Recent *Hard Probes* Results from ALICE

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筑波大学 University of Tsukuba
T G S W TSUKUBA GLOBAL SCIENCE WEEK

Fundamental question:

How do collective phenomena and macroscropic properties of matter arise from the elementary interactions of a non-abelian quantum field theory?

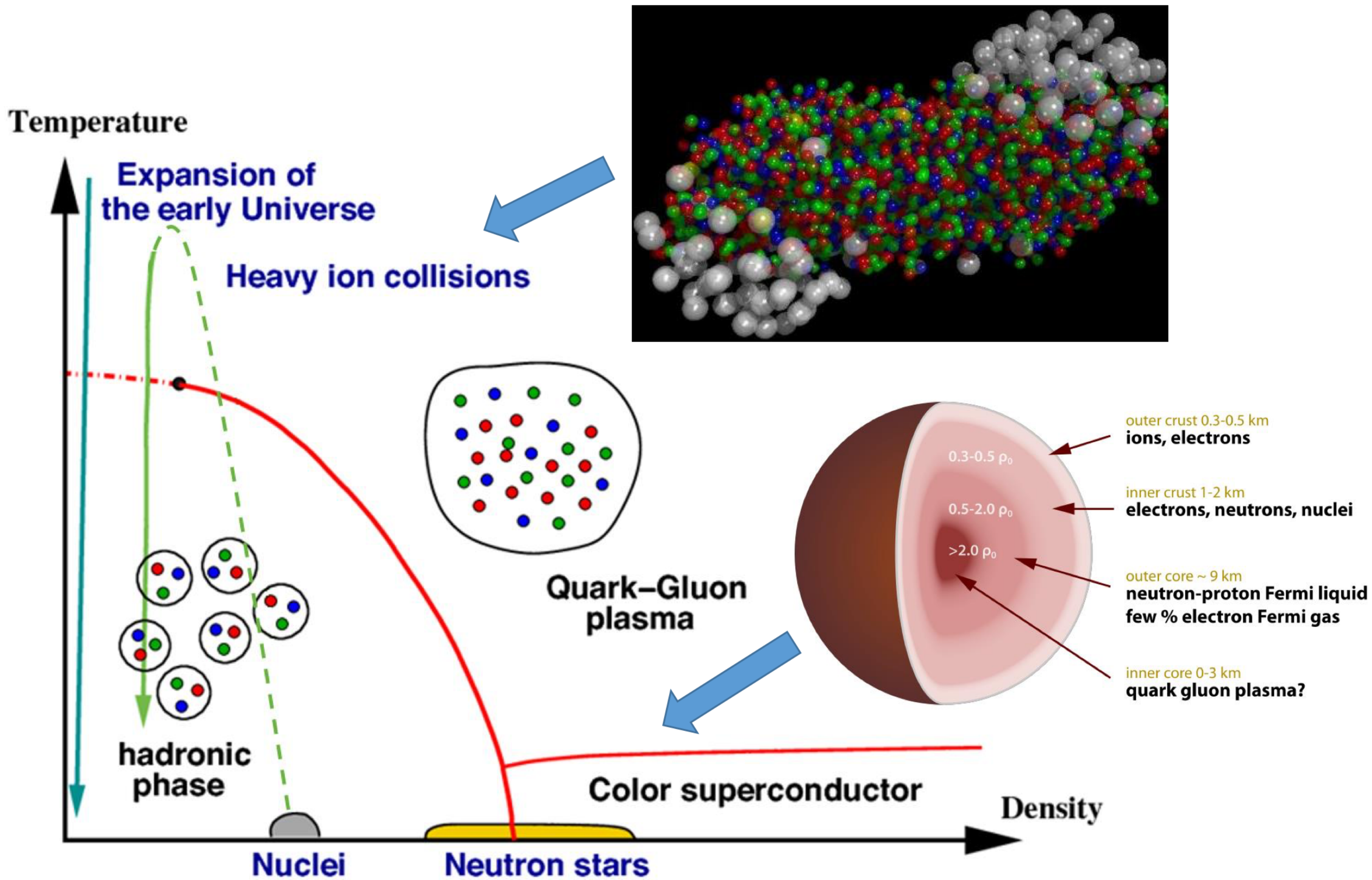
Opportunities	Tools	Status
Constraining equilibrium properties of QCD matter (eos, $\eta/s\,,\xi\,,\tau_\pi\,\ldots$)	Flow and fluctuation measurements in AA	advanced
Measuring medium properties with hard auto-generated probes ($\hat{q}\,,\hat{e}\,,T\,,\ldots$)	Quarkonia, R_{AA}'s , photons	in progress
Accessing microscropic structure of QCD matter in AA	Jet substructure, heavy flavor transport	in reach
Controlling initial conditions	pA (light AA) runs, npdf global fits, small-x	in reach
Testing hydrodynamization and thermalization	Combined jet and flow analyses	strategy t.b.d.
Understanding "heavy-ion like behavior" in small systems (pp, pA)	Flow, hadrochemistry, jets	recent surprises

Urs Wiedemann

List to be refined and extended

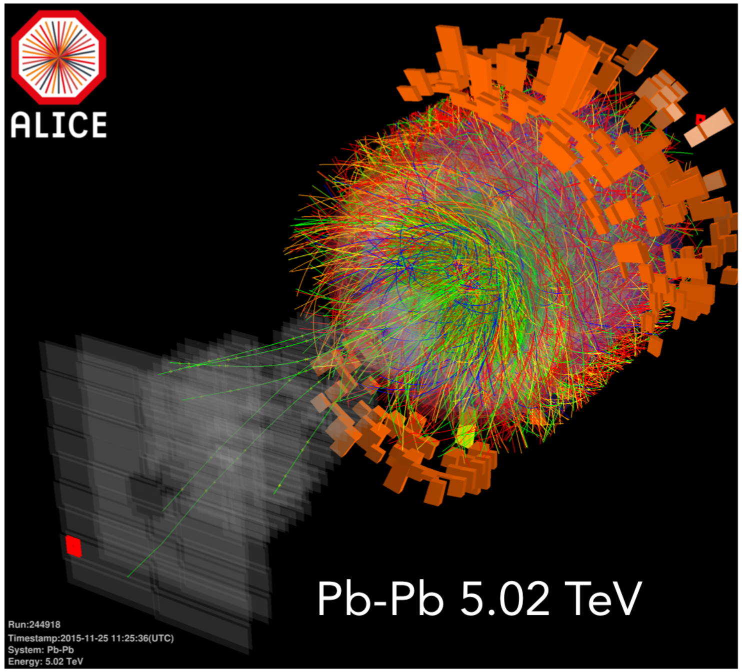
The QCD phase diagram

- Understand the behaviour of QCD matter at the limit of high density and/or temperature



The ALICE program

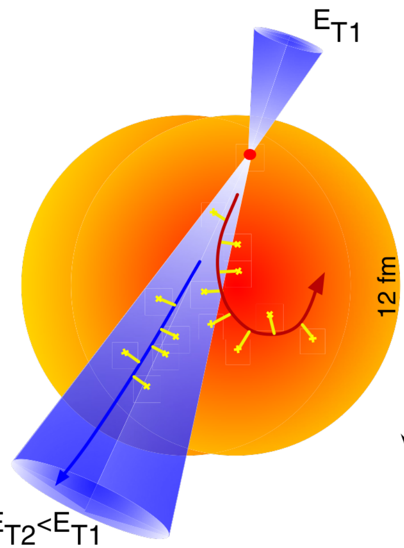
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	by end of 2018	*5.02*	*~1 nb^{-1}*
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2017	13	~25 pb^{-1}

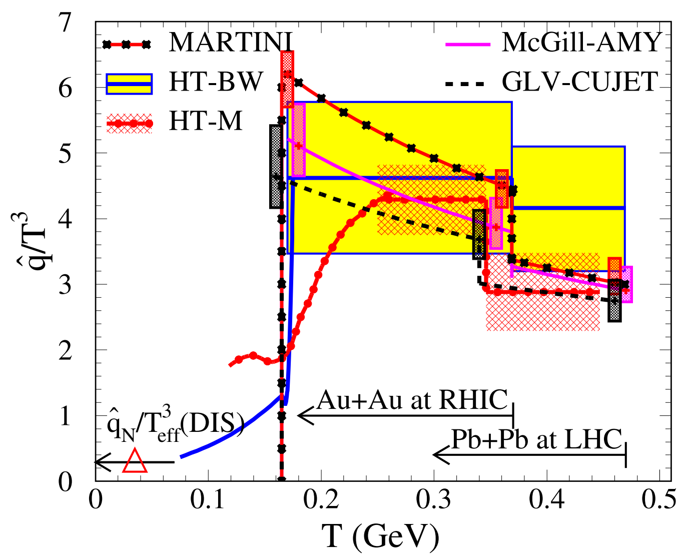


- LHC Run 2 data analysis is in full swing!
- Significant increase in integrated luminosity in pp, p-Pb, and Pb-Pb collisions allows more and more precise investigation of statistics hungry probes
- LHC will have done 12 ~one month heavy-ion runs between 2010 and 2030 (LS4)
  - 5/12 done already
  - LHC scheduled 3.5 weeks of Pb-Pb collision in November 2018

Jets physics in heavy-ion collisions

- Jets are collimated sprays of hadrons
  - Proxies for short-distance quarks & gluons
- Jets are a **self-generated** probes of the medium
  - High-p_T partons produced in the very early stage of the collisions ($\tau \sim 1/Q \ll 1$ fm) w/ production rate calculable w/i pQCD
  - Medium-modified parton cascade due to (in)elastic energy loss
    - Elastic rescatterings of the hard partons off the medium color charges ($\propto L$)
    - Medium-induced soft gluon radiation ($\propto L^2$)
- Jet physics in heavy-ion collisions is a **multiscale** problem
  - From hard to soft scales ($\sim T$)



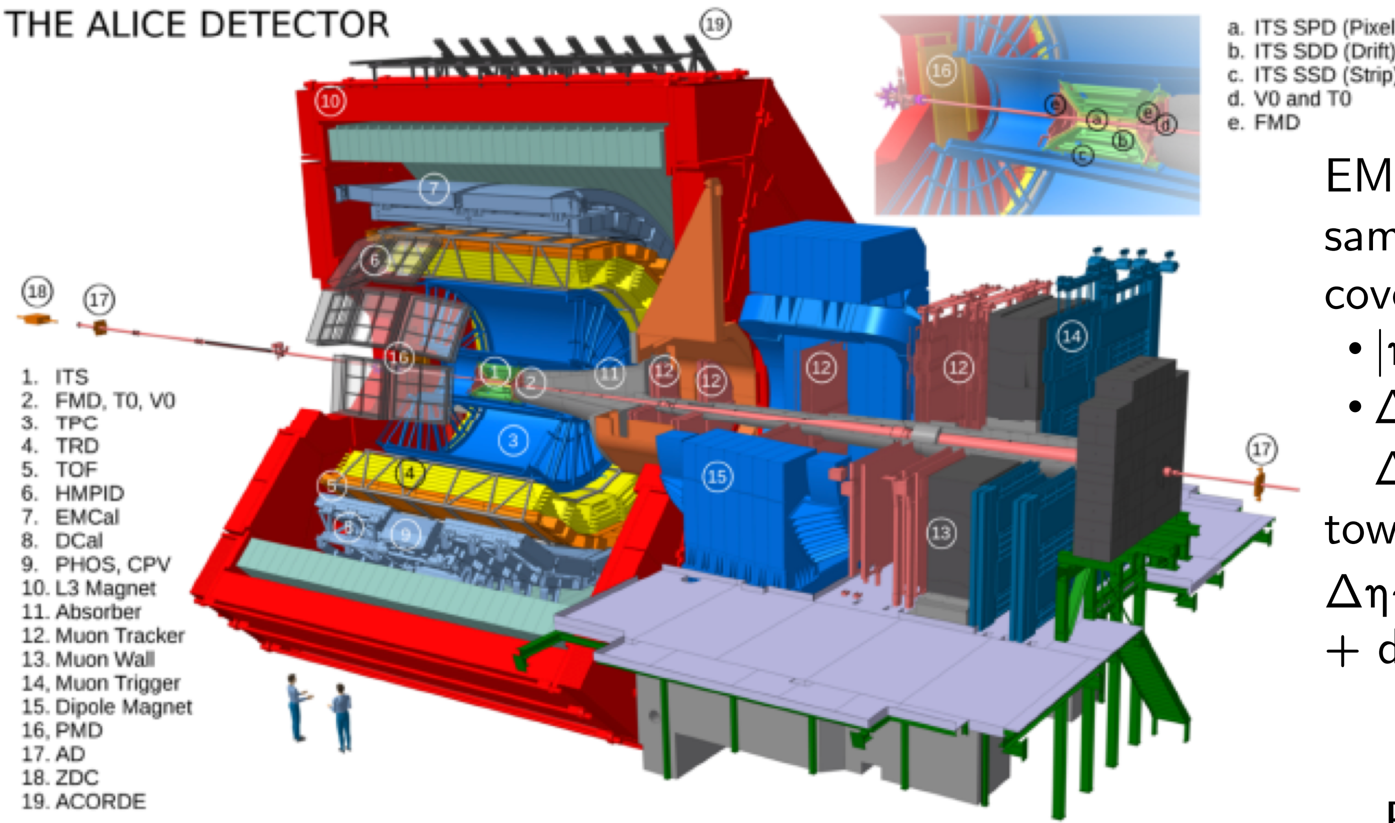


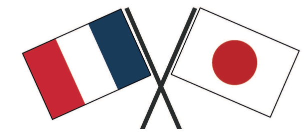
PRC **90**, 014909 (2014)

$\hat{q} \sim 3.7 \pm 1.4\ \mathrm{GeV}^2/\mathrm{fm}$

Qualitative extraction of medium properties (temperature and jet energy dependence of the jet transport coefficient $\hat{q} = \langle p_T^2 \rangle / \lambda$) through phenomenological study of jet quenching

Jets at ALICE





EMCal/DCal Pb-scintillator sampling calorimeter which covers:

- $|\eta| < 0.7$,
- $\Delta\varphi_{EMCAL} \sim 110°$, $\Delta\varphi_{DCAL} \sim 60°$

tower $\Delta\eta \sim 0.014 \times \Delta\varphi \sim 0.014$

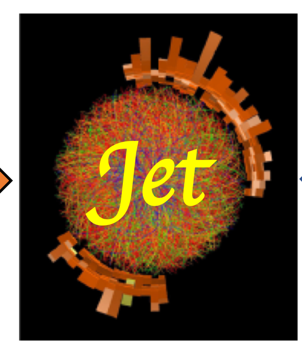
+ dedicated L1-jet trigger

Remove contamination from charged particles

Tracking: $|\eta| < 0.9$, $0 < \varphi < 2\pi$

- TPC: gas drift detector
- ITS: silicon detector

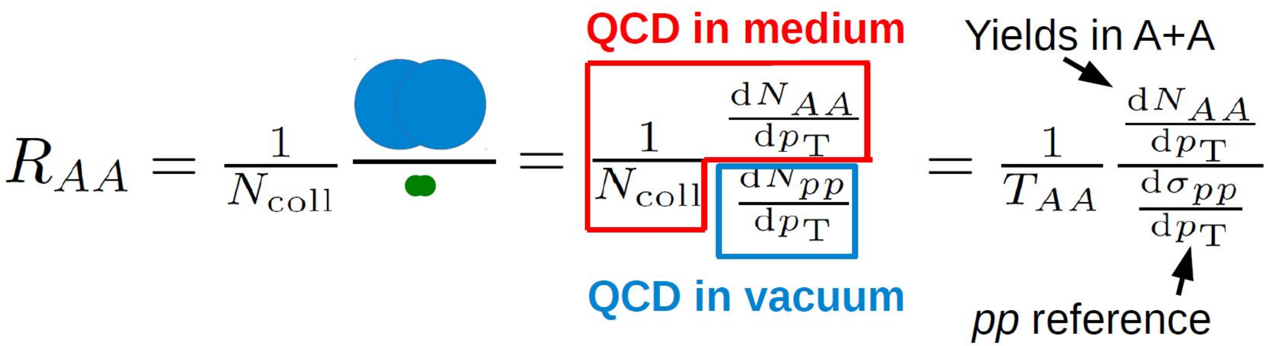
Charged constituents



Neutral constituents

Charged jet nuclear modification factor R_{AA}

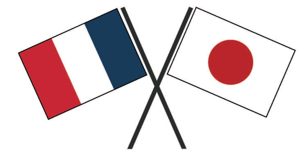
- R_{AA} quantifies the magnitude of jet suppression, which arise mainly from final-state interactions with constituents of the medium
- Compares HI and pp collisions and removes the geometrical scaling

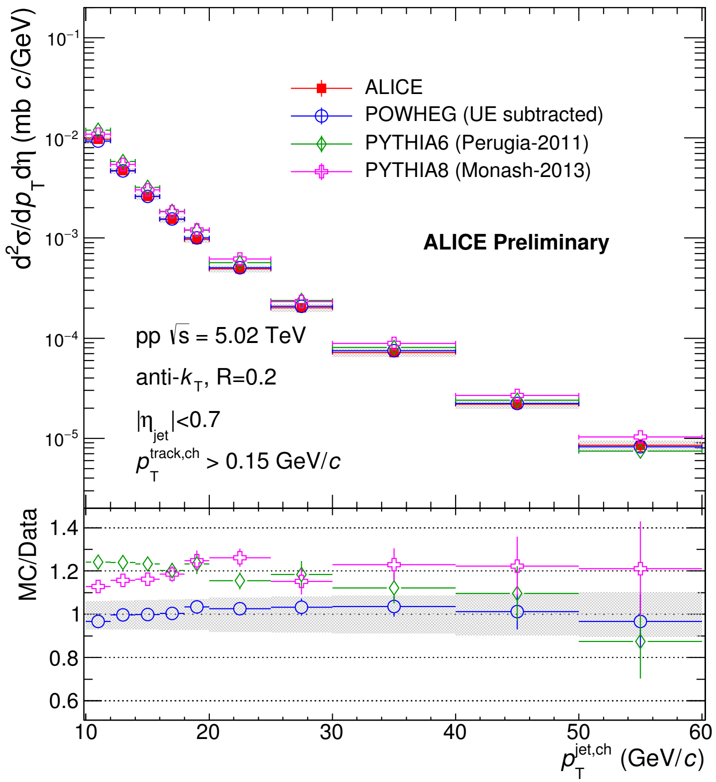


$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}{\frac{\mathrm{d}N_{pp}}{\mathrm{d}p_{\mathrm{T}}}} = \frac{1}{T_{AA}} \frac{\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}{\frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}p_{\mathrm{T}}}}$$

Jet R_{AA}

Inclusive yields in pp





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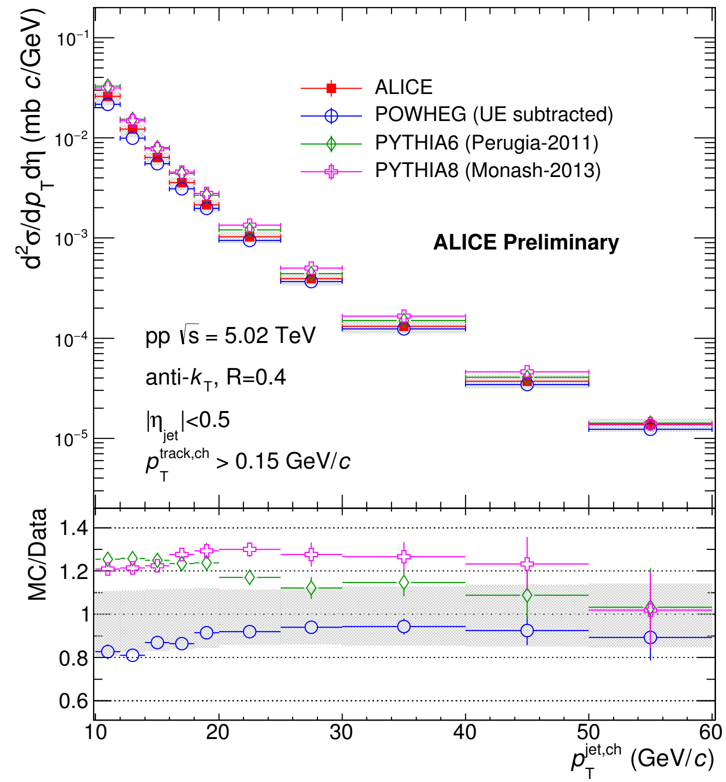
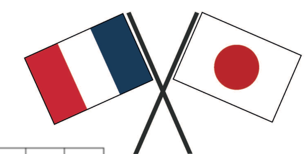


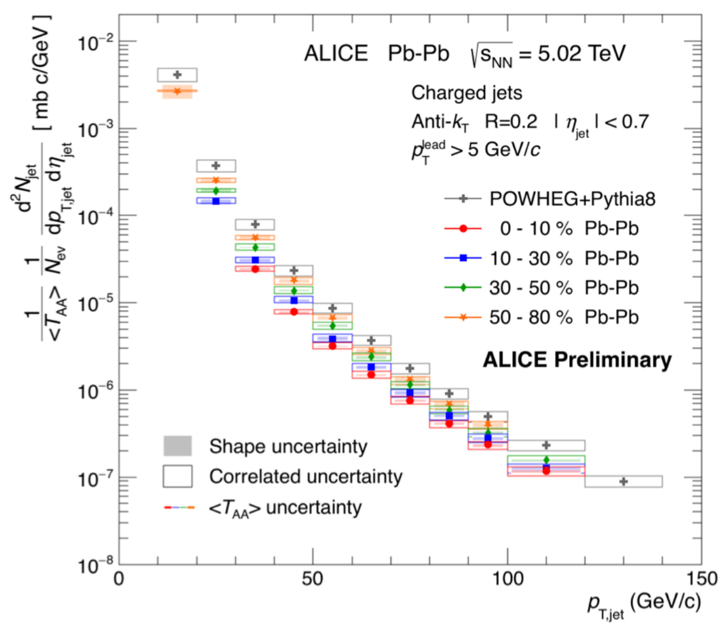
ALI-PREL-113806

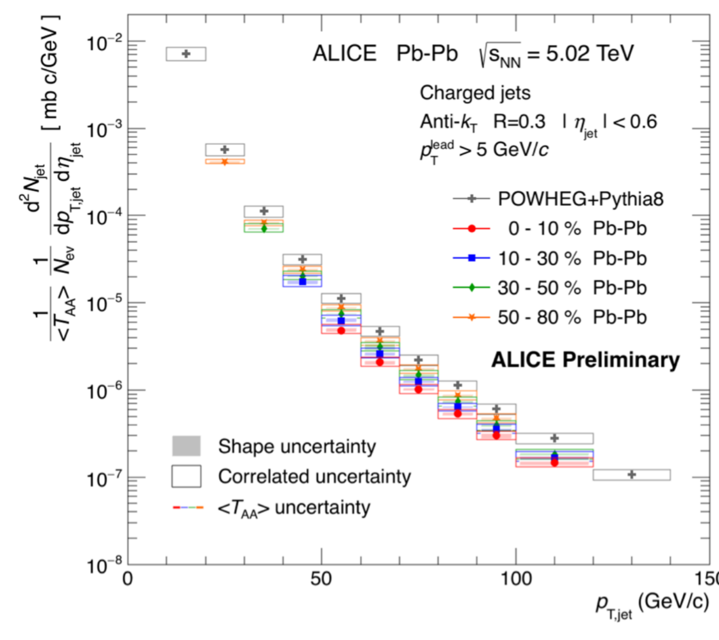
- NNLO jet cross section calculations are getting mature, see arXiv:1801.06415

Jet R_{AA}
Inclusive yields in Pb-Pb

- Reconstructed jets are required to have a $p_{\mathrm{T}} > 5\ \mathrm{GeV}/c$ leading charged particle
- The spectra are unfolded for detector effects and background fluctuations

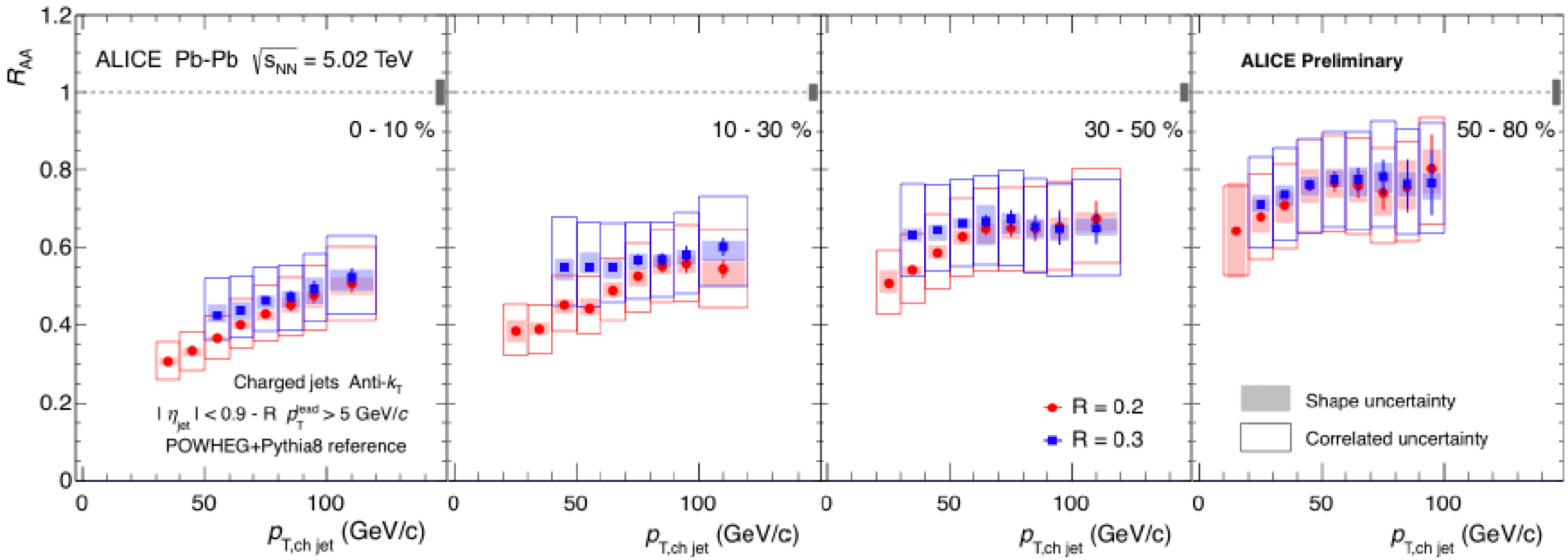






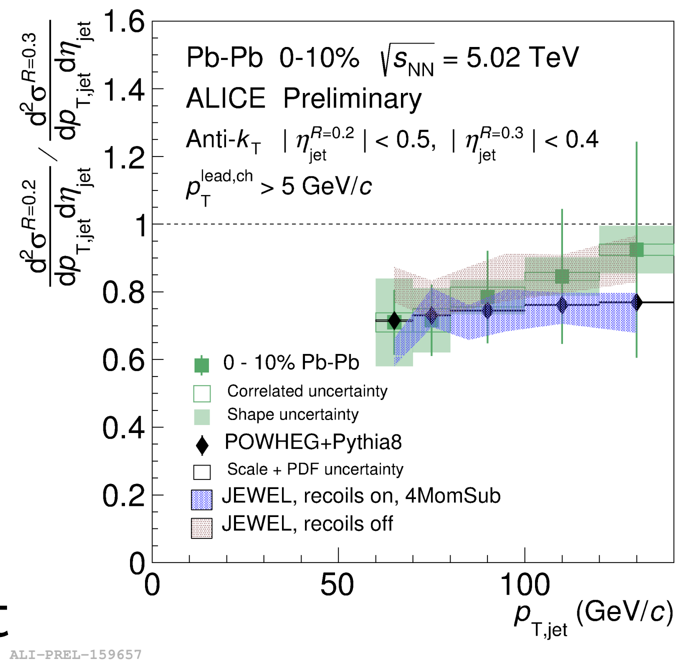
Jet R_{AA}

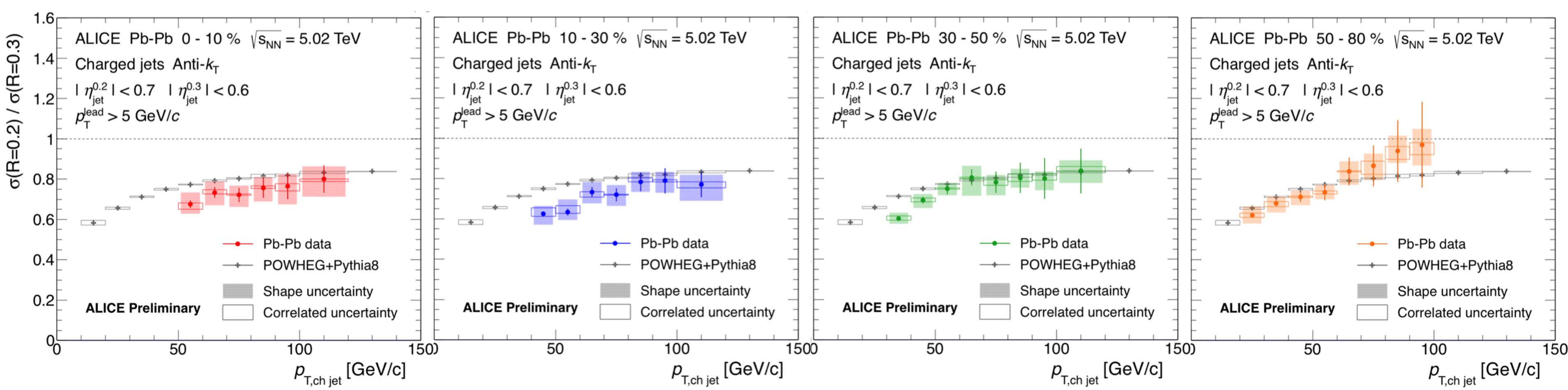
- Strong jet suppression ($R_{\mathrm{AA}} = 0.3 \div 0.5$) observed in central Pb-Pb collisions
  - Slowly rising with $p_{\mathrm{T,jet}}$ (flattening for $p_{\mathrm{T,jet}} \gtrsim 200\ \mathrm{GeV}/c$)
- Suppression stronger for more central collisions
  - Longer average path length, denser medium
- Similar suppression observed in R=0.2 and R=0.3
- Very complementary p_{T} coverage w/ ATLAS & CMS



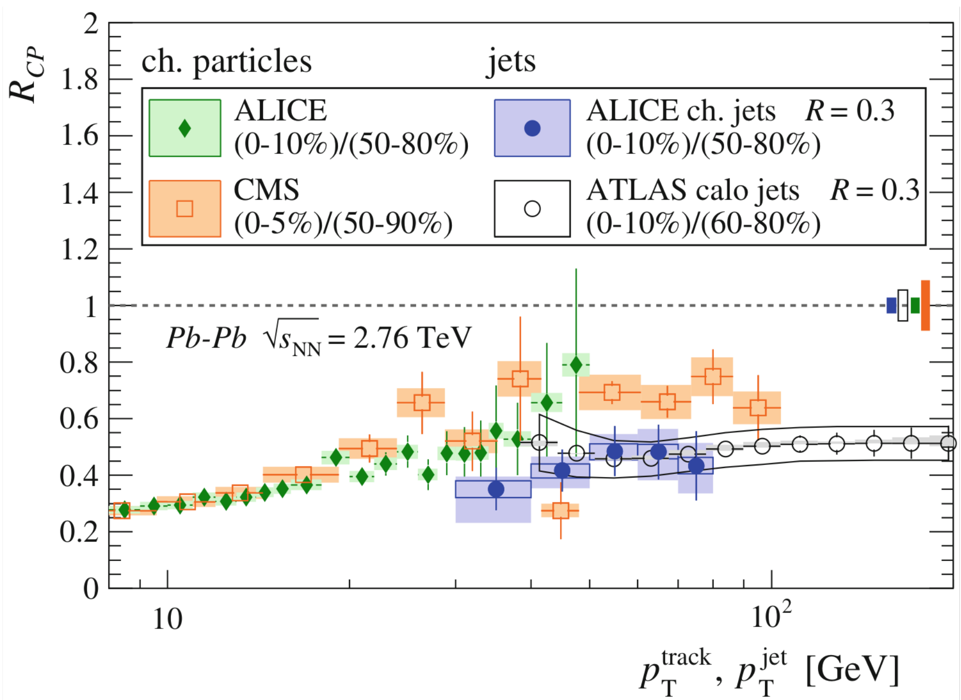
Jet cross-section ratio $R=0.2/R=0.3$

- The ratio of jet cross-sections at different R is an inclusive jet shape observable, sensitive to the R-dependence of jet energy loss
- Such ratios are infrared and collinear safe and are sensitive to the transverse energy profile of the jets
- With the current precision, consistent with the NLO pQCD prediction





Energy loss of charged particles and jets

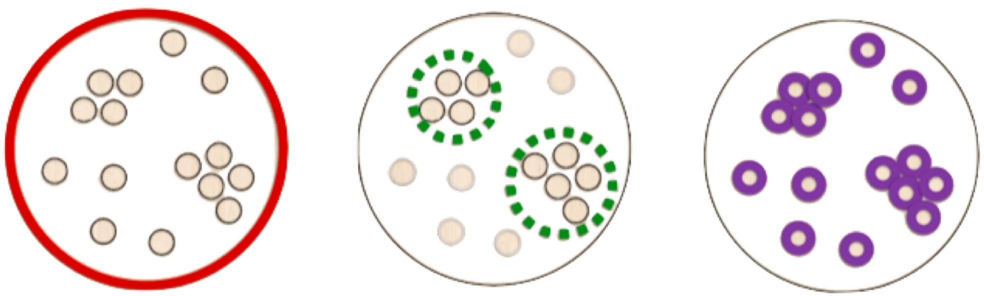


R_{CP} is the ratio of central to peripheral collisions yields

- Charged jet R_{CP} is **similar** to that observed for single hadrons over a broad momentum range
  - This is contrary to the expectation of jet suppression to be smaller than for hadrons (since jet reconstruction collects multiple jet fragments into the jet cone, thus recovering some of the medium-induced fragmentation)
  - The momentum is redistributed to angle larger than R=0.3 by interaction with the medium

Jet structure

- Modifications of perturbative parton showers induced by interactions with the color charges in the dense partonic medium

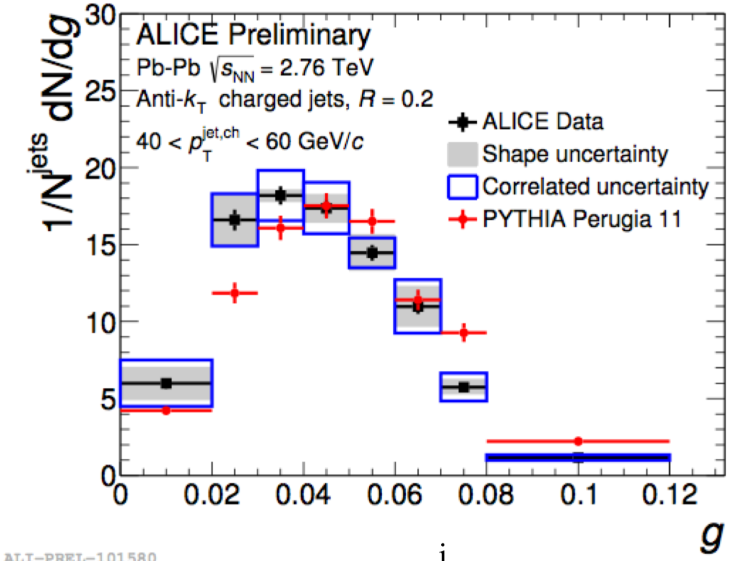


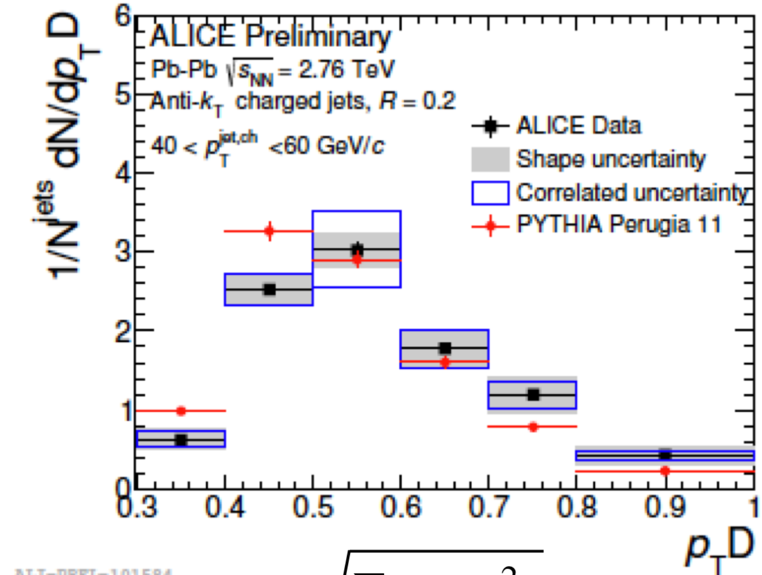
	Full jet	Large structure	Constituents
Observables	R_{AA}, A_J	Jet mass, z_g	Jet shape

+ jet flavor dependence!

Jet structure

Jet shape functions





$$g = \sum_{i \in jet} \frac{p_T^i}{p_{T,jet}} |\Delta R_{i,jet}|$$

Radial energy profile

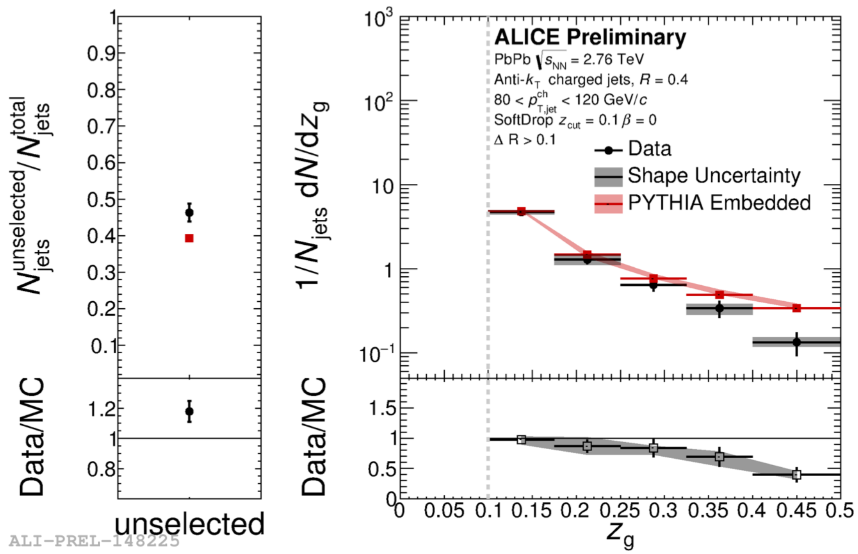
$$p_T D = \frac{\sqrt{\sum_{i \in jet} p_{T,i}^2}}{\sum_{i \in jet} p_{T,i}}$$

2nd moment constituent p_T distribution

- The jet core is more collimated and fragments harder than in vacuum!

Jet structure

- Where in the shower evolution the medium-modifications occur?
- Jet *grooming*
  - Isolate the hard prongs of a jet and remove soft wide-angle radiation
  - Momentum sharing z_g between leading subjets



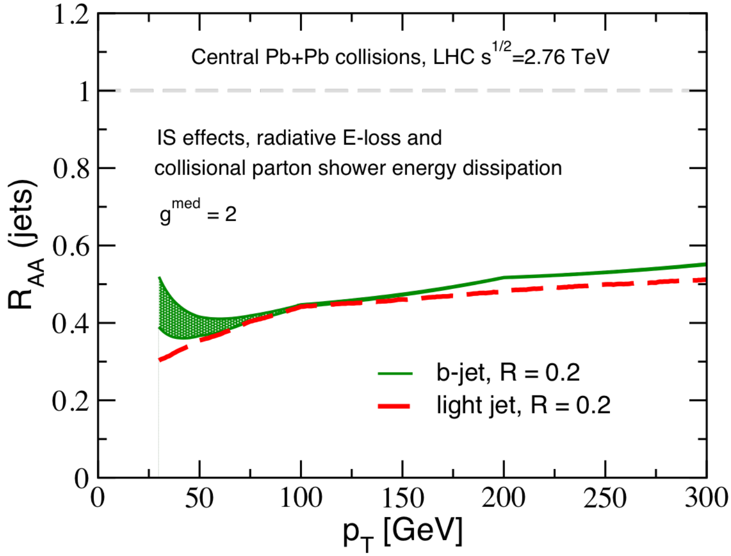
The splitting into two branches becomes increasingly more unbalanced as the Pb-Pb collisions becomes more central

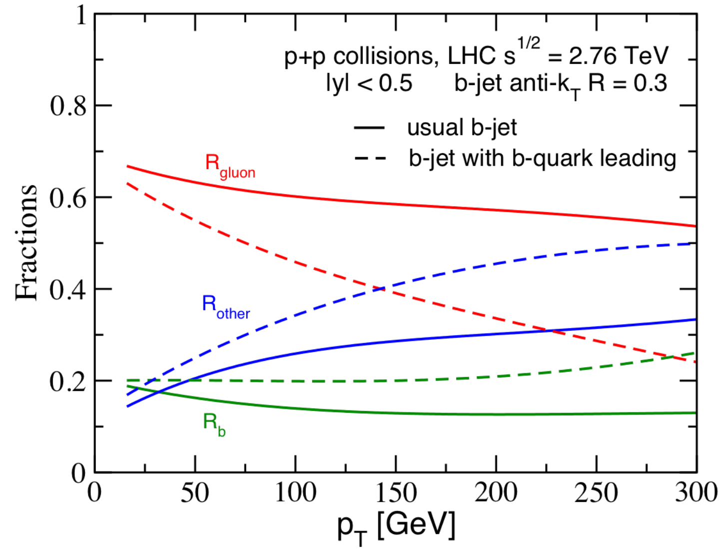
- Partons in the medium act as decoherent emitters?
  PLB 725 (2013) 357

Heavy flavor jets

arXiv:1306.0909

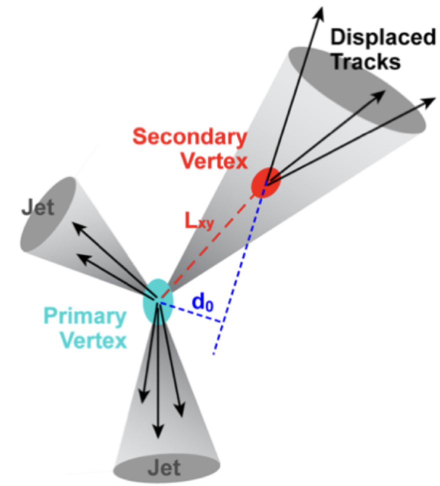
- $\Delta E_{\mathrm{g}} > \Delta E_{\mathrm{q}} > \Delta E_{\mathrm{Q}}$
  - Quark vs. gluon energy loss
  - Mass effect: radiation damping in *dead cone*
- Small rate of thermal production in the QGP ($m_{\mathrm{c,b}} \gg T$)
- Heavy quark jets vs. hadrons
  - Access the kinematics of hard scattering in an unbiased way (potentially contain more information)
  - Easier to measure (detection efficiency, systematics, HQ FFs...)
  - Typically larger energies

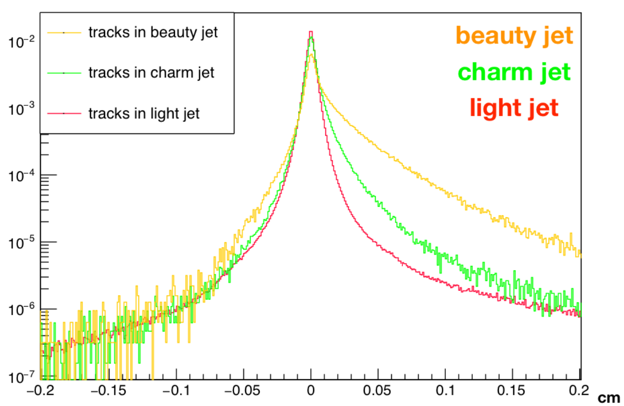


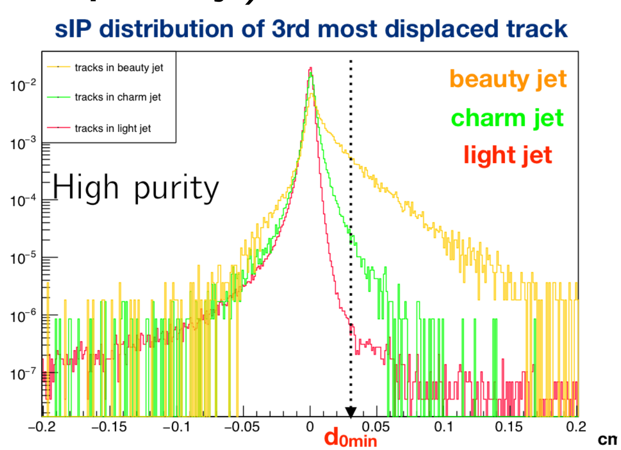


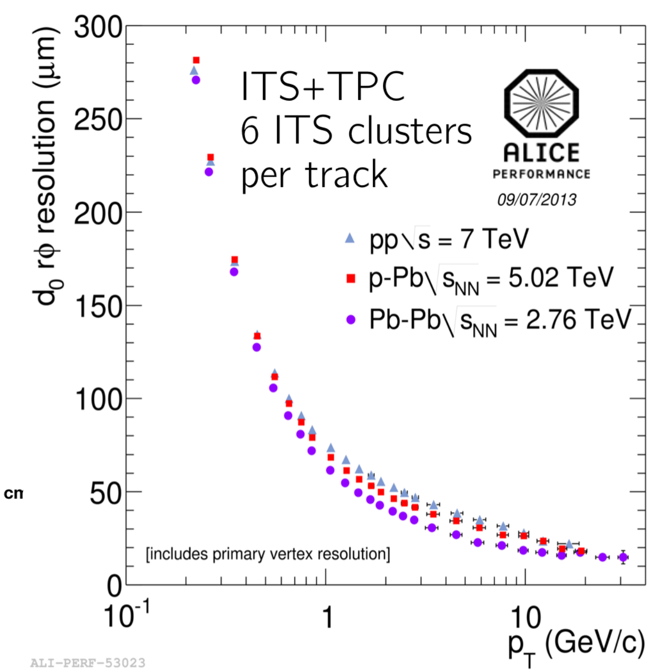
Impact parameter based *b*-tagging in pp and p-Pb

- Track Counting algorithm
  - Discriminator defined as the signed impact parameter (d.c.a. to the primary vertex) significance of the N^{th} most displaced track (N value driven by efficiency & purity)





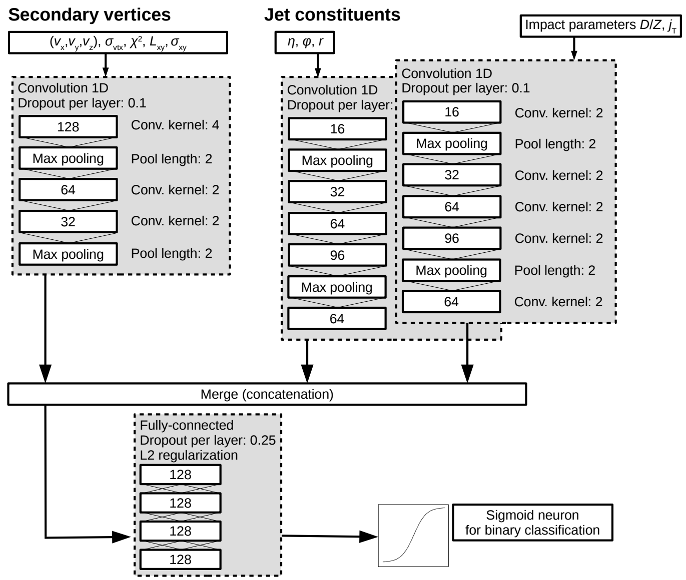




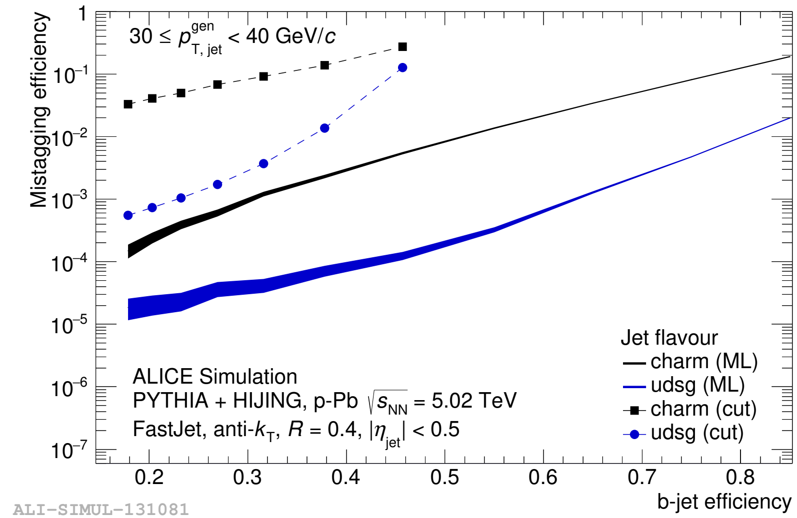
+ other taggers (SV, electrons...)

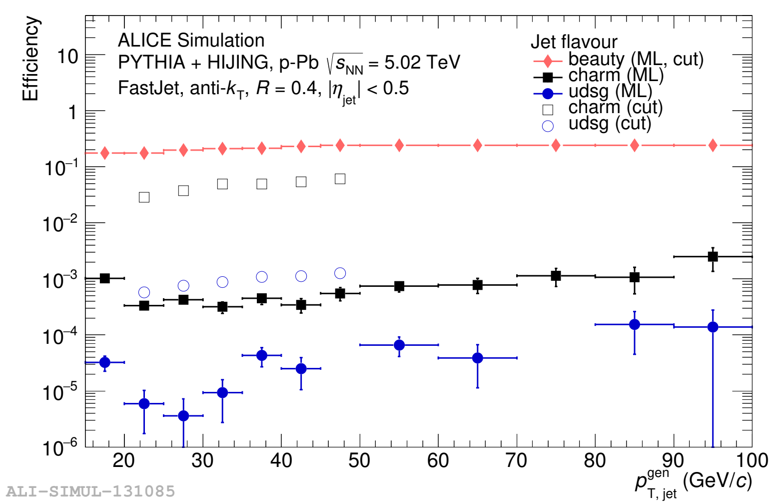
Deep-learning *b*-tagging

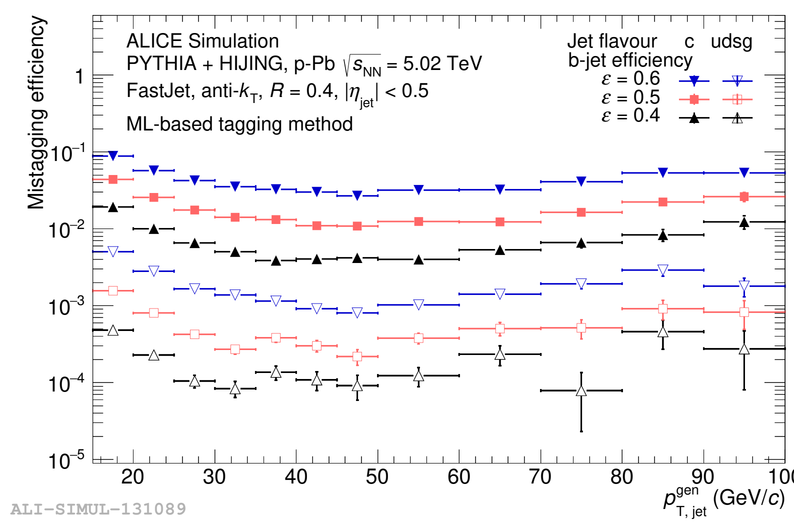
Multilayered CNNs



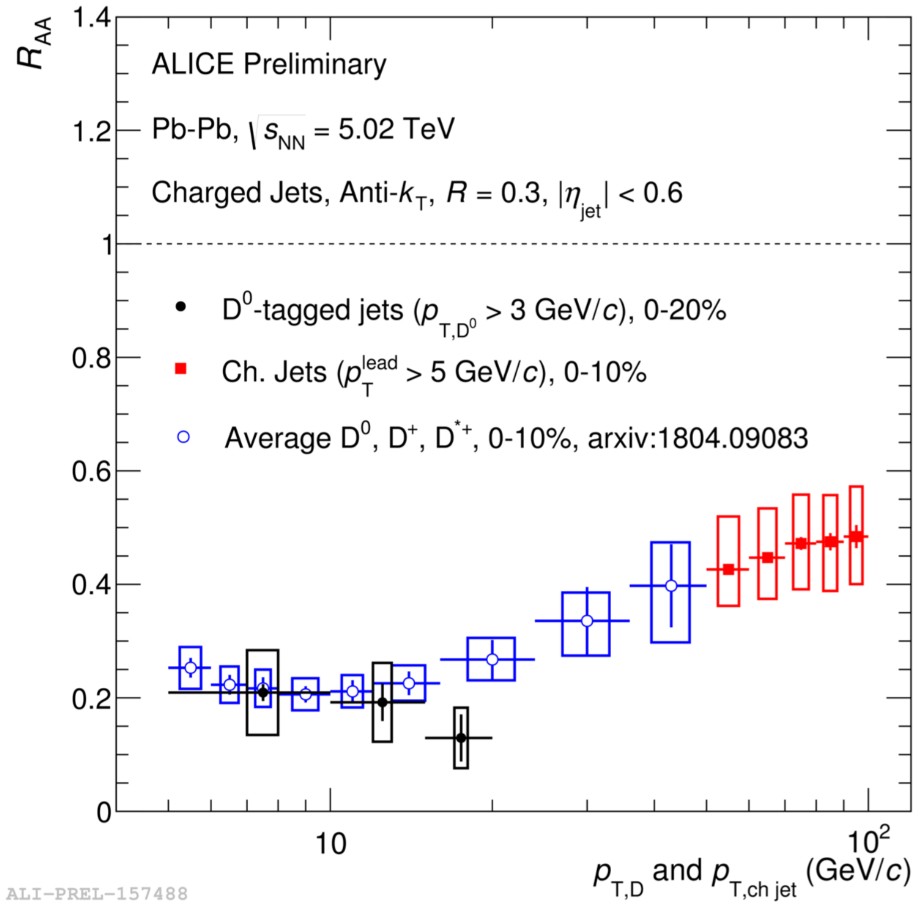
arXiv:1709.08497







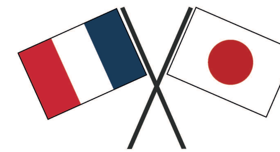
What about charm jets?



- Charged jets containing a D meson among their constituents
  - Invariant mass analysis to extract D-jet raw spectrum
  - Background spectrum from the side bands
- Strong suppression of the D^0-tagged jets in central Pb-Pb collisions
  - Hint of more suppression of low p_T D^0-jets than inclusive jets at higher p_T
  - Similar to D meson R_{AA}

Conclusion

- Inclusive jet suppression in 5.02 TeV Pb-Pb collisions
- Exploring jet substructure
- Heavy-flavor jet tagging
- Measurement of hadron-jet/jet-hadron correlations



- The rise of Machine Learning for jets
  - Discriminating quark and gluon jets
  - Heavy-flavor tagging...
- Even after 25 years, this is just the beginning
  - Large upgrade program in preparation!
    - Continuous read-out of 50 kHz Pb-Pb collisions
    - Upgrade of ITS, TPC, MFT will be installed starting from next year
  - ALICE will continue to take data at least until 2028 (LS4)