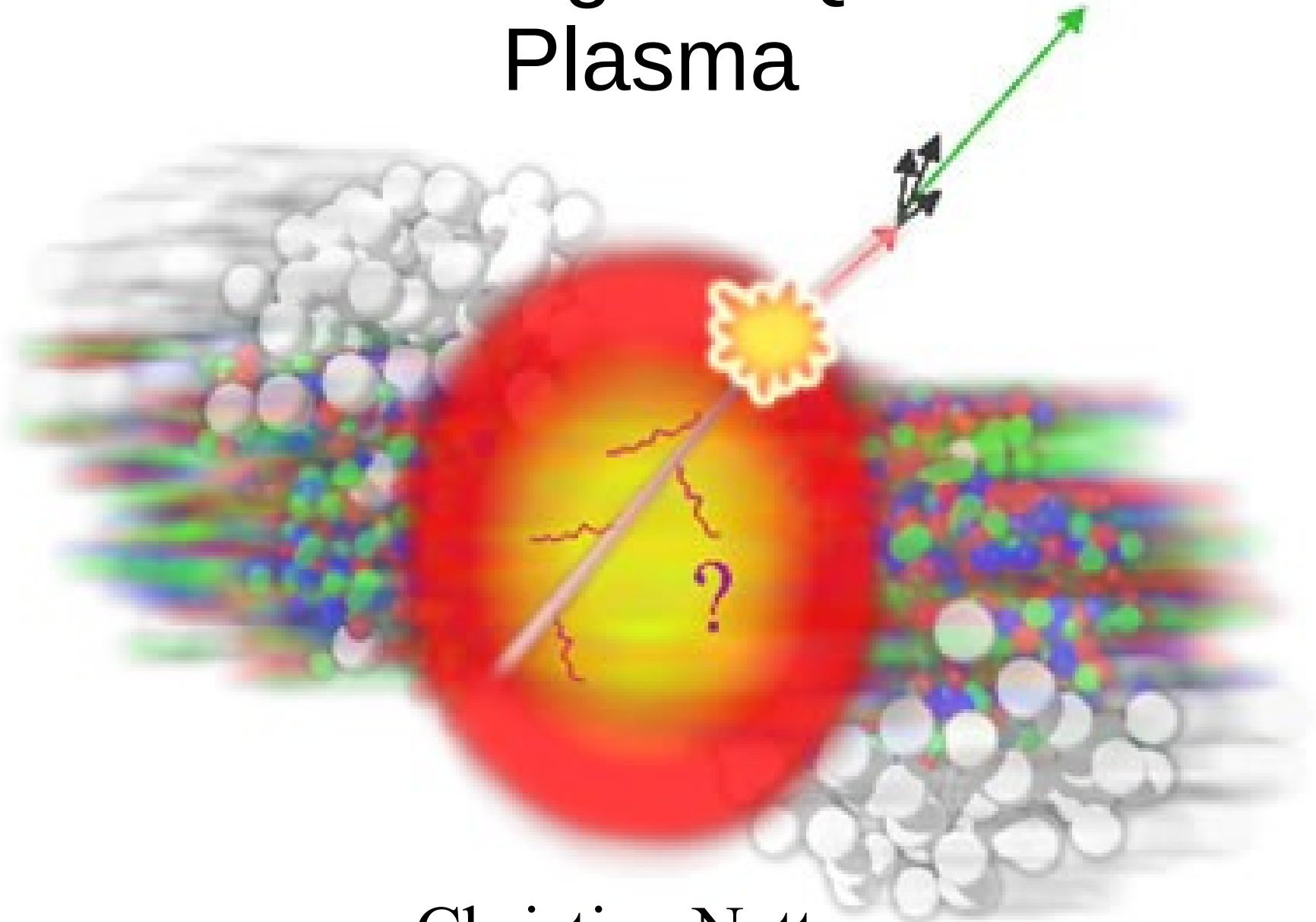
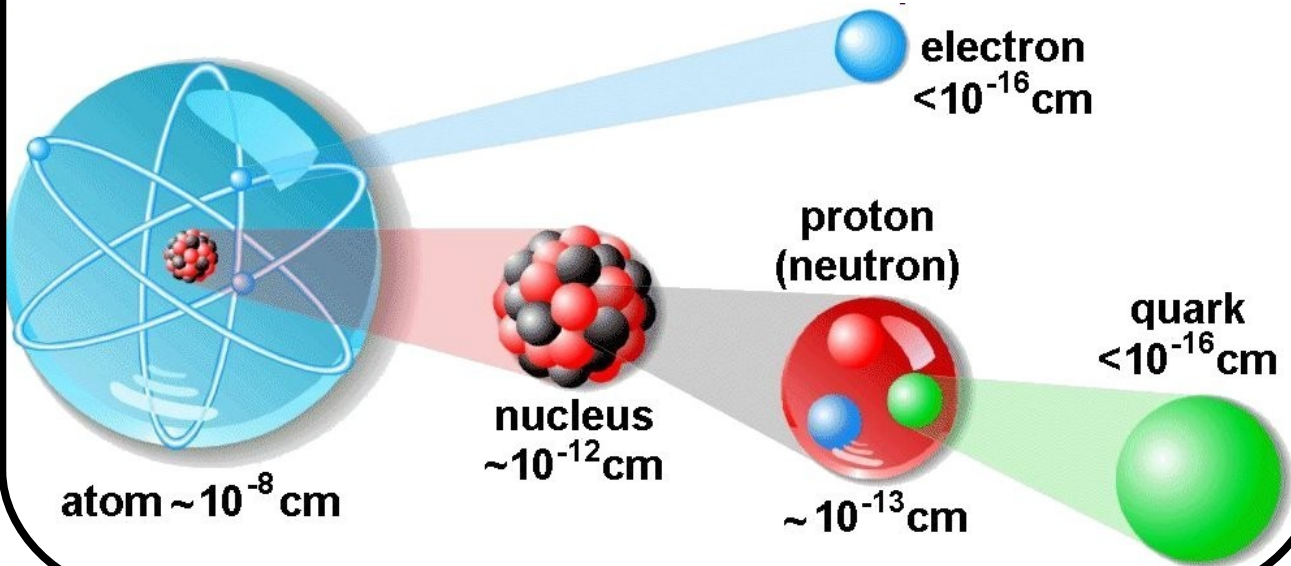


Understanding the Quark Gluon Plasma



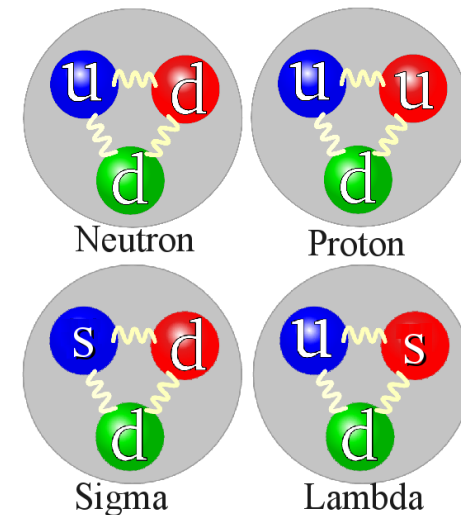
Christine Nattrass
University of Tennessee, Knoxville

Structure of matter



Hadrons

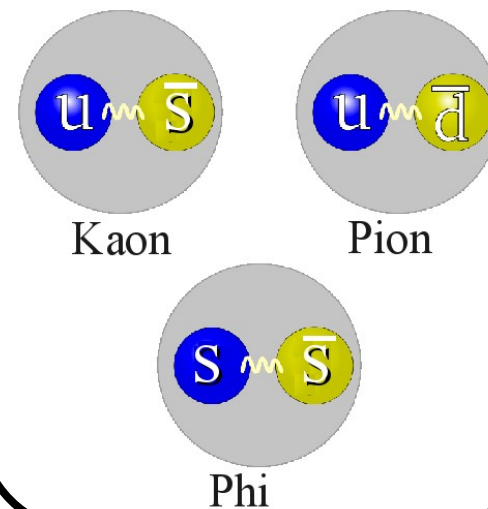
Baryons



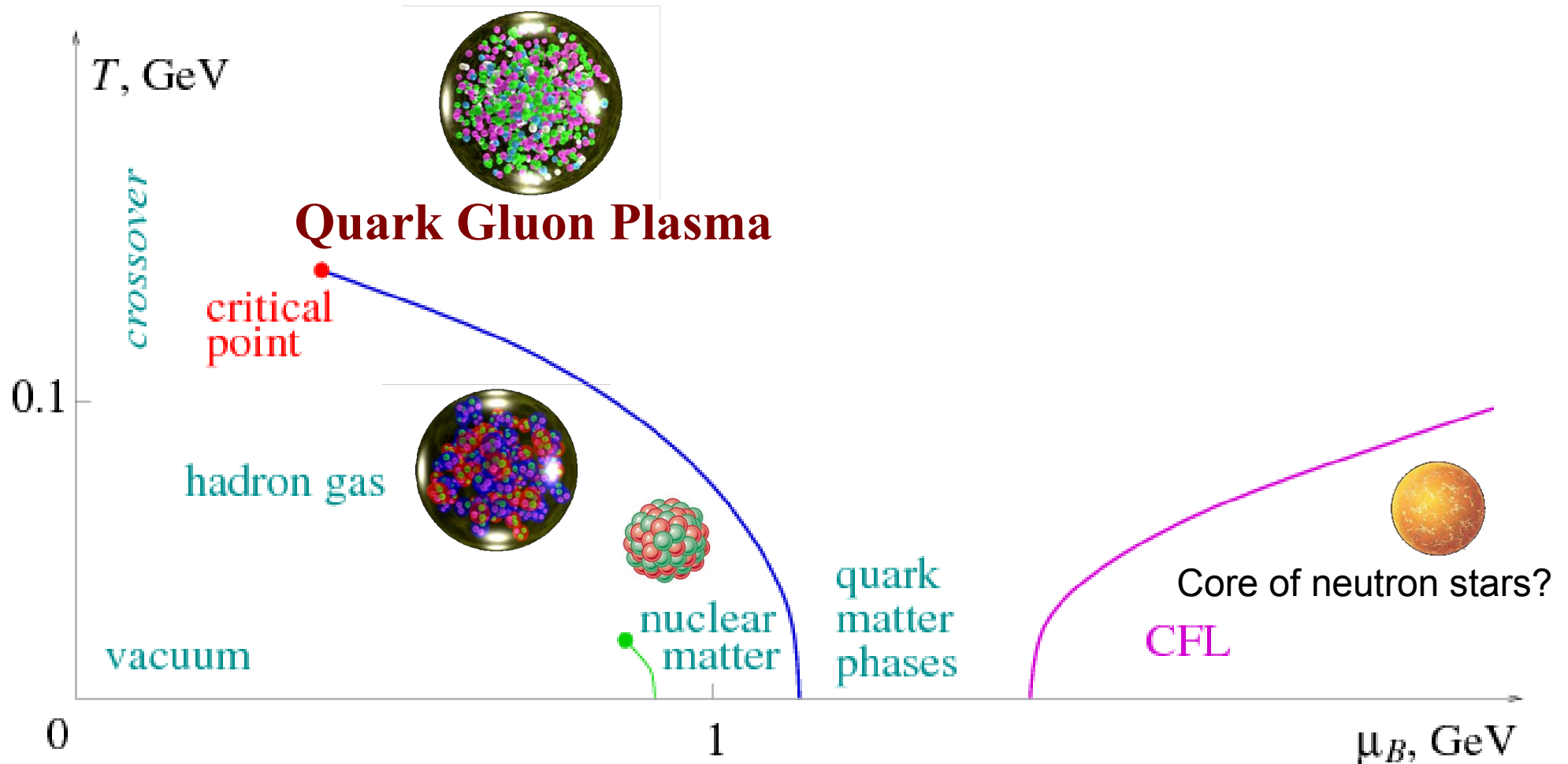
Standard model

QUARKS	2.75 UP	1300 CHARM	178000 TOP	FORCE CARRIERS: BOSONS	91188 Z^0
	6 DOWN	110 STRANGE	4500 BOTTOM		80430 W^+/W^-
	0.511 ELECTRON	105.7 MUON	1777 TAU		$< 10^{-23}$ PHOTON
LEPTONS	$< 3 \cdot 10^{-6}$ NEUTRINO e	< 0.19 NEUTRINO μ	< 18.2 NEUTRINO τ	theory: 0 GLUON	125000 Higgs

Mesons

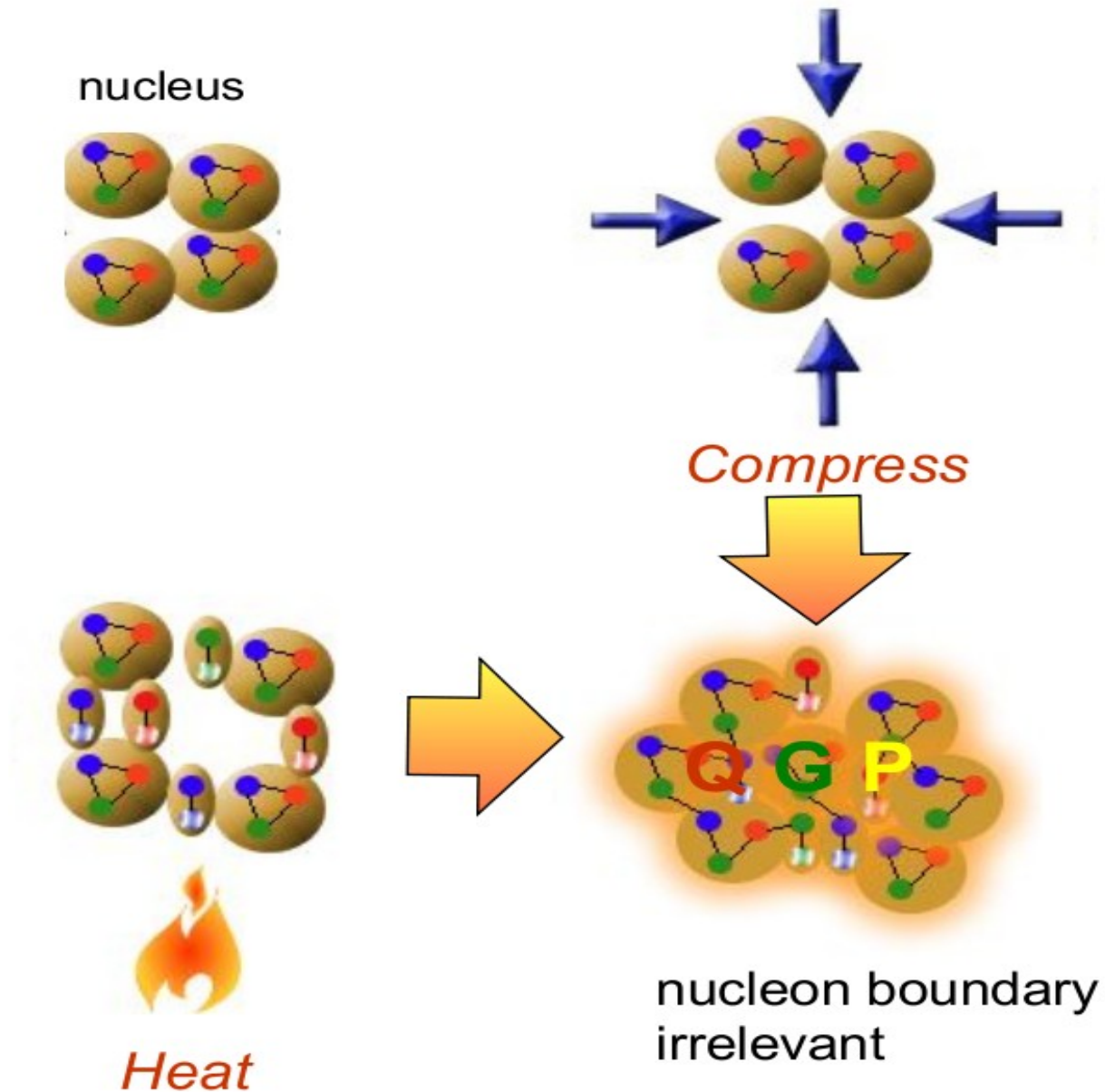


Phase diagram of nuclear matter

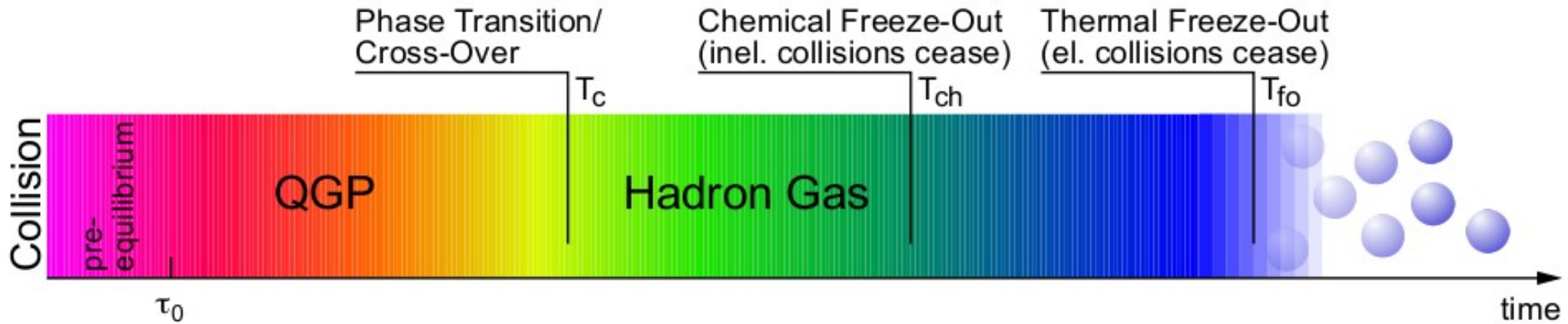
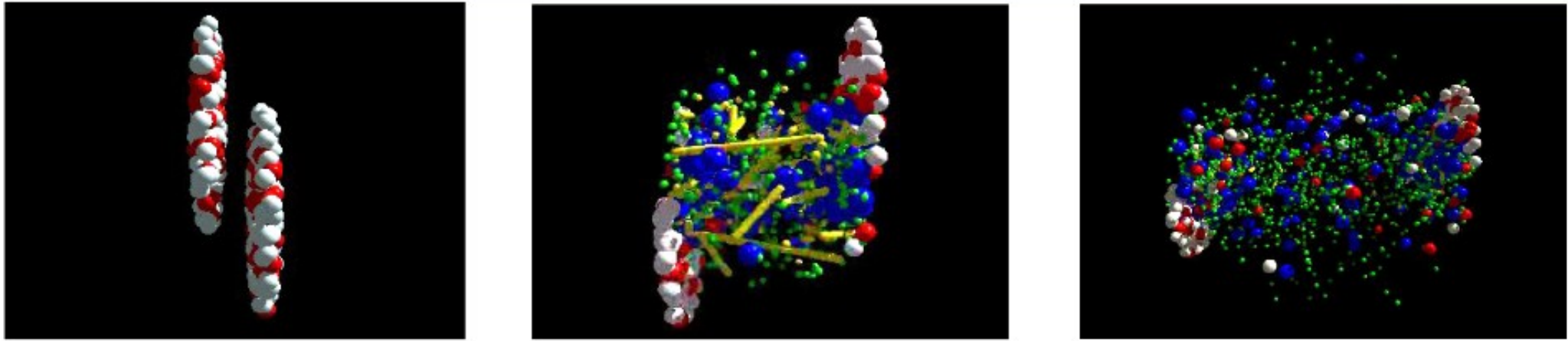


Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~ 170 MeV ($2 \cdot 10^{12}$ K) – over a million times hotter than the core of the sun

How to make a Quark Gluon Plasma



The phase transition in the laboratory



Relativistic Heavy Ion Collider



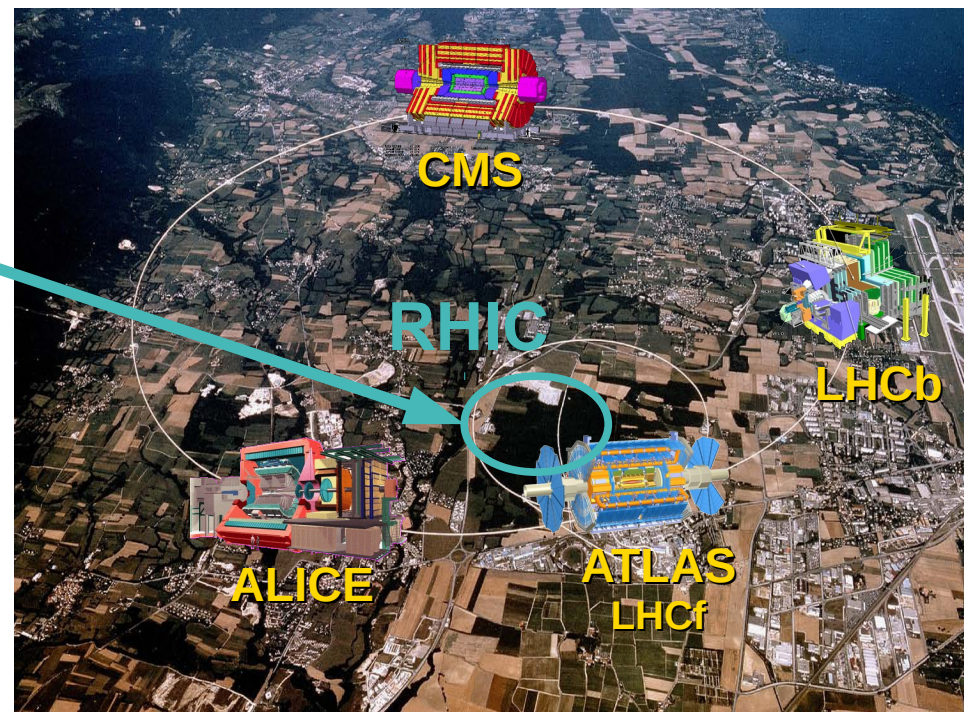
Upton, NY

1.2km diameter

$p+p, d+Au, Cu+Cu, Au+Au, U+U$

$\sqrt{s_{NN}} = 9 - 200 \text{ GeV}$

Large Hadron Collider

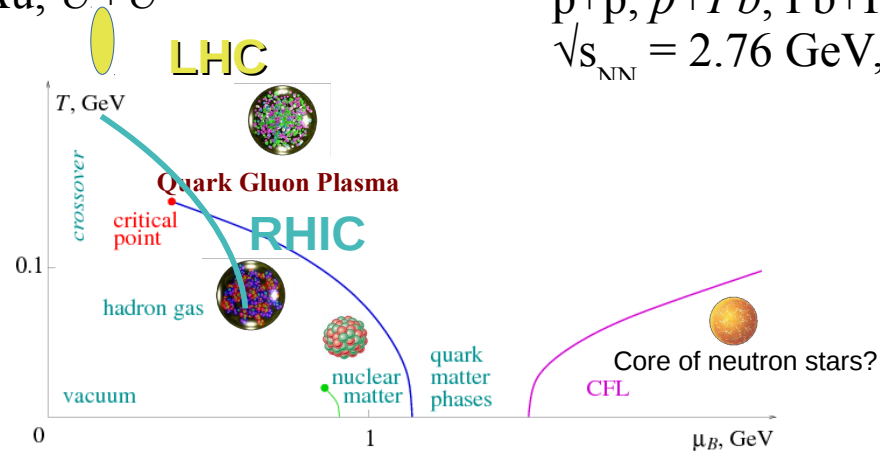


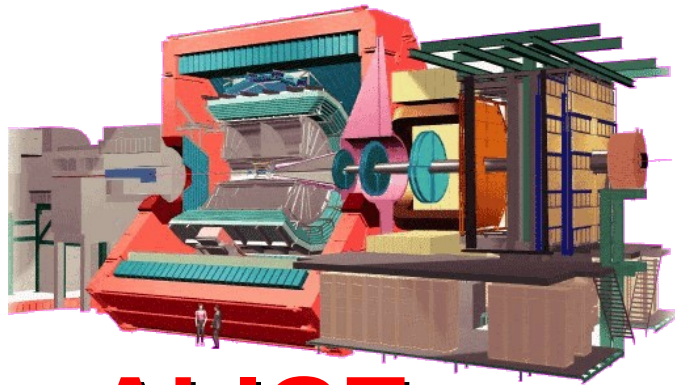
Geneva, Switzerland

8.6km diameter

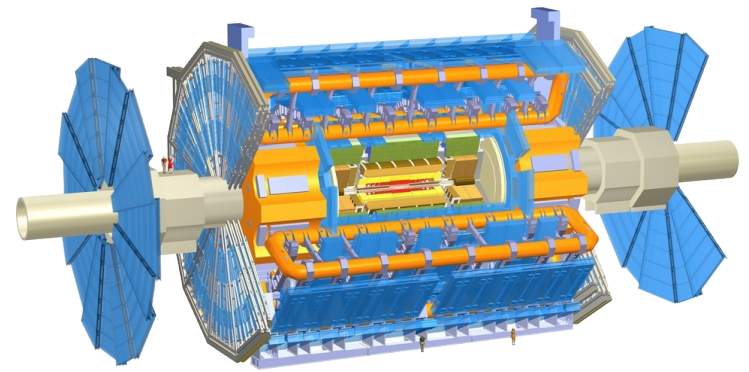
$p+p, p+Pb, Pb+Pb$

$\sqrt{s_{NN}} = 2.76 \text{ GeV}, 5.5 \text{ TeV}$

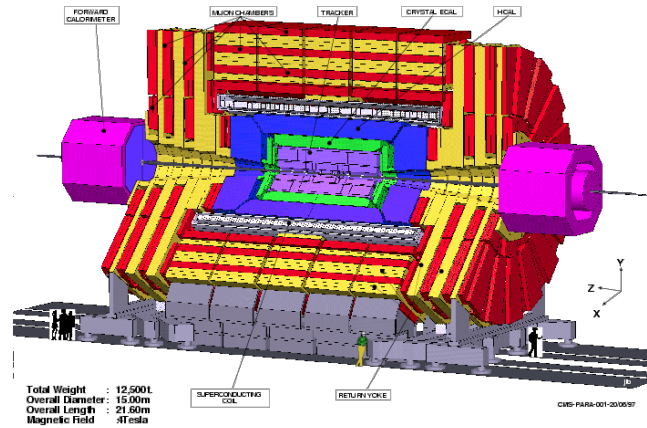




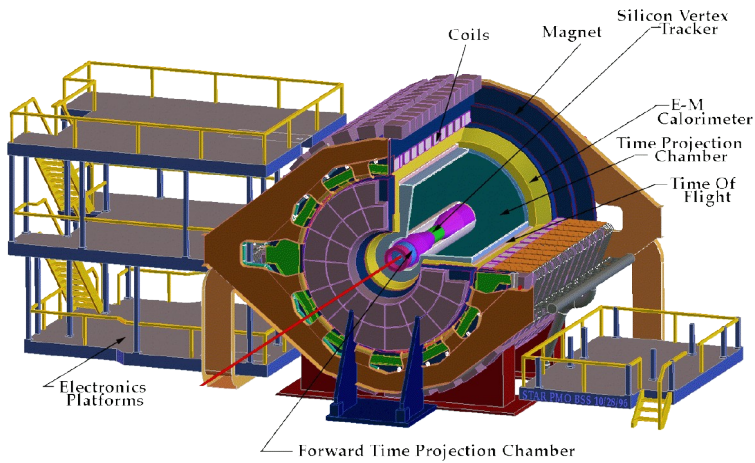
ALICE



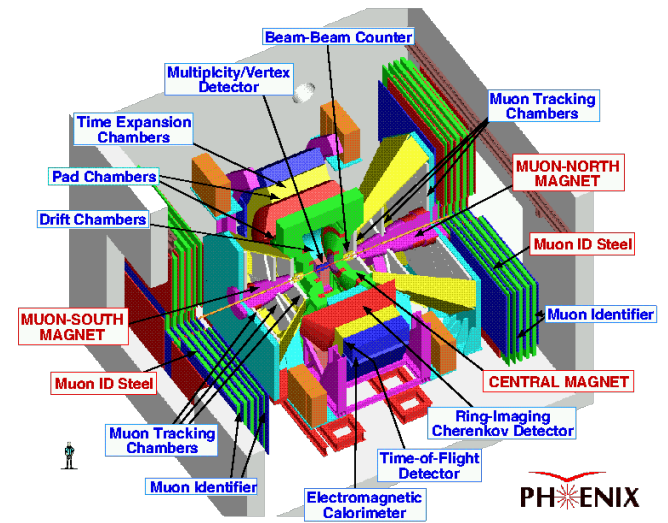
ATLAS



CMS



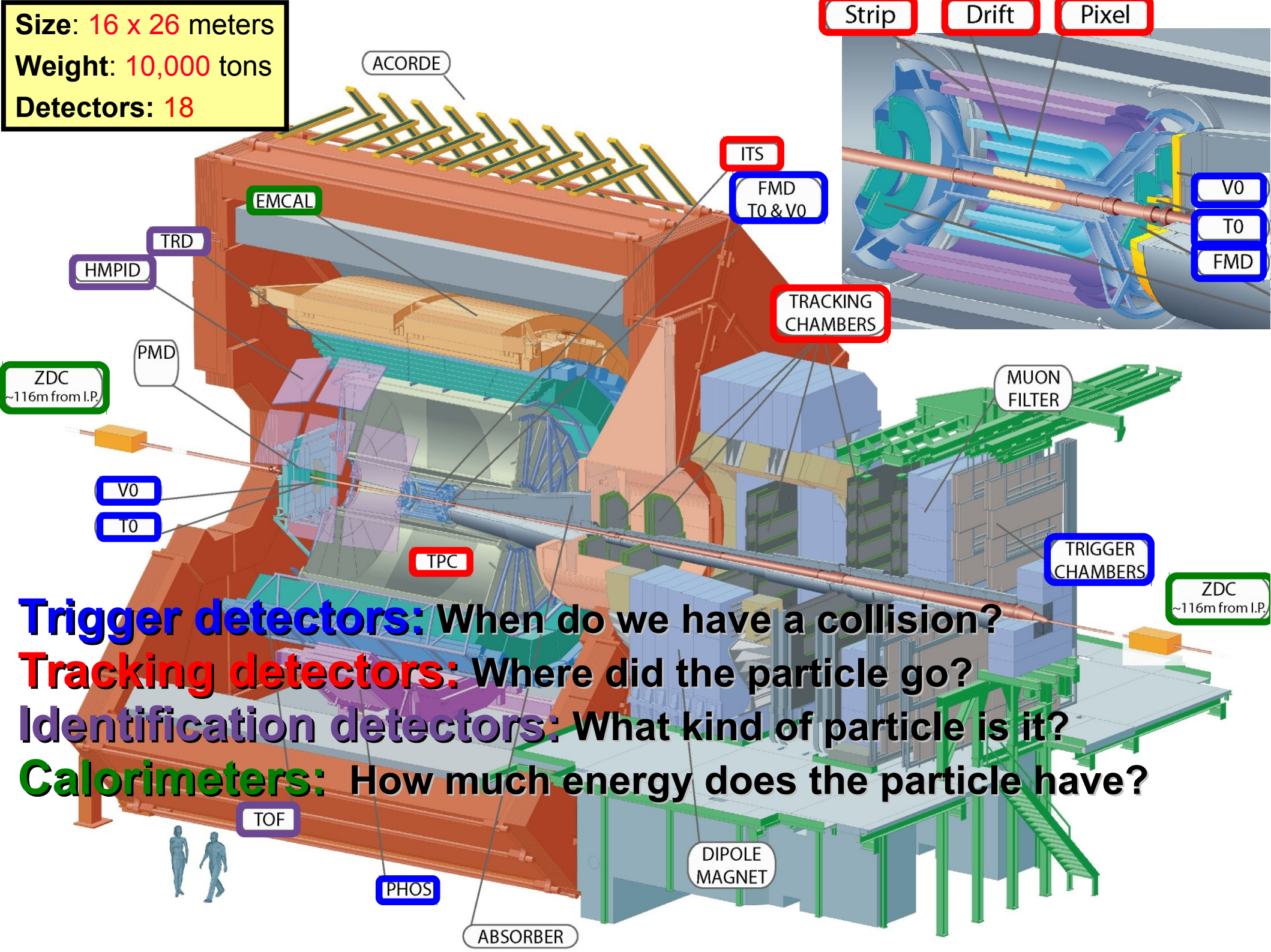
STAR



PHENIX

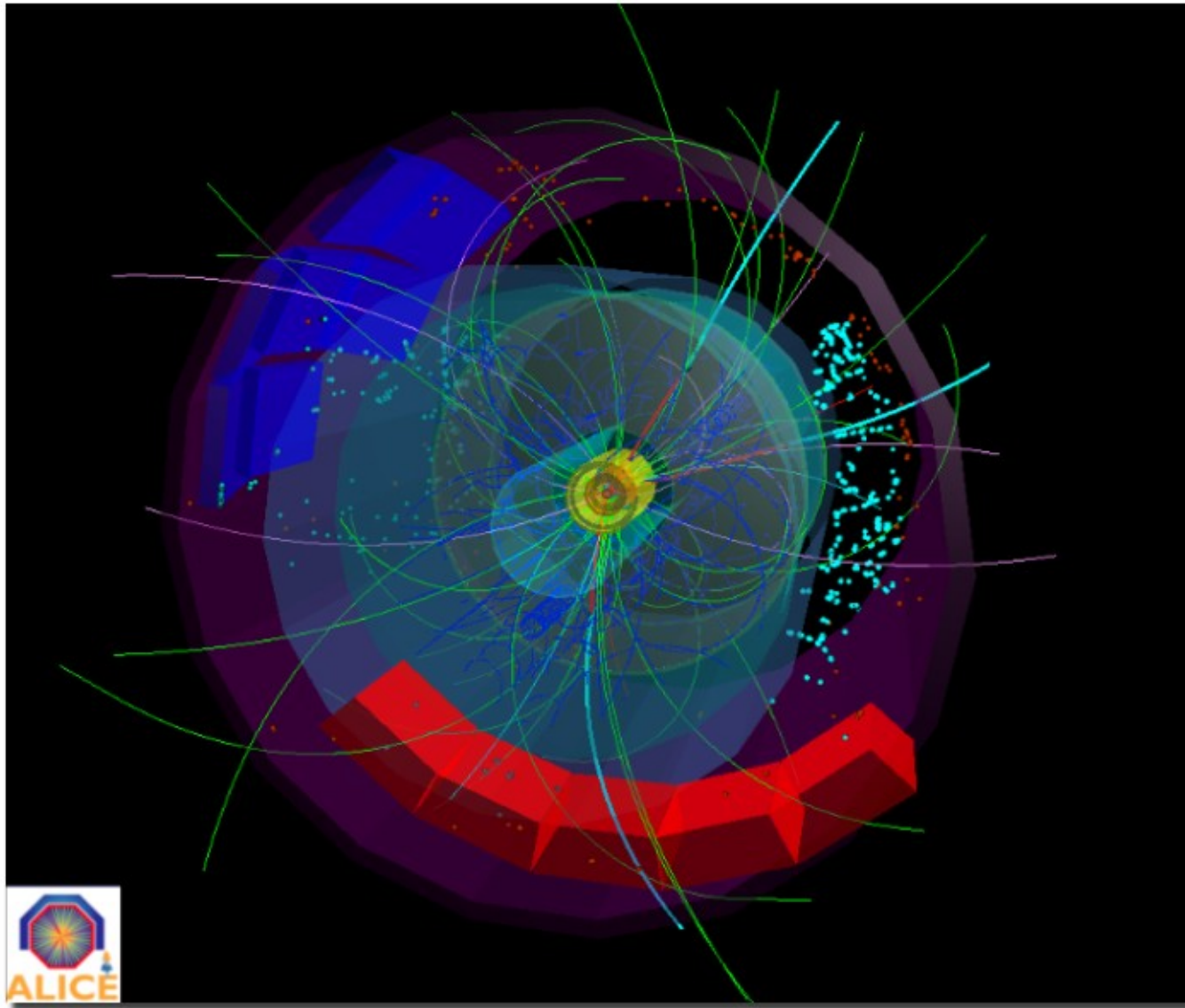


Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18



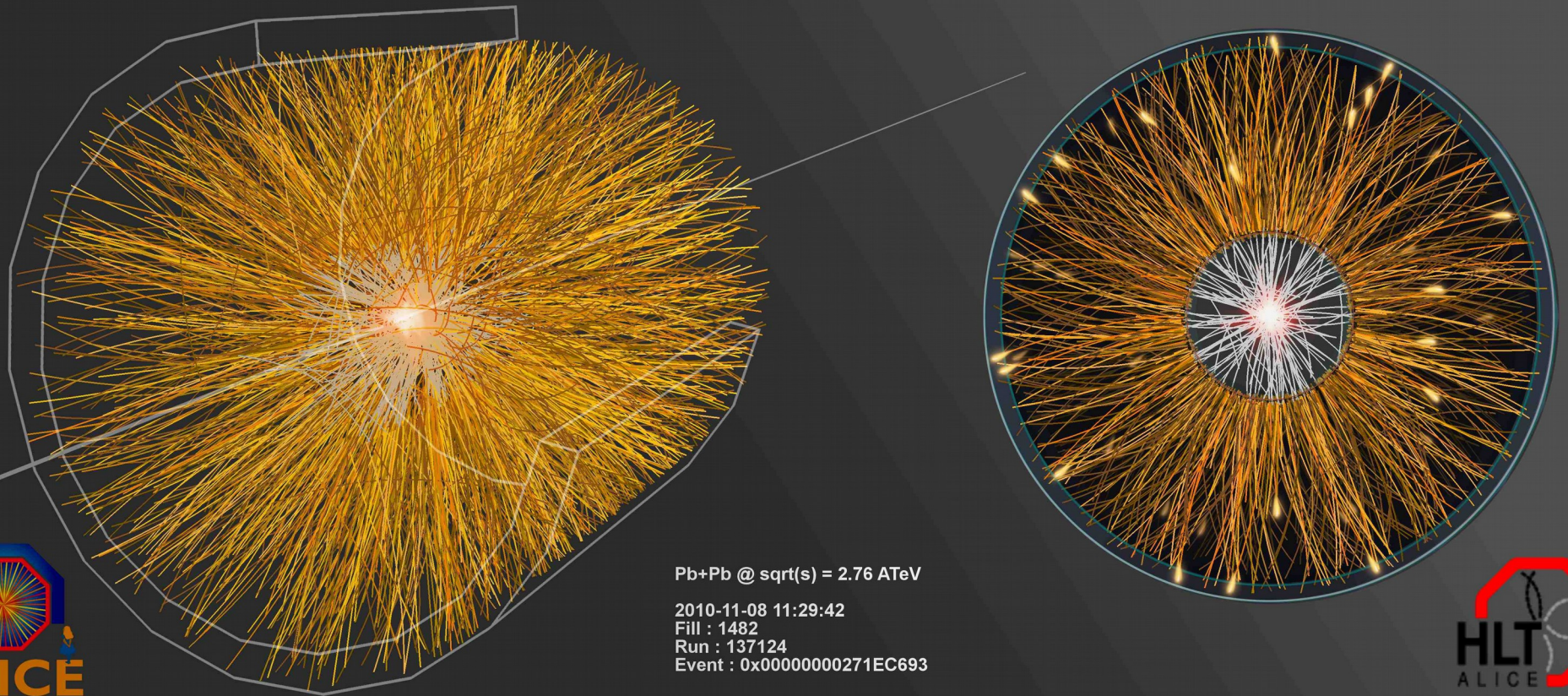
Trigger detectors: When do we have a collision?
Tracking detectors: Where did the particle go?
Identification detectors: What kind of particle is it?
Calorimeters: How much energy does the particle have?

p+p collisions



3D image of each collision

Pb+Pb collisions

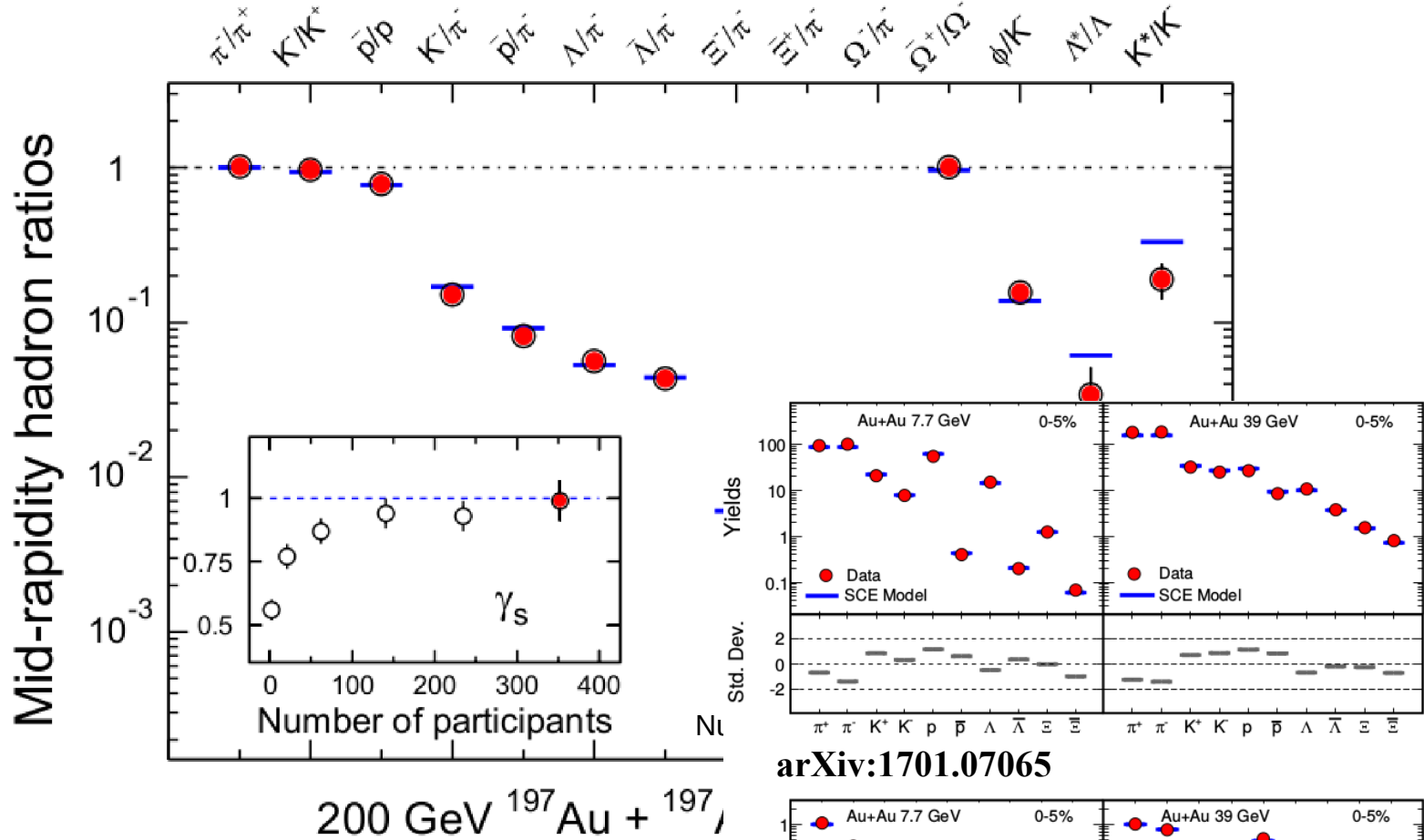


contactmiko@yahoo.de
agalki13@gmail.com
NIKOS EMMANOULIDIS
AGEUKI MANTA

QGP Chemistry

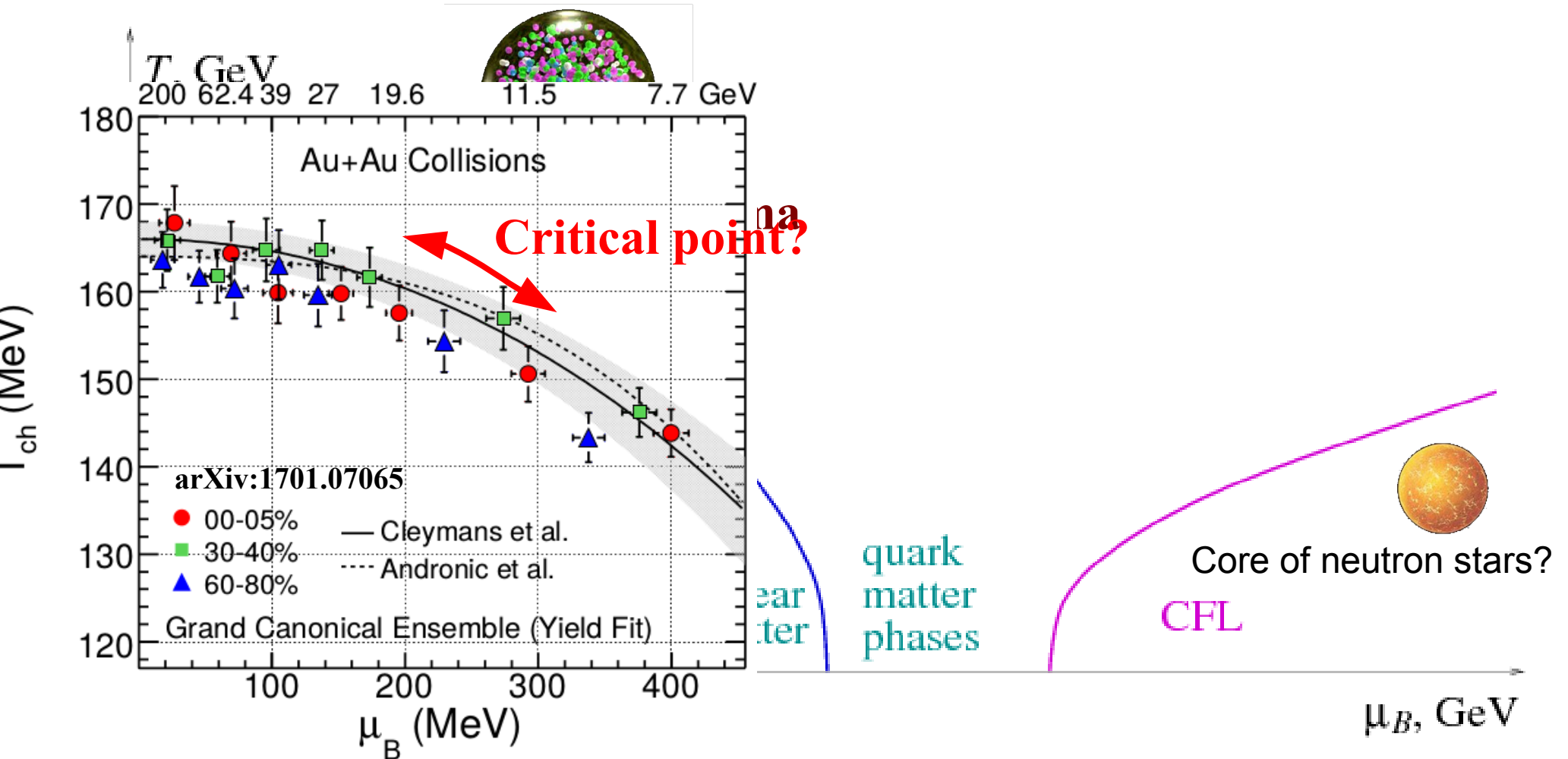
Chemistry - equilibrium

$T \sim 170$
MeV

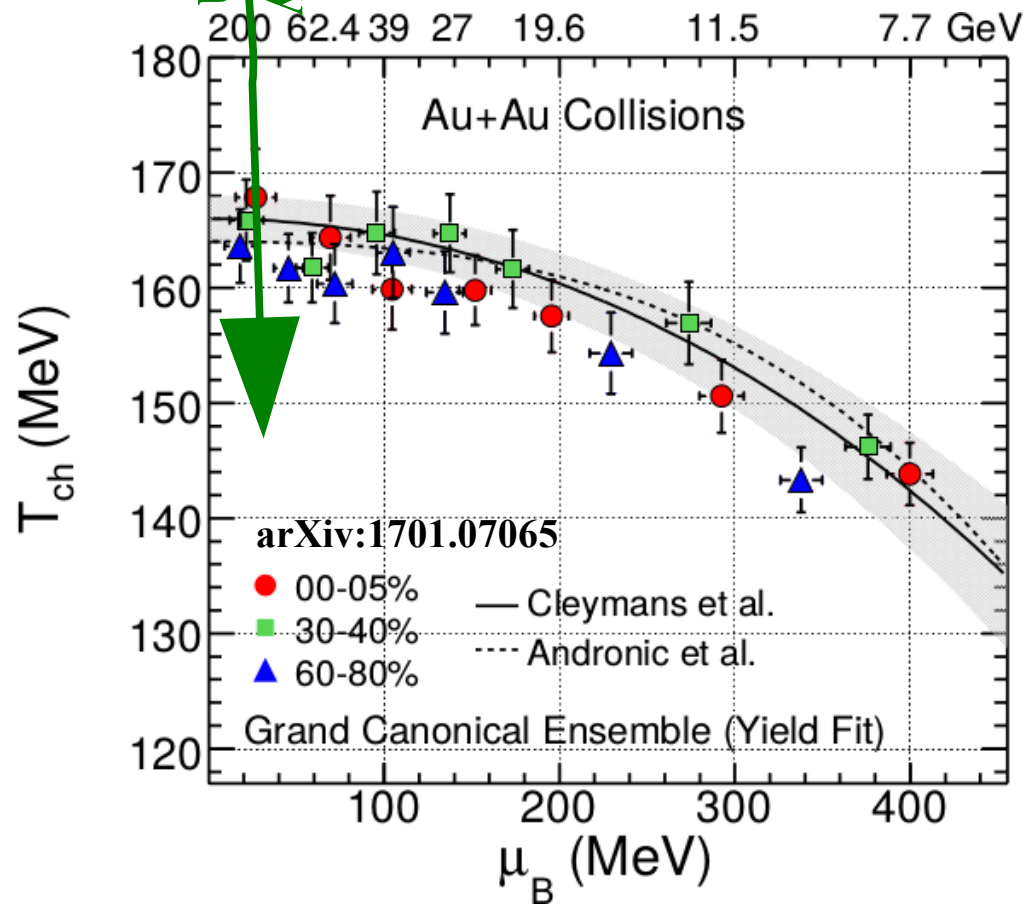


- Ratios of particles expected from a hadron gas
- Even strange quarks are at equilibrium

Phase diagram of nuclear matter

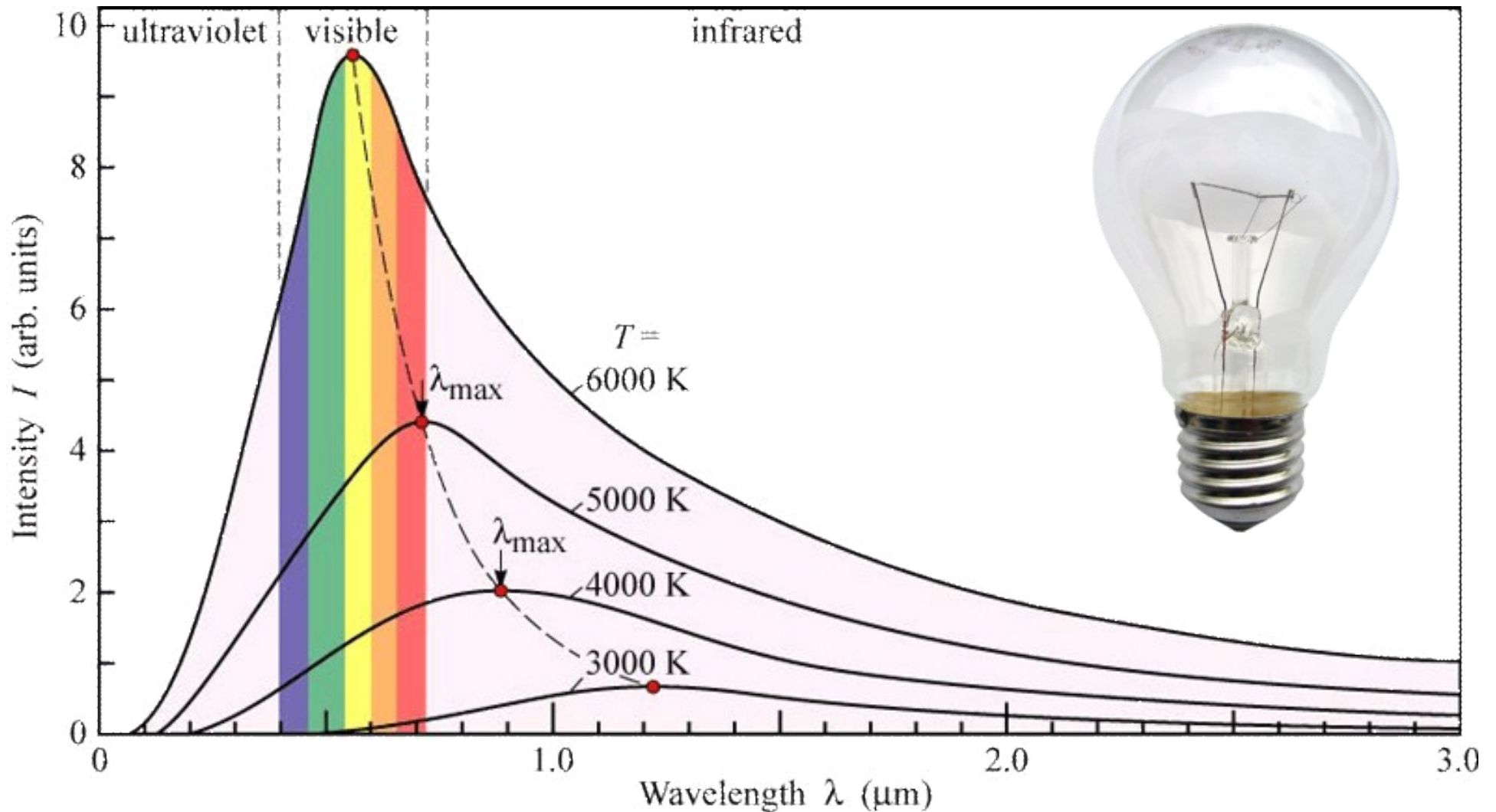


Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~ 170 MeV ($2 \cdot 10^{12}$ K) – over a million times hotter than the core of the sun



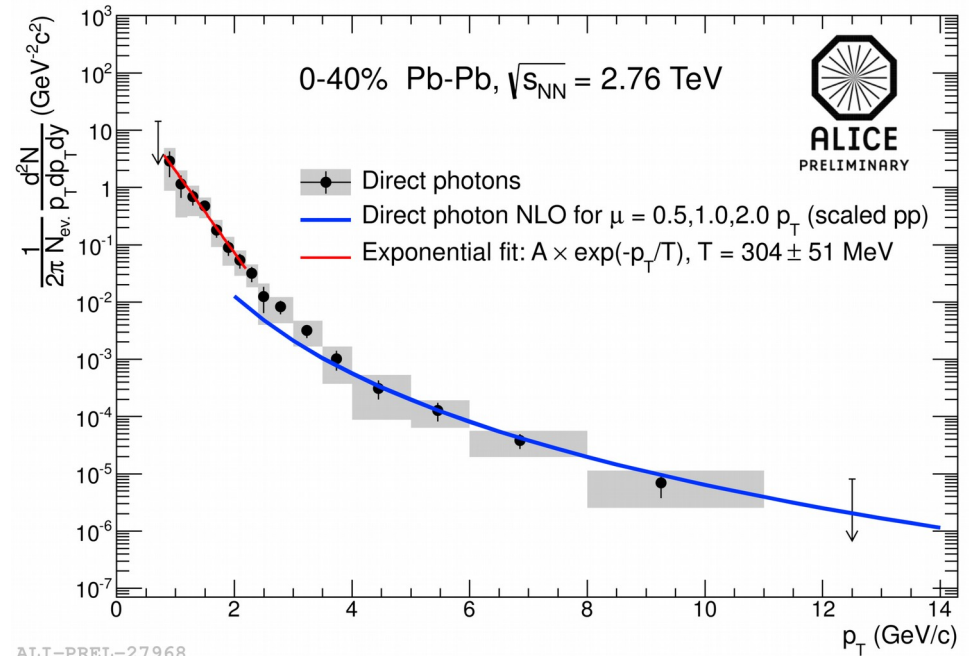
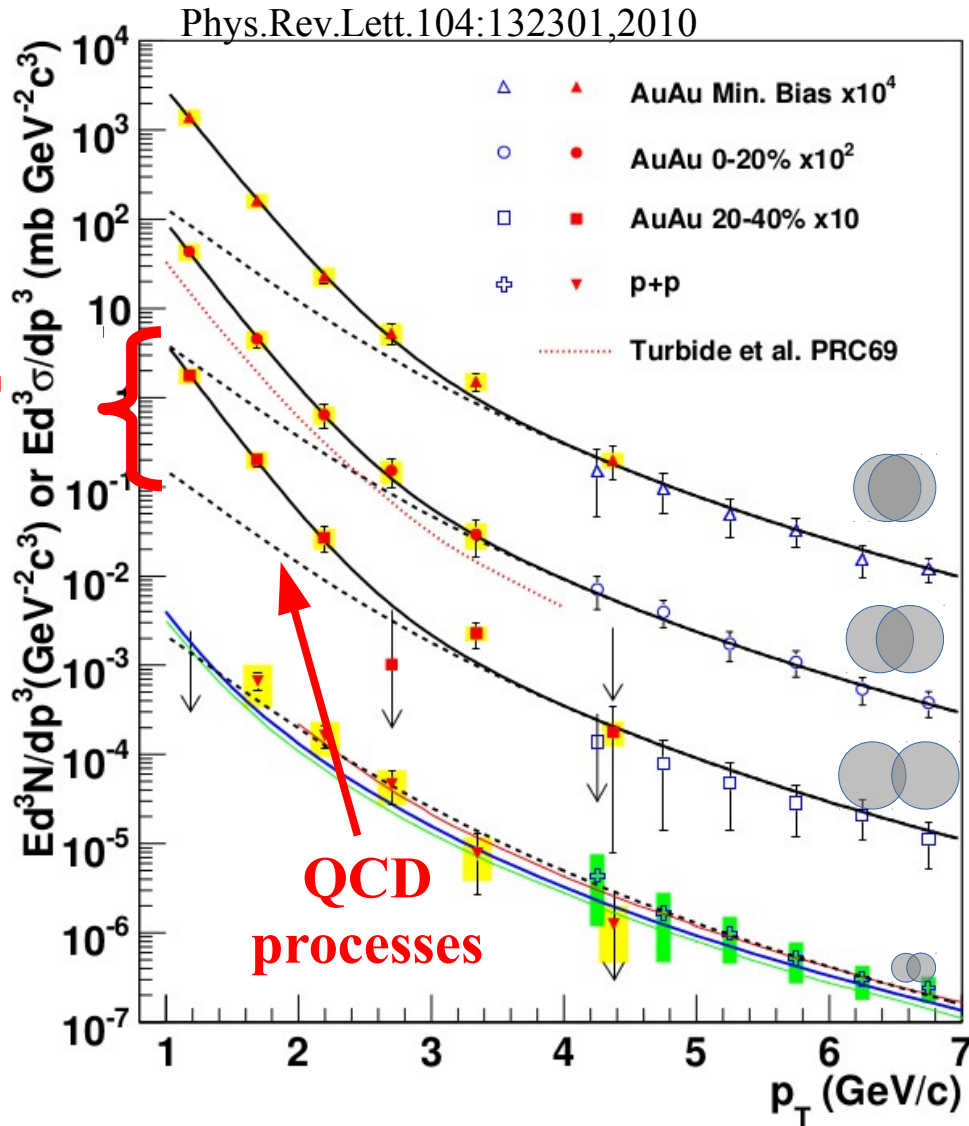
QGP Thermometers

Measuring temperature



Thermal photons

Thermal photons



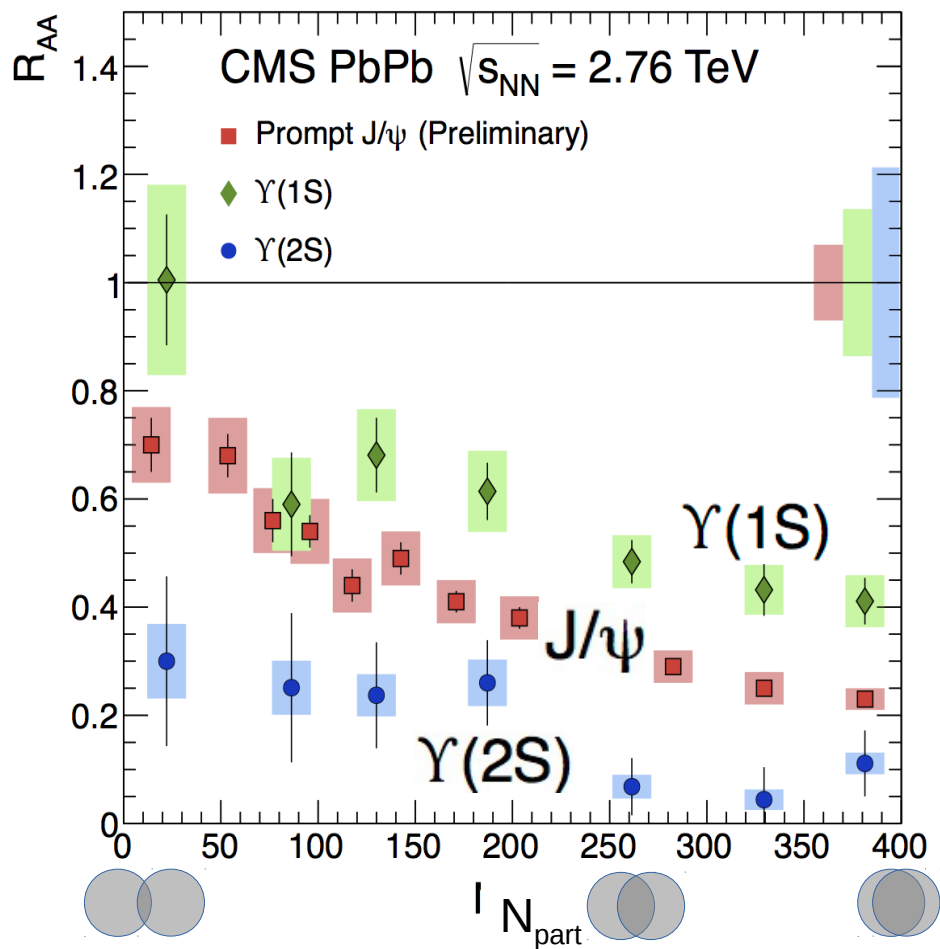
ALICE collaboration:
 Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
Inverse slope: $T = 304 \pm 51$

PHENIX collaboration: Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

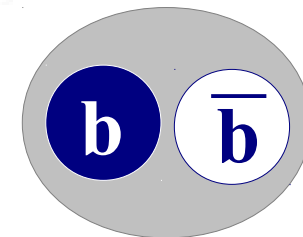
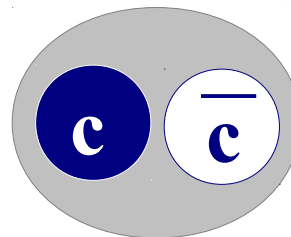
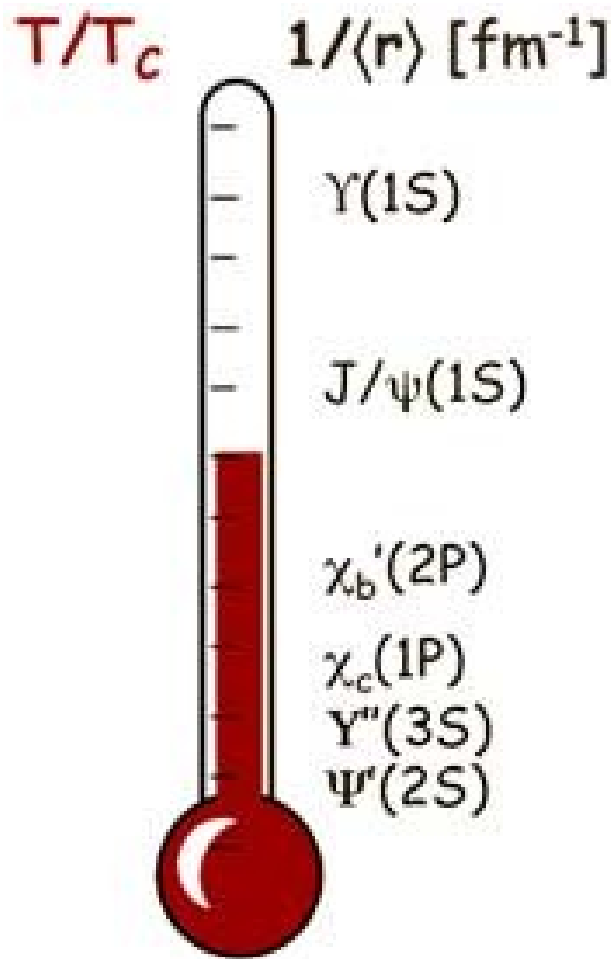
Inverse slope: $T = 221 \pm 19$ (stat) ± 19 (syst) MeV

Building a quarkonium-thermometer

CMS-PAS HIN-11-011

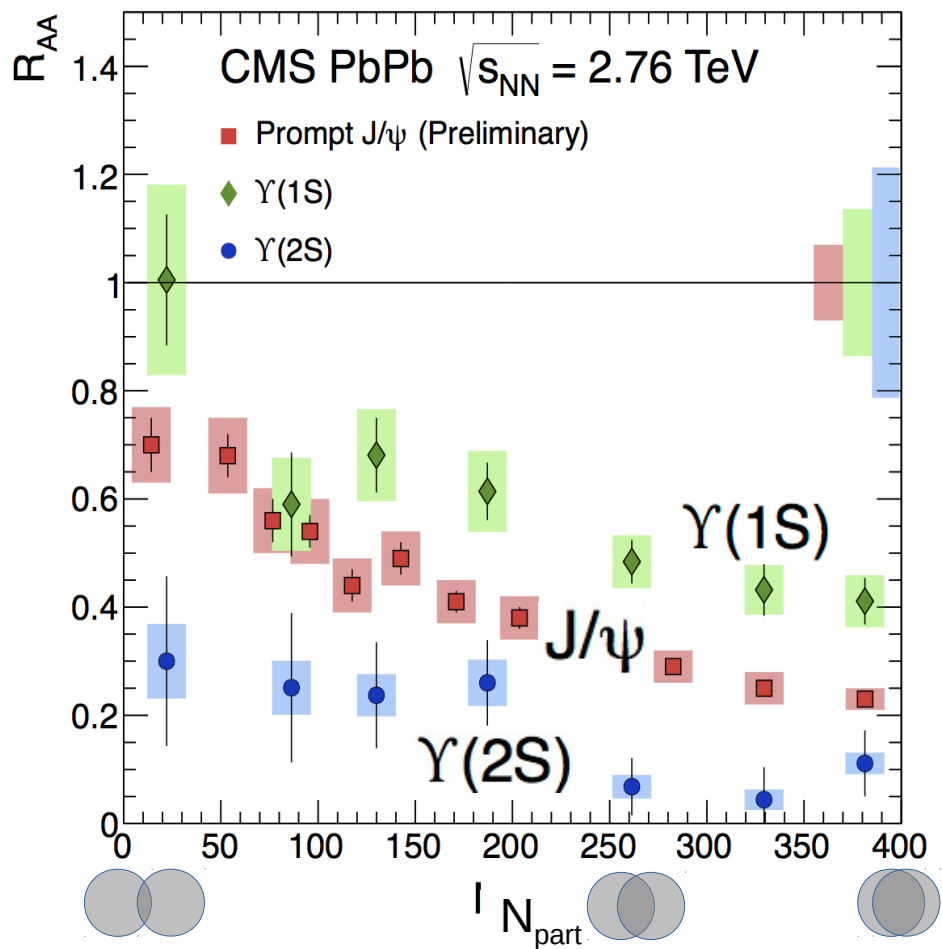


Clear hierarchy in R_{AA} of different quarkonium states



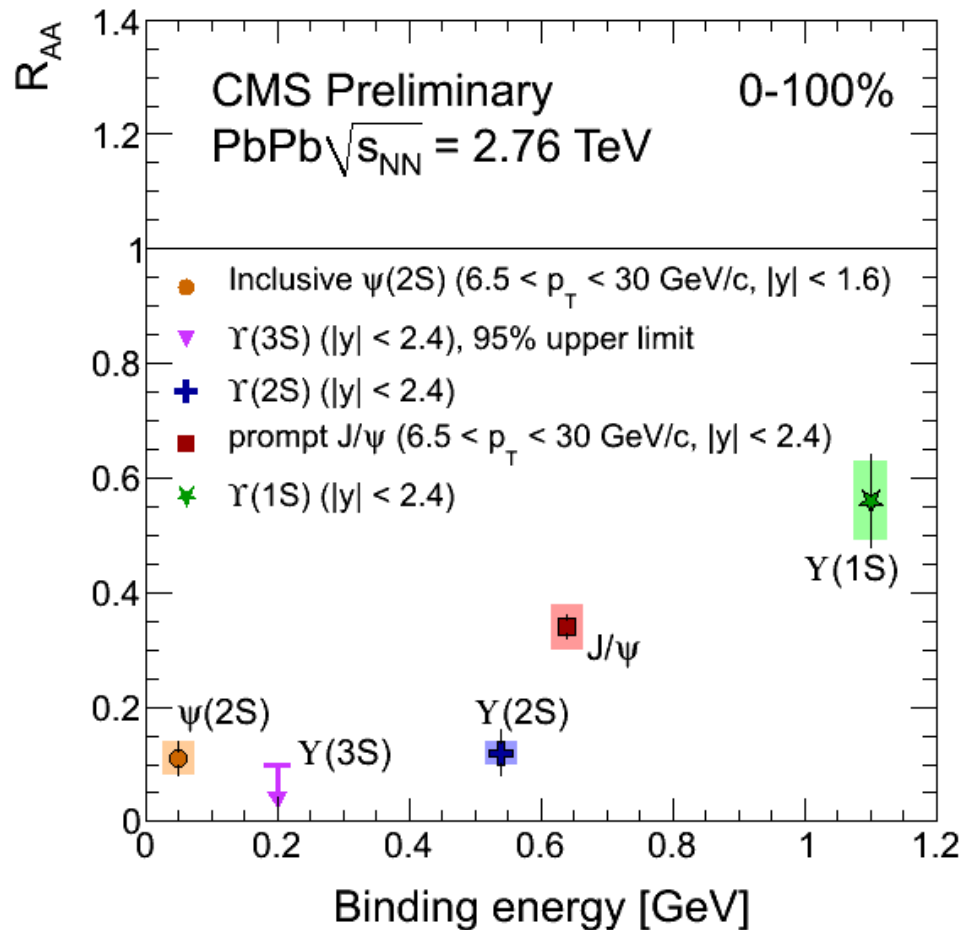
Building a quarkonium-thermometer

CMS-PAS HIN-11-011



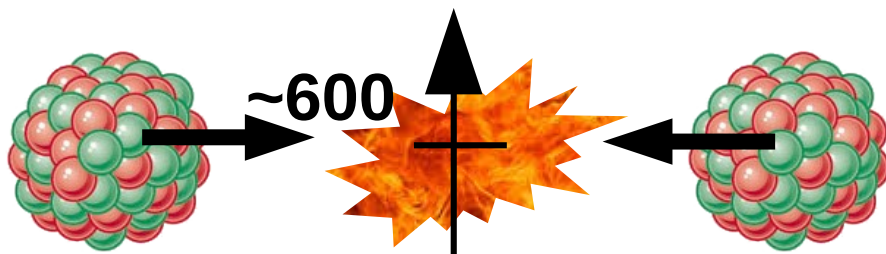
Clear hierarchy in R_{AA} of different quarkonium states

Note: $6.5 < p_T < 30$ GeV for J/ ψ and $\psi(2s)$

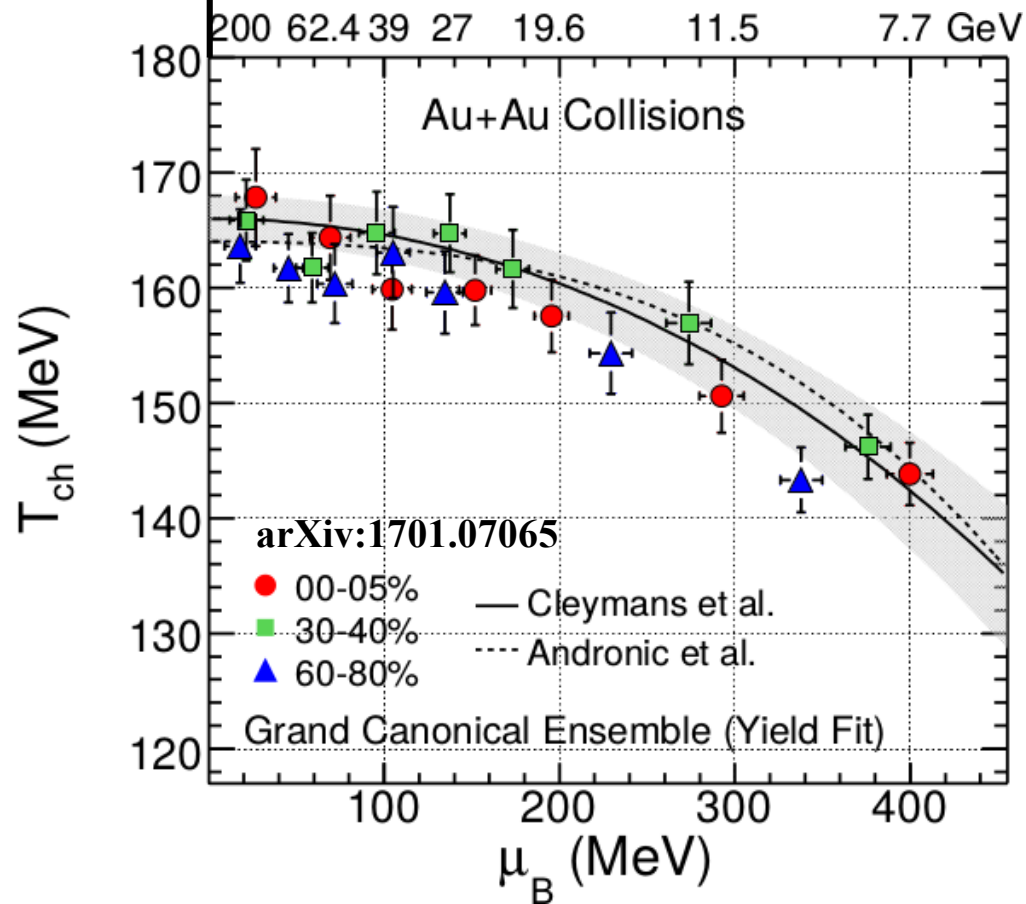


Expected in terms of binding energy

CMS-PAS HIN-12-014, HIN-12-007



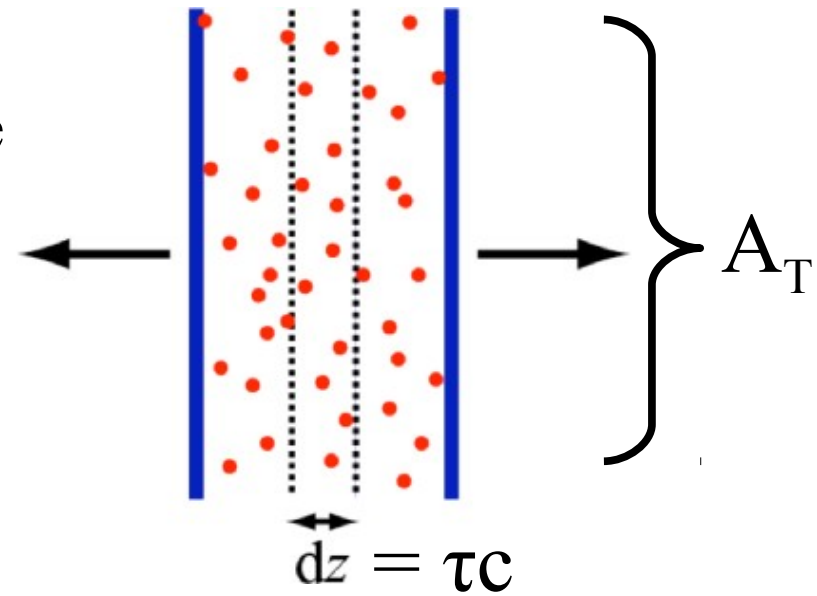
trajectory
of system



QGP Energy Density

How can we estimate the energy density?

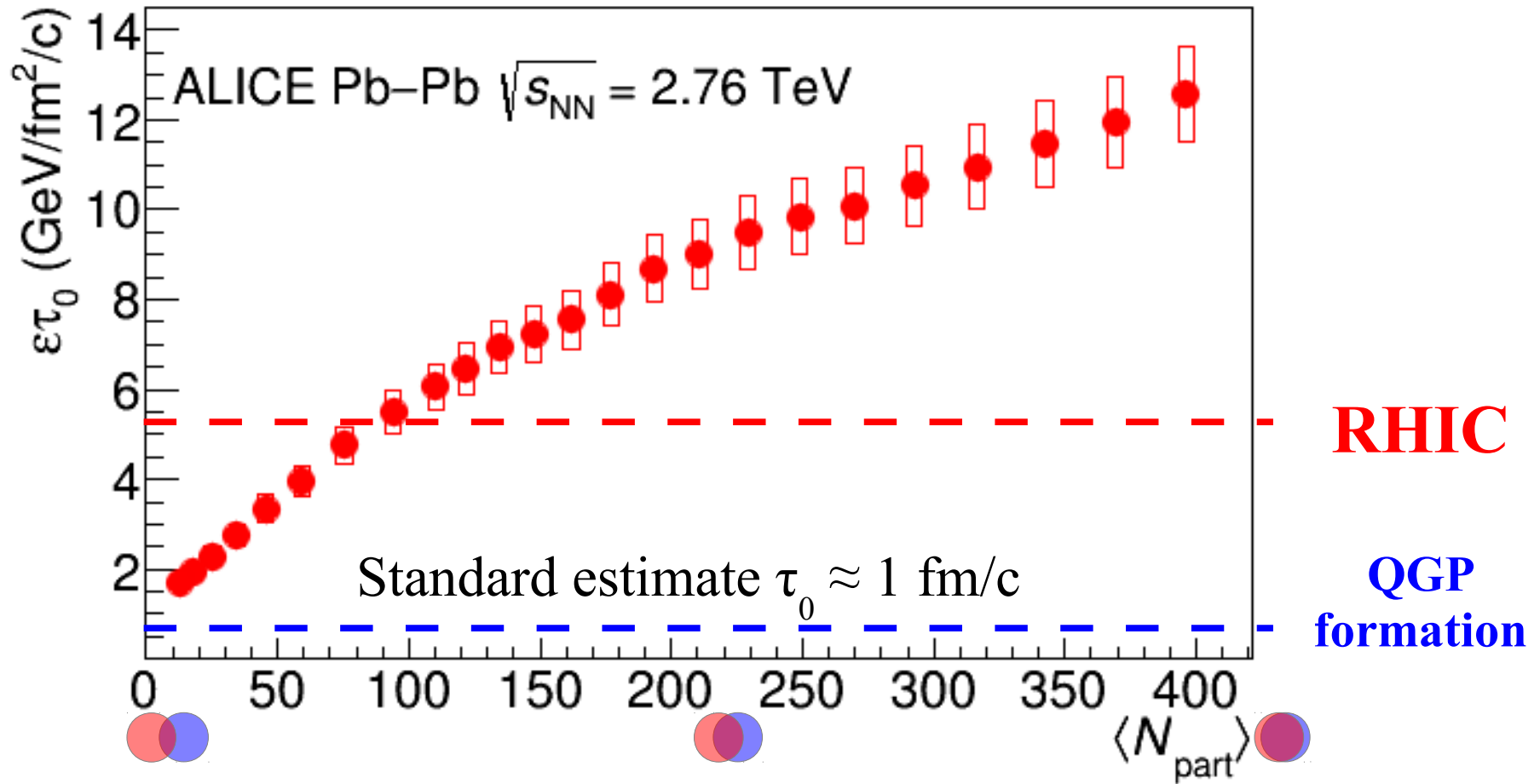
- Transverse energy (E_T)
 - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ϵ



$$\epsilon = \frac{1}{V} \frac{dE_T}{dy} = \frac{J}{A_T \tau c} \frac{dE_T}{d\eta}$$

- QGP formation for $\epsilon > 0.5 \text{ GeV}/\text{fm}^3$

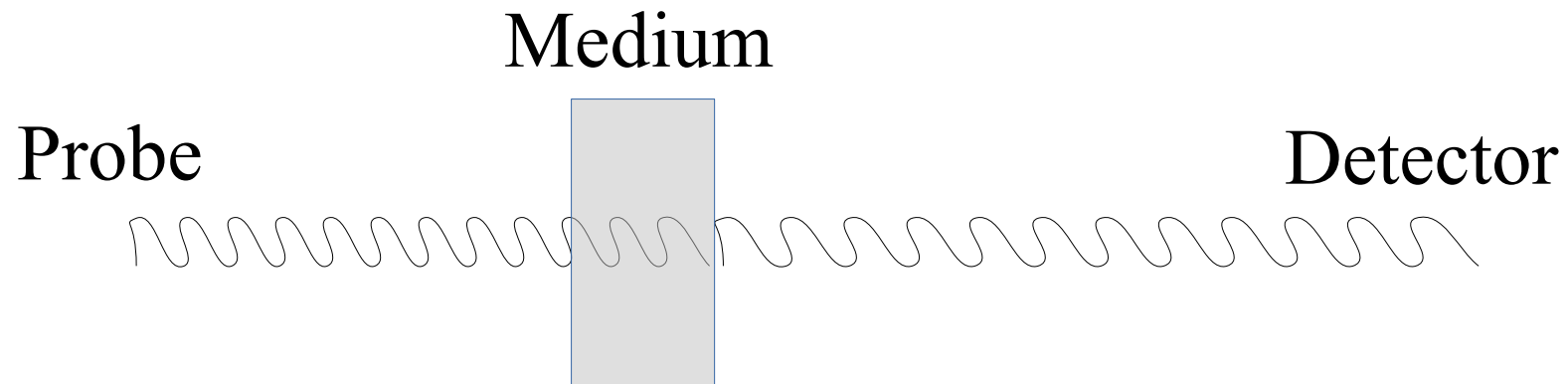
Energy density



$$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$$

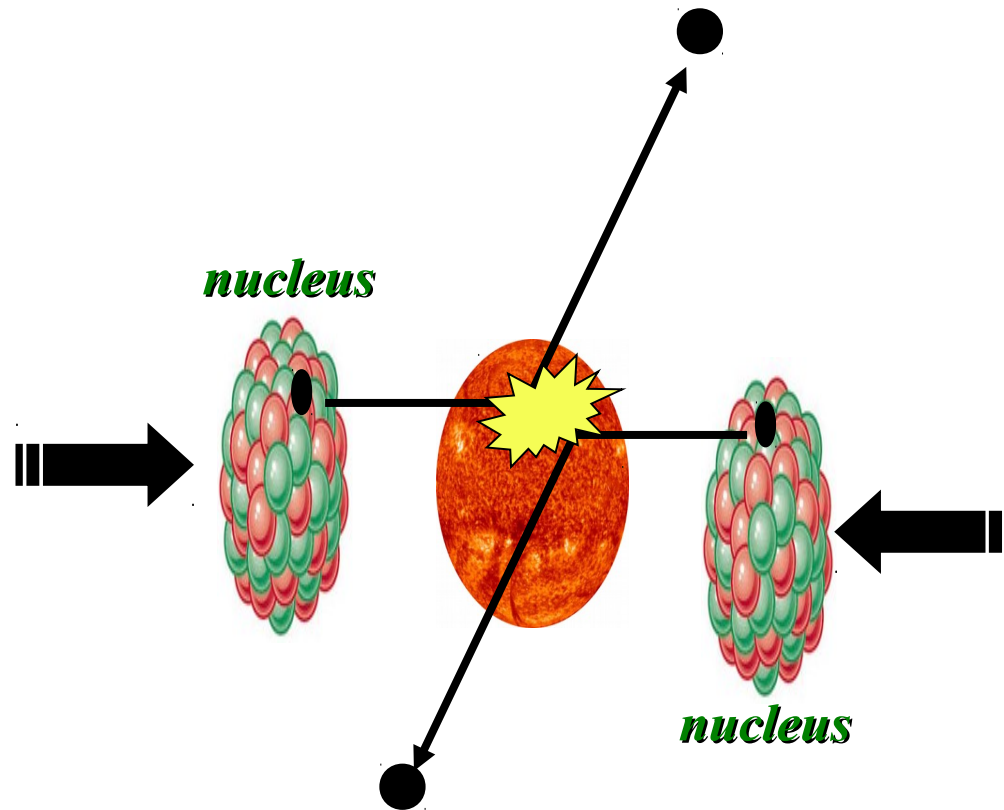
QGP Spectroscopy

Probing the Quark Gluon Plasma



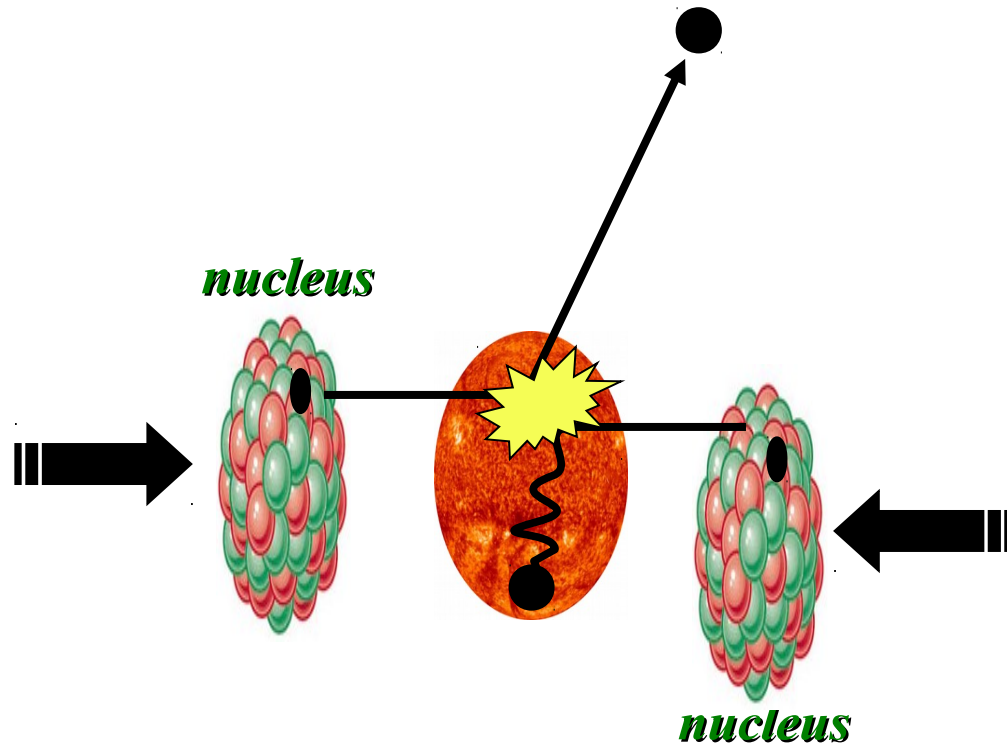
Want a probe which traveled through the collision
QGP is very short-lived ($\sim 1-10$ fm/c) \rightarrow
cannot use an external probe

Probes of the Quark Gluon Plasma



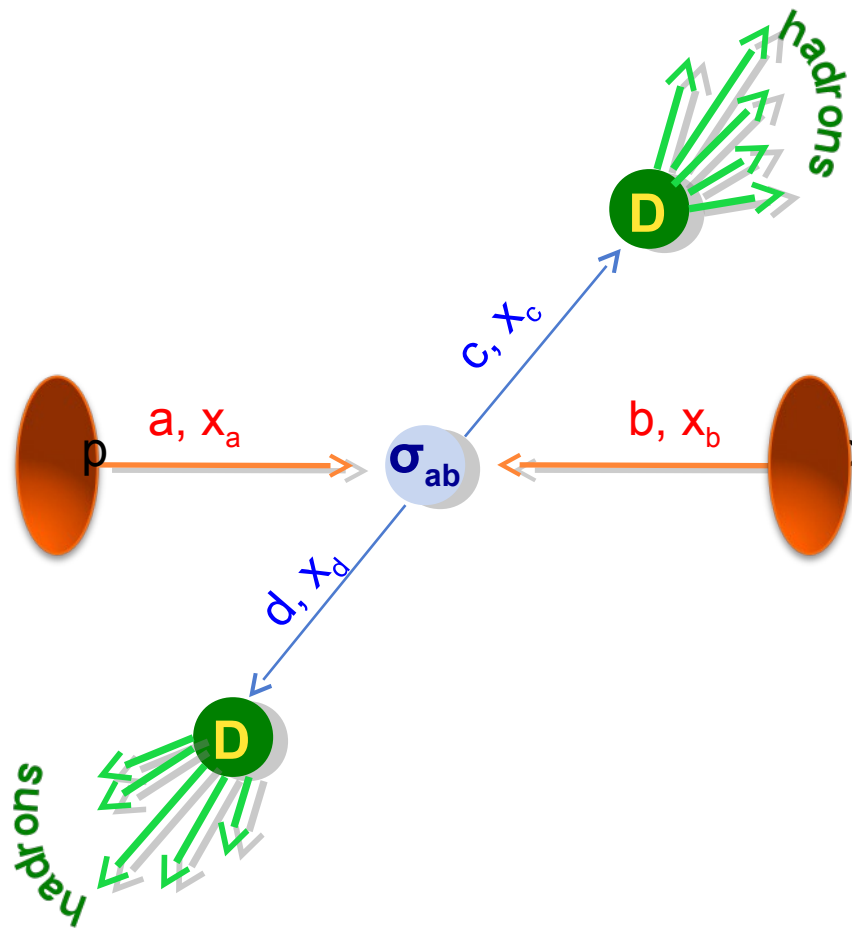
Want a probe which traveled through the medium
QGP is short lived \rightarrow need a probe created in the collision

Probes of the Quark Gluon Plasma

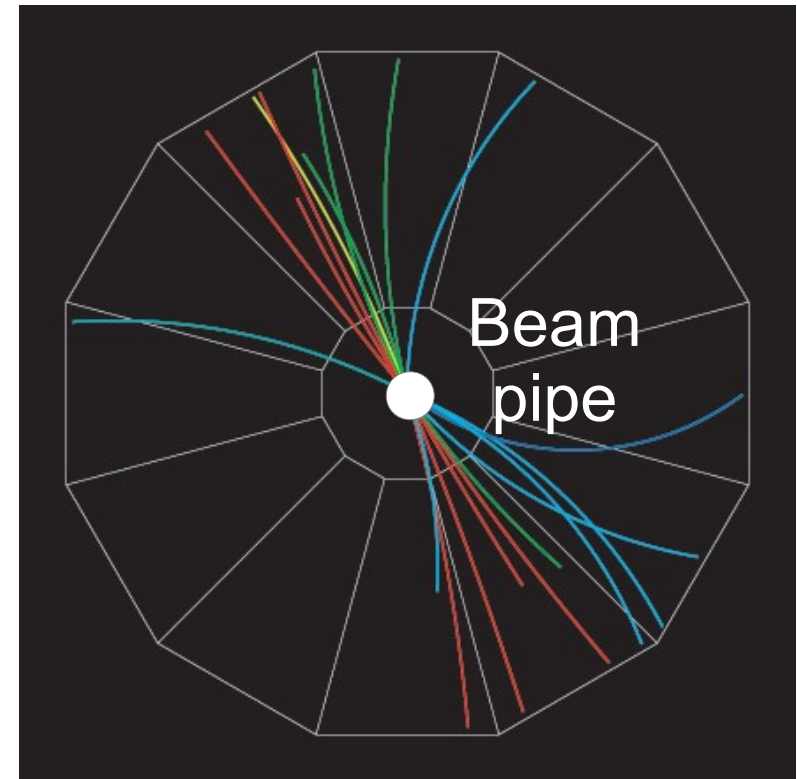


Want a probe which traveled through the medium
QGP is short lived \rightarrow need a probe created in the collision
We expect the medium to be dense \rightarrow absorb/modify probe

Jets



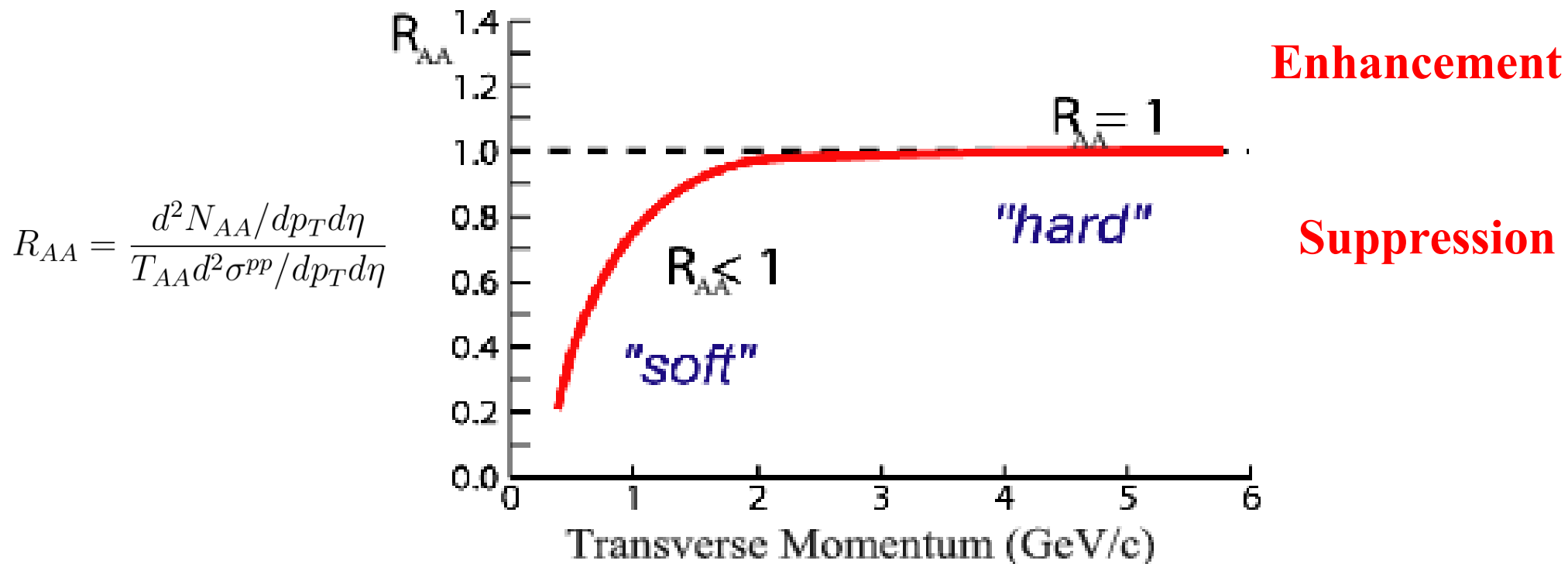
p+p \rightarrow dijet



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

Nuclear modification factor

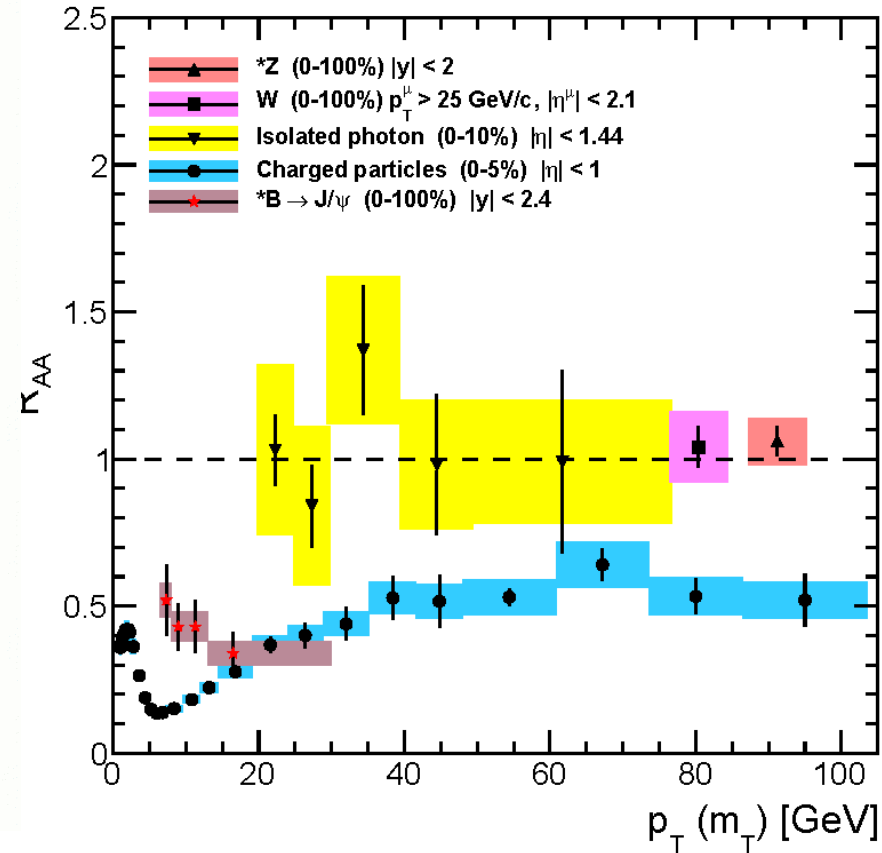
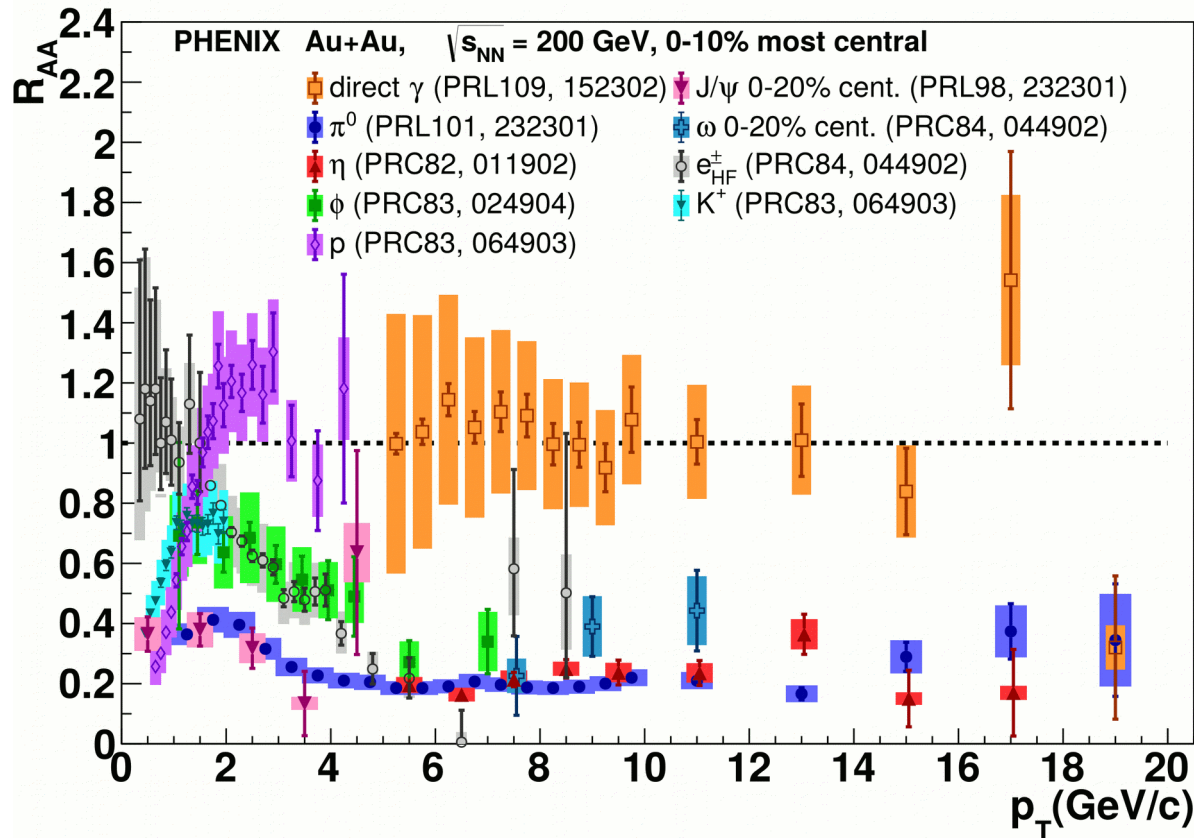
- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high- p_T probes (jets) are suppressed, this is evidence of jet quenching



Nuclear modification factor R_{AA}

RHIC

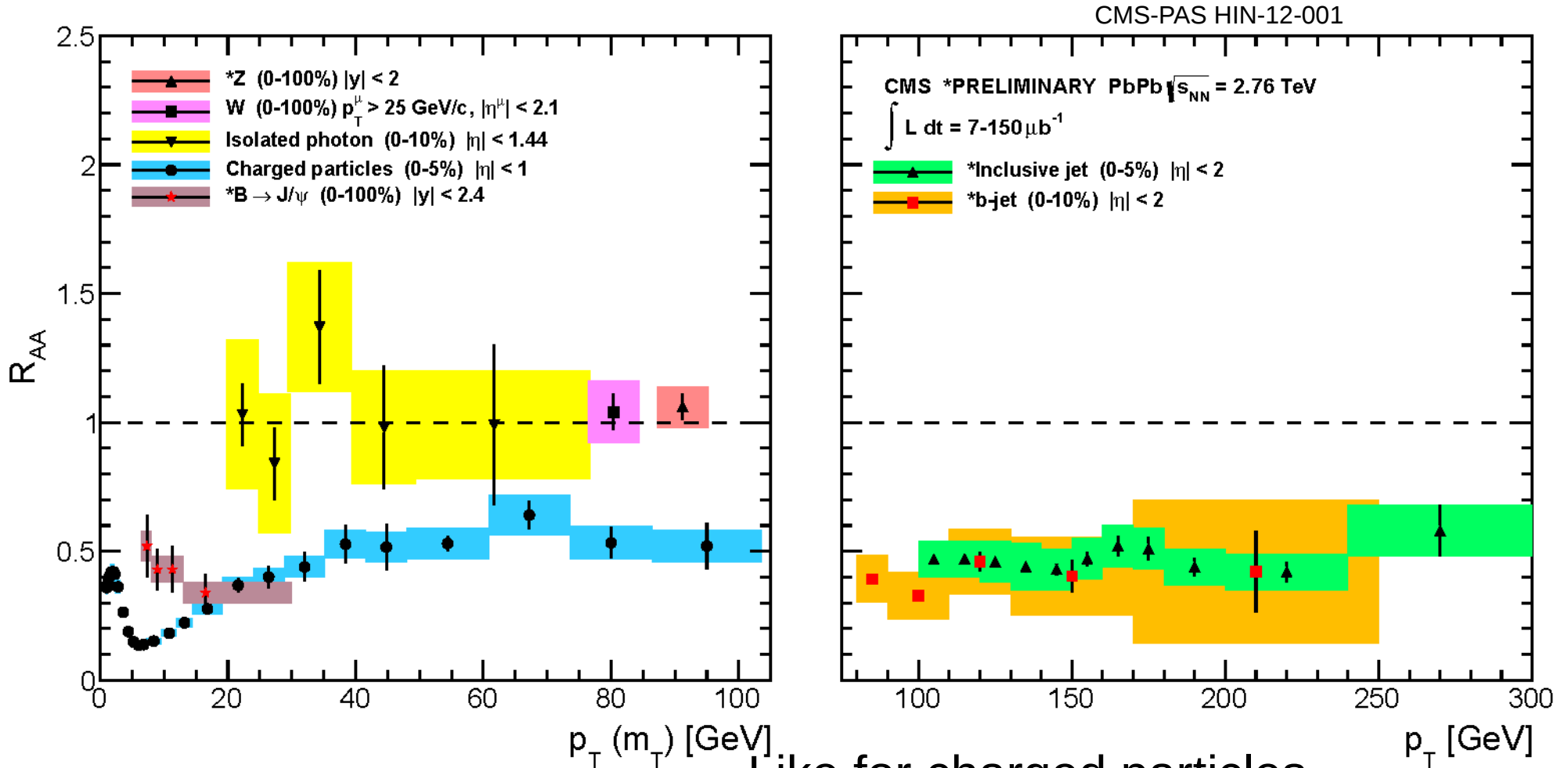
LHC



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

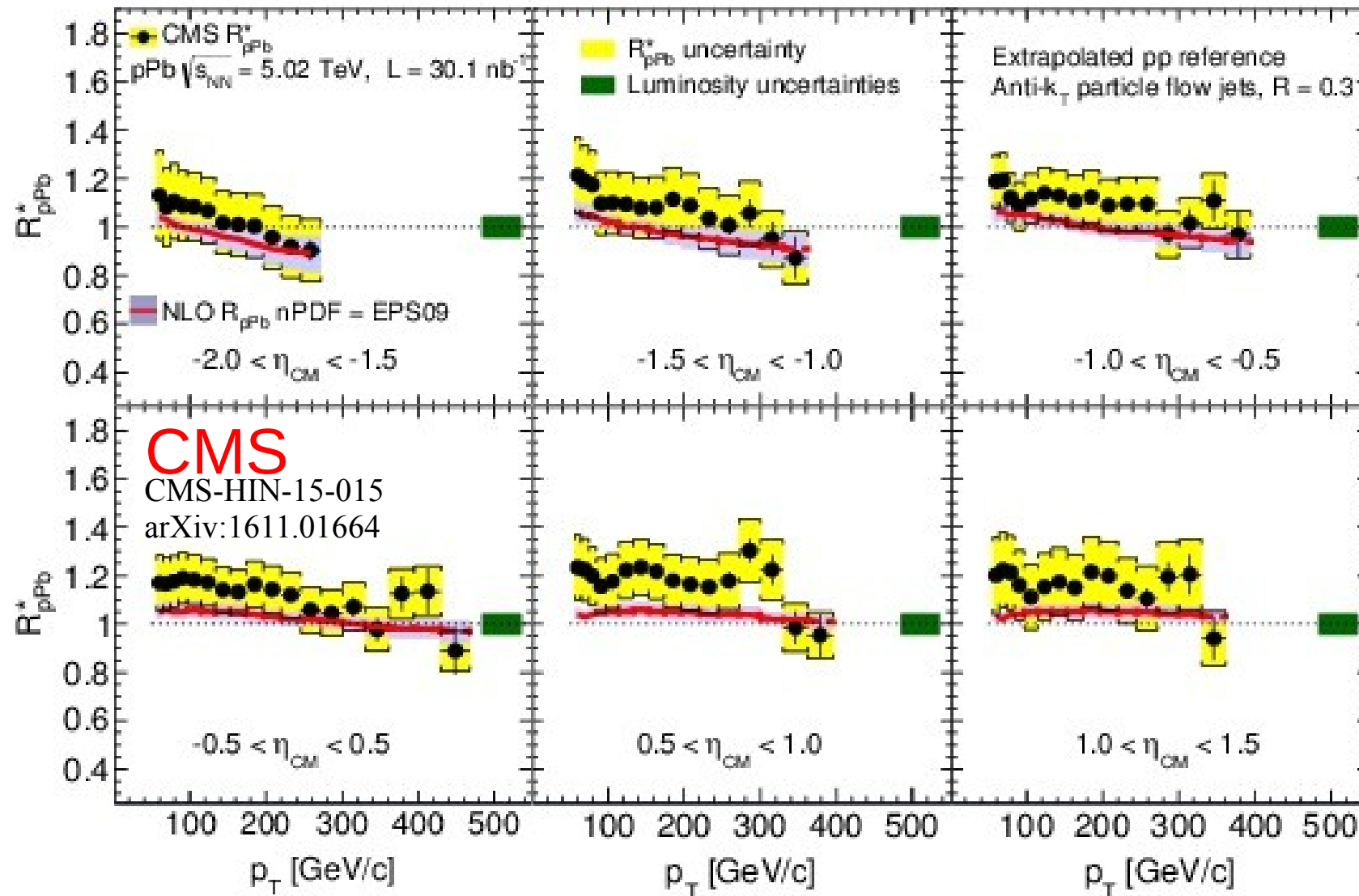
Nuclear modification factor R_{AA} at LHC

Fully unfolded inclusive jet R_{AA}
pp 2.76 TeV reference



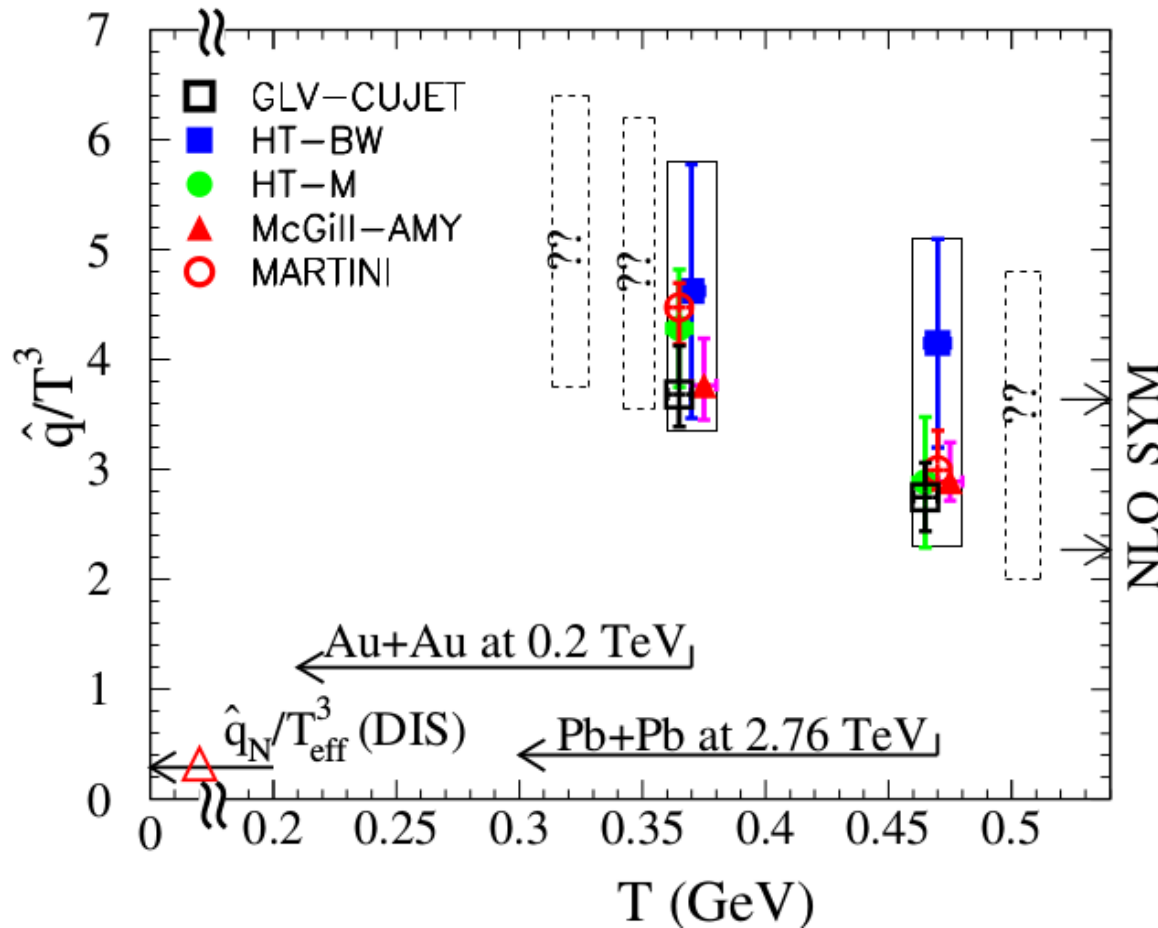
Like for charged particles,
high- p_T jet R_{AA} flat at ≈ 0.5

p+Pb as a control



Quantifying \hat{q}

Phys. Rev. C 90, 014909 (2014)



Jet Collaboration: For a 10 GeV quark traveling 4 fm

$\hat{q} \approx 1.2 \pm 0.3 \text{ GeV}^2/\text{fm}$ at $\tau_0 = 0.6 \text{ fm}/c$ in Au+Au at

$\sqrt{s_{\text{NN}}} = 200 \text{ GeV} \rightarrow \text{loses } 2.2 \text{ GeV}$

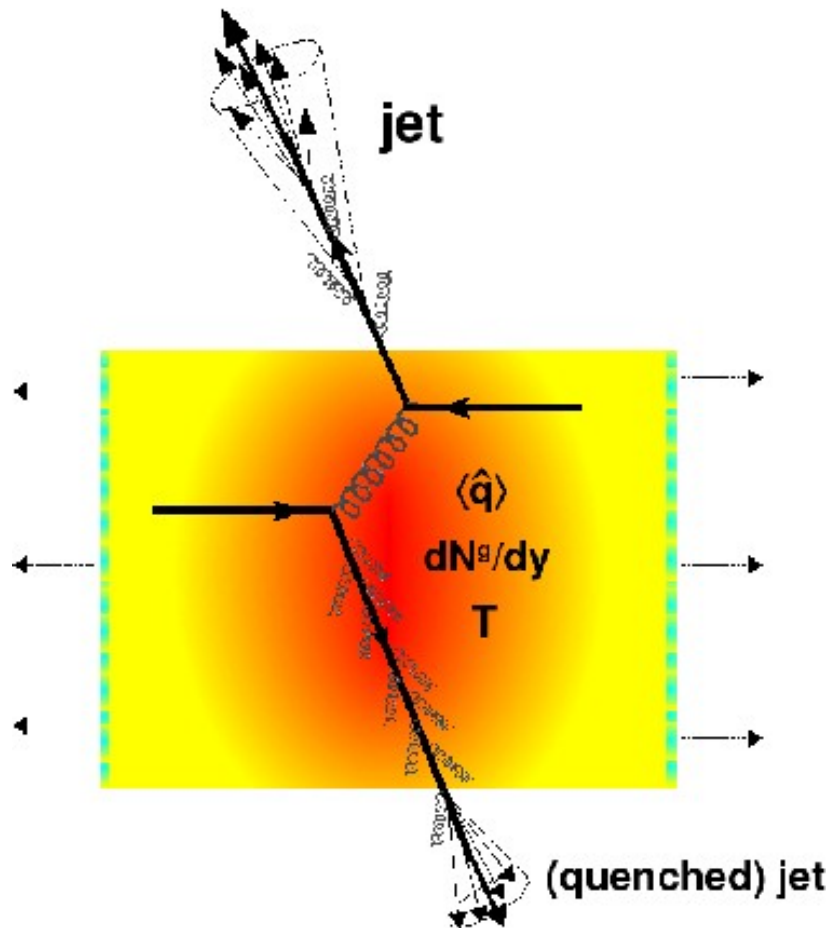
$\hat{q} \approx 1.9 \pm 0.7 \text{ GeV}^2/\text{fm}$ in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

$\rightarrow \text{loses } 2.8 \text{ GeV}$

$$\hat{q} = Q^2 / L$$

Q = Momentum transfer from parton to medium
L = path length

Gluon bremsstrahlung

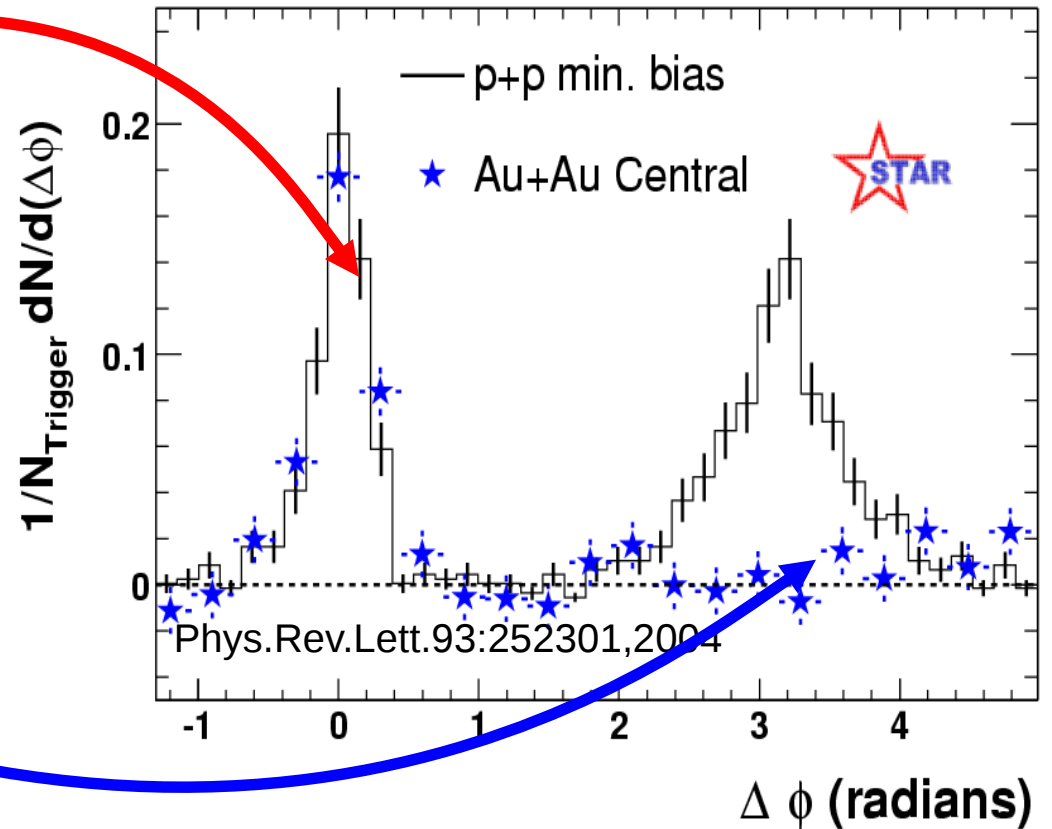
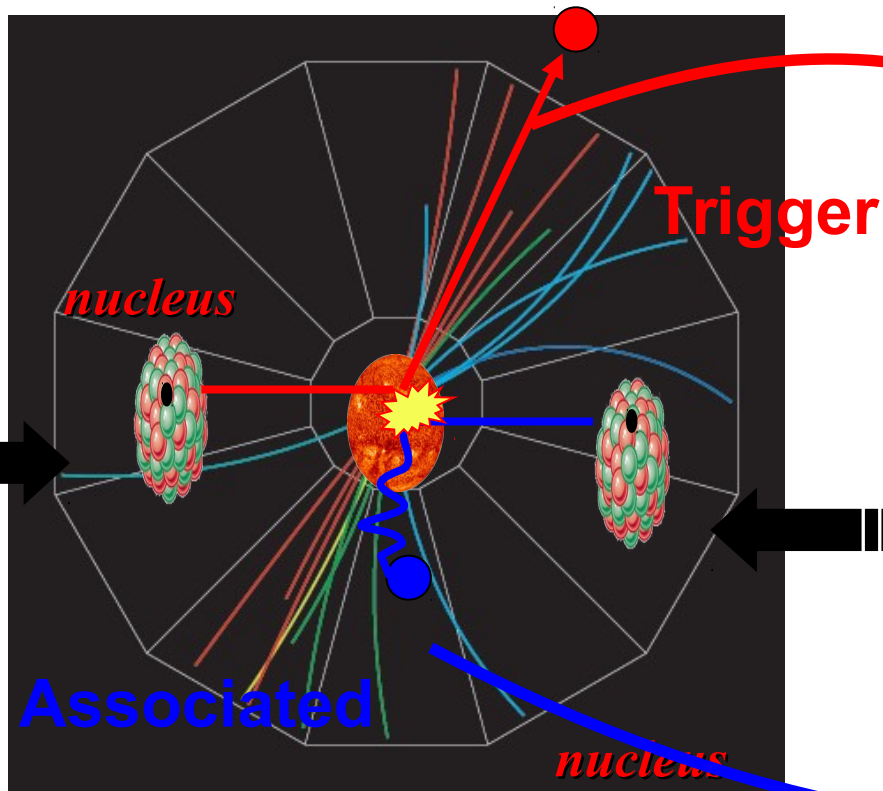


- Softer constituents
- Broader radius

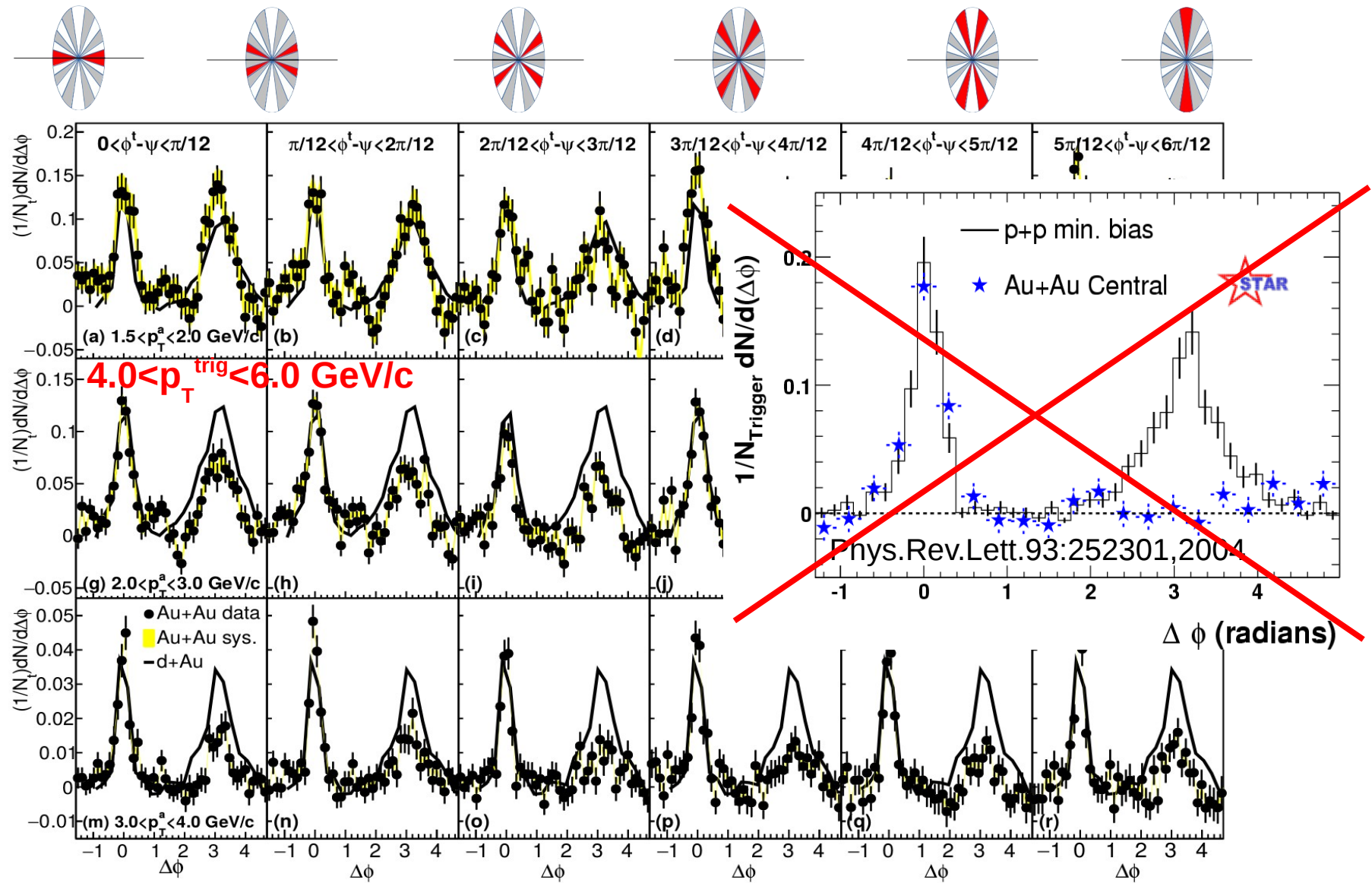
Figure from Nucl.Phys. A827 (2009) 356C-364C arXiv:0902.2488 [nucl-ex]

Azimuthal correlations

$p+p \rightarrow \text{dijet}$



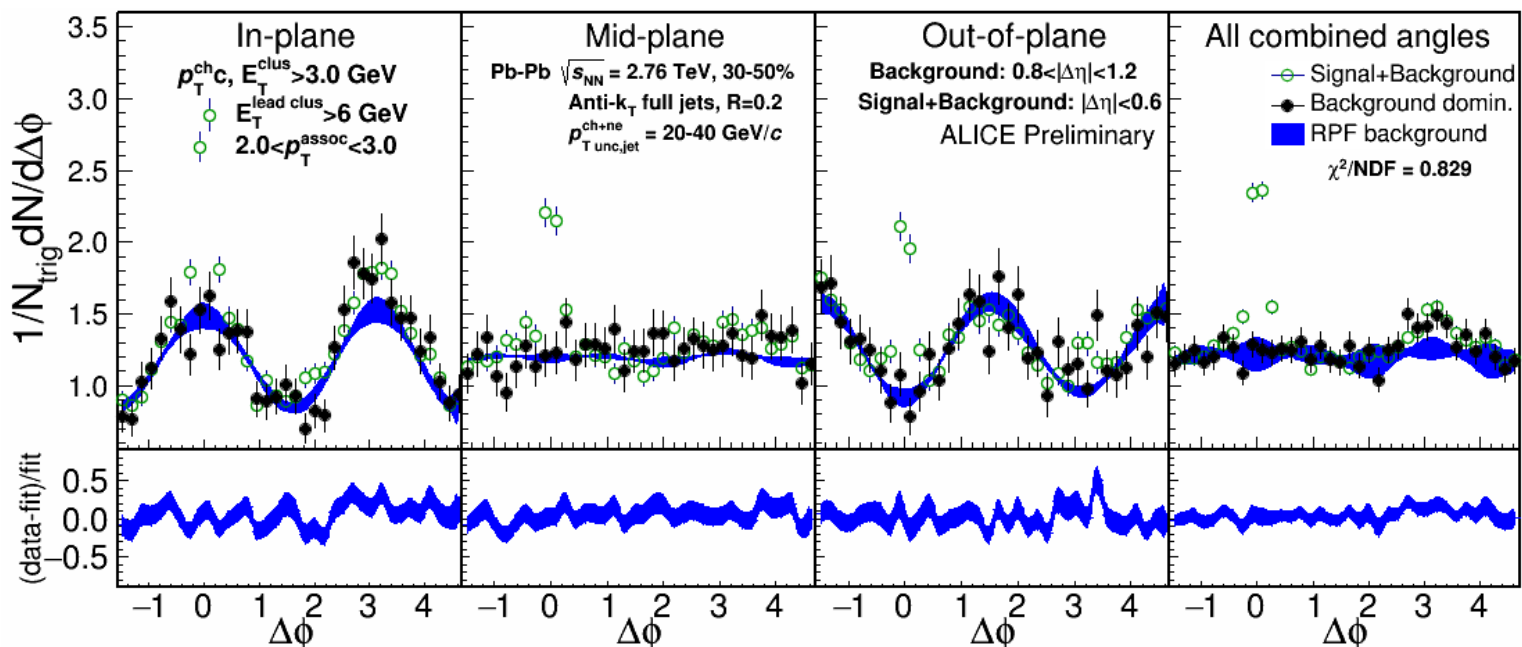
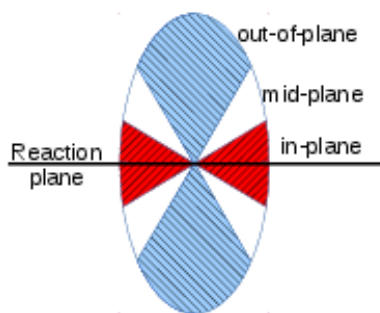
Dihadron correlations



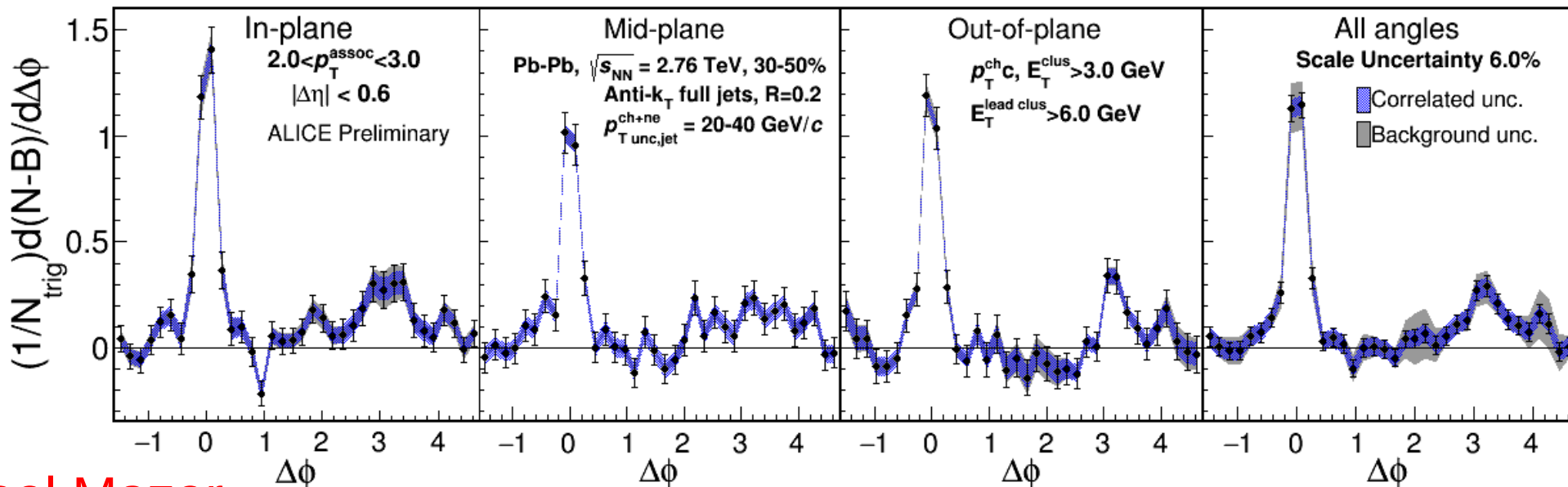
Sharma, Mazer, Stuart, Nattrass: [\(Phys. Rev. C 93, 044915 2016\)](#)

2.0-3.0 GeV/c p_T^{assoc}

- 1) signal+bkgrd
- 2) bkgrd dominated
- 3) bkgrd RPF fit



Correlation function



Joel Mazer

Hot Quarks 2016

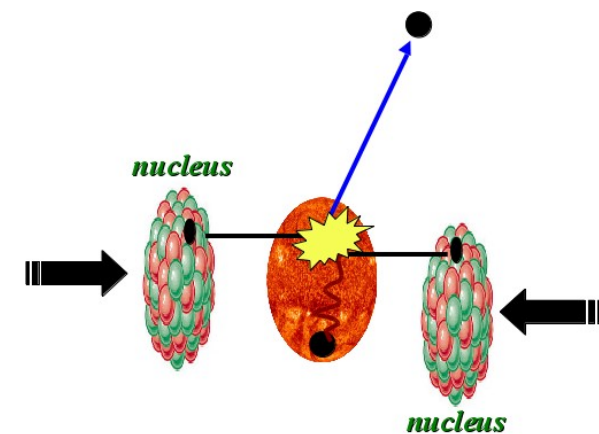
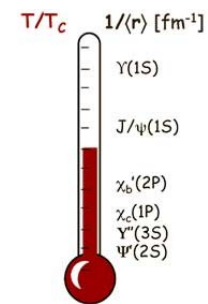
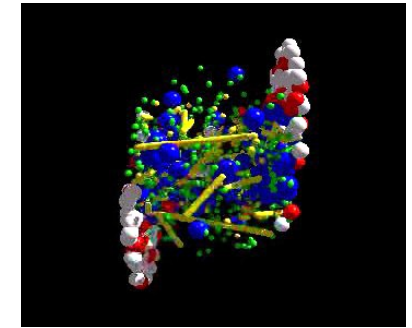
• Away side clearly there and suppressed

Little/no path length dependence?

- Path length dependence naively predicted by every model
 - No path length dependence seen in rxn plane dependent A_j either
- Insufficient sensitivity?
- Statistical variation in energy loss is more important than path length dependence
 - J. G. Milhano and K. C. Zapp, “Origins of the di-jet asymmetry in heavy ion collisions,” arXiv:1512.08107
 - F. Senzel, O. Fochler, J. Uphoff, Z. Xu, and C. Greiner, “Influence of multiple in-medium scattering processes on the momentum imbalance of reconstructed di-jets,” J. Phys. G42 no. 11, (2015) 115104, arXiv:1309.1657 [hep-ph].

Take home messages

- If we get nuclear matter dense enough, we make a new phase of matter, which we produce in high energy heavy ion collisions.
- This medium is extremely hot and dense...
- ...and opaque to colored probes and translucent to electromagnetic probes.



Comparison of colliders

	RHIC	LHC	
\sqrt{s}_{NN} (GeV)	9-200	2760, 5500	<i>center of mass energy</i>
$dN_{ch}/d\eta$	~ 1200	~ 1600	<i>number of particles</i>
T/T_c	1.9	3.0-4.2	<i>temperature</i>
ε (GeV/fm ³)	5	12, 16	<i>energy density</i>
τ_{QGP} (fm/c)	2-4	>10	<i>lifetime of QGP</i>

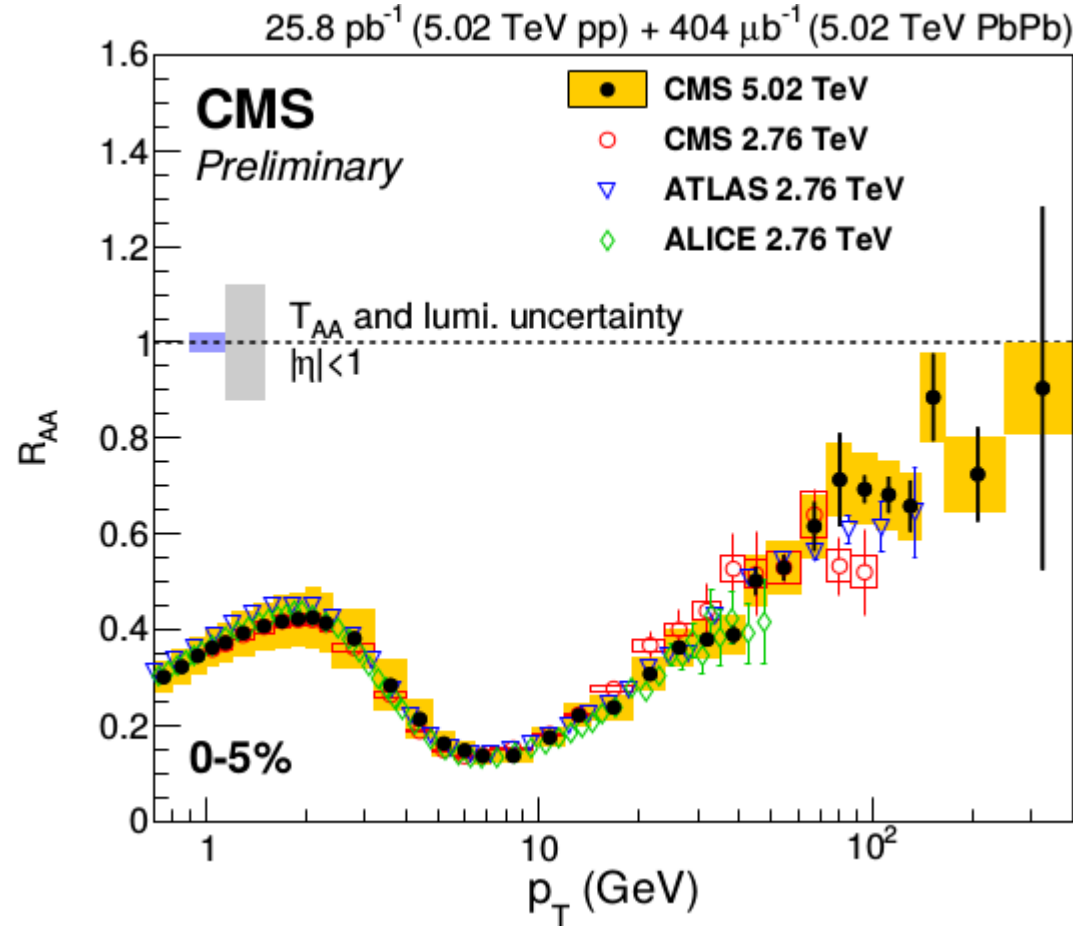
RHIC and LHC:

Cover 2 –3 decades of energy ($\sqrt{s}_{NN} = 9 \text{ GeV} - 5 \text{ TeV}$)

To discover the properties of hot nuclear matter at $T \sim 150 - 600 \text{ MeV}$

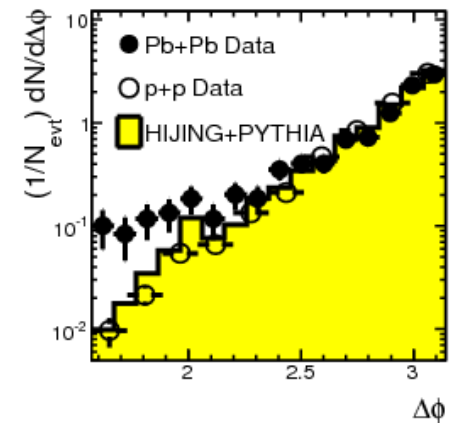
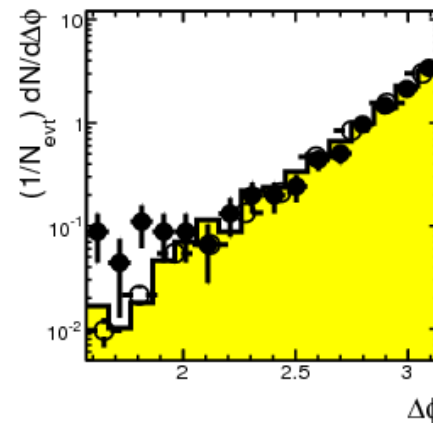
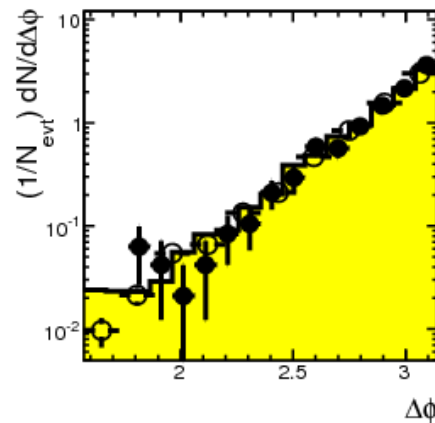
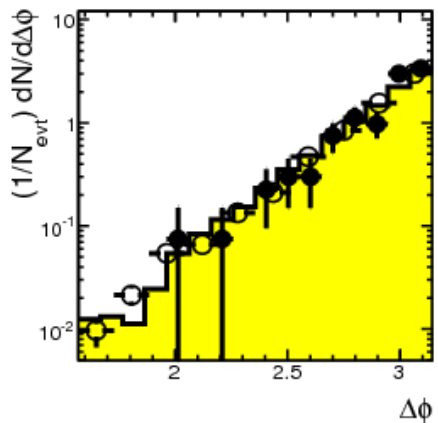
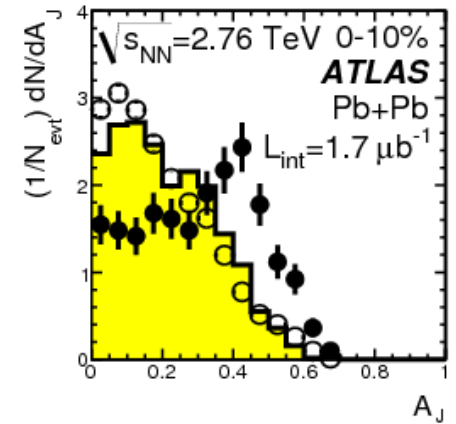
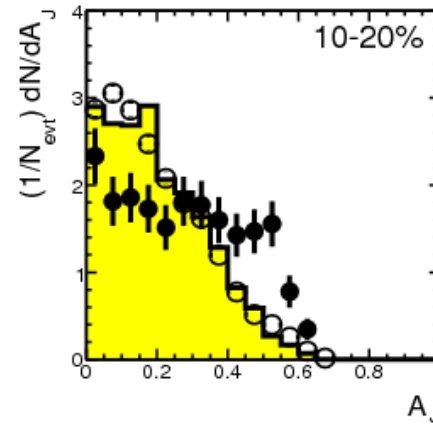
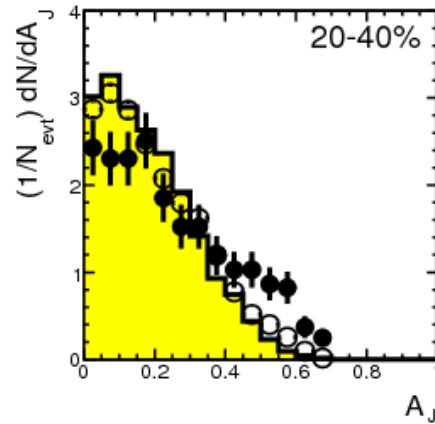
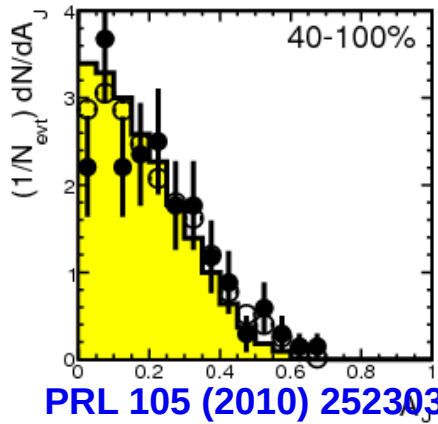
Nuclear modification factor R_{AA}

Single particles at the LHC



- Reaches 1 at very high p_T
- Must happen due to causality
- Feature of all QCD-inspired models

Di-jet asymmetry



$$A_j = \frac{p_T^{\text{Leading jet}} - p_T^{\text{Subleading jet}}}{p_T^{\text{Leading jet}} + p_T^{\text{Subleading jet}}}$$

Jets in principle

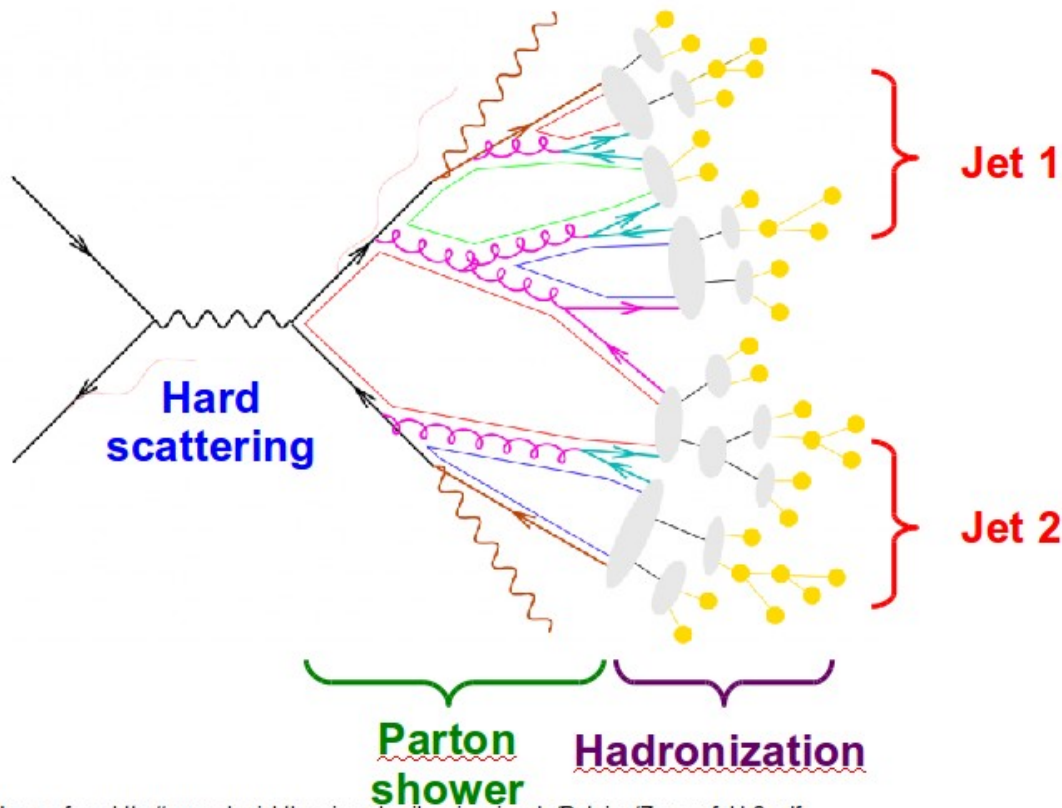
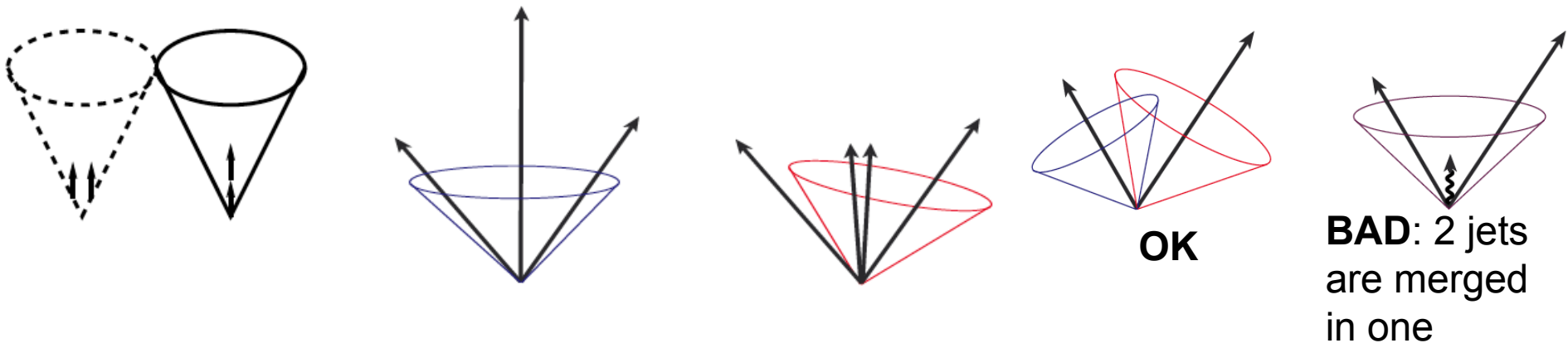


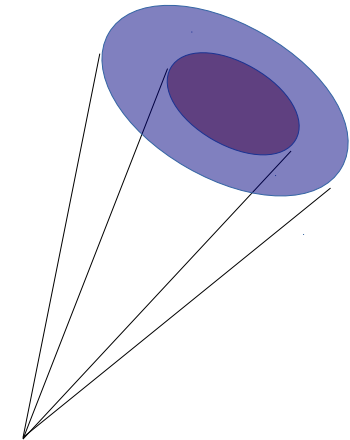
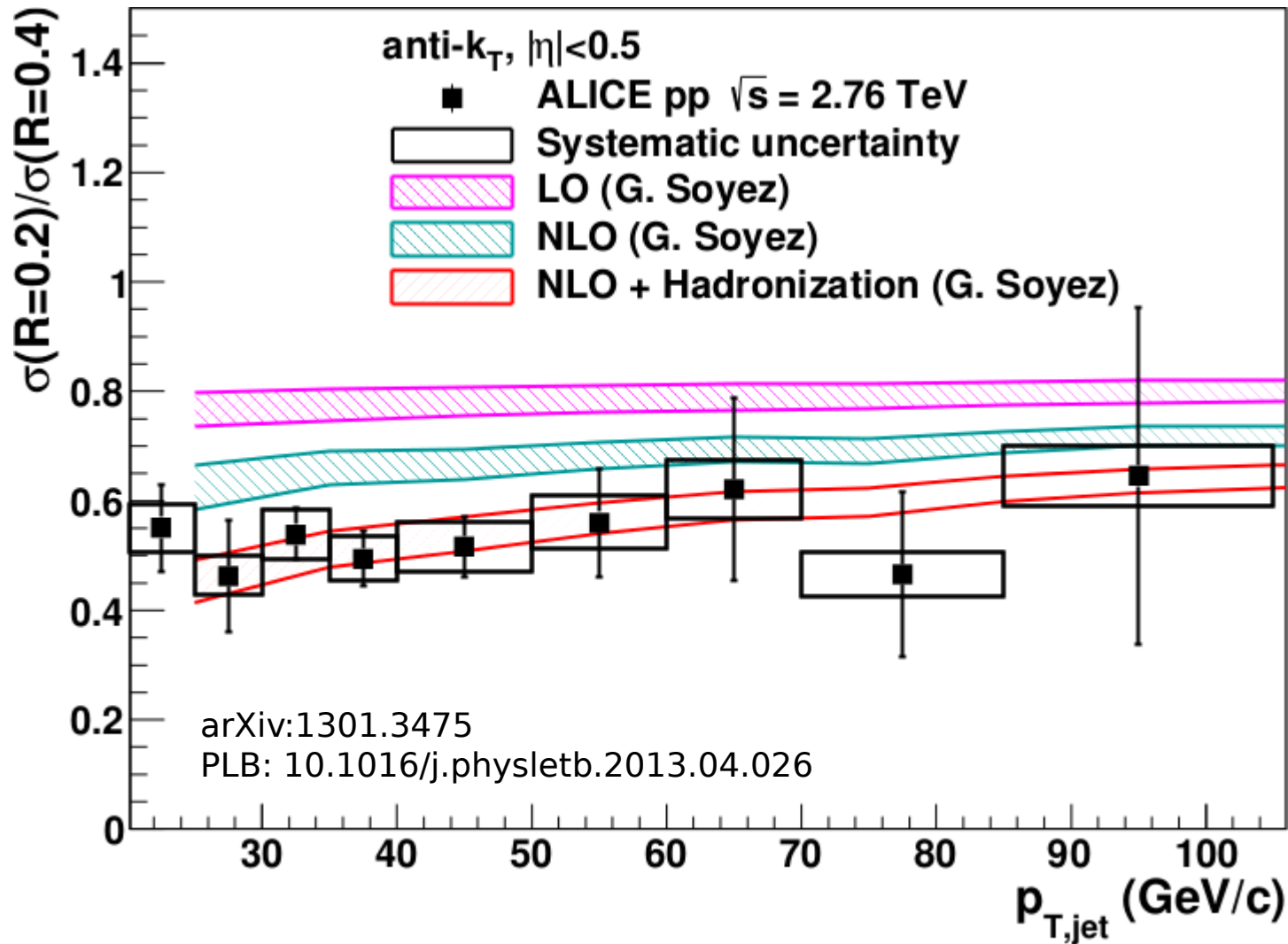
Image from <http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf>

- Jet measures **partons**
- Hadronic degrees of freedom are integrated out
- Algorithms are infrared and collinear safe



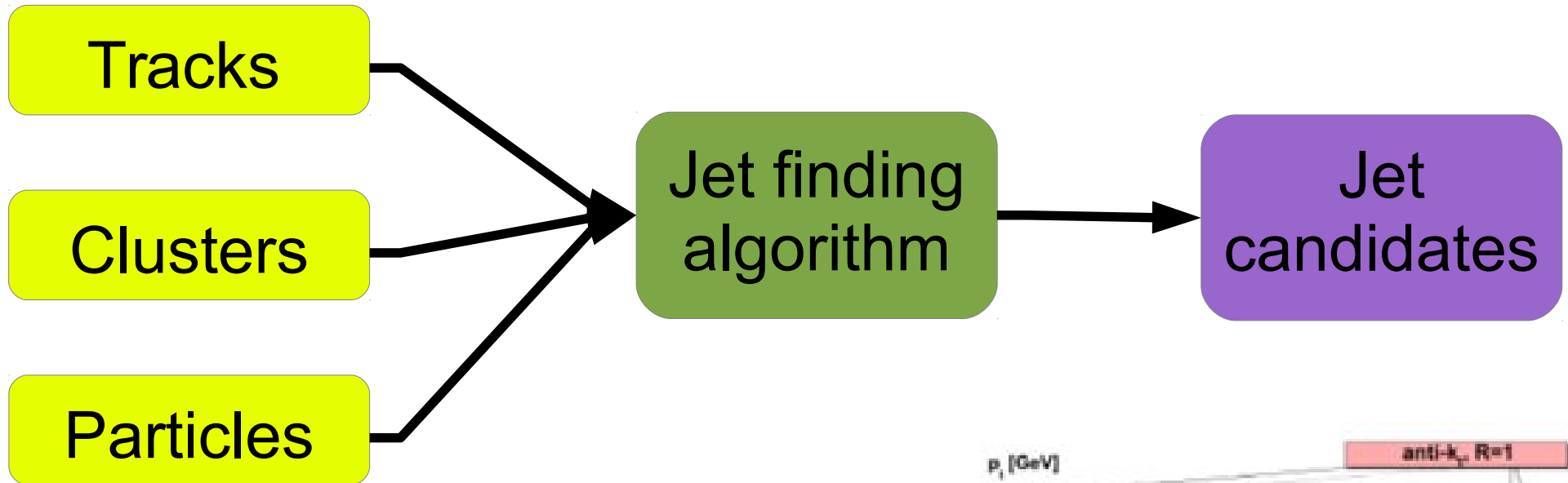
Full jet ratios in pp

$\sqrt{s} = 2.76$ TeV, $R = 0.2, 0.4$ Inclusive

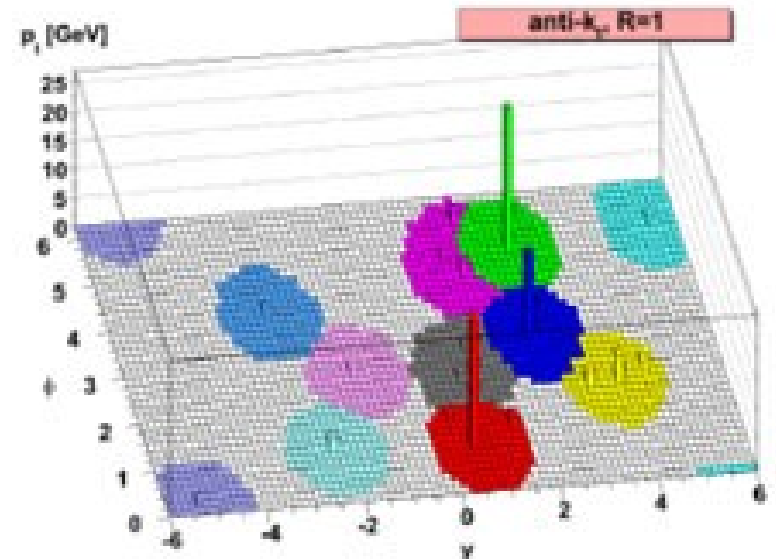


Hadronization is important even in pp collisions!

Jet finding algorithms



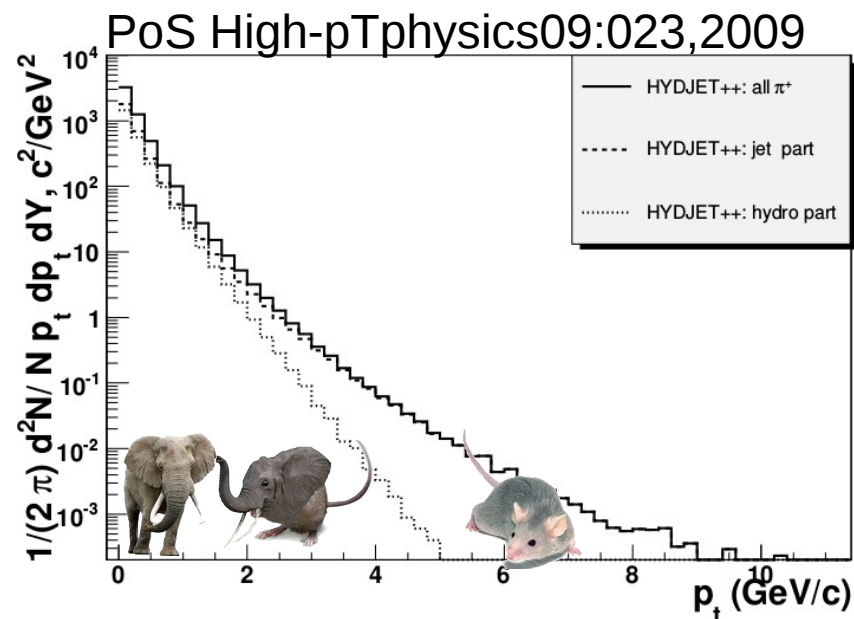
- Any list of objects works as input
- Use the same algorithm on theory & experiment
- Output only as good as input



M. Cacciari, G. P. Salam, G. Soyez, JHEP 0804:063,2008

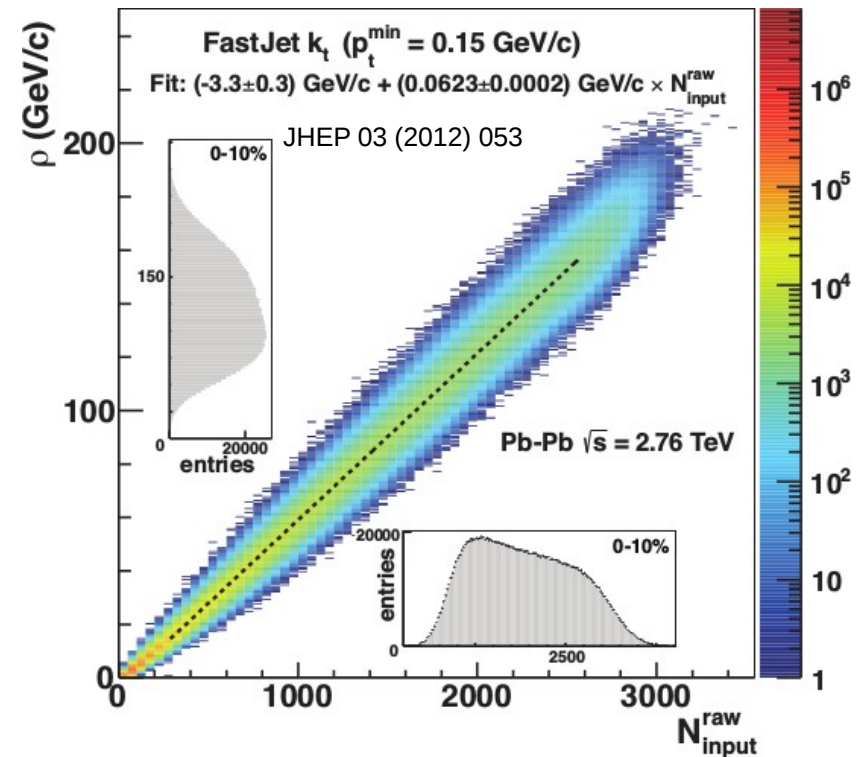
Focus on high p_T

- Pros:
 - Reduces combinatorial background
- Cons:
 - Cuts signal where we expect modifications
 - Could bias towards partons which have not interacted
 - Biases sample towards quarks



Focus on smaller angles

- Pros
 - Background is smaller
 - Background fluctuations smaller
- Cons:
 - Modifications expected at higher R
 - Biases sample towards quarks



ALICE/STAR

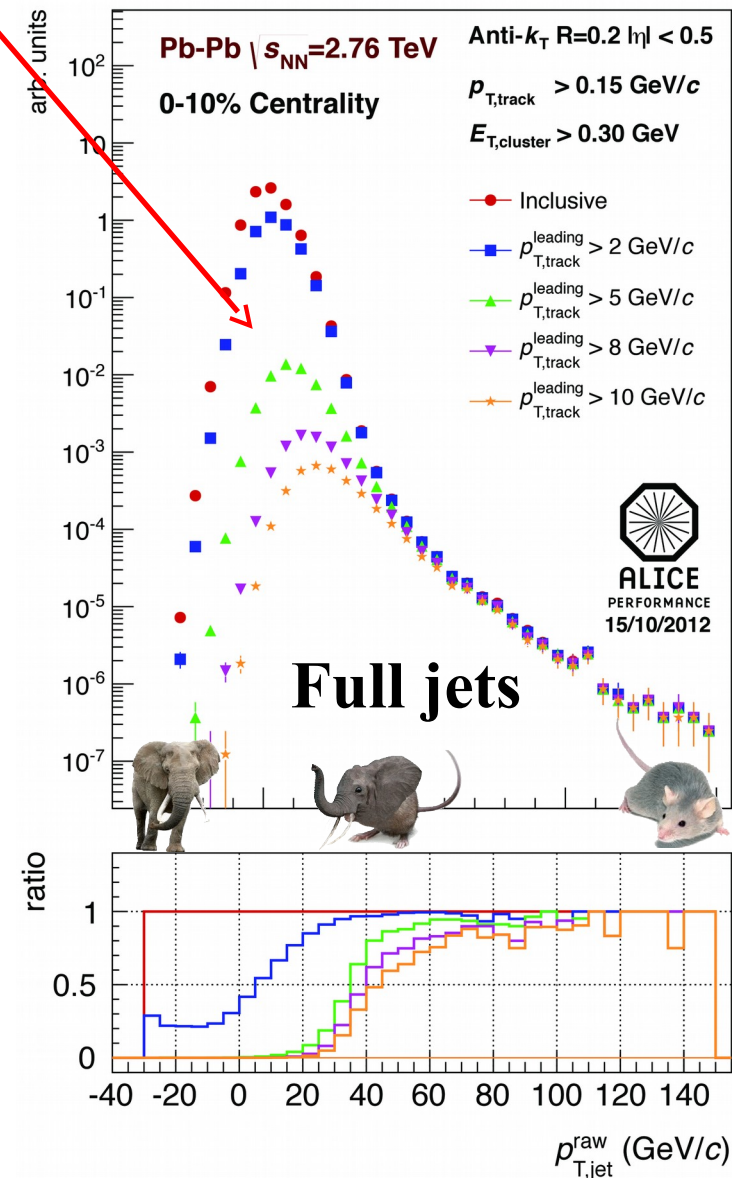
Combinatorial “jets”

- Estimate combinatorial jet contributions and its fluctuations from data
- Require leading track $p_T > 5 \text{ GeV}/c$
 - Suppresses combinatorial “jets”
 - Biases fragmentation
- No threshold on constituents
- Limited to small R

Measured spectra:

$$\rho_{T,jet}^{unc} = \rho_{T,jet}^{rec} - \rho A$$

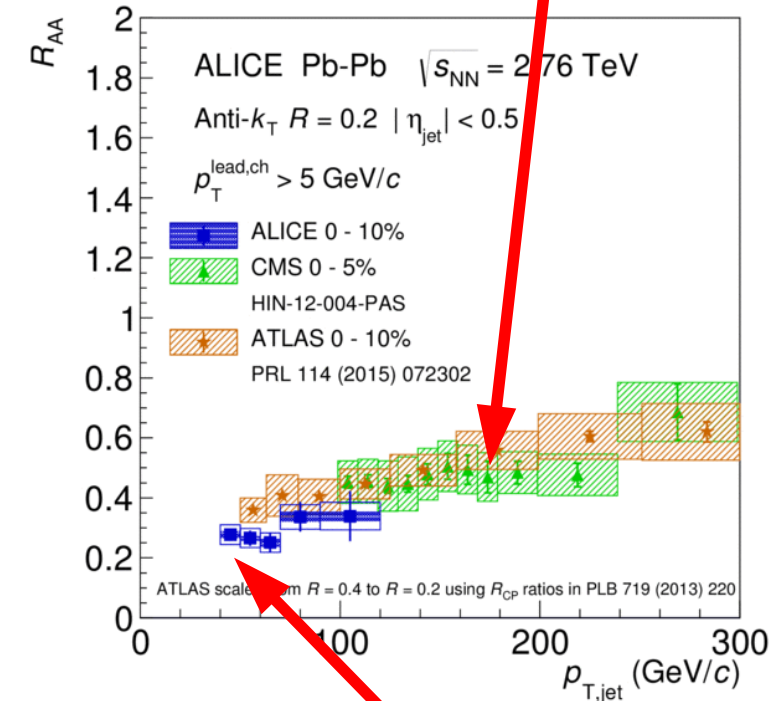
Where $\rho_{T,jet}^{rec}, A$
comes from FastJet anti- k_T algorithm



ATLAS

- Iterative procedure
 - **Calorimeter jets:** Reconstruct jets with $R=0.2$. v_2 modulated $\langle \text{Bkgd} \rangle$ estimated by energy in calorimeters excluding jets with at least one tower with $E_{\text{tower}} > \langle E_{\text{tower}} \rangle$
 - Track jets:** Use tracks with $p_T > 4$ GeV/c
 - Calorimeter jets from above with $E > 25$ GeV and track jets with $p_T > 10$ GeV/c used to estimate background again.
- Calorimeter tracks matching one track with $p_T > 7$ GeV/c or containing a high energy cluster $E > 7$ GeV are used for analysis down to $E_{\text{jet}} = 20$ GeV

Constituent biases don't matter that much up here



But they do matter down here!

Definitely imposes a bias, especially at 20 GeV!
 We should treat that bias as a tool, not a handicap

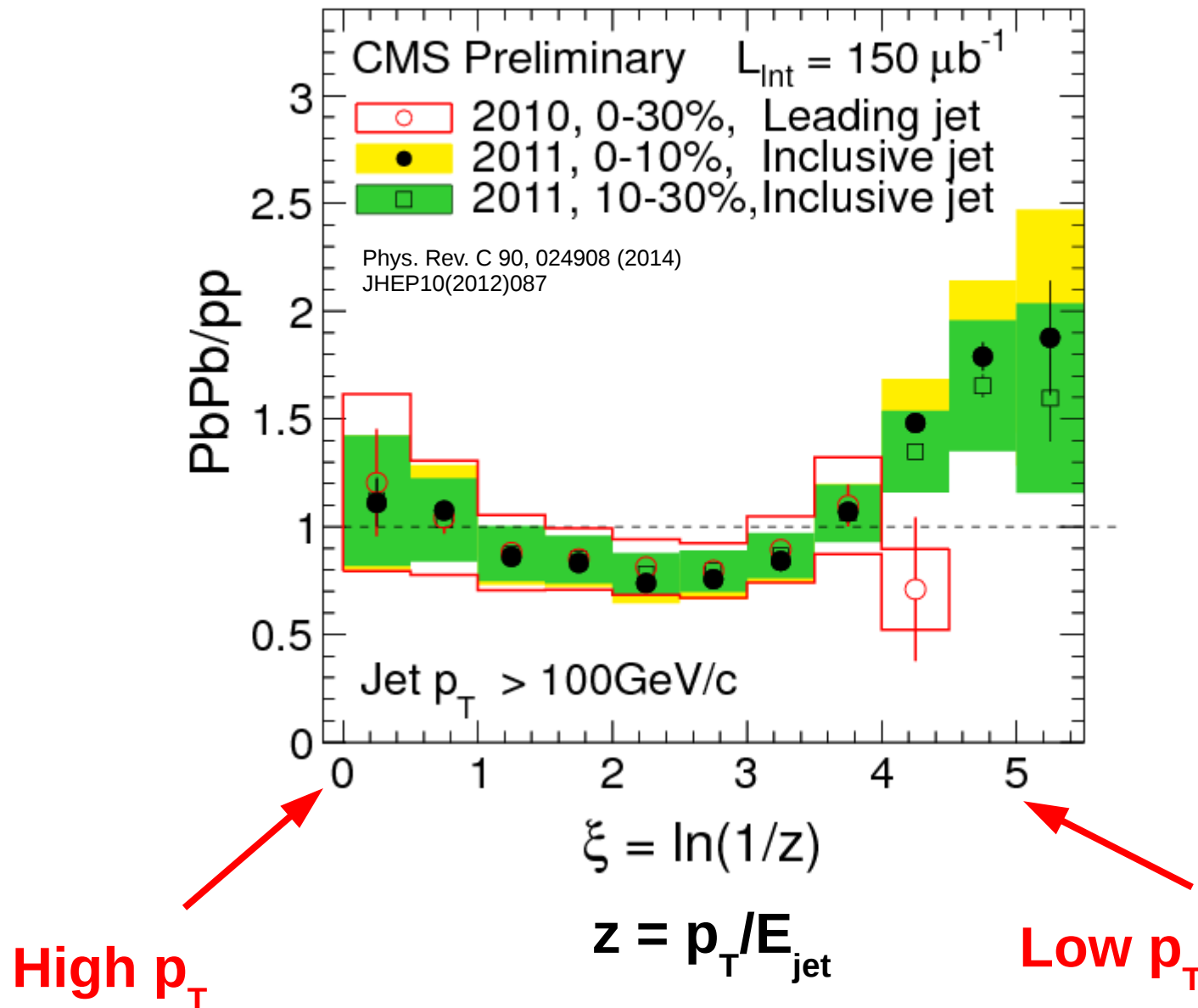


Bias

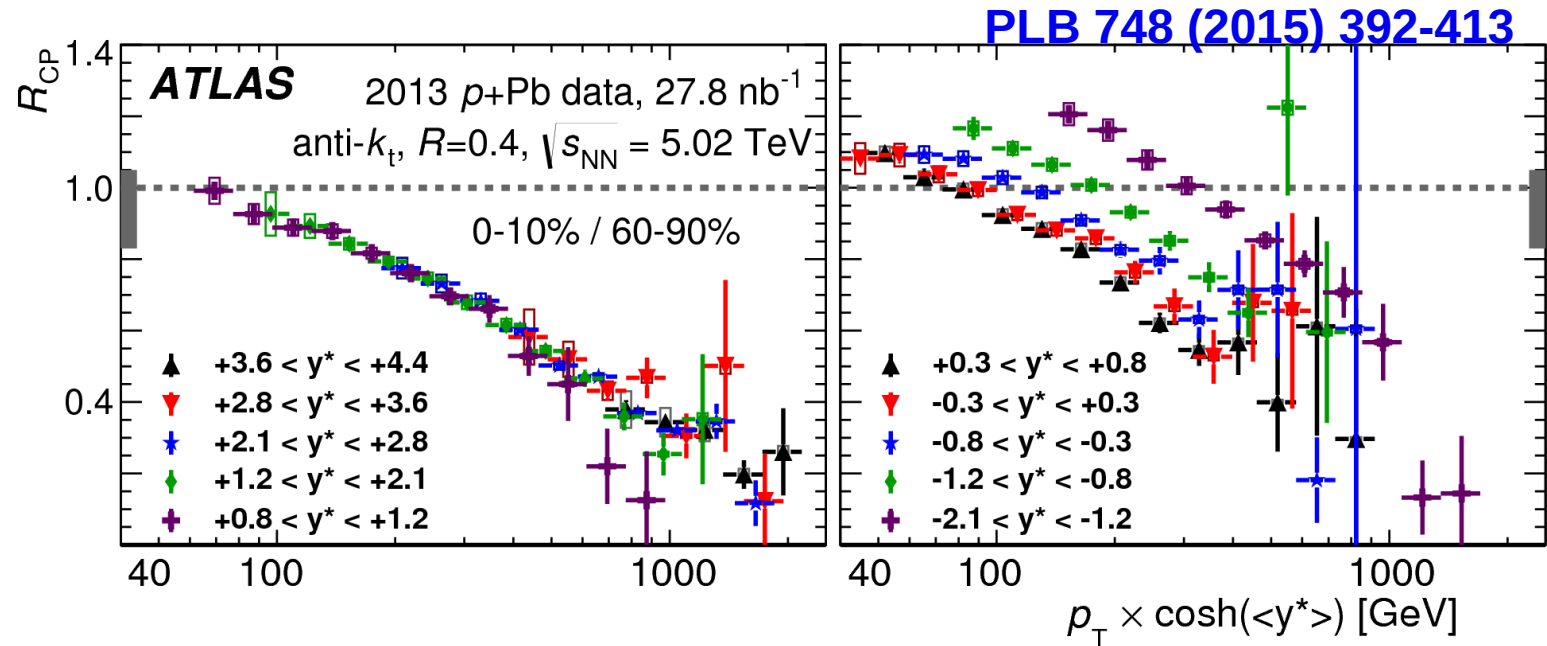


- **Modified jets probably look more like the medium**
- **Quark jets are narrower, have fewer tracks, fragment harder [Z Phys C 68, 179-201 (1995), Z Phys C 70, 179-196 (1996),]**
- **Gluon jets reconstructed with k_T algorithm have more particles than jets reconstructed with anti- k_T algorithm [Phys. Rev. D 45, 1448 (1992)]**
- **Gluon jets fragment into more baryons [EPJC 8, 241-254, 1998]**

What you see depends on where you look



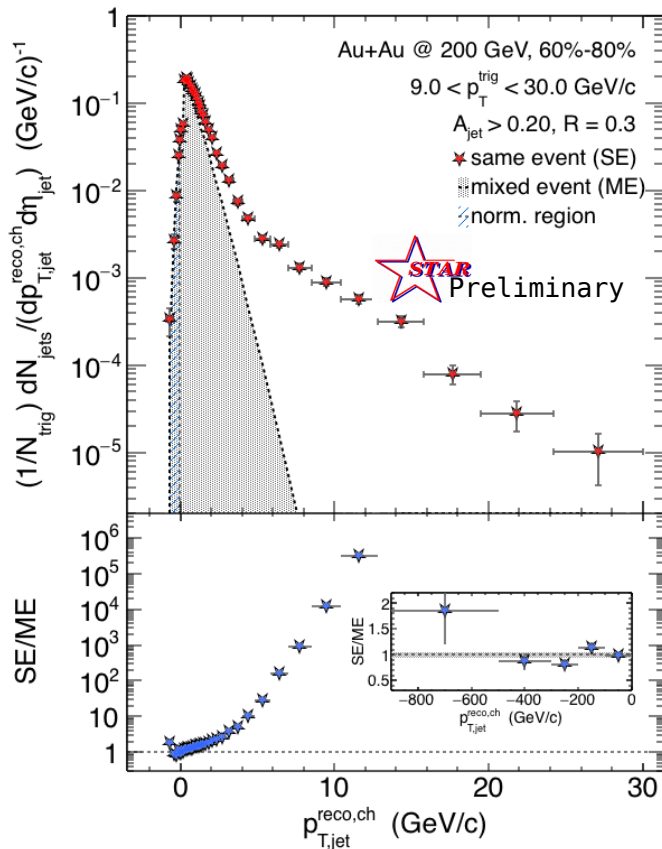
Cold Nuclear Matter effects



- No indication of modified jet structure in cold nuclear matter (d+Au and p+Pb collisions) [Phys.Rev.C73:054903,2006, Phys.Rev.Lett.96:222301,2006]
- Minimum bias R_{pPb} , R_{dAu} for charged particles, jets consistent with 1 [Phys.Rev.Lett.98:172302,2007,Phys.Rev.C81:064904,2010,Phys. Rev. Lett. 110 (2013) 082302, arXiv:1605.06436]
- Indications of modification at forward rapidities from dihadron correlations [Phys. Rev. Lett. 107, 172301 (2011)]
- Centrality dependence observed [PLB 748 (2015) 392-413, Phys. Rev. Lett. 116, 122301 (2016)]

Event mixing

Peripheral



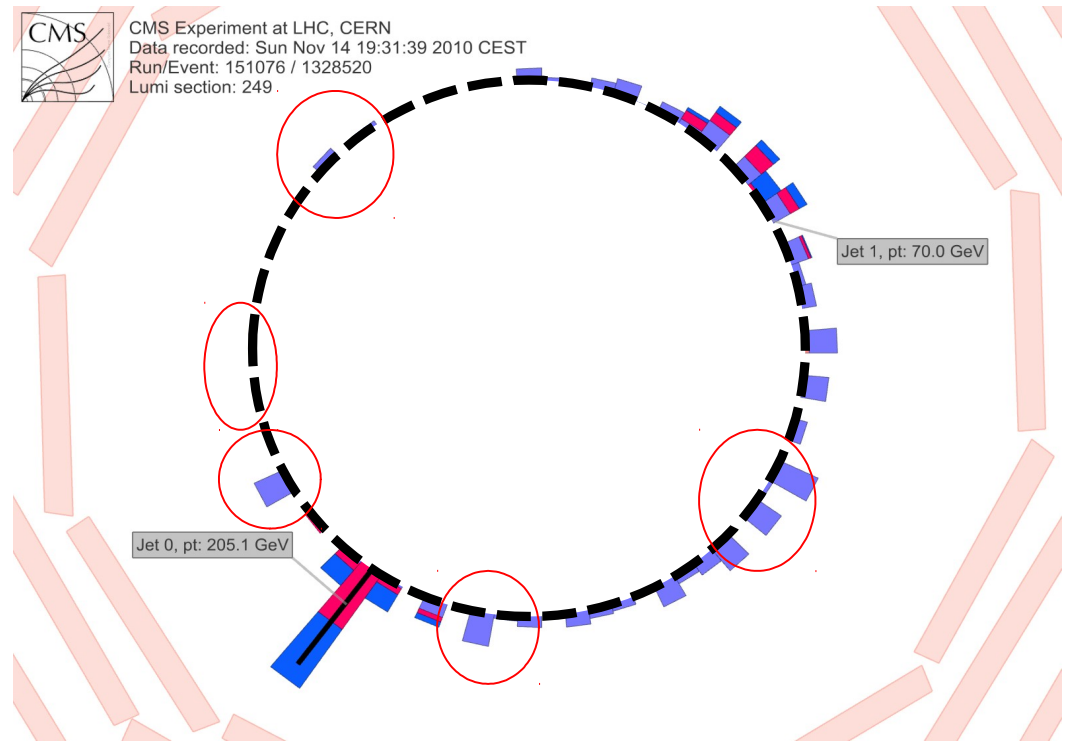
- Reference spectrum: peripheral collisions
- Much less combinatorial background compared to most central data
- Excellent signal/background ratio down to 3 GeV/c
- Requires normalization at low p_T
- All physical correlations treated like jets

Alex Schmah, Hard Probes 2015

CMS: Iterative Pile-Up Event Background Subtraction

Background is estimated

- for each calorimeter ring of constant η
- subtracted before jet finding
- re-iterated after excluding the jets found in the first iteration



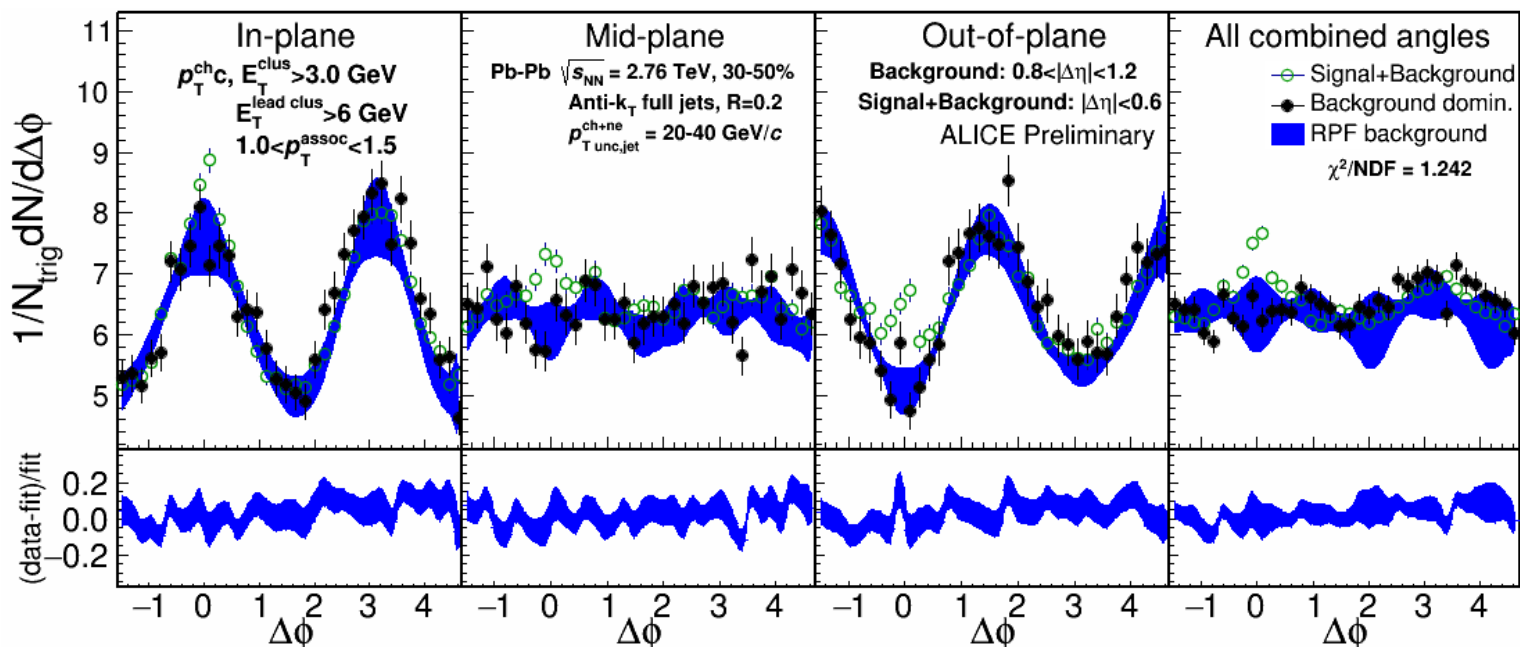
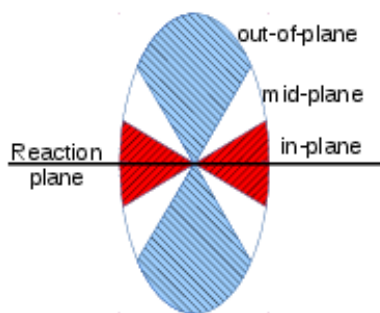
Fake Jets: After the background subtraction, some local fluctuations remain!
Fluctuations will deteriorate the jet resolution in central events.

Sevil Salur

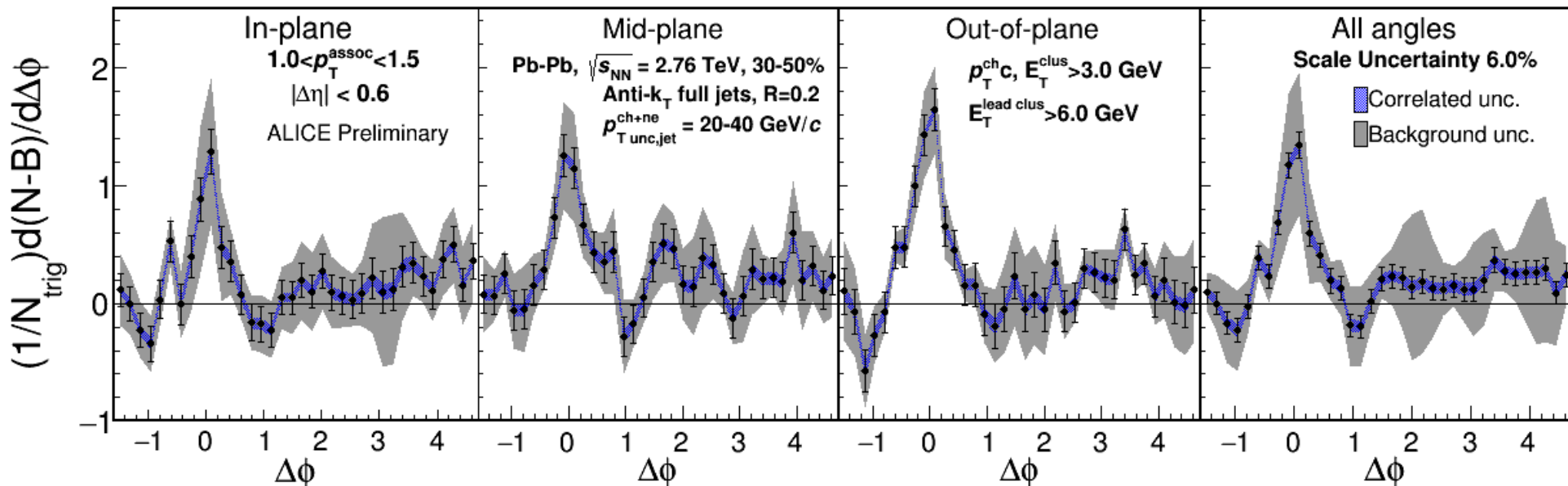
55

1.0-1.5 GeV/c p_T^{assoc}

- 1) signal+bkgrd
- 2) bkgrd dominated
- 3) bkgrd RPF fit



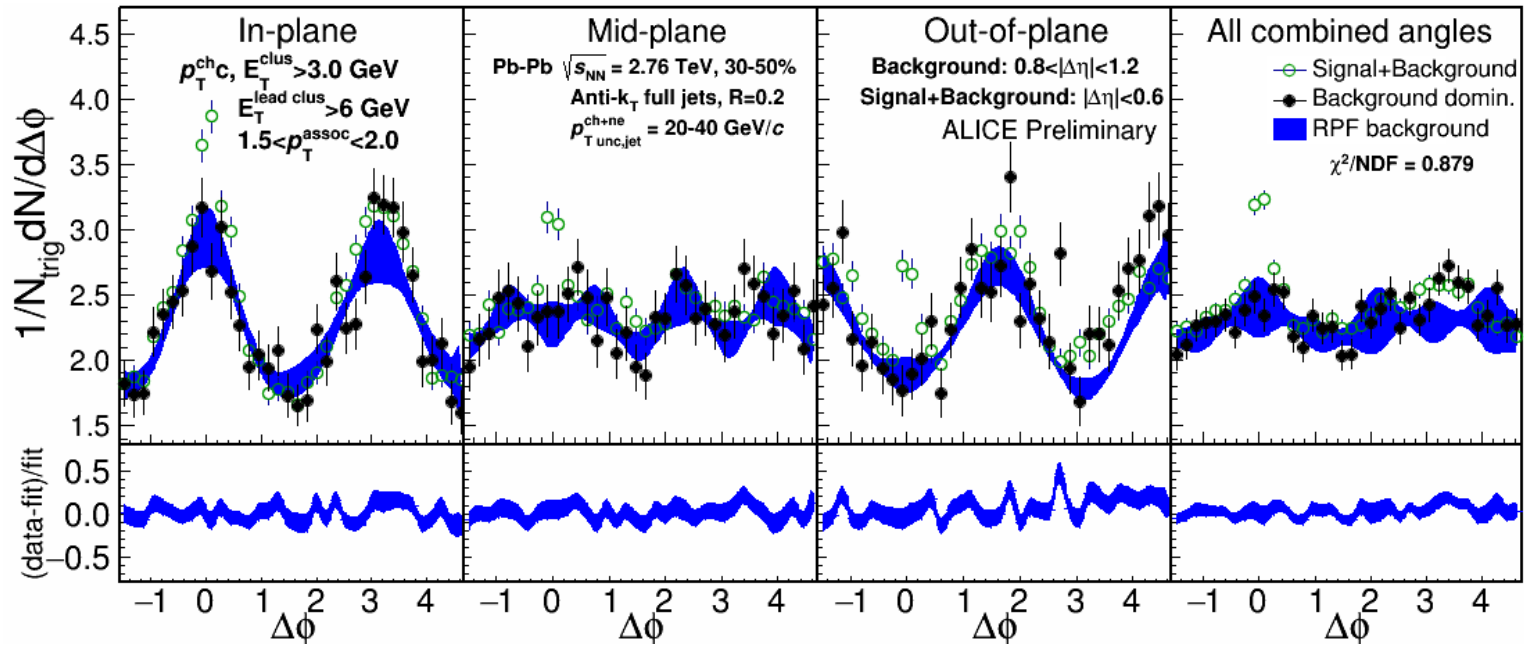
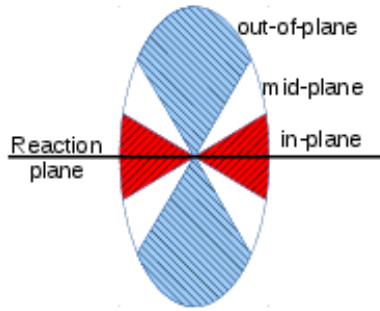
Correlation function



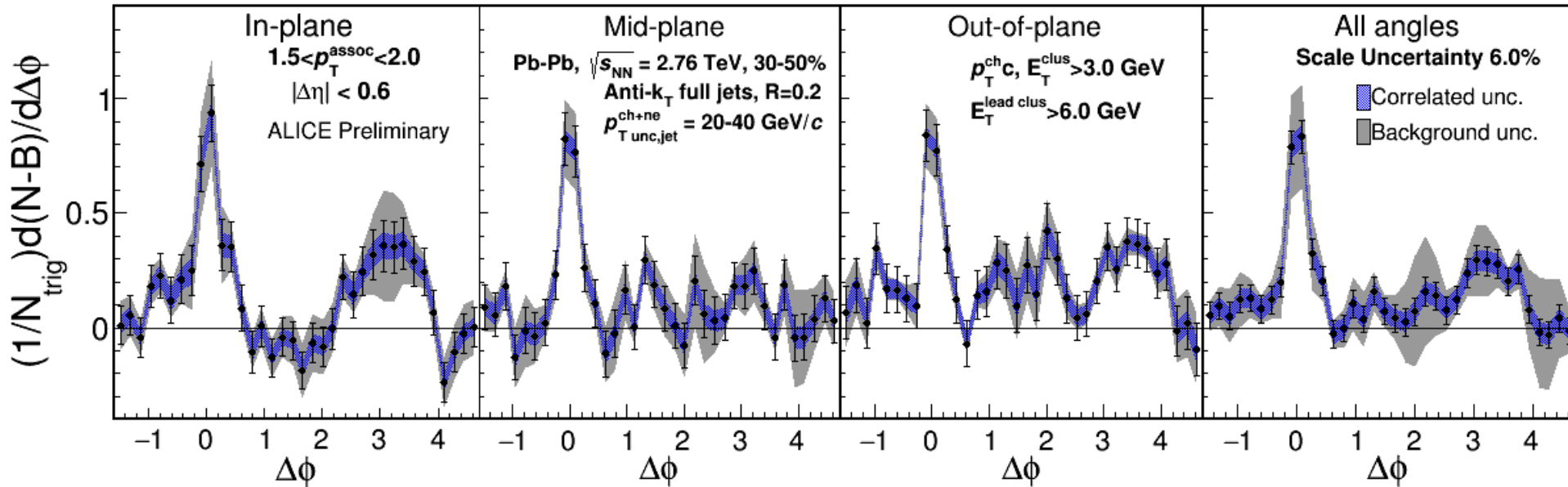
- Uncertainties dominated by statistics
- Background uncertainty is non-trivially correlated point-to-point

1.5-2.0 GeV/c p_T^{assoc}

- 1) signal+bkgrd
- 2) bkgrd dominated
- 3) bkgrd RPF fit



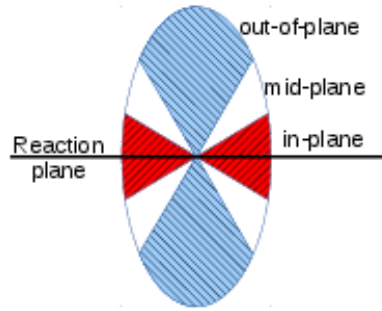
Correlation function



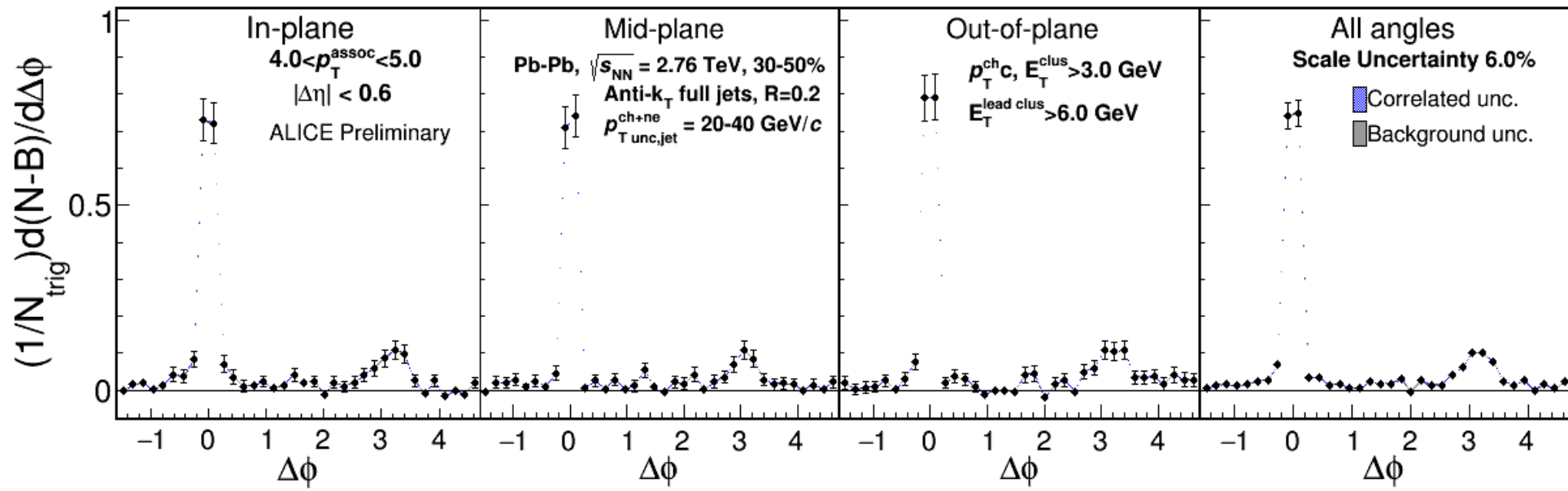
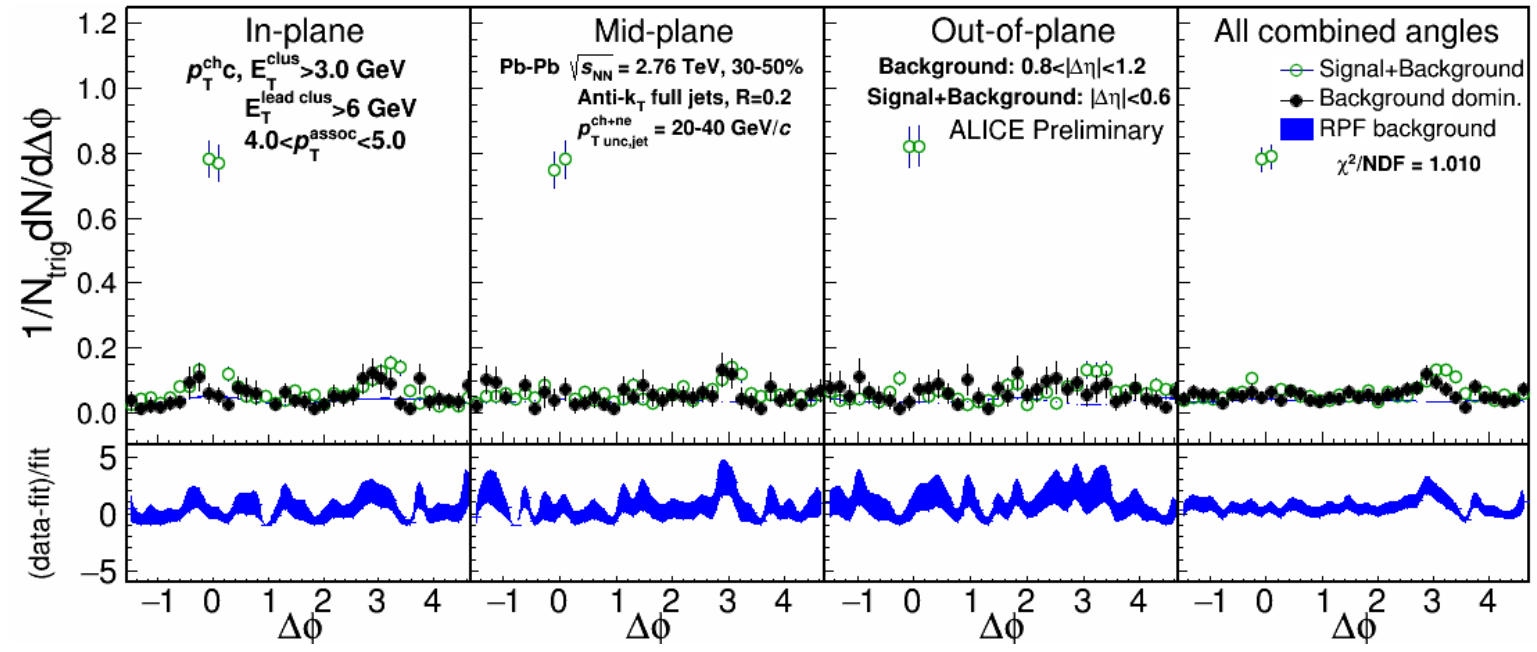
- v_3 and v_4 components important
- Background uncertainty is non-trivially correlated point-to-point

4.0-5.0 GeV/c P_T^{assoc}

- 1) signal+bkgrd
- 2) bkgrd dominated
- 3) bkgrd RPF fit



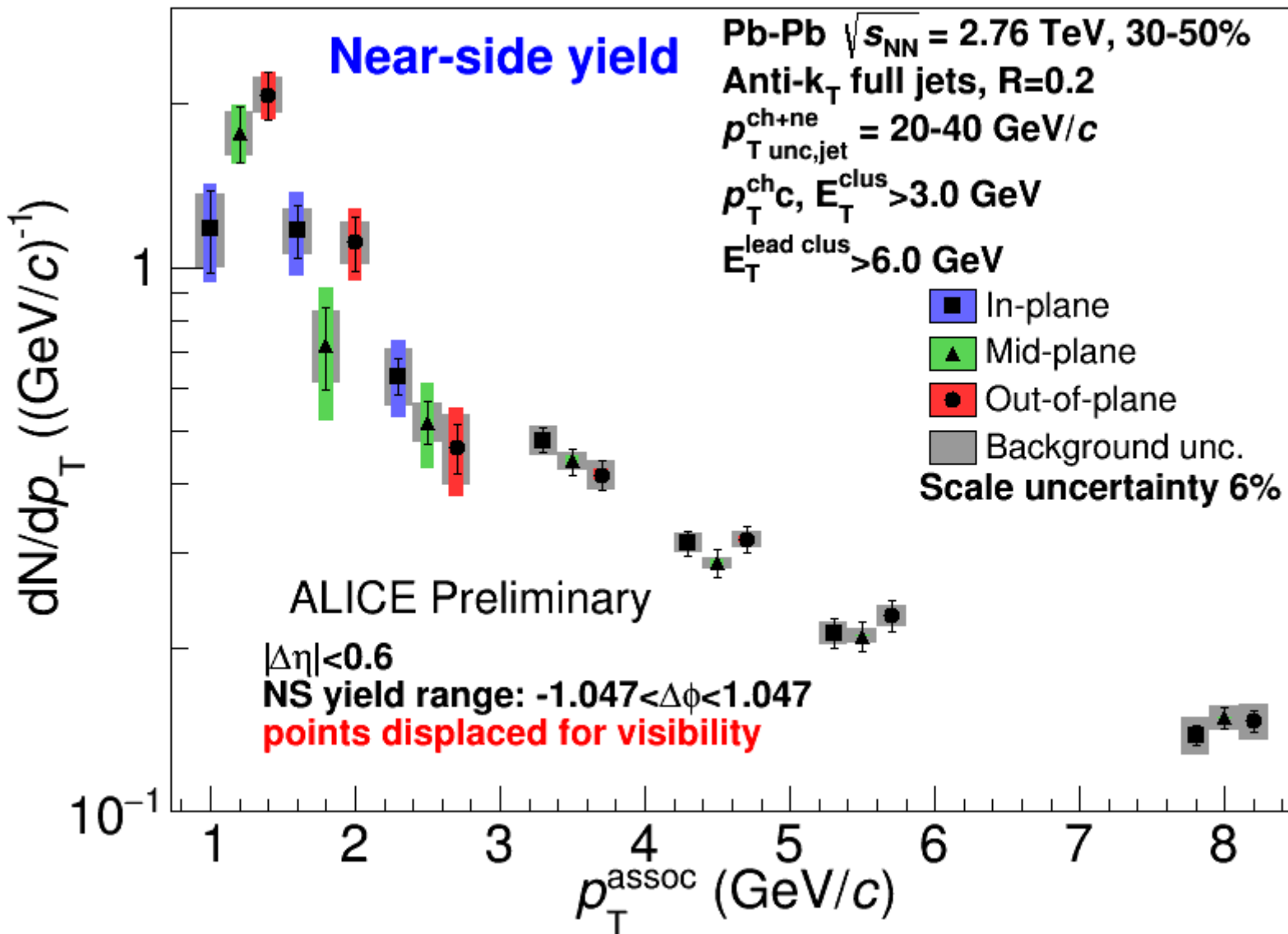
Correlation function



• Background level negligible

Near-side jet yields vs EP

Jets 20-40 GeV/c, 30-50% centrality



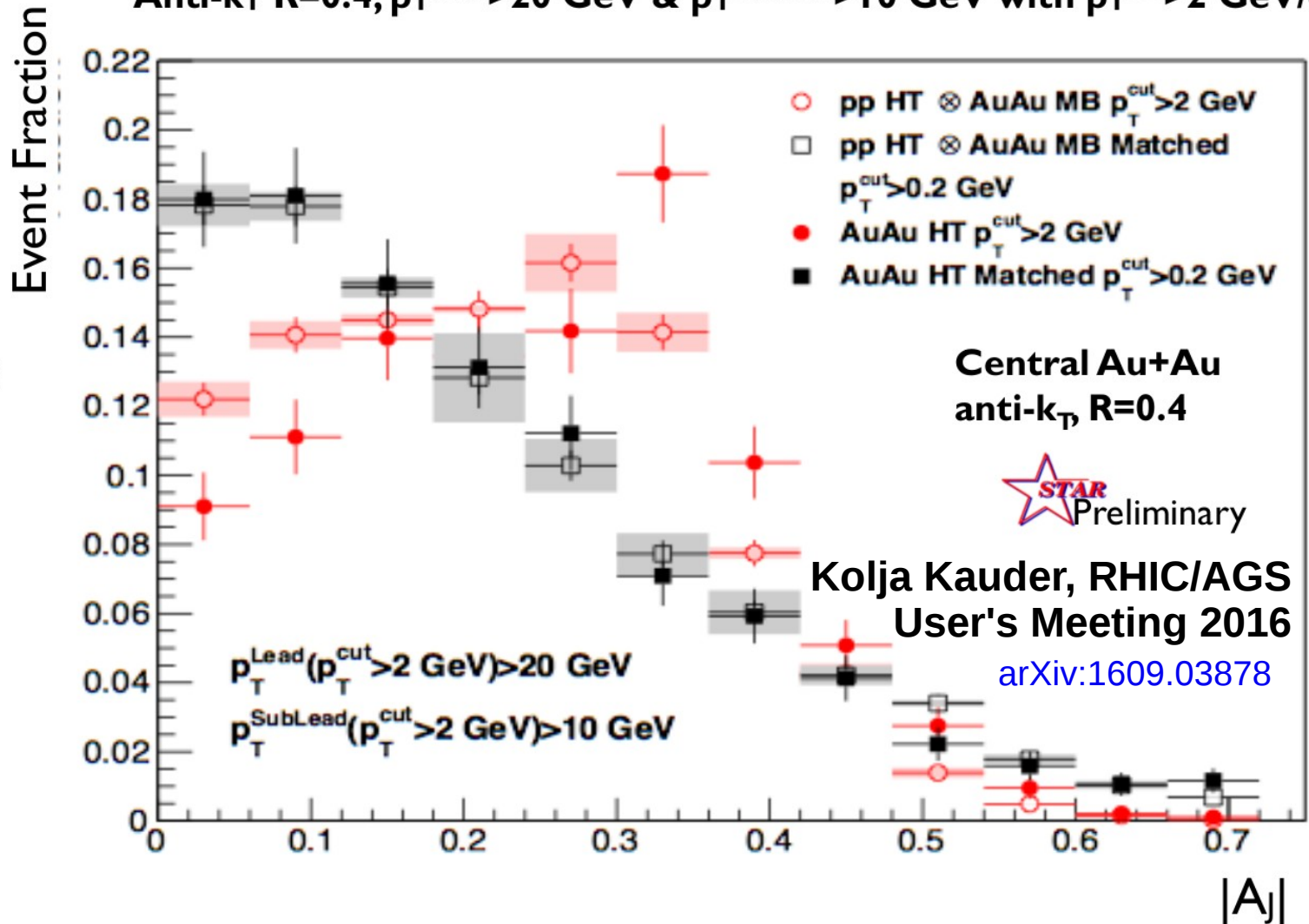
Within uncertainties of current statistics, no event plane ordering

• Different effects in different p_T associated bins

- Competing effects
- 1) Quenching
 - 2) Bremsstrahlung
 - 3) etc

Di-jet asymmetry

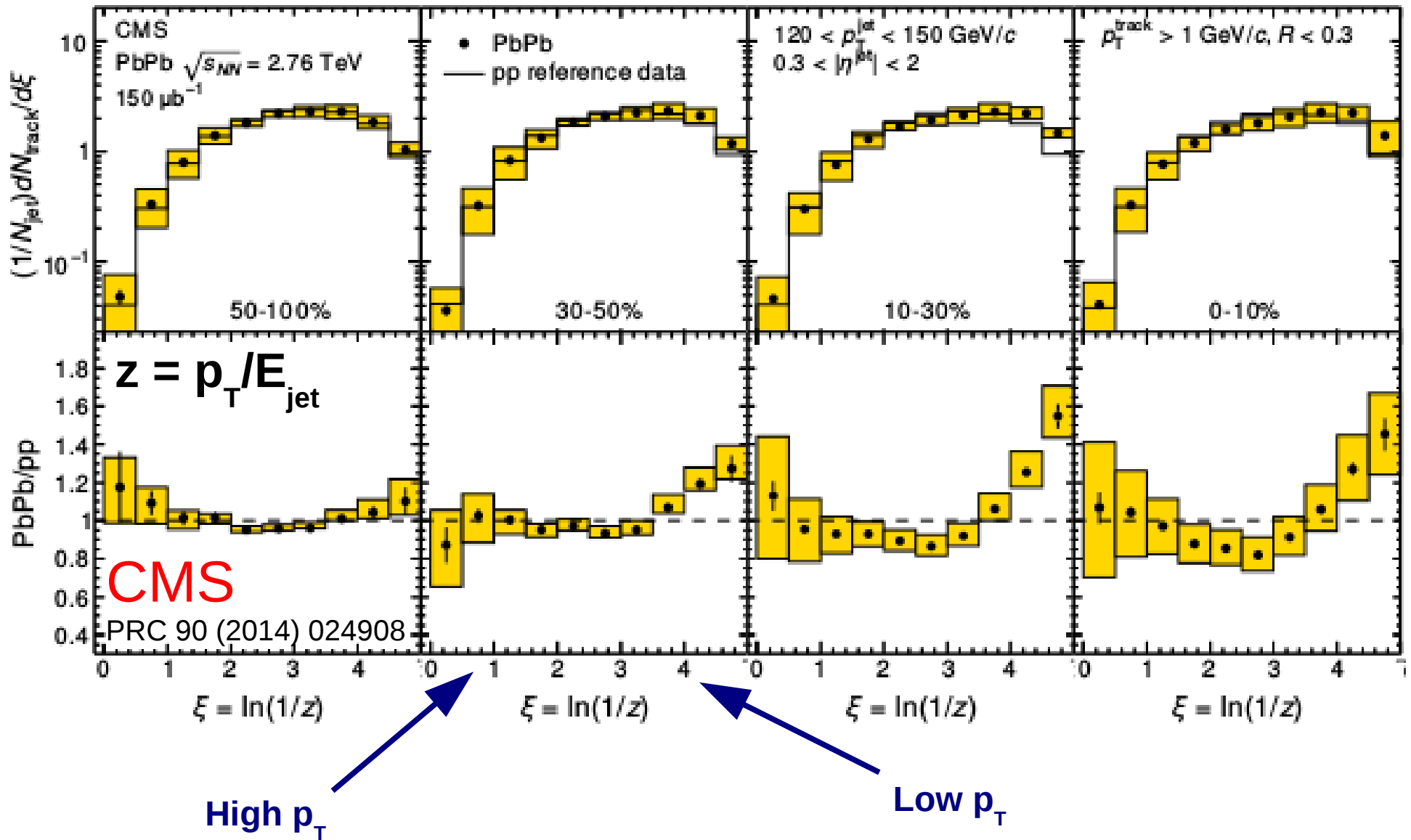
Anti- k_T $R=0.4$, $p_{T}^{\text{Lead}} > 20 \text{ GeV}$ & $p_{T}^{\text{SubLead}} > 10 \text{ GeV}$ with $p_{T}^{\text{cut}} > 2 \text{ GeV}/c$



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Au+Au di-jets more imbalanced than p+p for $p_{T}^{\text{cut}} > 2 \text{ GeV}/c$
 Au+Au $A_j \sim$ p+p A_j for matched di-jets ($R=0.4$)

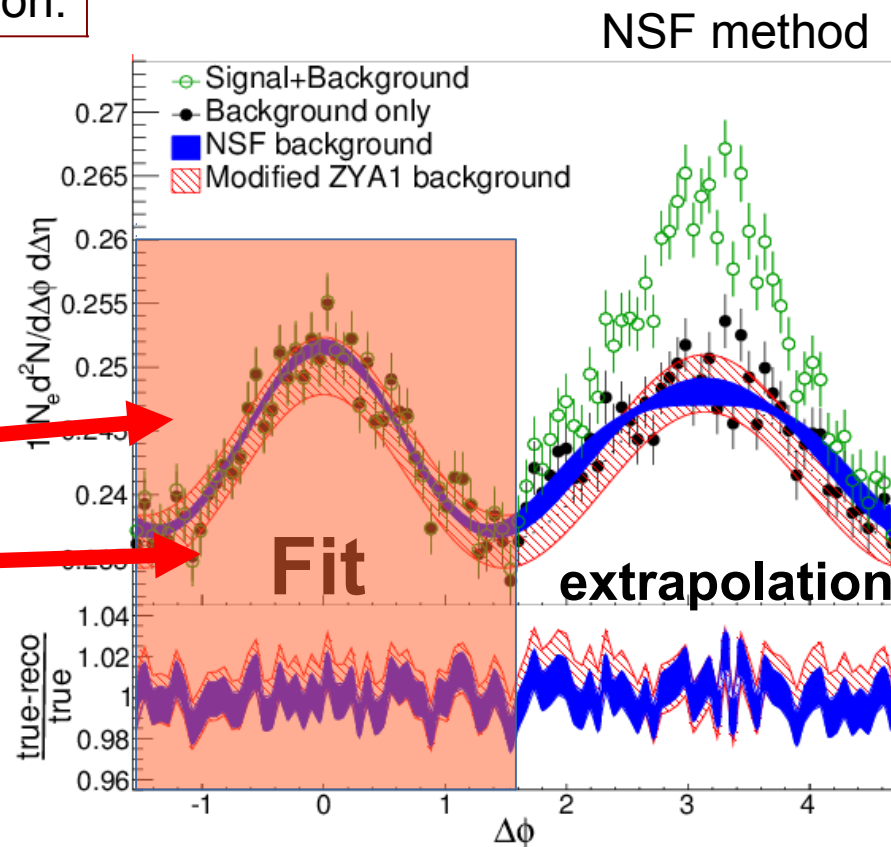
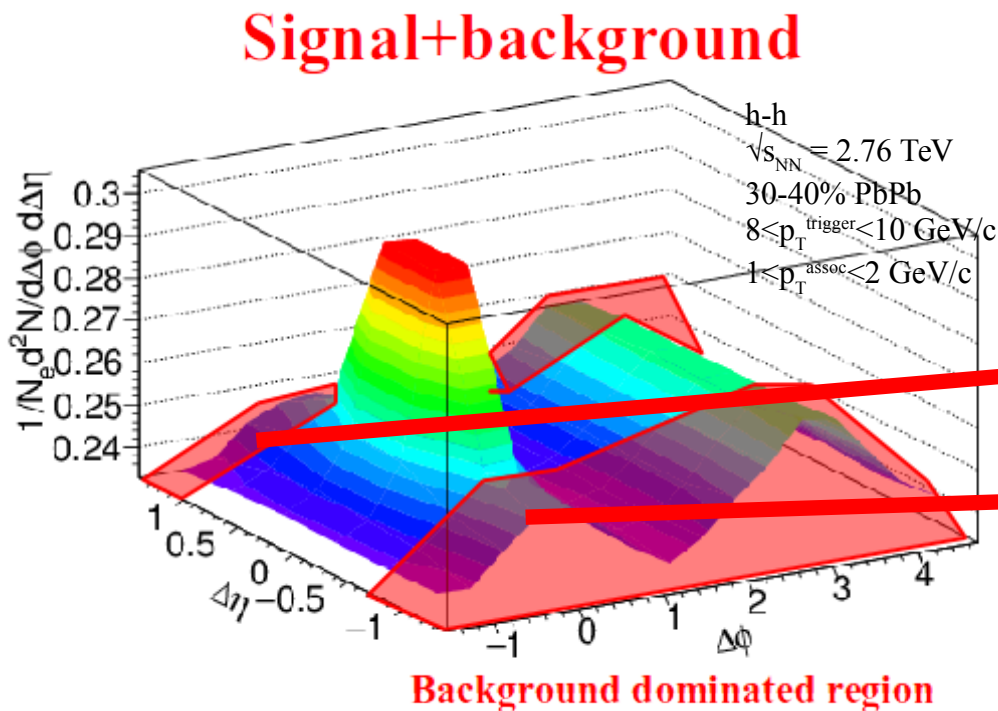
Fragmentation functions



Reaction plane fit (RPF) method

TOY MODEL

- Signal is negligible at large $\Delta\eta$ and small $\Delta\Phi$ region.



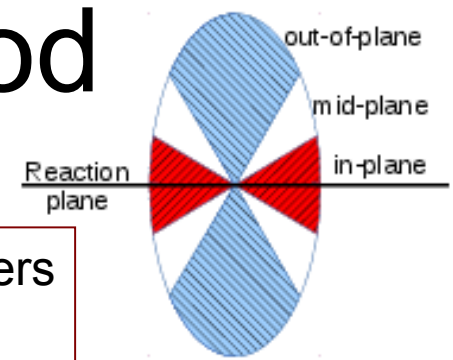
- Project signal+background over $0.8 < |\Delta\eta| < 1.2$
- Fit background in $|\Delta\phi| < \pi/2$
- Fitting till 4th order v_n term, total 6 fit parameters: B , v_2^{assoc} , v_2^{trig} , $v_3^{\text{assoc}} \times v_3^{\text{trig}}$, v_4^{assoc} , and v_4^{trig}

Sharma, Mazer, Stuart, Nattrass: ([Phys. Rev. C 93, 044915 2016](#))

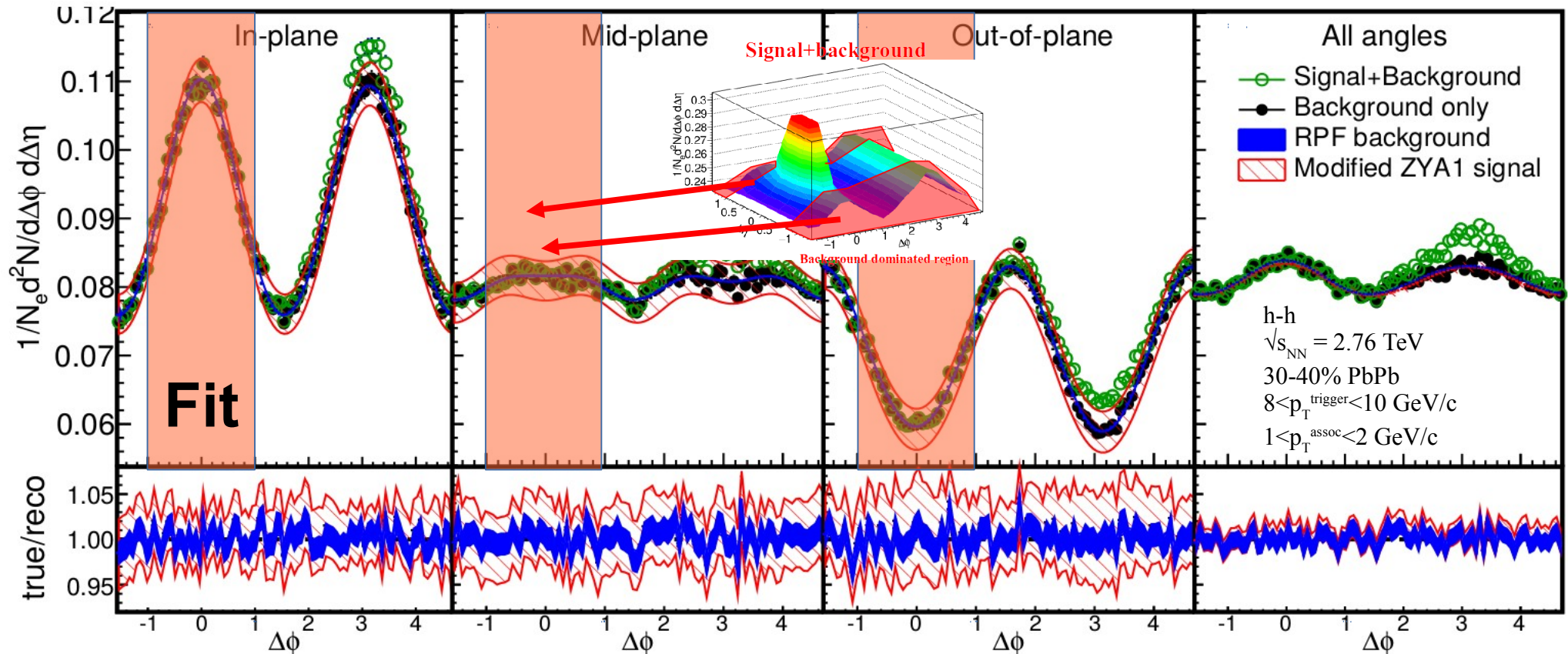
Nattrass, Sharma, Mazer, Stuart, and Bejood: ([Phys. Rev. C 94, 011901\(R\) 2016](#))

Reaction plane fit (RPF) method

30-40% central (simulation) **TOY MODEL**



- Each orientation has different functional form, but require same parameters
- More robust method, now have a higher constrained background with more information going into fit



Project signal+background over $0.8 < |\Delta\eta| < 1.2$

- v_n and B extracted
- Fewer assumptions and bias than ZYAM while having much smaller errors