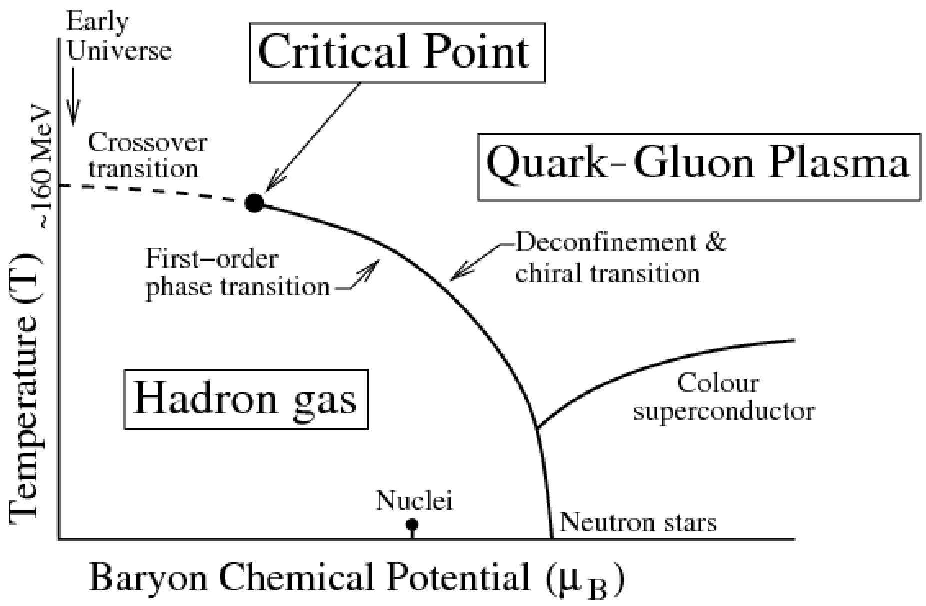
Heavy Flavor jets in ALICE

Artem Isakov for the ALICE collaboration

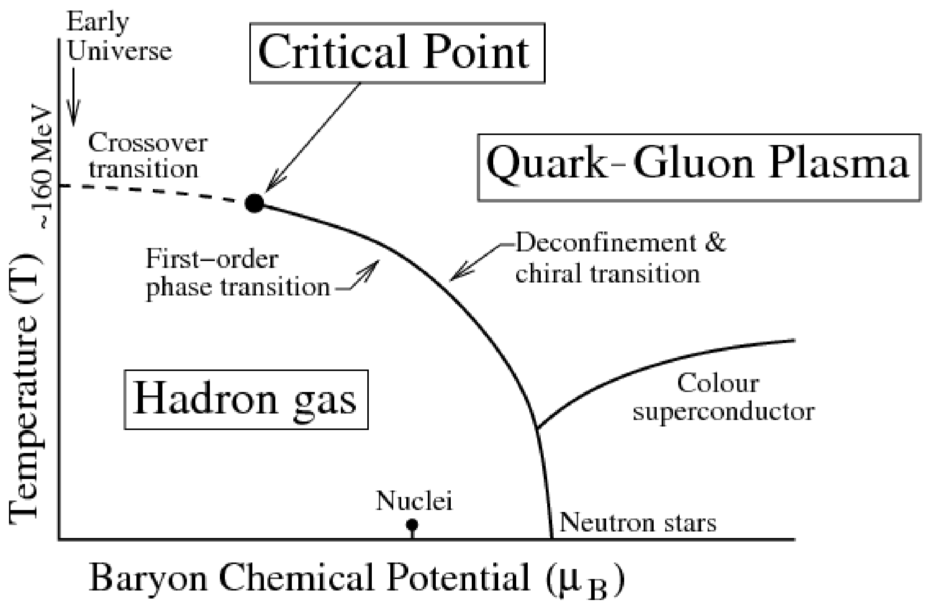
NPI CAS

ICNFP 2019, Crete, 28.05.2019

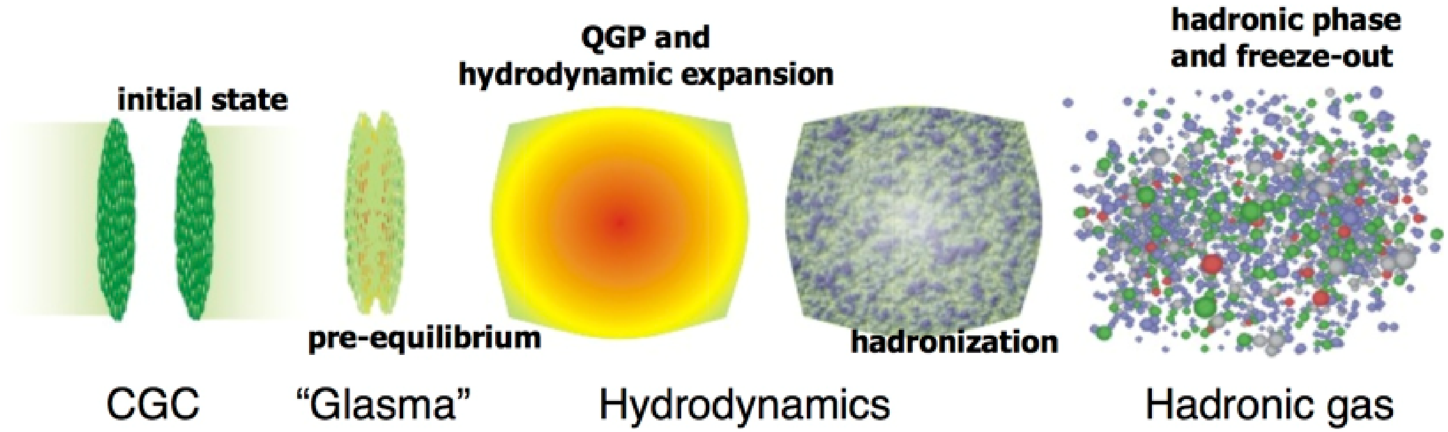
Introduction



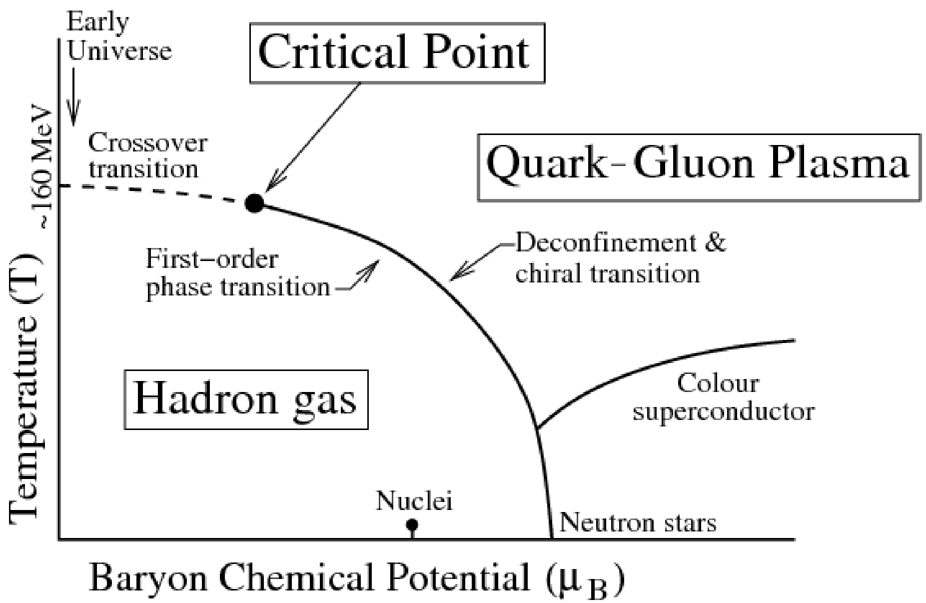
Introduction



Quark Gluon Plasma (QGP) is created in heavy-ion collisions



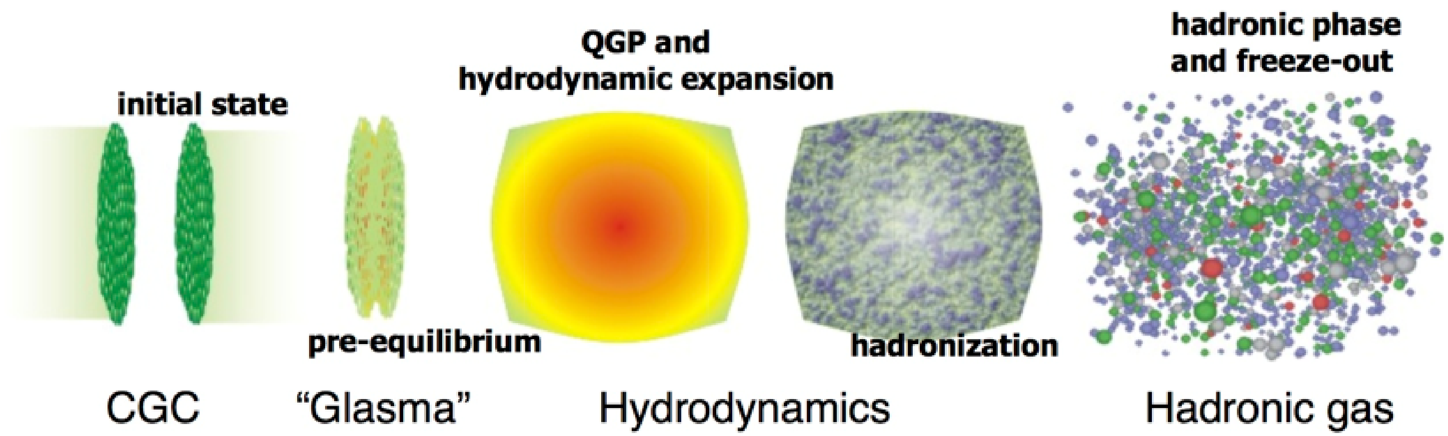
Introduction



Signatures of QGP:

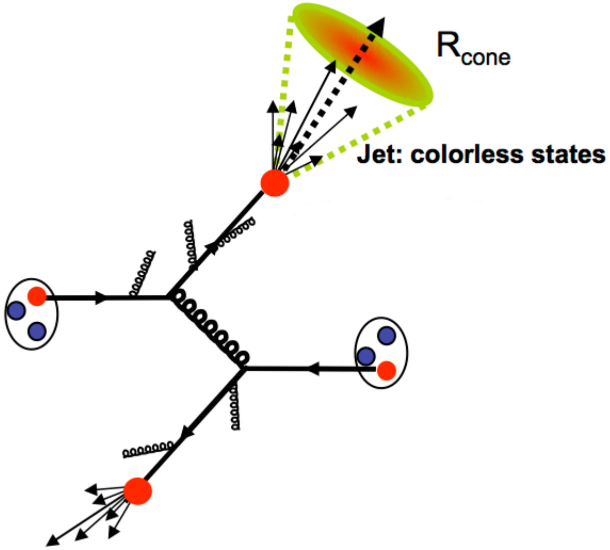
- **Collective flow:**
  QGP acts like nearly-perfect liquid
- ***Jet quenching:***
  QGP slows penetrating patrons
- …..

Quark Gluon Plasma (QGP) is created in heavy-ion collisions



Jets

Jet – a collimated spray of hadrons, created during hadronization of quark or gluon after hard scattering, defined via algorithm



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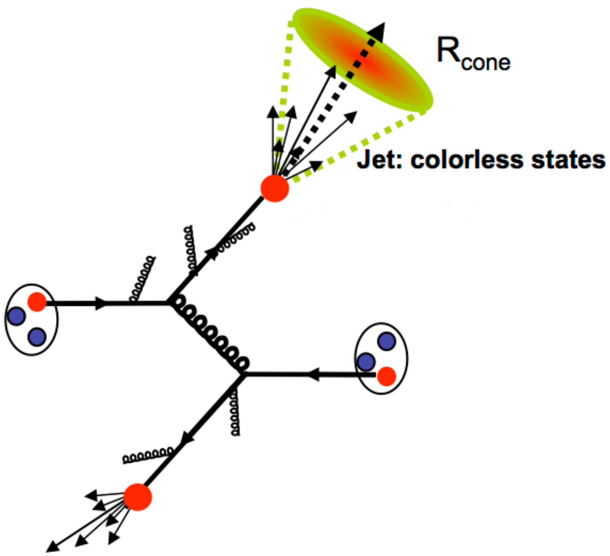


Features of heavy-flavor quarks:

- Large mass → it can be created only in initial hard scatterings. Its production rate can be calculated from pQCD
- Long lifetime → it survives through the whole evolution of QGP
- Smaller energy loss by radiative process for quarks with higher mass (Dead-cone effect[*])

$$\Delta E_{g}^{rad} > \Delta E_{u,s,d}^{rad} > \Delta E_{c}^{rad} > \Delta E_{b}^{rad}$$

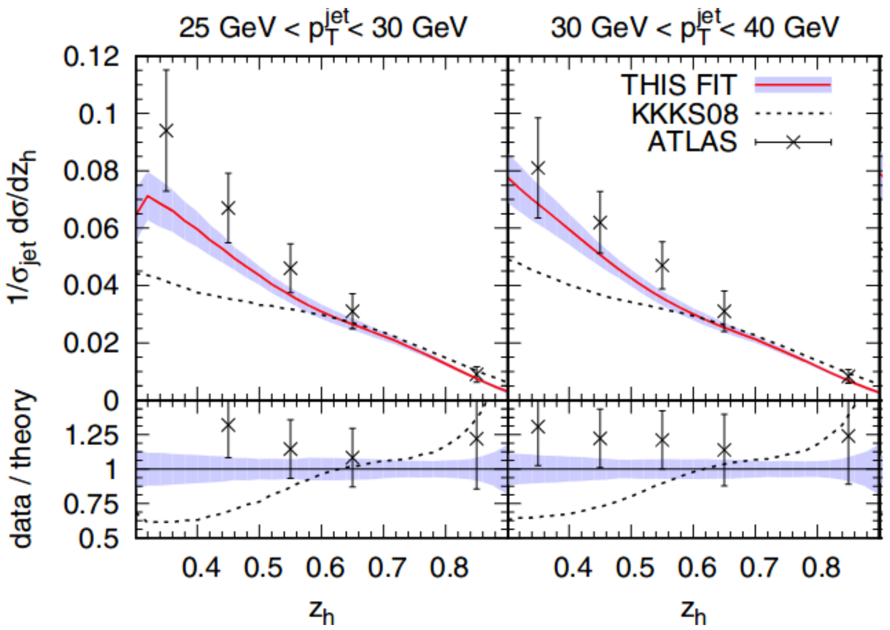
[*] Yu.L. Dokshitzer, D.E. Kharzeev - "Heavy Quark Colorimetry of QCD Matter", arXiv:hep-ph/0106202]

Fragmentation function

- **Fraction of the jet momentum** carried by the tagged meson along axis direction

$$z_{\|}=\frac{\vec{p}_{\mathrm{jet}}\cdot\vec{p}_{\mathrm{tagged}}}{\vec{p}_{\mathrm{jet}}\cdot\vec{p}_{\mathrm{jet}}}$$

- In **pp**, constrains models
- In **AA** collisions, enables to study medium-induced modification of collinear **fragmentation for HF quarks**



D.P. Anderle et al., D*±-jets, pp, 7 TeV. [PRD 96 (2017) 034028]

Nuclear modification factor

- **Nuclear modification factor** compares particle yield in HI and binary scaled pp collisions

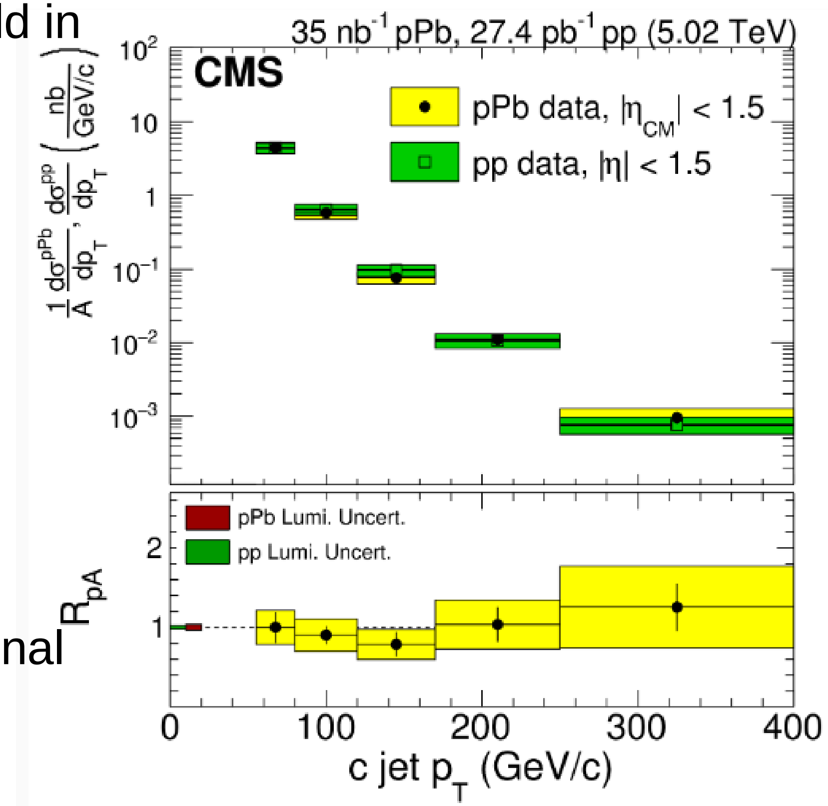
$$R_{AA} = \frac{dN_{AA}/dp_T}{<N_{coll}> \cdot dN_{pp}/dp_T}$$

In pA collision system:

- If R_{pA} != 1 → presence of CNM effects

In AA collision system:

- If $R_{AA} < 1$ at intermediate-high p_T → indication of final state effects (in medium energy loss)



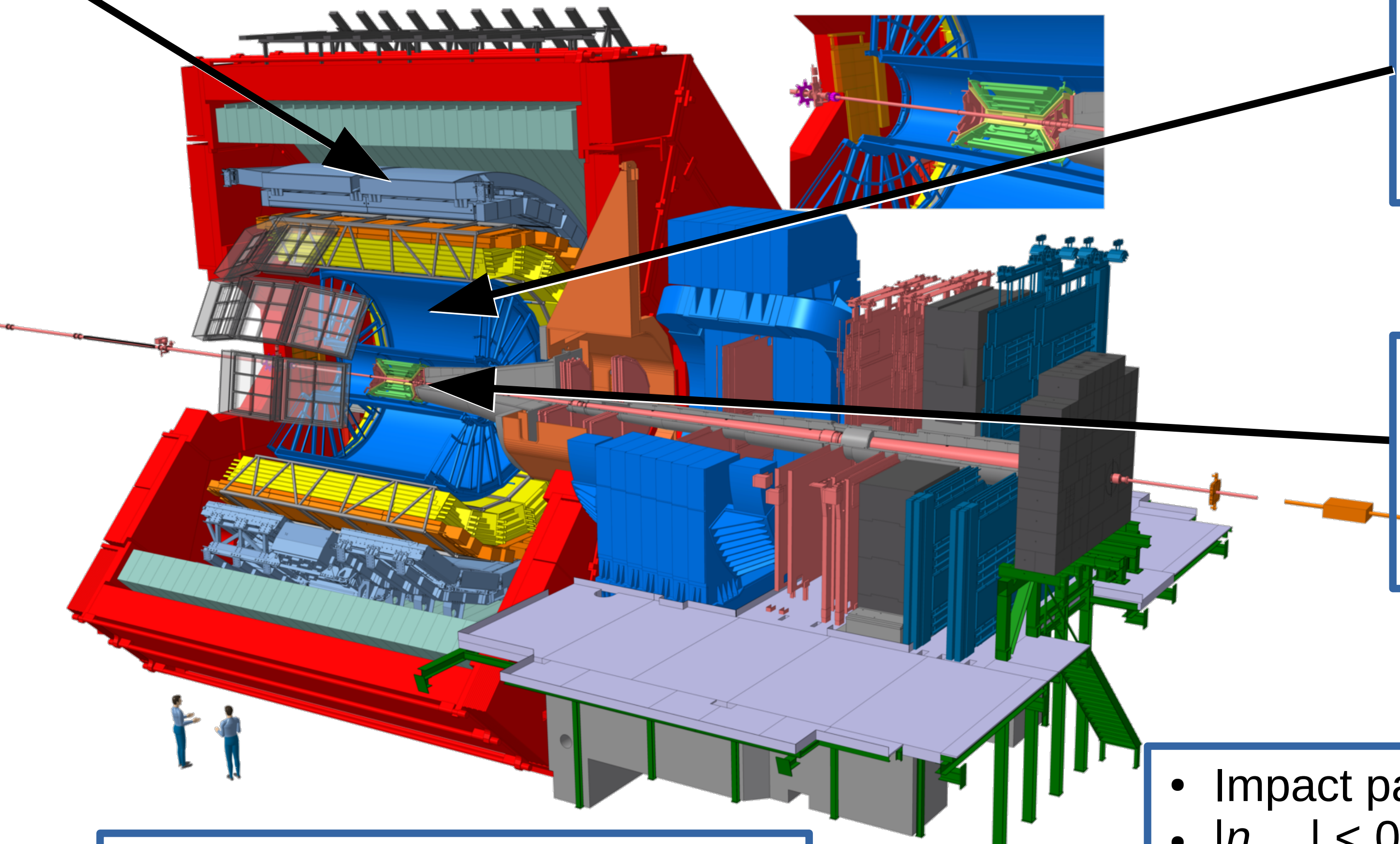
CMS, Phys.Lett. B 772 (2017) 306–329er

ALICE is focused on **low-p_T sector**

ALICE experiment

EMCal
- Triggering and reconstrunction of high-p_T jets
- Measurements of high-p_T $e^{\pm}$ and γ

Time Projection Chamber
- Track reconstruction
- Particle identification via dE/dx



Inner Tracking System
- Track reconstruction
- Primary and secondary vertex reconstruction

V0
- Scintillator array for triggering
- Estimation of centrality

- Impact param. res. < 70 μm at 1 GeV/c
- $|\eta_{track}| < 0.9$
- Full azimuth
- 0.5 T solenoid

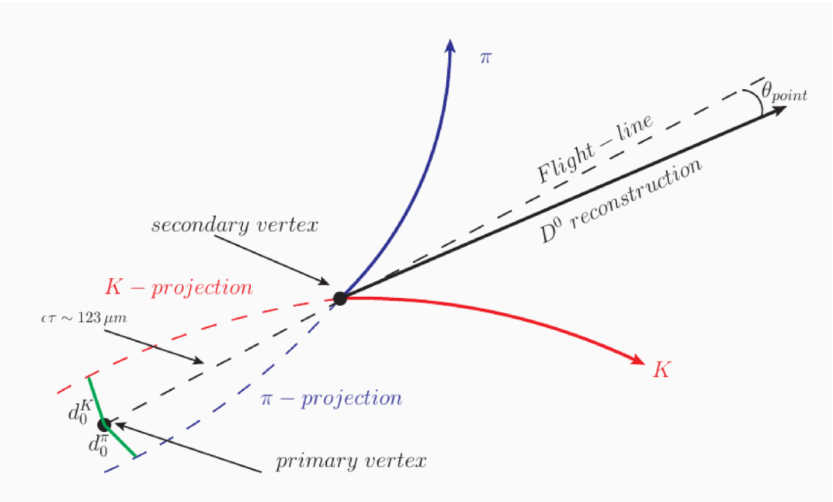
D^0 - tagged jets in pp at $\sqrt{s}$ = 7 TeV: Analysis overview

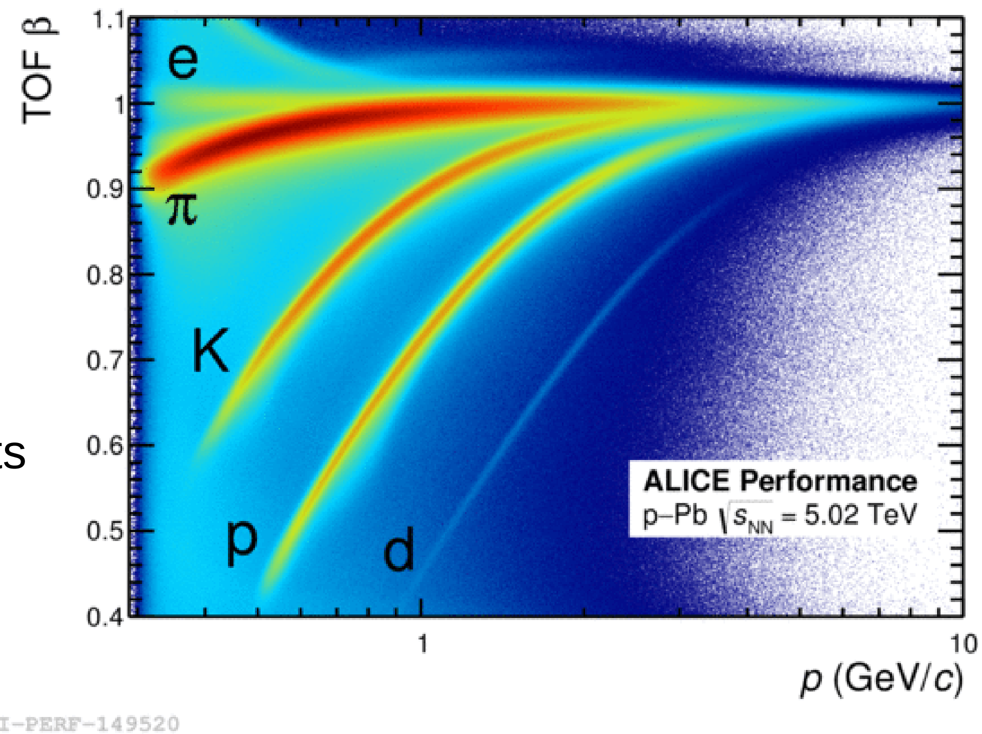
1) D^0 - meson selection

- Hadronic decay channel:

$$D^0 \rightarrow K^- \pi^+, \text{BR} = 3.89\%$$
$$\overline{D^0} \rightarrow K^+ \pi^-$$

- D^0 decay vertex is reconstructed from a pair of tracks with opposite charge
  - $|\eta_{track}| < 0.8$
  - $p_{T,\,track} > 0.3$ GeV/c
- PID selection: TPC dE/dx, TOF
- Topological cuts
  - Sum of D^0 daughter momenta points to the PV
  - Geometrical selections





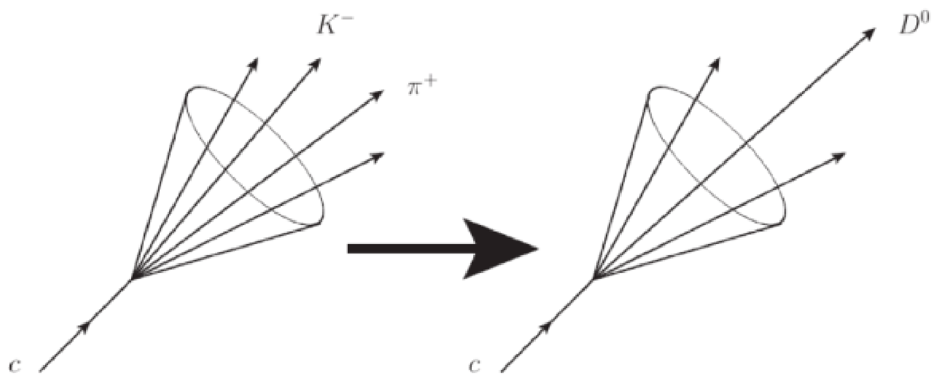
ALICE, to be published in JHEP

D^0 - tagged jets in pp at $\sqrt{s}$ = 7 TeV: Analysis overview

1) D^0 - meson selection

2) Jet reconstruction and D^0-meson tagging

- Before jet reconstruction π and K daughters are removed and replaced by the mother D^0
- Charged tracks
- $|\eta| < 0.8$
- FASTJET Anti-k_T jet finding algorithm with jet radius R = 0.4
- $p^{ch}_{T,jet} > 5$ GeV/c, $p_{T,D} > 3$ GeV/c
- Only one D^0 candidate per one jet



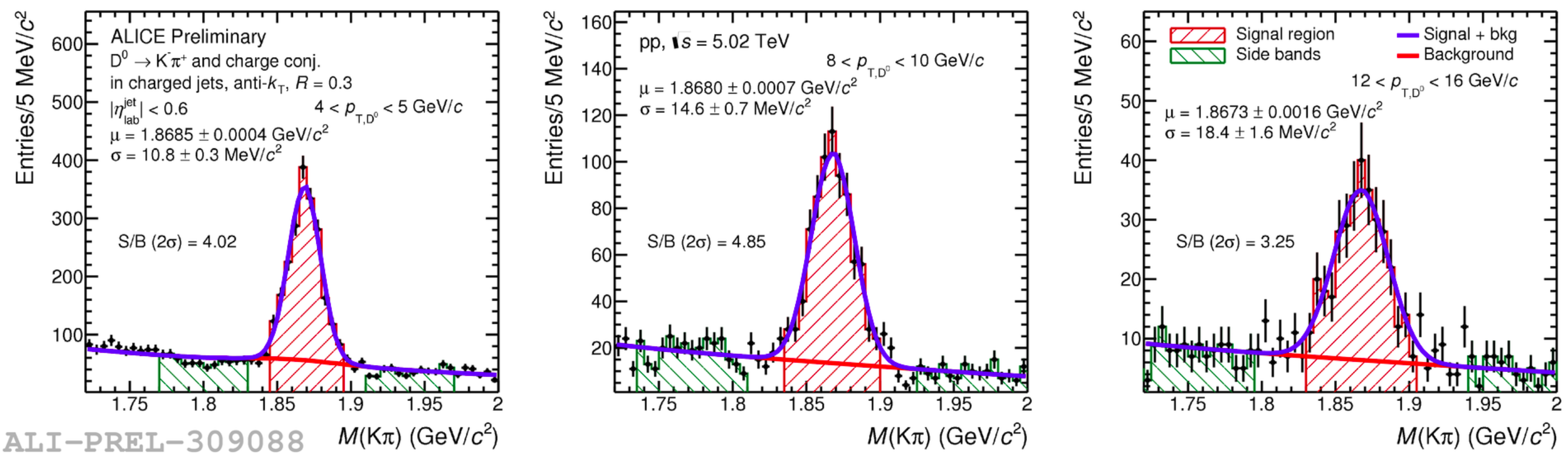
D^0 - tagged jets in pp at $\sqrt{s}$ = 7 TeV: Analysis overview

1) D^0 - meson selection

2) Jet reconstruction and D^0-meson tagging

3) D^0-meson tagged jet yield extraction

- For each D^0 p_T bin, K and π invariant mass spectrum was fitted with a sum of background, reflection template and signal shapes
- D^0-jet candidates were corrected for background by means of side-band method



D^0 - tagged jets in pp at $\sqrt{s}$ = 7 TeV: Analysis overview

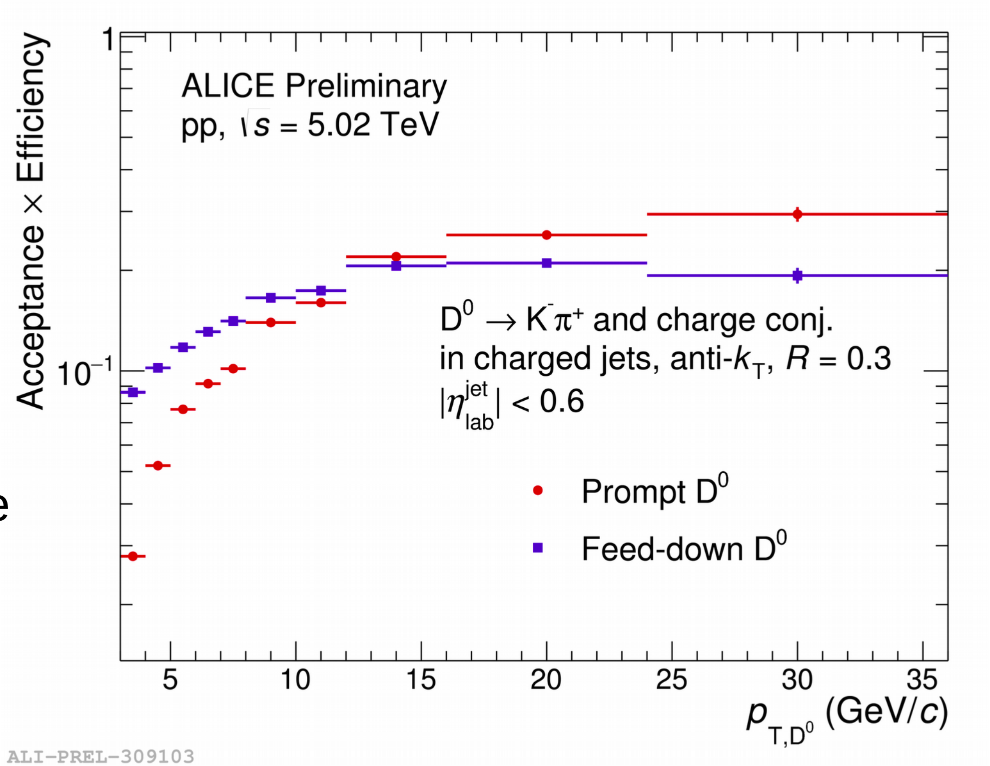
1) D^0 - meson selection

2) Jet reconstruction and D^0-meson tagging

3) D^0-meson tagged jet yield extraction

4) Corrections

- Efficiency of the track reconstruction and of the topological cuts (PYTHIA6 Perugia 2011)
- B Feed-down contrubution (PYTHIA6 + POWHEG)
- Unfolded for detector effects
- Cross-section calculted with formula:

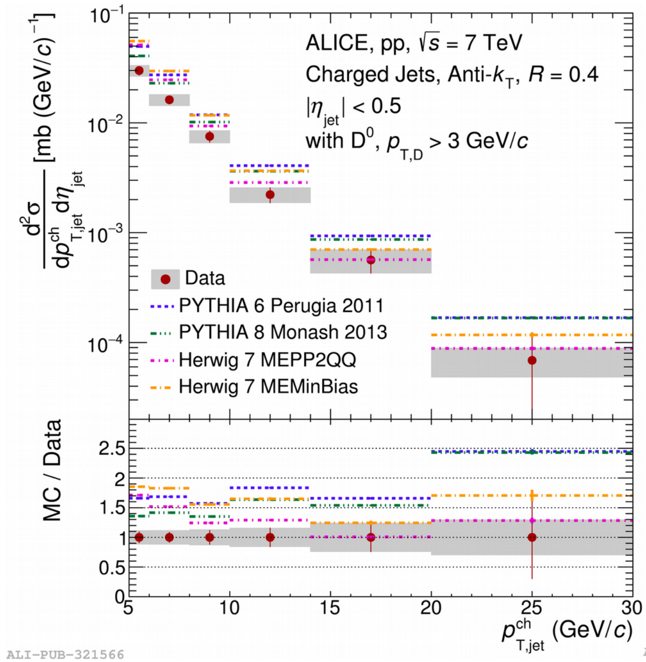


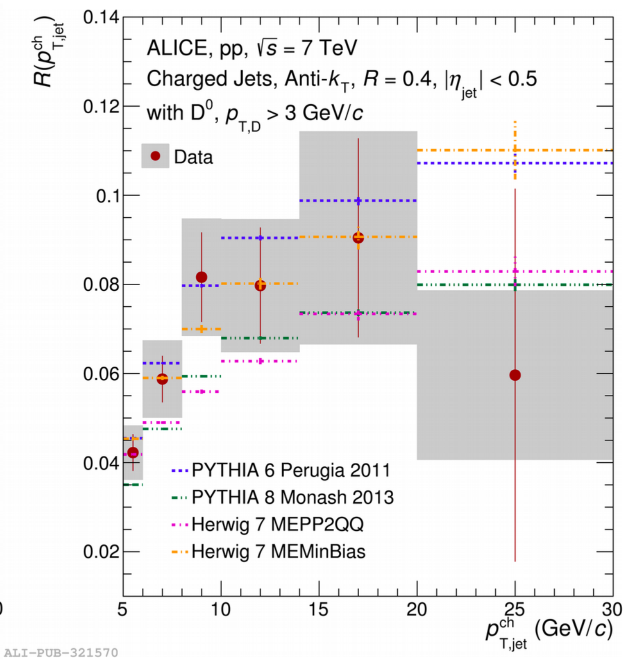
$$\frac{d^2\sigma}{d\,p^{ch}_{T,jet}\,d\,\eta_{jet}}\left(p^{ch}_{T,jet}\right)=\frac{1}{\mathscr{L}}\,\frac{1}{BR}\,\frac{N\left(p^{ch}_{T,jet}\right)}{\Delta\,\eta_{jet}\,\Delta\,p^{ch}_{T,jet}}$$

D^0 - tagged jets in pp at $\sqrt{s}$ = 7 TeV: Production cross-section

Fraction of D^0 jets in inclusive jets:

$$R\left(p_{\mathrm{T,jet}}^{\mathrm{ch}}\right)=\frac{N_{\mathrm{D^0\,jet}}\left(p_{\mathrm{T,jet}}^{\mathrm{ch}}\right)}{N_{\mathrm{inclusive\ jet}}\left(p_{\mathrm{T,jet}}^{\mathrm{ch}}\right)}$$





Comparison to models:

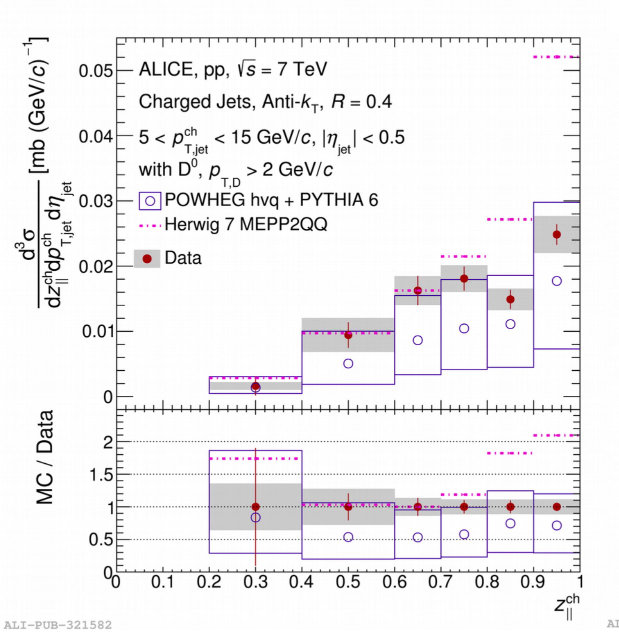
- Cross-section: Both versions of PYTHIA overestimate the yield by a factor ≈ 1.5
- Ratio for D^0 and inclusive jets: All models describe quite well the ratio of D^0-meson tagged jets over the inclusive jet production

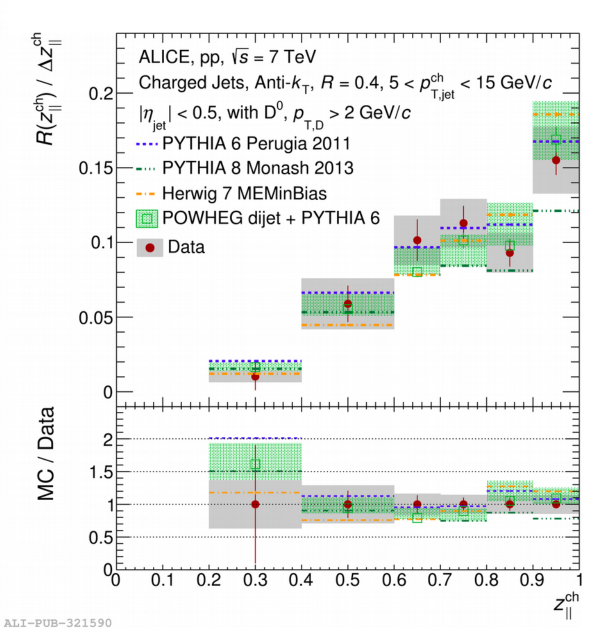
D^0 - tagged jets in pp at $\sqrt{s}$ = 7 TeV: D^0-jet cross section as a function of $z_{||}^{ch}$

- Momentum fraction carried by the D^0 meson in the direction of the jet axis:

$$z_{||}^{ch} = \frac{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{D^0}}{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{ch jet}}}$$

$$R(p_{\text{T,jet}}^{ch}, z_{||}^{ch}) = \frac{N_{D^0 \text{jet}}(p_{\text{T,jet}}^{ch}, z_{||}^{ch})}{N_{\text{inclusive jet}}(p_{\text{T,jet}}^{ch})}$$





- **5 < $p^{ch}_{\text{T, jet}}$ < 15 GeV/*c***

- Good agreement with Herwig 7 and PYTHIA6/8 generators, POWHEG+ PYTHIA6 simulations

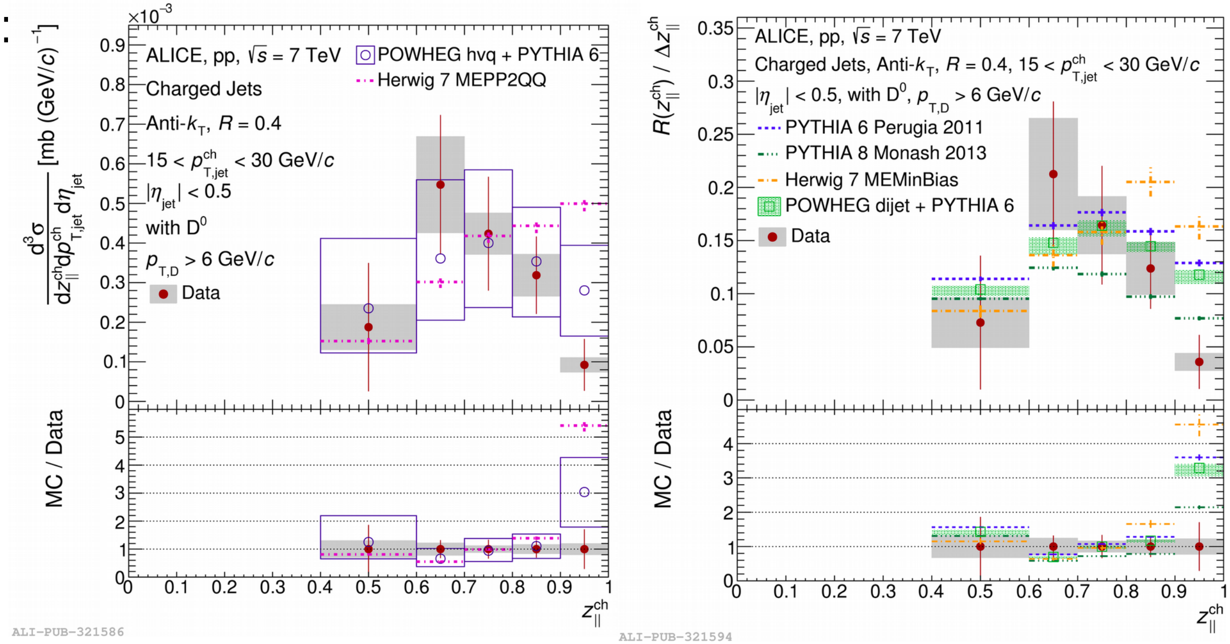
D^0 - tagged jets in pp at $\sqrt{s}$ = 7 TeV: D^0 jet cross section as a function of $z_{||}^{ch}$

- Momentum fraction carried by the D^0 meson in the direction of the jet axis:

$$z_{||}^{ch} = \frac{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{D^0}}{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{ch jet}}}$$

$$R\left(p_{\text{T,jet}}^{ch}, z_{||}^{ch}\right) = \frac{N_{D^0\,\text{jet}}\left(p_{\text{T,jet}}^{ch}, z_{||}^{ch}\right)}{N_{\text{inclusive jet}}\left(p_{\text{T,jet}}^{ch}\right)}$$

- **15 < $p^{ch}_{\text{T, jet}}$ < 30 GeV/c**

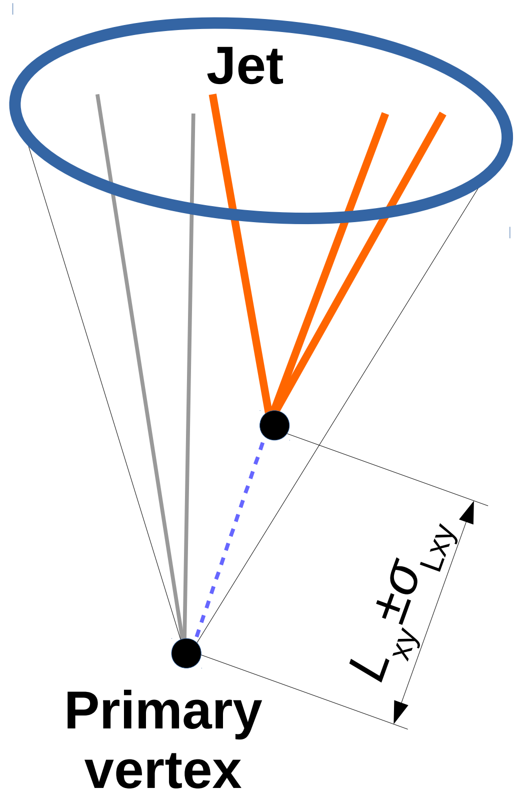


- Good agreement with PYTHIA6/8 generators, but Herwig7 shows some tension at high $z_{||}^{ch}$
- POWHEG+ PYTHIA6 simulations for $z_{||}^{ch}$ < 0.9

B jets in p-Pb at $\sqrt{s_{NN}}$= 5.02 TeV: Analysis overview

1) Jet reconstruction

- Charged anti-k_T, R = 0.4
- $p_{T,\ constituent}$ > 0.15 GeV/c
- $|\eta_{jet}| < 0.9 - R < 0.5$
- $|z_{vtx}|$ < 10 cm
- p_T of the jets corrected on the mean underlying event density



1) Jet reconstruction

2) B-Jet candidate selection

- SV constructed out of 3 prongs
- The most displaced SV considered in each event
- Discrimination variables:

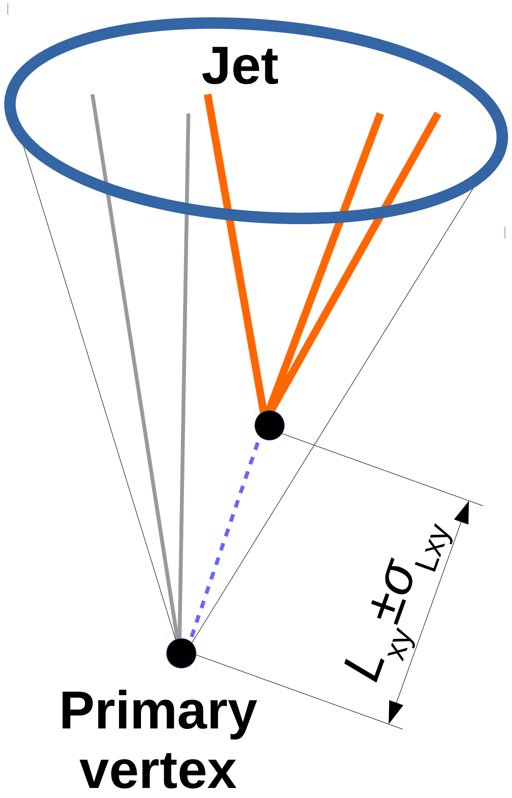
1) Significance of the distance between PV and SV:
- SLxy = Lxy/σLxy > 5, 6, 7, 8, 9

- 2) Dispersion of the SV σ_{SV} < 0.02, 0.03, 0.04, 0.05 cm

$$\sigma_{SV}=\sqrt{\sum_{i=1}^{3} d_i^2}$$

d_i – distance of the closest approach (DCA) of *i*-th prong to SV

3) Invariant mass in SV *(reserved for purity estimation)*



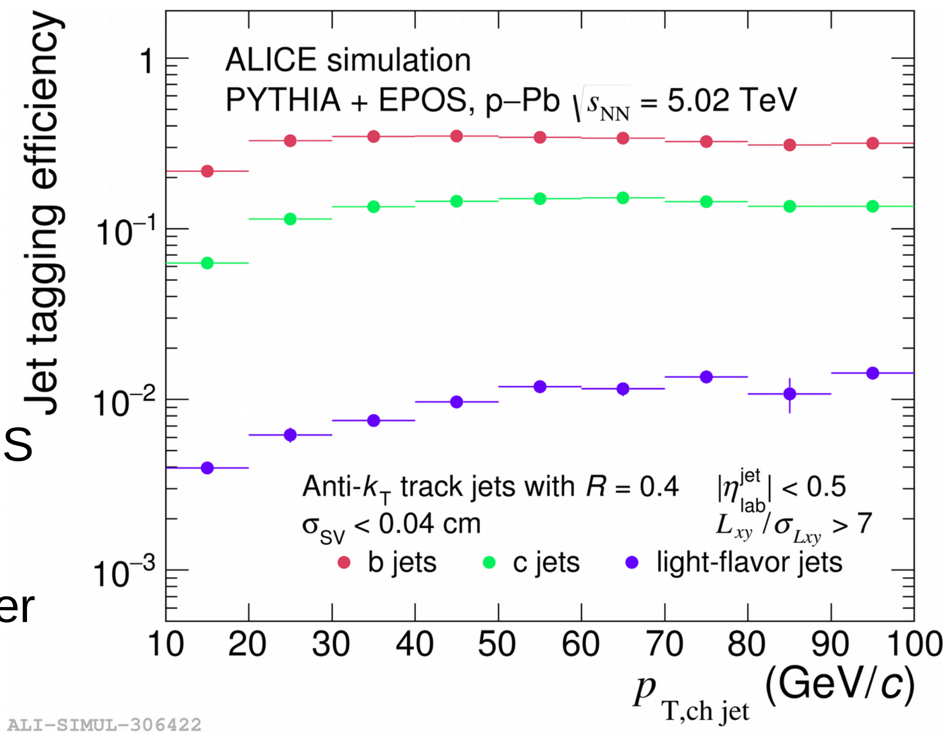
B jets in p-Pb at $\sqrt{s_{NN}}$= 5.02 TeV: Analysis overview

1) Jet reconstruction

2) B-Jet candidate selection

3) Correction on SV tagging efficiency

- Jet yield estimated based on PYTHIA+EPOS simulation
- Efficiencies for different b-jet candidates after imposing the default cut:



$$\varepsilon_b \approx 35\ \%\ ,\ \varepsilon_c \approx 11\ \%,\ \varepsilon_{LF} \approx 1\ \%$$

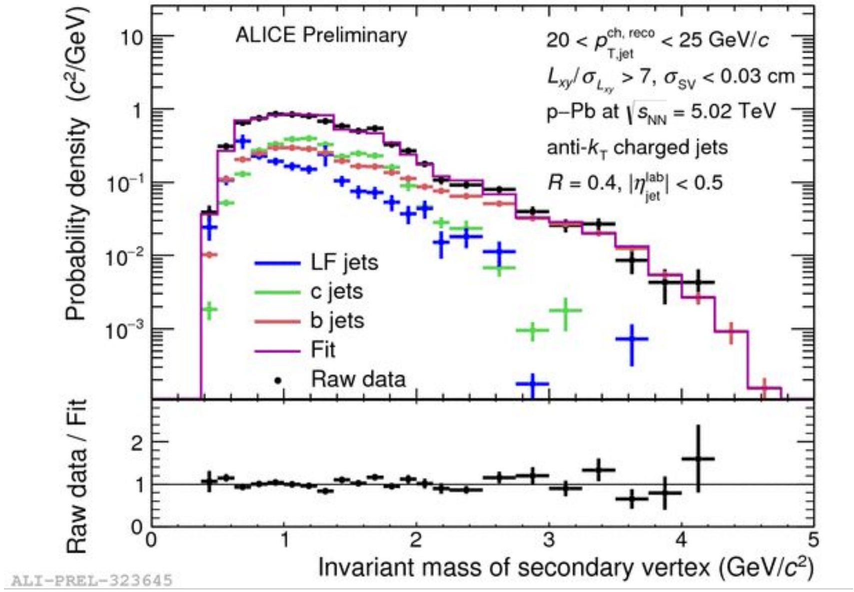
B jets in p-Pb at $\sqrt{s_{NN}}$= 5.02 TeV: Analysis overview

1) Jet reconstruction

2) B-Jet candidate selection

3) Corrections on efficiency and purity

- Jet yield was corrected on efficiency of SV tagging (estimated with PYTHIA + EPOS)
- Purity of b jets was estimated using the following method:
  - Data-driven template fit method



B jets in p-Pb at $\sqrt{s_{NN}}$= 5.02 TeV: Analysis overview

1) Jet reconstruction

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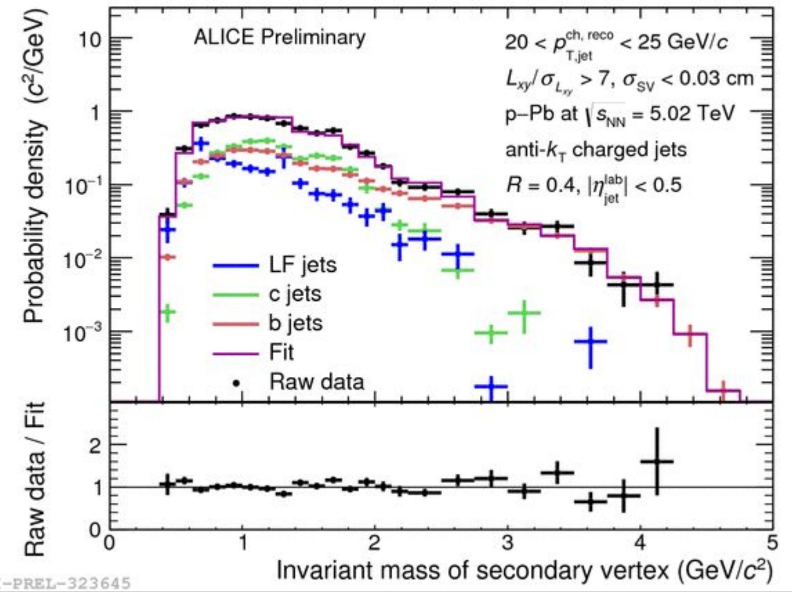

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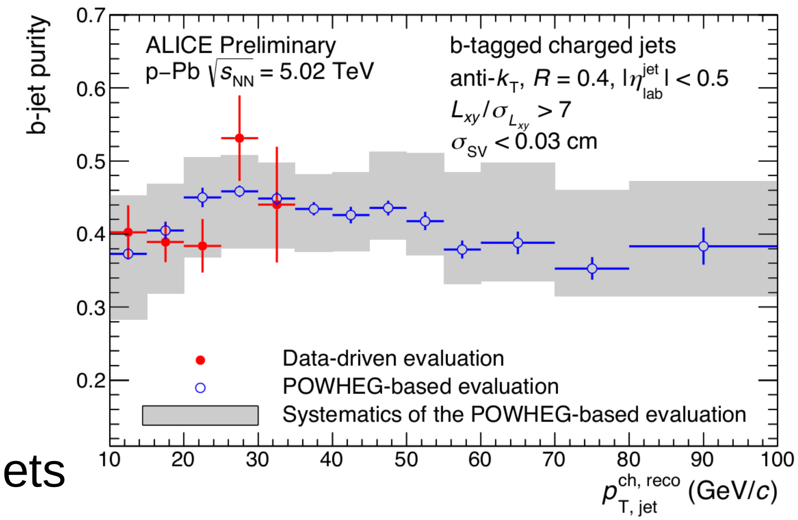

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$$P_b = \frac{N_b \varepsilon_b}{N_b \varepsilon_b + N_c \varepsilon_c + N_{LF} \varepsilon_{LF}}$$

N_b, N_c – folded <u>POWHEG</u> p_T spectrum of *b* and *c*-jets

N_{LF} = *<u>RAW</u> p_T spectrum of inclusive jets* – N_b – N_c

ε_b, ε_c, ε_{LF} – *efficiency* of SV tagging for b, c and LF-jets for given SL_{xy} and σ_{SV}

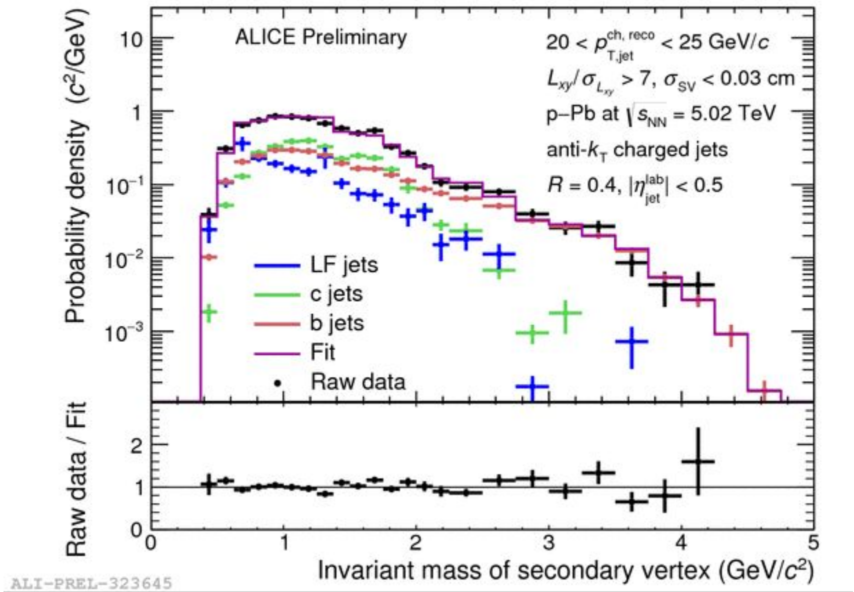
B jets in p-Pb at $\sqrt{s_{NN}}$= 5.02 TeV: Analysis overview

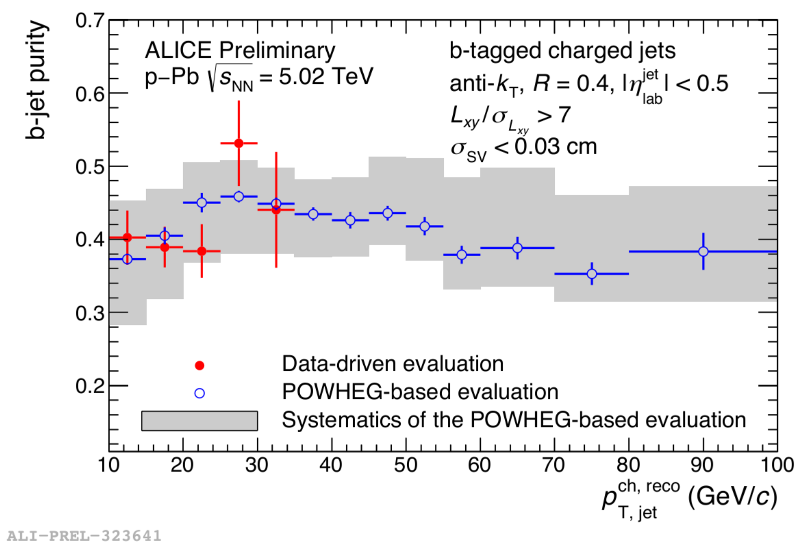
1) Jet reconstruction

2) B-Jet candidate selection

3) Corrections on efficiency and purity

- Jet yield was corrected on efficiency of SV tagging (estimated with PYTHIA + EPOS)
- Purity of b-jet was estimated using the following method:
  - Data-driven template fit method
  - POWHEG + PYTHIA simulation was used to calculate purity for high-p_T region
  - Purities obtained based on different POWHEG settings were compared with the template fit results.





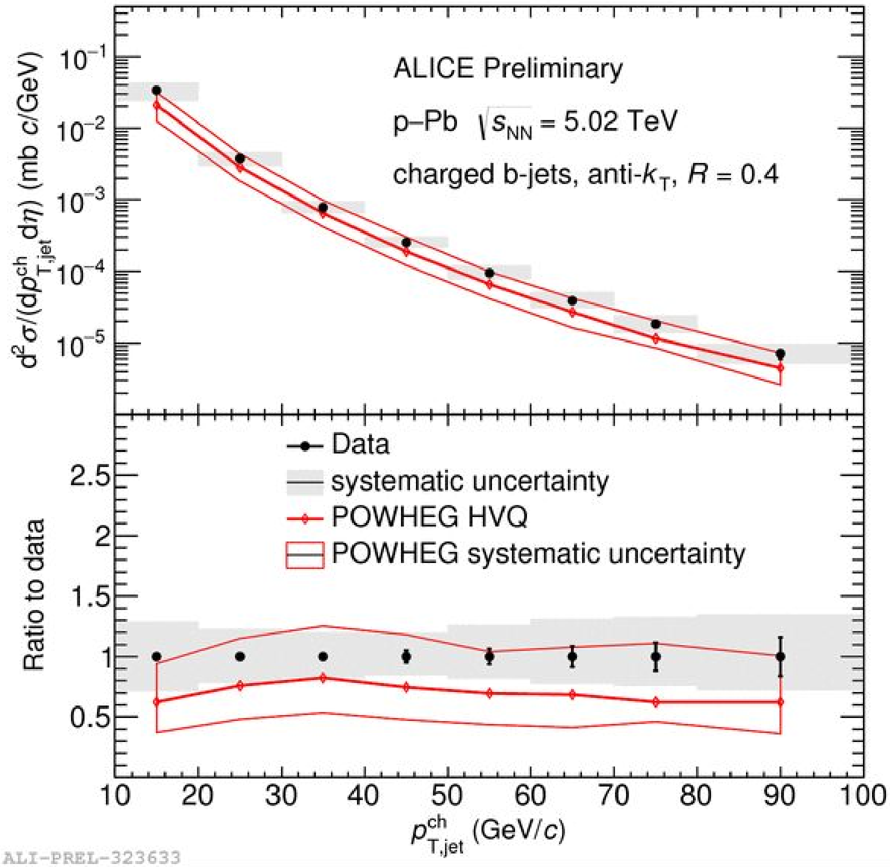
B jets in p-Pb at $\sqrt{s_{NN}}$= 5.02 TeV: Production cross-section

- p_T spectrum of the b jets was corrected:

$$\frac{d N^{\text{primary}}_{\text{b-jet}}}{d p_{\text{T, jet ch}}} = \frac{d N^{\text{raw}}_{\text{b-jet candidates}}}{d p_{\text{T, jet ch}}} \times \frac{P_b}{\varepsilon_b}$$

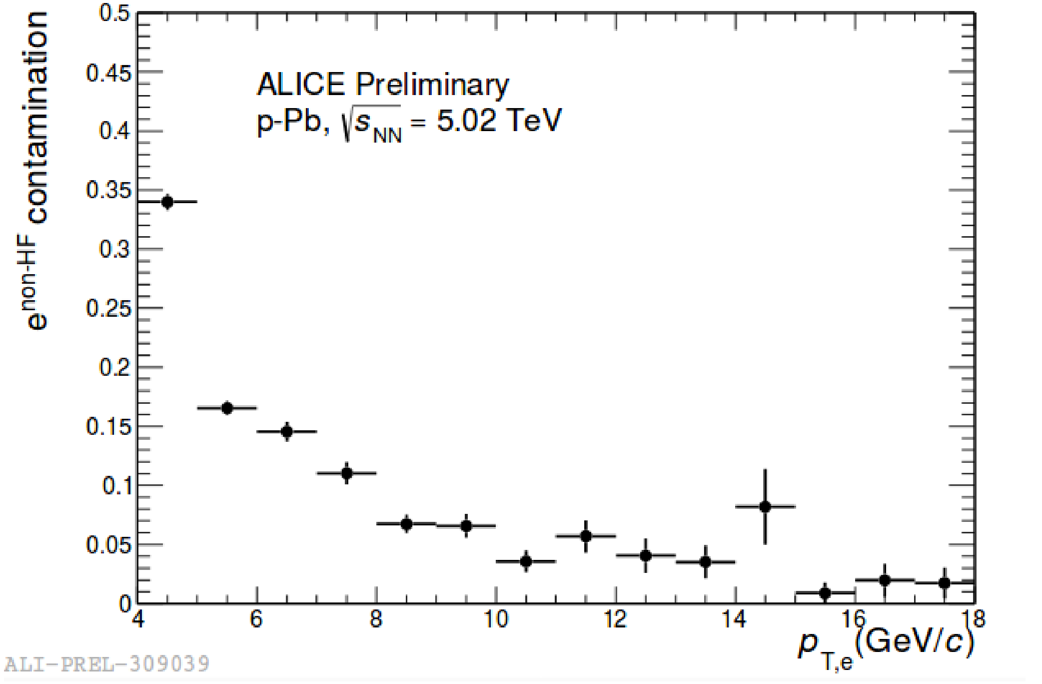
- Jet momentum smearing due to instrumental effects and local background fluctuations was corrected by unfolding

- Result cross section shows good agreement with the model (POWHEG HVQ)



1) HF electrons selection

- c, b -> semileptonic decay producing $e^{\pm}$
- PID selection: TPC dE/dx, EMCal
- $p_{T, e}$ > 4 GeV/c



HFe jets in p-Pb at $\sqrt{s_{NN}}$= 5.02 TeV: Analysis overview

1) HF electrons selection

2) Jets reconstruction

- Charged tracks
- FASTJet anti-k_T algorithm
- Jet radius R = 0.3, 0.4, 0.6
- $|\eta_{jet}| > 0.9 - R$
- $p^{ch}_{T,jet} > 10$ GeV/c
- Jets with reconstructed electrons
- p_T of the jets corrected on the mean background density

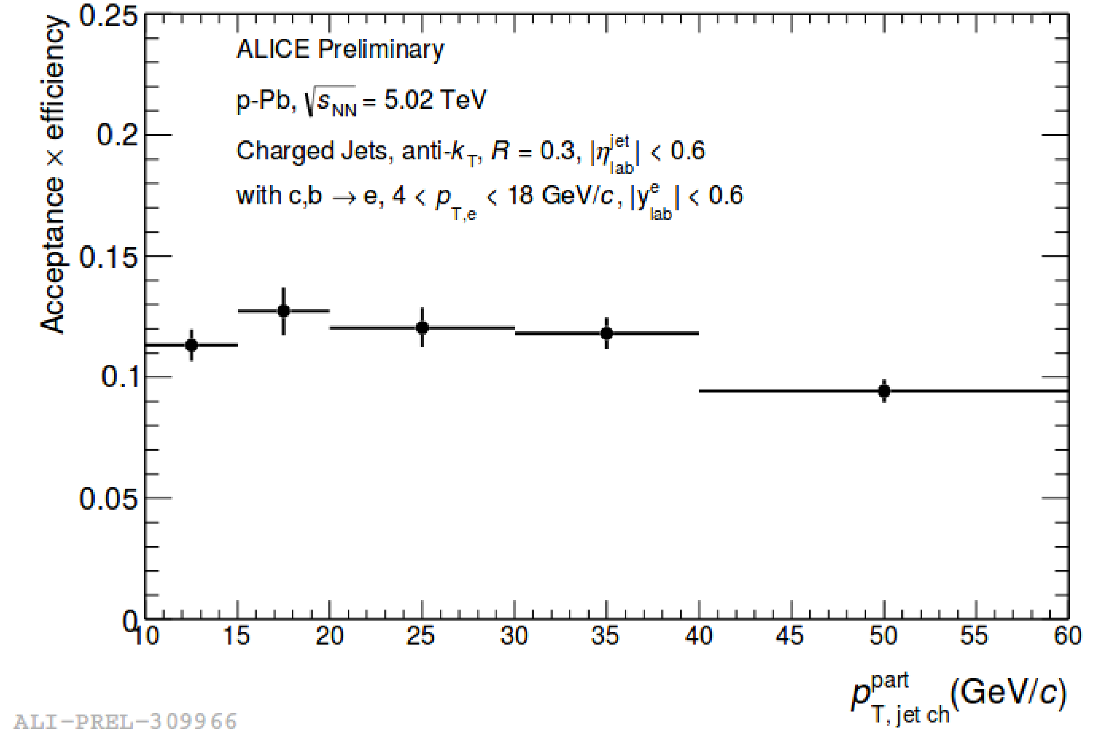
HFe jets in p-Pb at $\sqrt{s_{NN}}$= 5.02 TeV: Analysis overview

1) HF electrons selection

2) Jets reconstruction

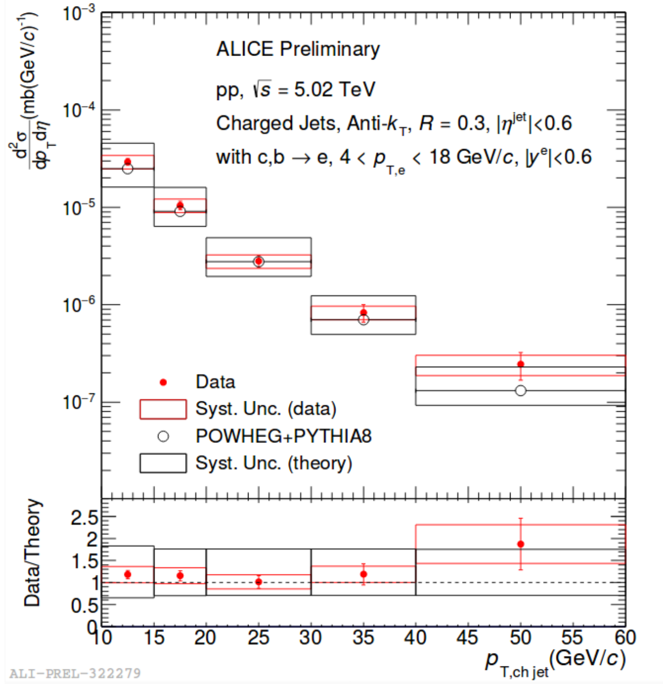
3) Corrections

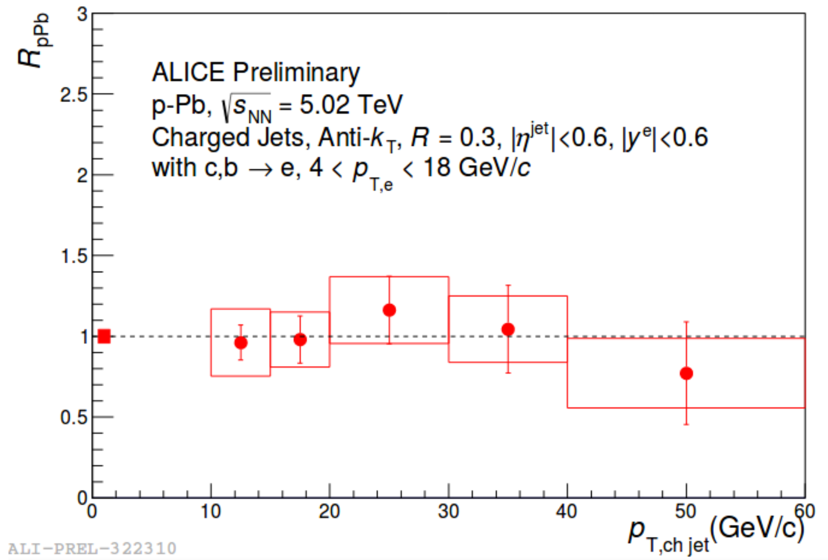
- Background from photonic $e^{\pm}$
- Hadron contamination
- Reconstruction efficiency



HFe jets in p-Pb at $\sqrt{s_{NN}}$= 5.02 TeV: cross-section

- Measured cross-section shows good agreement with the model (POWHEG+PYTHIA8)
- R_{pA} is compatible with unity. No sign of suppression





Summary

- Measurement of D^0-tagged jets in pp at $\sqrt{s} = 7$ TeV:
  - $z^{\parallel}_{ch}$ cross-section
  - Cross-section of D^0 tagged jets production
- Measurement of b – jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV:
  - First results in cross-section of B-jets production
- Measurement of HFe jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV:
  - No sign of jet quenching is observed or other medium-induced modification

Backup

B jets in pPb: Physics motivation

pPb collisions:

- Study cold nuclear matter (CNM) effects (nPDF, shadowing, gluon saturation, k_T-broadening, energy loss in CNM in the initial and final states)
- Study of the possible collective effects

ALICE wants to study b-jets at lower momenta where CNM effects will be more significant

Was used two independent approaches:

- Most displaced Secondary Vertex (SV)
- Track counting algorithm (IP)

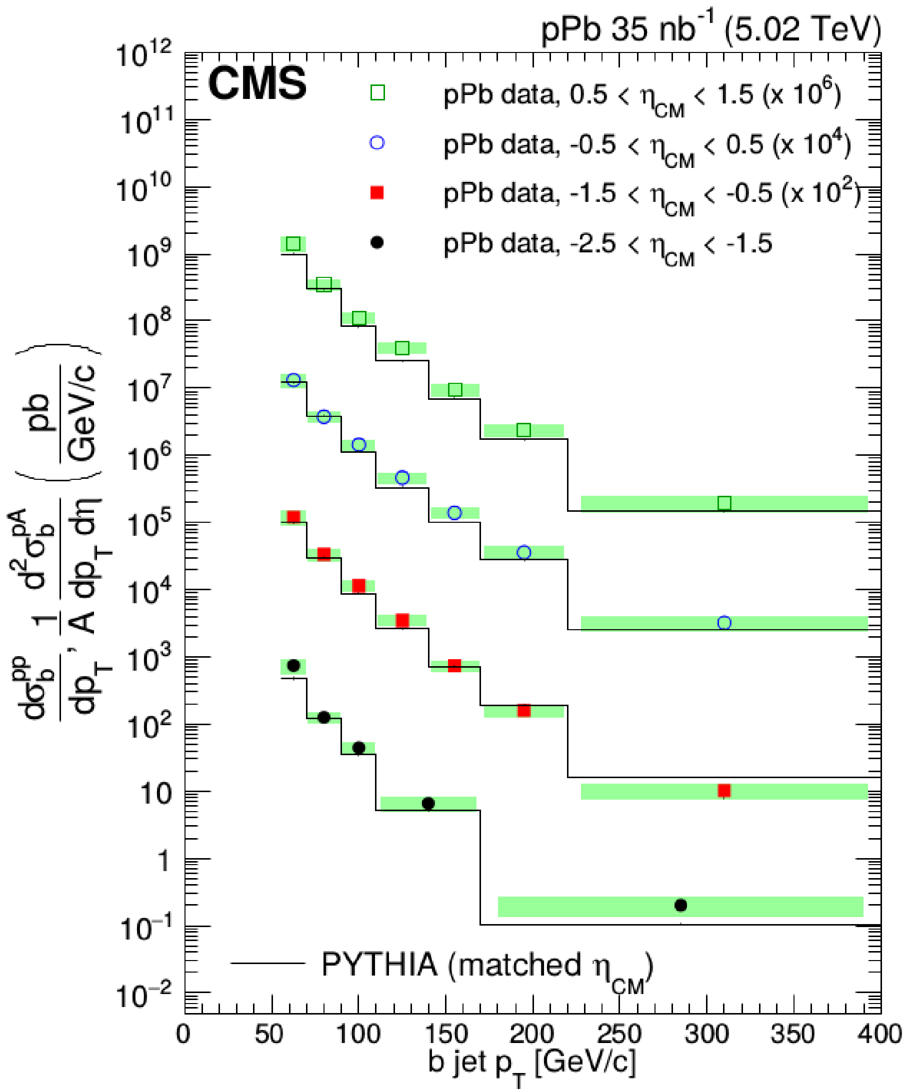
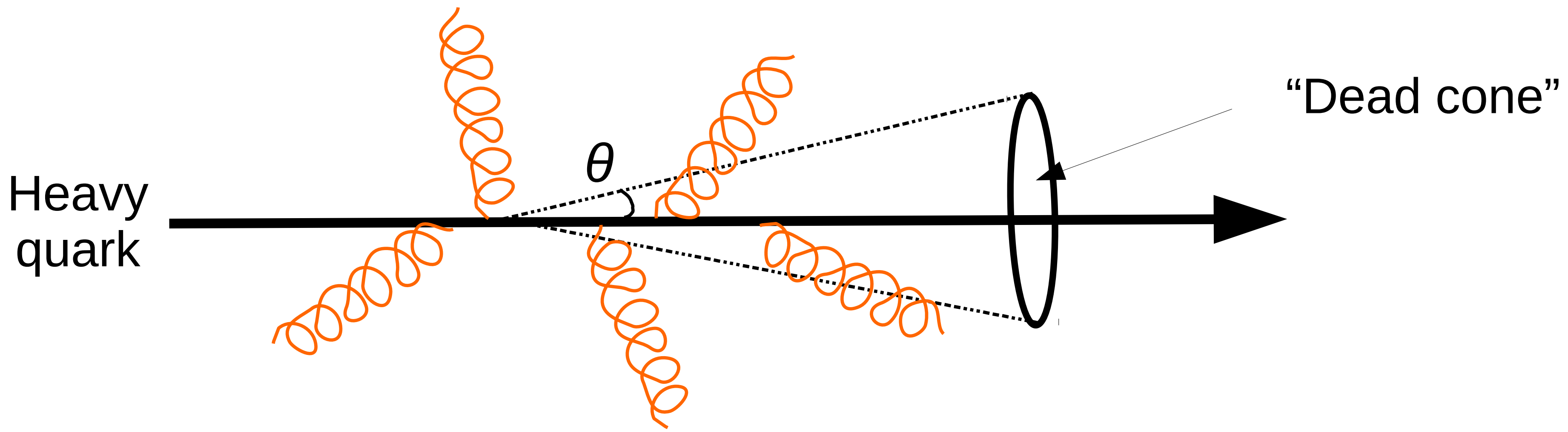


Figure 1. CMS Results
(pPb, 5.02 TeV, full jets 2018)

Dead cone effect

"Gluonsstrahlung" - process of gluon radiation by quarks (or gluons)



"Dead cone" effect – gluon radiation from massive quarks is suppressed at angles $\theta < m/E$ → Less E loss inside the medium for heavy quarks expected

[Yu.L. Dokshitzer, D.E. Kharzeev - "Heavy Quark Colorimetry of QCD Matter", arXiv:hep-ph/0106202]

Gluonsstrahlung probability

$$\sim \frac{\theta^2}{[\theta^2 + (m/E)^2]^2}$$

Probability of gluon emission

For light quarks:

$$dP_0 \simeq \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{dk_T^2}{k_T^2} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2}$$

For heavy quarks:

$$dP_{HQ} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_T^2 dk_T^2}{\left(k_T^2 + \omega^2 \theta_0^2\right)^2} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\theta^2 d\theta^2}{\left(\theta^2 + \theta_0^2\right)^2}$$

$$\theta_0 = \frac{M}{E}$$

Where

ω - Energy, C_F - "color charge", k_T - transverse momenta

dP_0 - Probability to radiate gluon

Probability of gluon emission

For light quarks:

$$dP_0 \simeq \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{dk_T^2}{k_T^2} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2}$$

For heavy quarks:

$$dP_{HQ} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_T^2 dk_T^2}{\left(k_T^2 + \omega^2 \theta_0^2\right)^2} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\theta^2 d\theta^2}{\left(\theta^2 + \theta_0^2\right)^2}$$

$$\theta_0 = \frac{M}{E}$$

Where

ω - Energy, C_F - “color charge”, k_T - transverse momenta

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