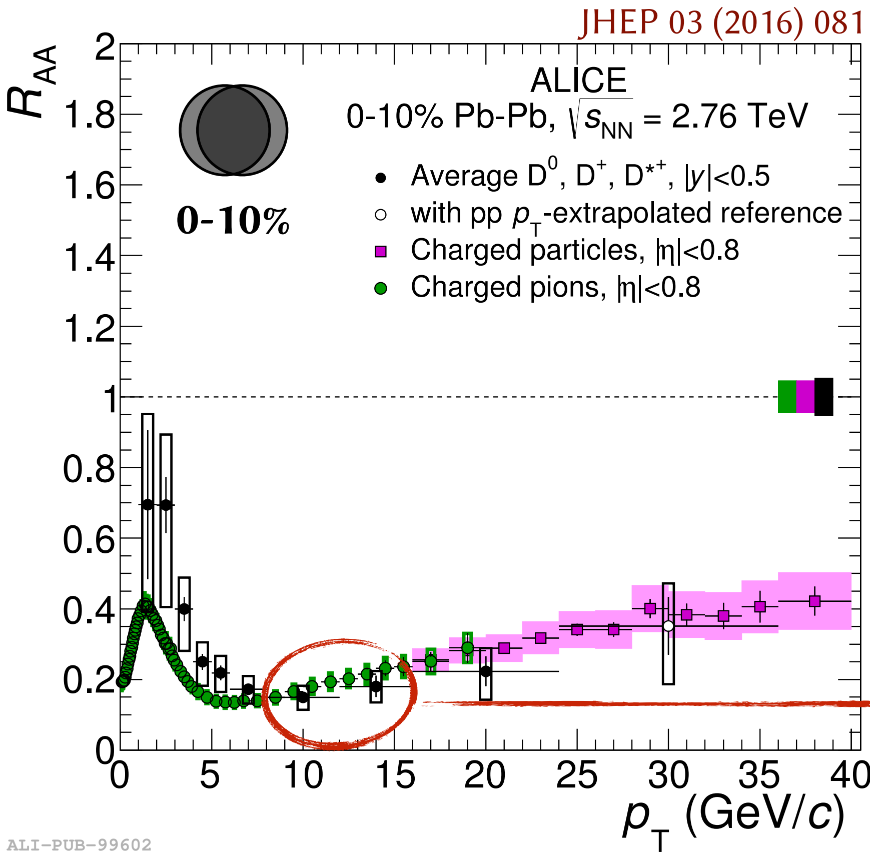
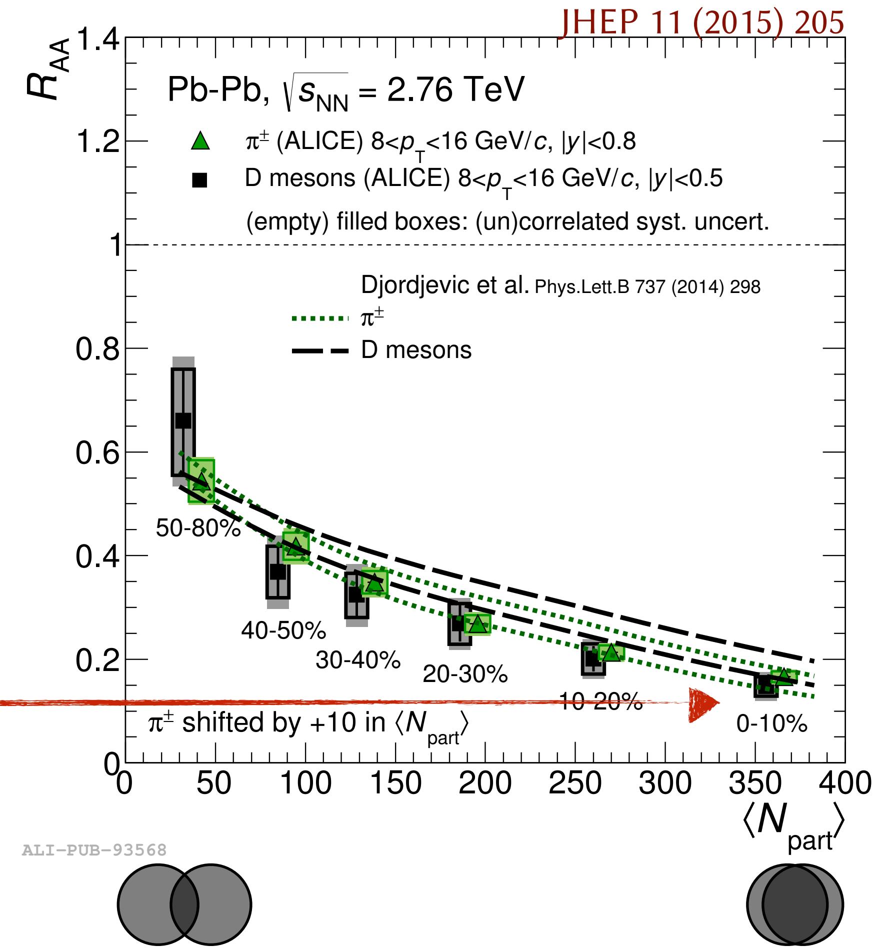
R_{AA}(D$^+$, D^0, D^{*+}) < R_{AA}(D$_s^+$) ?

- **TAMU** assumes charm quark recombination mechanisms and expects enhancement of the D$_s^+$/D in heavy-ion collisions
- No firm conclusion with this first measurement in Pb-Pb collisions

Colour-charge dependence of energy loss





?

$R_{AA}(\pi) < R_{AA}(D)$ at high p_T

- **D mesons** vs. **charged $\pi^\pm$**
- **Charged particles** dominated by **$\pi^\pm$**
- R_{AA}(**D**) ≈ R_{AA}(**$\pi^\pm$**) for p_T > 8 GeV/c

$R_{AA}(\pi) \approx R_{AA}(D)$ at high p_T in agreement with models (***Djordjevic*** ■■) taking into account:

- $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c)$
- *harder* p_T and *fragmentation* distribution for charm quarks than for gluons

Direct interpretation of R_{AA}(**D**) and R_{AA}(**$\pi^\pm$**) also complicated by:

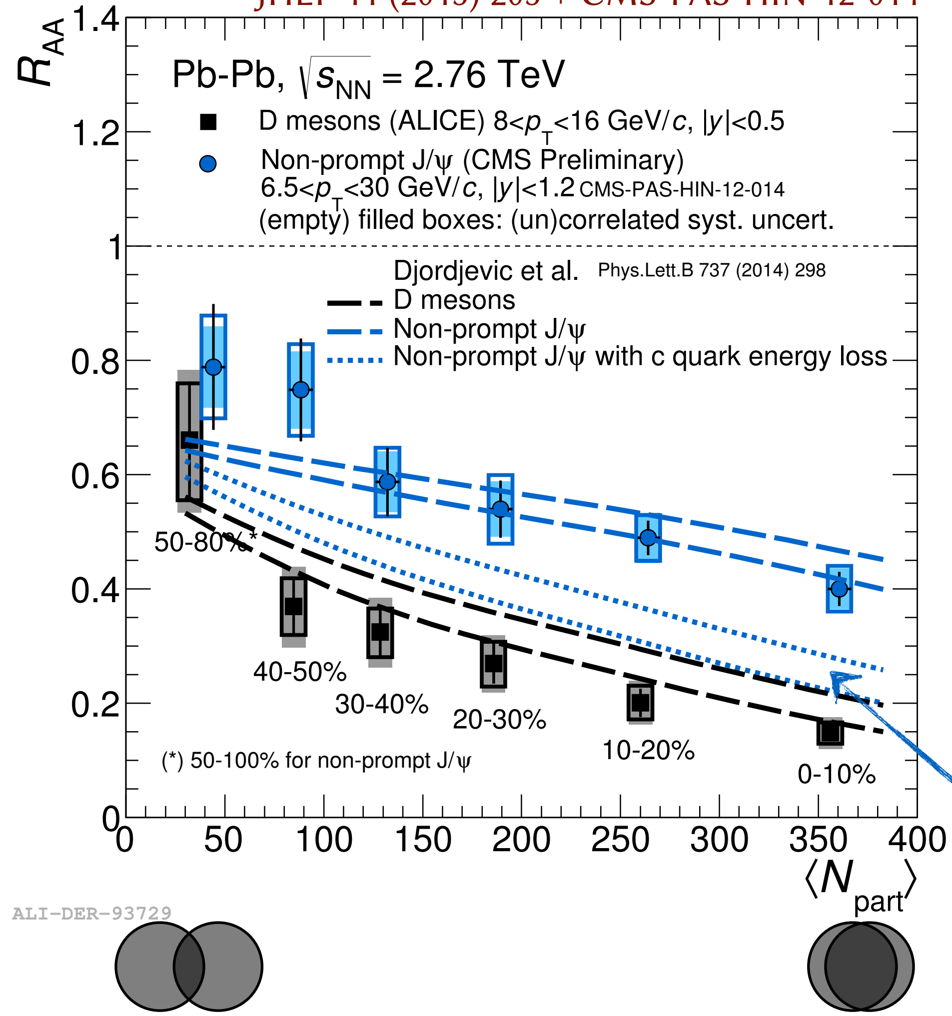
- π could have large contribution from radial flow, up to 2-3 GeV/c *(which doesn't scale with binary nucleon-nucleon collisions)*
- different CNM effects between π and D

Mass dependence of energy loss

?

$R_{AA}(D) < R_{AA}(B)$

JHEP 11 (2015) 205 + CMS-PAS-HIN-12-014



ALICE/CMS combined results in a (almost) similar kinematic range: central rapidity, $<p_T>$ ~ 10 GeV/c

$R_{AA}(D) < R_{AA}(J/\Psi \longleftarrow B)$ as expected since $\Delta E(c) > \Delta E(b)$

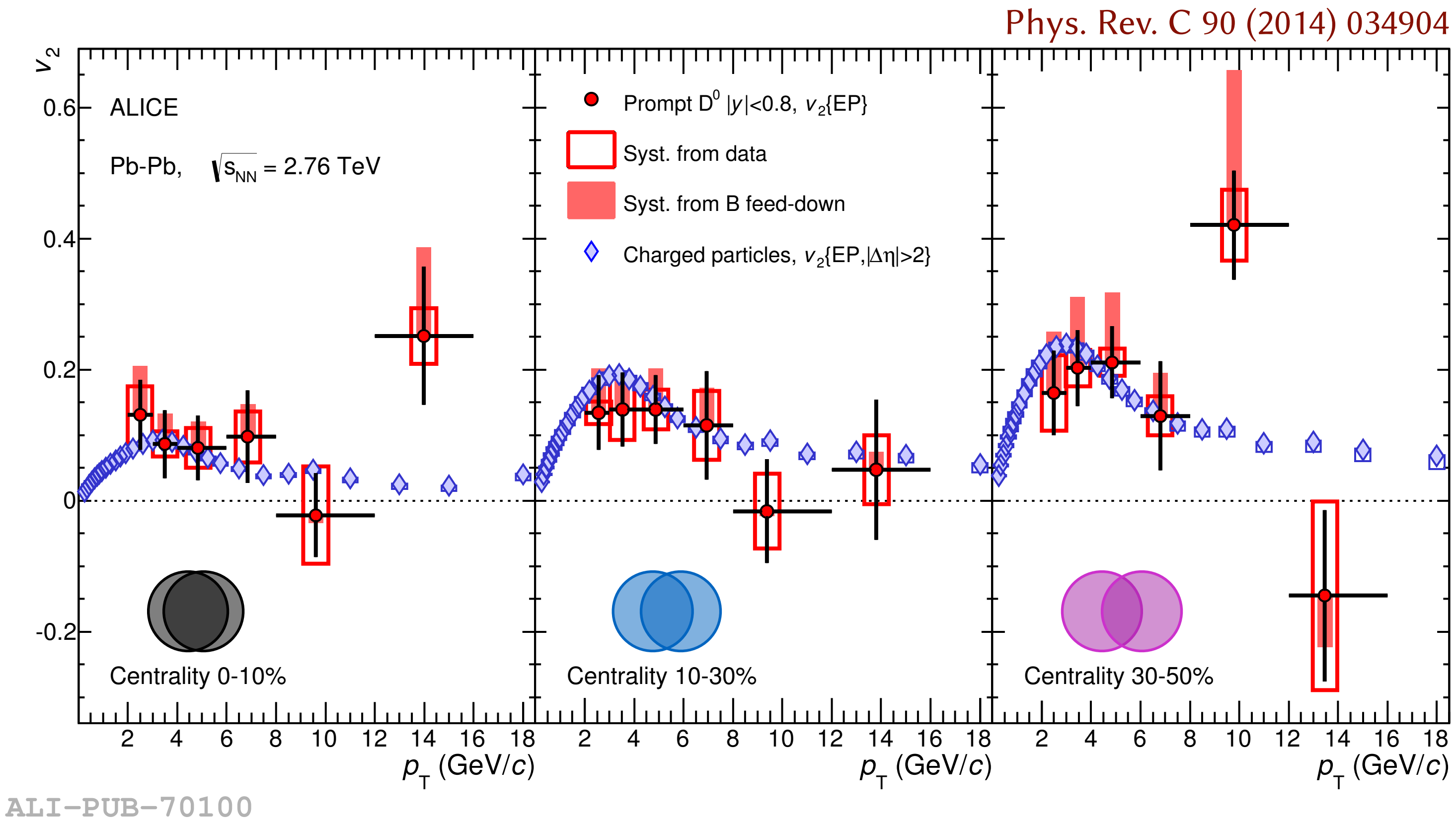
- ***Djordjevic*** model in qualitative agreement with data and contains:
  - Mass-dependent energy loss for gluons, light and heavy quarks: radiative & collisional
  - Hadronization by fragmentation outside the medium

$R_{AA}(D) \approx R_{AA}(J/\Psi \longleftarrow B)$ when the c quark mass is assigned to the b quark

→ the R_{AA} difference derives from the quark mass dependence of parton energy loss

Similar trends for other models: MC@sHQ+EPOS2, TAMU elastic

D-meson elliptic flow compared to light hadrons



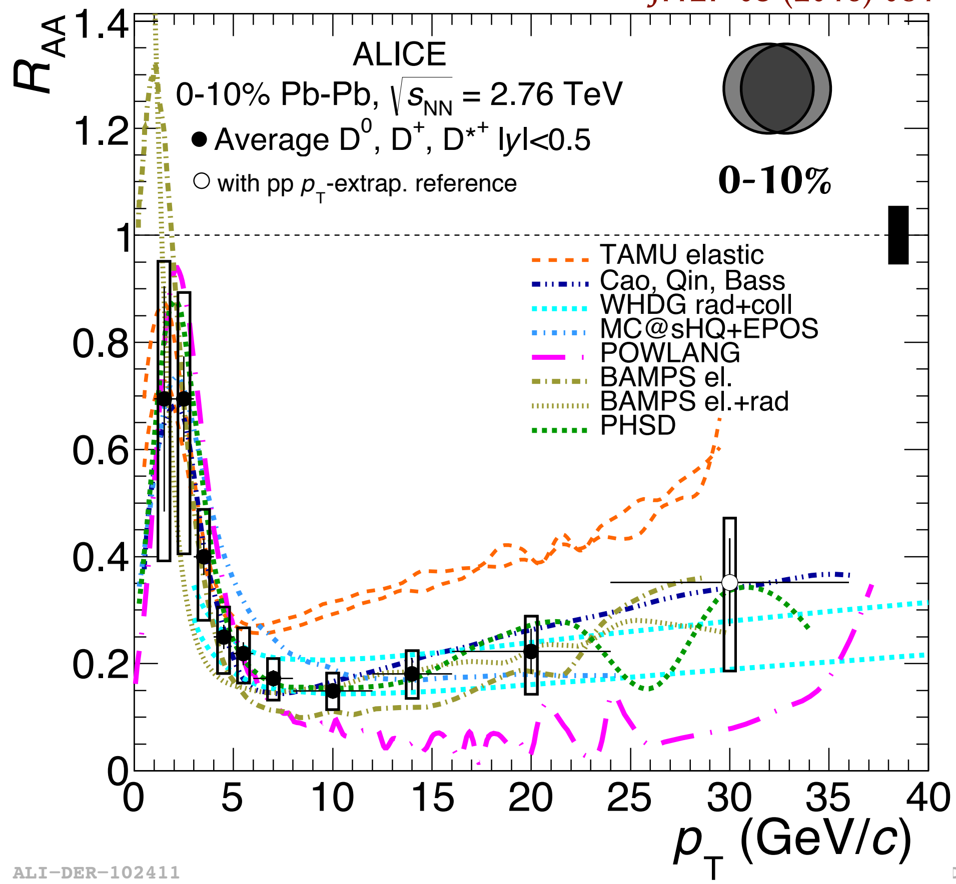
- Positive v_2 of D meson for $2 < p_T < 6$ GeV/c (5.7 σ)
- Similar v_2 magnitude of **D mesons** and **charged particles**
- Hint for increasing v_2 from **central** to **semi-central** collisions

$v_2 > 0$ at low p_T: indication that charm quarks participate to the collective expansion of the medium

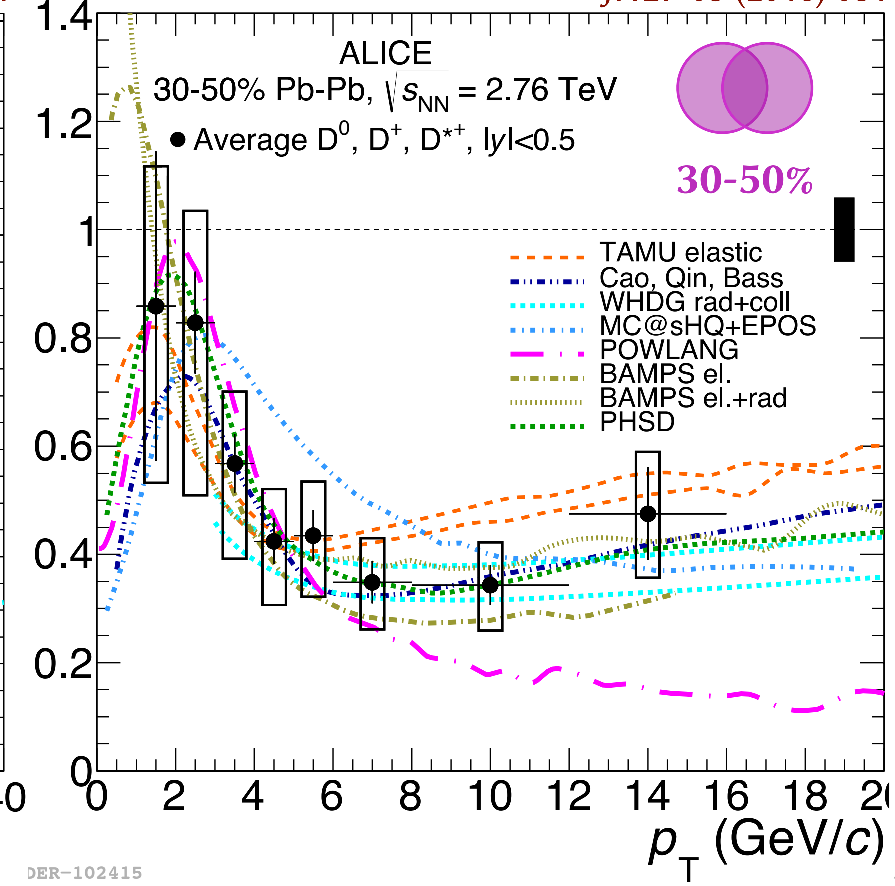
High-p_T v_2: sensitive to the path-length dependence of the energy loss. Gyulassy, Vitev, Wang: Phys. Rev. Lett. 86 (2001) 2537
More statistics is needed to quantify the v_2 above 6 GeV/c
⟶ R_{AA} in the in-plane and out-of-plane direction have been measured by ALICE (Phys. Rev. C 90 (2014) 034904)

Simultaneous description of D-meson data

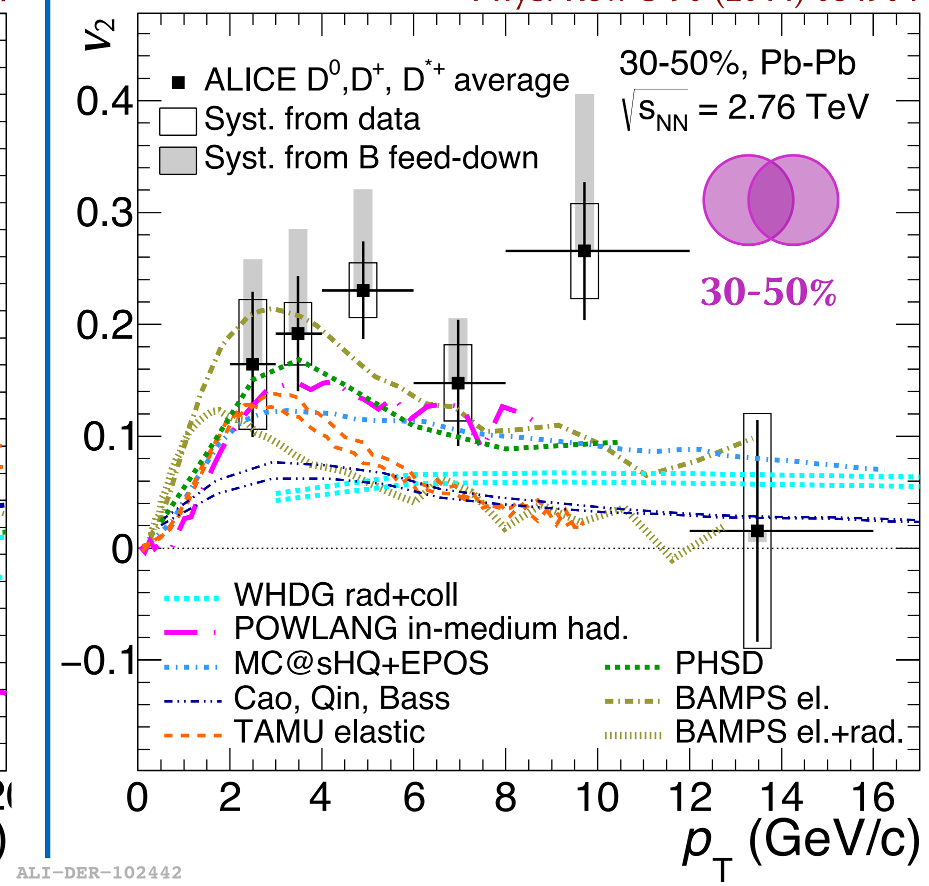
JHEP 03 (2016) 081



JHEP 03 (2016) 081



Phys. Rev. C 90 (2014) 034904



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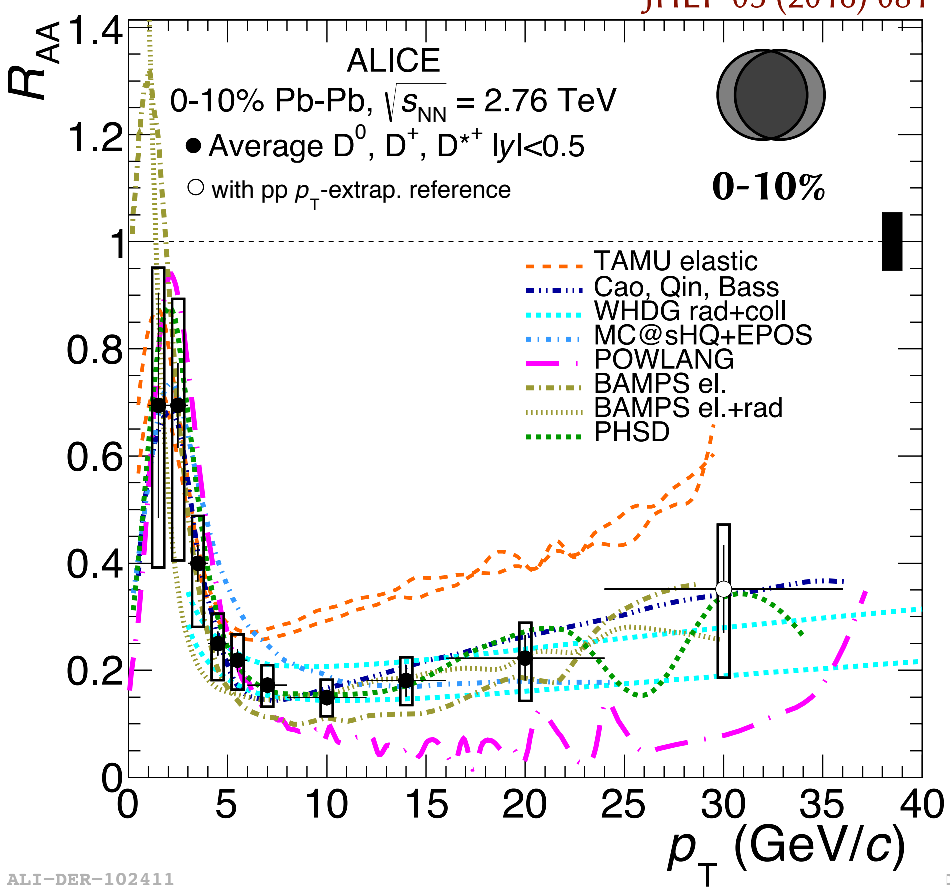

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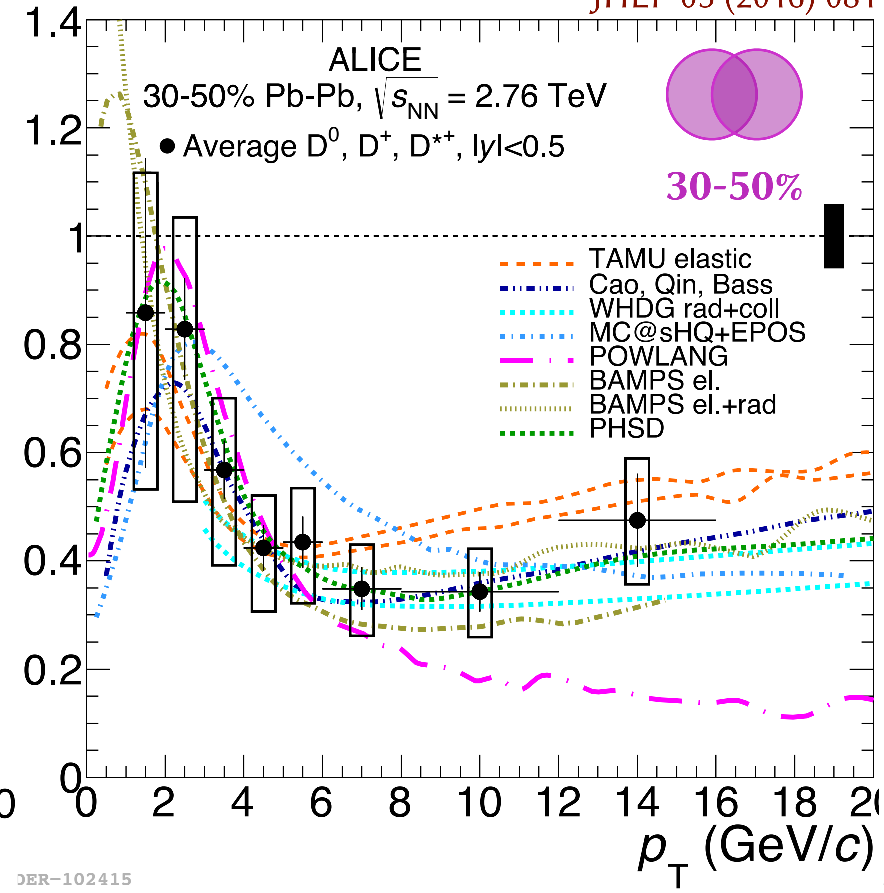

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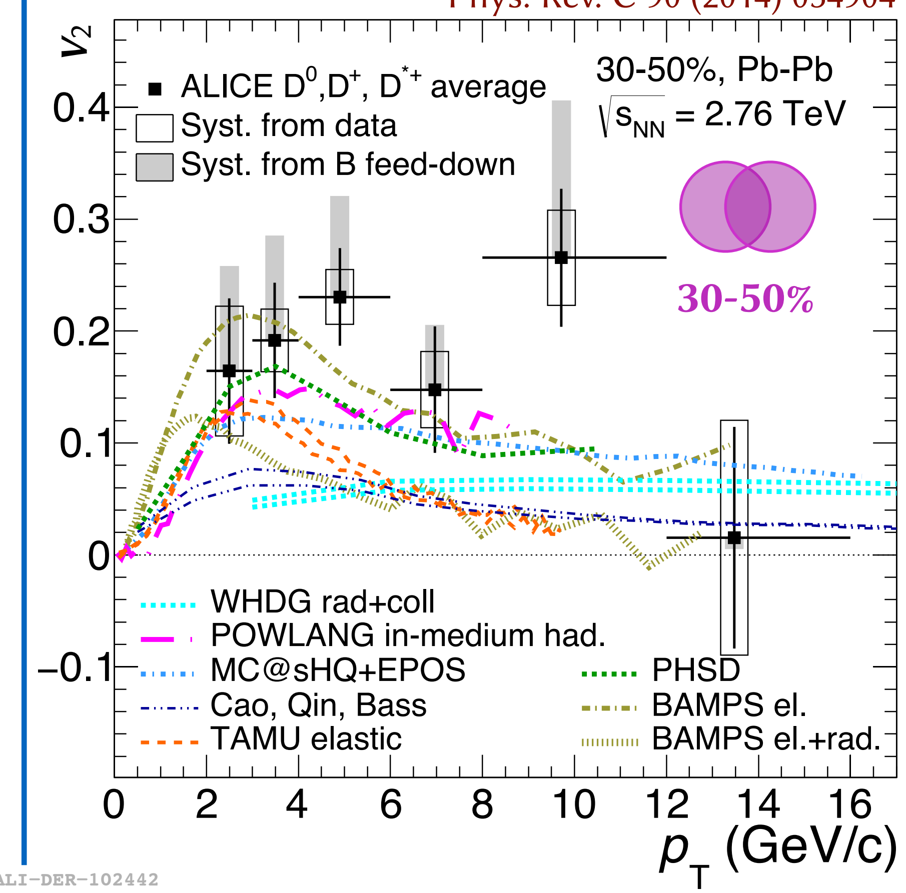
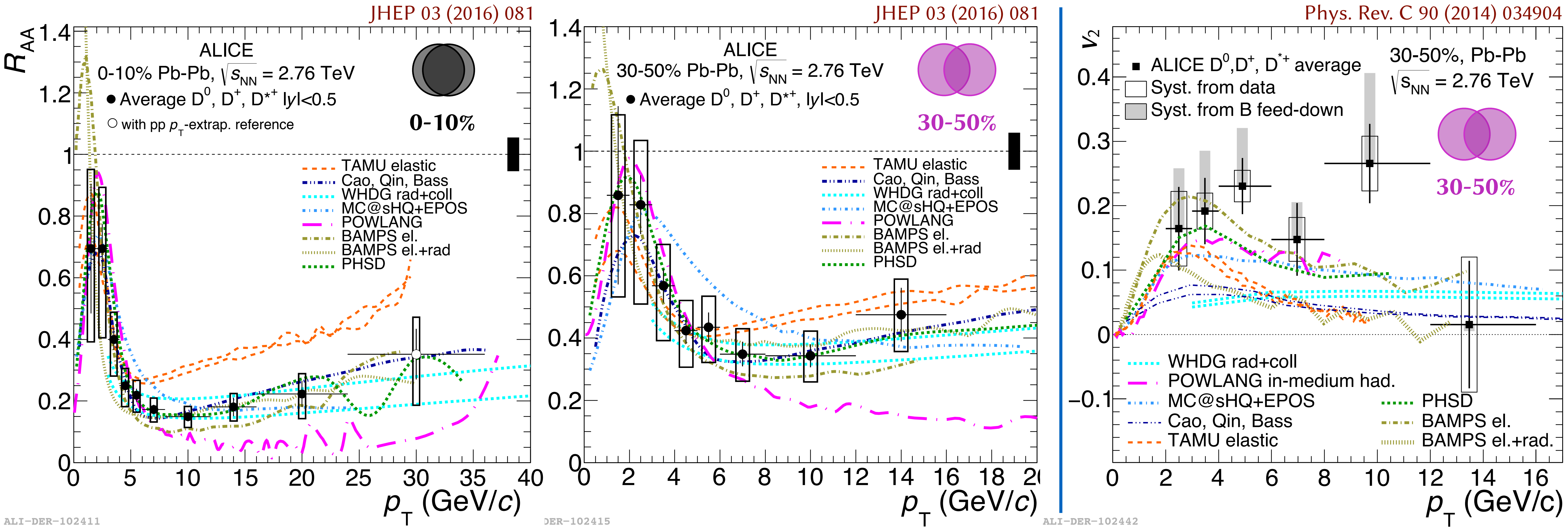


	Medium modelling	Heavy quark interactions	Hadronization
TAMU elastic	Expanding medium (3+1d <u>ideal</u> hydrodynamic)	Collisional energy loss (HQ transport + <u>scattering</u> in hadronic phase)	Fragmentation Recombination
POWLANG	Expanding medium (2+1d <u>viscous</u> fluid)	Collisional energy loss (HQ transport)	Fragmentation Recombination

- R_{AA} is overestimated (underestimated) at high p_T, where gluon radiation might dominate
- v_2 is fairly described qualitatively

Simultaneous description of D-meson data



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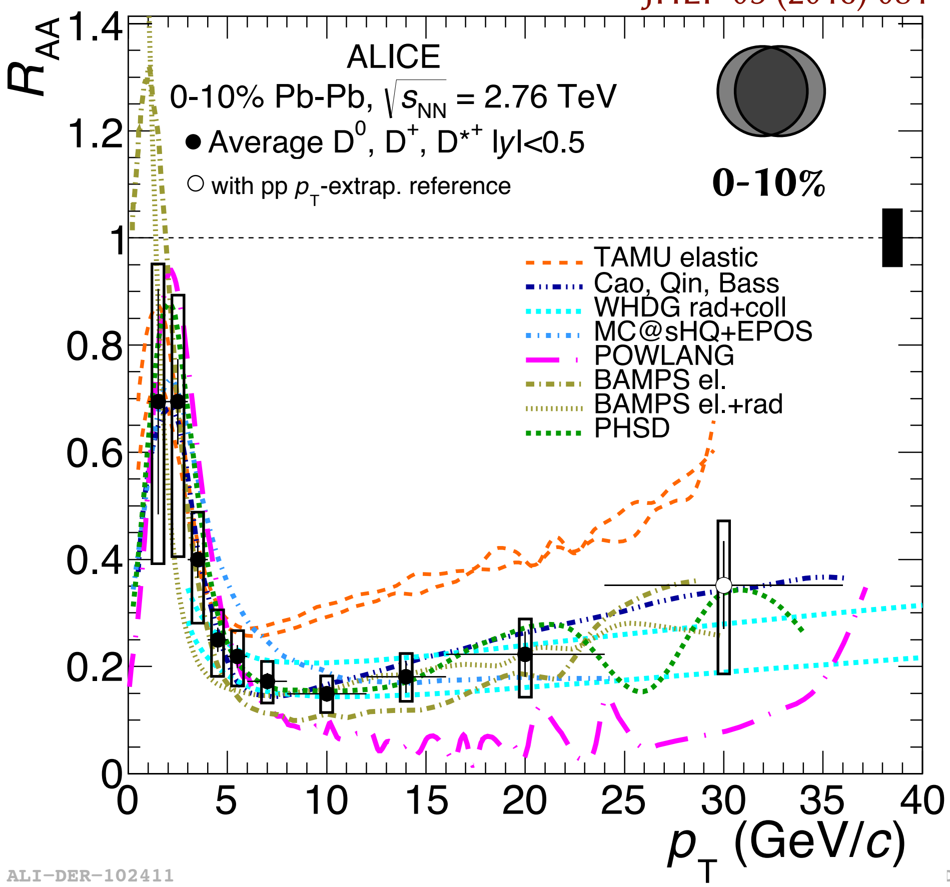
BAMPS el (+rad)	Expanding medium (3+1d viscous fluid)	Collisional (+ Radiative) energy loss (HQ transport)	Fragmentation ∅

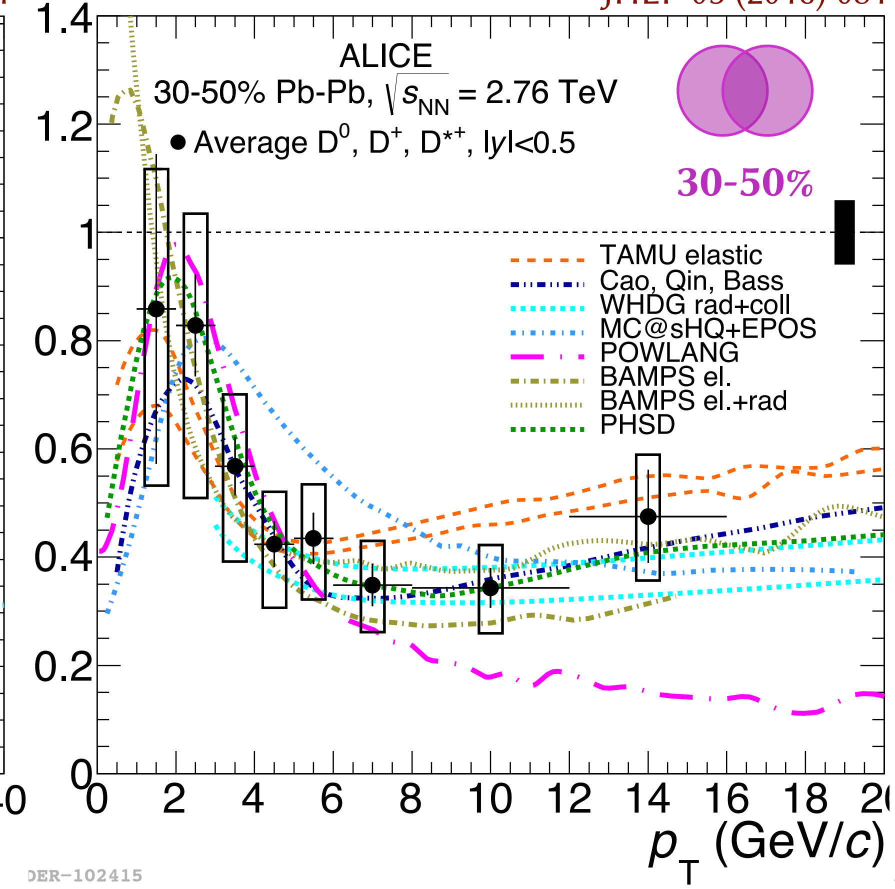
- Better agreement with R_{AA} data
- v_2 is fairly described without radiative energy loss

Simultaneous description of D-meson data

JHEP 03 (2016) 081



JHEP 03 (2016) 081



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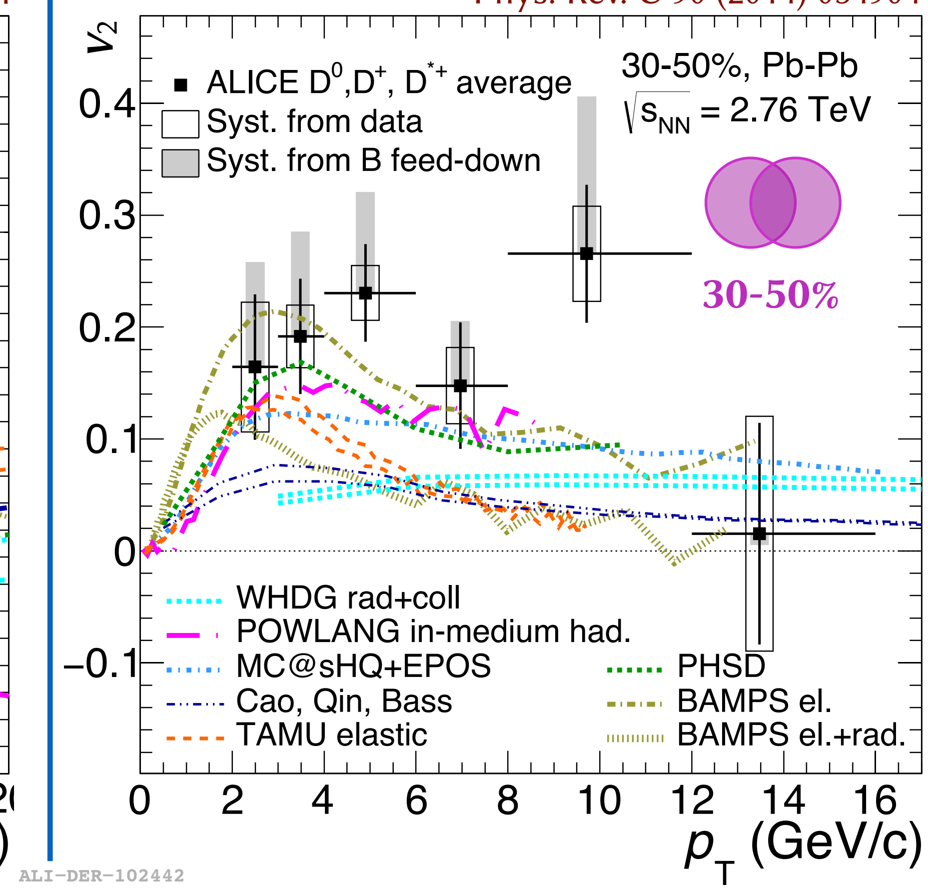

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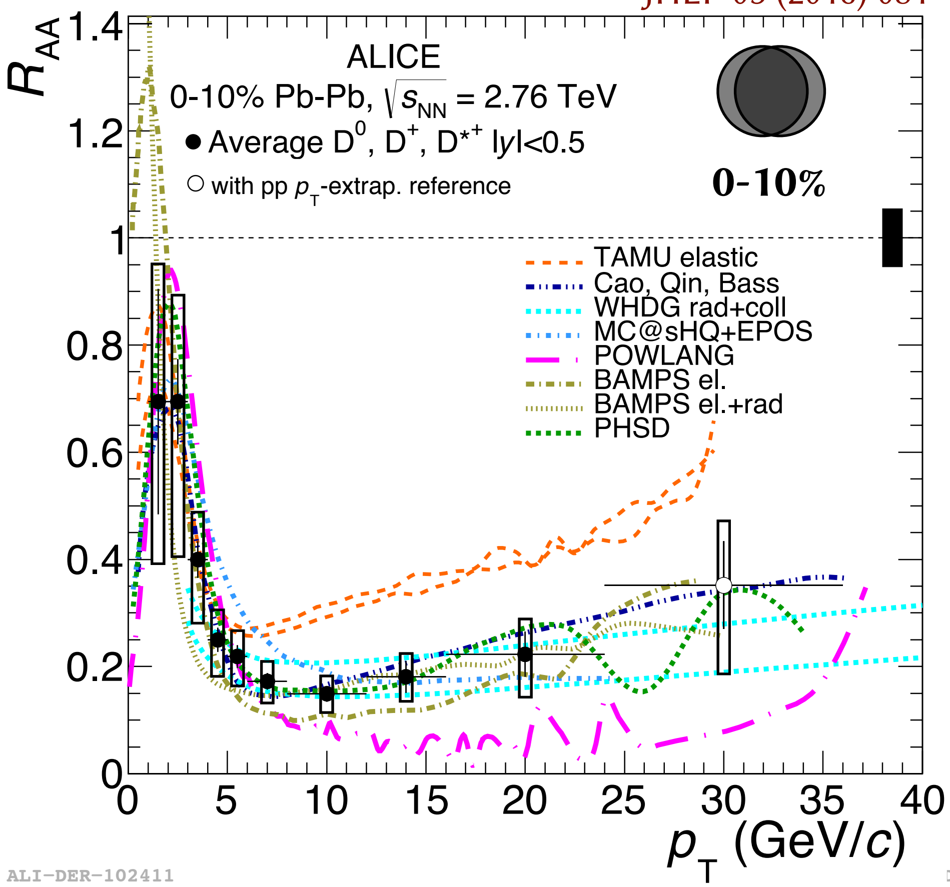
BAMPS el (+rad)	<u>Expanding</u> medium (3+1d viscous fluid)	Collisional (+ Radiative) energy loss (HQ transport)	Fragmentation ∅
WHDG	<u>No fluid dynamics</u> (Glauber model collision geometry)	Collisional + Radiative energy loss	Fragmentation ∅

- R_{AA} is still well described at high p_T
- v_2 features are not reproduced

Simultaneous description of D-meson data

JHEP 03 (2016) 081



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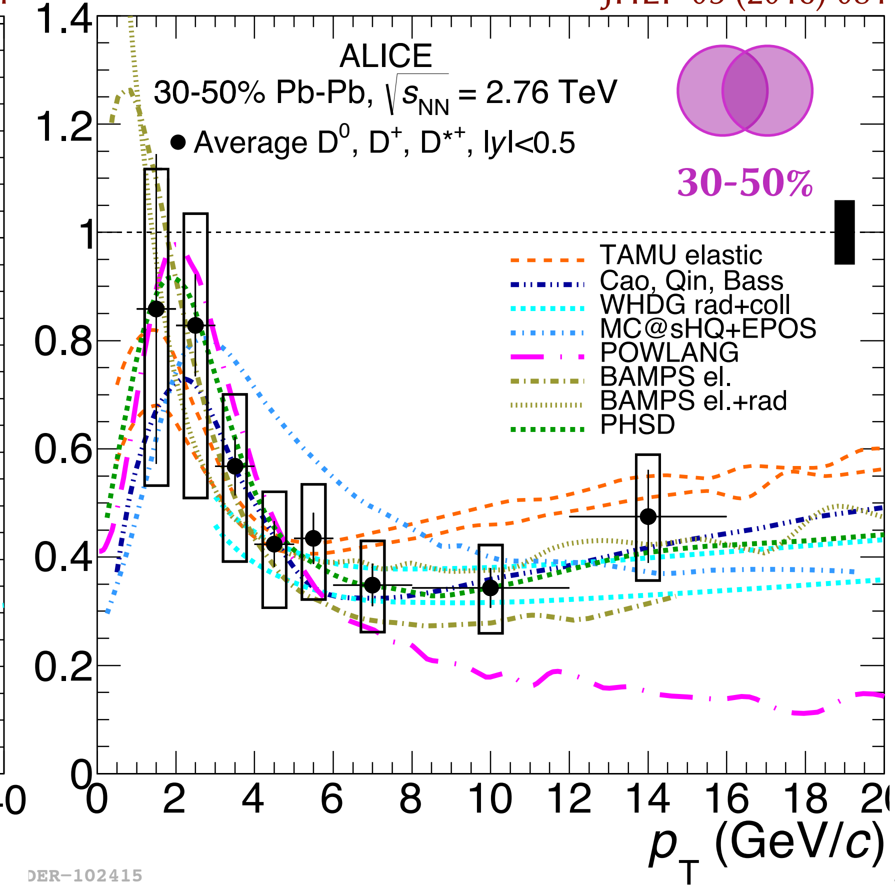

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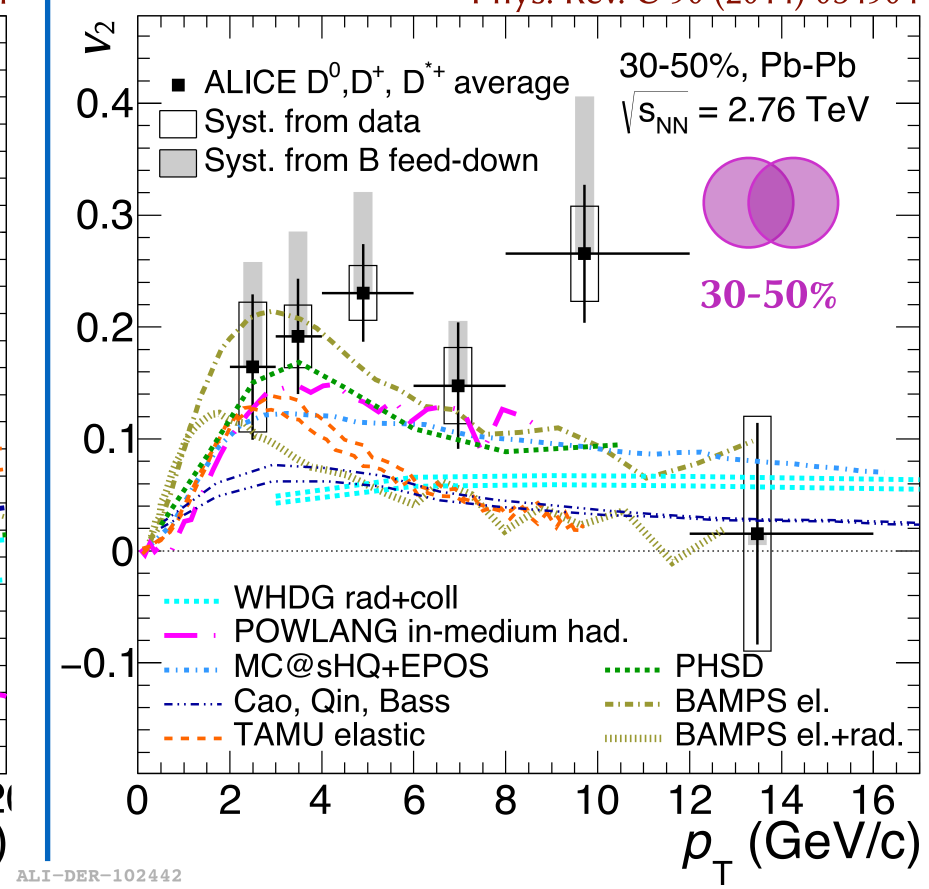

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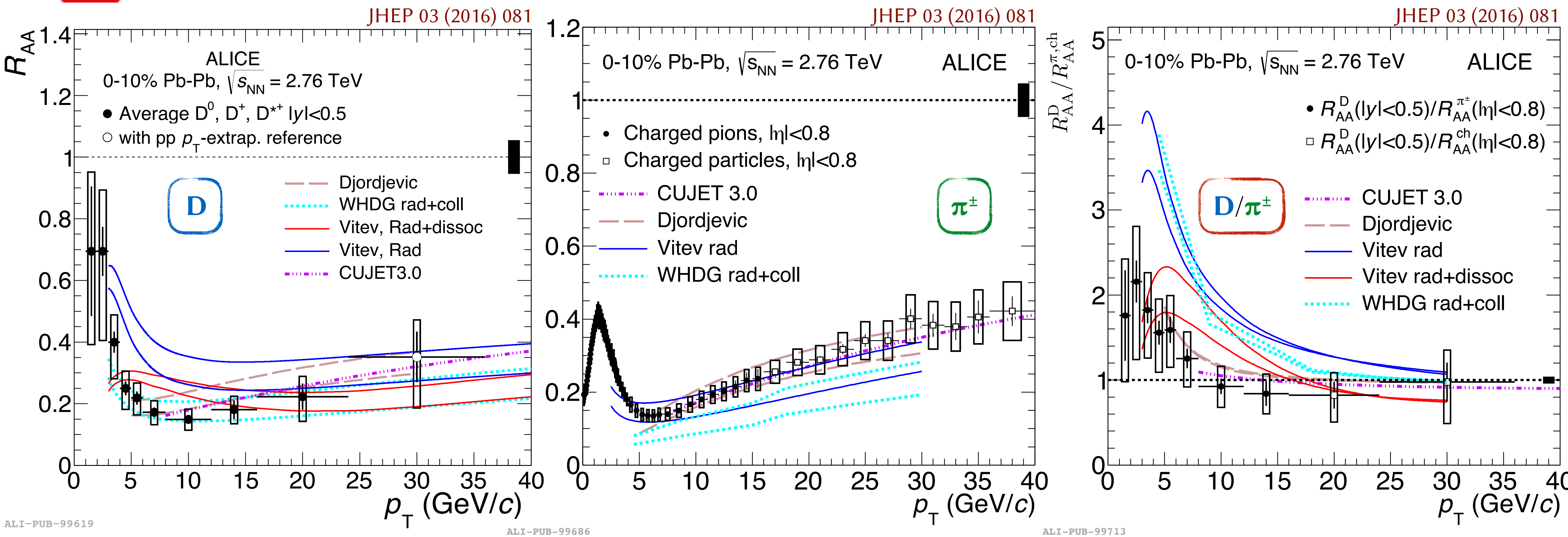
Both energy loss processes and an expanding medium seem to be needed to describe R_{AA} and v_2

Role of recombination not clear (expected to help describing v_2 at low p_T)

Simultaneous description of D and π R_{AA} (high p_T)

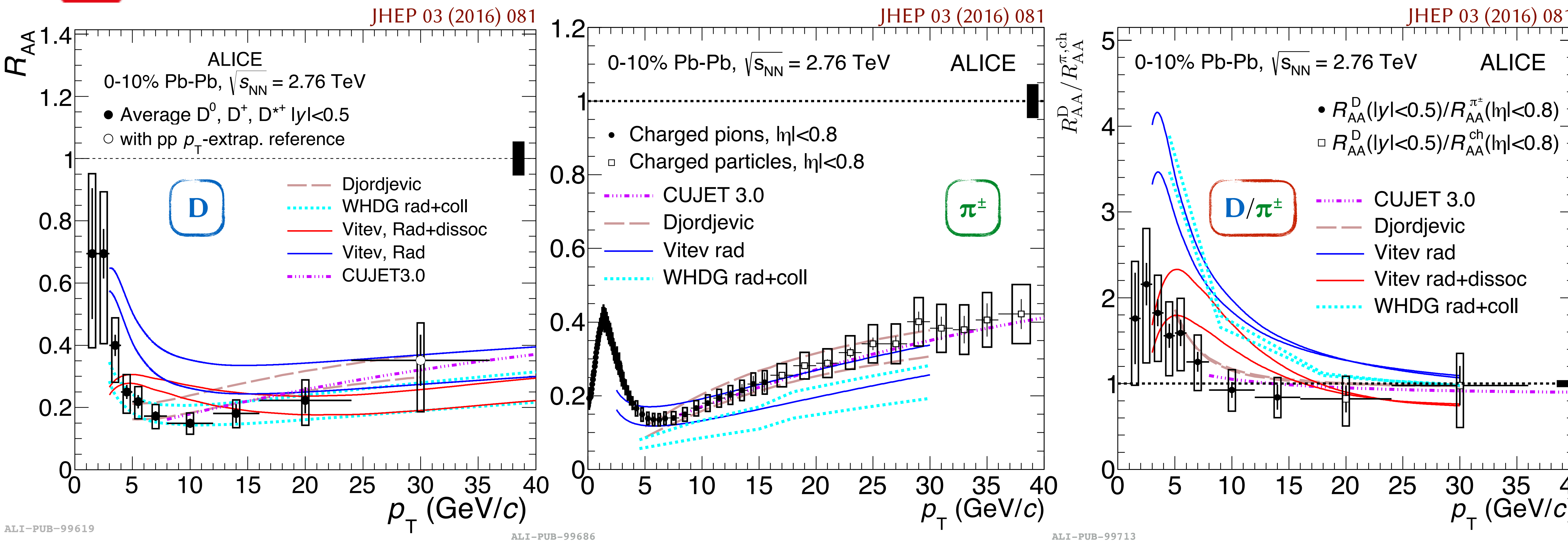


Models fairly describing D-meson data do not necessarily manage to simultaneously reproduce $\pi^\pm$ data (e.g. **WHDG**)

	Medium modelling	Heavy quark interactions	Hadronization
Djordjevic	No fluid dynamics (Glauber model collision geometry)	Collisional + Radiative energy loss	Fragmentation ∅
CUJET3.0	Expanding medium (2+1d viscous fluid)	Collisional + Radiative energy loss	Fragmentation ∅

- Good description of R_{AA}(D) and R_{AA}(π) at the same time, for $p_T > 6$ GeV/c

Simultaneous description of D and π R_{AA} (high p_T)



Models fairly describing D-meson data do not necessarily manage to simultaneously reproduce π± data (e.g. **WHDG**)

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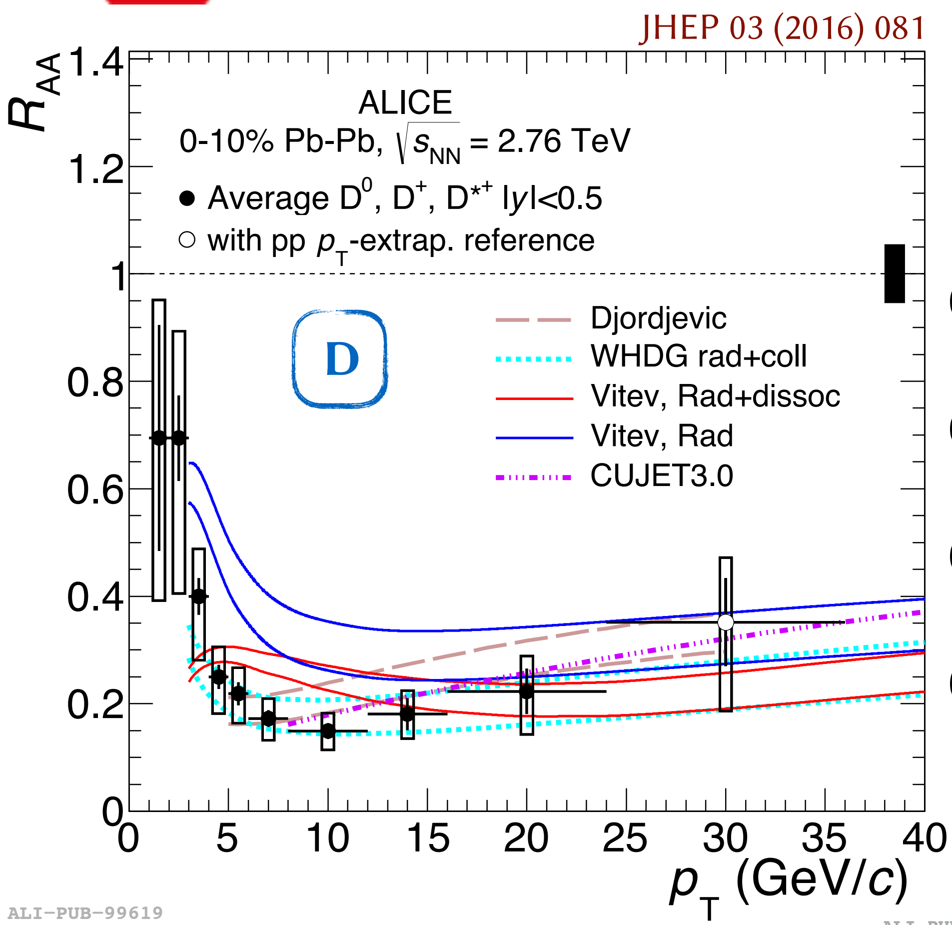
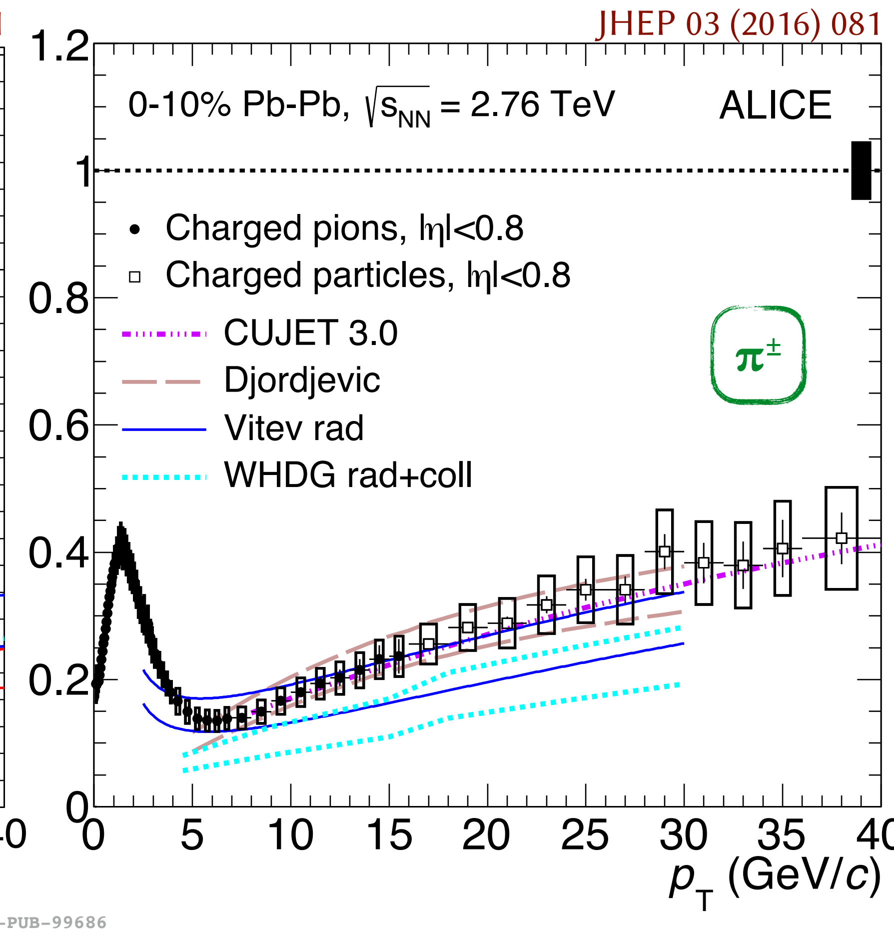
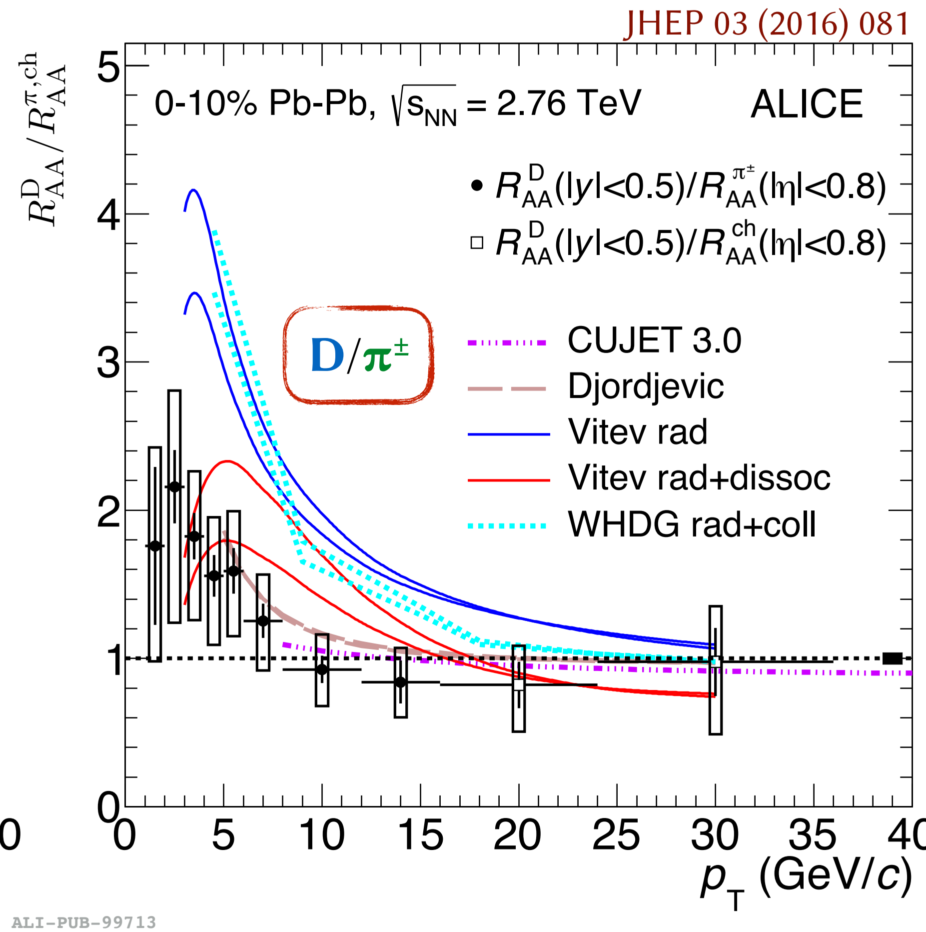
- Agreement with data when taking into account in-medium dissociation processes?

Simultaneous description of D and π R_{AA} (high p_T)







Models fairly describing D-meson data do not necessarily manage to simultaneously reproduce π± data (e.g. **WHDG**)

	Medium modelling	**Heavy quark interactions**	**Hadronization**
Djordjevic	No fluid dynamics (Glauber model collision geometry)	Collisional + Radiative energy loss	Fragmentation ∅
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ALICE open-charm measurements start providing constraints on models

Conclusion and prospects

Open-charm measurements** (hadronic decays, central rapidity) **with ALICE:

- Good agreement with pQCD calculations: down to $p_{\mathrm{T}} = 0$ GeV/c, in pp collisions
- Strong suppressions: observed in Pb-Pb collisions, with respect to pp collisions (with $R_{\mathrm{pPb}} \sim 1$)
- Non-zero (positive) v_2: measured in Pb-Pb collisions

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Heavy-quark in-medium interaction depictions with models:

- Simultaneous description of data: is very challenging, since one has to consider R_{AA} and v_2 for π, D and B
- Colour- and mass-dependent energy loss:
  Dead-cone effect has been uncovered ($R_{\mathrm{AA}}(\mathrm{D}) < R_{\mathrm{AA}}(\mathrm{J}/\Psi \longleftarrow \mathrm{B})$)
  $R_{\mathrm{AA}}(\pi) \approx R_{\mathrm{AA}}(\mathrm{D})$ differ from the straight expectation but can be reproduced by models
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  Collisional and *radiative* processes seem to be needed to reproduce the whole set of measurements
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Prospects:

- Larger data samples: will allow to perform more precise D-meson measurements during LHC Run II and III
- Extended hadron measurements: $\Lambda_c^+ \longrightarrow \mathrm{pK}^-\pi^+, \mathrm{pK}^0_S$
  $\mathrm{D}^+ \longrightarrow \mathrm{K}^0_S\pi^+, \mathrm{D}_s^+ \longrightarrow \mathrm{K}^0_S\mathrm{K}^+$ (my PhD work)
- More sophisticated models: to draw a clear picture of the interaction mechanisms occurring inside the QGP

Backup

	Medium modelling	HQ interactions	Hadronization	R_{AA}(D)	v_2(D)	R_{AA}(D)/R_{AA}(π)
TAMU elastic	Expanding medium (3+1d ideal hydrodynamic)	Collisional	Fragmentation Recombination	Overestimated	✔	✘
POWLANG	Expanding medium (2+1d viscous fluid)	Collisional	Fragmentation Recombination	Underestimated	✔	✘
BAMPS el (+rad)	Expanding medium (3+1d viscous fluid)	Collisional (+ Radiative)	Fragmentation ∅	✔	✔ (underestimated)	✘
WHDG	No fluid dynamics (Glauber model collision geometry)	Collisional + Radiative	Fragmentation ∅	✔	✘	Overestimated
Djordjevic	No fluid dynamics (Glauber model collision geometry)	Collisional + Radiative	Fragmentation ∅	✔	✘	✔
CUJET3.0	Expanding medium (2+1d viscous fluid)	Collisional + Radiative	Fragmentation ∅	✔	✘	✔
Vitev rad+dissoc	No fluid dynamics (Glauber model collision geometry)	Collisional + In-medium meson dissociation	Fragmentation ∅	✔	✘	Overestimated

D^0 signal extraction

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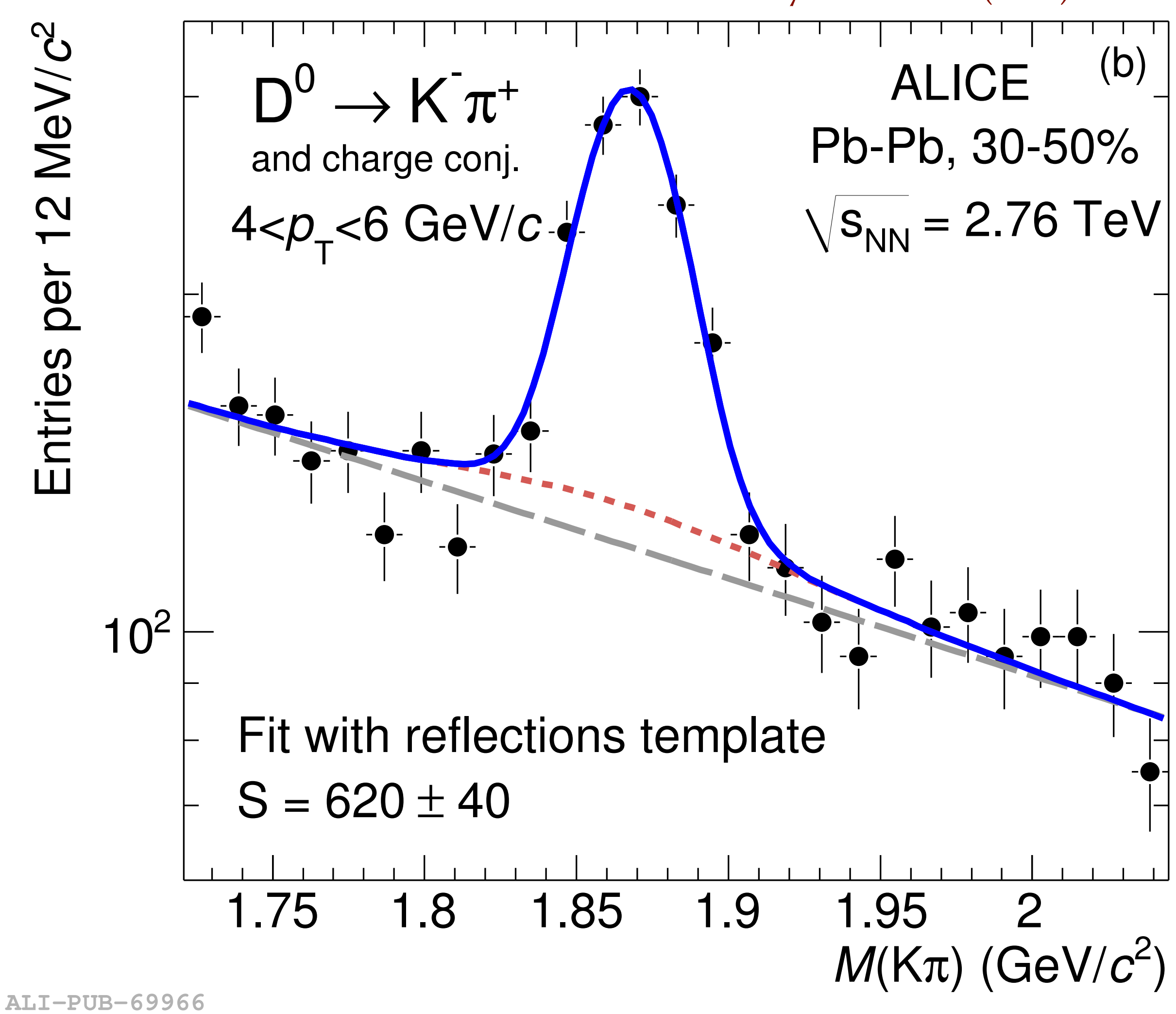


Without template

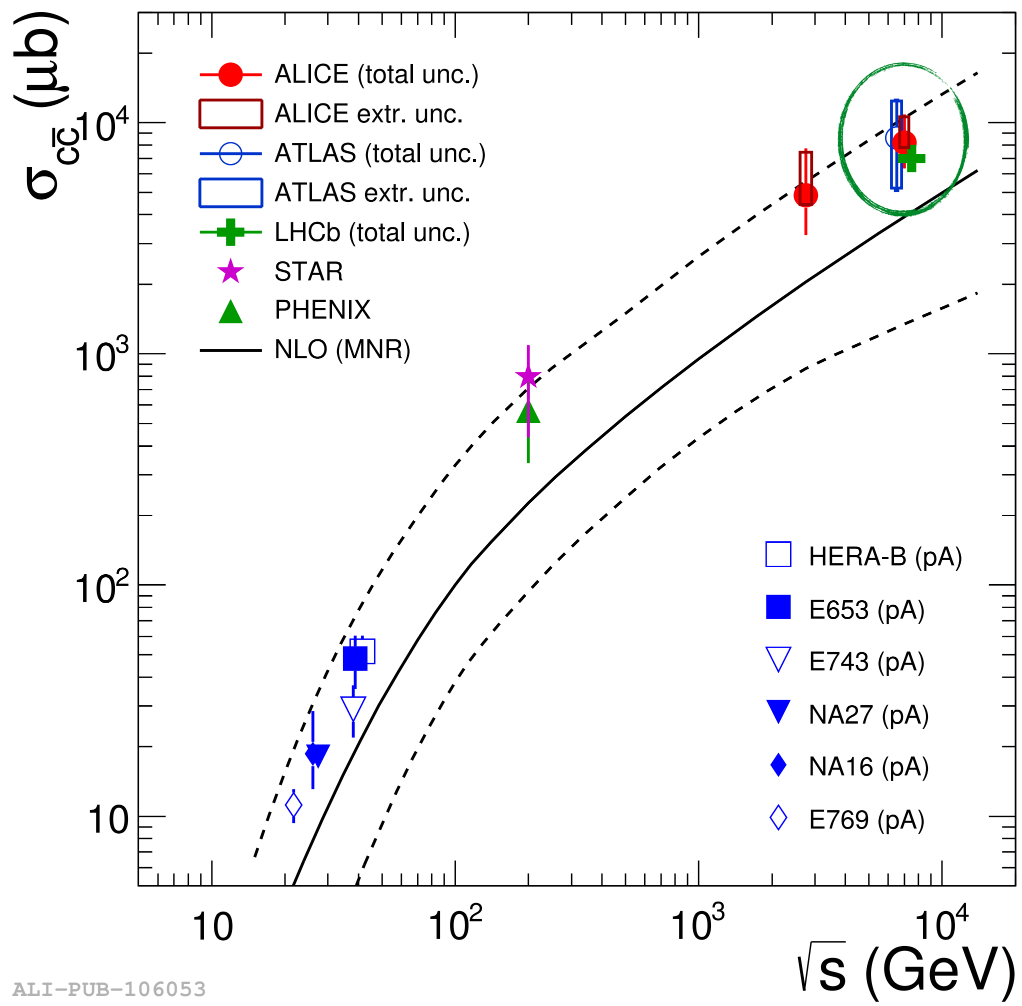
- $S(3\sigma)$ = 673 ± 45
- $B(3\sigma)$ = 1072 ± 14
- $S/B(3\sigma)$ = 0.63
- Significance(3σ) = 16.1 ± 0.9

With template

- $S(3\sigma)$ = 620 ± 40
- $B(3\sigma)$ = 1080 ± 14
- $S/B(3\sigma)$ = 0.57
- Significance(3σ) = 15.0 ± 0.8

$S/B(3\sigma)$ = 0.1 - 0.9 for D^0, depending the p_T

arXiv:1605.07569



ATLAS: $\sigma_{c\bar{c}} = 8.6^{+3.9}_{-3.5}(\text{tot.}) \quad \text{with} \quad ^{+3.8}_{-3.4}(\text{extrapolation})$ mb

- $3.5 < p_{\mathrm{T}}(\mathrm{D}) < 20$ GeV/c and $|\eta(\mathrm{D})| < 2.1$

  Nucl. Phys. B 907 (2016) 717

ALICE: $\sigma_{c\bar{c}} = 8.18^{+2.7}_{-1.8}(\text{tot.}) \quad \text{with} \quad ^{+2.4}_{-0.4}(\text{extrapolation})$ mb

- $0 < p_{\mathrm{T}}(\mathrm{D}^0) < 16$ GeV/c and $|y(\mathrm{D}^0)| < 0.5$

  arXiv:1605.07569

LHCb: $\sigma_{c\bar{c}} = 6.1 \pm 0.93(\text{tot.}) \quad (\text{extrapolation with PYTHIA})$ mb

- $0 < p_{\mathrm{T}}(\mathrm{D}) < 8$ GeV/c and $2.0 < y(\mathrm{D}) < 4.5$

  CERN-LHCb-CONF-2010-013

ATLAS: $\sigma^{\text{tot}}_{c\bar{c}} = 8.6 \pm 0.3\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.3\,(\text{lum}) \pm 0.2\,(\text{ff})^{+3.8}_{-3.4}\,(\text{extr})\text{ mb}$

ALICE: $\sigma^{c\bar{c}}_{\text{pp, 7 TeV}} = 8.18 \pm 0.67\,(\text{stat.})\,^{+0.90}_{-1.62}\,(\text{syst.})\,^{+2.40}_{-0.36}(\text{extr.}) \pm 0.29\,(\text{lumi.}) \pm 0.36\,(\text{FF})\text{ mb}$

LHCb: $\sigma(c\bar{c})_{p_{\mathrm{T}}<8\,\text{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\text{stat}) \pm 116\,(\text{syst}) \pm 65\,(\text{frag})\ \mu\text{b}$ Nucl. Phys. B 871 (2013) 1

	HQ production	Medium modelling	Heavy quark interactions	Hadronization
TAMU elastic	FONLL + EPS09 shadowing	Expanding medium (3+1d ideal hydrodynamic)	Collisional energy loss (Langevin transport eq. + scattering in hadronic phase)	Fragmentation Recombination
POWLANG	POWHEG + EPS09 shadowing	Expanding medium (2+1d viscous fluid)	Collisional energy loss (Langevin transport eq.)	Fragmentation Recombination
BAMPS el (+rad)	MC@NLO no shadowing	Expanding medium (3+1d viscous fluid)	Collisional (+ Radiative) energy loss (Boltzmann transport eq.)	Fragmentation ∅
WHDG	FONLL no shadowing	No fluid dynamics (Glauber model collision geometry)	Collisional + Radiative energy loss	Fragmentation ∅
Djordjevic	FONLL no shadowing	No fluid dynamics (Glauber model collision geometry)	Collisional + Radiative energy loss	Fragmentation ∅
CUJET3.0		Expanding medium (2+1d viscous fluid)	Collisional + Radiative energy loss	Fragmentation ∅
Vitev rad+dissoc	Non-zero-mass VFNS no shadowing	No fluid dynamics (Glauber model collision geometry)	Collisional + In-medium meson dissociation	Fragmentation ∅
MC@$_s$HQ+EPOS2	FONLL + EPS09 shadowing	Expanding medium (3+1d EPOS model)	Collisional energy loss (Boltzmann transport eq.)	Fragmentation Recombination
Cao, Qin, Bass	pQCD (LO) + EPS08 shadowing	Expanding medium (2+1d viscous fluid)	Collisional + Radiative energy loss (Langevin transport eq. + scattering in hadronic phase)	Fragmentation Recombination

Azimuthal anisotropy if D meson in Pb-Pb collisions

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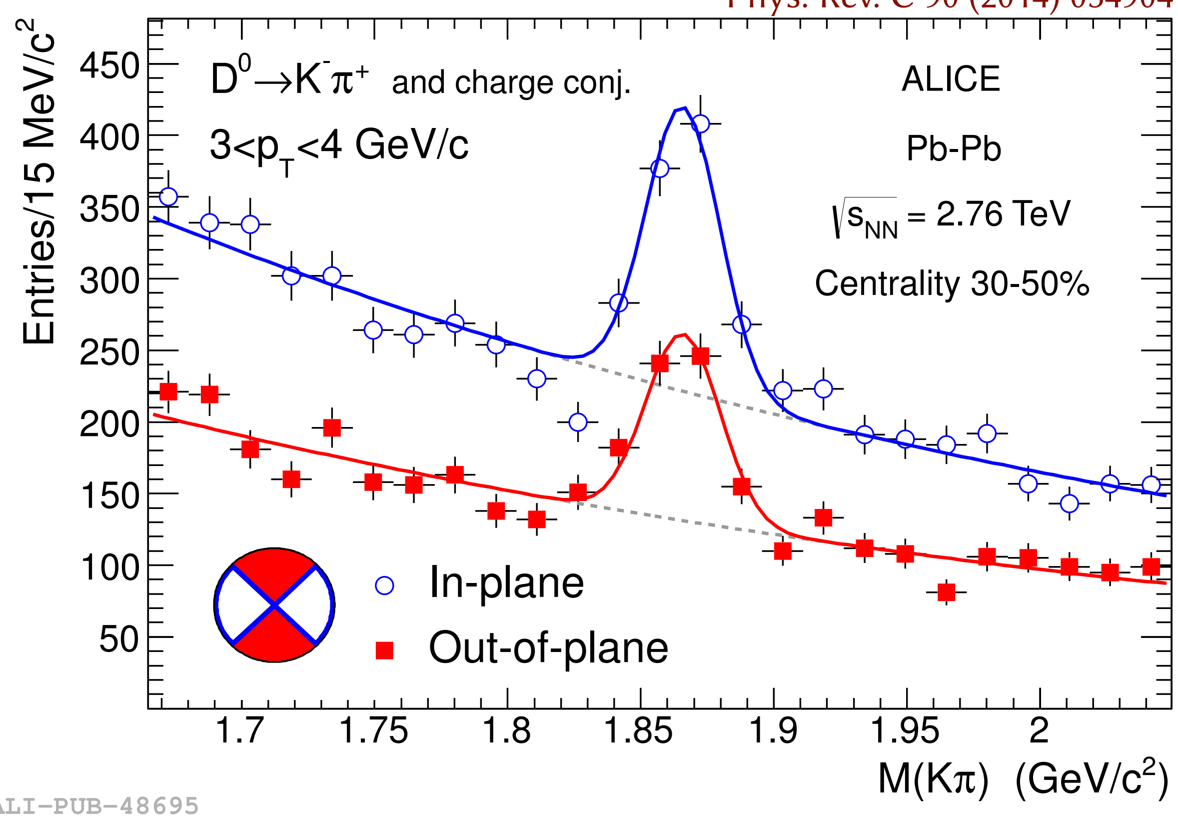
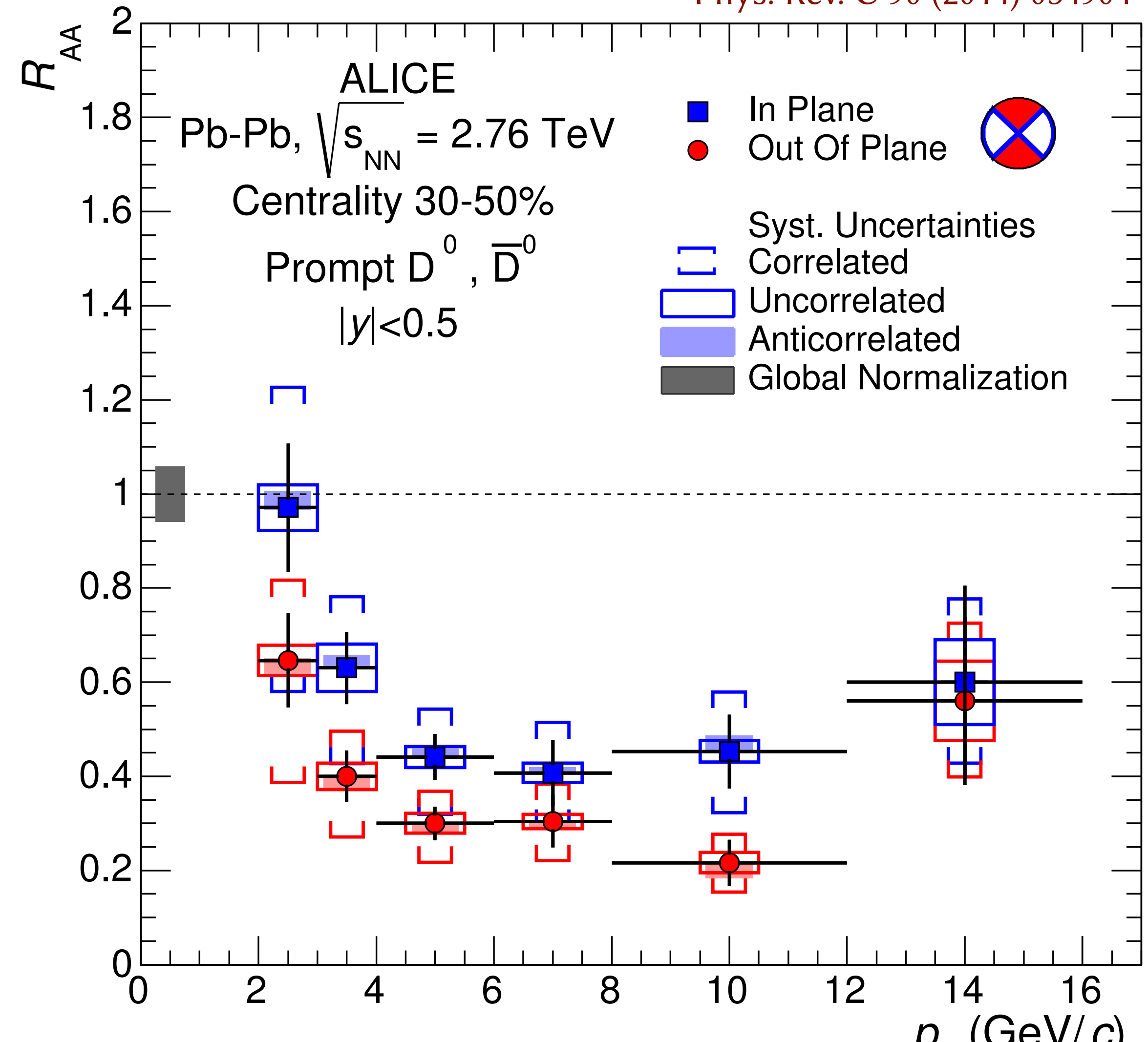


ALI-PUB-48695

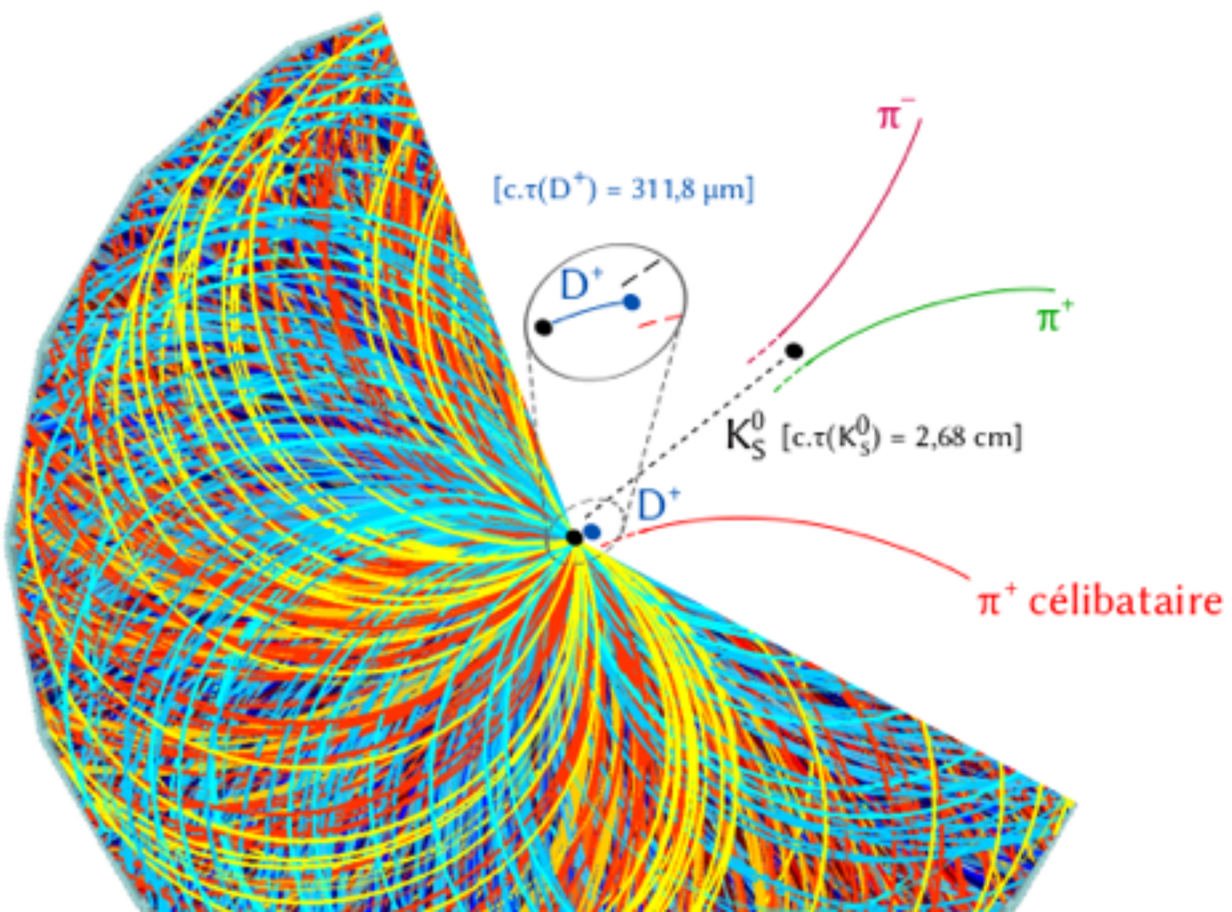
Phys. Rev. C 90 (2014) 034904



ALI-PUB-70131

D-meson decay channels

Hadron	Mass (MeV/c^2)	c.τ (μm)	Usual decay channels	Alternatives (IPHC)
D^+ $(c\bar{d})$	1869	311,8	$K^- 2\pi^+$ (9,13 ± 0,19 %)	$K^0_S \pi^+$ (1,47 ± 0,07 %)
D^0 $(c\bar{u})$	1864	122,9	$K^- \pi^+$ (3,88 ± 0,05 %)	$K^0_S \pi^+ \pi^-$ (2,83 ± 0,20 %)
D^{*+} $(c\bar{d})$	2010	∼ 0	$D^0 \pi^+$ (67,7 ± 0,5 %)	—
D_s^+ $(c\bar{s})$	1968	149,9	$\phi(1020)\, \pi^+$ (2,28 ± 0,12 %)	$K^0_S K^-$ (1,48 ± 0,08 %)
$\phi(1020)$ $(s\bar{s})$	1019	∼ 0	$K^+ K^-$ (48,9 ± 0,5 %)	
K^0_S $(d\bar{s})$	497	26 844	$\pi^+ \pi^-$ (69,20 ± 0,05 %)	



Stay tuned...