High-density QCD Matter

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Office of Science

EPS-HEP
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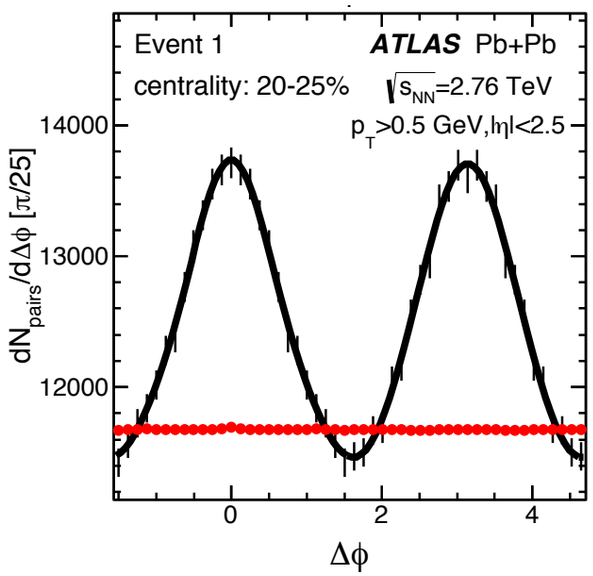
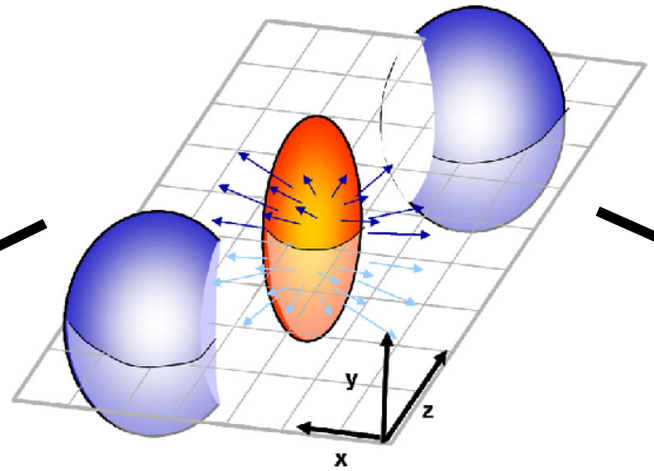
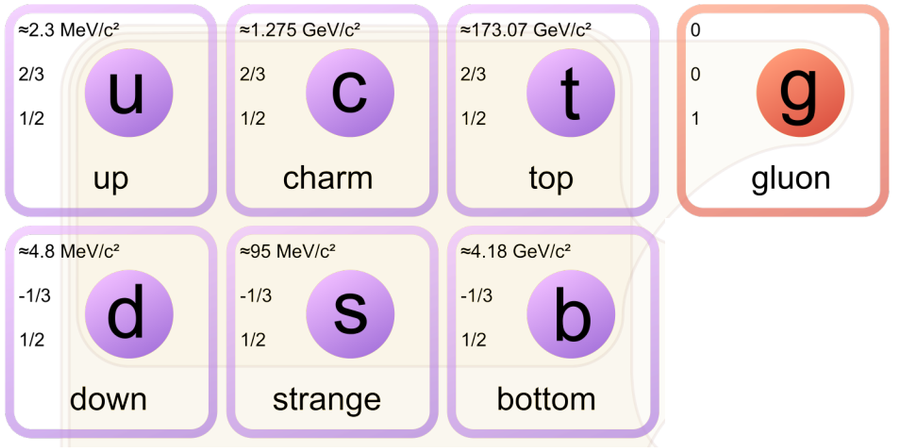
Ghent, Belgium

emergent near-perfect fluidity





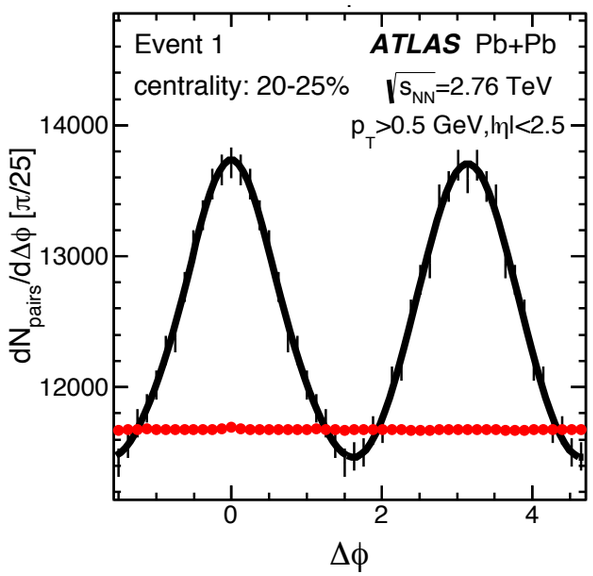
fundamental interaction & degrees of freedom exactly known

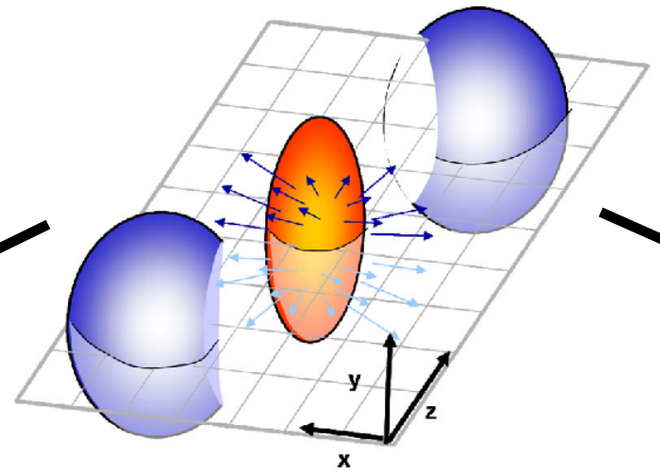


collective, ***strongly-coupled****, long-distance behavior*

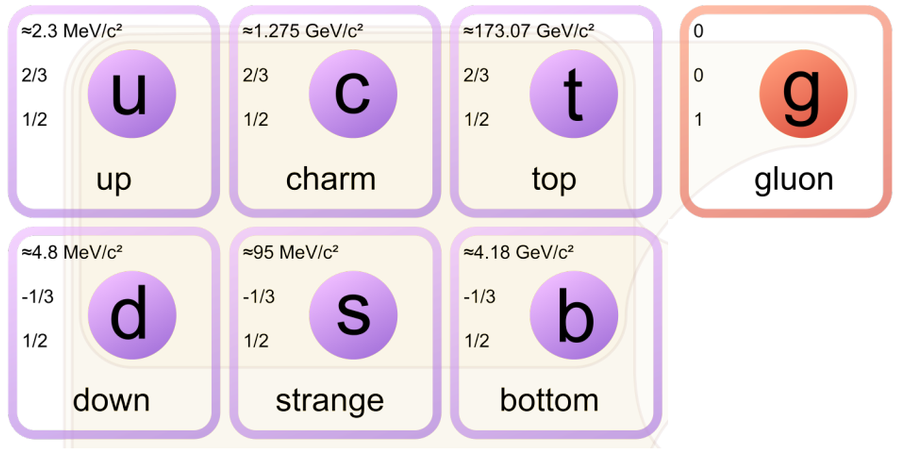
short-distance, ***asymptotically free*** *quarks and gluons*

emergent near-perfect fluidity





fundamental interaction & degrees of freedom exactly known

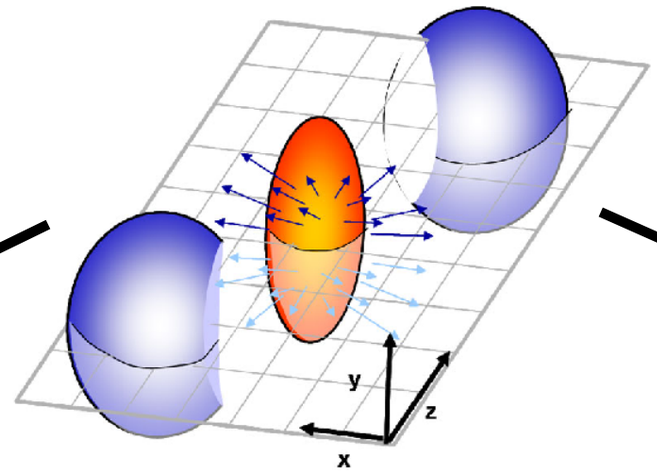


collective, ***strongly-coupled****, long-distance behavior*

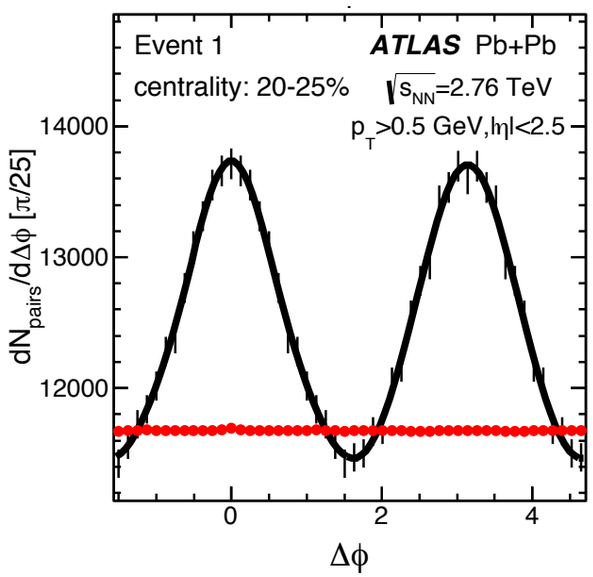
short-distance, ***asymptotically free*** *quarks and gluons*

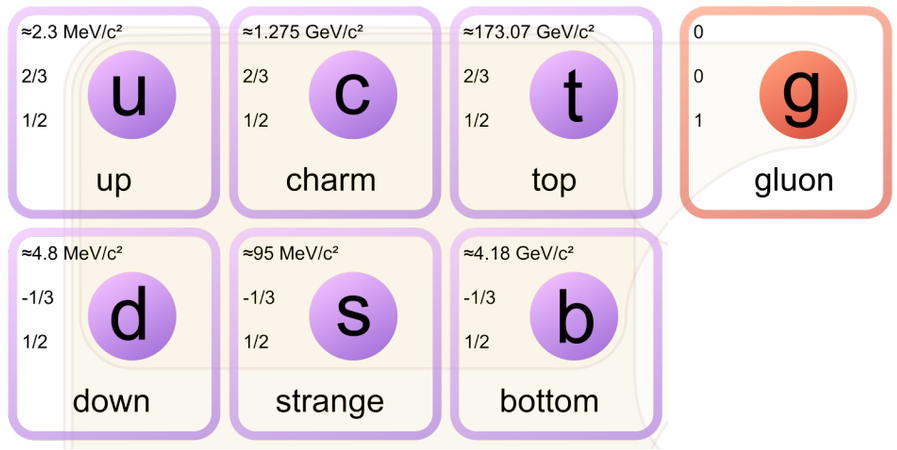
How does the behavior of Quark-Gluon Plasma emerge from the microscopic QCD theory?

emergent near-perfect fluidity



fundamental interaction & degrees of freedom exactly known





collective, ***strongly-coupled****, long-distance behavior*

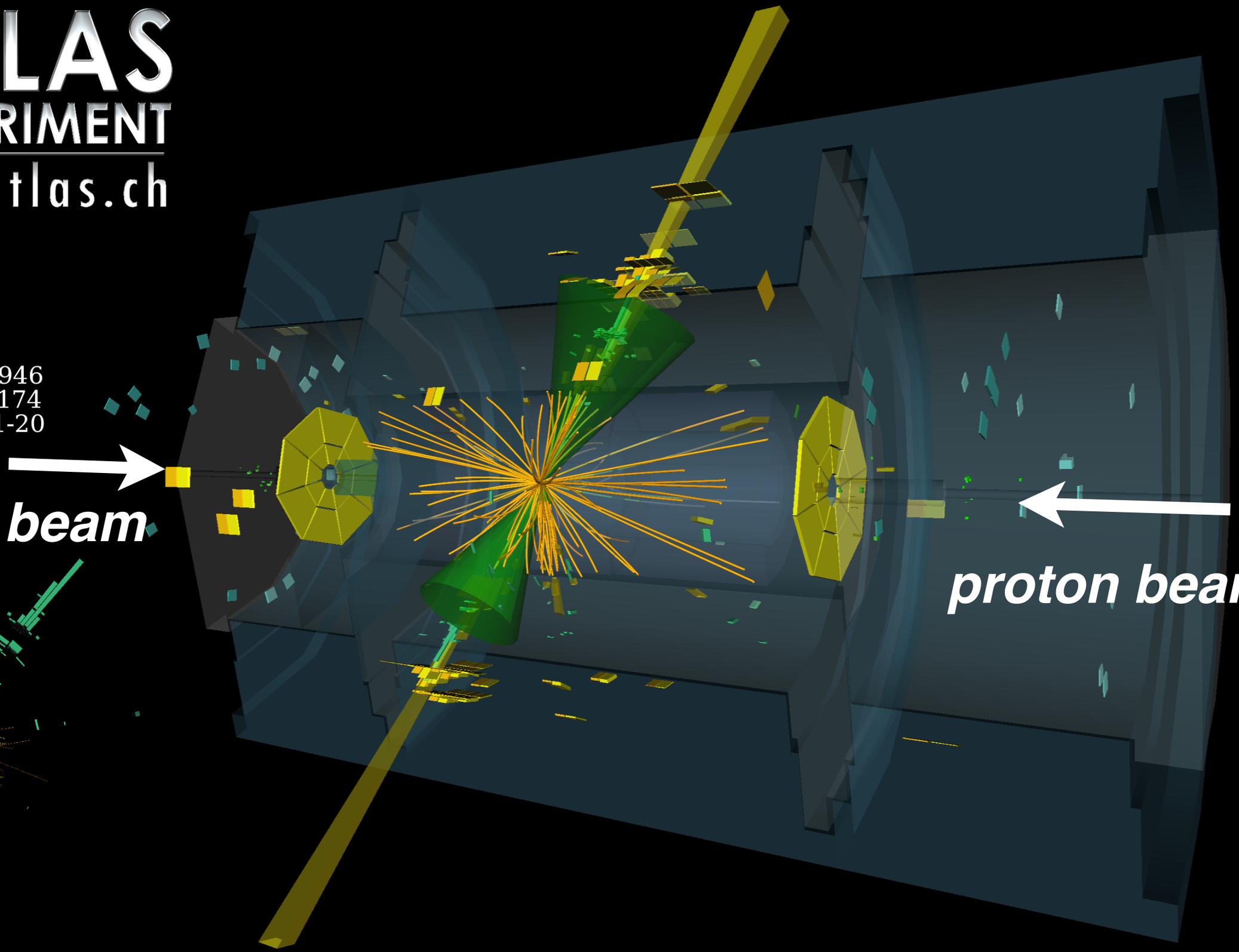
short-distance, ***asymptotically free*** *quarks and gluons*

jets*: multi-scale, internally generated probes of the* ***QGP*** *medium…*

ATLAS EXPERIMENT

http://atlas.ch

Run: 217946
Event: 13617174
Date: 2013-01-20

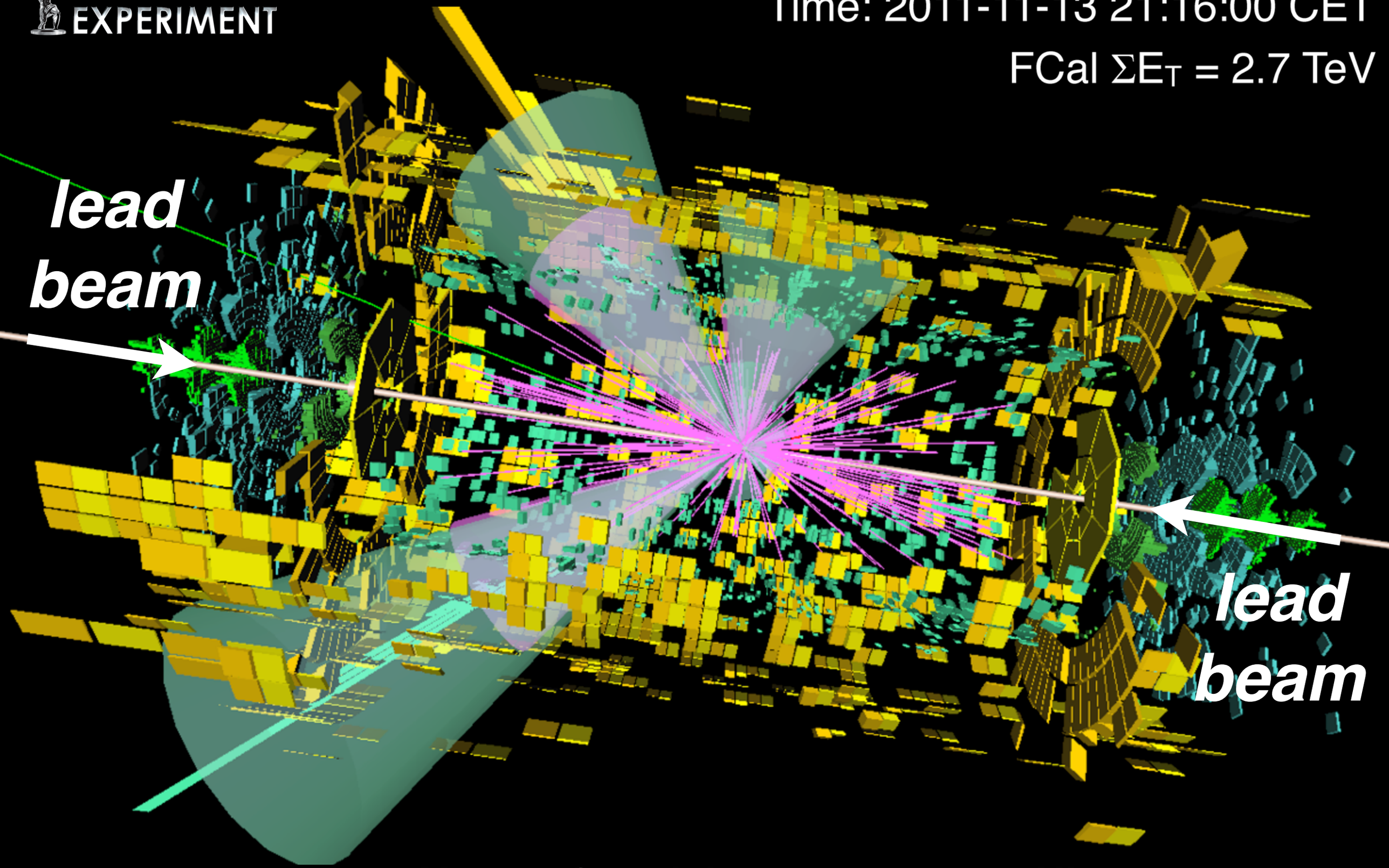


Precision tools, near-ubiquitous in modern HEP…

ATLAS EXPERIMENT

Run 193291, Event 2731321,
Time: 2011-11-13 21:16:00 CET

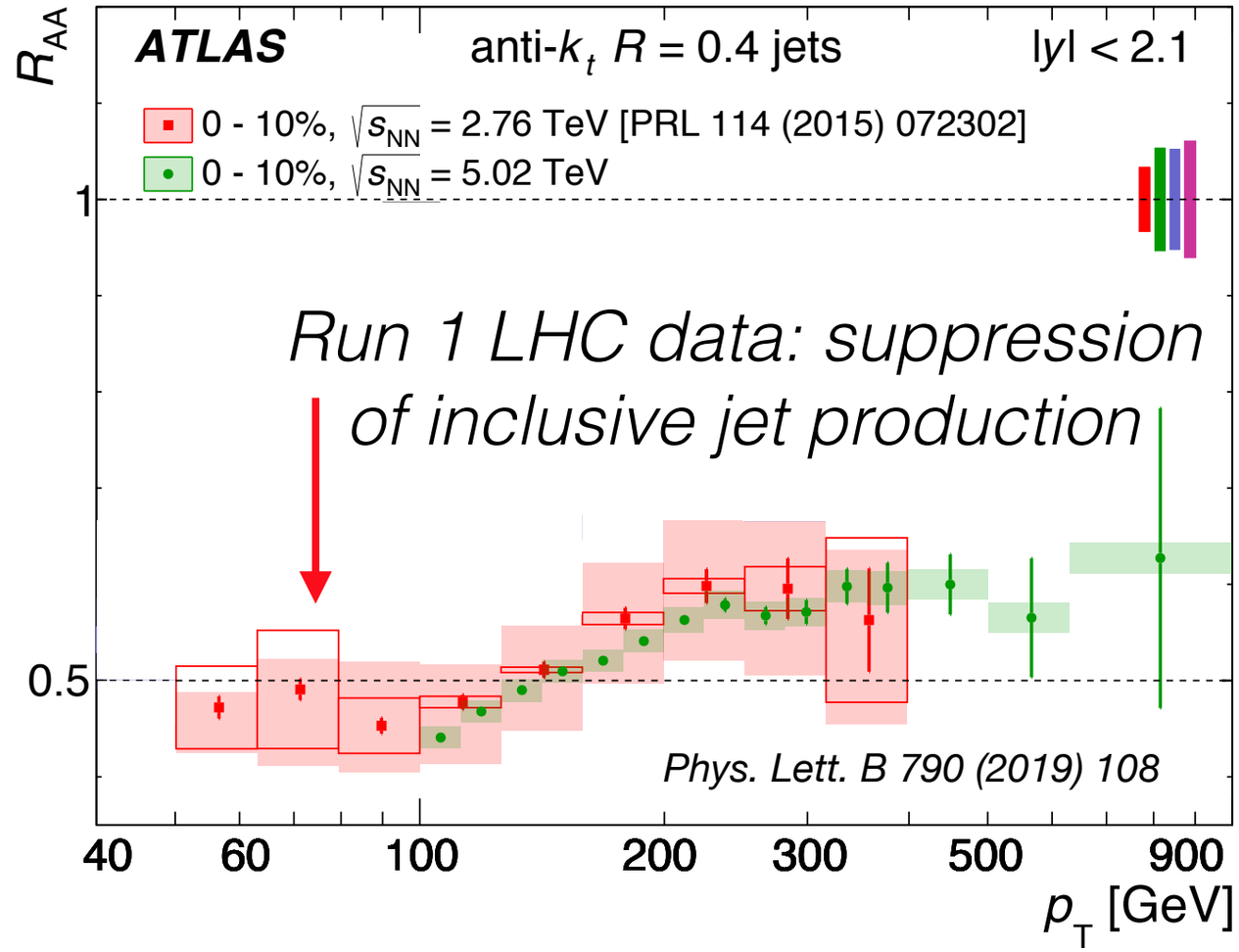
FCal ΣE_T = 2.7 TeV



Years of work by many across HI community to make / improve reconstructed jet measurements!

Jet R_{AA}

Nuclear modification factor (Pb+Pb/pp ratio) for inclusive jets



Jet R_{AA}

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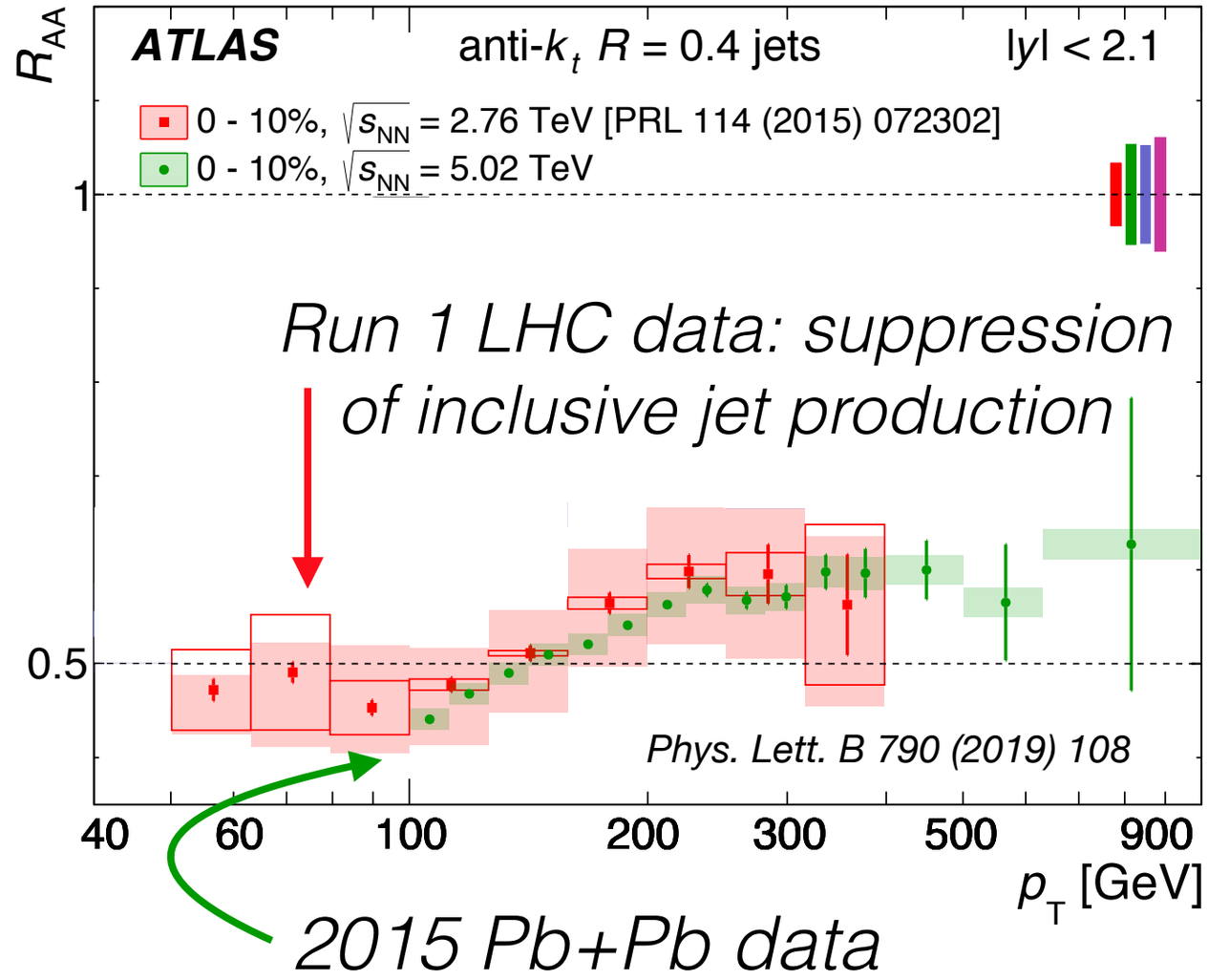
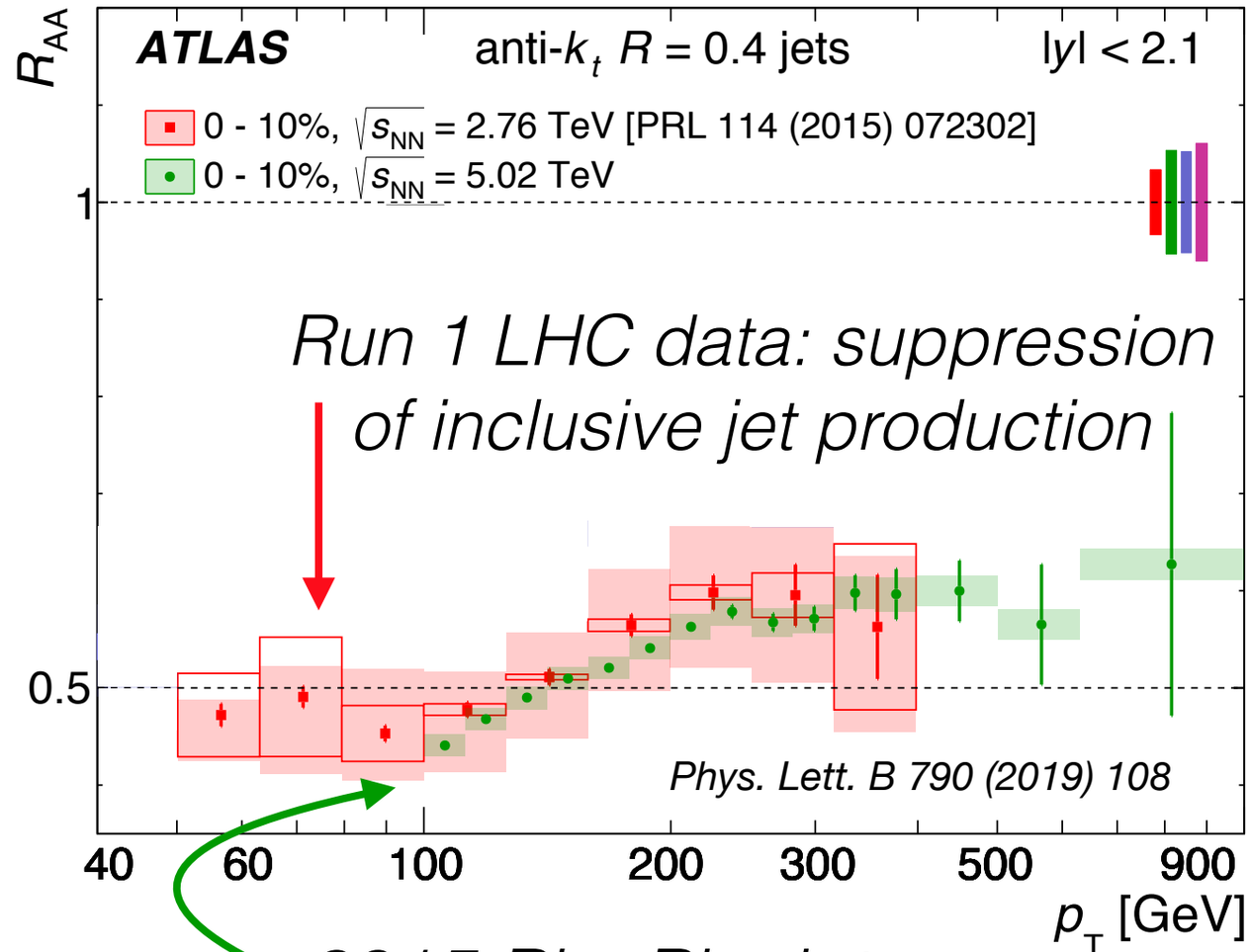


1. Significant improvements in systematic control over jet energy scale

Jet R_{AA}

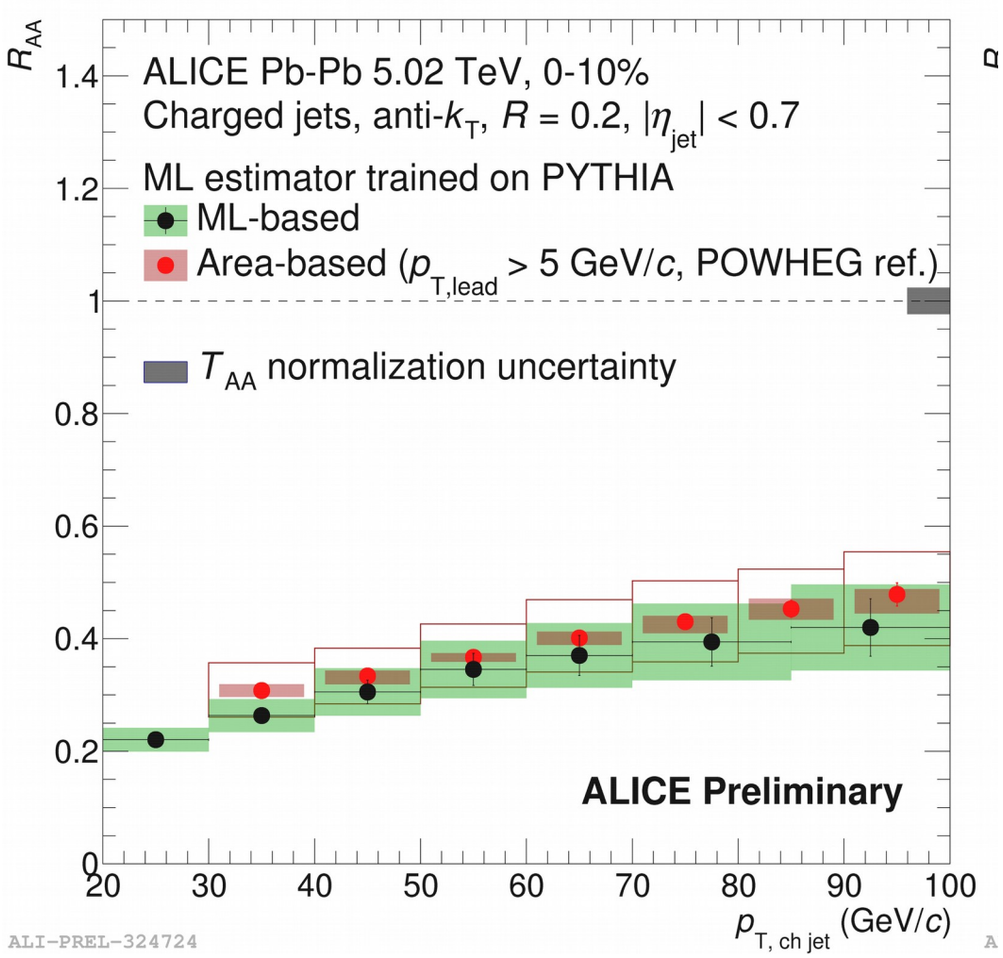
Nuclear modification factor (Pb+Pb/pp ratio) for inclusive jets

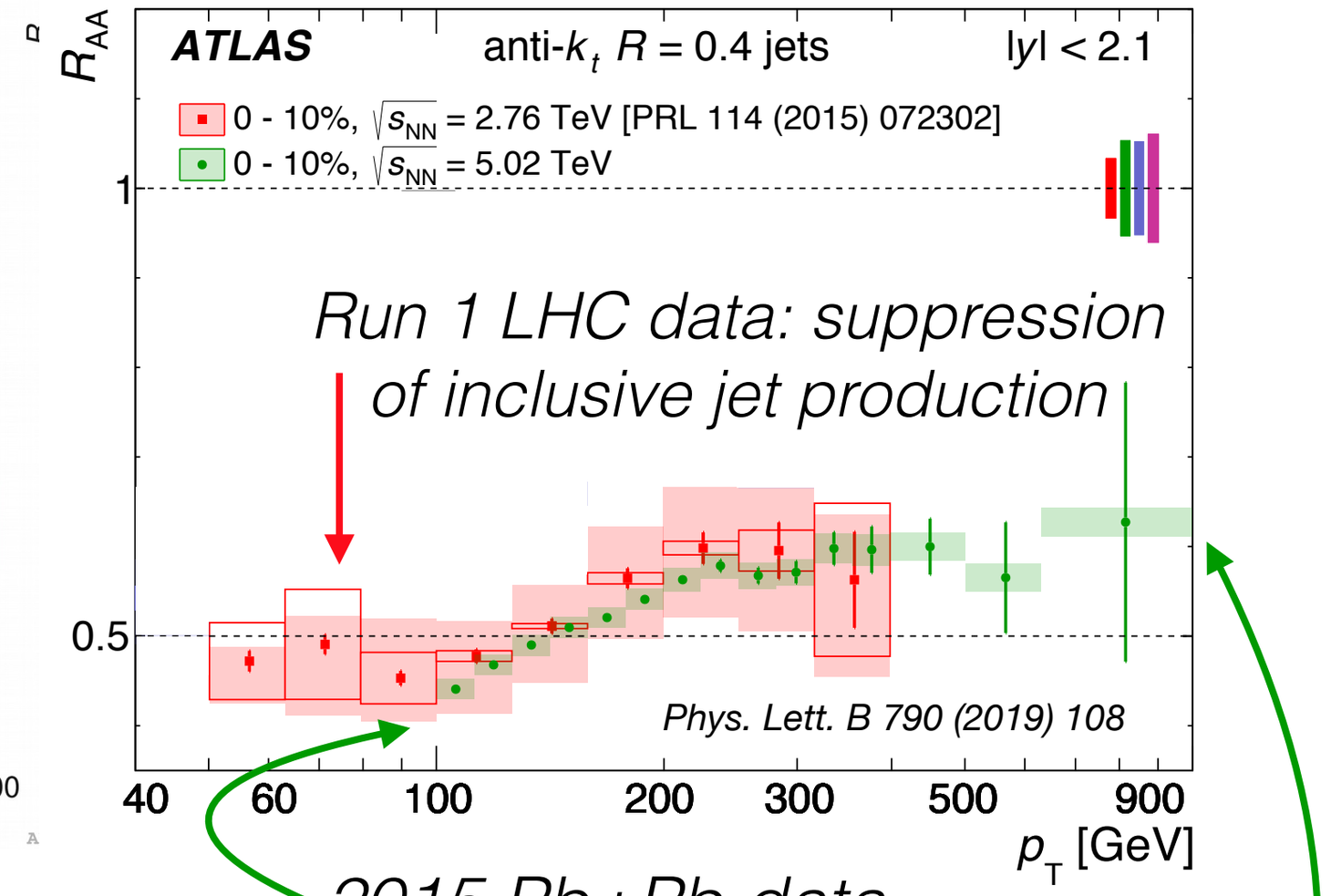


1. Significant improvements in systematic control over jet energy scale

2. Extension of kinematic reach + more differential measurements (2018 data 3.5x luminosity for ATLAS+CMS)

Jet R_{AA}



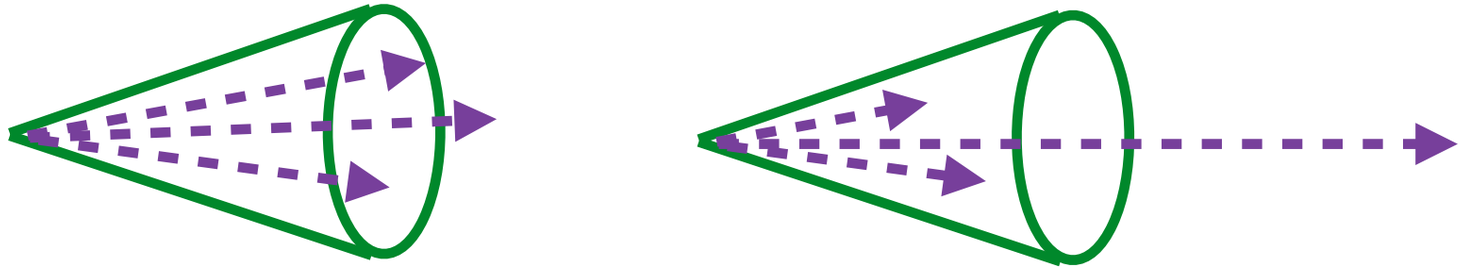


3. Advanced techniques to separate lower-p_T jets from the HI background

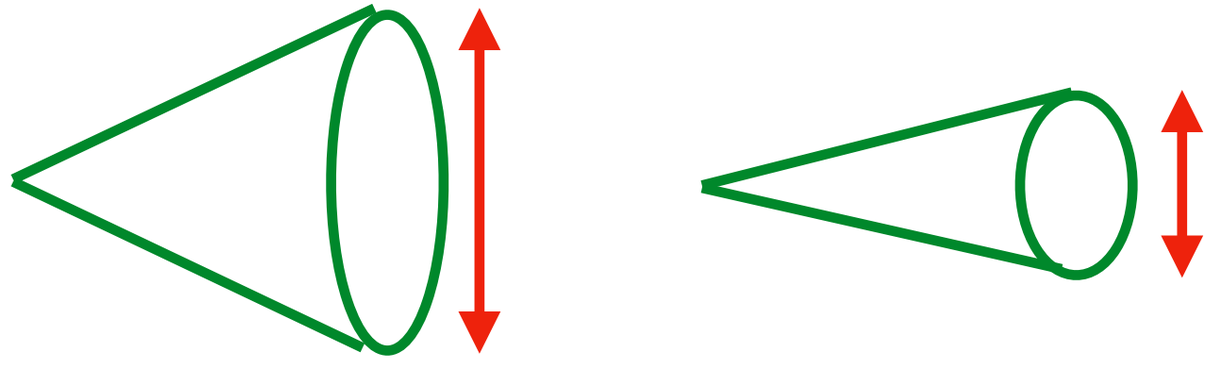
1. Significant improvements in systematic control over jet energy scale

2. Extension of kinematic reach + more differential measurements (2018 data 3.5x luminosity for ATLAS+CMS)

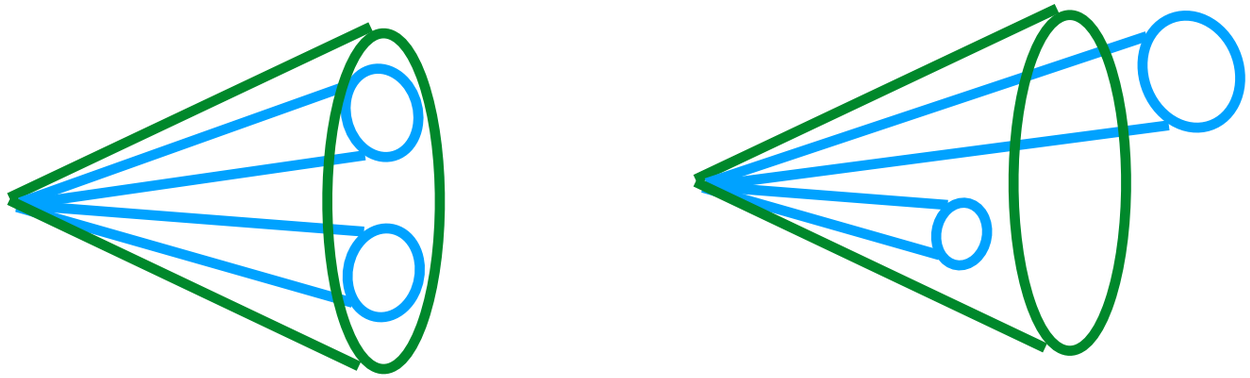
(longitudinal momentum) fragmentation function



jet mass

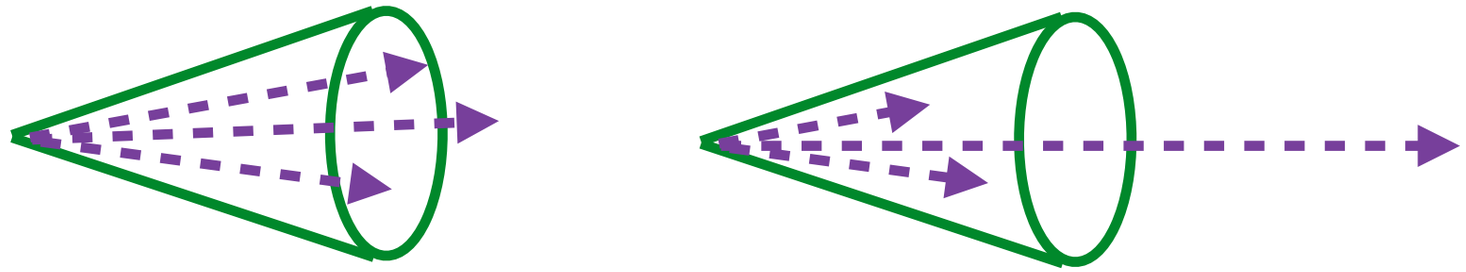


splitting function



Jet (sub)structure in Heavy Ions - growing topic with lots to learn from HEP community

(longitudinal momentum) fragmentation function

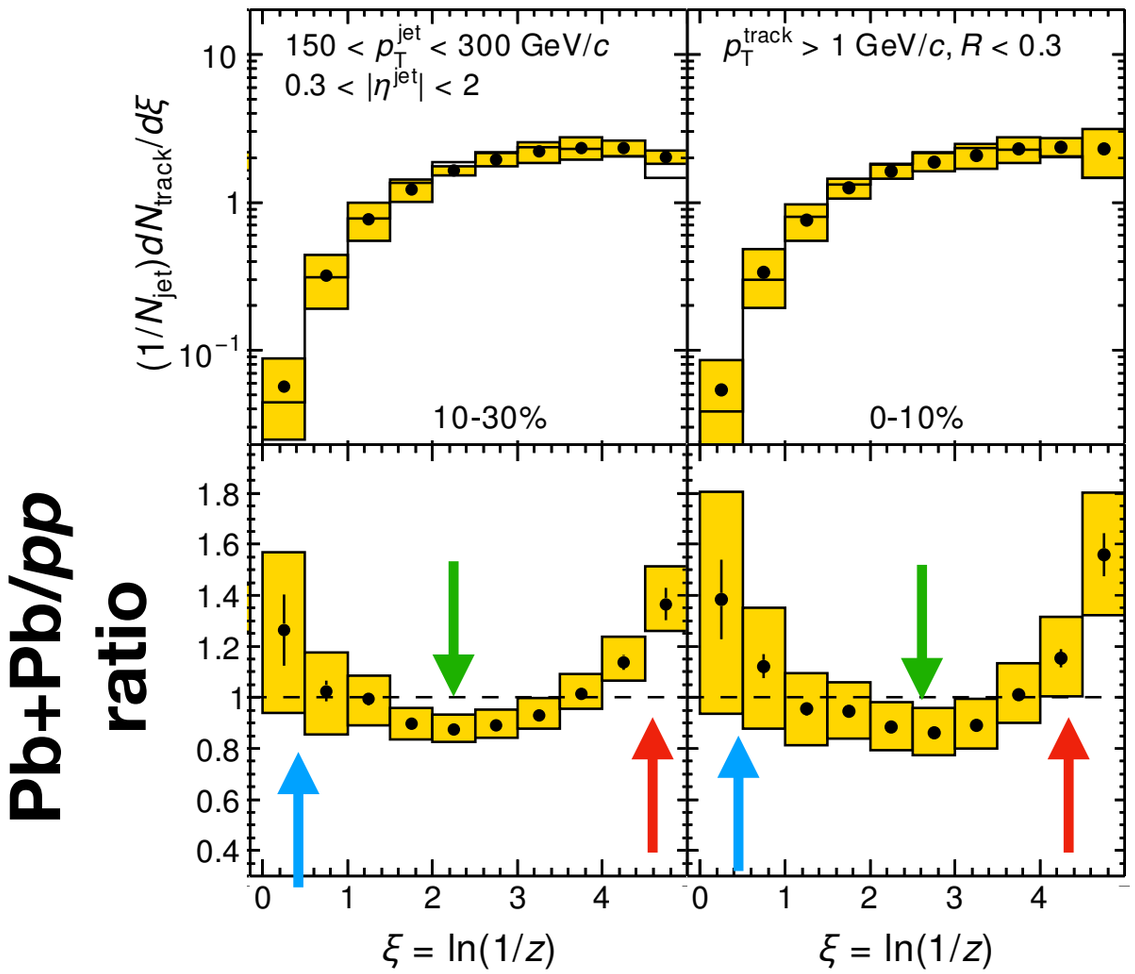


how is development of parton shower modified?

structure of in-cone radiated energy / thermal QGP “response"?

Fragmentation functions

Phys. Rev. C 90 (2014) 024908



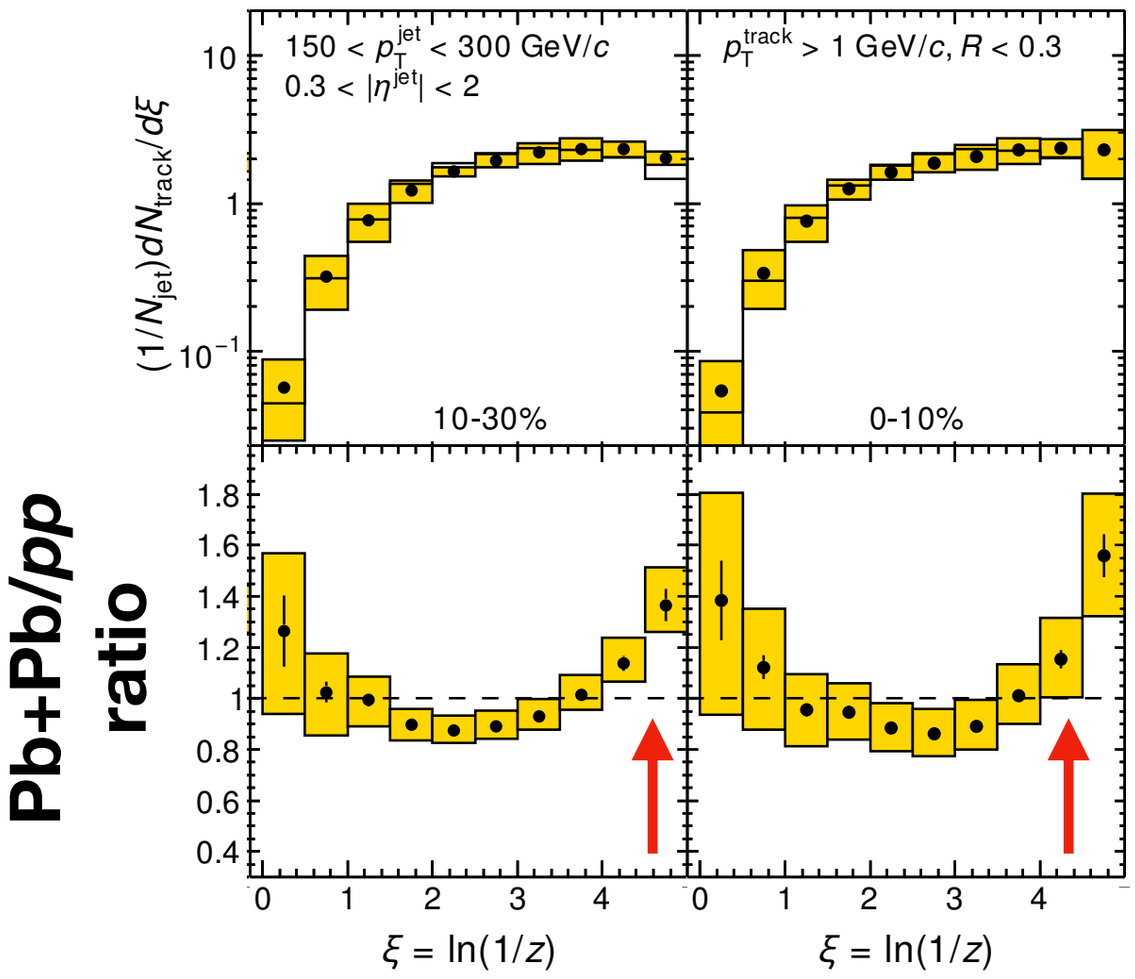
increase in soft particles

"softening" in moderate-p_T region

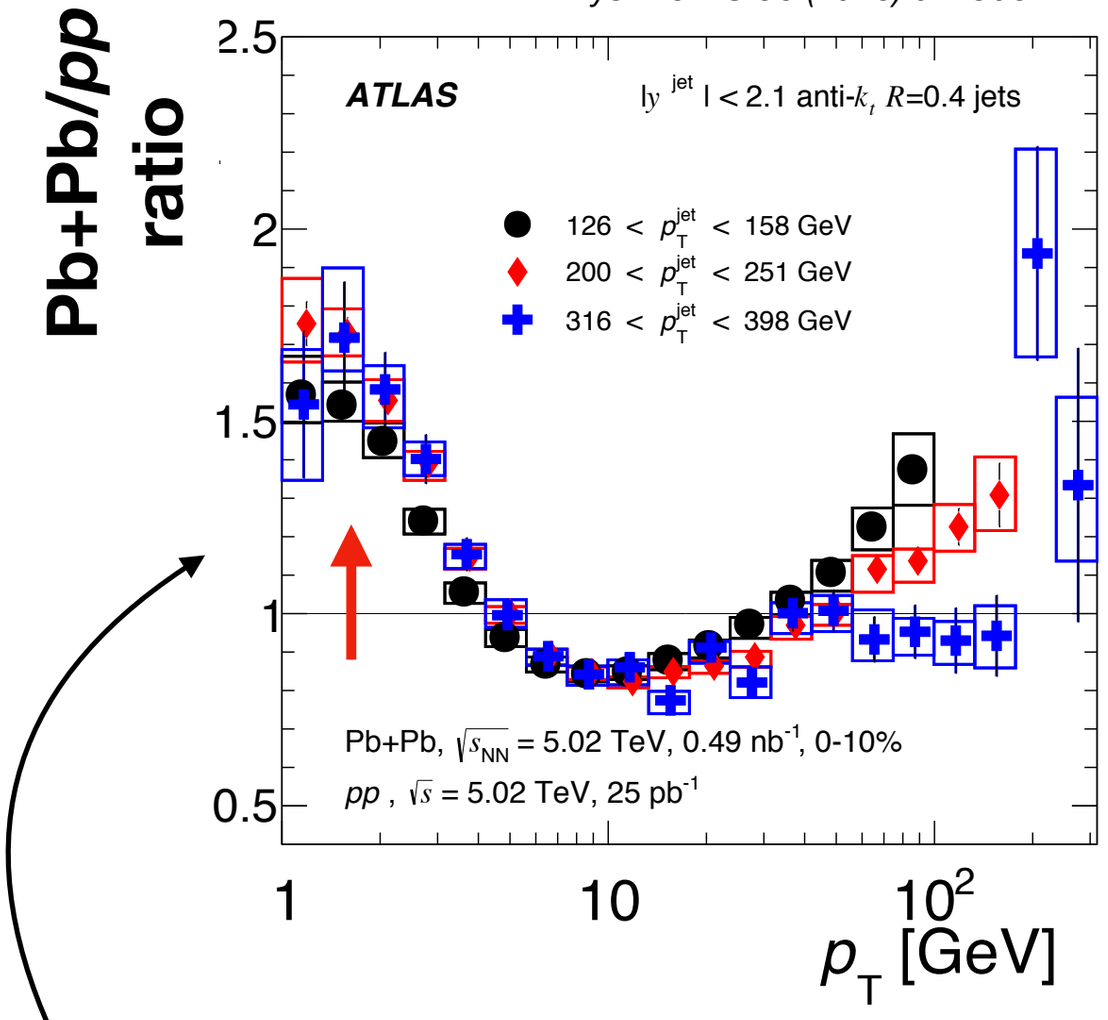
survivor bias? (also note p_T sum rule)

Fragmentation functions

Phys. Rev. C 90 (2014) 024908



Phys. Rev. C 98 (2018) 024908



↑ *increase in soft particles*

Ratios at small p_T^h similar at all p_T^{jet}…

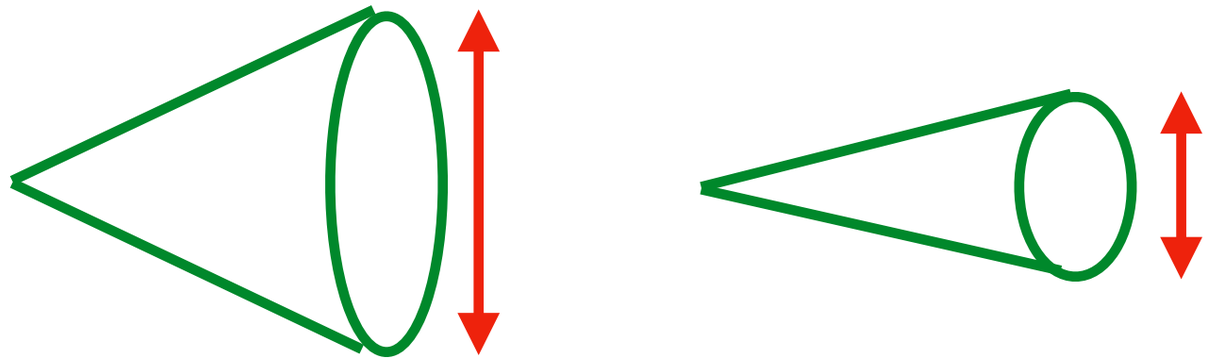
must be related to absolute <u>QGP scales</u> (soft thermal response)

(longitudinal momentum) fragmentation function

how is development of parton shower modified?

structure of in-cone radiated energy / thermal QGP “response"?

jet mass

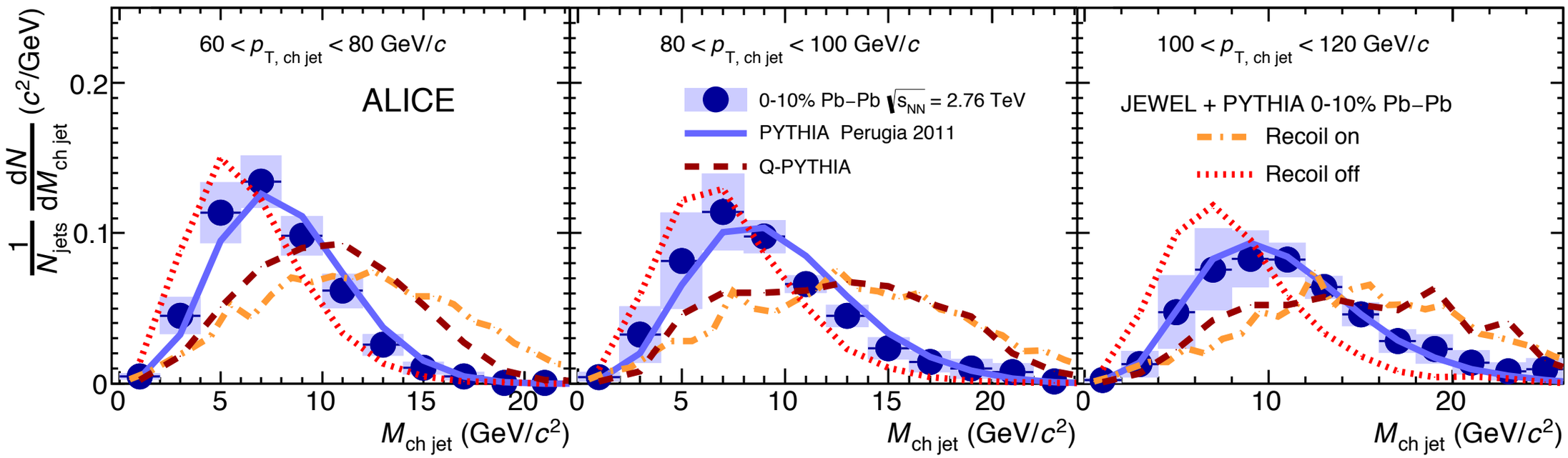


does QGP filter out soft modes, leaving hard core (decrease mass)?

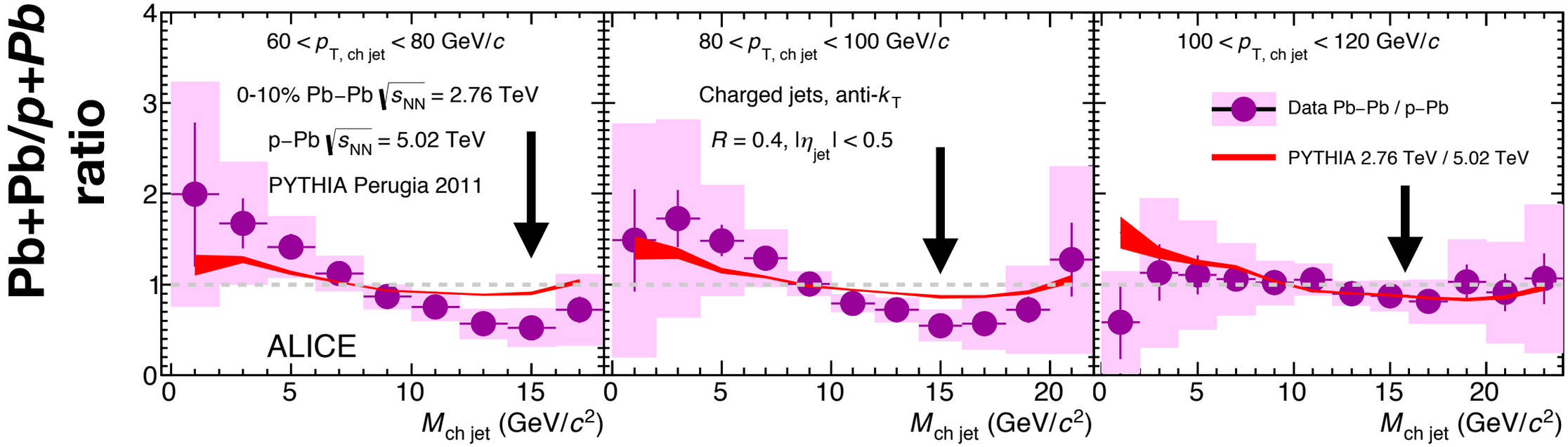
soft particle response to deposited energy (increase mass)?

Jet mass

PLB 776 (2018) 249



ungroomed mass in p_T^{jet} selections



selected/surviving jets have smaller mass…

(longitudinal momentum) fragmentation function

how is development of parton shower modified?

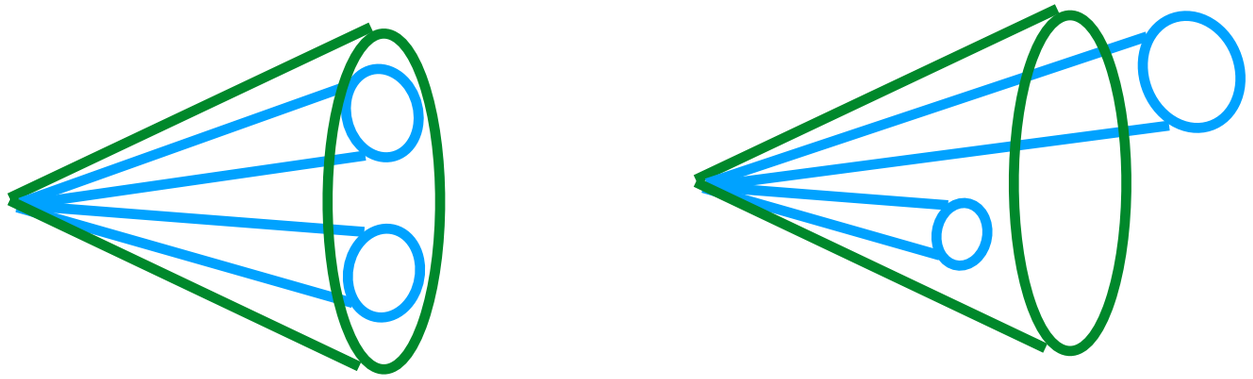
structure of in-cone radiated energy / thermal QGP “response"?

jet mass

does QGP filter out soft modes, leaving hard core (decrease mass)?

soft particle response to deposited energy (increase mass)?

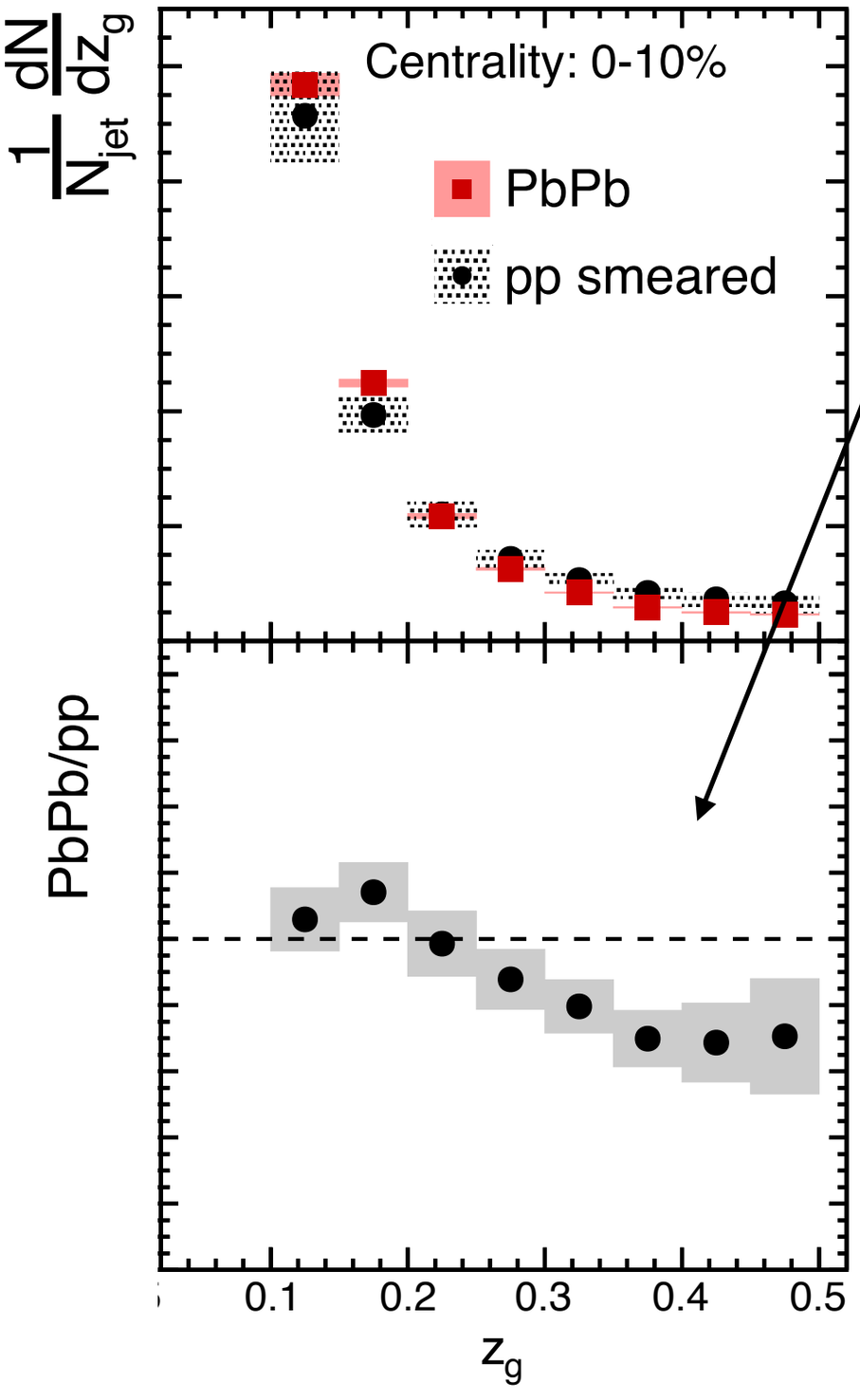
splitting function



do nearby subjets lose energy the same way (stochasticity of E-loss)?

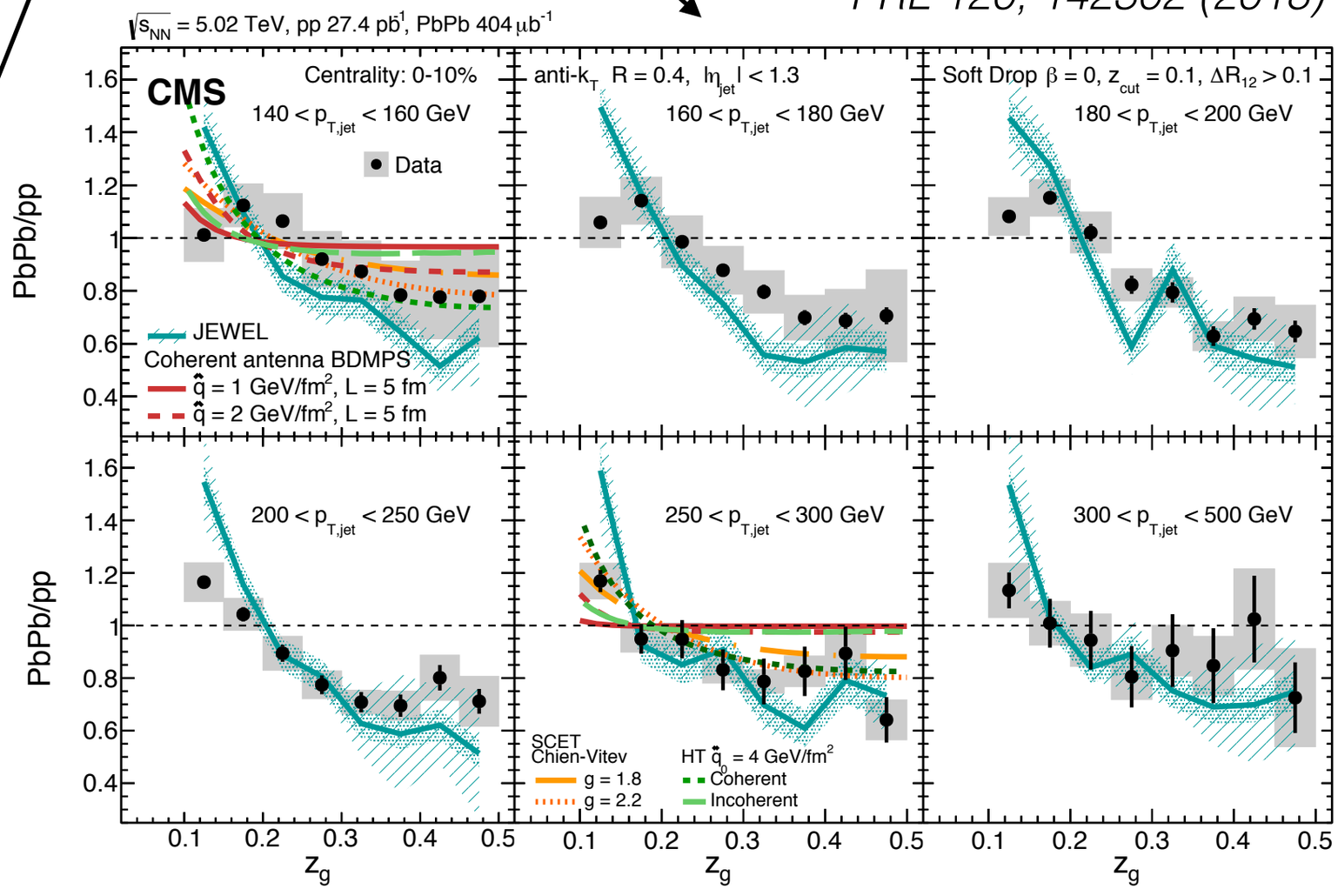
can the medium resolve independent subjets (color coherence)?

Splitting function



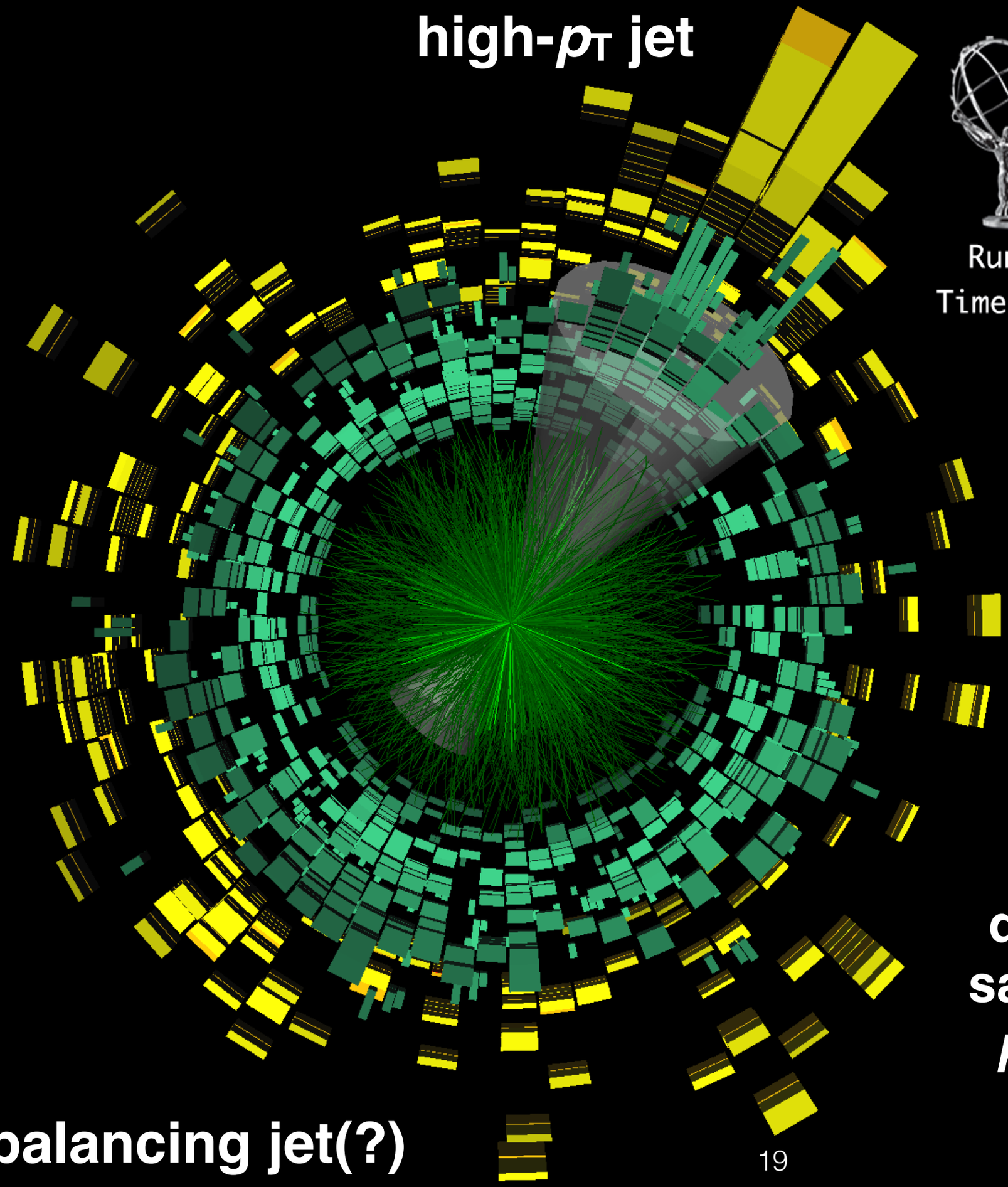
subjet p_T-sharing modified by QGP

PRL 120, 142302 (2018)



additional advantage: some substructure observables robust by construction against HI background…

high-p_T jet



balancing jet(?)

ATLAS EXPERIMENT

Run 168795, Event 7578342

Time 2010-11-09 08:55:48 CET

did both jets lose energy?

was the surviving jet created near surface?

do selected jets have same flavor fraction as *pp* comparison jets?

Run: 286834
Event: 124877733
2015-11-28 01:15:42 CEST
Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV
photon + multijet event
ΣE_T^{FCal} = 4.06 TeV

EW boson-tagged jet quenching

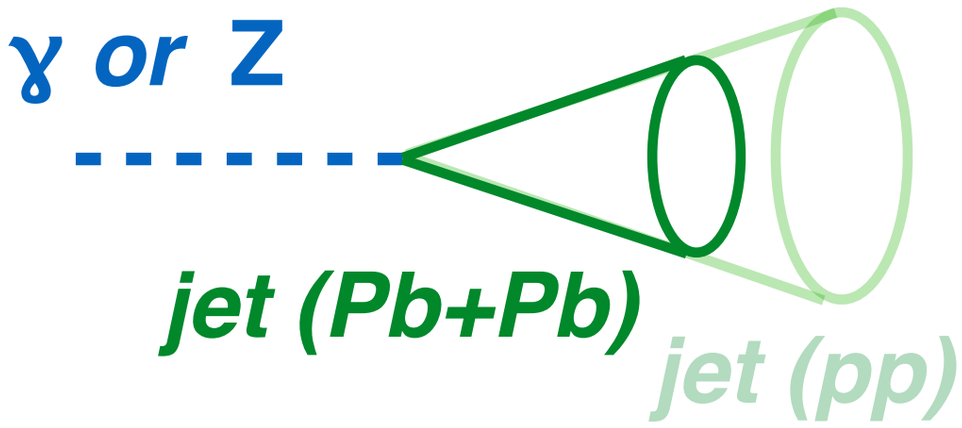
p_T = 200 GeV *photon*

EMCal

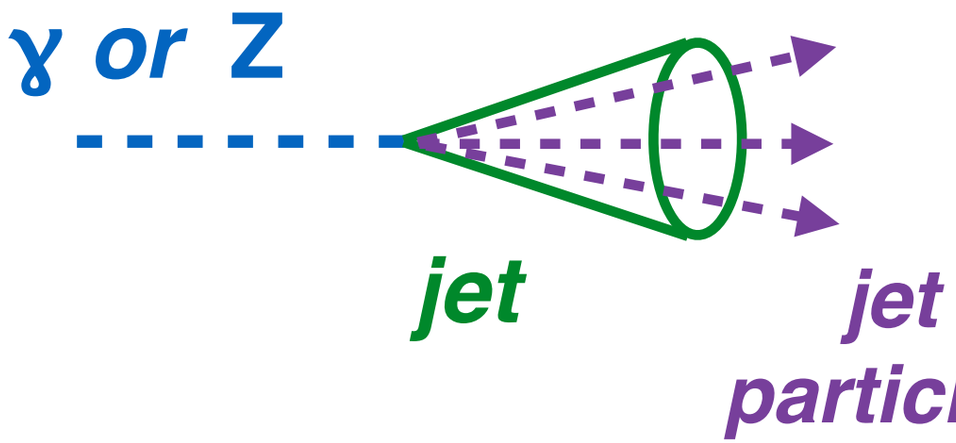
HCal

balancing jet(s)?

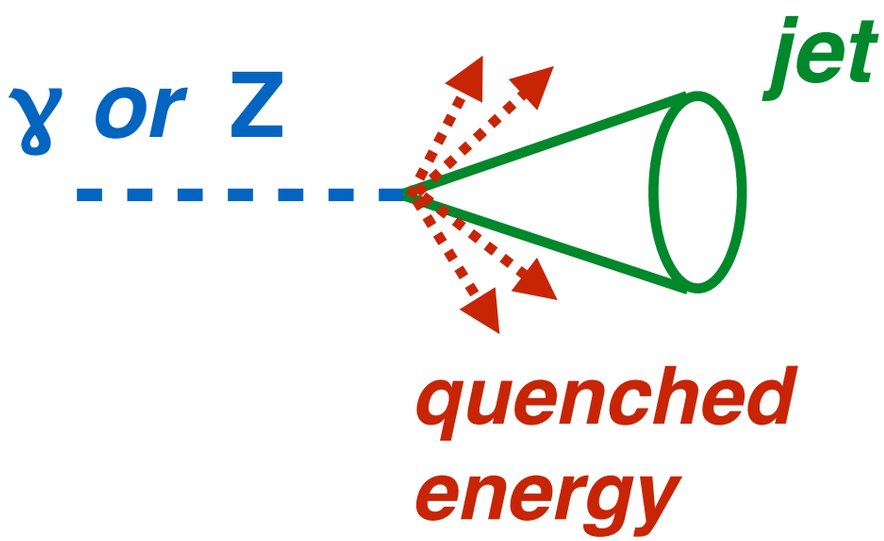
ATLAS EXPERIMENT



What is the (absolute) amount of energy lost in cone?



How is the parton shower in cone modified by medium?



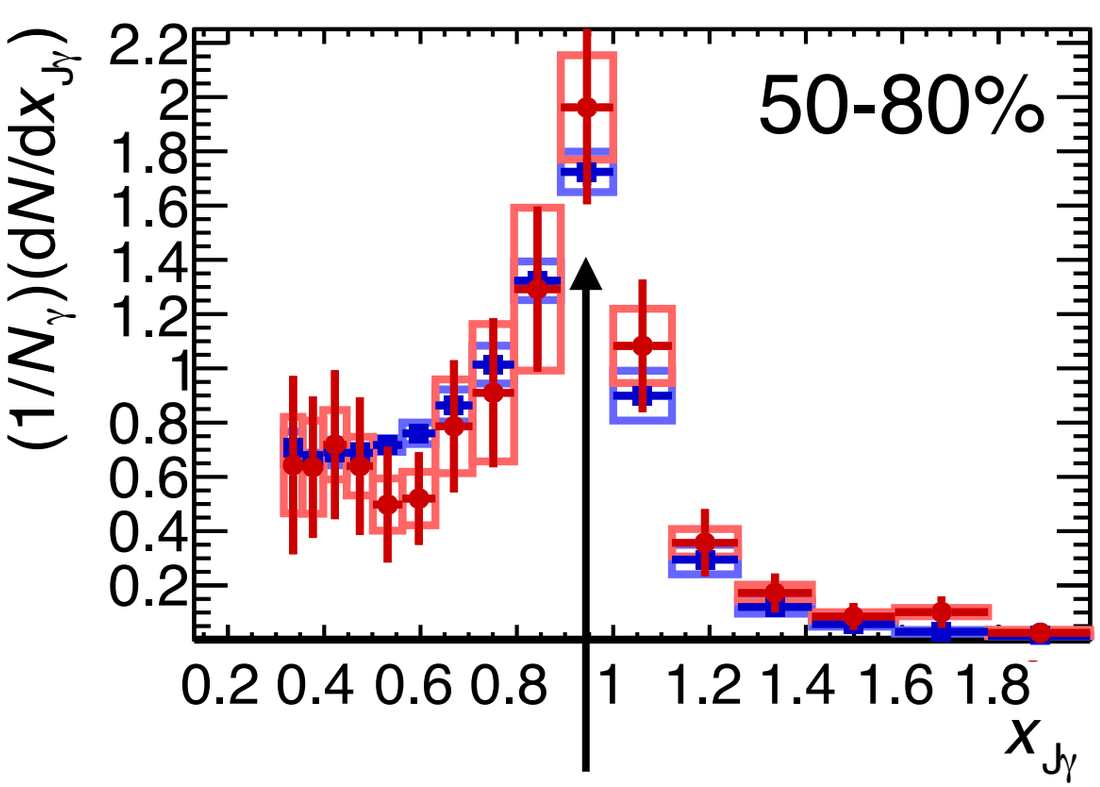
Where does the lost energy end up (angular and momentum modes)?

Photon+jet p_T balance

$$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$$

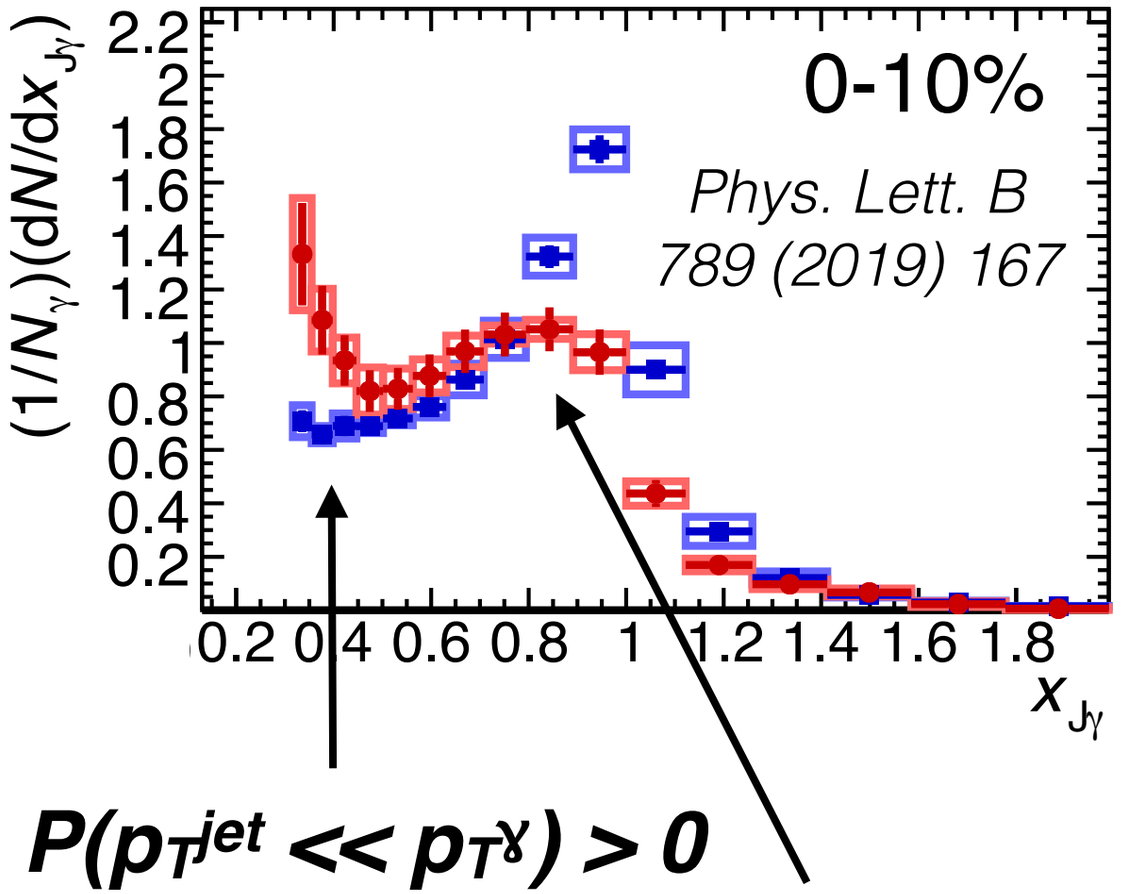
ATLAS
pp 5.02 TeV, 25 pb^{-1}
Pb+Pb 5.02 TeV, 0.49 nb^{-1}

p_T^{γ} = 100-158 GeV
pp (same each panel)
Pb+Pb



P($p_T^{jet} \sim p_T^{\gamma}$) = large

*in **50-80%** Pb+Pb events, sharp peak at $x_{J\gamma}$~1, as in **pp***

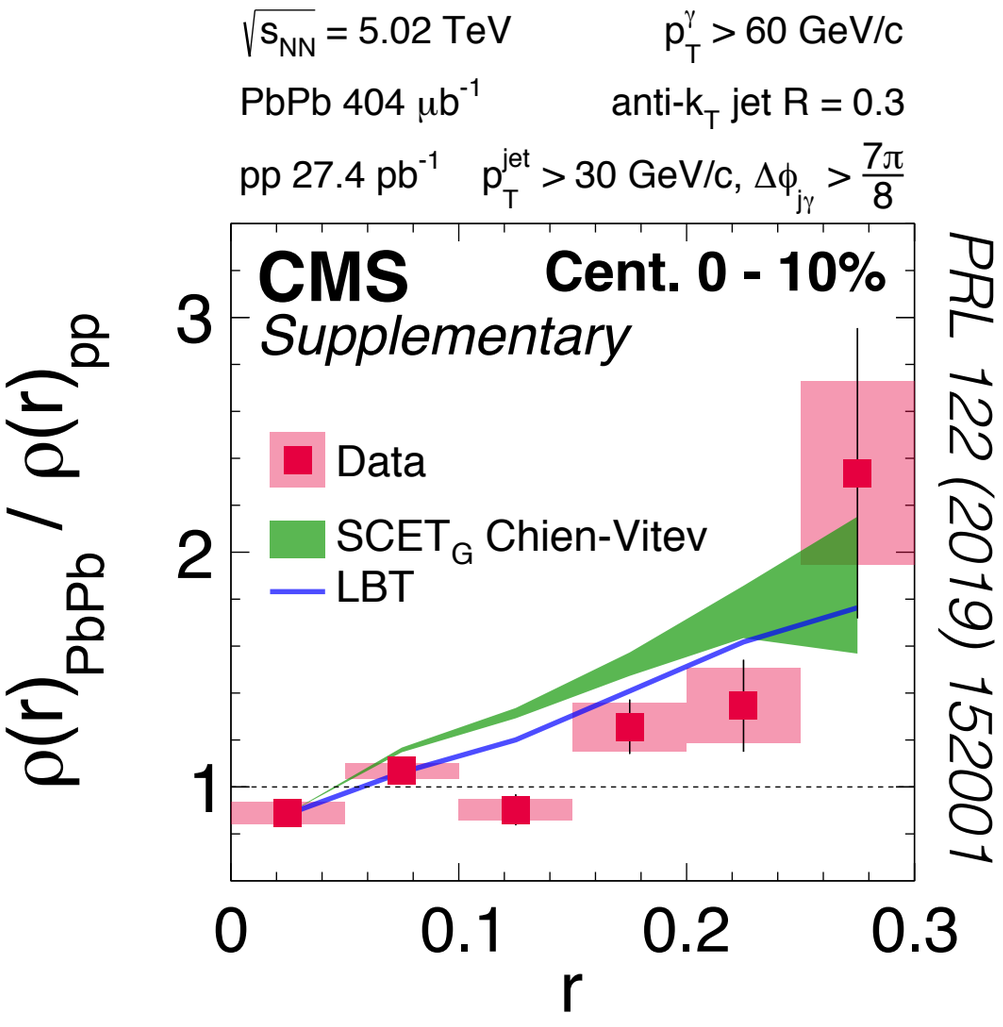


P($p_T^{jet} << p_T^{\gamma}$) > 0

P($p_T^{jet} \sim p_T^{\gamma}$) > 0

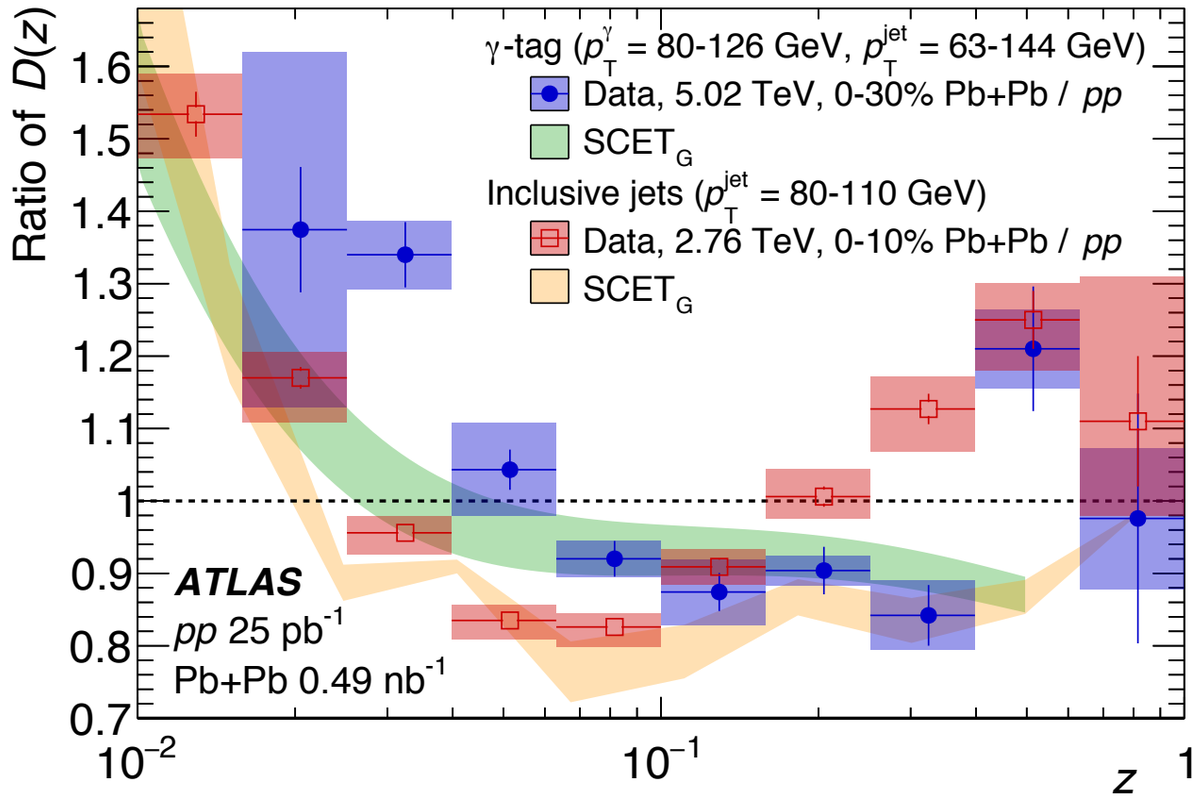
*in **0-10%** Pb+Pb events, distribution of outcomes!*

Photon-tagged jet structure



ratio of (radial) jet shape for photon-tagged jets

nucl-ex/1902.10007, in press PRL

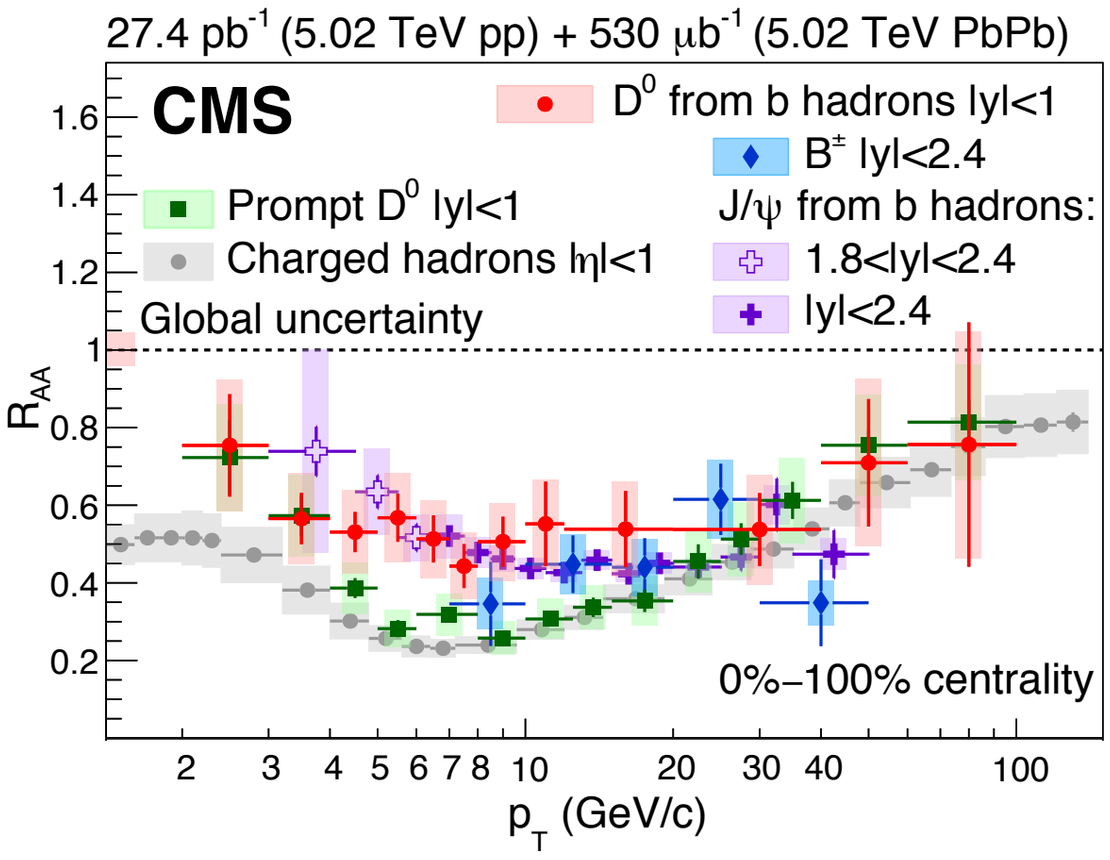


*compare photon-tagged (**quark**) and inclusive jet (**gluon**) frag function ratios*

test multiple aspects of theory: flavor difference, multiple momentum scales, etc.

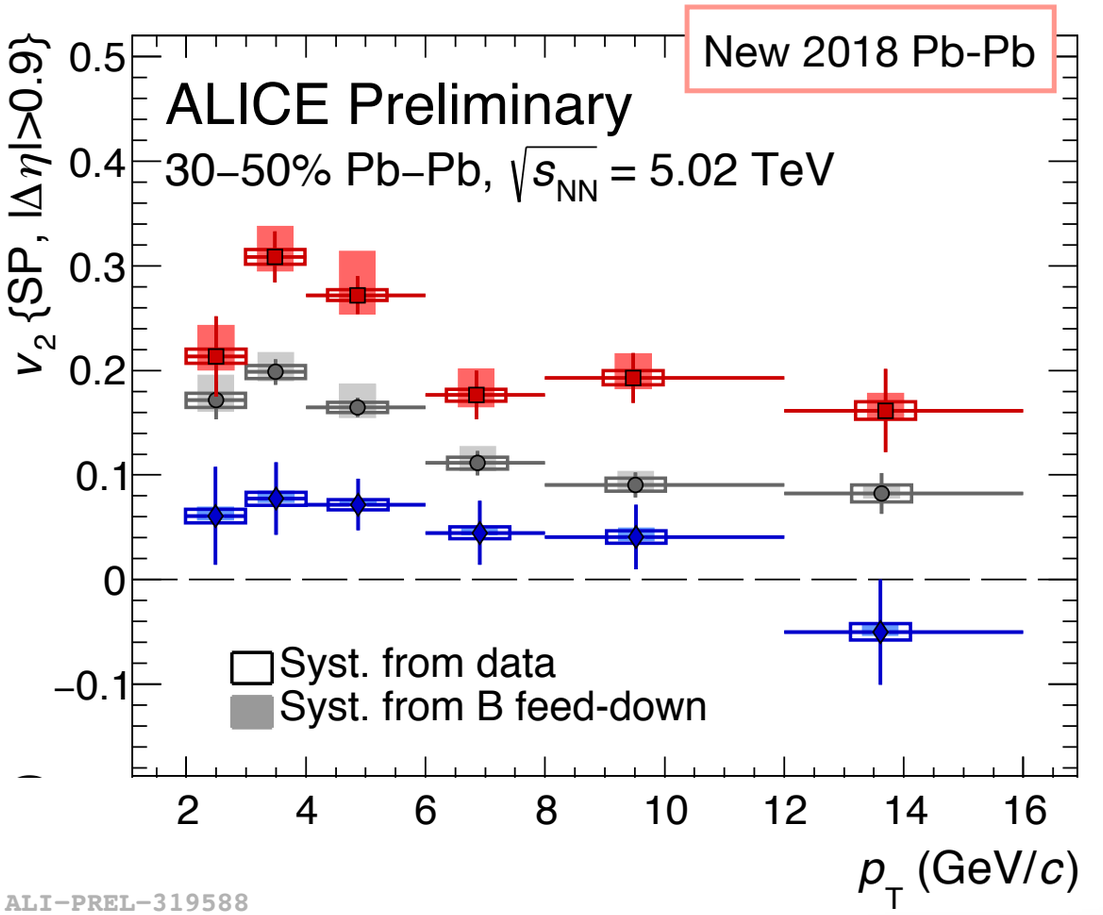
Heavy flavor probes

PRL 123 (2019) 022001

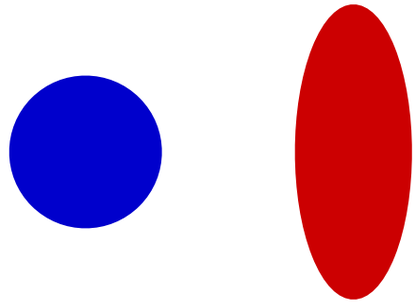


data compatible with physically intuitive ordering of E-loss:

light < charm < bottom



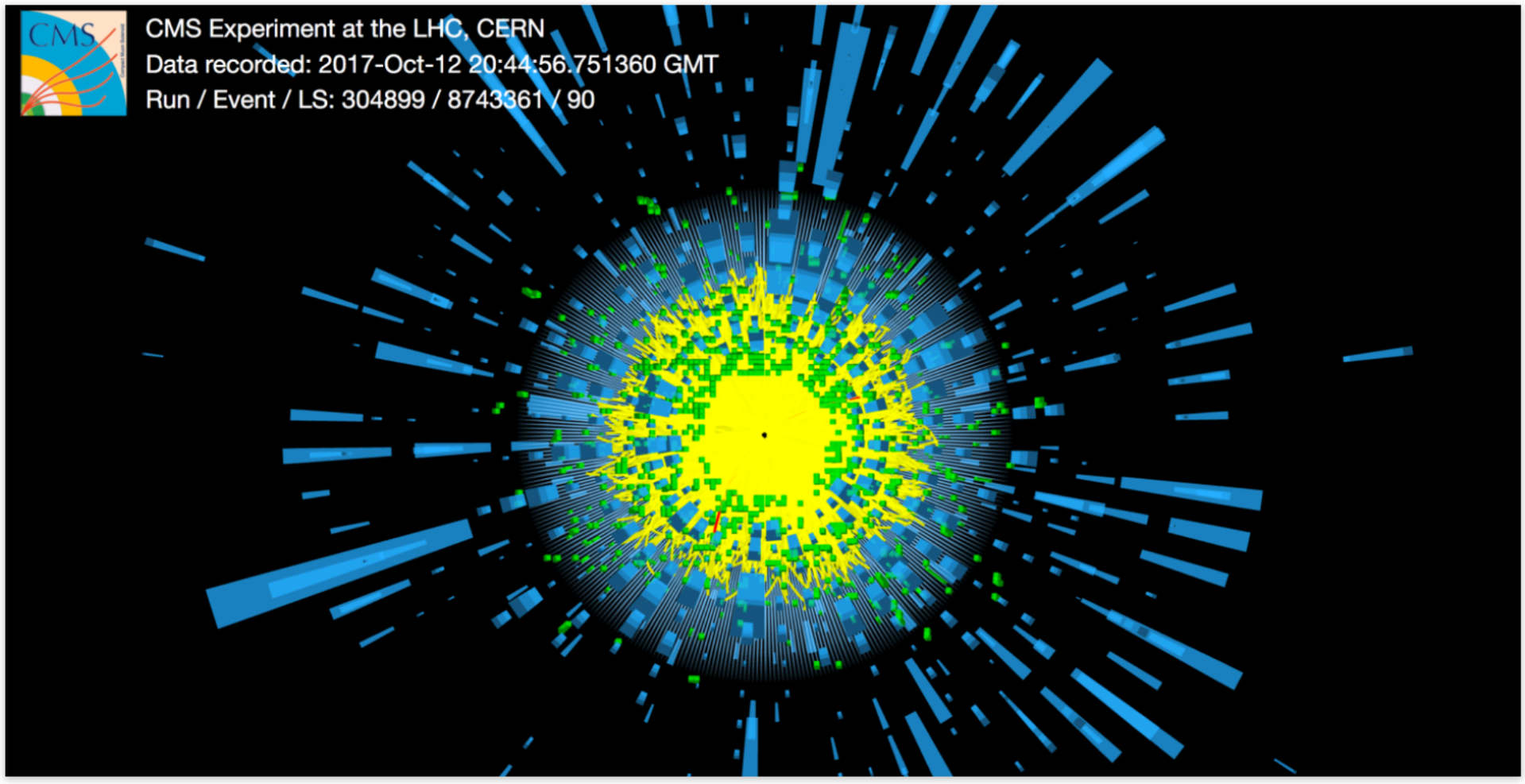
charm "feels the shape" of the QGP region



LHC report: xenon in action

The LHC had the unique opportunity of colliding xenon nuclei over several hours

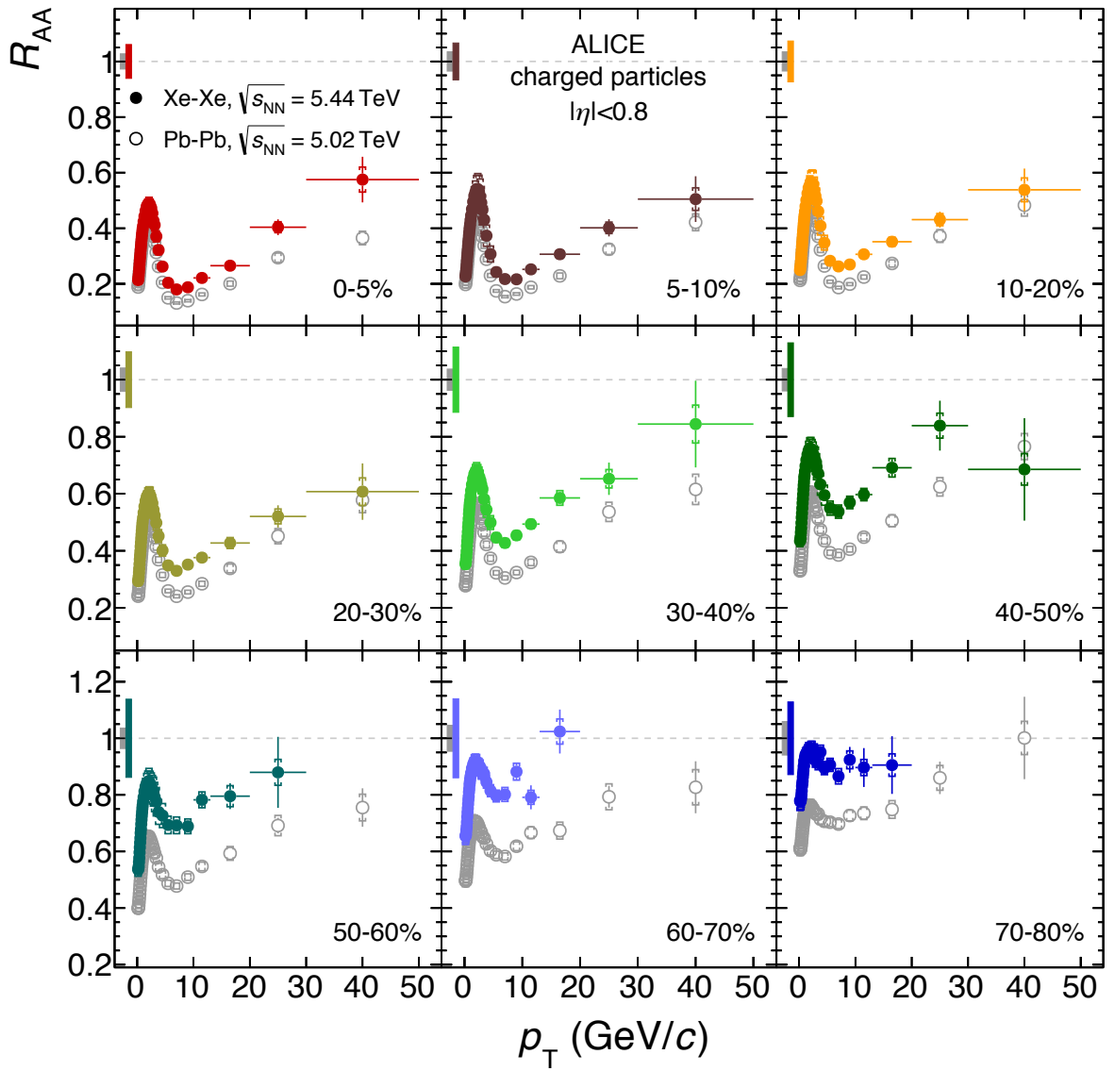
24 OCTOBER, 2017 | By Michaela Schaumann for the LHC team



One of the xenon ion collisions recorded by the CMS detector. (Image: CMS/CERN)

Change nuclear species: change QGP size/shape/ temperature — crucial lever arm for nuclear physics!

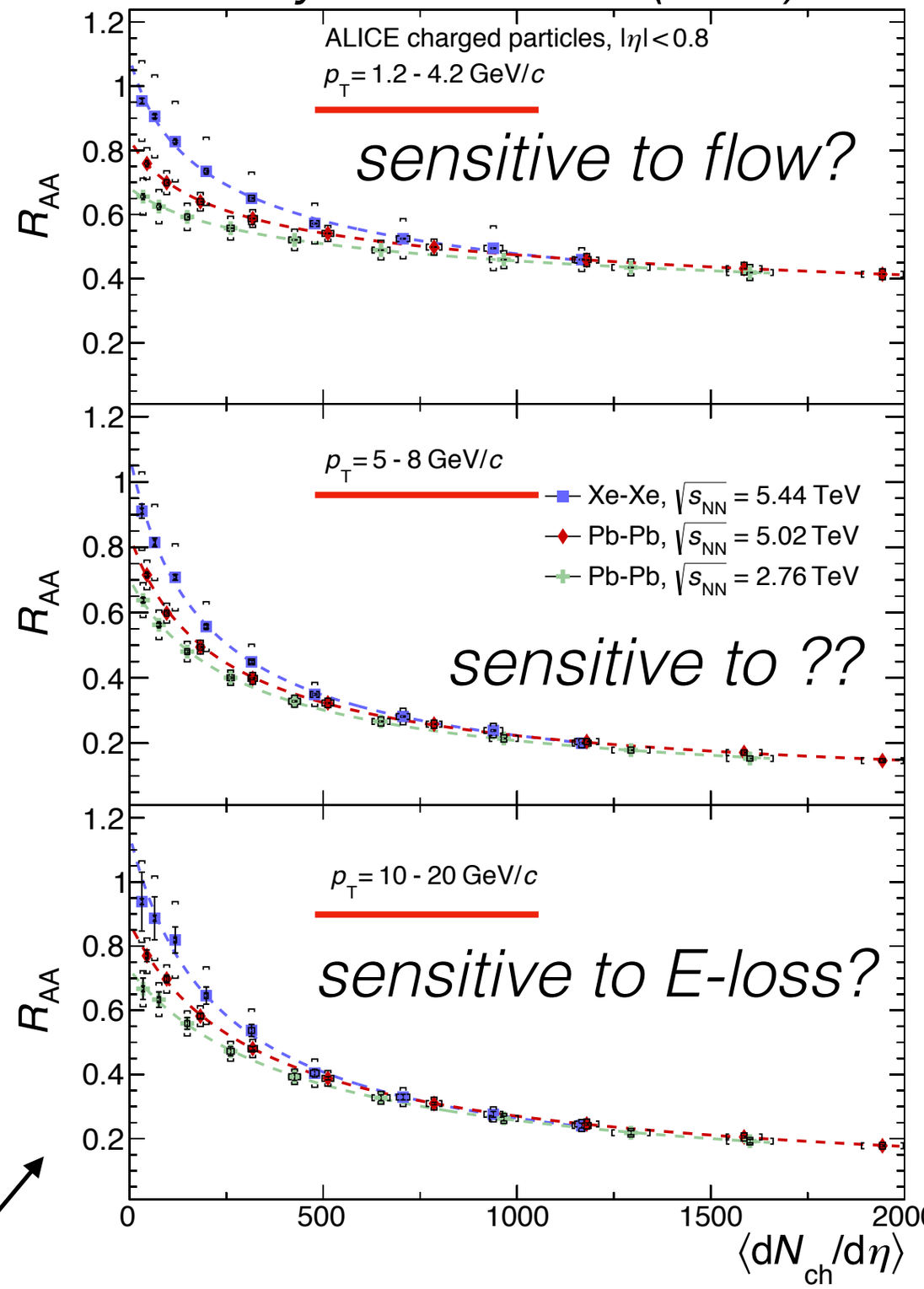
How does energy loss depend on system size?



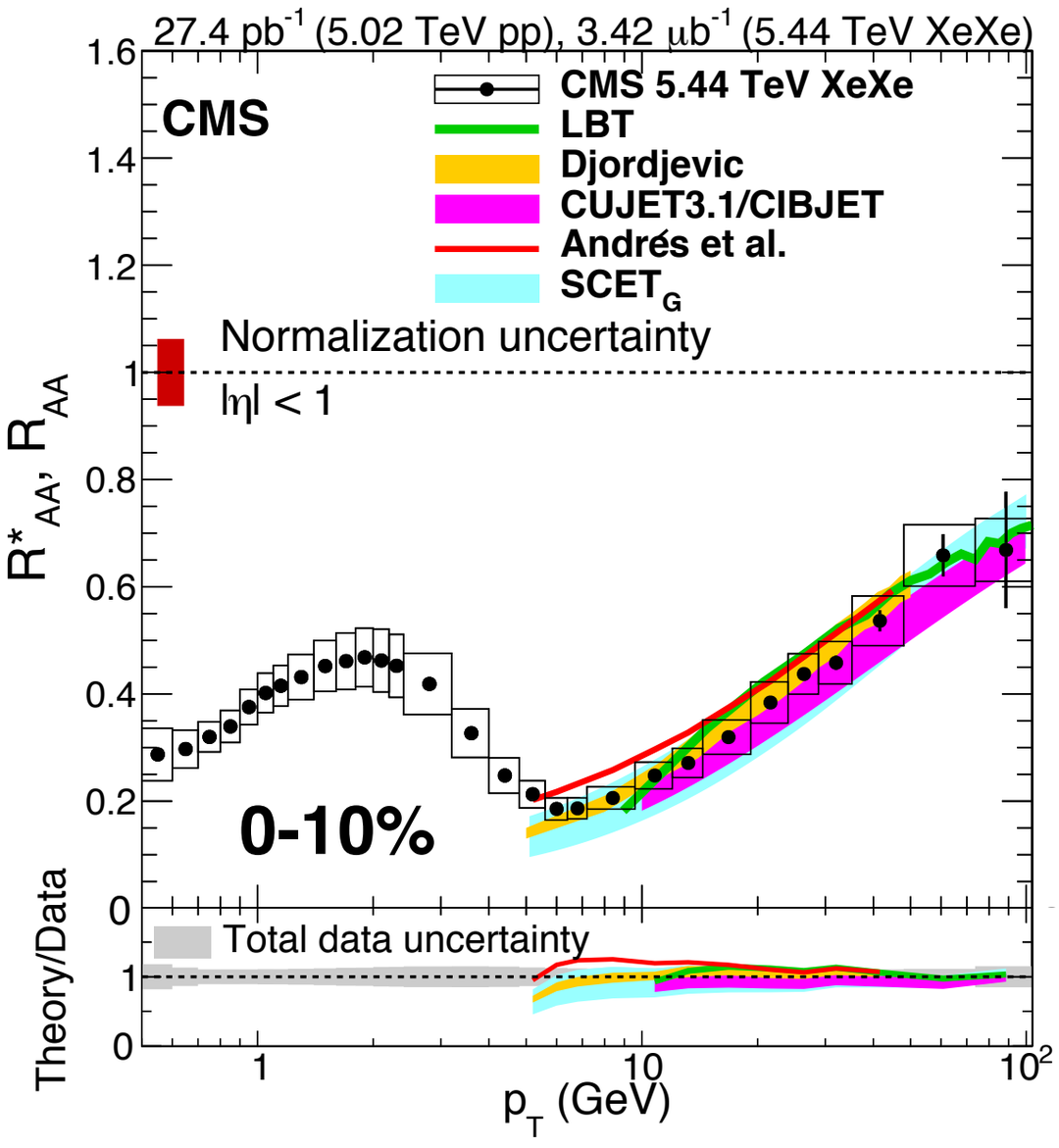
Obvious "non-scaling" in relative fractions of AA cross-section…

…select same (dN/dη) range — i.e. similar εL^2 (radiative E-loss?)

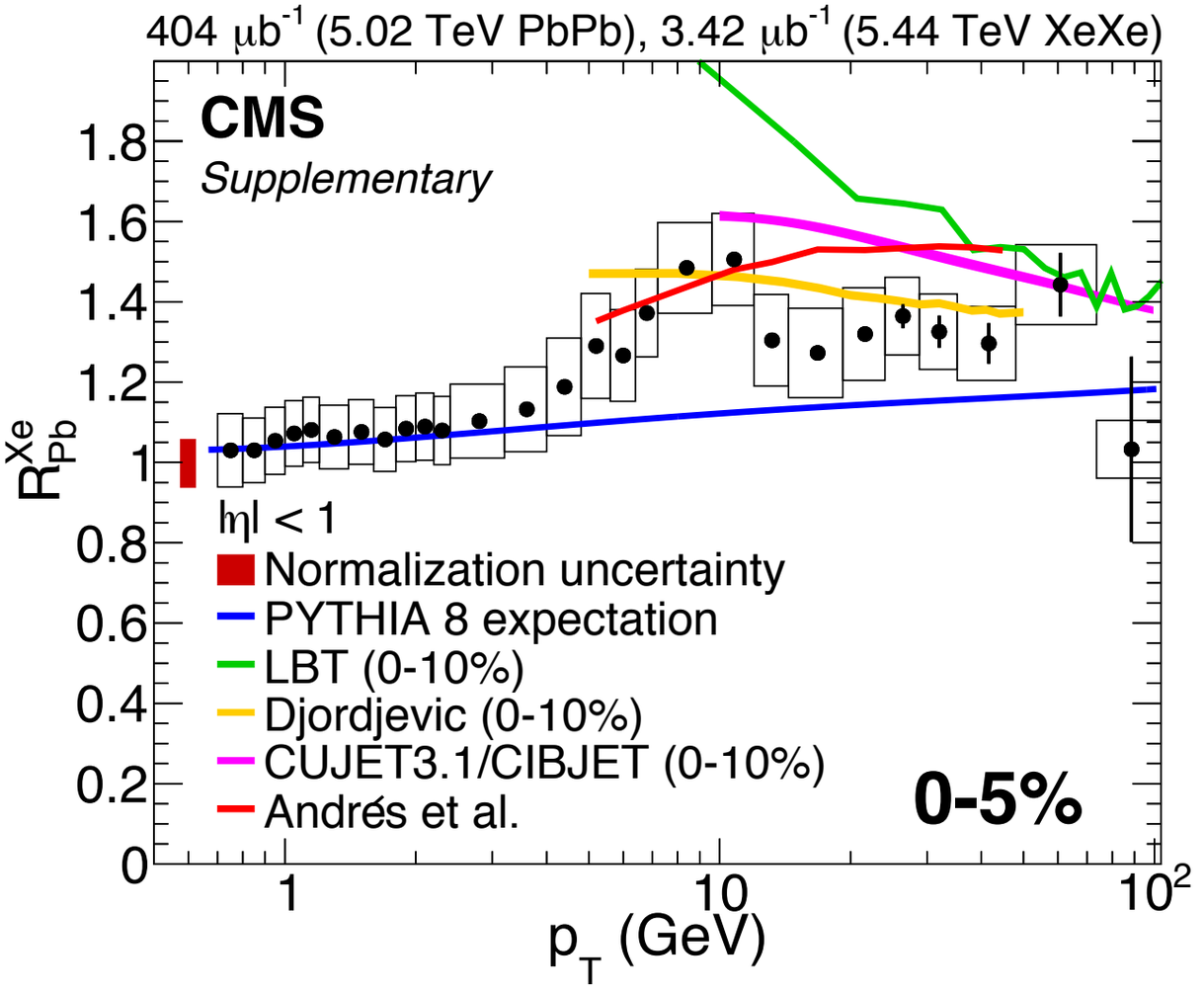
Phys. Lett. B 788 (2019) 166



Impact on theory comparisons…



At a glance, good matching to theory models…



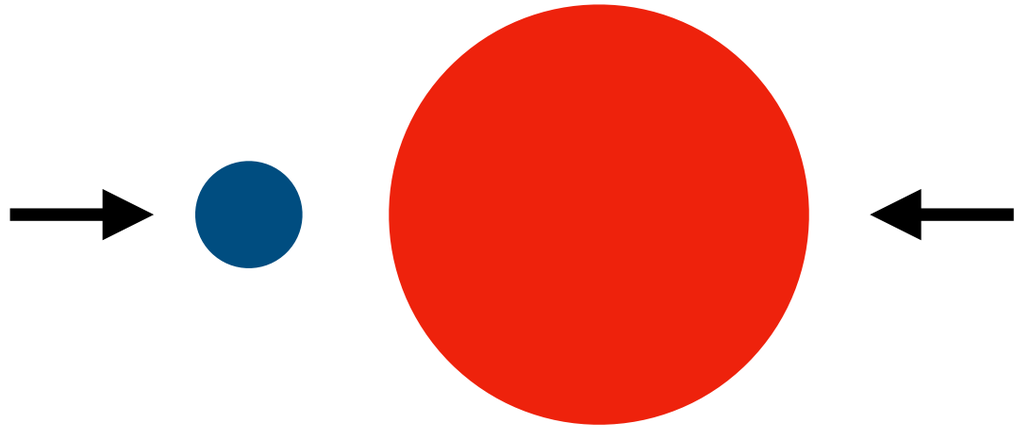
Cancel common data & theory uncertainties in the Pb/Xe ratio…

… better extract temperature / path-length dependence of E-loss

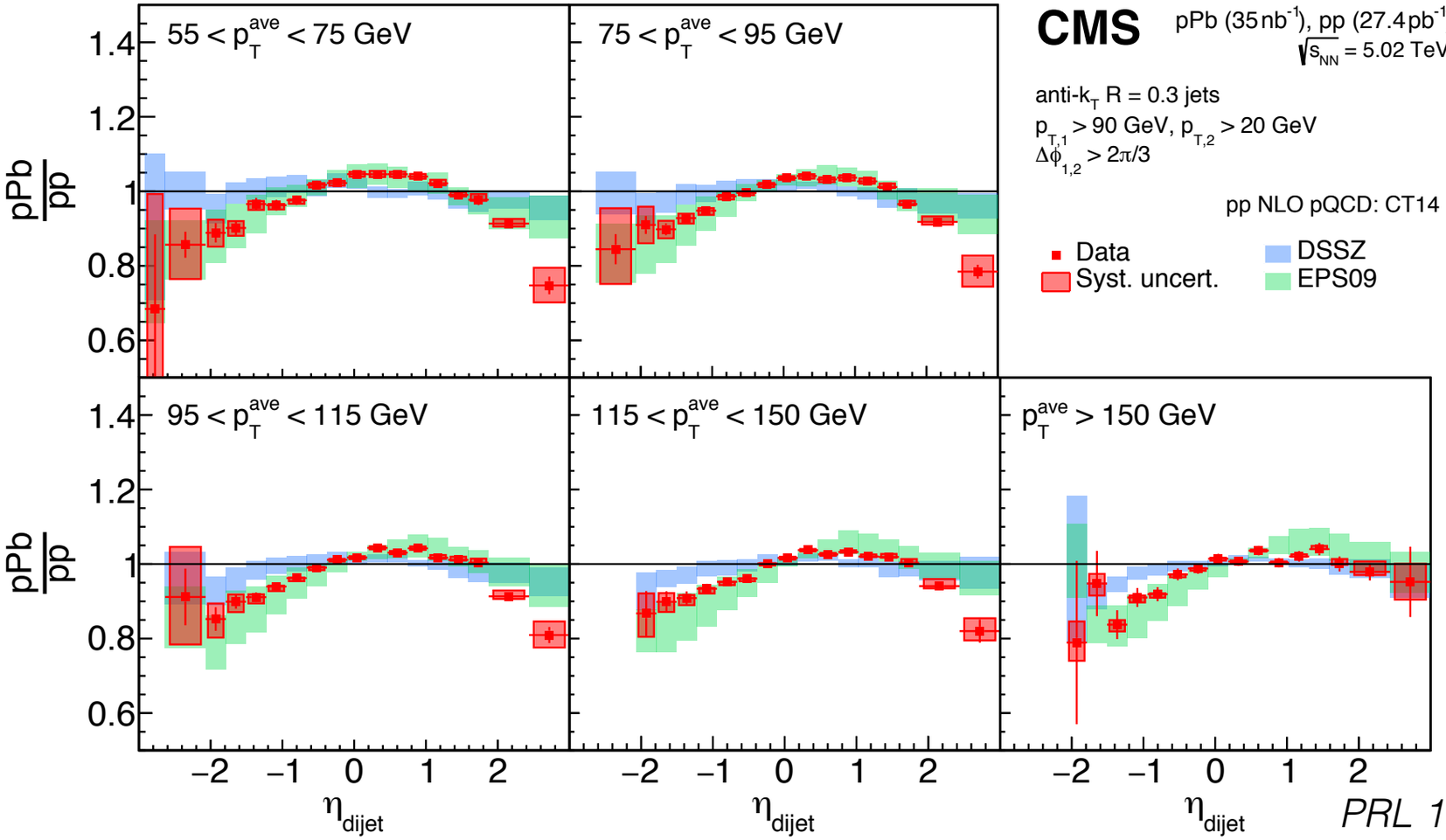
not shown: ATLAS dijet p_T balance, anisotropic flow measurements

How does the nucleus affect hard processes *before QGP effects*?

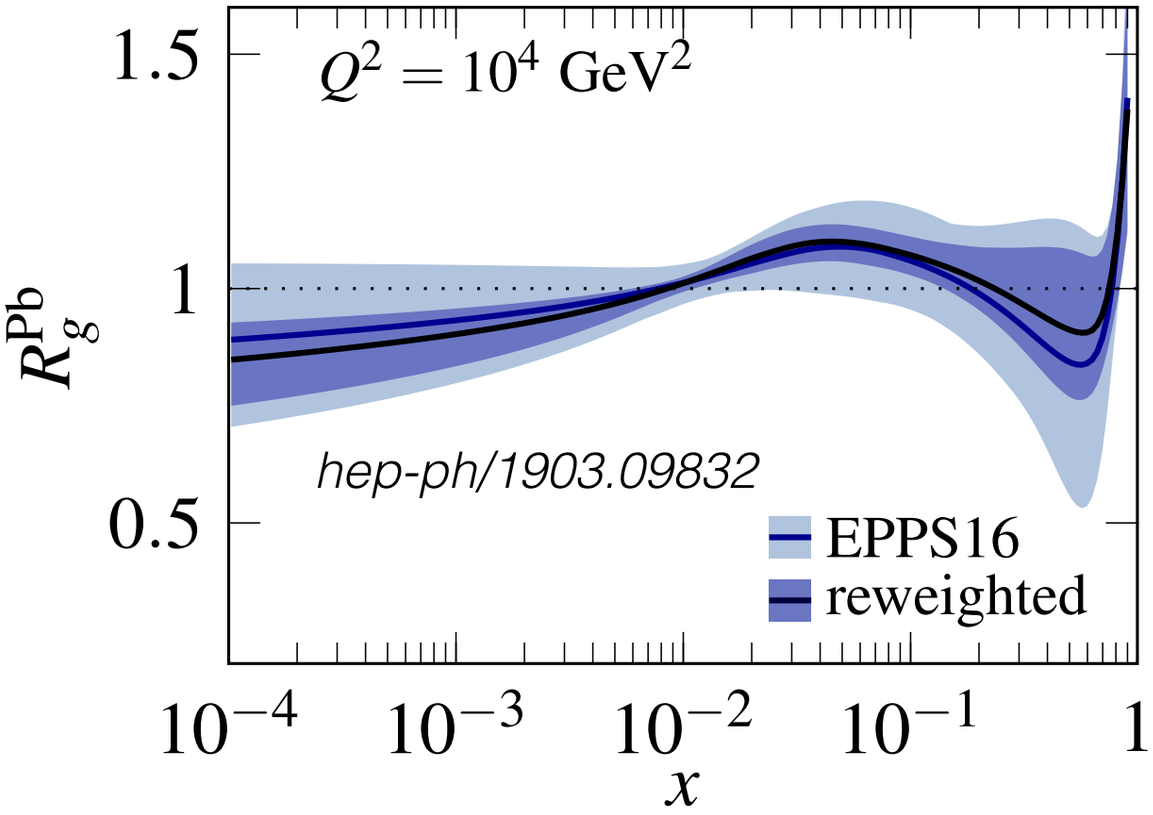
⇒ *test in p+Pb collisions*



Run 1 p+Pb/pp ratios of dijet-η, bins of p_T^{avg}

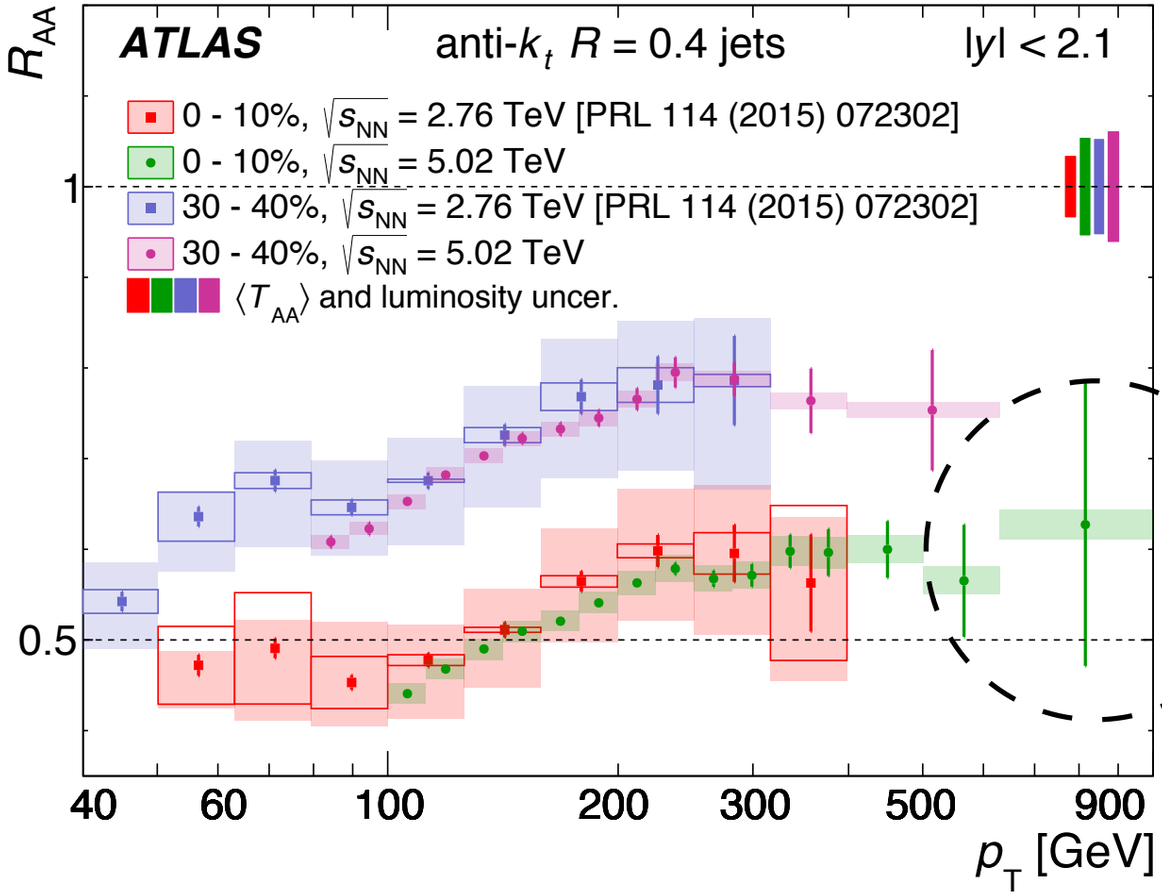


PRL 121, 062002 (2018)



Input for universal "nuclear-PDF" picture

impact of Run 1 dijet data on nPDF modification for gluons

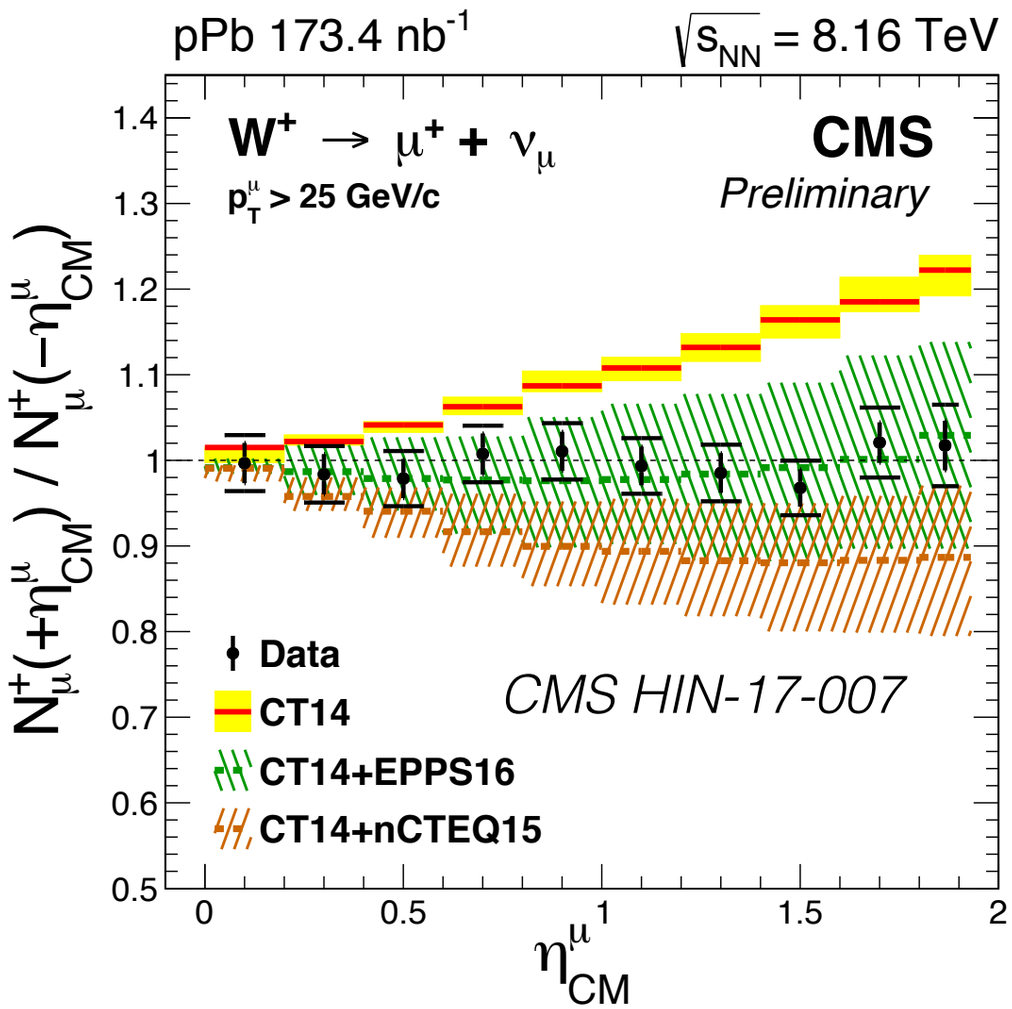


Information on "cold" nuclear effects before "hot" quenching

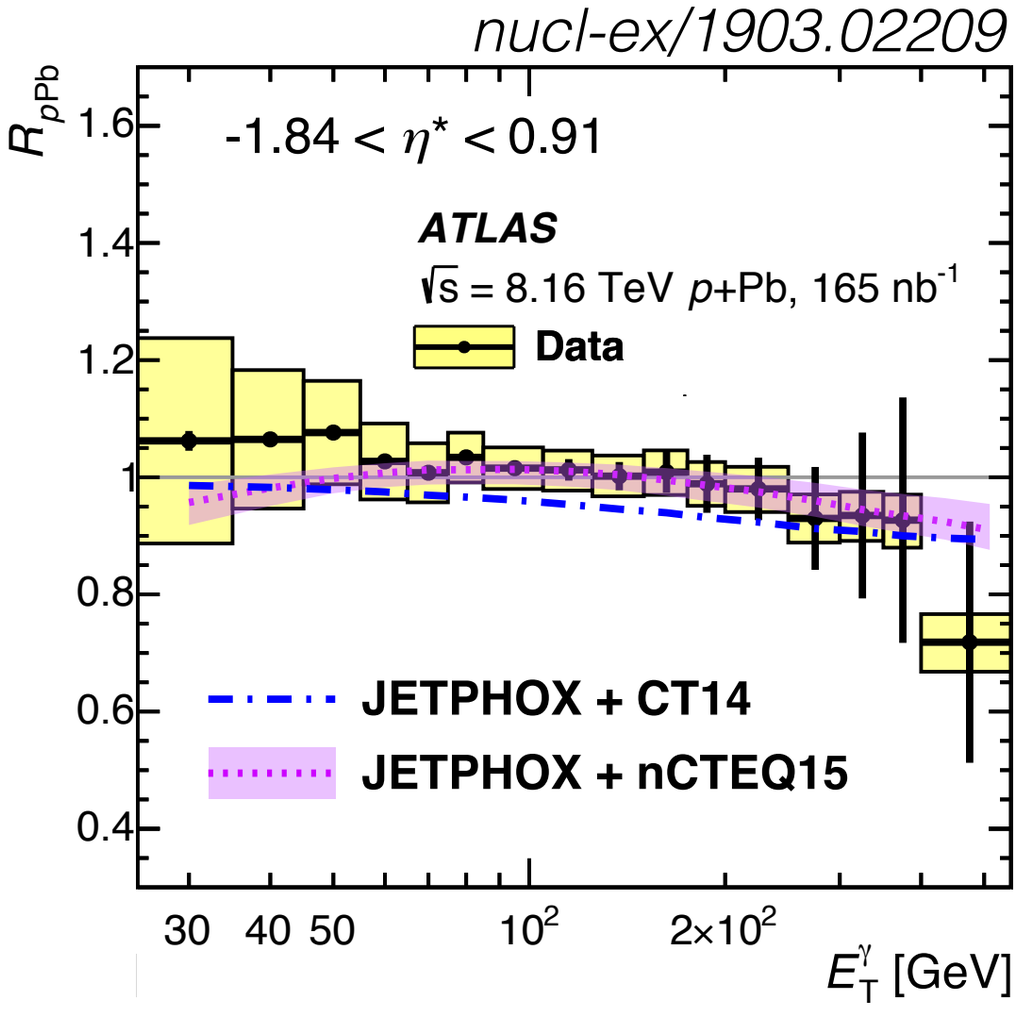
large-x EMC effect region!

Phys. Lett. B 790 (2019) 108

EW probes in Run 2 *p*+Pb 8.16 TeV



Forward/backward ratios of W production



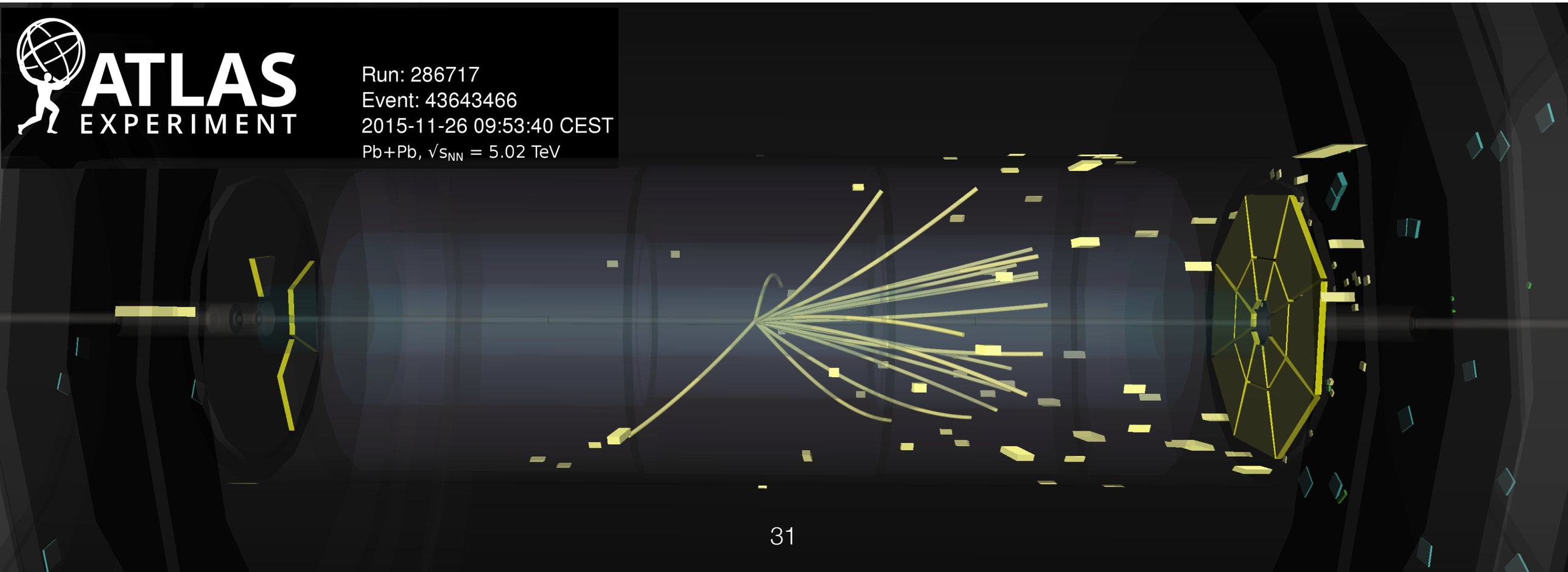
p+Pb/pp ratio of isolated γ production

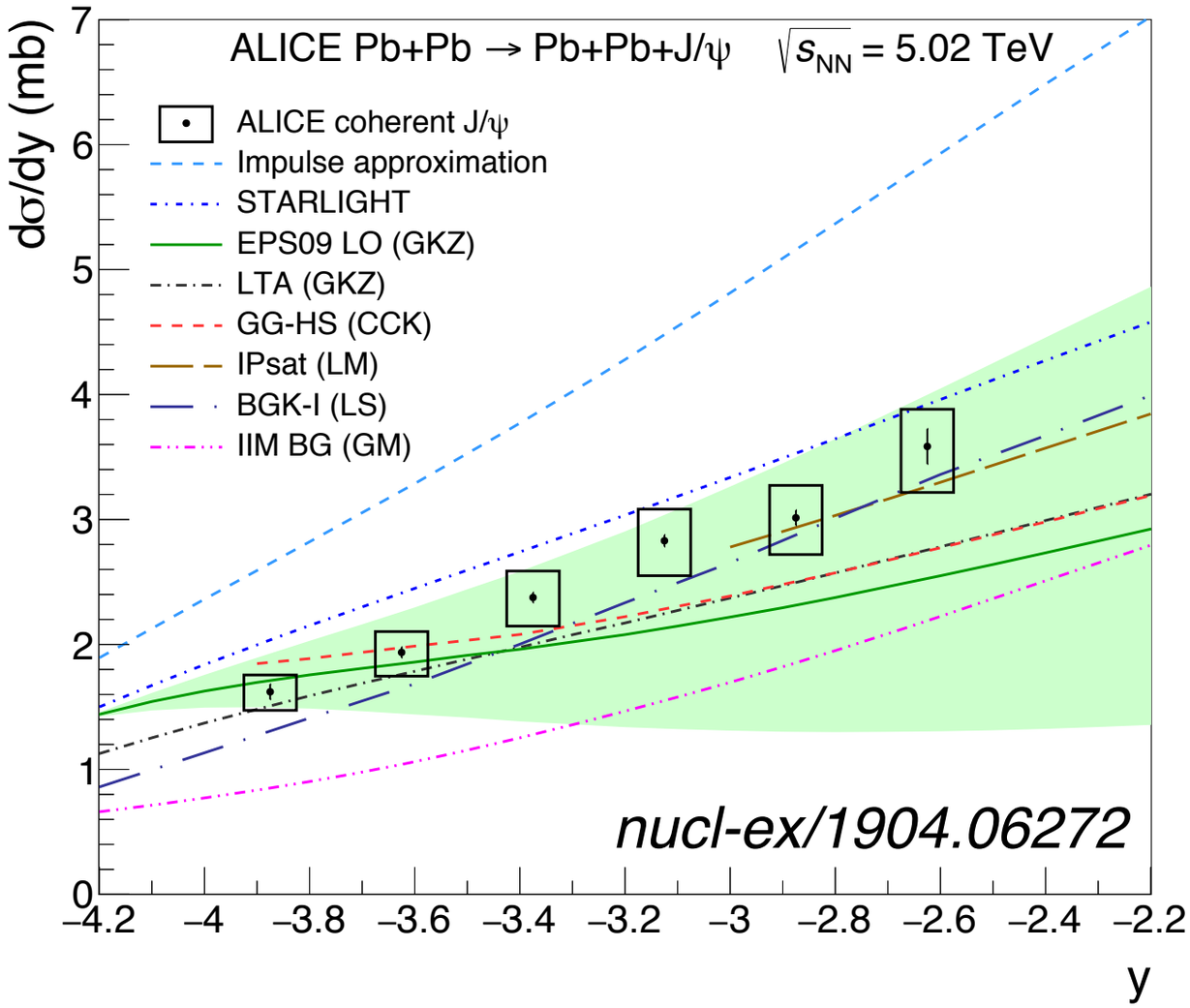
Ultra-peripheral processes

- EM interactions with nuclei separated, such as light-by-light scattering
- Photo-nuclear (γ+A) interactions:

  ➡ significantly cleaner environment than *p*+Pb

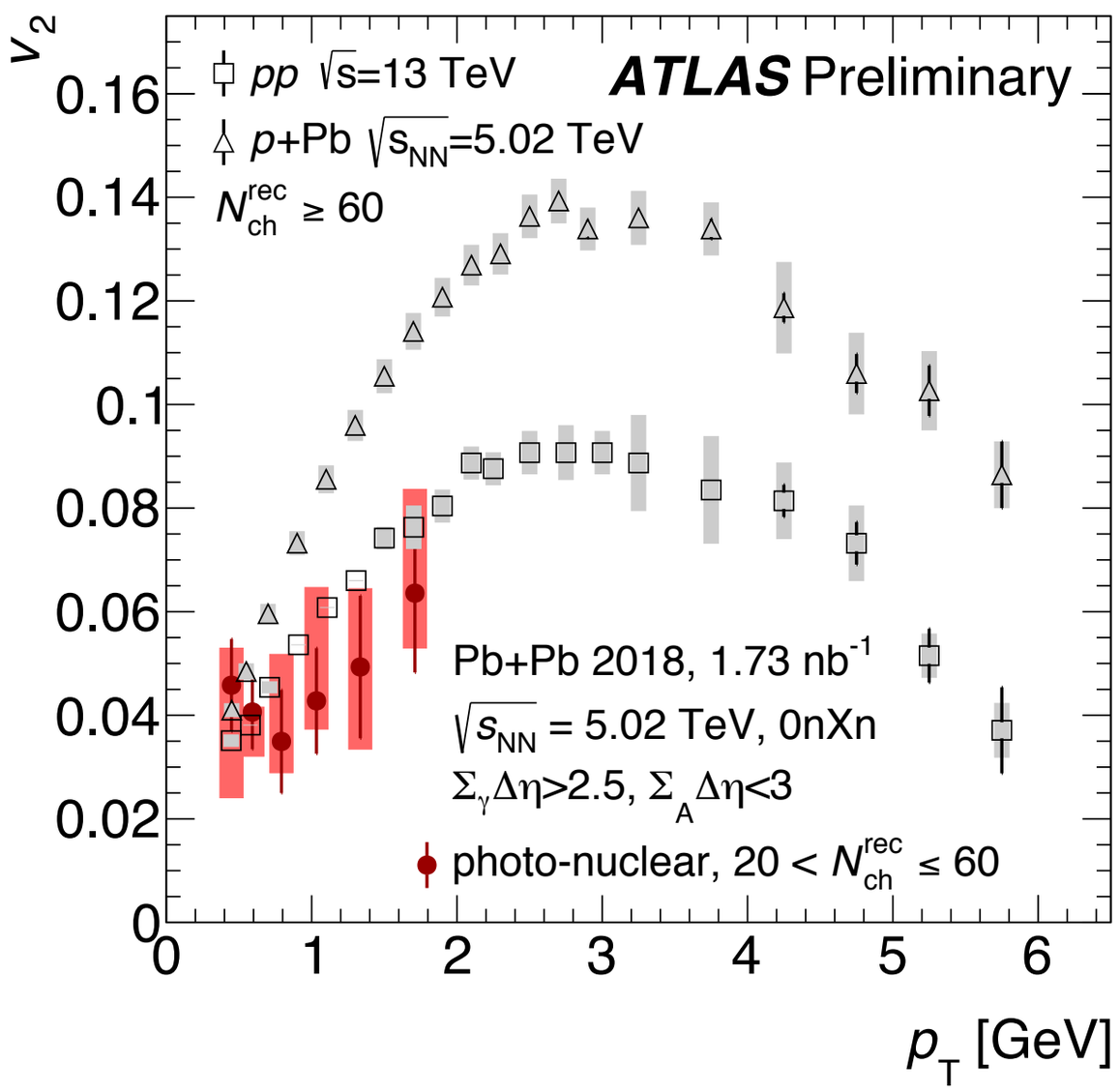
  ➡ opportunity to do some “nuclear-DIS”-like physics before LHeC/EIC





Coherent photo-production of J/ψ as probe of nuclear gluon content

(see also: photo-nuclear dijets in ATLAS, Upsilon in CMS, far forward J/ψ in LHCb)

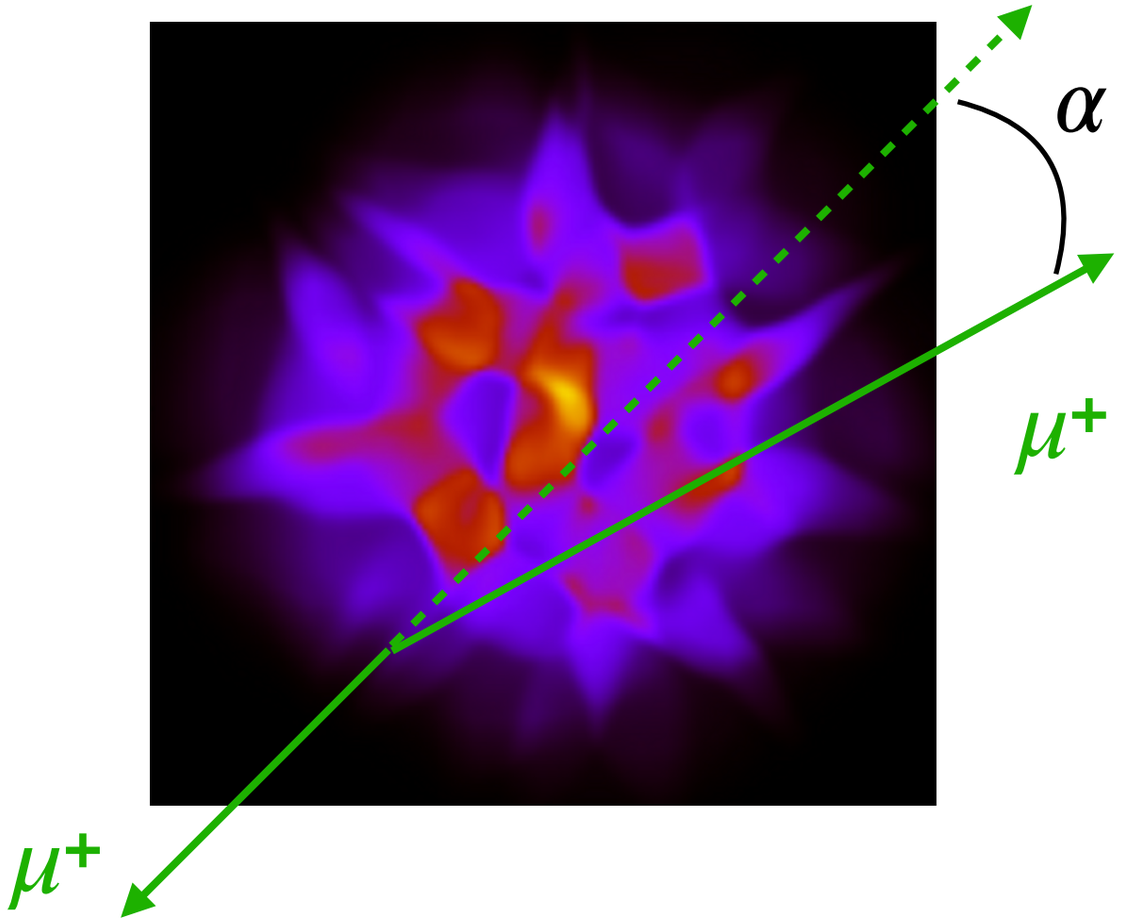


symmetric "ridge" in high-multiplicity **γ+A** *events! Interpreted here as v_2…*

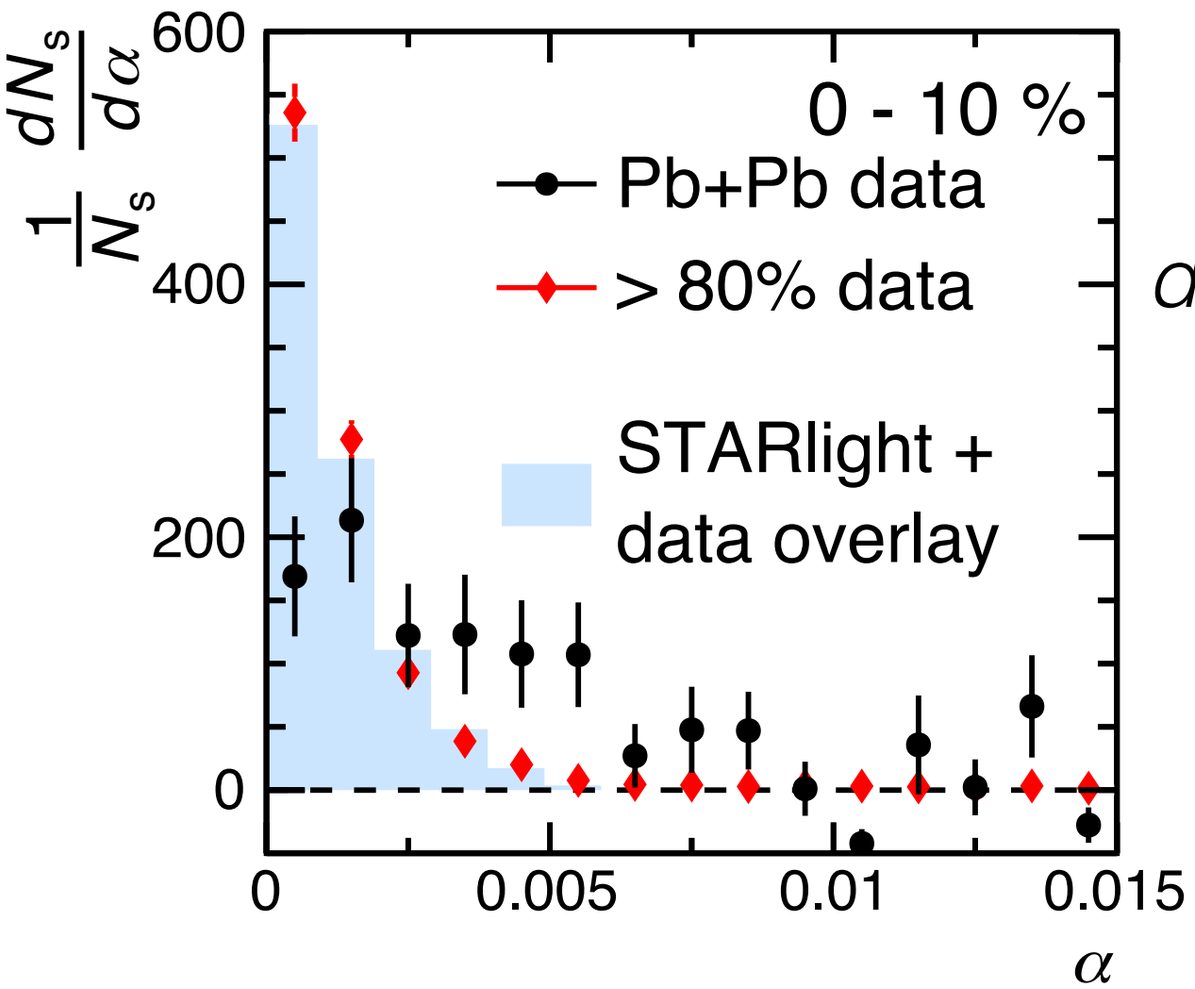
…QGP-like signatures even in lower-energy ρ+A collisions?

Electromagnetic processes still occur <u>even if</u> nuclei overlap

Recent interest in $\gamma\gamma \rightarrow \ell^+\ell^-$ *as probe of the <u>QED</u> content of QGP*



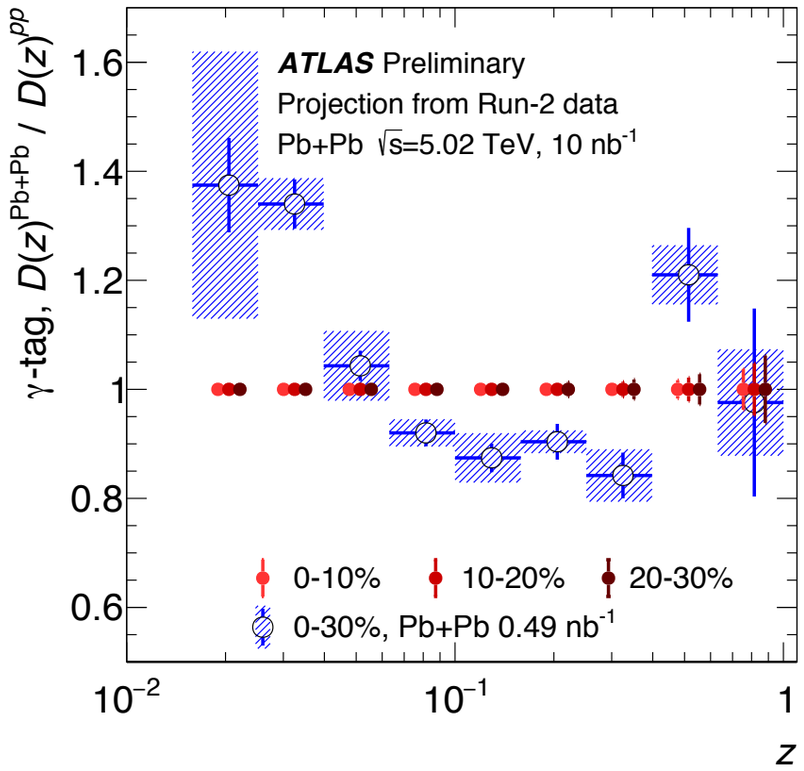
PRL 121, 212301 (2018)



di-muons balanced in ***UPC events****…*

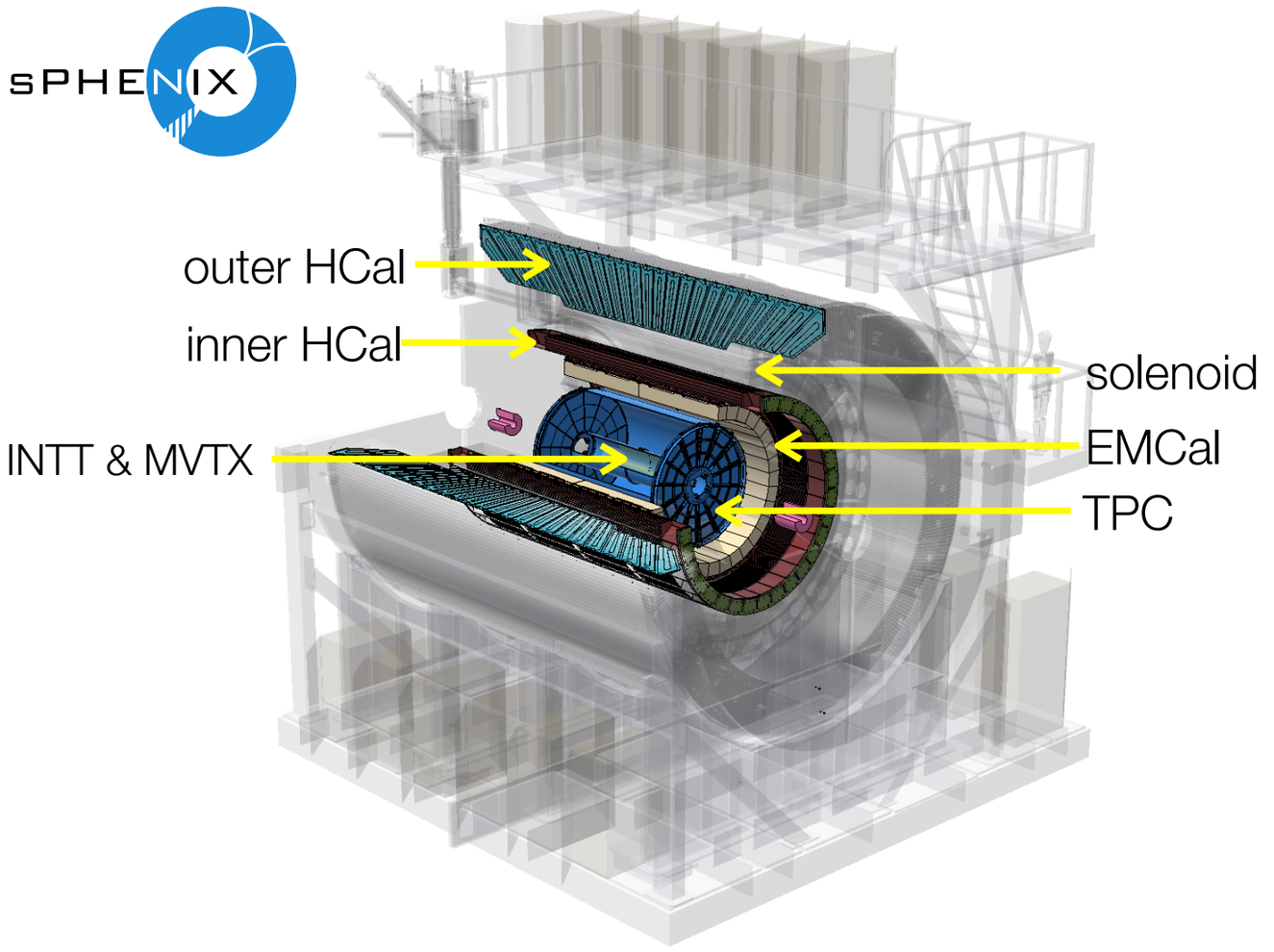
…but acquire ***an acoplanarity*** *when passing through the deconfined quarks of QGP*

Future hard probes of QCD matter



HL-LHC WG5 report for HI physics opportunities in Run 3+4:

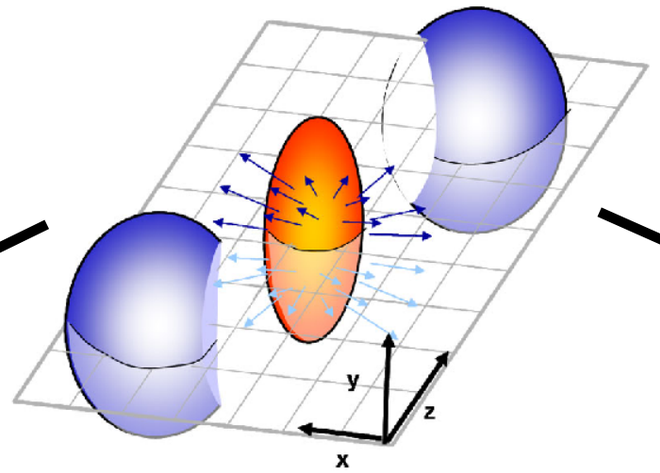
Higher luminosity, detector upgrades, smaller collision systems



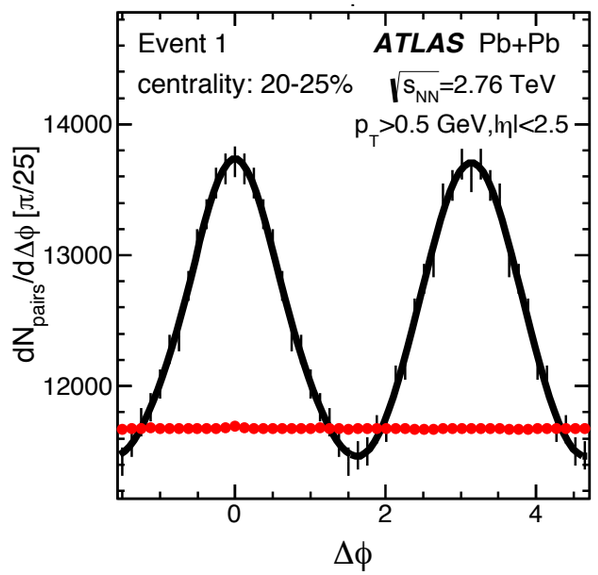
sPHENIX @ RHIC: dedicated "LHC-style" jet detector in early 2020's

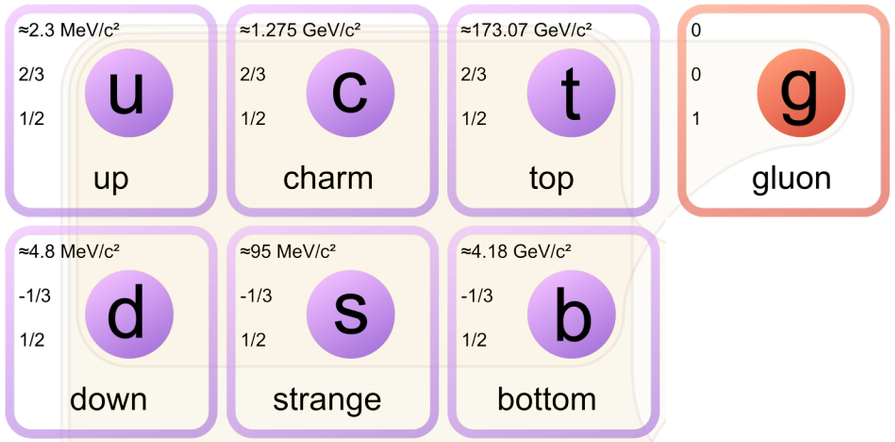
Complementary scientifically (colder QGP, smaller UE) and technically (uses copy of ALICE ITS upgrade)

emergent near-perfect fluidity

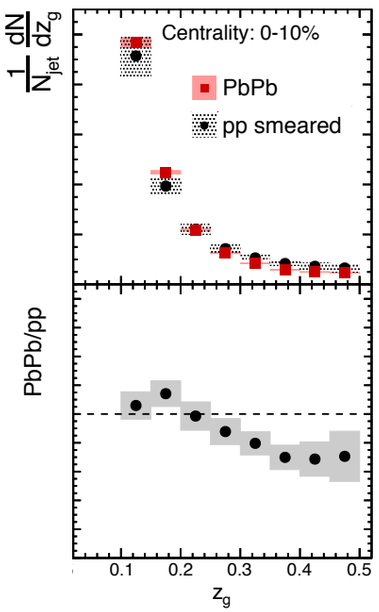


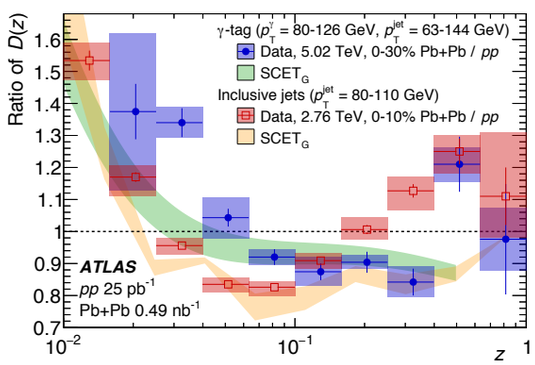
fundamental interaction & degrees of freedom exactly known

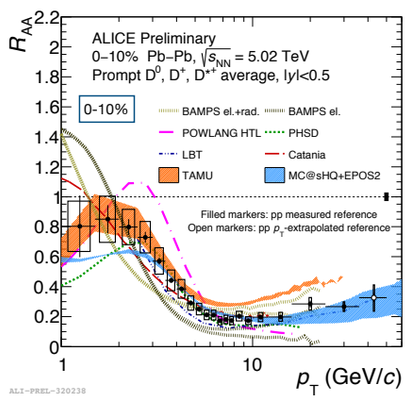


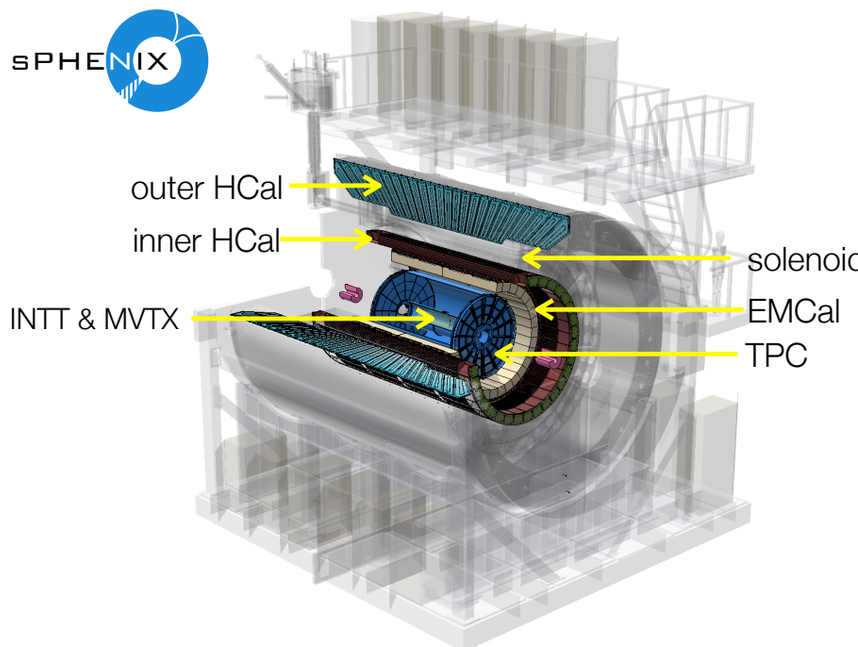


QGP









(sub)structure *EW+jet* *heavy flavor* *future probes*