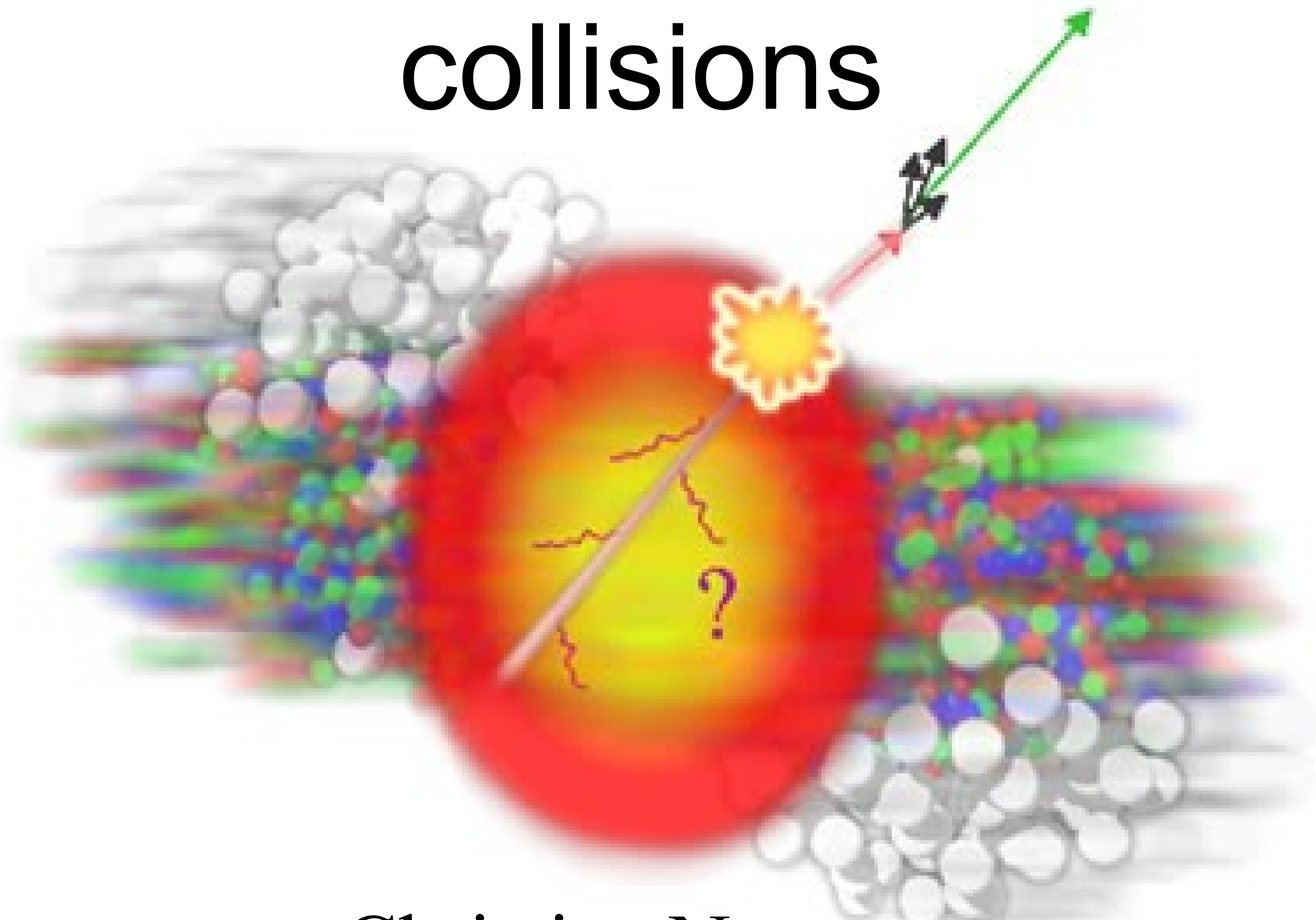
Measurements of jets in heavy ion collisions

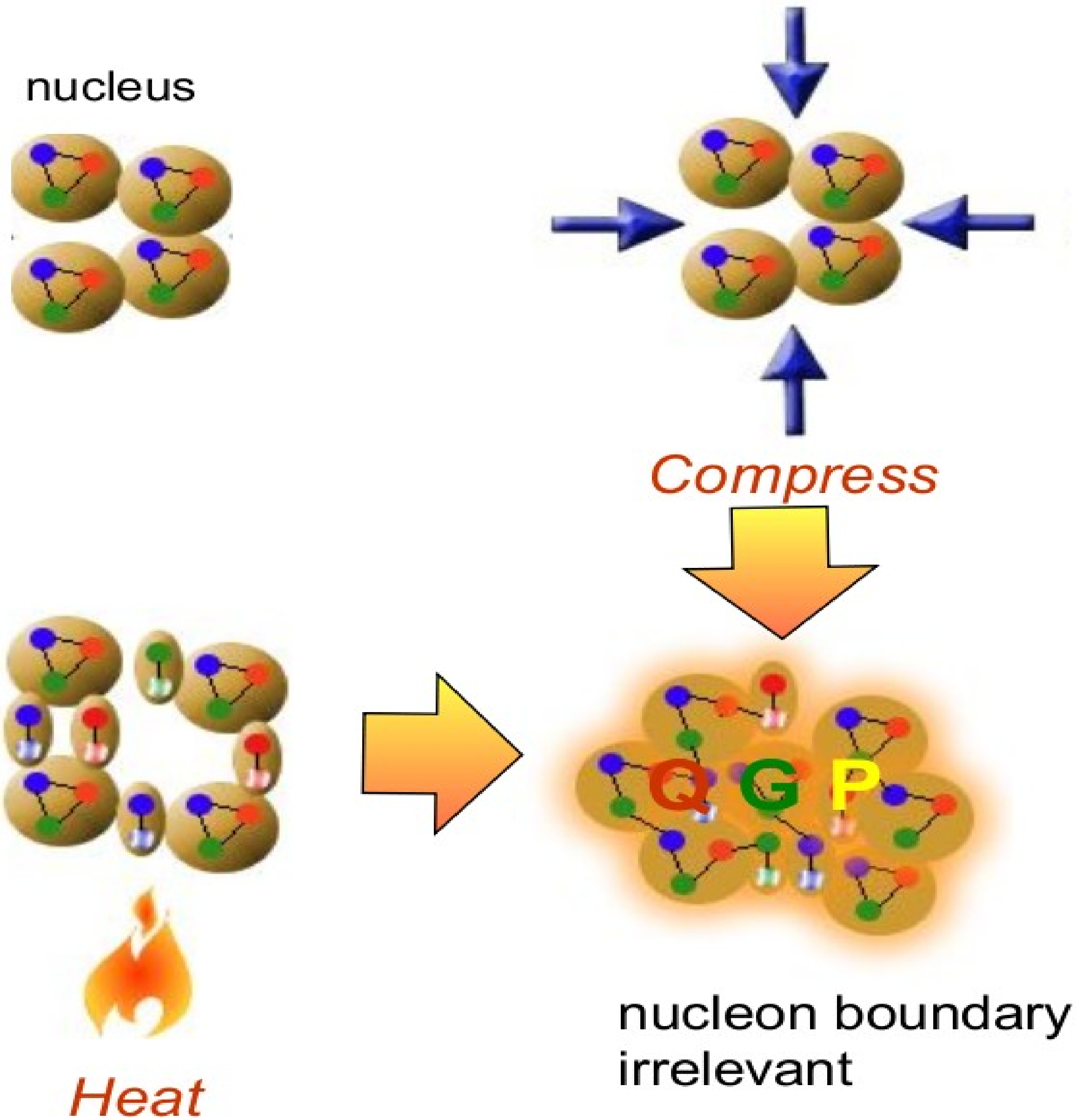


Christine Nattrass
University of Tennessee, Knoxville

Largely based on Connors, Nattrass, Reed, & Salur

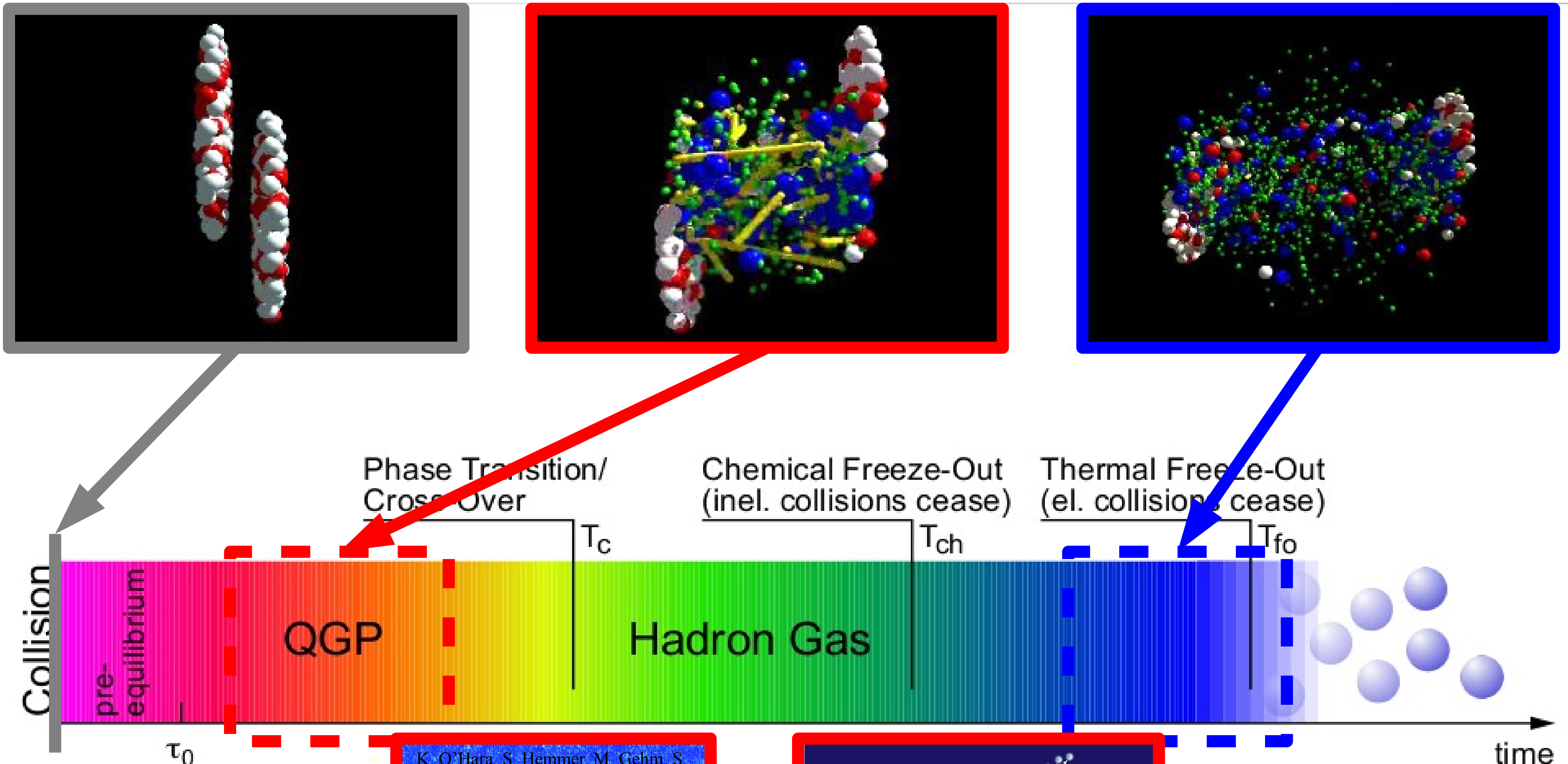
arxiv:1705.01974, accepted in RMP

How to make a Quark Gluon Plasma

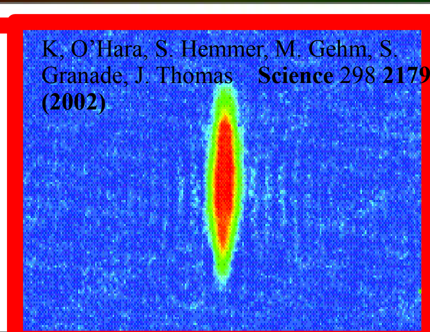


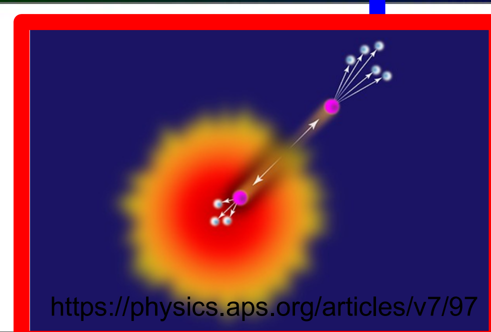
The phase transition in the laboratory

Initial State **QGP** **Freeze-out**



Hydrodynamical flow



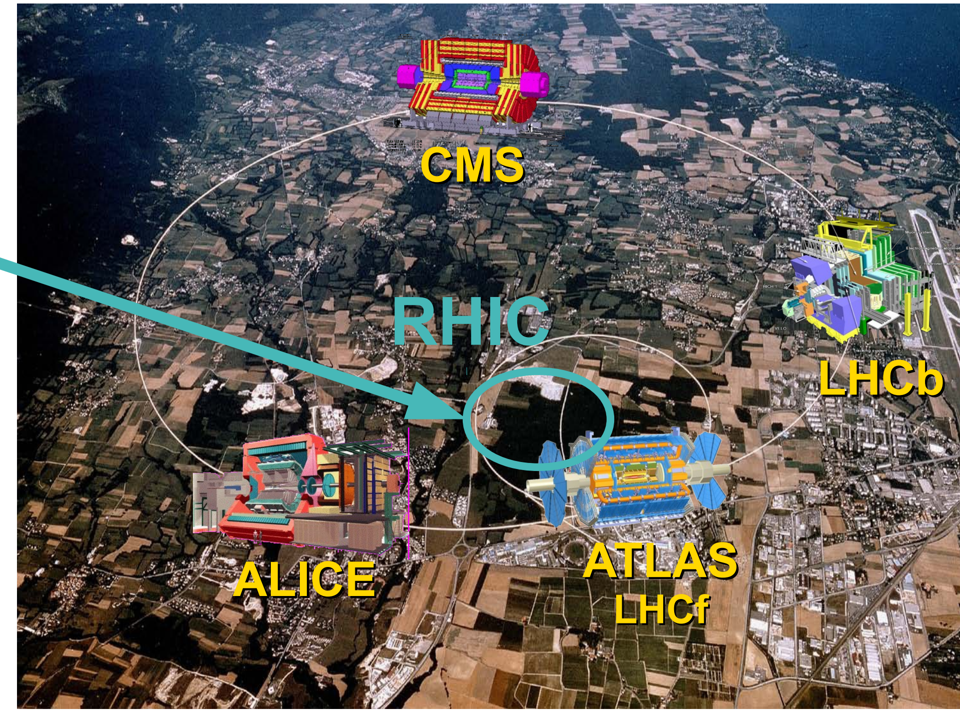


Jet quenching

Relativistic Heavy Ion Collider

Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

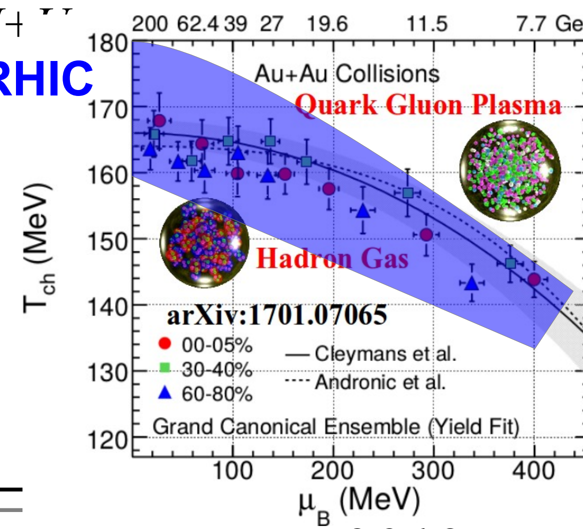
Large Hadron Collider

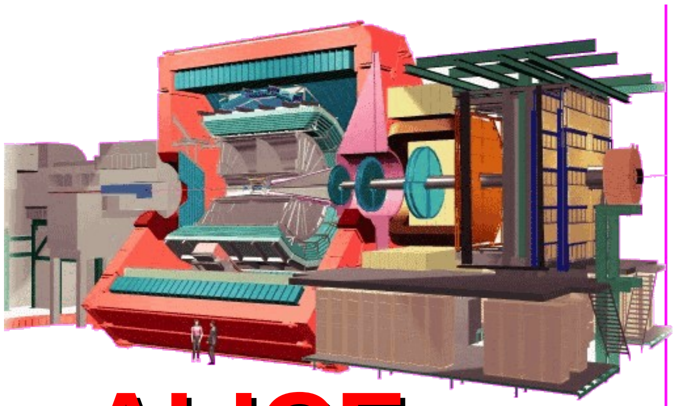


Geneva, Switzerland
8.6km diameter
+*Pb*, Pb+Pb
2.76 GeV, *5.5 TeV*

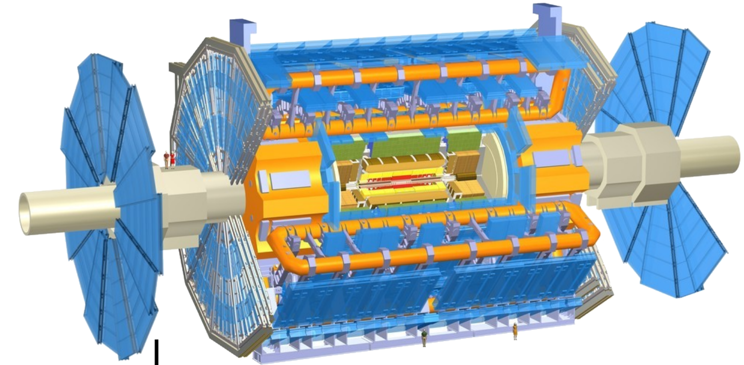
LHC

RHIC

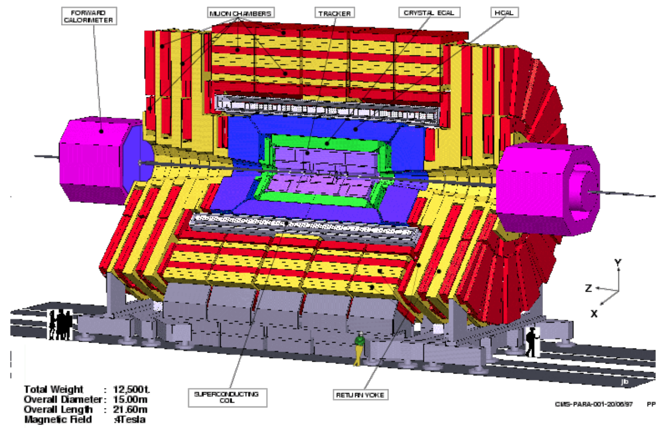




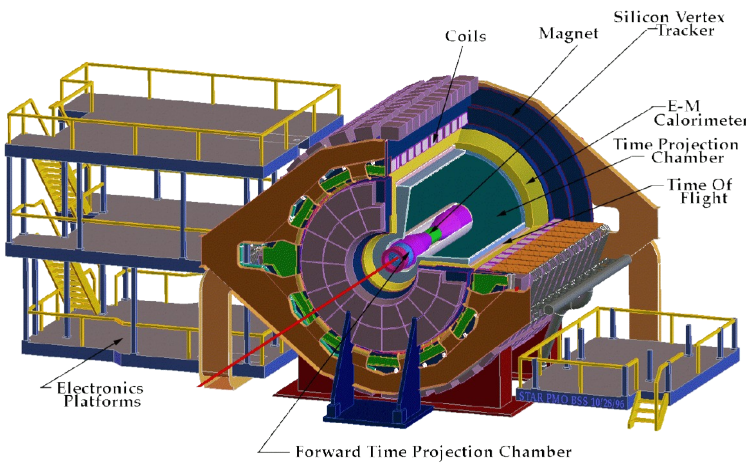
ALICE



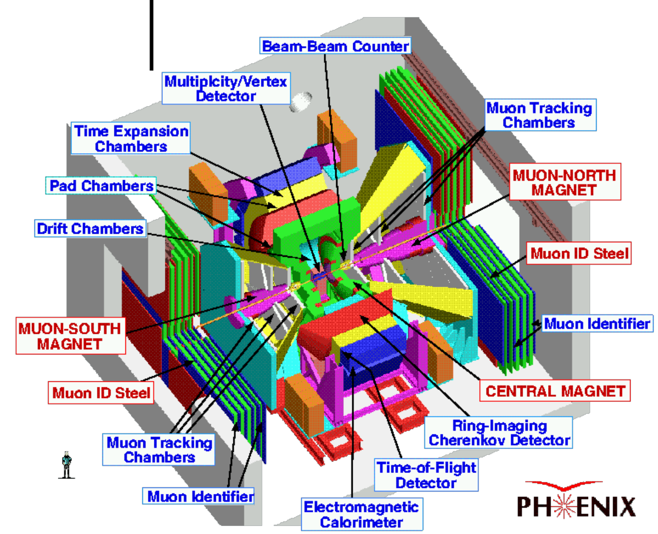
ATLAS



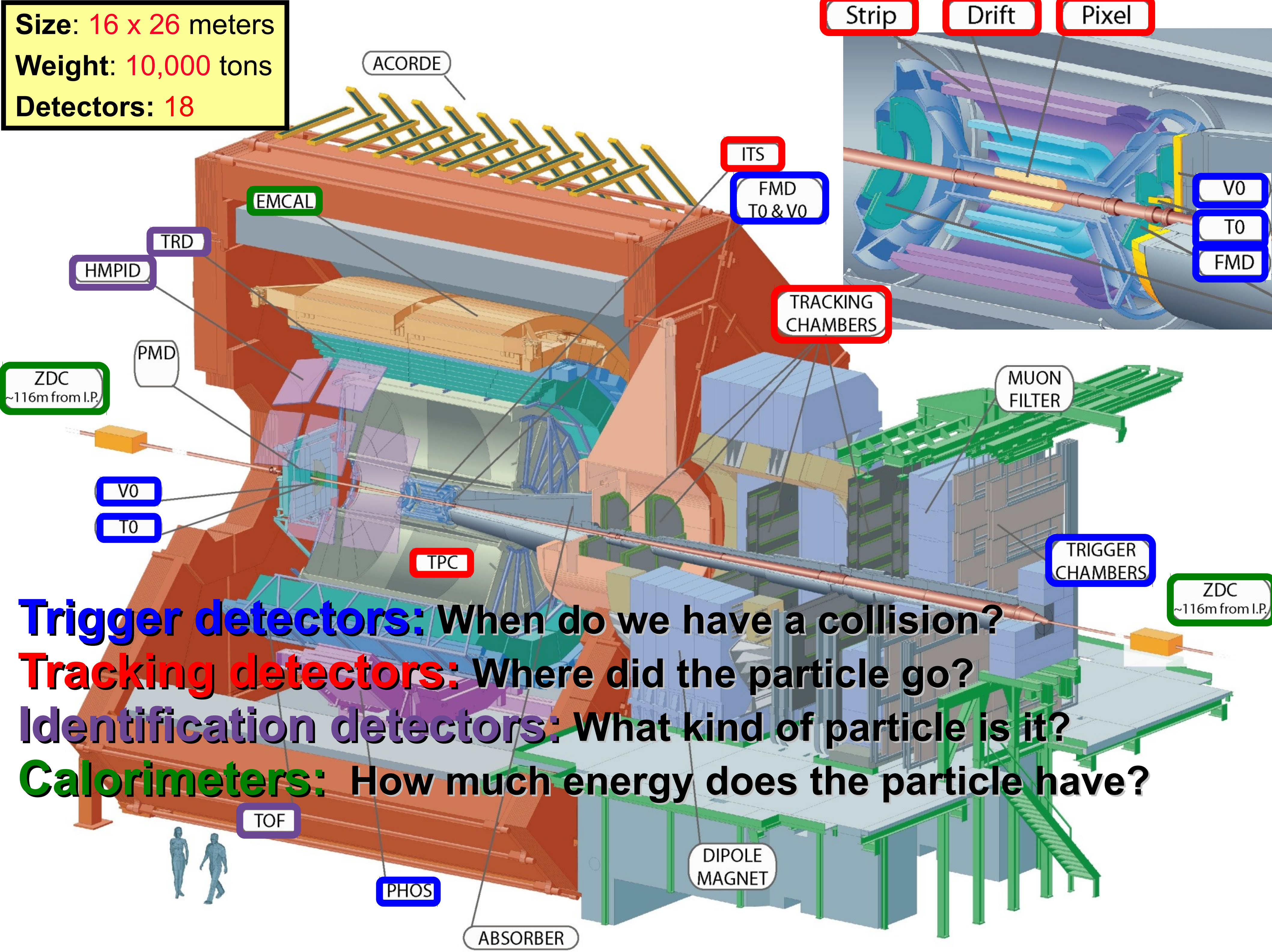
CMS



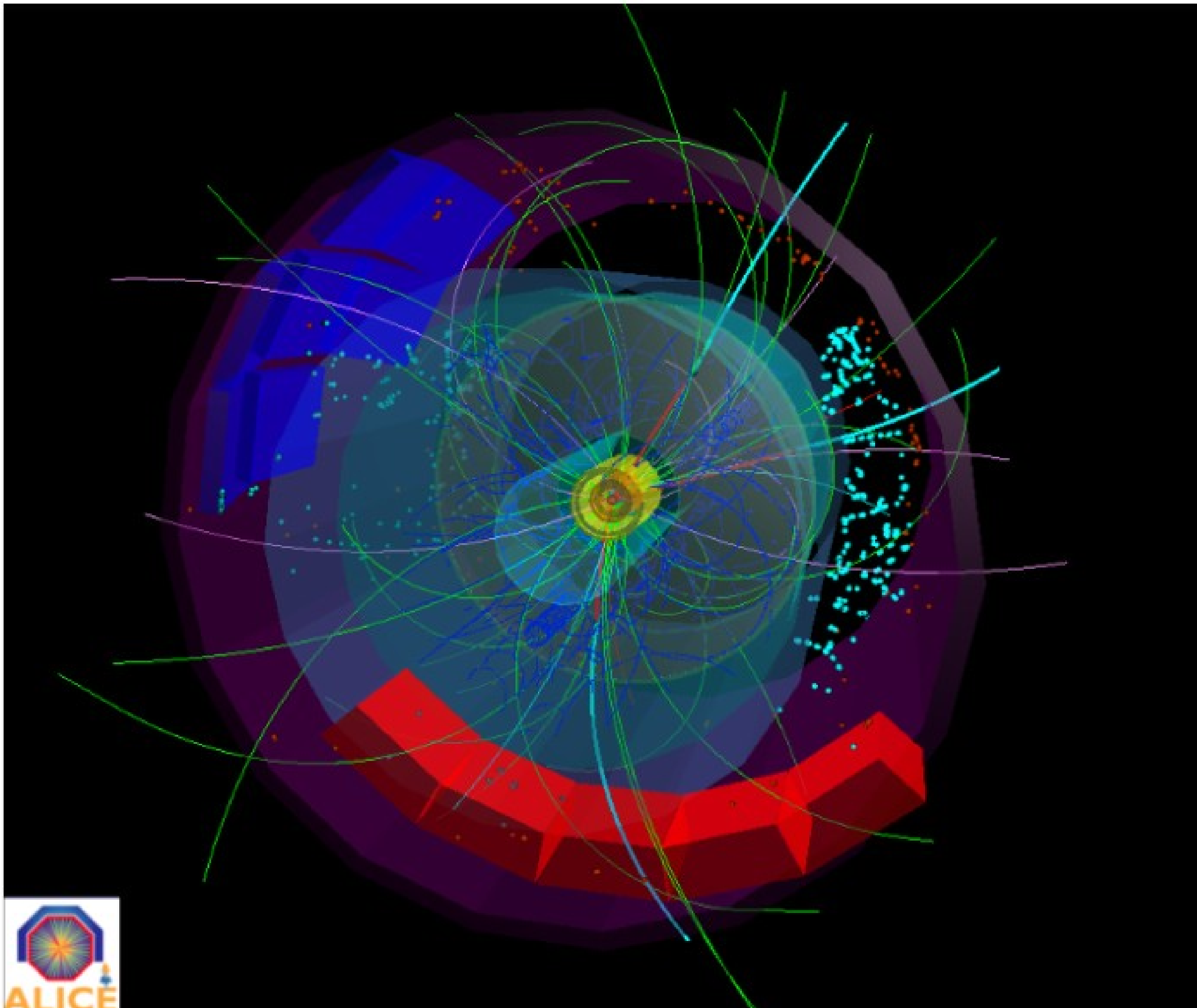
STAR



PHENIX

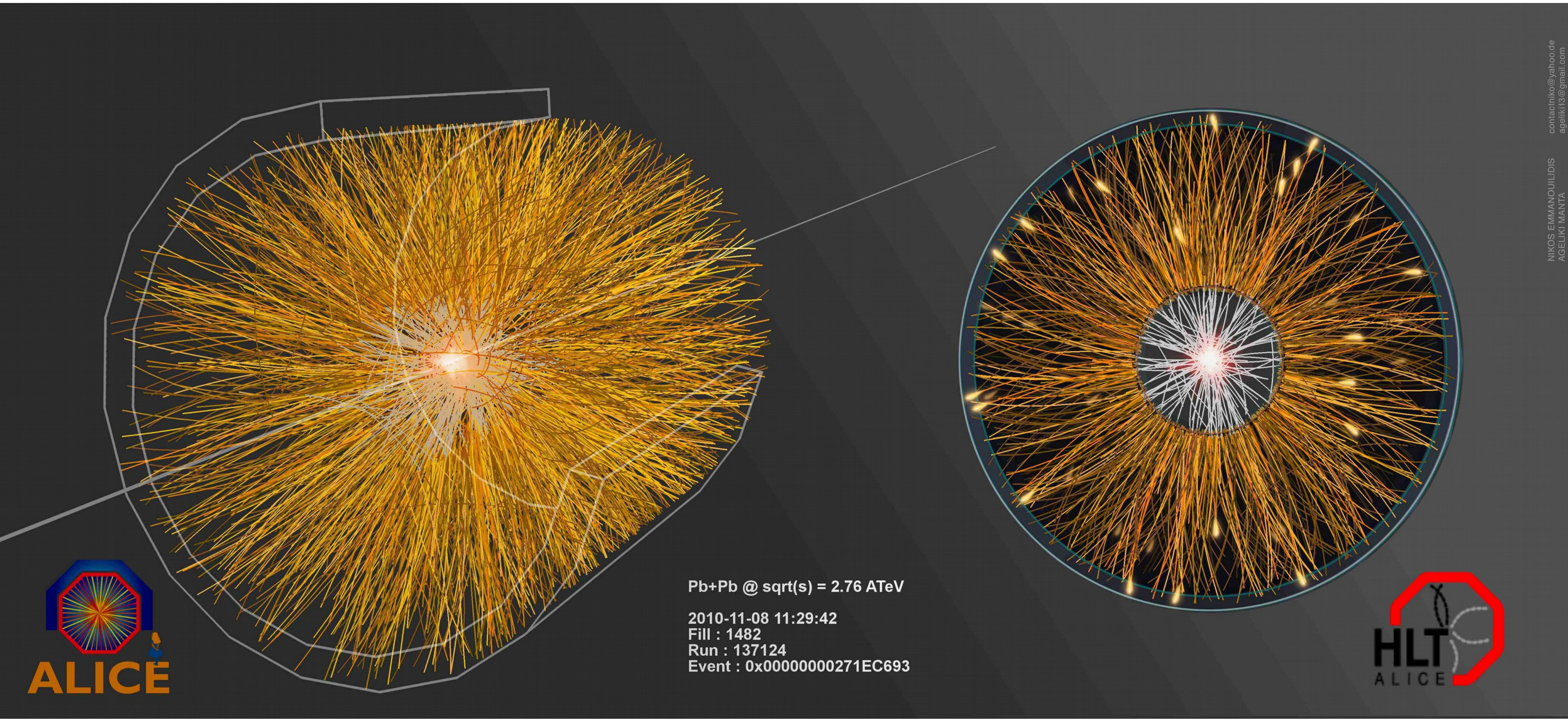

Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18
ACORDE
Strip
Drift
Pixel
ITS
FMD
T0 & V0
EMCAL
TRD
HMPID
V0
T0
FMD
TRACKING
CHAMBERS
PMD
ZDC
~116m from I.P.
MUON
FILTER
V0
T0
TPC
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
Trigger detectors: When do we have a collision?
Tracking detectors: Where did the particle go?
Identification detectors: What kind of particle is it?
Calorimeters: How much energy does the particle have?
TOF
PHOS
DIPOLE
MAGNET
ABSORBER

p+p collisions

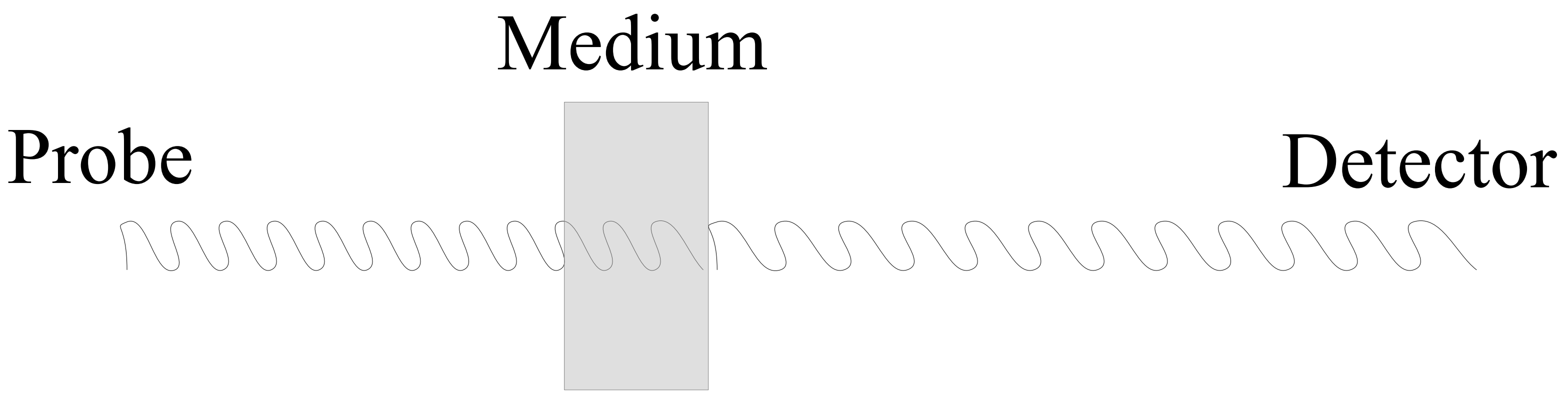


3D image of each collision

Pb+Pb collisions

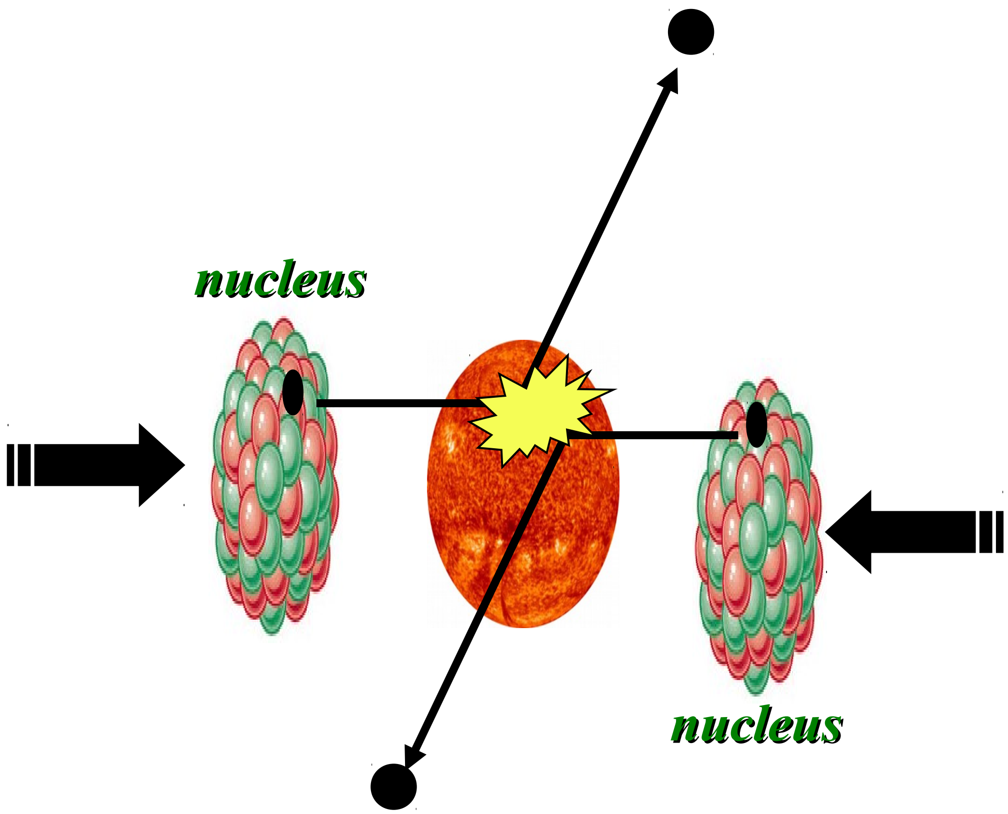


Probing the Quark Gluon Plasma



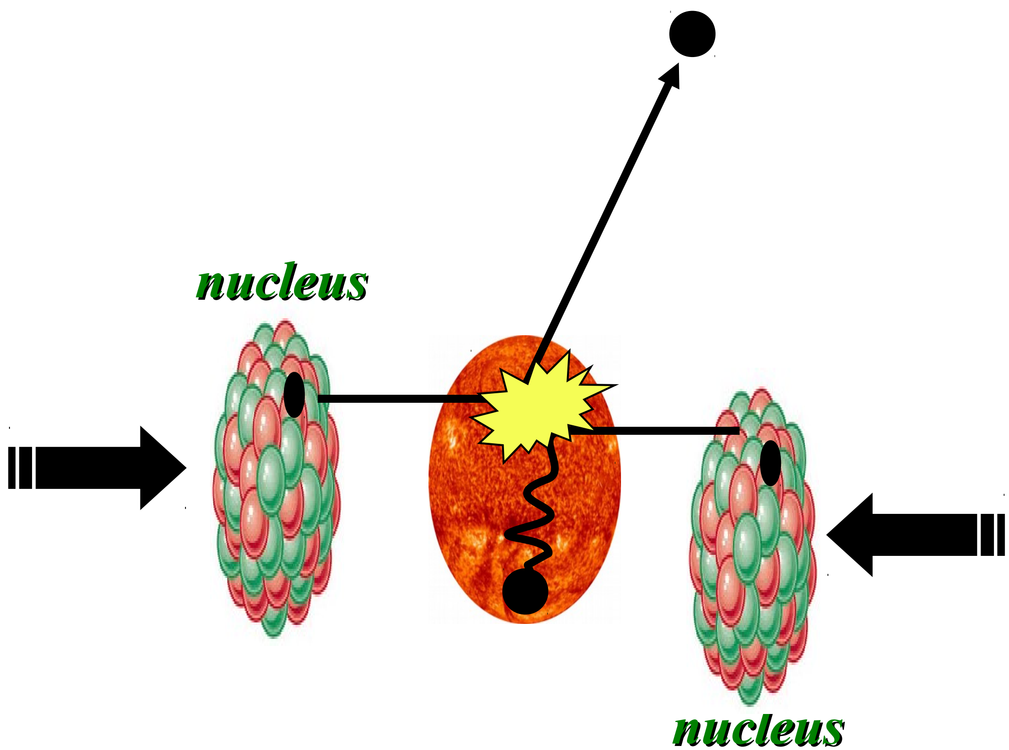
Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

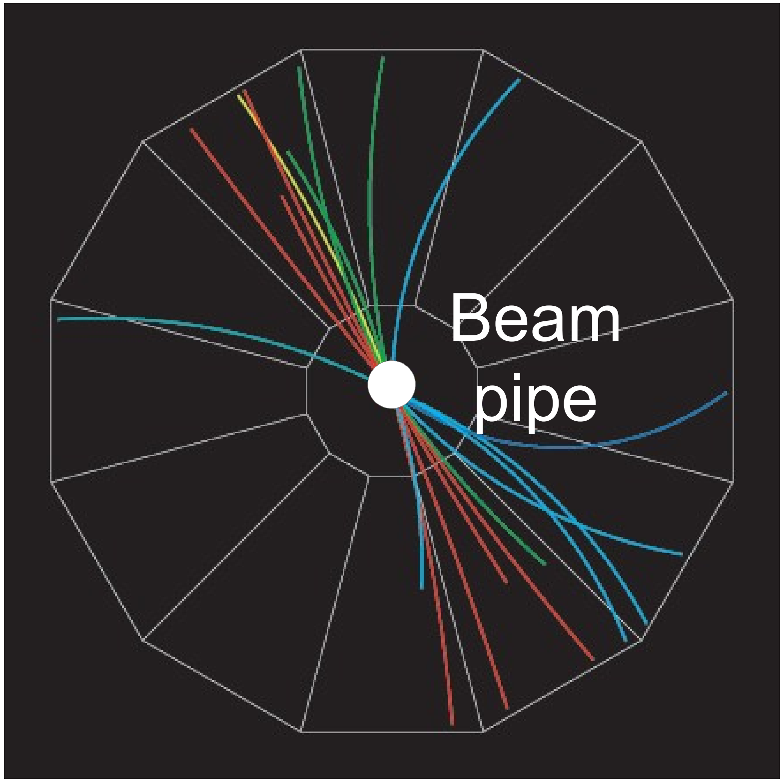


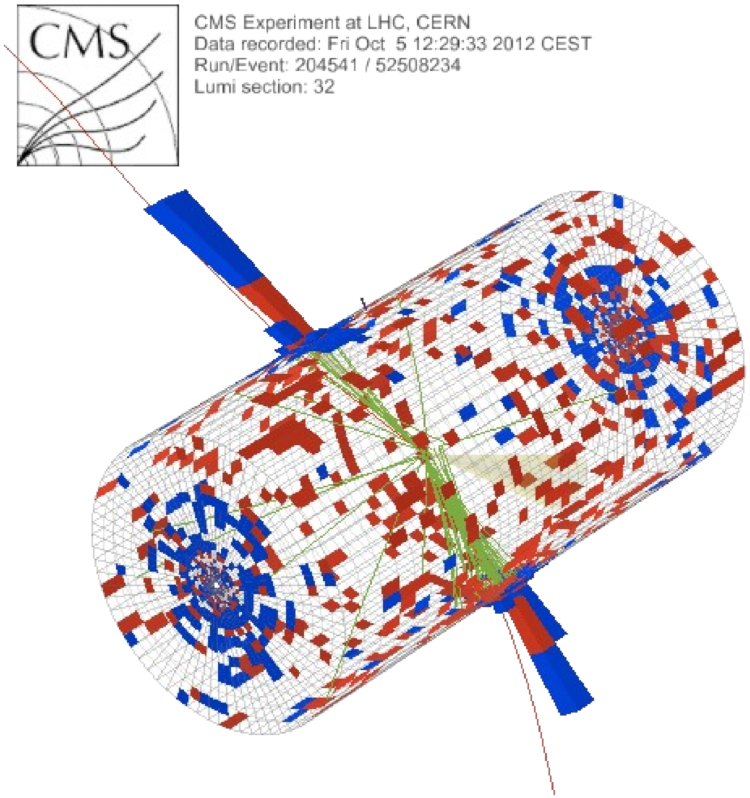
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

What is a jet?

What is a jet?

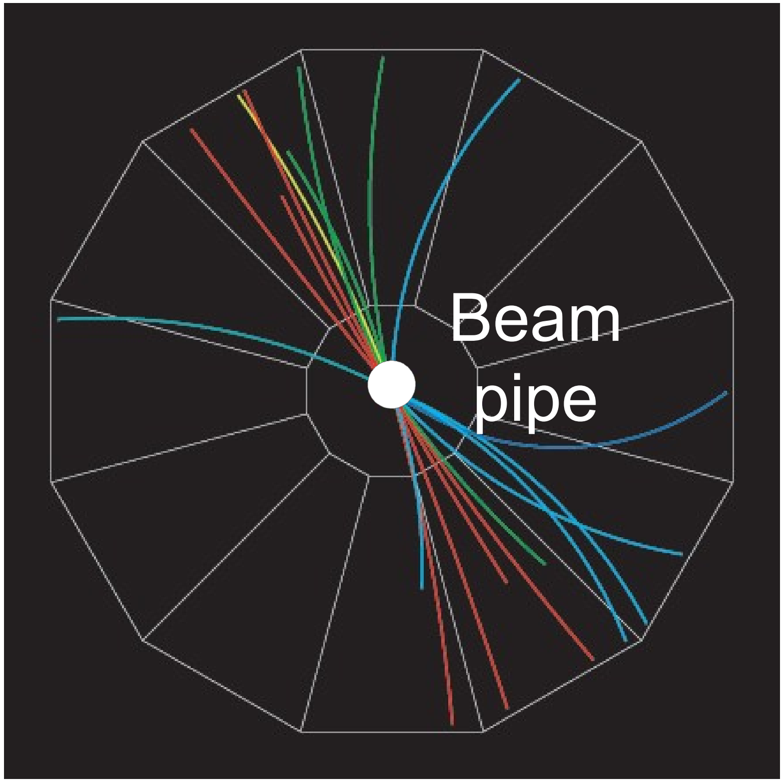
p+p → dijet

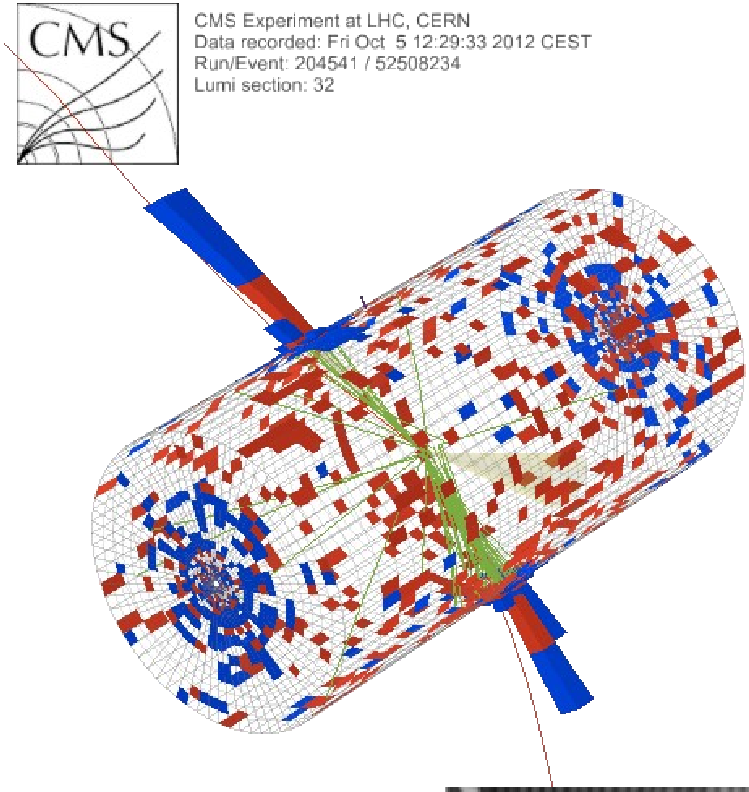




What is a jet?

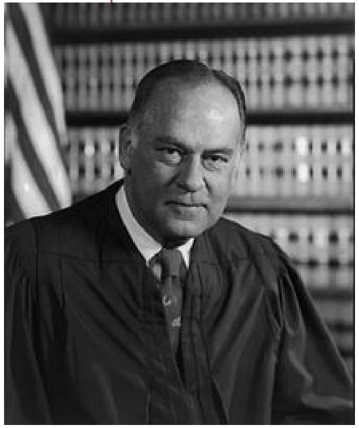
p+p → dijet





"I know it when I see it"

US Supreme Court Justice Potter Stewart,
Jacobellis v. Ohio



Jet finding in pp collisions

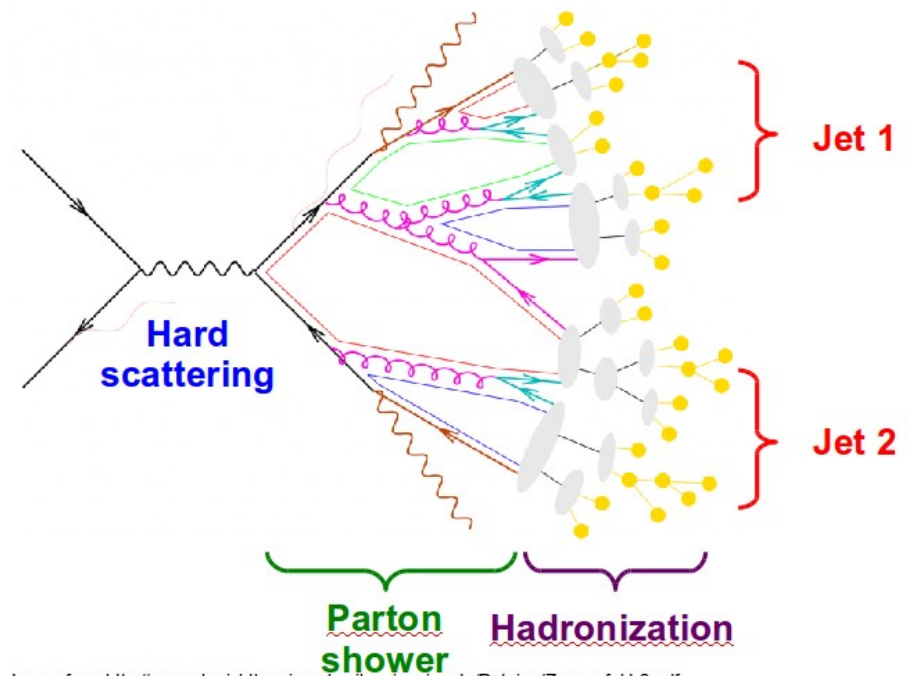


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Jet finder: groups final state particles into jet candidates
  - Anti-k_T algorithm
    JHEP 0804 (2008) 063 [arXiv:0802.1189]
- Depends on hadronization
- Ideally
  - Infrared safe
  - Colinear safe

Snowmass Accord: Theoretical calculations and experimental measurements should use the same jet finding algorithm. Otherwise they will not be comparable.

A jet is what a jet finder finds.

Jet finding in AA collisions

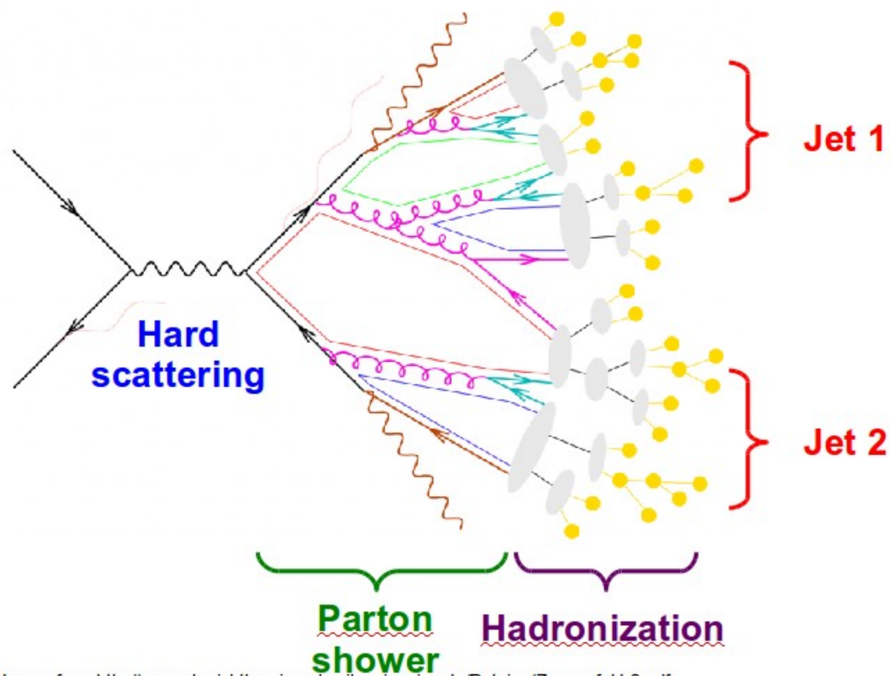
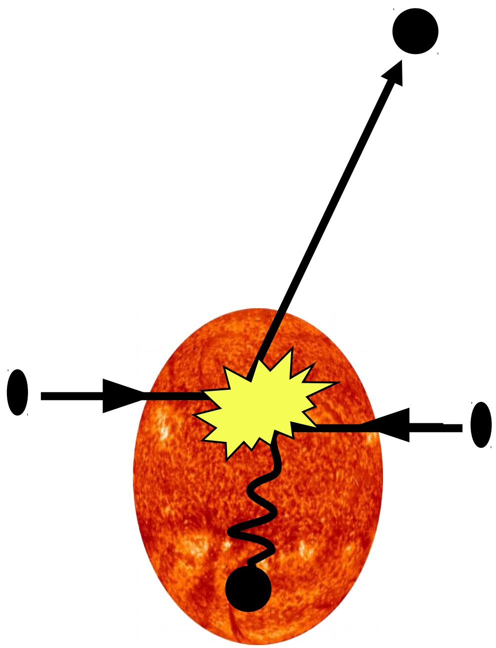


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Jet finder: groups final state particles into jet candidates
  - Anti-k_T algorithm
    JHEP 0804 (2008) 063 [arXiv:0802.1189]
- Combinatorial jet candidates
- Energy smearing from background
- Large, fluctuating, correlated background
- Sensitive to methods to suppress combinatorial jets and correct energy
- Focus on narrow/high energy jets

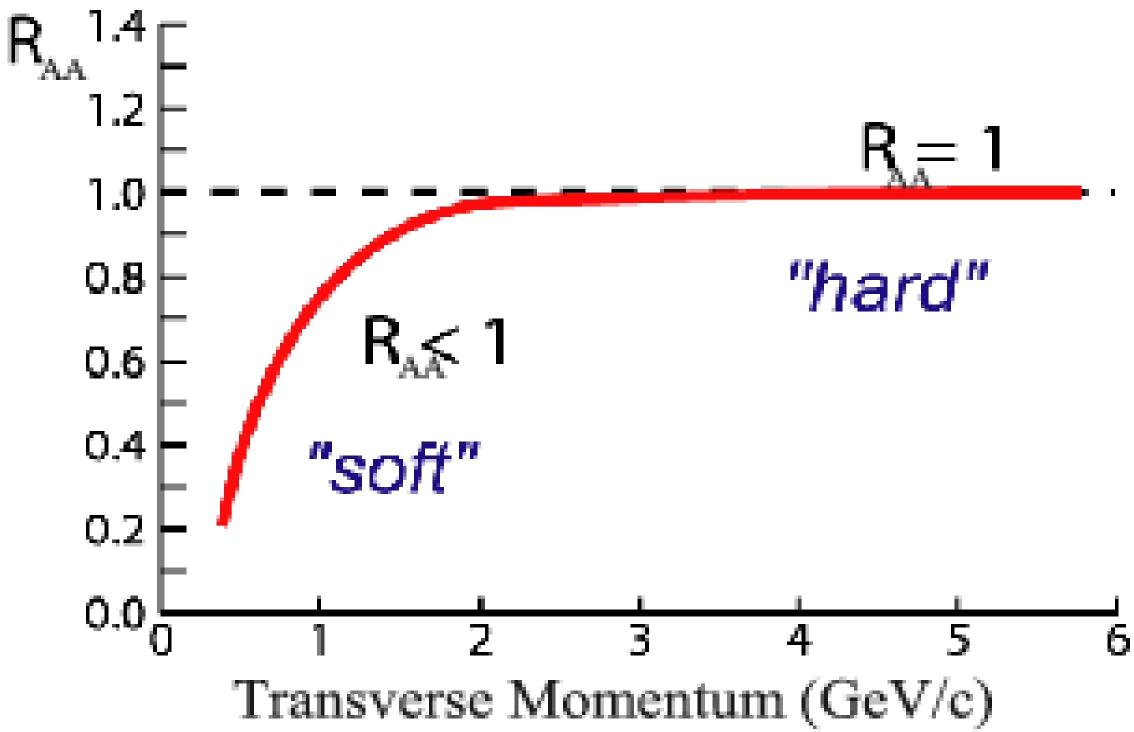
Energy loss



Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-p_T probes (jets) are suppressed, this is evidence of jet quenching

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$

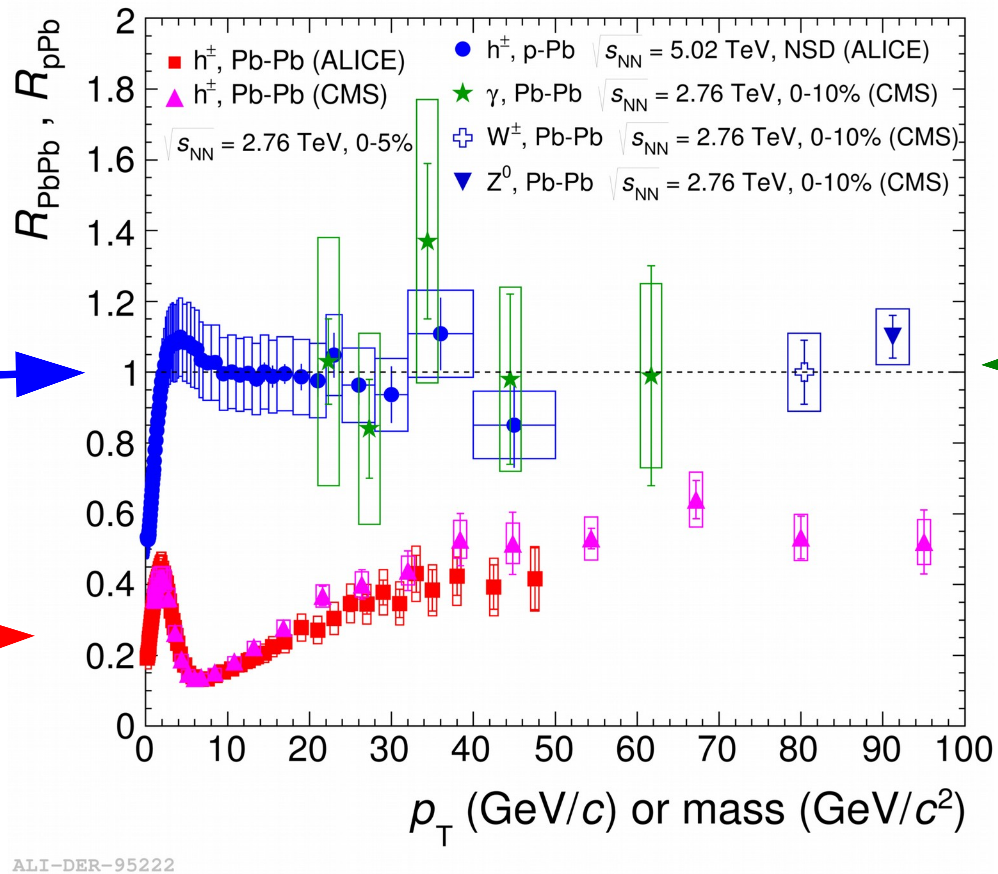


Enhancement

Suppression

Nuclear modification factor

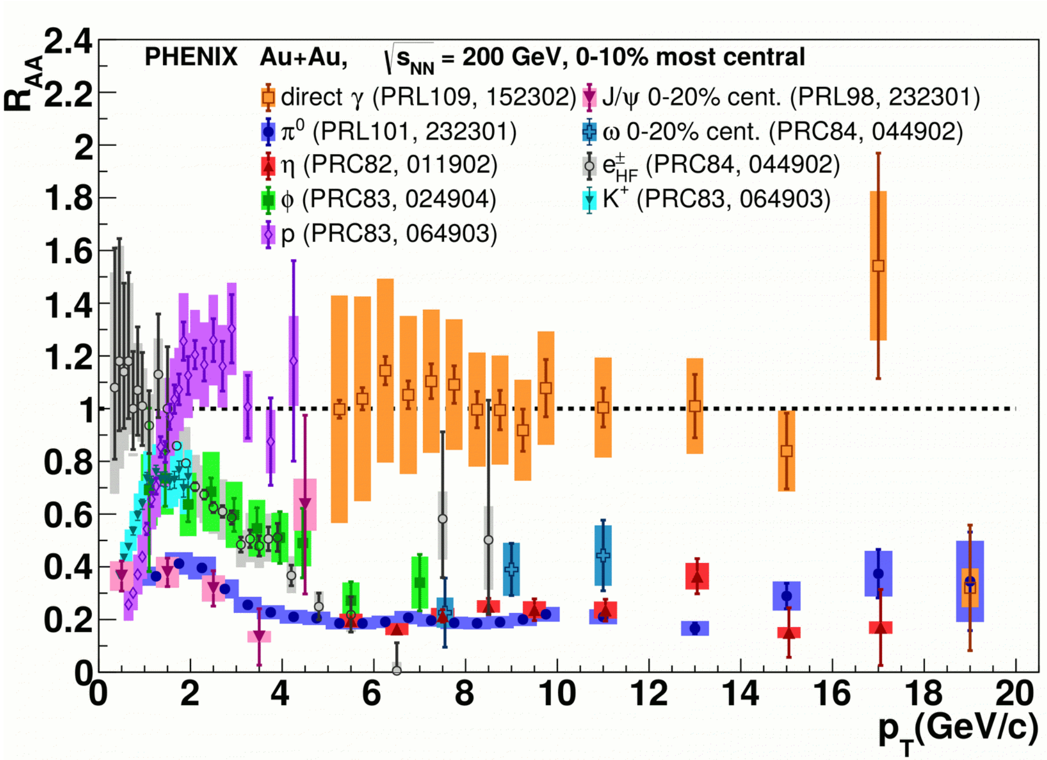
Control
Control
Probe

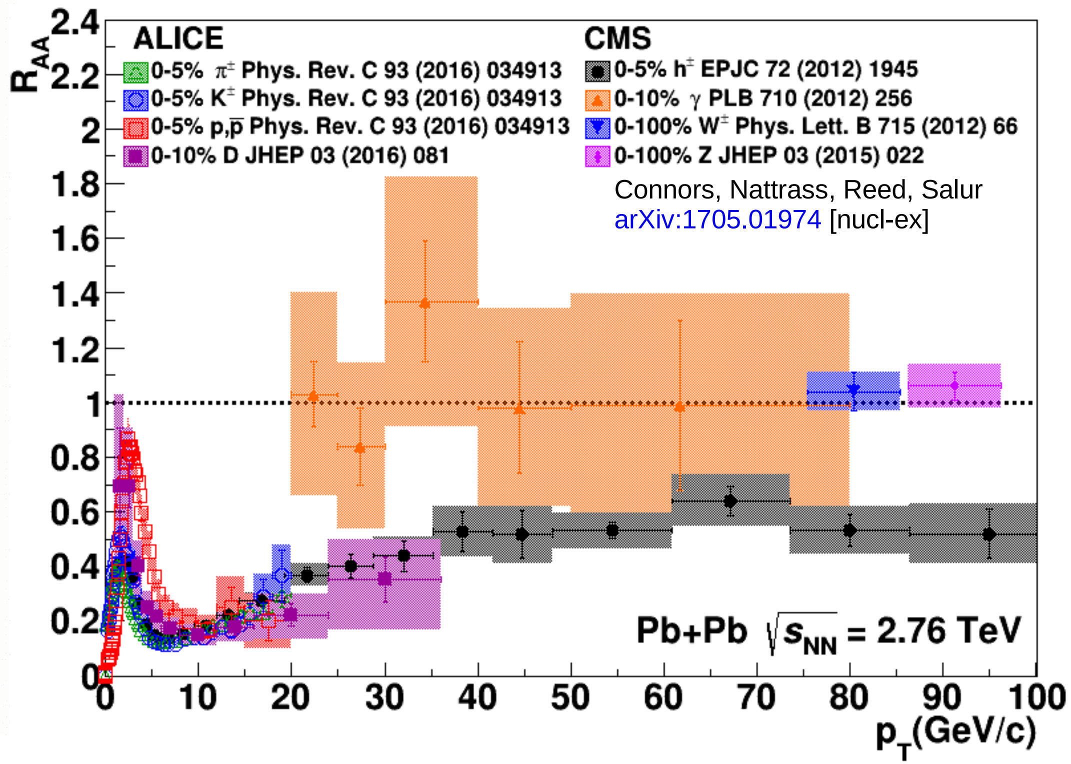


- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb

Nuclear modification factor R_{AA}

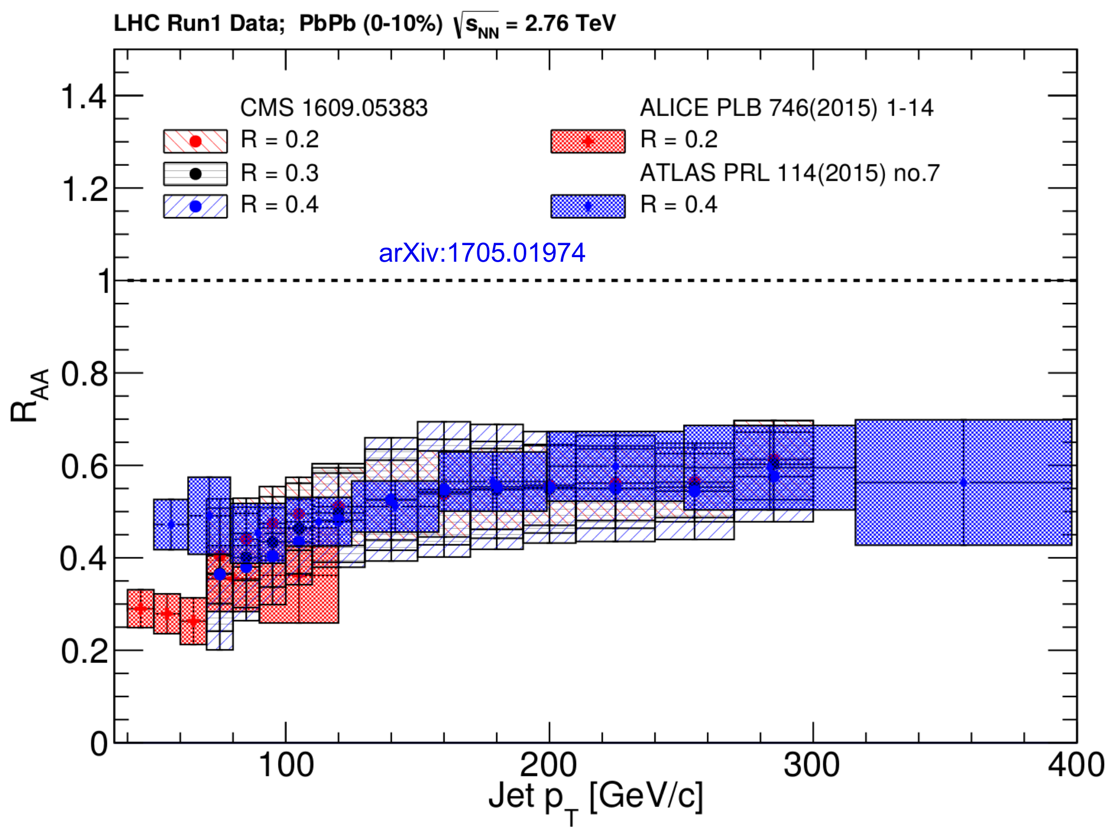
RHIC **LHC**





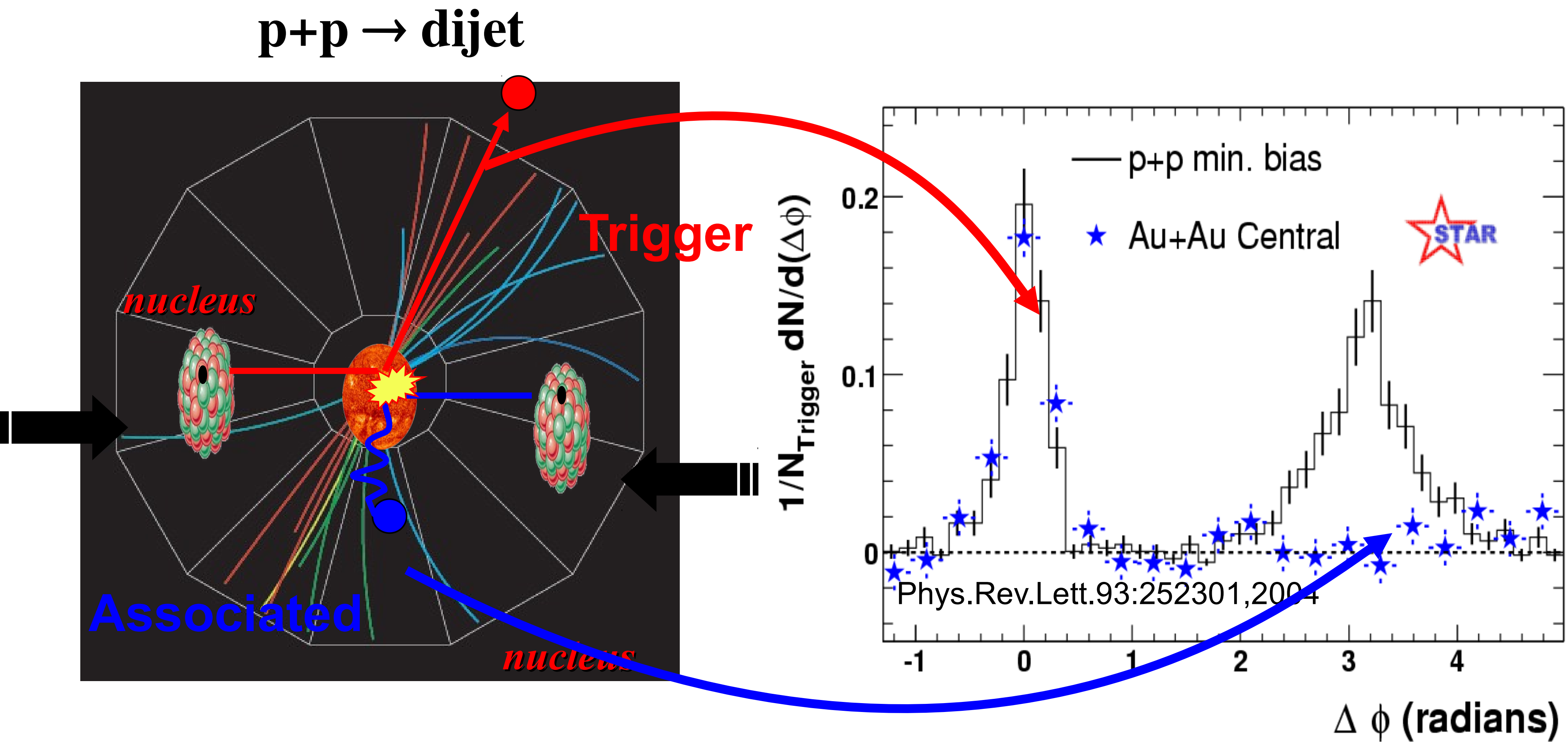
- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them - even heavy quarks!

Jet R_{AA}

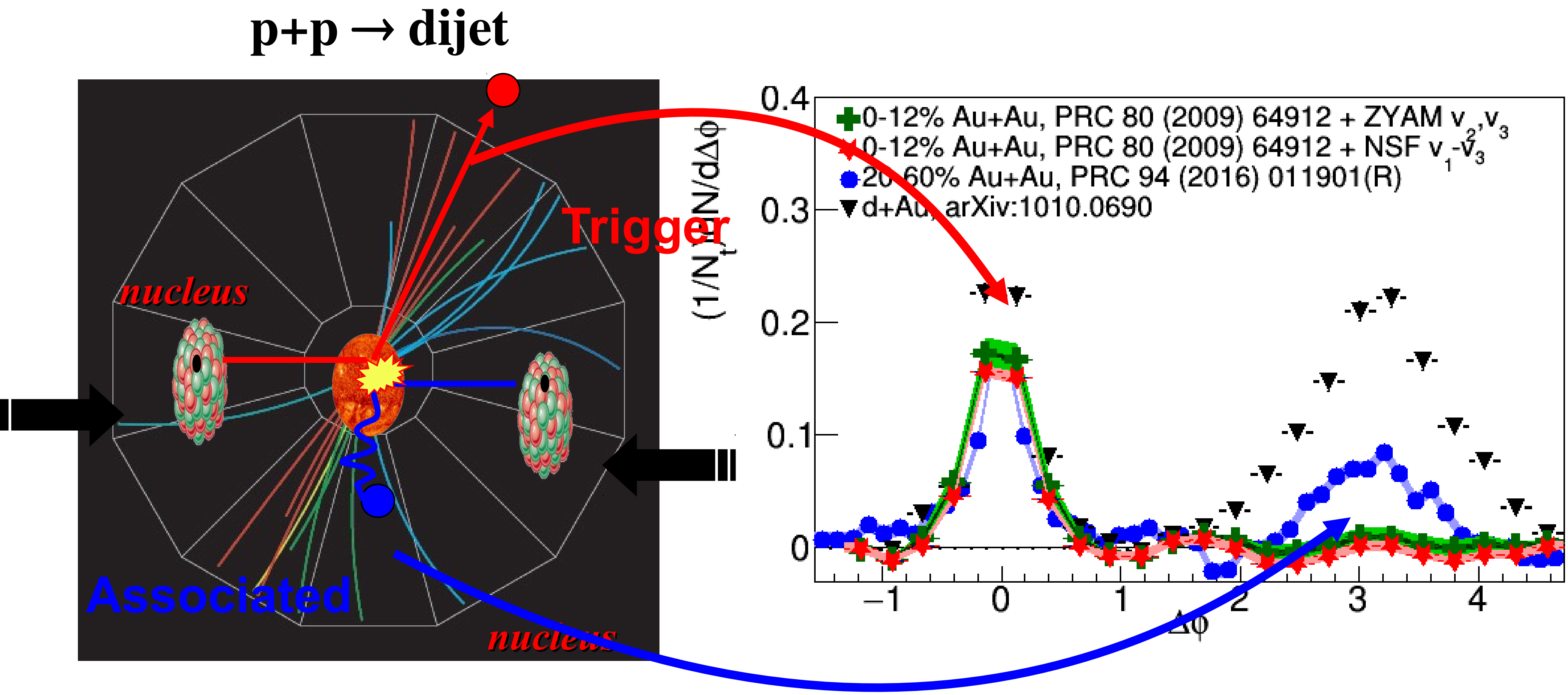


- Jet R_{AA} also demonstrates suppression

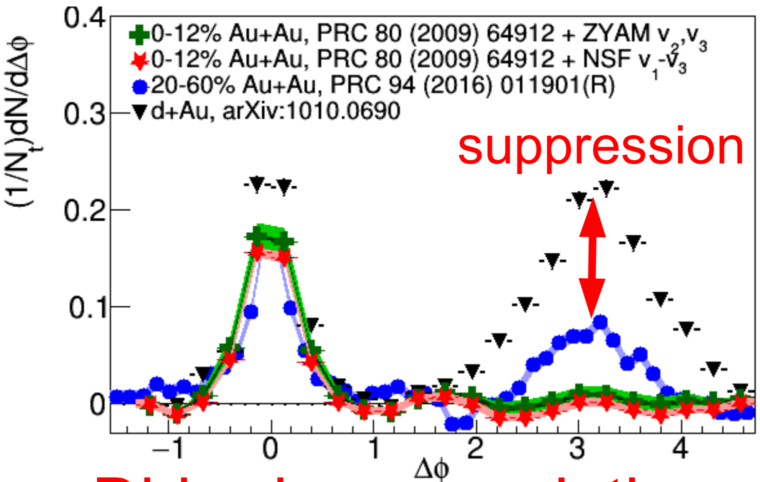
Di-hadron correlations



Di-hadron correlations



Updated to include latest information about background

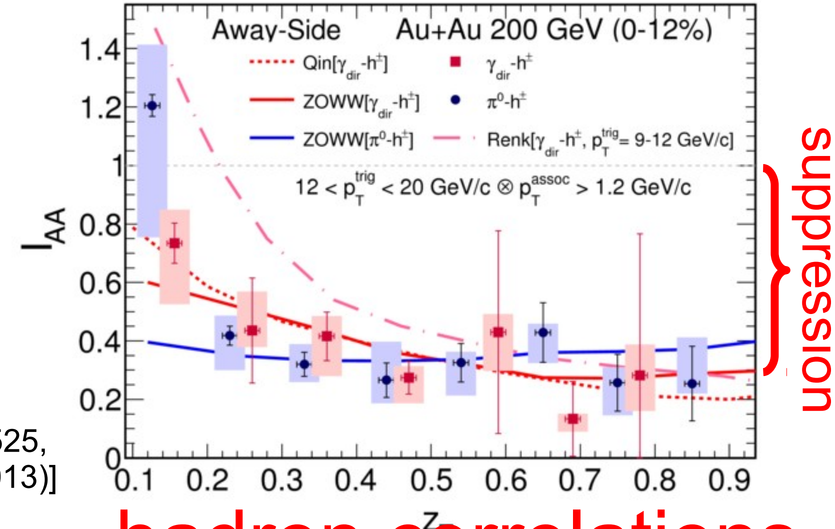


Di-hadron correlations

[Too many to list]

Jet v_2

[Phys.Lett. B 753 (2016) 511-525, Phys. Rev. Lett.111 152301 (2013)]

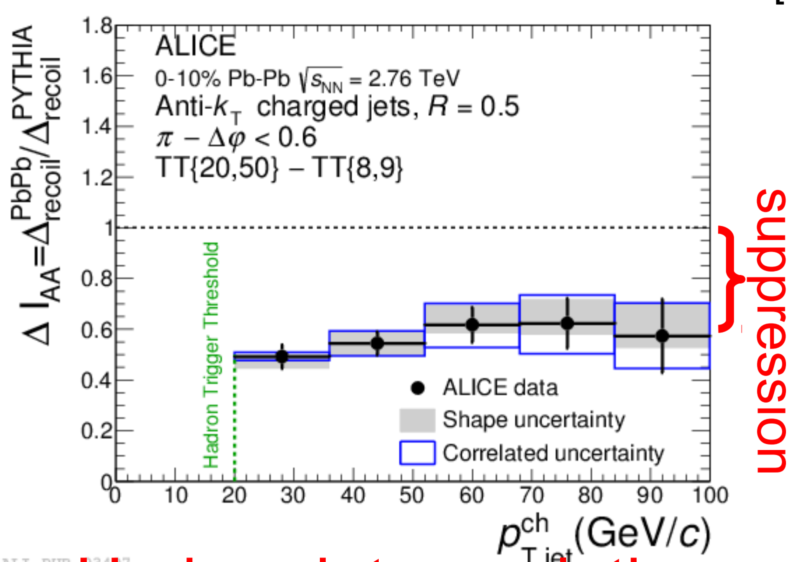


γ-hadron correlations

[Phys.Rev.C80:024908,2009, Phys.Rev.D82:072001,2010, Phys.Rev.C82:034909,2010 Physics Letters B 760 (2016)]

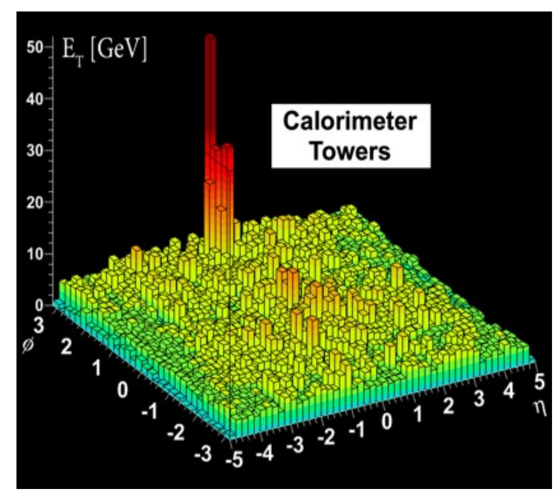
γ-jet correlations

[Phys. Lett. B 718 (2013) 773]



High-p_T hadron v_2

[too many to list]



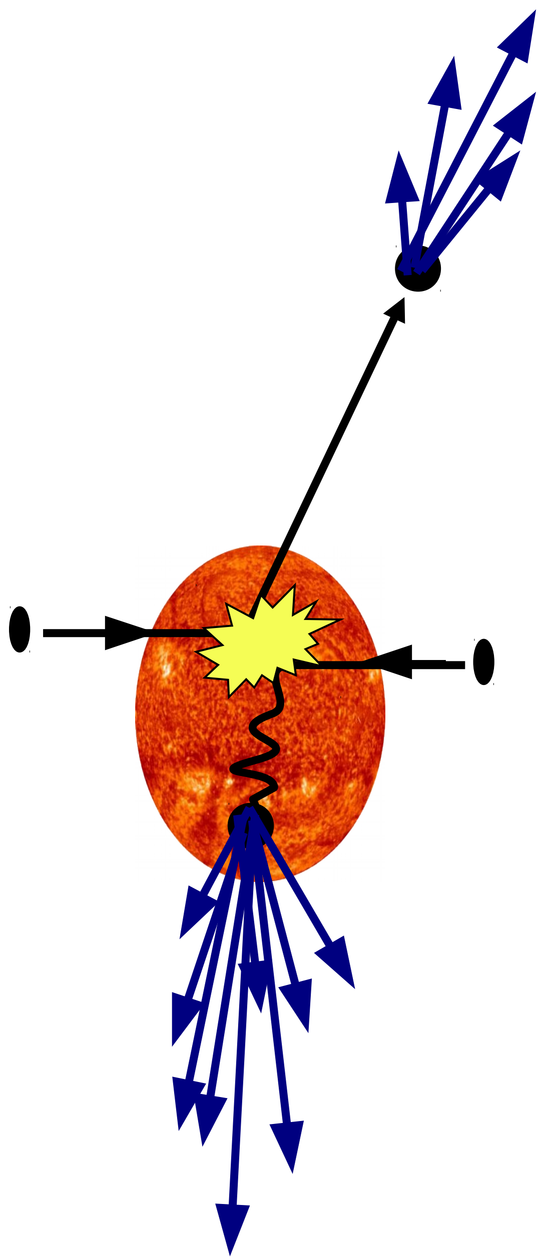
Hadron-jet correlations

[JHEP 09 (2015) 170, Phys. Rev. C 96, 024905 (2017)]

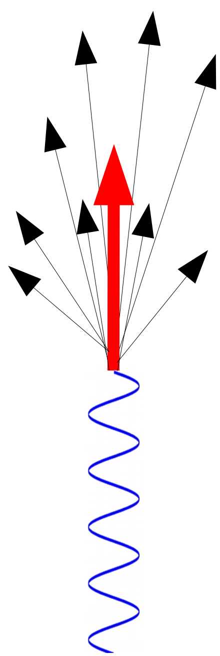
Dijet asymmetry

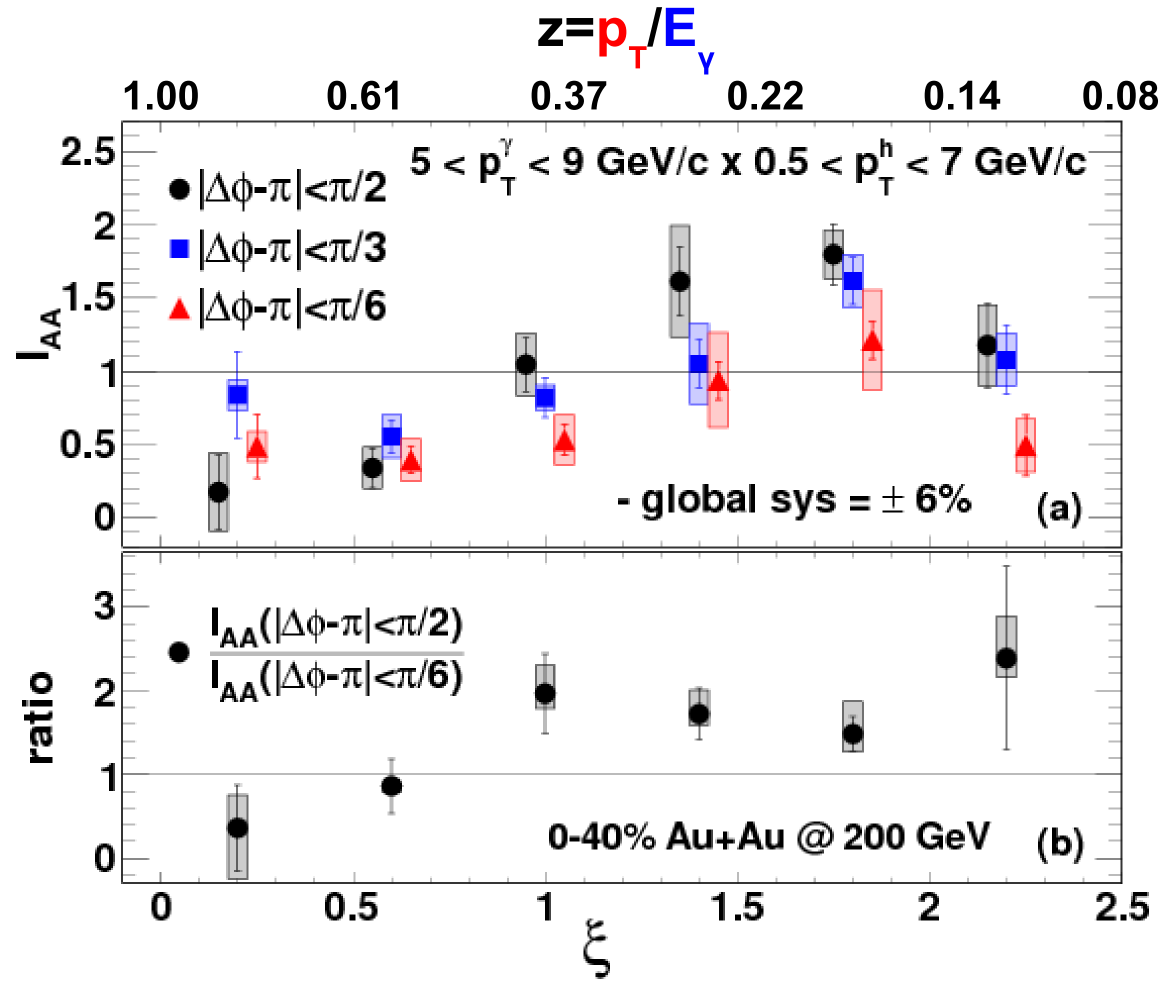
[Phys.Rev.C84:024906,2011, Phys. Lett. B 712 (2012) 176, Phys.Rev.Lett.105:252303,2010, Phys. Rev. Lett. 119, 062301 (2017)]

Fragmentation



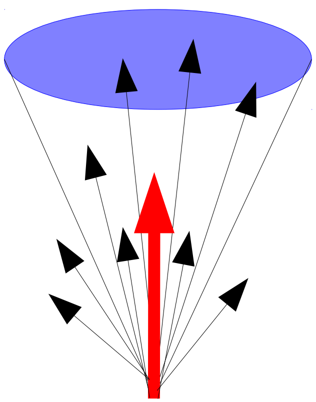
Fragmentations from γ-hadron correlations

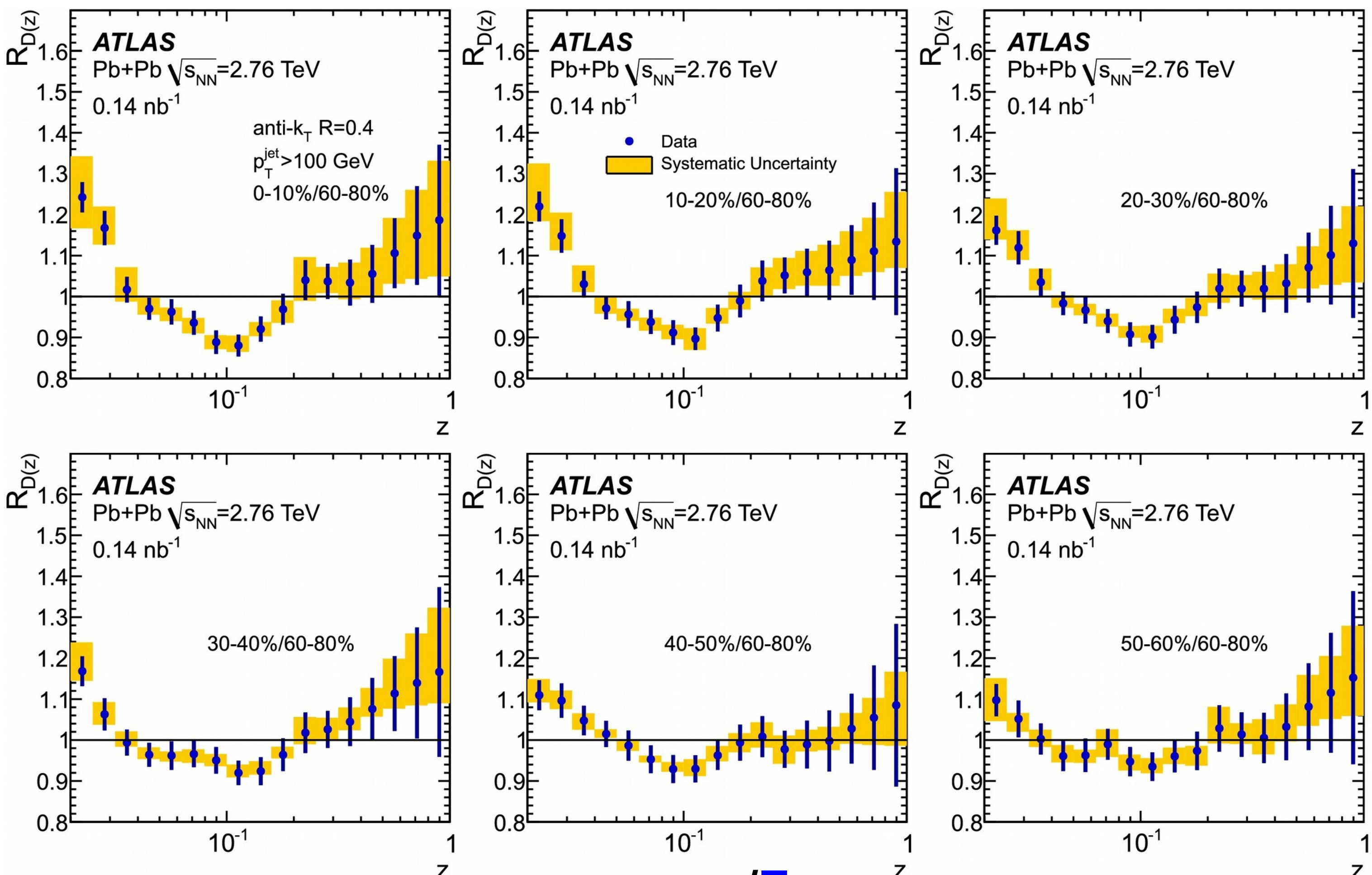




- Enhancement at low z
- Slight suppression at high z

Modified fragmentation



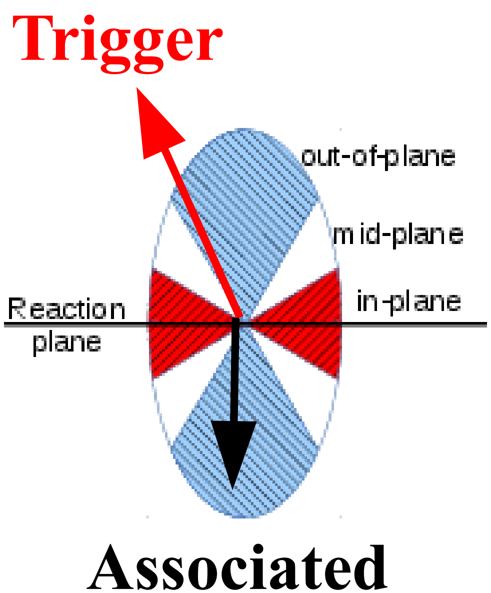


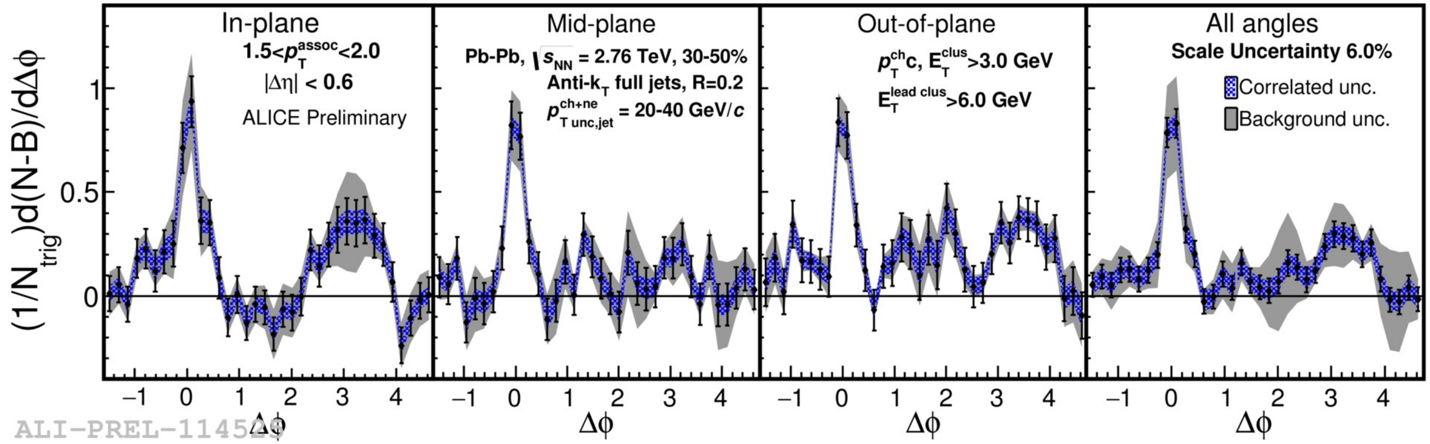
$z = p_T / E_\gamma$

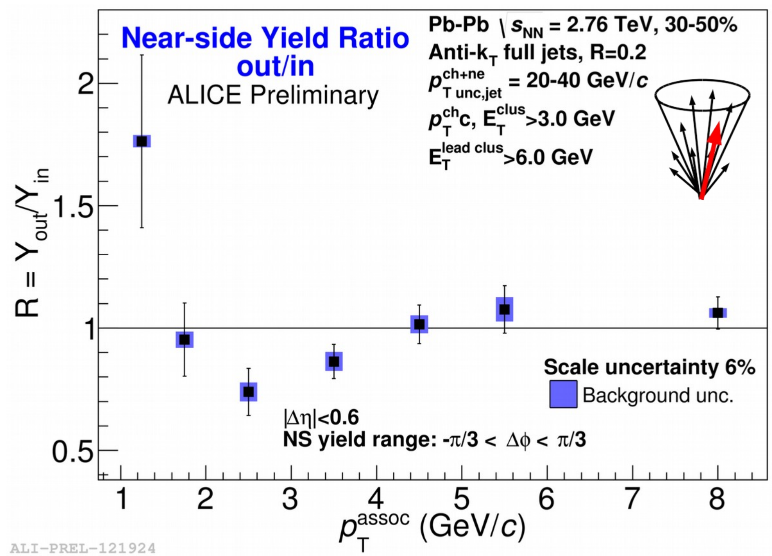
- Enhancement at low z
- No modification/enhancement at high z?

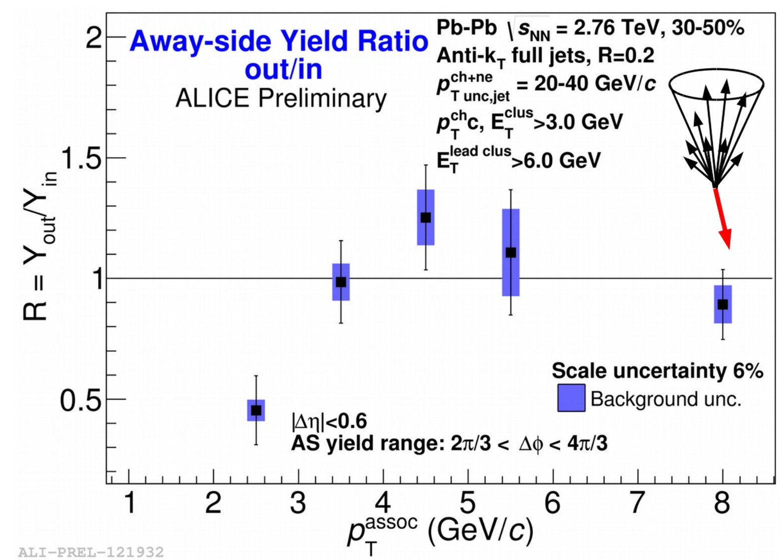
Jet-hadron correlations vs reaction plane

Full jets
1) signal+bkgd
2) bkgd dominated
3) bkgd RPF fit







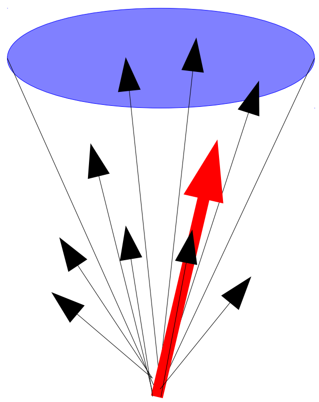


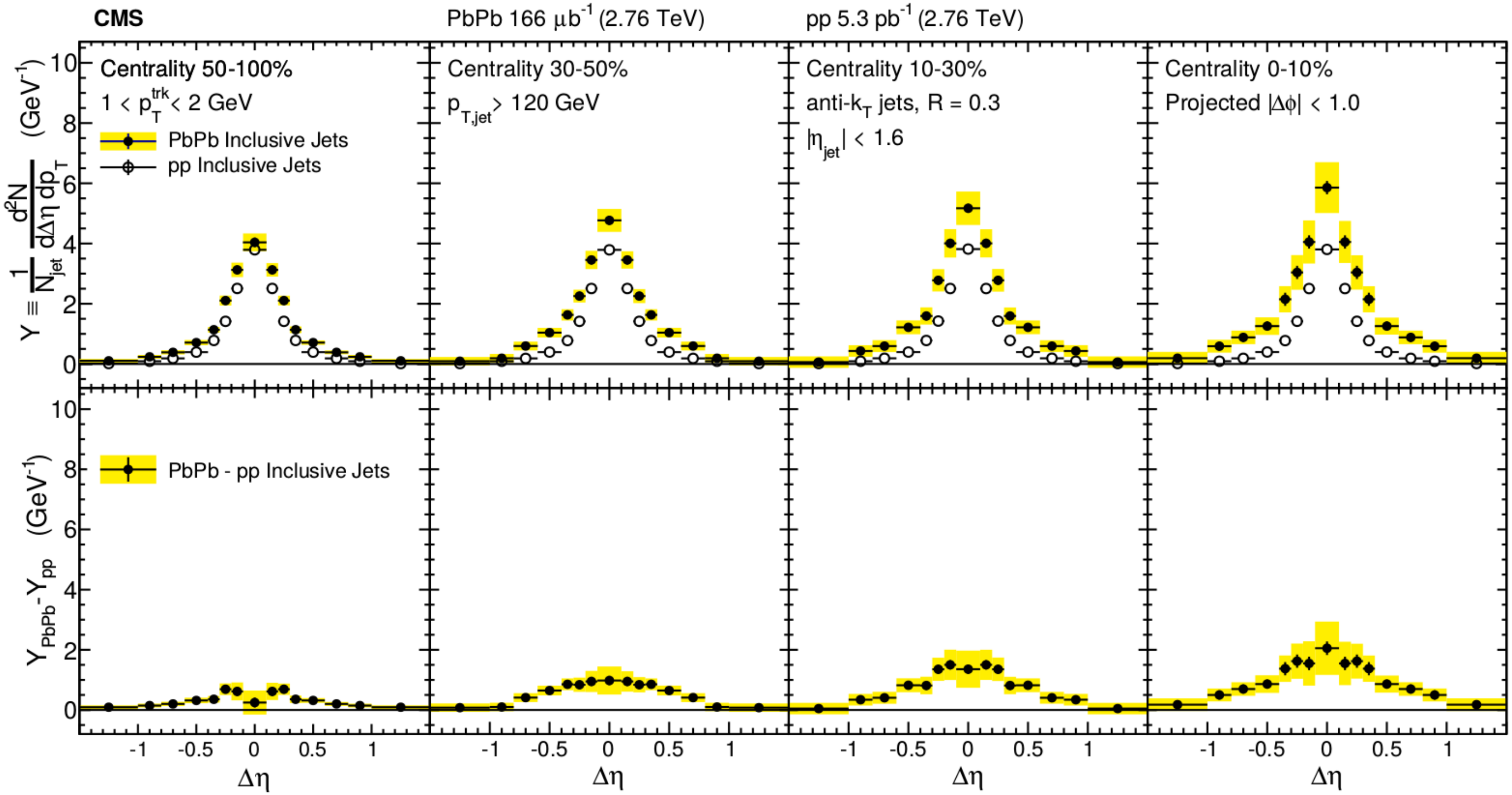
- No modification of constituents relative to reaction plane

  → Jet-by-jet fluctuations more important than path length [PLB 735 157(2014)]

  – Also needed to explain high p_T v_2 [PRL 116 252301 (2016)]

Jet-hadron correlations

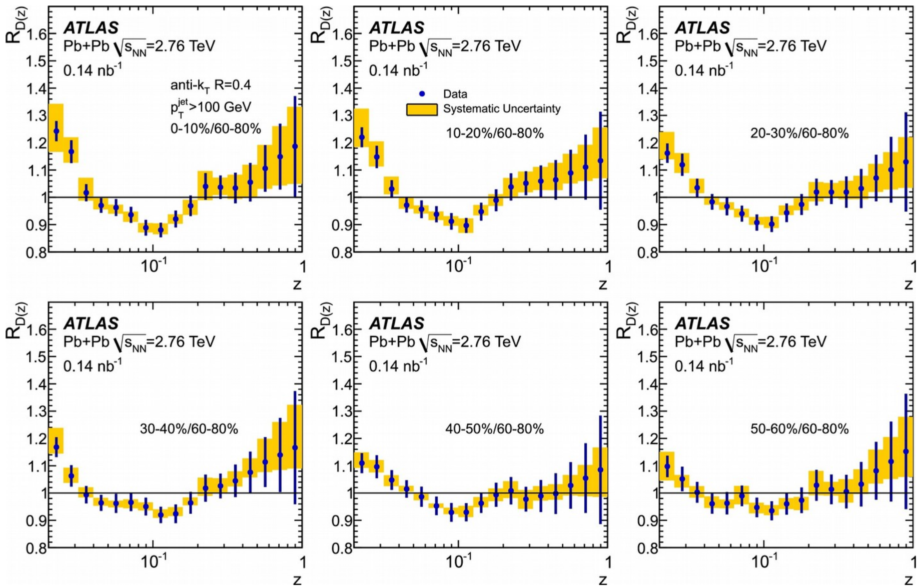


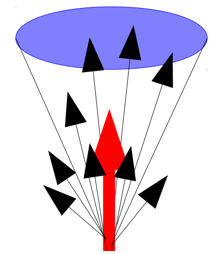


- Jets are broader, constituents are softer
- Also seen in:
  - Di-hadron correlations [Lots of papers]
  - Jet shapes [arXiv:1708.09429, arXiv:1512.07882, arXiv:1704.03046]
  - Dijet asymmetry with soft constituents [PRL119 (2017) 62301]

Modified fragmentation

Fragmentation functions with jets





$z = p_T / E_\gamma$

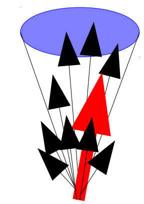
Di-hadron correlations

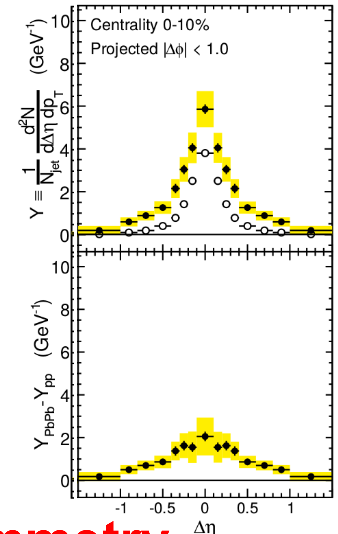
[Lots of papers]

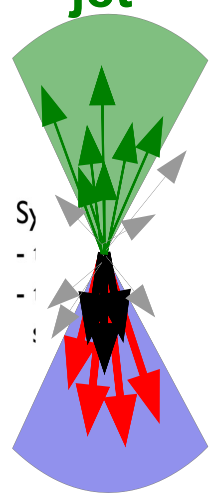
Jet shapes

[arXiv:1708.09429, arXiv:1512.07882, arXiv:1704.03046]

Jet-hadron correlations

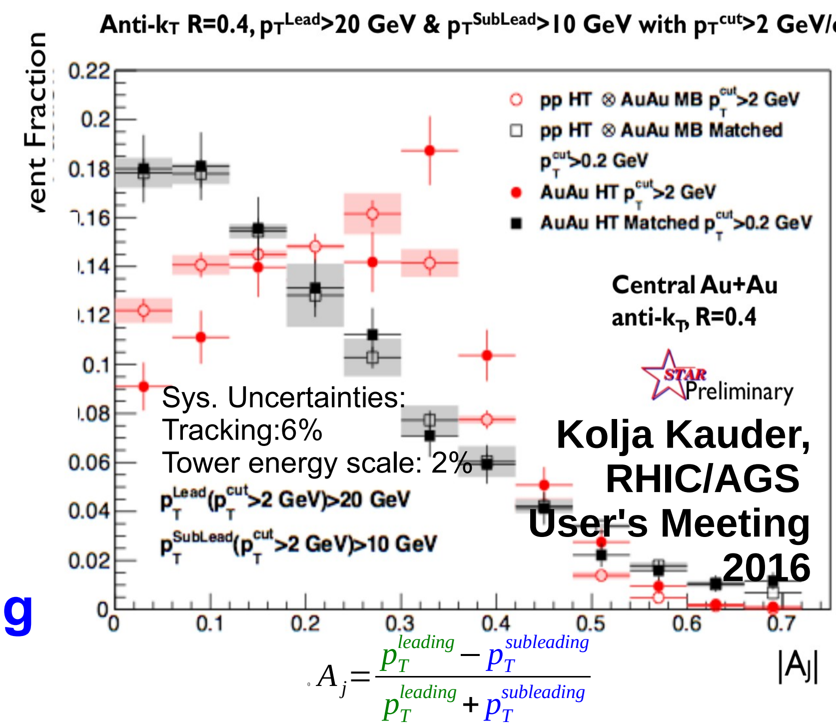




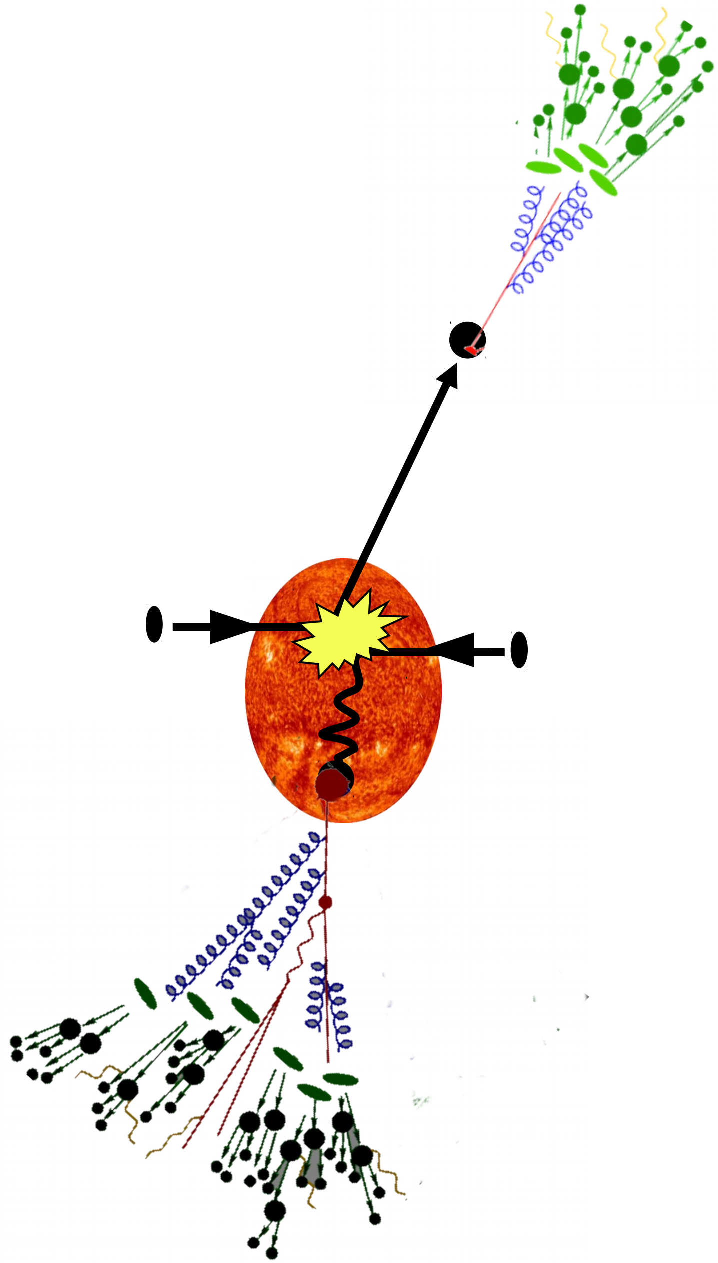


Di-jet asymmetry

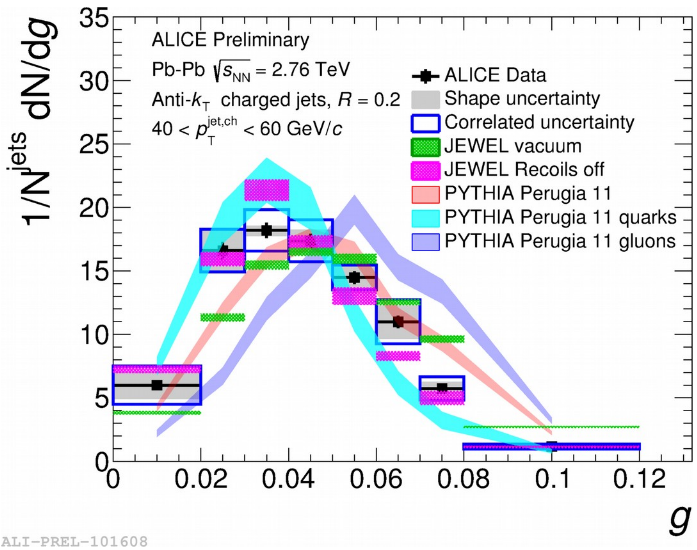
arXiv:1609.03878



Jet structure

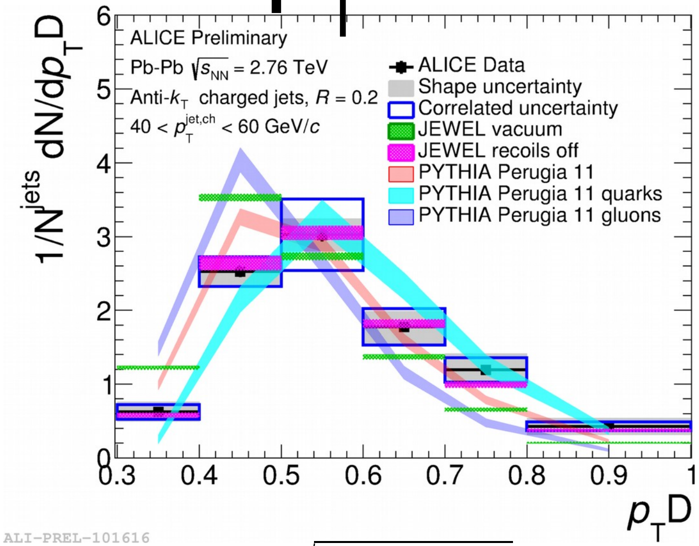


Girth g



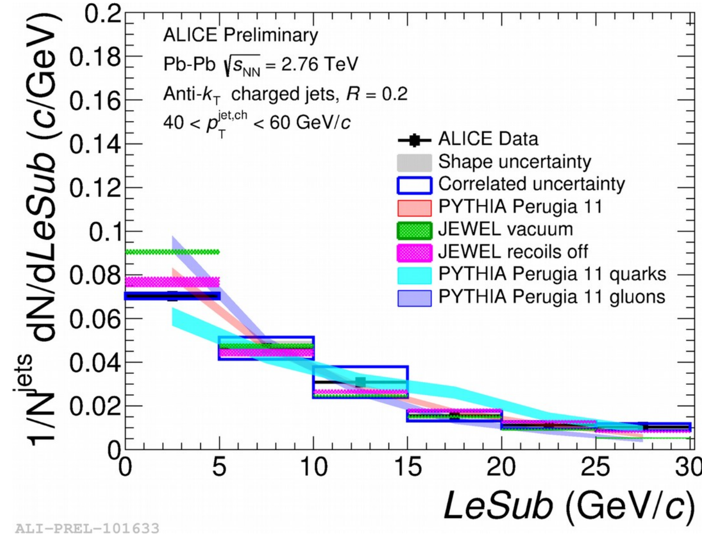
$$g = \sum_{i \in jet} \frac{p_T^i}{p_T^{jet}} r_i$$

Dispersion $p_T D$



$$p_T D = \frac{\sqrt{\sum_{i \in jet} (p_T^i)^2}}{\sum_{i \in jet} p_T^i}$$

LeSub



$$LeSub = p_T^{leading} - p_T^{subleading}$$

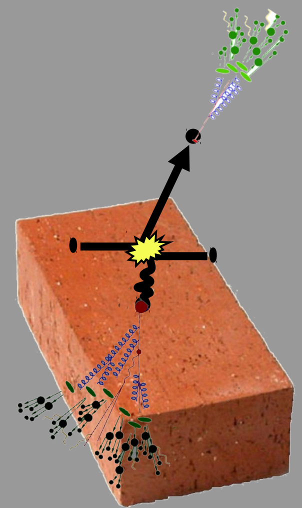
Jets are slightly more collimated than in pp

Agrees with PYTHIA

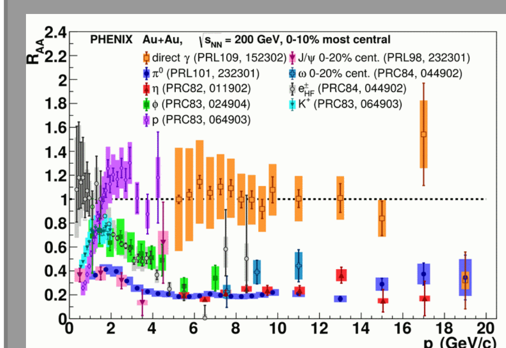
Theory

JET collaboration

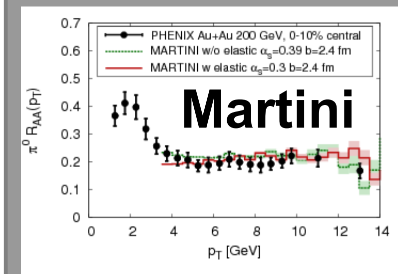
Phys. Rev. C 90, 014909 (2014)

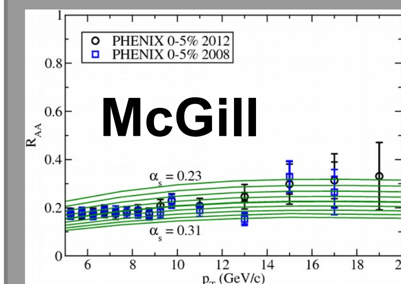


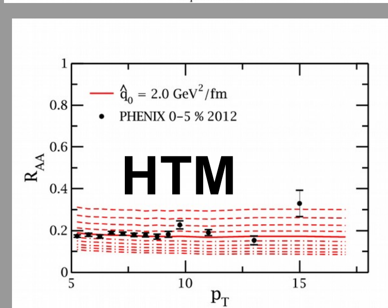
QGP brick + jet

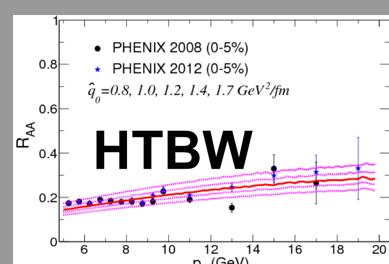


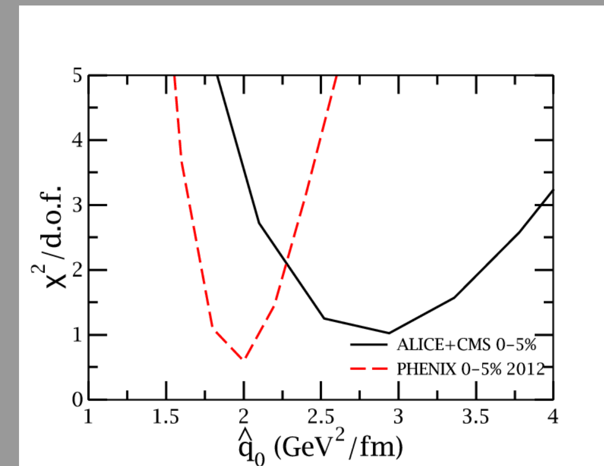
Data



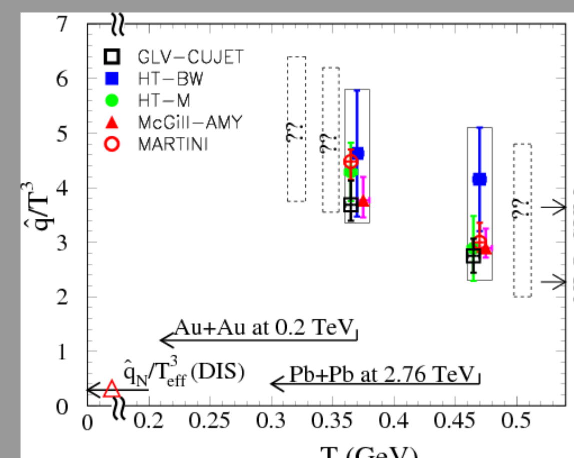








χ^2 *minimization*



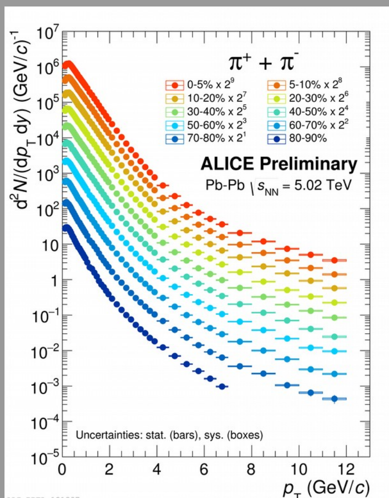
$\hat{q} = 1.2 \pm 0.3 \quad GeV^2$ 200 GeV Au+Au

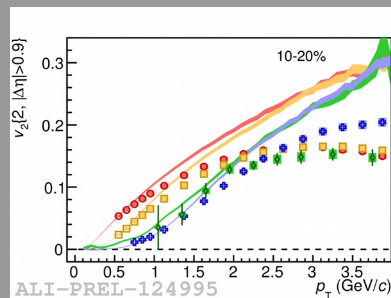
$\hat{q} = 1.9 \pm 0.7 \quad GeV^2$ 2.76 TeV Pb+Pb

Bayesian Statistical Analysis

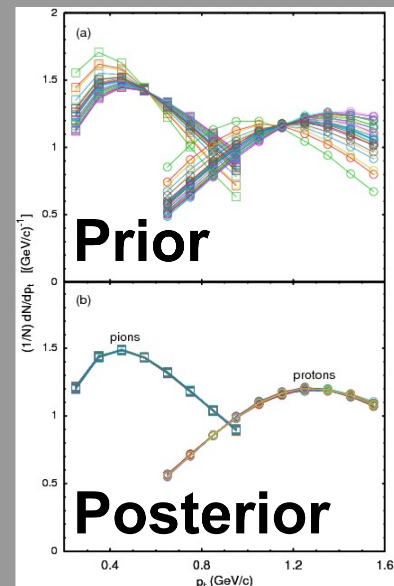
Models and Data Analysis Initiative

http://madai.us

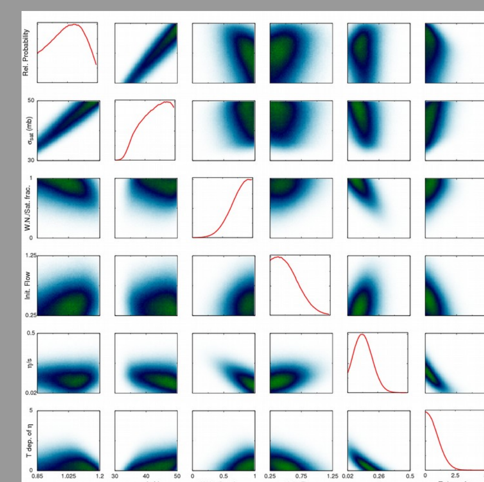




Data



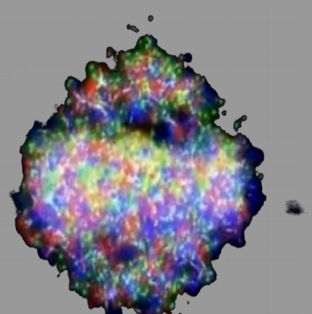
Optimization



Constraint of QGP properties

Novak et al, Phys.Rev. C89 (2014) no.3, 034917

Monte Carlo models



Model emulation

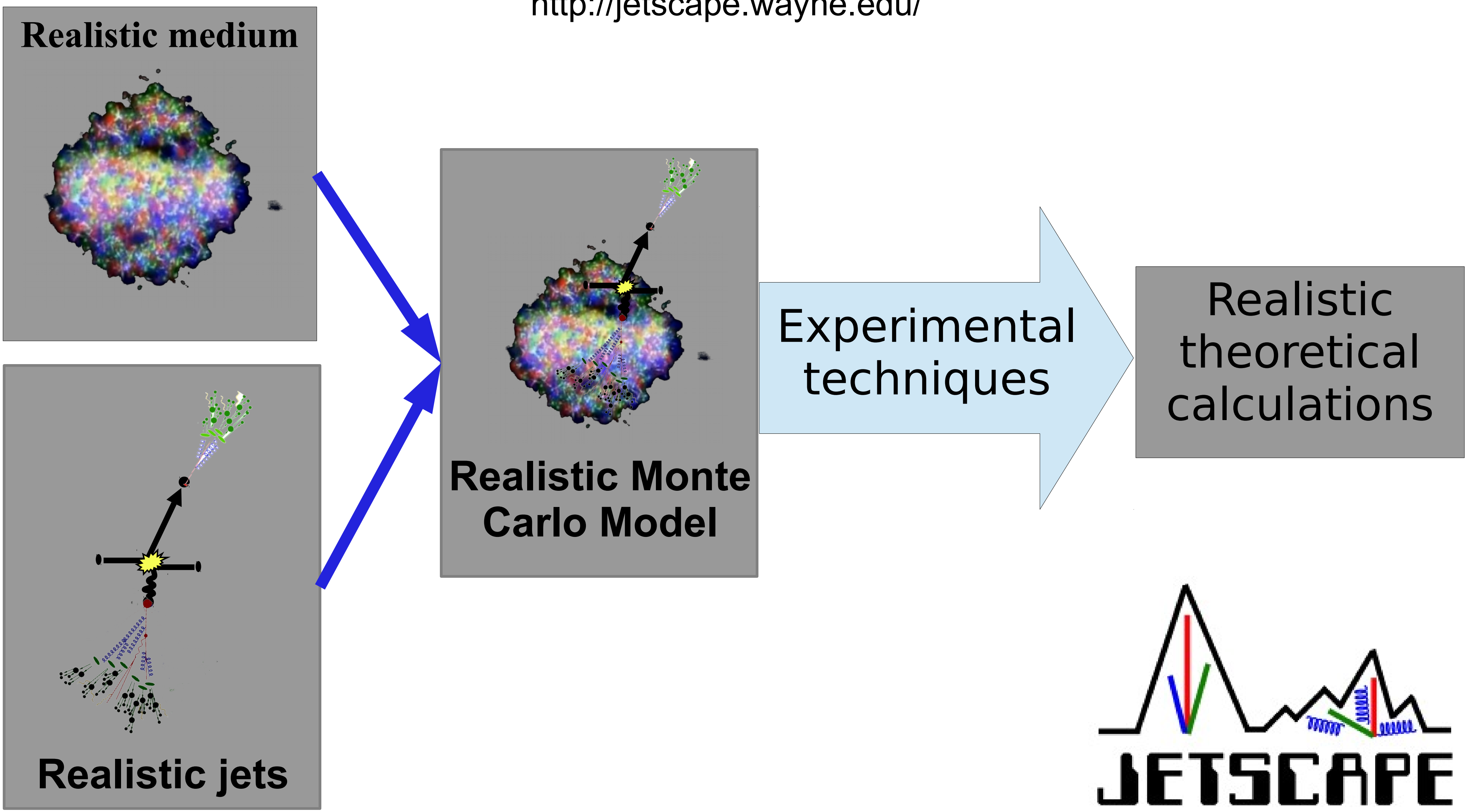
1) Run full model ~1000 times
2) MCMC parameter search uses emulator (interpolator) in lieu of full model

JETSCAPE

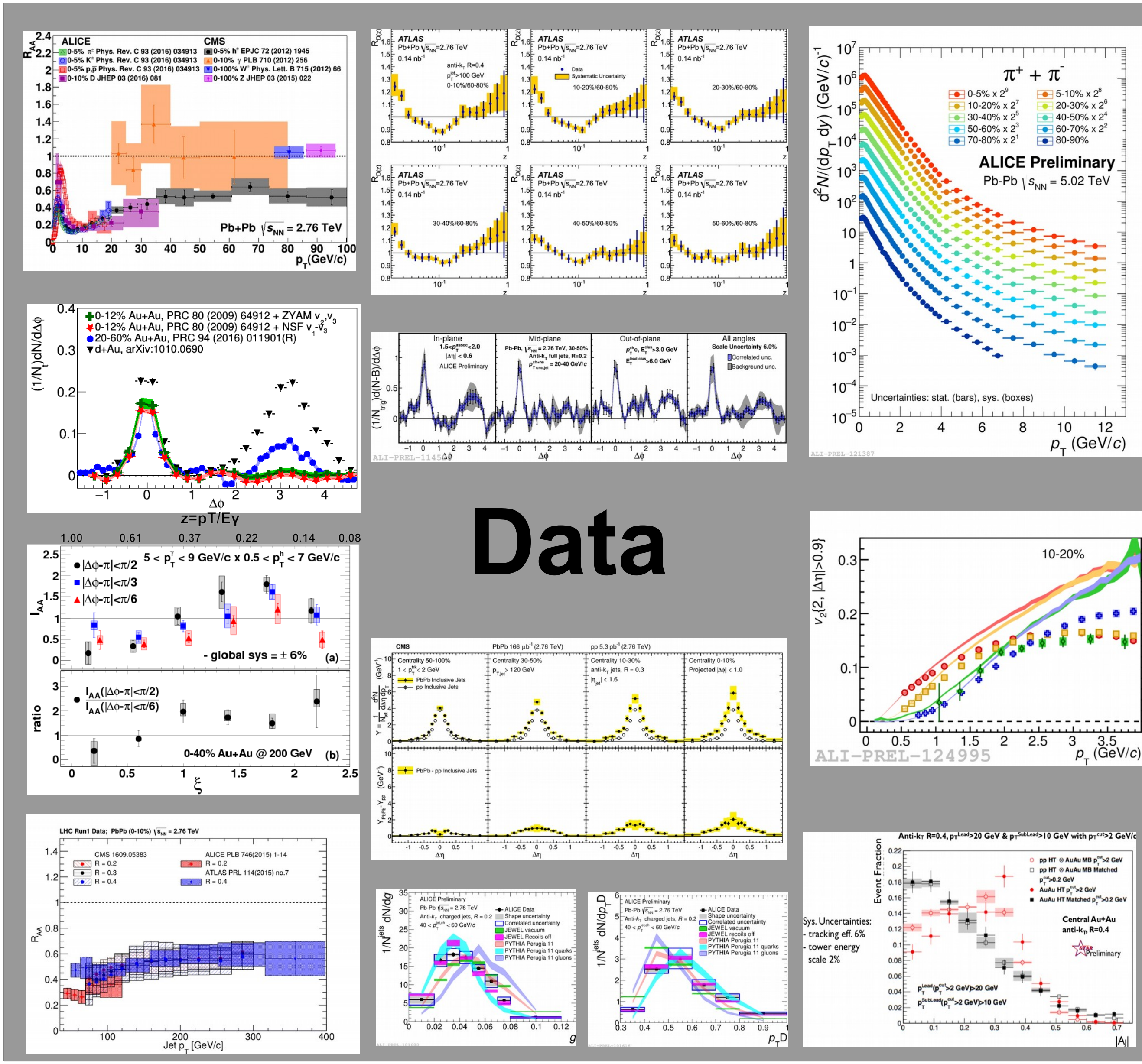
Event generator

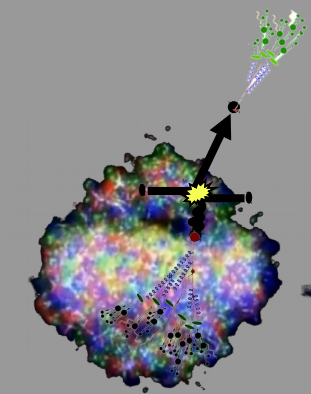
Jet **E**nergy-loss **T**omography with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvelope

http://jetscape.wayne.edu/



Event Generator + Bayesian Statistical analysis





Realistic theoretical calculations

Bayesian Statistical Analysis

Constraint of QGP properties

Undergraduates!*

Left to right: Ricardo Santos (Berea), James Neuhaus, Jerrica Wilson, Mariah McCreary, Christine Nattrass, Austin Schmier (UTK)

*And one beginning graduate student with no programming experience.

We acknowledge substantial support from the US NSF and the JETSCAPE Collaboration

Course-based undergraduate research experience

CBE—Life Sciences Education, Vol. 15, No. 2 | Articles

Free Access

Early Engagement in Course-Based Research Increases Graduation Rates and Completion of Science, Engineering, and Mathematics Degrees

Stacia E. Rodenbusch, Paul R. Hernandez, Sarah L. Simmons, and Erin L. Dolan

Jennifer Knight, Monitoring Editor:

Published Online: 13 Oct 2017 | https://doi.org/10.1187/cbe.16-03-0117

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Abstract

National efforts to transform undergraduate biology education call for research experiences to be an integral component of learning for all students. Course-based undergraduate research experiences, or CUREs, have been championed for engaging students in research at a scale that is not possible through apprenticeships in faculty research laboratories. Yet there are few if any studies that examine the long-term effects of participating in CUREs on desired student outcomes, such as graduating from college and completing a science, technology, engineering, and mathematics (STEM) major. One CURE program, the Freshman Research Initiative (FRI), has engaged thousands of first-year undergraduates over the past decade. Using propensity score–matching to control for student-level differences, we tested the effect of participating in FRI on students' probability of graduating with a STEM degree, probability of graduating within 6 yr, and grade point average (GPA) at graduation. Students who completed all three semesters of FRI were significantly more likely than their non-FRI peers to earn a STEM degree and graduate within 6 yr. FRI had no significant effect on students' GPAs at graduation. The effects were similar for diverse students. These results provide the most robust and best-controlled evidence to date to support calls for early involvement of undergraduates in research.

Phys 494 – Course-based Undergraduate Research Experience in Relativistic Heavy Ion Physics

Instructor:
Dr. Christine Nattrass
Office: SERF 609
Phone: 974-6211
Email: christine.nattrass@utk.edu
Office hours: TBA

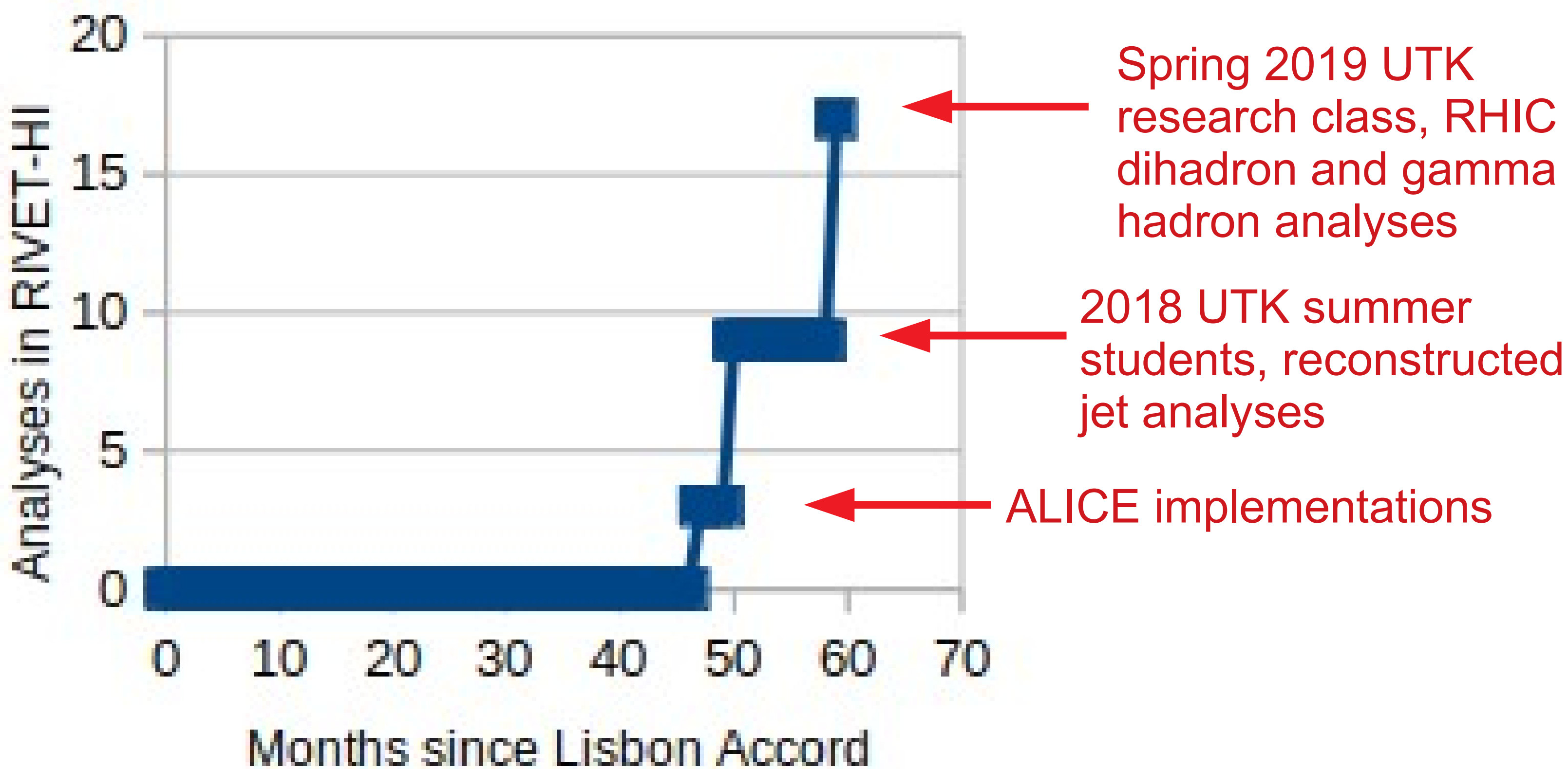
Teaching assistant: N/A

Class time & Location: TR 12:40-1:55 SERF 210

Course Description:
This course will incorporate undergraduates into a research project in high energy nuclear physics in a course setting. Each student will be responsible for implementing a heavy ion analysis in the program RIVET so that it can be used by the JETSCAPE collaboration to make comparisons between Monte Carlo models and data. Each student's project will be incorporated into a public software repository so that it is available to the field and, if possible, it will be validated by the relevant experiment and incorporated into the official RIVET software.

https://i.ytimg.com/vi/mZnv6LXD9qs/maxresdefault.jpg

Analyses (almost) implemented in UTK copy of RIVET



https://github.com/cnattras/rivet-hi

Need to be finalized! Hold me to it!

What have we accomplished?

- **Qualitative confirmation of partonic energy loss models**
- **Quantitative constraints of $\hat{q}$**
- **Lots of measurements**

What do we still have to do?

- **Understand bias**
- **Make quantitative comparisons to theory**
- **Make more differential measurements**
- **We need an accord on how to treat background**

Connors, Nattrass, Reed, Salur arXiv:1705.01974 [nucl-ex]