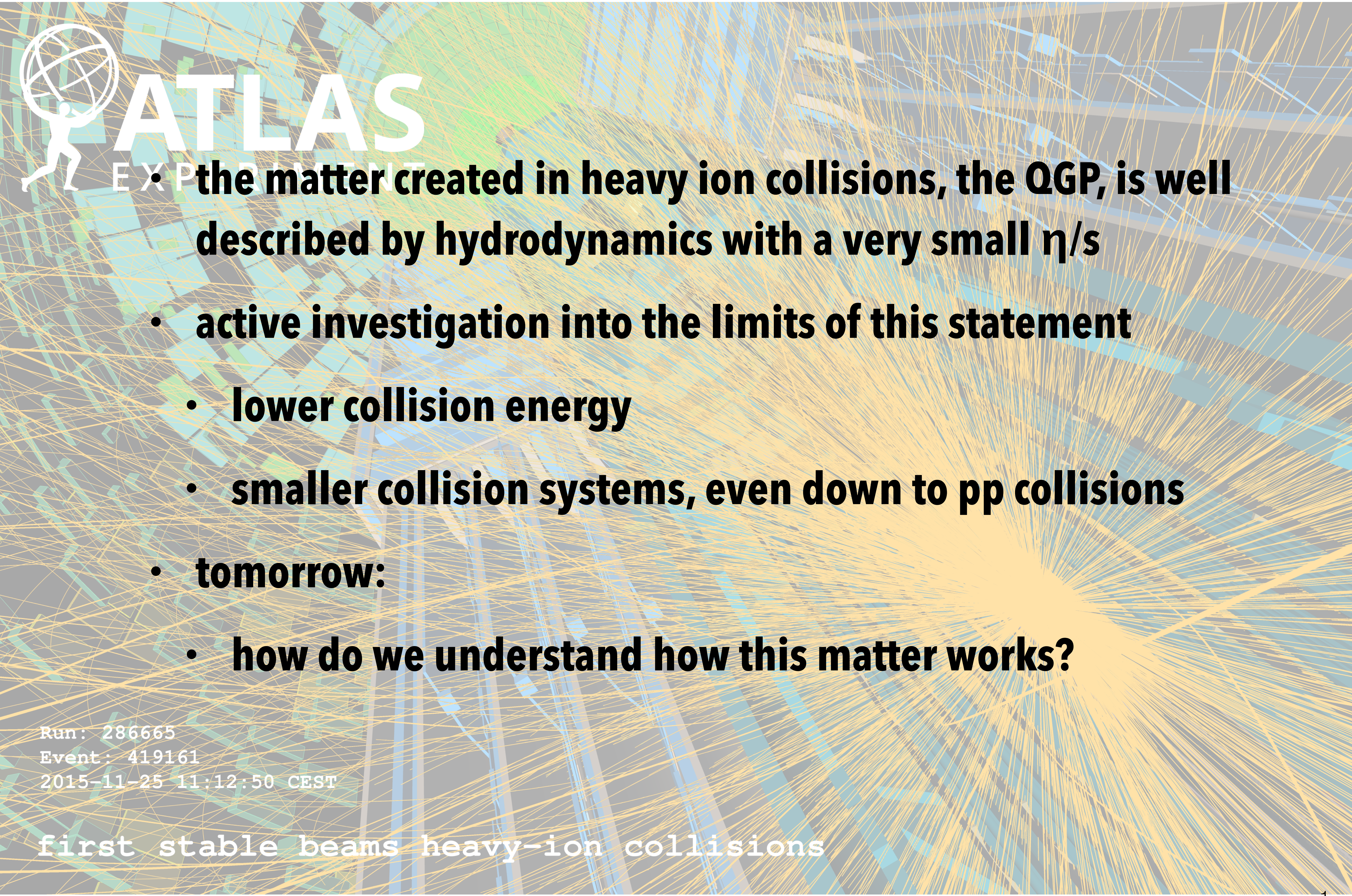
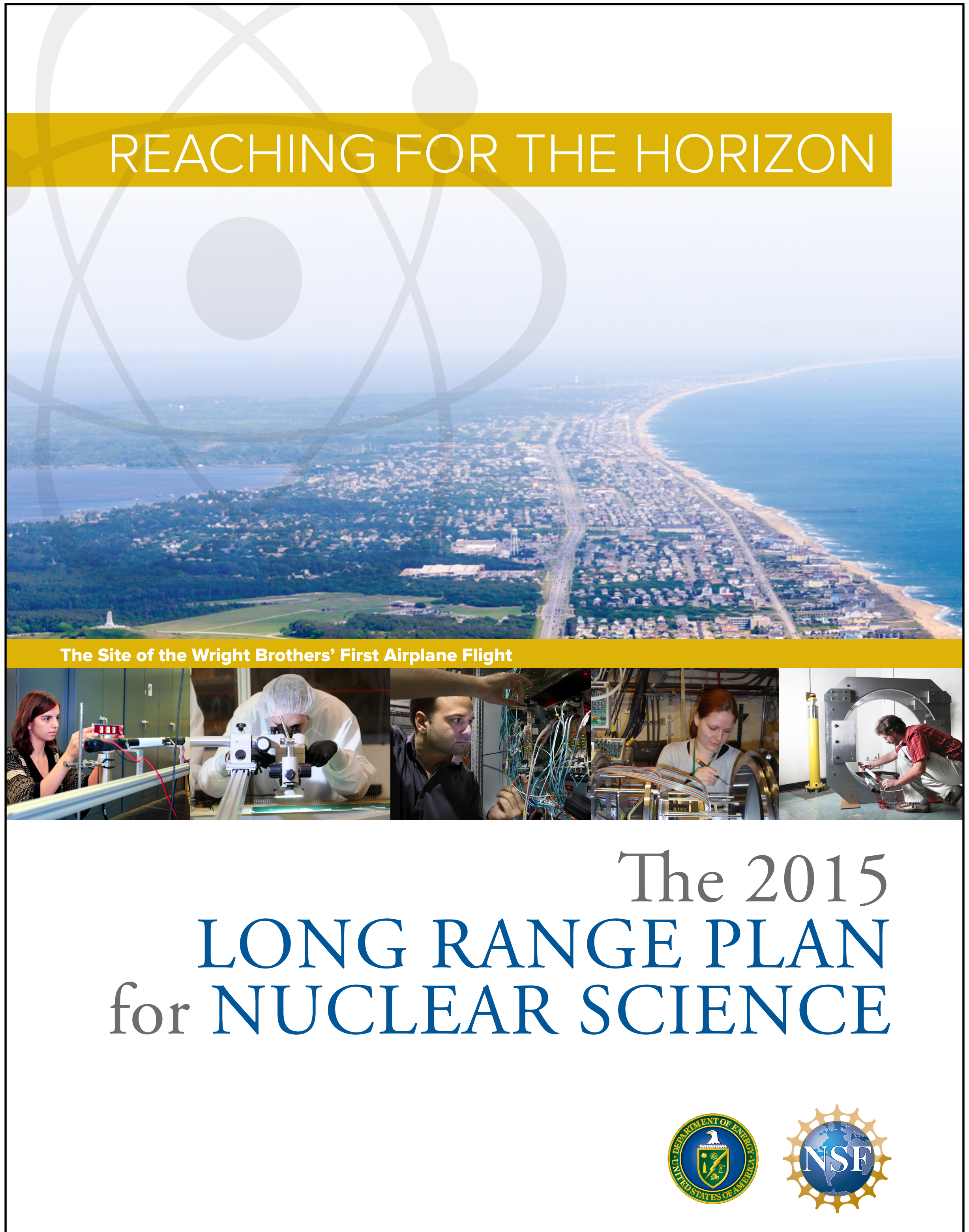
summary of part 1



- **the matter created in heavy ion collisions, the QGP, is well described by hydrodynamics with a very small η/s**
- **active investigation into the limits of this statement**
  - **lower collision energy**
  - **smaller collision systems, even down to pp collisions**
- **tomorrow:**
  - **how do we understand how this matter works?**

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 does the low viscosity liquid come to be?

liquid QGP

- why does QCD matter at extremely high temperature behave like a fluid?
  - interactions between quarks and gluons drive fluid behavior but QCD known for asymptotic freedom at short distances
- η / s needed to describe QGP viscosity within a factor of a 2-3 of conjectured theoretical bound of $\eta / s = 1/4\pi$

PRL **94,** 111601 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics

P. K. Kovtun,[1] D. T. Son,[2] and A. O. Starinets[3]

[1]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA*
[3]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
(Received 20 December 2004; published 22 March 2005)

The ratio of shear viscosity to volume density of entropy can be used to characterize how close a given fluid is to being perfect. Using string theory methods, we show that this ratio is equal to a universal value of $\hbar/4\pi k_B$ for a large class of strongly interacting quantum field theories whose dual description involves black holes in anti–de Sitter space. We provide evidence that this value may serve as a lower bound for a wide class of systems, thus suggesting that black hole horizons are dual to the most ideal fluids.

liquid QGP

- why does QCD matter at extremely high temperature behave like a fluid?
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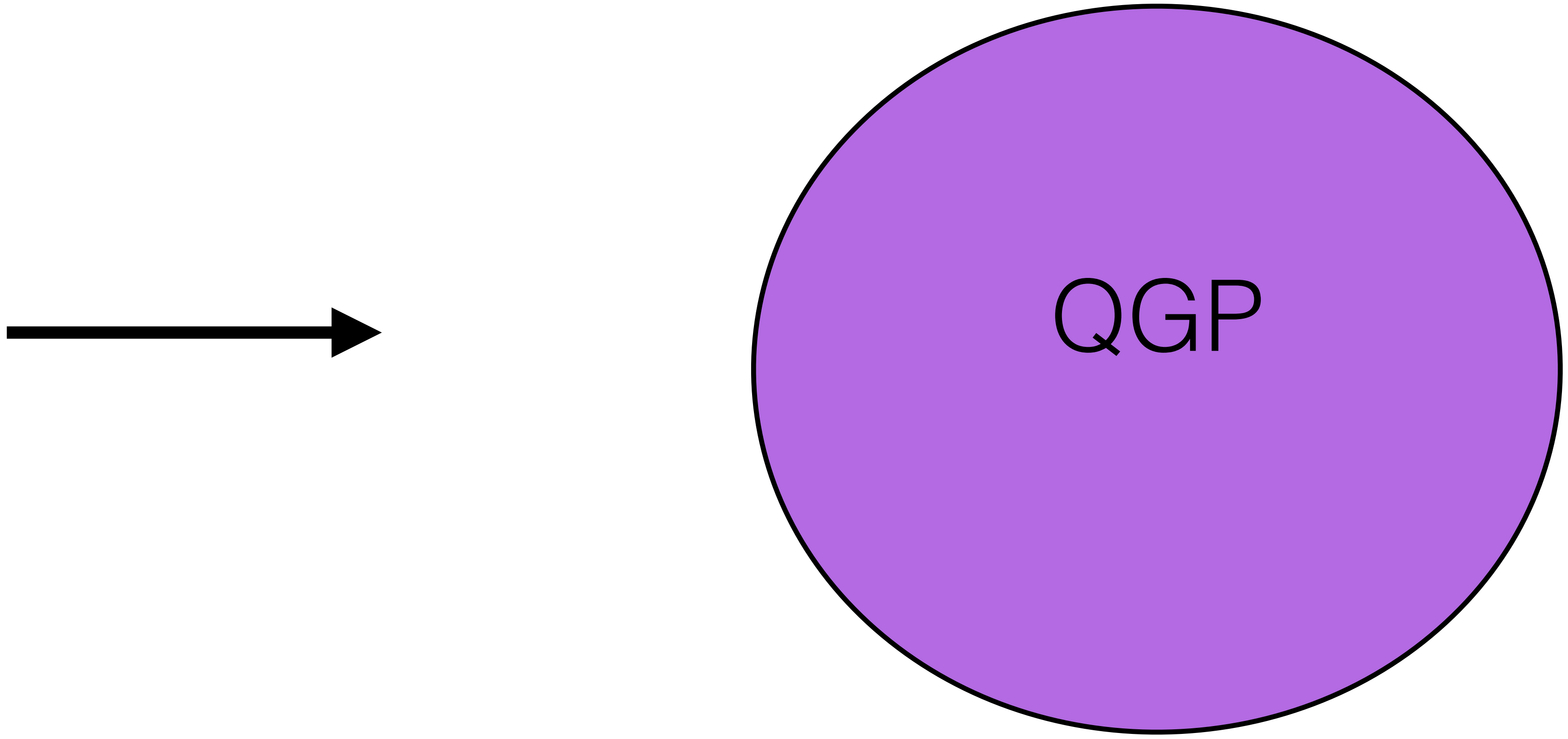
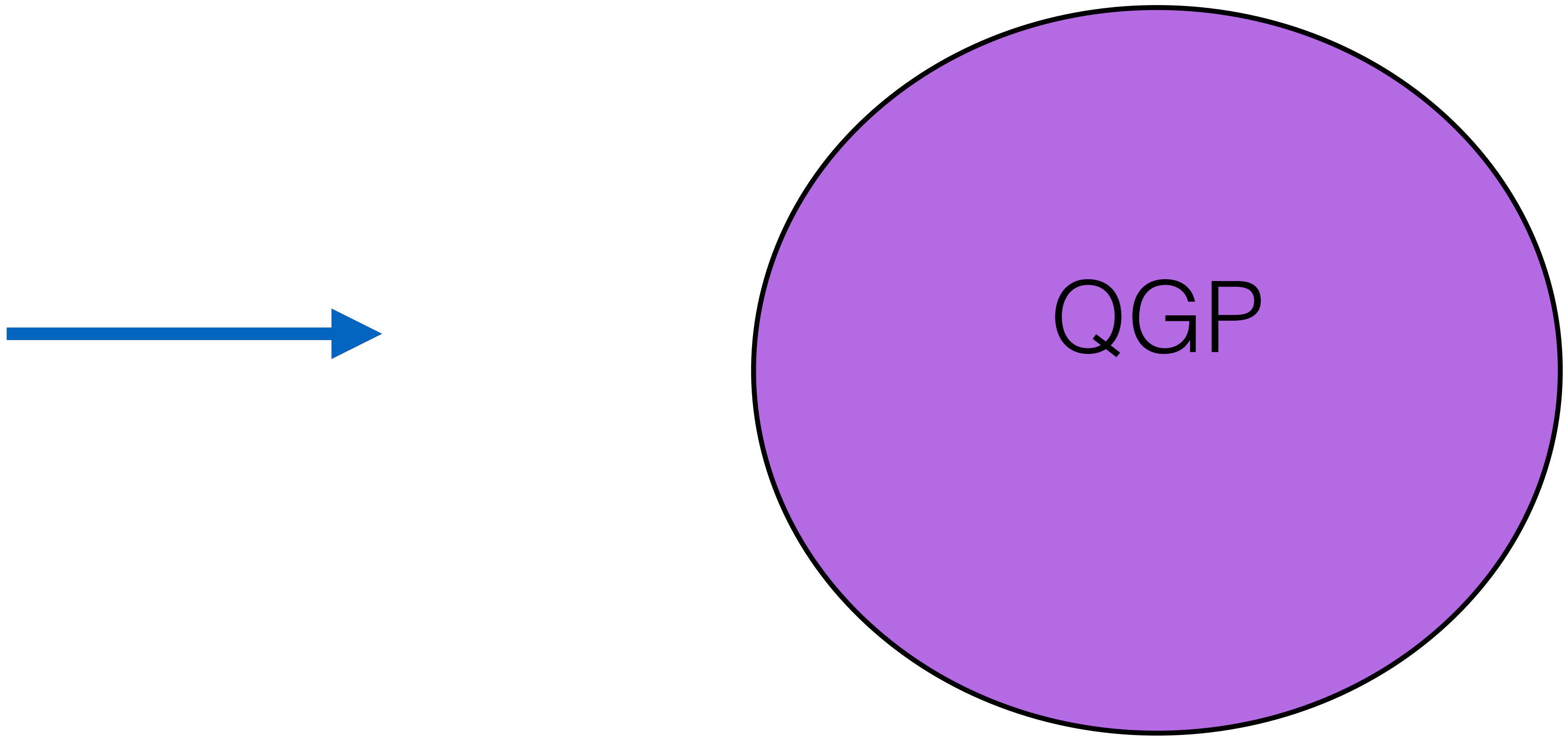
need to probe the plasma on *short length scales* sensitive to the *interactions which give rise to the fluid behavior*

how we'd like to measure the QGP

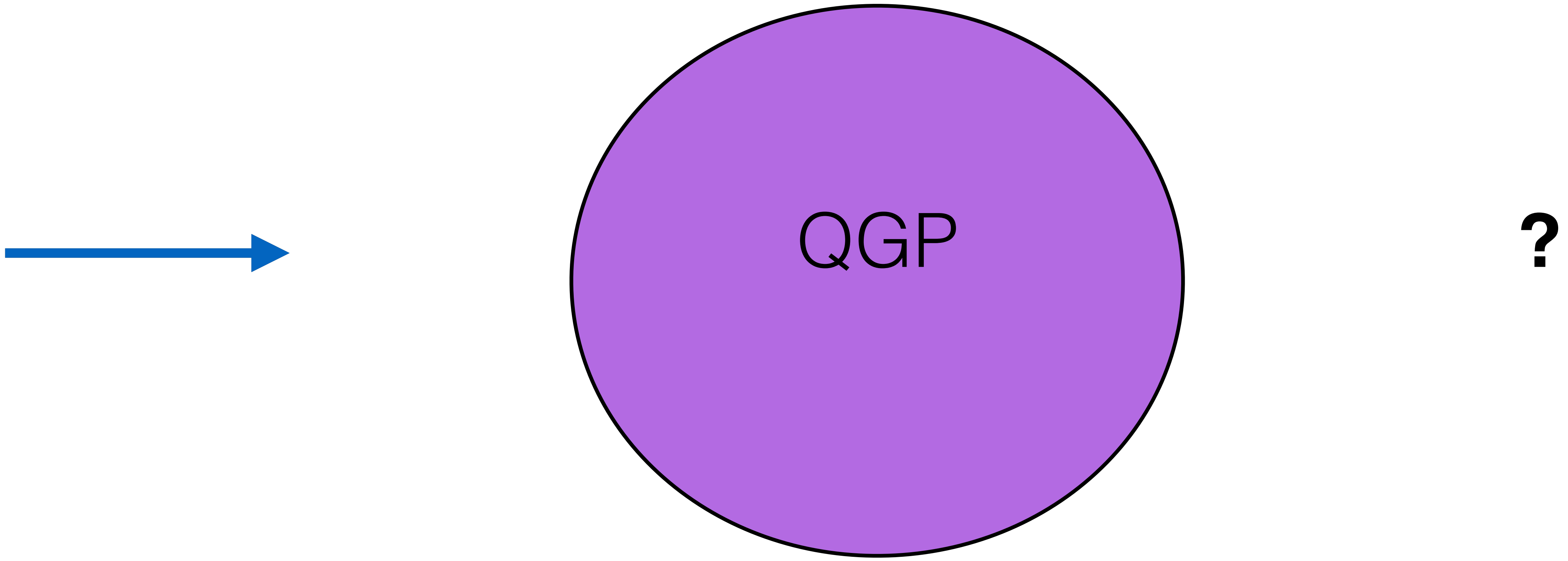
how we'd like to measure the QGP

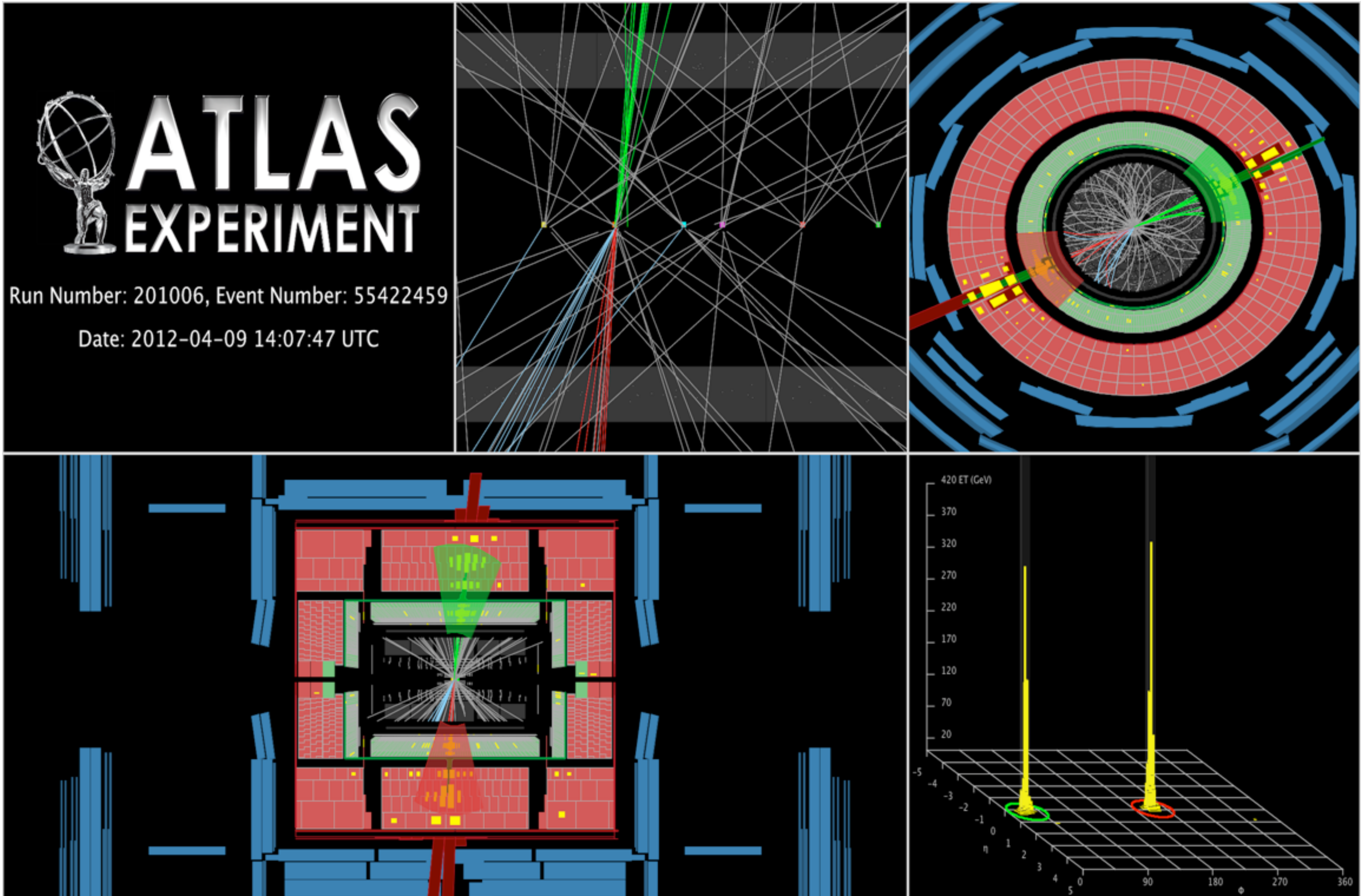


how we'd like to measure the QGP

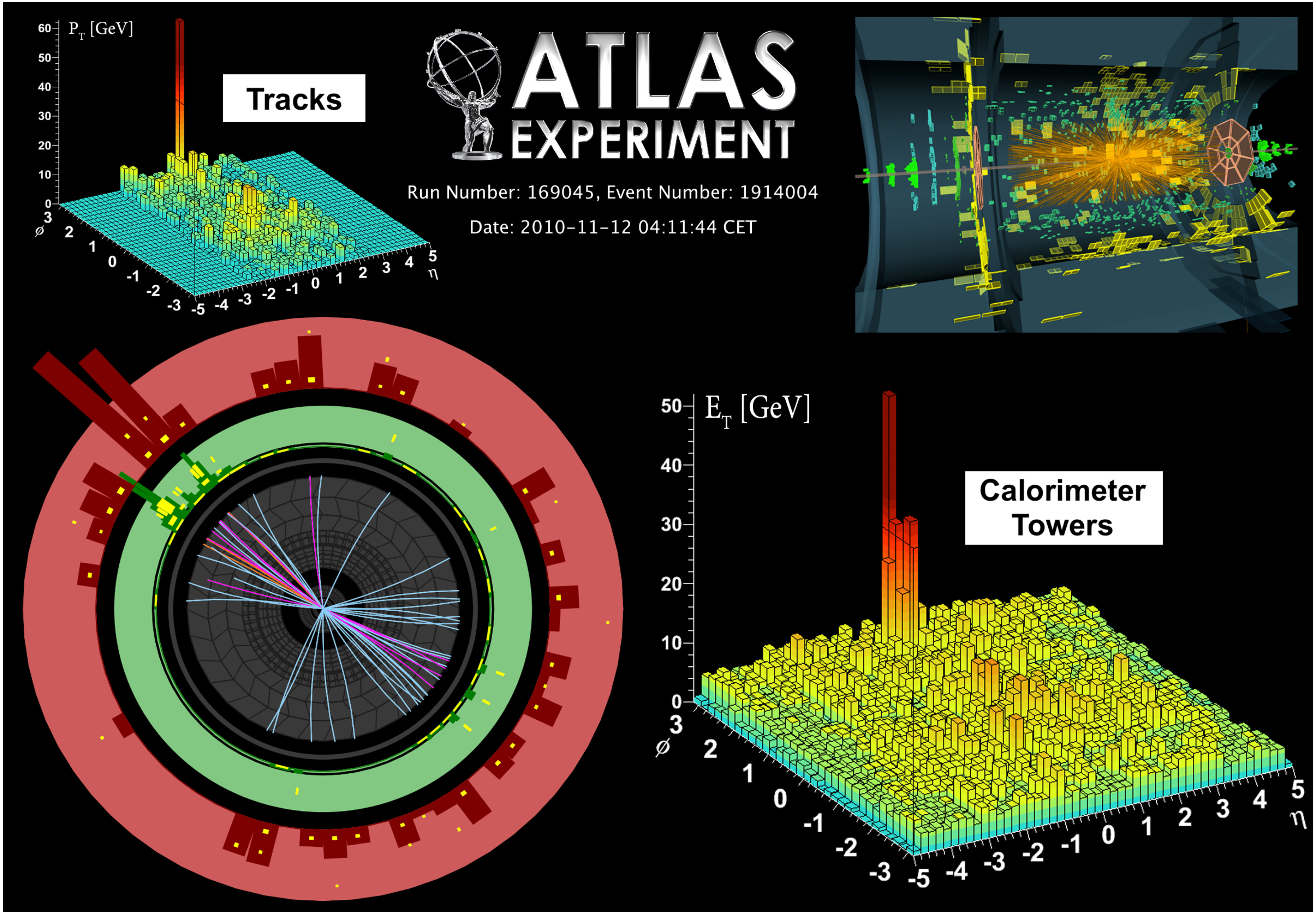


how we'd like to measure the QGP



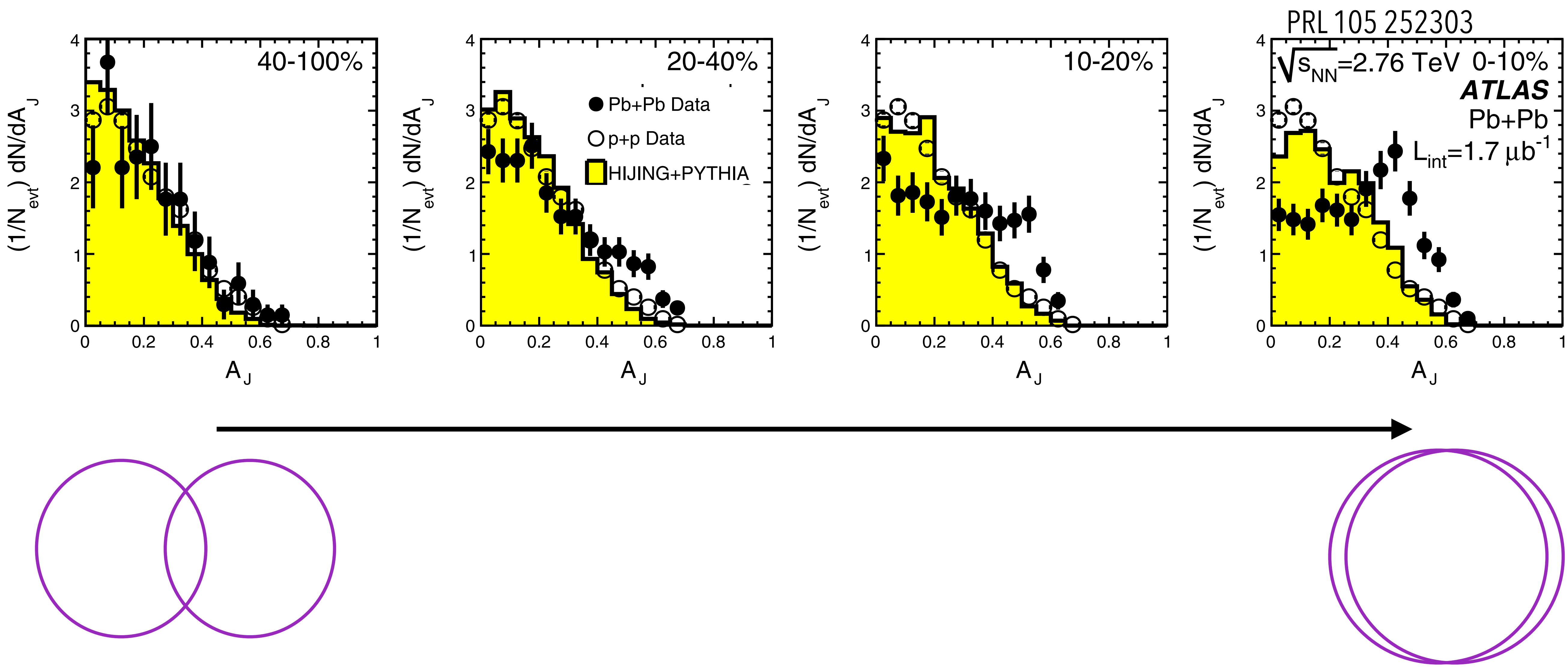

ATLAS
EXPERIMENT
Run Number: 201006, Event Number: 55422459
Date: 2012-04-09 14:07:47 UTC
420 ET (GeV)
370
320
270
220
170
120
70
20
-5
-4
-3
-2
-1
0
η
1
2
3
4
5
0
90
180
270
360
ϕ

di-jets in the QGP become mono-jets



momentum asymmetry in dijet pairs

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



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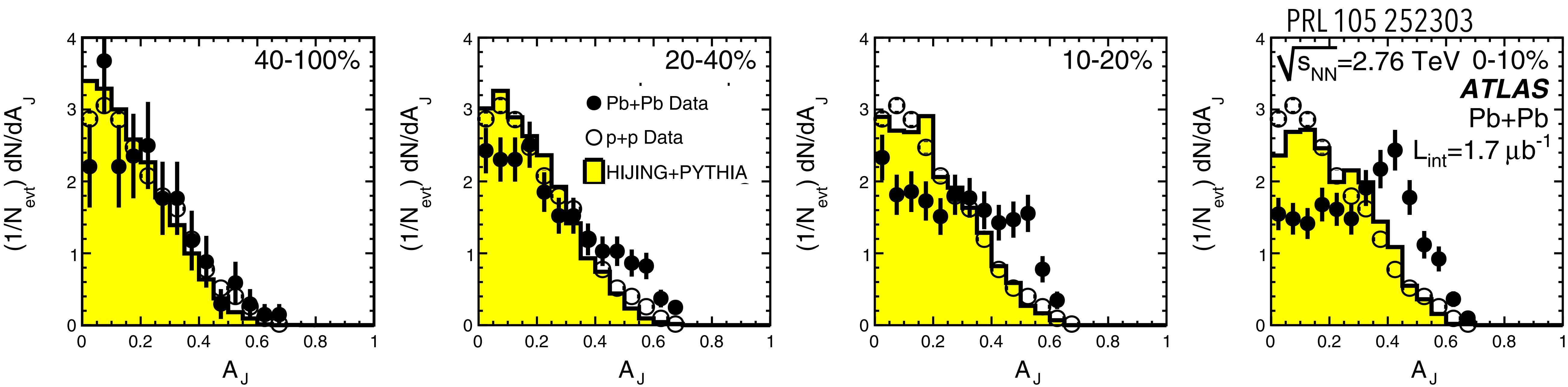
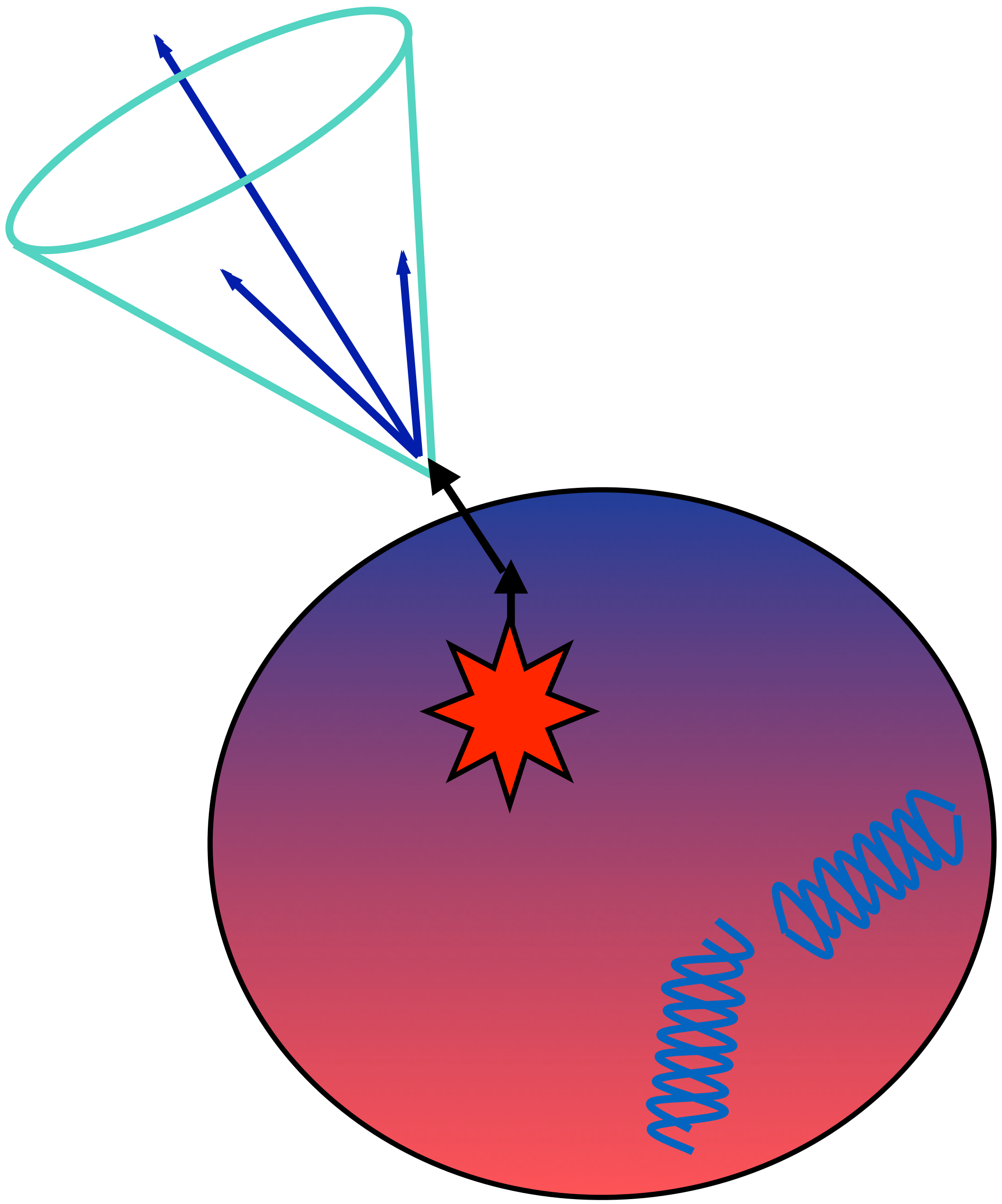


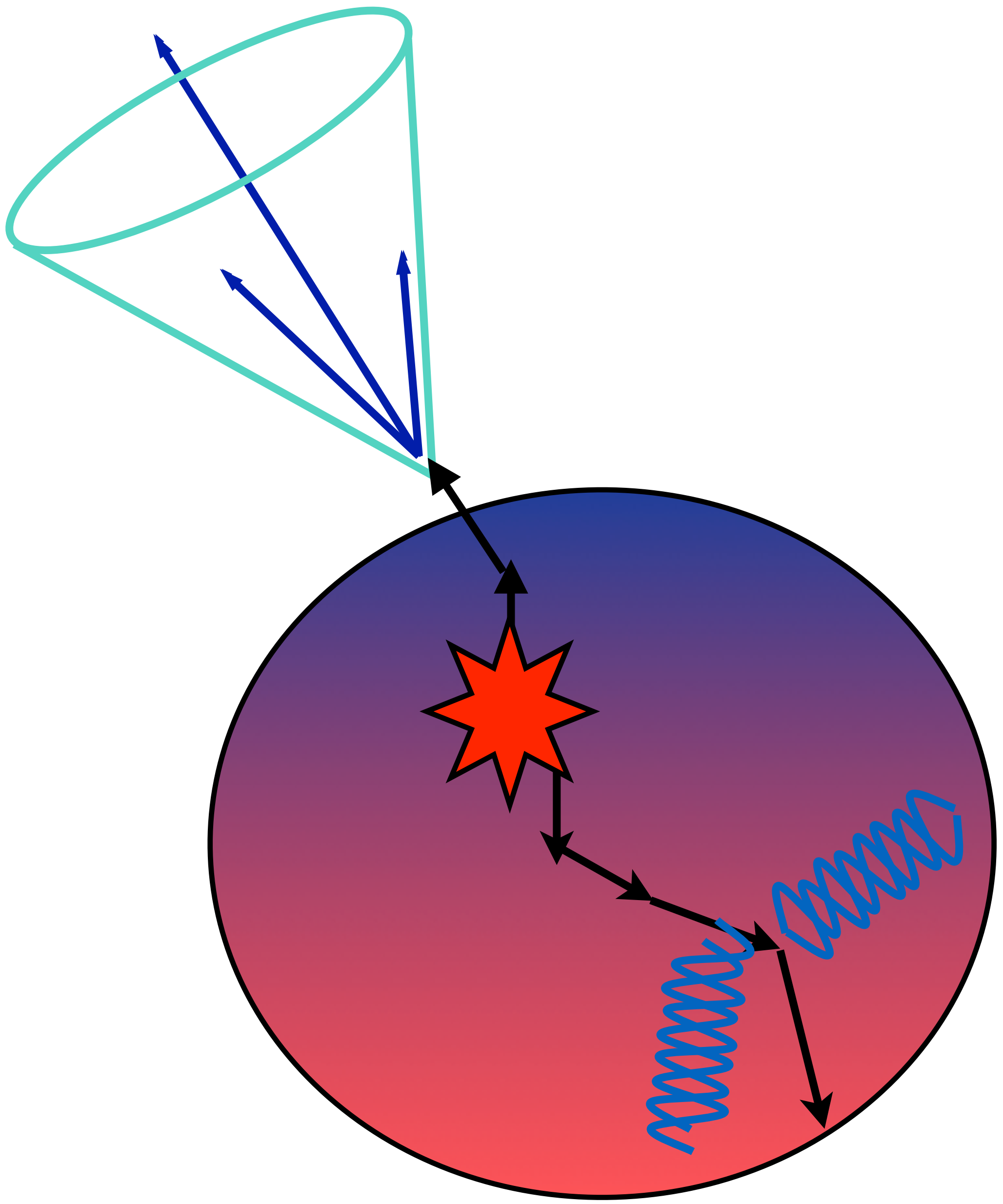
how do the jets loose their energy? where does it go? how does it depend on the jet momentum?

cartoon



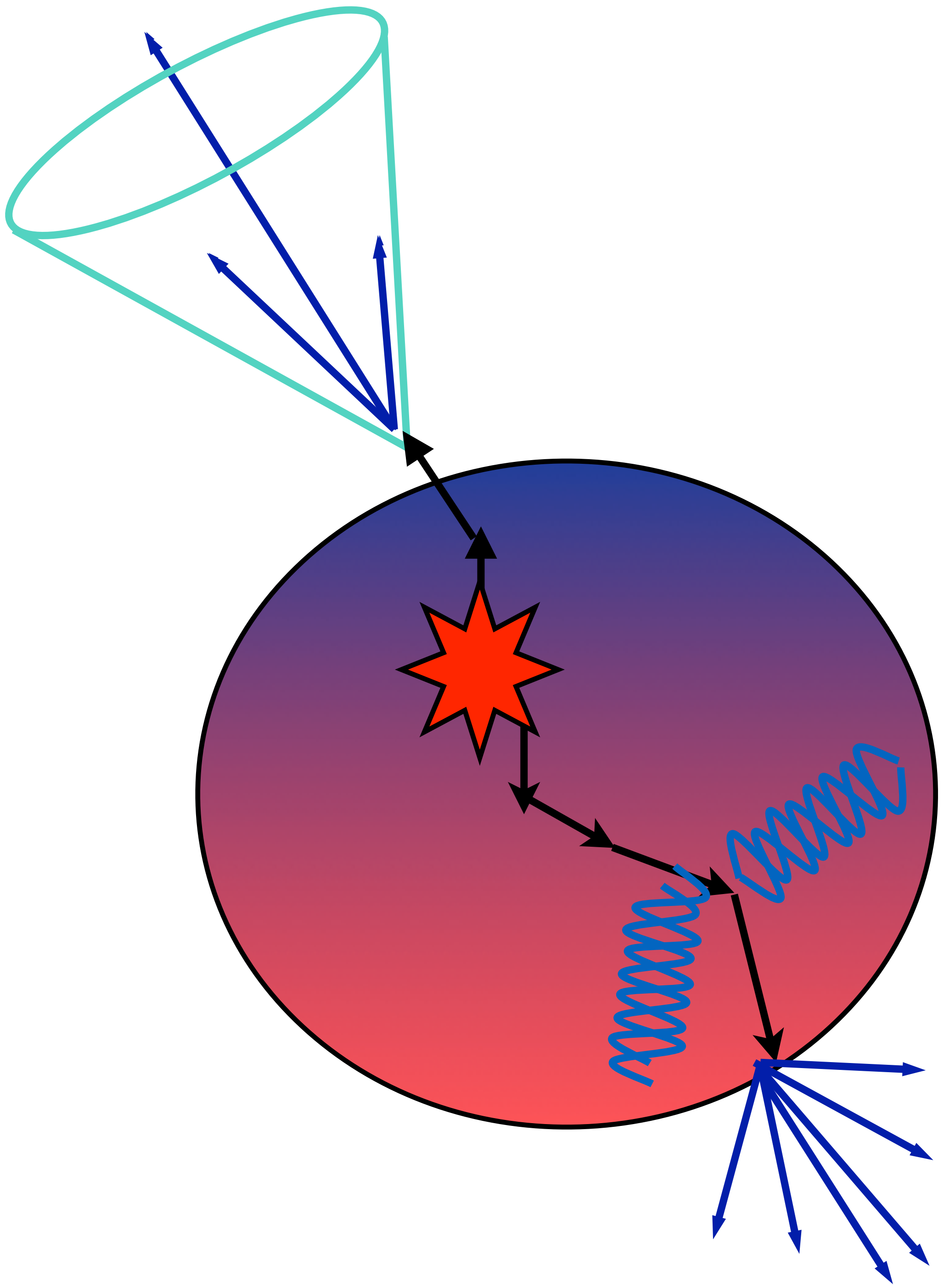
PRL 105 252303

cartoon



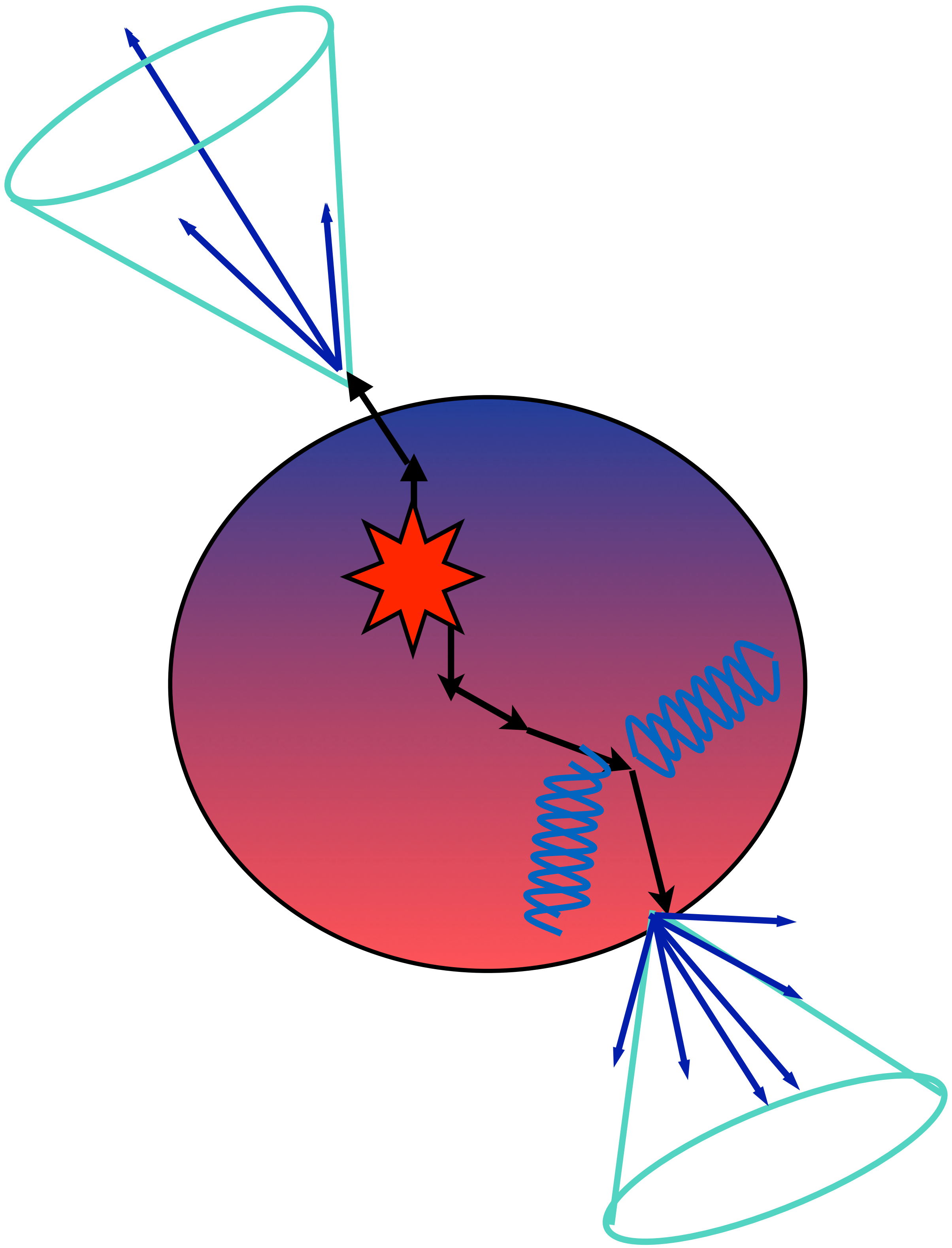
PRL 105 252303

cartoon



PRL 105 252303

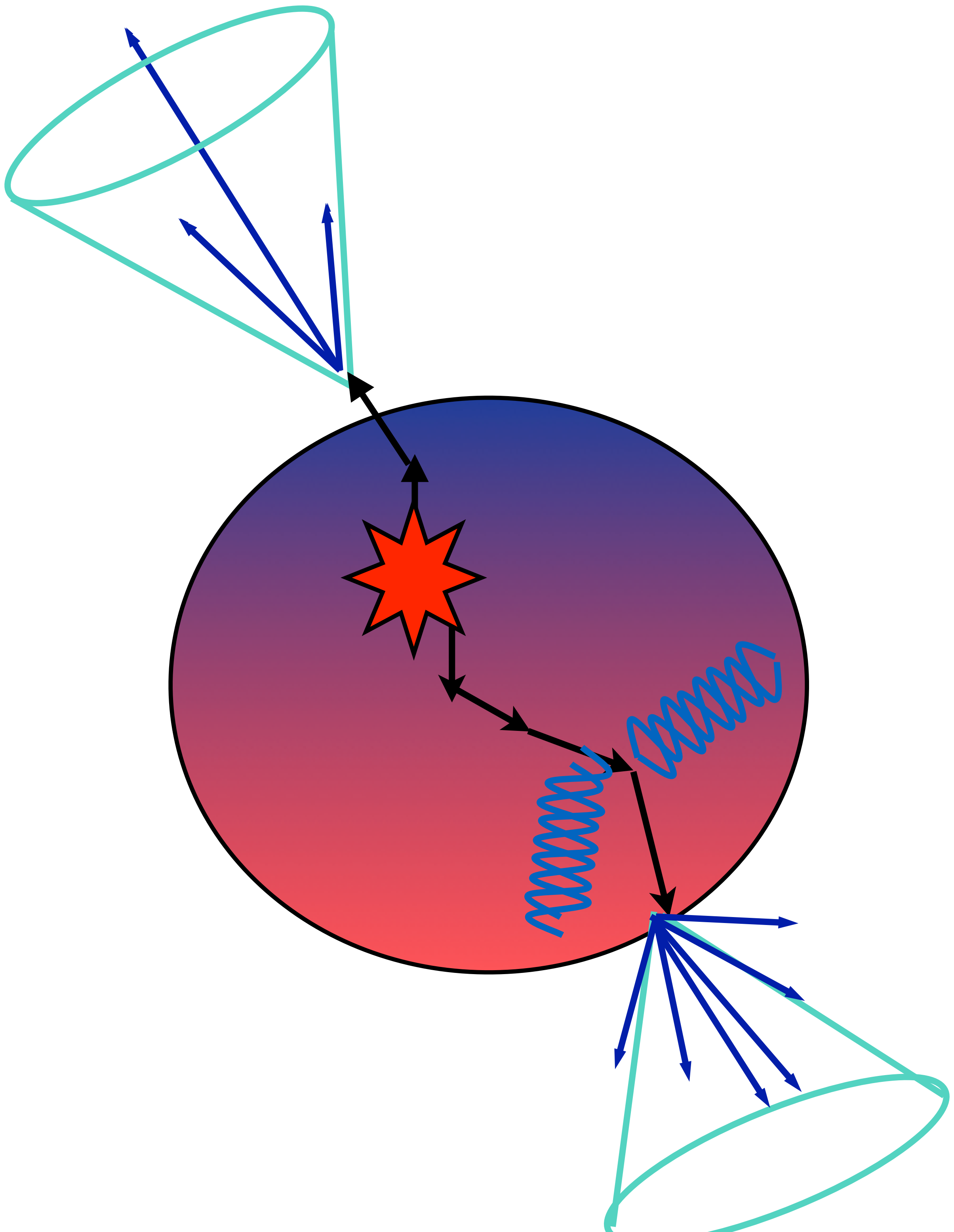
cartoon



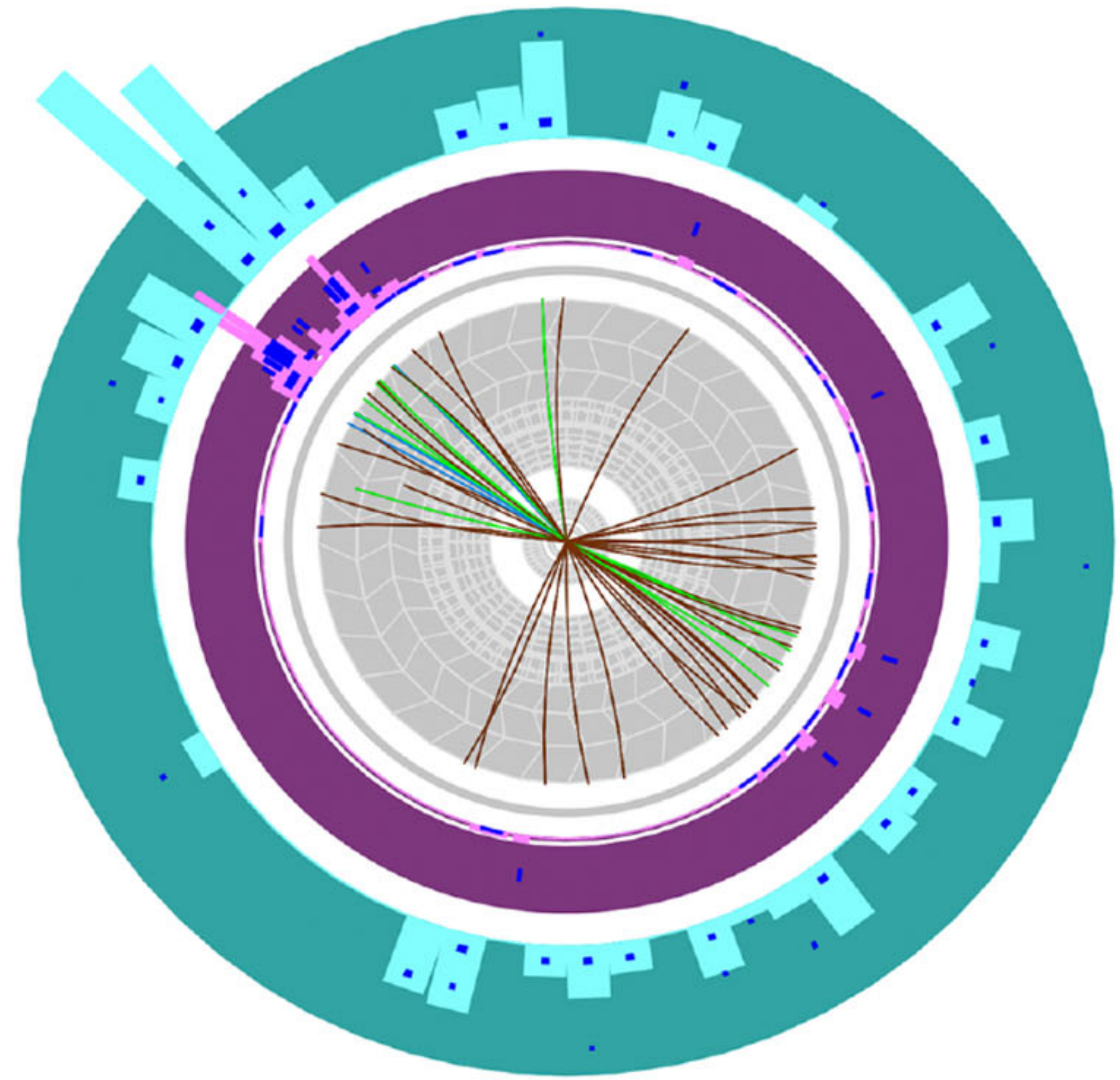
PRL 105 252303

jet quenching in action

cartoon



actual event measured in ATLAS



PRL 105 252303

a 30 year old prediction

Fermi National Accelerator Laboratory

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

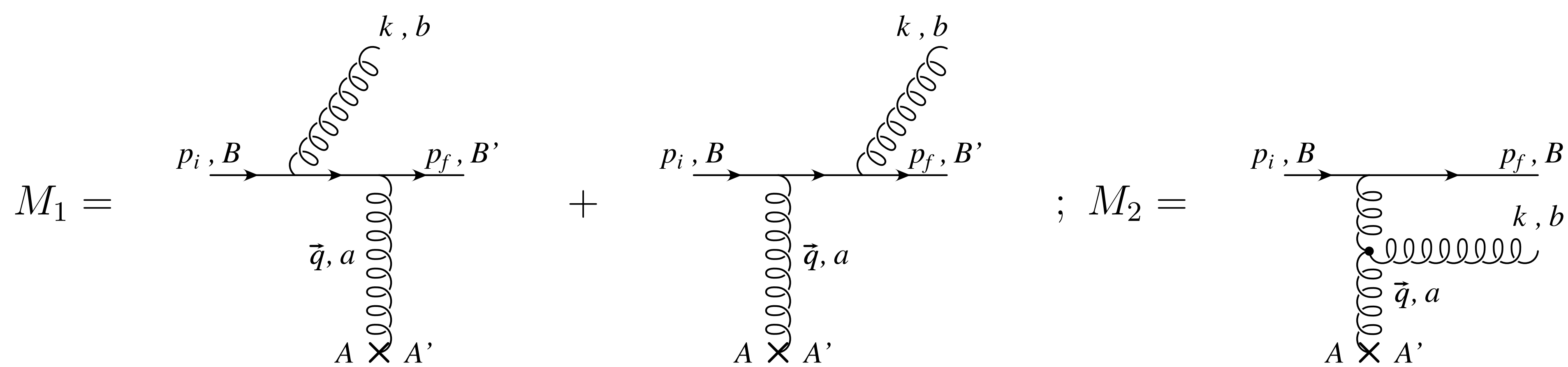
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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.

modern theory



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

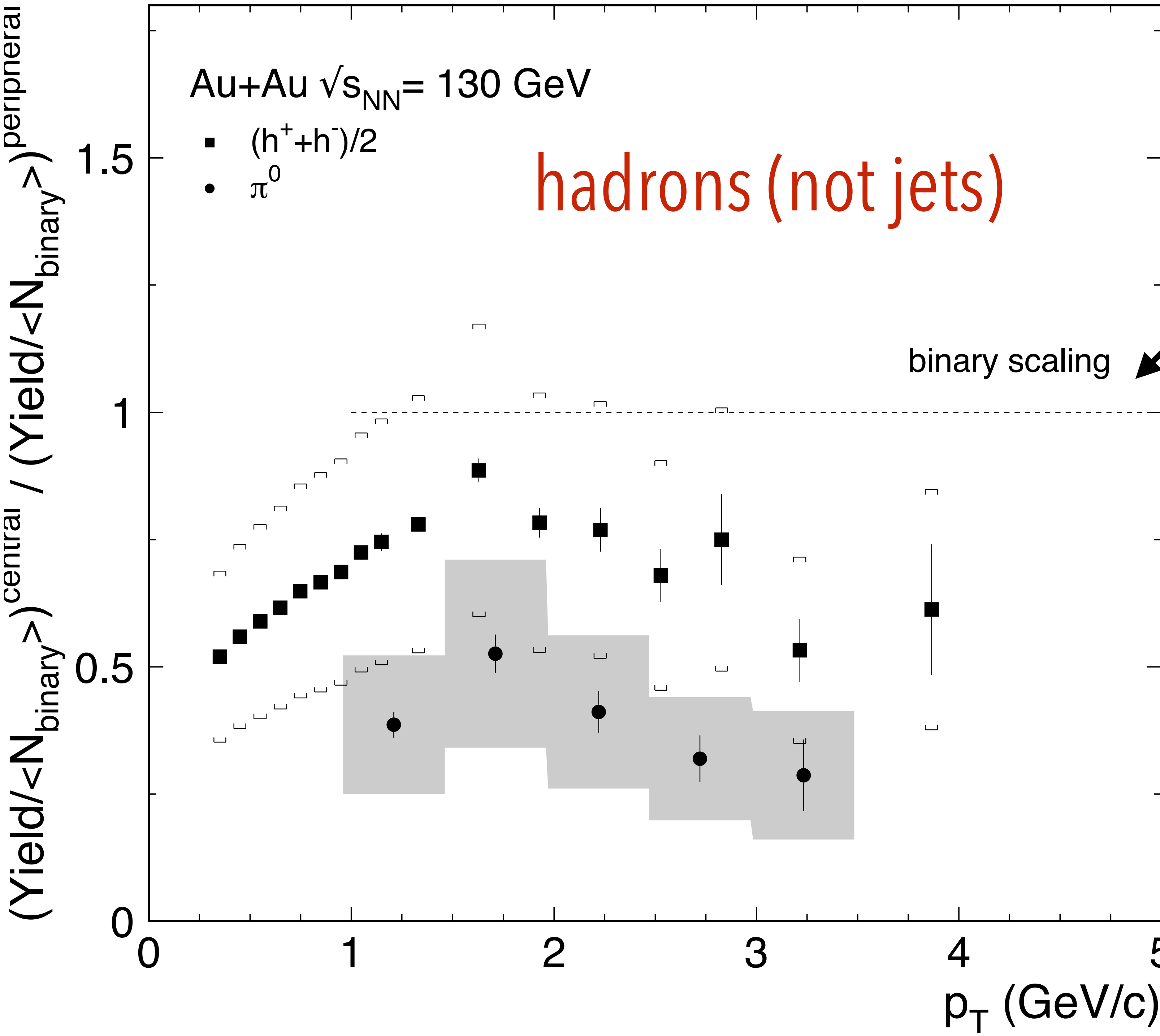
R. Baier [1], Yu. L. Dokshitzer [2], A. H. Mueller* [3, 4], S. Peigné [3] and D. Schiff [3]

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

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

obvious question:
do you trust your model enough to say that your expectations were valid?

PHENIX, PRL 88 022301 (2002)

Glauber model

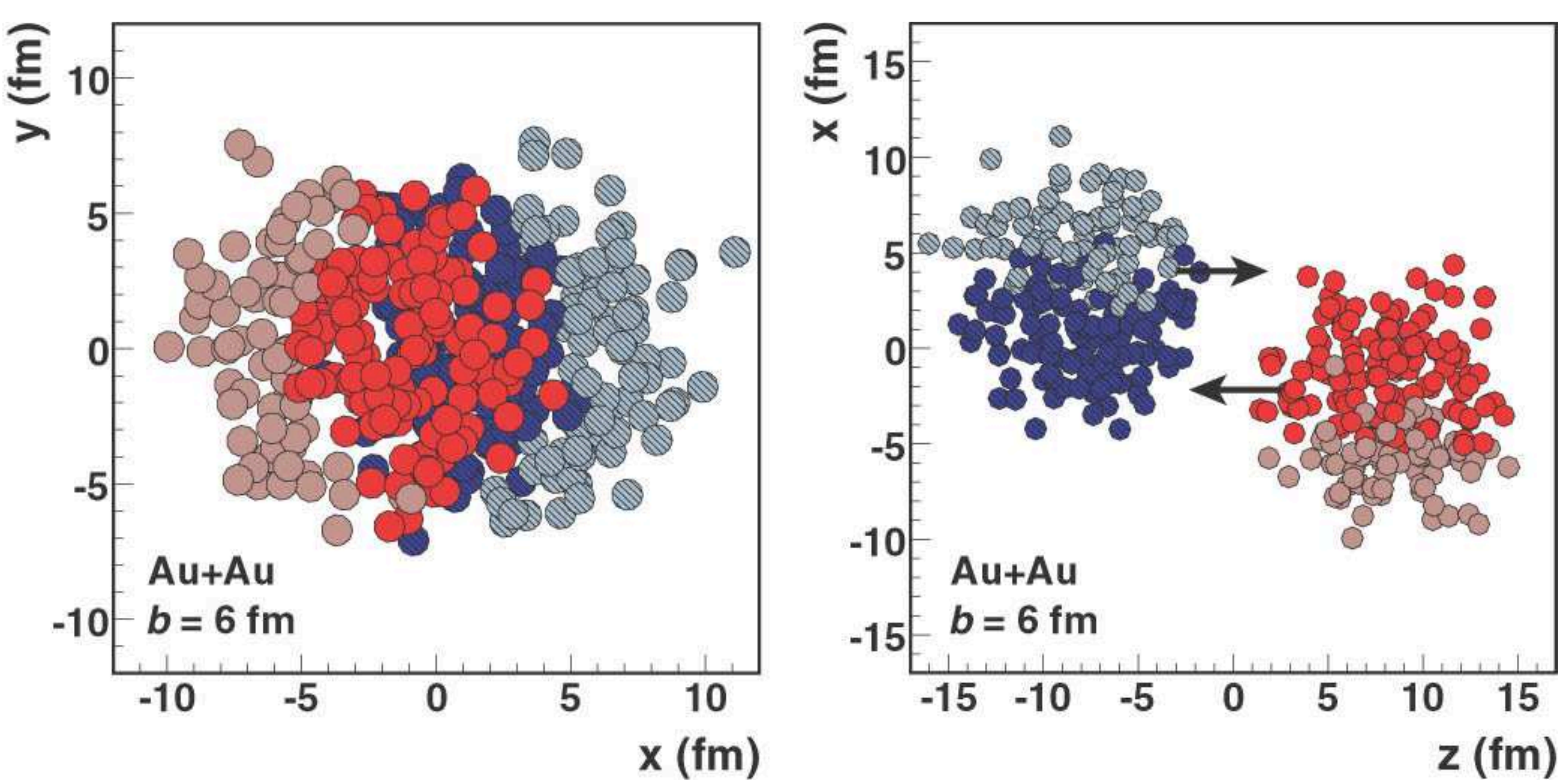
model the distributions of nucleons in nucleus
(Woods-Saxon for spherical nuclei)

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

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

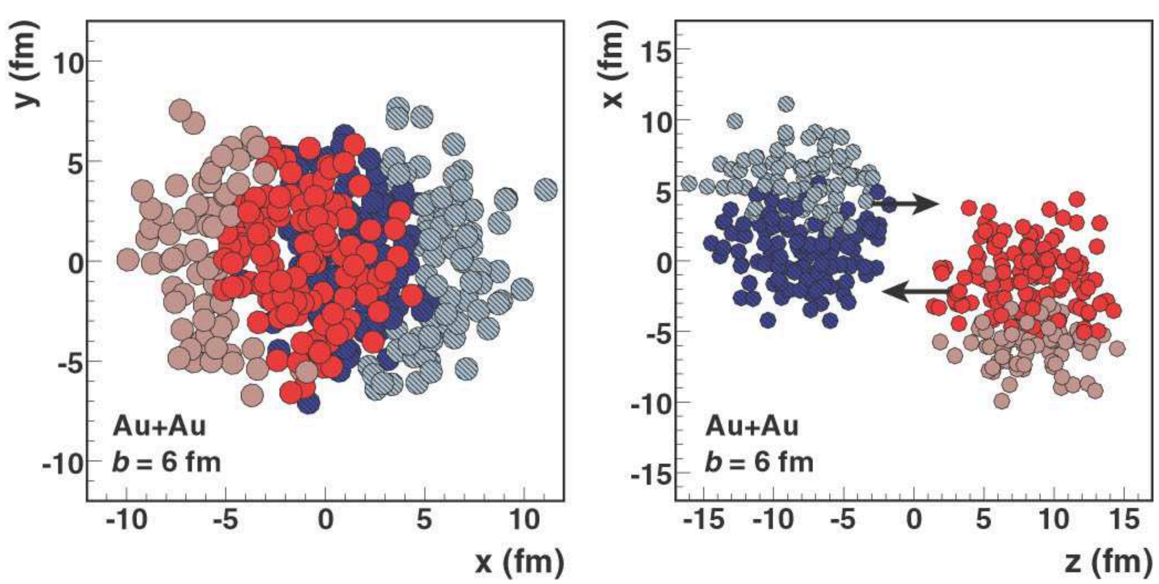
Miller, et al, Ann Rev Nuc Part 57 (2007) 205
C. Loizides, et al Software X 1-2 (2015) 13
C. Loizides, et al PRC 97 054910

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



$Z \to l^+ l^-$, no color charge can't interact with the QGP

ATLAS-CONF-2017-010

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

N_{coll} ~ 2000 in the most central collisions

counting: pp vs PbPb

$Z \rightarrow l^+l^-$, no color charge can't interact with the QGP

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

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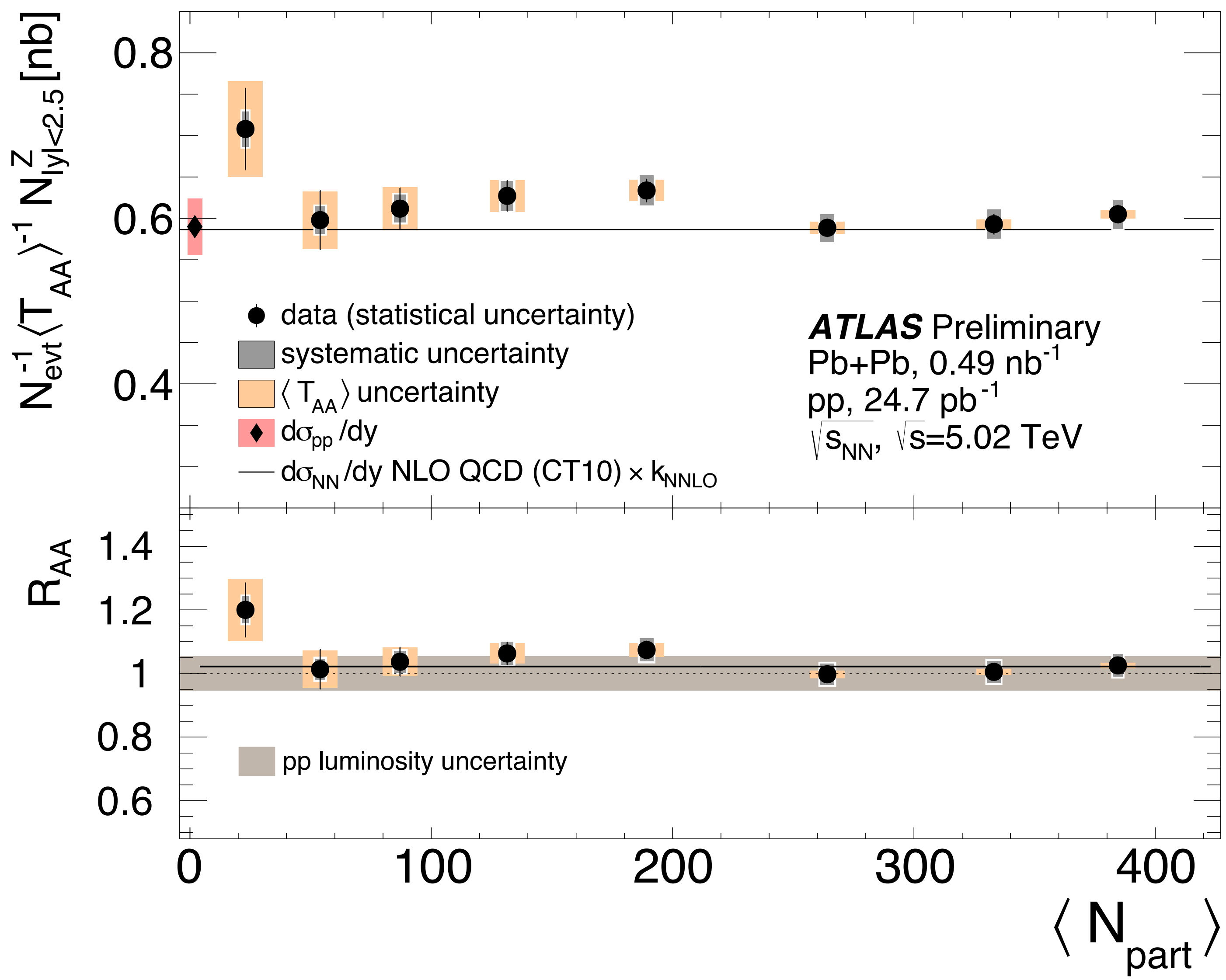
Z bosons

ATLAS-CONF-2017-010



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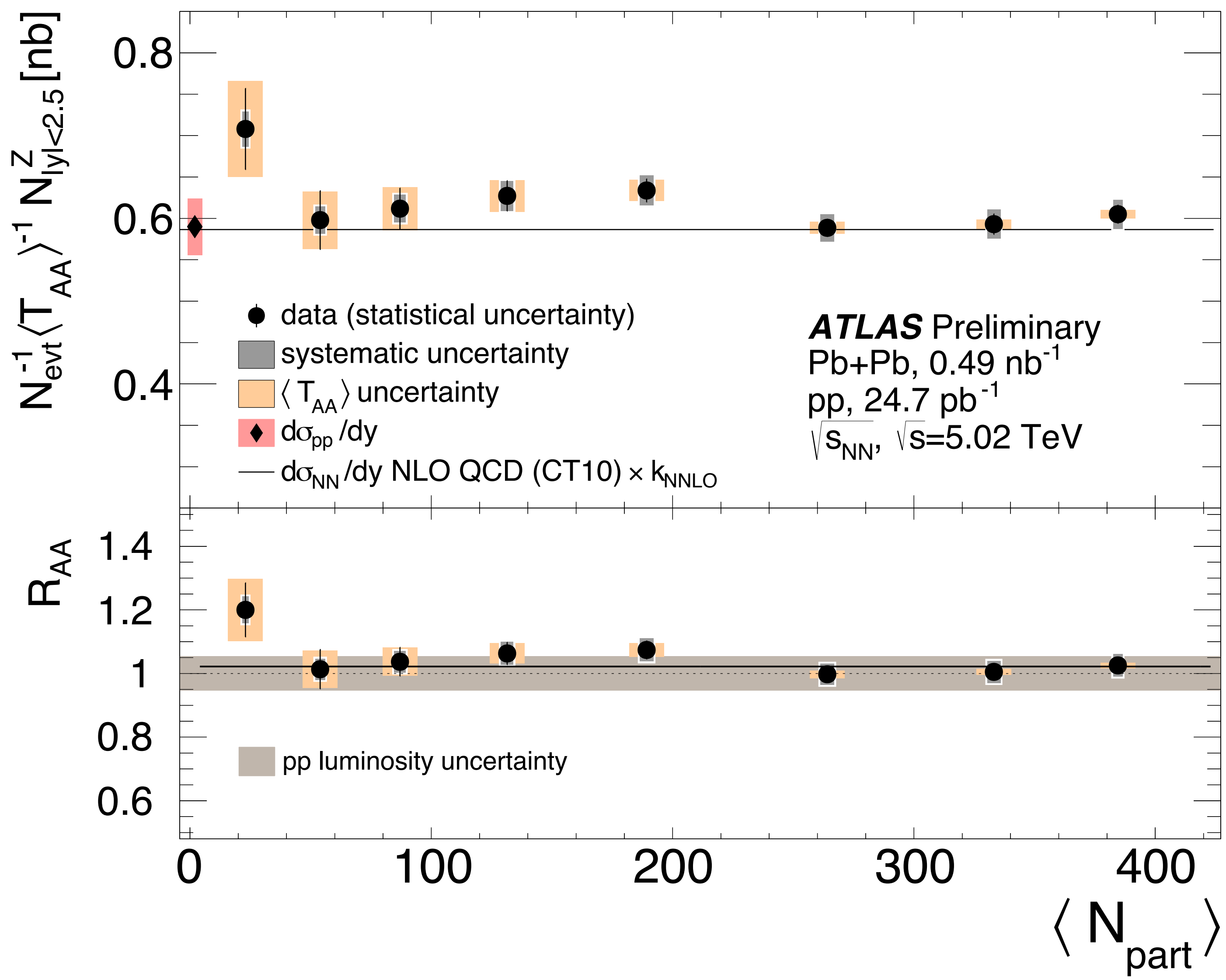
ATLAS-CONF-2017-010



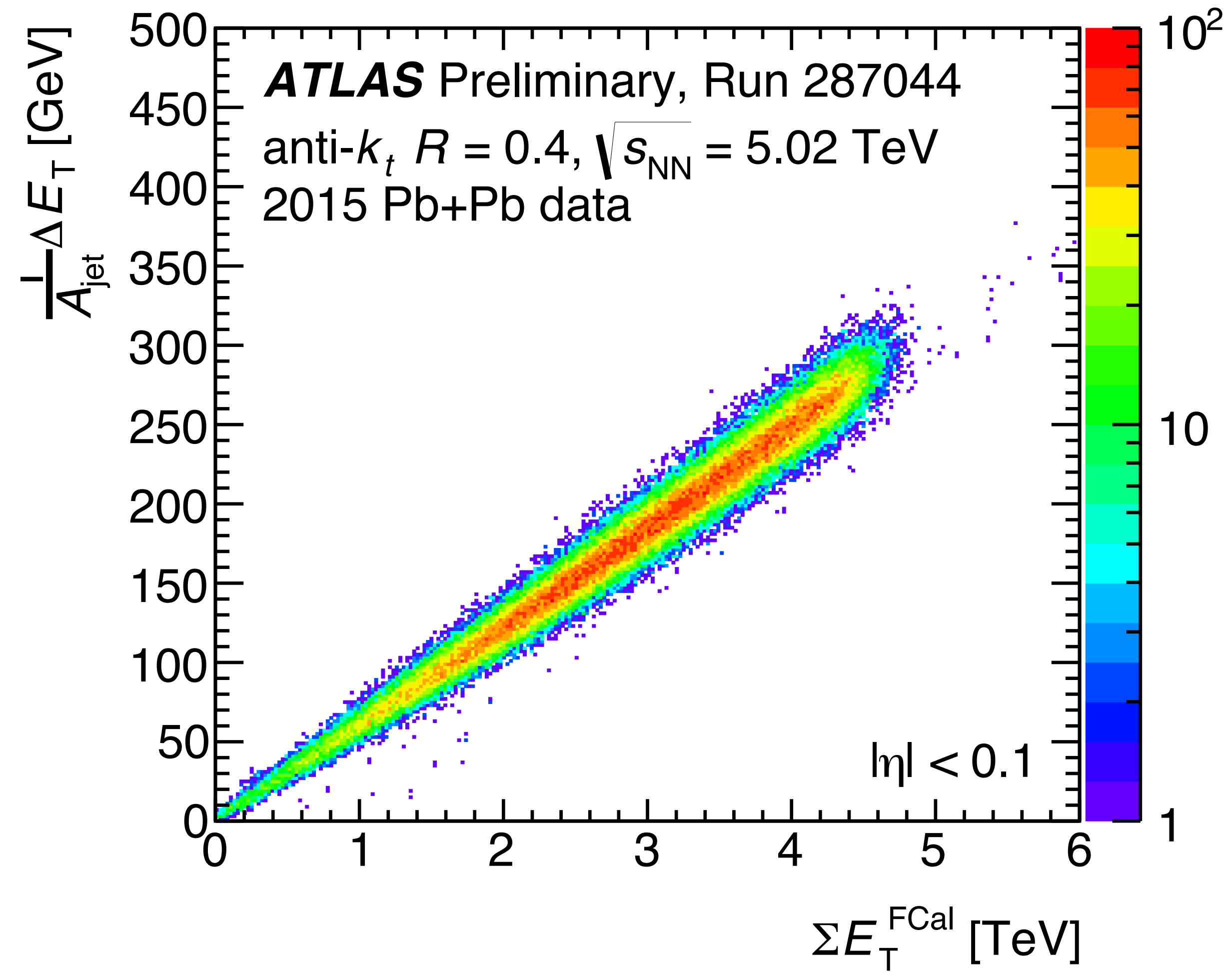
more central collisions

experimental verification with particles that are unmodified by the QGP (also been checked with photons & $W^{\pm}$)

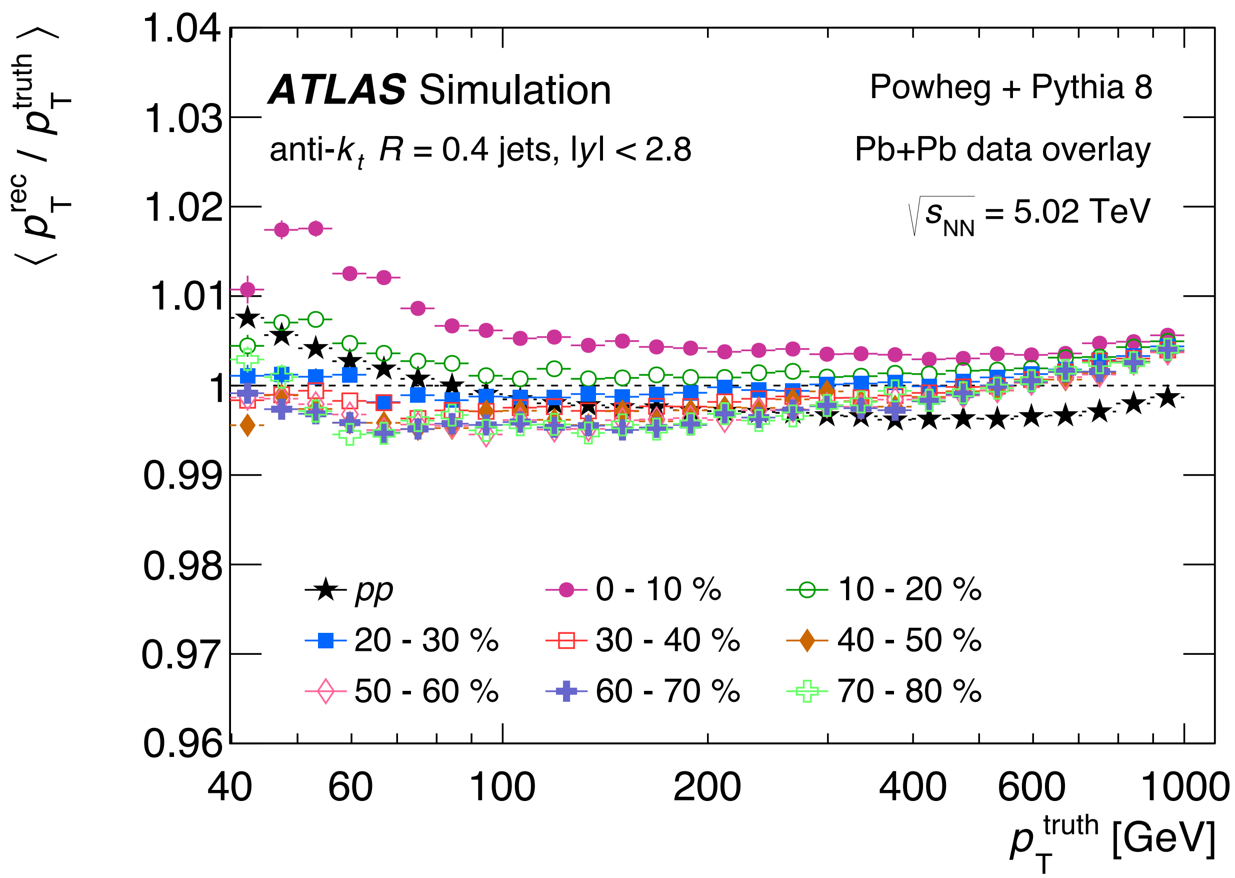
HI collisions are a challenging place to measure jets

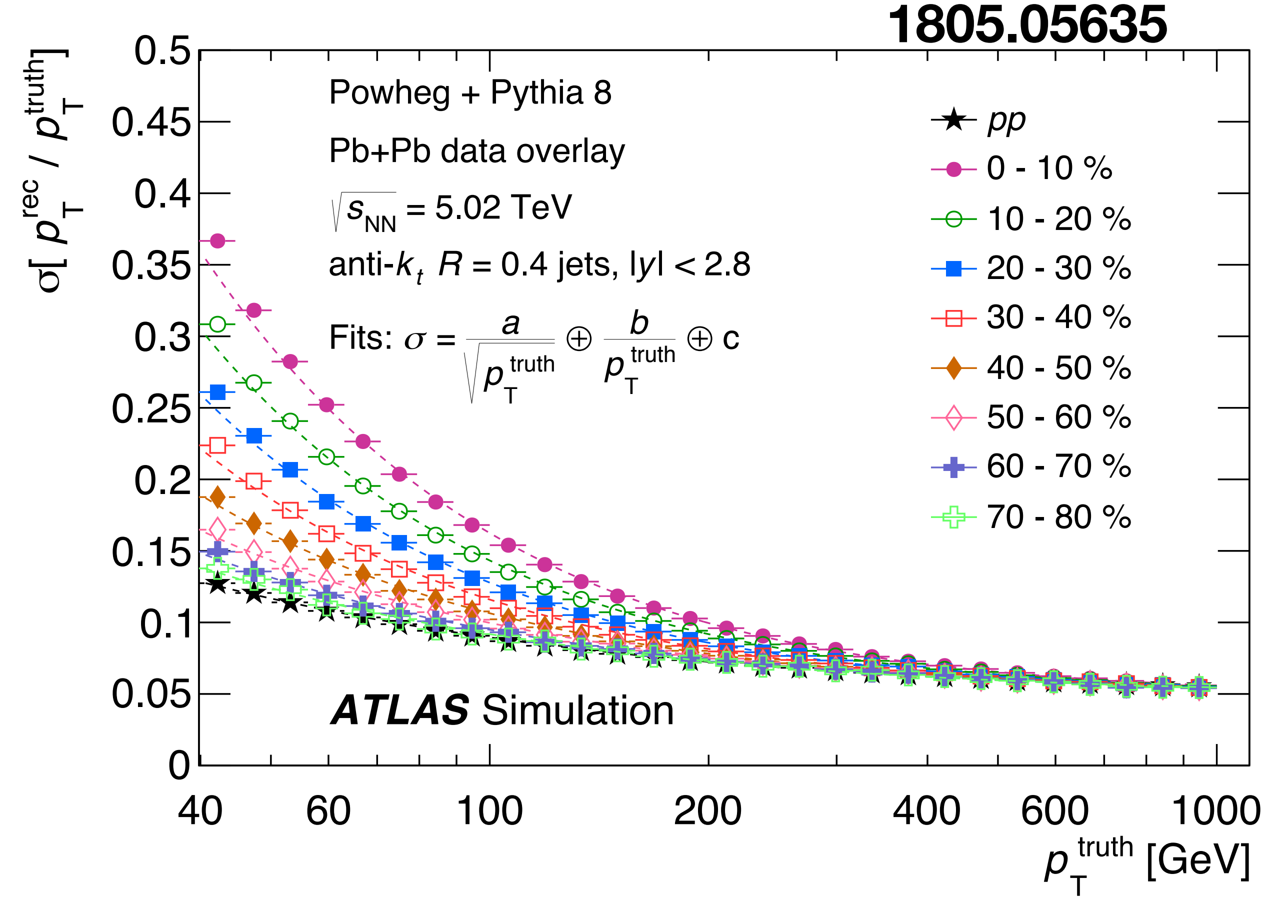
- an R = 0.4 cone in a PbPb collision at 5 TeV has up to 150 GeV of energy from the underlying event (UE) which has to be subtracted
  - UE to subtract goes as R^2 (see C. McGinn CMS at Quark Matter 2018)
- ATLAS uses an iterative procedure to estimate the UE; ALICE and CMS use Constituent Subtraction

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



1805.05635

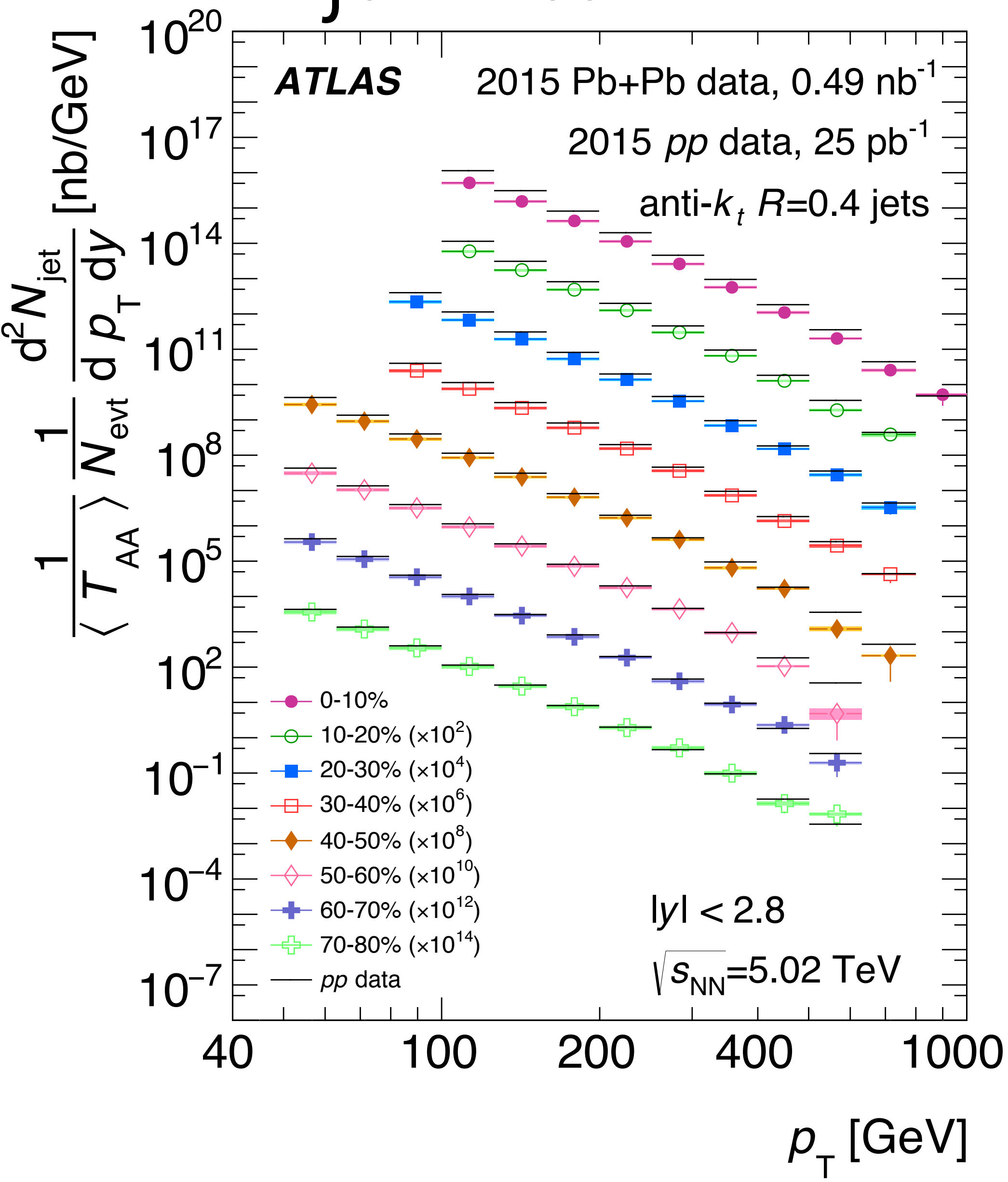




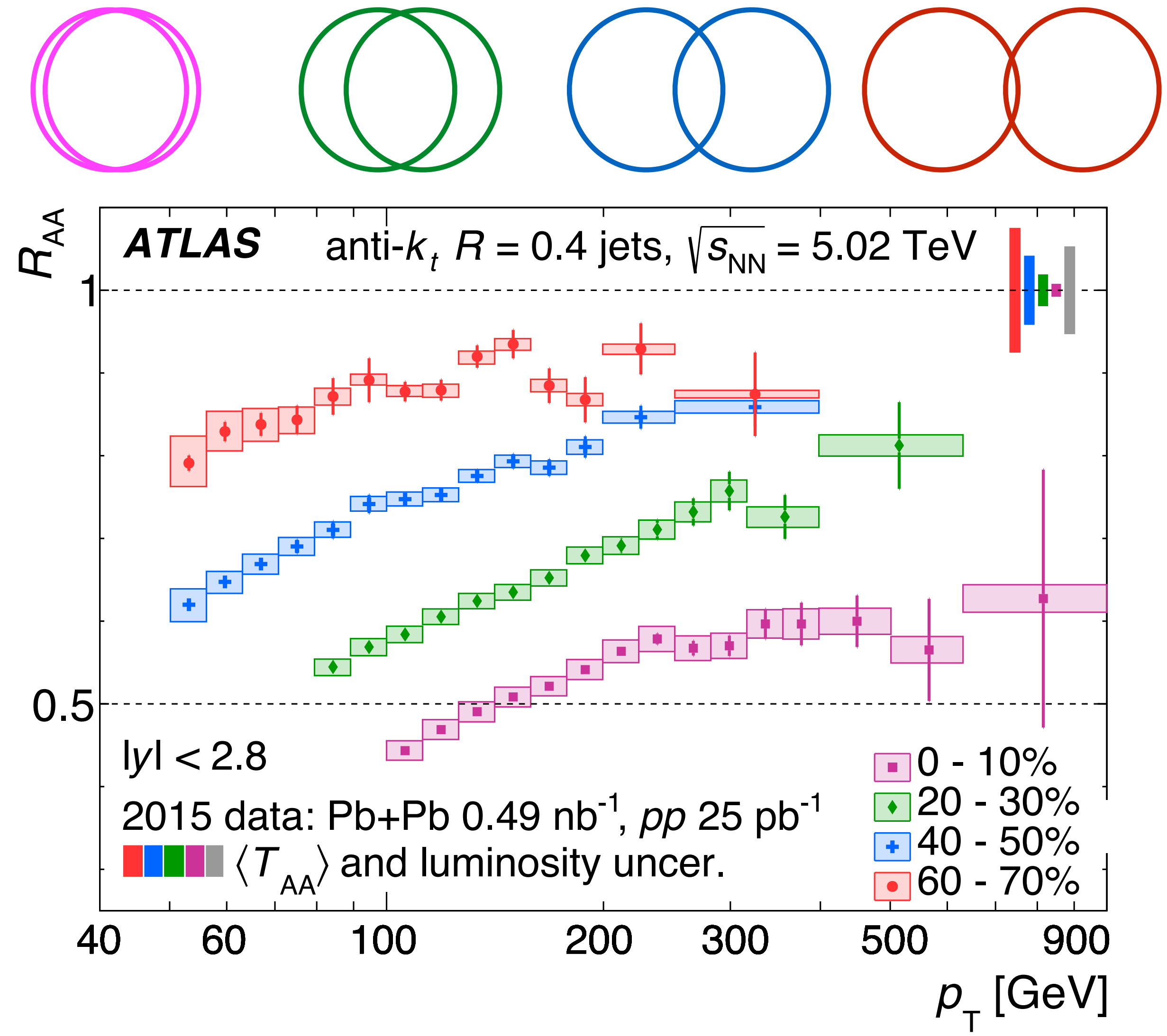
- Jet Energy Scale: ~1% centrality dependence above 100 GeV
- Jet Energy Resolution: degraded in central collisions due to underlying event fluctuations

jet counting

jet rates



jet rates / expectations

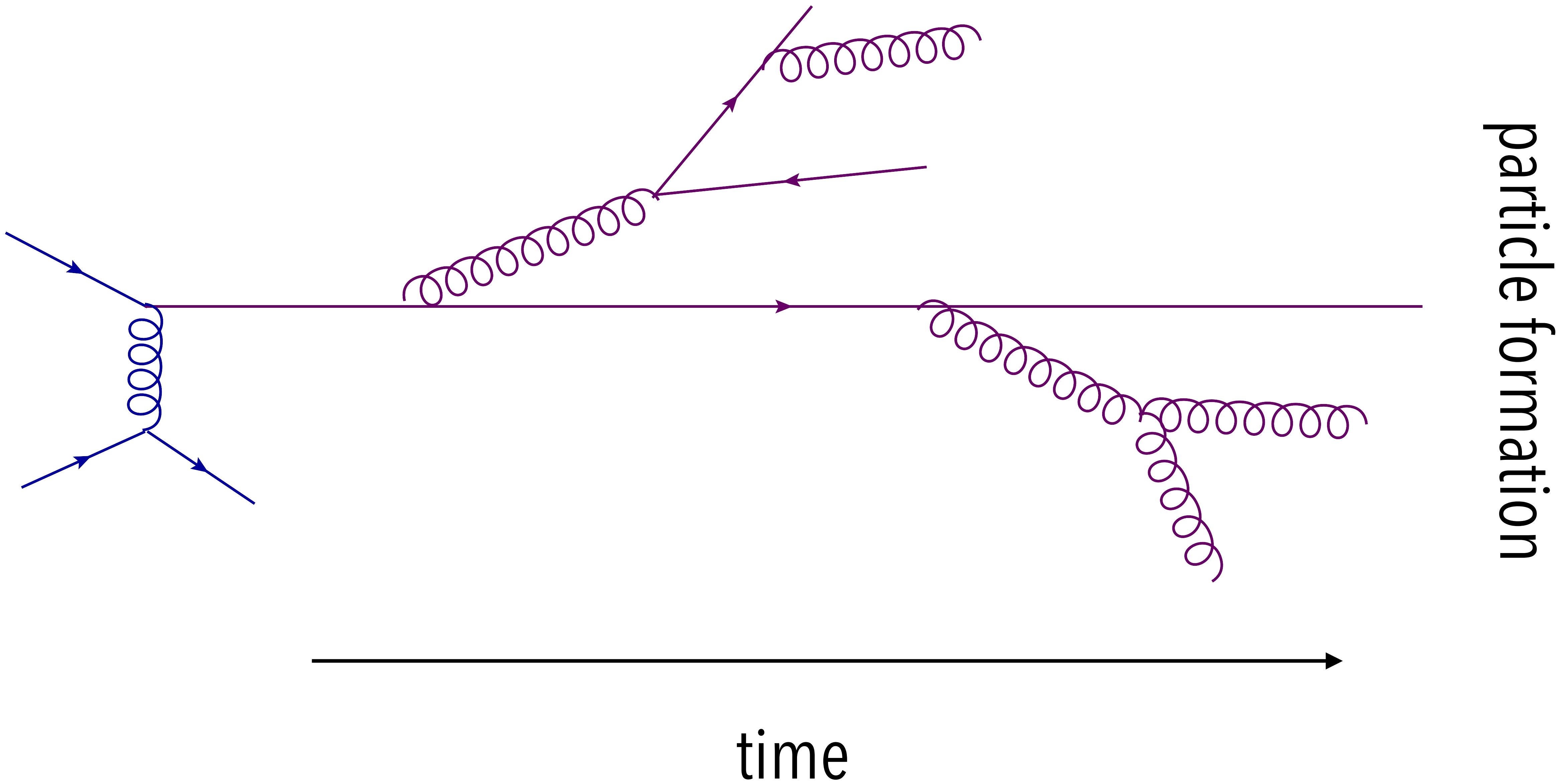


jet momentum (p_T) (GeV)

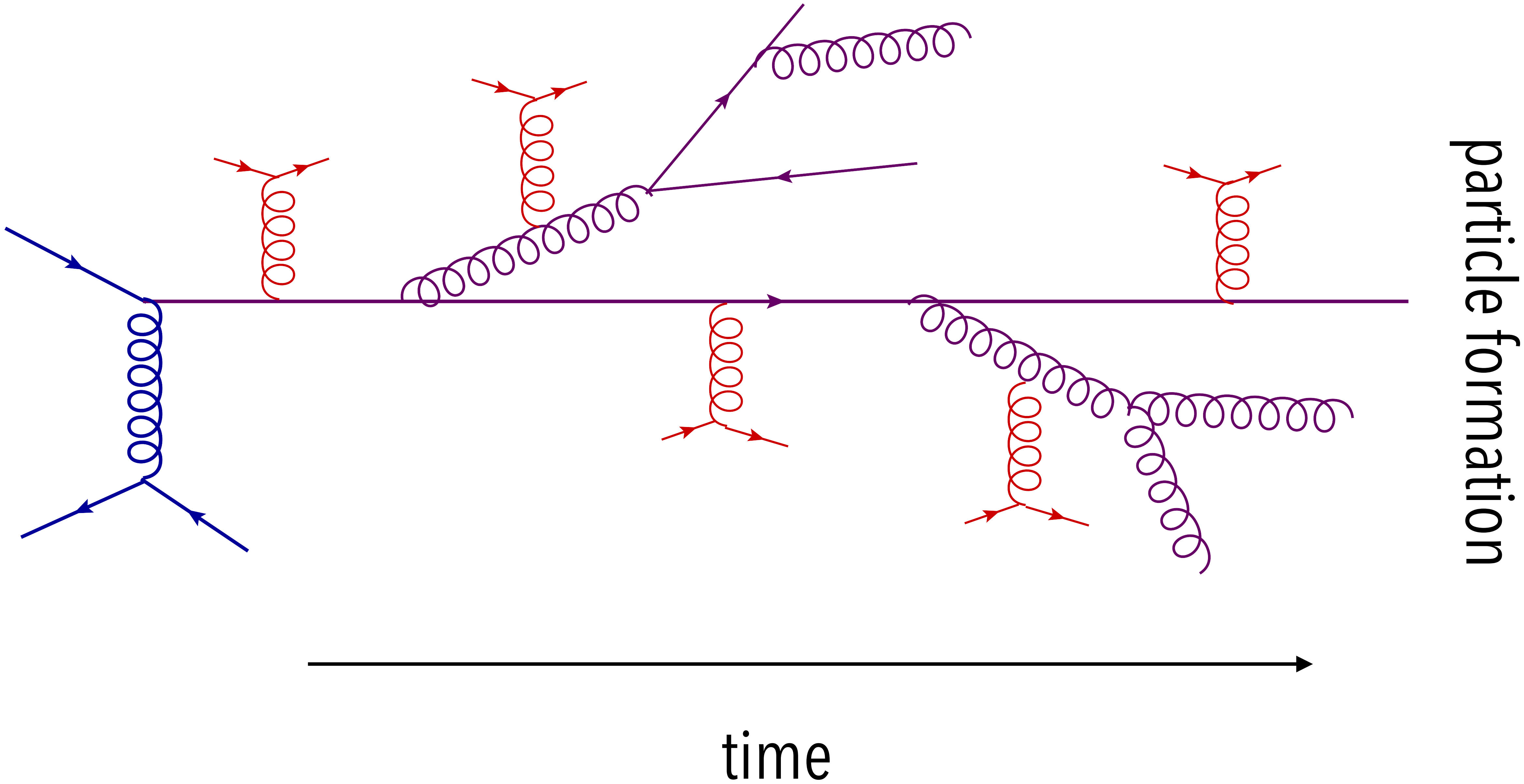
- fewer jets when there is more QGP
- jets shift downward in momentum → "jet quenching"
- quenching ~independent of jet momentum out to TeV scale jets

1805.05635

in vacuum (p+p collisions)

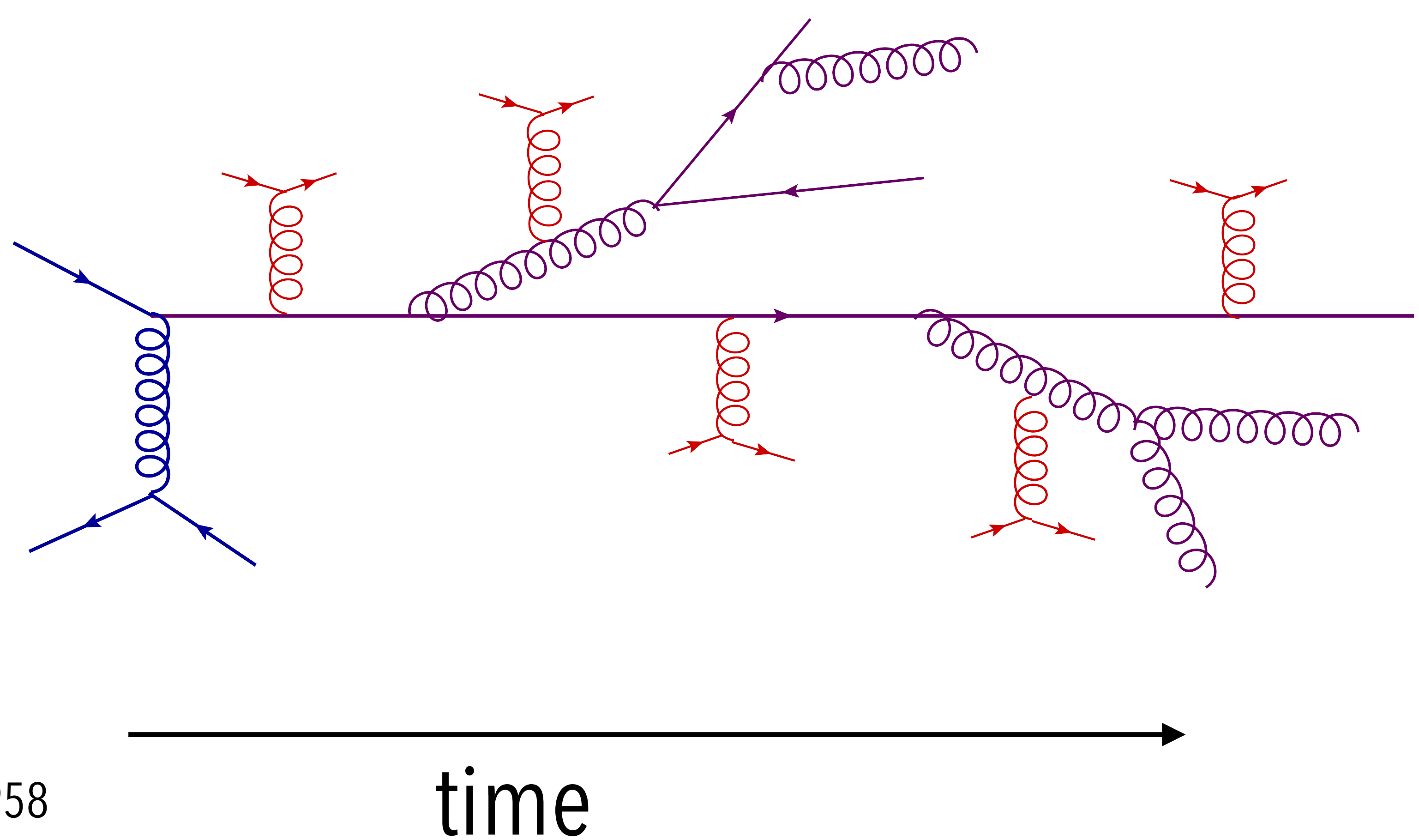


in QGP



jet fragmentation

- **how do the jet and QGP interact?**
  - are the scatterings independent?
  - how is the jet resolved by the QGP?
  - is there evidence for quasiparticles at some scale?

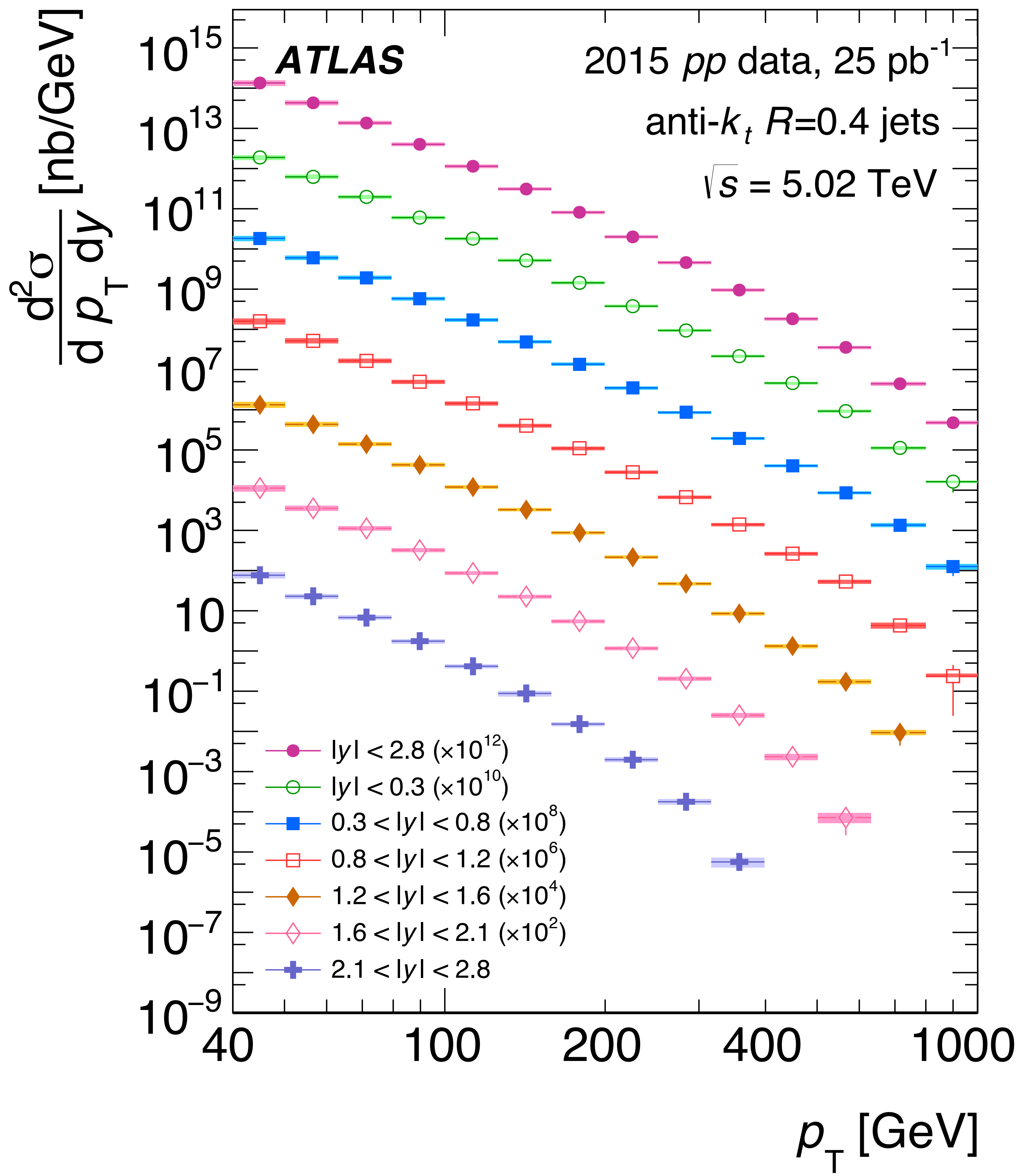


reviews:
Qin & Wang 1511.00790
Blaizot & Mehtar-Tani 1503.05958

- 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 overconstrain theoretical models with **systematic, differential** data

rapidity dependence

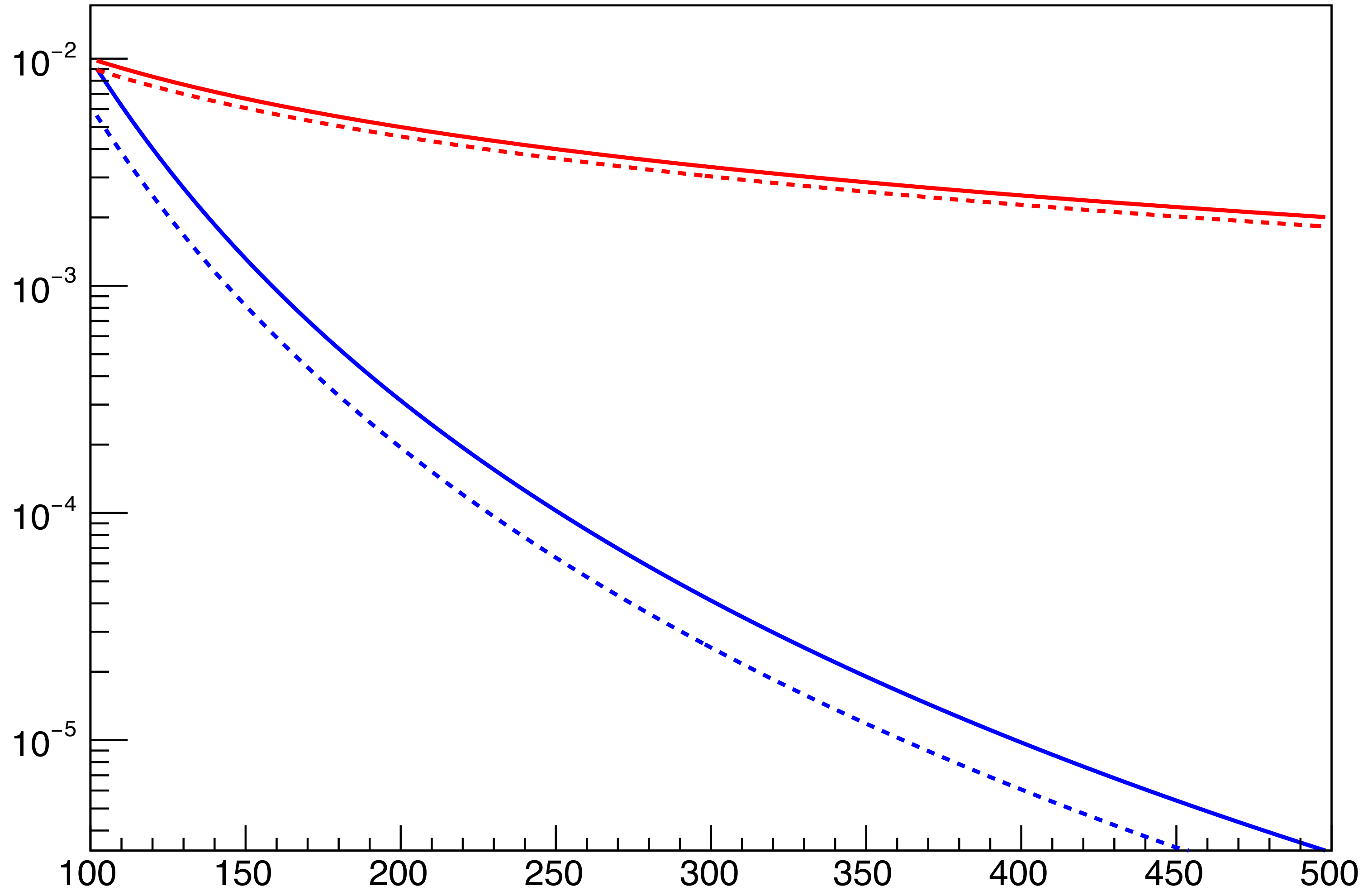


- at fixed pT increasing y, increases p and increases the fraction of jets which are quark jets
- at the same time, the spectra become steeper with increasing y

1805.05635

beware of ratios!

dashed lines: solid lines with 10% “quenching”

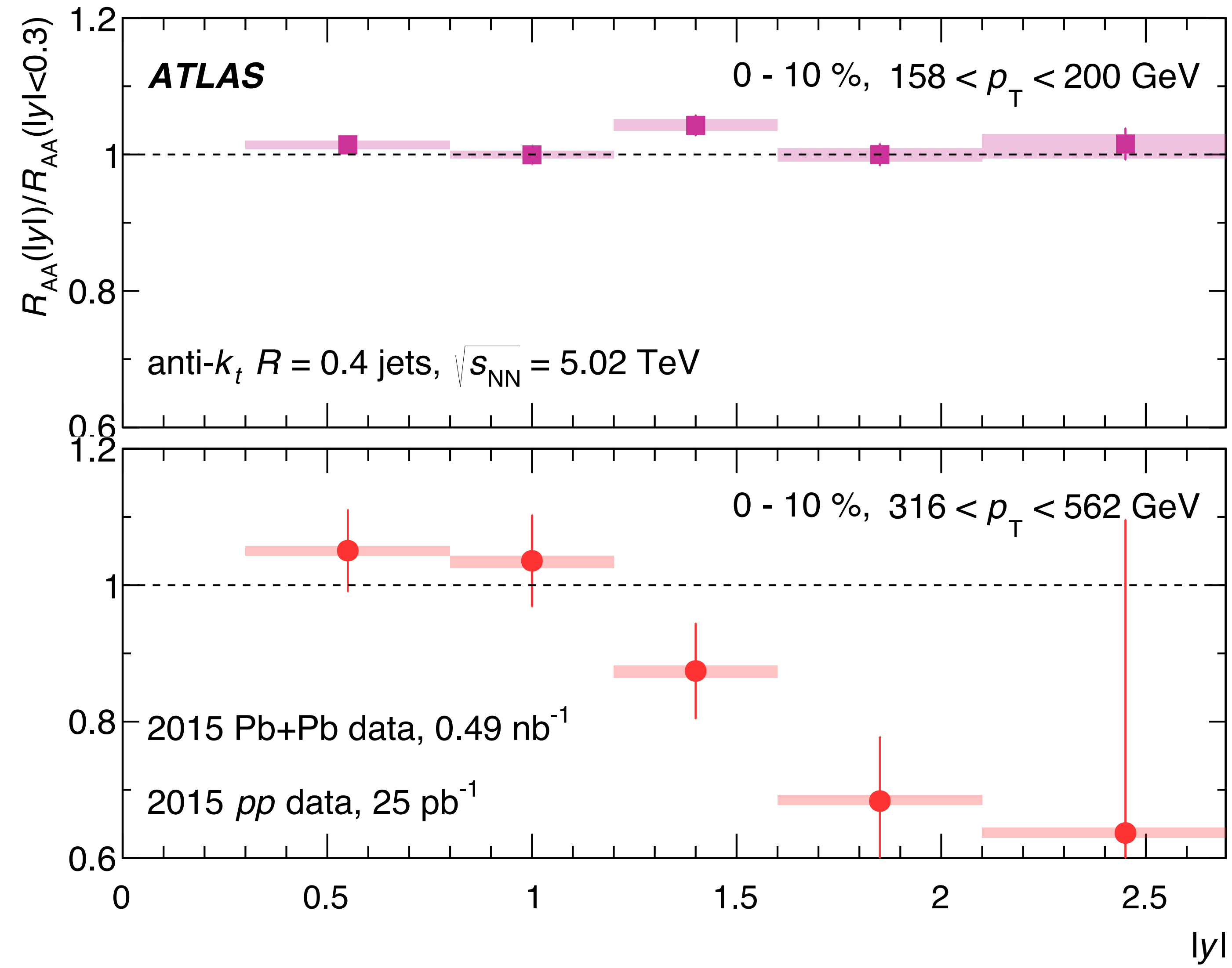


R_{AA} = dashed / solid

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

- why rapidity?
  - fraction of quark jets increases with |y| at fixed jet p_T
  - jet p_T spectra become steeper with increasing |y|
    - **decrease R_{AA} with |y|**
  - quarks jets should lose less energy than gluon jets (larger color charge)
    - **increase R_{AA} with |y|**

$R_{AA}(y) / R_{AA}$ (|y| < 0.3)



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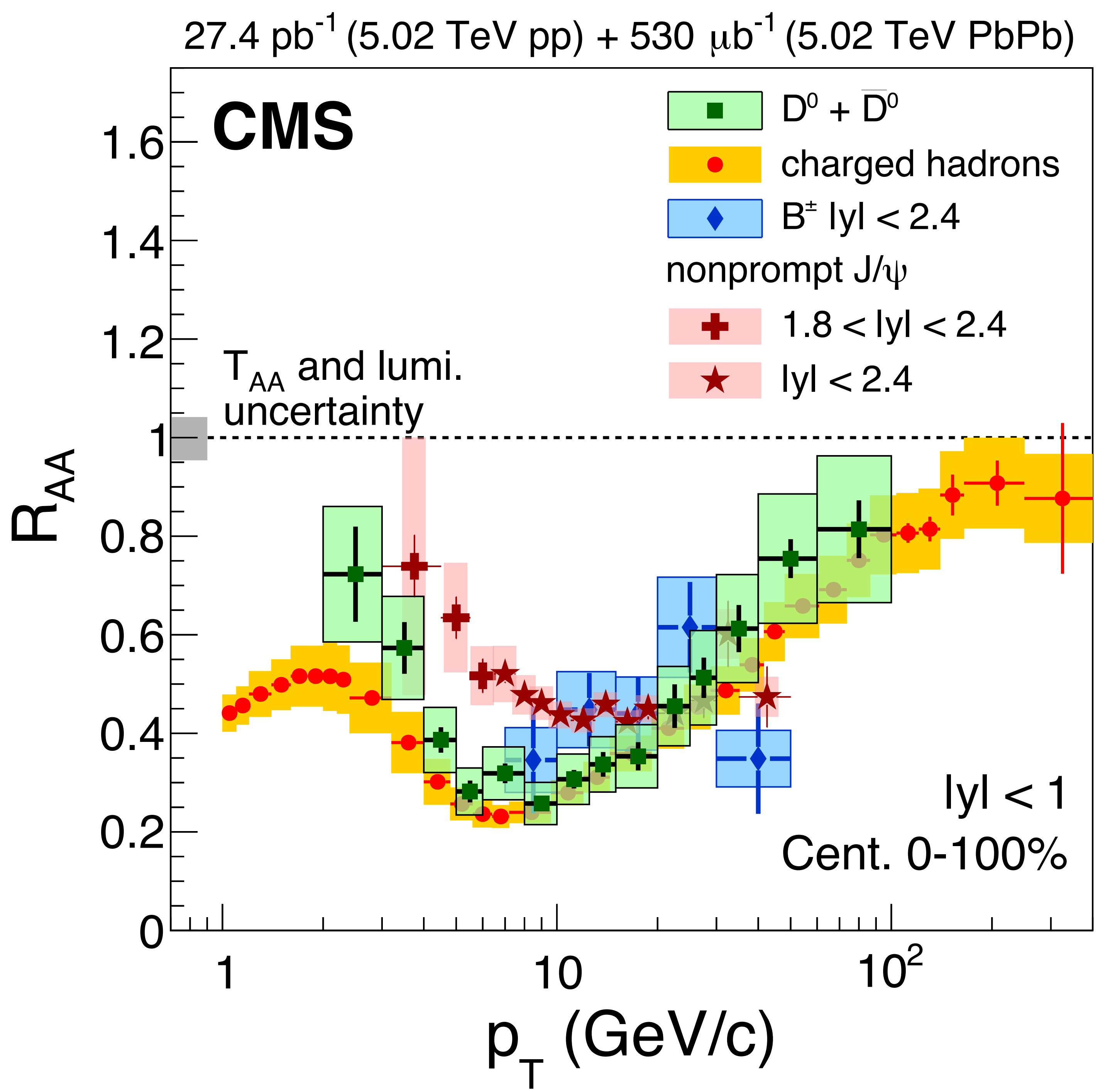
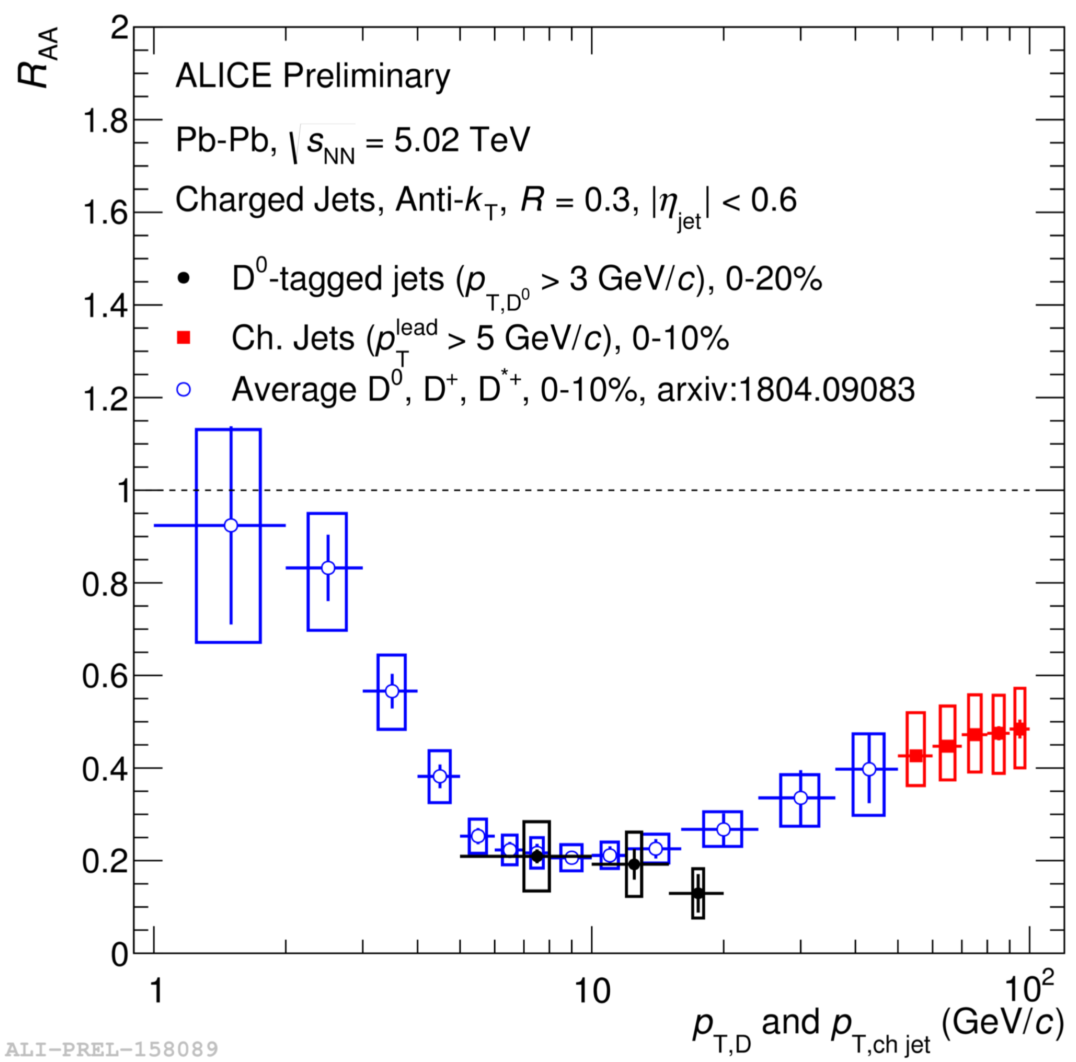
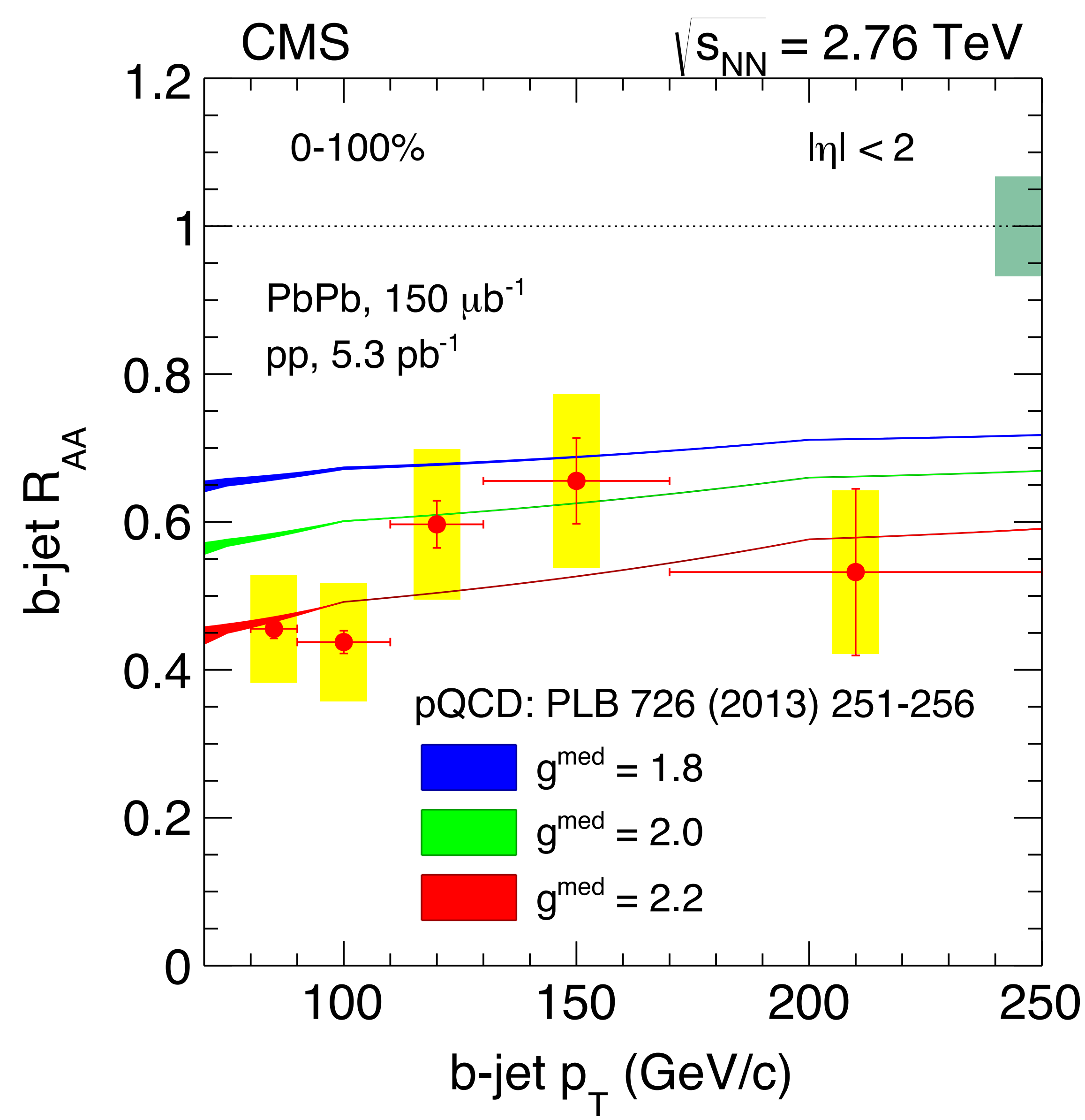


b and c jets are especially interesting because their mass should suppress radiation in the QGP (Dokshitzer & Kharzeev Phys.Lett. B519 (2001) 199-206)

Phys. Lett. B 782 (2018) 474

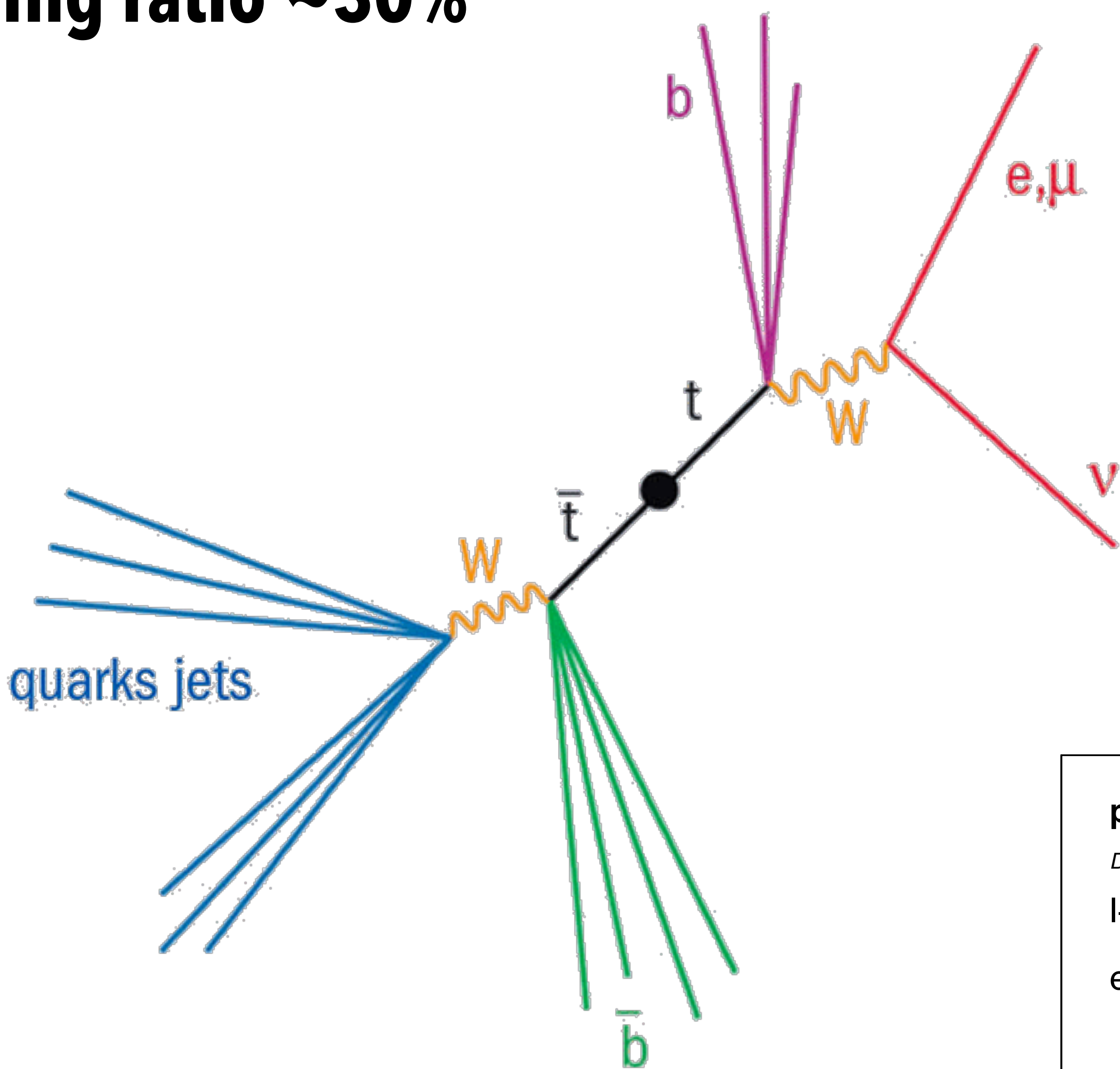
HF tagged jets

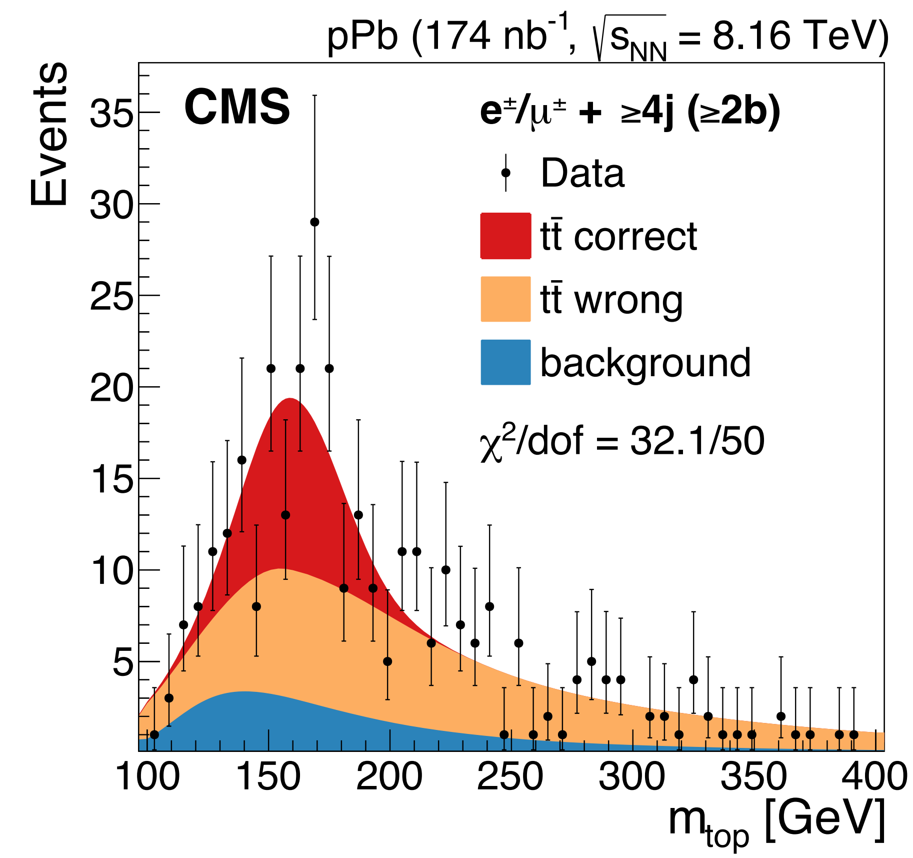




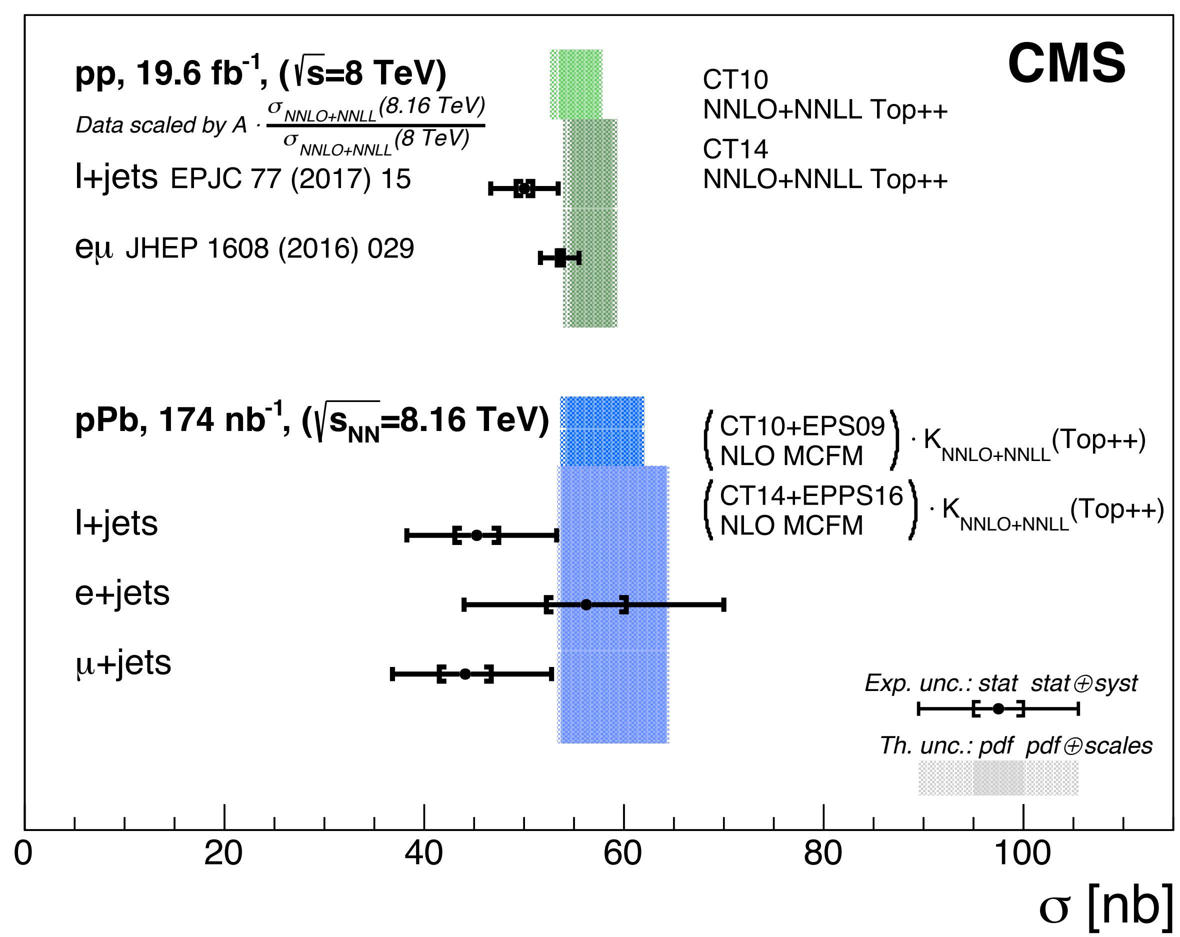
top in pPb

branching ratio ~30%





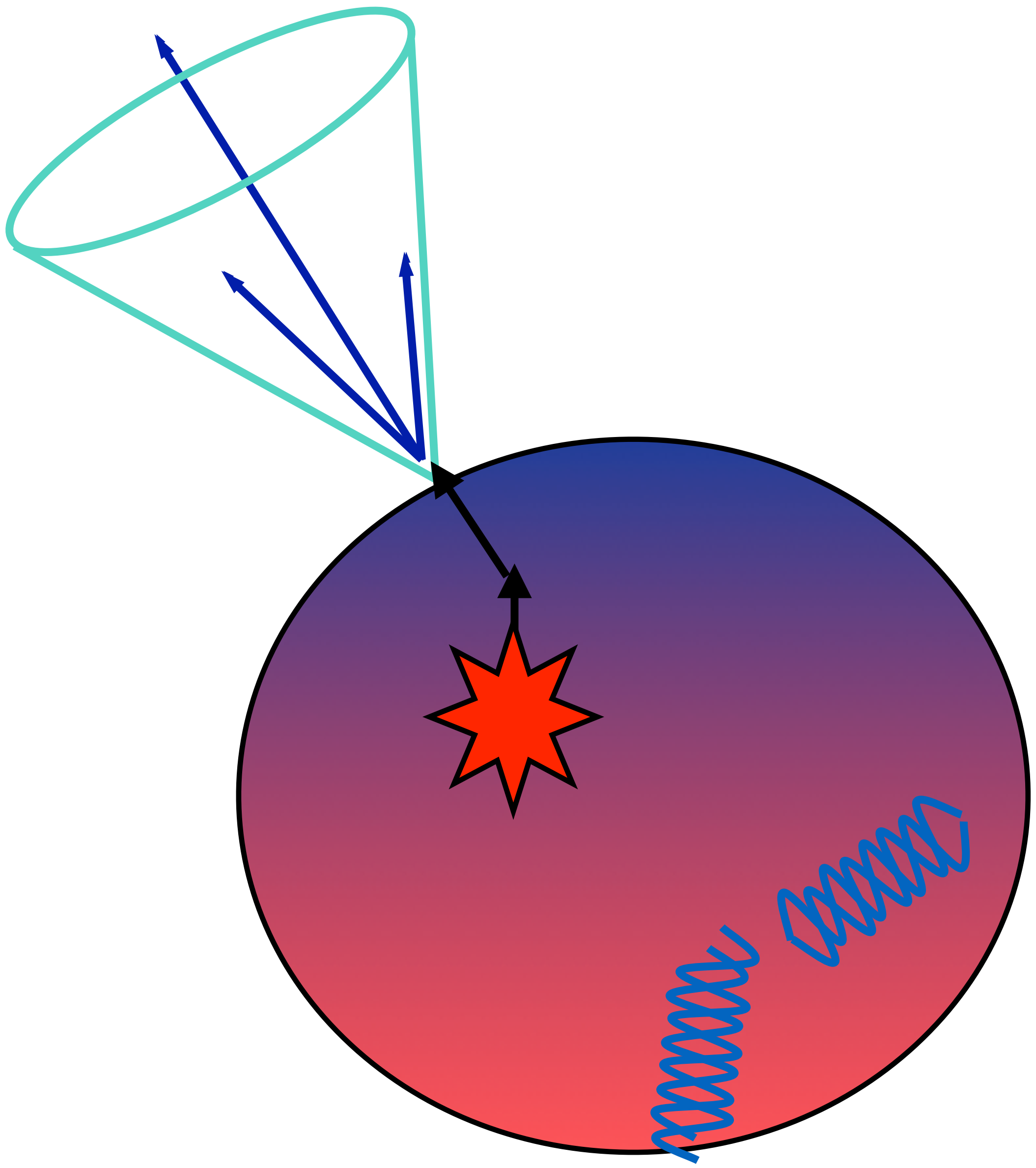
cross section in agreement with expectations based on pp collisions scaled by A



talk: M. Verweij, 1709.07411

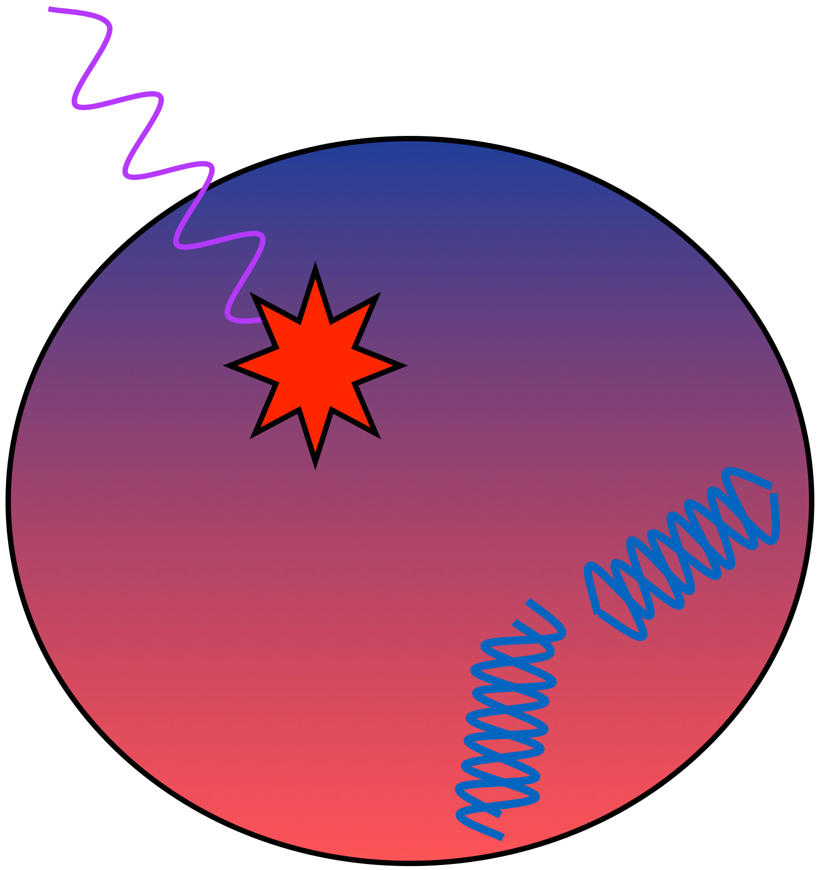
photon-jets

dijets→both jets interact



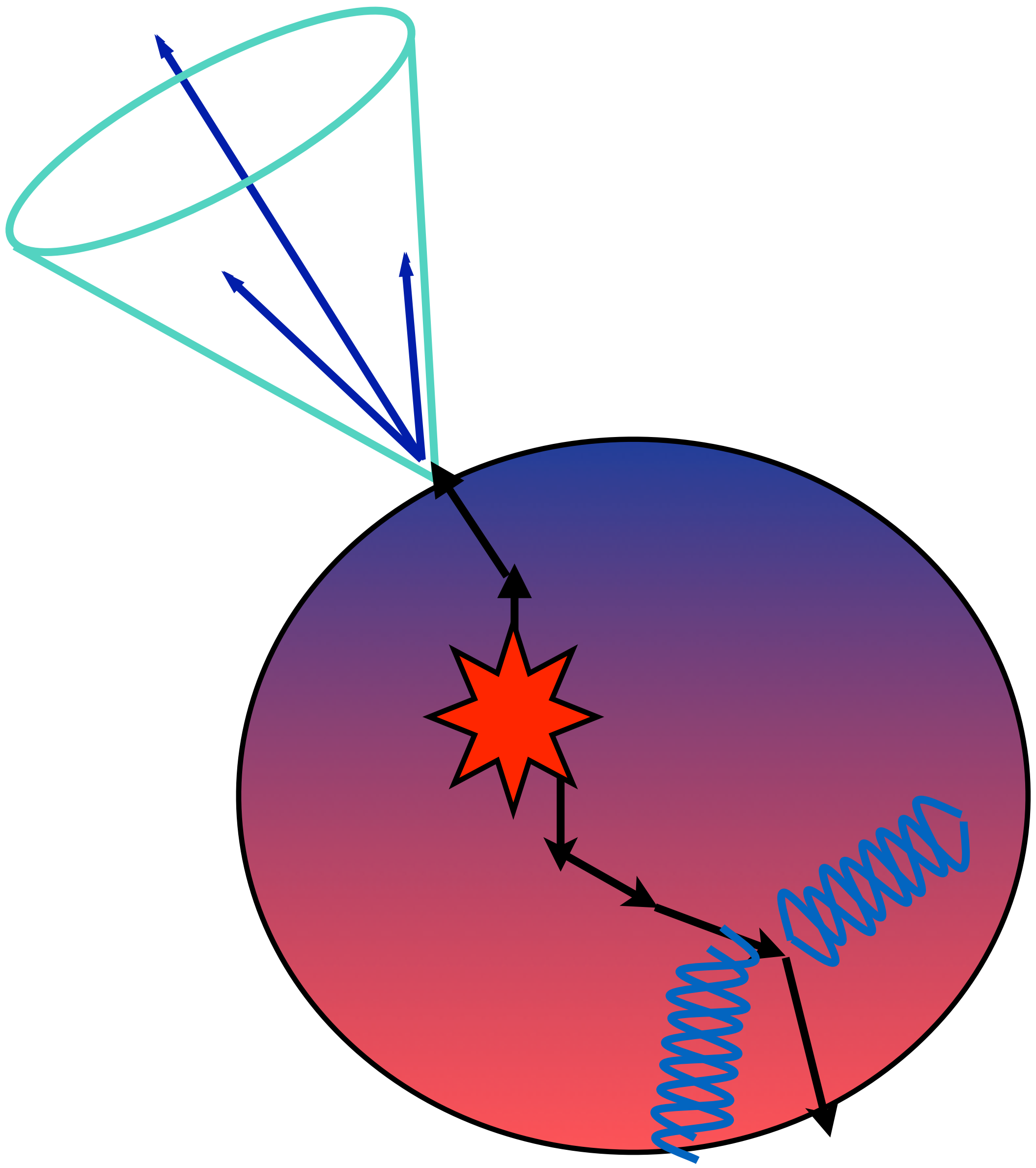
γ-jets→only the jet interacts

γ provides unmodified information about the hard scattering



Wang & Huang PRL 77 (1996) 231

dijets → both jets interact



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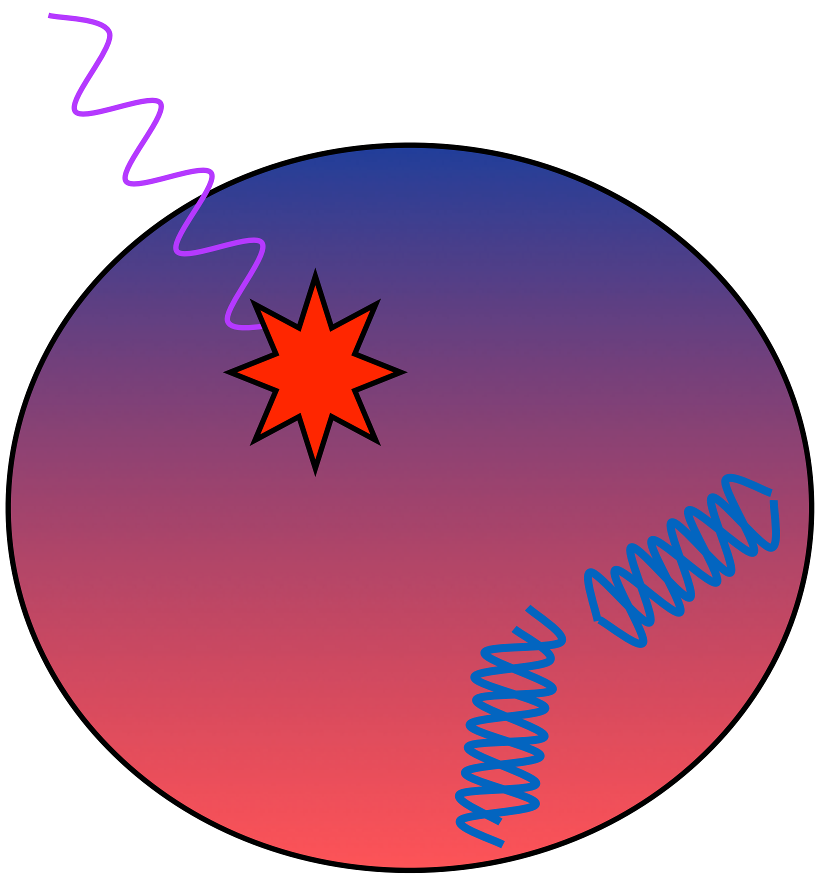

Wang & Huang PRL 77 (1996) 231

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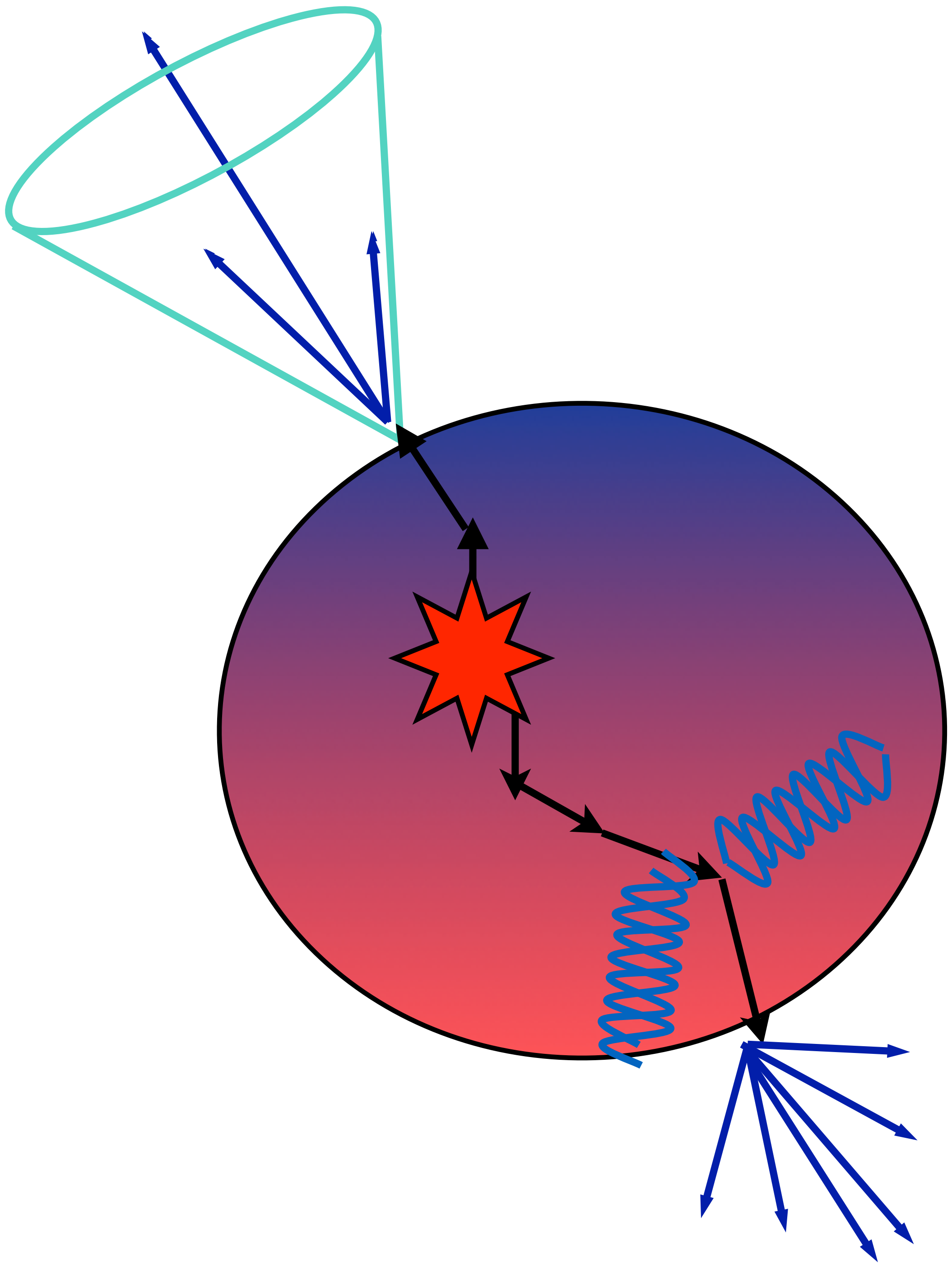

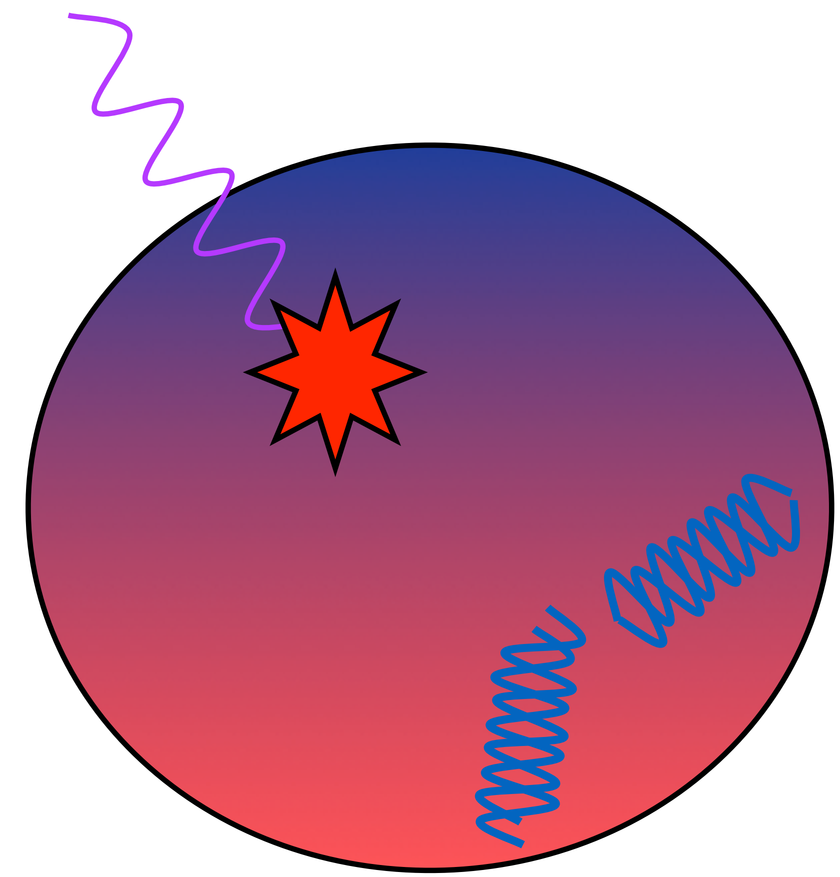

Wang & Huang PRL 77 (1996) 231

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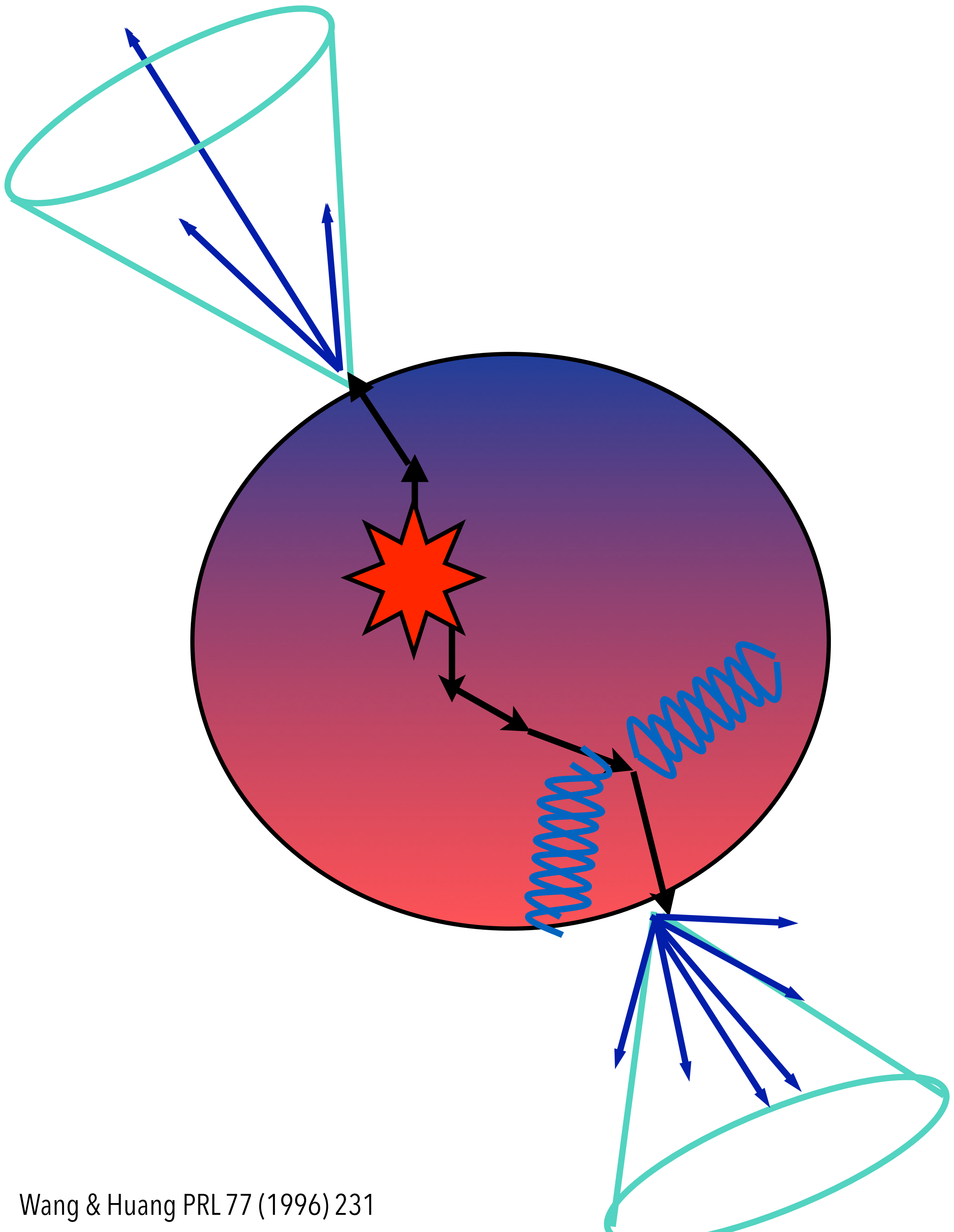
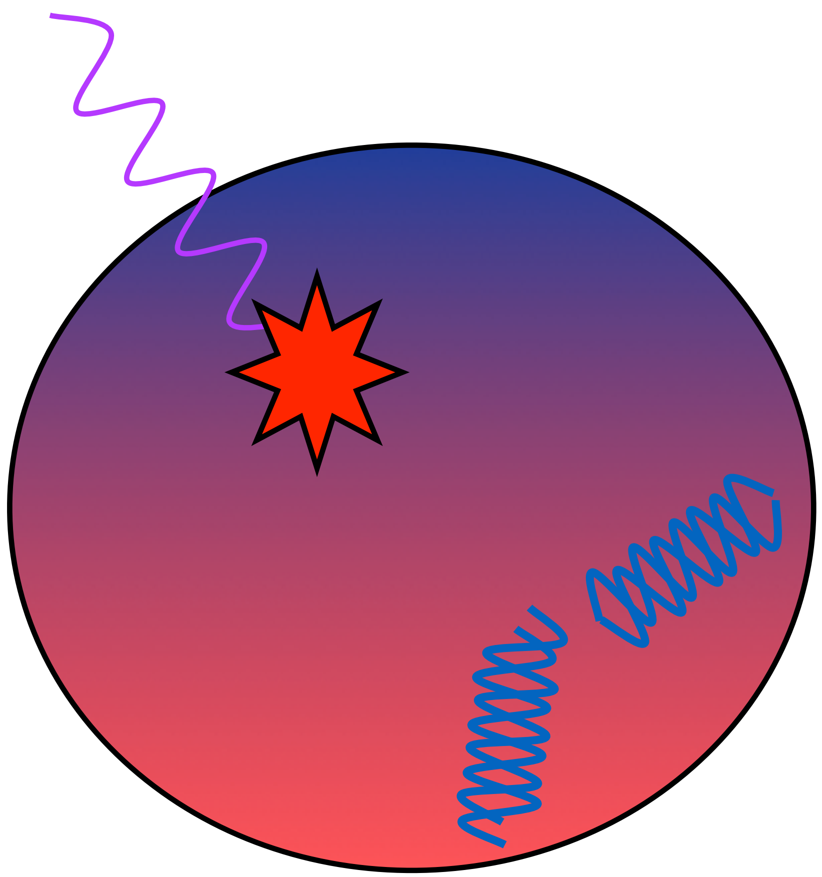
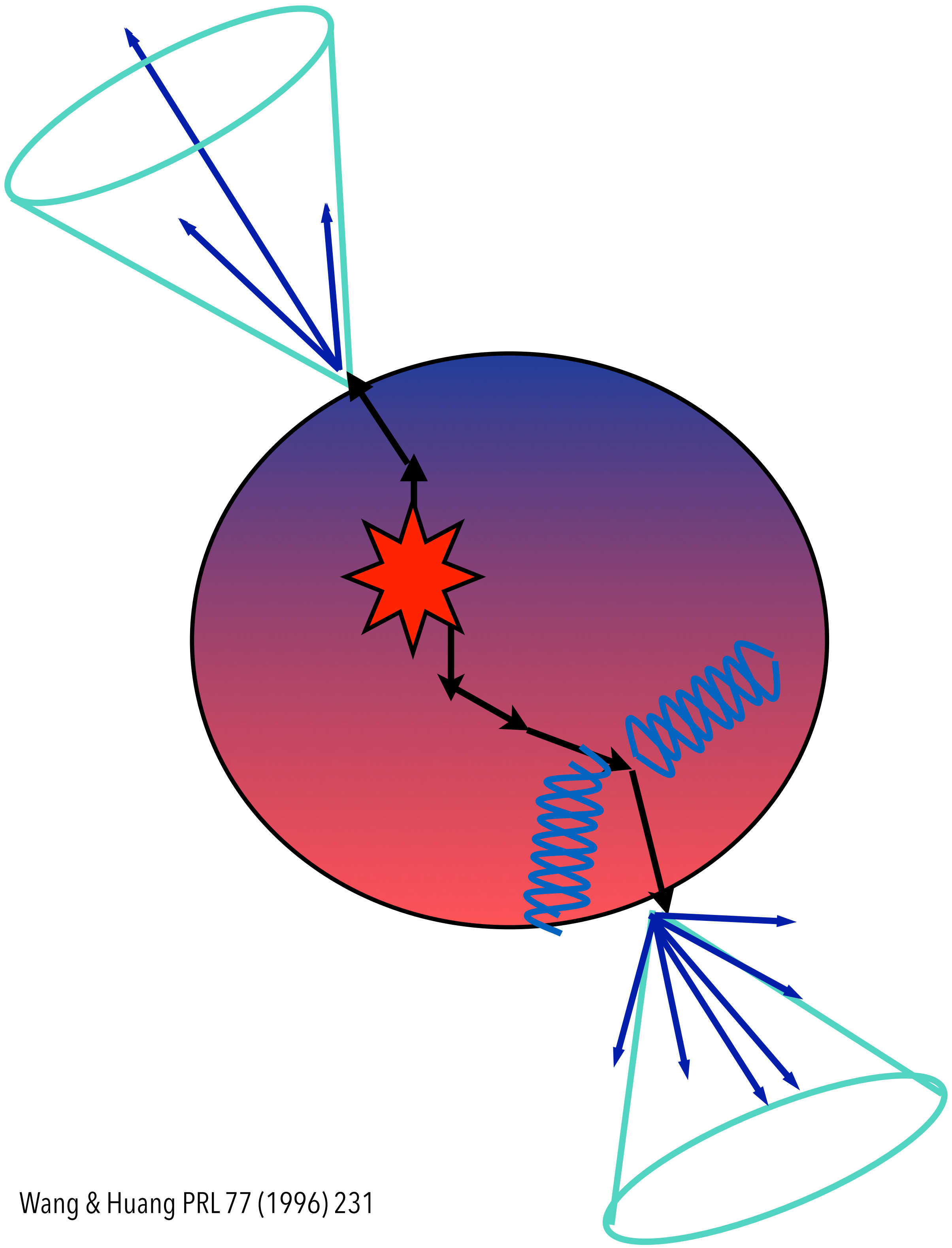




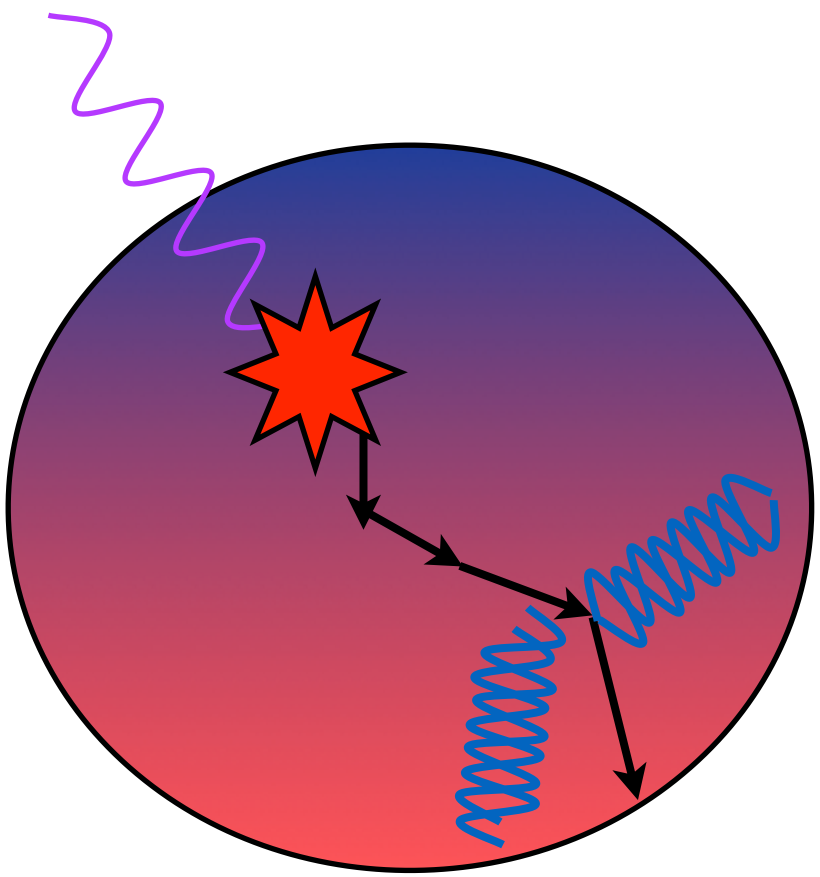
Wang & Huang PRL 77 (1996) 231

dijets → both jets interact



γ-jets → only the jet interacts

γ provides unmodified information about the hard scattering



Wang & Huang PRL 77 (1996) 231

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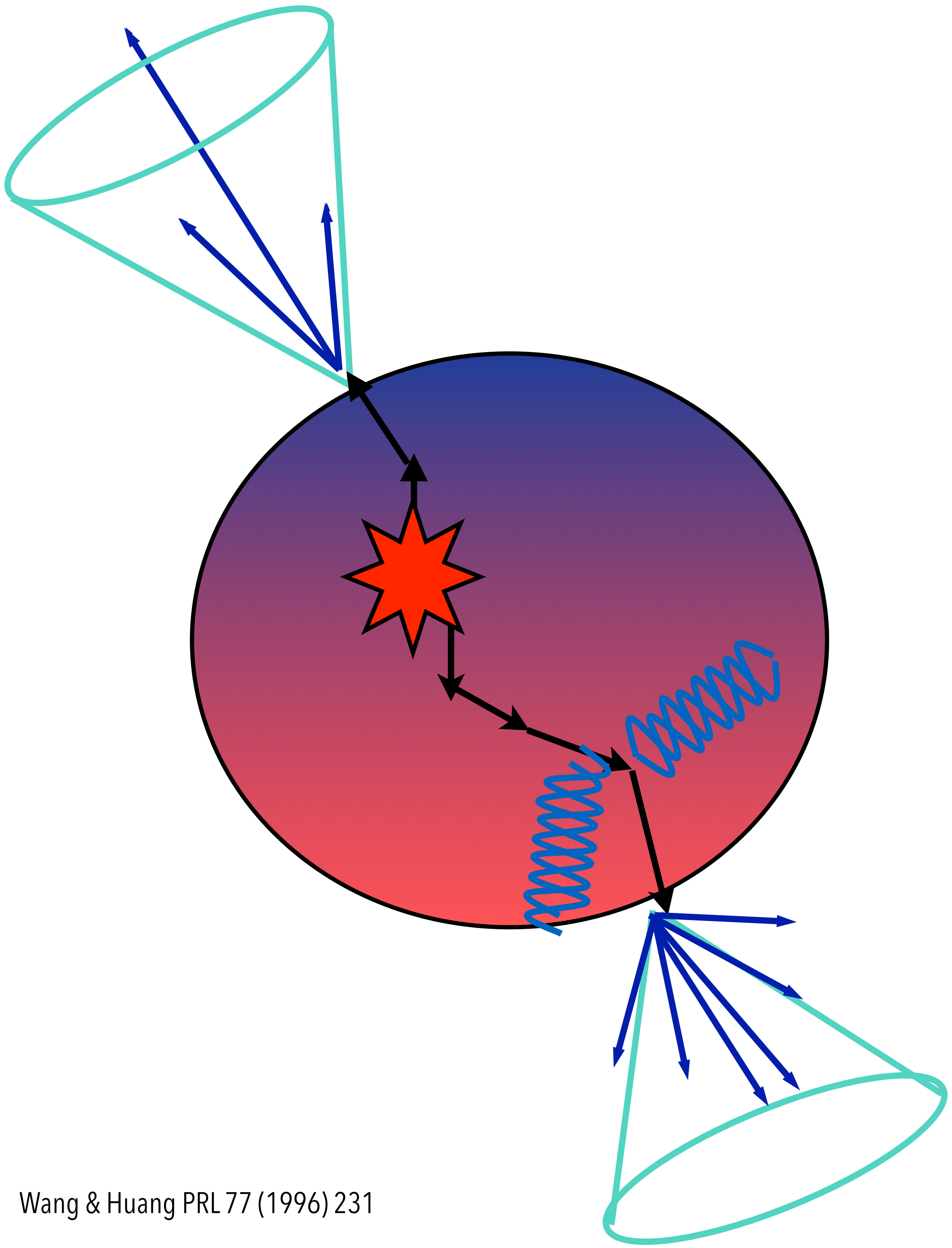

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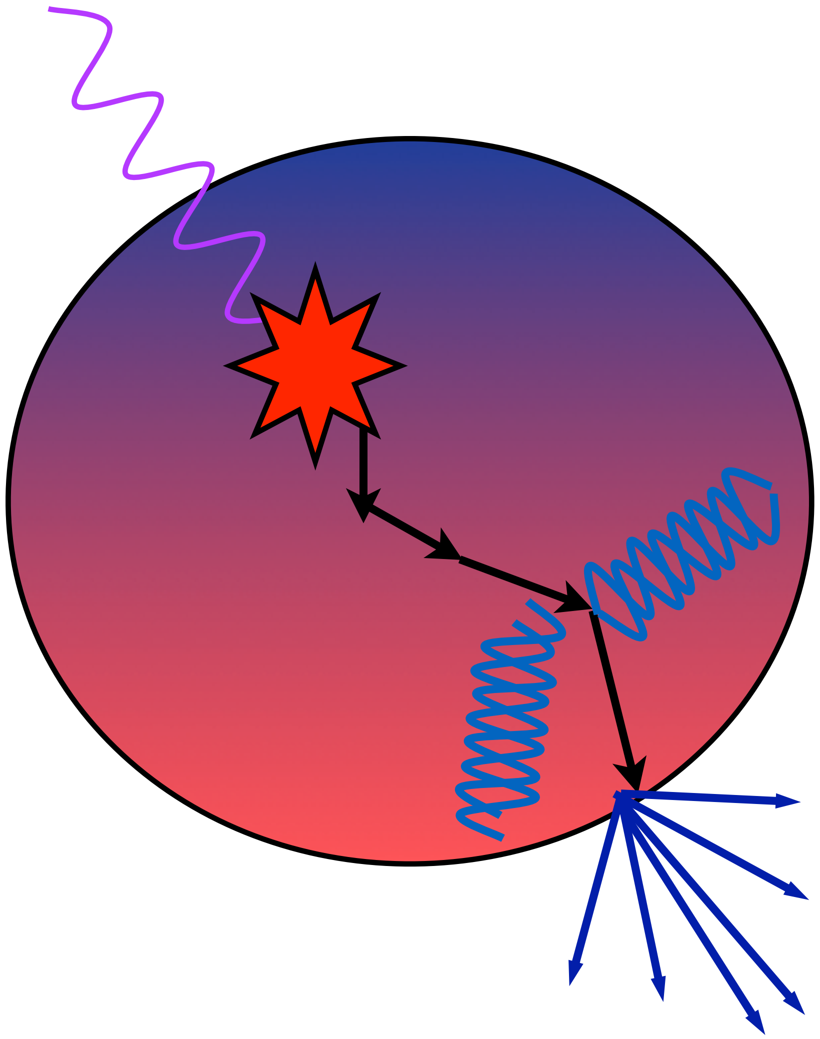

Wang & Huang PRL 77 (1996) 231

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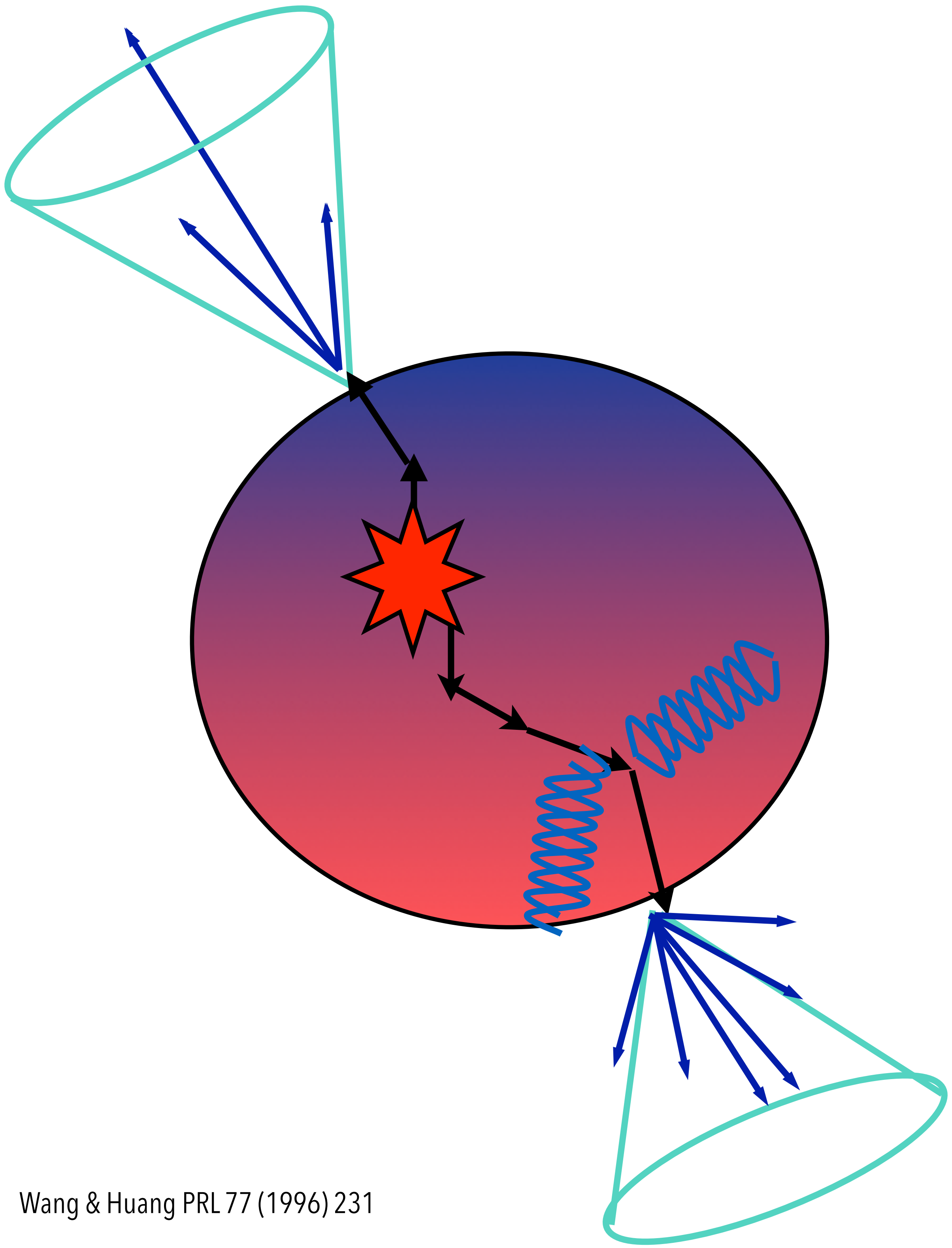
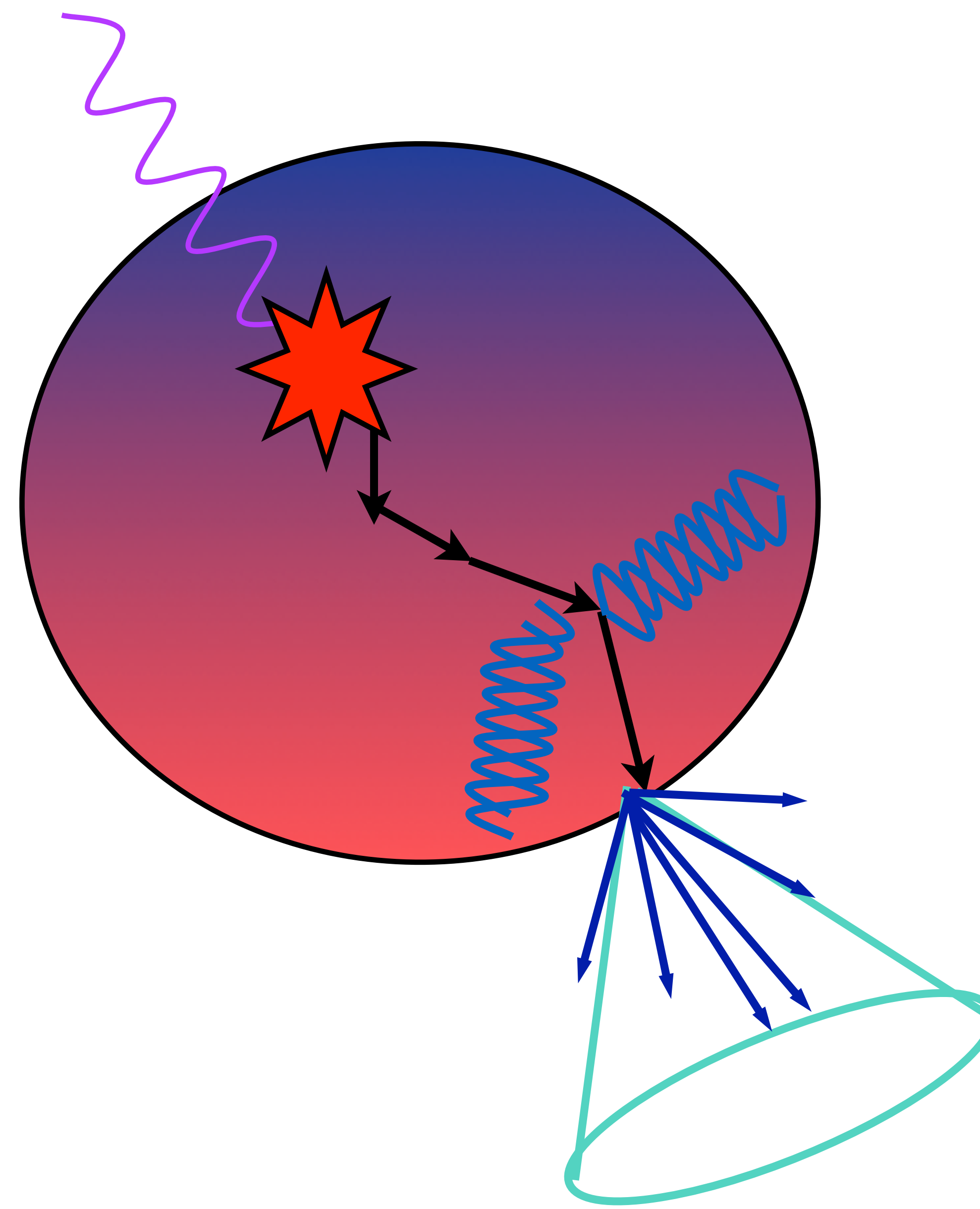
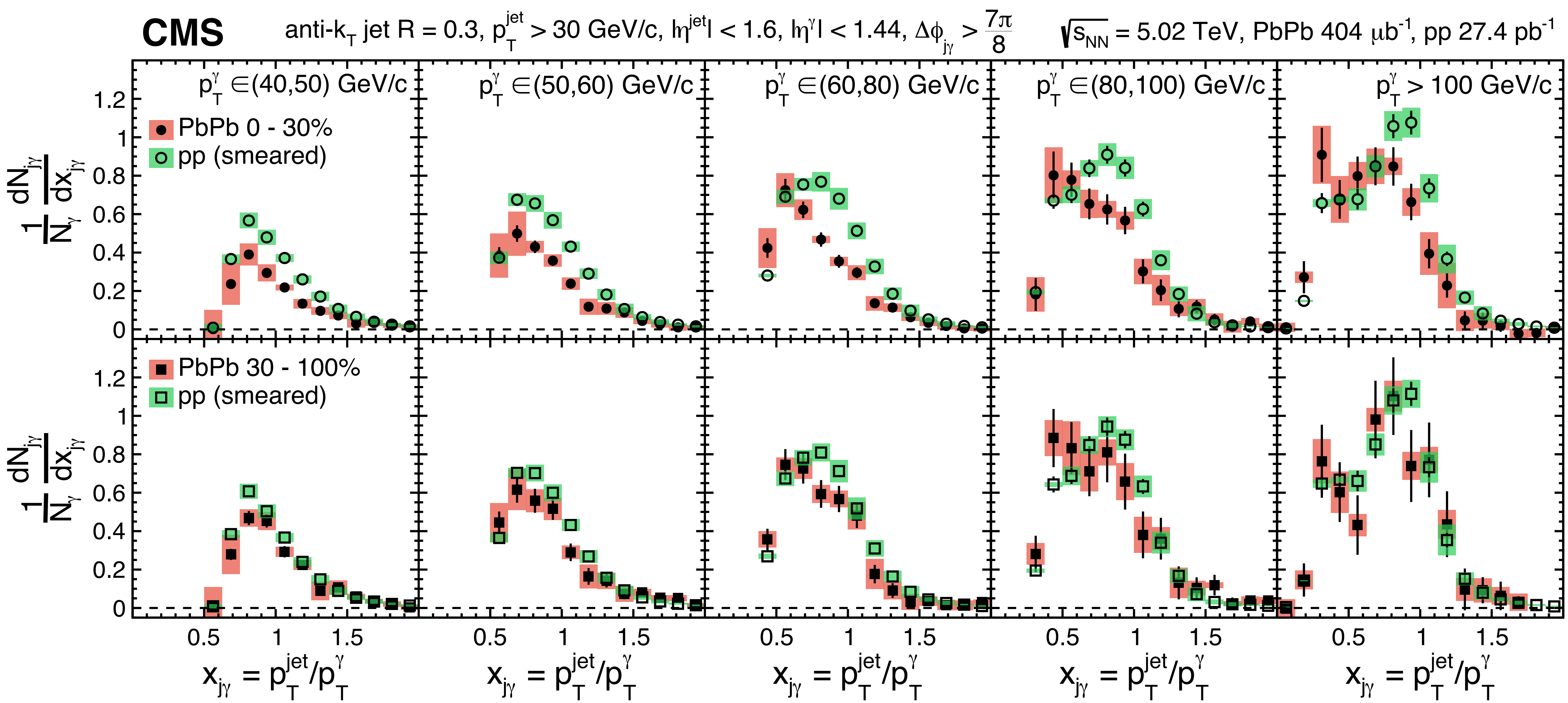




Wang & Huang PRL 77 (1996) 231

photon-jet balance



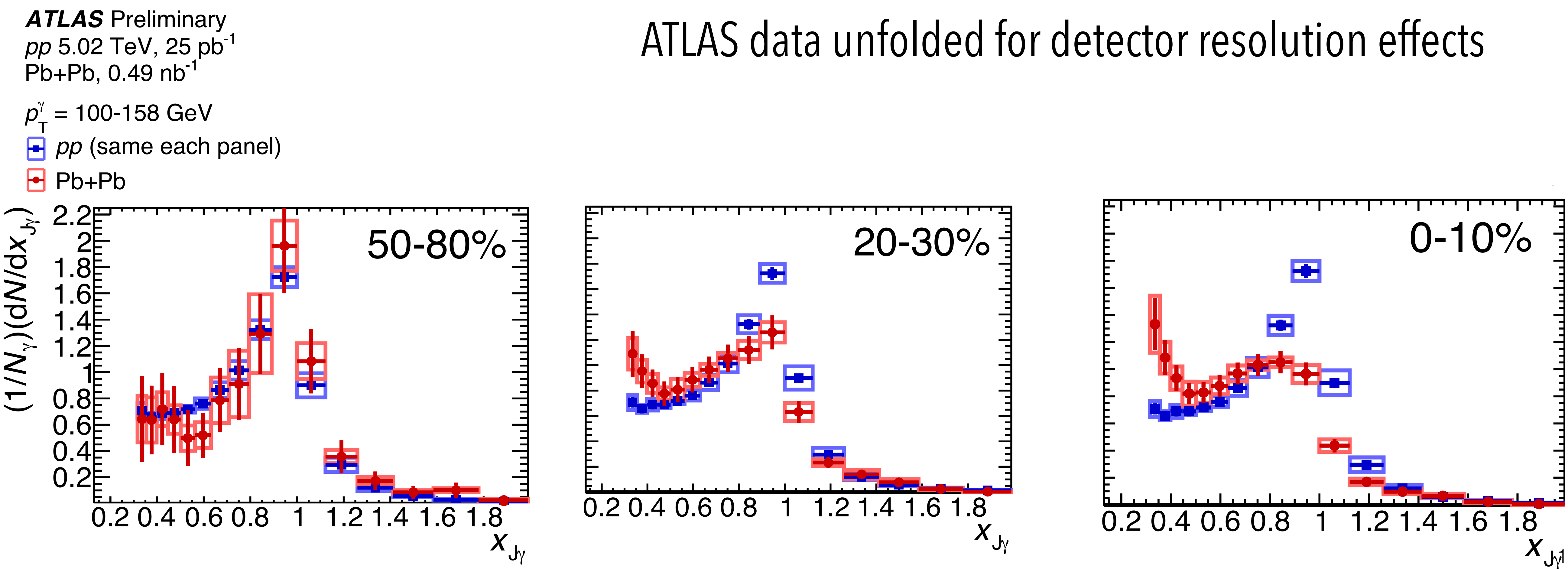
pp: different in each panel because it is smeared by the p_T and centrality dependent additional resolutions effects to match PbPb collisions

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

1711.097328

photon p_T: 100-158 GeV

ATLAS data unfolded for detector resolution effects

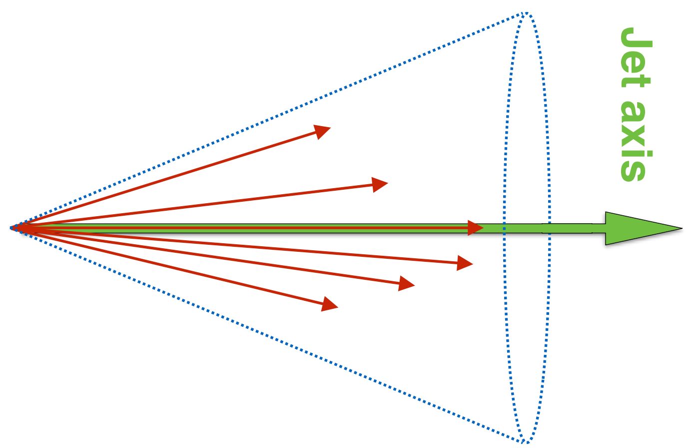


peak for nearly balanced pairs even in PbPb collisions

ATLAS-CONF-2018-009

1711.097328

measurement of fragmentation functions

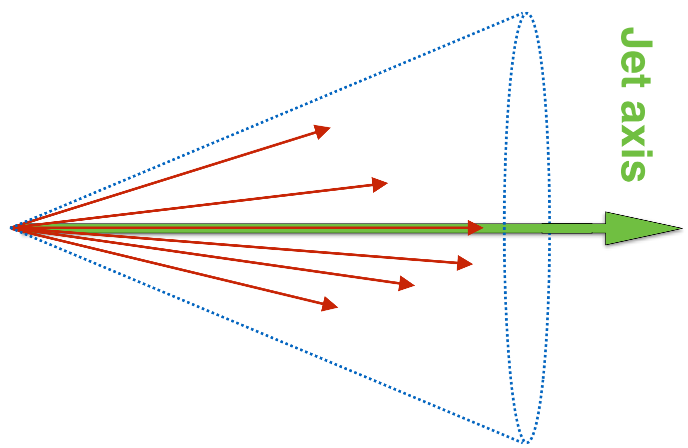


$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{dn_{\mathrm{ch}}}{dz}$$

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

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

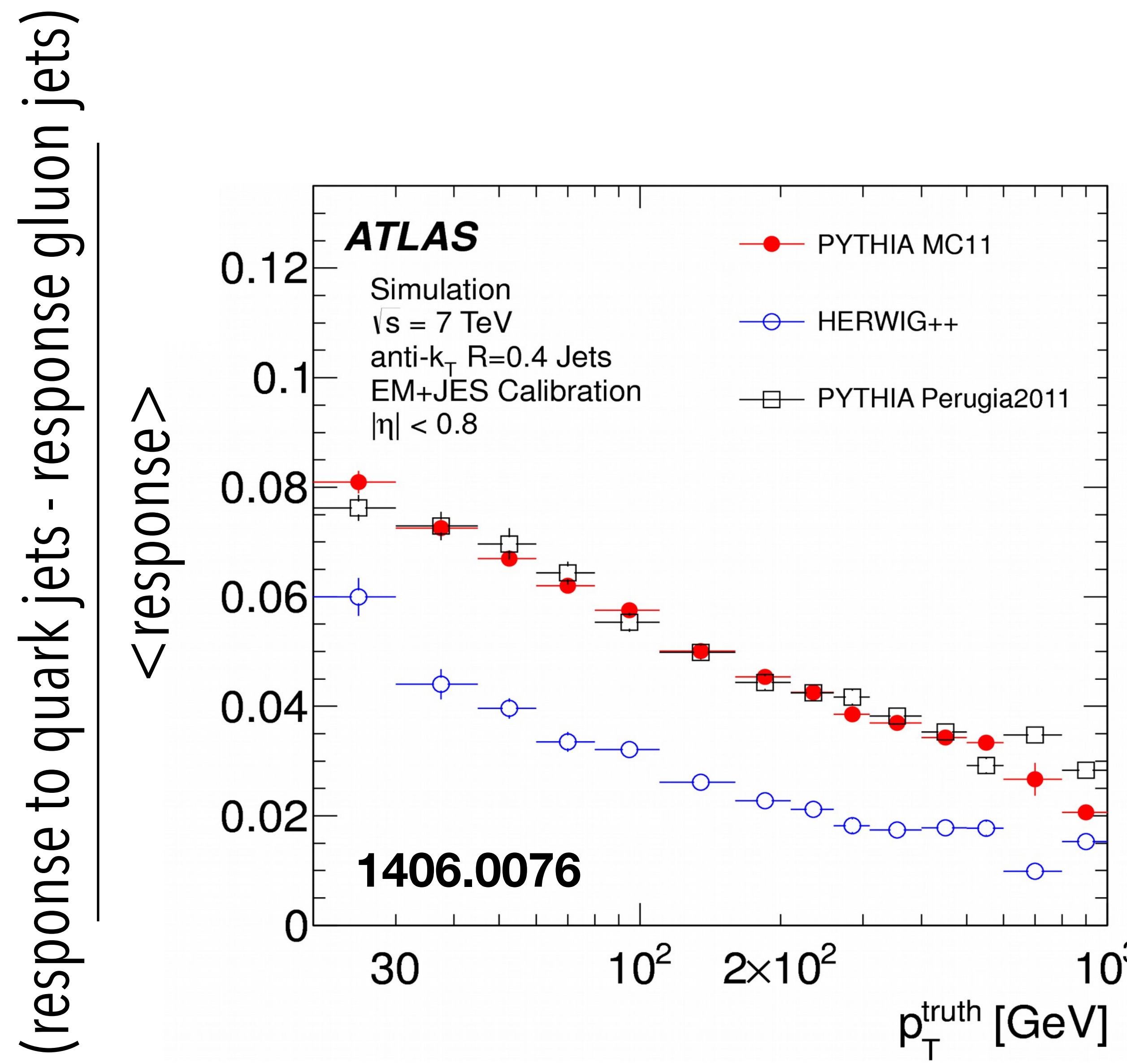
measurement of fragmentation functions



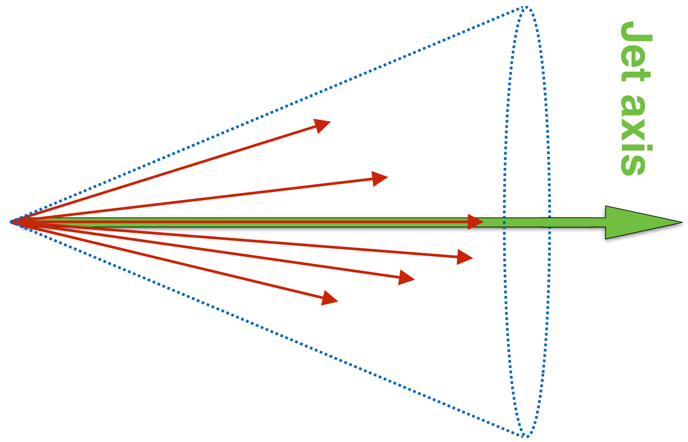
$$D(z) \equiv \frac{1}{N_{\rm jet}} \frac{dn_{\rm ch}}{dz}$$

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

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



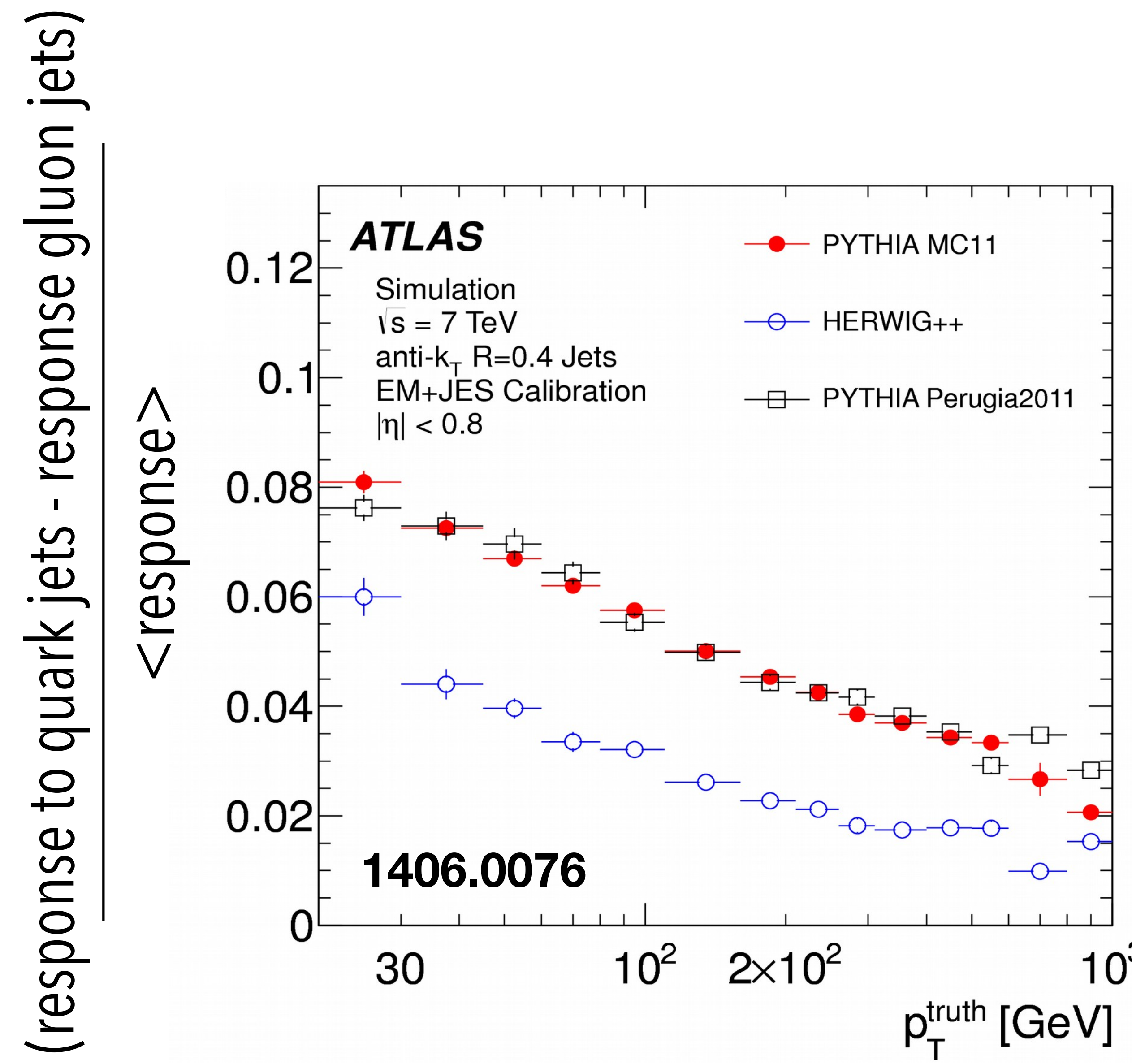
measurement of fragmentation functions



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

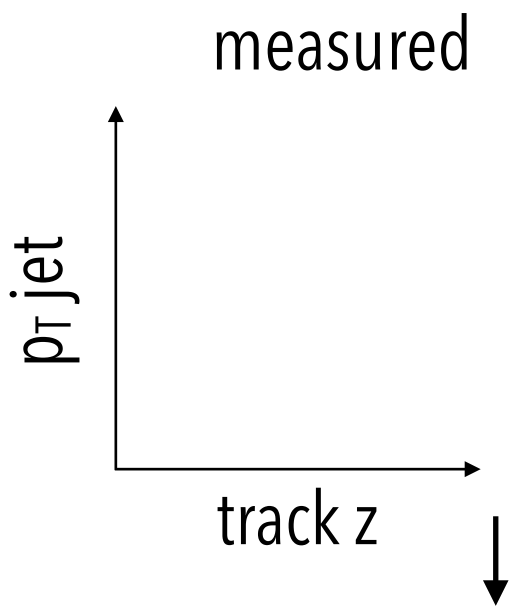
$$z \equiv p_{\mathrm{T}} \cos \Delta R \,/\, p_{\mathrm{T}}^{\mathrm{jet}}$$

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

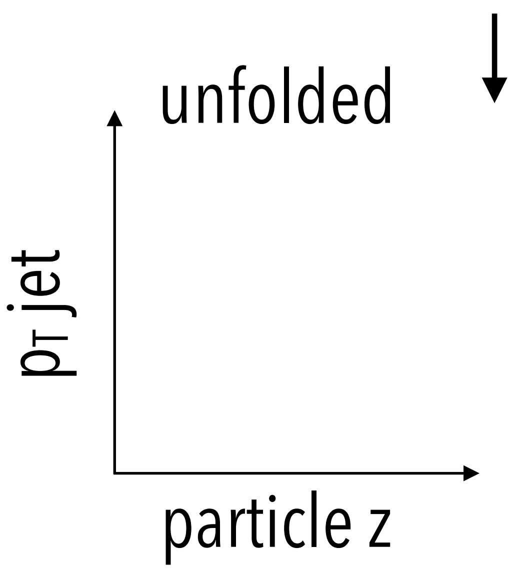


jet energy measurement is correlated with how the jet fragments!

2 -dimensional unfolding

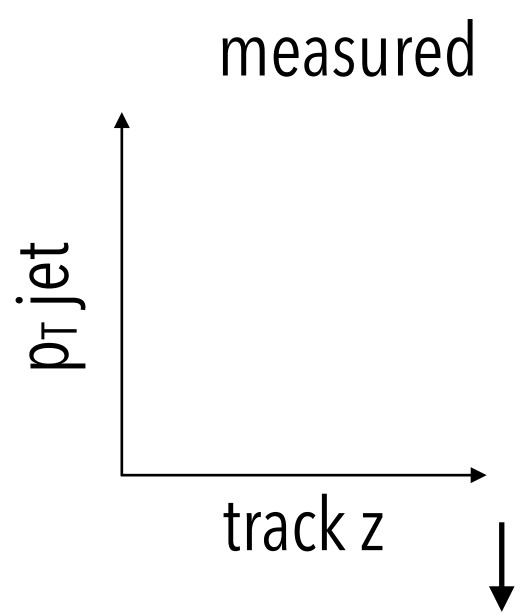


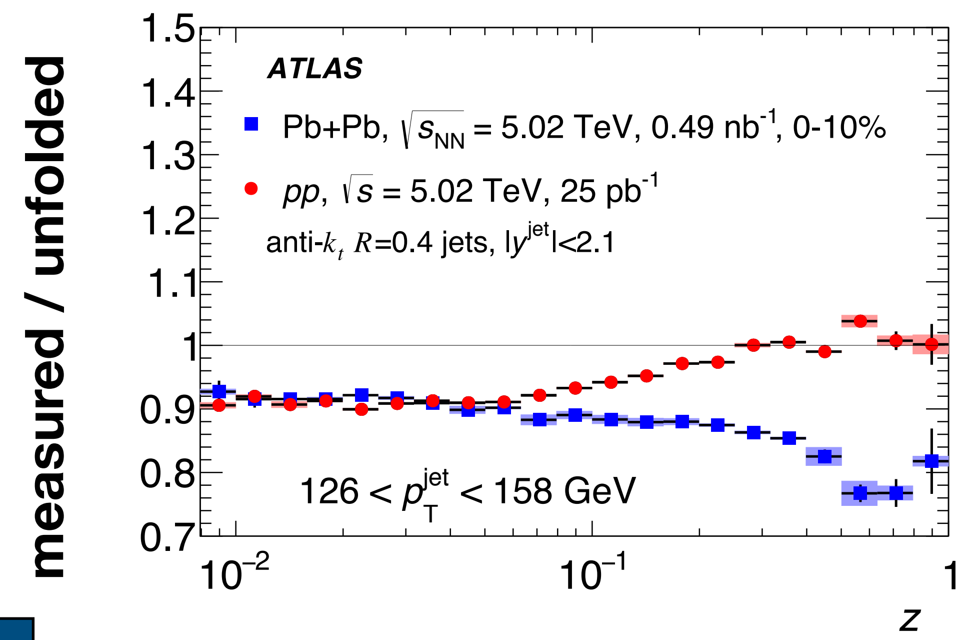
response matrix in $p_{T,meas}$, $p_{T,true}$, z_{meas}, z_{true}



PRC 98 024908 (2018)

2 -dimensional unfolding

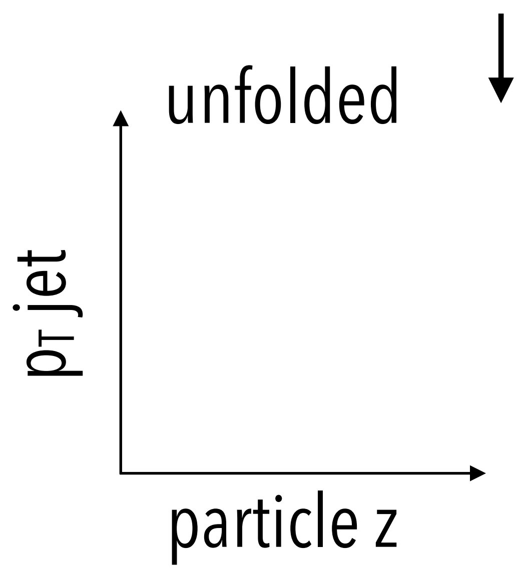


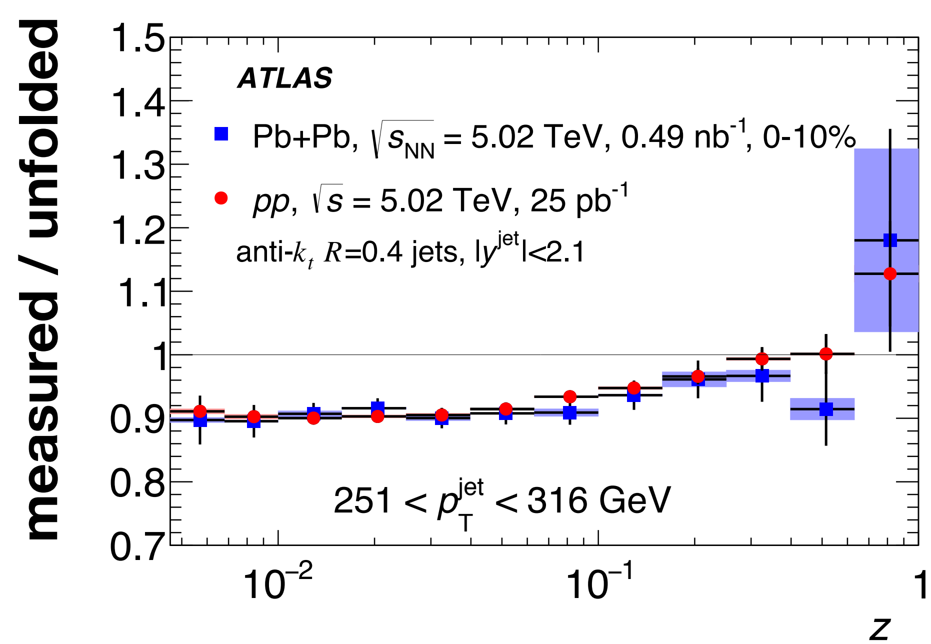


p_{Tjet}: 126 - 158 GeV

large JER centrality dependence to JER due to UE fluctuations

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



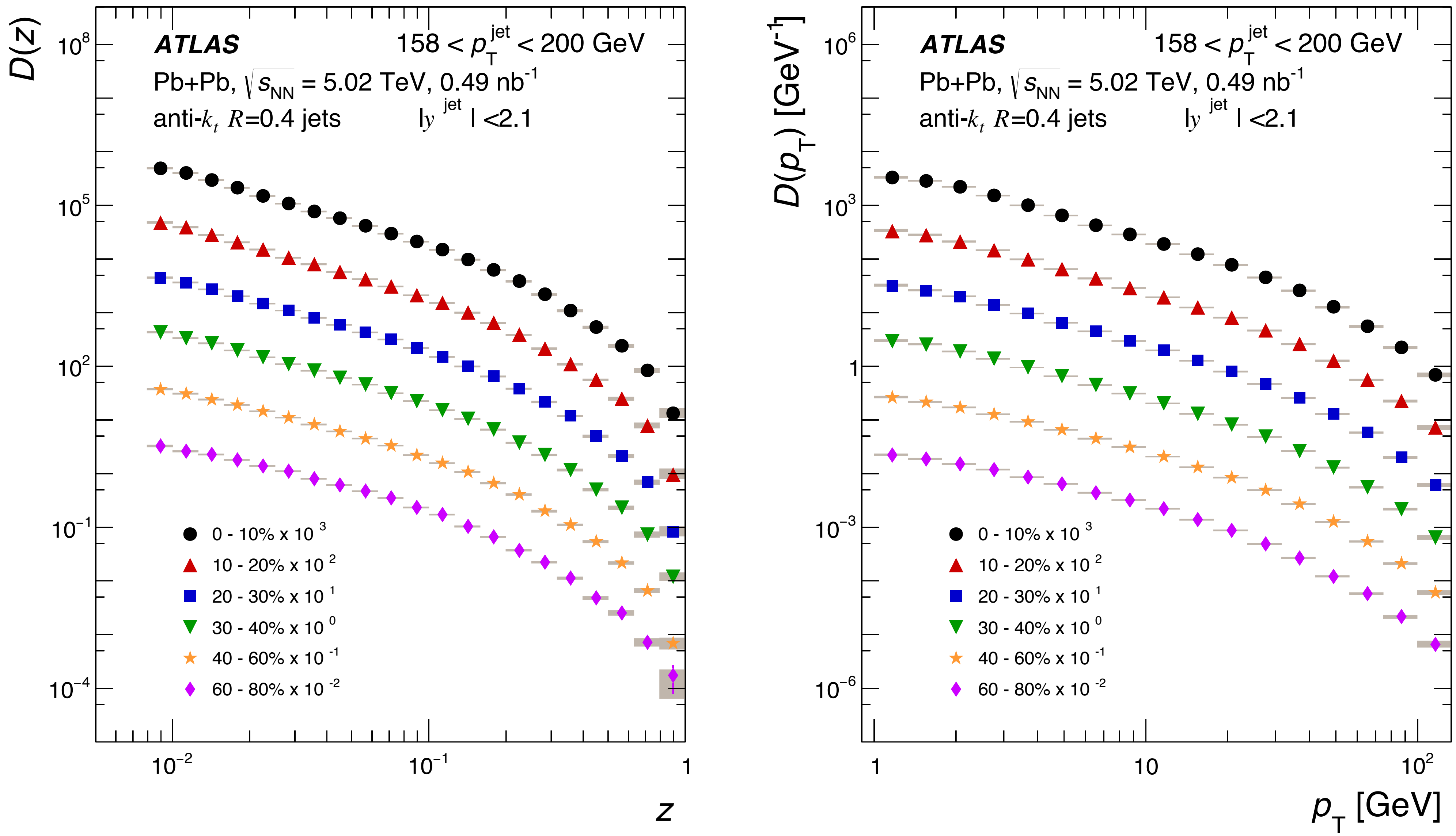


p_{Tjet}: 251-316 GeV

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

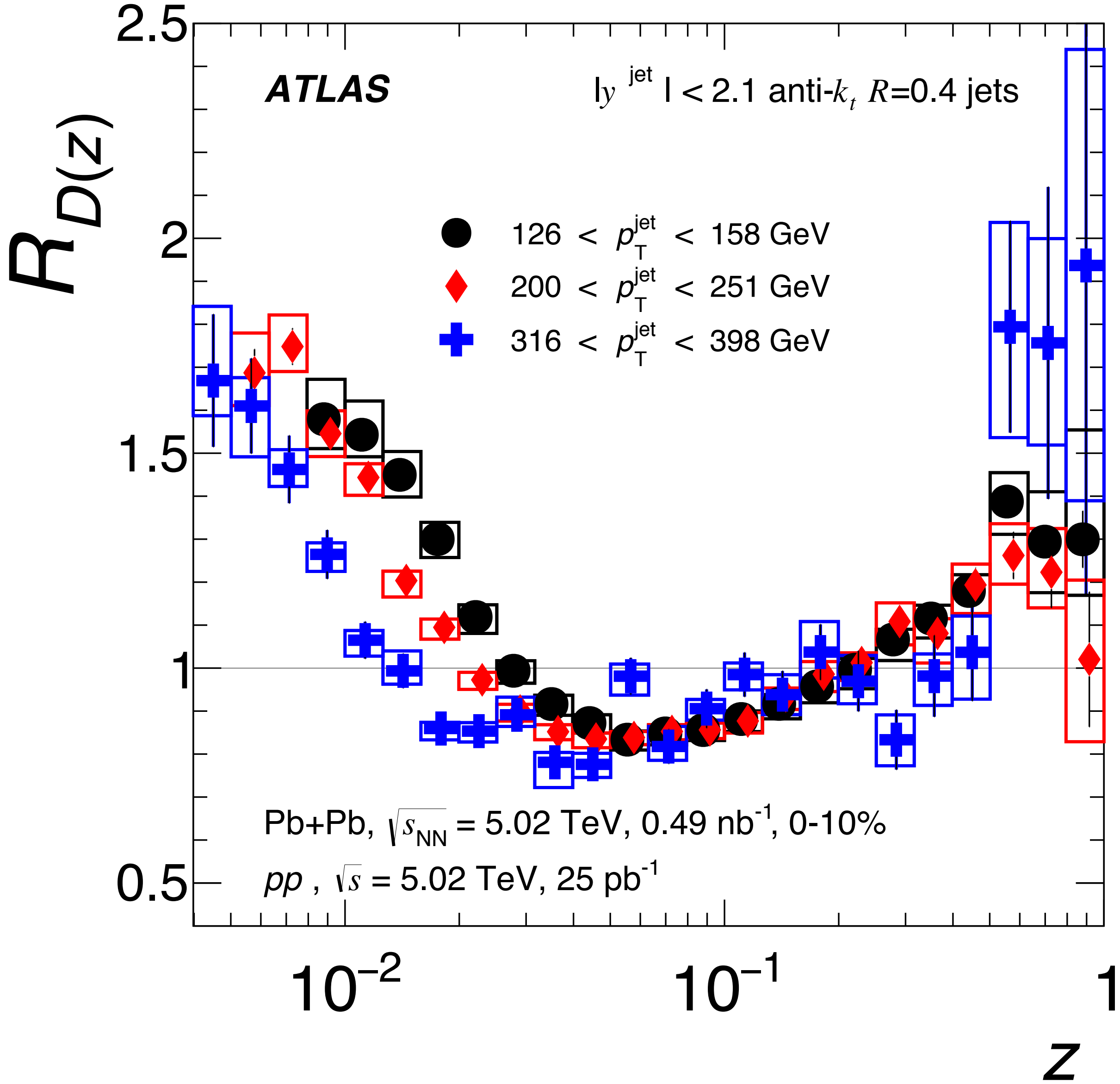
$$R_{D(z)} \equiv \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{pp}},$$

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

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

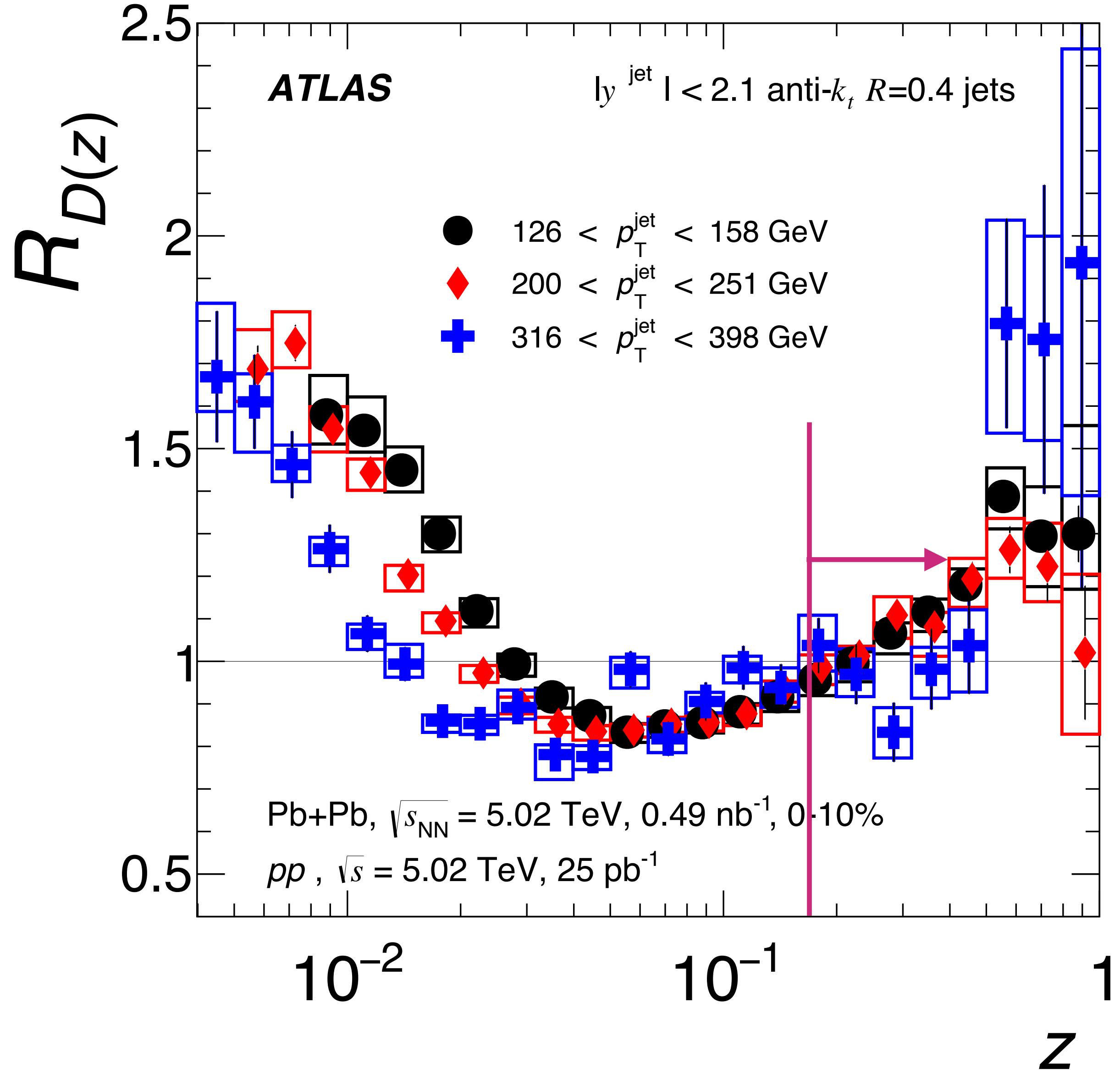
PRC 98 024908 (2018)

ratios of fragmentation functions in PbPb / pp



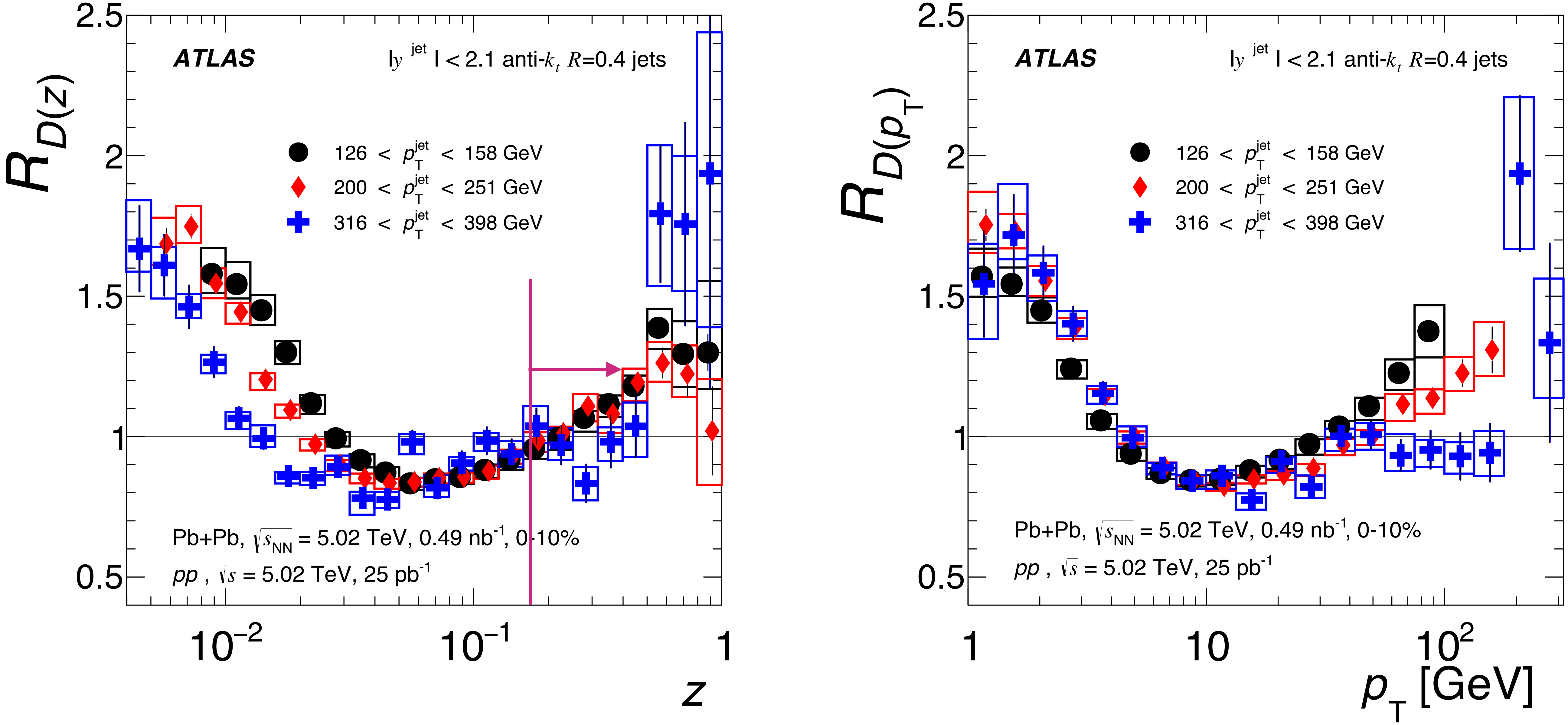
PRC 98 024908 (2018)

ratios of fragmentation functions in PbPb / pp



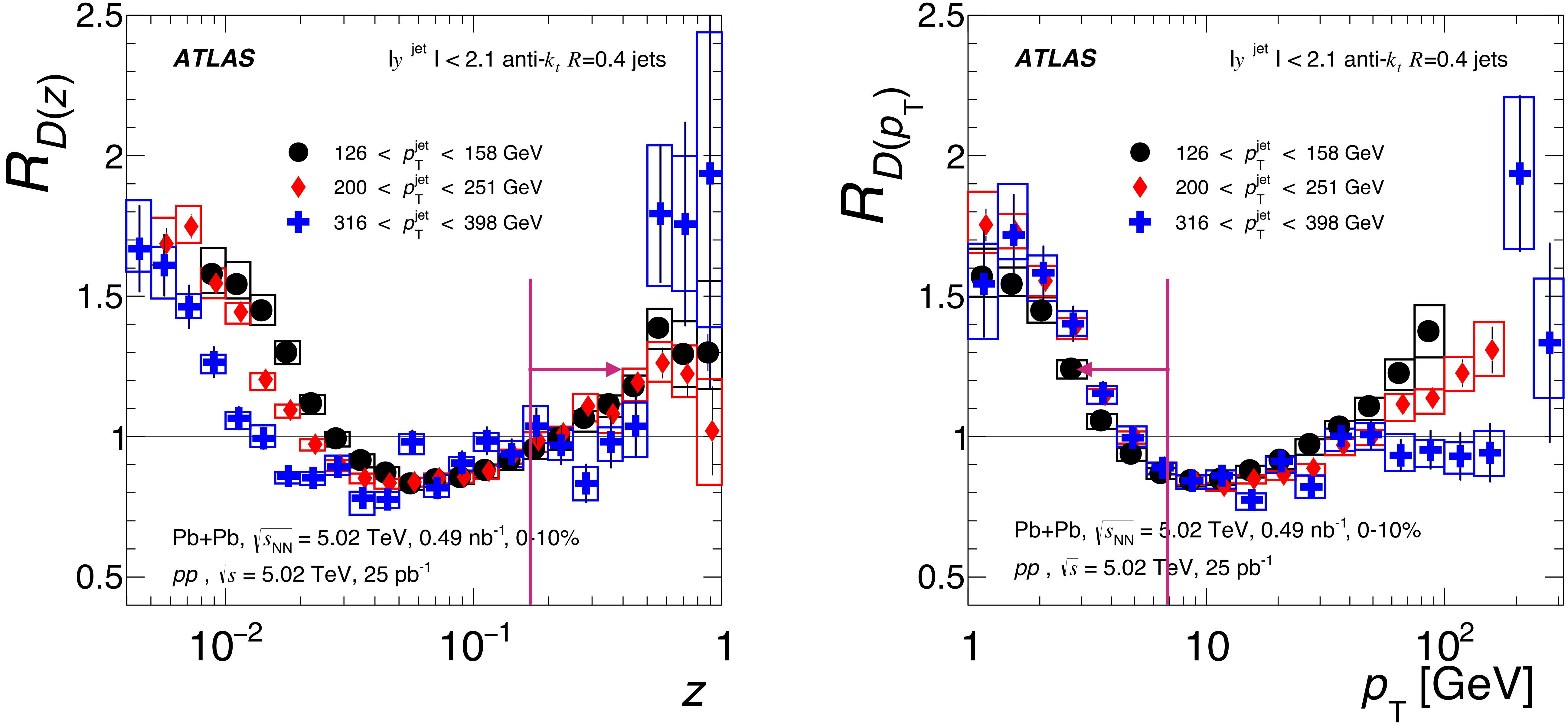
PRC 98 024908 (2018)

ratios of fragmentation functions in PbPb / pp



PRC 98 024908 (2018)

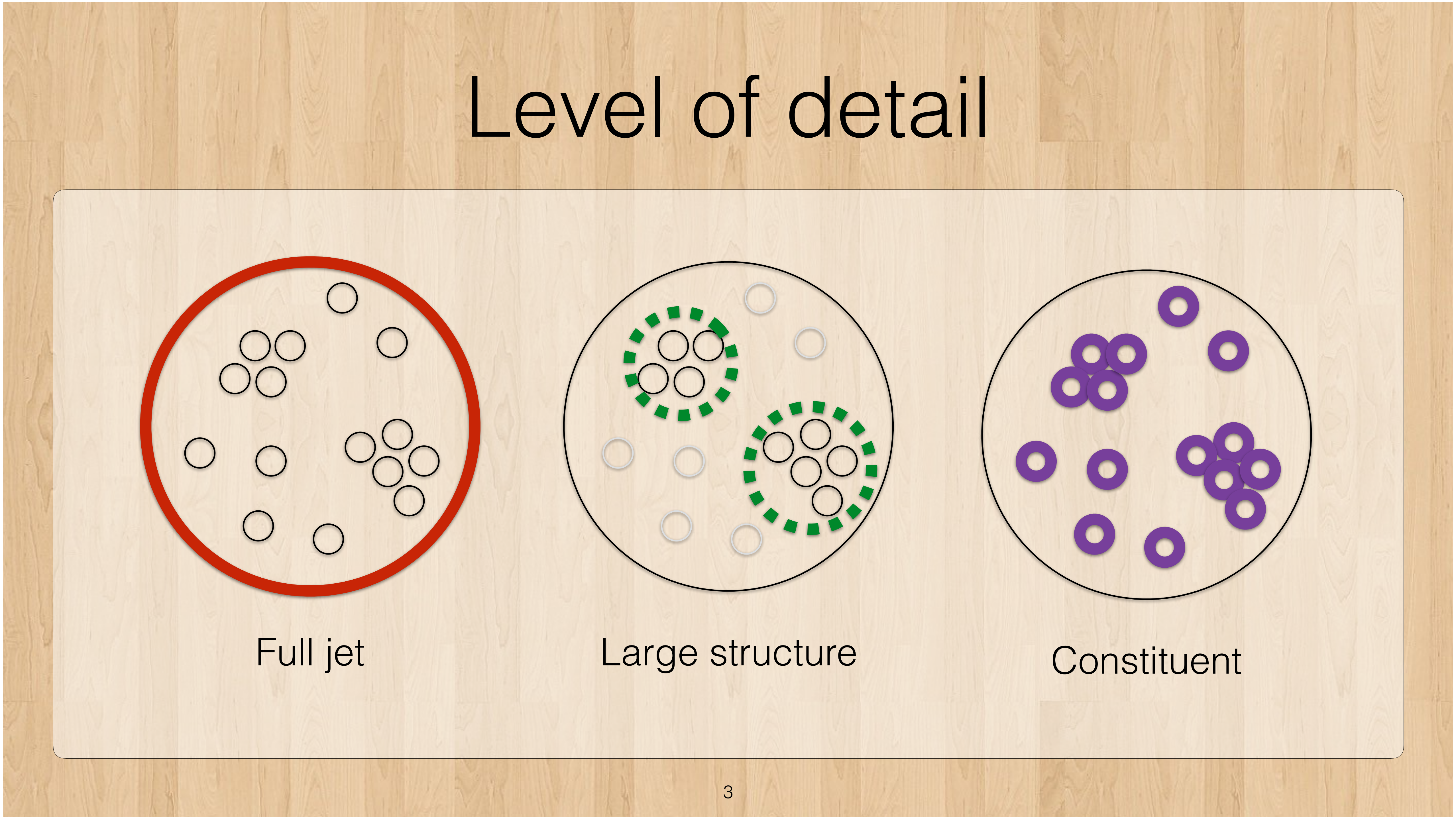
ratios of fragmentation functions in PbPb / pp



PRC 98 024908 (2018)

how do we look at jets?

illustration, Yi Chen



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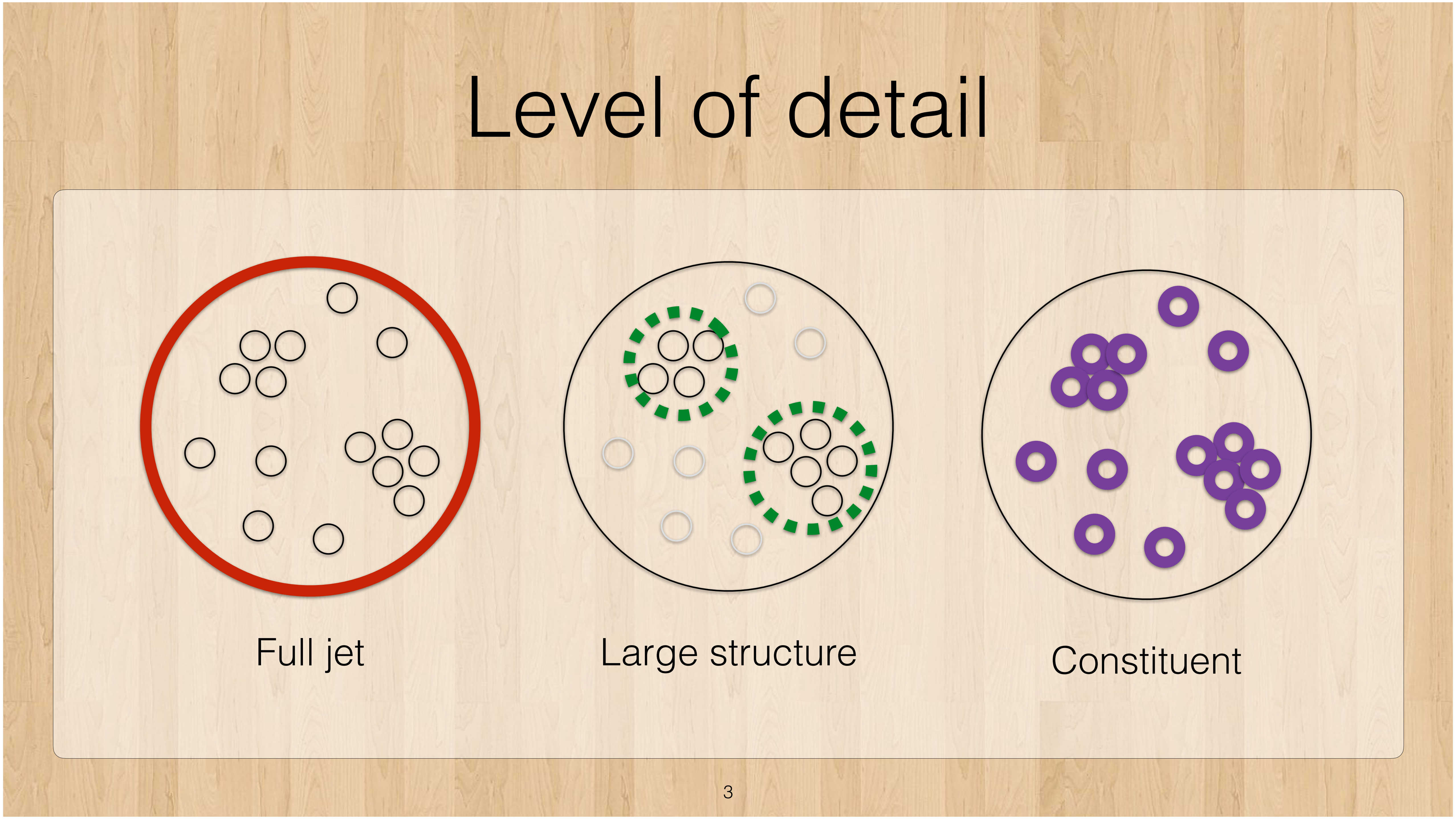
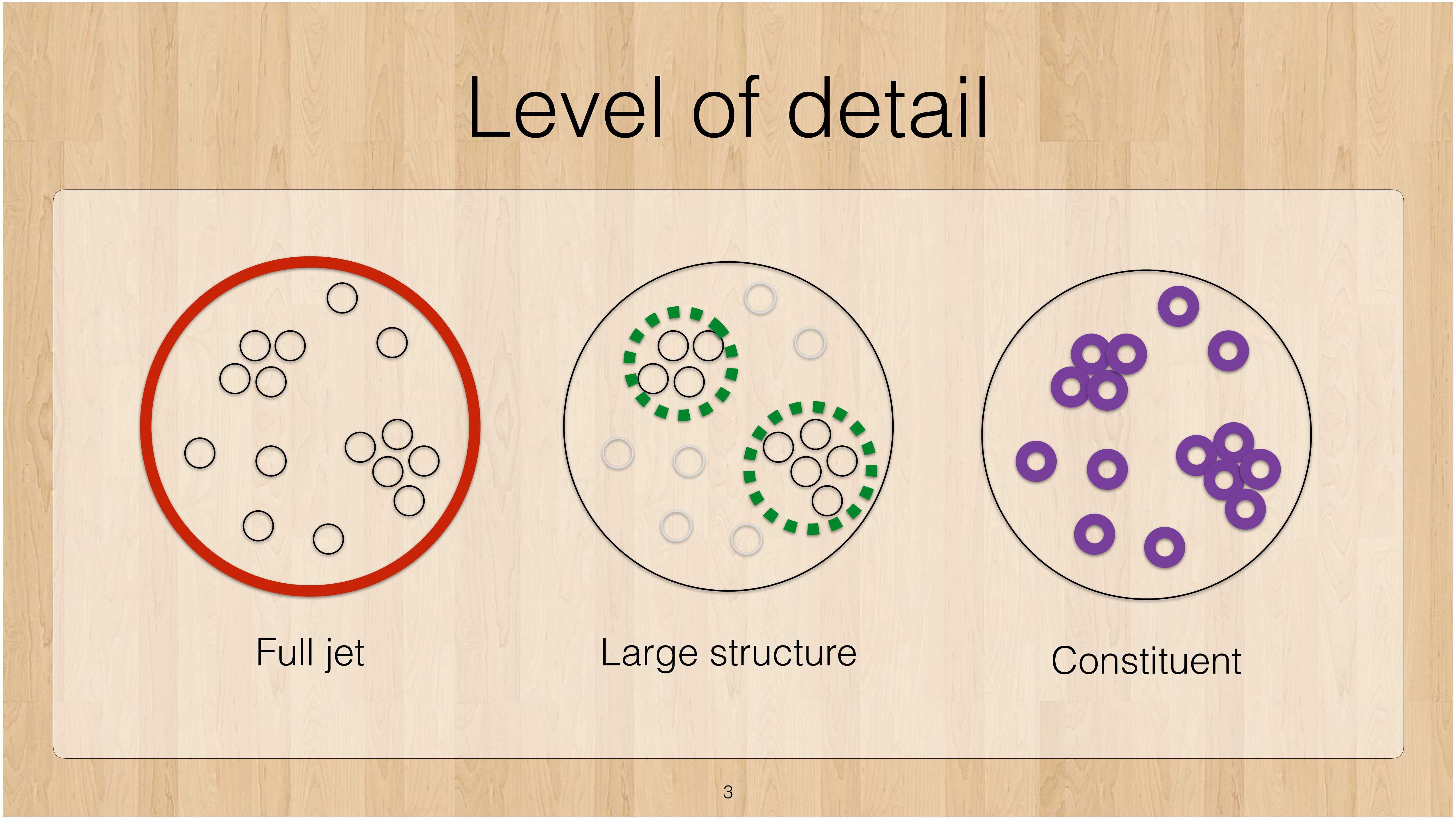


RAA

how do we look at jets?

illustration, Yi Chen

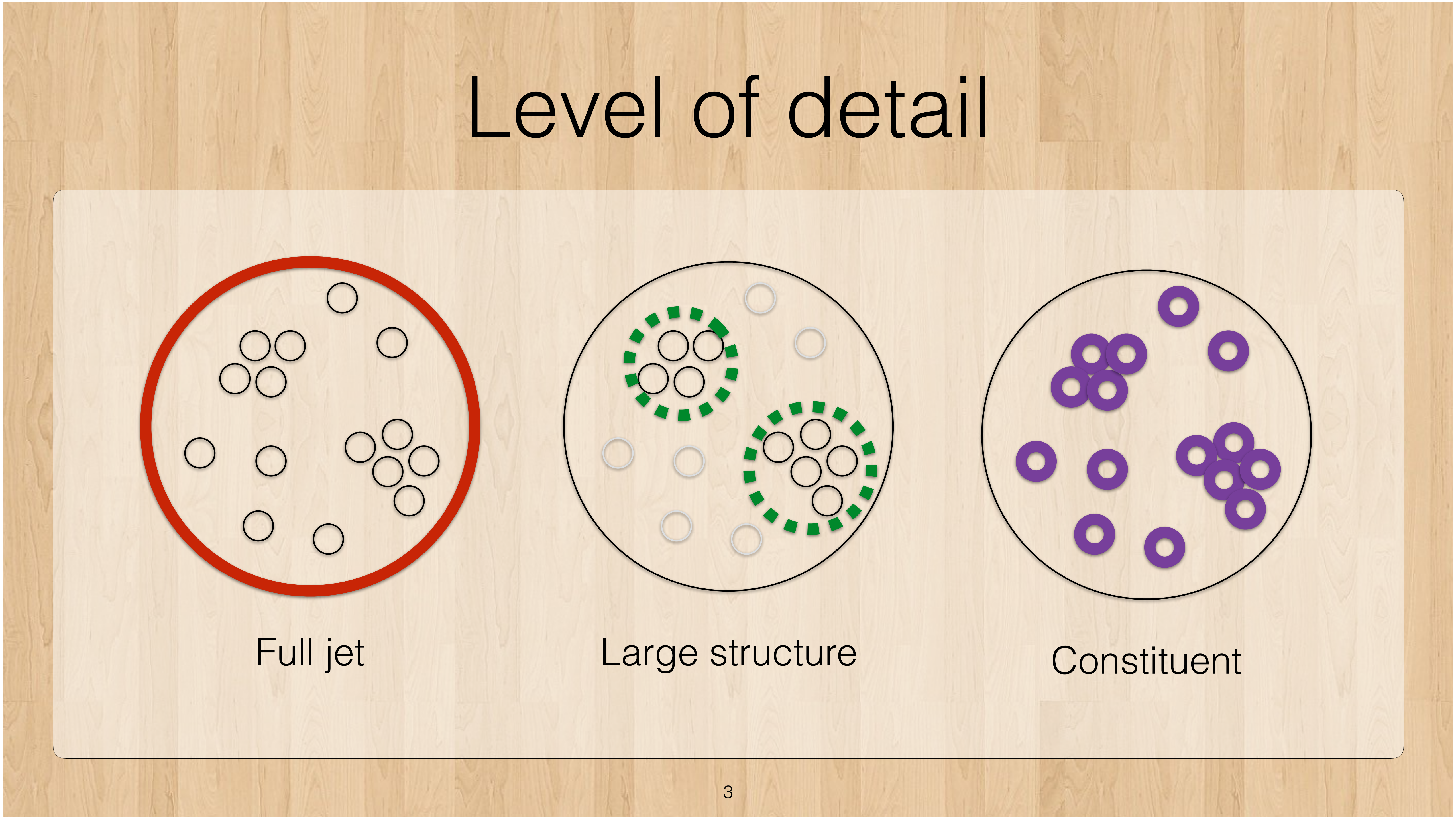


R_{AA}

fragmentation functions

how do we look at jets?

illustration, Yi Chen



R_{AA} jet mass fragmentation functions

jet mass

Physics Letters B 725 (2013) 357–360

Contents lists available at SciVerse ScienceDirect

Physics Letters B

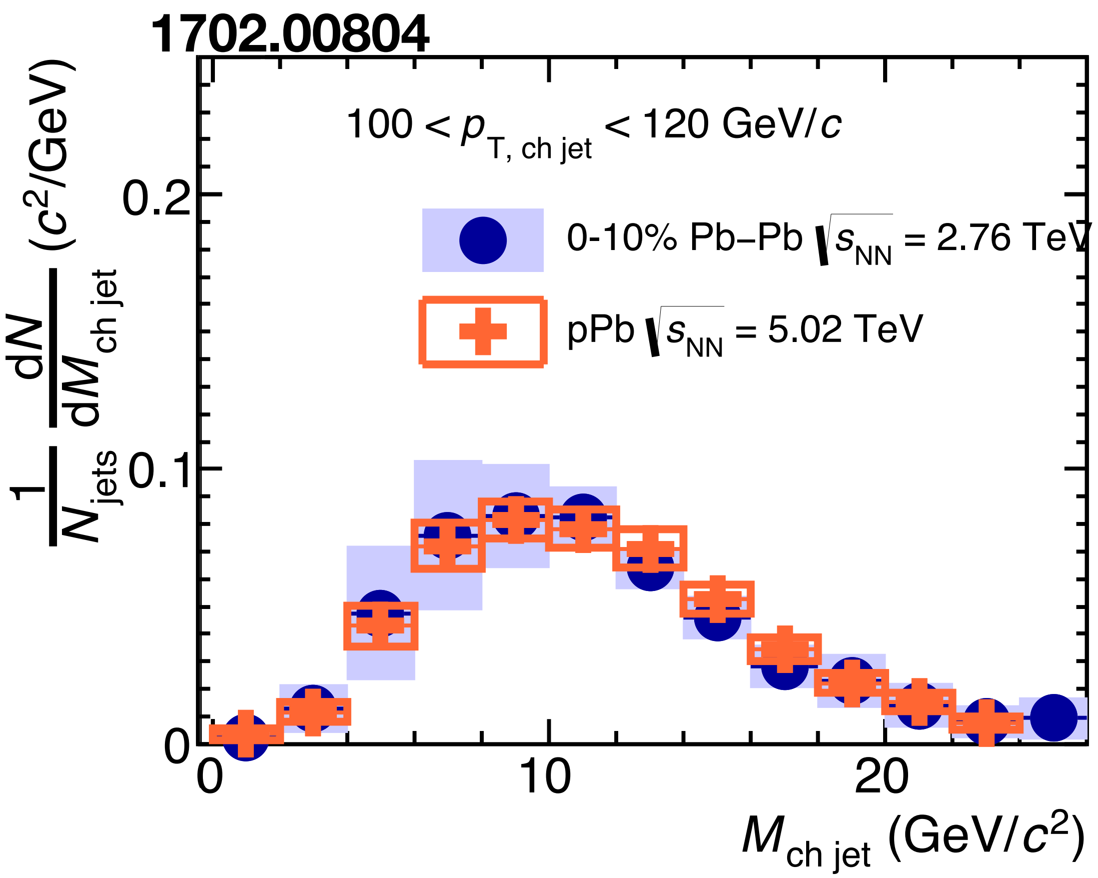
www.elsevier.com/locate/physletb

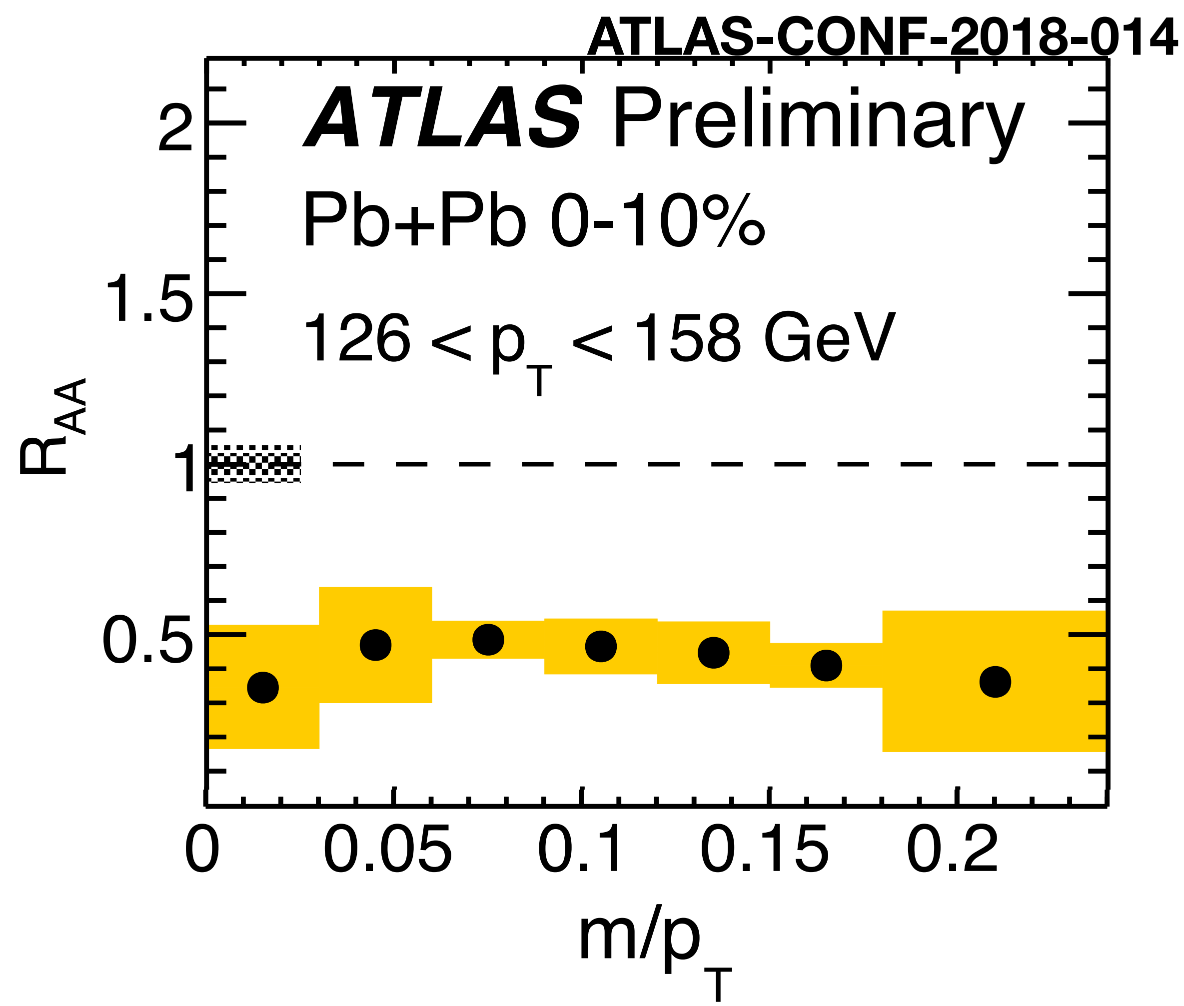
New picture of jet quenching dictated by color coherence

Jorge Casalderrey-Solana [a], Yacine Mehtar-Tani [b], Carlos A. Salgado [c], Konrad Tywoniuk [d,*]

- m/p_T is related to the angular width of the jet
- question:
  - does the QGP see a jet as a single or multiple sources?
    - if different parts of the jet lose energy incoherently, wide jets could have a larger quenching effect
  - do particles from gluon radiation make the jet broader
  - how does jet grooming in HI collisions affect the physics?
- no calculation of jet mass currently available in PbPb collisions

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





no significant mass modification observed in PbPb

jet grooming with soft drop

soft drop: recluster the jet with Cambridge-Aachen then go through the constituents and exclude the softer leg unless

1805.05145

$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

Larkoski et al. 1402.2657

exclude jet if final 2 subjets are at ΔR_{12} < 0.1 (30%)

calculate mass from these two subjets

for more on substructure in heavy ion collisions see talks at BOOST 2018

jet grooming with soft drop

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Larkoski et al. 1402.2657

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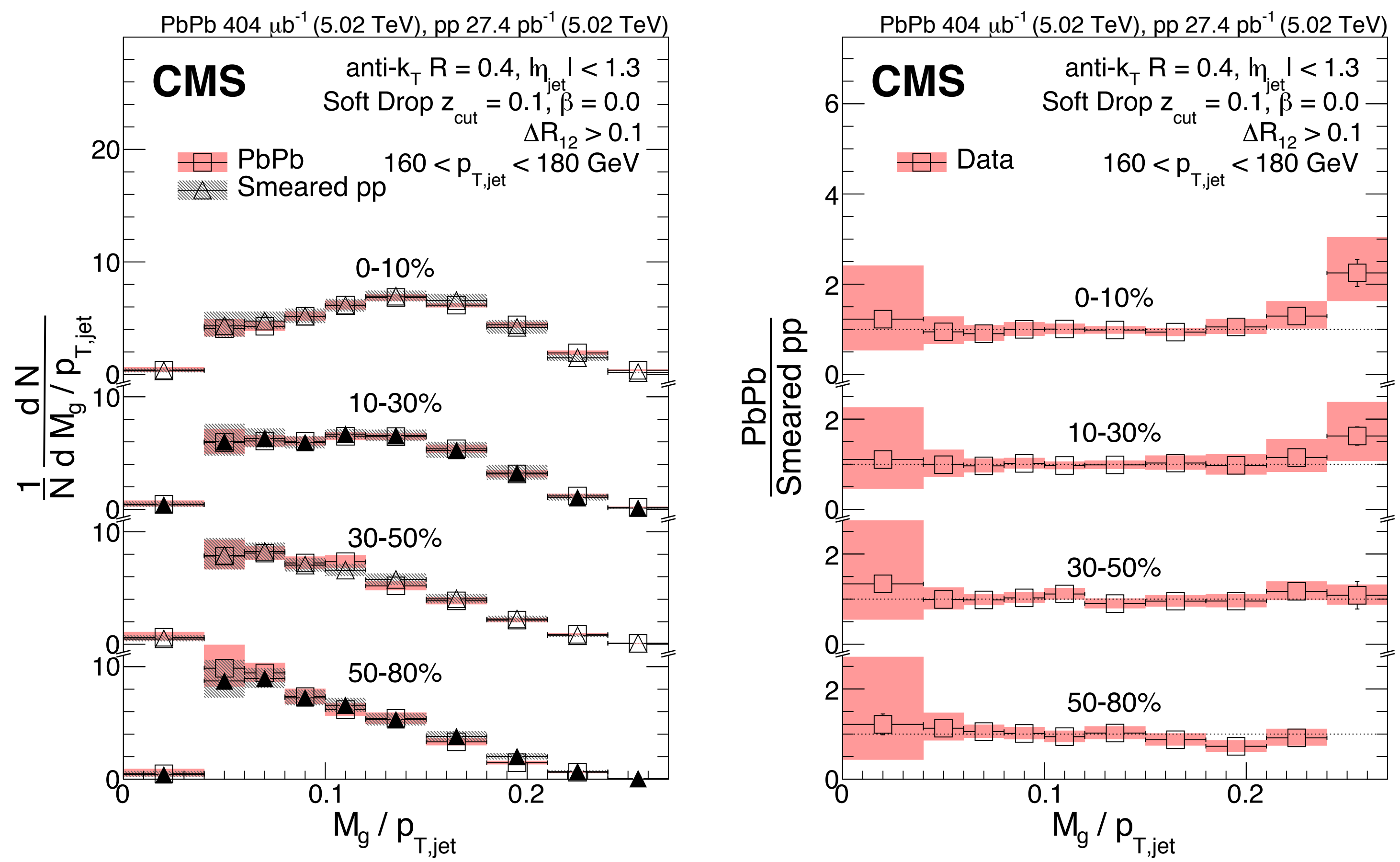
1805.05145



for more on substructure in heavy ion collisions see talks at BOOST 2018

jet quenching in pA collisions?

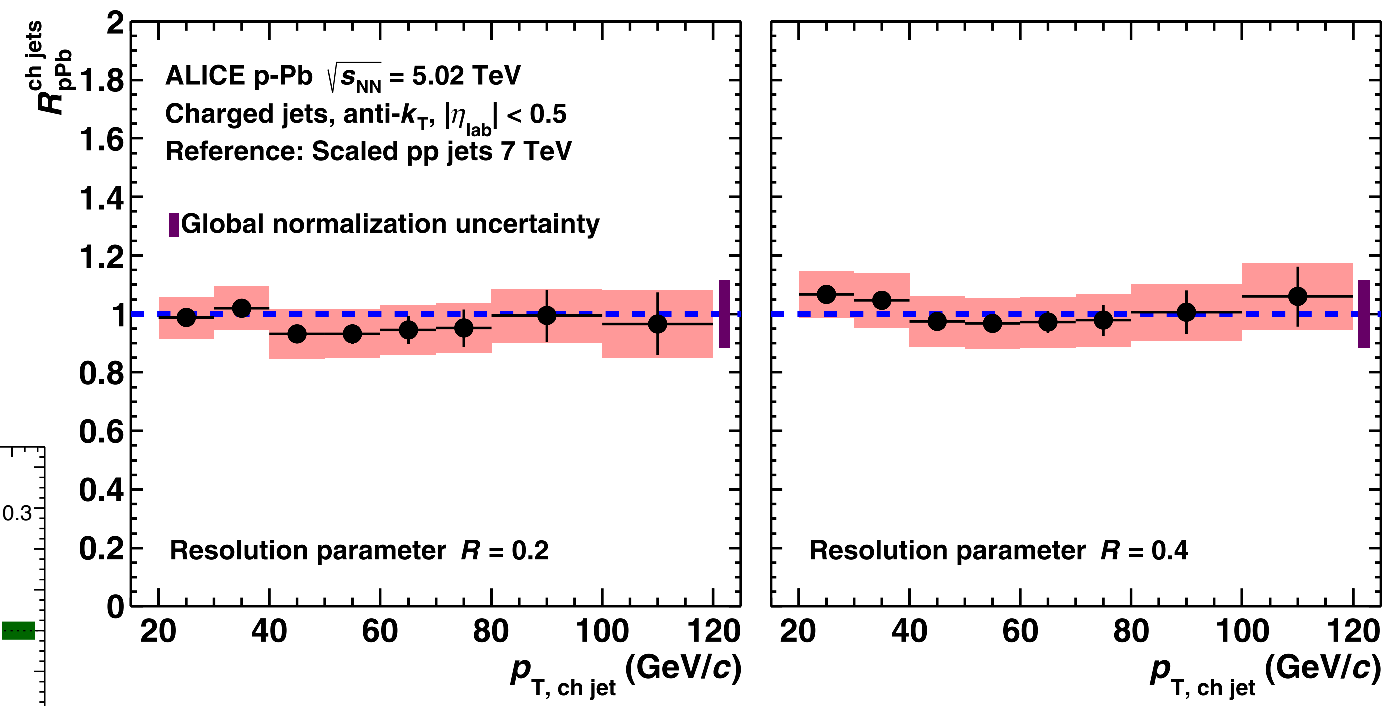
- yesterday: discussed whether a small QGP was being created in pA collisions
  - if that is the case, should jet quenching be observable in pA collisions?
- it has not been observed, either because it's not there or because we don't have sensitive enough measurements to see it
  - I expect more on this subject both experimentally and theoretically in the couple years, especially given the large 8 TeV dataset from 2016 in pPb collisions

D. Perepelitsa Quark Matter 2017
Anne Sickles Initial Stages 2017
Mangano & Nachman 1708.08369, …

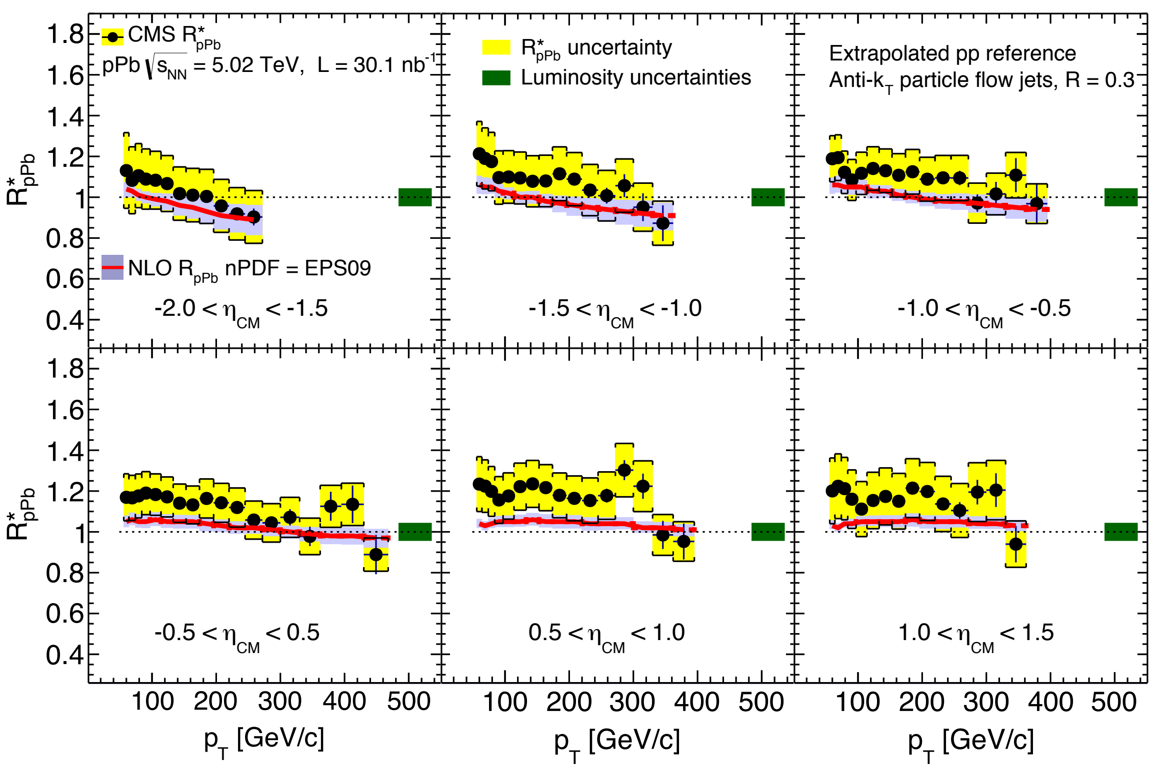
jet production in pPb collisions

ALICE PLB 749 68

can calculate R_{AA}



CMS EPJC 76 372

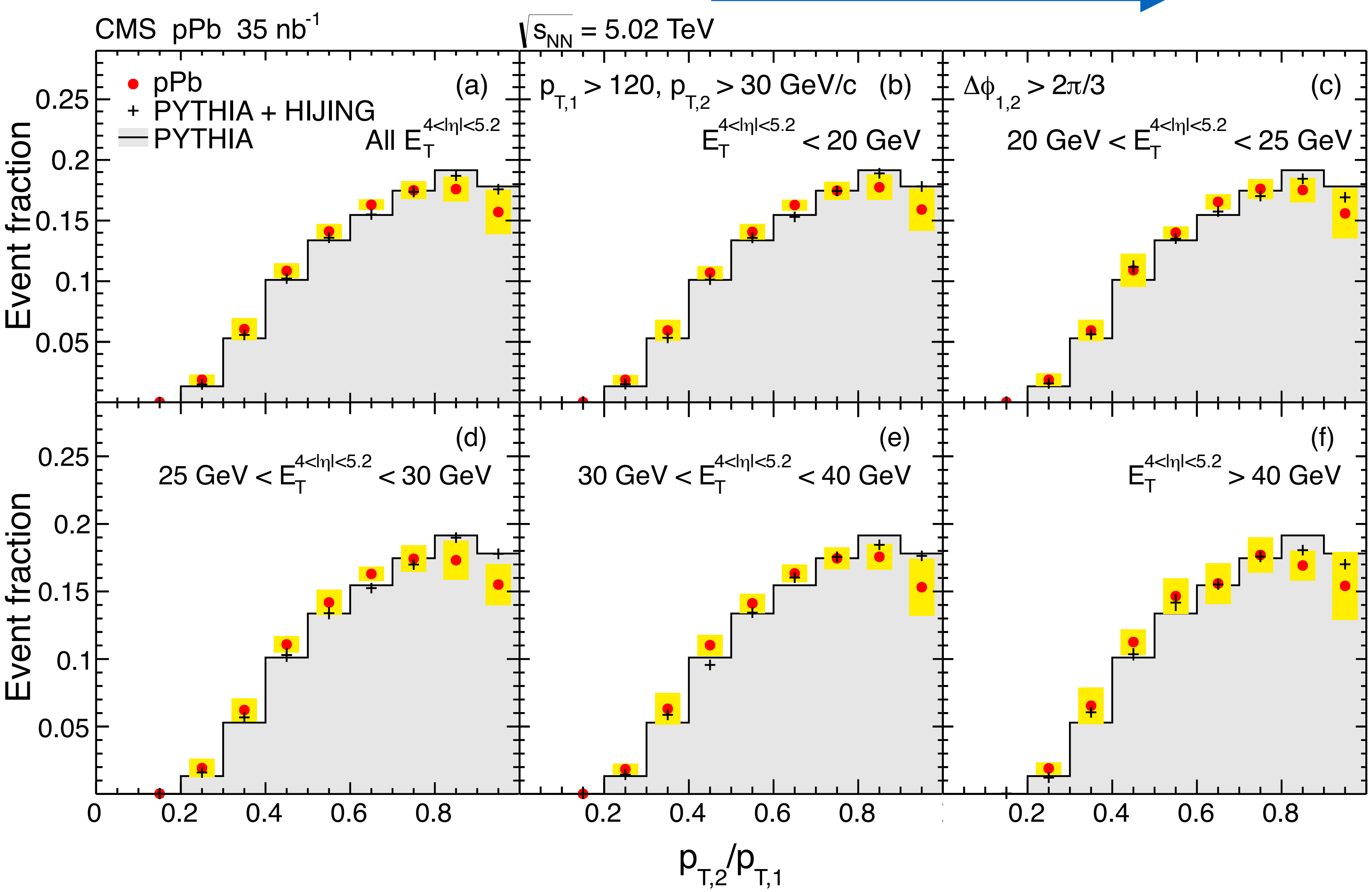


find that R_{AA} is consistent with unity, no jet quenching observed, but uncertainties might mask any jet quenching effect

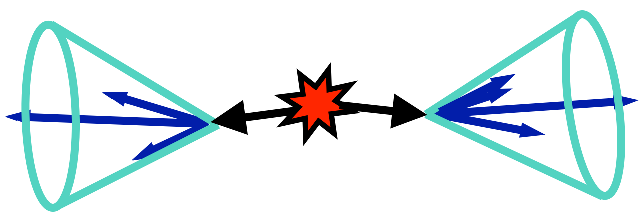
D. Perepelitsa Quark Matter 2017

Mangano & Nachman 1708.08369, …

dijet p_T balance in pPb

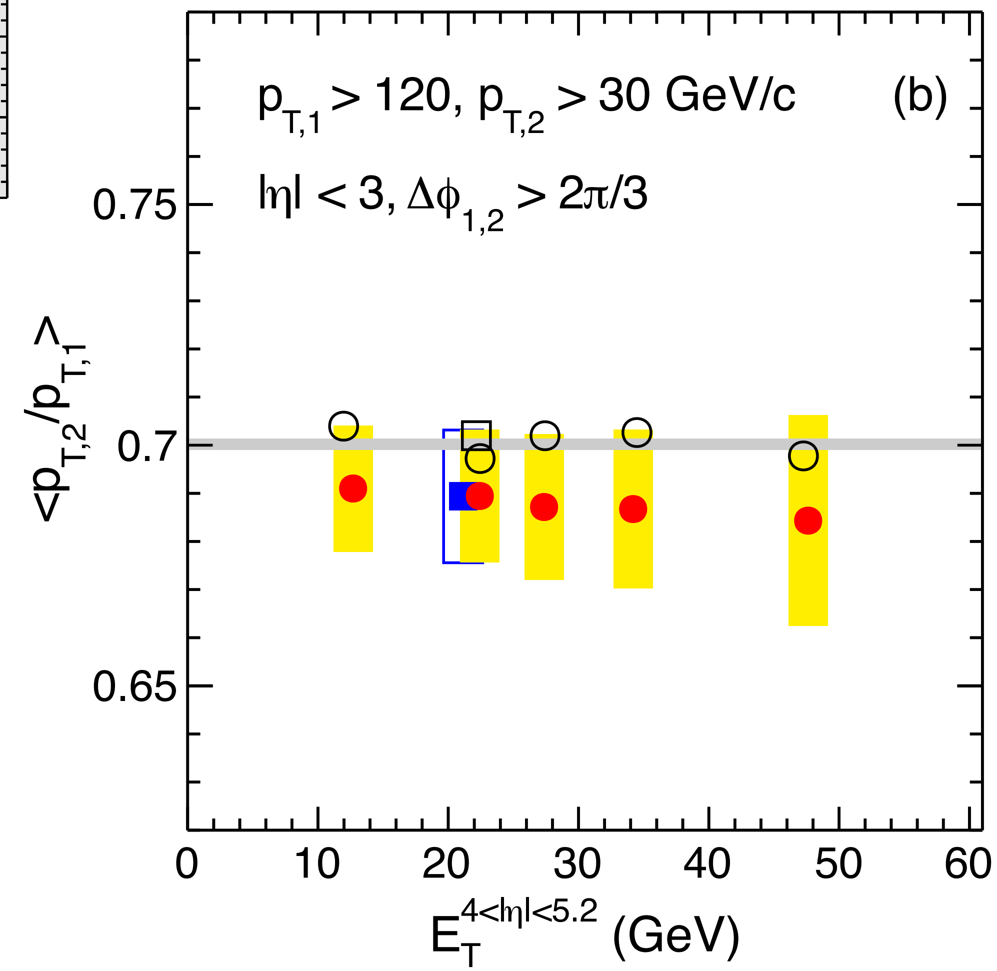


increasing forward E_T



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

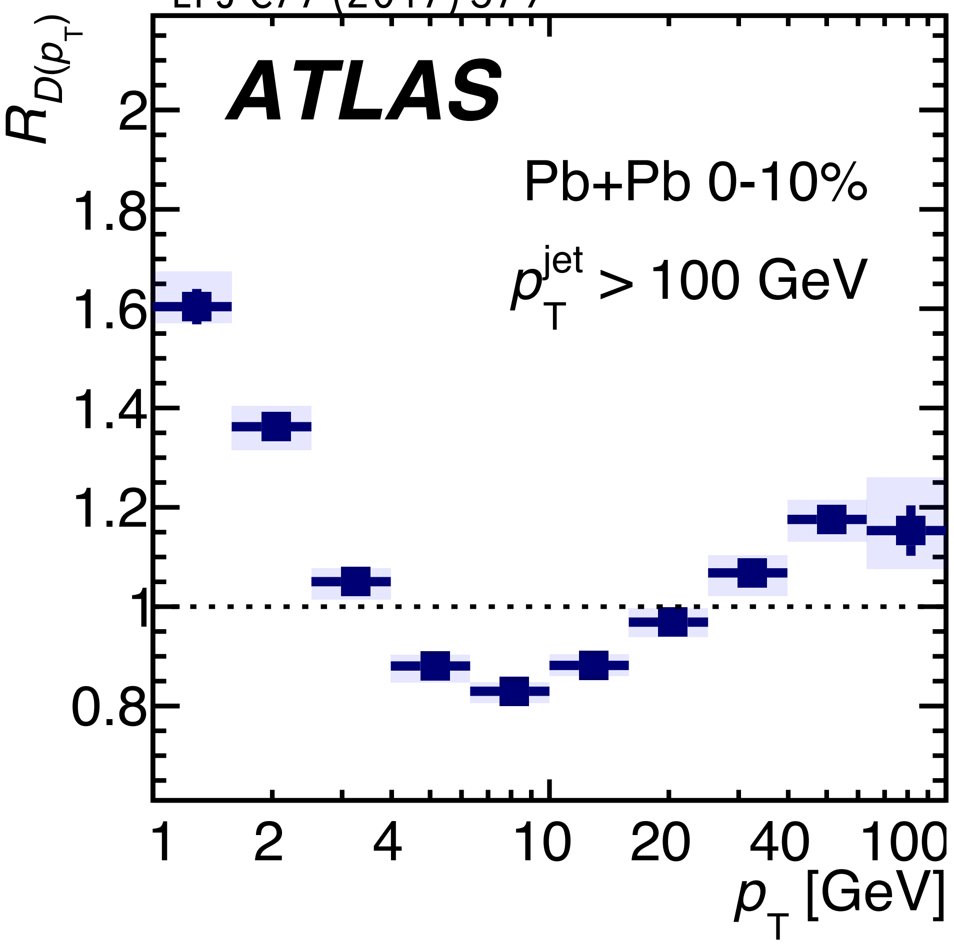
no significance modification of the dijet p_T balance



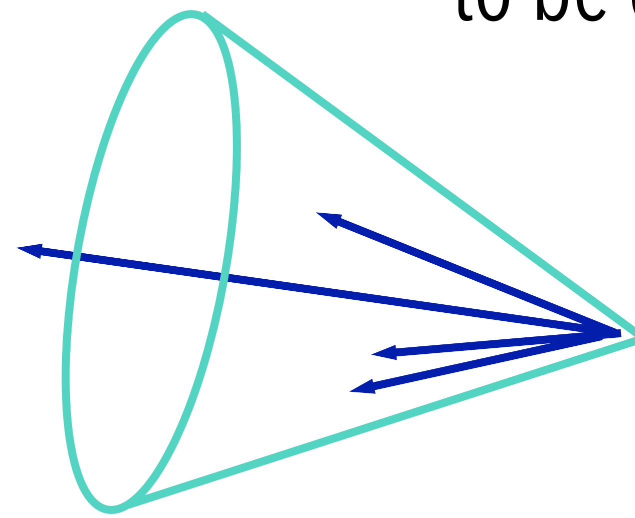
EPJ C74 (2014) 2951

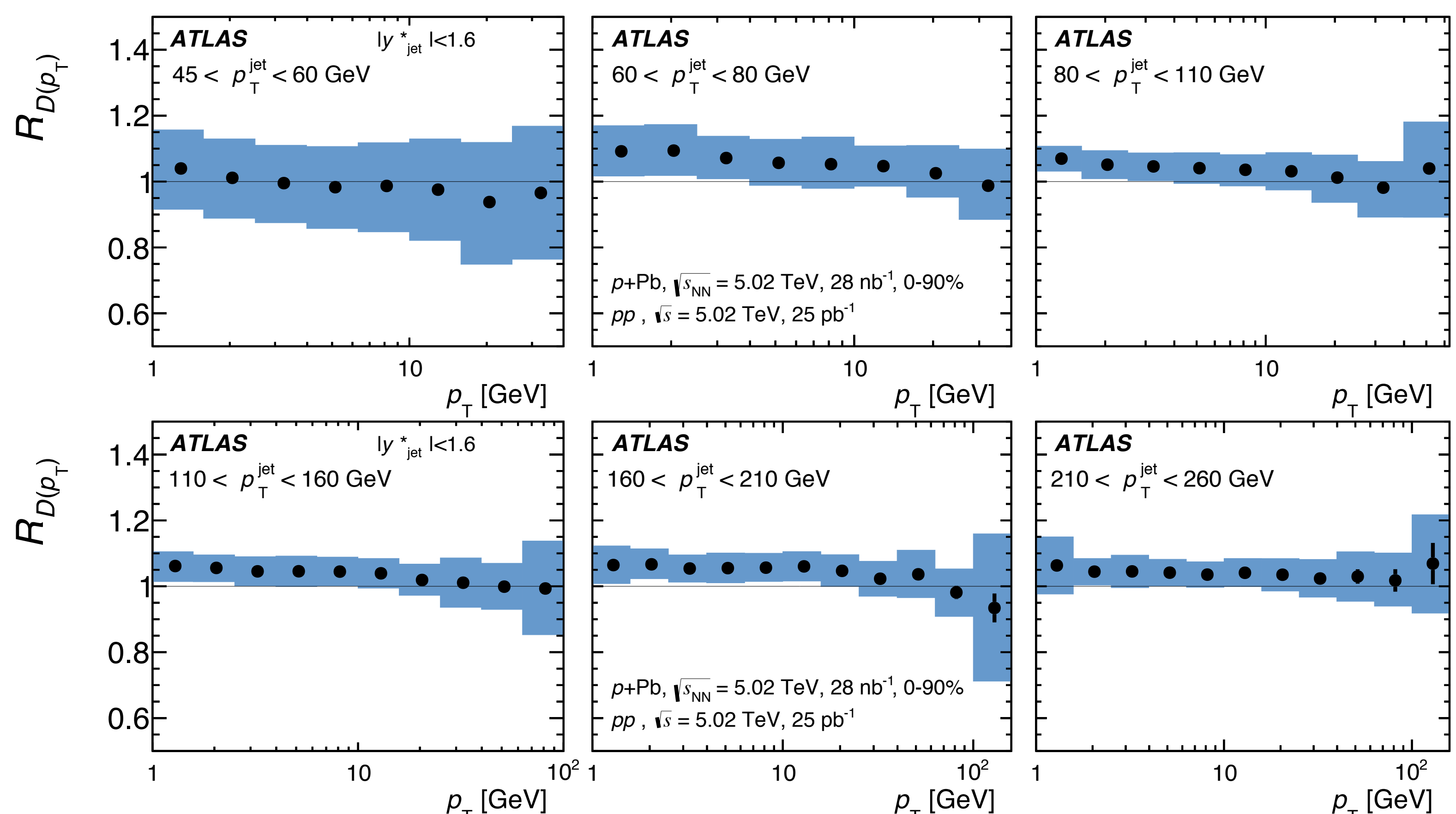
pPb fragmentation functions

EPJ C77 (2017) 379



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



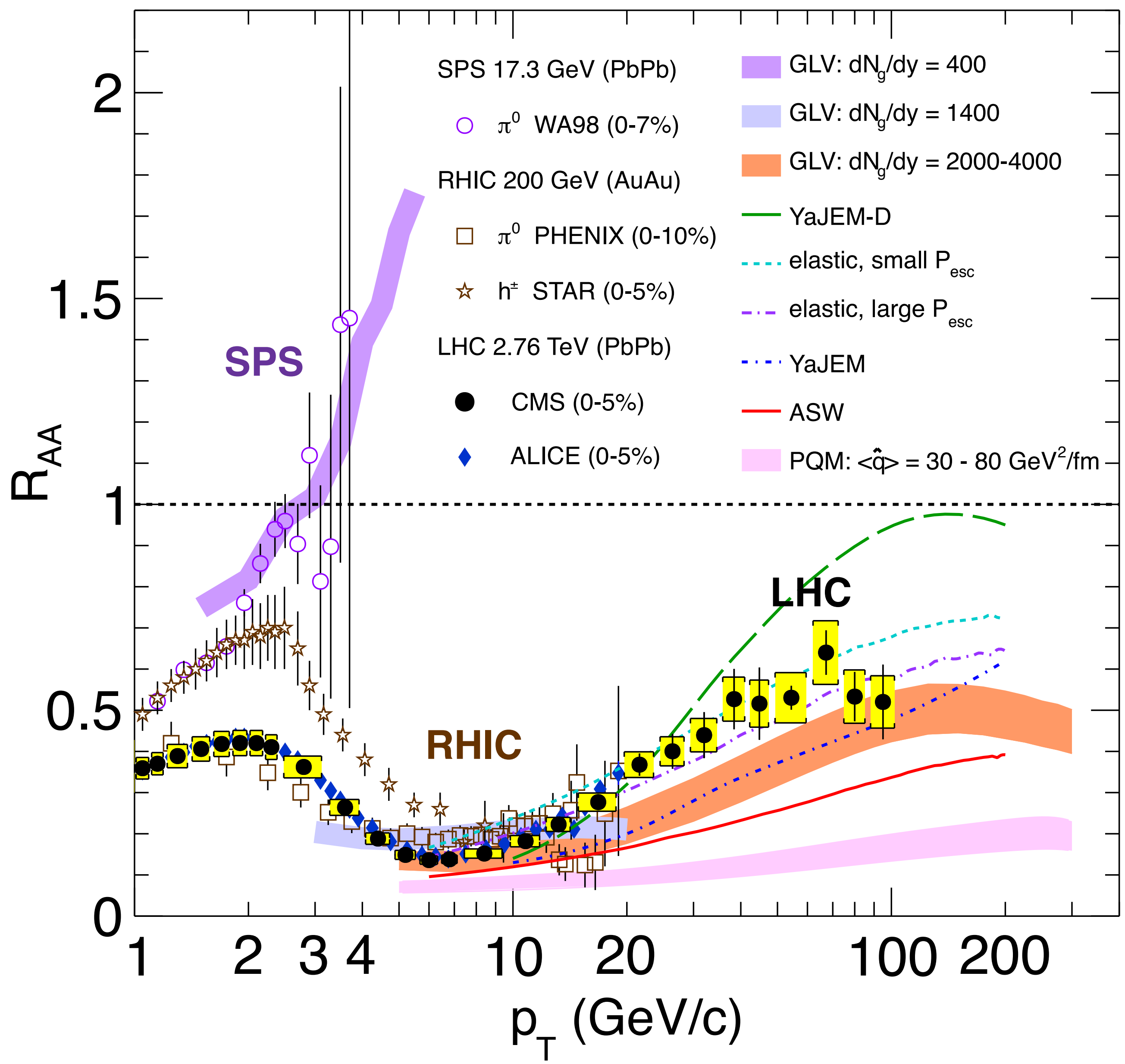


1706.02859

pPb fragmentation functions show no similar excess

RHIC

EPJC 72 (2012) 194



how the jet probes the QGP

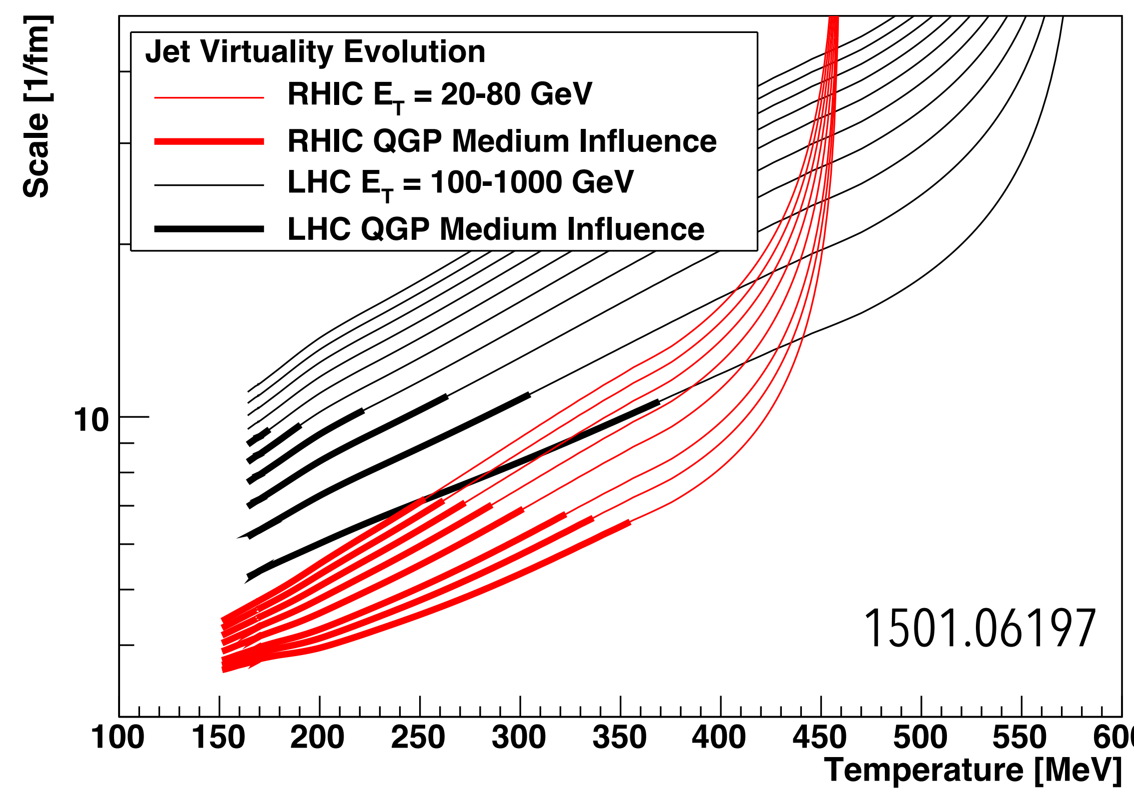


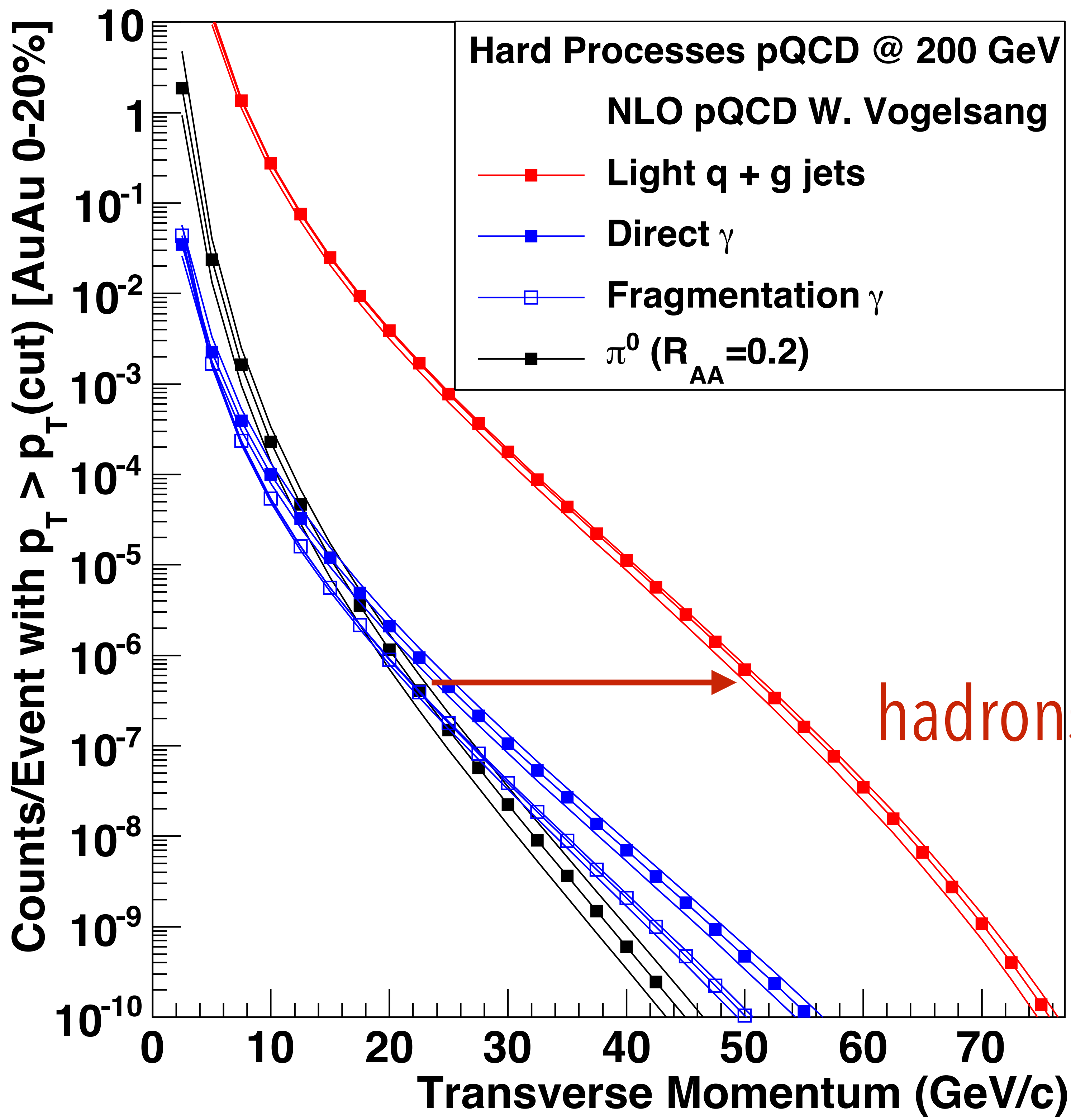
Figure 1.18: Scale probed in the medium in [1/fm] via high energy partons as a function of the local temperature in the medium. The red (black) curves are for different initial parton energies in the RHIC (LHC) medium.

R_{AA} of charged particles at 10-20 GeV similar to the LHC

that does not mean that the quenching is the same

20 GeV only part of kinematic range of RHIC

using reconstructed jets to extend measurements at RHIC



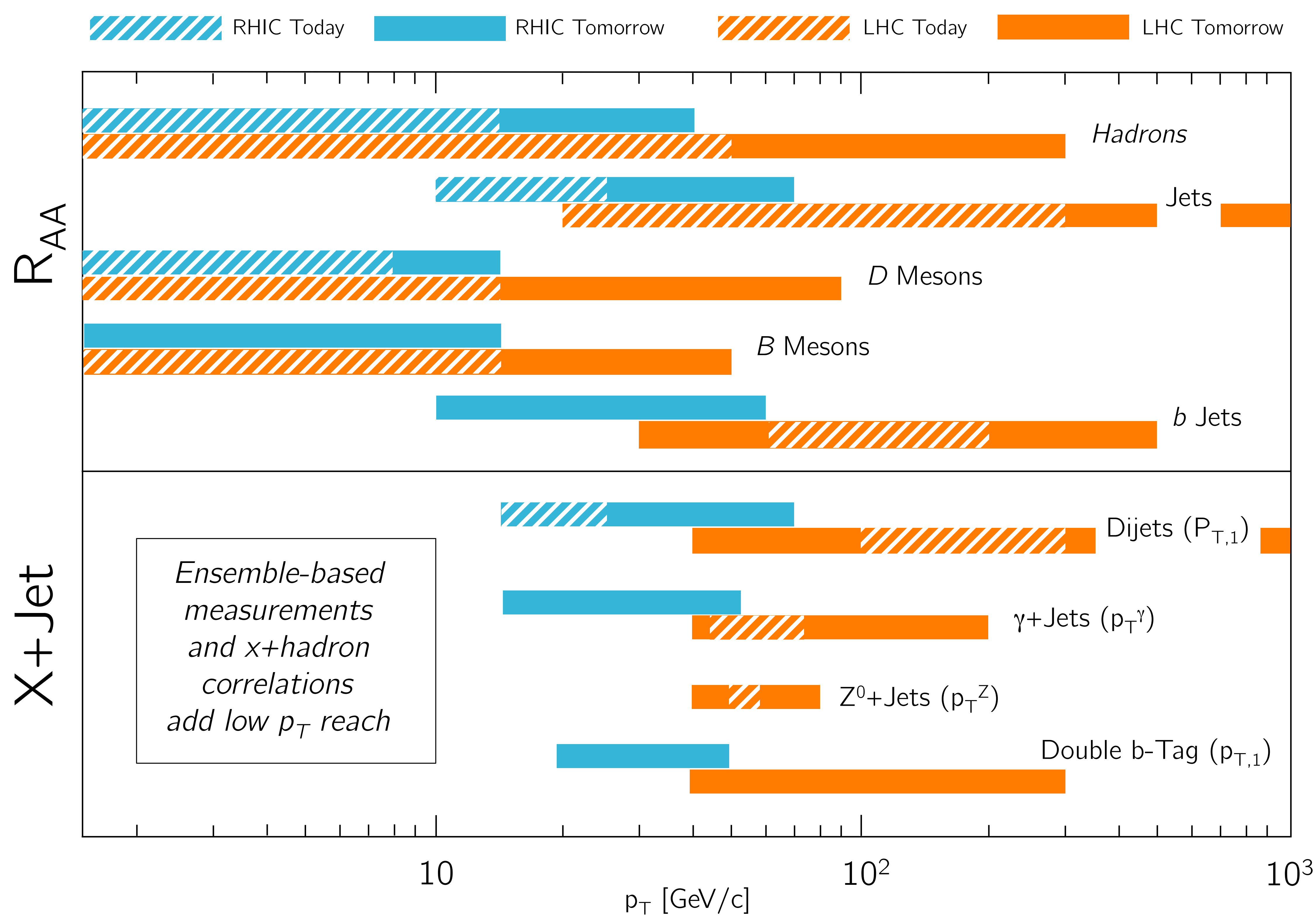
motivation to build an optimized high rate jet detector for RHIC (other motivations include photons, upsilons, …)

hadrons to calorimeter jets

jets and dijets provide precise knowledge of the kinematics which charged hadrons (which are the jet cross sections convoluted with the FFs) don't

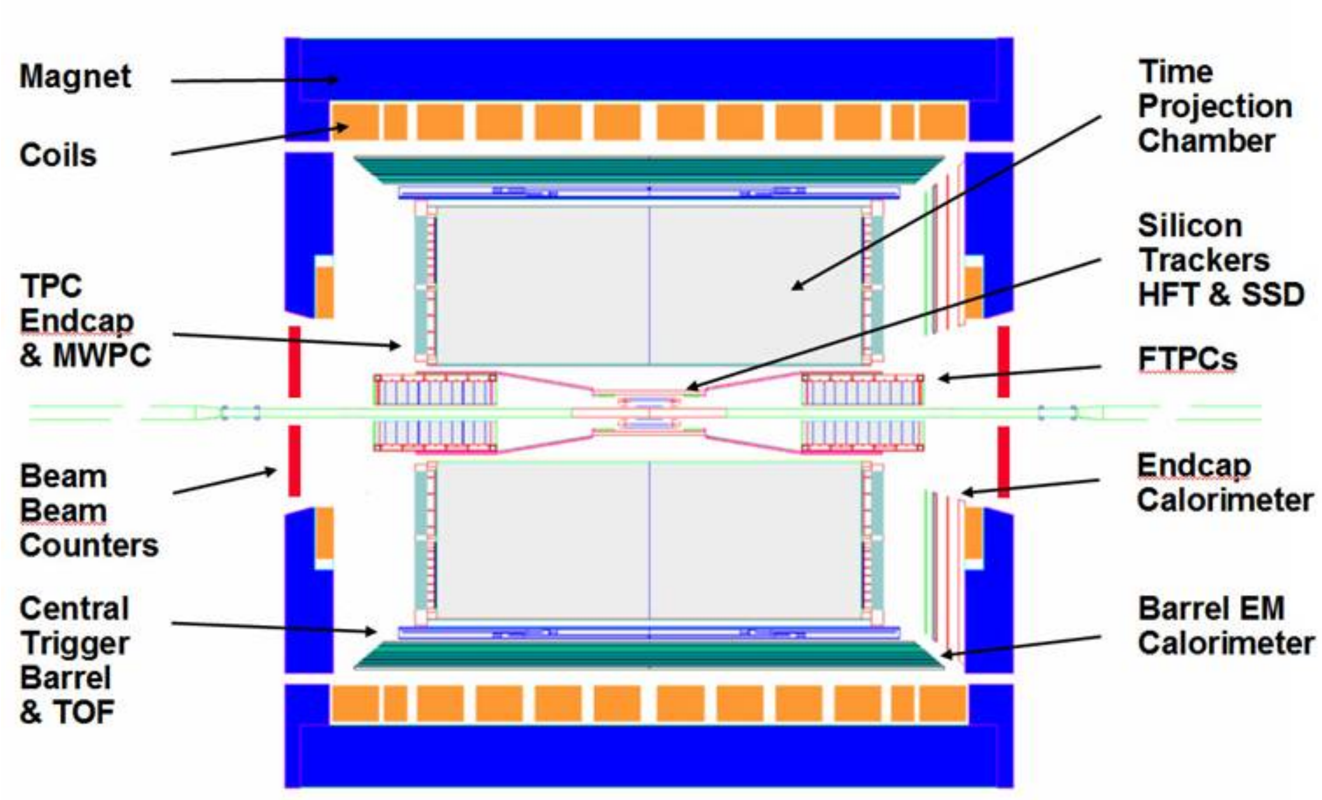
1501.06197

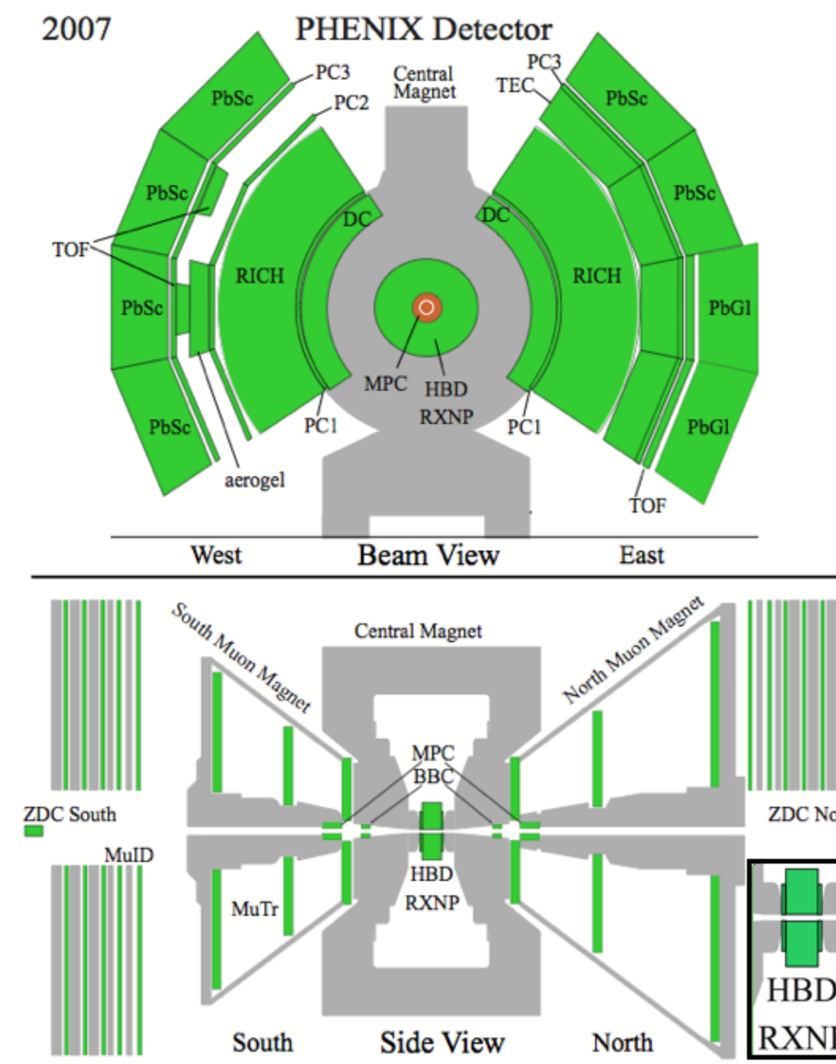
overlapping measurements with the LHC



large detectors at RHIC

STAR





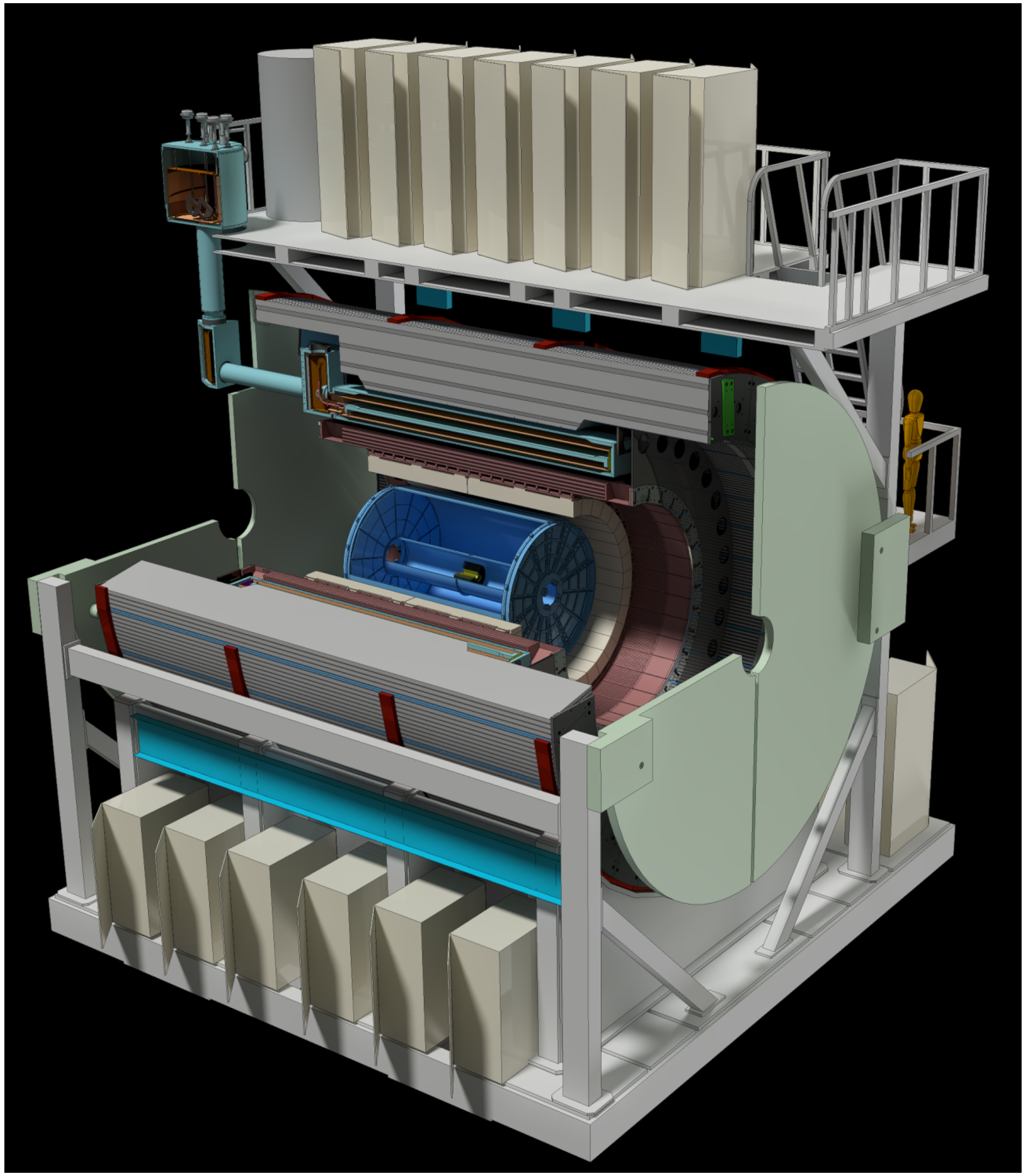
large acceptance TPC, TOF, EM calorimeter solenoid magnet

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



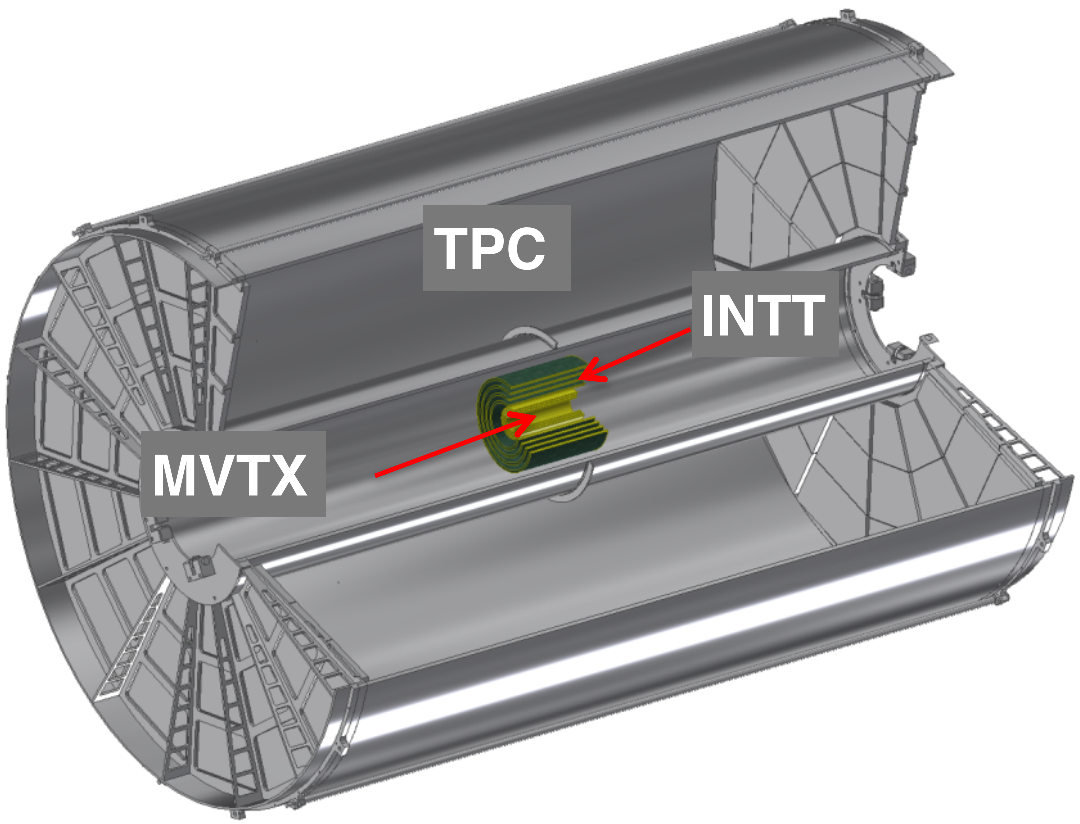
Babar solenoid headed to it's new life in NY

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

large acceptance, high rate, electromagnetic & hadronic calorimetry

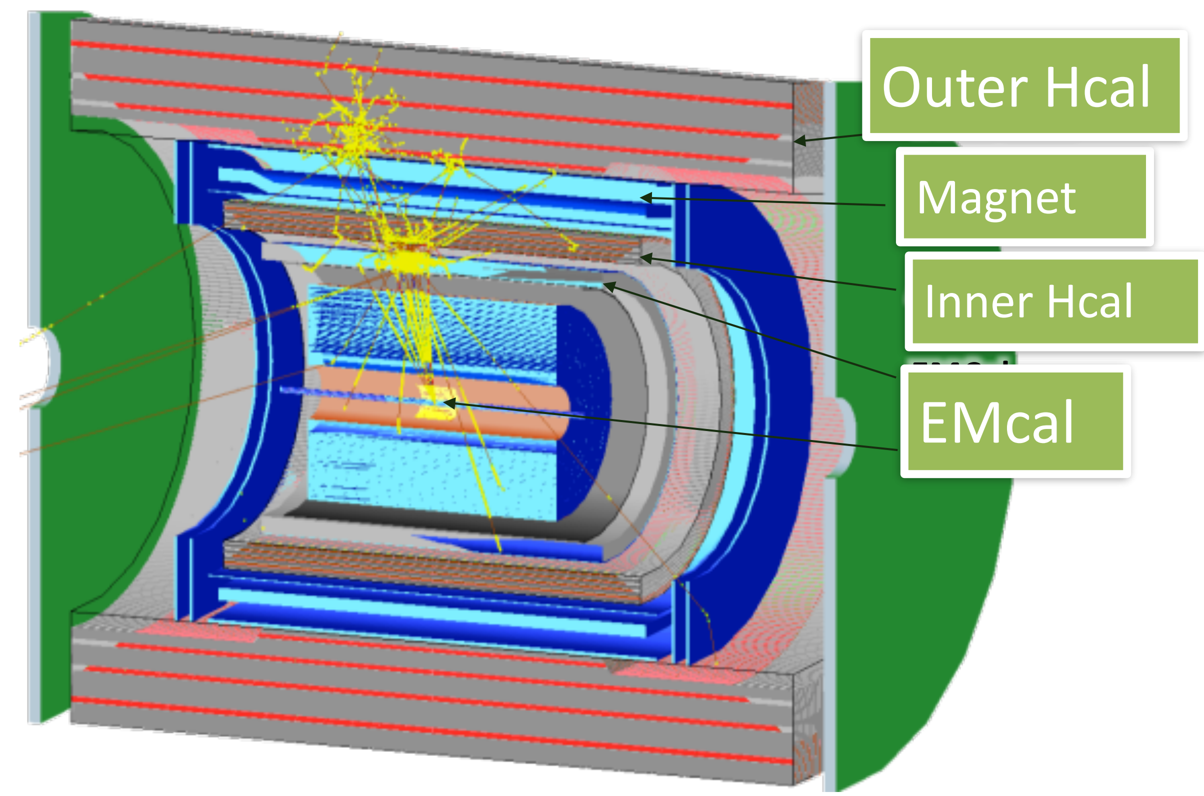
excellent tracking and calorimetry

Tracking



Continuous Readout **TPC**
Silicon Strip Intermediate Tracker **(INTT)**
3-layer MAPS μ vertex **(MVTX)**

Calorimetry



Hcal
EMcal
2π coverage

summary jets

- we using jets to understand the microscopic interactions in the
    - from the experimental side, many advances in the last few years and more to come
    - MC modeling improving quickly (JEWEL and JETSCAPE are two examples)
    - theoretical progress in understanding the physics and optimizing observables
- expect a large PbPb dataset in 2018 plus 10/nb over Runs 3 & 4
- pPb collisions are an important question that is still under investigation

summary heavy ions

- I've left much out: particle fluctuations, quarkonia, EW bosons, new flow observables, hadron formation, …
- I've included several review articles in the slides already
  - if you are interested, go back and read the original works!
  - slides from previous summer schools (including US National Nuclear Physics Summer School) are also very useful
- talk to your collaborators, this is an evolving field and perspectives differ
- I'd be happy to answer questions that you have via email

thanks for the organizers for the invitation, this has been a great experience to put together and you have asked many interesting questions!

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

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