Open Heavy Flavour production

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Trailer

Goal of the talk is to present:

- the main physics motivations to measure open heavy flavour production in heavy-ion collisions
- a selection of the main results and open points
    - also for non-experts
    - as a trailer for next days, no spoiler!

I will not show results that were made public (as preliminary or submitted to arxiv) in 2018

Soft and hard probes

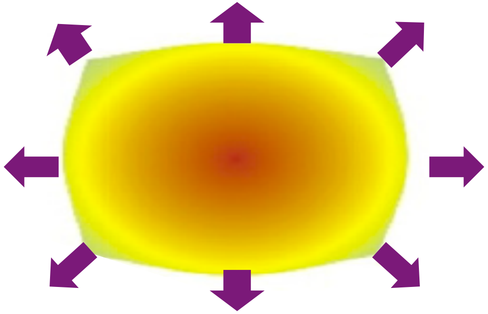
N.b. a simplistic and incomplete classification!

"Soft" probes

(e.g. light-flavour particle spectra and flow at low p_T)

Probe system as a whole

Test hydrodynamic description to extract global properties of the medium and of its evolution (e.g. temperature, density, viscosity, expansion velocity)



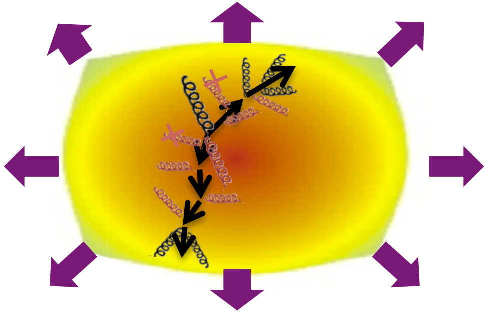
"Hard" probes

(e.g. high p_T particles, heavy flavours, quarkonia, jets)

Access **microscopic processes in the medium**

Resolve medium constituents (quarks and gluons)

Address transport coefficients, mean free path,…



⇩

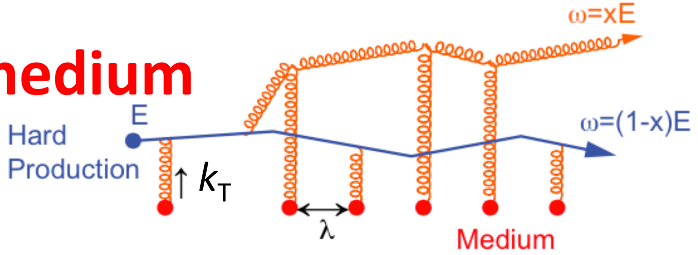
Connection of global medium properties with "local" interactions

Microscopic description of the medium

QGP tomography with high-energy partons

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium

⇨ **"Calibrated probes" of the medium**



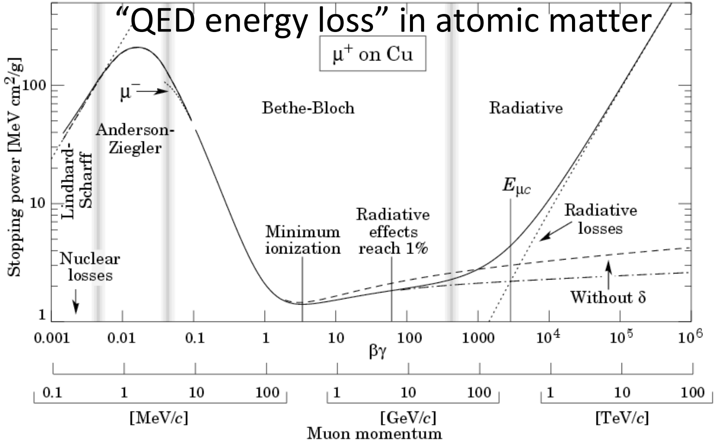
Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional (elastic) processes

~ Study QCD "Bethe-Block" curve for partons in the QGP

⇩

Connection of "local" interactions with global medium properties



QGP tomography with high-energy partons

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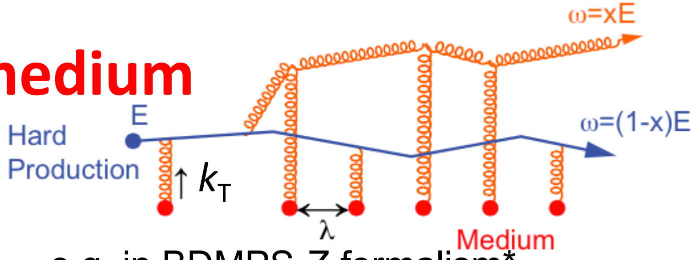


e.g. in BDMPS-Z formalism*

Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional (elastic) processes

~ Study QCD "Bethe-Block" curve for partons in the QGP

$$\langle \Delta E \rangle^{\mathrm{rad}} \propto \alpha_s C_R \hat{q} L^2$$

$$\hat{q} = \frac{\langle k_{\mathrm{T}}^2 \rangle}{\lambda} = \langle k_{\mathrm{T}}^2 \rangle \rho\sigma$$

More by K. Zapp

Transport coefficient(s)

Connection of "local" interactions with global medium properties

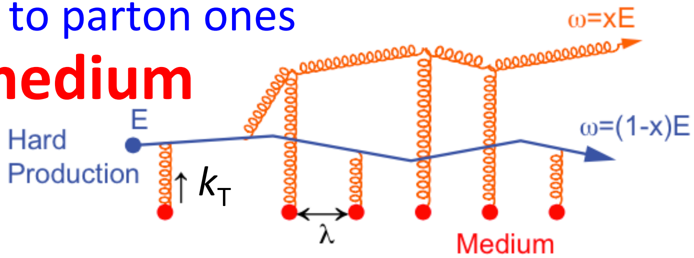
*Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.

QGP tomography with heavy quarks

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium
- Hard fragmentation ➜ measured meson properties closer to parton ones

at all p_T for charm and beauty (large masses >> Λ_{QCD})

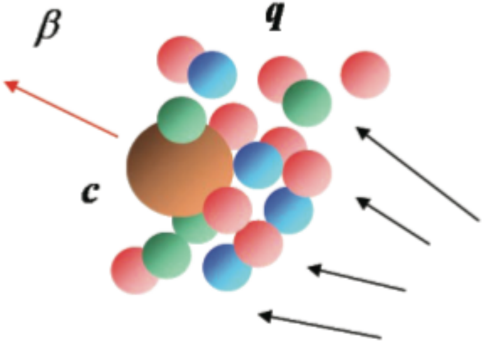
⇨ **"Calibrated probes" of the medium**



Thermal production and annihilation rate expected small at LHC (negligible for beauty)

Unique feature: **identified partons → "markers" of the medium**

- quarks
- massive (m_c~1.2-1.5 GeV/c^2, m_b~4.5 GeV/c^2)



The nuclear modification factor

Nuclear modification factor (R_{AA}): compare particle production in nucleus-nucleus (A-A) collisions with that in pp scaled by a "geometrical" factor (from Glauber model)

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

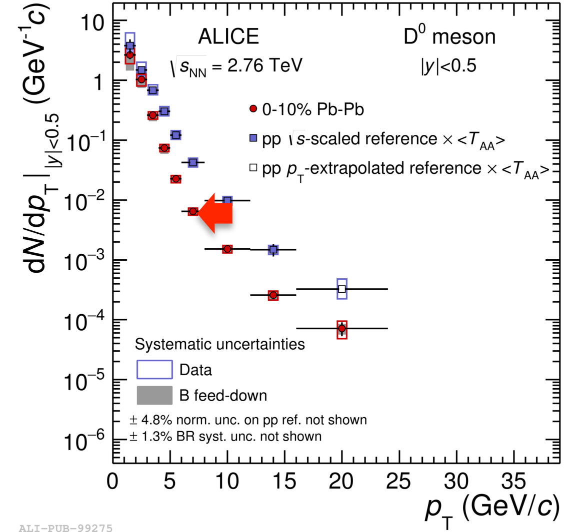
A-A

pp

Nuclear overlap function, encodes collision geometry

If $R_{AA}=1$ → no nuclear effects

If $R_{AA}\neq 1$ → nuclear effects



Energy loss →"redshift" of the initial p_T-spectrum, which is steeply falling with p_T

→ R_{AA}<1 at moderate/high p_T

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$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}} / \mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}} \rangle \times \mathrm{d}\sigma_{\mathrm{pp}} / \mathrm{d}p_{\mathrm{T}}}$$

If $R_{AA}=1$ → no nuclear effects
If $R_{AA}\neq 1$ → nuclear effects

Never forget:

$$\frac{dN_{AA}}{dp_T} = \begin{matrix}\text{"vacuum"} \\ \text{parton spectra}\end{matrix} \otimes \begin{matrix}\text{initial-state} \\ \text{effects}\end{matrix} \otimes \begin{matrix}\text{parton interaction} \\ \text{with the medium}\end{matrix} \otimes \begin{matrix}\text{(modified?)} \\ \text{hadronization}\end{matrix} \otimes \begin{matrix}\text{hadronic} \\ \text{phase}\end{matrix} \left(\otimes \begin{matrix}\text{decay kinematics} \\ \text{e.g. for leptons}\end{matrix} \right)$$

Measured spectra in AA collisions result from a convolution of many pieces
→ must measure observables with different sensitivity to the various ingredients
→ Physics program requires precise measurements in pp, p-A, A-A collisions
→ interpretation of the results requires comparison with models

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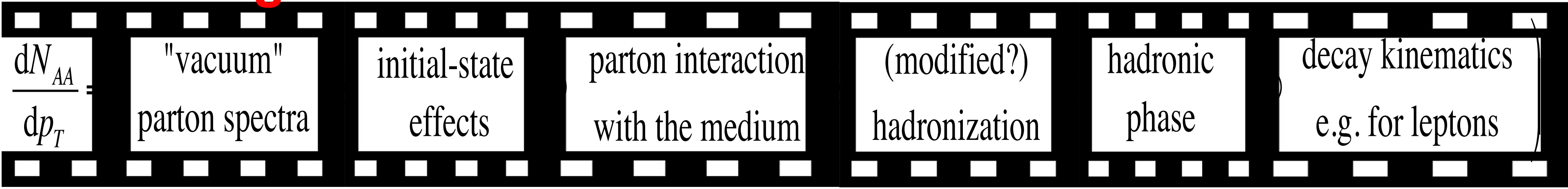
If R_{AA}=1 → no nuclear effects
If R_{AA}≠1 → nuclear effects

Never forget:



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Prologue:
what do we actual measure?

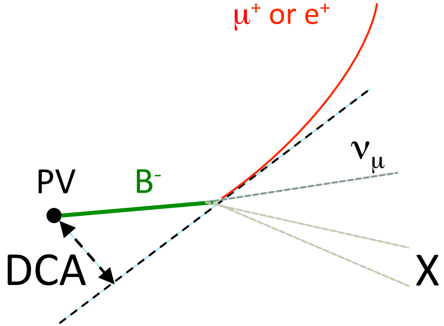
HF signals in experiments

Leptons:

c,b(->c)-hadrons → eX

c,b(->c) hadrons → μX

BR~10%



Analyses with muons

- absorbers → identification
- exploited also for triggering

Typical problem: rejection/subtraction of non-HF muons from decay of π,K (at low p_T , depends on detector configuration), charmonia/ bottomonia, and W,Z (at high p_T)

Analyses with electrons

- PID detectors: TPC, TOF, TRD, EMCAL (*E*/*p*)

Typical problem: rejection/subtraction of non-HF electrons from γ-conversions, light pseudo-scalar meson Dalitz decay (e.g. $\pi^0 \rightarrow \gamma e^+ e^-$), charmonia/bottomonia, and W,Z (at high p_T)

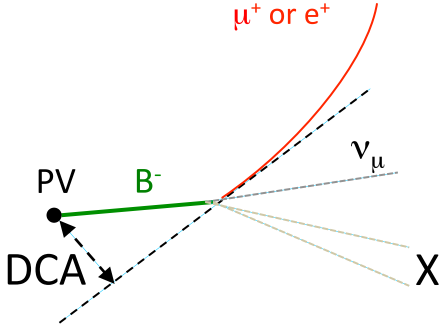
Main **advantage**: relatively abundant signals, muons are a rather "clean" signal
Main **limitation**: p_T-dependence of physics effect **"smeared" by decay kinematics** over a wide p_T interval + cannot disentangle effects dependent on **parent particle species** (strangeness content, baryon vs. mesons, mass)

HF signals in experiments

Beauty Leptons:

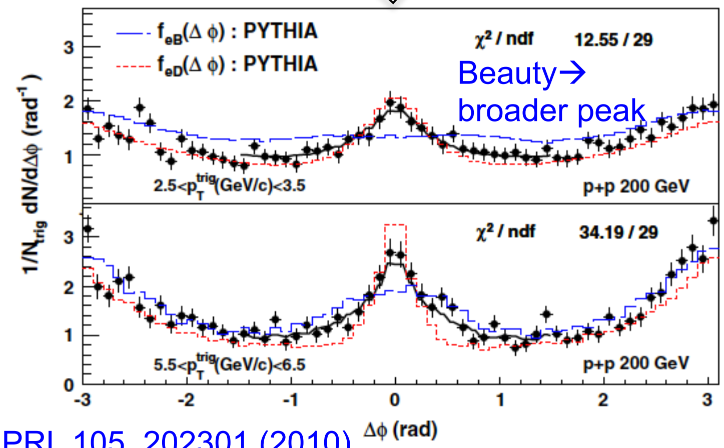
b(->c)-hadrons → eX

b(->c)-hadrons → μX



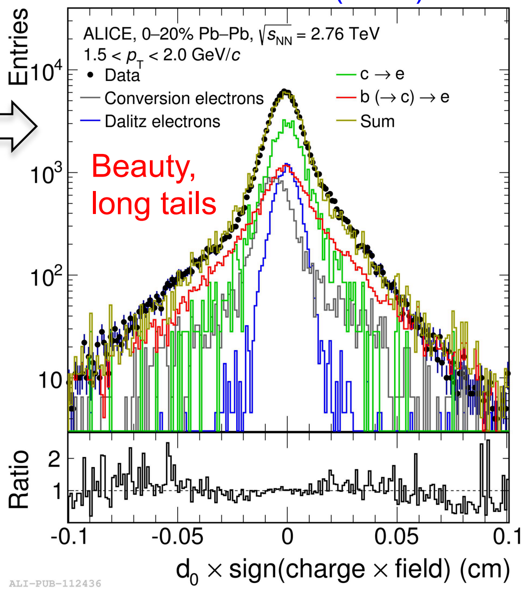
Exploit "Distance of Closest Approach" (DCA) to separate charm and beauty components

Or azimuthal correlations of leptons with charged particles



STAR, PRL 105, 202301 (2010)

JHEP 07 052 (2017):



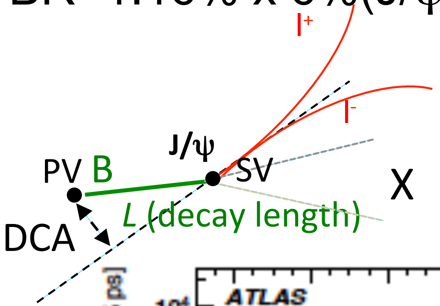
b-hadron $c\tau$~450 μm

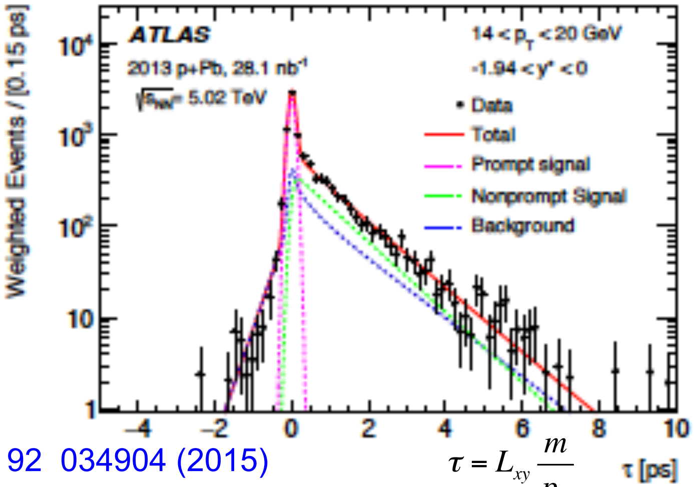
c-hadron $c\tau$~30-312 μm

HF signals in experiments

Displaced J/ψ from b-hadron decay

BR~1.16% x 6%(J/ψ→l^+l^-) ~0.07%





$$\tau = L_{xy} \frac{m}{p_T}$$

PRC 92 034904 (2015)

Signature: displaced secondary vertex
Usually 2D (decay-length, inv. mass) fit to separate prompt and non-prompt fractions
→ needs detectors that grant precision on track position at the Primary Vertex
→ **silicon tracker, pixels**

Rare signal! But can trigger on J/ψ (di-muon pair)

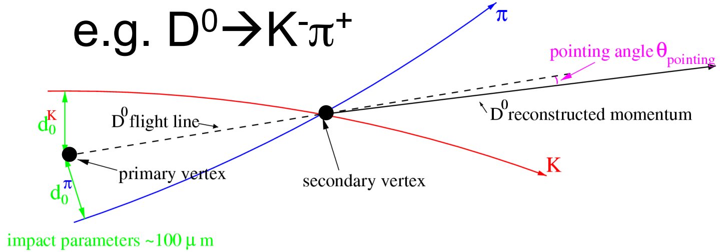
J/ψ kinematics closer to B meson kinematics than b(->c)->l lepton ones → **more direct connection with p_T-trends of physical effects**

HF signals in experiments

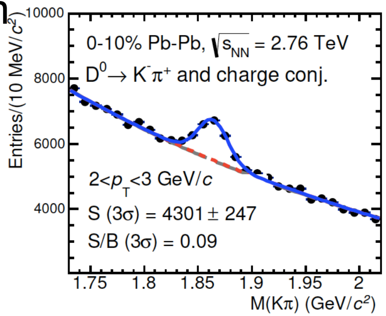
Full reconstruction of hadronic decay channels

BR: typically 2-10% for charm hadrons
For beauty (e.g. $B^+ \rightarrow J/\psi K^+$):
~0.1% x 6%($J/\psi \rightarrow l^+l^-$) ~ 0.006%!!

e.g. $D^0 \rightarrow K^-\pi^+$



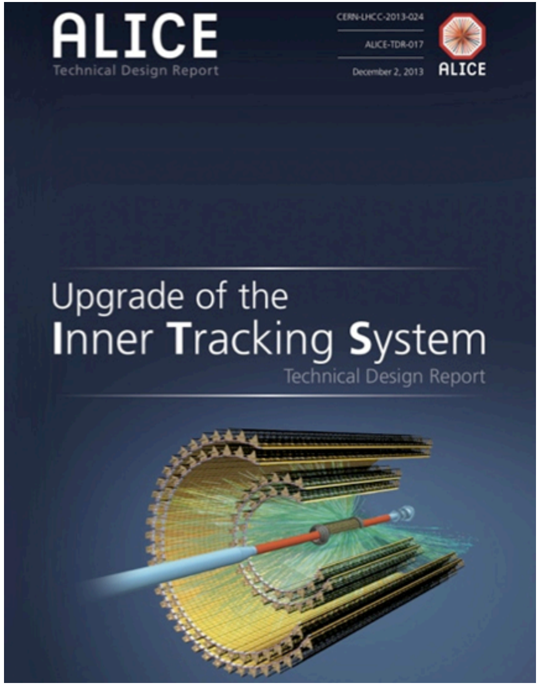
D $c\tau$~123-312 μm
Λ_c $c\tau$~60 μm
B,Λ_b $c\tau$~450 μm

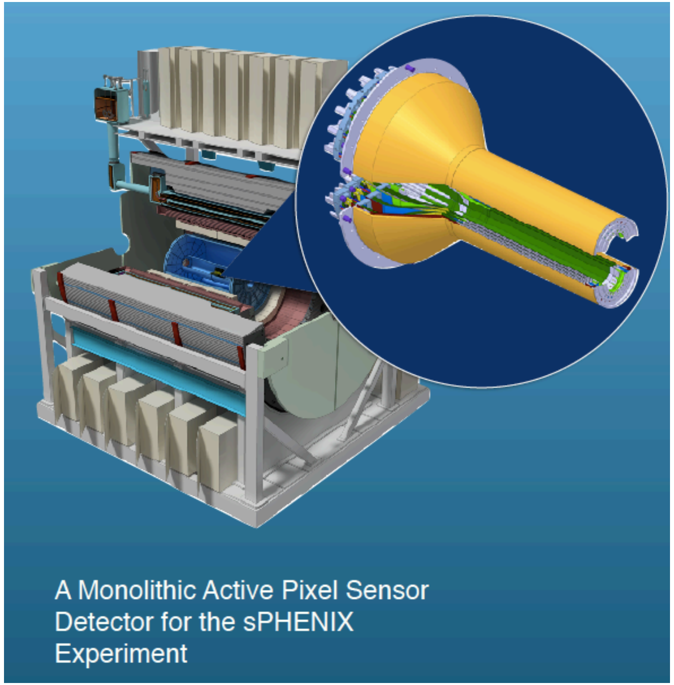


Ideal observables!
No decay kinematics, differentiation of particle-species-dependent effects
Very challenging:
- rare signals (very rare for beauty)
- combinatorial background increases with the power of n_{prongs} → very low S/B w/o cuts

Signature: displaced secondary vertex topology + PID of daughter tracks (K,p ID for charm, muons for B for channels with J/ψ)
→ **ten(s)-micron resolution at PV needed for charm!**
→ Require **silicon tracker, pixel detectors**
Invariant mass analysis to extract the raw yield

Vertex detectors:
key role now and in the future





→ Detector upgrade session!

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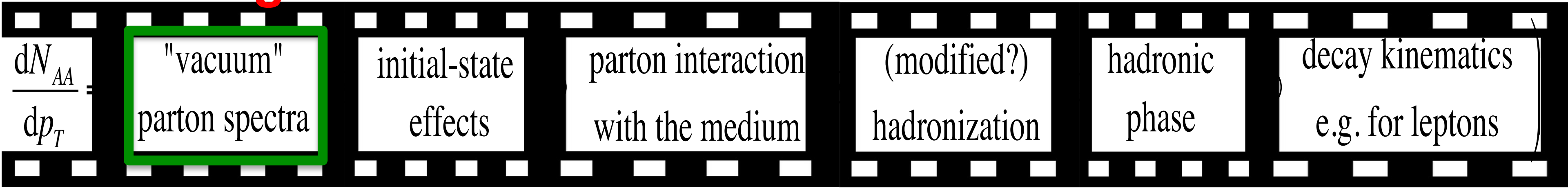

Measured spectra in AA collisions result from a convolution of many pieces
→ must measure observables with different sensitivity to the various ingredients
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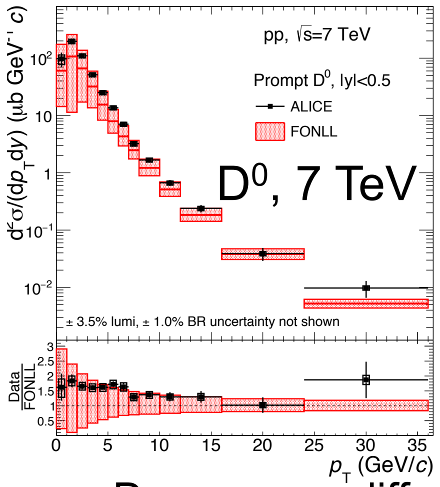
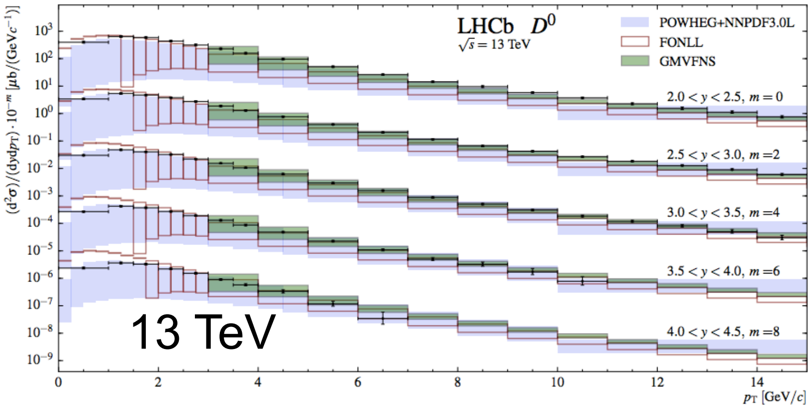
Heavy-flavour production in pp collisions

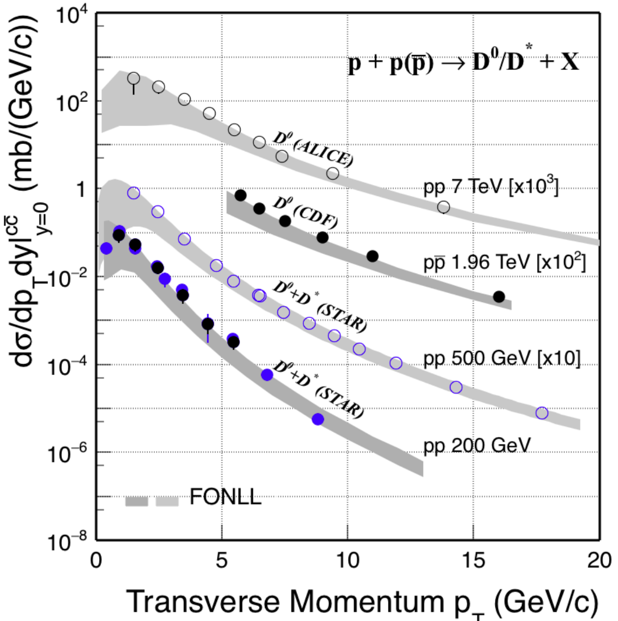
Charm production in pp collisions

EPJ C77 550 (2017)



JHEP 03 (2016) 159, 09 (2016) 013





STAR, PRD 86 (2012) 072013, QM14
CDF, PRL 91 (2003) 241804
ALICE, JHEP 01(2012) 128, arXiv: 1702.00766
LHCb, JHEP 03 (2016) 159, 09 (2016) 013

D-meson p_T-differential cross section described by pQCD calculations based on collinear factorisation

$$\frac{d\sigma^D}{dp_T^D}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$

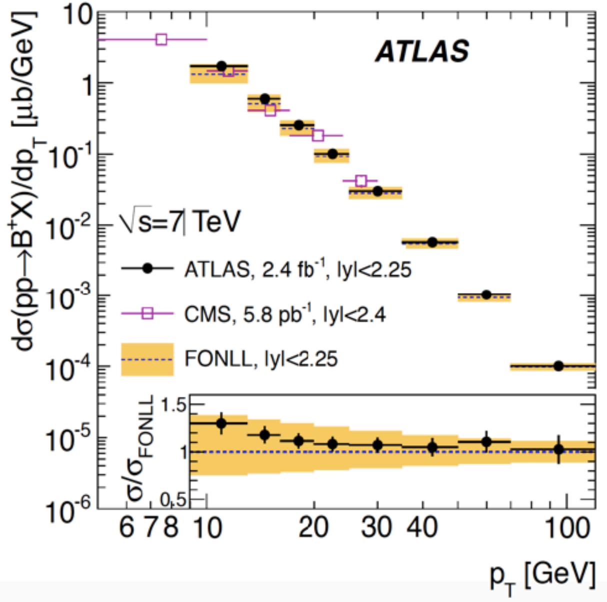
Parton Distribution Function

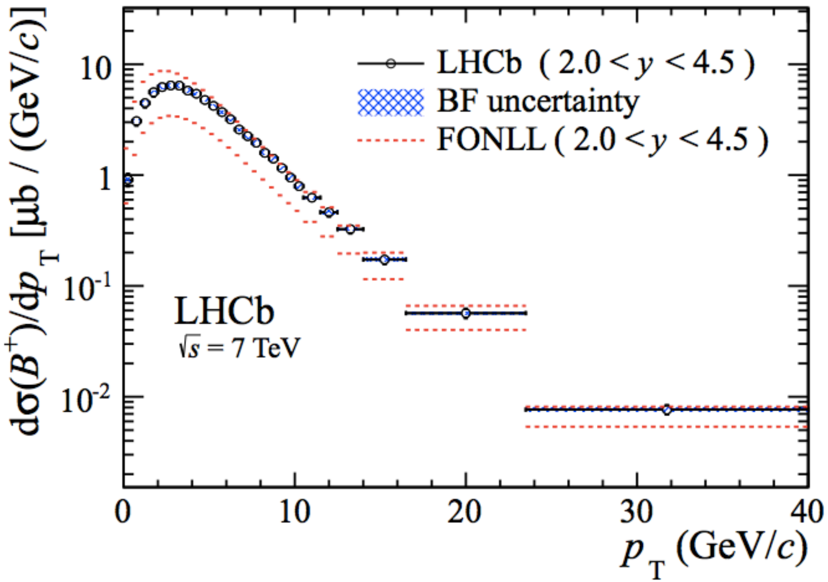
Partonic cross section

Fragmentation Function extracted from e^+e^- and e^-p data

Very precise data, on upper edge of FONLL uncertainty band (which is large at low p_T)

Beauty production in pp collisions



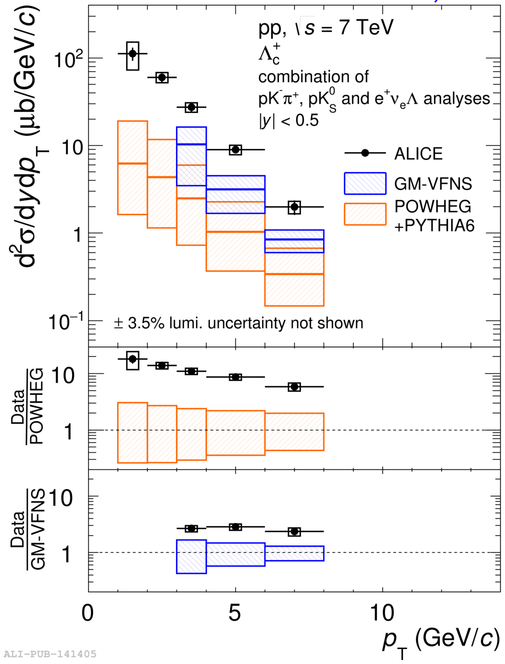


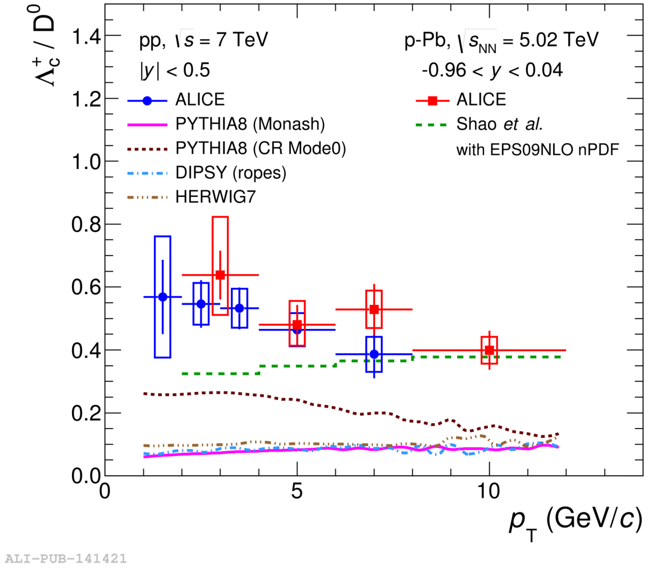
B-meson production also described by pQCD

… so far so good, HF production theoretically under control in pp collisions

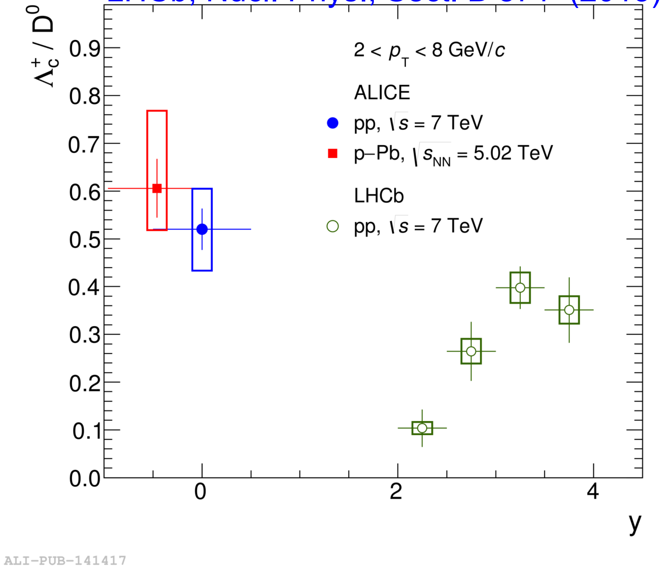
Charm baryons

ALICE, arxiv 1712.09851





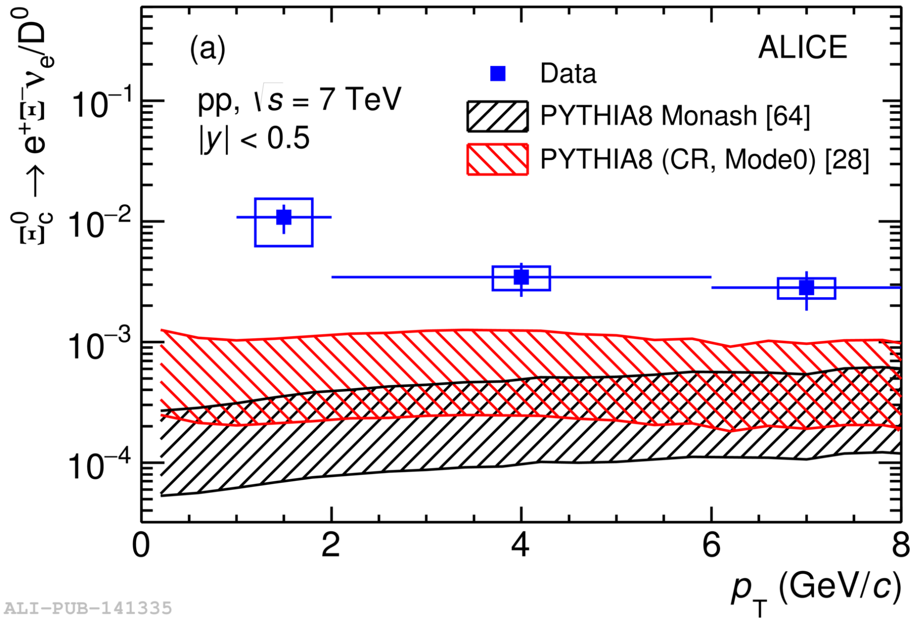
LHCb, Nucl. Phys., Sect. B 871 (2013)



- Λ_c production cross section higher than theoretical expectations
- Λ_c/D^0 higher than theoretical expectations (large uncertainties)
  - Rapidity trend?

Charm baryons

PLB 781 8-19 (2018)



Also $(\Xi_b \to)\Xi_c^0/D^0$ X BR higher than theoretical expectations (large uncertainties)

→ **Is charm hadronisation understood?**

→ Need to reduce experimental uncertainties to provide more precise input to models

The nuclear modification factor

Nuclear modification factor (R_{AA}): compare particle production in nucleus-nucleus (A-A) collisions with that in pp scaled by a “geometrical” factor (from Glauber model)

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

If $R_{AA}=1$ → no nuclear effects
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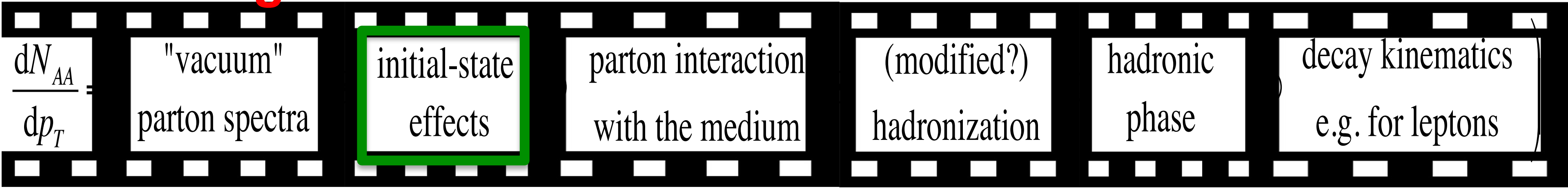
Never forget:



- **How can we prove that N_{coll}-scaling works?**
  - **R_{AA} can deviate from unity in nuclear collisions also w/o the formation of a QGP**

Proton (d) - nucleus collisions to address Cold Nuclear Matter effects

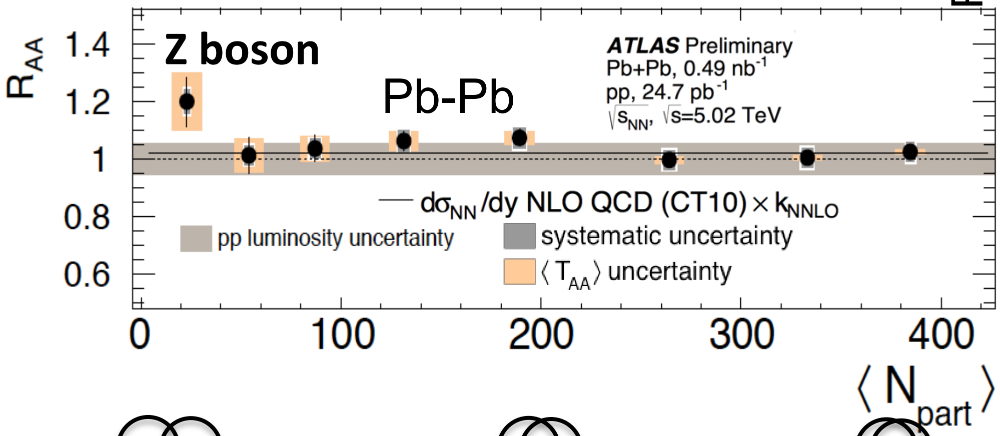
The original goal for d-Au, p-Pb collisions

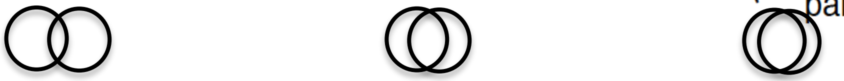
How can we be sure that we have the collision geometry under control?

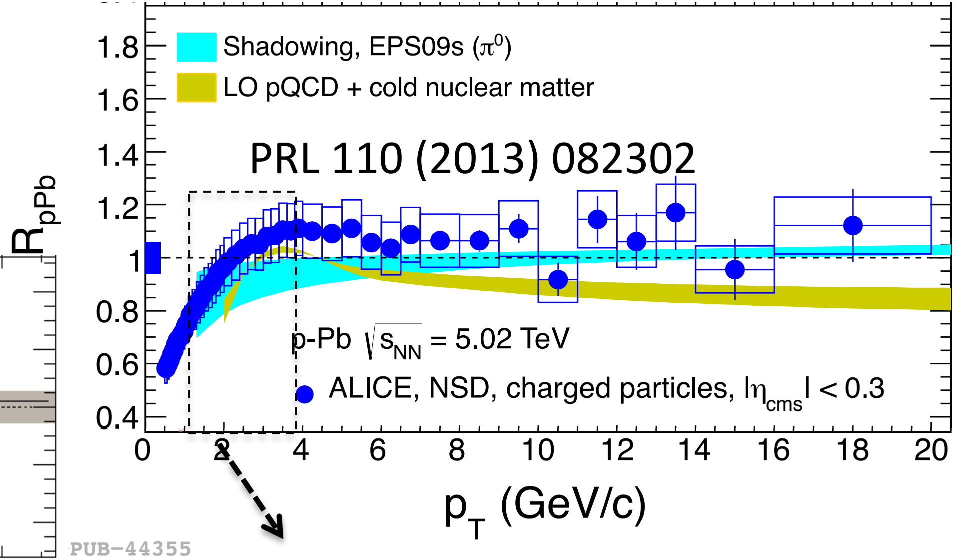
→ Smaller/simpler collision systems (QGP not formed / not big impact on hard-probe production)

↓

Probes not sensitive to medium formation
→ electroweak signals (γ,W, Z bosons)





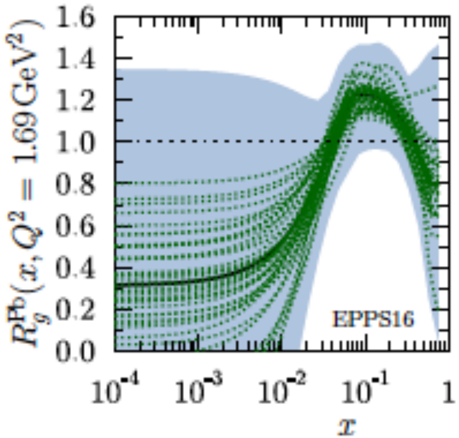


Caveats: initial/final-state cold-nuclear matter effects, mainly at low p_T

Cold nuclear matter effects

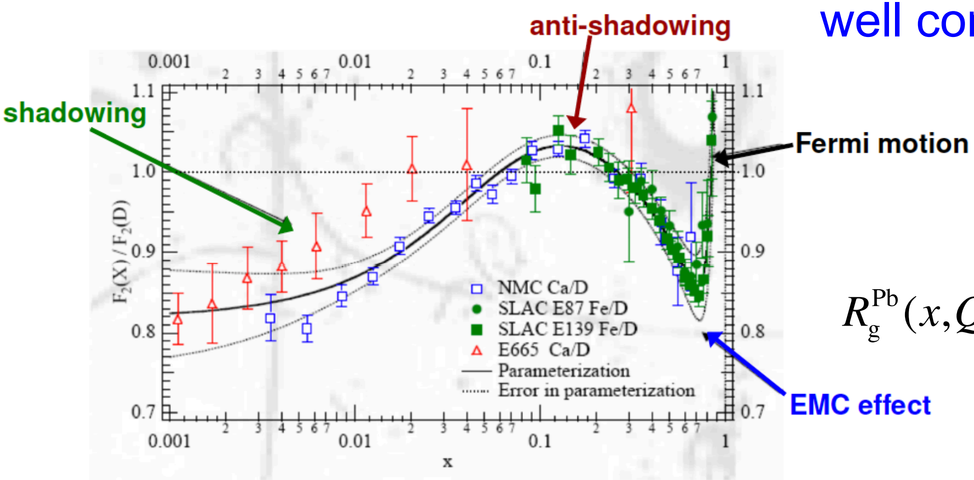
Effects, not ascribed to QGP, that can modify open-HF production in nuclear collisions:

- **Nuclear modification of the PDFs**
  - shadowing at low Bjorken-*x* dominant effect for open HF at LHC energies, anti-shadowing also relevant at RHIC



Gluon PDF at low *x* not well constrained by data

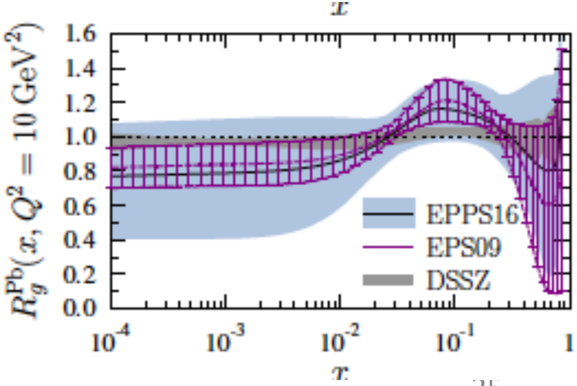
K. Eskola et al., EPJ C 77 (2017)



"bound" proton PDF in Pb nucleus

$$R_g^{Pb}(x,Q^2) = \frac{f_g^{p/A}(x,Q^2)}{f_g^{p}(x,Q^2)}$$

"free" proton PDF

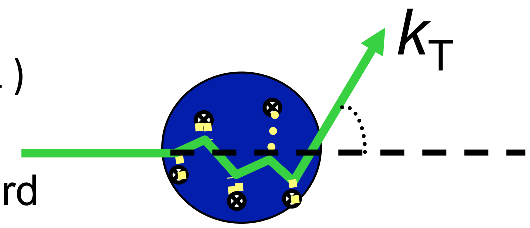


Cold nuclear matter effects

Effects, not ascribed to QGP, that can modify open-HF production in nuclear collisions:

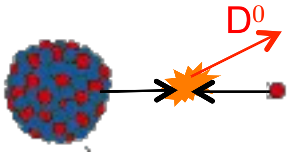
- **Nuclear modification of the PDFs**
  - shadowing at low Bjorken-*x* dominant effect for open HF at LHC energies, anti-shadowing also relevant at RHIC
  - "**saturation**" at low *x* → non-linear PDF evolution → need different calculation schemes (e.g. Colour-Glass Condensate, e.g. H.Fujii and K.Watanabe, Nucl.Phys.A915(2013) 1)
- **k_T-broadening**

  Due to multiple elastic collisions of the parton before the hard scattering → can cause R_{pA} >1 around 2-3 GeV/*c*



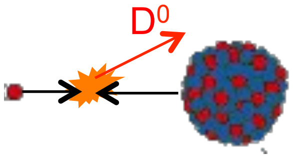
- **energy loss in the initial or final state in cold nuclear matter**

D^0-meson R_{pPb} at LHC: forward, backward y



Pb-p, “Backward”

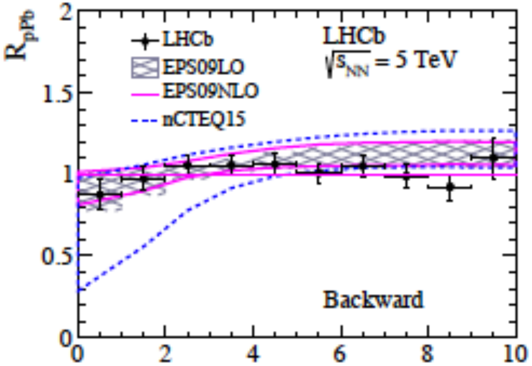
Probing large-x in Pb nucleus



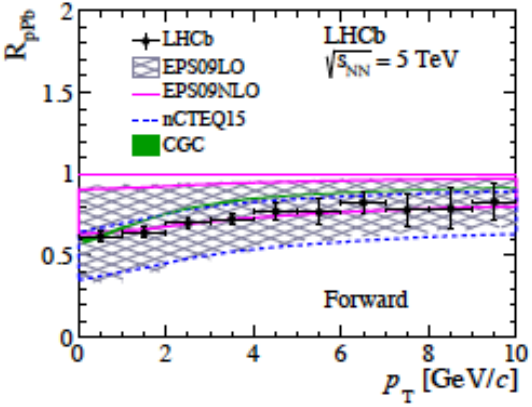
p-Pb, “Forward”

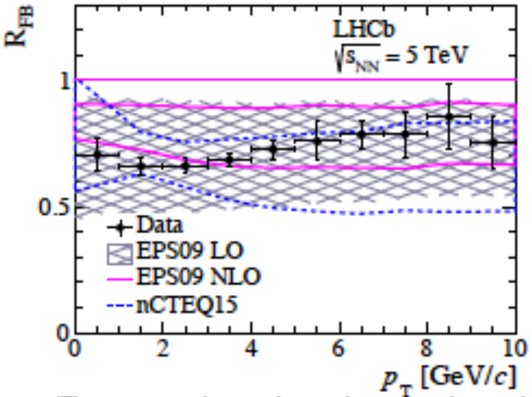
Probing low-x in Pb nucleus

Asymmetric collision system, nucleon-nucleson cms moves with y_{cms}=0.465 (towards p beam)



JHEP 1710 (2017) 090

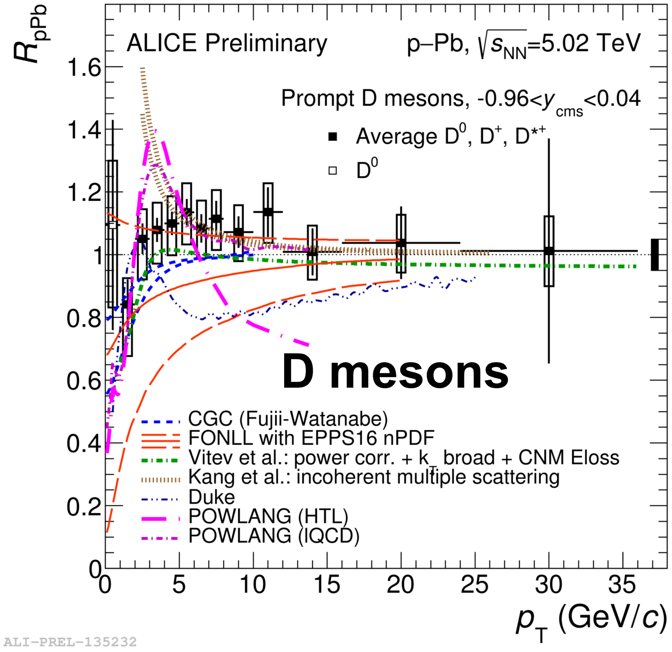


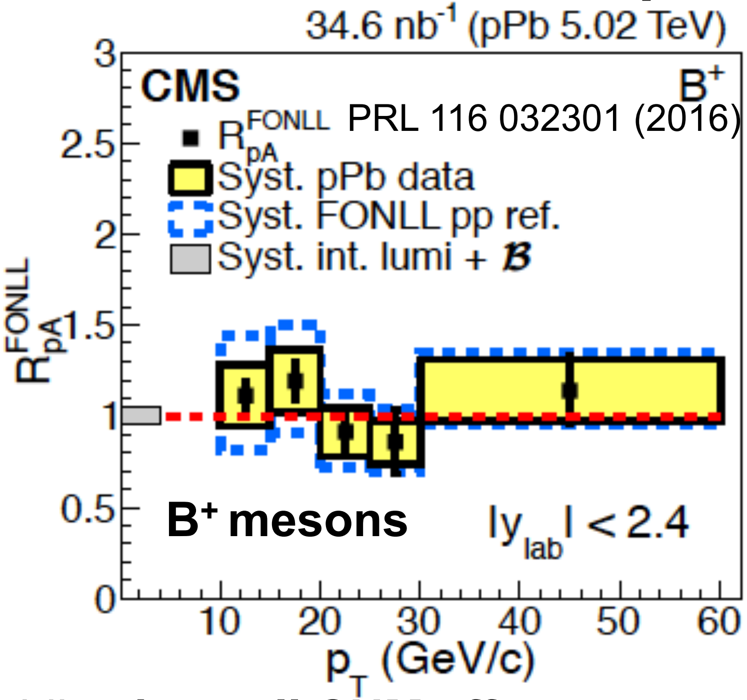


Forward-to-backward ratio

- Significant deviations of R_{pPb} and forward-to-backward ratio from unity
- Data described by nPDF and CGC

D,B-meson R_{pPb} at LHC: mid-rapidity



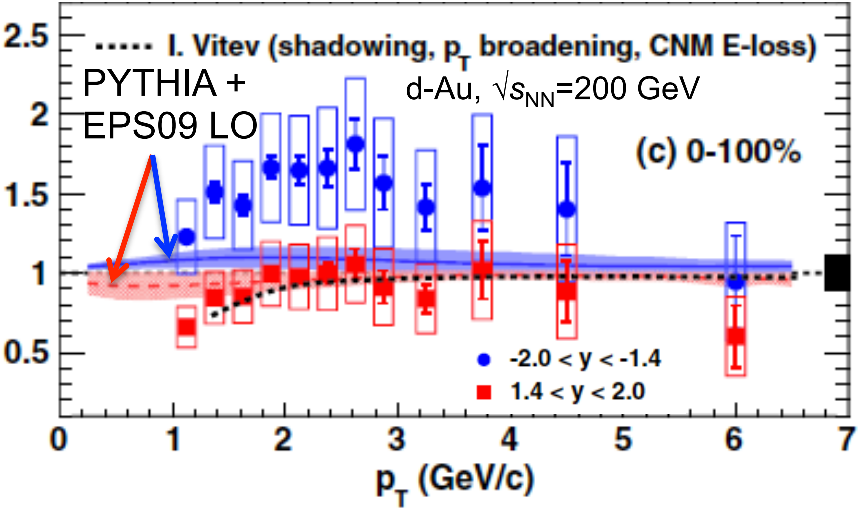


- R_{pPb} consistent with unity at mid-rapidity → **small CNM effects**
- Described by CNM models as well as by models assuming QGP formation in p-Pb, within uncertainties
  - 20% D-meson suppression at high p_T disfavoured by data

Open-HF nuclear modification factor in d-Au at RHIC

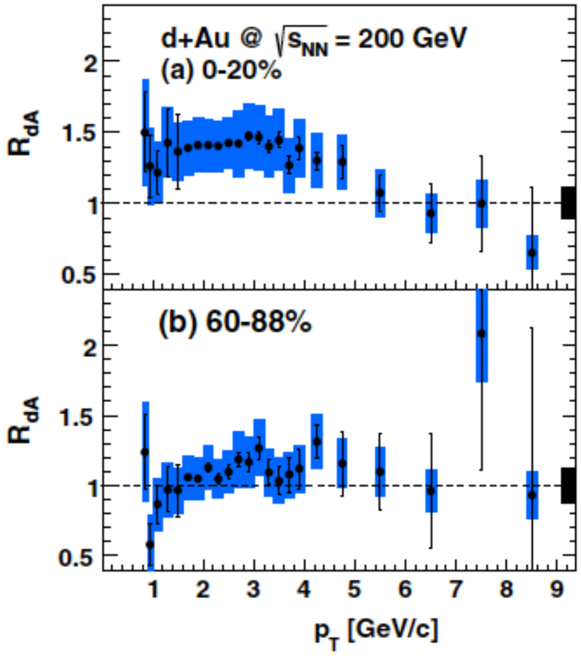
HF muons at forward/backward rapidity

PRL 112 252301 (2014)



HF electrons at midrapidity

PRL 109 242301 (2012)



- Indications of for R_{dAu}>1 at backward rapidity and in "central" collisions at midrapidity
- k_T-broadening, gluon anti-shadowing?

The nuclear modification factor

Nuclear modification factor (R_{AA}): compare particle production in nucleus-nucleus (A-A) collisions with that in pp scaled by a "geometrical" factor (from Glauber model)

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}} / \mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}} \rangle \times \mathrm{d}\sigma_{\mathrm{pp}} / \mathrm{d}p_{\mathrm{T}}}$$

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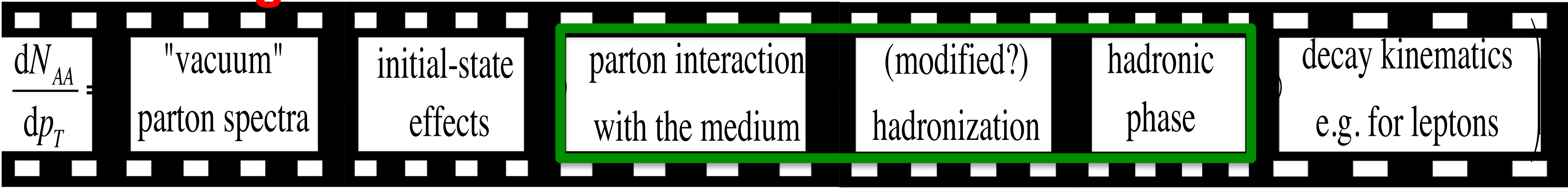
If $R_{AA}\neq 1$ → nuclear effects

Never forget:



Measured spectra in AA collisions result from a convolution of many pieces

→ must measure observables with different sensitivity to the various ingredients
→ Physics program requires precise measurements in pp, p-A, A-A collisions
→ interpretation of the results requires comparison with models

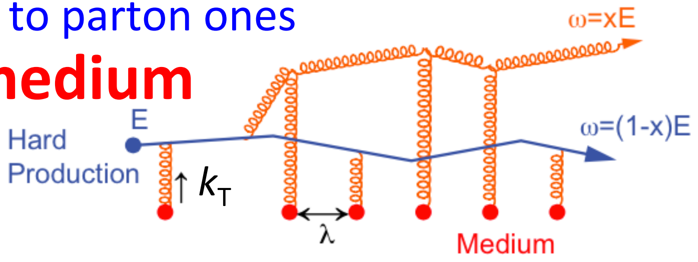
QGP tomography with heavy quarks

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD

at all p_T for charm and beauty (large masses >> Λ_{QCD})

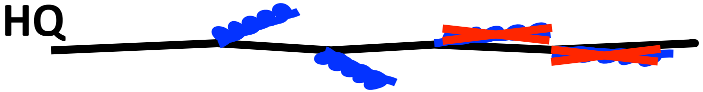
- Strongly interacting with the medium
- Hard fragmentation ➜ measured meson properties closer to parton ones

⇨ **"Calibrated probes" of the medium**



Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional (elastic) processes
  - path length and medium density
  - **color charge** (Casimir factor)
  - **quark mass** (e.g. from dead-cone effect)



Gluonsstrahlung probability

$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

"Dead-cone" implies

- Harder fragmentation (also in vacuum)
- Smaller in-medium radiative energy loss

Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

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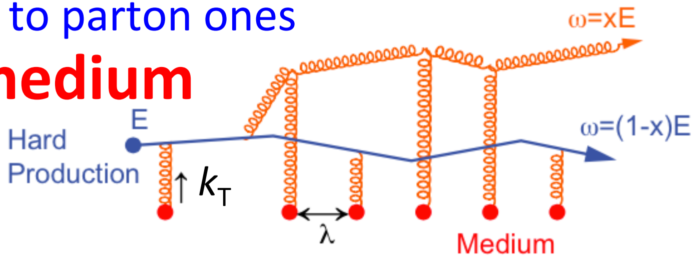

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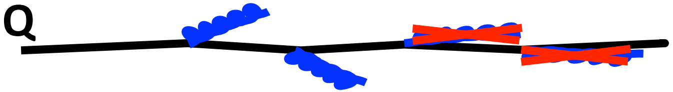
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$



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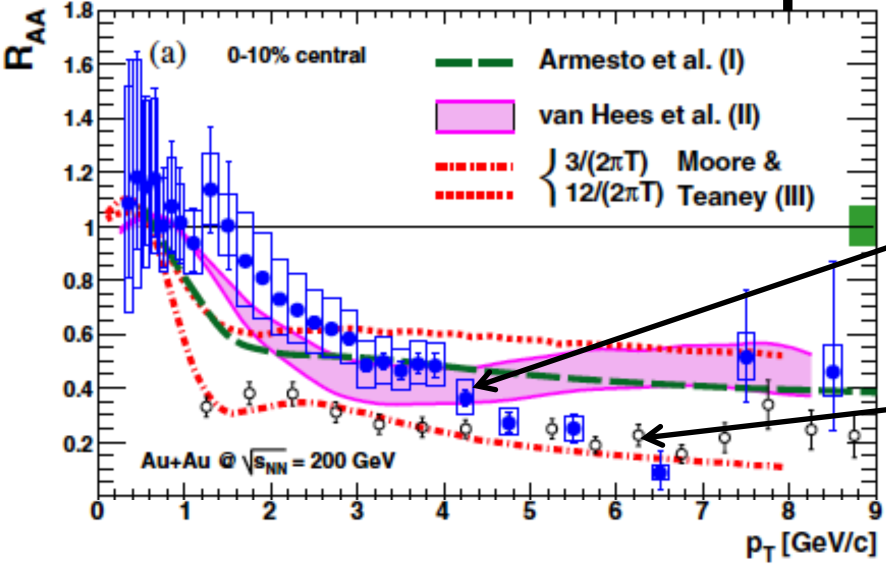
The RHIC surprise (>10 years ago)

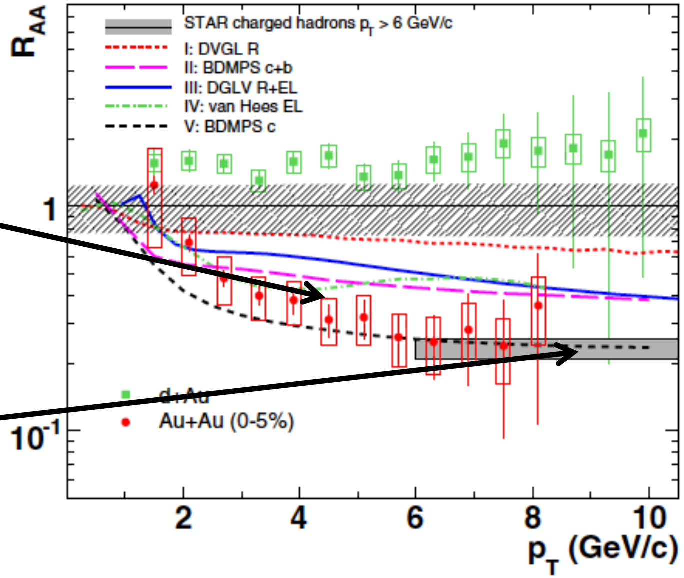


PRL 98 172391 (2007)

(Look at data)

Heavy-flavour hadron decay electrons

π^0, charged hadrons



PRL 98 192301 (2007)

Similar R_{AA} of heavy-flavour hadron decay electrons and π^0/charged hadrons at moderate/high p_T

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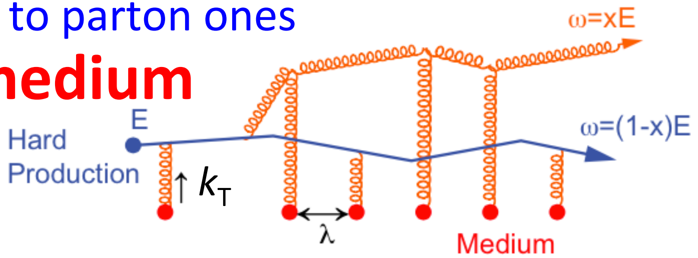

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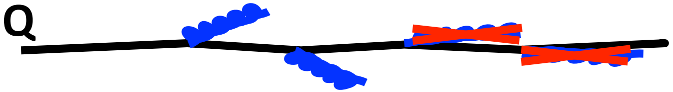
$$\Delta E_g > \Delta E_{u,d,s} \ ? > \Delta E_c > \Delta E_b$$

HQ



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Dokshitzer and Kharzeev, PLB 519 (2001) 199.

… let’s not rush too much…

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If R_{AA}=1 → no nuclear effects
If R_{AA}≠1 → nuclear effects

Never forget:

$$\frac{dN_{AA}}{dp_T} = \begin{matrix}\text{"vacuum"} \\ \text{parton spectra}\end{matrix} \otimes \begin{matrix}\text{initial-state} \\ \text{effects}\end{matrix} \otimes \begin{matrix}\text{parton interaction} \\ \text{with the medium}\end{matrix} \otimes \begin{matrix}\text{(modified?)} \\ \text{hadronization}\end{matrix} \otimes \begin{matrix}\text{hadronic} \\ \text{phase}\end{matrix} \left(\otimes \begin{matrix}\text{decay kinematics} \\ \text{e.g. for leptons}\end{matrix} \right)$$

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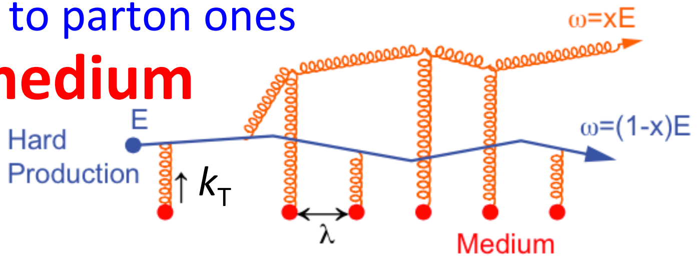

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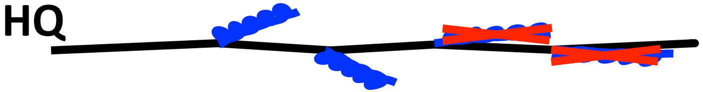
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

?

$$R_{AA}(\mathrm{B}) > R_{AA}(\mathrm{D}) > R_{AA}(\pi)$$



Gluonsstrahlung probability

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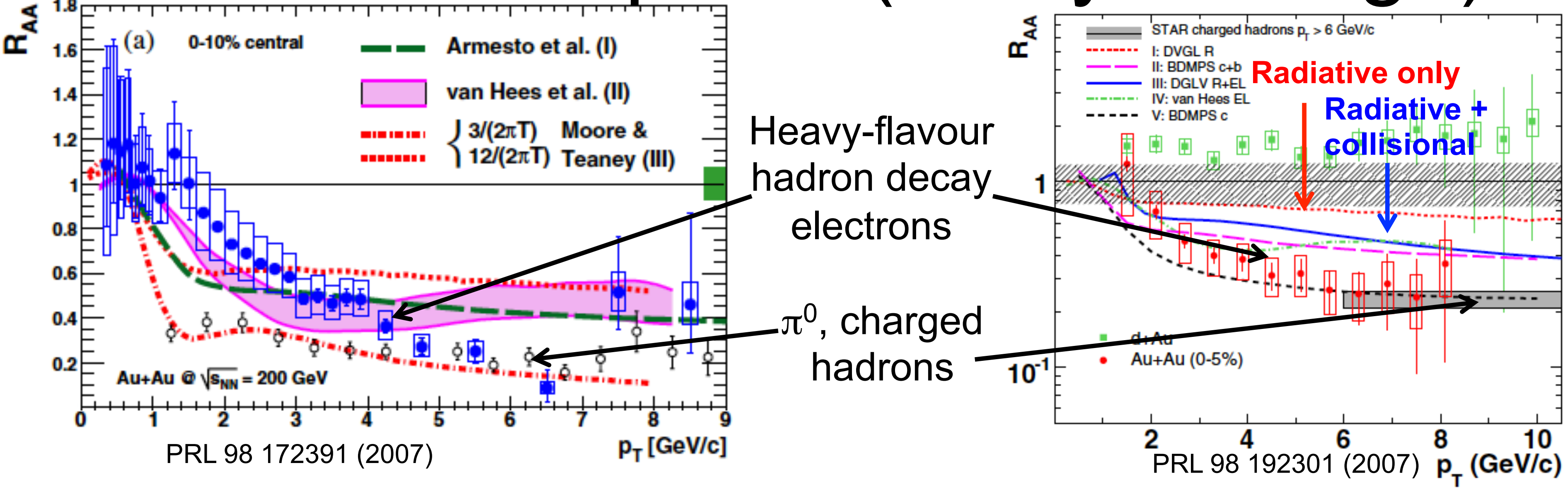
Not straightforward!
Initial-spectrum shape, fragmentation functions + plethora of effects

The RHIC surprise (>10 years ago)



(Look at models: they do incorporate the proper initial spectrum and decay kinematics!)

Very difficult to describe data within a "radiative-only" scenario!

(further constraints from elliptic flow, discussed later)

Collisional energy loss can play an important role for heavy quarks!

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at all p_T for charm and beauty (large masses >> Λ_{QCD})

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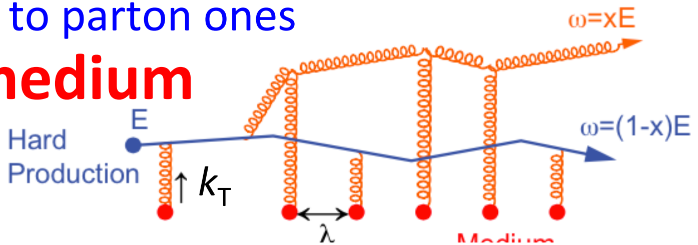
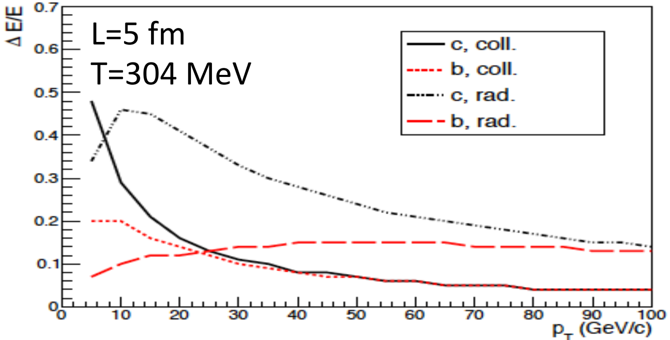
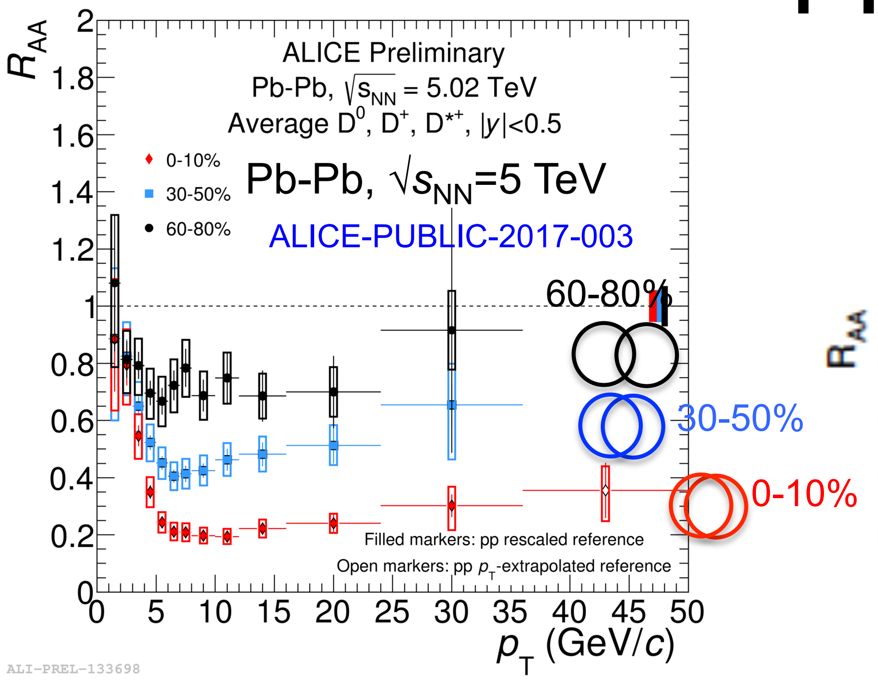


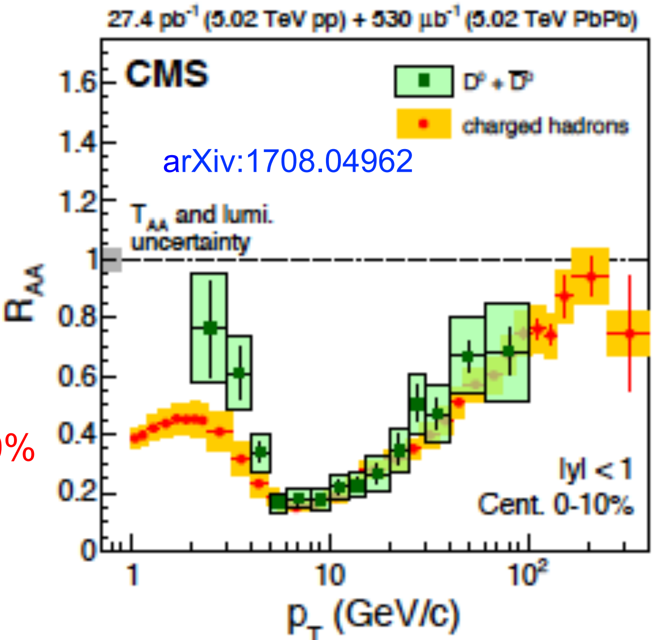


- **"Collisional energy loss" expected to be the dominant energy-loss process at low p_T**
- **ΔE_{coll}(charm)>ΔE_{coll} (beauty)**

Figure from A. Andronic *et al.*, EPJC C76 (2016)
M. Djordjevic, Phys. Rev. C80 064909 (2009), Phys. Rev. C74 064907 (2006).

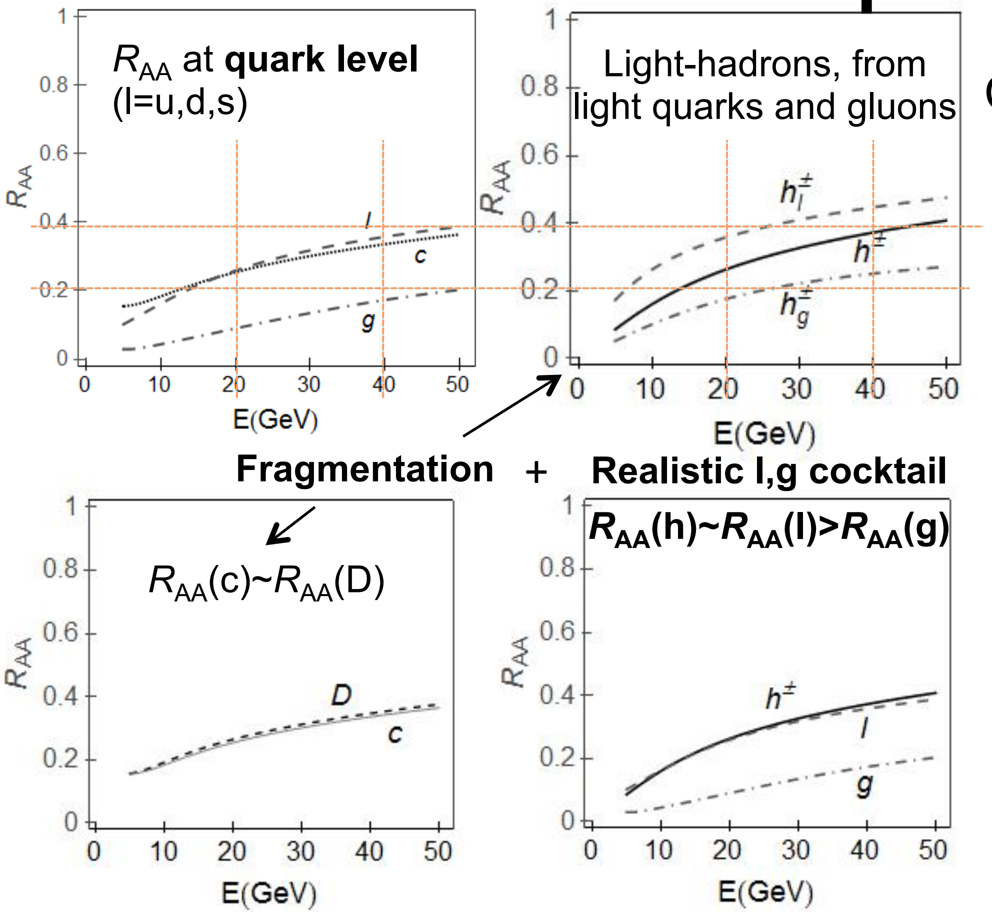
D-meson suppression at LHC





- Strong suppression of high-p_T D-meson production in central Pb-Pb collisions.
- Suppression increasing with centrality.
- Very similar D-meson and charged-particle R_{AA} from p_T~5 to 100 GeV/c
  - Similar rise above 10 GeV/c

D meson vs. pion R_{AA}, high p_T



M. Djordjevic, PRL112 (2014) 042302

Colour-charge dependence of energy loss and small charm-mass effects lead to:

$\Delta E_g > \Delta E_{uds} \geq \Delta E_c$

$R_{AA}(g) < R_{AA}(uds) \sim R_{AA}(c)$

(effect of different partonic spectra included)

R_{AA} of hadrons from light quarks, gluon strongly influenced by (soft) fragmentation

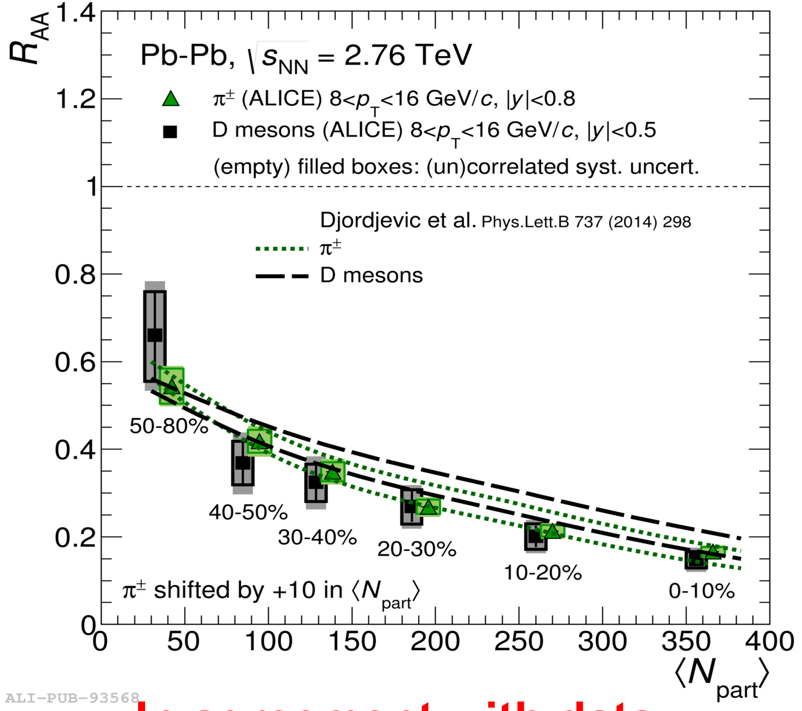
$R_{AA}(h_l) > R_{AA}(l)$

$R_{AA}(h_g) > R_{AA}(g)$

Expected hierarchy (at high p_T):

$\boldsymbol{R_{AA}(g) < R_{AA}(uds) \sim R_{AA}(h) \sim R_{AA}(D) \sim R_{AA}(c)}$

D meson vs. pion R_{AA}, high p_T



In agreement with data
...but can this work at all p_T and collision energies?

M. Djordjevic, PRL112 (2014) 042302

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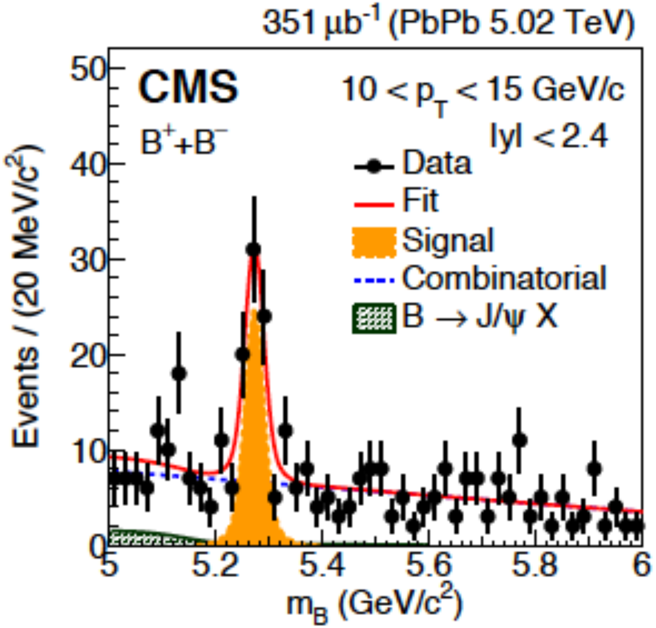
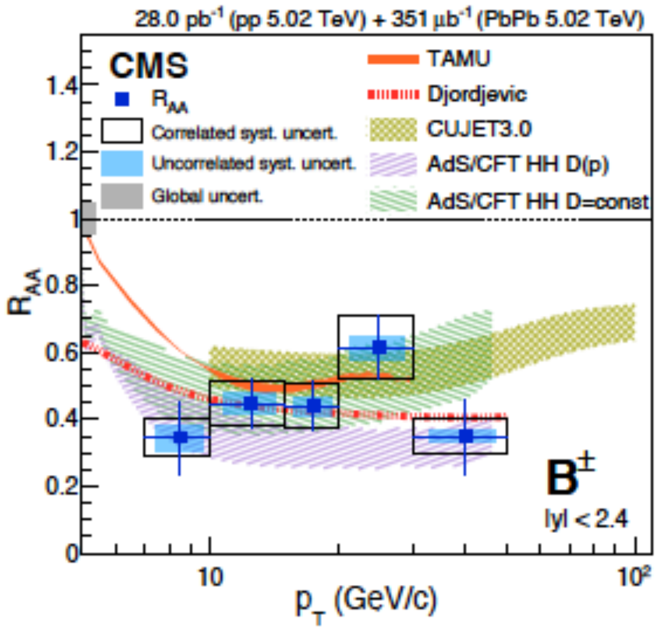
Beauty suppression at high p_T

PRL 119 no.15, 152301 (2017)



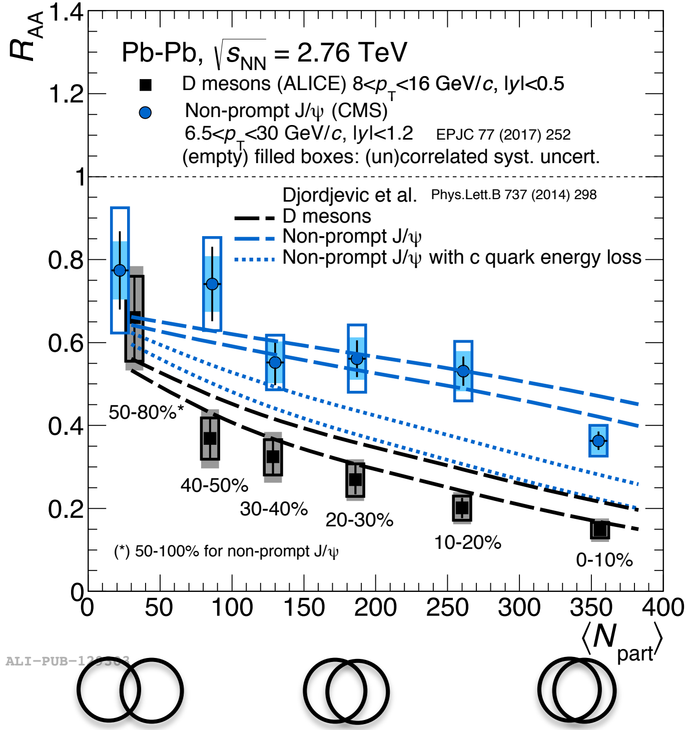


- B-meson R_{AA} ~0.4 from 7 to 50 GeV/*c*
- Described by models including radiative and/or collisional energy loss: data precision does not set stringent constraints yet

→ key measurement in the future (news at QM?)

Did we observe a mass effect?

ALICE, JHEP 1511 (2015) 205, JHEP 1706 (2017) 032
CMS, EPJ C 77 (2017) 252



At high p_T :

R_{AA} (J/ψ from B) > **R_{AA}(D)** in central collisions

Indication of R_{AA} (B) > R_{AA}(D) (*)

The different suppression and the centrality dependence as expected from models with quark-mass dependent energy loss ($\Delta E_g > \Delta E_{lq} \geq \Delta E_c > \Delta E_b$)

Major goal for the future:
from indication to real quantification!

(*) The median pt for J/ψ in 6.5<p_T<30 GeV/c is ~10 GeV/c
→consistent comparison with D mesons in 8<p_T<16 GeV/c

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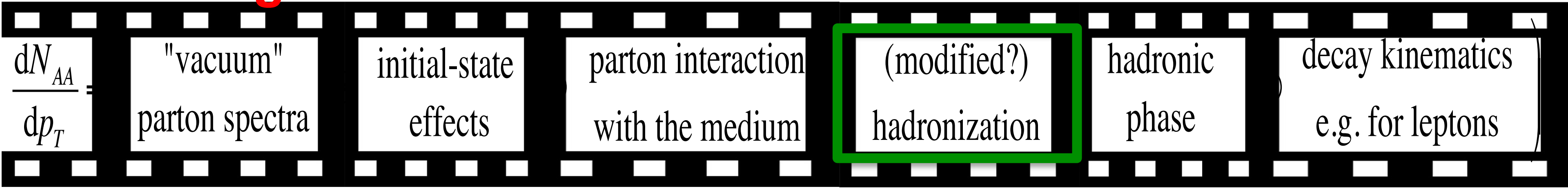

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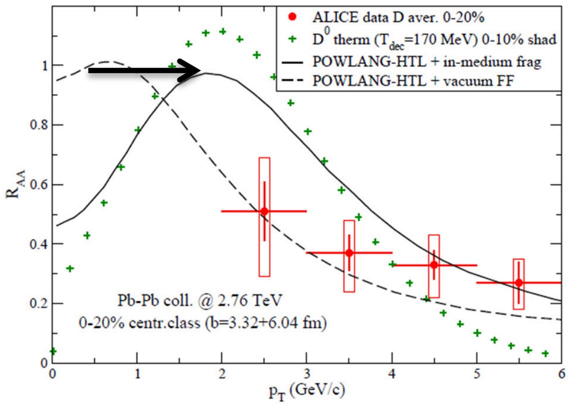
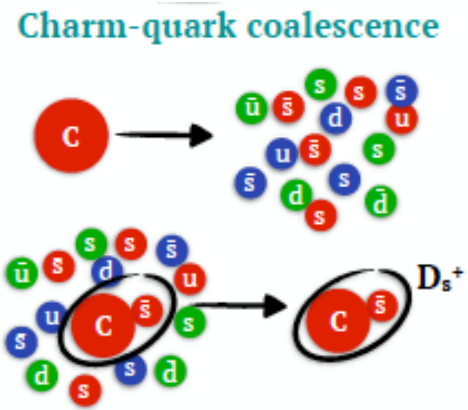
Hadronisation via coalescence

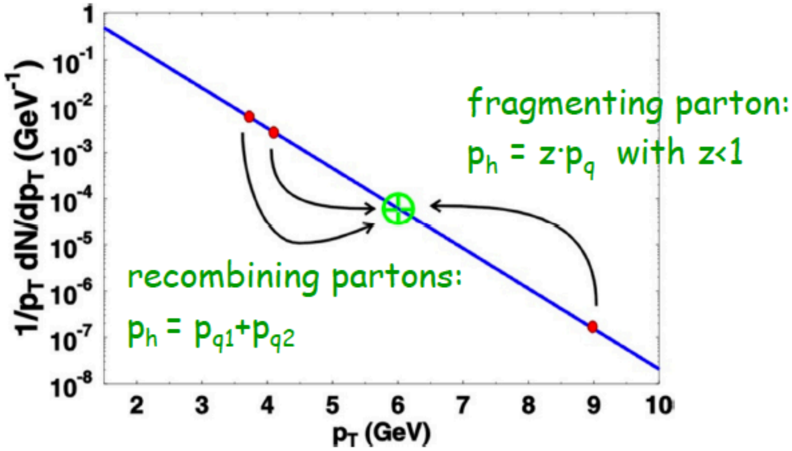
Effects:

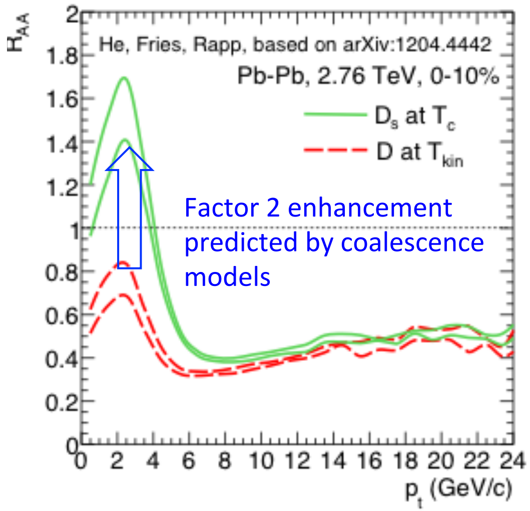
- Modify momentum distribution of HF-hadron
  - Radial flow "bump"
- Enhance HF-hadron v2 (light-parton contribution)
- Modify "hadrochemistry": D_s, Λ_c enhancement



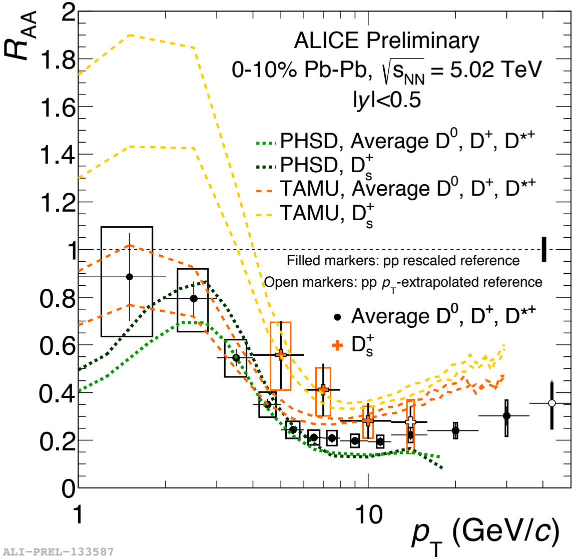


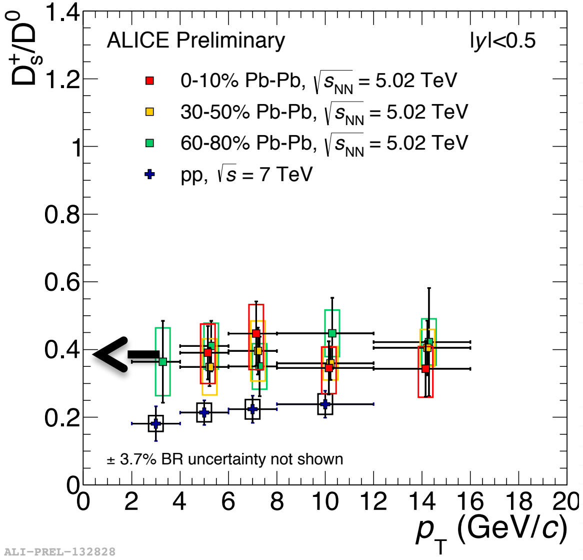
Sketch by F. Grosa

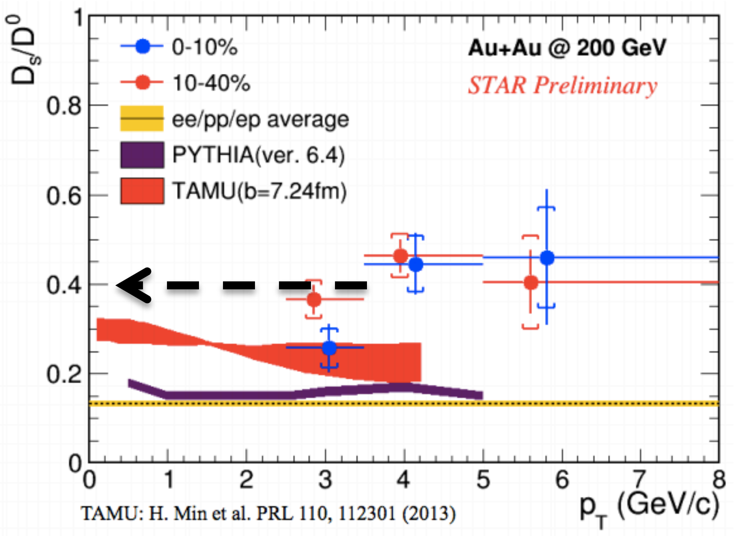




Hadronisation: D_s^+ enhancement



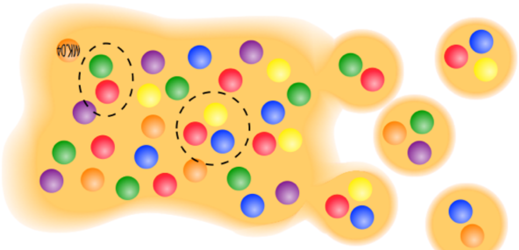




- Hint for $R_{AA}(D_s^+)>R_{AA}$ (non-strange D) at low p_T.
- Hint for higher D_s^+/non-strange-D-meson ratio in Pb-Pb and Au-Au than in pp collisions, w/o evident centrality dependence

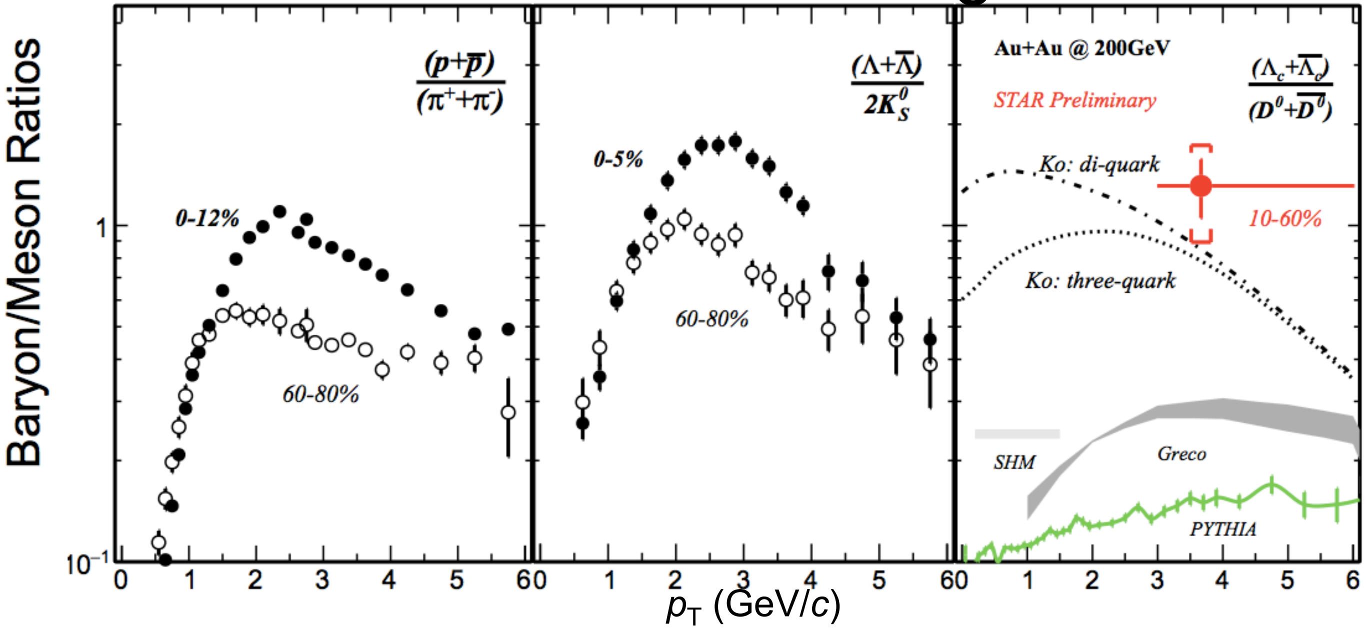
→**Hadronisation via coalescence in a strangeness-rich environment?**

D_s^+/D close to Statistical Hadronisation Model prediction (0.35-0.4)

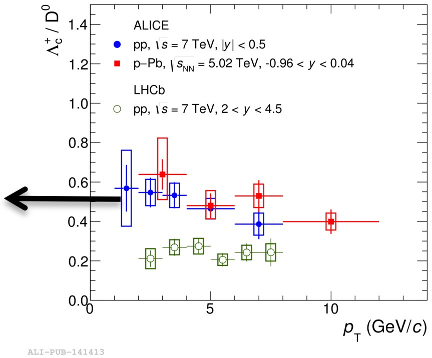


A. Andronic et al., PLB 571 (2003) 36

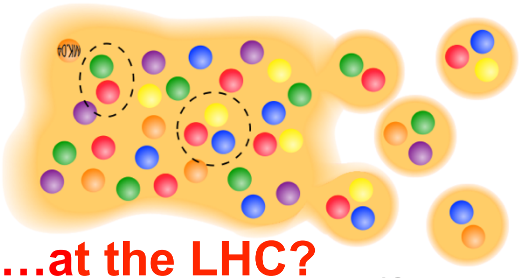
Hadronisation: Λ_c^+ enhancement



Ko model :
Y. Oh, et.al. PRC 79 (2009) 044905;
Greco:
S.Ghosh, et. al. PRD 90 (2014) 054018



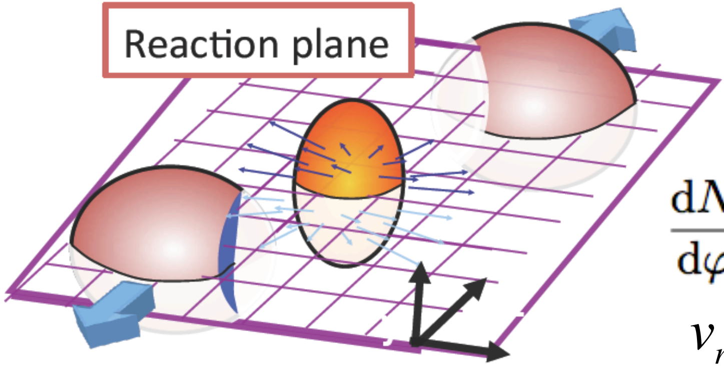
- Significant enhancement of Λ_c/D baryon-to-meson ratio compared to PYTHIA/vacuum-fragmentation baseline, as well as to ALICE/LHCb measurements in pp and p-Pb collisions
- Similar values than light flavor baryon-to-meson ratios
- Consistent with coalescence + thermalized charm quarks



…at the LHC?

Azimuthal anisotropy

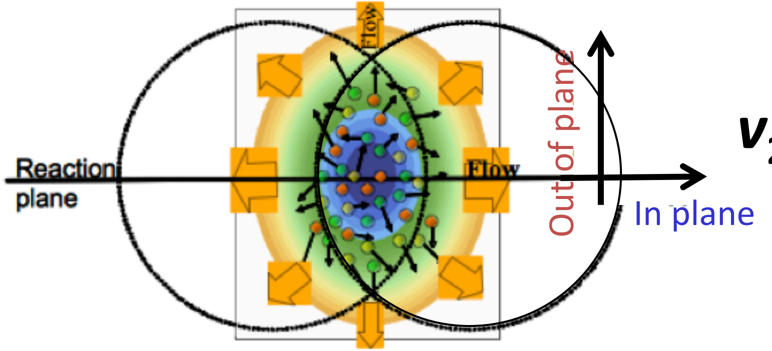
Azimuthal anisotropy: elliptic flow



Initial spatial anisotropy → momentum anisotropy

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \dots\right)$$

$$v_n = \langle \cos(n[\varphi - \psi_n]) \rangle$$

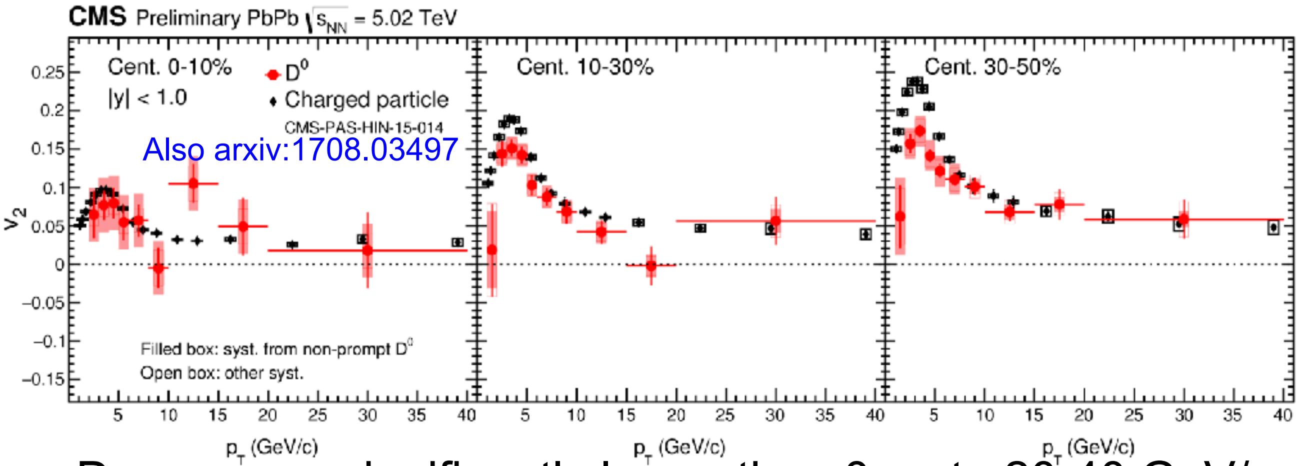


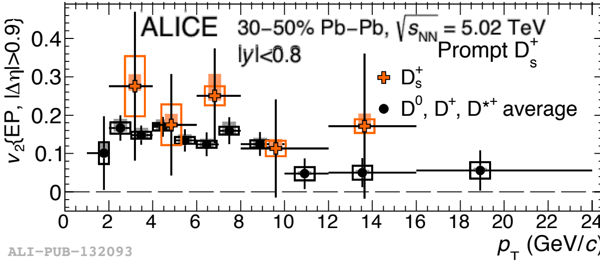
v_2>0 → Thermalization/collective motion (at low p_T)

→ Path length dependence of energy loss (at high p_T)

v_2+ R_{AA}: complementary information → improve sensitivity to relative contribution of collisional and radiative energy losses and to coalescence

D-meson v_2 at LHC

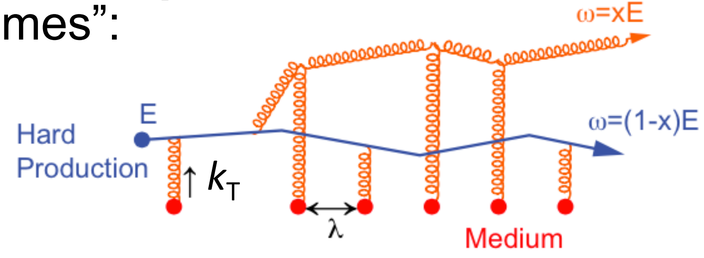




- D-meson v_2 significantly larger than 0 up to 20-40 GeV/c
  - → (low p_T) charm quarks sensitive to medium collective motion
    - → **Strong coupling to the system**
  - → (high p_T) set constraints to path-length dependence of energy loss
- v_2 (0-10%) < v_2 (10-30%) ~ v_2 (30-50%)
- D_s–meson v_2: compatible with non-strange D-meson v_2 within uncertainties.
- Indication of D-meson v_2 < charged-particle v_2 at low p_T
  - Similar at high p_T

Models: low and high p_T regimes

In a oversimplified scheme we can identify two "regimes":



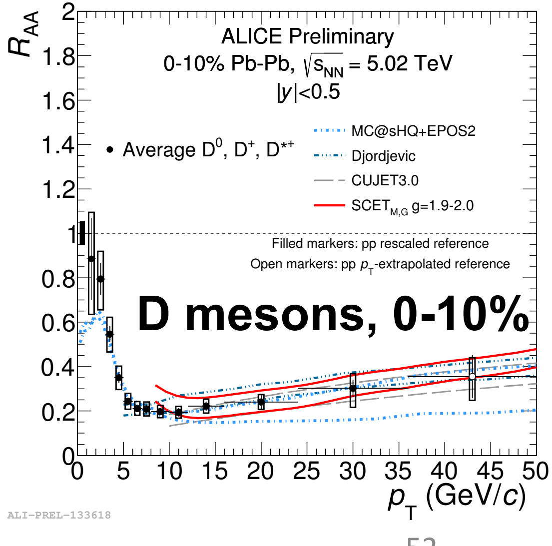
High p_T:

- region **dominated by radiative energy loss**
- Quantum interferences in multiple scattering important (LPM effect)
- Relevant parameter: $\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$

pQCD-based models provide fair description

pQCD e-loss MODELS	Collisional energy loss	Radiative energy loss	Coalescence	Hydro	nPDF
CUJET3.0 JHEP 02 (2016) 169	✔	✔	✘	✘	✘
Djordjevic PRC 92 (2015) 024918	✔	✔	✘	✘	✔
MC@sHQ+EPOS PRC 89 (2014) 014905	✔	✔	✔	✔	✔
SCET JHEP 03 (2017) 146	✔	✔	✘	✘	✔

Table: courtesy of E. Bruna



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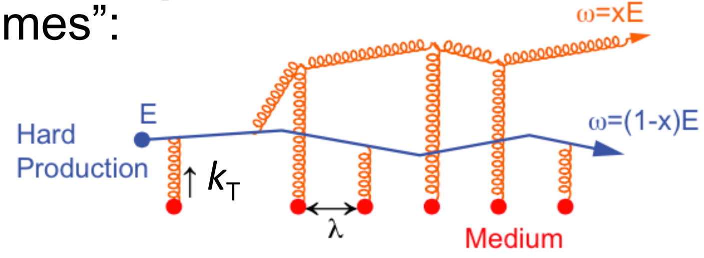

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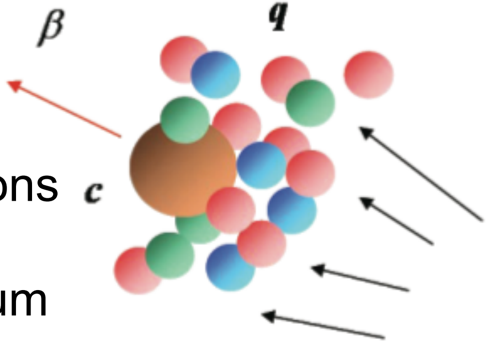


Low p_T:

- Region **dominated by "collisional" energy loss**
- Heavy quarks undergo many soft and incoherent elastic collisions **~Brownian motion**
- Goal: study how and if HQ reach the equilibrium with the medium
- Relevant parameter: **spatial diffusion coefficient, D_s**

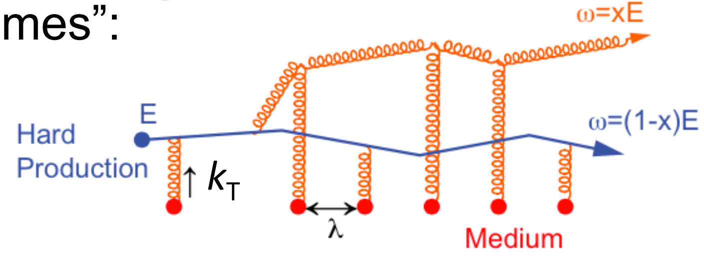
Injecting a particle at *x*=0 and *t*=0, the mean squared position at time *t* is:

$$\langle x^2(t) \rangle = 6 D_s t$$

Strong coupling with the system → small D_s

Models: low and high p_T regimes

In a oversimplified scheme we can identify two "regimes":



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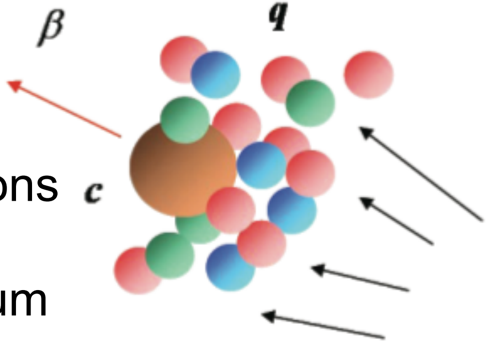

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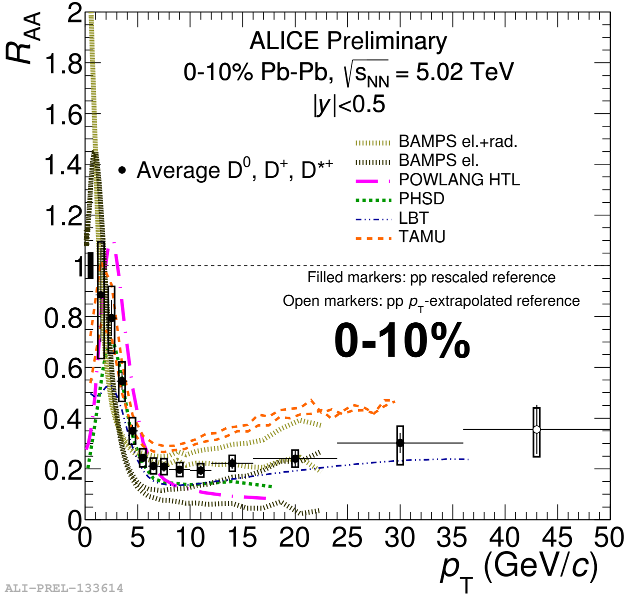
- Goal: study how and if HQ reach the equilibrium with the medium
- Relevant parameter: **spatial diffusion coefficient, D_s**
- **Realistic description of medium evolution required**

→ **"Transport models"** based on Boltzmann/Fokker-Plank/Langevin equations

Nice review: F. Prino, R. Rapp, J. Phys. G43 no. 9 093002 (2016)

Models vs. data at low p_T



Low p_T: fairly good description with transport models

→ important role of **elastic scatterings and description of medium evolution**

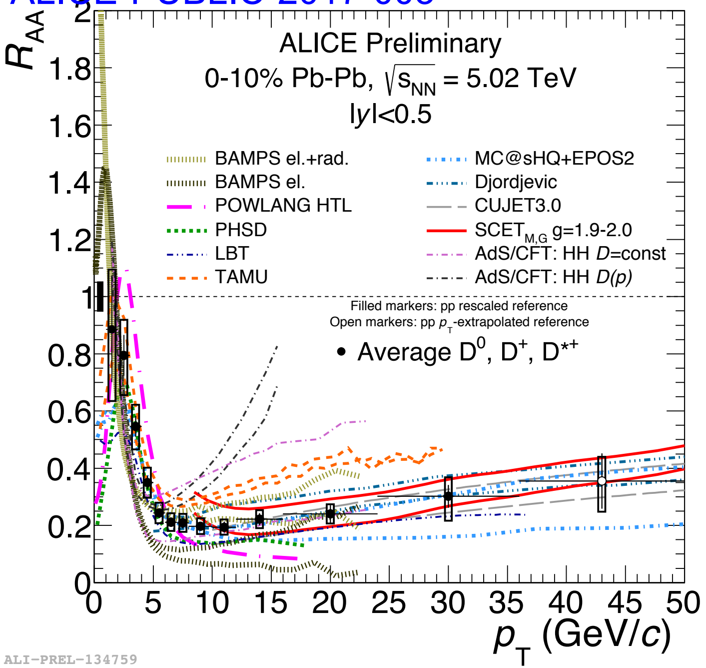
→ Important role of coalescence

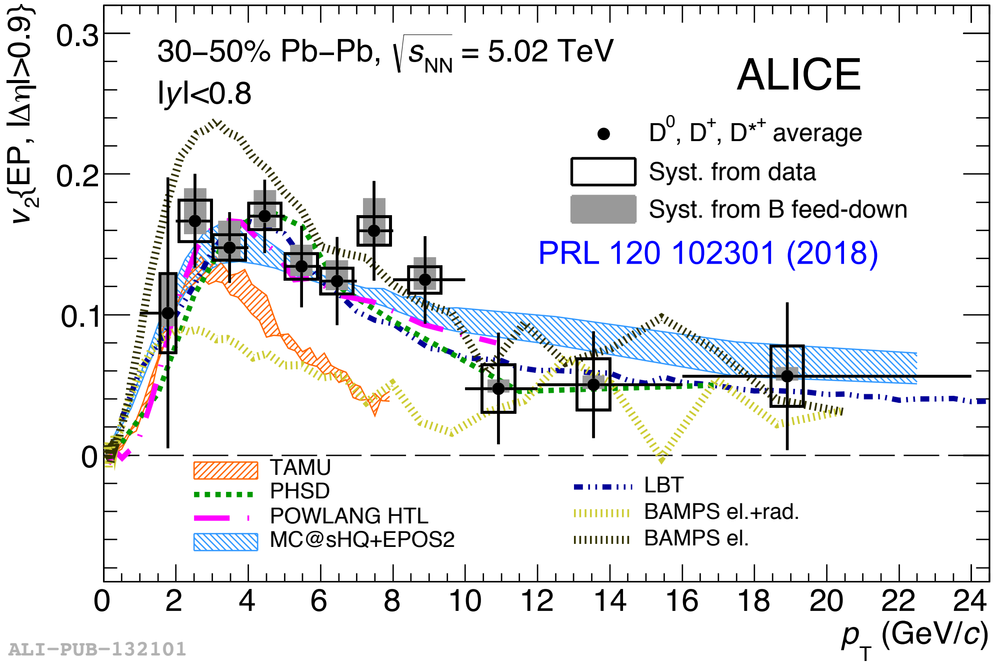
Table: courtesy of E. Bruna

TRANSPORT MODELS	Collisional energy loss	Radiative energy loss	Coalescence	Hydro/ dynamics	nPDF
BAMPS J. Phys. G42 (2015) 115106	✔	✔	✘	✔	✘
LBT arXiv:1703.00822	✔	✔	✔	✔	✔
PHSD PRC 93 (2016) 034906	✔	✘	✔	✔	✔
POWLANG EPJC 75 (2015) 121	✔	✘	✔	✔	✔
TAMU Phys. Lett. B735 (2014) 445	✔	✘	✔	✔	✔

Models vs. data: R_{AA} and v_2 together

ALICE-PUBLIC-2017-003



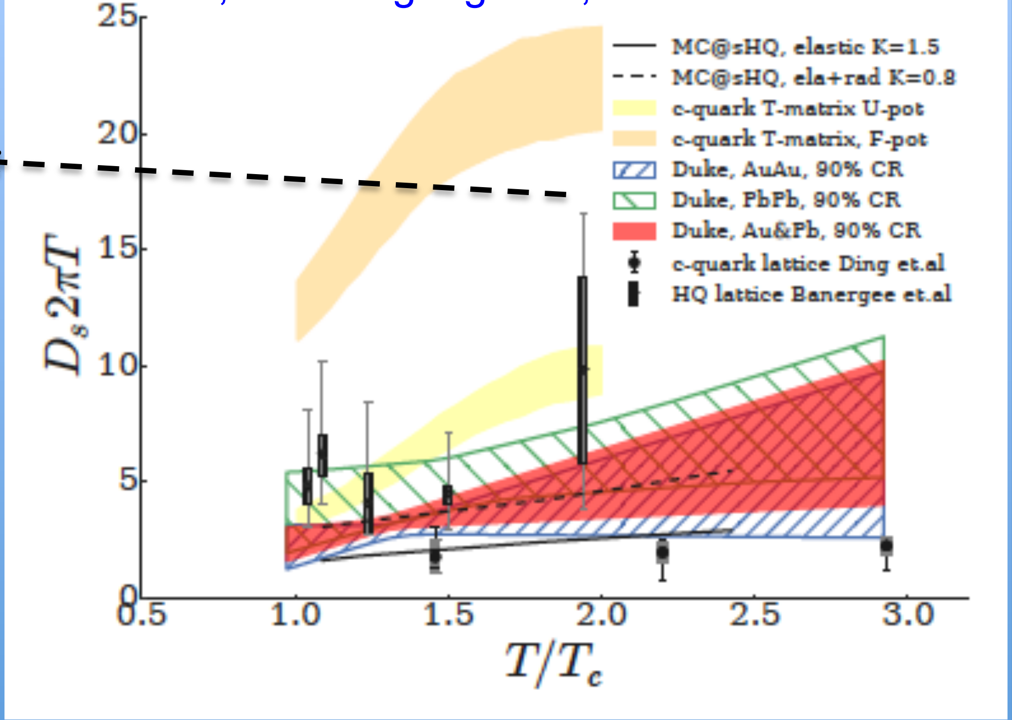


- Models able to reproduce v_2 favour diffusion coefficient $2\pi T D_s(T)$ in the range 1.5-7 at T_c with a corresponding thermalisation time τ_{charm}=3-14 fm/c.
- **Powerful constraints by considering complementary observables (R_{AA} and v_2 of non-strange D and D_s^+) over wide p_T ranges and in different centrality classes.**

Example from last QM

R_{AA} and v_2 D-meson data (RHIC and LHC run 1) used to constrain diffusion coefficient with a Bayesian model-to-data analysis

Y. Xu, M. Nahrgang et al, arxiv 1704.078001v1



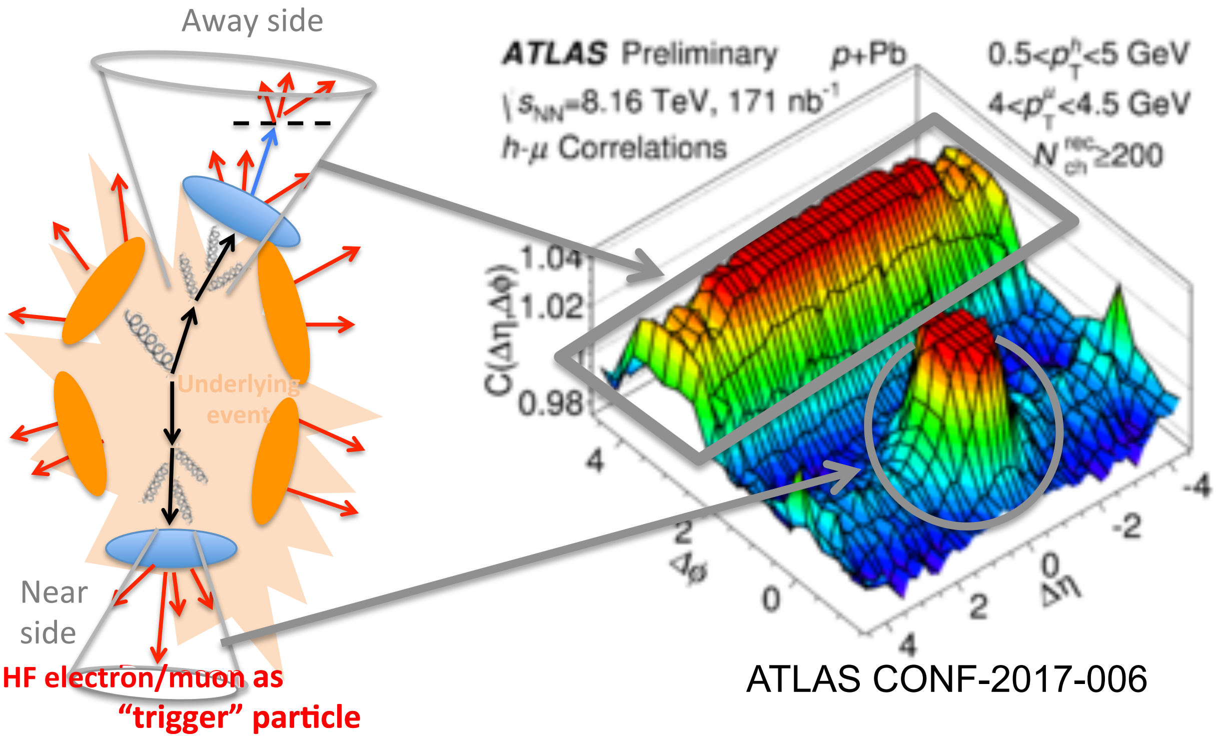
Several ongoing efforts of theorists and experimentalists to infer medium parameters!

Additional content (if time allows)

Collective-like effects in proton - nucleus collisions

More by L. Bianchi

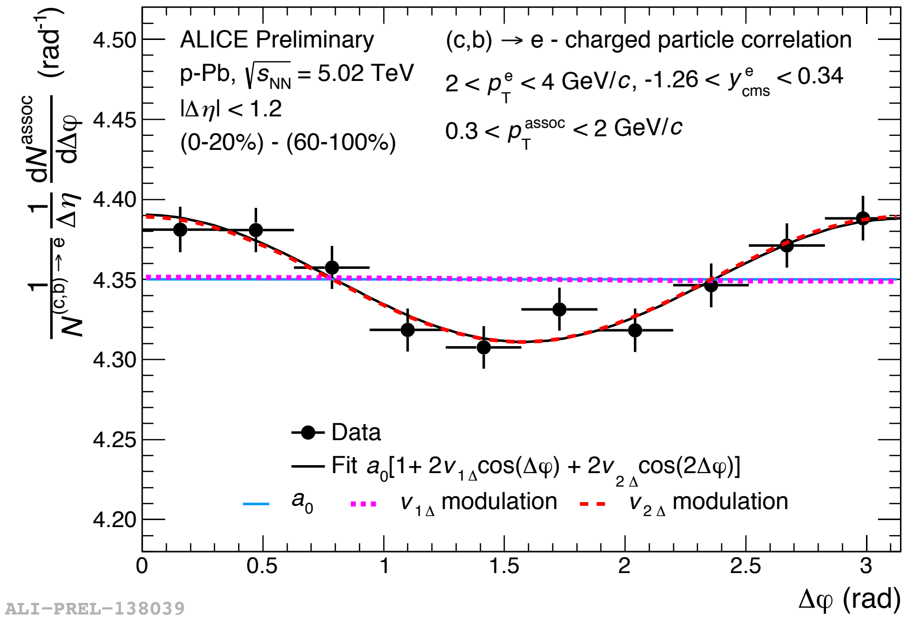
Charm flows in p-Pb at LHC?

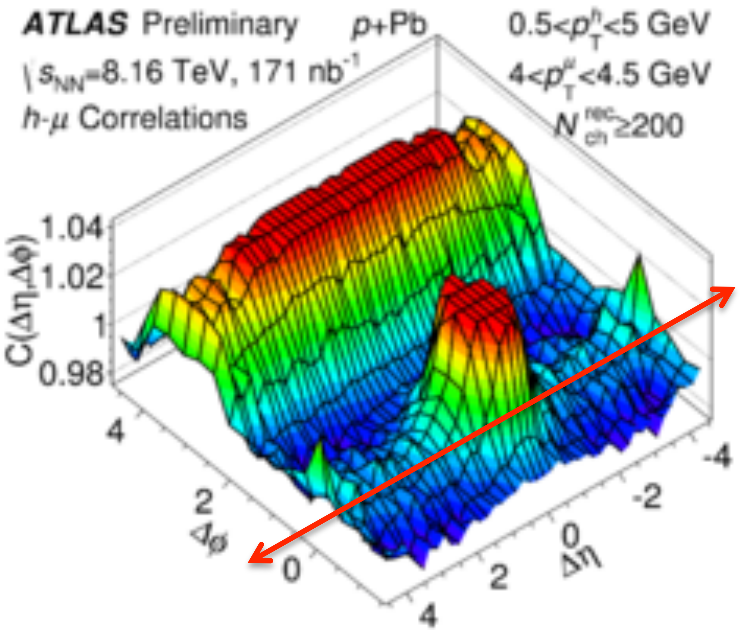


ATLAS CONF-2017-006

Azimuthal correlation of HF electrons (ALICE) and HF muons (ATLAS) with charged particles in p-Pb collisions: main structures from jets

Charm flows in p-Pb at LHC

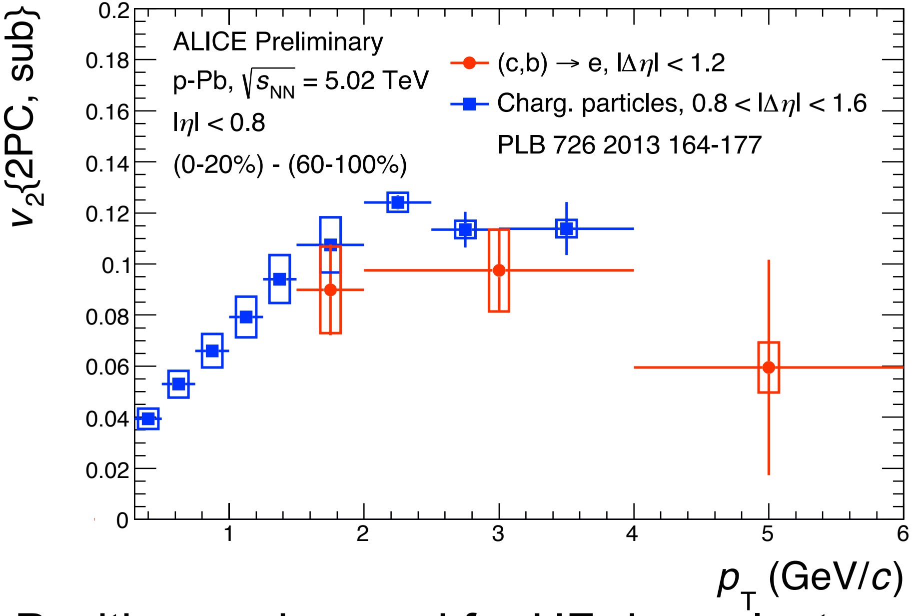


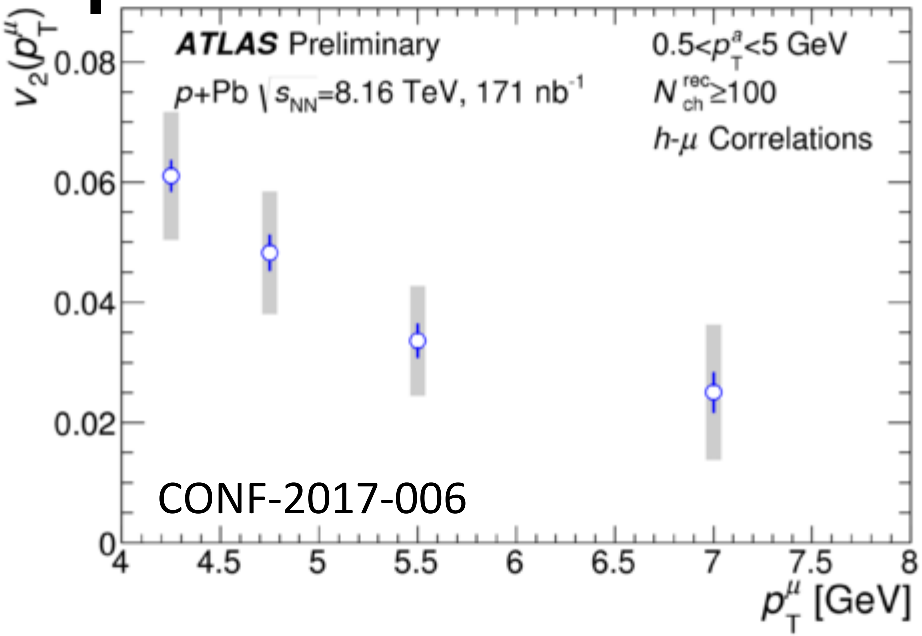


ATLAS CONF-2017-006

- After removing jet contribution: ***v_2*-like modulation** of azimuthal correlation of HF lepton with charged particles in **p-Pb collisions at high multiplicity**
- **“long-range”** (=extended in $\Delta\eta$) in near- and away-side, a typical signature of collective behaviour (N.B. origin of effect is debated!)

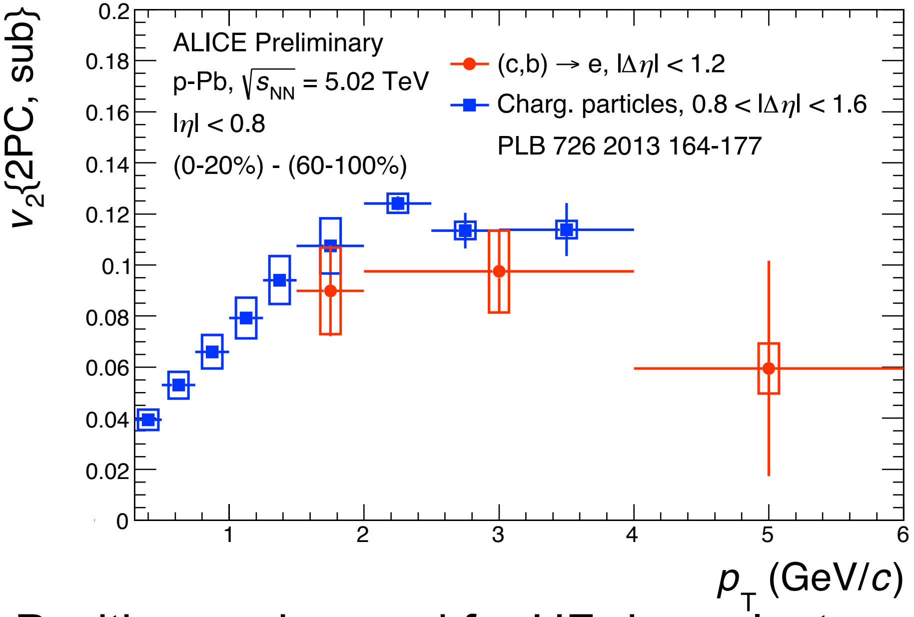
Charm flows in p-Pb at LHC

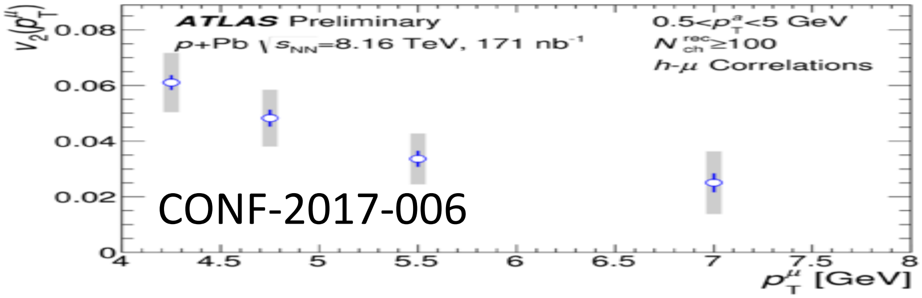




Positive v_2 observed for HF-decay leptons in $1.5<p_T<7$ GeV/c

Charm flows in p-Pb at LHC





Positive v_2 observed for HF-decay leptons in $1.5<p_T<7$ GeV/c

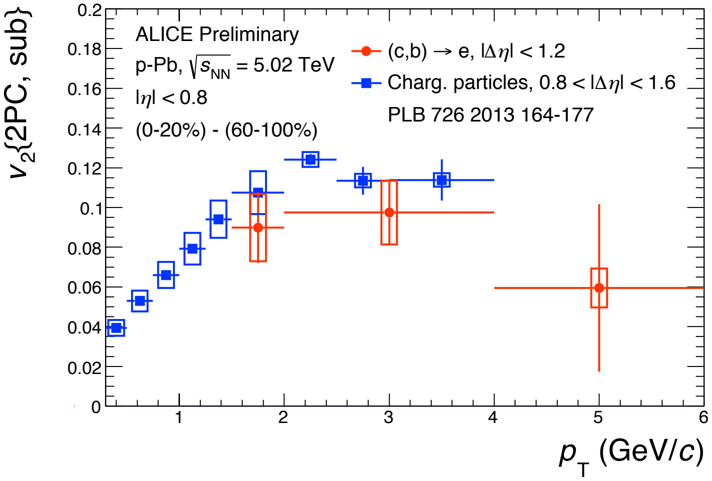
Consistent results between the 2 analyses

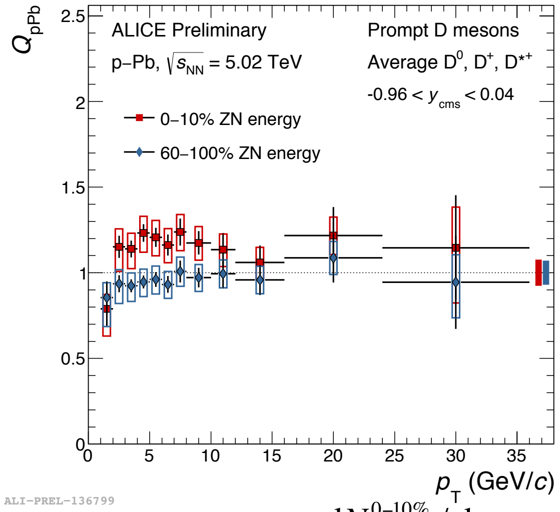
Maximum values close to what measured for charged particles

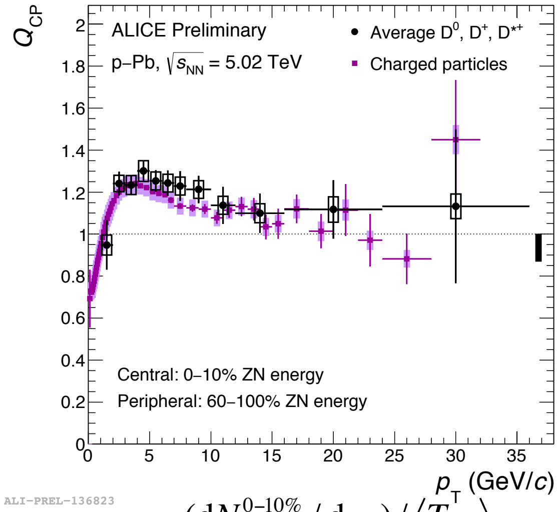
New exciting results for D mesons are already on arxiv… for sure among this QM highlights!! Do not miss them!

One of the main open questions

How can it be that we see flow for open HF but R_{pPb}~1 (at mid-rapidity where nPDF effects are small)?







$$Q_{pPb}^{0-10\%}(p_T) = \frac{dN_{pPb}^{0-10\%}/dp_T}{\langle T_{AA}\rangle_{0-10\%} \times d\sigma_{pp}/dp_T}$$

$$Q_{CP} = \frac{(dN_{pPb}^{0-10\%}/dp_T)/\langle T_{AA}\rangle_{0-10\%}}{(dN_{pPb}^{60-100\%}/dp_T)/\langle T_{AA}\rangle_{60-100\%}}$$

Hint of a modification of the D-meson spectra in central p-Pb collisions
→is there a connection with HF v_2? Radial flow push? … but could just be IS

Summary

Heavy quarks → unique opportunity to investigate microscopic interactions in the medium and extract QGP transport coefficients.

Many effects at play: energy loss dependent on mass and colour-charge from radiative and elastic processes, coalescence, flow, initial-state effects.

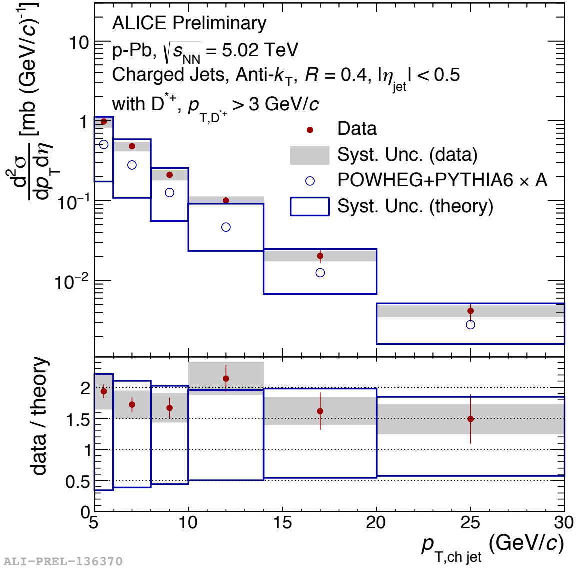
Rich phenomenology, sometimes concurrent effects → detailed physics program requiring precise measurements of different observables in pp, p(d)-A, A-A collisions.

… ongoing… but will take time (and detectors will be upgraded/built on purpose!)

Look at the abstracts of the HF session: possibly many exciting new results to come in the next days (new insights on charm baryons, charm flow, charm jets, Xe-Xe, …)

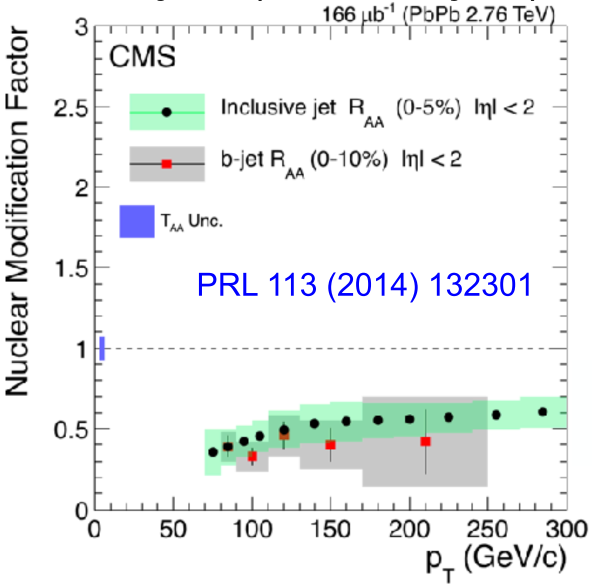
Could not cover…

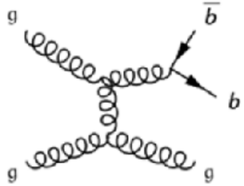
Charm and D-tagged jets

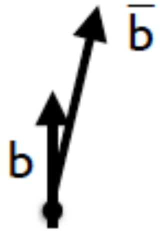


Unique opportunity, along with correlations, to study jets with an identified (the main?) parton

b-jets (and di-b-jets)







NLO process: Gluon splitting
→ dominant at low opening angles

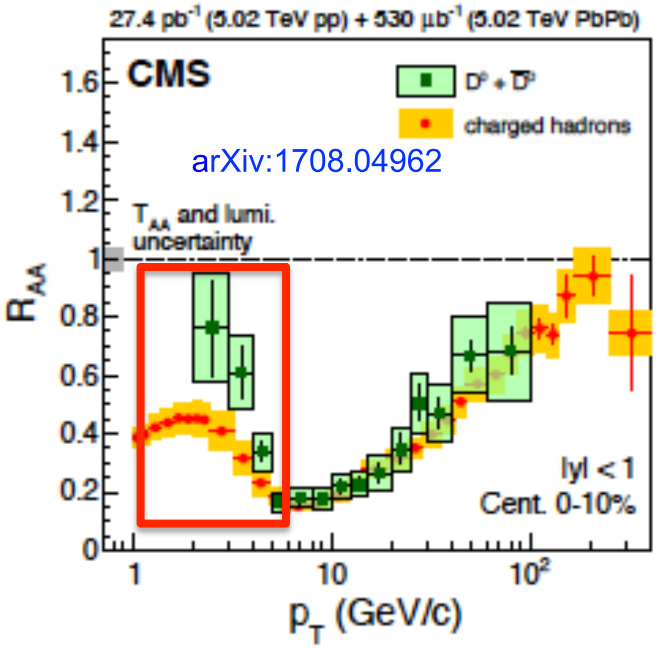
Mass difference negligible at high p_T
Large contribution of gluon-splitting processes.
In GSP we may not be measuring b-quark E_{loss}
a "fat" gluon E_{loss}

Thanks…

and enjoy the conference

Extra

D-meson vs. pion R_{AA}, low p_T

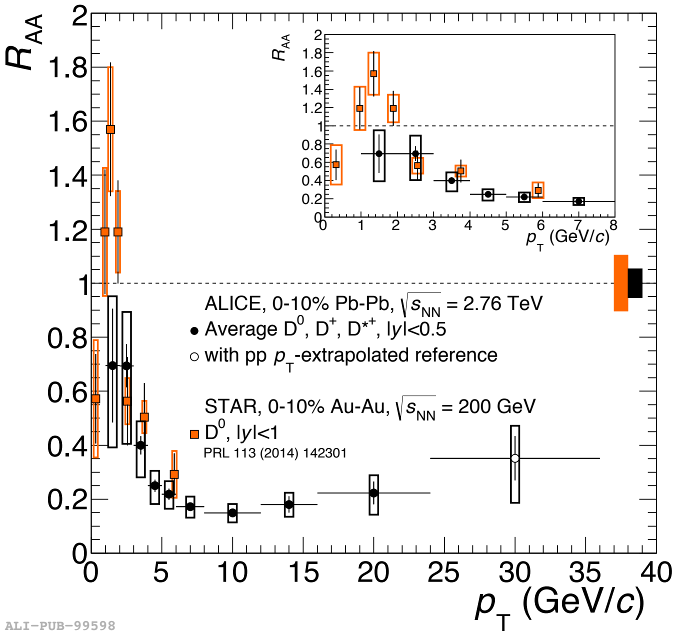


Indication of R_{AA}(D)>R_{AA}(π) but interpretation not straightforward:

- soft-particle production not expected to scale with N_{coll} down to p_T=0 (while binary scaling + energy loss could even lead to R_{AA}>1 at low p_T, if no shadowing)
- different impact of shadowing (nPDF)
- different intial spectra and fragmentation
- different impact of collisional energy loss, radial flow, modification of particle-species abundances

Nevertheless, with improving data precision, reproducing in the mean time D-meson (all species) and pion R_{AA} is an important goals for models

D mesons: RHIC vs. LHC data

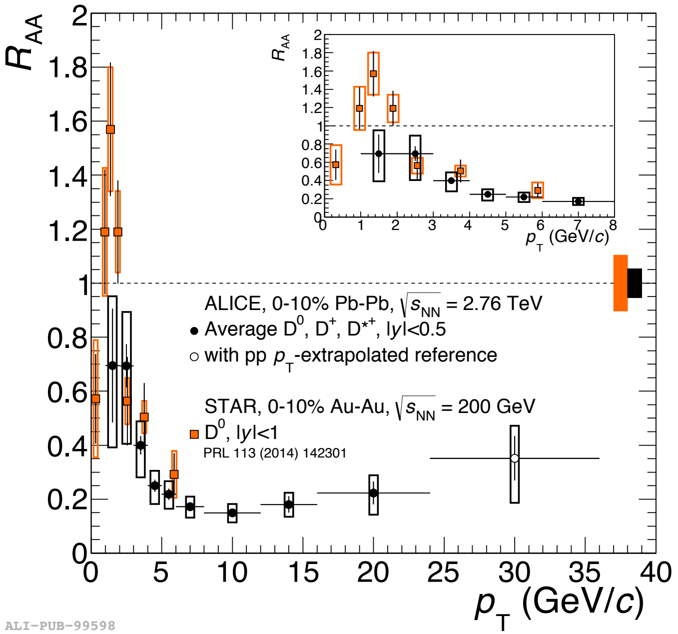


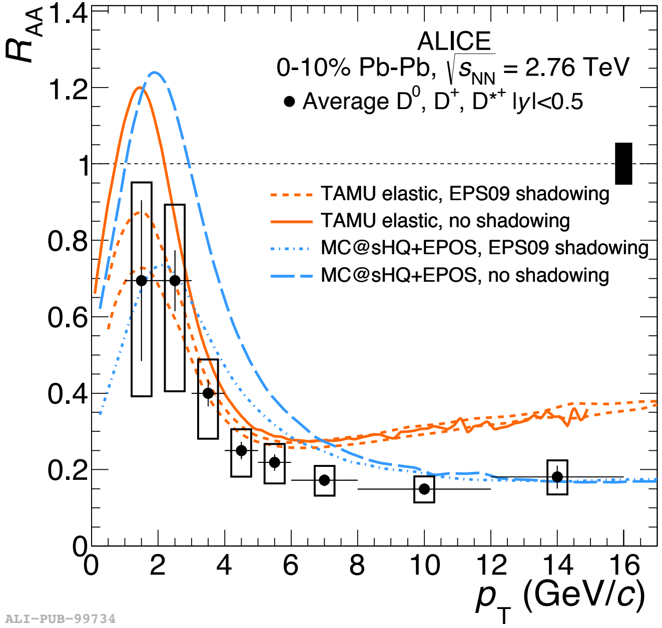
Different trend at RHIC and LHC for p_T<2 GeV/c?

Several ingredients at play: stronger shadowing, different impact of radial flow and coalescence on the R_{AA} considering the less steep pp spectrum at the LHC.

Some models (e.g. TAMU at low p_T, Phys. Lett. B 735 (2014) 445) can describe both measurements

D mesons: RHIC vs. LHC data





Shadowing needed by models to describe D mesons at low p_T at LHC

Different trend at RHIC and LHC for p_T<2 GeV/*c*?

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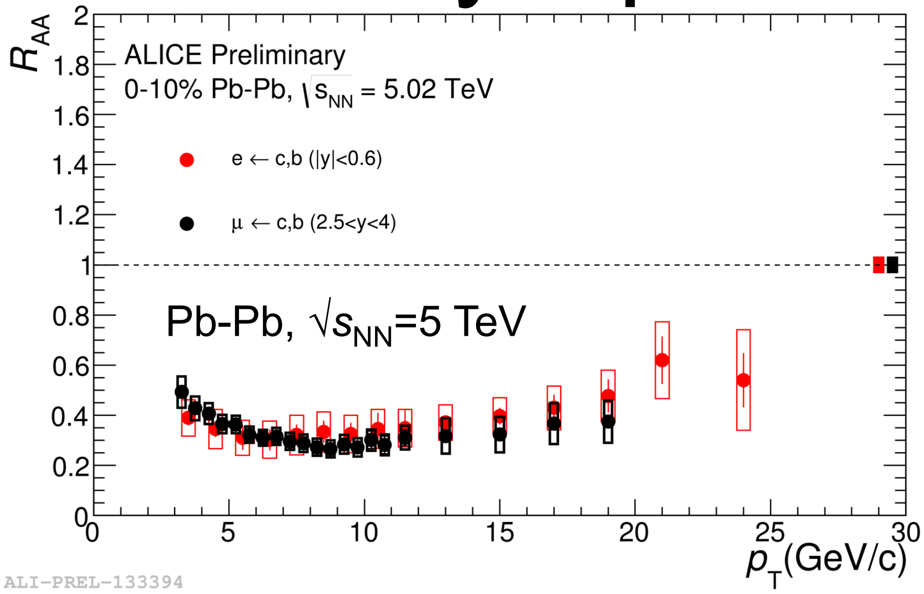
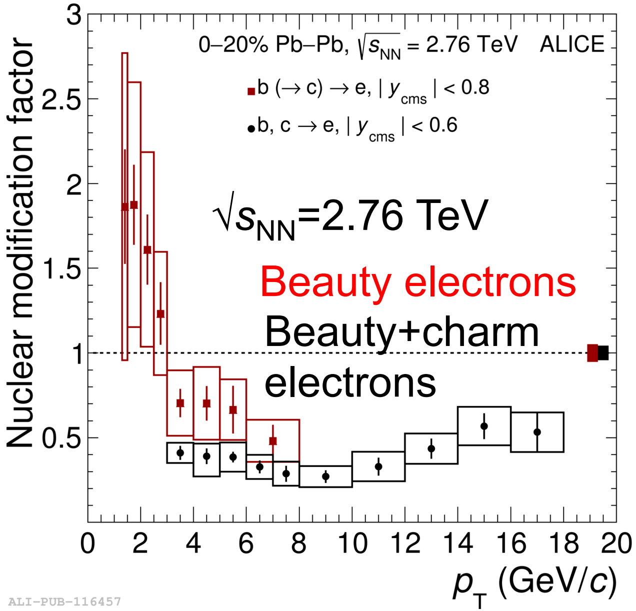
HF-decay leptons in Pb-Pb at the LHC

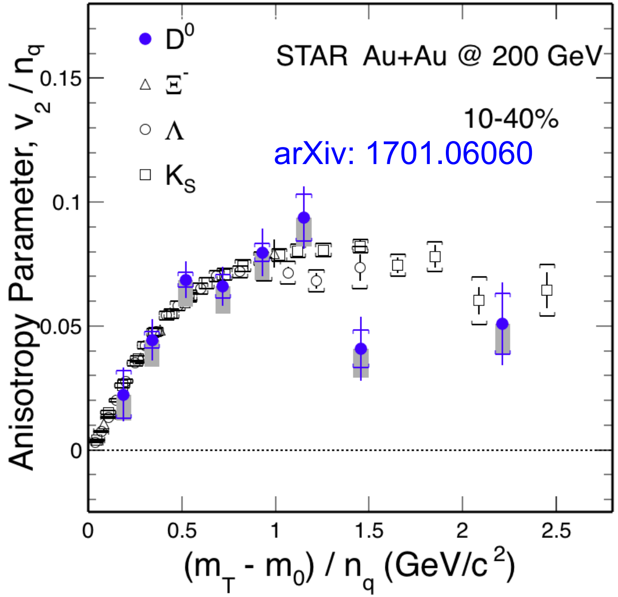


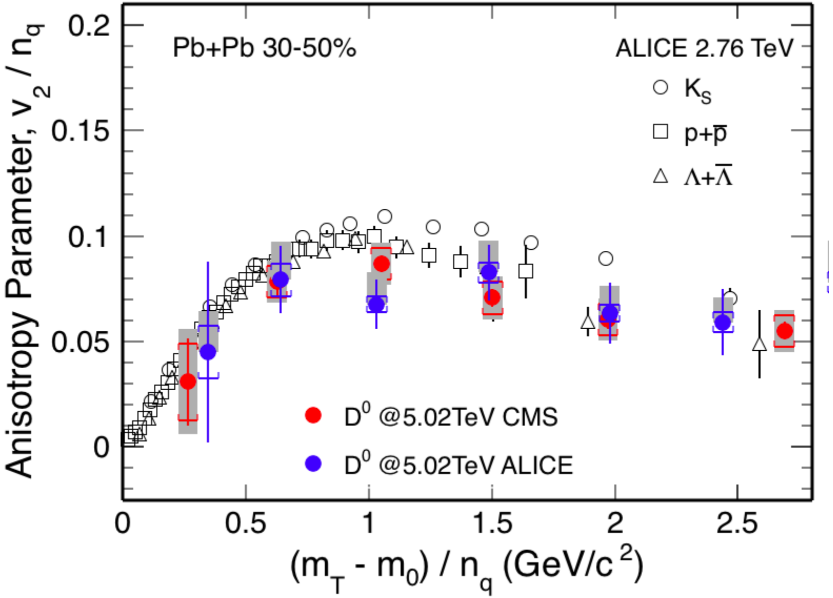


JHEP 07 (2017) 052
PLB 771 (2017) 467-481

- Strong suppression of heavy-flavour decay leptons in central Pb-Pb collisions.
- Similar results at central and forward rapidity.
- Beauty main component from p_T > 5 GeV/*c* (FONLL and pp measurements)
  →**indication of beauty suppression at high p_T**
- Beauty-electron R_{AA} measured directly with impact parameter fit (at 2.76 TeV): indication of suppression for p_T>3 GeV/*c*

D-meson elliptic: m_T,n_q scaling





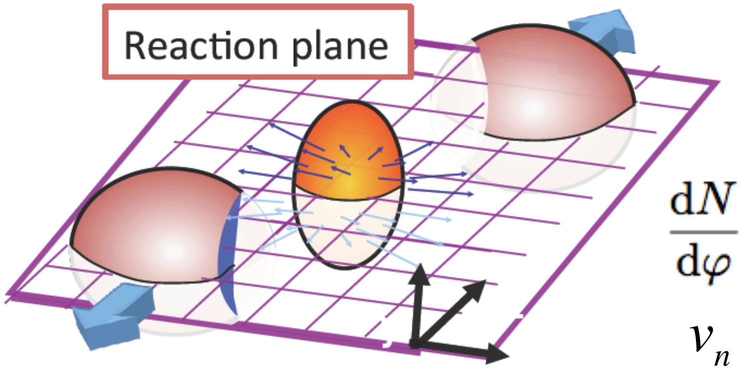
Similar v_2 of charm and light quarks?
Strong coupling to the system, charm thermalises at low p_T, coalescence?

Model overview

From F. Prino, R. Rapp,
J. Phys. G43 no. 9 093002 (2016)

Model	Heavy-quark production	nPDFs	Medium modelling	Quark-medium interactions	Hadronization	Hadron phase
			Transport models			
BAMPS [28, 38, 75]	MC@NLO	No	Boltzmann parton 3+1D	Boltzmann pQCD coll+rad	frag	no
Cao *et al.*/Duke [82, 83, 201]	MC@NLO	EPS09	Hydro 2+1D viscous	Langevin coll+pQCD rad	frag+ reco	yes
MC@sHQ+EPOS [46, 73, 74]	FONLL	EPS09	Hydro 3+1D (EPOS)	Boltzmann pQCD coll+rad	frag+ reco	no
PHSD [40, 51]	PYTHIA	EPS09	off-shell parton transport	off-shell trans pQCD coll	frag+ reco	yes
POWLANG [36, 48, 122]	POWHEG	EPS09	Hydro 2+1D viscous	Langevin pQCD coll	string- reco	no
TAMU [65, 76, 124]	FONLL	EPS09	Hydro 2+1D ideal	Langevin T-mat coll	frag+ reco	yes
			Energy-loss models			
AdS/CFT (HG) [295, 296]	FONLL	No	Glauber no hydro	AdS/CFT drag	frag	no
CUJET 3.0 [222, 223]	FONLL	No	Hydro 2+1D viscous	rad+coll	frag	no
Djordjevic *et al.* [297, 298]	FONLL	No	Glauber no hydro	rad+coll+ magn. mass	frag	no
Vitev *et al.* [72, 299]	non-zero mass VFNS	No	Glauber+ 1D Bjorken exp	rad+ in-med dissoc	frag	no
WHDG [84, 220]	FONLL	No	Glauber no hydro	rad+coll	frag	no

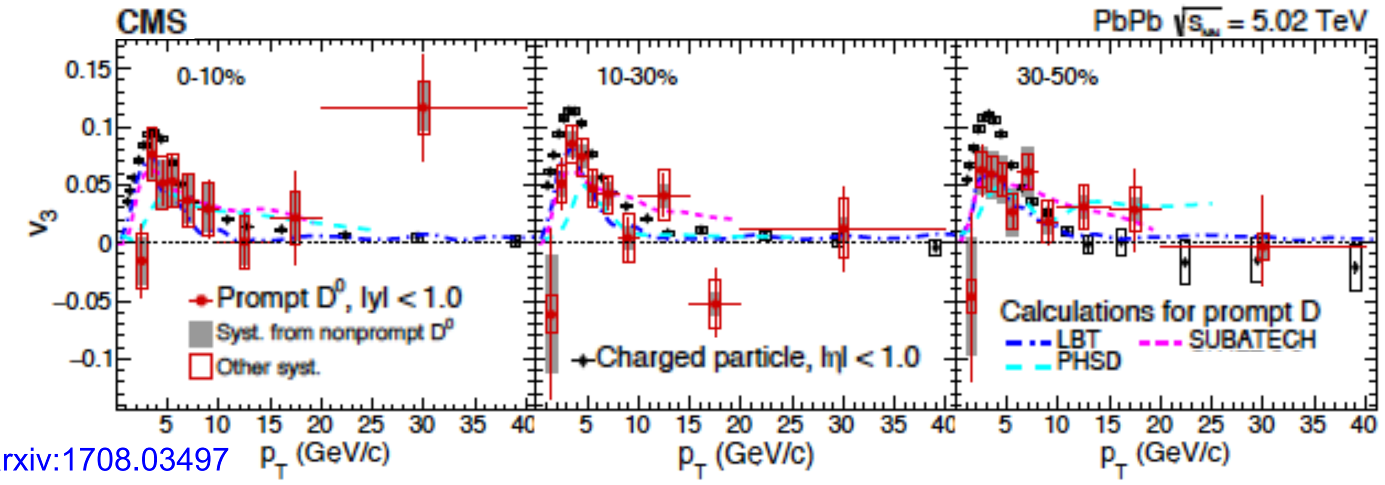
Azimuthal anisotropy: "triangular" flow



Initial spatial anisotropy → momentum anisotropy

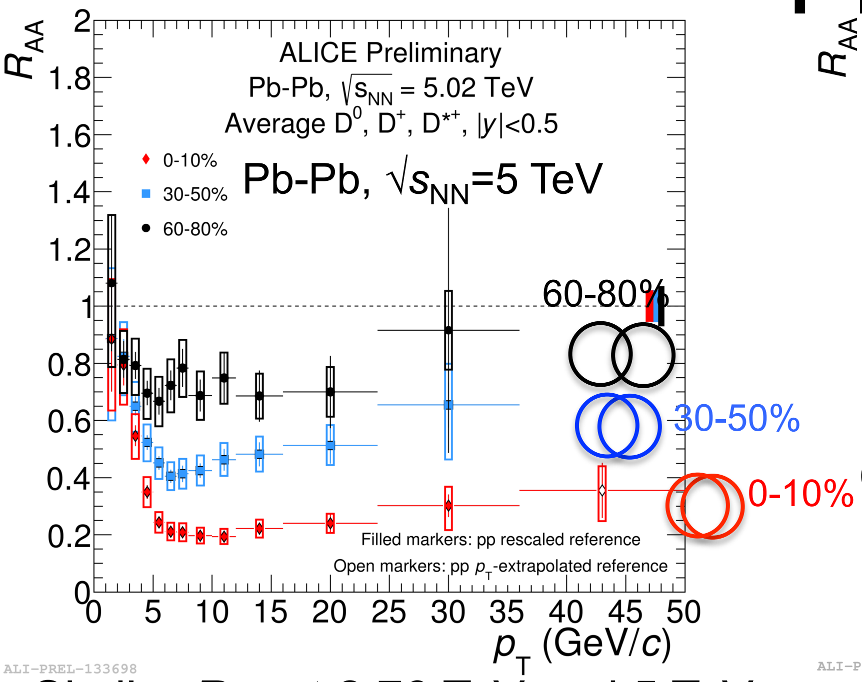
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$

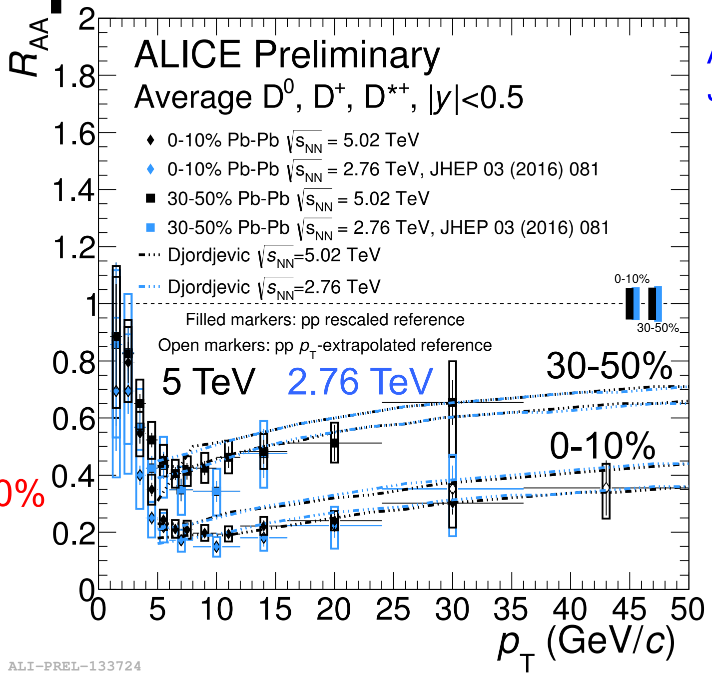
$$v_n = \langle \cos(n[\varphi - \psi_n]) \rangle$$



arxiv:1708.03497

D-meson suppression at LHC





ALICE-PUBLIC-2017-003
JHEP 03 (2016) 081

- Similar R_{AA} at 2.76 TeV and 5 TeV
  - Expected in models from balancing of denser medium and harder spectrum

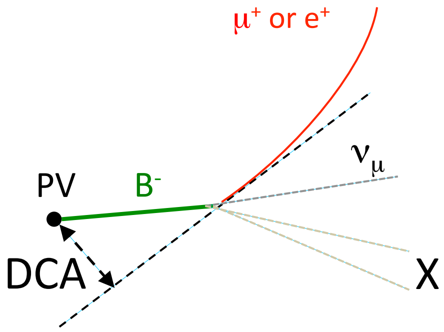
Djordjevic, Phys. Rev. C92 (2015) 024918

HF signals in experiments

Beauty Leptons:

b(->c)-hadrons → eX

b(->c)-hadrons → μX



Particle	Mass (GeV/c^2)	$c\tau$ (μm)	BR (approximate)
Average charm		/	~9.6%
D^+	1.86961	311.8	16%
D^0	1.86483	122.9	6.5%
D^{*+}	2.01026	strong decay	/
D_s^+	1.96828	149.9	6.5%
Λ_c^+	2.28646	59.9	4.5% (3.6% in $e^+\Lambda\nu$)
Ξ_c^+	2.46787	132	?
Ξ_c^0	2.47087	33.6	?
Ω_c^0	2.6952	21	?

Open Charm signals in experiments

Charm hadron to leptons

Particle	Mass (GeV/c^2)	$c\tau$ (μm)	BR (approximate)
Average charm		/	~9.6%
D^+	1.86961	311.8	16%
D^0	1.86483	122.9	6.5%
D^{*+}	2.01026	strong decay	/
D_s^+	1.96828	149.9	6.5%
Λ_c^+	2.28646	59.9	4.5% (3.6% in $e^+\Lambda\nu$)
Ξ_c^+	2.46787	132	?
Ξ_c^0	2.47087	33.6	?
Ω_c^0	2.6952	21	?

Typical hadronic decay channels studied

Particle	Mass (GeV/c^2)	$c\tau$ (μm)	Typical decay channel	BR (approximate)
D^+	1.86961	311.8	$K^-\pi^+\pi^+$	8.98%
D^0	1.86483	122.9	$K^-\pi^+$	3.89%
D^{*+}	2.01026	strong decay	$D^0\pi^+$	67.7%
D_s^+	1.96828	149.9	$\phi\pi^+(K^-K^+\pi^+)$	4.5%(2.27%)
Λ_c^+	2.28646	59.9	$pK^-\pi^+$ pK^0_s	6.35% 1.58%

Open beauty signals in experiments

Beauty hadron to leptons

Particle	**Mass (GeV/c^2)**	**$c\tau$ (μm)**	**BR (approximate)**
Average b		/	10.7%
B^+	5.27932	491.1	11%
B^0	5.27963	455.7	10.3%
B^{*+}			
B_s^0	5.36689	451.2	9.6%
Λ_b^0	5.61958	440.7	~10.4%

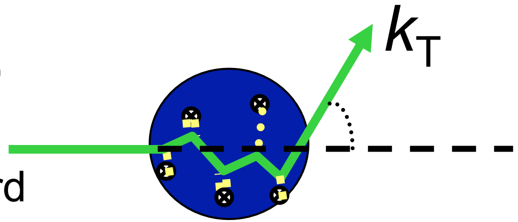
Typical hadronic decay channels studied

Particle	**Mass (GeV/c^2)**	**$c\tau$ (μm)**	**Typical decay channel**	**BR (approximate)**
B^+	5.27932	491.1	$J/\psi K^+$	0.103%
B^0	5.27963	455.7	$J/\psi K^*(892)$	0.128%
B_s^0	5.36689	451.2	$J/\psi\phi$ ($J/\psi K^-K^+$)	0.108% (0.054%)

CNM in p-A… and beyond

Effects, not ascribed to QGP, that can modify open-HF production in nuclear collisions:

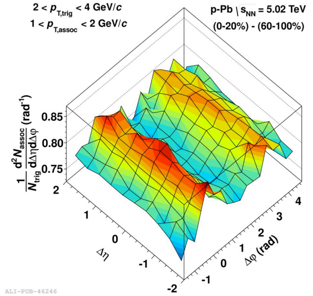
- **Nuclear modification of the PDFs**
  - ➢ shadowing at low Bjorken-*x* dominant effect for open HF at LHC energies, anti-shadowing also relevant at RHIC
  - ➢ "**saturation**" at low *x* → non-linear PDF evolution → need different calculation schemes (e.g. Colour-Glass condensate, e.g. H.Fujii and K.Watanabe, Nucl.Phys.A915(2013) 1)



- **k_T-broadening**

  Due to multiple elastic collisions of the parton before the hard scattering → can cause R_{pA} >1 around 2-3 GeV/*c*

- **energy loss in the initial or final state in cold nuclear matter**



Other final-state effects? (e.g. from system collectivity/hydro)