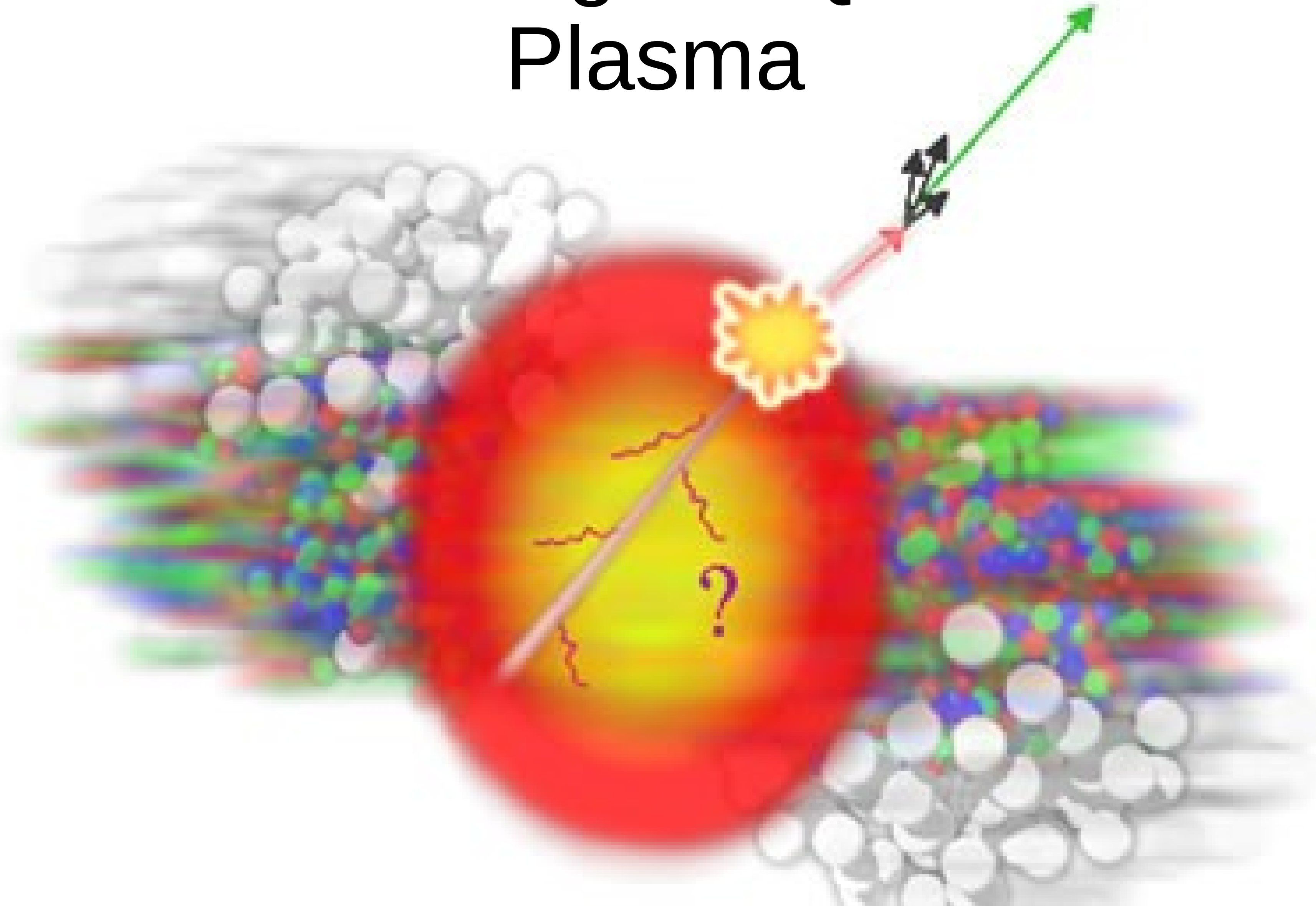
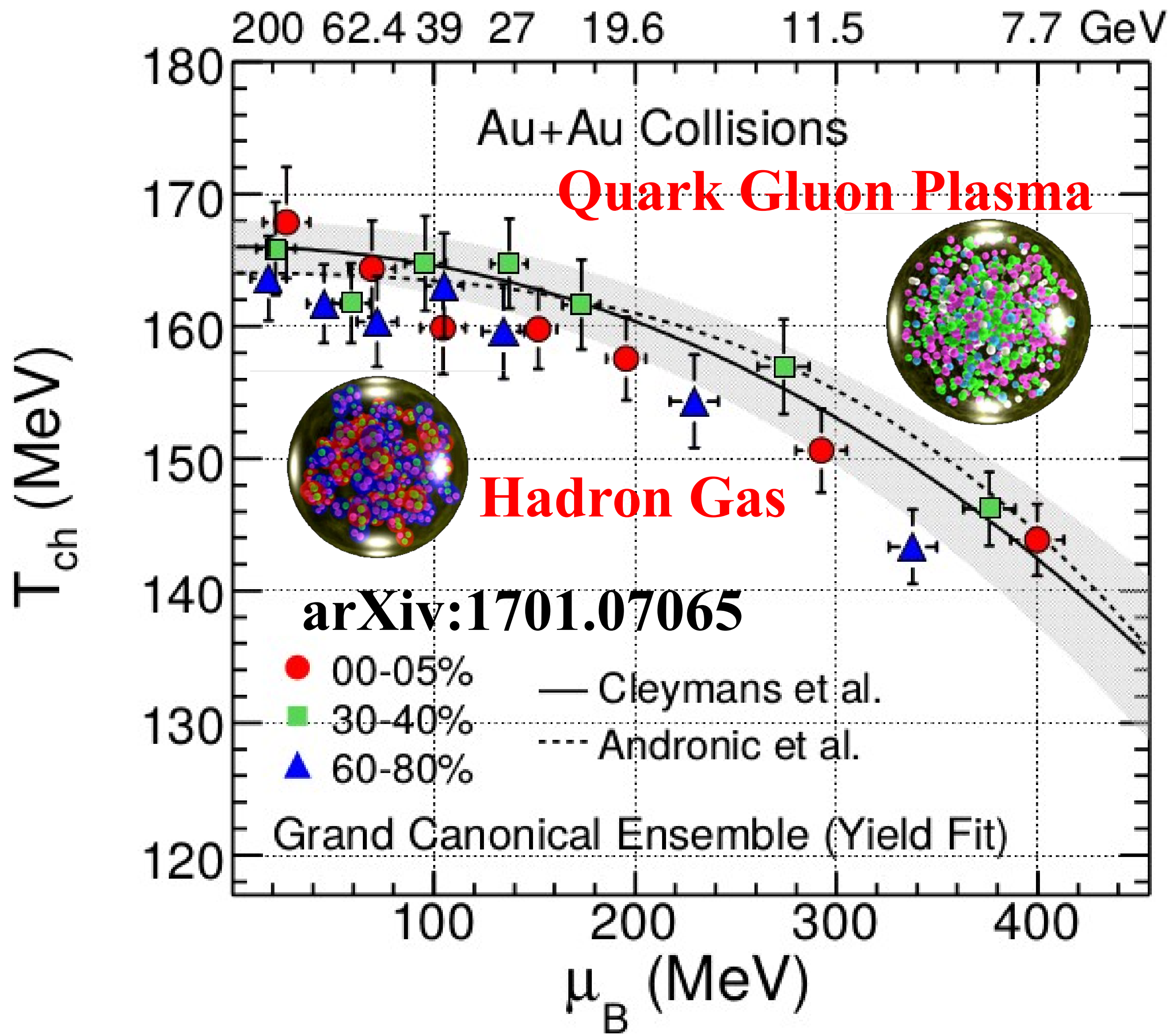
Understanding the Quark Gluon Plasma

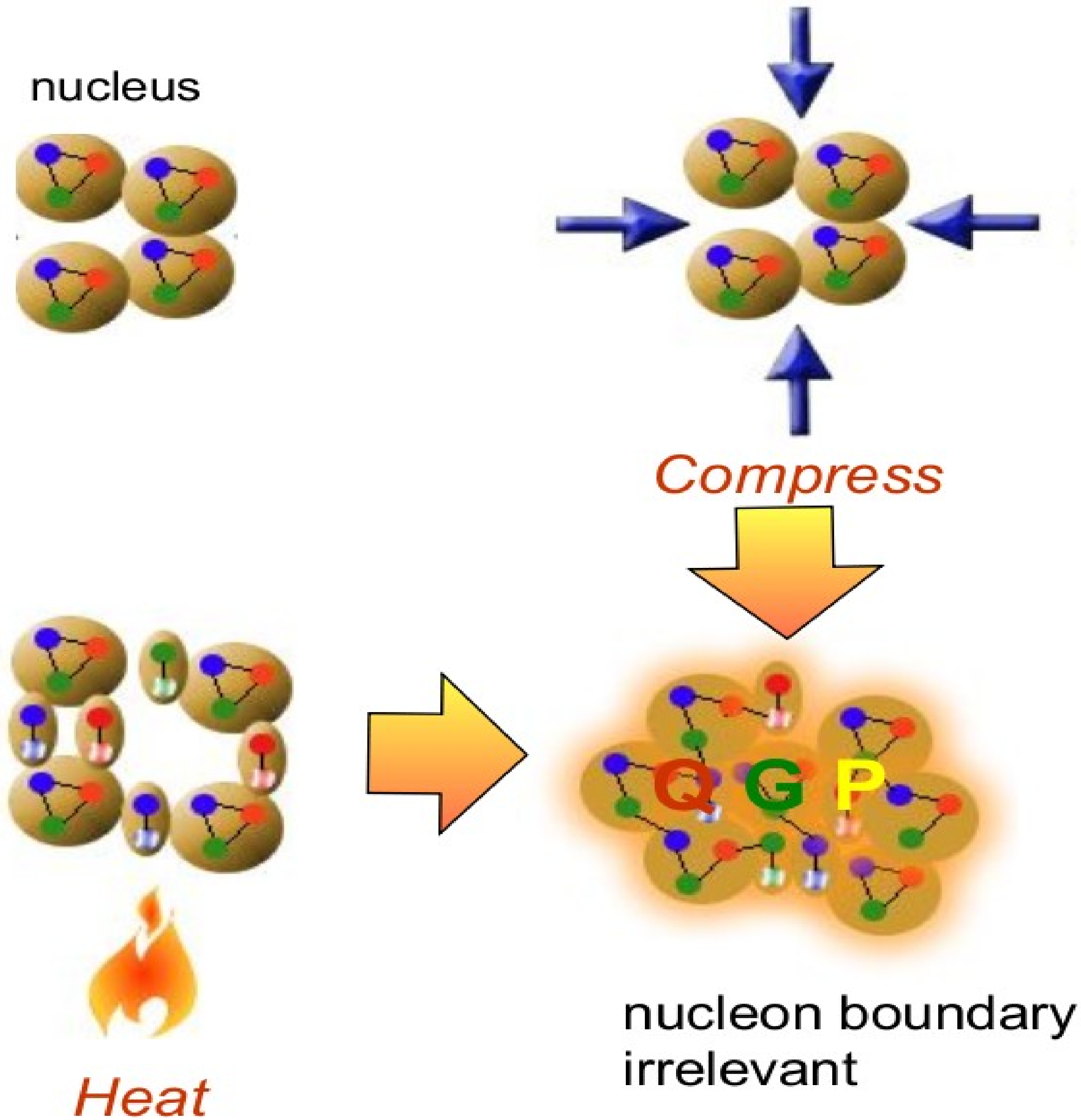


Christine Nattrass
University of Tennessee, Knoxville

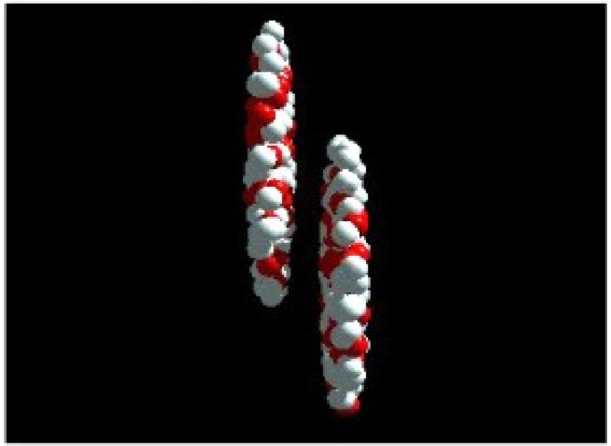
QCD Phase Diagram

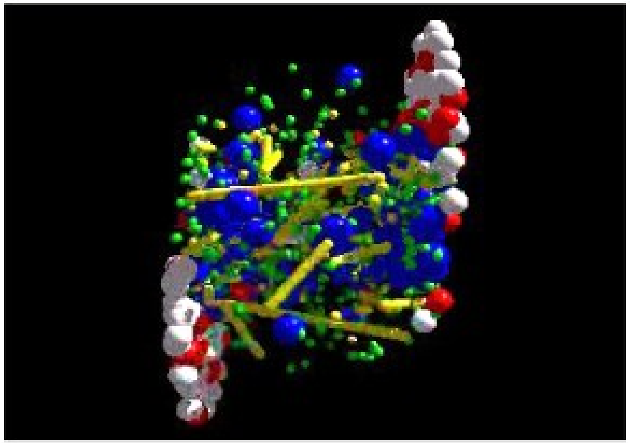


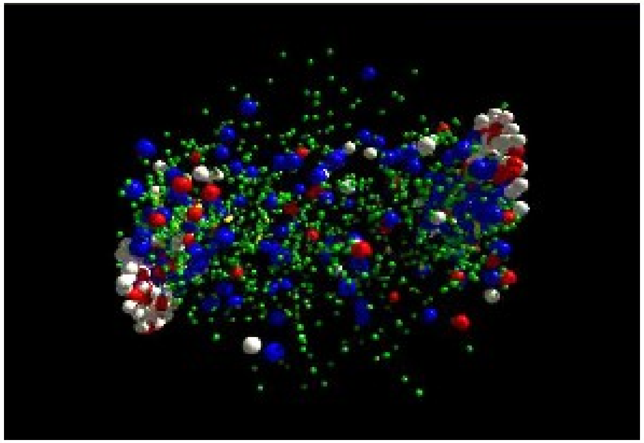
How to make a Quark Gluon Plasma

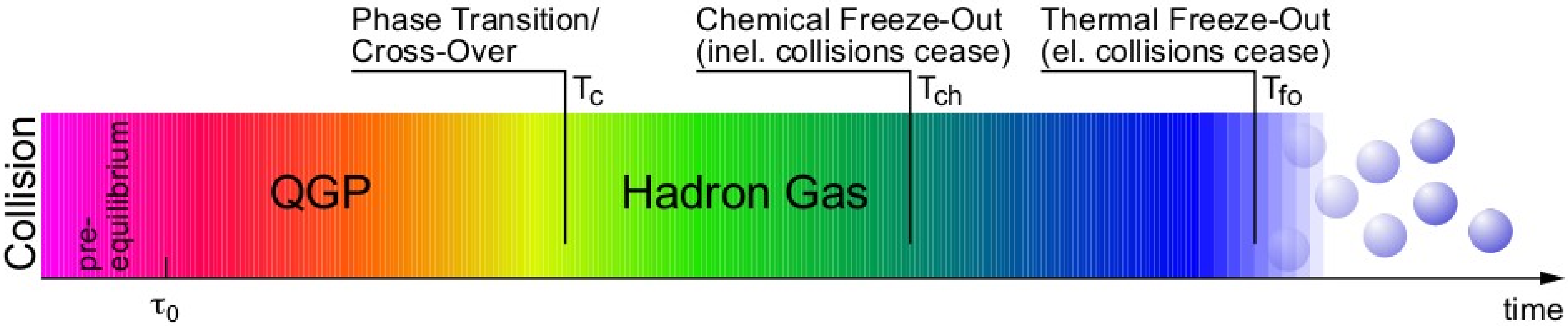


The phase transition in the laboratory

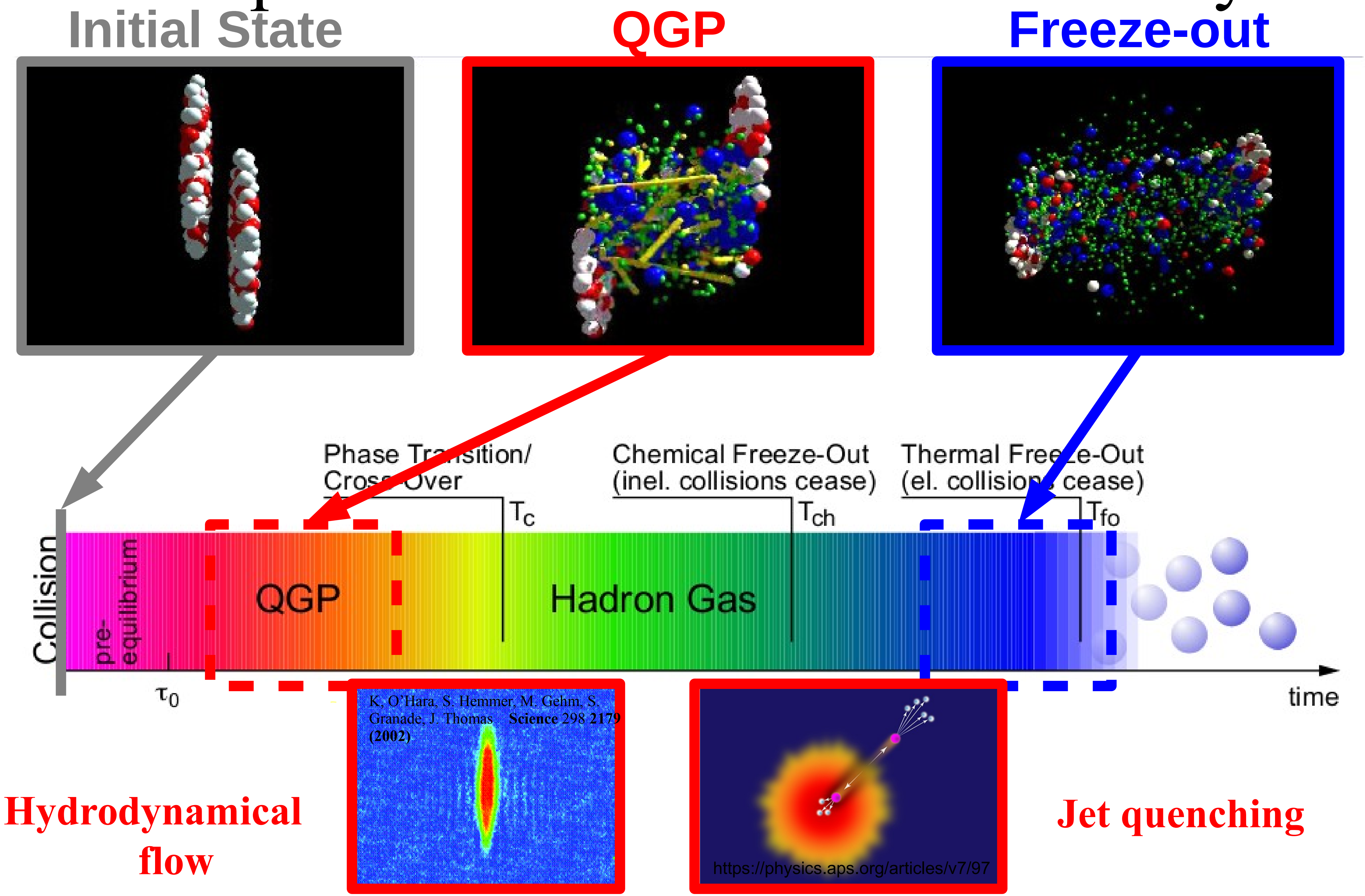






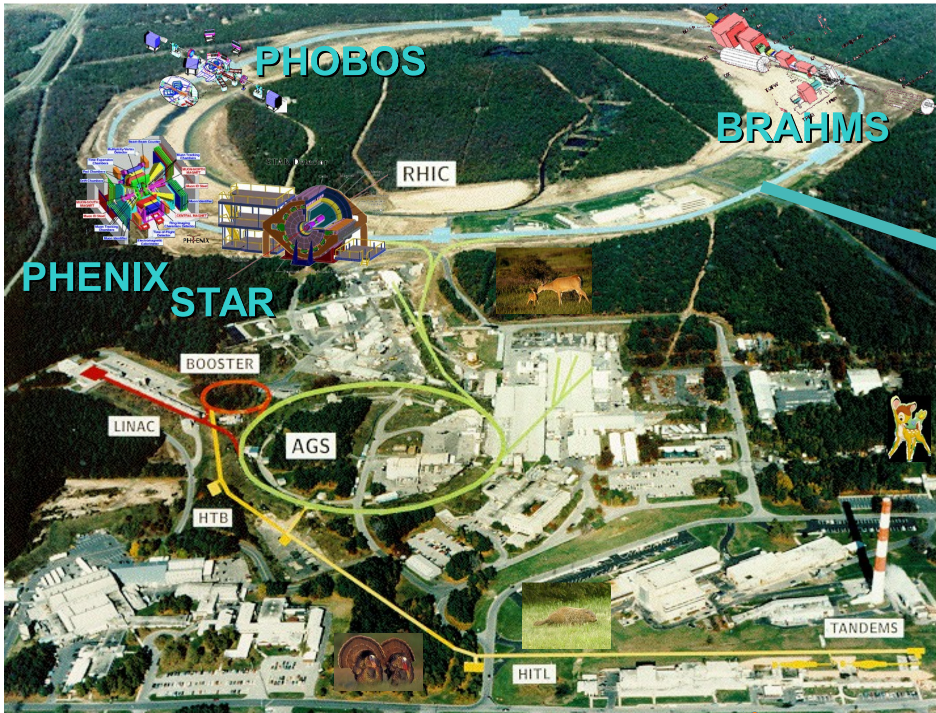


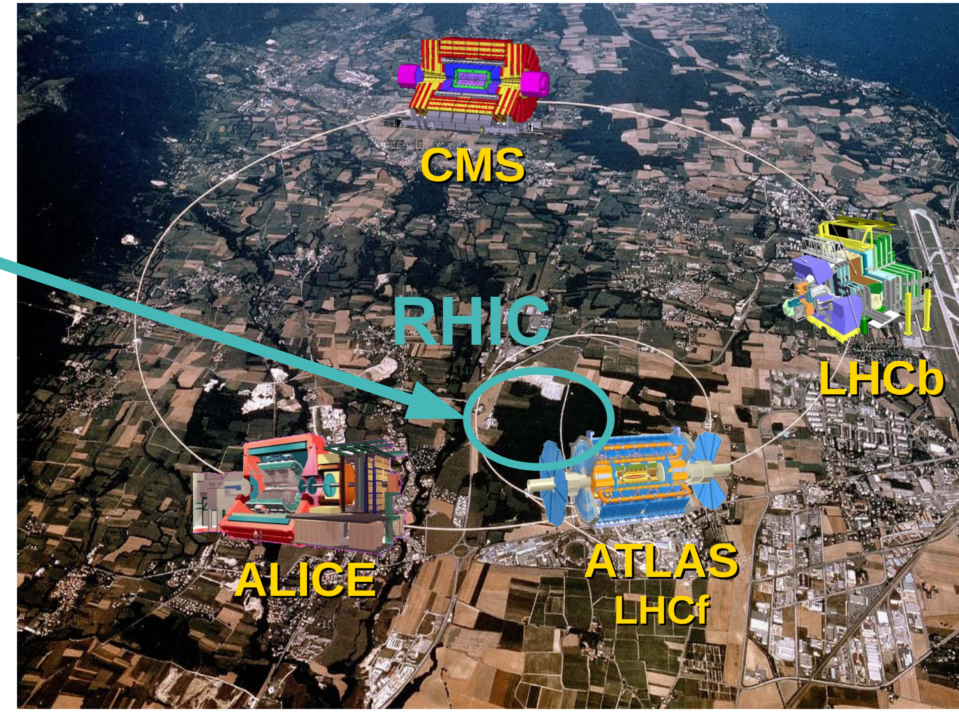
The phase transition in the laboratory



Relativistic Heavy Ion Collider

Large Hadron Collider

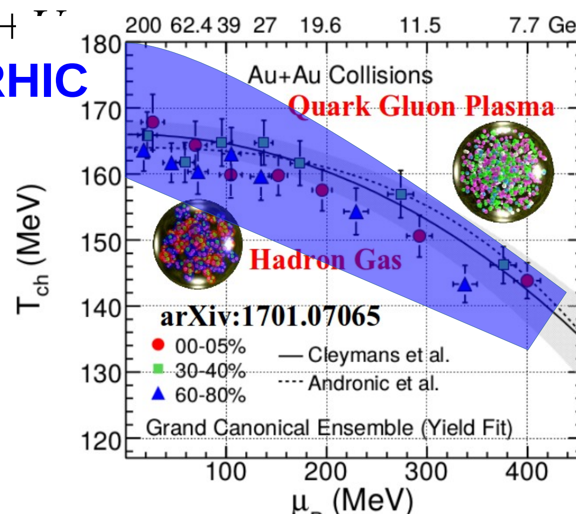




Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

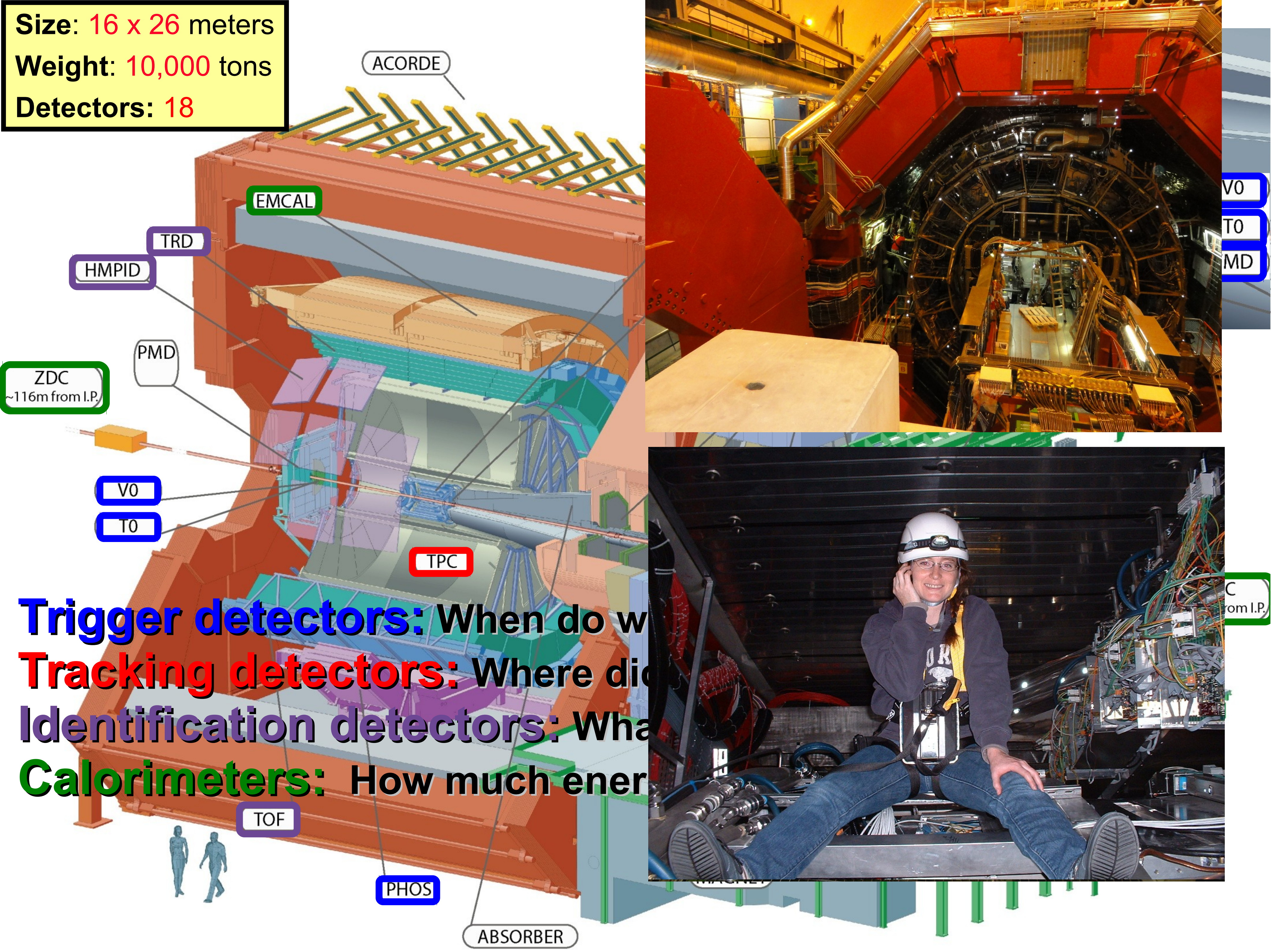
LHC

RHIC



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

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



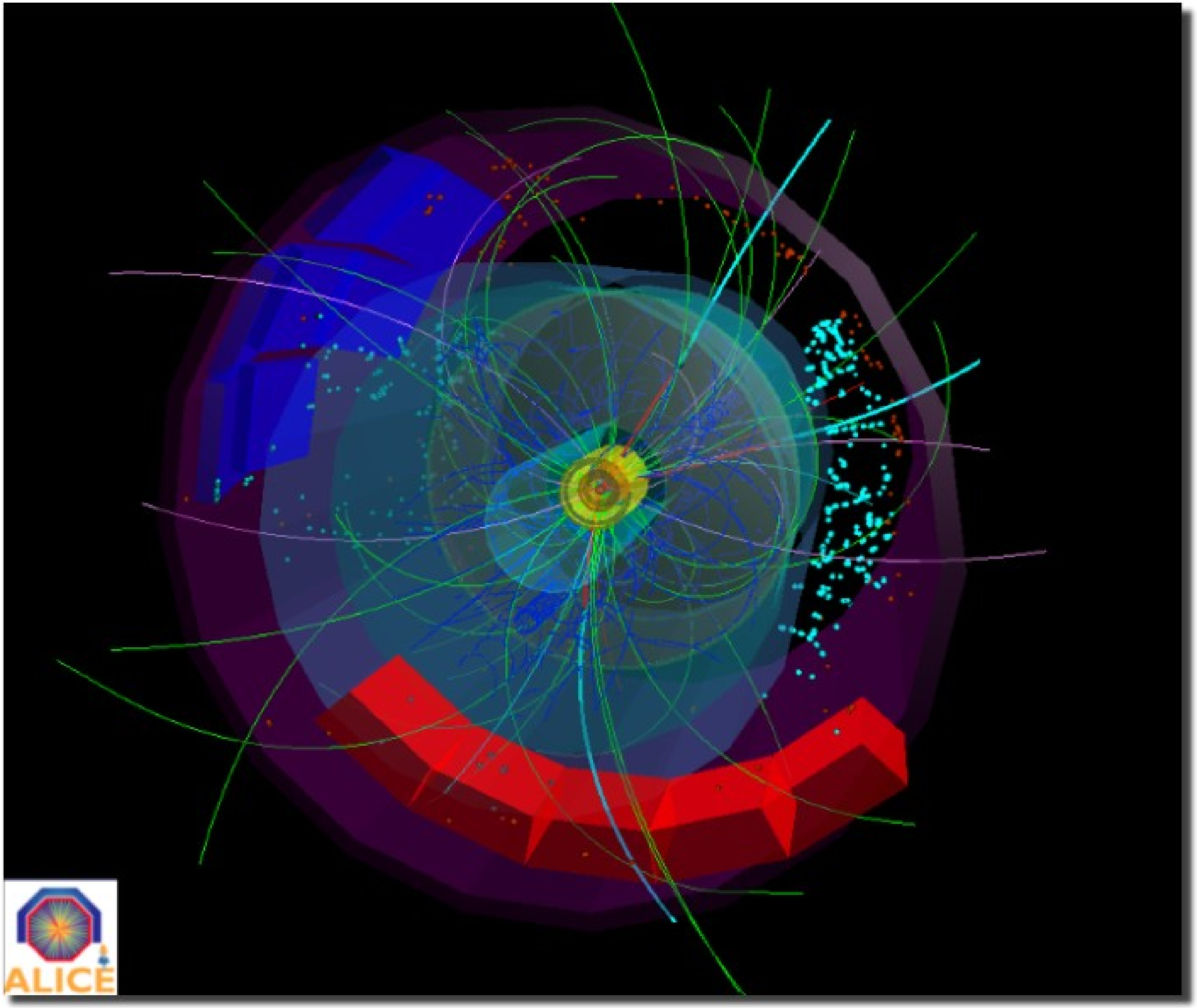
Trigger detectors: When do w

Tracking detectors: Where di

Identification detectors: Wha

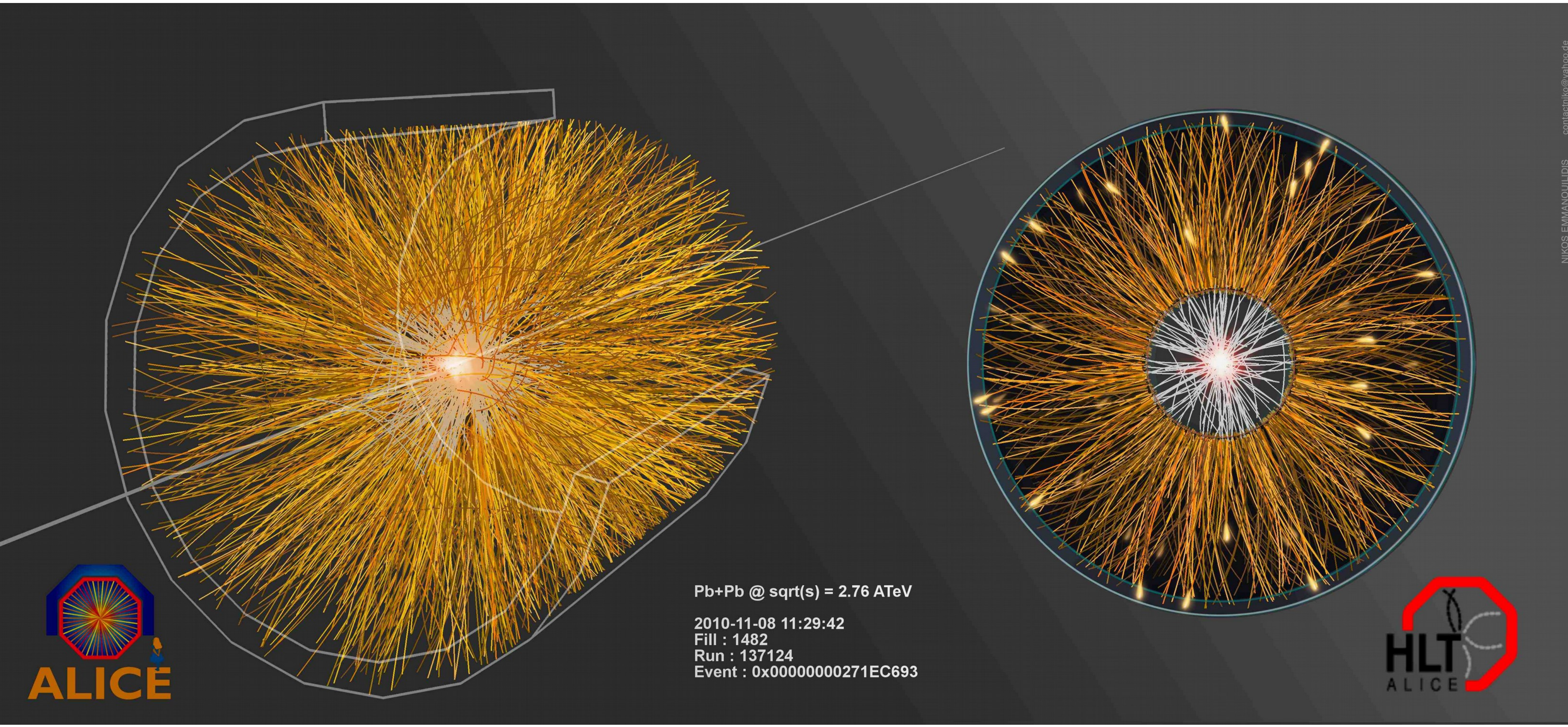
Calorimeters: How much ener

p+p collisions



3D image of each collision

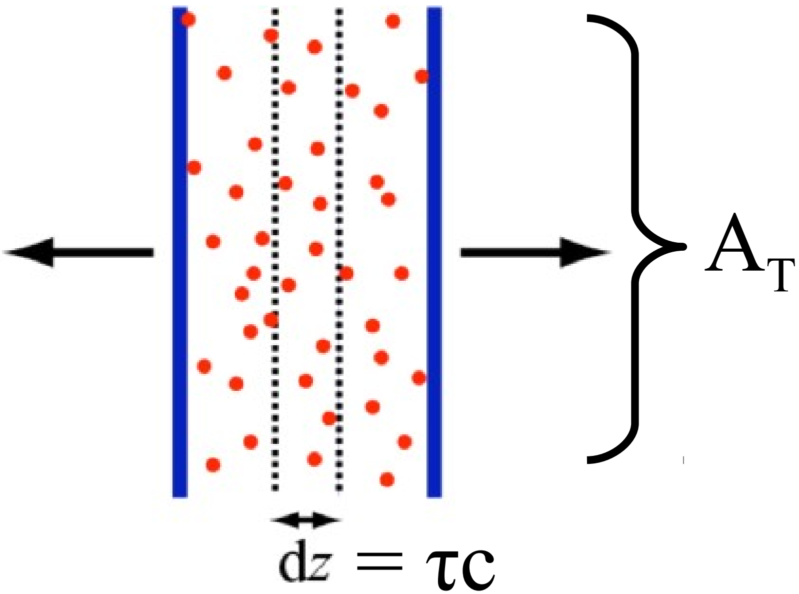
Pb+Pb collisions



Forming the QGP

How can we estimate the energy density?

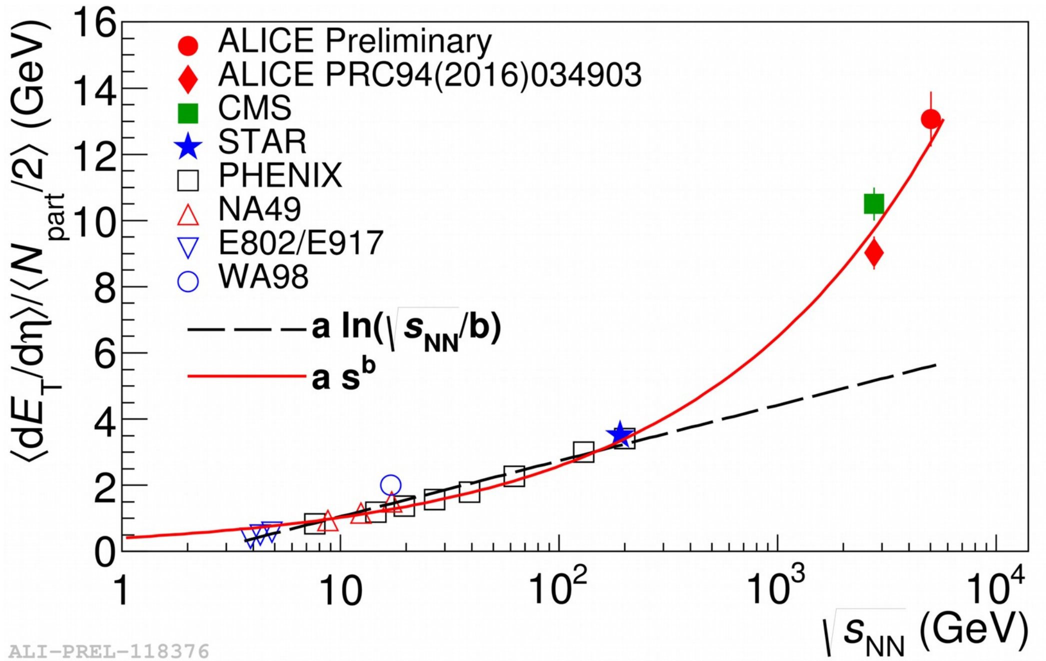
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε



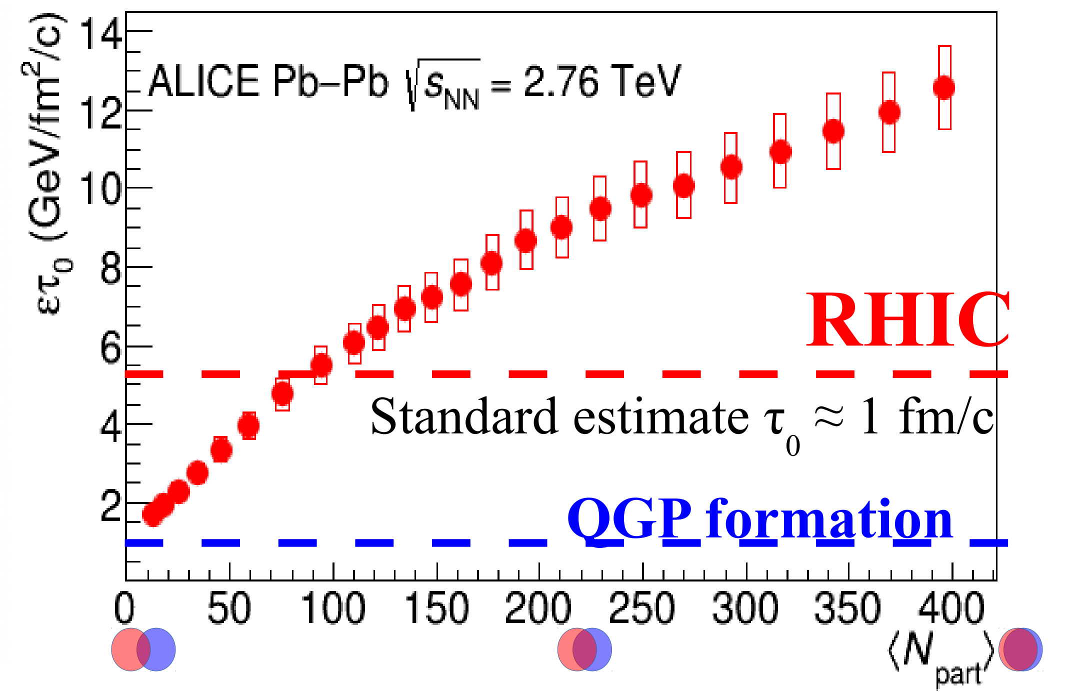
$$\epsilon = \frac{1}{V}\frac{dE_T}{dy} = \frac{J}{A_T \tau c}\frac{dE_T}{d\eta}$$

- QGP formation for $\varepsilon > 0.5$ GeV/fm^3

Energy dependence from dE_T/dy



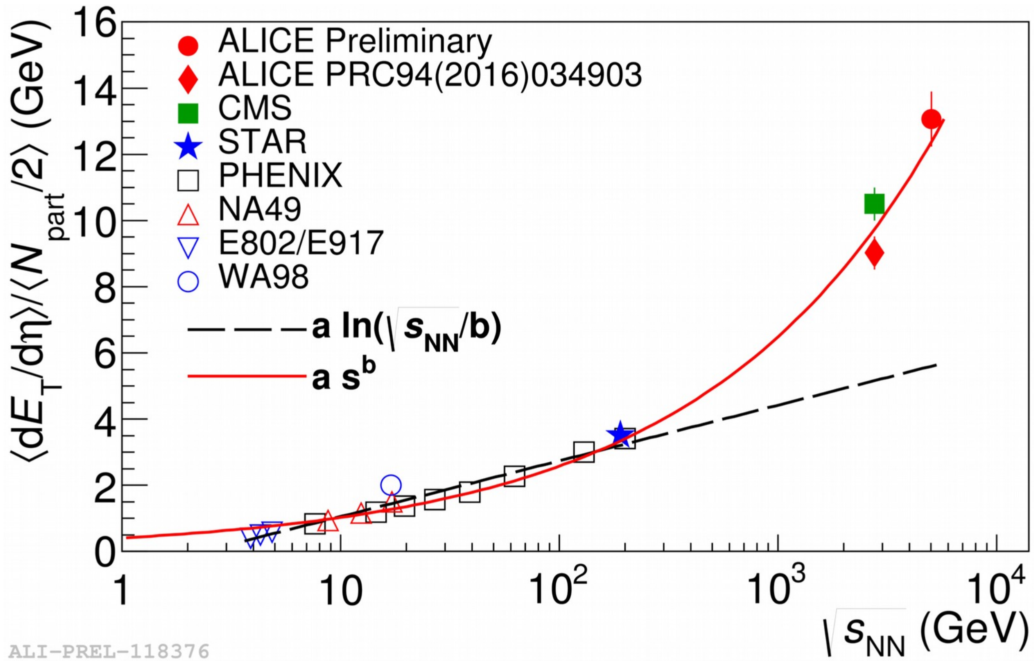
Collision energy

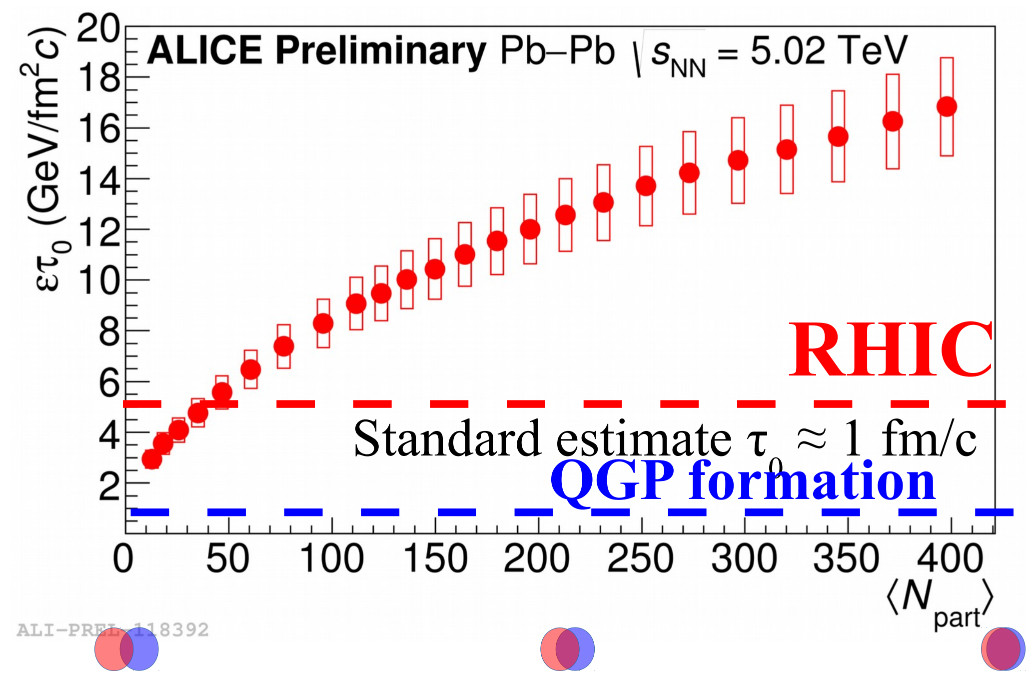


$$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$$

➔ Higher than extrapolations of RHIC data

Energy dependence from dE_T/dy



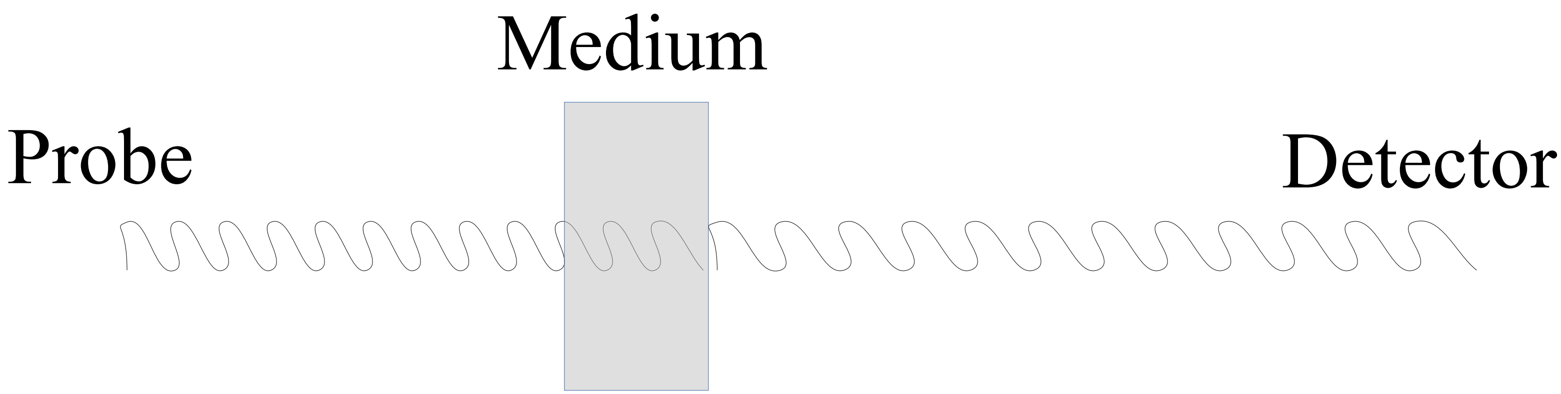


$$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$$

➔ Higher than extrapolations of RHIC data

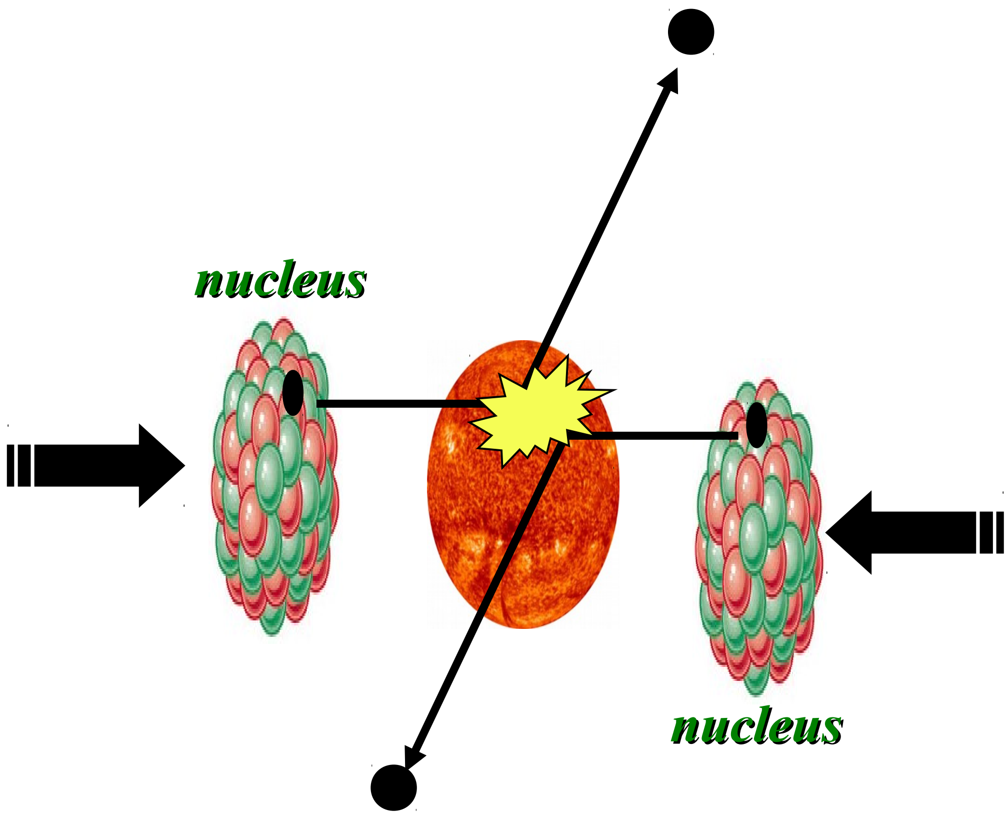
QGP Spectroscopy

Probing the Quark Gluon Plasma



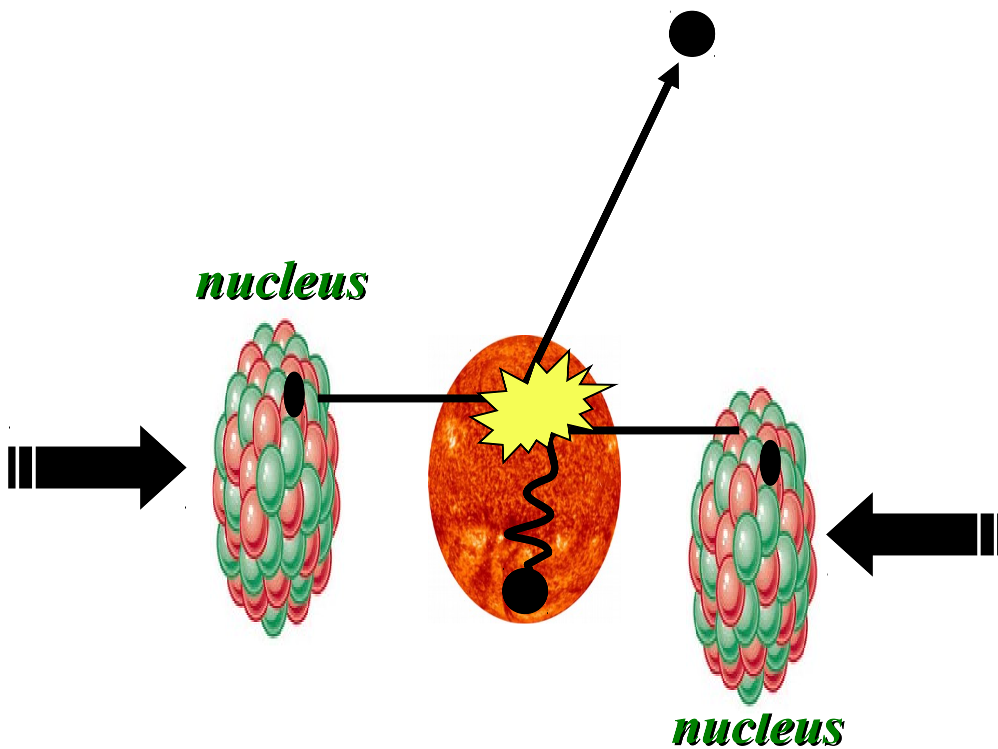
Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



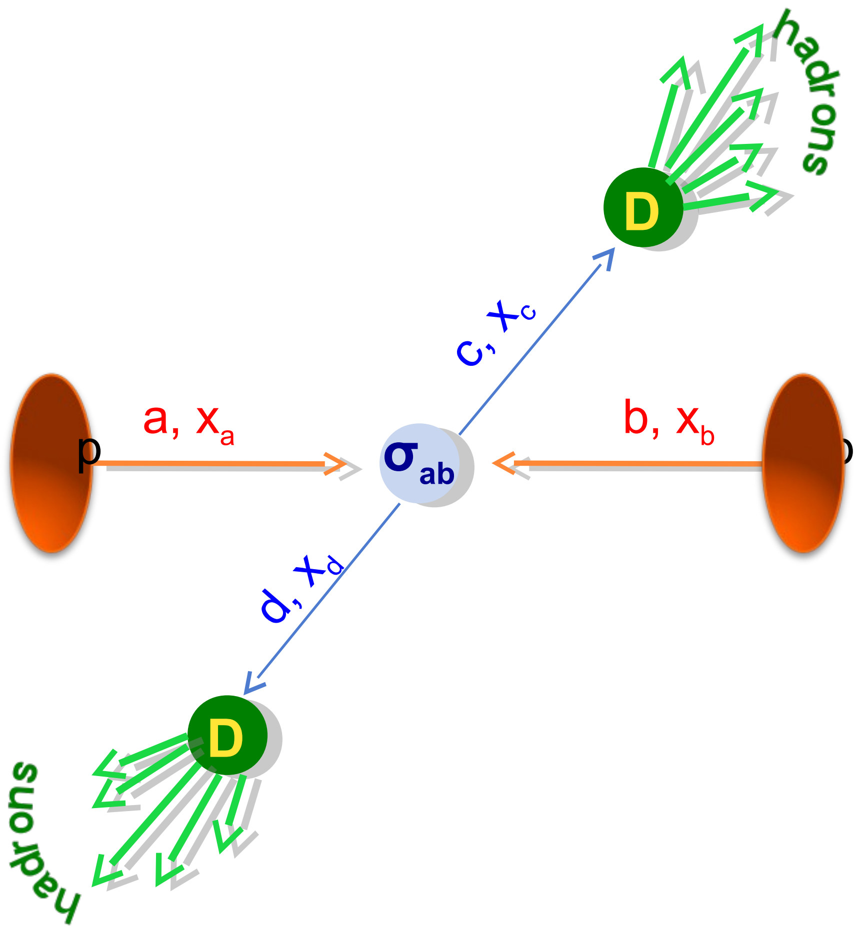
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

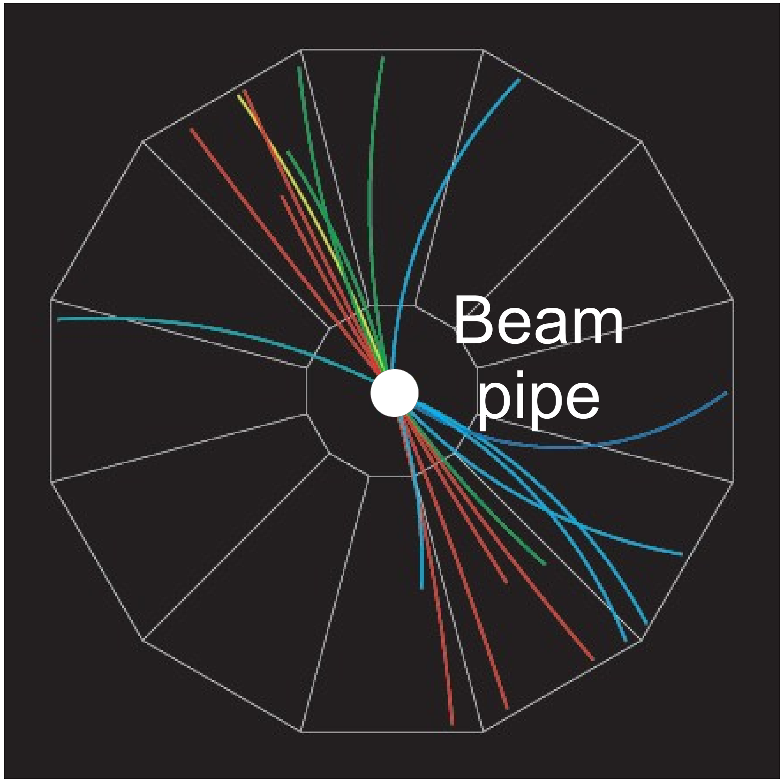


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets



p+p → dijet

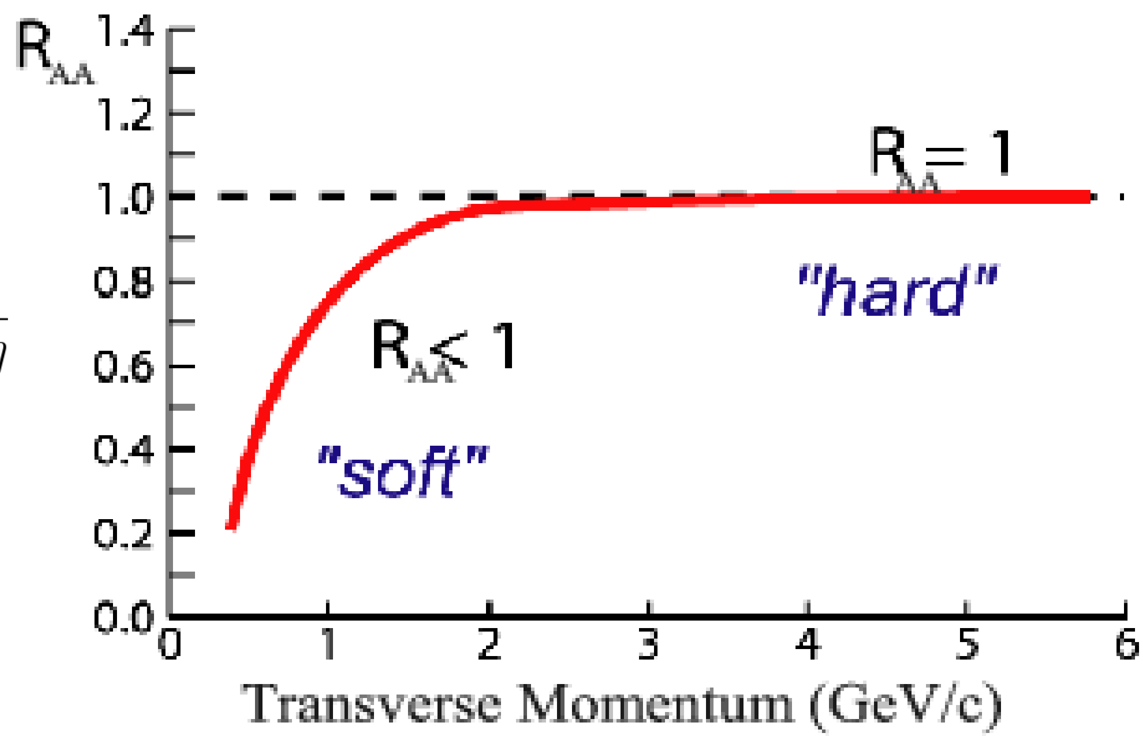


Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

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

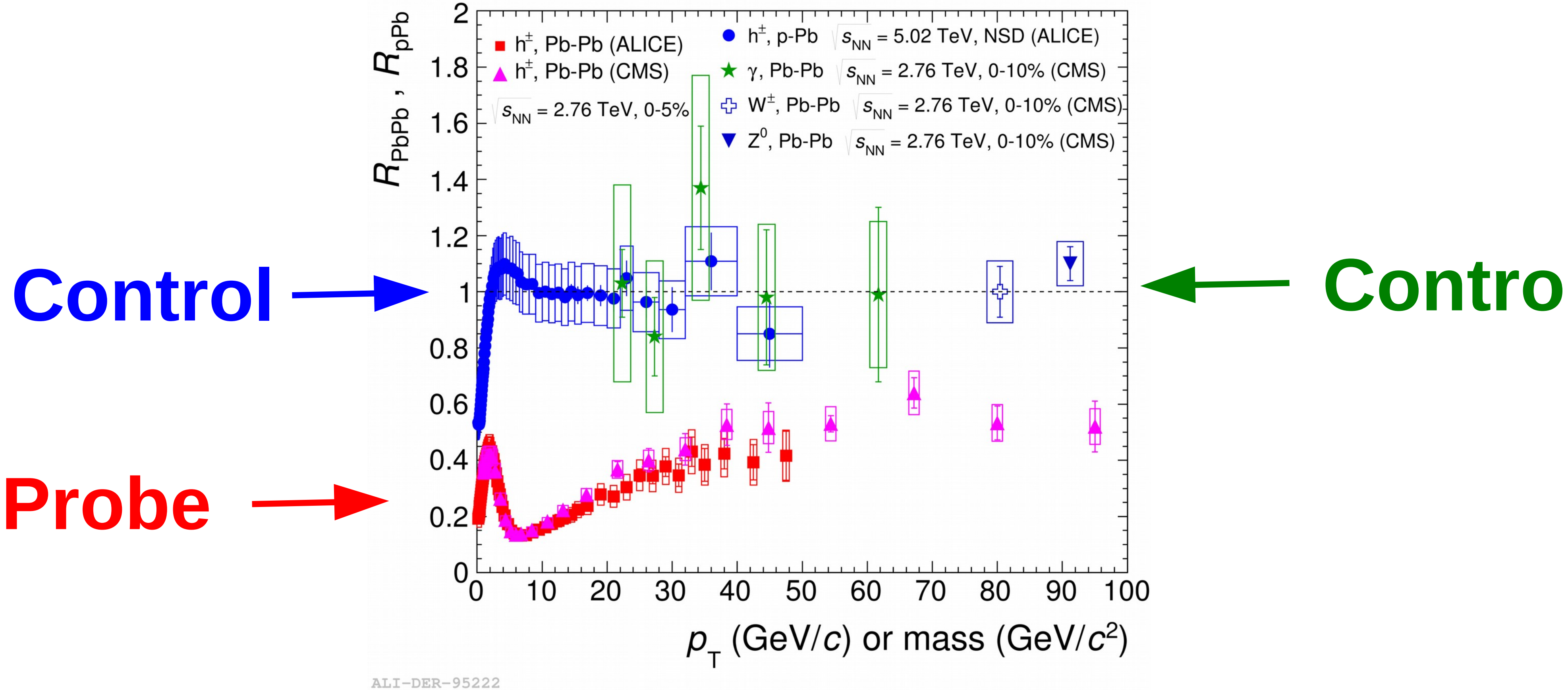
$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$



Enhancement

Suppression

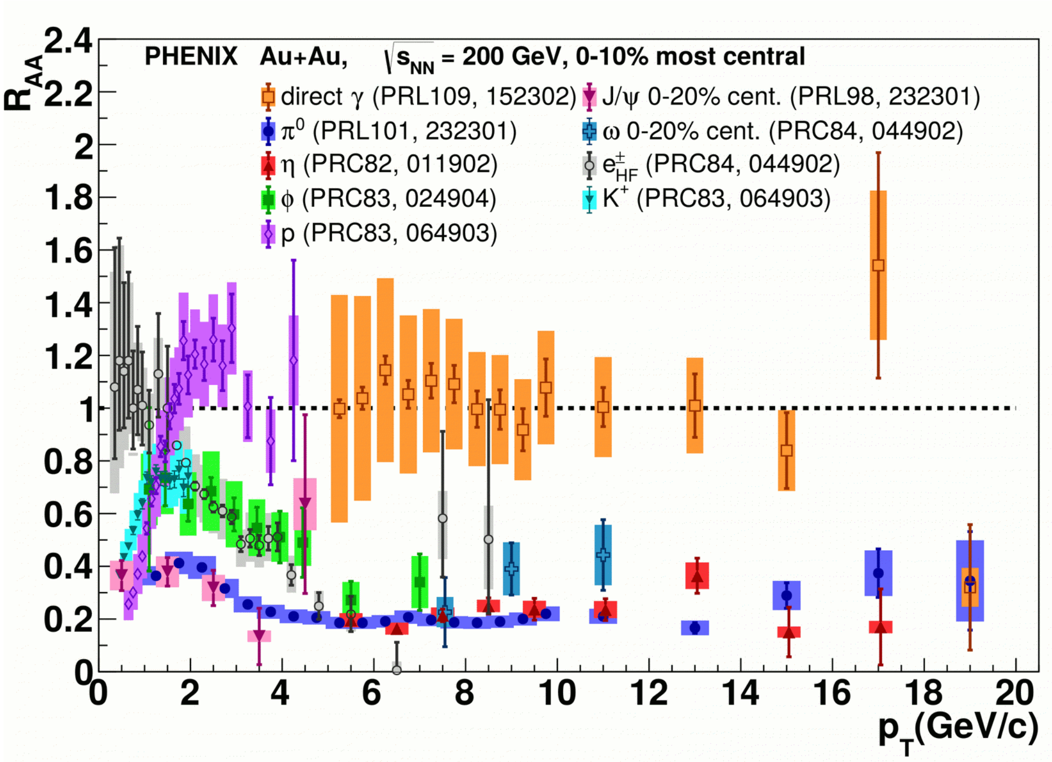
Nuclear modification factor

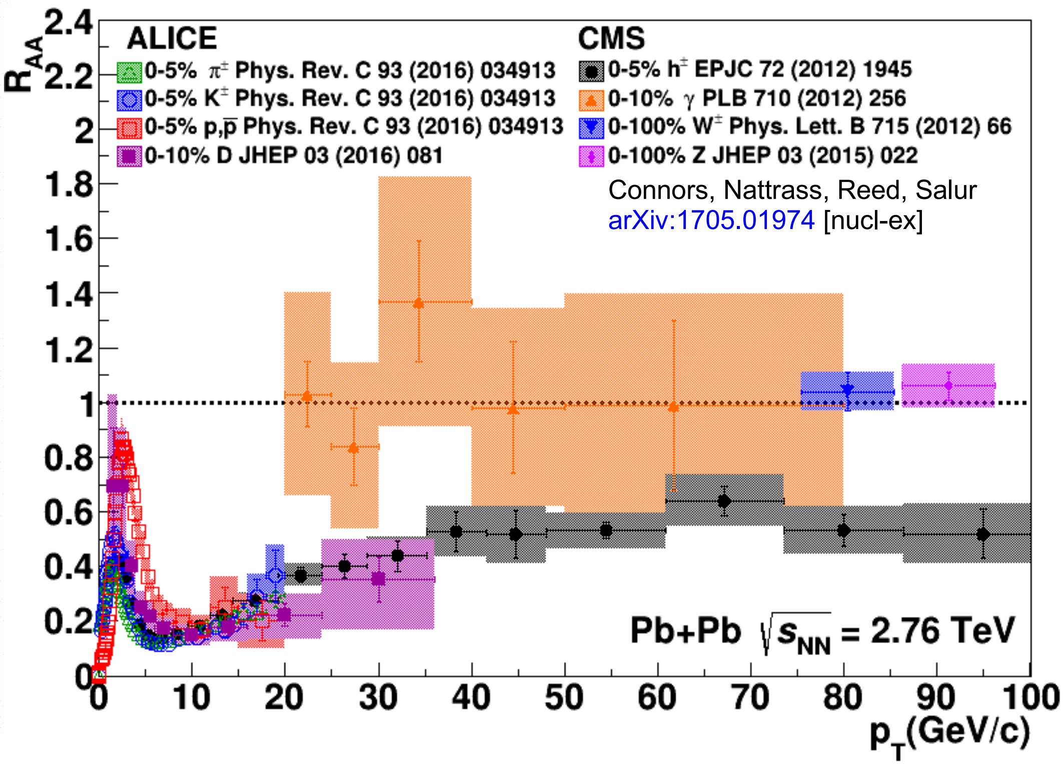


- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb

Nuclear modification factor R_{AA}

RHIC **LHC**

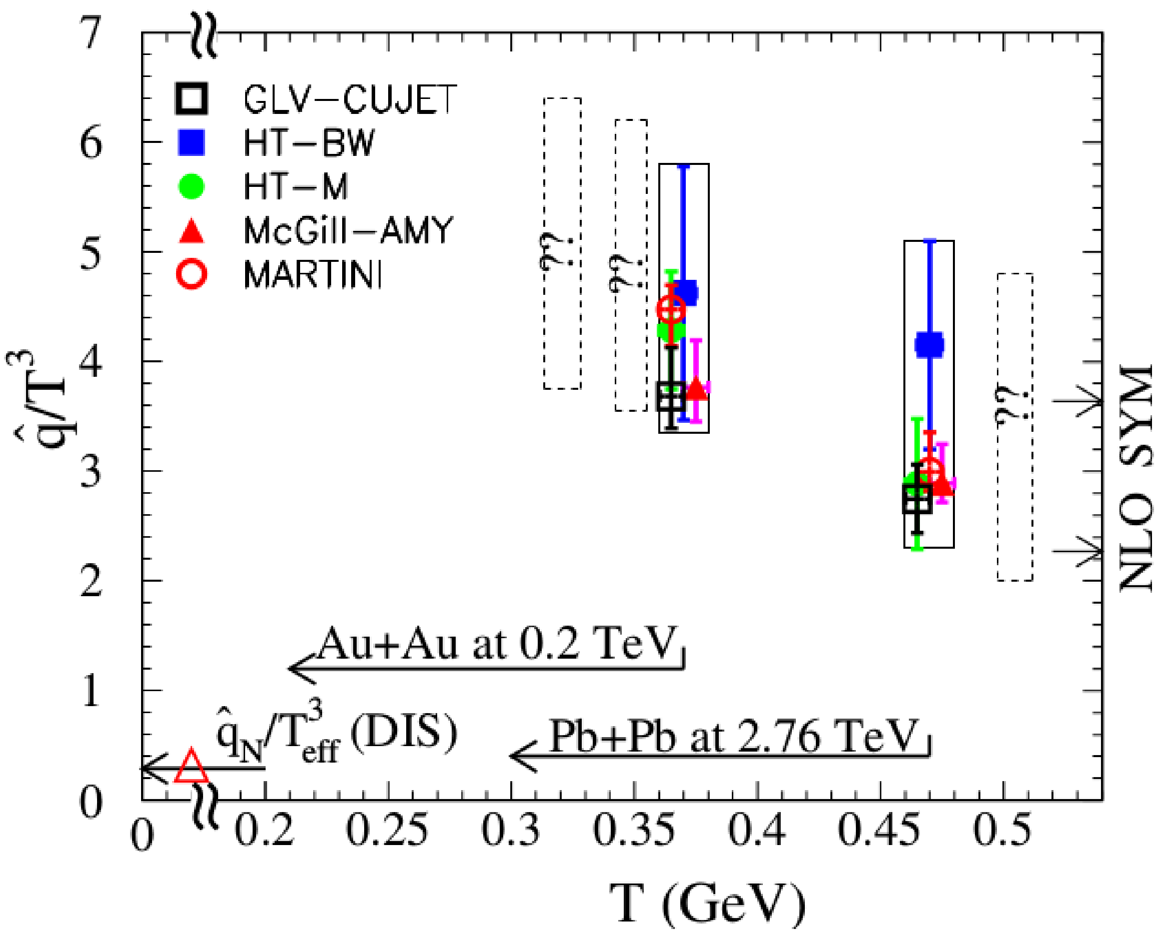




- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them - even heavy quarks!

Quantifying $\hat{q}$

Phys. Rev. C 90, 014909 (2014)



Jet Collaboration: For a 10 GeV quark traveling 4 fm

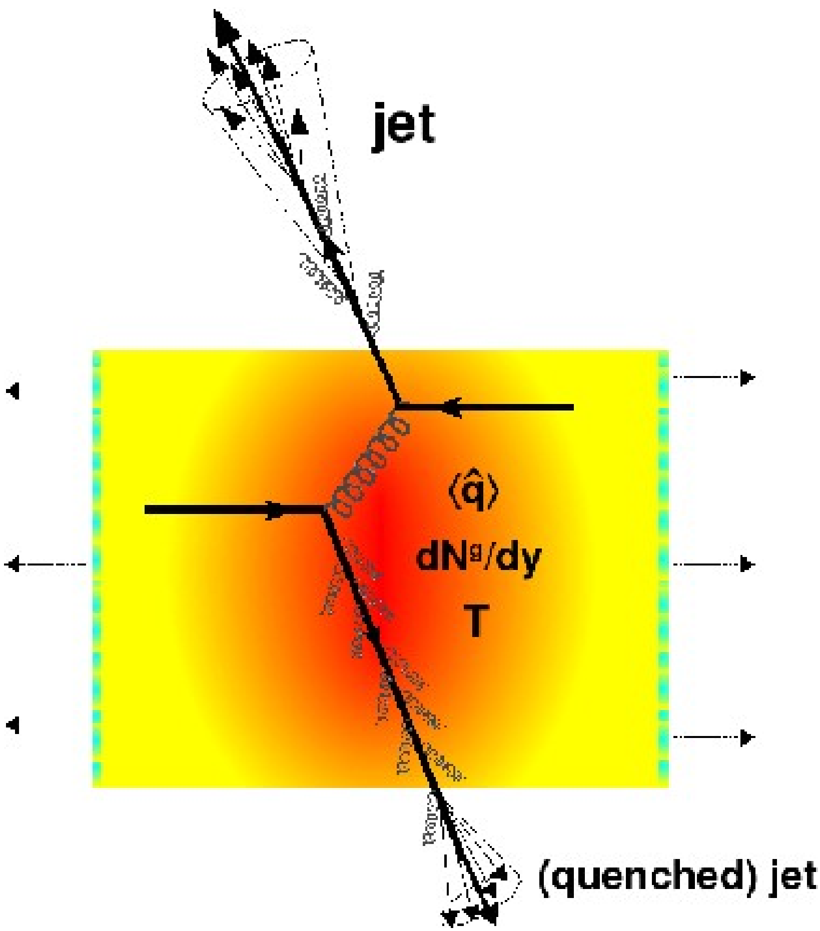
$\hat{q}$ ≈1.2±0.3 GeV^2/fm at τ_0=0.6 fm/c in Au+Au at $\sqrt{s_{NN}}$=200 GeV →loses 2.2 Gev

$\hat{q}$≈1.9±0.7 GeV^2/fm in Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV →loses 2.8 Gev

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

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

Gluon bremsstrahlung

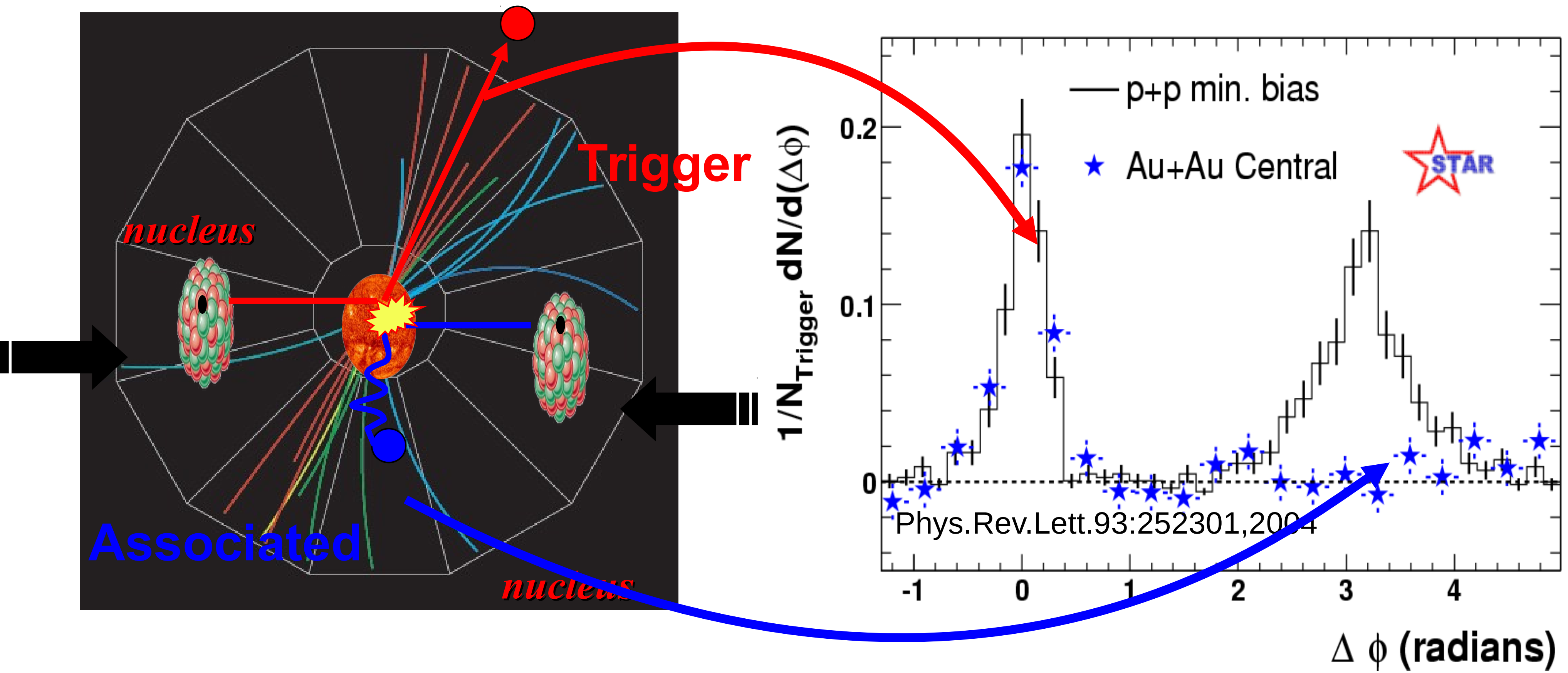


- Softer constituents
- Broader radius

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

Di-hadron correlations

p+p → dijet



Jet-hadron correlations

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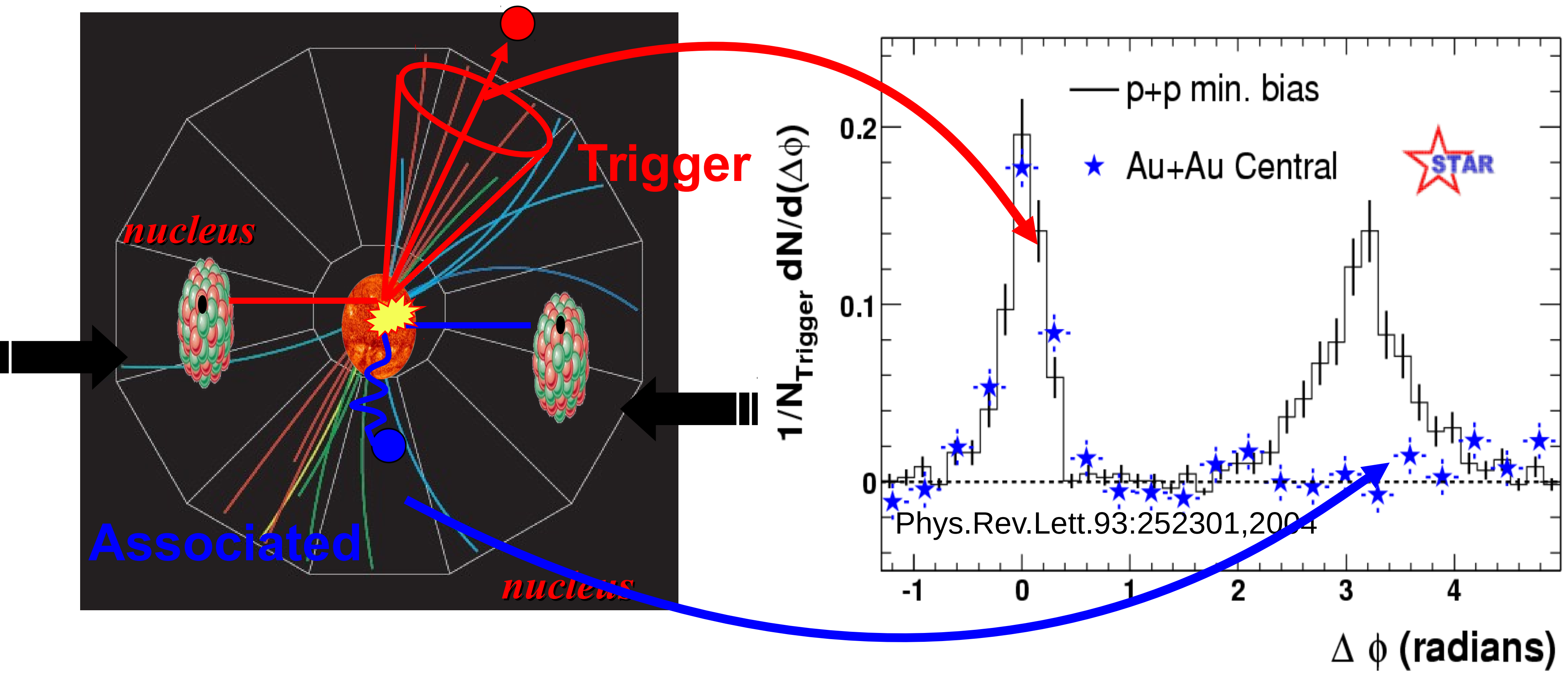
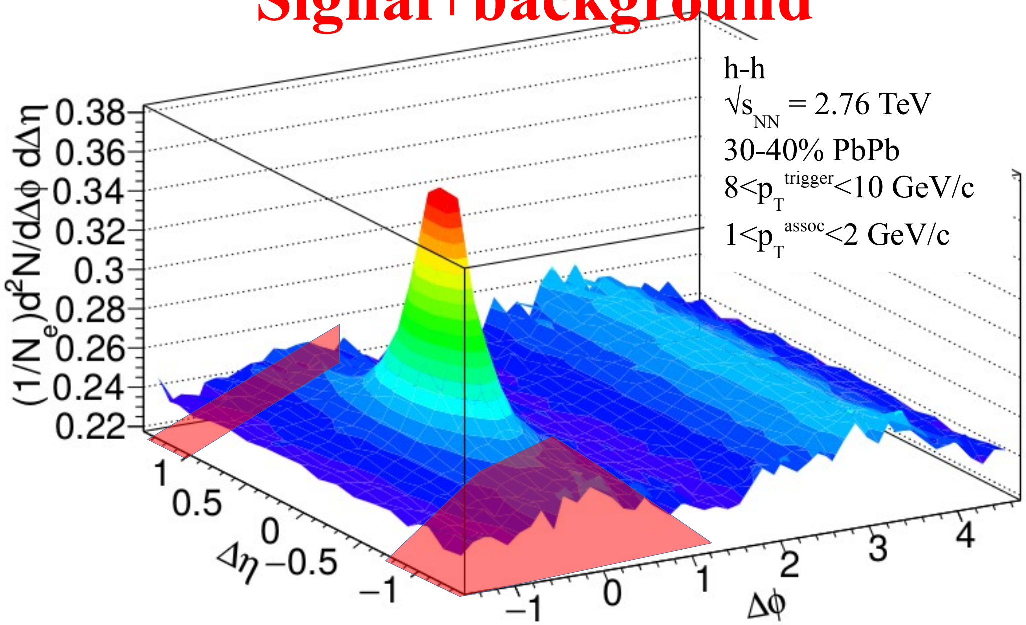


Separating the signal and the background
Testing with a model

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

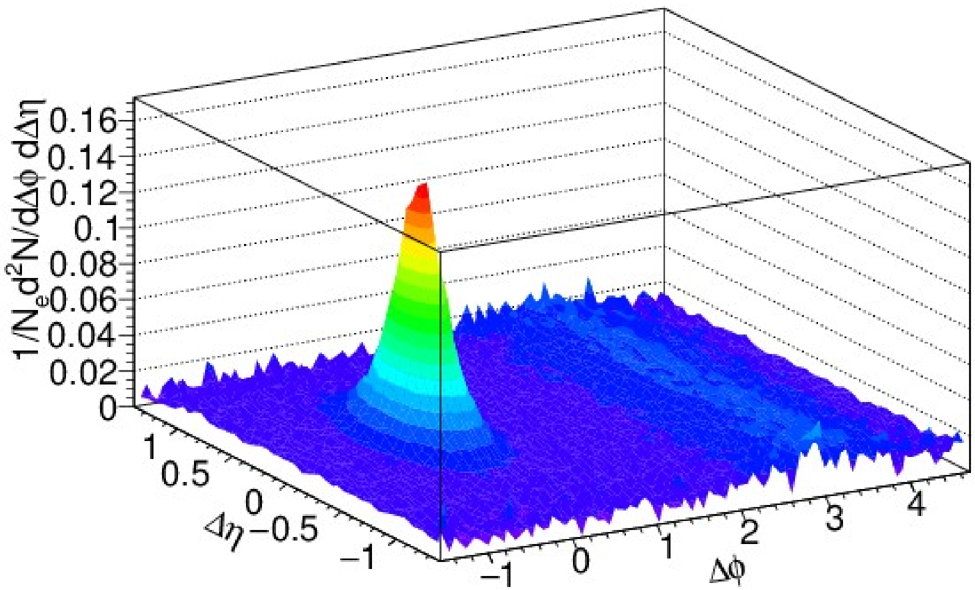
Separating signal+background

Signal+background

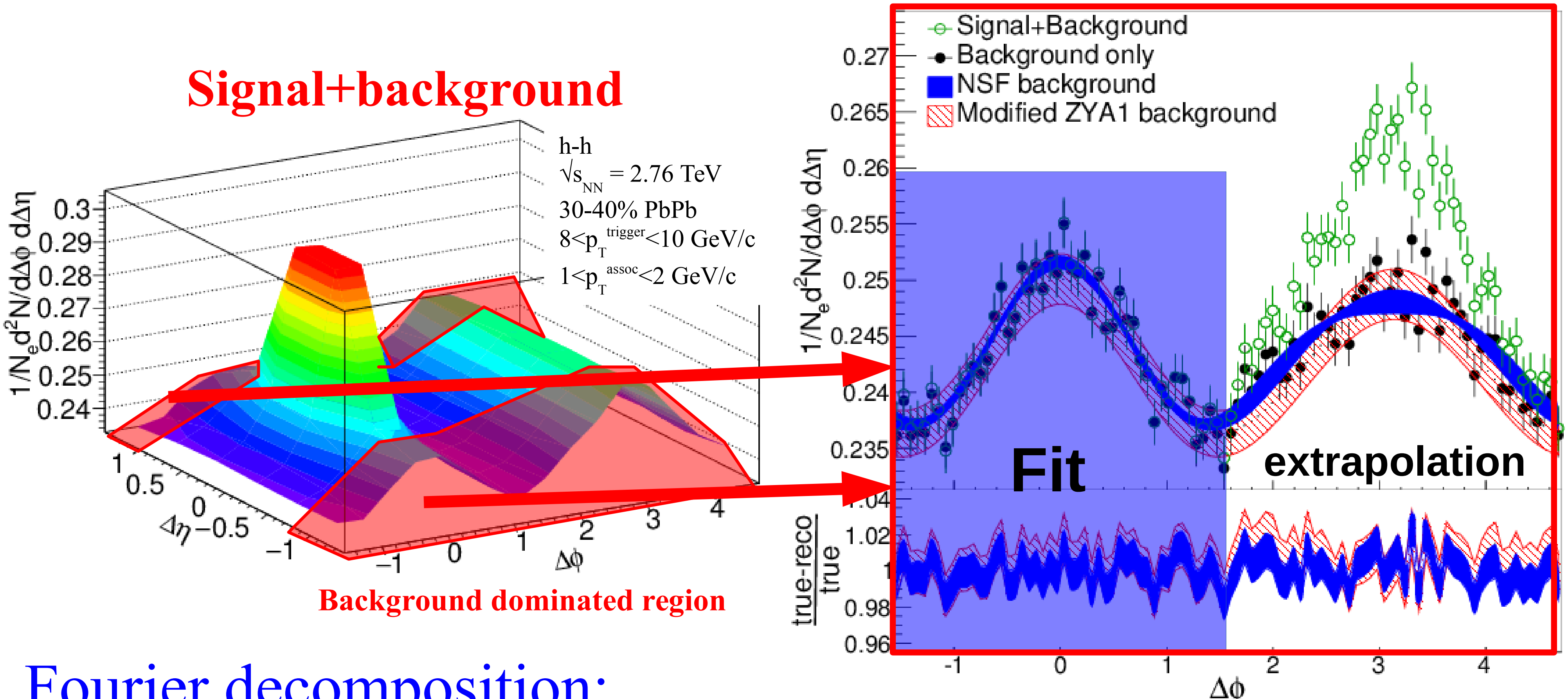


Background dominated region

Signal only

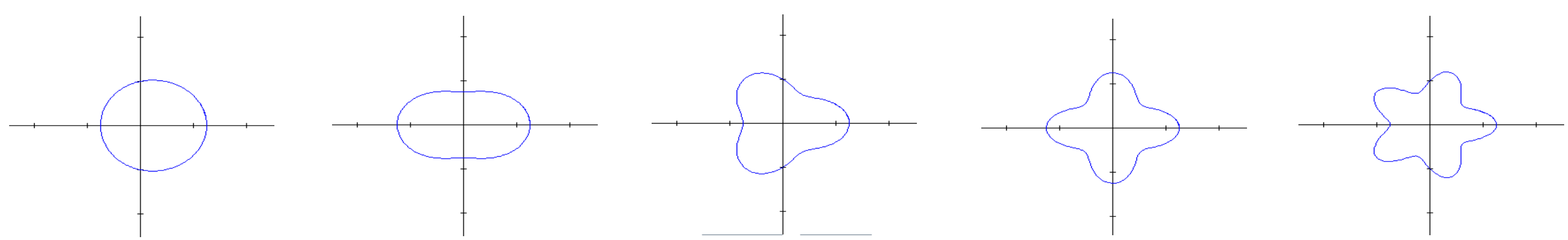


Background in correlations

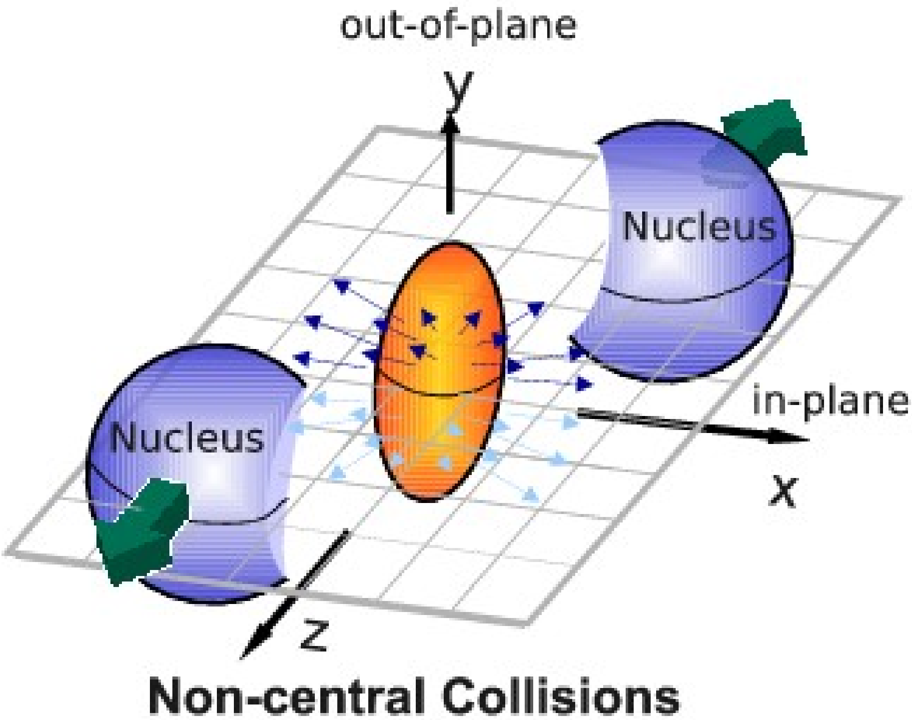


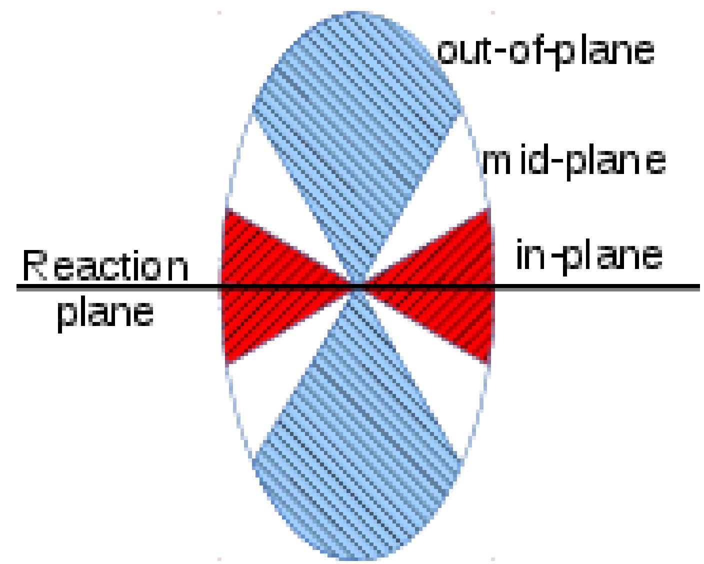
Fourier decomposition:

$$\frac{d^2N}{dp_T\, d\phi} \approx 1 + 2v_1\cos(d\phi) + 2v_2\cos(2d\phi) + 2v_3\cos(3d\phi) + 2v_4\cos(4d\phi) + 2v_5\cos(5d\phi) + \ldots$$



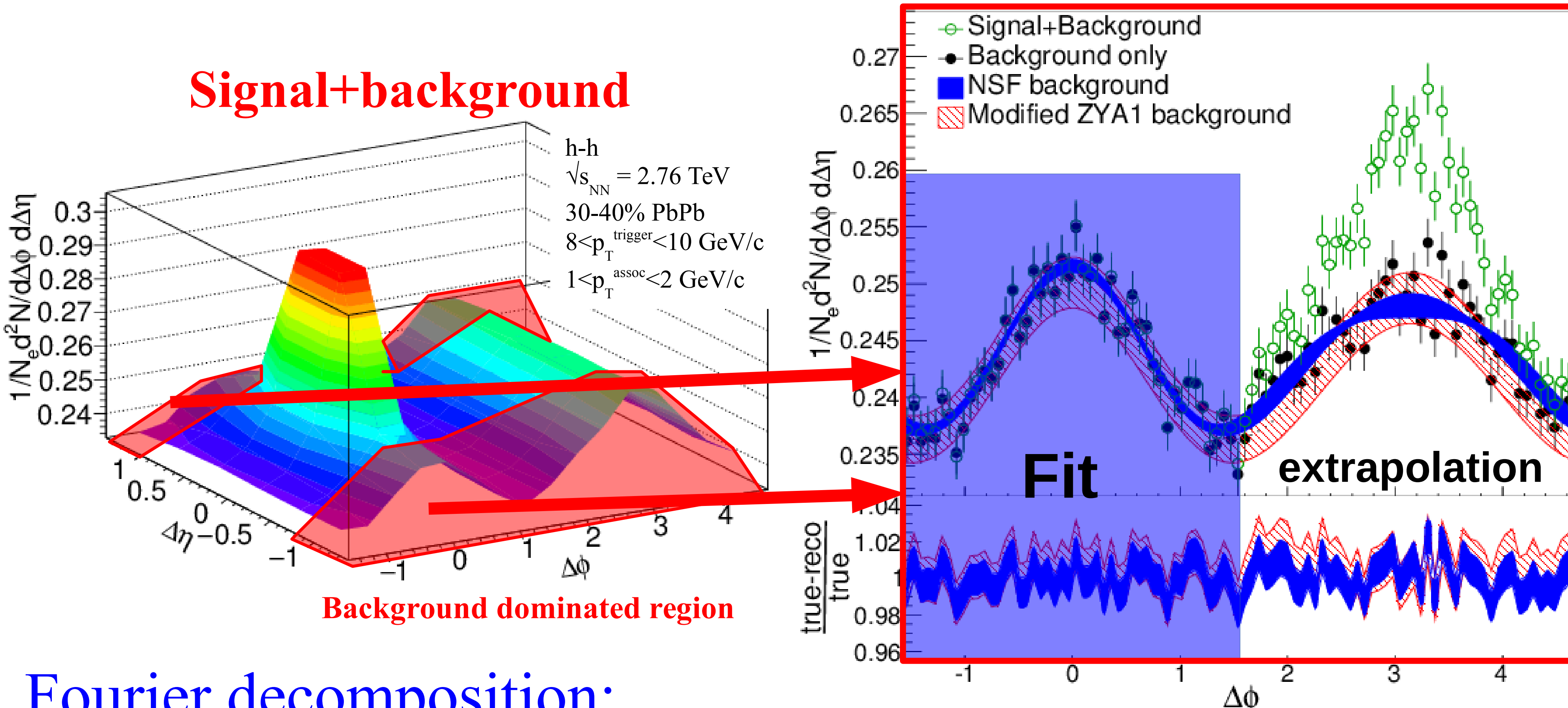
Reaction plane





- Can reconstruct from outgoing particles
- Changes background
- Also changes path length traversed by a parton

Background in correlations



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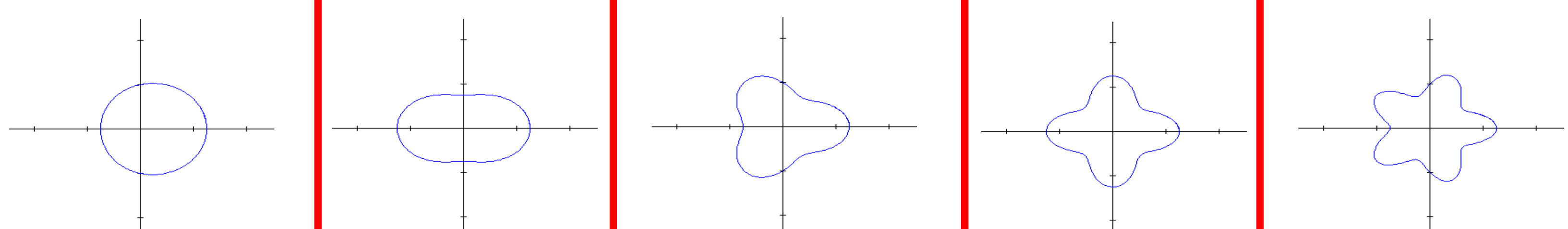
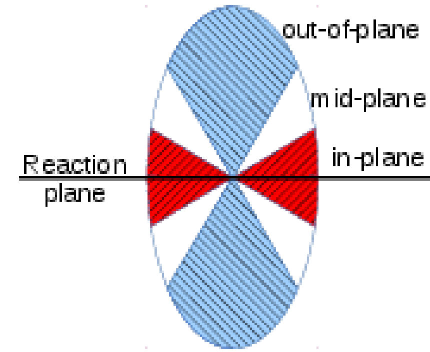
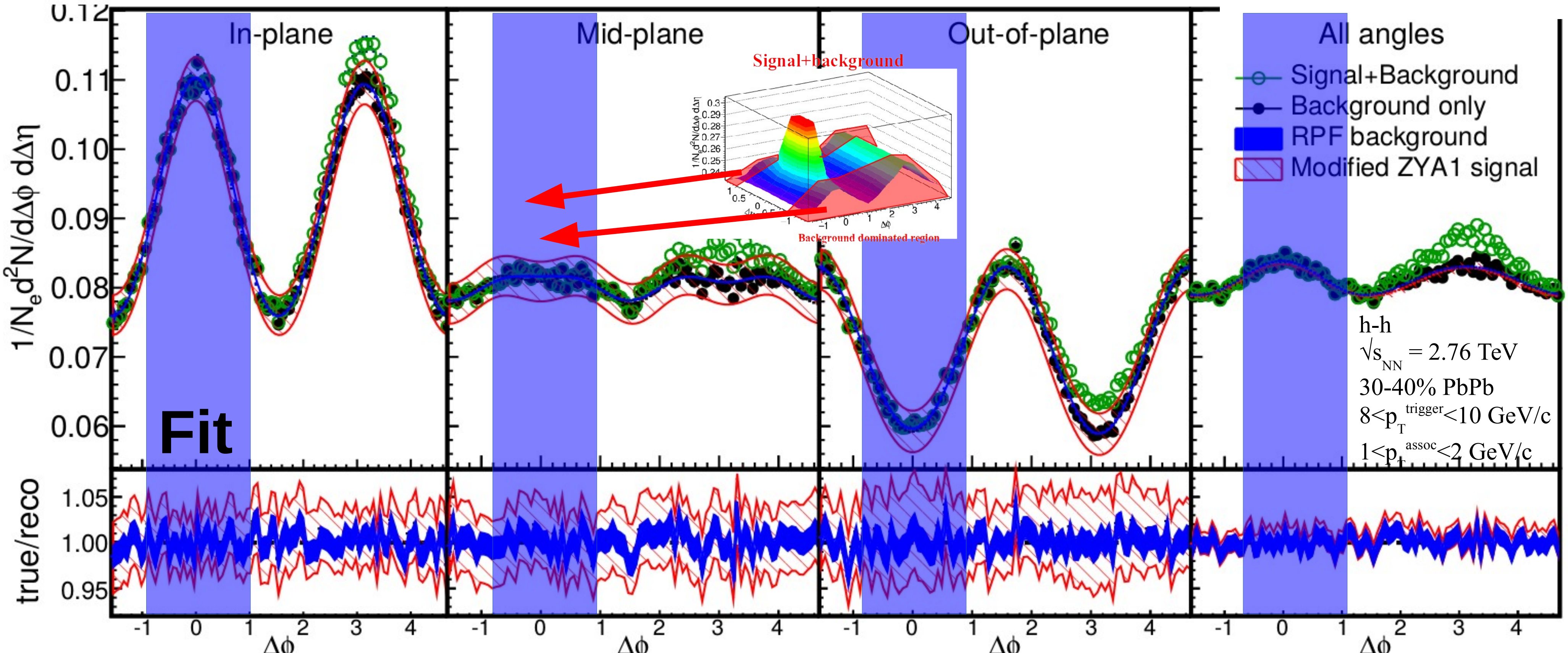


Change with reaction plane

Reaction Plane Fit (RPF) method

30-40% central

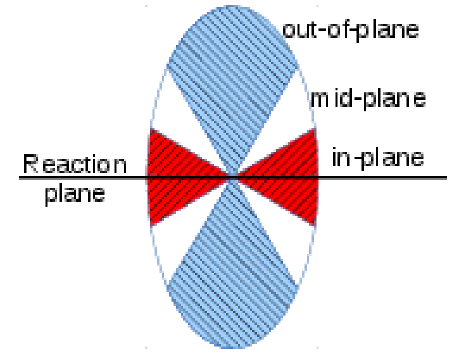


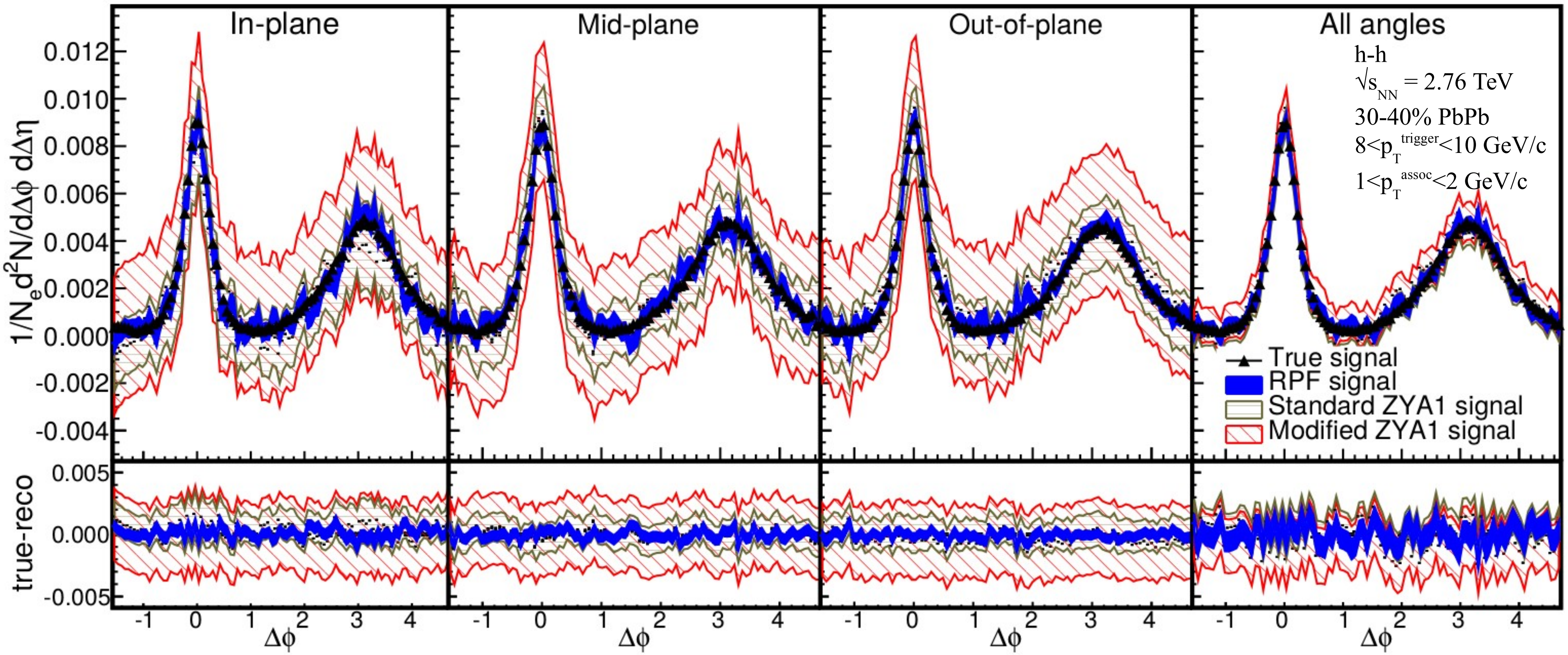


- Project signal+background over $1.0<|\Delta\eta|<1.4$
- Fit background in $|\Delta\varphi|<1$ including reaction plane dependence
- v_n and B extracted with v_n up to n=4

Reaction Plane Fit (RPF) method

30-40% central

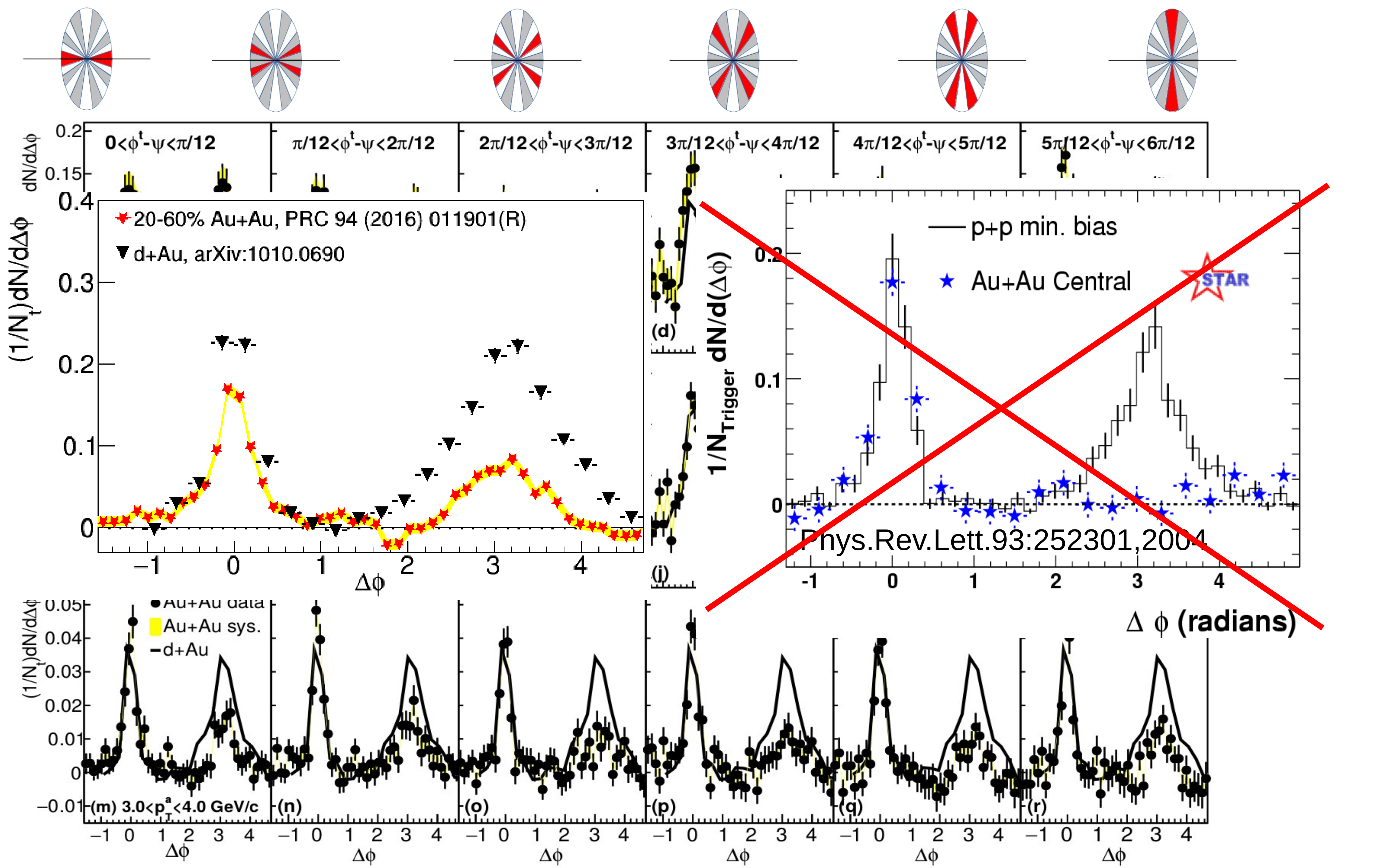




	near-side $Y \times 10^{-3}$				away-side $Y \times 10^{-3}$			
	in-plane	mid-plane	out-of-plane	All	in-plane	mid-plane	out-of-plane	All
True	$5.78 \pm 0.03 \pm 0.13$	$5.77 \pm 0.03 \pm 0.14$	$5.65 \pm 0.03 \pm 0.13$	$17.1 \pm 0.1 \pm 0.2$	$6.74 \pm 0.03 \pm 0.13$	$6.72 \pm 0.03 \pm 0.14$	$6.52 \pm 0.03 \pm 0.13$	$19.9 \pm 0.1 \pm 0.2$
Mod. ZYA1	$6.3 \pm 5.9 \pm 1.7$	$5.7 \pm 6.0 \pm 0.3$	$6.8 \pm 6.1 \pm 0.9$	$18.9 \pm 4.2 \pm 1.2$	$7.3 \pm 5.9 \pm 1.7$	$6.8 \pm 6.0 \pm 0.3$	$7.7 \pm 6.1 \pm 0.9$	$21.9 \pm 4.2 \pm 1.2$
Std. ZYA1	$4.5 \pm 2.3 \pm 1.7$	$5.5 \pm 2.3 \pm 0.3$	$5.6 \pm 2.3 \pm 0.9$	$15.7 \pm 1.6 \pm 1.2$	$5.5 \pm 2.3 \pm 1.7$	$6.5 \pm 2.3 \pm 0.3$	$6.5 \pm 2.3 \pm 0.9$	$18.7 \pm 1.6 \pm 1.2$
RPF ($\lvert\Delta\phi\rvert < \pi/2$)	5.5 ± 0.4	5.7 ± 0.3	5.9 ± 0.3	17.0 ± 0.7	6.6 ± 0.4	6.8 ± 0.3	6.8 ± 0.3	20.1 ± 0.7
RPF ($\lvert\Delta\phi\rvert < 1$)	5.7 ± 0.4	5.8 ± 0.4	5.9 ± 0.3	17.4 ± 0.7	6.8 ± 0.4	6.8 ± 0.4	6.8 ± 0.3	20.4 ± 0.7

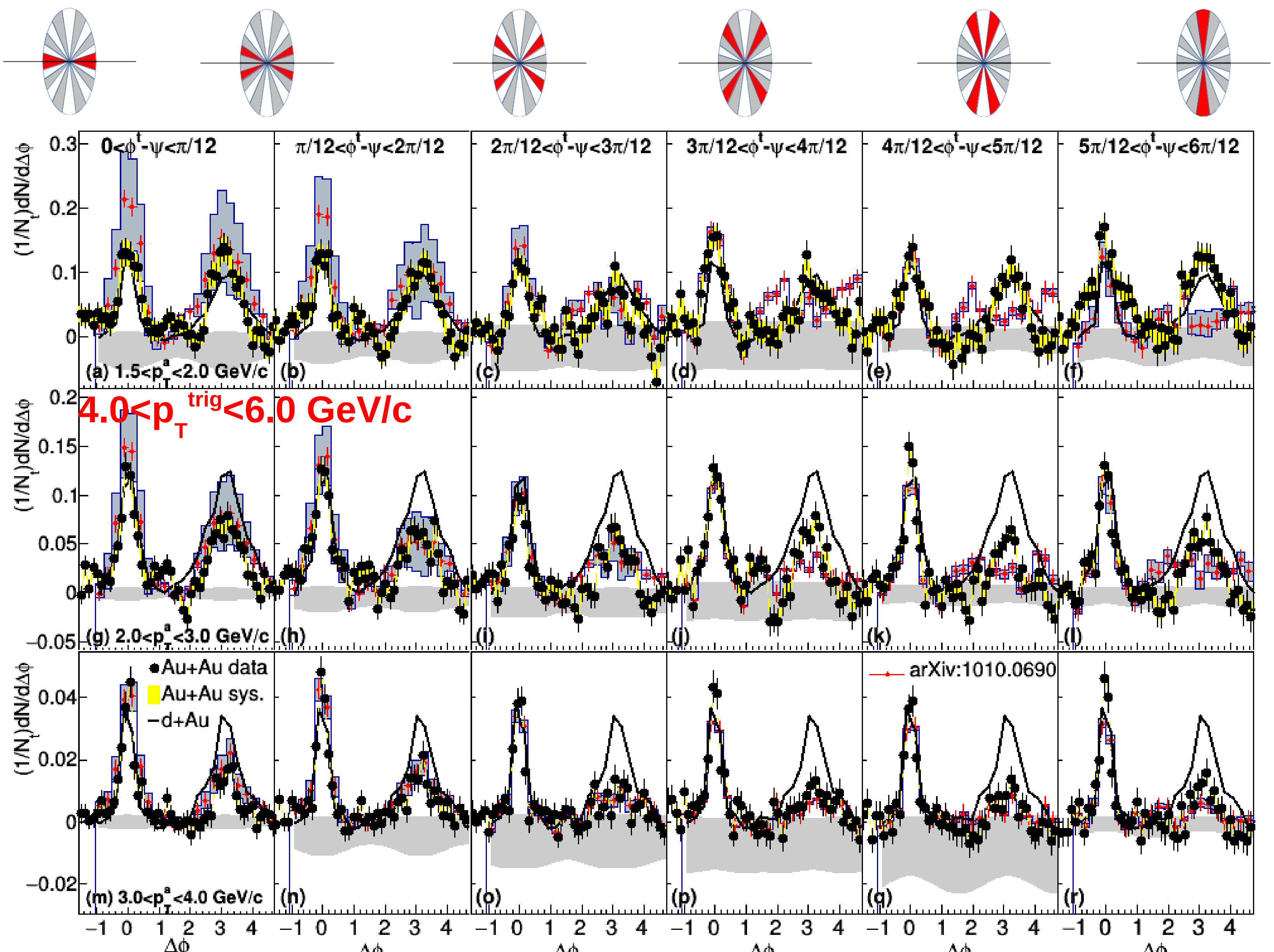
Applying the method to data

Dihadron correlations



Nattrass, Sharma, Mazer, Stuart, Bejnood Phys. Rev. C 94, 011901(R) 2016

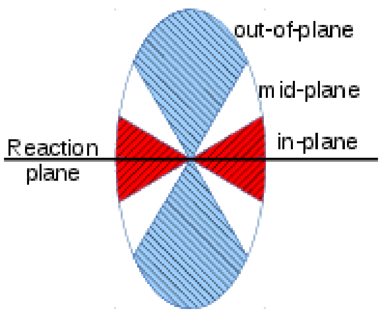
Dihadron correlations

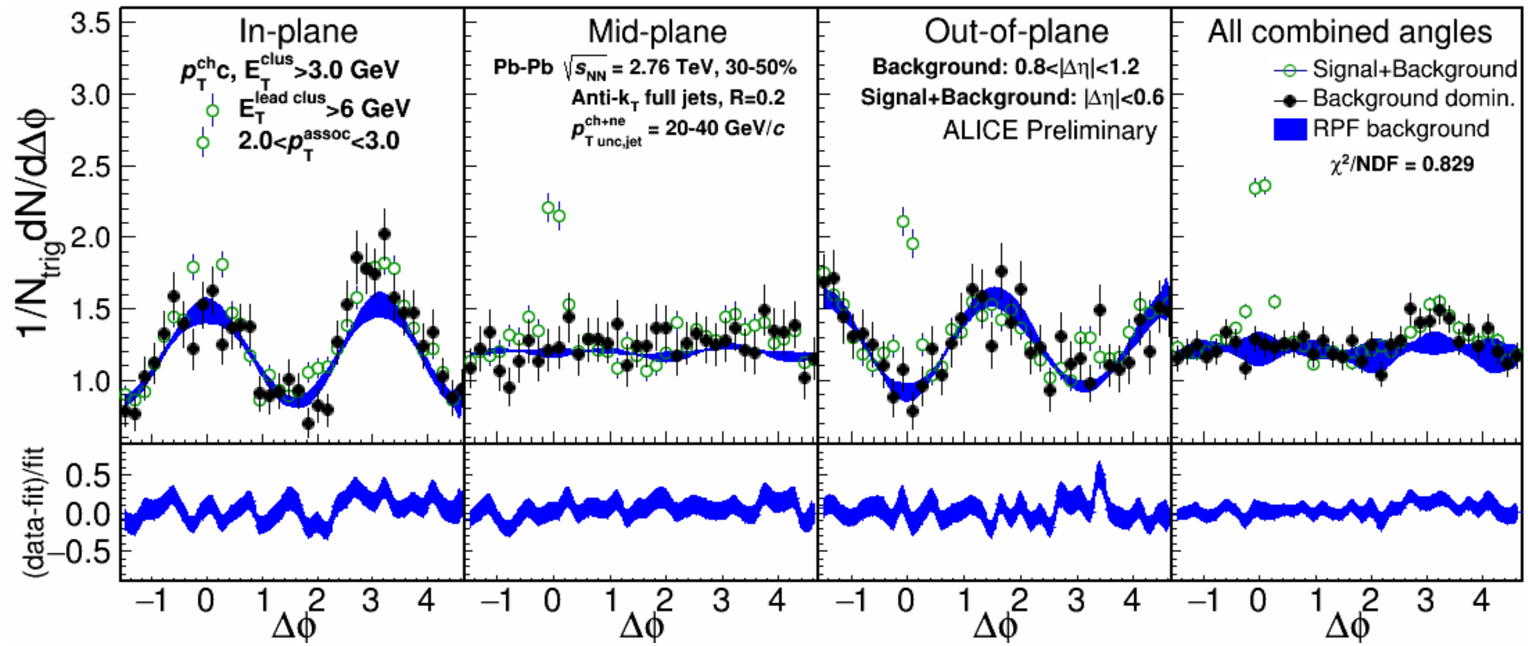


Nattrass, Sharma, Mazer, Stuart, Bejnood Phys. Rev. C 94, 011901(R) 2016

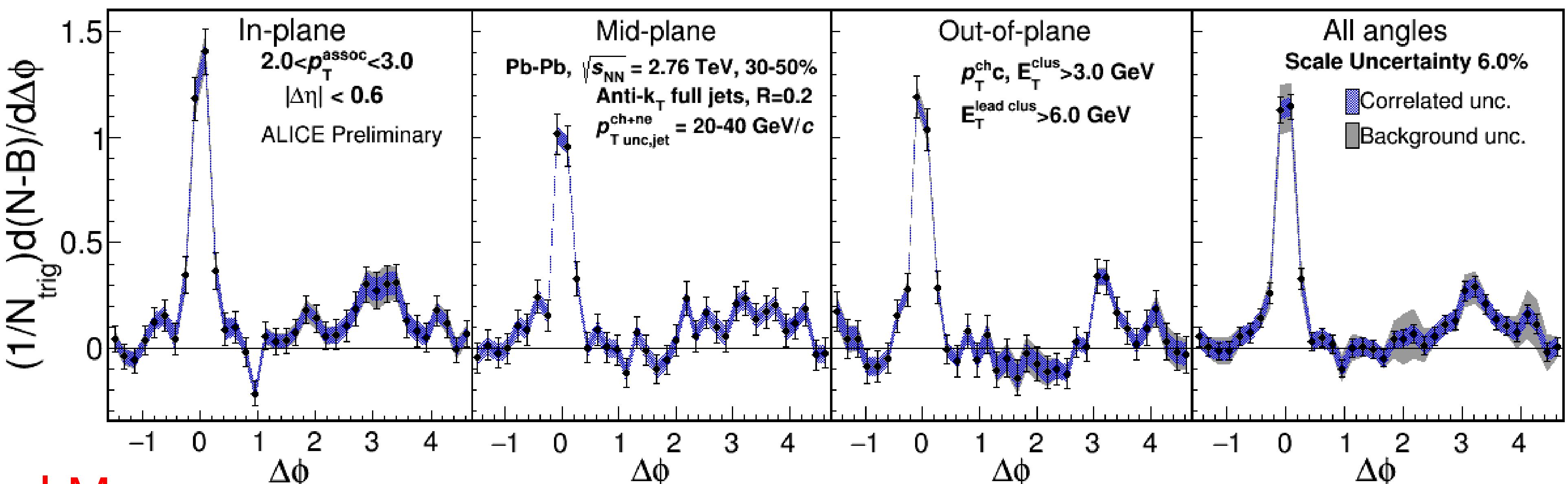
2.0-3.0 GeV/c p_T^{assoc}

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





Correlation function



Joel Mazer
Quark Matter 2017

- Away side clearly there and suppressed

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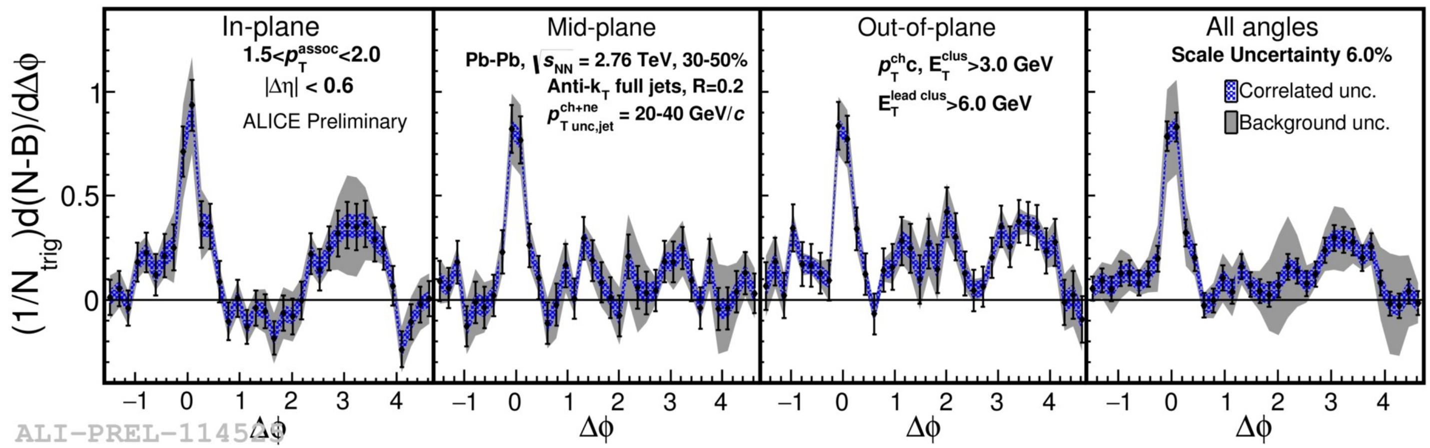
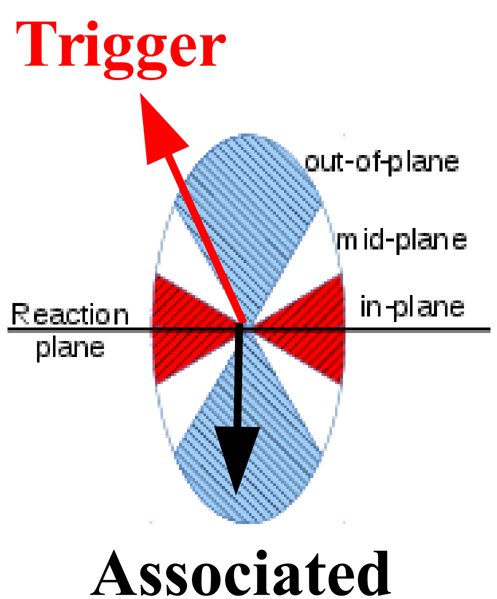
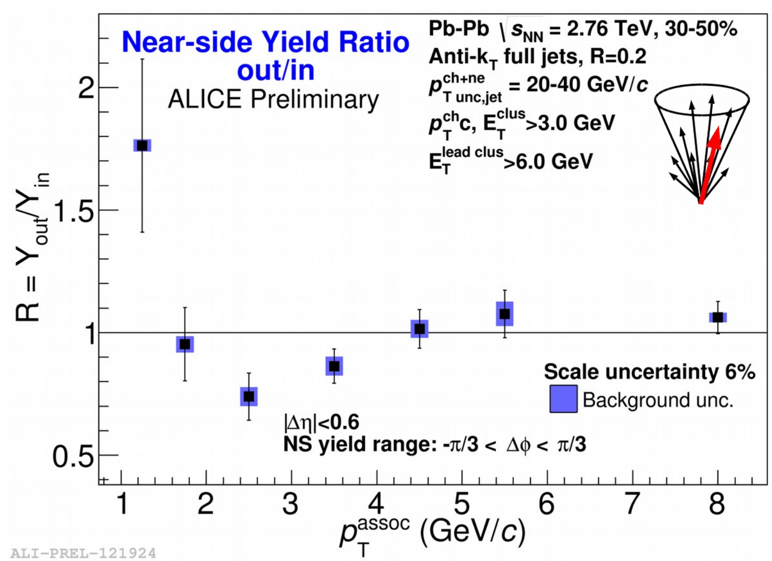
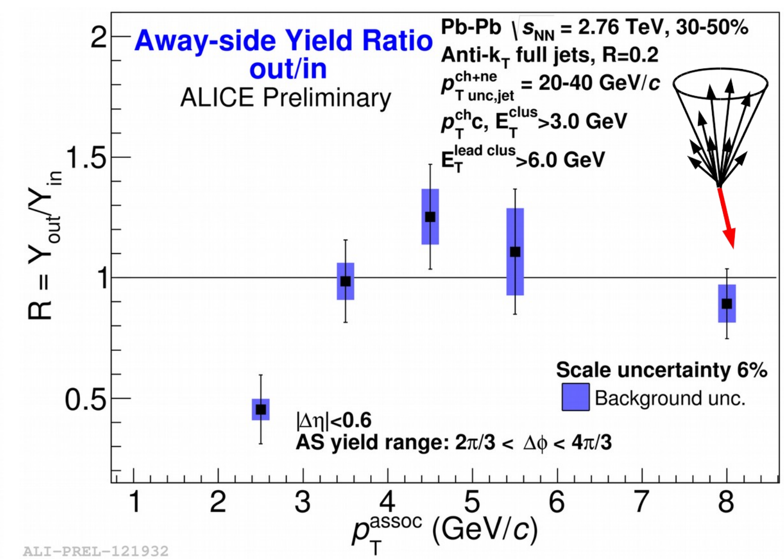
Jet-hadron correlations vs reaction plane

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









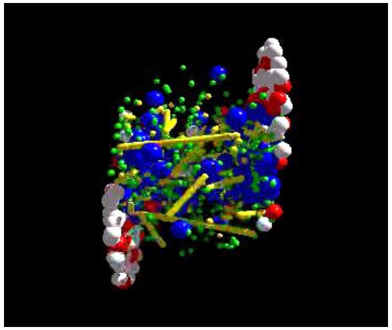
- No modification of constituents relative to reaction plane

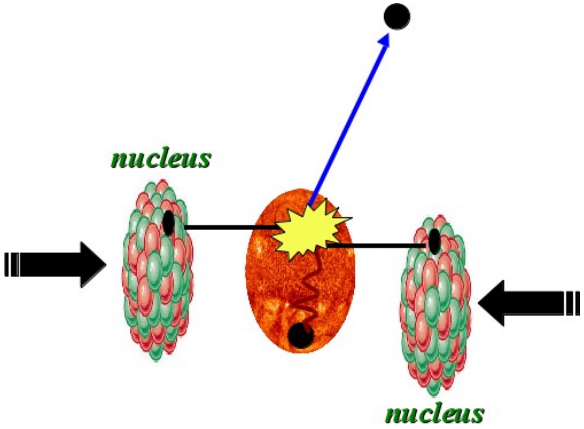
→ Jet-by-jet fluctuations more important than path length [PLB 735 157(2014)]

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

Conclusions

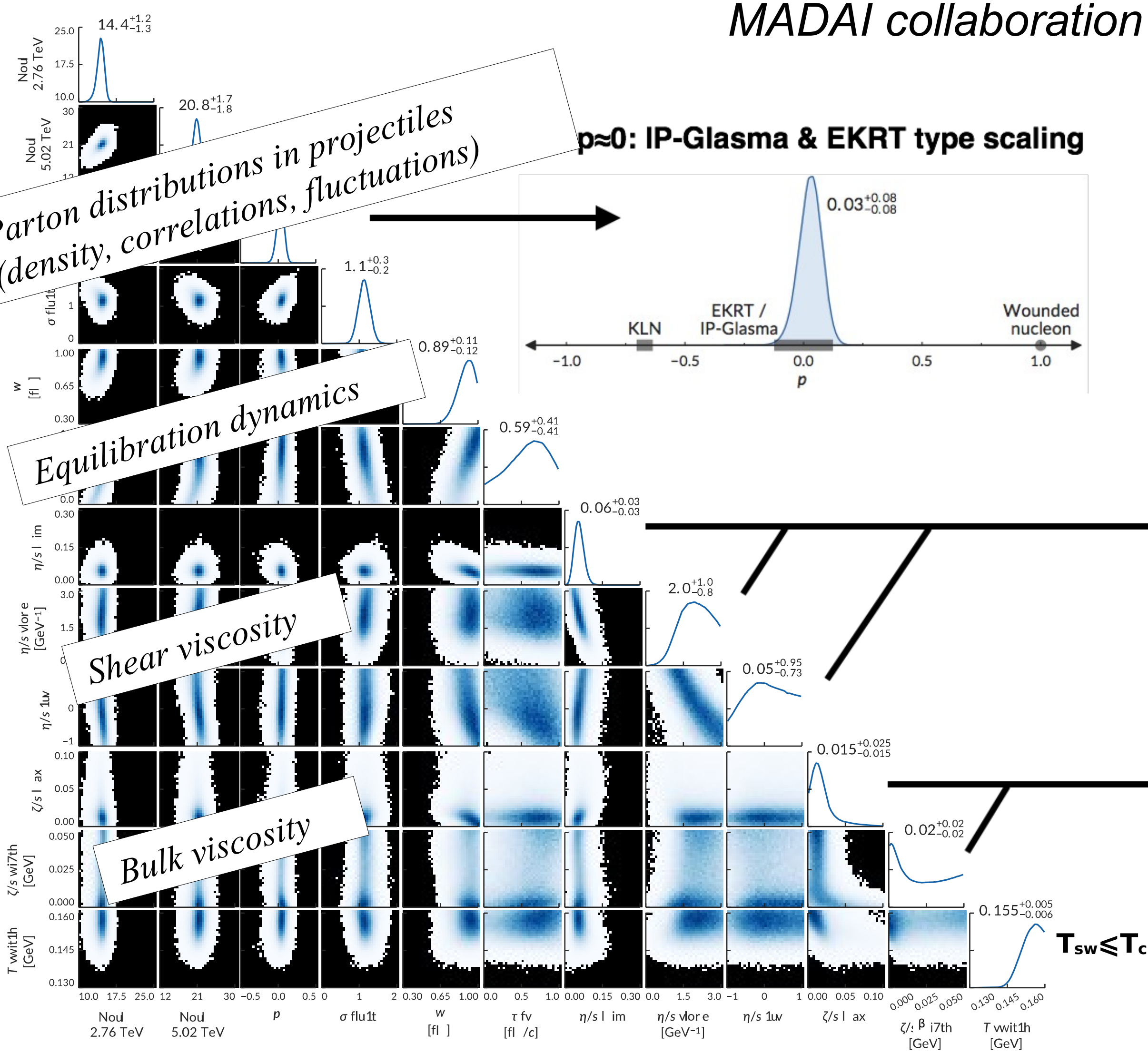
- If we get nuclear matter dense enough, we make a new phase of matter, which we produce in high energy heavy ion collisions.
- This medium is opaque to colored probes and translucent to electromagnetic probes.
- We see little path length dependence in the modifications to these probes.





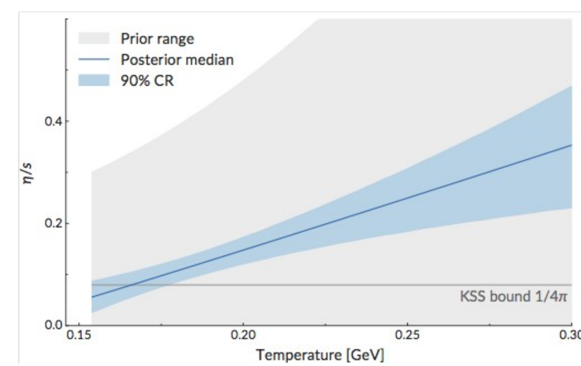
Next step: global fits of models to wide array of heavy ion collision data

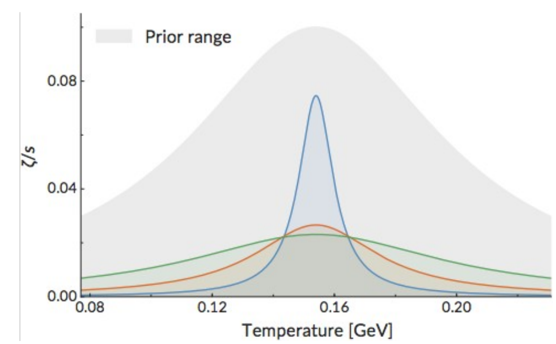
Global Bayesian Analysis; S. Bass, Quark Matter 2017
MADAI collaboration



- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

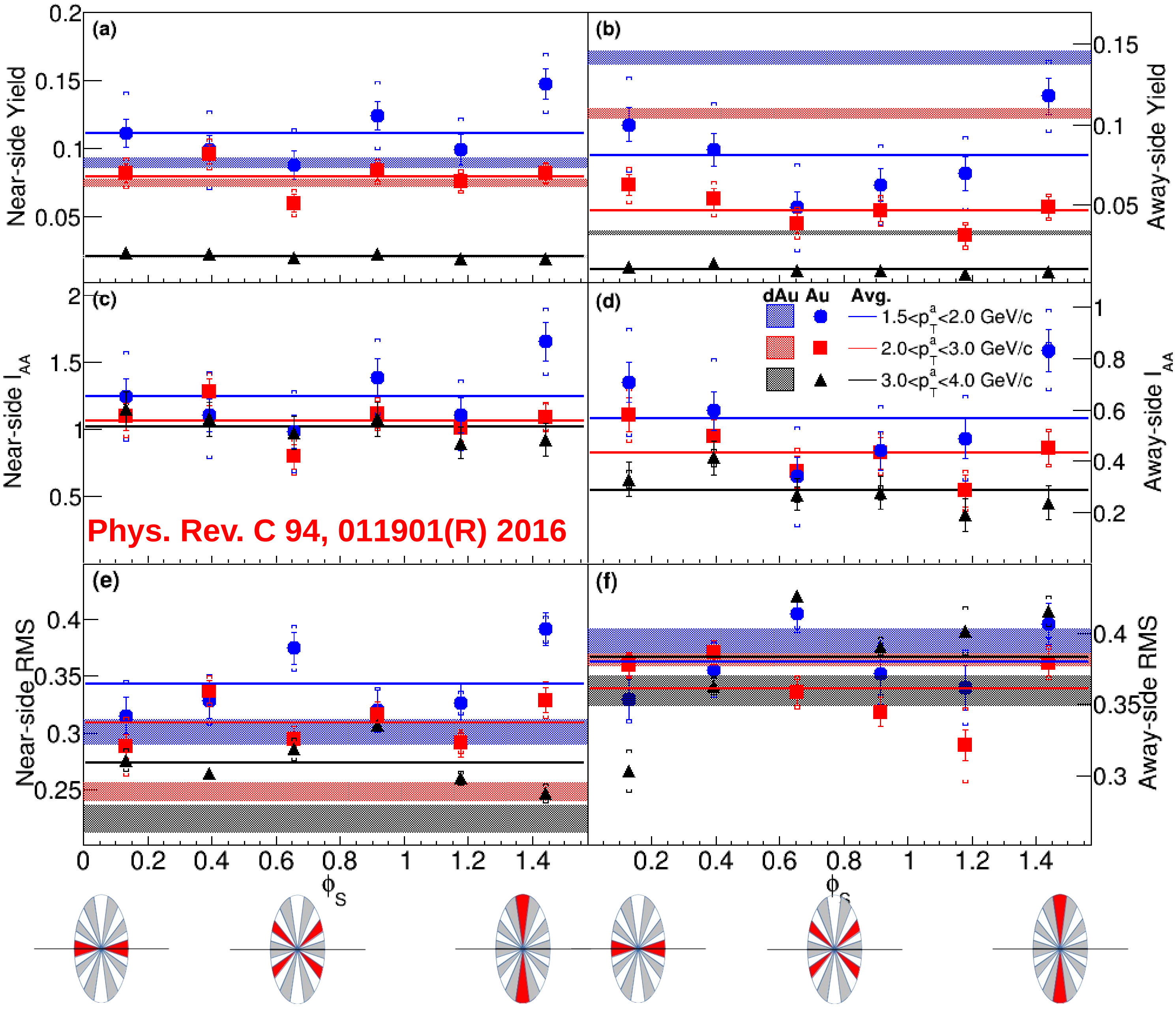
temperature-dependent viscosities:





arXiv:1706.03666, Phys. Rev. C 94, 024907 (2016)

Dihadron correlations



Comparison of colliders

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

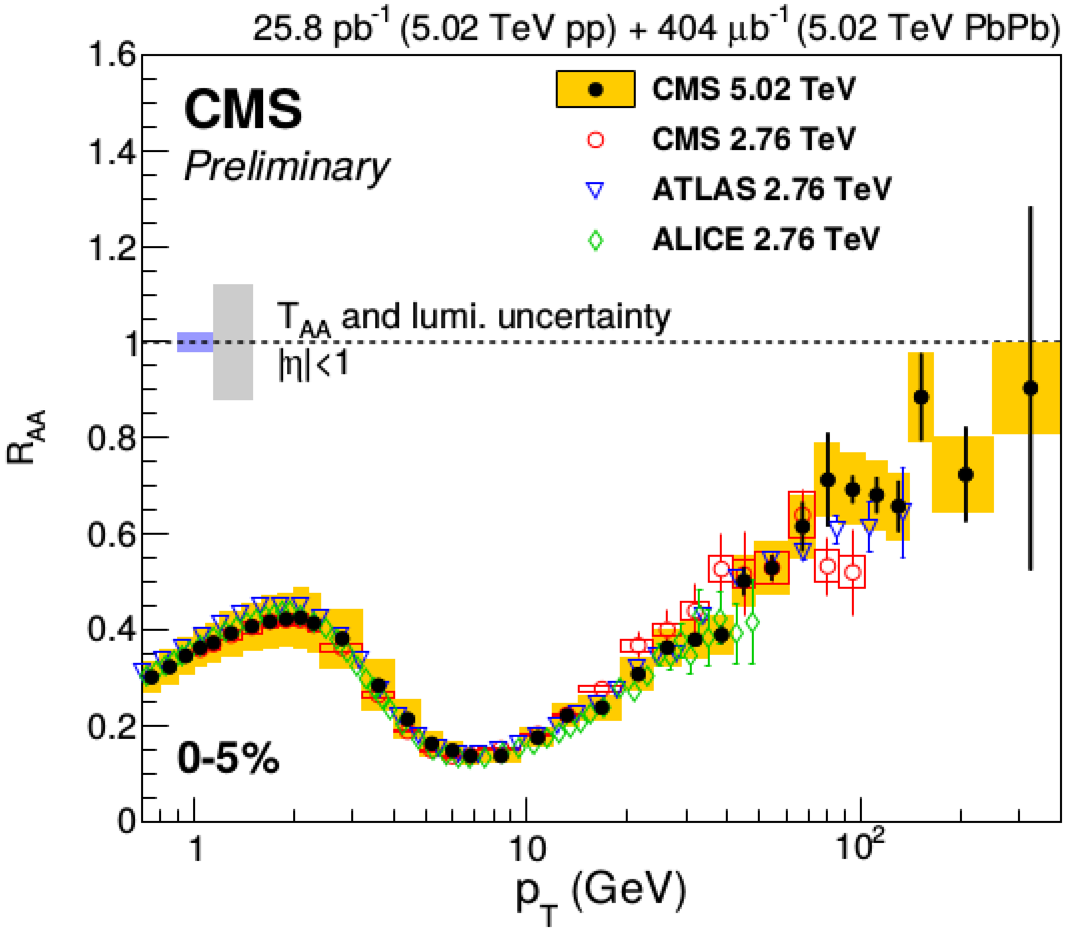
RHIC and LHC:

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

To discover the properties of hot nuclear matter at T ~ 150 –600 MeV

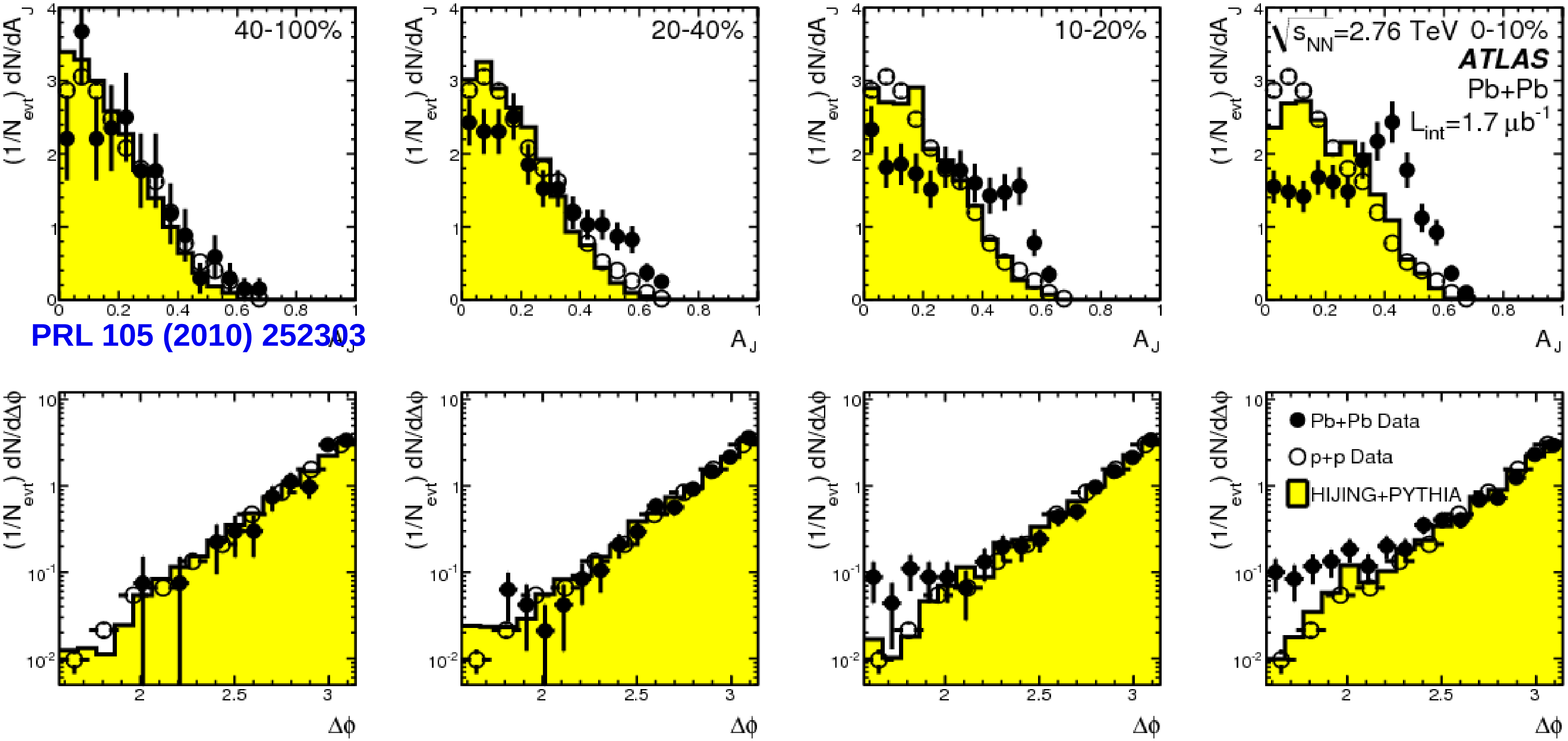
Nuclear modification factor R_{AA}

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



PRL 105 (2010) 252303

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

Jets in principle

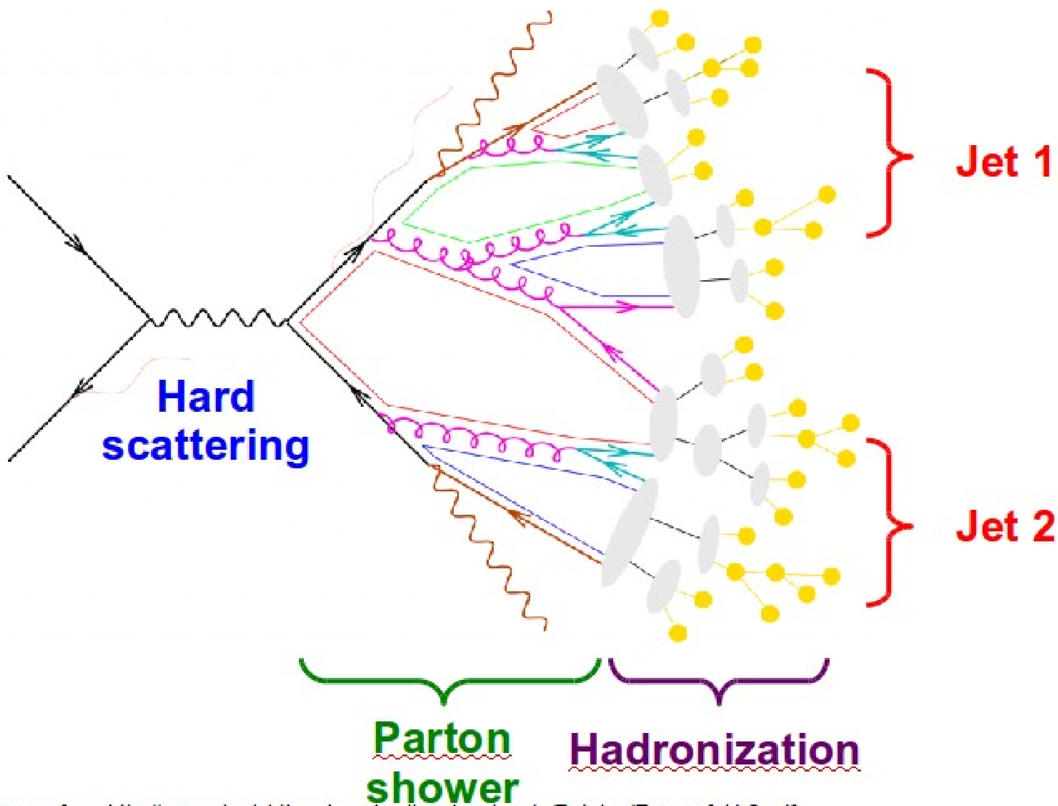
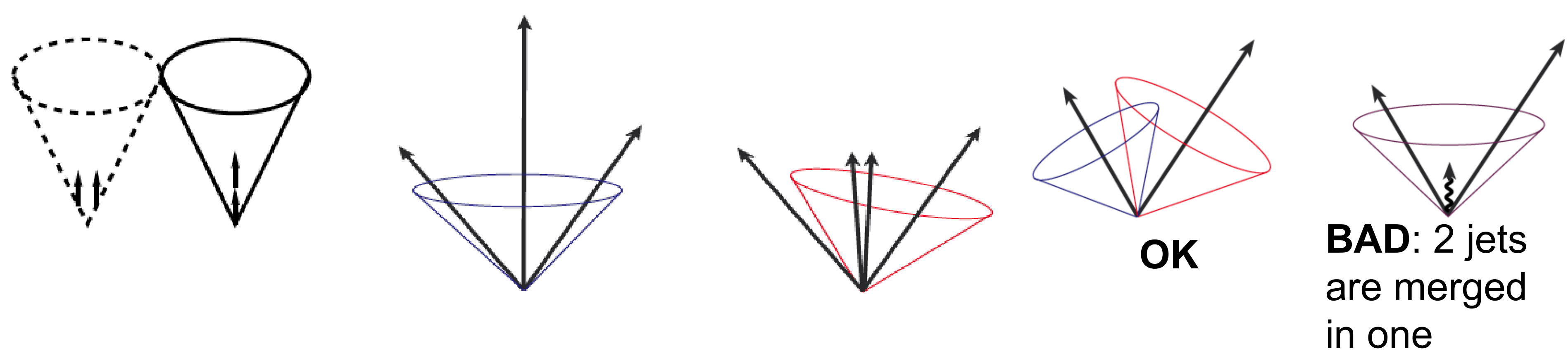


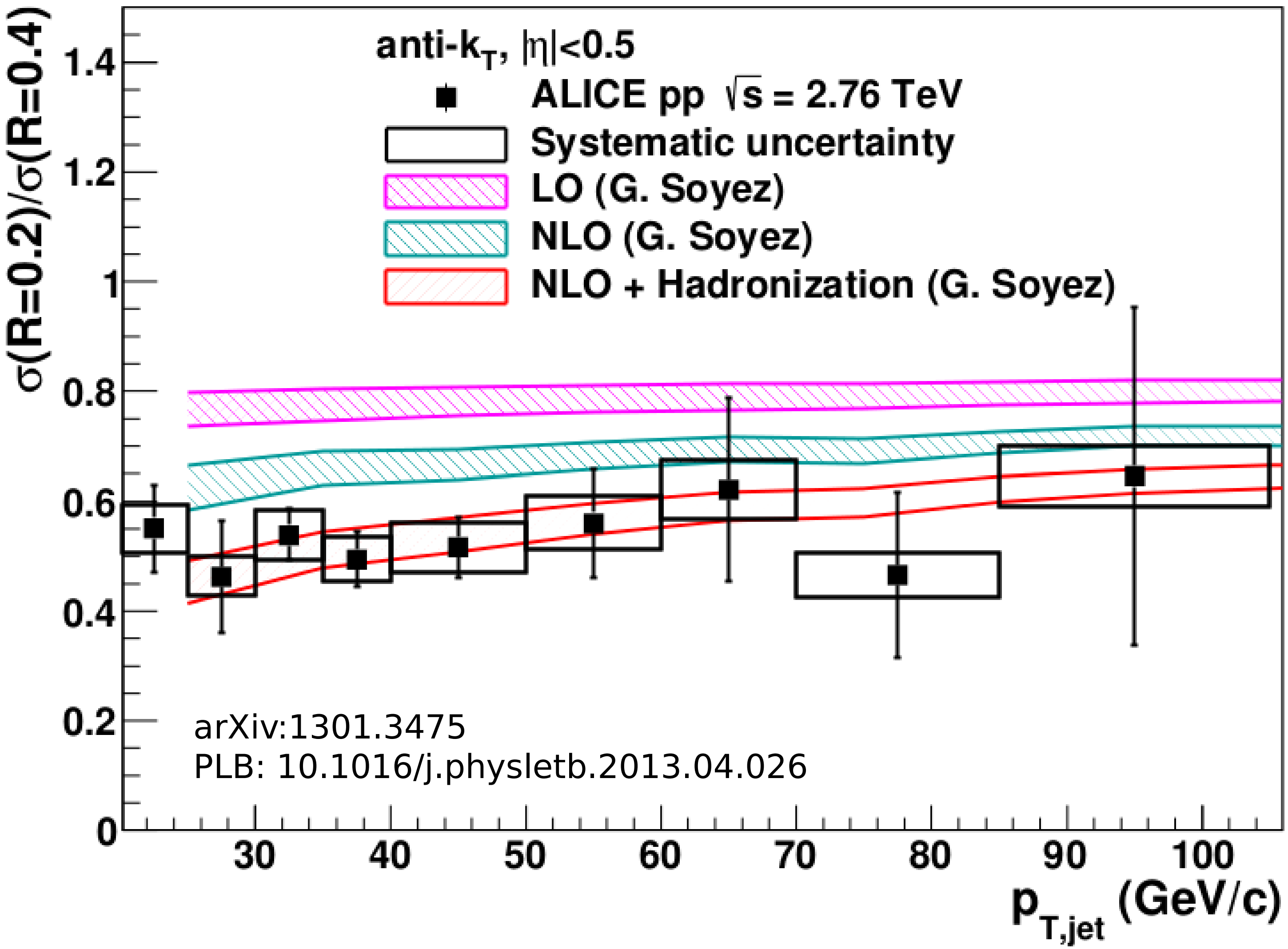
Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

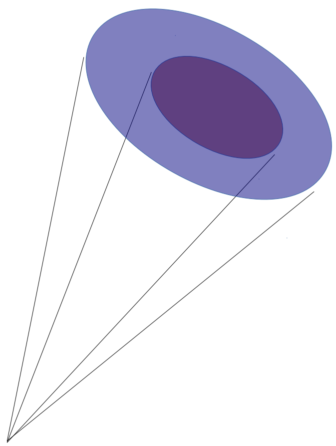
- Jet measures **partons**
- Hadronic degrees of freedom are integrated out
- Algorithms are infrared and colinear safe



Full jet ratios in pp

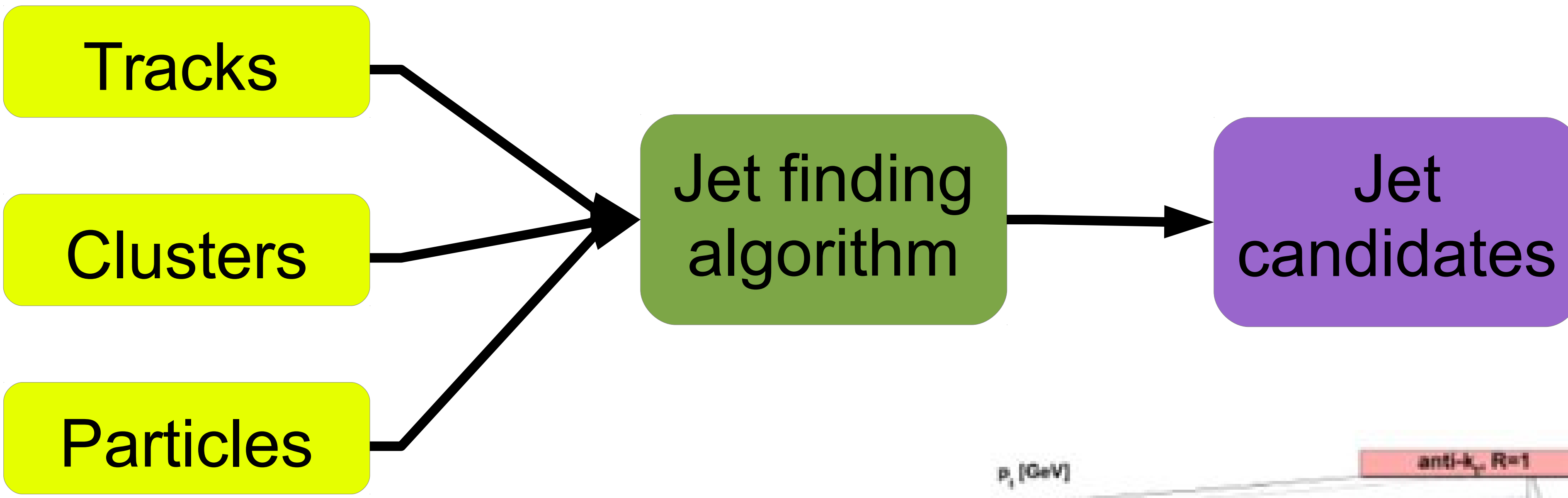
$\sqrt{s}$ = 2.76 TeV, R = 0.2, 0.4 Inclusive



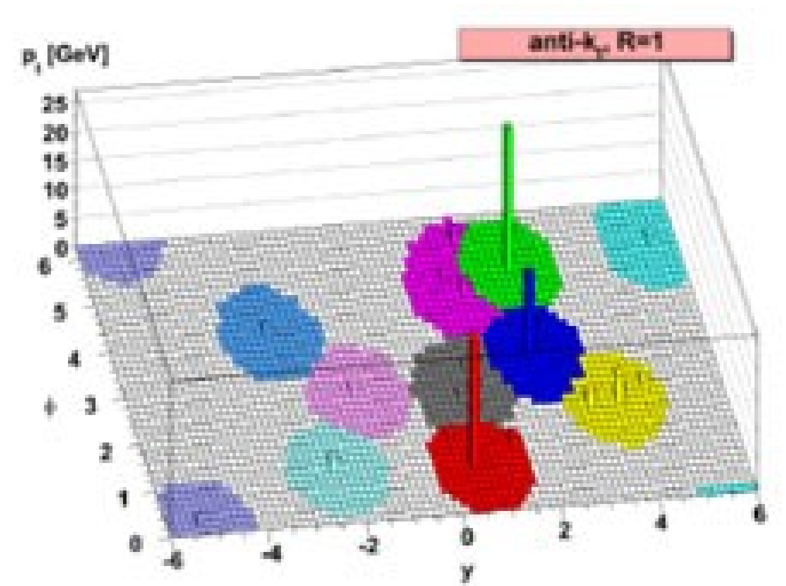


Hadronization is important even in pp collisions!

Jet finding algorithms



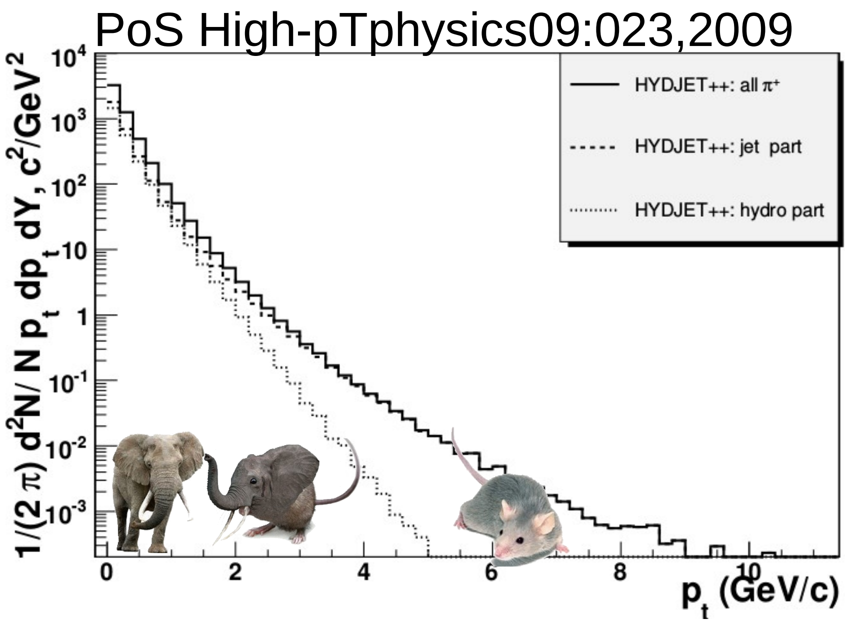
- Any list of objects works as input
- Use the same algorithm on theory & experiment
- Output only as good as input



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

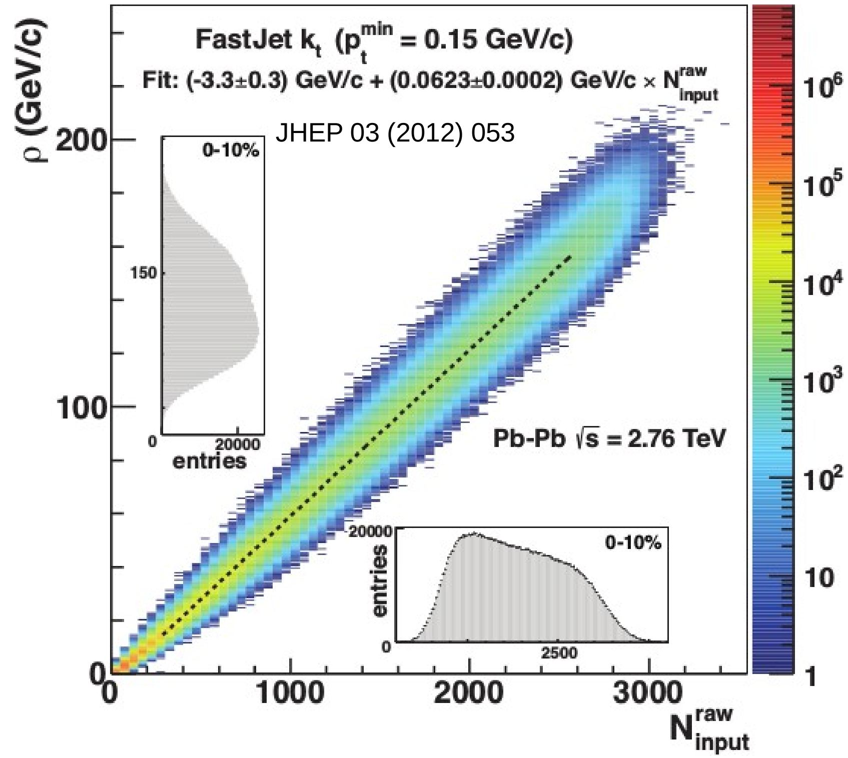
Focus on high p_T

- 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

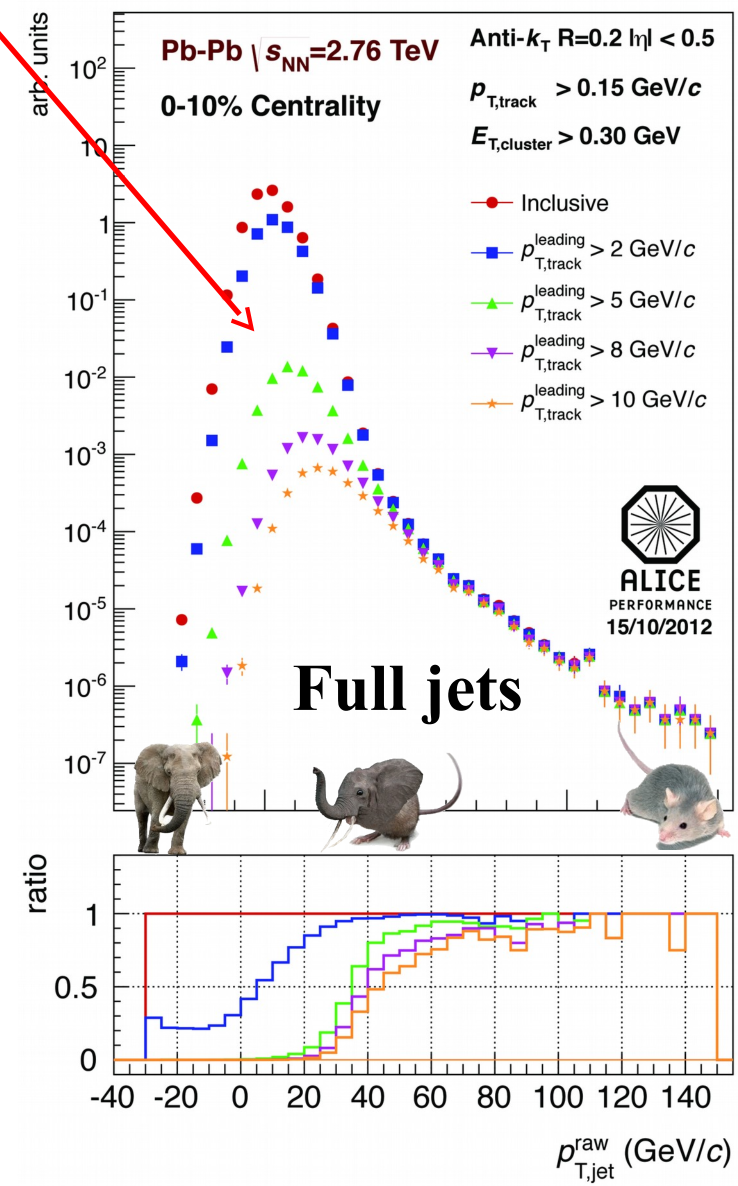
Combinatorial "jets"

- Estimate combinatorial jet contributions and its fluctuations from data
- Require leading track p_T > 5 GeV/c
  - Suppresses combinatorial "jets"
  - Biases fragmentation
- No threshold on constituents
- Limited to small R

Measured spectra:

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

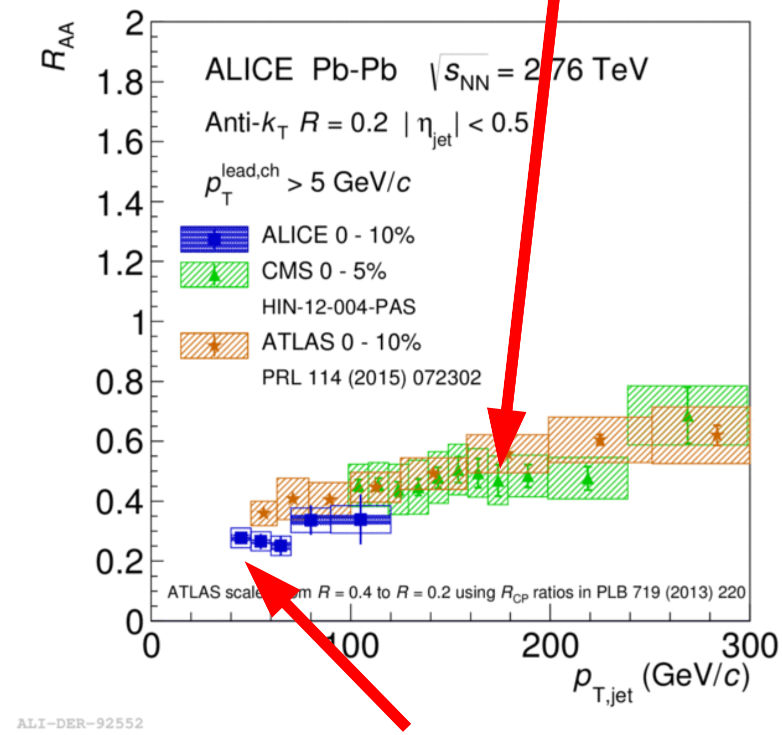
Where $p_{\mathrm{T,jet}}^{rec}, A$ comes from FastJet anti-k_T algorithm



ATLAS

- Iterative procedure
  - **Calorimeter jets:** Reconstruct jets with R=0.2. v_2 modulated <Bkgd> estimated by energy in calorimeters excluding jets with at least one tower with $E_{tower} > \langle E_{tower} \rangle$
    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_{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

Phys. Lett. B 719 (2013) 220-241

http://www.boredpanda.com/animal-camouflage/

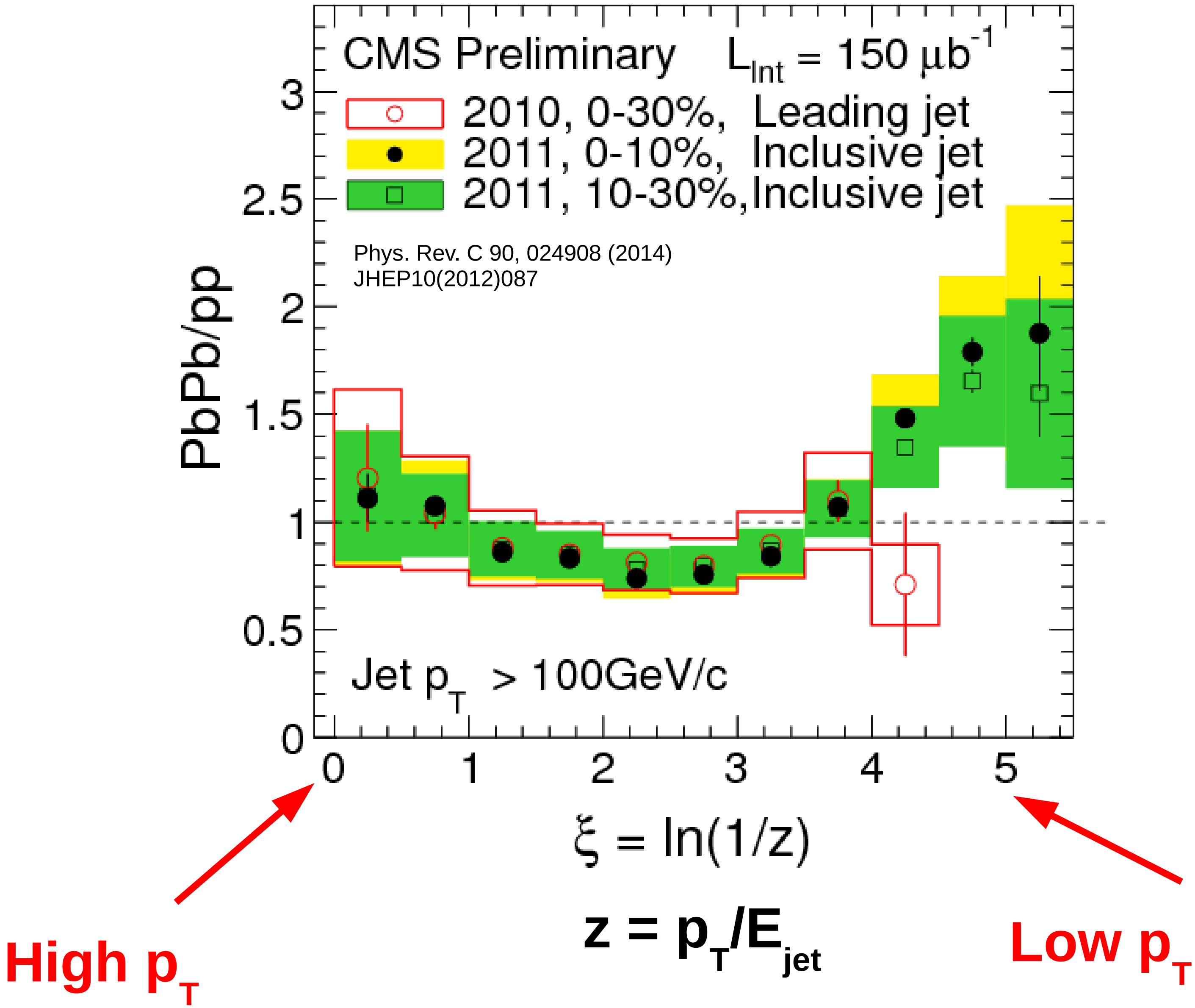
Bias

- **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]**

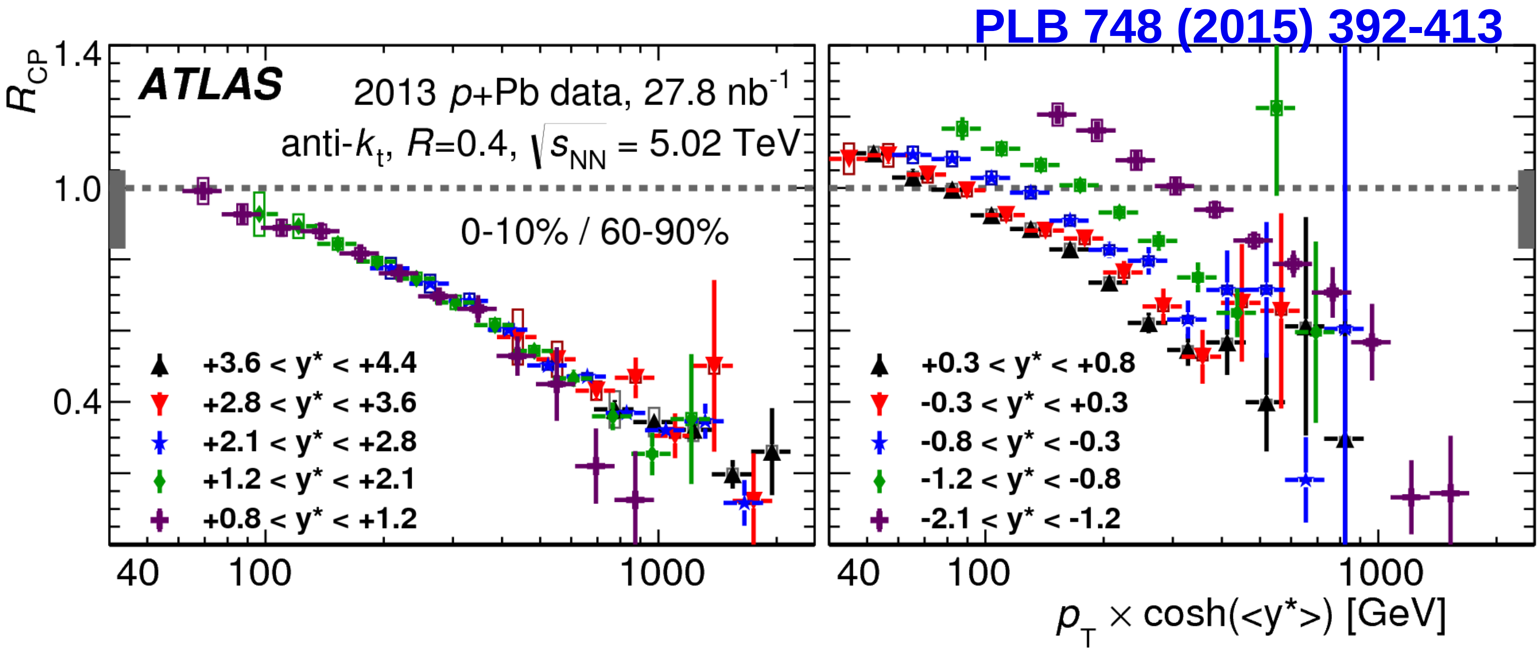
Piet Grobler 2009

http://www.boredpanda.com/animal-camouflage/

What you see depends on where you look



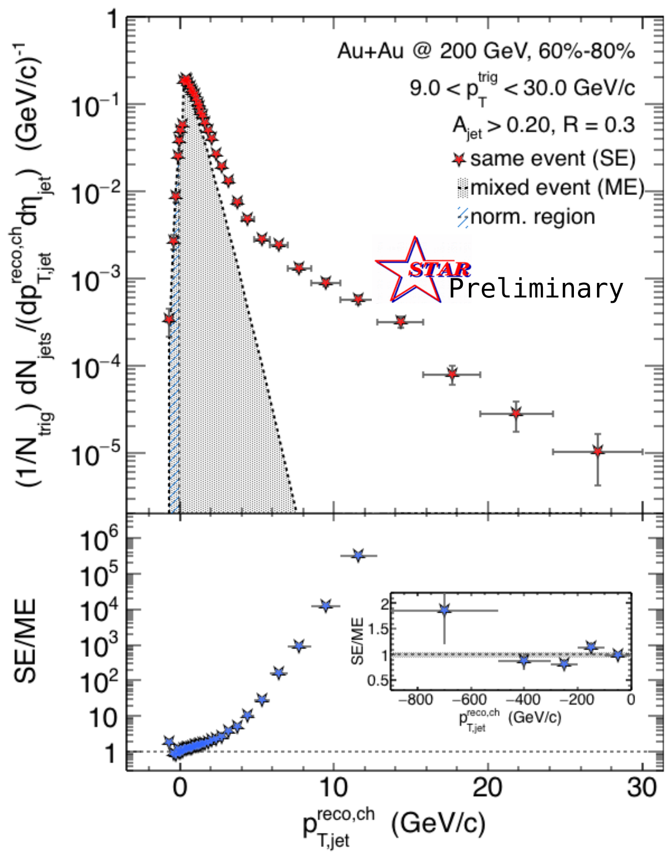
Cold Nuclear Matter effects



- 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

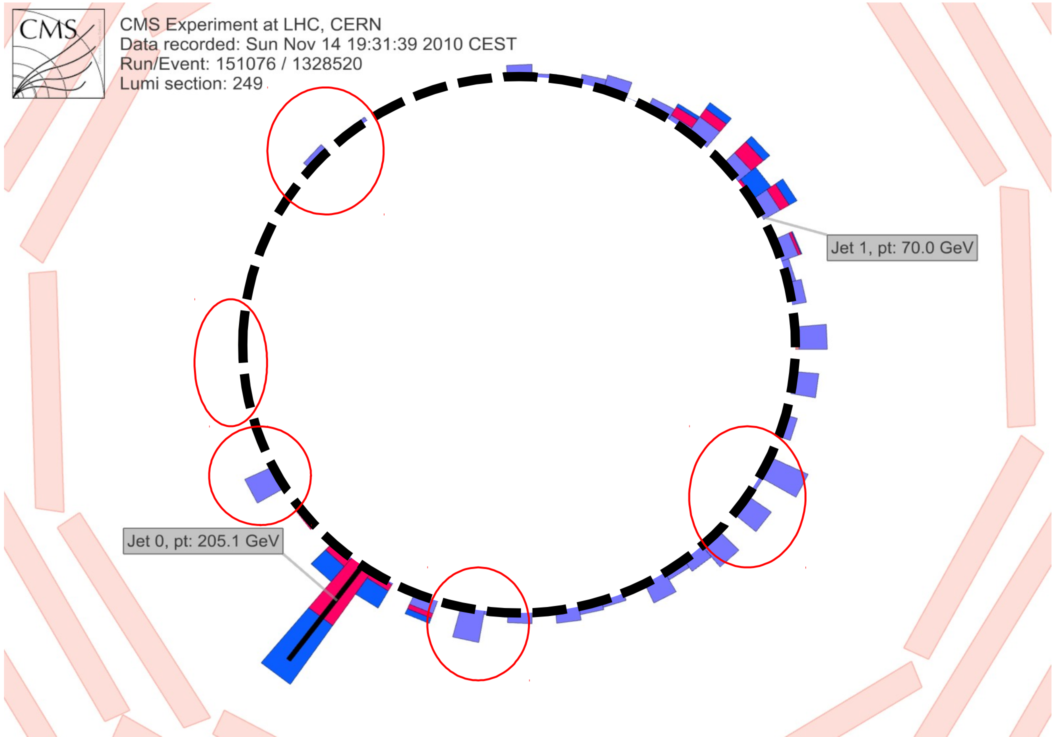


- Reference spectrum: peripheral collisions
- Much less combinatorial background compared to most central data
- Excellent signal/background ratio down to 3 GeV/c
- Requires normalization at low p_T
- *All physical correlations treated like jets*

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

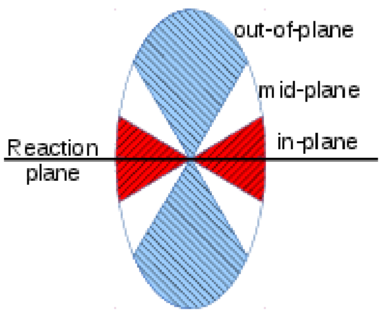


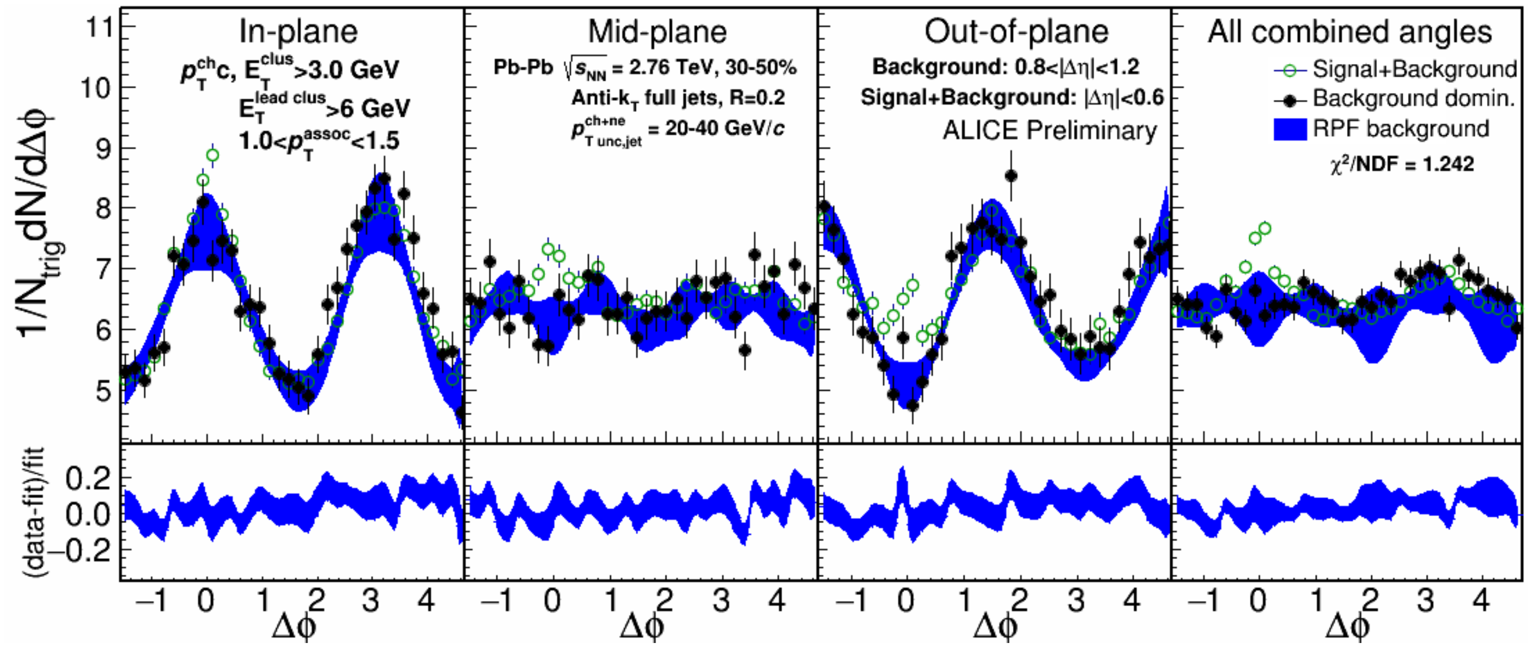
Fake Jets: After the background subtraction, some local fluctuations remain!
Fluctuations will deteriorate the jet resolution in central events.

Sevil Salur 56

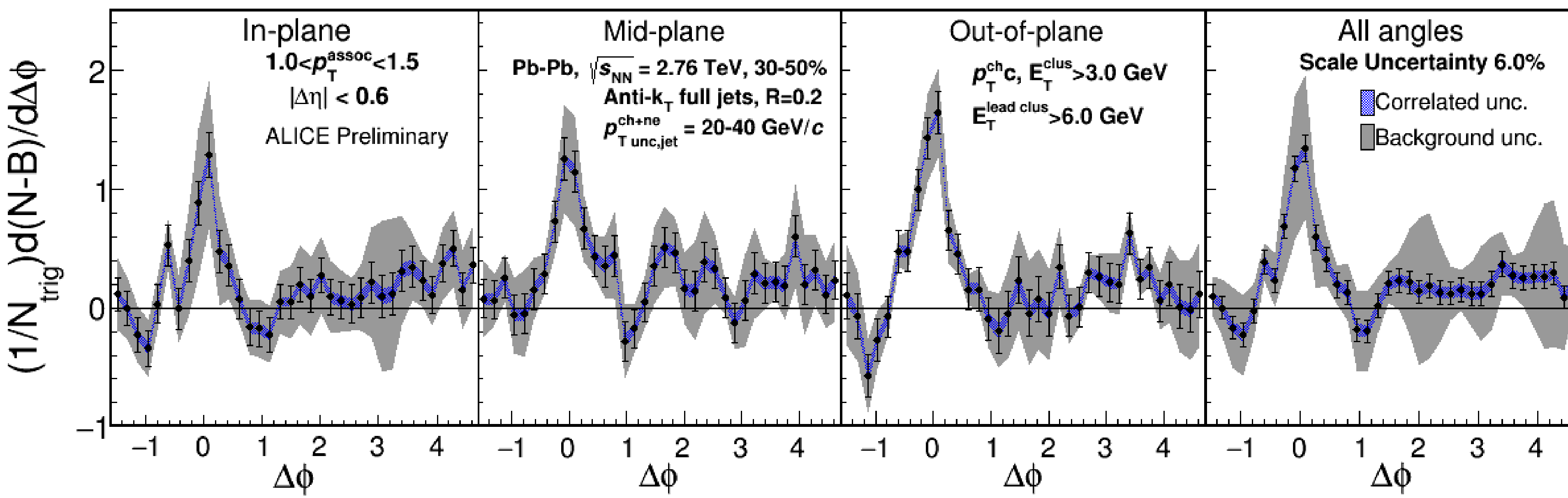
1.0-1.5 GeV/c p_T^{assoc}

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





Correlation function

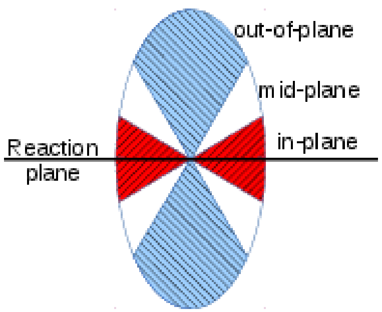


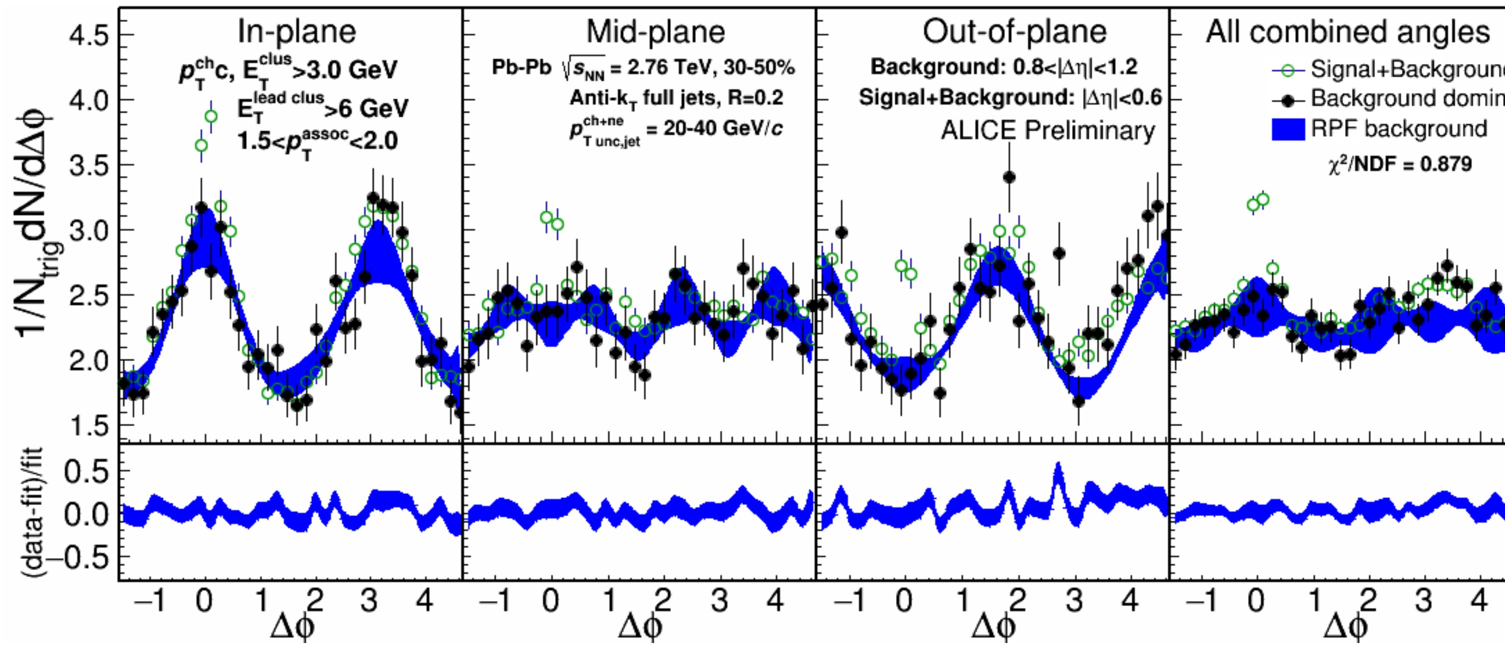
- Uncertainties dominated by statistics
- Background uncertainty is non-trivially correlated point-to-point

57

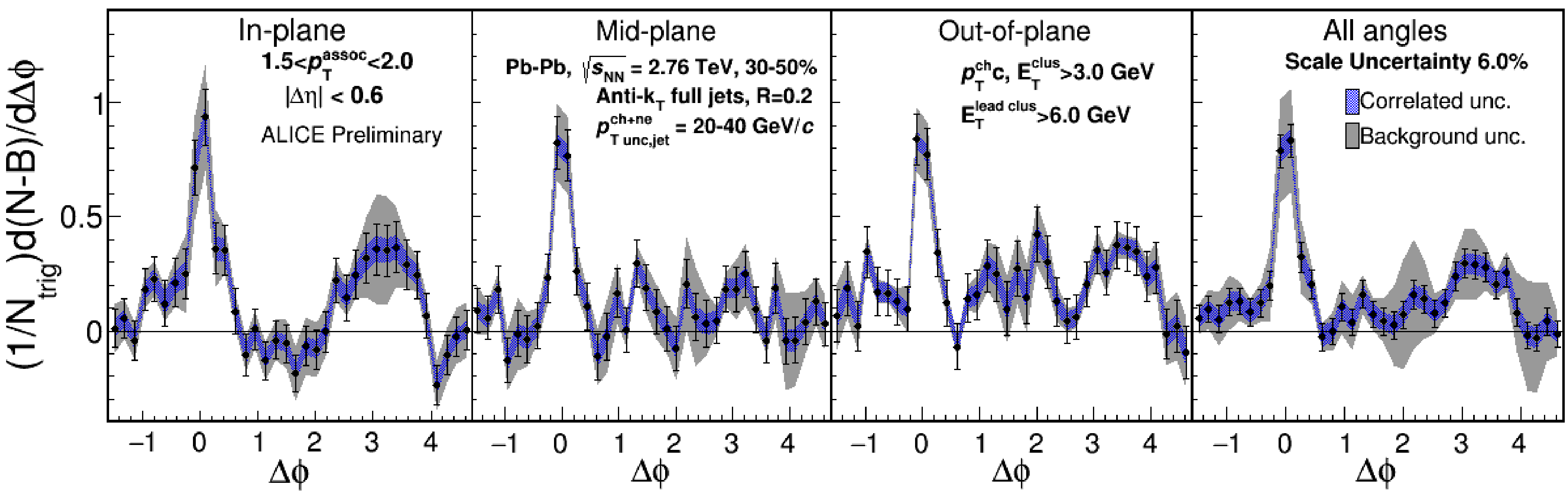
1.5-2.0 GeV/c p_T^{assoc}

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





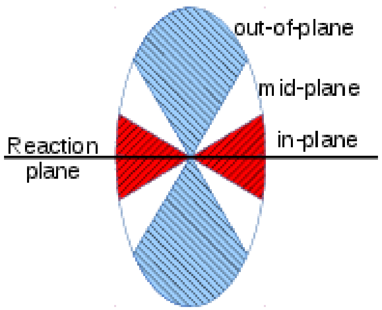
Correlation function

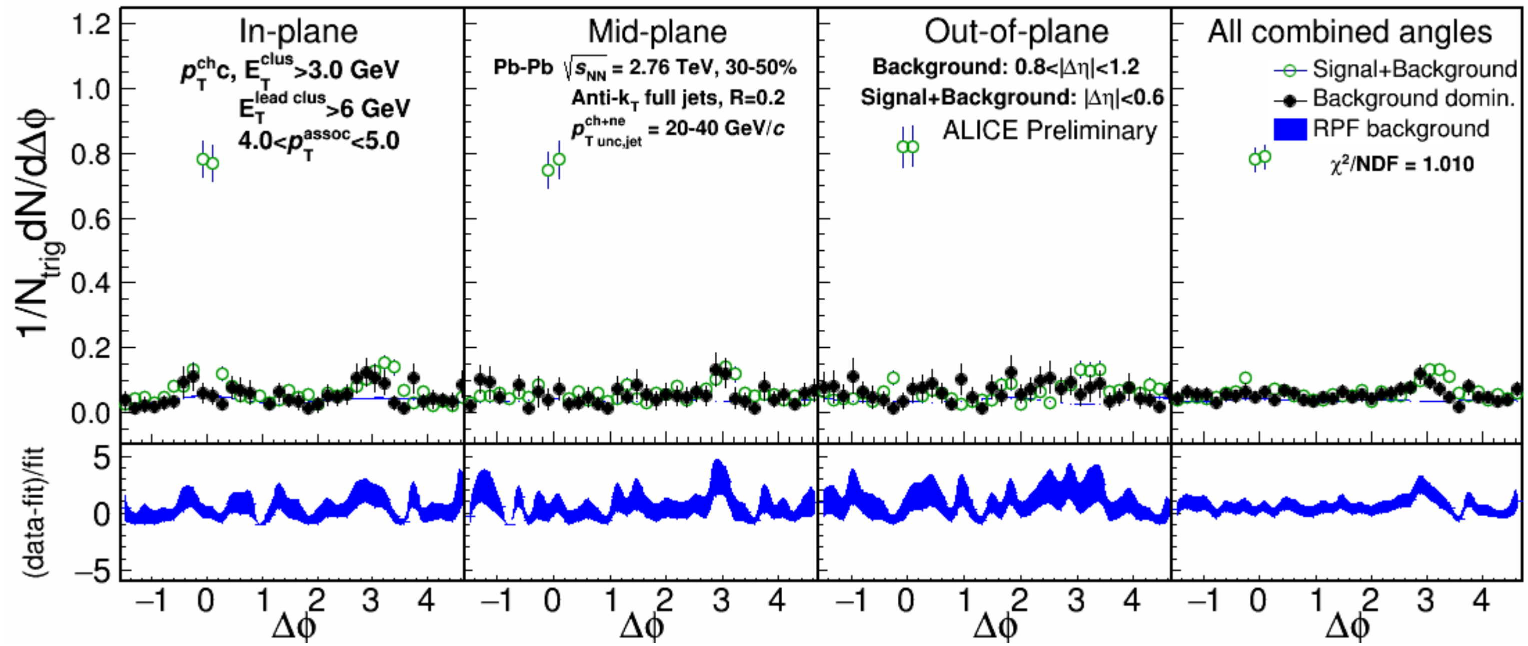


- v_3 and v_4 components important
- Background uncertainty is non-trivially correlated point-to-point

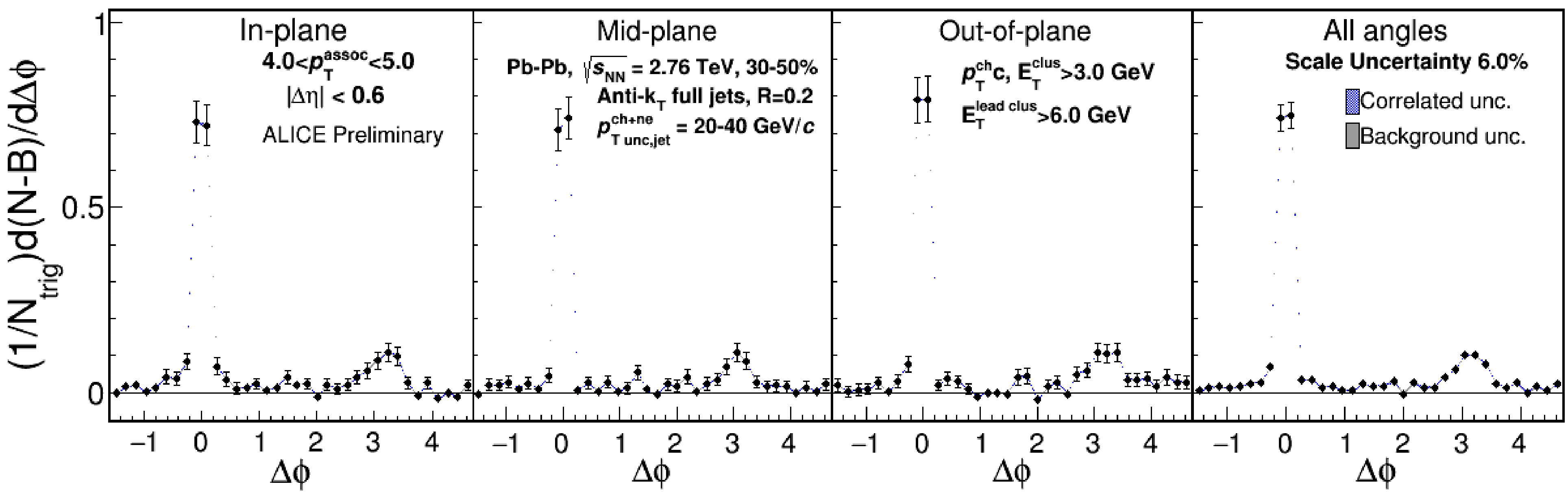
4.0-5.0 GeV/c p_T^{assoc}

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





[Correlation function](#)



- Background level negligible

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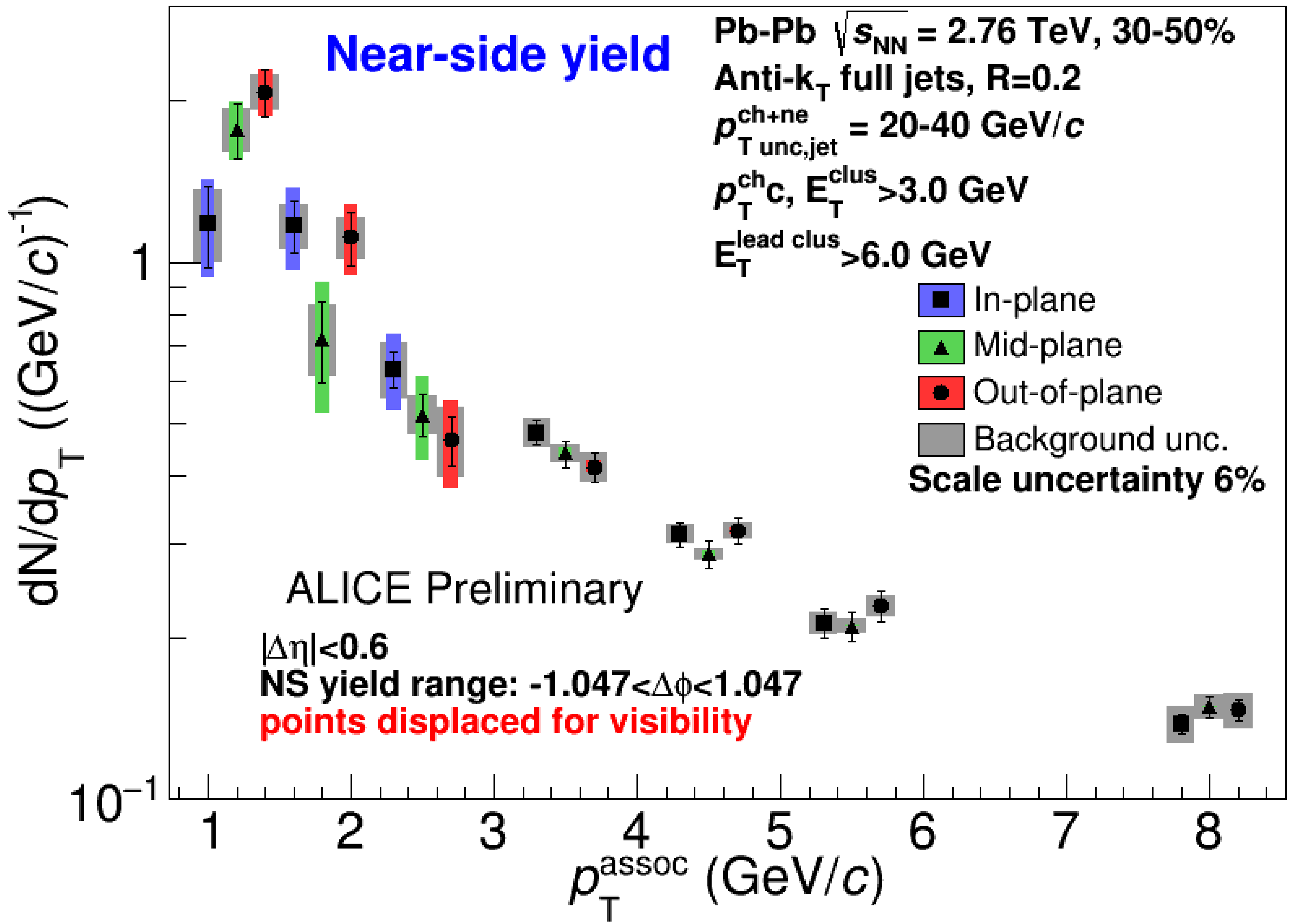
Near-side jet yields vs EP

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

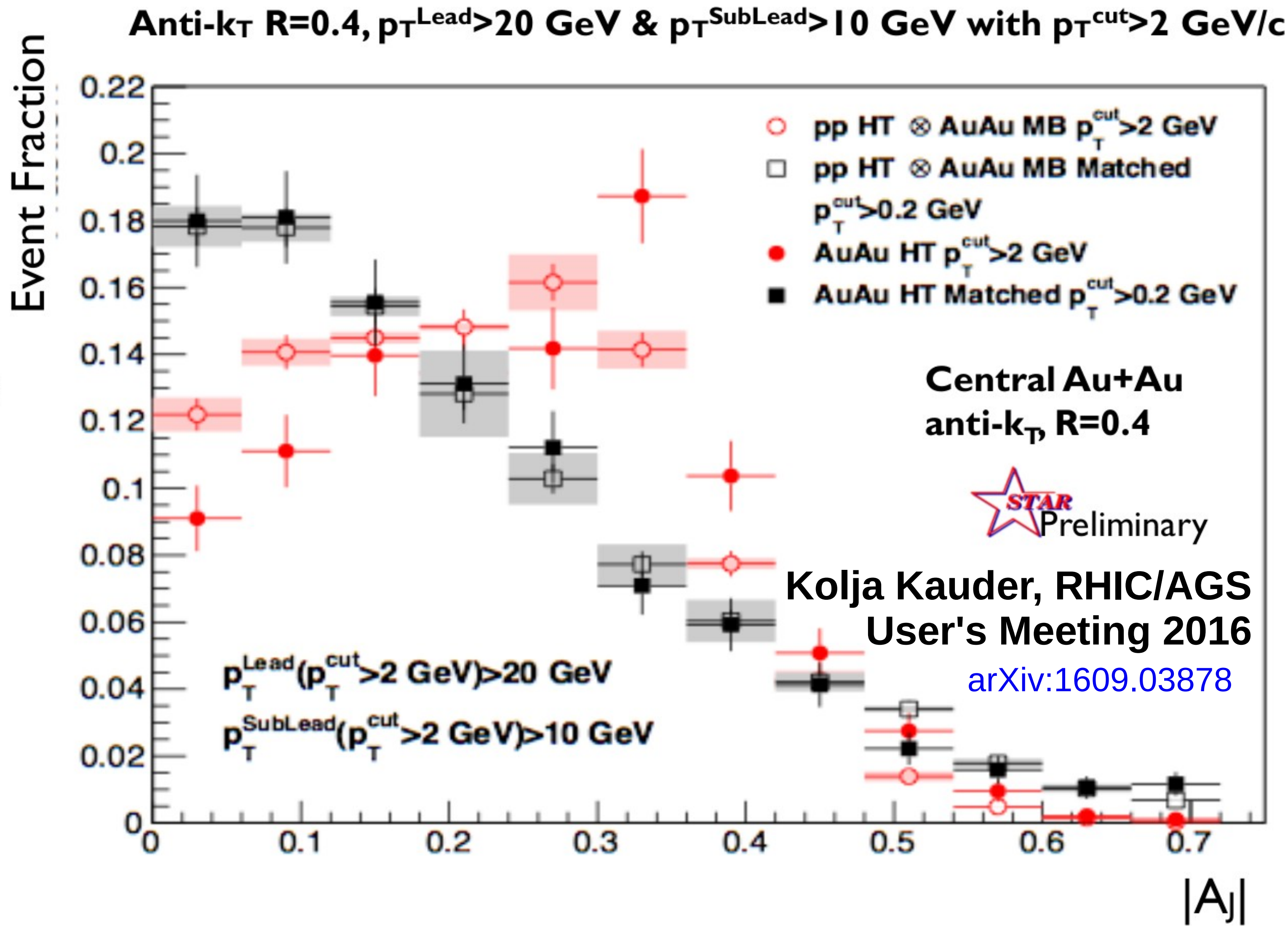


Within uncertainties of current statistics, no event plane ordering

- Different effects in different p_T associated bins

Competing effects
1) Quenching
2) Bremsstrahlung
3) etc

Di-jet asymmetry

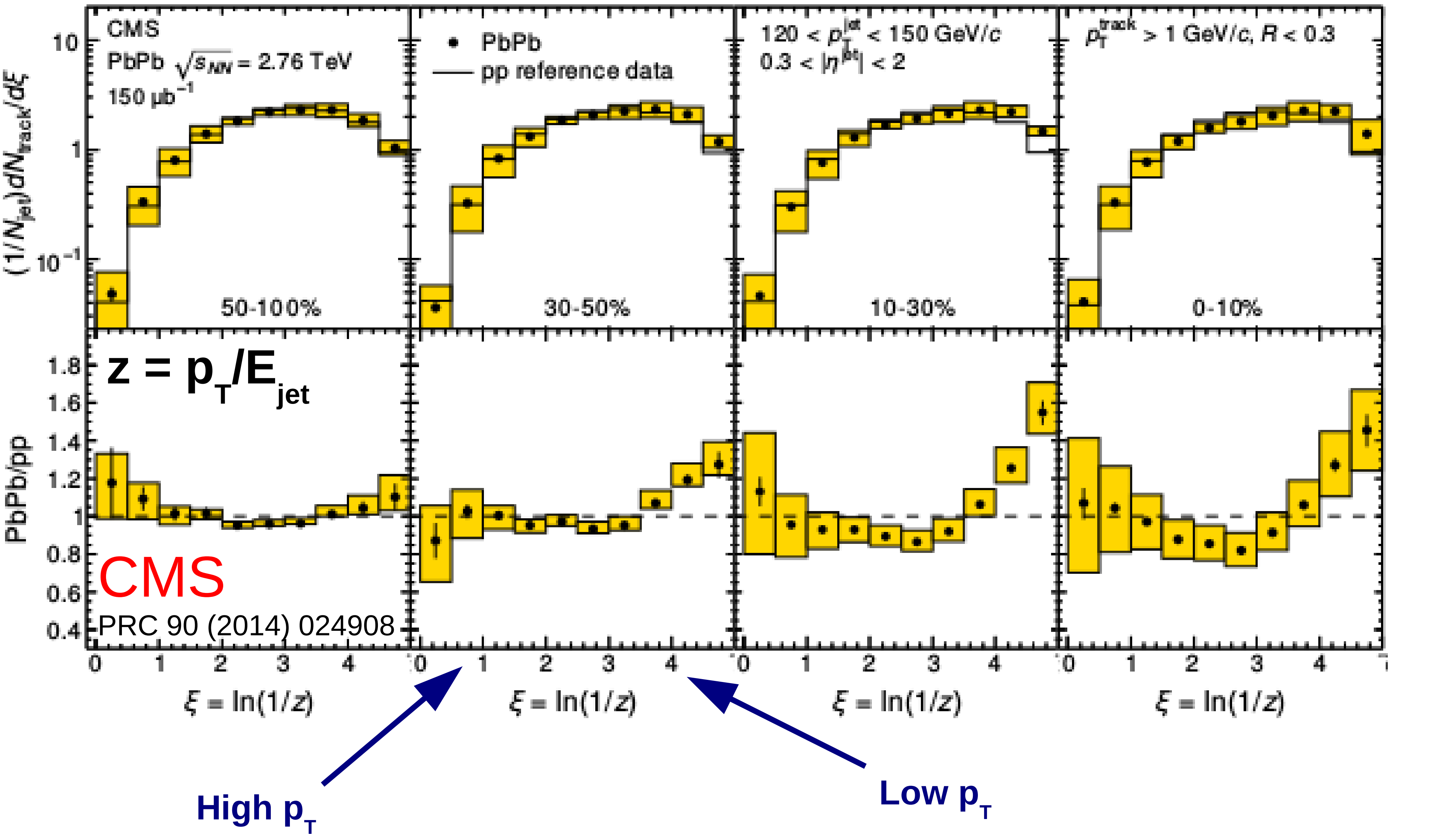


Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Au+Au di-jets more imbalanced than p+p for p_{Tcut}>2 GeV/c

Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

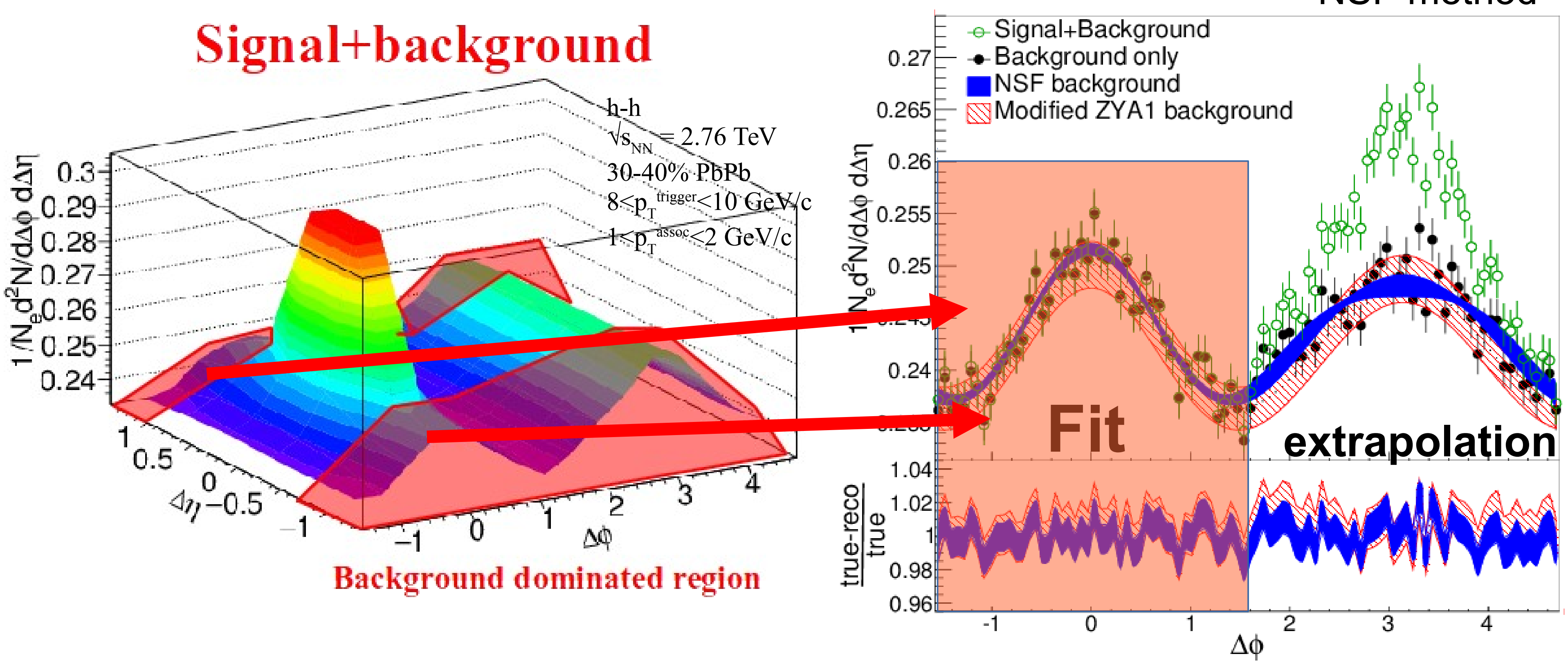
Fragmentation functions



Reaction plane fit (RPF) method

TOY MODEL

- Signal is negligible at large Δη and small ΔΦ region.



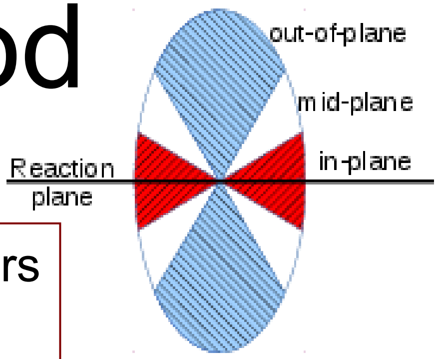
- Project signal+background over $0.8 < |\Delta\eta| < 1.2$
- Fit background in $|\Delta\varphi| < \pi/2$
- Fitting till 4th order v_n term, total 6 fit parameters: B, v_2^{assoc}, v_2^{trig}, $v_3^{assoc} \times v_3^{trig}$, v_4^{assoc}, and v_4^{trig}

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

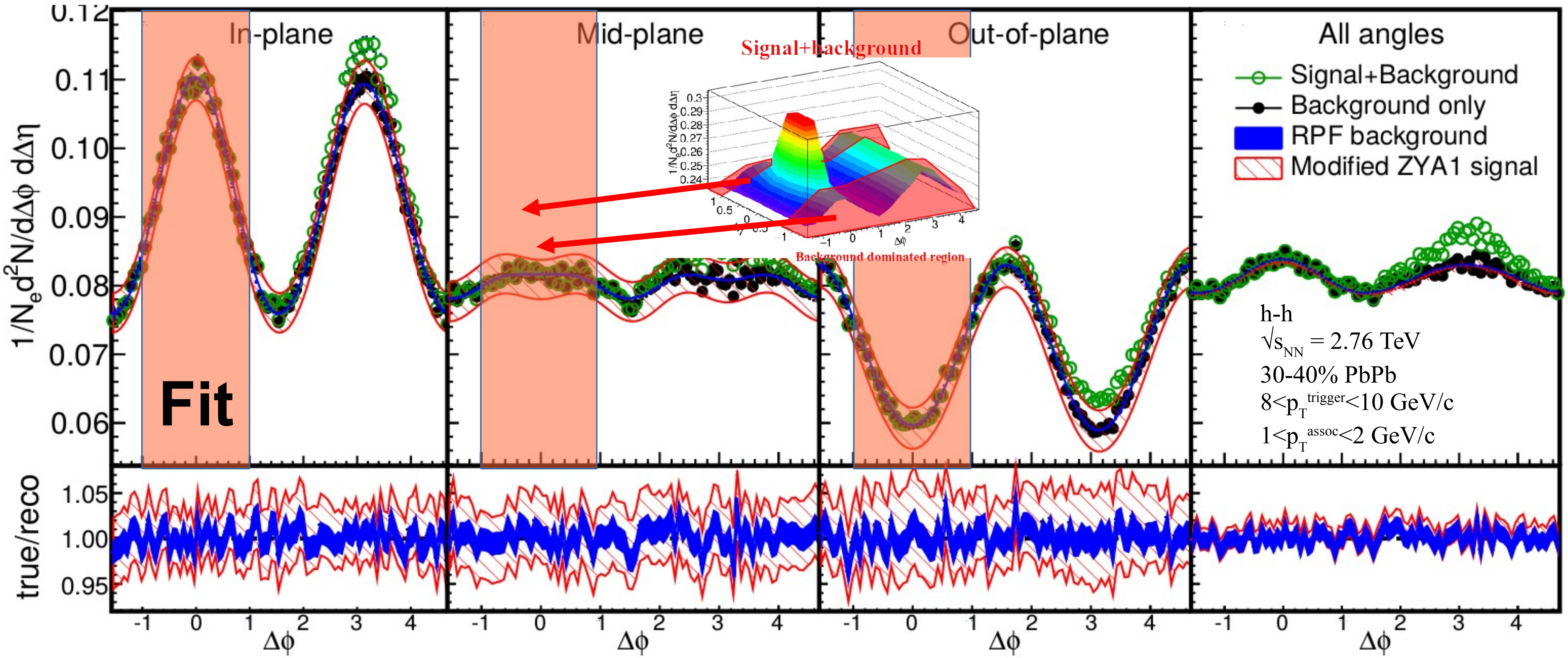
Nattrass, Sharma, Mazer, Stuart, and Bejnood: (Phys. Rev. C 94, 011901(R) 2016)

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

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Background in correlations

- All reaction plane angles

$$B\left(1+\sum_{n=2}^{\infty} v_n \cos(n\Delta\phi)\right)$$

- When trigger is restricted relative to reaction plane
  - Background level modified

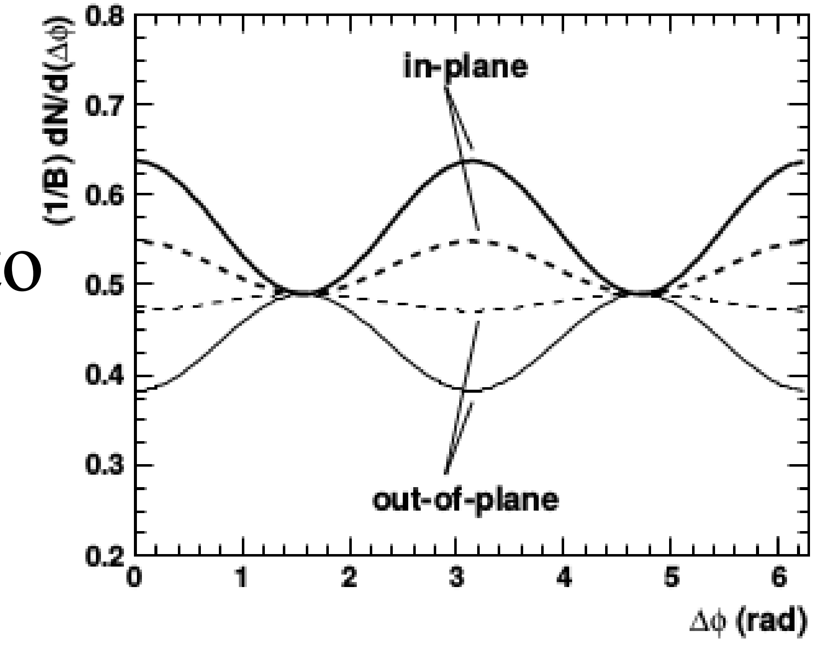
$$B=1+\sum_{k=2,4,6\ldots}^{\infty} 2v_k \cos(k\phi_S)\frac{\sin(kc)}{kc}R_n$$

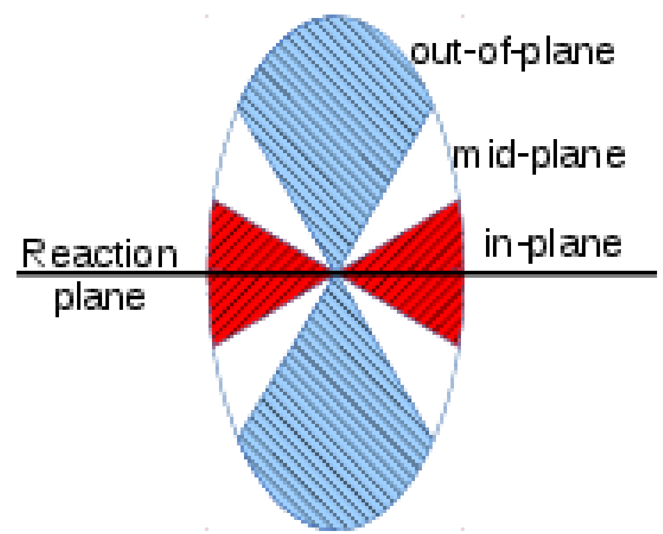
  - Effective v_n modified

$$v_n^{R,t}=\frac{v_n+\cos(n\,8_S)\frac{\sin(nc)}{nc}R_n+\sum_{k=2,4,6\ldots}^{\infty}(v_{k+n}+v_{k-n})\cos(k\phi_S)\frac{\sin(kc)}{kc}R_n}{1+\sum_{k=2,4,6\ldots}^{\infty}2v_k\cos(k\phi_S)\frac{\sin(kc)}{kc}R_n}$$

φ_S is the angular threshold

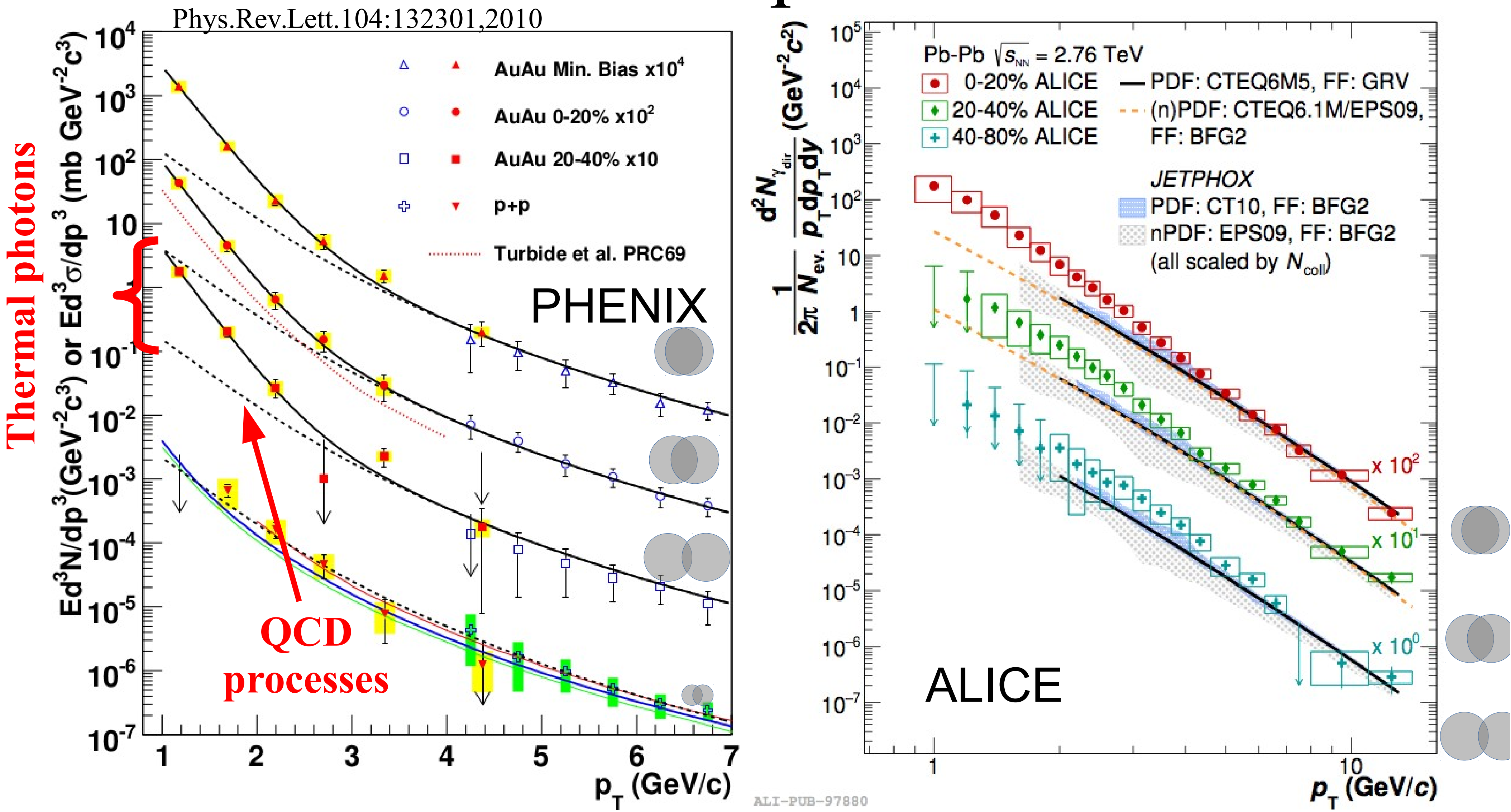
$$R_n=\langle\cos(n(\psi_{true}-\psi_{reco}))\rangle$$





Phys.Rev. C69 (2004) 021901 arXiv:nucl-ex/0311007

Thermal photons



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

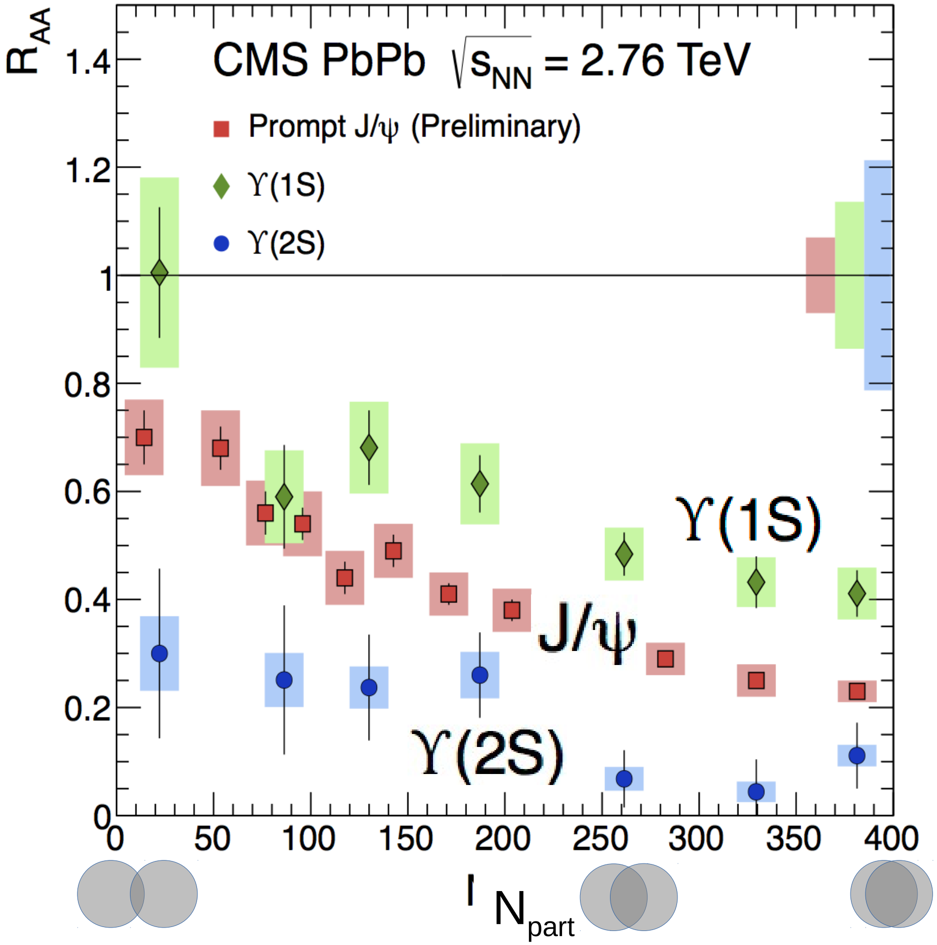
Inverse slope: T = 221 +/- 19 (stat) +/- 19 (syst) MeV

Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

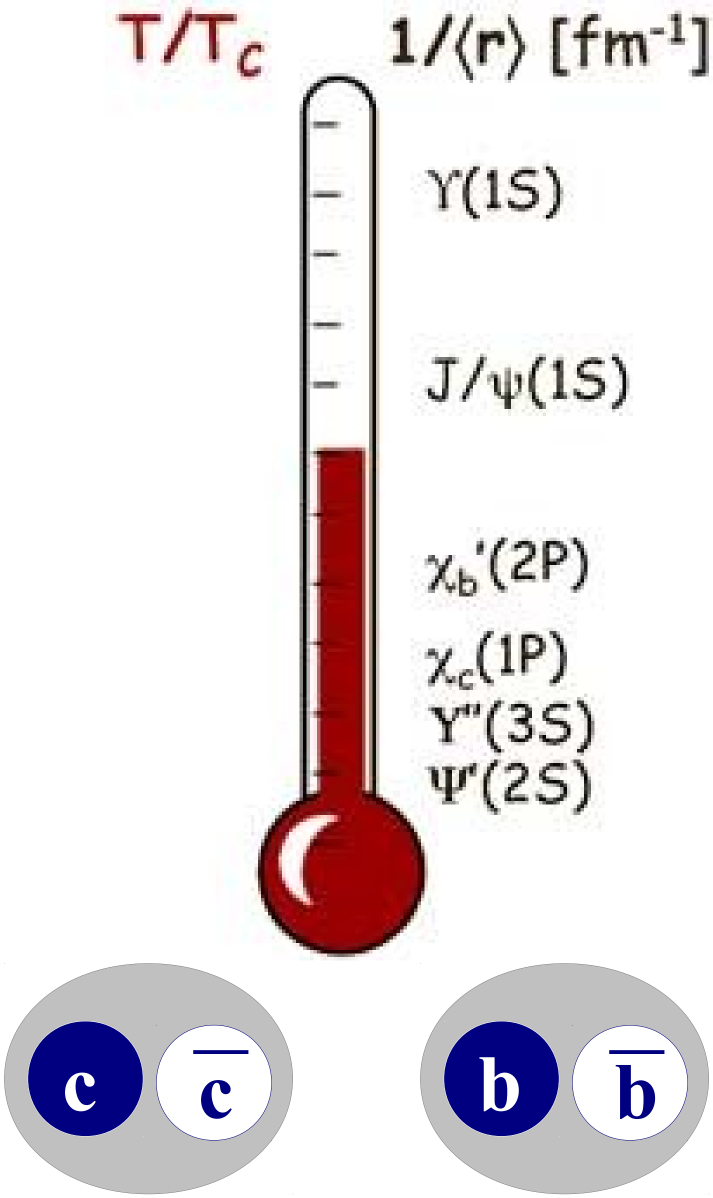
Inverse slope: T = 304 +/-51 MeV

A quarkonium-thermometer

CMS-PAS HIN-11-011
arXiv:1708.04962 [nucl-ex]

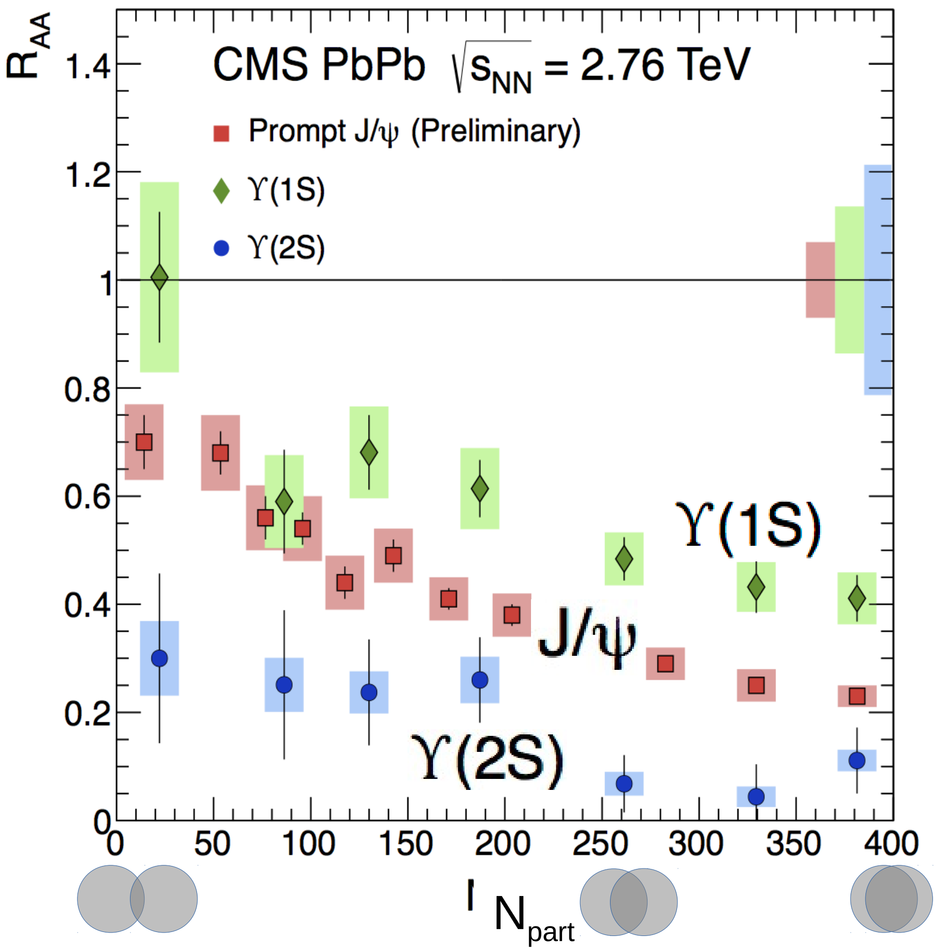


Clear hierarchy in R_{AA} of different quarkonium states

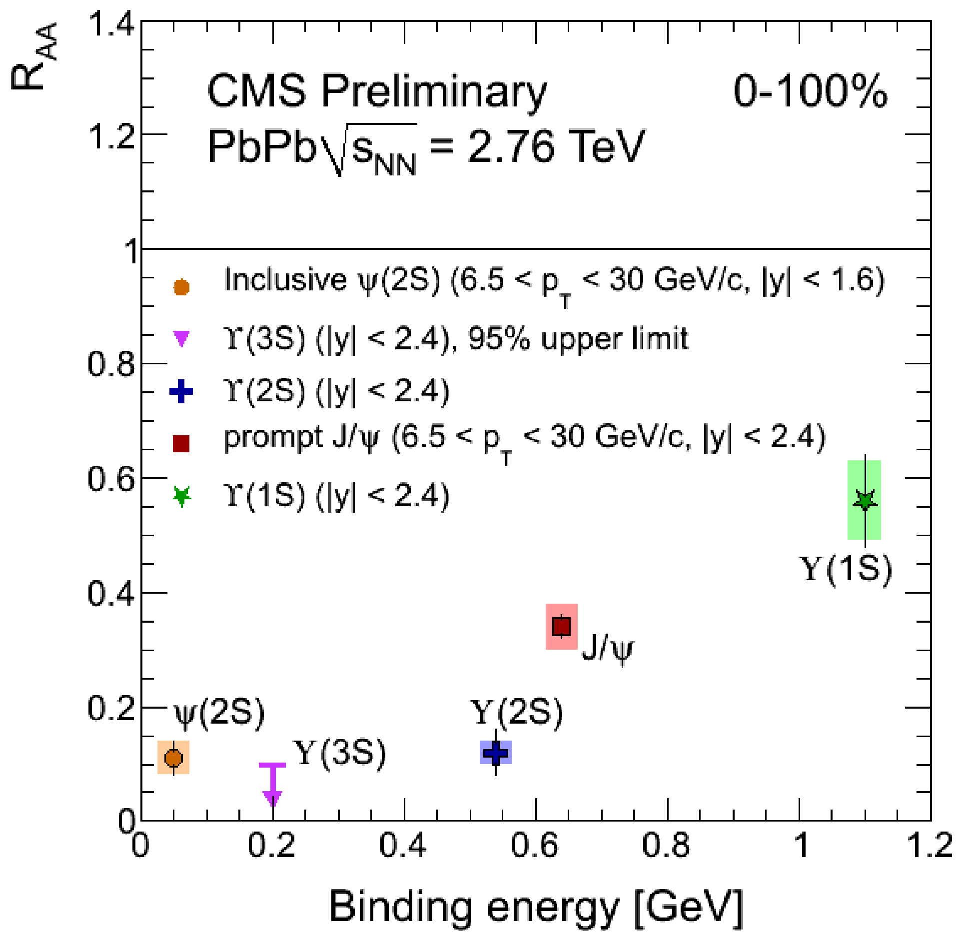


A quarkonium-thermometer

CMS-PAS HIN-11-011
arXiv:1708.04962 [nucl-ex]



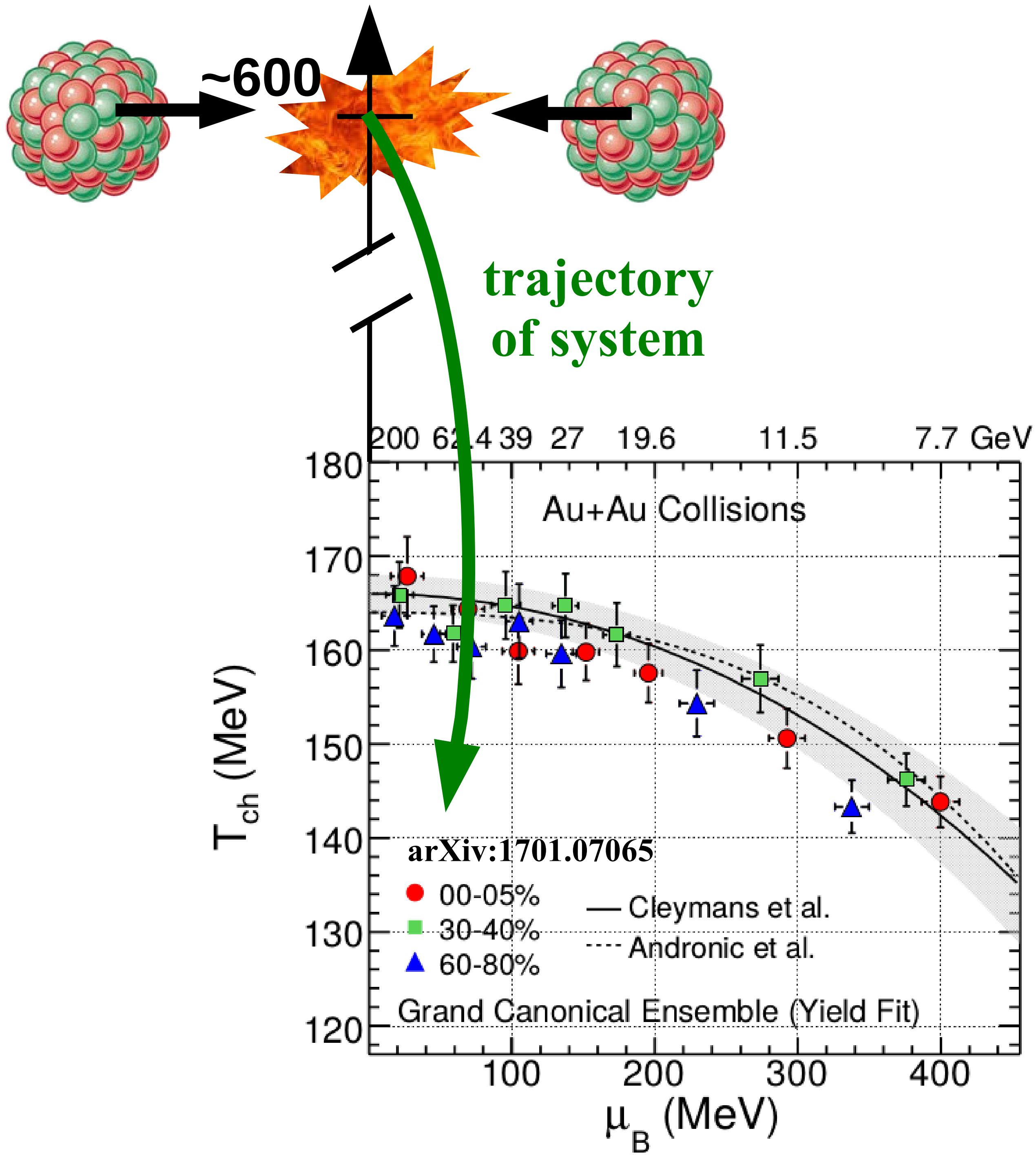
Note: 6.5<p_T<30 GeV for J/ψ and ψ(2s)



Clear hierarchy in R_{AA} of different quarkonium states

Expected in terms of binding energy

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


~600
trajectory
of system
200 62.4 39 27 19.6 11.5 7.7 GeV
Au+Au Collisions
arXiv:1701.07065
00-05%
30-40%
60-80%
Cleymans et al.
Andronic et al.
Grand Canonical Ensemble (Yield Fit)
T_ch (MeV)
μ_B (MeV)
180
170
160
150
140
130
120
100
200
300
400