Beauty production measurements in pp, p–Pb and Pb–Pb collisions with the ALICE detector

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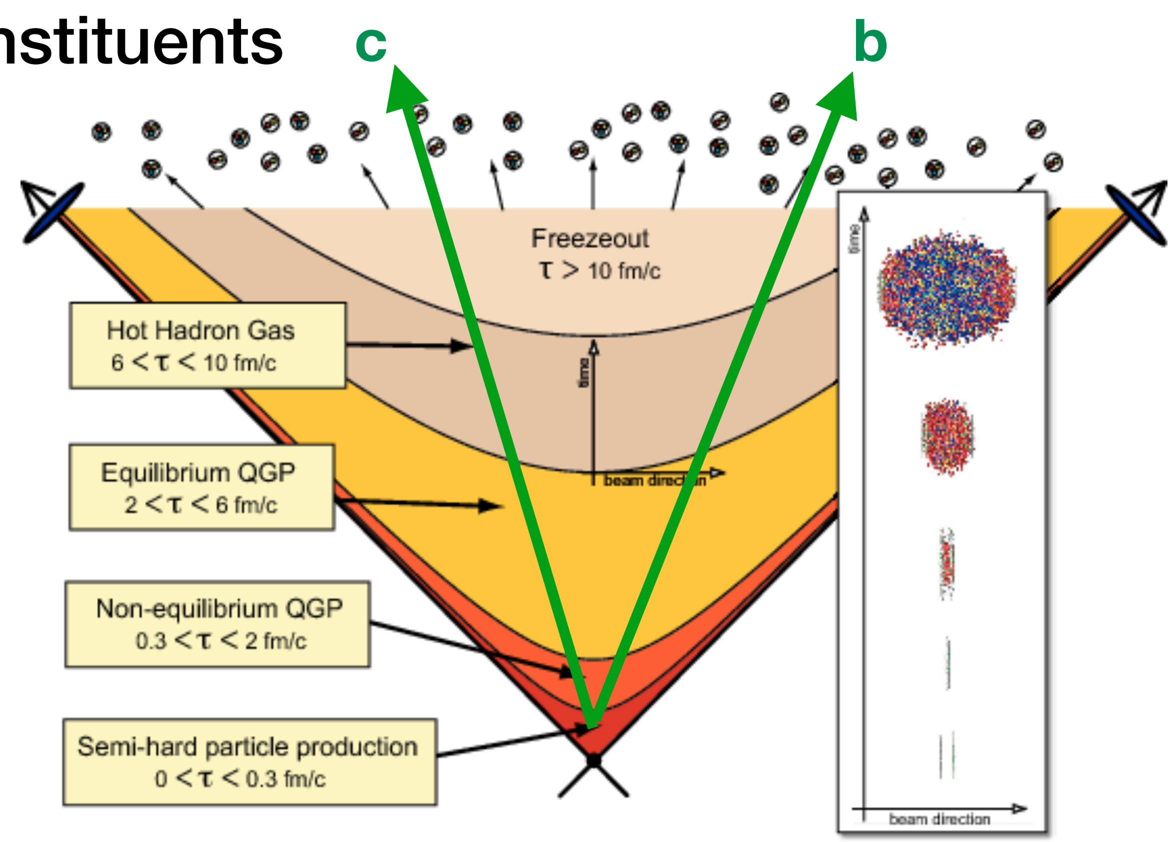
Heavy quarks in heavy-ion collisions

- **Heavy-ion (HI) collisions at the LHC energies**
  - Quark-Gluon Plasma (QGP) phase expected (lifetime ~ O(10 fm/c))
- **Heavy quarks**
  - Large masses ($m_q \gg \Lambda_{QCD}$) → produced in the early stages of the HI collision with short formation time (t_{charm} ~ $1/m_c$ ~ 0.1 fm/c << τ_{QGP} ~ O(10 fm/c)), traverse the medium interacting with its constituents
    - ➡ **natural probe of the hot and dense medium created in HI collisions**
  - Interactions with QGP don't change flavour identity
  - Uniqueness of heavy quarks: cannot be destroyed/created in the medium
    - ➡ **transported through the full system evolution**



arXiv:1410.5786

Heavy-flavour physics program in pp, p-Pb, Pb-Pb collisions

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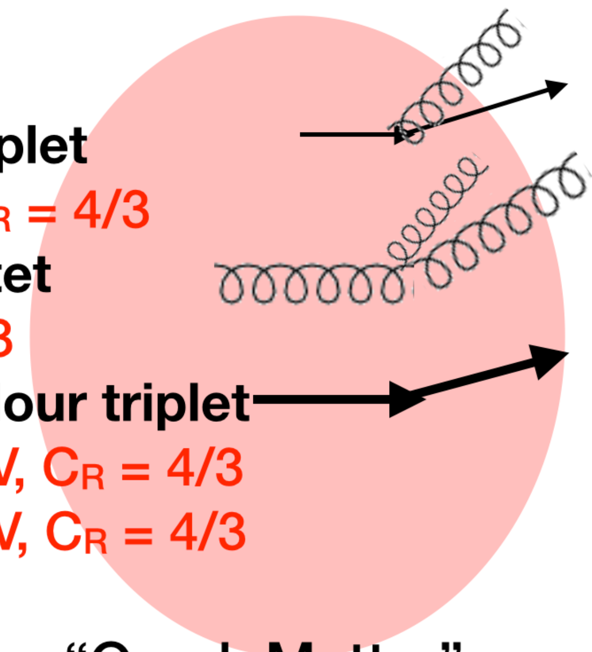
- **Pb-Pb collisions**
  - **Study the interaction of heavy quarks with the medium via parton energy loss (radiative vs collisional) which depends on :**
    - color charge
    - parton mass
    - path length in the medium
    - medium density and temperature
    - ➡ **expect: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$**
  - **Collectivity in the medium**

quarks : colour triplet
u,d,s : m~0, $C_R = 4/3$
gluons: colour octet
g : m=0, $C_R = 3$
heavy quarks : colour triplet
c : m ~ 1.5 GeV, $C_R = 4/3$
b : m ~ 4.5 GeV, $C_R = 4/3$



"Quark Matter"

- **pp collisions**
  - **Reference for p-Pb and Pb-Pb collisions**
  - **Test heavy-quark production mechanisms**

- **p-Pb collisions**
  - **Control experiment for the Pb-Pb measurements**
  - **Address cold nuclear matter effects**
    - nuclear modification of parton distribution functions, k_T broadening, energy loss in cold nuclear matter,…

shadowing: K.J. Eskola et al., JHEP 0904 (2009) 65 , gluon saturation, Color Glass Condensate: H. Fuji & K. Watanabe, NPA 915(2013) 1

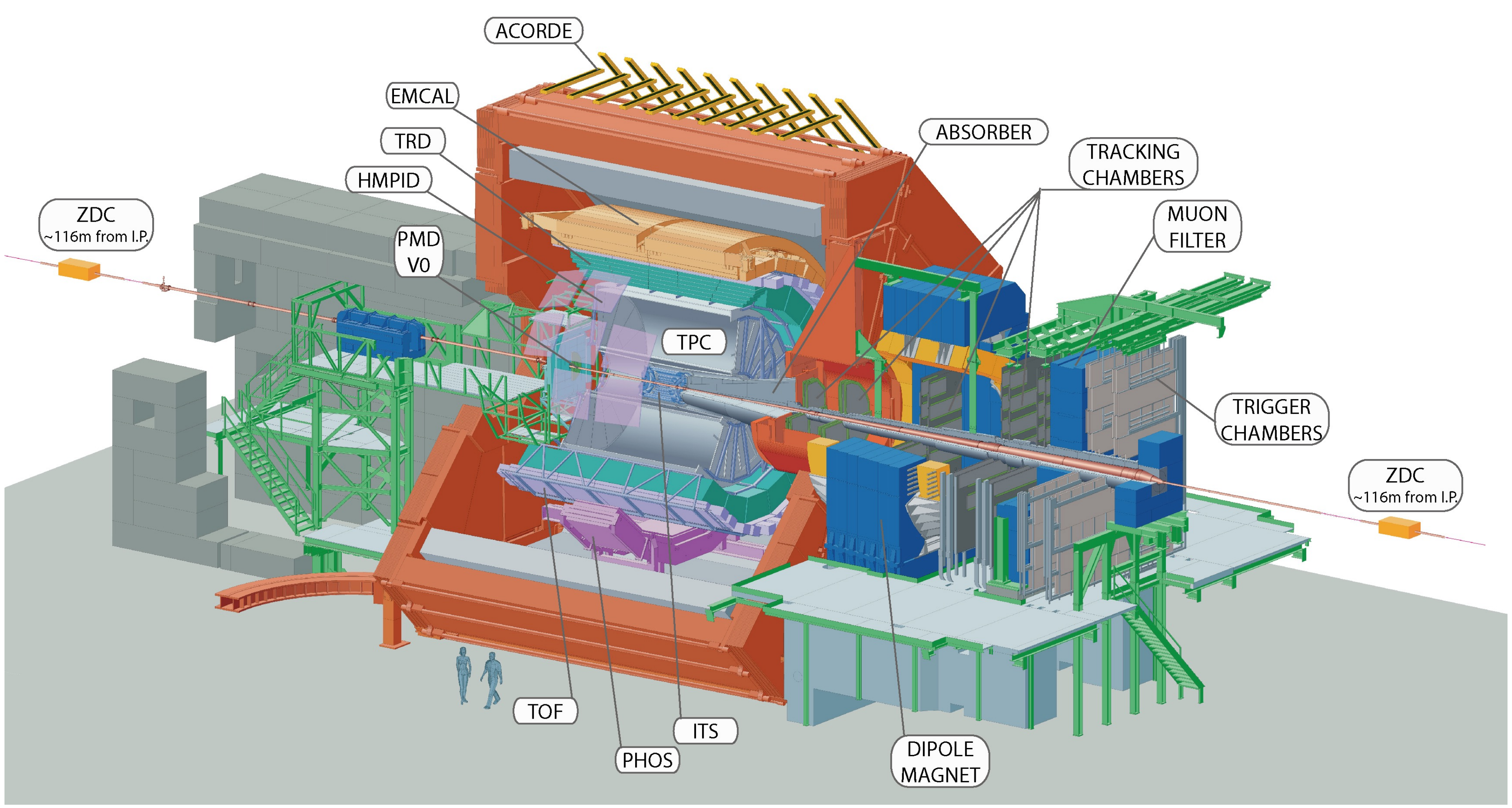
I. Vitev at al., PRC 75 (2007) 064906

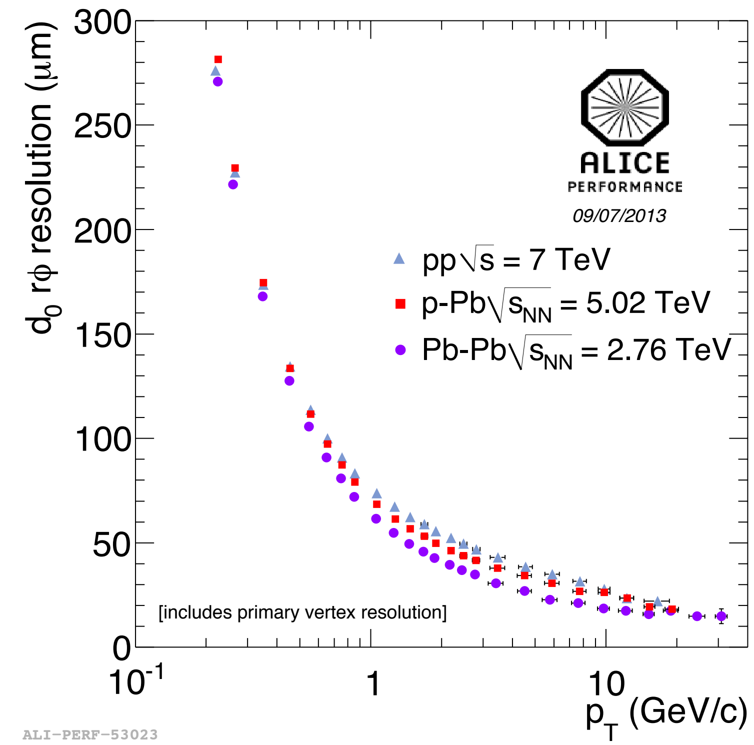
Beauty production measurements with ALICE

- **Measurement of b-quark production via :**
  - electrons from semi-leptonic decays of beauty hadrons
  - J/ψ from weak decays of beauty hadrons (non-prompt J/ψ) through e^+e^- decay channel

  ➡ exploit long lifetime ($c\tau$ ~ 500μm) of B hadrons

  ➡ Excellent vertex and impact parameter resolution of ITS and eID capability in ALICE





➡ **ITS (inner tracking system) : tracking & vertexing**

➡ **TPC : tracking & PID**

➡ **EMCAL, TRD, TOF : PID**

➡ **V0 : centrality determination**

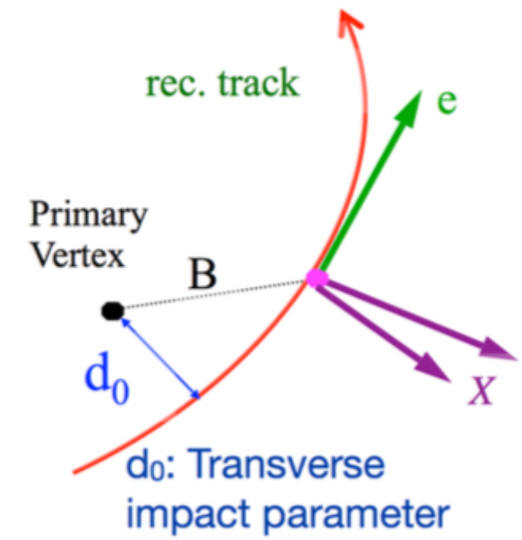
Experimental results

Measurement of beauty-decay electrons

- **Electrons from semi-leptonic decays of beauty hadrons :**

  $b \rightarrow e + X$ (~11%), $b \rightarrow c \rightarrow e + X$ (~10%)

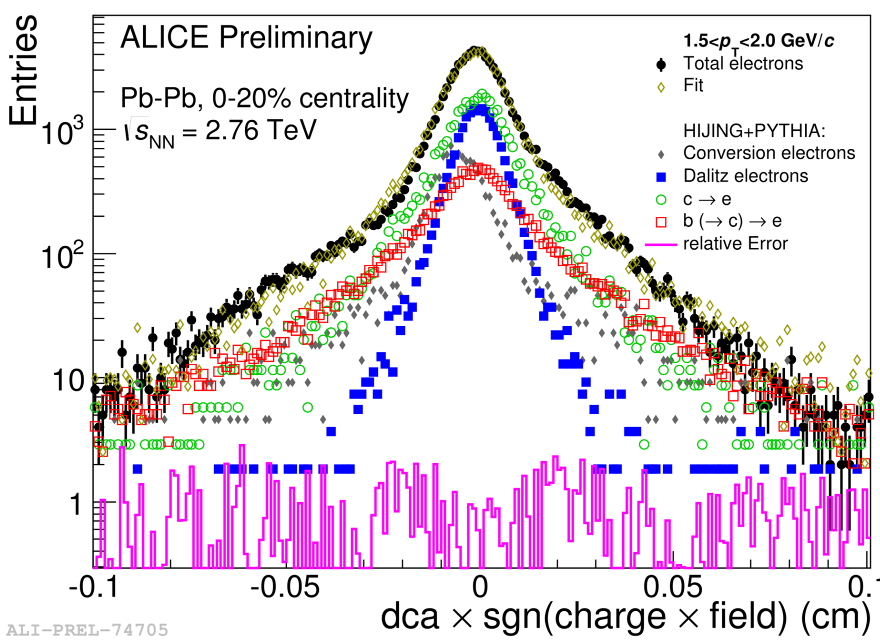
  Long lifetime of B hadrons (cτ ~ 500μm) leads to larger impact parameter of electrons coming from B hadrons

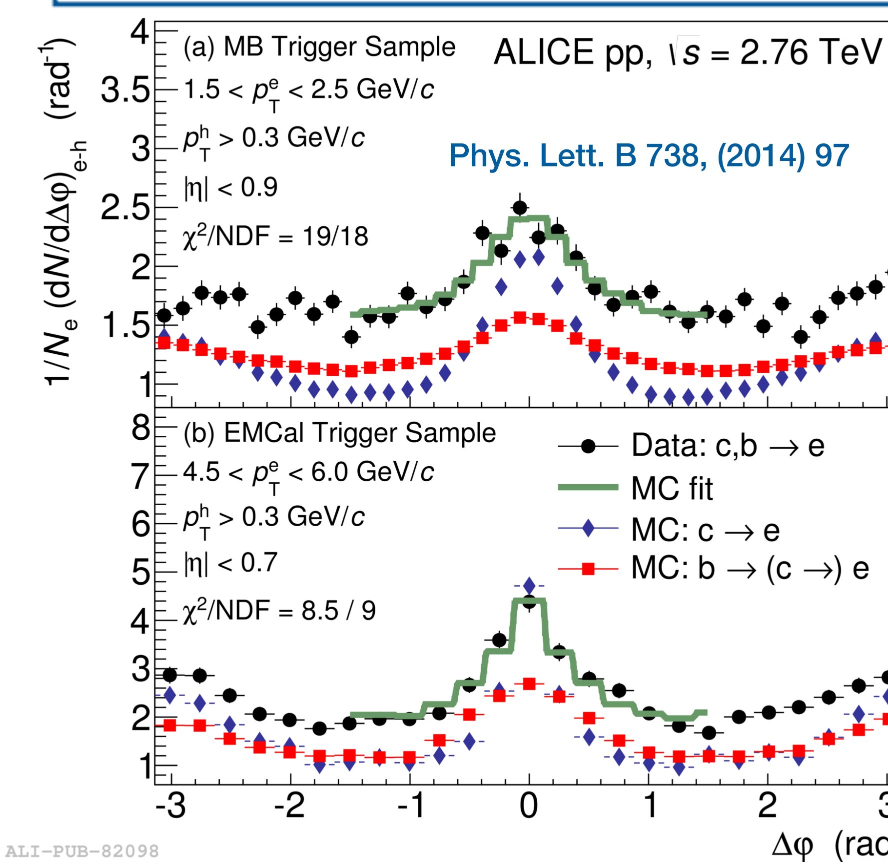


Impact parameter :

Track's transverse distance closest approach to the primary vertex

- **Analysis strategies :**
  - **applying minimum impact parameter cut** and subtracting remaining background based on measured light-meson and D-meson spectra
  - **fit templates of impact parameter distributions** of signal and background contributions





- Exploit different decay kinematics of D and B hadrons → The width of near-side correlation distribution is larger for B hadrons compared to D hadrons

p_T-differential cross sections of b→e in pp collisions

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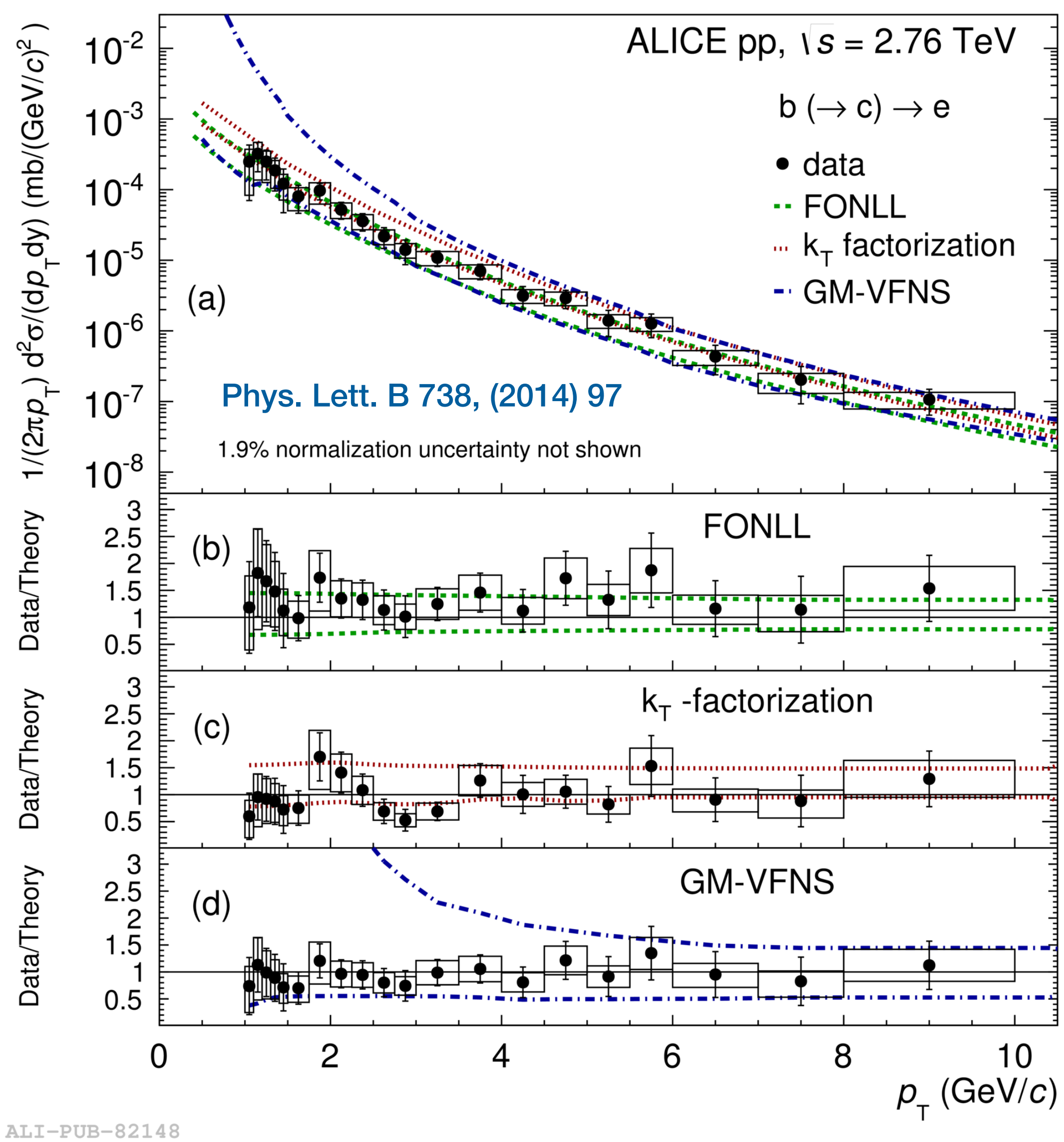
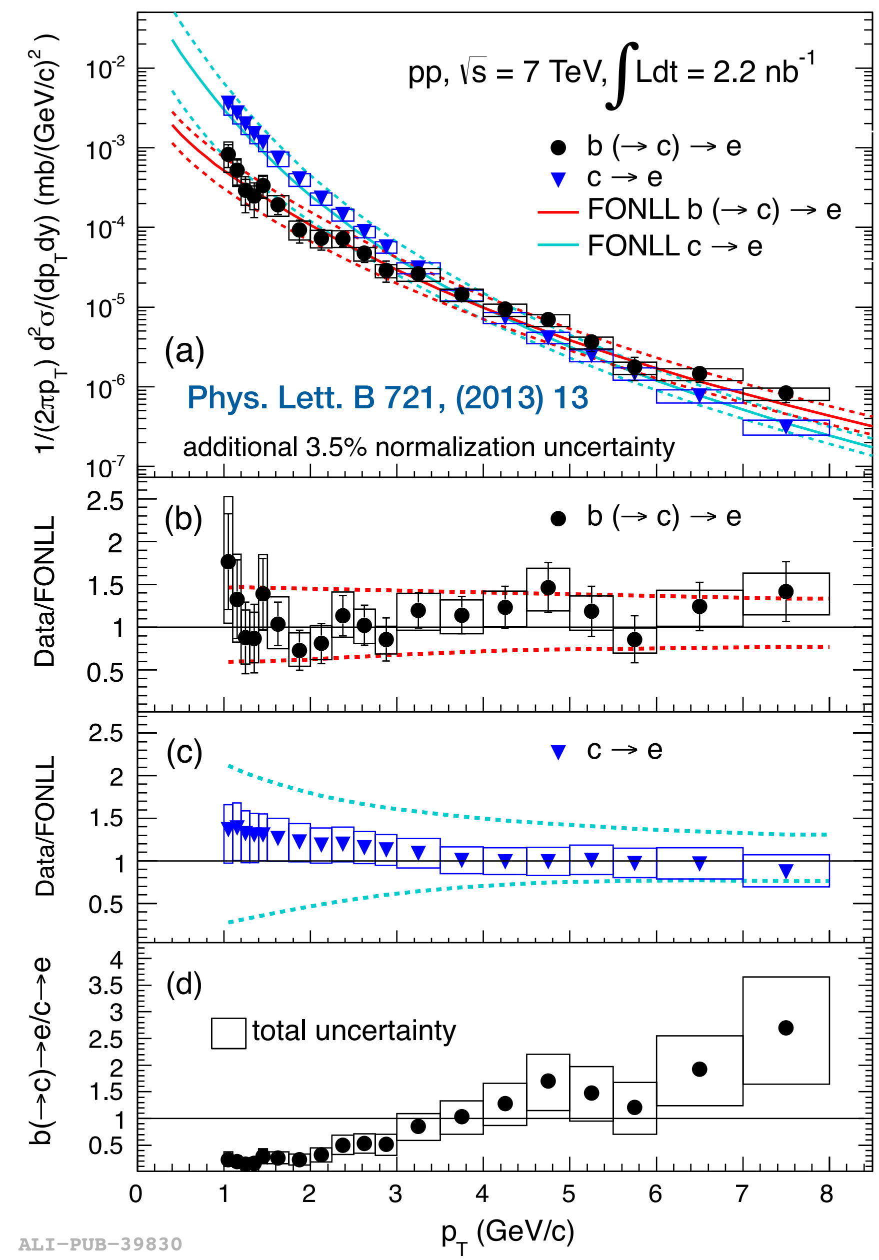
pp, $\sqrt{s}$= 2.76 TeV



pp, $\sqrt{s}$= 7 TeV



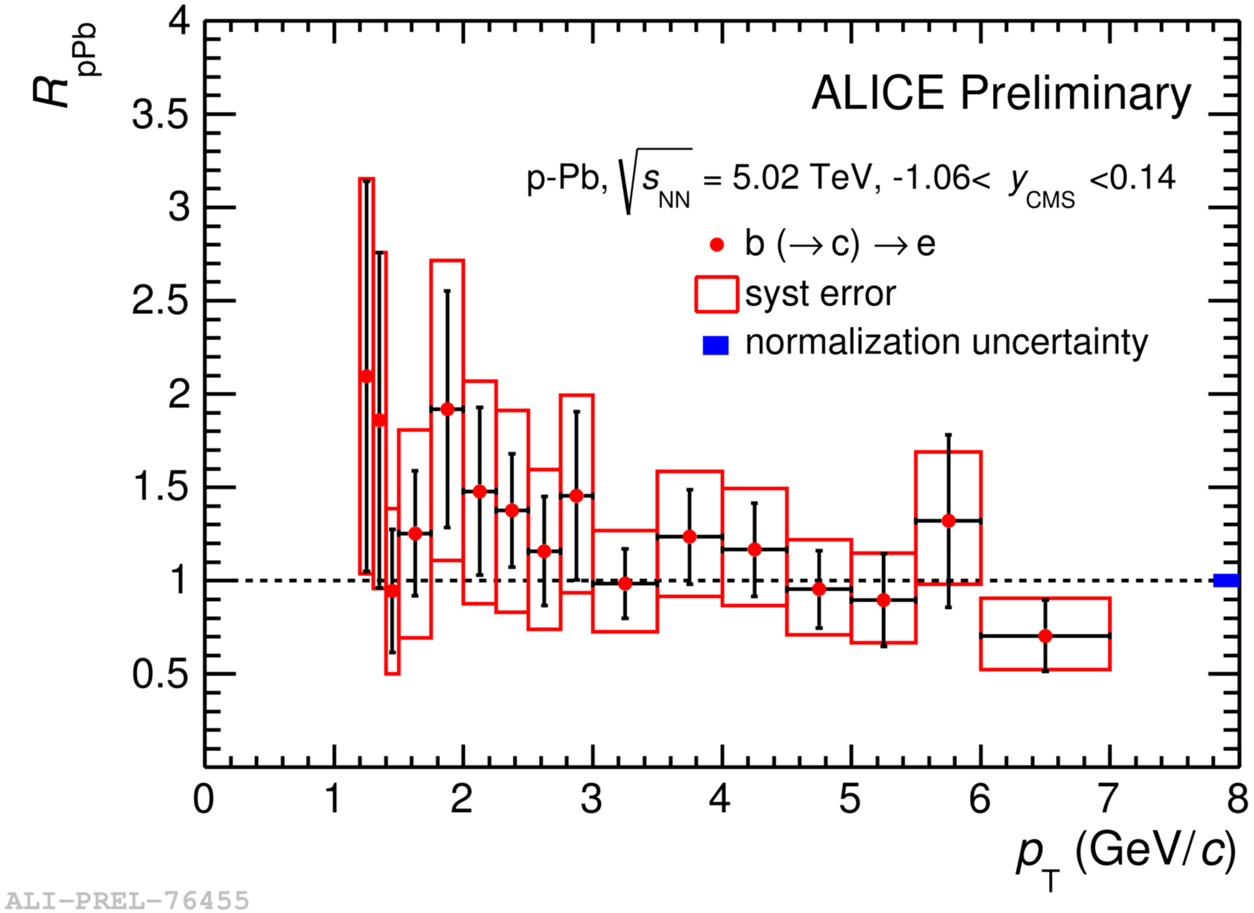
- Beauty-decay electron cross sections reproduced by pQCD-based calculations (FONLL, GM-VFNS, k_T - factorization)

FONLL : JHEP 1210 (2012) 137, k_T-factorization : Phys.Rev. D87 no. 9, (2013) 094022, GM-VFNS : Nucl.Phys. B872 (2013) 253

Nuclear modification factors of b→e

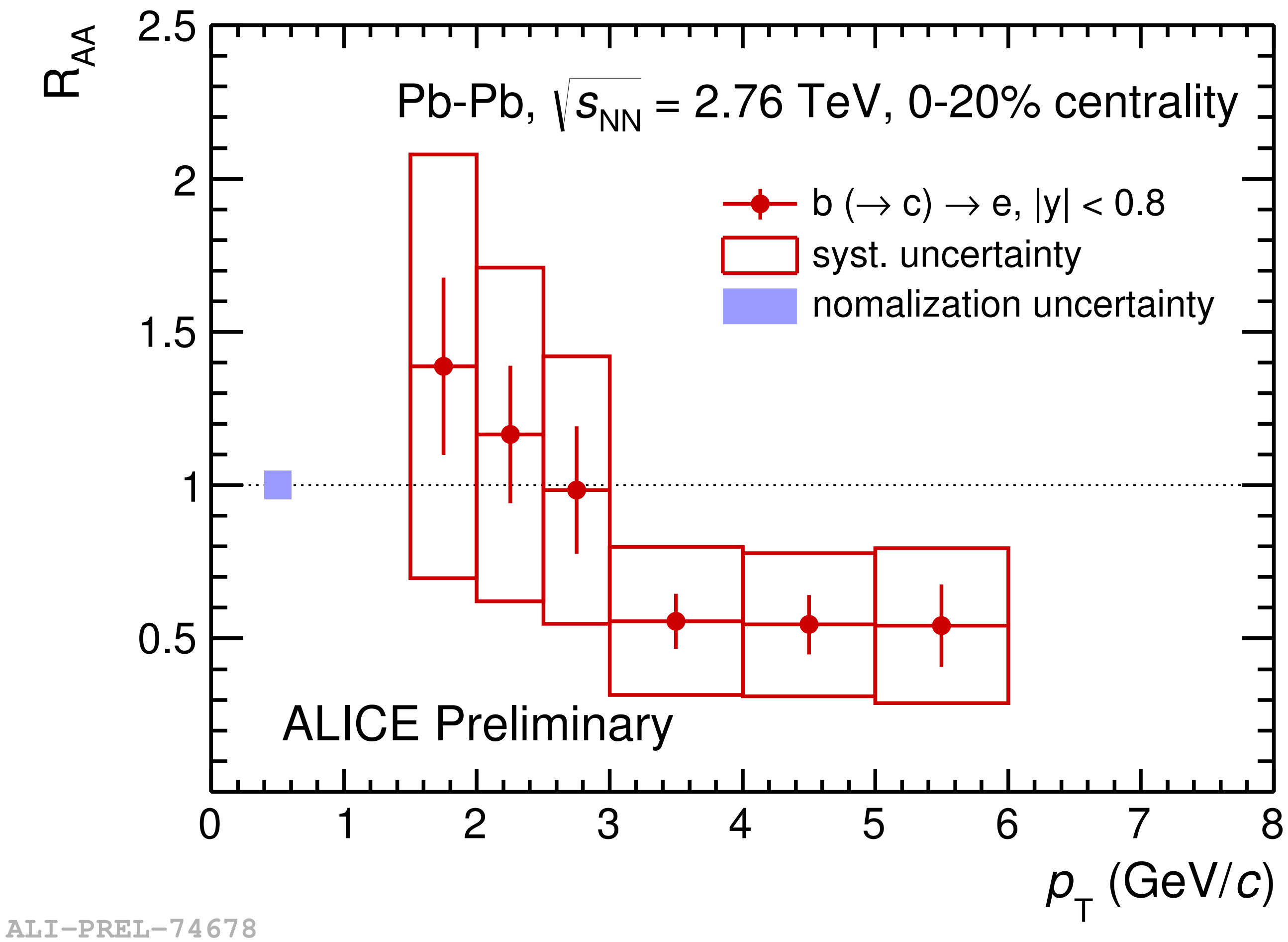
p-Pb $\sqrt{s_{NN}}$= 5.02 TeV

- $R_{pA} = \frac{1}{A}\frac{d\sigma_{pA}/dp_T}{d\sigma_{pp}/dp_T}$, A: number of nucleons in the nucleus
- $R_{pA} \neq 1$: Address possible cold nuclear matter effects



Pb-Pb $\sqrt{s_{NN}}$= 2.76 TeV

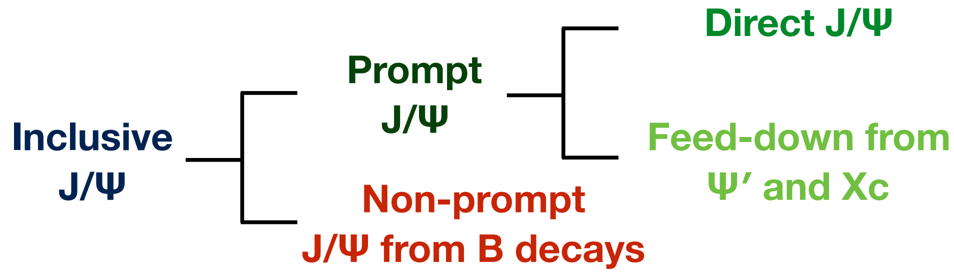
- $R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T}$, <N_{coll}>: number of binary collisions
- RAA ≠ 1 : medium effect at high p_T



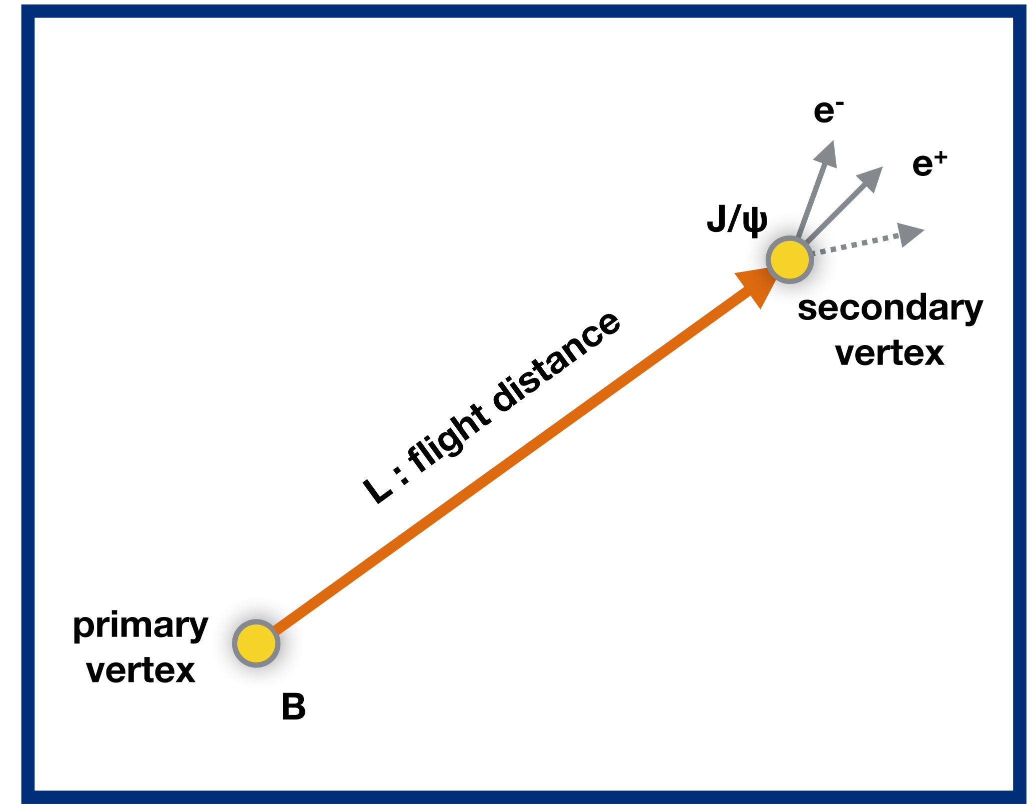
- Nuclear modification factor of beauty-decay electrons in p-Pb collisions is compatible with unity within uncertainties
- Suppression of beauty-decay electrons for p_T > 3 GeV/c in 0-20% central Pb-Pb collisions
- Suppression measured in Pb-Pb collisions is due to the parton energy loss in the hot and dense medium

Measurement of non-prompt J/ψ

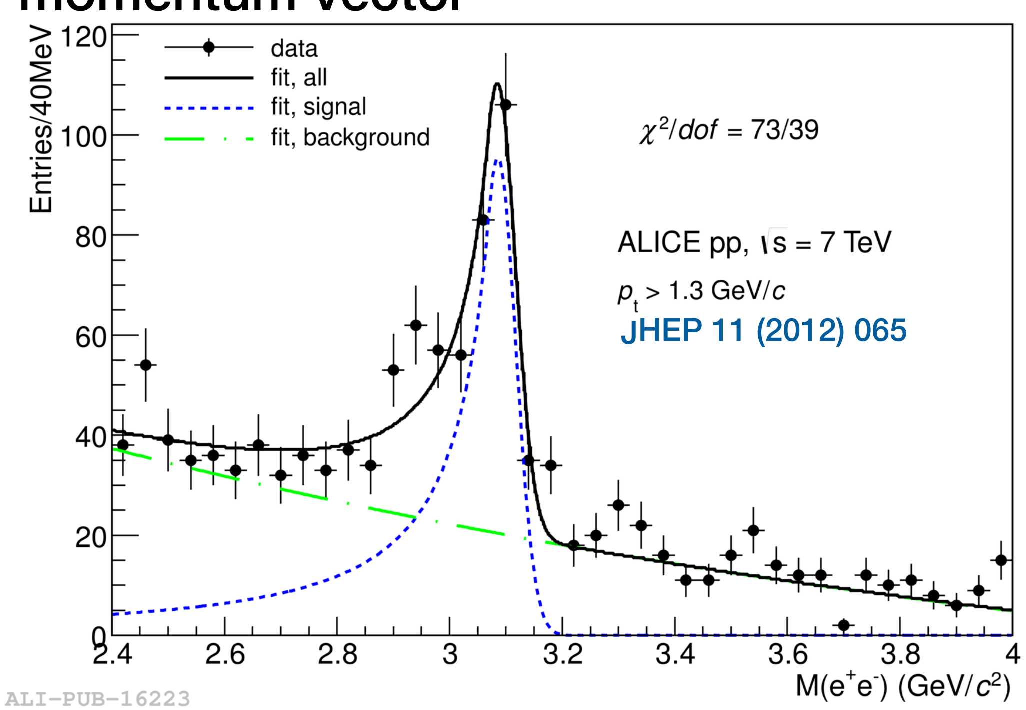
- **Measurement of non-prompt J/ψ :**

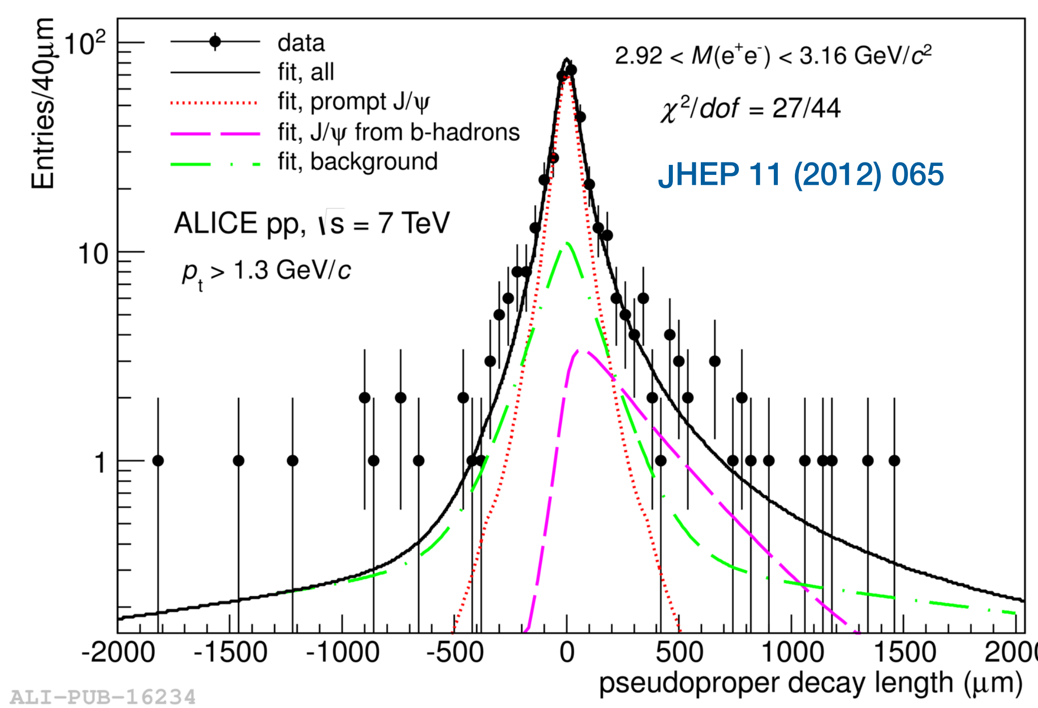


Long lifetime of B hadrons (cτ ~ 500μm) leads to larger flight distance of electrons coming non-prompt J/ψ



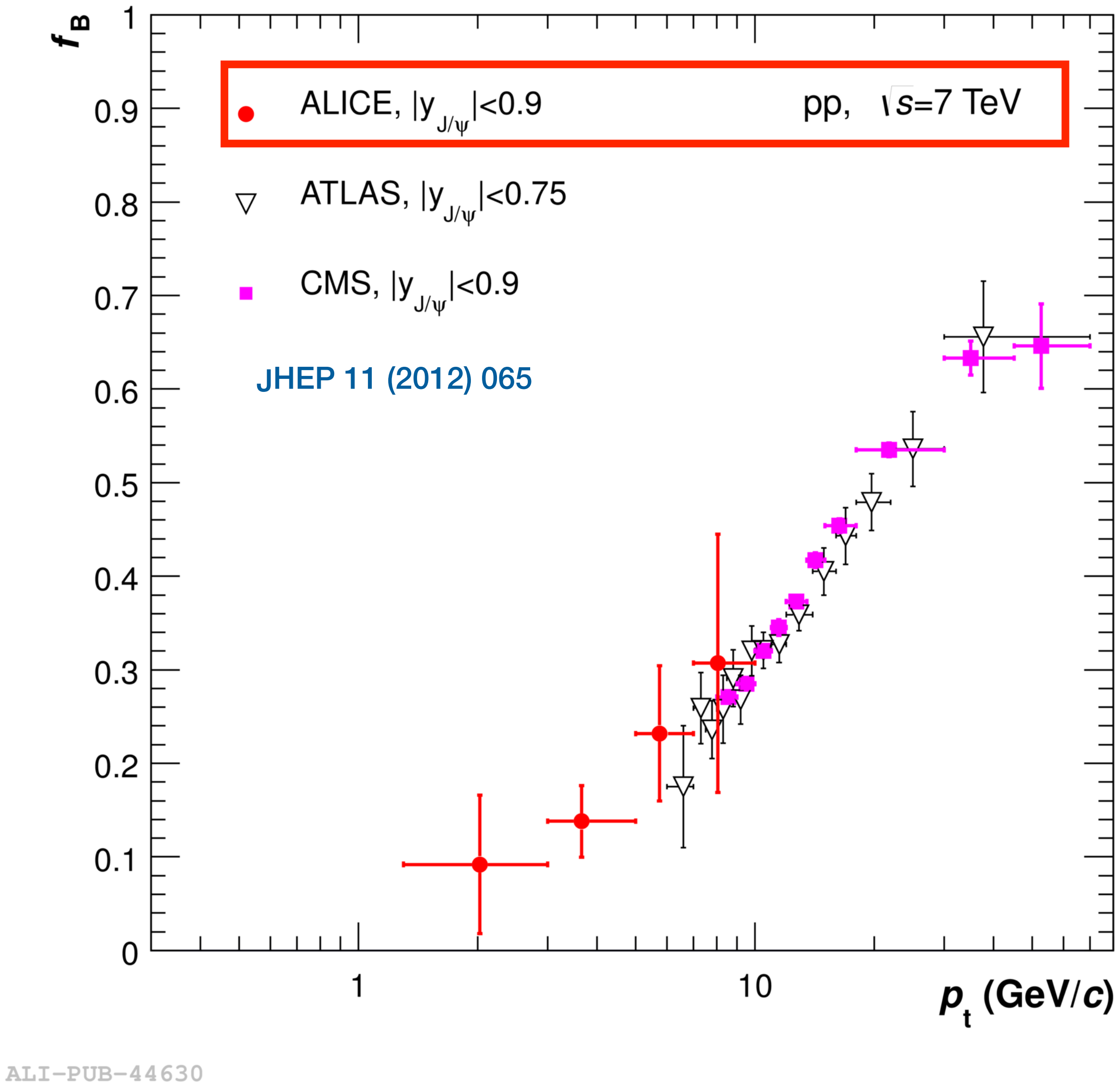
- **Analysis strategy**
  - 2-dimensional simultaneous fit for M_{ee} and pseudo-proper decay length x
    - $x = c \cdot L_{xy} \cdot m_{J/\psi} / p_T^{J/\psi}$
    - L_{xy} : projection of the flight distance onto its transverse momentum vector



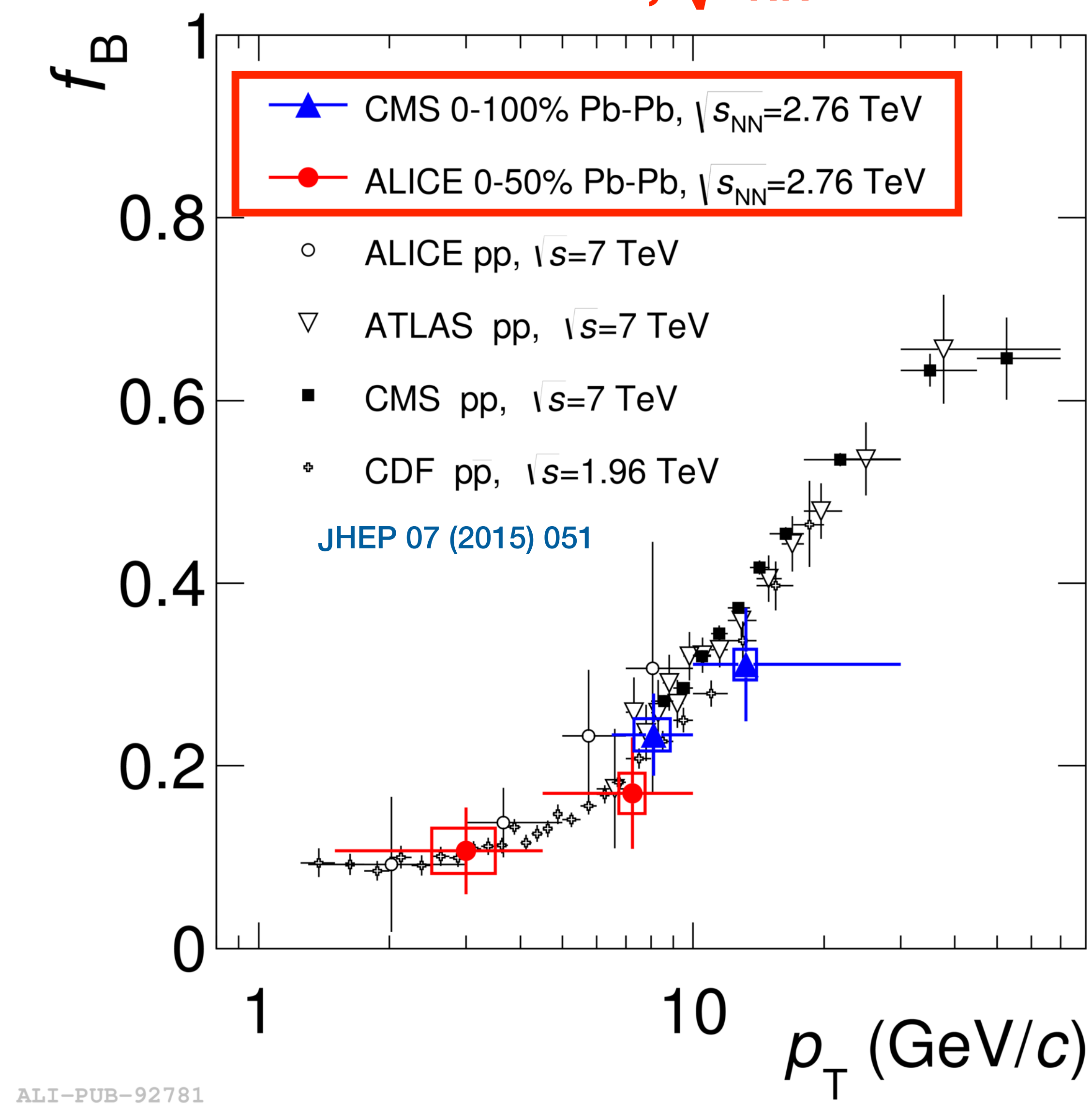


Fraction of J/ψ from the decay of beauty hadrons

pp, √s= 7 TeV



0 - 50 % Pb-Pb, √sNN= 2.76 TeV



- The fraction of J/ψ from beauty-hadron decays is determined for pp and Pb-Pb collisions.
- The fraction in Pb-Pb collisions has a similar p_T dependence as in pp collisions
  ➡compensation of the medium effects on the prompt component (J/ψ dissociation and recombination) and on the non-prompt part (b-quark energy loss) ?

Nuclear modification factor of non-prompt J/ψ

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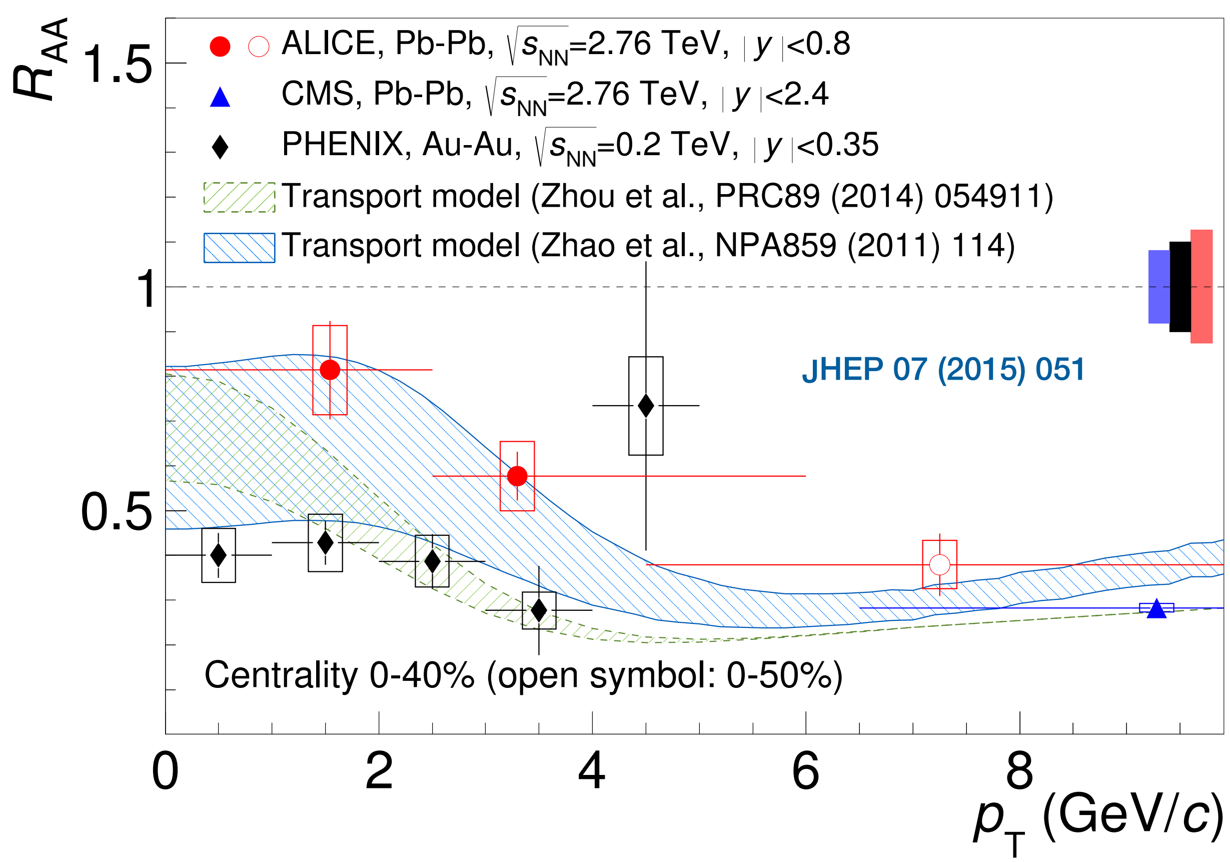
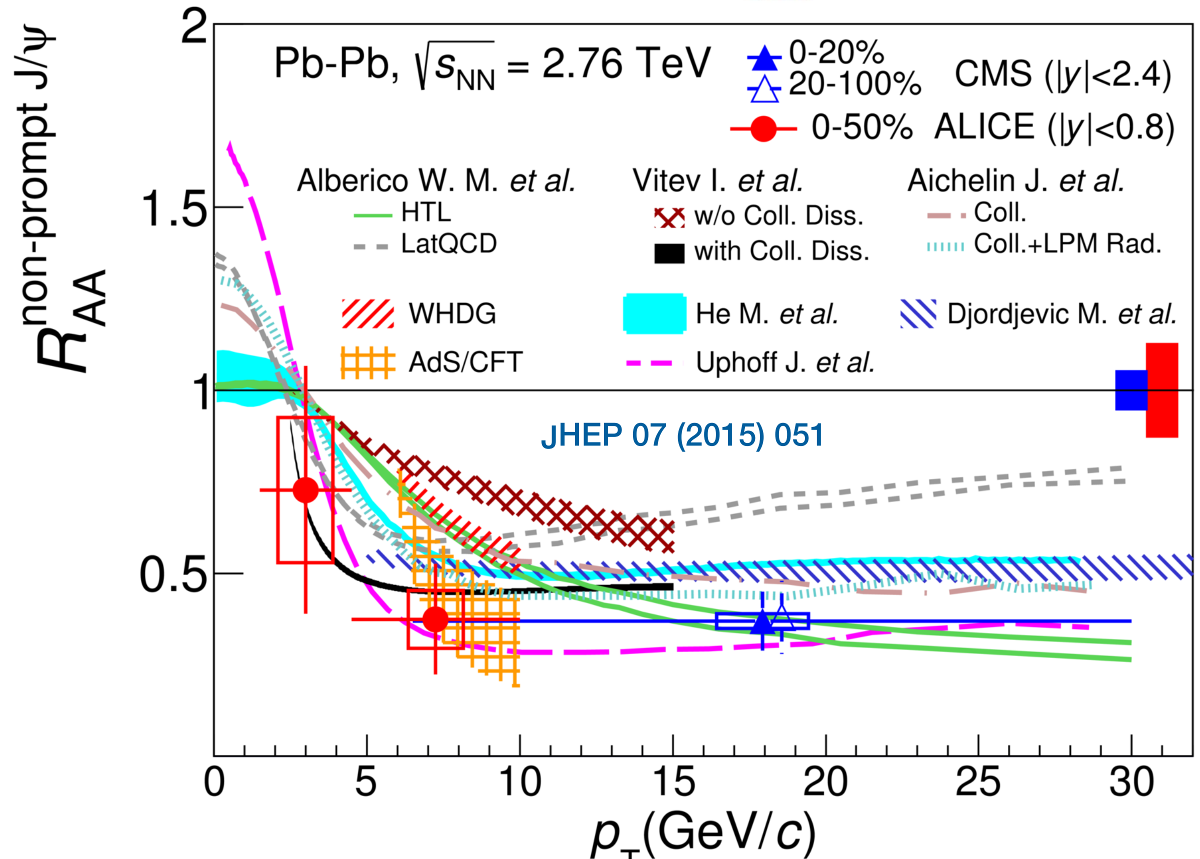
inclusive J/ψ,
0 - 40 % Pb-Pb, $\sqrt{s_{NN}}$= 2.76 TeV
mid-rapidity (|y| < 0.8)



non-prompt J/ψ
0 - 50 % Pb-Pb, $\sqrt{s_{NN}}$= 2.76 TeV
mid-rapidity (|y| < 0.8)

$$R_{AA}^{\text{non-prompt J}/\psi} = \frac{f_B^{\text{Pb-Pb}}}{f_B^{pp}} R_{AA}^{\text{incl. J}/\psi}$$



ALI-PUB-93214

- **Based on the measurement of inclusive J/ψ R_{AA}, R_{AA} of non-prompt J/ψ is obtained**
- **Result of non-prompt J/ψ extends the coverage of CMS to the low p_T region**
- **In 4.5 < p_T < 10 GeV/c, non-prompt J/ψ suppression tends to be stronger than what predicted by most of the models**

Ongoing studies

Measurement of b jets

- **Tag jets coming from fragmentation of beauty quarks:**
  - unbiased selection on the kinematics of the hard scattering, even in the presence of an (underlying) heavy-ion collision
  - allow the study of energy loss redistribution in Pb-Pb collisions

- **Main analysis steps:**
  1. Jet-finding: jet reconstruction with charged tracks
  2. b-jet tagging: exploit long lifetime ($c\tau$ ~ 500μm) and large mass (~ 5 GeV/c^2) of B mesons
  3. Corrections: unfold jet energy resolution and correct for b-tagging efficiency and charm/light flavour contamination

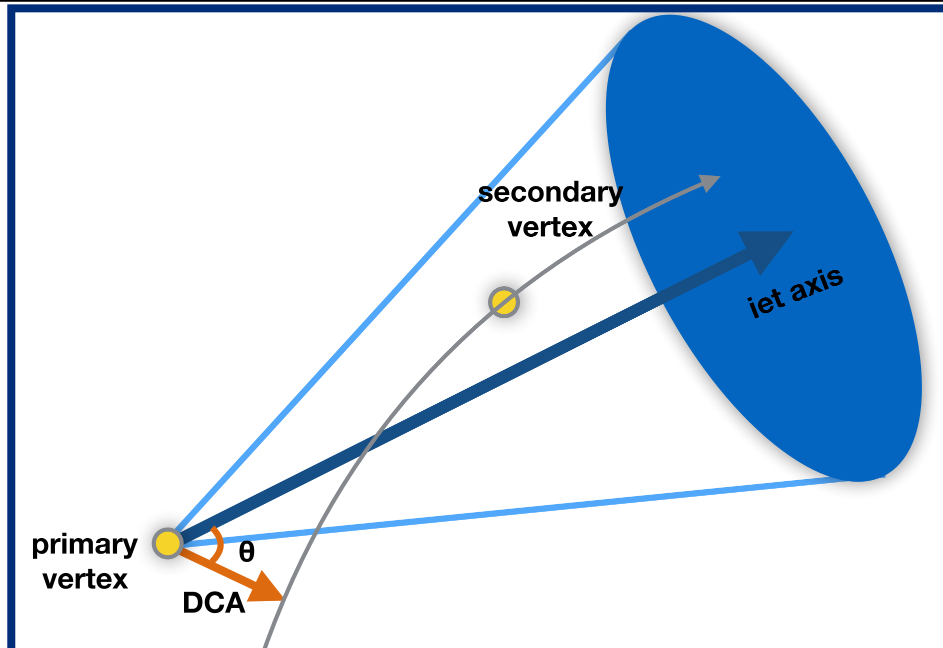
- **b-jet tagging:**
  - impact parameter of tracks within jet cone
  - reconstruction of secondary vertexes (SV) and its properties

b-jet tagging via track impact parameter

- **b-jet tagging via track signed impact parameter :**

The probability to have several tracks with high positive values is high for b jets due to the displaced secondary vertex.

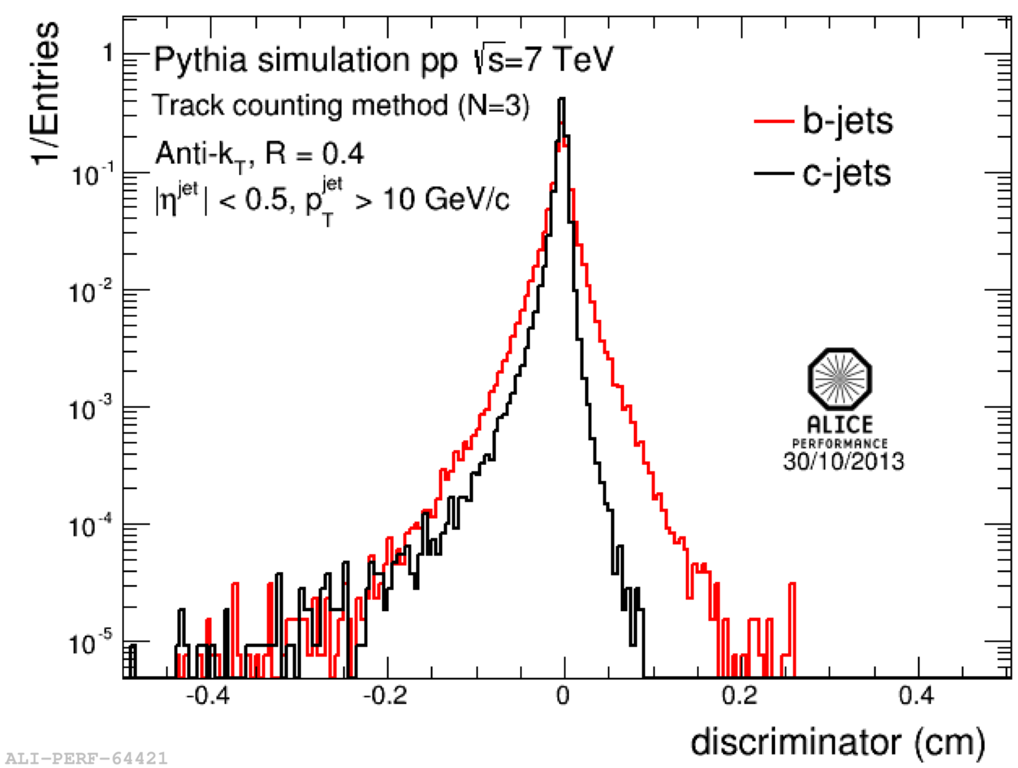
1. Sort tracks in a jet by decreasing values of the signed impact parameter
2. Impact parameter of the Nth most displaced track used as discriminator
3. Select jets which have large discriminator exceeding certain threshold (d_{0min})
4. Subtract contamination from charm and light-flavour jets and correct for efficiency



sign : sign of scalar product of jet direction and the vector from primary vertex to the point of DCA

$\theta < \pi/2 \rightarrow$ positive (+)

$\theta > \pi/2 \rightarrow$ negative (-)



b-jet tagging via secondary vertex reconstruction

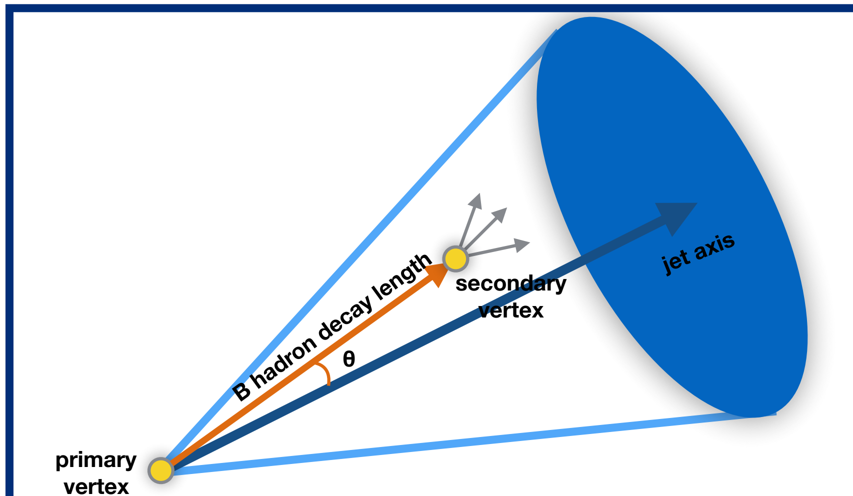
- **b-jet tagging via secondary vertex reconstruction :**

reconstruct secondary vertices (SV) in a jet with N tracks (N=2,3,..) within a jet and use the signed flight distance (significance) and SV dispersion.

- transverse flight distance L_{xy} : projection of the flight distance onto transverse plane
- SV dispersion σ_{vtx} : the dispersion of the tracks in the vertex

$$\sigma_{vtx} = d_1^2 + d_2^2 + d_3^2,$$

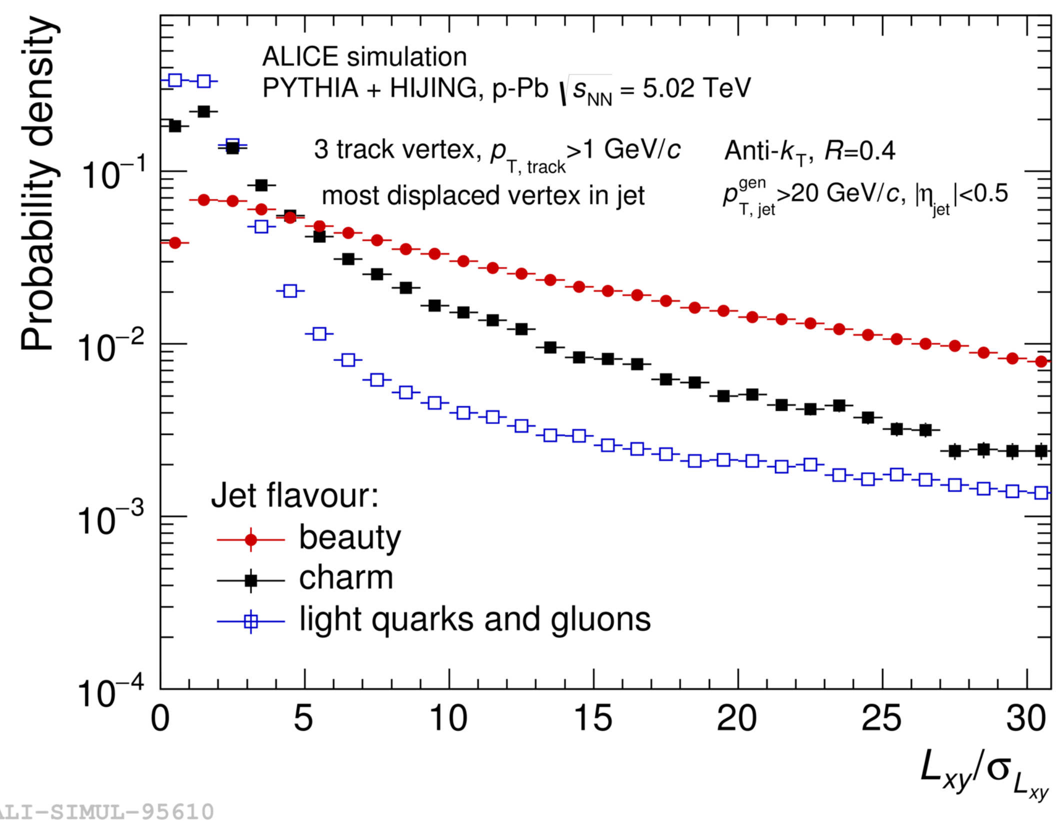
where $d_{1,2,3}$ are the distances of the three tracks from SV

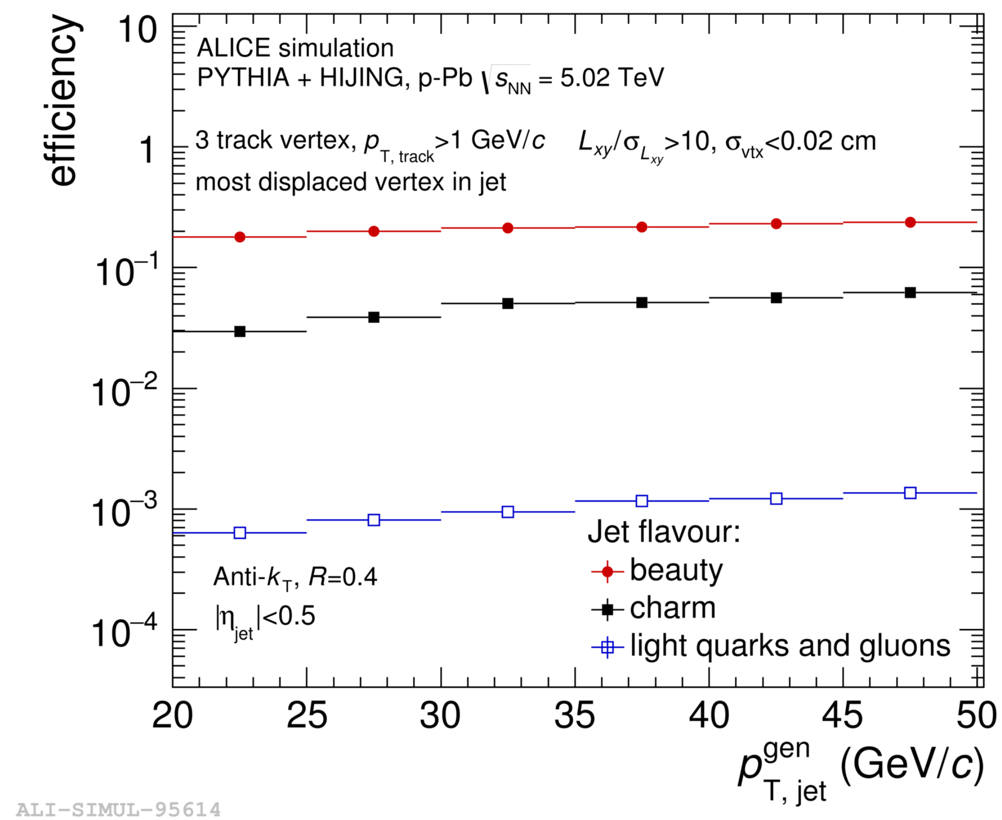


sign : sign of scalar product of jet direction and the vector from primary vertex to the secondary vertex

θ < π/2 → positive (+)

θ > π/2 → negative (-)





➡ tagging/mis-tagging efficiencies do not strongly vary with p_T

➡ efficiency for b-tagging is higher about x100 for light quarks gluon and ~x3-5 for charm

Prospects with RUN2 & RUN3

Beauty measurements in RUN2 and RUN3

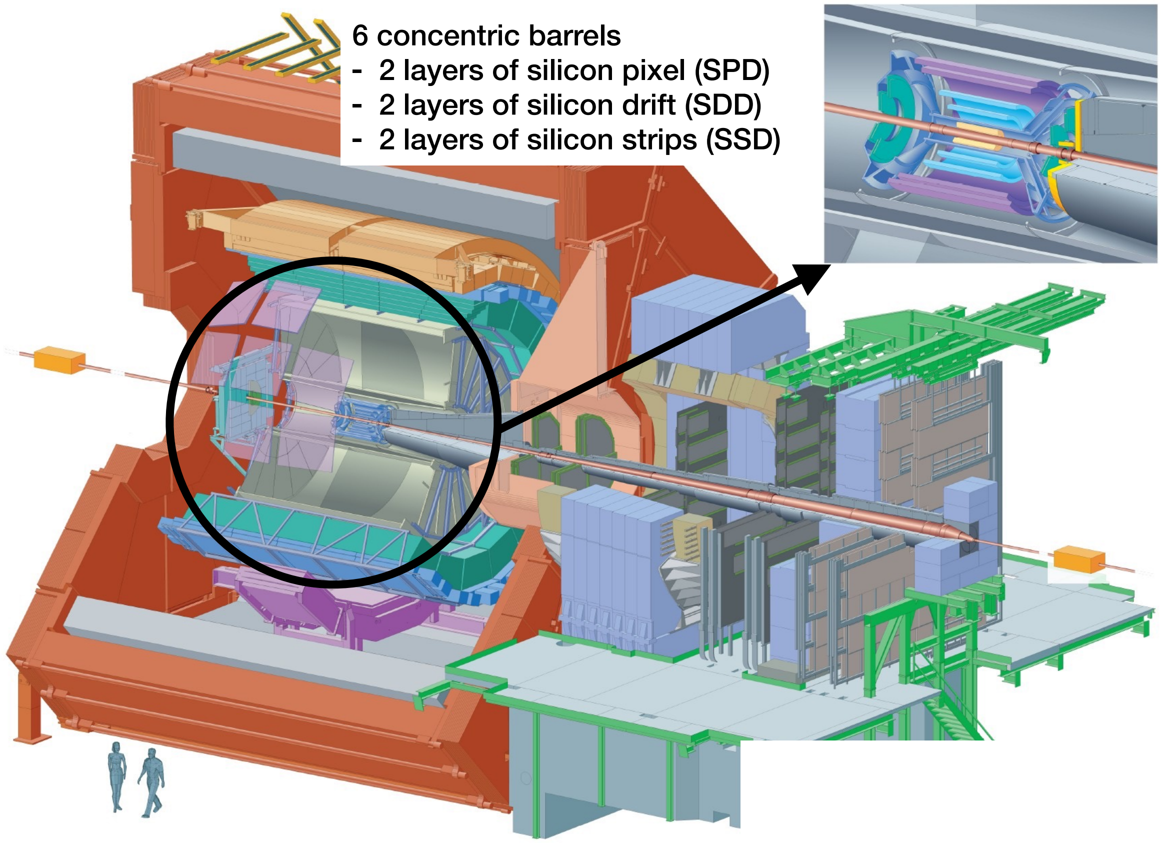
- **RUN2: 2015 - 2018**
  - new higher energy : pp collisions up to $\sqrt{s}$ = 13 TeV, p-Pb collisions and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV
  - significant increase of statistics (L~1nb^{-1} for Pb-Pb collisions) allows to reduce systematic uncertainties

  ➡ **more precise measurements in an extended p_T coverage of beauty will be possible**

- **Run 3: 2021 - 2023**
  - ~10 more statistics w.r.t. Run 2 (L ~ 10 nb^{-1} for Pb-Pb collisions)
  - improving the tracking precision at central and forward rapidity via **ITS and MFT upgrades**
  - increasing the readout capabilities of the detectors up to a rate of 50 kHz (from 1 kHz) with TPC readout upgrade (MWPC → GEM) and new combined Online-Offline system for calibration and data compression

  ➡ **Better precision, more statistics** and **extended p_T coverage** measurements with **new observables** will be possible

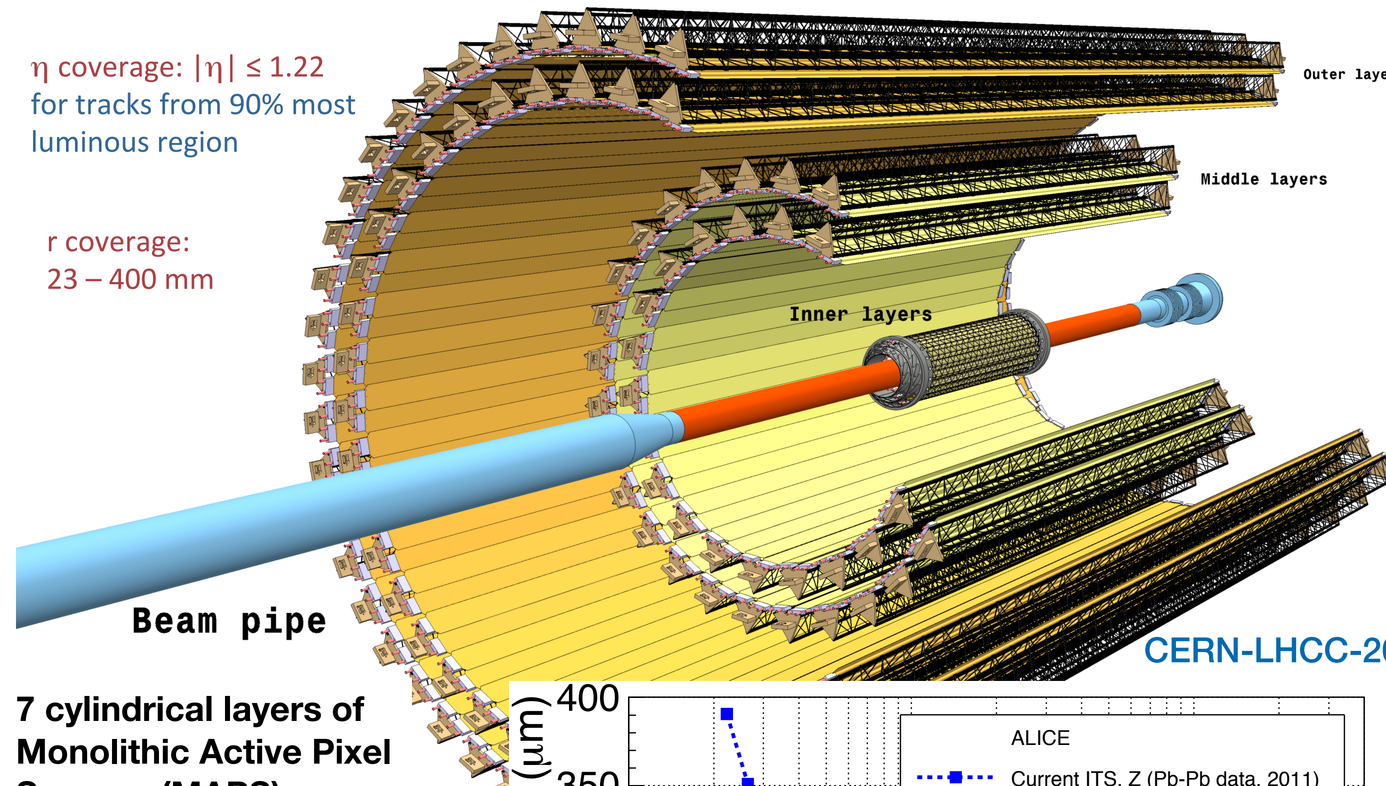
Upgraded Inner Tracking System (ITS)



- **Upgraded ITS :**

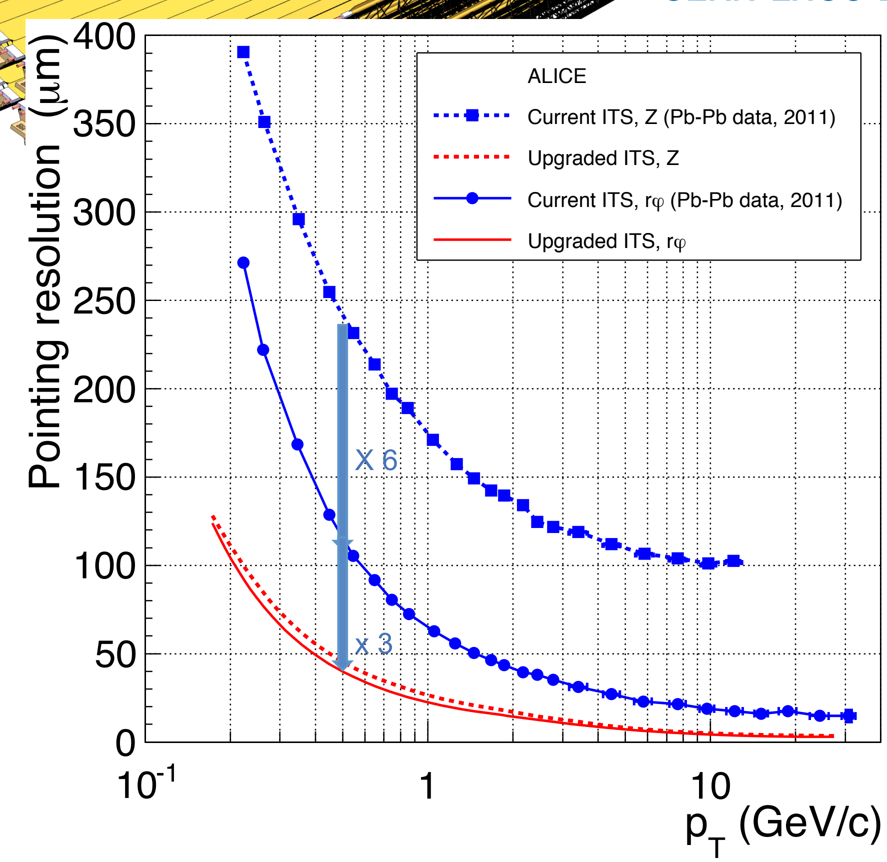
η coverage: |η| ≤ 1.22 for tracks from 90% most luminous region

r coverage: 23 – 400 mm



CERN-LHCC-2013-24

7 cylindrical layers of Monolithic Active Pixel Sensors (MAPS)



✓ **Improve impact parameter resolution by a factor of ~3**
- Get closer to IP (position of first layer): 39mm → 23mm
- Reduce x/X_0/layer: ~1.14% → ~ 0.3% (for inner layers)
- Reduce pixel size: currently 50µm x 425µm → O(30µm x 30µm)

✓ **Improve tracking efficiency and p_T resolution at low p_T**
- Increase granularity:
  - 6 layers → 7 layers
  - silicon drift and strips → pixels

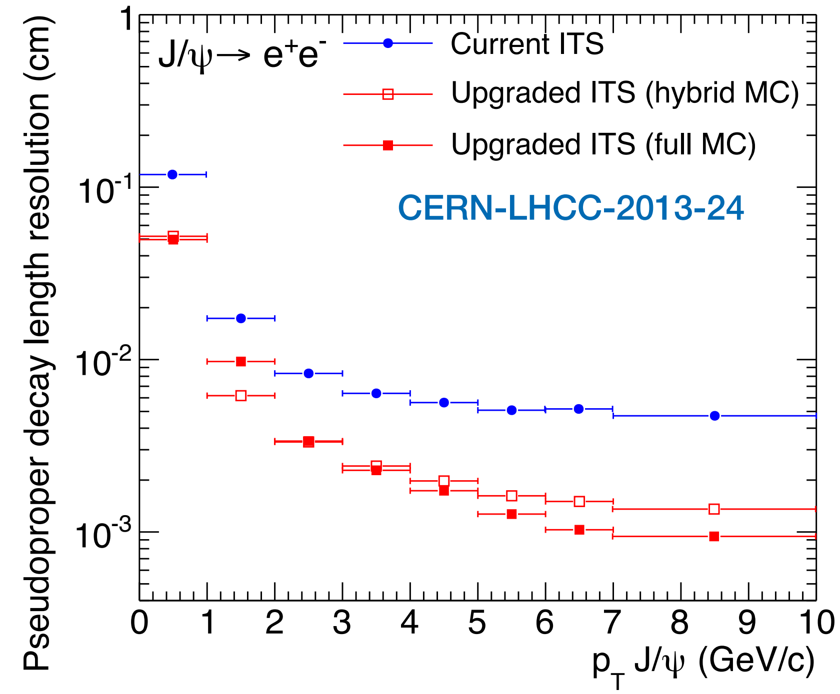
✓ **Fast readout**

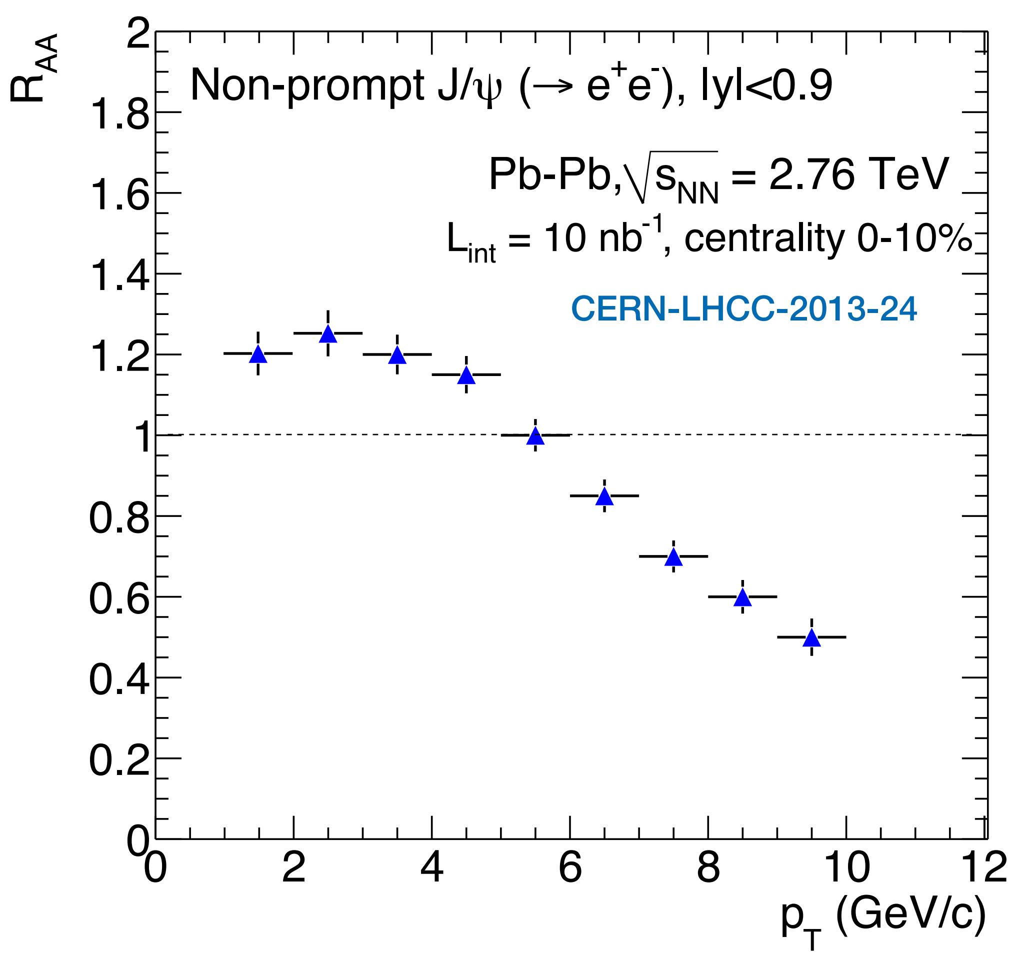
✓ **Fast insertion/removal for yearly maintenance**

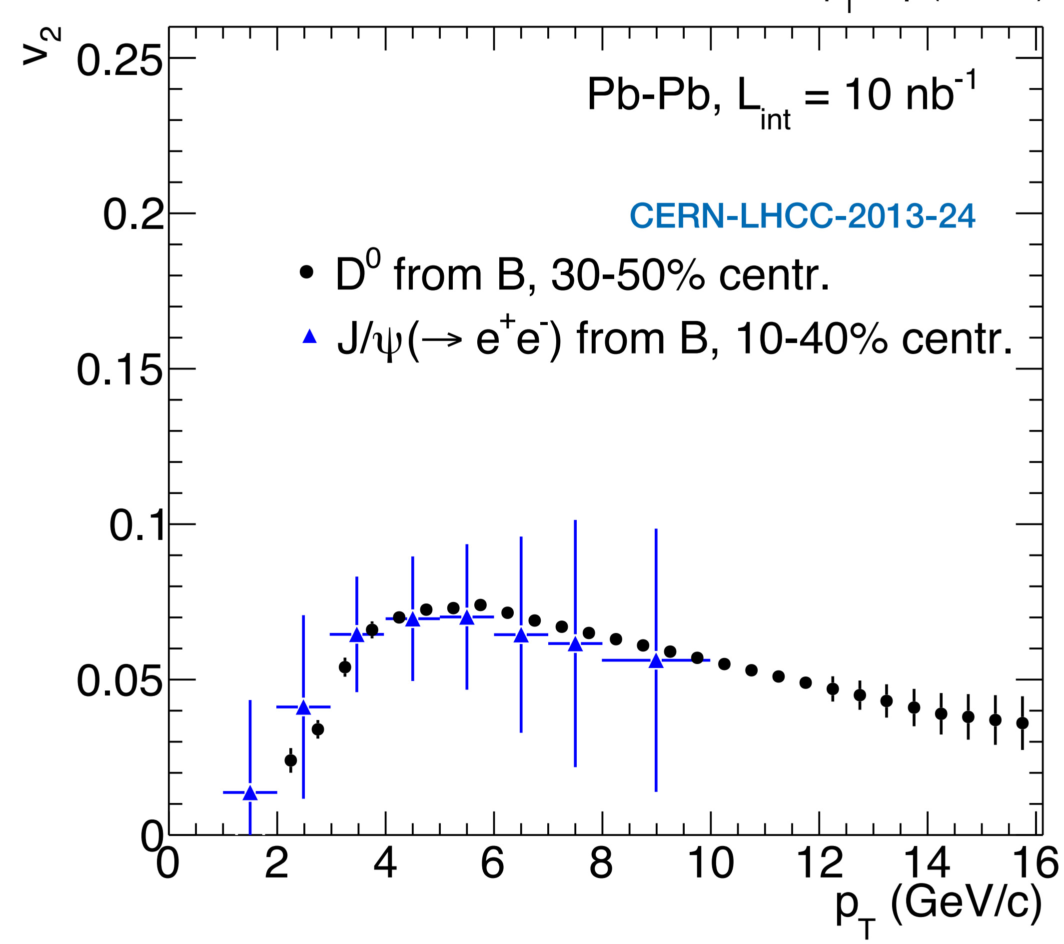
Upgraded ITS - Physics performance

- **Improve the results of current observables :**
  - **non-prompt J/ψ in the e^+e^- decay channel**
  - **improved pointing resolution with upgraded ITS**
    ➔ improve pseudoproper decay length resolution

➡ extended p_T and more precision measurement of non-prompt J/ψ R_{AA} and v_2 together with increased statistics

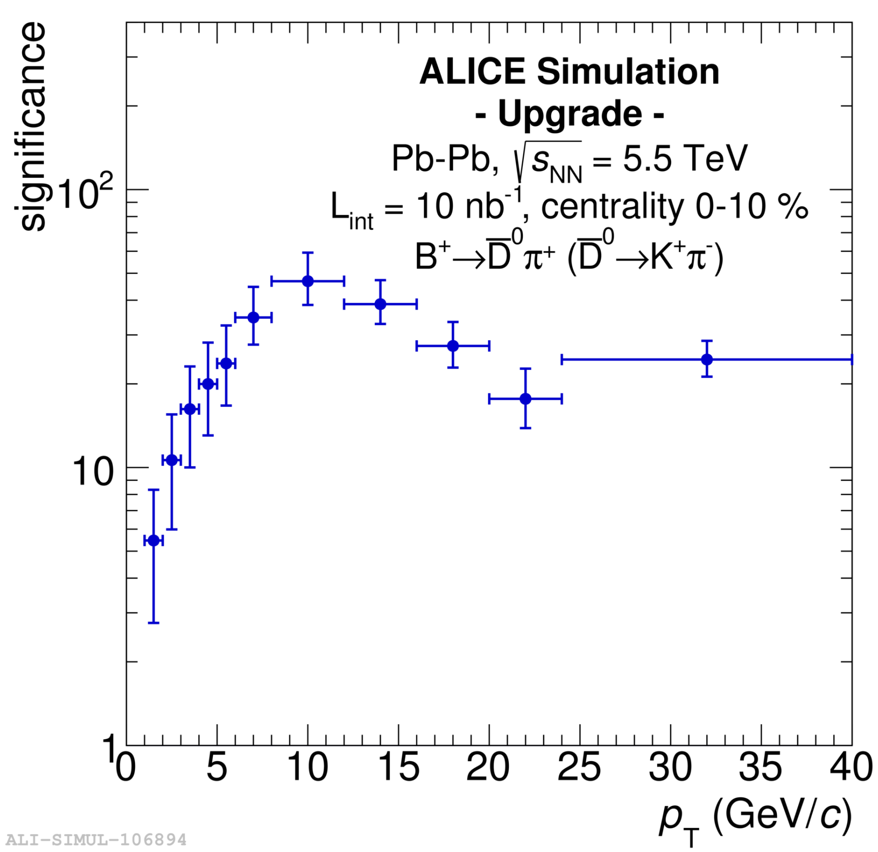


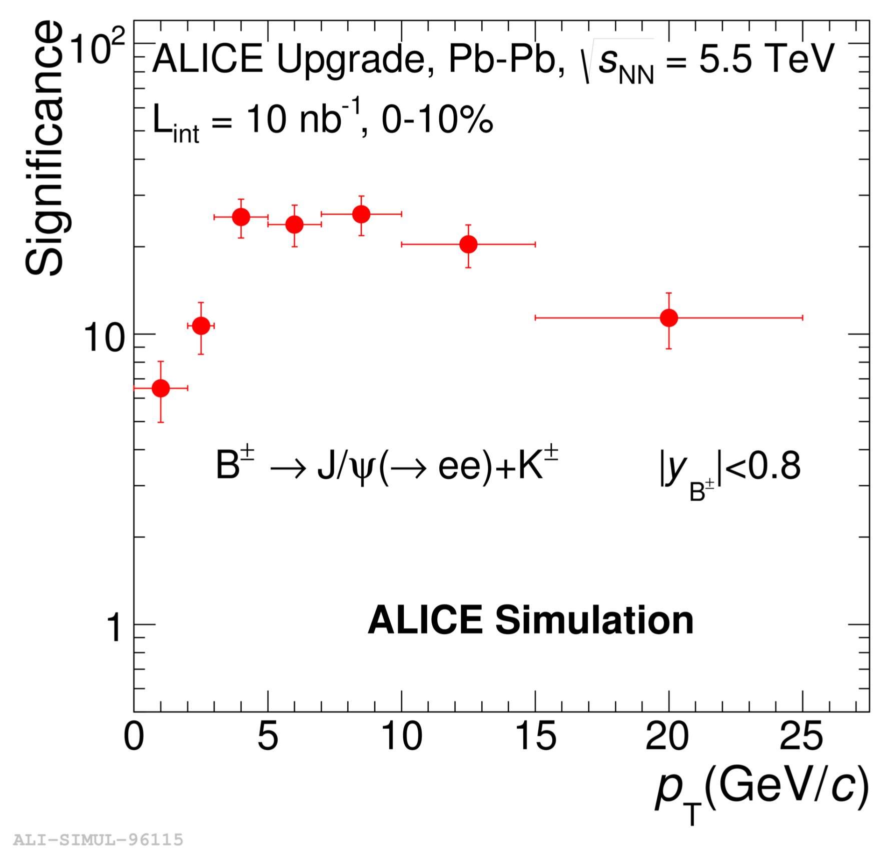


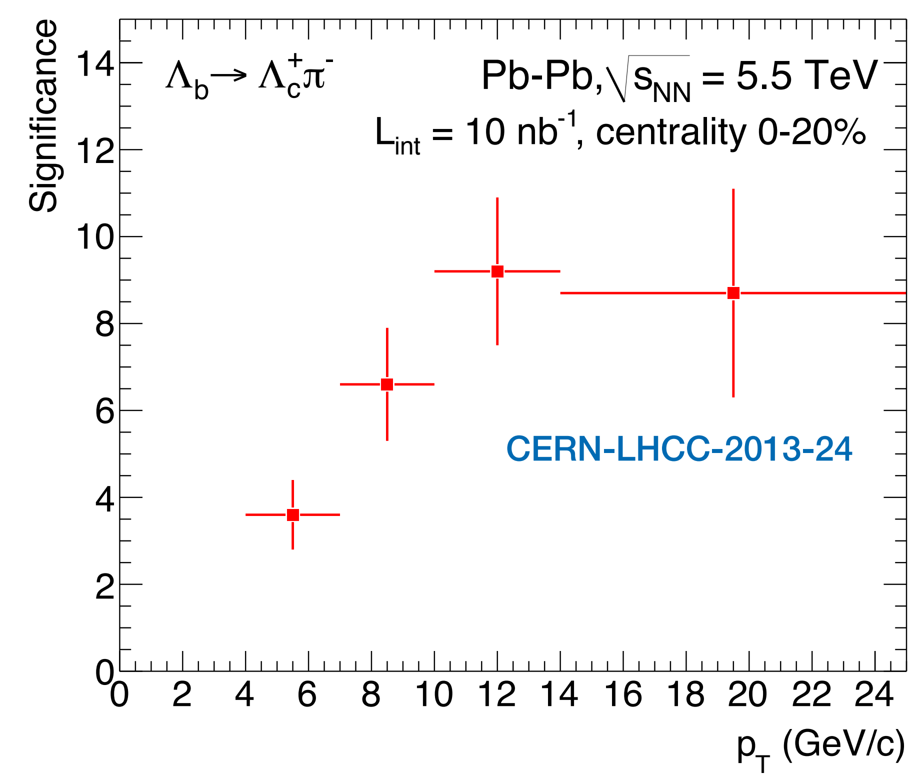


Upgraded ITS - Physics performance

- **Full kinematic reconstruction of beauty hadrons:**
  - **Distinct decay topologies and kinematics allow for efficient full reconstruction of beauty mesons and baryons**
  - $B^+ \rightarrow D^0\,\pi^+$ ($D^0 \rightarrow K^+\pi^-$) , combined branching ratio ~ 1.9×10^{-4}
  - $B^+ \rightarrow J/\psi\, K^{\pm}$($J/\psi \rightarrow e^+e^-$) , combined branching ratio ~ 6.1×10^{-5}
  - $\Lambda_b^0 \rightarrow \Lambda_c^+\,\pi^-$ ($\Lambda_c^+ \rightarrow pK^-\pi^+$) , combined branching ratio ~ 3×10^{-4}







Upgraded Muon Spectrometer - Muon Forward Tracker (MFT)

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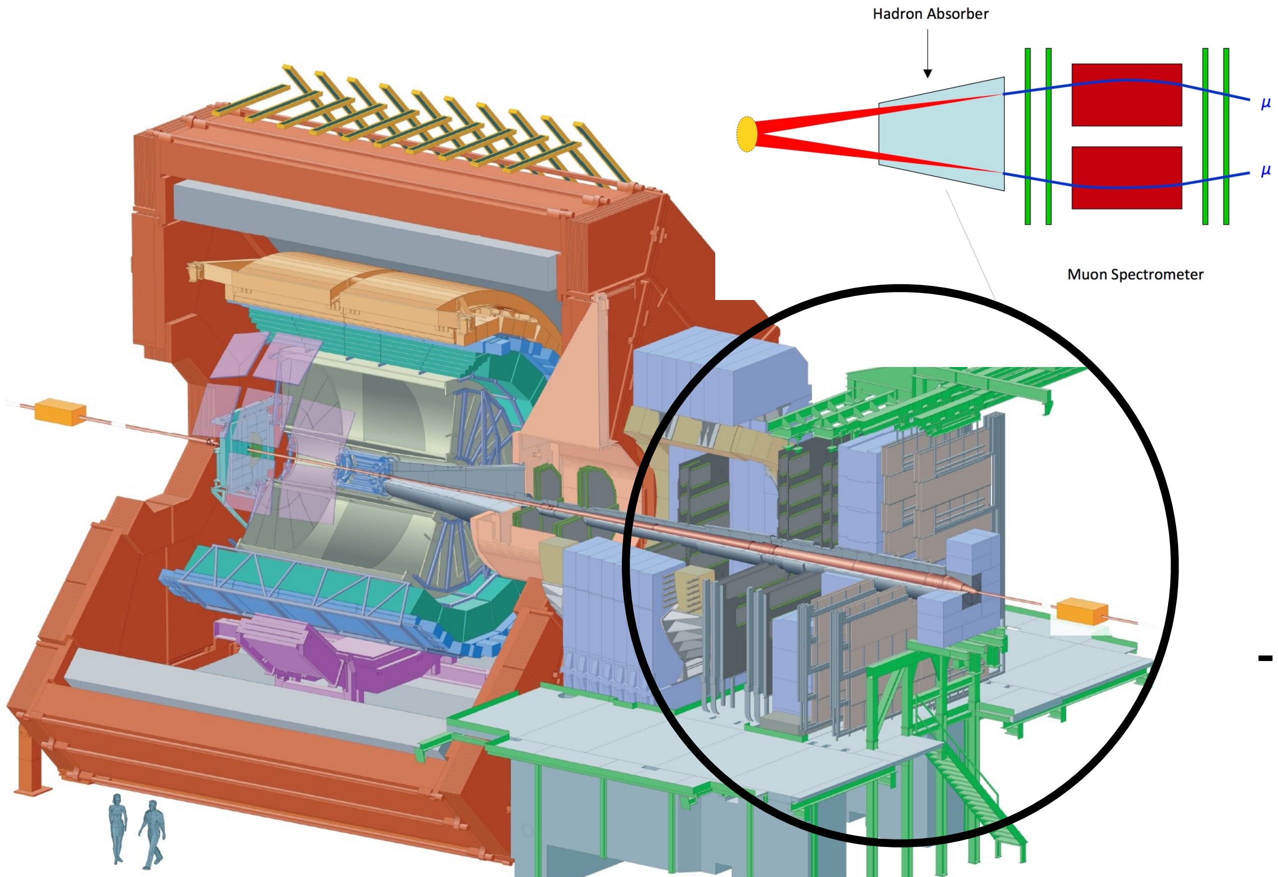
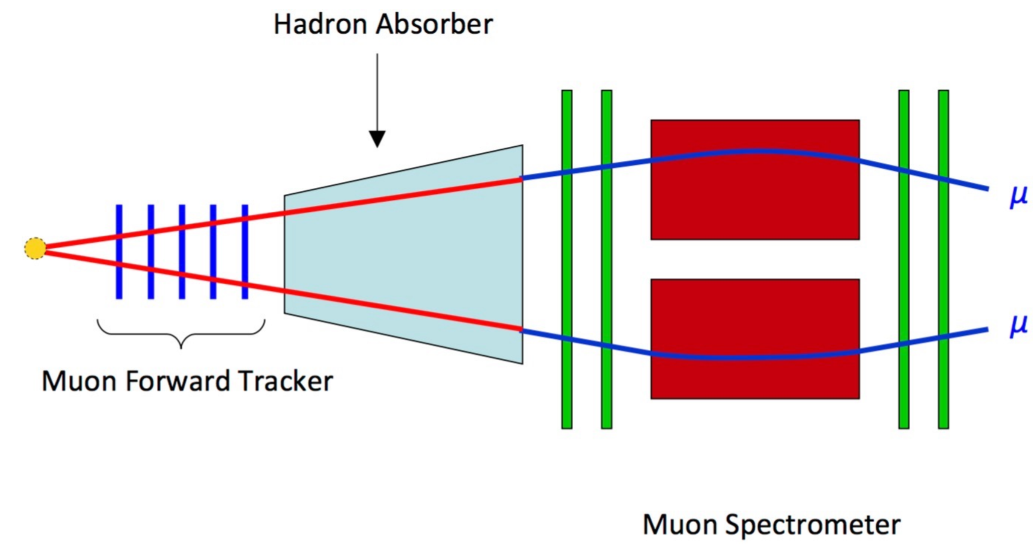


Muon spectrometer
$-4 < \eta < -2.5$

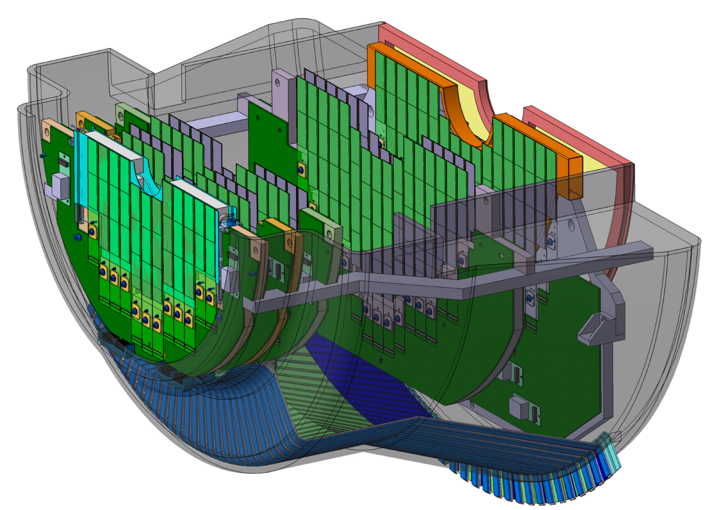
- **muon spectrometer + MFT :**

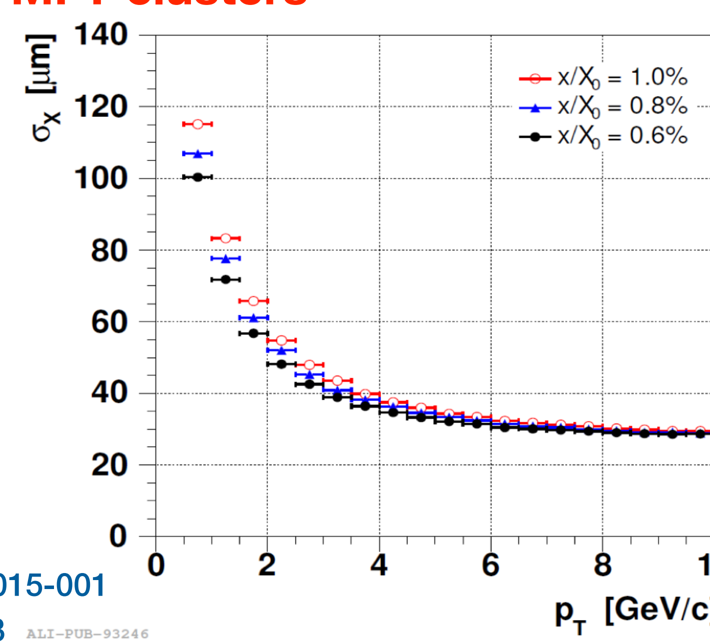


- Current limitation : blind to the details of the vertex region, because of the hadron absorber : extrapolating back to the vertex region **degrades the information** on the kinematics
- **High pointing accuracy gained by the muon tracks after matching with the MFT clusters**

- **MFT layout :**

  - 10 half-disks, material budget of about 0.6% X_0 and 2 detection planes each
  - Same silicon pixel technology as the ITS upgrade (MAPS)
  - Nominal acceptance: $-3.6 < \eta < -2.5$, full azimuth





CERN-LHCC-2015-001
ALICE-TDR-018

MFT - Physics performance

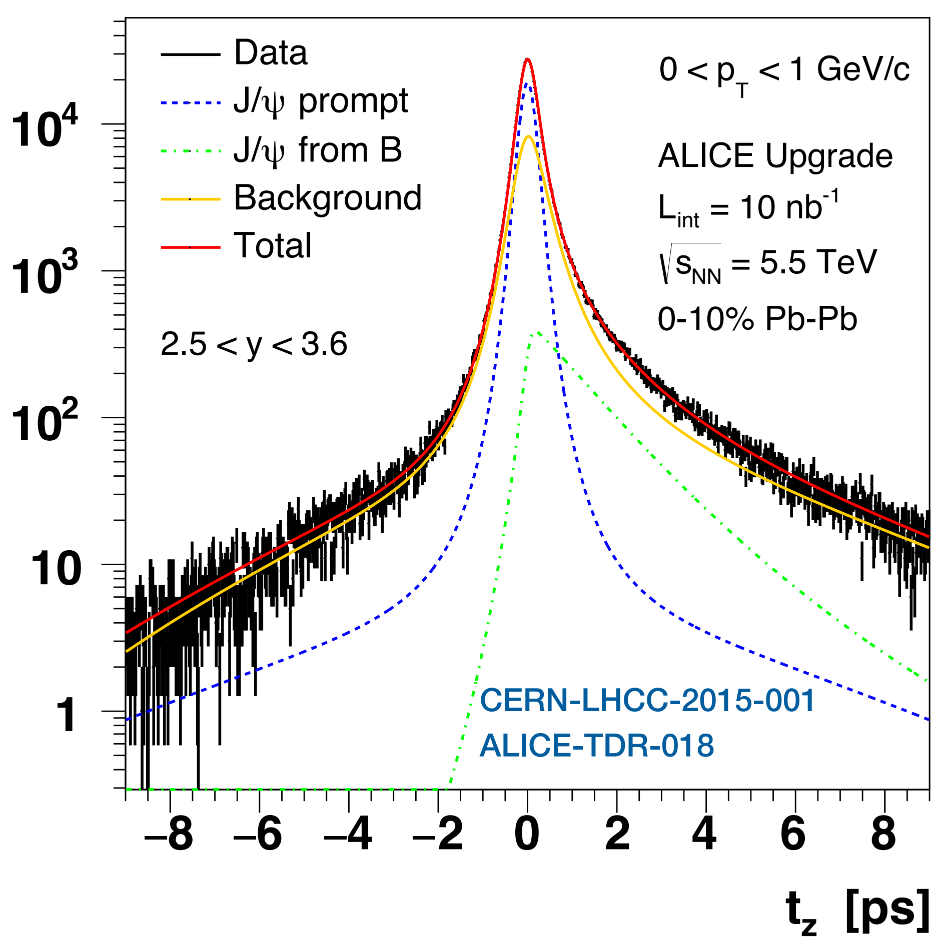
- **non-prompt J/ψ decays of beauty hadrons :**

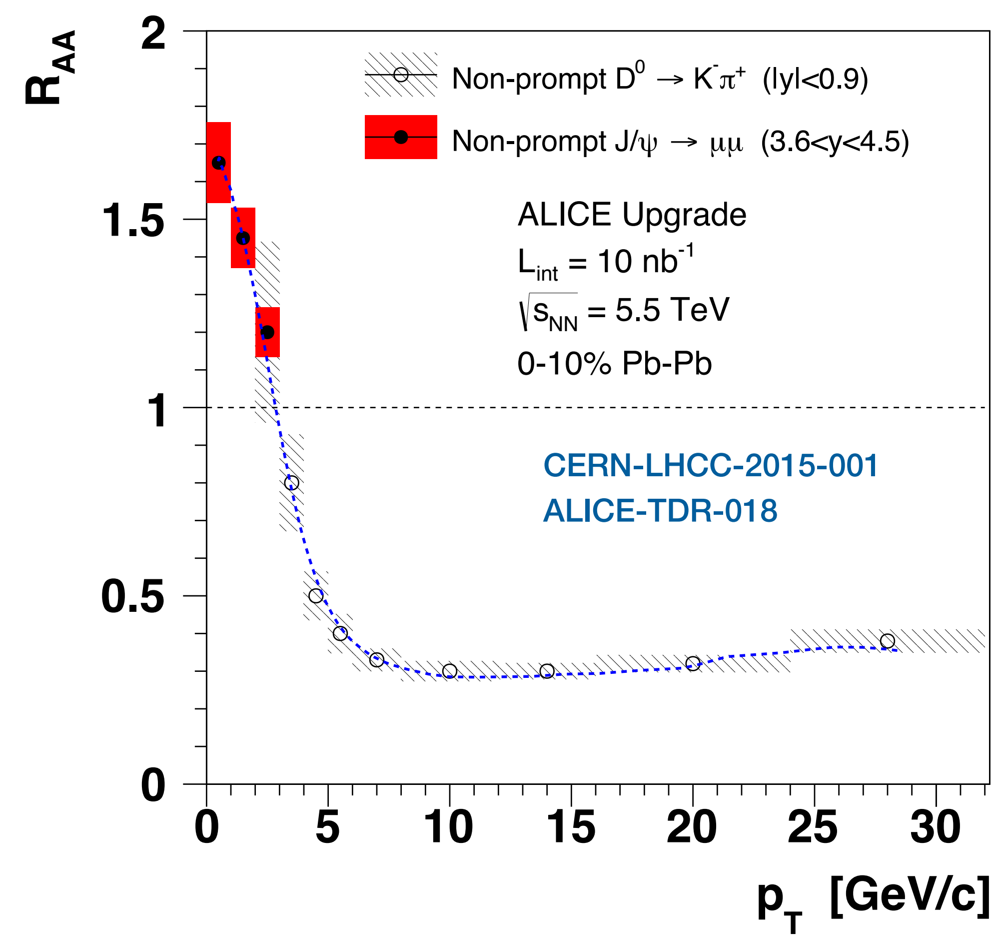
- **measurement of beauty production at forward rapidity**
- longitudinal pseudo-proper decay time :

$$t_z = \frac{\left(z_{J/\psi} - z_{\rm vtx}\right) \cdot M_{J/\psi}}{p_z}$$

  - p_z : longitudinal momentum of J/ψ
  - $z_{J/\psi}$ - z_{vtx} : distance between z-coordinates of the J/ψ production vertex and the primary vertex of the collision.

- template fit of pseudo-proper decay time distribution in narrow p_T intervals





➡ **Precise measurement of beauty down to $p_T = 0$ at forward rapidity will be possible**

Summary

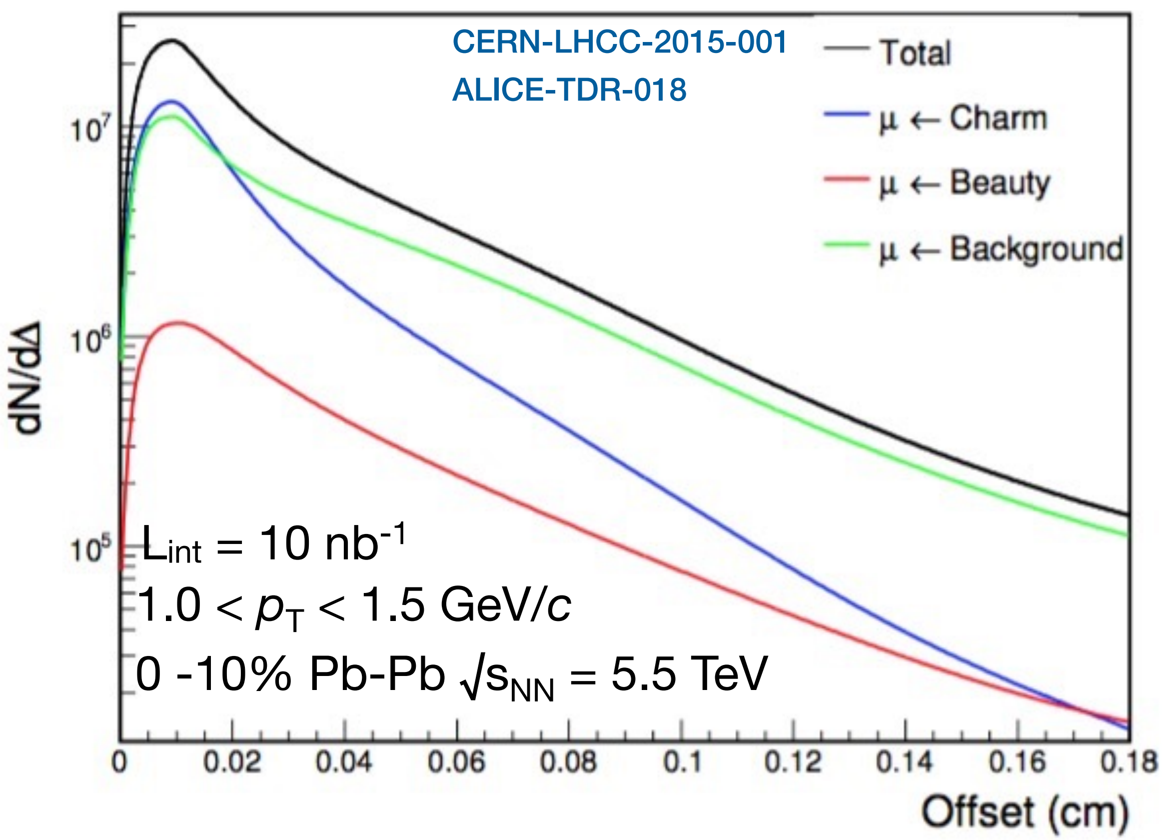
- Thanks to excellent tracking, vertexing and particle-identification capabilities provided by ALICE, beauty production is studied via **semi-leptonic decay channels in pp, p-Pb and Pb-Pb collisions** and **non-prompt J/ψ in the $e^{+}e^{-}$ decay channel in pp and Pb-Pb collisions**
  - **b→e :** since R_{pPb} is close to unity, the suppression of R_{AA} shown in p_{T} > 3 GeV/c is due to the parton energy loss in the hot and dense medium
  - **non-prompt J/ψ :** in 4.5 < p_{T} < 10 GeV/c, the suppression tends to be stronger than what predicted by most of the models
- Ongoing studies allow us to study more about beauty :
  - **b-jet tagging :** study of in medium energy loss of beauty without bias on the kinematics of the hard scattering and energy redistribution
- **Better precision, more statistics** and **extended p_{T} coverage** measurements with **new observables** will be possible with Run-II and RUN-III data

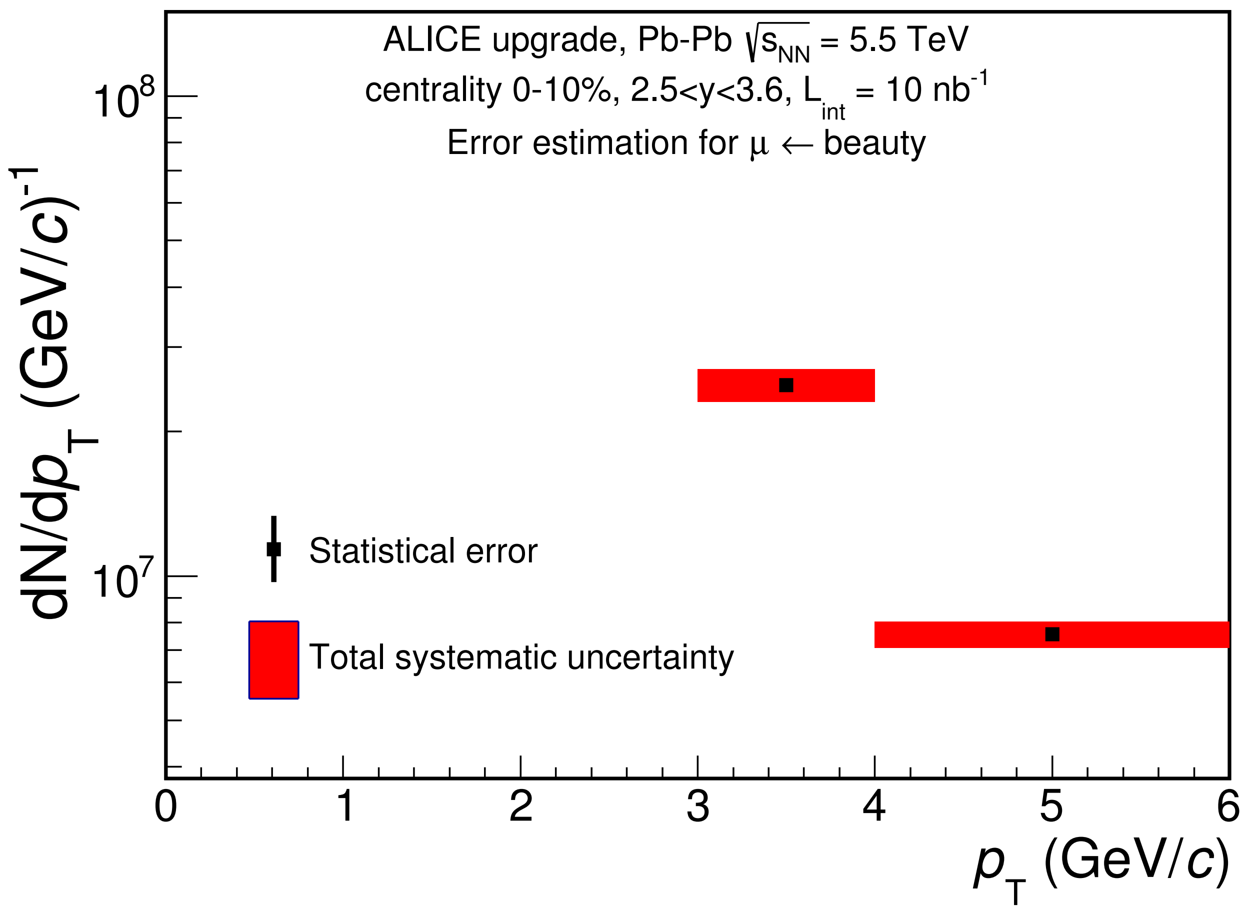
Thanks for your attention!

Backup

MFT - Physics performance

- **Muon electron from semi-leptonic decays of beauty-hadron:**
  - measurement of beauty production at forward rapidity
  - offset : $\Delta = \sqrt{(x_{\rm V} - x_{\rm Extrap})^2 + (y_{\rm V} - y_{\rm Extrap})^2}$
    - (x_V, y_V) : the transverse coordinates of the primary vertex measured by the ITS
    - (x_{Extrap}, y_{Extrap}) : the coordinates in the plane transverse to the beam line of the extrapolated track evaluated at the z of the primary vertex.
  - template fit of track-to-vertex offset distribution in narrow p_T intervals

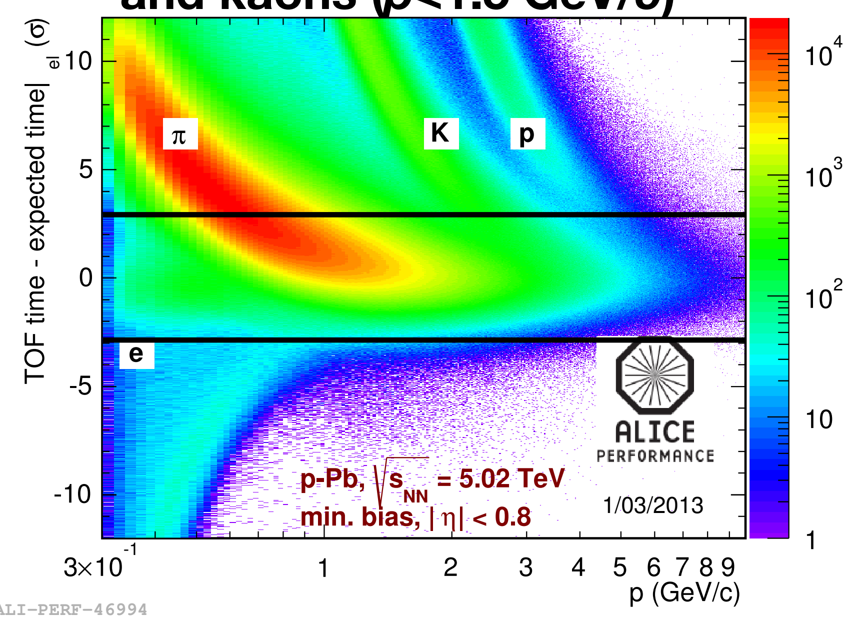




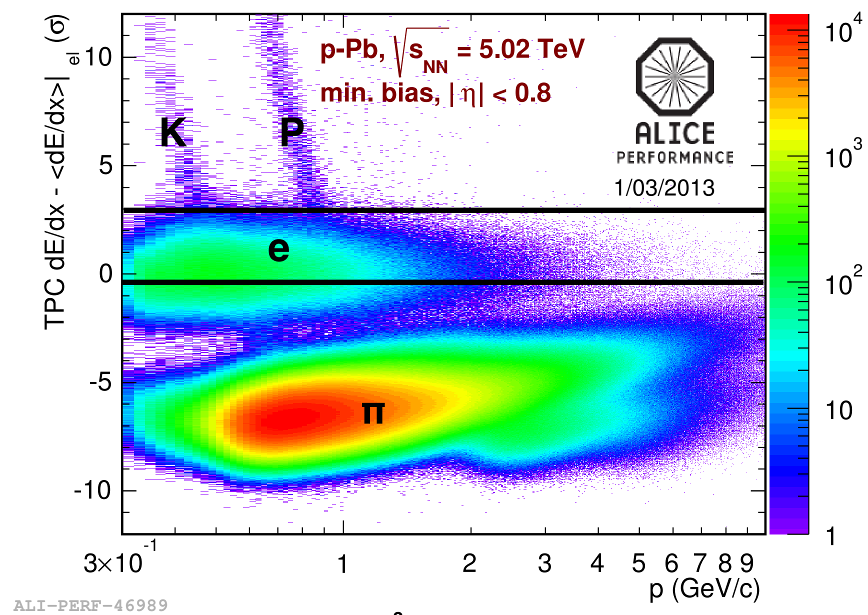
Heavy-flavour decay electrons in ALICE

• Electron identification

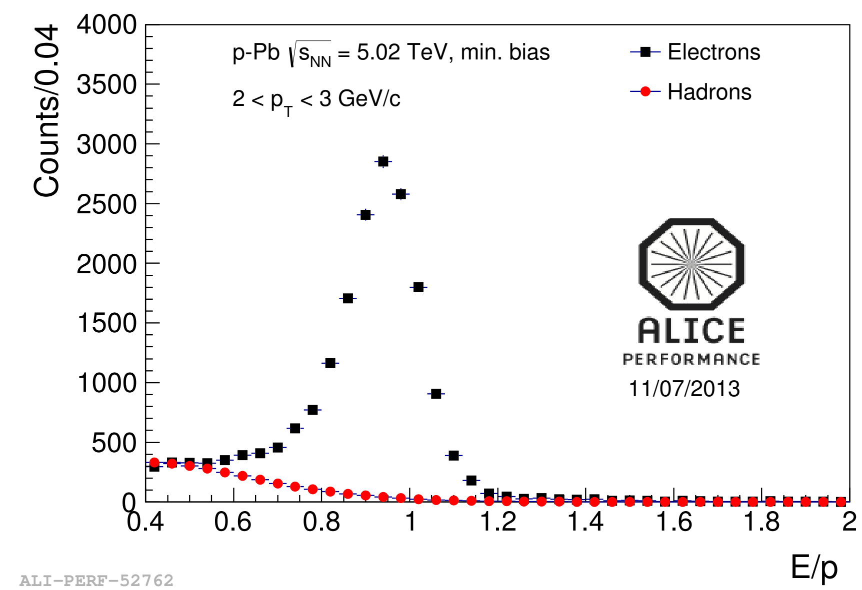
TOF :
±3σ on electron hypothesis
reject protons (p<3 GeV/c)
and kaons (p<1.5 GeV/c)



TPC :
0 (-0.5σ) ~ 3σ on electron hypothesis
reject most of pions



EMCAL :
0.8 < E/p < 1.2

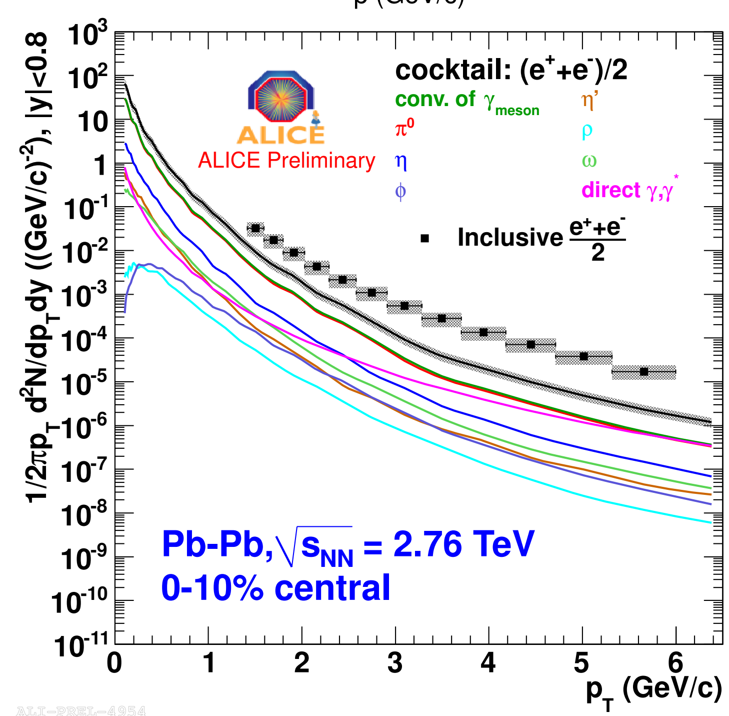


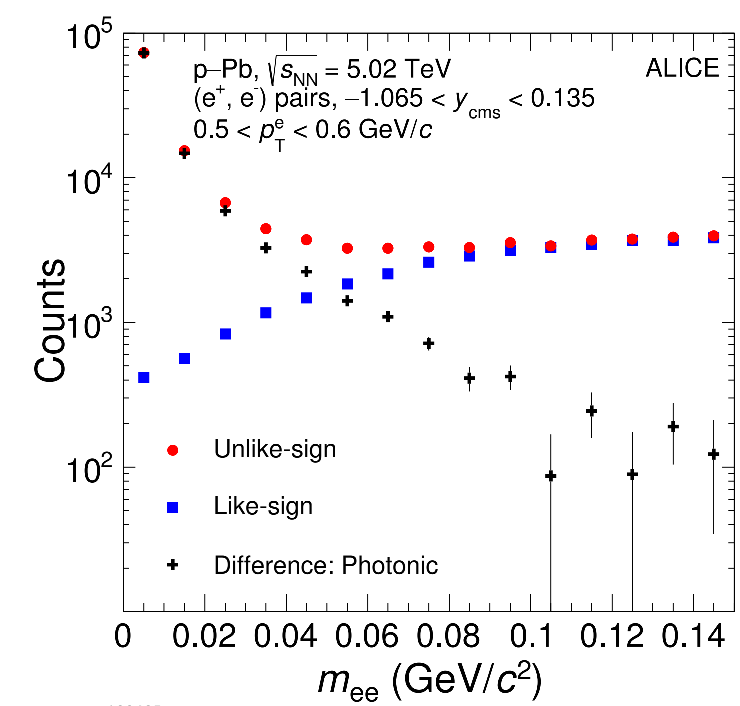
• Background electrons

Dalitz decays of neutral light mesons, photon conversions are main background sources.

Subtracted after electron identification via :

- **cocktail method** : based on measured spectrum of light mesons
- **invariant mass method :** reconstruction of electron-positron pairs from decays of neutral mesons and photon conversions.

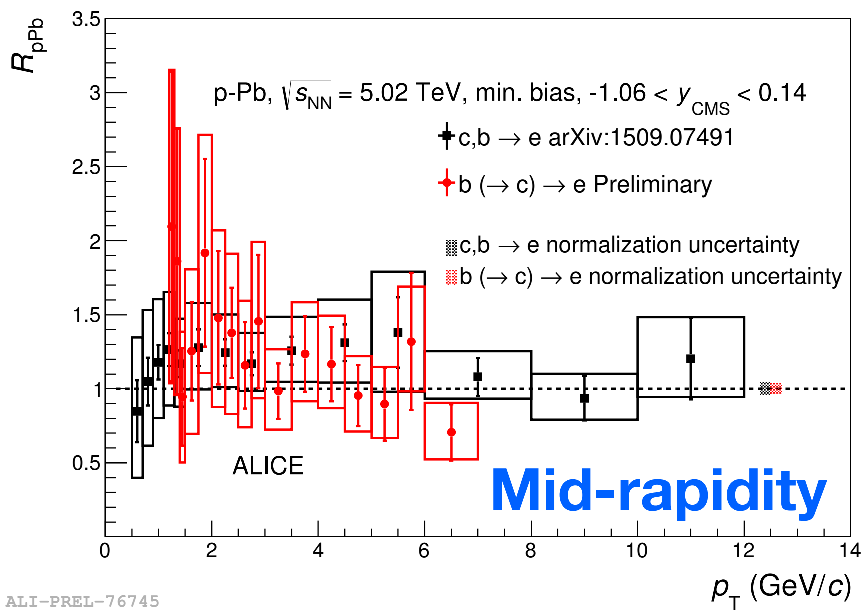




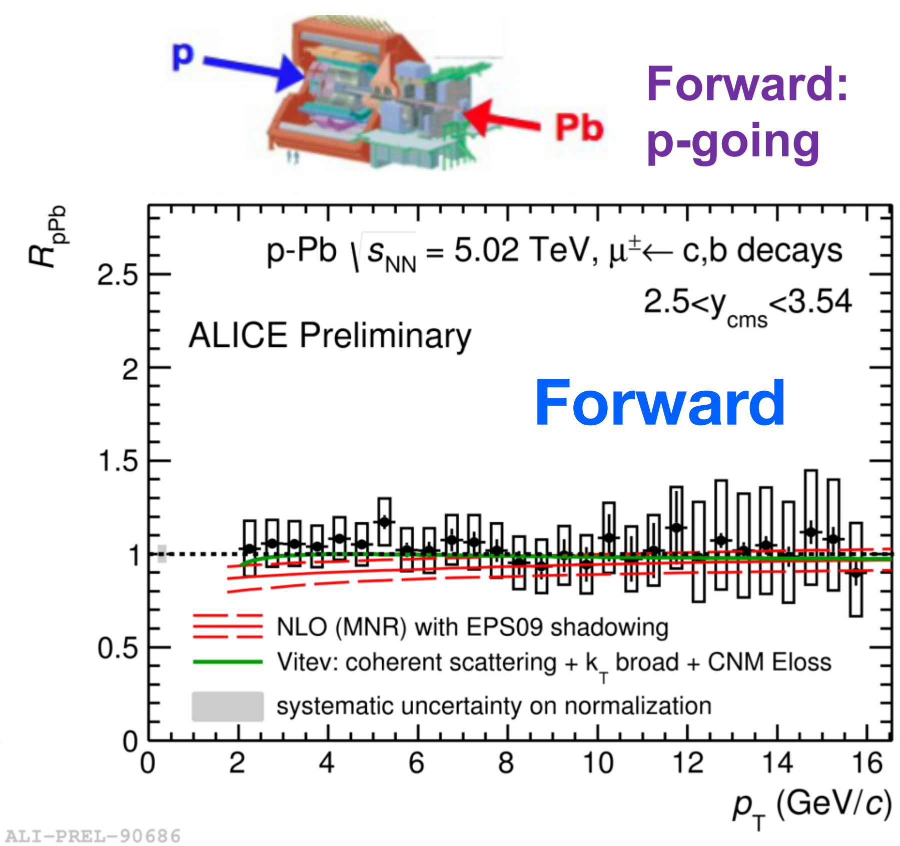
Heavy-flavour nuclear modification factor R_{pPb}

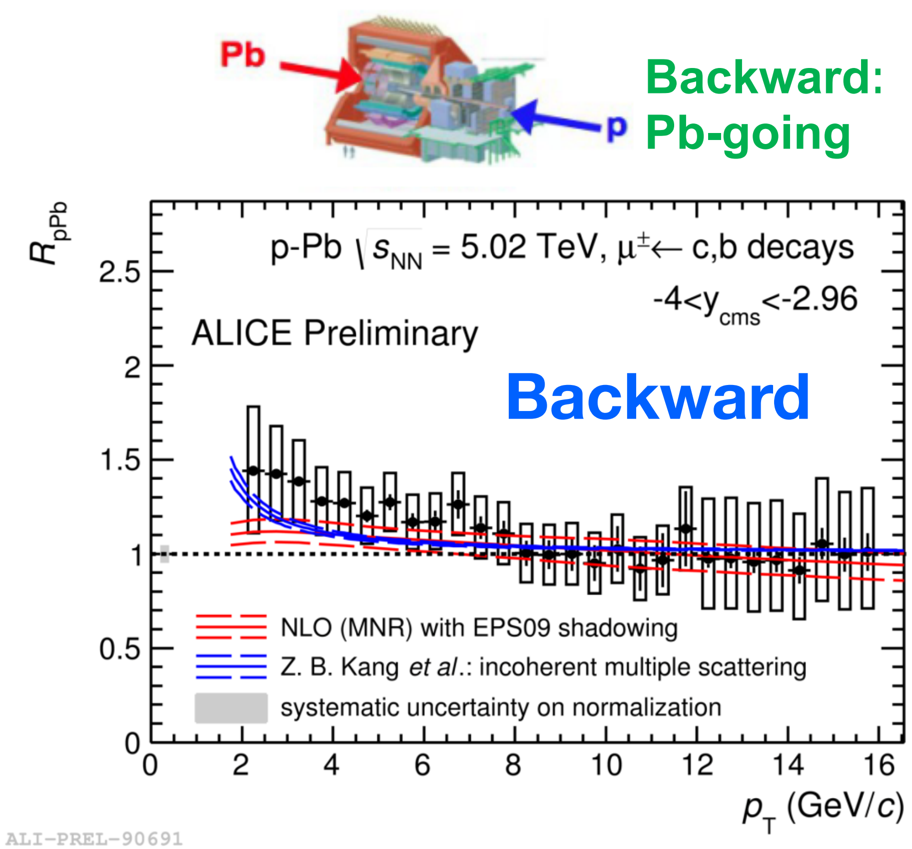
HF-decay electrons

b,c→e
b(→c)→e



HF-decay muons

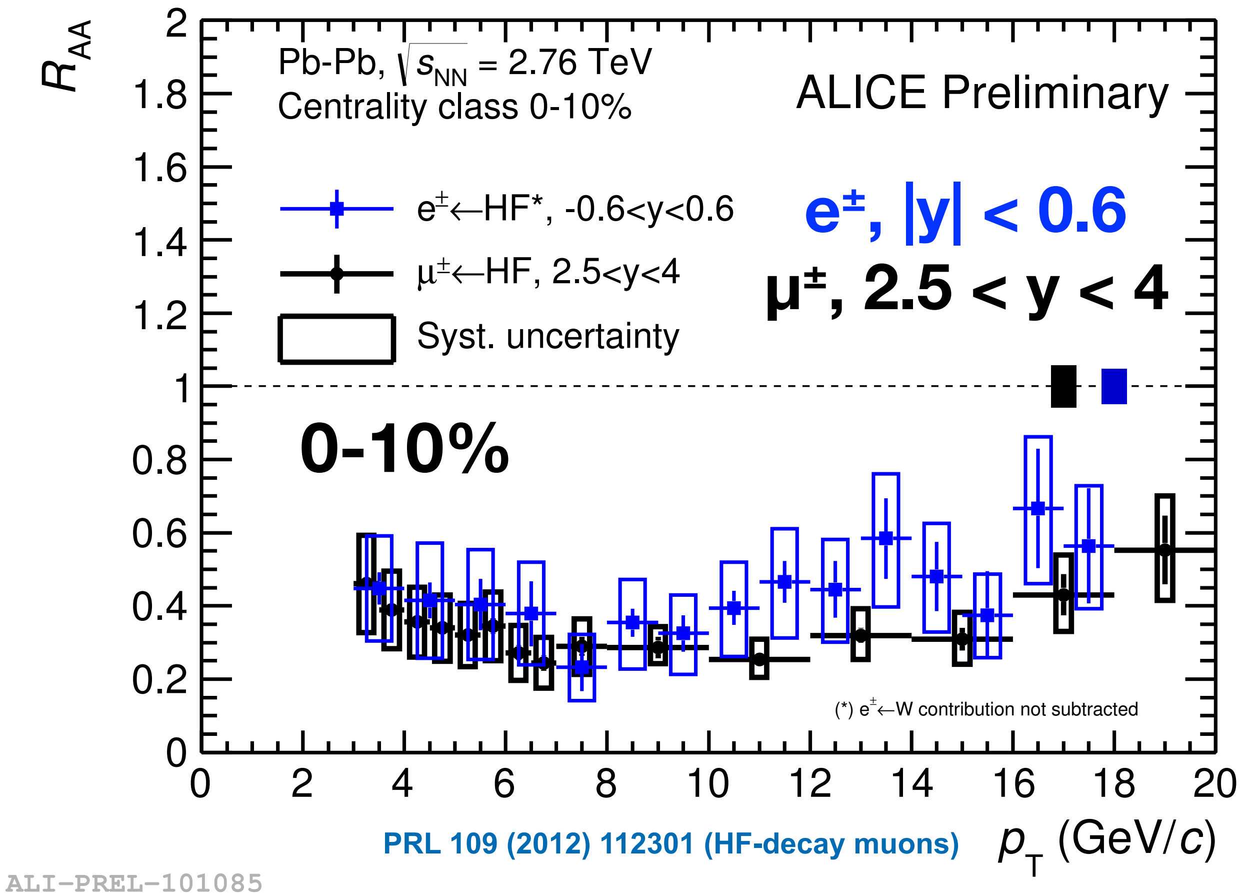




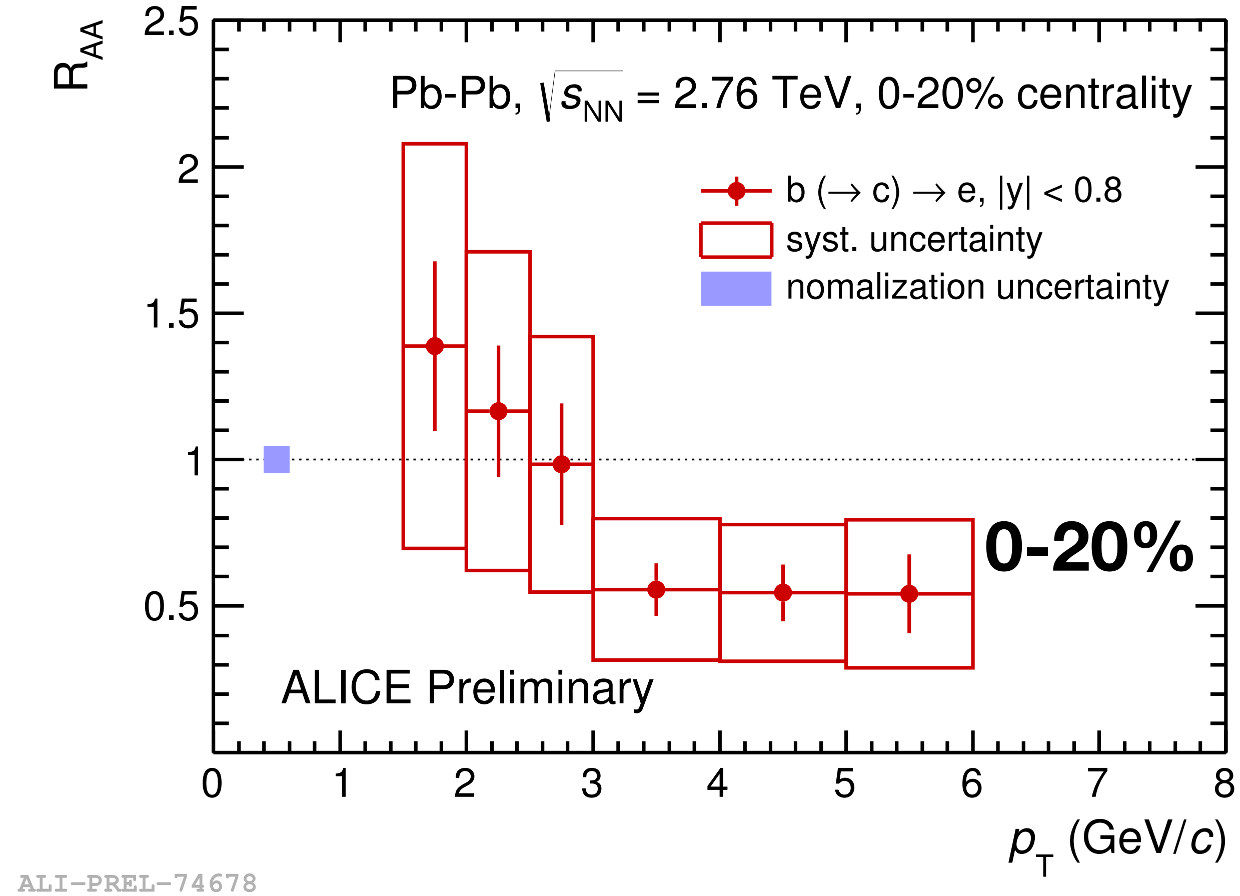
- Different *x* regions can be explored in different rapidity ranges
- Heavy-flavour decay lepton R_{pPb} close to unity for forward/backward and mid rapidity
- Slight enhancement at backward rapidity for 2 < p_T < 4 GeV/c
- Within uncertainties, measurements can be described by models based on pQCD calculations including cold nuclear matter effects

Heavy-flavour nuclear modification factor R_{AA}

inclusive heavy-flavour (c,b) results



beauty-decay electron

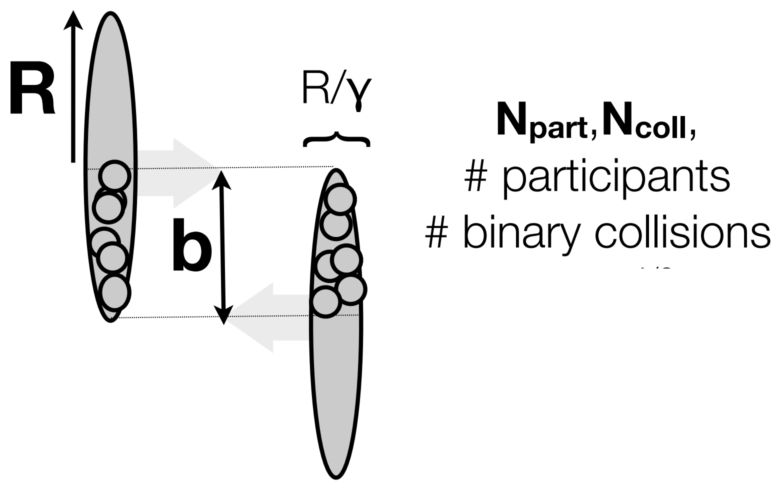


- R_{AA} of heavy-flavour decay electrons (mid rapidity) consistent with that of muons (forward rapidity) ; strong suppression of heavy-flaour decay muons and electrons in the 10% most central collisions
- Suppression of beauty-decay electrons for p_T > 3 GeV/c in 0-20% central Pb-Pb collision.
- Cold nuclear matter effect are not seen in p-Pb collisions → suppression shown here is due to the parton energy loss in the hot and dense medium!

Quantification of medium effects: R_{AA}

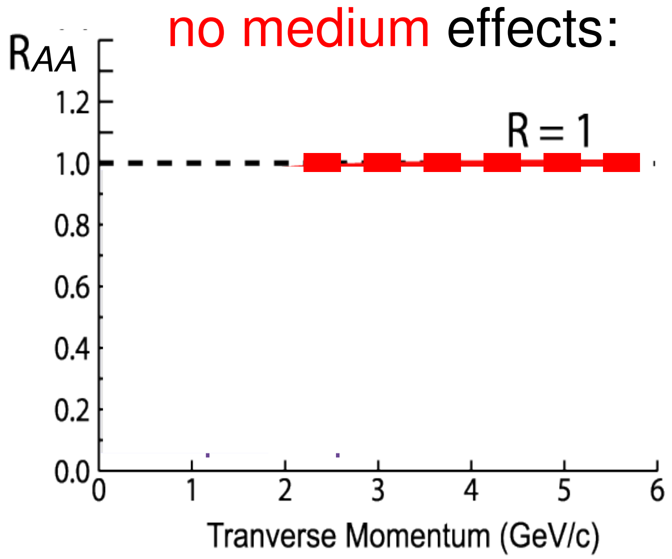
- The standard method to quantify the effects of the medium on the yield of a hard probe in a AA reaction is given by the nuclear modification factor

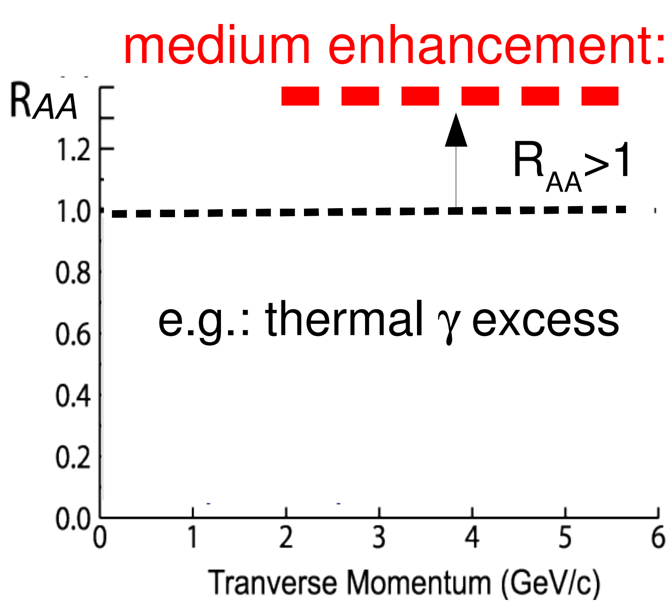
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

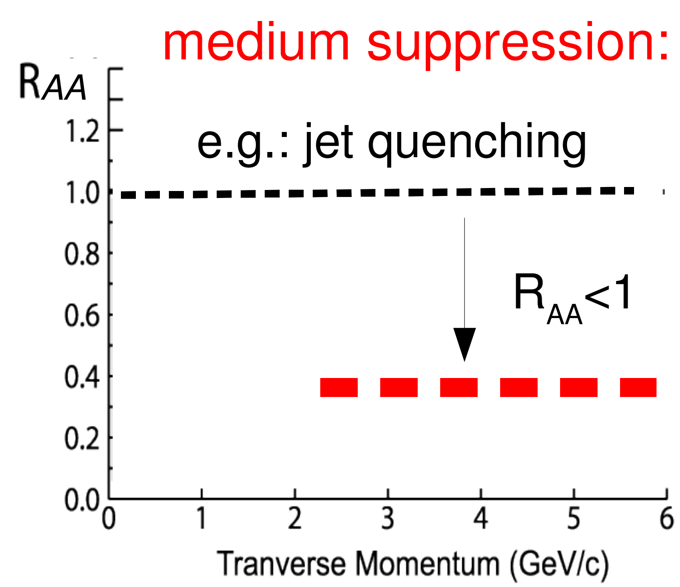


Binary scaling based on the Glauber Model

- R_{AA}=1: AA collision ~ incoherent superposition of NN collisions



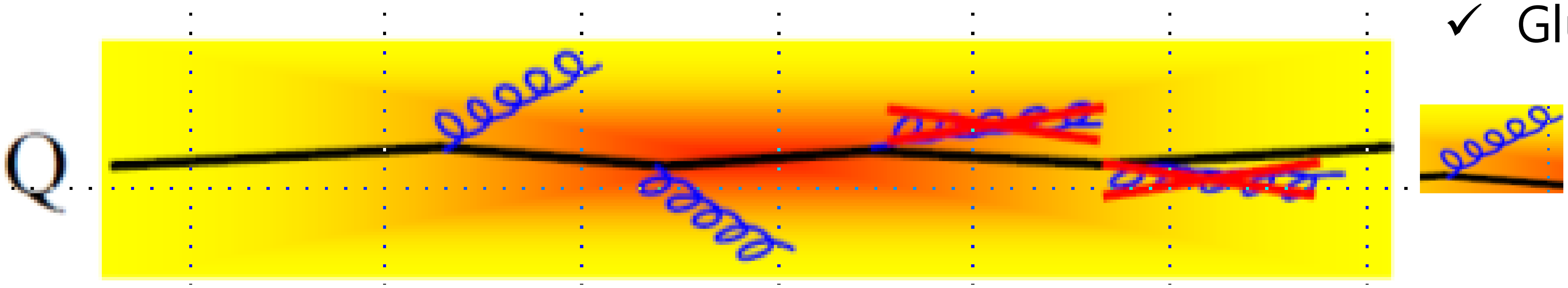




Quantification of medium effects: R_{AA}

Dead Cone Effect

In vacuum, suppression of the small-angle gluon radiation for heavy quark



✓ Gluonsstrahlung Probability

$$\propto \frac{1}{[\theta^2 + (\frac{M}{E})^2]^2}$$

In medium, dead cone implies lower energy loss for heavy quark

Color Charge Dependence of Energy Loss

Gluon radiation spectrum by the parton propagation in the medium

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega)$$

$$where \quad C_R = 3 \;\; for\, g, \; \frac{4}{3} \;\; for\, q$$

Nuclear Modification Factor (R_{AA})

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}$$

$$R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$$

Mass effect

Pions mainly come from gluon

Quantification of medium effects: R_{AA}

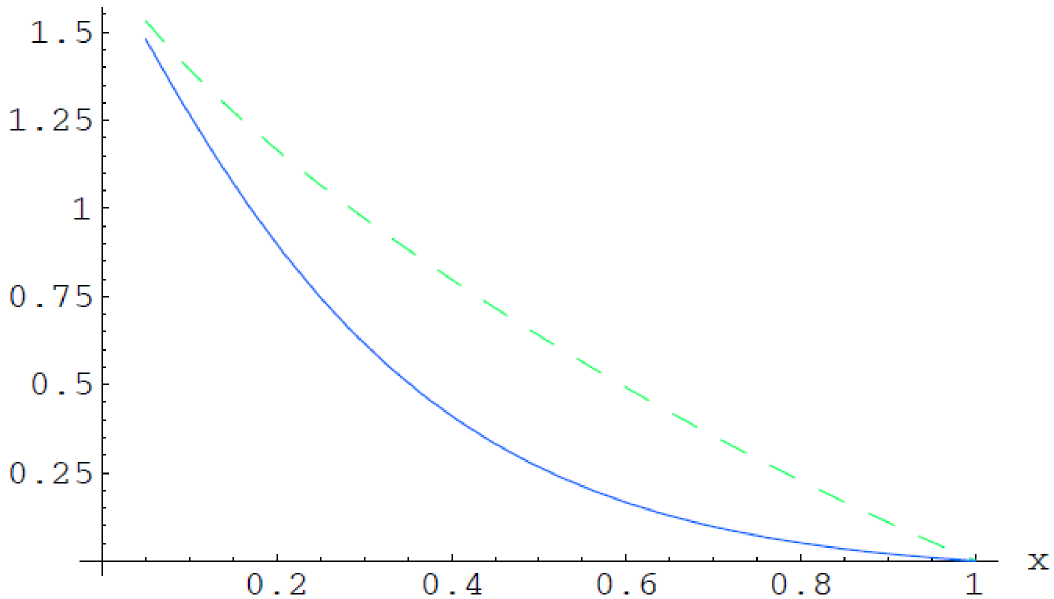
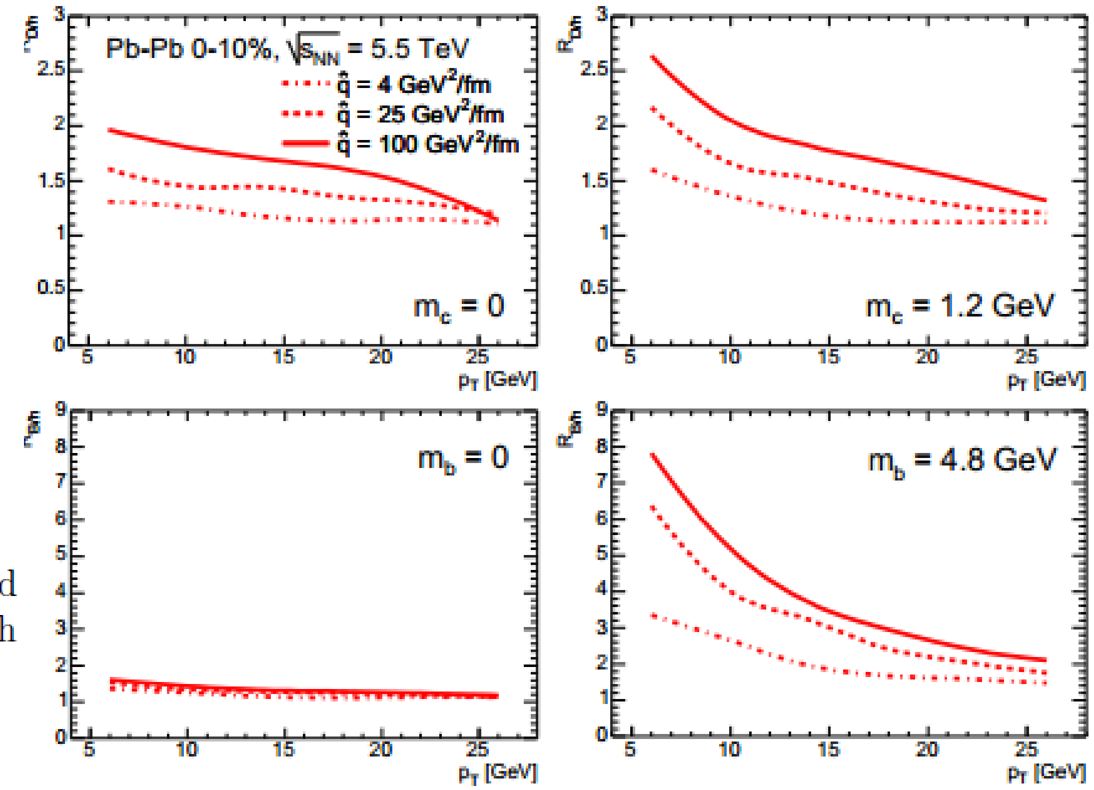


Figure 2: Comparison of energy distributions $\sqrt{x}I(x)$ of gluons radiated off charm (solid line) and light (dashed line) quarks in hot matter with $\hat{q} = 0.2\,\mathrm{GeV}^3$ ($p_\perp = 10\,\mathrm{GeV}$, $L = 5\,\mathrm{fm}$).

$$I(\omega) = \omega\frac{dW}{d\omega} = \frac{\alpha_s\, C_F}{\pi}\sqrt{\frac{\omega_1}{\omega}}\;\frac{1}{(1+(\ell\,\omega)^{3/2})^2},$$

$$\ell \equiv \hat{q}^{-1/3}\,\left(\frac{M}{E}\right)^{4/3}.$$



. 5. Heavy-to-light ratios for D mesons (upper plots) and B mesons (lower for the case of a realistic heavy quark mass (plots on the right) and for a case in which the quark mass dependence of parton energy loss is neglected (plots e left).

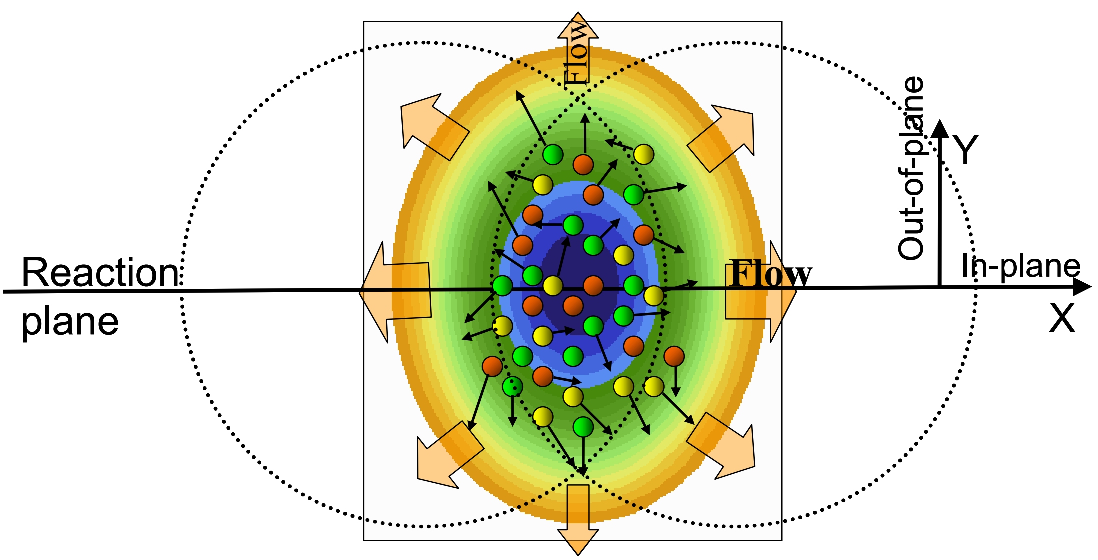
Dokshitzer, Yuri L. *et al.* Phys.Lett. B519 (2001)

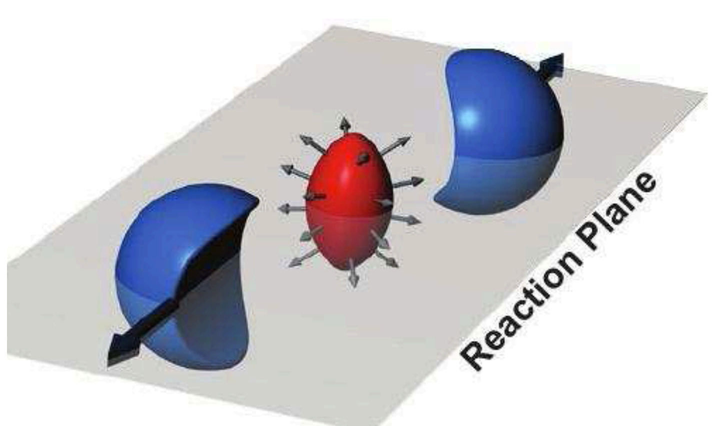
Anisotropic transverse flow: v_2

Initial spatial anisotropy $\xrightarrow[\text{in the medium}]{\text{via re-scatterings}}$ momentum anisotropy of particle emission

The anisotropy is quantified via a Fourier expansion in azimuthal angle (φ) with respect to the reaction plane (Ψ_{RP})

$$\frac{dN}{\;} = \frac{N_0}{\;}(1 + 2v_1\cos(\varphi - \Psi_{RP}) + \boxed{2v_2\cos[2(\varphi - \Psi_{RP})]} + \ldots)$$





- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium
  - $v_2(b) < v_2(c)$
- Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium
  - Transported through the full system evolution

Electrons from B Hadron Decay via IP cut method

1. Charged particle tracks selected fulfilling **track quality** and **eID cuts** (composed by electrons from photon conversion, Dalitz, charm hadron decays, beauty hadron decays)

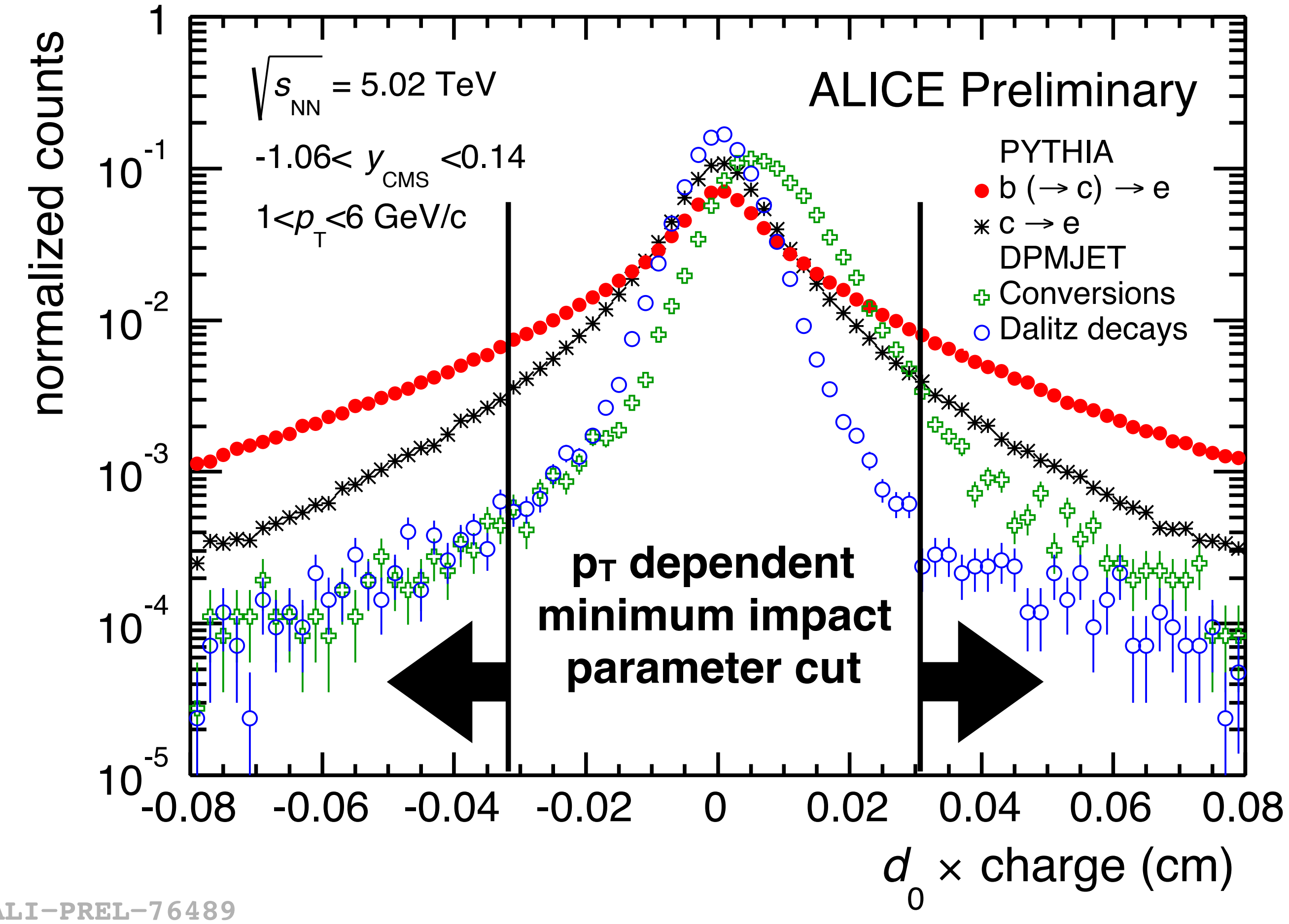
2. Beauty hadron has **cτ ≃ 500 μm** and **hard momentum spectrum,** which leads to **larger impact parameter** of decay electrons than those from background.

➡ Electron tracks from beauty hadron decays features **broader IP distribution** compared to that from background

3. **Minimum impact parameter cut to increase S/B ratio**

4. **Subtract remaining background(nonHFE and charm hadron decay electrons)** based on ALICE measurement

5. Correct subtracted electron spectra for acceptance and efficiency

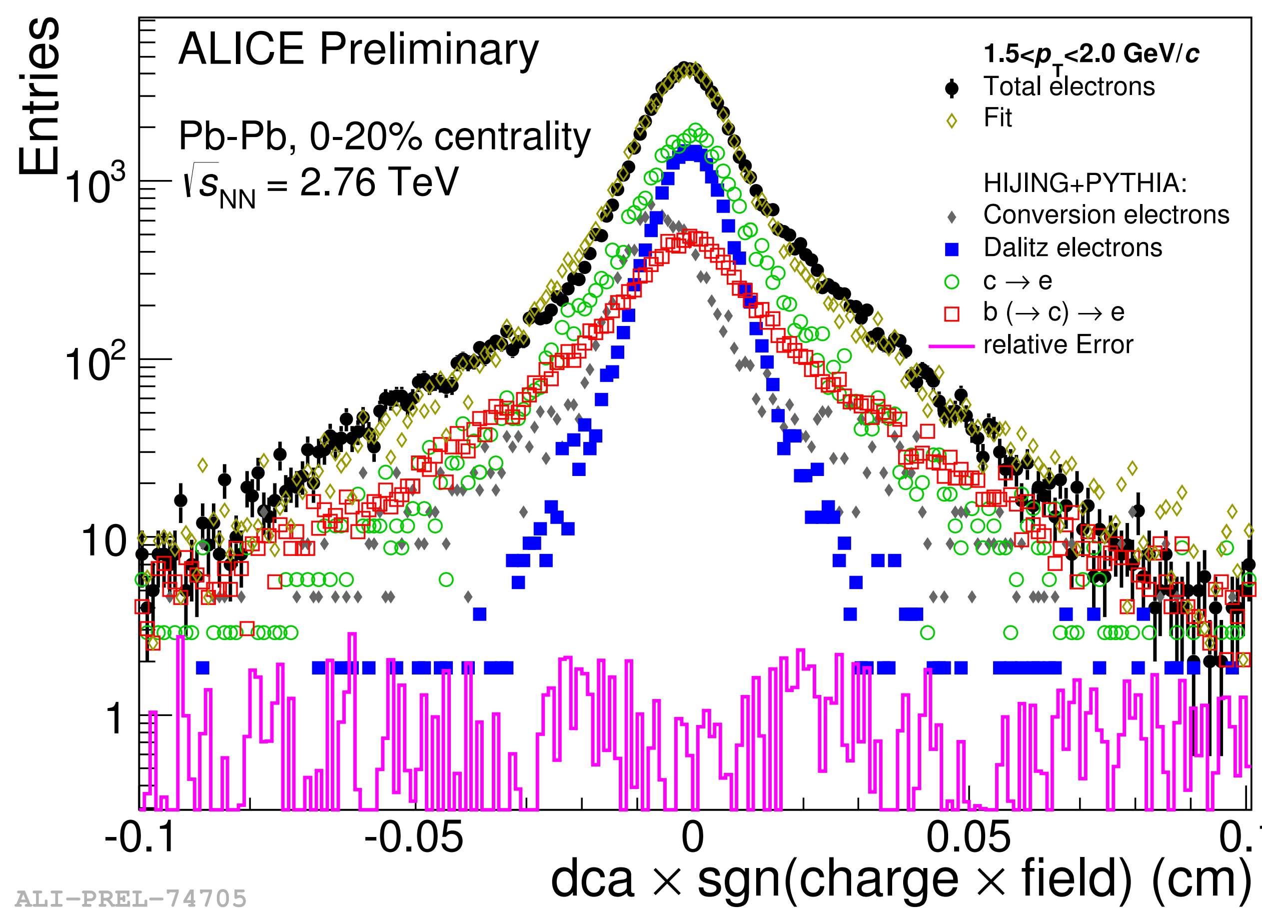


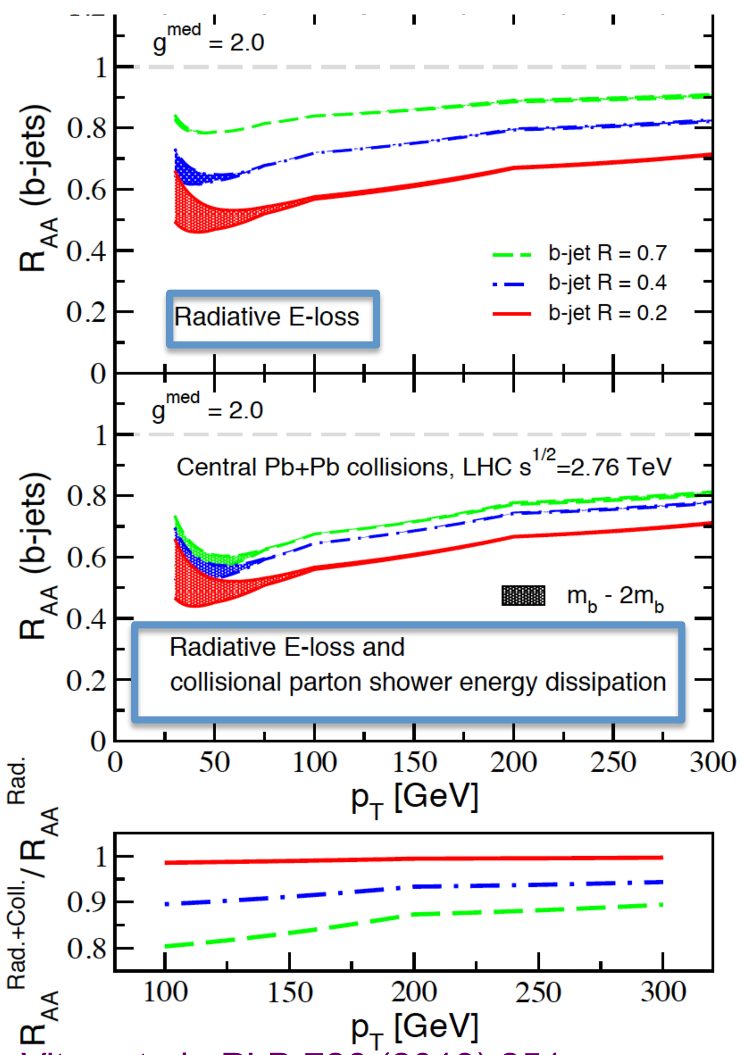
Electrons from B Hadron Decay via IP fit method

1. Charged particle tracks selected fulfilling **track quality** and **eID cuts** (composed by electrons from photon conversion, Dalitz, charm hadron decays, beauty hadron decays)
2. Beauty hadron has **cτ ≃ 500 μm** and **hard momentum spectrum,** which leads to **larger impact parameter** of decay electrons than those from background.

➡ Electron tracks from beauty hadron decays features **broader IP distribution** compared to that from background

3. **Get Impact Parameter distributions of electrons from different sources from MC as template for each p_T bins**
4. Assume unknown expectation value of MC templates in each bin(additional free parameters)
5. The sum of the expectation values for each source weighted by the fit parameter is the expectation value for all electrons in each bin
6. Look for the maximum likelihood for the variation of all free parameters
7. Maximization for many free parameters possible





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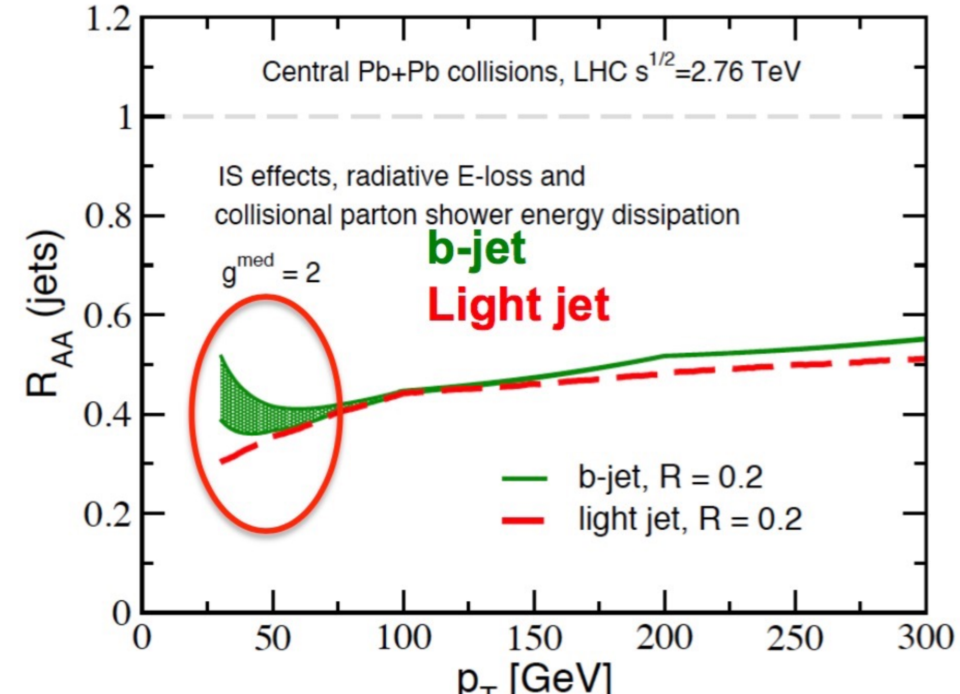
R_{AA} for different R:

Information on **dissipation of energy** in the medium

Information on **different energy loss mechanisms**: radiative vs collisional

extension to low pT region is necessary



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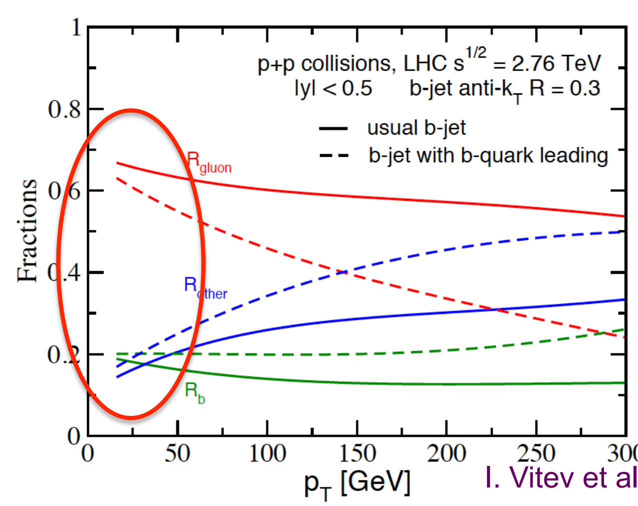
Fraction of b-jets coming from:
- **bb pair creation**
- **Gluon splitting**
- **Other**

(Based on PYTHIA, model dependent)



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pp collisions 2.76 TeV

B-jets dominated by gluon splitting in large p_T range

Time for gluon splitting < medium size. In HI, the mass effect could still be observed as consequence of the massive gluon traversing the QGP.

Azimuthal correlation studies and/or jet shapes could give sensitivity to the contribution of b-jets from gluon splitting