Charm quark production from SPS to LHC (and back again)

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Iceland Liechtenstein Norway grants

CHARMHI – Charm in heavy-ion collisions

- Polish-Norwegian joint project for the next 3 years
- Primary objectives:
  - Measure charm hadron production in Pb-Pb collisions
    - The first in the SPS energy regime
    - Reference for charmonium suppression measurements
  - Upgrade read-out electronics of the Time Projection Chambers (TPC) of the NA61/SHINE experiment
    - Increase recorded dataset to ~5x10^8 central Pb-Pb collisions

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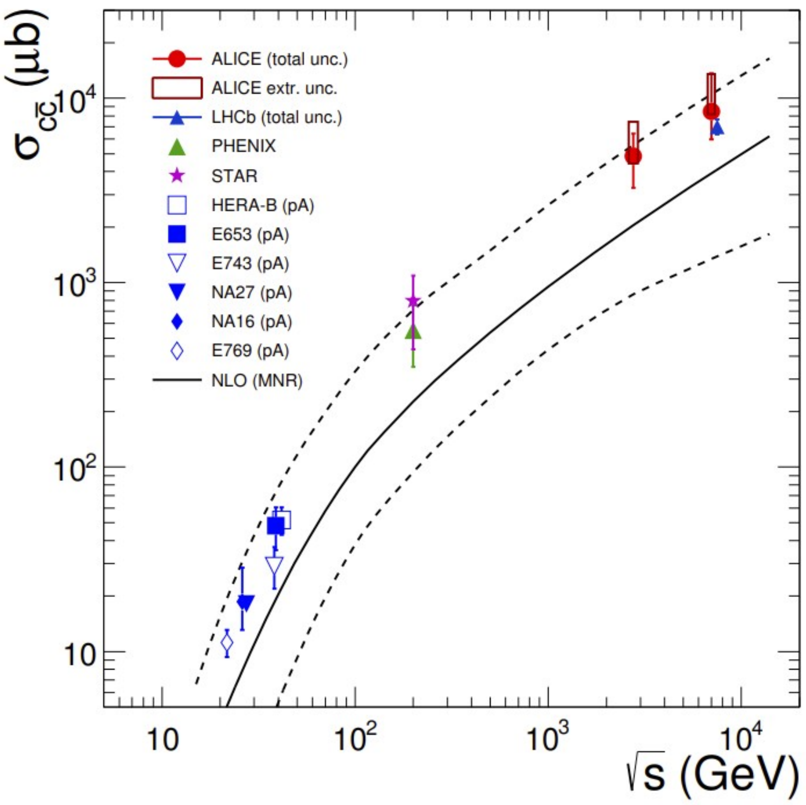
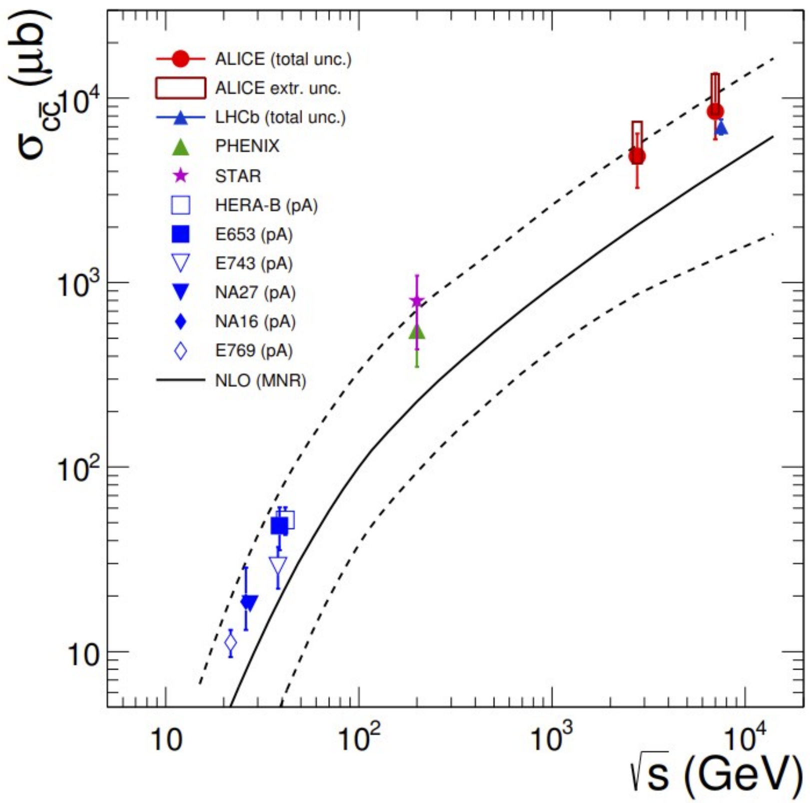
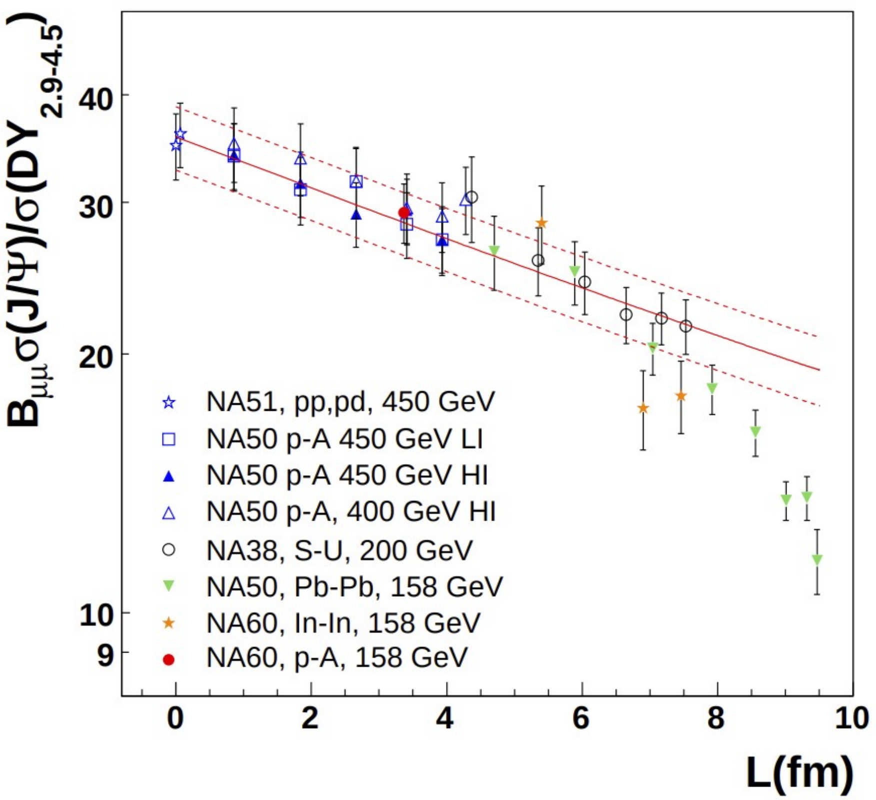
Charmed hadrons production in the SPS energy range



- Open charm production was always a sought after measurement, but always plagued by large uncertainties, both experimental and theoretical
  - No measurements in the SPS range in pp or A+A collisions

Charmed hadrons production in the SPS energy range

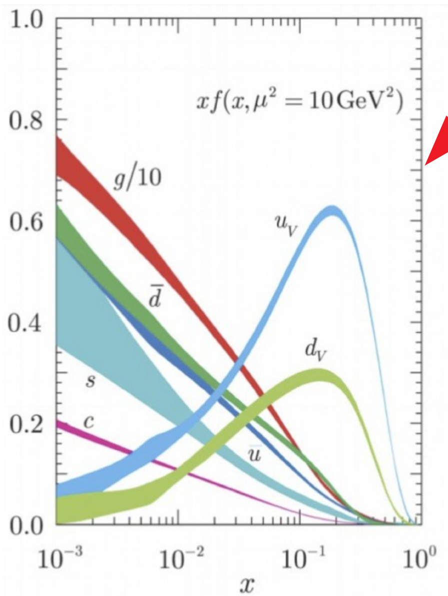


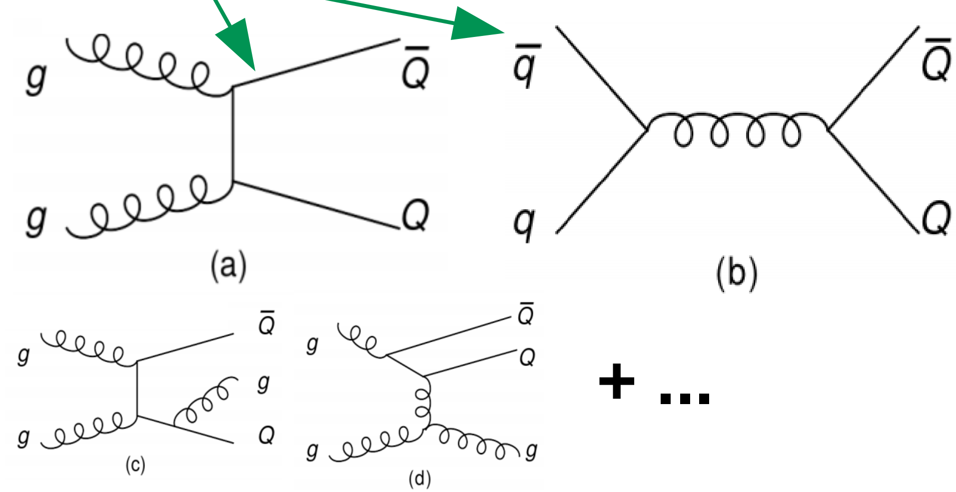


- Total $c\bar{c}$ production cross-section important not just by itself, but also as a reference in charmonium suppression studies
  - Anomalous J/ψ suppression in central Pb-Pb at top SPS energy was reported wrt Drell-Yan production

How is charm produced?

$$d\sigma^{Q+X} \simeq \sum_{i,j} f_i^A \otimes f_j^B \otimes d\tilde{\sigma}_{i,j \to Q+X}$$





- Test case for Quantum Chromodynamics (QCD)
  - $m_c >> \Lambda_{QCD}$ → perturbative calculation
  - Assume factorization of the partonic PDFs and short distance matrix elements
  - Two main theoretical approaches: FONLL, GM-VFNS
- Hadronization of charm quarks (non-perturbative) is done using fragmentation functions

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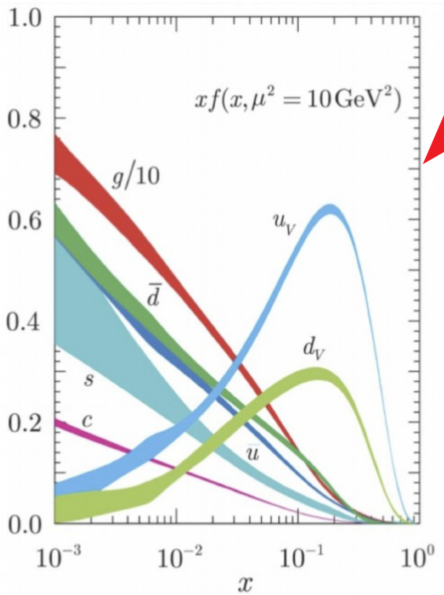
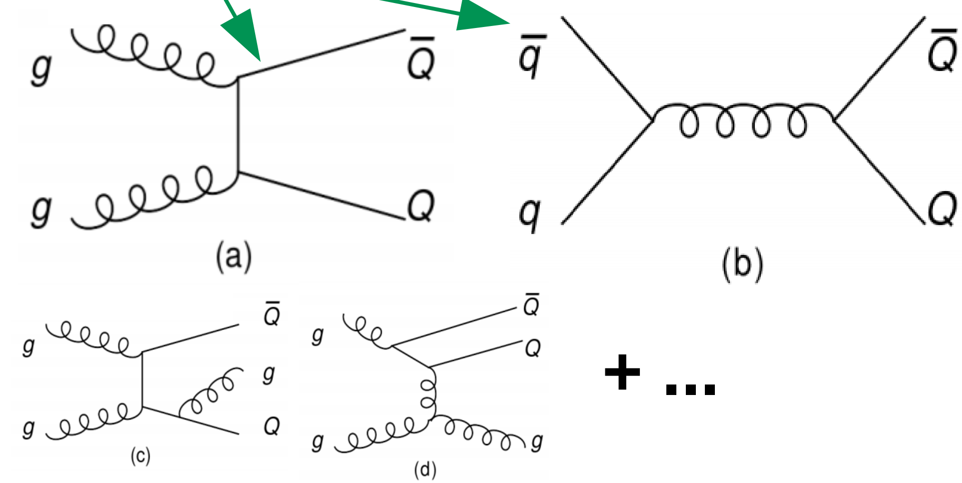
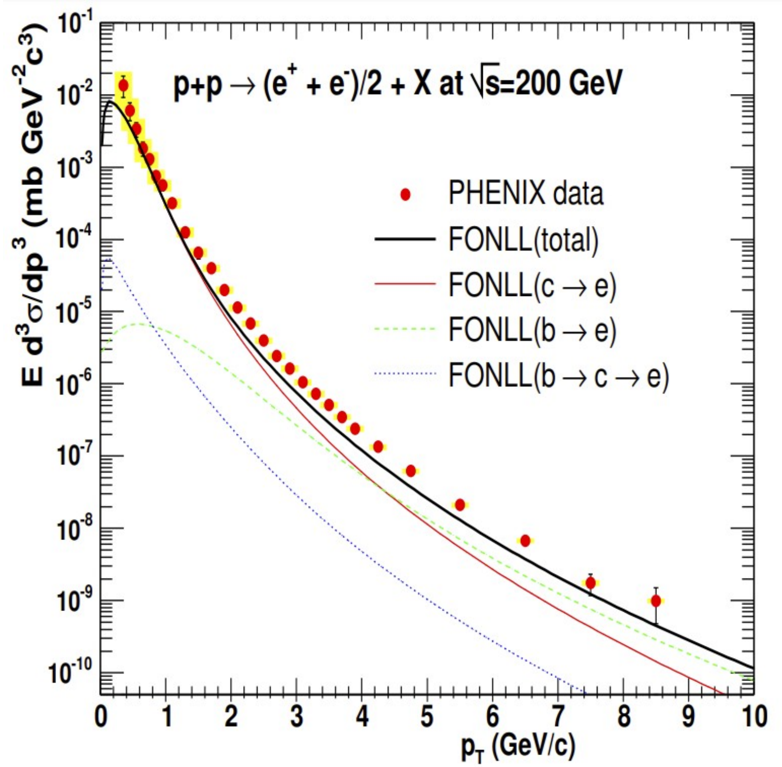


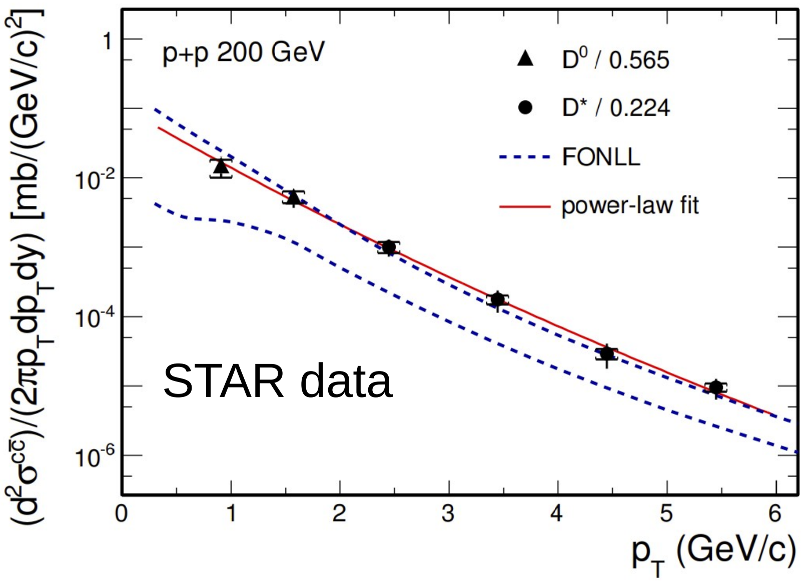


+ ...

- Experimentally open charm hadron production is measured via
  - Exclusive hadronic decay channels (e.g., $D^0 \rightarrow K^+ + \pi^-$)
  - Indirectly via detection of leptons from semi-leptonic decays
- Open charm hadrons are long lived → exploit in analysis by reconstructing displaced secondary vertices using high spatial resolution detectors (e.g. SAVD in NA61, ITS in ALICE, etc.)

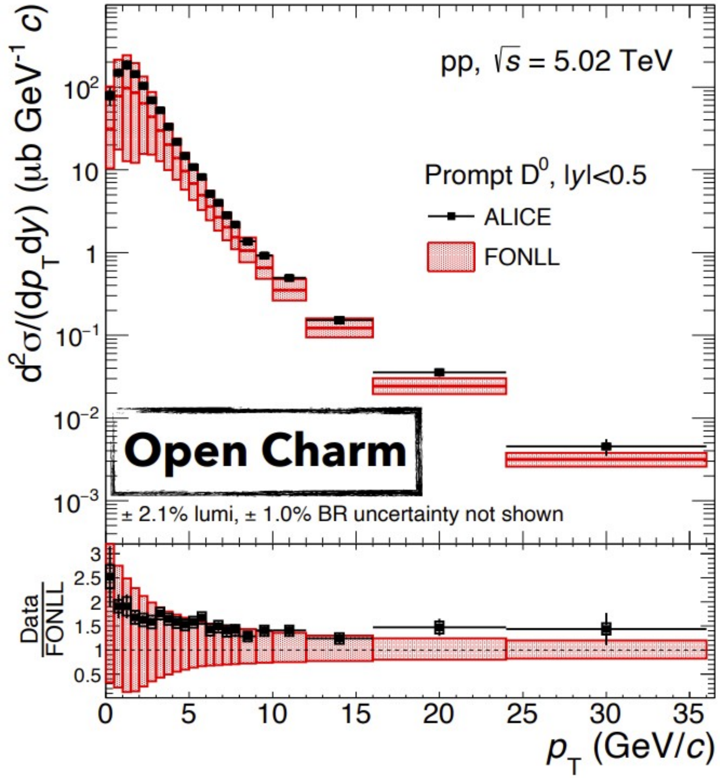
Charm production in pp collisions at RHIC

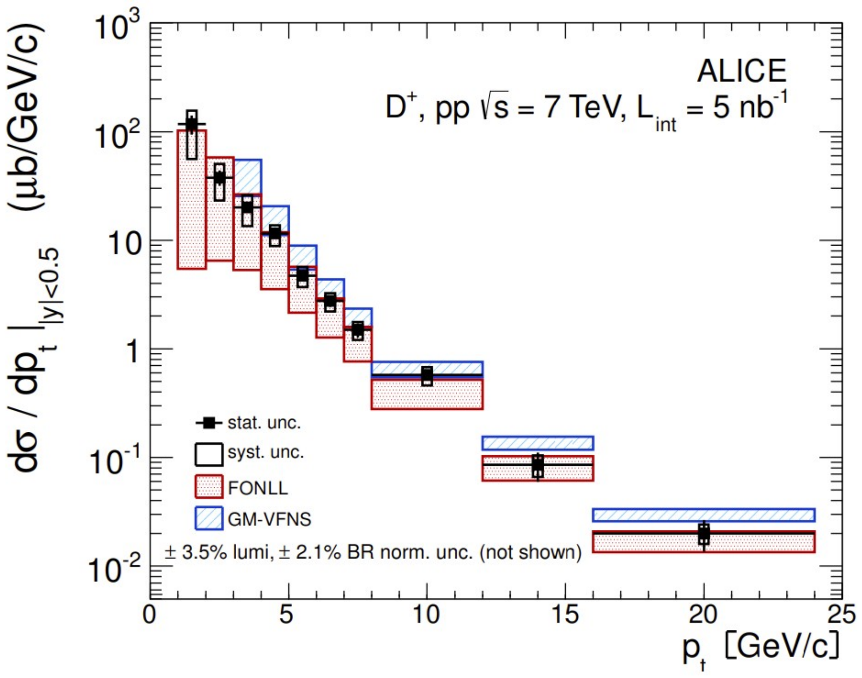




- Heavy quark production in pp collisions measured via D-mesons or heavy flavor electrons relatively well explained by pQCD calculations (FONLL)

D-mesons in pp collisions at LHC

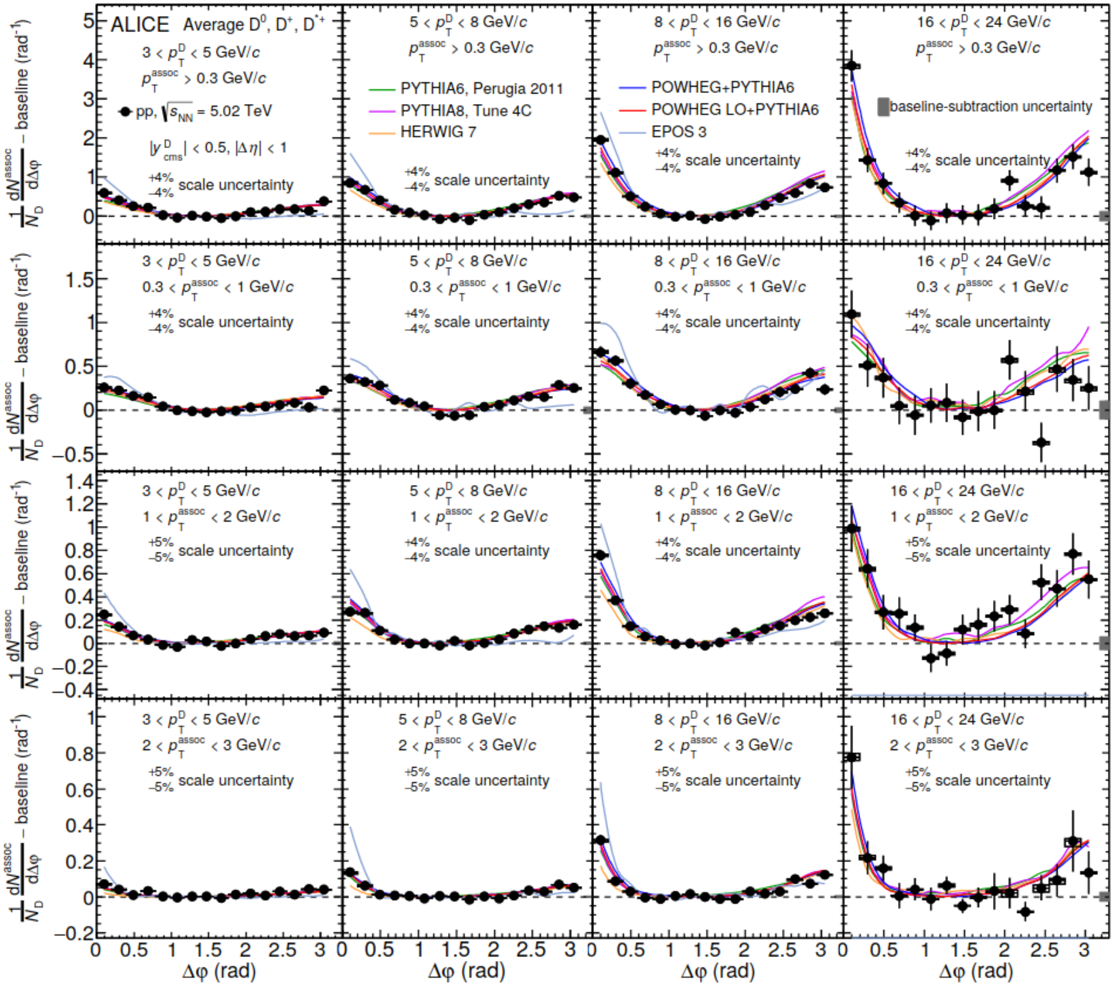




- D^0 and D^+ yields measured down to low p_T by ALICE (p_T= 0 for D^0)
- FONLL calculations tend to underestimate the data
- GM-VFNS overestimate + diverges towards p_T=0
- Theoretical uncertainties due to the factorization and renormalization scales

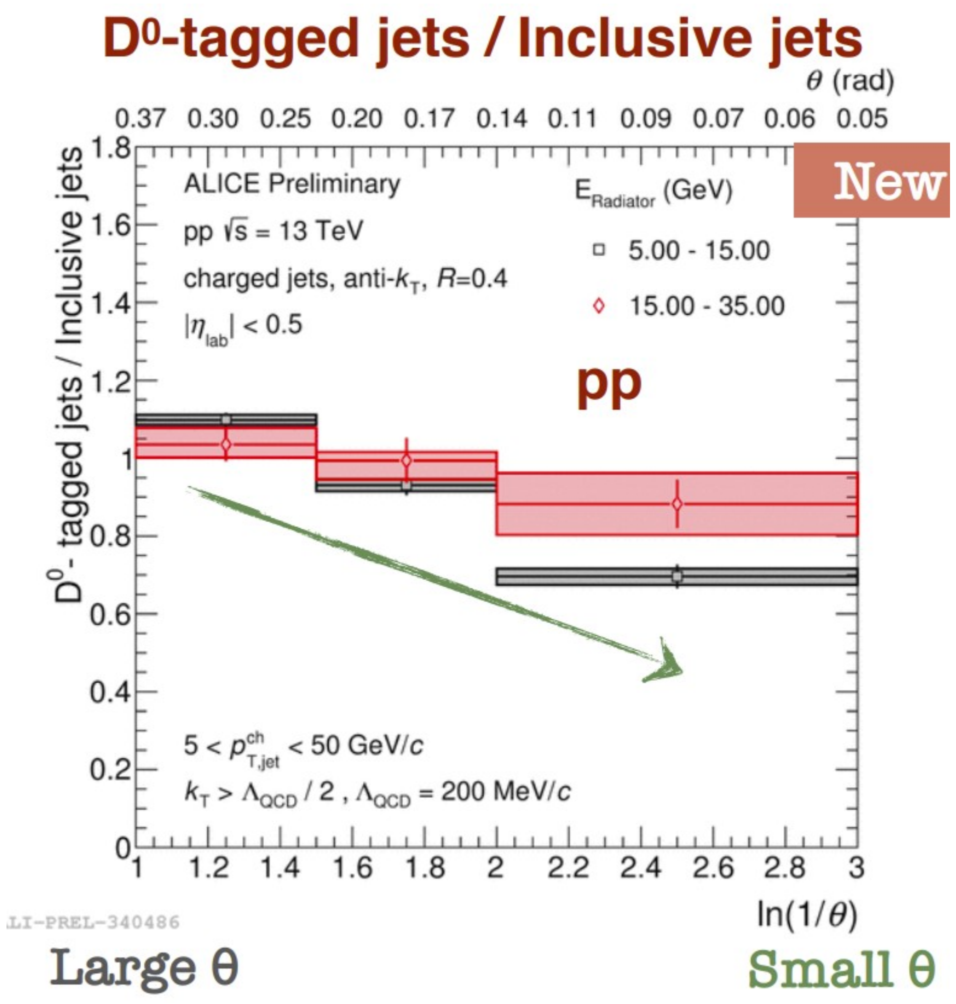
D-hadron correlations at LHC

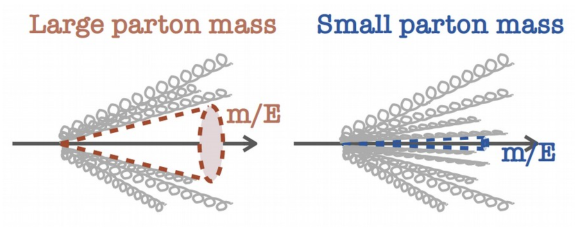
ALICE, arxiv1910.14403



- D-meson hadron correlations well described by Monte-Carlo generators in pp collisions

Dead-cone effect in pp collisions





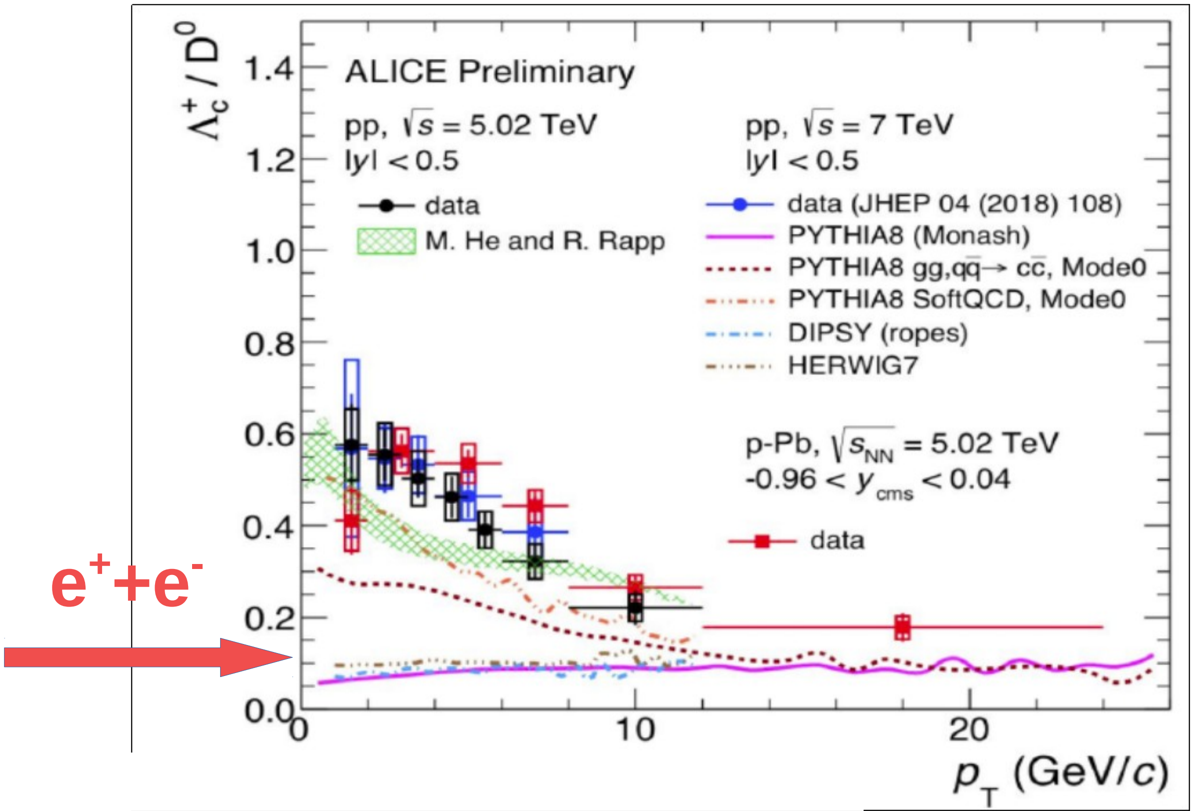
- The dead-cone effect:

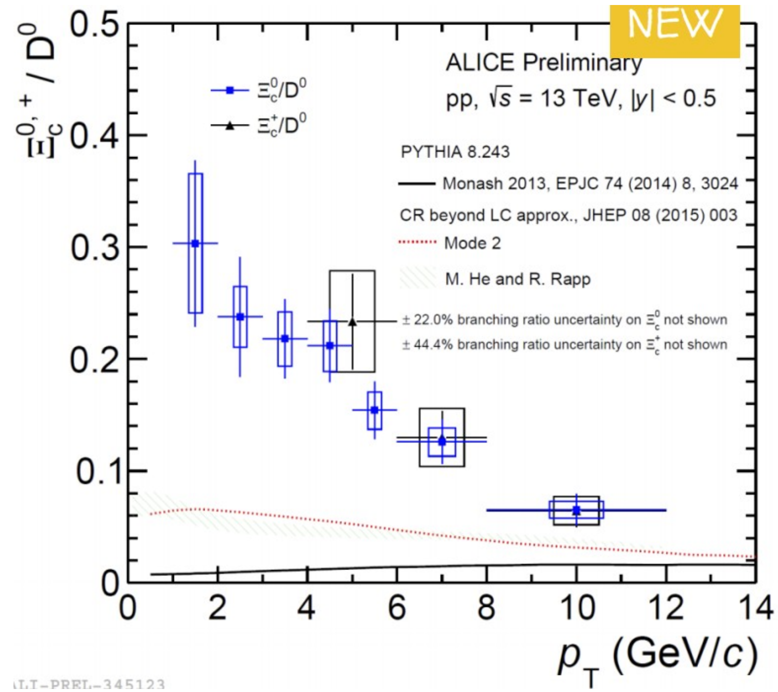
$$\omega \frac{dI}{d\omega} \propto \left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

Dokshitzer and Kharzeev 2001

- Radiation (both in vacuum and medium) is suppressed inside a cone *θ<m/E*
- D-tagged jets have less splittings at small angles wrt inclusive jets
- Effect increases for lower energy jets

What about charm baryons ?

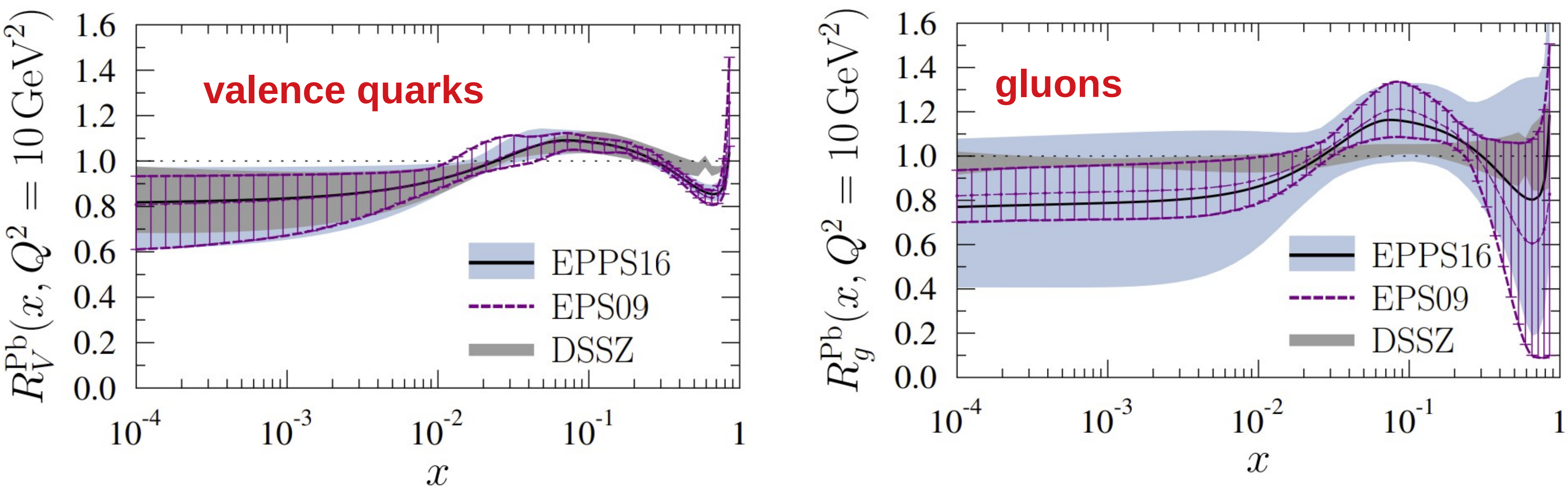




- Charm baryons thought to account for only a small fraction of the total $c\bar{c}$ cross-section (based on measurements from electron colliders)
- Sizable charm baryon/meson ratio (Λ_c and Ξ_c) observed by ALICE in pp and p-Pb collisions
- Non-negligible effects in the estimation of total $c\bar{c}$ cross-section

proton – nucleus collisions

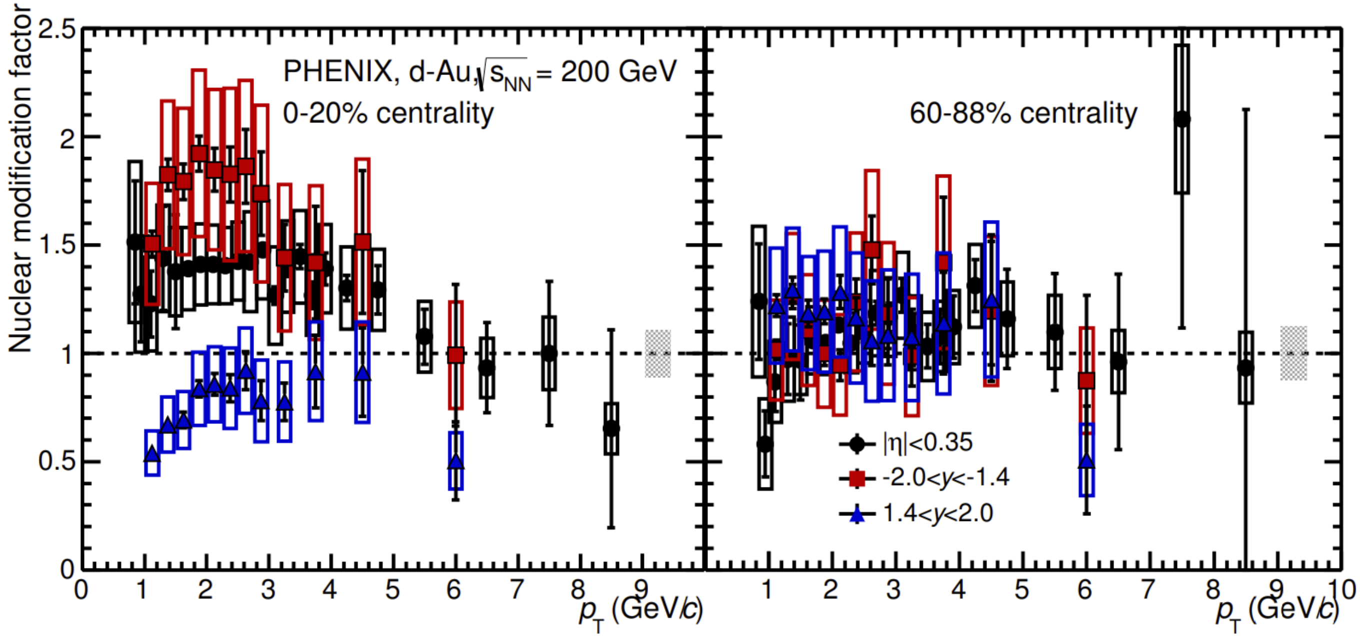
Eskola et al., EPJC77 (2017) 163



- p-A collisions : probe the so-called Cold Nuclear Matter (CNM) effects
- Modification of the parton PDFs in nuclear environment
  - Shadowing, anti-shadowing, EMC effect
  - Gluon saturation (Color Glass Condensate)
- Multiple scatterings of partons
  - Parton energy loss
  - k_T broadening (aka Cronin effect)
- Large theoretical uncertainties !

Heavy flavor electrons in d-Au at RHIC

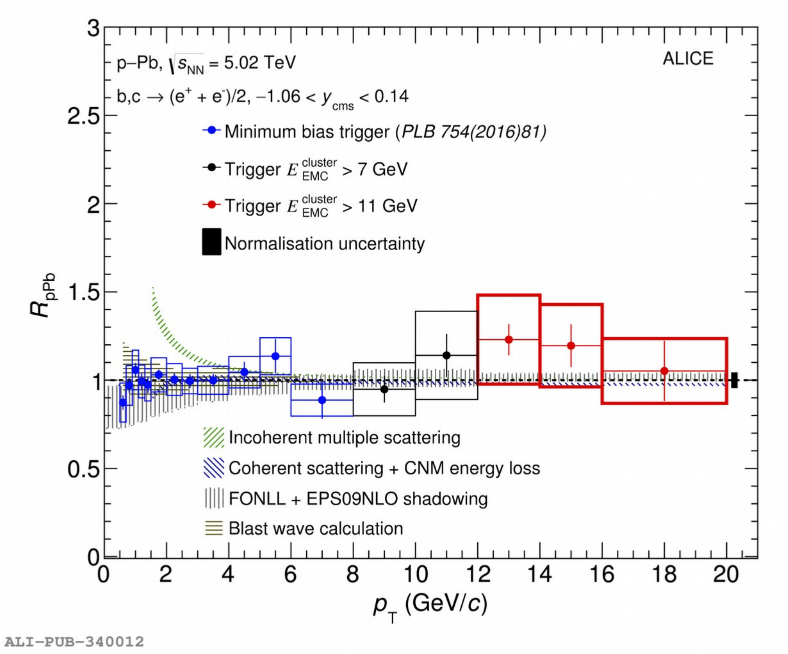
PHENIX



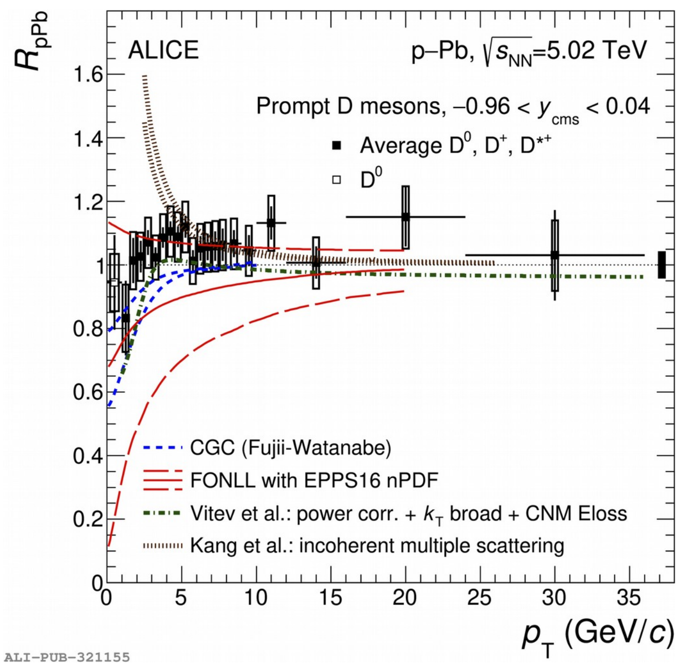
- RHIC (heavy flavor leptons):
  - "central" d-Au collisions: rapidity and p_T dependent suppression
  - "peripheral" d-Au: consistent with no effect

Heavy quark production in p-Pb at LHC

Heavy flavor leptons, ALICE



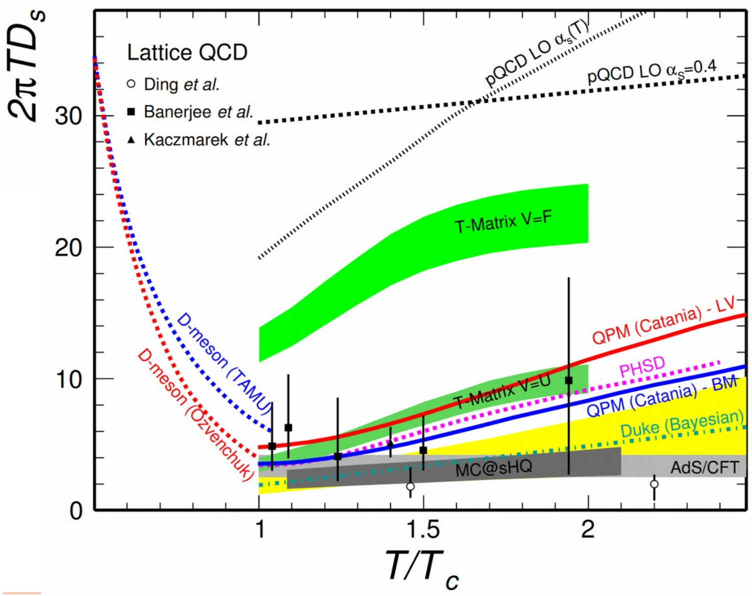
D-mesons, ALICE

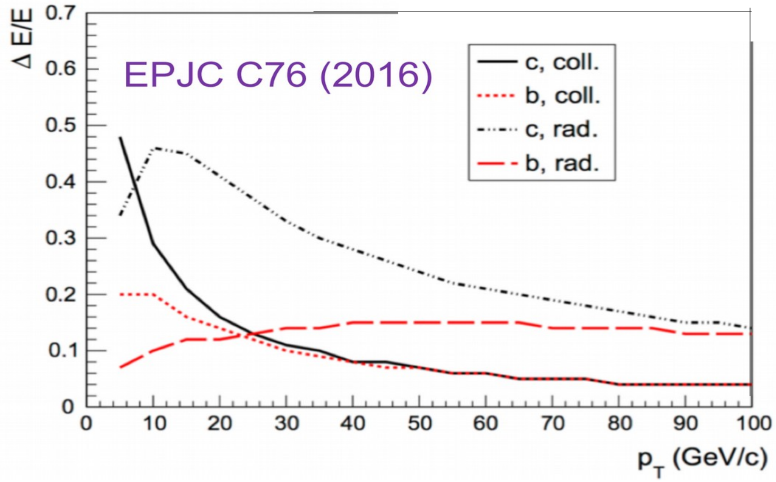


- Both heavy flavor electrons and D-mesons are compatible with none or moderate nuclear modifications at low p_T
- Large nuclear effects excluded by the data

Charm production in A+A collisions

- pQCD initial production (+ possible CNM effects)
- τ_0<0.1 fm/c << τ_{QGP} : probes all collision stages
- m_c >> $T_{RHIC,LHC}$: negligible thermal production
- Long thermalization time wrt light quarks/gluons
  - Carry more information on their evolution
- Strongly affected by the QGP phase
  - Collisional and radiative energy loss
  - Sensitive to the transport coefficient of QCD matter, $D_s(T)$
- Modification of the fragmentation to hadrons sensitive to the fireball chemical properties



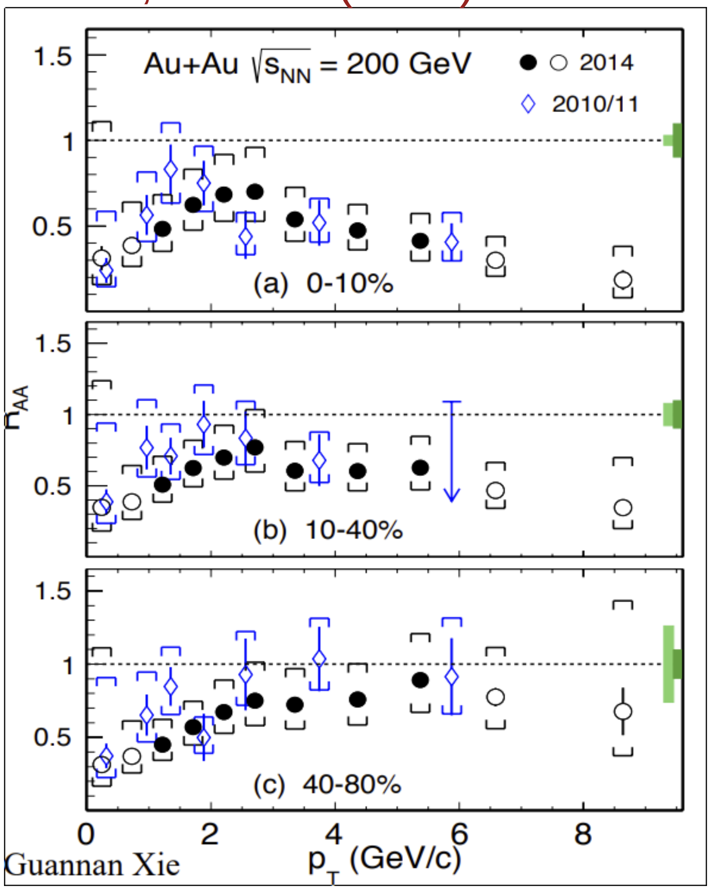


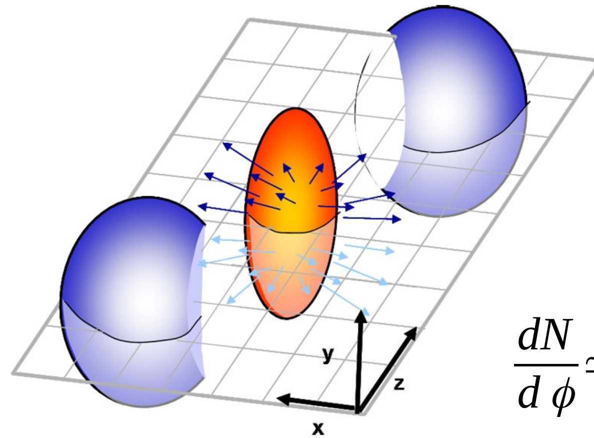
Charm production in A+A collisions

- Charm production and transport modeling in AA collisions is done in several approaches
  - pQCD or pQCD-inspired calculations of radiative and collisional energy loss: Gossiaux et al. (MC@sHQ), Beraudo et al. (POWLANG), Djordjevic et al., Vitev et al., Uphoff et al. (BAMPS)
  - In-medium formation and dissociation of heavy-flavor hadrons: Vitev et al.
  - Transport coefficients calculations using the T-matrix approach with non-perturbative potential extracted from lattice QCD (Rapp et al. - TAMU) or via ab initio lattice-QCD calculations (POWLANG)
  - Heavy quark energy loss modeling integrated into the PHSD transport theory
  - AdS/CFT approach for the calculation of transport coefficients: Horowitz et al.
- Besides the charm interaction with the hot medium, all the above models incorporate various assumptions on
  - the initial production of heavy flavor,
  - space-time description of the QGP evolution,
  - Hadronization and interactions with hadronic matter

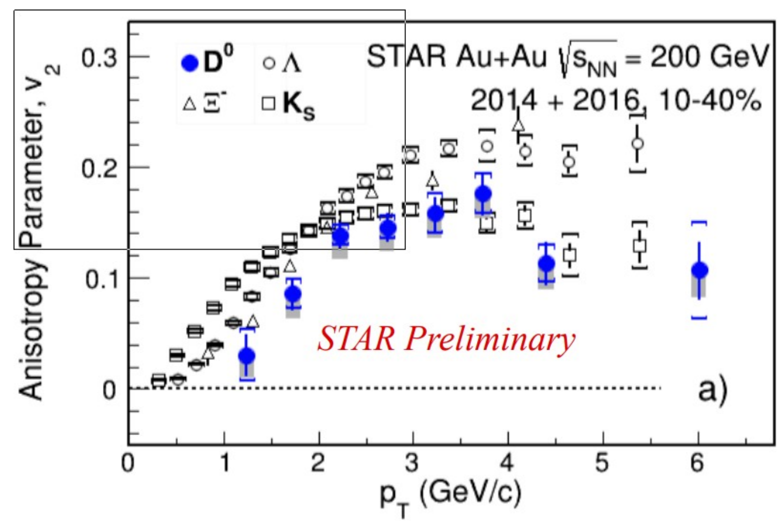
D-meson nuclear modification at RHIC

STAR, PLB655(2007)104





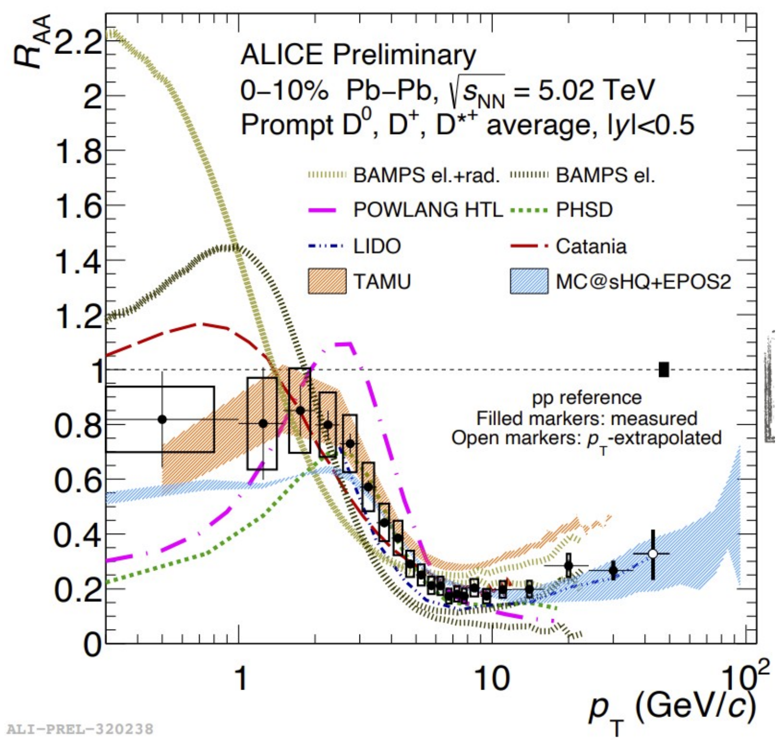
$$\frac{dN}{d\phi} \simeq 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]$$



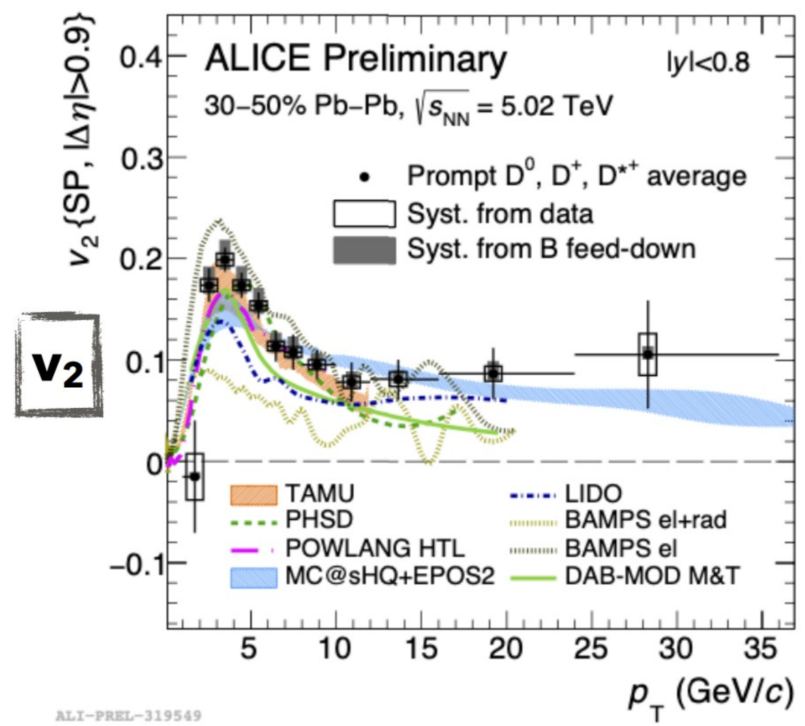
- Strong D-meson suppression, especially in central collisions
  - Consistent with lage in-medium energy loss
- Large D-meson elliptic flow
  - suggestive of charm thermalizing in the QGP

D-meson nuclear modification at LHC

Central Pb-Pb collisions

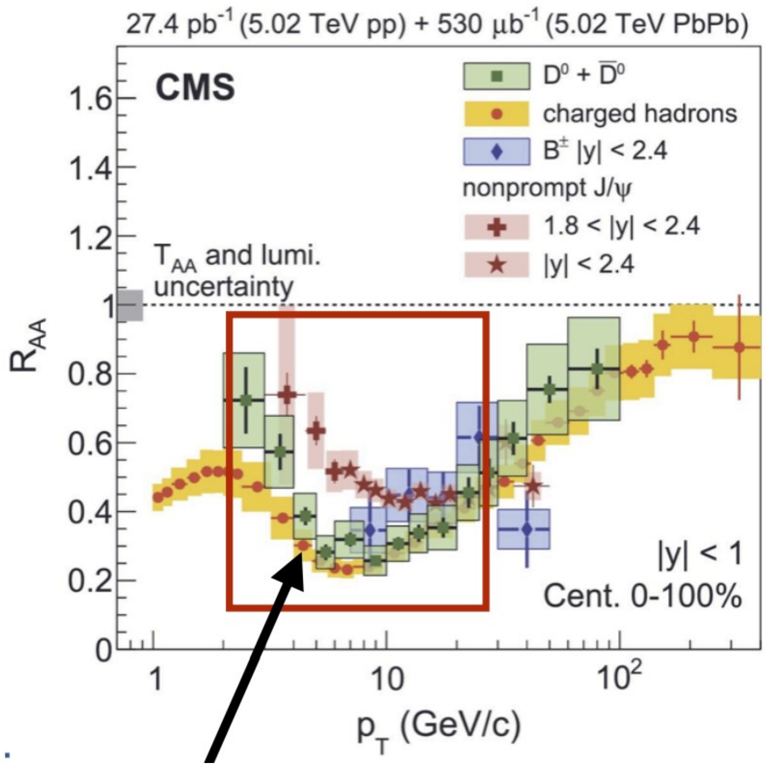


Semi-central Pb-Pb collisions

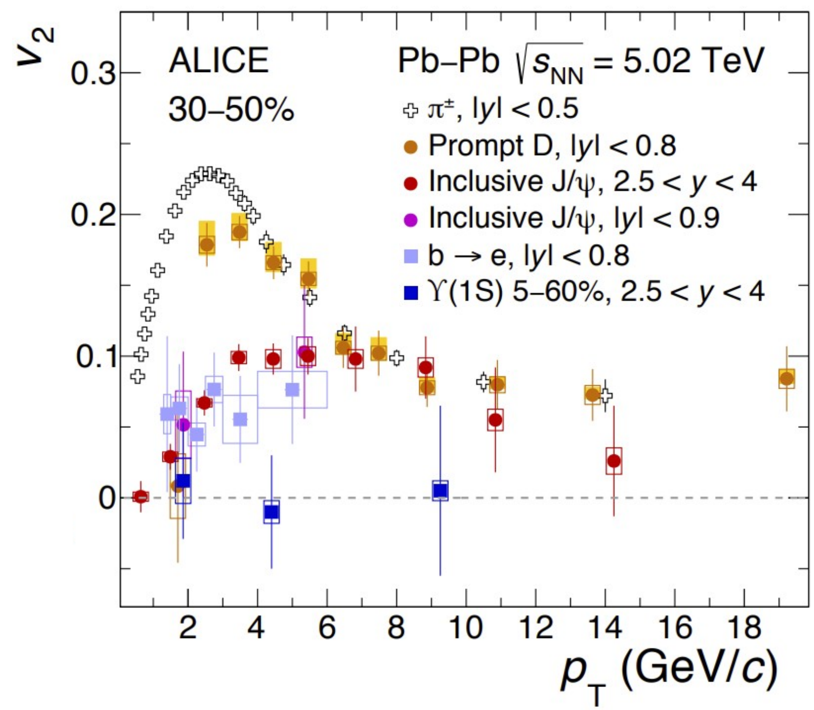


- High-pT: strong charm nuclear modification (factor of ~5 suppression)
- Low-pT: little or no suppression
  - Charm quark conservation ?
- Consistent description of both nuclear modification factor and elliptic flow is problematic for most models

Flavor dependence of hot medium effects (LHC)



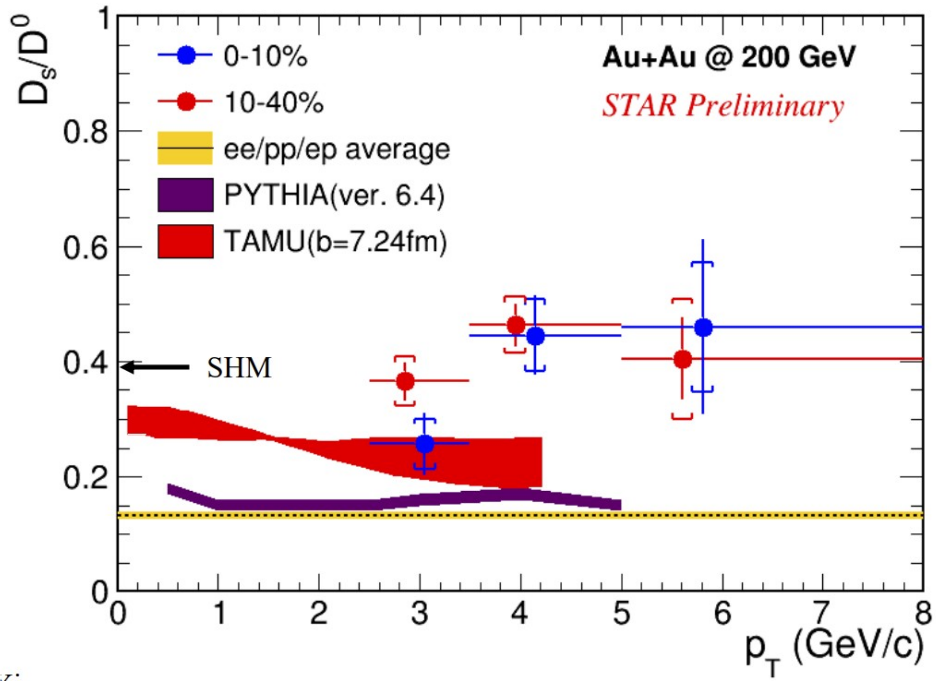
arXiv.2005.11130

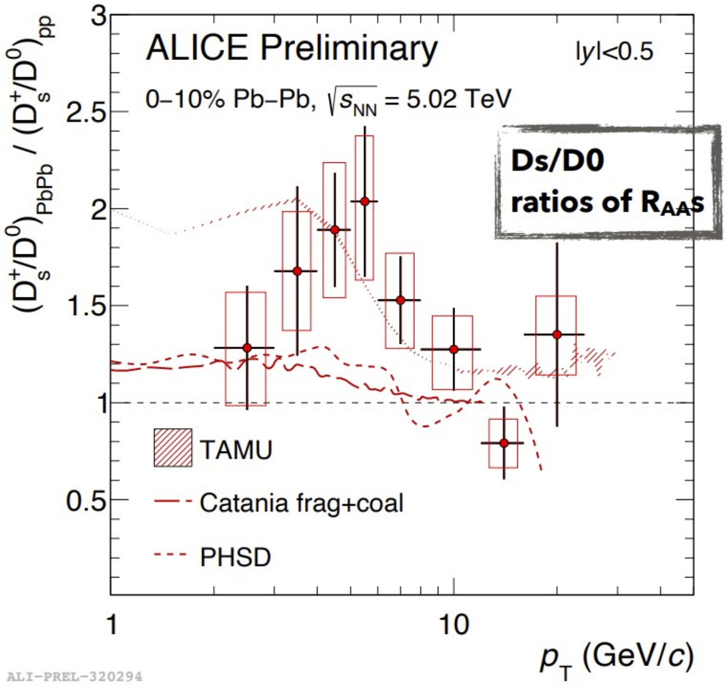


- Hint of flavor/mass dependent energy loss in the intermediate p_T region:
  - $\Delta E(q,g) > \Delta E(c) > \Delta E(b)$: consistent with the dead cone effect

- Similar mass hierarchy observed for elliptic flow for pT<6-7 GeV
  - v2(q,g) > v2(D) > v2(J/ψ) > v2(b→e) > v2(Y)

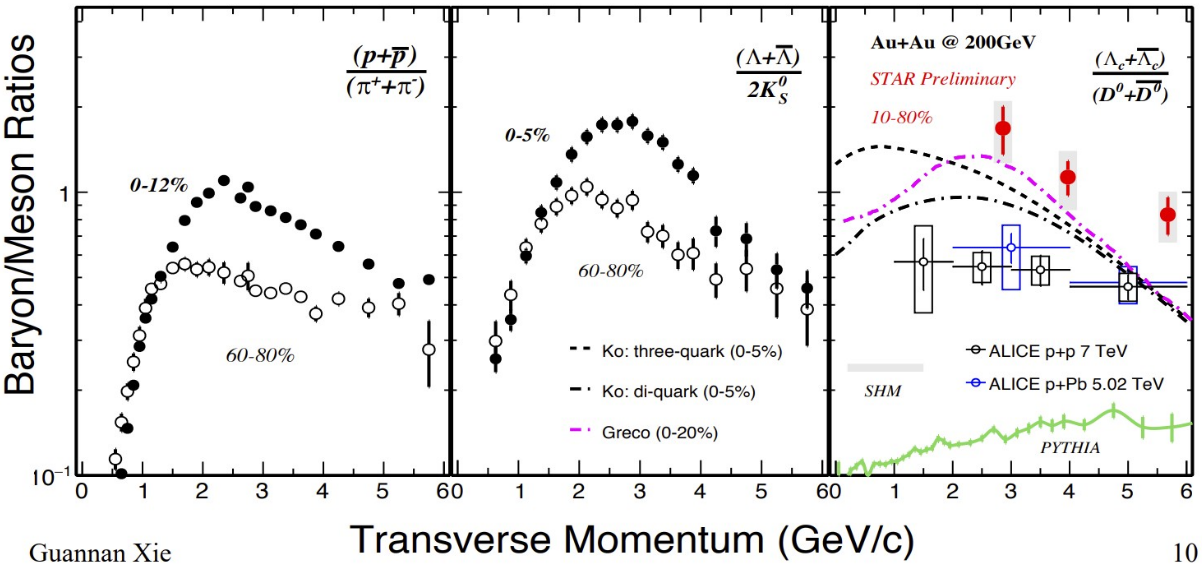
Hadronization effects (strange D-mesons)

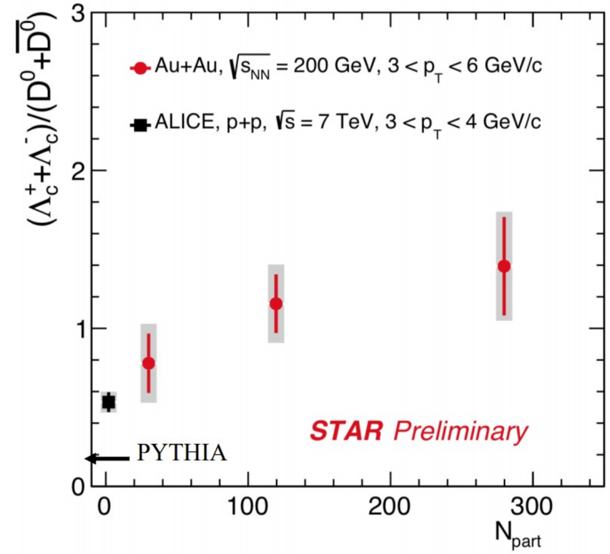




- Strange to non-strange D-mesons ratio larger in A+A wrt expectations from ee or pp collisions
  - Effect observed both at RHIC and LHC
  - Hadronization of charm affected by the strange-quark rich medium

Hadronization effects (baryon/meson) - STAR

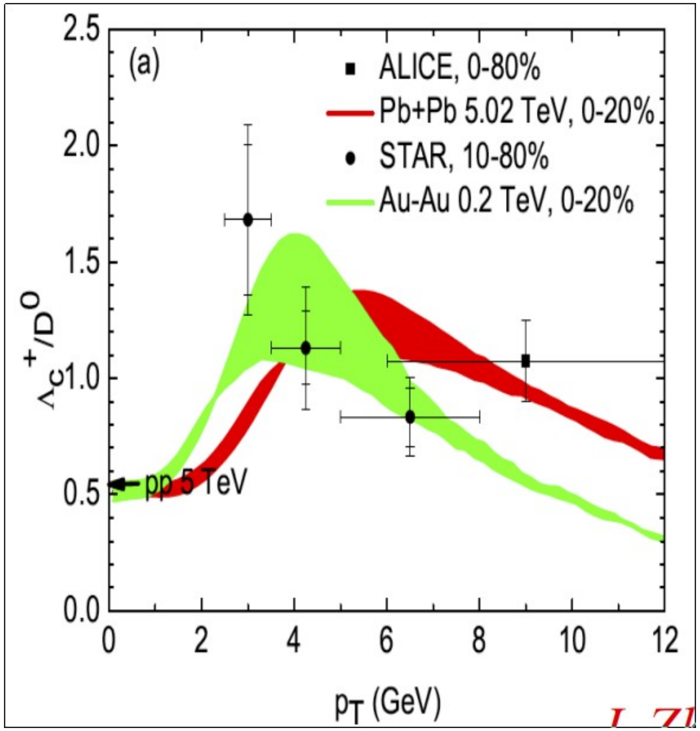




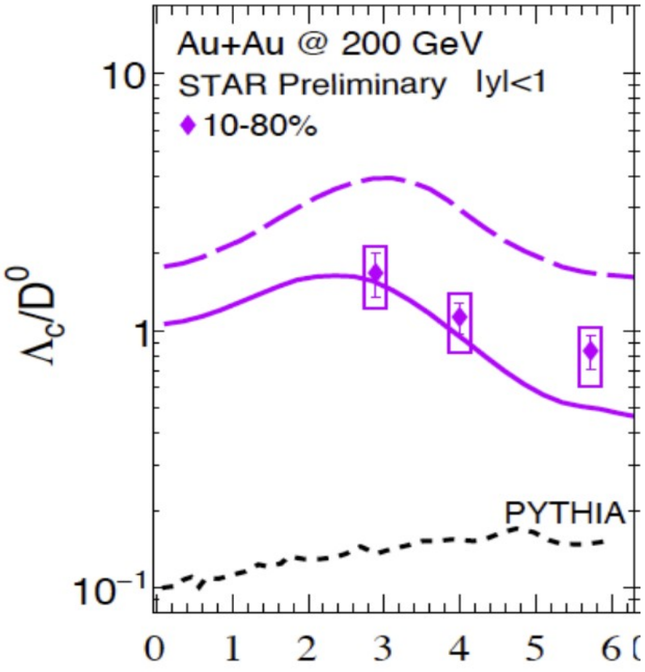
- Significantly larger Λ_c/D^0 ratio observed in Au+Au collisions wrt pp collisions
- Λ_c/D ratio comparable to light flavor baryon / meson ratios
- Enhancement seems more pronounced in central collisions
- Consistent with charm quark hadronization via coalescence

Hadronization effects (baryon/meson) - STAR

He and Rapp, arxiv:1905.09216

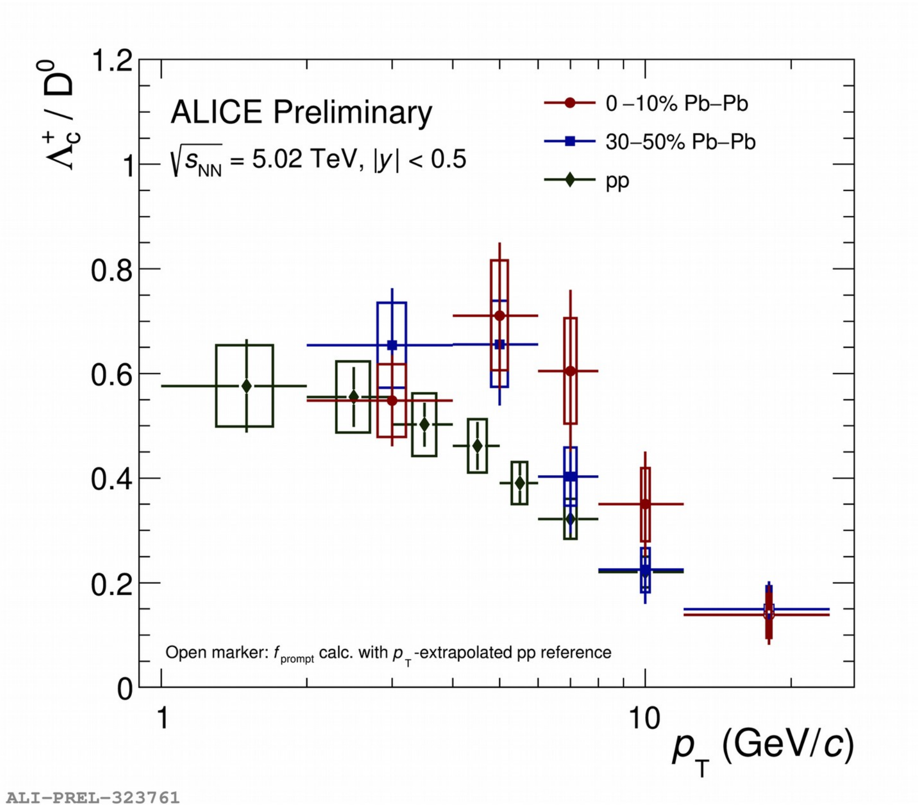


Zhao and Zhuang, arxiv:1805.10858



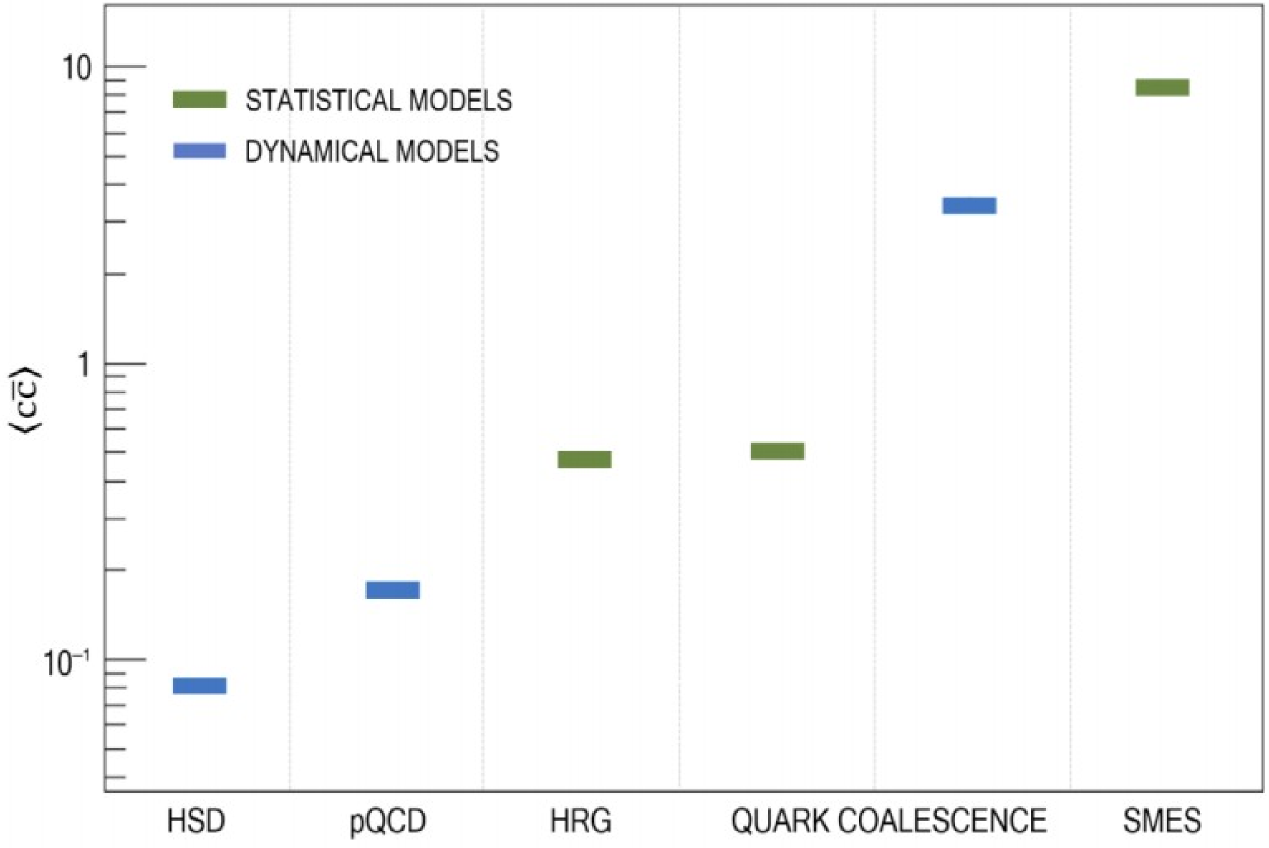
- Transport model calculations (TAMU and Tsingua) also seem to reproduce the data

Hadronization effects (baryon/meson) - ALICE



- Λ_c/D^0 ratio larger in Pb-Pb than in pp collisions also at LHC energies

Charm production in AA collisions the SPS



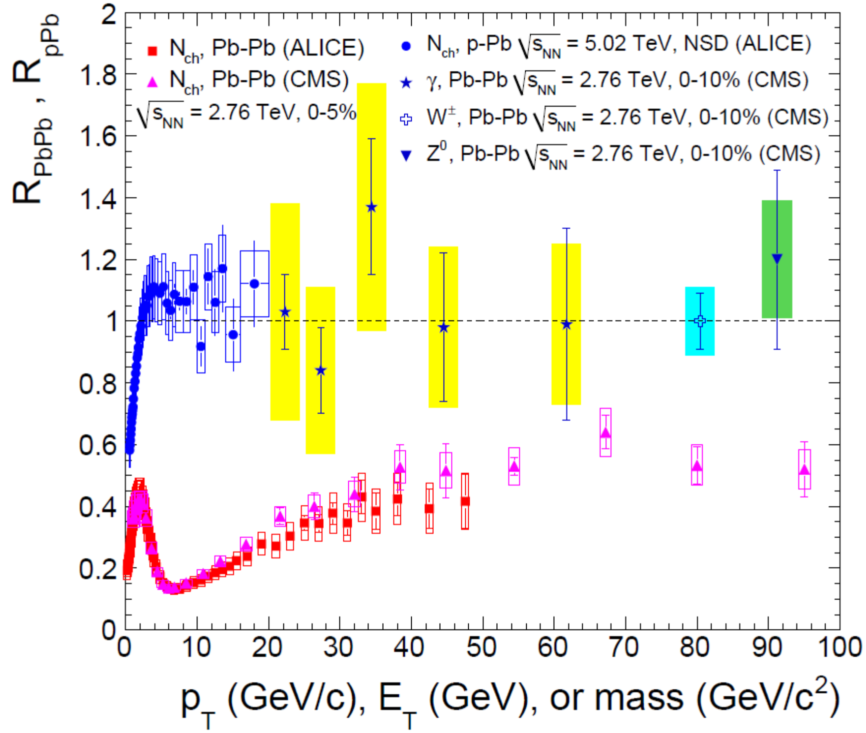
- Production of charm in AA collisions in the SPS energy range is experimentally unknown
- Theoretical predictions vary by 2 orders of magnitude → good opportunity for NA61 to make strong constrains
- Proposed as a signal of the onset of deconfinement
- More details in Pawel's presentation

Summary and conclusions

- Charm (and bottom) hadron production is one of the most active area of studies in AA collisions at the LHC and RHIC energies
- Strong nuclear suppression observed at intermediate and high pT at the LHC consistent with large in-medium energy loss effects
- Large elliptic flow suggests possible cham-quark thermalization in the QGP
- Observations of enhanced production of D_s and charm baryons (Λ_c,Ξ_c) wrt expectations from ee collisions
  - Sizable contributions to total $c\bar{c}$ cross-section, largely unexpected
  - Approximation of $c\bar{c}$ cross-section with the light D-mesons yields not good enough
    - Should be tested even at SPS energies
- Open charm production physics in AA collisions features rich phenomena (some not discussed here)
  - Its time for NA61/SHINE to join :)

Backup

The nuclear modification factor



N_{ch} p-Pb: *ALICE PRL110(2013)082302*
N_{ch} Pb-Pb: *ALICE, Phys.Lett.B720 (2013)52*
N_{ch} Pb-Pb: *CMS, EPJC (2012) 72*
γ: *CMS, PLB 710 (2012) 256*
$W^{\pm}$, *CMS, PLB715 (2012) 66*
Z^0, *CMS, PRL106 (2011) 212301*

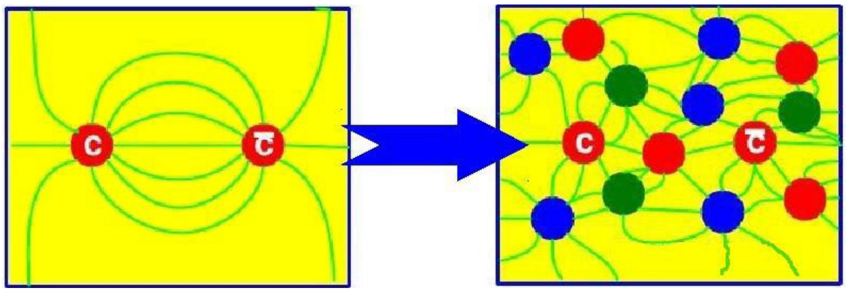
$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y_{AA}}{Y_{pp}}$$

N_{coll}: the number of binary nucleon-nucleon collisions
Y_{AA}: yield in AA collisions
Y_{pp}: yield in pp collisions

- Superposition of NN collisions → $R_{AA} = 1$
- Suppression → $R_{AA} < 1$
- Enhancement → $R_{AA} > 1$

- Weakly interacting particles are not affected by the QGP
  - Photons, $W^{\pm}$ and Z^0 bosons R_{AA} are compatible with 1

Heavy quarkonia in the QGP



- Vacuum potential: $V_{total}=(-q)\frac{q}{4\pi r}+kr$
- In a deconfined medium
  - string tension disappears
  - Coulomb potential is screened (Debye)
- The quark-antiquark potential becomes a Yukawa-like short range potential

$$V_{medium}(\boldsymbol{r})=\frac{q}{4\pi}\frac{e^{-r/\lambda_D}}{r}$$

$$\lambda_D \simeq \frac{1}{T}$$ - Debye screening length

- Quarkonium states will be melted if $r > \lambda_D$

Matsui and Satz, PLB178 (1986) 416