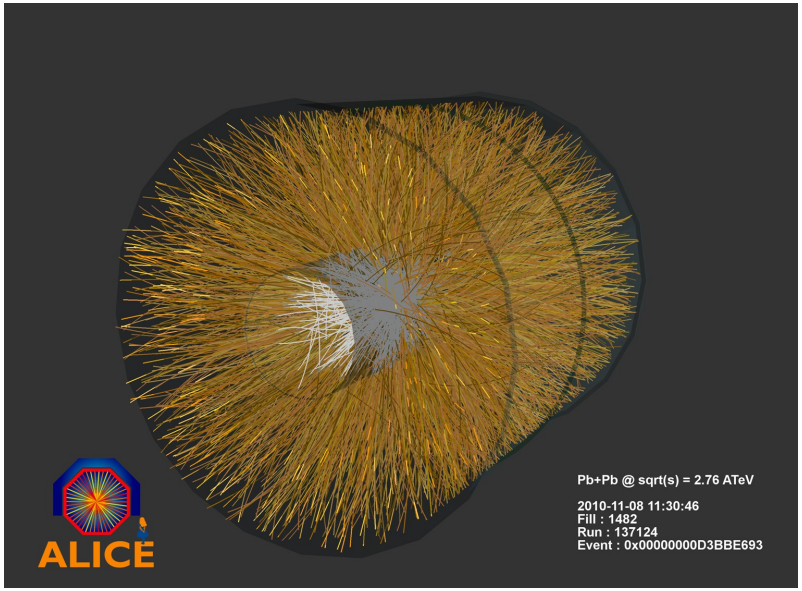
Heavy-Flavour jets with ALICE



A. Rossi, Padova INFN

ALICE

Outline

Physics motivations for measuring HF jets

HF-jet tagging with ALICE:

- b-jet
- Jets with heavy-flavour electrons
- D-tagged jets

Measurement of D-jet production in pp and p-Pb collisions

Summary

Physics motivation

Complementary information than single-heavy-flavour-hadron observables

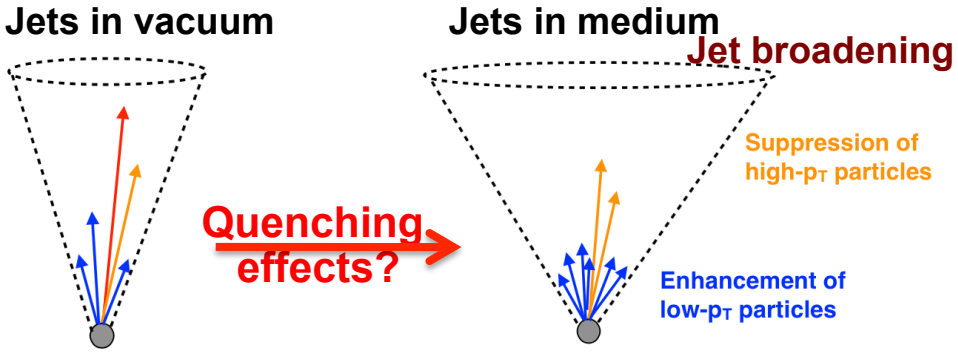
Information on spatial distribution of parton lost energy (jet suppression → out-of-cone radiation)

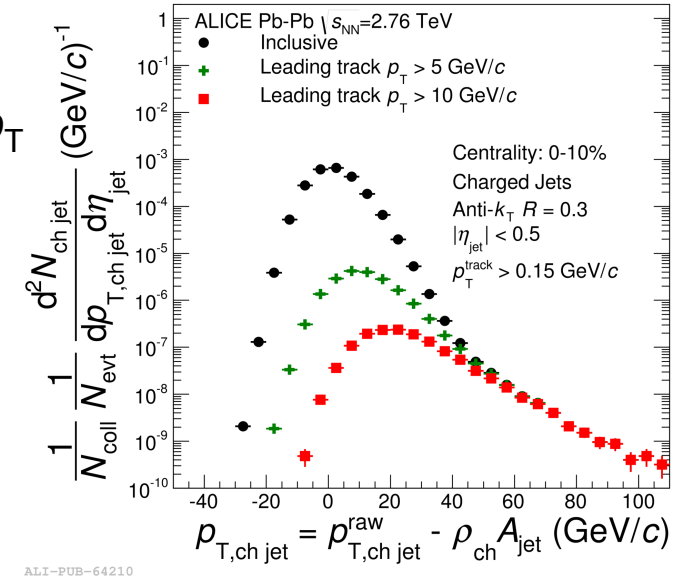
Address possible modification of jet properties and parton fragmentation in the medium

- Is the jet internal structure modified?
  - Kinetic properties
  - Spatial distribution of jet constituents
  - Particle specie composition
- Jets → individual object
- Correlations → statistical ensemble (but jet-model independent) → F. Colamaria

Can HF-jet provide complementary information to inclusive jets?

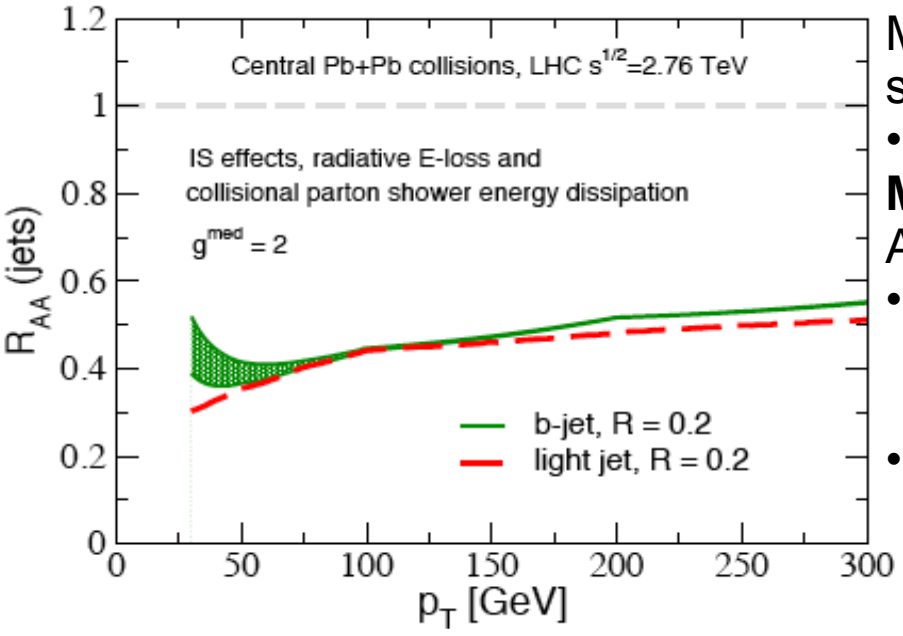
- (heavy) "quark tagging"
- smaller background of "fake" jets from combinatorics at low p_T
- better jet-energy scale (depending on observable)?

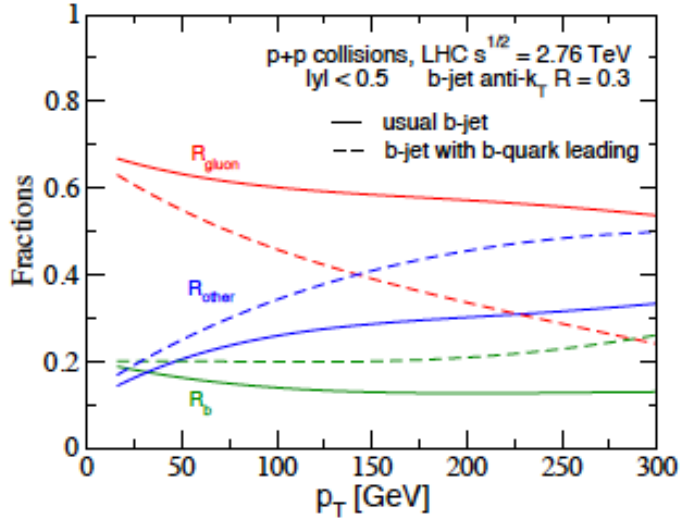




Physics motivation: beauty jet suppression

J. Huang et al., PLB 726, 1–3, 251-256 (2013)





Model with radiative energy loss + collisional parton shower energy dissipation.

- From p_T>30 GeV/c: hadronisation effects negligible.

Mass effects relevant for p_T<75 GeV/*c*

At higher p_T:

- mass effects disappear in fully-coherent gluonsstrahlung regime (LPM destructive interference)… interesting per se!
- $b\bar{b}$ pair from g→$b\bar{b}$ looses energy as a massive gluon
  - not because the gluon loses energy and then splits:
    - τ_{split}<1 fm even for p_T (jet)~200 GeV/*c*
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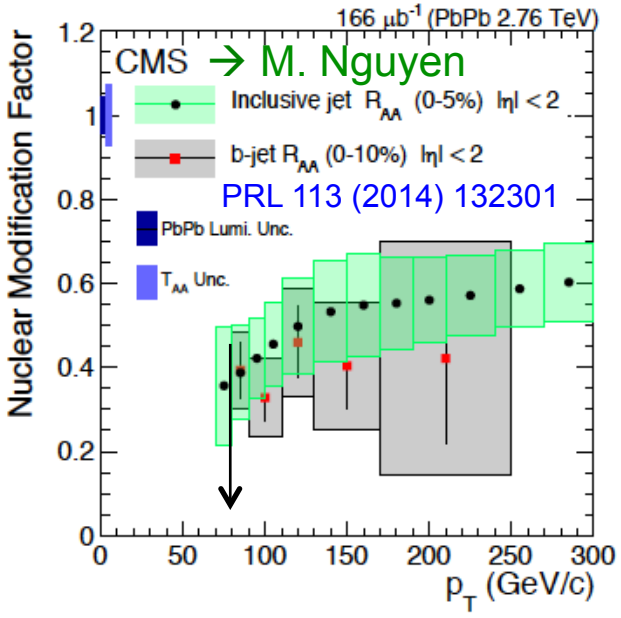

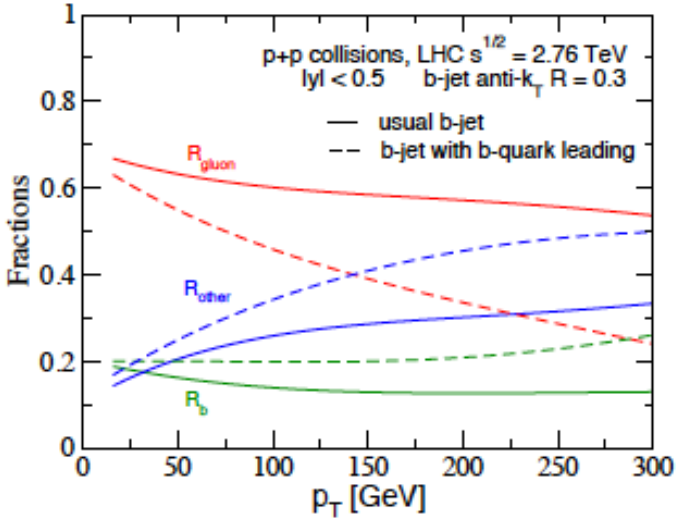

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What about lower p_T?

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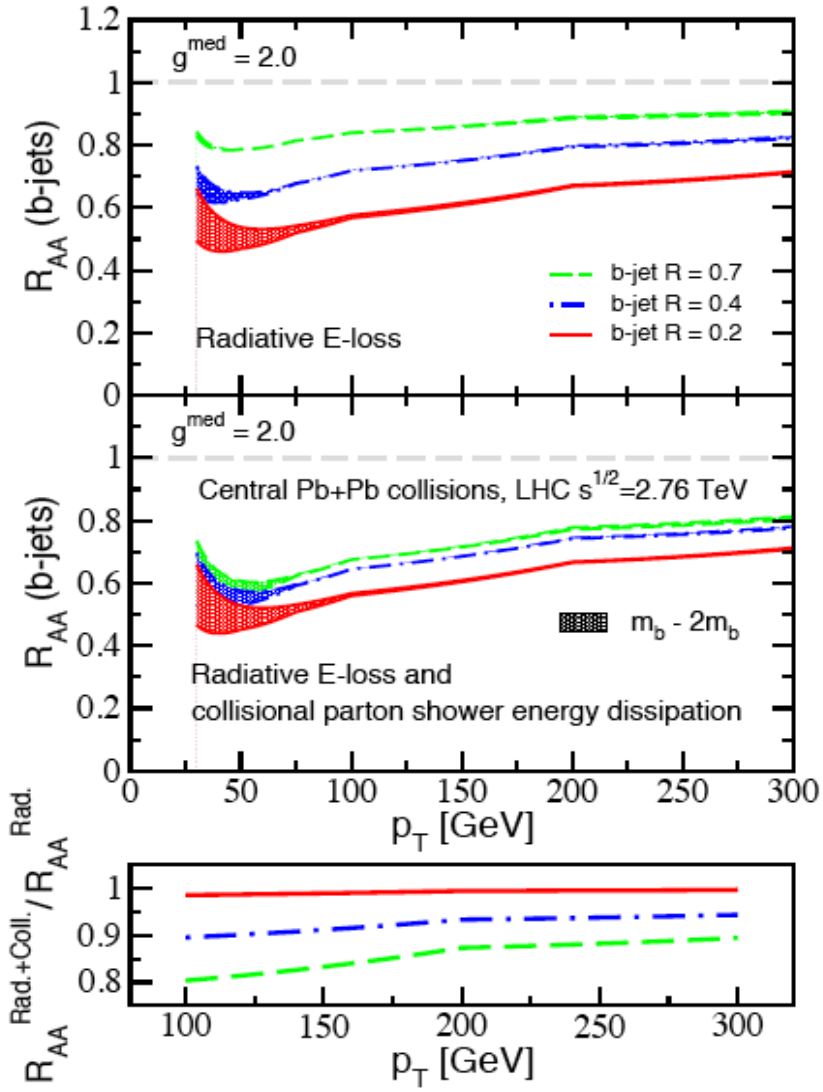

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Study of *R* dependence of R_{AA} important to characterise medium-induced parton shower and quantify the dissipation of its energy

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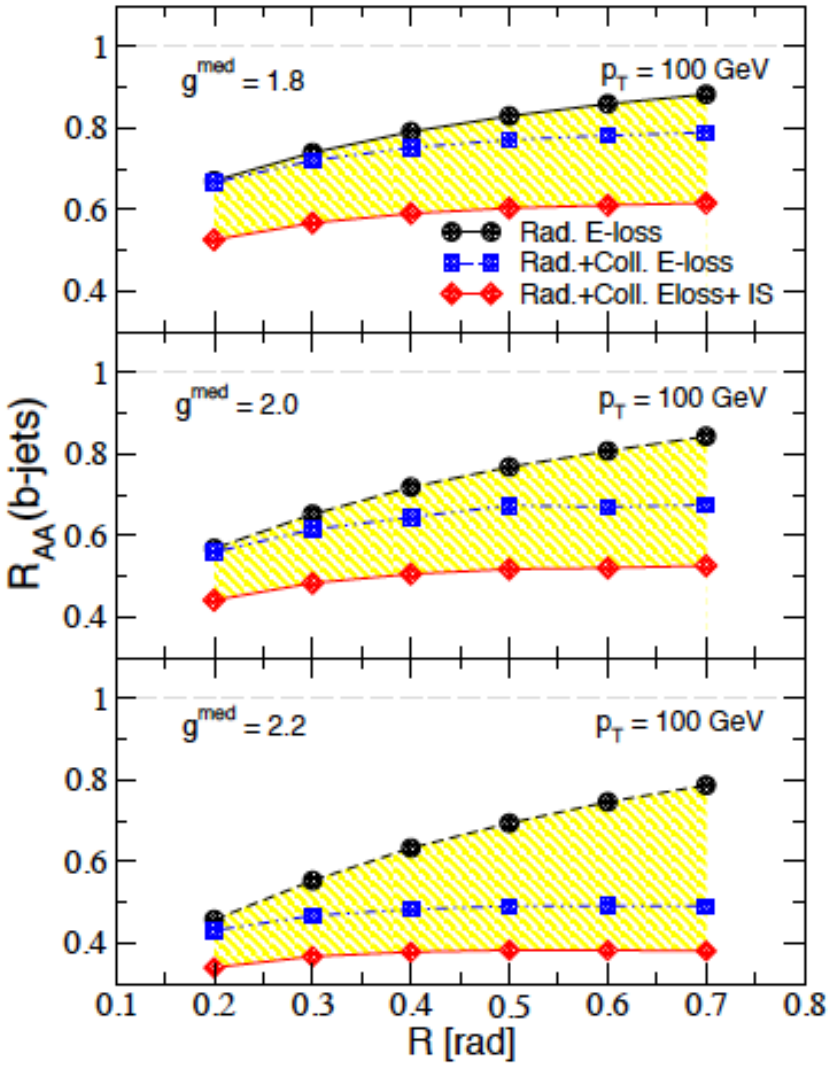

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Study of *R* dependence of R_{AA} important to characterise medium-induced parton shower and quantify the dissipation of its energy

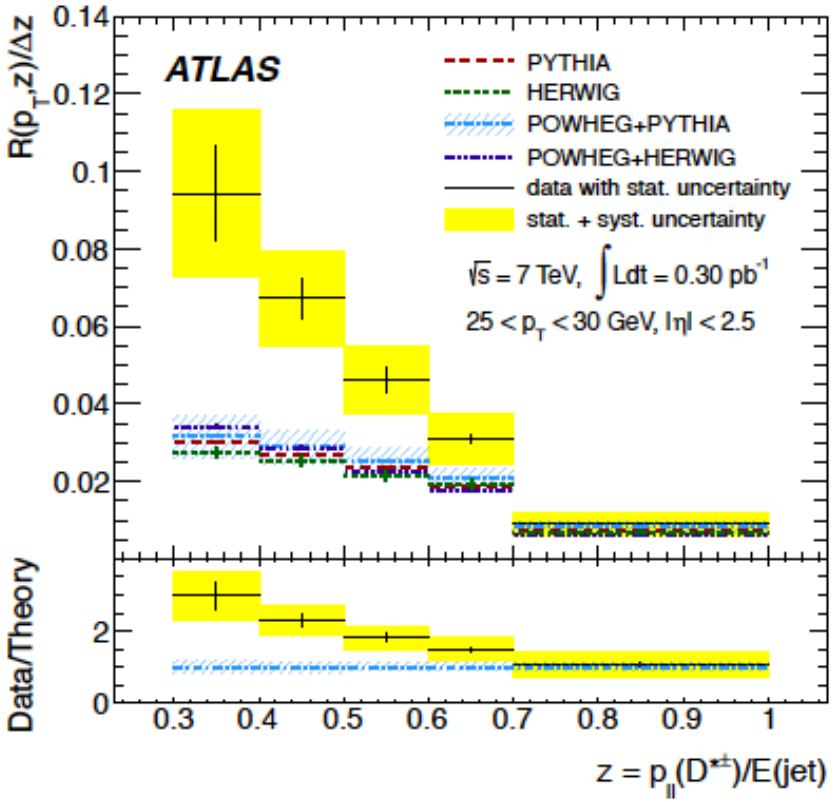
Sensitivity to Initial-State effects

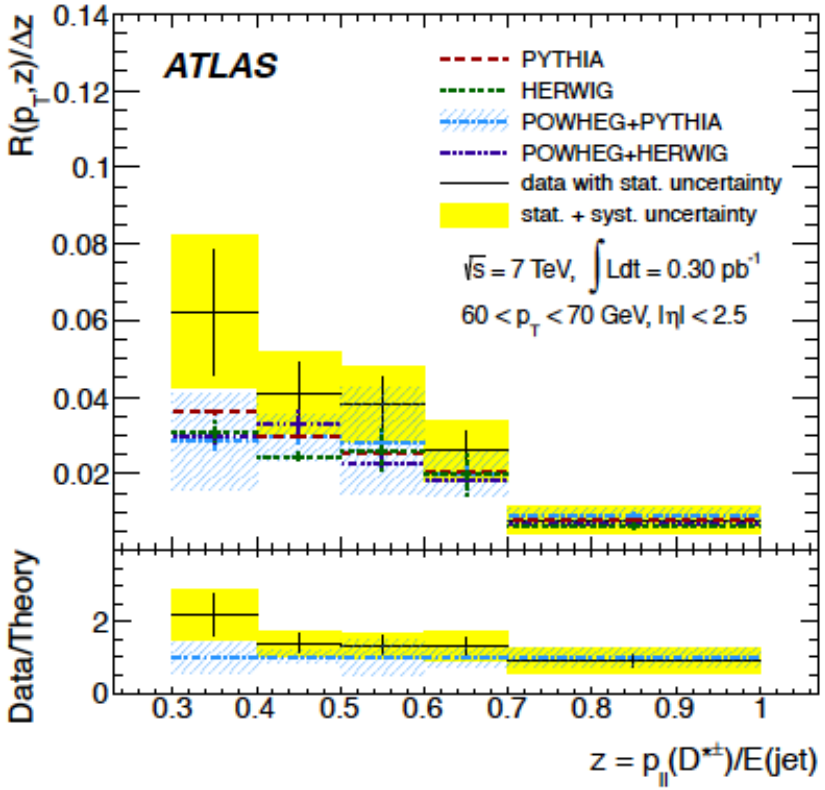
- Need constraints from p-A data

What about charm jets? Lack of theoretical inputs

ATLAS D^{*+}-jet measurement in pp collisions

Phys. Rev. D85 052005 (2012)



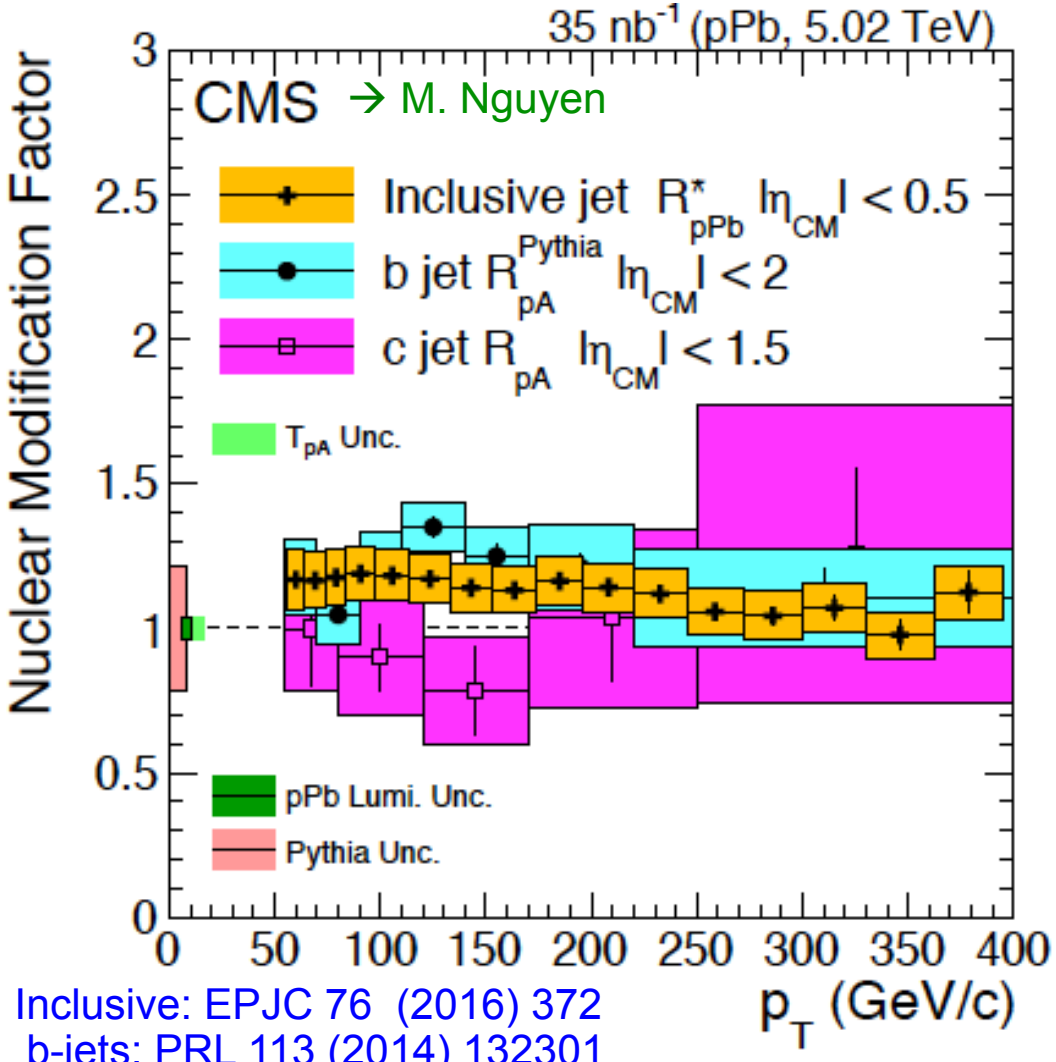


R (p_T,z) = [D^{*+}-jet (p_T,z) yield] / [inclusive-jet yield (p_T)]
z = [D^{*+} momentum along the jet direction] / [jet energy]

R(D^{*+}-jet/inclusive jets)=0.025±0.001(stat.) ±0.004(syst.) (for 0.3<z<1, |η|<2.5, 25<p_T<70 GeV/c)

D^{*+}-jet production w.r.t. inclusive jet production underestimated in models at low z
Larger discrepancy at lower p_T

Charm jets in p-Pb collisions



Inclusive: EPJC 76 (2016) 372
b-jets: PRL 113 (2014) 132301
c-jets: arxiv 1612.08972

R_{pPb} compatible with unity and with inclusive and b-jet R_{pPb} from p_T>50 GeV/c

→ M. Nguyen

What about lower p_T?

Study of recoiling jet: inclusive jets

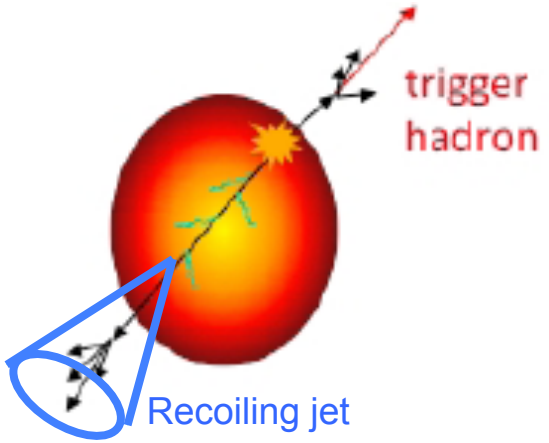
High p_T track – jet correlations

no fragmentation bias on recoiling jet + can be calculated by pQCD-based models

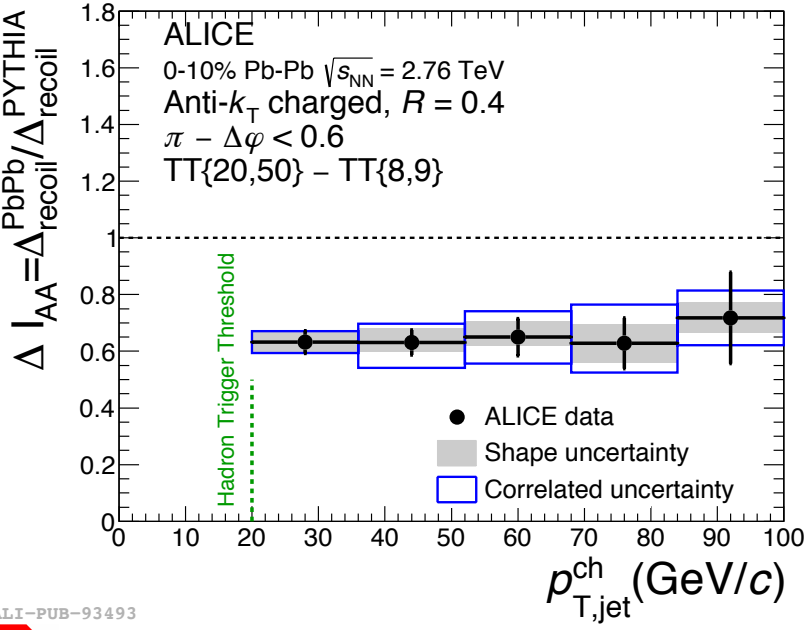
→ key observable

Trigger differential analysis to remove background

$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{dN_{jets}}{dp_T}\bigg|_{signal} - f \frac{1}{N_{trig}} \frac{dN_{jets}}{dp_T}\bigg|_{reference}, \quad \Delta I_{AA} = \frac{\Delta_{recoil}^{AA}}{\Delta_{recoil}^{pp}}$$



JHEP 09 (2015) 170



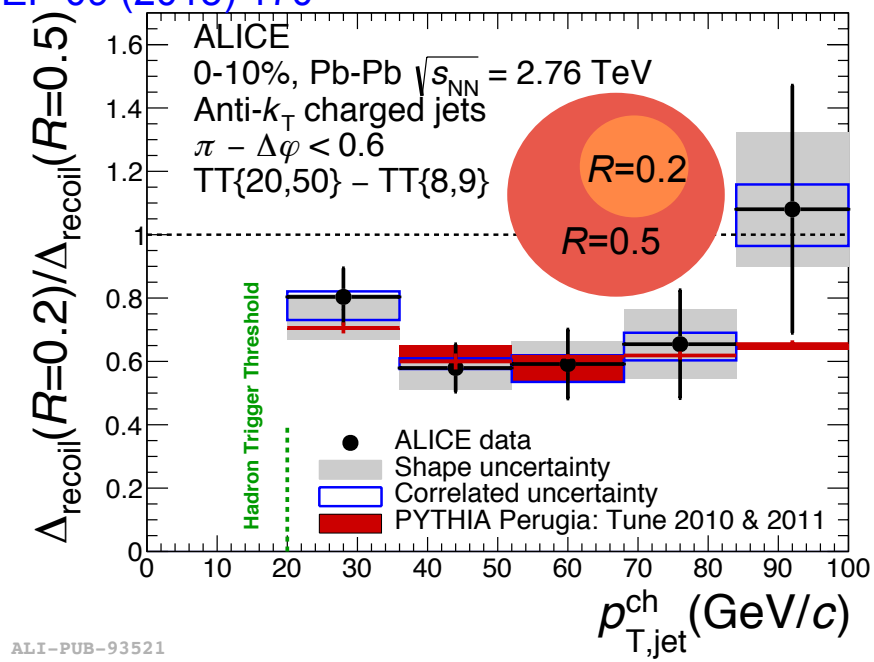
ALI-PUB-93493

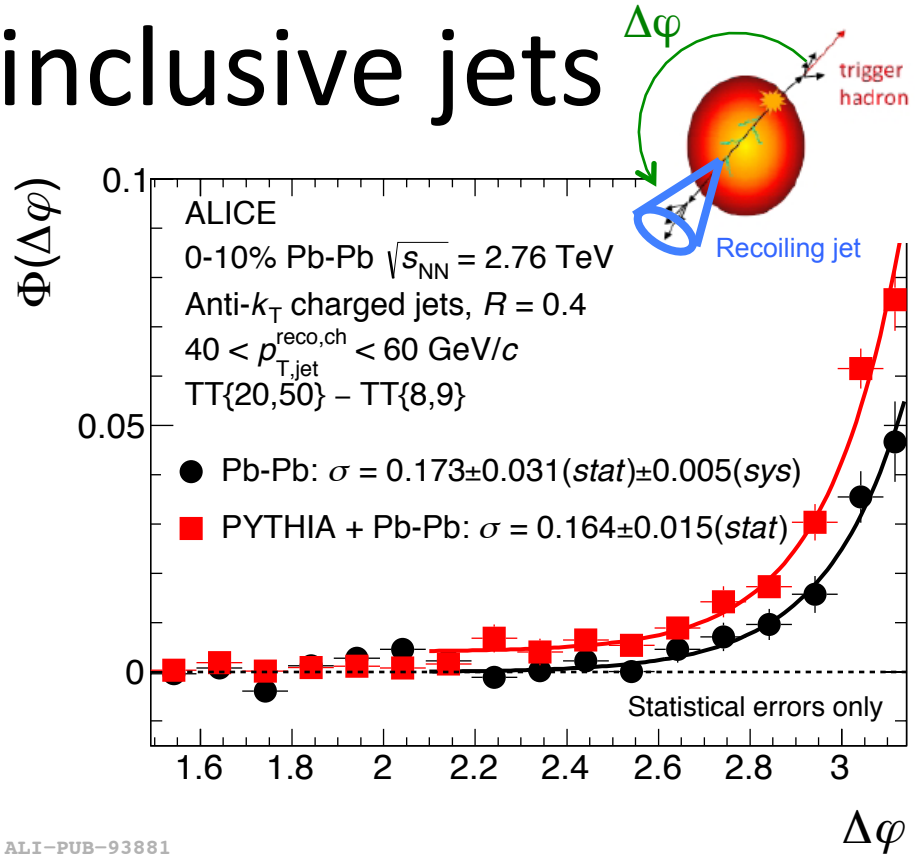
$\Delta I_{AA} < 1$ → "additional" recoiling jet suppression

Suggest constant ΔE~8 GeV/c (in range of measurement)

Study of recoiling jet: inclusive jets

JHEP 09 (2015) 170



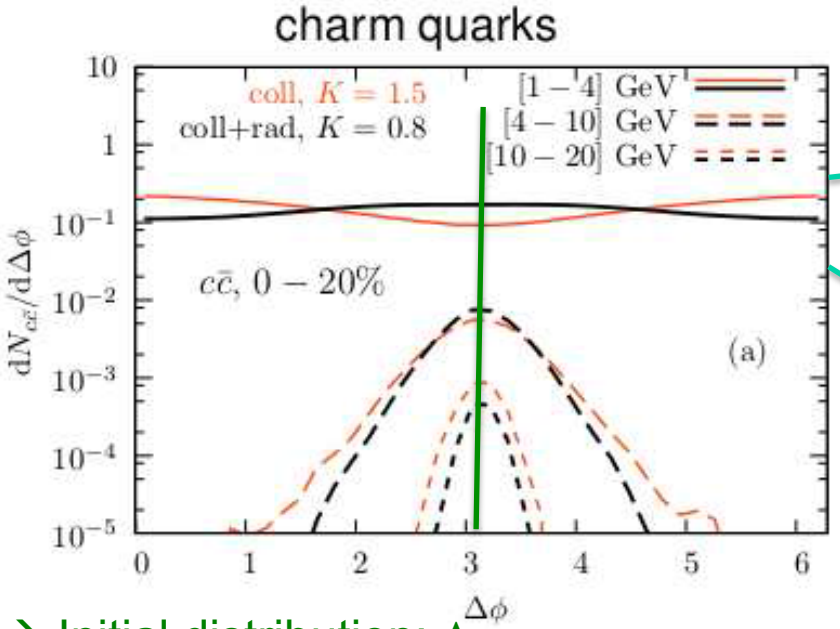


- **No evidence for intra-jet broadening**
- **No evidence for medium-induced acoplanarity**
- **No evidence for large-angle Moliere scatterings**

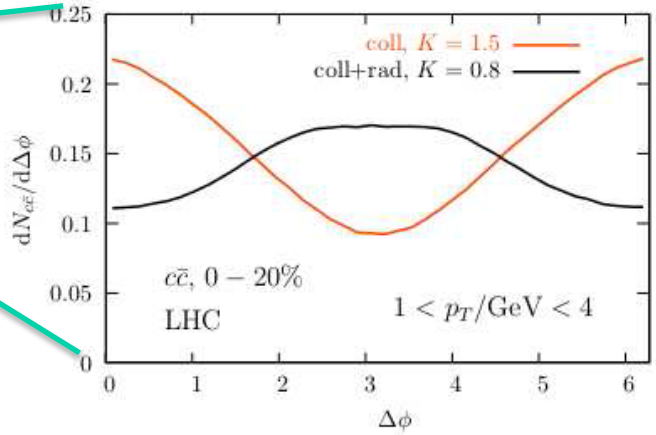
Expected for light jets? What about HF jets at low p_T?

HF case: radiative vs. collisional energy loss?

MC@sHQ+EPOS: M. Nahrgang, J. Aichelin, et al, Phys. Rev. C 90, 024907 (2014)

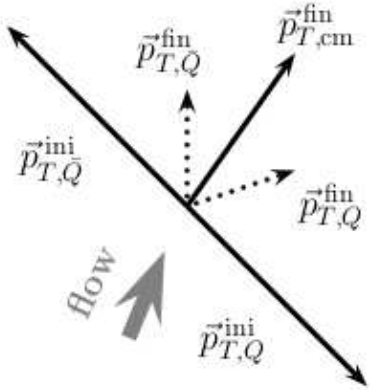


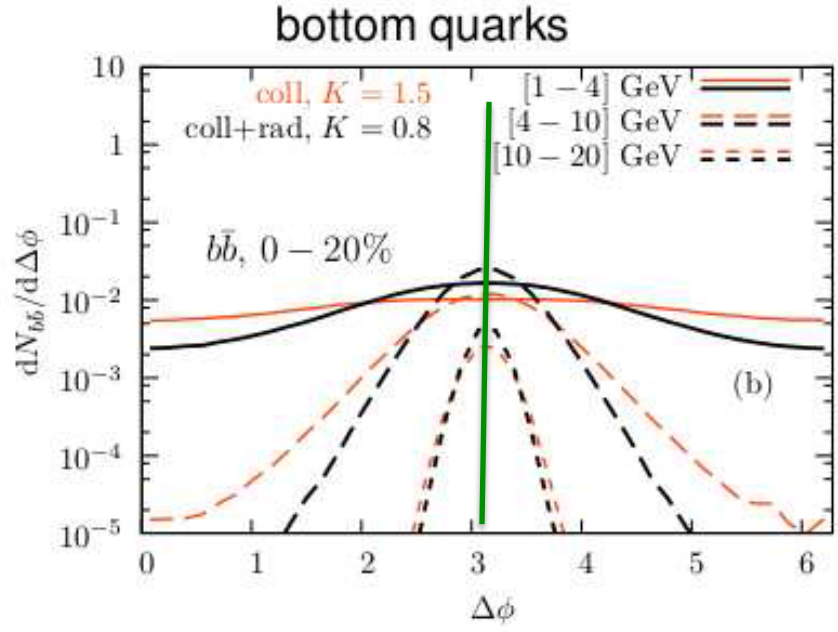
(Boltzman equation, radiative + collisional energy loss)



LO→ Initial distribution: $\Delta\varphi=\pi$

PARTONIC WIND



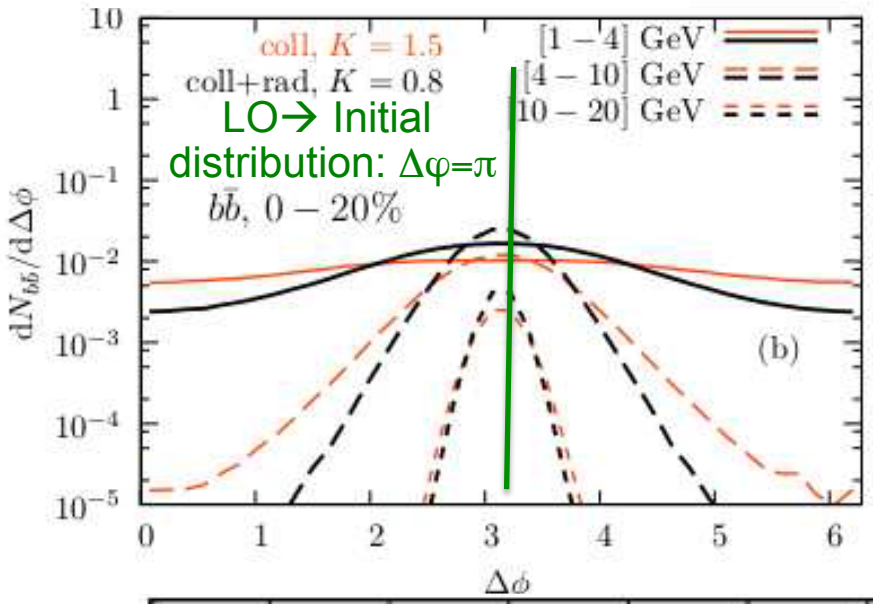


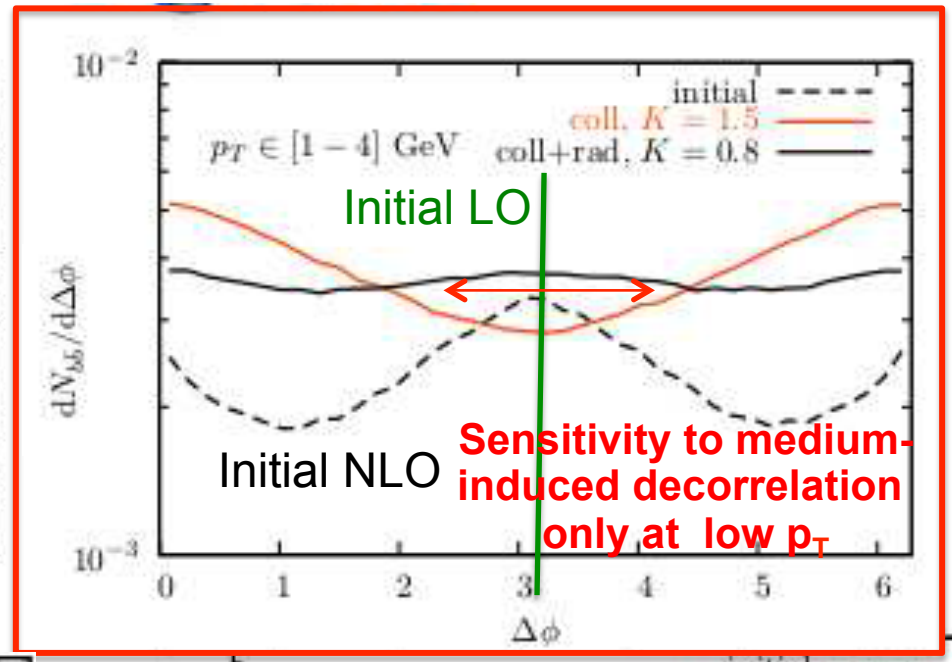
Radial flow pushes quarks from a pair toward the same direction.
-- effective only with collisional processes --

Medium de-correlation "dilution" into NLO initial de-correlation

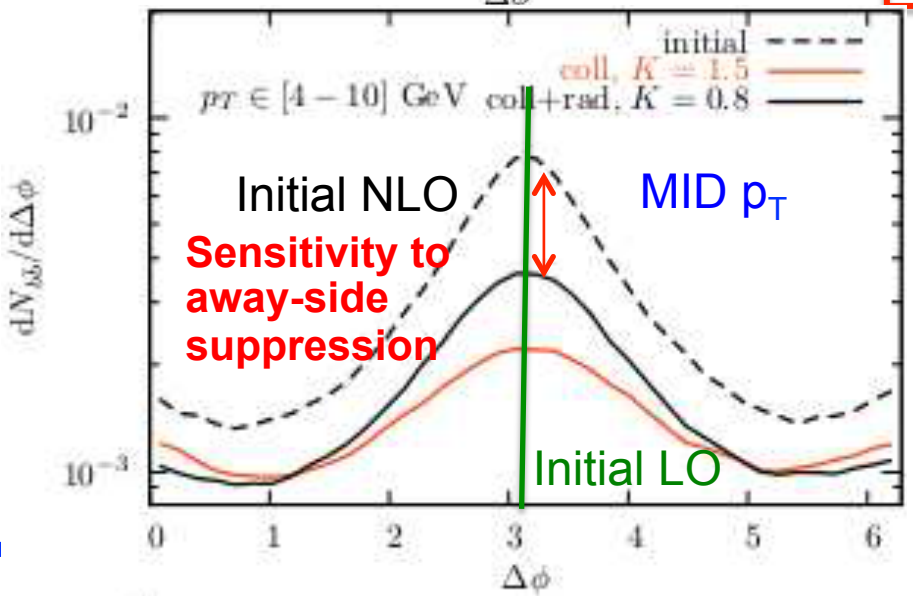
MC@sHQ+EPOS: M. Nahrgang, J. Aichelin, et al, Phys. Rev. C 90, 024907 (2014)

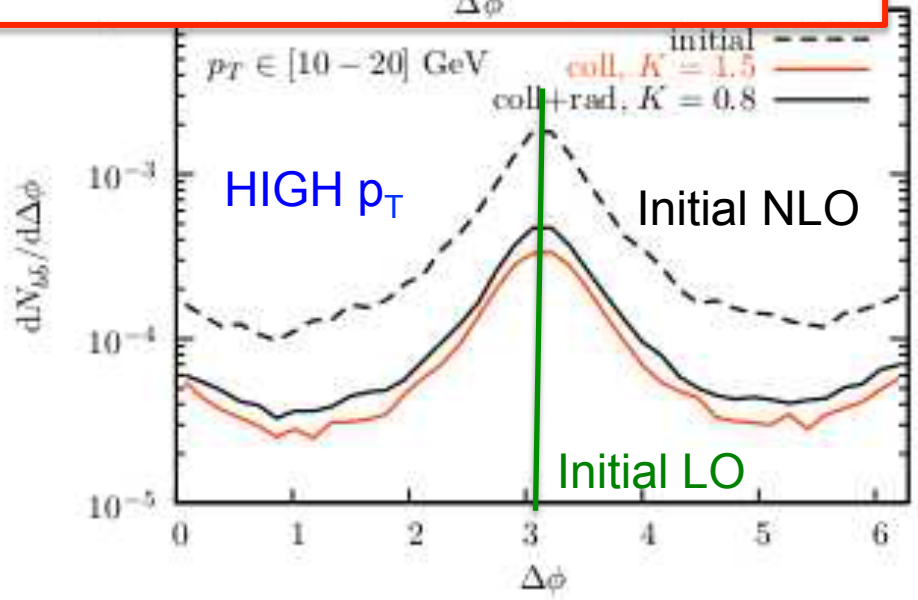
bottom quarks





QQbar correlations! …not directly commutable to jets!

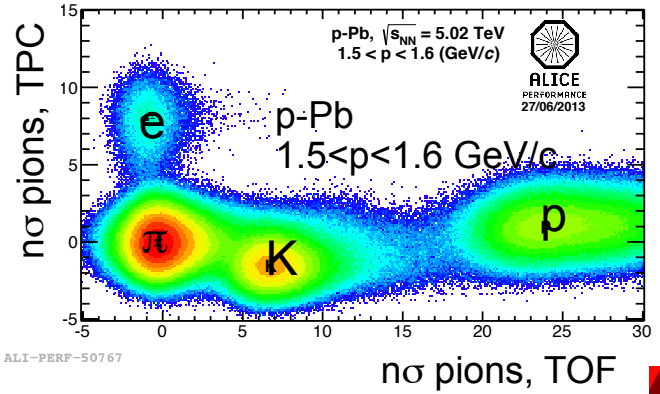


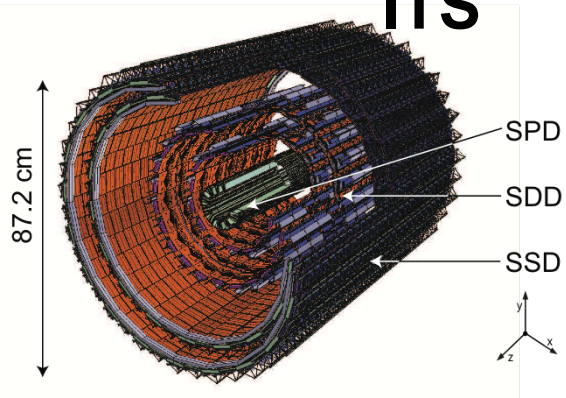


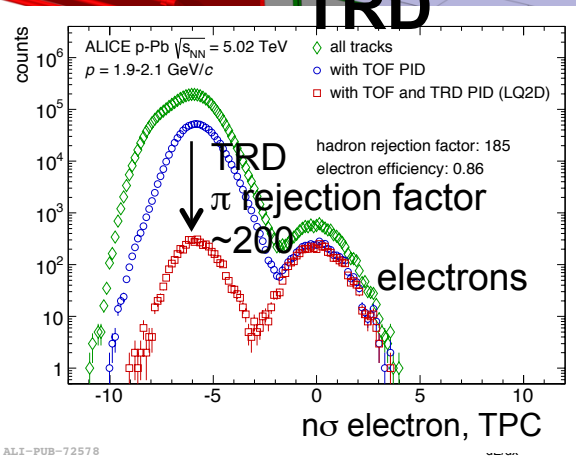
D-meson reconstruction
→ F. Prino, E. Bruna,
F. Colamaria. Z.Conesa del Valle

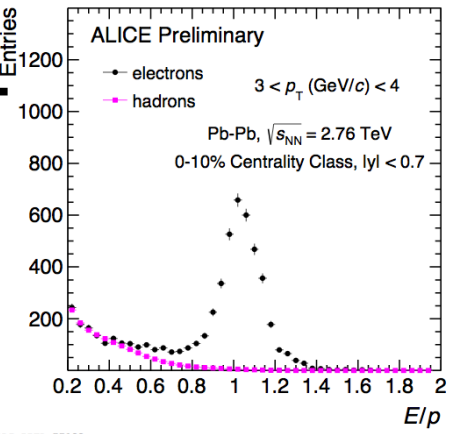
The ALICE detector

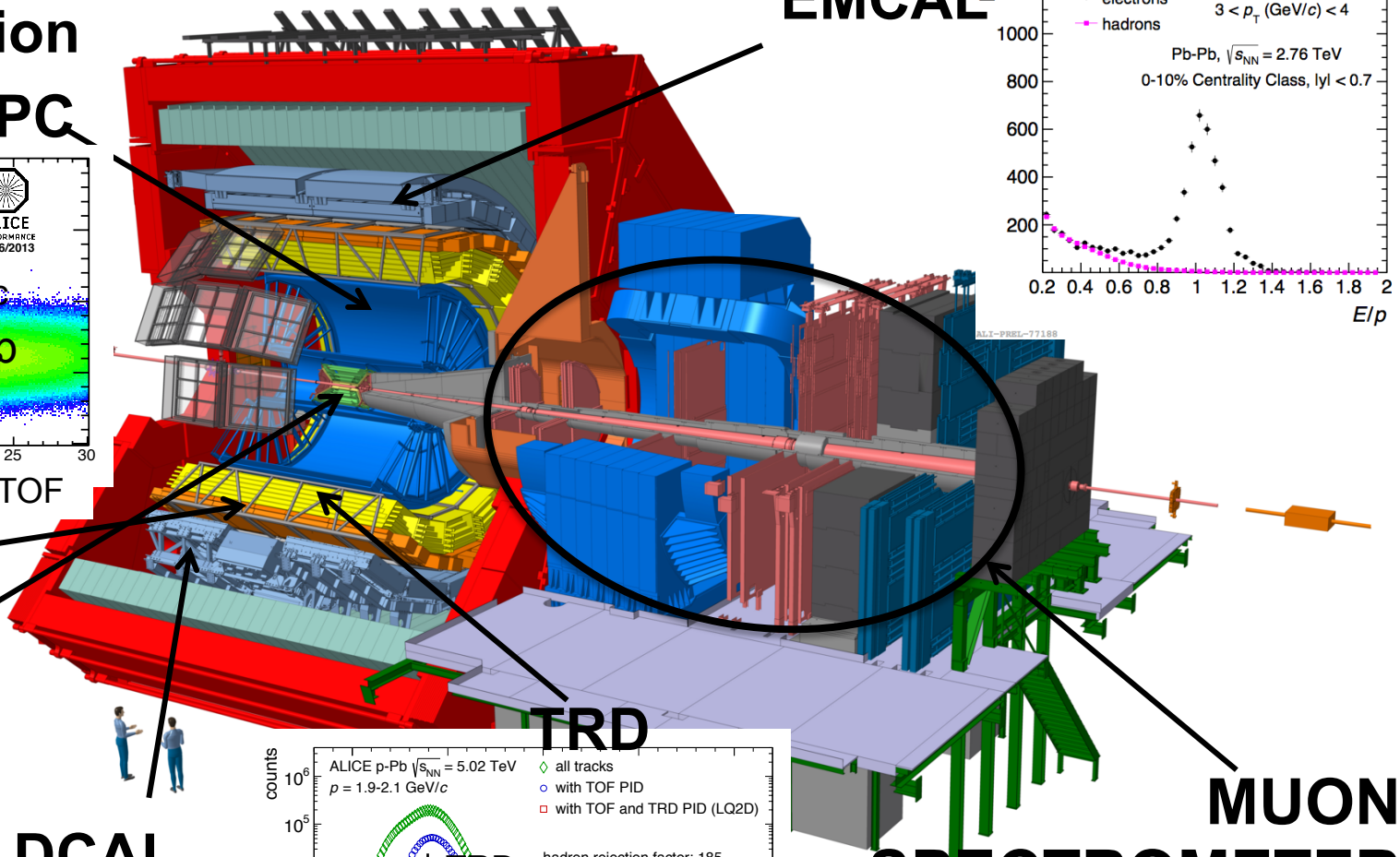
Central barrel (|η|<0.9, B=0.5 T)
Track and vertex reconstruction (TPC, ITS)
Particle Identification





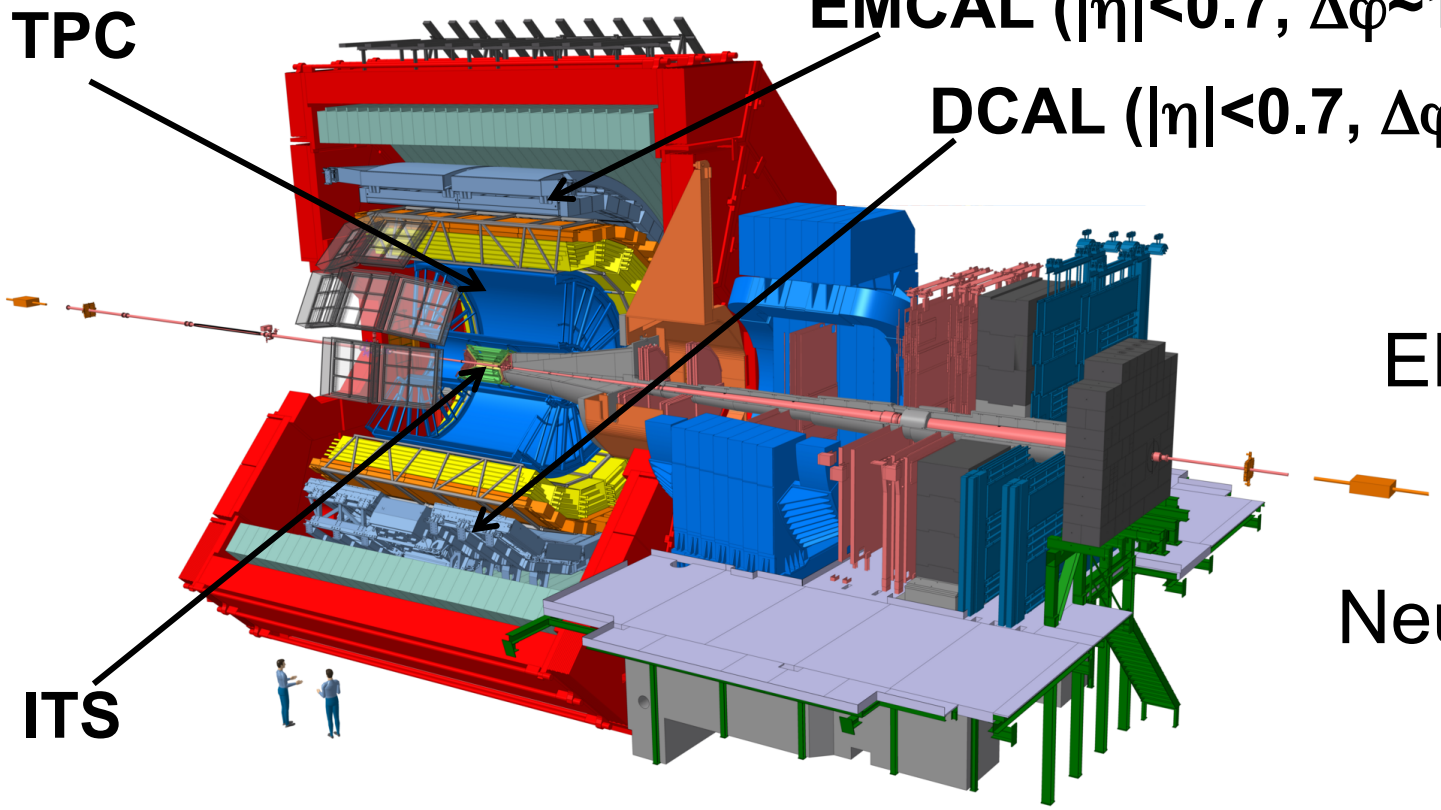






Jets reconstruction in ALICE

CENTRAL BARREL: $|\eta|<0.9$, B=0.5 T



EMCAL, DCAL

↓

Neutral constituents

↓

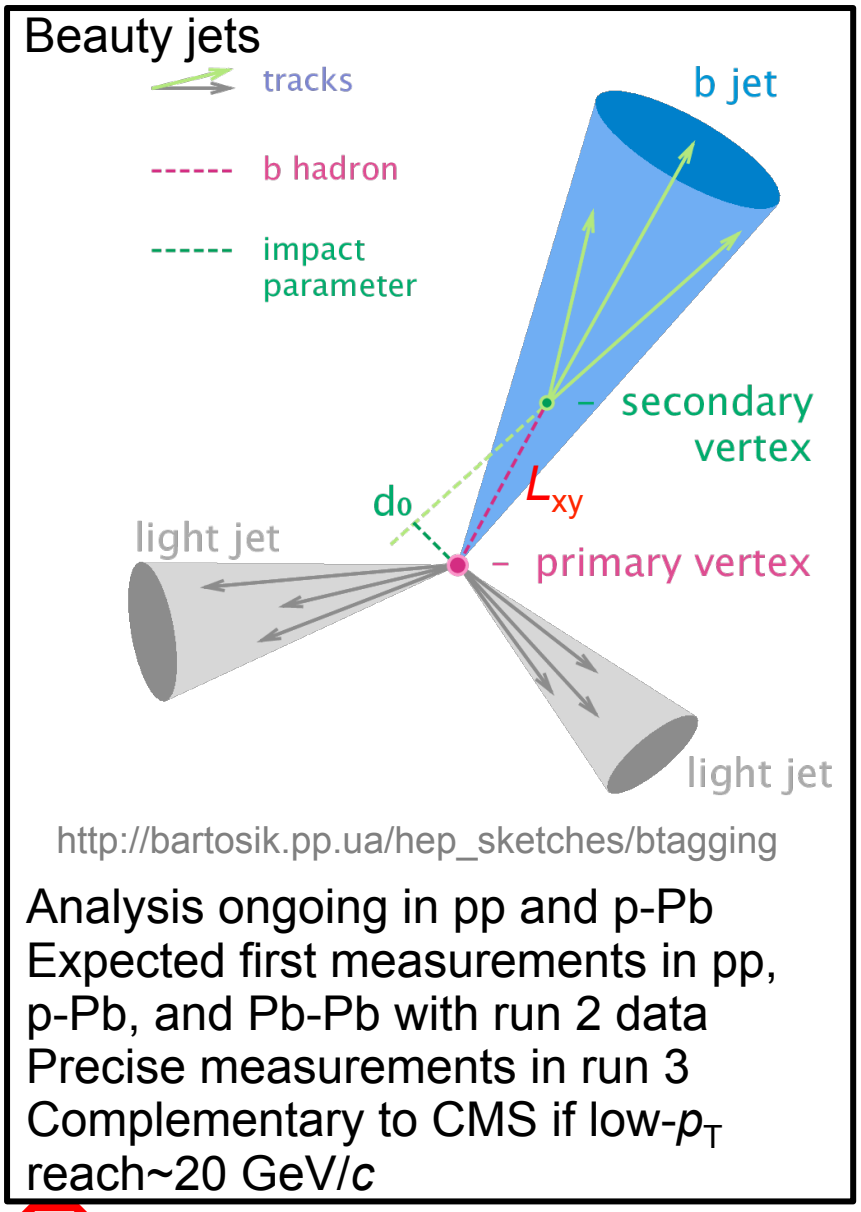
TPC, ITS → Charged constituents → **Jet**

↓

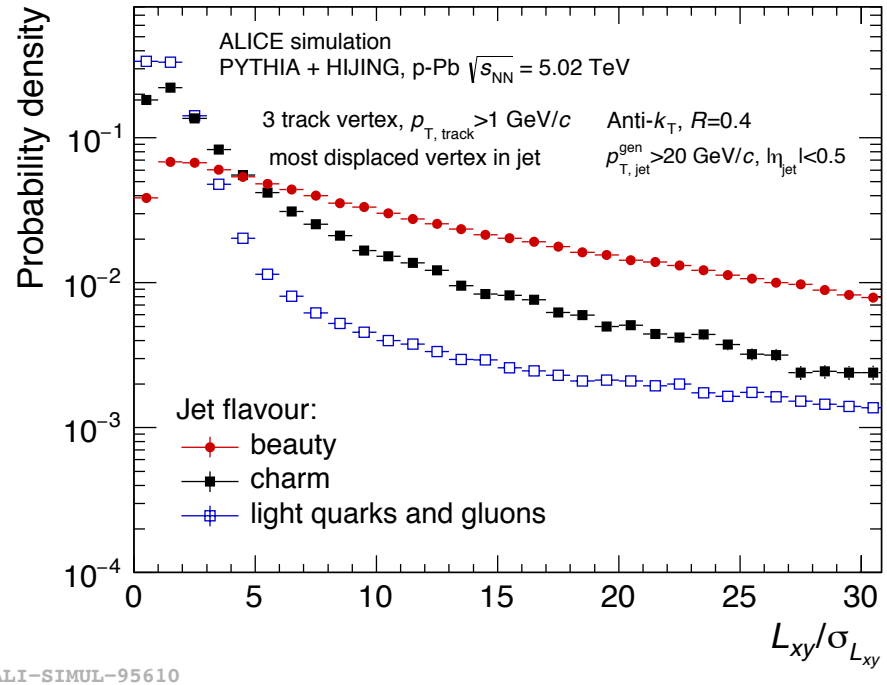
"Charged jet"

N.B. p_T scale is not the same!
Very roughly speaking: 3/2 factor from charged to "full"-jet p_T

Heavy-flavour jet tagging with ALICE



Analysis ongoing in pp and p-Pb
Expected first measurements in pp, p-Pb, and Pb-Pb with run 2 data
Precise measurements in run 3
Complementary to CMS if low-p_T reach~20 GeV/*c*



3 approaches:

- Single-track distance-to-closest approach (DCA)
- Secondary vertex reconstruction + selections to identify displaced topology
- Single track, secondary vertices, constituent information → Machine-Learning based classification

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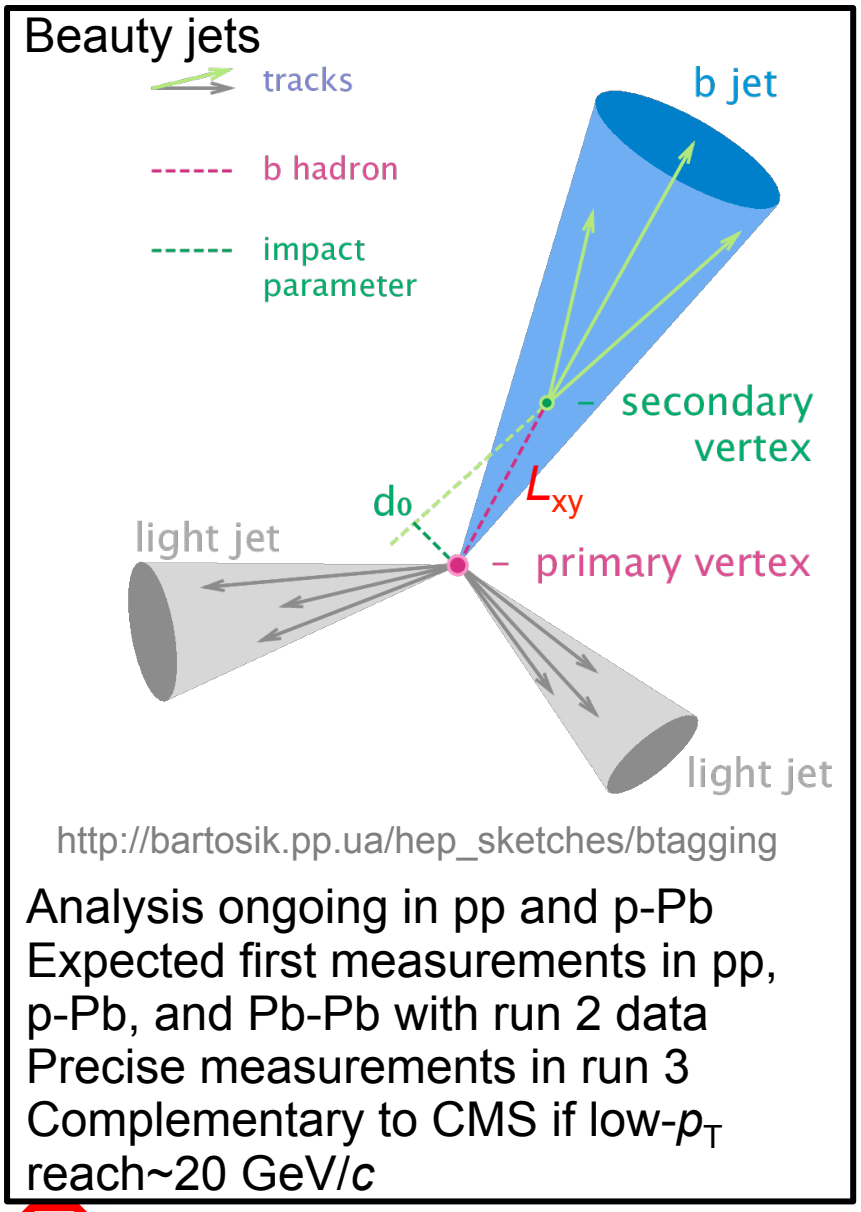

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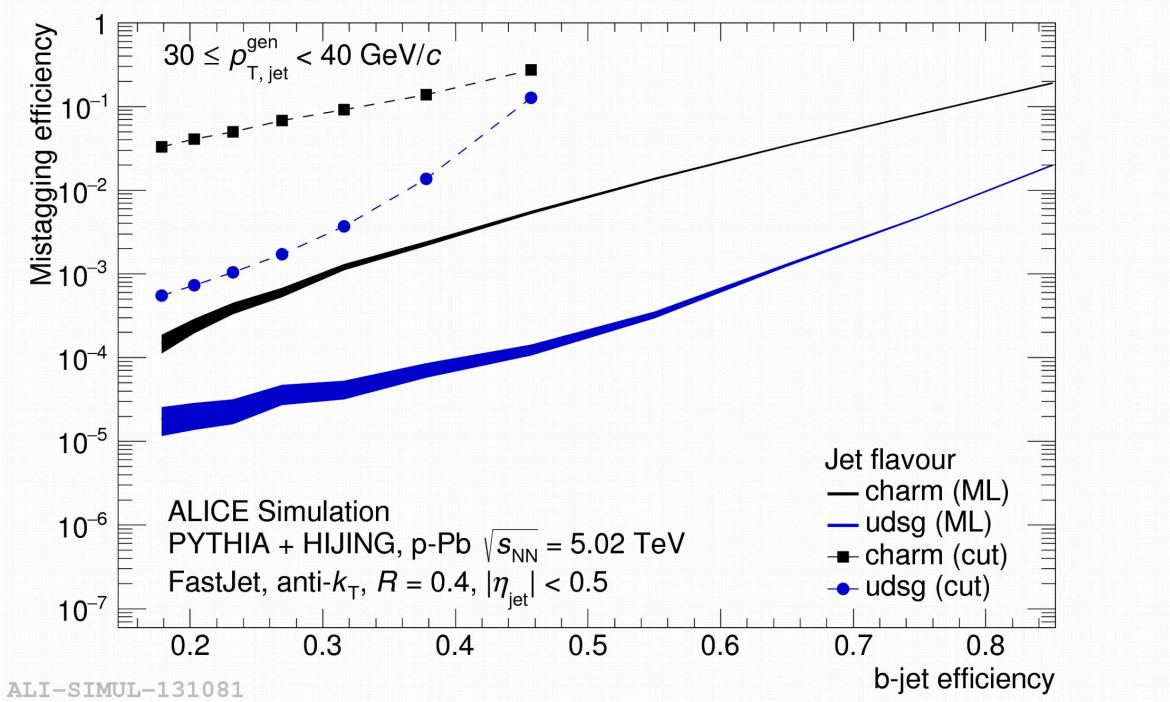
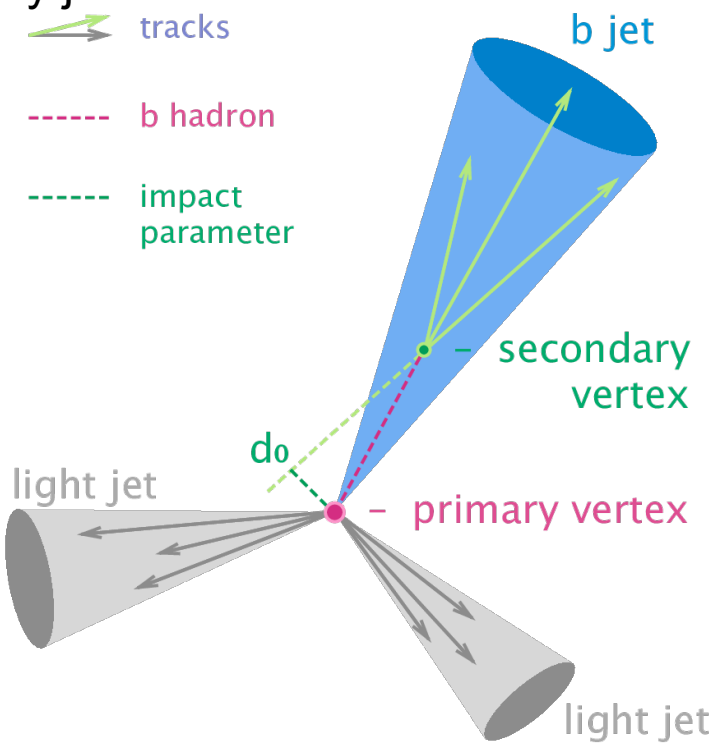


3 approaches:

- Single-track distance-to-closest approach (DCA)
- Secondary vertex reconstruction + selections to identify displaced topology
- Single track, secondary vertices, constituent information → Machine-Learning based classification
  - Huge gain in discrimination power between beauty and c/light-jets
  - Started to explore only recently

Heavy-flavour jet tagging with ALICE

Beauty jets



http://bartosik.pp.ua/hep_sketches/btagging

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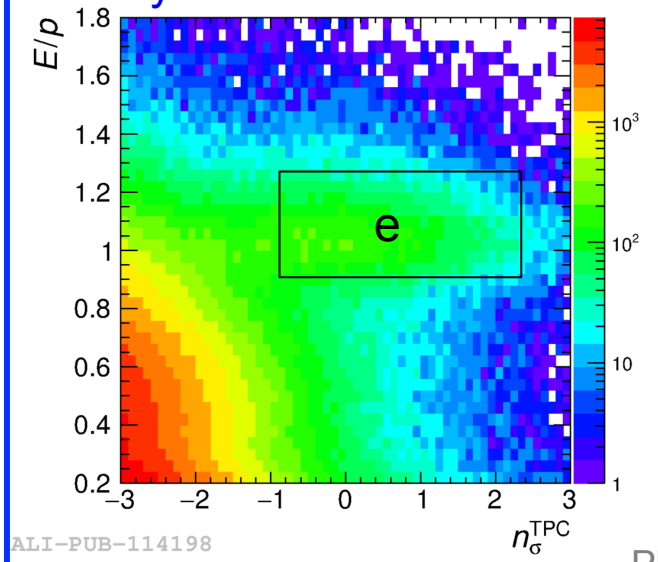
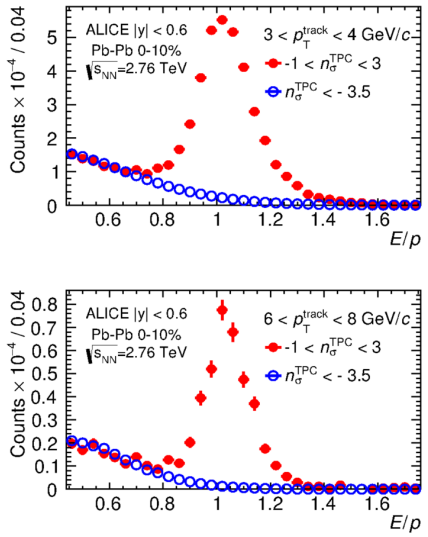
Heavy-flavour electrons →Charm + beauty jets

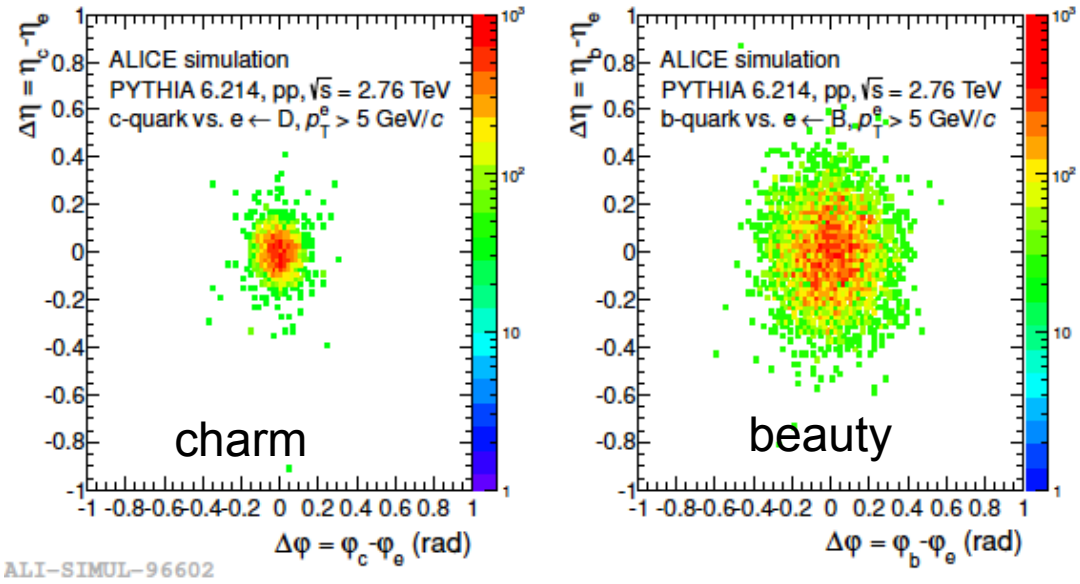




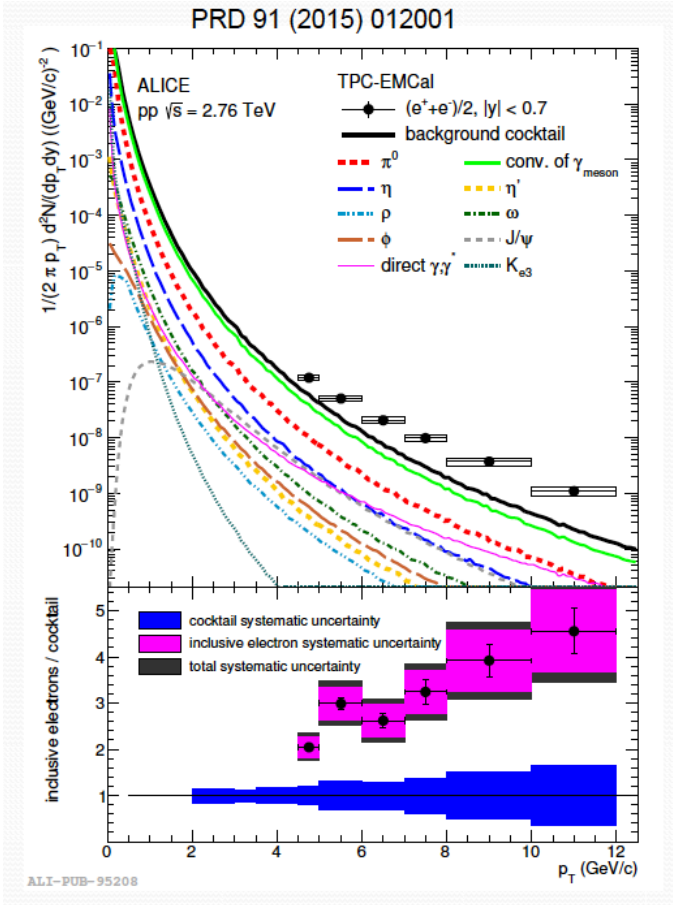
Phys. Lett. B 771 (2017) 467-481

Analysis ongoing in Pb-Pb

HFe-jet tagging



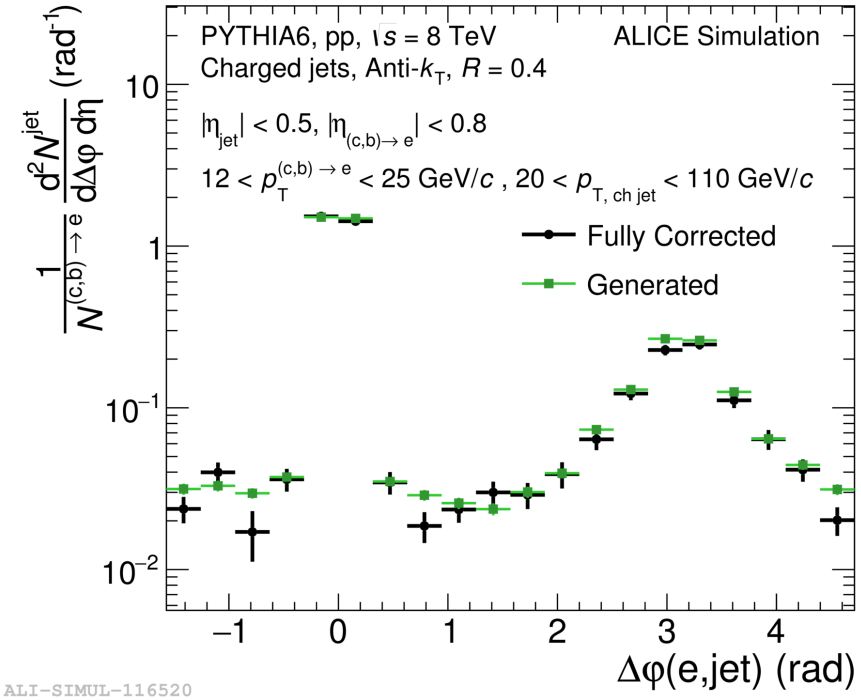
Electron with p_T>5 GeV/c preserve the parent-quark direction
Inside HF-jet radius: >95% for R=0.3

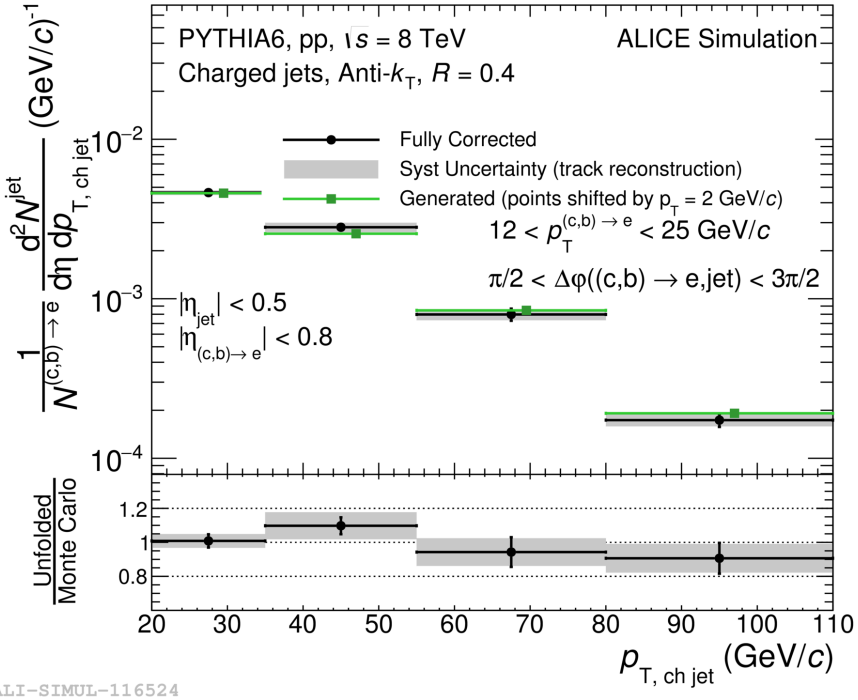


- "Raw" electron yield dominated by heavy-flavour hadron decay electrons for p_T>3 GeV/c
- Electrons from γ-conversions and Dalitz decay removed with invariant mass cut (→ identify e^+e^- pair) → 90% purity of HFe/ inclusive electrons
- Beauty dominance at high p_T (>5 GeV/c in pp at 7 TeV)
- Accessible electron p_T range: 3<p_T<25 GeV/c

Measurement of HFe-tagged jet production ongoing in Pb-Pb collisions with run-2 data: possible p_T-reach: 20<p_T(jet)<80 GeV/c

HFe-jet angular correlations →recoil jet

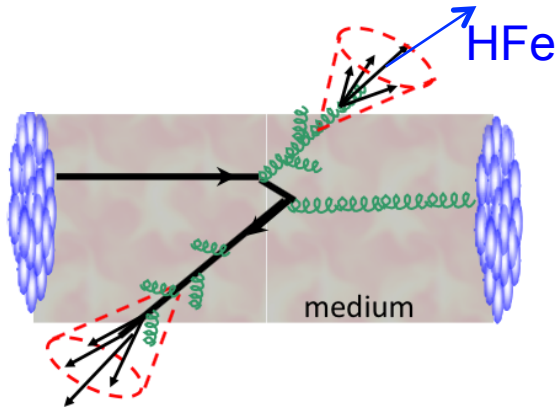




Feasibility study performed for pp collisions
Analysis on data ongoing.

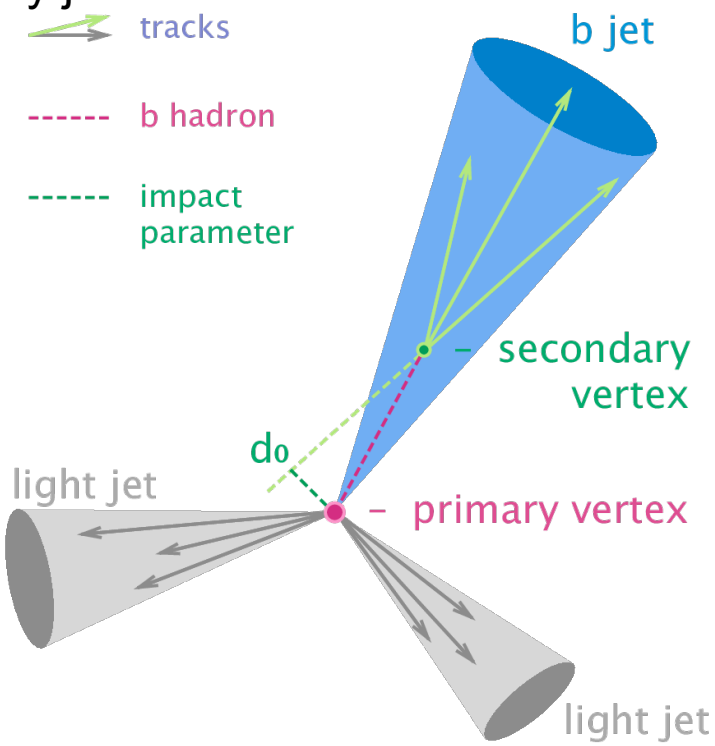
N.B. Not all jets in the away-side are from c,b quarks! (gluon splitting)
Still potentially complementary information than h-jet (but need theoretical inputs!):

- Different cocktail of q,g jets
- Different “surface bias”



Heavy-flavour jet tagging with ALICE

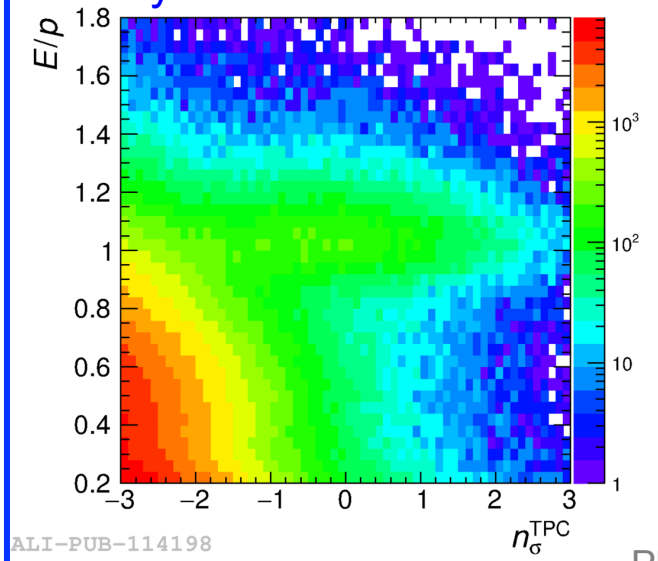
Beauty jets

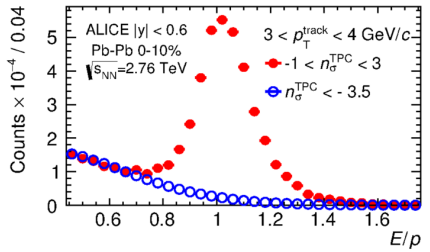


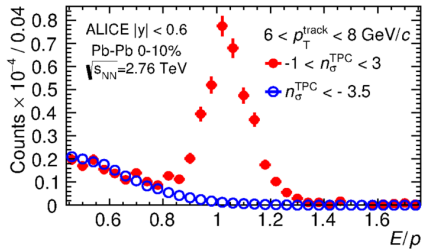
http://bartosik.pp.ua/hep_sketches/btagging

Analysis ongoing in pp and p-Pb
Expected first measurements in pp, p-Pb, and Pb-Pb with run 2 data
Precise measurements in run 3
Complementary to CMS if low-p_T reach~20 GeV/c

Heavy-flavour electrons →Charm + beauty jets





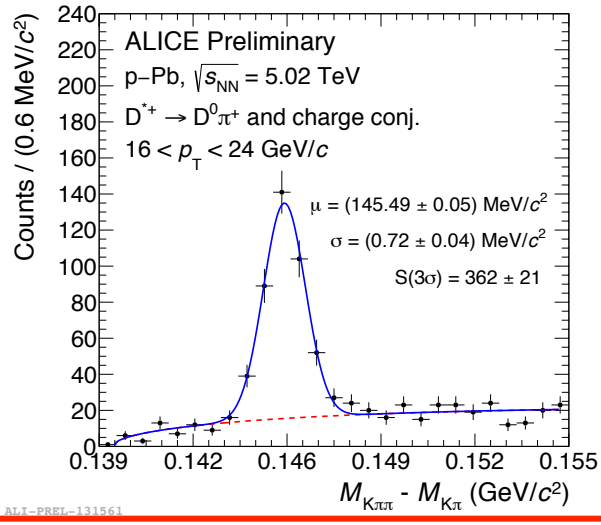


Phys. Lett. B 771 (2017) 467-481

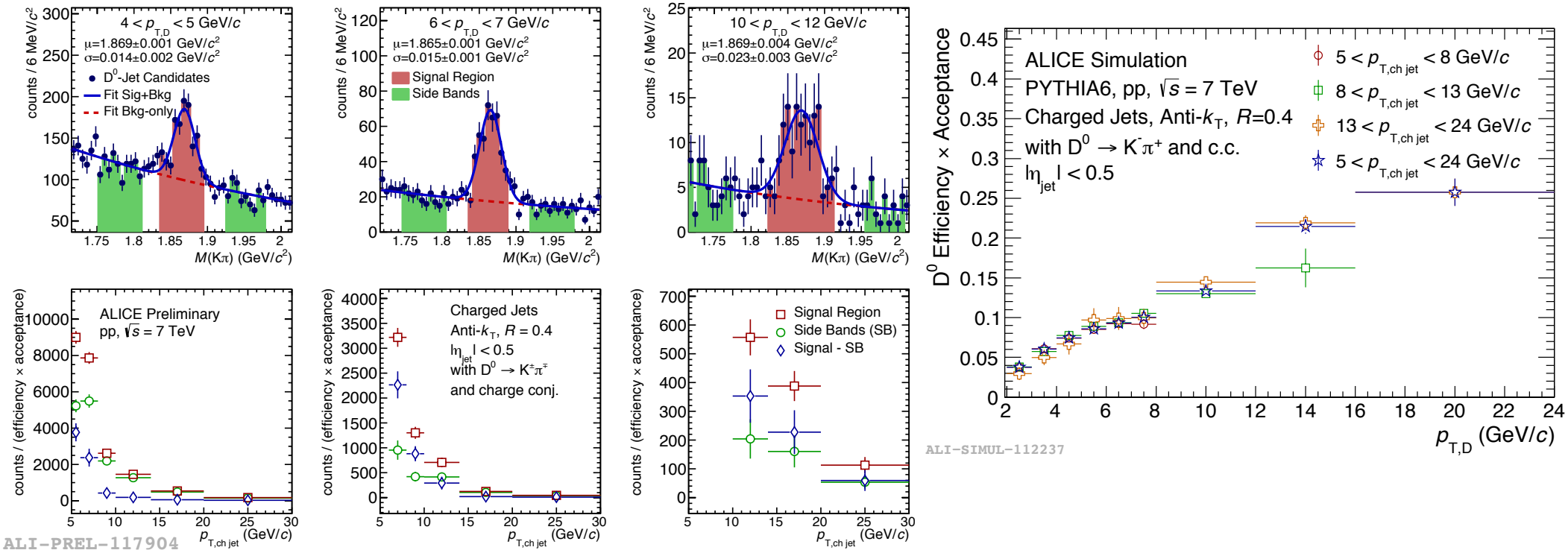
Analysis ongoing in Pb-Pb

D meson → charm jets

Tagging jet by presence of D-meson, with fully reconstructed decay

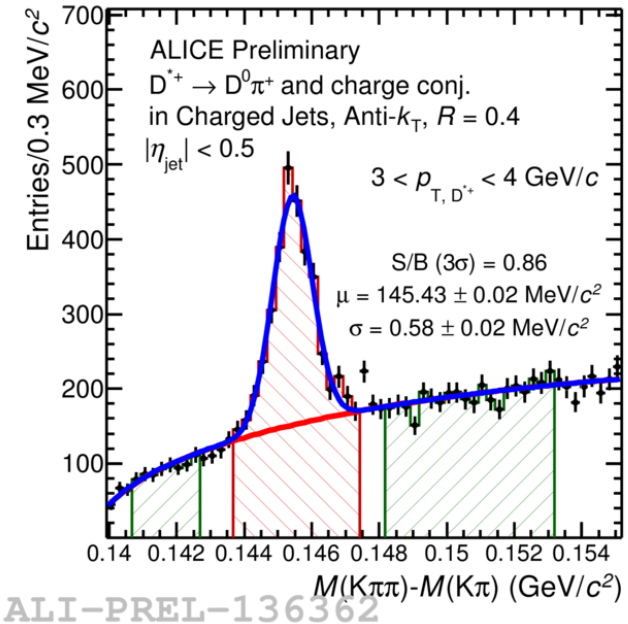


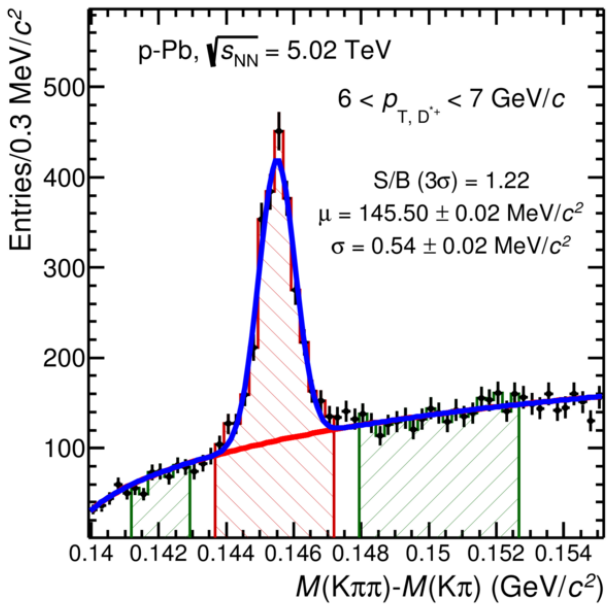
D-jet tagging

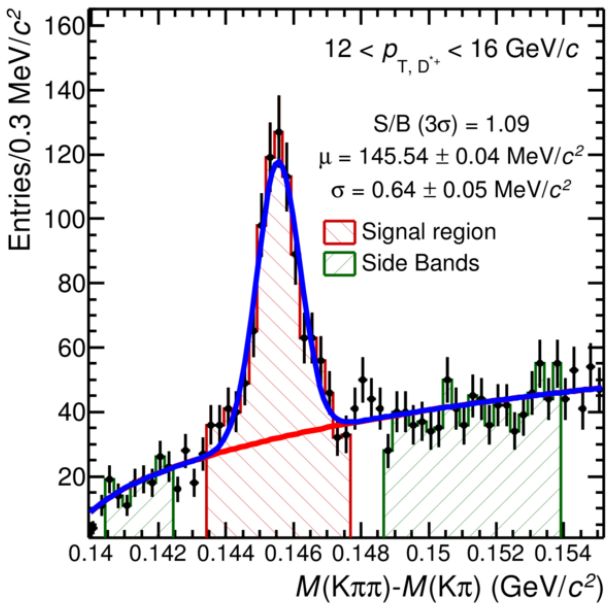


- In events with a selected D-meson candidate, jets are reconstructed replacing the D meson daughters with the reconstructed D-meson particle.
- D-jets = jets with D-meson as one of the constituents
- Spectrum of real D-jets obtained by subtracting the spectrum of jets with background D in the invariant mass sidebands from the spectrum in the D mass peak
- Correction for efficiency
- Feed-down subtraction based on POWHEG+PYTHIA simulations and efficiencies
- Integrate over D-meson p_T bins
- Unfolding for detector effects and underlying event fluctuations in p-Pb collisions

D-jet tagging: p-Pb collisions

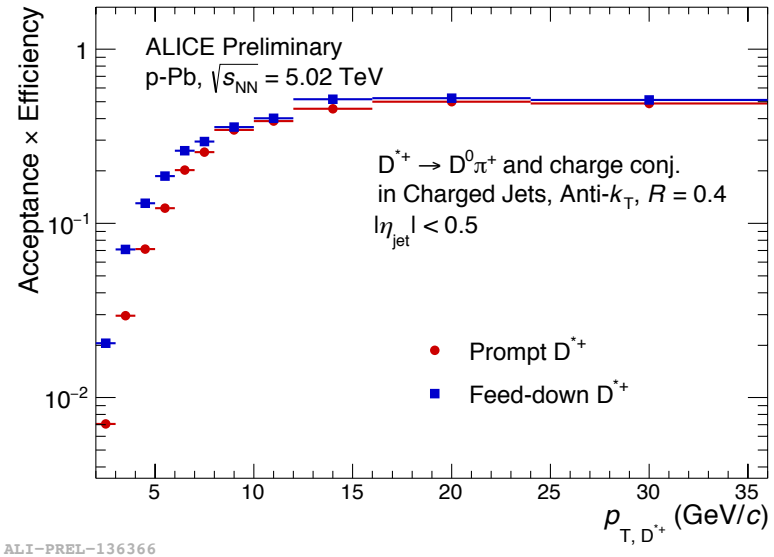






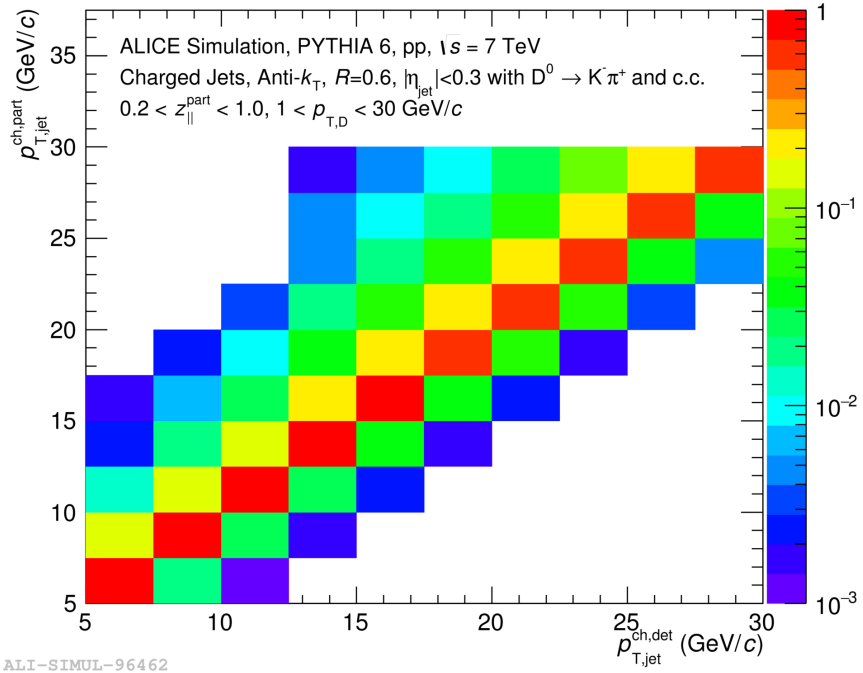
ALI-PREL-136362

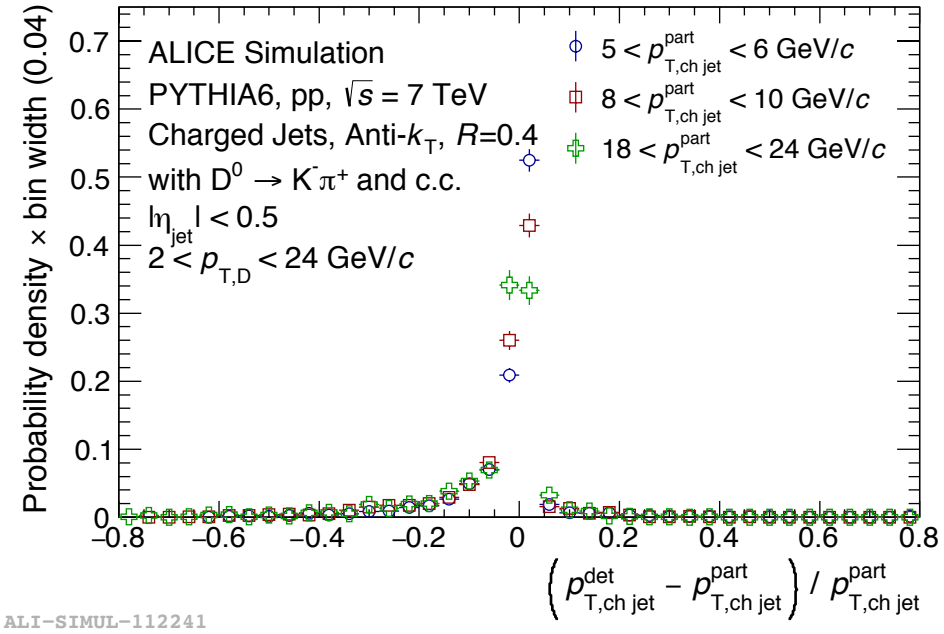
$D^{*+} \rightarrow D^0\pi^+$ channel exploited in p-Pb collisions
Typically higher S/B than $D^0 \rightarrow K^-\pi^+$ but less signal

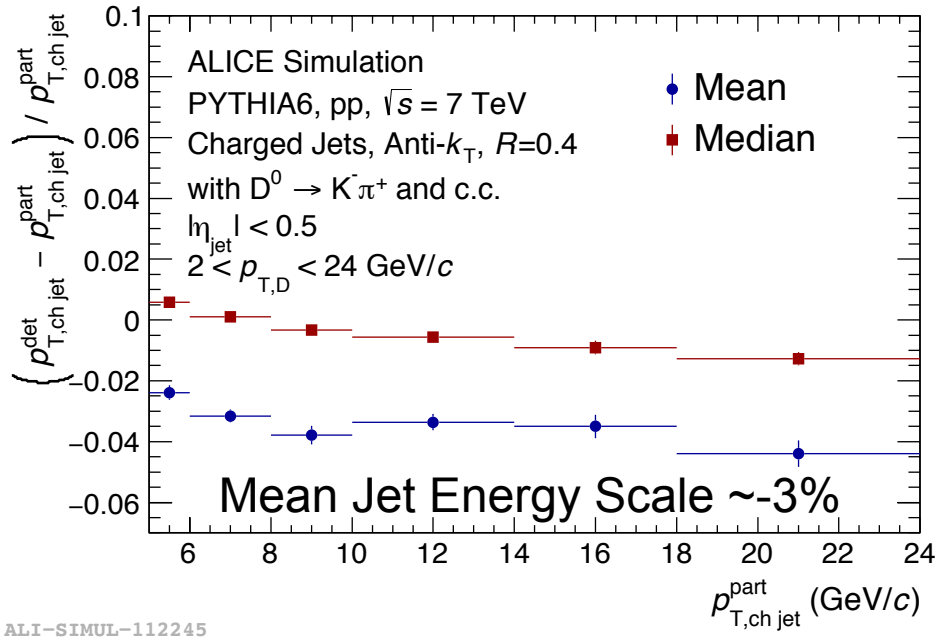


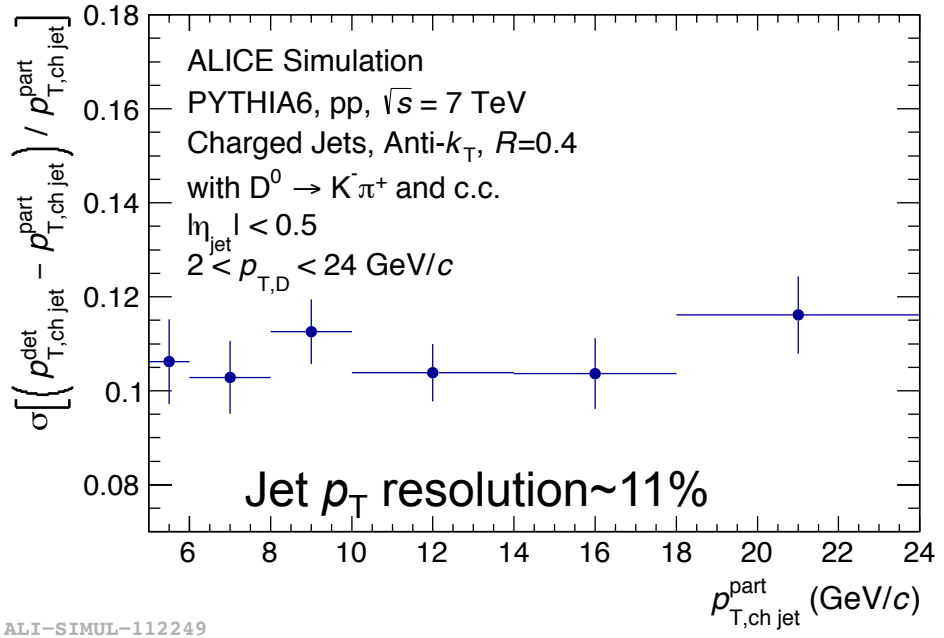
ALI-PREL-136366

D^0-tagged jet in pp: detector performance

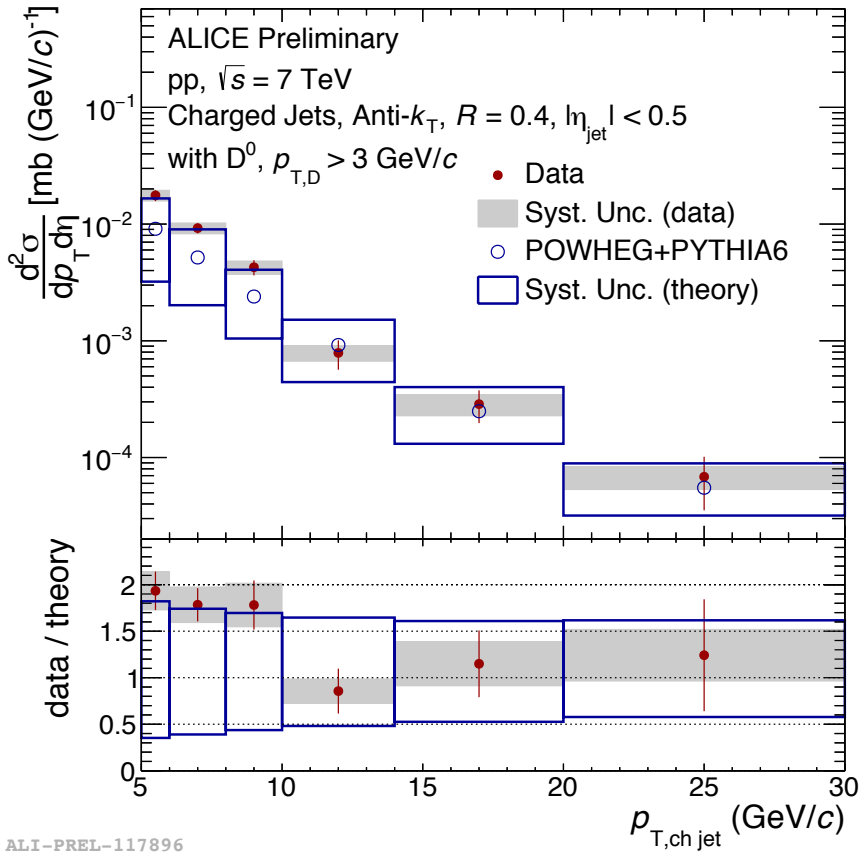


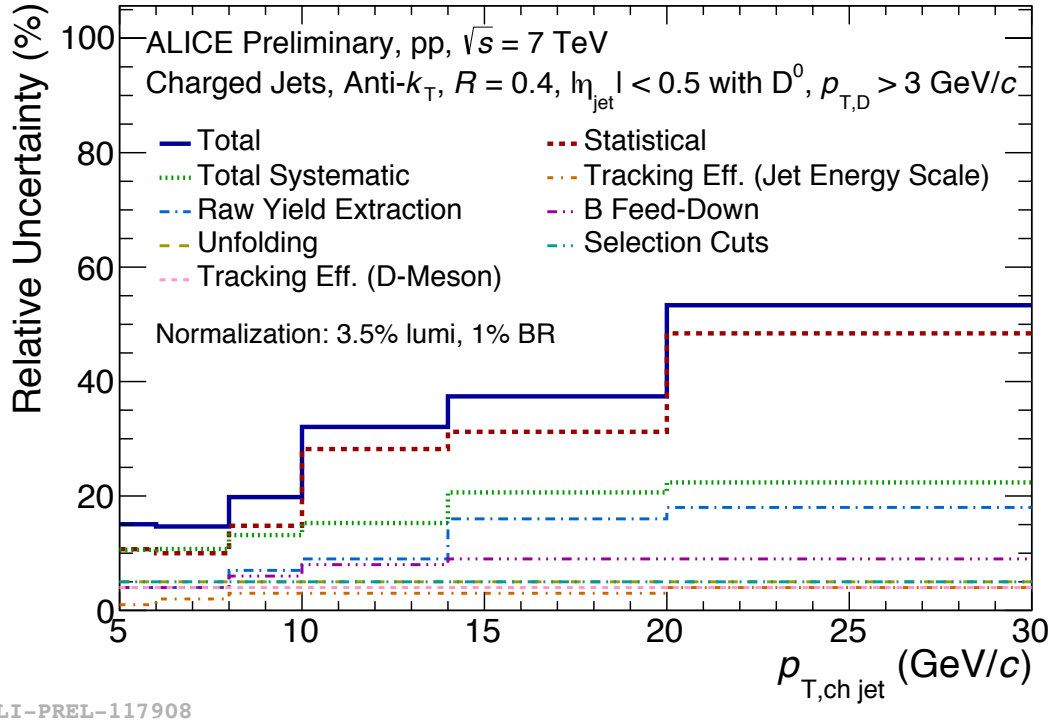






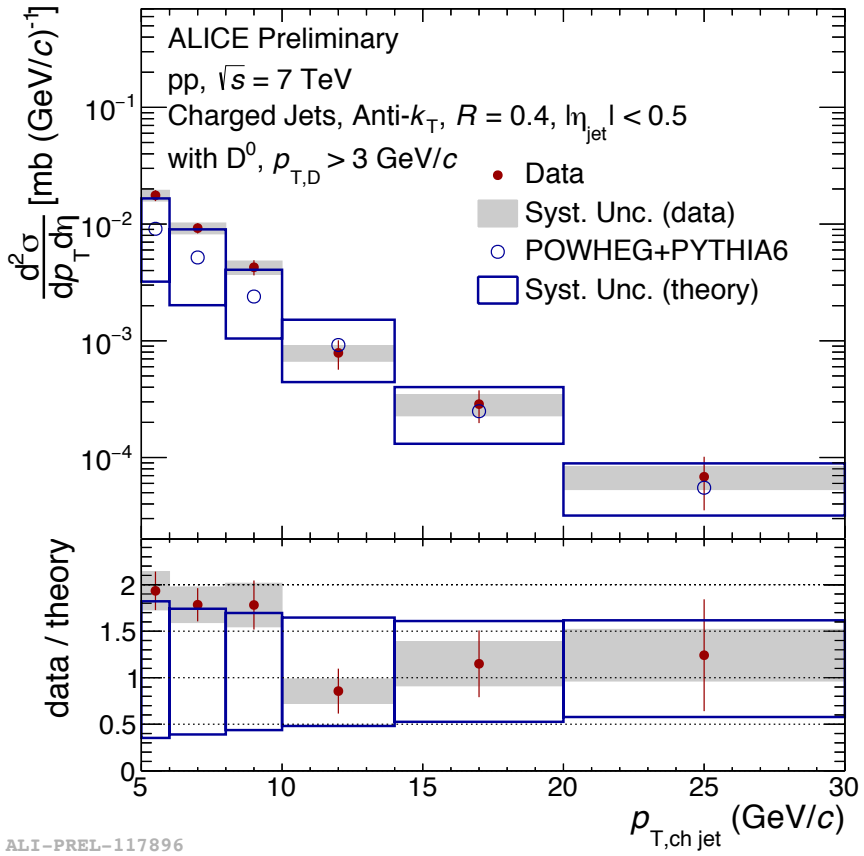
D-jet in pp collisions

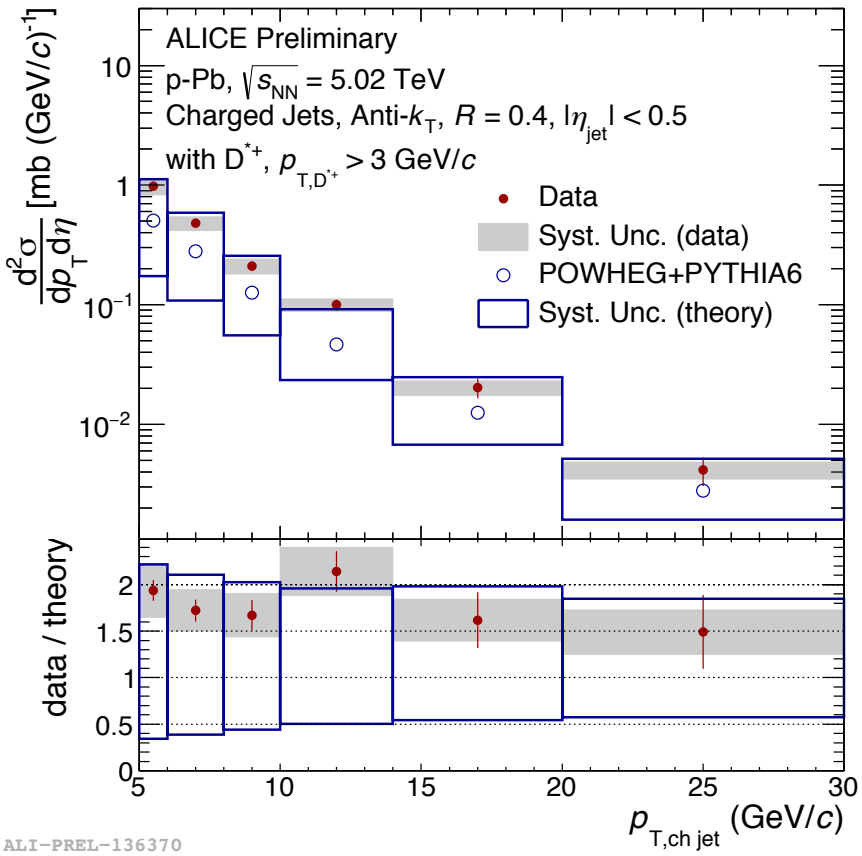




D-jet spectrum measured from p_T=5 GeV/c to 30 GeV/c
Main syst. uncertainties: yield extraction, feed-down subtraction, unfolding
Described by POWHEG+PYTHIA6 (Perugia 2011 tune) simulation within uncertainty

D-jet in pp and p-Pb collisions

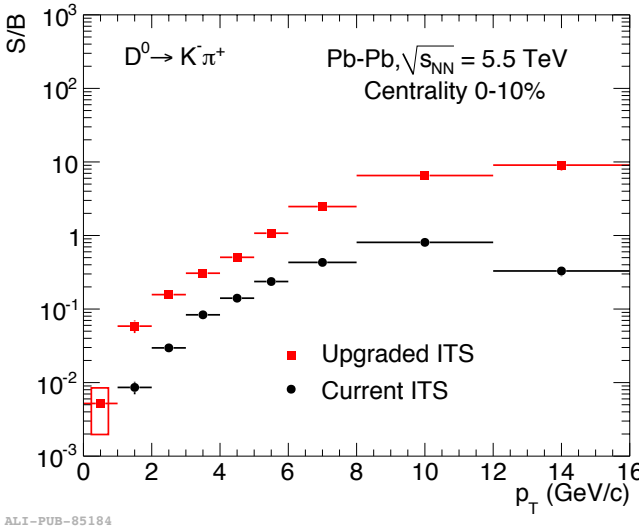




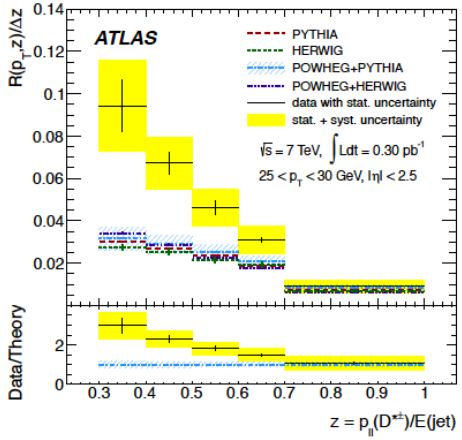
D-jet spectrum measured from p_T=5 GeV/c to 30 GeV/c
Main syst. uncertainties: yield extraction, feed-down subtraction, unfolding.
Described by POWHEG+PYTHIA6 (Perugia 2011 tune) simulation within uncertainty

D-jet measurements: prospects

- More precise measurements in pp collisions from larger data samples at 13 TeV and 5 TeV (from 2017 run t.b.c. by September)
  - Exploit all mesons (D^0, D^{*+}, D^+) to improve precision and calculate nuclear modification factors
- Pb-Pb data:
  - first measurement with run 2 data
  - precise measurement after detector upgrade:
    - x100 statistics + improved spatial resolution → A. Uras



- First step for measuring charm-jet properties and investigating their substructure
  - Study momentum fraction (à la ATLAS), but accessing lower momentum range
  - Study cross-section ratio for different *R*
  - Study jet-shapes
    - Can we identify jets with D (or HFe) from gluon-splitting?



Summary

HF-jet measurements can provide additional information w.r.t. single particle observables

Access parton shower in the medium → further insight in energy loss process and spatial distribution of lost energy

ALICE started to measure HF-jet production

- D-jet production measured in pp collisions at $\sqrt{s}$=7 TeV and p-Pb colllisions at $\sqrt{s_{NN}}$=5.02 TeV
- Described by POWHEG+PYTHIA6 within uncertainty
- Further analyses ongoing to measure b-jet and charm+beauty jet production

Very good opportunities with Run 2 and especially Run 3 and Run 4 data

However, we really need theoretical inputs to

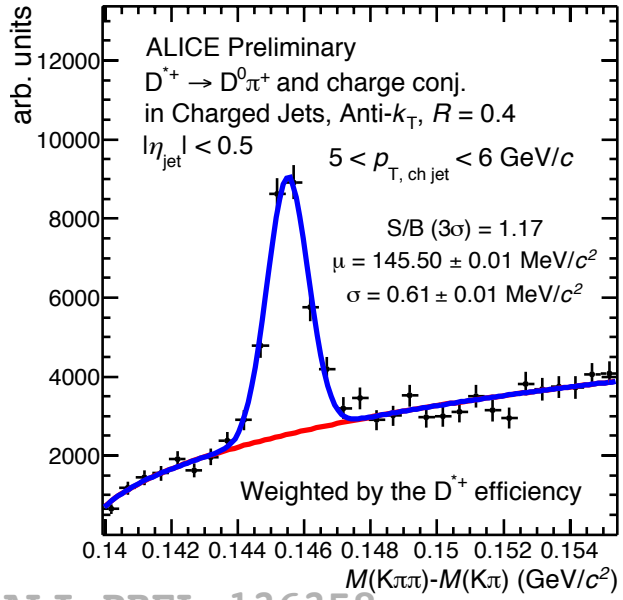
- Have quantitative predictions
- Identify best observables

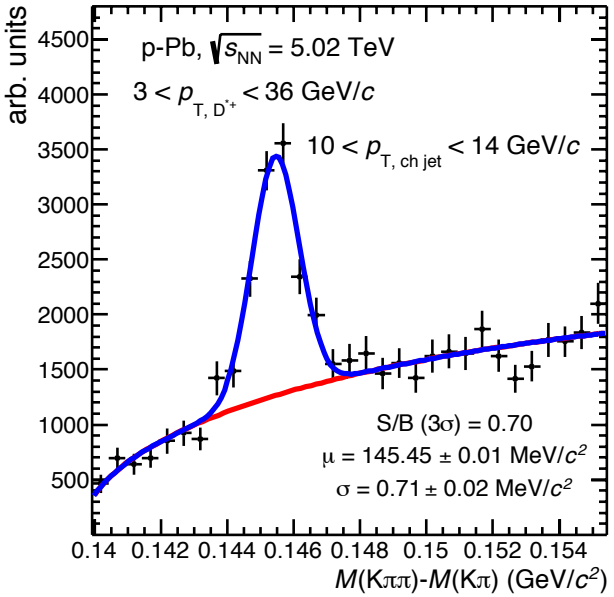
Thanks
… and find the jets!
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
ALICE

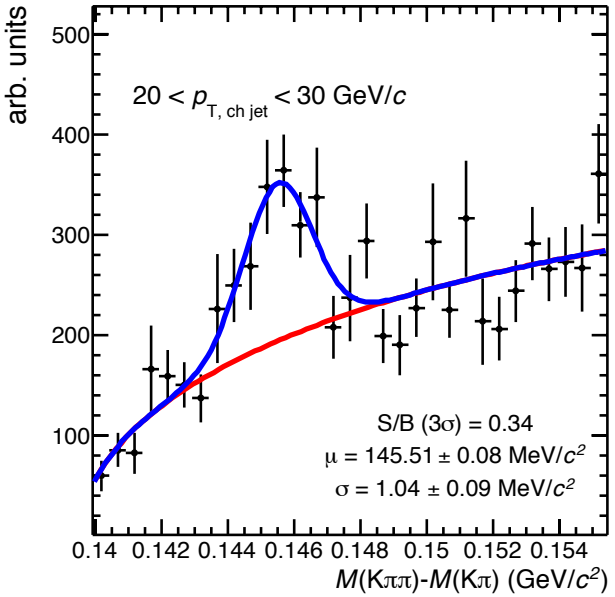
D-jet tagging

Cross-checked with alternative procedure in which we look at D-meson signal in bins of jet p_T (similar to ATLAS procedure, Phys. Rev. D85 052005 (2012))

- Different handling of efficiency correction and signal extraction (mass fit)
- Very consistent results w.r.t. standard approach



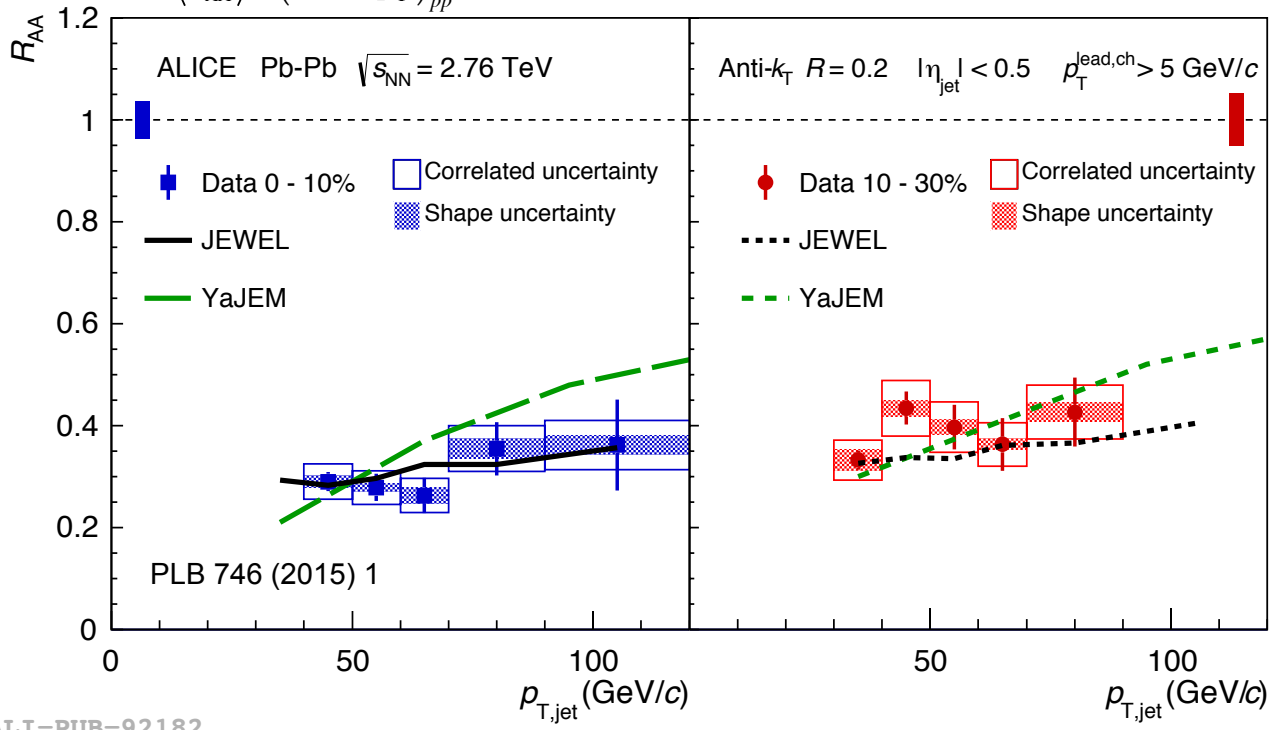


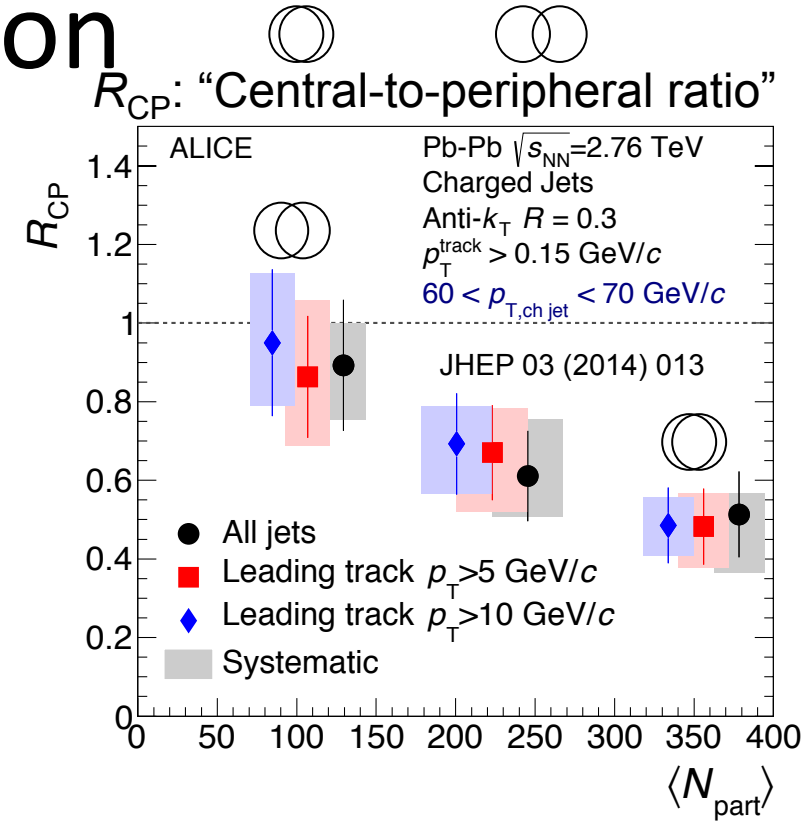


ALI-PREL-136358

Jet suppression

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{Pb-Pb}}{\langle T_{AA}\rangle \times (d\sigma/dp_T)_{pp}}$$





ALI-PUB-92182

Suppression of jet production by a factor ≥ 2 in central collisions

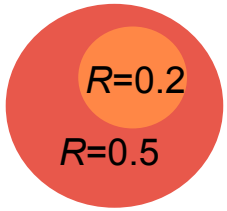
→ part of energy radiated by partons dissipated out of jet cone

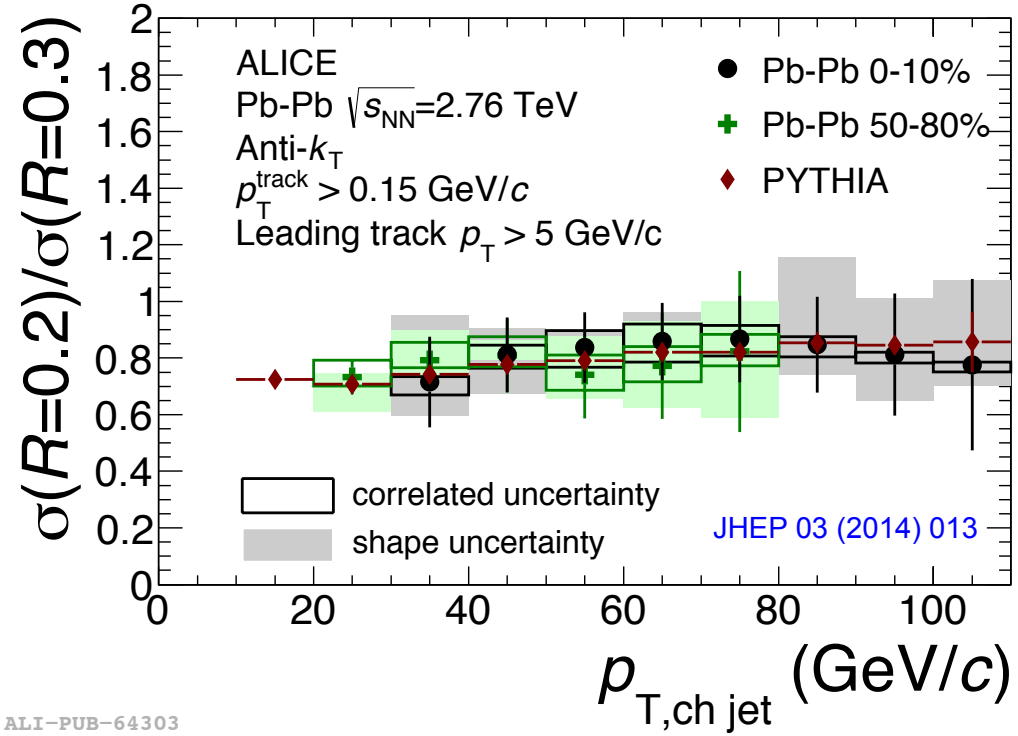
No significant p_T dependence (within uncertainties) in $40<p_T<120$ GeV/c

Suppression increasing with collision centrality

Suppression value and p_T trend described by models within uncertainties

Probing modification of jet structure





Ratio of spectrum of jets reconstructed with R=0.2 and R=0.3 compatible with expectations from PYTHIA within uncertainties

Jet reconstruction in ALICE: heavy-ion collisions

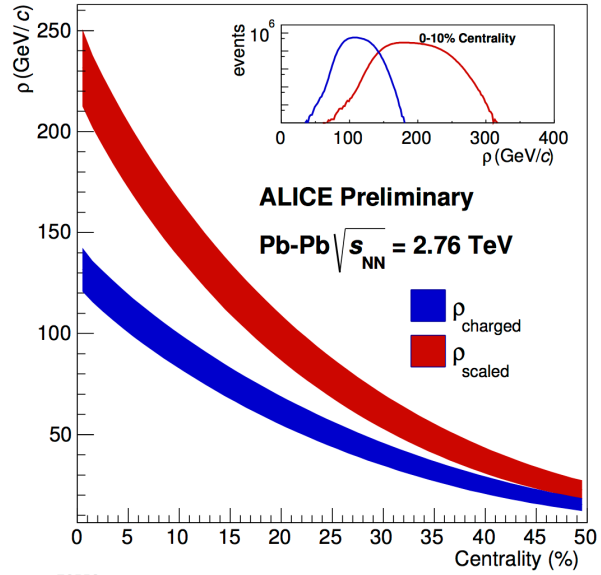
Large background of uncorrelated particles → energy density estimated on an event-by-event

$$\rho^{ch} = median\left\{\frac{p_{T,i}}{A_i}\right\} \qquad \rho^{ch+em} = S_{EMC} \bullet \rho^{ch} \qquad S_{EMC} = \frac{\sum E_T^{cluster} + \sum p_T^{track}}{\sum p_T^{track}}$$

$p_{T,i}$, A_i: transverse momentum and area of jets reconstructed with k_T algorithm

→ **Subtract ρ*A* on a jet-by-jet basis** to build measured "raw" spectrum

~200 GeV/*c* per unit area in central collisions
→ ~25 GeV/*c* for $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2} = 0.2$



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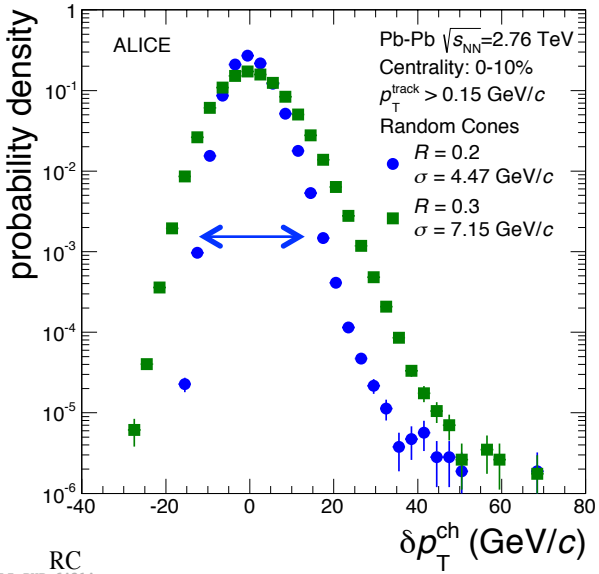
$p_{T,i}$, A_i: transverse momentum and area of jets reconstructed with k_T algorithm

→ **Subtract ρ*A* on a jet-by-jet basis** to build measured "raw" spectrum

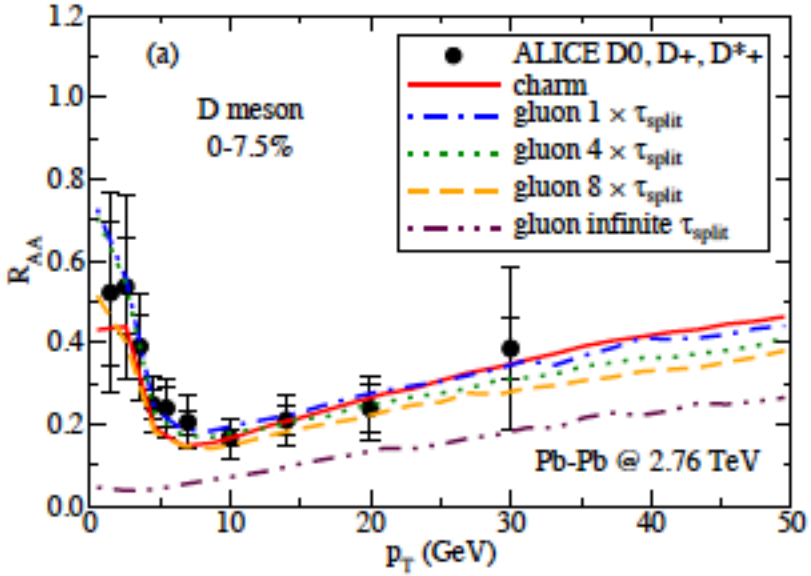
→ **Unfolding** with "response matrix" to correct for
- Detector effects, which shift and smear the spectrum
- Background fluctuations, which smear the spectrum

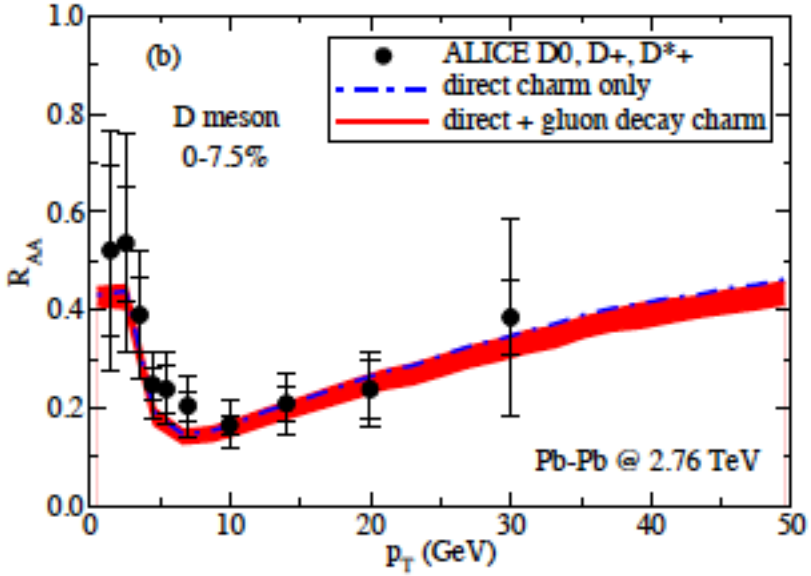
→ **Corrected spectrum**



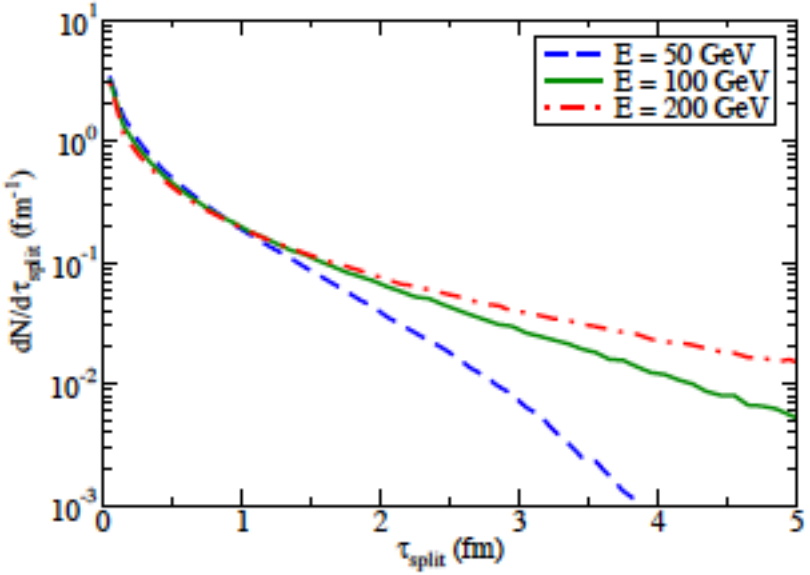
$$\delta p_T^{ch} = \sum_i^{RC} p_T^i - \rho A^{RC}, \quad \text{RC="Random Cones"}$$

Impact of gluon splitting to D-meson R_{AA}





S. Cao et al, Phys. Rev. C 93, 024912 (2016)

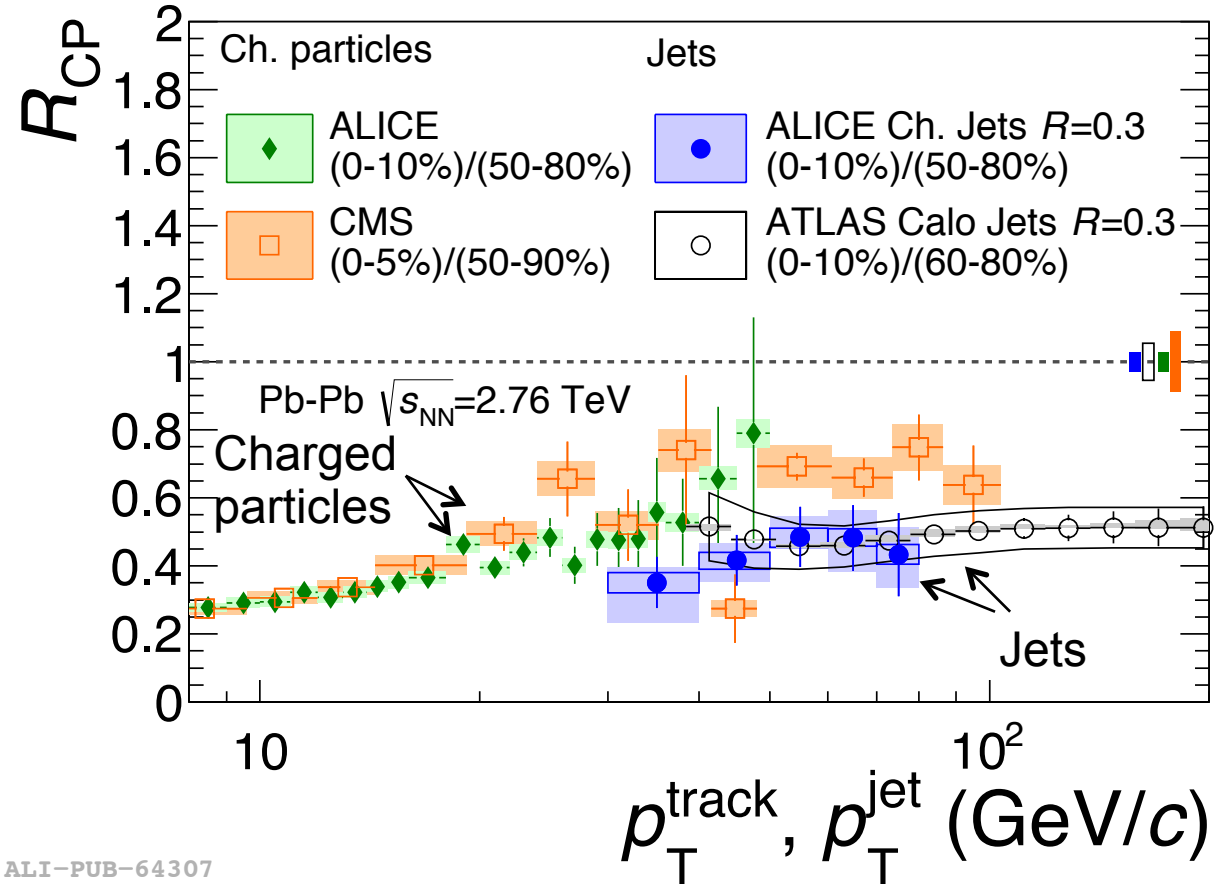


Most of gluons split very early
Gluon energy loss before splitting does not impact much the D meson R_{AA}

Can this be confirmed/probed with experimental information?

Jets vs. single particles

R_{CP}: "Central-to-peripheral ratio"



High-p_T particles → "core" of jets

→ Suppression of high-p_T constituents of jets

ALICE upgrade: New ITS

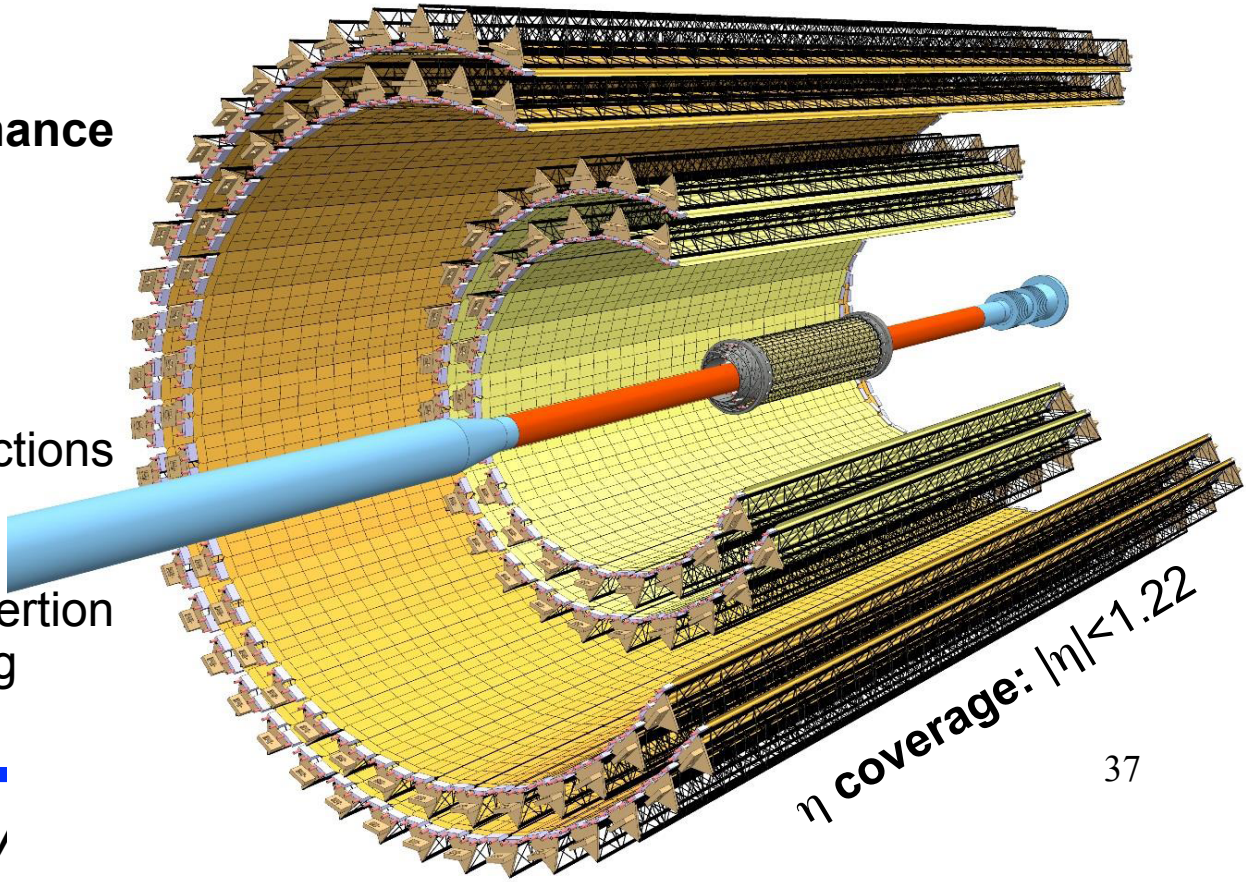
Design requirements:

1. **Improve impact parameter resolution by a factor ~3 (5) in rφ (z)**
   - ➜ Reduce pixel size (currently 50 μm x 425 μm)
     - monolithic (MAPS) with size ~ 29 μm x 27 μm
   - ➜ Go closer to interaction point:
     - ➜ new smaller beam pipe: 2.9 cm ➞ 1.9 cm
     - ➜ first layer with smaller radius (2.2 cm, currently 3.9 cm)
   - ➜ Reduce material thickness: 50 μm silicon, X/X_0 from current ~1.13% to ~0.3(0.8)% per layer

2. **High standalone tracking performance** (efficiency, spatial and momentum resolutions)
   - ➜ Increase granularity
   - ➜ Add 1 layer (from 6 to 7)

3. **Faster (x50) readout**: Pb-Pb interactions up to 100 kHz

4. **Maintenance:** allow for removal/insertion of faulty detector components during annual winter shutdown



ALICE data-taking in Run-2

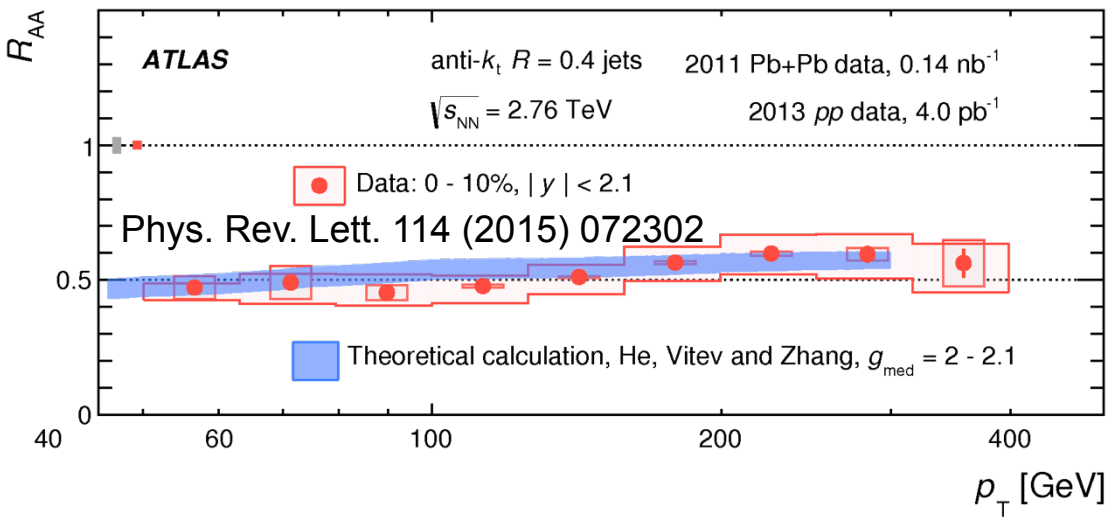
System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2015-2016	13	~14 pb^{-1}
pp	2015 (~4 days)	5.02	~100 nb^{-1}
p-Pb	2016	5.02	~3 nb^{-1}
p-Pb	2016	8.16	~20 nb^{-1}
Pb-p	2016	8.16	~20 nb^{-1}
Pb-Pb	2015	5.02	~0.4 nb^{-1}

Goals for 2017-18:

Pb-Pb: reach 1/nb target

pp 13 TeV: reach 40/pb target

High statistics pp 5 TeV sample



Models can reproduce measured trend