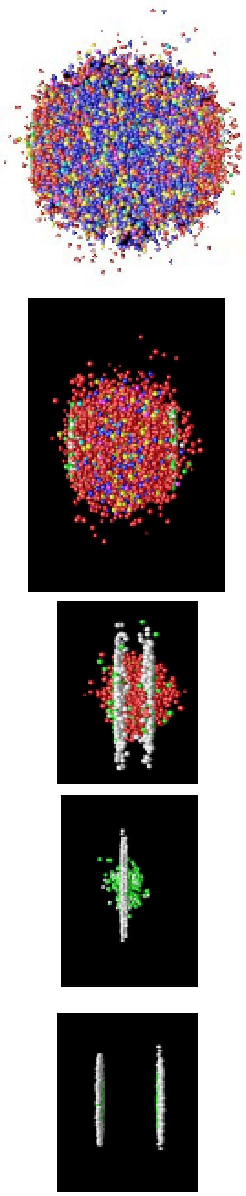
Study of Heavy Ion Collisions with Hard Probes

24th Rencontres de Blois

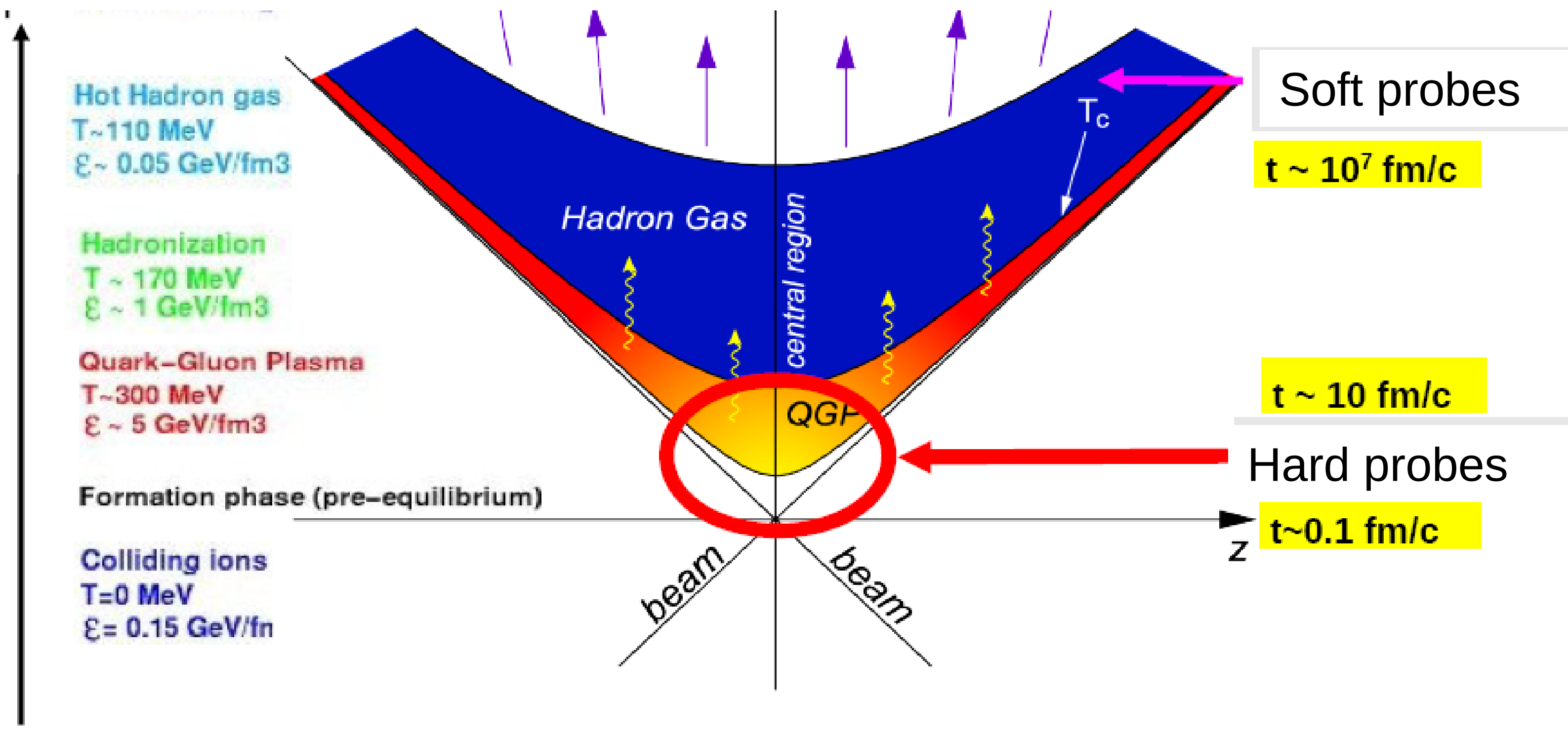
Bolek Wyslouch

May 31, 2012

Creating hot and dense matter in the laboratory

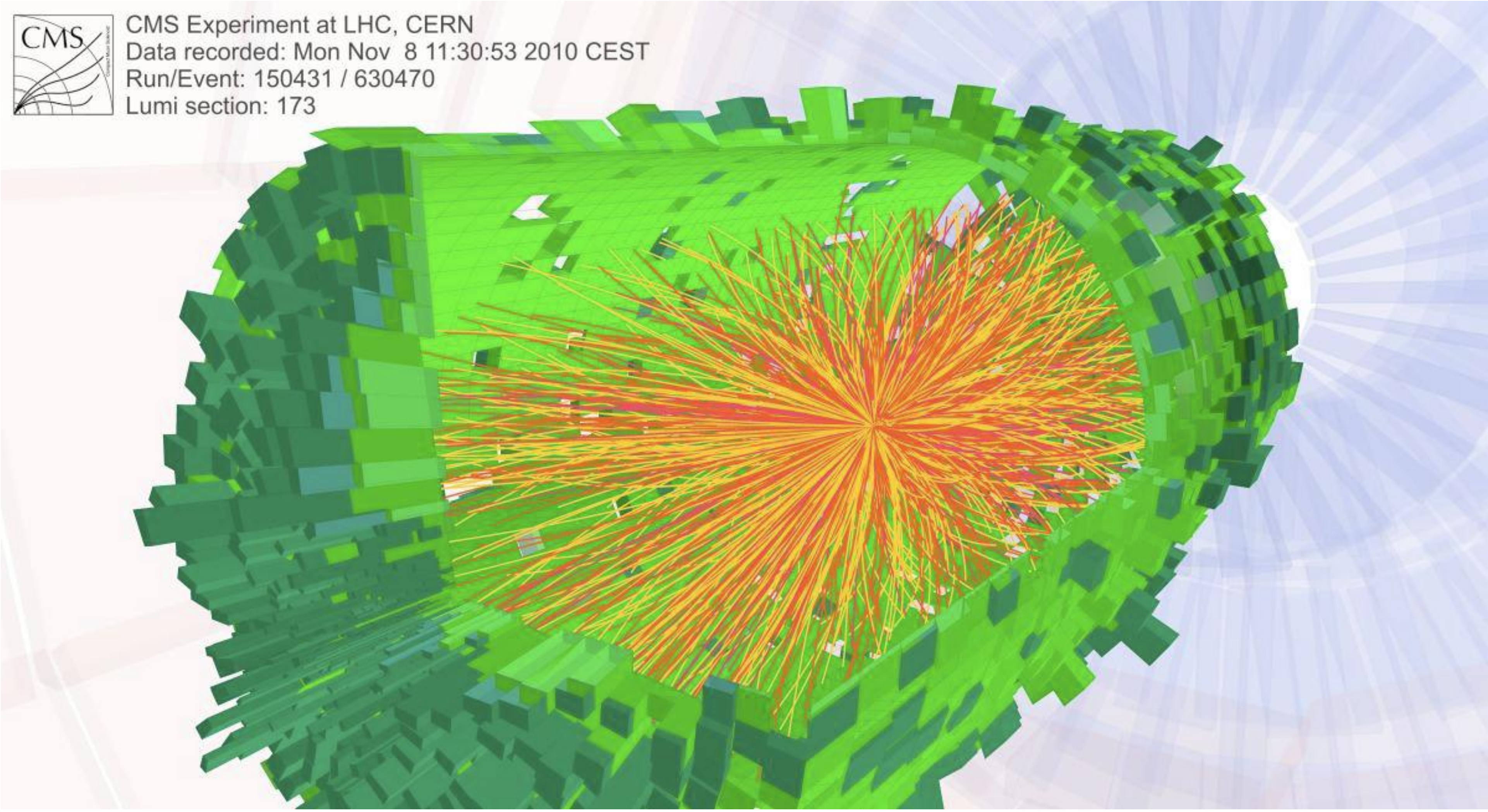


- High energy nucleus-nucleus collisions at highest energies RHIC@Brookhaven: $\sqrt{s_{NN}}$= 200 GeV, LHC,@CERN $\sqrt{s_{NN}}$= 2760 GeV
- Expanding plasma of quarks and gluons with volume of ~1000 fm^3 temperature of few * 10^{12} K (200-800 MeV) and energy density 10-20 GeV/fm^3
- Particle "probes" sensitive to the matter at different stages of the expansion

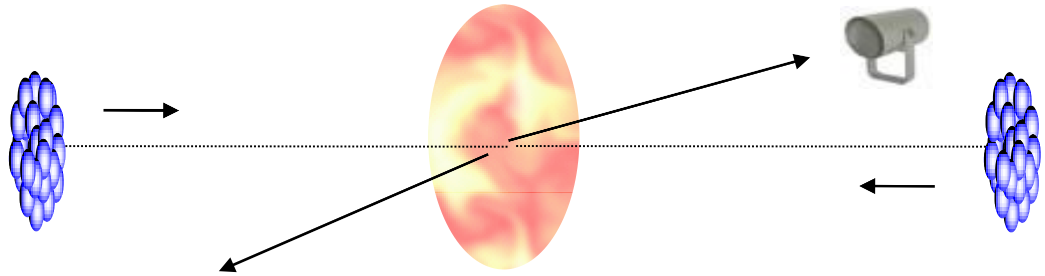


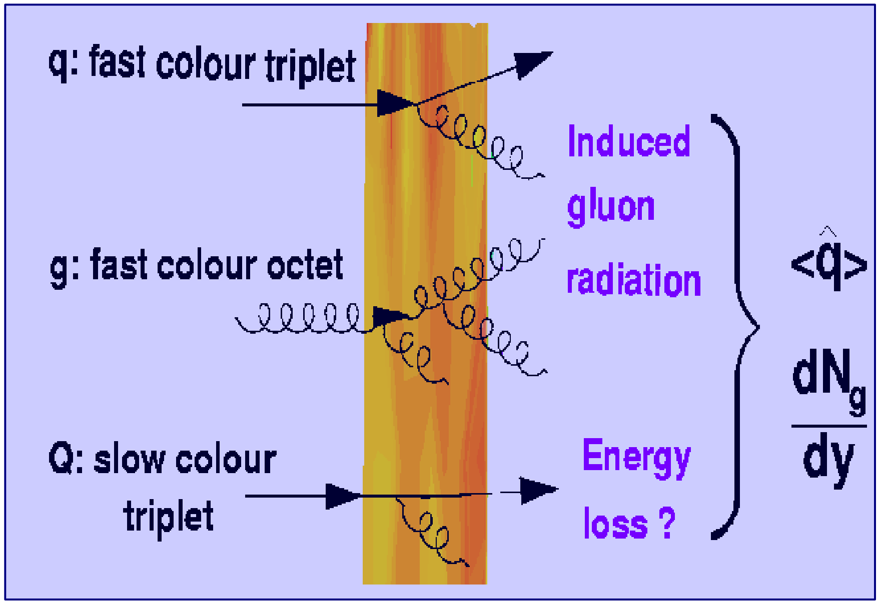
PbPb collision at LHC

- Central collision (b≈0 fm) at $\sqrt{s_{NN}}$ = 2.76 TeV
- >10000 charged particles produced

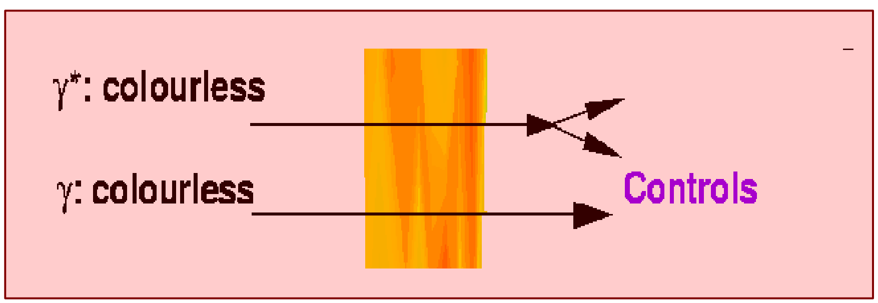


Hard probes in nuclear collisions





Jets, Quarkonia : originated from the hard scattered partons which carry color charges and interact with the medium. Probe the medium



Hot and dense medium

Photons, W, Z : Colorless, provide initial state information. Nuclear parton distribution function (nPDF).

How do we look at hard probes?

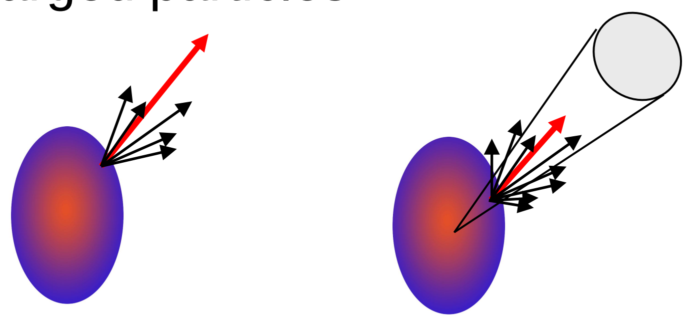
- Nuclear modification factors (R_{AA})

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{“Hot Medium”}}{\text{“Vacuum”}}$$

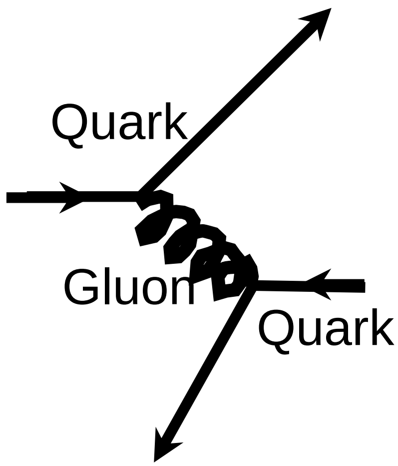
- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

<u>PbPb measurements</u>	<u>pp reference spectrum</u>
Charged particle, K^0, Λ, D, b-quark, jets γ, W, Z	pp collisions at same CM energy

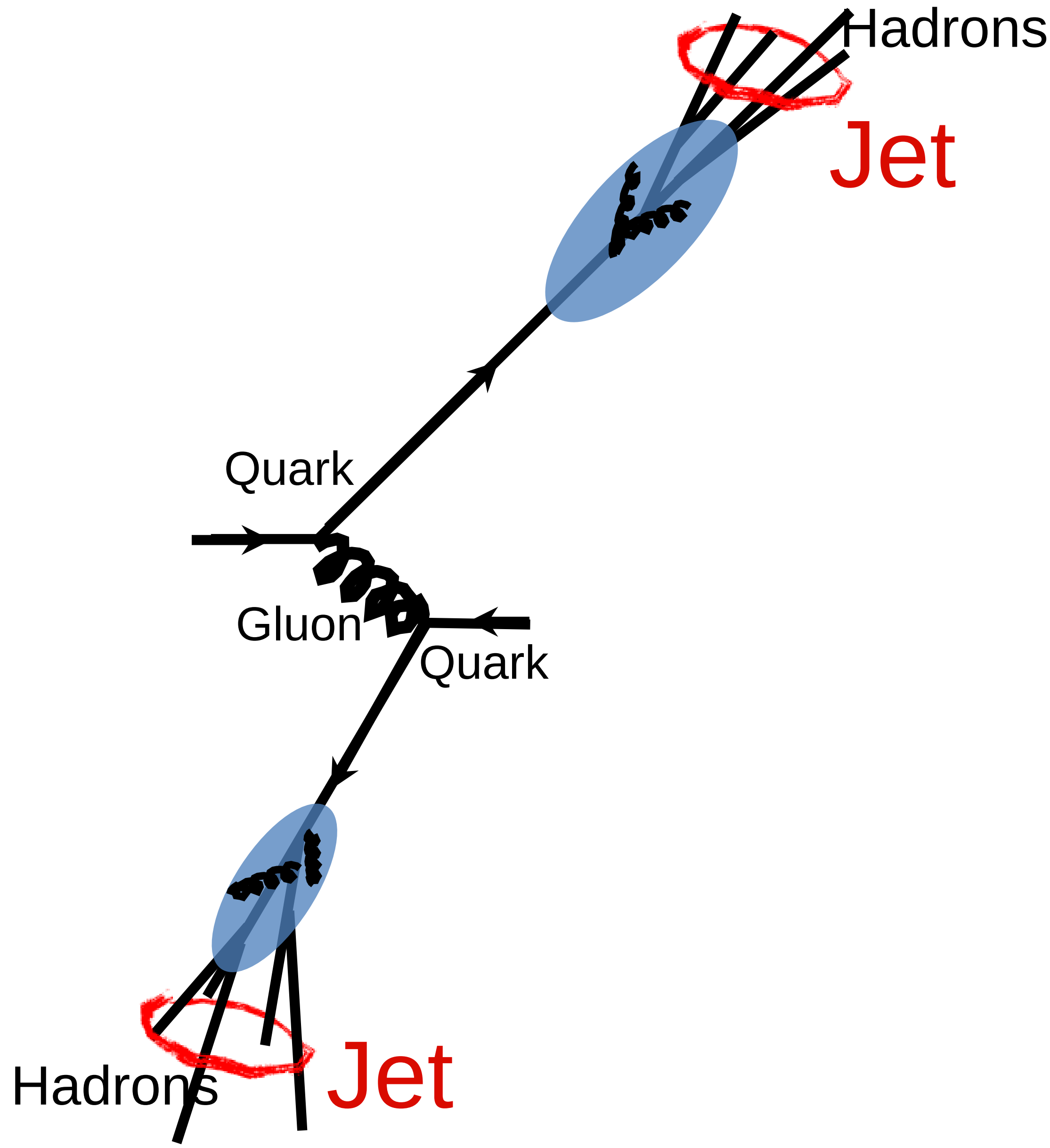
- Direct jet reconstruction:
  - Dijet correlation
  - Jet-track correlation



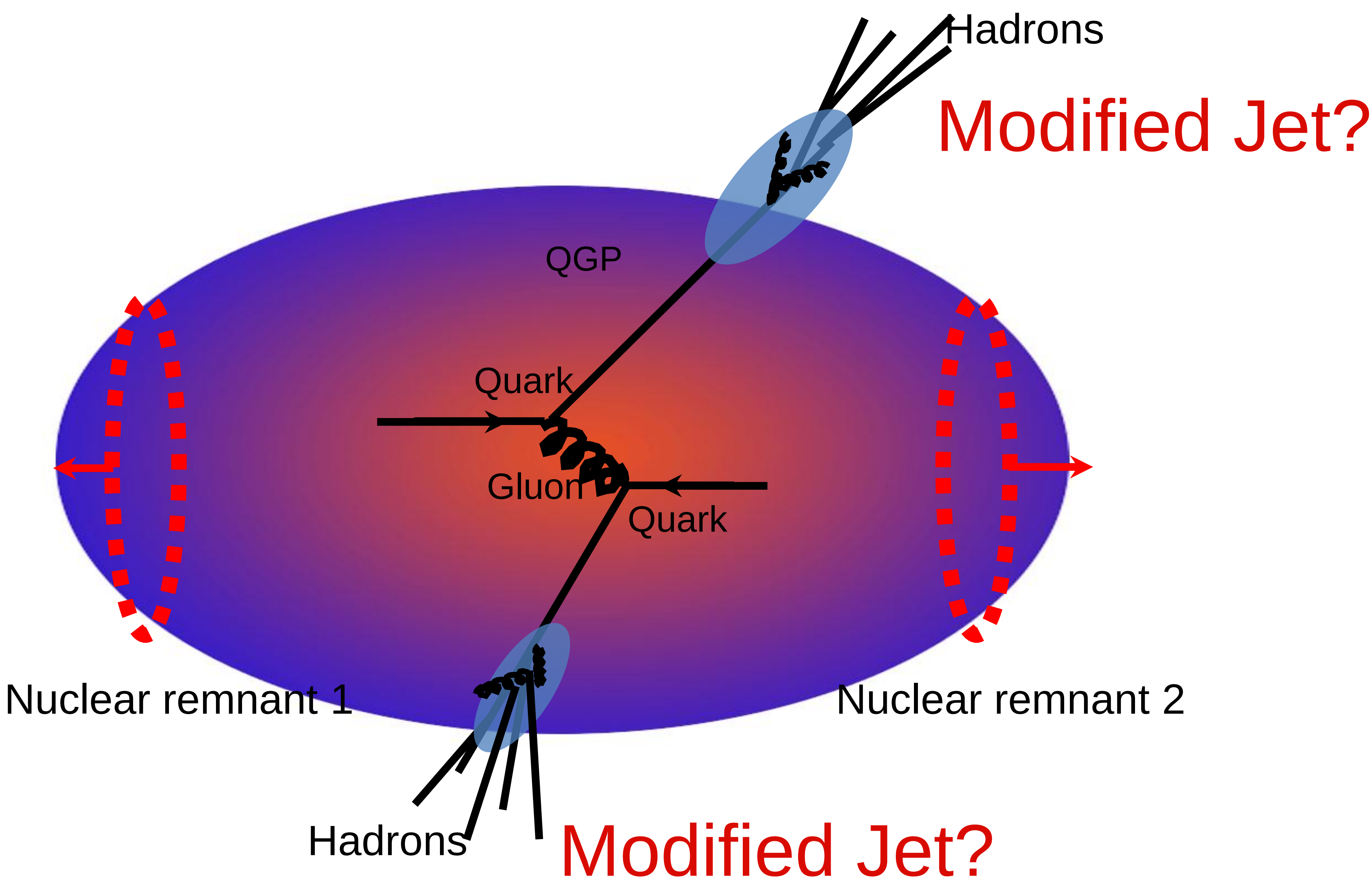
Example “hard probe”: pair of high p_T quarks



Typical pp collision: formation of jets



Nuclear collision: partons propagate through medium

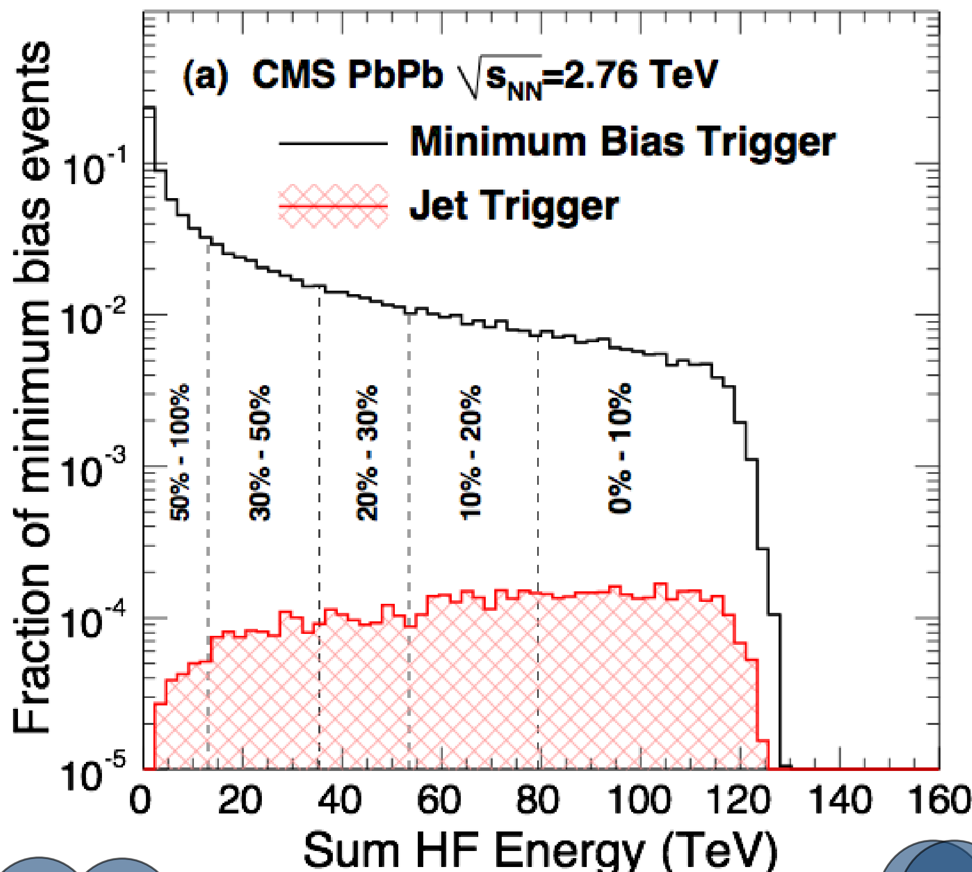


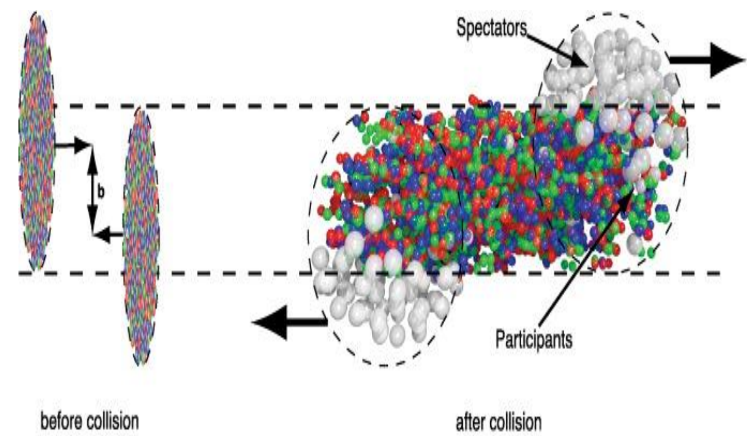
Tomographic probes of the medium

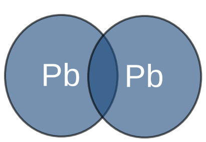
- Use hard processes, well understood and/or measured in the pp collisions
  - Quarks, gluons-> hadrons, jets
  - γ, Z, W
  - Quarkonia, heavy mesons
- Compare to the same processes in heavy ion collisions (and pA or dA collisions)
- Deduce properties of the hot medium by measuring energy loss, changes in fragmentation, cross section modifications

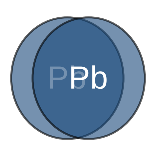
Centrality in the heavy ion collisions

- Ions are large, R~7 fm, collisions occur with random impact parameter that cannot be directly measured
- Measure the overlap of two ions or number of "participating" or "colliding" nucleons by measuring energy in forward calorimeters







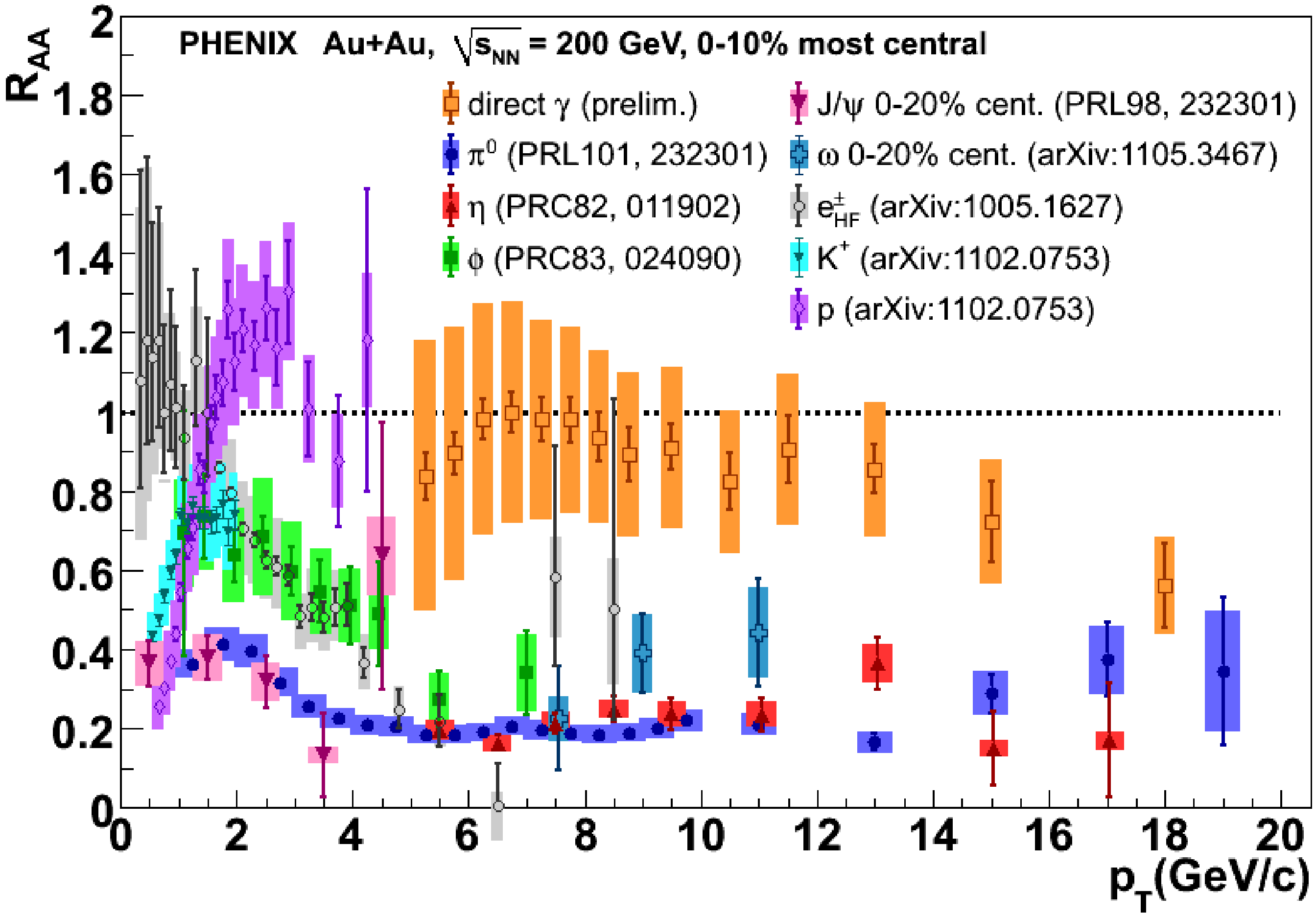


- Energy in calorimeters is ~ to the number of participating nucleons in the overlap region
- Rate of high p_T processes is ~ to the number of colliding pairs of quarks and gluons

Nuclear modification factor at RHIC: single particles

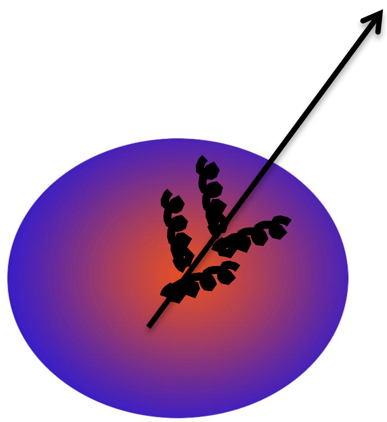
- Comparison to proton-proton

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma_{NN}/dp_T d\eta}$$



- Very strong suppression of hadrons, x5 less than in pp

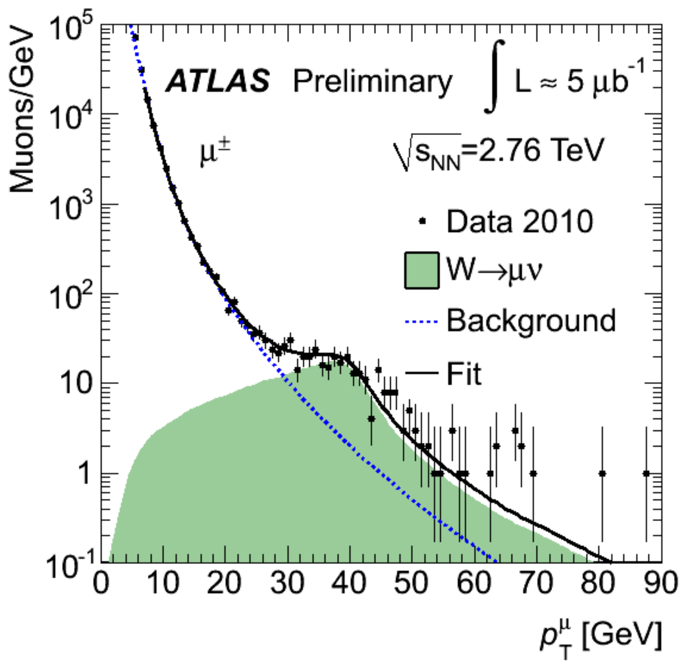
- Photons are not suppressed!

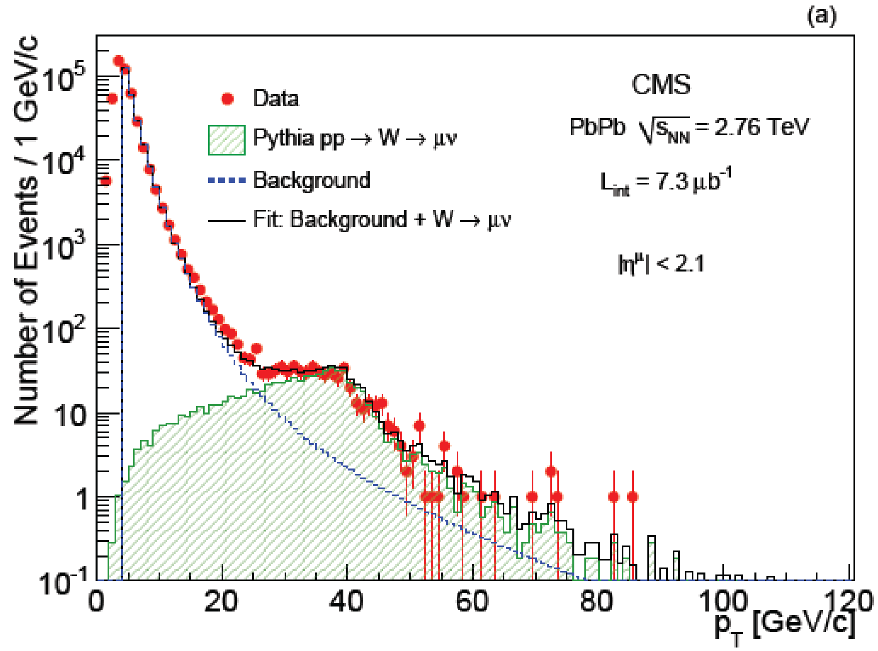


New hard probes at LHC: W and Z bosons

No interactions with the hot medium, no energy loss expected!

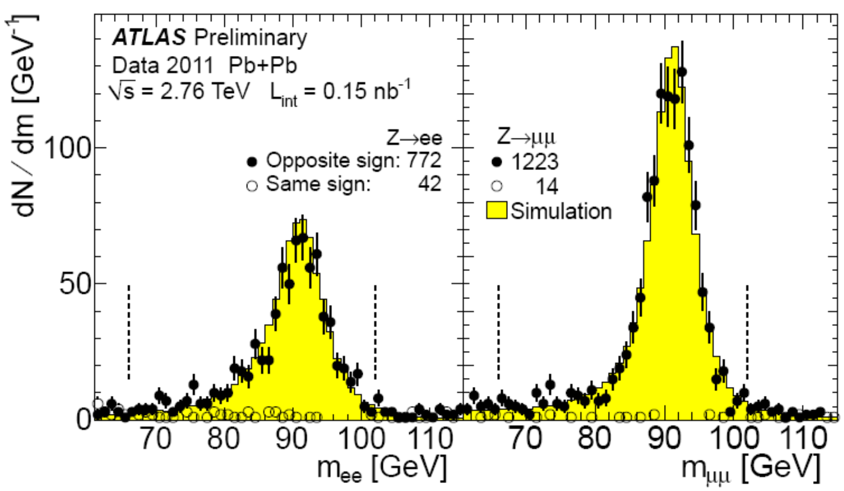
W

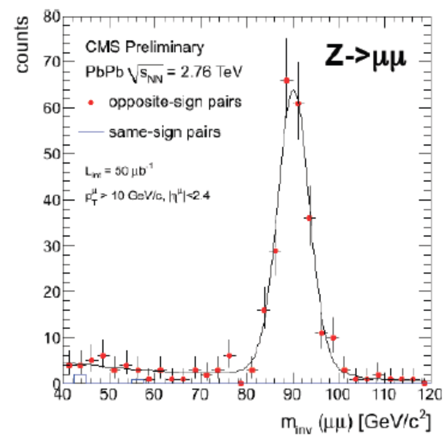


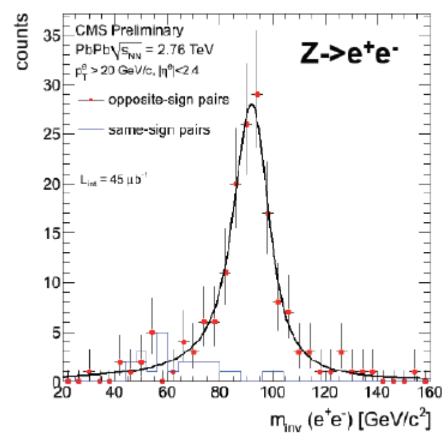


arXiv:1205.6334v1

Z

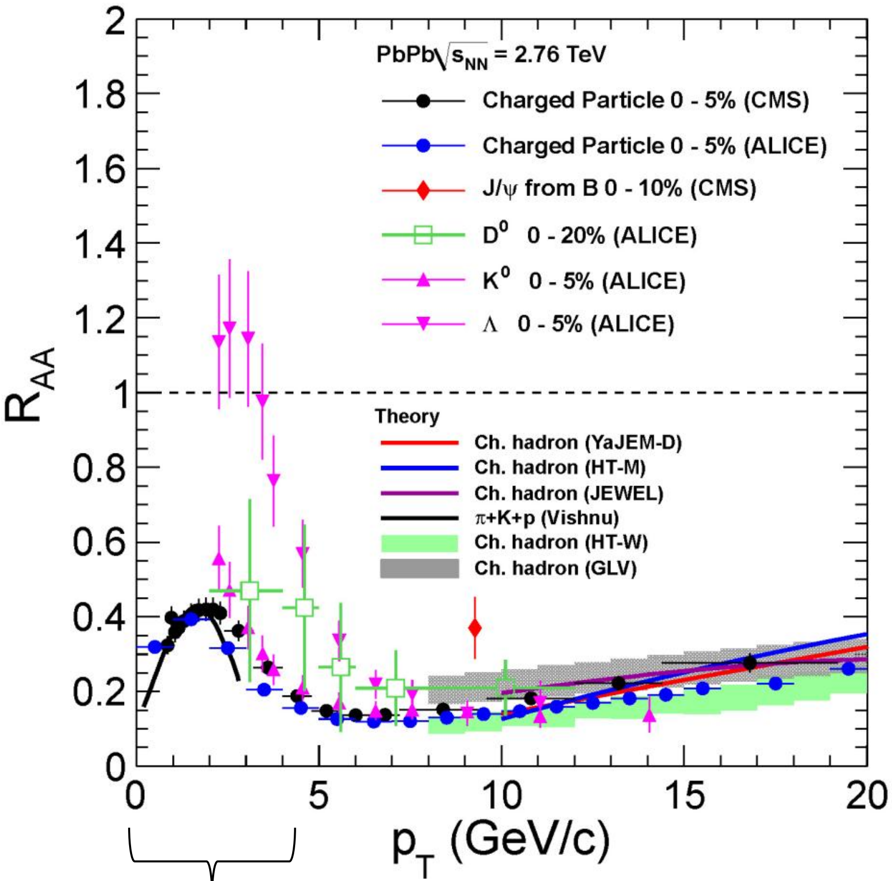


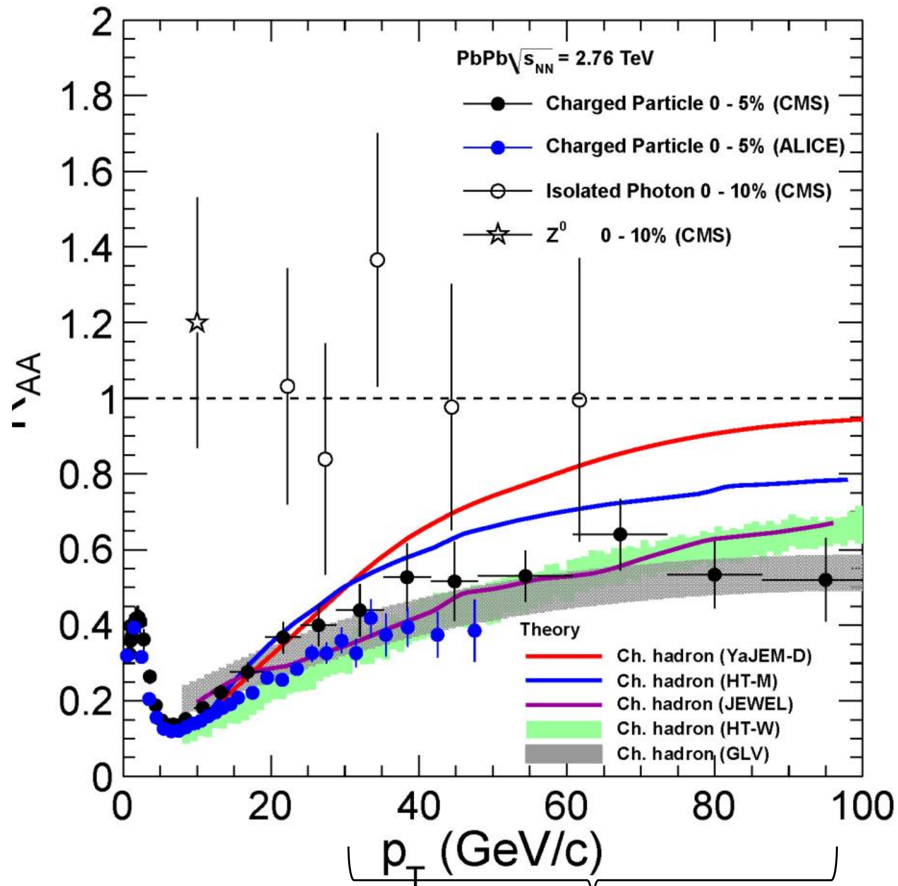




LHC confirms large energy loss of hadrons

- Colorless probes are not suppressed: γ, W, Z!
- Strongly interacting particles are suppressed with suppression diminishing towards high p_T: all charged, D, K^0, Λ, b-quark



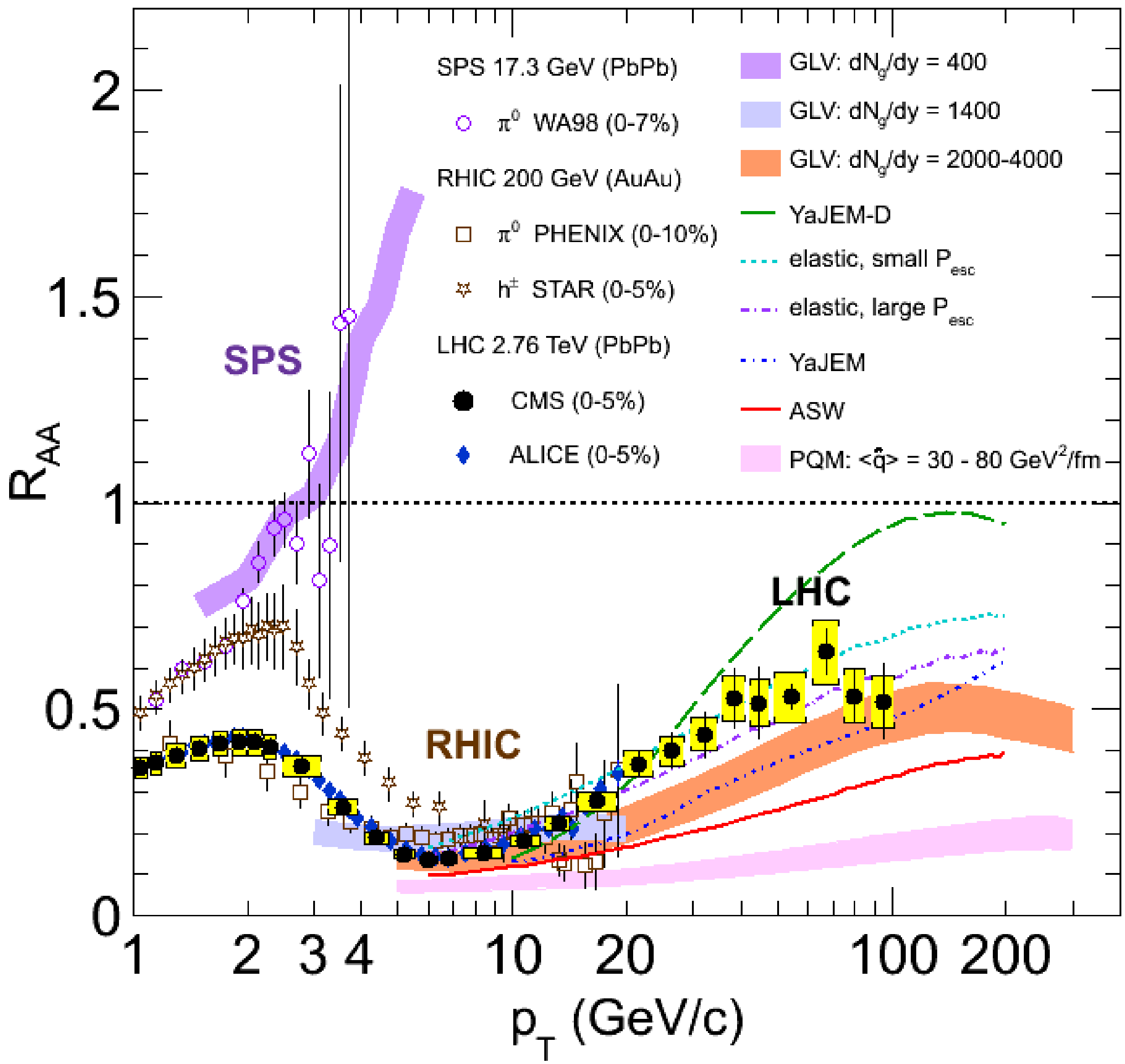


Dominated by hydrodynamics

pQCD models of energy loss give reasonable predictions

arXiv:1202.3233v1

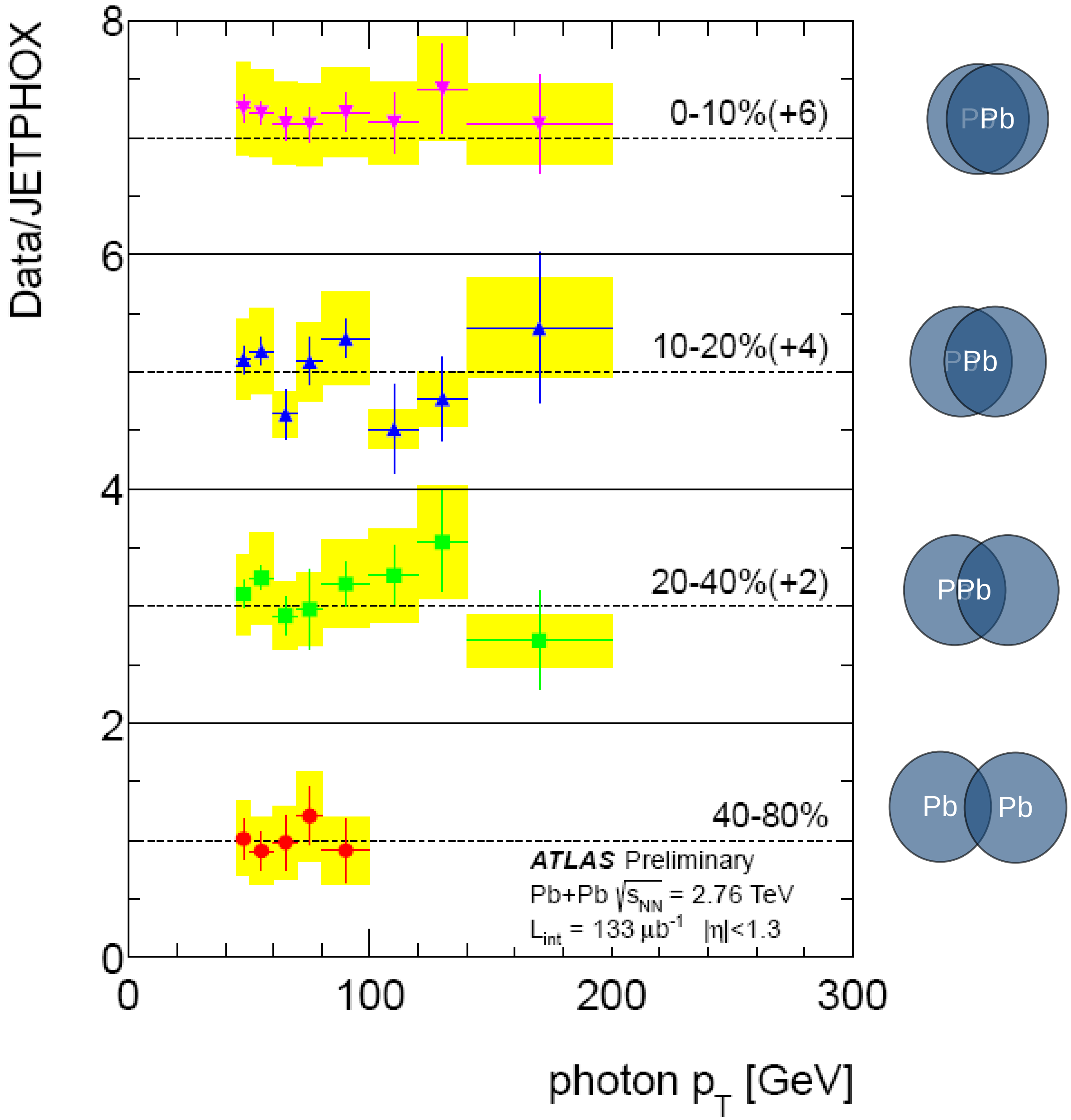
R_{AA} across the accelerators



Eur. Phys. J. C 72 (2012) 1945

Photons in ATLAS

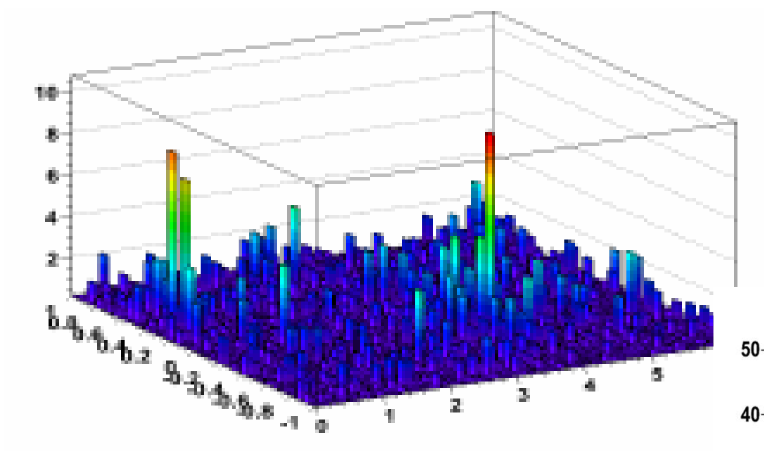
- Hot off the press from ATLAS, confirms that γ escape unquenched..
- Photon yield normalized the Monte Carlo without quenching



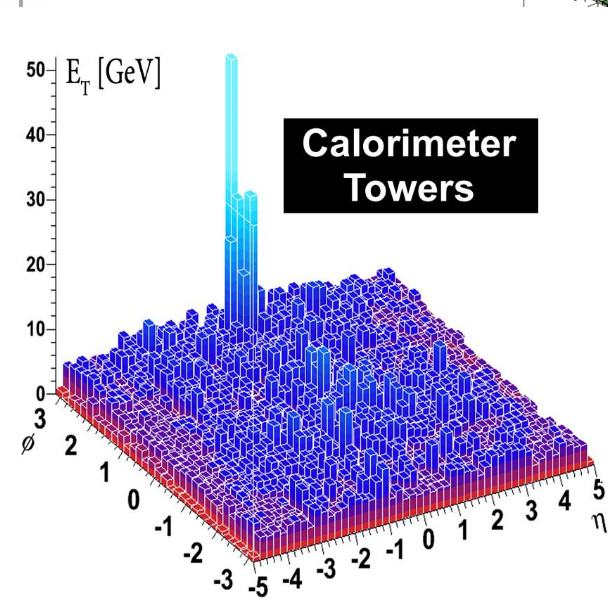
ATLAS-CONF-2012-051

Jet quenching: measuring fully formed jets

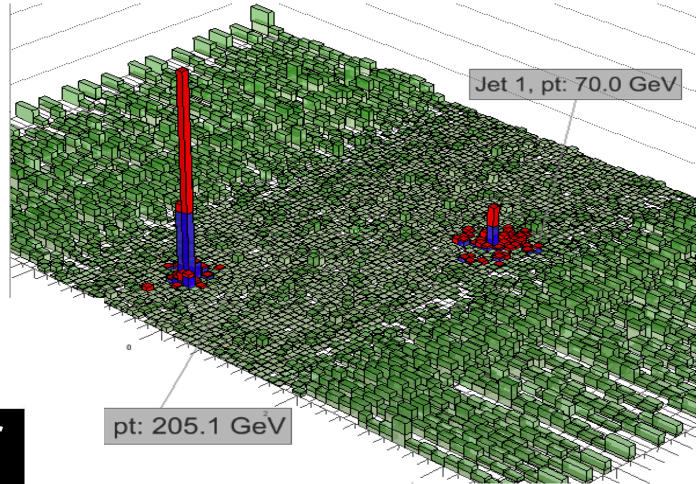
- High p_T hadrons are typically seen inside jets, can we see the full jet suppression?
- Interactions with hot medium can reduce overall jet rate, modify jet energy, affect fragmentation. Details of energy loss mechanism can distinguish between models of the medium



STAR@RHIC



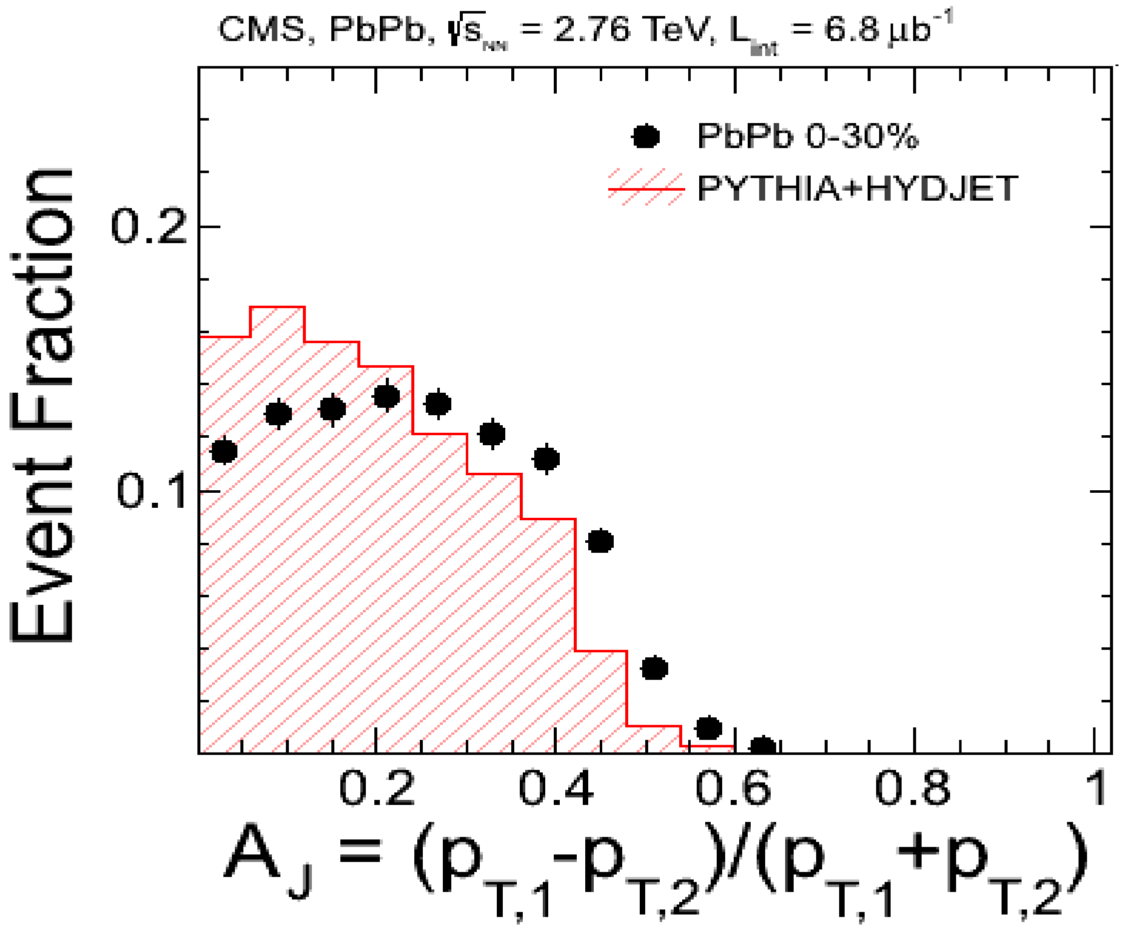
ATLAS@LHC

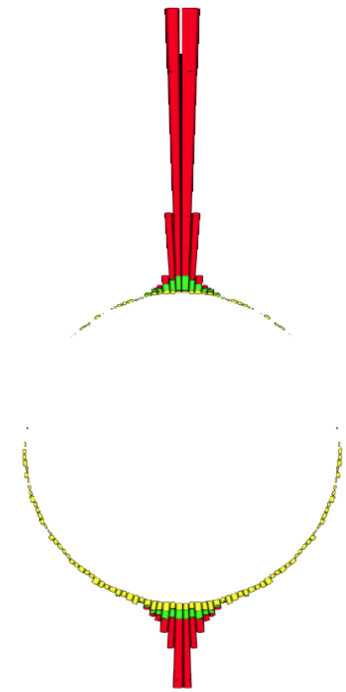


CMS@LHC

Disappearing jets I

- We observe large number of dijets with different jet energies
- Interestingly: the two jets are always back-to-back, no angular decorrelations

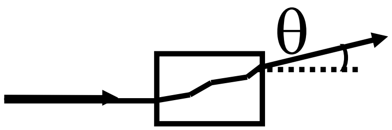




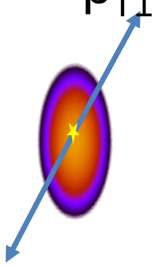
PLB 712 (2012) 176

Dijet Angular Correlations

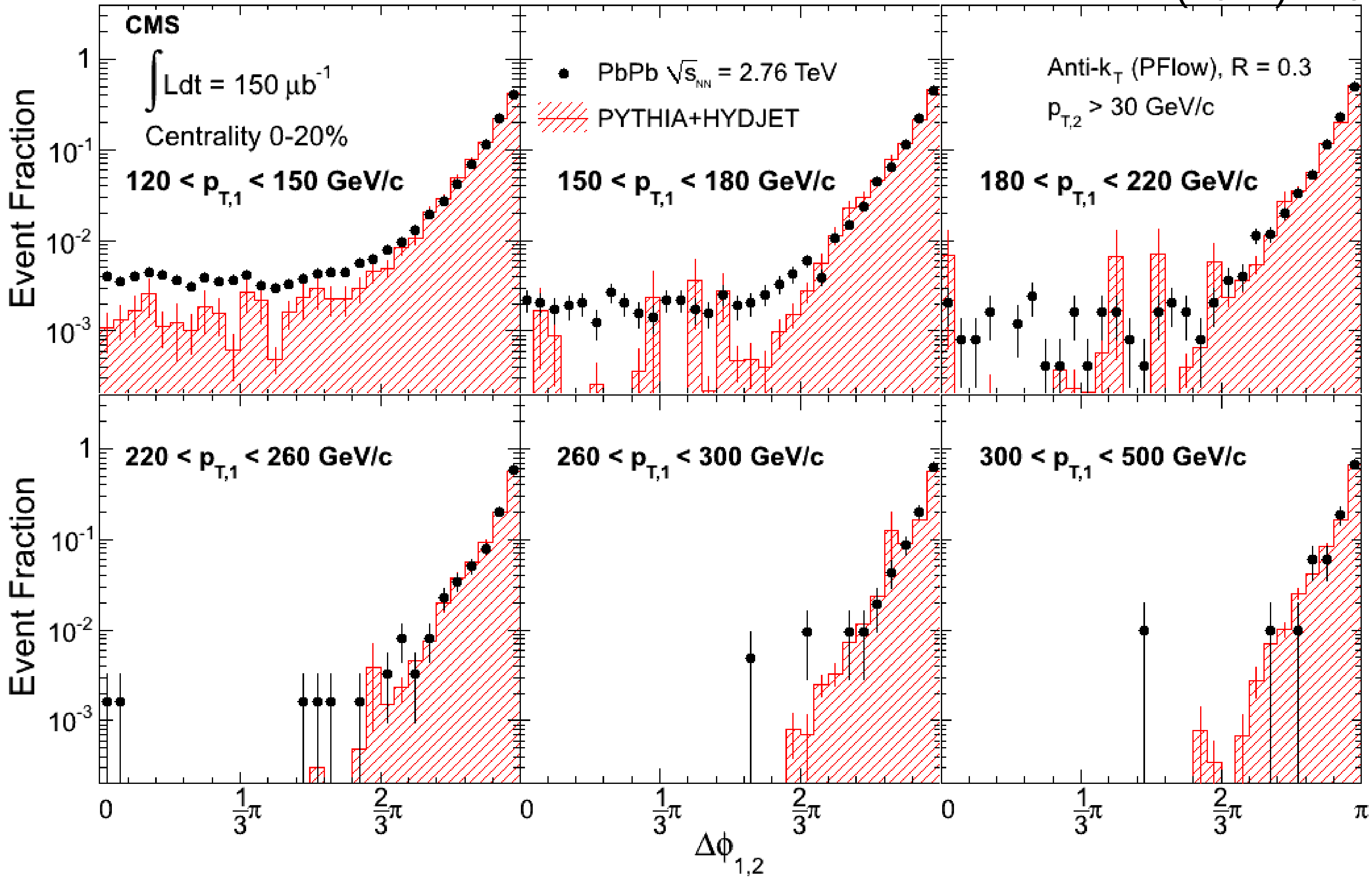
QED:



QCD:



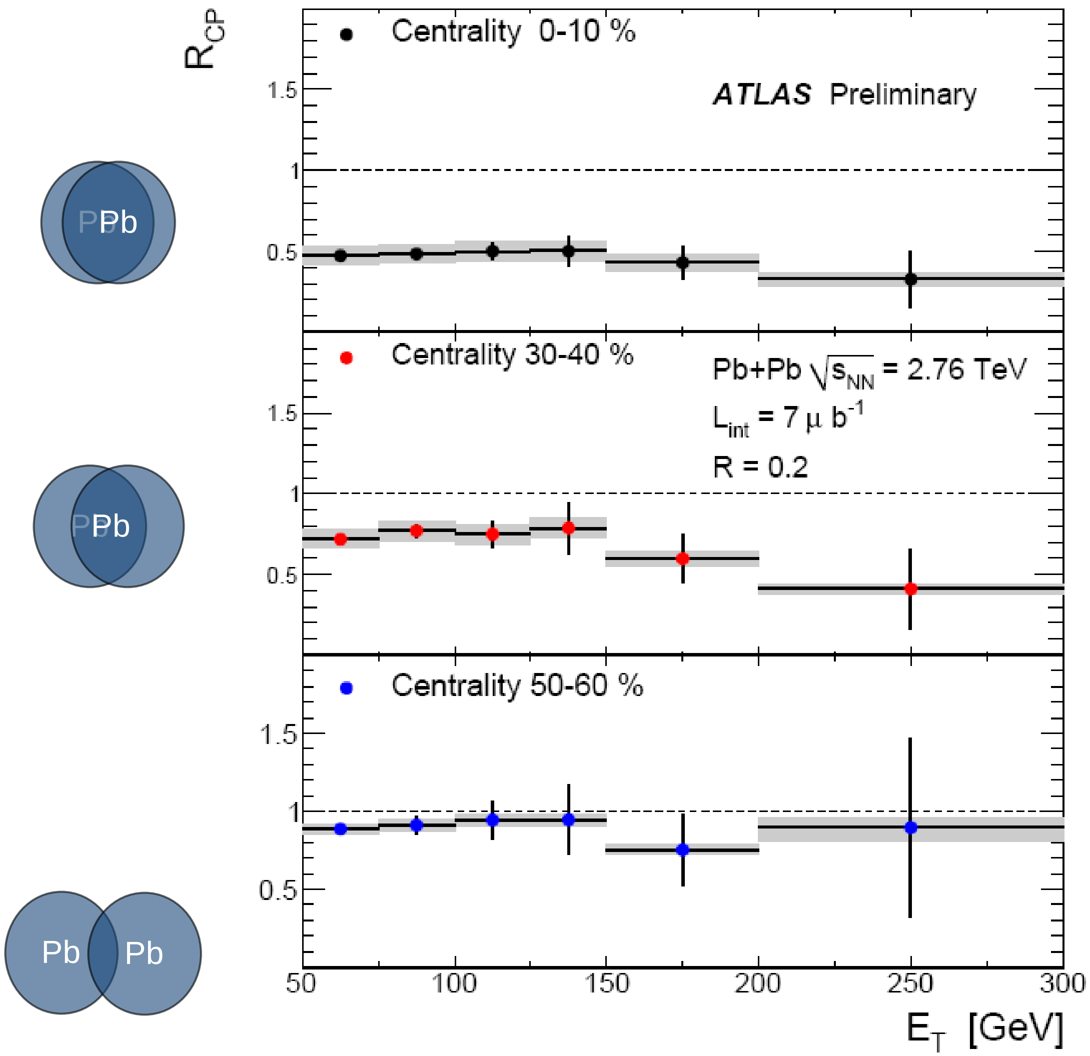
PLB 712 (2012) 176

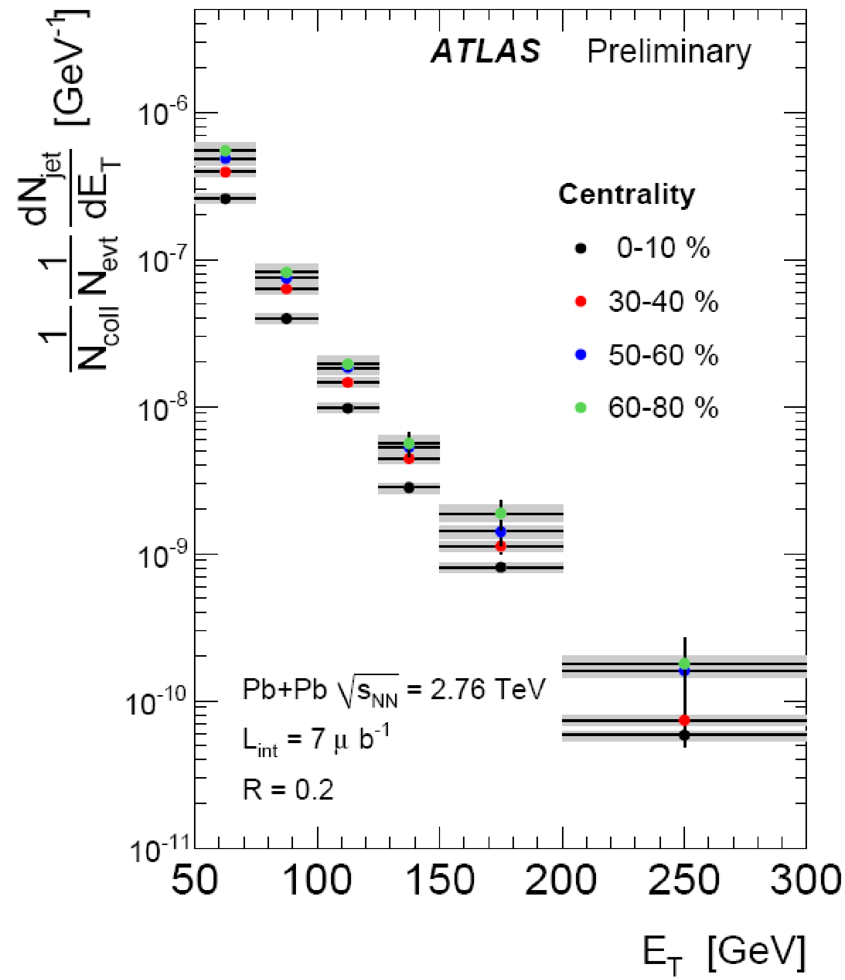


Correlation peak is the same in data and Pythia across all values of p_T, even in central events

PLB 712 (2012) 176

Disappearing jets II



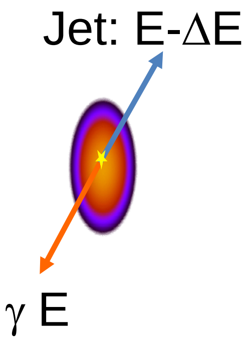


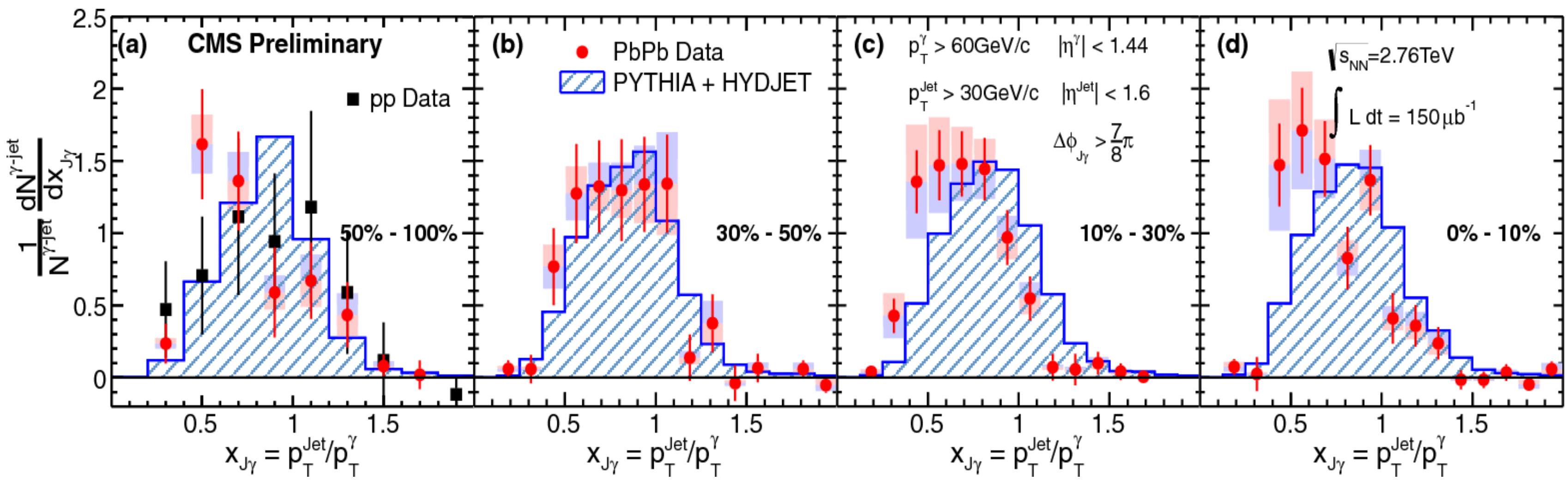
- Overall rate of jets is reduced by factor of ~2 for most central collisions

$$R_{CP} = \frac{\text{Jets in central collisions}}{\text{Jets in peripheral collisions}}$$

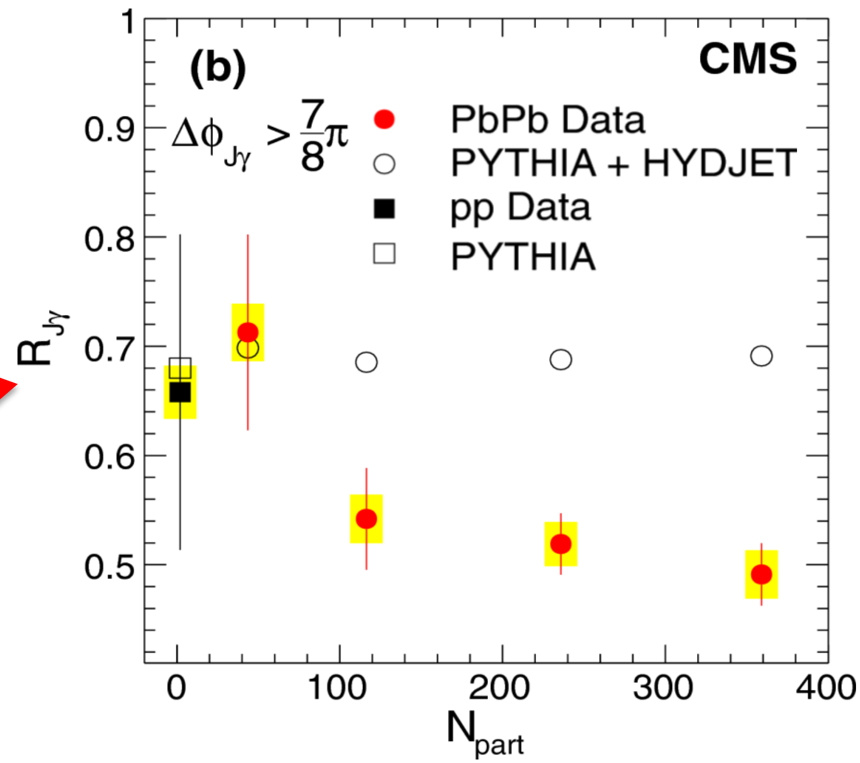
ATLAS-CONF-2011-075

Effect confirmed in γ+jet events



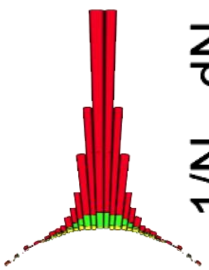


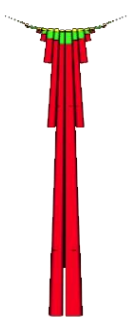
- Photons do not lose energy in the medium, γ+jet allows to see directly jet energy loss
- The number of jets accompanying photons decreases with centrality

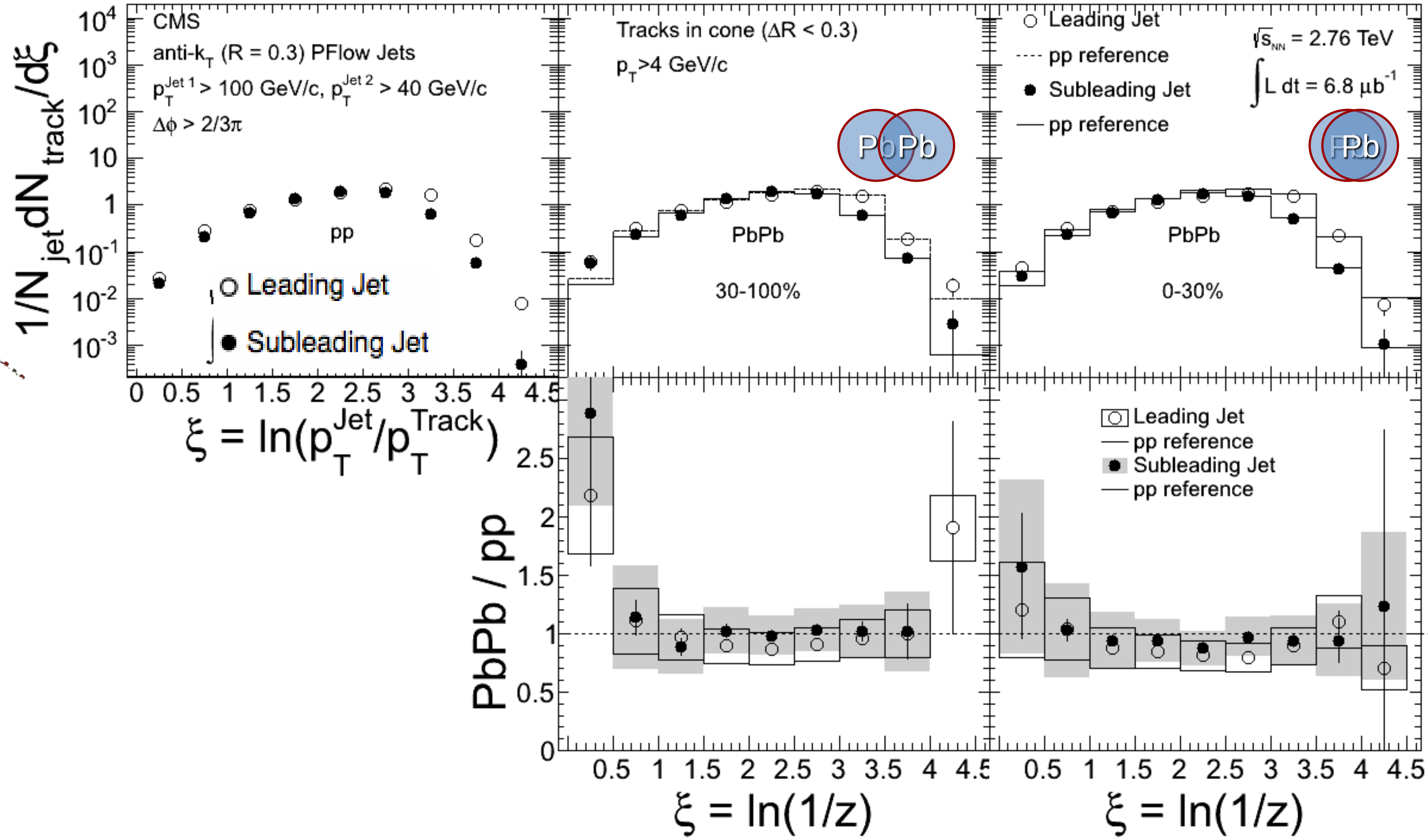


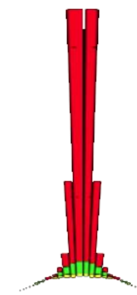
arXiv:1205.0206v1

Fragmentation Functions, pp and PbPb









Leading and subleading jet in PbPb fragment like jets of corresponding energy in pp collisions

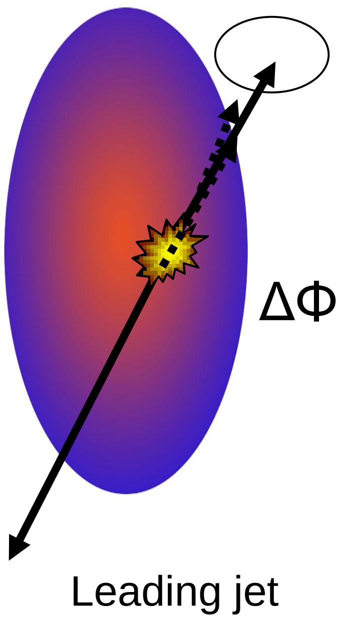
arXiv:1205.5872v1

Possible explanations for jet quenching mechanism

Collinear soft gluon emission

→ Excess of low p_T particles inside the jet cone.
→ Modified jet fragmentation function

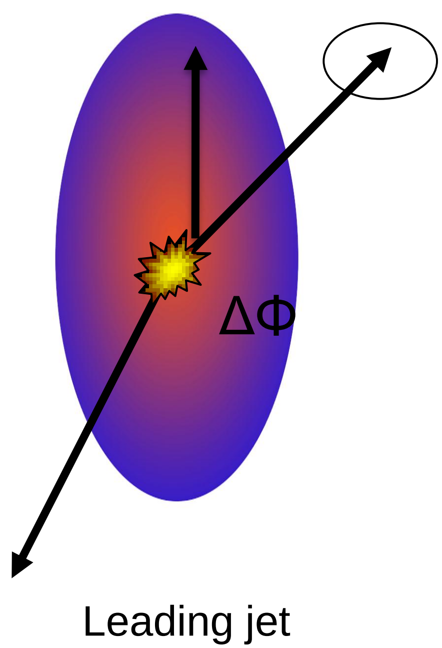
Main idea of many pre-LHC models



Semi-hard, large angle medium induced radiation

→ Large dijet p_T asymmetry
→ Δφ broadening
→ Third jet / excess of high p_T particles out-of-cone

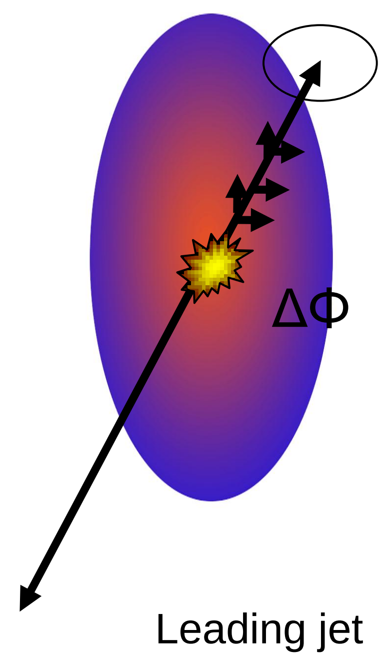
PYTHIA inspired models



Soft, multiple large angle gluon radiation

→ Large dijet p_T asymmetry
→ Mild Δφ broadening
→ Excess of low p_T particles out-of-cone

AdS/CFT, QCD antenna

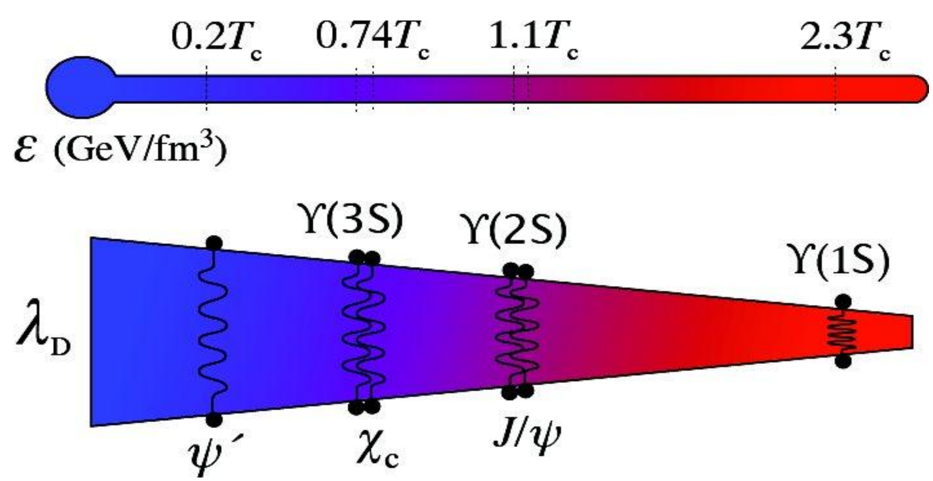


Quarkonia and the QGP

- Heavy quarks
  - produced in the initial hard-scattering process
- Colour screening in QGP leads to melting of quarkonia
- Different binding energy of bound states lead to sequential suppression of 1S states with increasing temperature

State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

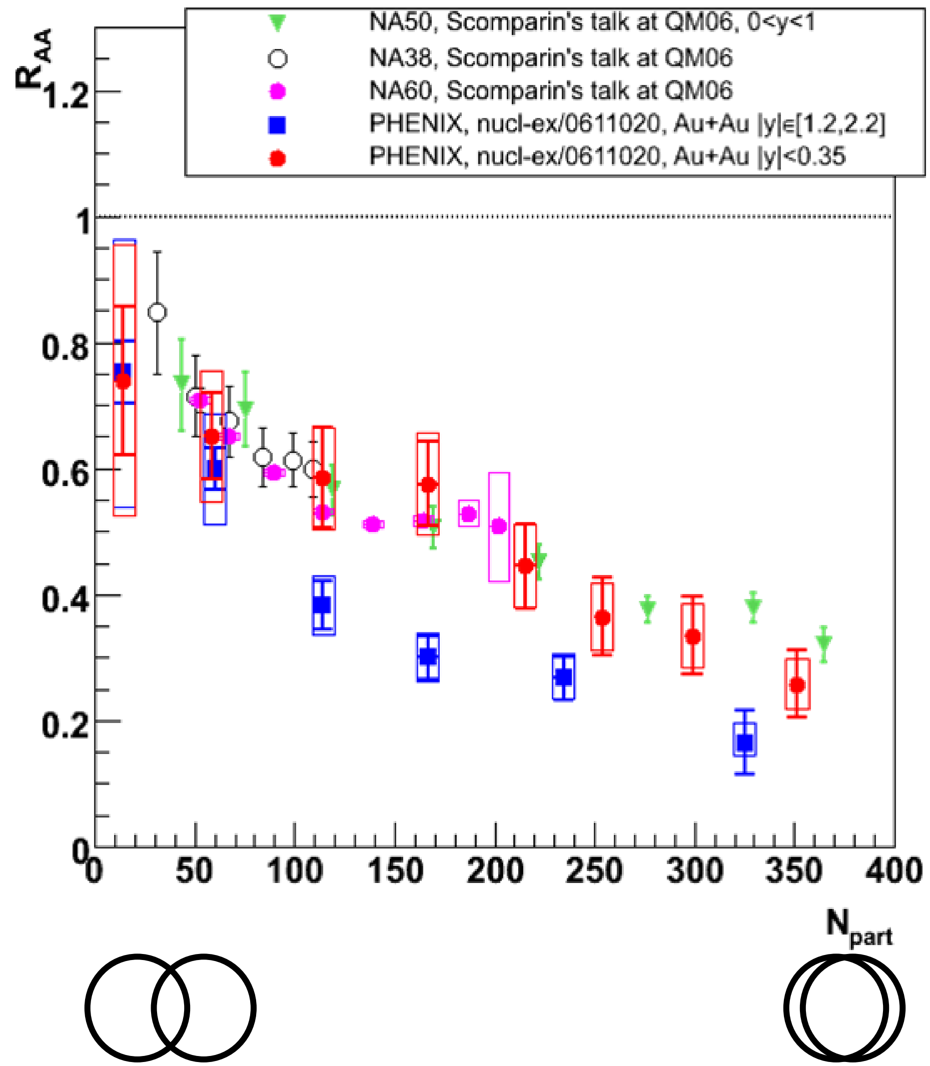
Υ (1S)	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
9.46	9.99	10.02	10.26	10.36
0.28	0.44	0.56	0.68	0.78



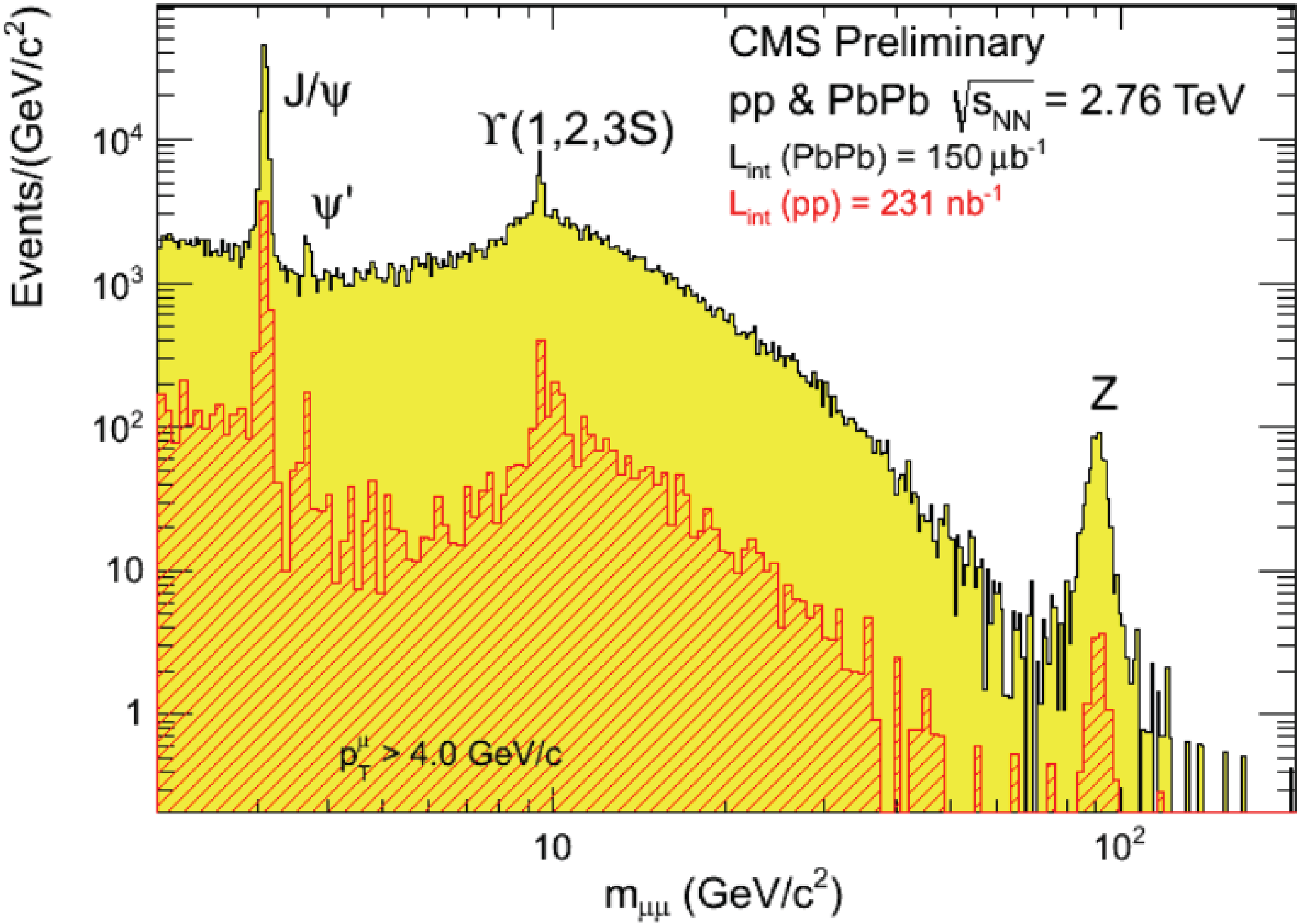
Matsui & Satz
PLB 178 (1986) 416

Comparing pp and AA at SPS and RHIC

- Similar J/ψ suppression at the SPS and RHIC!
  - despite 10 × higher $\sqrt{s_{NN}}$
- Suppression does not increase with local energy density
  - R_{AA}(forward)<R_{AA}(mid)
- Possible ingredients
  - cold nuclear matter effects
  - sequential melting
  - regeneration
- What happens at the LHC?
  - higher energy + higher luminosity
  - more charm (more regeneration?)
  - more bottom → a new probe

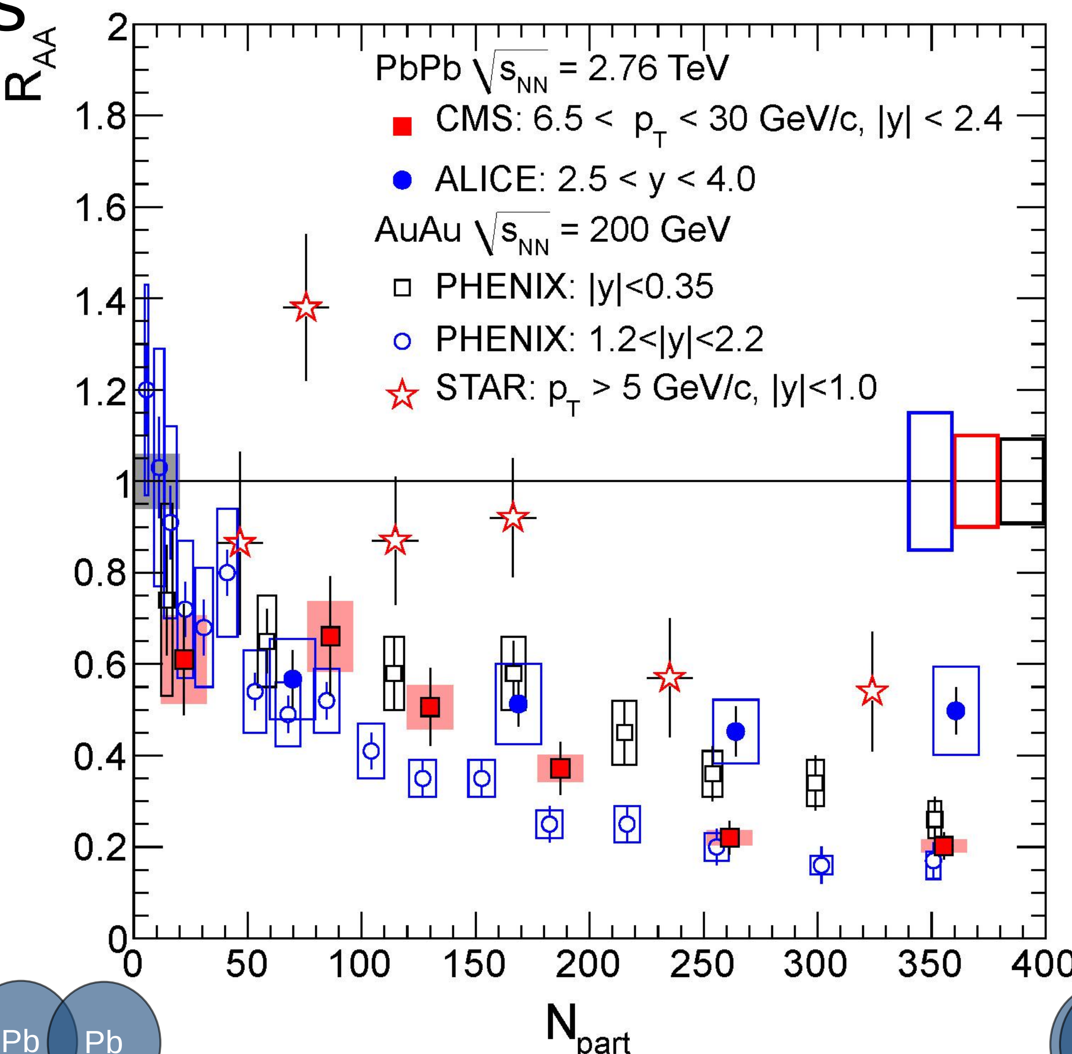


Muon Pairs in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

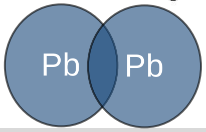


New results from LHC, compared to RHIC

- Overall similar J/ψ suppression pattern but differences start to emerge for different rapidity and p_T ranges



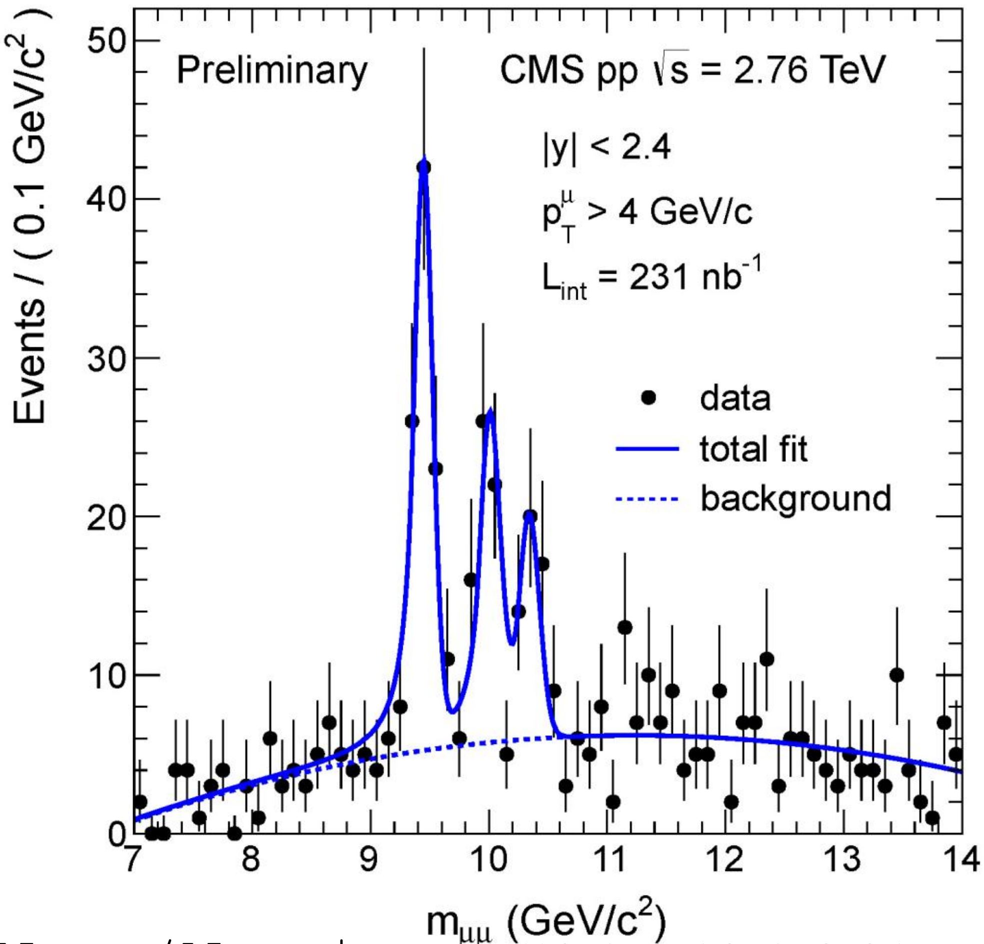
PHENIX (PRL 98 (2007) 232301)
STAR (arXiv:1107.0532)
ALICE (arXiv:1202.1383)
CMS (JHEP 1205 (2012) 063)



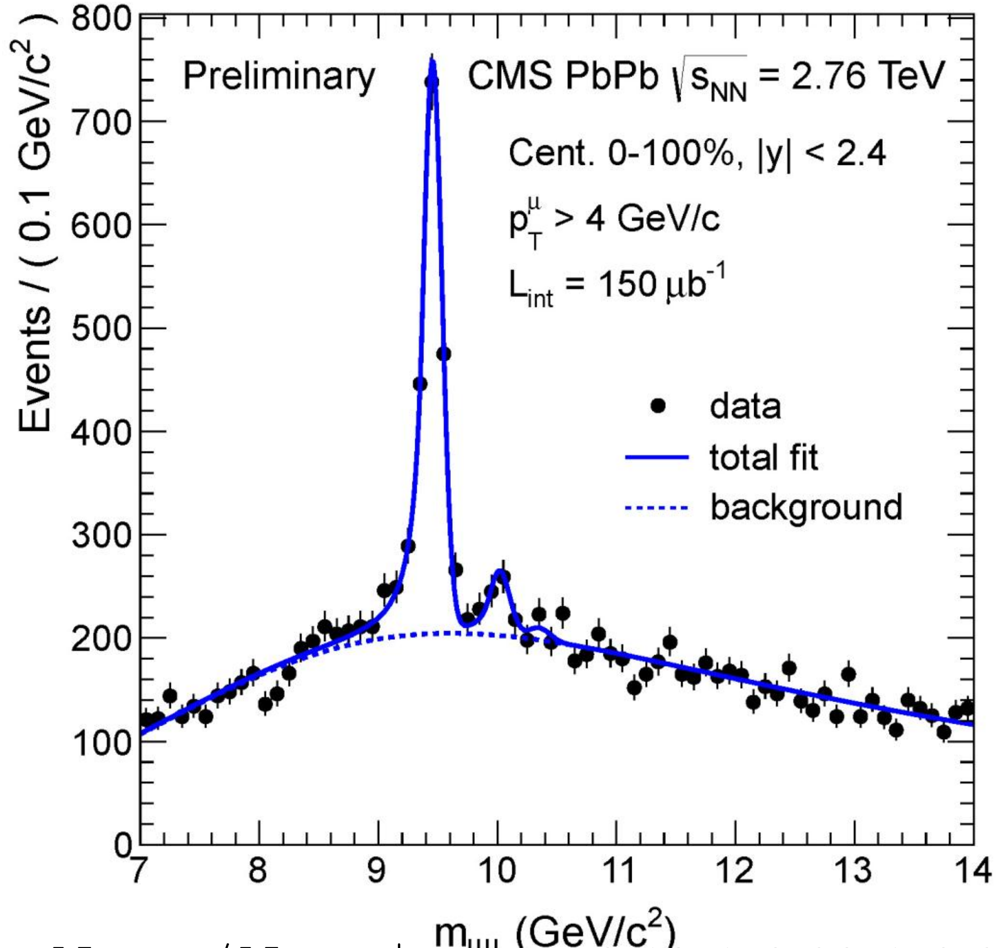
New hard probe at LHC: Upsilon family

Visible difference between states differing only by the binding energy!

pp



PbPb



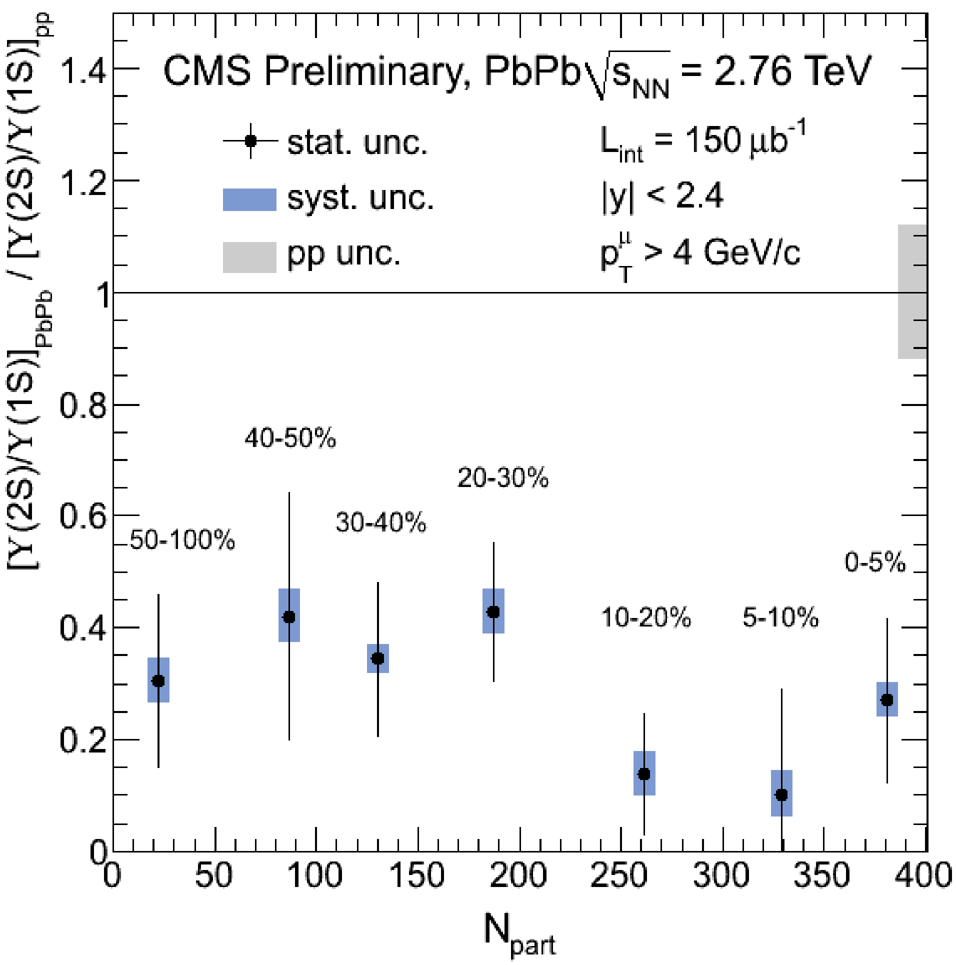
$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$

$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$

$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$

$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$ 95% CL

$\Upsilon(2S)/\Upsilon(1S)$ double ratio



- In 2010 (7.28μb^{-1}):
  - combined 2S+3S result

$$\frac{N_{\Upsilon(2S+3S)}/N_{\Upsilon(1S)}|_{PbPb}}{N_{\Upsilon(2S+3S)}/N_{\Upsilon(1S)}|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

  - PRL 107 (2011) 052302
- In 2011 (150μb^{-1}):
  - separated 2S and 3S

$$\frac{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb}}{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp}} = 0.21 \pm 0.07 \pm 0.02$$

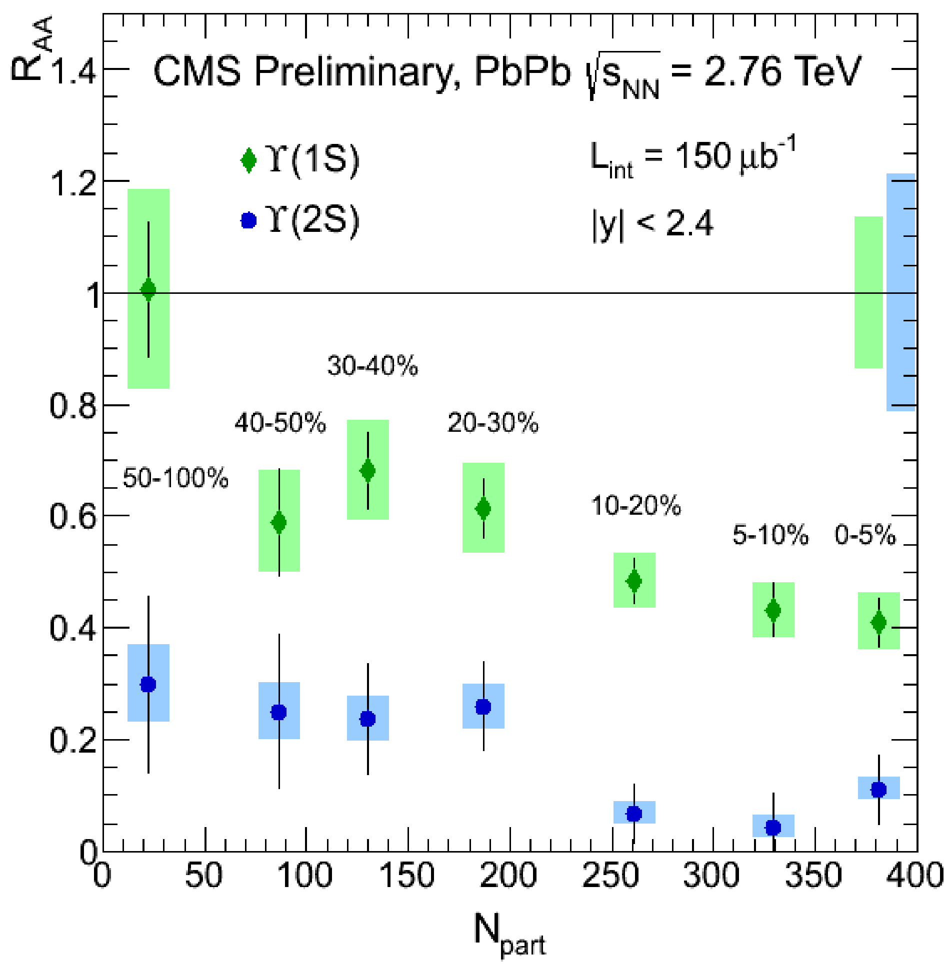
$$\frac{N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb}}{N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp}} < 0.1 \text{ (95\% C.L.)}$$

  - no strong centrality dependence

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011

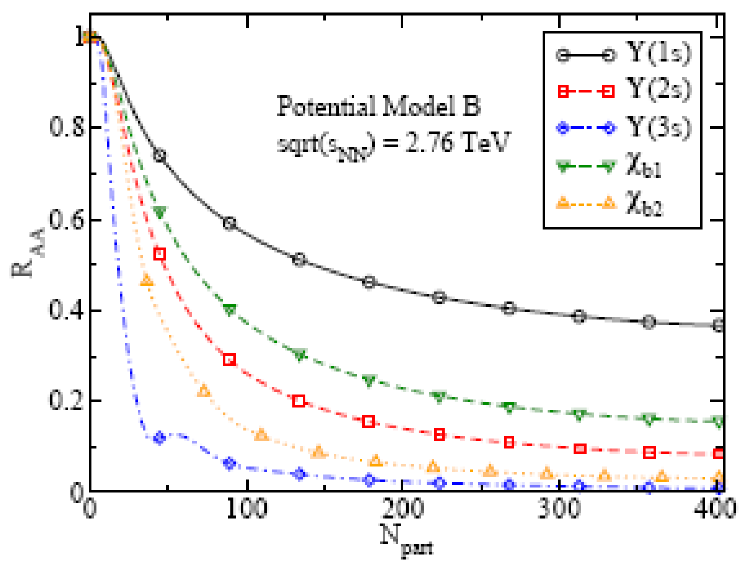
Nuclear Modification Factor: R_{AA}

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}(\Upsilon(\mathrm{nS}))}{N_{pp}(\Upsilon(\mathrm{nS}))} \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb}}}$$



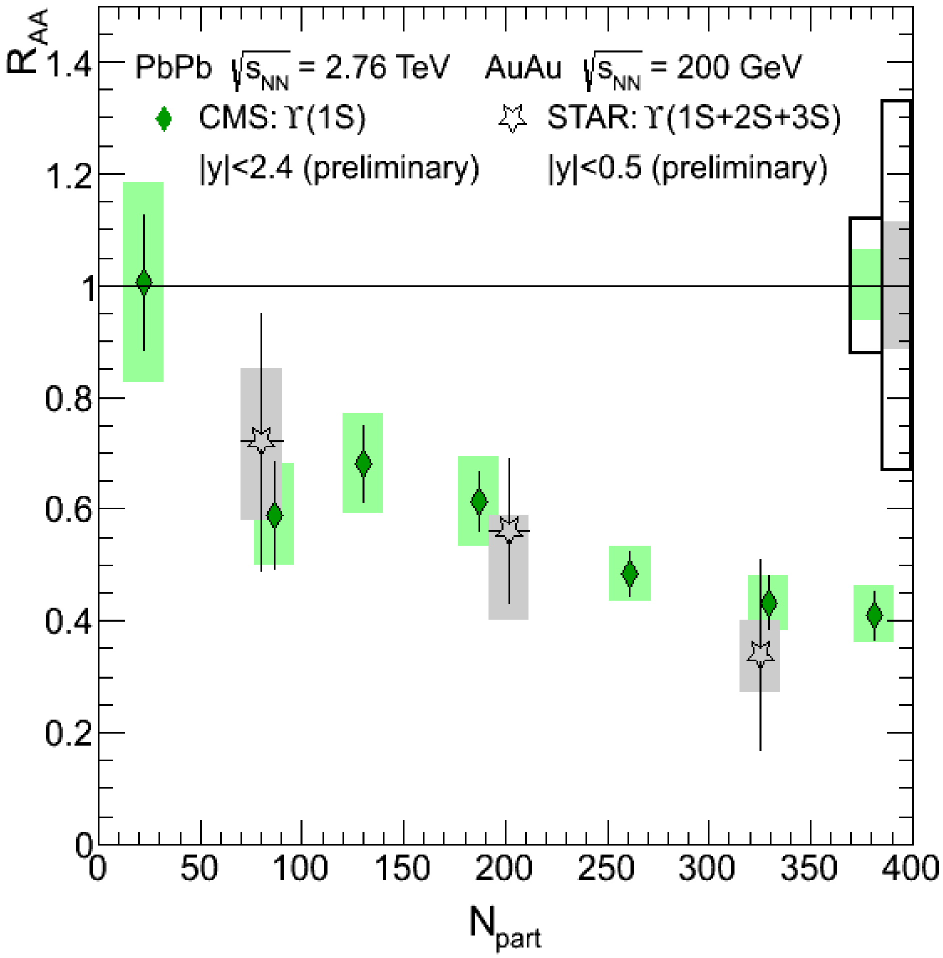
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011

- Familiar suppression pattern of Υ(1S) and Υ(2S)
- Note: Υ(1S) suppression consistent with excited state suppression only (~50% feed down)



M. Strickland, D. Bazow, arXiv:1112.2761v4

Comparison to RHIC



- STAR measured R_{AA} of ϒ(1S+2S+3S) combined
- CMS: measured R_{AA} of individual states

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011

Summary

- Collisions of heavy ions allow us to study hot and dense nuclear matter at densities ~10-20 GeV/fm^3 corresponding to temperatures reaching few 10^{12} K in volumes of ~10^3 fm^3
- We use self-produced hard probes and comparing AA collisions to pp at different impact parameters and transverse momenta we do "precision tomography" of the medium.
- Strongly interacting partons are suppressed by the interaction with the medium. New and interesting details are emerging from the recent data.
- Data on quarkonium production and decay is consistent with the sequential melting of states. New probes, e.g. Υ family improve precision of our measurements.