# HARD PROBES FROM RHIC TO LHC

MÁTÉ CSANÁD @ PIC 2017, AUG 5, 2017

EÖTVÖS UNIVERSITY, BUDAPEST, HUNGARY

# CONTENT OF THIS TALK

- INTRODUCTION
  - Universe history, Big Bang and Little Bangs
  - Time evolution of heavy ion collisions, phases of QCD
- HARD PROBES, BASIC OBSERVATIONS
  - Nuclear modification of high energy particles and jets
  - Nuclear modification of hadrons versus photons
  - Heavy flavors
- RECENT RESULTS
  - Suppression in asymmetric/small/low-energy systems
  - Heavy flavors: beauty and charm, medium temperature
  - Jet structure: energy loss via fragmentation and jet correlations

# 3 INTRODUCTION

Universe history, Big Bang and Little Bangs

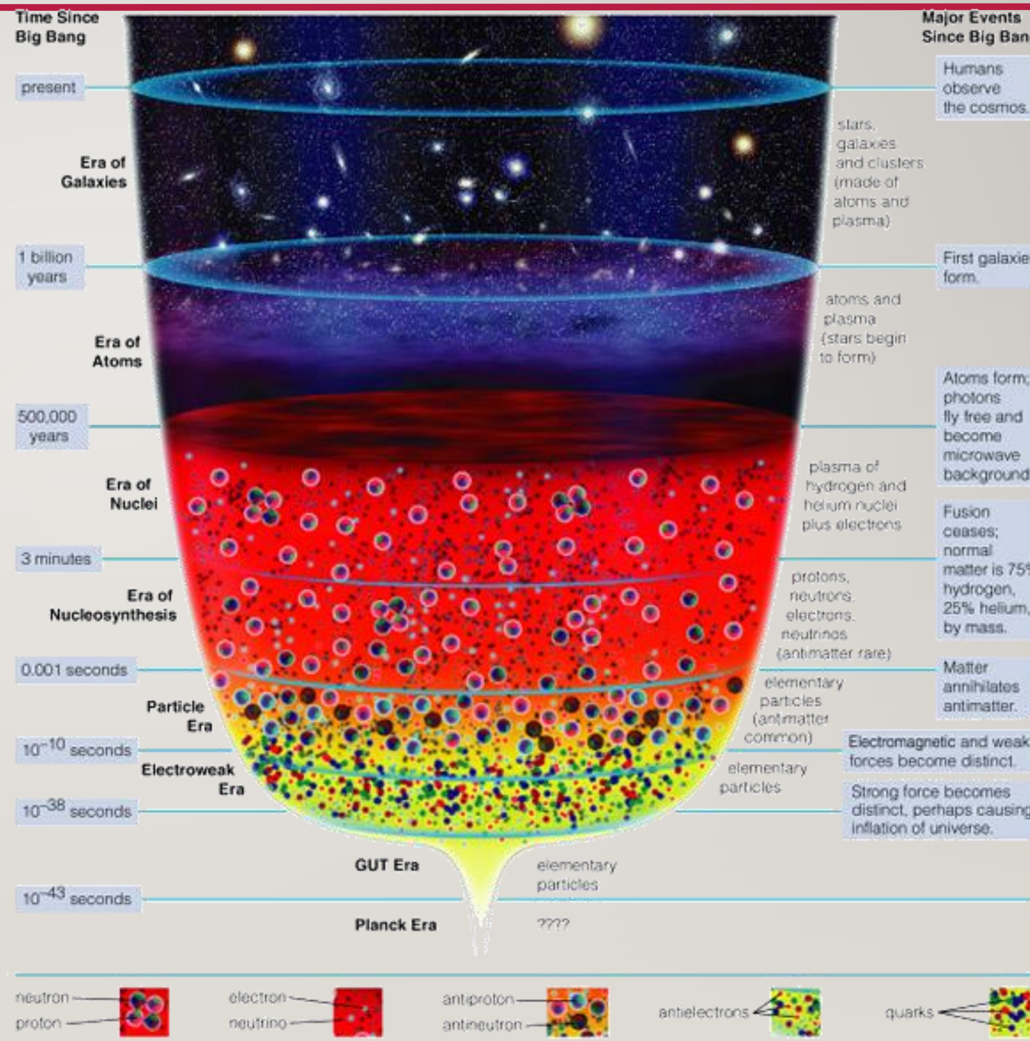
Time evolution of heavy ion collisions

Phase map of QCD and the experimental control parameters

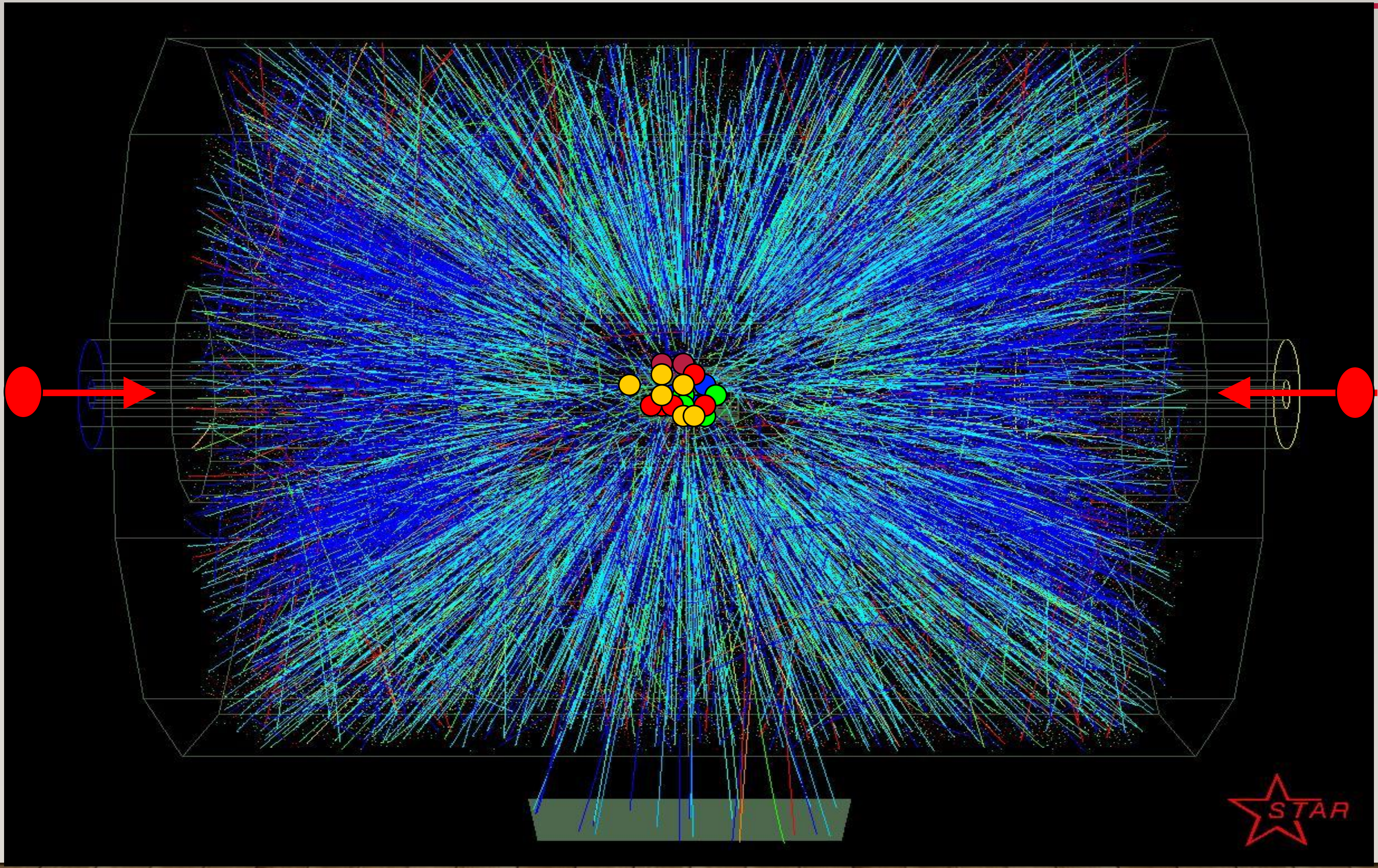
Accelerators, experiments

# BIG BANG IN THE LAB

- Ages of the Universe:
  - Stars & Galaxies
  - Atoms
  - Nuclei
  - Nucleosynthesis
  - Elementary particles
  - … ?
- How to investigate?
- Create little bangs
- Collisions of heavy ions
- Record outcoming particles

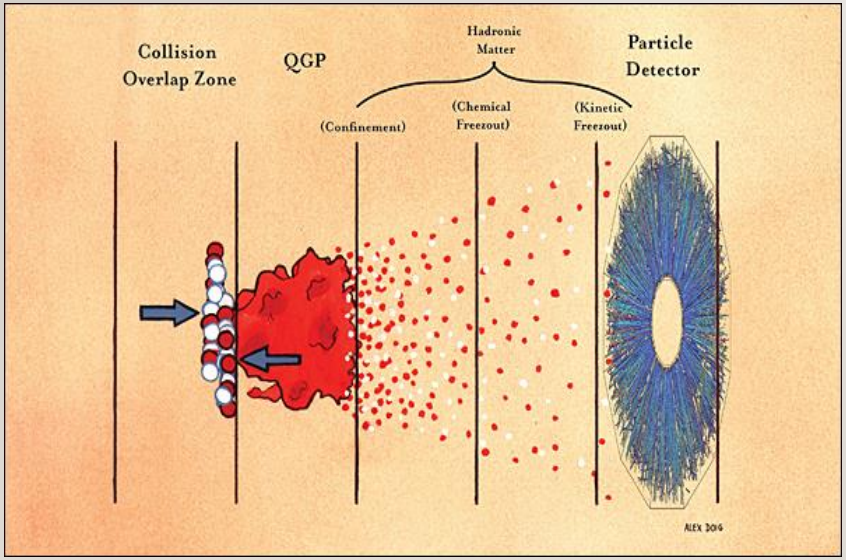


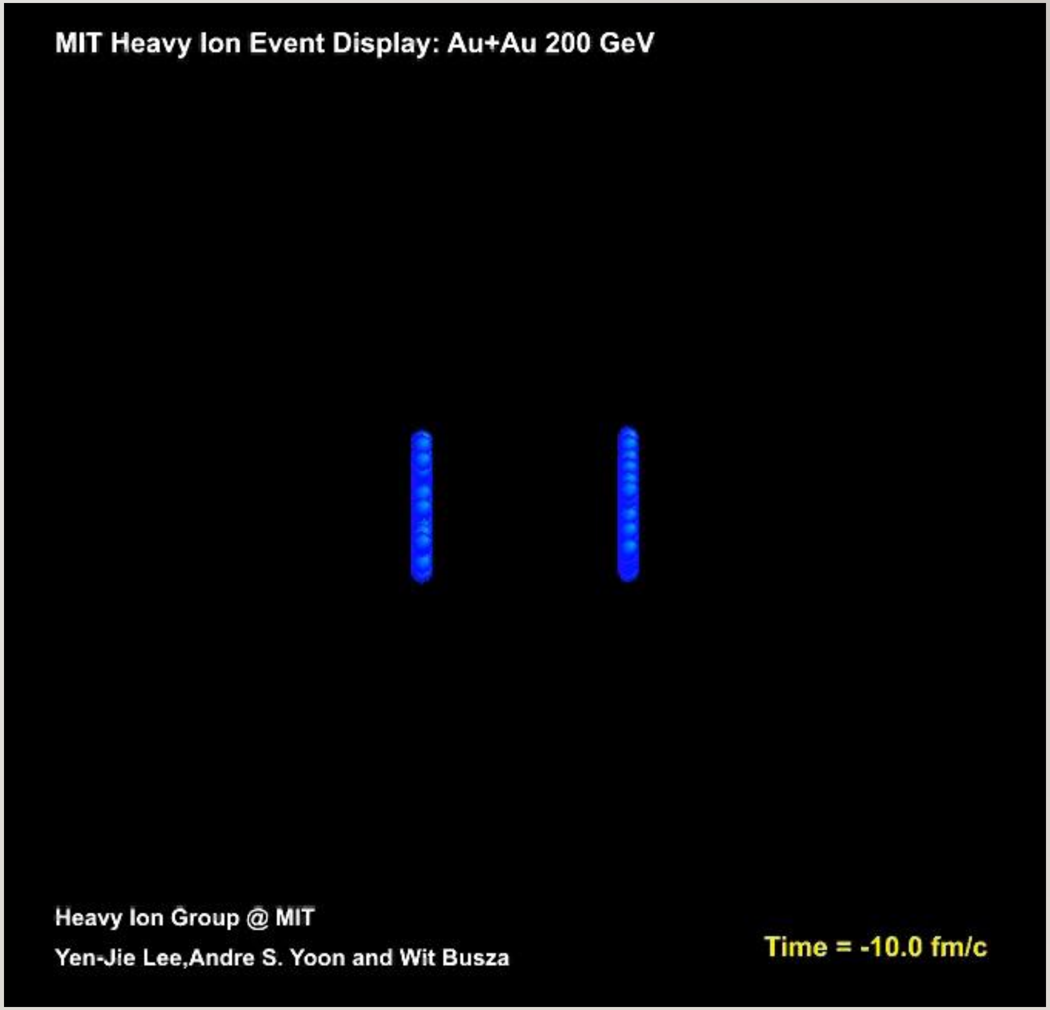
# HOW TO INVESTIGATE THESE LITTLE BANGS?



# TIMELINE OF A HEAVY ION COLLISION

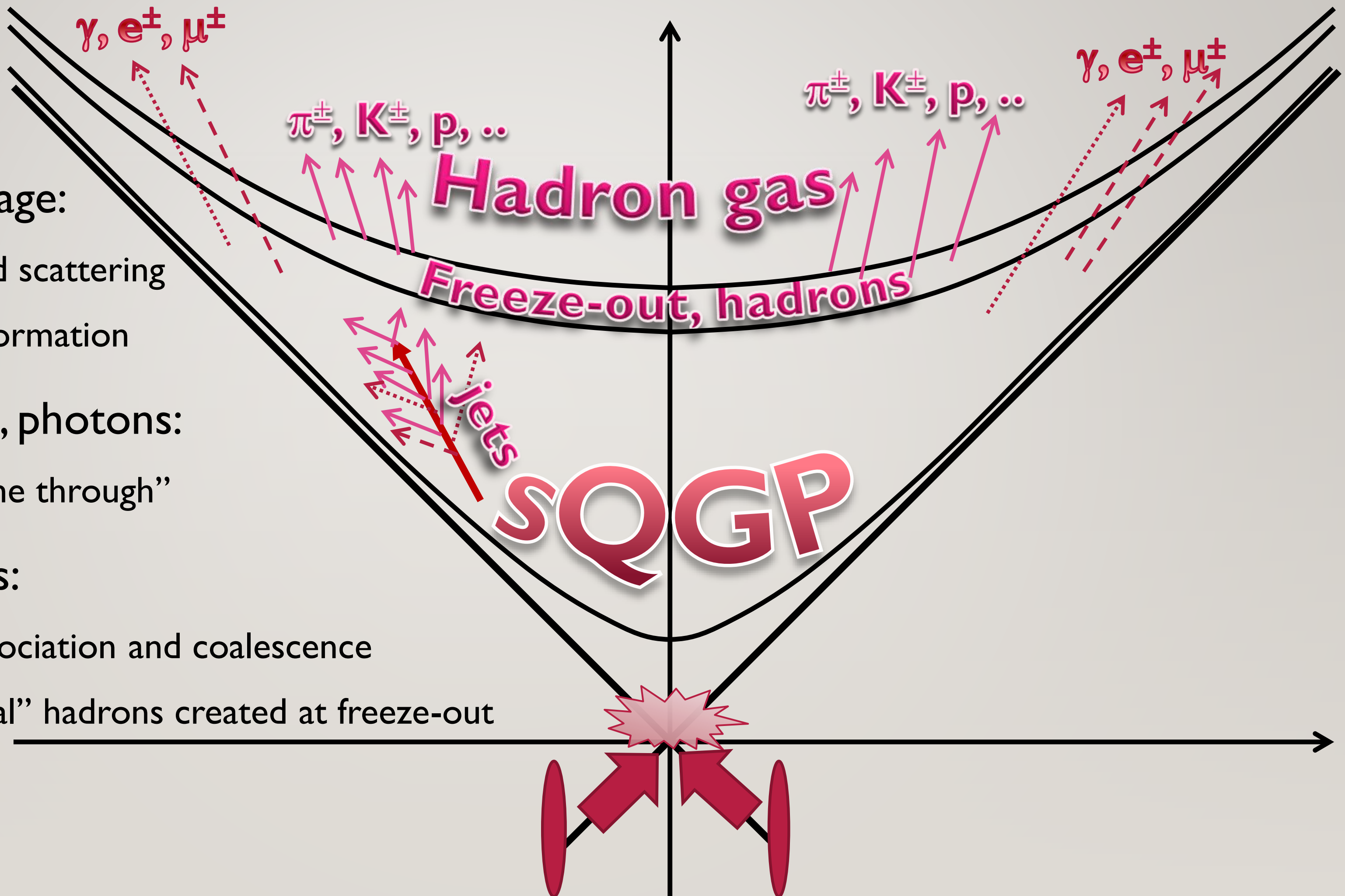
- Pre-thermalization stage: ~1 fm/cm
- Quark-hadron transition: ~7-10 fm/c
- Chemical + kinetic freeze-out



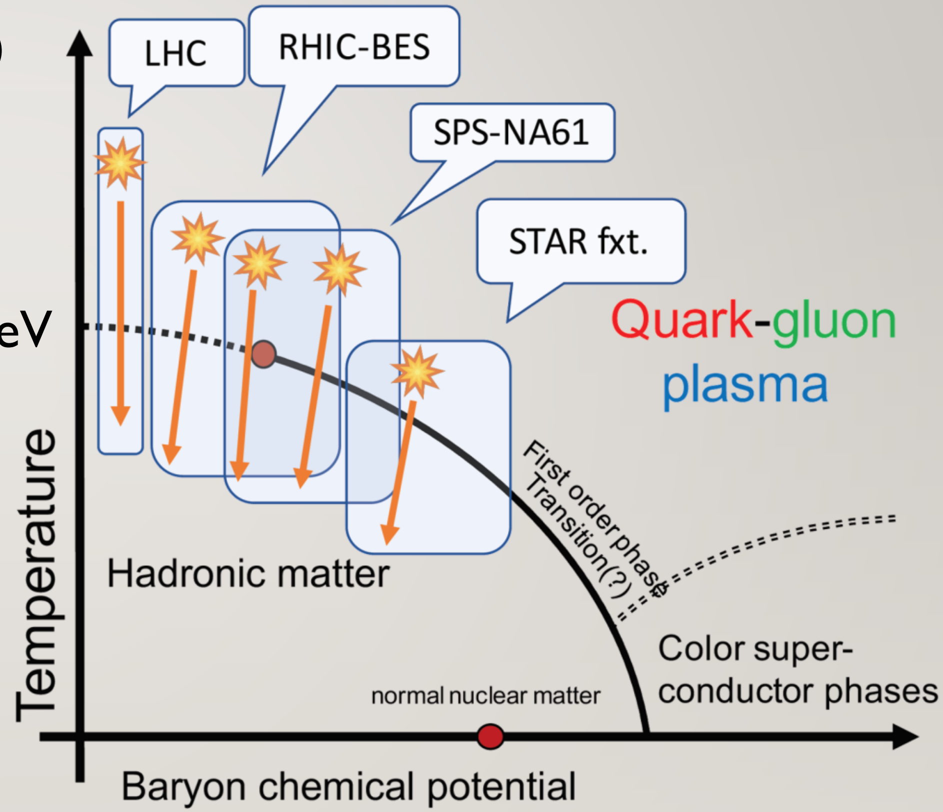
#  TIME EVOLUTION OF A HEAVY ION COLLISION

- Initial stage:
  - Hard scattering
  - Jet formation
- Leptons, photons:
  - ”shine through”
- Hadrons:
  - Dissociation and coalescence
  - ”Final” hadrons created at freeze-out



# EXPLORING THE PHASE MAP OF QCD

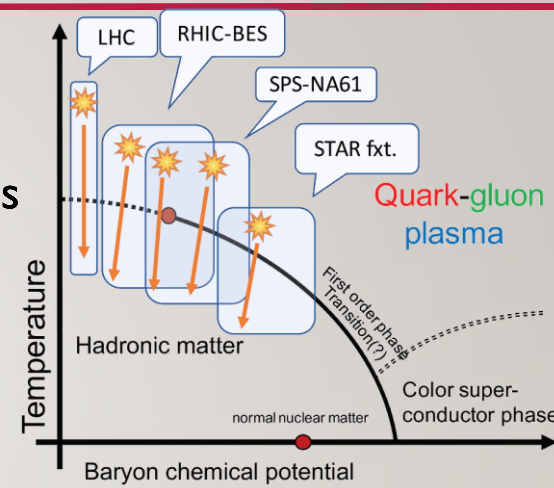
- Phase map: temperature versus matter excess (baryochem. pot. $\mu_B$)
- 1st order quark-hadron phase transition at high $\mu_B$
- Crossover at low $\mu_B$ and T≅170 MeV
- 170 MeV ↔ ~$10^{12}$ K
- Control parameters:
  - Collision energy
  - Collision system
  - Collision geometry

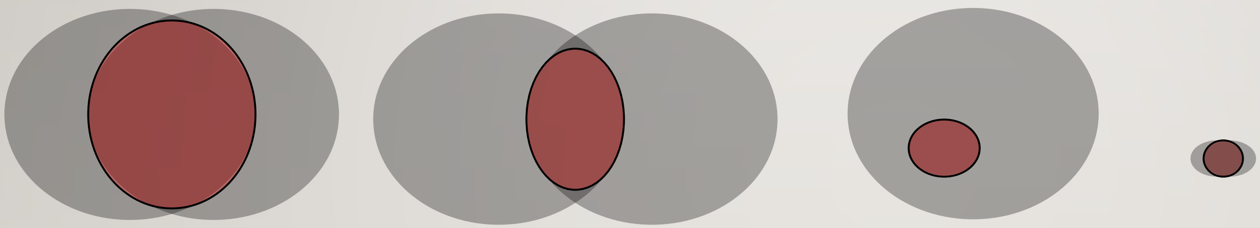



- High $\mu_B$: nuclear matter, neutron stars, color superconductors…

# EXPERIMENTAL CONTROL PARAMETERS

- Collision energy: controls initial temperature, initial $\mu_B$
- Collision system & centrality: controls available volume
- Event geometry: reaction plane, event plane, fluctuations
- Important parameters: $N_{part}$ (system size), $N_{coll}$ (x-sect)



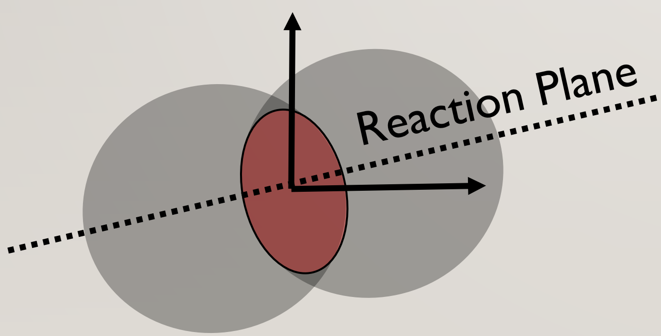



Central Au+Au $N_{part}$~300

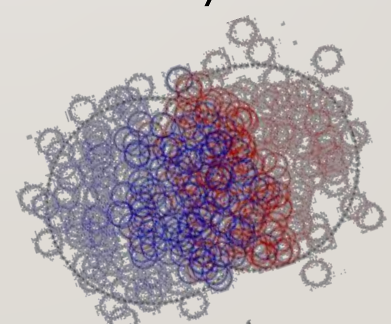
Peripheral Au+Au $N_{part}$~50

d+Au

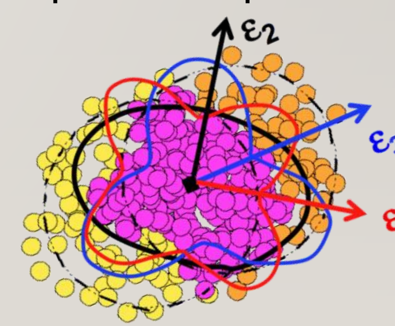
p+p



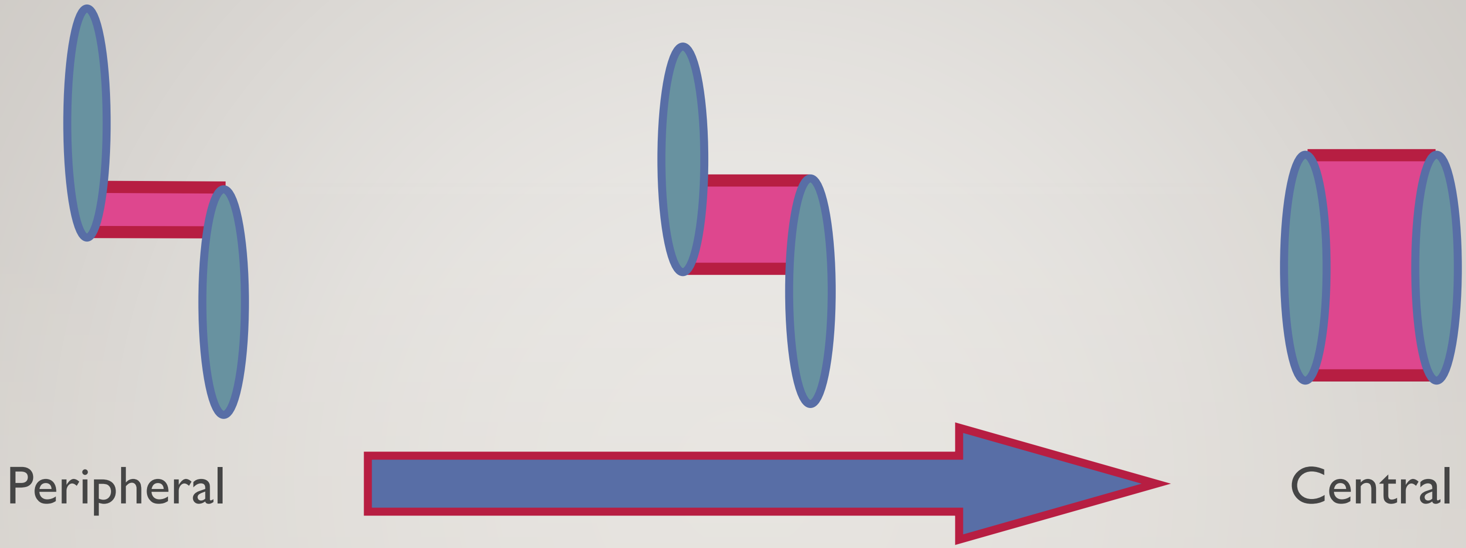

Reality

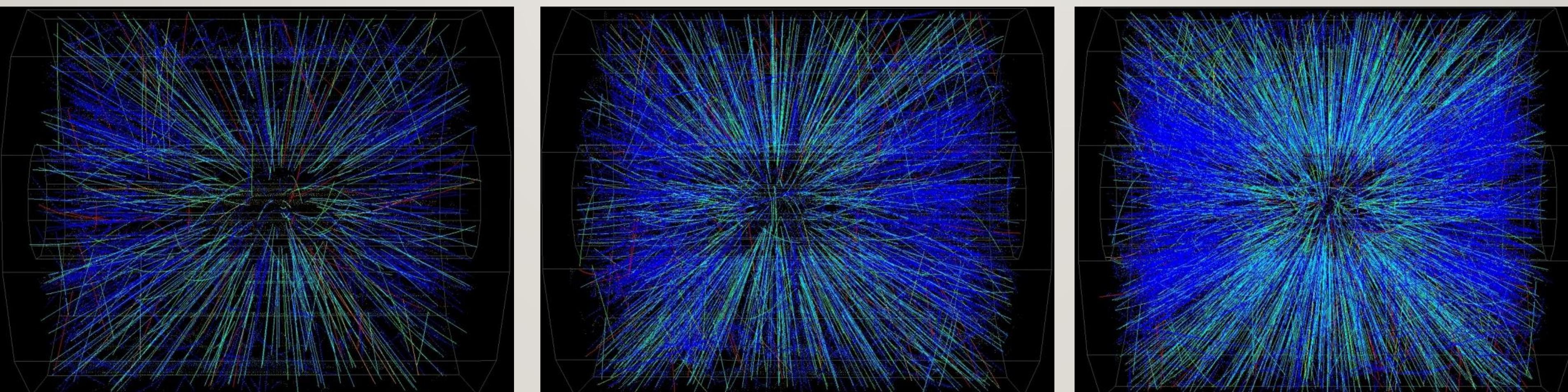


Multipole event planes



# COLLISIONS OF DIFFERENT CENTRALITY



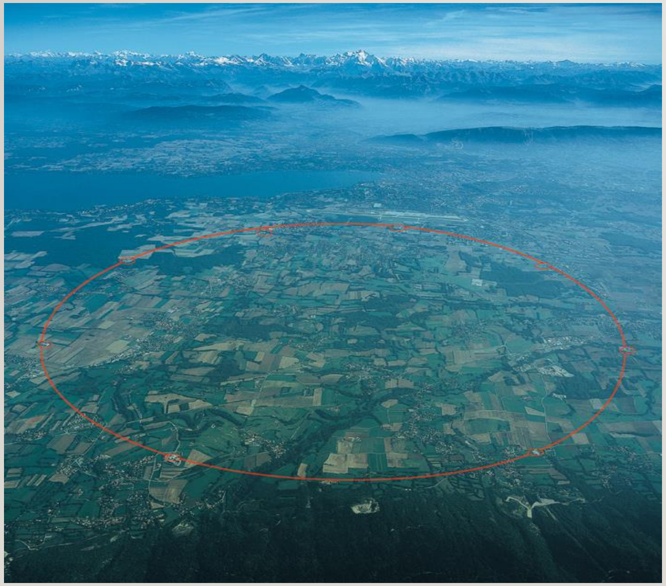



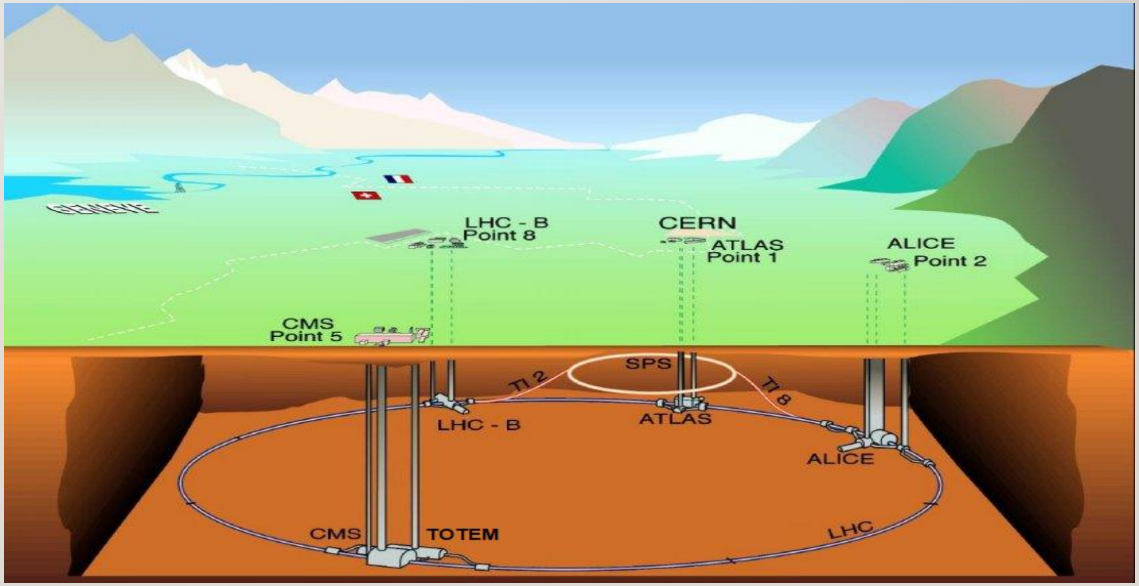
# FACILITIES: RELATIVISTIC HEAVY ION COLLIDER

- At the Brookhaven National Laboratory, Long Island, New York, USA
- Collisions of: $\vec{p}$, d, $^3$He, Al, Cu, Au, U
- Collision energies: 7-200 GeV/nucleon, even 0.5 TeV for $\vec{p}$
- Experiments: PHENIX & STAR; future: sPHENIX; past: BRAHMS & PHOBOS

# FACILITIES: LARGE HADRON COLLIDER

- Past high energy physics facilities: LEP, SPS (also currently in use)
- LHC collisions: p+p, p+Pb and Pb+Pb
- Energies: from 2.76 TeV/nucleon to 13 TeV (p+p only)
- Experiments: ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL, TOTEM





13

# HARD PROBES, BASIC OBSERVATIONS

Nuclear modification: $R_{AA}$

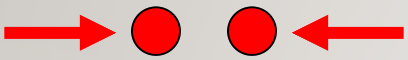
Jet quenching

Hadrons, photons

Heavy flavors

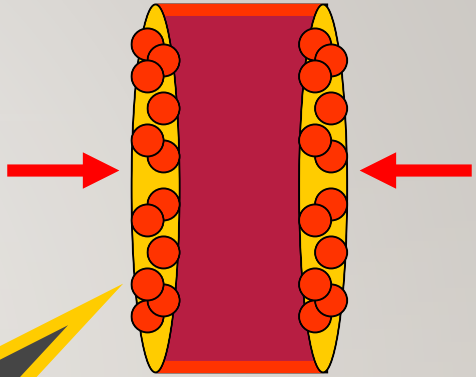
# NUCLEAR MODIFICATION: TOMOGRAPHY!

proton+proton



Simply just more?
A+A = many p+p?

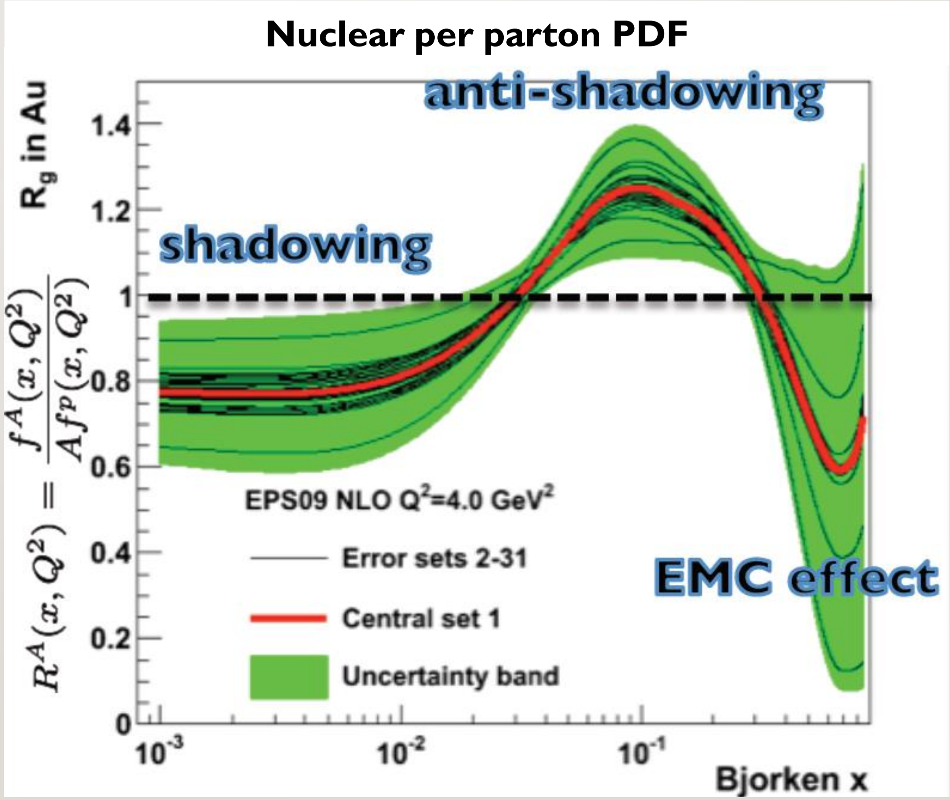
nucleus+nucleus



$$R_{AA} = \frac{\text{High } p_T \text{ particle yield in A+A}}{\text{High } p_T \text{ particle yield in p+p} \times \text{Number of p+p collisions}}$$

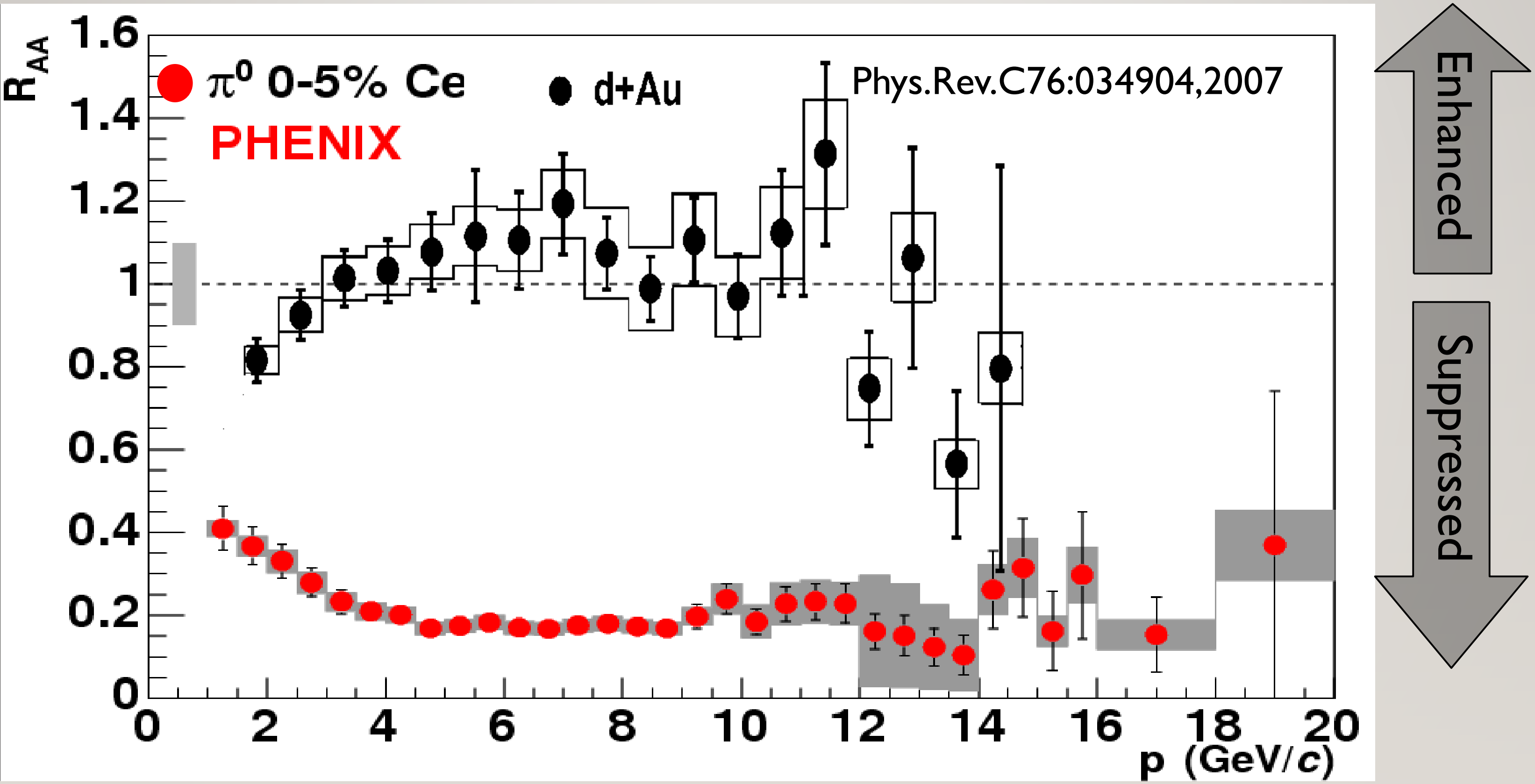
# COLD VERSUS HOT NUCLEAR MATTER EFFECTS

- Modification of $R_{AA}$ may be due to hot or cold nuclear matter effects
- Hot matter: suppression/quenching of hard particles
- Cold matter: initial state effect
  - Nuclear modification of PDF's
  - Shadowing
  - Energy loss of partons in nucleus
  - kT broadening
- Idea: hot nuclear matter not present in d+Au
- Cold nuclear matter: also in d+Au



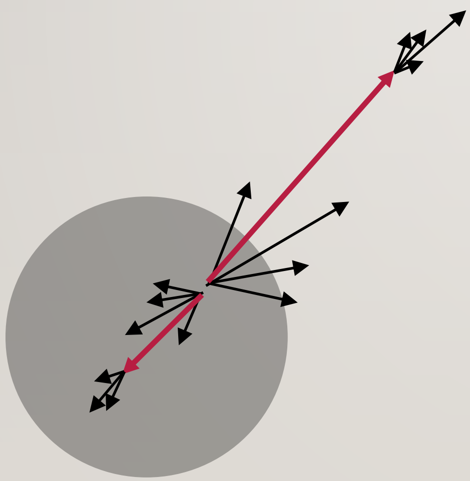
# SUPPRESSION AS A FUNCTION OF CENTRALITY

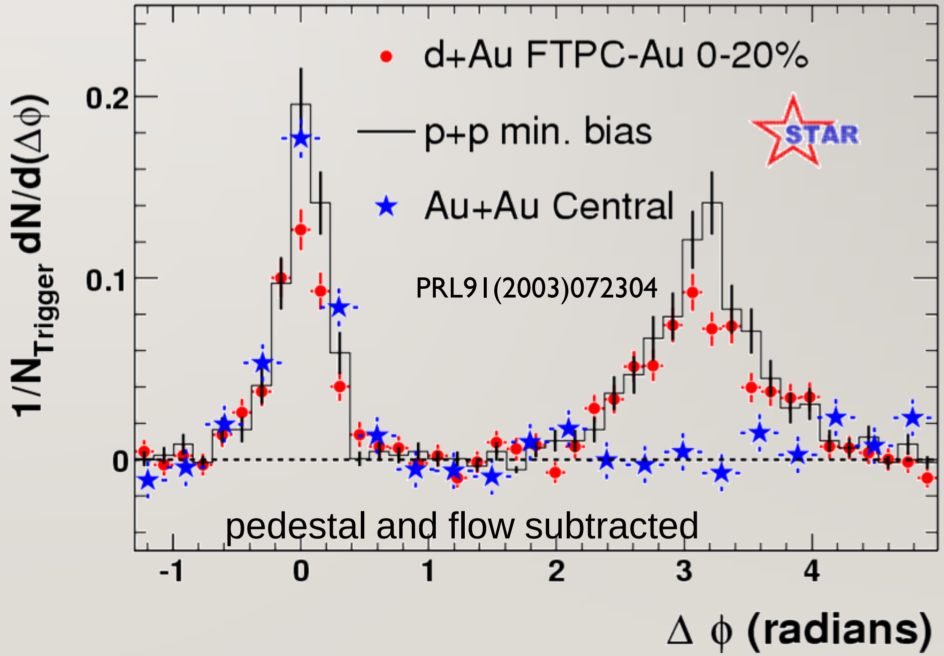
- No suppression in d+Au or peripheral Au+Au; strong suppression in central!



# SUPPRESSION OF THE AWAY SIDE JET

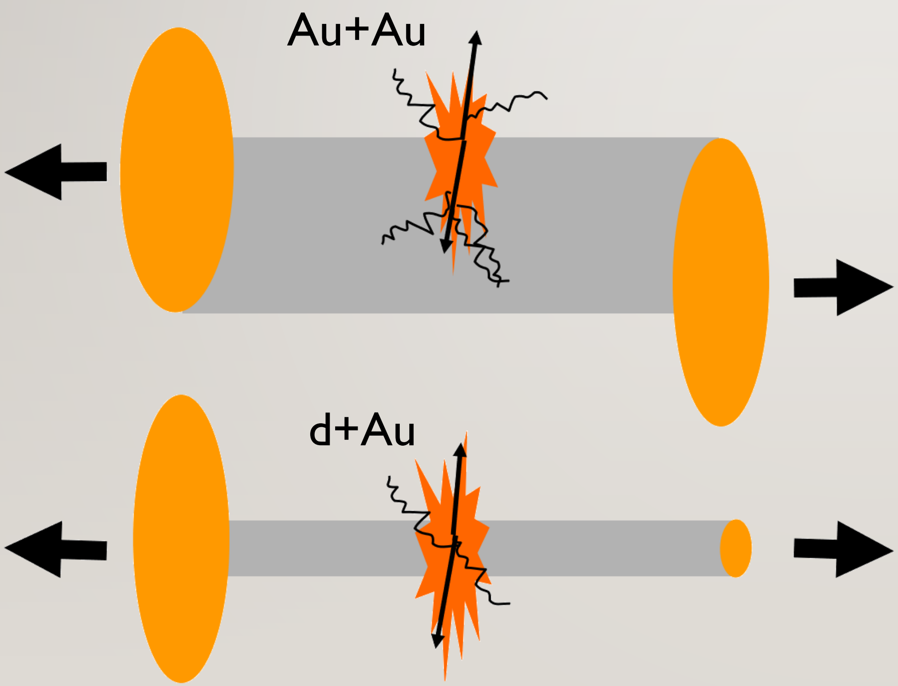
- Angular correlation of high energy hadrons
- Outgoing jet: similar in p+p, d+Au, Au+Au
- Inward going (away side) jet: missing in central Au+Au

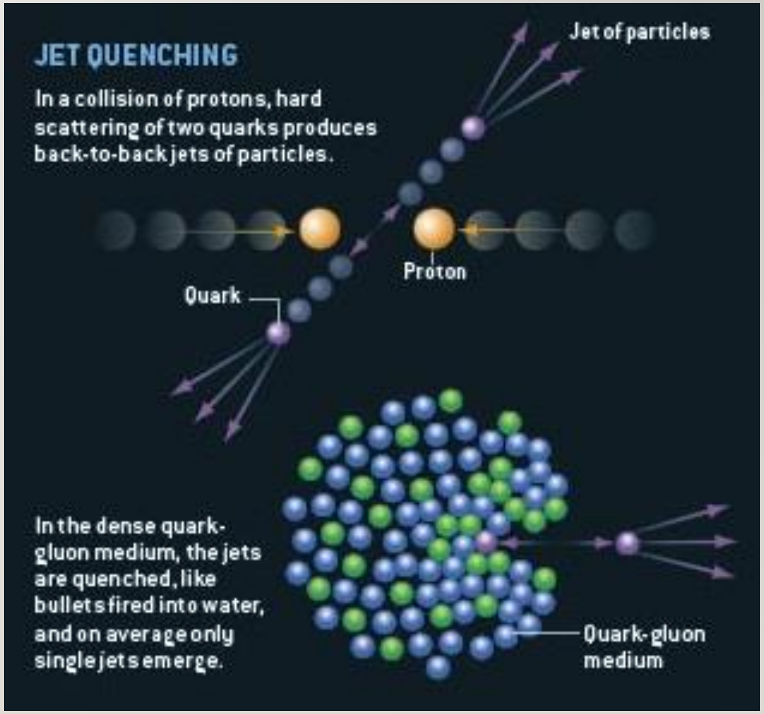




# SUPPRESSION OF HIGH ENERGY PARTICLES

- Suppression in Au+Au collisions: 1st milestone
- Lack of suppression in d+Au: 2nd milestone
- Two PRL covers

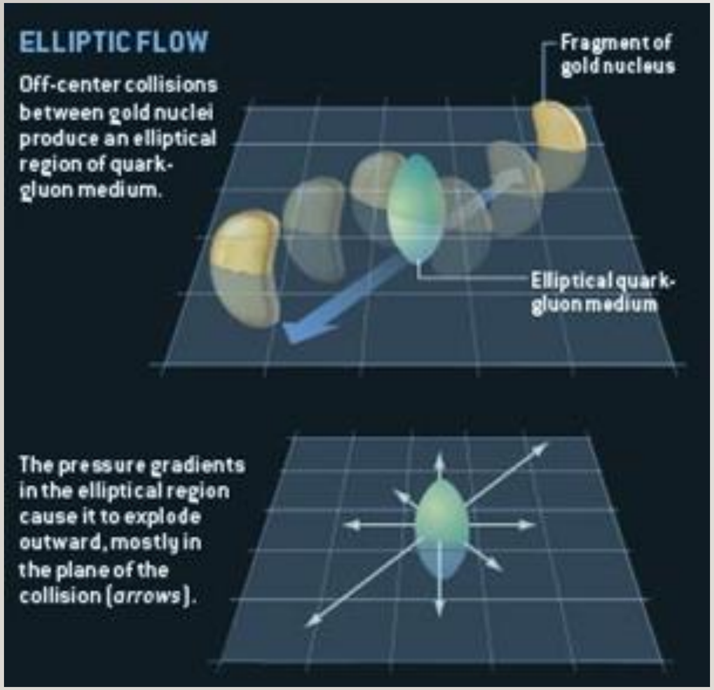


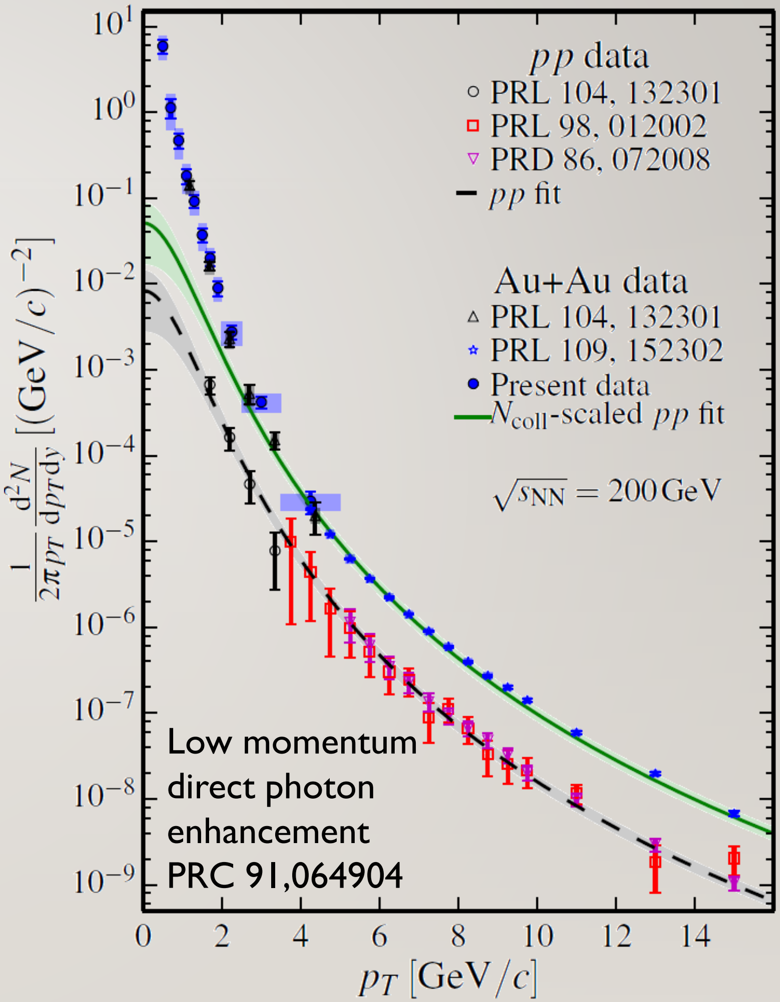

Zajc, Riordan, Scientific American

# A NEW TYPE OF MEDIUM FORMED

- More evidence from soft probes:
  - Flow: strong coupling, hydro behavior
  - Direct and thermal photons: large initial temp.

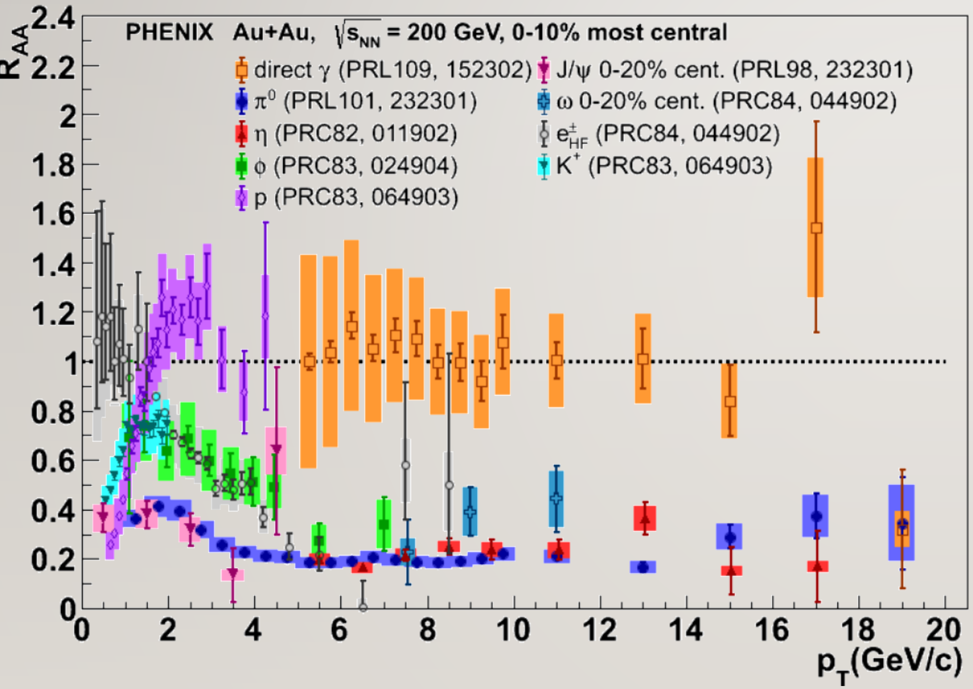


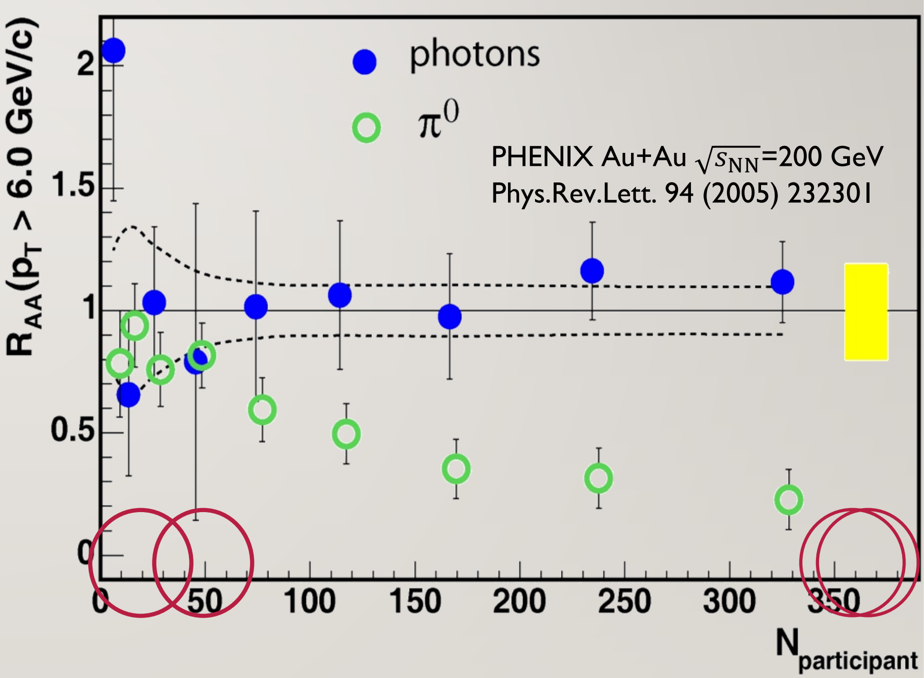

Zajc, Riordan, Scientific American



# HOW DO OTHER PARTICLES BEHAVE?

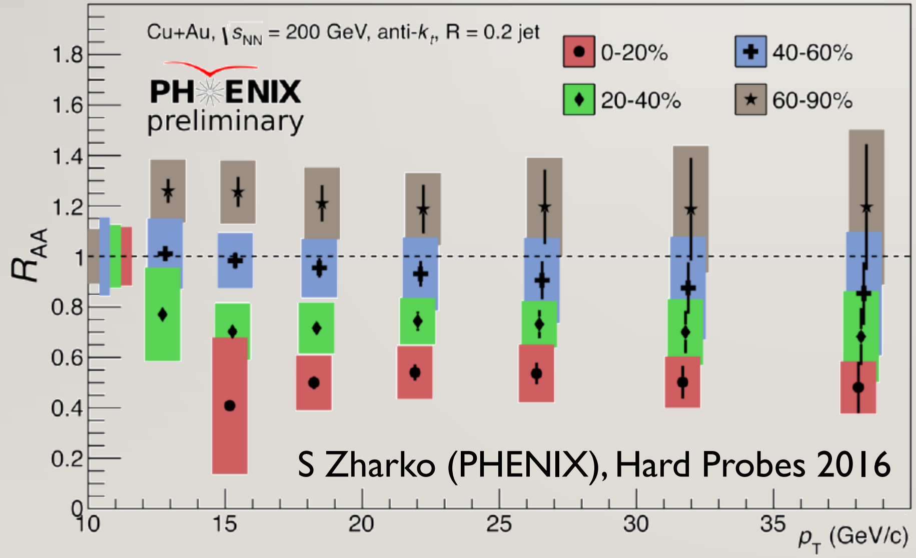
- All hadrons suppressed, direct photons „shine through"
- Suppression dependent of system size (controlled by centrality or $N_{part}$)

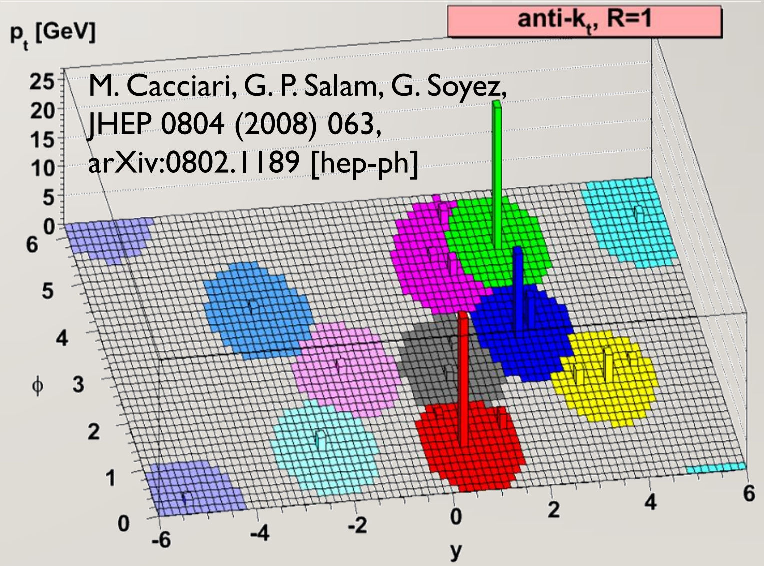


# JET RECONSTRUCTION

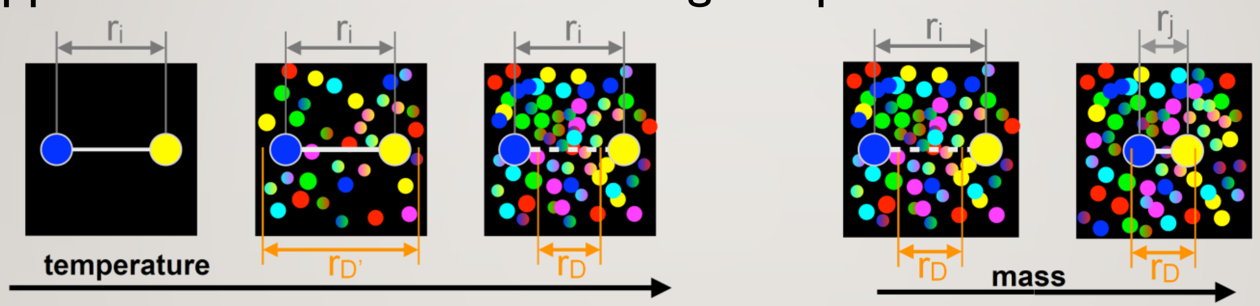
- Basic way to analyze suppression: yield of identified particles
- Advanced medium probe: reconstructed jets (and their correlations…)
- Jet measurement: algorithm required
  - Define jet/particle distance: $d_{ij} = \frac{\min\left(k_{T.i}^{2p}, k_{T.j}^{2p}\right)\left(\Delta y_{ij}^2 + \Delta\phi_{ij}^2\right)}{R^2}, \quad d_{i,\mathrm{Beam}} = k_{T.i}^{2p}$
  - Widely used: anti-k$_T$, $p = -1$

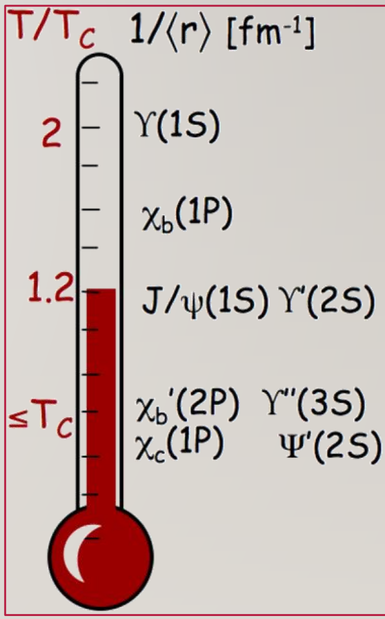


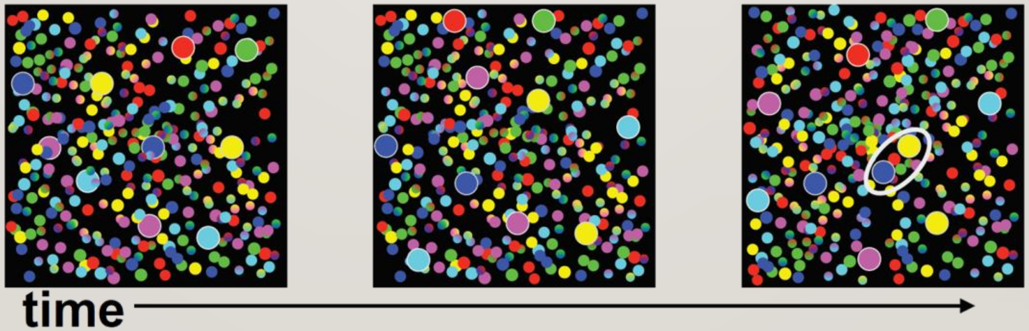
# WHAT ABOUT HEAVY FLAVOR MESONS?

- Timeline: quarkonium ($q\bar{q}$) formation → QGP evolution → $q\bar{q}$ decay
- Quarkonia experience the whole QGP evolution, competing processes
- Suppression due to color-screening: temperature and size/mass dependence



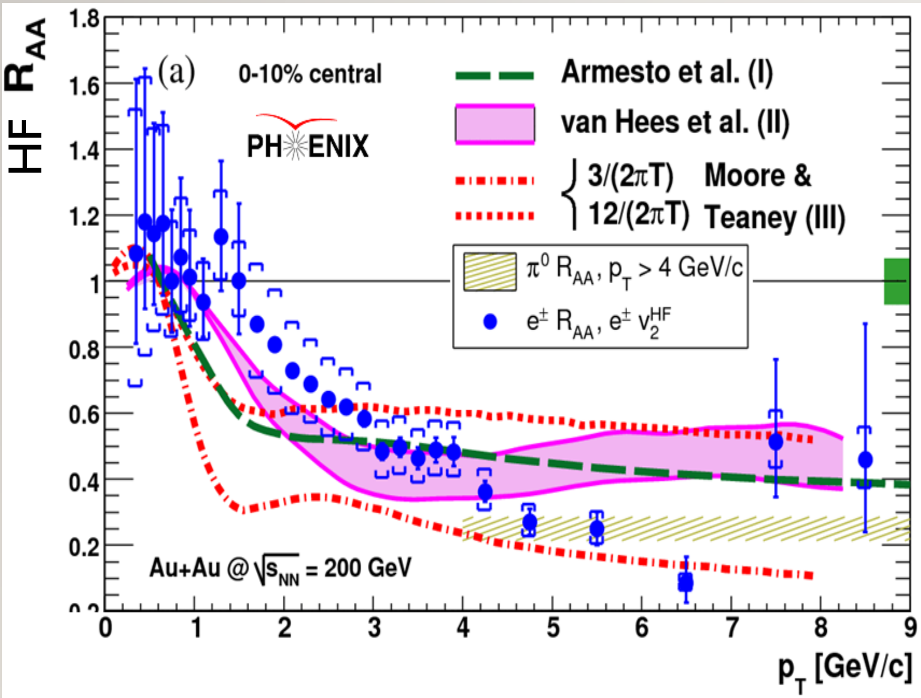

- Statistical regeneration in time:



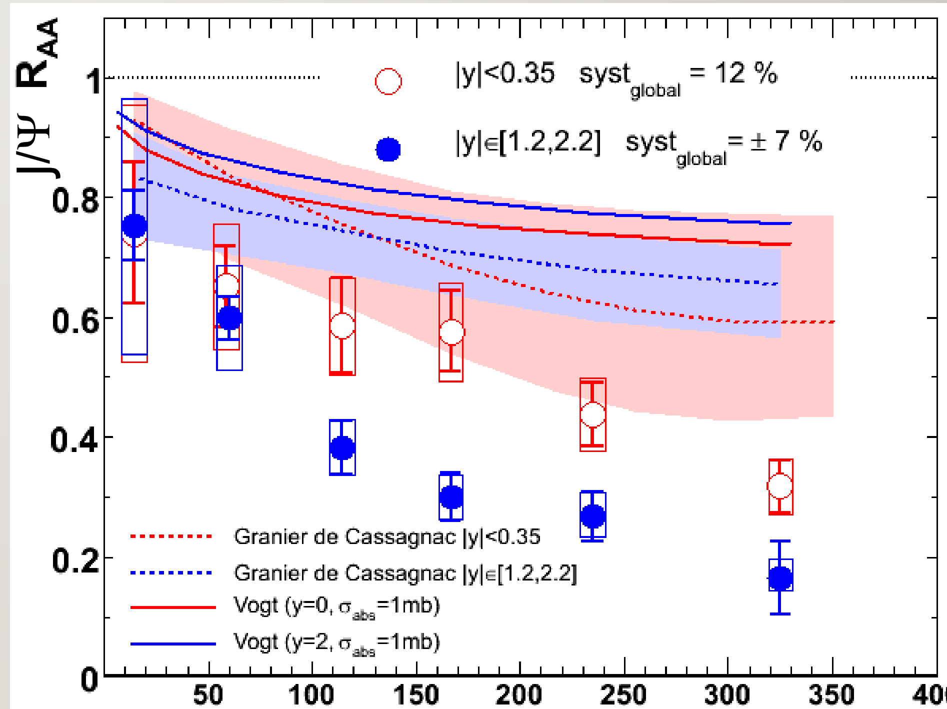

Images from J Castillo, SQM17 and A Mócsy, HardProbes2009

# SUPPRESSION OF HEAVY FLAVOR

- Electrons from HF decays are suppressed (collision or radiation, mass ordering)
- J/Ψ are also suppressed
- Described by strong coupling, large transport coefficients



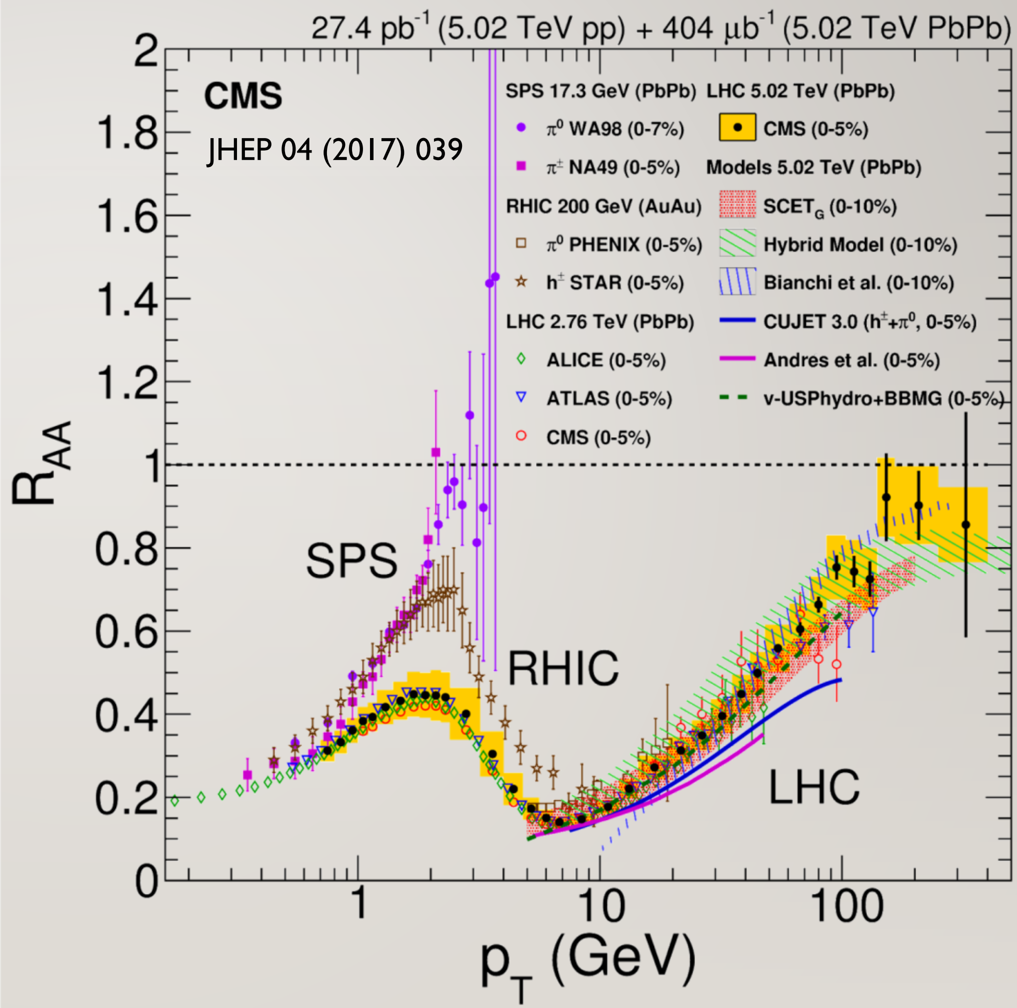

Phys. Rev. Lett. 98, 172301 (2007)




Phys. Rev. Lett. 98, 232301 (2007)

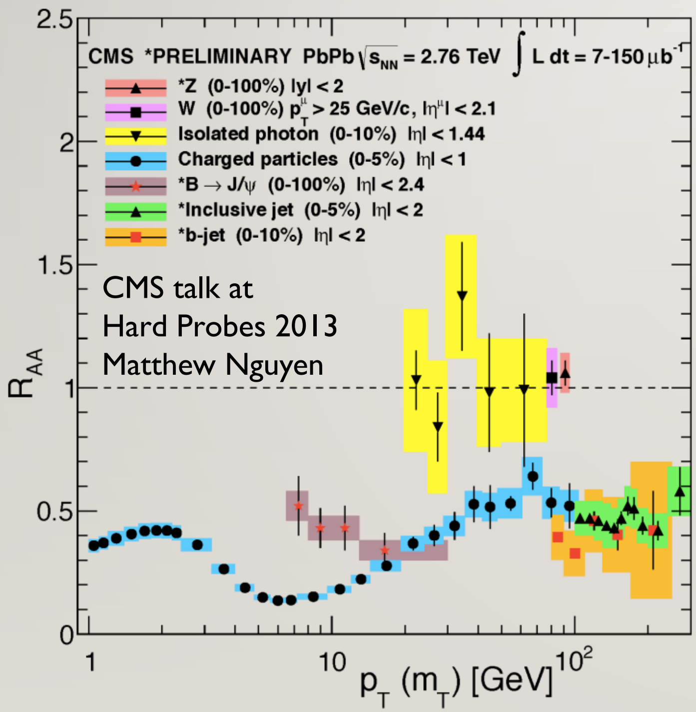
# HADRON SUPPRESSION: SPS → RHIC → LHC

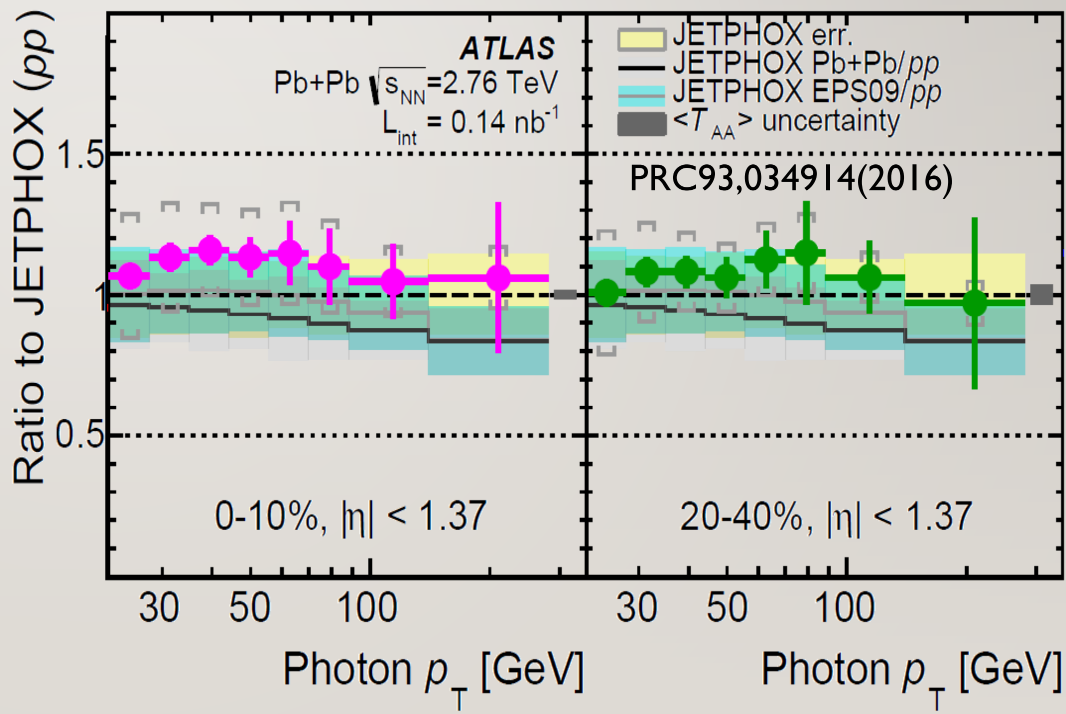
- Similar results at $\sqrt{s}$=2.76 and 5.02 TeV
- Local maximum at $p_T$~2 GeV
- Minimum at $p_T$~7 GeV
- Less suppression at very high momenta!
- RHIC and LHC similar?
- Competing effects:
  - Spectra flattening with incr. $\sqrt{s}$
  - Energy loss increasing with $\sqrt{s}$



# PHOTONS SHINE THROUGH AT THE LHC ALSO

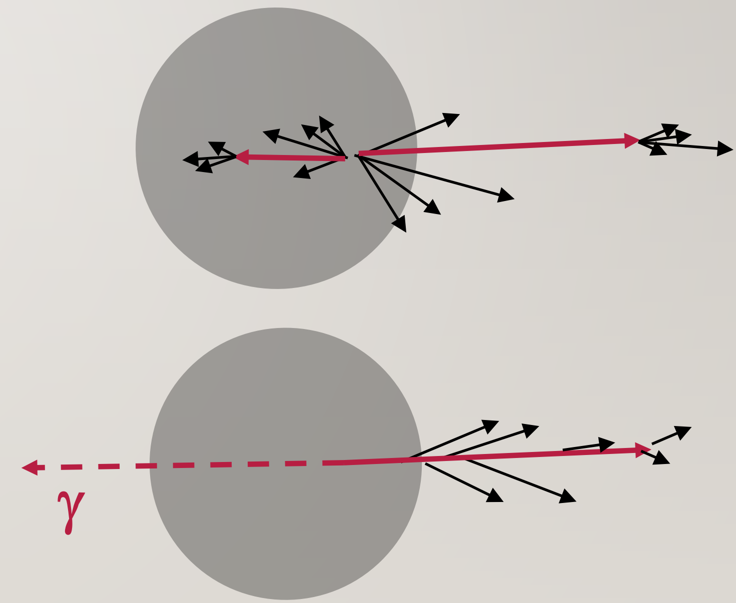
- No photon suppression for any energy or any centrality
- Electroweak bosons also not suppressed
- Comparison to MC (JETPHOX) up to $p_T$ of 200 GeV: similar conclusion



# SUMMARY OF THE STATUS QUO

- Jet suppression in A+A, lack of suppression in d+A:
  new, strongly interacting medium created at RHIC
- Confirmed by soft probes: elliptic flow and thermal photons
- Also heavy flavor hadrons suppressed
- Photons shine through
- Observations confirmed by the LHC
- Rising trend for very large momenta
- Jet reconstruction possible



# 27 RECENT RESULTS

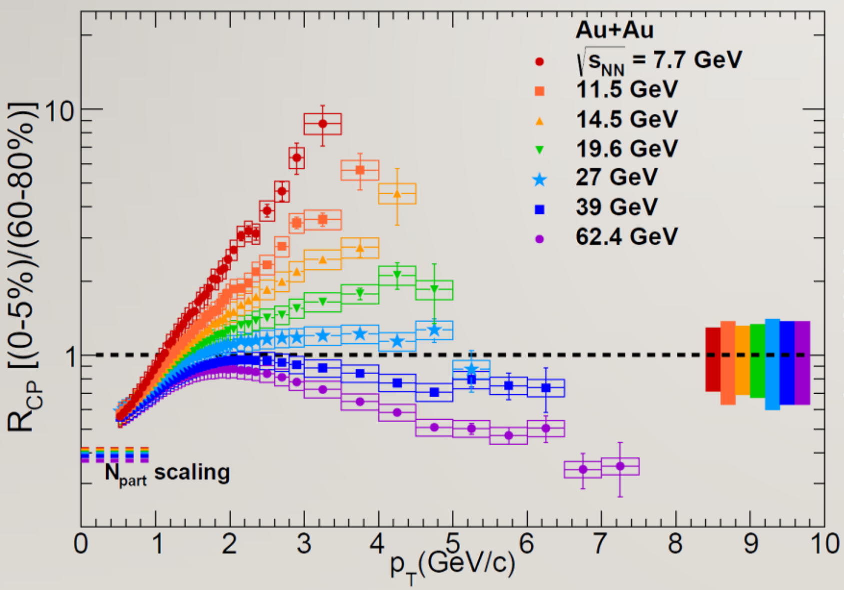
Suppression in asymmetric/small/low-energy systems

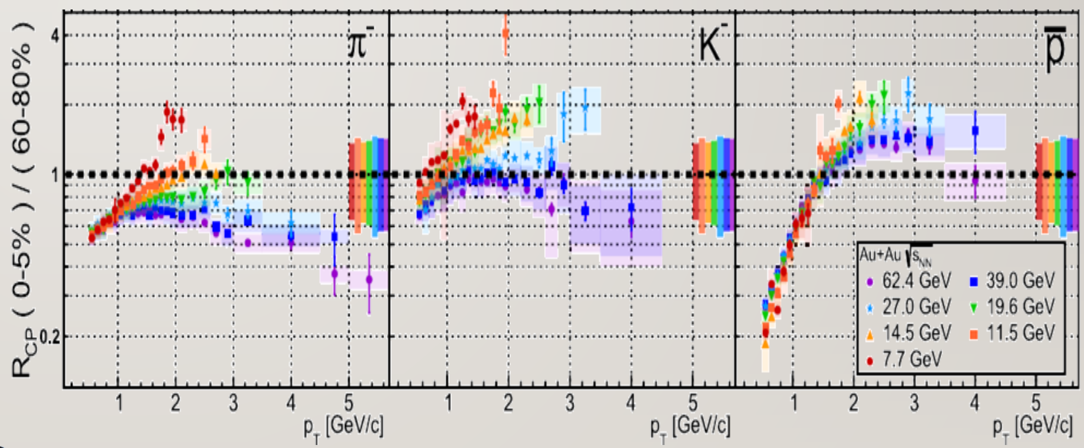
Heavy flavors: charm and beauty

Jets and jet correlations

# SUPPRESSION IN THE BEAM ENERGY SCAN

- $R_{CP}$ analyzed here instead of $R_{AA}$, transition above one with collision energy
- Hadron enhancement: Cronin-effect, radial flow, coalescence domination
- Identified particles: less suppression for kaons, enhancement for protons

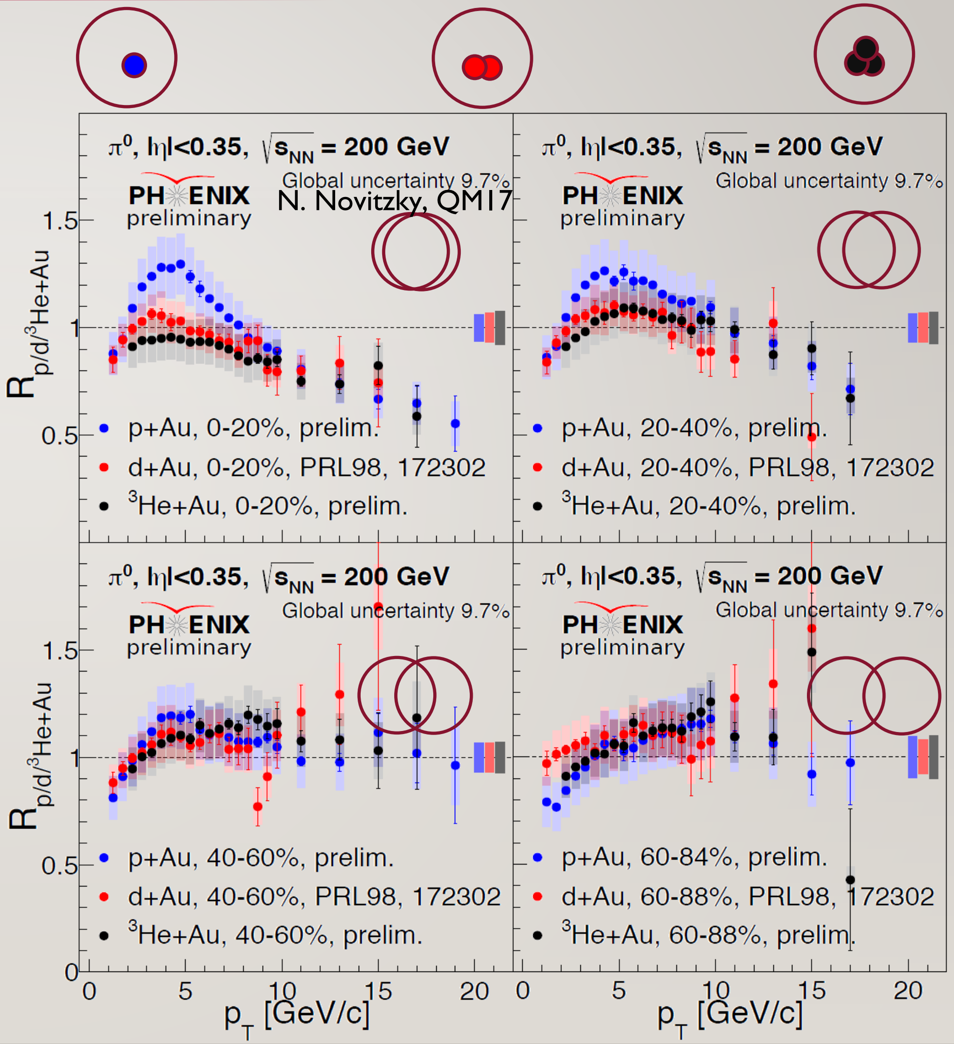



STAR collaboration, arXiv:1707.01988

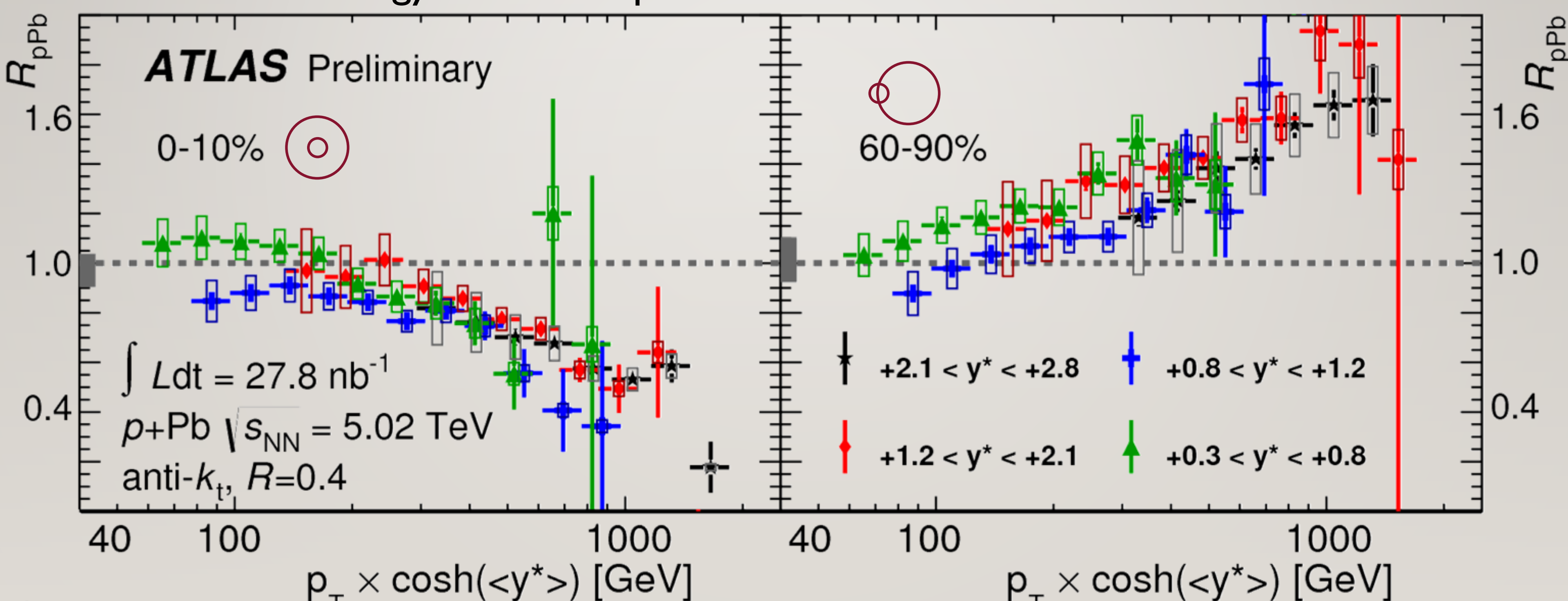
# SUPPRESSION IN SMALL SYTEMS AT RHIC

- p+Au, d+Au, $^3$He+Au compared
- Centralities determined as for large systems
- New p+Au results show large centrality dependence
- System sizes agree at high pT
- At moderate pT, ordering seen
- Model comparision:
  - Vitev, HIJING++ investigated
  - No full match of ordering, peak location, etc



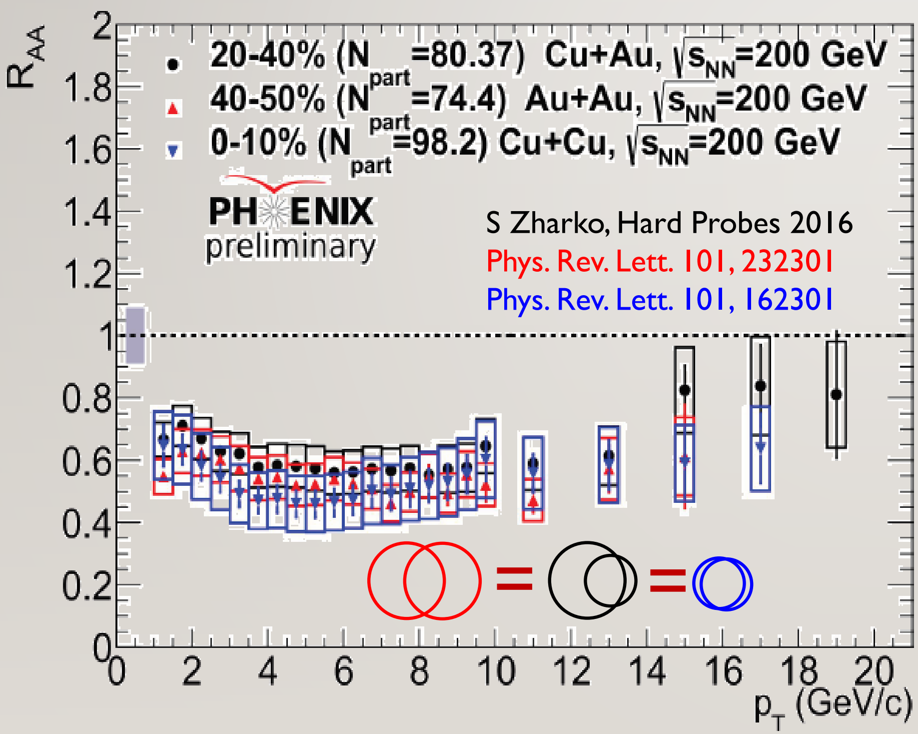
# SUPPRESSION IN SMALL SYSTEMS AT LHC

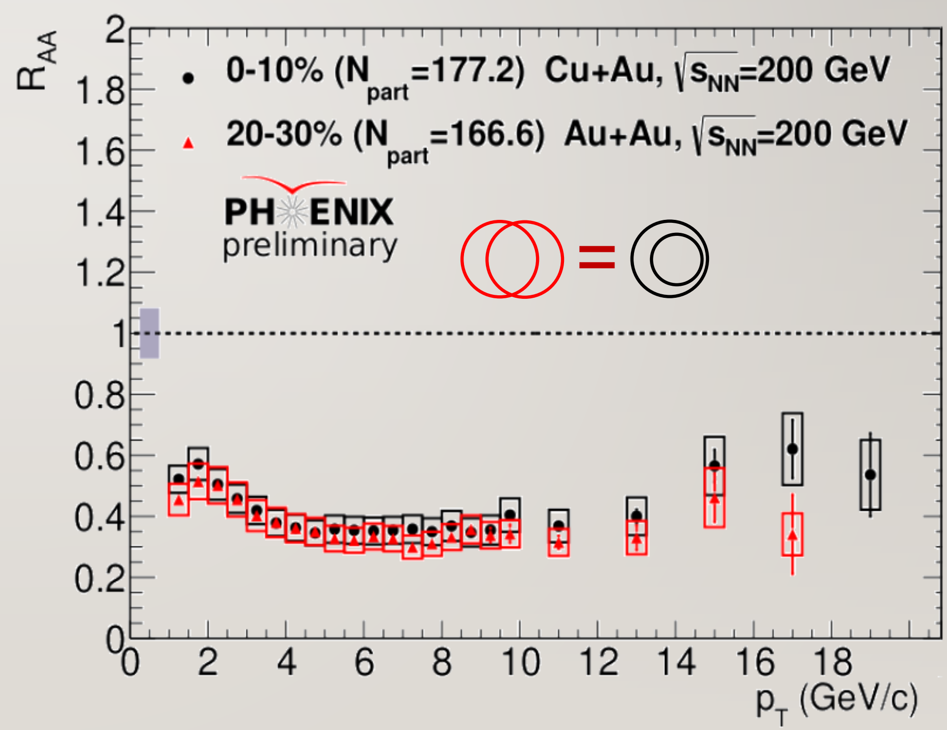
- Jet energy dependence observed at LHC
- Suppression/enhancement in central/peripheral pPb
- Parton energy fraction dependent mechanism?



# DEPENDENCE ON THE INITIAL SYSTEM

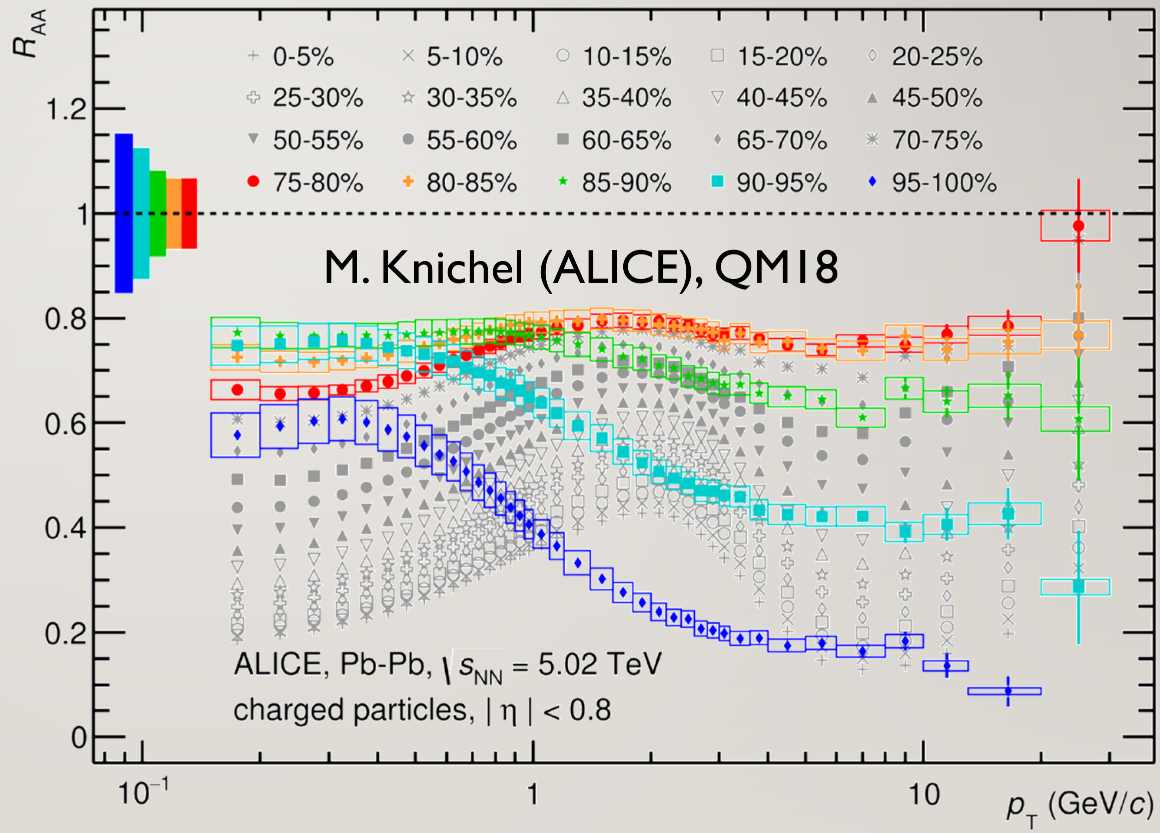
- Comparing different systems of the same size: Cu+Cu, Cu+Au, Au+Au
- Different centrality but same number of nucleon participants ($N_{part}$)
- Clear $N_{part}$ dependence („participant scaling”)



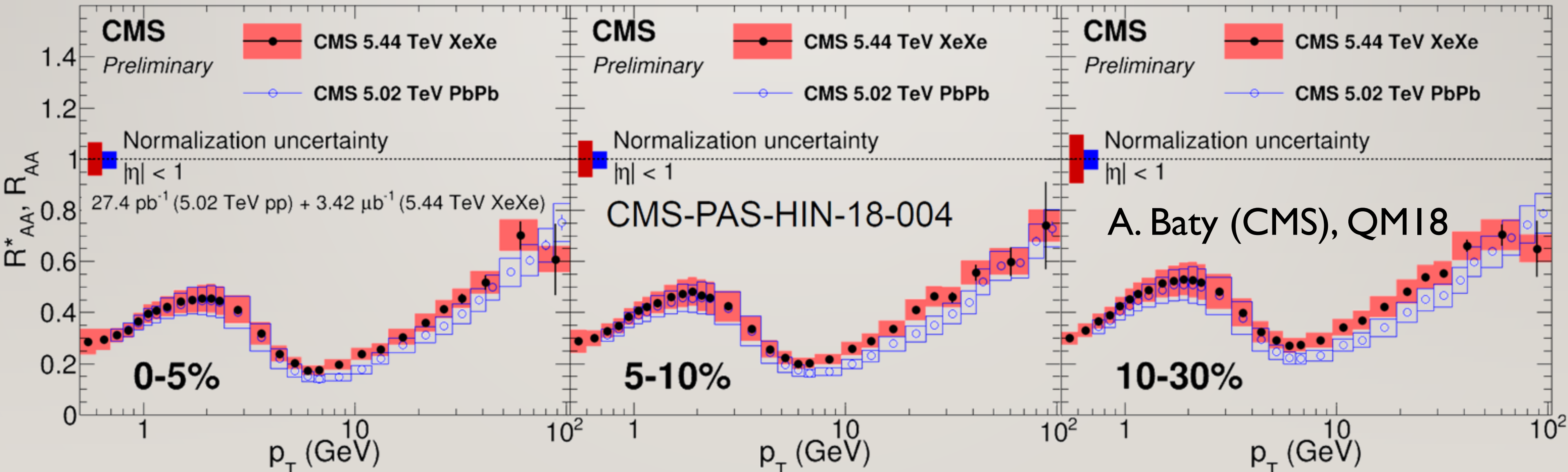
# 32/59 CENTRALITY DEPENDENCE OF SUPPRESSION

- Fine centrality binning up to very peripheral
- Significant change of behavior beyond 80%
- Biases in event selection and collision geometry?
- Pythia without nuclear modification explains this
- No need for quenching in peripheral PbPb?



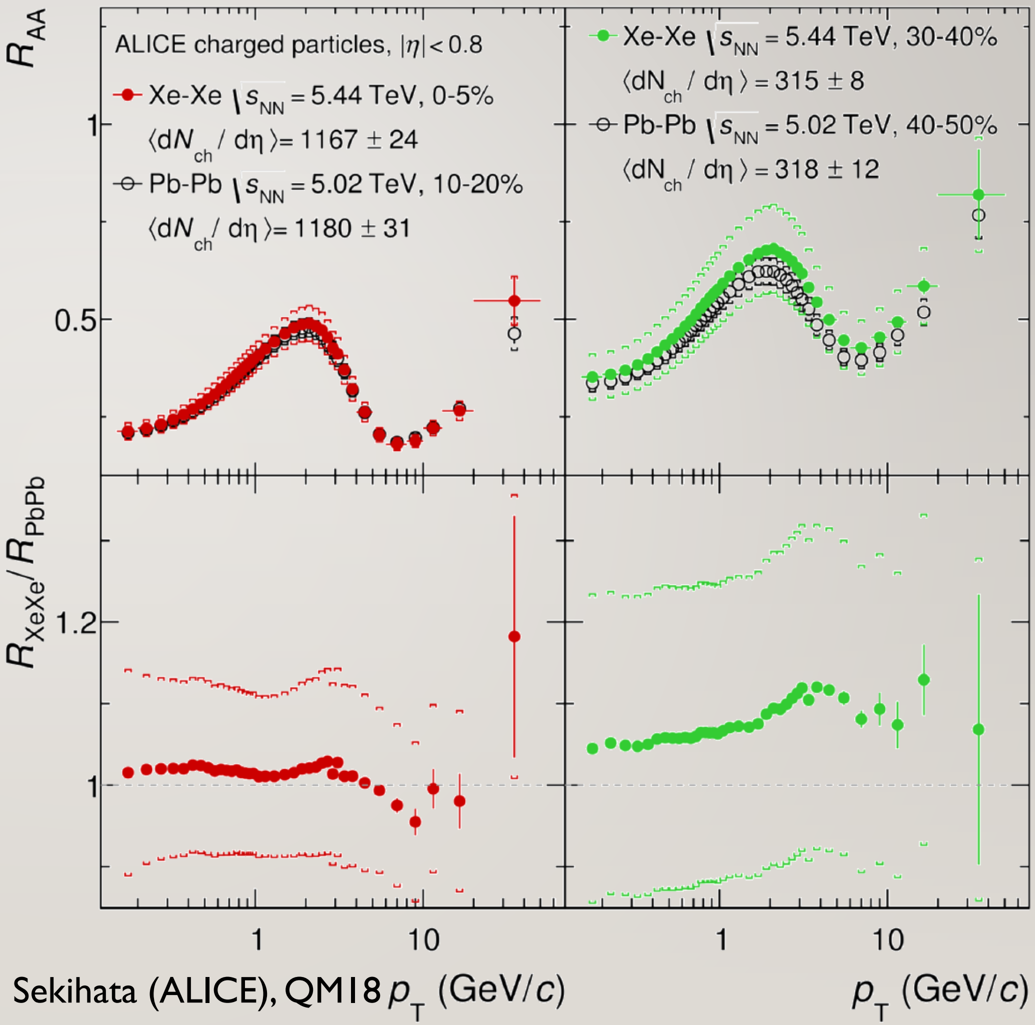
# PB+PB VERSUS XE+XE, CMS

- Extrapolated reference used ($R^*$)
- Compared at same centrality: same oscillatory shape, agreement below 3 GeV
- Less suppression in Xe+Xe at high $p_T$
- Note $p_T$-dependent event selection bias for peripheral collisions (not shown)



# PB+PB VERSUS XE+XE, ALICE

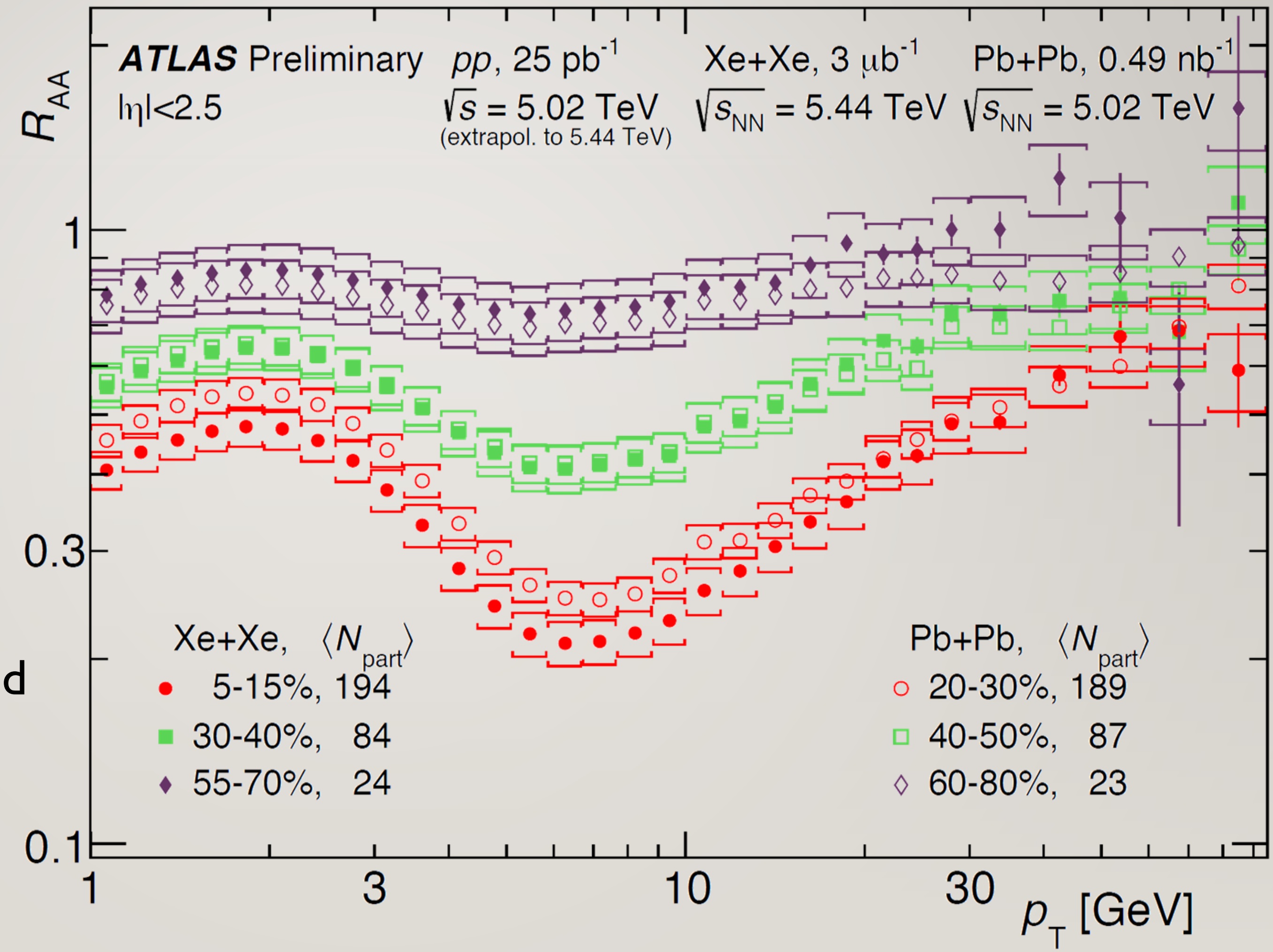
- Xe+Xe is very similar to Pb+Pb if same multiplicity is chosen
- Not the initial state is the same!
- Possible reason: non-trivial interplay of geometry and path length dependence




Sekihata (ALICE), QM18

# PB+PB VERSUS XE+XE, ATLAS

- Characteristic shape: minimum around 7 GeV
- Xe+Xe and Pb+Pb very similar
- Central events: Xe+Xe a bit more suppressed
- Also shape difference

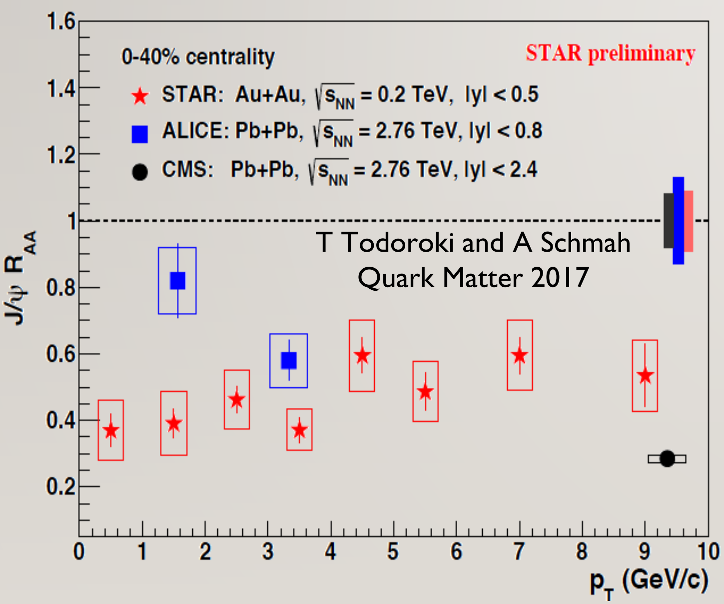


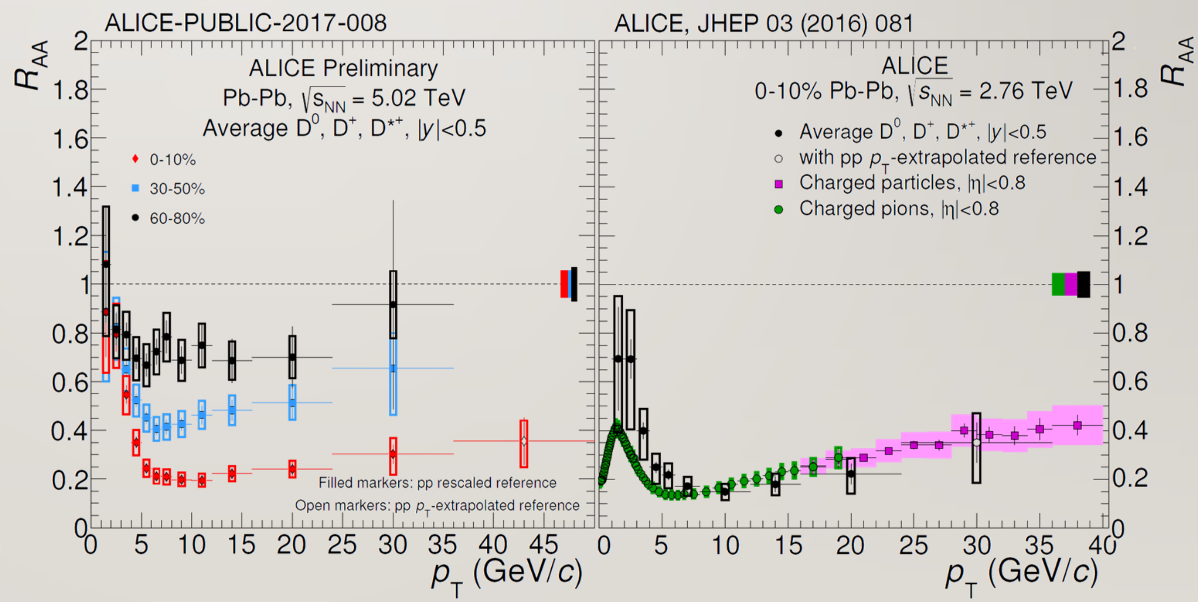
# RECENT HEAVY FLAVOR RESULTS

- Heavy flavor folklore:
    - Light quarks: u, d, s
    - Heavy quarks: c, t, b
    - Open charm: D (qc) or Lambda$_c$ baryons
    - Hidden charm / charmonium: $\eta_c$, J/Ψ (Ψ), X, …; excitations: 1S, 2S, 3S, …
    - Open beauty: B (qb)
    - Hidden beauty / bottomonium: $\eta_b$, ϒ, $X_b$, …
    - Unfortunately, no T meson or "toponium" ☺
- Goal in hadron physics: spectroscopy
- Goal in heavy ion physics: dynamics, suppression, melting, regeneration, …
- Recall sequential melting, heavy quark thermometer effect

# J/Ψ AND D SUPPRESSION AT RHIC & LHC

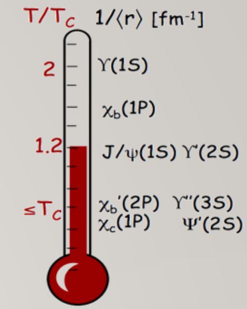
- Recall: heavy flavor probes medium beyond light quark mesons
- Low $p_T$ J/Ψ more suppressed at RHIC, smaller regeneration cross-section
- High $p_T$ J/Ψ more suppressed at LHC: more dissociation due to higher temp.
- Strong D (open charm) suppression at LHC, comparable to light hadrons



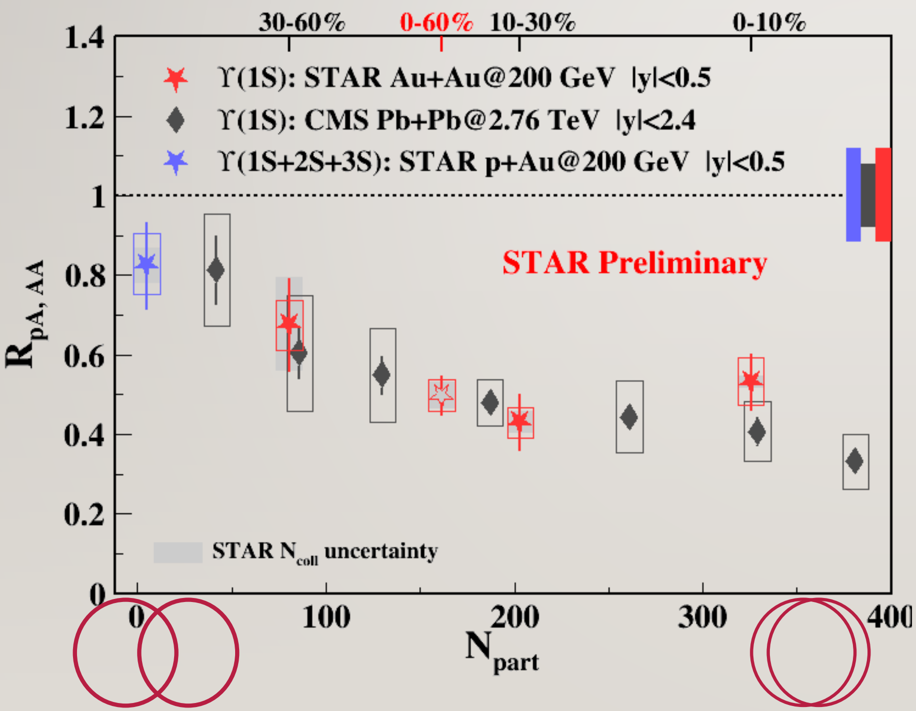



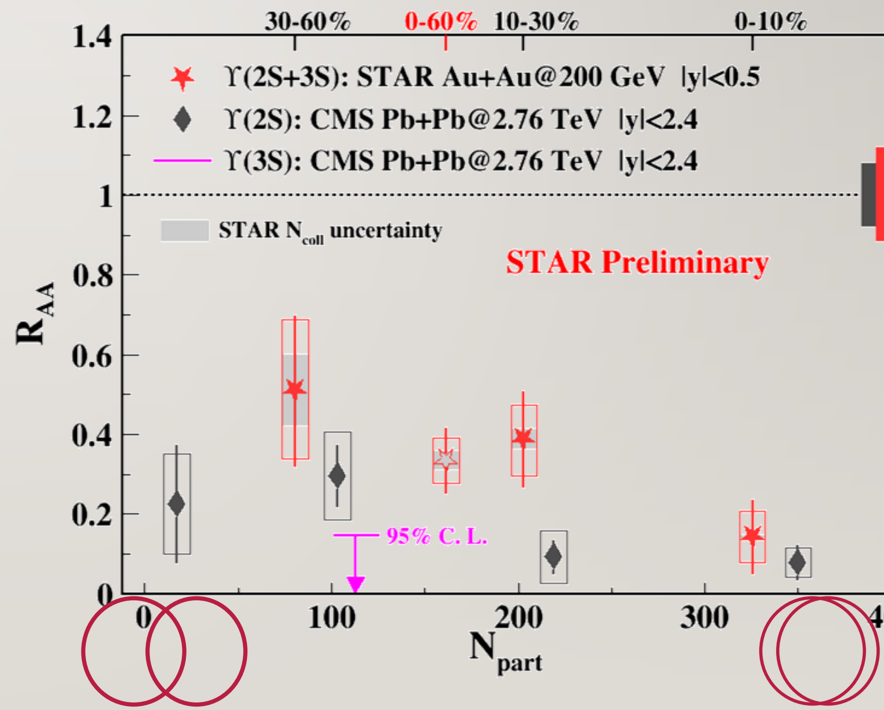
# QUARKONIUM SUPPRESSION AT RHIC & LHC

- Upsilon (Υ(1-2-3S), $b\bar{b}$): more suppression in central collisions
- Sequential melting: Υ(1S) less suppressed than Υ(2S+3S)



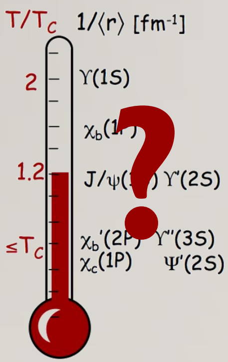

Zaochen Ye and Alexander Schmah, Quark Matter 2017

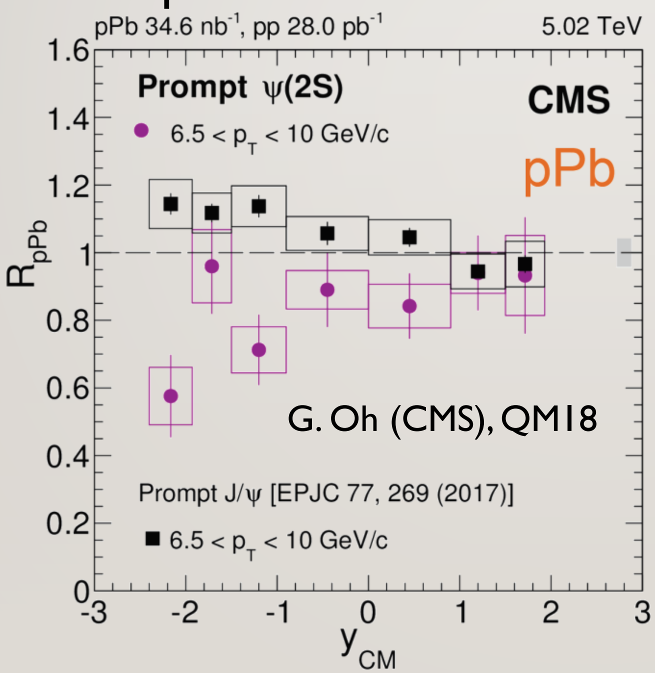


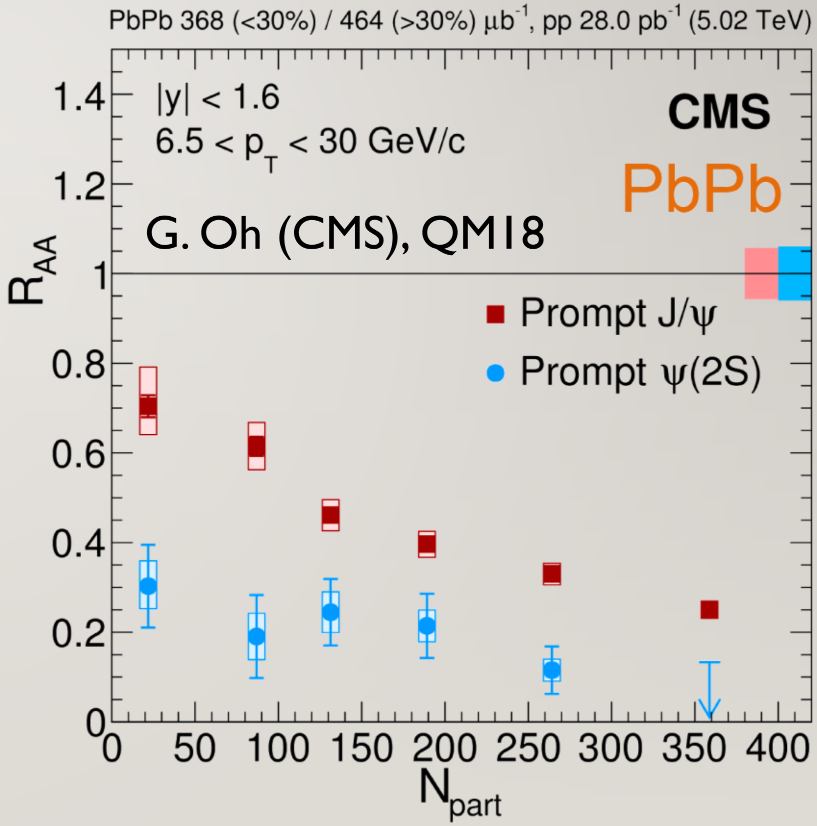



# COLD NUCLEAR EFFECTS VIA J/Ψ IN P+PB

- Suppressed Ψ(2S) compared to J/Ψ
- Prompt J/Ψ enhanced at Pb-going rapidity and at midrapidity
- Effect beyond shadowing and energy loss in p+Pb?

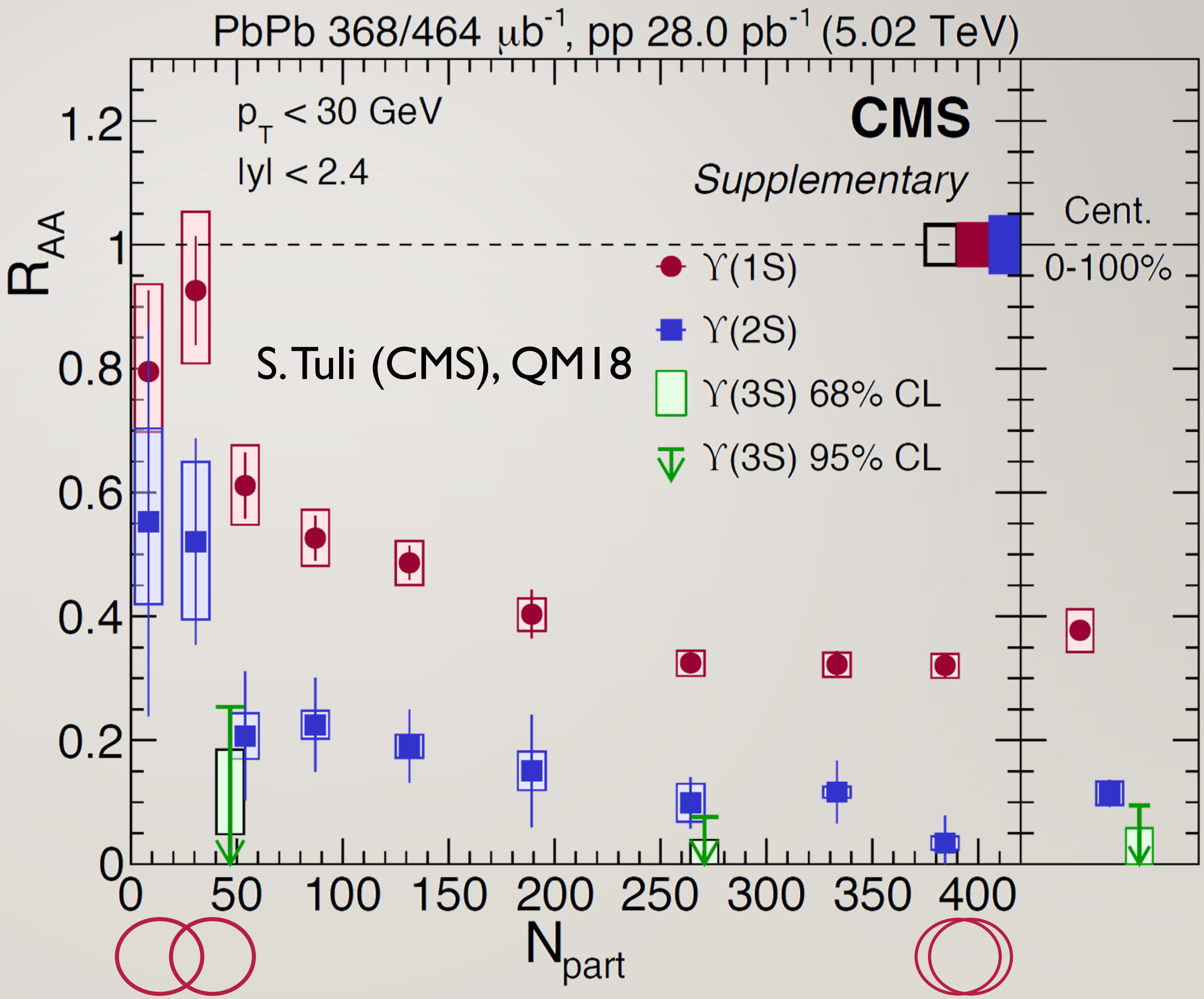


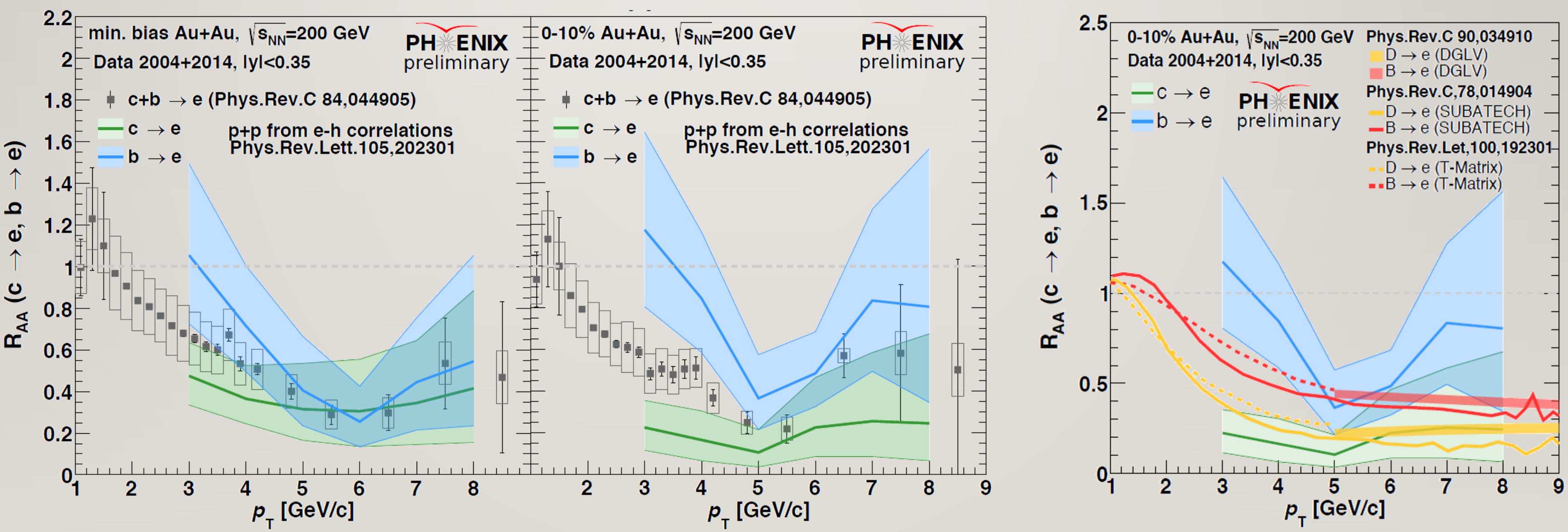
# BOTTOMONIUS STATES WITH CMS

- Clear suppression of all Υ(nS) states
- Sequential suppression for all centralities
- Υ(3S) not seen in Pb+Pb, limits only
- Theory comparision: $T_{ini}$ = 500-800 MeV (Strickland, Rapp)



# BEAUTY VERSUS CHARM SUPPRESSION AT RHIC

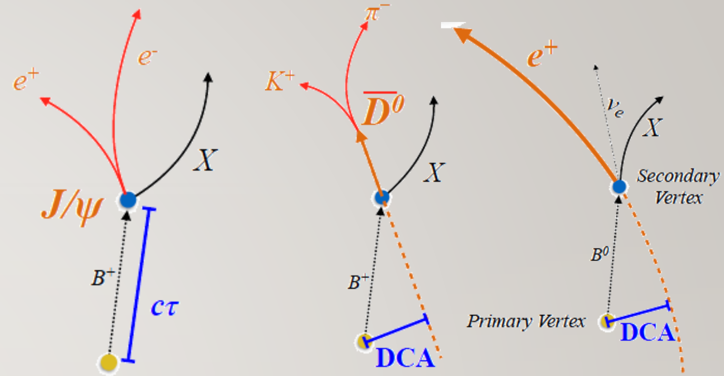
- Nuclear modification factor for c→e, b→e, using unfolding results
- Beauty is less suppressed than charm for 3-5 GeV/c
- Charm in 0-10% is more suppressed than in Minimum Bias
- Reasonable agreement with theory, strong coupling, very small diffusion coeff

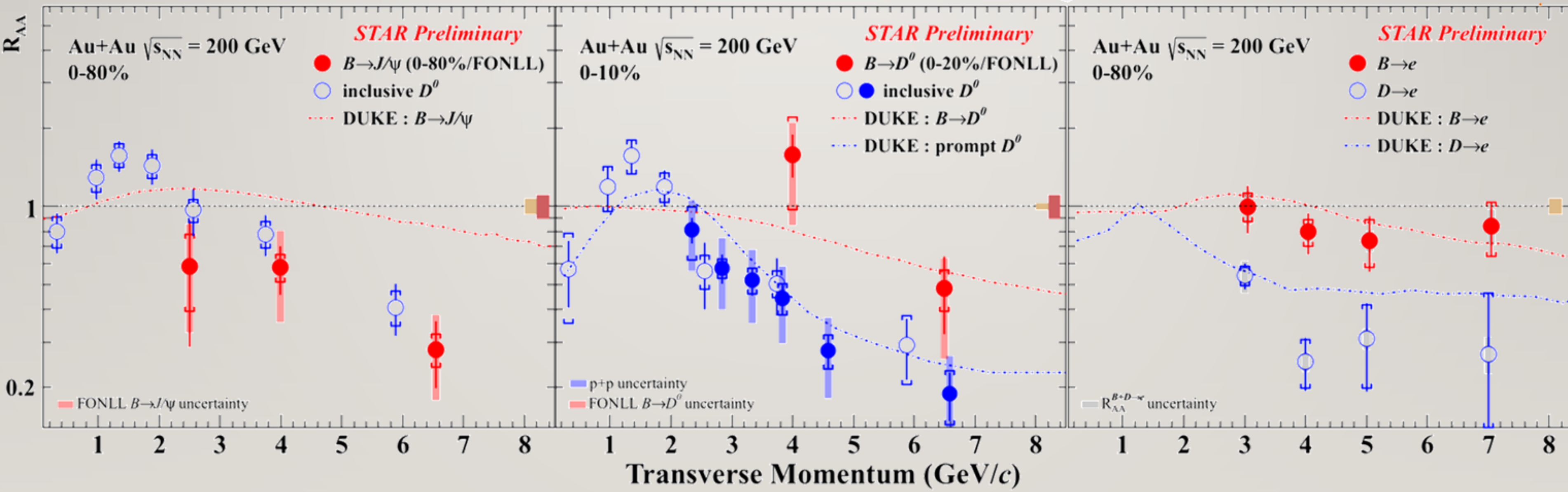



K. Nagashima (PHENIX), Quark Matter 2017

# B MESON SUPPRESSION AT RHIC

- Three ways of measuring B (q+b): J/Ψ, $D^0$, e
- Suppression observed for all channels
- Less suppression of B (qb) than D (qc)?

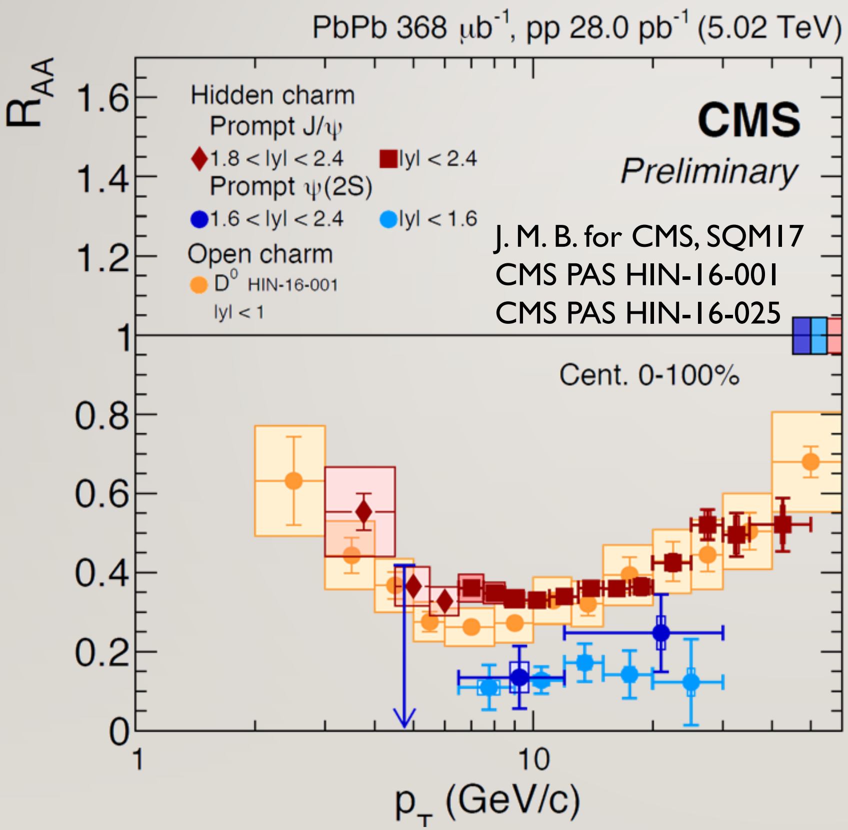


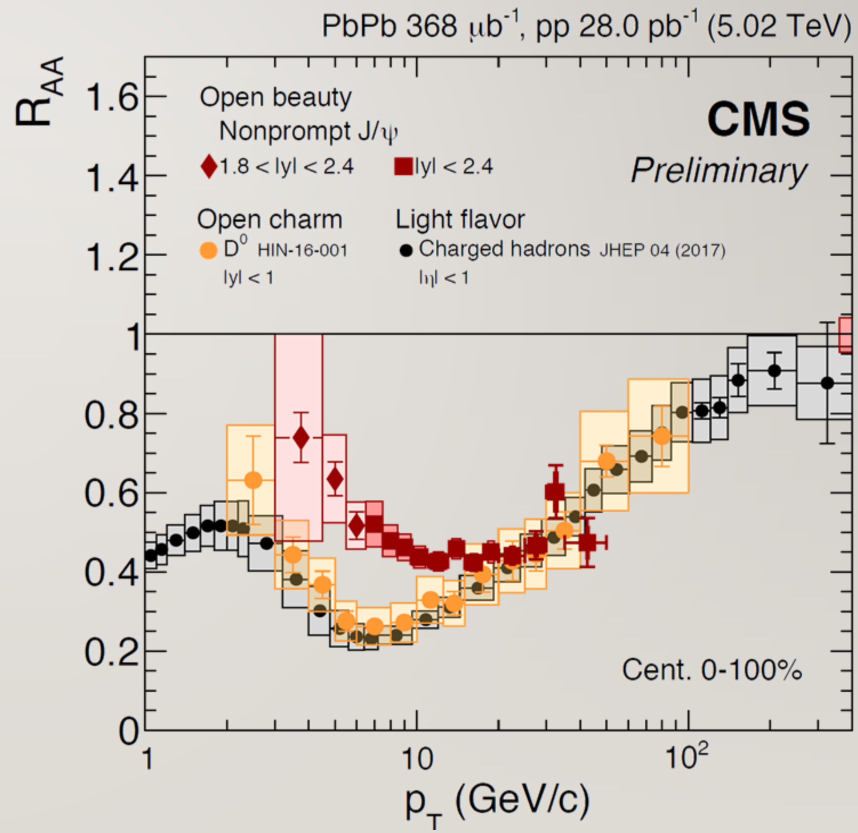




Kunsu Oh and Alexander Schmah, Quark Matter 2017

# MEDIUM EFFECTS WITH HEAVY FLAVOR AT CMS

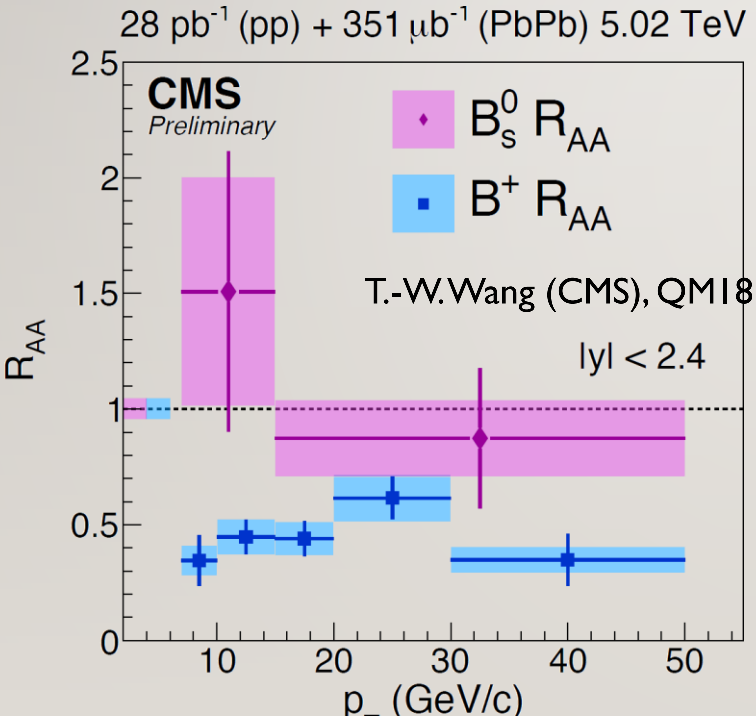
- Similar prompt J/Ψ and $D^0$: charmonium suppression through energy loss?
- High pT: flavor-independent energy loss; low pT: smaller b energy loss

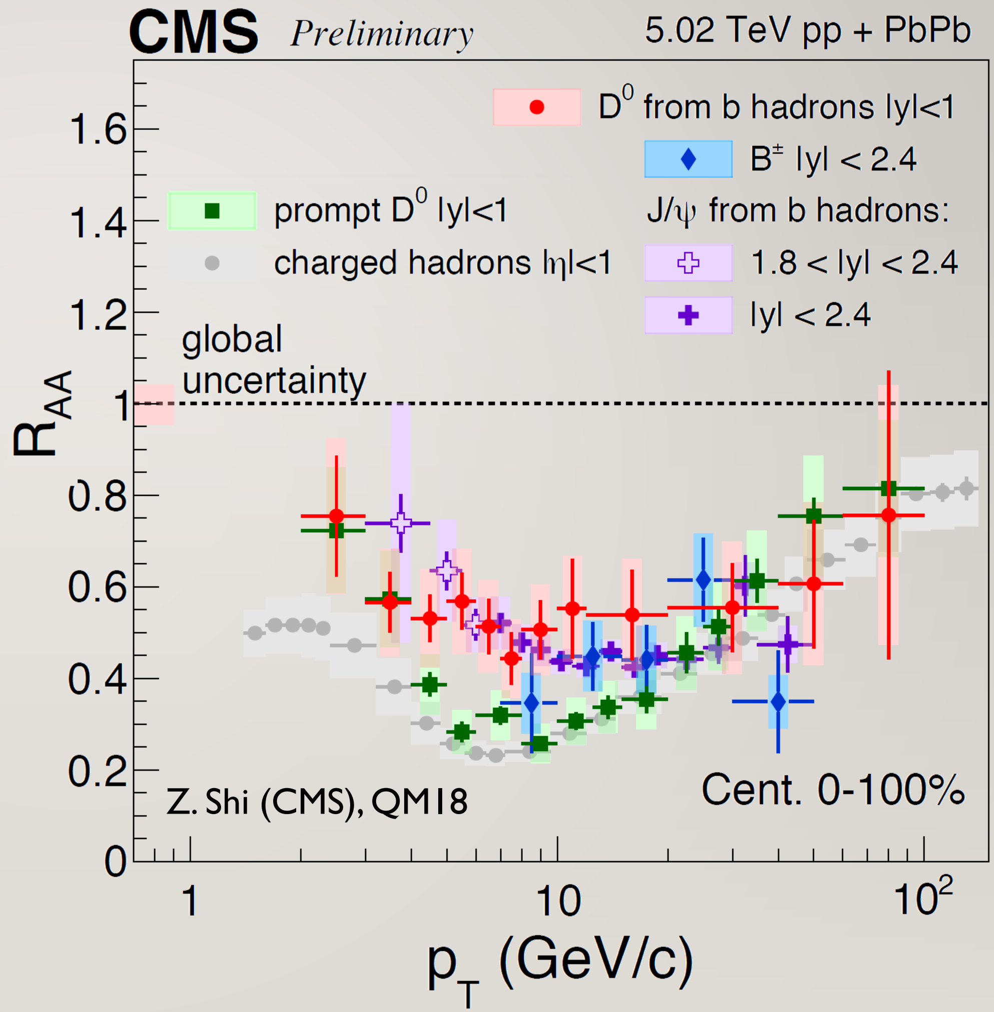


# BEAUTY SUPPRESSION VIA D MESON

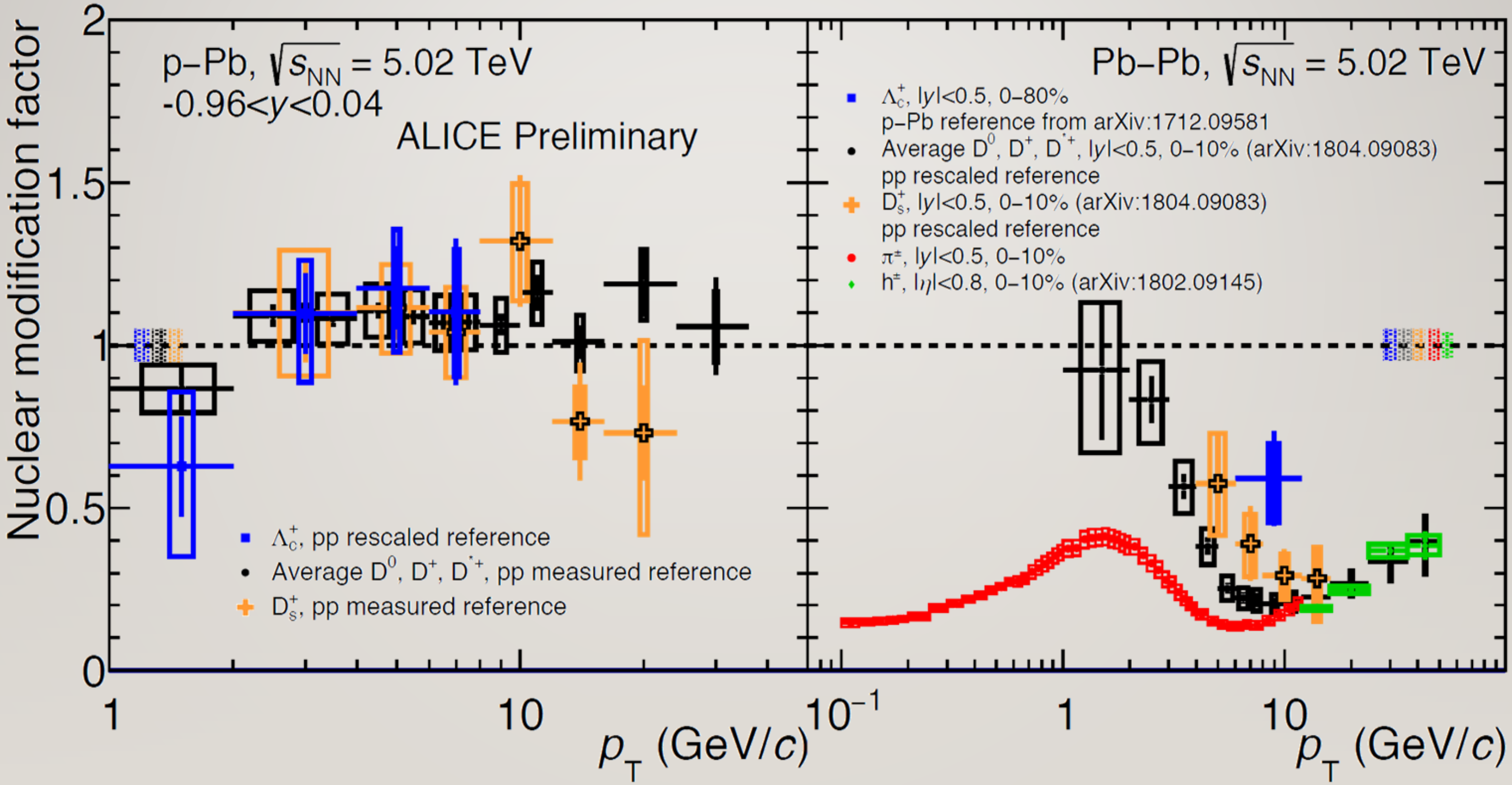
- Similar suppression for light and heavy at high pT
- Enhanced $B_s$: recombination and strangeness enhancement?



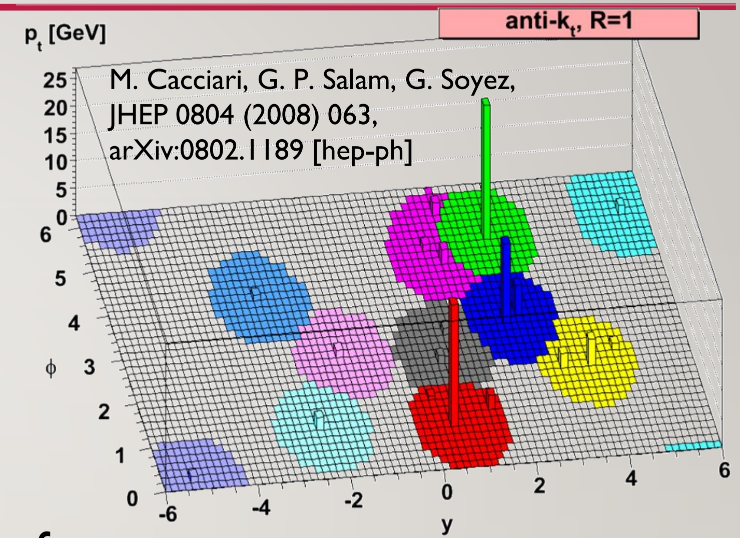



# FAMILY PORTRAIT OF HEAVY FLAVOR RAA

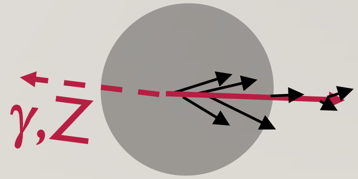
- Even $\Lambda_c$ and $D_s$ measured
- Ordering consistent with recombination expectations



# RECENT JET RESULTS

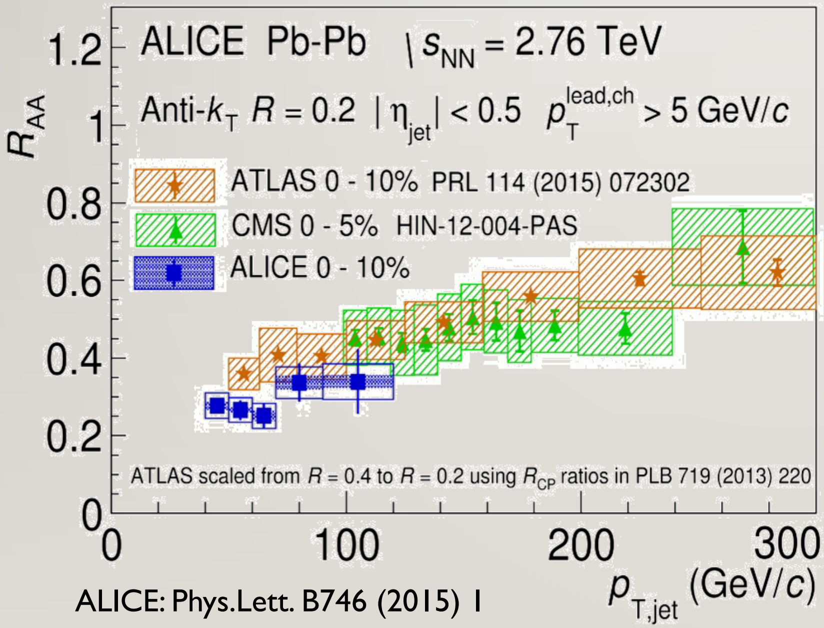



- Jet reconstruction works very well
- High energy physics: missing energy, new decay channels, etc
- Heavy ion physics: jet dynamics, interaction with the medium
- Basic observation: suppression as a function of …
- New directions: jet structure
  - Jet balance/asymmetry with leading/subleading jet
  - Jet fragmentation with internal jet structure
  - Jet-boson correlations: direct medium tomography!

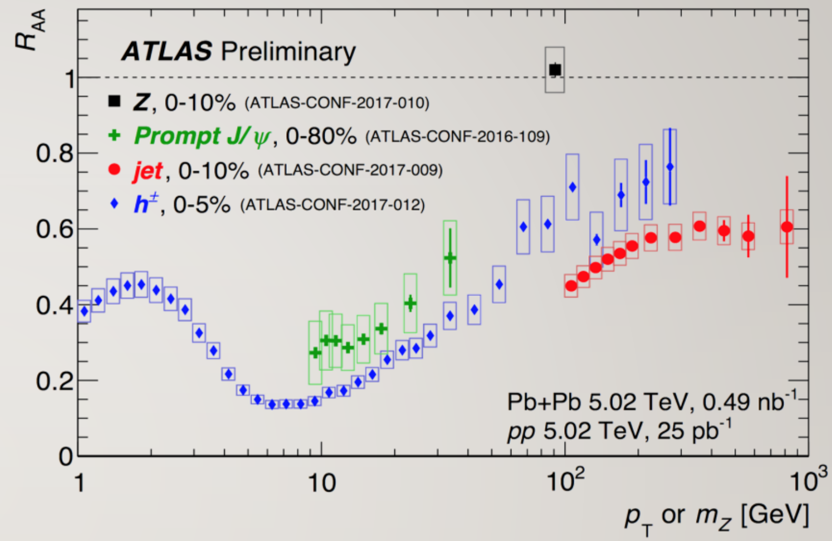


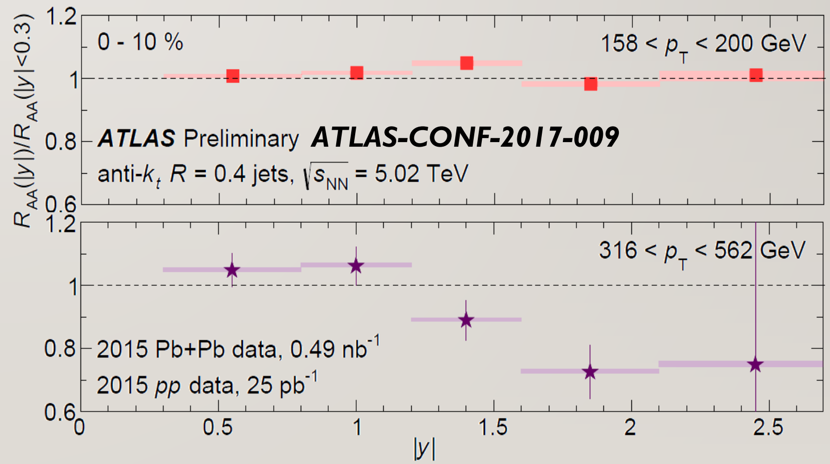
# JET SUPPRESSION AT VERY HIGH PT

- Recall jet reconstruction
- ALICE, ATLAS, CMS: compatible
- Jets more suppressed than $h^{\pm}$
- Note fwd suppression at high pT!



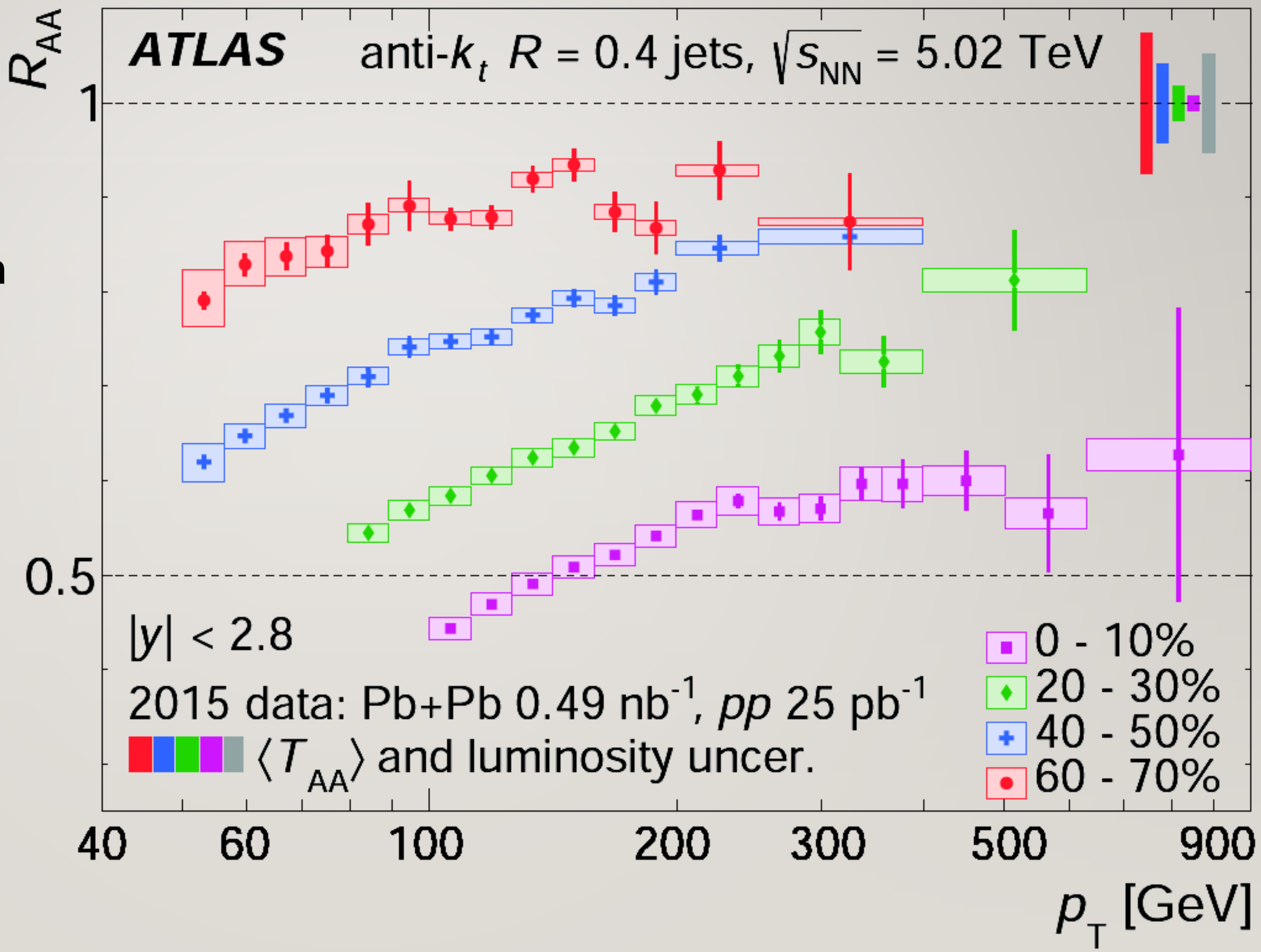

ALICE: Phys.Lett. B746 (2015) 1



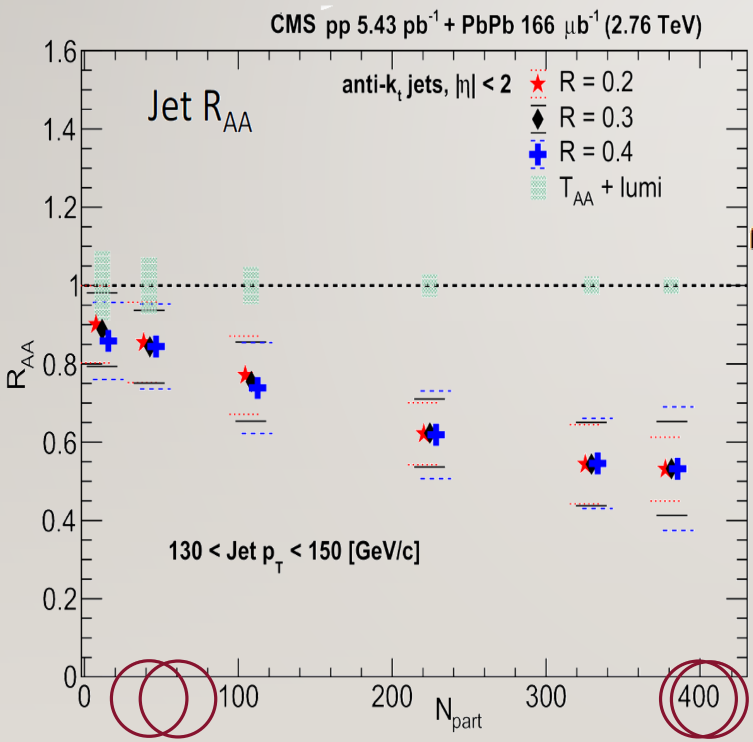
# JET SUPPRESSION VERSUS CENTRALITY

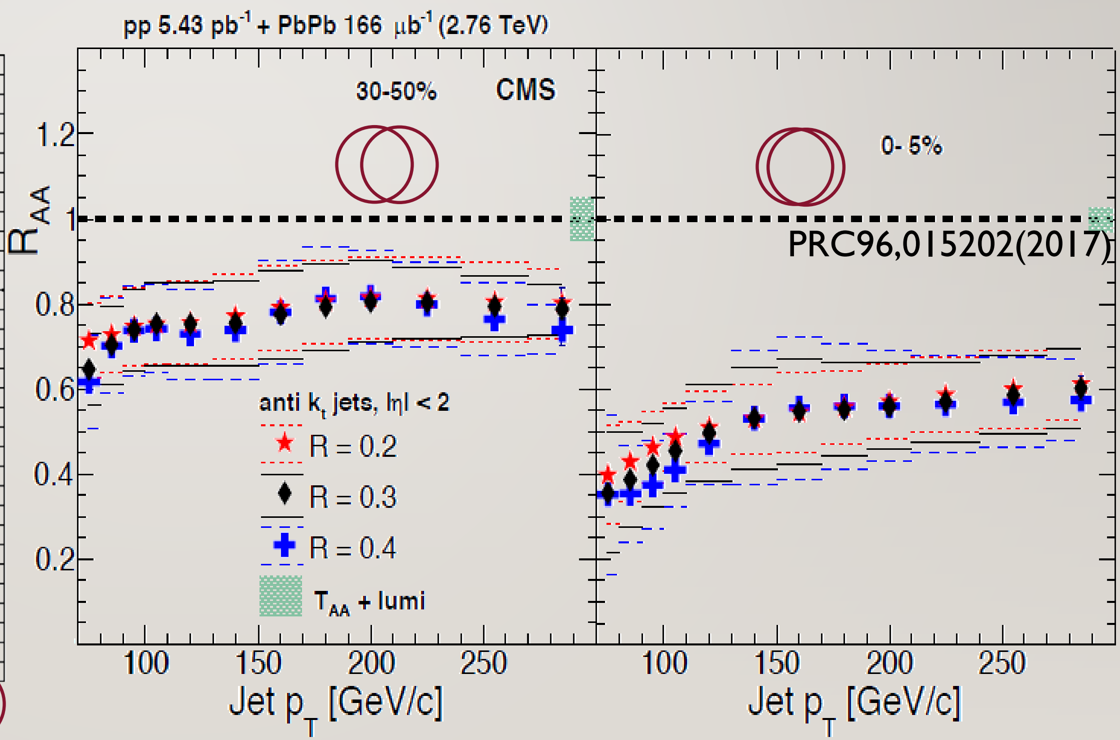
- Significant suppression even at 60-70%
- Flattening at high momenta
- Not shown here
  - No $\sqrt{s_{NN}}$ dependence
  - Strong forward supression at high momenta
  - Note: m/$p_T$ dependence also analyzed



#  CENTRALITY DEPENDENT JET $R_{AA}$ AT LHC

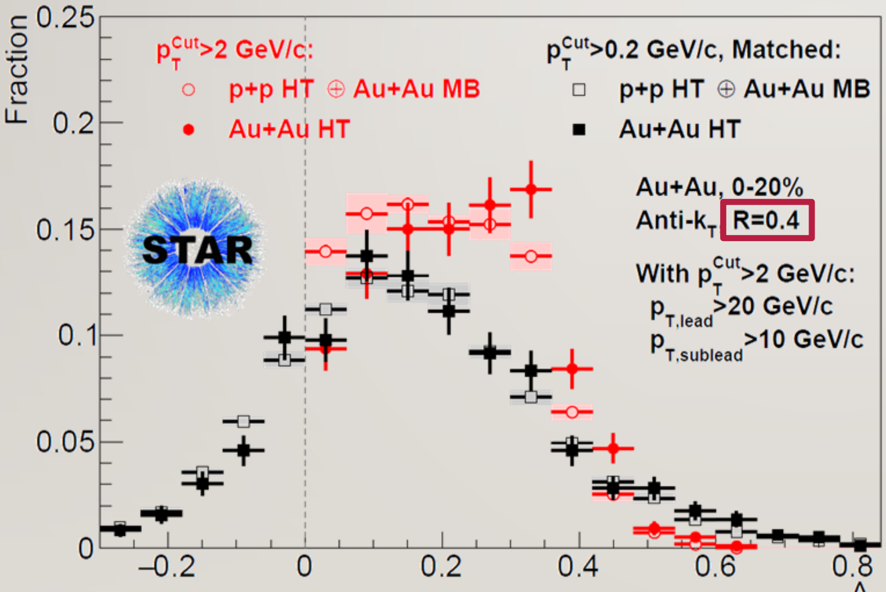
- Fully reconstructed anti-$k_T$ jets analyzed with various jet cone parameters
- No dependence on jet cone radius (for these small values)
- Clear centrality dependence



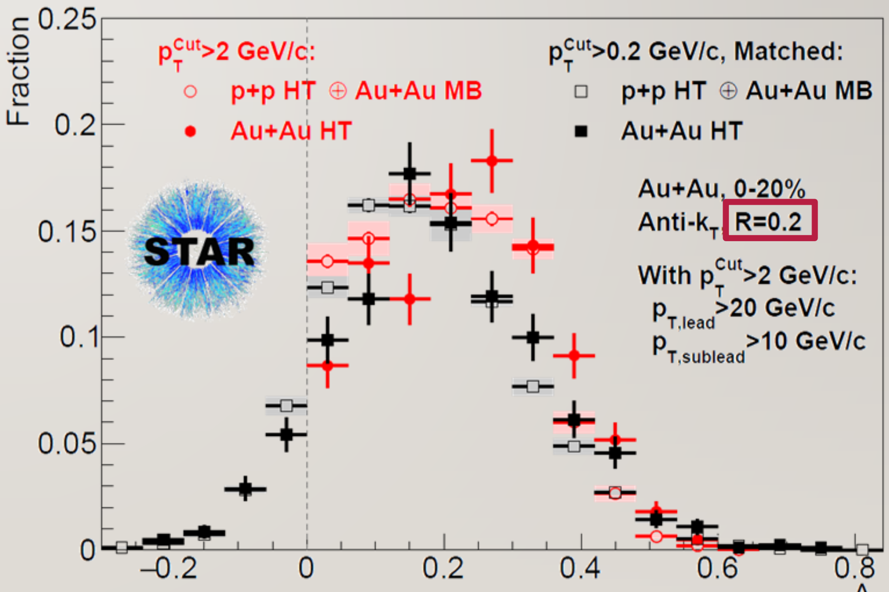



# DIJET IMBALANCE AT RHIC

- Dijet imbalance: $A_J = (p_{T,\mathrm{lead}} - p_{T,\mathrm{sublead}})/(p_{T,\mathrm{lead}} + p_{T,\mathrm{sublead}})$
- $p_T$>2 GeV jets in Au+Au significantly more imbalanced than p+p di-jets
- $p_T$>0.2 GeV: energy balance can be restored to p+p level
- Smaller jet cone: not even jets with softer constituents compatible
- Jet energy loss re-emerges via soft jet constituents, small broadening in Au+Au



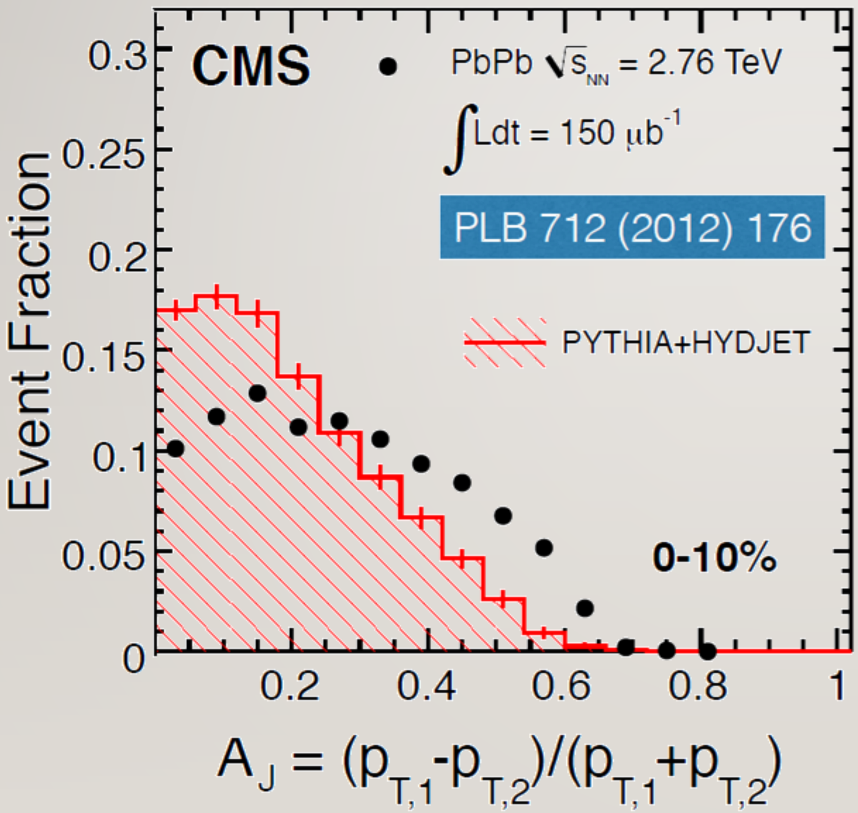

Phys. Rev. Lett. 119, 062301 (2017)

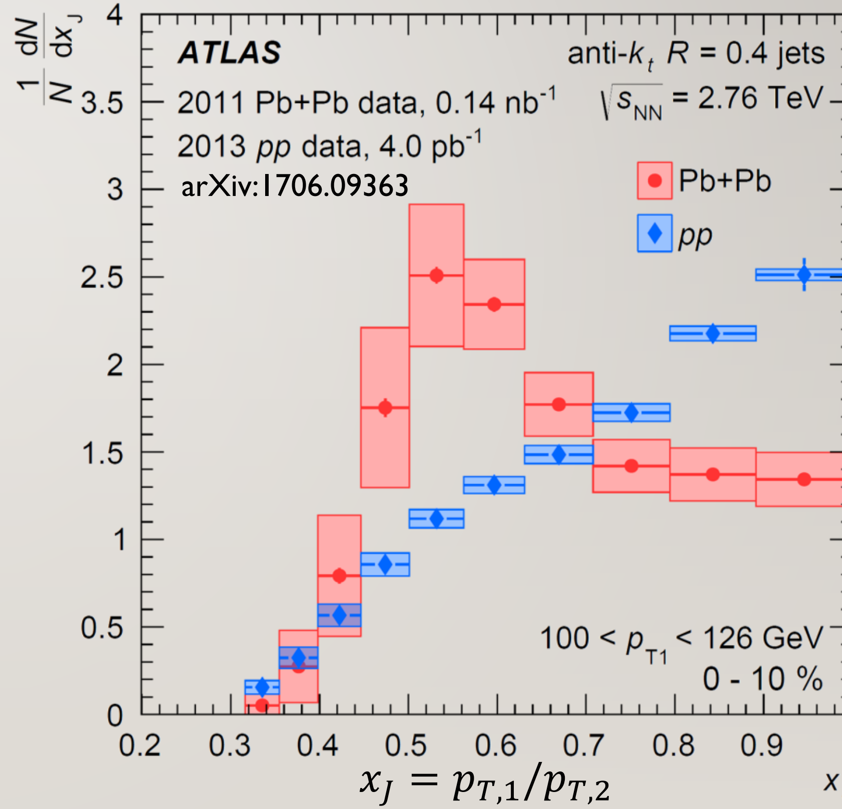



Phys. Rev. Lett. 119, 062301 (2017)

# 51 /59 DIJET ASYMMETRY AT THE LHC

- Modified asymmetry compared to MC and pp, signature of jet-quenching
- Consistent with medium-induced jet energy loss (quenching)



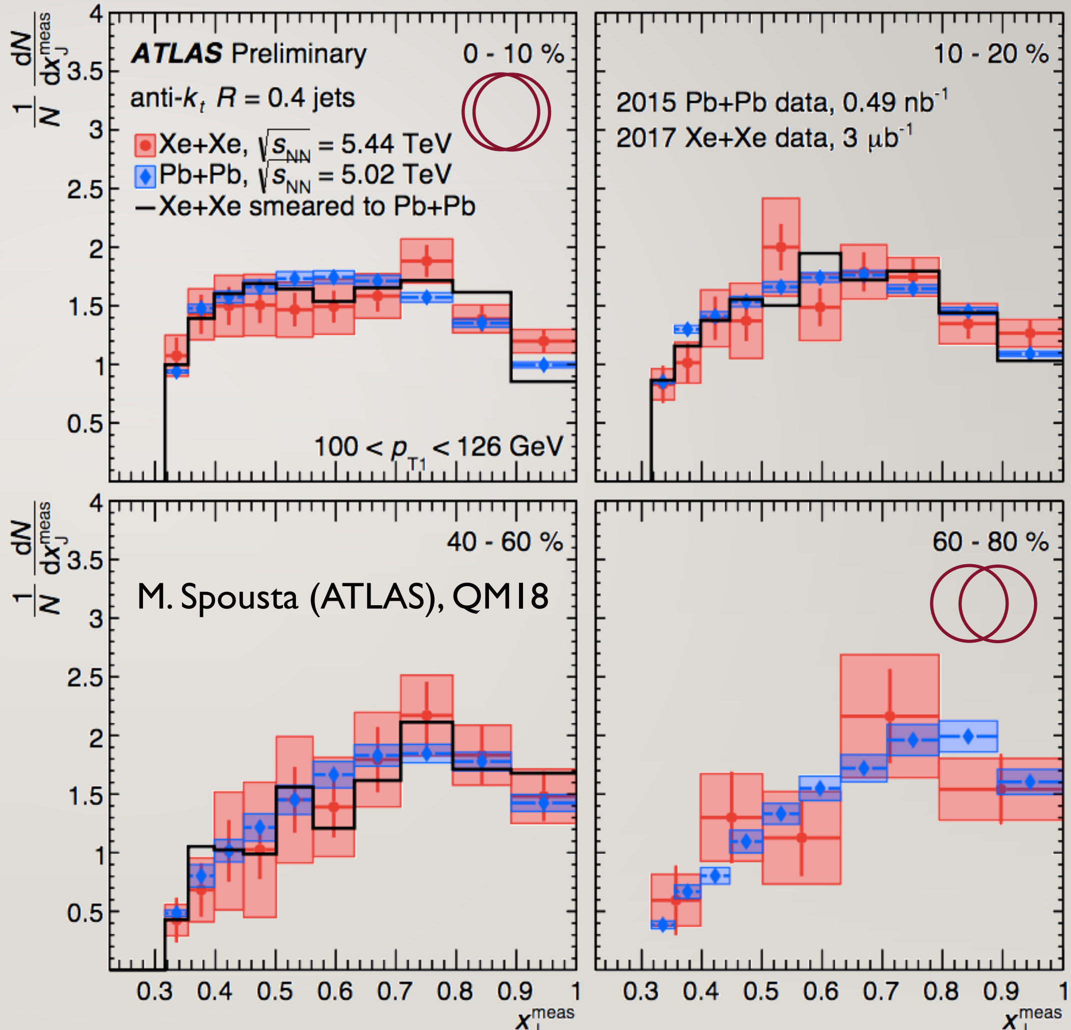



# DIJET ASYMMETRY: XE+XE VS PB+PB

- Dijet asymmetry:

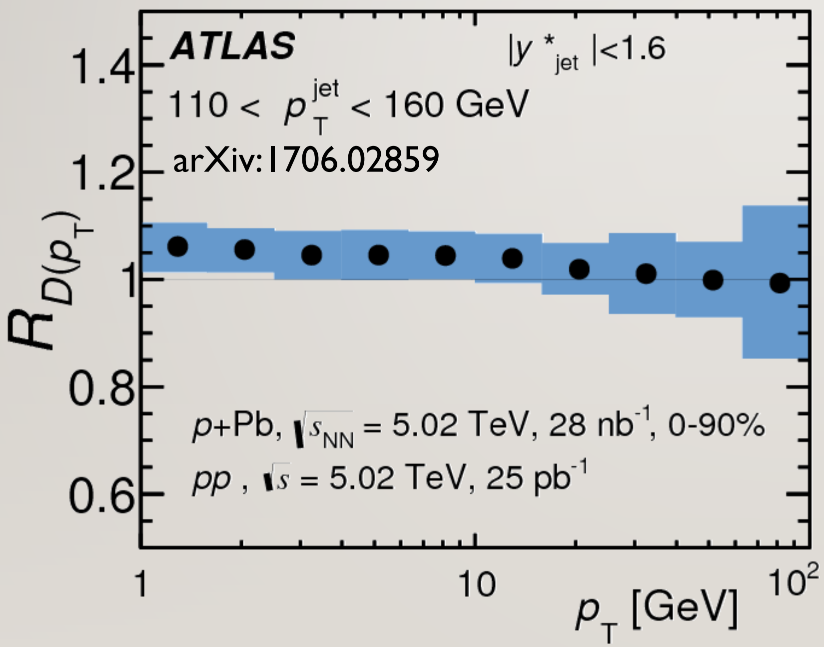
$$x_J = \frac{p_T^{\text{sublead}}}{p_T^{\text{lead}}}$$

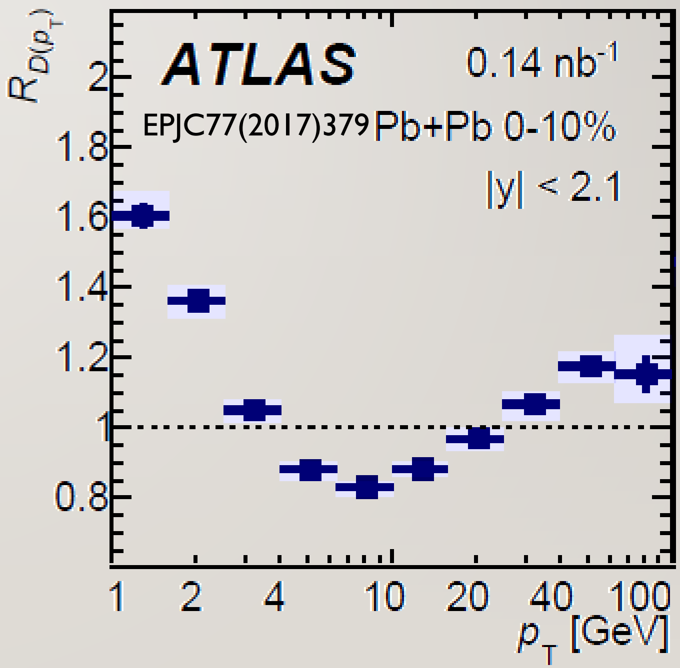
- Reminder: very different in p+p and Pb+Pb
- Xe+Xe: smaller system, larger eccentricity, what happens?
- Compared at the same centrality
- Xe+Xe and Pb+Pb consistent
- No unfolding for detector effects
- Smeared: calorimeter fluctuations used



# JET FRAGMENTATION WITH ATLAS

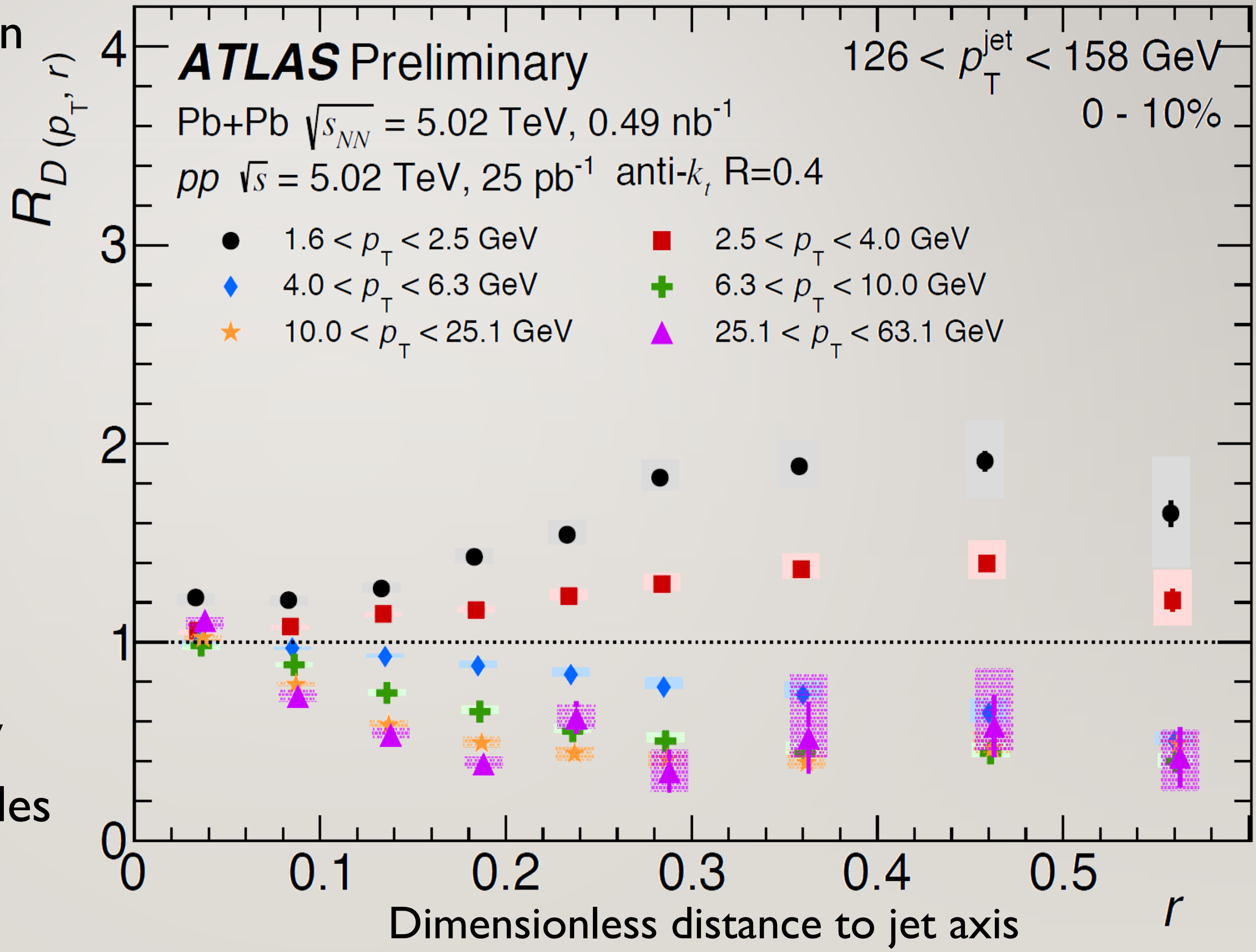
- Jet fragmentation: $D(p_\mathrm{T}) = N_\mathrm{jet}^{-1} dN_\mathrm{ch}/dp_\mathrm{T}$, ratio: $R = D(p_T)_{AA}/D(p_T)_{pp}$
- Clear enhancement/reduction pattern in Pb+Pb, no modification in p+Pb
- Soft enhancement: jet energy loss transferred to soft particles
- Large $p_\mathrm{T}$ enhancement unexpected, detailed quenching calculations required



# 54/59 JET SUBSTRUCTURE WITHIN GIVEN RADIUS

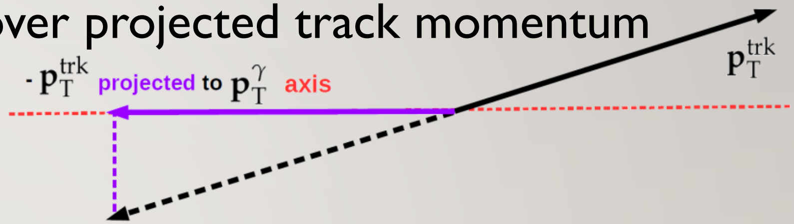
- $D(p_T, r)$: $p_T$ distr. in the jet, within $r$
- $R_D$: $D_{\rm PbPb}/D_{pp}$
- Low $p_T$: enhancement
- Higher $p_T$: suppression
- Energy lost is transferred to low momentum particles at large angle (r)



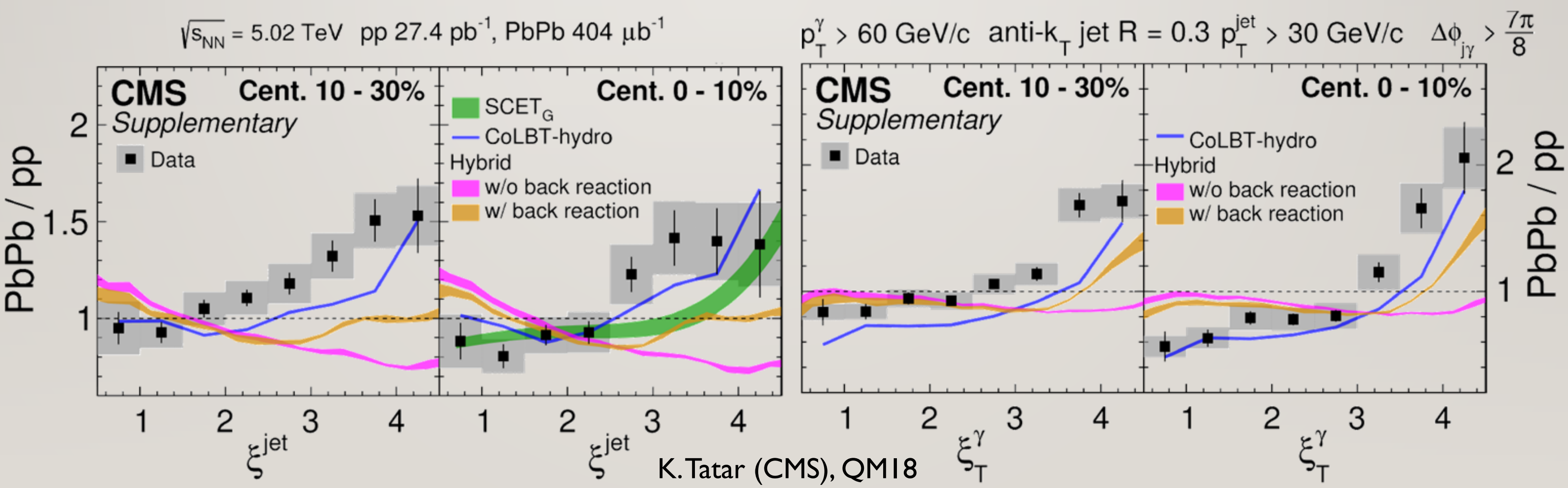
# PHOTON TAGGED JET SUBSTRUCTURE

- Jet with photon counterpart: controls jet initial state
- Useful variable: jet or gamma momentum over projected track momentum

$$\xi_T^\gamma = \ln \frac{-\left|p_T^\gamma\right|^2}{p_T^{trk} \cdot p_T^\gamma} \text{ or } \xi^{\text{jet}} = \ln \frac{-\left|p_T^{\text{jet}}\right|^2}{p_T^{trk} \cdot p_T^{\text{jet}}}$$



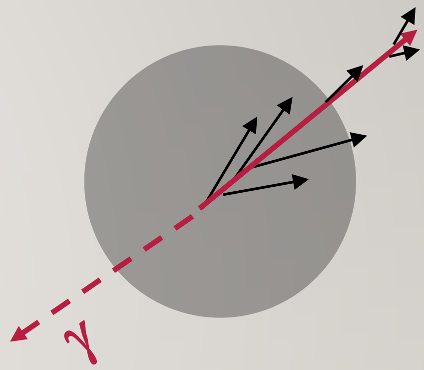

- Depletion at high $p_T$ (small $\xi$): understanding of jet modification

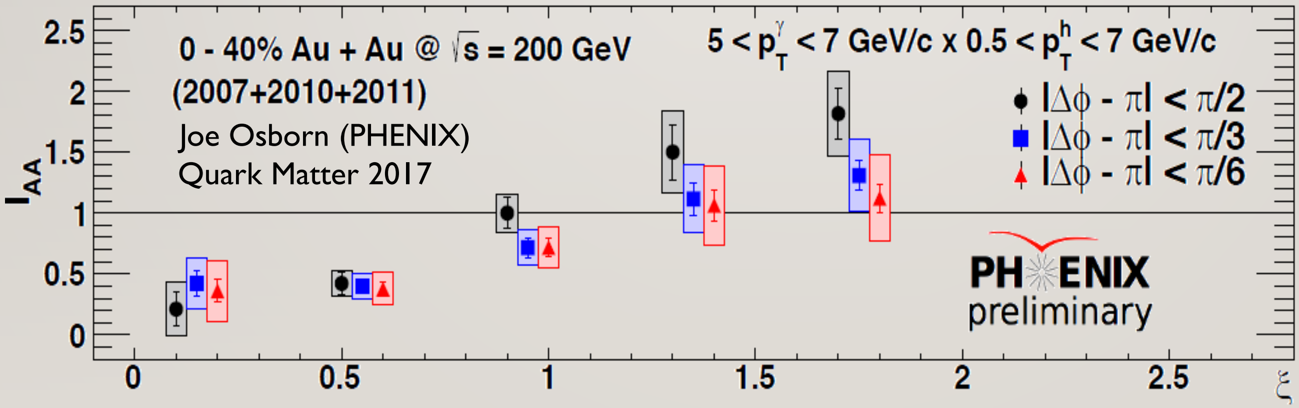


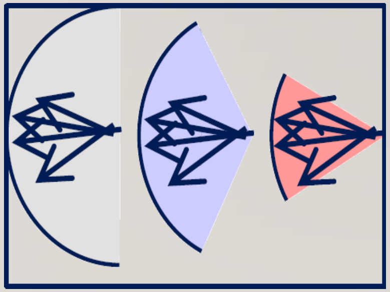

K. Tatar (CMS), QM18

# DIRECT PHOTON – HADRON CORRELATIONS

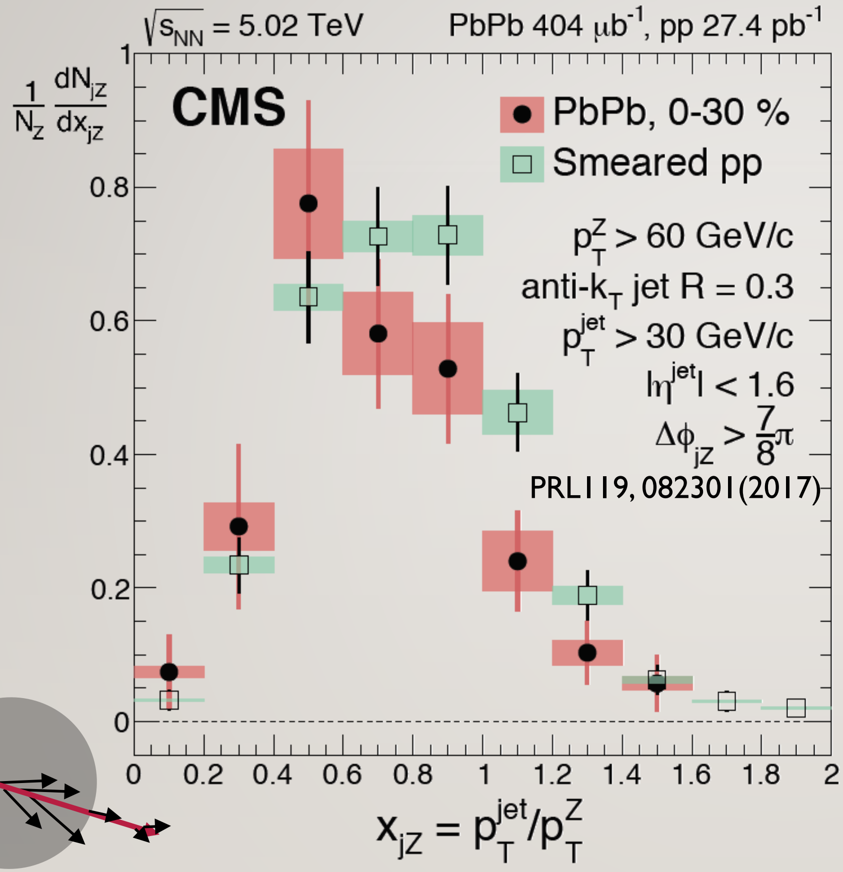
- Photon as a trigger particle for the jet: unmodified momentum, no surface bias
- Introduce $z_T = p_T^h / p_T^\gamma$, define $\xi = \ln(1/z_T)$
- Measure for fragmentation, broadening: $I_{AA}$=$Yield_{AA}/Yield_{pp}$
- Energy redistribution leads to:
  small pT and large angle hadron production
- Compare $I_{AA}$ for different away side ranges
- Transition from suppression to enhancement at $\xi \approx 1$

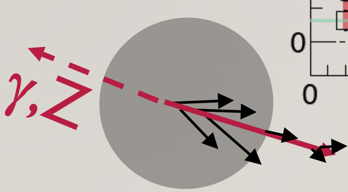


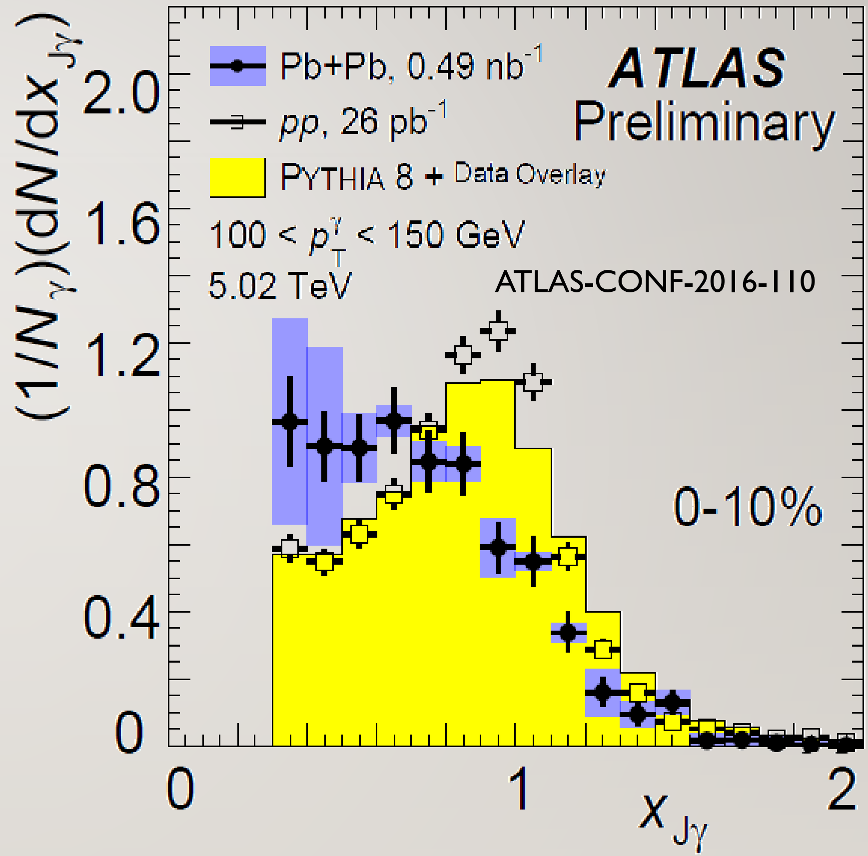



# JET ASYMMETRIES IN JET-BOSON



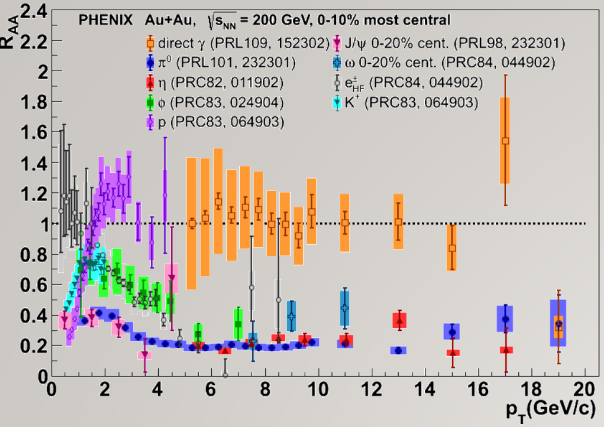



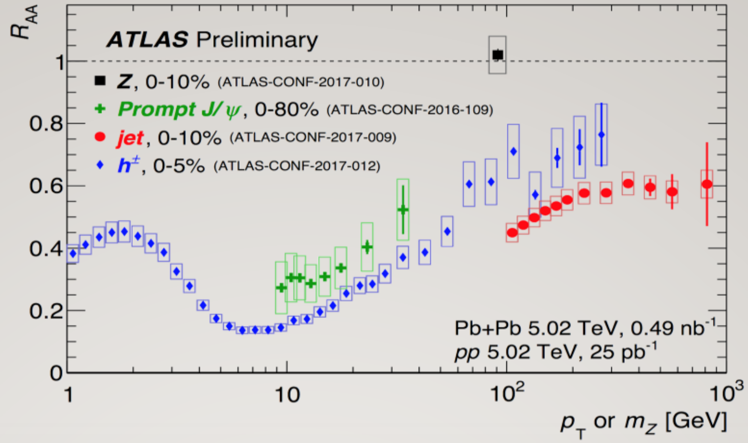



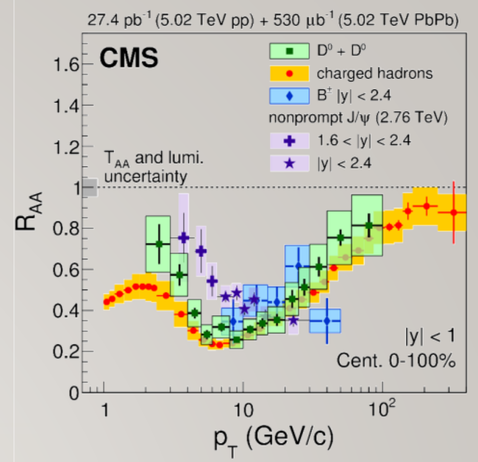

- Modification of momentum balance compared to pp at CMS and ATLAS
- Constrains parton energy loss

# SUMMARY

- Little Bangs @ RHIC & LHC, probed w/ high energy particles and jets
- Energy loss of very high momentum probes on very short distances
- Photons & E-W bosons do not lose energy
- Strongly interacting medium formed, non-hadronic medium
- Medium properties explored in detail:
  - Cold nuclear matter effects under control with systems of different sizes, energies
  - Full jet reconstruction now possible
  - Photon-jet correlations and jet fragmentation show details of jet quenching
  - Heavy flavor probes: hadron creation and melting, temperature
- Ongoing efforts for new, sophisticated results



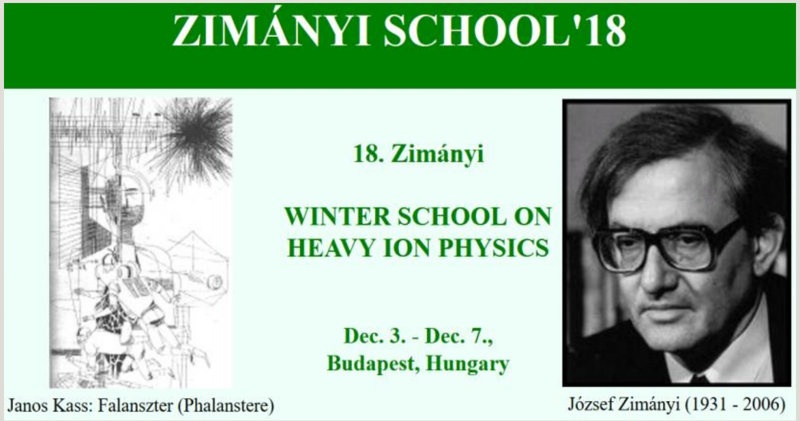





59

# THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects, come to our
Zimányi School 2018
December 3-7., Budapest, Hungary

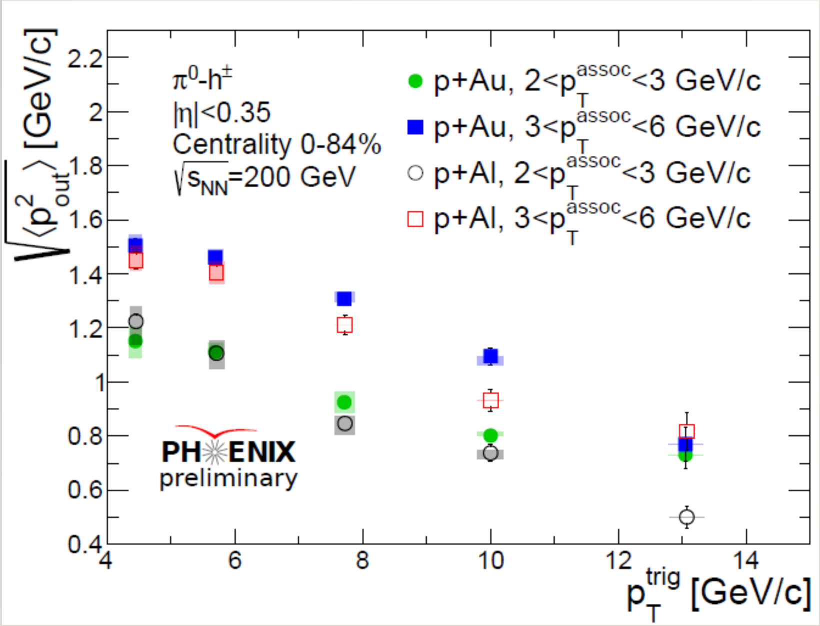


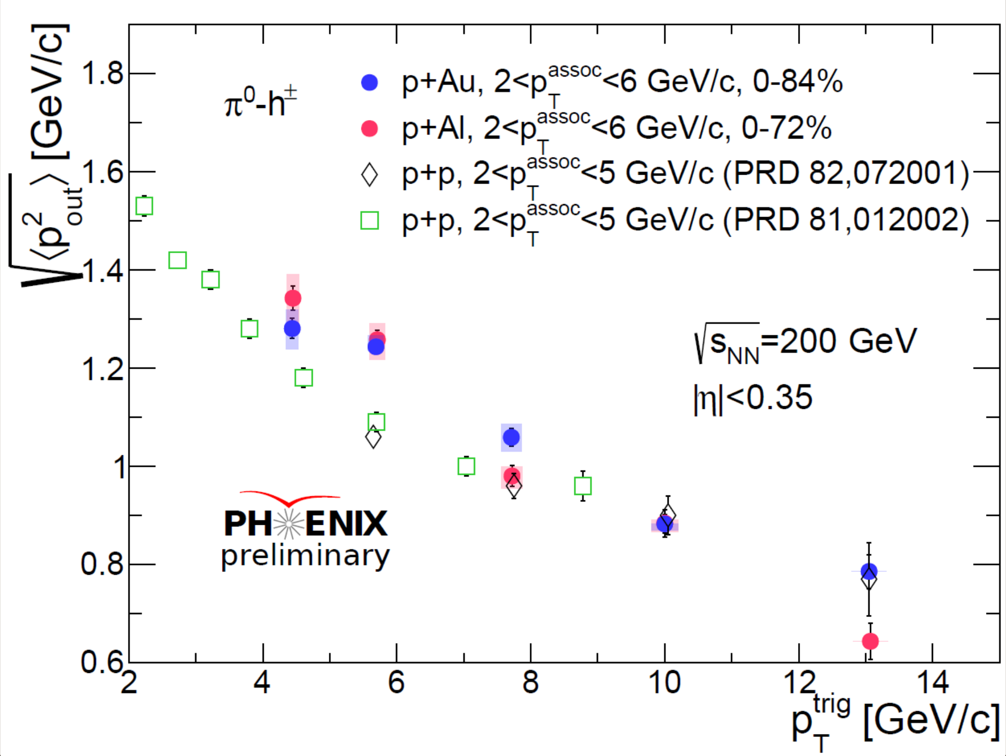

http://zimanyischool.kfki.hu/18

# BACKUP

# NEUTRAL PION – HADRON CORRELATIONS

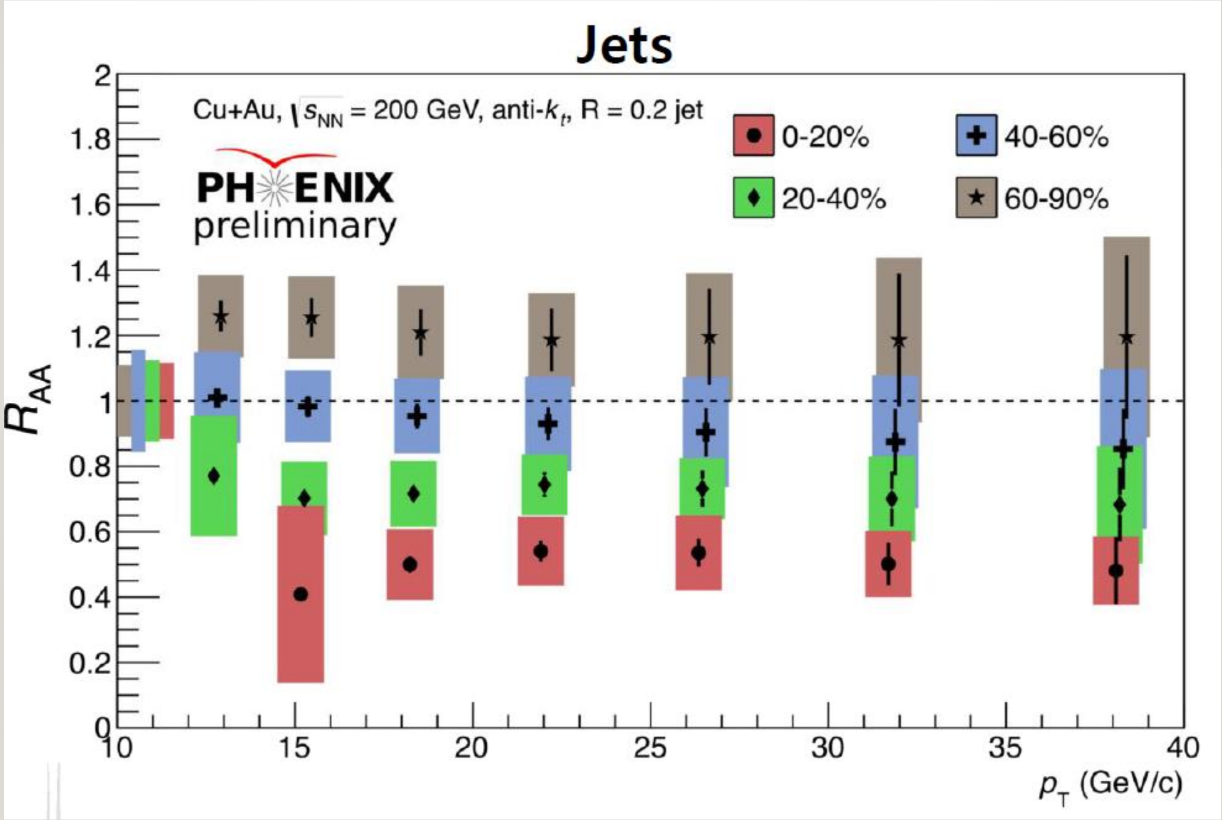
- Neutral pion as a trigger particle for the jet: unmodified momentum
- $p_{out}$: non-perturbative momentum width
- Increase in acoplanarity compared to pp
- Decrease for p+Al versus p+Au



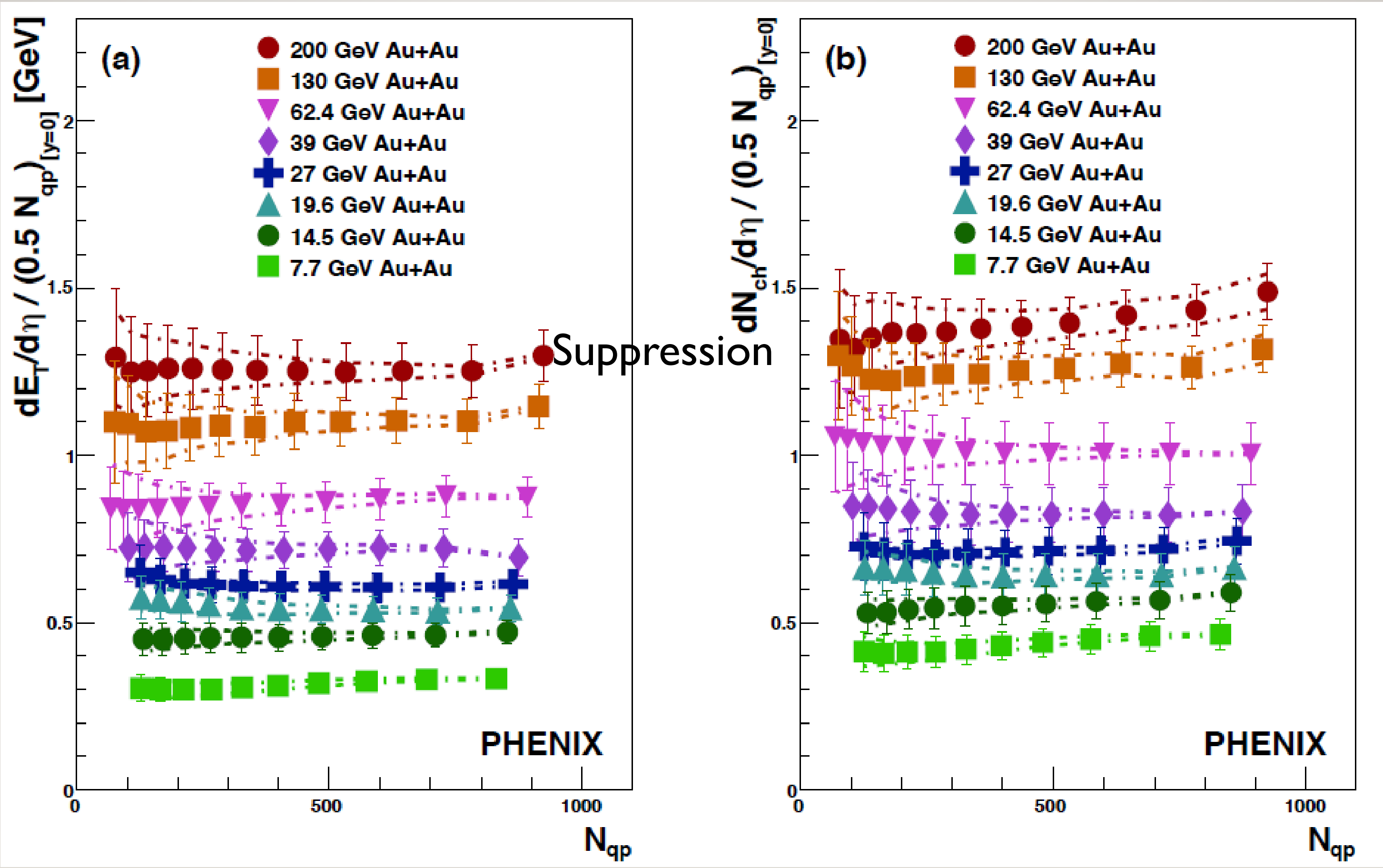
# JET SUPPRESSION IN CU+AU

- Similar behavior to usual Au+Au observations



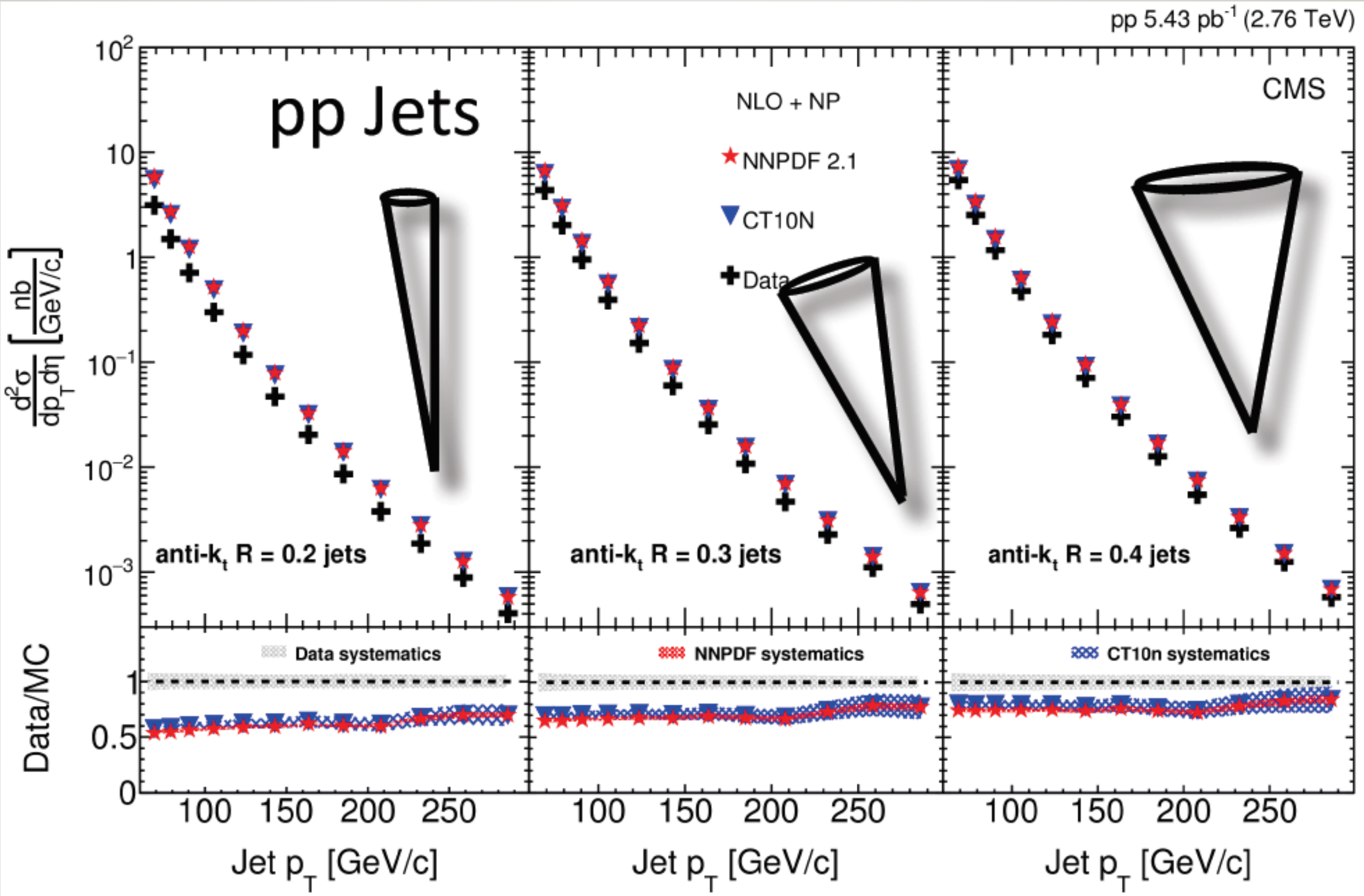
# QUARK PARTICIPANT SCALING

- fds



# 64/59 JET RADIUS DEPENDENCIES IN PP AT LHC

- independent on jet cone radius



# HEAVY FLAVOR SUPPRESSION IN CU+AU

- Charmonia, bound $c\bar{c}$ (prompt J/Ψ): suppressed due to breaking/melting
- Open beauty (via non-prompt J/Ψ): unsuppressed
- Consistent with expectations (EPS09)
- Slight backward enhancement?