Overview of hadron production results from ALICE

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on behalf of the ALICE Collaboration

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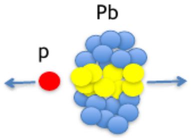
Hard hadron production in different systems

Hard scattering + underlying event

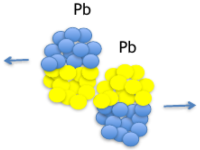
- Improvement of PDF/FF parameterization
- long-range correlations;
- flow-like effects in high multiplicity events => MPI?

Set of pp collisions + cold nuclear matter effects



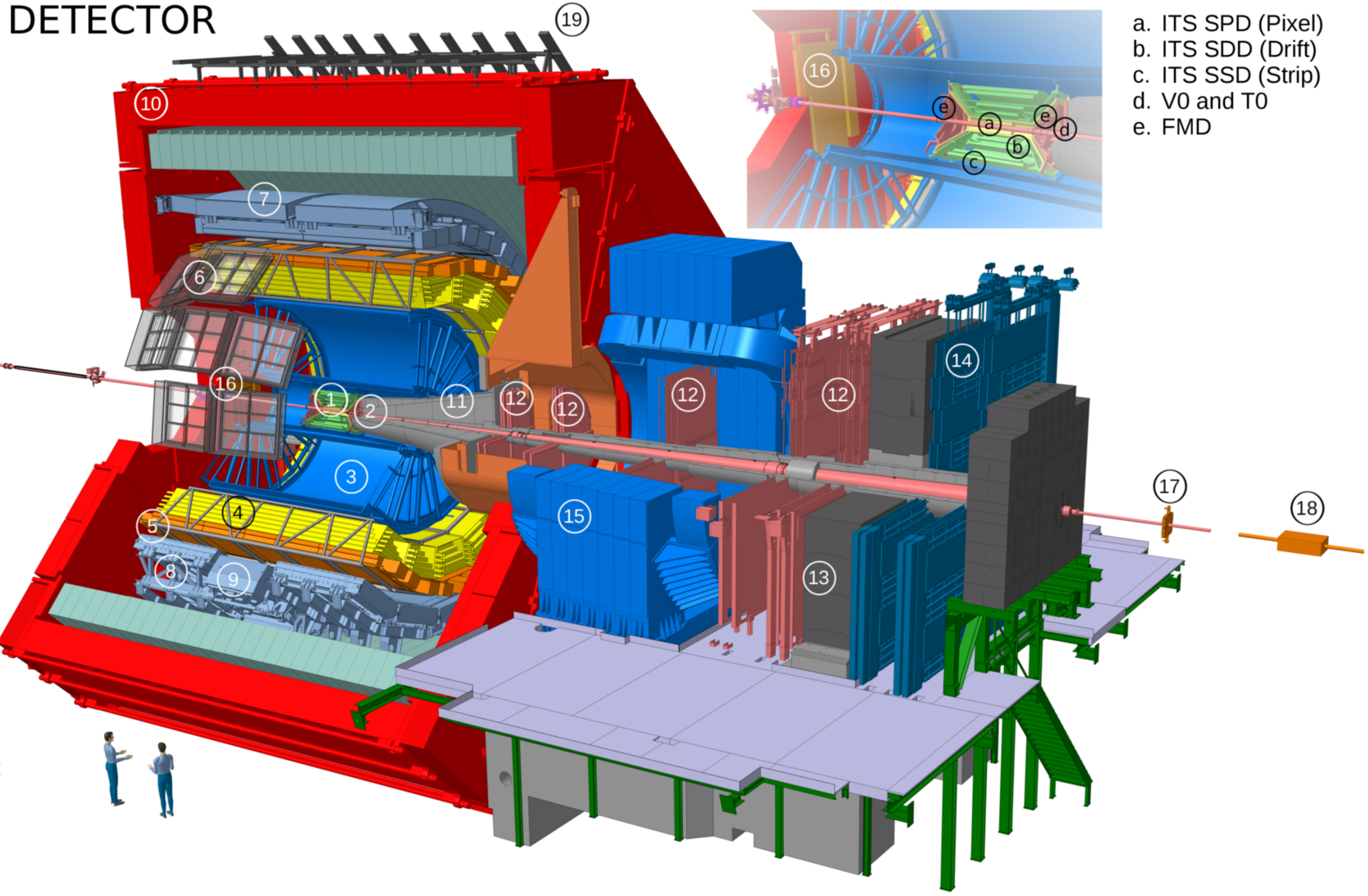
- Modification of PDF in nuclei
- Interaction with cold nuclear matter.
- Flow-like effects => smooth transition from pp to Pb-Pb

Collective hydro-like behavior + hard parton interacting with hot matter



- Details of energy loss of light and heavy quarks
- Path-length dependence
- Modification of parton fragmentation in hot matter

THE ALICE DETECTOR

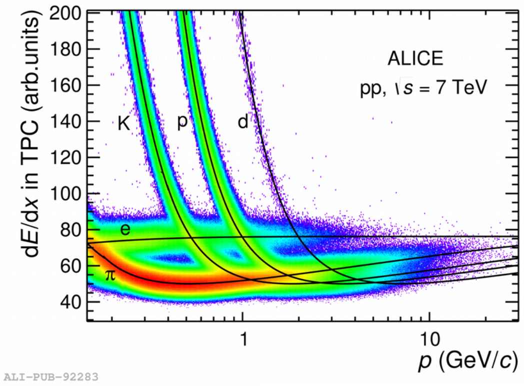


a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

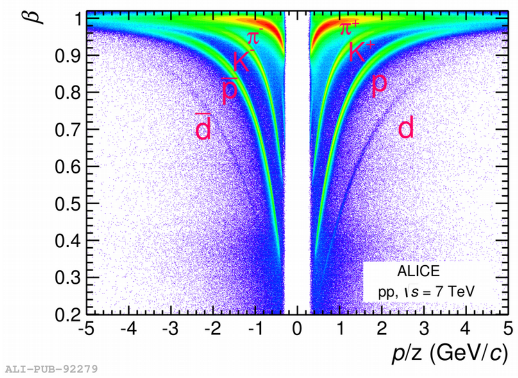
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

ALICE PID capabilities

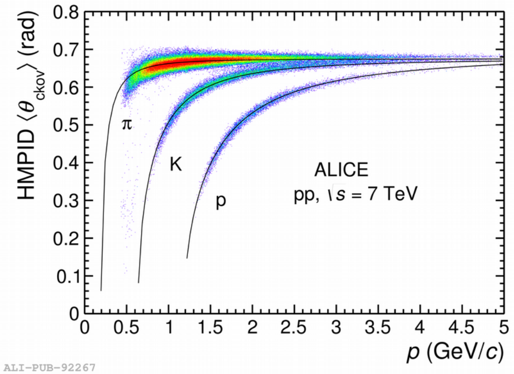
- ALICE exploits the combination of different particle identification (PID) techniques
- Energy loss (ITS, TPC)
- Time of flight (TOF)
- Cherenkov radiation (HMPID)
- Transition radiation (TRD)
- Calorimetry (EMCal/DCal, PHOS)
- Topological PID



- Up to 159 pad raws in Ne-CO_2 (Ar-CO_2) gas mixture
- The best separation at low p_T<0.7 GeV/c
- For high p_T>3-20 GeV/c statistical PID is done based on dE/dx in relativistic rise regime



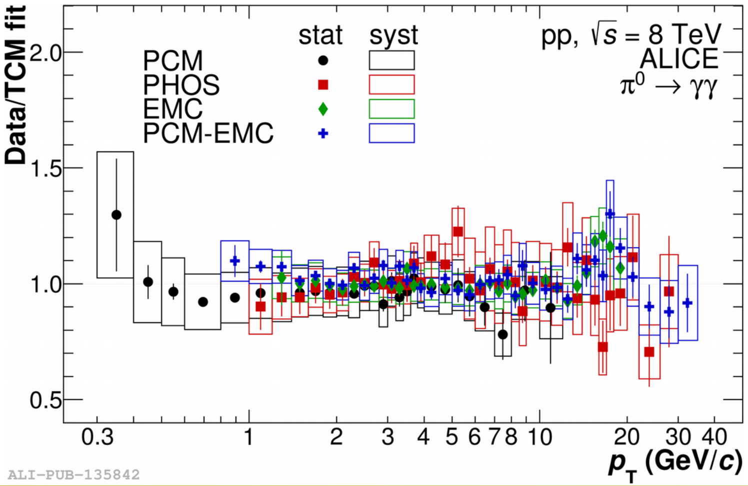
- PID performed by means of statistical unfolding of the time of flight
- Time of flight measurements enable 3σ separation for π/K up to 2.5 GeV/c and K/p up to 4 GeV/c

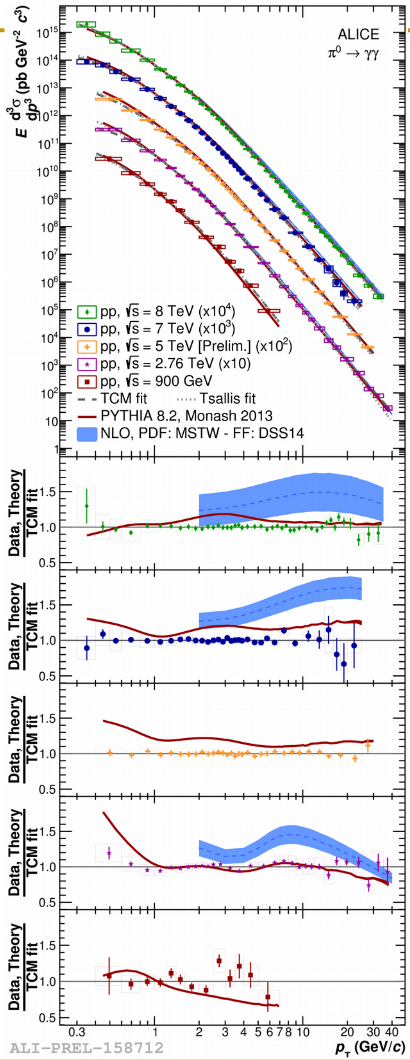


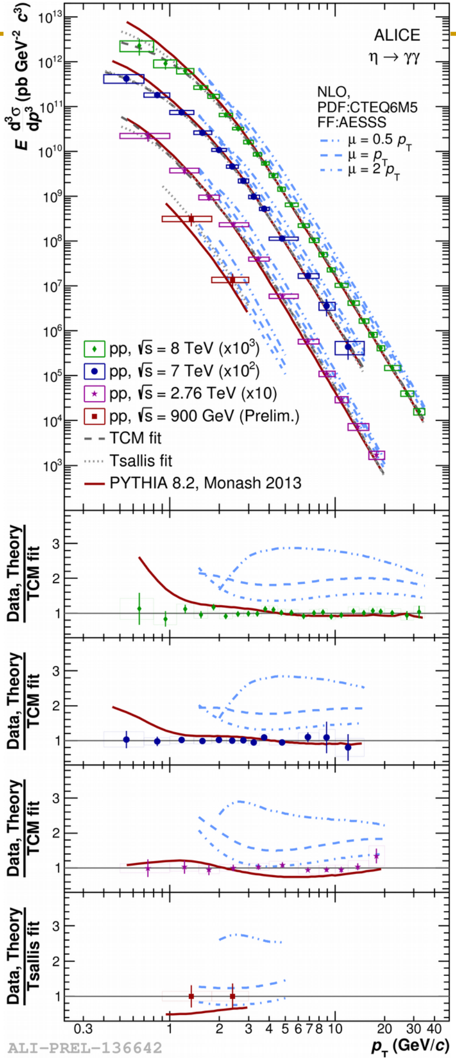
- PID performed by means of statistical unfolding of the Cherenkov angle
- 3σ separation for π/K up to 3 GeV/c and K/p up to 5 GeV/c

pp collisions

- π⁰ and η-meson spectra were measured in pp collisions at several energies with different methods
- Pythia 8 reproduces data, while NLO pQCD calculations predict 20-50% (π⁰) or 50-100% (η) higher yield
- Precision data can be used for FF and/or PDF global fits







8 TeV: Eur. Phys. J C (2018) 78:263
2.76 TeV: Eur. Phys. J C (2017) 77:339
7 TeV: Phys.Lett B (2012) 717:162

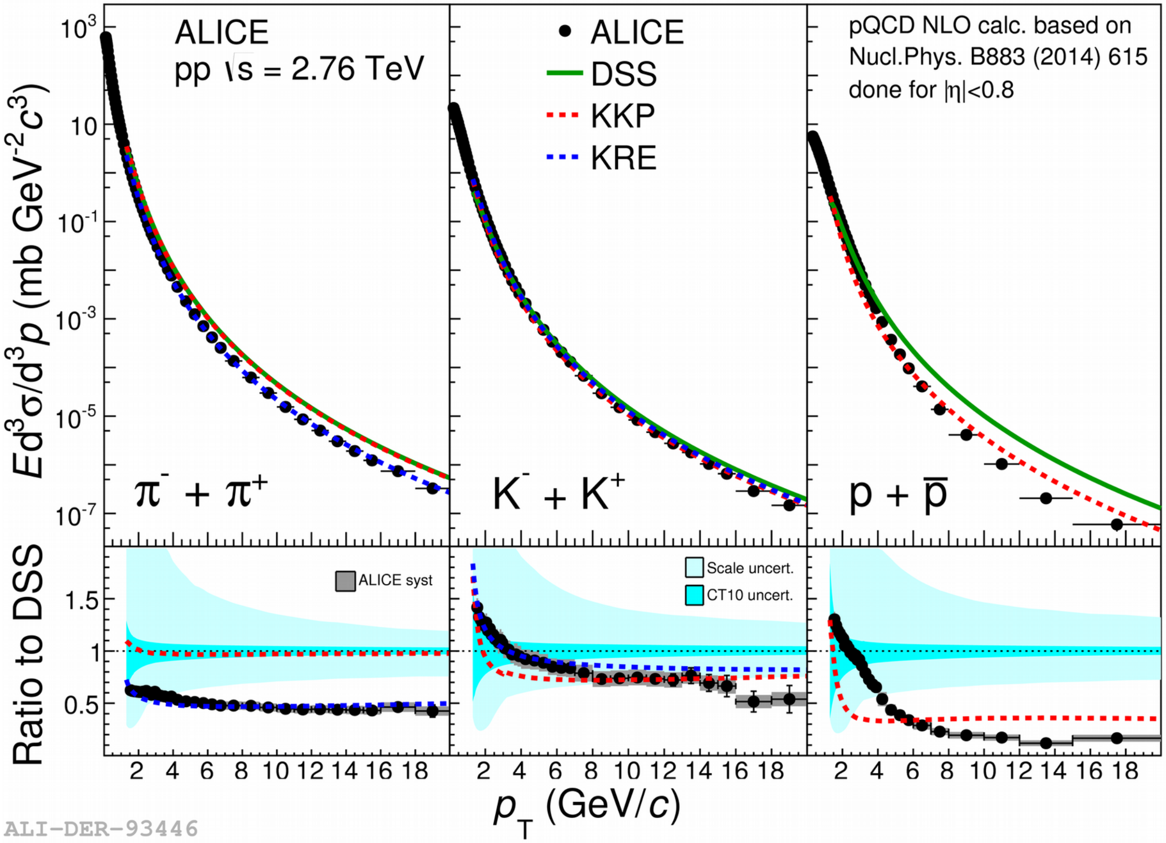
pp collisions

DSS: de Florian, Sassot and Stratmann, PRD 75 (2007) 114010 and PRD 76 (2007) 074033

KKP: Kniehl, Kramer and Potter, NPB 582 (2000) 514

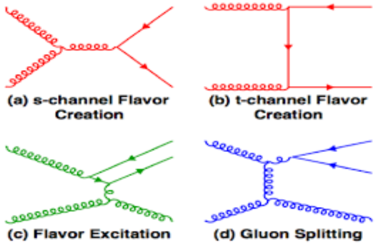
KRE: Kretzer, PRD 62 (2000) 054001

- The Kretzer Fragmentation Functions (KRE) describe well the charged pion and the kaon spectra
- DSS and KKP predict up to 2 times higher yield for pions and protons, but agree within uncertainties for kaons.
- Another input for FF global fits

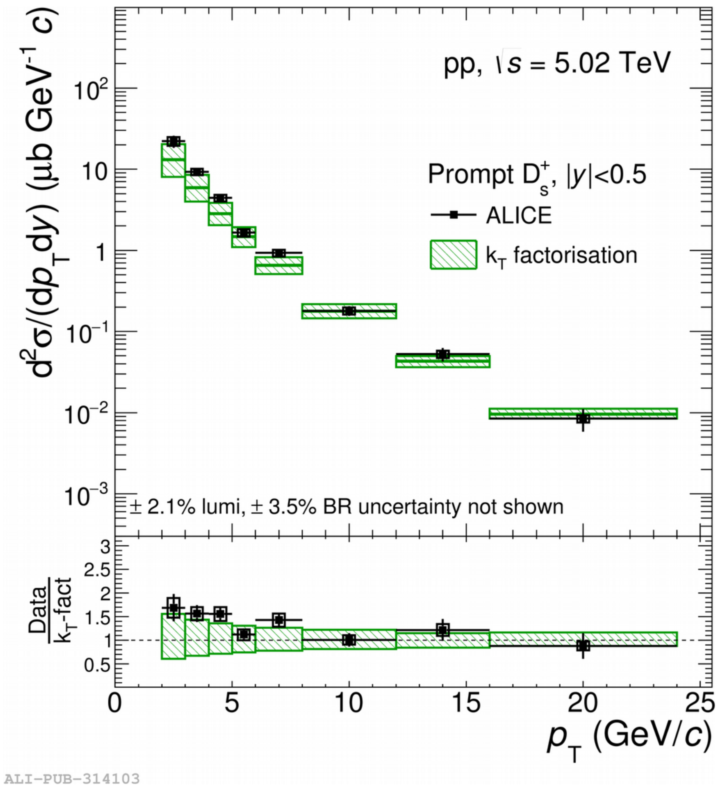


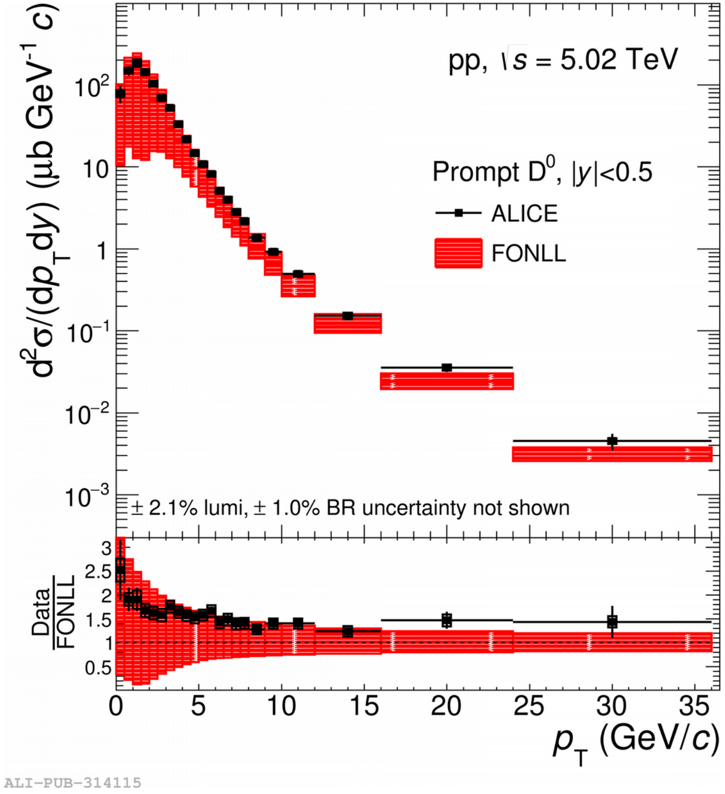
0.9 TeV: Eur. Phys. J. C 71 (2011) 1655
2.76 TeV: Phys.Lett. B(2014) 736:196
7 TeV: EPJC 75 (2015) 226

pp:heavy flavor production



- Probe gluon PDF at low x
- pQCD calculations performed in different schemes able to reproduce data, though data concentrated around the upper edge of uncertainties

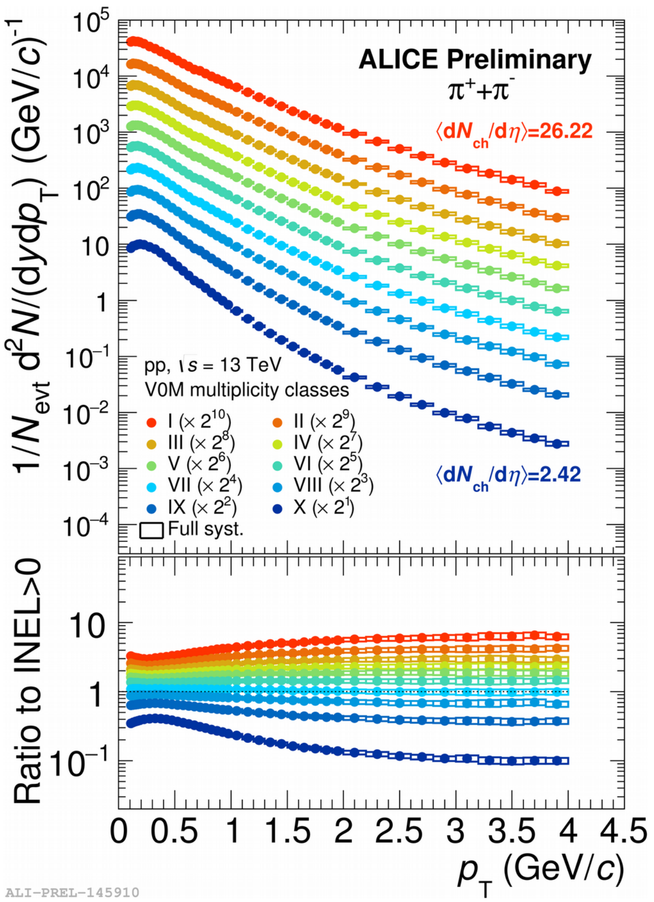


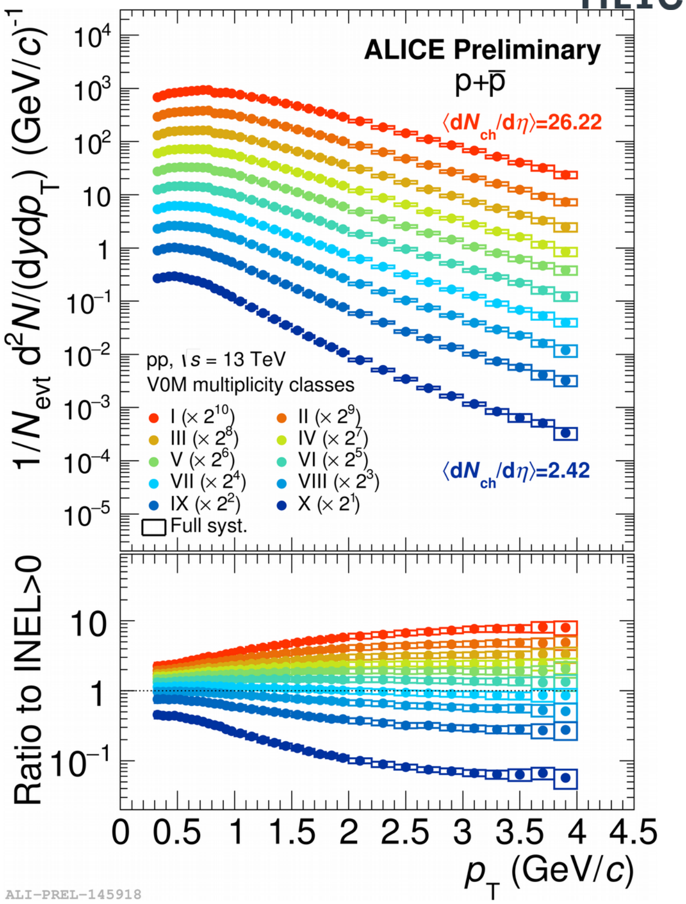


5 TeV: Eur.Phys.J. C79 (2019) no.5, 388
7 TeV: Eur.Phys.J. C77 (2017) 550

pp: multiplicity dependence

- Hardening with multiplicity and particle mass at low p_T (< 2 GeV/c)
- Indication for collective effects, reminiscent of observed effects in Pb-Pb, attributed to radial flow





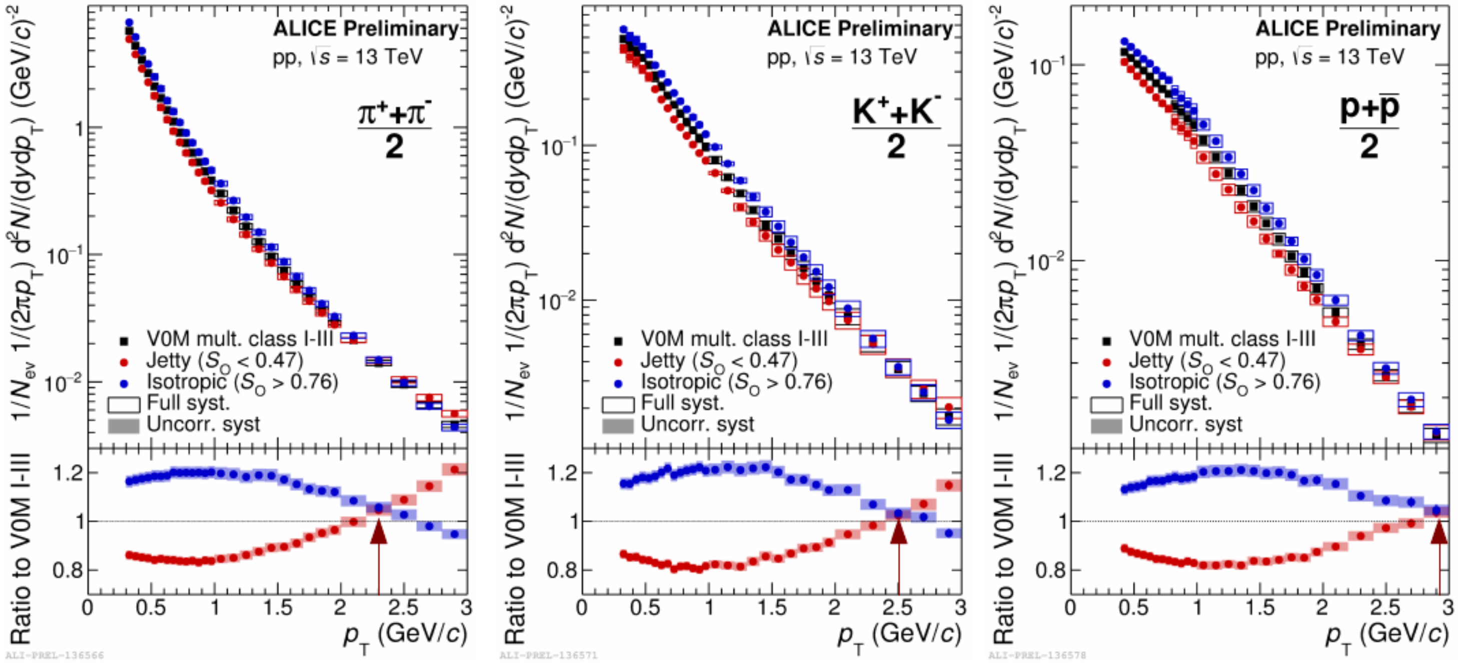
Transverse spherocity

$$S_O = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\sum_i \vec{p}_{T,i} \times \hat{n}}{\sum_i p_{T,i}} \right)^2$$

Jetty: $S_O \rightarrow 0$

Isotropic: $S_O \rightarrow 1$

- Spectra softer in isotropic events
- Crossing point increase with particle mass
- Indication for larger contribution of collective effects in isotropic events



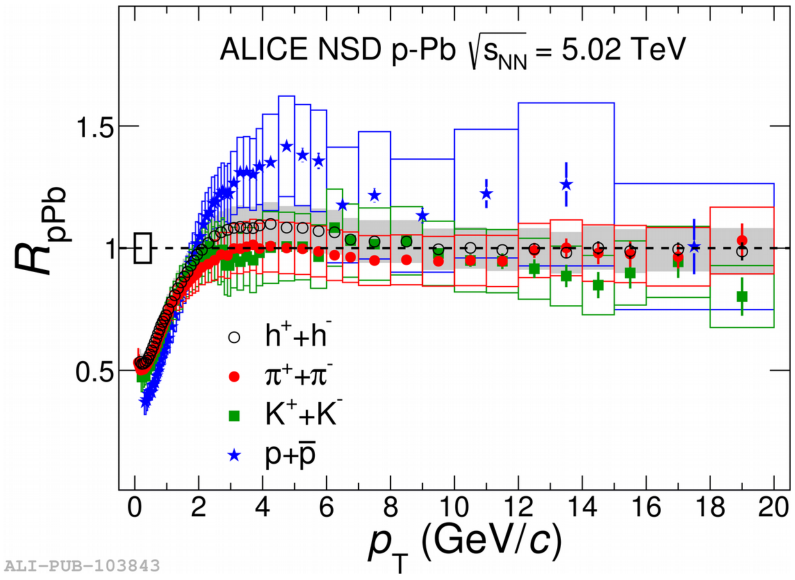
arXiv:1905.07208

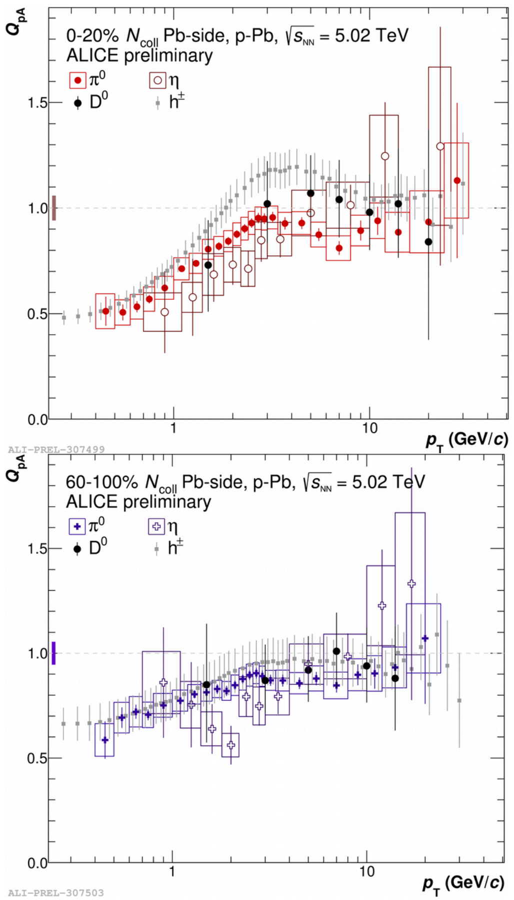
p-Pb collisions

$$R_{pPb} = \frac{d^2 N_{pPb}/dydp_T}{\langle N_{coll} \rangle d^2 N_{pp}/dydp_T}$$

- No modification of hadron spectra at high p_T observed in p-Pb collisions
- Some enhancement of proton production at intermediate p_T is observed
- Scaling with N_{coll} holds at high p_T for all centralities for h$^{\pm}$, unflavored, strange and heavy flavored hadrons

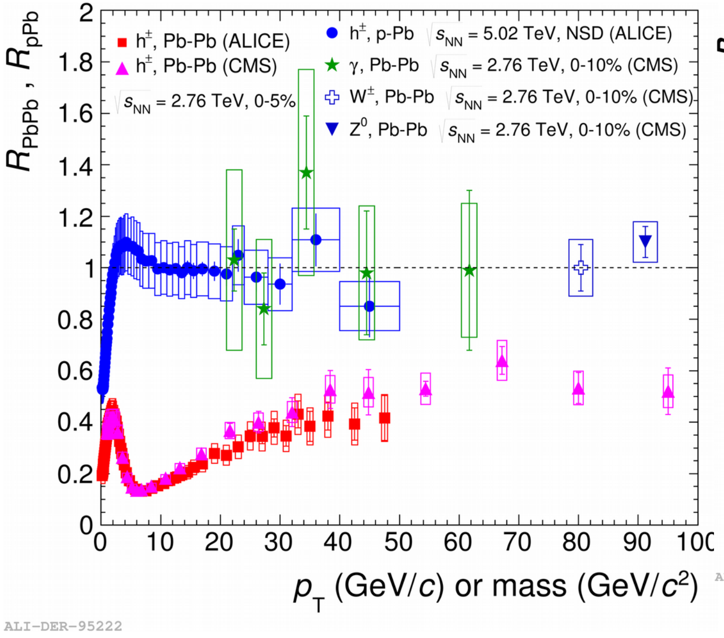
JHEP 1811 (2018) 013

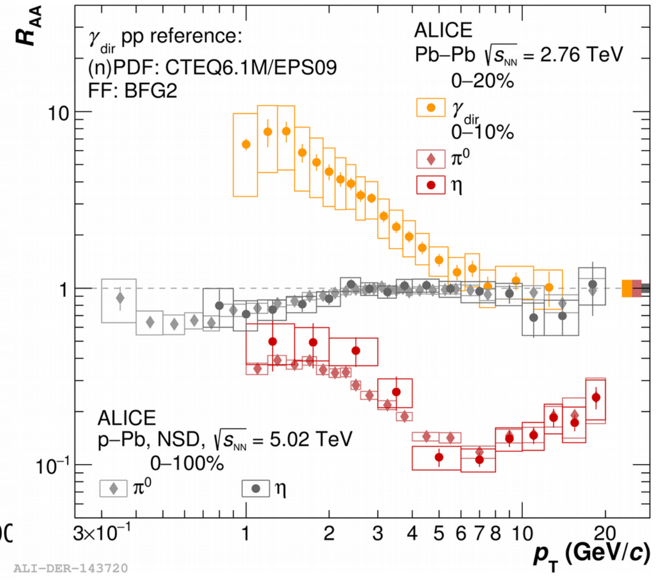




Pb-Pb collisions

- Strong suppression observed in central Pb-Pb collisions for hadrons.
- Initial state tested with colorless probes: no modification within uncertainties





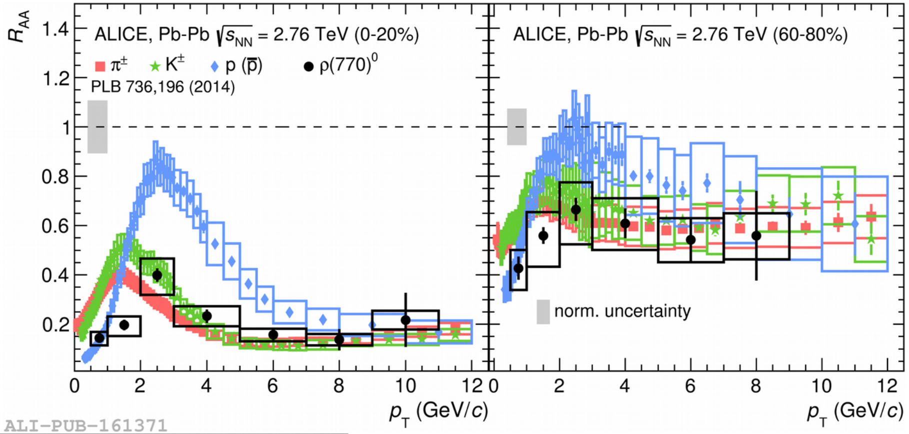
ALICE: PLB 720, 52; EPJ. C74, 3054
CMS:JHEP 1503 (2015) 022;
EPJ. C72, 1945; PLB 710, 256; PLB 715, 66

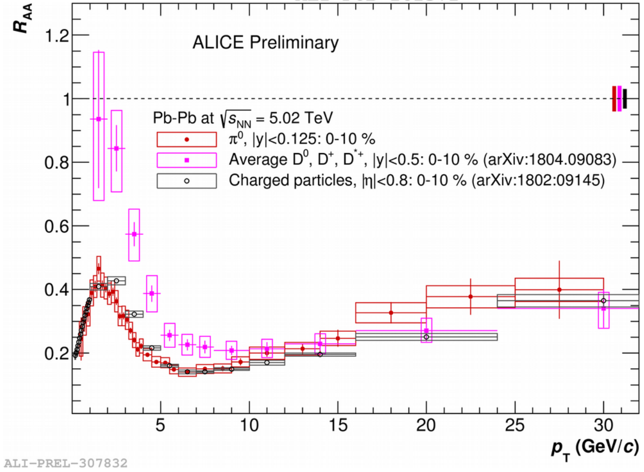
See D. Blau talk on direct photon production

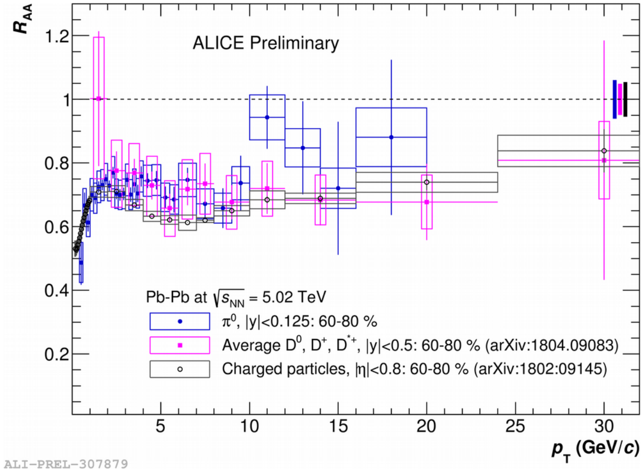
Different particle species

Phys.Rev. C99 (2019) no.6, 064901

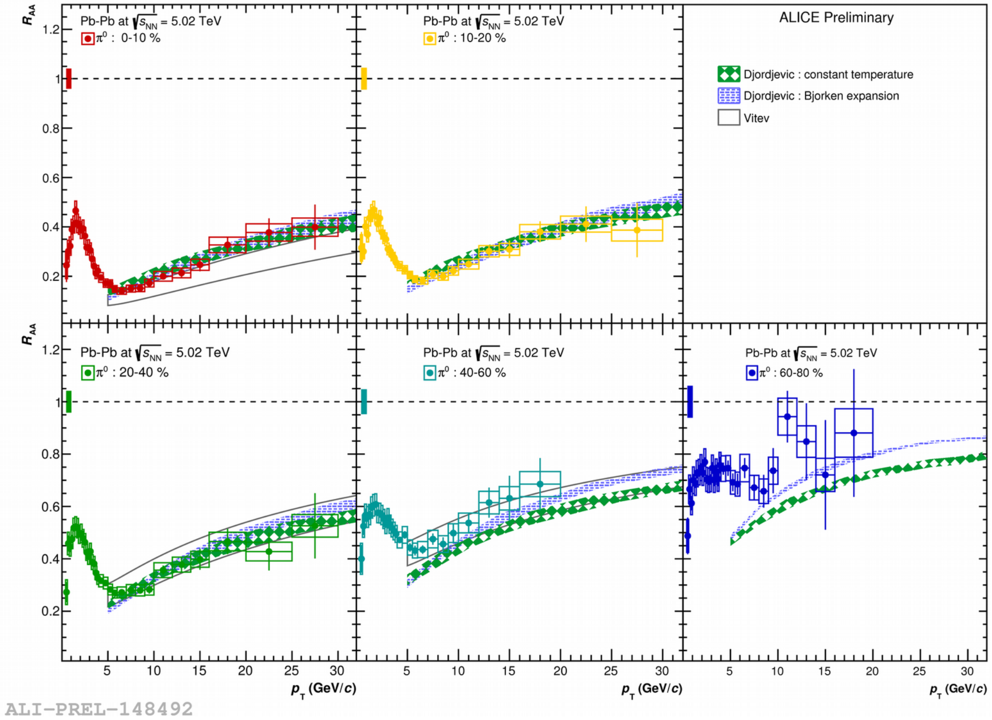
- Different light-flavored hadrons show same suppression
- Baryon/meson ratio strongly depends on centrality (recombination/ collective flow?)
- Open charm hadrons show similar suppression at high p_T>8 GeV/c and smaller at lower p_T: difference in quark mass, flow, recombination, initial state effects,...?

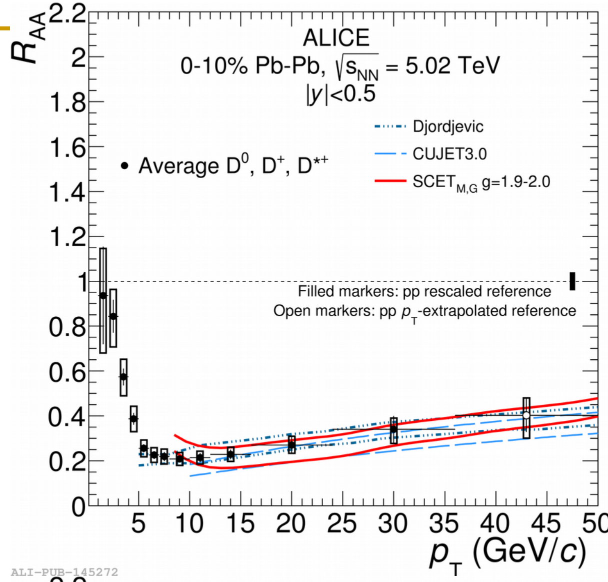


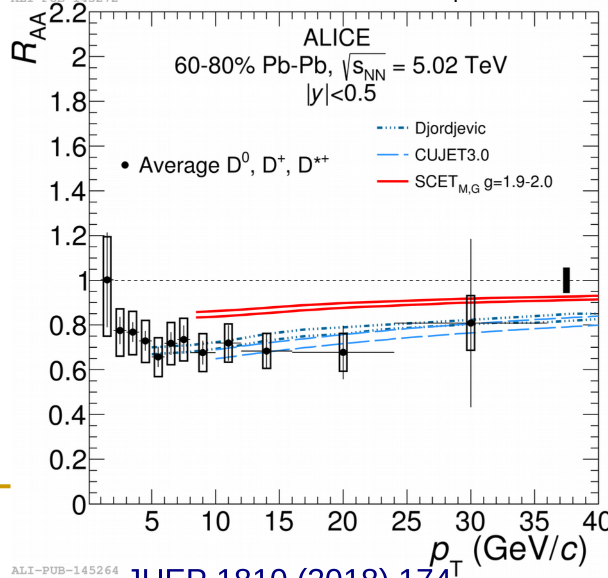




Comparison to models







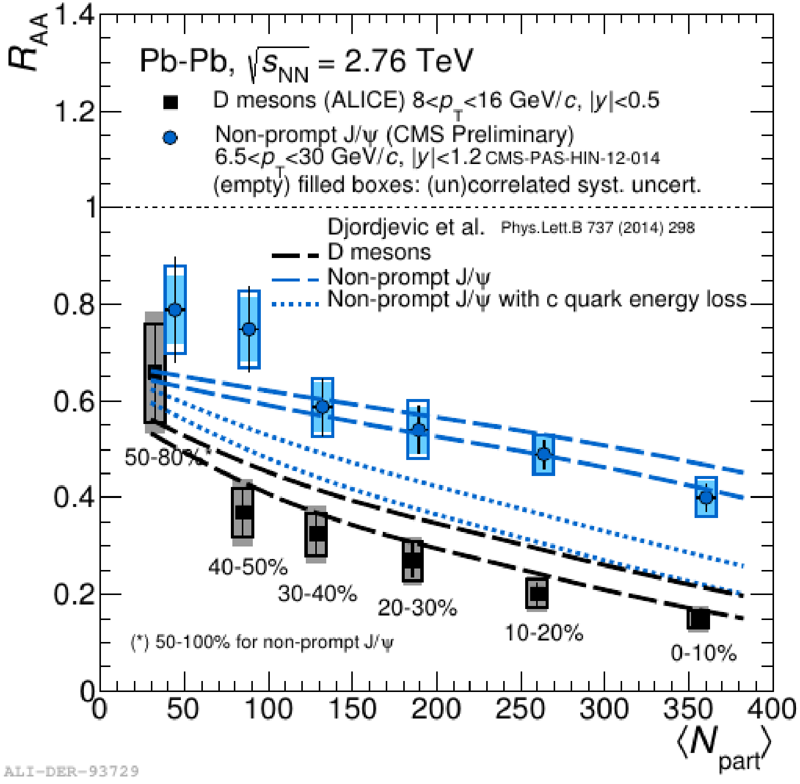
JHEP 1810 (2018) 174

Models able to reproduce energy loss of light and heavy quarks simultaneously.
M. Djordjevic, Phys. Rev. Lett. 112 no. 4, (2014) 042302

Heavy flavors

- Compare
  - charm: D-mesons
  - beauty: non-prompt J/psi
- Larger suppression for charm than for beauty
- Agrees with expected ‘dead-cone effect’ energy loss reduced when v < c

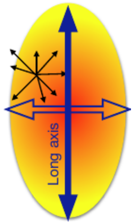
ALICE, JHEP11, 205

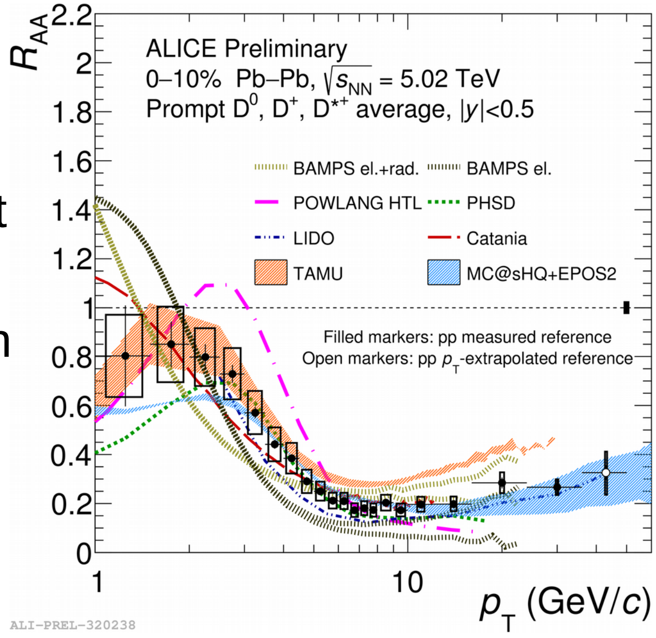


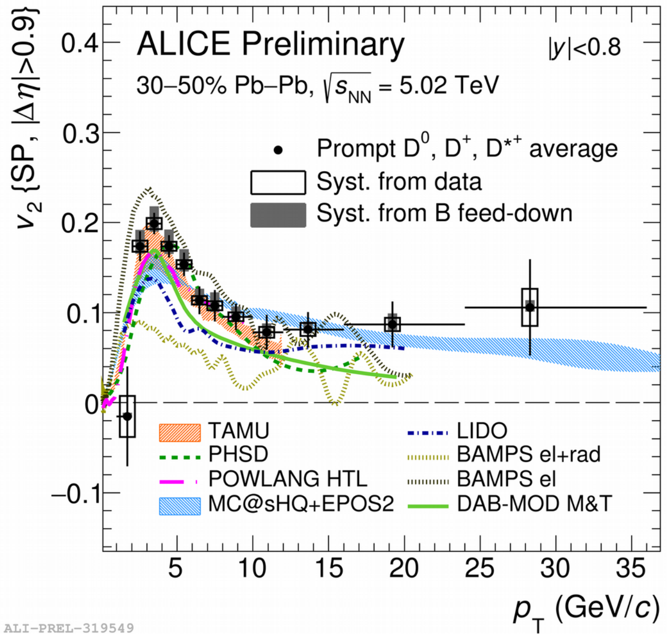
Azimuthal anisotropy

- Sources of anisotropy:
  - A-la hydrodynamic, conversion of pressure gradient to velocity asymmetry (dominant at late formation times);
  - Difference in path length (dominant for early formation times: heavy flavors, high p_T probes)

$$\Delta E \sim \alpha_s \hat{q} L^2$$



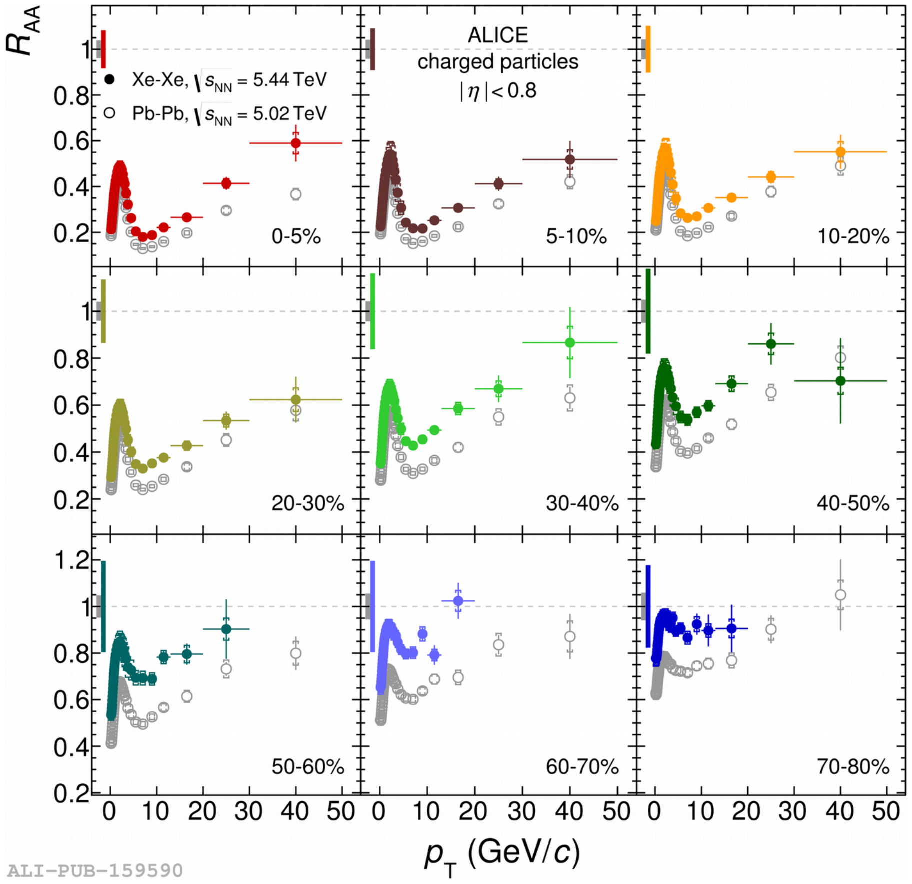


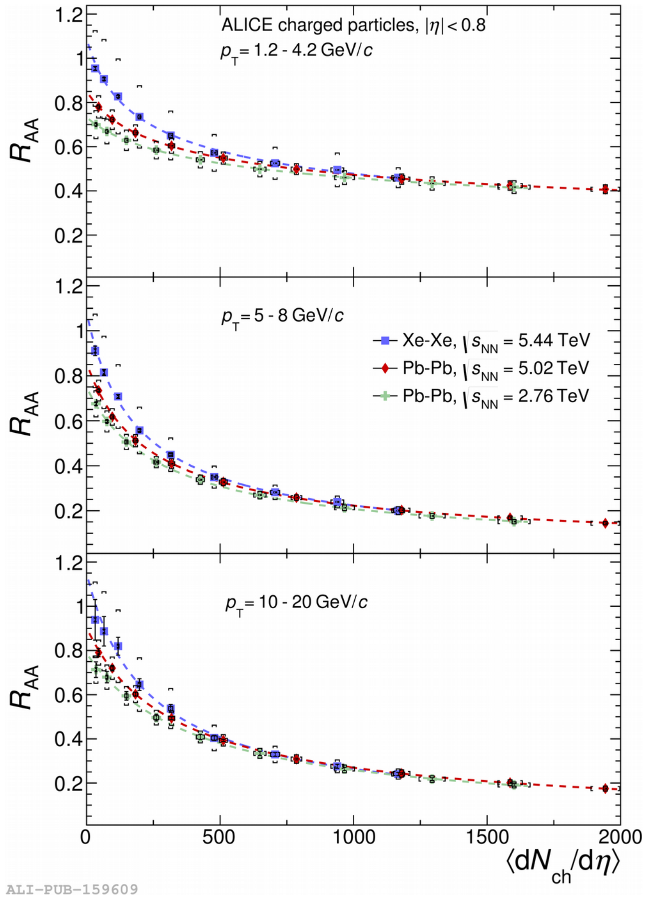


Simultaneous reproduction of both observables is challenging for models

Pb-Pb vs Xe-Xe

- Suppression in Xe-Xe smaller than in Pb-Pb in same centrality class.
- However, plotted vs mean charged multiplicity shows very similar amount



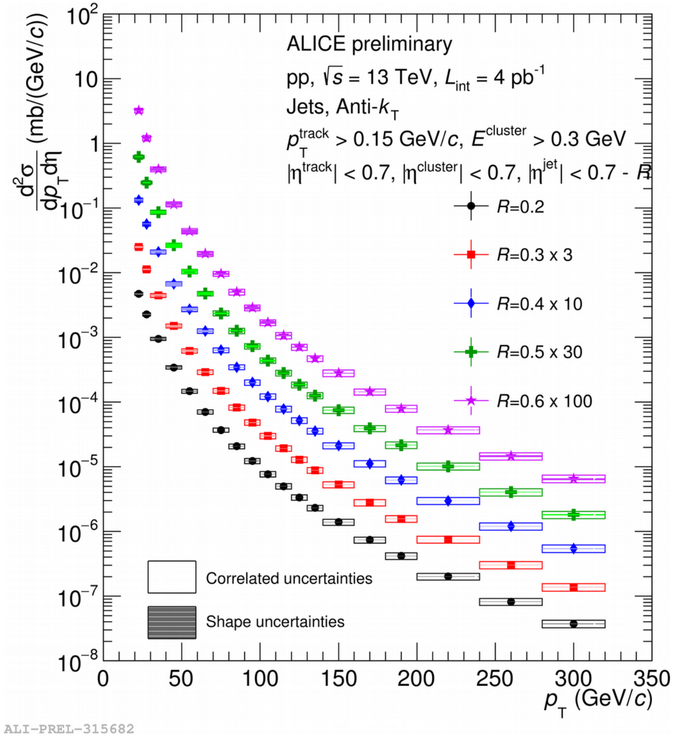


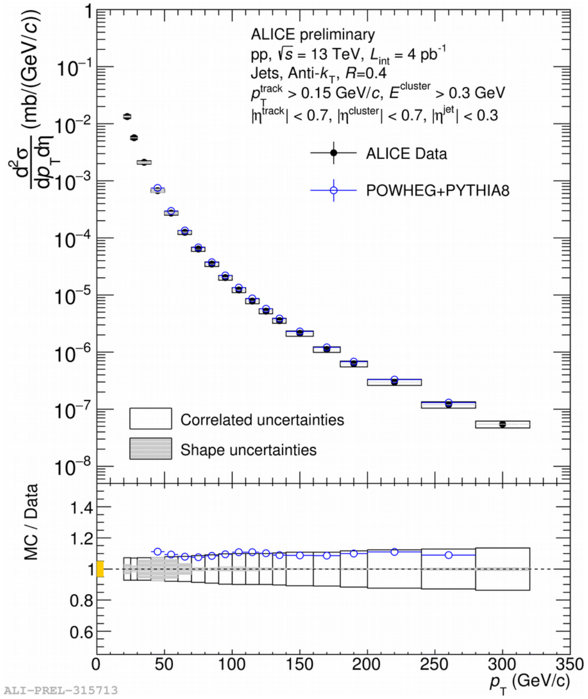
Phys. Lett. B 788 (2019) 166

Jets

Jets in pp collisions

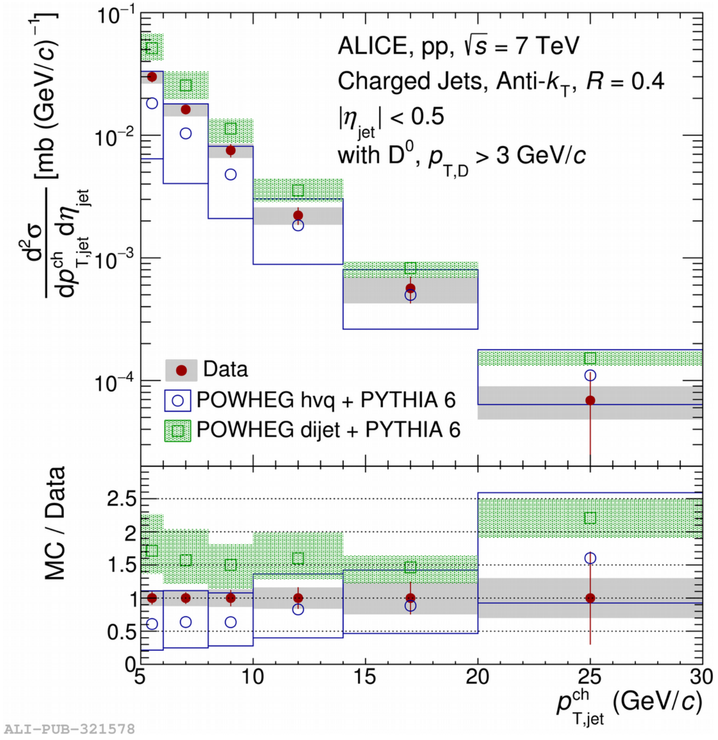
- Jet spectra measured for different R
- For all R POWHEG+PYTHIA8 agrees with data though at upper edge of uncertainties





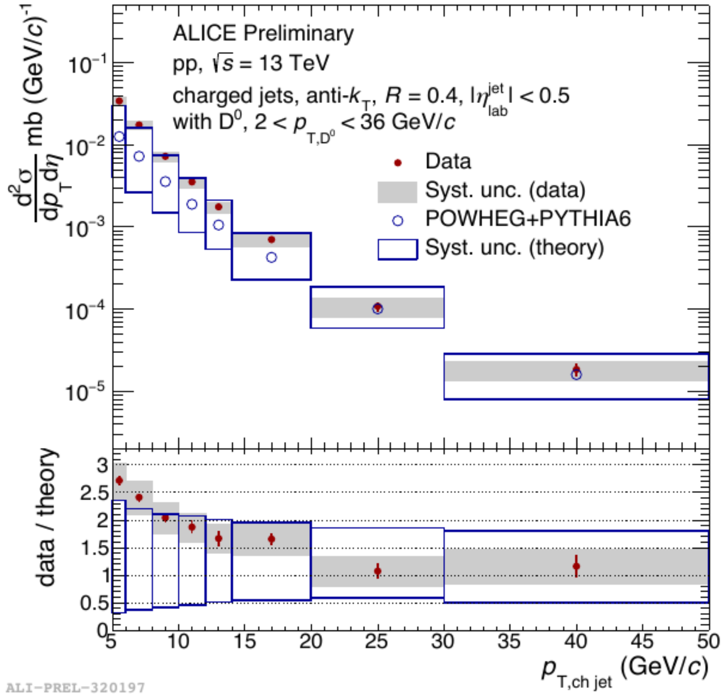
Jets tagged with D-mesons

- Pythia reproduces proportion of charmed jets, but not absolute yield
- POWHEG with dijet implementation over-predicts data, while heavy quark implementation agrees better

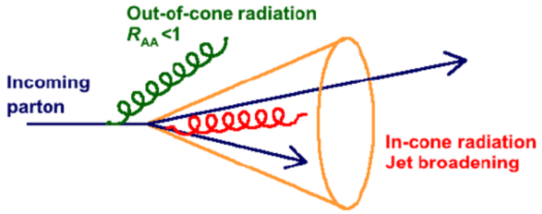


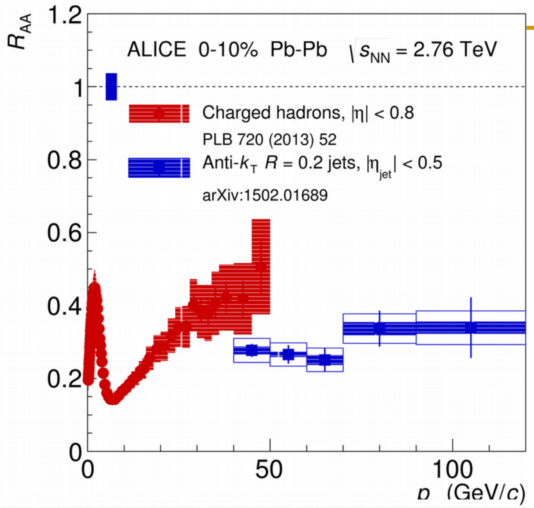
JHEP (2019) 1908, 133

Charm jets

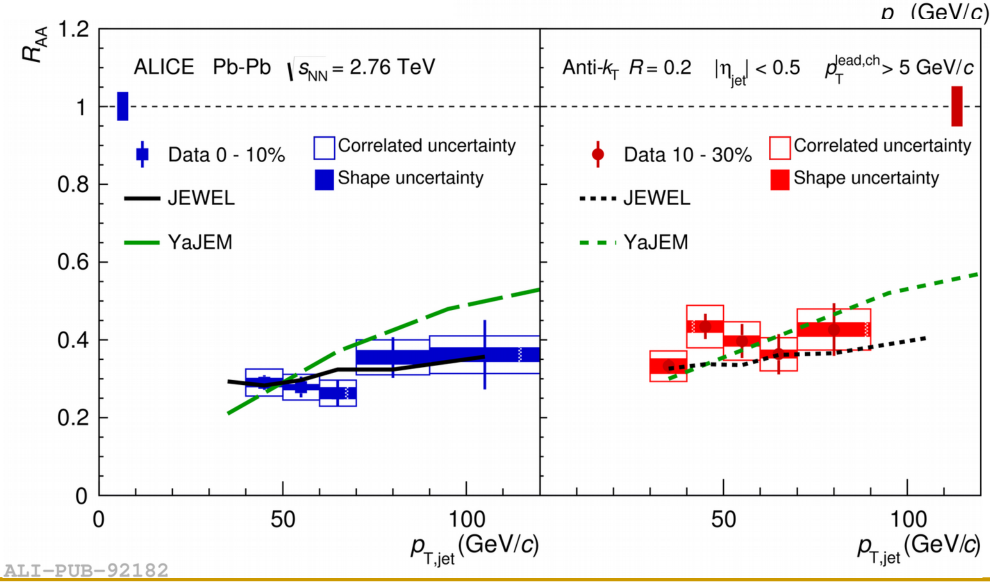


Jet R_{AA}

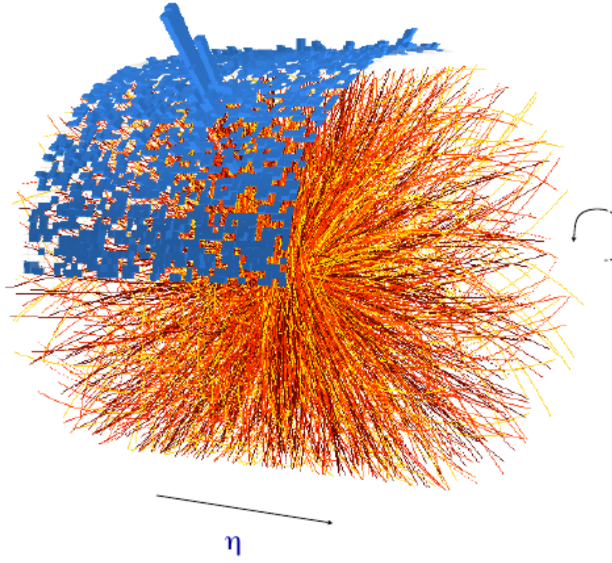




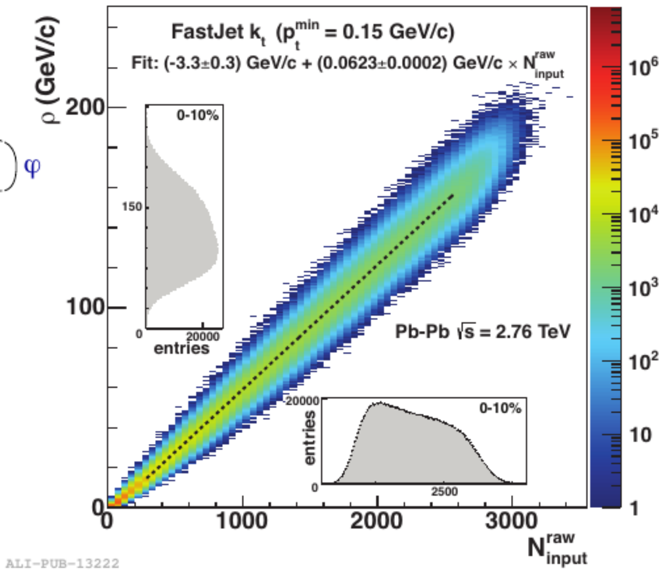
- Two qualitatively different scenarios:
  - In-cone radiation: R_{AA}=1
  - Out-of-cone radiation: R_{AA}<1
- Jet suppression (R=0.2) similar to charged particle suppression
- Suppression/out-of-cone radiation reasonably well described by energy loss MC models



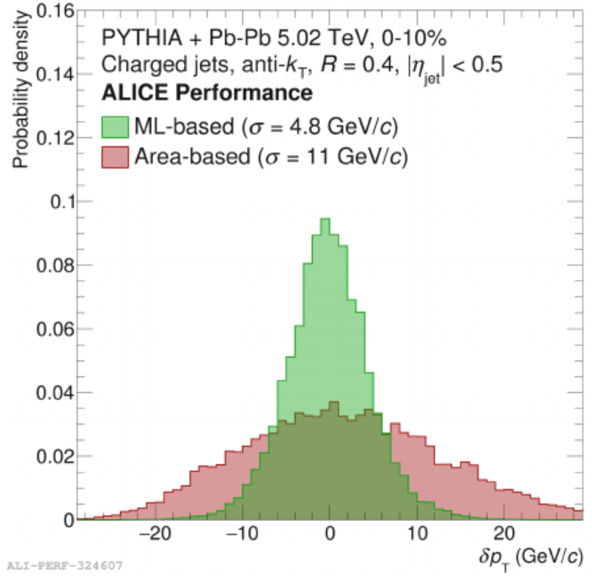
Jet reconstruction in Pb-Pb



JHEP 03 (2012) 053



Machine-learning technique



Standard technique: measure background E_T density outside jet ‘Area based’

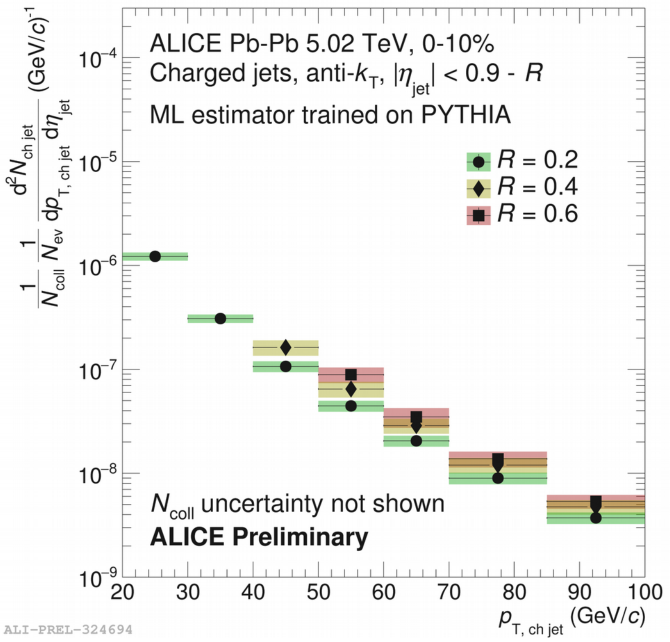
Background subtraction refined based on e.g. leading particle p_T
Reduces fluctuations

Residual fluctuations due to finite number statistics

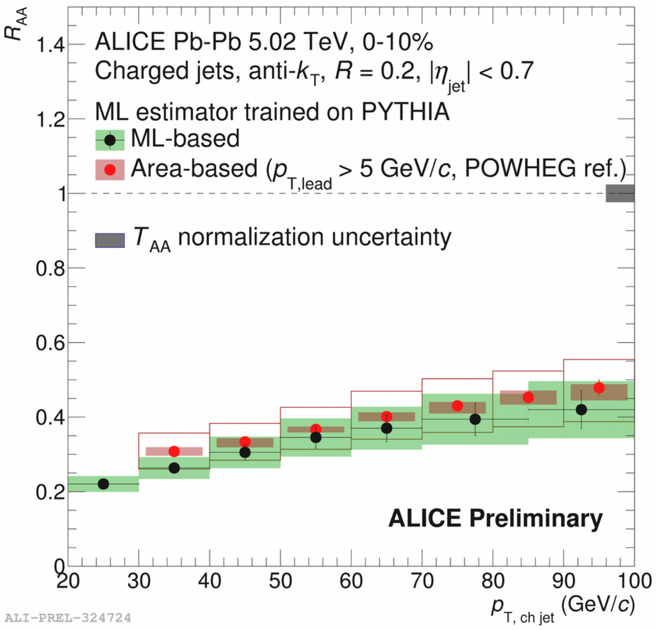
Allows to measure jets with larger R, lower p_T

Jets in Pb-Pb

Jet spectra

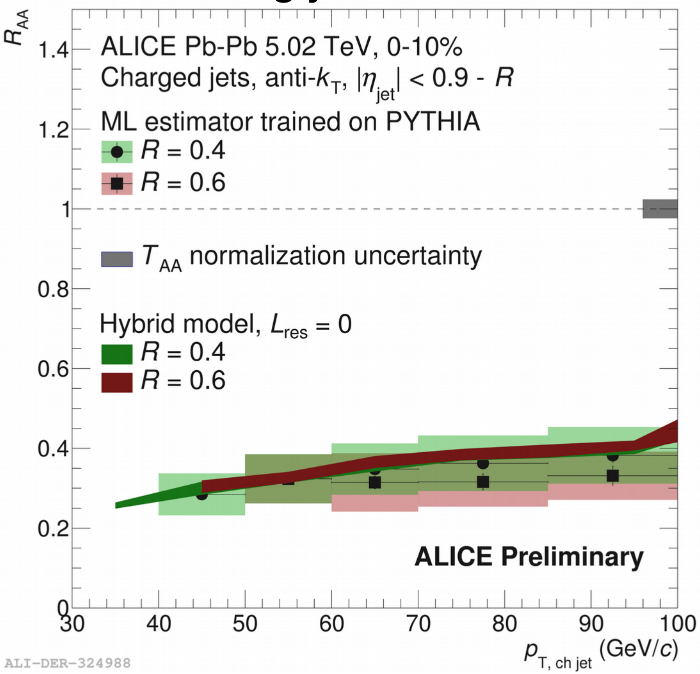


R_{AA} for R=0.2



Good agreement between standard and ML methods

Increasing jet radius R=0.4,0.6

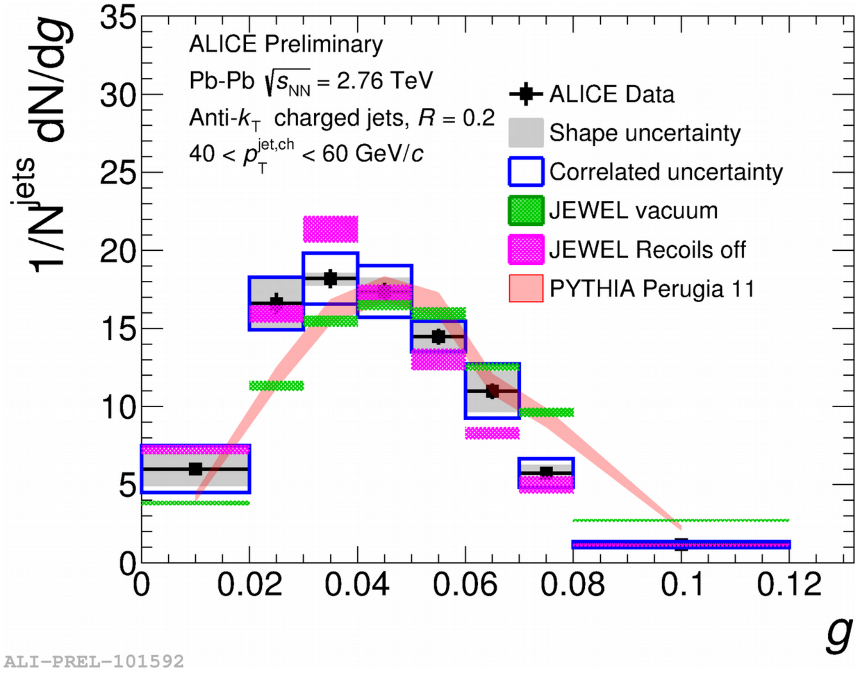


Suppression even for R=0.6

Jet shape: radial moment (girth)

$$g \equiv \frac{\sum_{tracks} p_{T,i} r}{p_{T,jet}}$$

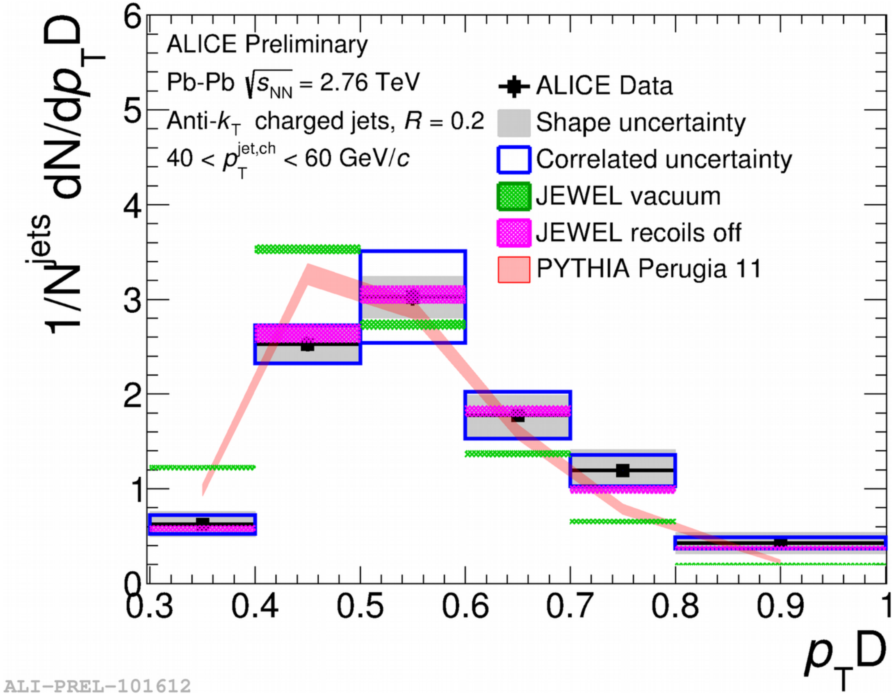
- Explores transverse jet size
- Radial moment in Pb-Pb smaller than in pp (PYTHIA)
- JEWEL model shows similar trend
- Jets in medium narrower than in vacuum



Jet shape: p_T dispersion: p_TD

$$p_T D \equiv \frac{\sqrt{\sum_{tracks} p_{T,i}^2}}{p_{T,jet}}$$

- Explores longitudinal jet size
- p_TD in Pb-Pb larger than in pp (PYTHIA)
- JEWEL model shows similar trend
- Smaller multiplicity and/or harder fragment distribution



Conclusions

- ALICE measured spectra of unidentified and large number of identified hadrons with excellent precision in pp, p-Pb, Xe-Xe and Pb-Pb collisions
- pp collisions: check pQCD predictions and constrain gluon, light and heavy quark PDFs
- pA, AA collisions
  - Modification of (n)PDF
  - Interaction of partons with cold and hot nuclear matter
    - Difference of energy loss of light and heavy quarks
  - Modification of jet fragmentation in hot matter