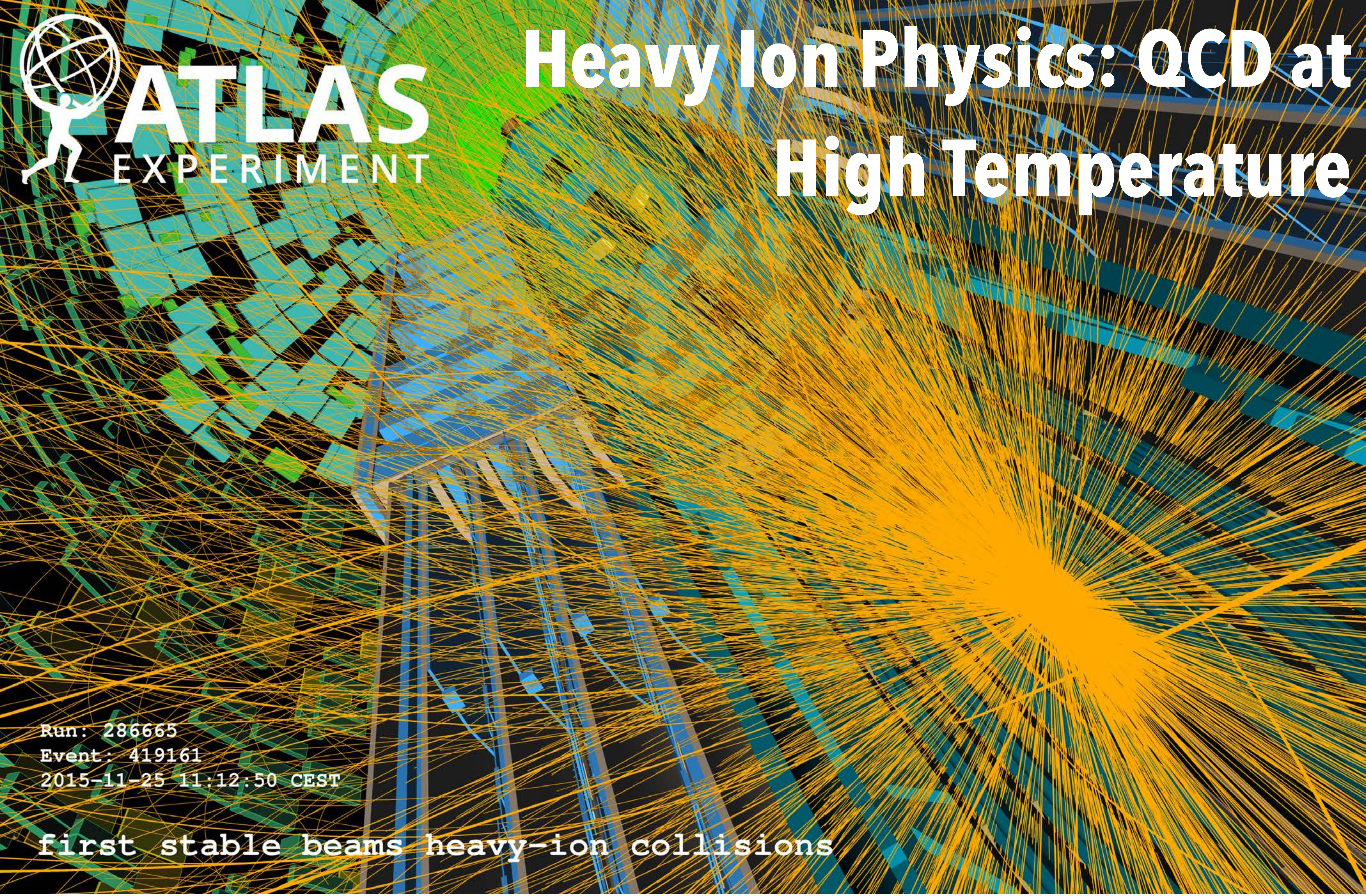
Heavy Ion Physics: QCD at High Temperature



ILLINOIS
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Anne M. Sickles

July 10-12, 2019

a couple of points to keep in mind

- goal: get across the main physics questions and the tools we have for answering them
- therefore, these lectures are not comprehensive
  - the details (many of which are omitted) are important and are only understood by critically reading the literature and asking questions
    - I have included the references with the slides, I will also provide a list of useful review articles at the end
- I am an experimentalist with the ATLAS and sPHENIX experiments

read the papers! what are the assumptions in the calculations? what is actually measured? how is it measured?

please ask questions during the talks!

Large Hadron Collider @ CERN

collide pairs of lead nuclei at
5 TeV / nucleon pair center of mass collision energy

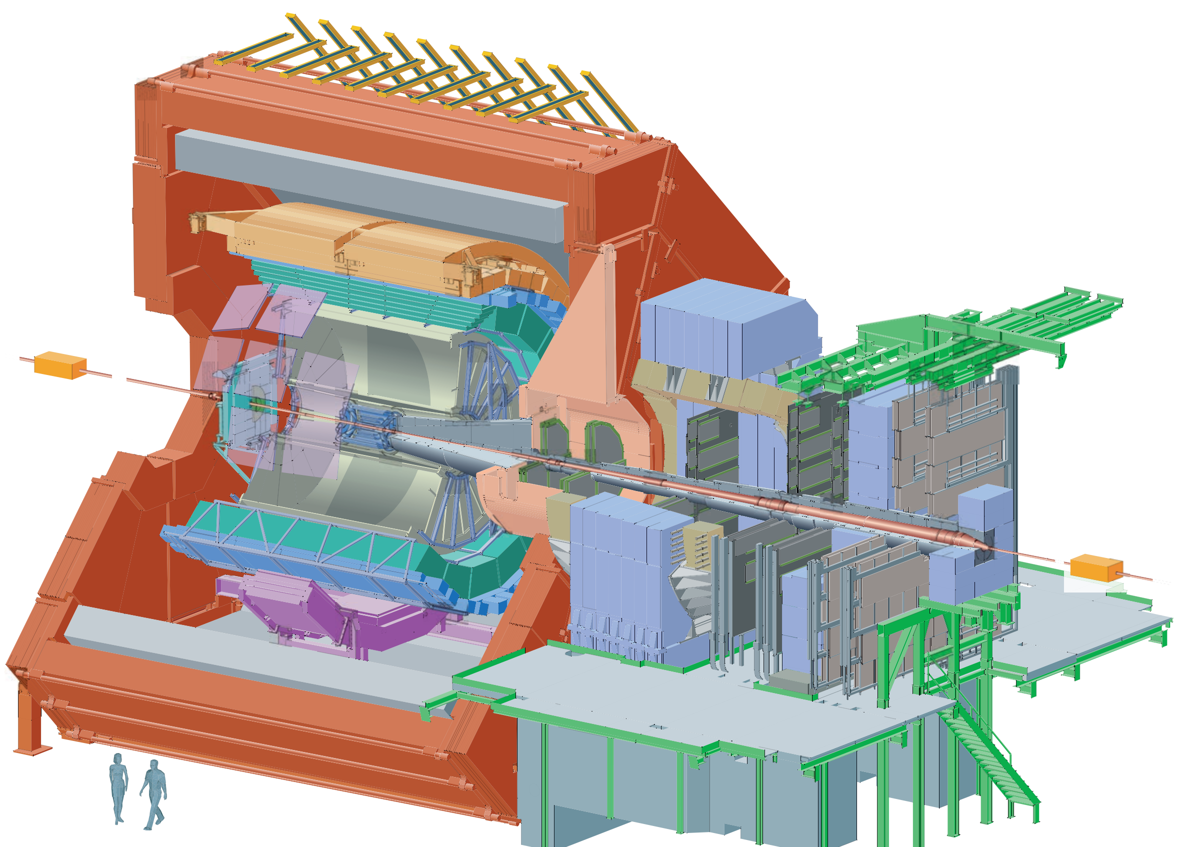
different data than the high energy LHC program but the same experiments are used

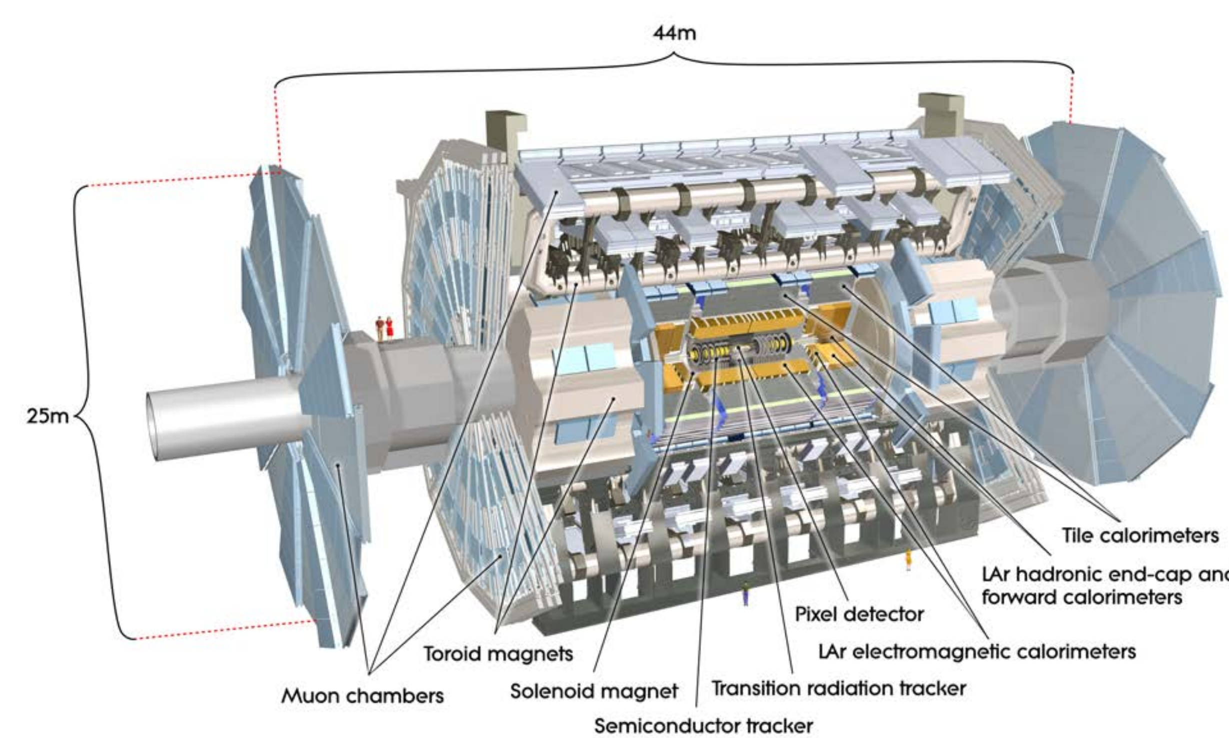
~1 month / year of data

~70 of the 3000 ATLAS authors work directly on this physics
more in CMS, lots more in ALICE and less in LHCb

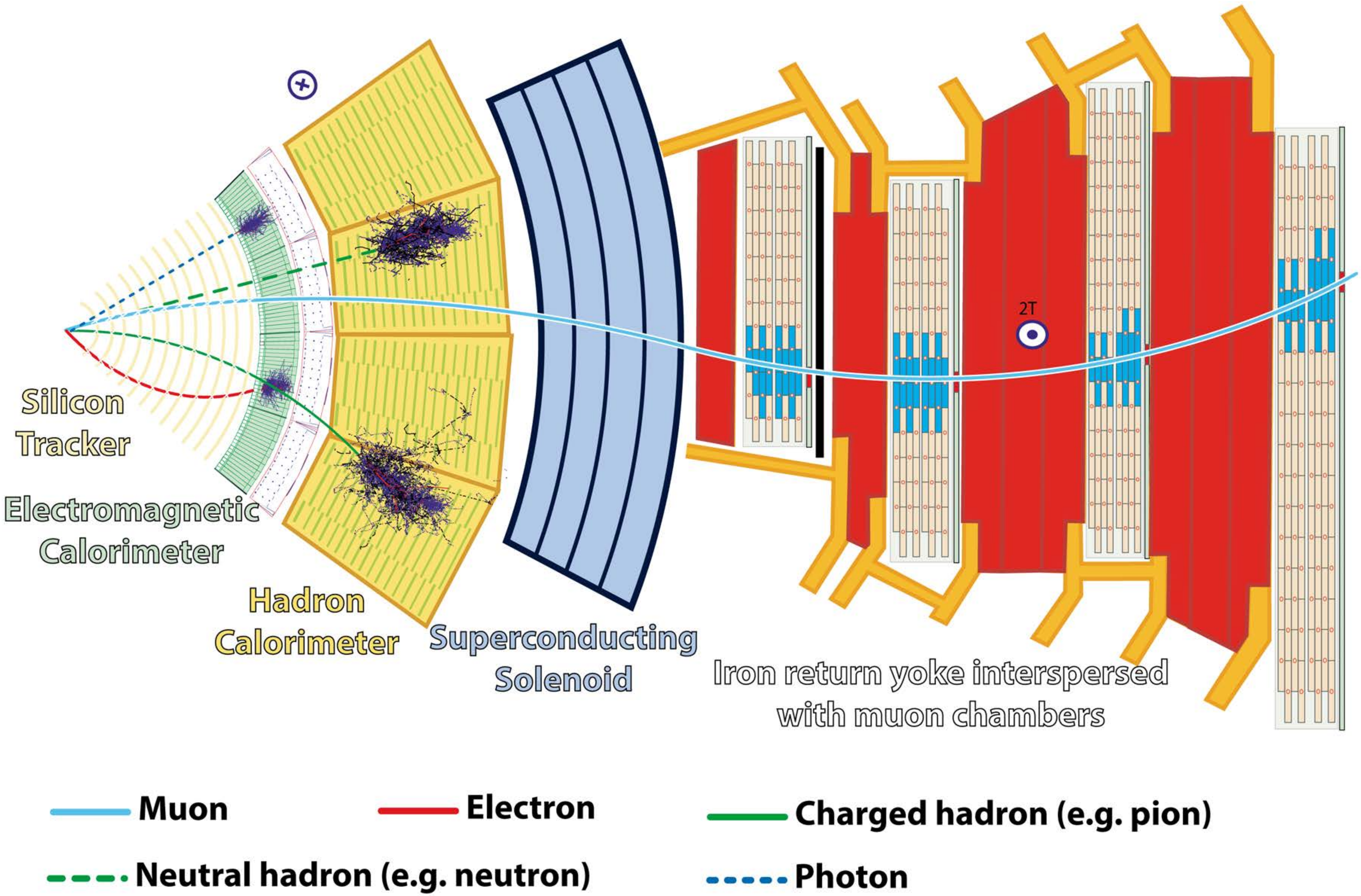
LHC experiments

- ATLAS & CMS: optimized for high energy physics, but suitable for many heavy ion measurements
  - emphasis on calorimetry and silicon tracking
- ALICE: designed for heavy ion measurements
  - emphasis on particle identification and tracking measurements
- LHCb: specialized detector with some HI physics (not discussed here)
- complementary approaches increase physics coverage
- O(1000) person collaborations





a trip through CMS

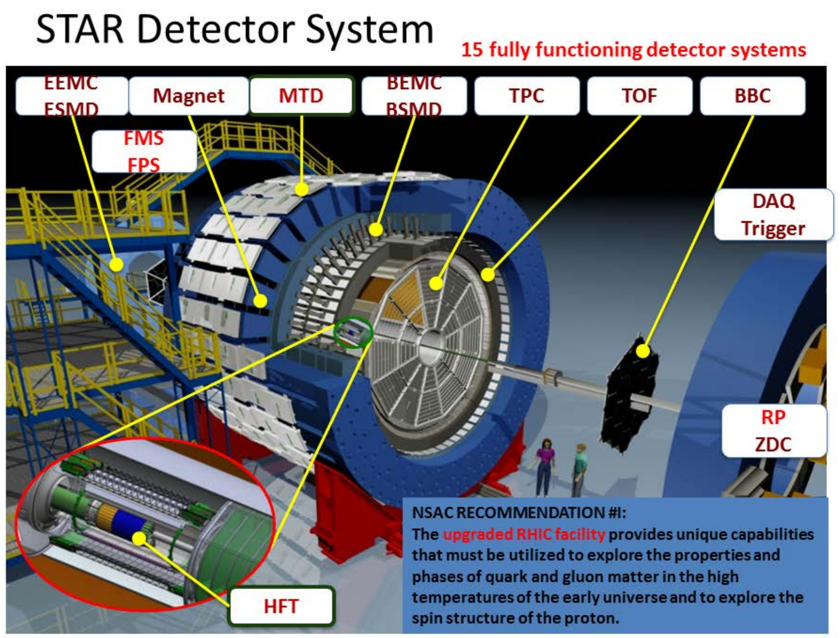


Relativistic Heavy Ion Collider @ Brookhaven

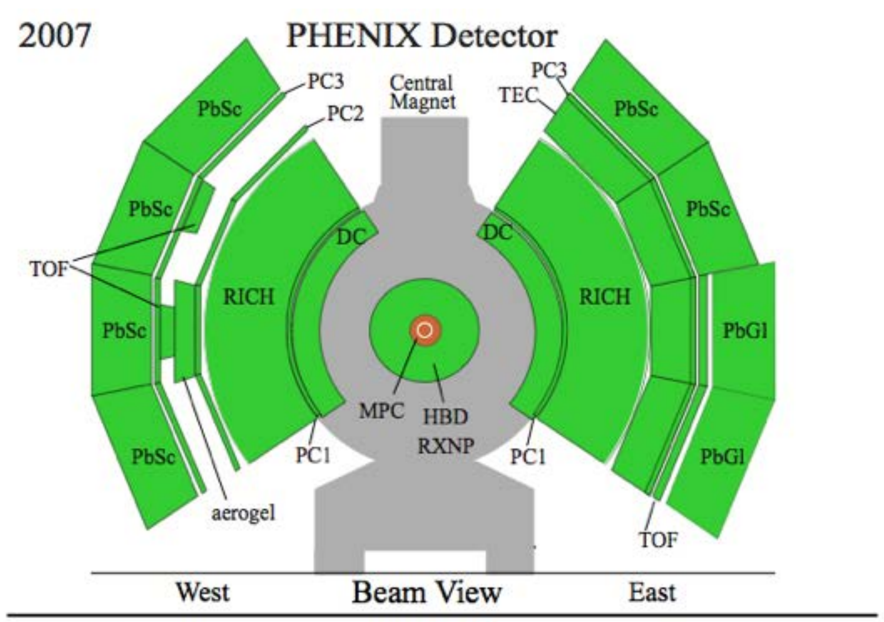
- 200 GeV collision energy
- long HI running times
- flexible collision species
- 2 experiments:
    - STAR: large acceptance
    - PHENIX (2001-2016) → sPHENIX new rare probes / large acceptance detector (2023-)
    - 2 smaller experiments in early RHIC years: PHOBOS and BRAHMS

RHIC experiments

- STAR:
  - large acceptance, low rate, designed for correlations, PID, photons, leptons
- PHENIX:
  - high rate, small acceptance, designed for photons, lepton and other rare probes
- both STAR and PHENIX designed in the 1990s and evolved through many upgrades over the last ~20 years
- sPHENIX (2023+):
  - replacement for PHENIX, optimized for ATLAS/CMS style jet measurements and upsilons (more Friday)
- O(100) person collaborations



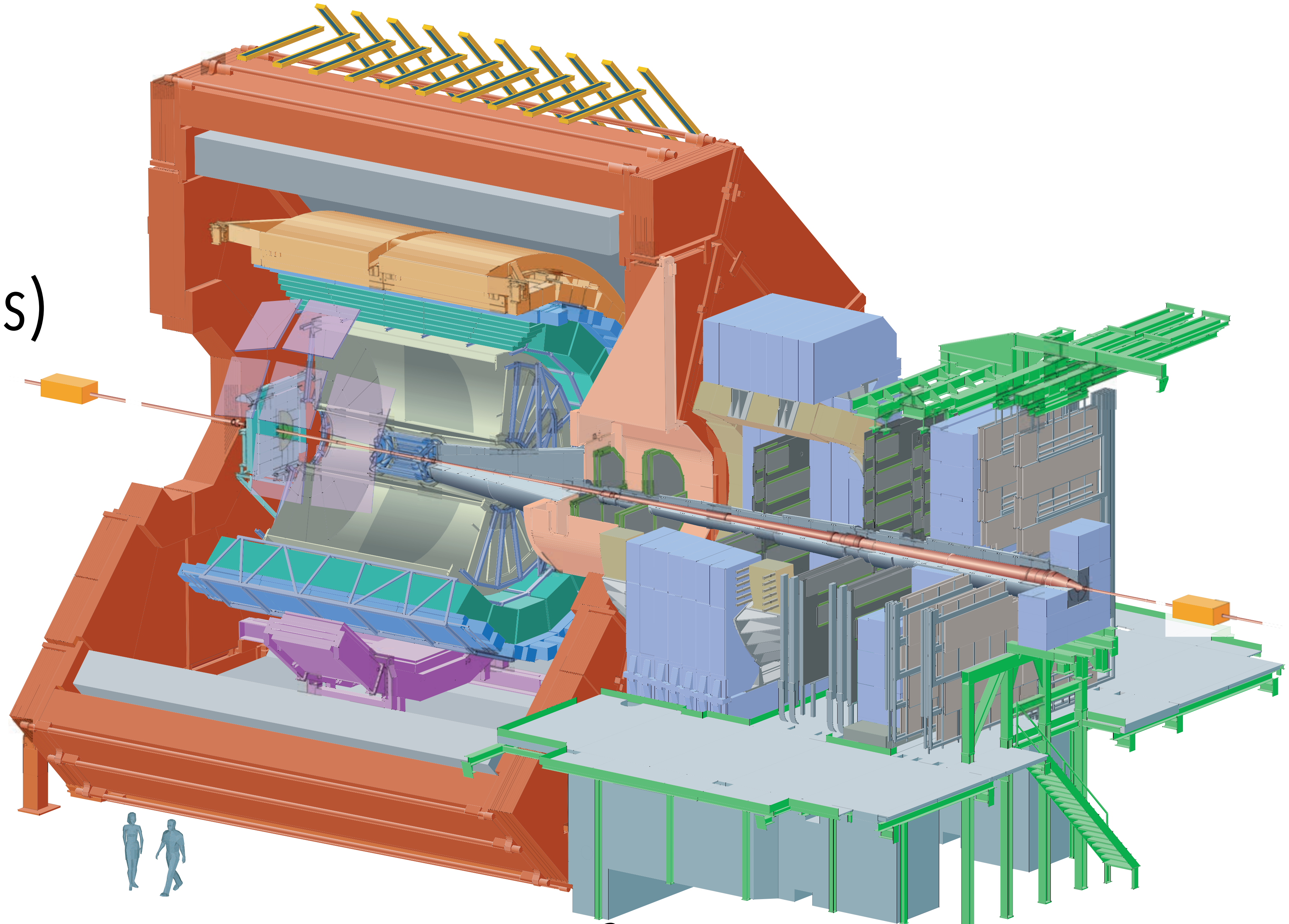
X10^3 increases in DAQ rate since 2000, most precise Silicon Detector (HFT)



collider coordinate system

ϕ (around the beam axis)

z axis
(beam axis)



$$\eta = -\ln(\tan\frac{\theta}{2})$$

Part 1
Hard Probes and Jets

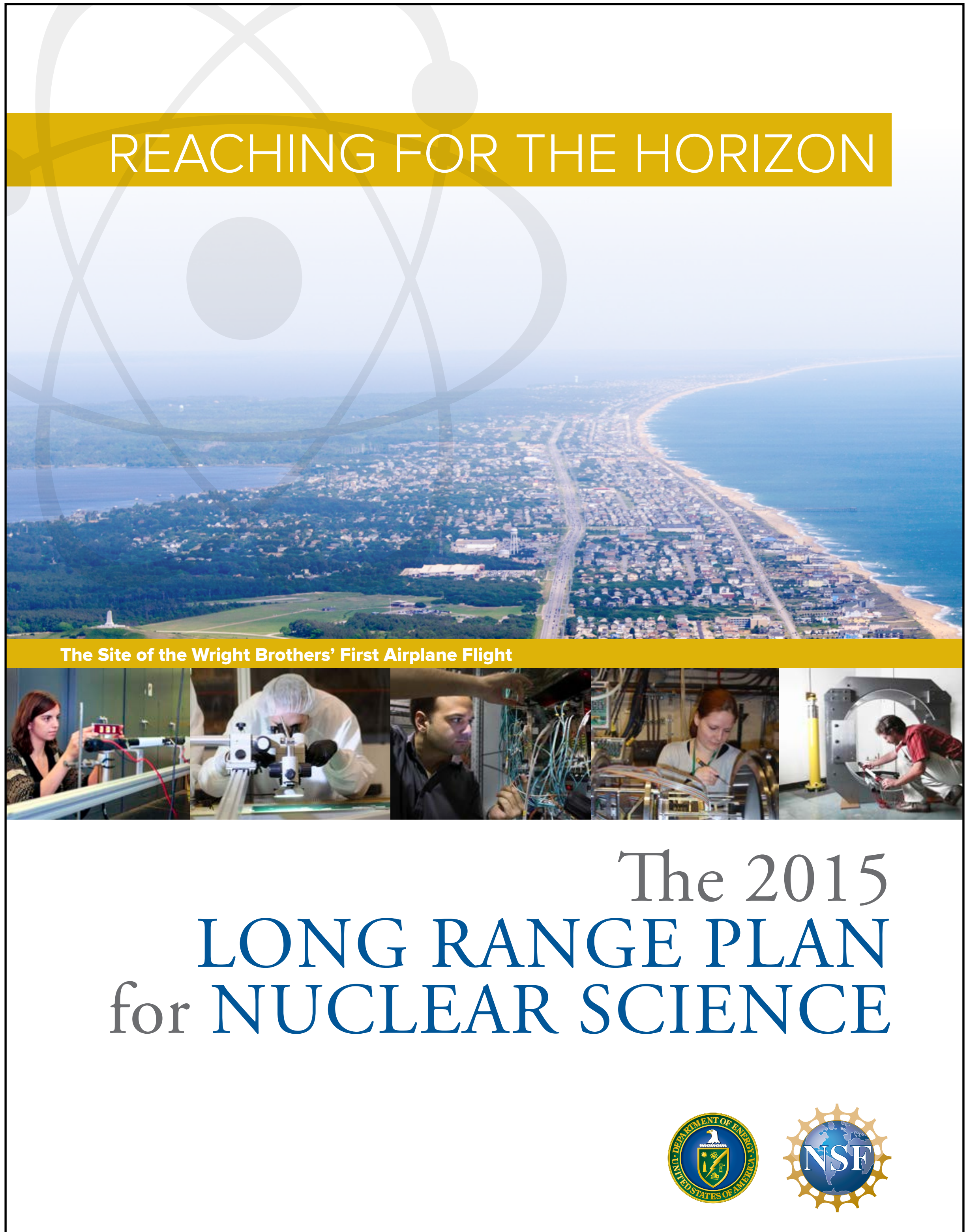
liquid QGP

- liquid behavior of the QGP is not apparent from the equations of QCD
  - this is emergent phenomena
- how does this behavior arise?

need to probe the plasma on *short length scales* sensitive to the *interactions which give rise to the fluid behavior*

→ *need large momentum scale processes*

a key question



"To understand the workings of the QGP, there is no substitute for microscopy. We know that if we had a sufficiently powerful microscope that could resolve the structure of QGP on length scales, say a thousand times smaller than the size of a proton, what we would see are quarks and gluons interacting only weakly with each other. **The grand challenge for this field in the decade to come is to understand how these quarks and gluons conspire to form a nearly perfect liquid.**"

how we'd like to measure the QGP

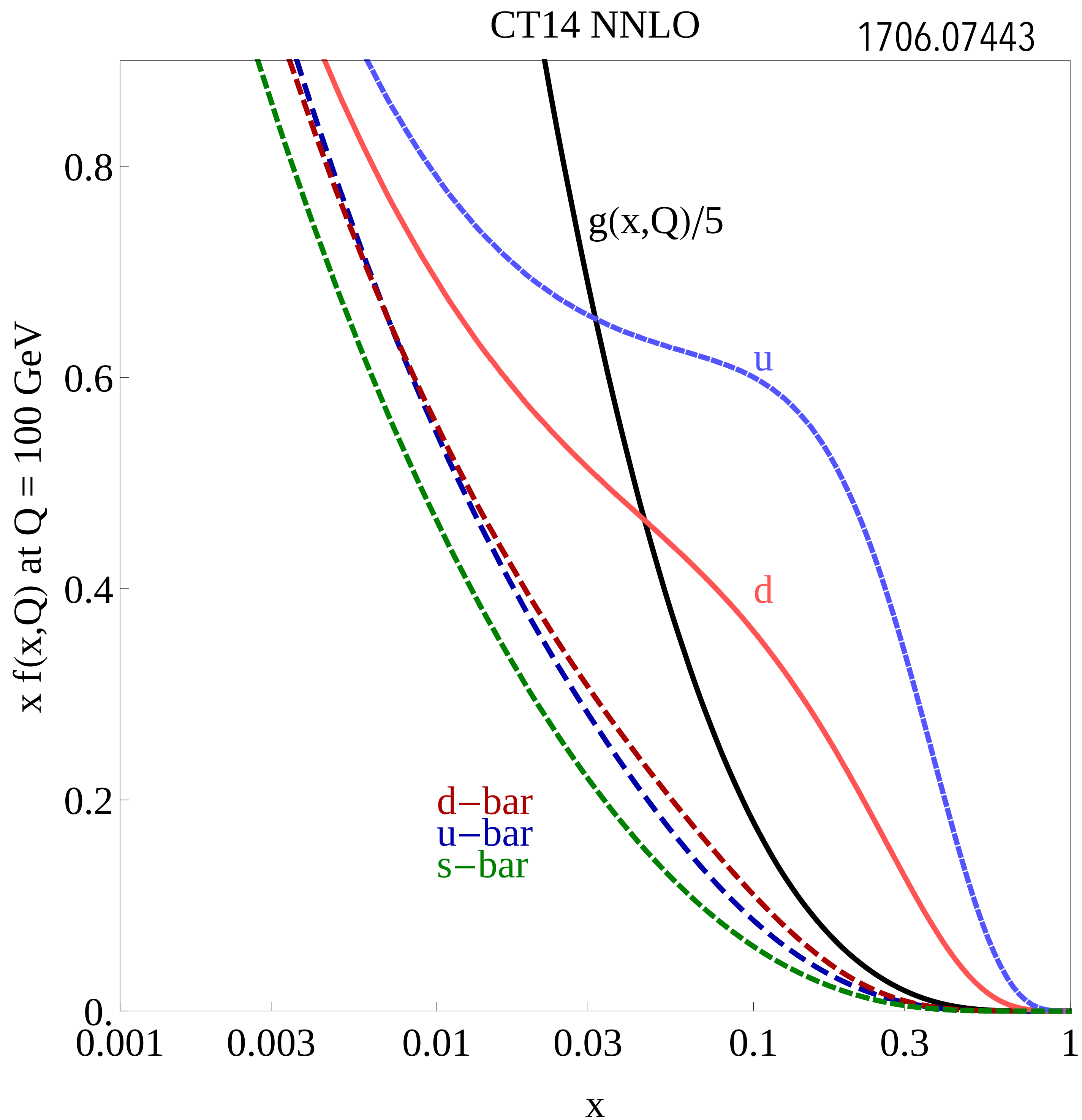
plan: set up something close to this concept by measuring *jets* in heavy ion collisions

jets in proton-proton collisions

protons are a source of partons

partons: quarks, anti-quarks and gluons

- *parton distribution functions* (PDFs) encode the distributions of partons inside protons as a function of:
  - x → longitudinal momentum fraction
  - Q → momentum transfer
- based on a global analysis of data from many experiments



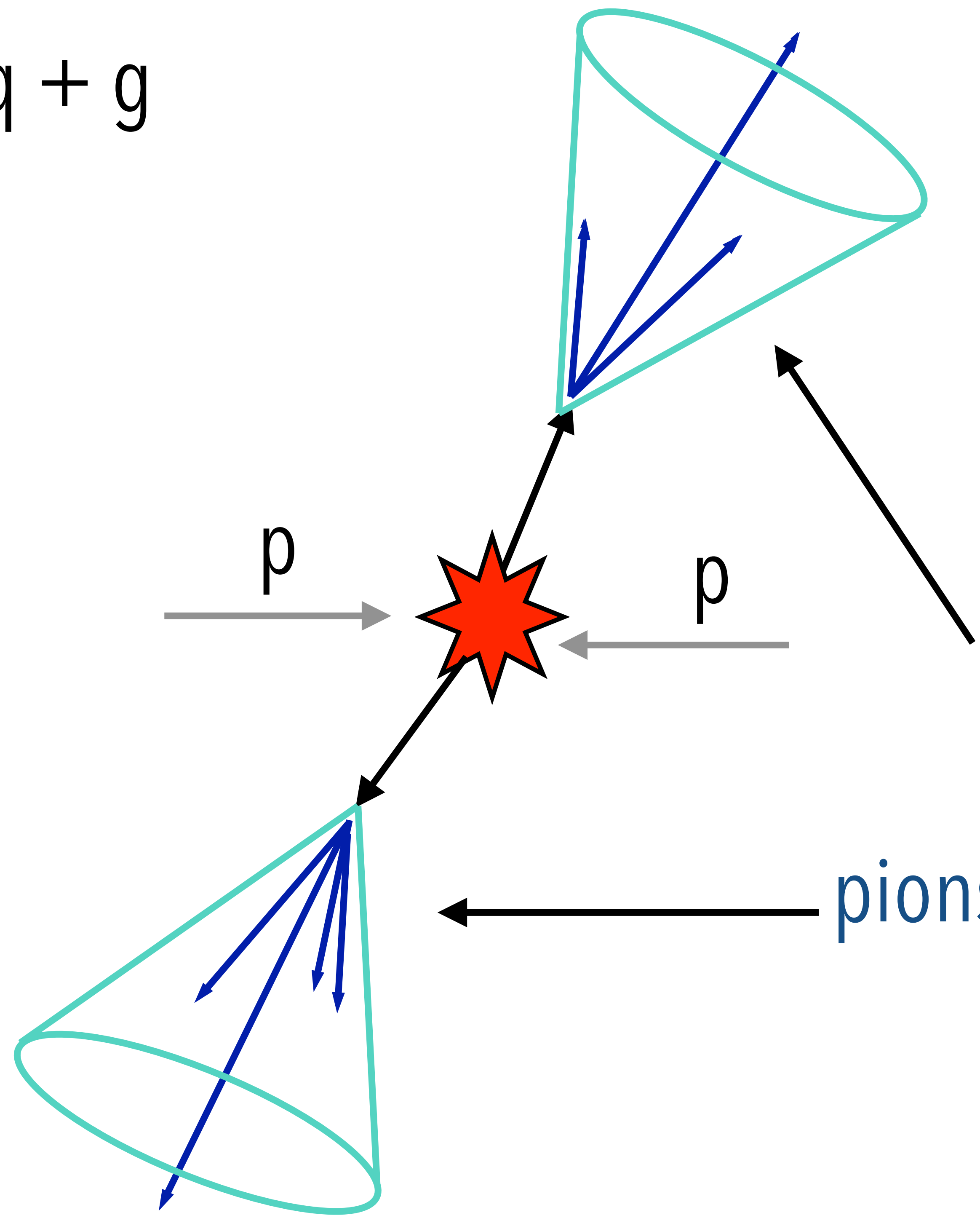
$$x = p_{parton}/p_{proton}$$

QCD jets: how we can measure the QGP

large momentum transfer QCD scattering

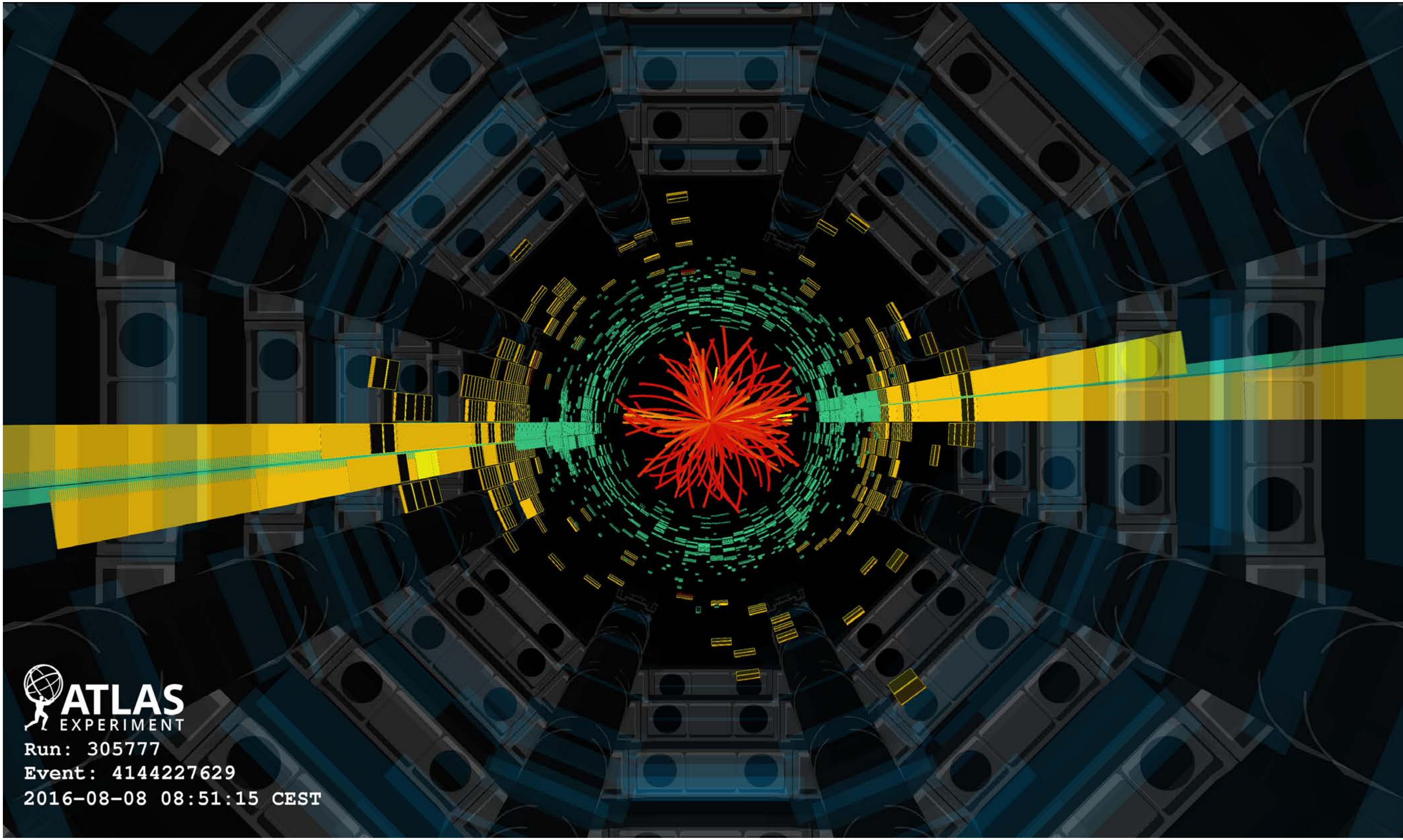
e.g.: $q + g \rightarrow q + g$

particles grouped together into jets via an algorithm (roughly into cones)



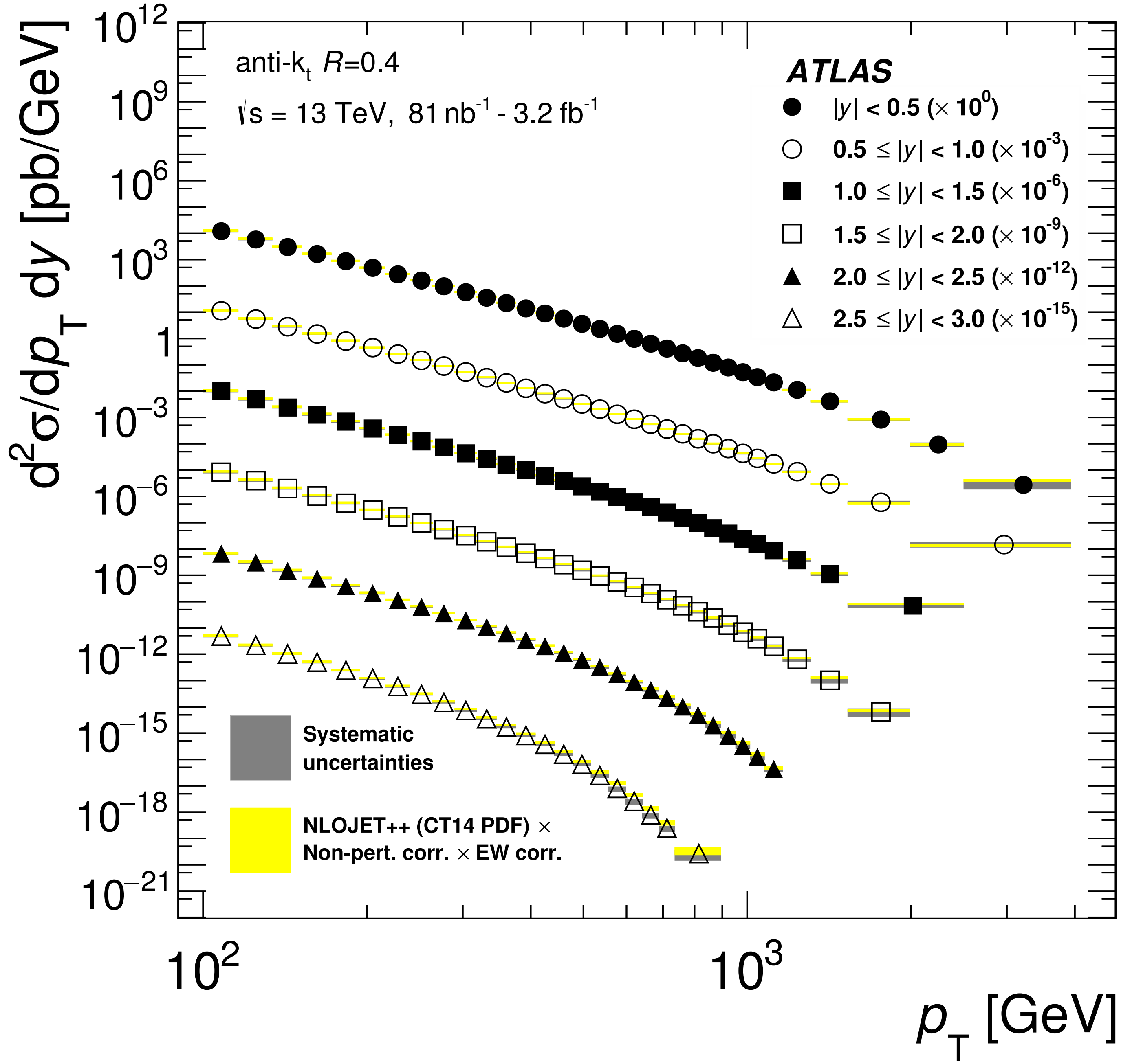
hadrons:
pions, kaons, protons, neutrons…

a dijet in pp collisions event



jets in pp collisions

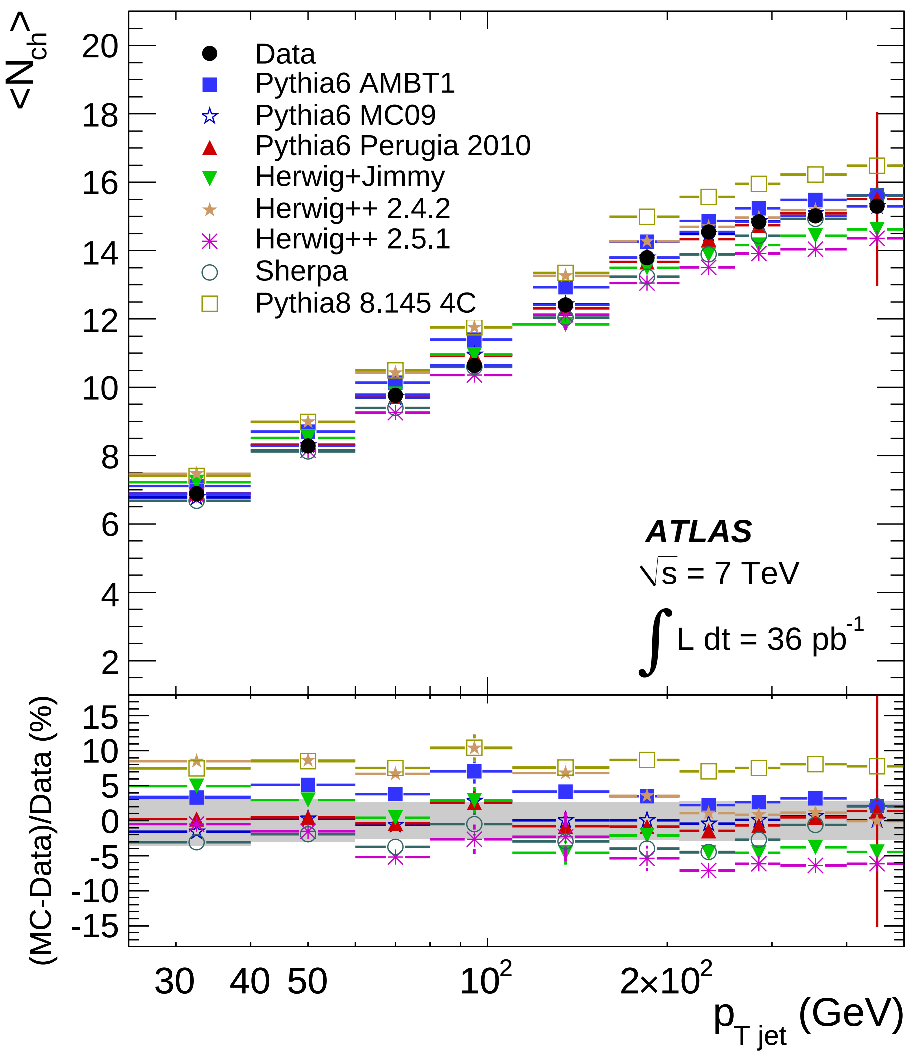
ATLAS, JHEP 05 (2018) 195

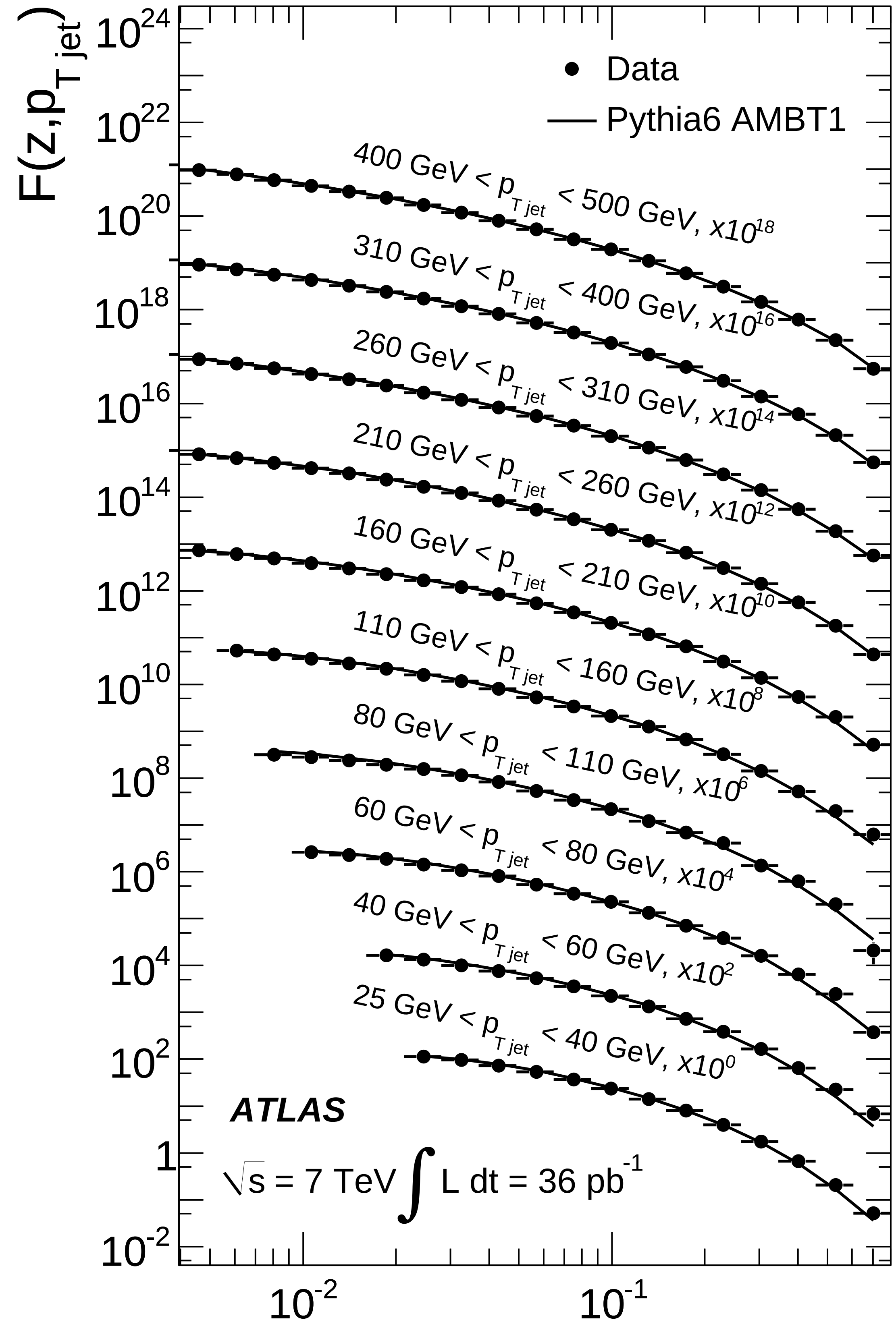


jet momentum (p_T) (GeV)

precise measurements over the available kinematic range

very good agreement with next to leading order QCD calculations





$$z \equiv p_T \cos \Delta R \,/\, p_T^{jet}$$

jets contain O(10) particles, most of which carry a small fraction of the jet momentum

EPJC71 1795 (2011)

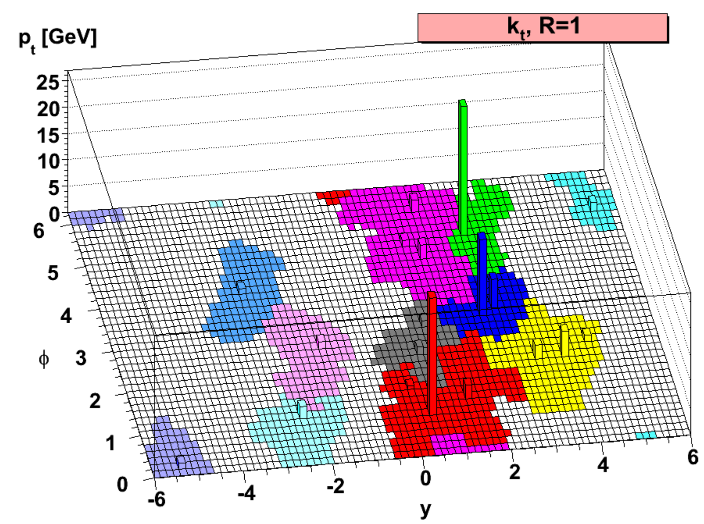
how is a jet defined?

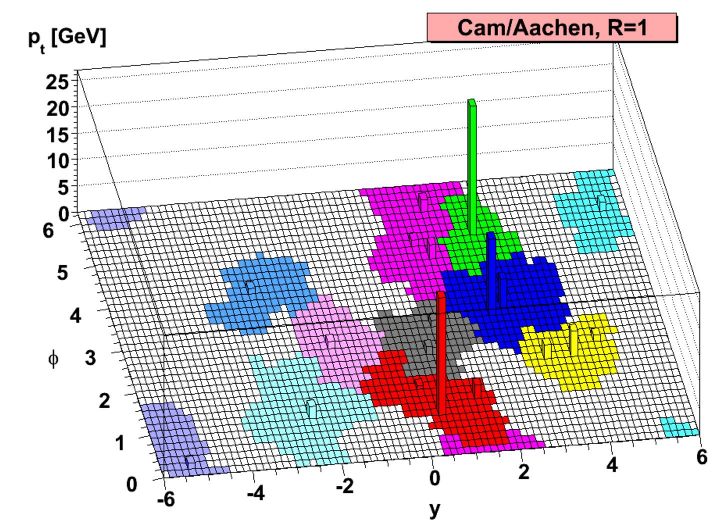
- jet definition must be handled in a stable way
    - technical terms: infrared & collinear safety

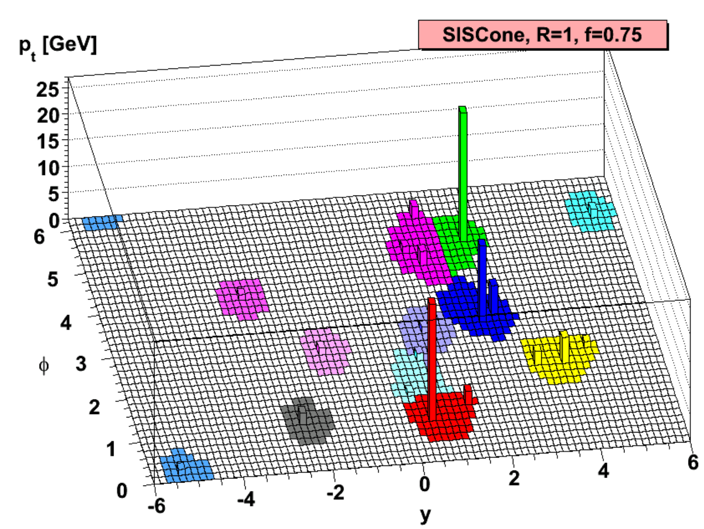
same event, different jet clustering algorithms

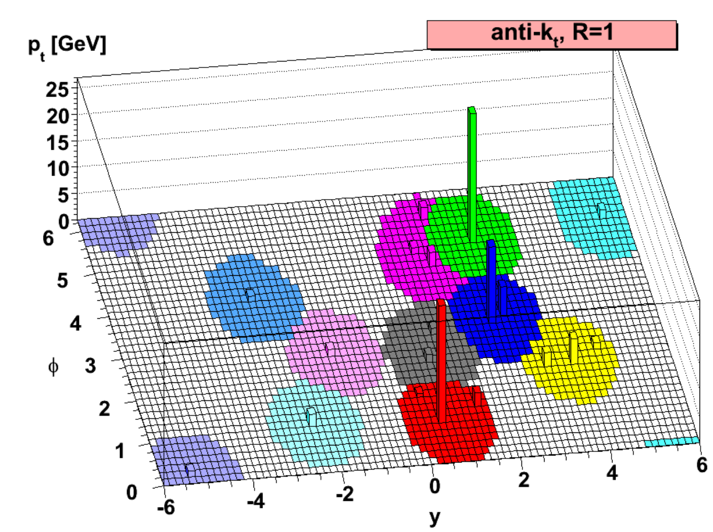
it is not possible to associate each particle back to a parton

similar, but not identical, groupings









in vacuum (p+p collisions)

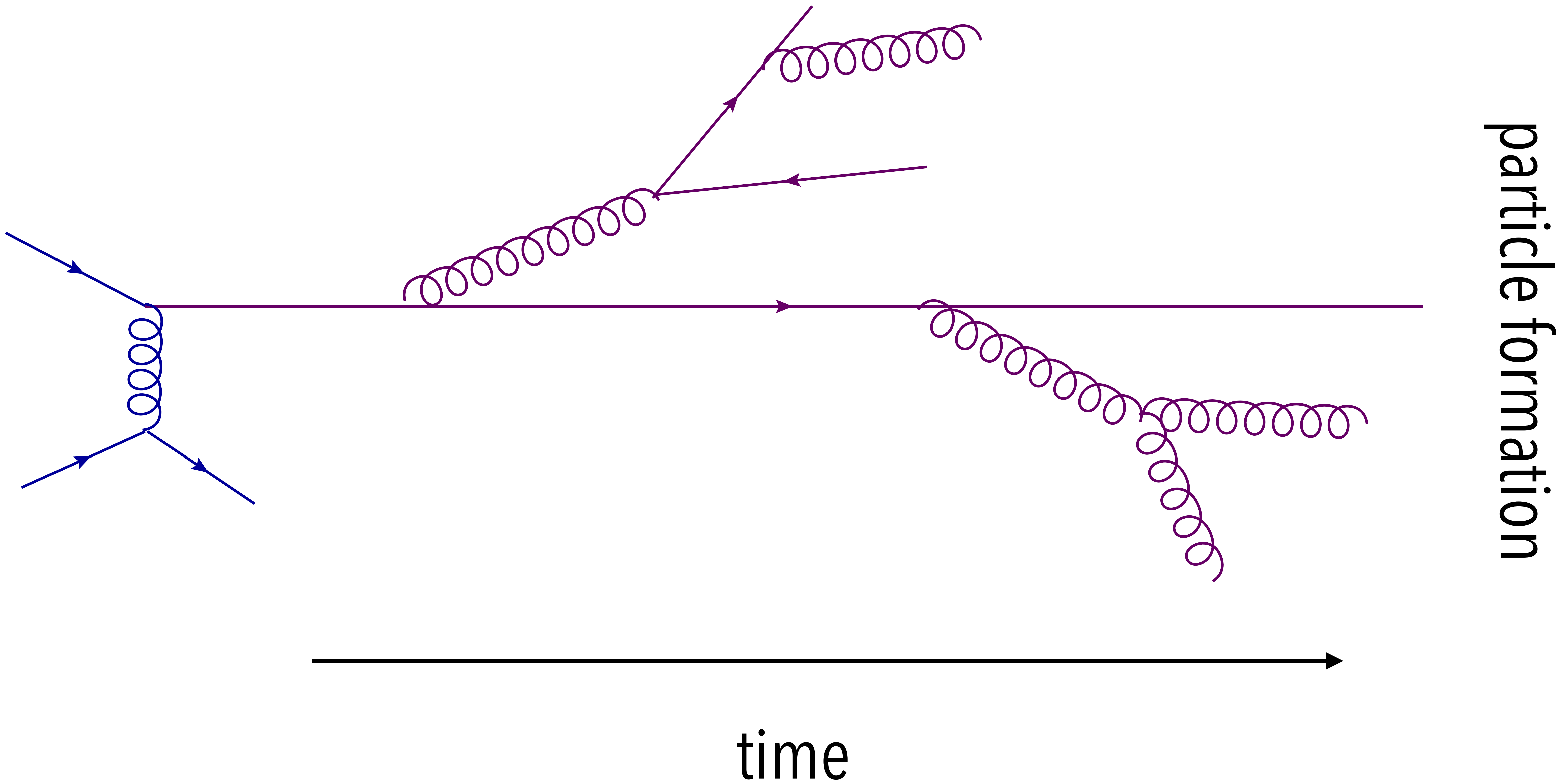


image: Y. Methar-Tani

a 40 year old prediction

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

in QGP

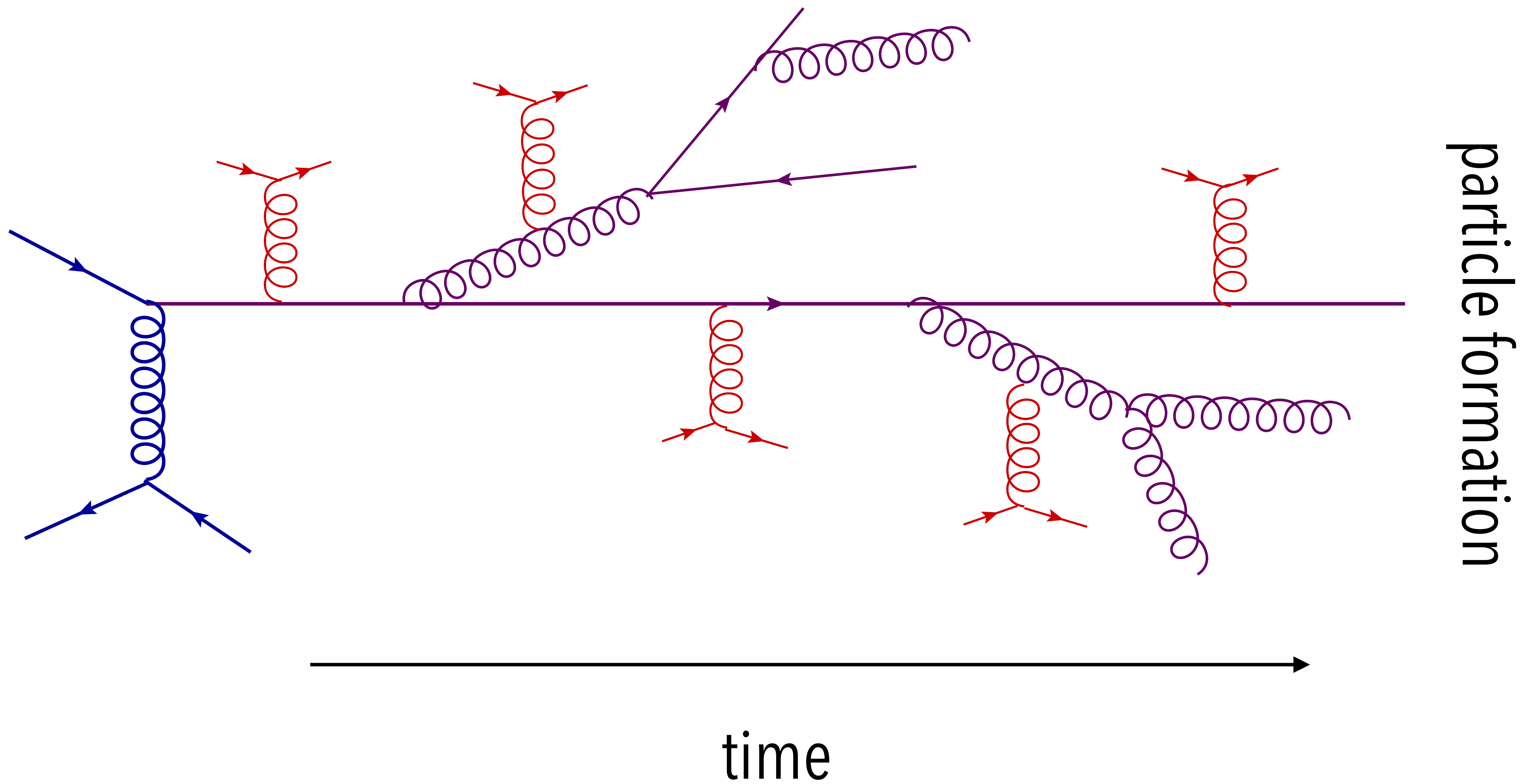
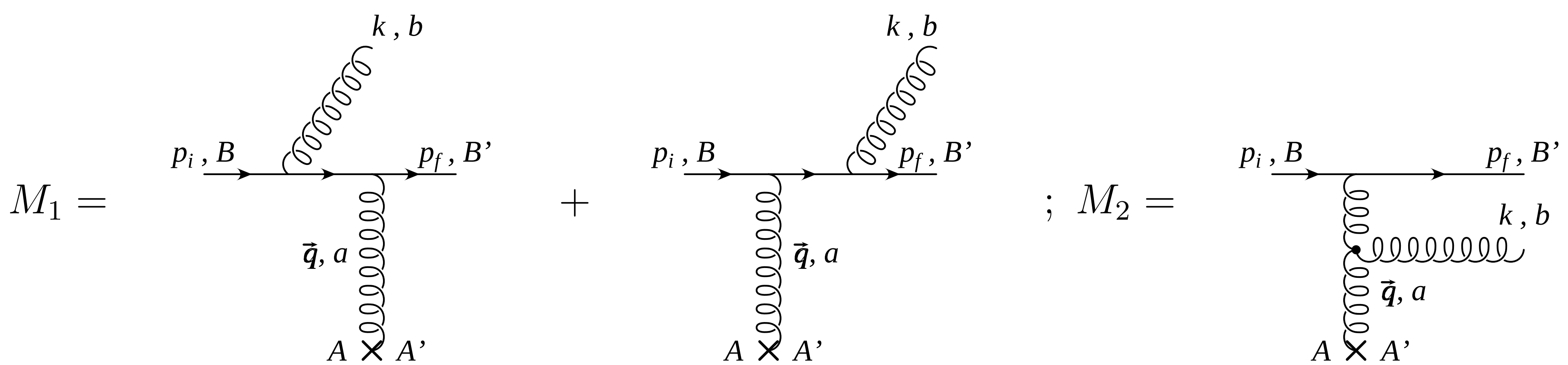


image: Y. Methar-Tani



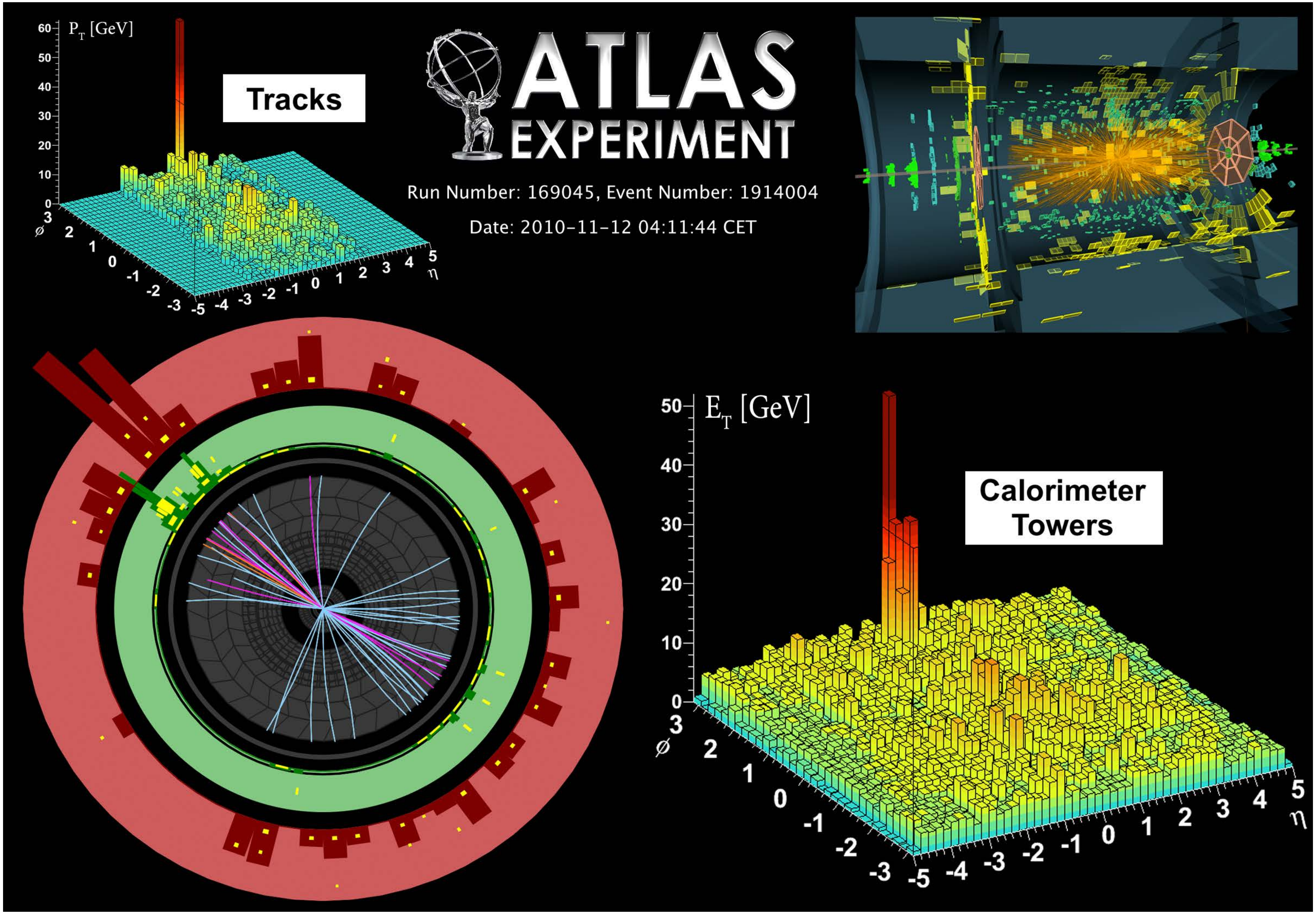
RADIATIVE ENERGY LOSS OF HIGH ENERGY QUARKS AND GLUONS IN A FINITE VOLUME QUARK-GLUON PLASMA

R. Baier [1], Yu. L. Dokshitzer [2], A. H. Mueller* [3, 4], S. Peigné [3] and D. Schiff [3]

a series of papers by these authors in 1996-97, modern review: Qin & Wang 1511.00790

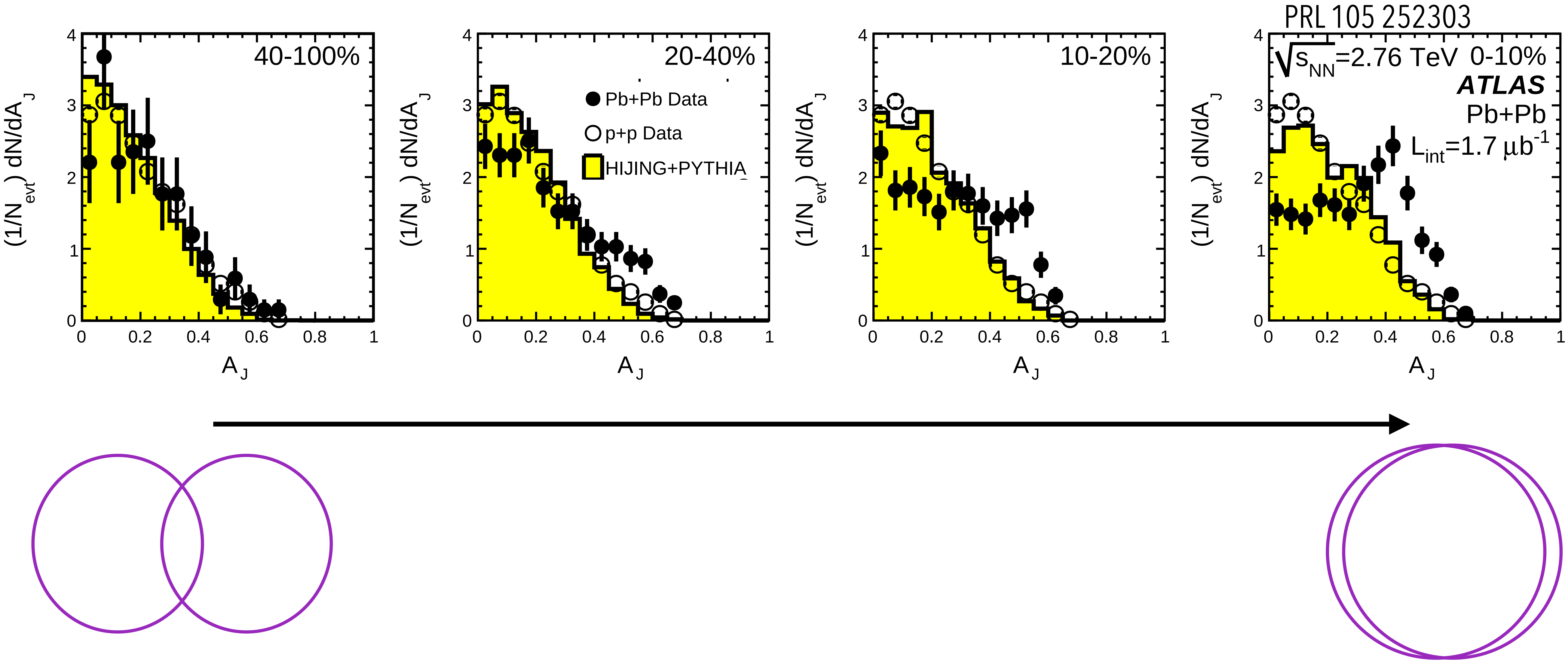
- strength of jet quenching usually encoded in the transport coefficient qhat, transverse momentum broadening / length
- like viscosity, qhat, is not directly measurable, but must be inferred from the data through a model

di-jets in the QGP become mono-jets



momentum asymmetry in dijet pairs

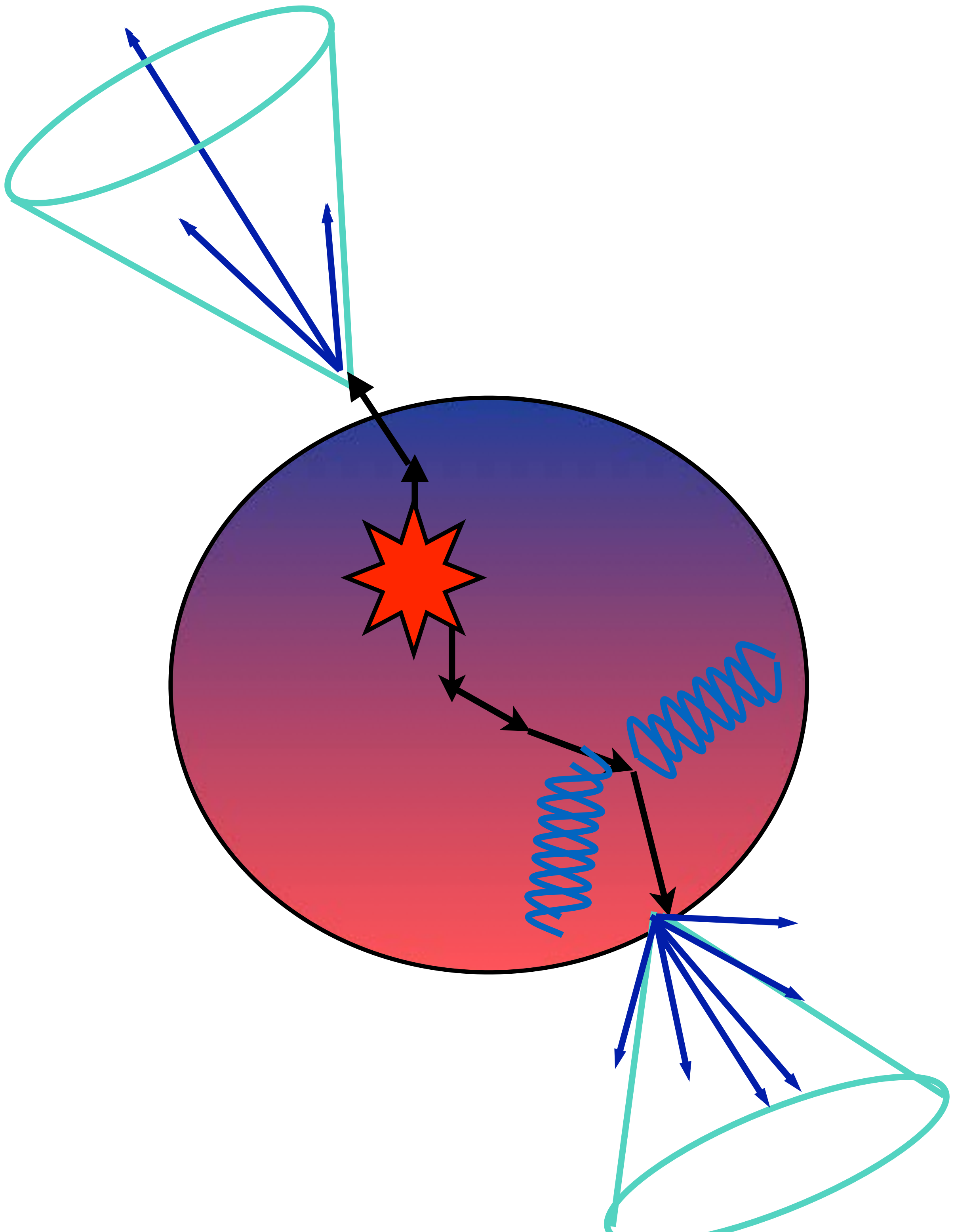
$$A_J = \Delta p / \Sigma p$$



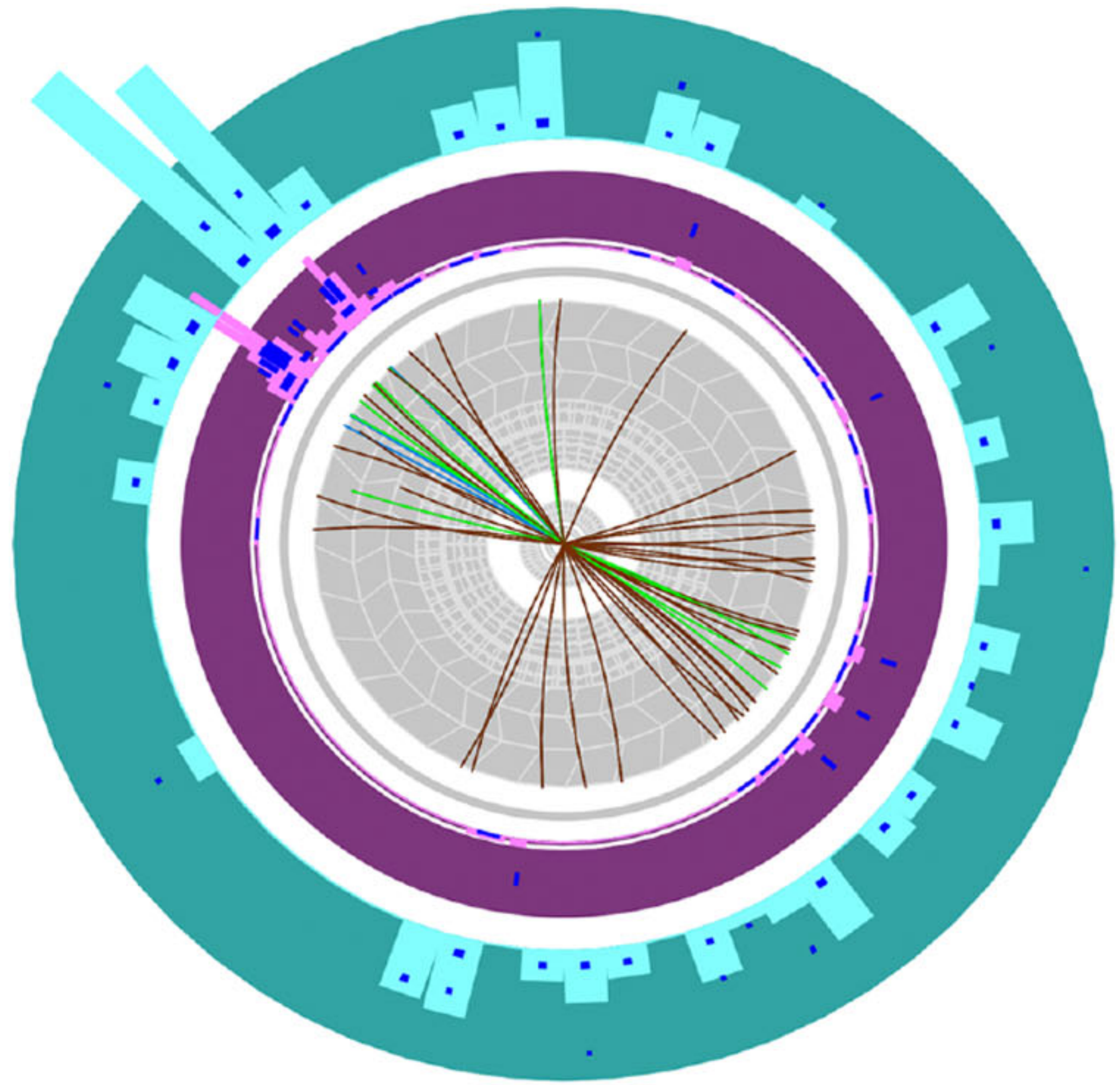
how do the jets loose their energy? where does it go? how does it depend on the jet momentum?

jet quenching in action

cartoon



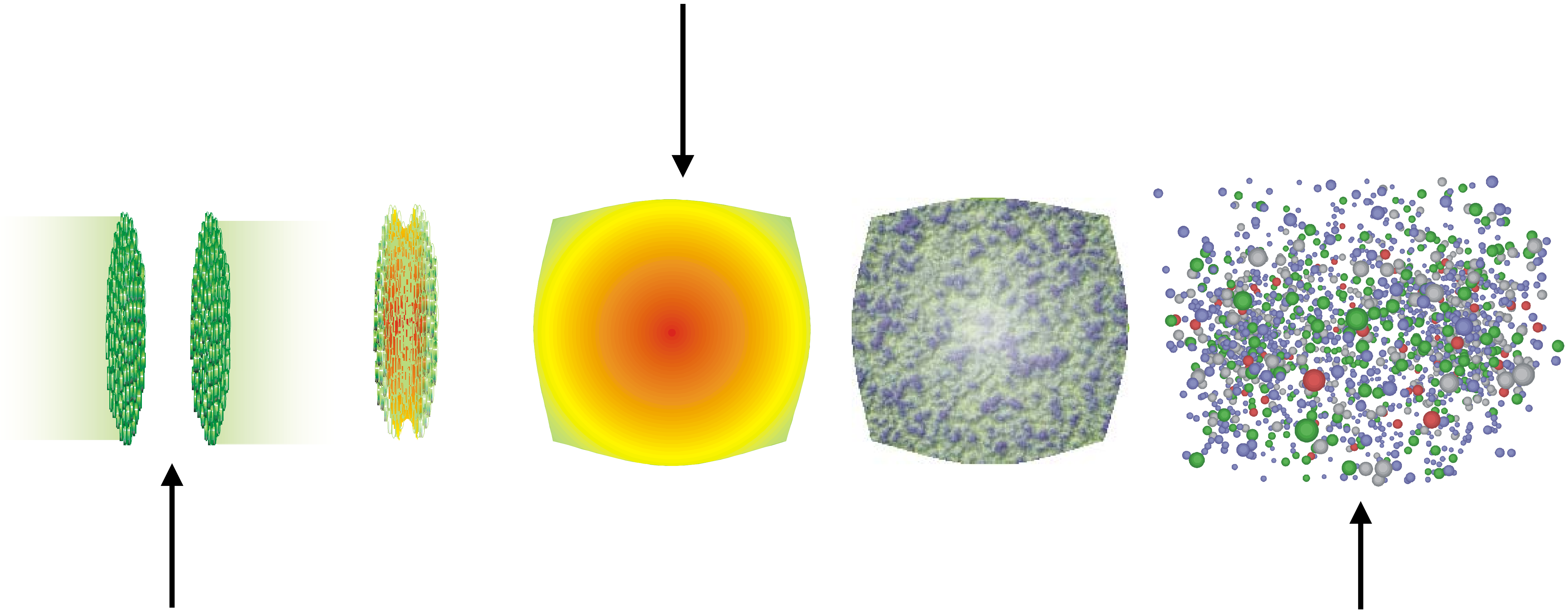
actual event measured in ATLAS



PRL 105 252303

QCD at T > 0 at colliders

quark gluon plasma

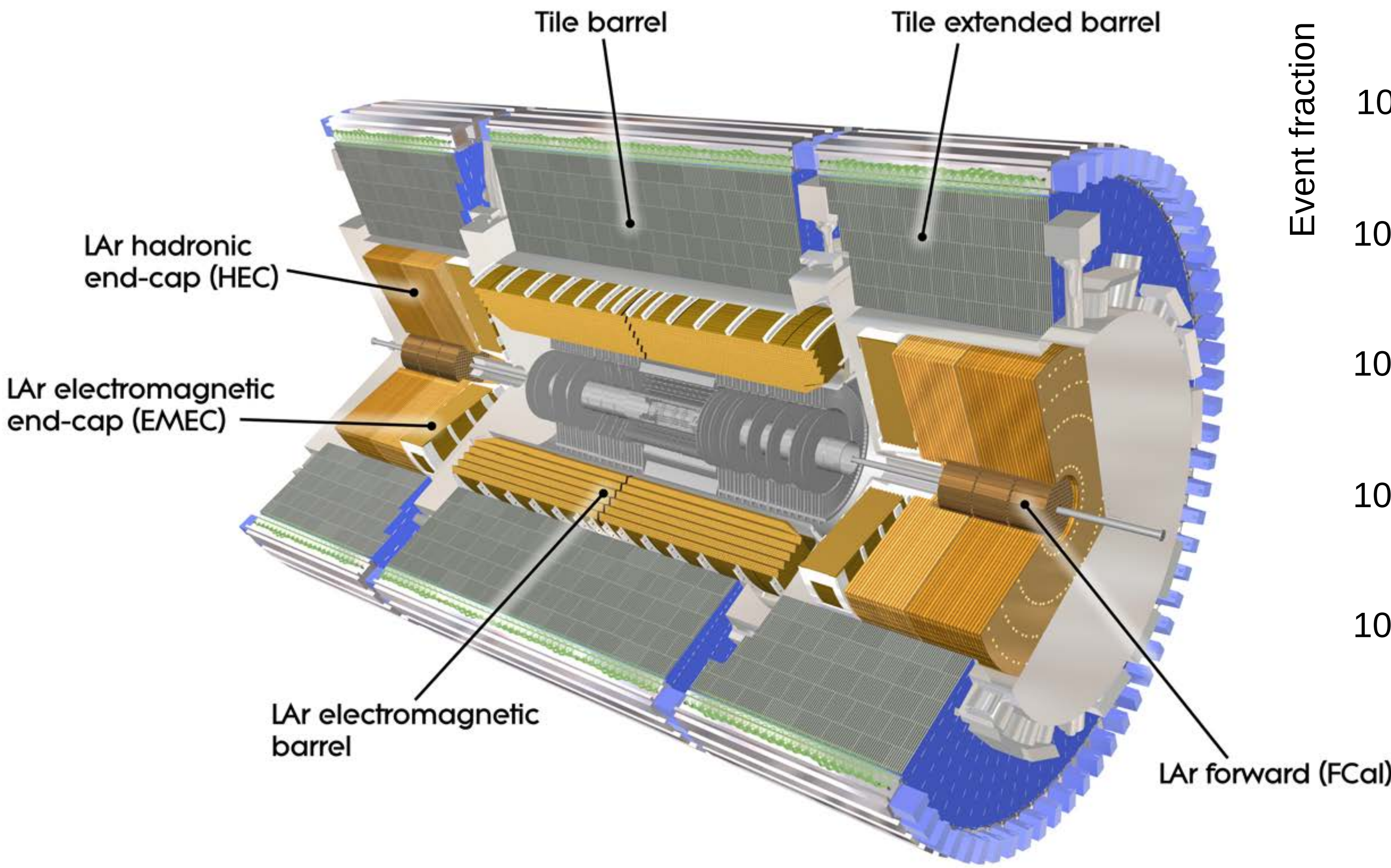


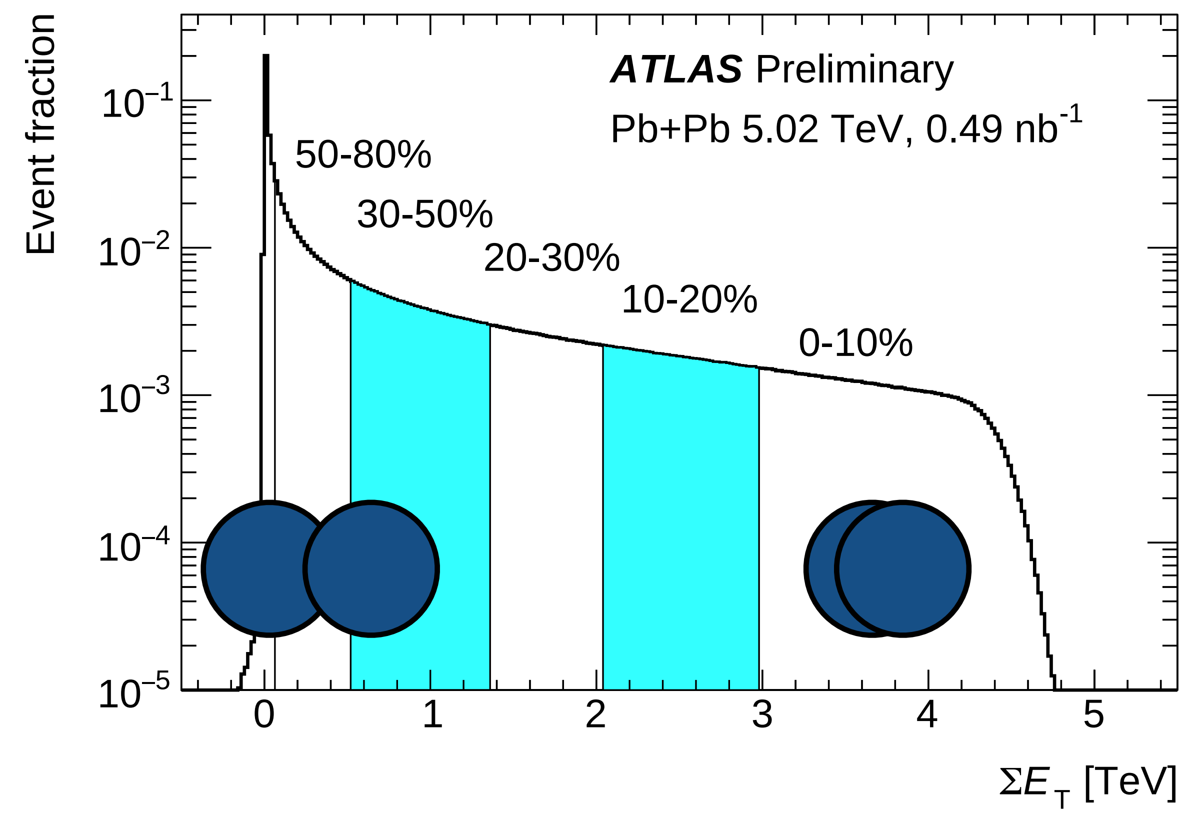
incoming Lorentz contracted nuclei

hadrons headed toward detector

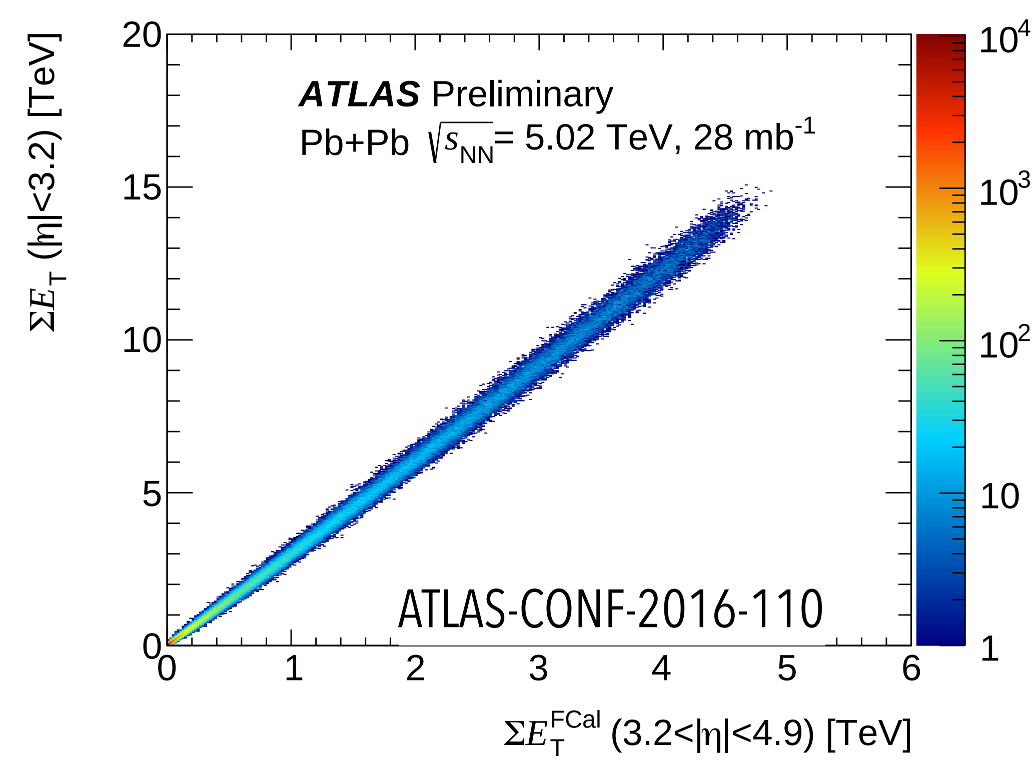
$\Delta t \sim 10\ \text{fm/c} \sim 10^{-22}\ \text{s}$

ATLAS Calorimeters





idea: FCal ΣE_T is correlated with collision impact parameter
(other experiments use slightly different quantities, but the idea is the same)



Glauber model

model the distributions of nucleons in nucleus
(Woods-Saxon for spherical nuclei)

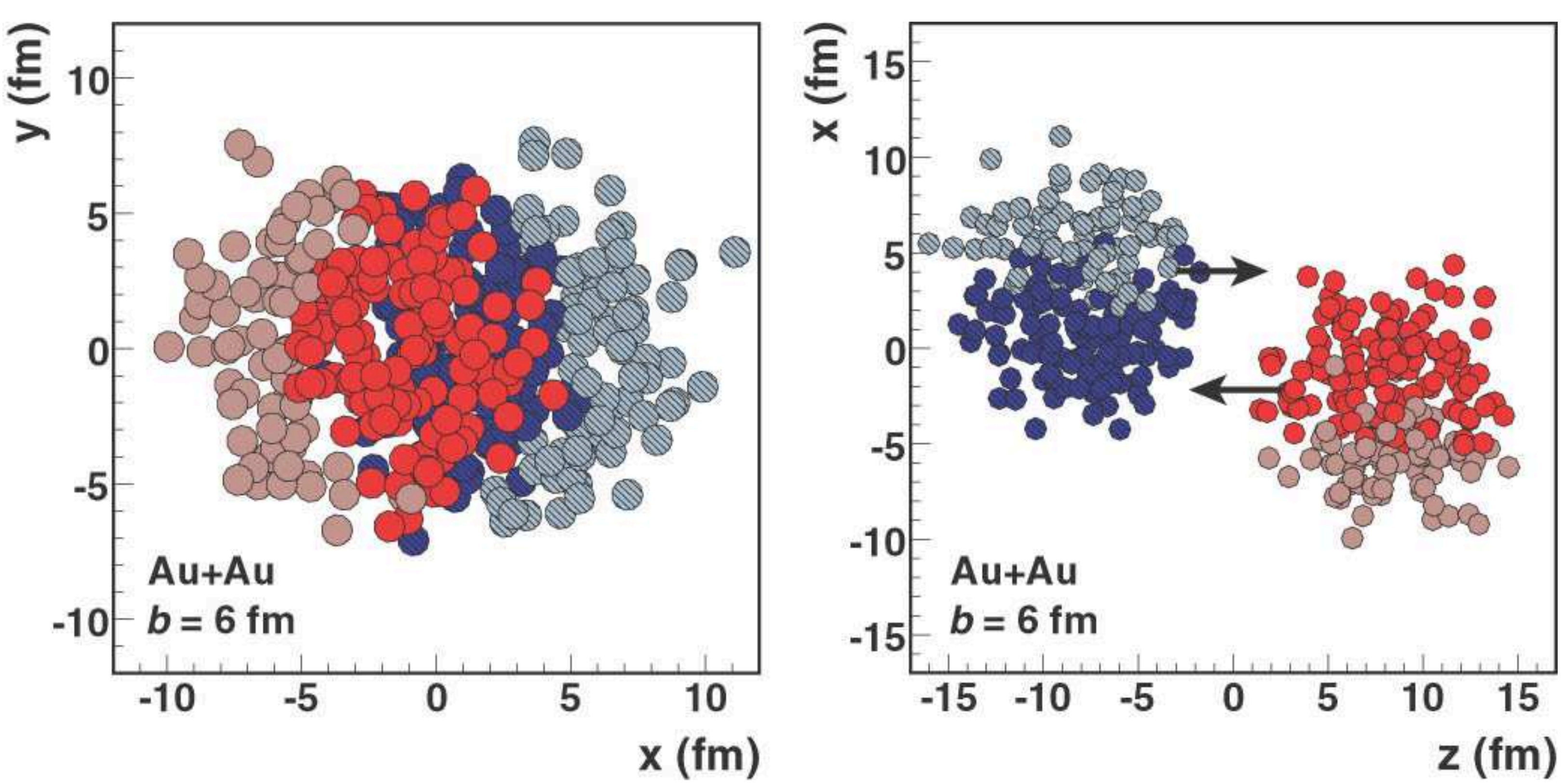
$$\rho(r) \propto \frac{1}{1 + exp(\frac{r-R}{a})}$$

sample from that distribution to get a unique distribution of nucleons for each nucleus

for each nucleon in nucleus A ask if it hits a nucleon from nucleus B

if so, that is a "**binary collision**" and the nucleons are "**participants**"

assume monotonic relationship between impact parameter and <multiplicity>



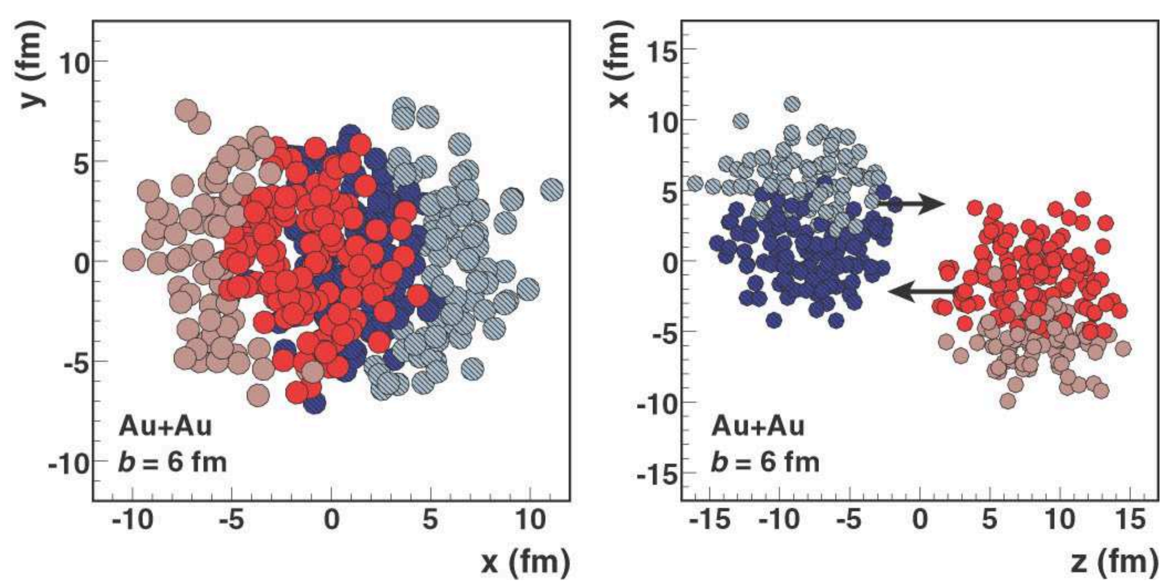
Miller, et al, Ann Rev Nuc Part 57 (2007) 205
C. Loizides, et al Software X 1-2 (2015) 13
C. Loizides, et al PRC 97 054910

relating HI and pp collisions

- each "binary collision" is like a proton-proton collision
  - we will ignore differences between protons and neutrons here
- hard processes (jets, photons, Z, W, …) are expected to be produced in at the rate in pp collisions x the number of binary collisions (N_{coll})

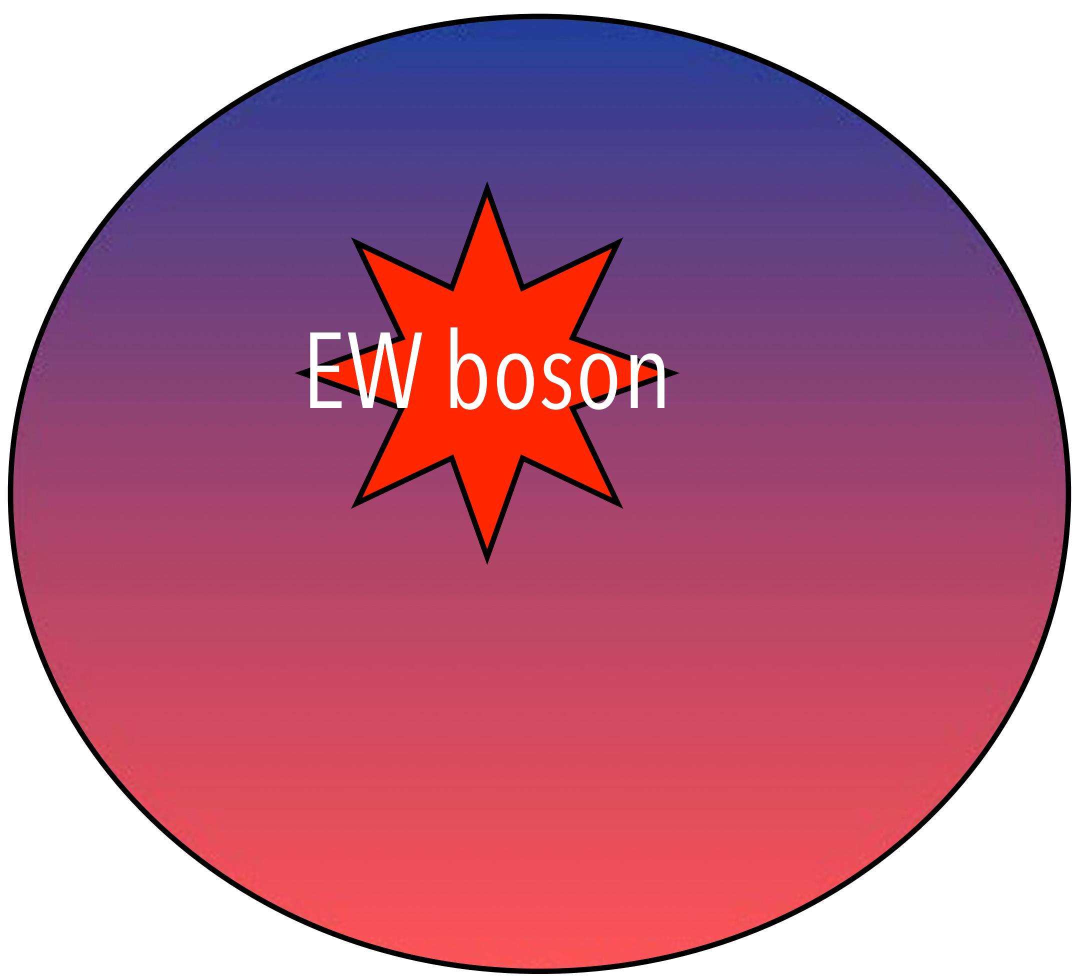
$$R_{AA} = \frac{N_{X,AA}}{N_{coll}\, N_{X,pp}}$$

- $R_{AA} = 1 \rightarrow$ AA collision consistent with Ncoll independent pp collisions



electro-weak bosons

photons, W and Z carry no color charge and thus cannot interact via QCD with the QGP



$$q + g \rightarrow q + \gamma$$

$$u + \bar{u} \rightarrow Z$$

$$u + \bar{d} \rightarrow W^{+}$$

$$\ldots$$

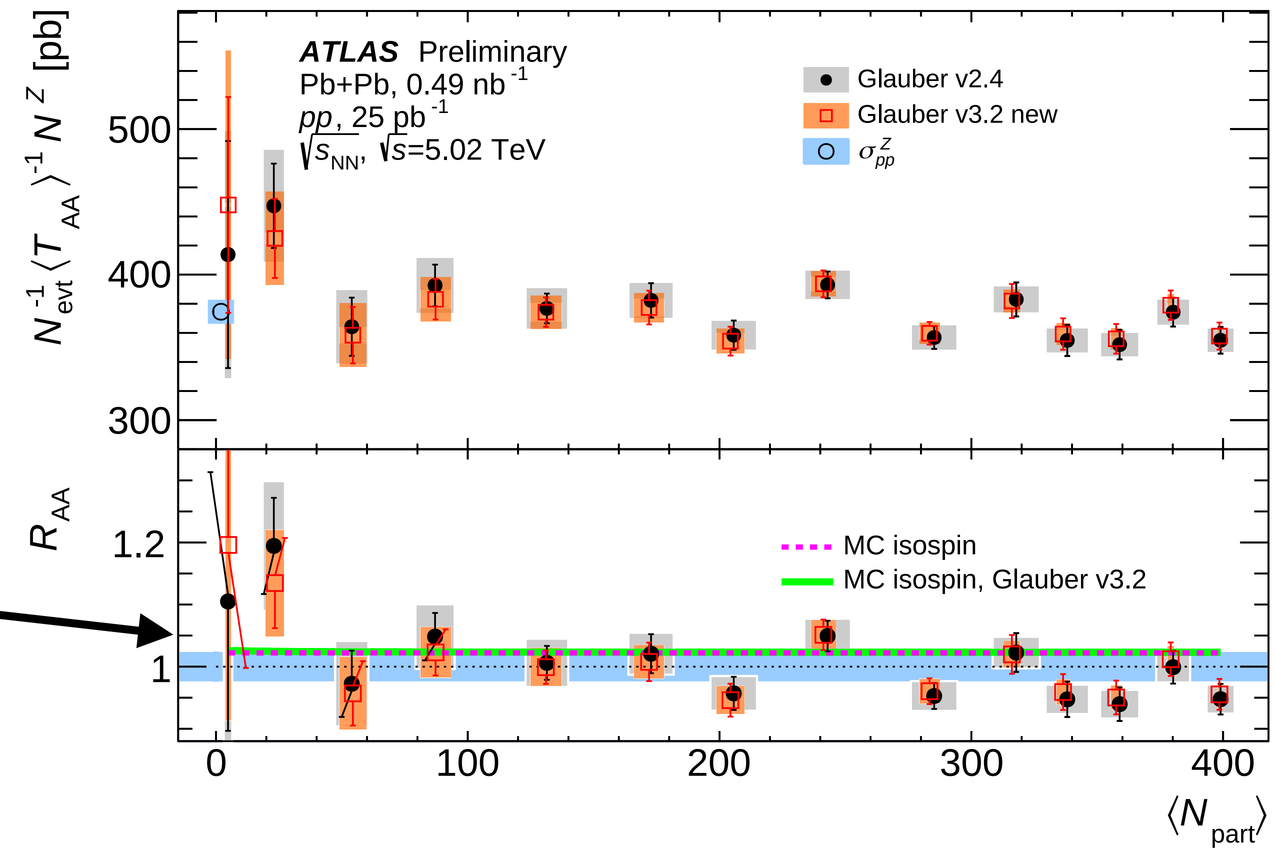
W/Z lifetime ~ much less than QGP lifetime so we measure decay into leptons (no color charge)

made in the same way as jets, lack of energy loss provides *validation* of jet production rates

W and Z bosons in PbPb collisions

some deviations in peripheral collisions

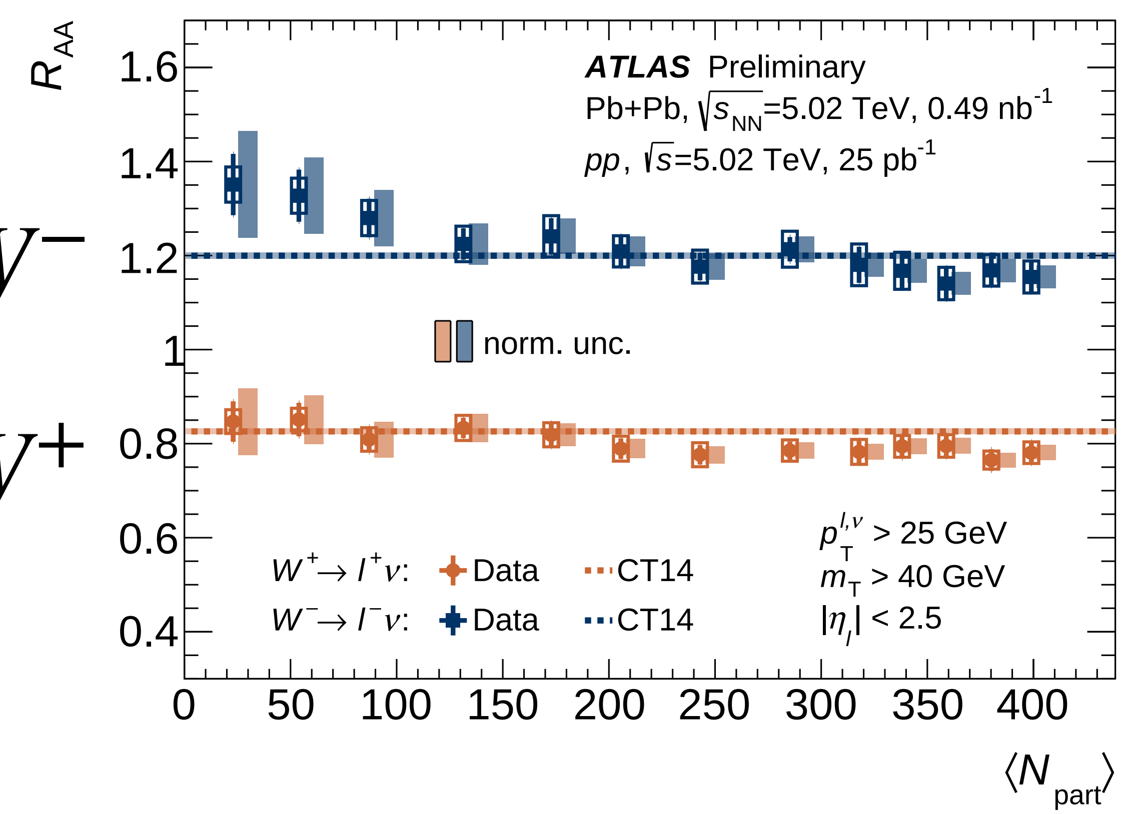
there are a lot of possible effects there and this is of interest



W+/W- difference due to neutrons in Pb→excess of d-quarks because of neutrons

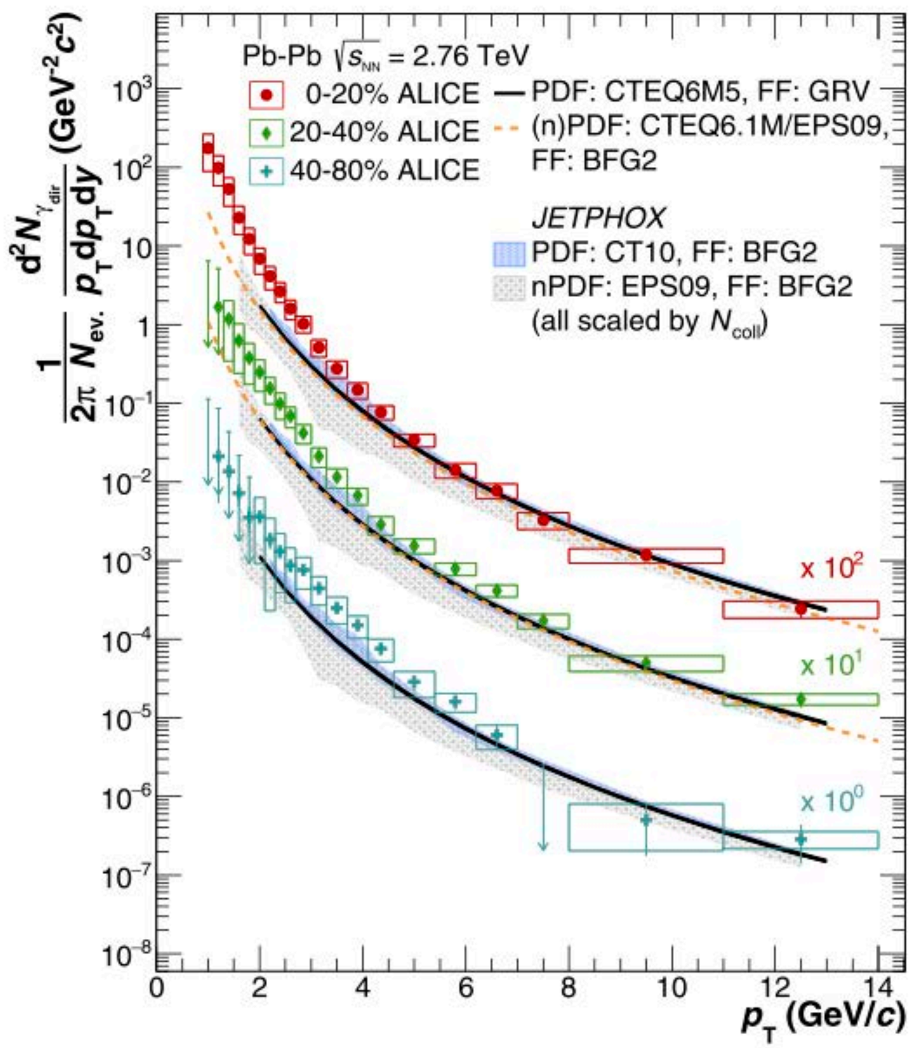
$$d + \bar{u} \rightarrow W^-$$

$$u + \bar{d} \rightarrow W^+$$



photons

Phys. Lett. B 754 (2016) 235

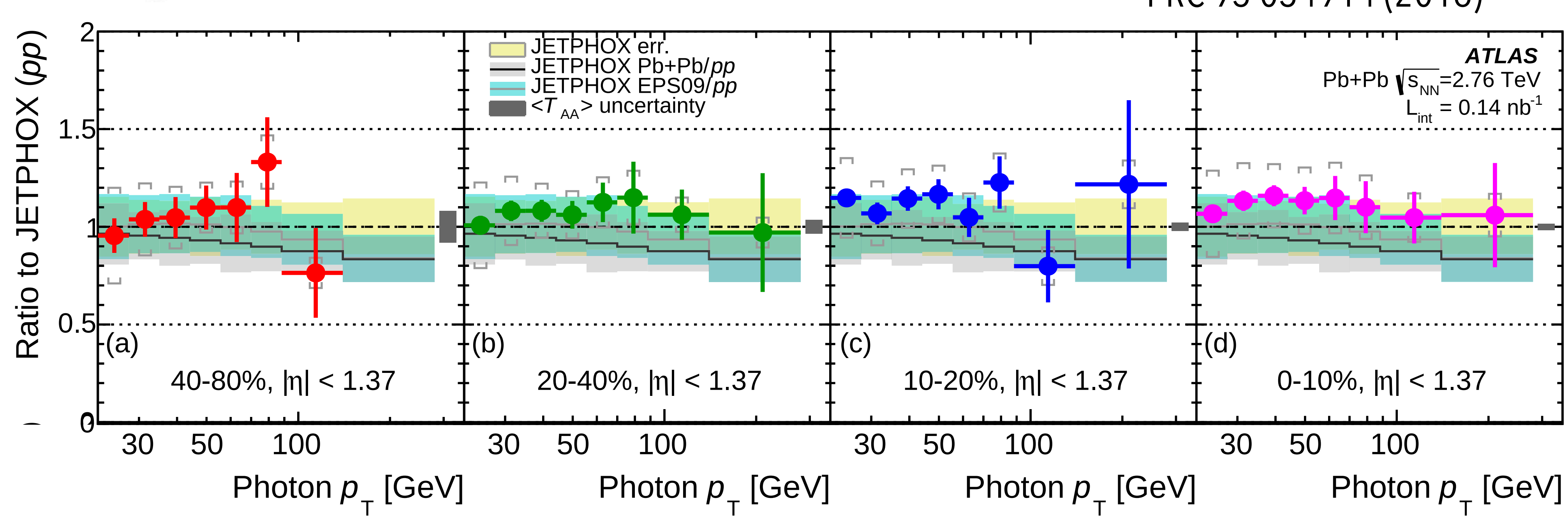


$$q + g \rightarrow q + \gamma$$

photon measurements are difficult due to the large number of decays into photons which much be removed

photon rate consistent with expectations based on pp (calculations)

PRC 93 034914 (2016)



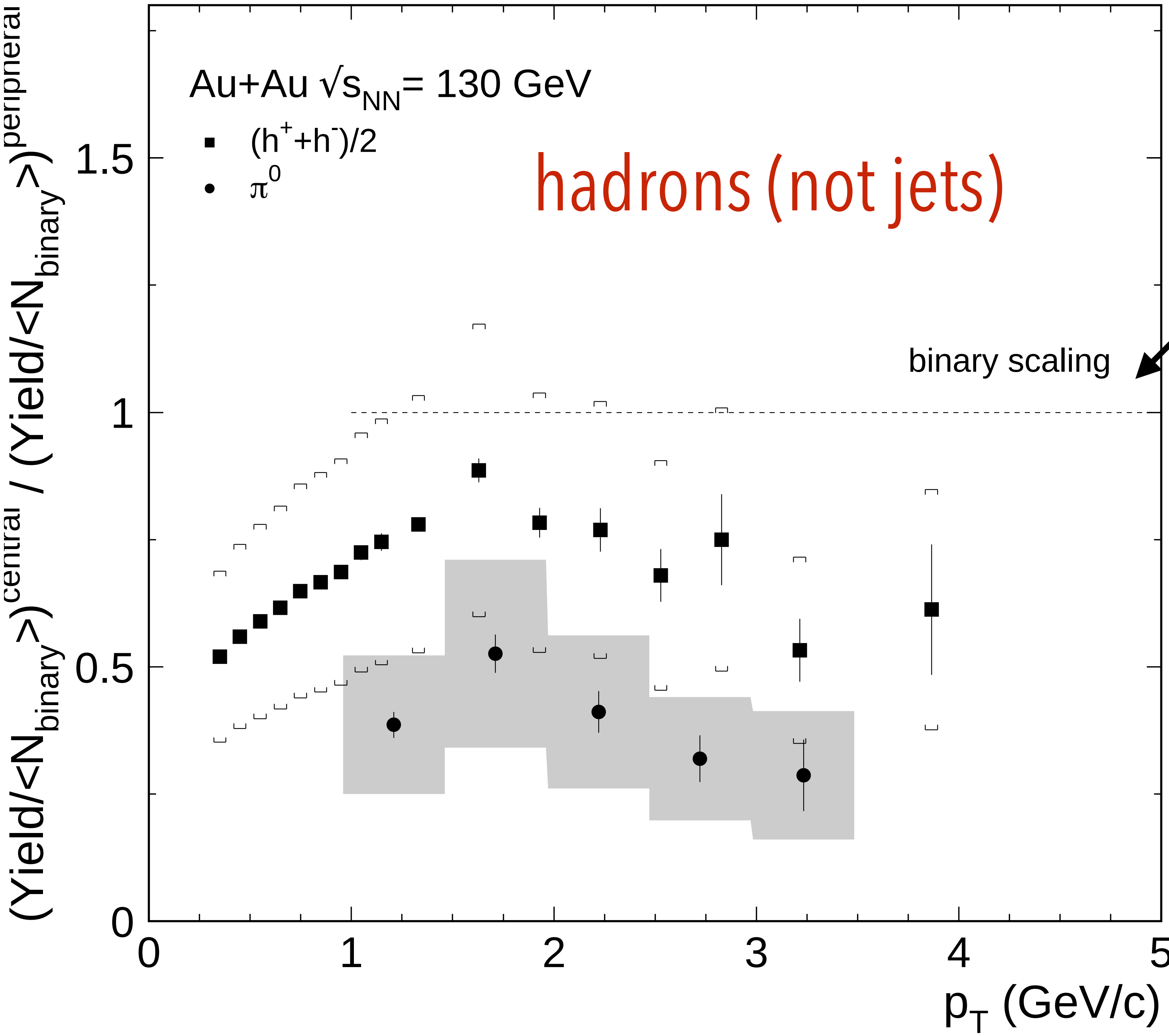
jet measurements in PbPb collisions

- **how do the jet and QGP interact?**
  - where does the energy lost by the jet go?
  - are the scatterings independent?
  - how is the jet seen by the QGP?

reviews:
Qin & Wang 1511.00790
Blaizot & Mehtar-Tani 1503.05958

observation of "jet" quenching at RHIC

yield in central collisions / yield in peripheral collisions scaled by number of nucleon-nucleon collisions

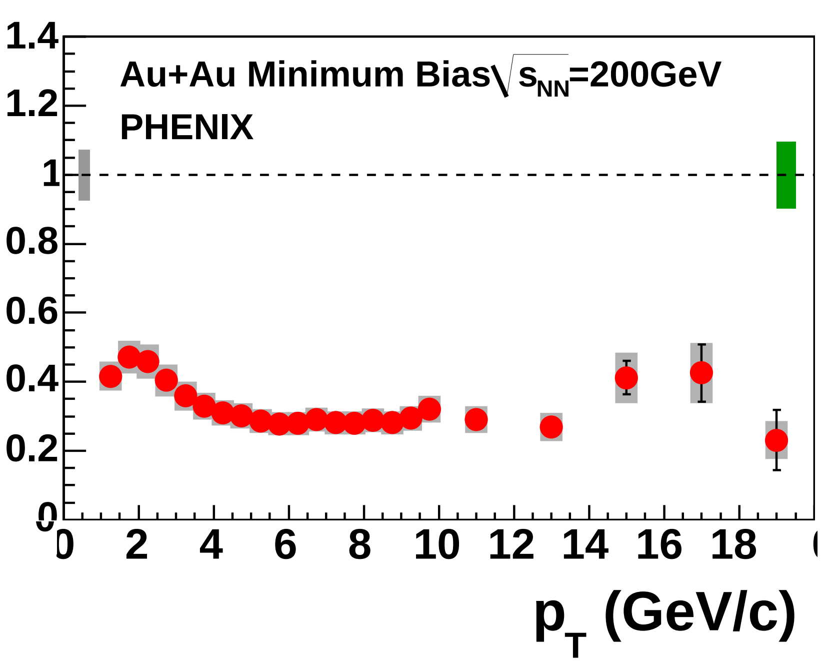


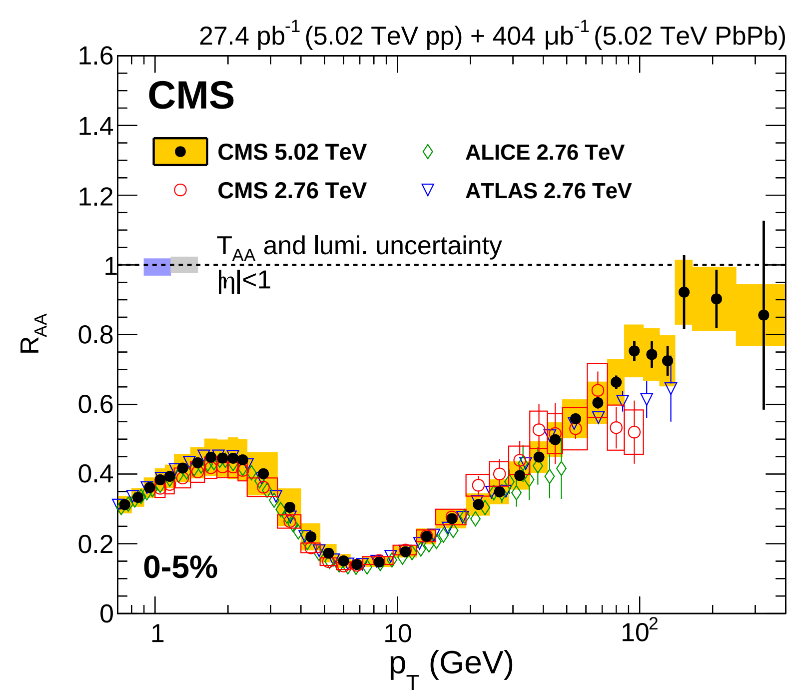
expectation if no jet quenching

PHENIX, PRL 88 022301 (2002)

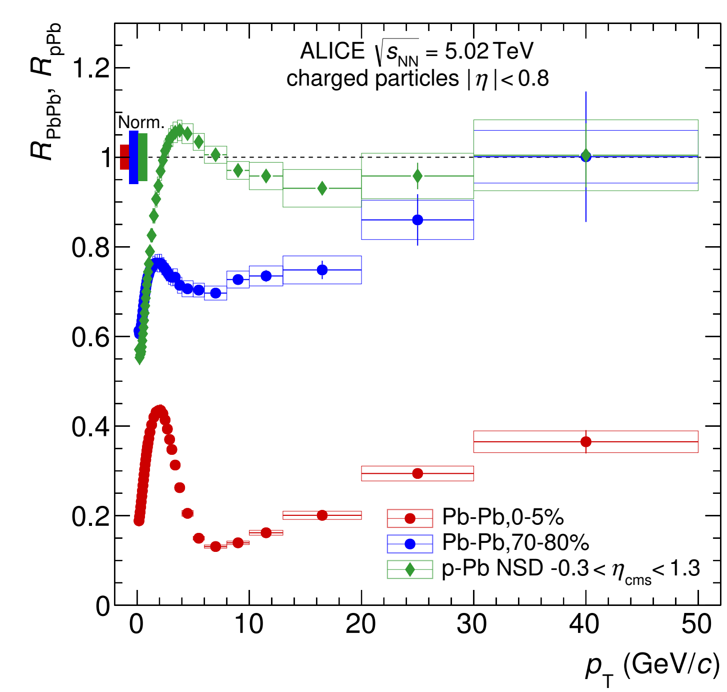
particle spectra suppression

- it is non-trivial to measure and define jets
- higher momentum: jet measurements become easier
- lower momentum: move to measuring the particles from jets
    - precise measurements at RHIC and the LHC





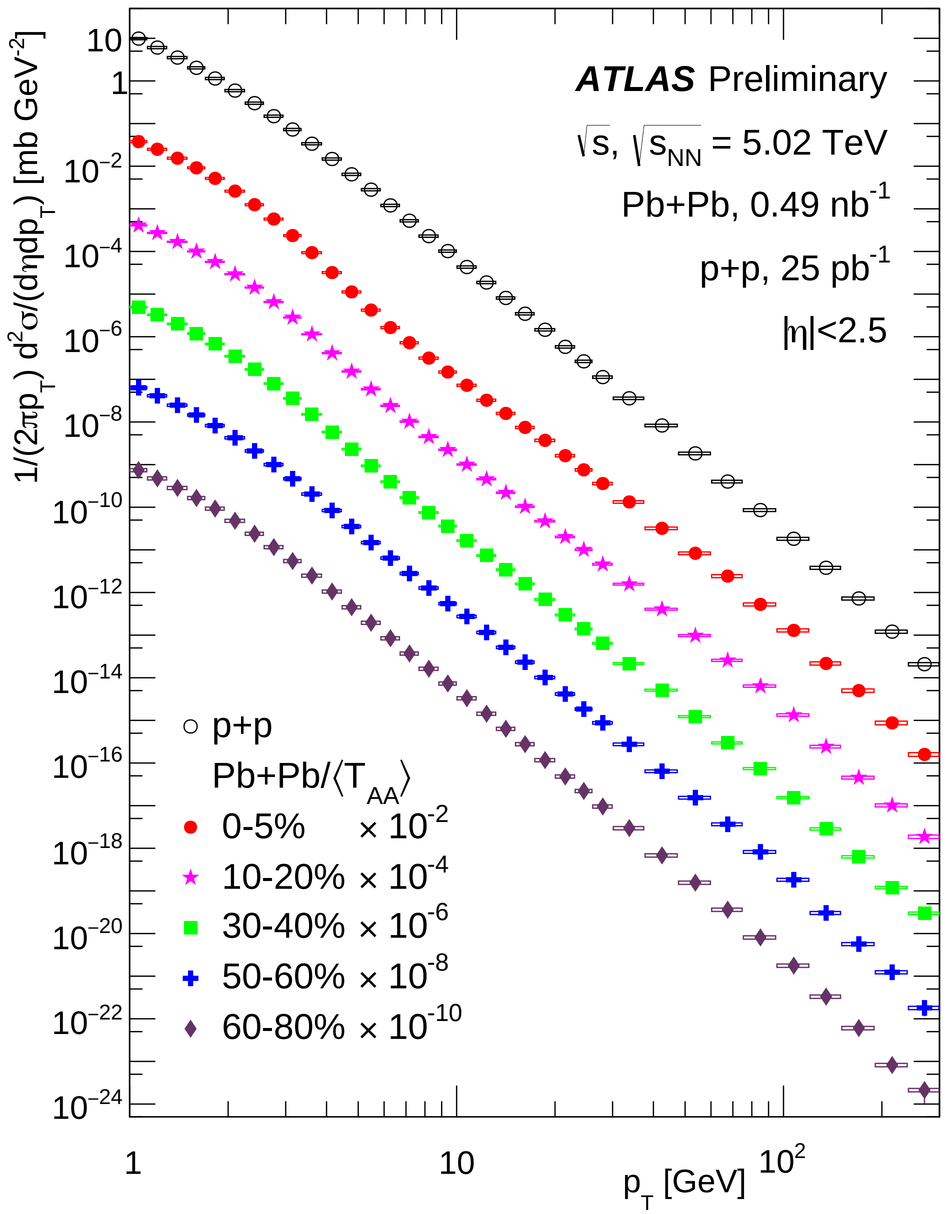
CMS, JHEP 1704 (2017) 039



ALICE, JHEP11 (2018) 013

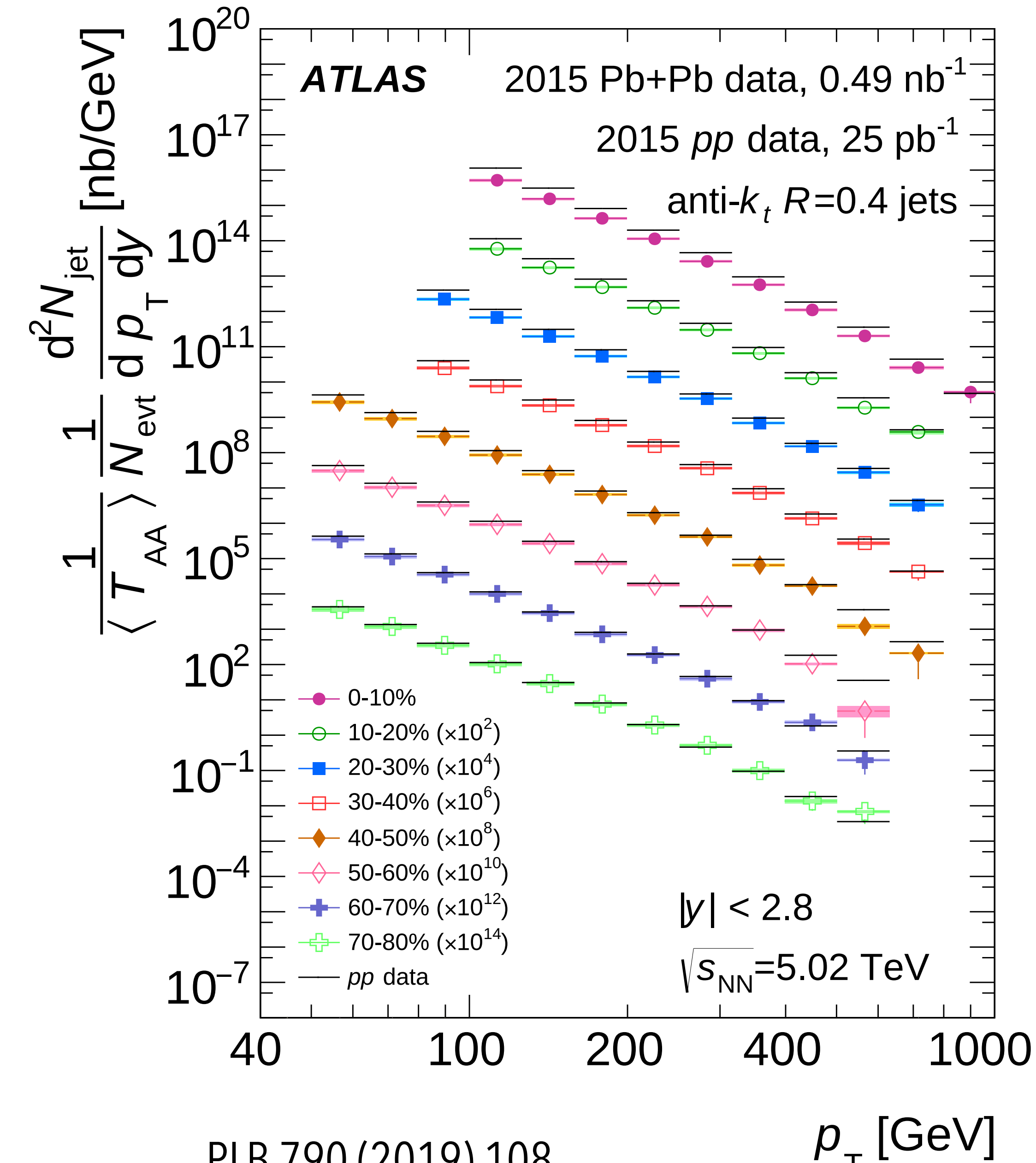
spectra vs reconstructed jets

charged particles



ATLAS-CONF-2017-012

reconstructed calorimeter jets



PLB 790 (2019) 108

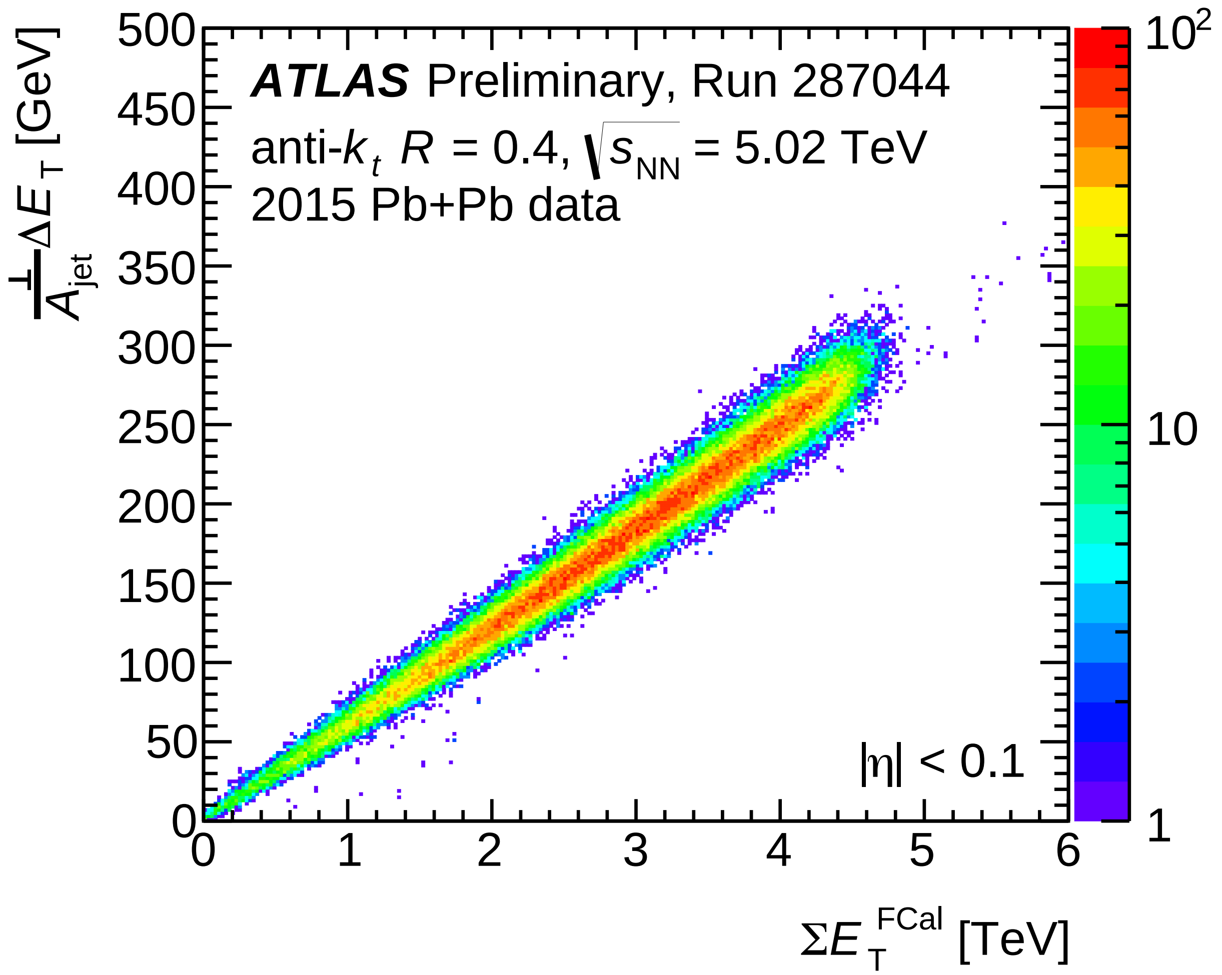
same data, same experiment, *4x higher* p_T range from reconstructed jets

additionally, measurements of the *structure of jets* provide additional information

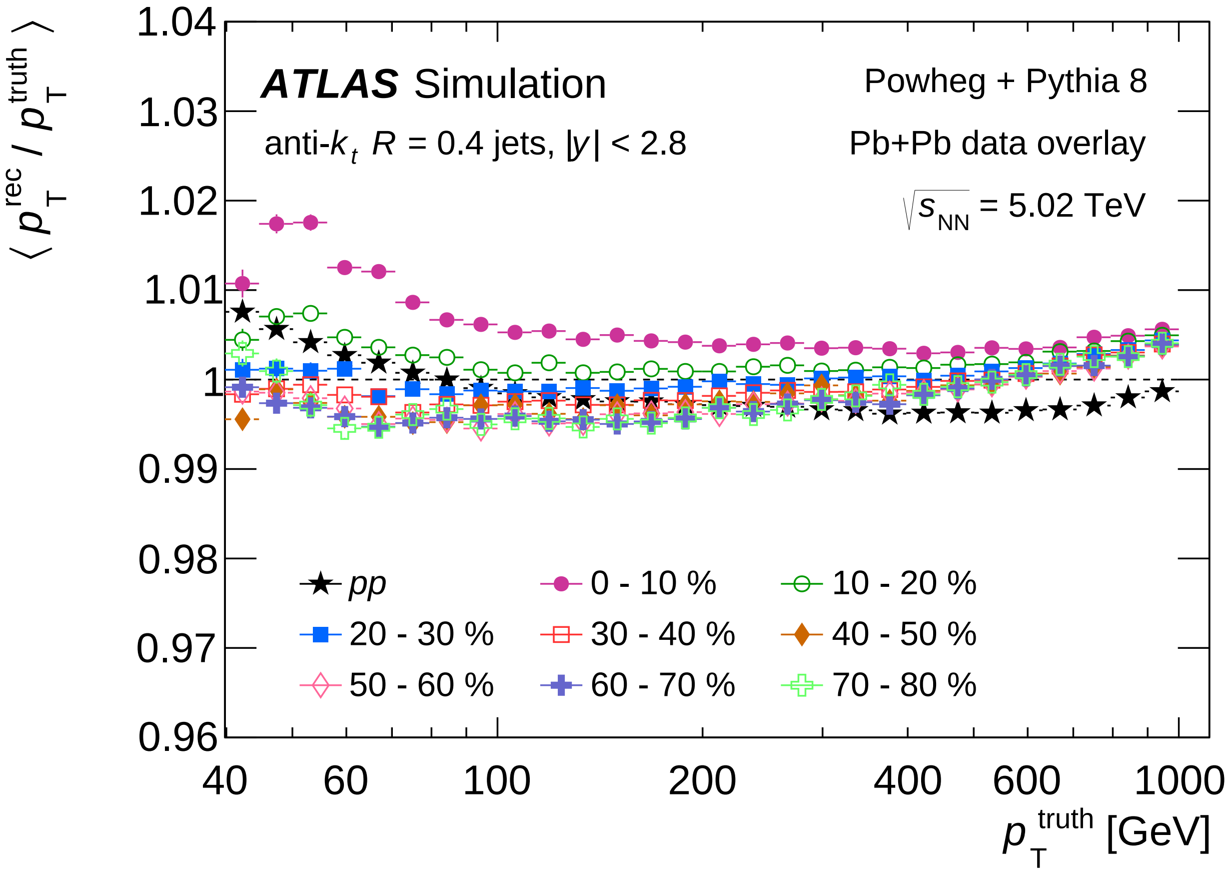
HI collisions are a challenging place to measure jets

- an R = 0.4 cone in a PbPb collision at 5 TeV has up to 150 GeV of energy from the underlying event (UE) which has to be subtracted
  - UE to subtract goes as R^2 (see C. McGinn CMS at Quark Matter 2018)
- ATLAS uses an iterative procedure to estimate the UE; ALICE and CMS use Constituent Subtraction

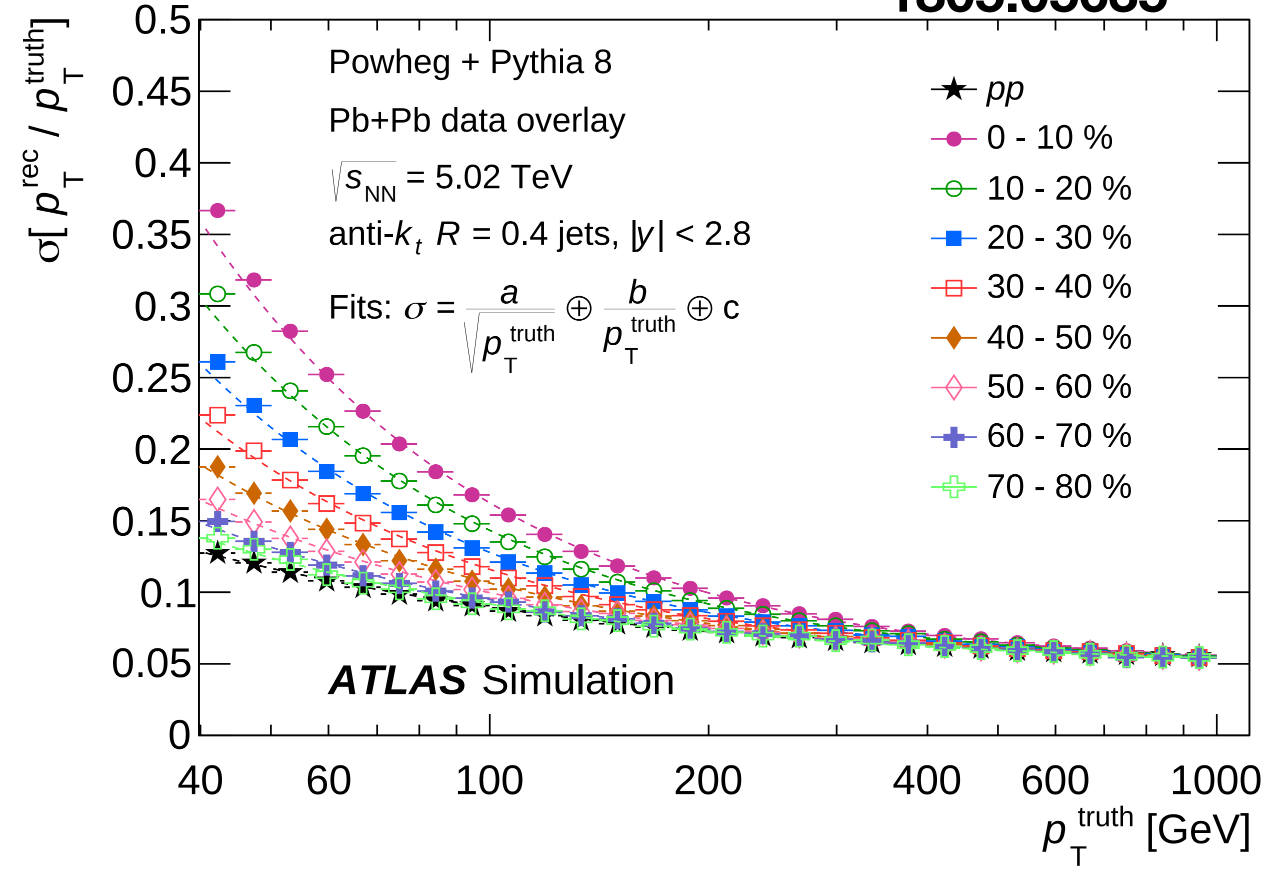
fluctuations in the UE can mimmic jets at lower p_T in ATLAS jet measurements in central collisions start at ~100 GeV



jet performance



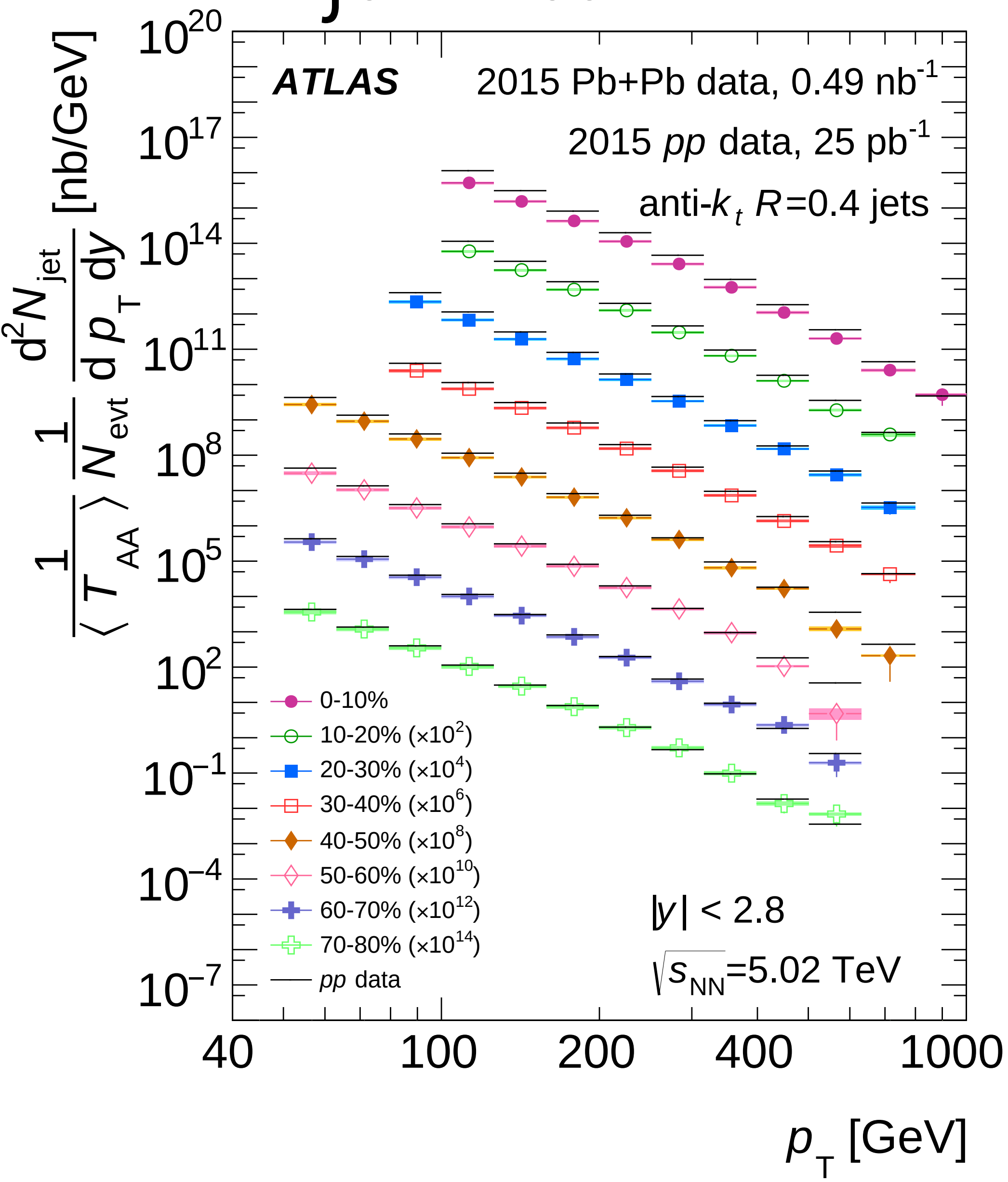
1805.05635



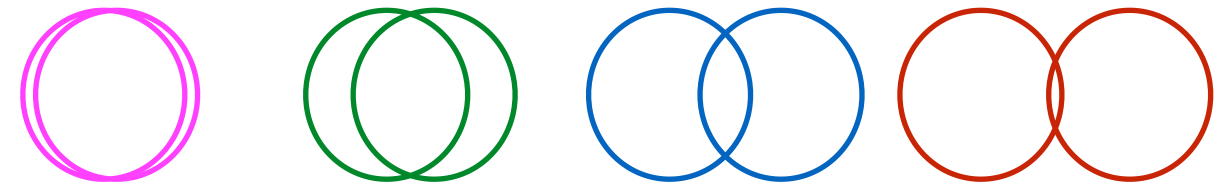
- Jet Energy Scale: ~1% centrality dependence above 100 GeV
- Jet Energy Resolution: degraded in central collisions due to underlying event fluctuations

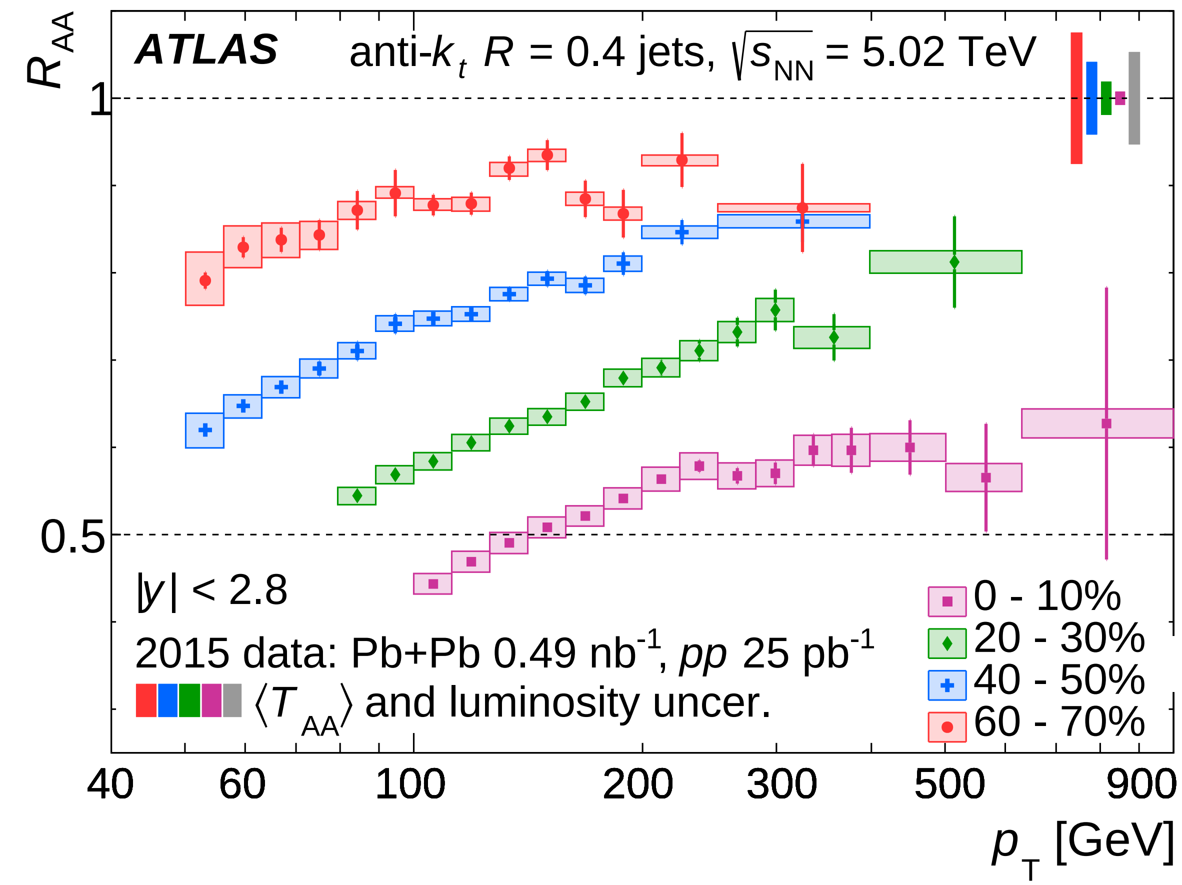
jet counting

jet rates



jet rates / expectations





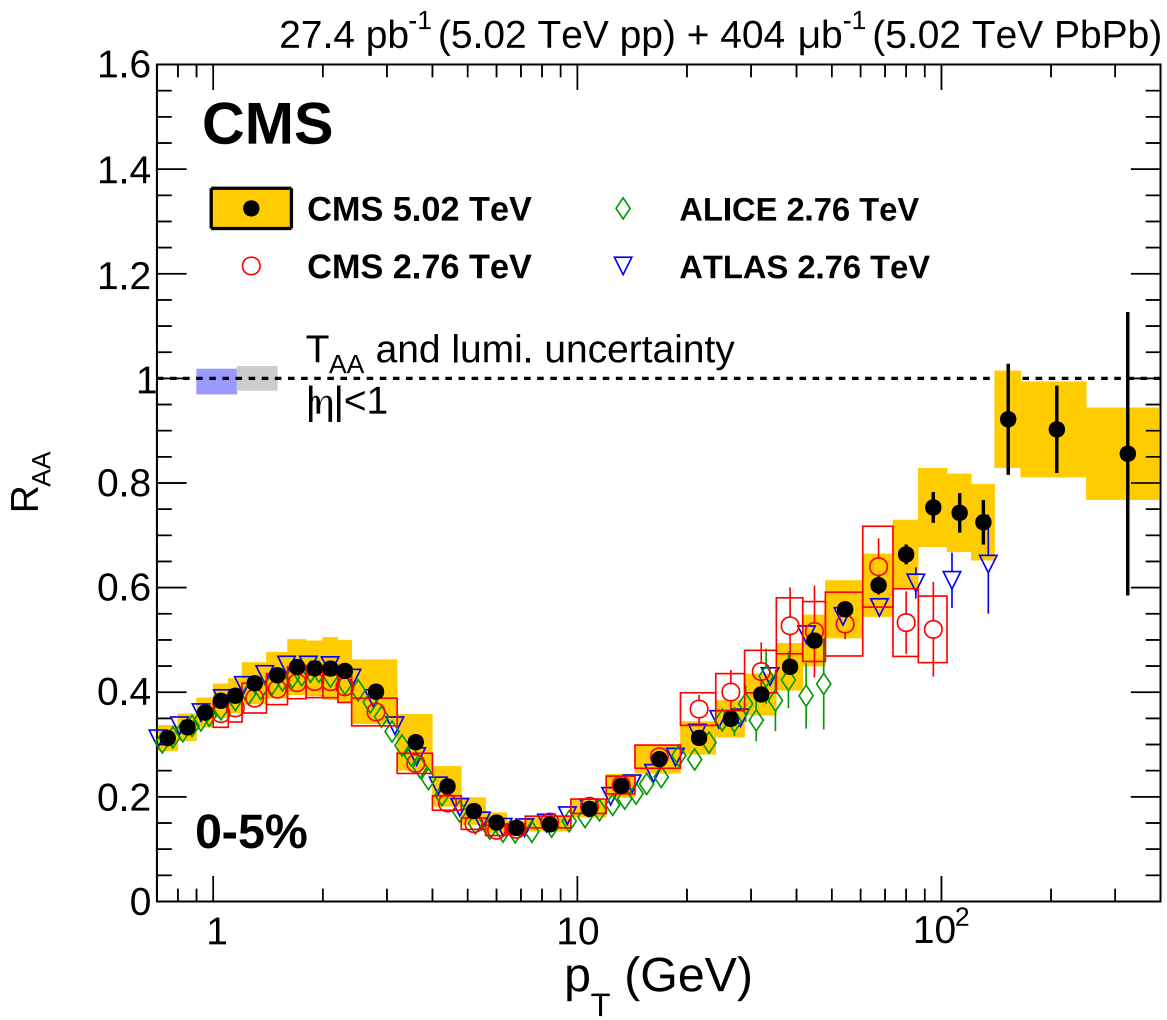
jet momentum (p_T) (GeV)

- fewer jets when there is more QGP
- jets shift downward in momentum → "jet quenching"
- quenching ~independent of jet momentum out to TeV scale jets

1805.05635

lecture 2

jet counting



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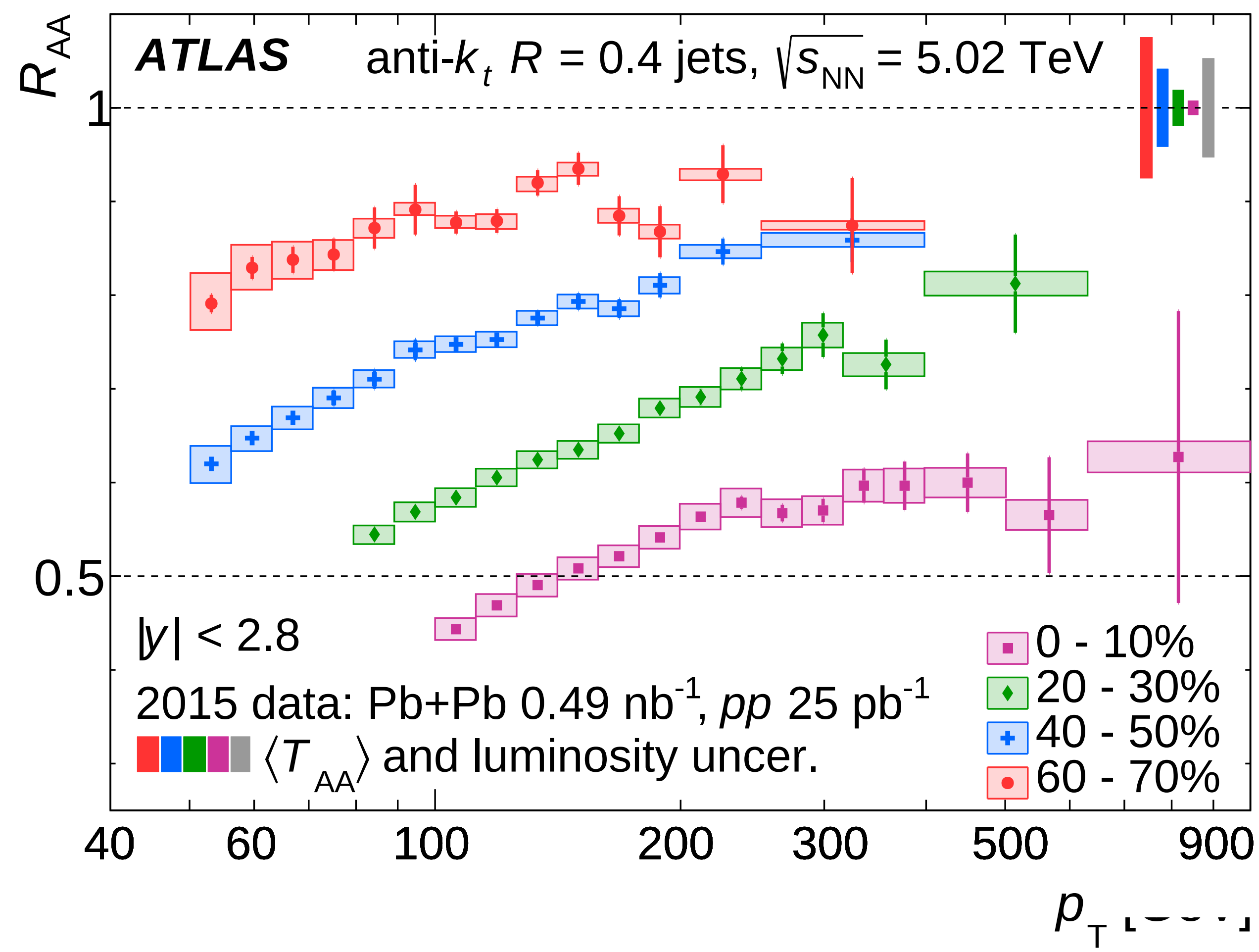
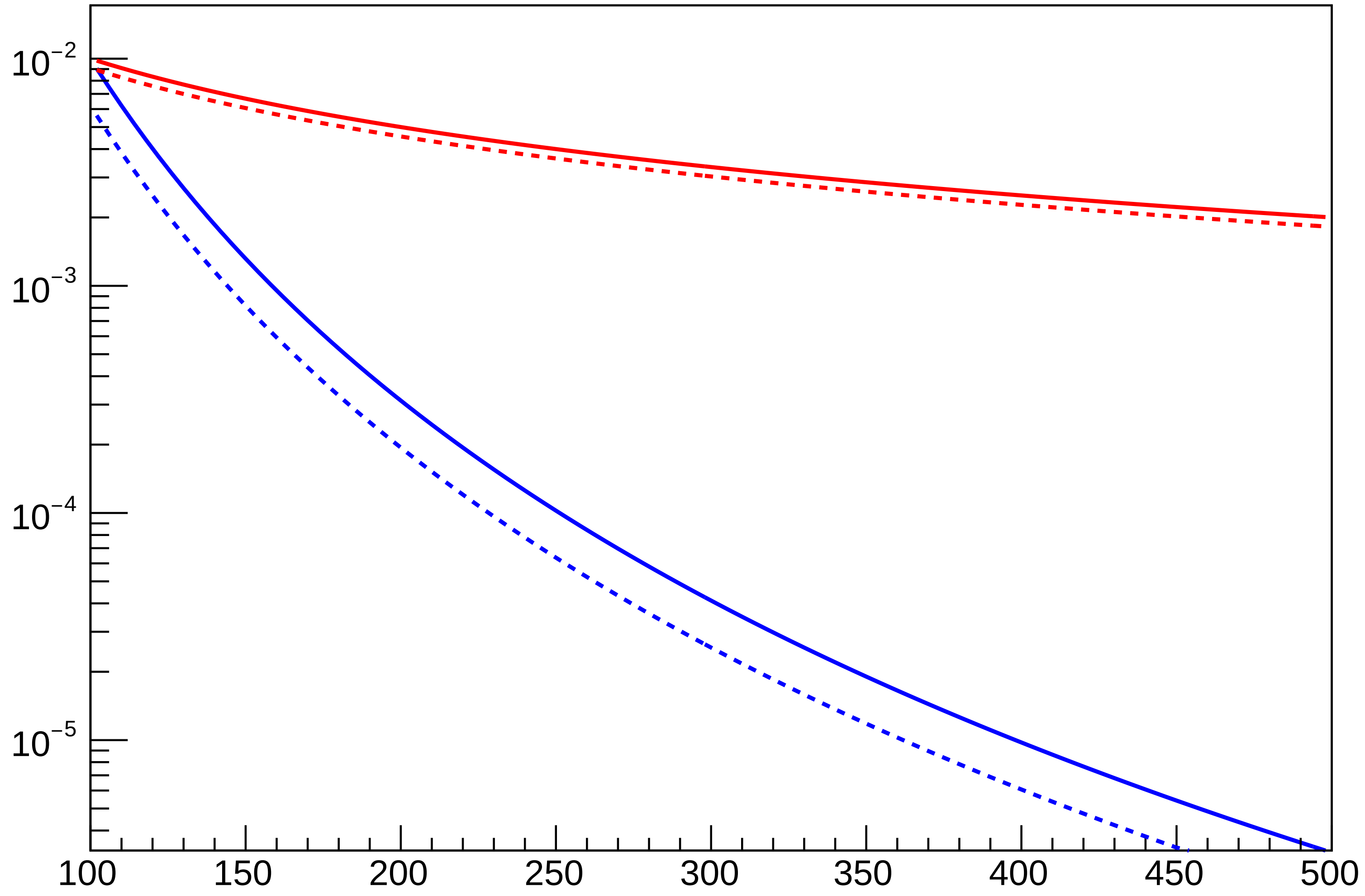


R_{AA} values are related to the strength of jet quenching, but are not a direct measure

beware of ratios!

dashed lines: solid lines with 10% “quenching”

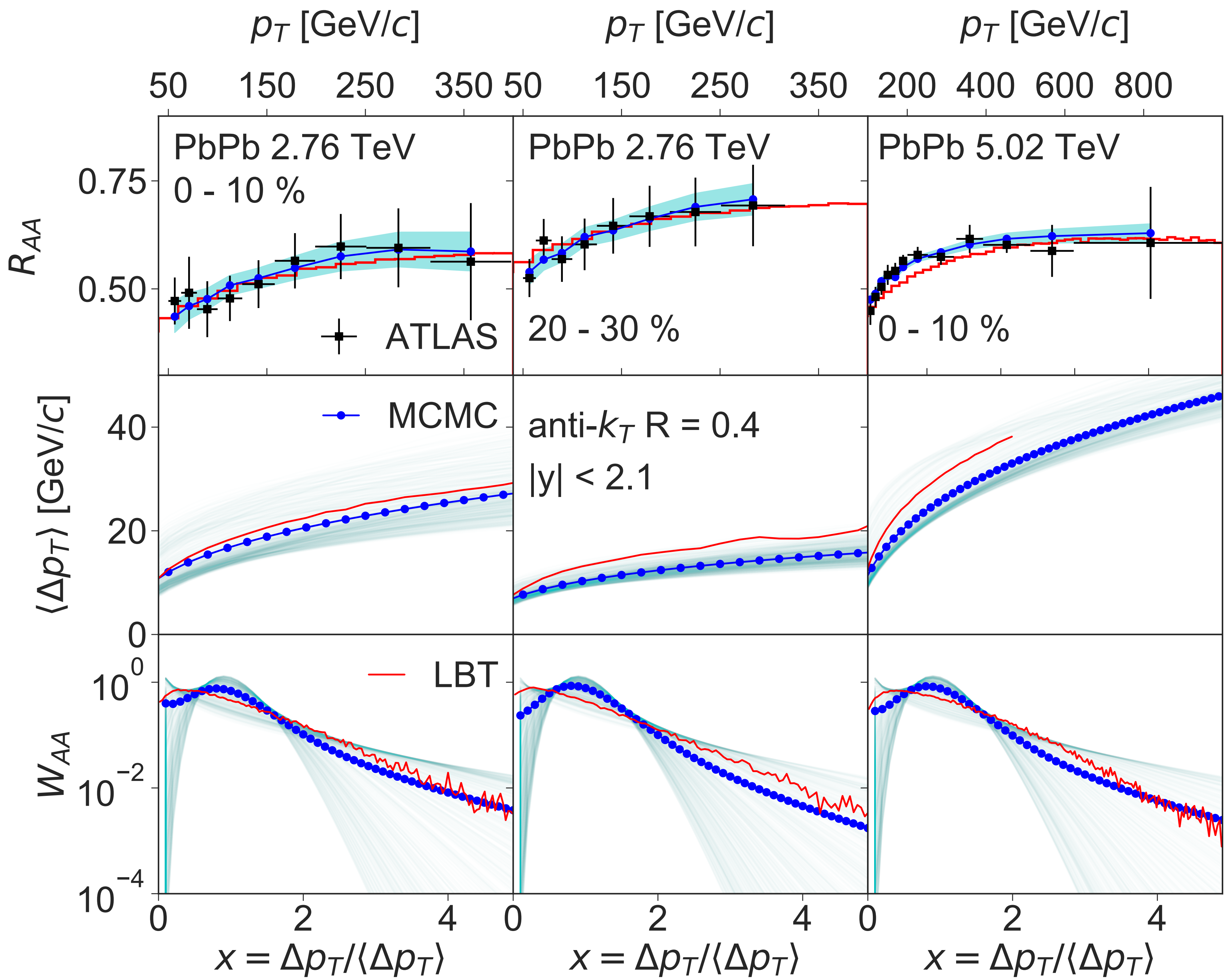


R_{AA} = dashed / solid

quenching is equal but R_{AA} will certainly not be

how much energy does the jet lose?

PRL 122 252302 (2019)



Bayesian analysis suggests jets lose 10s of GeV based on R_{AA} measurements

does this agree with the total amount of lost momentum recovered outside the jet?

experimental tools

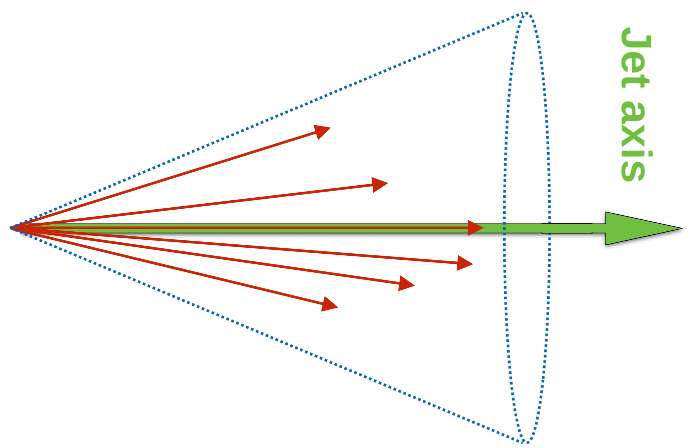
- change the parton flavor: light quarks/gluons/c and b quarks should each interact differently with the QGP
- look inside the jet: how do the particles make up the jet differently in AA collisions compared to pp collisions?
- what is around the jet?

there is no one observable that provides the answers

experimentally, we need to over-constrain theoretical models with **systematic, differential** data

need theoretical models which can describe multiple observables, collision energies, collision systems, etc

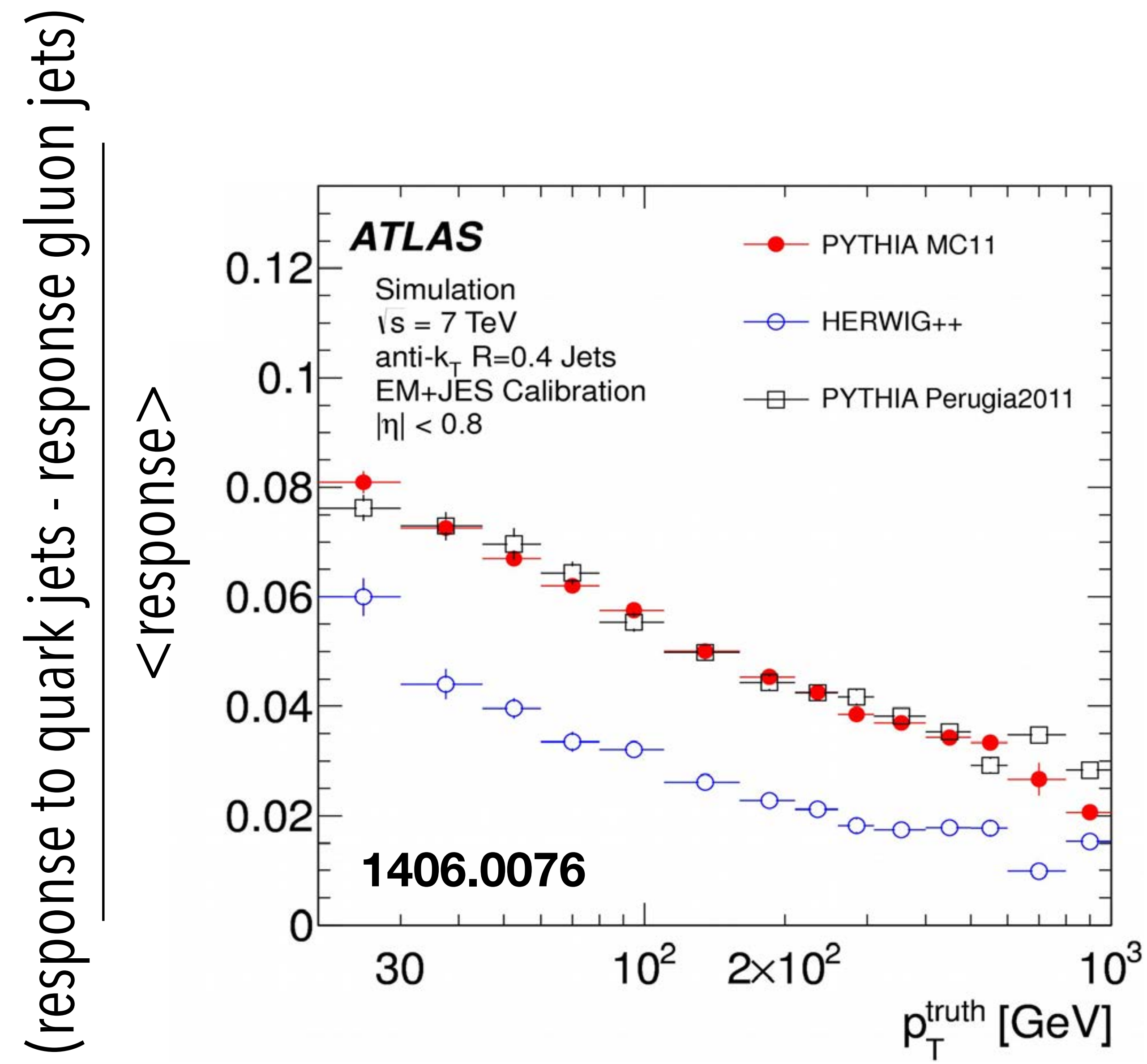
measurement of fragmentation functions



$$D(z) \equiv \frac{1}{N_{\rm jet}} \frac{dn_{\rm ch}}{dz}$$

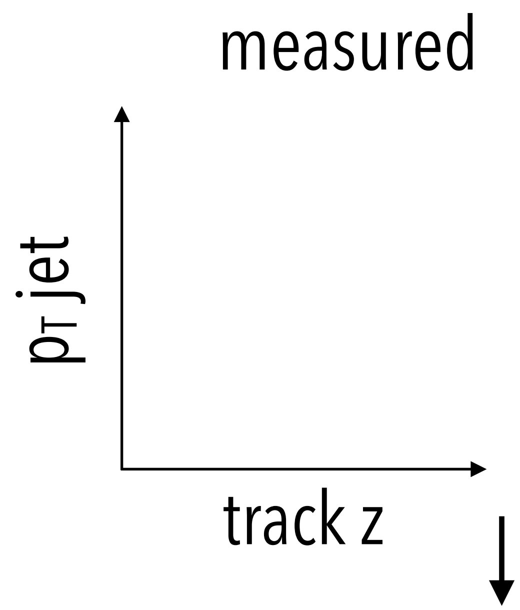
$$z \equiv p_{\rm T} \cos \Delta R \, / \, p_{\rm T}^{\rm jet}$$

$$D(p_{\rm T}) \equiv \frac{1}{N_{\rm jet}} \frac{dn_{\rm ch}}{dp_{\rm T}}$$

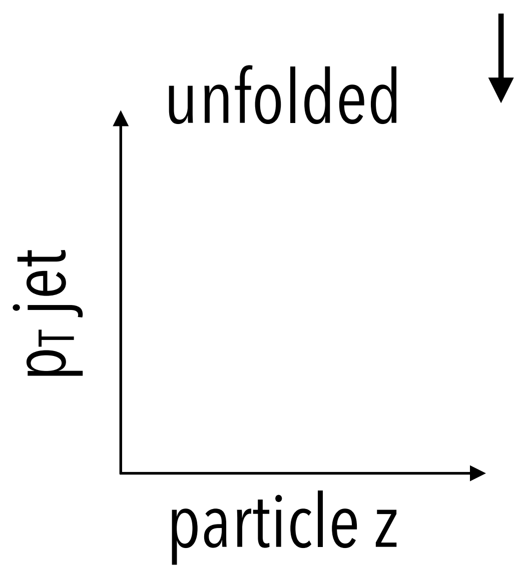


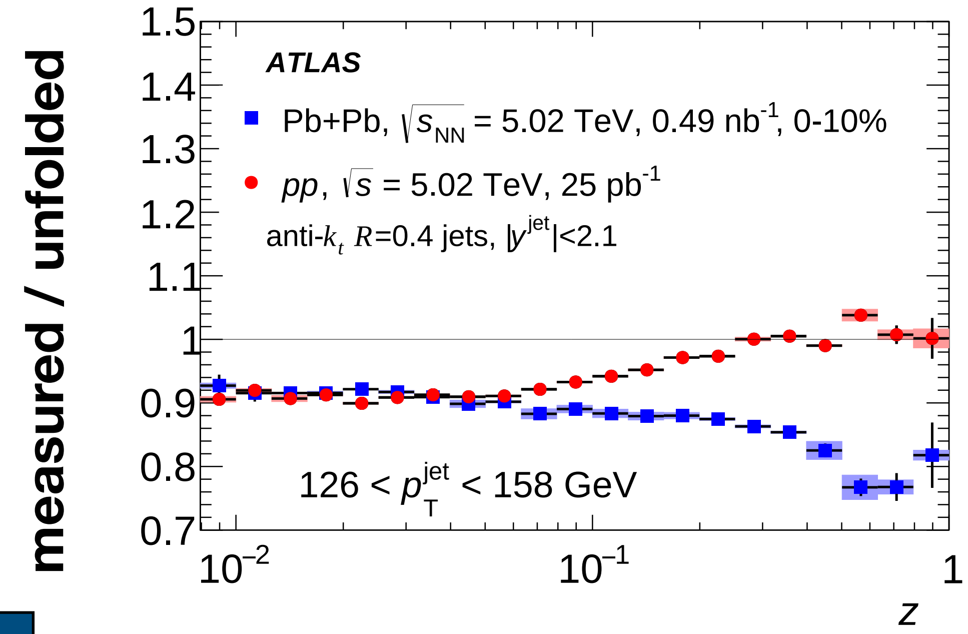
jet energy measurement is correlated with how the jet fragments!

2 -dimensional unfolding



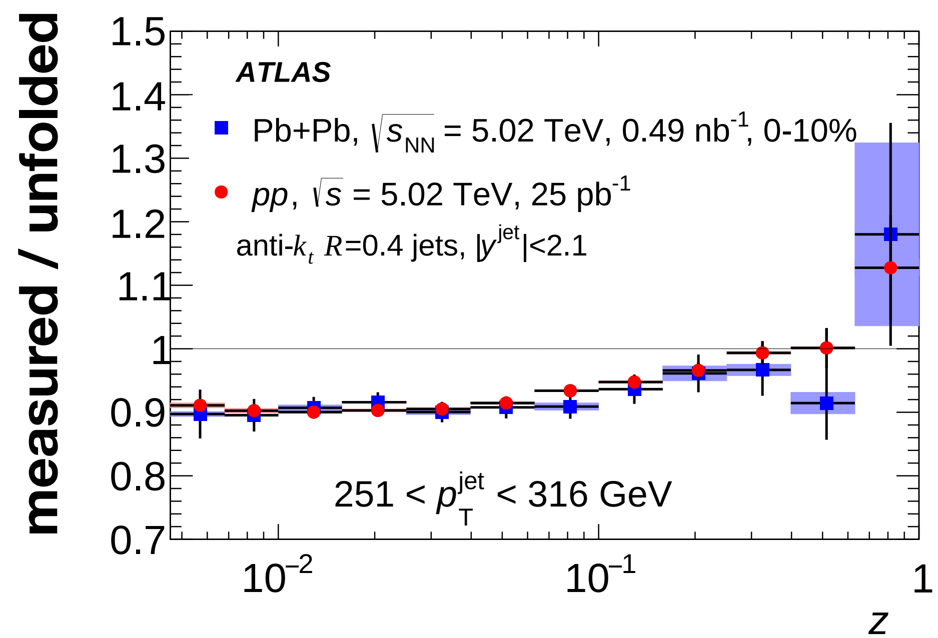
response matrix in $p_{T,meas}$, $p_{T,true}$, z_{meas}, z_{true}





p_{Tjet}: 126 - 158 GeV

large JER centrality dependence to JER due to UE fluctuations

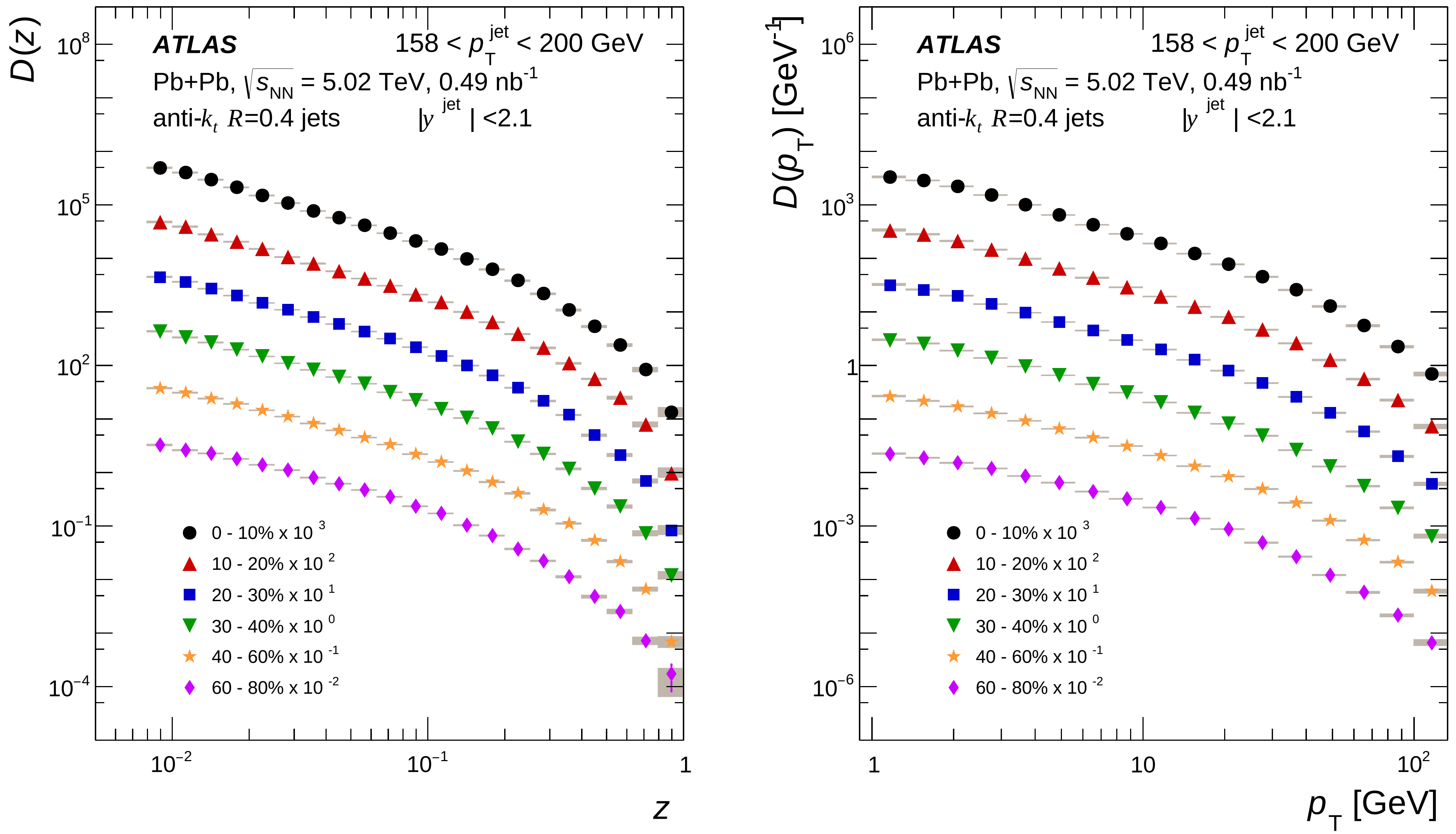


p_{Tjet}: 251-316 GeV

smaller UE effect similar unfolding change in pp & PbPb

PRC 98 024908 (2018)

fragmentation functions in PbPb collisions



to make sense of these, take ratios to the same quantity in pp collisions

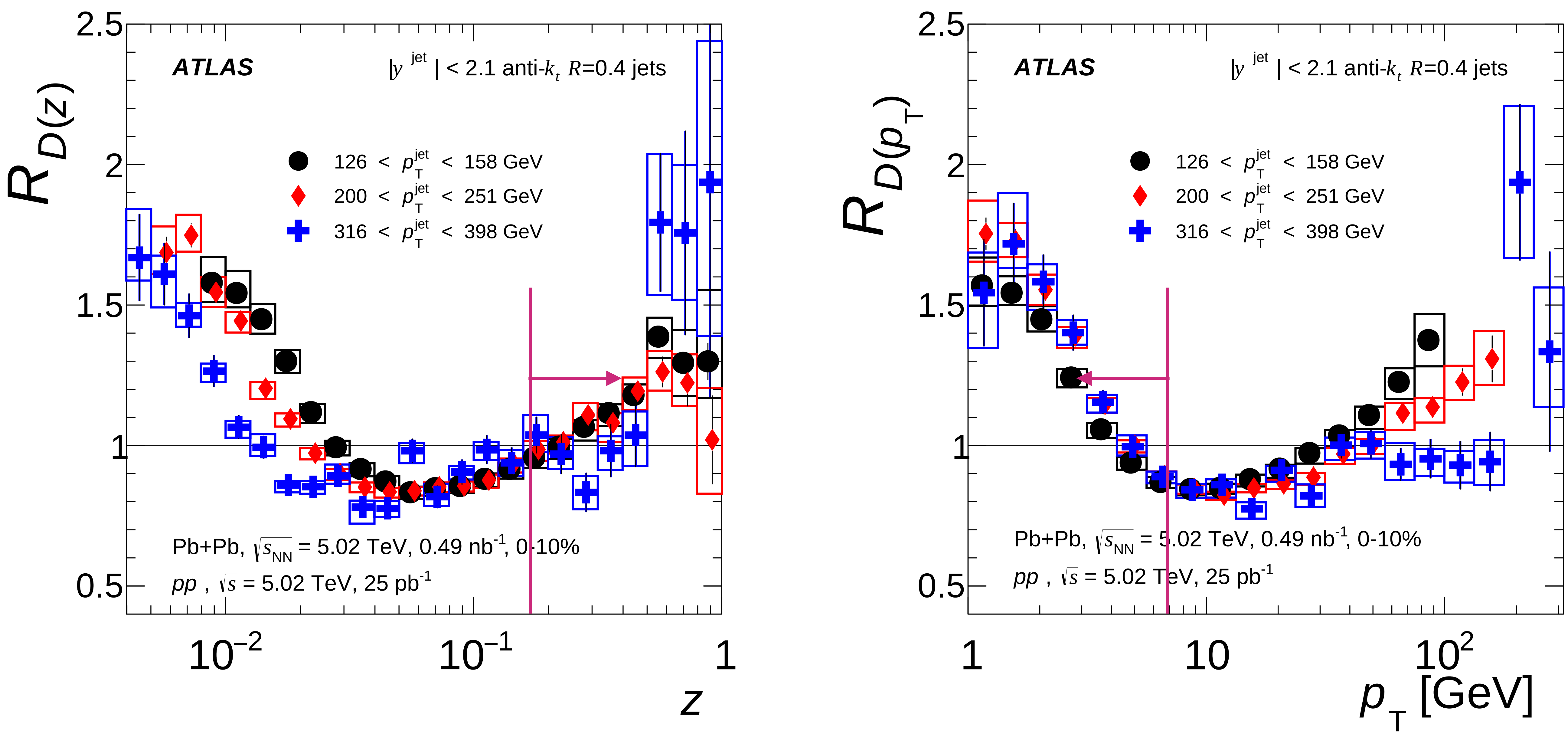
$$R_{D(z)} \equiv \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{pp}},$$

$$z \equiv p_{\mathrm{T}} \cos \Delta R \,/\, p_{\mathrm{T}}^{\mathrm{jet}}.$$

$$R_{D(p_{\mathrm{T}})} \equiv \frac{D(p_{\mathrm{T}})_{\mathrm{PbPb}}}{D(p_{\mathrm{T}})_{pp}}.$$

PRC 98 024908 (2018)

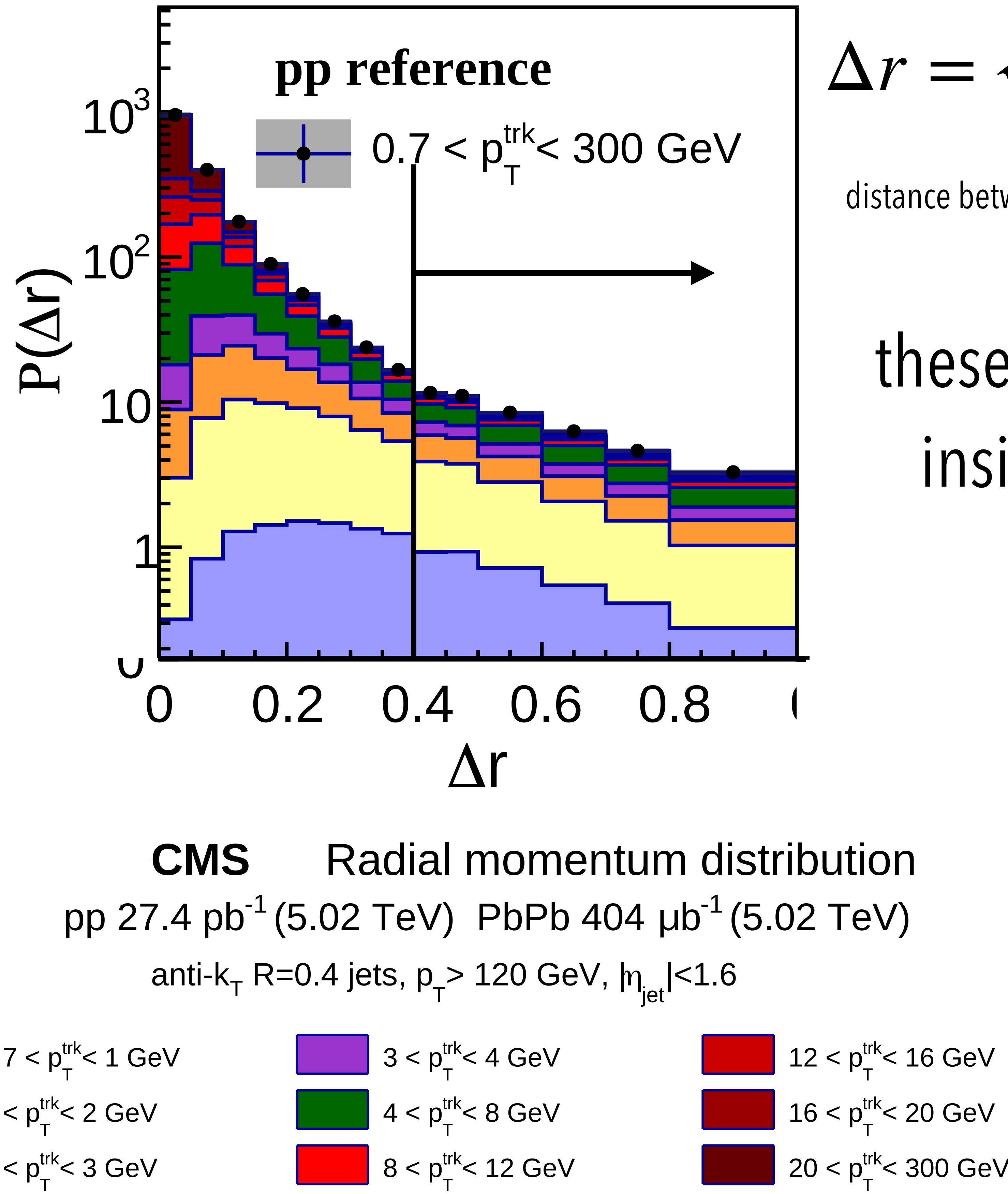
ratios of fragmentation functions in PbPb / pp



PRC 98 024908 (2018)

angle & momentum distributions of particles in jets

1803.00042



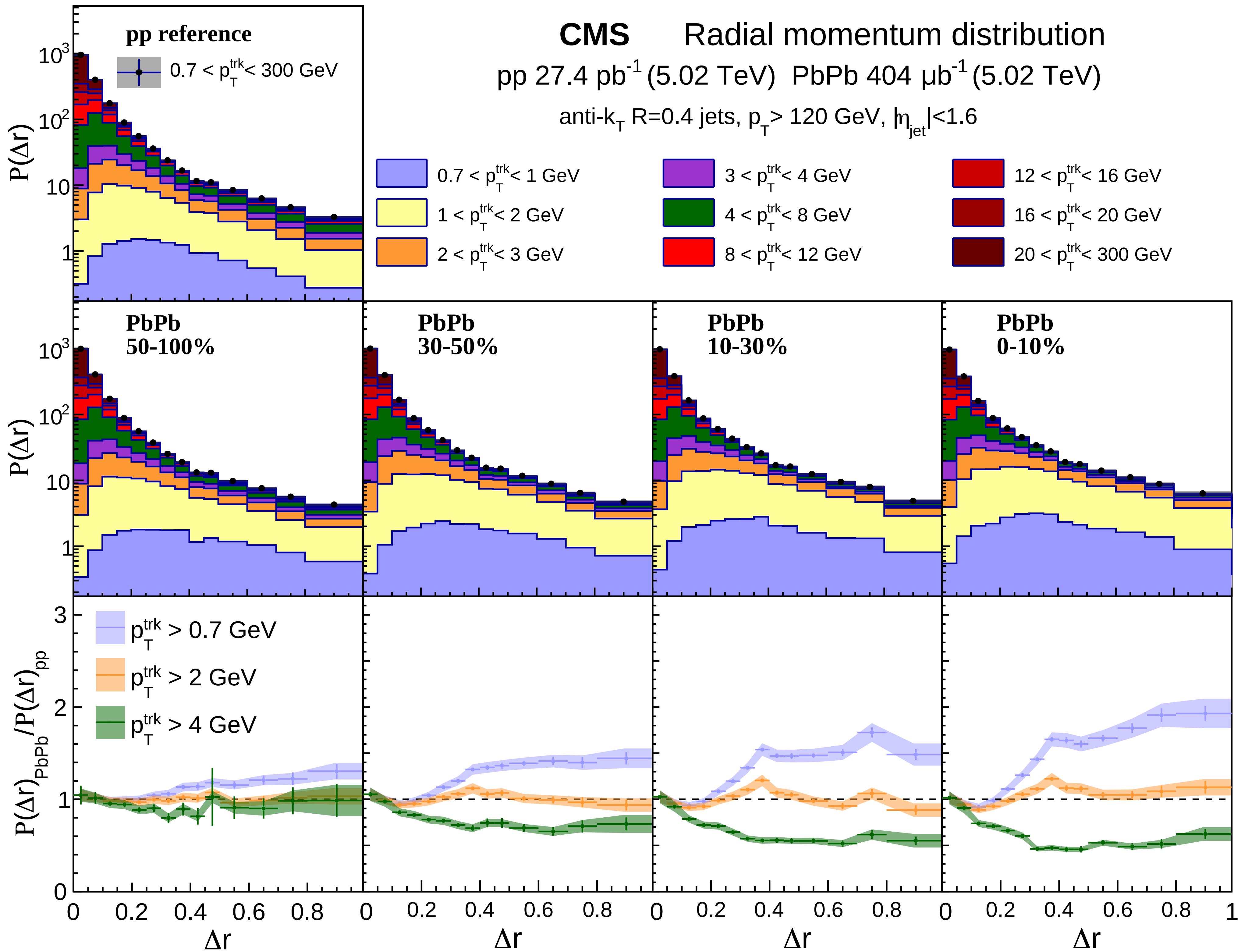
$$\Delta r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

distance between the jet axis and the particle

these particles are not inside the jet cone

where does the lost energy go?

1803.00042

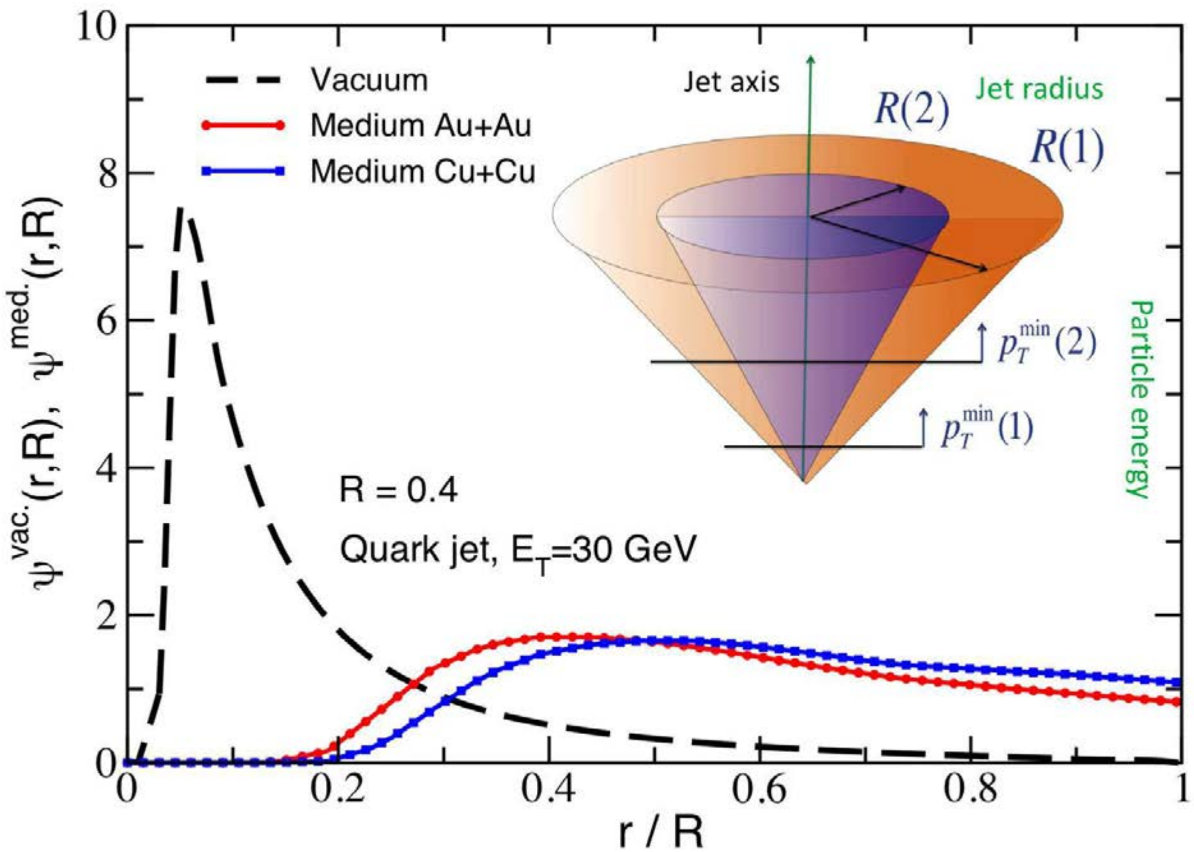


extra particles within and near to jets

where do the low p_T particles come from?

energy loss

relative energy distribution

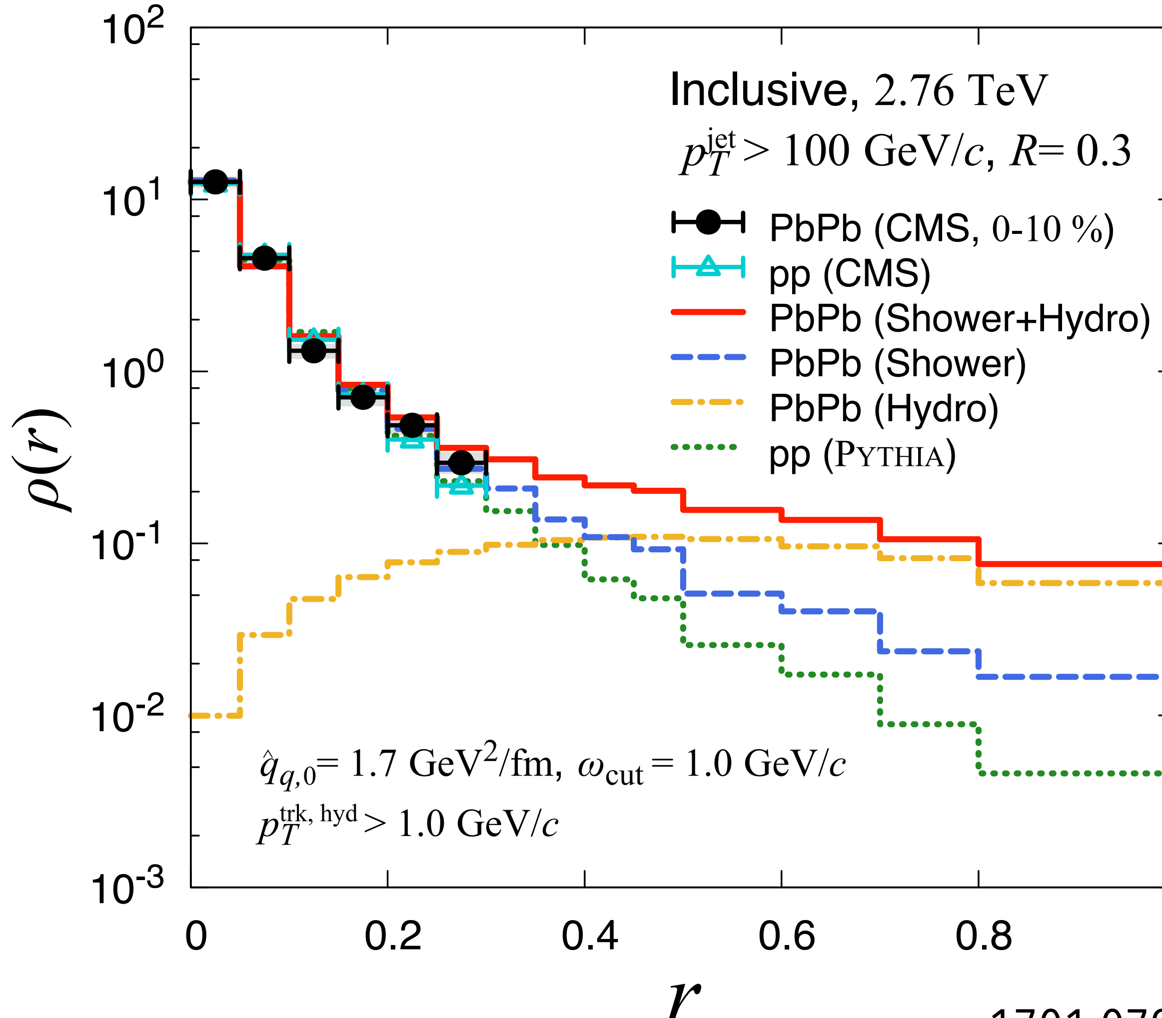


Vitev & Zhang PRL 104 132001 (2010)

pp jets: peaked near the jet axis

AA QGP-jet interactions: broader energy distribution

response of the QGP to the jet

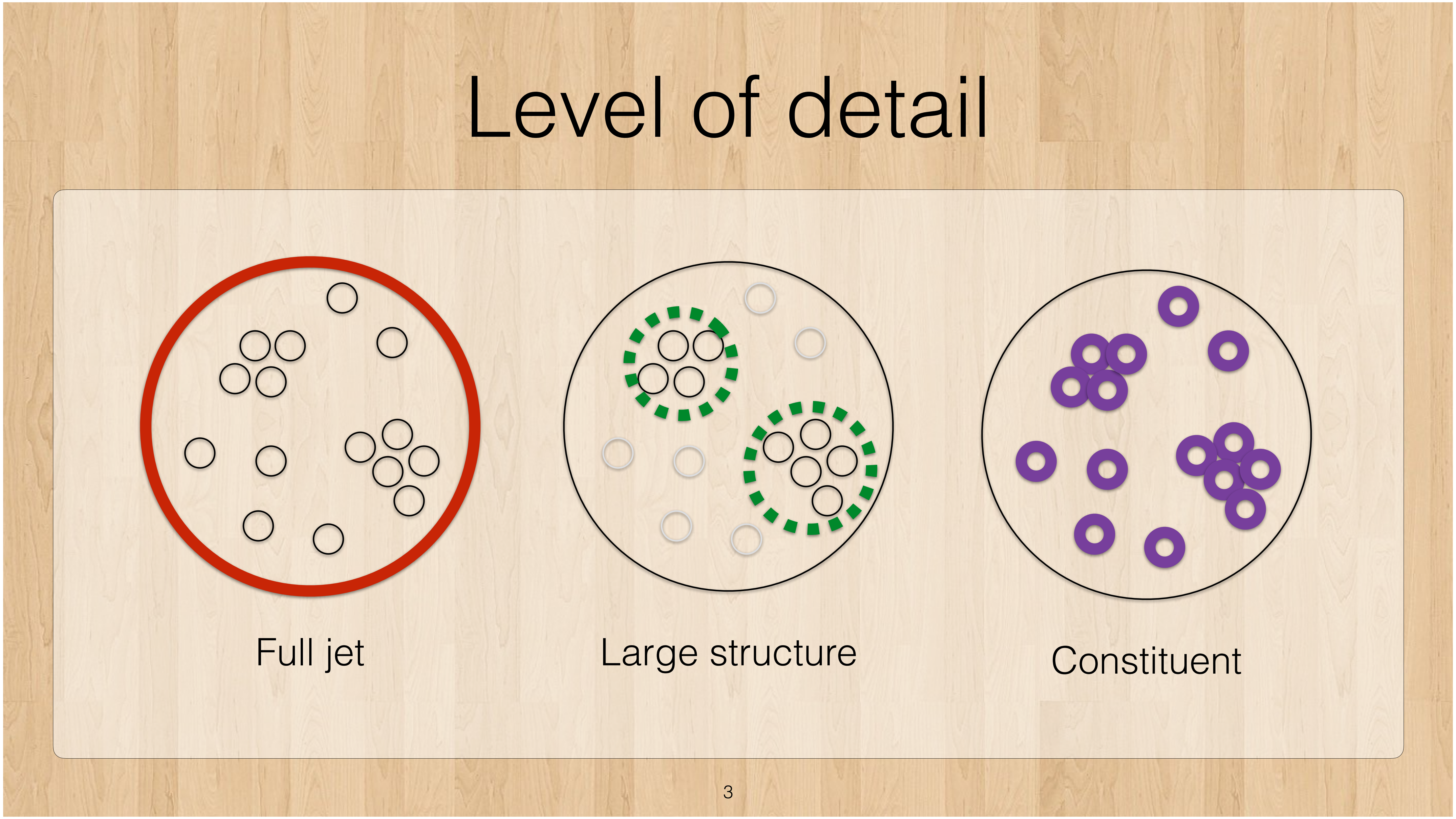


1701.07951

calculations suggest that the **response of the liquid QGP** in response to the jet can also add particles near to the jet

how do we look at jets?

illustration, Yi Chen

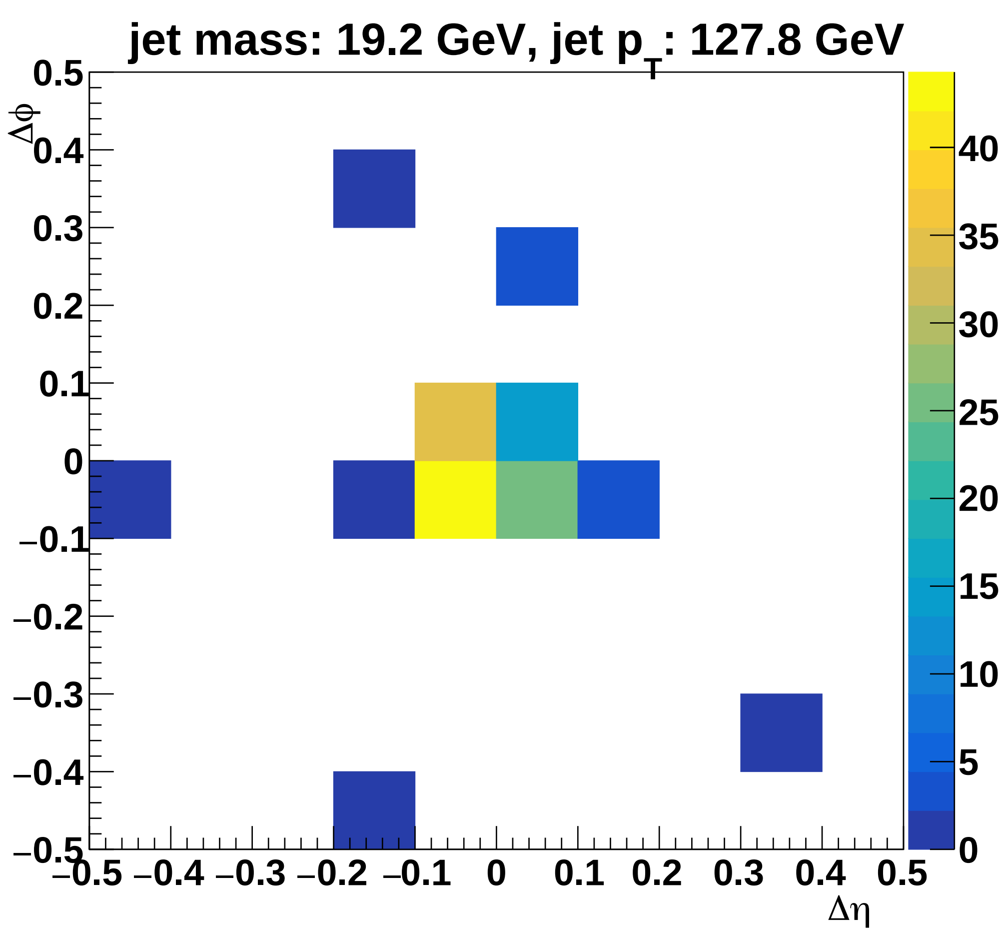


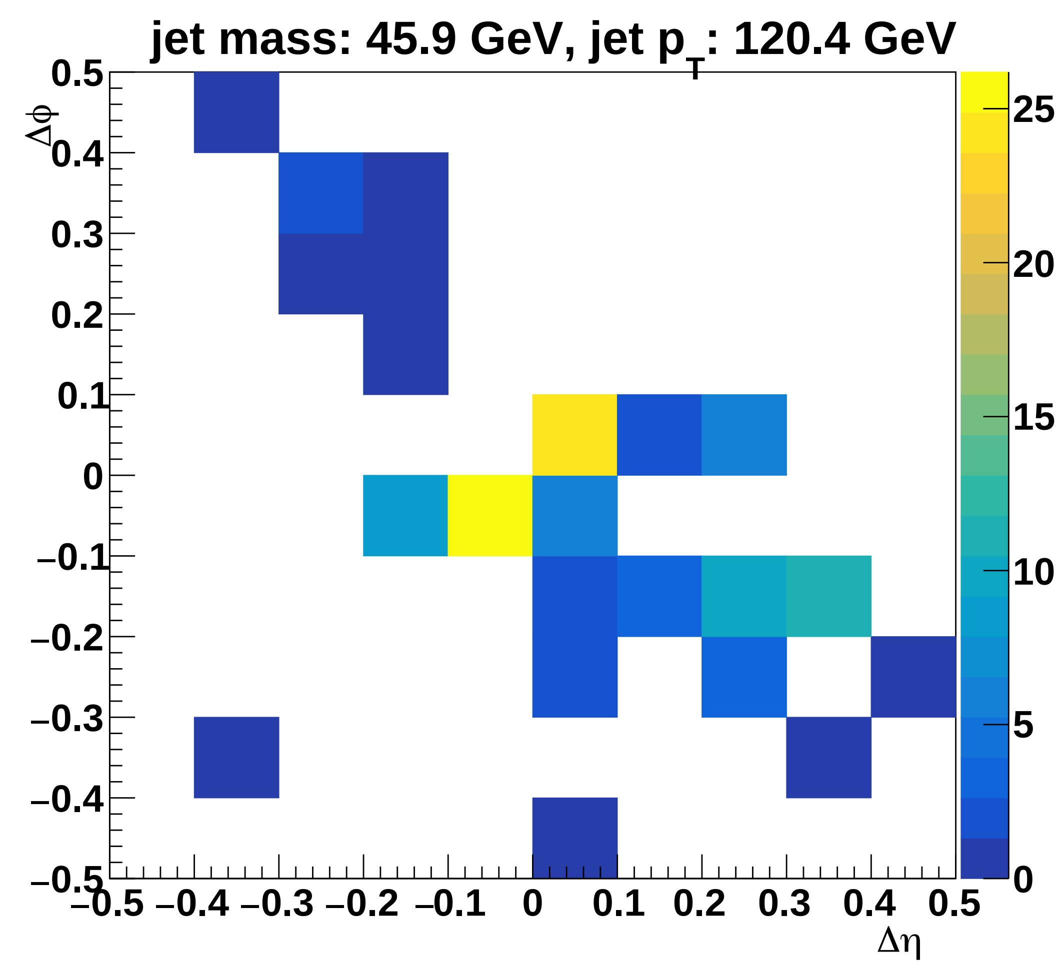
R_{AA} **jet mass** **fragmentation functions**

the mass of jets

how can we characterize the distribution of particles within a jet?

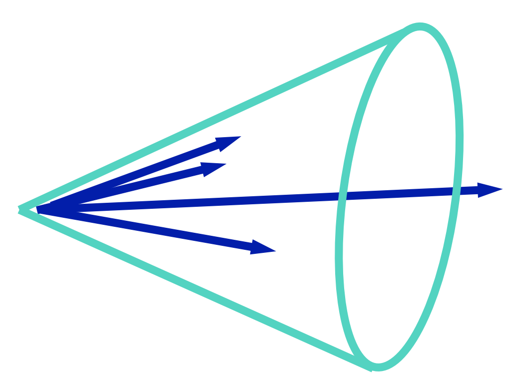
energy distribution within two simulated jets with the same p_T, but different mass





small mass

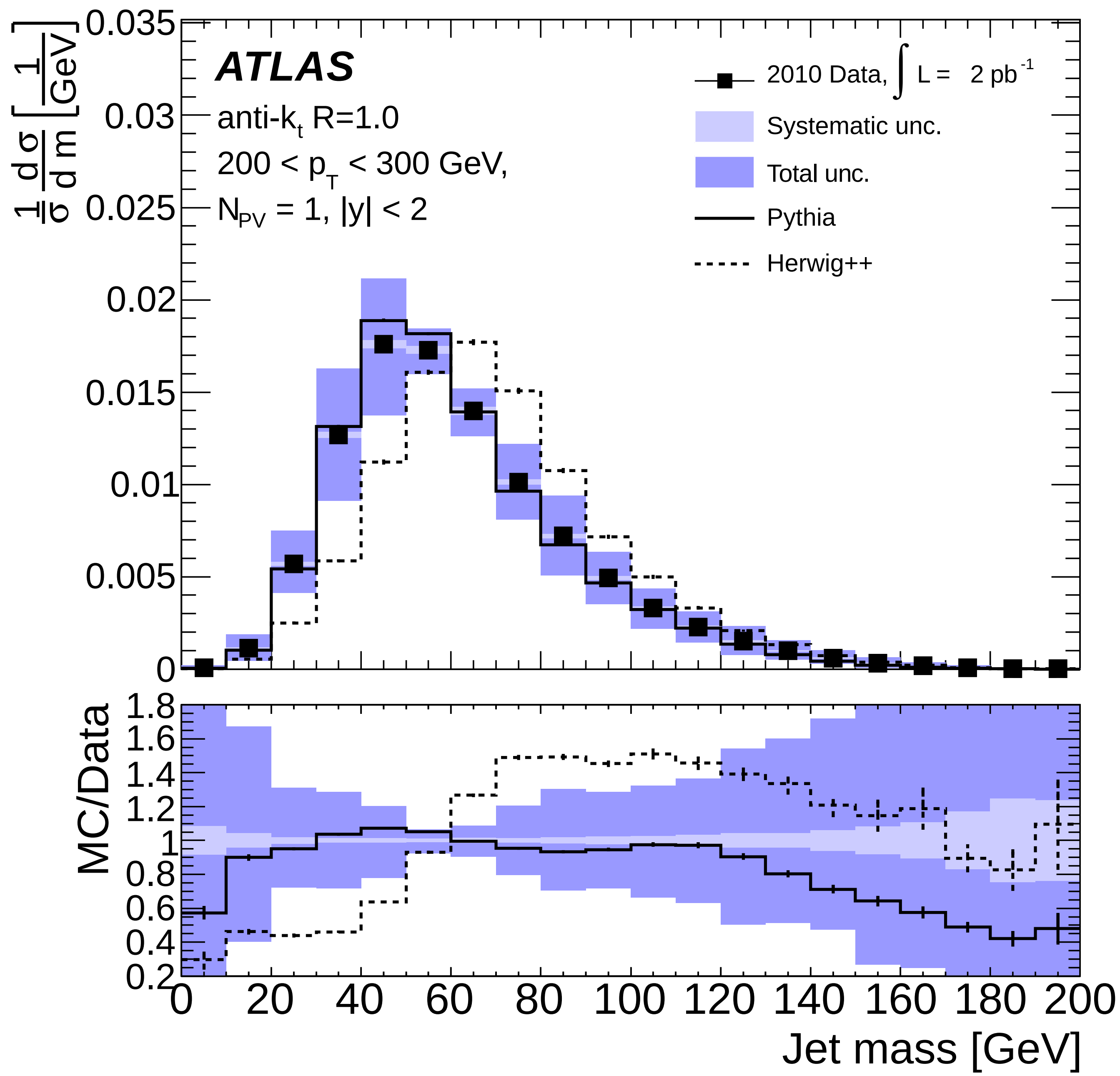
collimated



large mass

spread out

jet mass in proton-proton collisions



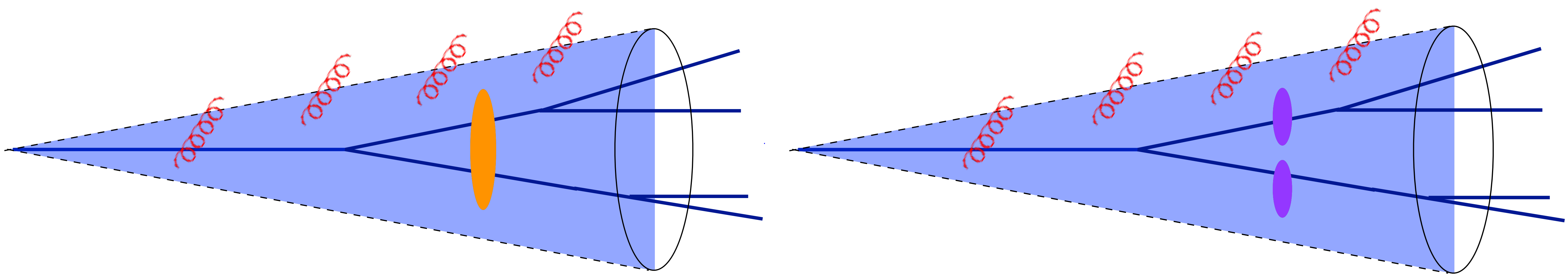
small mass — *collimated*

large mass — *spread out*

JHEP 05 (2012) 128

jet mass in PbPb collisions

physics question: how are the parton showers resolved by the QGP?



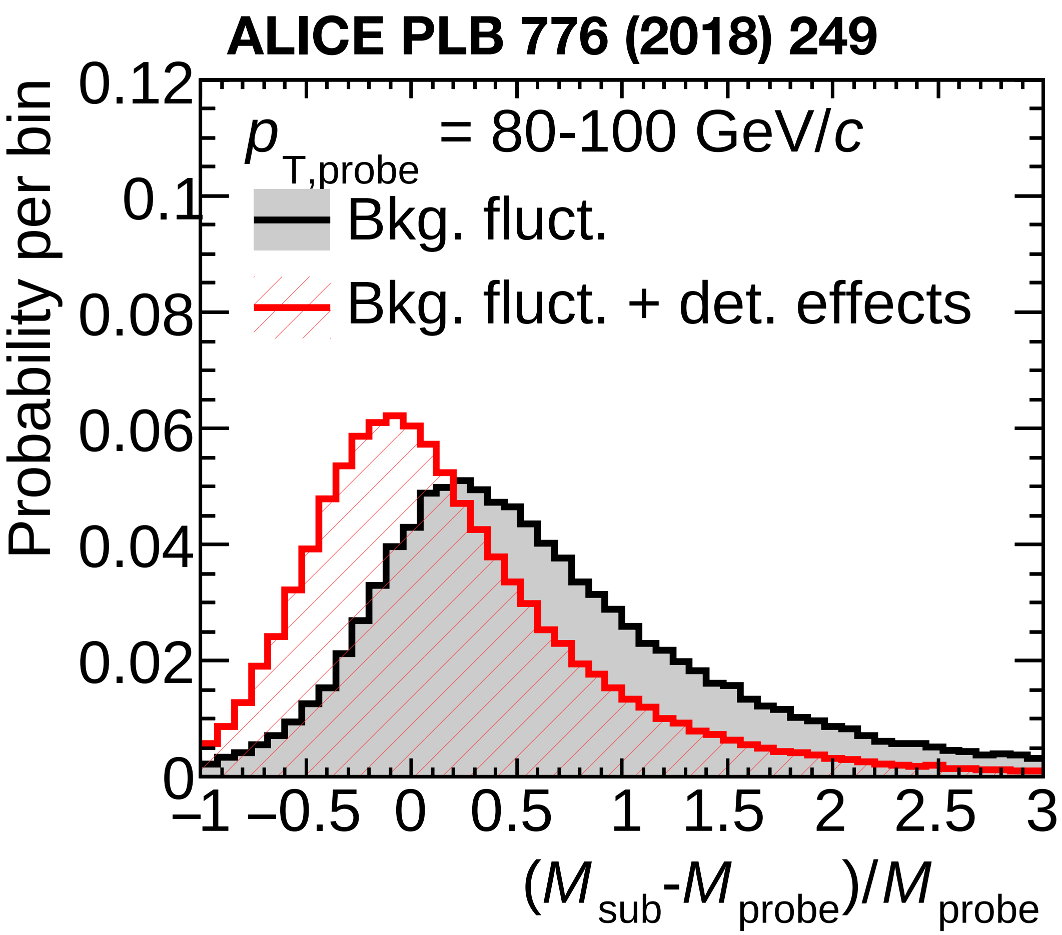
Casalderry-Solana, Mehtar-Tani, Salgado, Tywoniuk PLB 735 357
Mehtar-Tani, Tywoniuk JHEP 1704 125

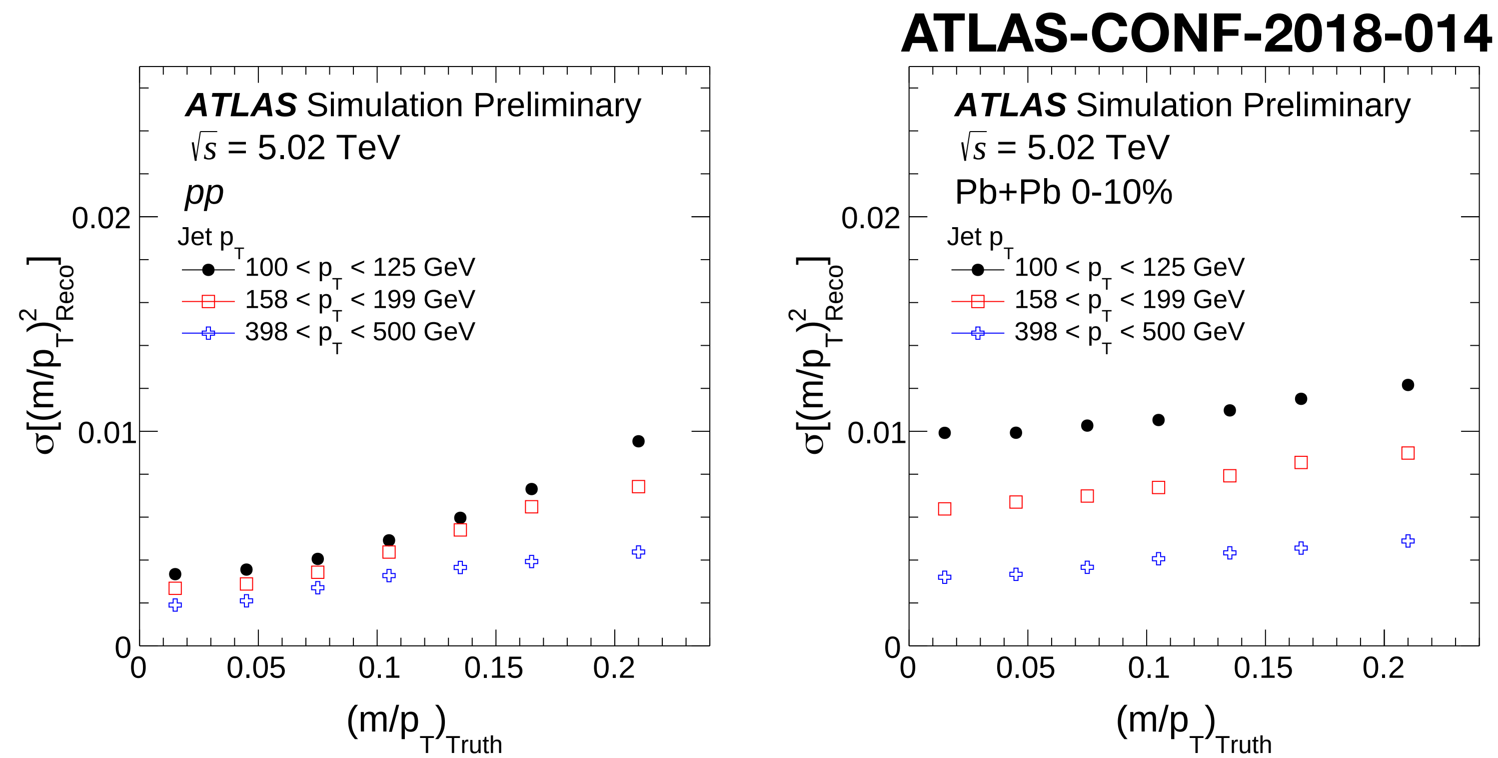
drawings: Y. Mehtar-Tani

is there a transition from coherent to incoherent energy loss as the jet mass increases?

experimental question: how does R_{AA} depend on m/p_T?

mass is complicated to measure





ALICE measurement: charged particles in charged particle jets

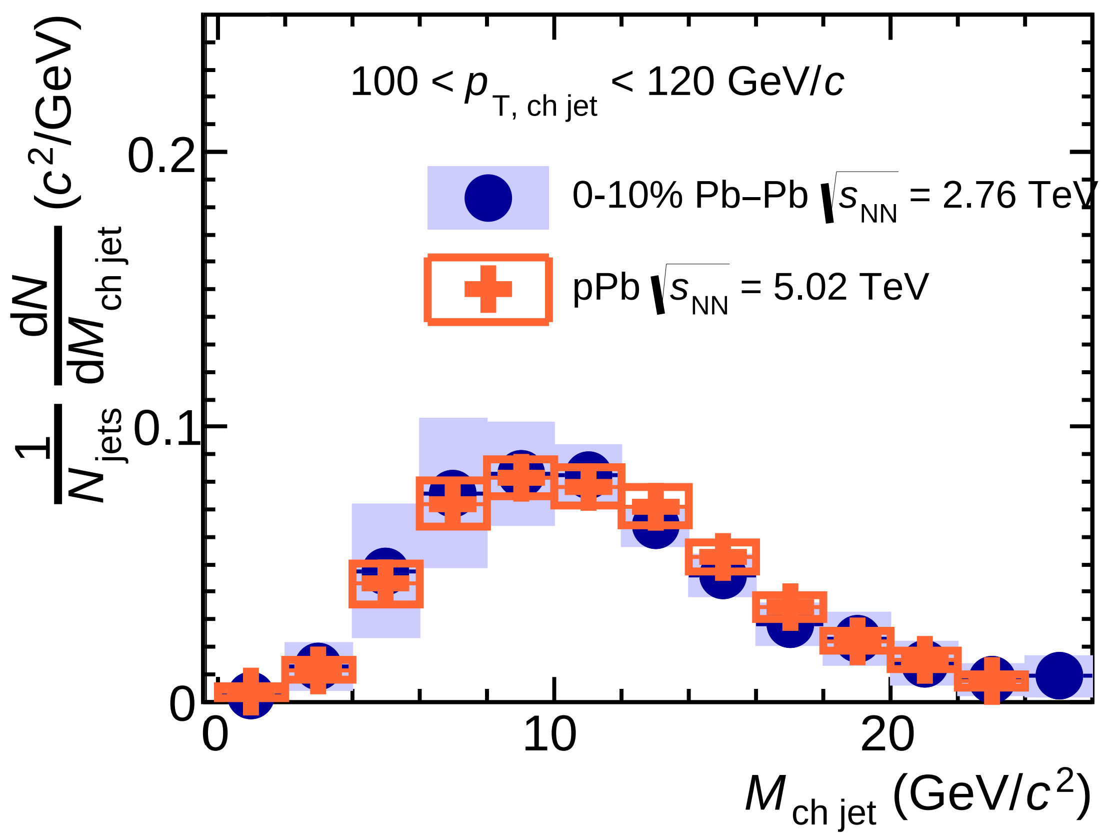
ATLAS measurement: calorimeter towers in calorimeter jets

in both cases mass resolution is very sensitive to UE fluctuations

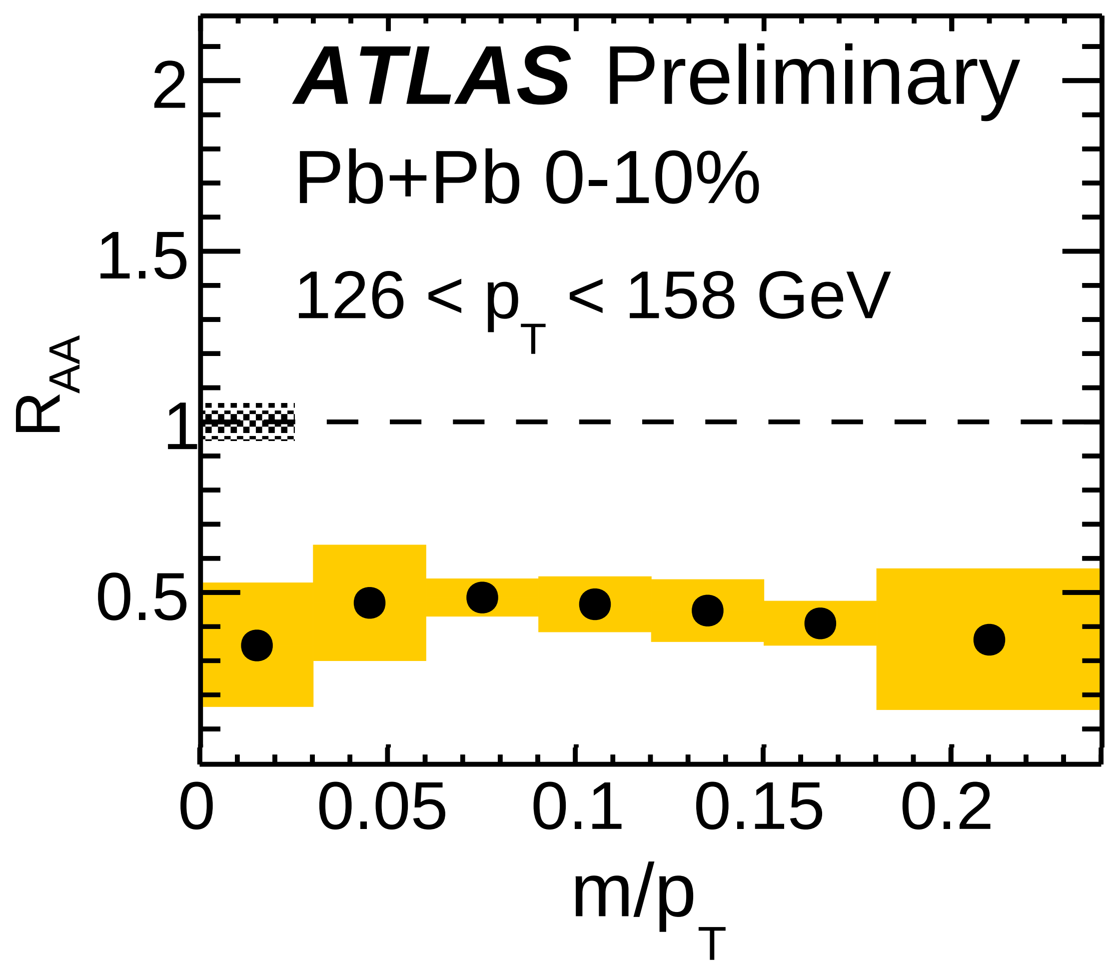
mass of the jet

ALICE: mass from charged particles **ATLAS: mass from calorimeter towers**

PLB 776 (2018) 249



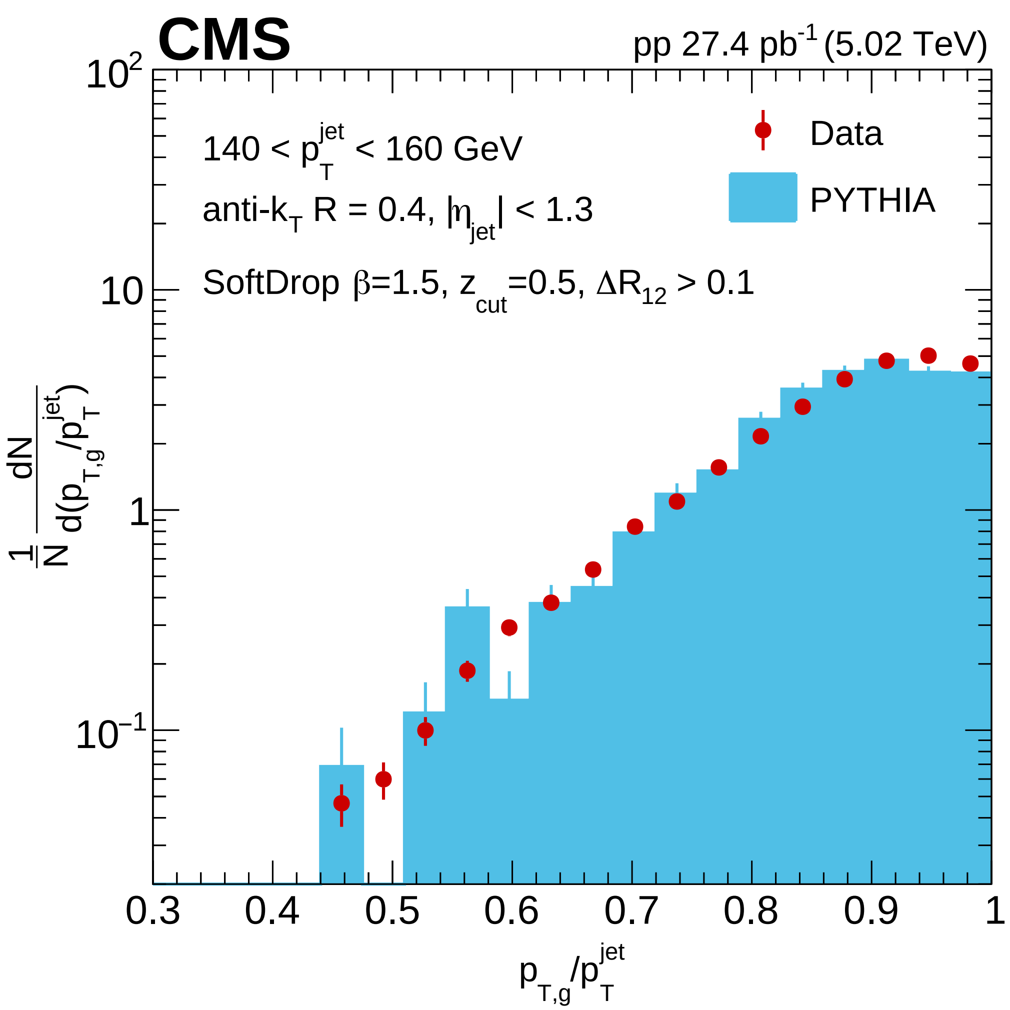
ATLAS-CONF-2018-014

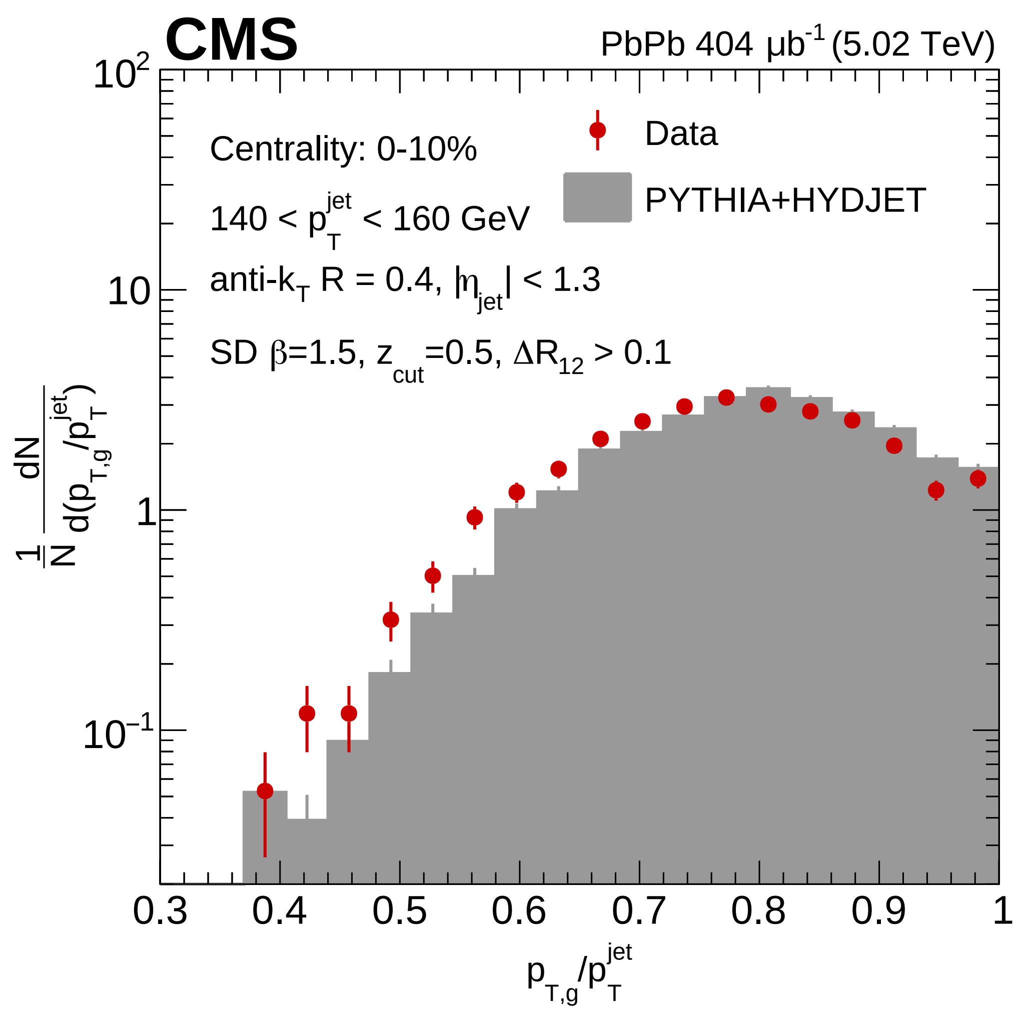


no significant mass modification observed in PbPb collisions

are we not looking in the right region? are the measurements not sensitive enough?

idea: *remove* low momentum parts of the jet in a controlled way ("soft-drop" algorithm)

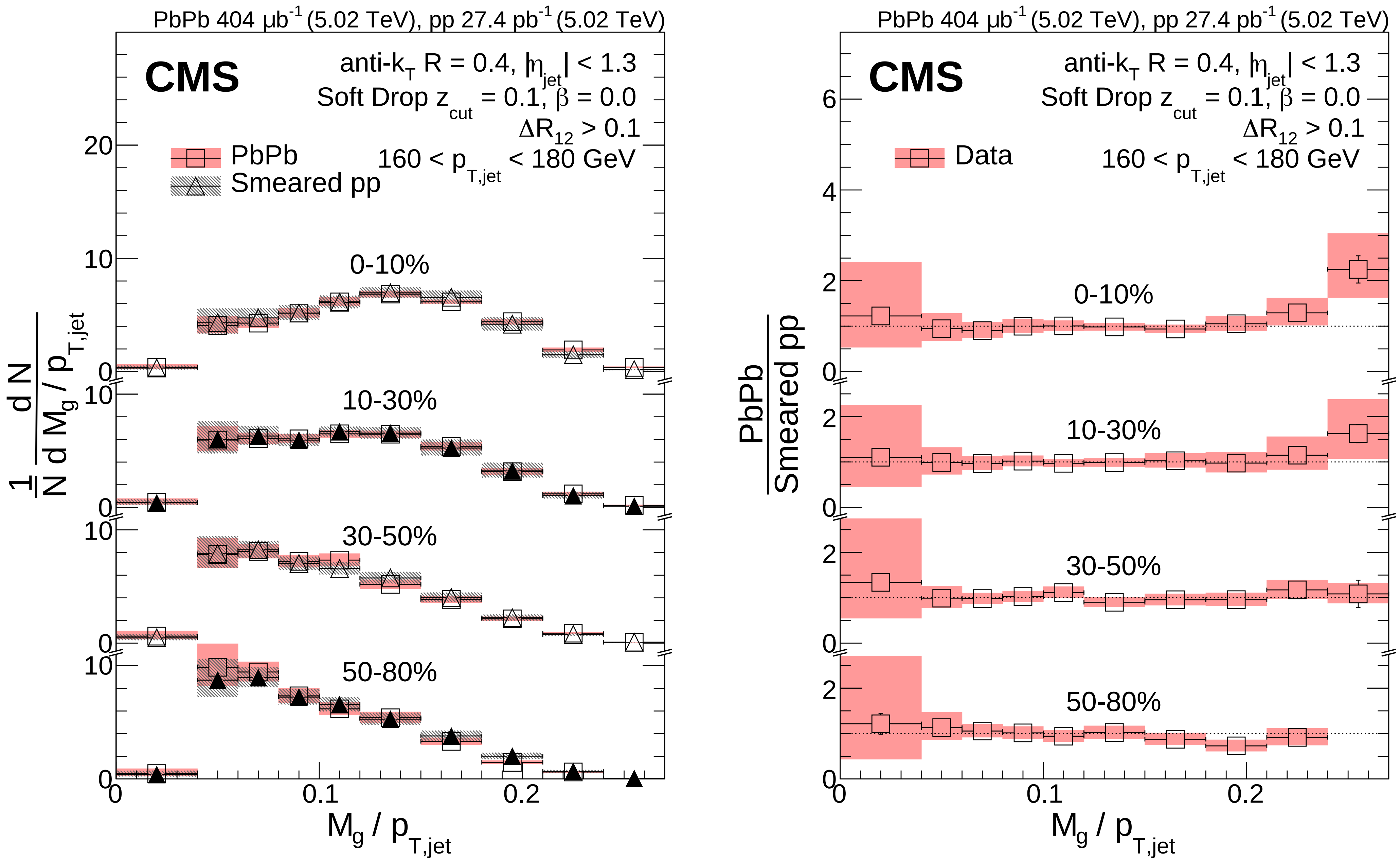




groomed p_T / original p_T

jet grooming with soft drop

1805.05145

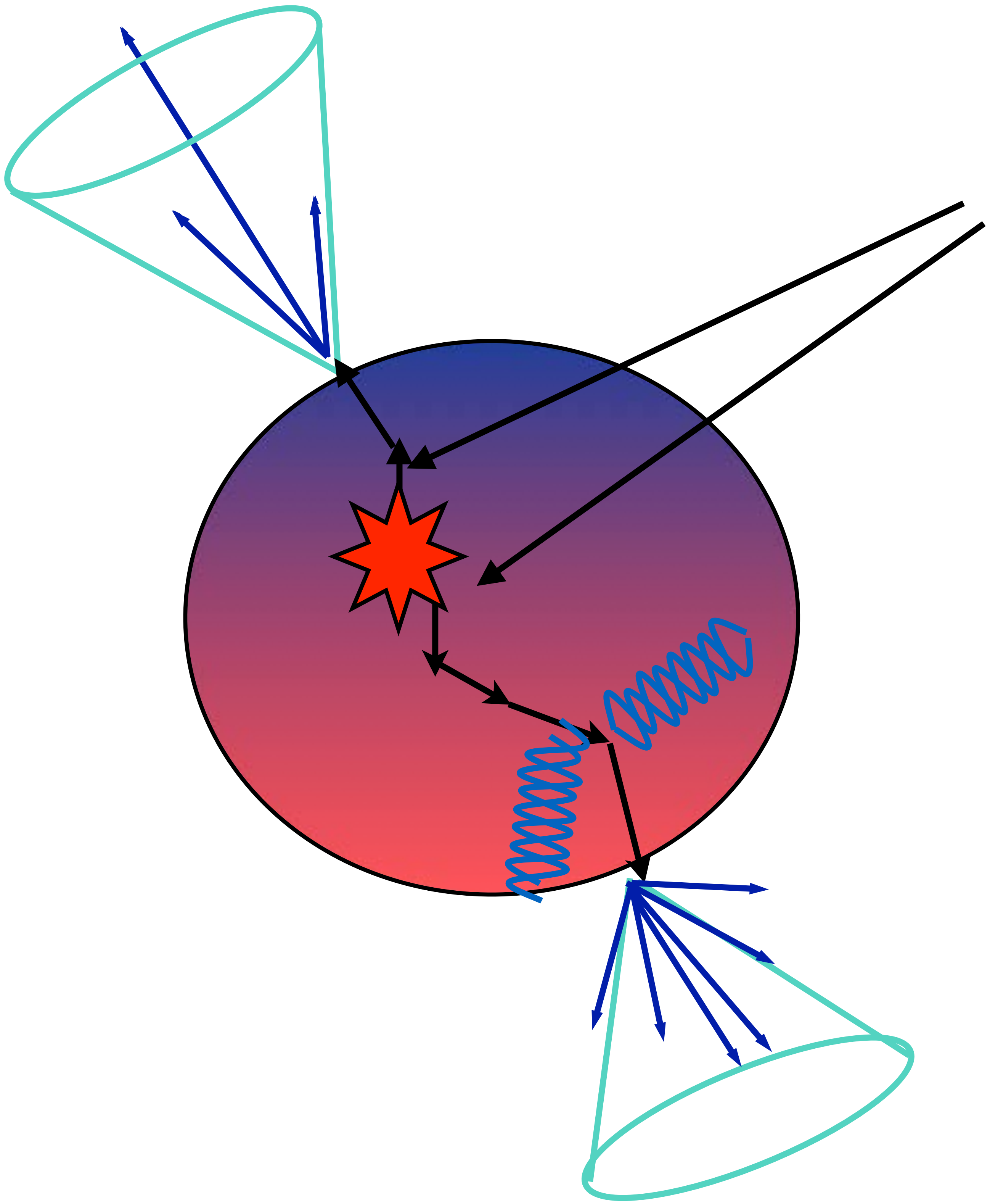


not corrected for resolution and scale → shift as a function of centrality

still, no mass dependent modifications

lecture 3

motivation for tagged jet measurements

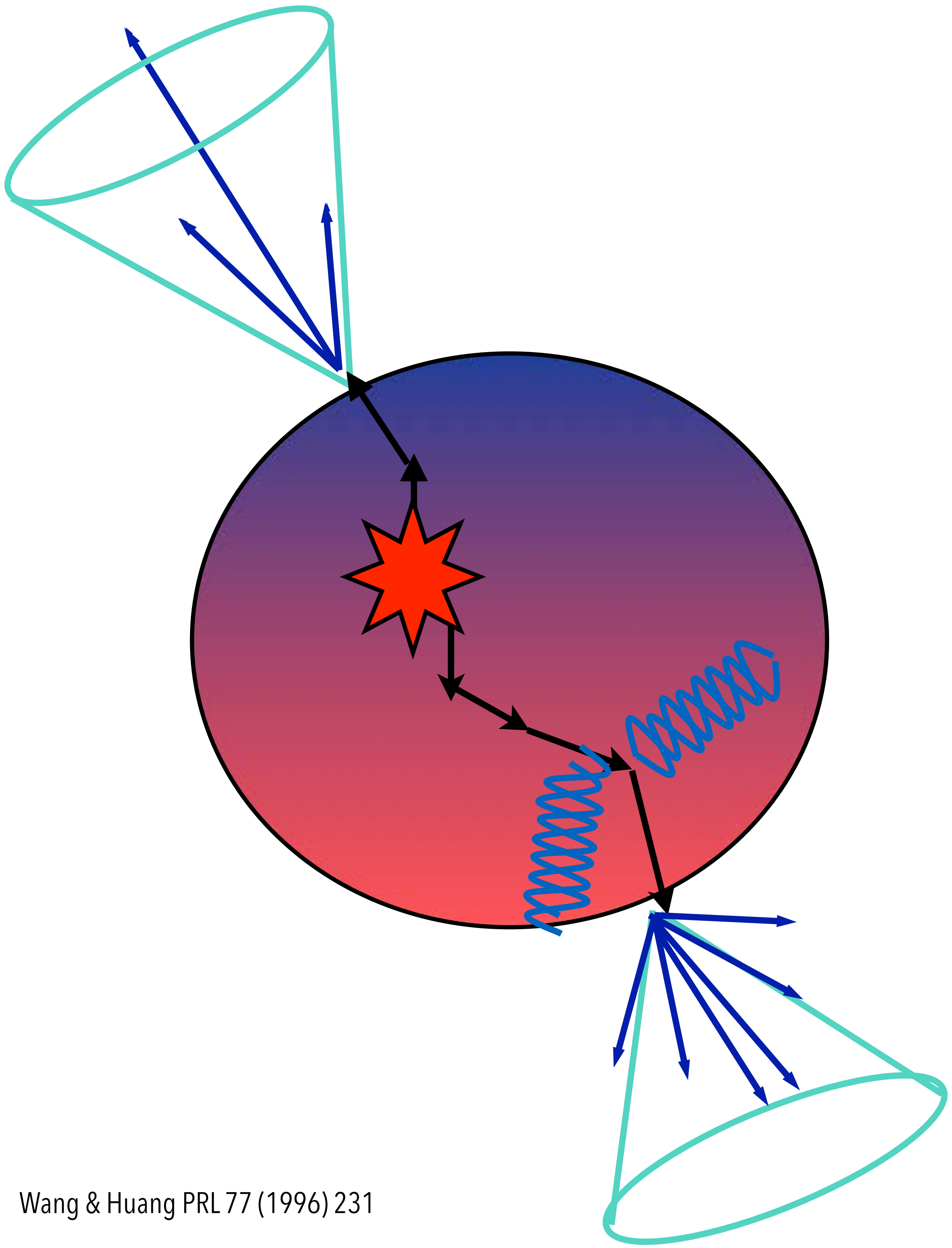


the partons coming out of the hard scattering are: gluons, up, down, strange, charm, bottom or top quarks

the parton-QGP interaction should depend on which type of partons we are looking at

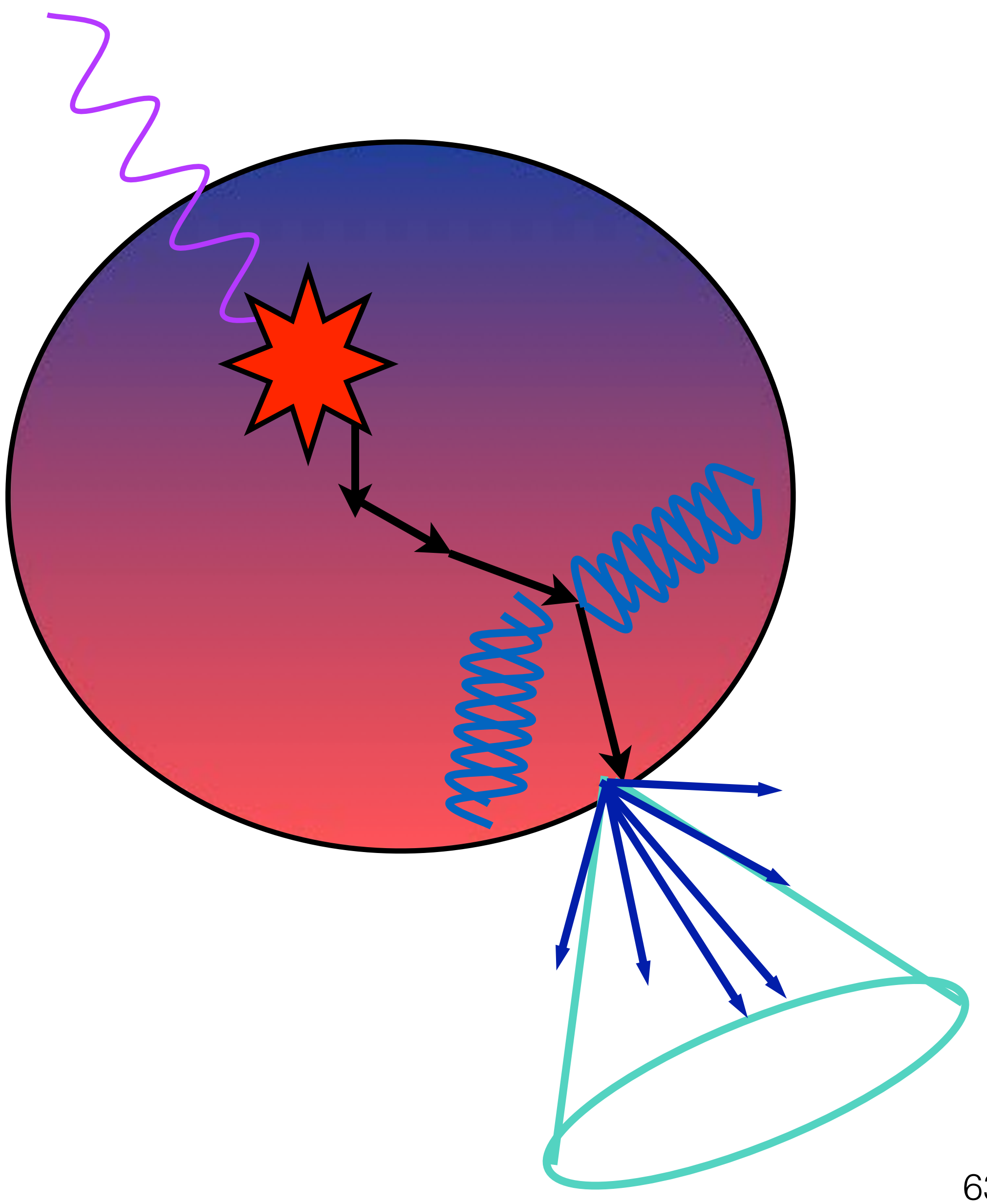
photon-jets

dijets → both jets interact



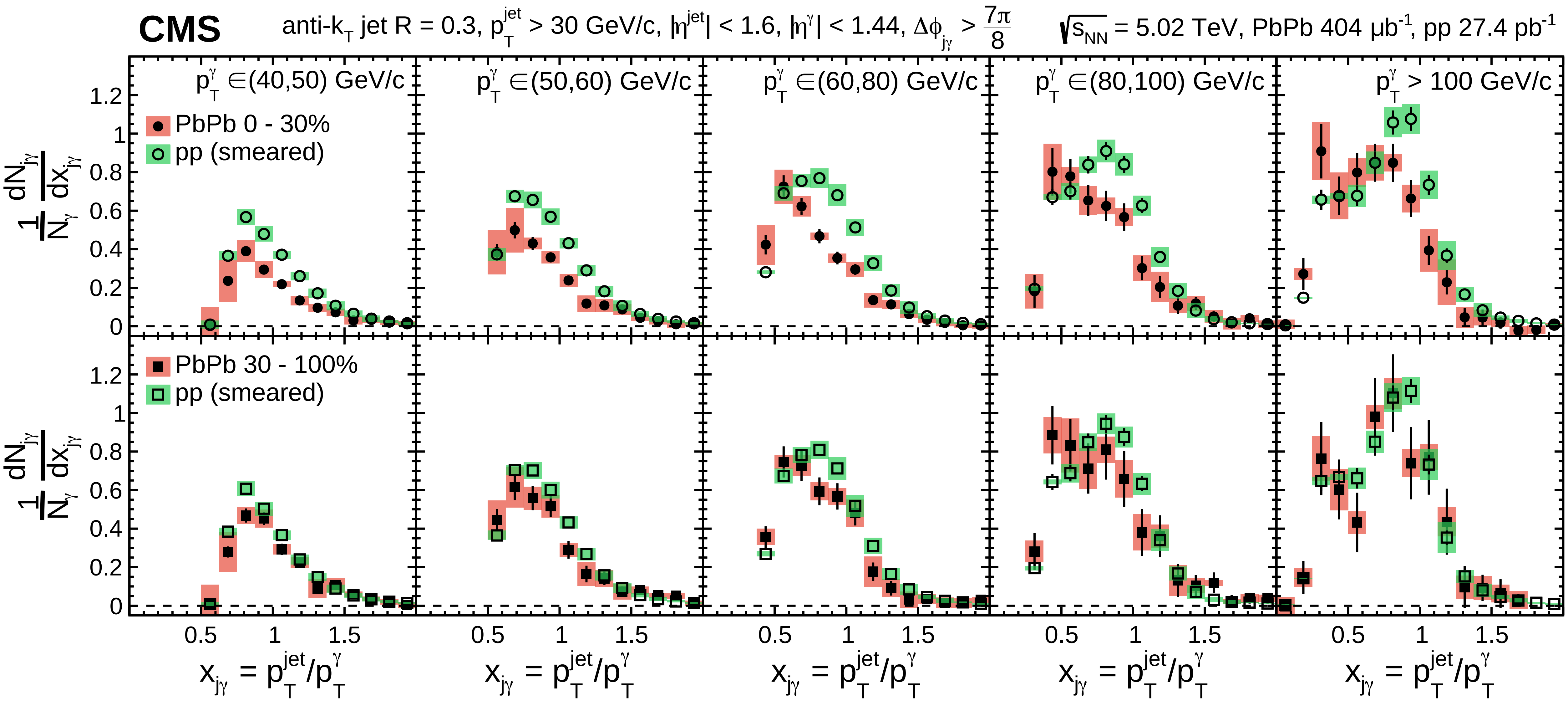
γ-jets → only the jet interacts

γ provides unmodified information about the hard scattering



Wang & Huang PRL 77 (1996) 231

photon-jet balance



pp: different in each panel because it is smeared by the p_T and centrality dependent additional resolutions effects to match PbPb collisions

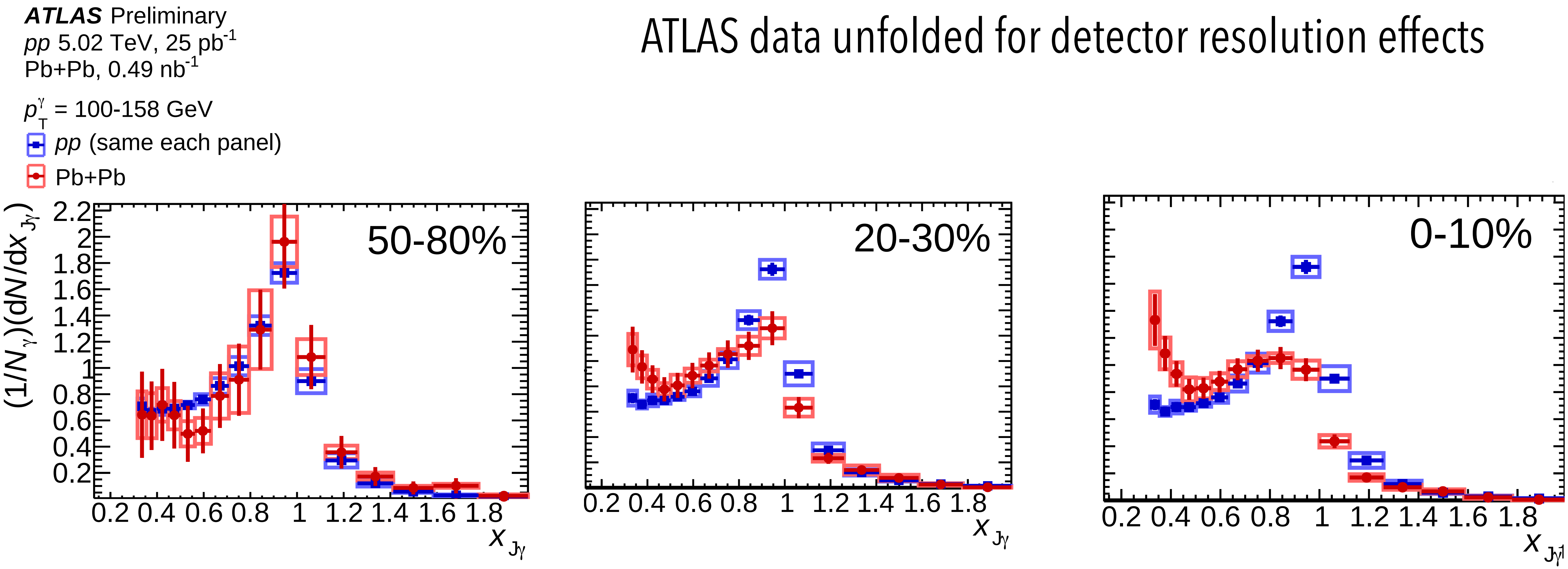
PbPb: distributions shifted to lower $x_{j\gamma}$–jet quenching

1711.097328

photon-jet balance

photon p_T: 100-158 GeV

ATLAS data unfolded for detector resolution effects

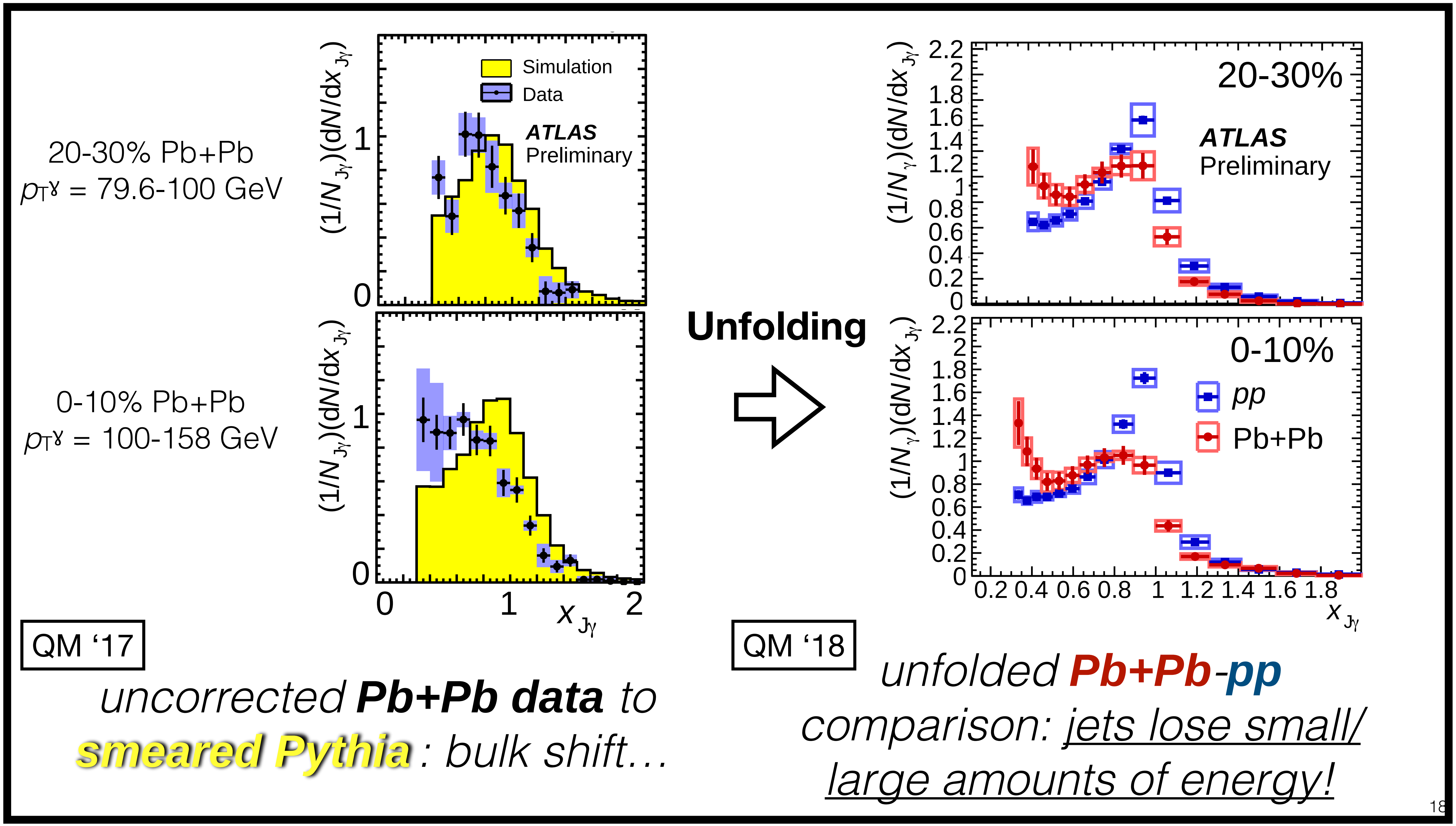


peak for nearly balanced pairs even in PbPb collisions

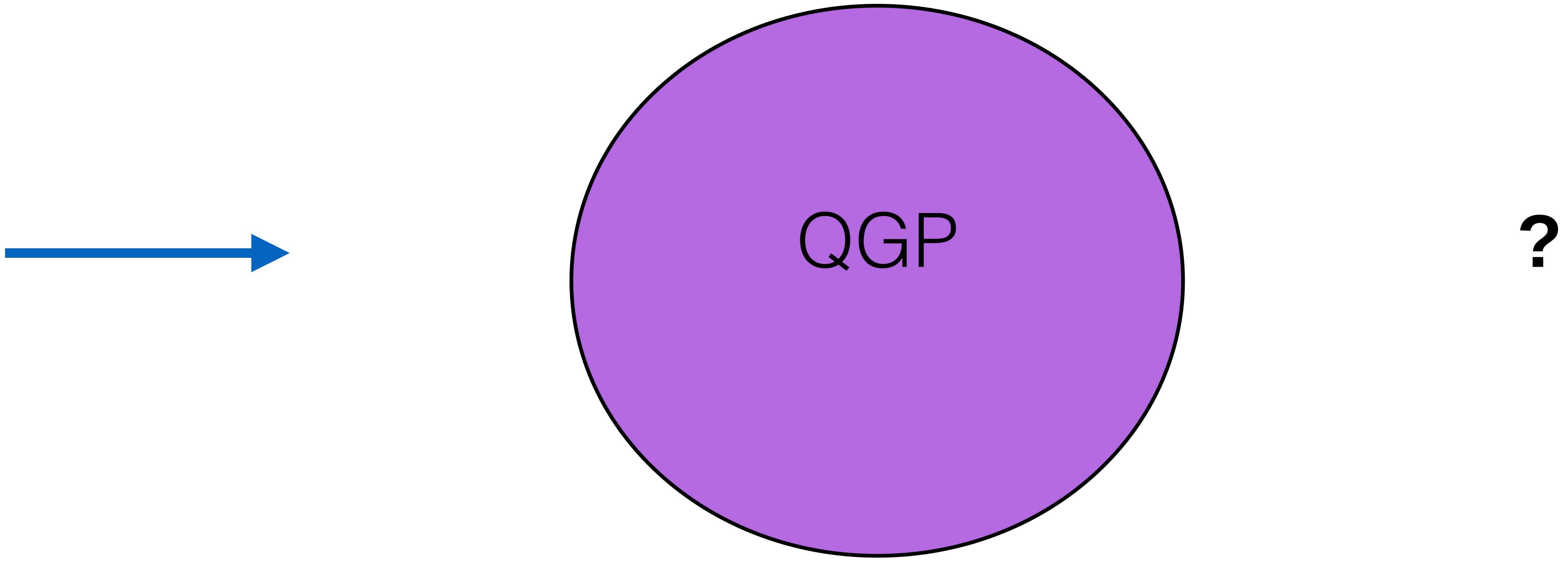
ATLAS-CONF-2018-009

1711.097328

unfolding again



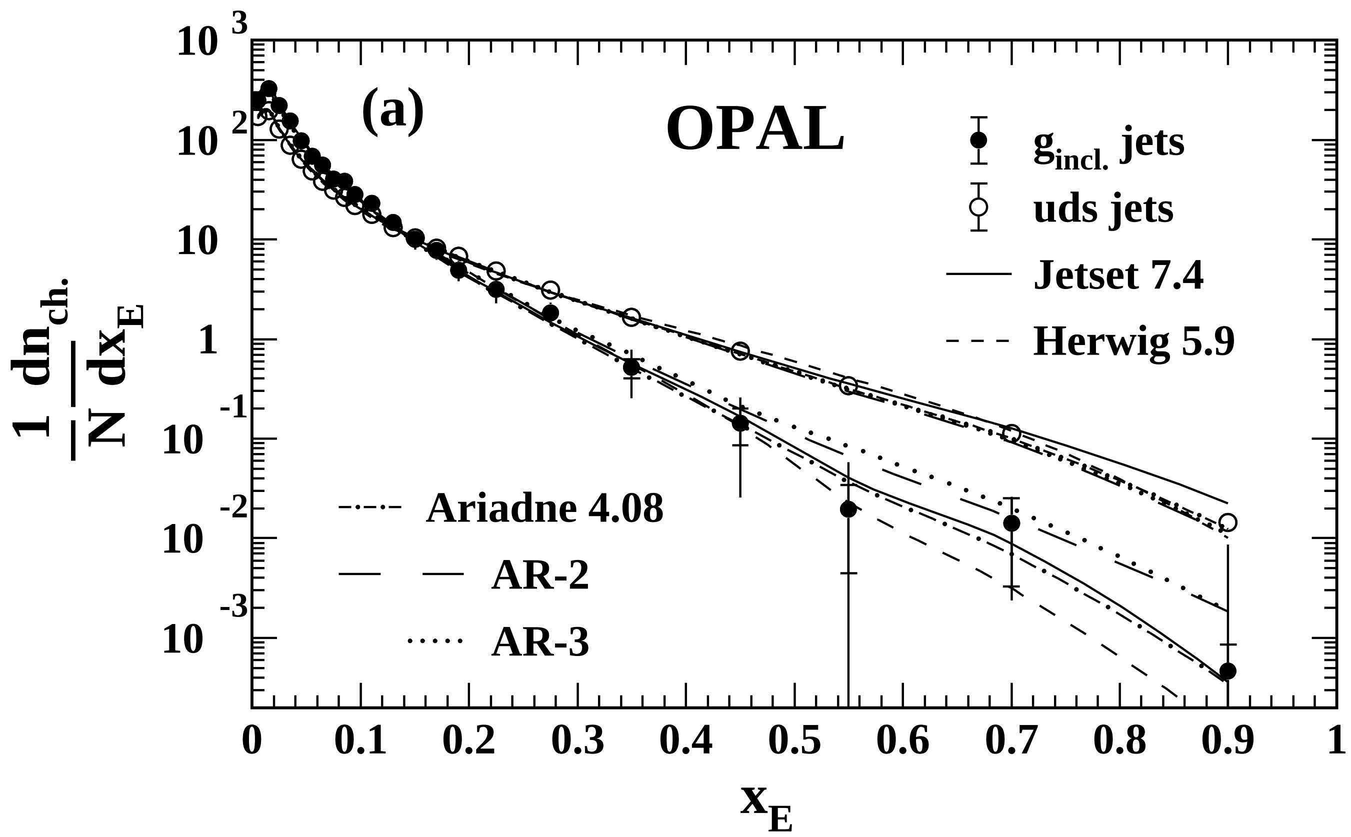
how we'd like to measure the QGP



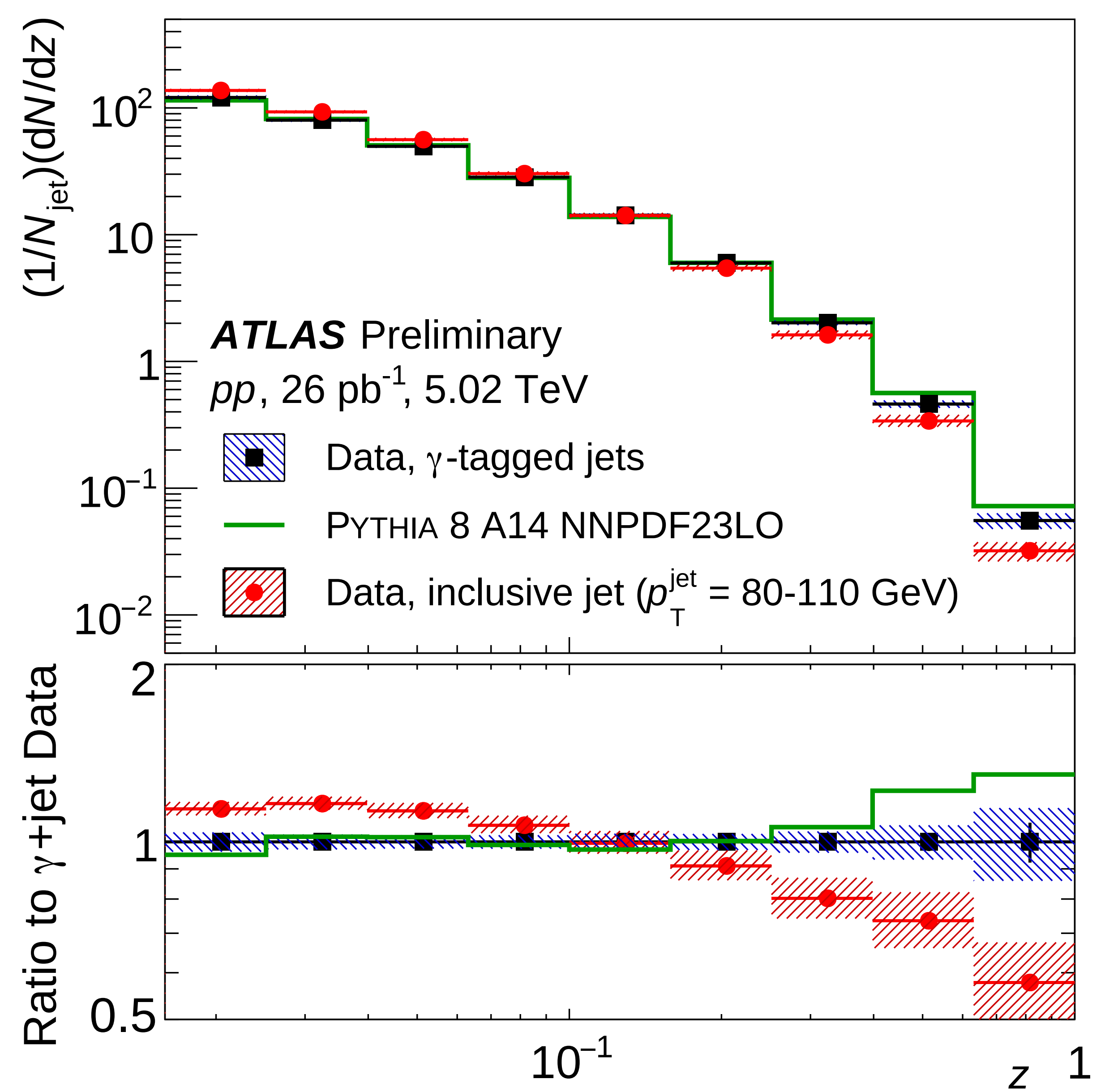
what happens when we probe the QGP by different kinds of partons?

- light quarks uds: small mass
- gluons: massless, larger color charge than quarks
- charm: 1.3 GeV mass
- bottom: 4.2 GeV mass
- temperature of the QGP: 400 MeV - 170 MeV

quark / gluon fragmentation function



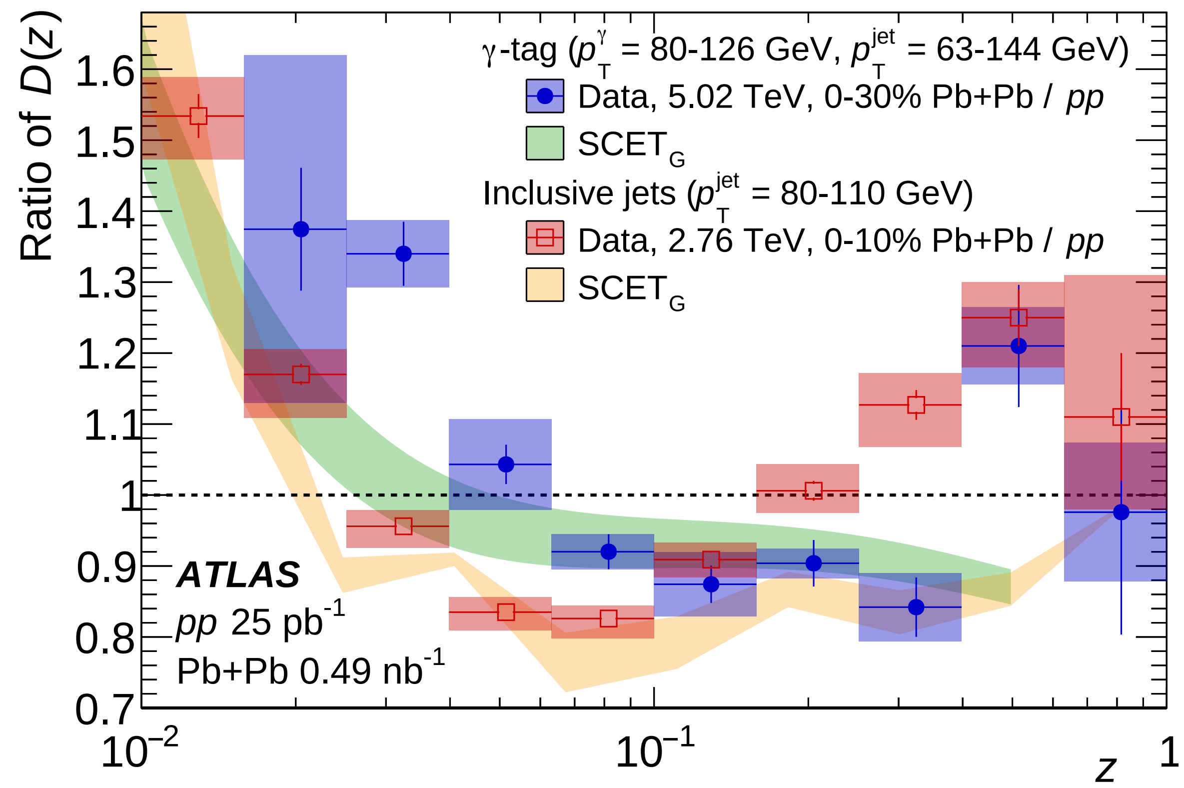
momentum of hadron relative to jet

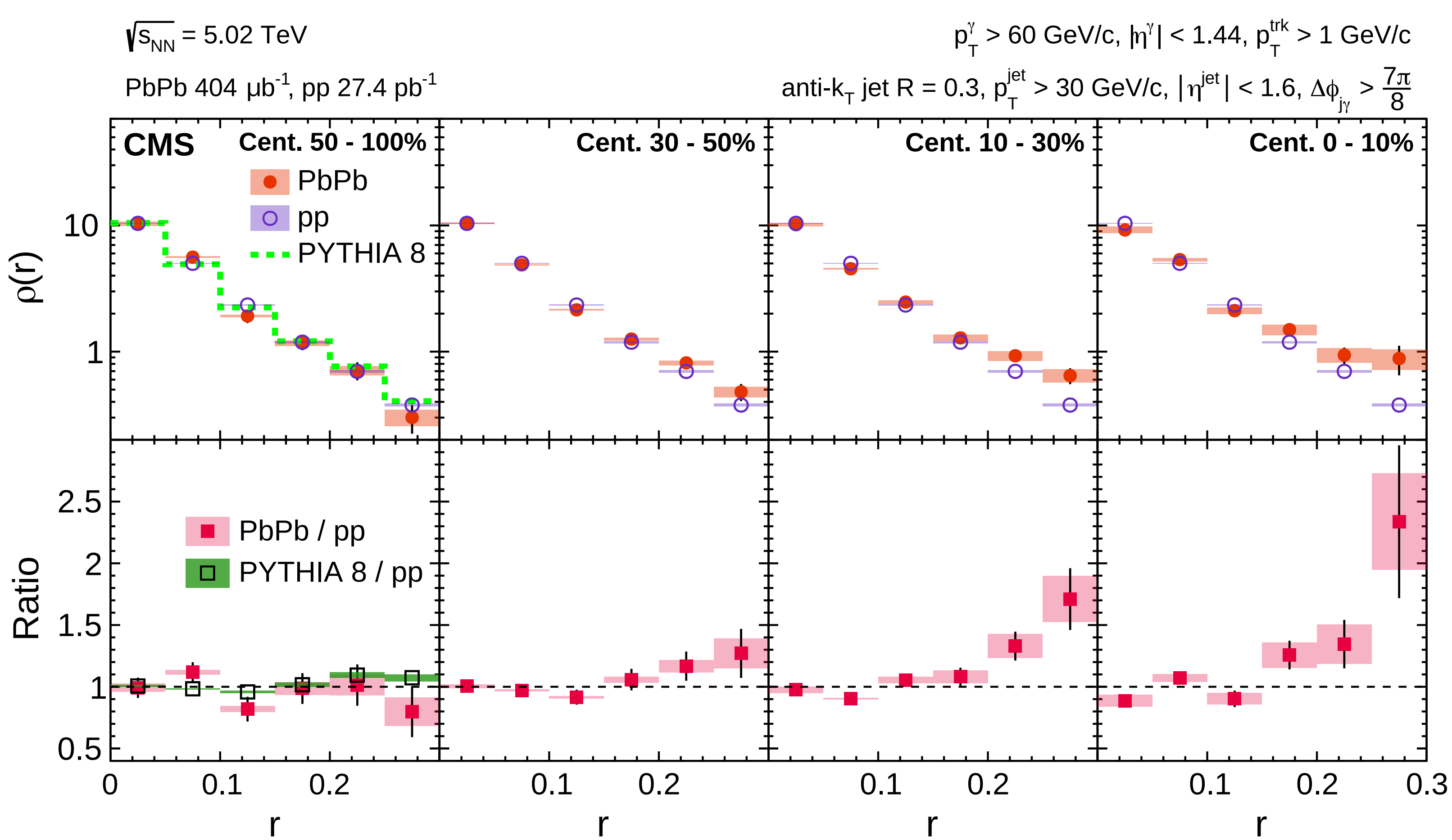


see expected quark / gluon fragmentation differences in photon-jet measurements

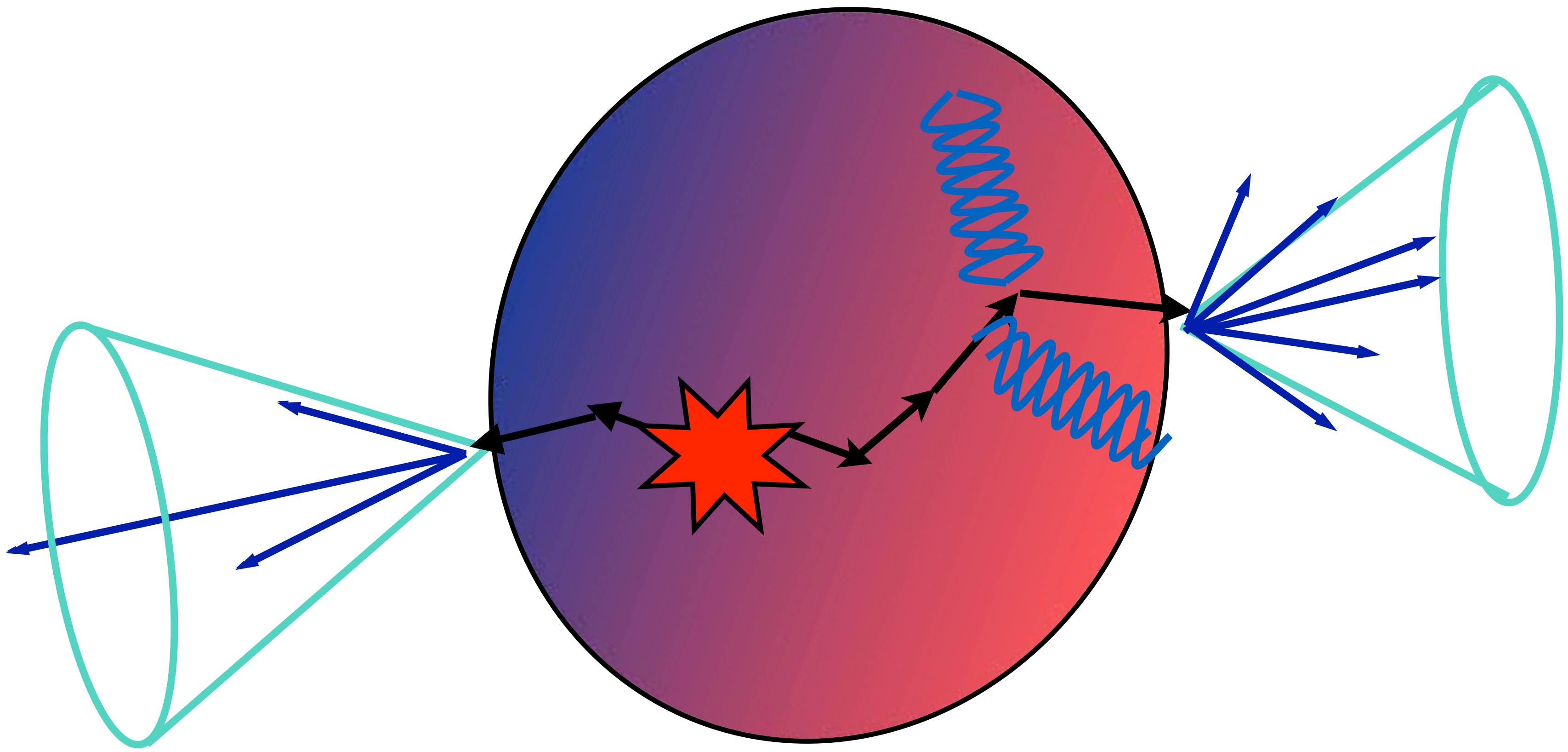
structure of jets opposite photons in PbPb collisions

these kinds of measurements provide some constraints on how light quarks and gluons interact differently in the QGP



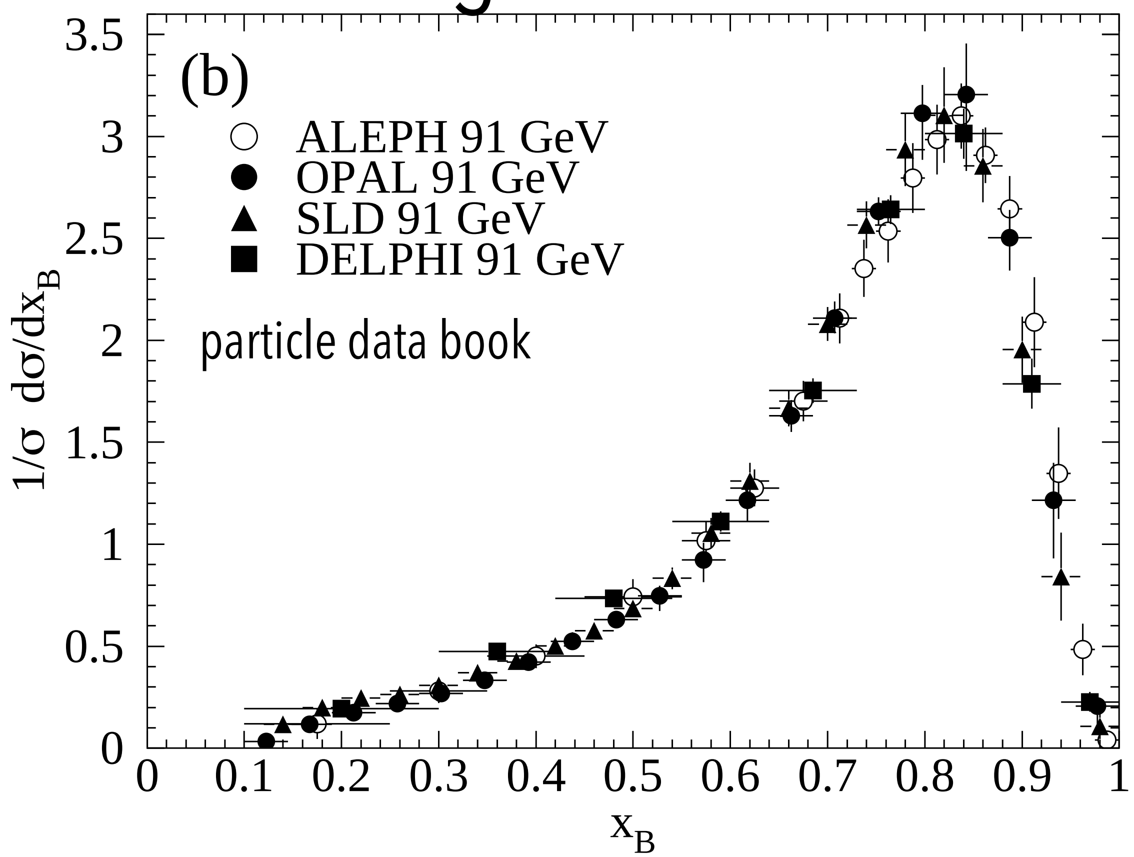


$$\rho(r) = \frac{1}{\delta r}\frac{\sum_{\mathrm{jets}}\sum_{r_a<r<r_b}(p_T^{trk}/p_T^{jet})}{\sum_{\mathrm{jets}}\sum_{0<r<r_f}(p_T^{trk}/p_T^{jet})}$$

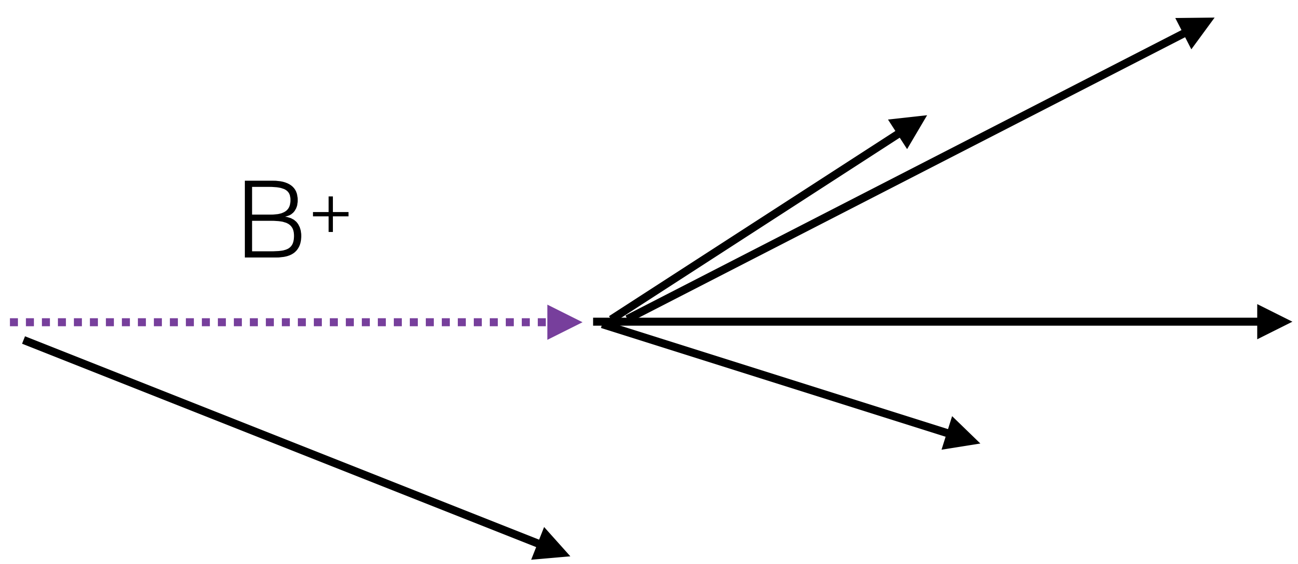


b and c jets are especially interesting because their mass should suppress radiation in the QGP (Dokshitzer & Kharzeev Phys.Lett. B519 (2001) 199-206)

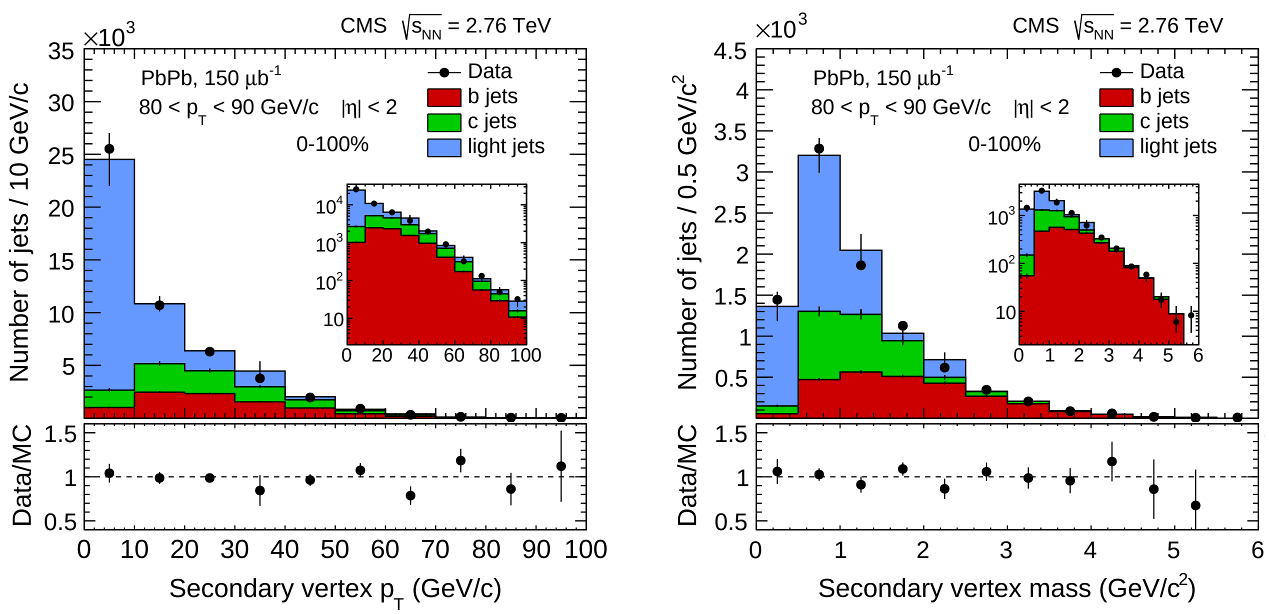
B hadron fragmentation function

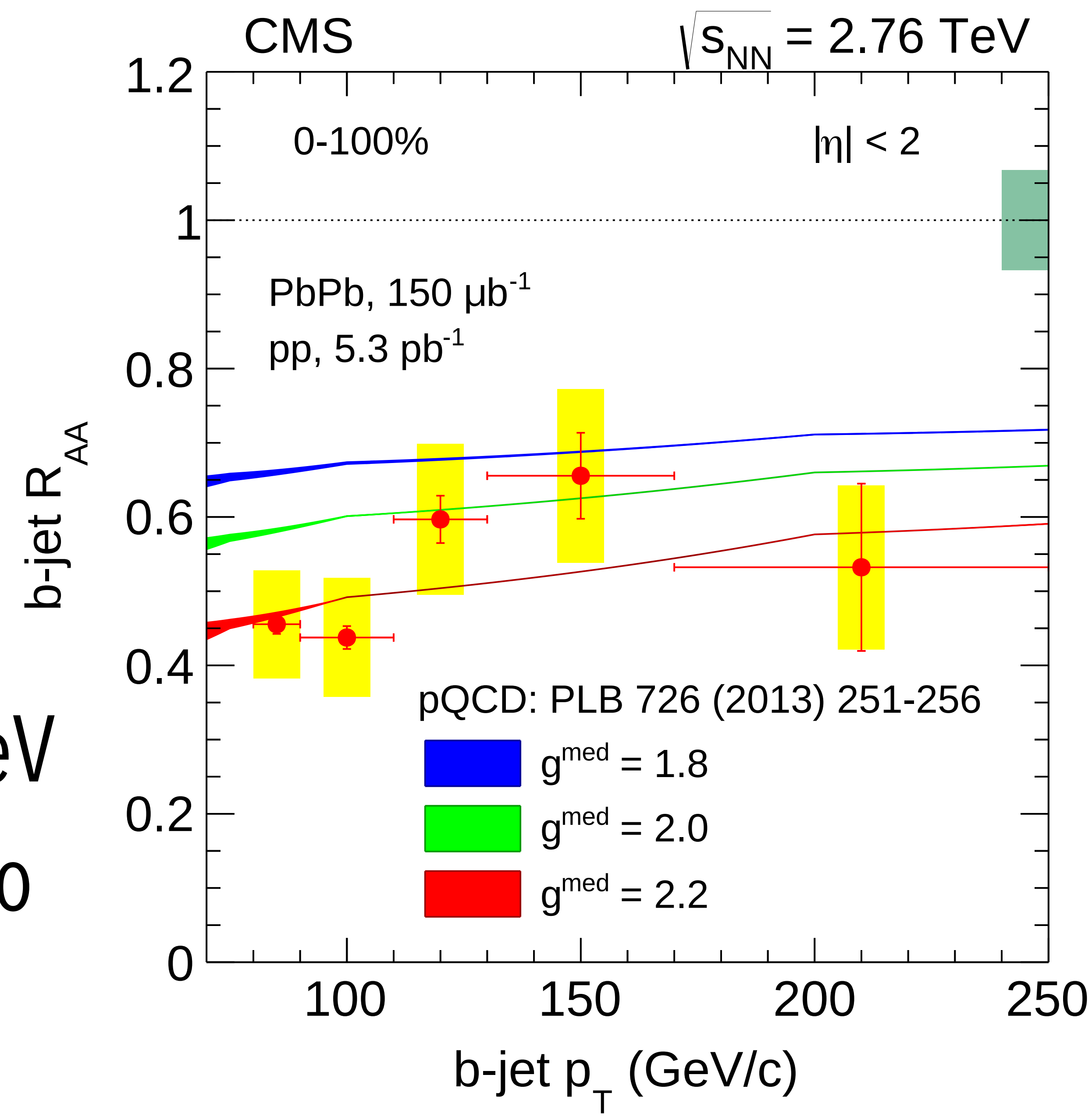


B hadron has a long enough lifetime (1.5×10^{-12}s) that it travels a measurable distance before it decays (100s μm)



b-jet R_{AA}



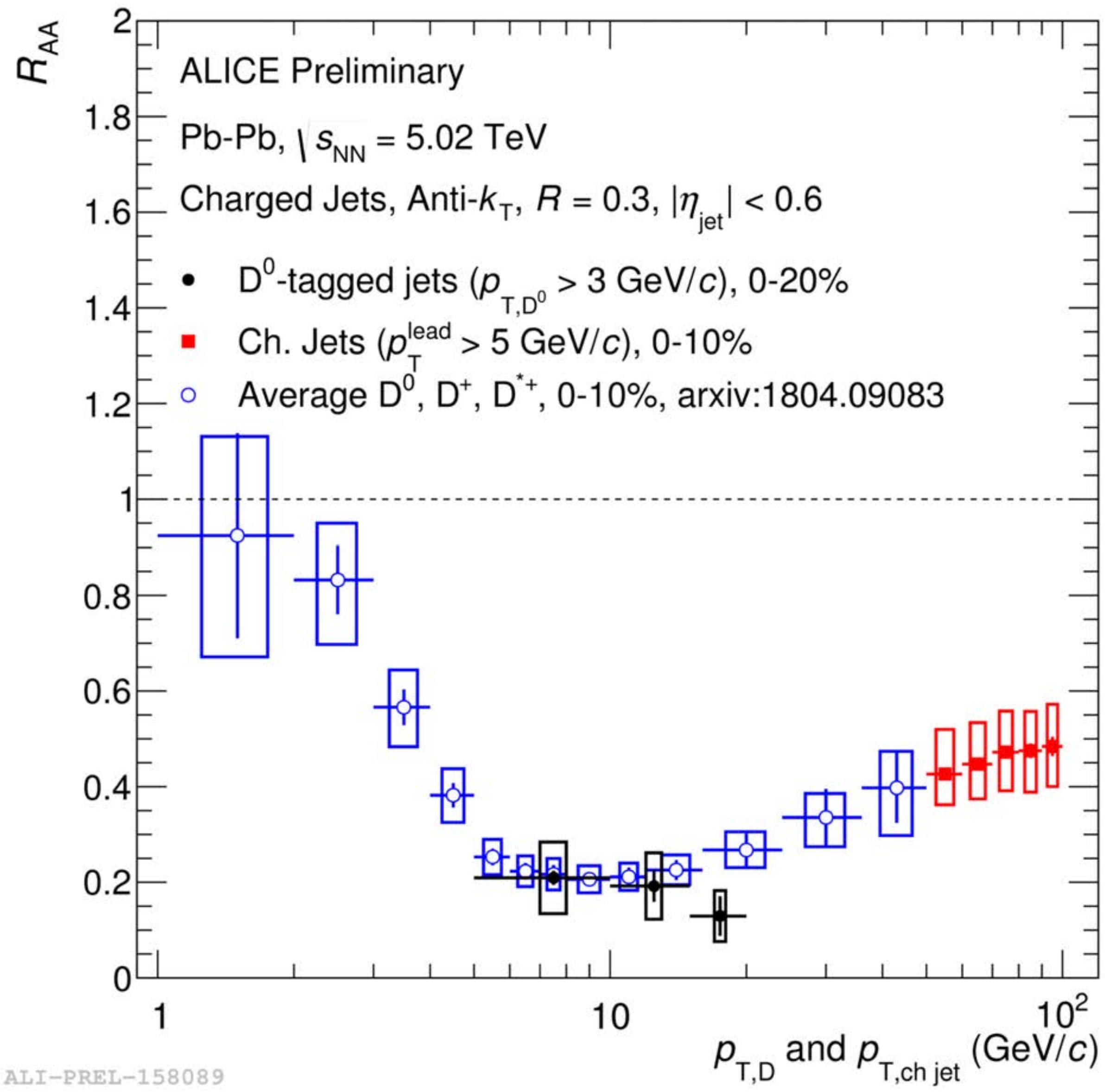


b-jets are suppressed above 50 GeV

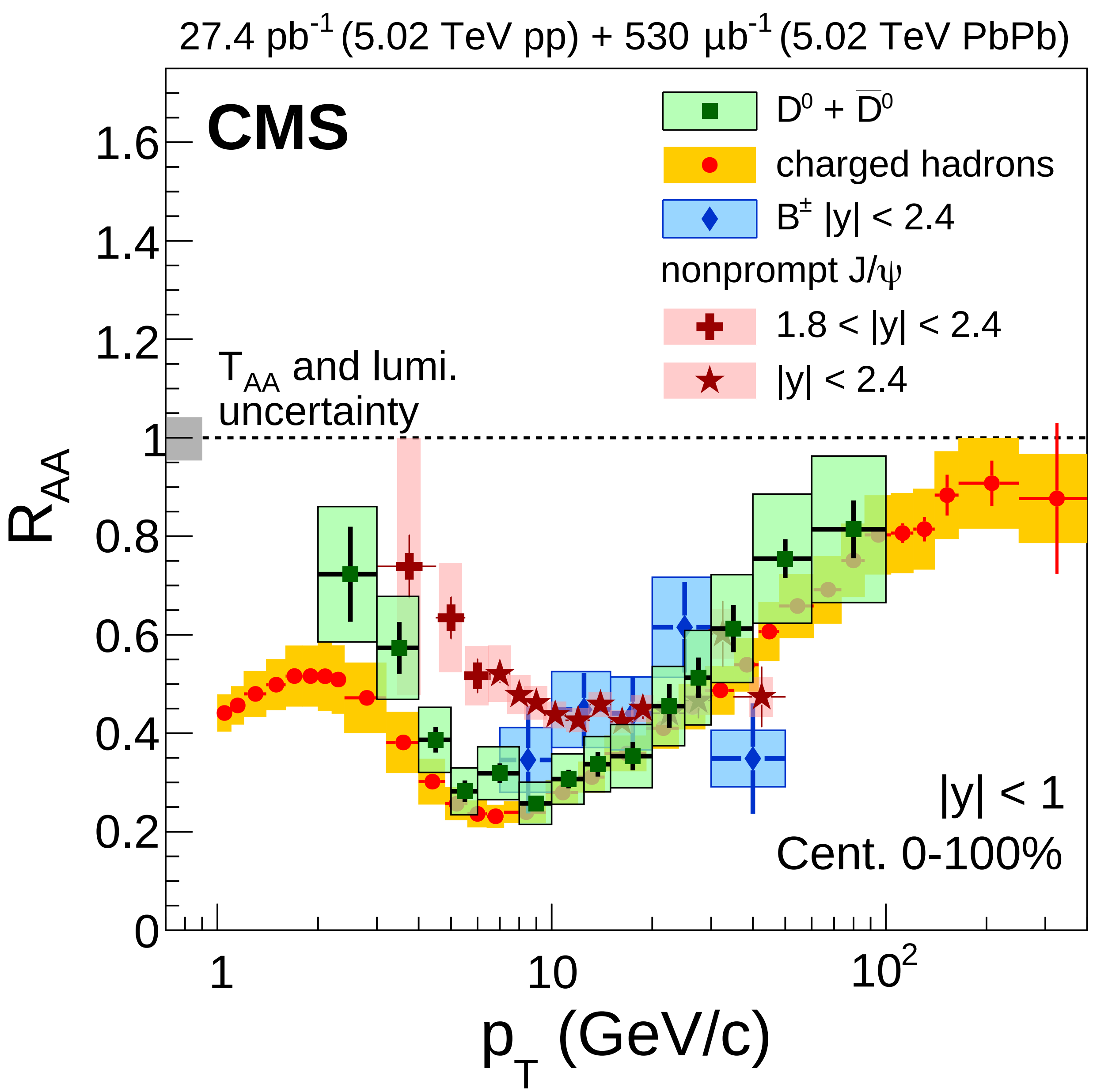
large uncertainties make it hard to discriminate between models

PRL 113 132301 (2014)

heavy flavor tagged jets



Phys. Lett. B 782 (2018) 474



new data will help improve these measurements!

jet summary

- fast partons provide a short distance scale probe of the QGP
- key question is how QCD at high temperature gives rise to fluid behavior
- measurements of particles, jets and jet structure provide sensitivity to how and where the energy the jet loses goes

next: what happens when we look differentially at partons of different types (gluons, light quarks, charm, and bottom)?

motivation behind quarkonia measurements in HI

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

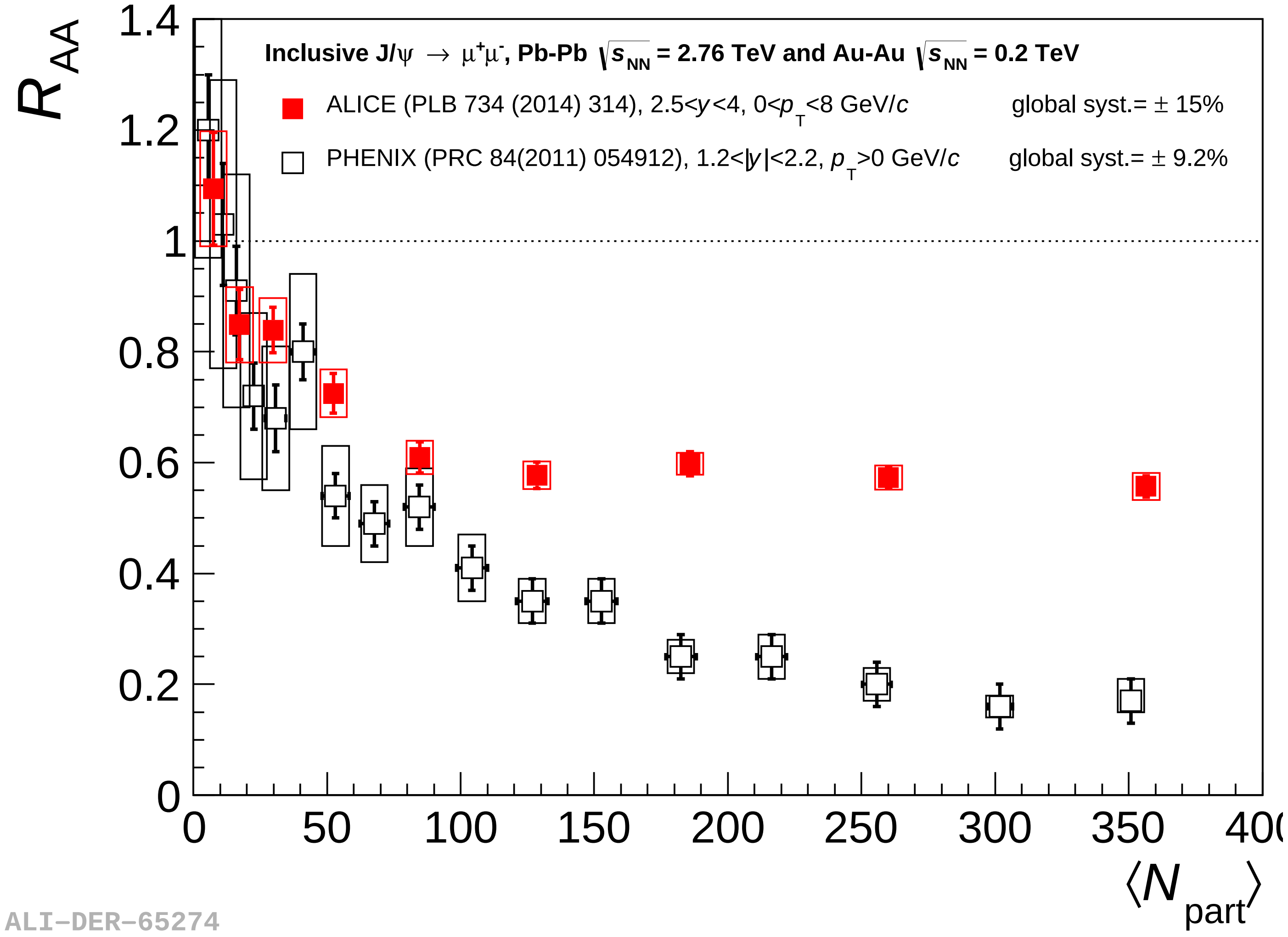
H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

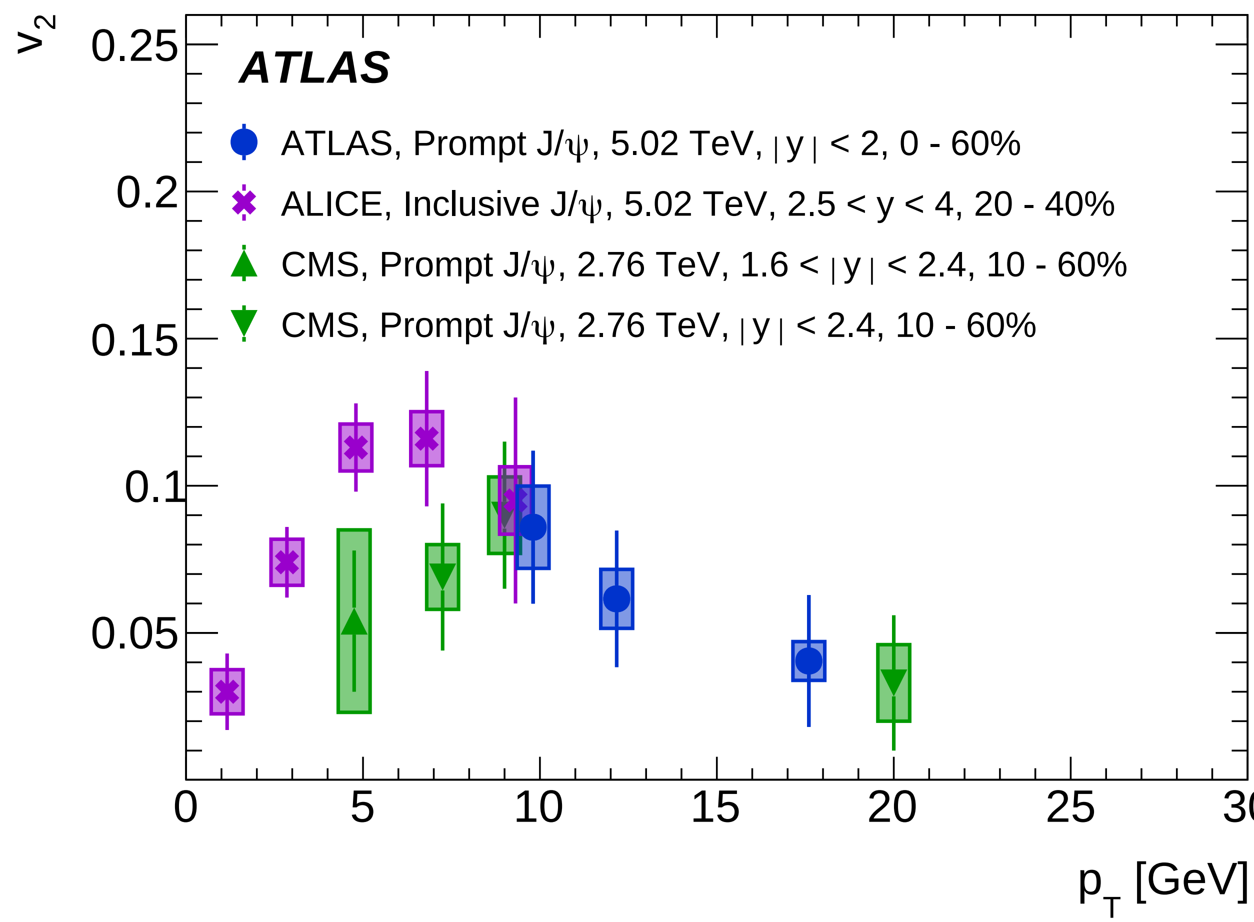
If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

PLB 178 416 (1986)

J/psi at the LHC



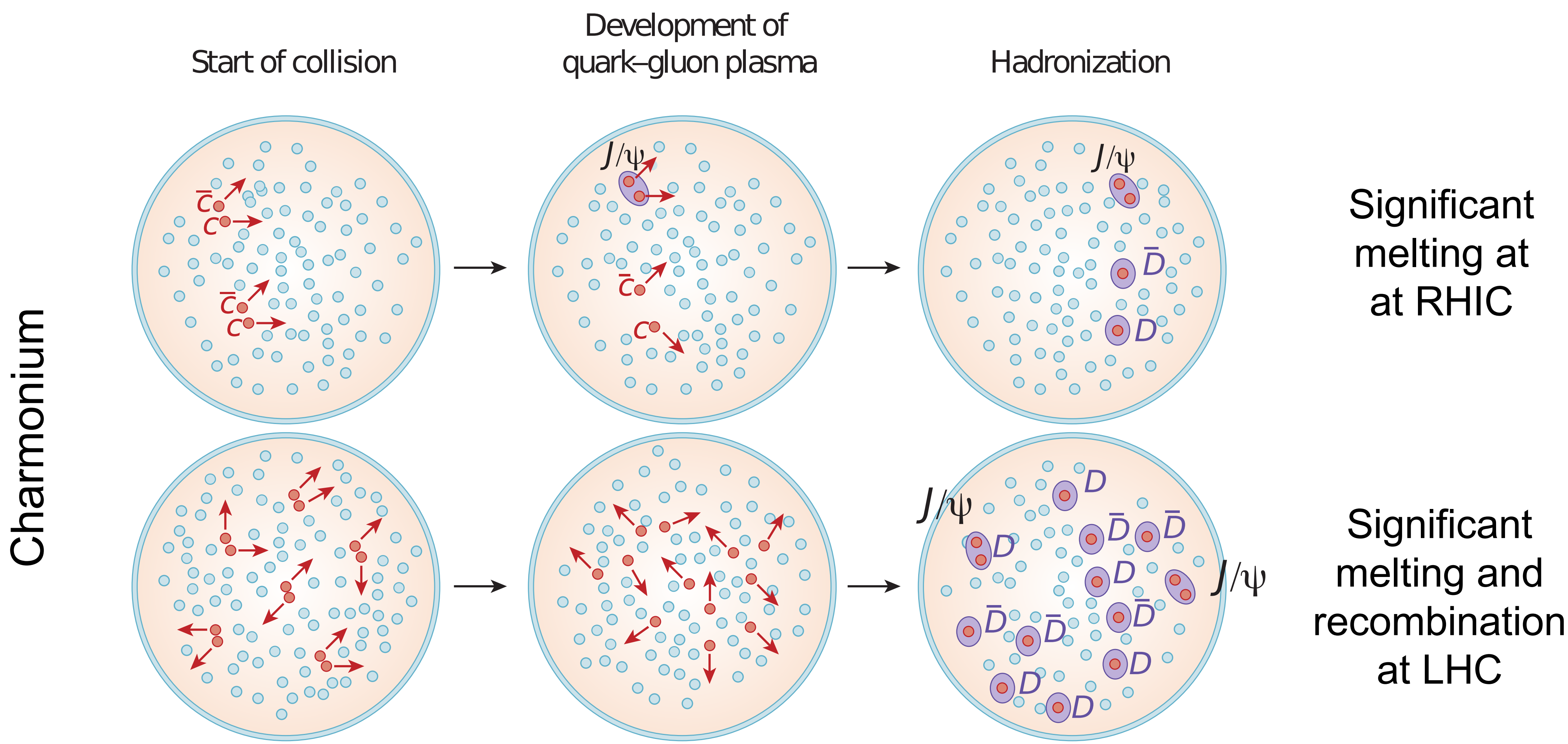
EPJC78 (2018) 784



observation: J/psi much less suppressed at LHC than at RHIC

regeneration

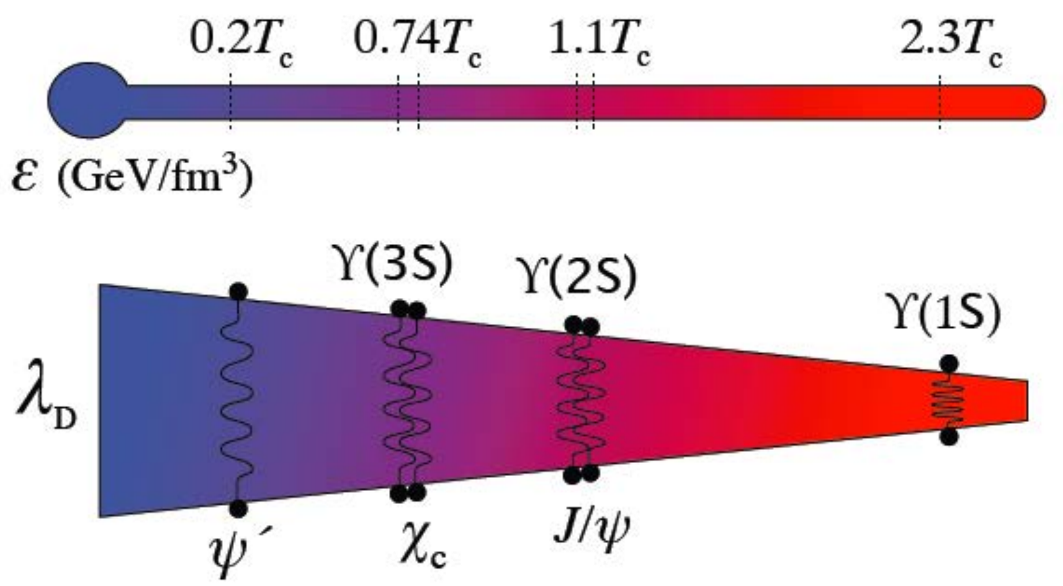
image: Alexander Rothkopf

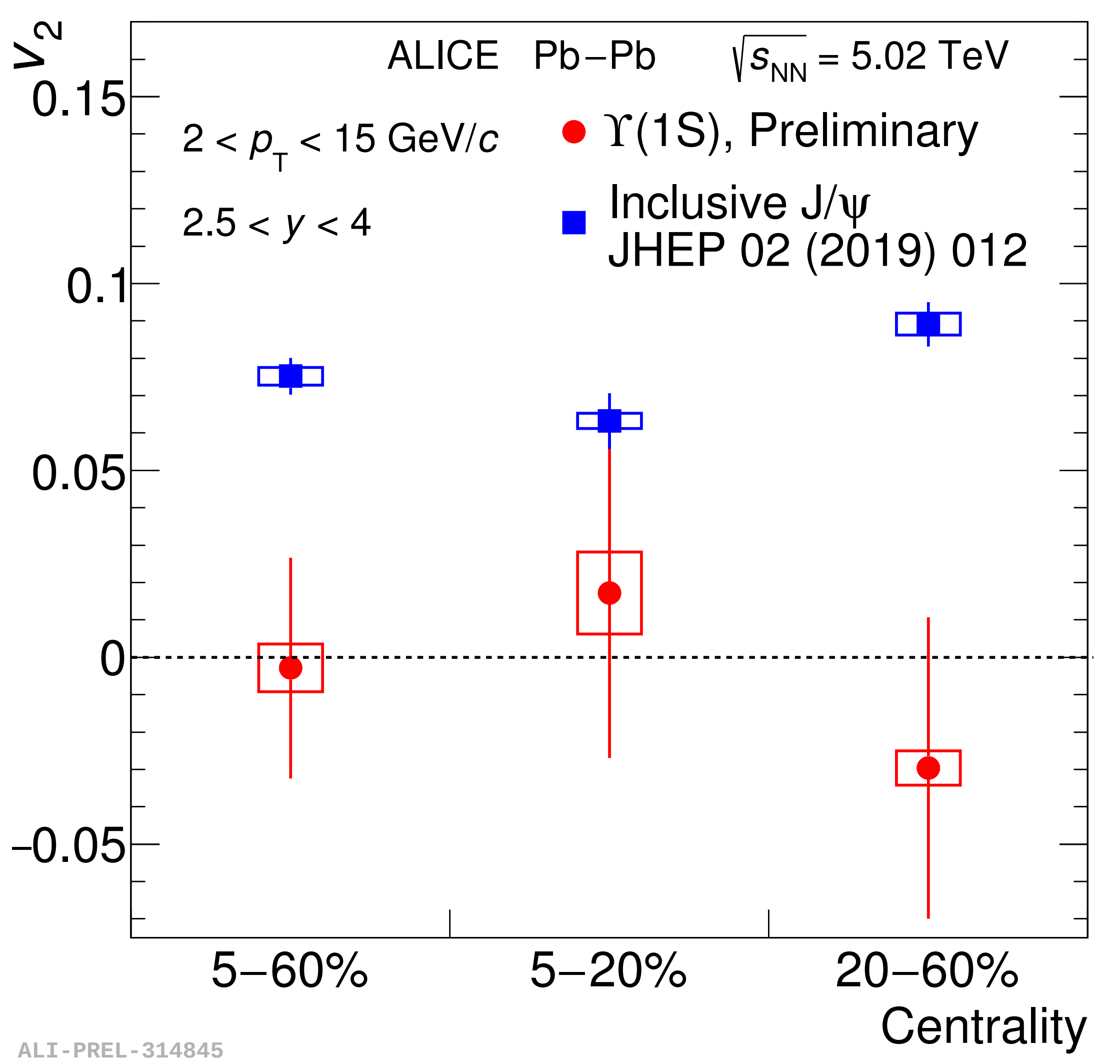


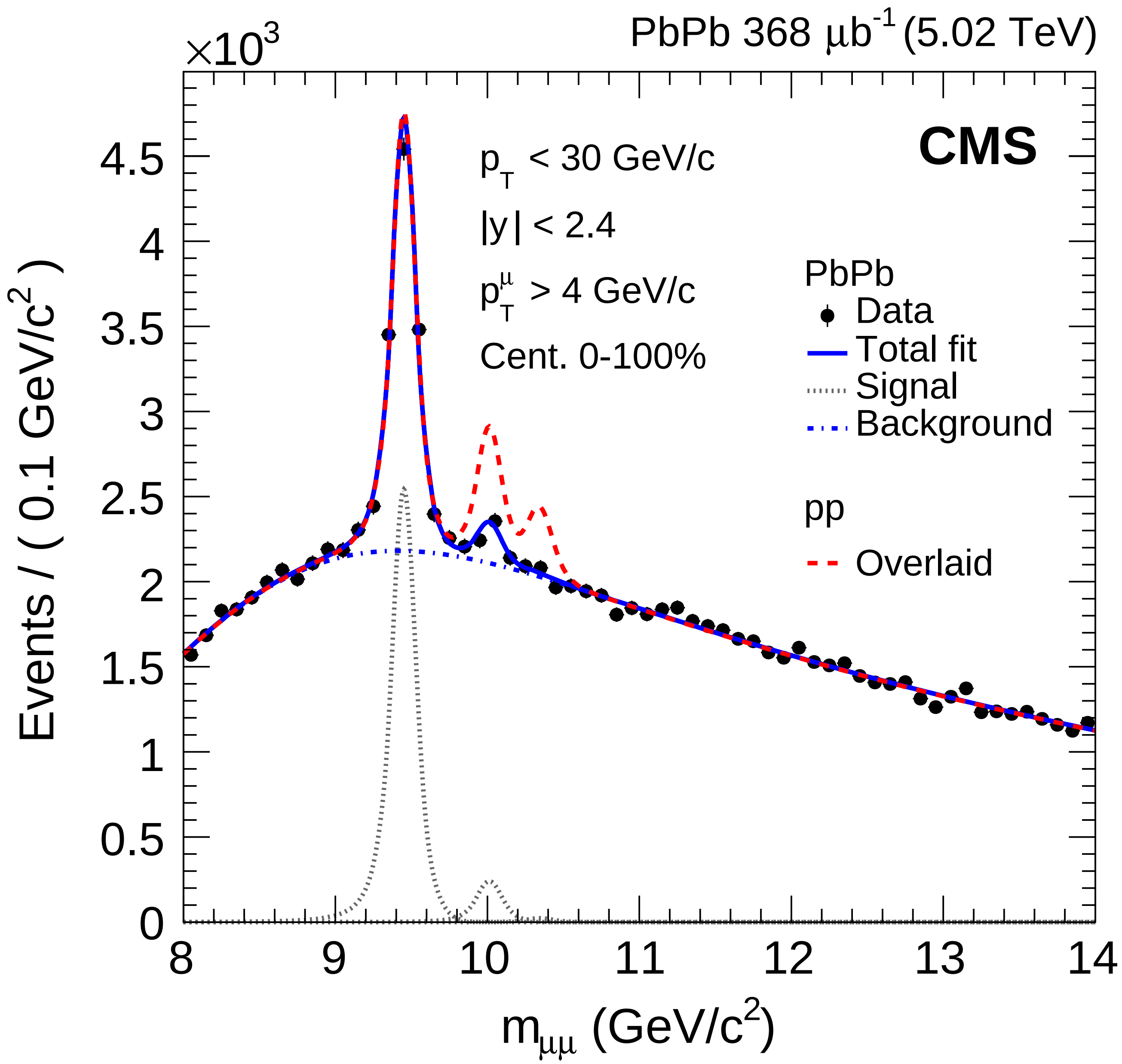
Central AA collisions	RHIC 200 GeV	LHC 5 TeV
N_{ccbar}/event	~10	~115

solution is to use bottomonia states: much less b-quark production → eliminates regeneration

upsilon thermometer



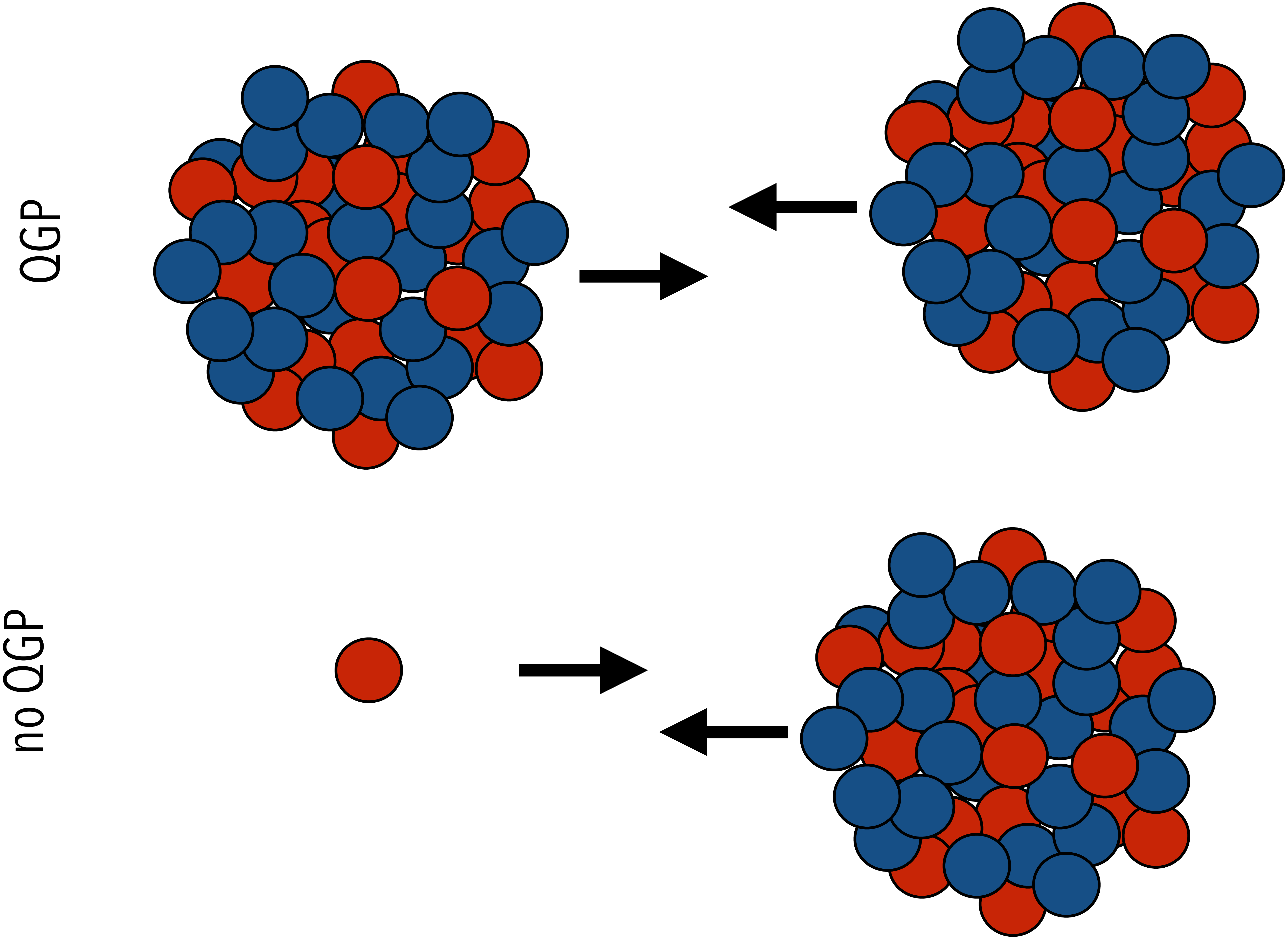




PRL 120 142301 (2018)

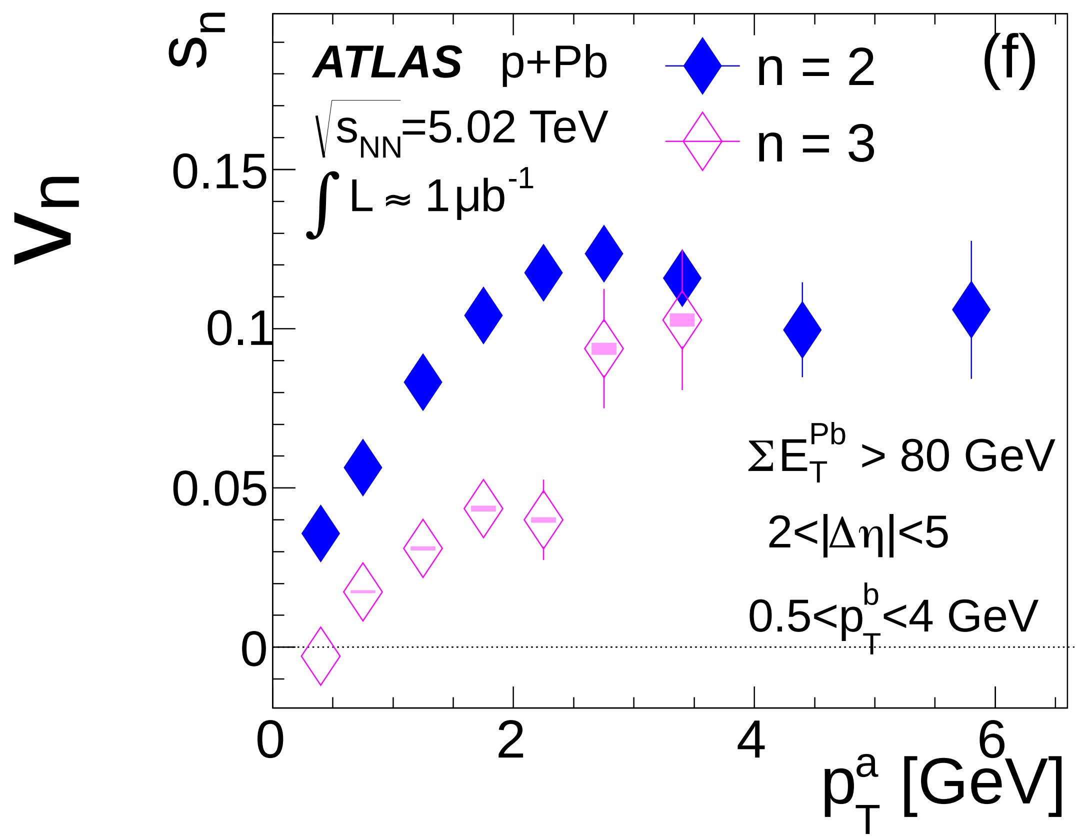
open questions & the future!

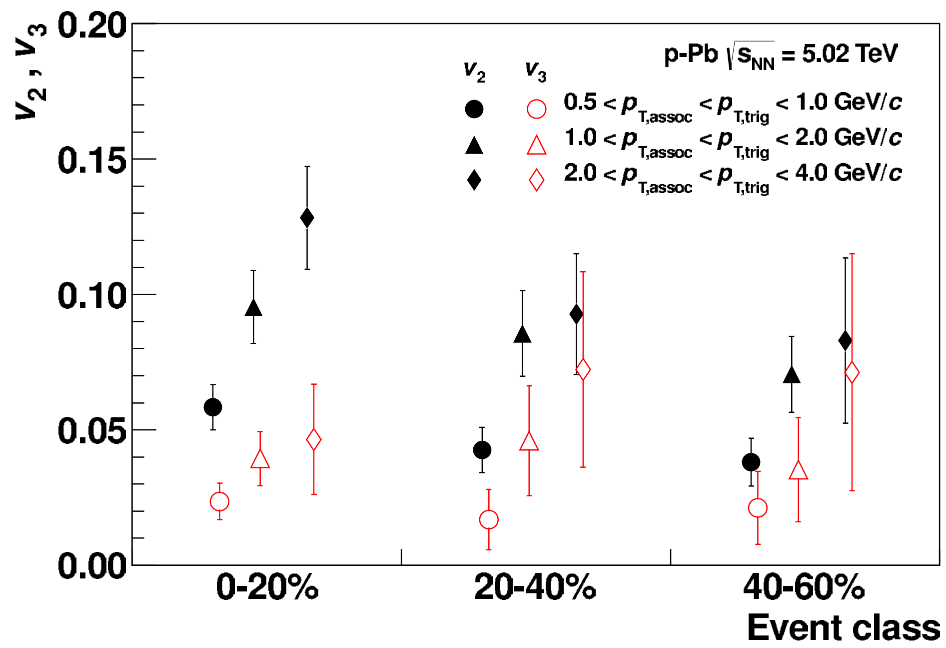
thinking 10 years ago

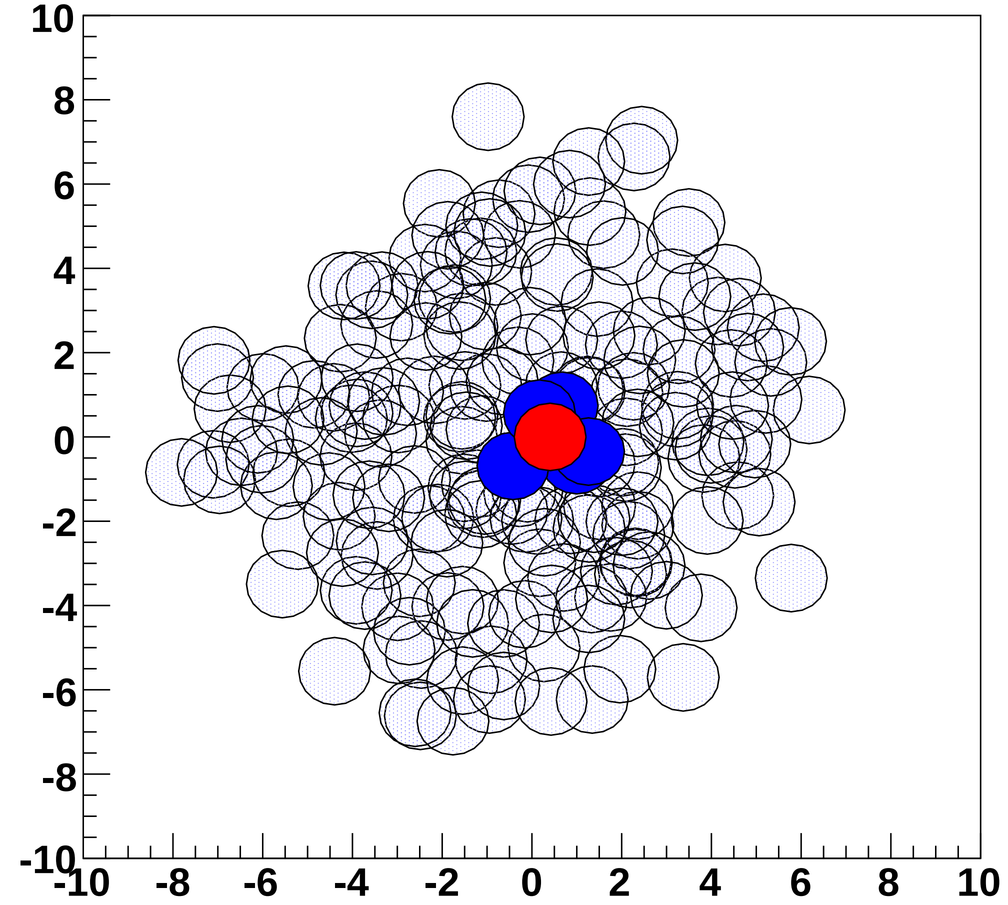


v_2 & v_3 in pPb collisions

ATLAS PRL 110 102303

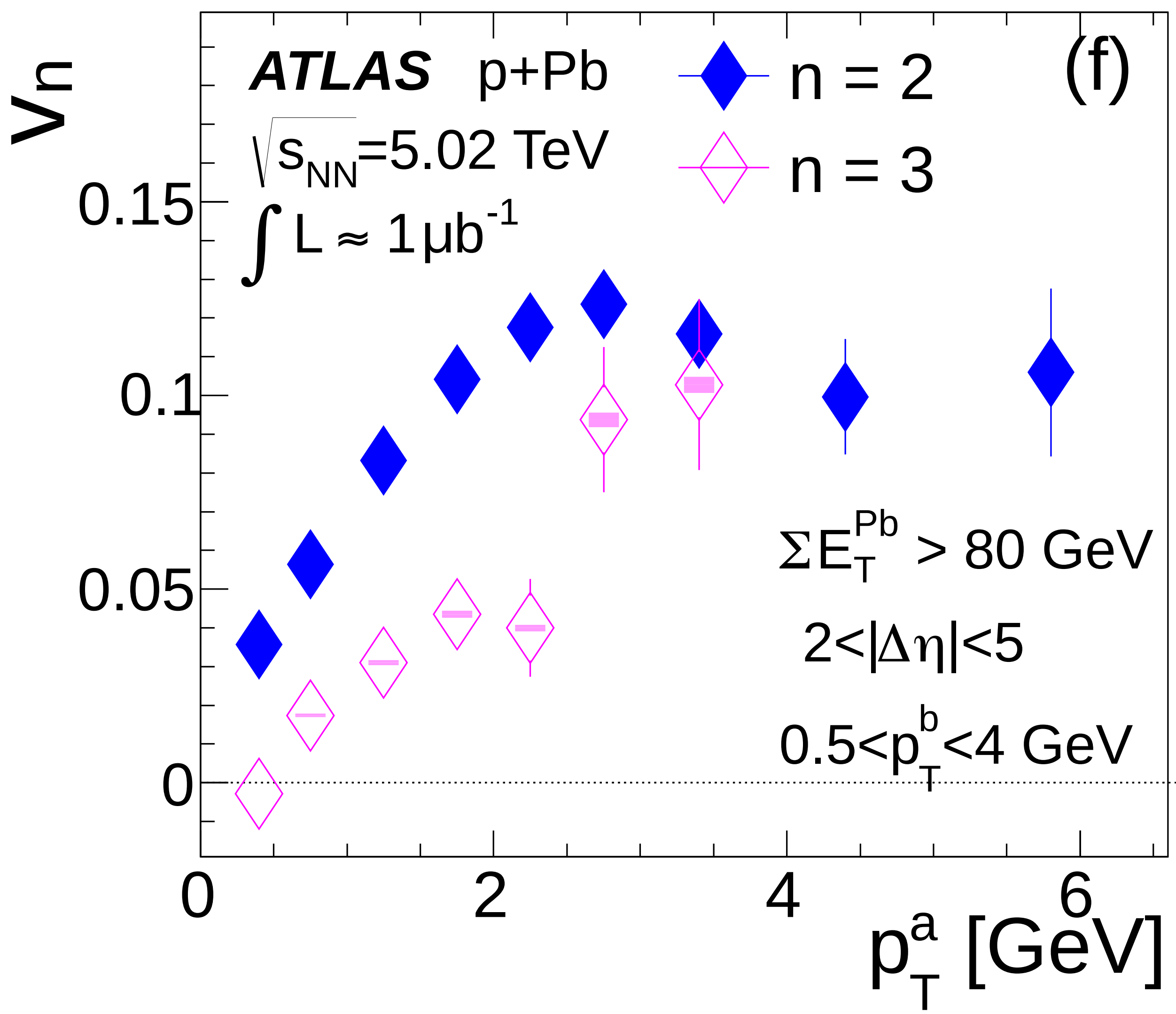




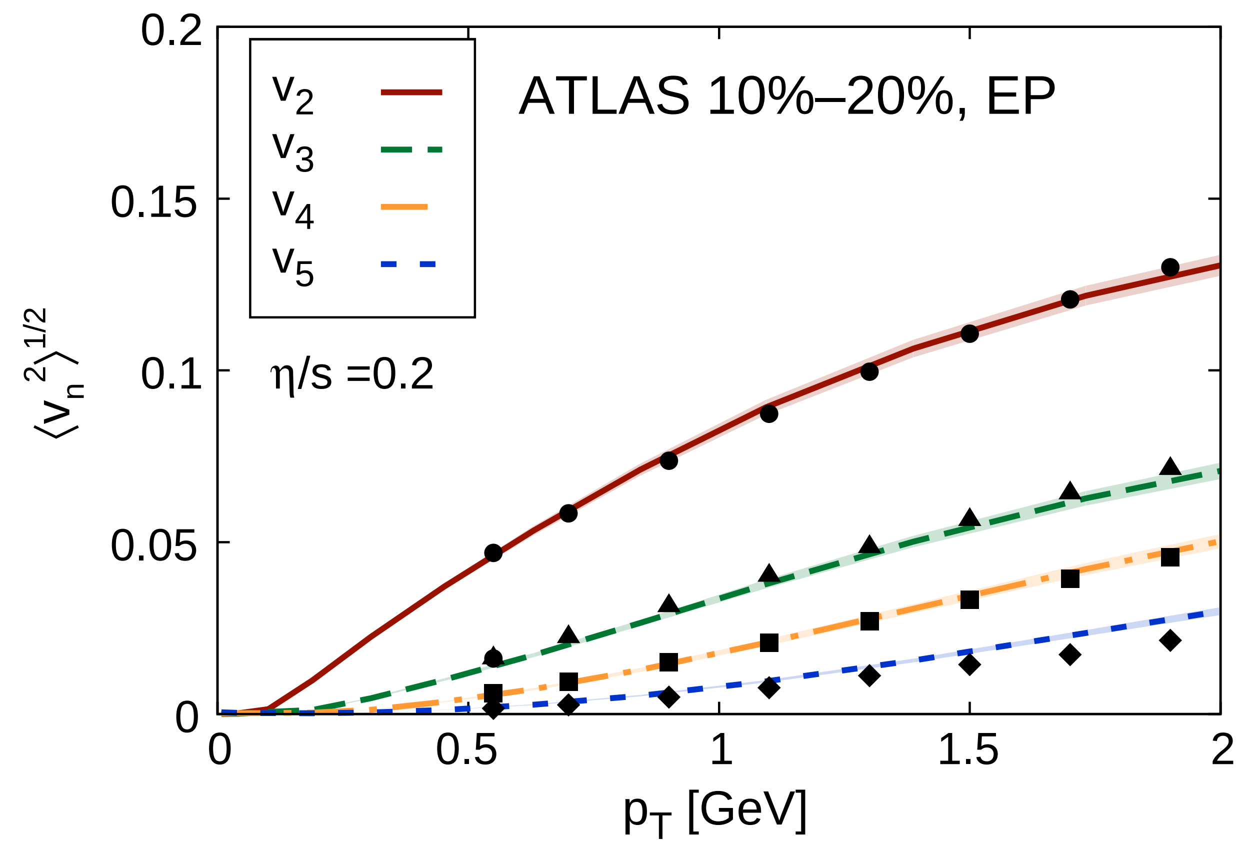


ALICE PLB 719 29 (2013)

are the pA and AA v_N related to the same physics?



very similar to AA results

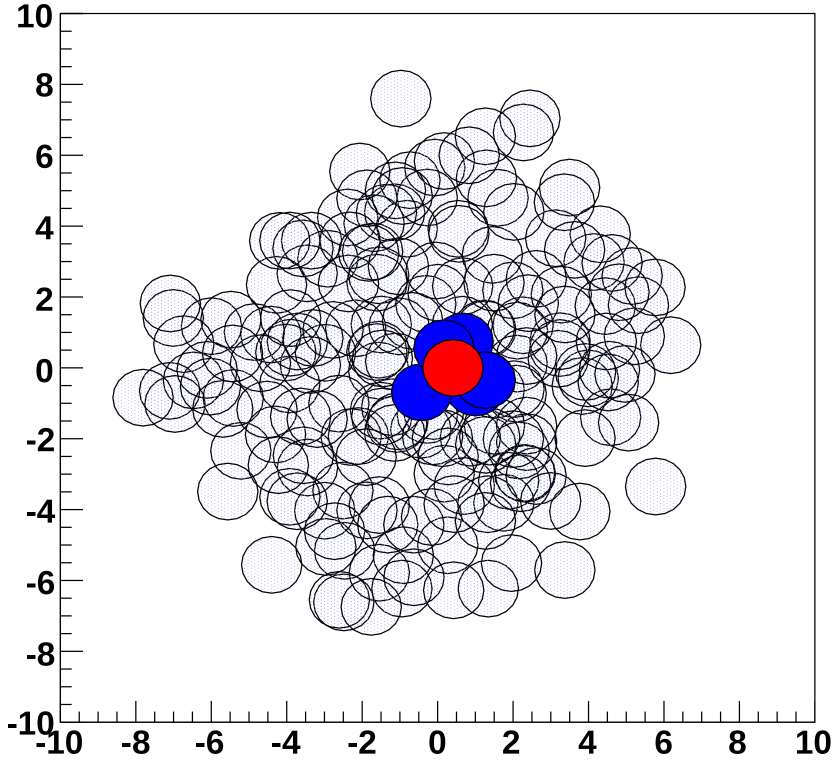


ATLAS PRL 110 102303

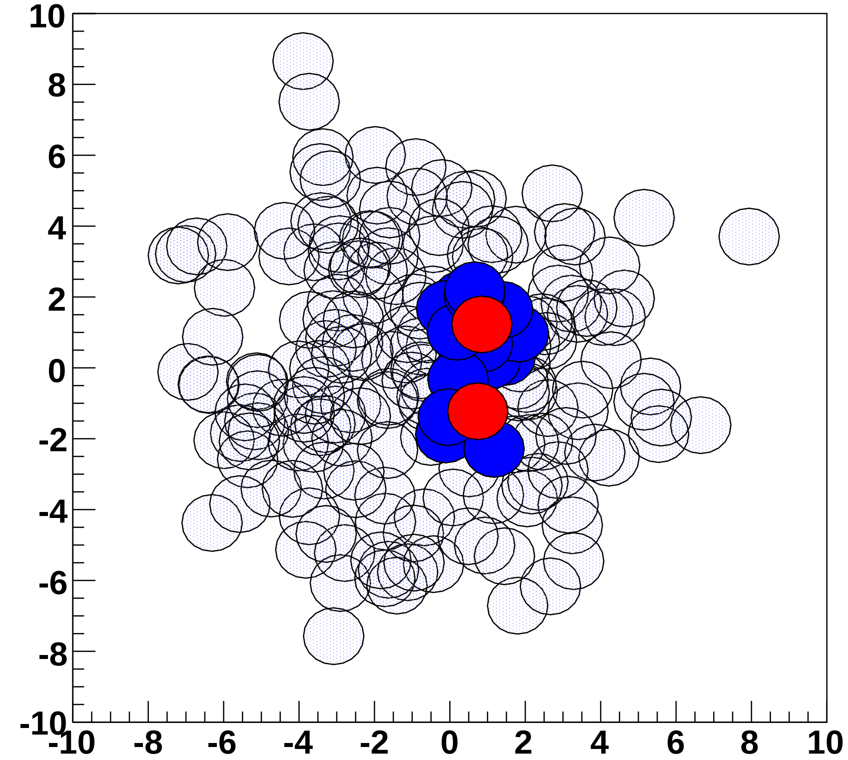
Gale, Jeon, Schenke, Tribedy, Venugopalan PRL 110 012302

variation of the small nucleus

pA



dA



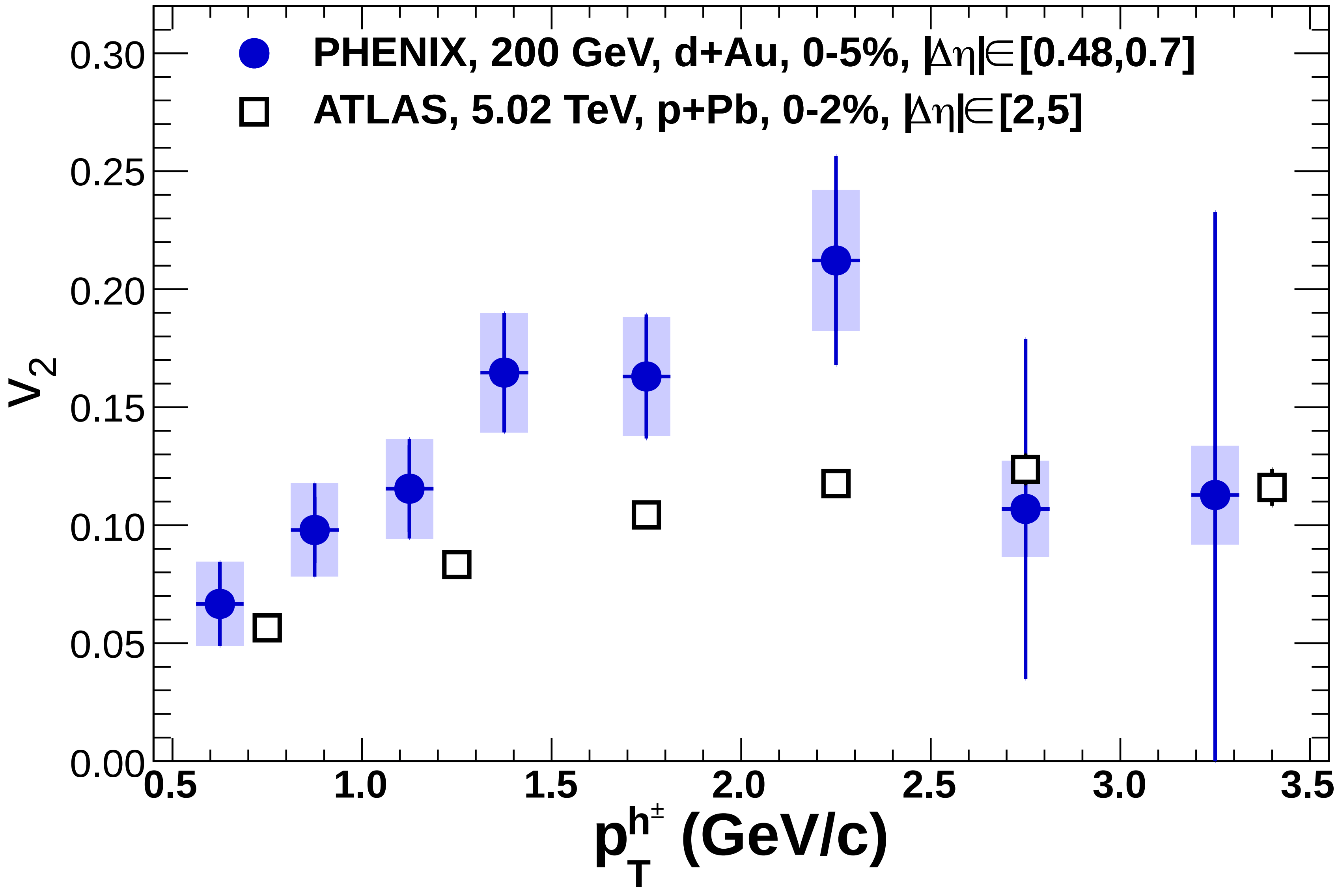
control the collision geometry by varying the small nucleus

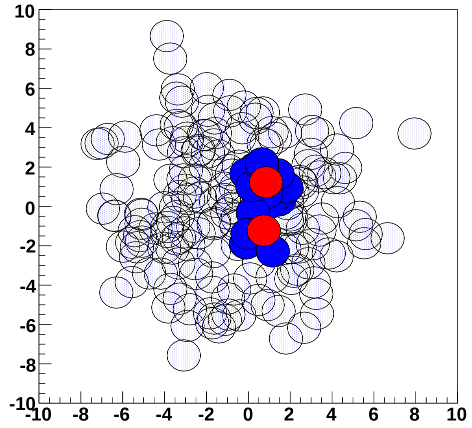
does v2 reflect the geometry of the initial state in p/d+A as in A+A?

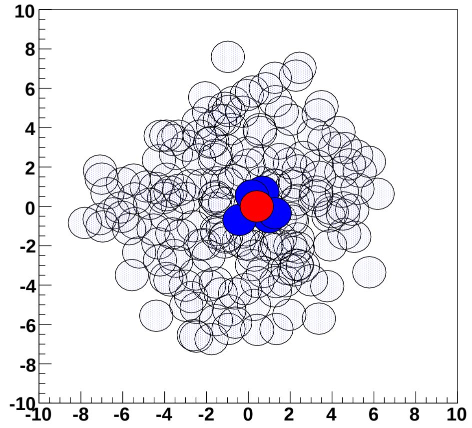
what can RHIC add?

RHIC had huge d+Au sample
25x smaller collision energy than the LHC

v2: pPb & dAu



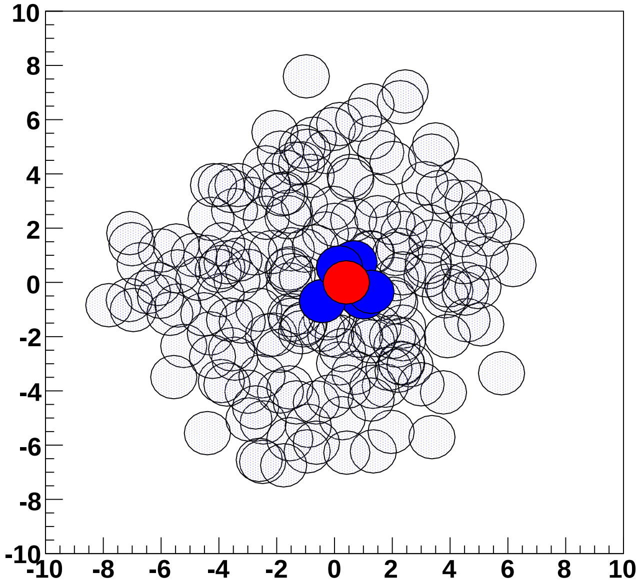




PHENIX PRL 111 212301 (2013)
ATLAS PRL 110 182302 (2013)

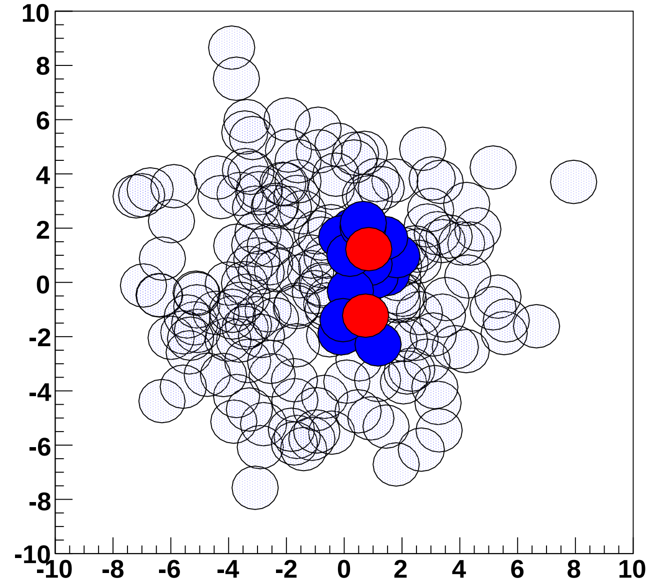
a small QGP?

pA



small ε_2

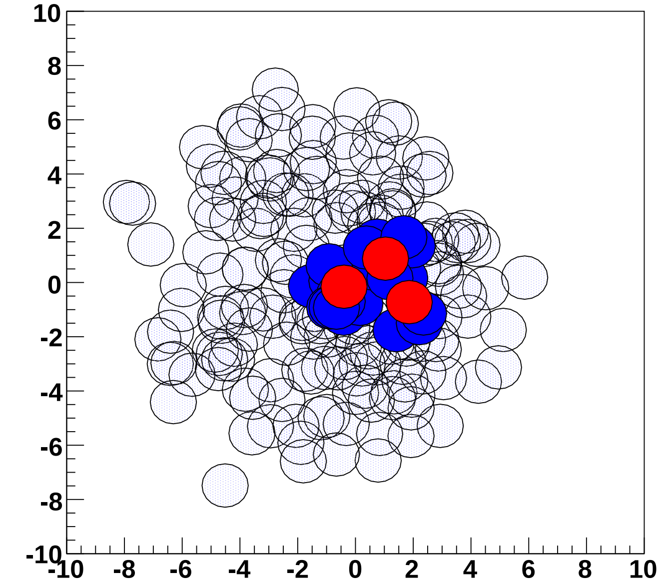
dA



large ε_2

small $\varepsilon 3$

^{3}HeA



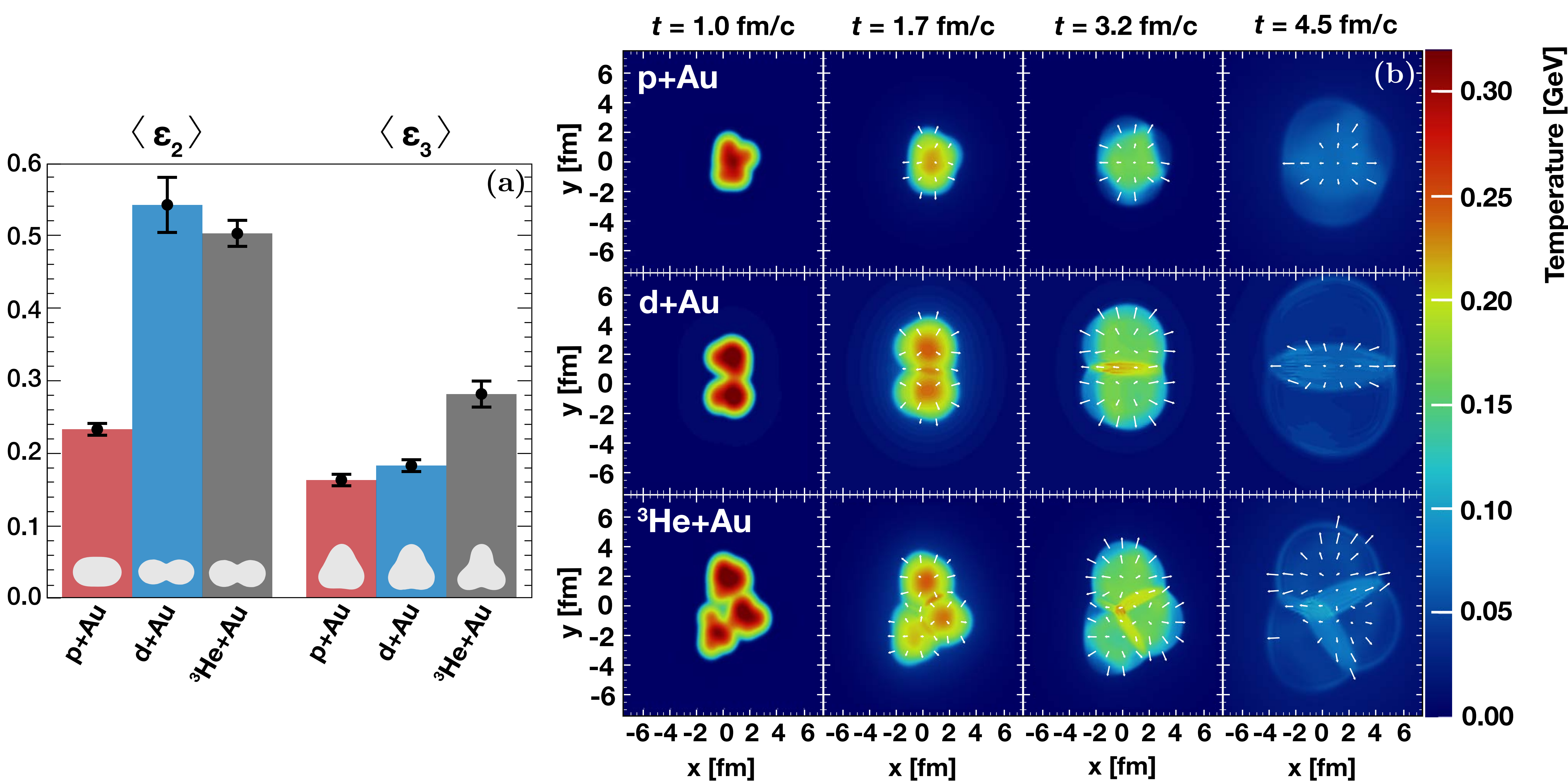
large $\varepsilon 3$

$$\varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\phi \rangle^2 + \langle r^2 \sin n\phi \rangle^2}}{\langle r^2 \rangle}$$

control the collision geometry by varying the small nucleus

geometry and hydrodynamics in small systems

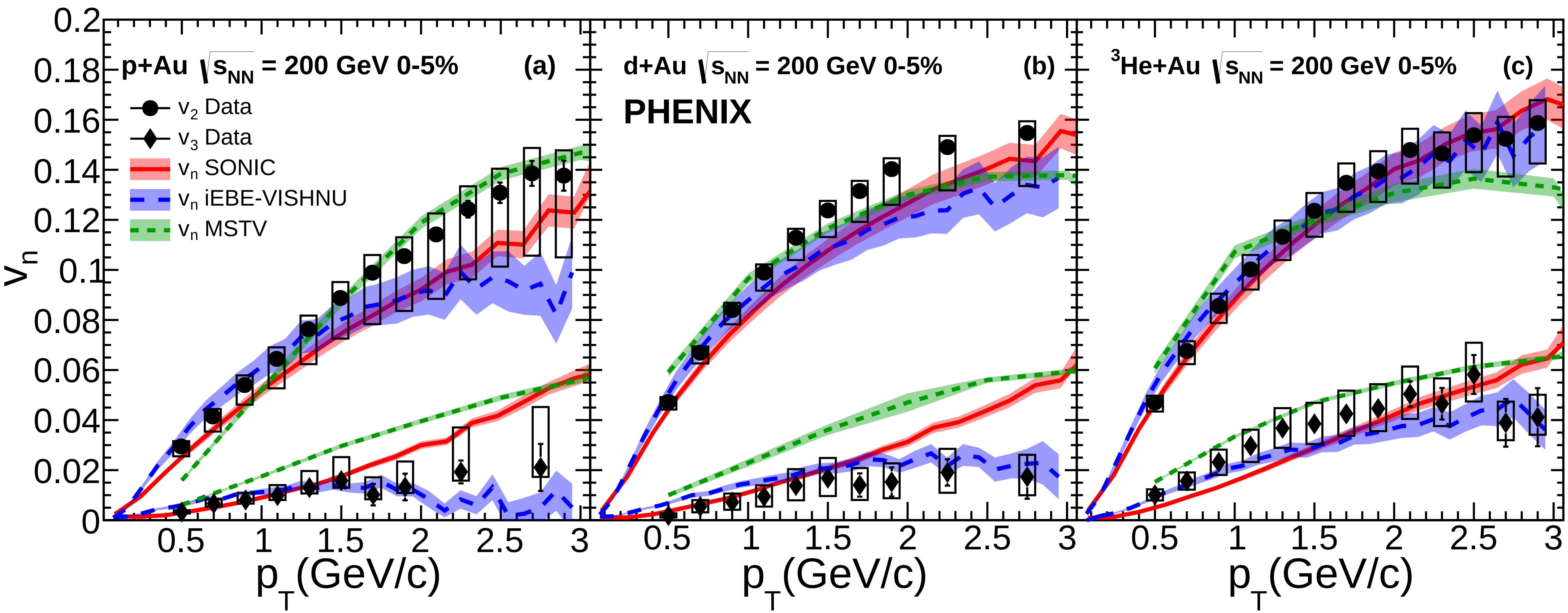
hydrodynamic evolution of pAu, dAu and 3HeAu collisions



PHENIX, 1805.02973

geometry and hydrodynamics in small systems

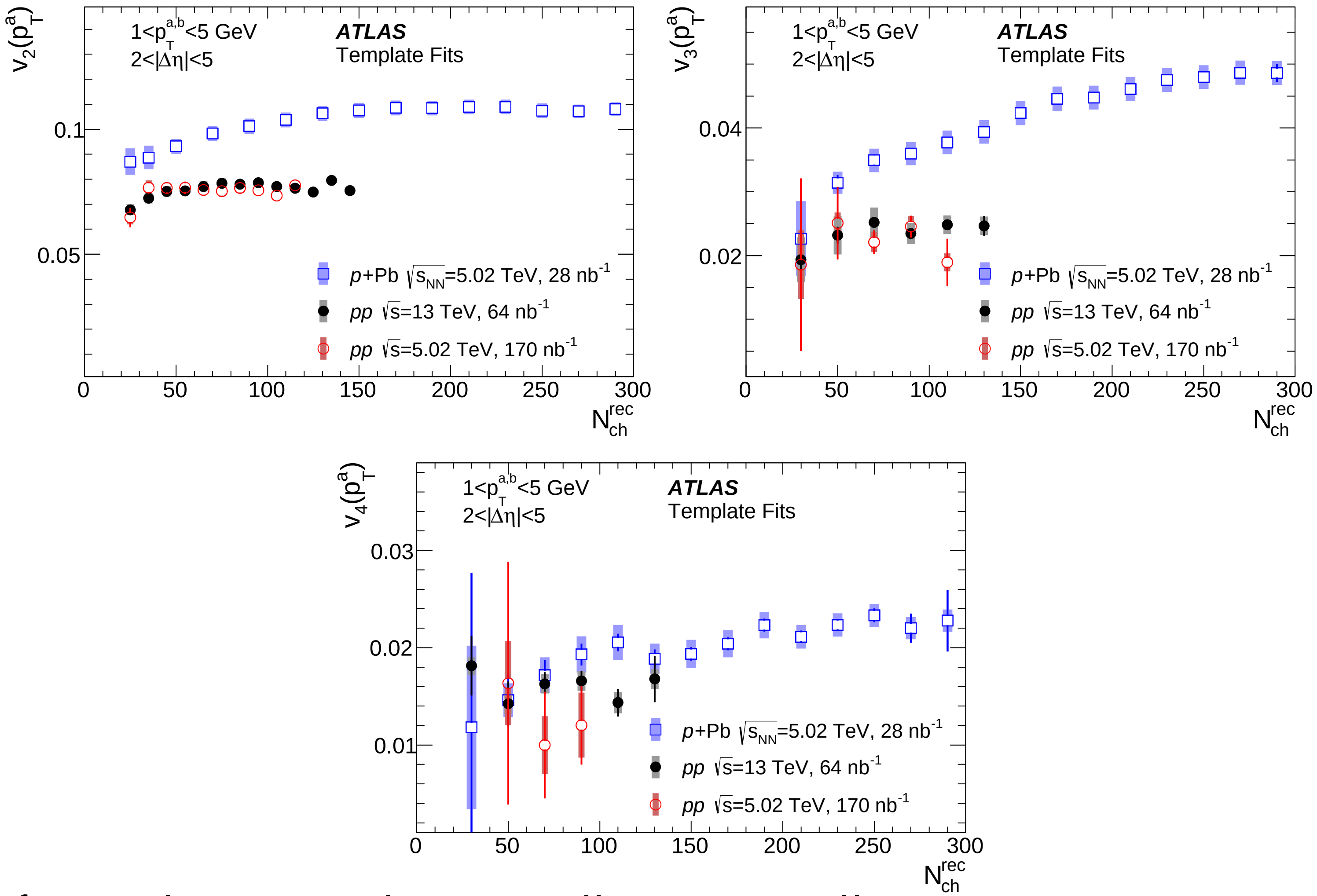
v_2, v_3 from pAu, dAu, ^{3}HeAu compared to two hydrodynamic models (SONIC & iEBE-VISHNU)



PHENIX, 1805.02973

pp collisions?

ATLAS, PRC 96 024908 (2016)



- evidence for similar v_N signals in pp collisions as well
- does that mean:
  - QGP in pp collisions?
  - vN is not evidence for hydrodynamics in AA collisions?
  - something else?
- what is the smallest size QGP you could make?

this is an area of very active discussion

Weller & Romatschke, PLB 774 351
Mace et al PRL 121 052301
Nagle & Zajc, 1808.01276
M. Strikland, Quark Matter 2018
…
plus many experimental papers

CERN-LPCC-2018-07
December 18, 2018

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

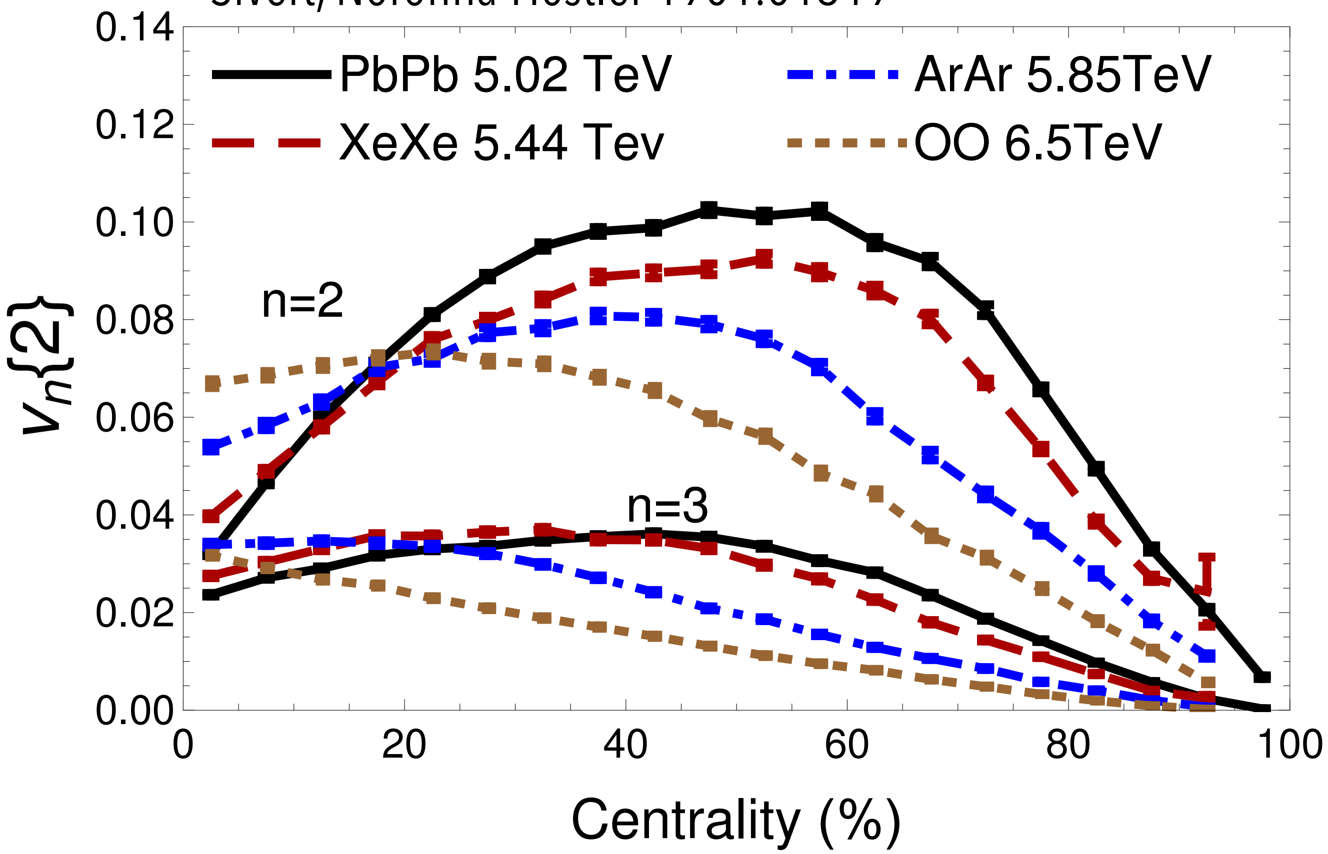
Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

The future opportunities for high-density QCD studies with ion and proton beams at the LHC are presented. Four major scientific goals are identified: the characterisation of the macroscopic long wavelength Quark–Gluon Plasma (QGP) properties with unprecedented precision, the investigation of the microscopic parton dynamics underlying QGP properties, the development of a unified picture of particle production and QCD dynamics from small (pp) to large (nucleus–nucleus) systems, the exploration of parton densities in nuclei in a broad (x, Q^2) kinematic range and the search for the possible onset of parton saturation. In order to address these scientific goals, high-luminosity Pb–Pb and p–Pb programmes are considered as priorities for Runs 3 and 4, complemented by high-multiplicity studies in pp collisions and a short run with oxygen ions. High-luminosity runs with intermediate-mass nuclei, for example Ar or Kr, are considered as an appealing case for extending the heavy-ion programme at the LHC beyond Run 4. The potential of the High-Energy LHC to probe QCD matter with newly-available observables, at twice larger center-of-mass energies than the LHC, is investigated.

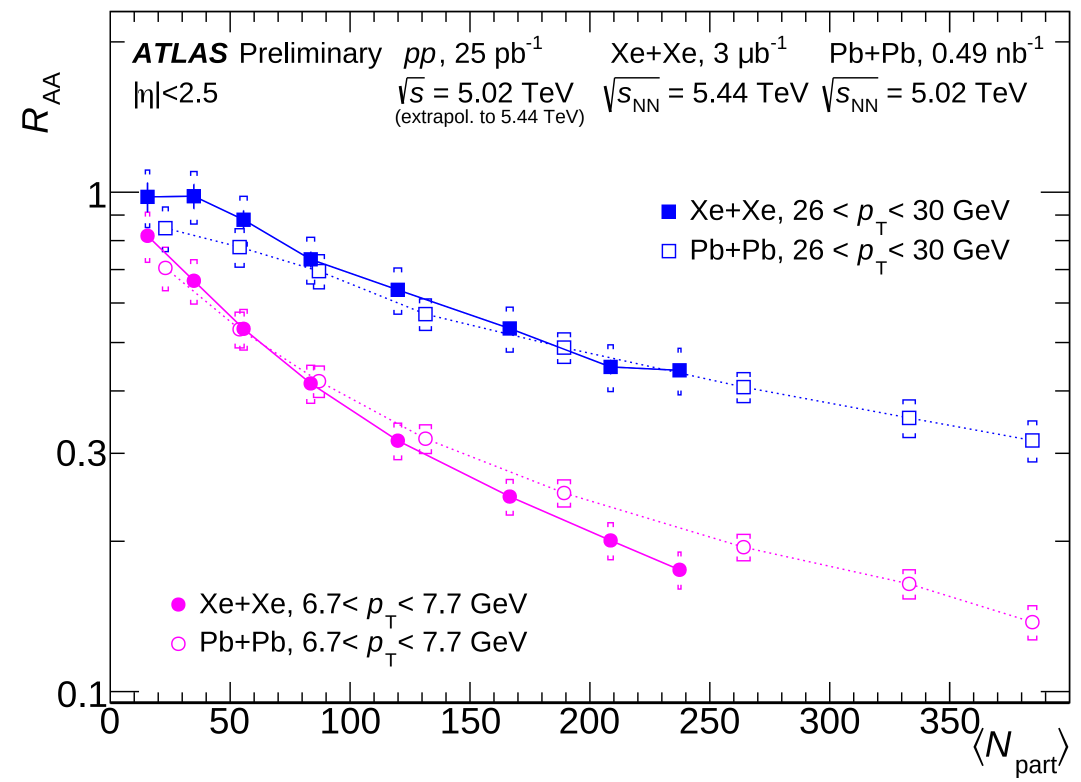
1812.06772

light ions

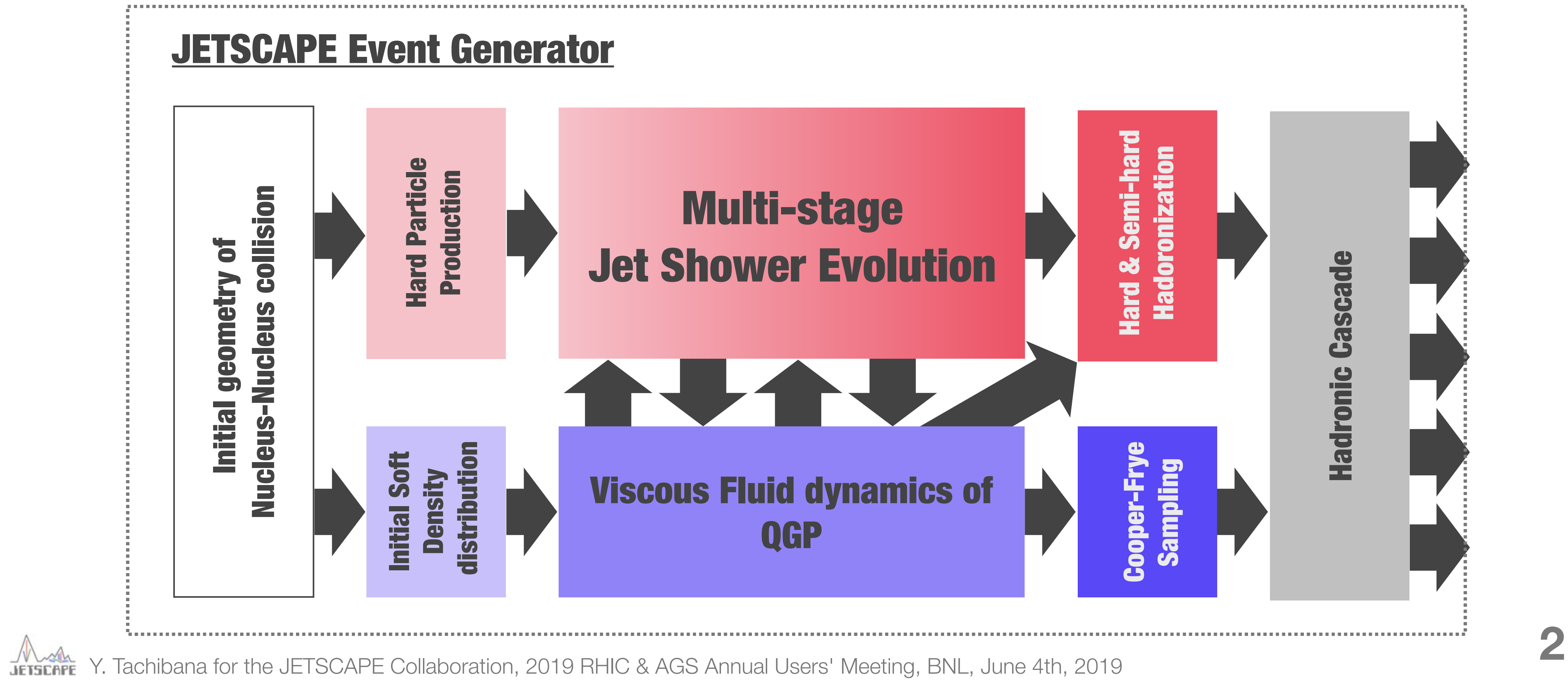
Sivert, Noronha-Hostler 1901.01319

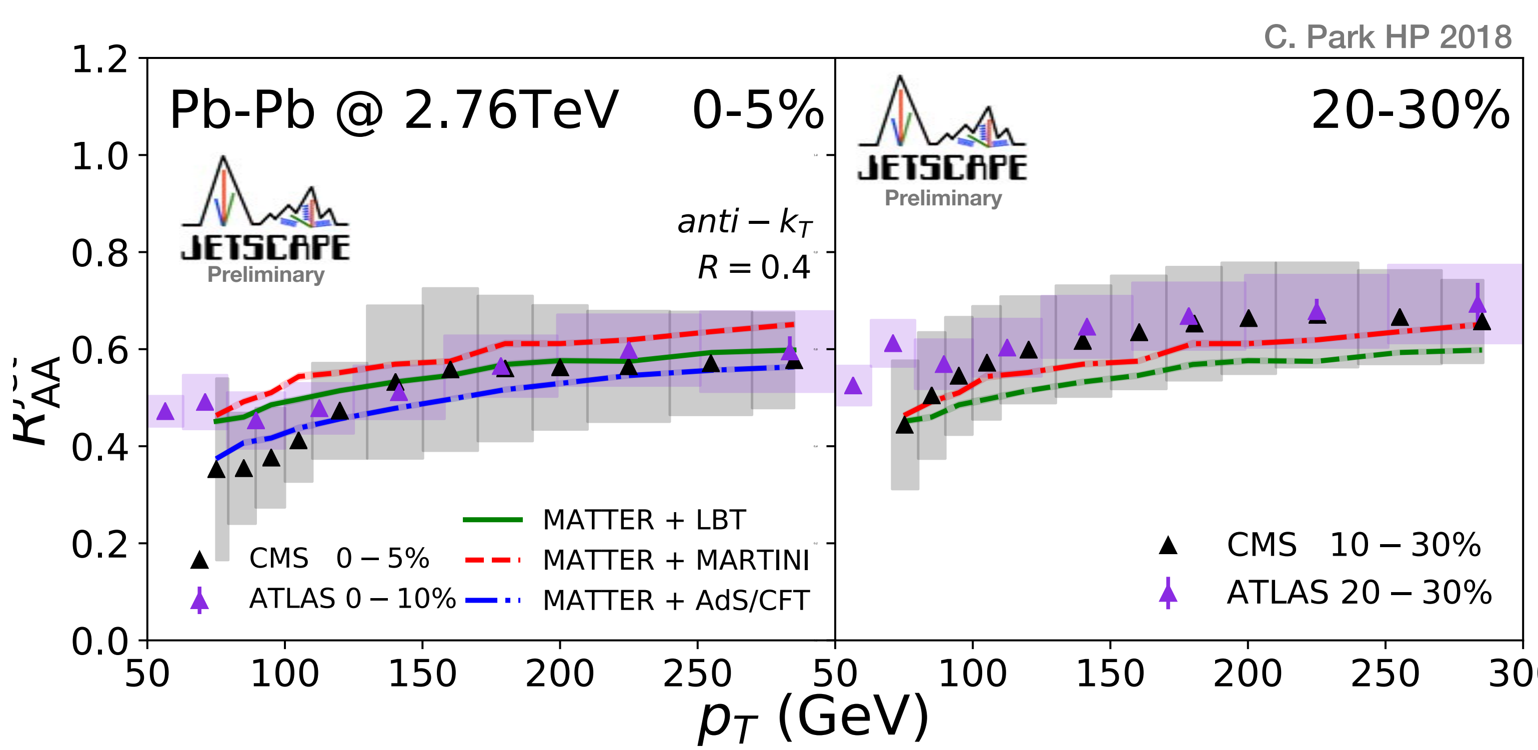


ATLAS-CONF-2018-007



small collision systems provide a way to bridge between pA and AA systems and provide information about flow and jet quenching


JETSCAPE Event Generator
Initial geometry of Nucleus-Nucleus collision
Hard Particle Production
Initial Soft Density distribution
Multi-stage Jet Shower Evolution
Viscous Fluid dynamics of QGP
Hard & Semi-hard Hadoronization
Cooper-Frye Sampling
Hadronic Cascade
2
Y. Tachibana for the JETSCAPE Collaboration, 2019 RHIC & AGS Annual Users' Meeting, BNL, June 4th, 2019


C. Park HP 2018
Pb-Pb @ 2.76TeV
0-5%
20-30%
JETSCAPE
Preliminary
anti − kT
R = 0.4
MATTER + LBT
MATTER + MARTINI
MATTER + AdS/CFT
CMS 0 − 5%
ATLAS 0 − 10%
CMS 10 − 30%
ATLAS 20 − 30%
pT (GeV)

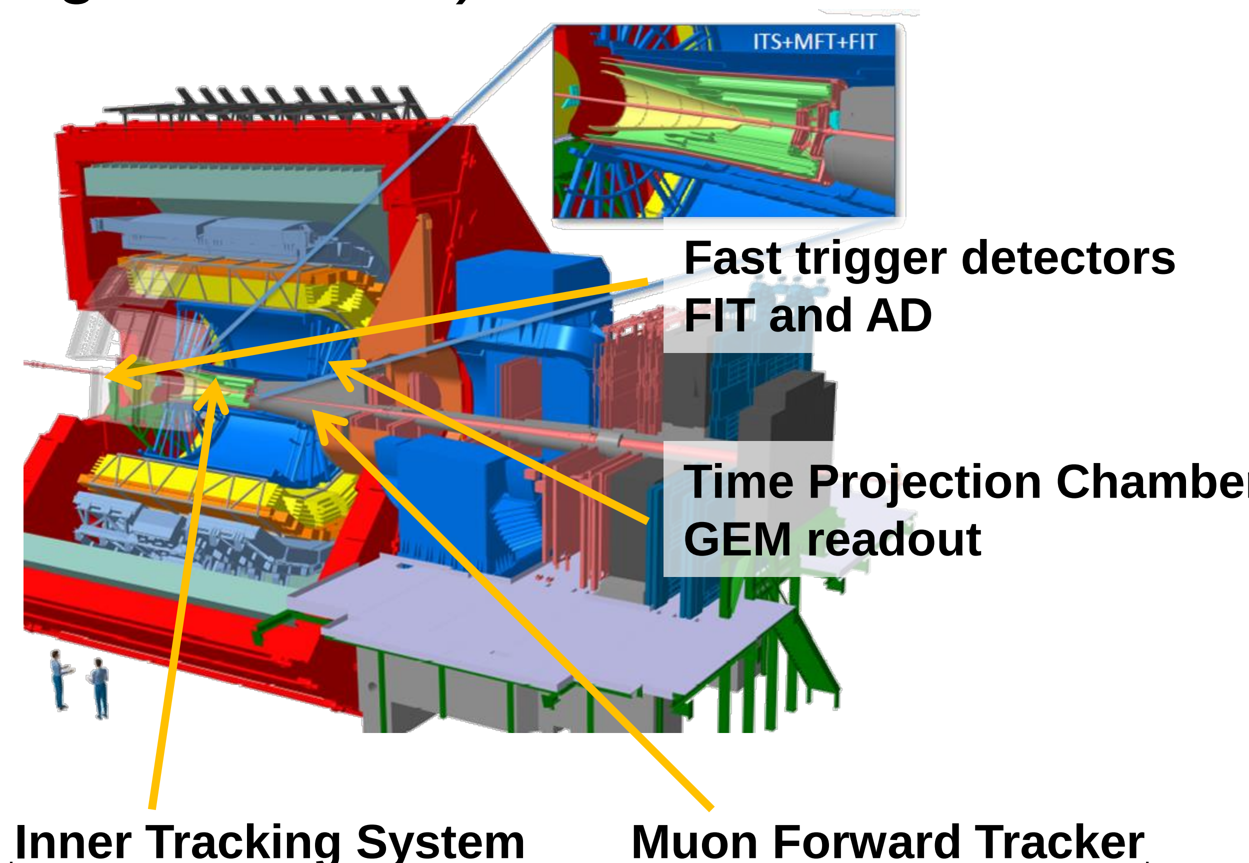
ALICE upgrades

from Quark Matter 2018

Approved and funded

ALICE @ LHC
(data taking from 2021)

- Significant upgrade, including
  - increasing data rate by factor 100
  - impact parameter resolution by factor 3
- Collision spacing < TPC drift time
  - No notion of event during data taking
- Continuous data-taking
  - 50 kHz Pb-Pb
  - Offline reconstruction determines which track belongs where
  - Online reduction 3.4 TB/s → 0.1 GB/s
  - 10 nb^{-1} = 10^{11} Pb-Pb events in 2021-29
- Focus on "untriggerable" signals with tiny signal over background

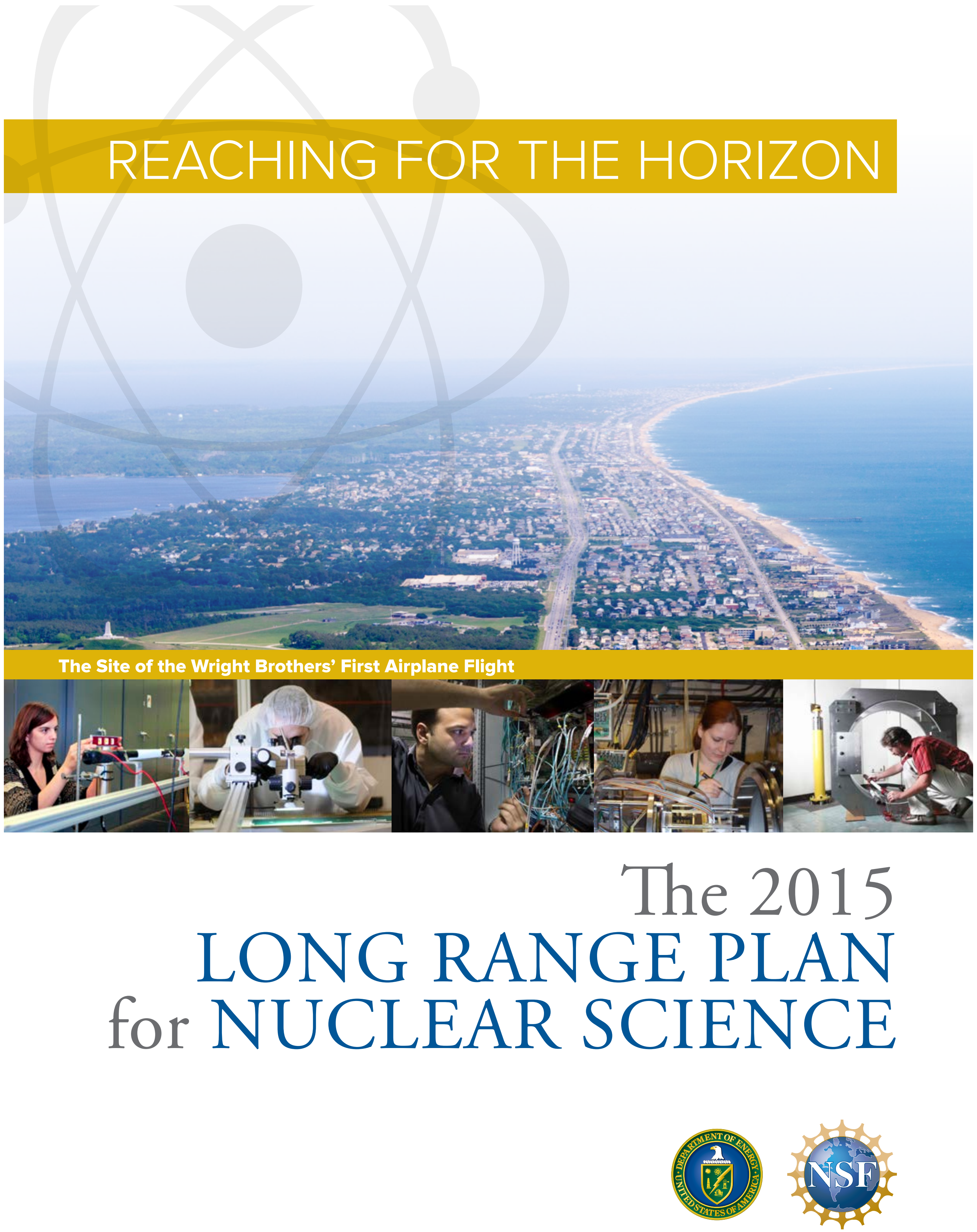


Monolithic active pixel sensors (MAPS) thinned down to 50 um

The Future of High-Energy Heavy-Ion Facilities - Jan Fiete Grosse-Oetringhaus 8

ALICE upgrades will improve performance for decays and other PID signals which are rare, but untriggerable

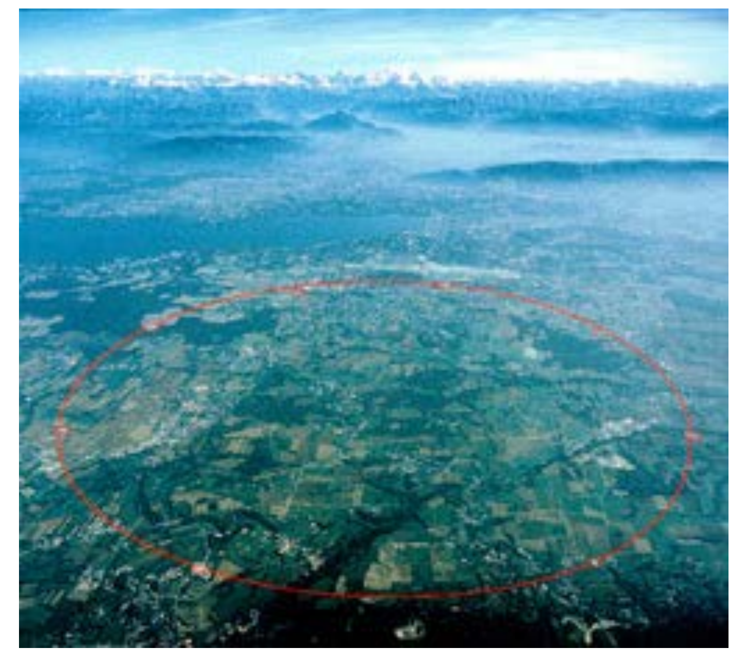
from description to understanding



"To understand the workings of the QGP, there is no substitute for microscopy. We know that if we had a sufficiently powerful microscope that could resolve the structure of QGP on length scales, say a thousand times smaller than the size of a proton, what we would see are quarks and gluons interacting only weakly with each other. **The grand challenge for this field in the decade to come is to understand how these quarks and gluons conspire to form a nearly perfect liquid."**

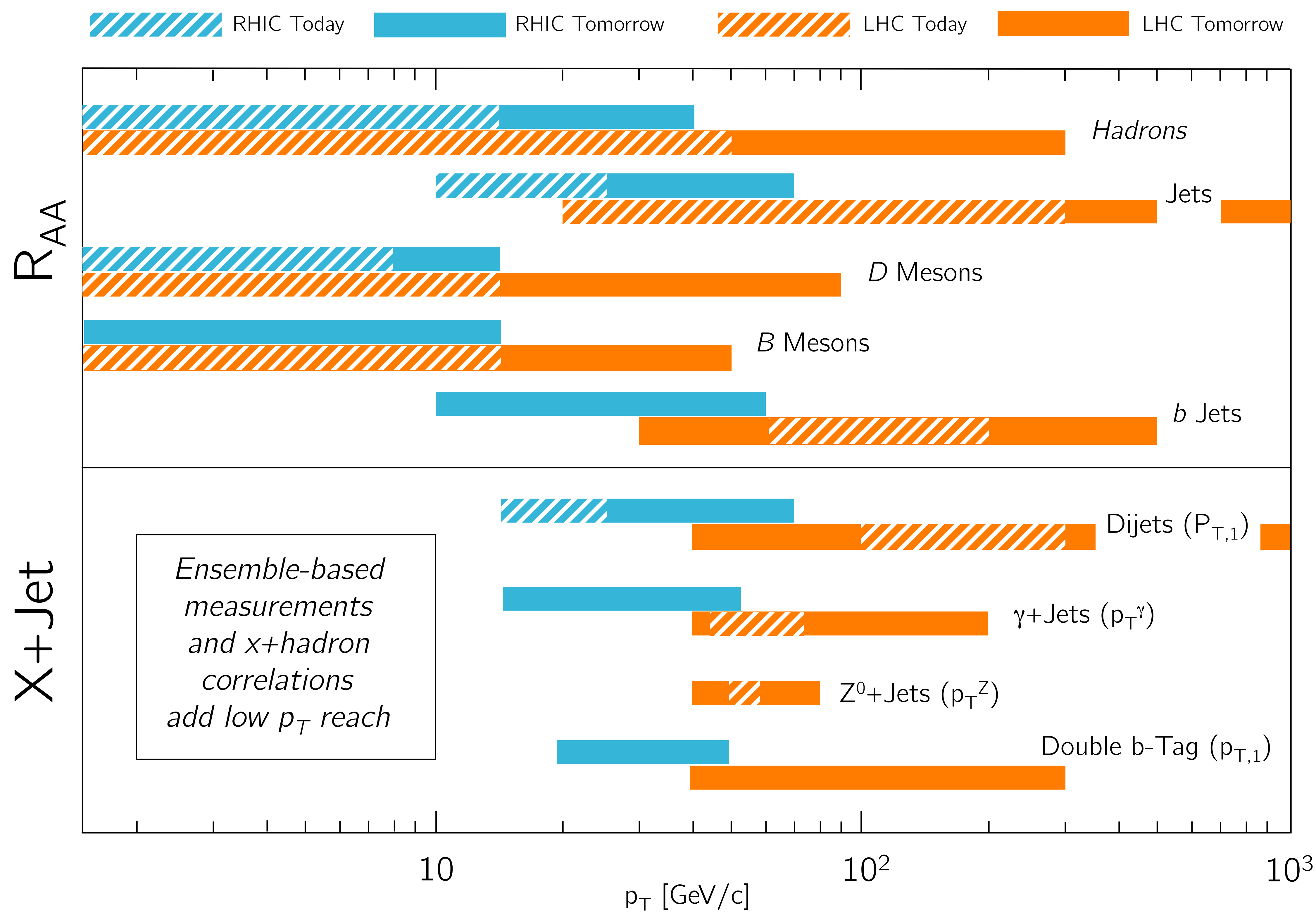
what do we need to measure?

Long Range Plan: "Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX."



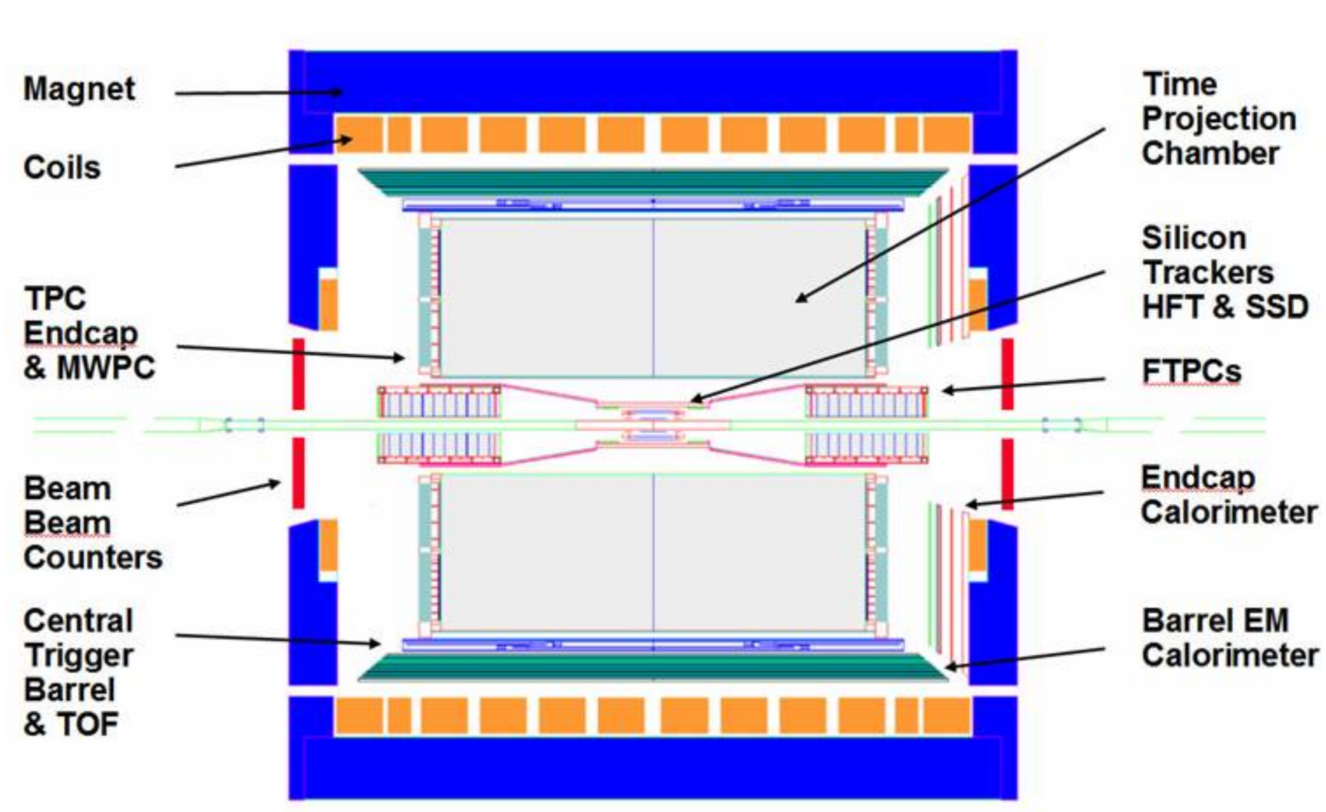
- jets, upsilons and photons with high statistics over a wide kinematic and collision energy range
  - jets from 20 GeV → 1 TeV
  - collision energy from 200 GeV → 5.5 TeV
  - luminosity for precision measurements at both facilities

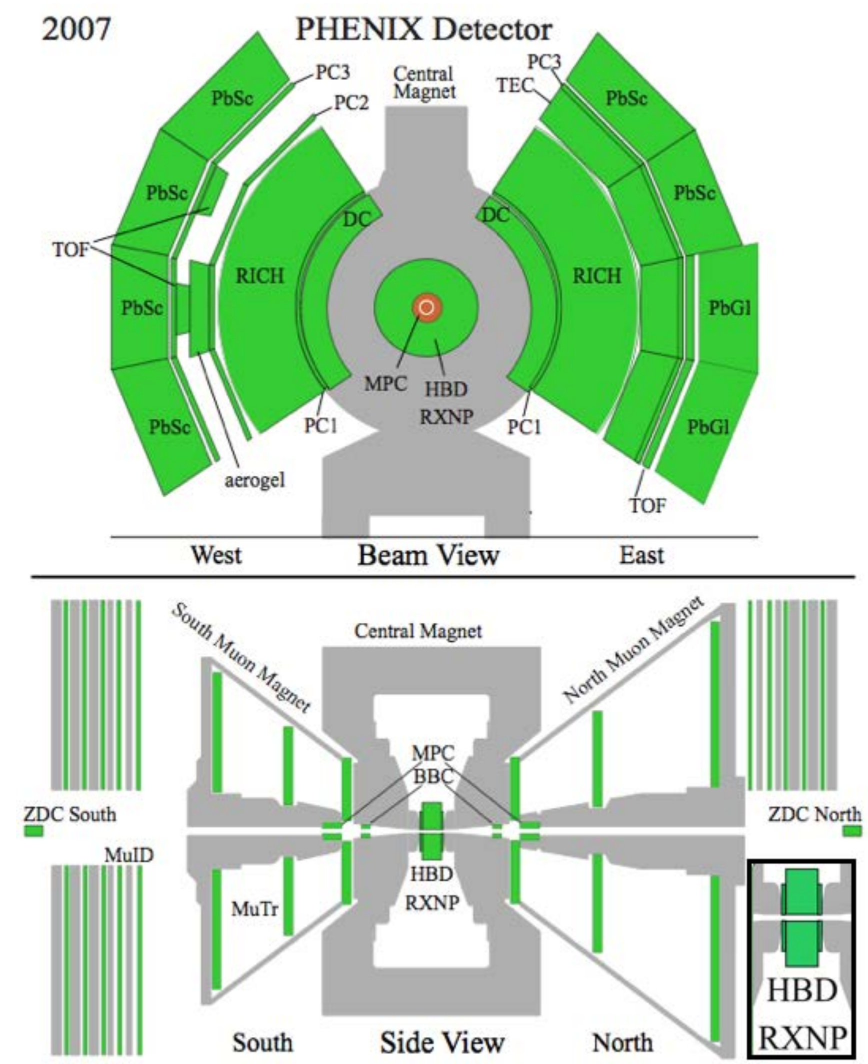
overlapping measurements with the LHC



large detectors at RHIC

STAR



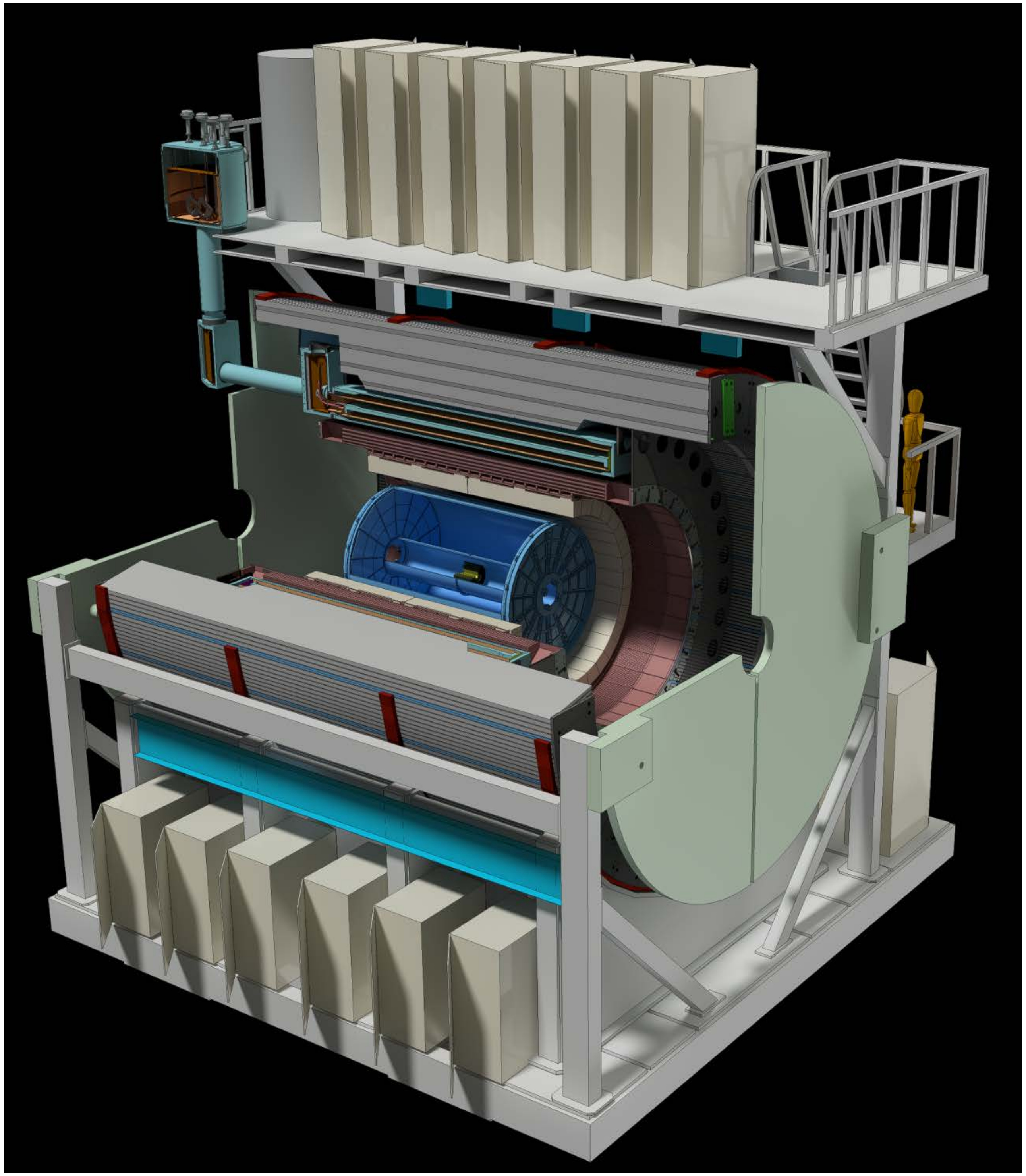


large acceptance TPC, TOF,
EM calorimeter
solenoid magnet

small acceptance, high rate,
EM calorimeter

both of these detectors have served the community very well since the turn on RHIC
neither of these detectors is optimized for high rate and large acceptance for jets, upsilons, …

sPHENIX



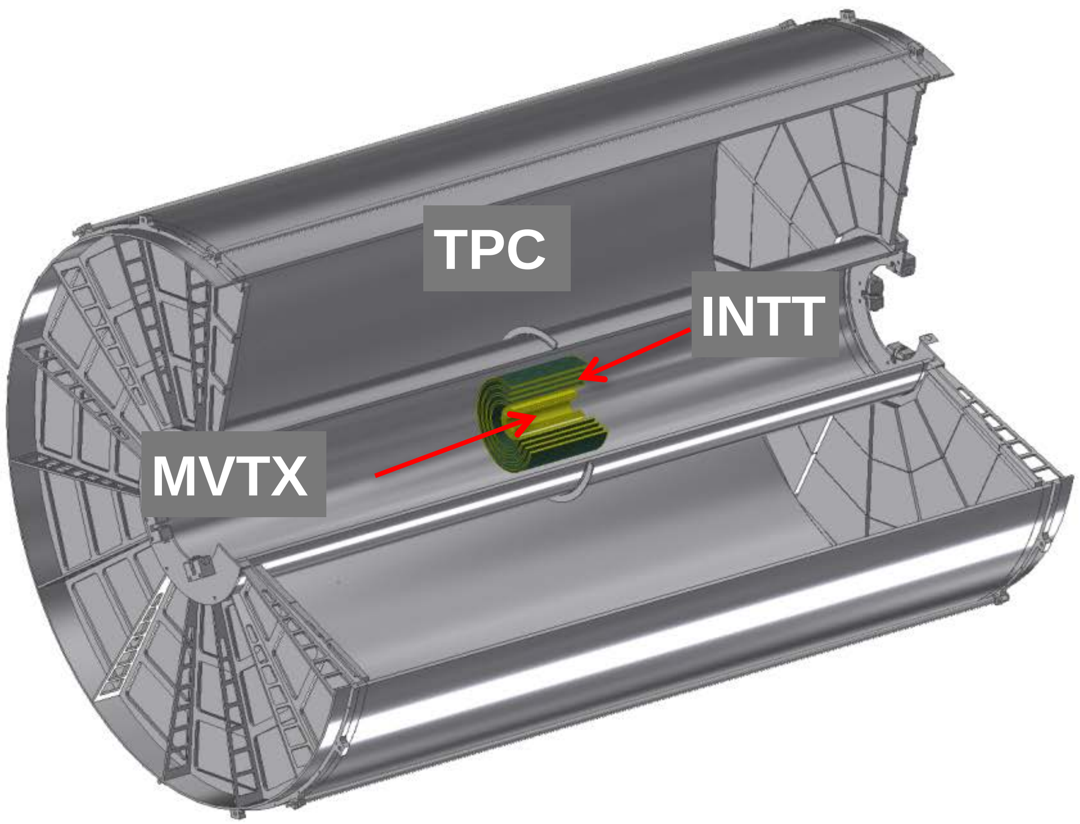
Babar solenoid headed to it's new life in NY

successfully operated at full field for the first time since Babar this year!

large acceptance, high rate, electromagnetic & hadronic calorimetry

excellent tracking and calorimetry

Tracking

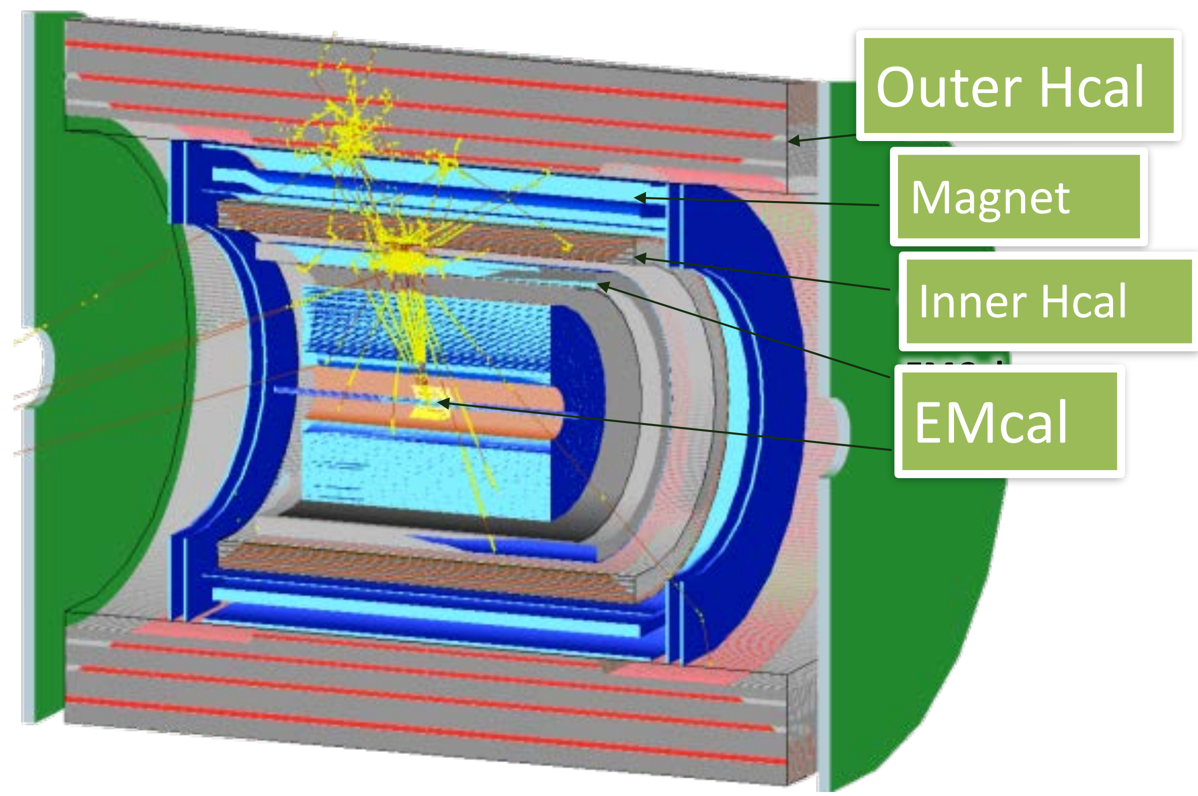


Continuous Readout **TPC**

Silicon Strip Intermediate Tracker **(INTT)**

3-layer MAPS µ vertex **(MVTX)**

Calorimetry

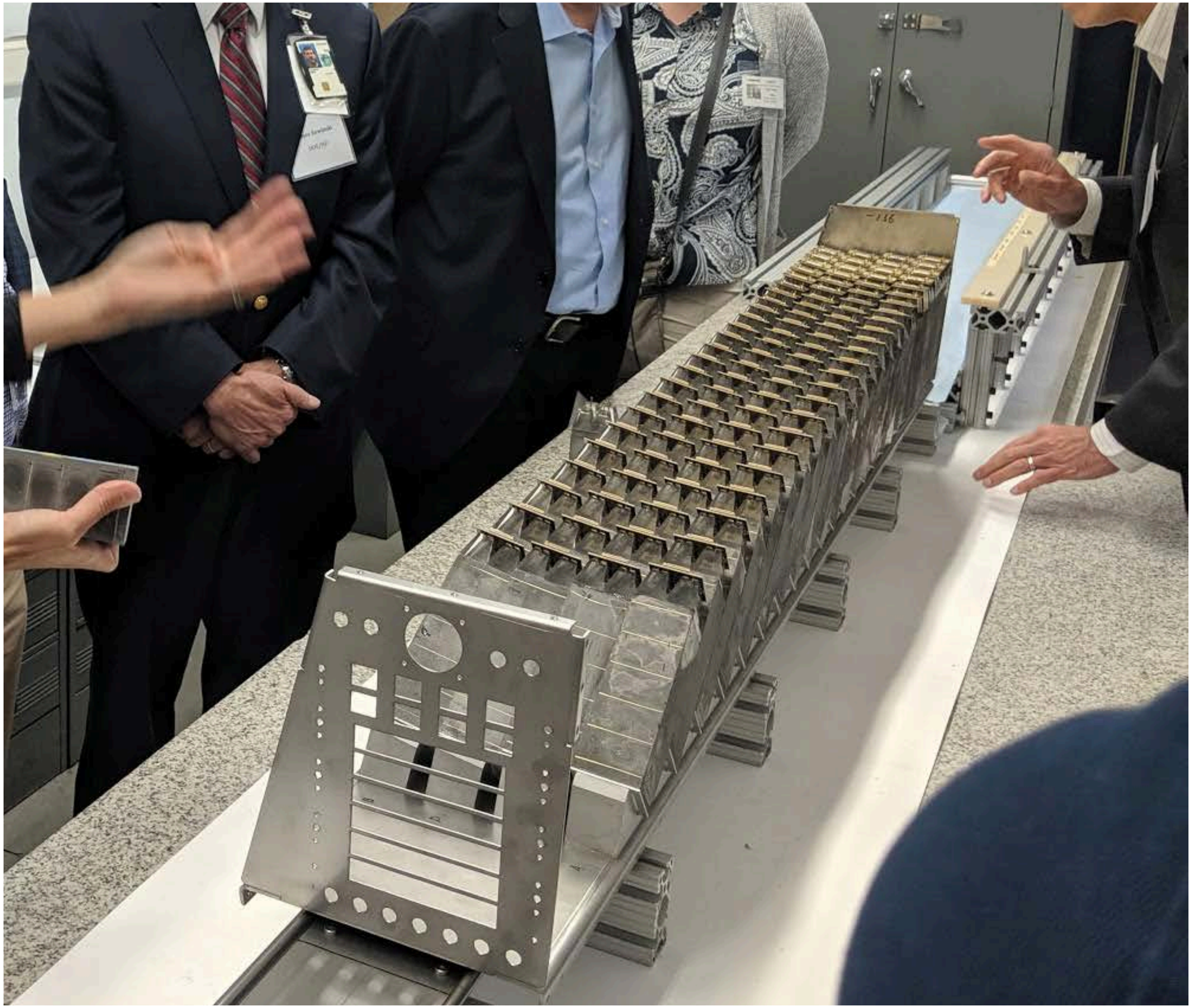


Hcal

EMcal

2π coverage

sPHENIX EMCal



- goal: try to understand the emergent liquid phenomena of the QGP at high temperature in QCD
- large momentum scale processes can be used to probe the QGP on short length scales
- future:
  - lower collision energy, lighter ions: smaller, cooler QGP
  - sPHENIX: high rate large acceptance at RHIC, jets and upsilons

a closer look at the nucleus/nucleon: electron ion collider–discussed on Monday!

other reviews (not comprehensive)

First Results from Pb+Pb collisions at the LHC

Berndt Muller (Duke U.), Jurgen Schukraft (CERN), Boleslaw Wyslouch (MIT)

Feb 2012 - 24 pages

Ann.Rev.Nucl.Part.Sci. 62 (2012) 361-386
DOI: 10.1146/annurev-nucl-102711-094910
CERN-OPEN-2012-005
e-Print: arXiv:1202.3233 [hep-ex] | PDF

Collective flow and viscosity in relativistic heavy-ion collisions

Ulrich Heinz (Ohio State U.), Raimond Snellings (Utrecht U.)

Jan 2013 - 29 pages

Ann.Rev.Nucl.Part.Sci. 63 (2013) 123-151
(2013)
DOI: 10.1146/annurev-nucl-102212-170540
e-Print: arXiv:1301.2826 [nucl-th] | PDF

From hadrons to quarks in neutron stars: a review

Gordon Baym (Nishina Ctr., RIKEN & Illinois U., Urbana & Bohr Inst.), Tetsuo Hatsuda (Wako, RIKEN & Nishina Ctr., RIKEN), Toru Kojo (Illinois U., Urbana & Hua-Zhong Normal U., LQLP & CCNU, Wuhan, Inst. Part. Phys.), Philip D. Powell (Illinois U., Urbana & LLNL, Livermore), Yifan Song (Illinois U., Urbana), Tatsuyuki Takatsuka (Nishina Ctr., RIKEN & Iwate U.)

Jul 16, 2017 - 38 pages

Rept.Prog.Phys. 81 (2018) no.5, 056902
(2018-03-27)
DOI: 10.1088/1361-6633/aaae14
RIKEN-ITHEMS-REPORT-17, RIKEN-QHP-316, RIKEN-iTHEMS-Report-17
e-Print: arXiv:1707.04966 [astro-ph.HE] | PDF

Small System Collectivity in Relativistic Hadron and Nuclear Collisions

James L. Nagle (Colorado U.), William A. Zajc (Columbia U.)

Jan 10, 2018 - 33 pages

e-Print: arXiv:1801.03477 [nucl-ex] | PDF

Heavy Ion Collisions: The Big Picture, and the Big Questions

Wit Busza (MIT, LNS), Krishna Rajagopal (MIT, LNS & MIT, Cambridge, CTP), Wilke van der Schee (MIT, Cambridge, CTP & Utrecht U.)

Feb 13, 2018 - 49 pages

MIT-CTP-4892
e-Print: arXiv:1802.04801 [hep-ph] | PDF

Phase transitions in the early and the present universe

D. Boyanovsky (Pittsburgh U. & Paris Observ. & Paris, LPTHE), H.J. de Vega (Paris, LPTHE & Paris Observ. & Pittsburgh U.), D.J. Schwarz (Bielefeld U.)

Feb 2006 - 42 pages

Ann.Rev.Nucl.Part.Sci. 56 (2006) 441-500
DOI: 10.1146/annurev.nucl.56.080805.140539
e-Print: hep-ph/0602002 | PDF

Results from the relativistic heavy ion collider

Berndt Muller (Duke U.), James L. Nagle (Colorado U.)

Feb 2006 - 47 pages

Ann.Rev.Nucl.Part.Sci. 56 (2006) 93-135
DOI: 10.1146/annurev.nucl.56.080805.140556
e-Print: nucl-th/0602029 | PDF

The Theory and Phenomenology of Perturbative QCD Based Jet Quenching

A. Majumder (Ohio State U.), M. Van Leeuwen (Utrecht U.)

Feb 2010 - 77 pages

Prog.Part.Nucl.Phys. 66 (2011) 41-92
DOI: 10.1016/j.ppnp.2010.09.001
e-Print: arXiv:1002.2206 [hep-ph] | PDF

Relativistic Fluid Dynamics In and Out of Equilibrium -- Ten Years of Progress in Theory and Numerical Simulations of Nuclear Collisions

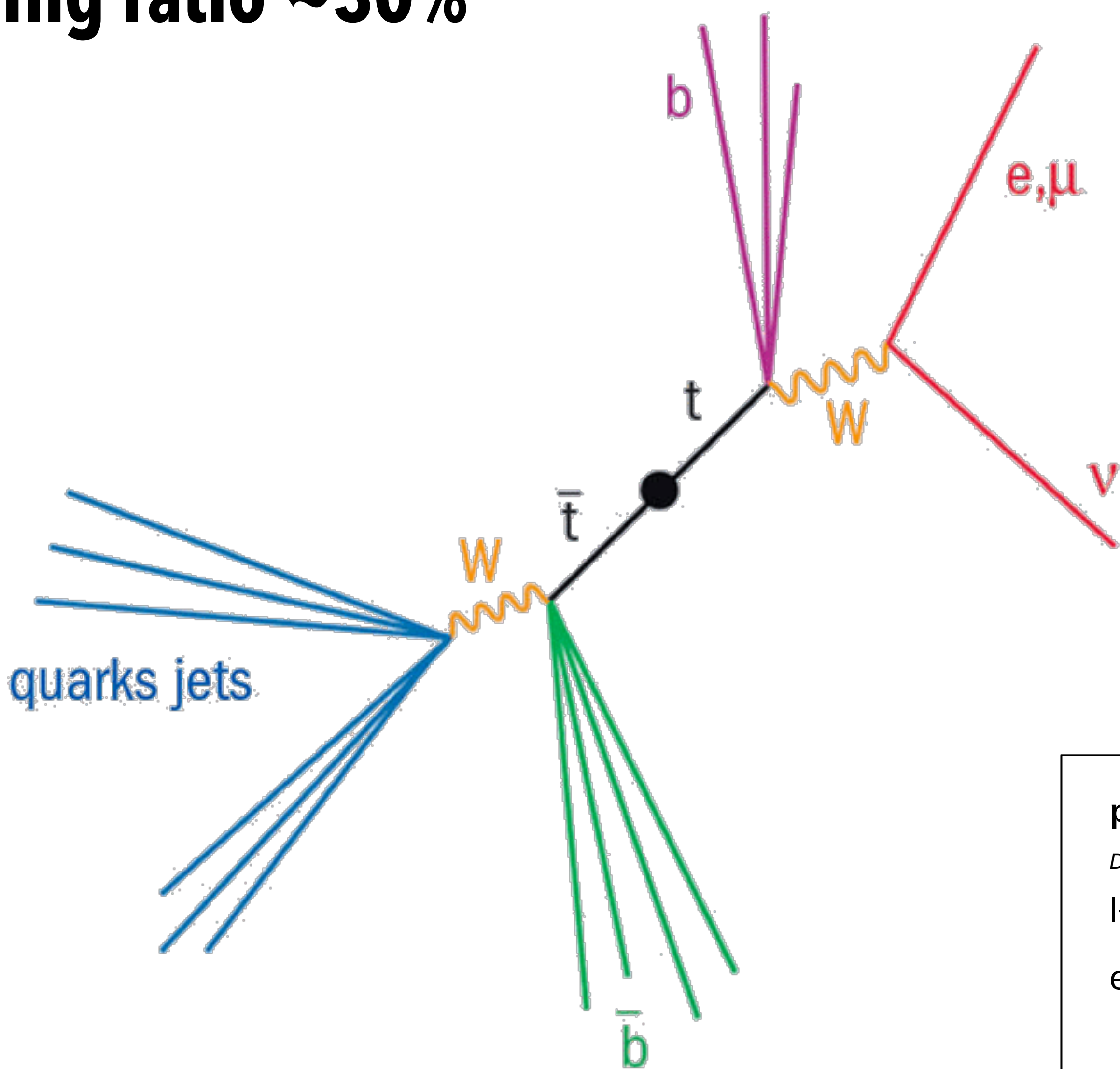
Paul Romatschke (Colorado U.), Ulrike Romatschke (Colorado U. & NCAR, Boulder)

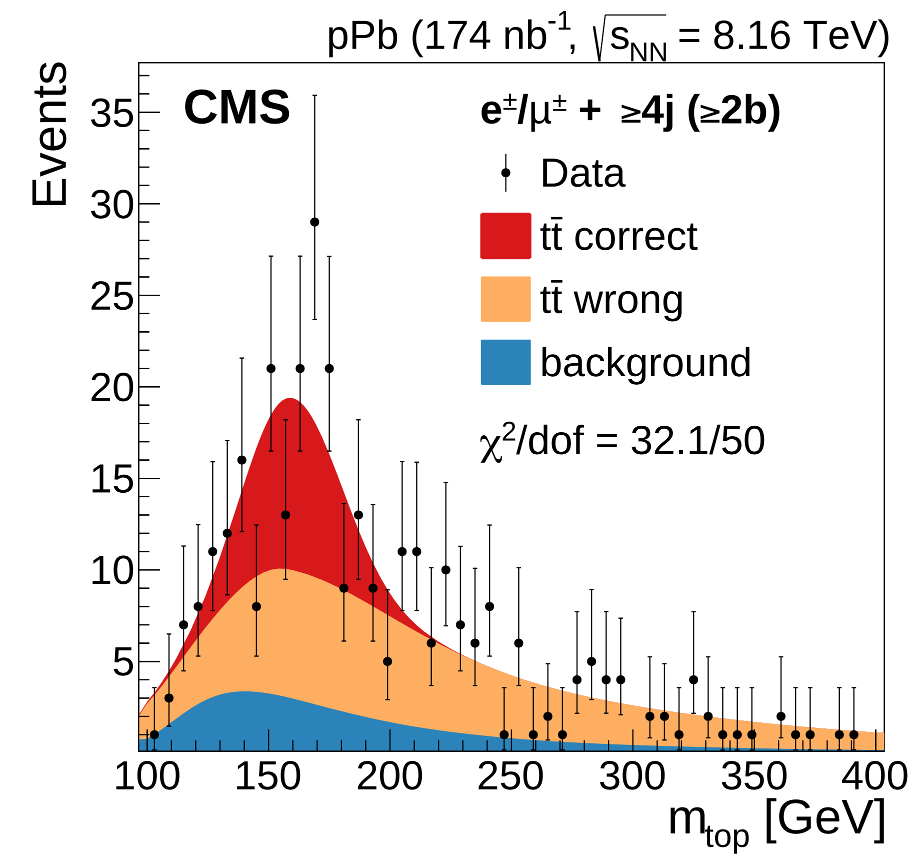
Dec 15, 2017 - 196 pages

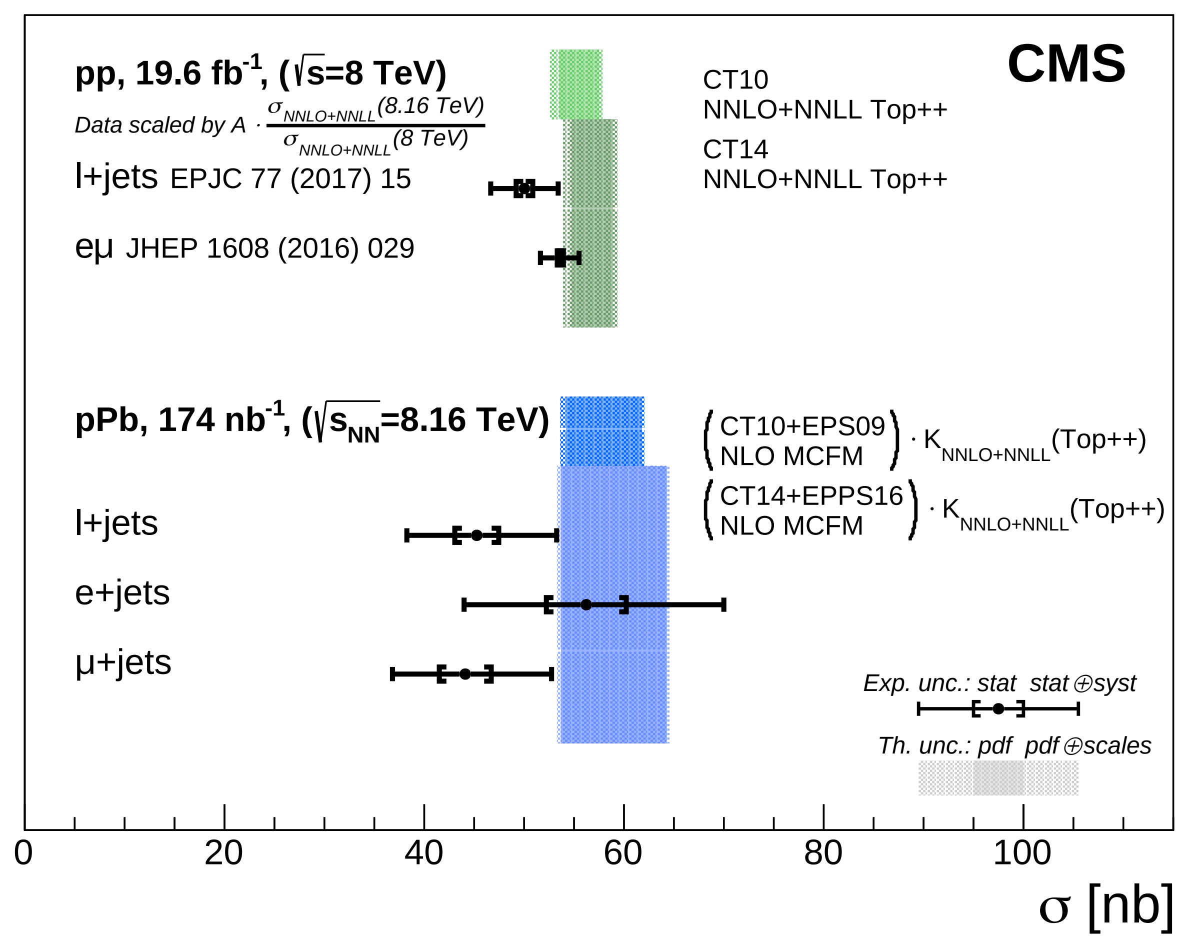
e-Print: arXiv:1712.05815 [nucl-th] | PDF

extras

branching ratio ~30%





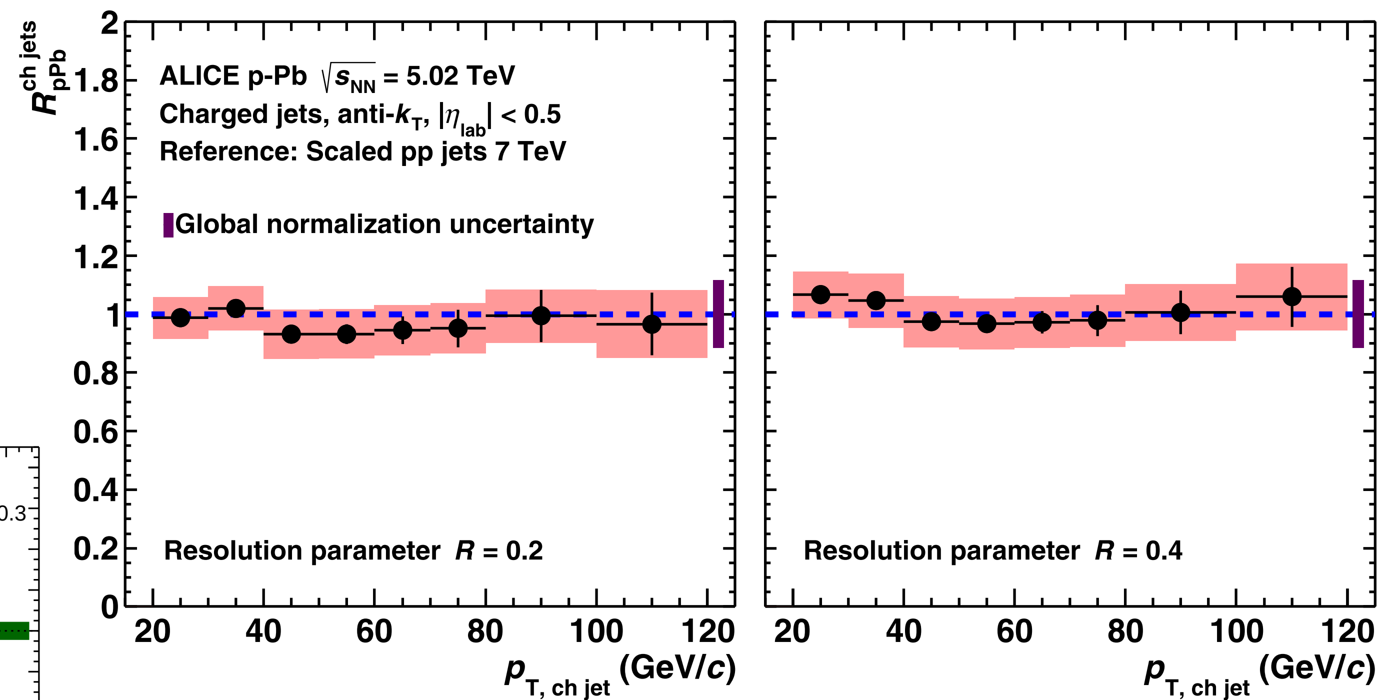


cross section in agreement with expectations based on pp collisions scaled by A

talk: M. Verweij, 1709.07411

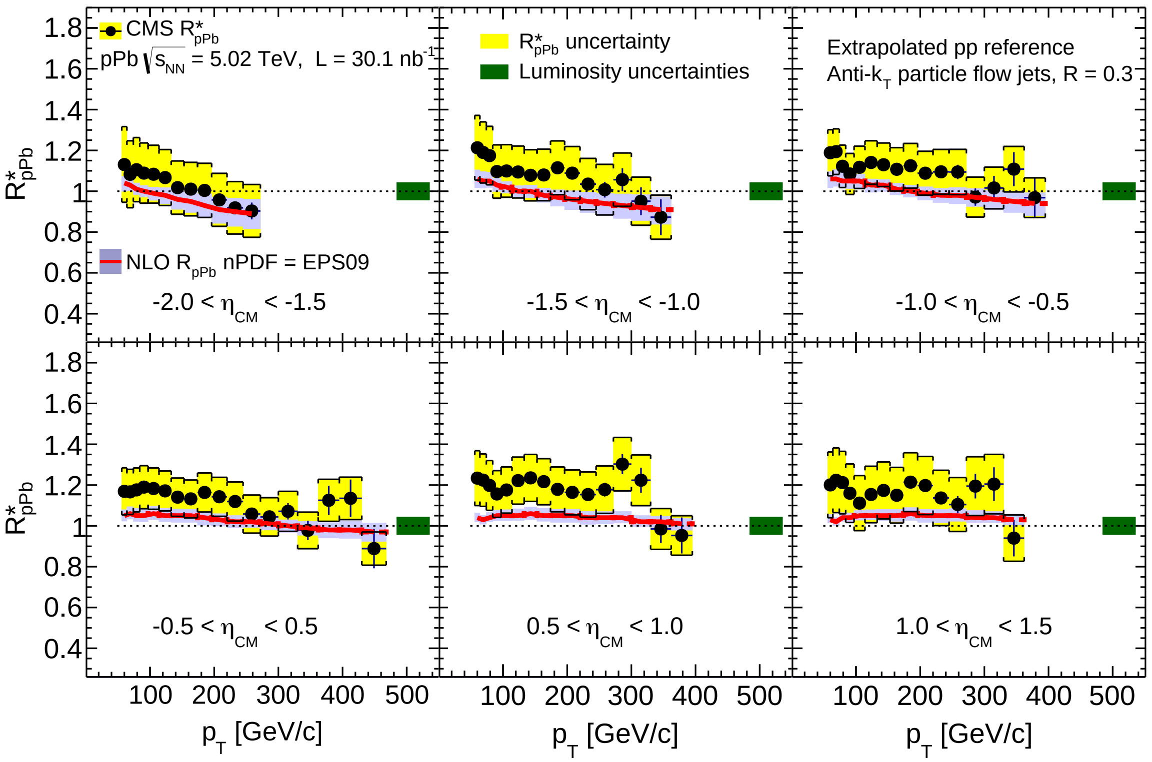
jet production in pPb collisions

ALICE PLB 749 68



can calculate R_{AA}

CMS EPJC 76 372

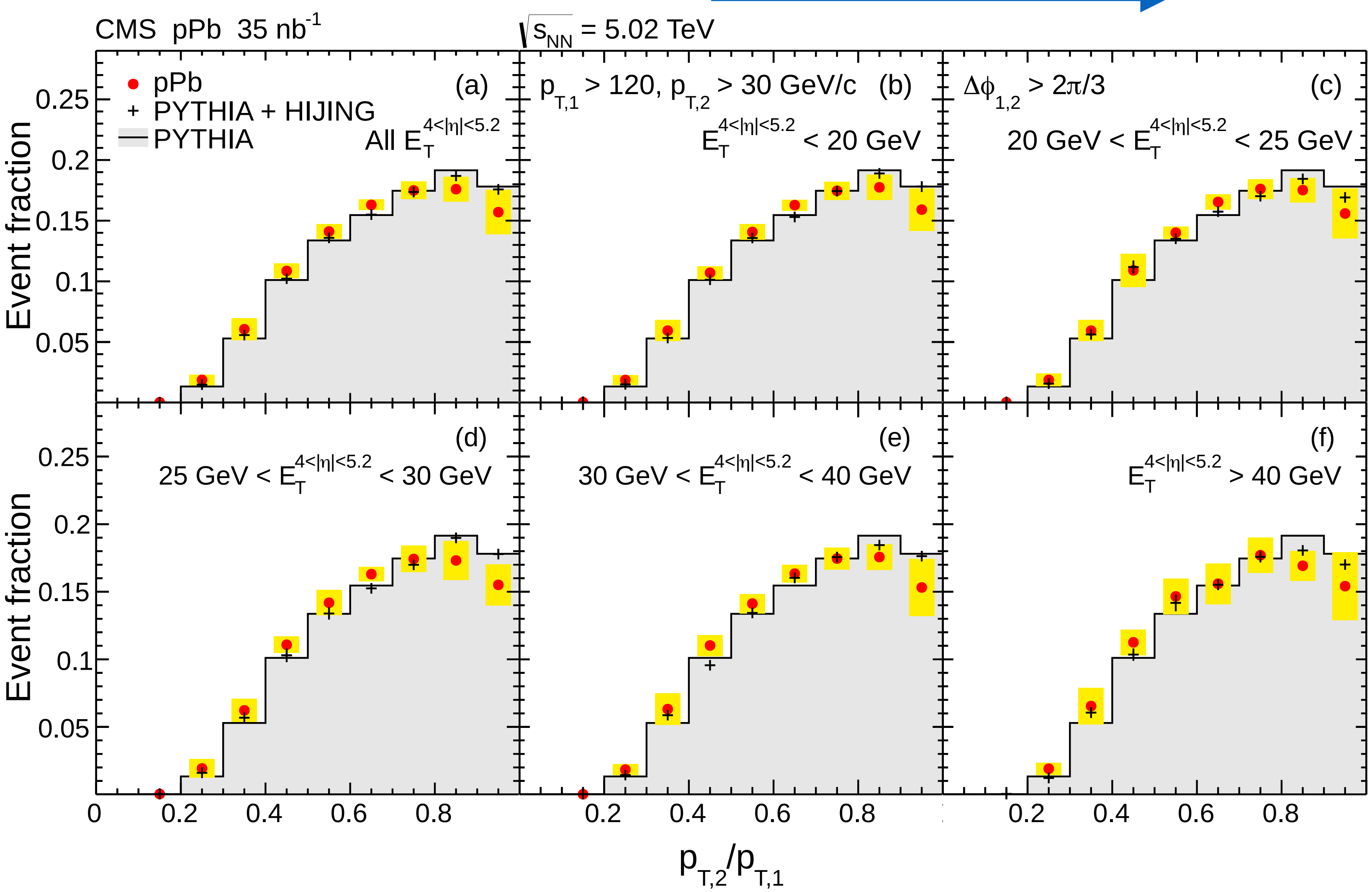


find that R_{AA} is consistent with unity, no jet quenching observed, but uncertainties might mask any jet quenching effect

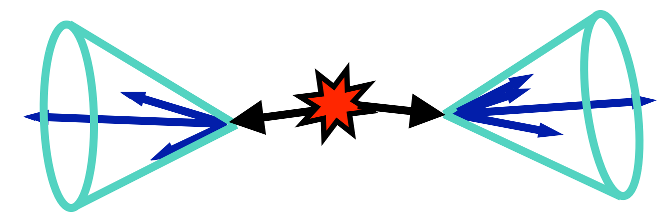
D. Perepelitsa Quark Matter 2017

Mangano & Nachman 1708.08369, …

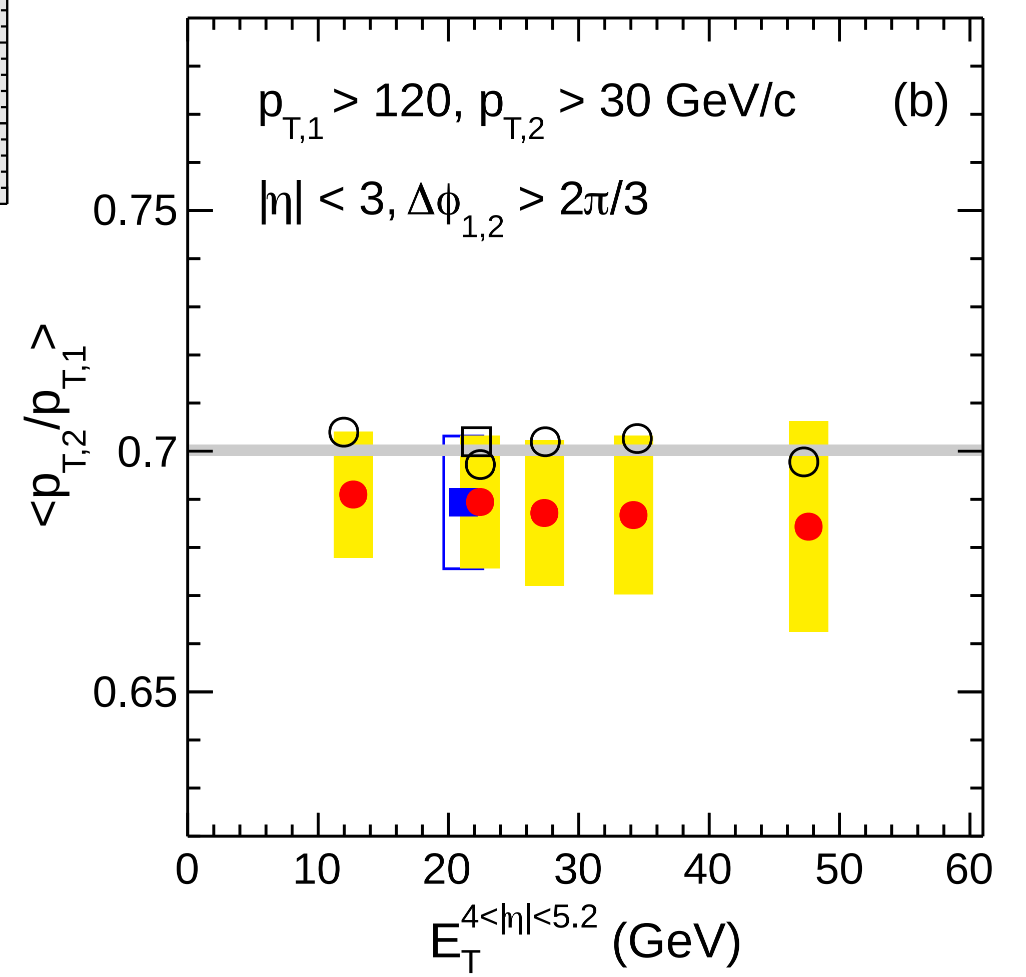
dijet p_T balance in pPb



increasing forward E_T



shift in the dijet balance in PbPb was the first jet quenching result at the LHC

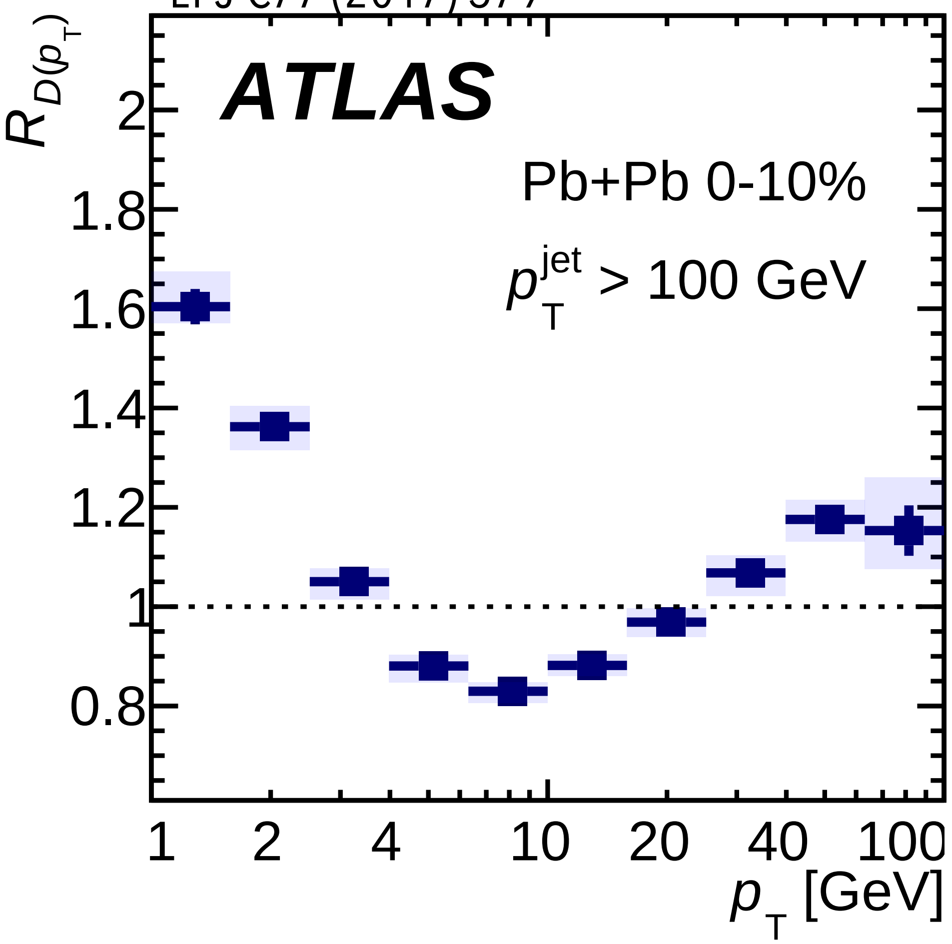


no significance modification of the dijet p_T balance

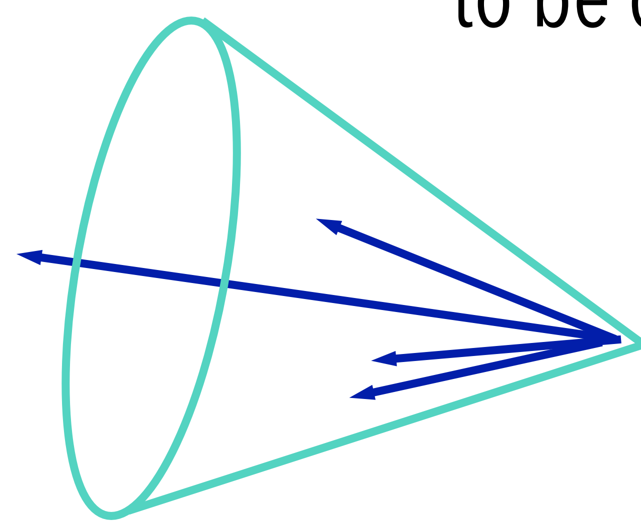
EPJ C74 (2014) 2951

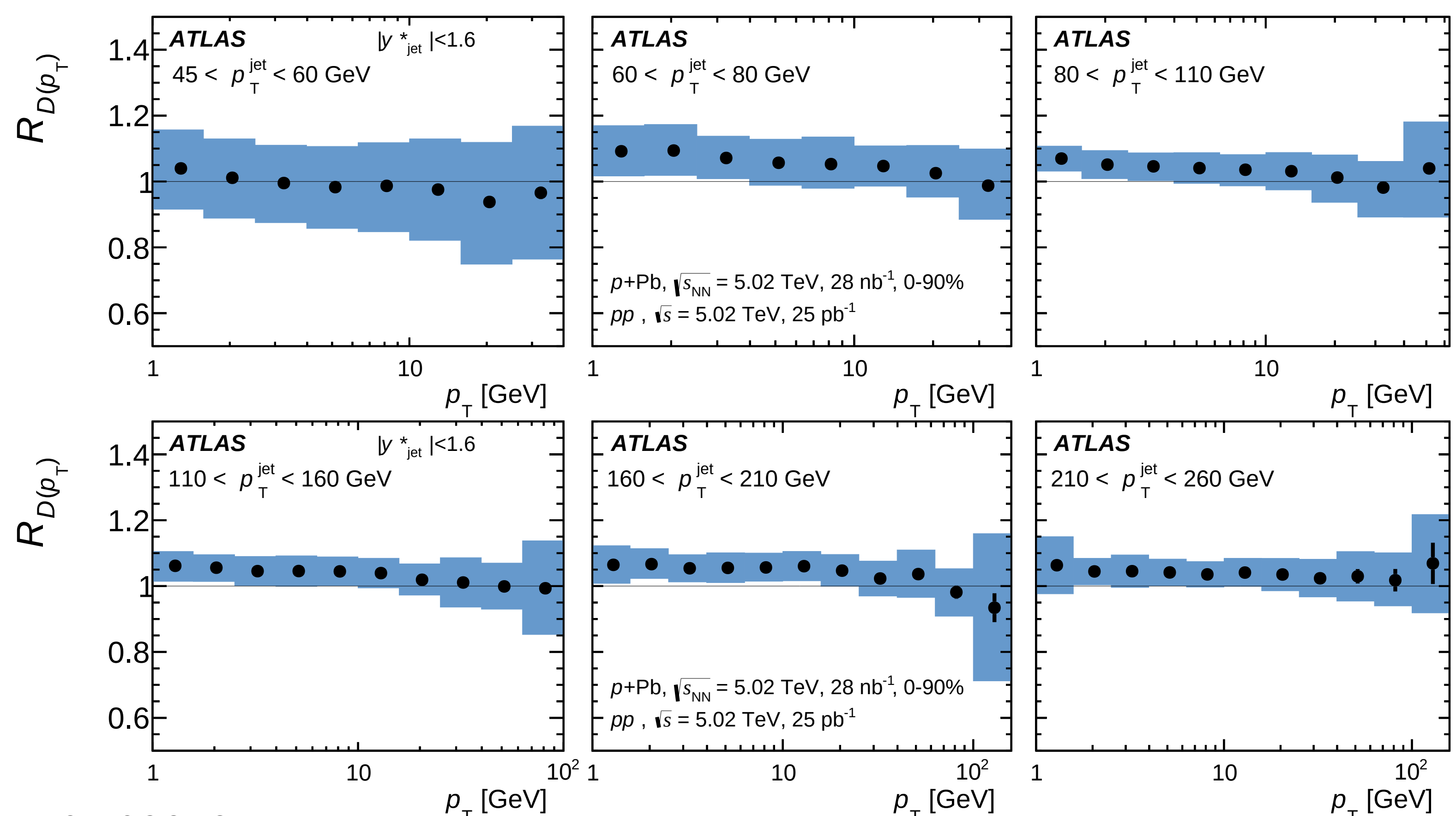
pPb fragmentation functions

EPJ C77 (2017) 379



modification of inclusive fragmentation functions in PbPb collisions understood to be due to QGP





pPb fragmentation functions show no similar excess

1706.02859