HARD QCD processes in ALICE

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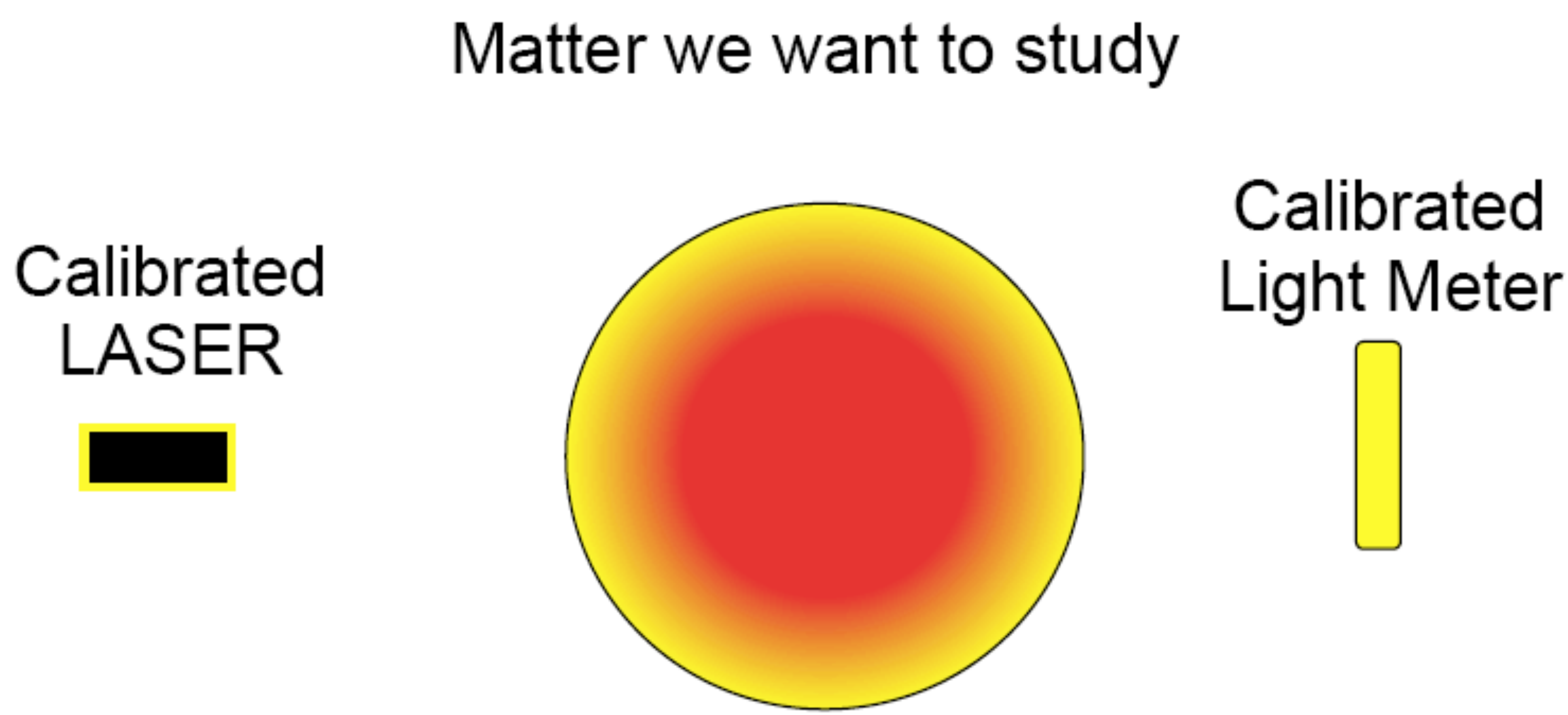
WE-Heraeus Physics School

QCD – Old Challenges and New Opportunities

Bad Honnef, Sept 24–30, 2017

How can we PROBE something?



* picture by T. Ullrich

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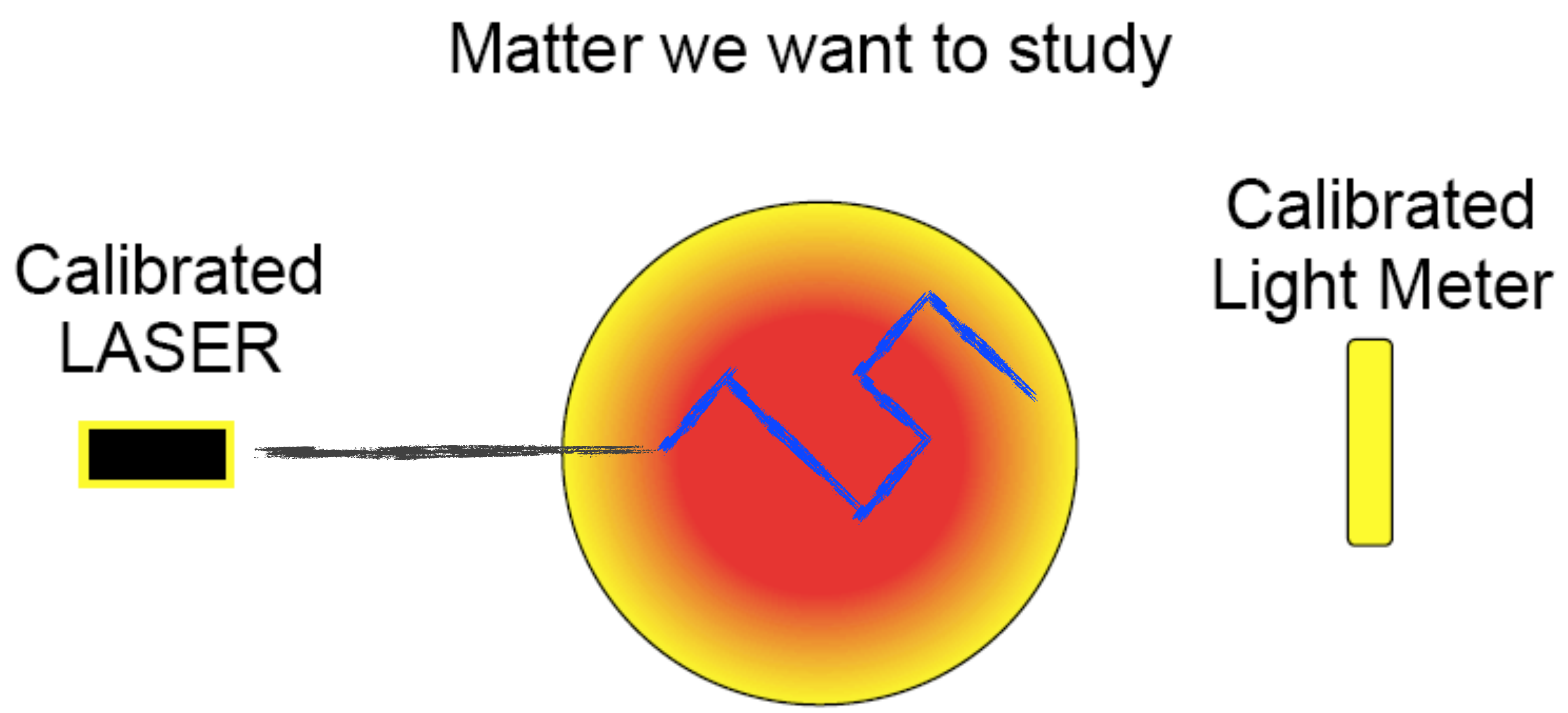

Interaction "matter - probe"

* picture by T. Ullrich

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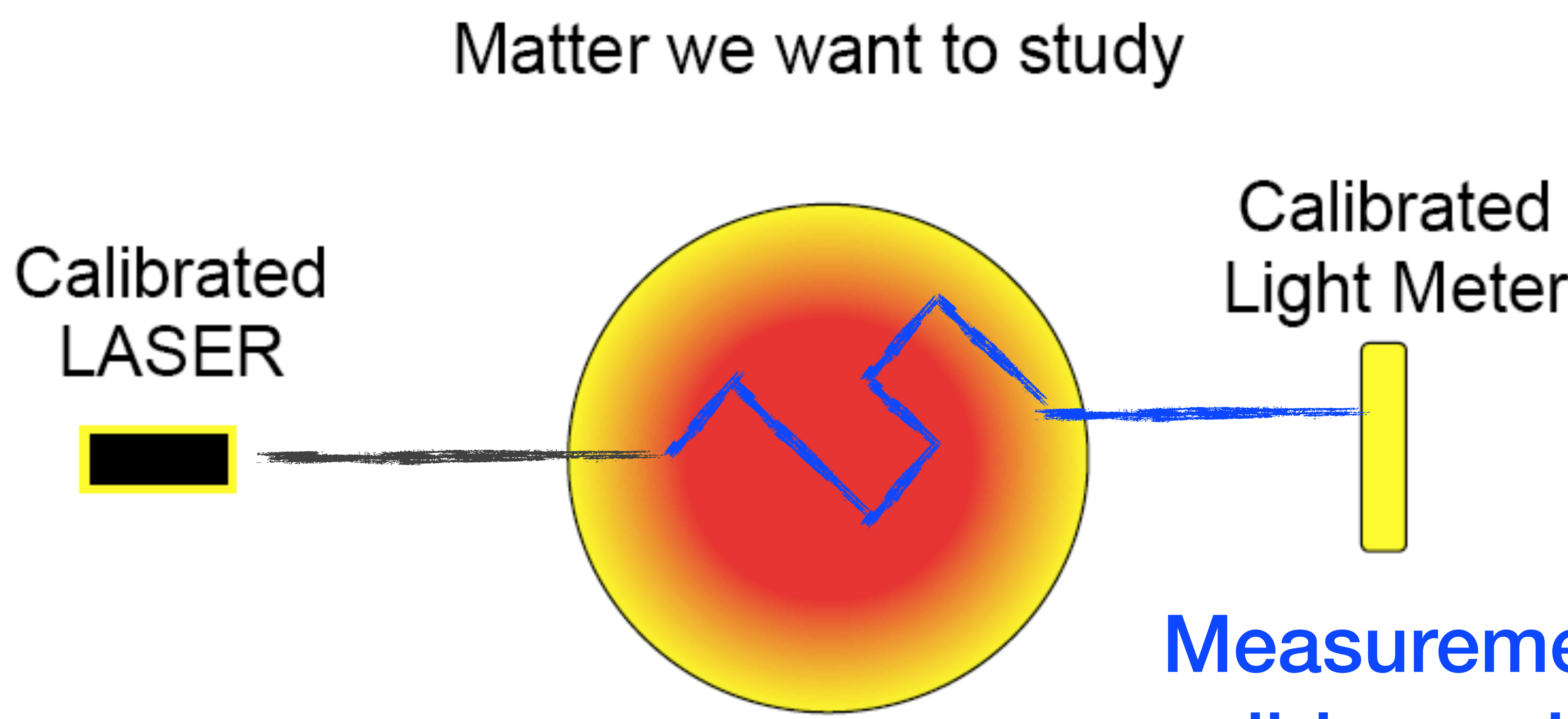
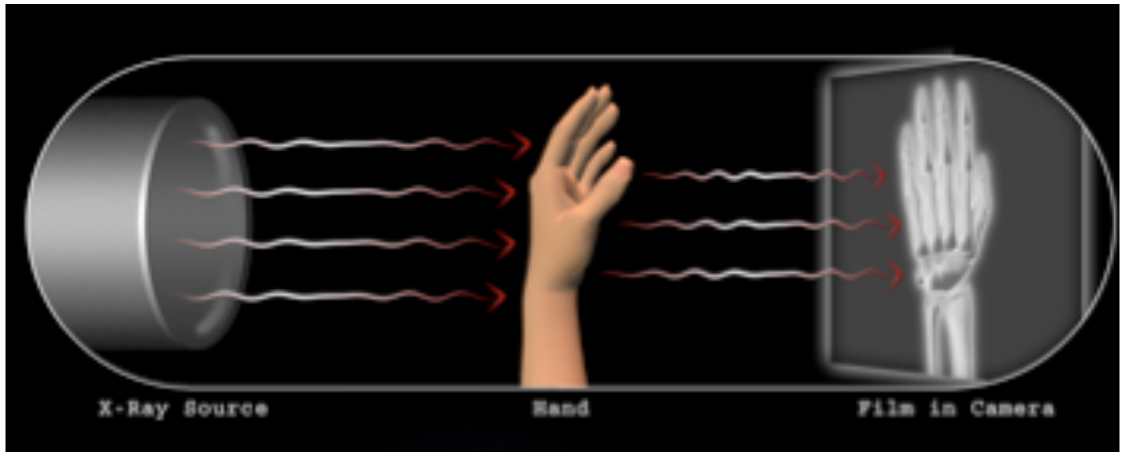


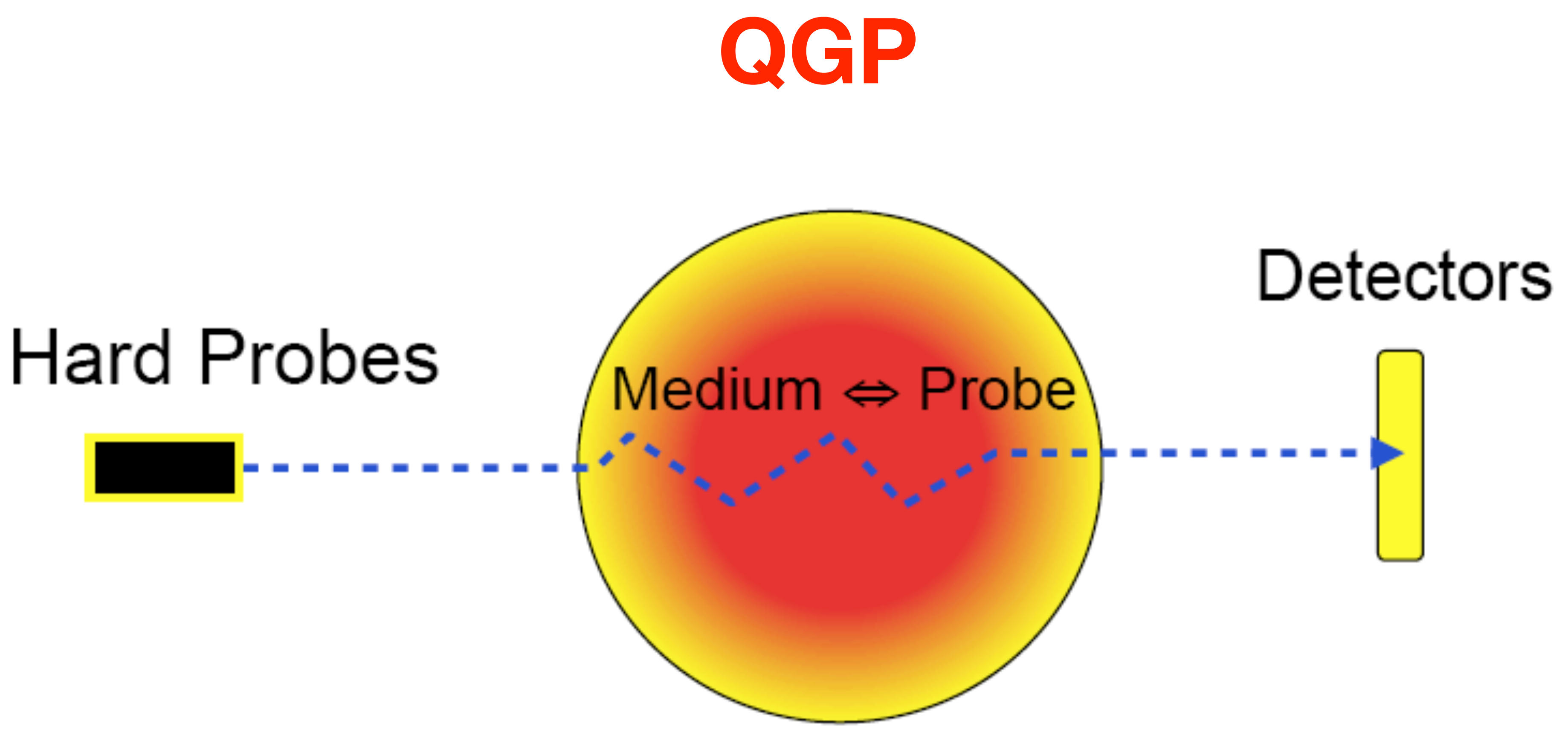
Measurement of possible modification due to interaction of the probe with medium



X-ray studies

* picture by T. Ullrich

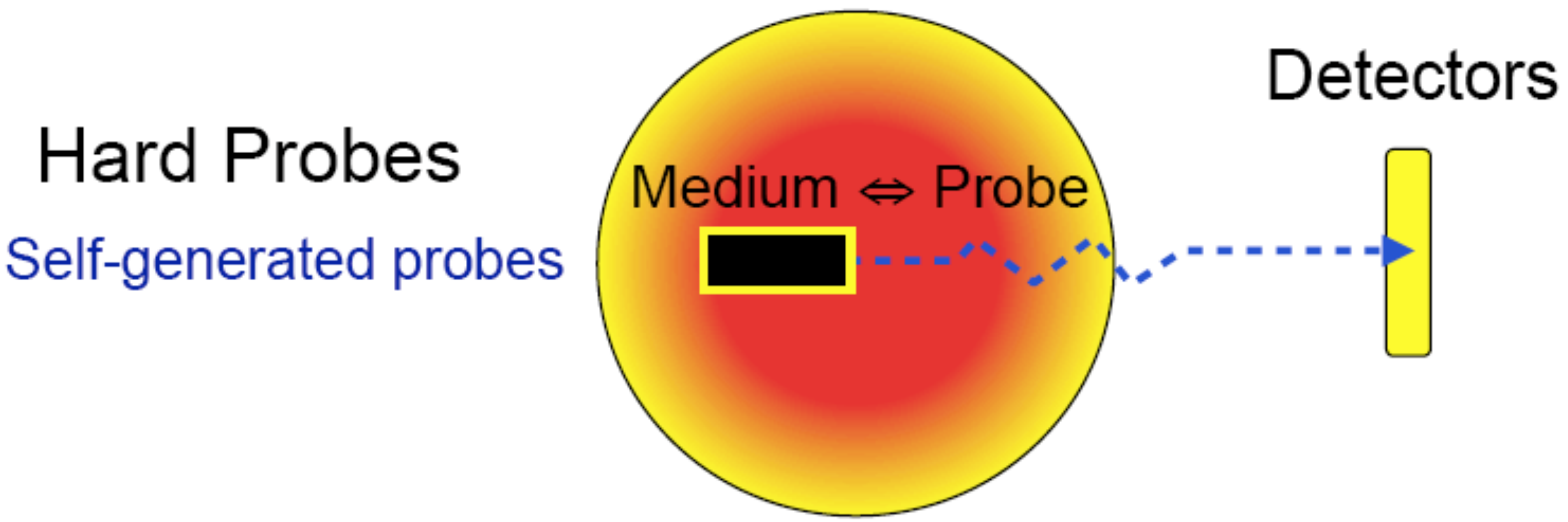
How can we PROBE something?



* picture by T. Ullrich

How can we PROBE something?

QGP



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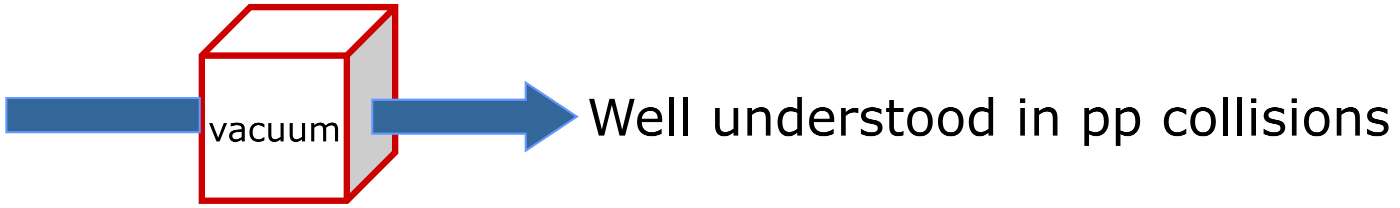
What does “well calibrated” probes mean?

* The behaviour of the probes should be well understood in “standard matter” (pp collisions) where there is no medium created.



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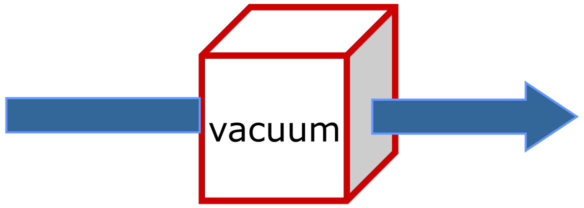
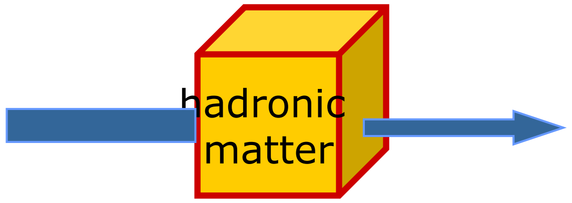


Well understood in pp collisions

* pA collisions allows to investigate the **Cold Nuclear Matter** effects. Those effects are related to the difference for a parton being part of a nucleons or a nucleus*.



Slightly affected by the hadronic matter and in a well understood way

* recents results show that new collective phenomena might be present in high-multiplicity pA collisions. being investigated if we still can consider if as reference

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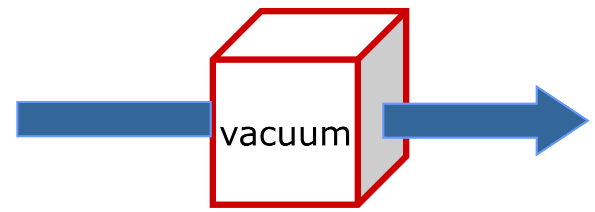

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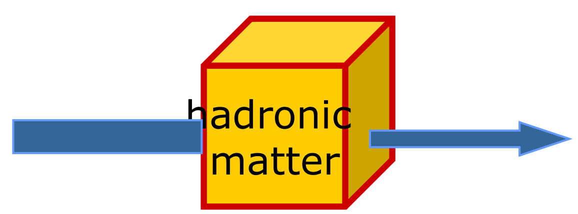
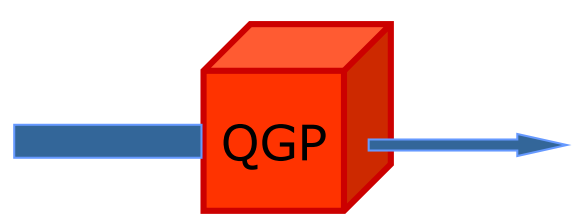


Slightly affected by the hadronic matter and in a well understood way

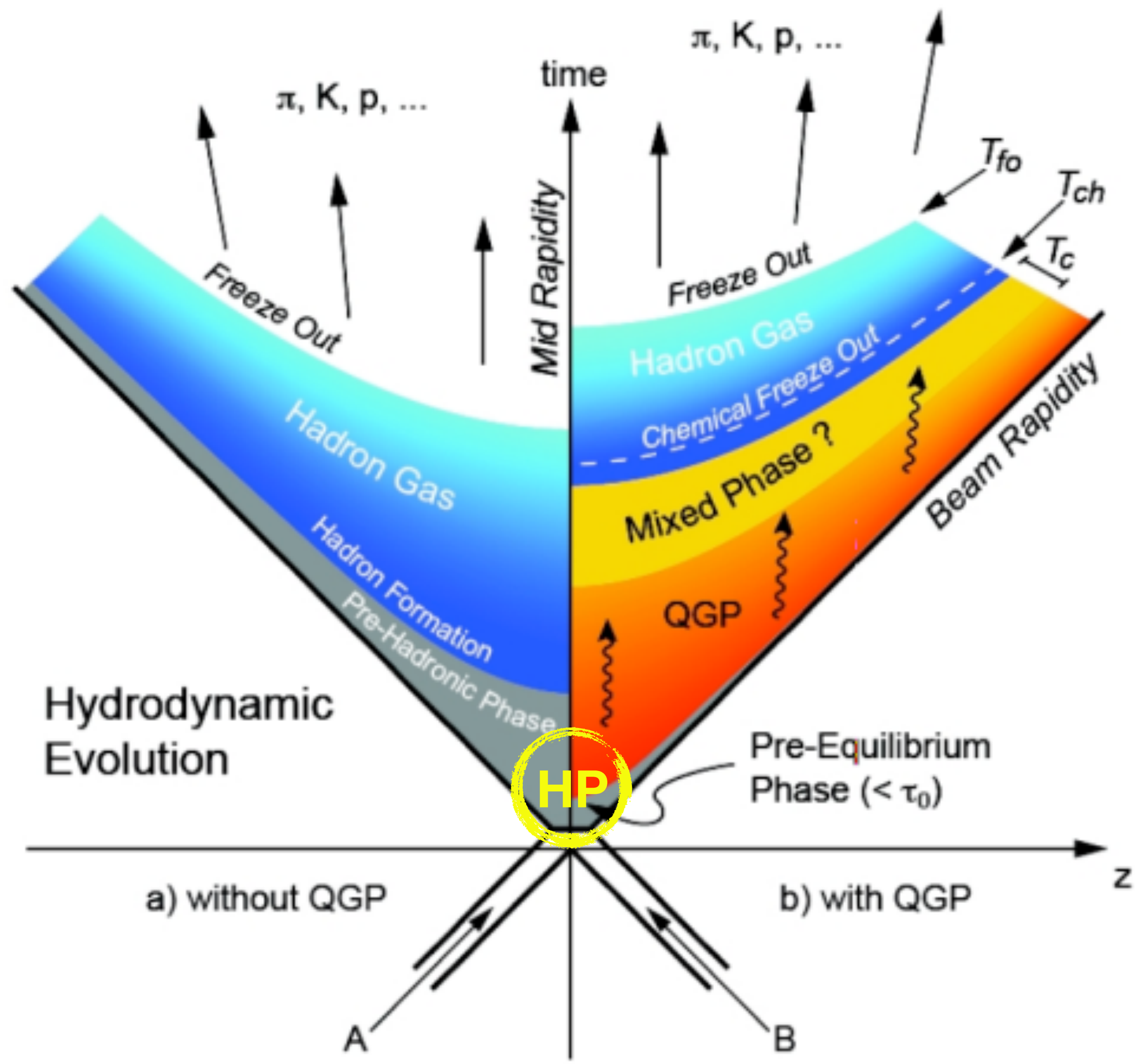
- AA collisions allows to investigate **strongly interacting matter at high energy density (QGP)**



Strongly affected by the deconfined medium

What are and why we use “hard probes”?

* Hard probes are elementary particles (q, g, ɣ, Z, …) usually produced in hard parton-parton scatterings in the early stage of the collisions.



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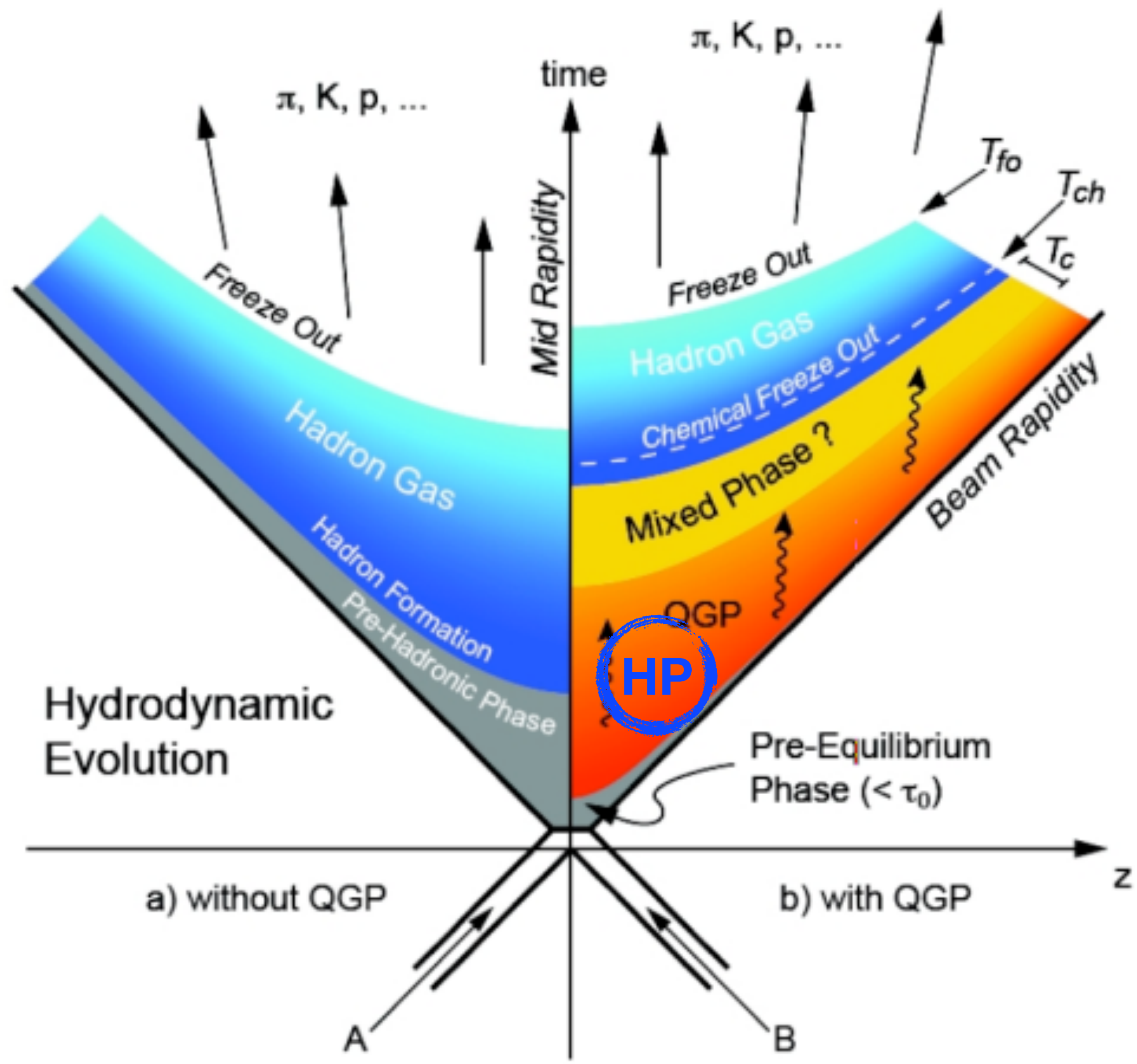
- They can “observe” the full evolution of the QGP and interact with it.



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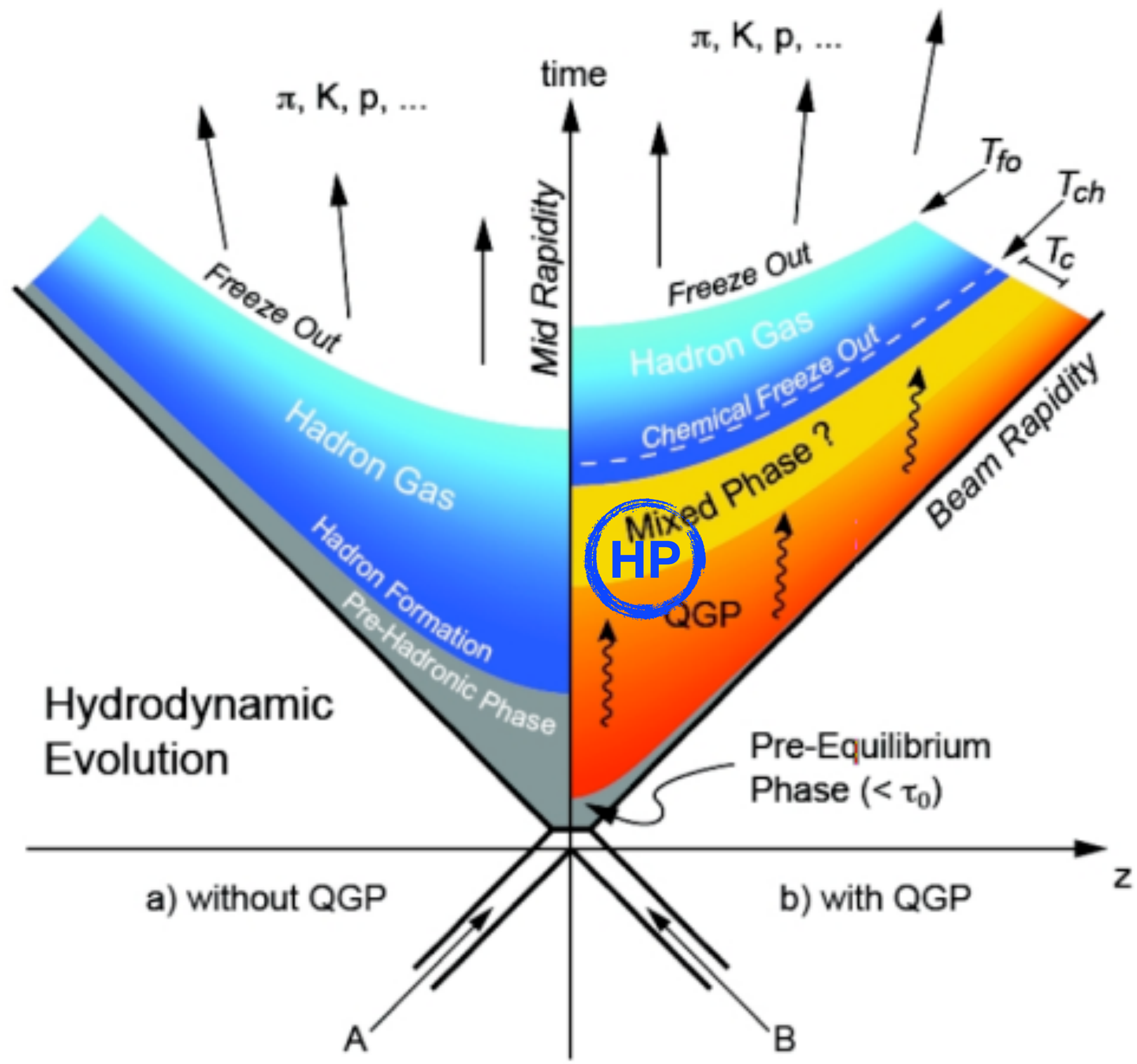

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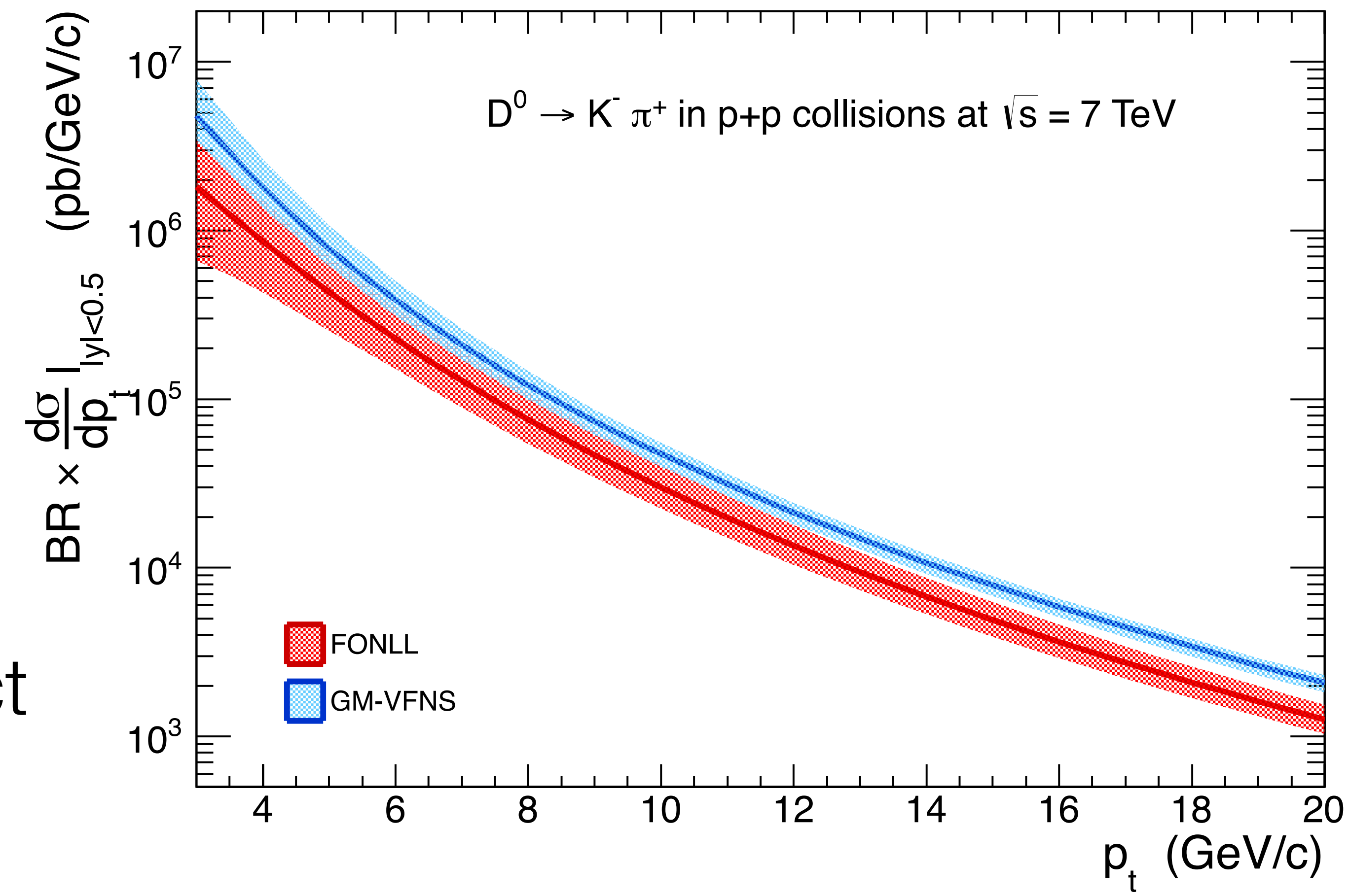
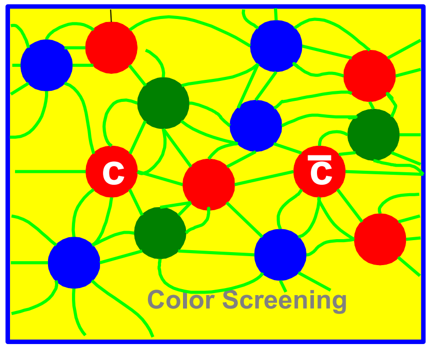


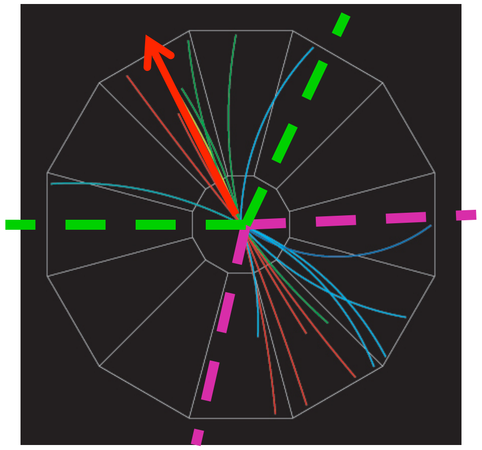
- Since they originate from hard processes, where large momentum transfer Q^2 is involved, their production can be computed using pQCD.

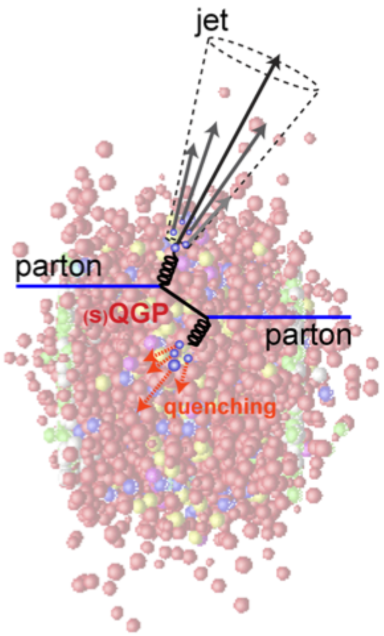
pQCD: perturbative theory can be applied to QCD when α_s is small in high energy or short distance interactions.

What do we measure in the detector?

- Products of fragmentation and hadronization of quark and gluons:
  - High-p_T hadrons
  - Jets
  - Open heavy flavour hadrons
  - Quarkonia







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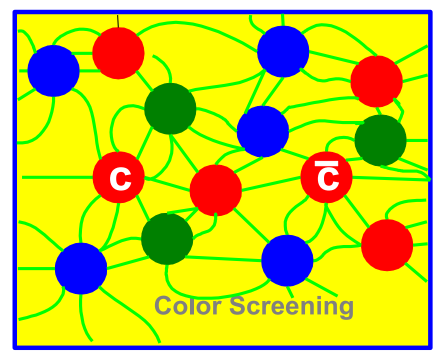

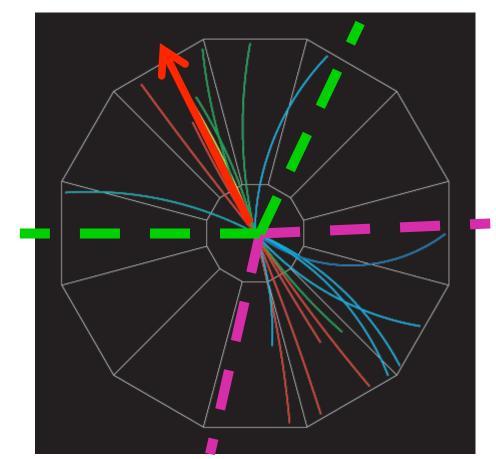

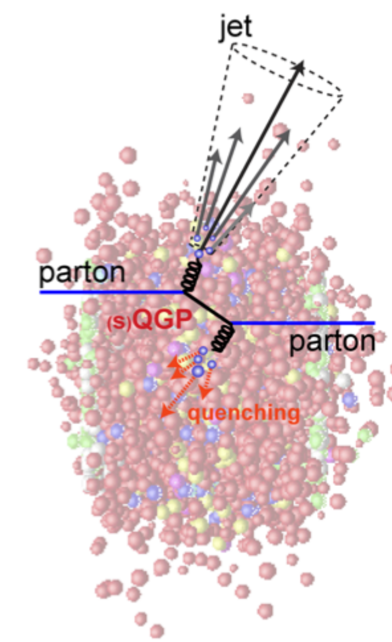

Coloured probes: sensitive to the strong medium interaction

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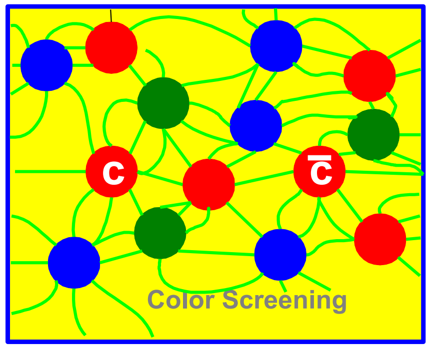
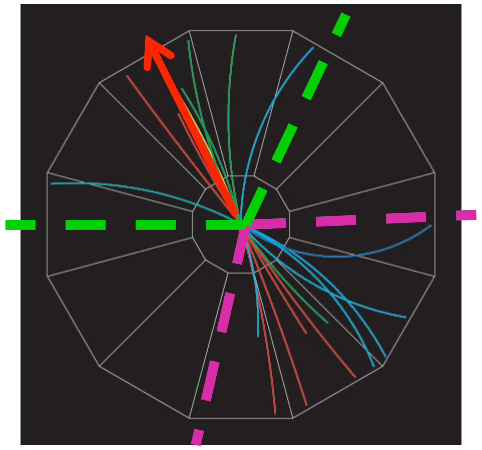
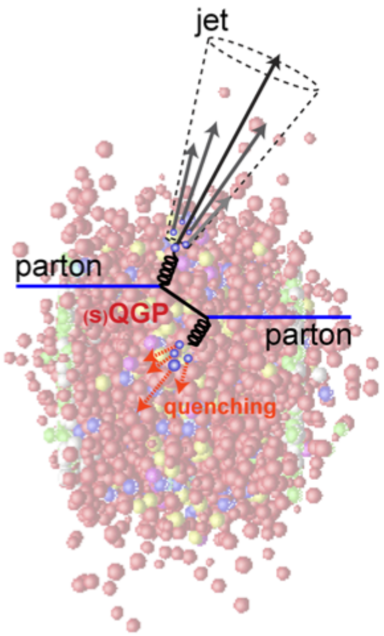






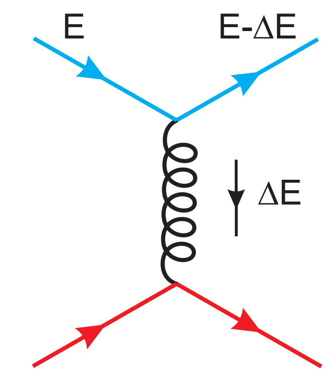
Coloured probes: sensitive to the strong medium interaction

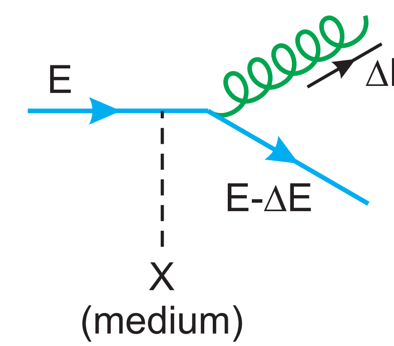
- **Electro-week bosons (W, Z)**
- **Direct photons**

Medium transparent probes: not sensitive to the strong medium interactions

Parton energy loss - jet quenching

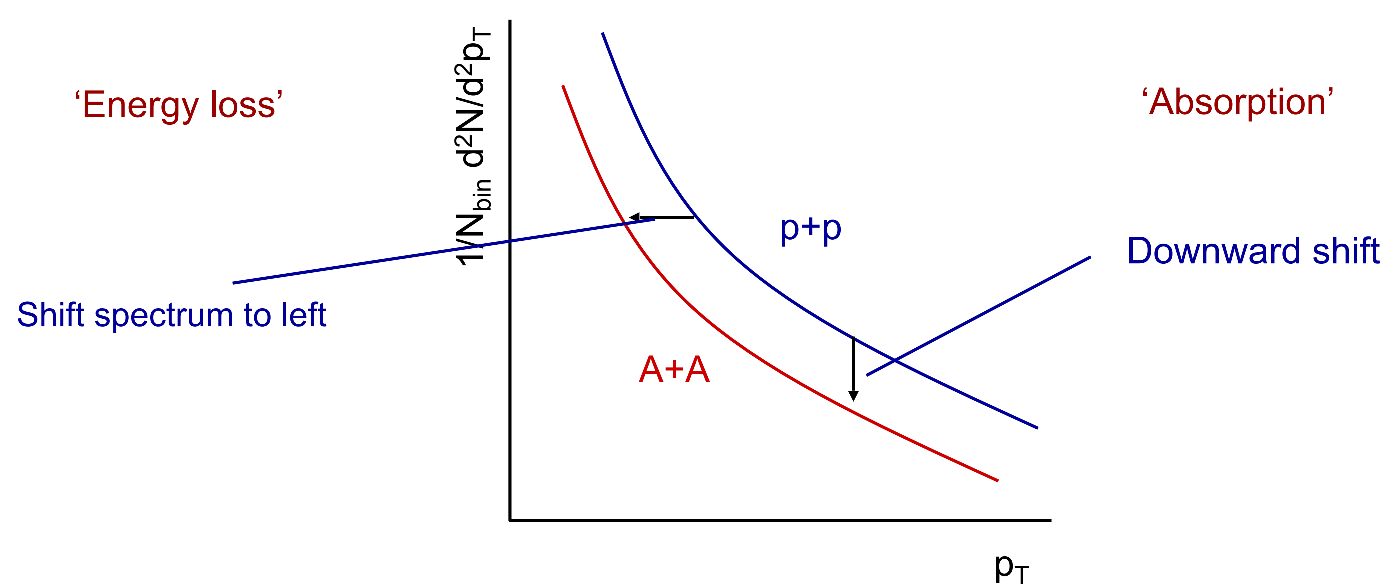
* Partons produced in hard scatterings travel in the QGP and interact with the other partons of the medium.
* In their path they can loose energy for two mechanisms:
  * **Scatterings with other partons** ➜ collisional energy loss
    ➜ dominates at low-p_T
  * **Gluon radiation** ➜ radiative energy loss
    ➜ dominates at high energy





* The reduction of the parton energy translates to a reduction in the average momentum of the produced hadron.

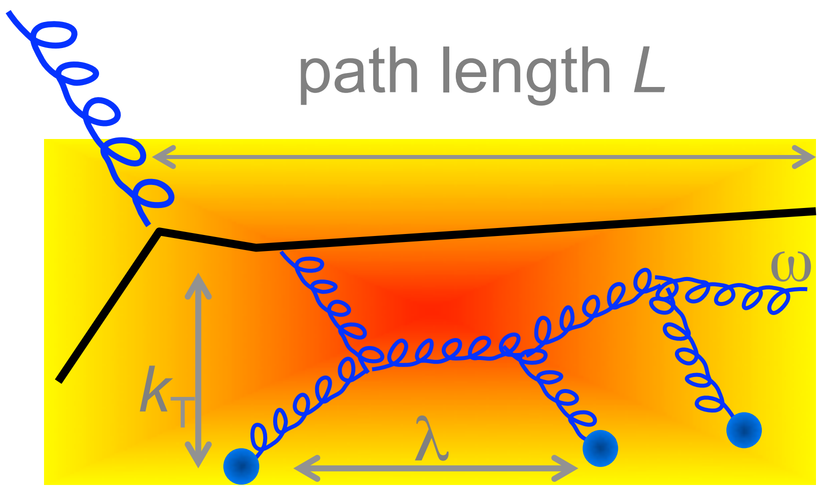
Gyulassy, Pluemer, Wang, Baier, Dokshitzer, Mueller, Peigné, Schiff, Levai, Vitev, Zhakarov, Salgado, Wiedemann,...



Baier, Dokshitzer, Mueller, Peigne‘, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

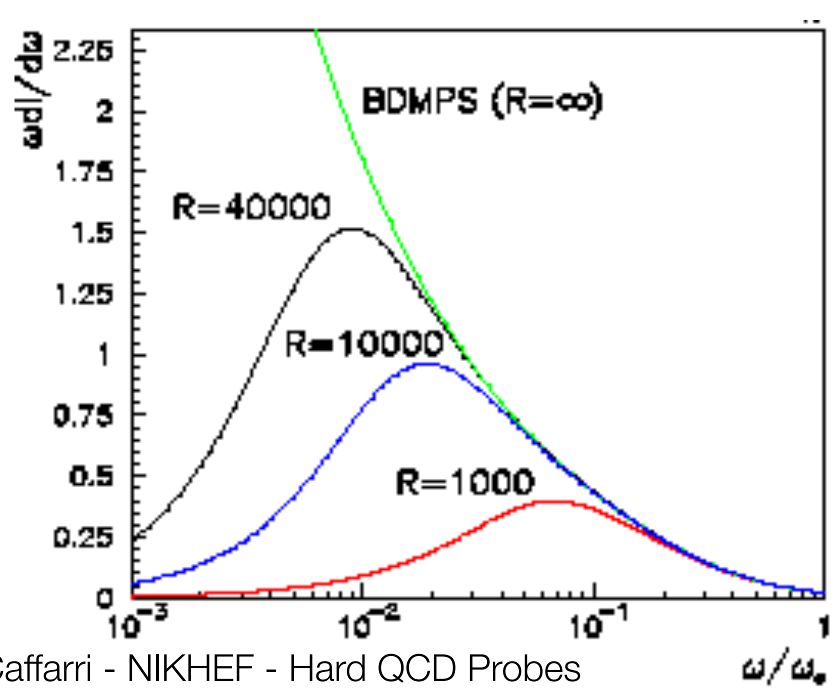
An example: BDMPS-Z formalism

- Medium modeled with static scattering centers
- Coherent gluon wave function accumulate k_T due to multiple inelastic scatterings ➜ the gluon decoheres and it is radiated.



Radiated gluon energy distrib:

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \begin{cases} \sqrt{\omega_c/\omega} & \text{for } \omega < \omega_c \\ (\omega_c/\omega)^2 & \text{for } \omega \geq \omega_c \end{cases}$$



C_R Casimir Factor: 4/3 for q, 3 for g

$\omega_c = \hat{q}L^2/2$ Scale of the radiated energy

$R = \omega_c L$ Constraint: $k_T < \omega$

$$\hat{q} = \frac{< k_T^2 >}{\lambda}$$

Transport coefficient related to the **medium characteristics** and to the **gluon density**

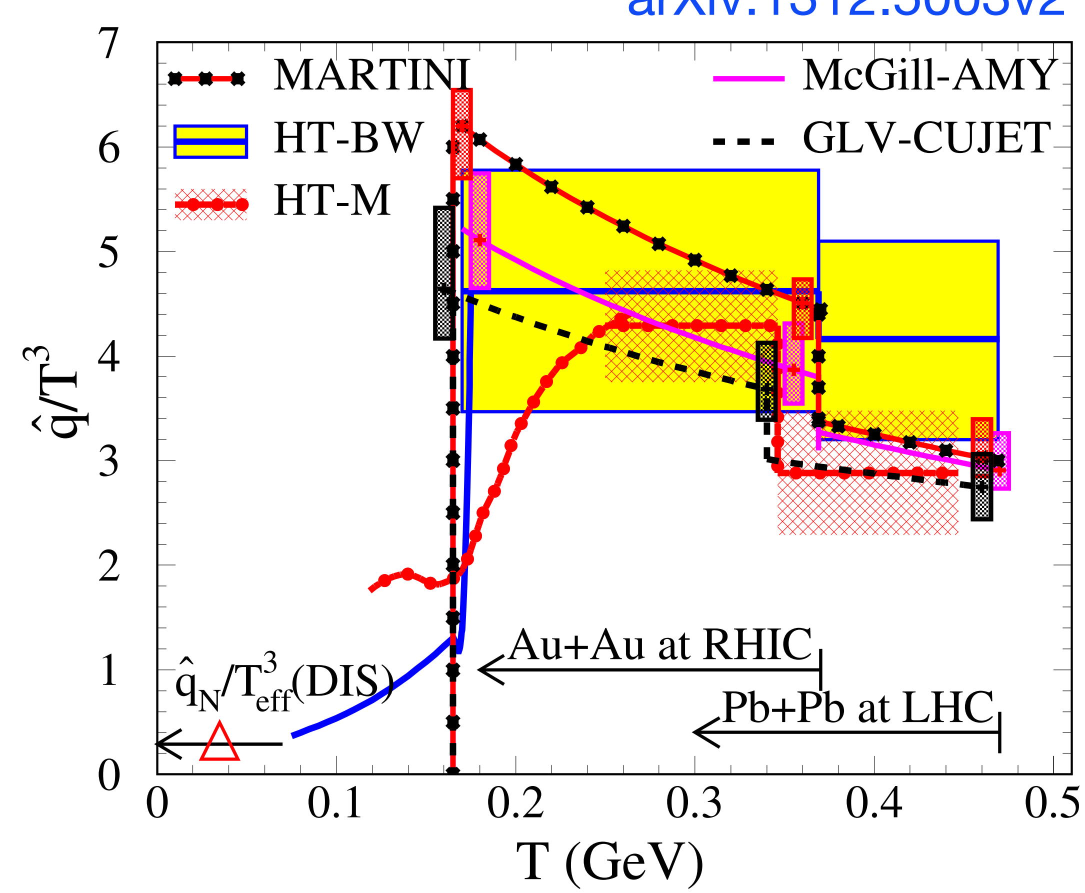
Transport coefficient and energy loss

$$< \Delta E > \approx \int_0^{\omega_c} d\omega \omega \frac{dI}{d\omega} \propto \alpha_s C_R \hat{q} L^2$$

$< \Delta E > \propto \hat{q} \propto$ parton volume density and interaction cross section

* In medium energy loss related to intrinsic medium parameters
  * medium energy density
* $\hat{q}$ can be extracted from theoretical models, using data (both RHIC and LHC) as constraint

arXiv:1312.5003v2



for a quark jet of starting energy 10 GeV

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \;\; \mathrm{at} \;\; \begin{matrix} \mathrm{T{=}370\ MeV}, \\ \mathrm{T{=}470\ MeV}, \end{matrix}$$

Transport coefficient and energy loss

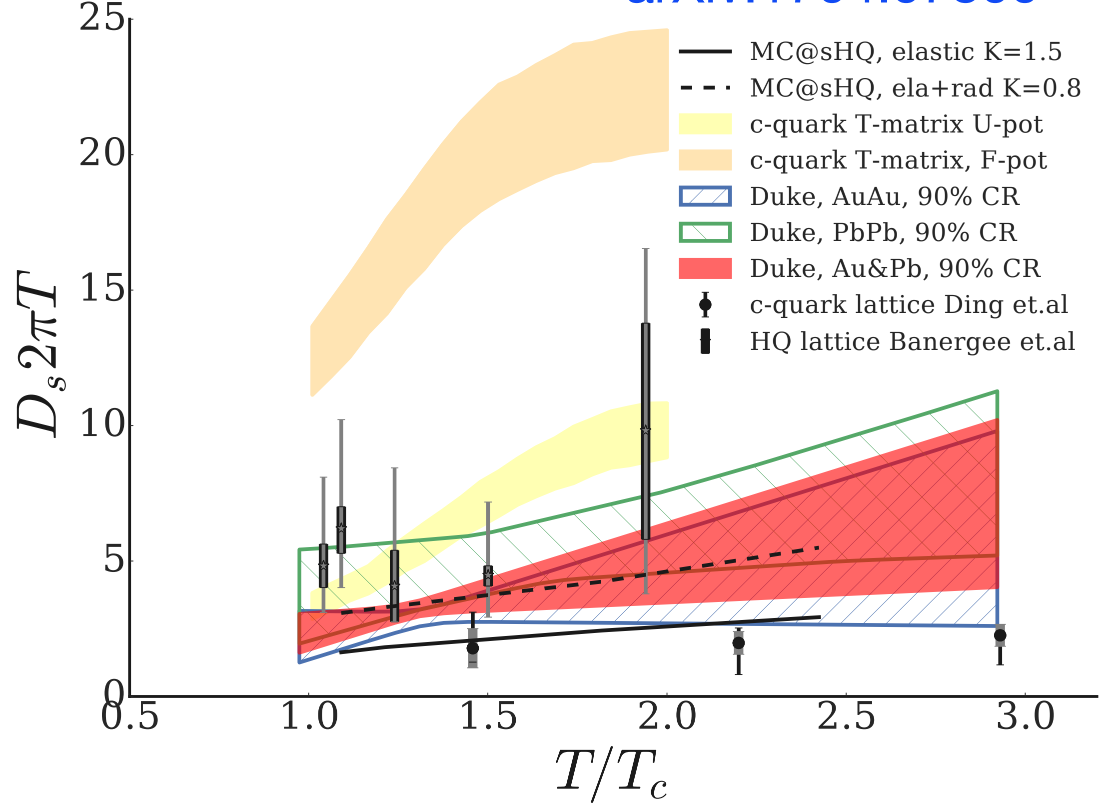
$$< \Delta E > \approx \int_0^{\omega_c} d\omega \omega \frac{dI}{d\omega} \propto \alpha_s C_R \hat{q} L^2$$

$< \Delta E > \propto \hat{q} \propto$ gluon volume density and interaction cross section density

- In medium energy loss related to intrinsic medium parameters
  - medium energy density
  - medium diffusion coefficient

- D_s extracted from Bayesian model-to-data analysis

arXiv:1704.07800

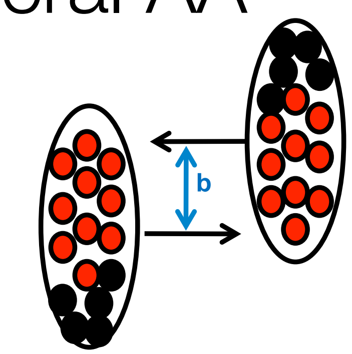


Observables

- **Nuclear modification factor (R_{AA}):**
  - Comparison of the spectra in pp and AA collisions
  - if AA collisions would be a “simple” superposition of many pp collisions $R_{AA} = 1$

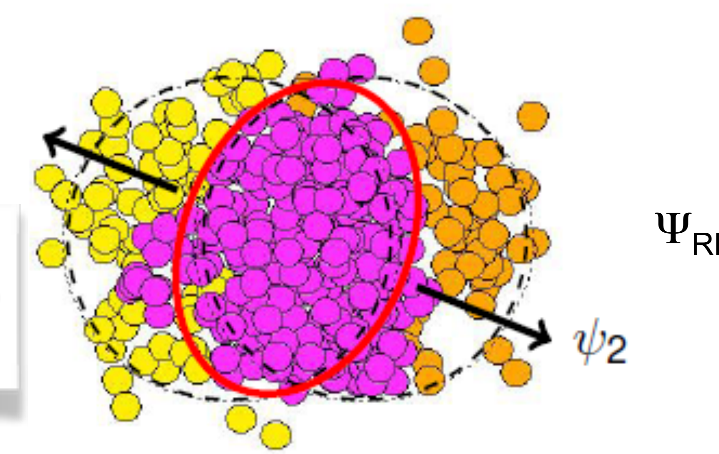
$$R_{AA}(p_T) = \frac{1}{< N_{coll} >} \times \frac{d^2N_{AA}/dp_T d\eta}{d^2N_{pp}/dp_T d\eta}$$

  - Similar ratio can be build comparing central and peripheral AA collisions (R_{CP})



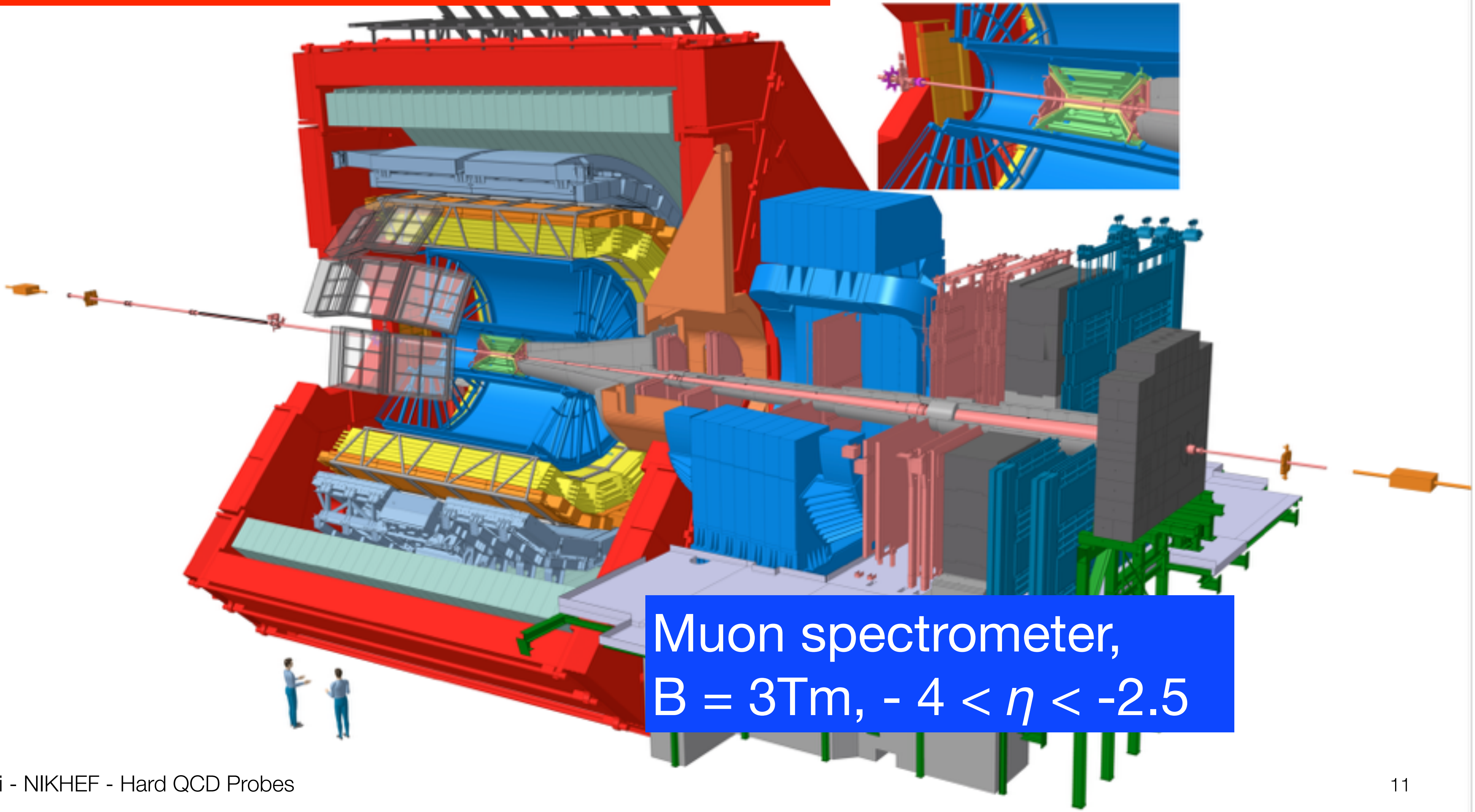
- **Azimuthal anisotropy (v_2) :**
  - Initial spatial anisotropy transferred to the momentum anisotropy of particles.

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



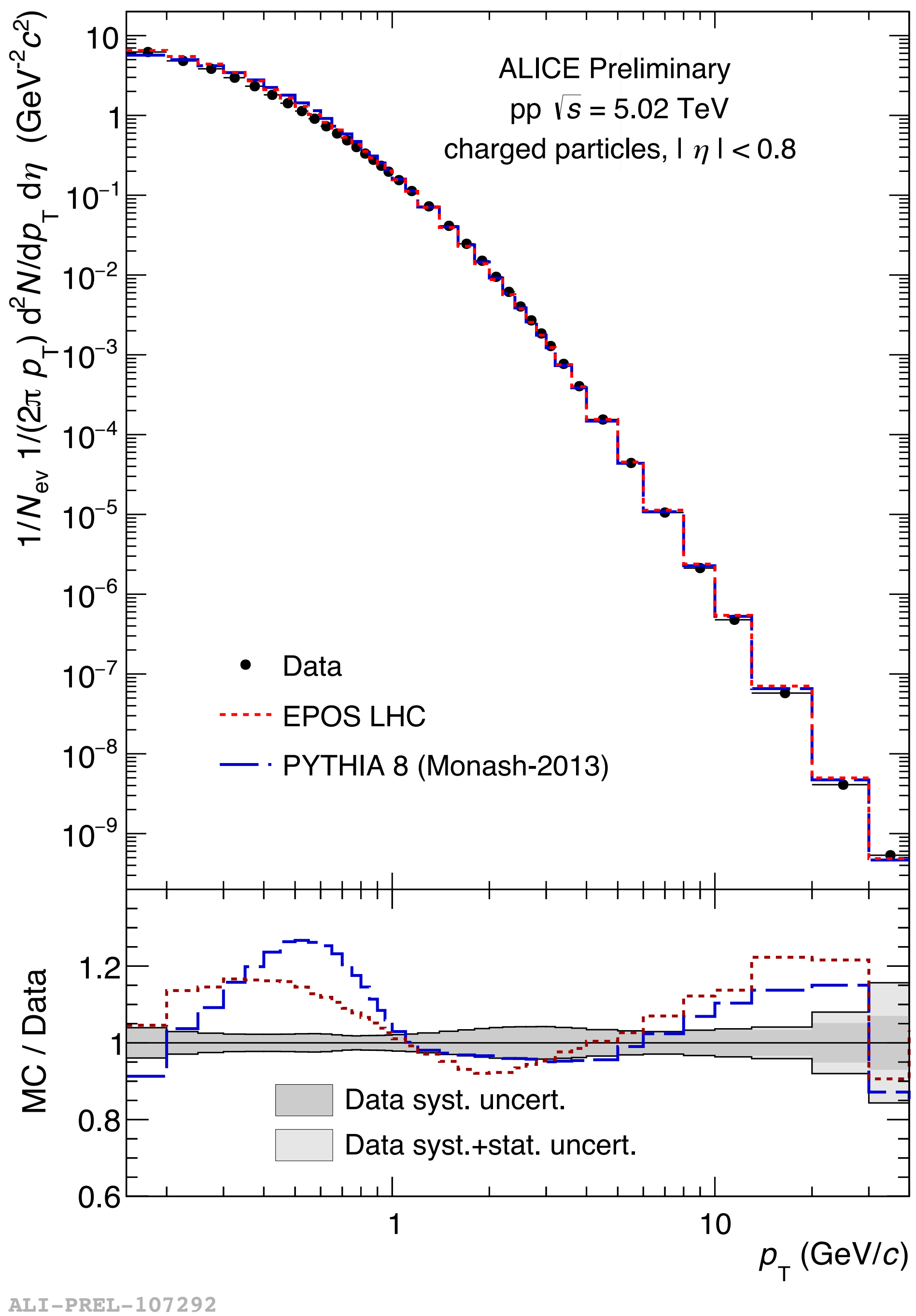
A Large Ion Collider Experiment - ALICE

Central barrel, B=0.5 T, $|\eta| < 0.9$
Tracking, vertexing, PID, Calorimeters



Muon spectrometer,
B = 3Tm, $-4 < \eta < -2.5$

High-p_T hadron suppression - pp reference

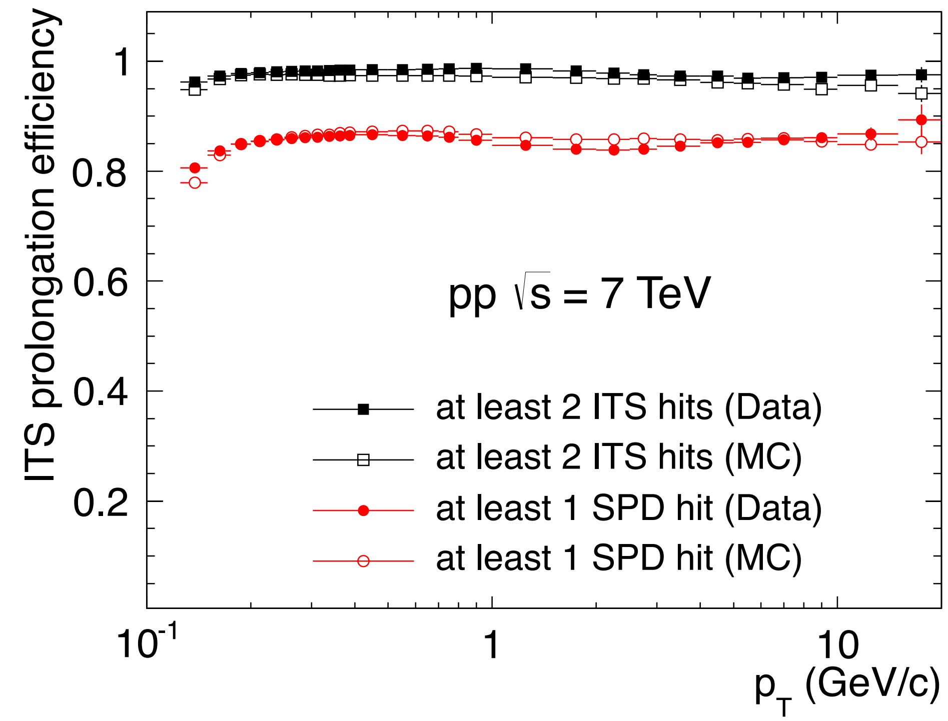


- Measure of the particle production in pp collisions at $\sqrt{s}$ = 5.02 TeV
  - data collected in 2015
  - $0.15 < p_T < 40$ GeV/c
- Comparison with Monte Carlo generators show an agreement with data within 20%
  - Important results in pp collisions to improve MC description.

… but lot of work to measure a particle spectra

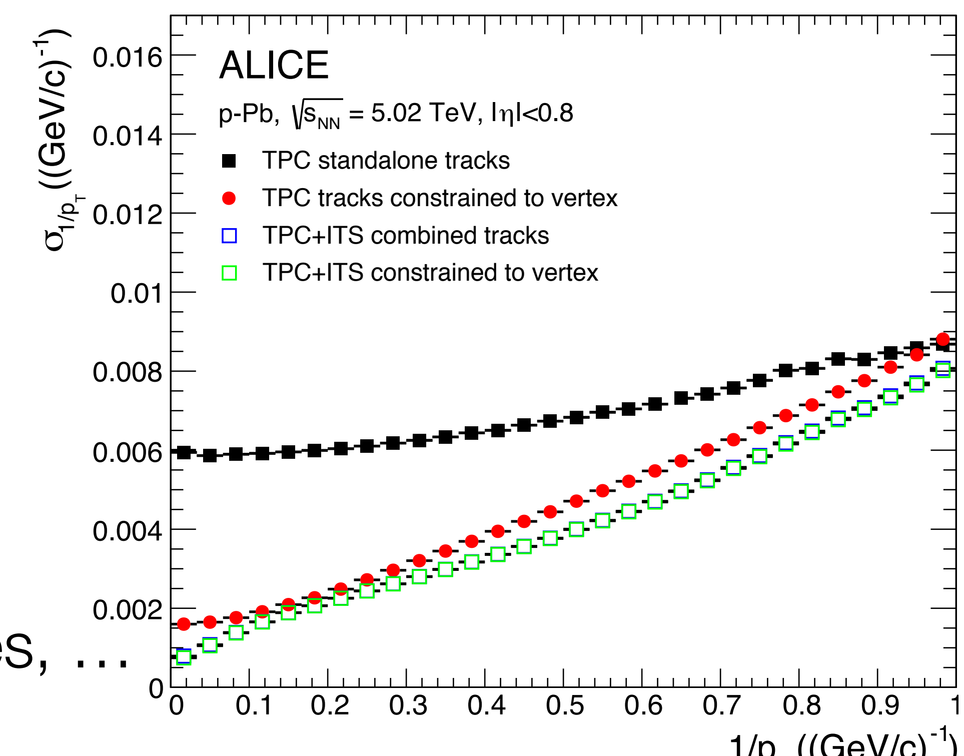
- Tracking efficiencies:
  - ~ 80% from 0.15 < p_T < 20 GeV/c in pp collisions
  - well reproduced in the Monte Carlo
  - similar for Pb-Pb collisions, even if with higher multiplicity → strength of ALICE

Int. J. Mod. Phys. A 29 (2014) 1430044



- Momentum resolution:
  - 0.8% precision on the momentum determination for tracks with p_T ~1 GeV/c
  - 1.8% for tracks with p_T ~10 GeV/c

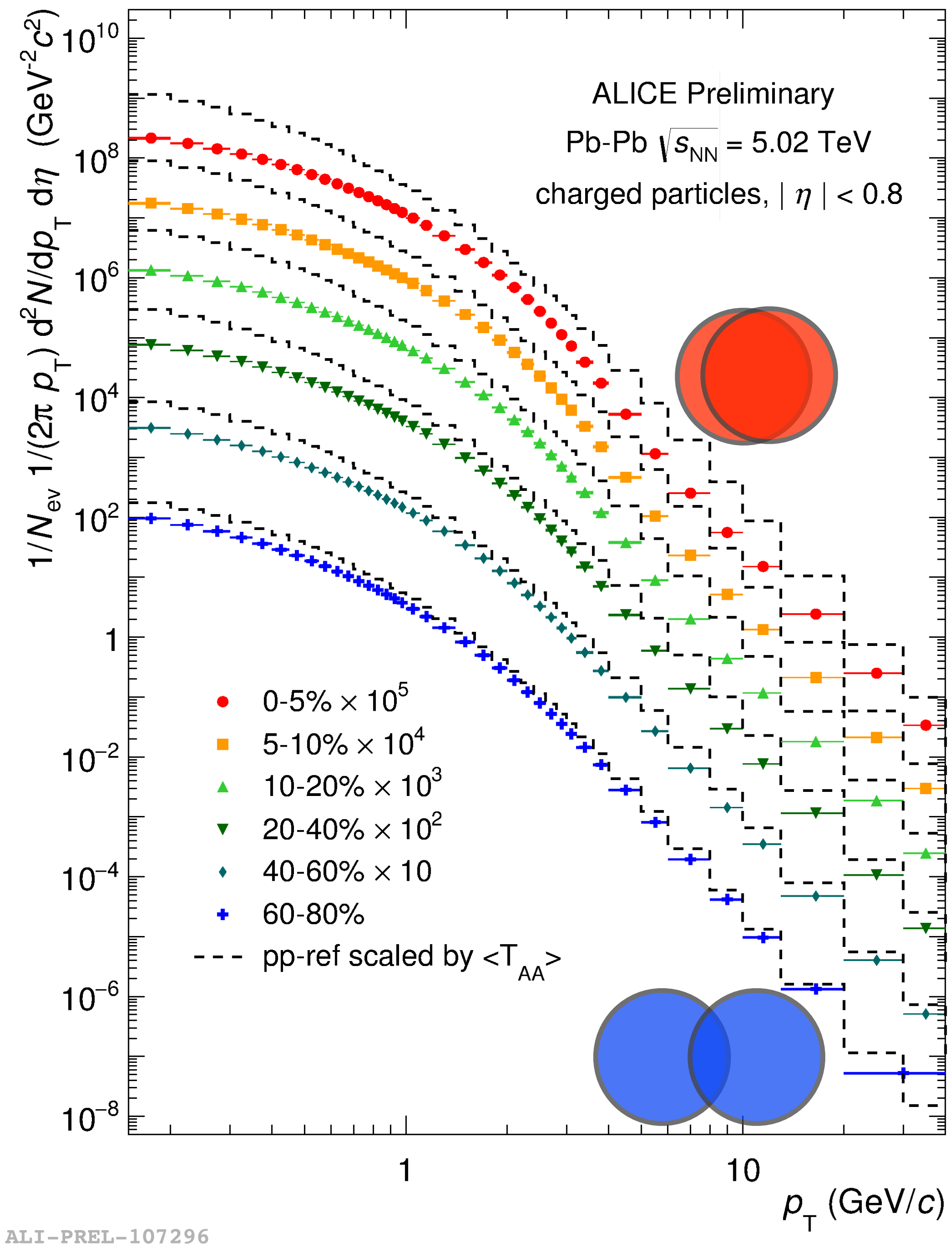
$$\frac{\sigma_{p_T}}{p_T} = p_T\, \sigma_{1/p_T}$$



+ Efficiencies depending on particle species, secondaries, …

High-p_T hadron suppression - Pb-Pb spectra

- Measure of the particle production in Pb-Pb collisions at $\sqrt{s}$ = 5.02 TeV
  - Pb-Pb data collected in 2015
  - $0.15 < p_T < 40$ GeV/c
  - for different centrality classes



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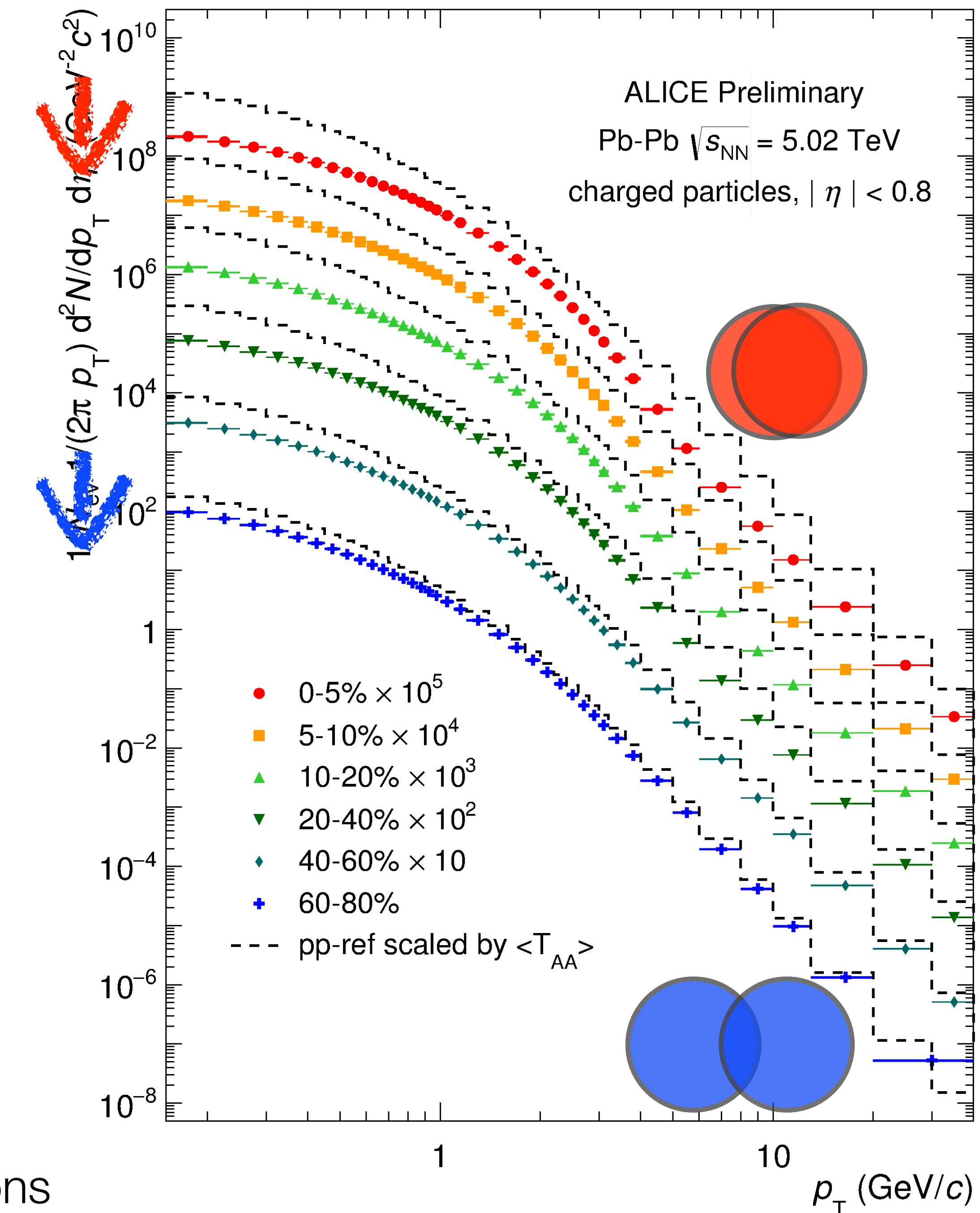
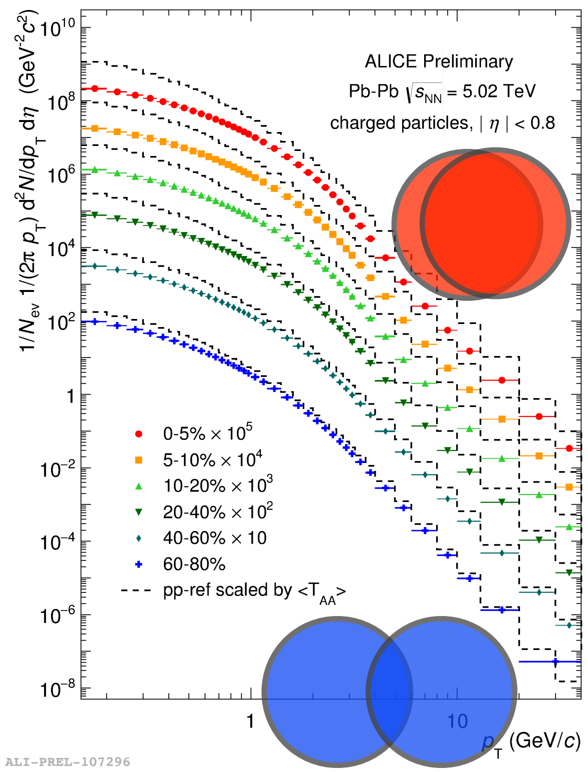


- Reduction of the particle yields in Pb-Pb collisions with respect to pp ones
  - larger decrease for **central** than for **peripheral** collisions

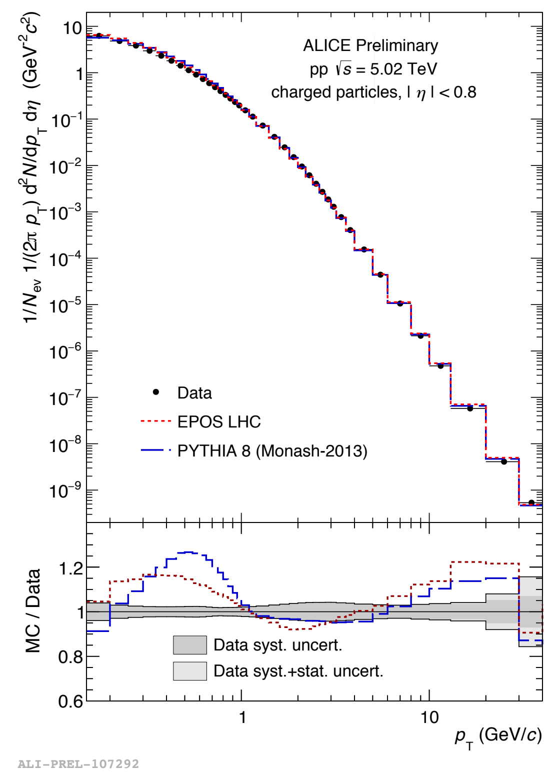
*pp scaled by the number of binary nucleon nucleon collisions

High-p_T hadron suppression - R_{AA}



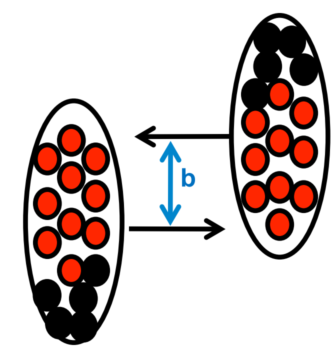
Pb-Pb

pp



X

N_{coll}



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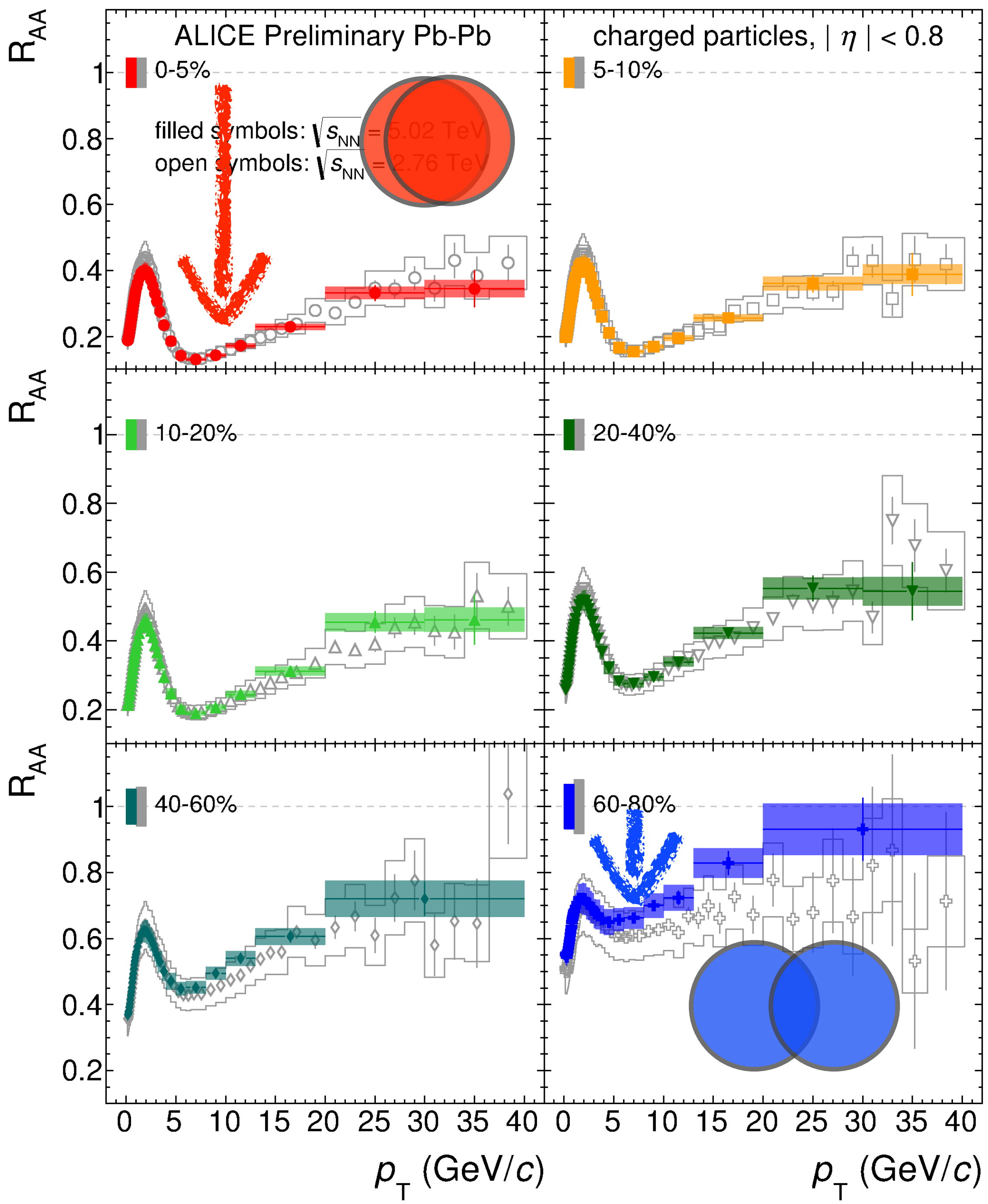
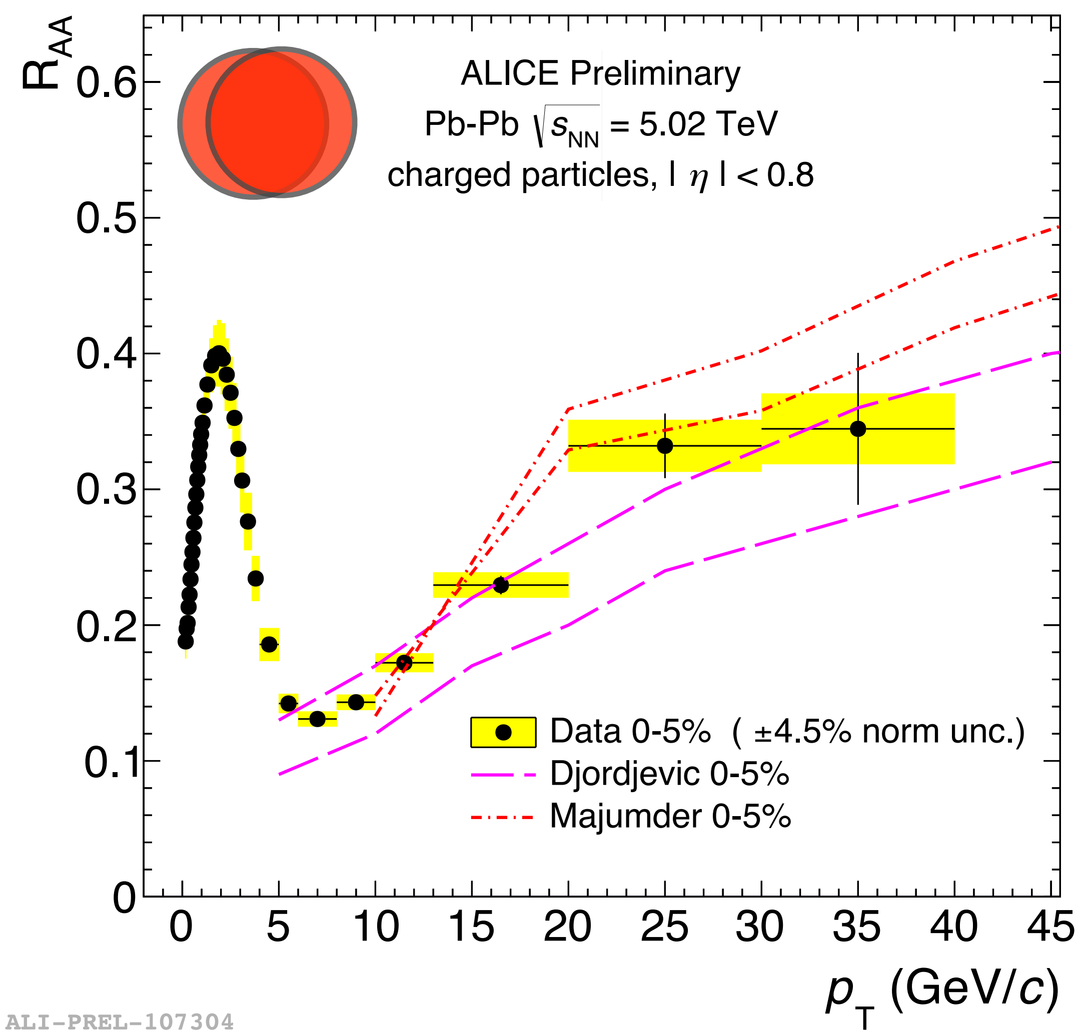


- Nuclear modification factors for charged hadrons:
  - $R_{AA} < 1$ for more central collisions
  - ~ factor 5 suppression at between $5 < p_T < 10$ GeV/c
  - ~ factor 3 suppression at 40 GeV/c
  - suppression decreases (larger R_{AA}) for more peripheral events

High-p_T hadron suppression - R_{AA}



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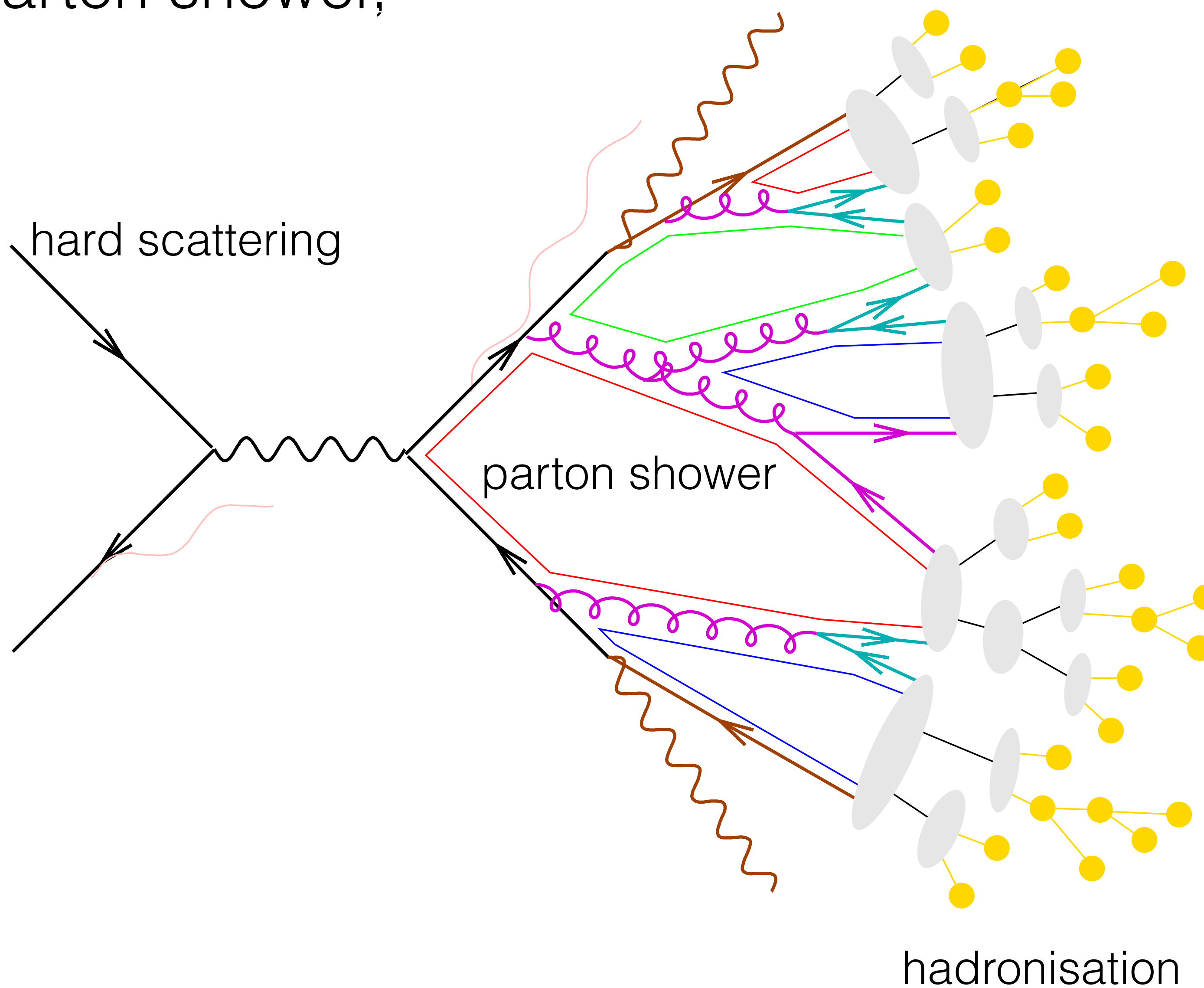
  - suppression decreases (larger R_{AA}) for more peripheral events
- Charged particle suppression described by models that include parton energy loss.

- LHC Run2 opens the era of precision measurements where models and experiments have similar precision. Important usage of data to constrain theoretical models.

Jets

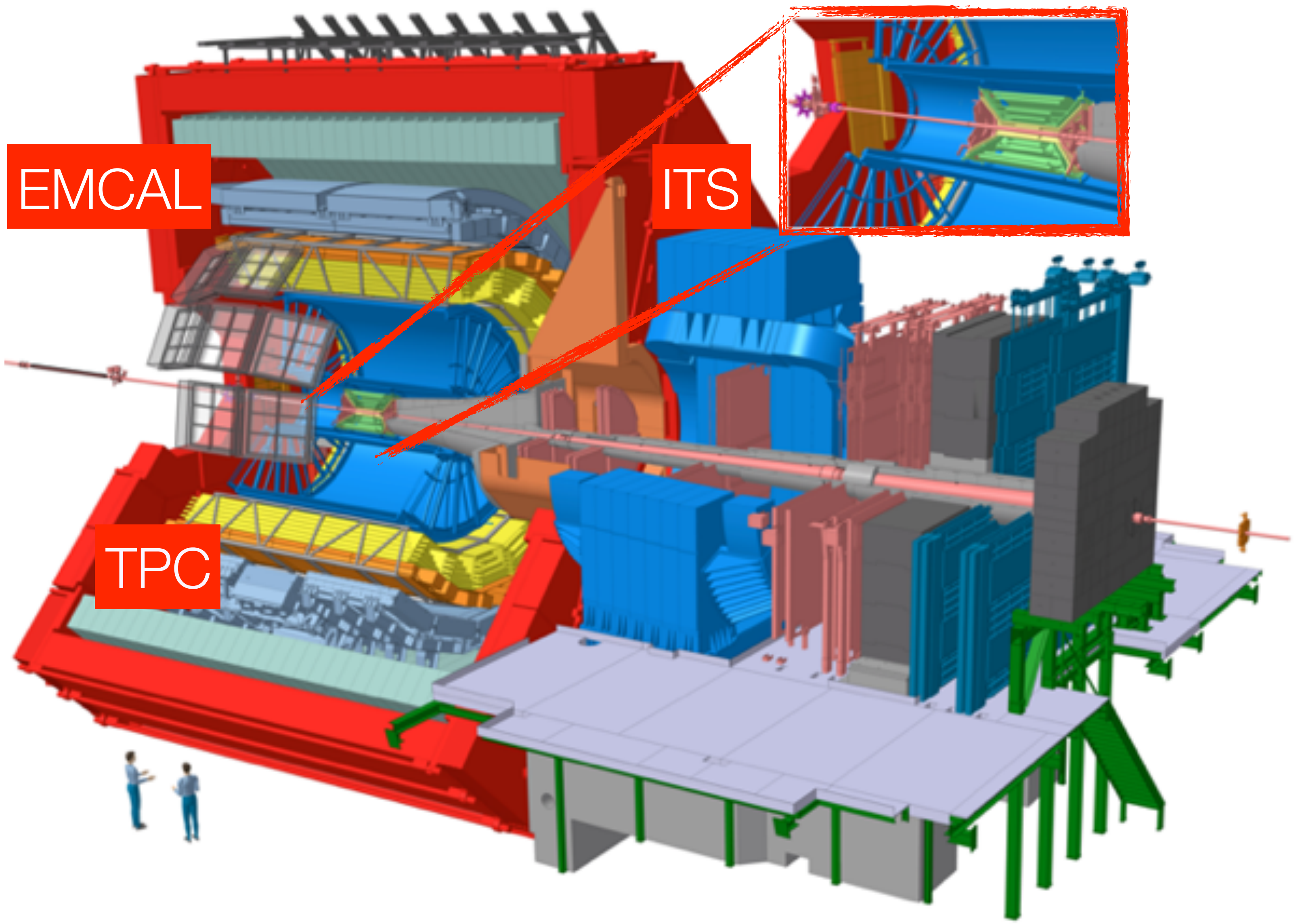
- High-p_T and virtuality partons are produced in initial hard scatterings:
  - virtuality evolution through parton shower,
  - hadronisation at Λ_{QCD} scale.



- No unambiguous definition of a jet:
  - "collimated bunch of hadrons"
  - experimental access to quarks and gluons

- In pp collisions:
  - calculable probes using pQCD,
  - allow to study hadronisation and underlying event effects.

Jets in ALICE



EMCAL: Pb scintillator sampling calorimeter
$|\eta| < 0.7$, $1.4 < \phi < \pi$
$\Delta\eta = \Delta\phi \approx 0.014$
Cluster $E_T > 300$ MeV

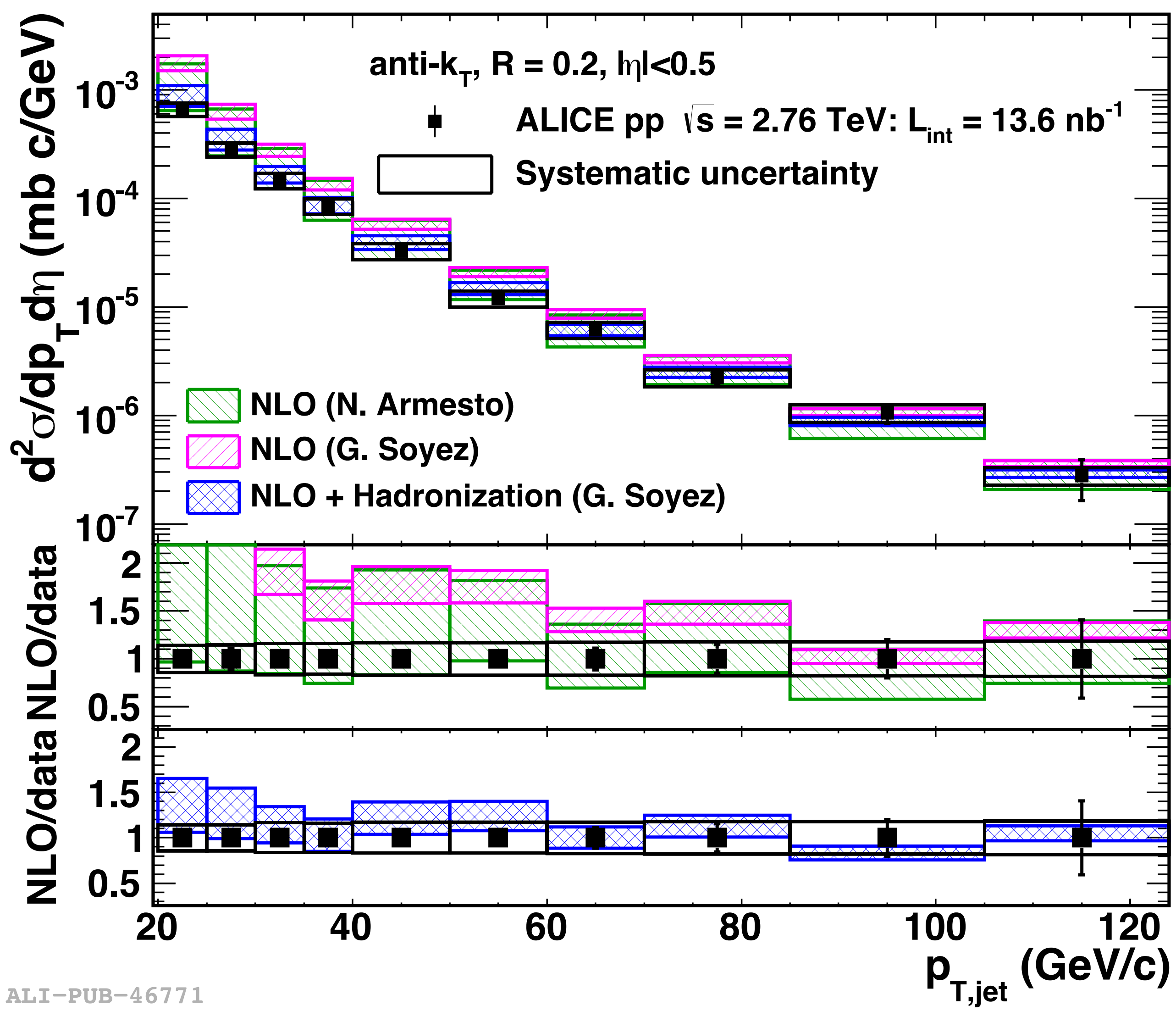
Neutral constituent jets

$|\eta| < 0.9$, $0 < \phi < 2\pi$
ITS: Inner Tracking System (silicon)
TPC: Time Projection Chamber
Track $p_T > 150$ MeV/c
Charged constituent jets (jet^{ch})

Full jet reconstruction
matching the neutral and charged constituents

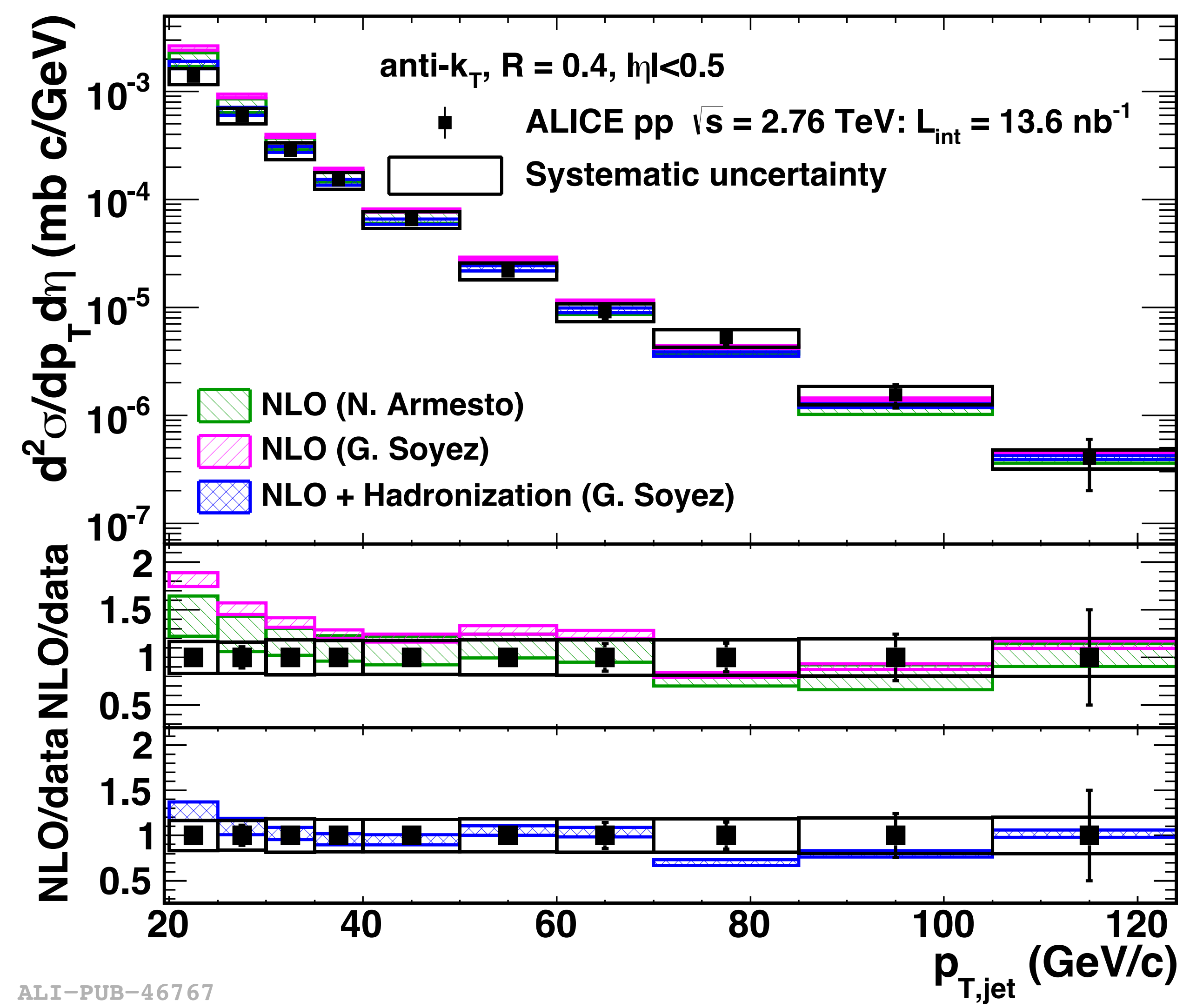
Jets in pp collisions

R = 0.2



R = 0.4

ALICE, Phys. Lett. B 722 (2013) 262-272



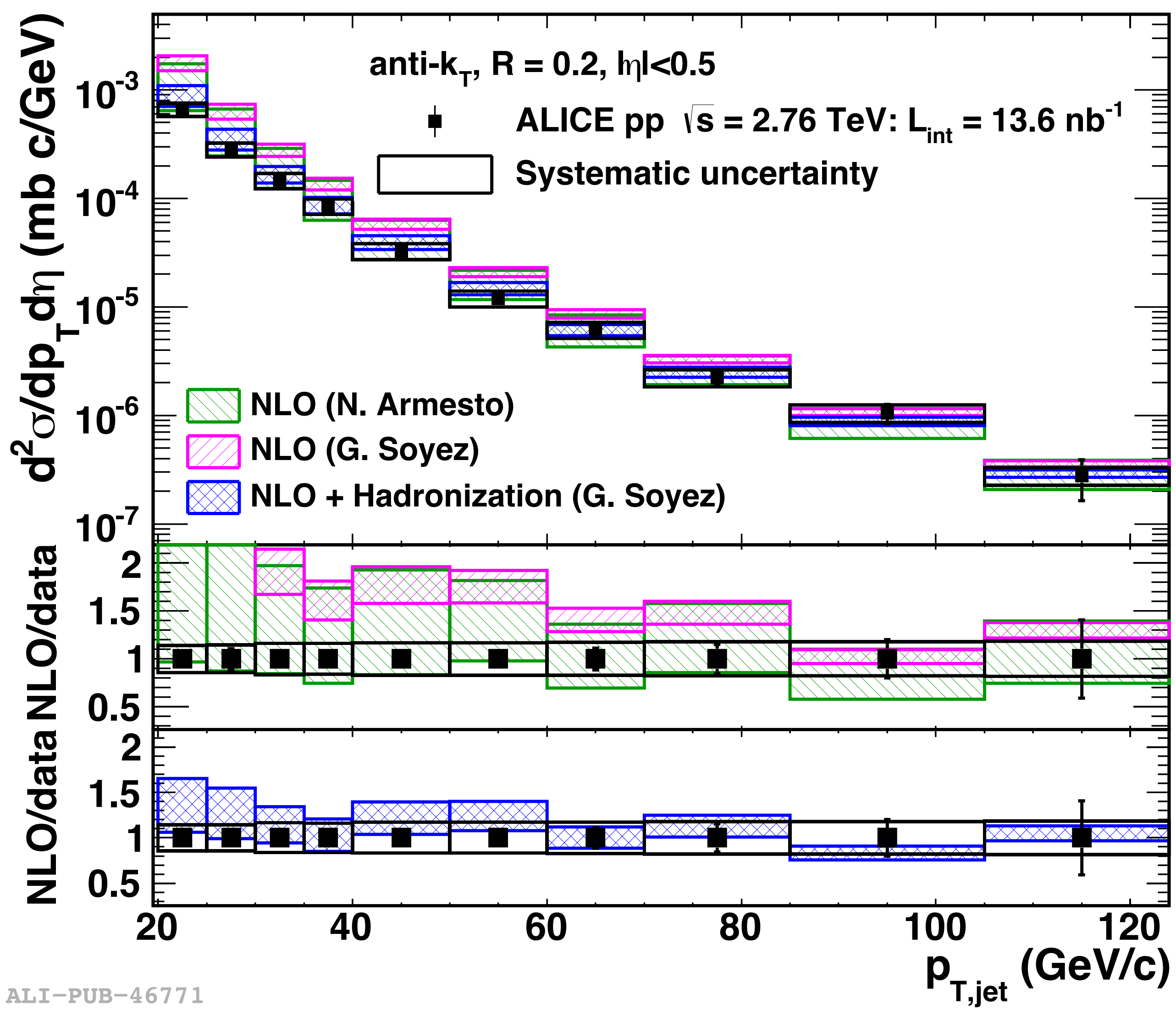
- Good agreement between data and NLO calculations for both *R*=0.2 and *R*=0.4

N. Armesto et al. based on Nucl. Phys. B507 (1997) 295-314
G. Soyez, Phys Lett B698 (2011) 59-62

R: jet resolution parameter, for cone algorithms is the cone radius

Jets in pp collisions

R = 0.2



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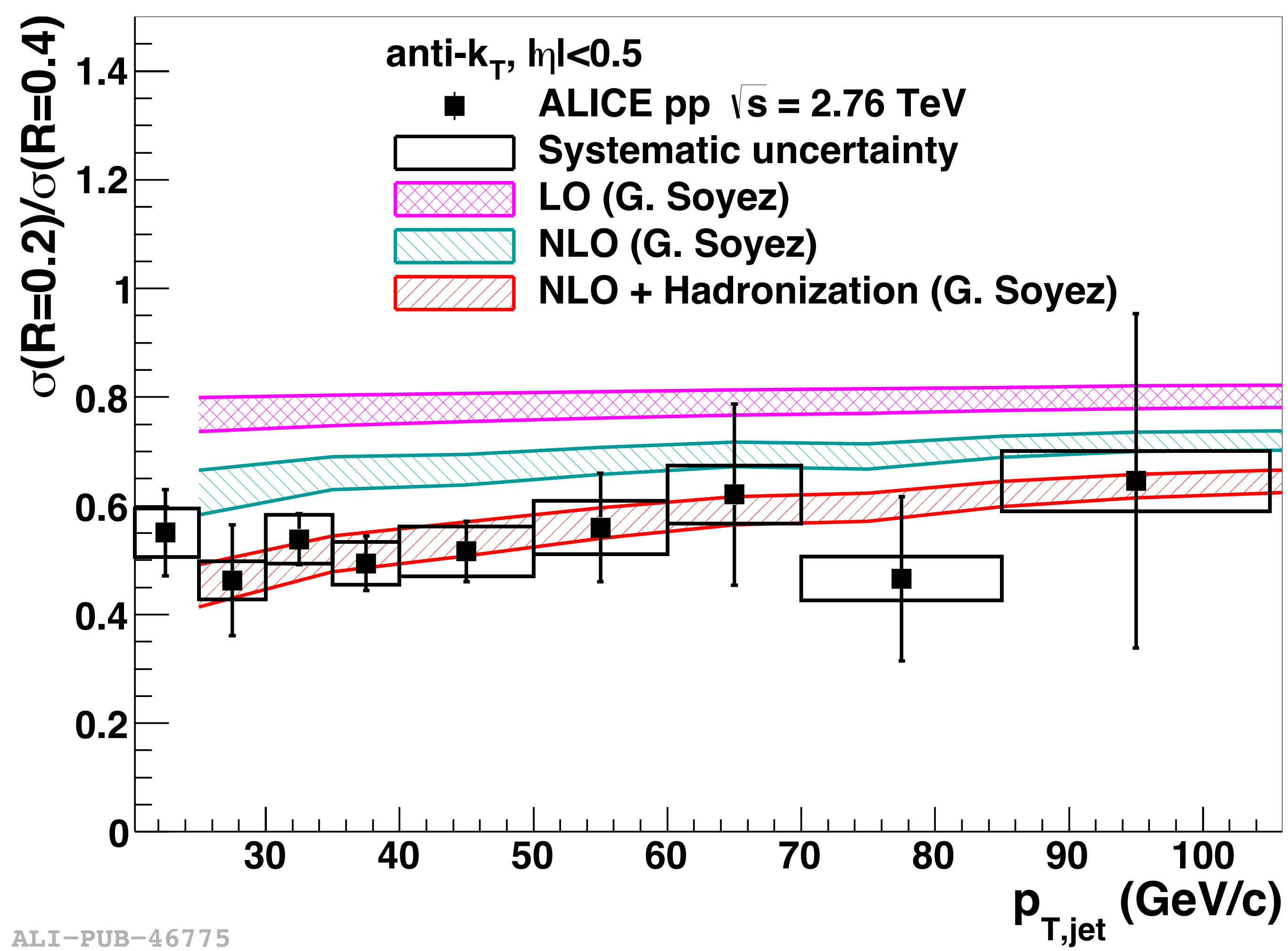

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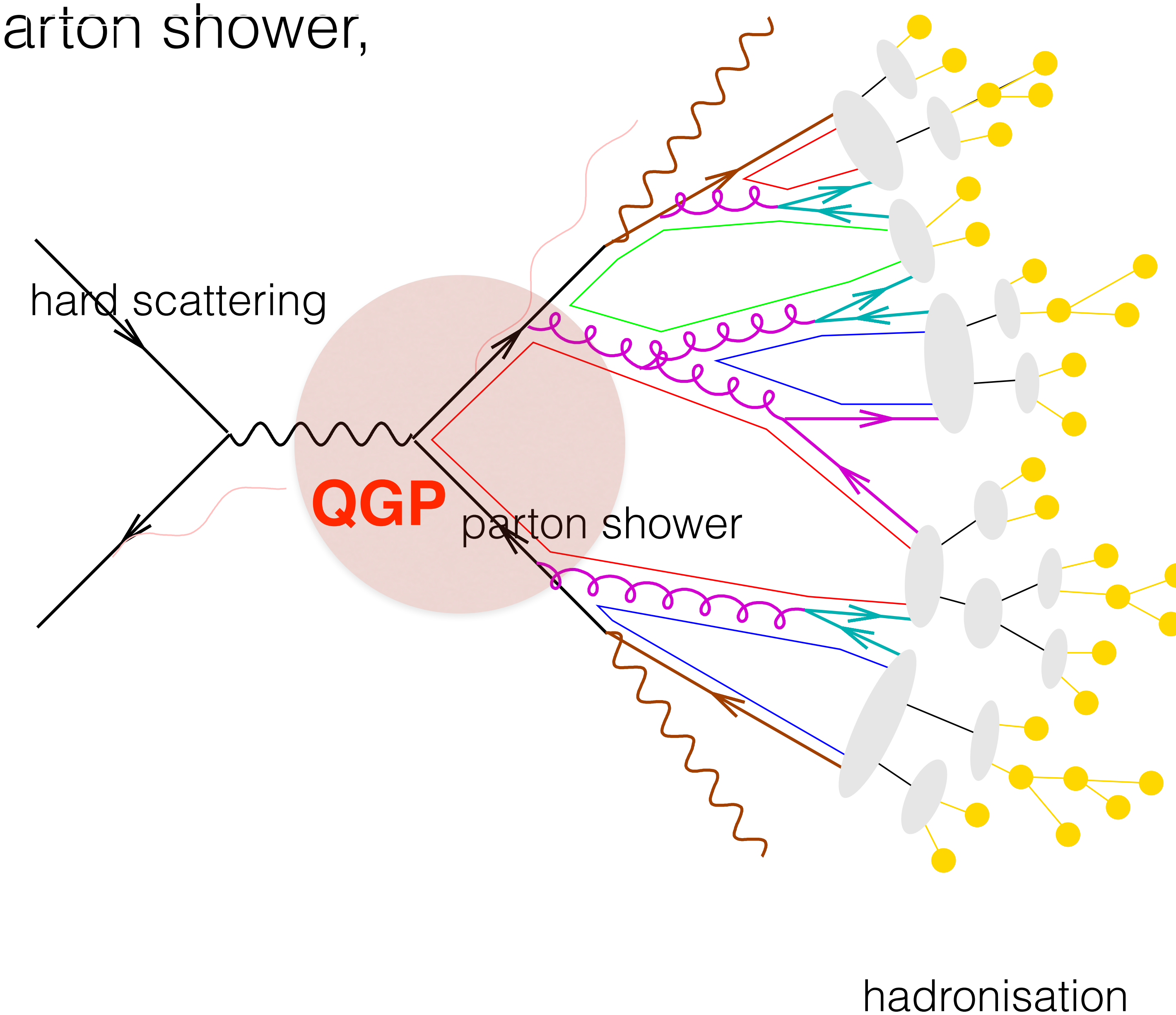
G. Soyez, Phys Lett B698 (2011) 59-62

- Better agreement for both the spectra and the jet profile if hadronization effects are taken into account in the calculations.

Jets in Pb-Pb collisions

- High-p_T and virtuality partons are produced in initial hard scatterings:
  - virtuality evolution through parton shower,
  - hadronisation at Λ_{QCD} scale.

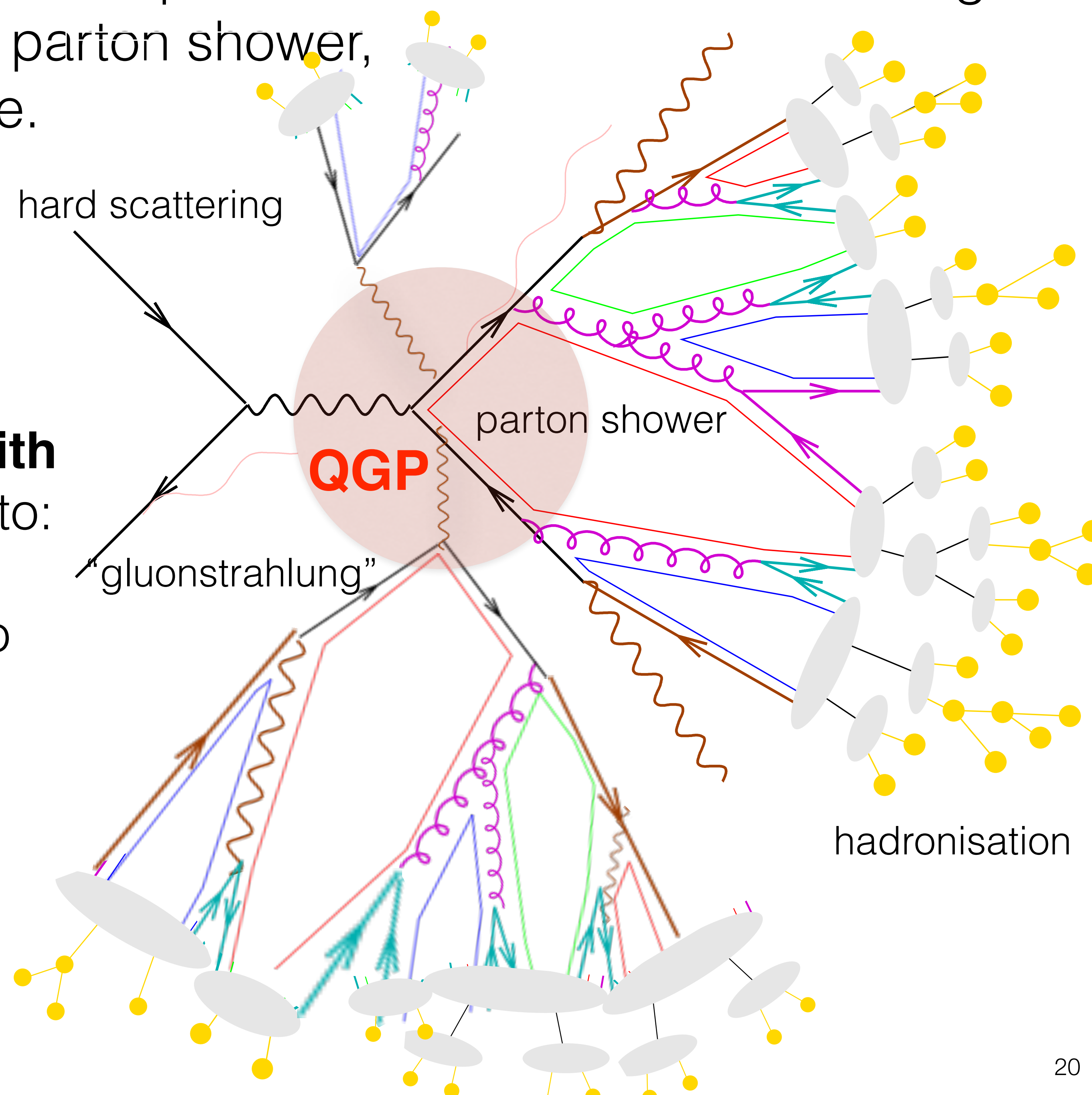


Jets in Pb-Pb collisions

- High-p_T and virtuality partons are produced in initial hard scatterings:
  - virtuality evolution through parton shower,
  - hadronisation at Λ_{QCD} scale.

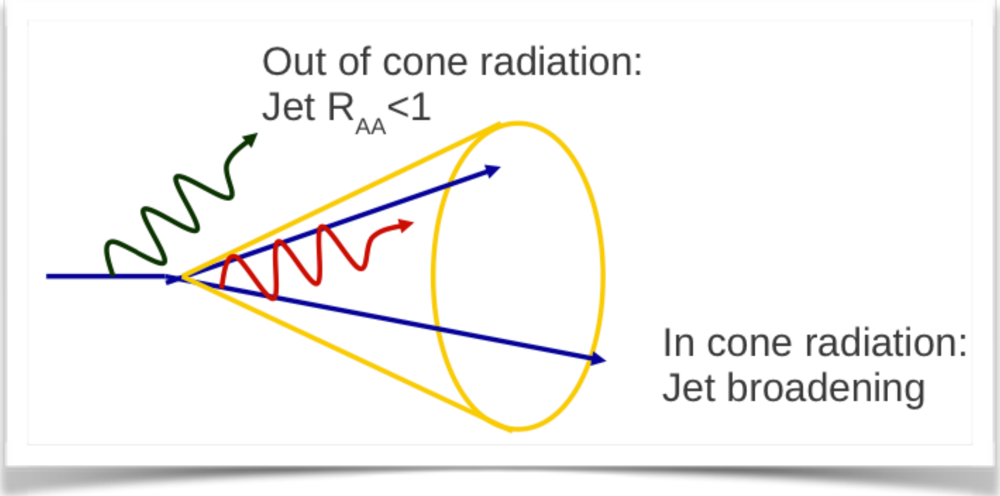
- Medium induced **gluon radiation**

- Via the **parton interactions with the medium**, jets can be used to:
  - study possible **modified fragmentation** with respect to the "vacuum" case (pp collisions),
  - probe jet and medium **properties.**



Jets in Pb-Pb collisions

- **In cone radiation:**
  - particles would be quenched inside the jet increasing his “area”: jet broadening
- **Out of cone radiation:**
  - particles would be emitted outside of the jet cone, suggesting a $R_{\mathrm{AA\ jets}} < 1$



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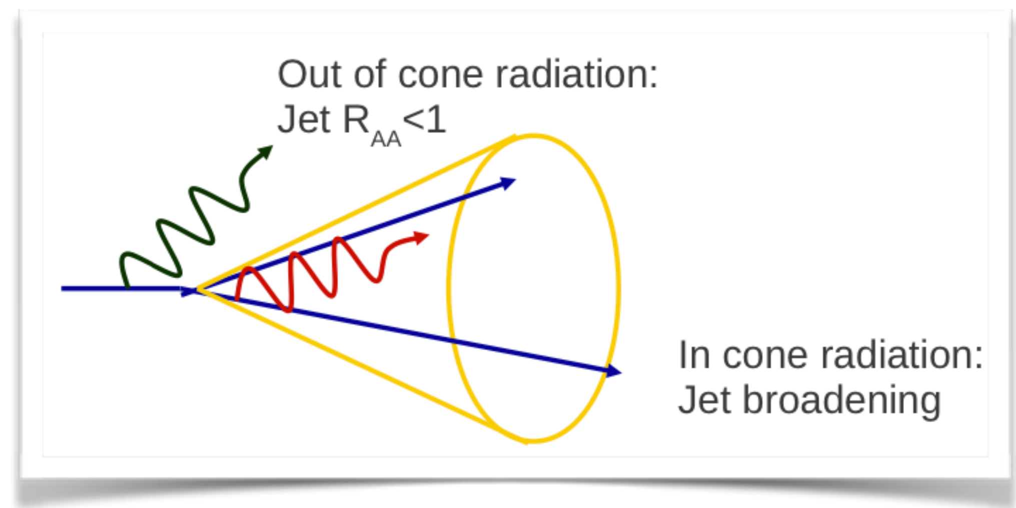
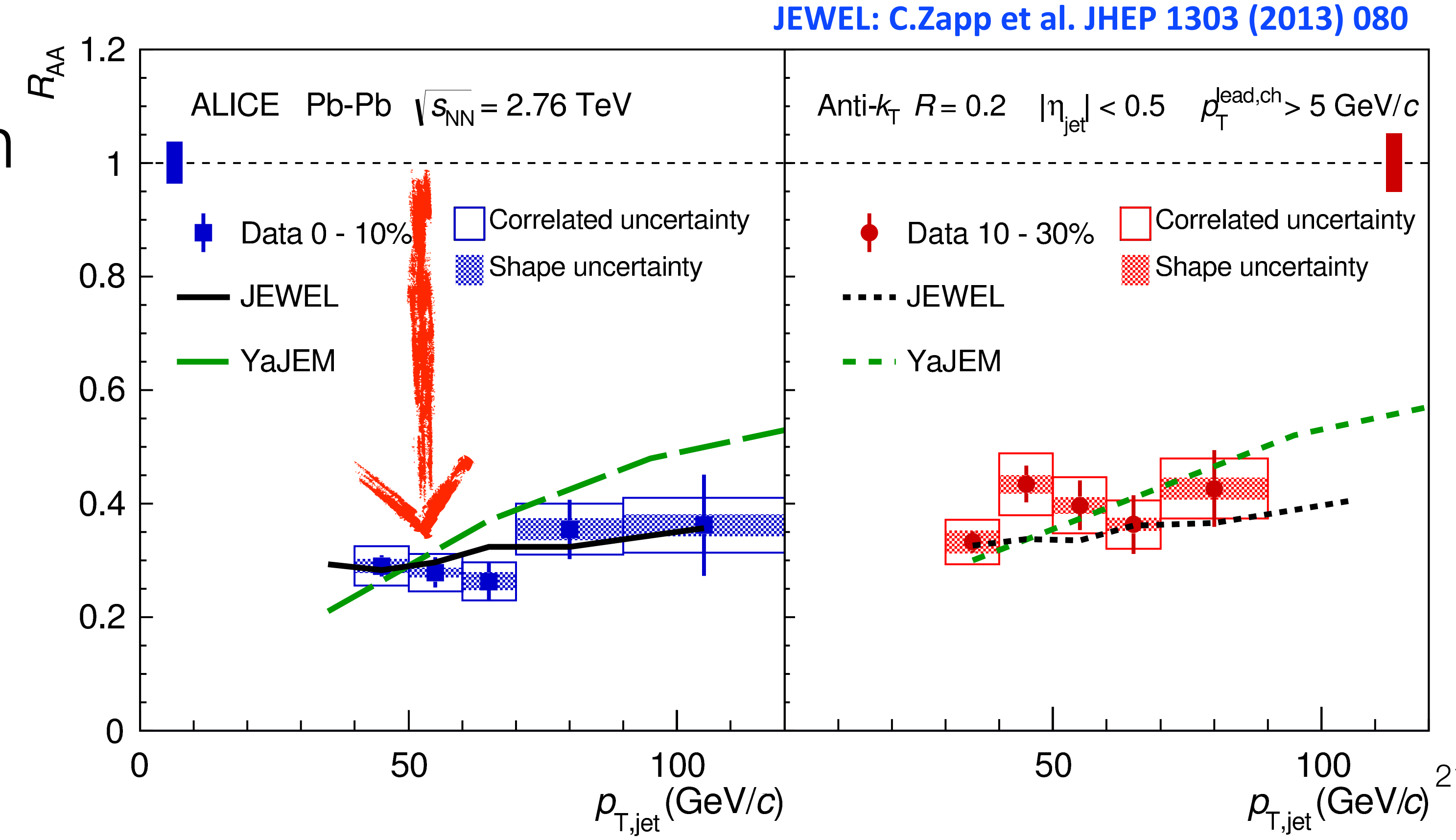


- Energy lost from the interaction of the parton within the medium not recovered within $R = 0.3$.

- R_{AA} not precise enough to distinguish between the two models

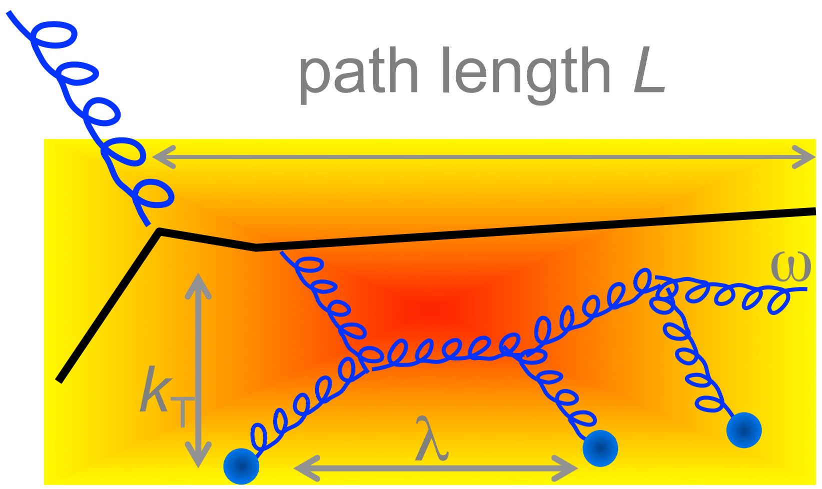
ALICE, Phys. Lett. B 746 (2015) 1
YaJEM: T. Renk , Phys Rev C 88 (2013) 014905
JEWEL: C.Zapp et al. JHEP 1303 (2013) 080



Baier, Dokshitzer, Mueller, Peigne‘, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

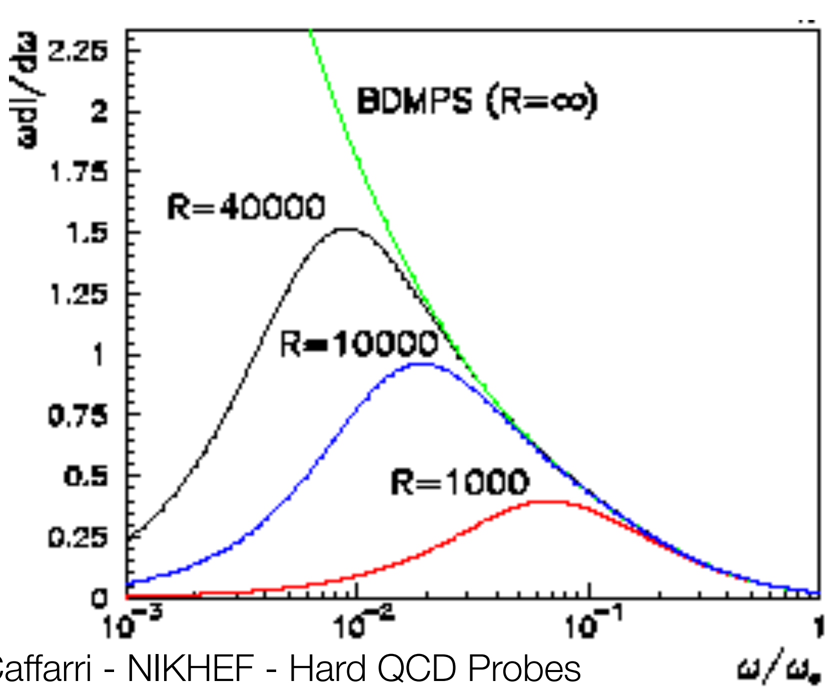
Charge dependence of the energy loss

- Medium modeled with static scattering centers
- Coherent gluon wave function accumulate k_T due to multiple scatterings ➜ the gluon decoheres and it is radiated.



Radiated gluon energy distrib:

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \begin{cases} \sqrt{\omega_c / \omega} & \text{for } \omega < \omega_c \\ (\omega_c / \omega)^2 & \text{for } \omega \geq \omega_c \end{cases}$$



C_R Casimir Factor: 4/3 for q, 3 for g

$\omega_c = \hat{q}L^2/2$ Scale of the radiated energy

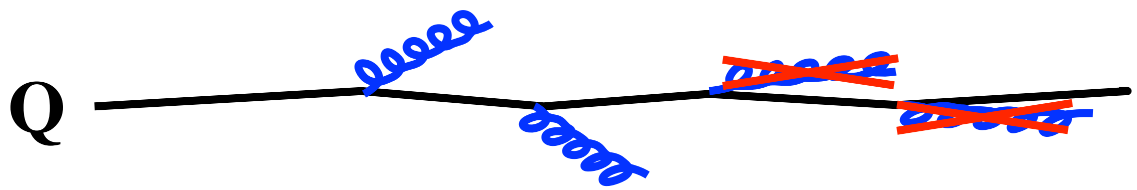
$R = \omega_c L$ Constraint: $k_T < \omega$

$$\hat{q} = \frac{< k_T^2 >}{\lambda}$$

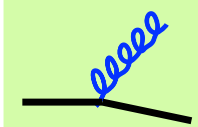
Transport coefficient related to the **medium characteristics** and to the **gluon density**

… and mass dependence

- Gluon radiation of heavy quarks is suppressed due to the introduction of a mass term in the propagator:
  - **Dead cone effect**



Gluonsstrahlung probability



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

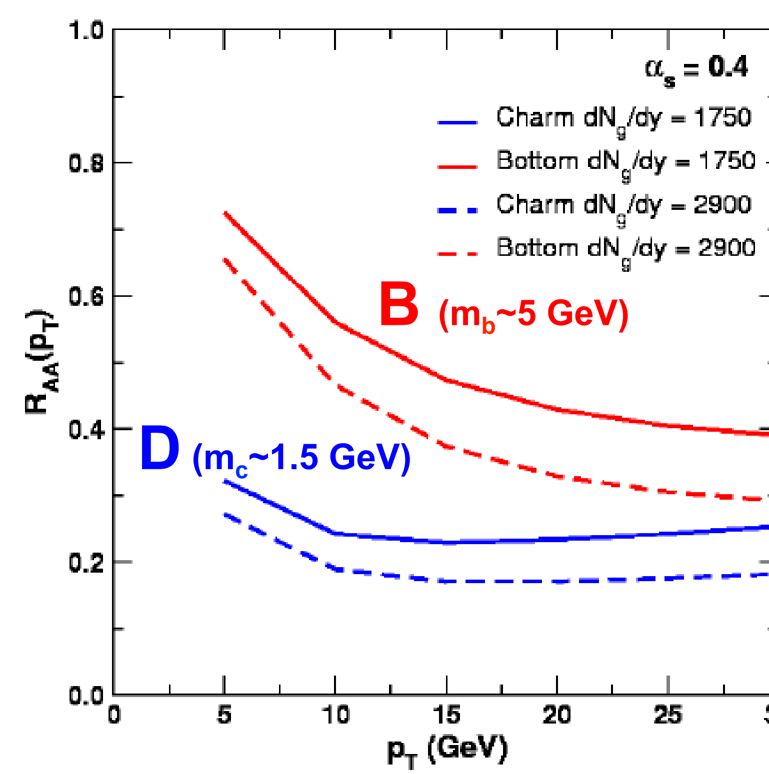
- Energy distribution of radiated gluons is suppressed by an angle-dependent factor: **heavy quarks might lose less energy in the medium ?**

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

$$\omega \frac{dI}{d\omega}\bigg|_{HEAVY} = \omega \frac{dI}{d\omega}\bigg|_{LIGHT} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

?

$\Delta E(\text{light}) > \Delta E(c) > \Delta E(b) \;\rightarrow\; R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$



Wicks, Gyulassy, "Last Call for LHC Predictions" workshop, 2007

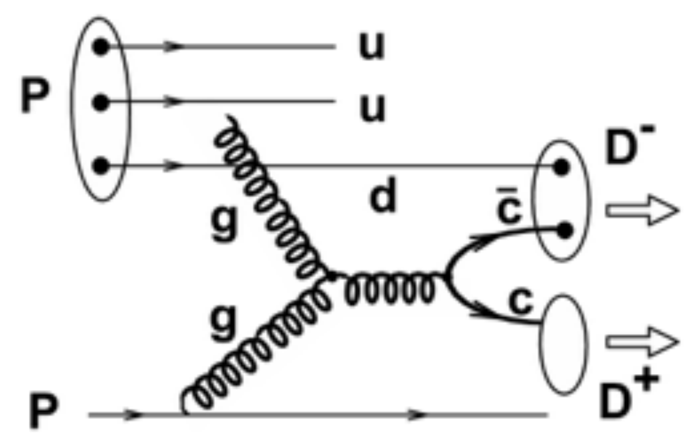
Heavy-quark production mechanisms

- Heavy-quark (c, b) pair production mechanisms:

@ LO:

$g + g \rightarrow Q + \bar{Q}$

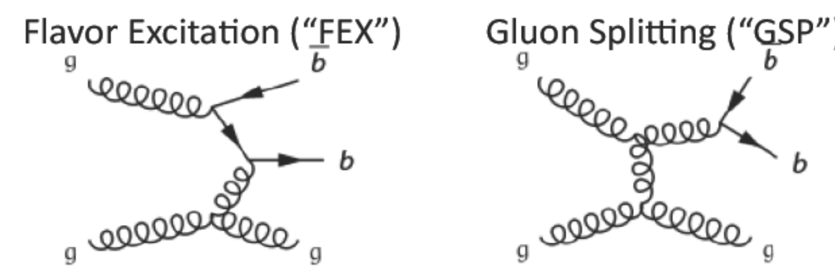
$q + \bar{q} \rightarrow Q + \bar{Q}$



@ NLO:

$g \rightarrow Q + \bar{Q}$ gluon splitting

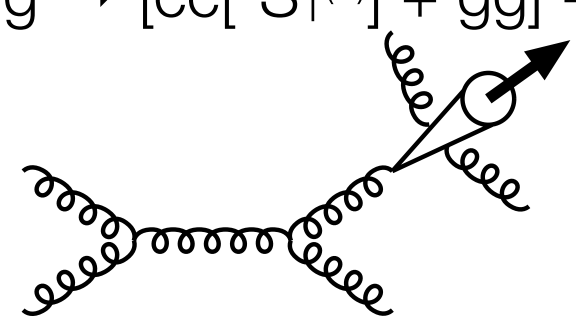
$Q^* \rightarrow Q + \bar{Q}$ flavour excitation



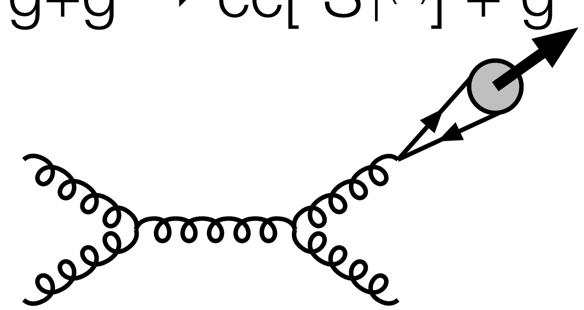
- Formation of the heavy-quark pair in a QQ (quarkonium) bound state related to long distance scales $\sim 1/m_Q v$ $\rightarrow$ non-perturbative approach needed (NRQCD)

Prog.Part.Nucl.Phys.47:141-201,2001

- Color-singlet fragmentation
  $g+g \rightarrow [c\bar{c}[^3S_1^{(1)}] + gg] + g$

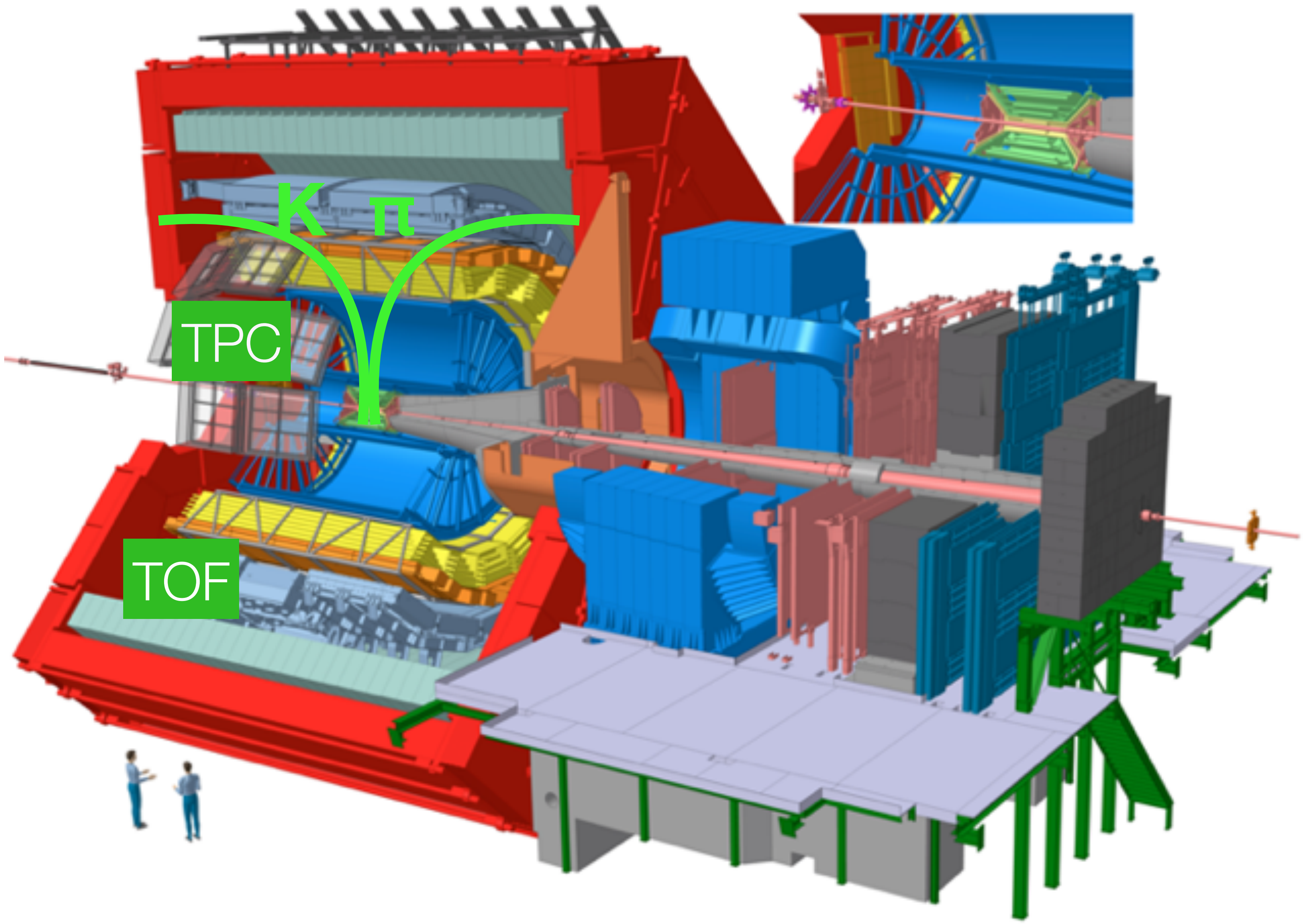


- Color-octet fragmentation
  $g+g \rightarrow c\bar{c}[^3S_1^{(8)}] + g$



Open heavy-flavour reconstruction in ALICE

D mesons

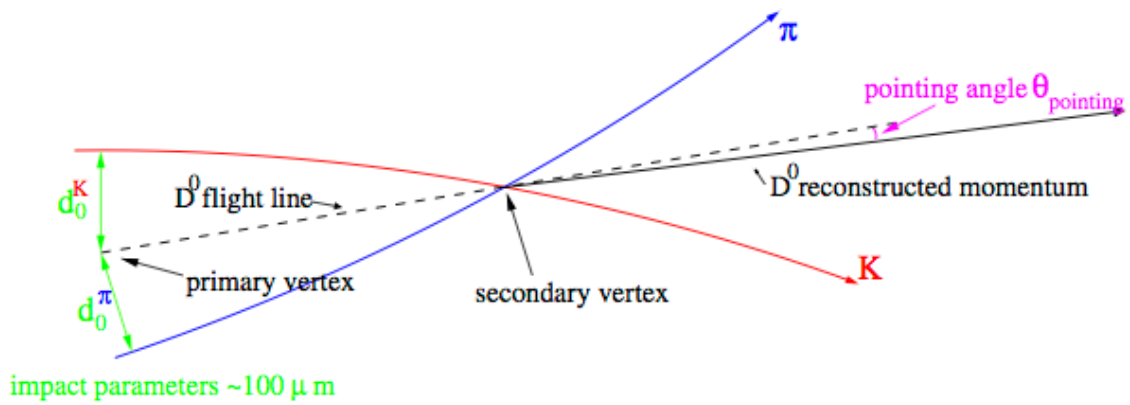


$D^0 \rightarrow K^- \pi^+$ (BR 3.88 ± 0.05%)
$D^+ \rightarrow K^- \pi^+\pi^+$ (BR 9.13 ± 0.19%)
$D^{*+} \rightarrow D^0 \pi^+$ (BR 67.7 ± 0.05%)
$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+\pi^+$
(BR 2.28 ± 0.12%)

$|\eta| < 0.9$
ITS: tracking, vertexing
TPC: tracking, PID
TOF: K-ID

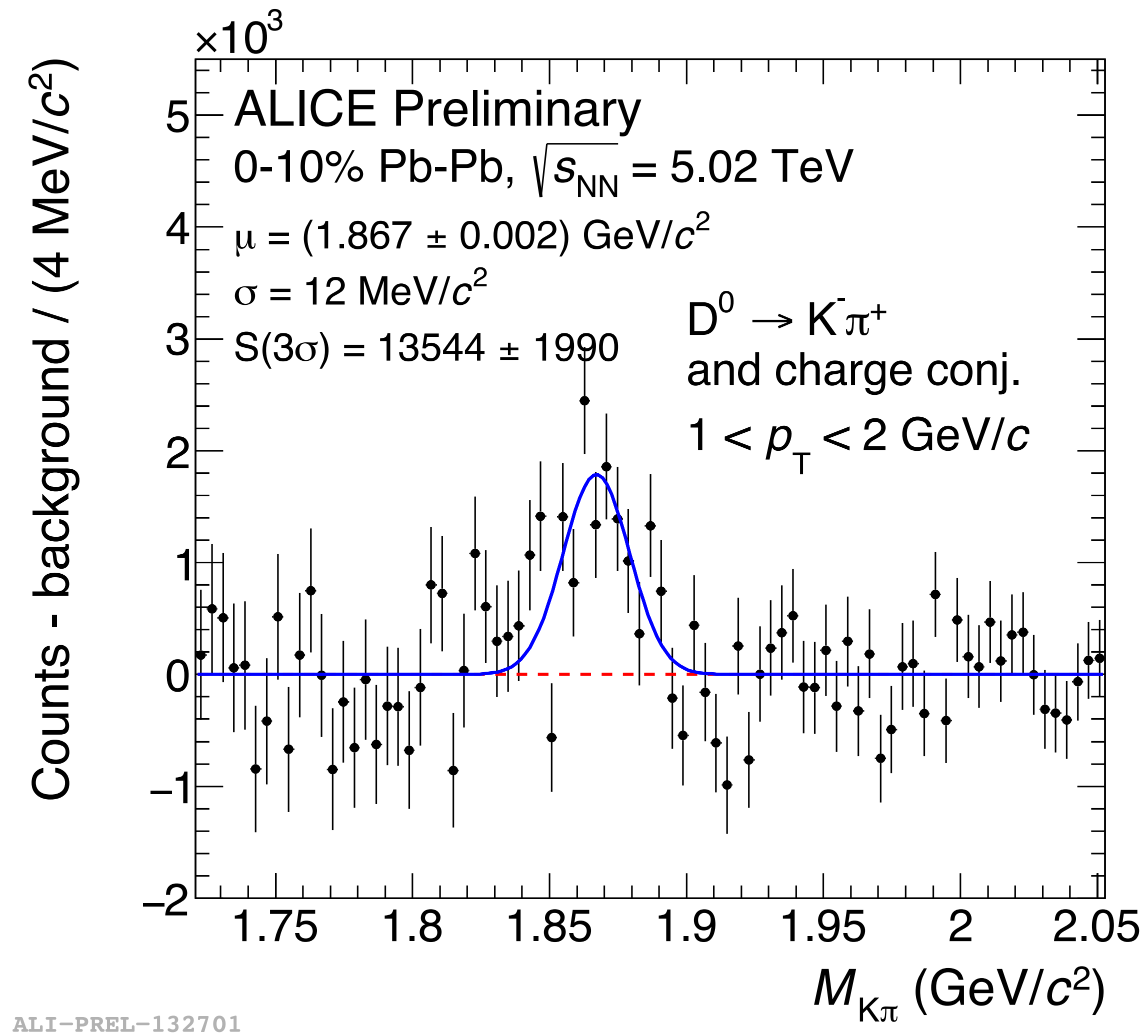
* Topological selections and PID selections used to reduce the combinatorial background

Open heavy-flavour reconstruction in ALICE



Invariant mass analysis
mainly based on:

* secondary vertex reconstruction
* Kaon identification



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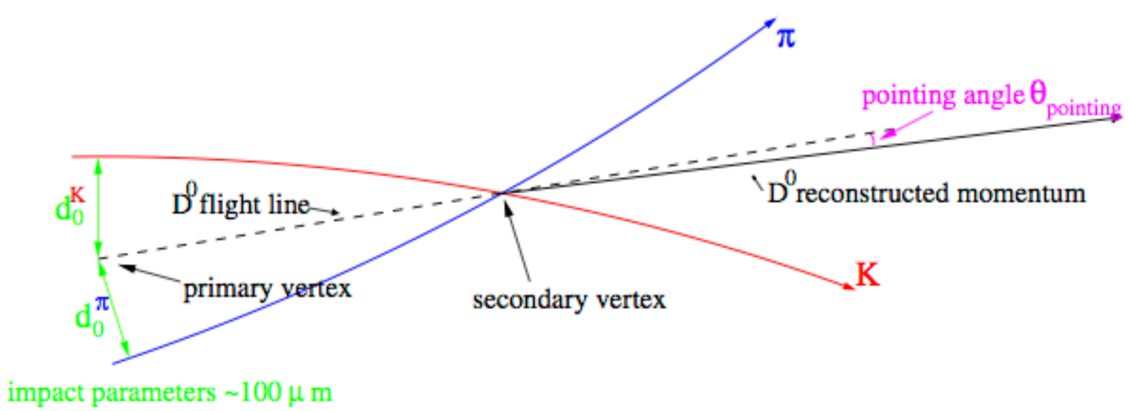
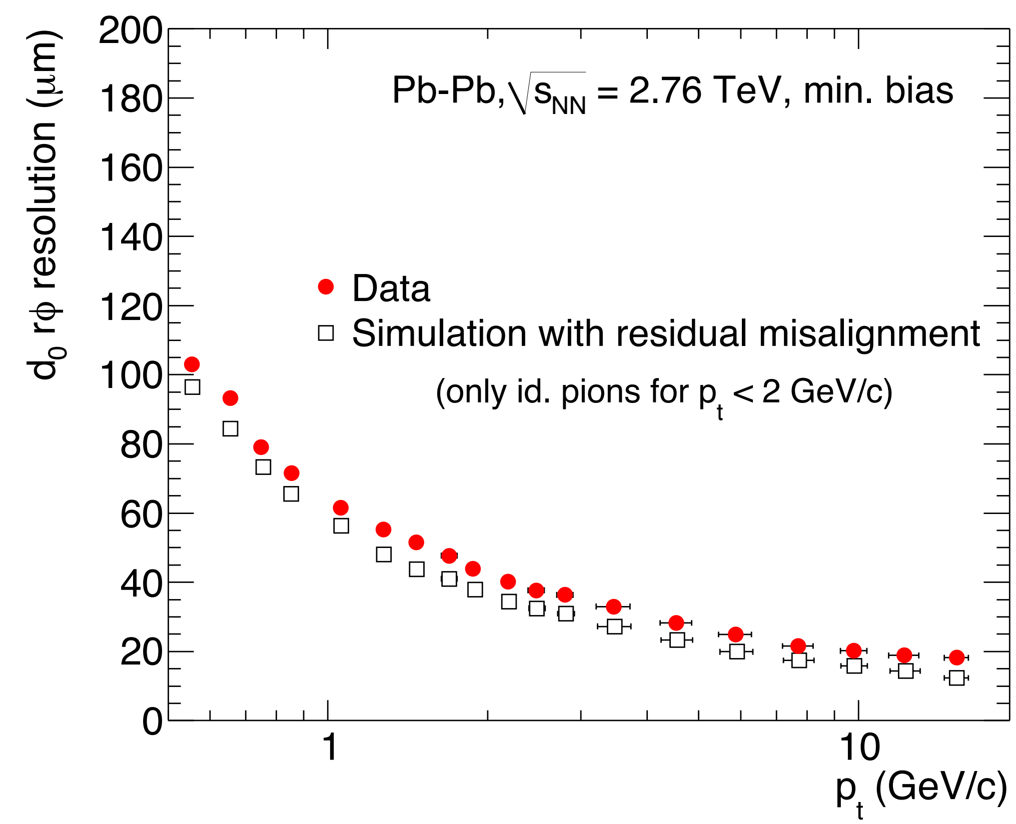


Invariant mass analysis mainly based on:

- secondary vertex reconstruction
- Kaon identification

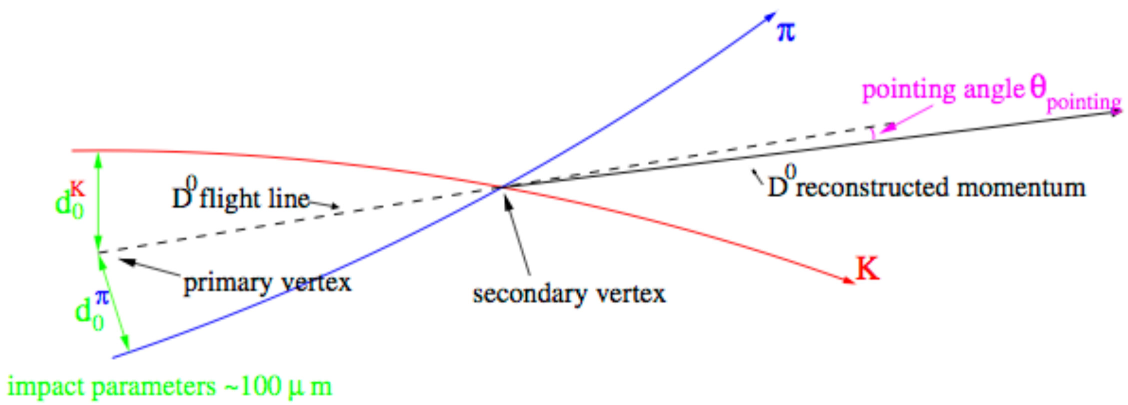
- Displaced vertex topology:
  - tracking and vertexing precision crucial for heavy flavour analysis
  - Inner Tracking System with 6 silicon detector layers: two pixel layers at 3.9 cm and 7 cm

JHEP 09 (2012) 112



- Impact parameter resolution ~ 60μm for p_T = 1 GeV/c

Open heavy-flavour reconstruction in ALICE

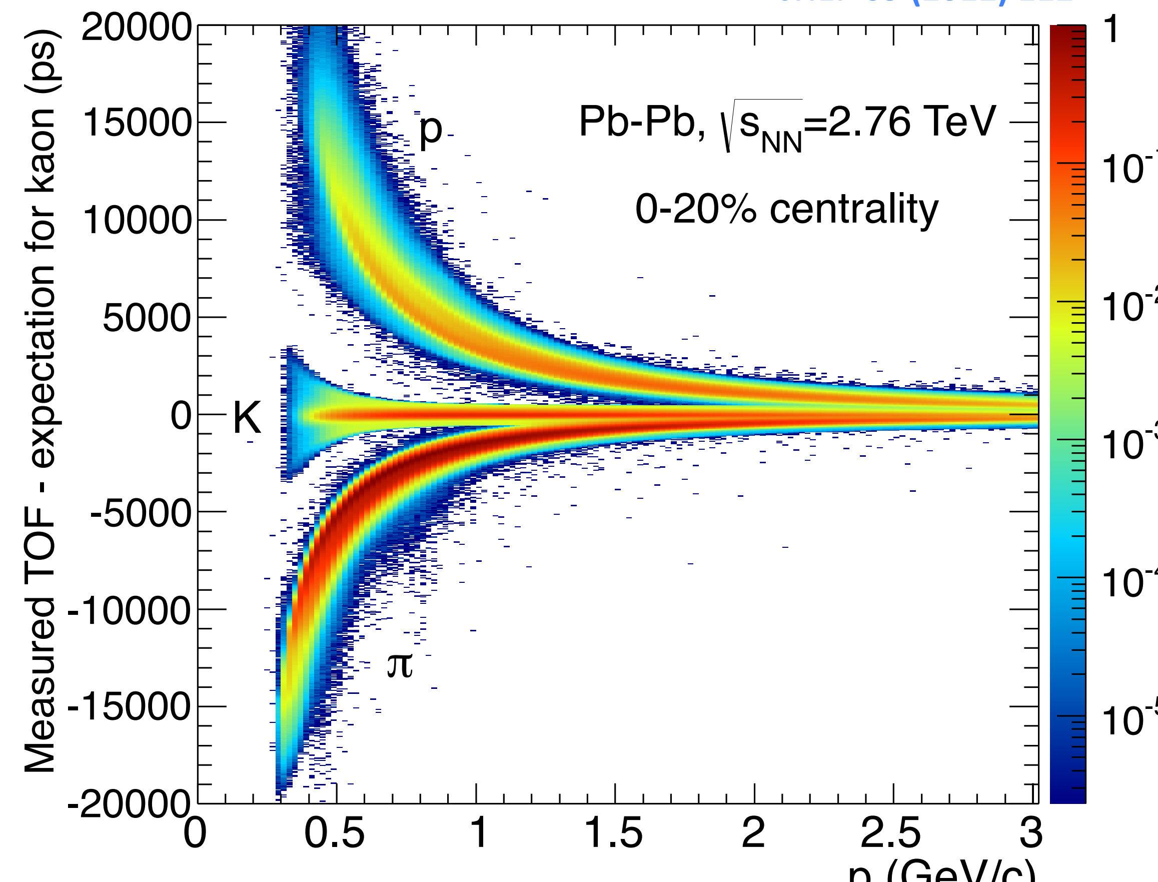


Invariant mass analysis
mainly based on:

- secondary vertex reconstruction
- **Kaon identification**

- Kaons are identified via:
  - the energy loss deposit in the TPC ($0.6 < p < 0.8$ GeV/c 2σ cut)
  - the velocity measurement in the TOF ($p < 2$ GeV/c 3σ cut)

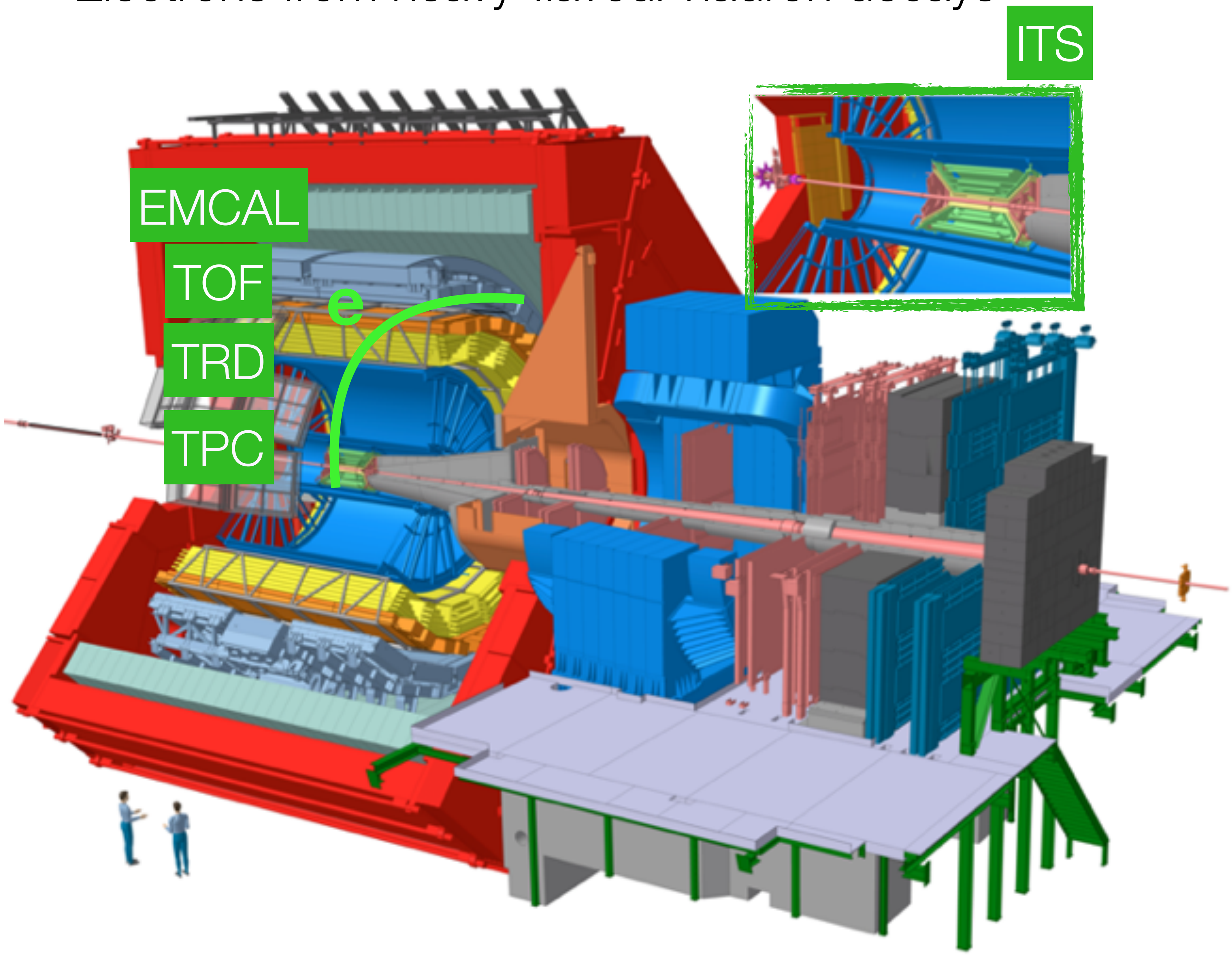
JHEP 09 (2012) 112



- Background reduction by a factor 3 for central Pb-Pb collisions

Open heavy-flavour reconstruction in ALICE

Electrons from heavy-flavour hadron decays



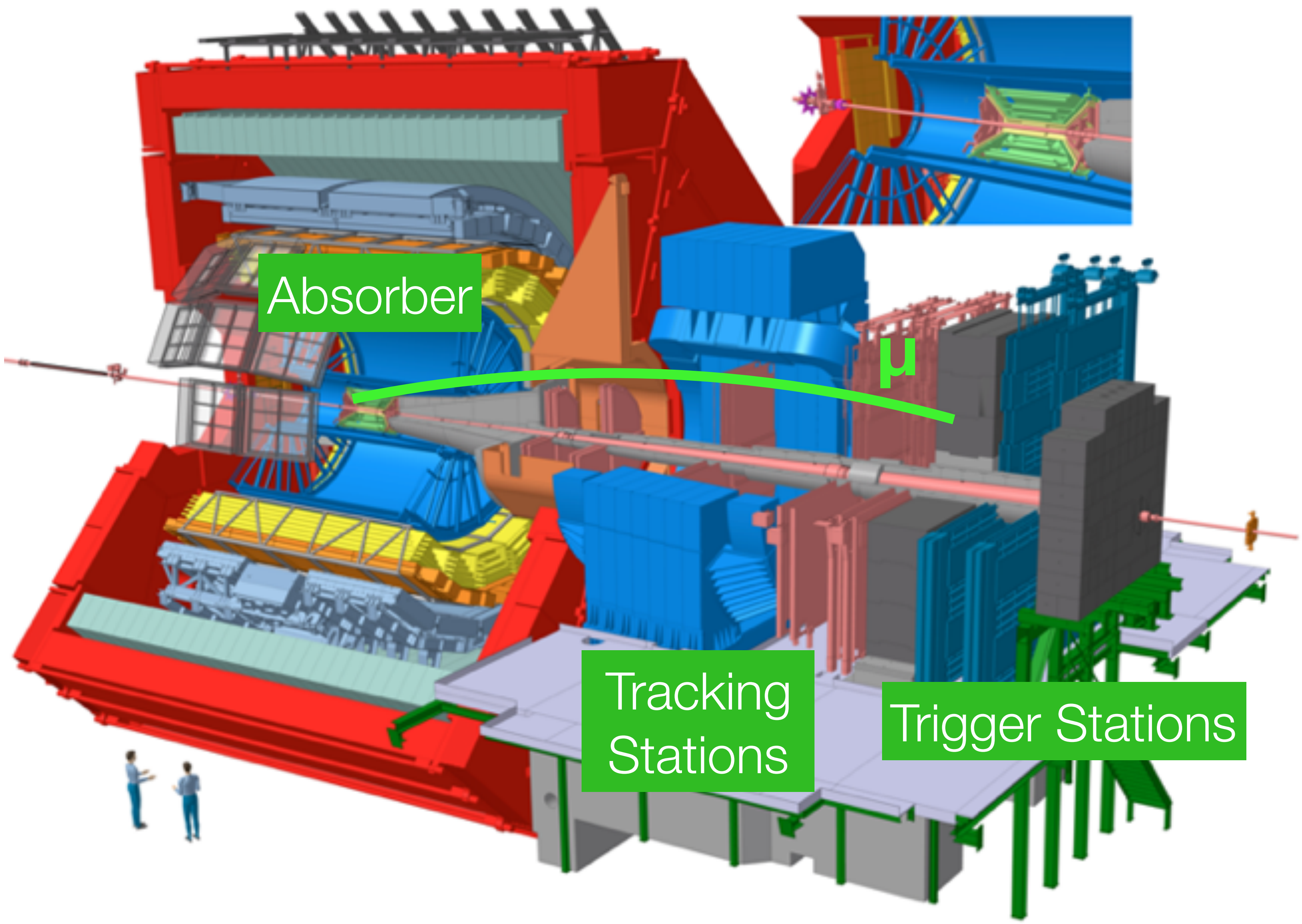
D,B, Λ_{c},... $\rightarrow$ **e**+X

$|\eta| < 0.9$
ITS: tracking, vertexing
TPC: tracking, PID
TOF, TRD, EMCAL: e-ID

* Background subtraction based on cocktail method and removal of Dalitz decay and photon conversion

Open heavy-flavour reconstruction in ALICE

Muons from heavy-flavour hadron decays

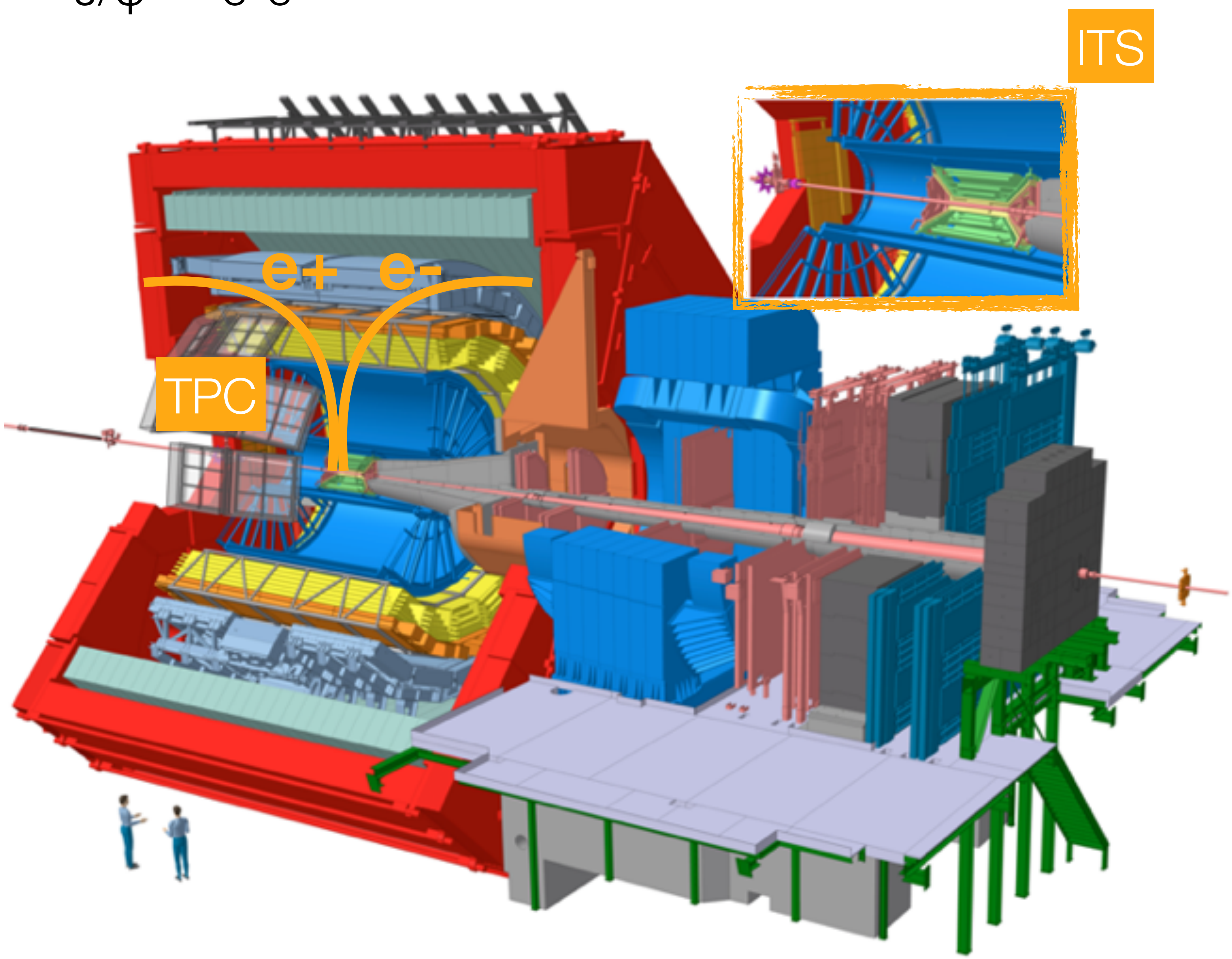


$$D, B, \Lambda_{c}, \ldots \rightarrow \mu + X$$

- Muon spectrometer: μ-ID via tracks matched with the trigger system $-4 < \eta < -2.5$
- Background coming from K and π decays estimated with Pythia MC simulations (pp collisions) and data-tuned MC cocktail (p-Pb and Pb-Pb collisions).

Quarkonia reconstruction in ALICE

$J/\psi \rightarrow e^{+}e^{-}$



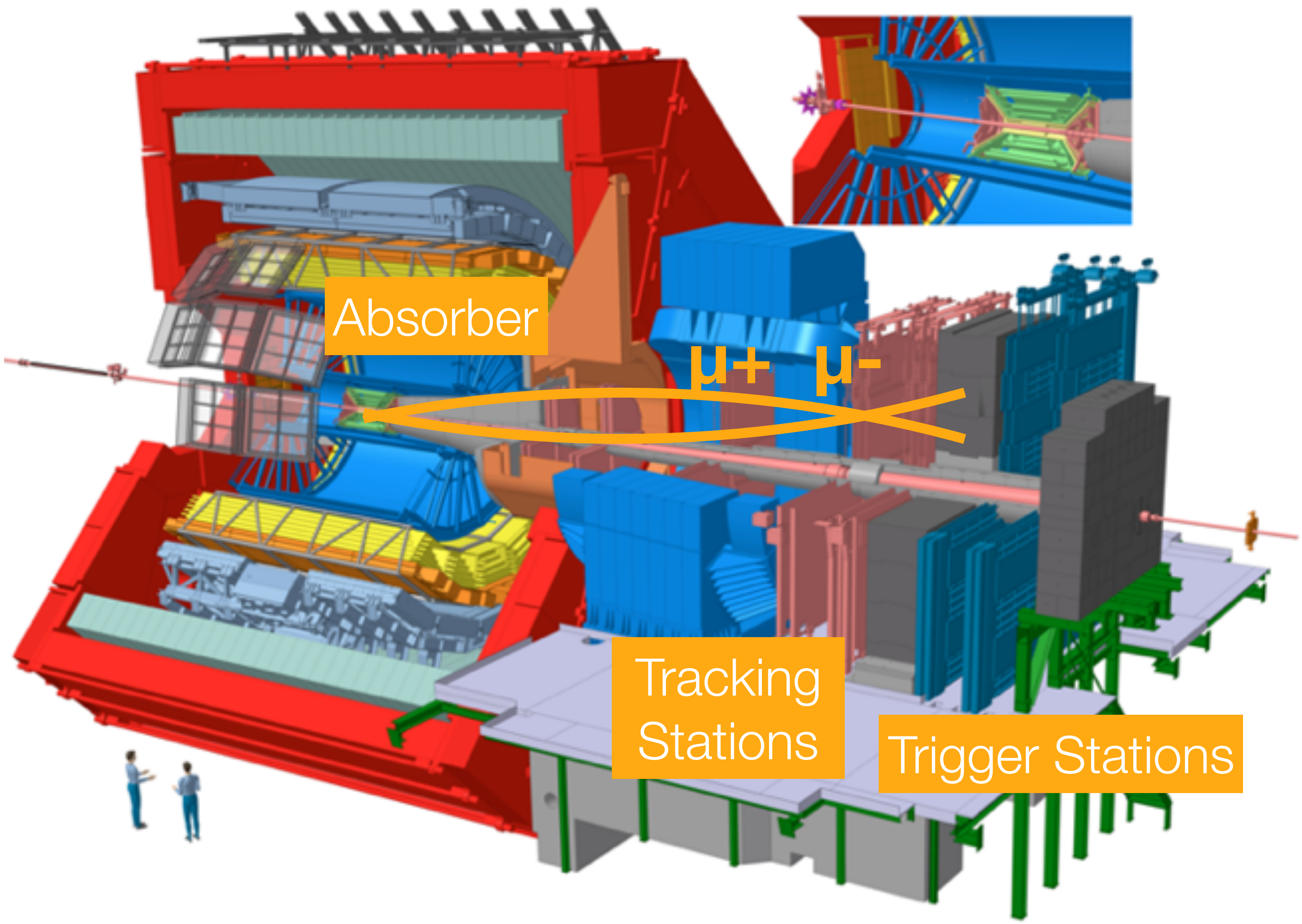
$|\eta| < 0.9$
ITS: tracking
TPC: tracking, PID

* Signal extraction obtained after background subtraction, estimated using event mixing, like sign, different fits techniques.

* Acceptance down to $p_T = 0$.

Quarkonia reconstruction in ALICE

$J/\psi \rightarrow \mu^+\mu^-$, $\psi(2S) \rightarrow \mu^+\mu^-$, $\Upsilon \rightarrow \mu^+\mu^-$

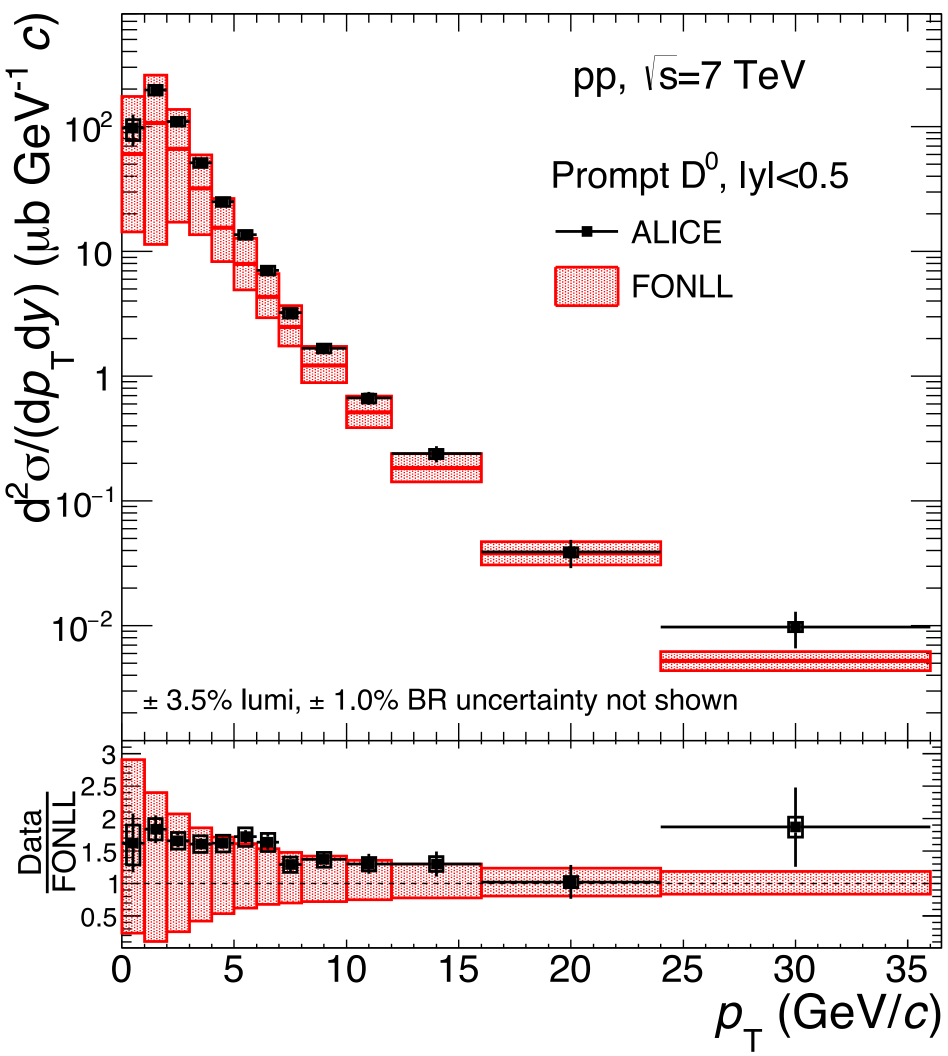


$-4 < \eta < -2.5$

- Di-muons triggered sample ($p_{T\mu} > 0.5 - 1$ GeV/c).
- μ-ID via tracks matched with the trigger system.
- Signal extracted with invariant mass fit procedure.
- Acceptance down to $p_T = 0$.

HF and quarkonia production in pp collisions

- Test of the theoretical approaches for open heavy-flavor and quarkonium production in **pp collisions**.



Eur.Phys.J. C77 (2017) 550

- pQCD based calculations are compatible with D-meson data.
  - **FONLL** (JHEP 05 1998) 007)
    - Fixed-Order-Next-To-Leading-Log calculations.
    - data systematically in the lower side of the theoretical uncertainty bands.

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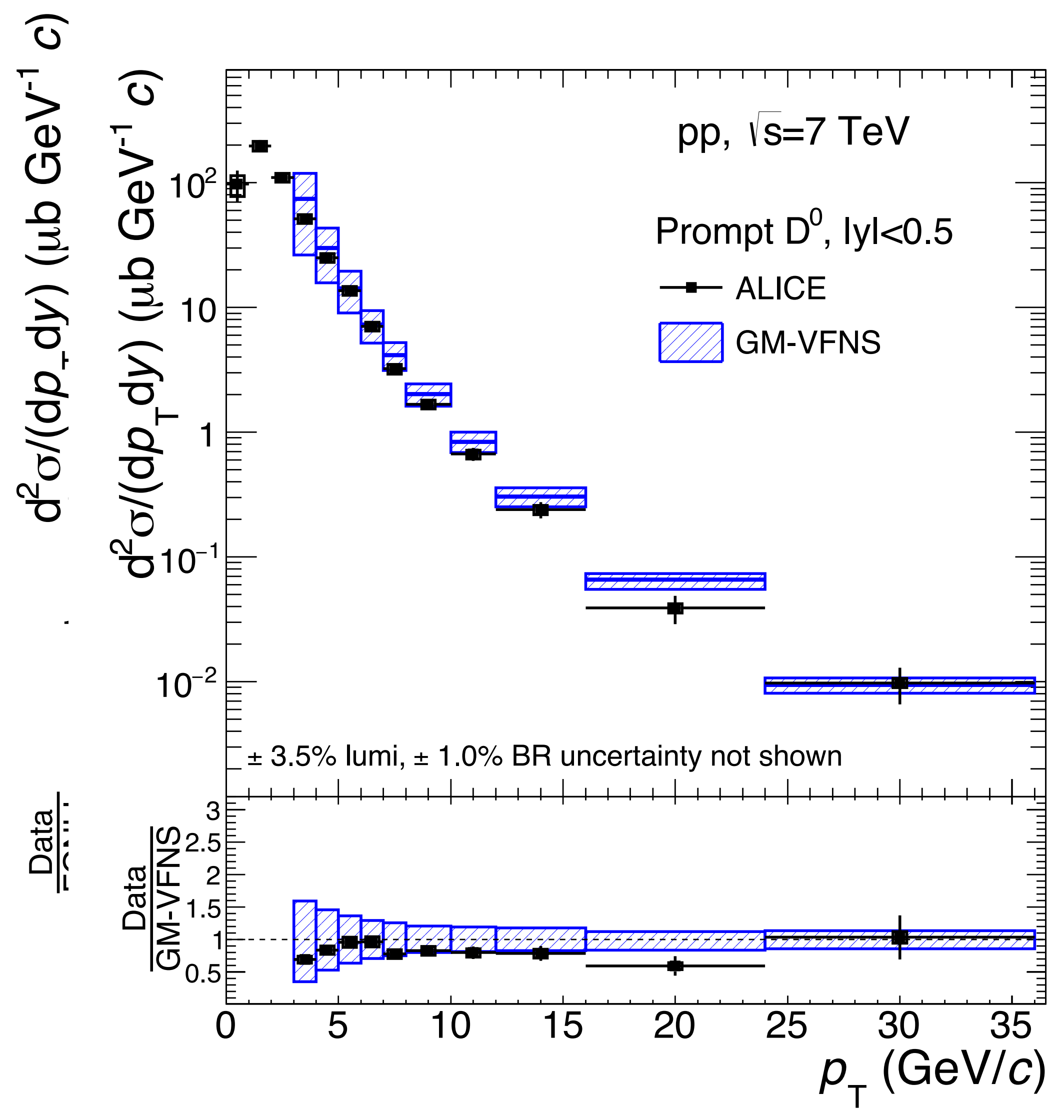

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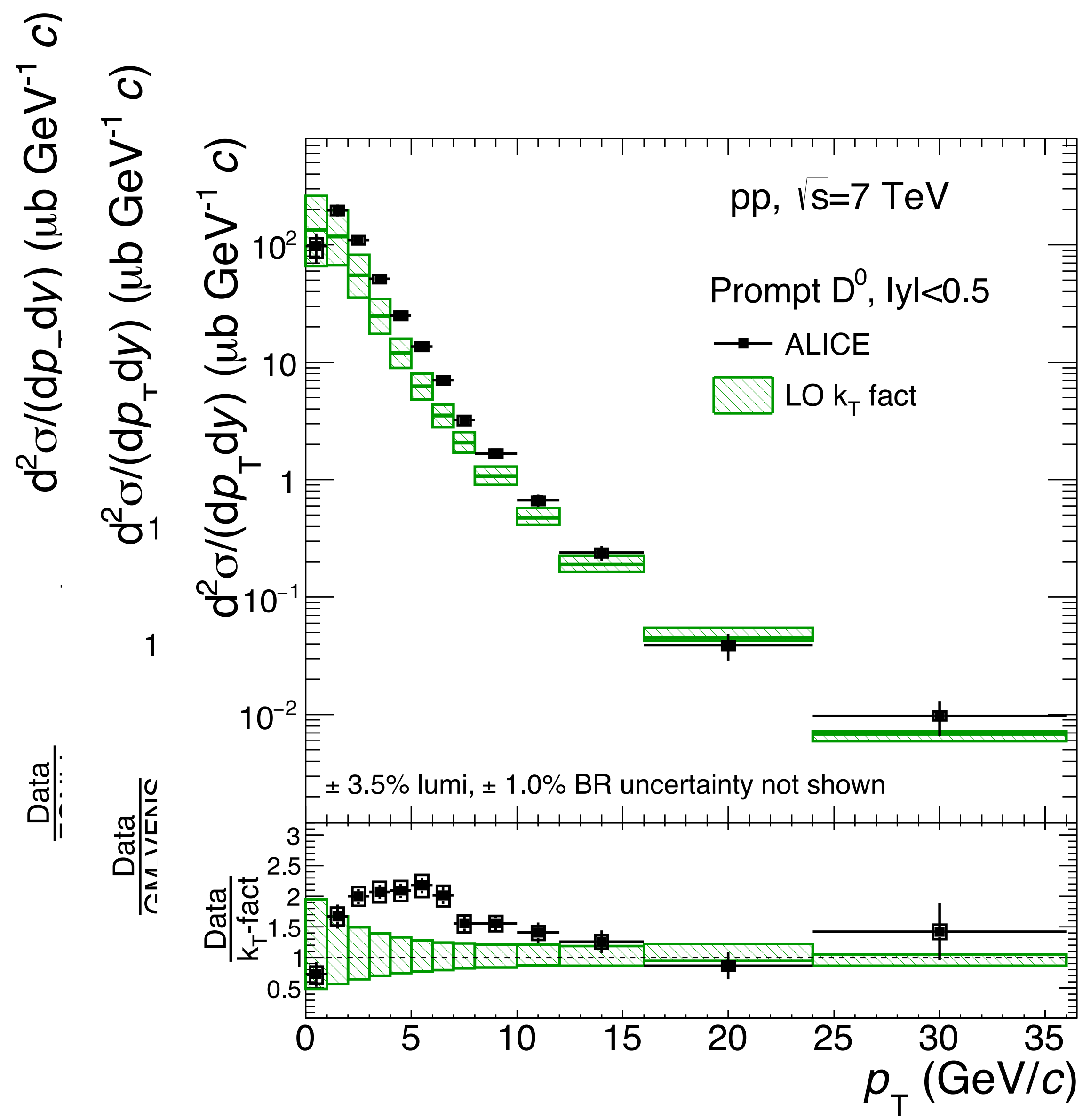

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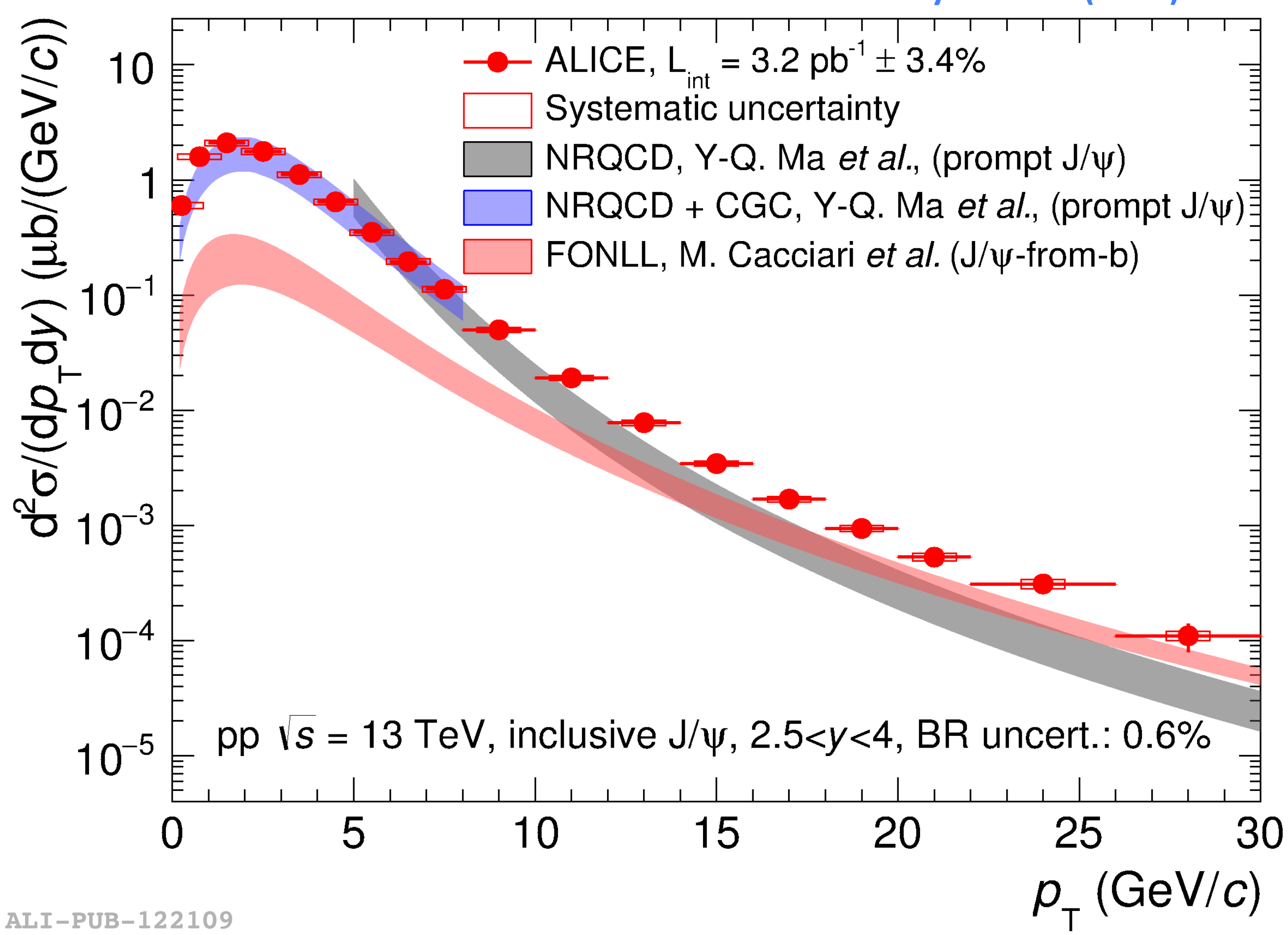
  - **k_T factorization**
    (Phys Rev D79 (2009) 034009)
    - calculation based on k_T factorization instead of collinear one
    - compatible results with data for $p_T < 2$ GeV/c and $p_T > 10$ GeV/c

HF and quarkonia production in pp collisions

- Test of the theoretical approaches for open heavy-flavor and quarkonium production in **pp collisions**.

Eur. Phys. J. C 77 (2017) 392



- **NRQCD**
  - coupled with CGC description of the proton at low-p_T
  - at low-pT, small contribution from non-prompt J/ψ (< 10%)
  - at high-pT non-prompt J/ψ constitute a sizable contribution to the inclusive cross section

NRQCD: Ma, Wang and Chao, PRL 106 (2011) 040202
NRQCD+CGC: Ma and Venugopalan, PRL 113 (2014) 192301
FONLL: Cacciari et al, JHEP 1210 (2012) 137

HF and quarkonia production in pp collisions

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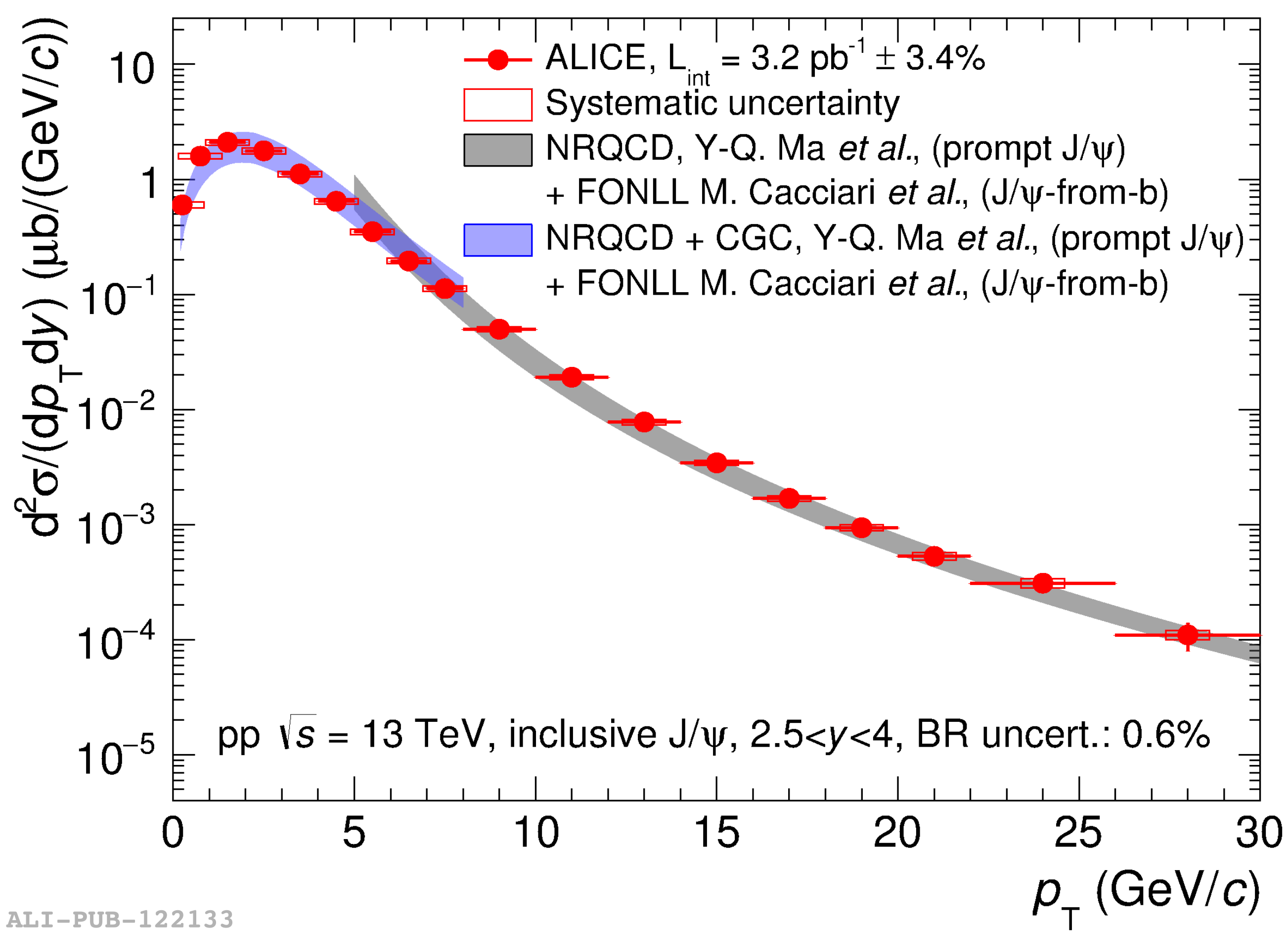
Eur. Phys. J. C 77 (2017) 392



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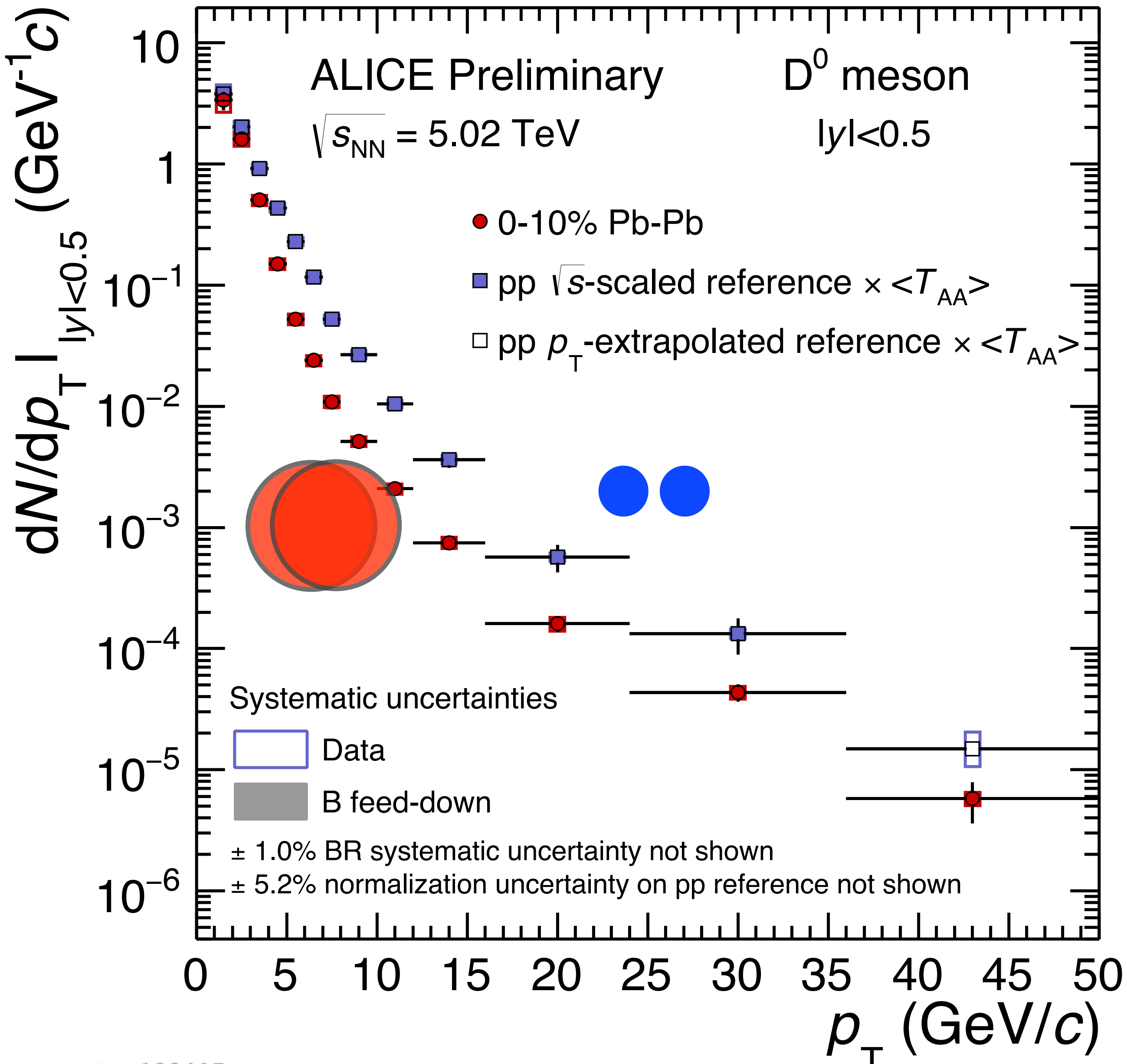
  * at high-pT non-prompt J/ψ constitute a sizable contribution to the inclusive cross section

* summing NRQCD and FONLL, good agreement with the data over the full p_T range

Open HF production in Pb-Pb collisions

- Measurement of D-meson production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - compared with pp collisions scaled by the number of binary collisions.



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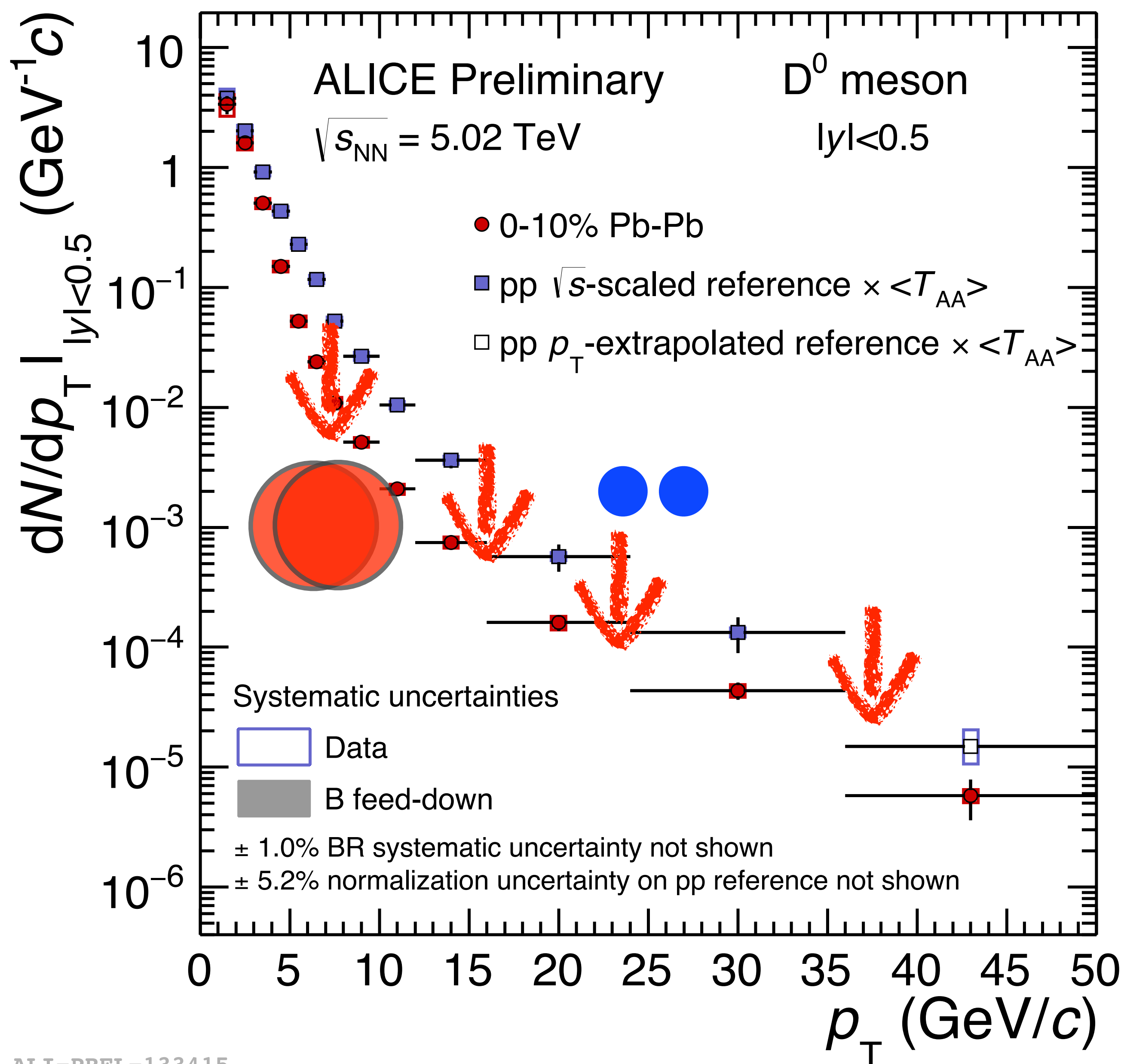
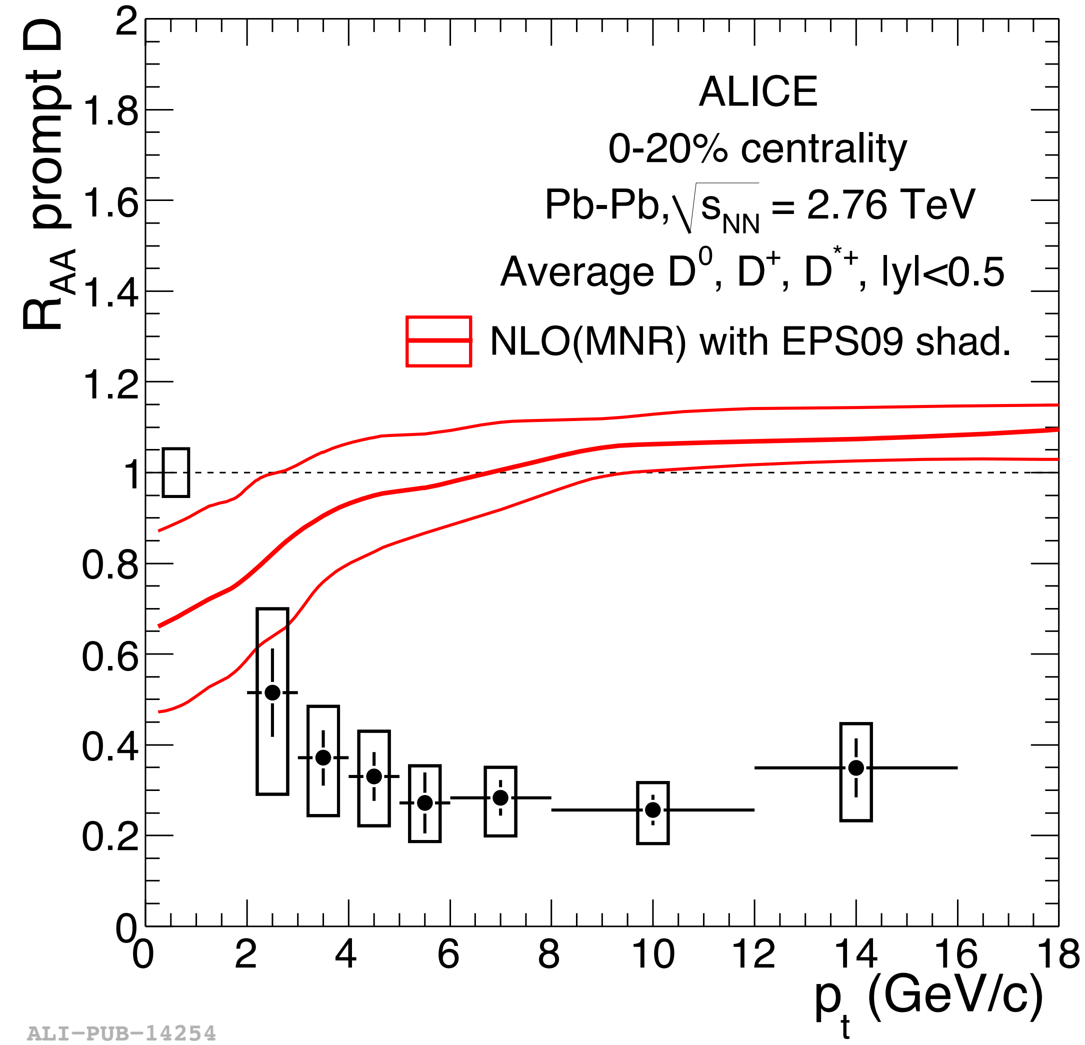


* Reduction of the yields in Pb-Pb collisions with respect to pp collisions scaled ones

Open HF production in Pb-Pb collisions

- First D-meson R_{AA} measurement at LHC by ALICE, published in 2012.



JHEP 9 (2012) 112

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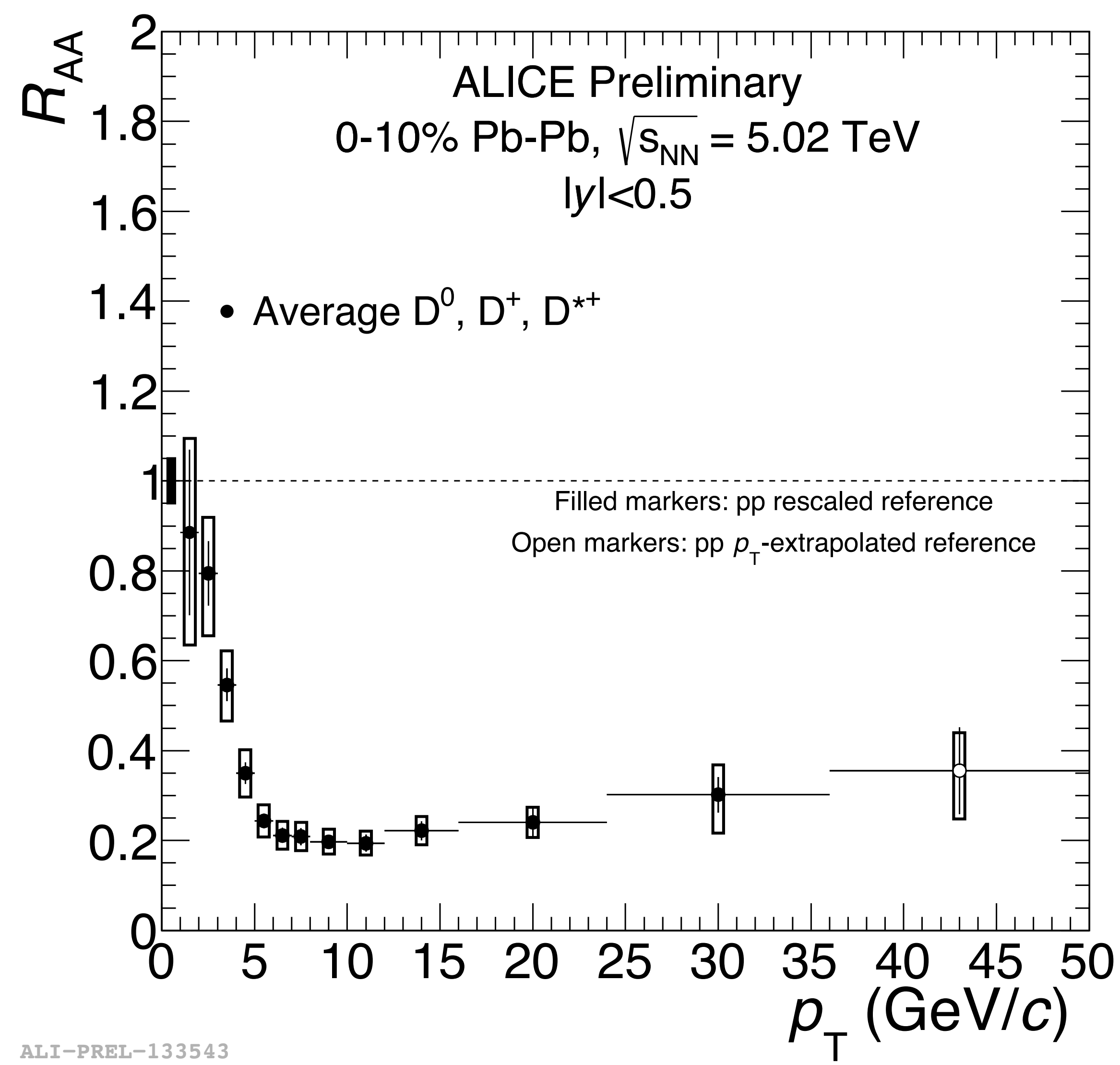

ALICE-PUB 2017 005

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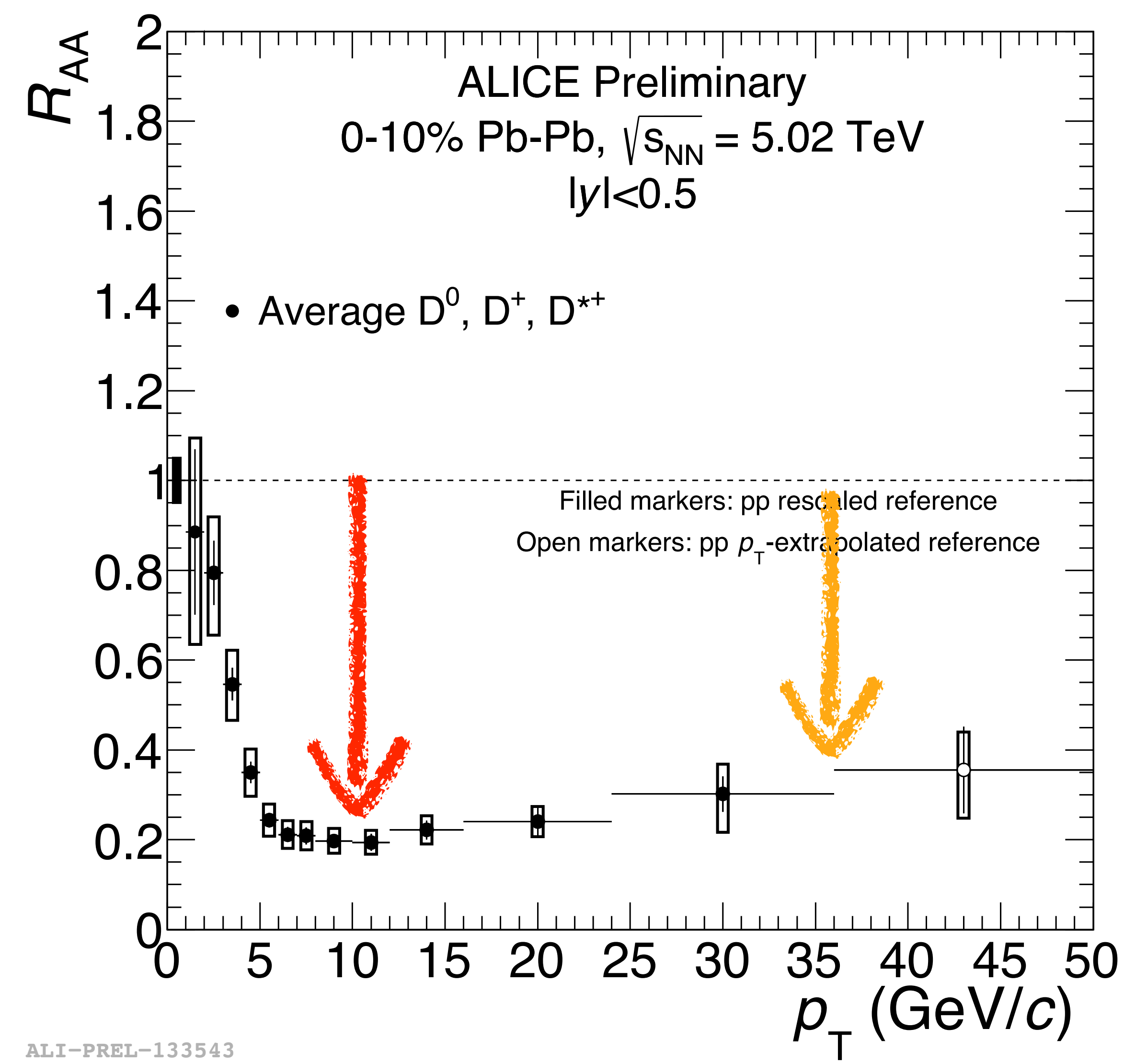
- Strong suppression observed:
  - ~ factor 5 for p_T ~ 10 GeV/c
  - ~ factor 3 for p_T ~ 30 GeV/c



ALICE-PUB 2017 005

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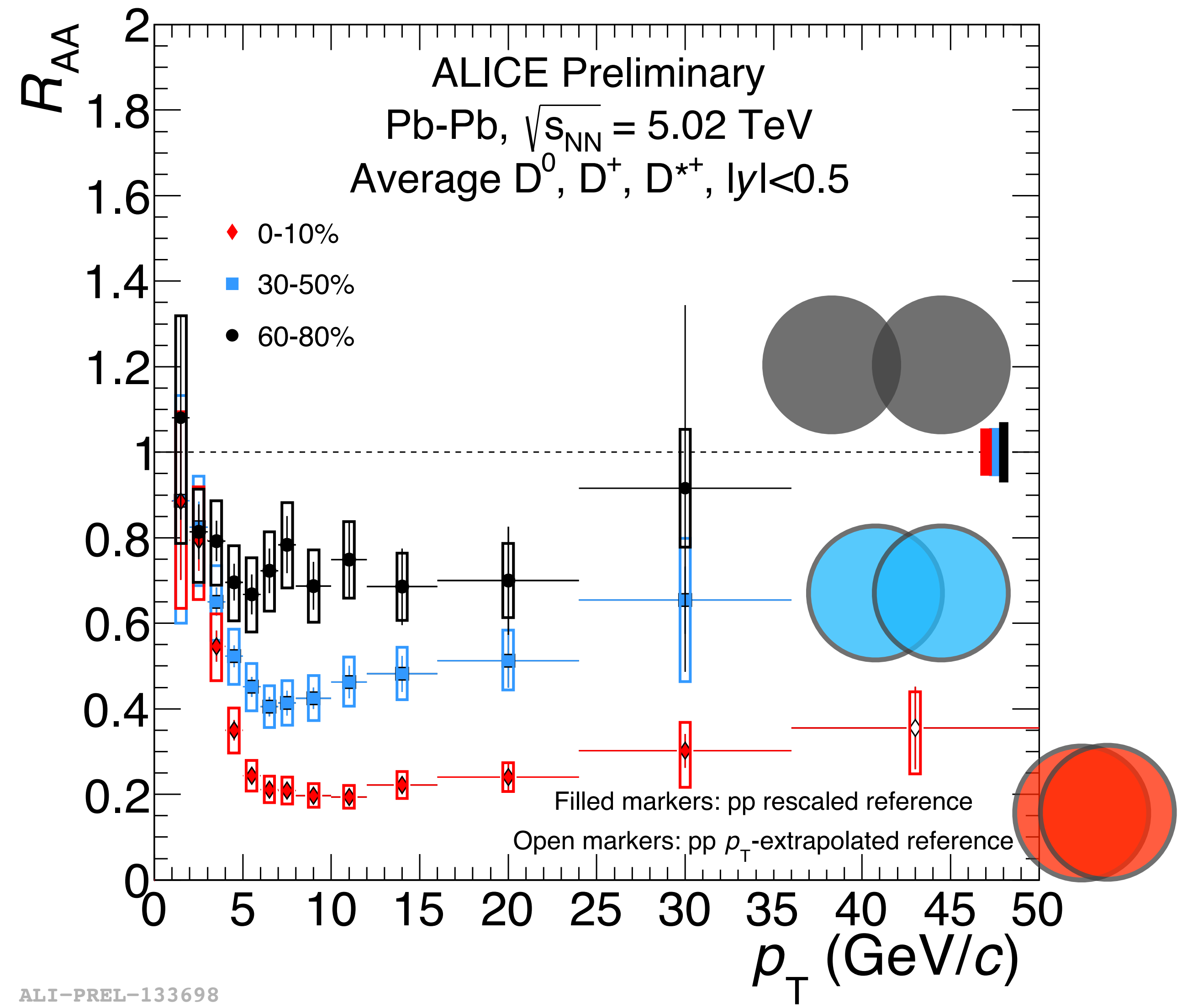

ALICE-PUB 2017 005

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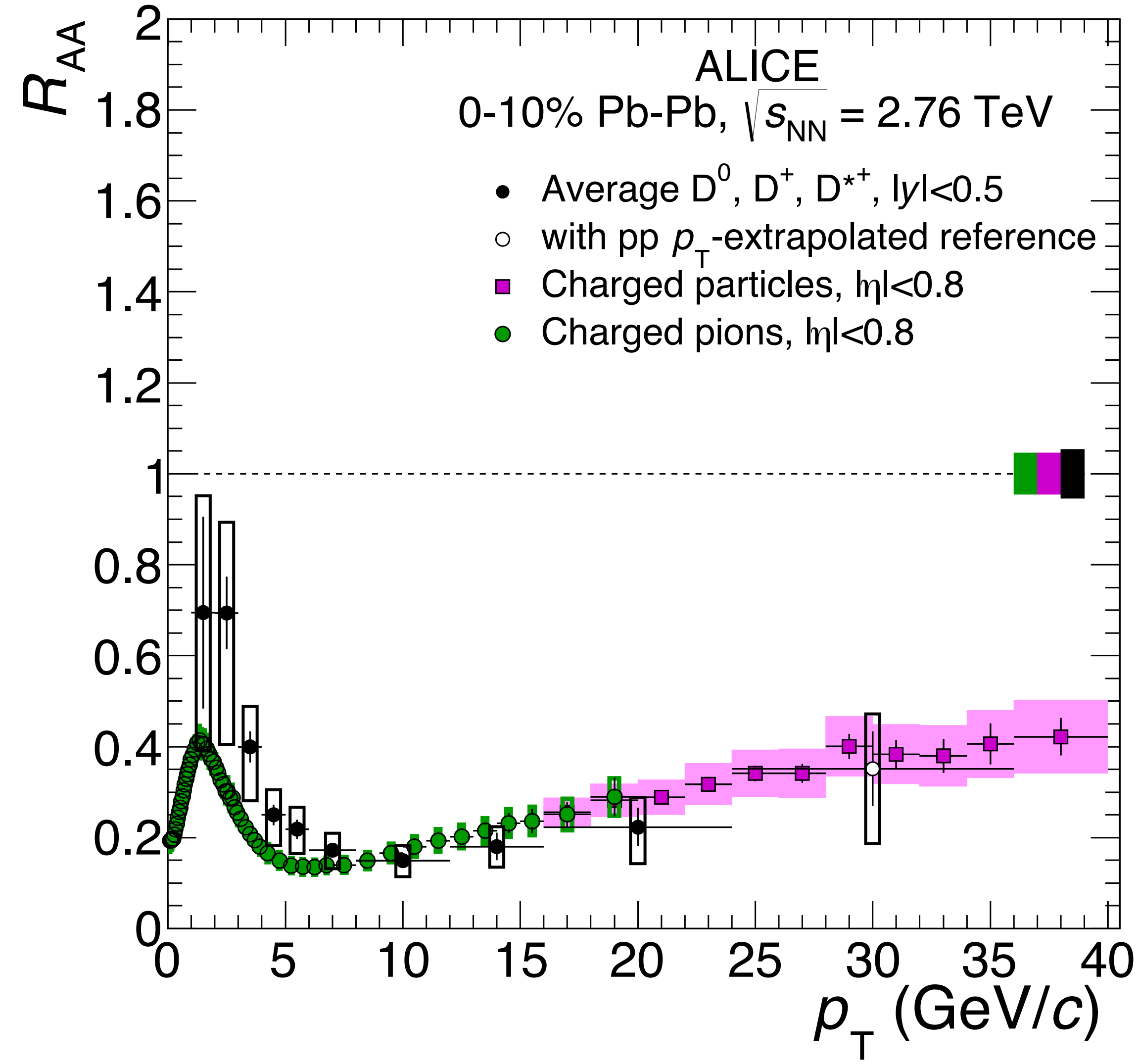
- At high-p_T similar suppression for D mesons and pions
- At low-p_T uncertainties are too large to conclude on possible energy loss mass effect

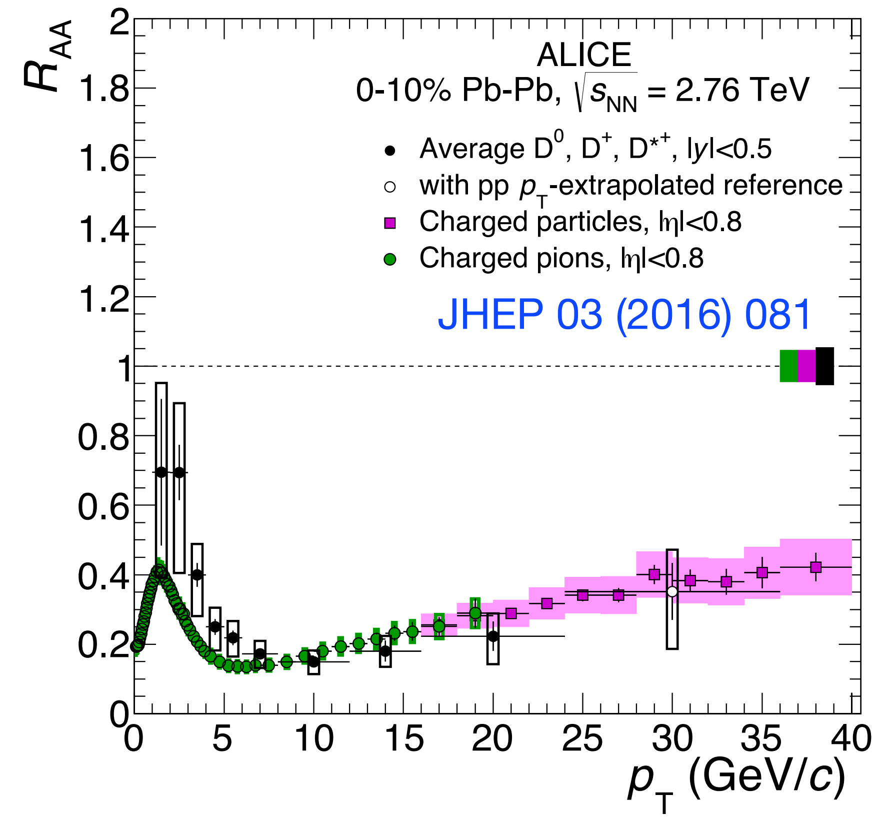


JHEP 03 (2016) 081

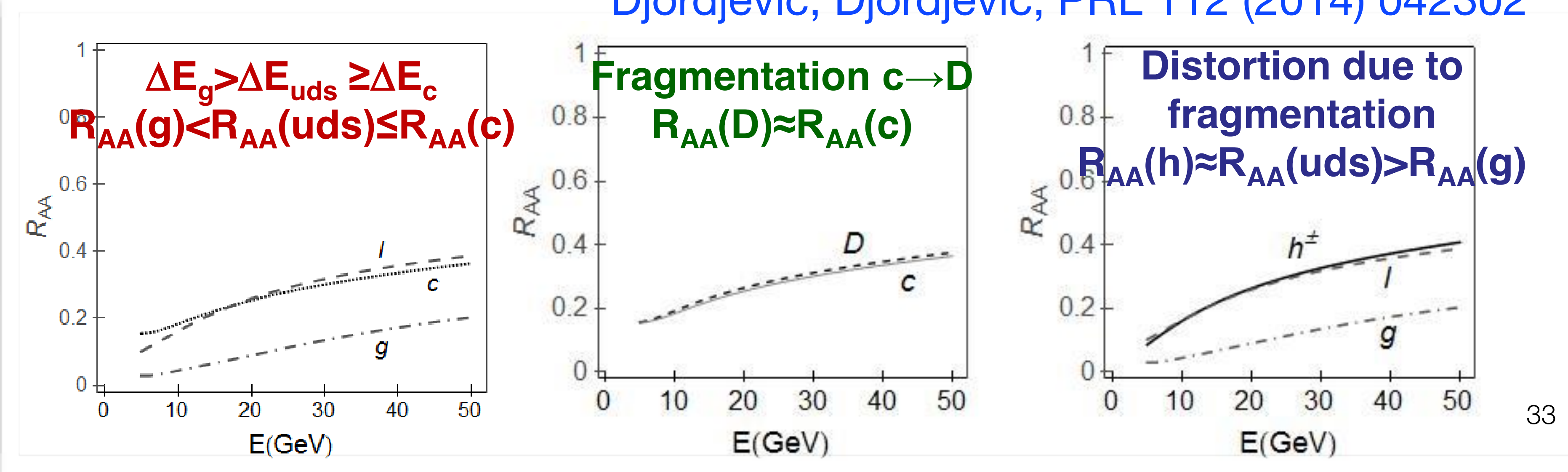
Charm vs light quarks

$$\Delta E(\text{light}) > \Delta E(c) > \Delta E(b) \overset{?}{\rightarrow} R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$

- At high-p_T similar suppression for D mesons and pions
- Described by models that consider:
  - mass and color dependence of the energy loss
  - different momentum spectra for light, heavy quarks and gluons
  - harder fragmentation function for charm than for light quarks and gluons



Djordjevic, Djordjevic, PRL 112 (2014) 042302

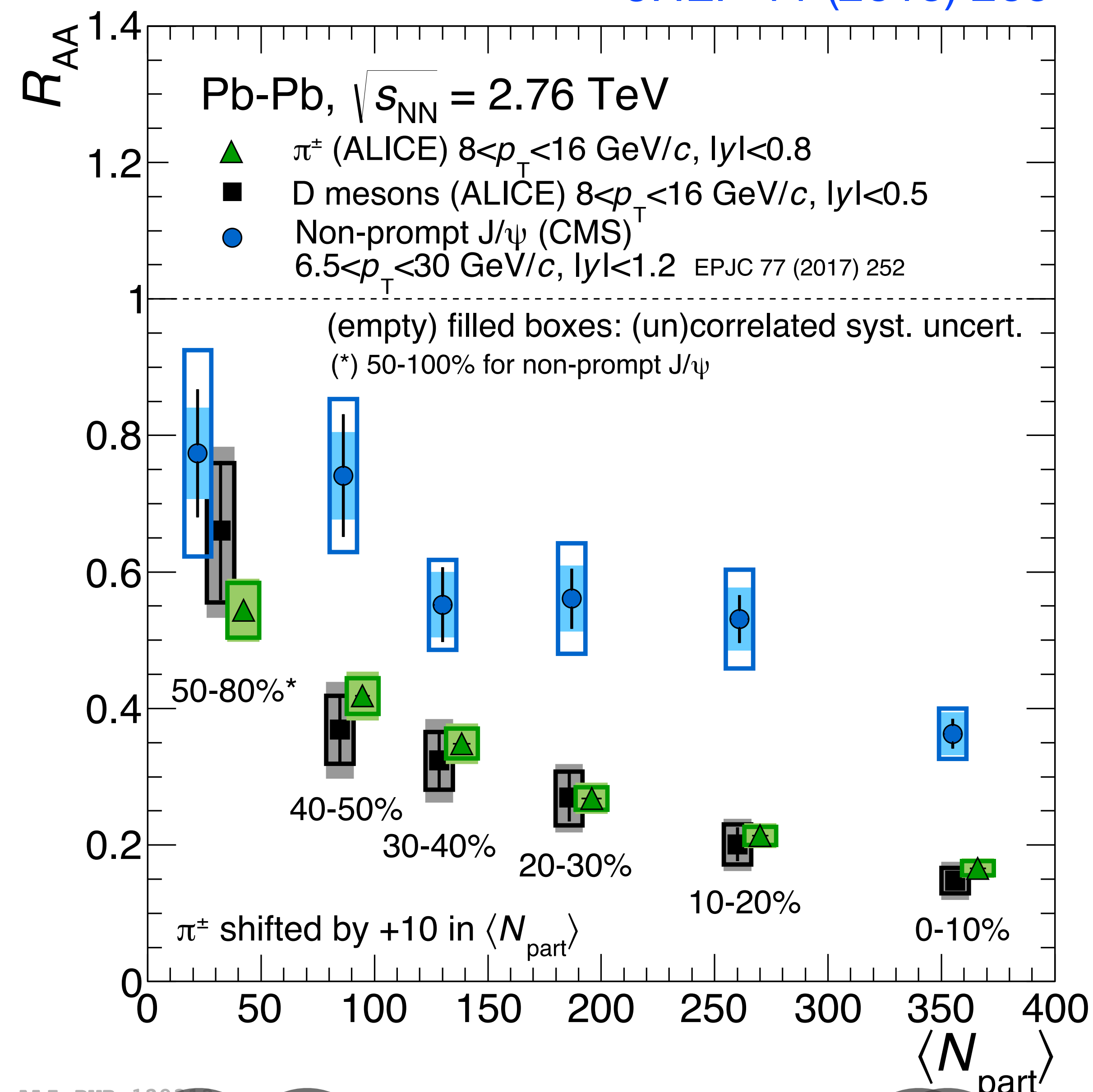


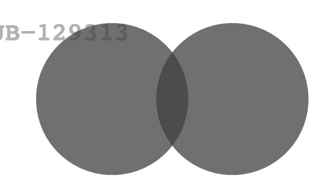
Charm vs Beauty quarks

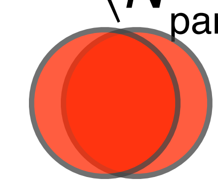
$\Delta E(\text{light}) > \Delta E(c) > \Delta E(b) \overset{?}{\rightarrow} R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

- ALICE D-mesons results compared with CMS non-prompt J/ψ in a similar kinematic range:
  - central rapidity region
  - B and D mesons $< p_T > \sim 10$ GeV/c
- Indication of larger suppression for D mesons than B mesons
  - $R_{AA}(B) > R_{AA}(D)$

JHEP 11 (2015) 205







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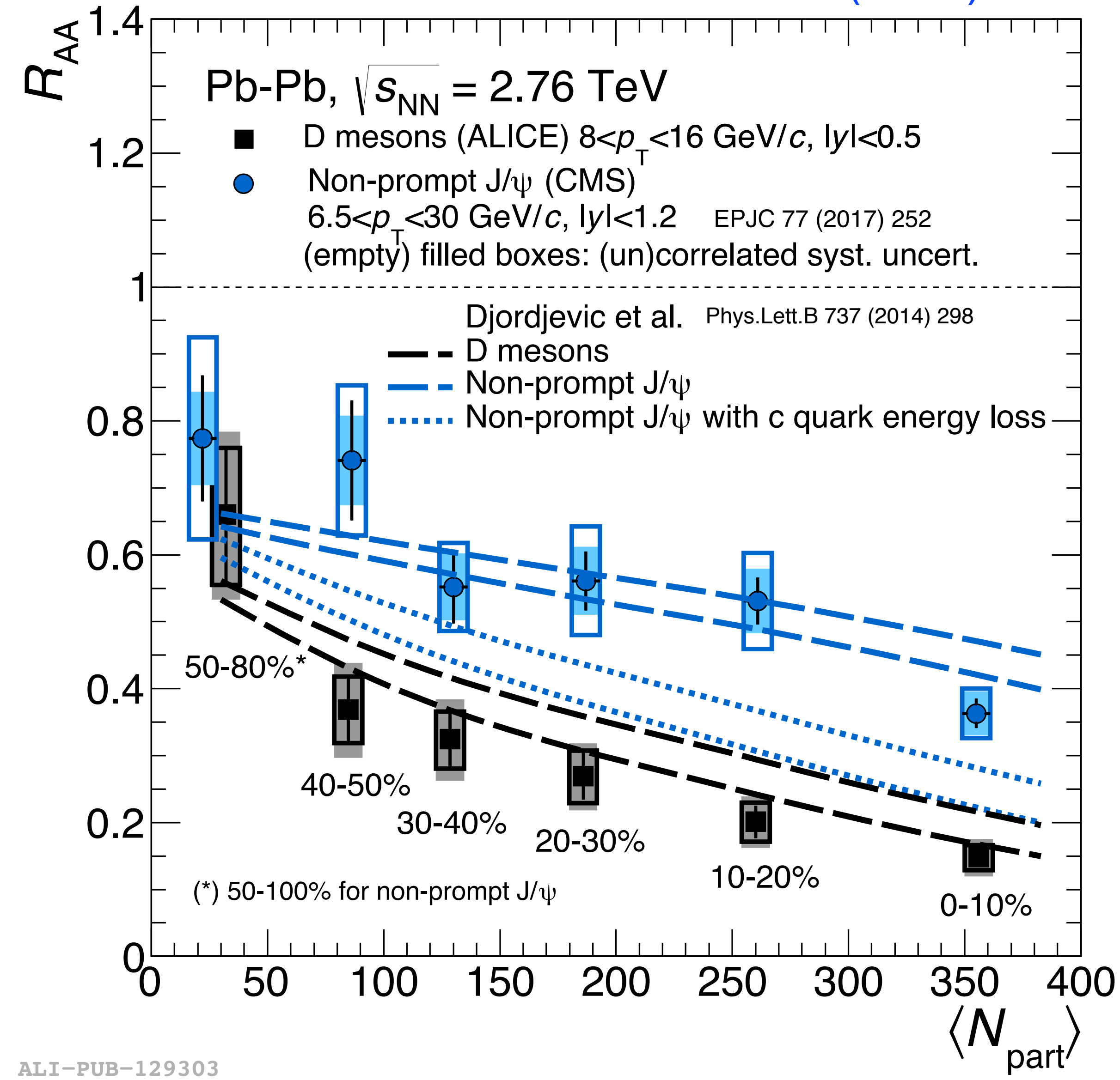
* Indication of larger suppression for D mesons than B mesons
  * $R_{AA}(B) > R_{AA}(D)$

* Models that include mass dependence of the energy loss quantify a difference in the R_{AA} of D and B mesons

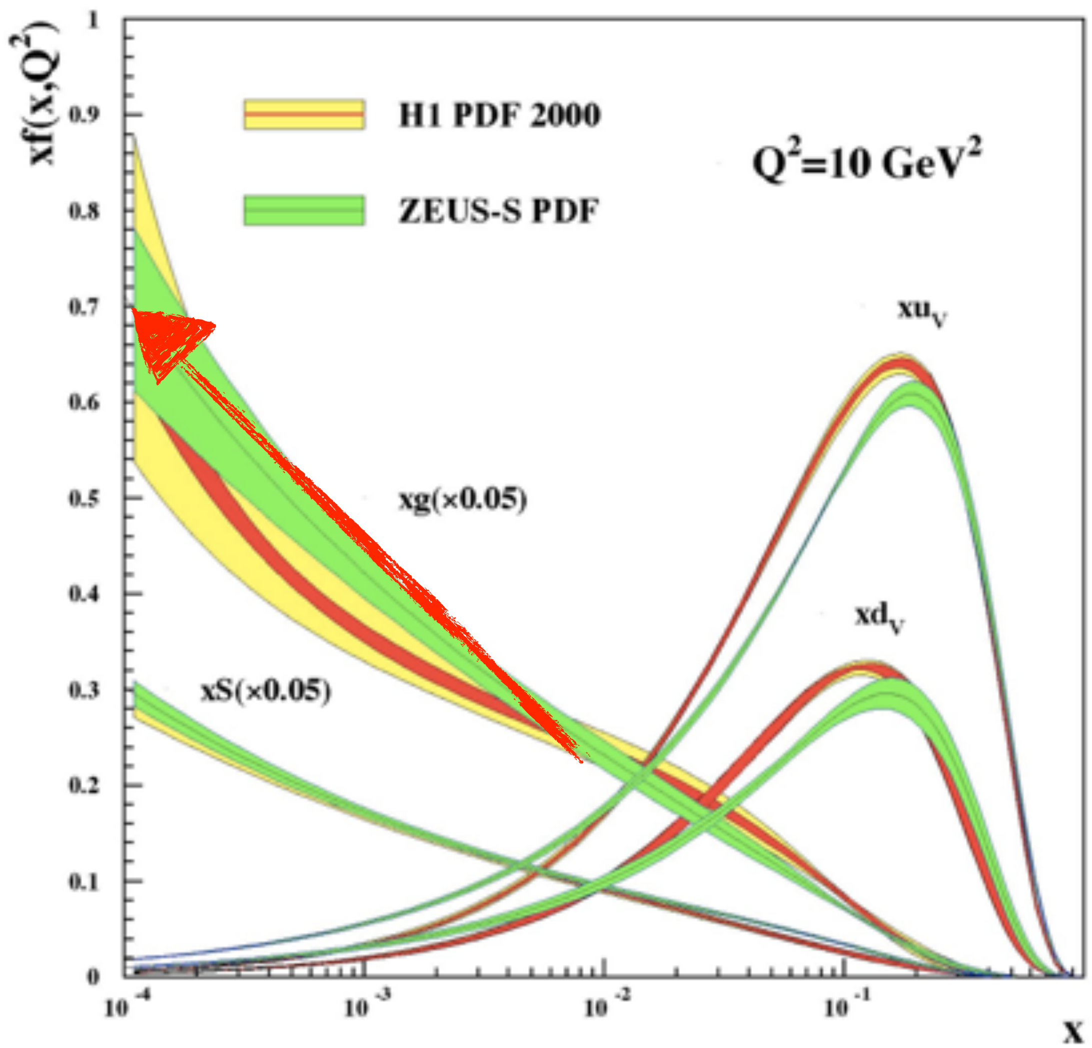
JHEP 11 (2015) 205



About p-A collisions

- The observed suppression might come from effects related to the cold nuclear matter? Modification of the partons distributions in the nuclei

- Bjorken *x* probed with HF production at the LHC < 10^{-2} (usually called small-*x*)
- Strong rise of the gluons density in the nucleus for this regime (factor $A^{1/3}$ ~ 6).
- QCD regime where gluons are dense and "extended", they can overlap → Saturation



Bjorken x is the fraction of momentum of the nucleon carried by a parton

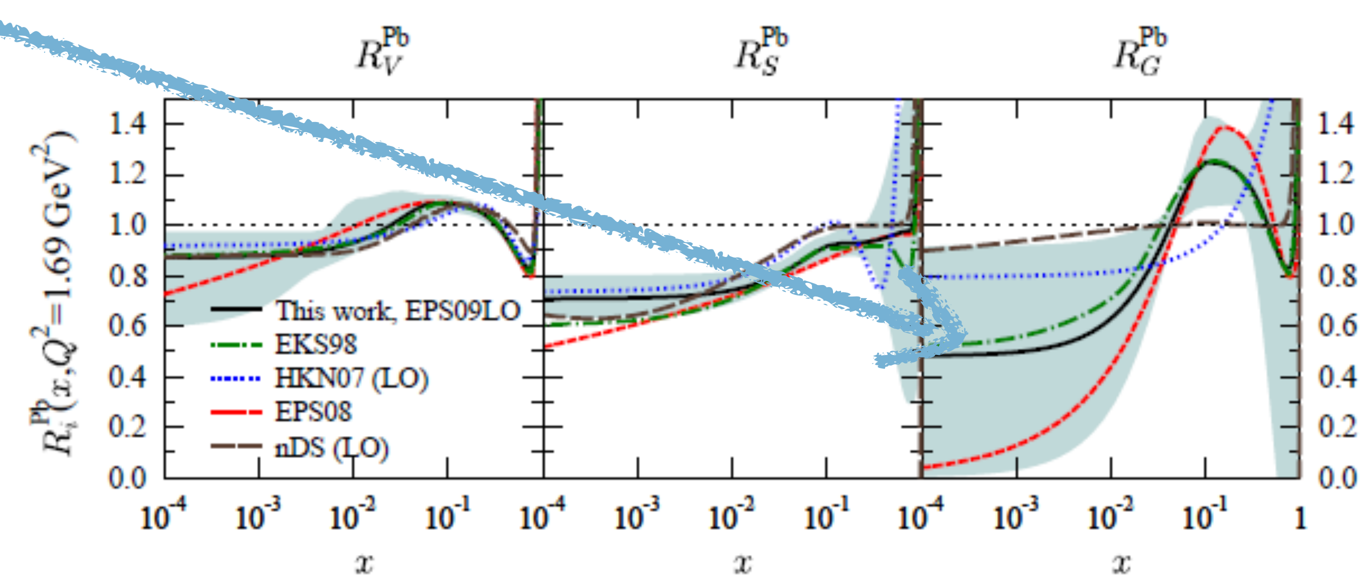
About p-A collisions

* The observed suppression might come from effects related to the cold nuclear matter? Modification of the partons distributions in the nuclei

* Shadowing: parton densities in nuclei are depleted with respect to free partons (“low-x gluon fusion”).

$$xG_A(x, Q^2) = A\, xg(x, Q^2)\, R_G^A(x, Q^2)$$

* Most of the low-x data are in non-perturbative range
* Difficult to constrain the pQCD calculations
* Large uncertainties on $R_G^A(x, Q^2)$

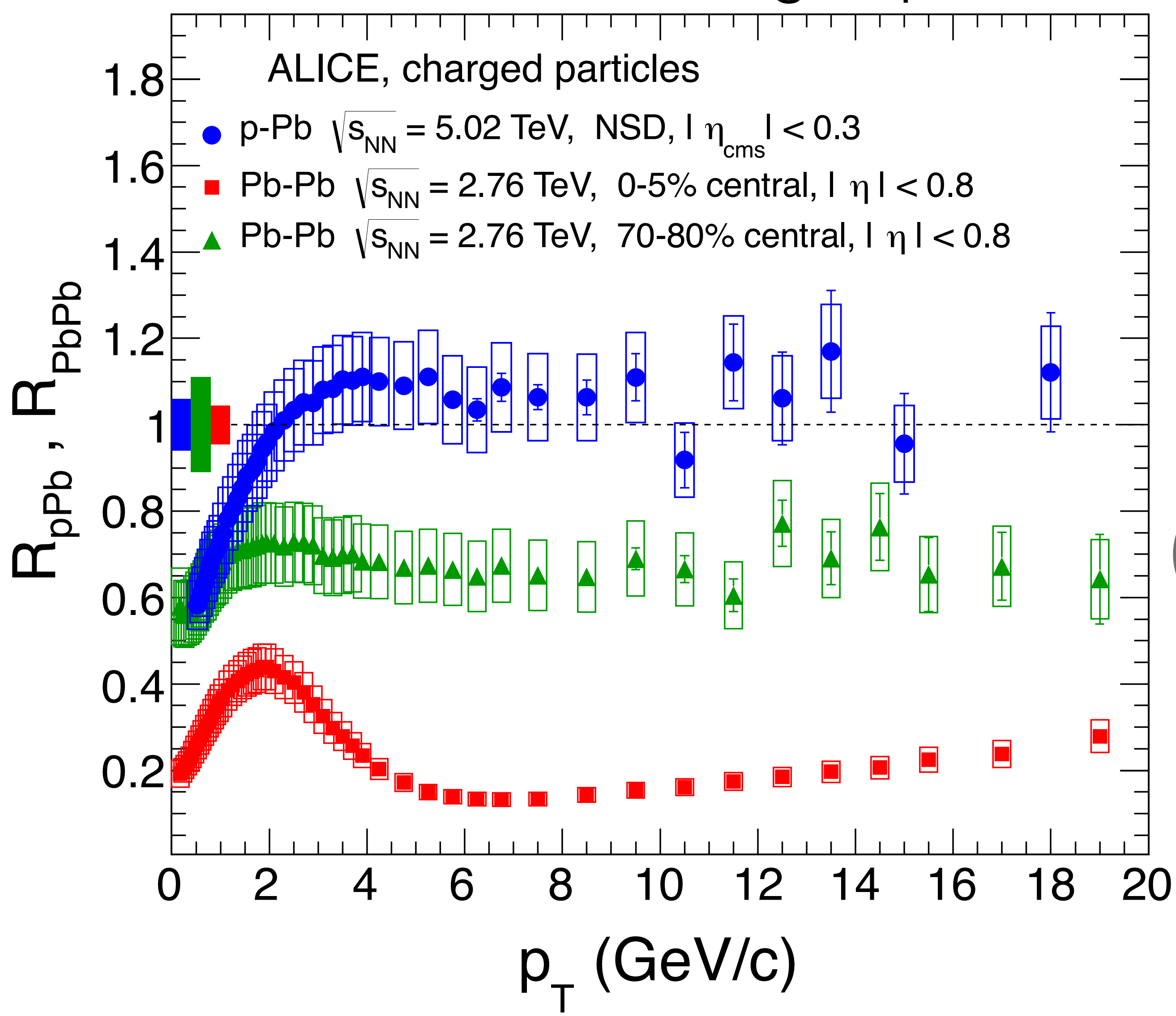


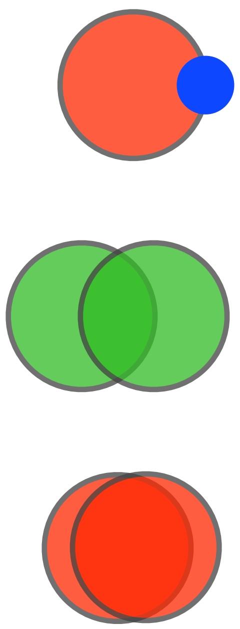
see e.g. Eskola et al. JHEP0904(2009)065

Control experiments

- No high-p_T suppression is observed in **pA collisions**.
- This is actually observed for
  - High-p_T hadrons

charged particles





ALICE, PRL110 (2013) 082302

Control experiments

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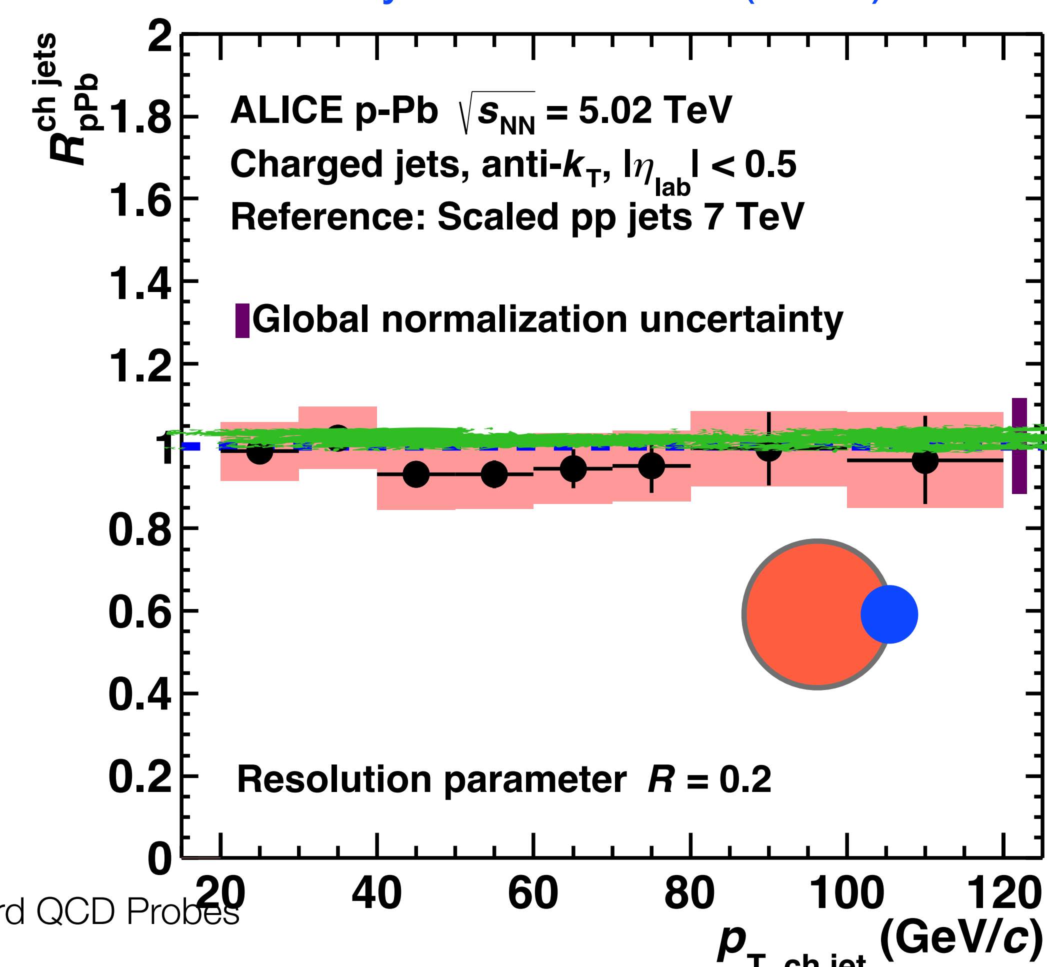
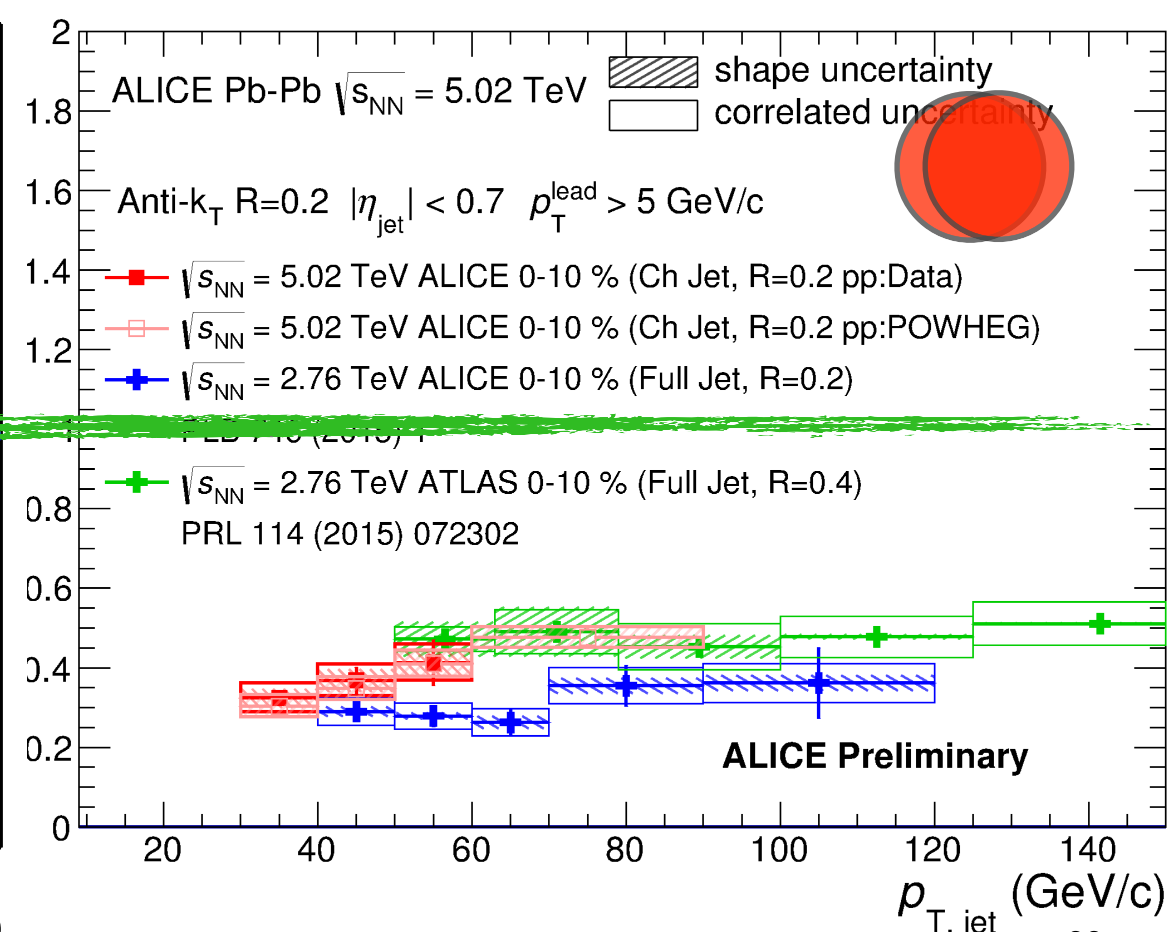
Phys. Lett. B 749 (2015) 68-81





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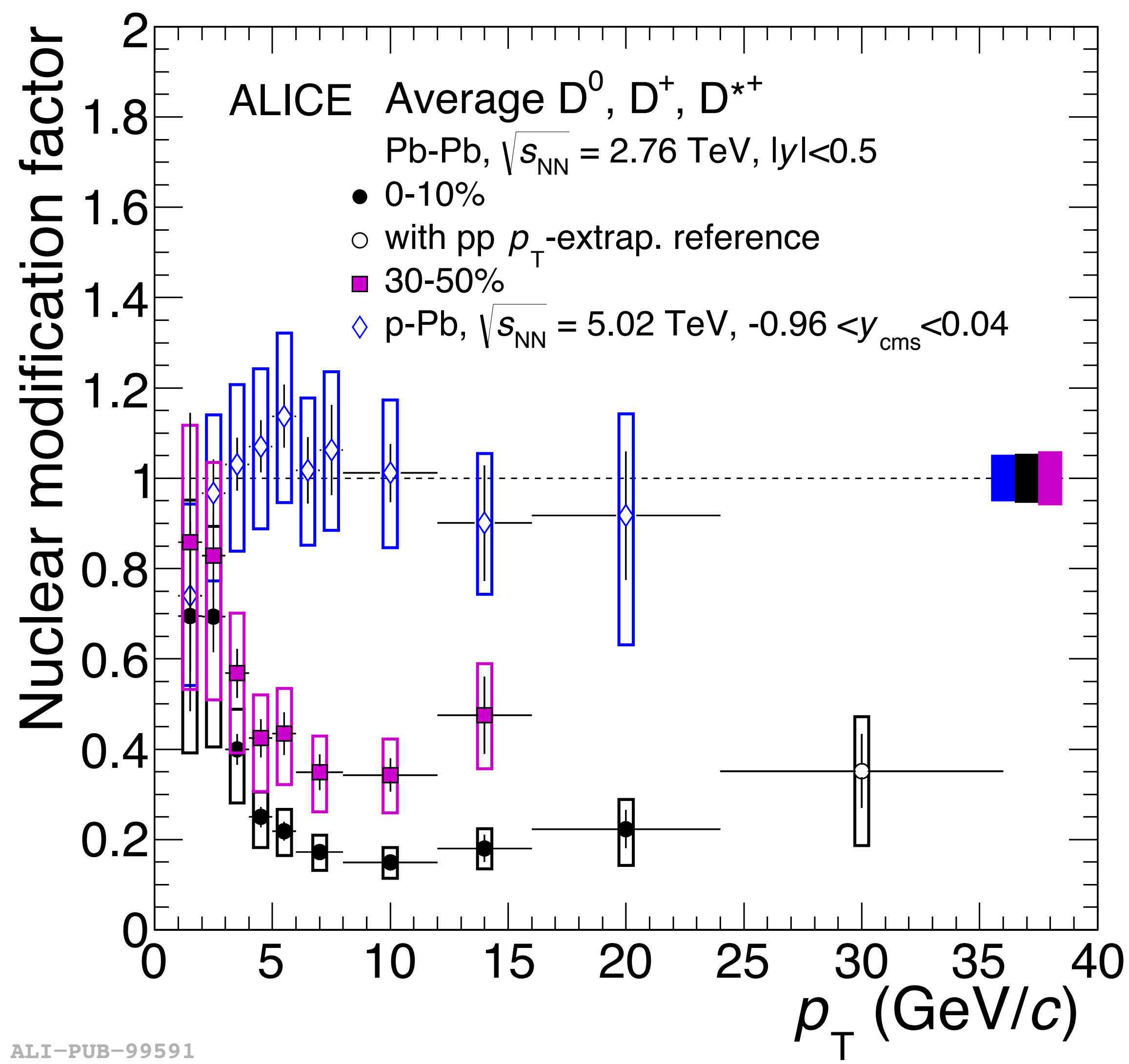
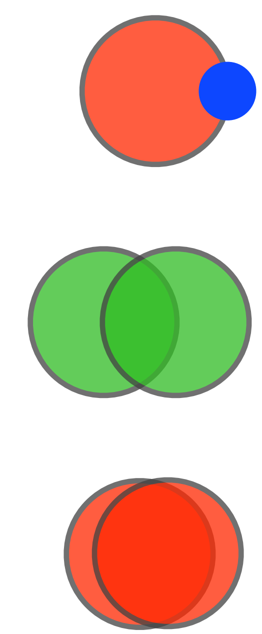
D mesons



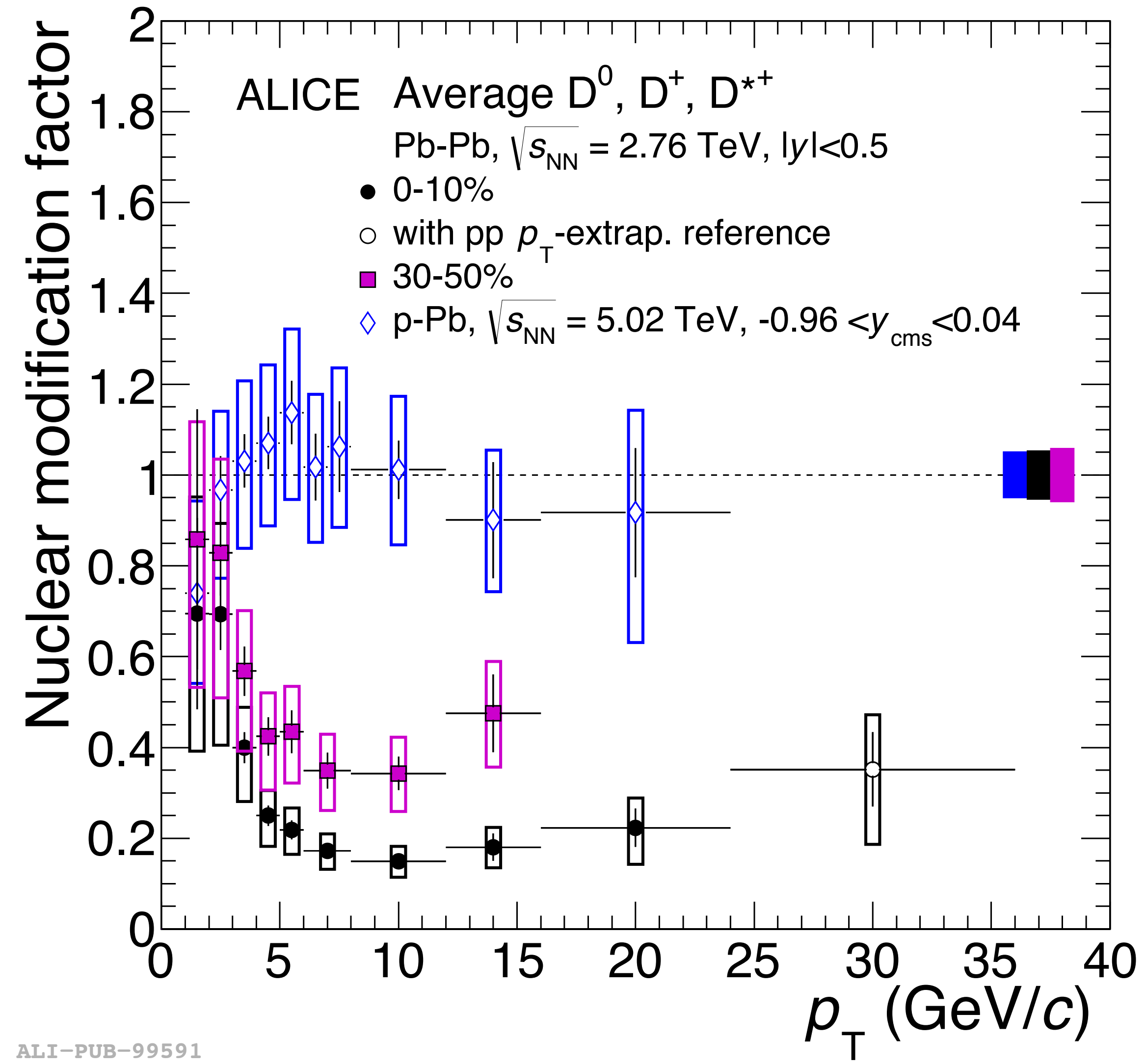
JHEP 03 (2016) 081



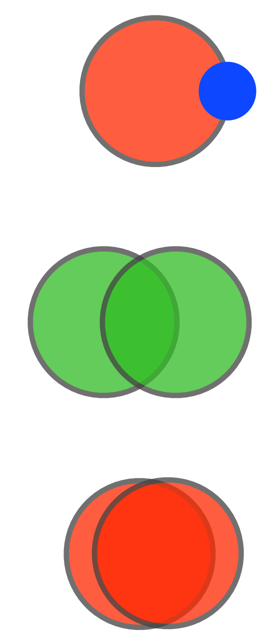
Control experiments

- No high-p_T suppression is observed in **pA collisions**.
- This is actually observed for
  - High-p_T hadrons
  - Jets
  - Heavy flavor production
- The suppression of high-pT hadrons, jets and D mesons observed in central AA collisions comes from a final-state effect(*).

D mesons



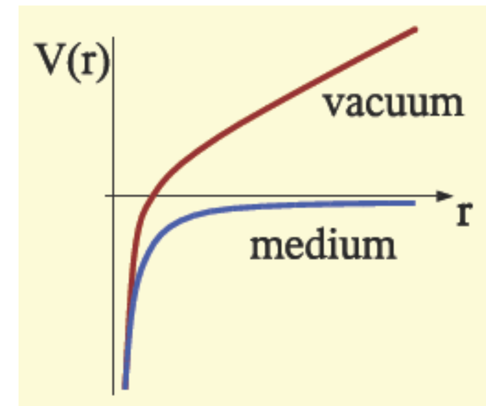
JHEP 03 (2016) 081

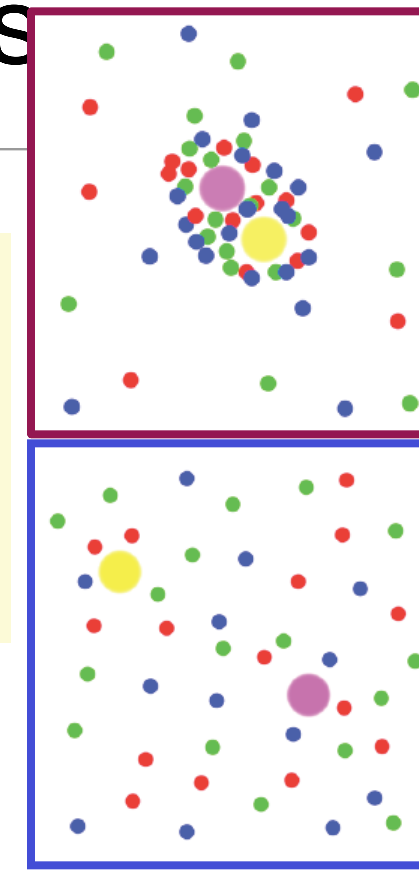


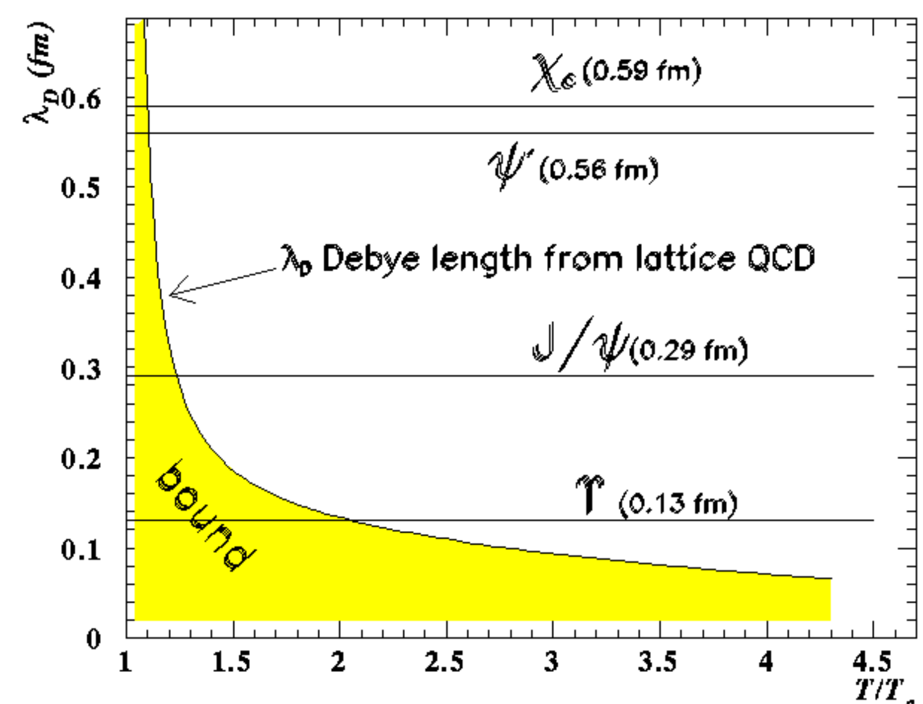
(*) not the case for quarkonia as we will see later

Quarkonia suppression in Pb-Pb collisions

- J/ψ suppression proposed as QGP signature by Matsui and Satz in 1986.
  Matsui, Satz, PLB178 (1986) 416
- In the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to the e.m. Debye screening).
- Charmonium and bottomonium states with distance > λ_D will not bind, expected suppressed production.
- λ_D and therefore which -onium states will be suppressed, depends on the temperature







Digal,Petrecki,Satz PRD 64(2001) 0940150

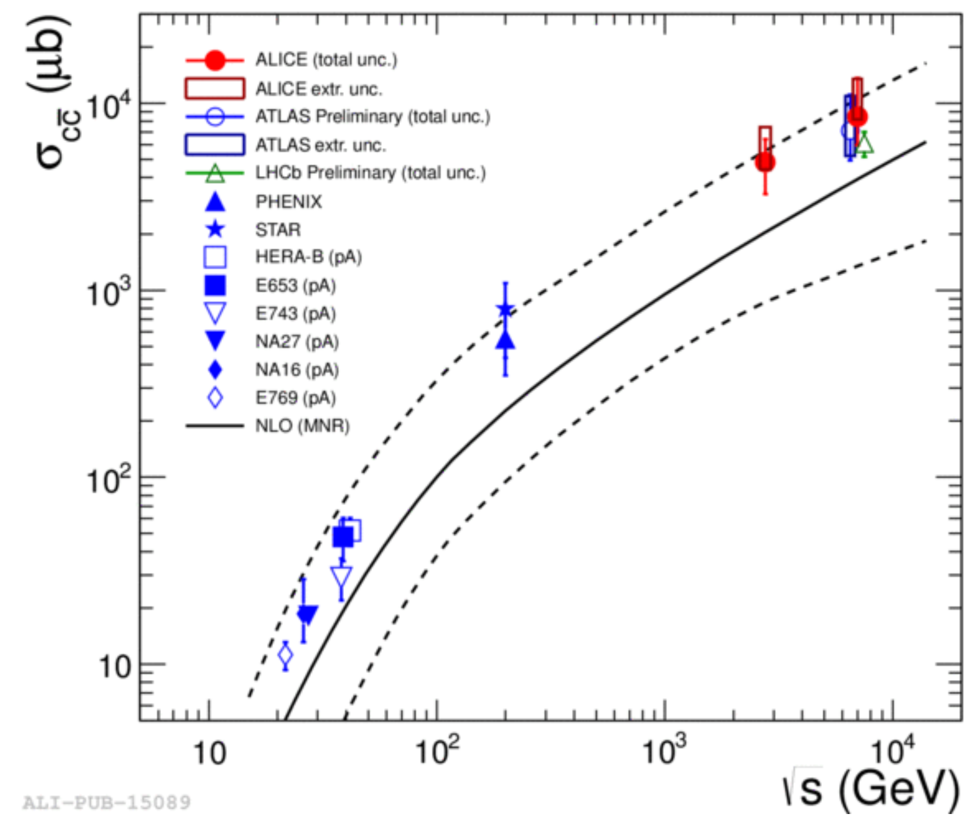
… but also maybe regeneration

- Uncorrelated c quarks from the medium could bind at the hadronization of the system and form charmonium.

- At RHIC and LHC, large number of charm pairs produced in central collisions

$$N_{c\bar{c}} = \frac{\sigma_{c\bar{c}}^{pp}}{\sigma_{inel}^{pp}} \cdot N_{coll} \sim \frac{\sigma_{c\bar{c}}^{pp}}{65\ \text{mb}} \cdot 1600$$

	SPS 20 GeV	RHIC 200 GeV	LHC 2.76 TeV
Ncc/ event	~0.1	~10	~100



JHEP1207 (2012) 191

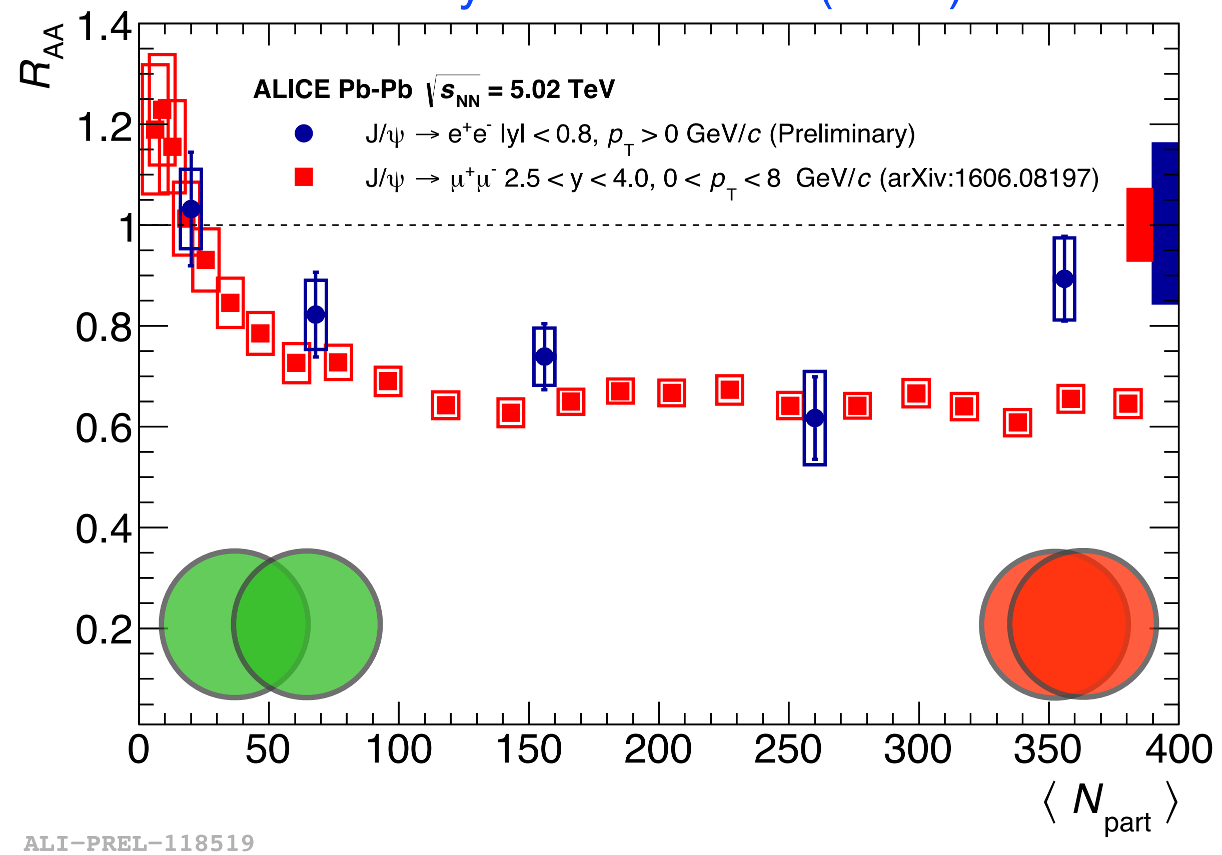
- Do we have indication that charm quarks take part in the evolution of the system? Thermalization?

P. Braun-Muzinger and J. Stachel, Phys. Lett. B490(2000) 196
R. Thews et al, Phys.ReV.C63:054905(2001)

J/ψ R_{AA} at $\sqrt{s_{NN}}$ = 5.02 TeV

- **At the low-p_T (p_T > 0) :**
  - Constant suppression vs centrality

Phys. Lett. B 766 (2017) 212-224



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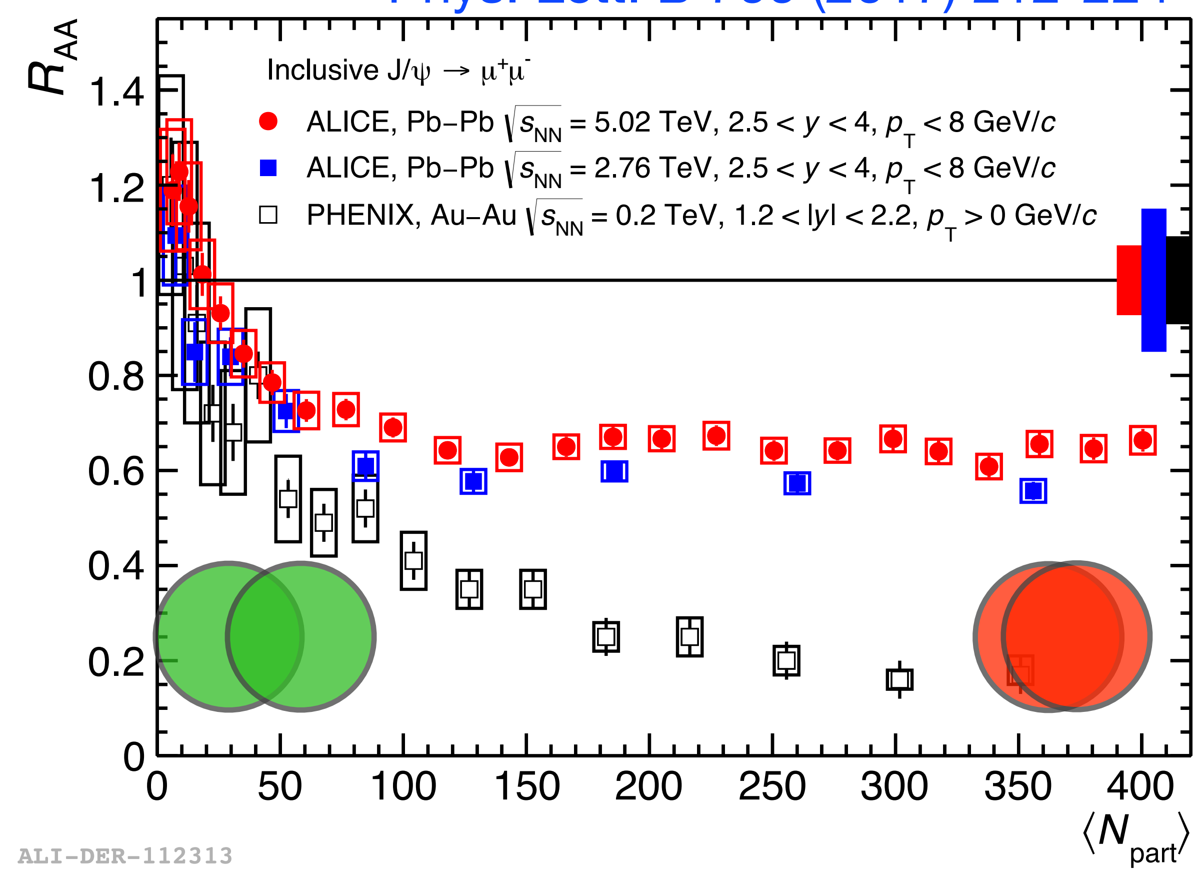

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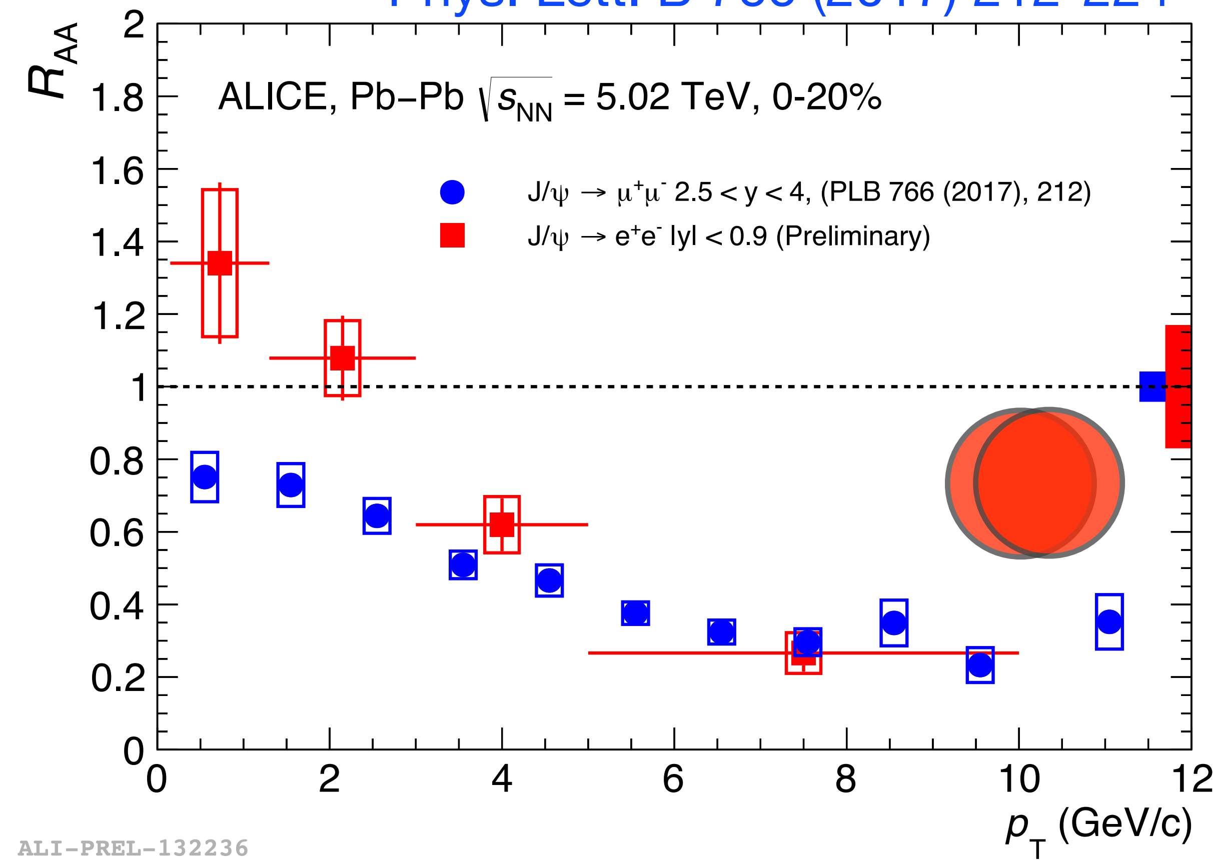

- **At high-p_T:**
  - J/ψ suppressed of a factor ~4 for p_T > 5 GeV/c

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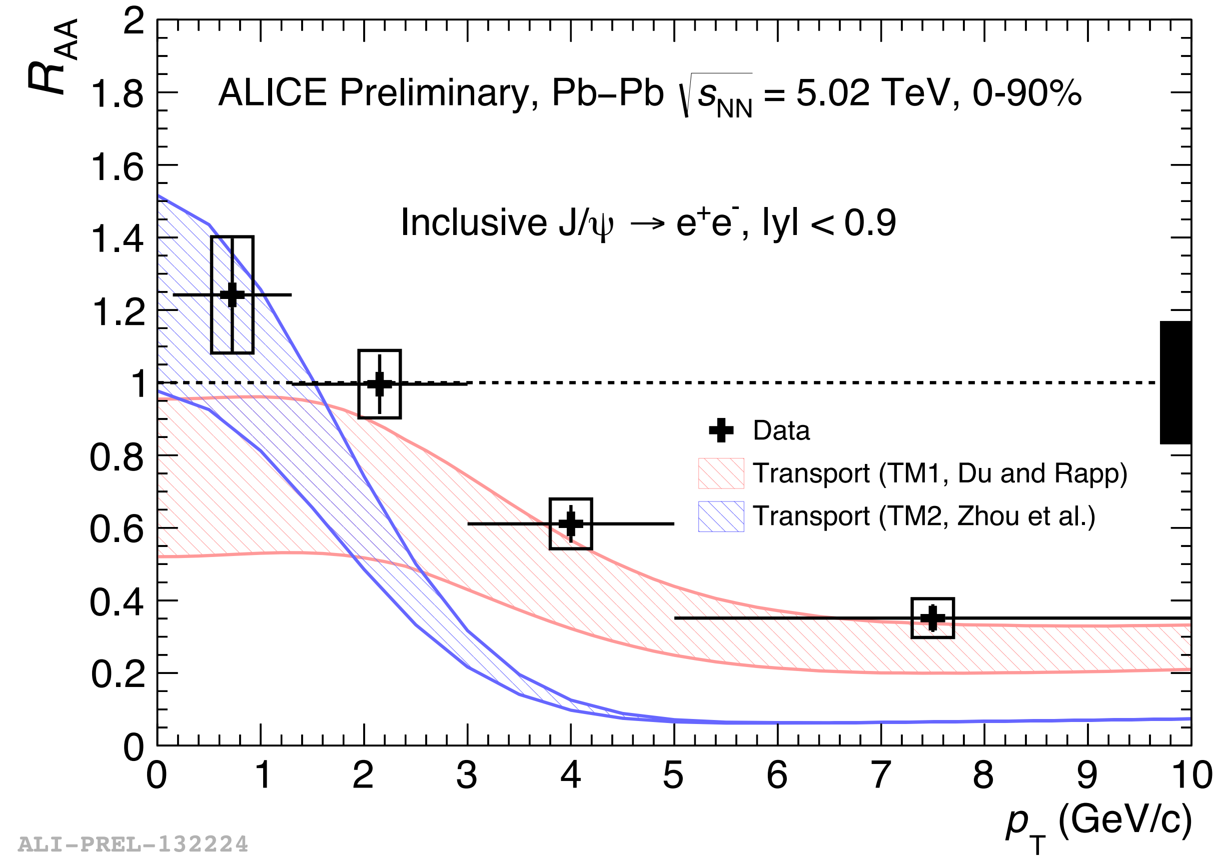


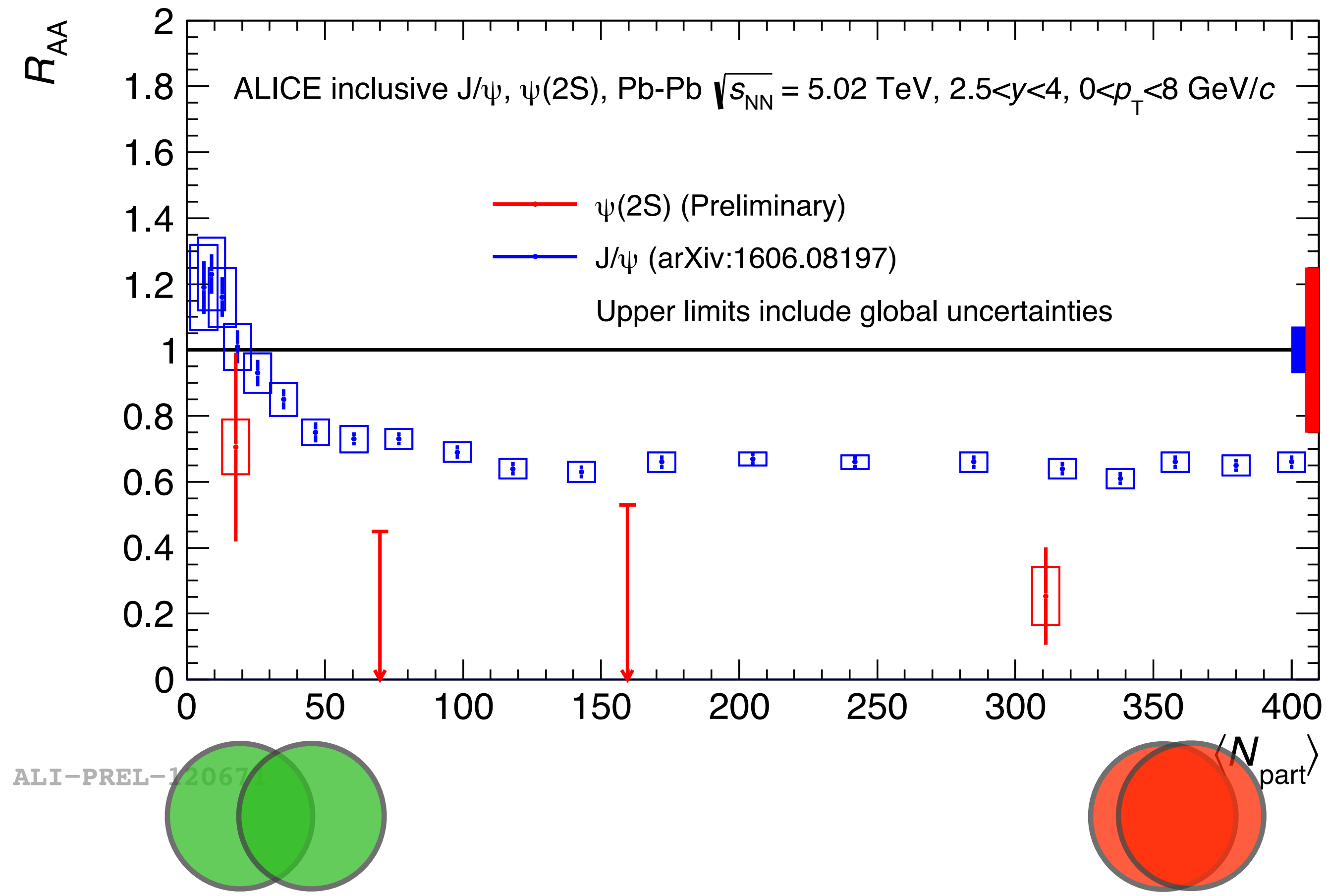
- **At high-p_T:**
  - J/ψ suppressed of a factor ~4 for p_T > 5 GeV/c

- Models that includes regeneration at low-p_T reproduce the data.

…but not only J/ψ

- **ψ(2S)** is even more suppressed than **J/ψ** for semi central and central collisions.
  - more statistic is needed to draw quantitative conclusion

Phys. Lett. B 766 (2017) 212-224



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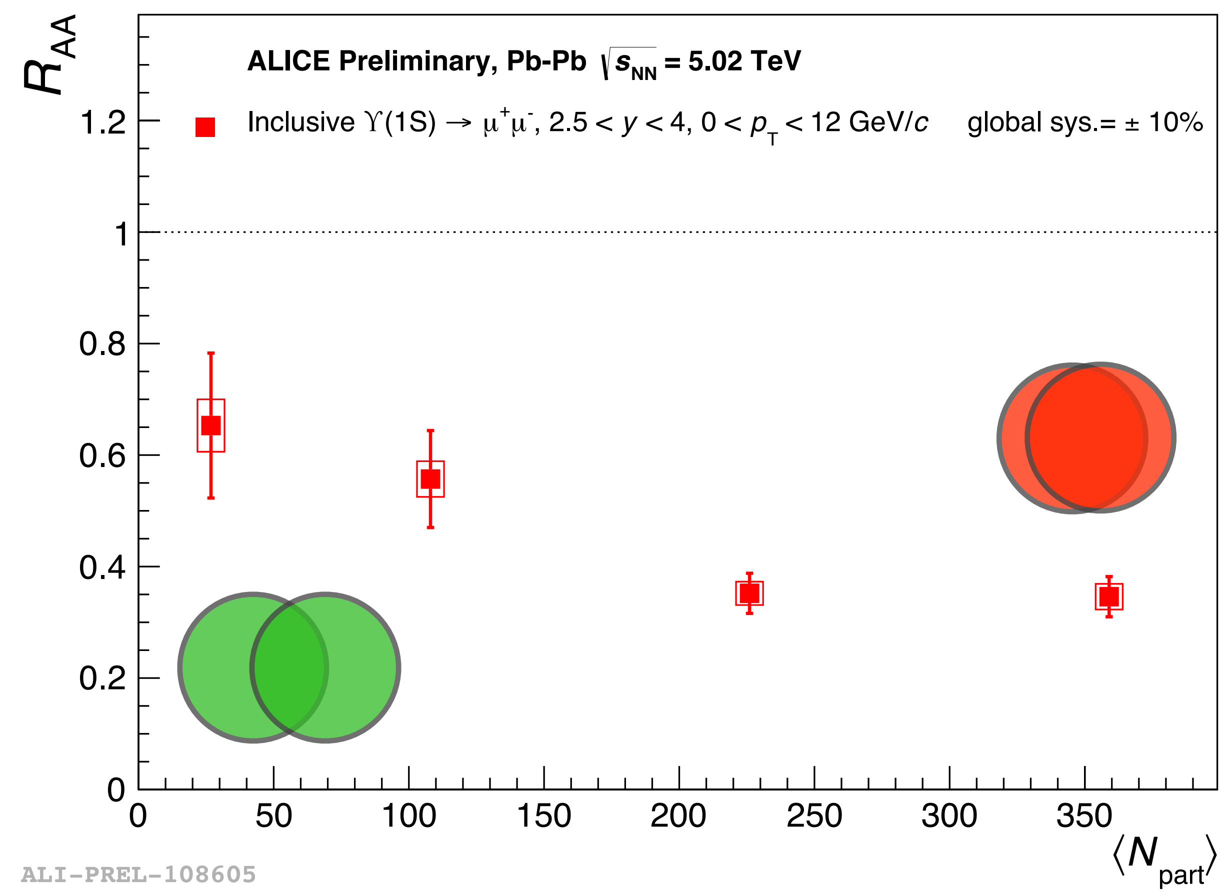
- Strong suppression of the Υ(1S) state. More statistic is needed to draw a quantitative conclusion



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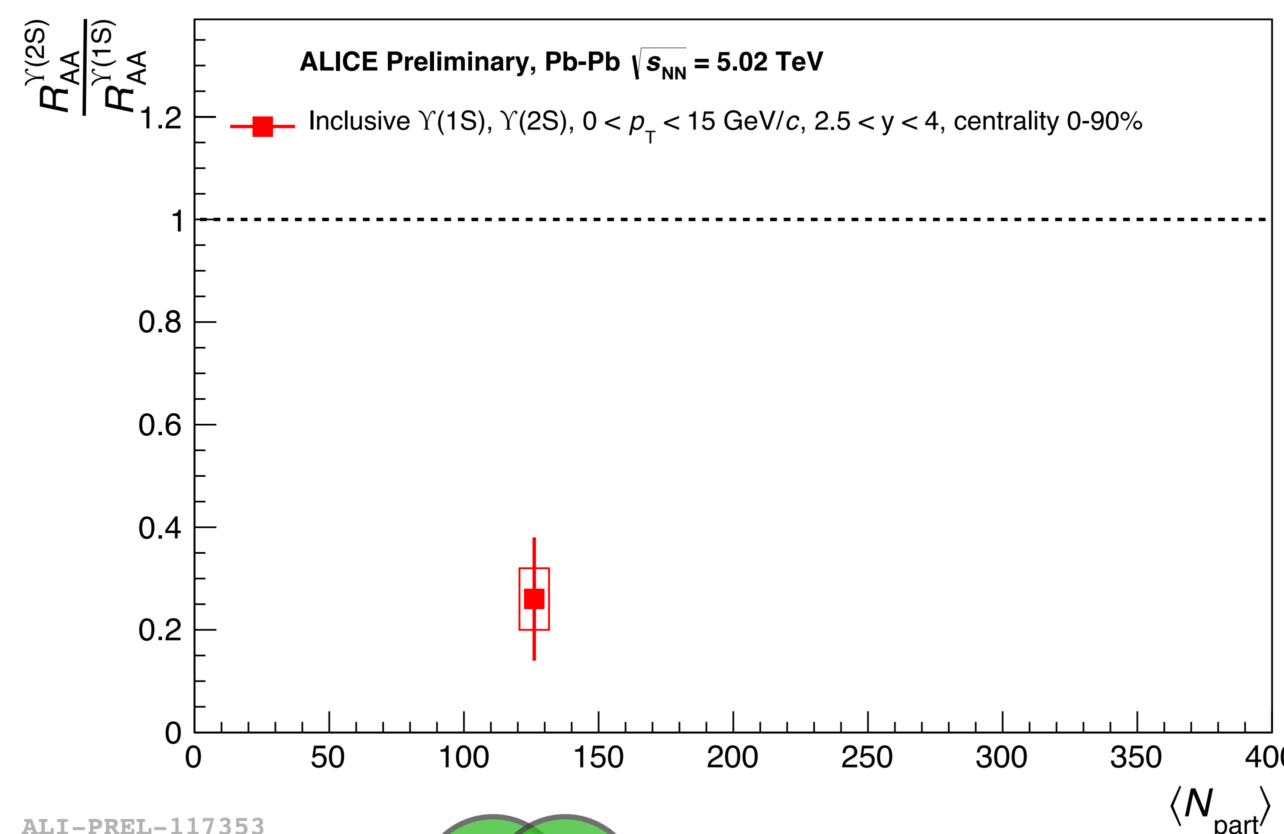
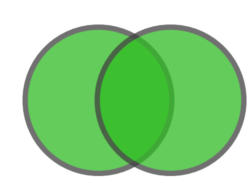
- Stronger suppression of the Υ(2S) state than the Υ(1S)
  - also here more statistics is needed to improve the results

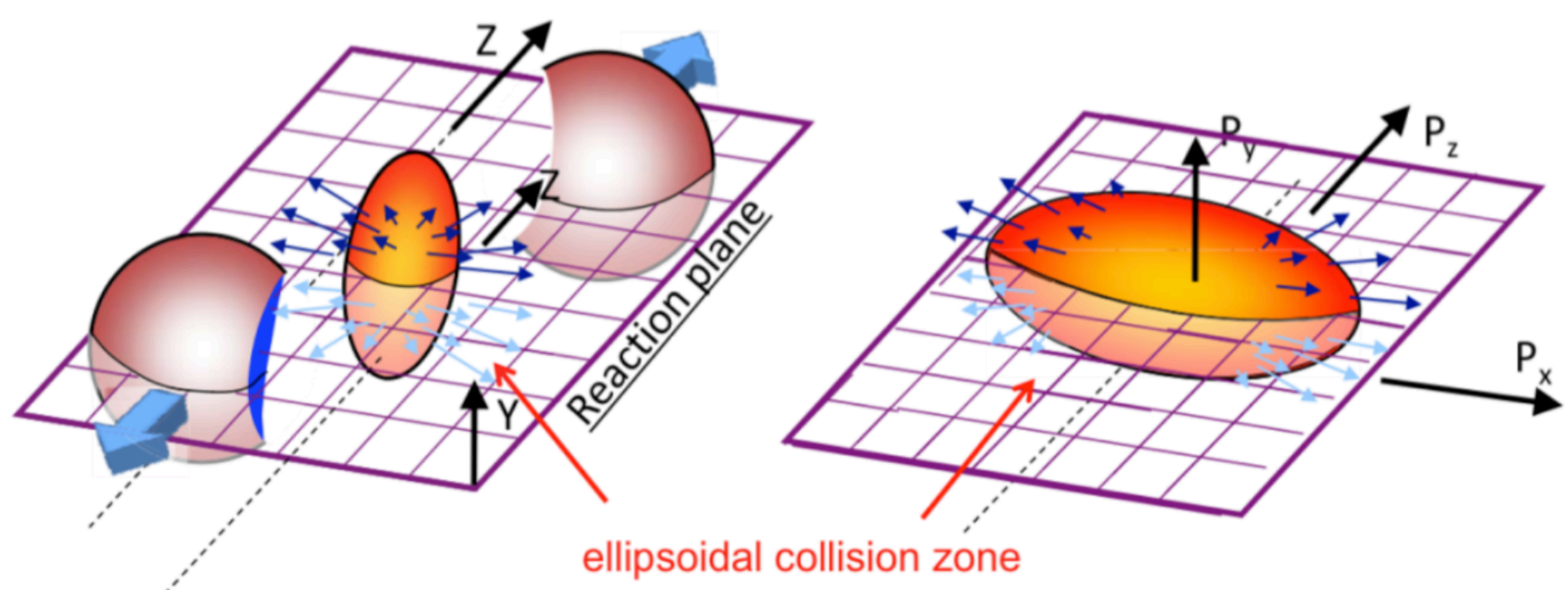




Does charm also flow?

- Azimuthal anisotropy of particle production related to collective expansion of the medium.

- Charm quark is a hard probe, can the medium be so strongly interacting to make charm become part of the medium?



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

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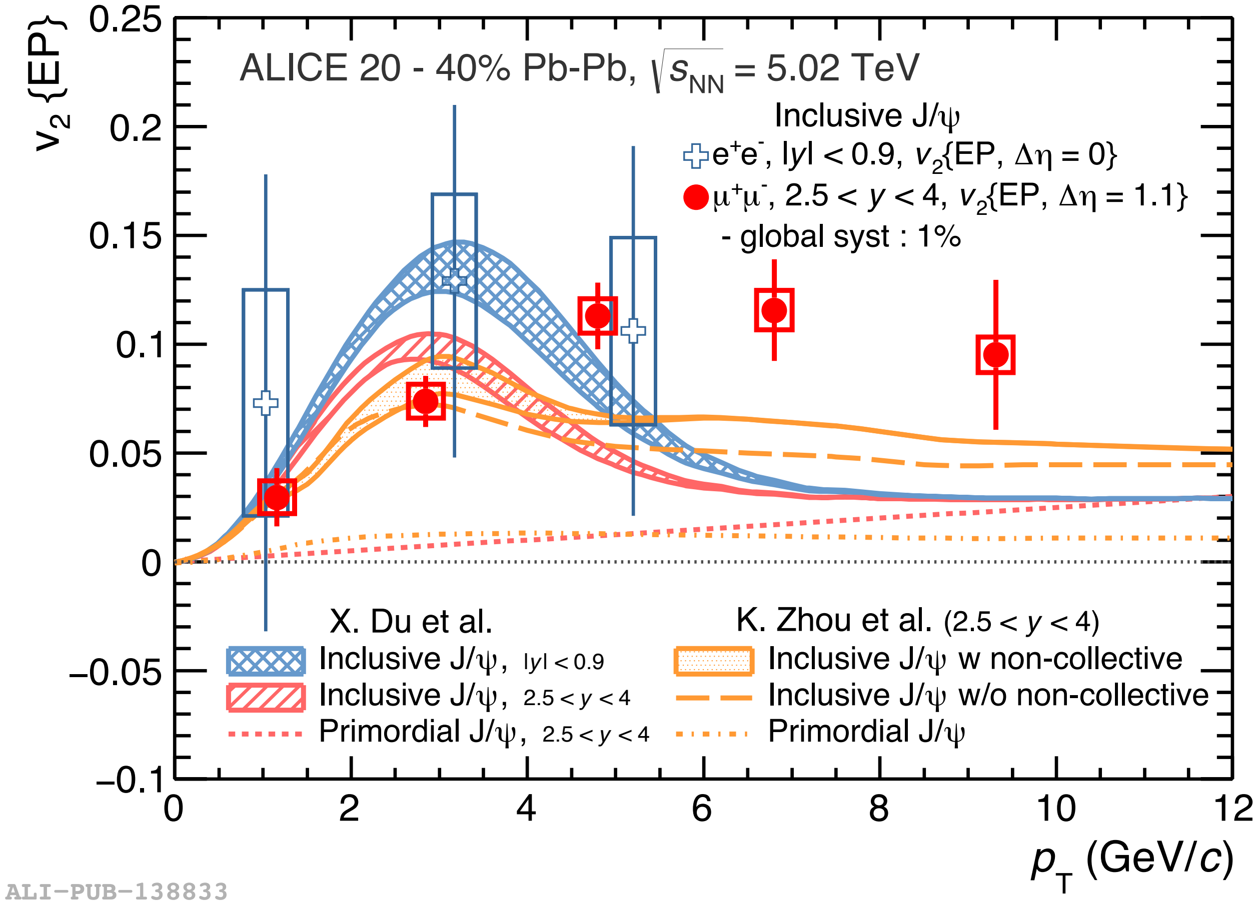
- Study of flow of hadrons with charm:
  - J/ψ



Submitted to PRL, arXiv:170905260

- J/ψ v_2 > 0 for intermediate p_T
- Models that include thermalization of charm quarks and J/ψ regeneration can describe the data
- Primordial J/ψ v_2 is expected to be very small

Does charm also flow?

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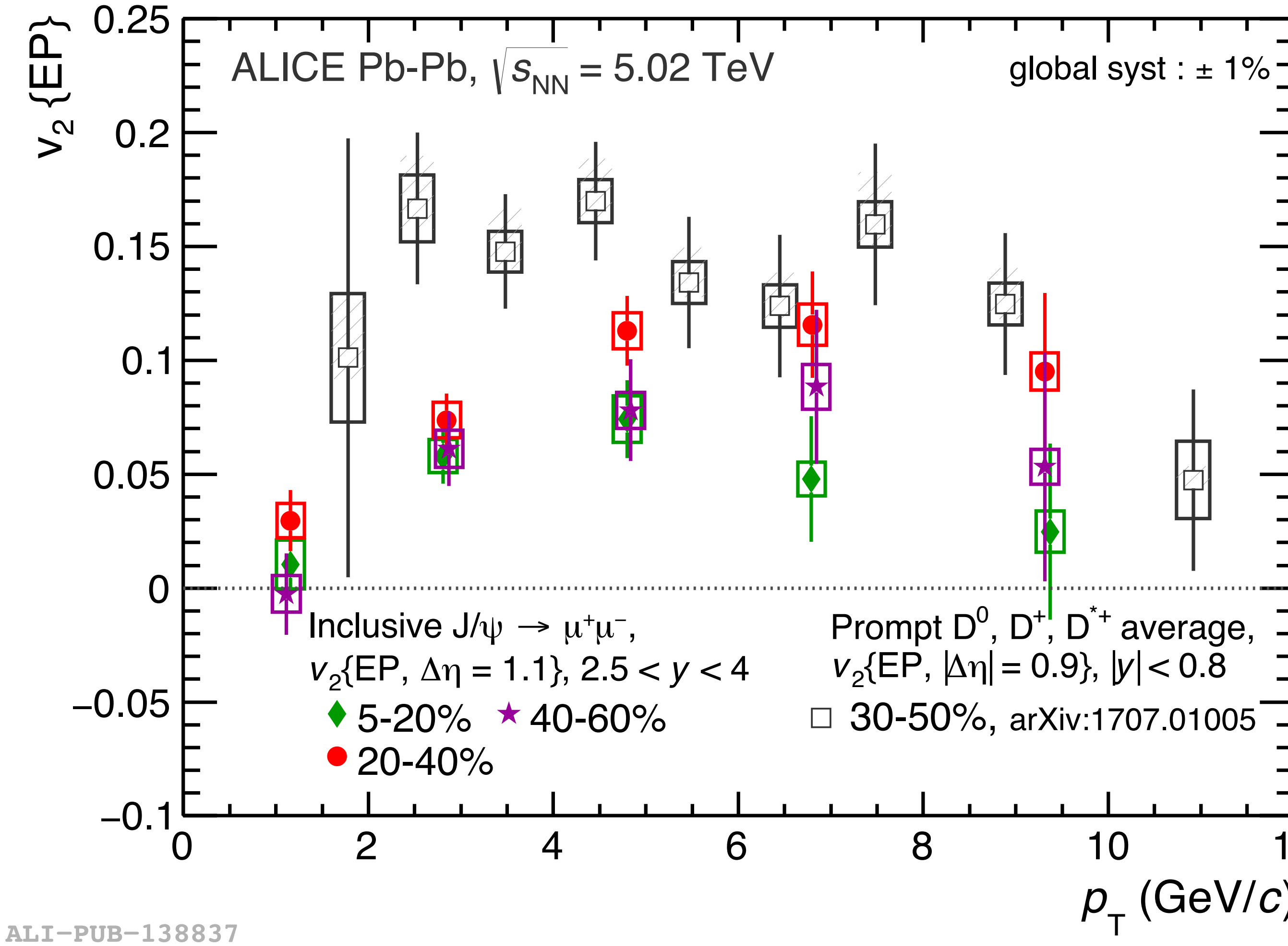
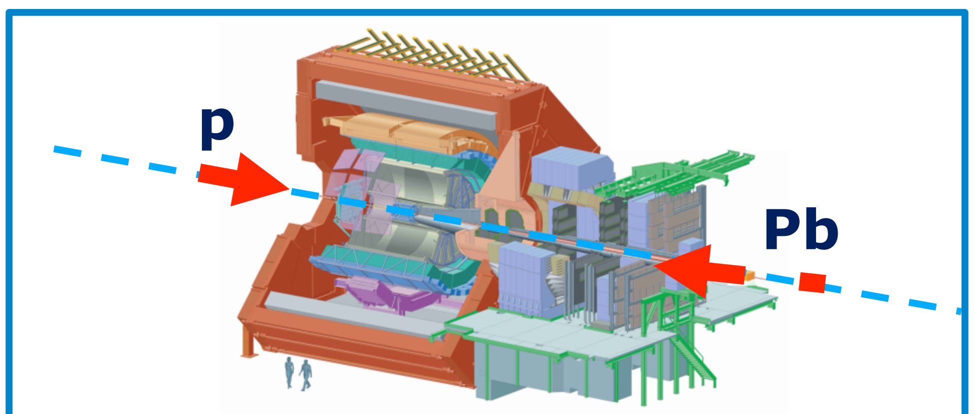


Submitted to PRL, arXiv:170905260

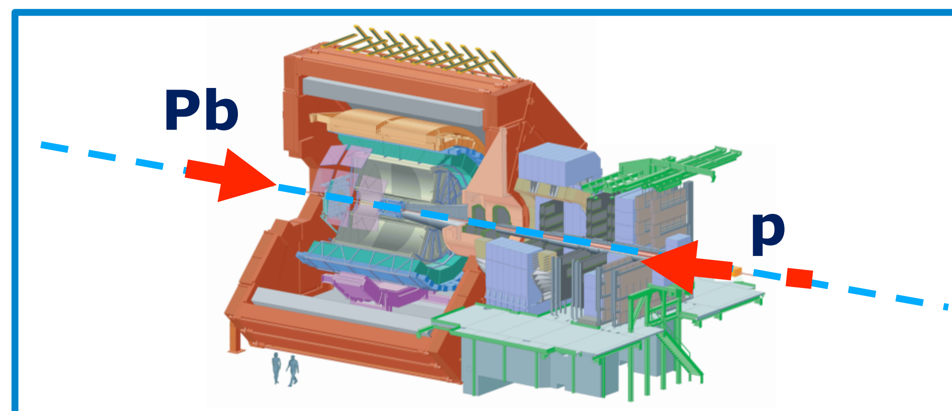
- D mesons $v_2 > 0$ for intermediate p_T
- Another confirmation that charm is slowed down in the medium.
- Recombination of charm and light quarks might generate an higher v_2 than for J/ψ

Quarkonia in p-Pb collisions

- Data collected in two configurations:
  - p-Pb:
    p going through the muon arm (forward direction)
    x investigated: $2 \times 10^{-5} < x < 9 \times 10^{-5}$
  - Pb-p:
    Pb going though the muon arm (backward direction)
    x investigated: $6 \times 10^{-4} < x < 3 \times 10^{-3}$



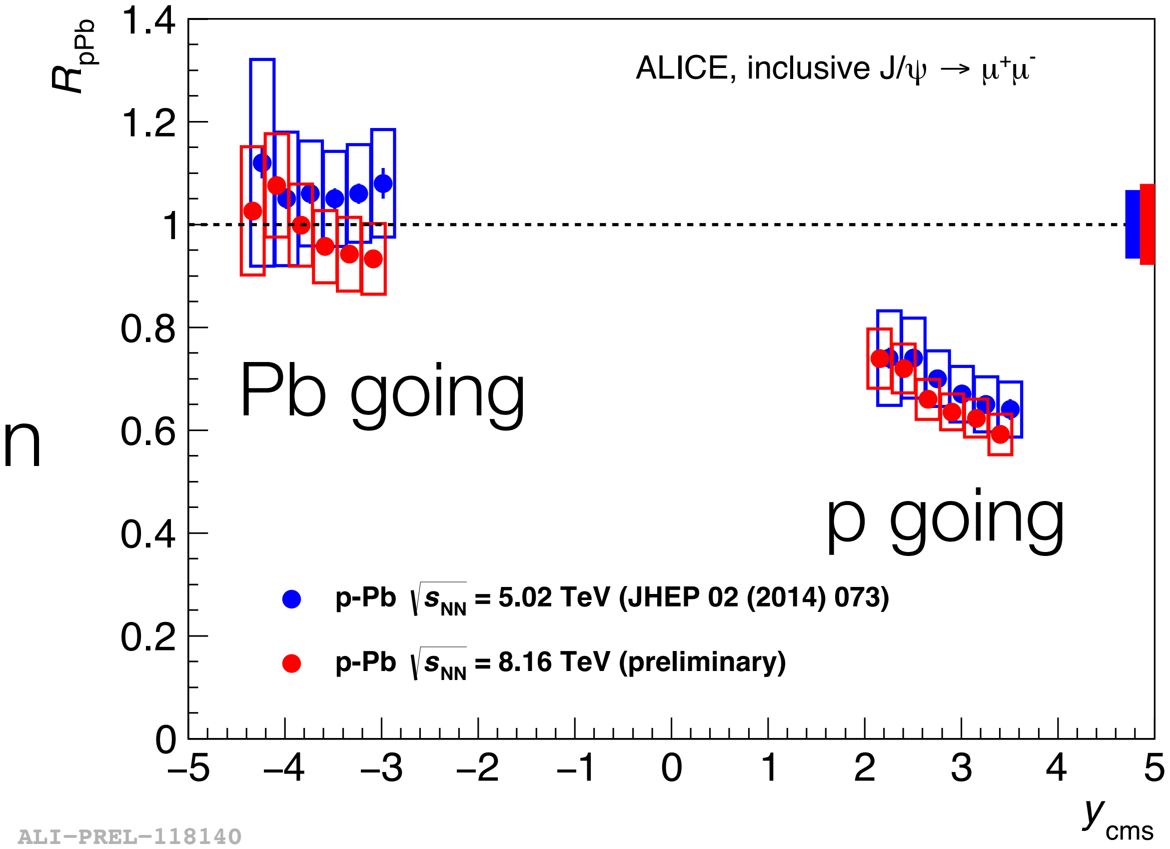
$2.03 < y_{CMS} < 3.53$



$-4.46 < y_{CMS} < -2.96$

J/ψ in p-Pb collisions

* J/ψ production is more affected by cold nuclear matter effects than open heavy flavour:
  * at forward rapidity the J/ψ production is suppressed by about 20%
  * not visible difference between $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV



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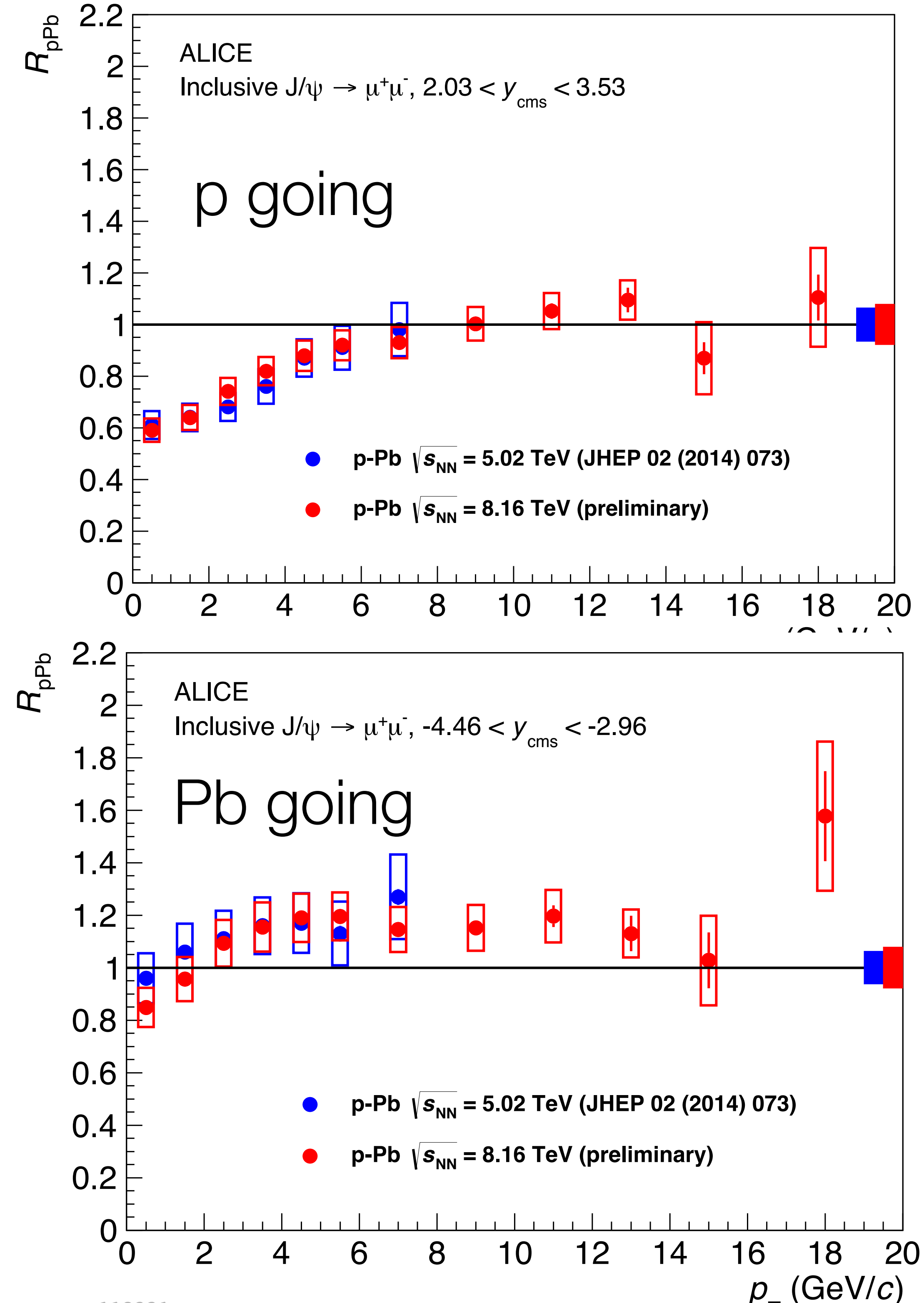
  - Pb-going direction R_{pA}~1 constant vs p_T



ALI-PREL-118321

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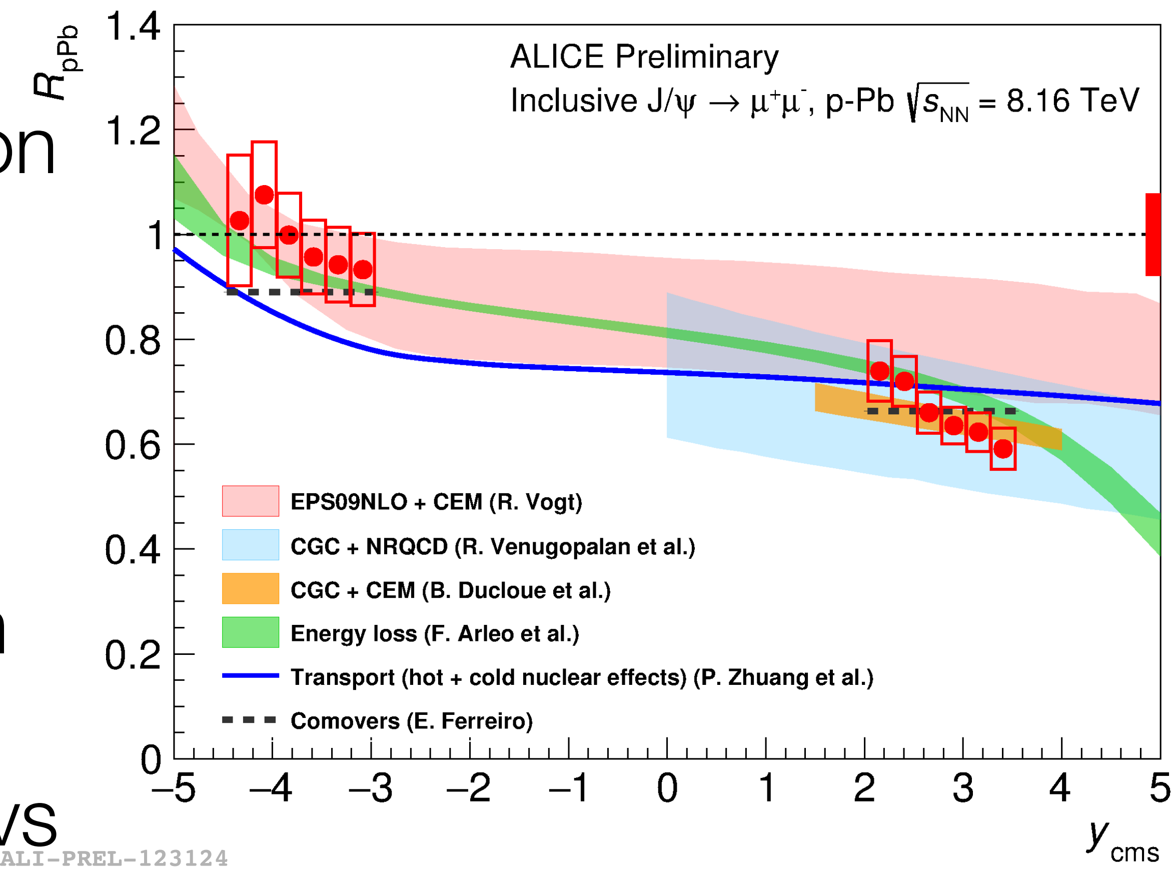
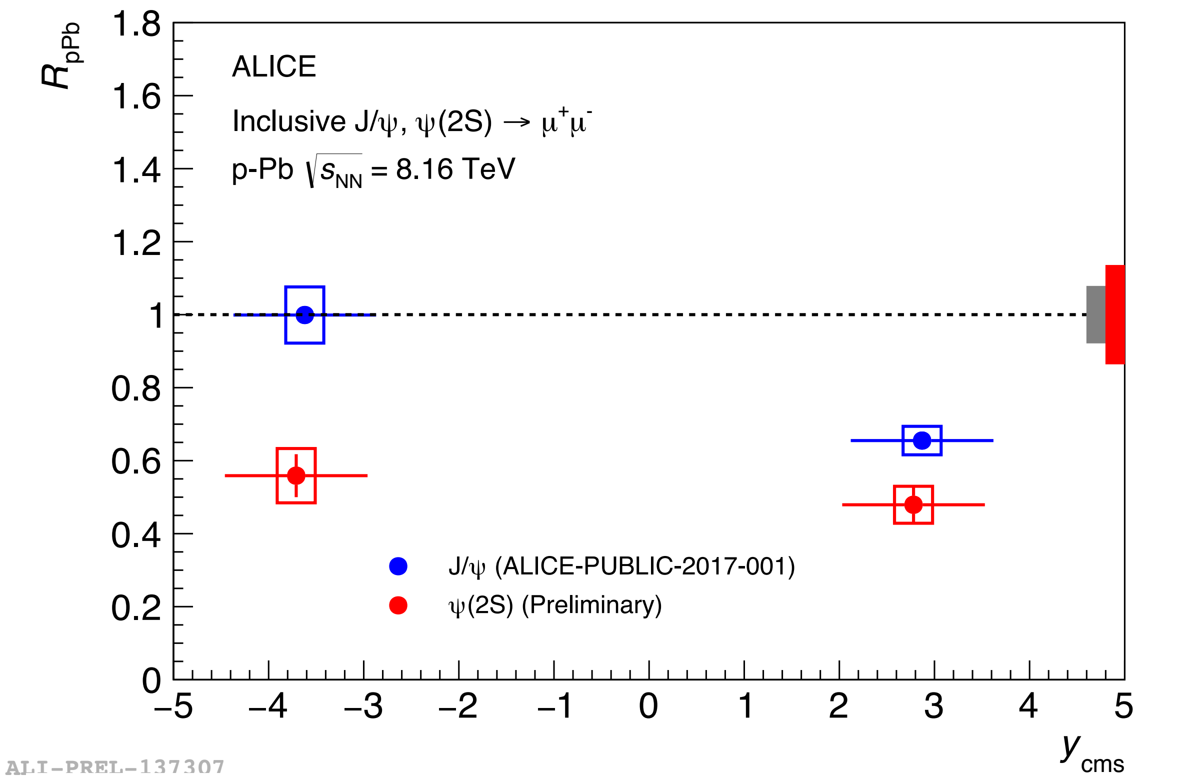
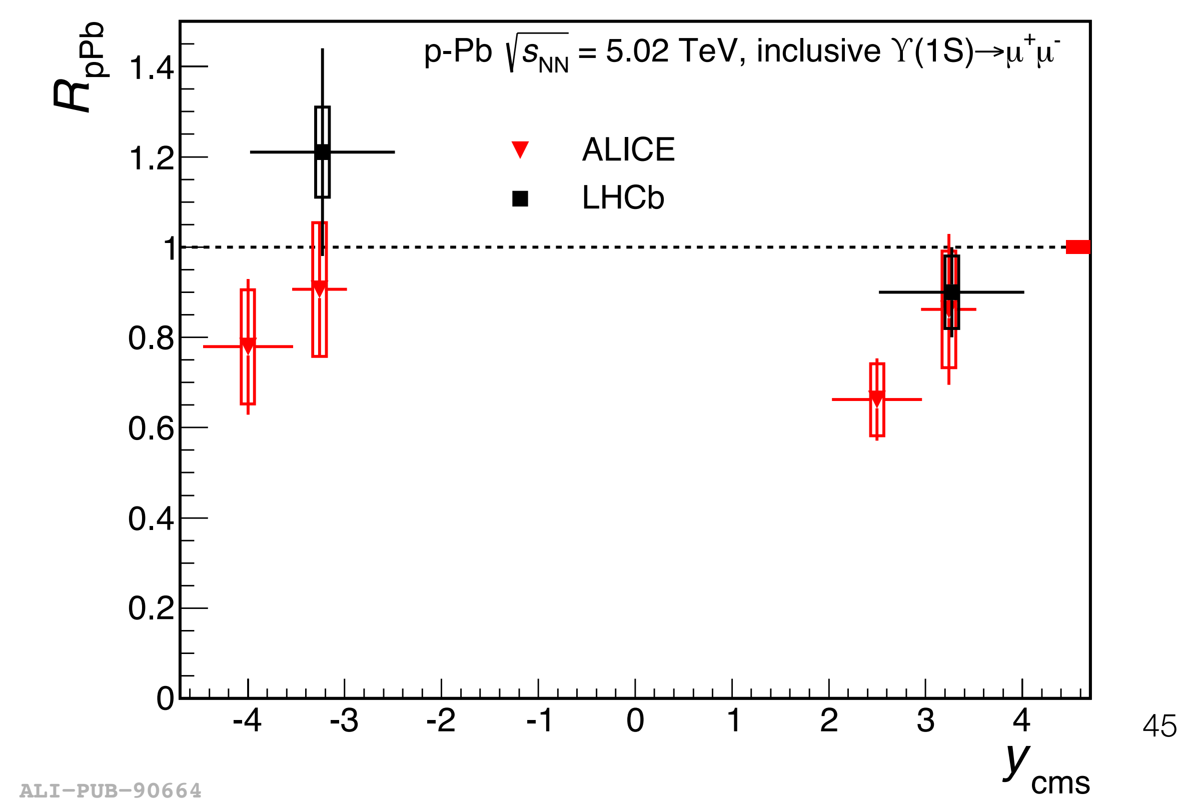


- J/ψ results compatible with models that include initial cold nuclear matter effects

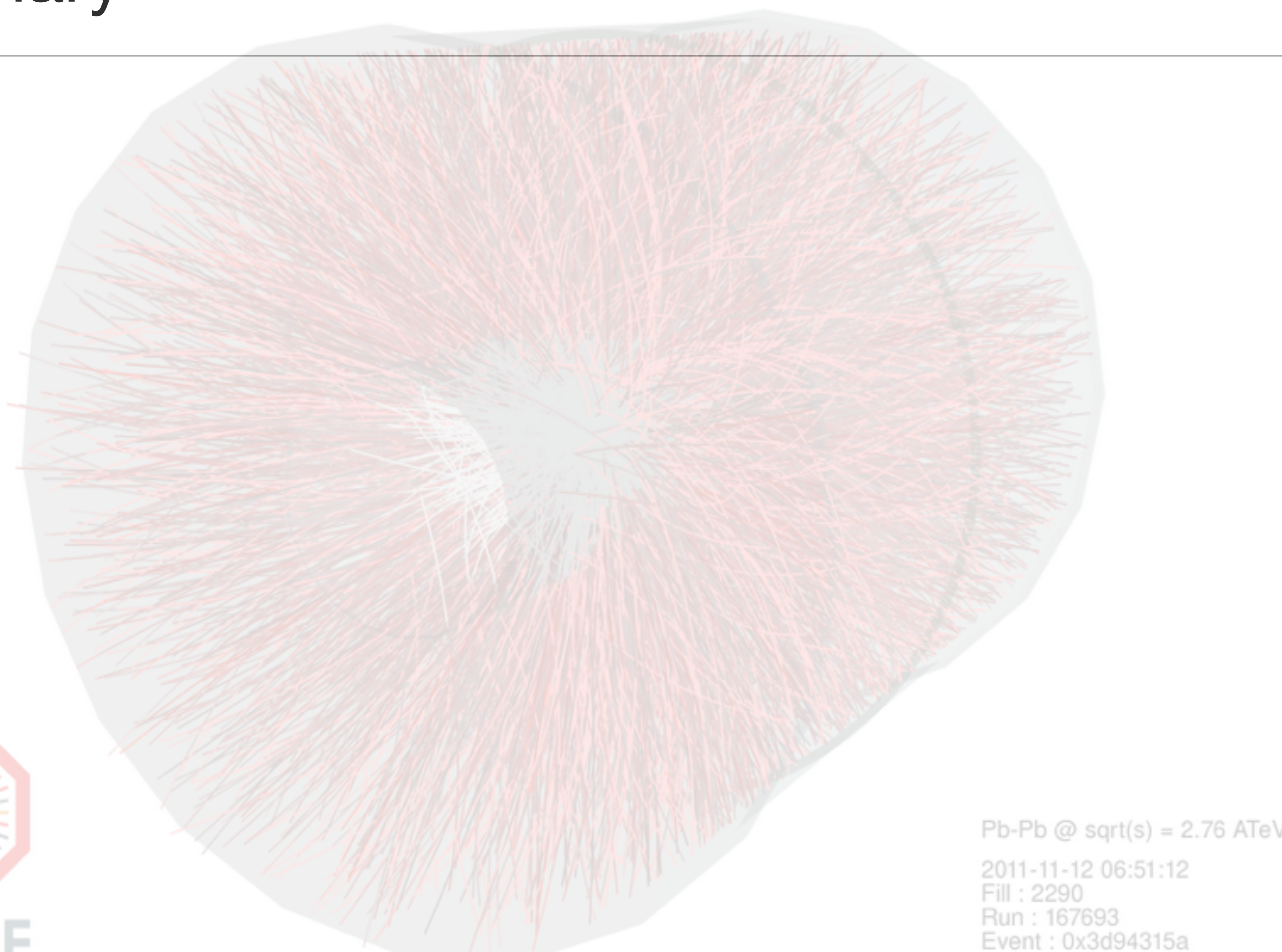
Quarkonia in p-Pb collisions

- **ψ(2S)** state even more suppressed than **J/ψ.** In particular in the Pb-going direction.
  - only initial state cold nuclear matter effects are not enough to explain the suppression at backward rapidity.
- **Υ(1S)** seems to be affected in the same way by cold nuclear matter effects at both forward and backward rapidity





Summary

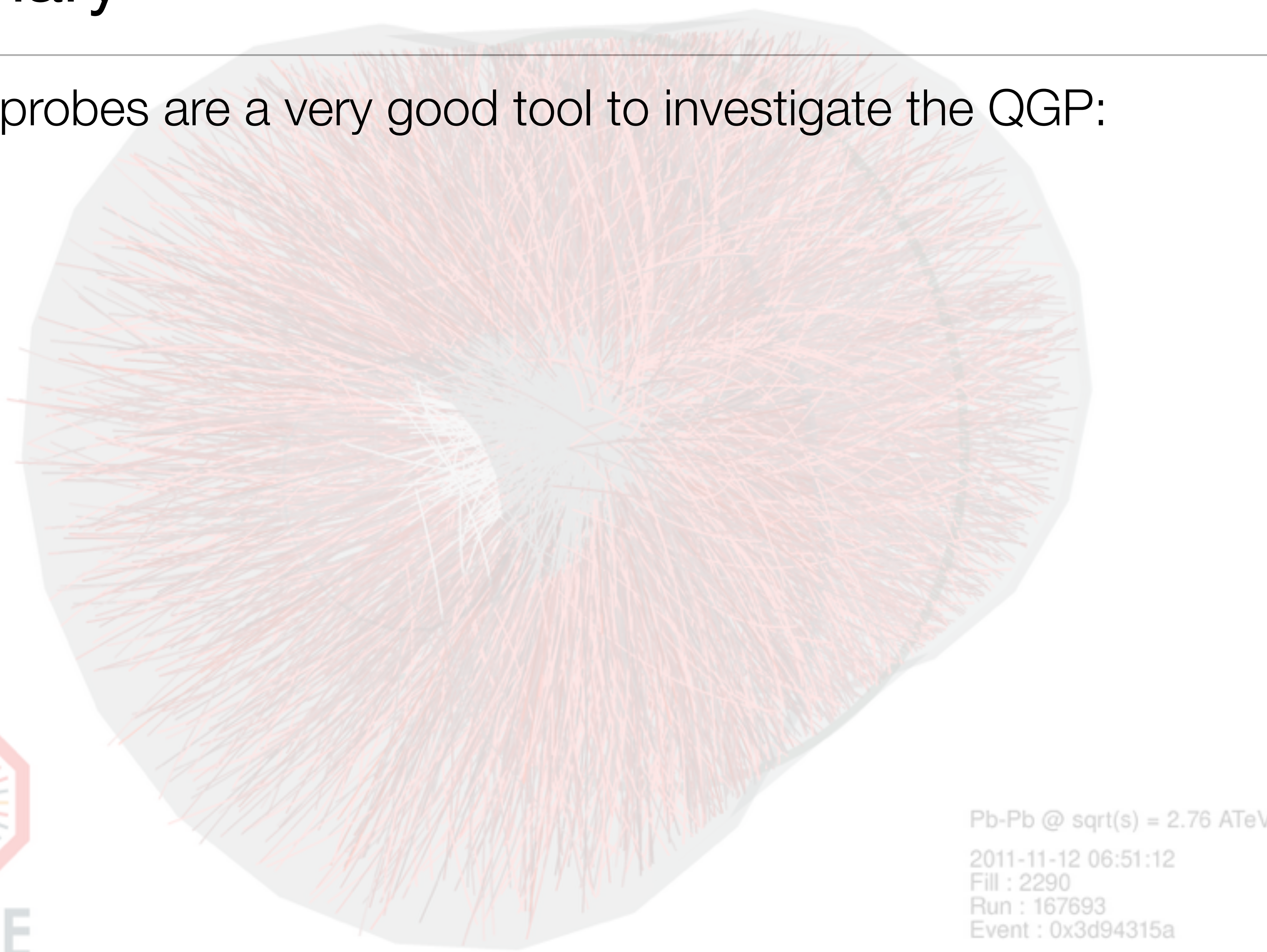

Pb-Pb @ sqrt(s) = 2.76 ATeV
2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

Summary

Too difficult to make one… let's try with a biased selection of take home messages

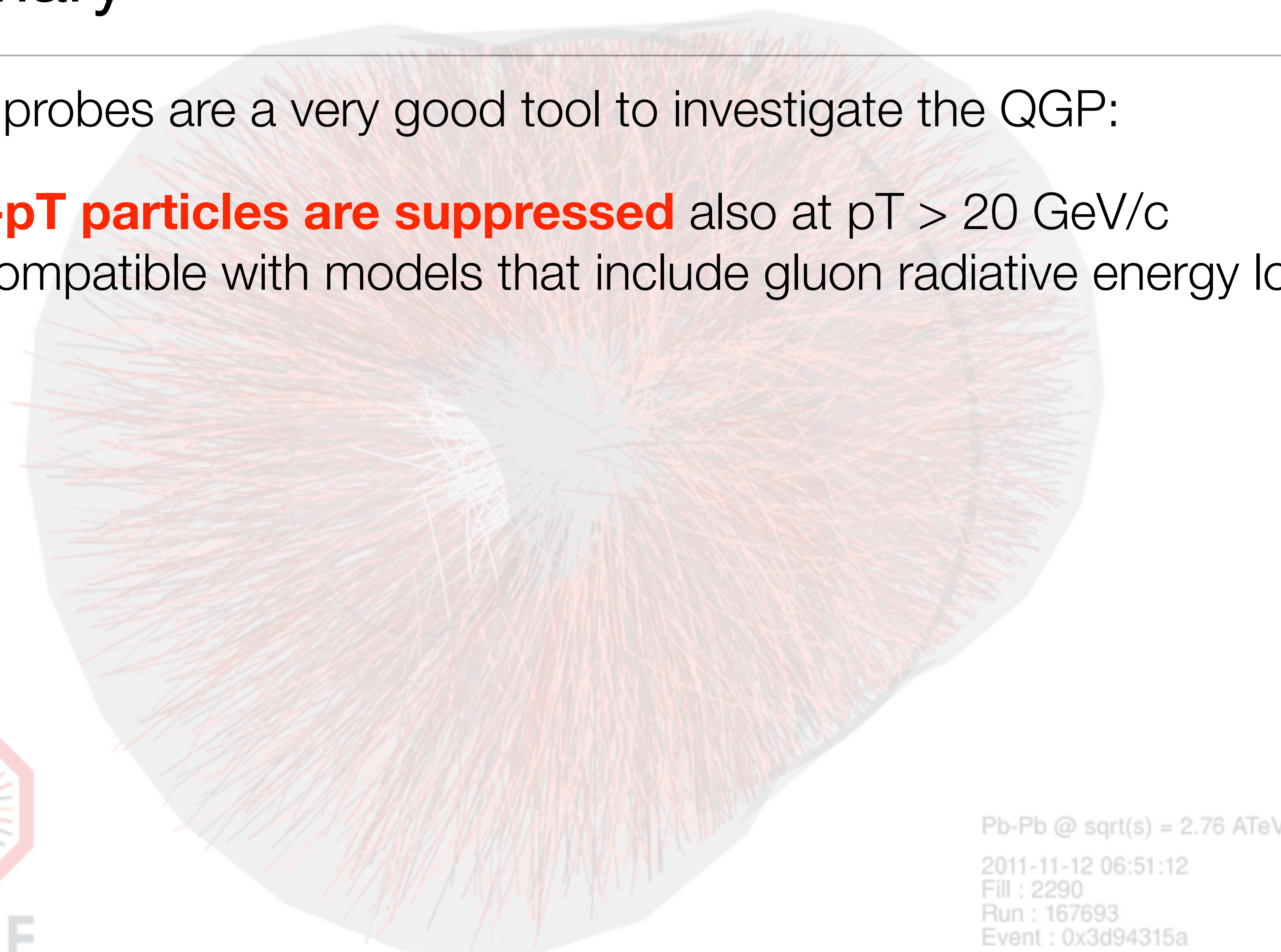
Summary

* Hard probes are a very good tool to investigate the QGP:



Summary

- Hard probes are a very good tool to investigate the QGP:
- **High-pT particles are suppressed** also at pT > 20 GeV/c
  - Compatible with models that include gluon radiative energy loss



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  - **as suppressed as pions,** but different fragmentation is important!
  - more suppressed than J/ψ from B hadrons → **mass dependence of the partonic energy loss**

Pb-Pb @ sqrt(s) = 2.76 ATeV
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ALICE
A JOURNEY OF DISCOVERY

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  - more suppressed than J/ψ from B hadrons → **mass dependence of the partonic energy loss**

- **J/ψ seems to:**
  - **be suppressed at high-pT, regenerated at low-pT**
  - **flow** → indication that charm take part of the medium expansion

Summary

- Hard probes are a very good tool to investigate the QGP:
- **High-pT particles are suppressed** al…
  - Compatible with mod… …s
- **Je…**
  no…
- **D m…**
  - **…ppressed as pions,** but different fragmentation is important!
  - more suppressed than J/ψ from B hadrons → **mass dependence of the partonic energy loss**
- **J/ψ seems to:**
  - **be suppressed at high-pT, regenerated at low-pT**
  - **flow** → indication that charm take part of the medium expansion

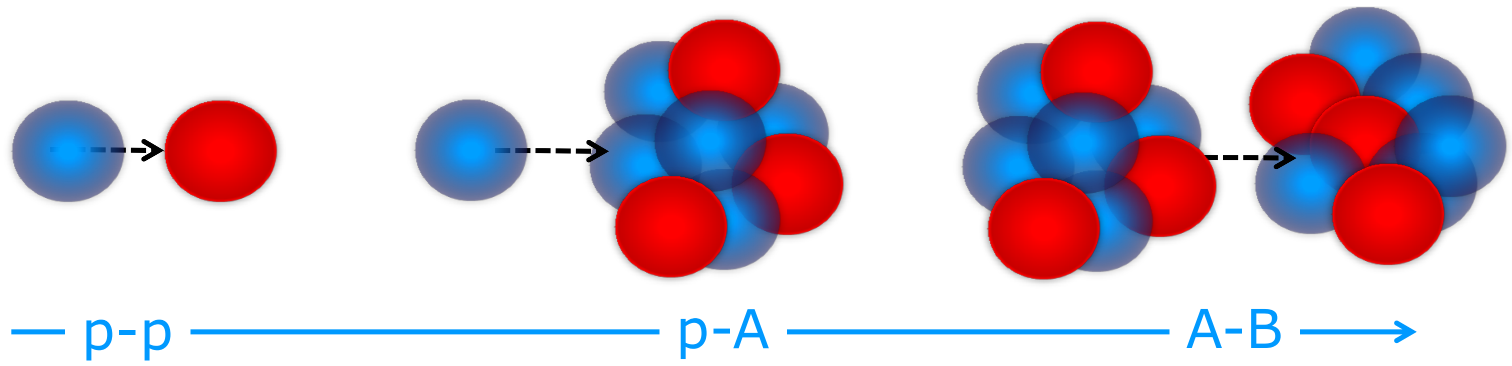
All these observables can be used to extract parameters of the QGP. With precise Run2 measurements, we are entering to a new precision phase also to constrain the model.

Summary

Thanks for your attention!
Hoping you are still alive/awake!

Back up slides

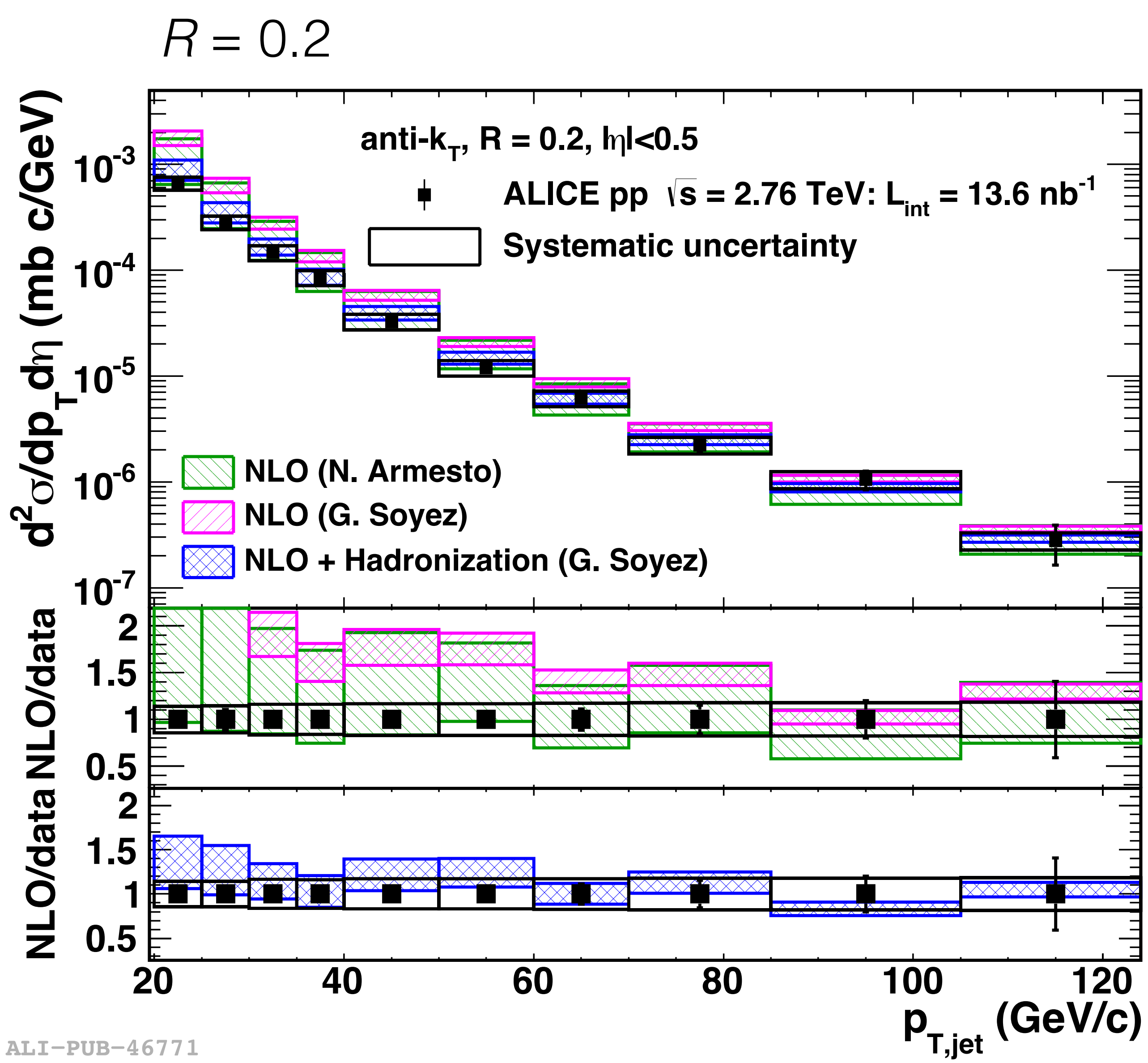
Observables



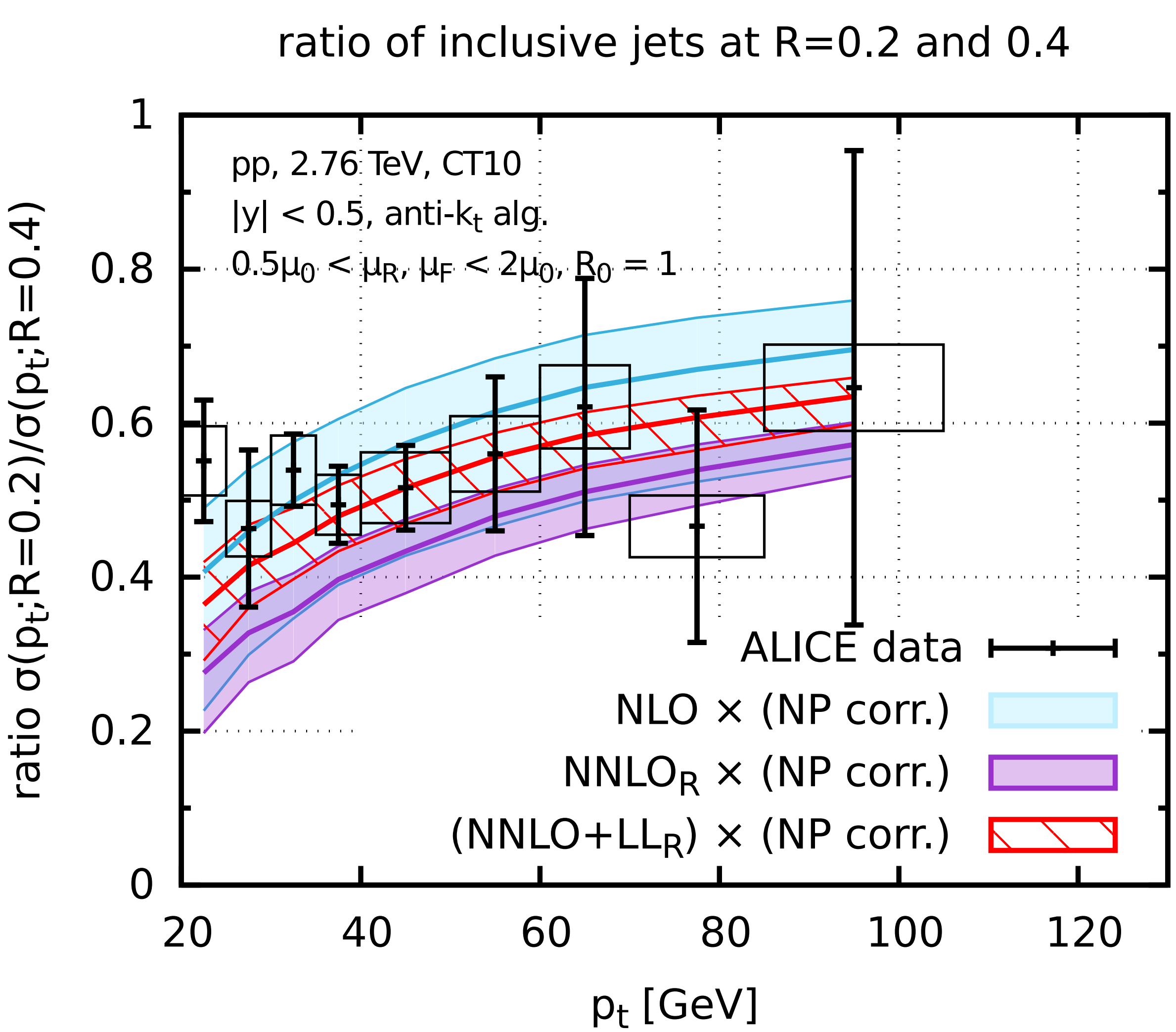
- At high collisions energies, hard probes production cross section is proportional to the number of possible hard scattering, i.e. to the number of nucleon-nucleon collisions.

- Difference from this scaling are related to **cold** or **hot** nuclear matter effects.

Jets in pp collisions



M. Dasgupta et al. JHEP 1606 (2016) 057



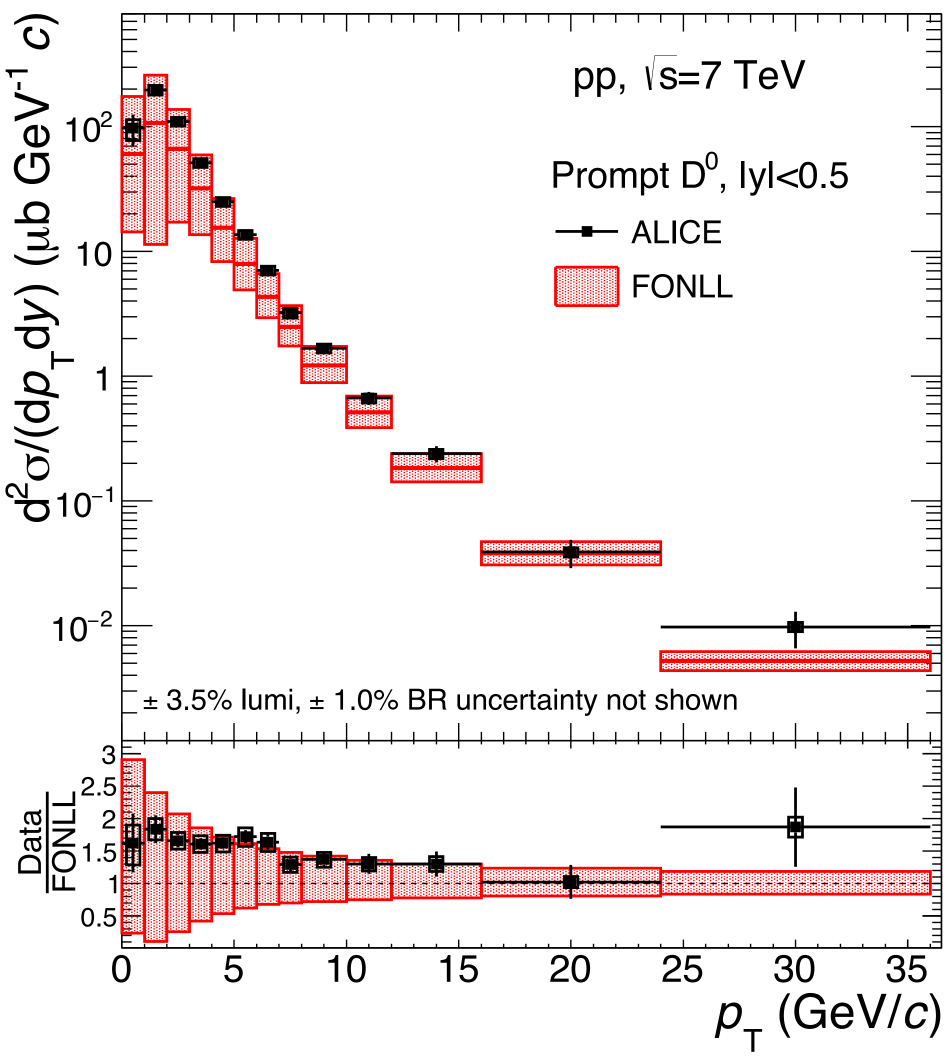
- Good agreement between data and NLO calculations for both R=0.2 and R=0.4

N. Armesto et al. based on Nucl. Phys. B507 (1997) 295-314
G. Soyez, Phys Lett B698 (2011) 59-62

- Recent calculation based on NNLO+LL$_R$ including UE and hadronization effects seems to be in better agreement than just NNLO calculations.

HF and quarkonia production in pp collisions

- Test of the theoretical approaches for open heavy-flavor and quarkonium production in **pp collisions**.



Eur.Phys.J. C77 (2017) 550

- pQCD based calculations are compatible with D-meson data.
  - **FONLL (JHEP 05 1998) 007)**
    - Fixed-Order-Next-To-Leading-Log calculations.
    - Fit of the moment of the fragmentation functions with Kartelishivili form
    - major improvement at high momentum

- data systematically in the lower side of the theoretical uncertainty bands.

HF and quarkonia production in pp collisions

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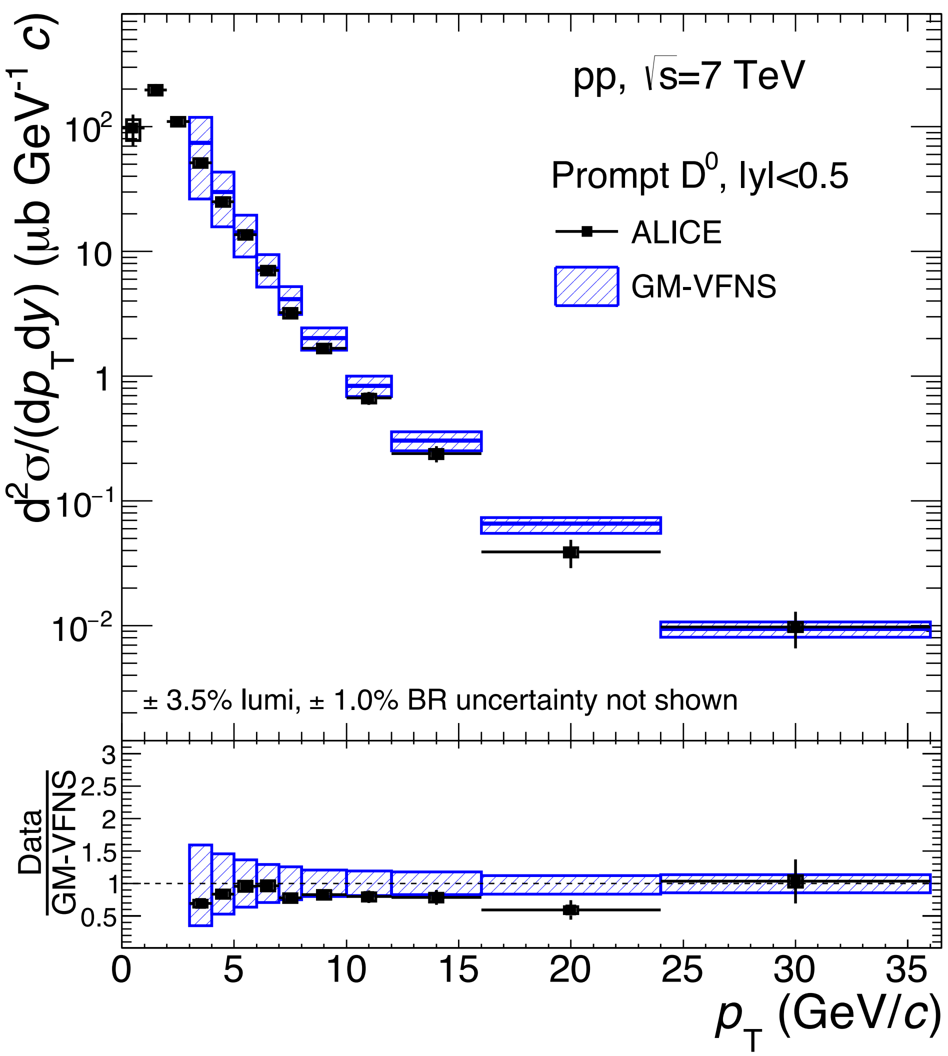
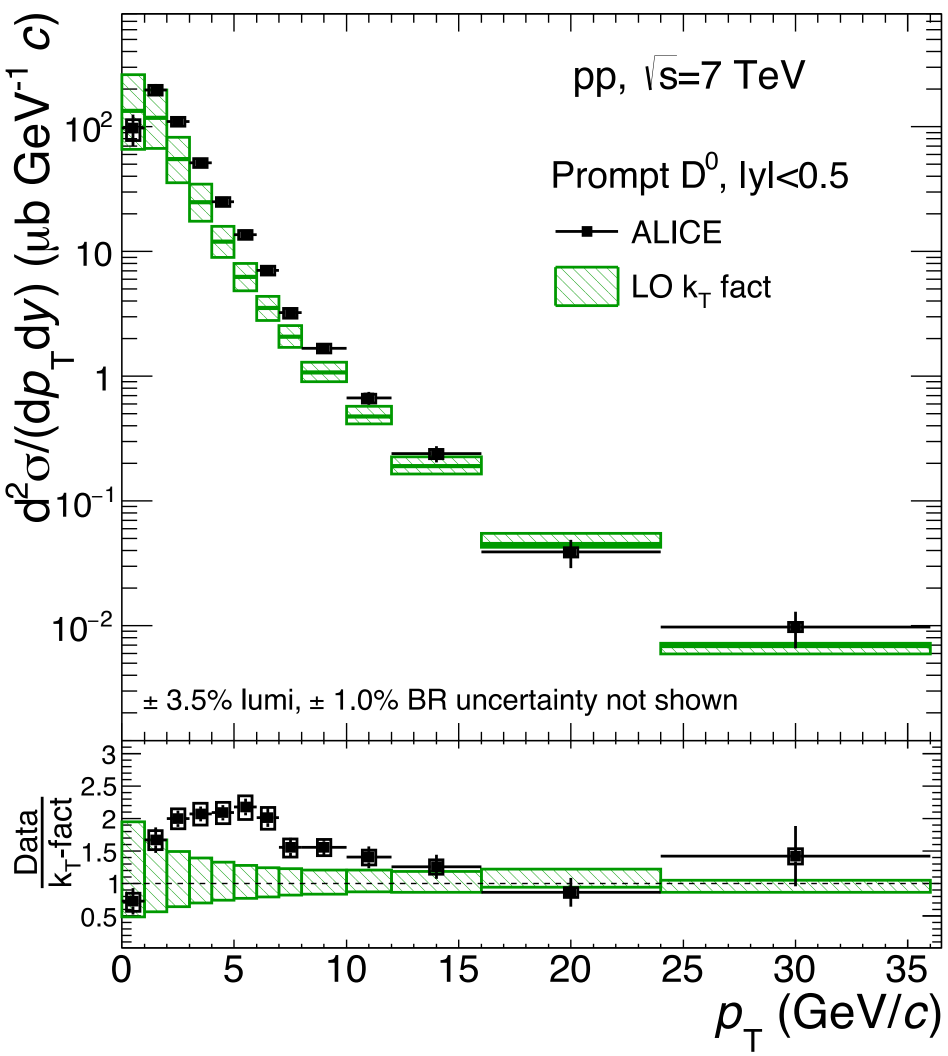


Eur.Phys.J. C77 (2017) 550

- pQCD based calculations are compatible with D-meson data.
  - **GM-VFNS** **(Phys Rev D71 (2005) 014018)**
    - General-Mass variable flavour number scheme
    - $p_T >> m$ (calculations start from 3 GeV/c)
    - $\ln(p_T^2/m^2)$ absorbed in c-quark PDF
- data systematically in the lower side of the theoretical uncertainty bands.

HF and quarkonia production in pp collisions

- Test of the theoretical approaches for open heavy-flavor and quarkonium production in **pp collisions**.



Eur.Phys.J. C77 (2017) 550

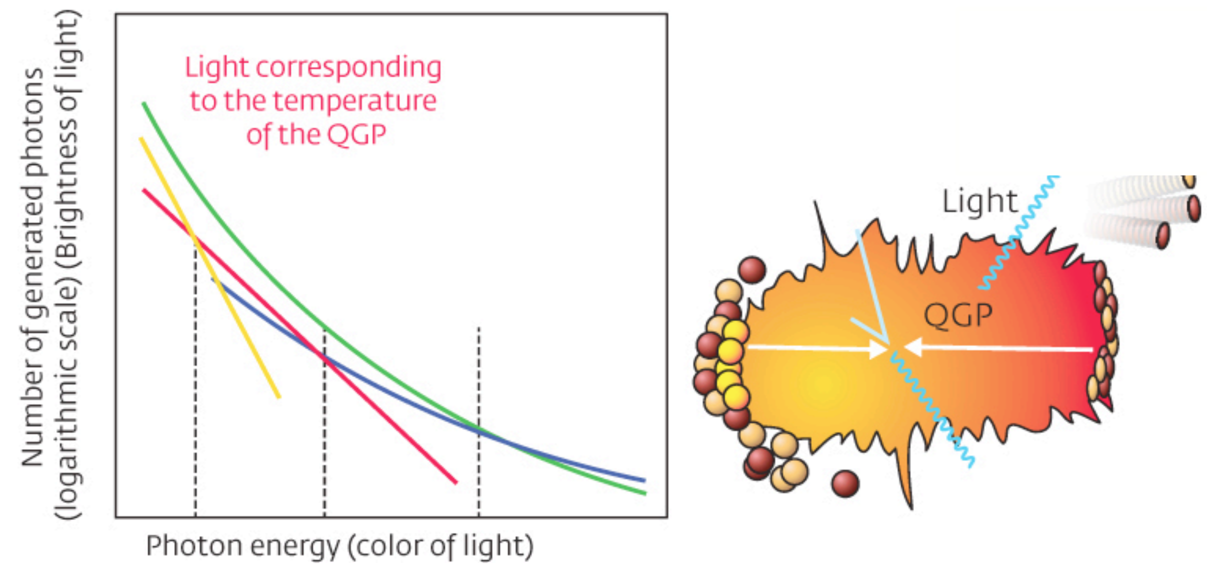
- pQCD based calculations are compatible with D-meson data.
  - **k_T factorization**
    (Phys Rev D79 (2009) 034009)
    - Leading Order calculation based on k_T factorization instead of collinear one.
    - Uncertainty on the charm mass taken into account (low-p_T)
    - updated gluons PDF used

- compatible results with data for $p_T < 2$ GeV/c and $p_T > 10$ GeV/c

Photons R_{AA}

- We can immagine the **QGP as a source of thermal radiation**, if this state of matter is in equilibrium.

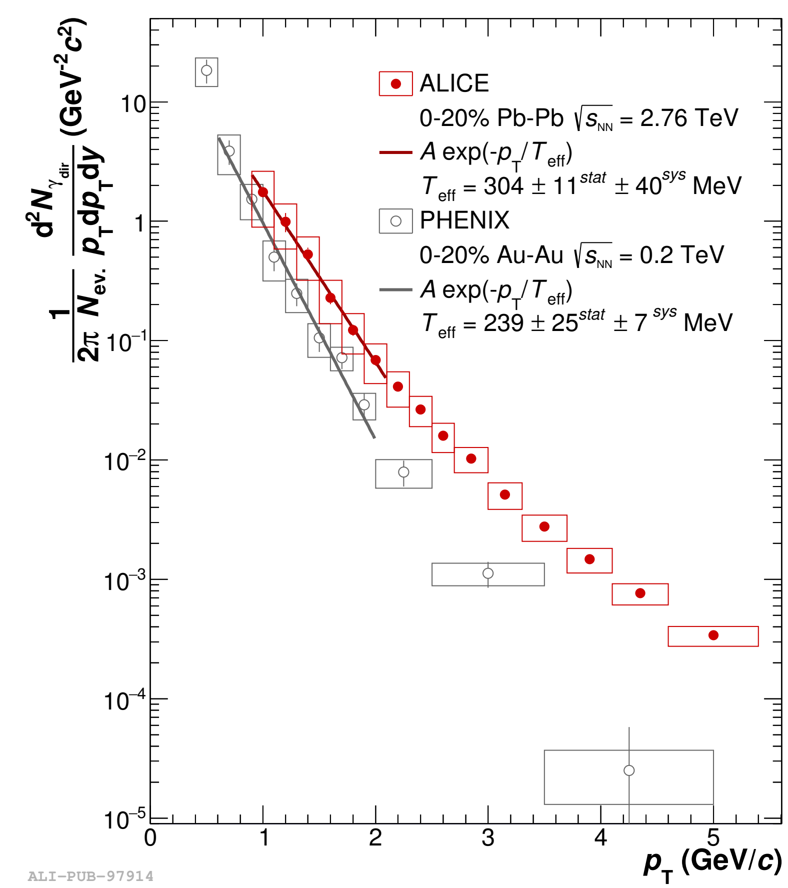
- From the **slope of the spectrum** of the **emitted direct photons** we can extract the **temperature** of the QGP



- Direct γ measurement very difficult due to high background, in particular at low-p_T

- Low-p_T γ measurement of the temperature of the source of the medium

slope parameter:
T = 304 ± 51stat+syst MeV



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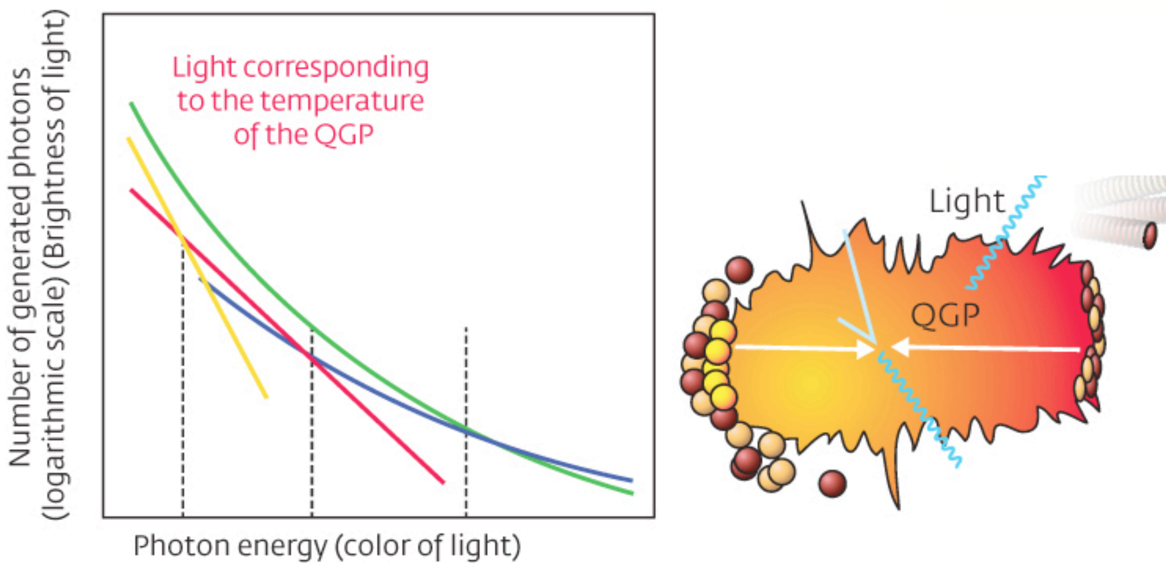

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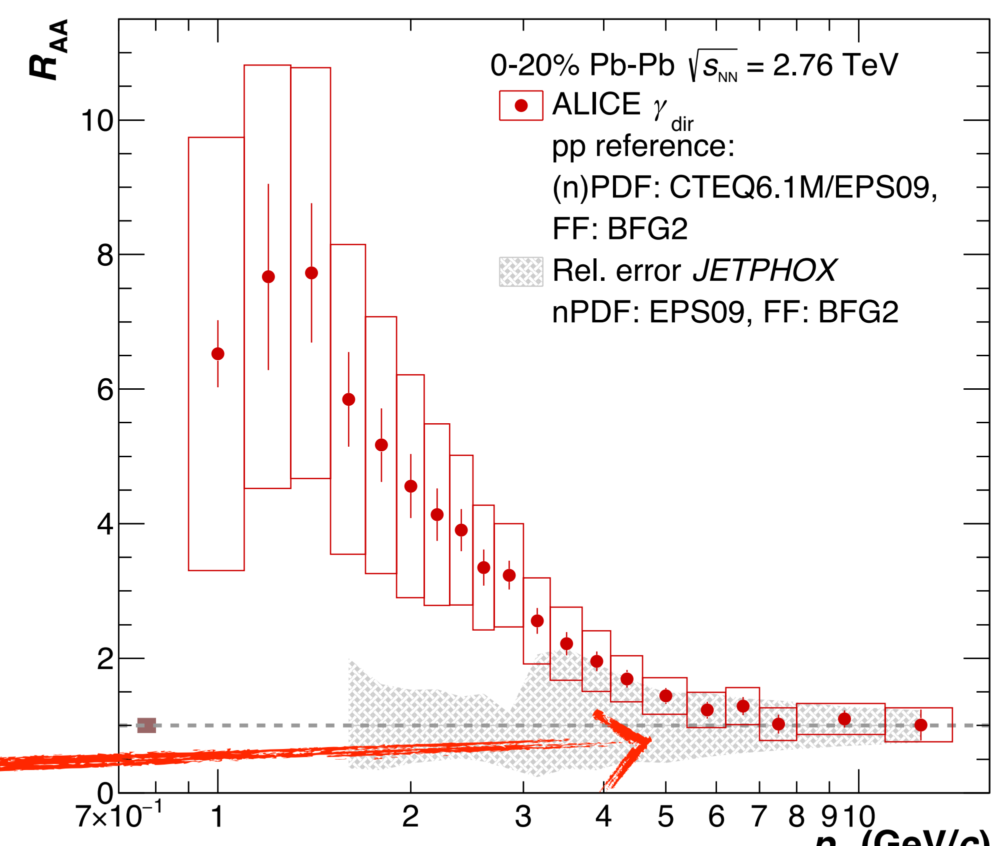
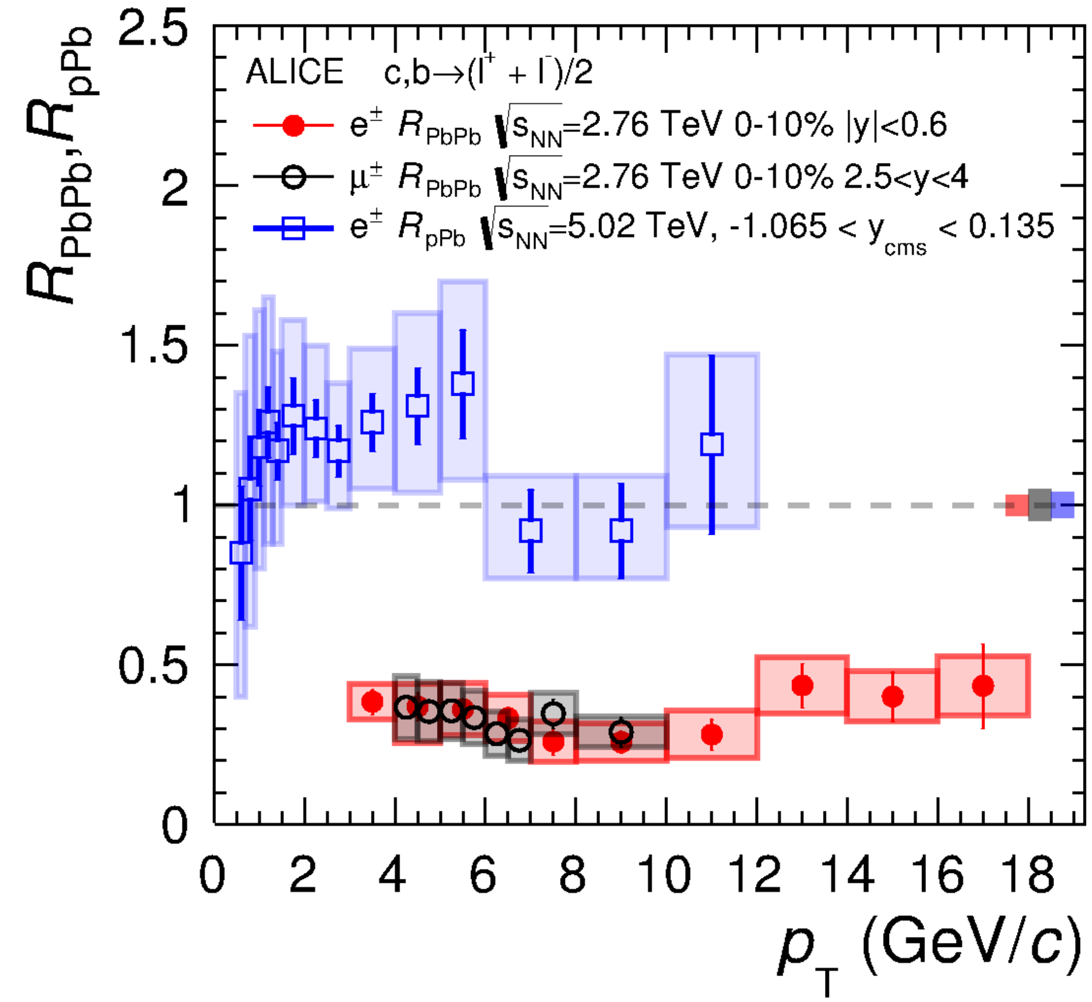


- High-p_T γ transparent to the strong interaction of the medium.
- No difference with respect to pp collisions

HF leptons measurements

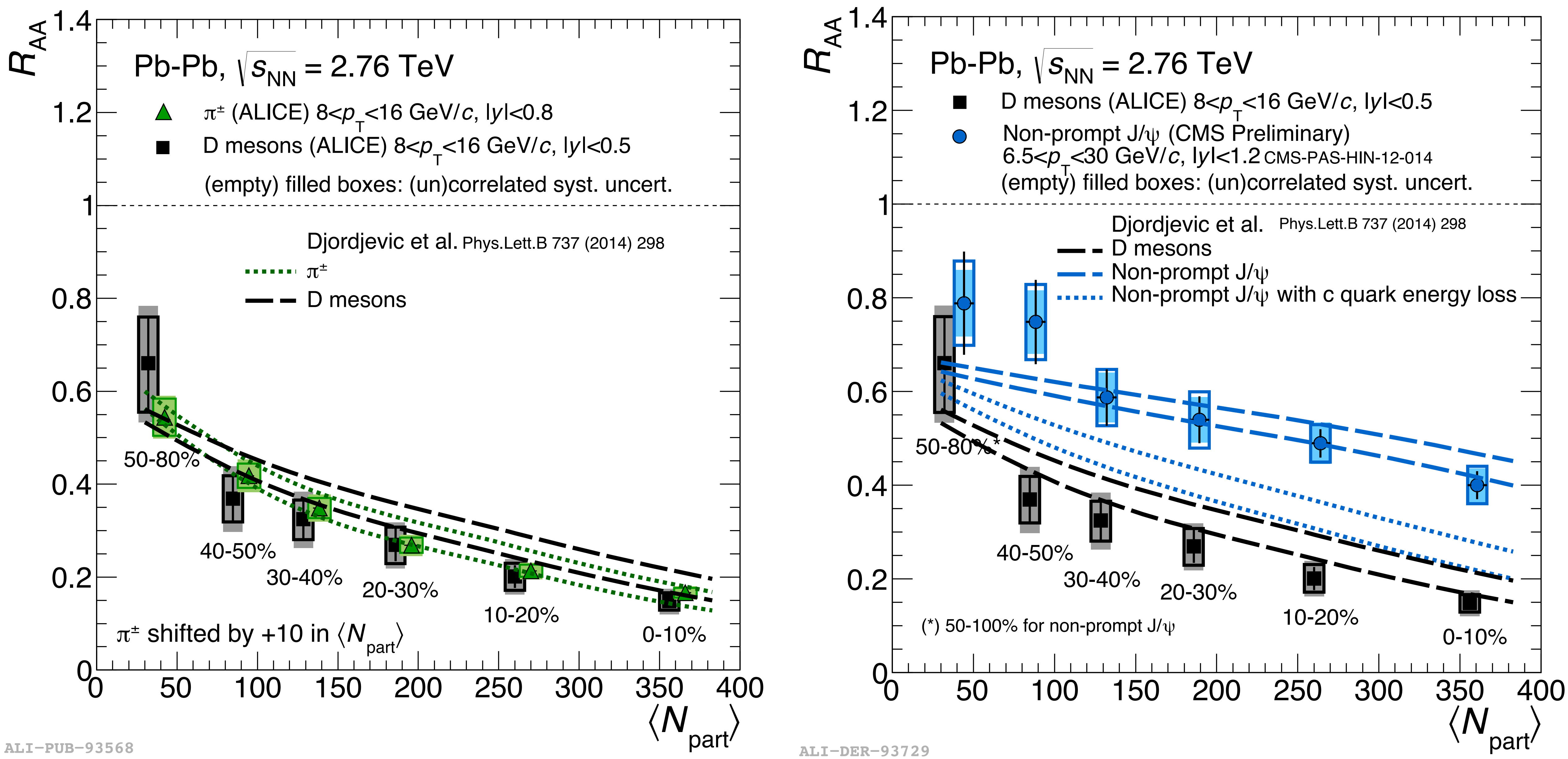
- Open Heavy-flavour R_{pPb} measurements compatible with unity within uncertainties for **backward**, **central** and **forward** rapidity.
- Open heavy-flavour production results are described by models that include Cold Nuclear Matter effects.

- Strong suppression of HF leptons in central Pb-Pb collisions,
- Similar suppression for muons and electrons even at different rapidity



ALI-PUB-114077

D mesons and Non-prompt J/ψ R_{AA}: theoretical models



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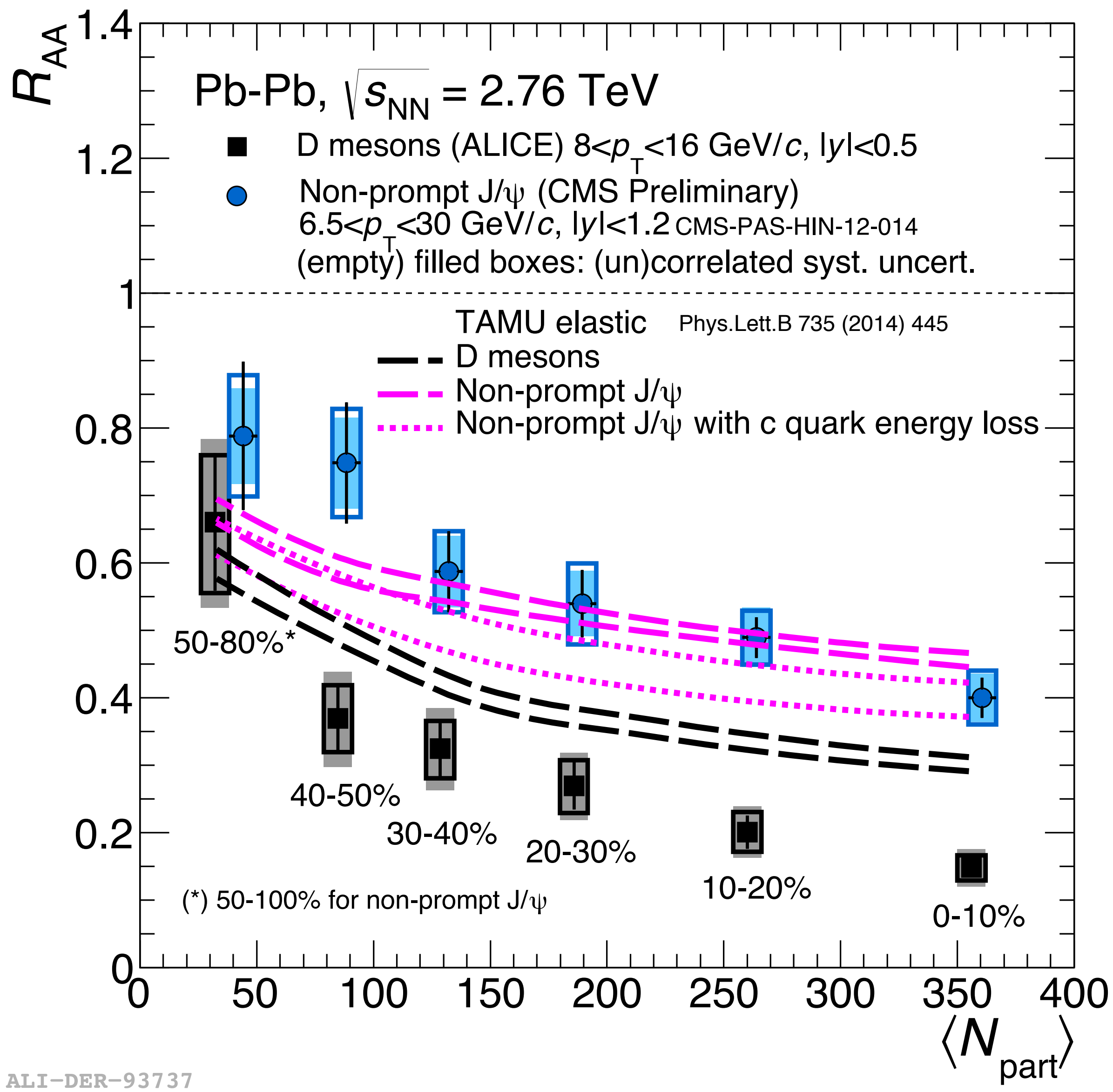
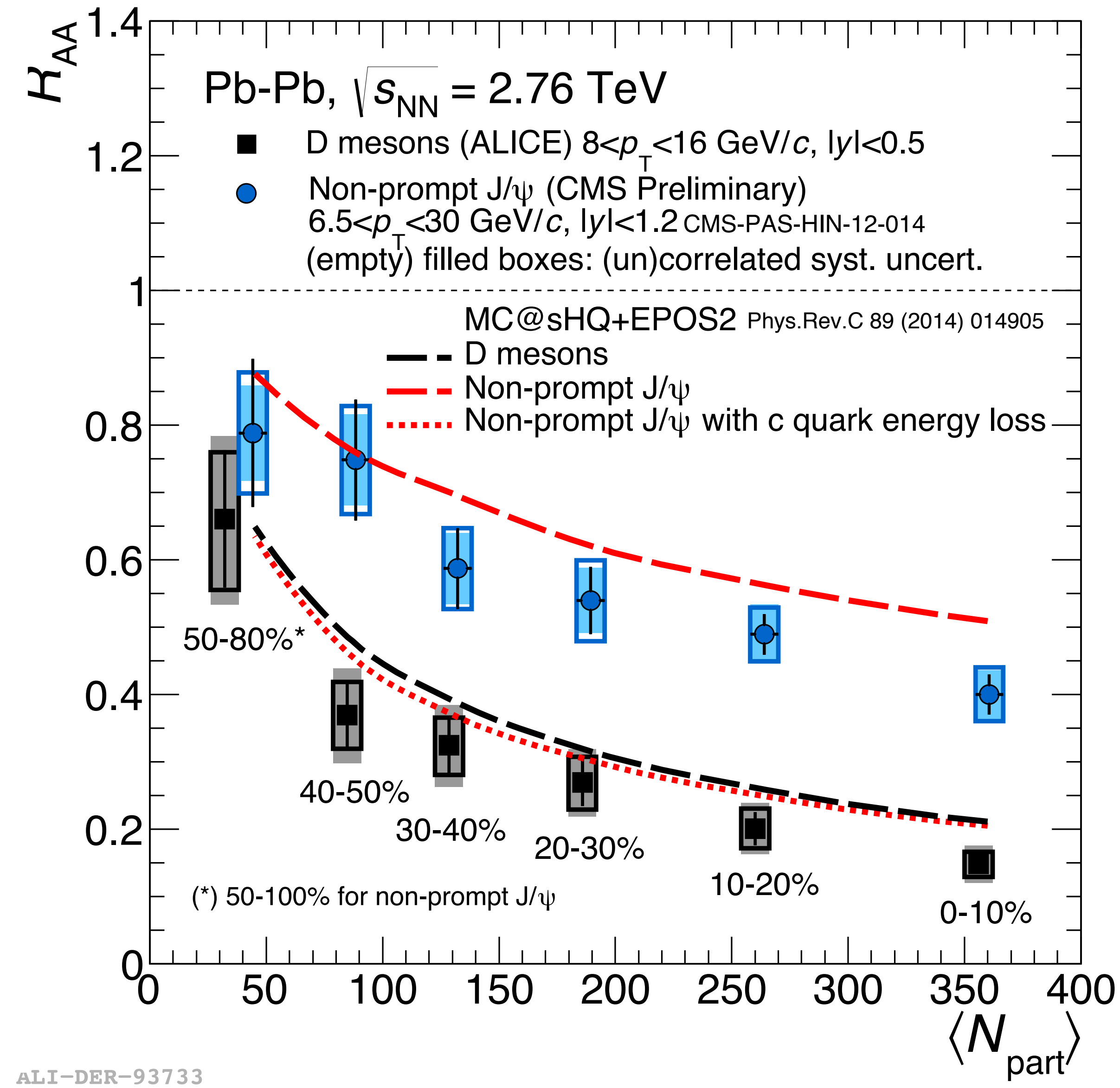
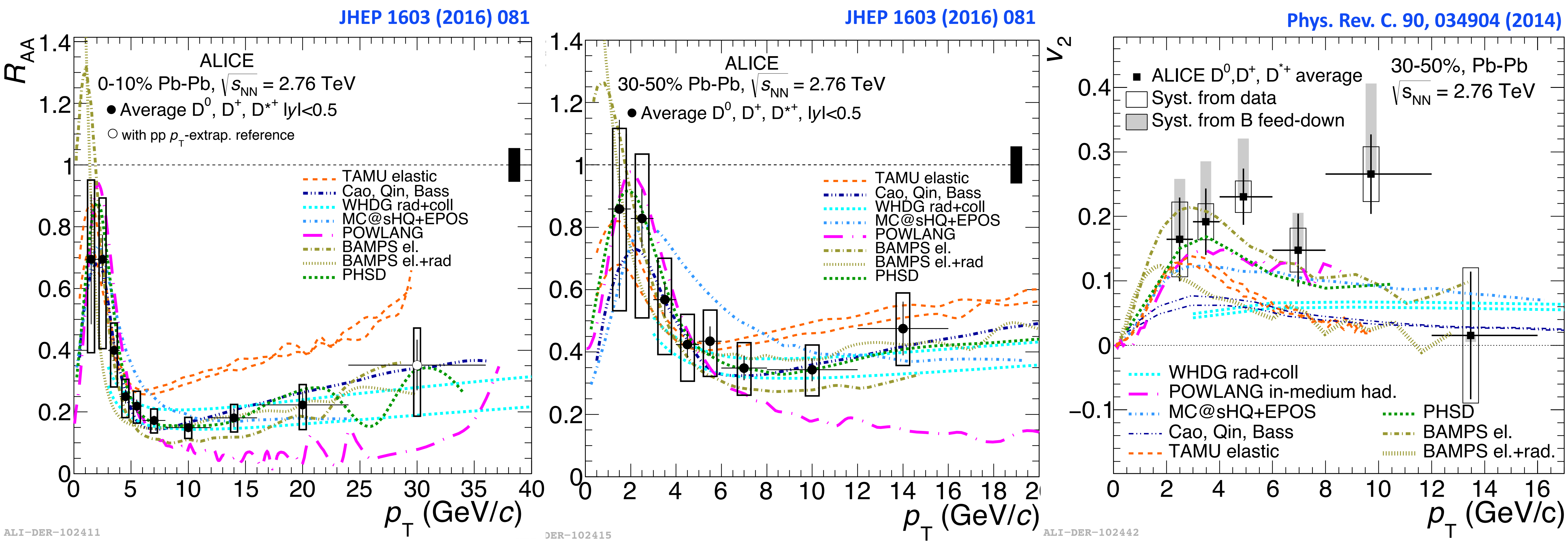




HF comparison with models

Simultaneous measurement/description of v_2 and R_{AA}

→ understanding of heavy quark transport coefficients of the medium



TAMU model does not include radiative energy loss and overestimate the R_{AA}

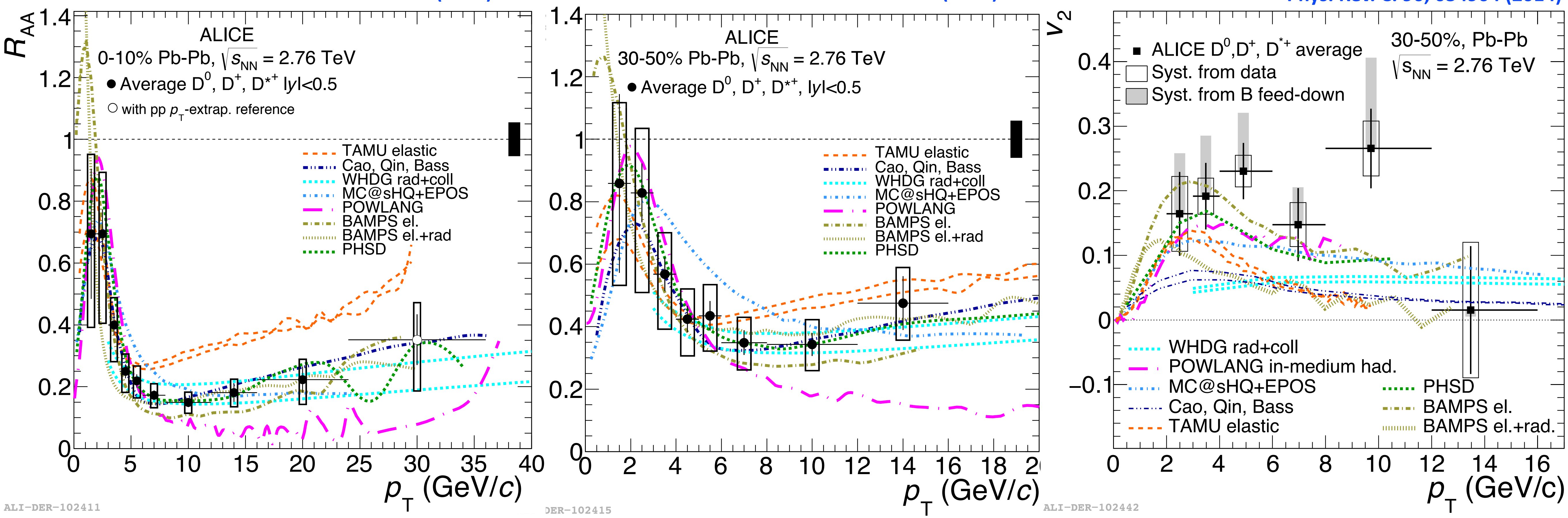
→ **Radiative energy loss needed to describe the R_{AA} in central collisions**

M. He et al, PLB 735 (2014) 445-450

HF comparison with models

Simultaneous measurement/description of v_2 and R_{AA}
→ understanding of heavy quark transport coefficients of the medium

JHEP 1603 (2016) 081 JHEP 1603 (2016) 081 Phys. Rev. C. 90, 034904 (2014)



WHDG does not include an expanding medium and underestimate v_2.
BAMPS, TAMU, MC@sHQ include both collisional energy loss in an expanding medium and recombination → better agreement with v_2 data

M. He et al, PLB 735 (2014), S.Wicks et al, Nucl. Pyhs. A784 (2007), J.Uphoff et al, PLB 717 (2010), M.Nahrgang et al., PRC 89 (2014)

HF comparison with models

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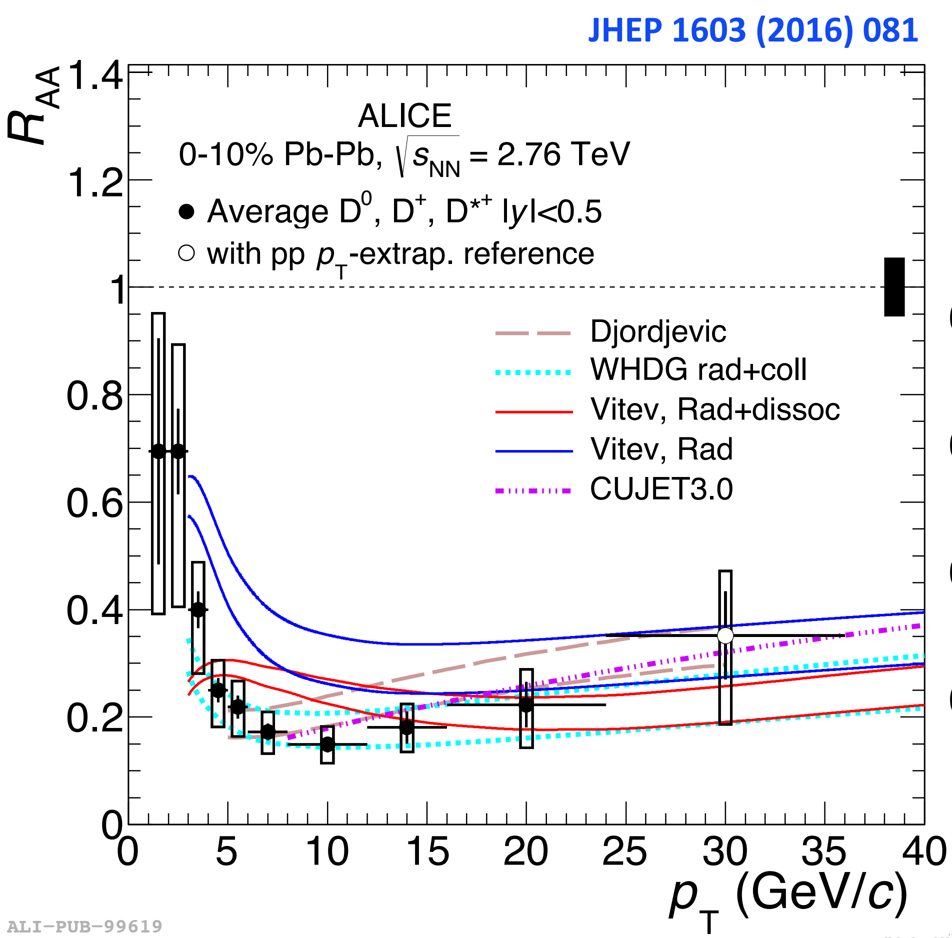
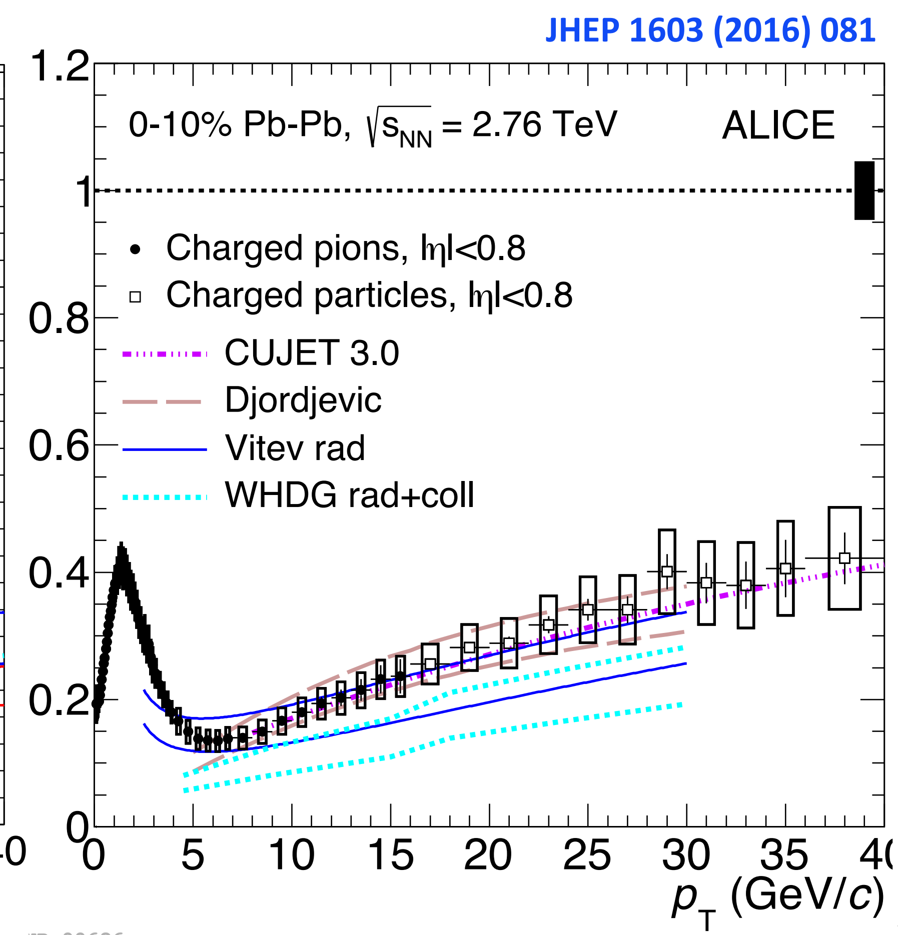
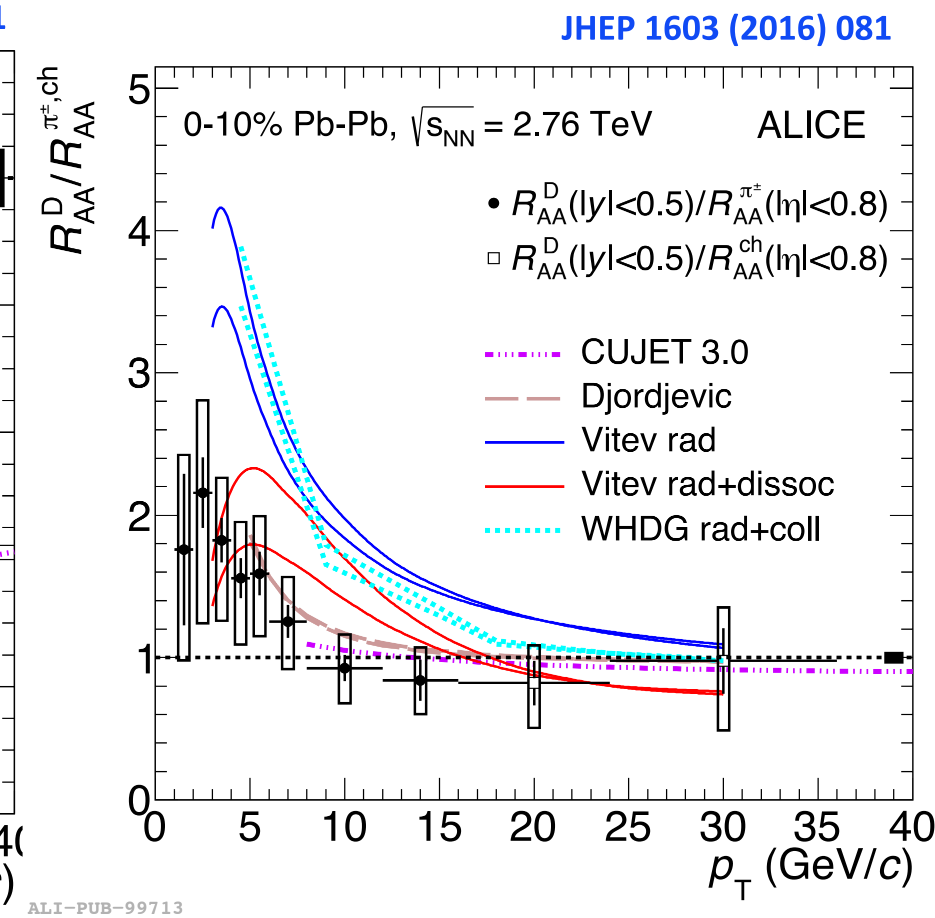






Only Djordjevic and CUJET 3.0 models can describe the two R_{AA} (p_T>5 GeV/c).
→they both include radiative and collisional energy loss.

Djordjevic et al., PLB 737 (2014), J. Xu et al.,arXiv:1508.00552

Heavy quarks in p-Pb collisions

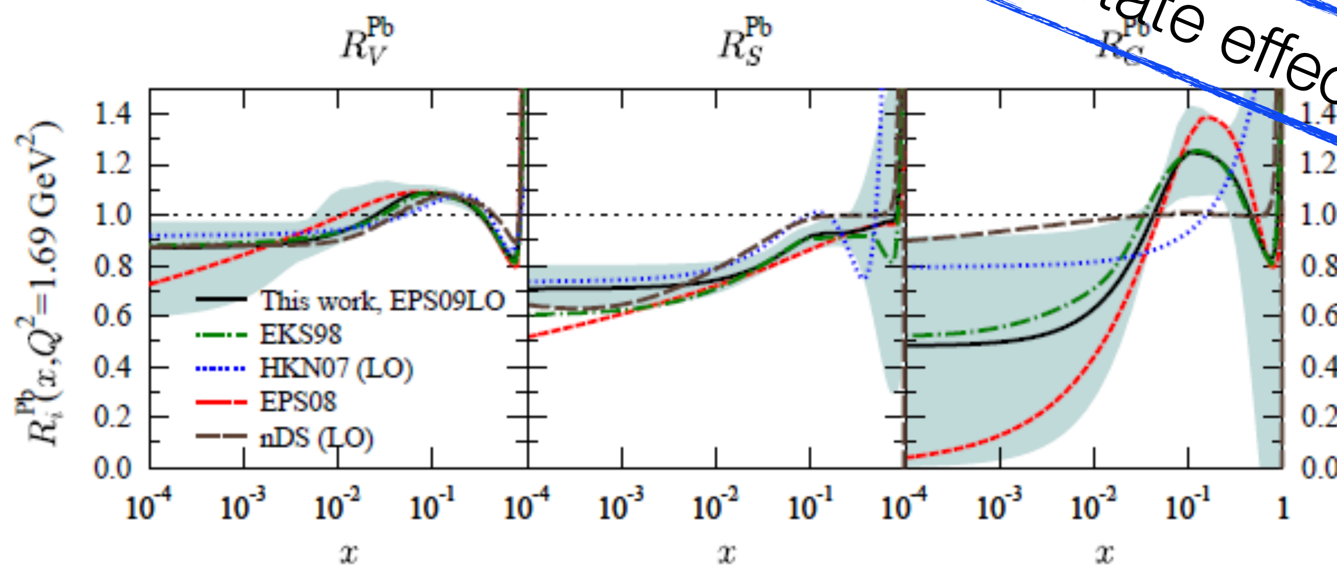
In p-Pb collisions, heavy-quark production affected by high gluon density regime at the LHC that can be implemented via:

modified PDF in case of partons bound in nuclei.

Initial state effects

Color Glass Condensate.

McLerran,Venugopalan PRD49 (1994) 2233,
Fujii-Watanabe, arXiv:1308.1258



see e.g. Eskola et al. JHEP0904(2009)065

Coherent energy loss:

Gluon radiation expected in scatterings of an incoming parton with a compact and colorful system of partons. Arleo, Peigné, Sami, PRD83 (2011) 114036

Final state effects

Comover interactions:

Quarkonium dissociation due to interactions with the comoving partonic medium that then associate again in the bound state.

Capella, Ferreiro, Kaidalov, PRL85 (2000) 2080–2083

Other cold nuclear matter effects

Colour Glass Condensate:

Effective theory used to approximate the saturation regime. Based on the high density of gluons that don't change their position rapidly.

McLerran,Venugopalan PRD49 (1994) 2233, Fujii-Watanabe, arXiv:1308.1258

kT broadening:

partons can reduce their transverse momentum due to multiple soft collisions before the hard scattering occurs.

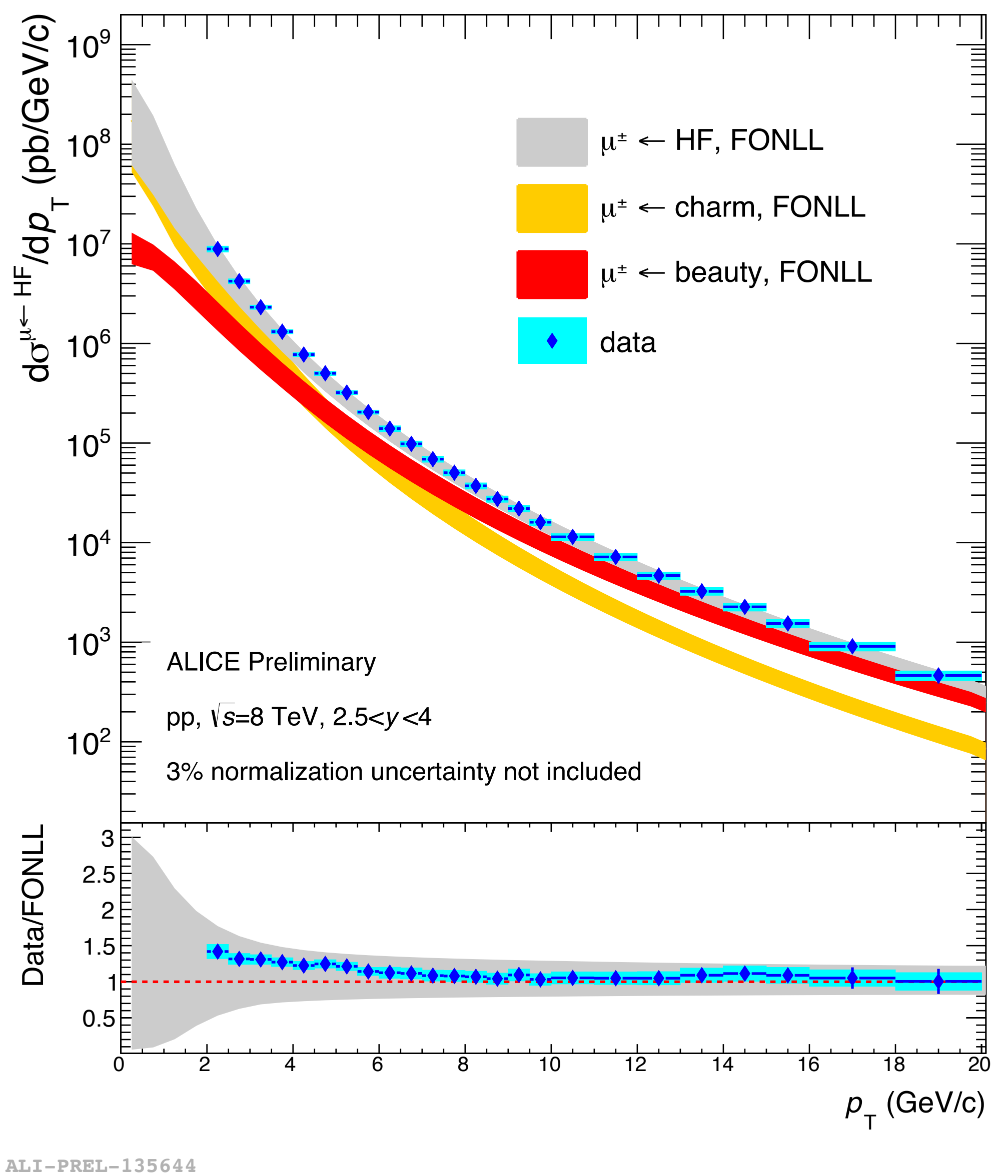
M. Lev and B. Petersson, Z. Phys. C 21 (1983) 155. , X. N. Wang, Phys. Rev. C 61 (2000) 064910.

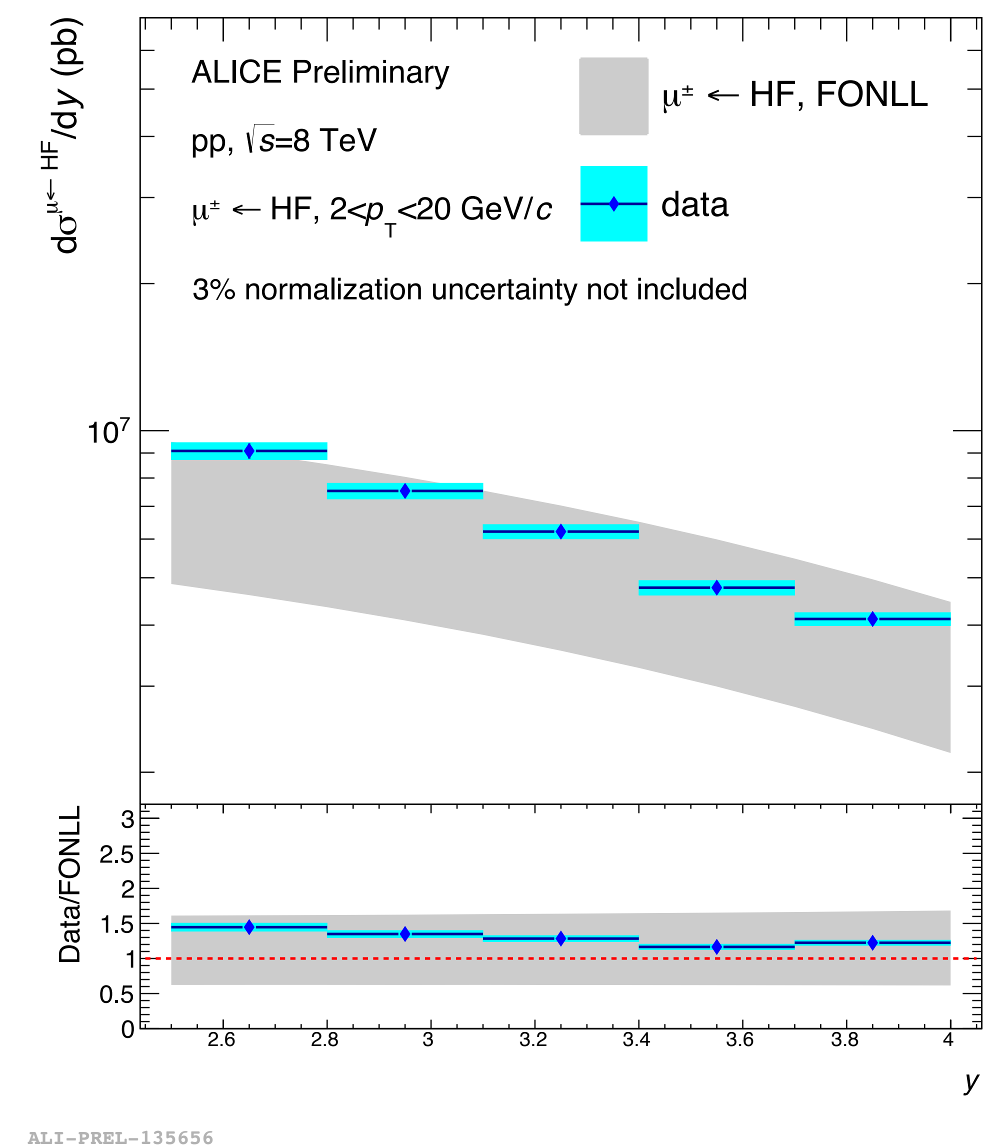
Parton energy loss:

recent calculations based on the possibility that cc pair are also affected by energy loss in pPb due to the high energy density reached at LHC energies.

F. Arleo, S. Peigne, T. Sami, Phys. Rev. D 83 (2011) 114036.

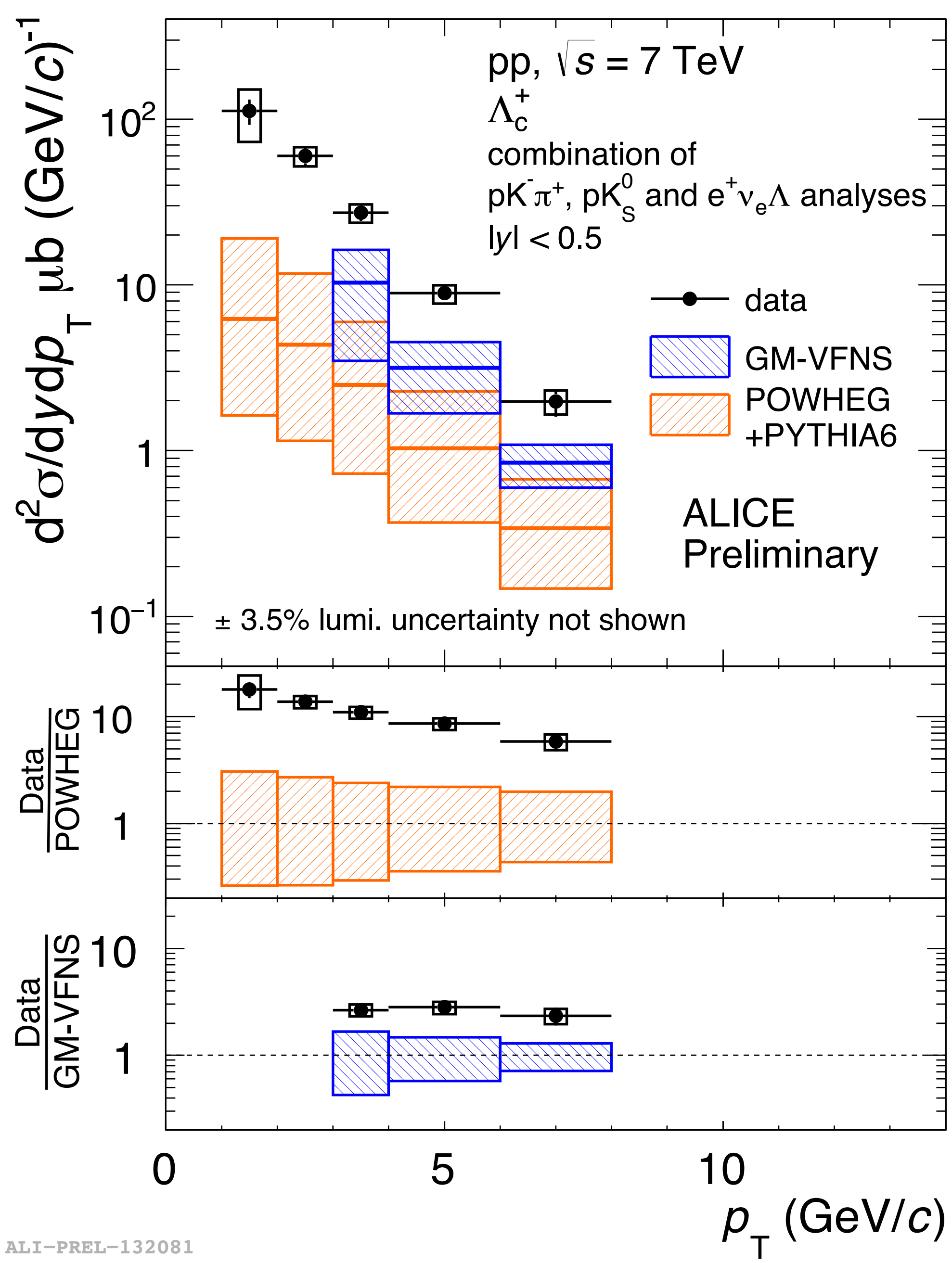
HF muons in pp collisions

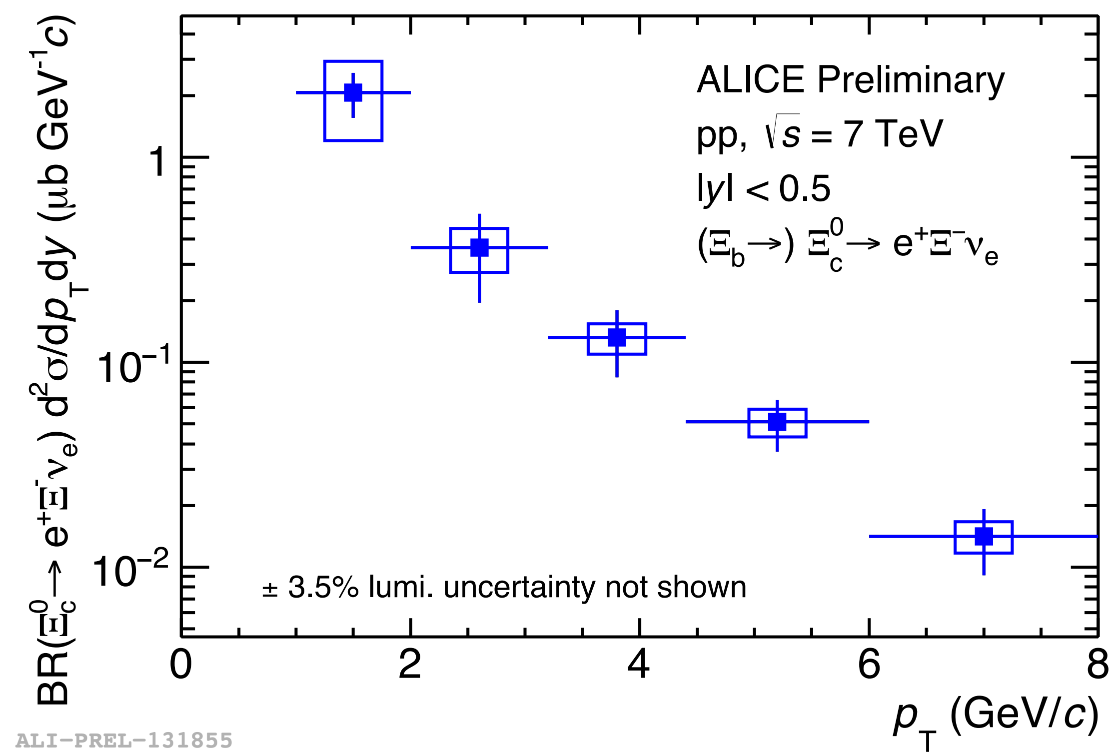




- multi-differential (p_T - y) HF muons cross section in pp collisions.
- good agreement with FONLL calculations
- data can provides constrain to models!

Charmed baryons





- First measurement of Ξ_c^0 p_T differential cross section in pp collisions at LHC (BR unknown)
- Λ_c^+ p_T differential cross section in underestimated by NLO calculations