Overview of (recent) QCD matter studies with hard probes

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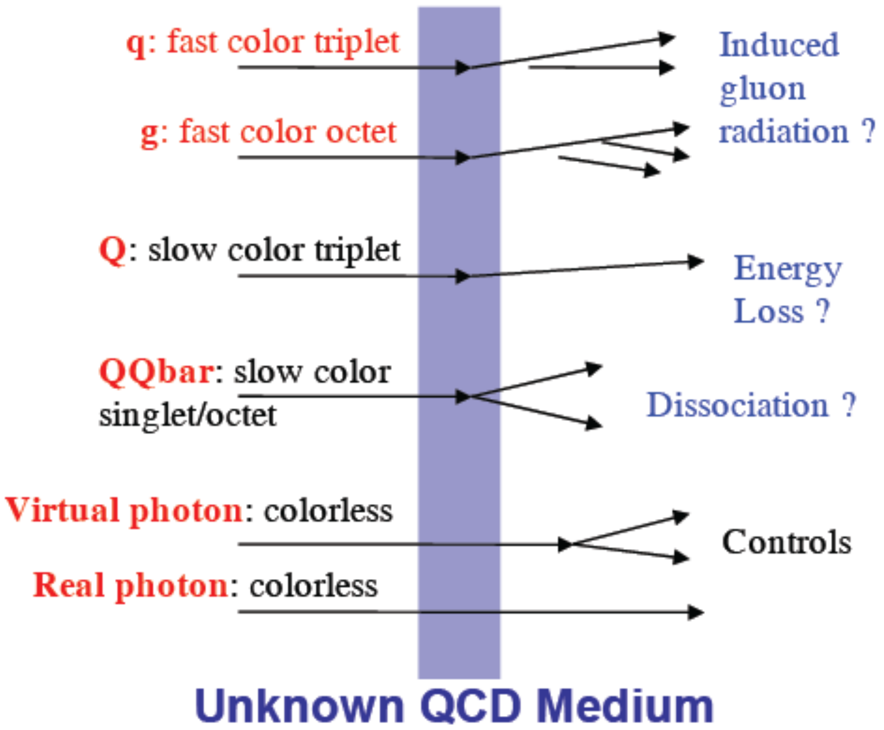
Hard probes: tomography of nuclear matter

Jets, heavy quarks, quarkonia :
originate from initial hard scattering
of partons which carry a color charge
interact with nuclear matter

Photons, W and Z bosons:
do not carry a color charge
provide information about initial state
nuclear parton distribution functions



Goal:
use in-medium parton energy loss to quantify medium properties

BUT!
Parton interaction with medium not trivial:
depends on strength of coupling,
dynamics of fireball …

… challenge for theorists

Hard probes: methodology

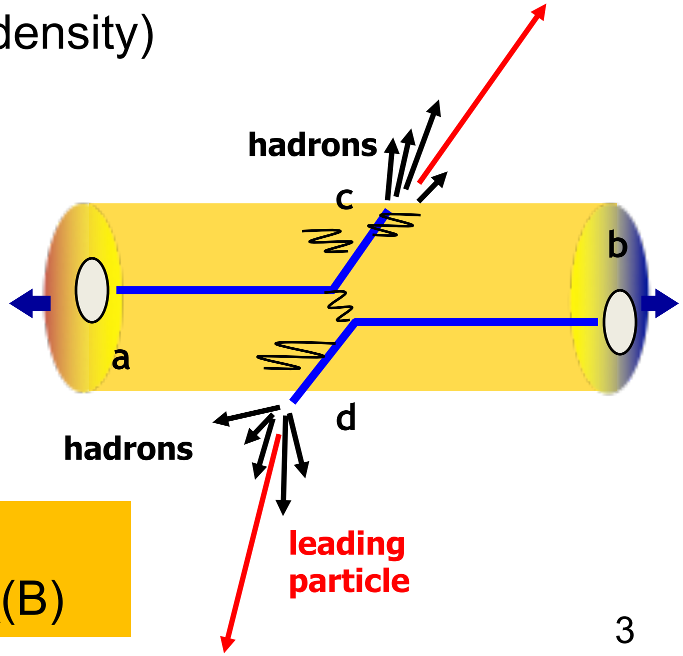
- formulate production in A+A collisions as a hard pQCD calculable process with factorizable final state interactions (FSI)

$$\frac{d\sigma^{h}_{pp}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \rightarrow cd) \frac{D^0_{h/c}}{\pi z_c}$$

Parton distribution function	Matrix element	Fragmentation function
measured in DIS	pQCD	e^+e^-
initial state (saturation?)		final state (energy loss?)

- FSI: model of medium (transport coefficient, gluon density)

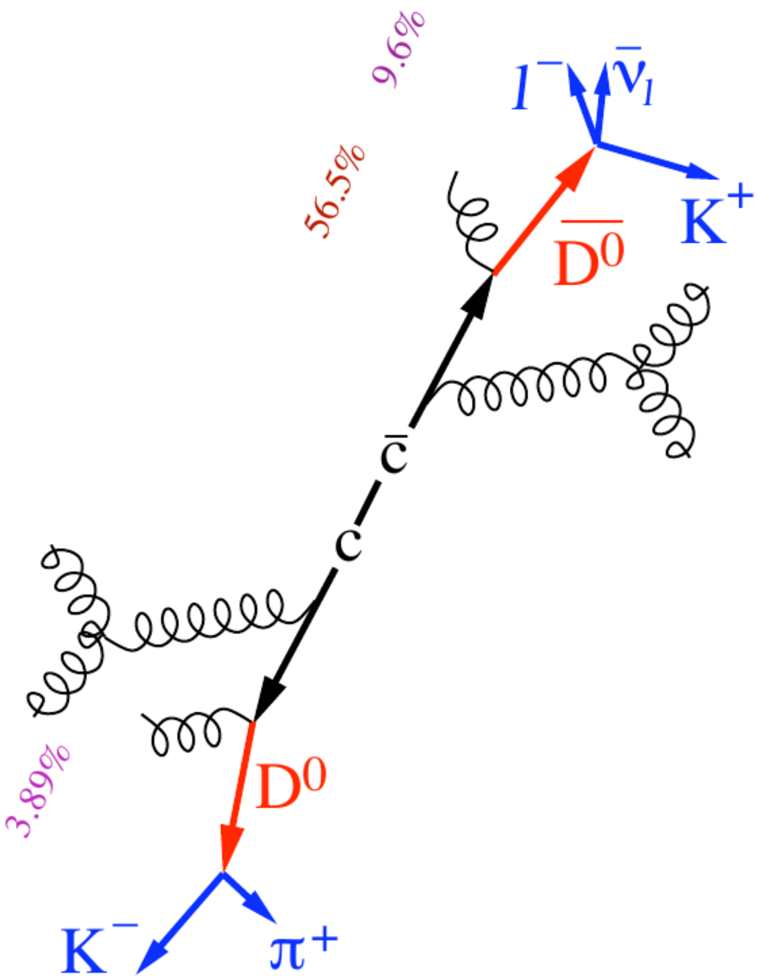
- partons traversing medium lose energy:
  gluon radiation, elastic collisions
  - energy loss different for g, light/heavy quarks
  (color factor, dead cone effect)



Expected hierarchy:
$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \longrightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

Open heavy-flavour production

Open heavy-flavour hadron production

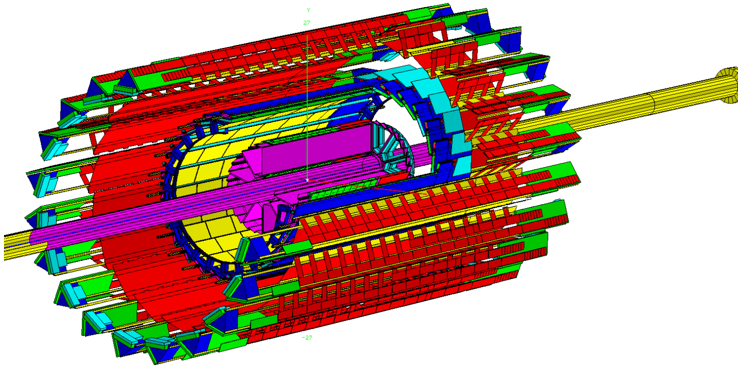


Non-photonic electrons:
(electrons from semi-leptonic heavy flavour hadron decays)

+ easy to trigger
- indirect access to heavy quark kinematics

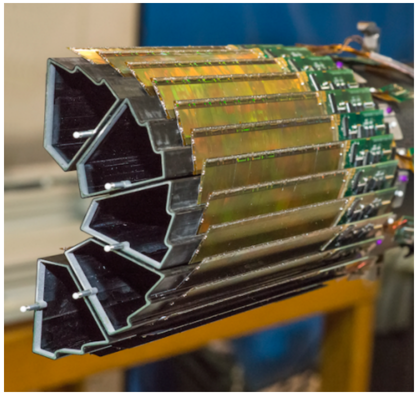
Direct open charm reconstruction:
+ direct access to heavy quark kinematics
- requires precise vertex tracking detector to suppress background
- difficult to trigger

Heavy Flavor Tracker

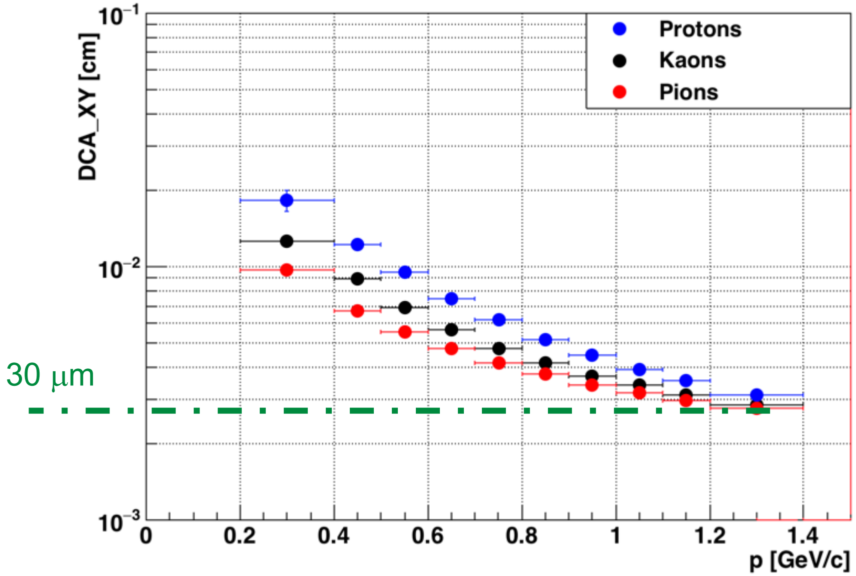


PiXeL (PXL):
- 2 layers of thin Monolithic Active Pixel Sensors (MAPS) with 365M 20.7x20.7 μm pixels
- excellent DCA resolution for HF studies

Intermediate Silicon Tracker (IST):
- 1 layer of fast readout single-sided double-metal Si-strip detector

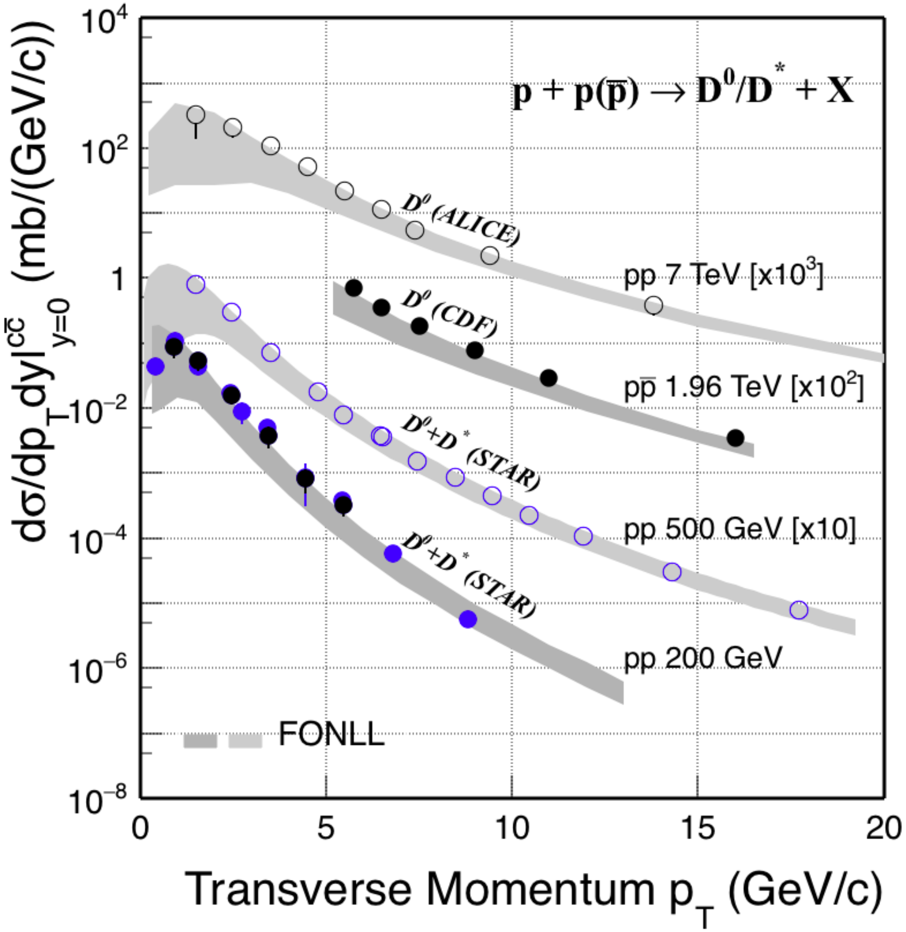


Silicon Strip Detector (SSD)
- existing one layer of double-sided Si-strip detector with upgraded electronics

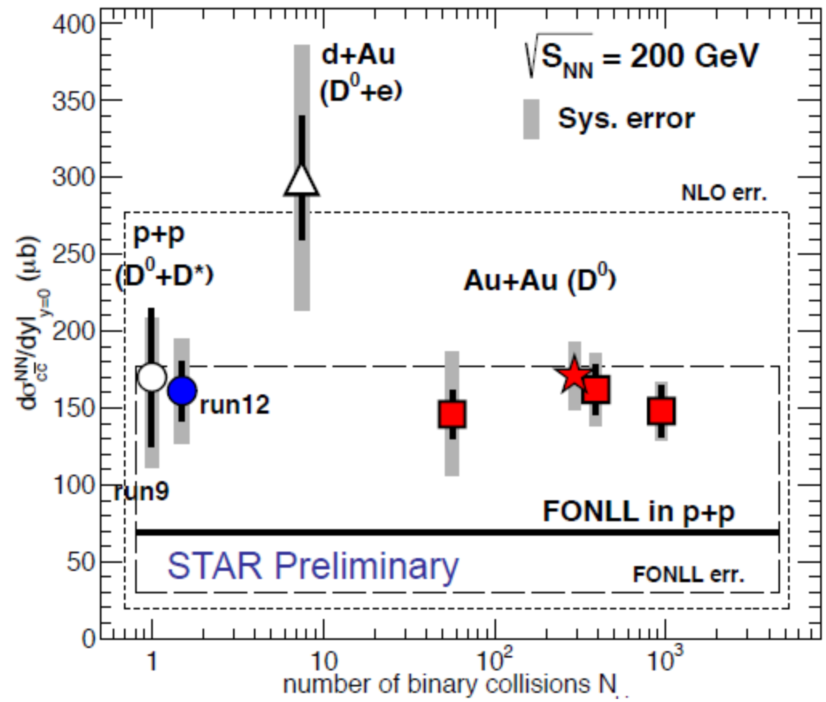


Detector	Radius (cm)	Hit resolution r/ϕ – z (μm)	Radiation length (X_0)
SSD	22	20 / 740	1%
IST	14	170 / 1800	< 1.5%
PXL	2.8/8	6 / 6	~0.4%

D meson production in pp



Theory: M. Cacciari et al., PRL 95 (2005) 122001
R. Vogt, EPJ ST 155 (2008) 213

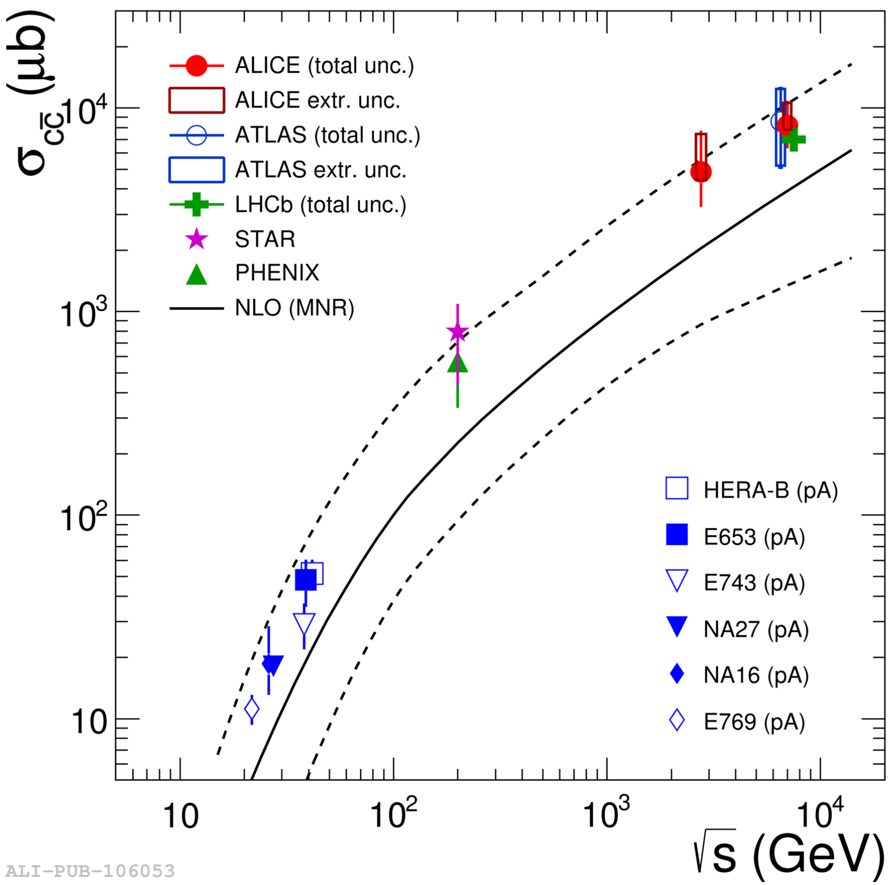


Measured D^0 and D^* cross section in p+p collisions at $\sqrt{s}$ = 200 and 500 GeV:

- constraints of pQCD calculations (data consistent with upper FONLL limit)
- a crucial reference for A+A collisions

Note: STAR results are pre-HFT results

$\sqrt{s}$ dependence of charm cross section



ALICE arXiv:1605.07569

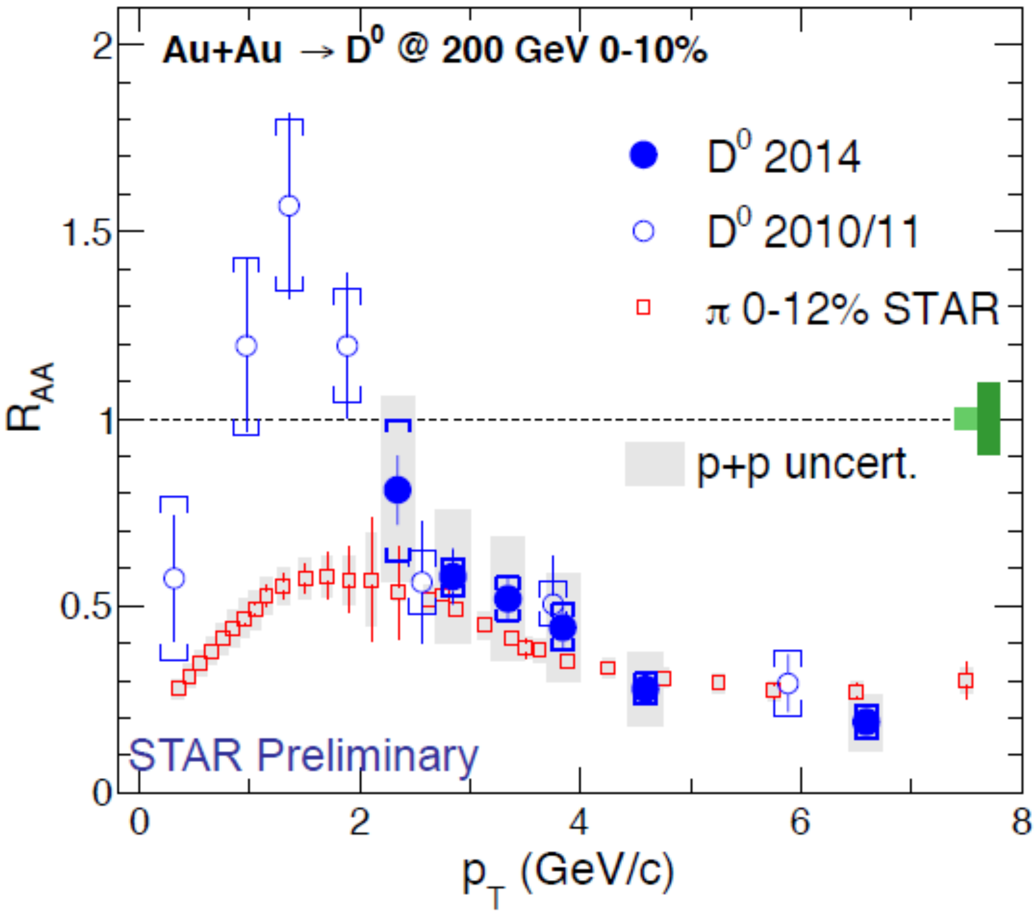
ALICE: D^0 measurement
"down to $p_T = 0$ GeV/c "

- access to total charm cross section
- essential for detailed regeneration effects consideration

Charm quark production well understood in pp collisions in the accessible $\sqrt{s}$ range

Nuclear modification factor of D mesons

STAR D^0 2010/11: PRL 113 (2014) 142301
STAR π: PLB 655 (2007) 104



- Low p_T: R_{AA}(D)>1

charm coalescence with a radially flowing bulk medium?

- High p_T: R_{AA}(D)<1

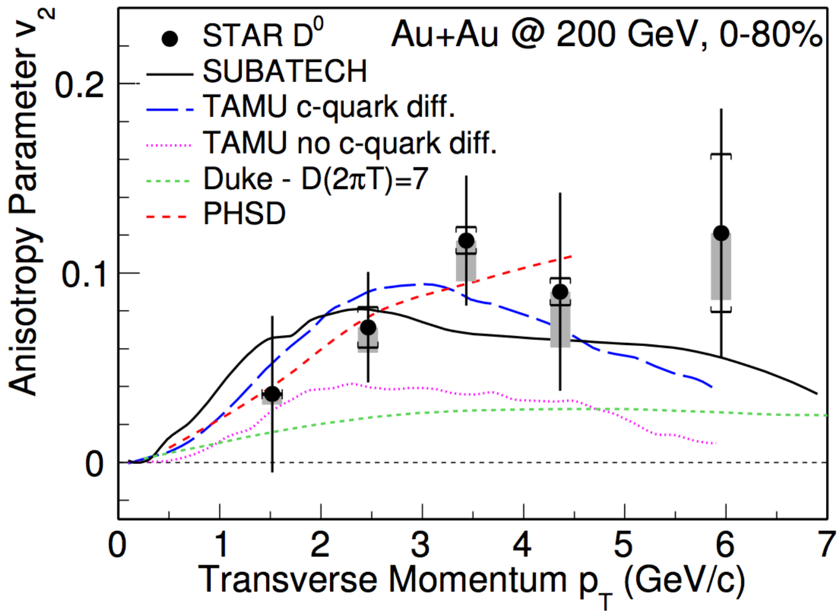
- significant suppression in central Au+Au collisions

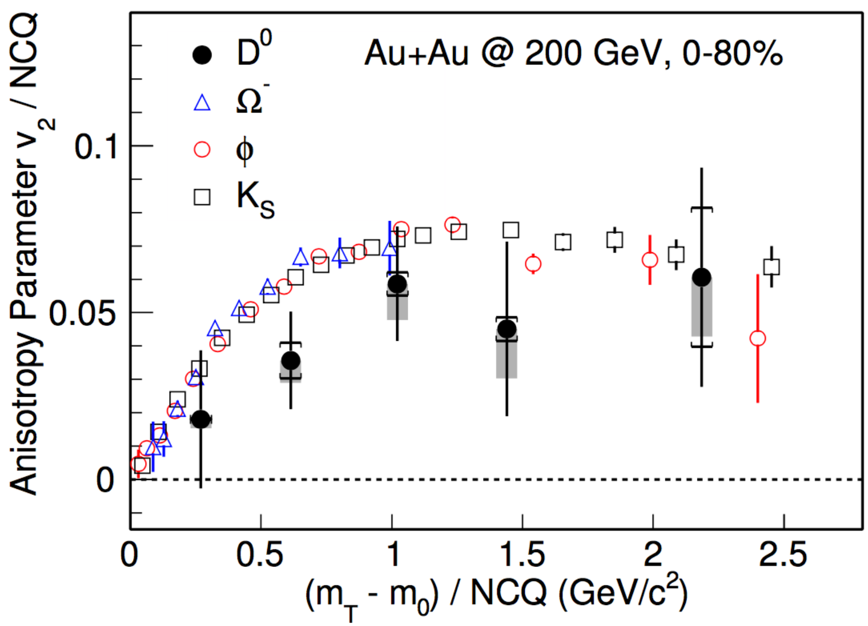
→ strong charm-medium interaction

- Comparison of light and heavy flavour particles:

R_{AA}(D) ~ R_{AA}(π) at p_T>4 GeV/c
similar suppression for light partons and charm quarks at high p_T

Direct evidence for charm flow





Finite D_0 v_2 for p_T>1 GeV/c
in Au+Au collisions measured

→ data favour charm quark diffusion

Theory curves:
SUBATECH: pQCD + hard thermal loop
TAMU: T-matrix, non-pert. model
with internal energy potential
PRC 86 (2012) 014903

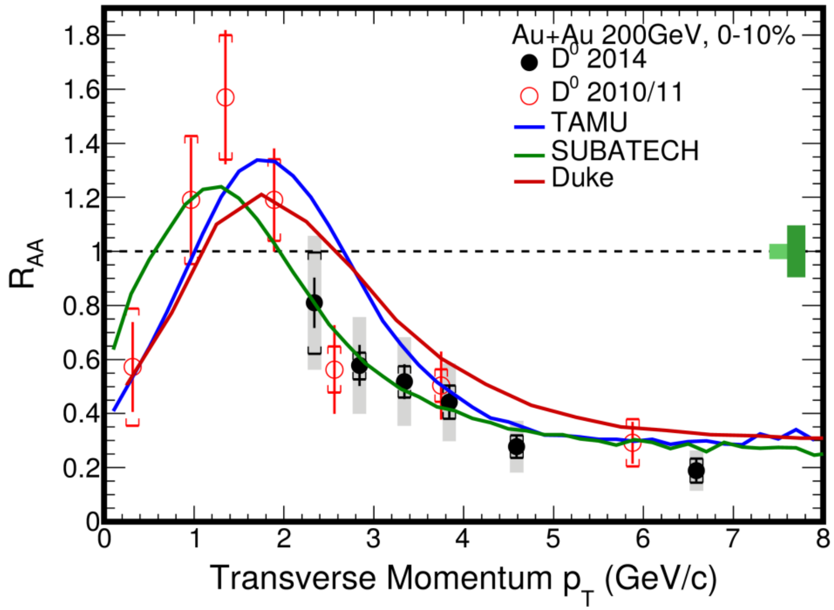
DUKE: Langevin equation + (2+1)D viscous
hydro, a free parameter fit to LHC data
PRC 88 (2013) 044907

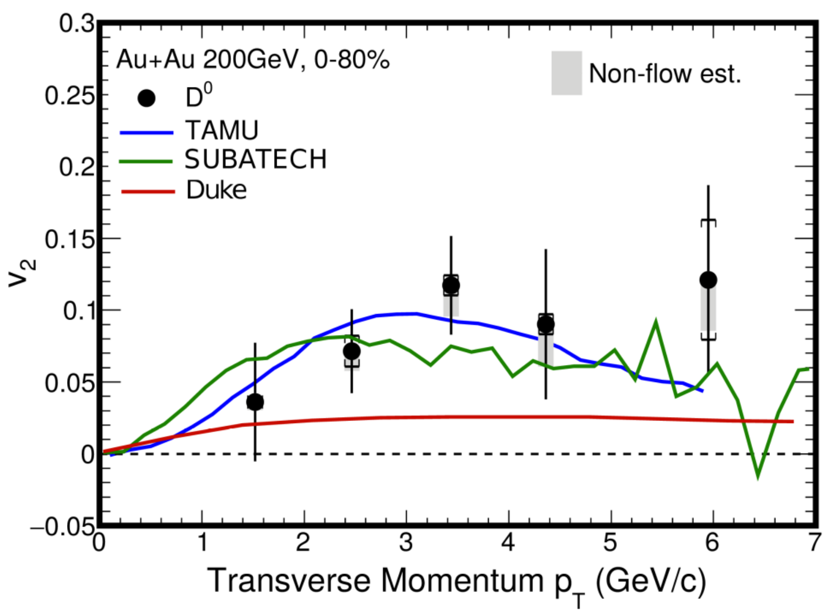
PHSD: Parton-Hadron-String Dynamics
transport model
PRC 90 (2014) 051901

$v_2(D) < v_2$ (light hadrons)

→ indicates that charm quarks
are not fully thermalized
with the medium

Simultaneous fit of D meson R_{AA} and v_2





TAMU: non-perturbative T-matrix
$D \times (2\pi T) = 2\text{-}11$

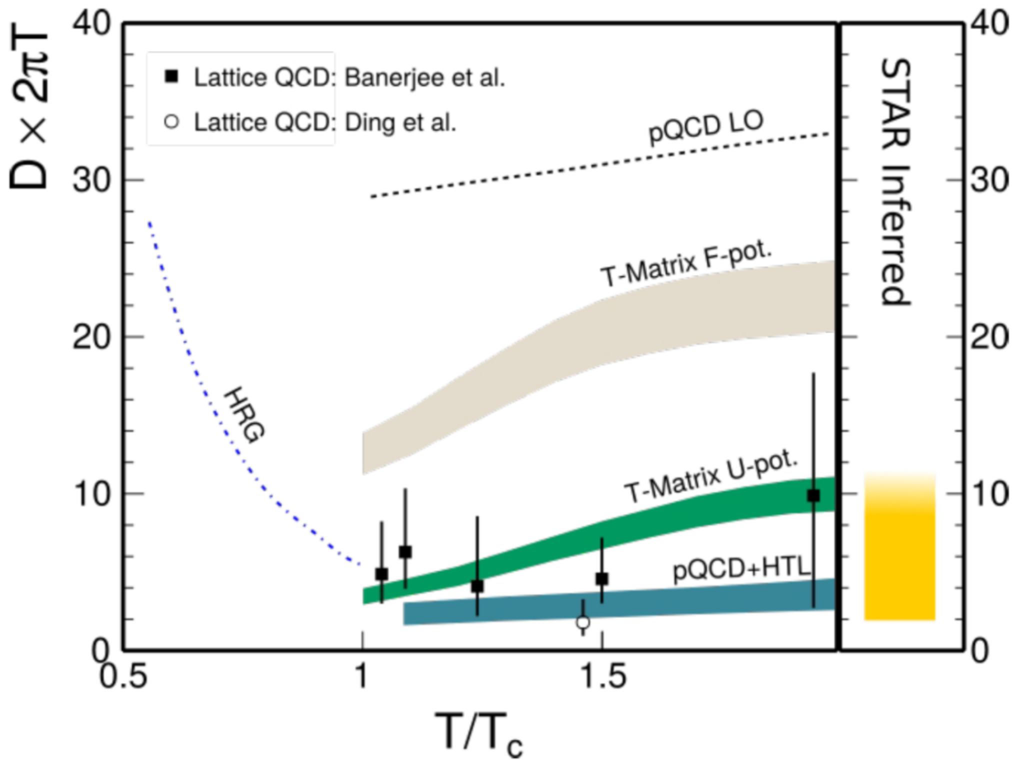
SUBATECH: perturb. + resummation
$D \times (2\pi T) = 2\text{-}4$

DUKE: Langevin simulation with a free parameter tuned to the LHC data
$D \times (2\pi T) = 7$

References:
TAMU: PRC 86 (2012) 014903
P RL 110 (2013) 112301
DUKE: PRC 92 (2015) 024907
A. Andronic et al. EPJ C76 (2016) 3, 107
(btw. a great review article)

TAMU and SUBATECH models give rather satisfactory simultaneous description of R_{AA} and v_2 data

Comparison with theory



Models with charm diffusion coefficient D=2-10 describe STAR D^0 R_{AA} and v_2 results.

Lattice QCD calculations are consistent with values obtained from the data.

More precise measurements from STAR expected:

Run15 (p+p, p+Au) and Run16 (Au+Au)

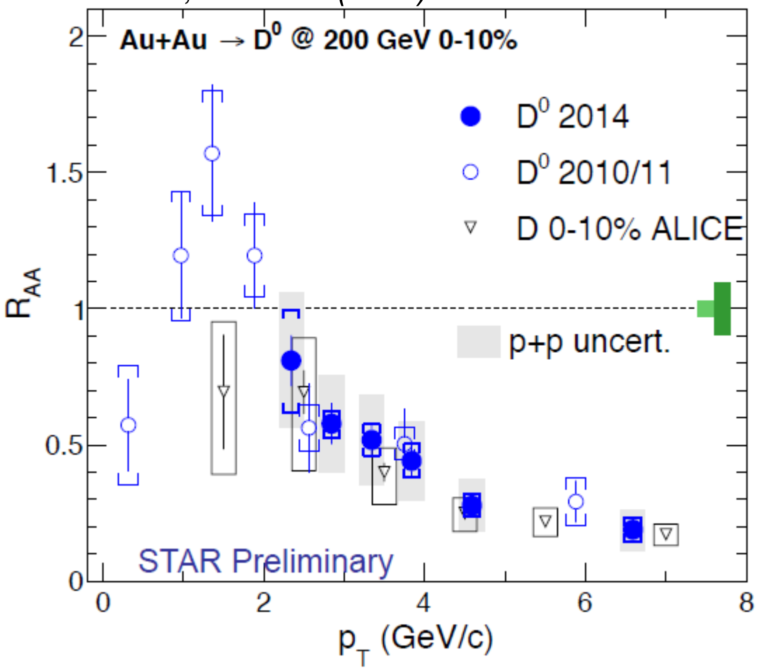
→ improved pp baseline

→ detailed understanding of cold nuclear matter effects

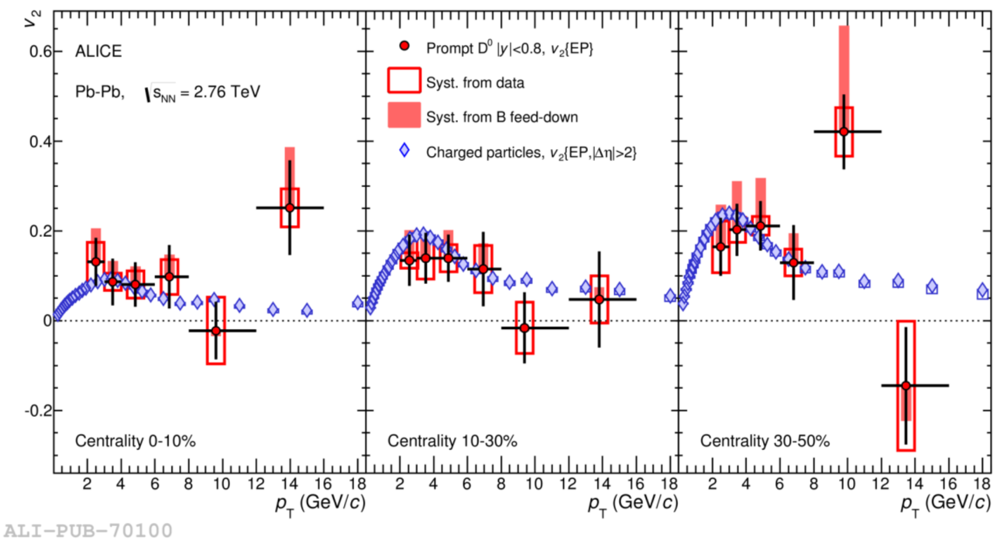
→ 3 x more statistics in Au+Au + improved DCA resolution at low p_T (Al cables for HFT-PXL)

Charm-medium interaction: RHIC vs LHC

ALICE, JHEP 09 (2012) 112



ALICE, PRC 90 (2014) 034904



Nuclear modification factor:

R_{AA} (D) @ RHIC ~ R_{AA} (D) @ LHC

strong charm-medium interaction both at RHIC and LHC energies

Elliptic flow:

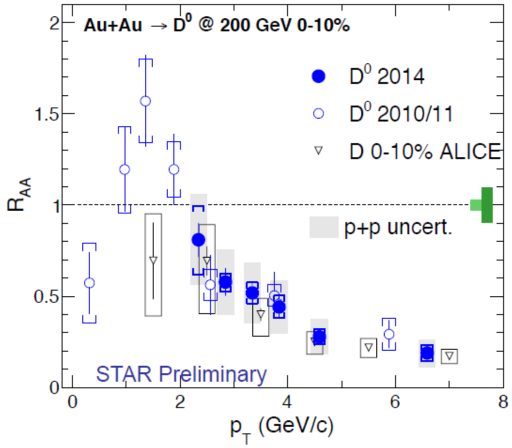
RHIC: $v_2(D^0)$ < v_2(light hadrons)

LHC: $v_2(D^0)$ ~ v_2(light hadrons)

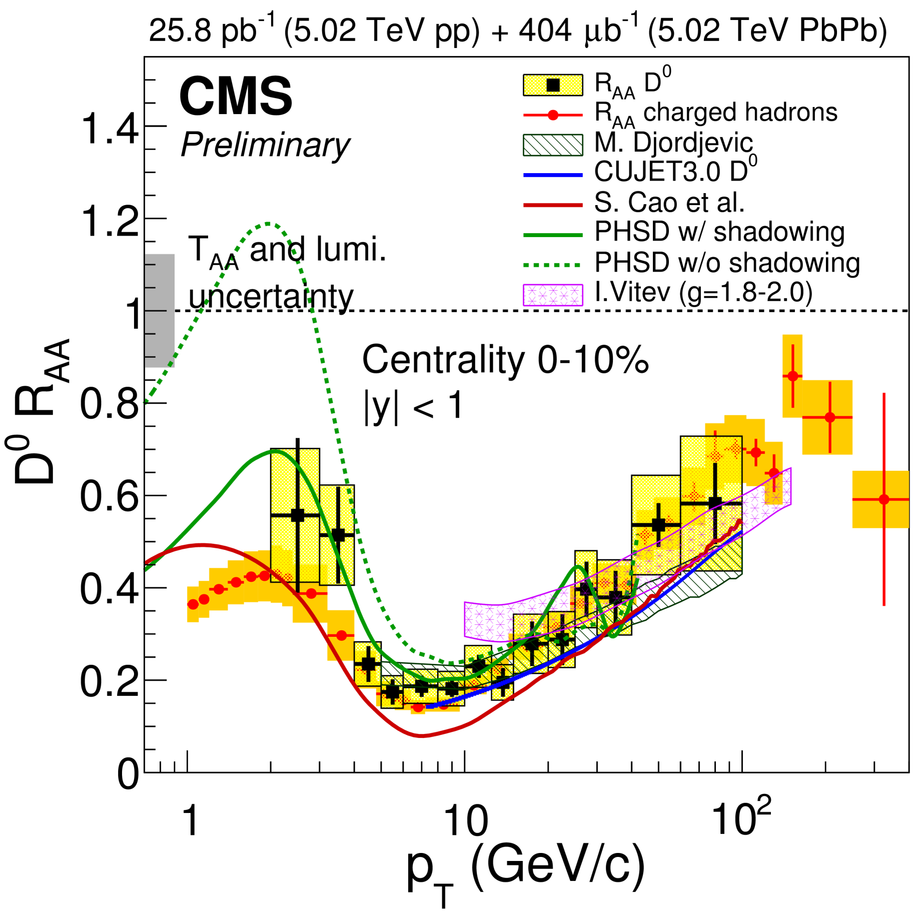
charm thermalized at LHC energy but not fully thermalized at RHIC?

… new Pb+Pb data at 5.02 TeV presented at HP2016 conference …

D meson R_{AA} in Pb+Pb collisions at 5 TeV



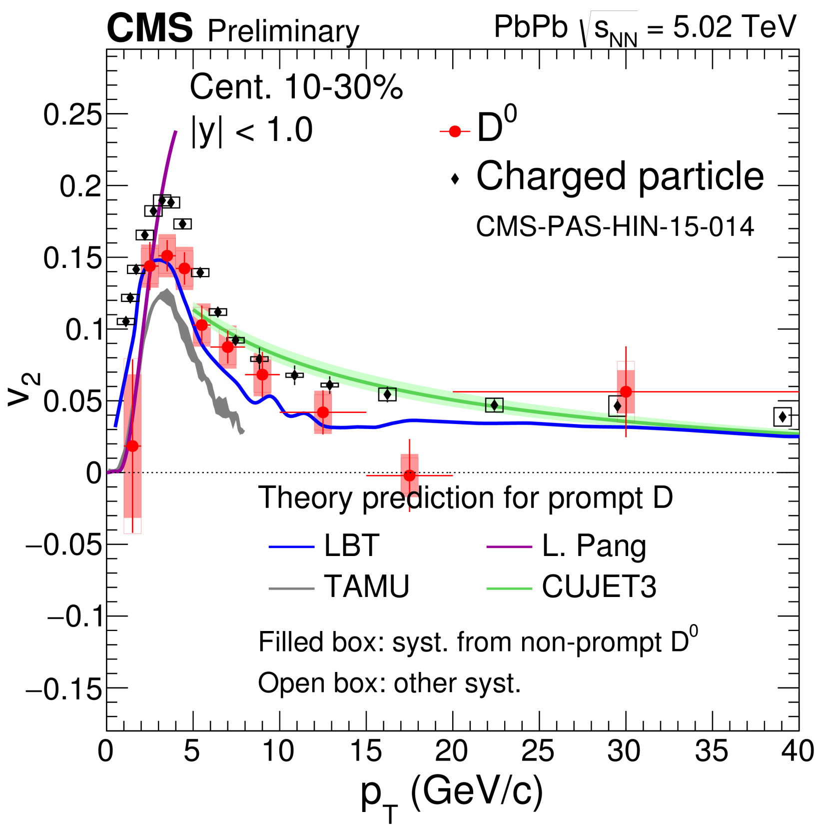
CMS-PAS-HIN-16-001

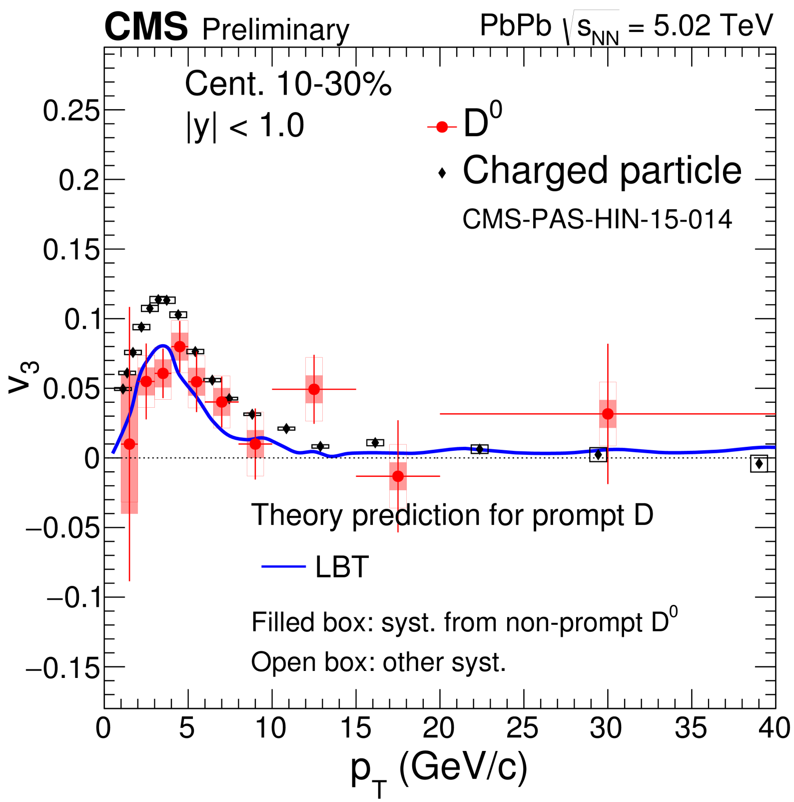


R_{AA} of D mesons at top LHC energy consistent with that of charged hadrons up to 100 GeV/c

Contributions from dead cone effect not significant at high p_T

D meson v_2 and v_3 in Pb+Pb collisions at 5 TeV





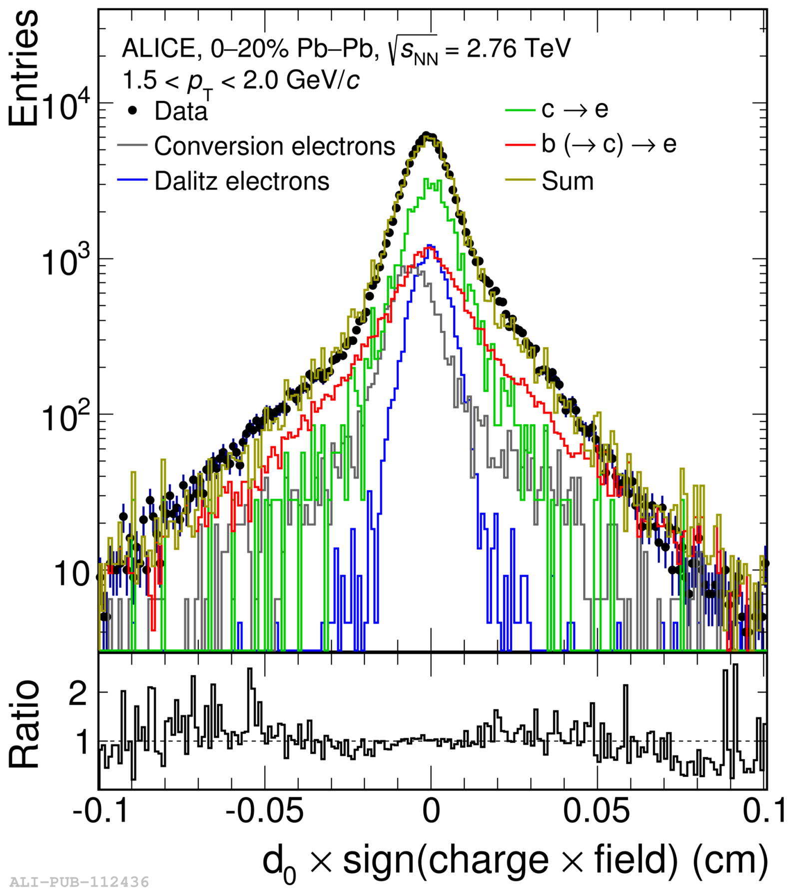
CMS-PAS-HIN-16-007

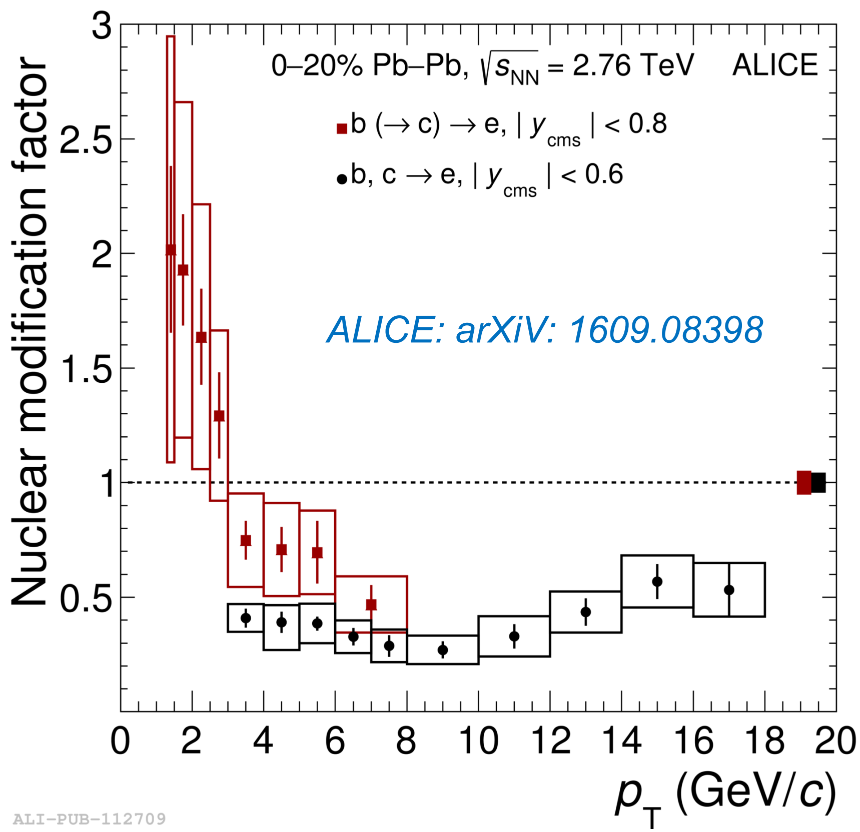
Not only v_2, but also v_3 of D mesons measured at the LHC!

Similarly as at RHIC, anisotropies are lower than those of charged particles

No full thermalization of charm at the top LHC energy!

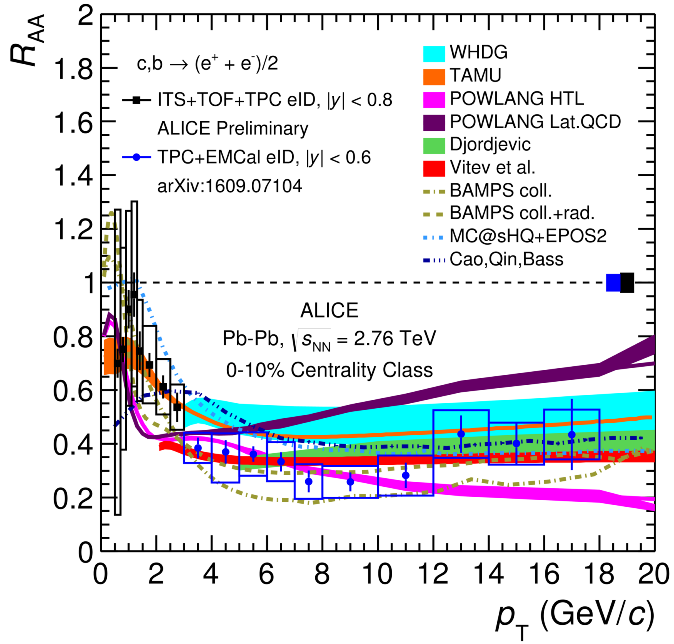
On the way to B mesons: ALICE



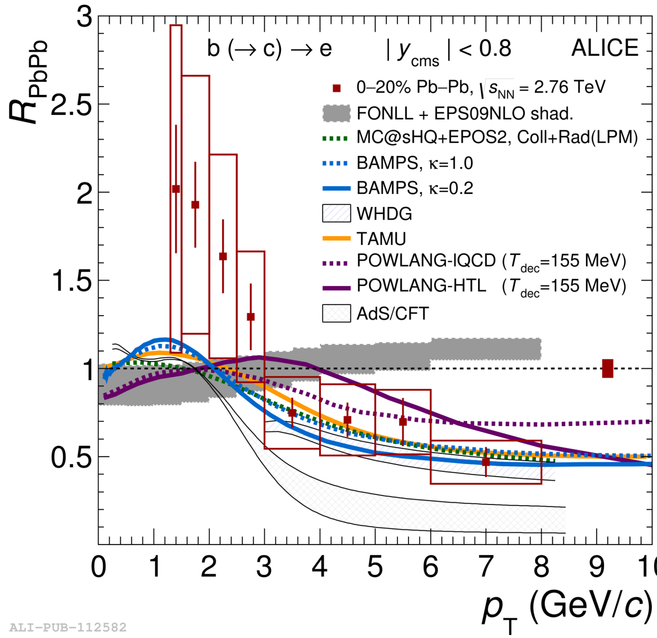


- first R_{AA} measurement of beauty-decay electrons:
  R_{AA}<1 for p_T > 3 GeV/c
- consistent with the picture of mass-dependent radiative and collisional energy loss

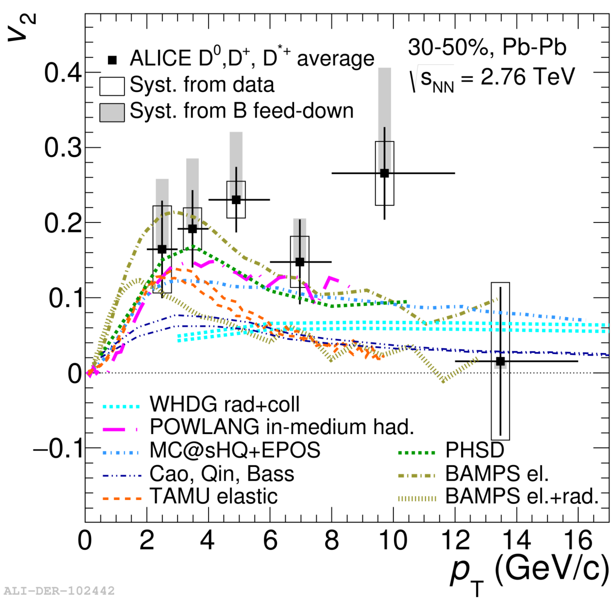
ALICE: HF electron production vs models



ALI-PREL-114353



ALI-PUB-112582

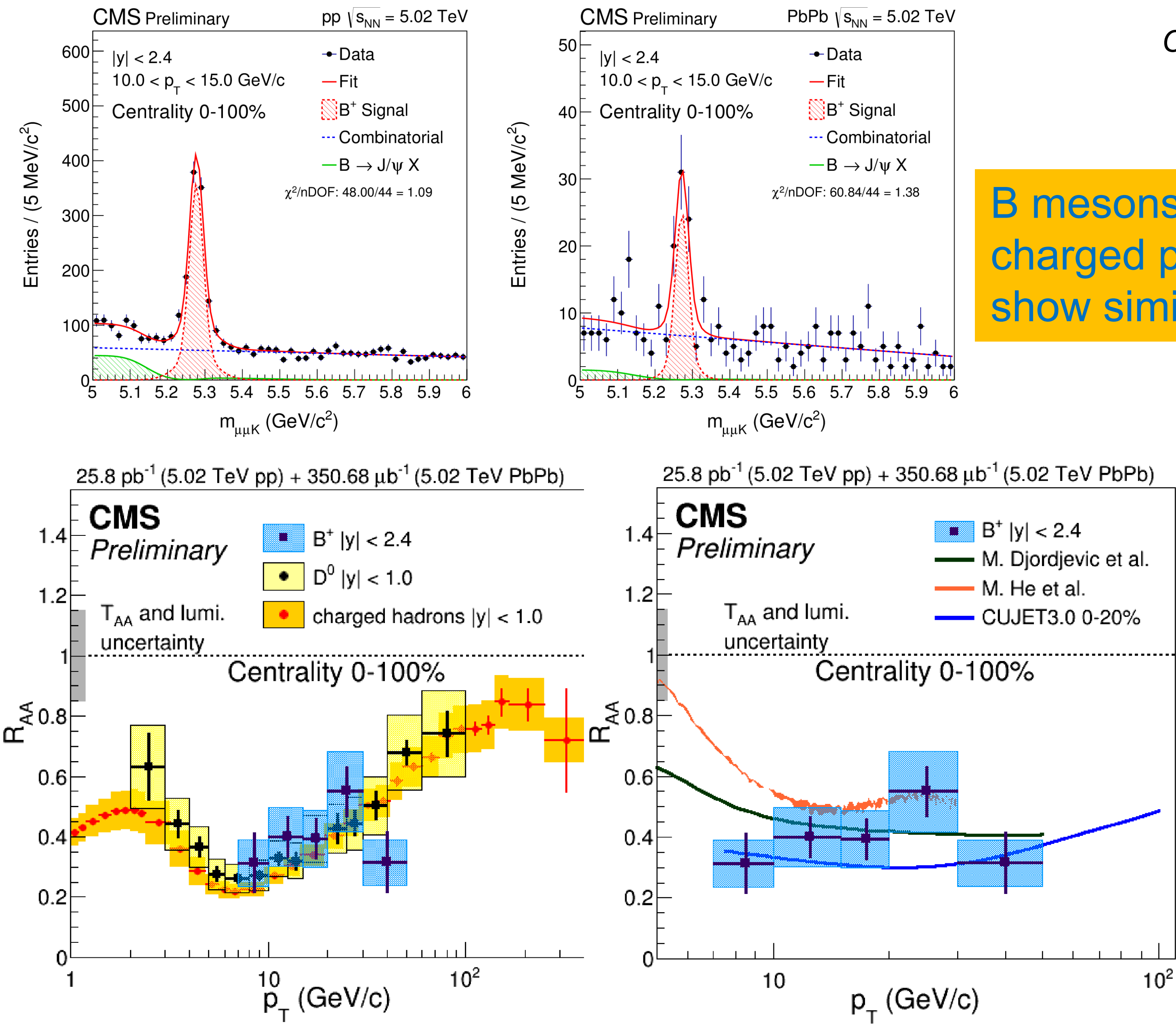


ALI-DER-102442

Collection of v_2 and R_{AA} measurements for different heavy-flavour decay channels

… getting there to provide constraints of models

CMS: B meson measurement at 5 TeV



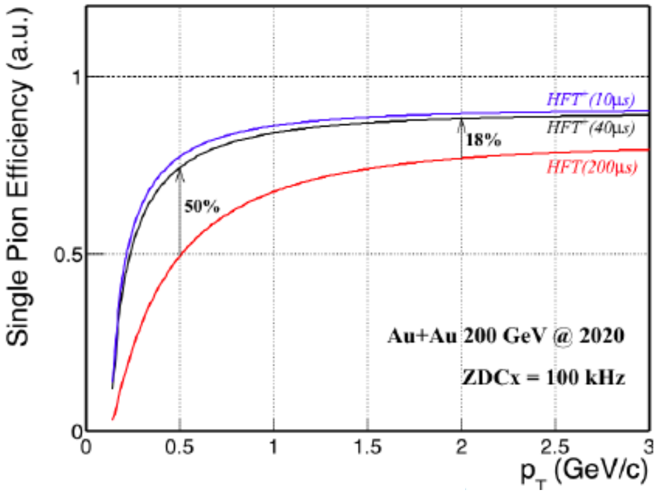
CMS-PAS-HIN-16-011

B mesons, D mesons and charged particles show similar suppression!

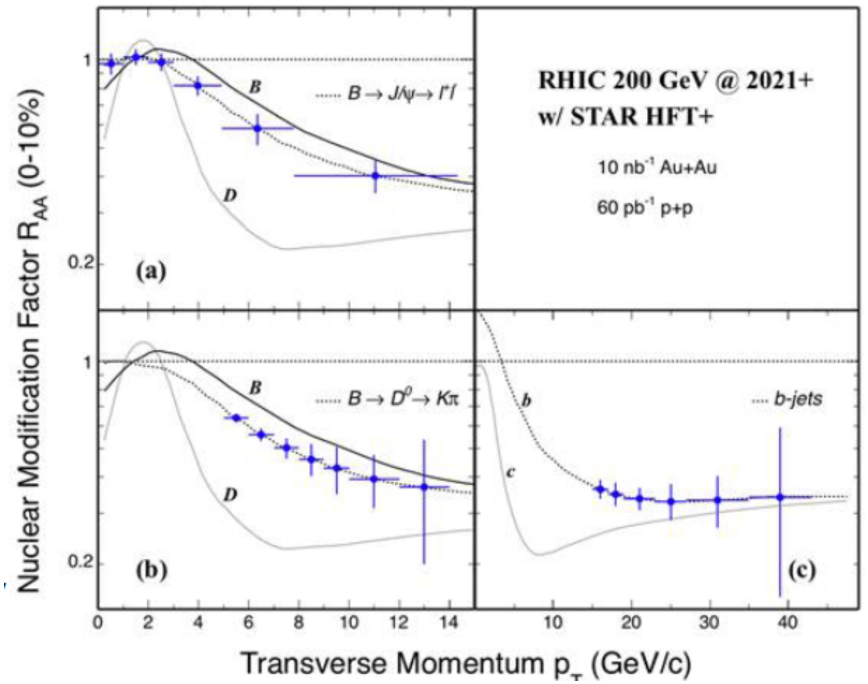
STAR Heavy Flavor Phase II: HFT+ (2021-2022)

HFT+ detector:

- will have faster MAPS sensors:
  integration time from ~185 μs to below 40 μs
  → less pile-up hits → improved tracking efficiency
- use chips developed for ALICE ITS upgrade
  and existing HFT infrastructure → cost effective



Projected R_{AA} stat. uncertainty
for RHIC pp and Au+Au data in 2021-22



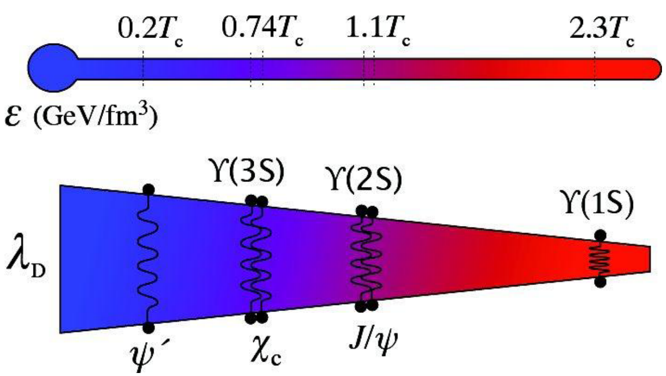
Precise bottom measurements
with HFT+ to complete heavy-flavor
physics program at RHIC.
Complementary to ALICE HF
and sPHENIX jet and Upsilon programs.

Quarkonia production
… focus on bottomonia only

Quarkonia as QGP thermometer

RHIC

Debye screening of heavy quark potential
→ sequential melting of quarkonia states

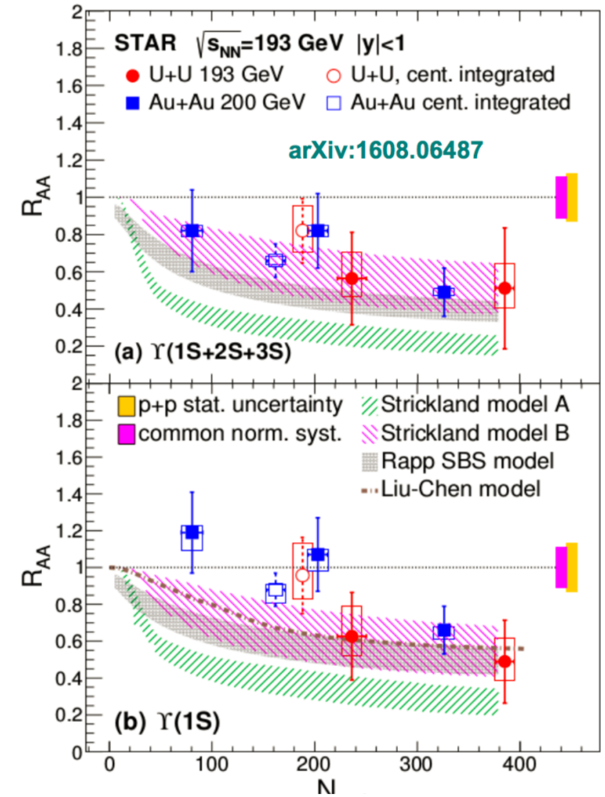


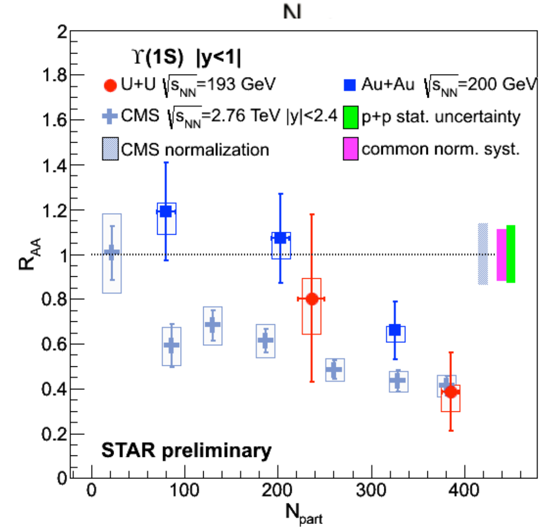
- Υ(1S) suppression in central Au+Au collisions
- U+U collisions reach by 20% higher N_{part} than Au+Au and our study further extends observed trend

Υ melting in hot and dense medium: suppression at RHIC and LHC energy comparable at high N_{part}.

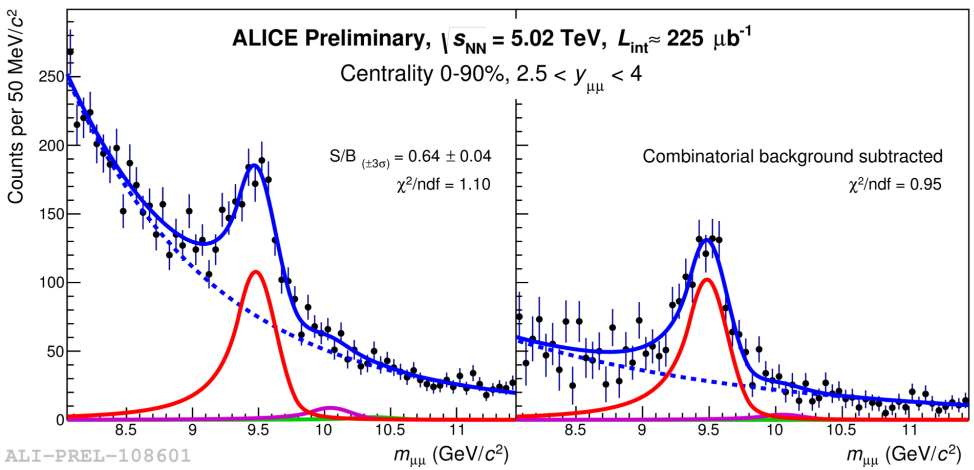
→ RHIC 2015 p+Au run: crucial for understanding role of cold nuclear matter effects

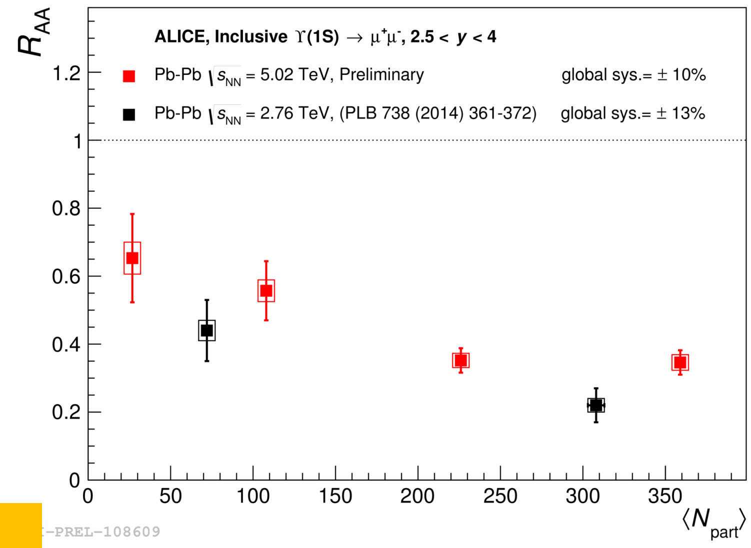
Note (bottom figure): U+U data plotted with preliminary syst. uncertainty, will have to be replotted also with newer CMS data





New Υ measurements at 5.02 TeV with ALICE

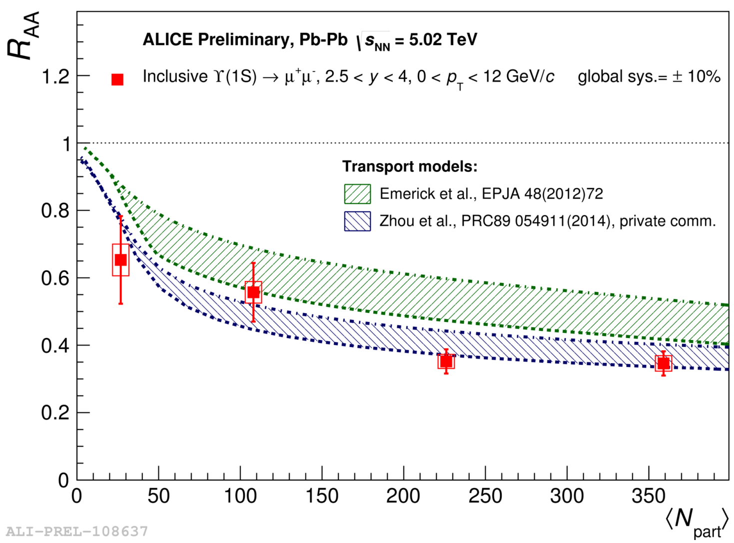




2.76 TeV: R_{AA} = 0.30 ± 0.05 (stat.) ± 0.04 (syst.)
5.02 TeV: R_{AA} = 0.40 ± 0.03 (stat.) ± 0.04 (syst.)

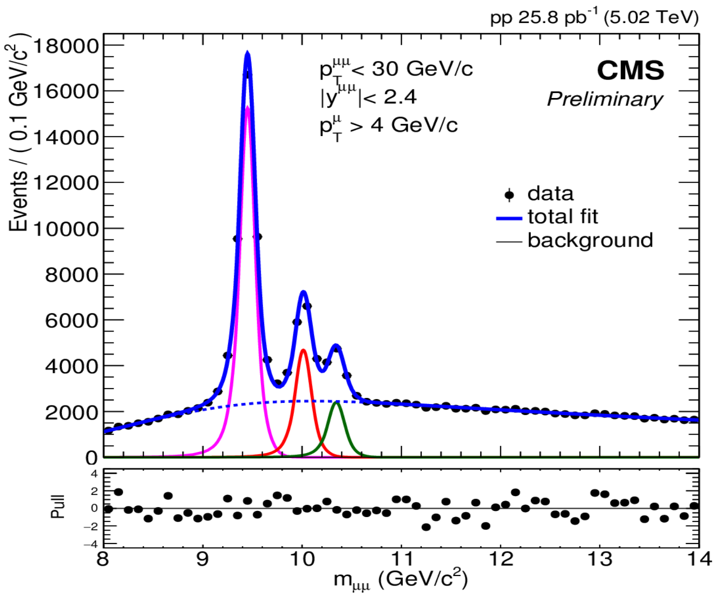
Emerick et al:
- includes regeneration
- feed-down fraction tuned to LHCb + ALICE
- band corresponds to variation of shadowing within 0-25%

Zhou et al:
- without regeneration
- band corresponds to varied feed down fractions
- CNM effects based on EKS98

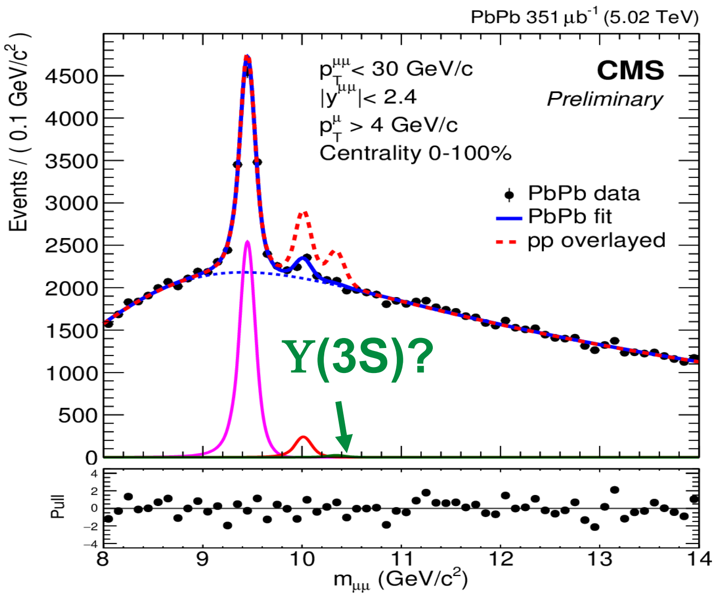


New Υ measurements at 5.02 TeV with CMS

pp @ 5.02 TeV



Pb+Pb @ 5.02 TeV



CMS-PAS-HIN-16-008

Excellent mass resolution of dimuon invariant mass spectra

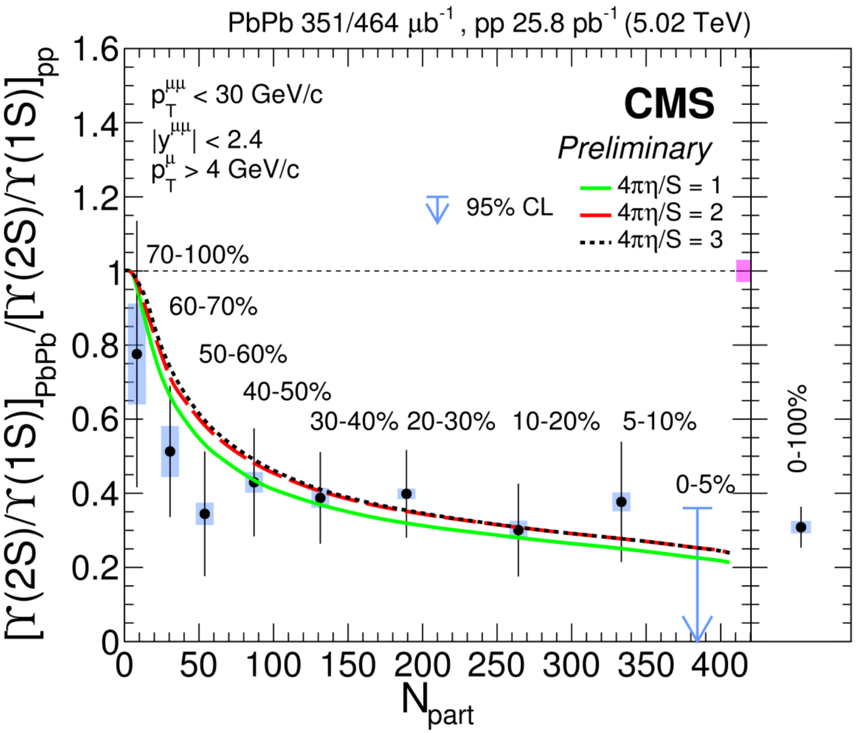
pp collisions: all three Υ states are present

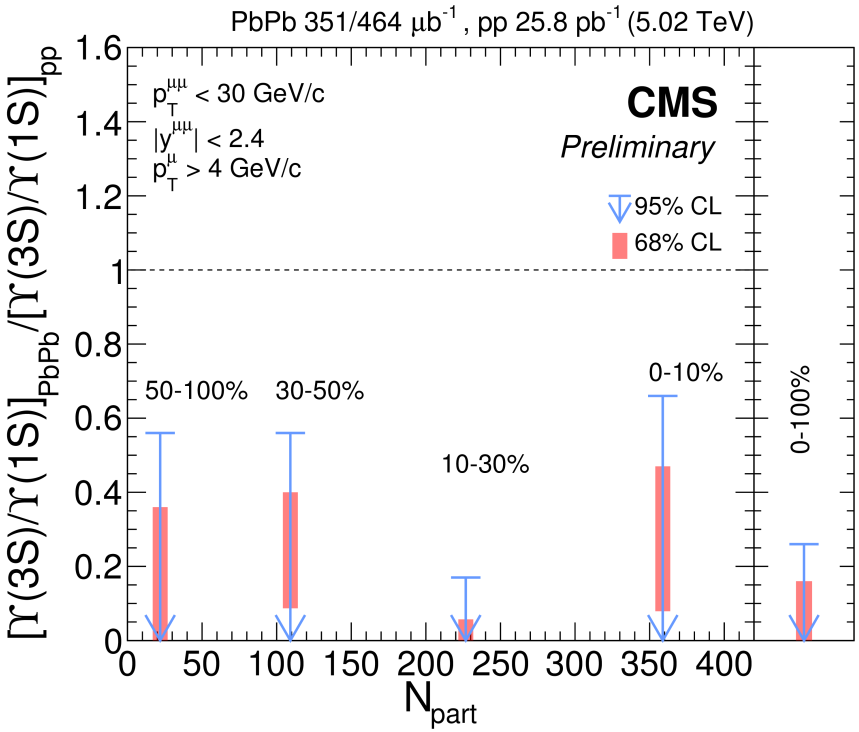
BUT

Pb+Pb collisions: Υ(3S) state not visible

Improvements relative to 2012: 2.3x luminosity of Pb+Pb and >100x of pp sample
+ cross-section increase from 2.76 to 5.02 TeV: 1.8

New Υ measurements at 5.02 TeV with CMS





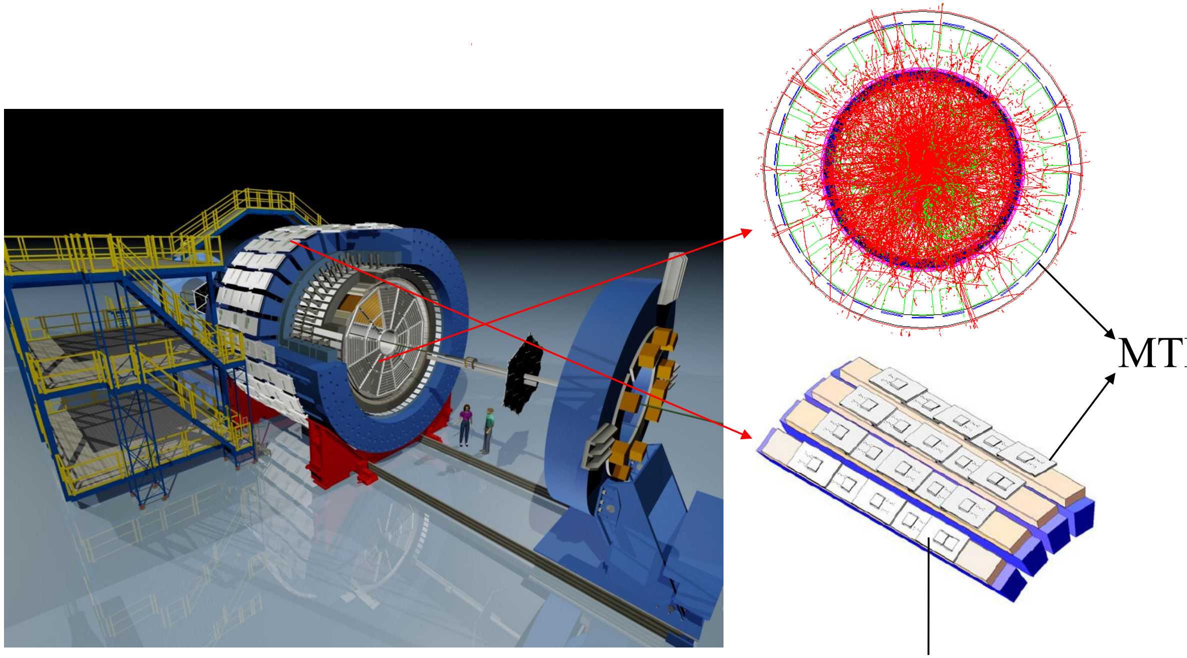
CMS-PAS-HIN-16-008

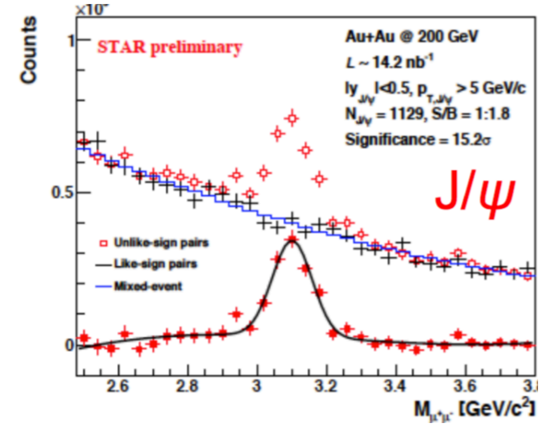
Centrality integrated double ratio:
Y(2S)/Y(1S) Pb+Pb/p+p:
0.308 ± 0.055(stat) ± 0.017(syst)

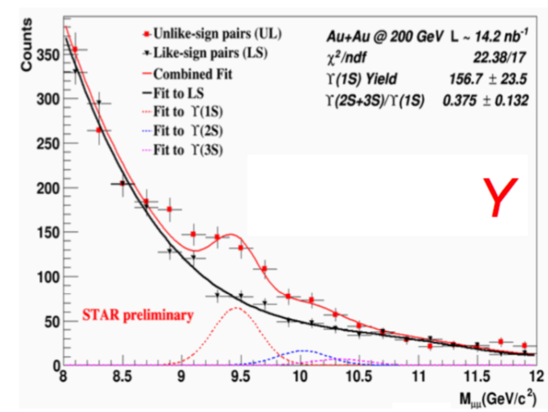
Y(3S)/Y(1S) Pb+Pb/p+p ratio:
is consistent with 0

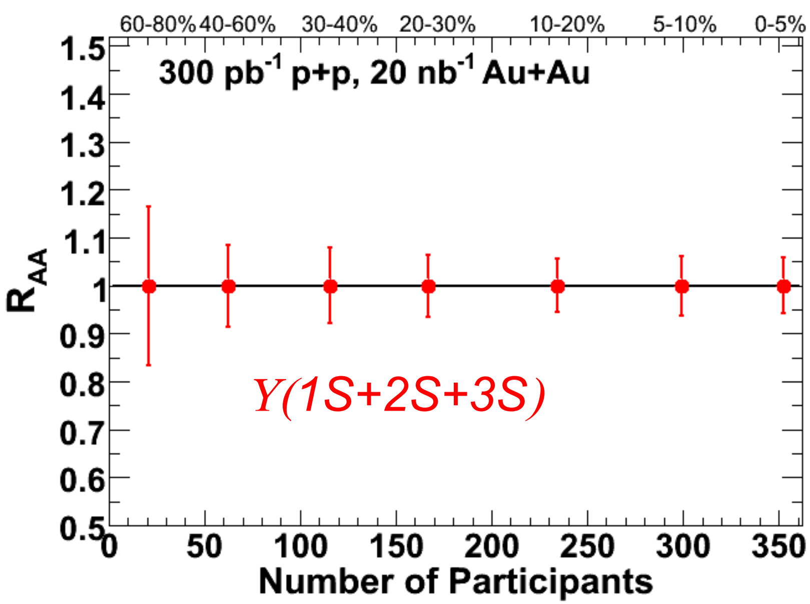
No strong variation of the suppression with p_T or rapidity observed
(not shown here)

Muon Telescope Detector of STAR









- muon trigger and PID
- MRPC outside of the STAR magnet (inner STAR material acts as absorber of other charged particles)
- time resolution ~100ps

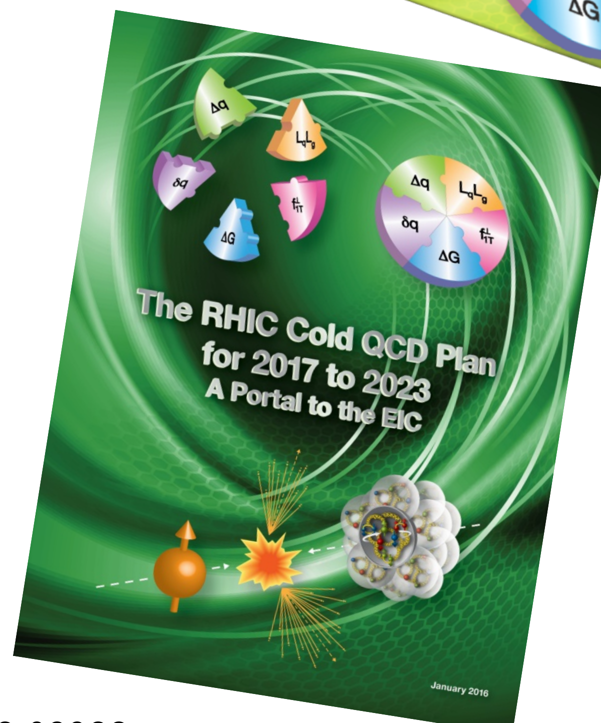
Summary and outlook

- Studies of QCD matter at RHIC and LHC are becoming more quantitative in the sector of c and b quarks

  thanks to recent detector upgrades of STAR (HFT, MTD) and planned upgrades of ALICE (ITS) + large statistics data samples

- also many new jet measurements including their internal structure and shape are coming (unfortunately no time to review themhere)

- Near future at RHIC:
  - Beam Energy Scan II
  - cold nuclear matter program at RHIC inevitable prior to the next frontier which is an Electron-Ion Collider …

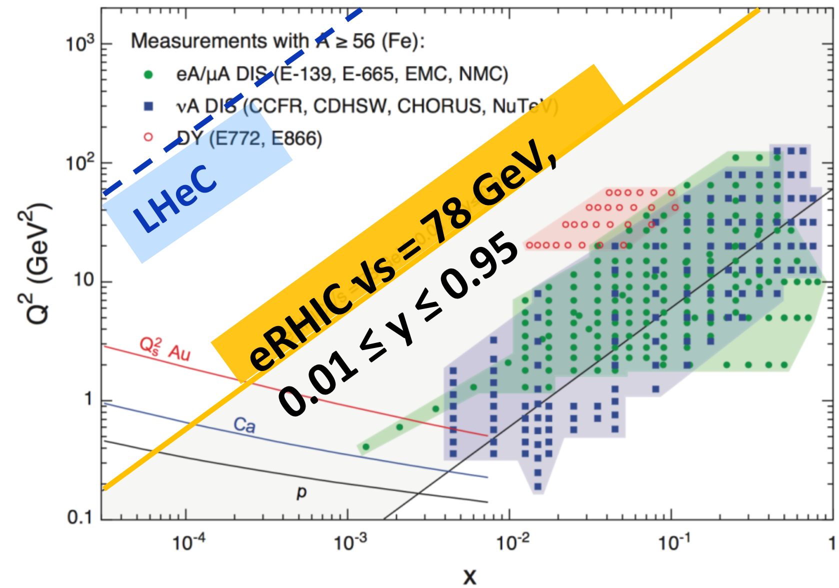


arXiv:1501.01220, arXiv: 1602.03922

Long term plan: toward an Electron-Ion Collider

Key questions:

- distribution of quarks (q) and gluons (g) in space and momentum inside the nucleus
- onset of gluon saturation
- nuclear environment effects on q and g distributions and their interactions in nuclei

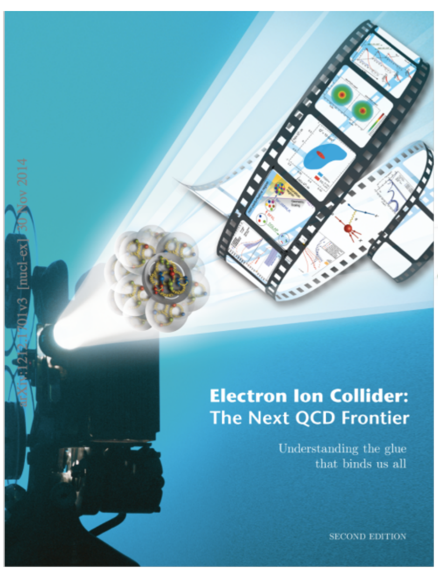


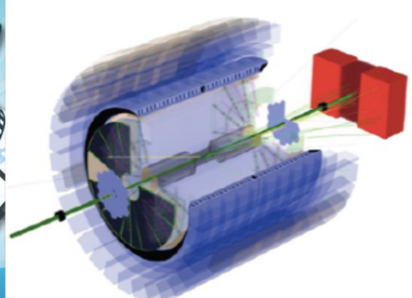
US based EIC: nuclei and *polarization (~2025)*

eRHIC at BNL or MEIC at Jefferson laboratory

Europe's EIC: nuclei and *energy*

LHeC post ALICE





eSTAR at eRHIC