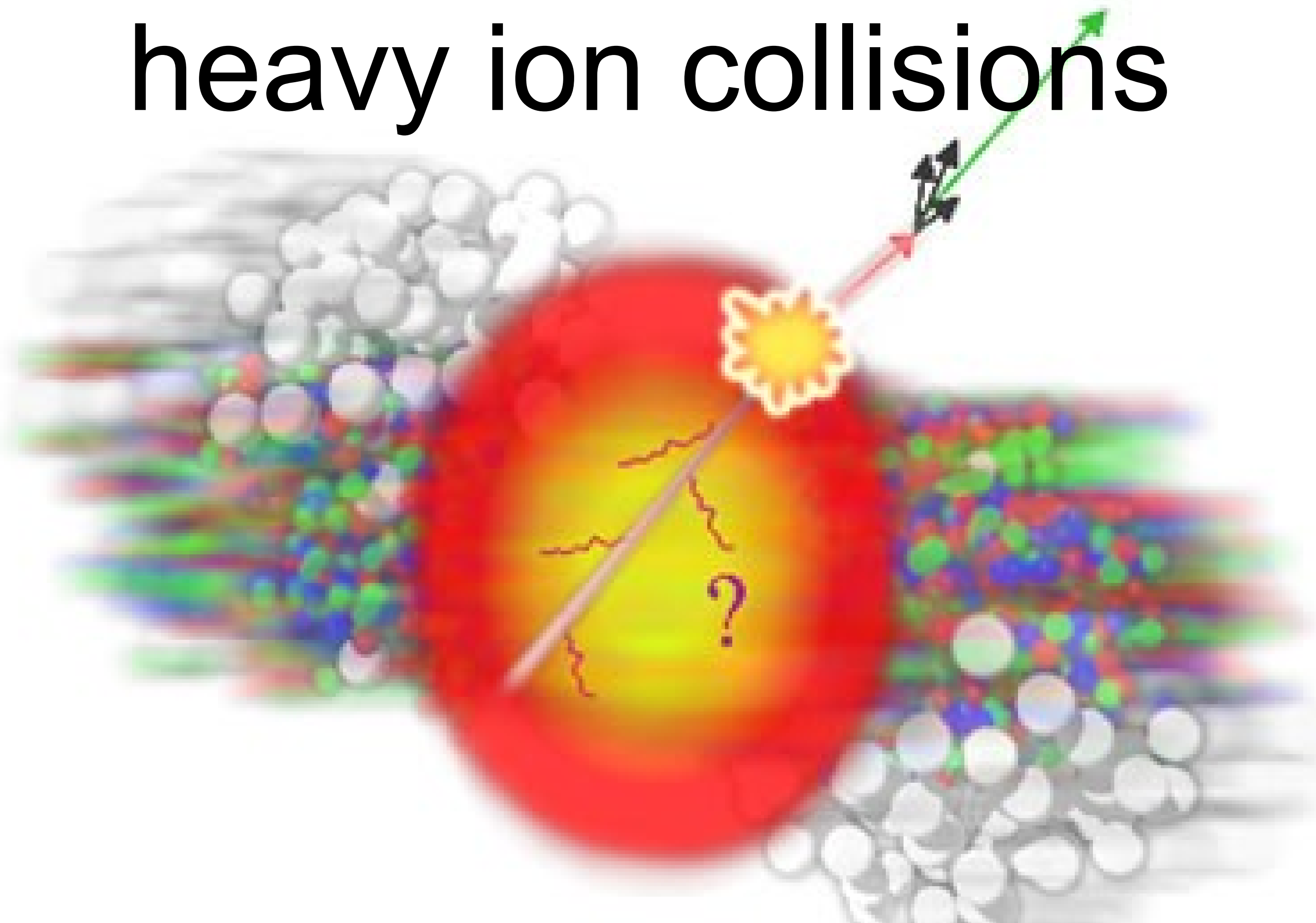
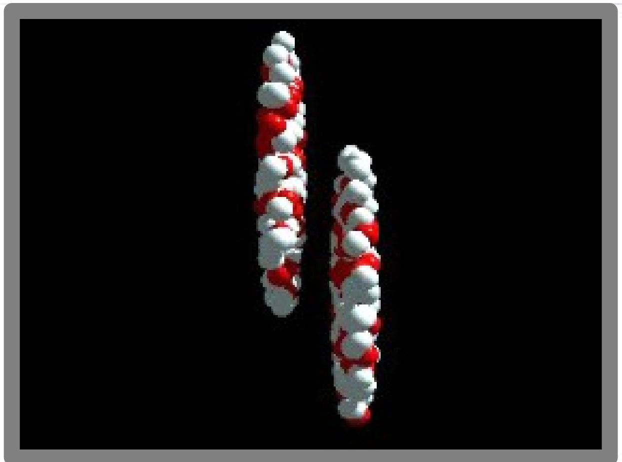
What have we learned from jets in heavy ion collisions



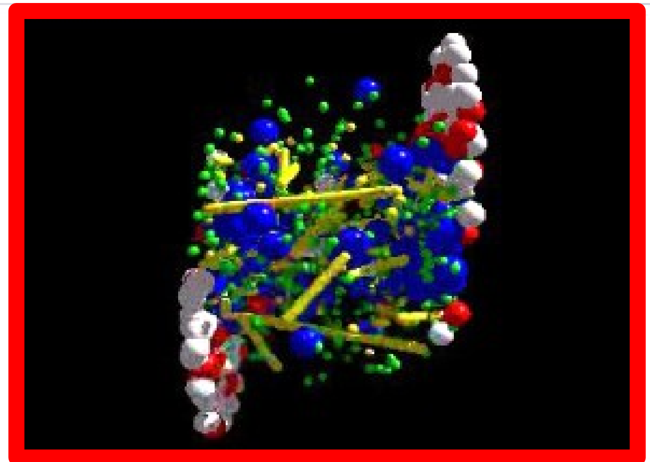
Christine Nattrass
University of Tennessee, Knoxville
Largely based on Connors, Nattrass, Reed, & Salur arxiv:1705.01974

The phase transition in the laboratory

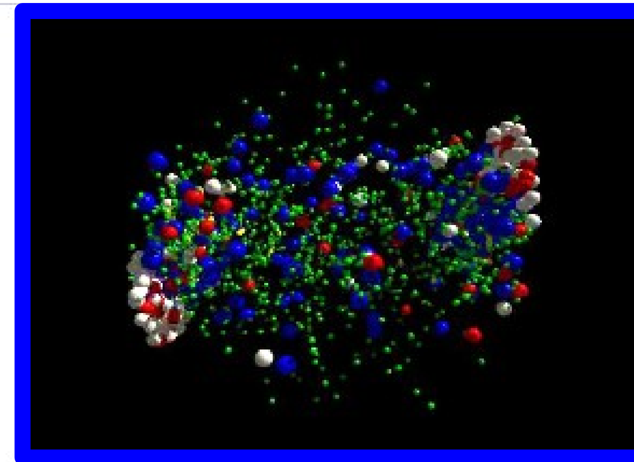
Initial State

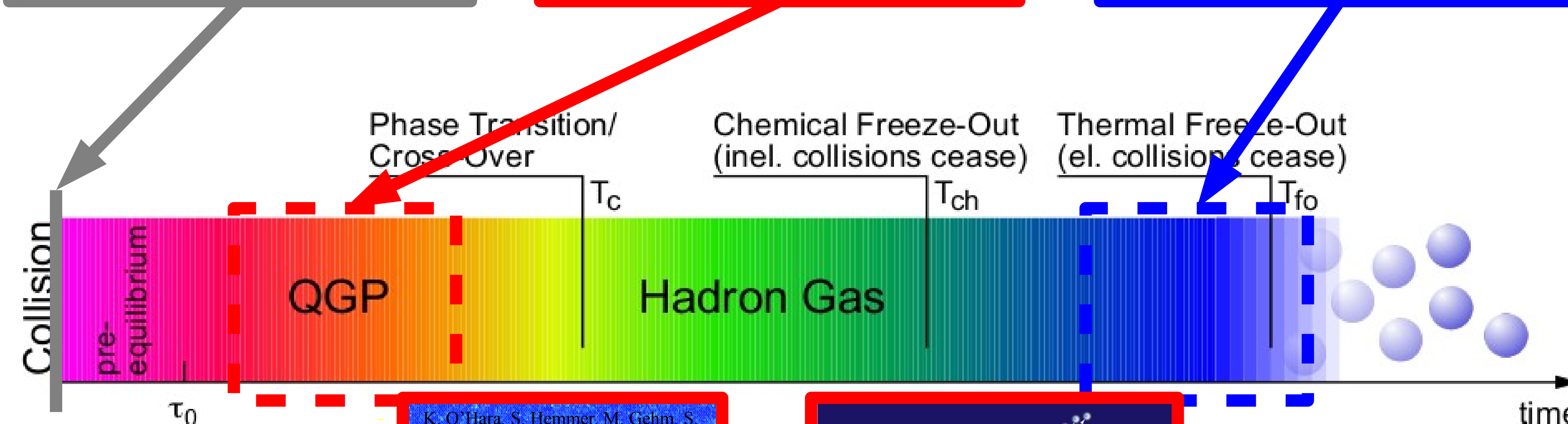


QGP

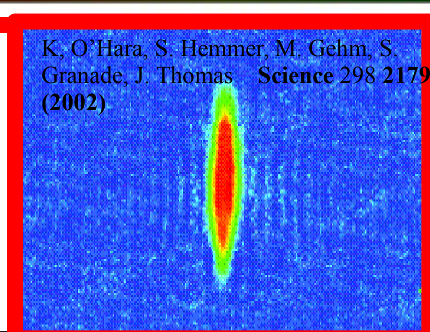


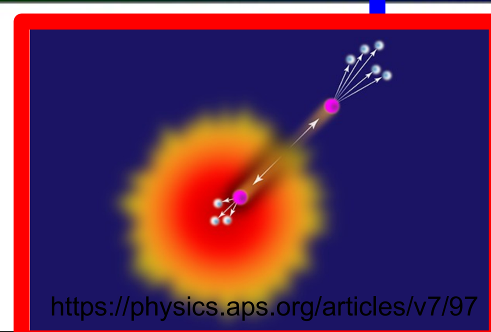
Freeze-out





Hydrodynamical flow

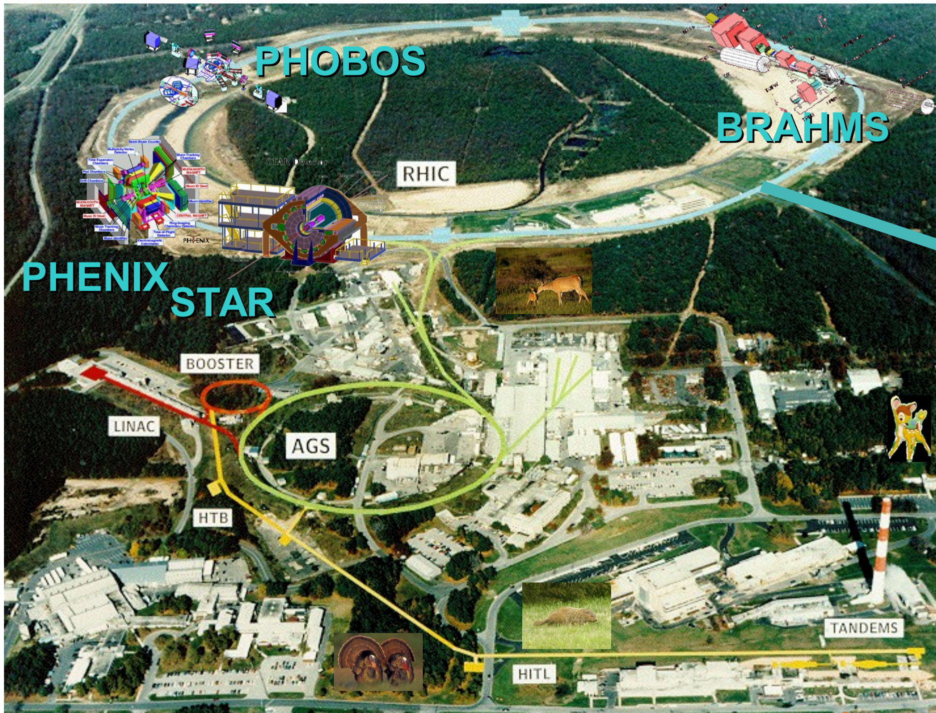


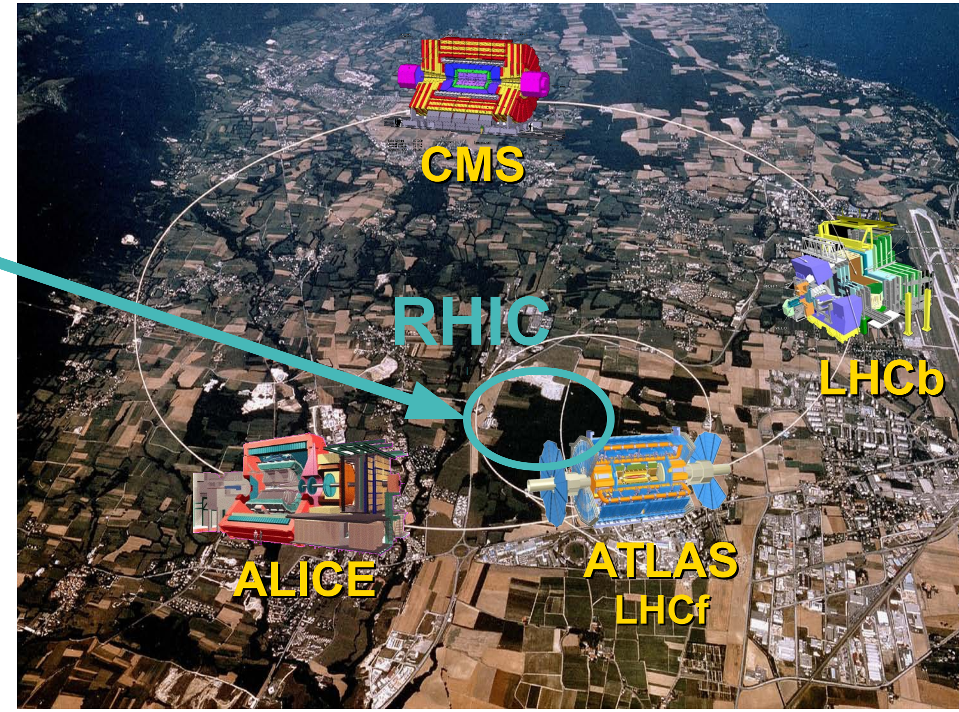


Jet quenching

Relativistic Heavy Ion Collider

Large Hadron Collider

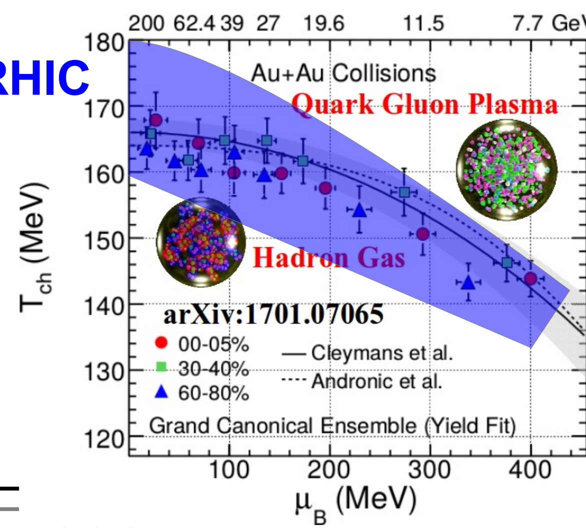




Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+U*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

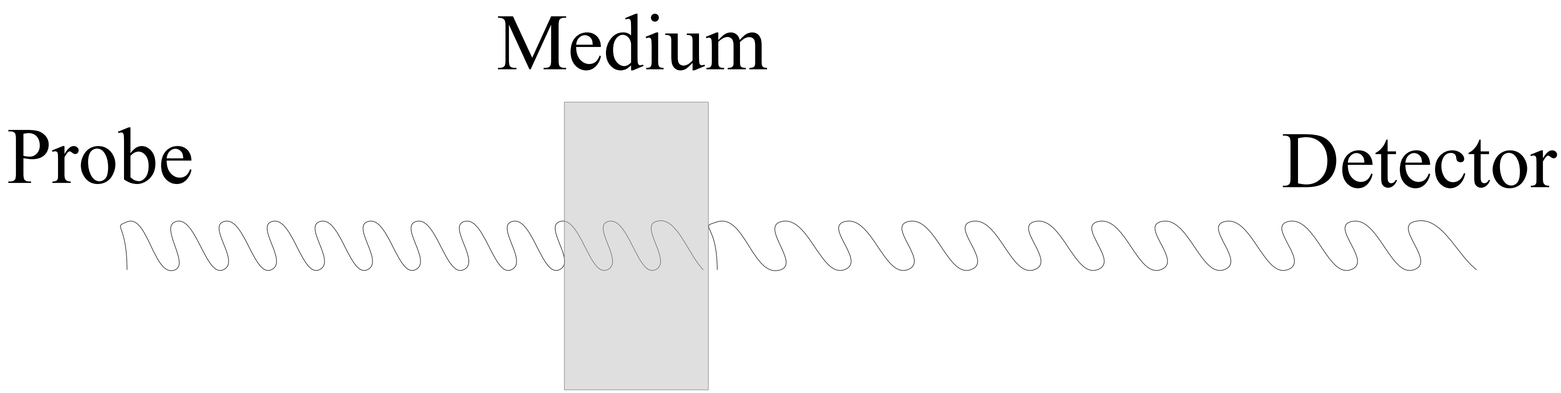
LHC

RHIC



Geneva, Switzerland
8.6km diameter
p+p, *p+Pb*, Pb+Pb
$\sqrt{s_{NN}}$ = 2.76 GeV, *5.5 TeV*

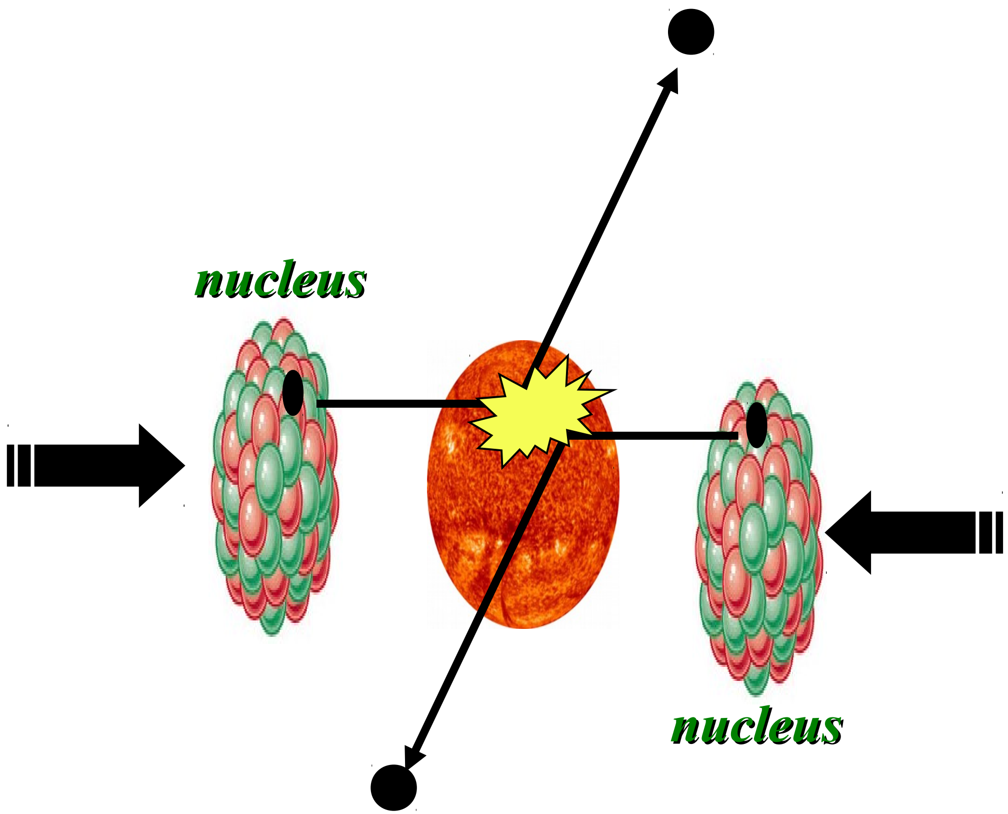
Probing the Quark Gluon Plasma



Want a probe which traveled through the collision

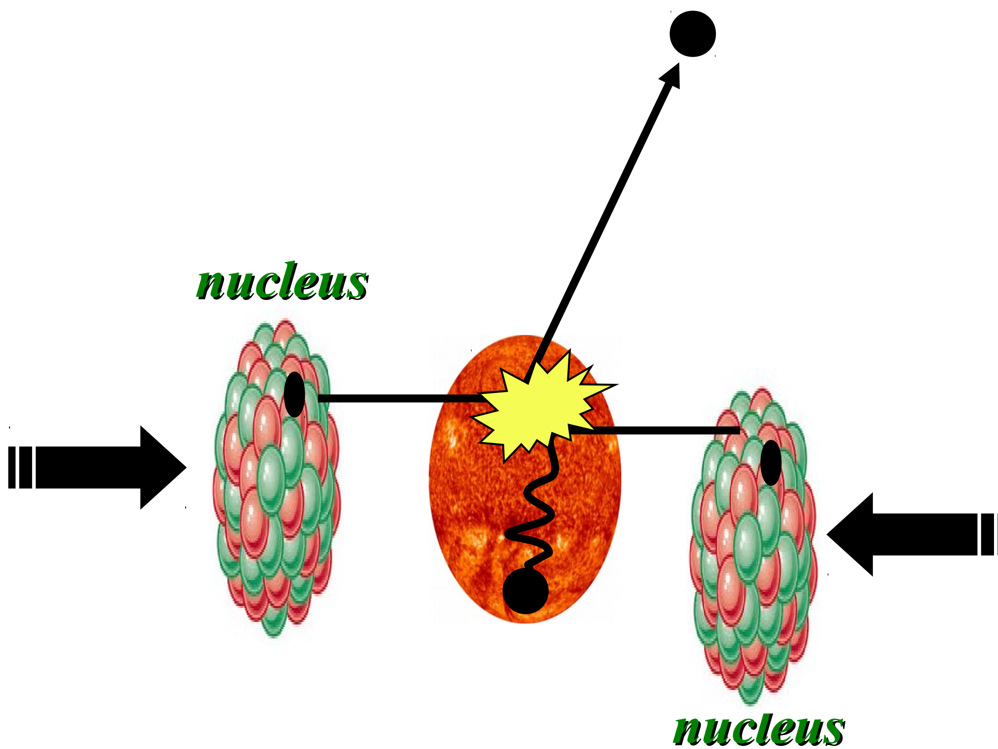
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



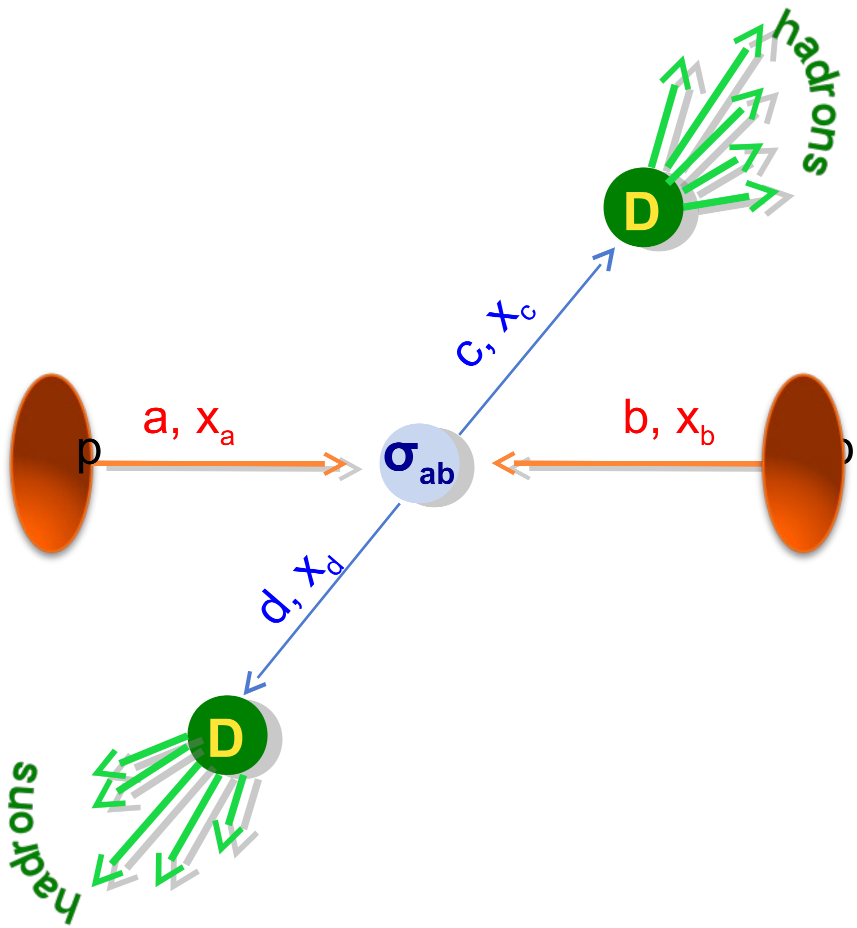
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

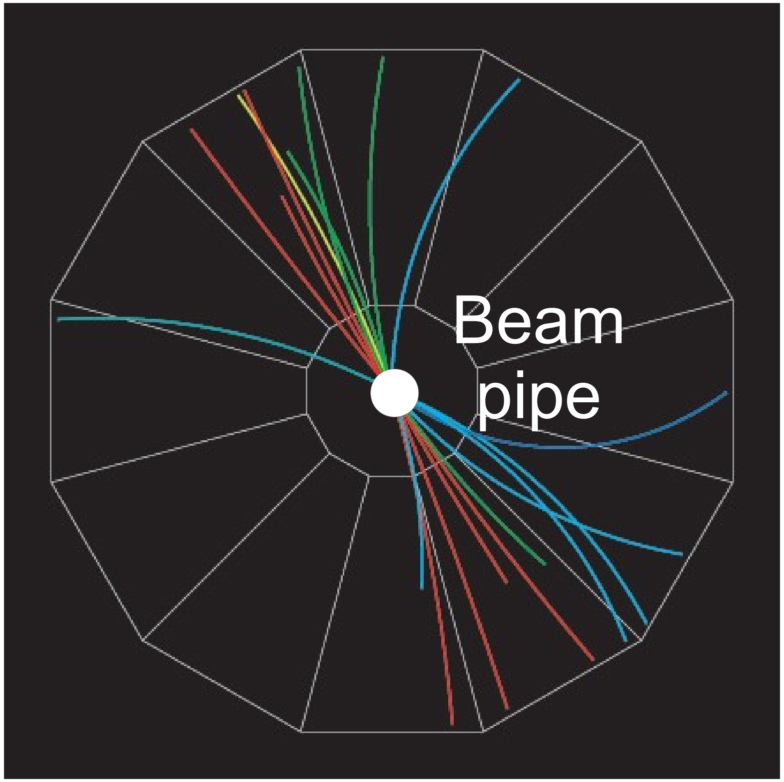


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets

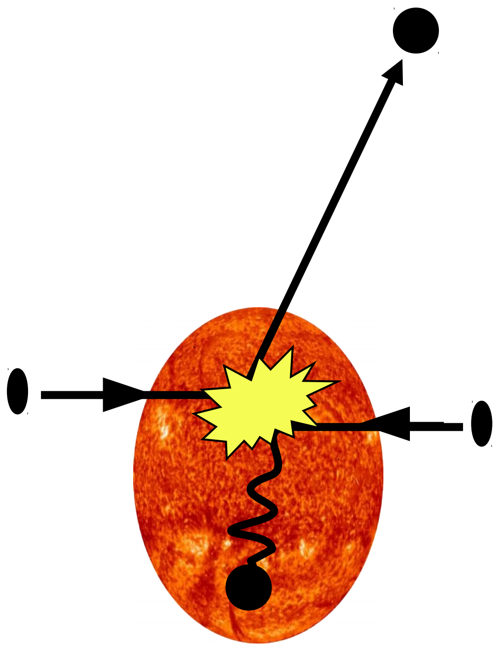


p+p → dijet



Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

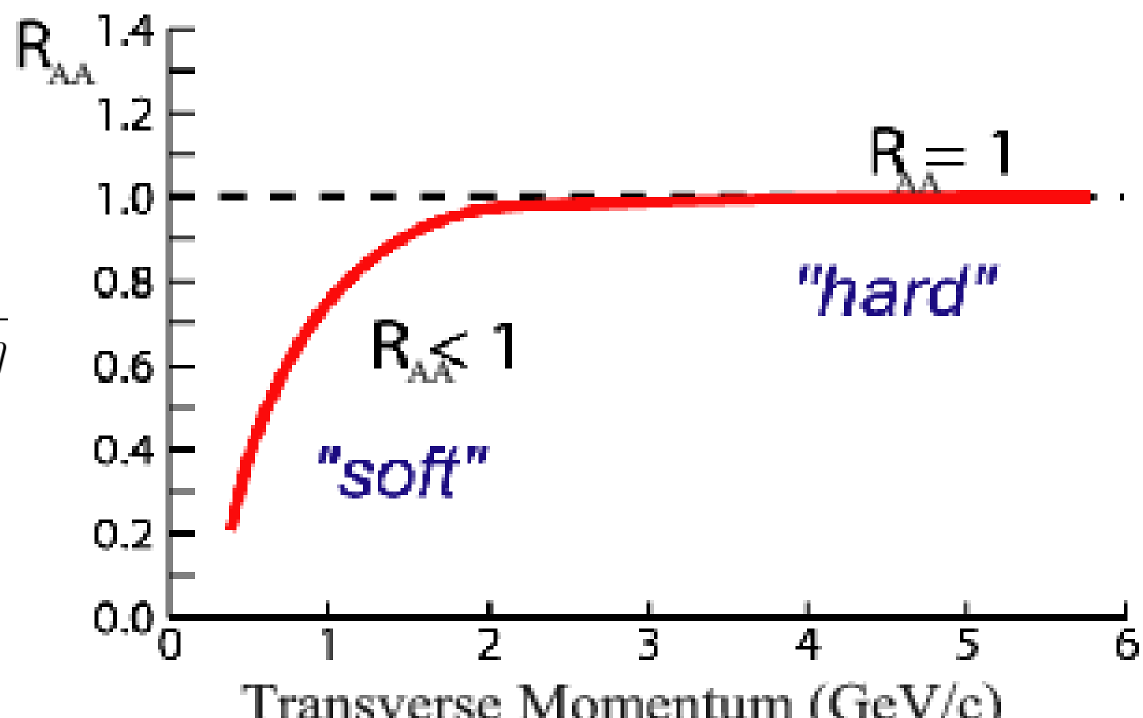
Energy loss



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

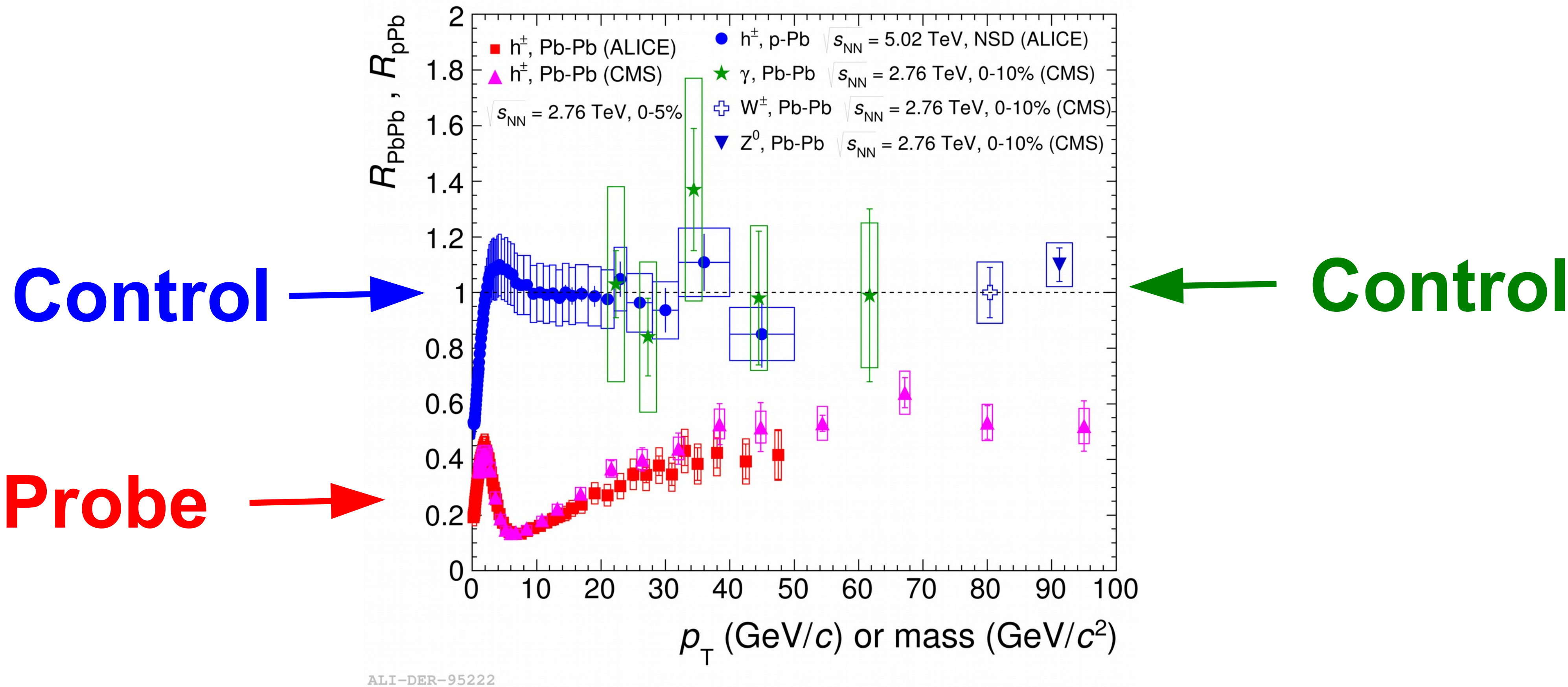
$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$



Enhancement

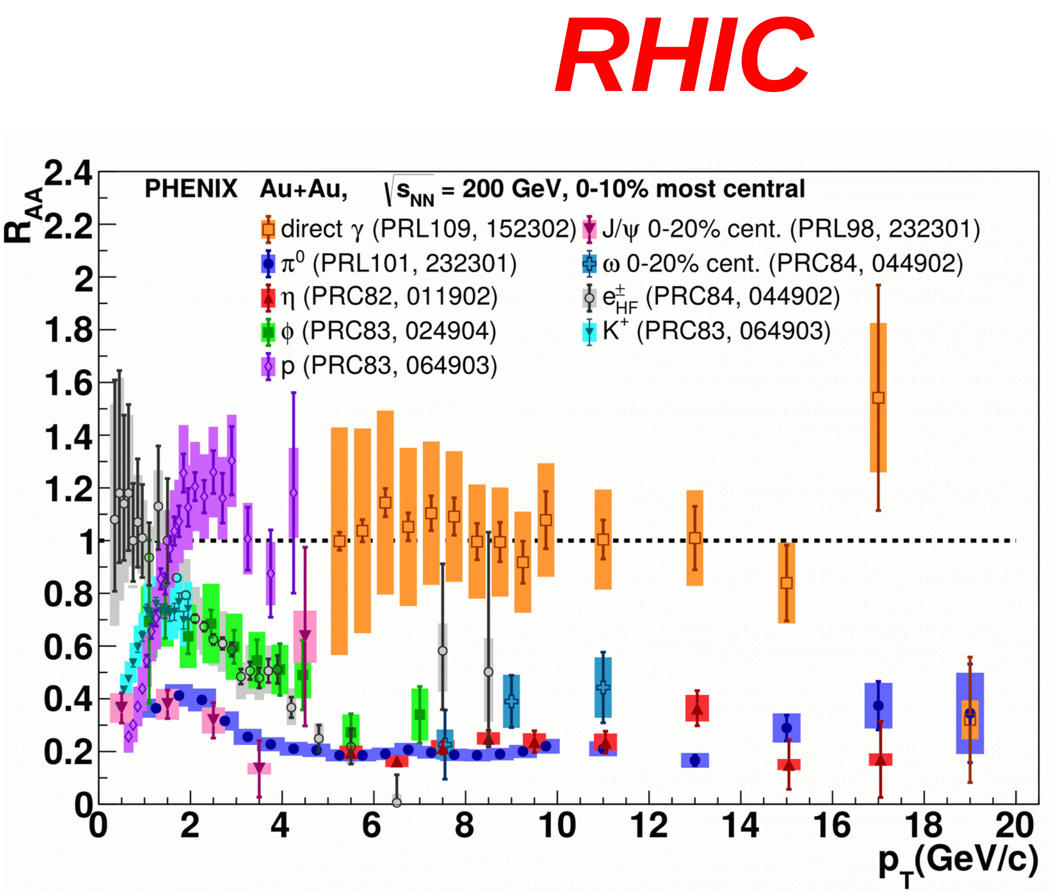
Suppression

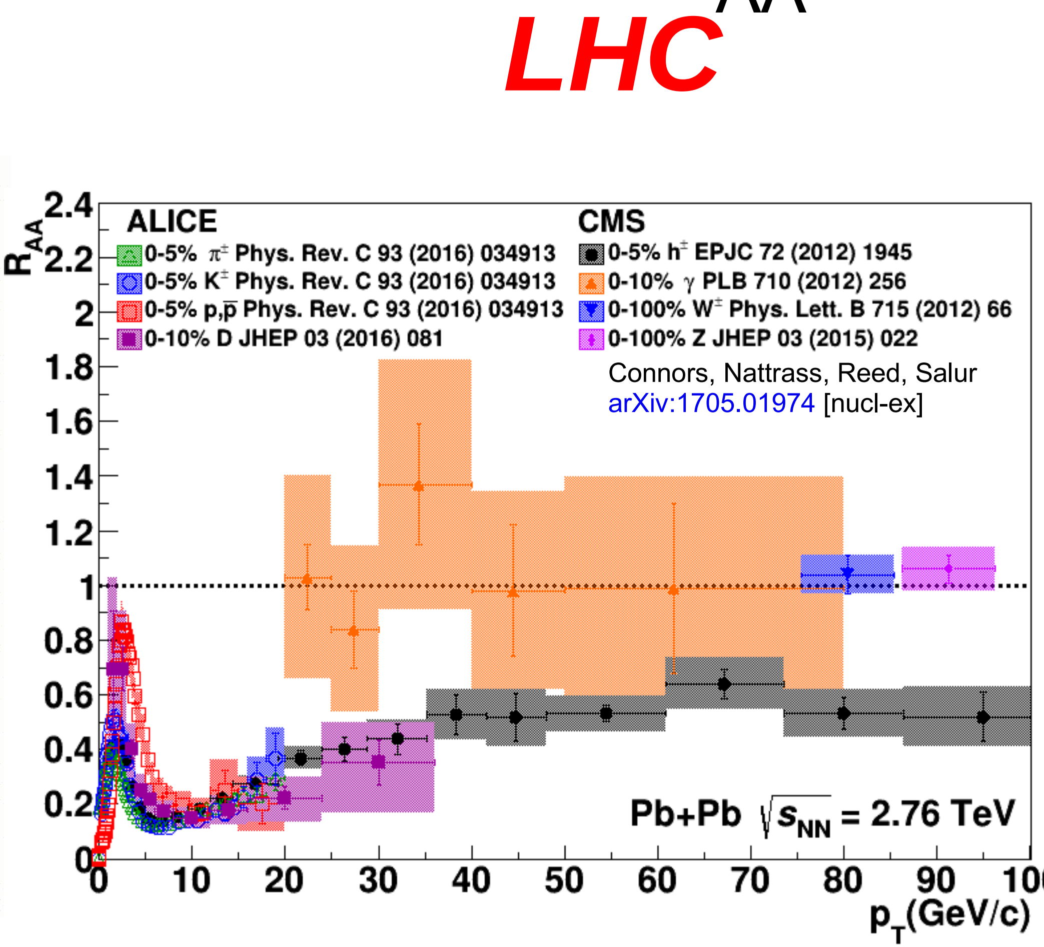
Nuclear modification factor



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

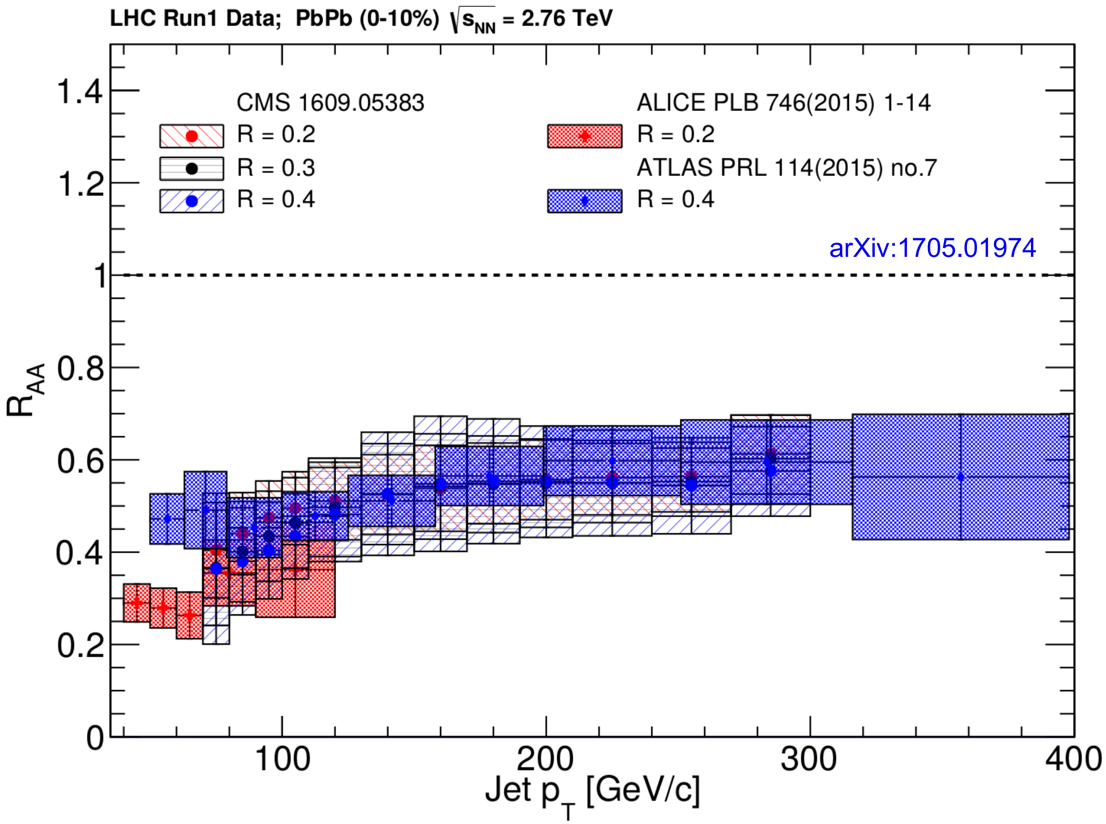
Nuclear modification factor R_{AA}

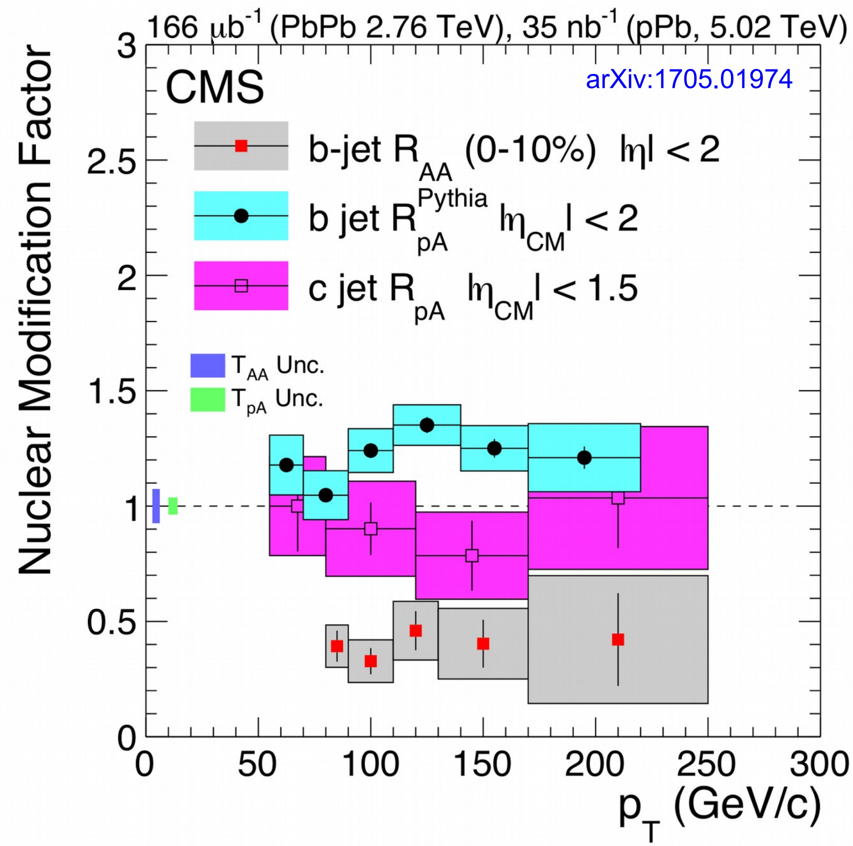




- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them - even heavy quarks!

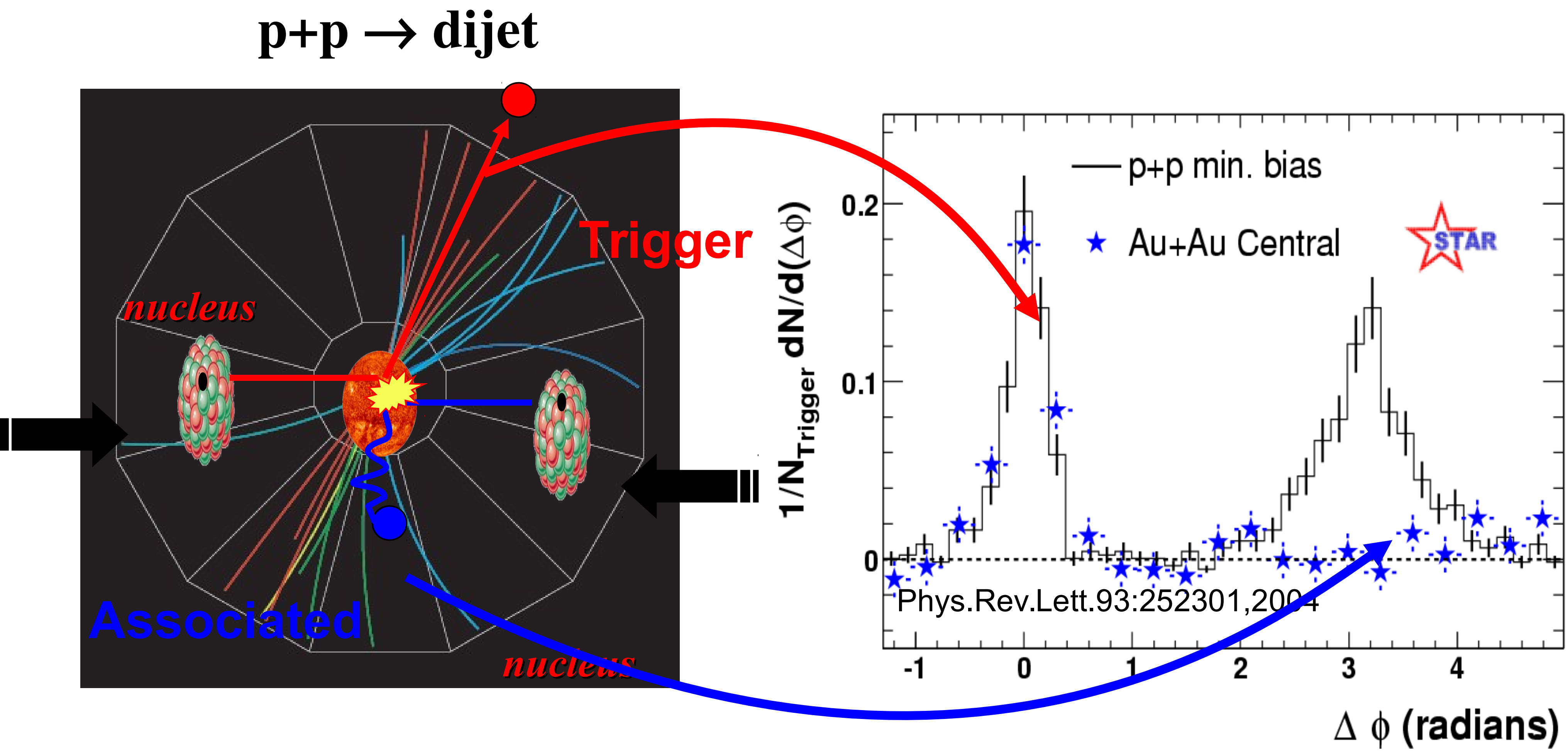
Jet R_{AA}





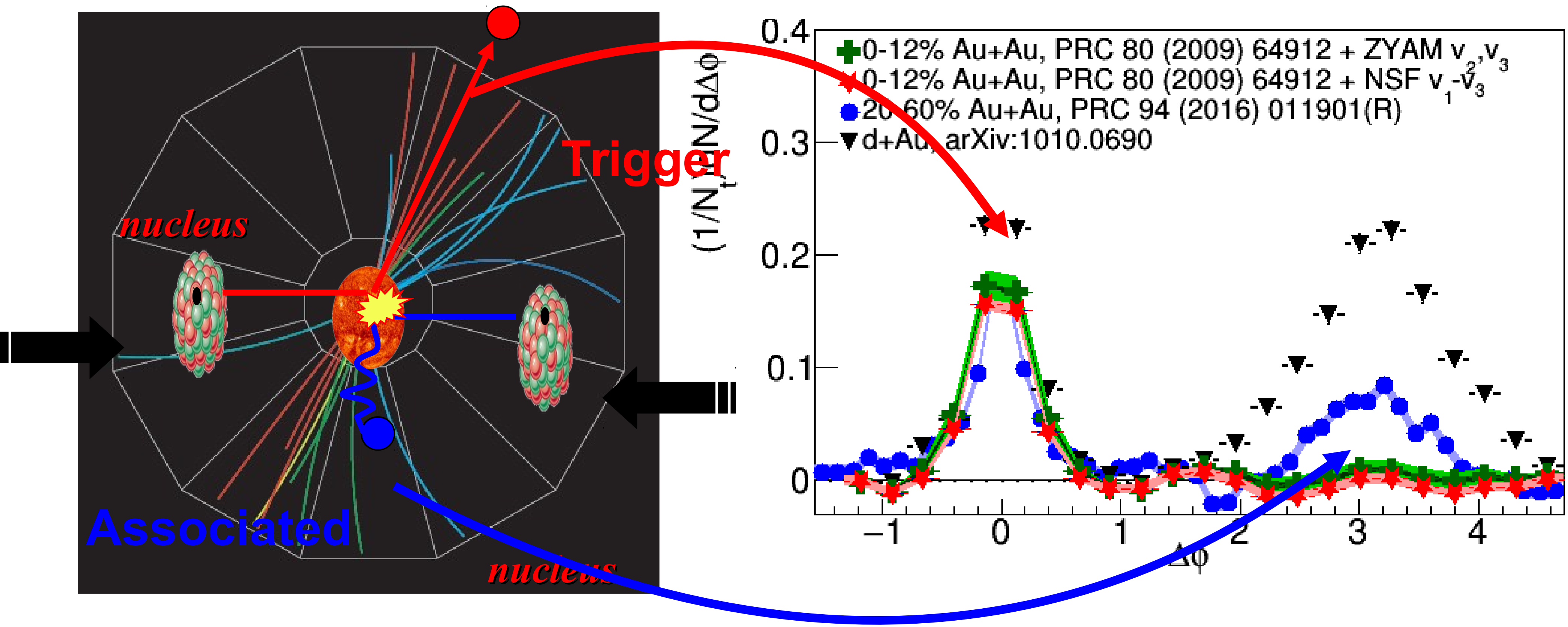
- Jet R_{AA} also demonstrates suppression
- Similar suppression of heavy quark jets?

Di-hadron correlations

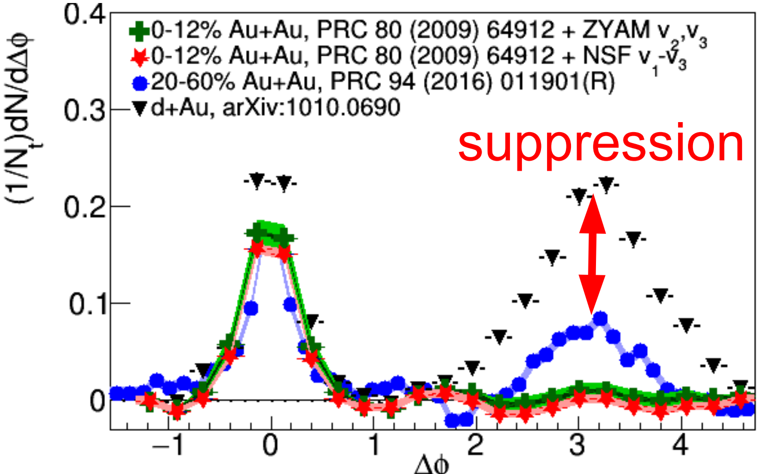


Di-hadron correlations

p+p → dijet



Updated to include latest information about background

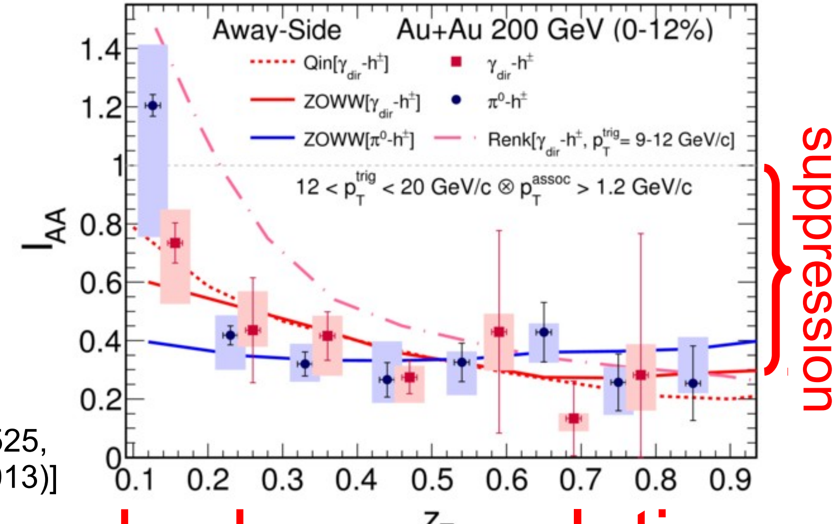


Di-hadron correlations

[Too many to list]

Jet v_2

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

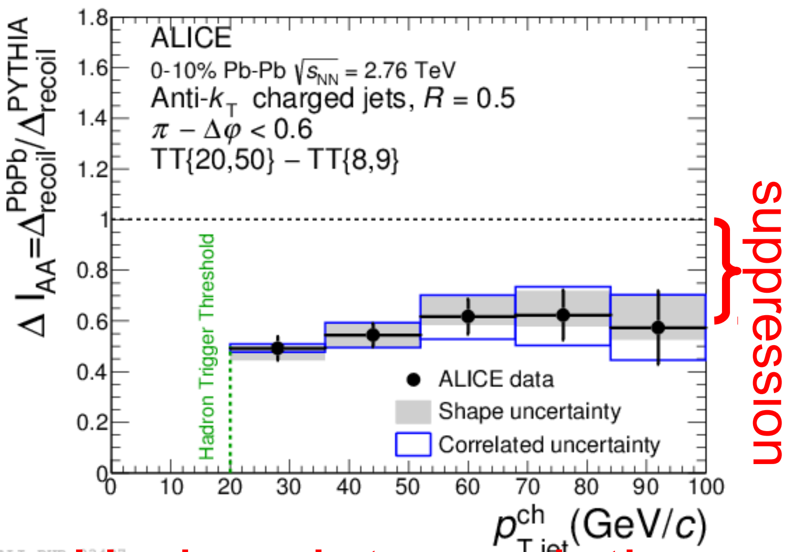


γ-hadron correlations

[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]

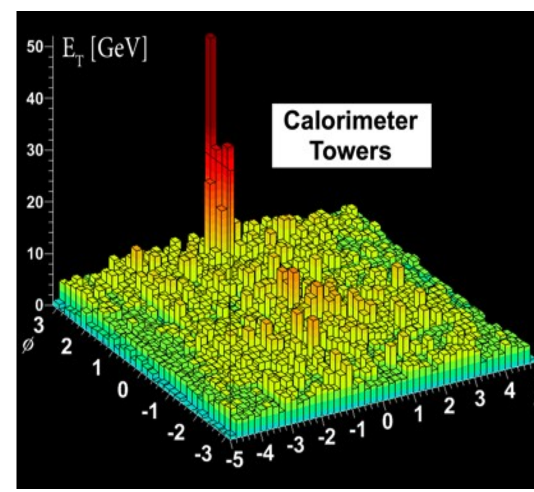


Hadron-jet correlations

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

High-p_T hadron v_2

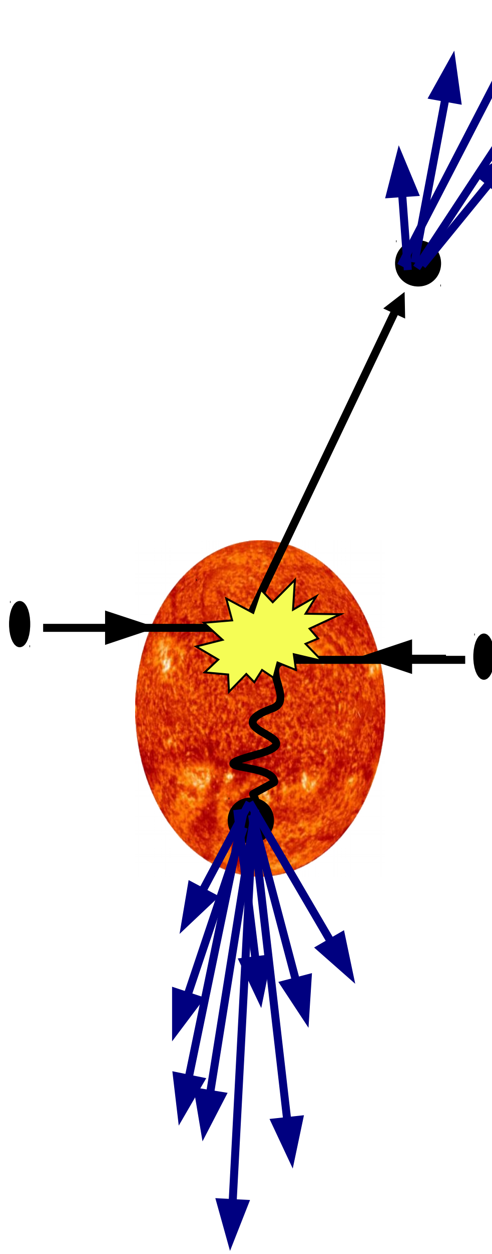
[too many to list]



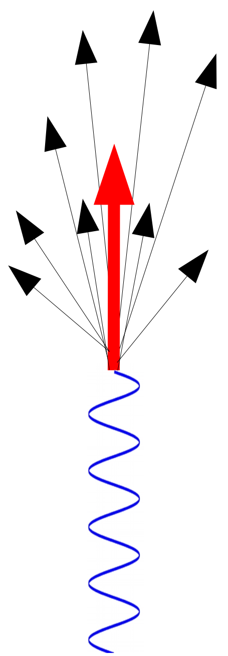
Dijet asymmetry

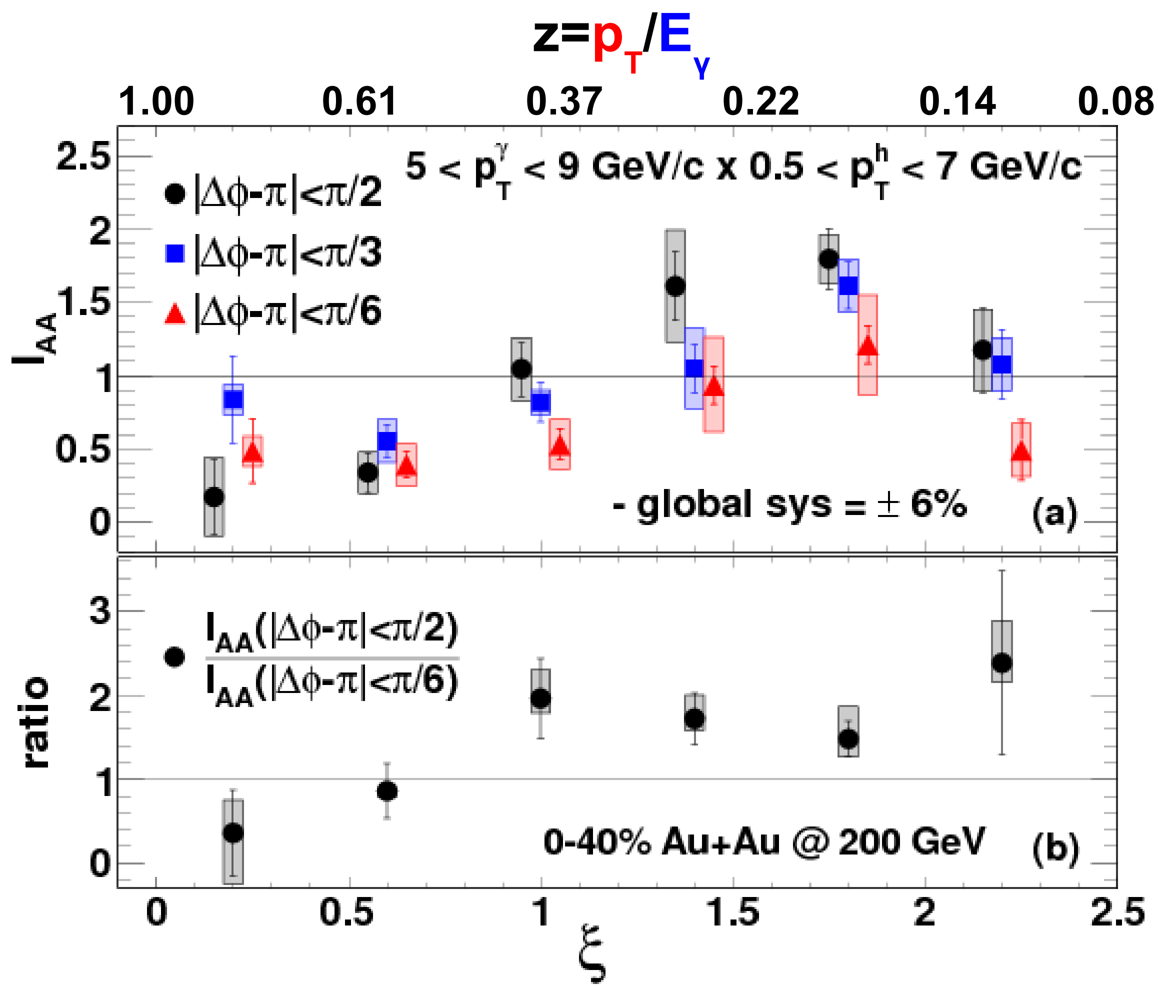
[Phys.Rev.C84:024906,2011,
Phys. Lett. B 712 (2012) 176,
Phys.Rev.Lett.105:252303,2010,
Phys. Rev. Lett. 119, 062301 (2017)]

Fragmentation



Fragmentations from γ-hadron correlations

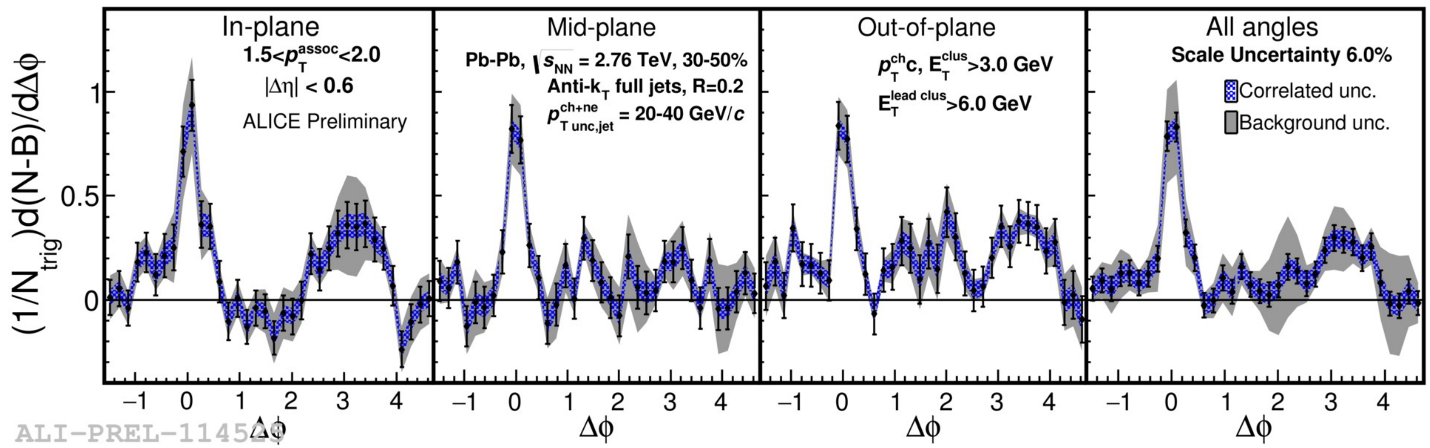


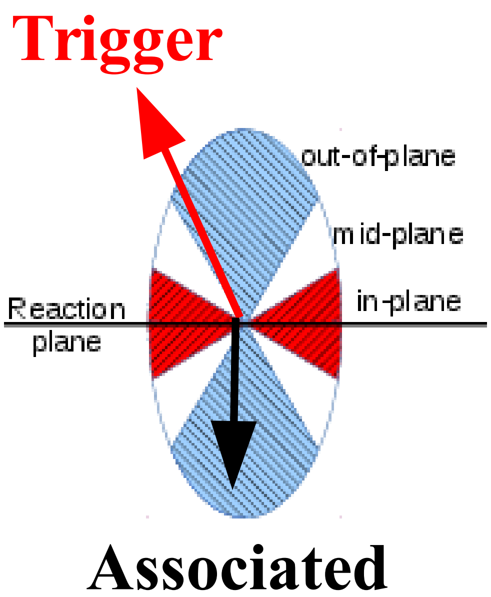


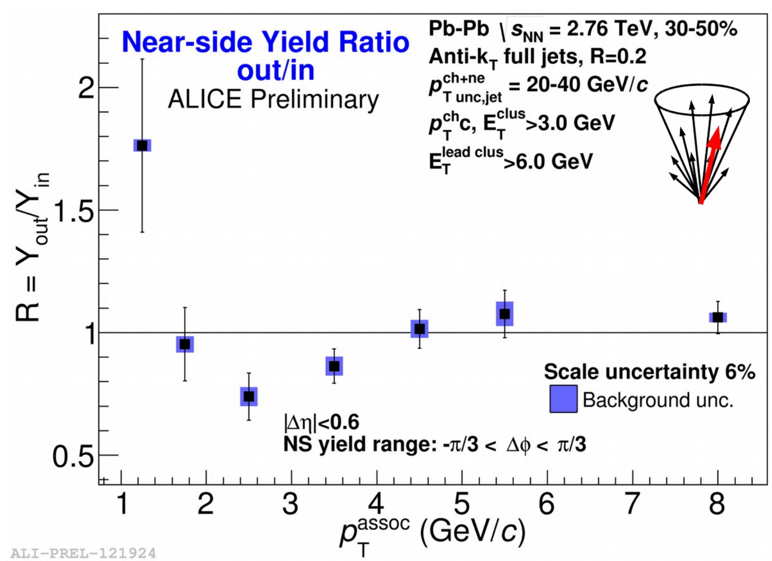
- Enhancement at low z
- Slight suppression at high z

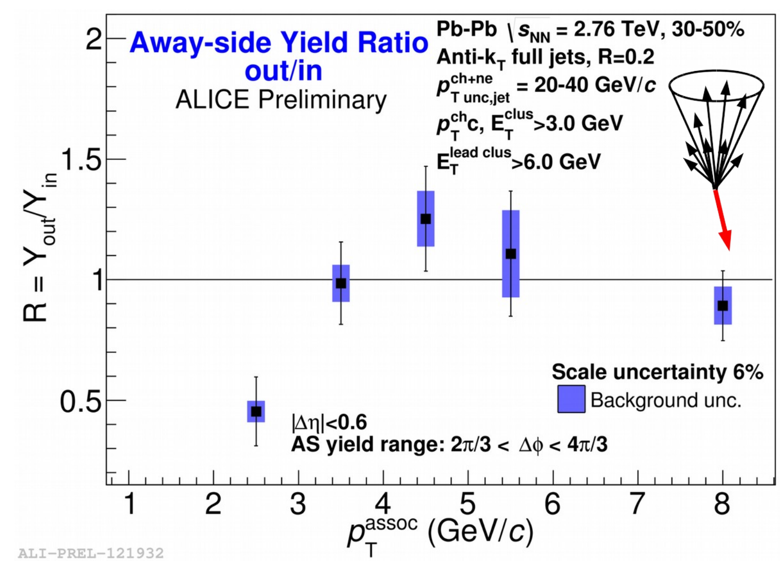
Jet-hadron correlations vs reaction plane

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









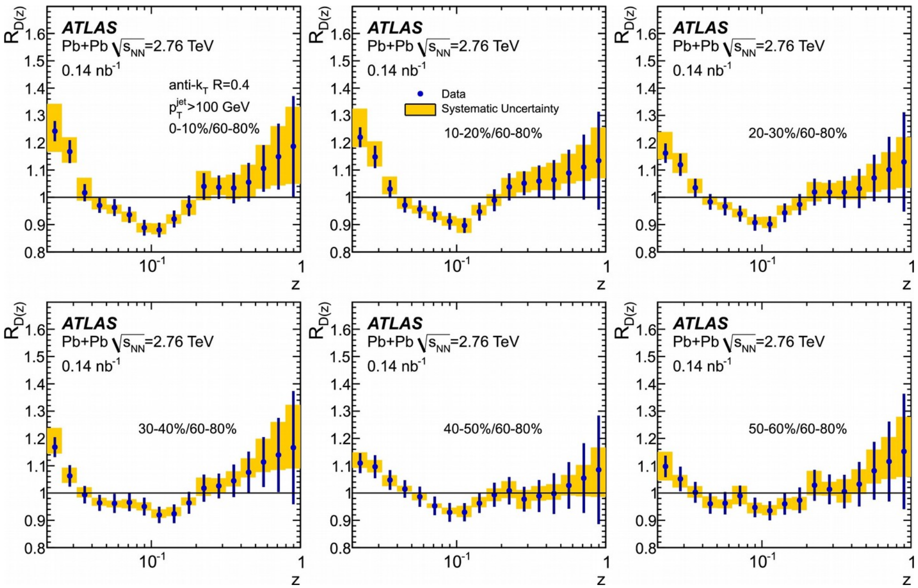
- No modification of constituents relative to reaction plane

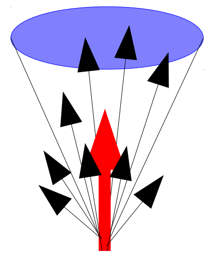
  → Jet-by-jet fluctuations more important than path length [PLB 735 157(2014)]

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

Modified fragmentation

Fragmentation functions with jets





$z=p_T/E_\gamma$

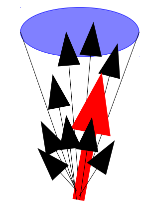
Di-hadron correlations

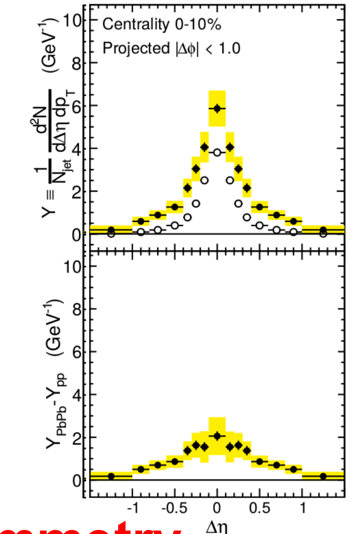
[Lots of papers]

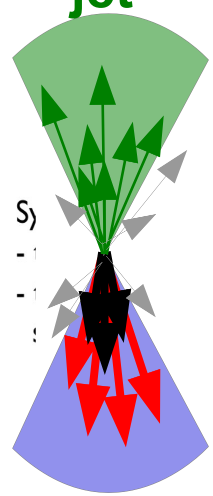
Jet shapes

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

Jet-hadron correlations

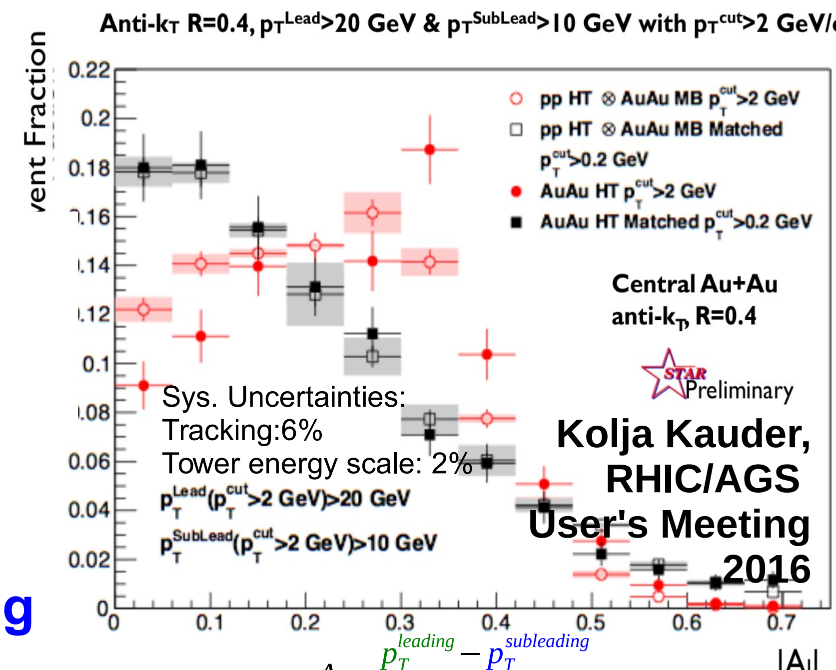






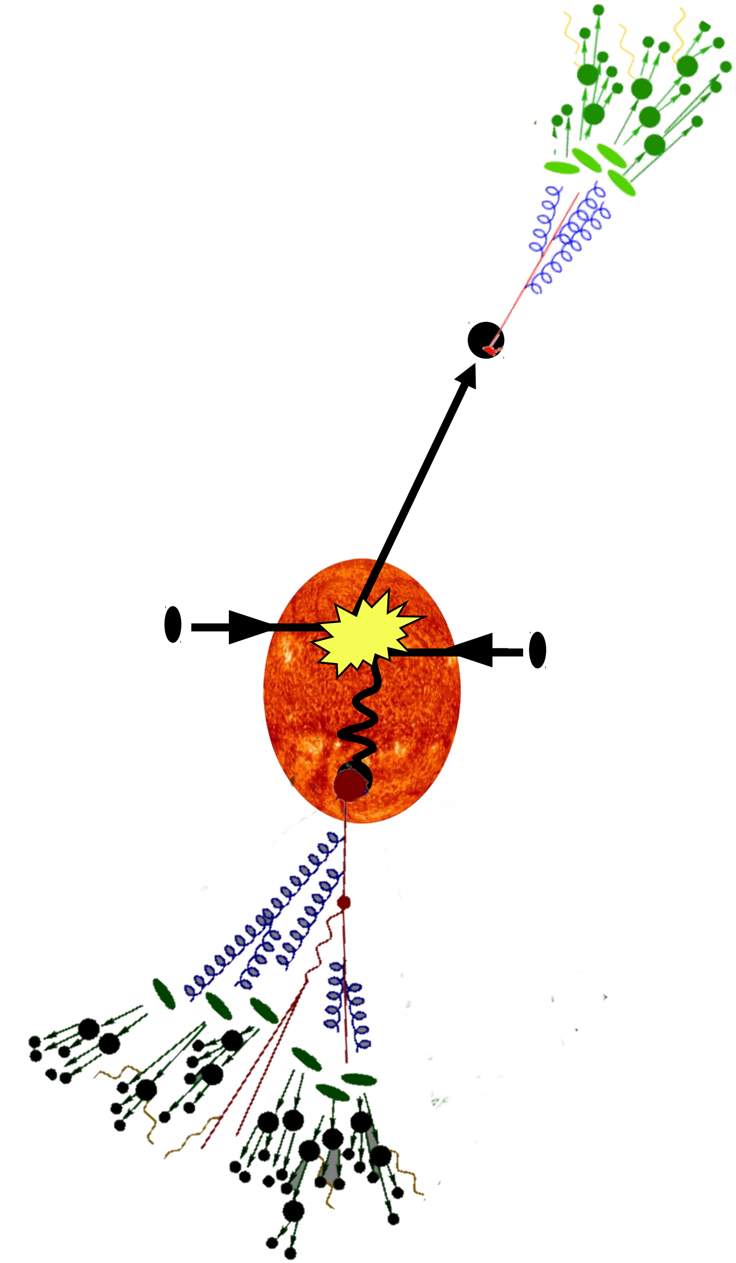
Di-jet asymmetry

arXiv:1609.03878

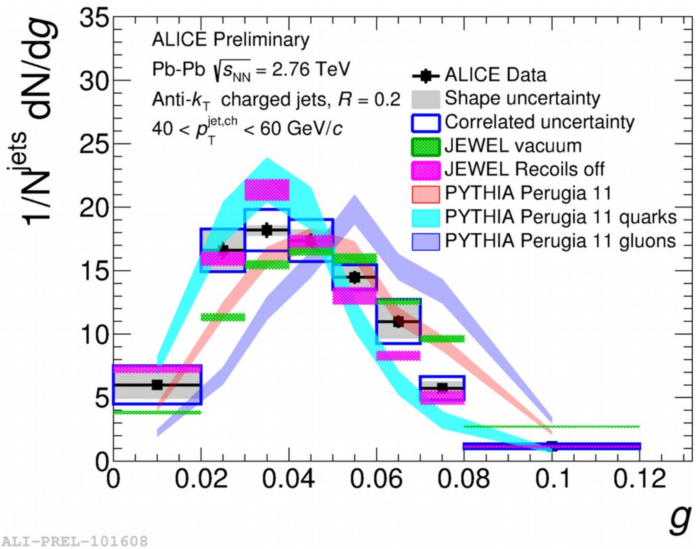


$$A_j = \frac{p_T^{leading} - p_T^{subleading}}{p_T^{leading} + p_T^{subleading}}$$

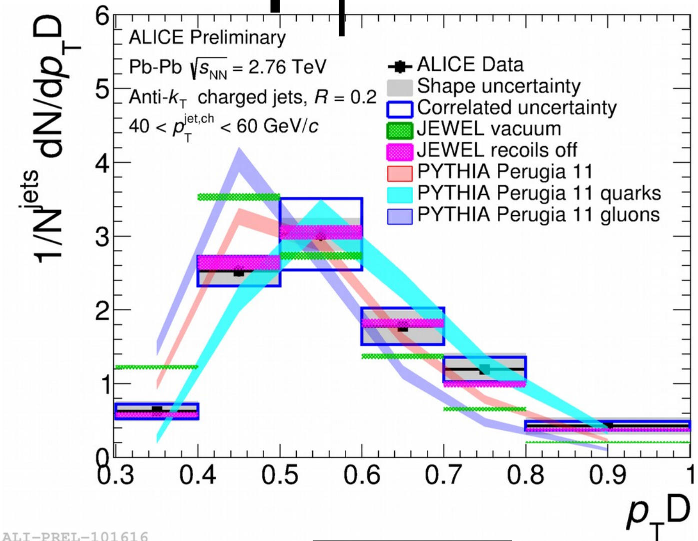
Jet structure



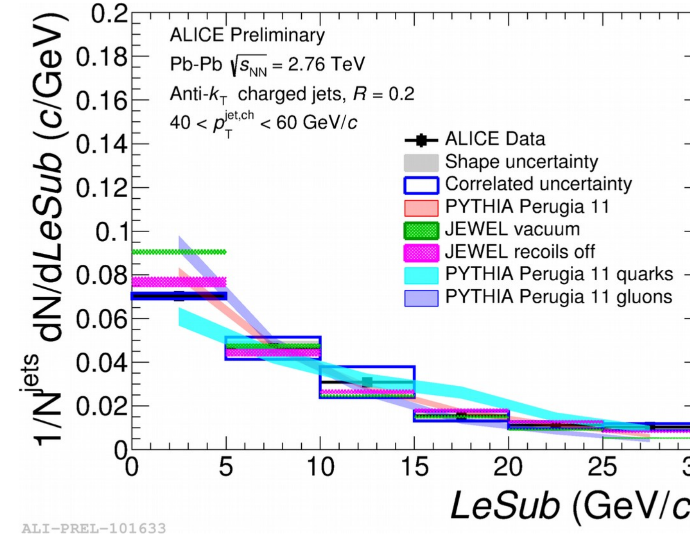
Girth g



Dispersion $p_T D$



LeSub



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

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

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

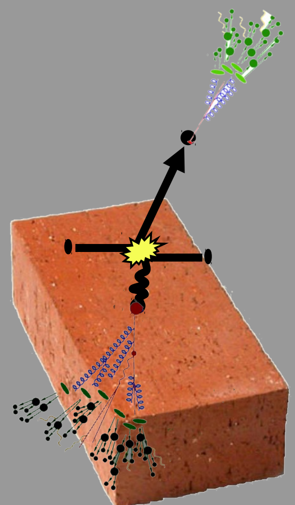
Jets are slightly more collimated than in pp

Agrees with PYTHIA

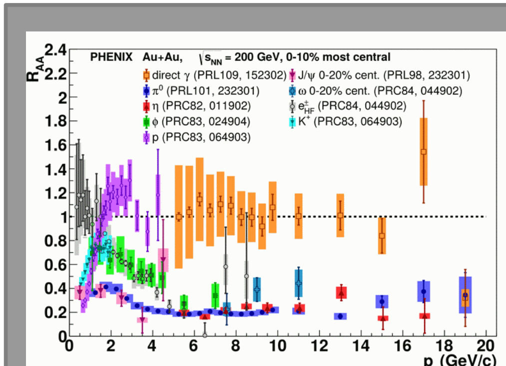
Theory

JET collaboration

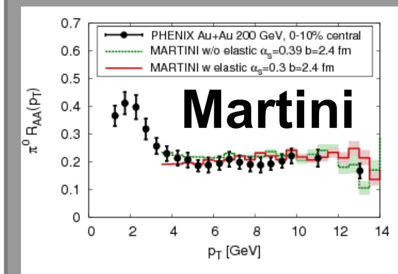
Phys. Rev. C 90, 014909 (2014)

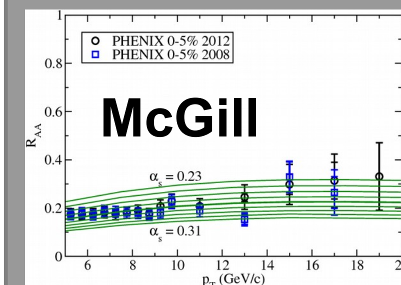


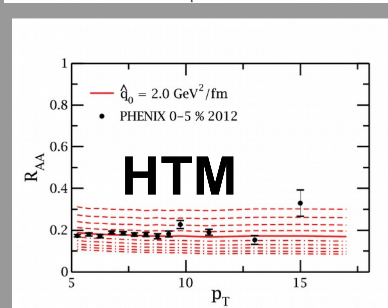
QGP brick + jet

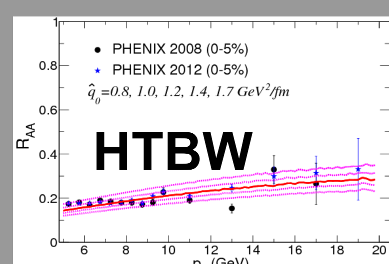


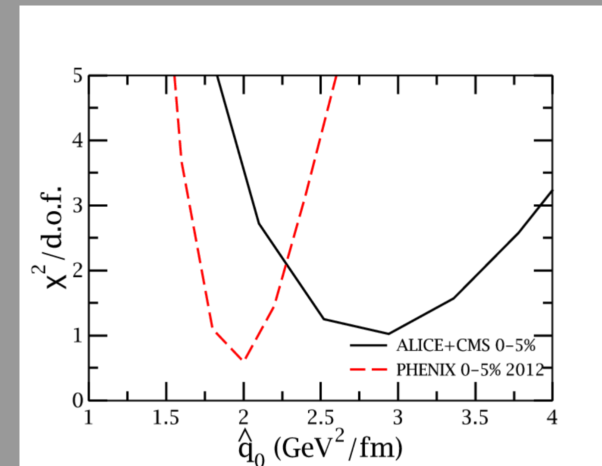
Data



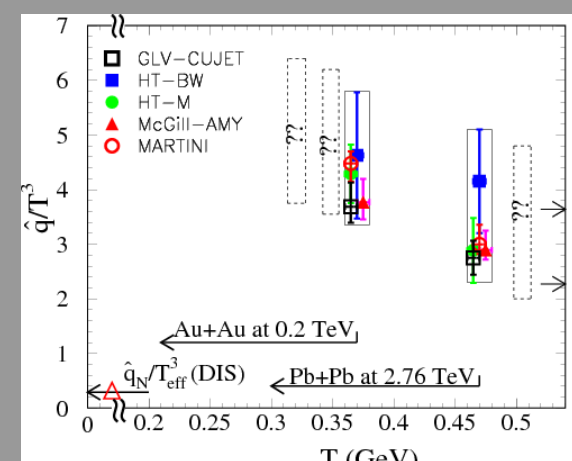








χ^2 *minimization*



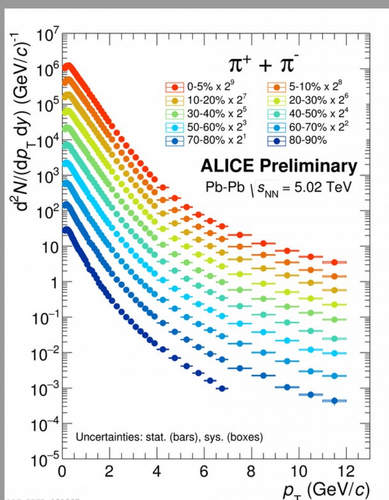
$\hat{q} = 1.2 \pm 0.3 \quad GeV^2$ 200 GeV Au+Au

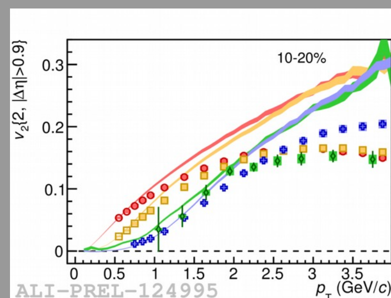
$\hat{q} = 1.9 \pm 0.7 \quad GeV^2$ 2.76 TeV Pb+Pb

Bayesian Statistical Analysis

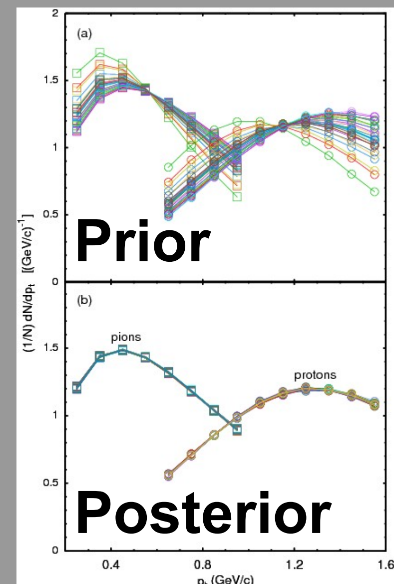
Models and Data Analysis Initiative

http://madai.us

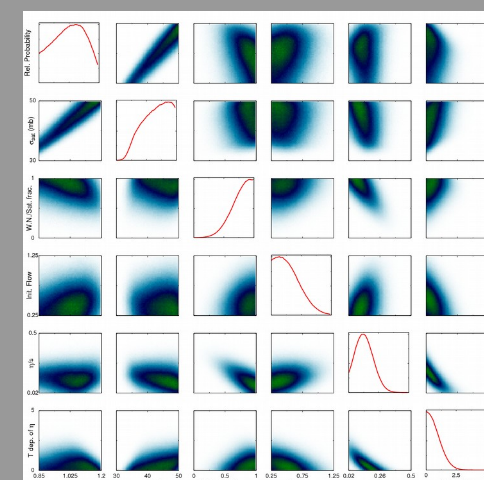




Data



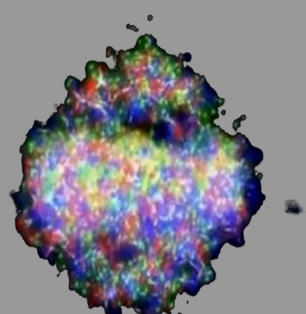
Optimization



Constraint of QGP properties

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

Monte Carlo models



Model emulation

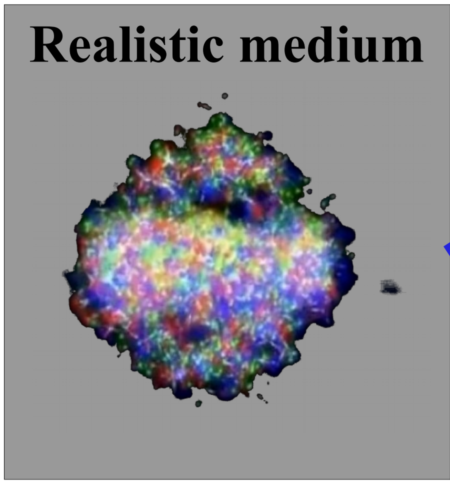
1) Run full model ~1000 times
2) MCMC parameter search uses emulator (interpolator) in lieu of full model

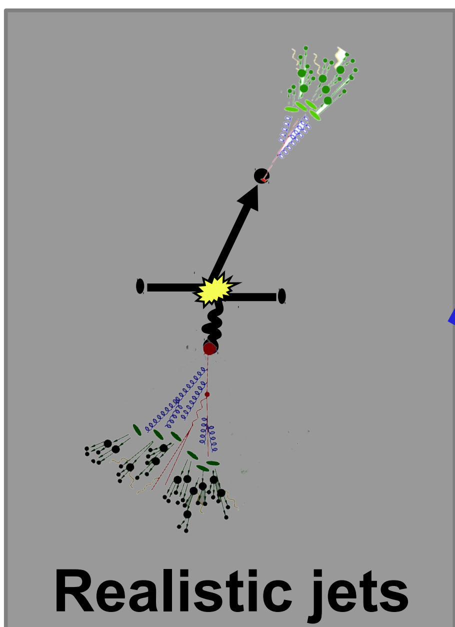
JETSCAPE

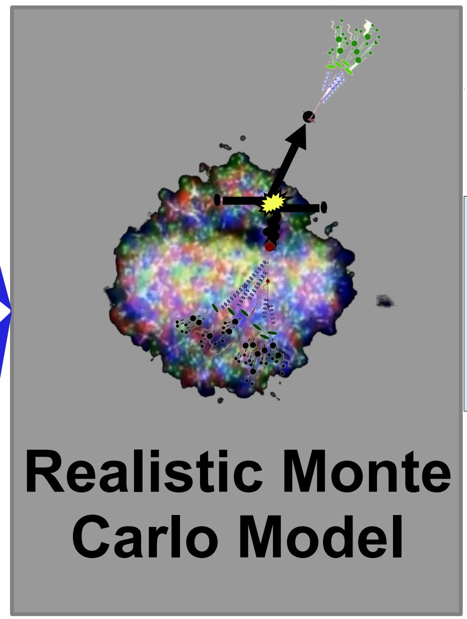
Event generator

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

http://jetscape.wayne.edu/





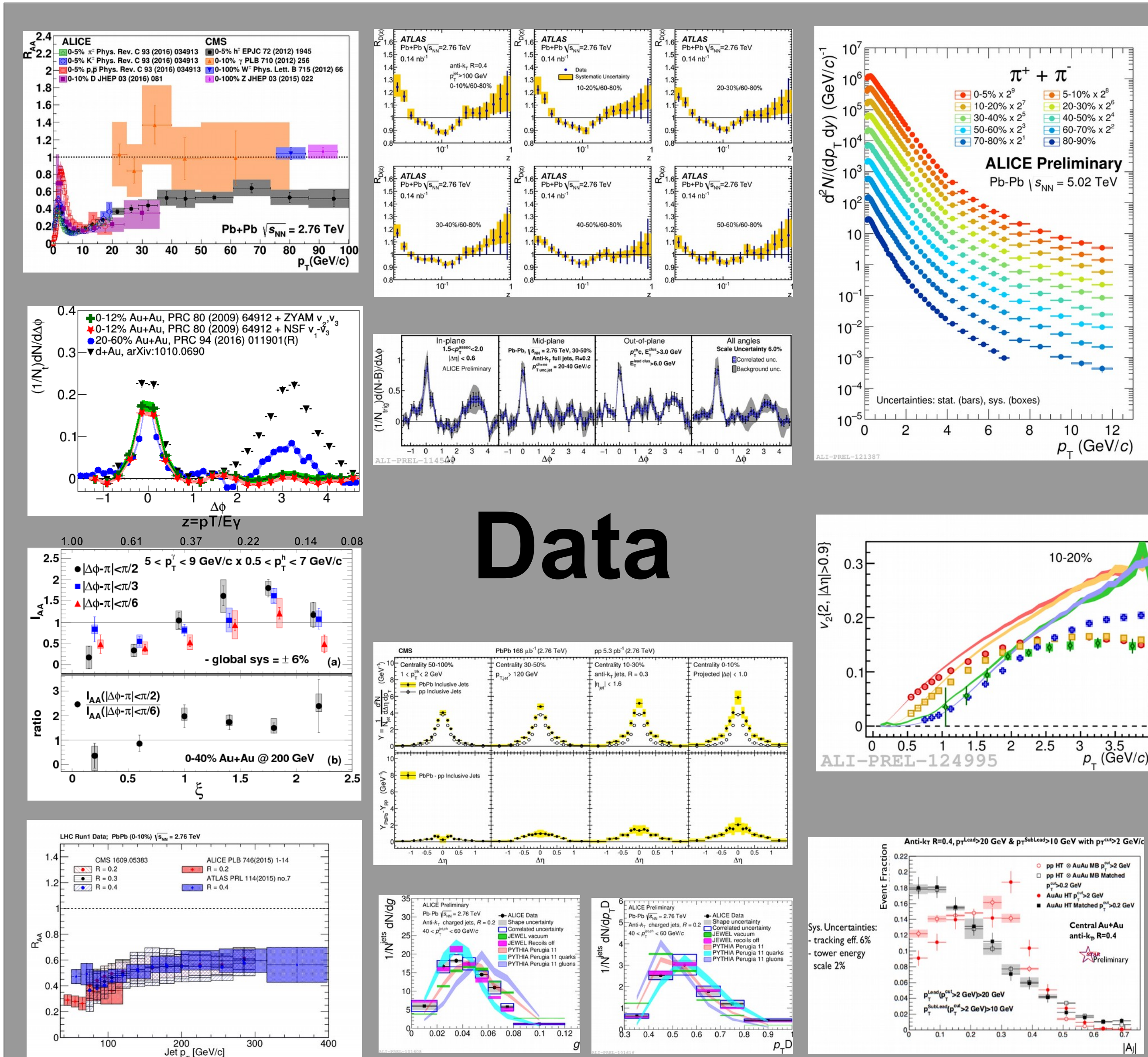


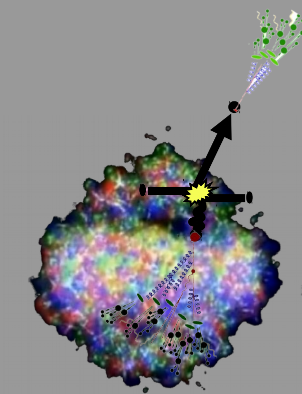
Experimental techniques

Realistic theoretical calculations

JETSCAPE

Event Generator + Bayesian Statistical analysis





Realistic theoretical calculations

↓

Bayesian Statistical Analysis

↓

Constraint of QGP properties

What have we accomplished?

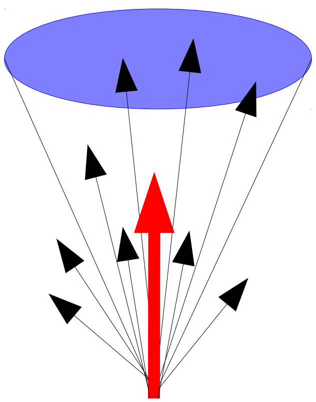
- **Qualitative confirmation of partonic energy loss models**
- **Quantitative constraints of $\hat{q}$**
- **Lots of measurements**

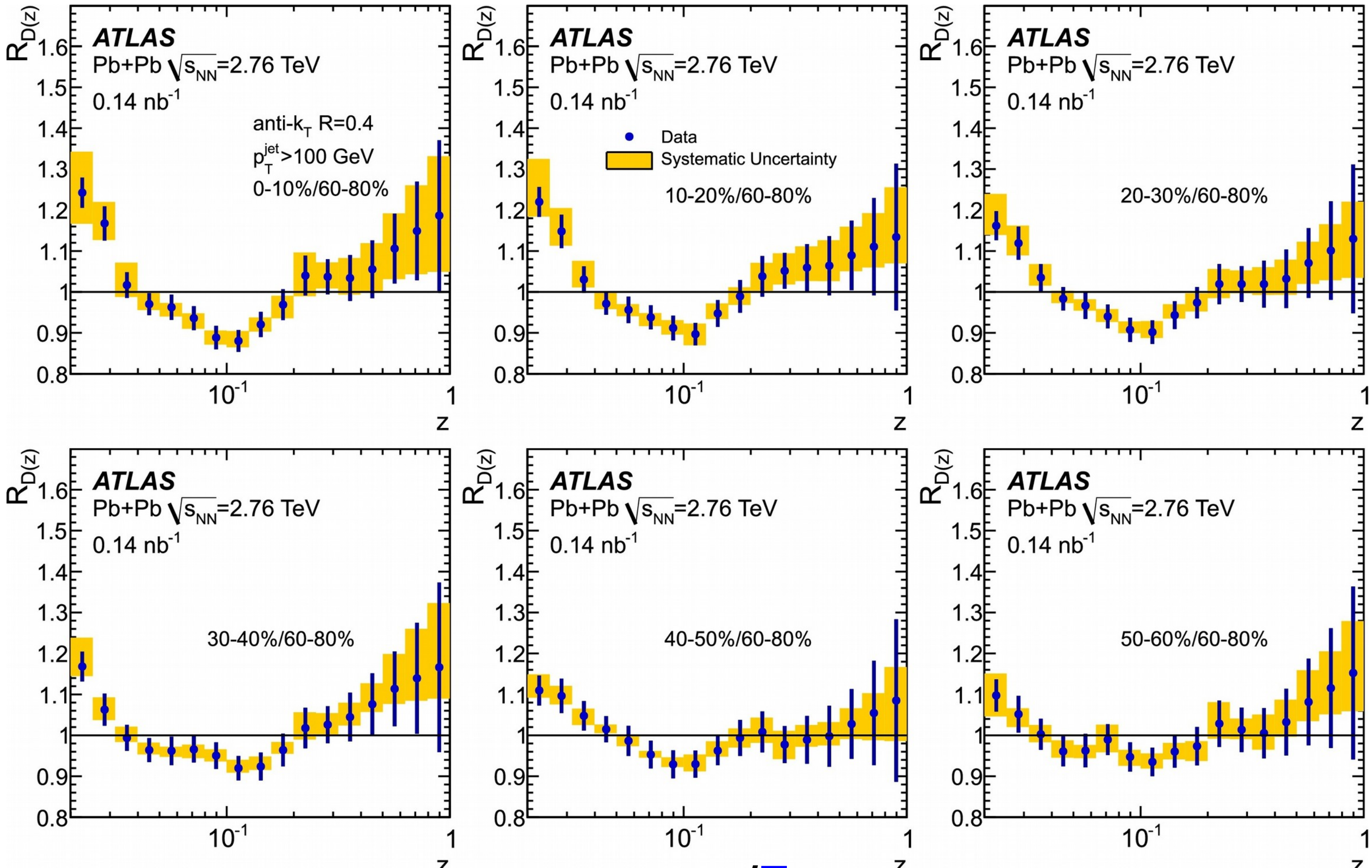
What do we still have to do?

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

Connors, Nattrass, Reed, SalurarXiv:1705.01974 [nucl-ex]

Modified fragmentation

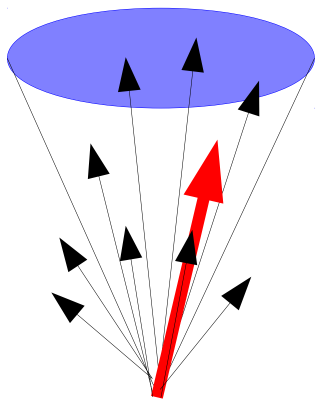


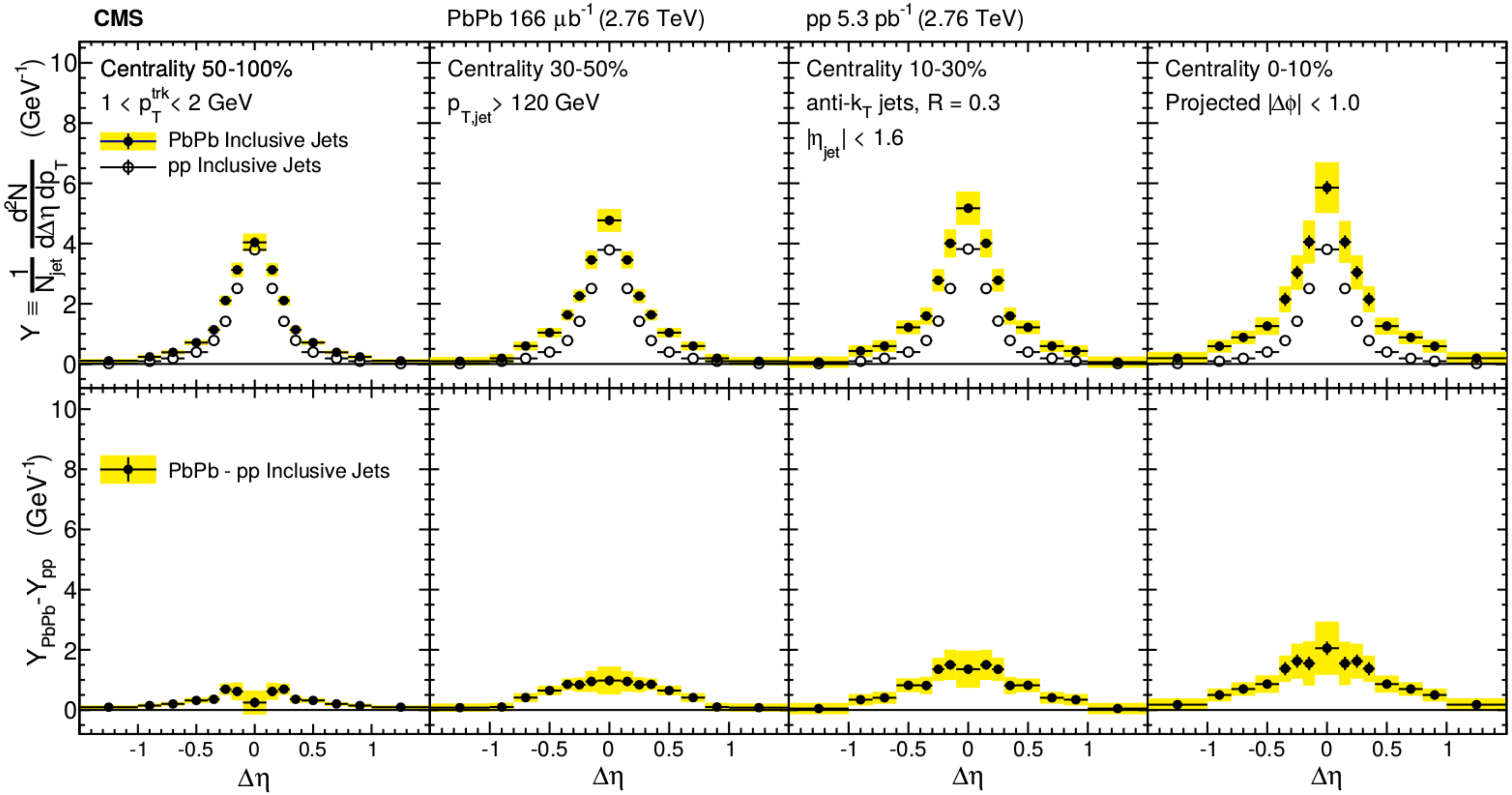


z=p_T/E_γ

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

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]