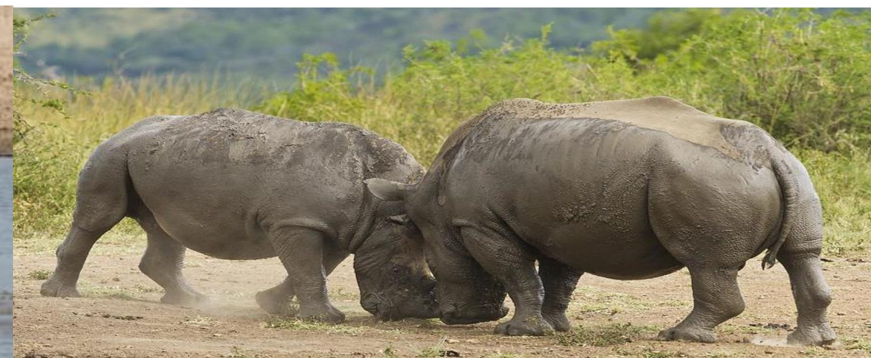
Probing the QGP with heavy quarks in ALICE at the LHC



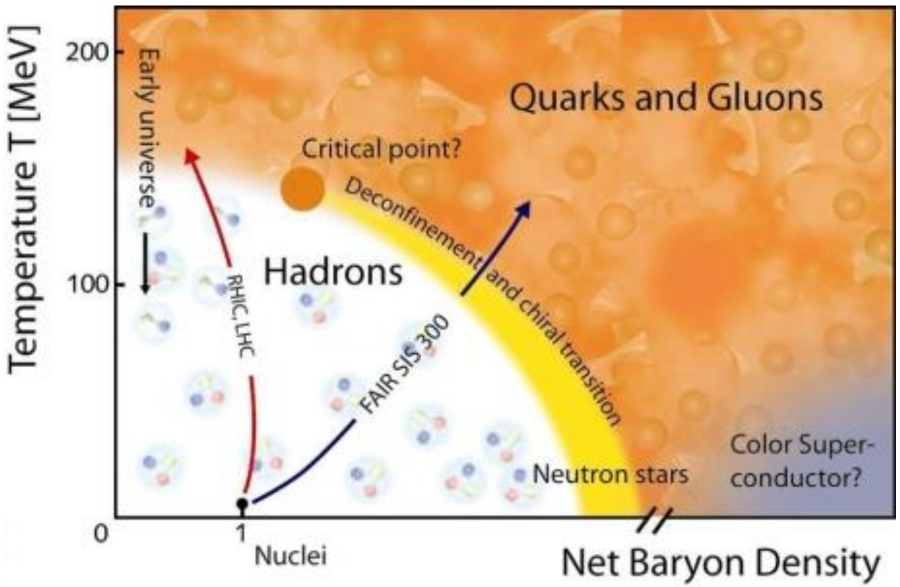
Edith Zinhle Buthelezi, for the **ALICE Collaboration**

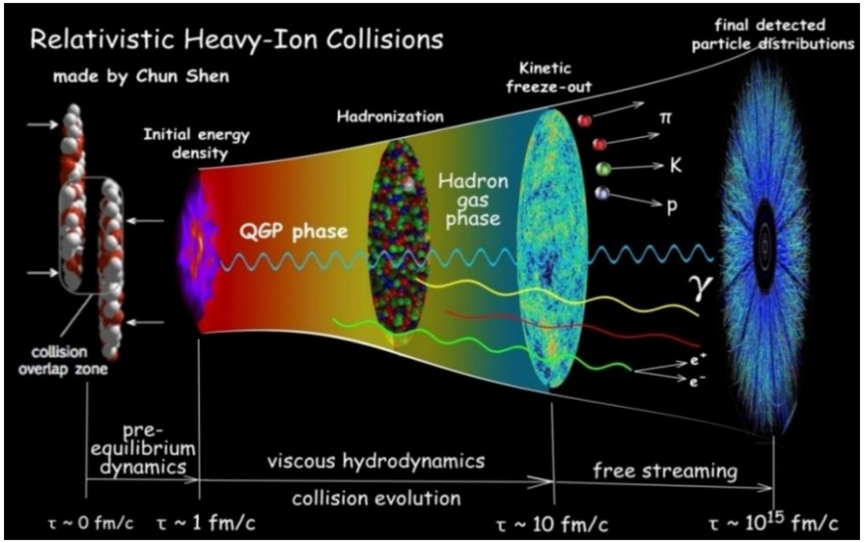
iThemba LABS, Somerset West, South Africa

African Nuclear Physics Conference,
Kruger National Park, South Africa, 1-5 July 2019

Quark-Gluon Plasma and heavy-ion collisions

- At extreme temperature and energy density, QCD predicts a phase transition from hadronic matter to a deconfined partonic matter, the Quark-Gluon Plasma (QGP)
- **Ultra-relativistic heavy-ion (A-A) collisions** provide perfect conditions for QGP production and characterization





- At **LHC energies** a hotter QGP is created with respect to RHIC (LHC energy ~ 30 x RHIC)
- Large cross sections for hard probes: heavy quarks and jets have been measured
  → **precision measurements**

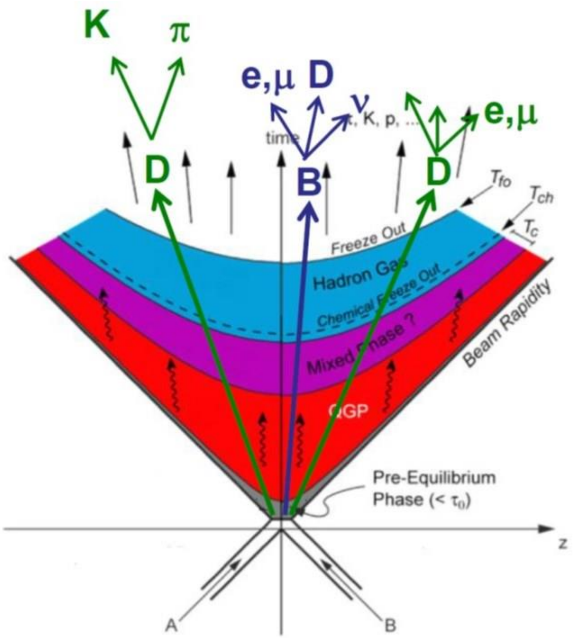
Heavy quarks as QGP probes

- Charm (c ~ 1.5 GeV/c^2) and beauty quarks (b ~ 5 GeV/c^2) are produced in hard scatterings with high Q^2 and short formation time $\tau_{c,b}$ ~ 0.1 fm/c << τ_{QGP} ~ 5 – 10 fm/c

- Their flavour is conserved in strong interactions

→ Transported through the full system evolution

→ Heavy quarks provide a benchmark for energy loss models



What can be tested in A-A collisions?

✓ Gluon radiation and collisional mechanisms

✓ Participate in collective expansion, thermalization of the QGP

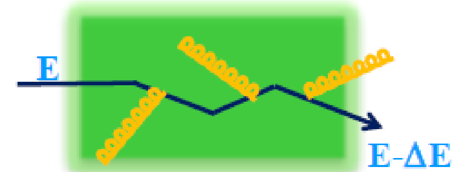
✓ Modification of the hadronization mechanisms in the medium

- **pp collisions**: provide a reference as well as a test for pQCD theoretical models and production mechanisms
- **p-A collisions** (control experiment): investigate cold nuclear matter effects: nuclear modification of PDFs (shadowing, gluon saturation,…), multiple scattering, energy loss,…

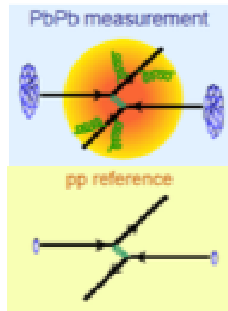
Nucl. Phys.B484, 265 (1997),Nucl. Phys.B594, 371(2001),Phys. Lett. B519,199 (2001)

Parton energy loss in the QGP

- In QGP partons are expected to lose energy via gluon radiation and elastic collisions with plasma constituents
- Energy loss can be quantified by the **nuclear modification factor**

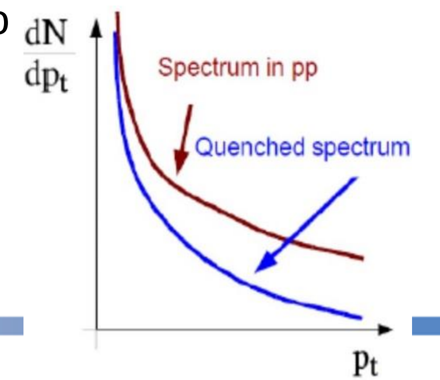


$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp X Ncoll}}$$



ArXiv"0902.2011[nucl-ex], arXiv:1002.2206v3[hep-ph]

- Reduction in parton energy translates to the reduction in the average *p* of produced hadrons
  → reduction of the yield at high p_T wrt pp collisions, $\boldsymbol{R_{AA} < 1}$
- Radiative energy loss expected as main mechanism at high p_T, whereas at low p_T an interplay with collisional energy is expected. The energy loss is sensitive to
  - ✓ Medium properties (density)
  - ✓ Path-length (L) of the parton in the QGP
  - ✓ Properties of the parton probing the medium



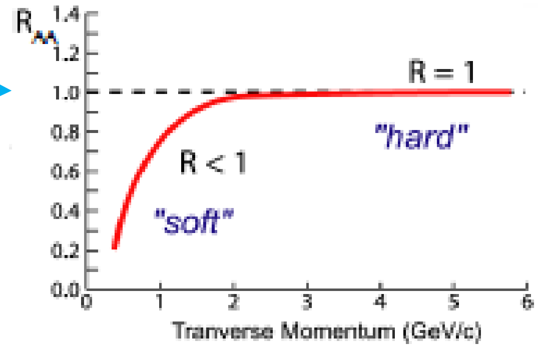
- Hierarchy: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ → R_{AA} **(b) >** R_{AA} **(c) >** R_{AA} **(π)**

Observables

- **Nuclear modification factor:**

$$R_{AA} = \frac{AA}{\text{rescaled } pp} = \frac{d^2N_{AA}/dp_T\,dy}{\langle N_{binary}\rangle\, d^2N_{pp}/dp_T\,dy}$$

R_{AA} = 1
if no medium effects

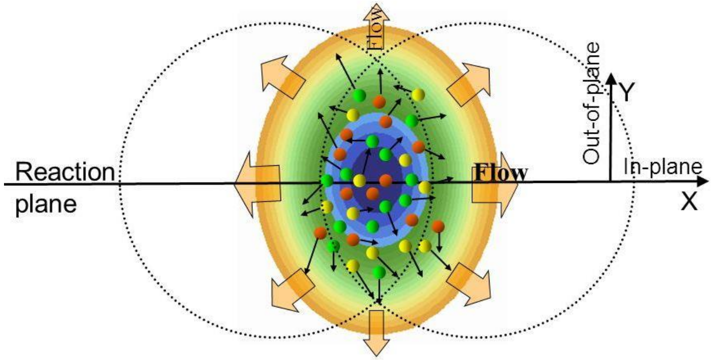


- **Elliptic flow**: initial spatial anisotropy+ hydro = final momentum anisotropy

Quantified by the second Fourier coefficient, v_2

$$\frac{dN}{d\varphi} = \frac{N}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)\right]$$

$$v_2 = < cos2(\varphi_{part} - \Psi_{EP}) >$$



Driven by overlap geometry

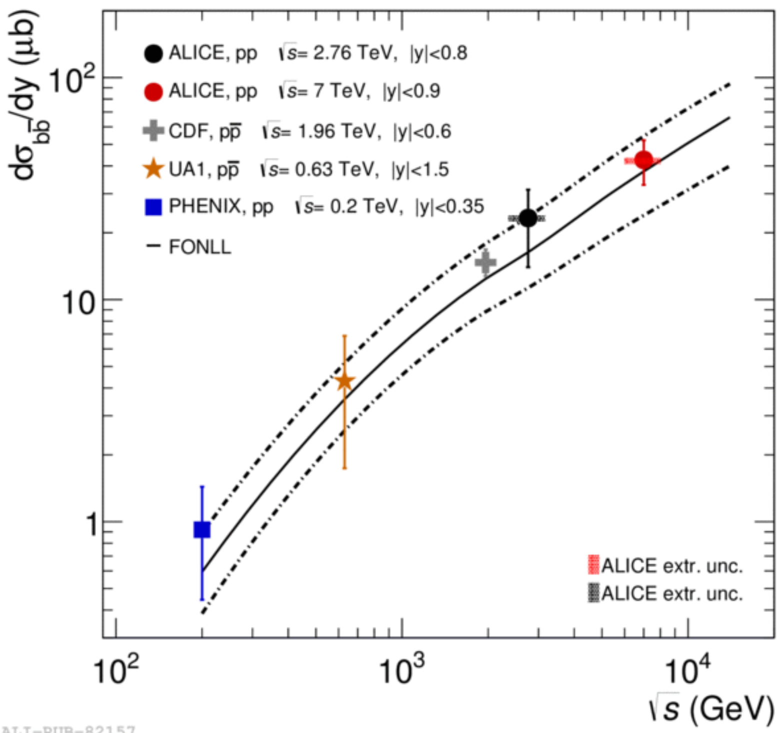
→ Related to pressure gradients & shear viscosity to entropy ratio (η/s)

→ Sensitive to thermalization of the system

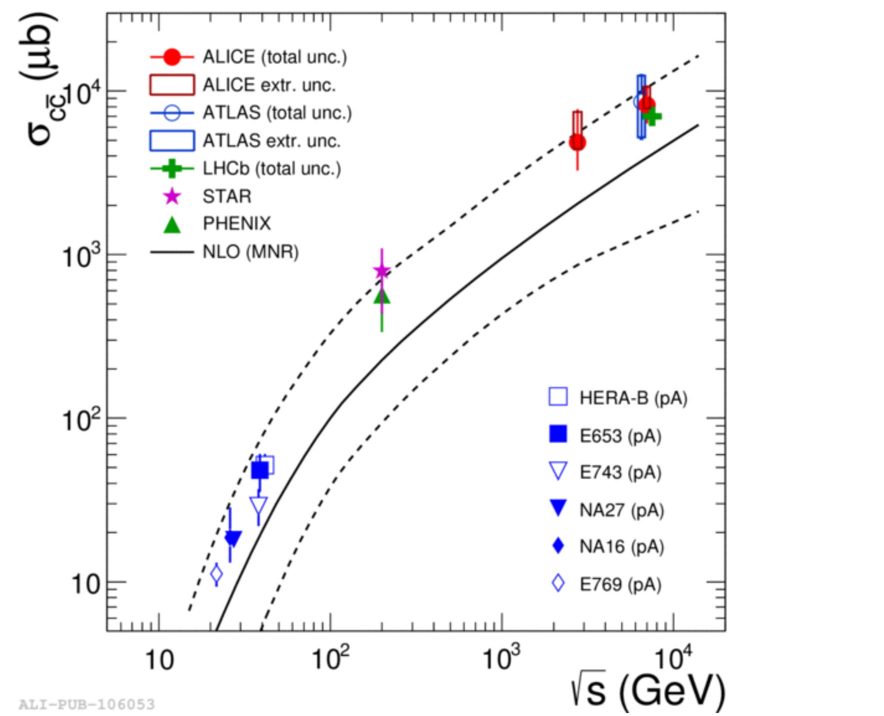
Heavy-quark production at the LHC

- Production cross sections calculated in pQCD
- Large amounts of charm and beauty hadron production at the LHC
  - ✓ $\sigma_c / \sigma_b \sim 5/50$ increase from RHIC to LHC
  - ✓ $\sigma_{c\bar{c}} / \sigma_{b\bar{b}} \sim 100/10$ increase from RHIC to LHC

Phys. Rev. C 94 (2016) 054908,
Phys. Lett. B 763 (2016) 507



PLB 738(2014) 97



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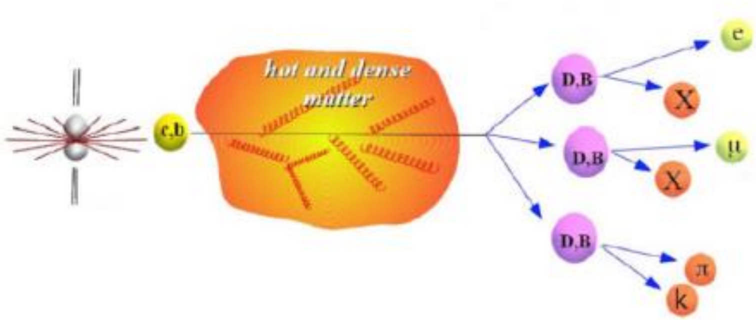
Two "historical" probes

Open heavy flavour: Charm hadrons (D^0, $D^{\pm}$, …), bottom hadrons (B^0, $B^{\pm}$,…)

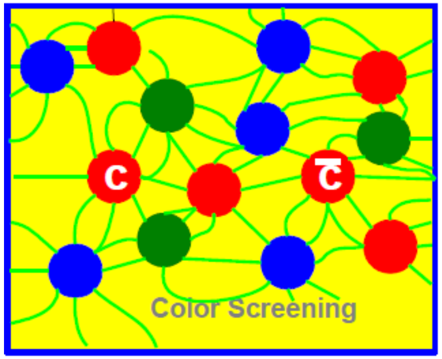
Mass dependence of radiative parton energy loss ("dead cone" effect) Dokshitzer and Kharzeev, Phys. Lett. B519(2001) 199[arXiv:hep-ph/0106202]



Probe of QCD interaction dynamics in extended systems

Quarkonia: charmonium ($c\bar{c}$): J/ψ, ψ',…, bottomonium ($b\bar{b}$): ϒ..

Dissociation ("melting") of $Q\bar{Q}$ via colour-screening Matsui and Satz, PLB178 (1986) 416



Probe of deconfinement & QGP medium temperature

Both probe medium transport properties via, e.g. the collective expansion of the QGP
Both pillars evolved and extended significantly over the years

THIS TALK

Two "historical" pillars

Open heavy flavour: Charm hadrons (D^0, $D^{\pm}$, …), bottom hadrons (B^0, $B^{\pm}$,…)

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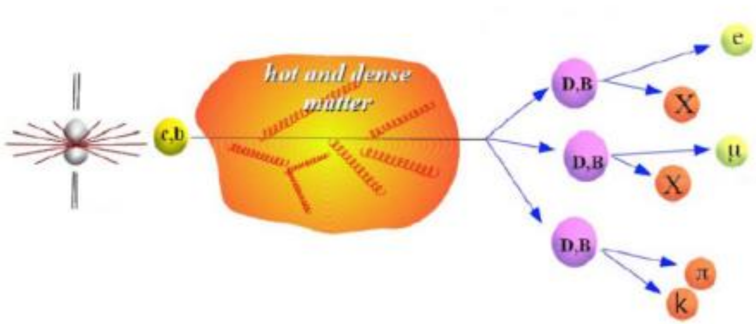

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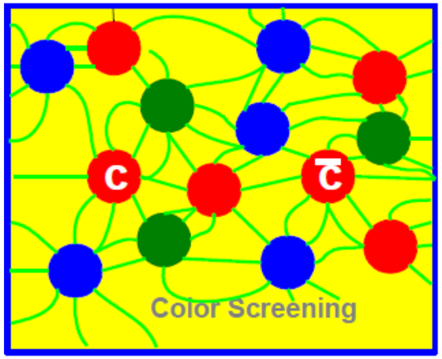


Probe of deconfinement & QGP medium temperature

Both probe medium transport properties via, e.g. the collective expansion of the medium
Both pillars evolved and extended significantly over the years

Open heavy-flavour hadrons

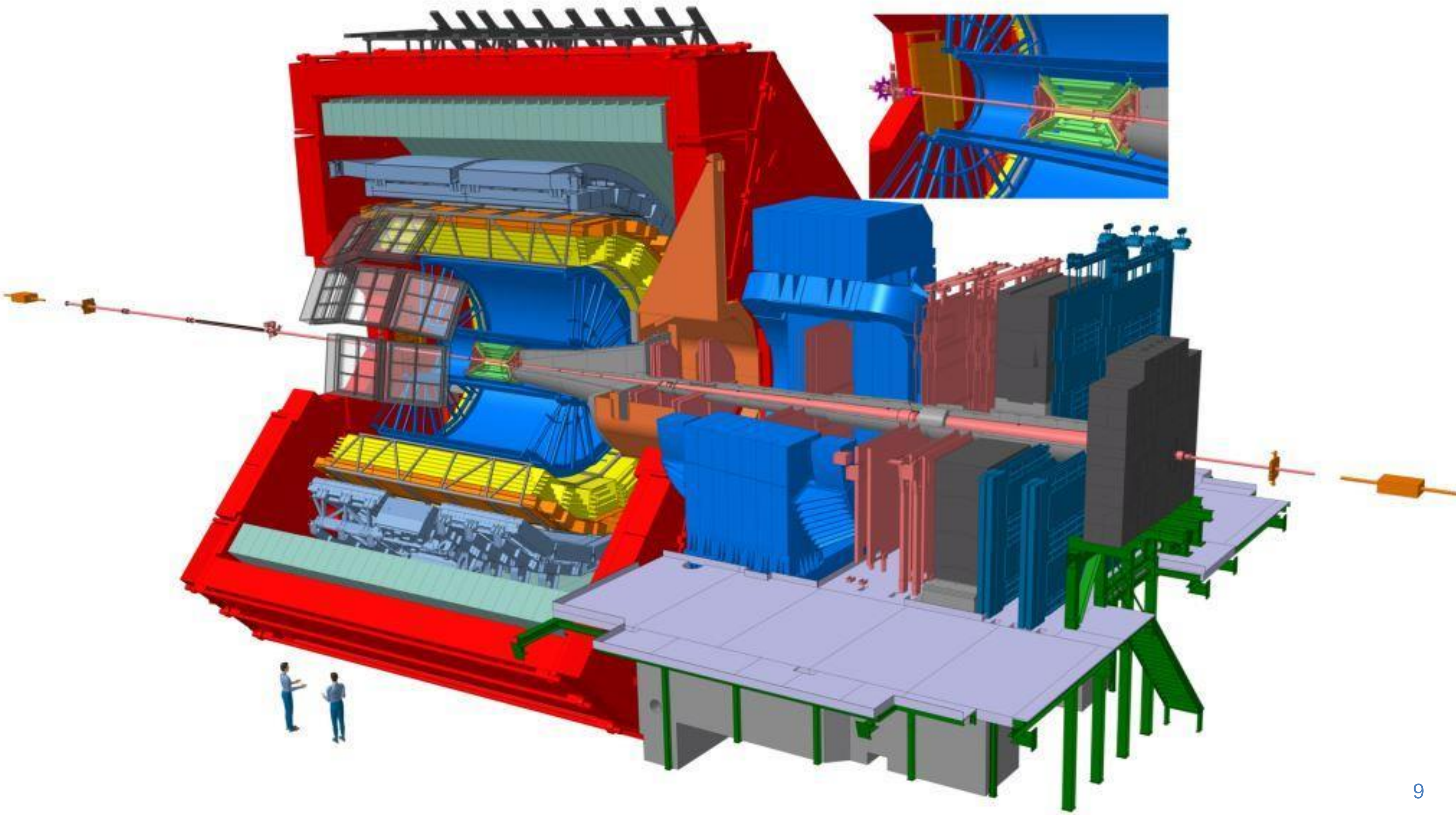
- **Open heavy flavour hadrons** are hadrons containing a charm (anticharm) or beauty (antibeauty) quark + a light antiquark (quark).
- Lower mass heavy-flavour hadrons decay weakly, have a lifetimes of ~ 0.5 -2 ps and decay length $c\tau$ ~ 100 - 500 μm
- Decay vertices are displaced by hundreds of μm from primary vertex

Hadron	Mass (MeV)	$c\tau$ (μm)
$D^+(c\bar{d})$	1869	312
$D^0(c\bar{u})$	1865	123
$D_s^+(c\bar{s})$	1968	147
$\Lambda_c^+(udc)$	2285	60
$\Xi_c^+(usc)$	2466	132
$\Xi_c^0(dsc)$	2472	34
$\Omega_c^0(ssc)$	2698	21

Hadron	Mass (MeV)	$c\tau$ (μm)
$B^+(u\bar{b})$	5279	501
$B^0(d\bar{b})$	5279	460
$B_s^0(s\bar{b})$	5370	438
$B_c^0(c\bar{b})$	≈ 6400	$100-200$
$\Lambda_b^0(udb)$	5624	368

- Decay modes branching ratios (B.R.):
  - ✓ **Semi-leptonic B.R. ~10%** → 10% of heavy-flavour hadrons decays to $e^{\pm}(\mu^{\pm})$
  - ✓ **Charm hadrons B.R. ~55% to kaons** → golden channel for exclusive reconstruction

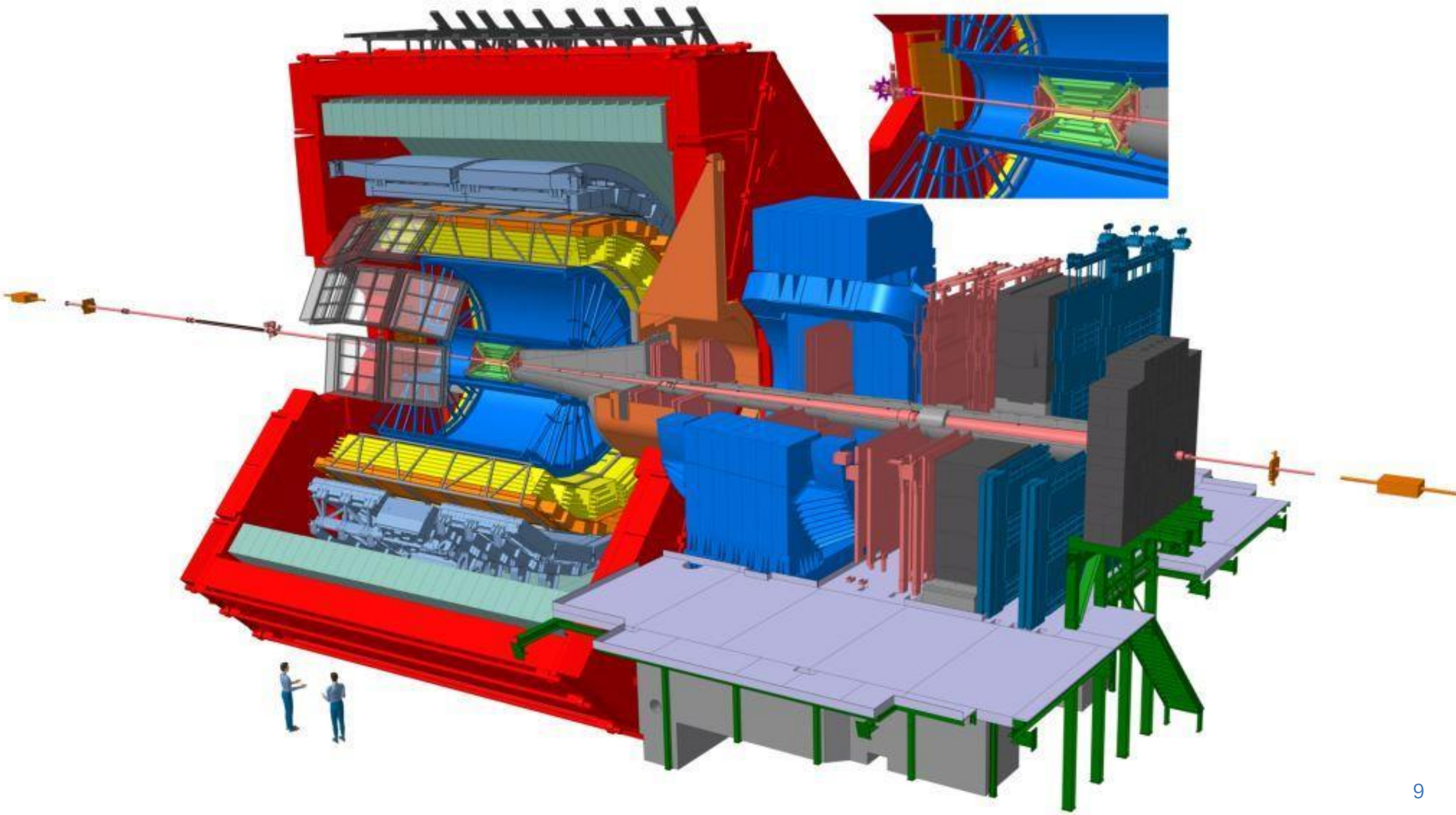
The ALICE Detector



The ALICE Detector

Central barrel |η| < 0.9

Solenoid magnetic field, $B = 0.5\ T$



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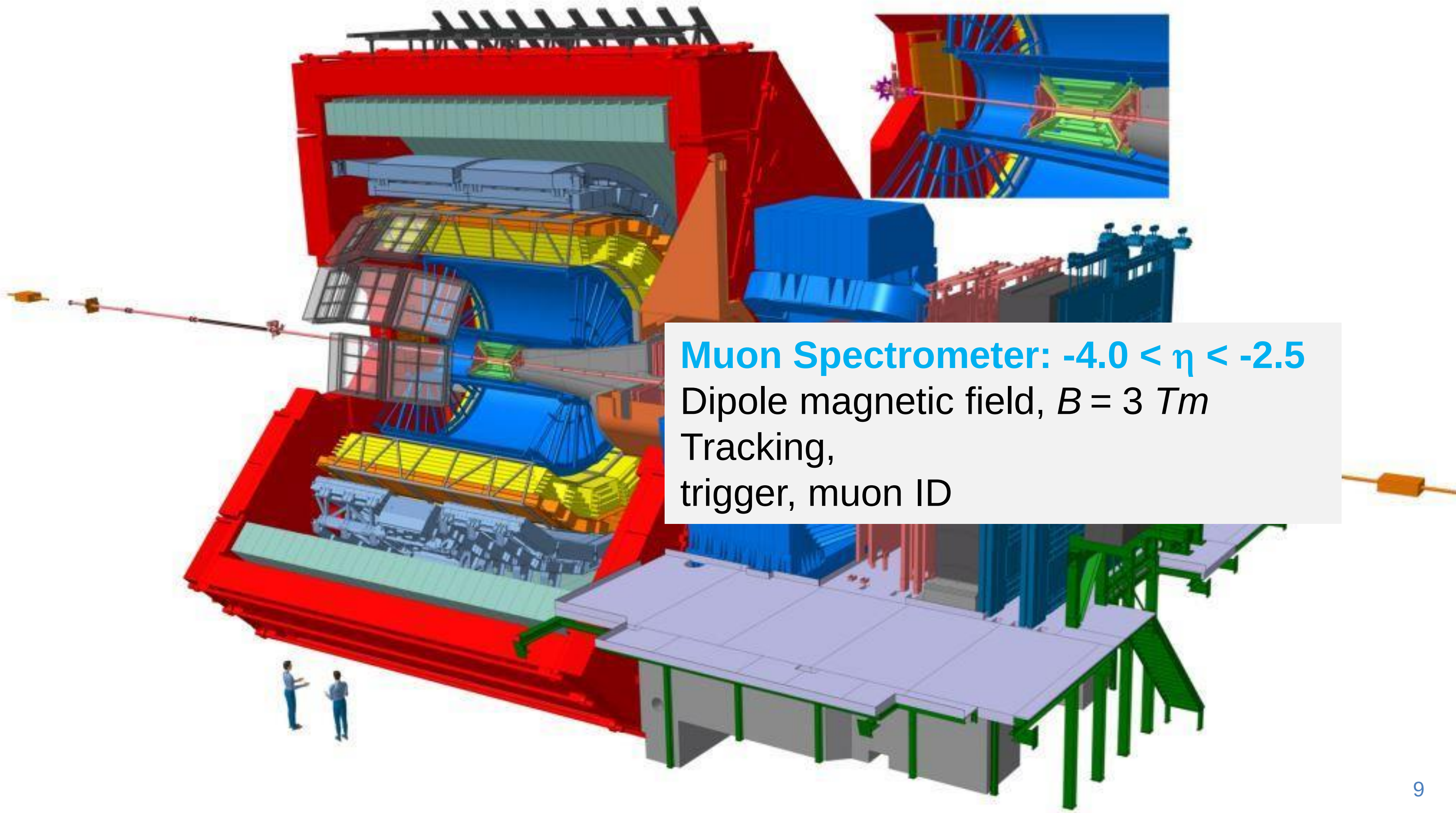

Muon Spectrometer: $-4.0 < \eta < -2.5$

Dipole magnetic field, $B = 3\ Tm$

Tracking,

trigger, muon ID

The ALICE Detector

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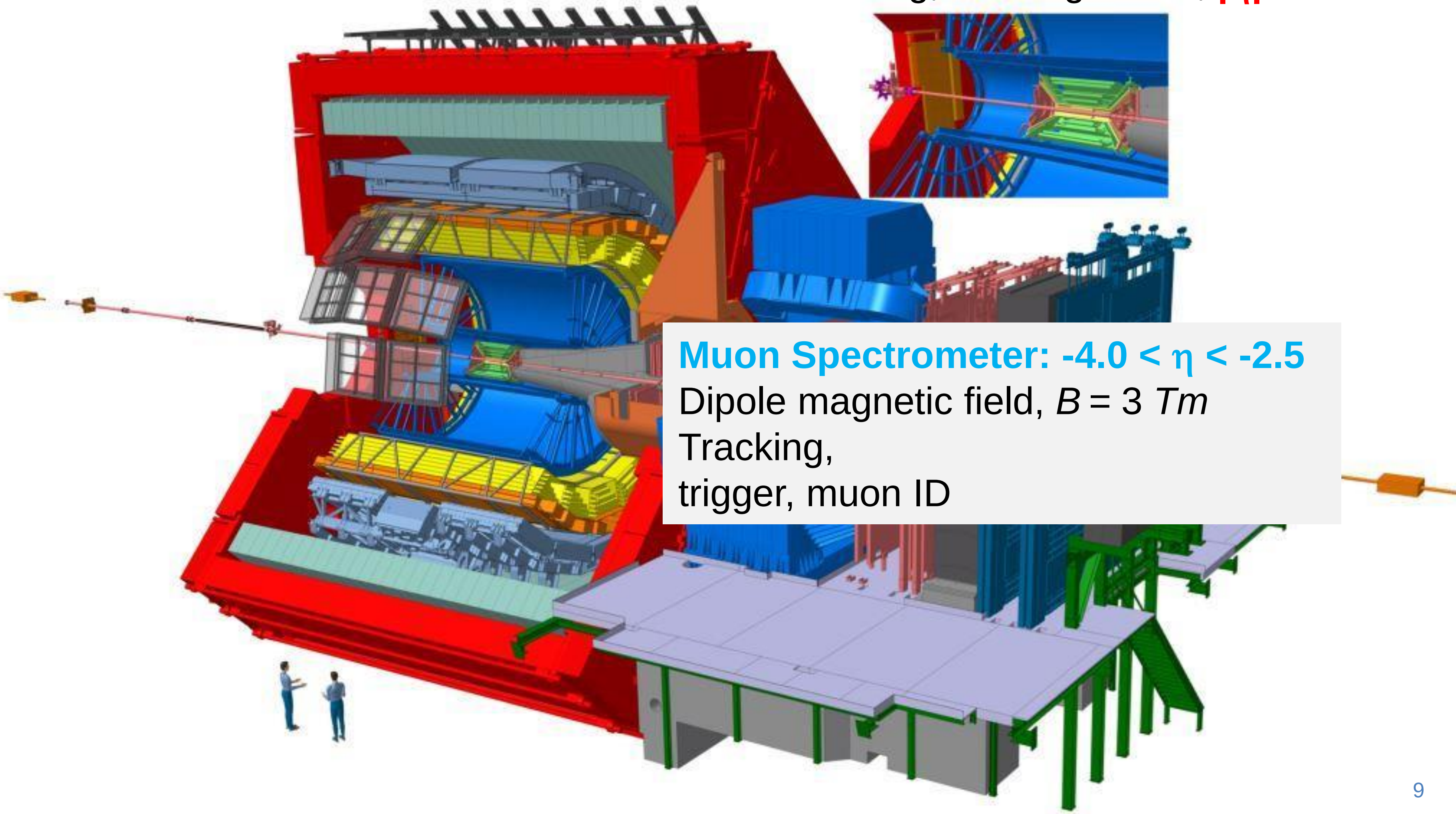
Solenoid magnetic field, $B = 0.5\ T$

Inner Tracking System (ITS)

Vertexing, tracking & PID, **$|\eta| < 0.9$**



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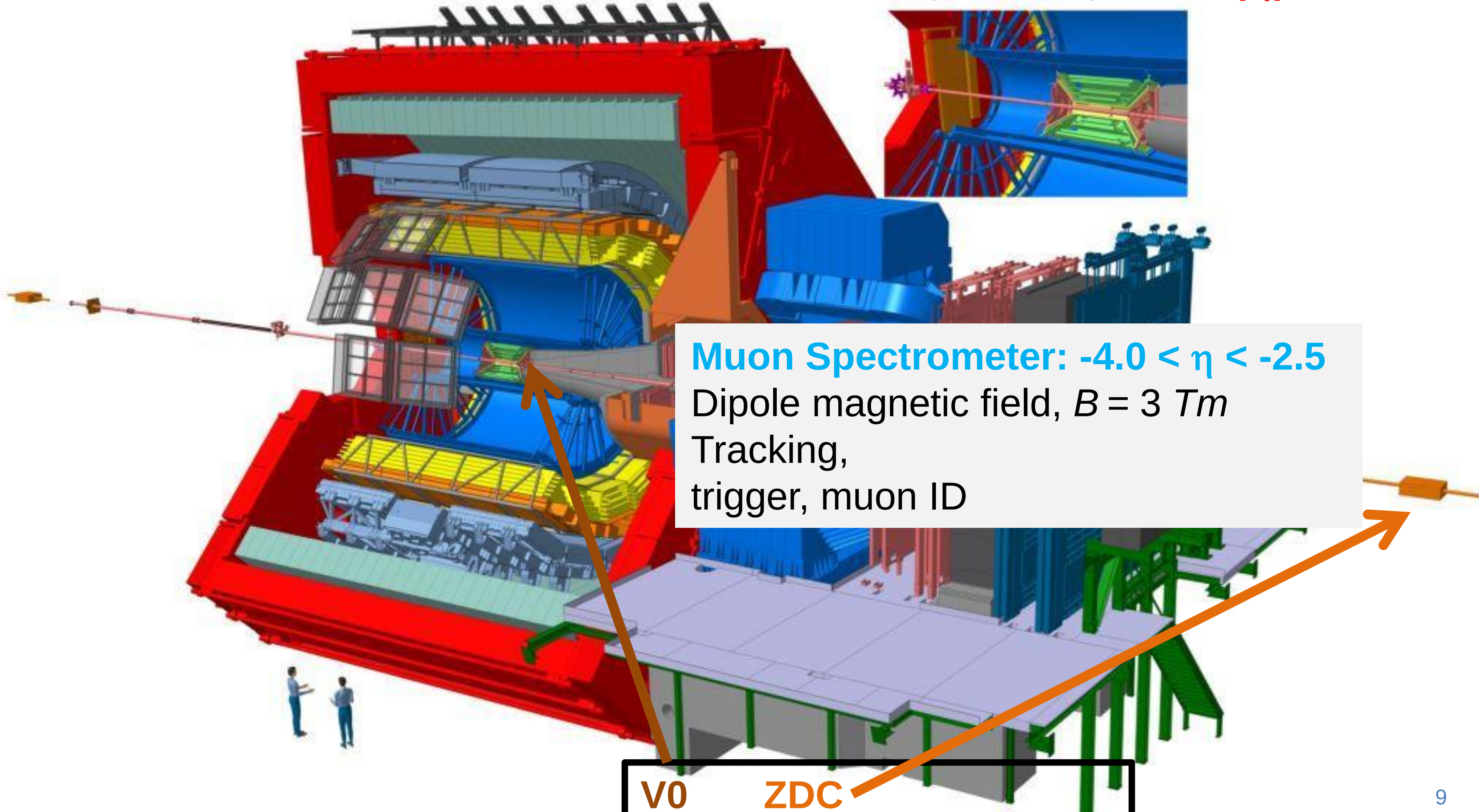

Muon Spectrometer: $-4.0 < \eta < -2.5$
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V0 ZDC
minimum bias (MB) trigger
event characterization

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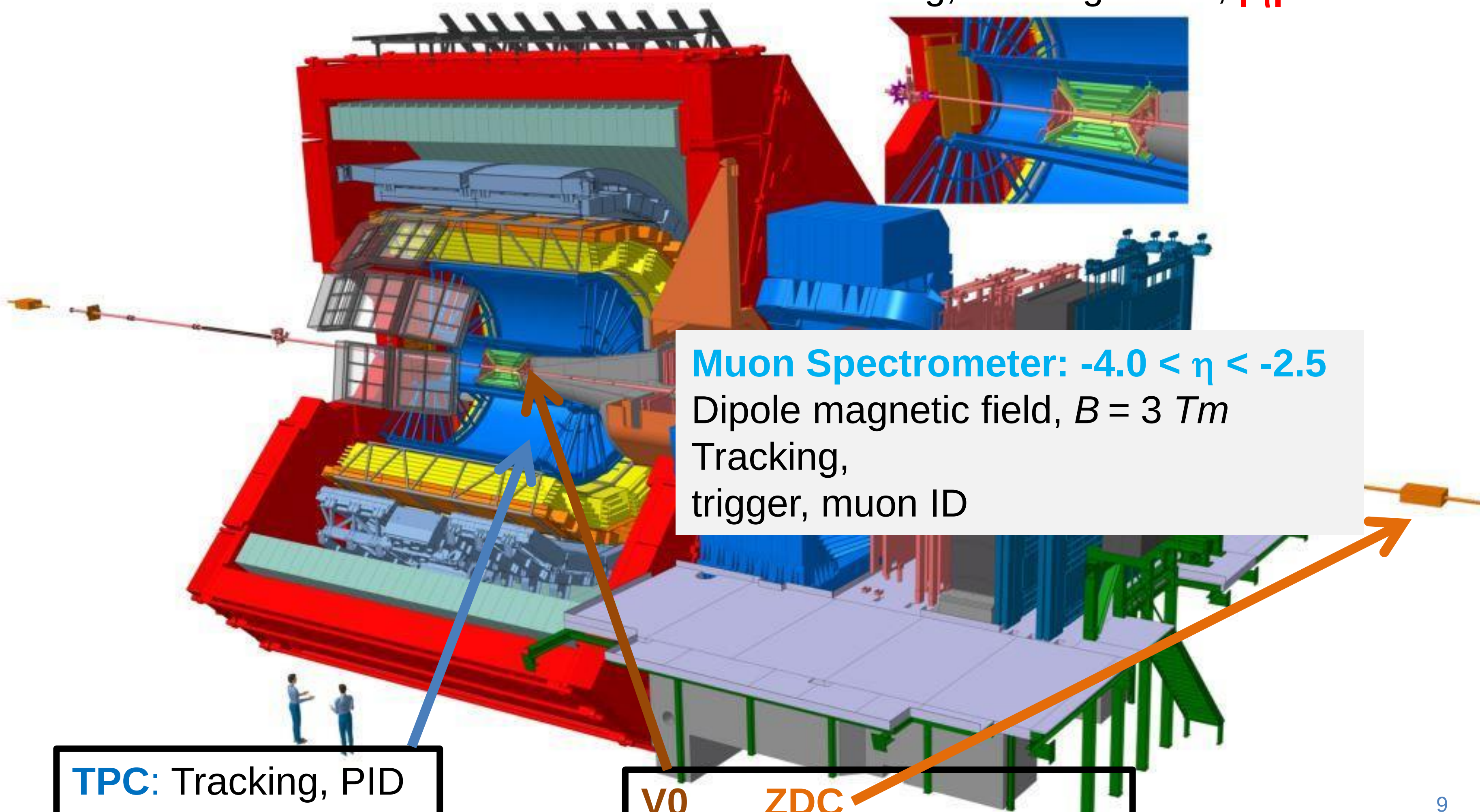


Muon Spectrometer: -4.0 < η < -2.5
Dipole magnetic field, *B* = 3 *Tm*
Tracking,
trigger, muon ID

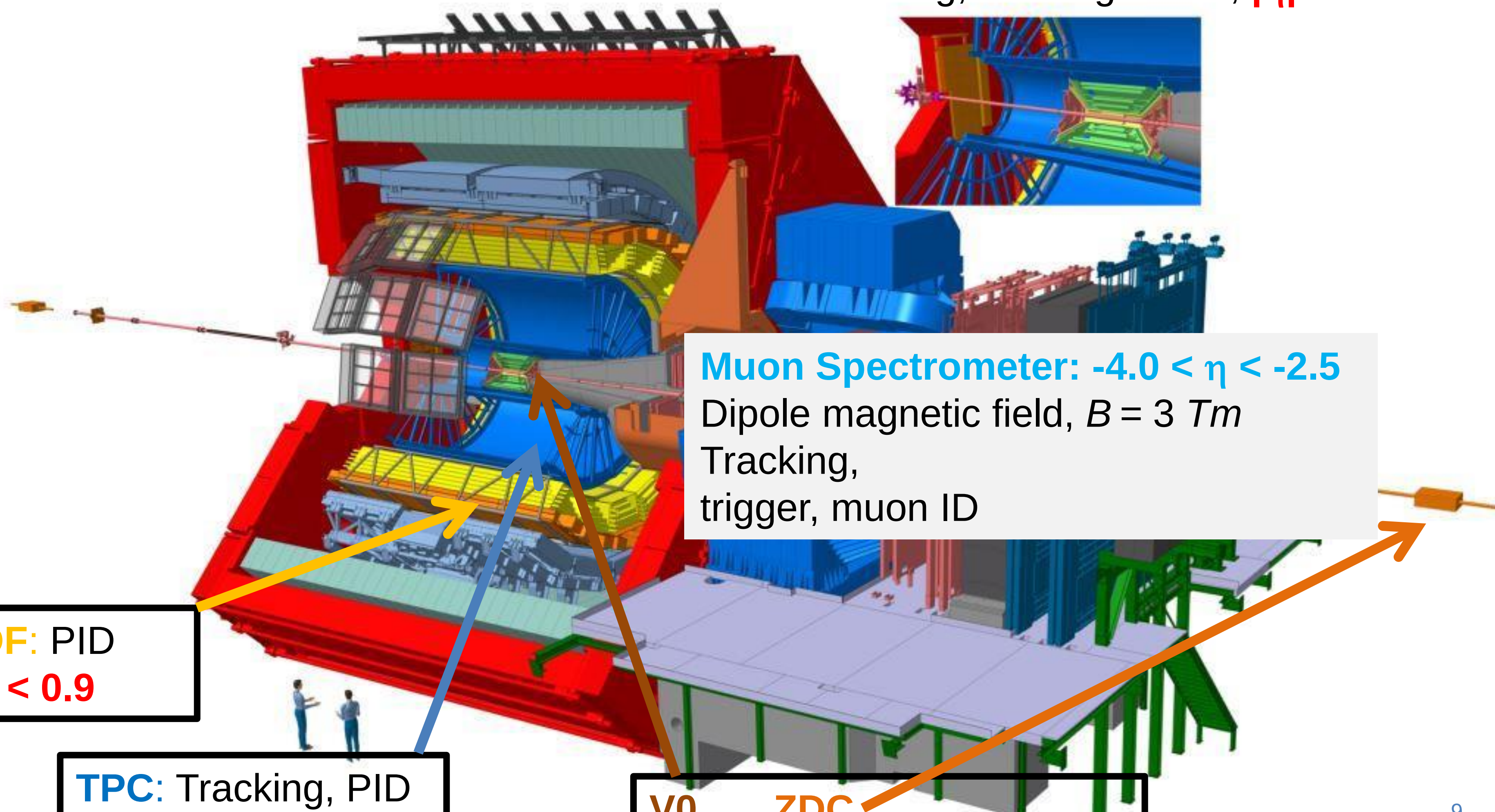
TPC: Tracking, PID
|η| < 0.9

V0 **ZDC**
minimum bias (MB) trigger
event characterization

The ALICE Detector

Central barrel $|\eta| < 0.9$
Solenoid magnetic field, $B = 0.5\ T$

Inner Tracking System (ITS)
Vertexing, tracking & PID, $|\eta| < 0.9$



Muon Spectrometer: $-4.0 < \eta < -2.5$
Dipole magnetic field, $B = 3\ Tm$
Tracking,
trigger, muon ID

TOF: PID
$|\eta| < 0.9$

TPC: Tracking, PID
$|\eta| < 0.9$

V0 **ZDC**
minimum bias (MB) trigger
event characterization

The ALICE Detector

ALICE

Central barrel $|\eta| < 0.9$
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Inner Tracking System (ITS)
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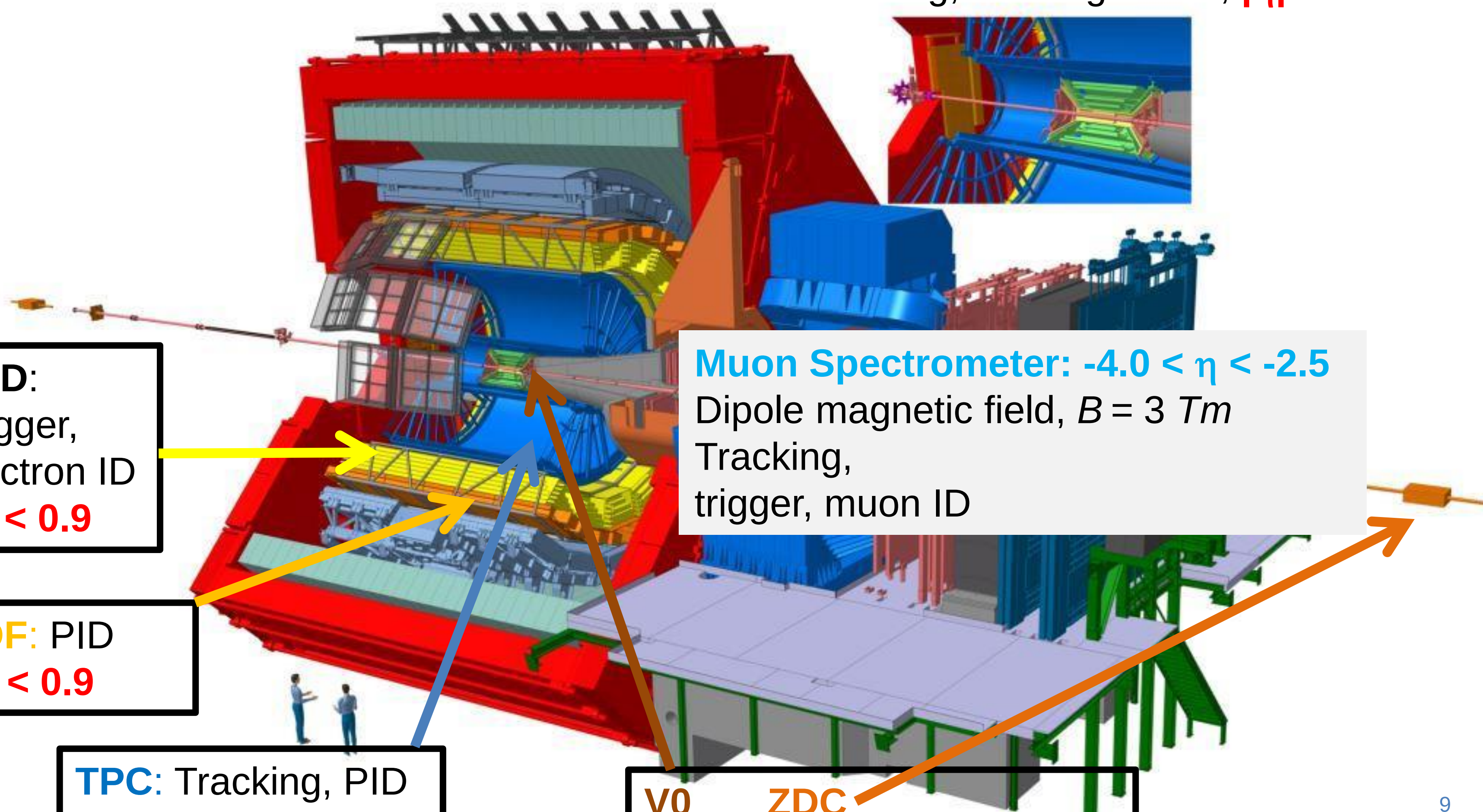

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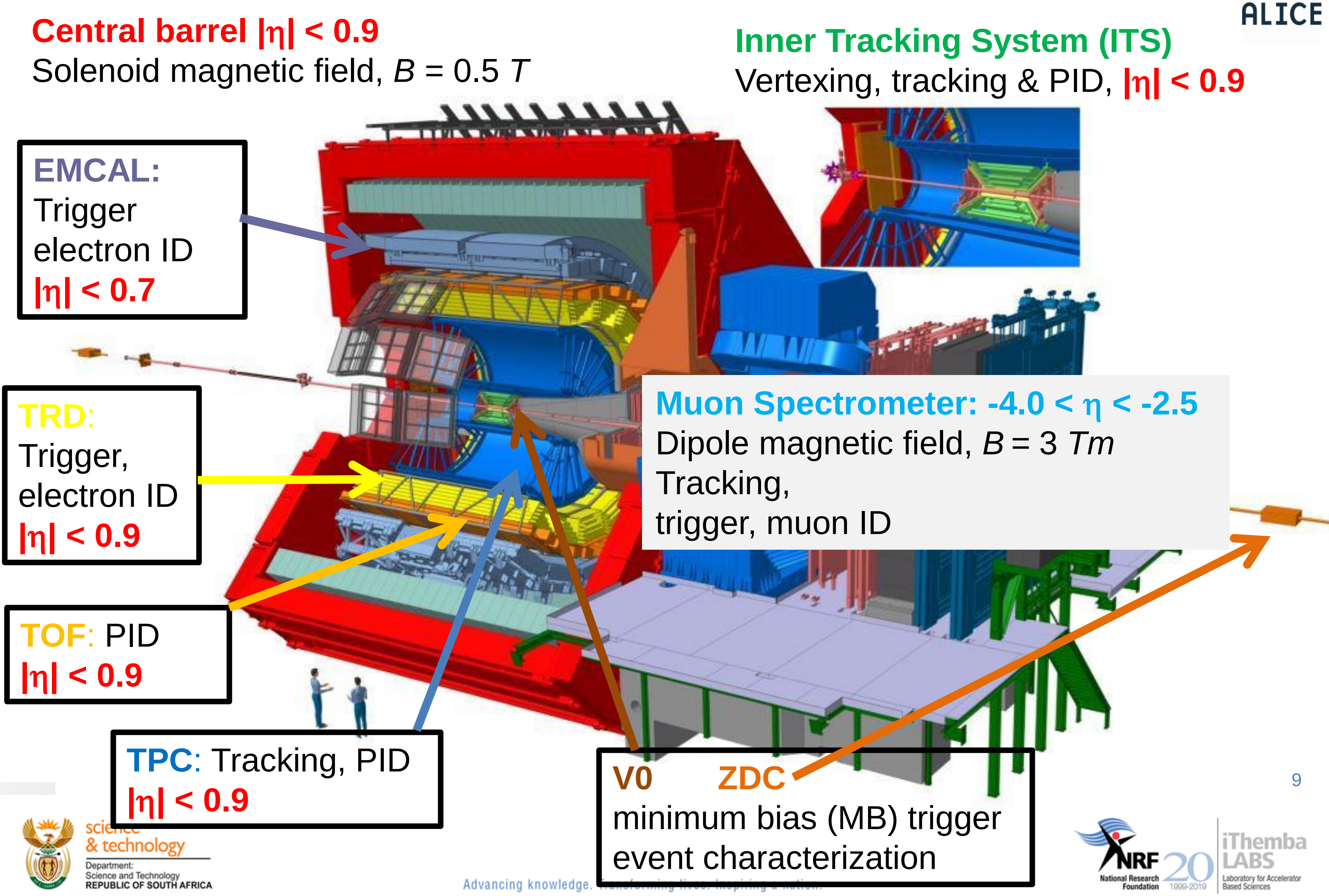


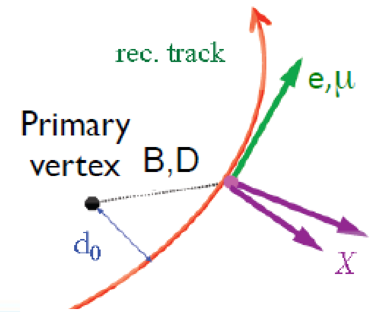
Open heavy-flavour hadron measurements in ALICE

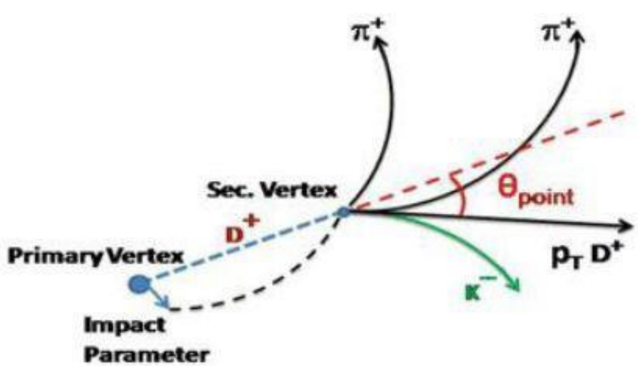
Hadronic decays:

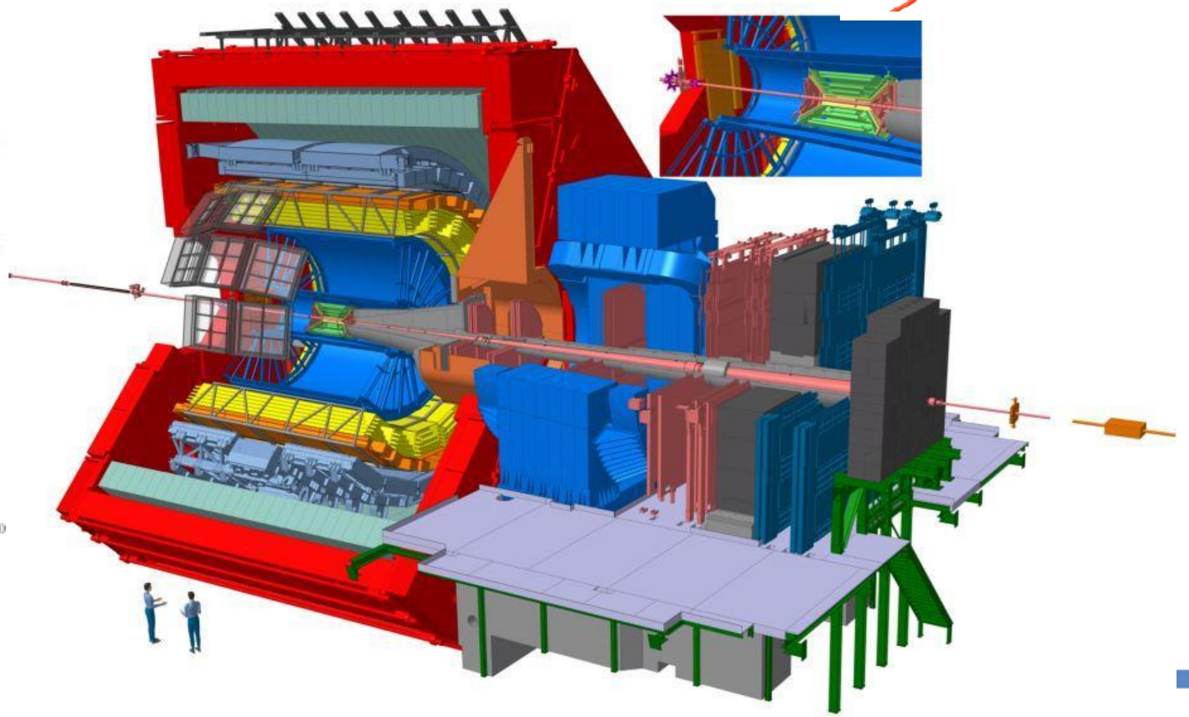
$D^0 \rightarrow K^-\pi^+,\ \ D^+ \rightarrow K^-\pi^+\pi^-,$
$D^{*+} \rightarrow D^0\pi^+,$
$D_s{}^+ \rightarrow K^+K^-\pi^+$
$\Lambda_c^+ \rightarrow \pi^+K^-p\ ,\ \Lambda_c^+ \rightarrow K_S^0 p$
$\Xi_c^0 \rightarrow e^+\Xi_{\nu_e}^- \rightarrow e^+\pi^+\Lambda\nu_e$

Electron from heavy-flavour hadron decay: D, B, Λ_c^+ → $e^\pm$ + X

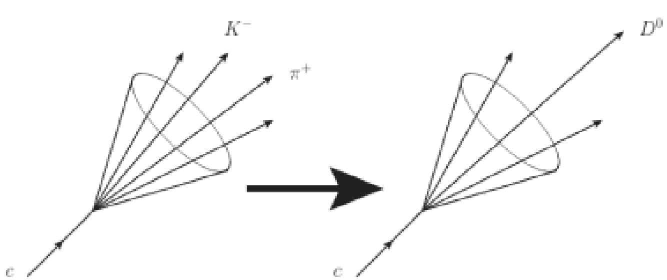
Muons from heavy-flavour hadron decay: D, B → $\mu^\pm$ + X







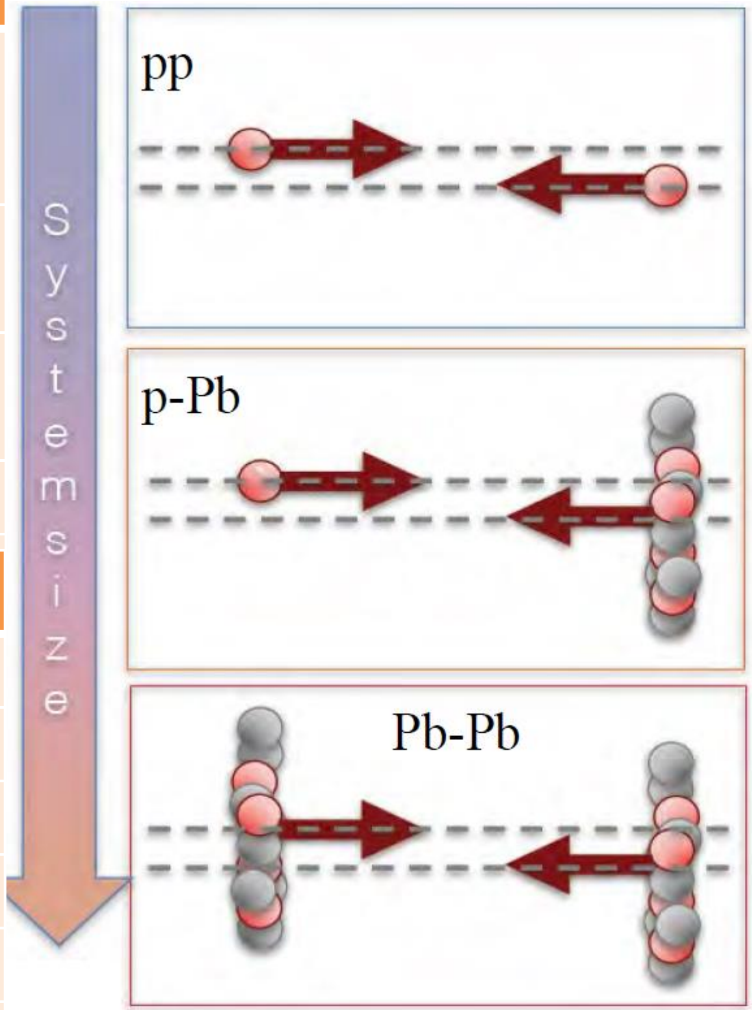
D⁰-tagged jets:



Collision systems in ALICE

Run 1 (2009-2013)		
System	**Energy(TeV)**	**L_{int} (minimum bias)**
pp	0.9, 2.76	$200\mu b^{-1}$ $100nb^{-1}$
	7,8	$1.5pb^{-1}$ $2.5\mu b^{-1}$
p-Pb	5.02	$15nb^{-1}$

Run 2 (2015-2018)		
pp	5.02	$1.3pb^{-1}$
	13	$35pb^{-1}$
p-Pb	5.02	$3nb^{-1}$
	8.16	$25nb^{-1}$
Xe-Xe	5.44	$0.3\mu b^{-1}$
Pb-Pb: 2015, 2018	5.02	$250\mu b^{-1}$ $536\mu b^{-1}$

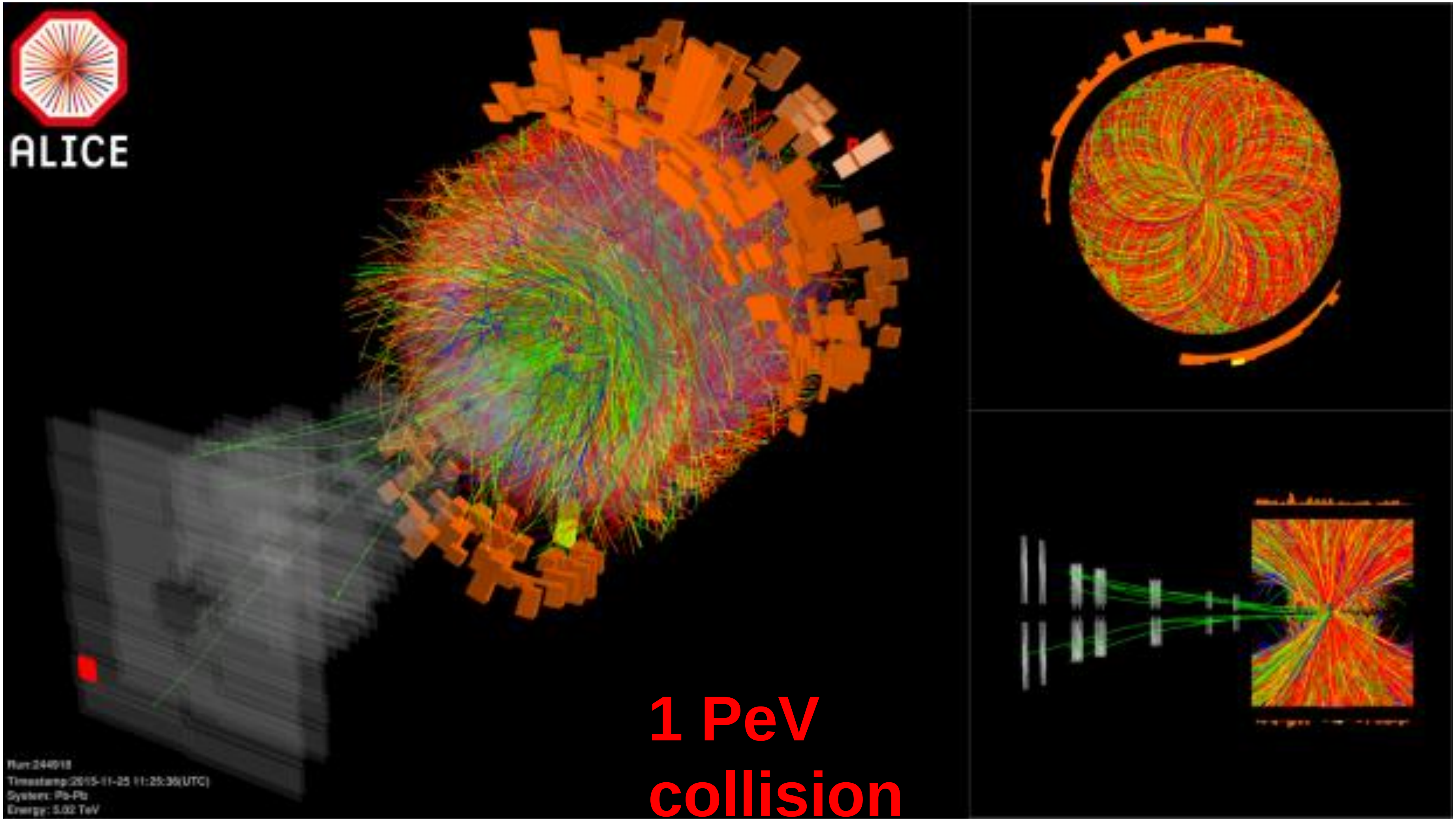


$$L_{int} = \int L dt$$

$$L = \frac{dN}{dt} / \sigma$$

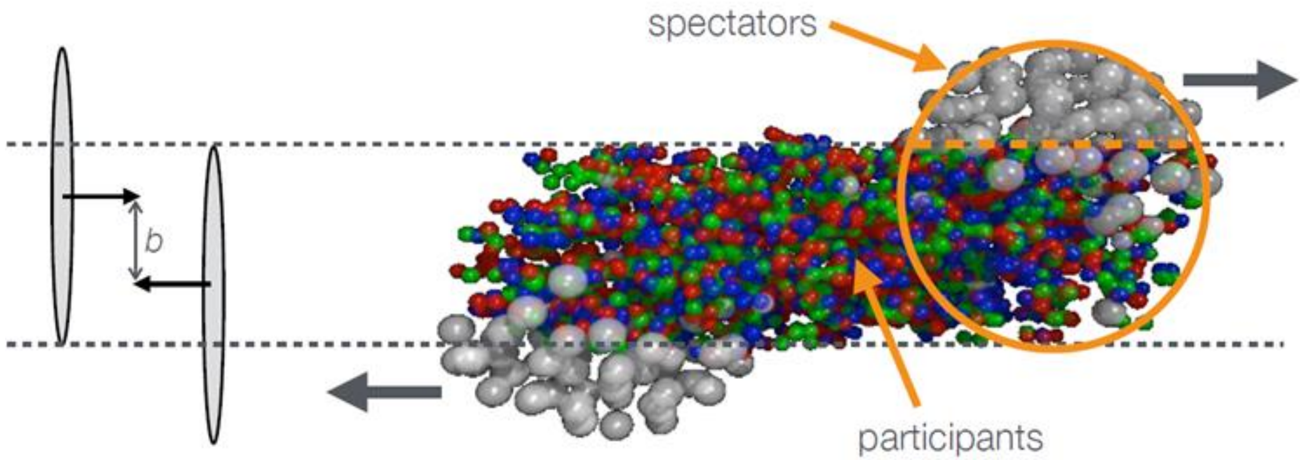
$$N = \sigma \frac{n}{A} l$$

ALICE Pb-Pb data taking in 2015



Collision geometry - centrality

- System size strongly dependent on collision centrality
- Given by the impact parameter, *b*

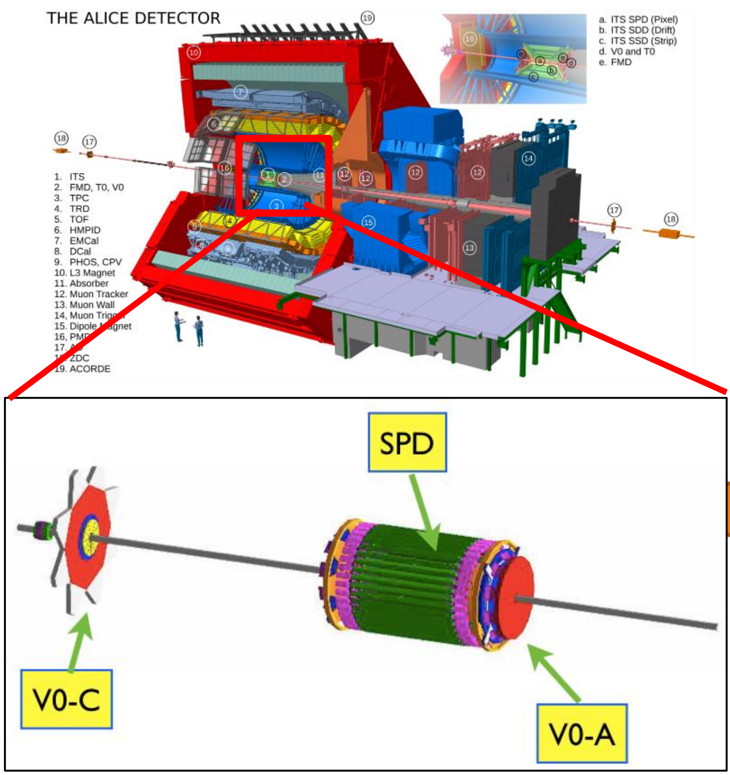


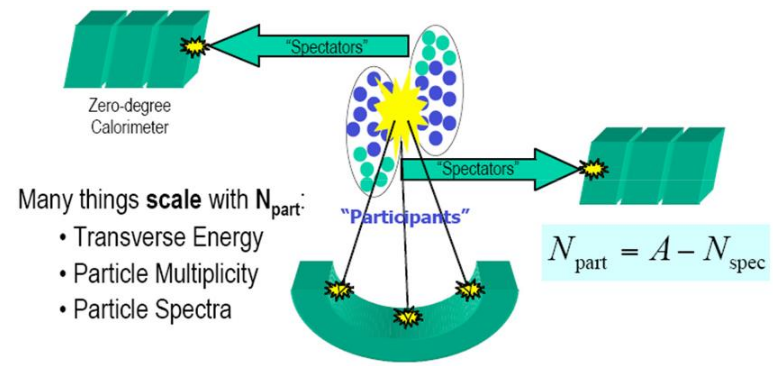
- N_{coll}: number of inelastic nucleon-nucleon collisions
- N_{part}: number of nucleons which underwent at least one inelastic nucleon-nucleon collision

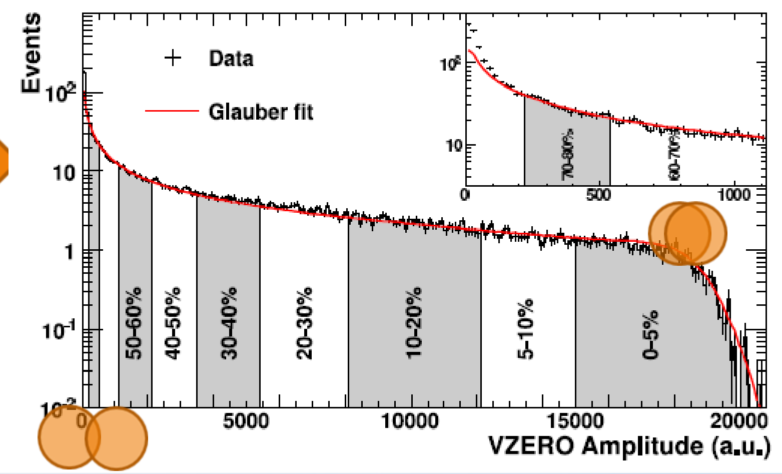
- **Central collisions (small b):** large N_{part} → less spectators, High multiplicity
- **Peripheral collisions (large b):** small N_{part} → more spectators, low multiplicity
- Events classified in **"centrality classes"** → percentiles of total hadronic AA cross section

How do we measure the centrality?

- Energy deposited is proportional to N_{part}
- Use multiplicity of produced particles in the acceptance of a given detector (V0, SPD) **or** measure the energy of the spectator nucleons in the ZDC
- Determine **$\langle N_{part} \rangle$** and **$\langle N_{coll} \rangle$** with a model of the collision geometry (Glauber model)







RESULTS

Only a selection of available results for the measurements of the

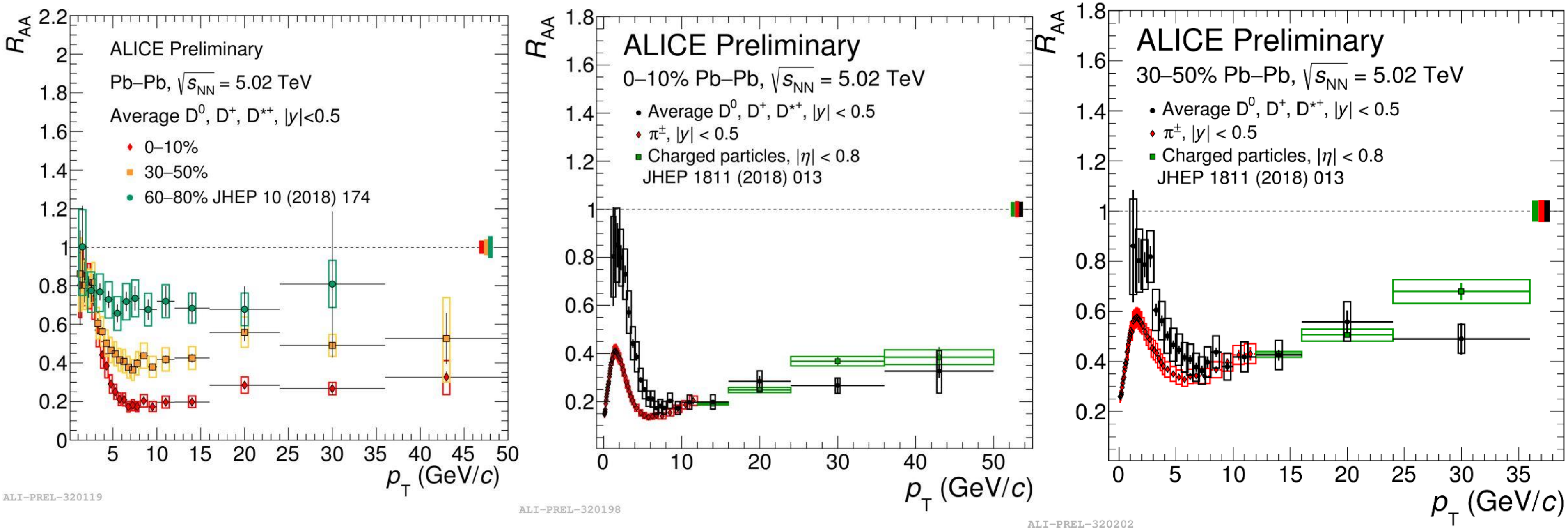
- Nuclear modification factor, $R_{AA} = \frac{d^2N_{AA}/dp_T\, dy}{\langle N_{coll}\rangle\, d^2N_{pp}/dp_T\, dy}$

- Anisotropic/elliptic flow $v_2 = < cos2(\varphi_{part} - \Psi_{EP}) >$

as a function of transverse momentum (p_T) in central, semi-central and peripheral Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 (2.76) TeV and where applicable, Xe-Xe at $\sqrt{s_{NN}}$ = 5.44 TeV

D-meson R_{AA}

- (D) compared with $R_{AA}(\pi^{\pm})$ and charged-particles in central (0-10%), semi-central (30–50%) and peripheral (60-80%) Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV → **Increasing suppression from peripheral (60-80%) to central (0-10%) Pb-Pb collisions**
- Quark-mass and colour-charge dependence: $\Delta E_{\pi} > \Delta E_{c} > \Delta E_{b} \overset{?}{\rightarrow} R_{AA}(\pi) < R_{AA}(c) < R_{AA}(b)$



- $R_{AA}(D) > R_{AA}(\pi)$ for p_T < 8 GeV/c but comparable R_{AA} for p_T > 8 GeV/c within uncertainties
- Possible mass and Cassimir effects, shadowing, interplay between different p_T spectra of charm, light quarks and gluons and different fragmentation fractions

→ $R_{AA}(D) \simeq R_{AA}(\pi^{\pm}) \simeq R_{AA}$(charged particles) for p_T > 8 GeV/c JHEP 1811 (2018) 013, PLB 782 (2018) 474-496

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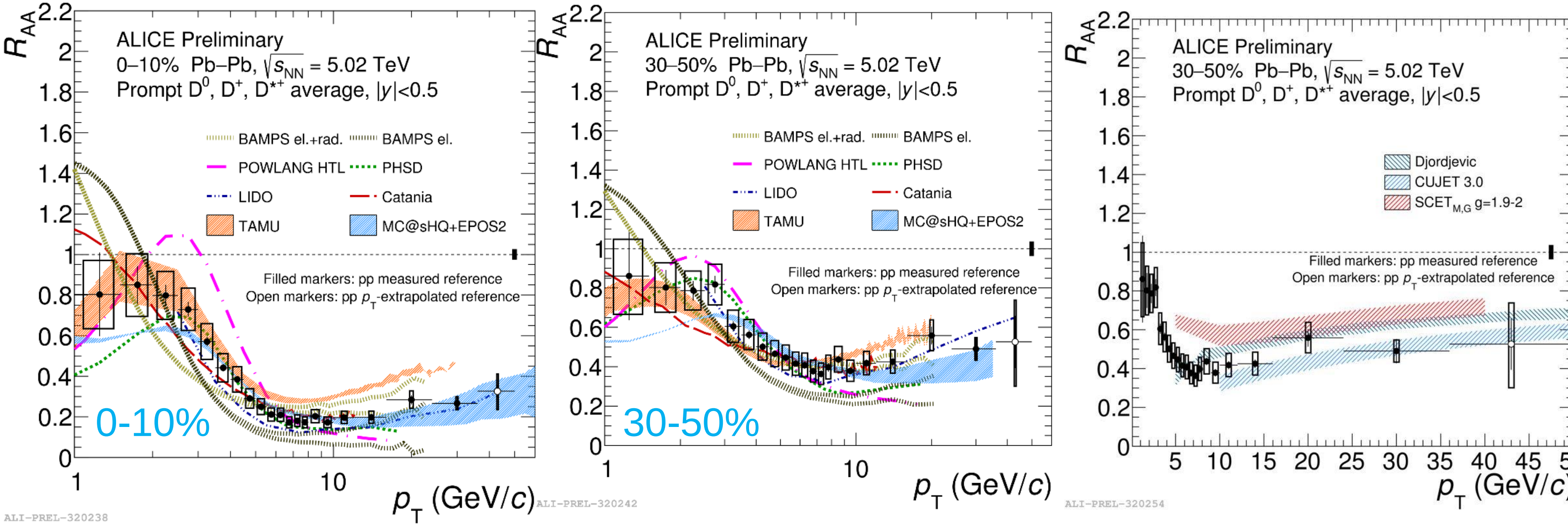
D-meson R_{AA}: comparison with various models

ALICE

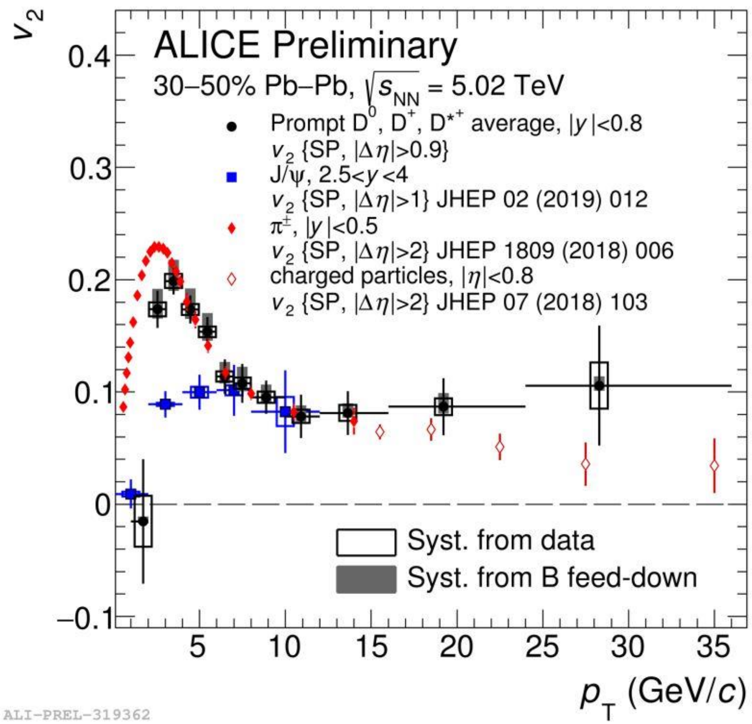
- D meson R_{AA} in in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared with transport and pQCD predictions

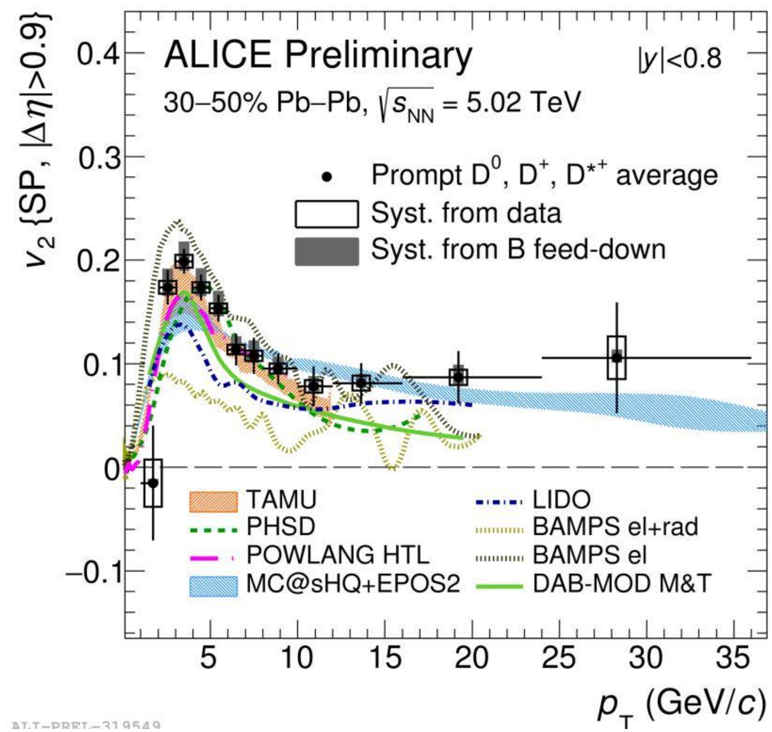
Transport models **pQCD energy loss models**



- Low p_T D-meson R_{AA} described by transport models
- High p_T D-meson R_{AA} described by pQD-based energy loss models

Elliptic flow, v_2 of D mesons

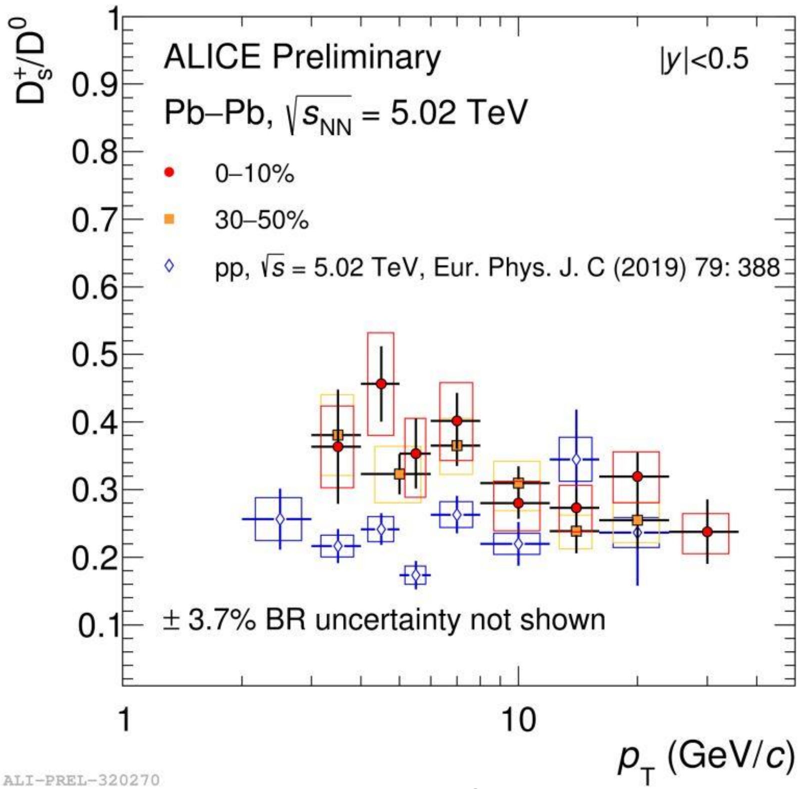


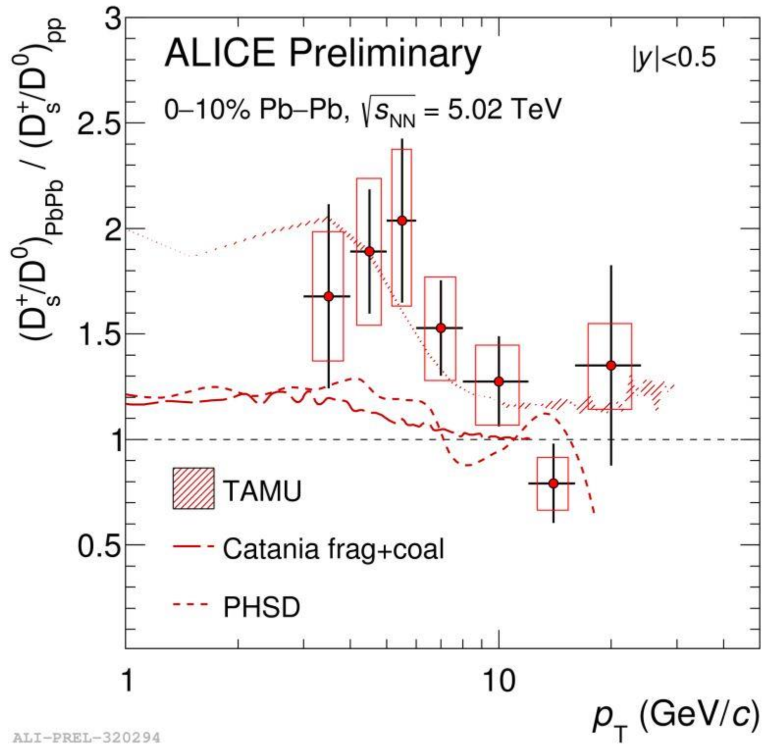


- Positive D-meson v_2 indicates participation of charm quark in the collective motion
- v_2 (D) $\simeq$ v_2 ($\pi^{\pm}$) for p_T > 3-4 GeV/*c* while at p_T < 3-4 GeV/*c* there is hint of v_2 (D) < v_2 ($\pi^{\pm}$)
- v_2 (D) > v_2 (J/Ψ) for p_T < 6 GeV/*c* → explained by charm-quark coalescence with flowing light-flavour quarks described by models JHEP 1809 (2018) 006 , JHEP 07 (2018) 103, JHEP 02 (2019) 012
- Models implementing energy loss (only elastic or elastic + radiative) and hadronization (fragmentation with/without recombination) reproduce the data

Strange to non-strange D meson ratio

D_s^+/D^0 in central (0-10%) and semi-central (30-50%) Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and pp collisions at 5.02 TeV





- Data hints to a higher D_s^+ / D^0 ratio in Pb-Pb than in pp collisions up to p_T = 6 GeV/c
- A similar p_T trend as predicted by theoretical models of charm-quark transport in a hydrodynamically expanding medium

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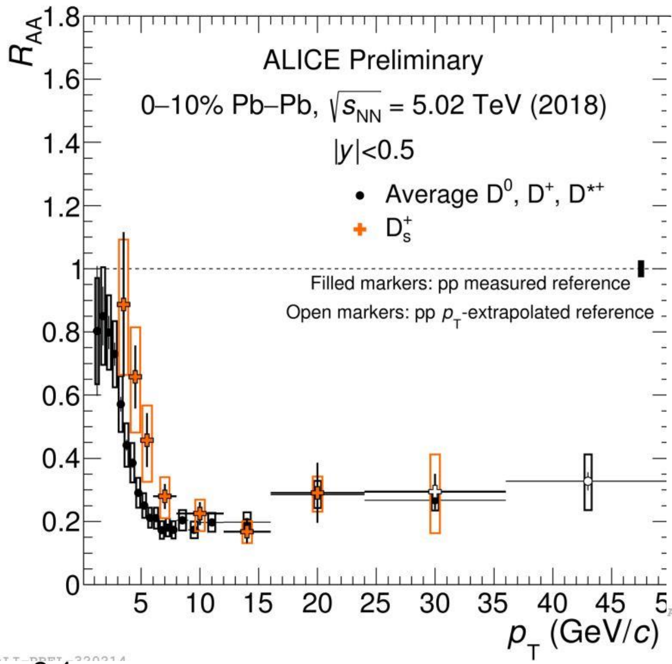
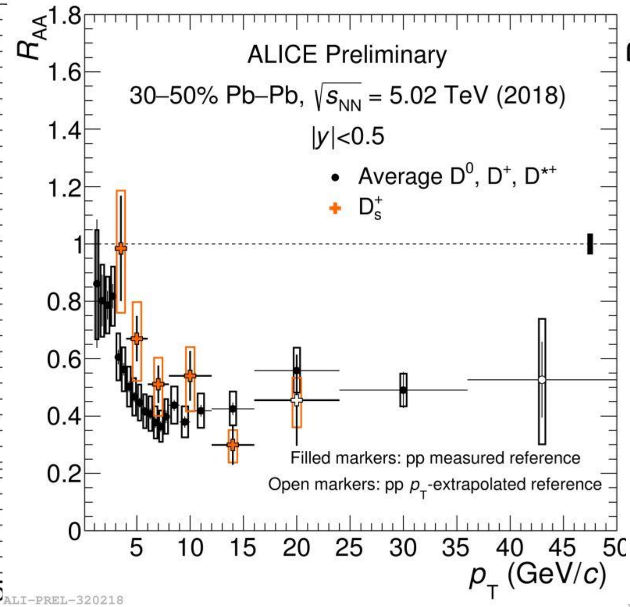
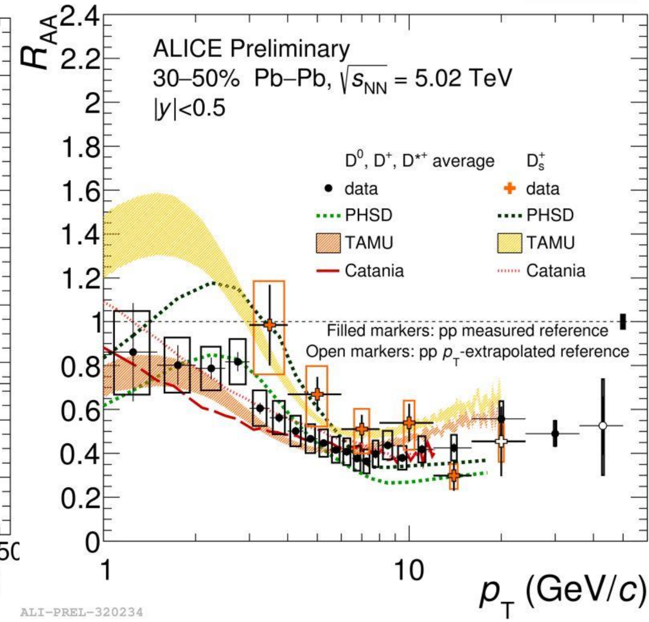
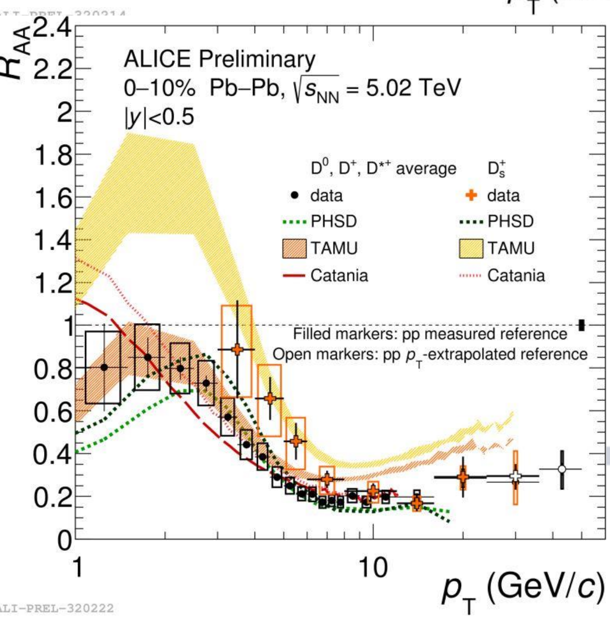
D_s^+ meson R_{AA}







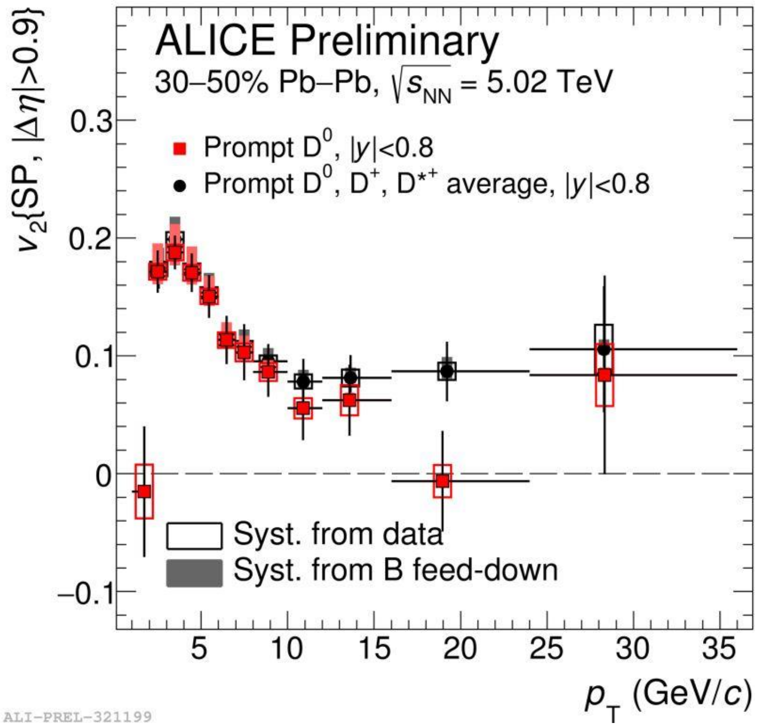


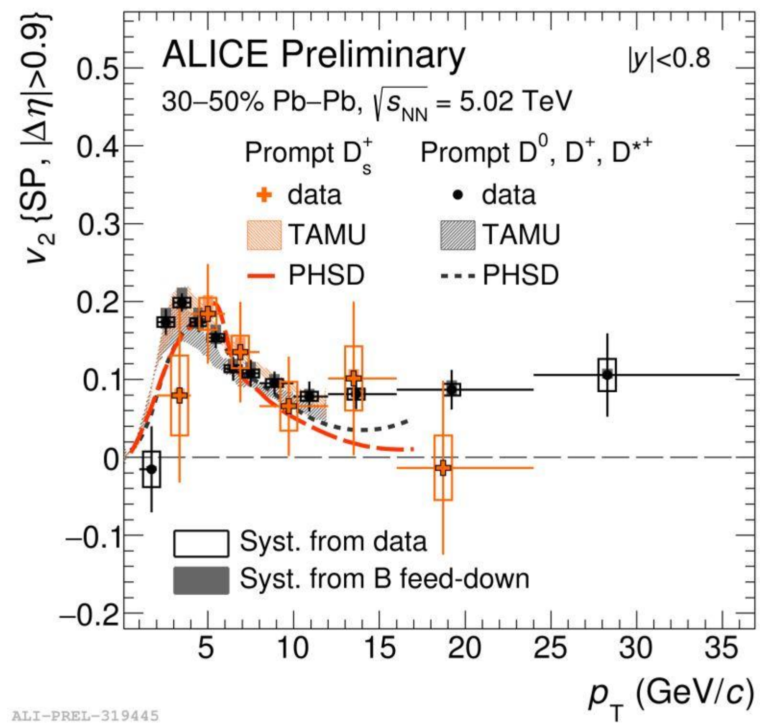
- Strong suppression for the average R_{AA} (D) → strong energy loss of charm
- Less suppression for D_s^+ compared to non-strange D mesons → Coalescence + strangeness enhancement?
- All models can describe the measured R_{AA}, predicting an increase of the D_s^+ especially for $p_T < 5$ GeV/c

Phys. Rev. C 93, 034906 (2016, Phys. Lett. B 735, 445 (2014), Eur. Phys. J. C (2018) 78: 348

D_s^+ meson v_2

- Prompt D_s^+ v_2 as a function of p_T compared the average non-strange D mesons semi-central 30--50% Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Data also compared with models implementing heavy-quark transport in an hydrodynamically expanding medium

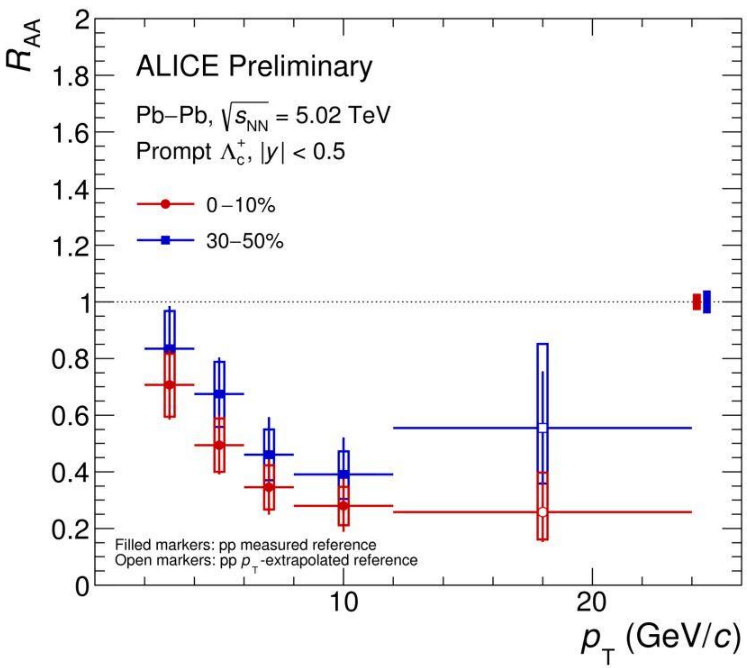




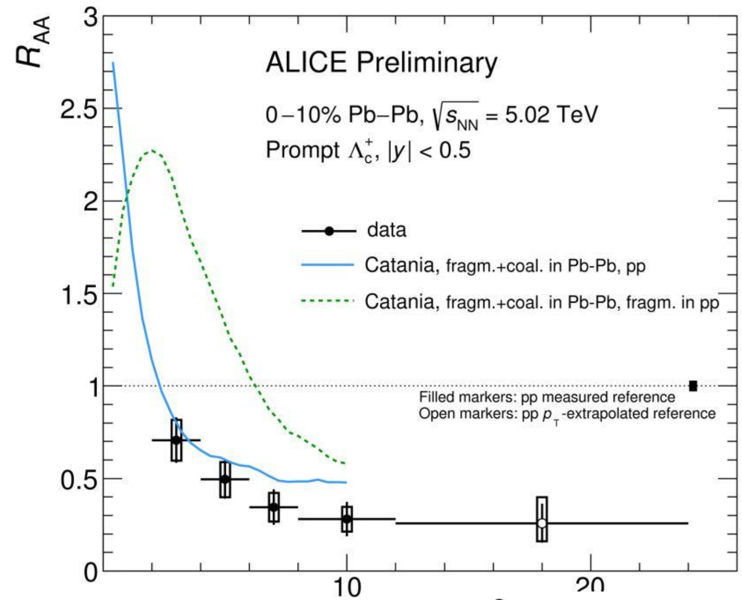
- Similar v_2 for strange and non-strange D mesons down to p_T = 3 GeV/c within the uncertainties
- Both models predict a similar v_2 for strange and non-strange D mesons → hadronization via quark recombination included

Phys. Lett. B 735, 445 (2014), Phys. Rev. C 93, 034906 (2016)

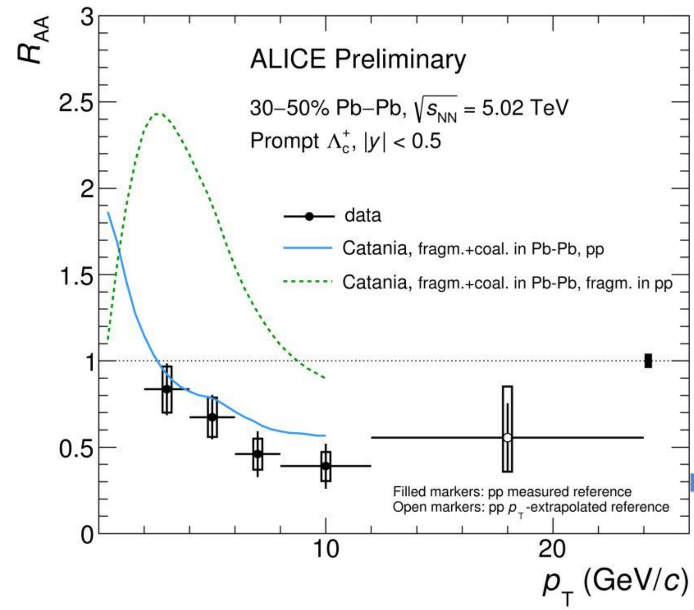
R_{AA} of charmed lambda baryon (Λ_c^+)



ALI-PREL-321861



ALI-PREL-321835



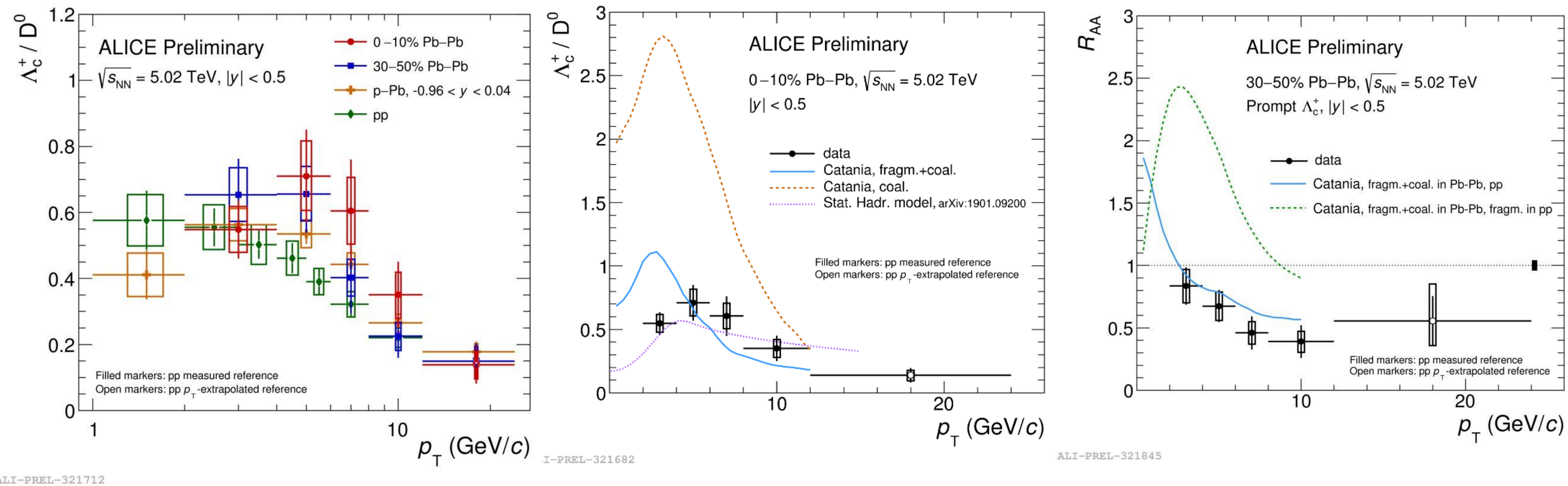
ALI-PREL-321845

- ➢ Hint to smaller R_{AA} for central collisions by factor ~1.5 up to p_T = 12 GeV/c, despite the compatibility within uncertainties,

→ Comparison with theory supports a scenario where both fragmentation and recombination are present in Pb-Pb and pp collisions.

Λ_c^+ to D^0 ratio

- Ratio Λ_c^+/D^0 in Pb-Pb larger (2σ) wrt pp and p-Pb collisions and described by a models including charm hadronization via quark coalescence

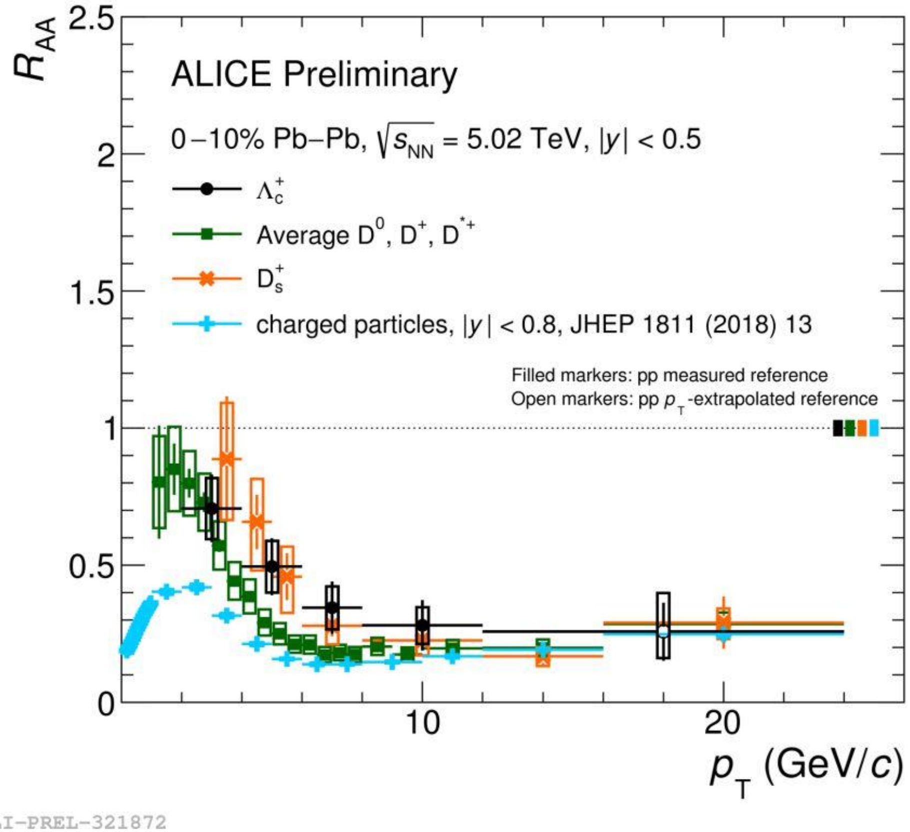


- Hint of higher Λ_c^+ / D^0 ratio in Pb-Pb collisions w.r.t. pp collisions.
- Understanding pp data is essential. Ratio is underestimated by models with fragmentation parameters derived from e^+e^- collision data.
- Λ_c^+ / D^0 ratio described by statistical hadronization model and Catania model including fragmentation and recombination

Eur. Phys. J. C (2018) 78: 348

Comparison of charm meson R_{AA}

- R_{AA} of non-strange, strange D mesons and Λ_c^+ at mid-rapidity, |y|<0.5 in central (0-10%) Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



- Strong suppression for the average R_{AA} of non-strange D mesons is observed

→ strong energy loss of charm

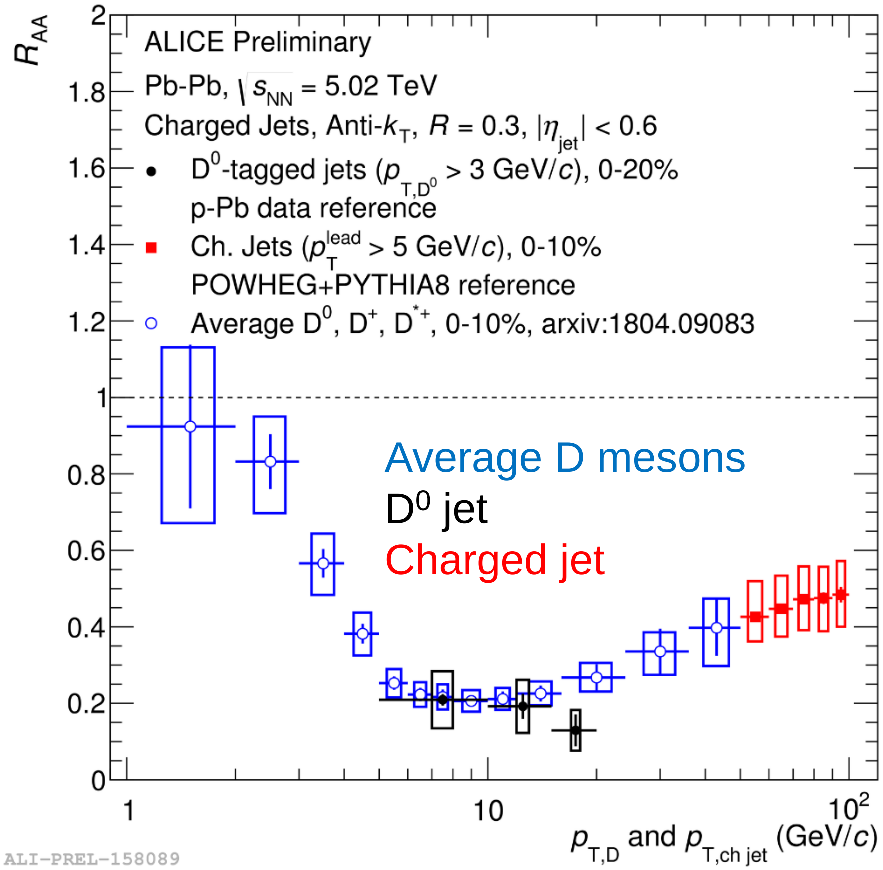
- Less suppression for D_s^+ compared to non-strange D mesons

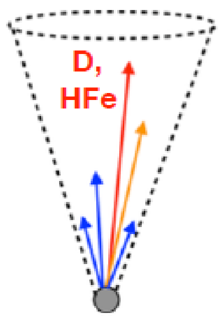
→ Coalescence + strangeness enhancement?

JHEP 1810 (2018) 174, PLB 782 (2018) 474-496

R_{AA} of heavy-flavour jets

- Jet containing a D meson with $p_T > 3$ GeV/c in 0-20% compared with R_{AA} of D mesons and charged jets in 0-10% Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

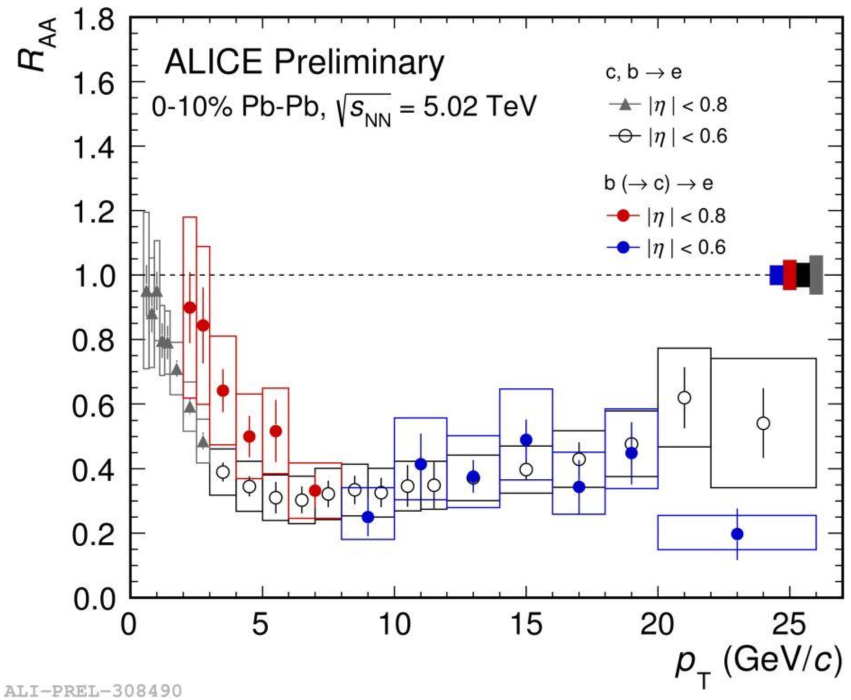


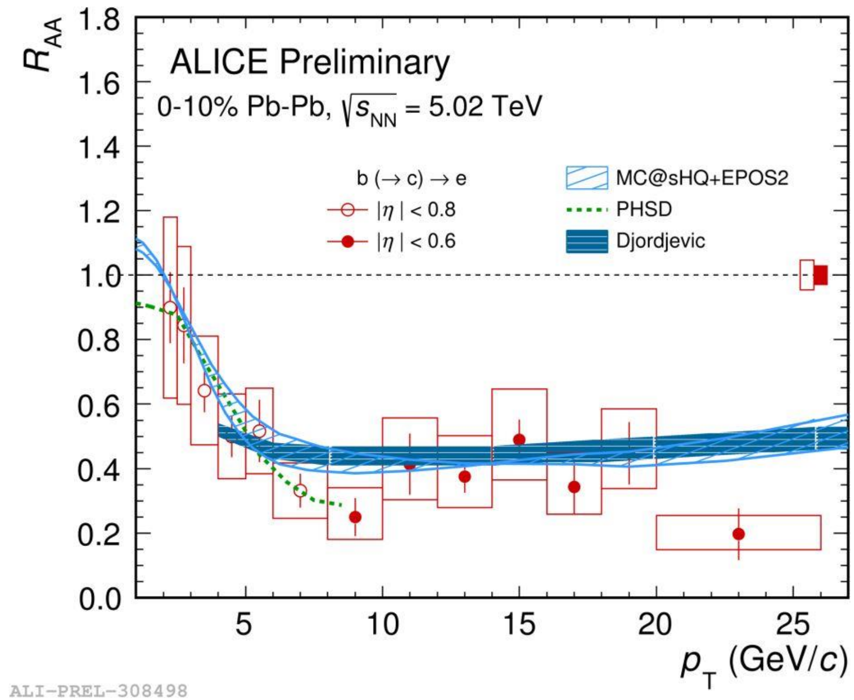


- Strong suppression of D^0 jets for $p_T > 5$ GeV/c
- Similar suppression for D^0 jets and D^0 mesons

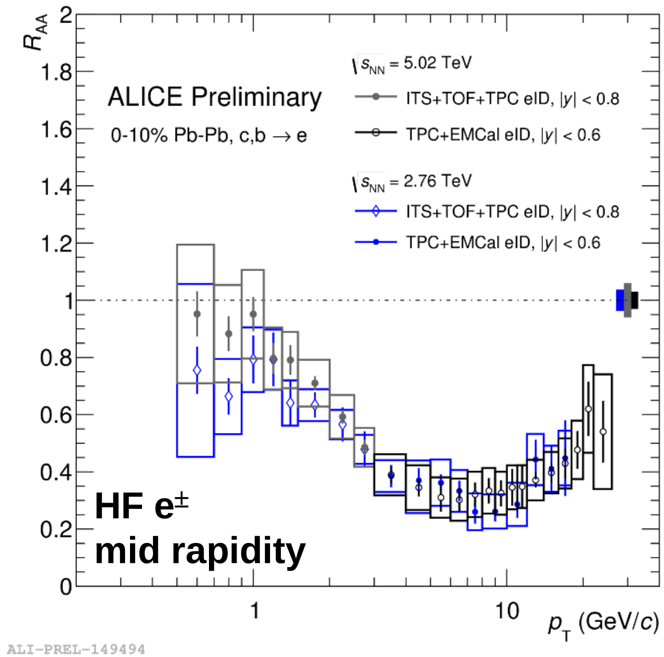
R_{AA} of electrons from beauty-hadron decays

- Indication of a small suppression for $p_T < 6$ GeV/c while a significant suppression observed for $p_T > 6$ GeV/c
- Models implementing mass-dependent energy loss reproduce the experimental data well

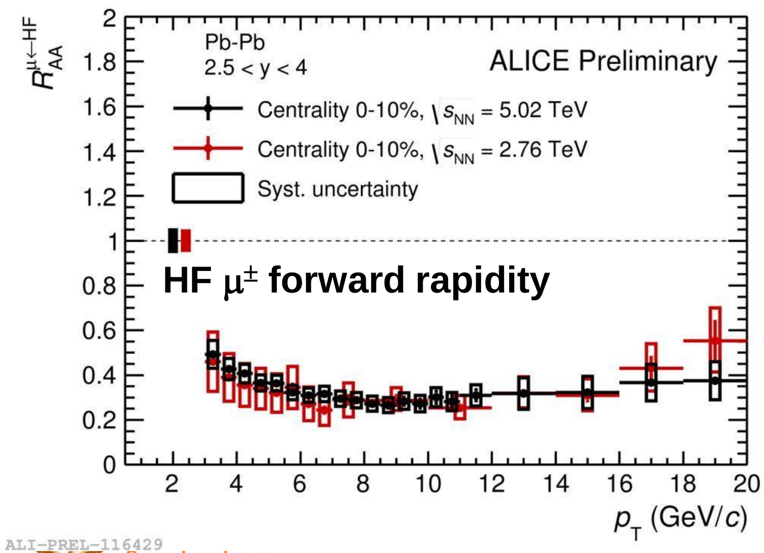


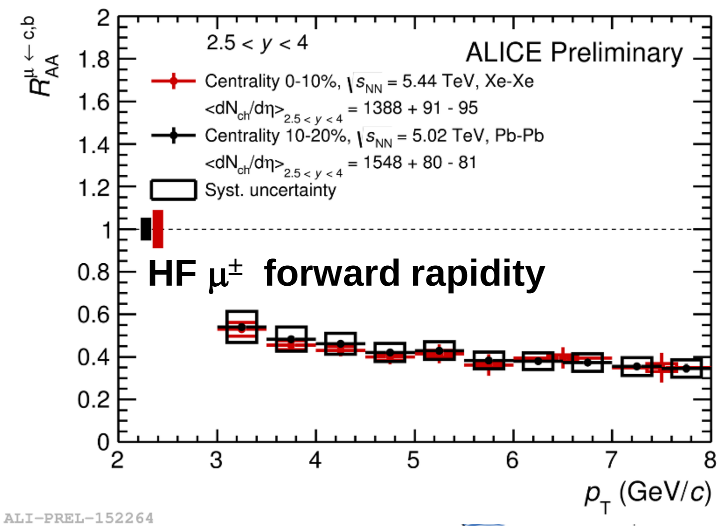


R_{AA} of leptons from heavy-flavour hadron decays



- R_{AA} of HF $e^{\pm}$ at mid-rapidity and $\mu^{\pm}$ at forward rapidity in 0-10% Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 & 5.02 TeV
  - ✓ Comparable suppression at mid and forward rapidity within systematic uncertainty
  - ✓ No dependence on system collisional energy
- Comparison of HF$\mu^{\pm}$ R_{AA} in Pb-Pb (5.02 TeV) and Xe-Xe (5.44 TeV) shows a similar suppression for both systems at same multiplicity
  → possible interplay of geometry and path-length dependence M. Djordjevic, et al., arXiv:1805.04030

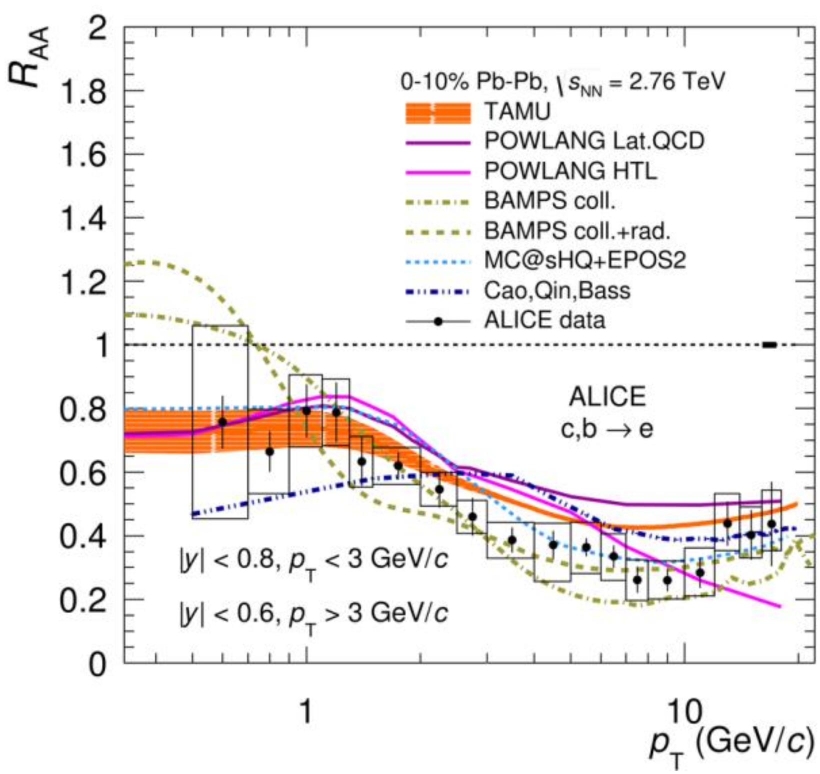


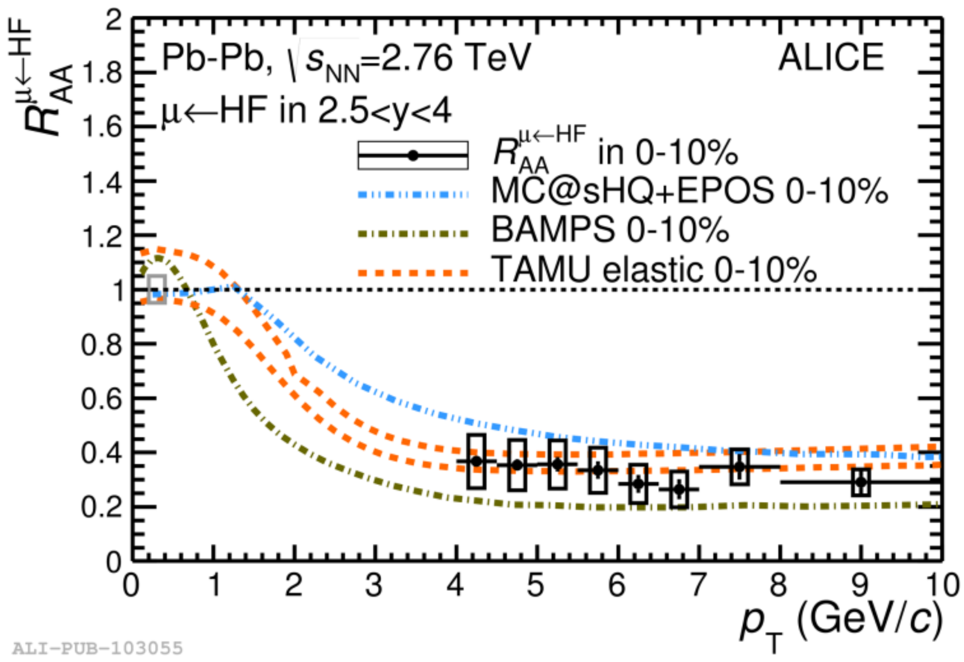


R_{AA} of leptons from heavy-flavour hadron decays: comparison with models

ALICE

- ➢ Models implementing mass-dependent energy loss reproduce the data

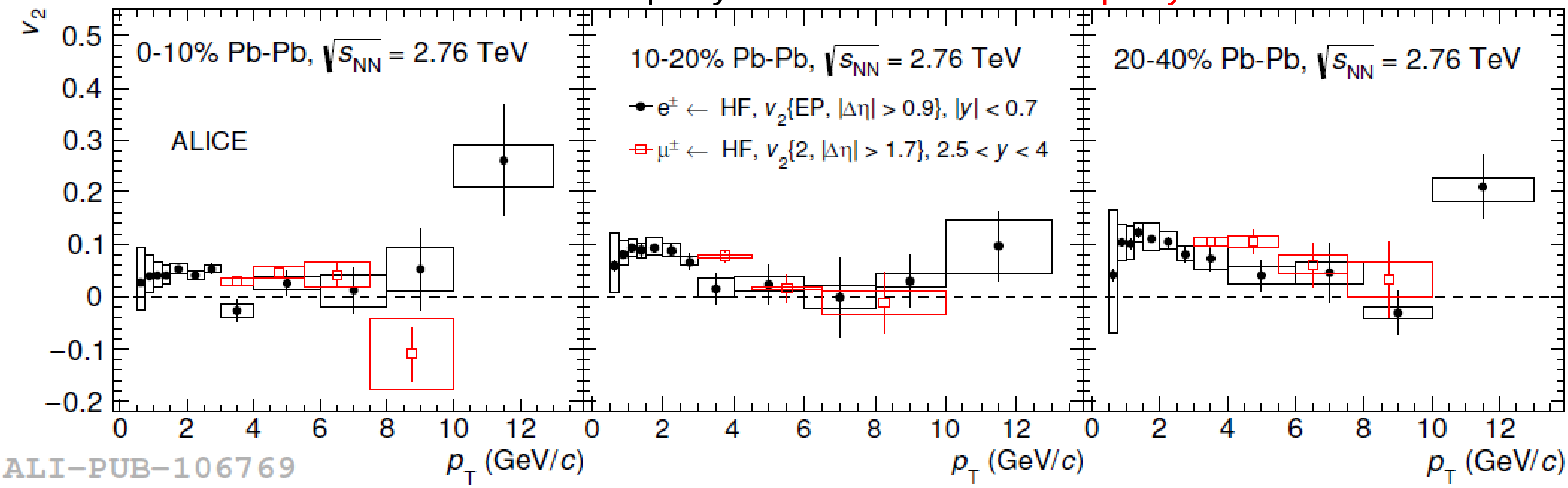




v_2 of leptons from heavy-flavour hadron decays

- Positive elliptic flow measured for leptons from heavy-flavor hadron decays
- Compatible results at mid and forward rapidity
  - → suggests that heavy quarks could participate in the collective expansion of the system

electrons: central rapidity muons: forward rapidity



Most central collisions mid central collisions

JHEP 1609, 028 (2016), Phys. Lett B 753, 41 (2016)

Summary

ALICE

- Strong suppression of heavy-flavour hadron production → qualitatively described by several models with different implementation of the heavy-quark energy loss
- Charmed-baryon, Λ_c^+ less suppressed than D mesons → coalescence production mechanisms at play
- Non-zero elliptic flow of charmed mesons, and for leptons from heavy-flavour hadron decays

→ heavy quark participation in the collective expansion of the QGP

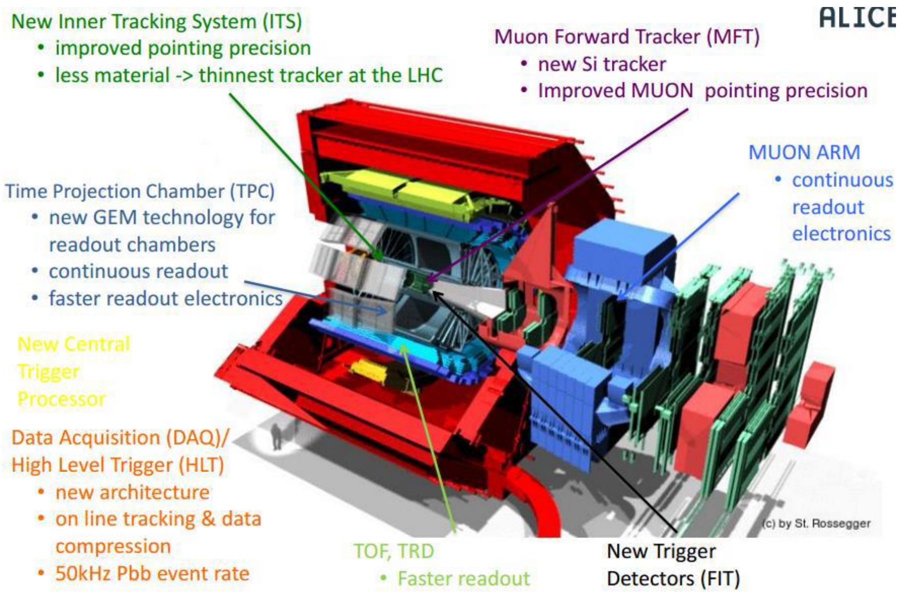
- Ongoing analysis of Pb-Pb (Xe-Xe) data collected in 2018 (2017) will provide precise and could help constrain the differences seen in model predictions

- **What is next?**

ALICE upgrade ongoing to prepare for the next LHC phase 3 (2021). Higher data rates are expected for precision measurements

Lot of interesting physics to come

Stay tuned!!



Thanks for your attention

EXTRA slides

Radiative energy loss

ALICE

- Gluon radiation expected t be the main mechanism of energy loss, where the amount of energy lost is sensitive to
  - ✓ The medium properties (density)
  - ✓ The path length (L) of the parton in deconned matter
  - ✓ The properties of the parton probing the medium
- Several models available, e.g. **BDMPS approach**

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

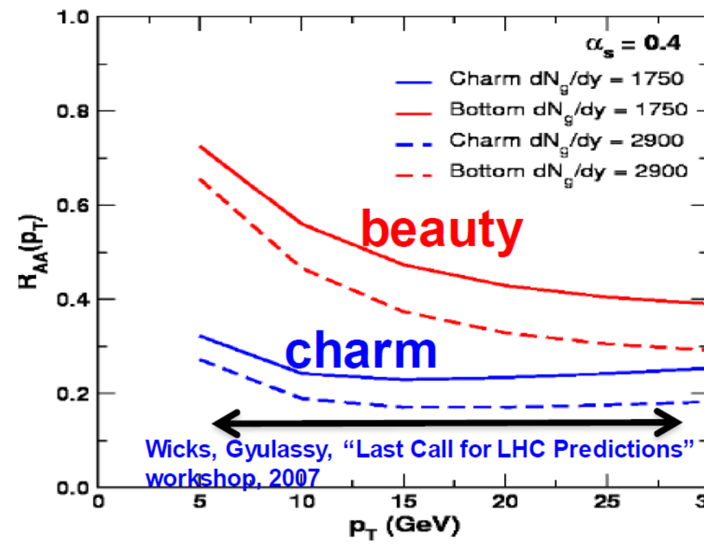
α_s - strong coupling constant, C_R – Casmir factor: 3 for gg fus and 4/3 for quark-gluon fusion, $\hat{q}$ - transport coefficient related the medium properties & gluon density

$$\Delta E_{quark} < \Delta E_{gluon}$$

$$\Delta E_{massive\ quark} < \Delta E_{light\ quark}$$

$$\Downarrow$$

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



- Radiative energy loss of charm + beauty quarks expected to be smaller (higher R_{AA}) wrt light hadrons due to
- **Dead cone effect:** gluon radiation is suppressed for angles $\theta < M_Q / E_Q$
- **Casmir factor** (colour charge dependence): heavy hadrons are mainly produced from heavy quark jets (while light hadrons are produced from gluon jets)

Quarkonia as QCD thermometer?

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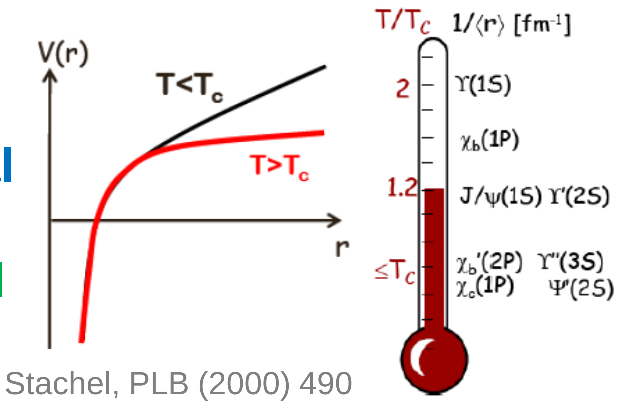
- **Quarkonia (J/ψ, Υ,...) probe the QGP temperature**
- Pre-resonant QQbar states "melt in the QGP (Debye screening) Matsui & Satz, PLB 168 (1986) 415)
- Different states melt at different temperatures (**sequential suppression)**
- Non-correlated quarks can recombine (**kinetic/statistical regeneration)**

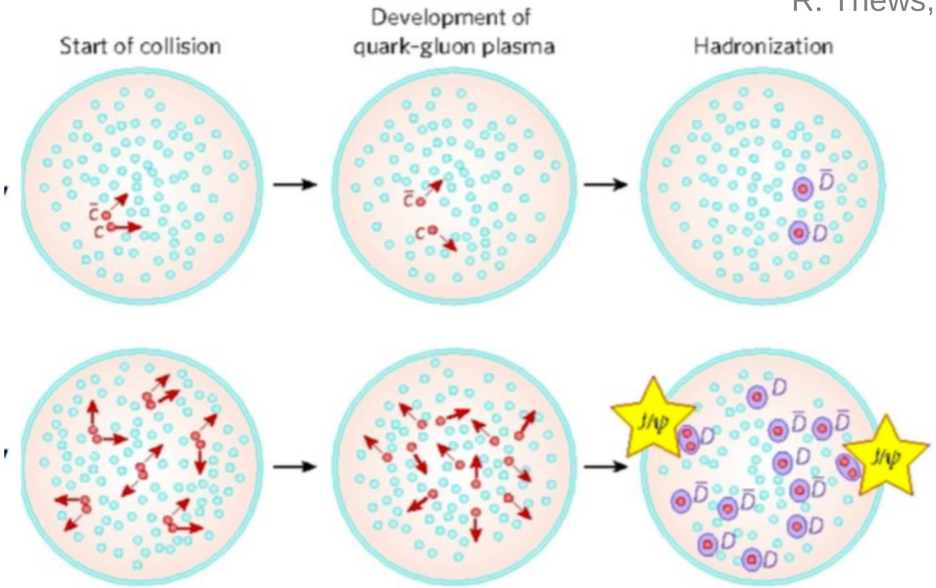


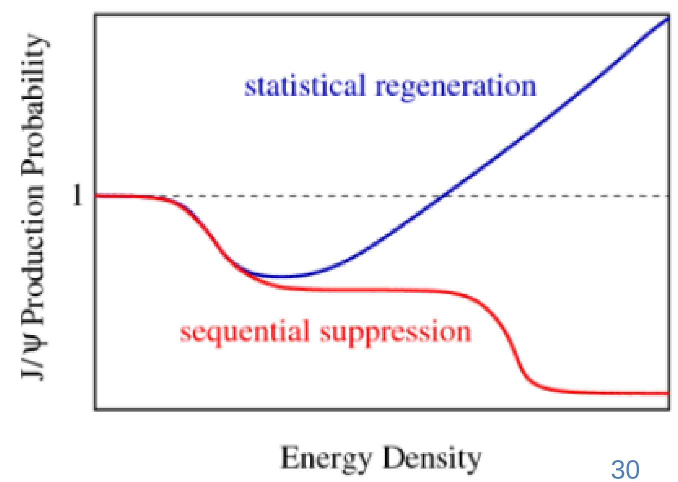
P. Braun-Muzinger, J Stachel, PLB (2000) 490
R. Thews, et al, PRC (2001) 054905

Pictures: A. Moczy, H. Satz

RHIC

LHC

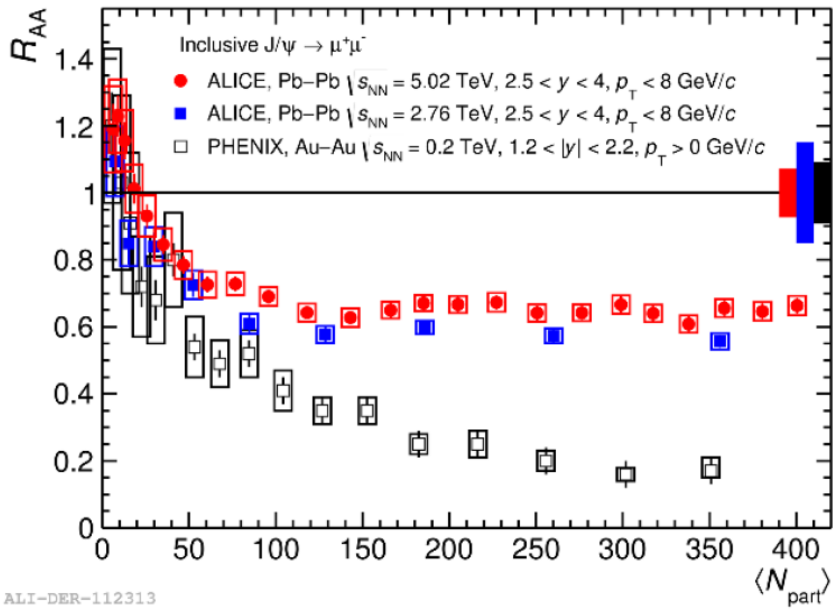




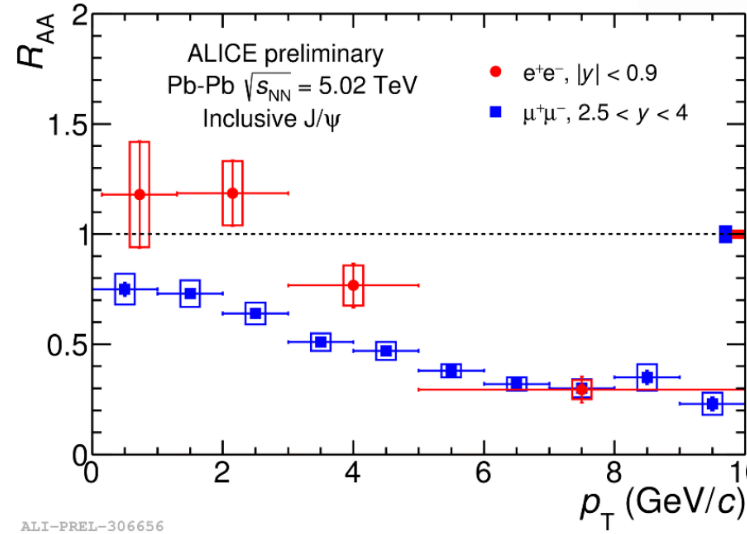
J/ψ suppression and regeneration

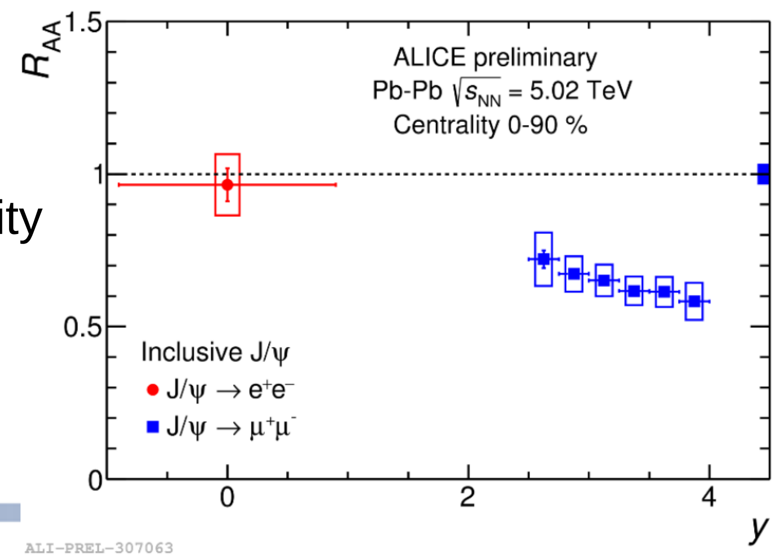
ALICE

- Results at 5.02 TeV with improved pp reference



PLB 766 (2017 212





- Large suppression of J/ψ at RHIC than LHC
- Less suppression at mid-rapidity wrt forward rapidity

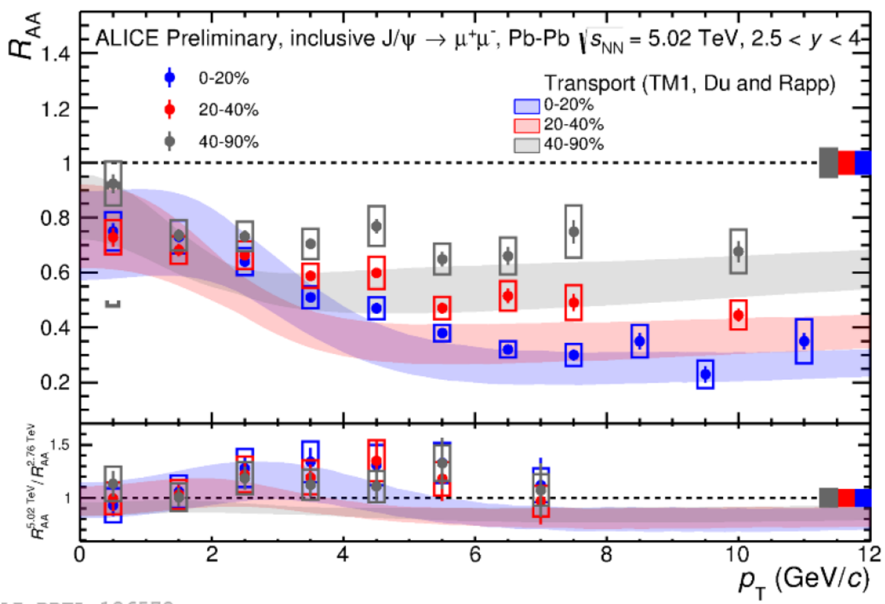
→ clear sign of charm-quark recombination → regenerated J/ψ's concentrated at low p_T

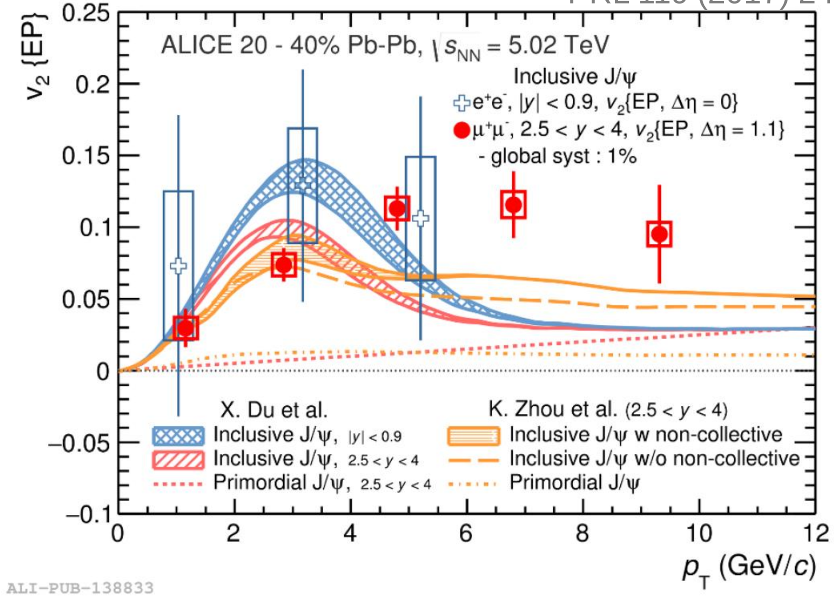
→ **Measurements support the regeneration hypothesis**

J/ψ regeneration

- The regeneration component is expected to contribute mainly at low p_T
- R_{AA} increase at $2 < p_T < 6$ GeV/c from $\sqrt{s_{NN}}$ = 2.76 to 5.02 TeV
- Transport models fairly reproduce the trend as a function of p_T and centrality

PRL 119 (2017) 242301





- Elliptic flow, v2, is non-zero in semicentral collisions → regenerated J/ψ inherit charm-quark flow in the QGP
- Described by models including a strong regeneration component from recombination of thermalized quarks in the QGP

Caveat: precise description of the data is a challenge for models especially at high p_T

Heavy flavour-tagged jets

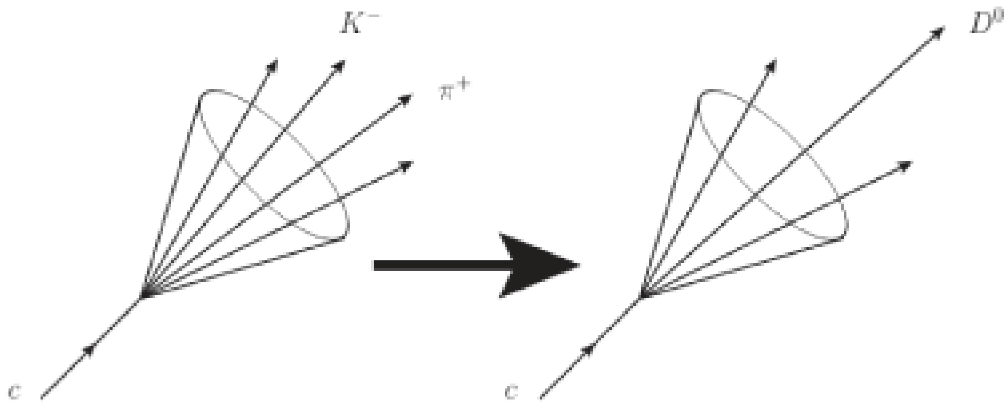
D0 meson selection:

- Decay channel: $D^0 \rightarrow K^- \pi^+$ (BR = 3.89%) [PDG PRD 98 (2018) 030001]
- K/π PID via d*E*/dx of TPC and TOF
- Topological selection (secondary vertex)
- $p_{T, D} > 2$ GeV/c

- D0 - meson candidates replace their decay products (K and π) in the jet reconstruction

Jet finding:

- Track-based jet reconstruction
- Anti-k_T , R= 0.3, 0.4
- $p_{T, ch\ jet} > 5$ GeV/c



Kinematic variables

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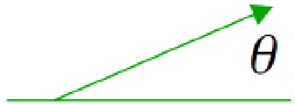
Rapidity: $$y = \frac{1}{2}\ln\left(\frac{E+P_Z}{E-P_Z}\right)$$ dimensionless

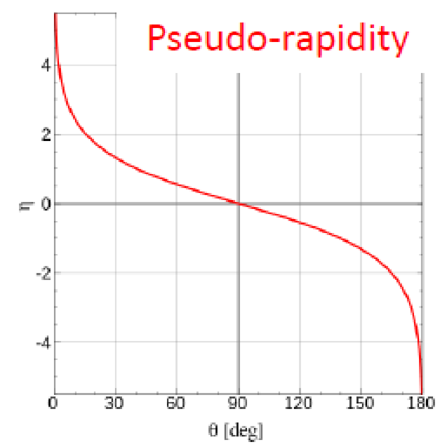
Pseudo-Rapidity: $$\eta = \frac{1}{2}\ln\left(\frac{|P|+P_Z}{|P|-P_Z}\right) = -\ln\left(\tan\frac{\theta}{2}\right)$$



$\eta \to y$ large momentum i.e. $P \to E$

Transverse Momentum: $$p_T = \sqrt{p_X^2 + p_Y^2}$$

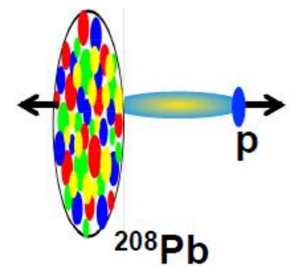
Transverse Mass: $$m_T = \sqrt{p_T^2 + m_0^2}$$



Heavy quark production in proton-nucleus (p-A) collisions

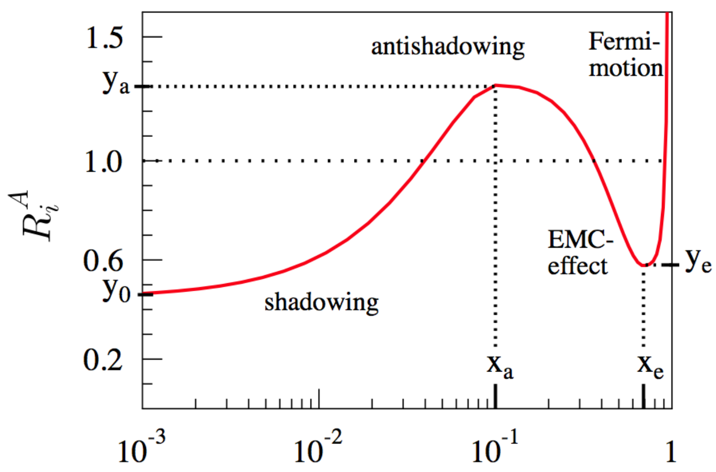
ALICE

Role of p-A collisions – control experiment



- ➢ Disentangle the cold nuclear matter effects (CNM) in initial and final states of the collision
- CNM effects:
  - Nuclear modification of parton distribution functions (shadowing, gluon saturation)
  - k_T broadening (due to multiple parton collisions befo hard scattering)
  - Energy loss in CNM
  - Multiple binary collisions
- ➢ Other final state effects?
  - Collective effects in high-multiplicity p-Pb events similar to those observed in A-A
  - Small-size QGP in p-Pb collisions?
- ➢ CNM effects may give $R_{AA} \neq 1$
- ➢ Reference for AA collisions

Eskola et al., JHEP 0904, 065 (2009)



$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}^2\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$