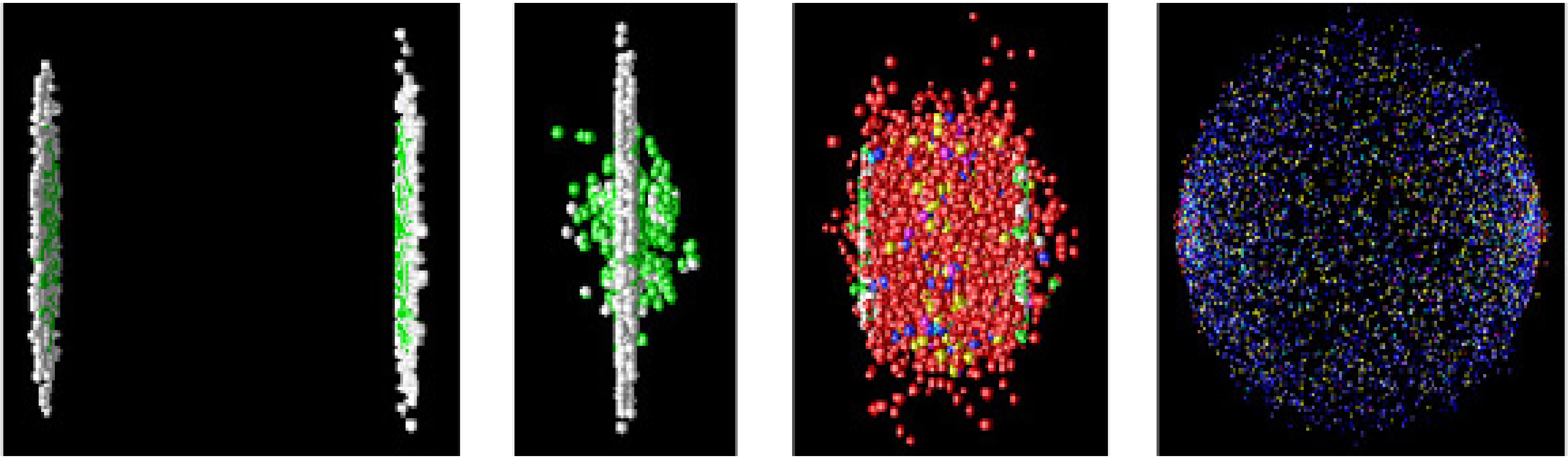
Results from heavy ion collisions at LHC

Bolek Wyslouch

École Polytechnique and MIT

Relativistic Heavy Ion Collisions



Ions at relativistic energies

High density of gluons and quarks

Interacting partons

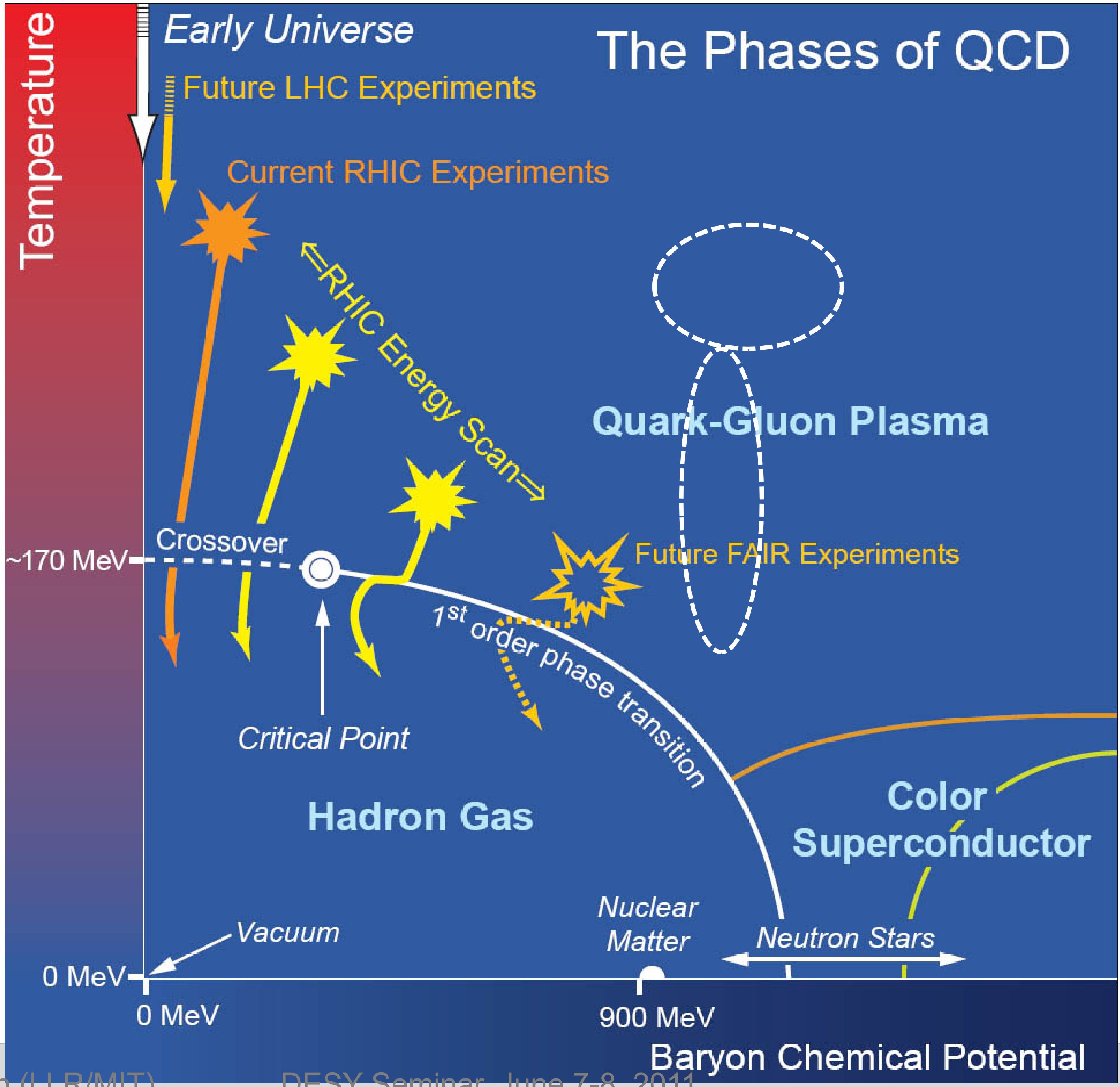
Frozen final state particles

Accelerate

Detect

High Density QCD Physics

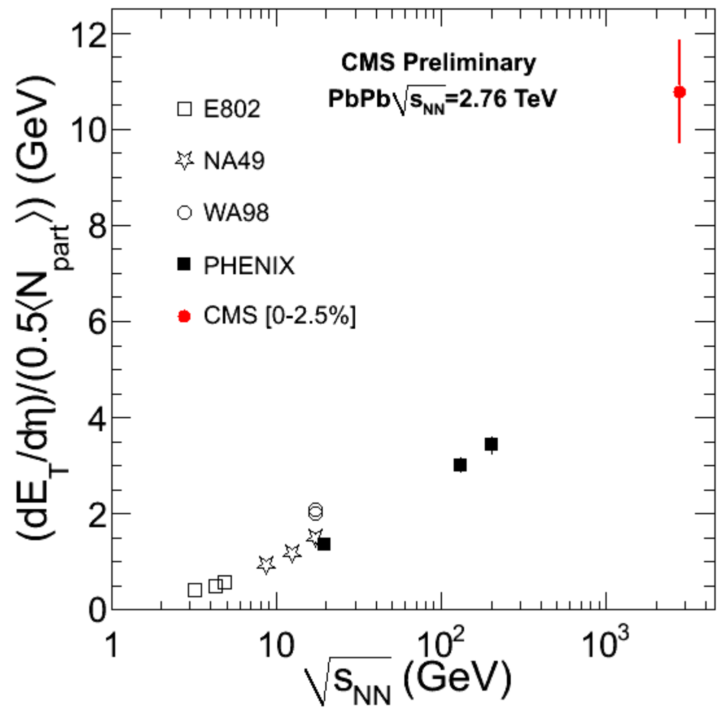
Motivation: temperature and density



What is new at LHC?

	AGS	SPS	RHIC	LHC
$\sqrt{s_{NN}}$ (GeV)	5	20	200	5500 (2760)
Increasing factor		x4	x10	X28(14)
η range	±1.6	±3.0	±5.3	±8.6

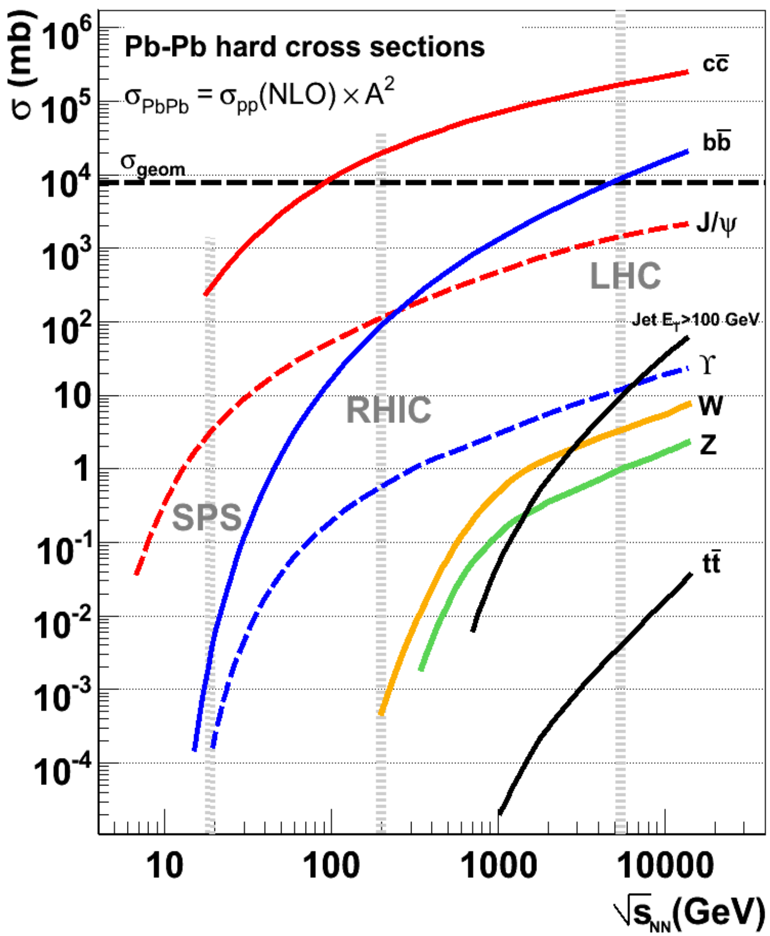
- LHC energies are far exceeding previous heavy-ion accelerators
  - A hotter, denser, and longer lived partonic matter

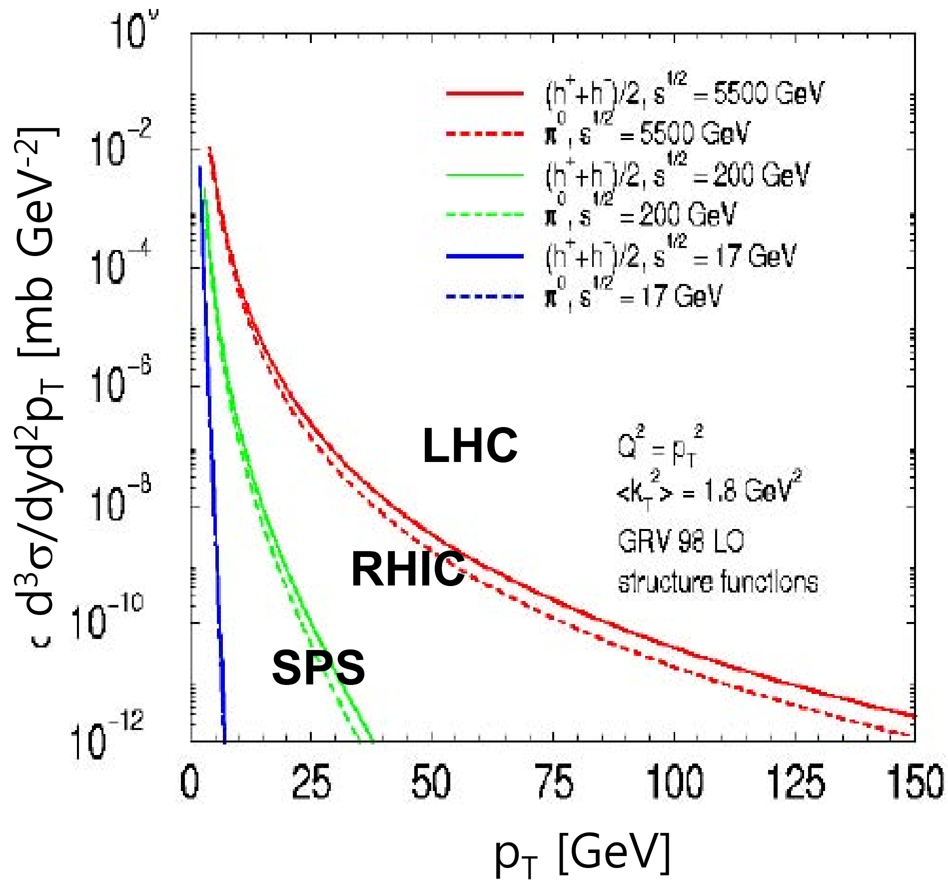


- E_T of about 2 TeV per unit pseudorapidity for central events
  - Translates to energy density three times higher than at RHIC ~15 GeV/fm^3

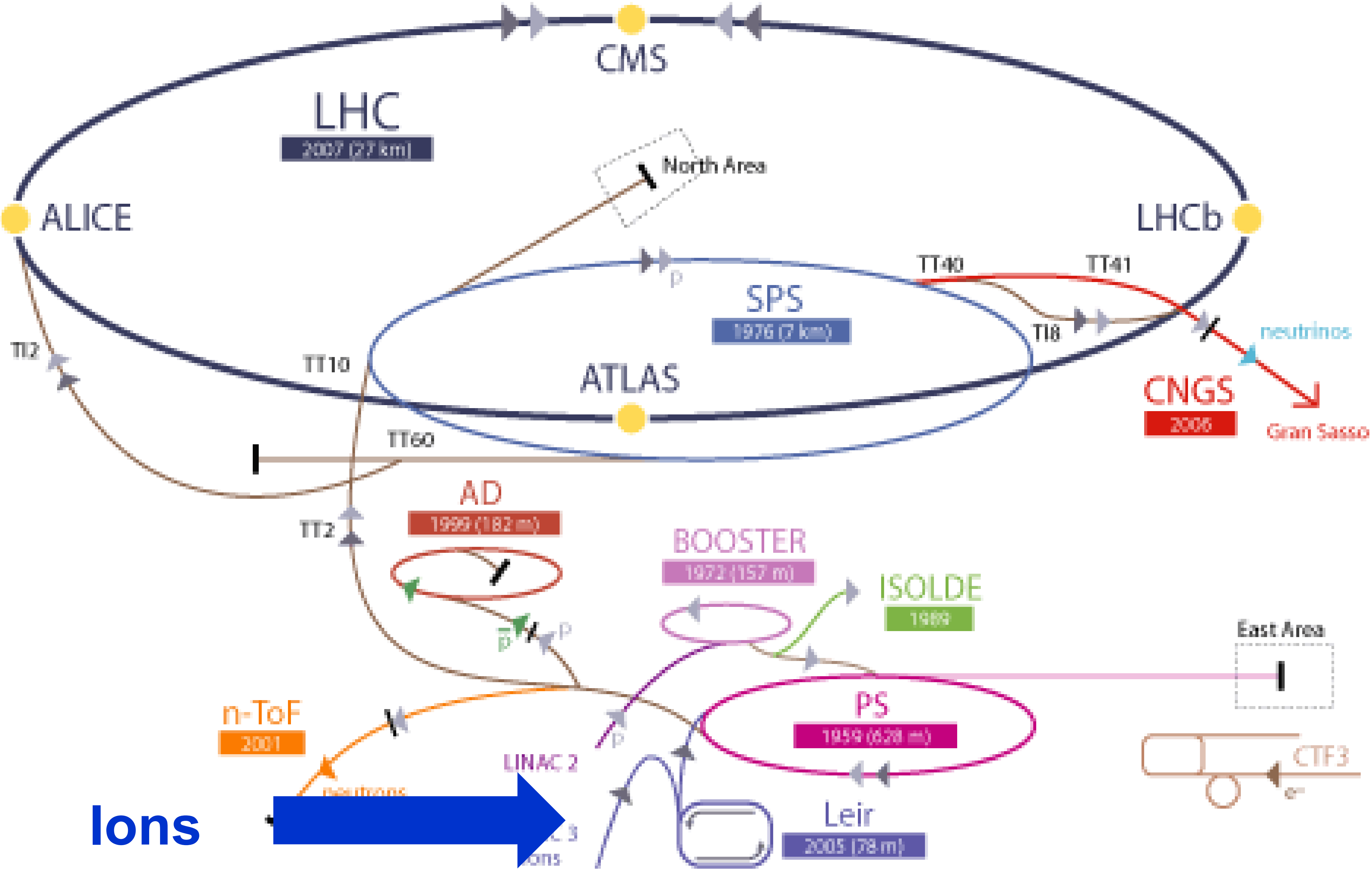
Production rates at LHC

- Large rates of various hard probes over a larger kinematic range
- Plenty of heavy quarks (*b* & *c*)
- Weakly interacting probes are available ($W^{\pm}$ & Z^0)





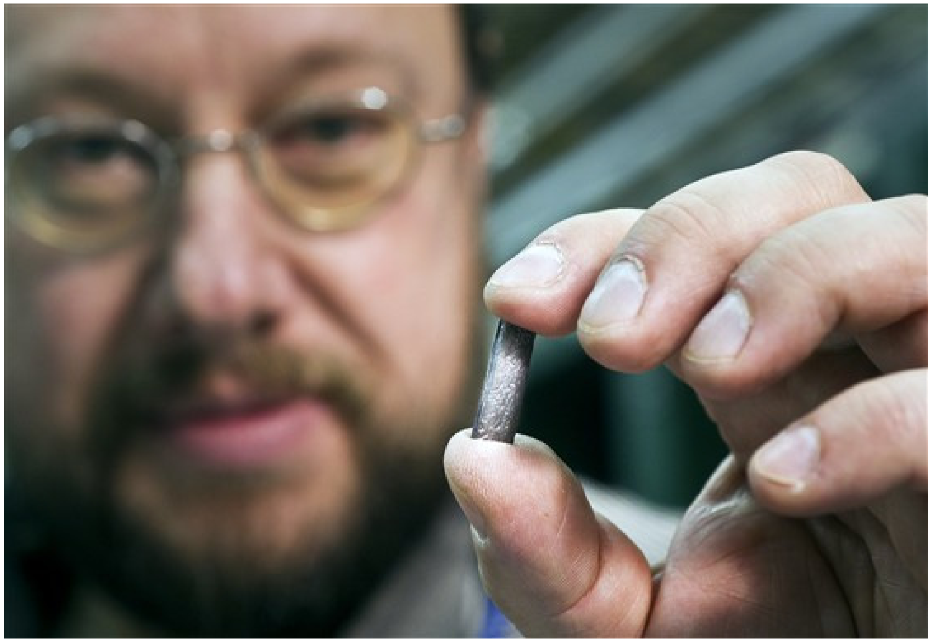
CERN Accelerator Complex

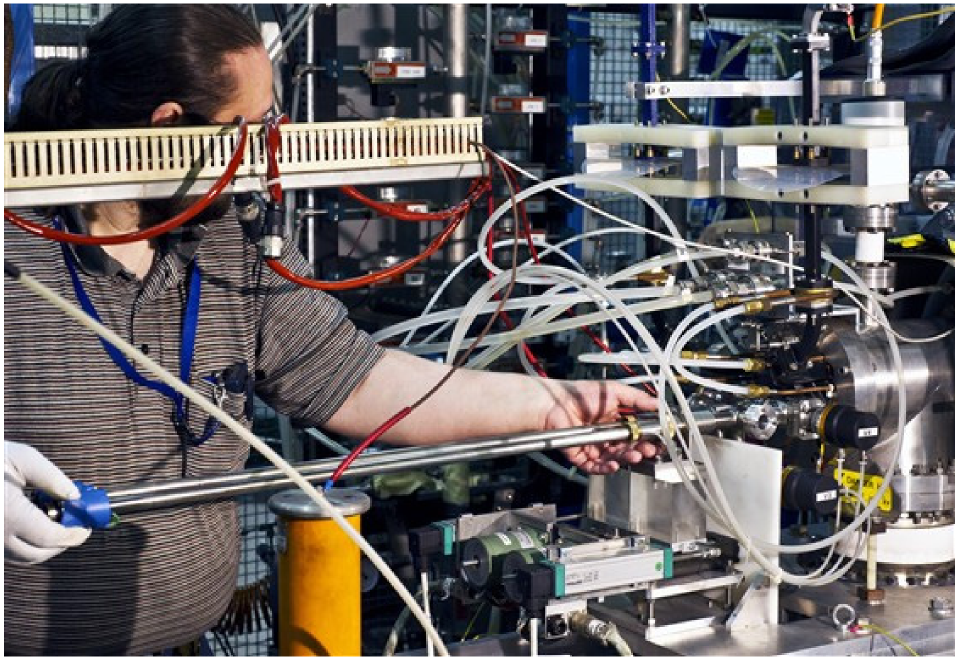


Lead Beams in LHC

- LHC is accelerating ions of ^{208}Pb, fully ionized, charge +82

ECR

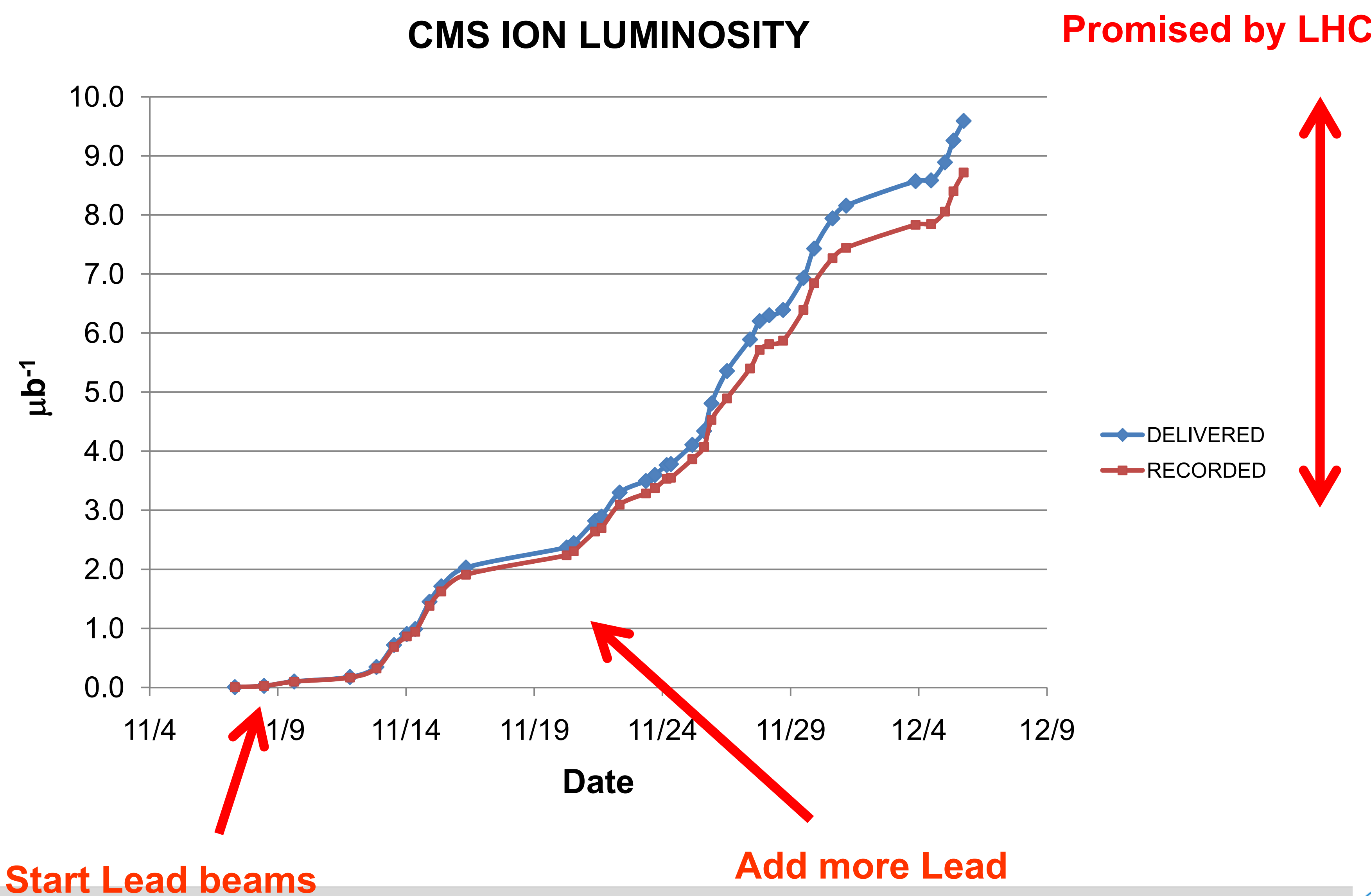




- Energy of 2.76 TeV/nucleon pair (82/208=0.4 times proton energy)
- “Only” 7 10^7 ions per bunch, much less than typical proton bunch of 10^{11} Electrostatics!
- In 2010 LHC collided up to ~140 bunches per beam, about 1/40 of nominal luminosity, ~200 Hz of inelastic collisions

Luminosity

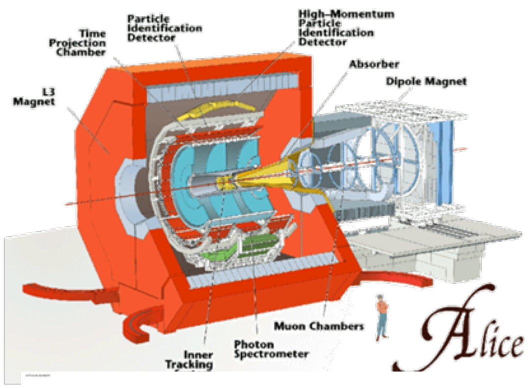
- The switch from pp to PbPb went really fast…



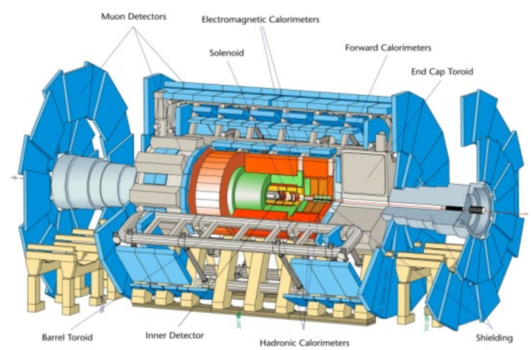
The experiments: complementary and redundant

State of the art!

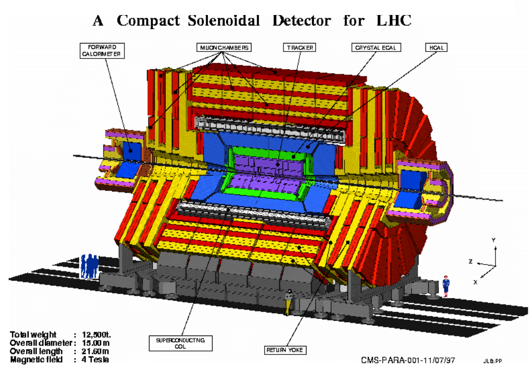
ALICE: Dedicated HI experiment with large suite of detectors optimized for high efficiency tracking and particle identification across large range of momenta from below ~100 MeV/c to above 100 GeV/c



ATLAS: Large acceptance, calorimetric system particularly well suited for detailed jet studies. A multi-purpose detector, designed to study relatively high p_T particles with p_T>~0.5 GeV/c

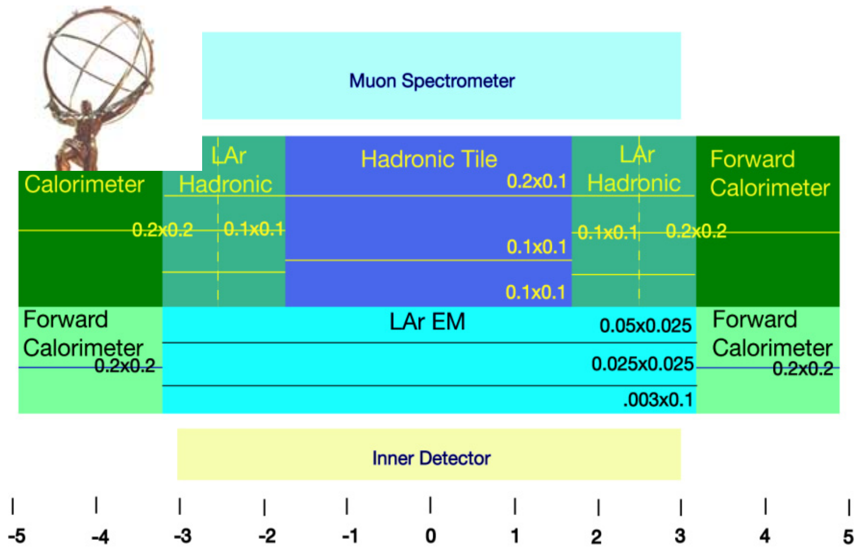


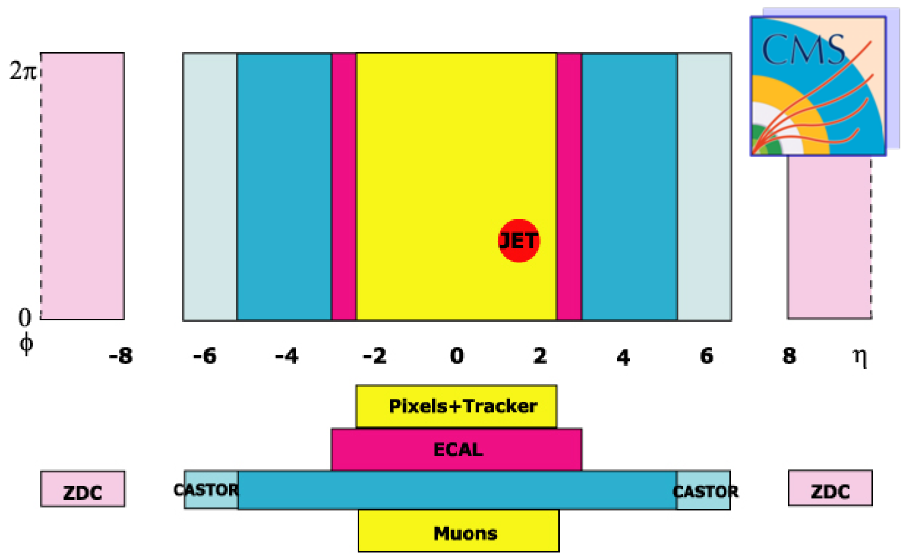
CMS: Particularly large calorimetric detector coverage, including very forward, and good momentum resolution due to high B field. A multi-purpose detector, designed to study relatively high p_T particles with p_T>~0.5 GeV/c.

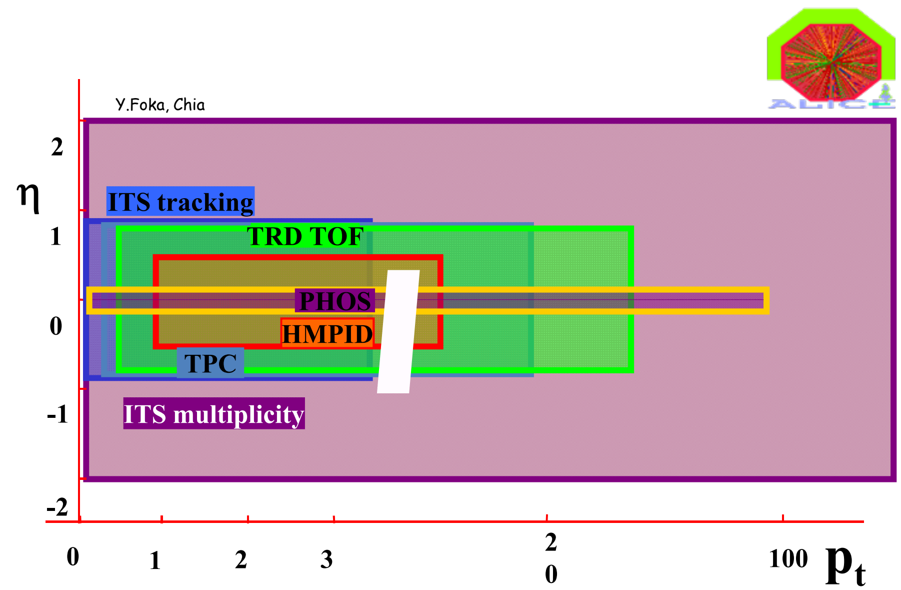


Differencent acceptance, p_T range, particle ID

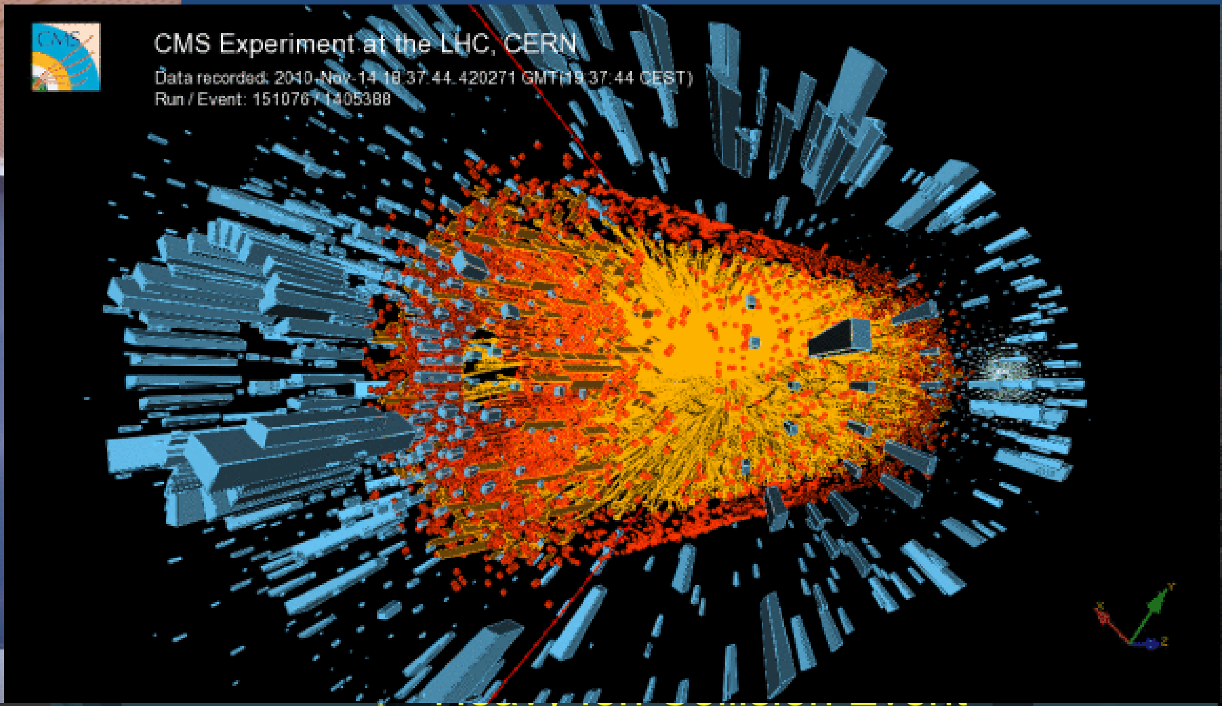
- Different B field: 0.5T, 2T, 4T
- Different emphasis on hermeticity
- Different emphasis on particle ID
- Different DAQ capabilities
- Different detector technologies

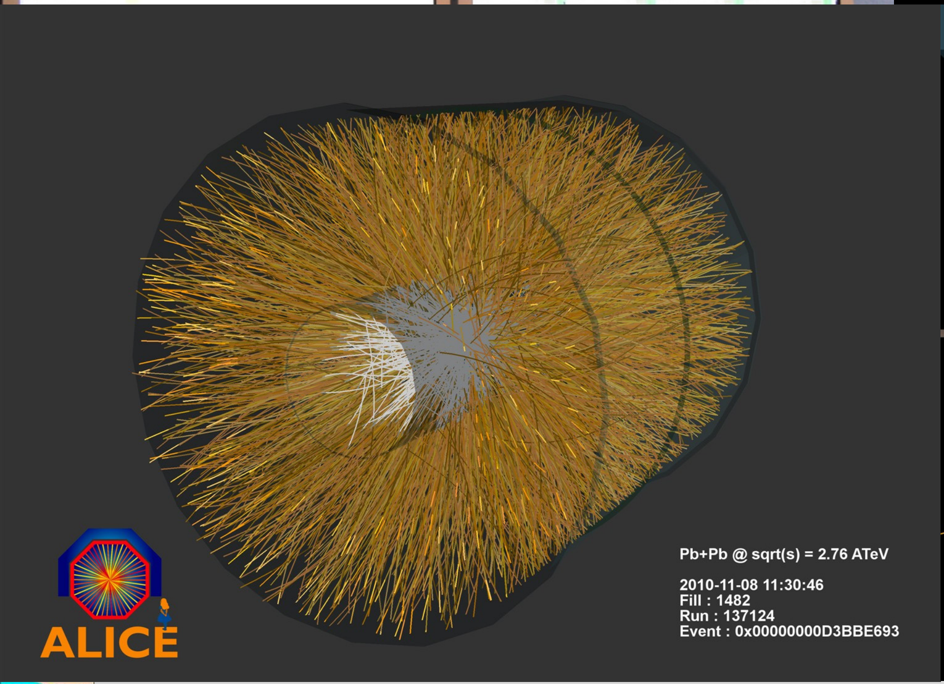


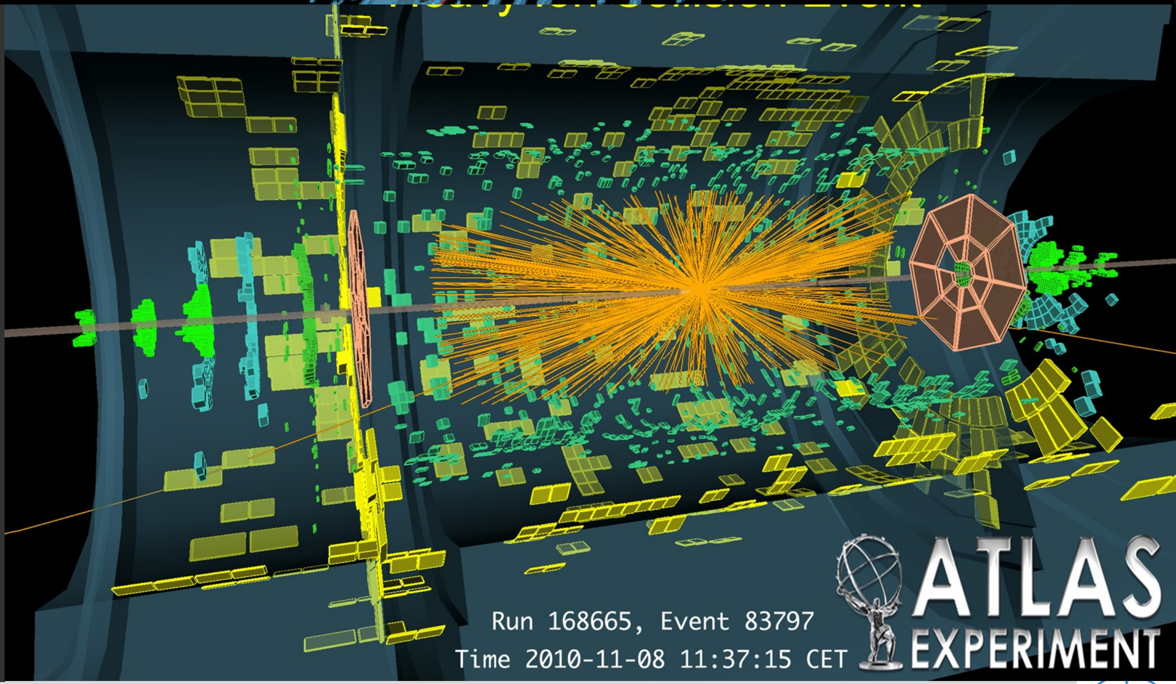




Data taking worked flawlessly

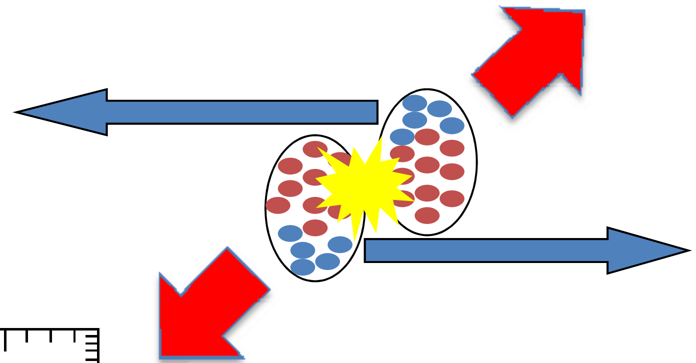


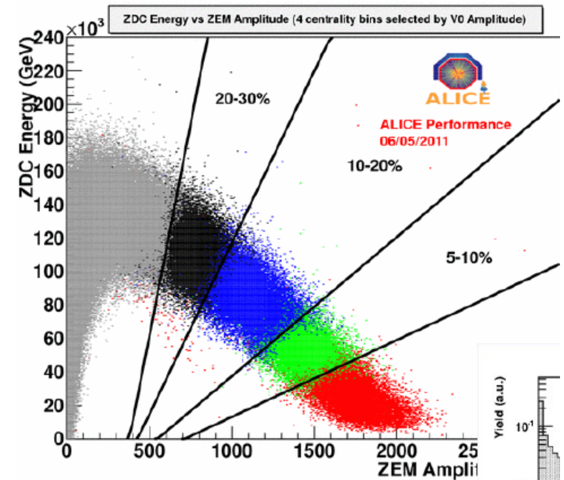


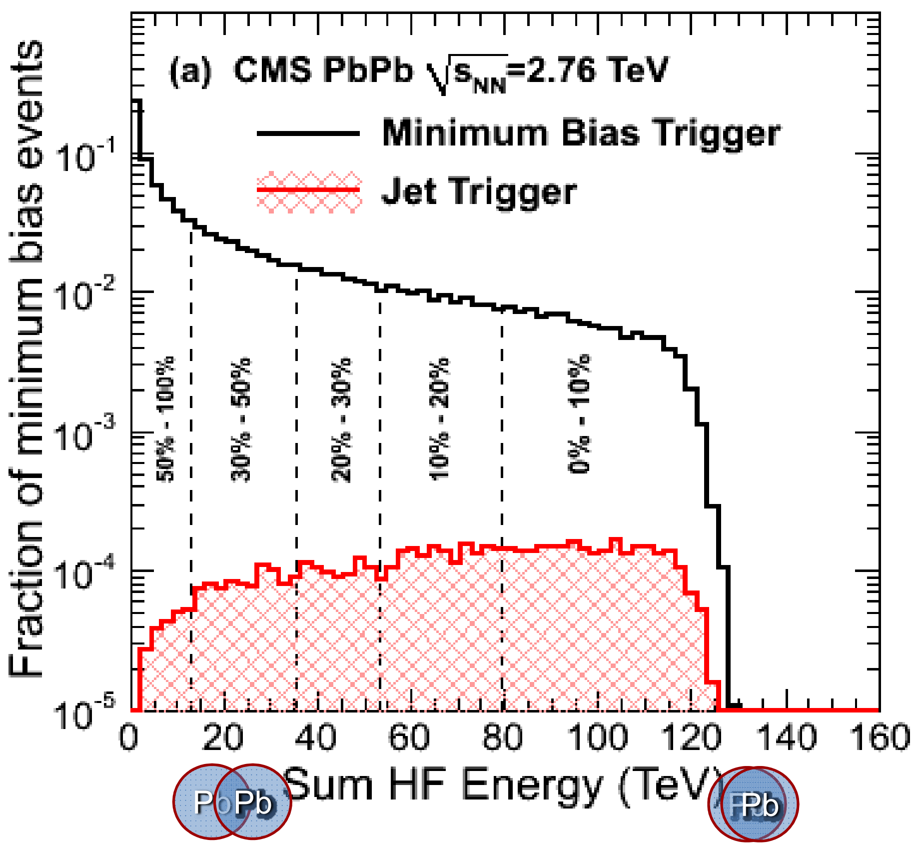


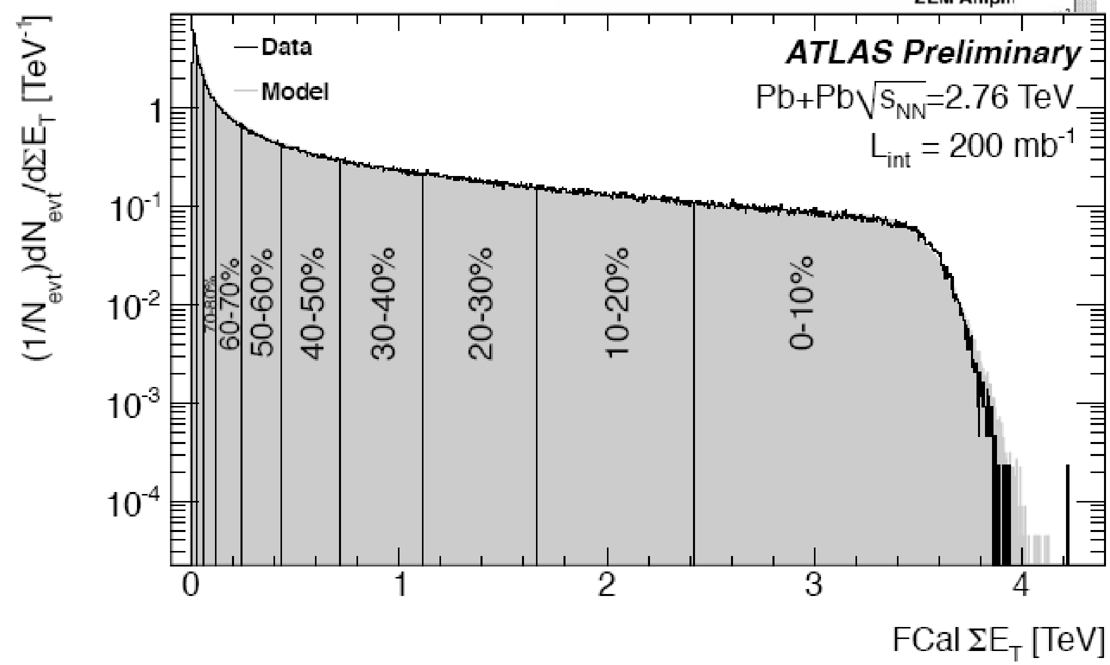
Centrality: overlap of colliding ions

- All experiments use forward detectors: Participants/multiplicity
- Additional information from Zero Degree Calorimeters: Spectators
- Essential for HI physics!

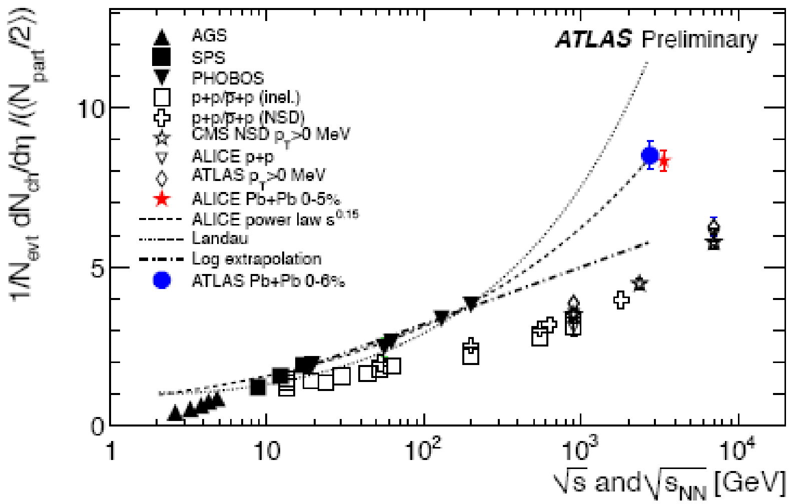




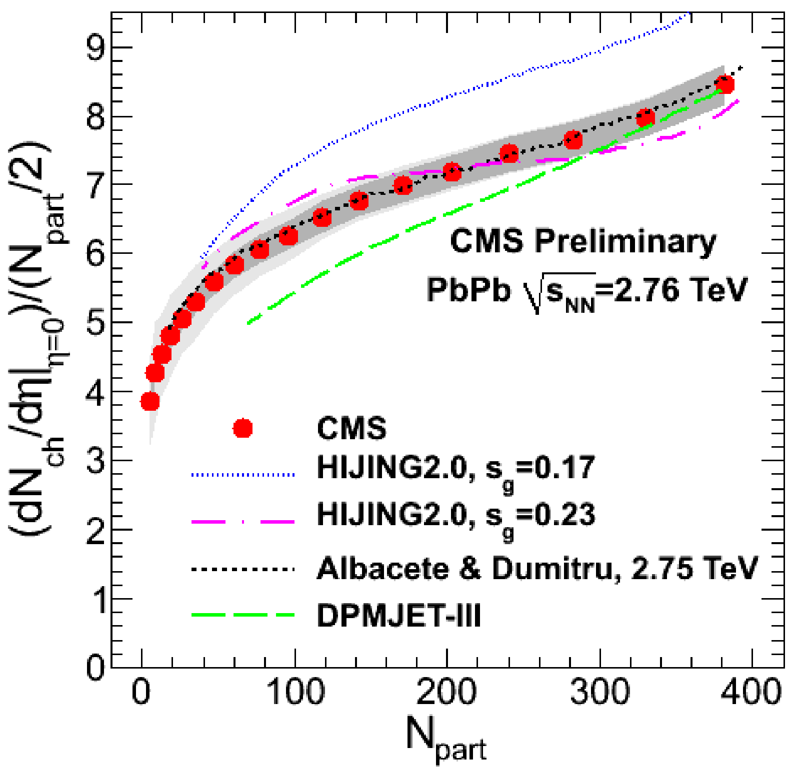


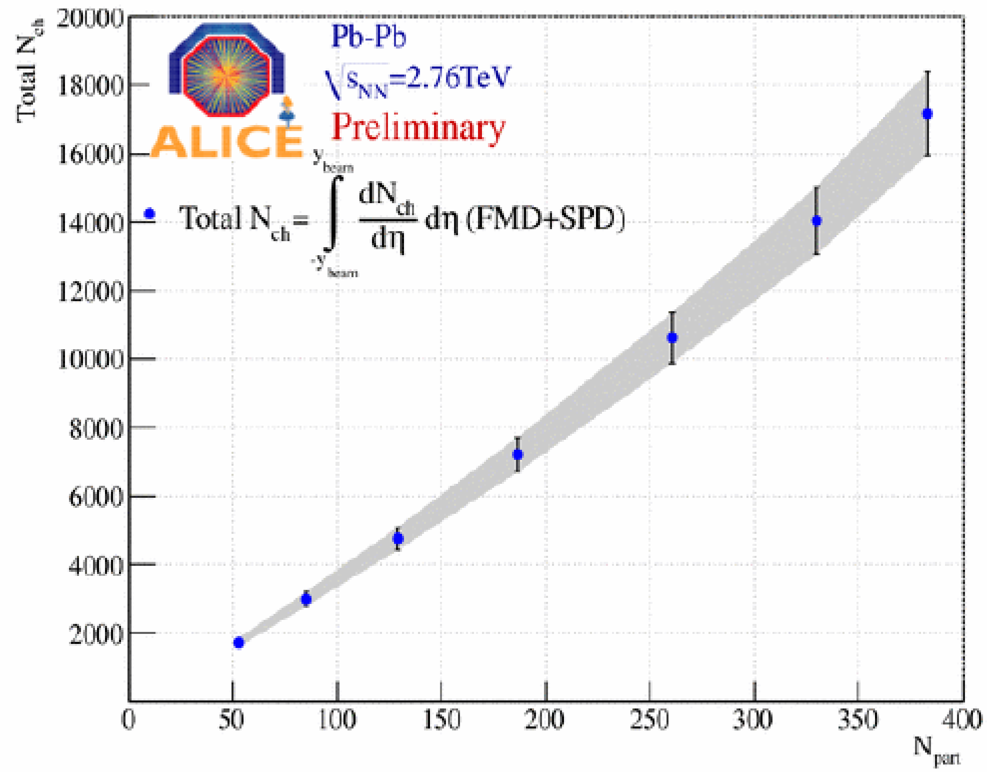


Charged particle multiplicity



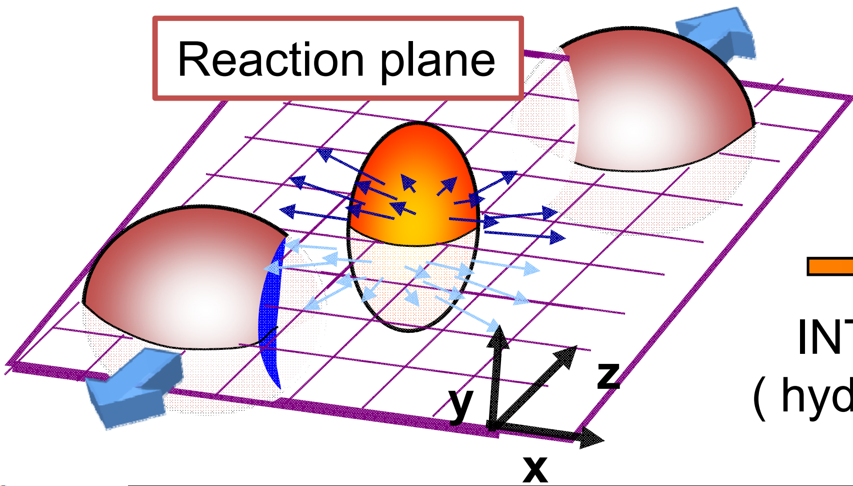
- ~17000 charged particles in most central collisions
- Large increase compared to lower energies
- Centrality dependence similar to lower energies





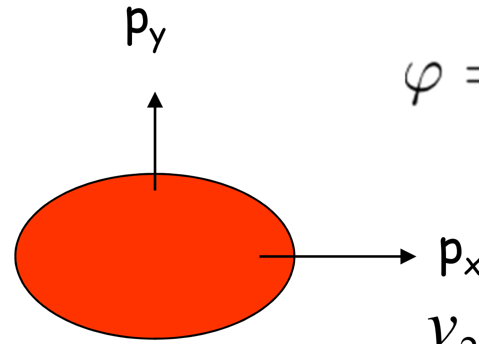
Particle production in Pb-Pb: azimuthal anisotropy

Initial spatial anisotropy



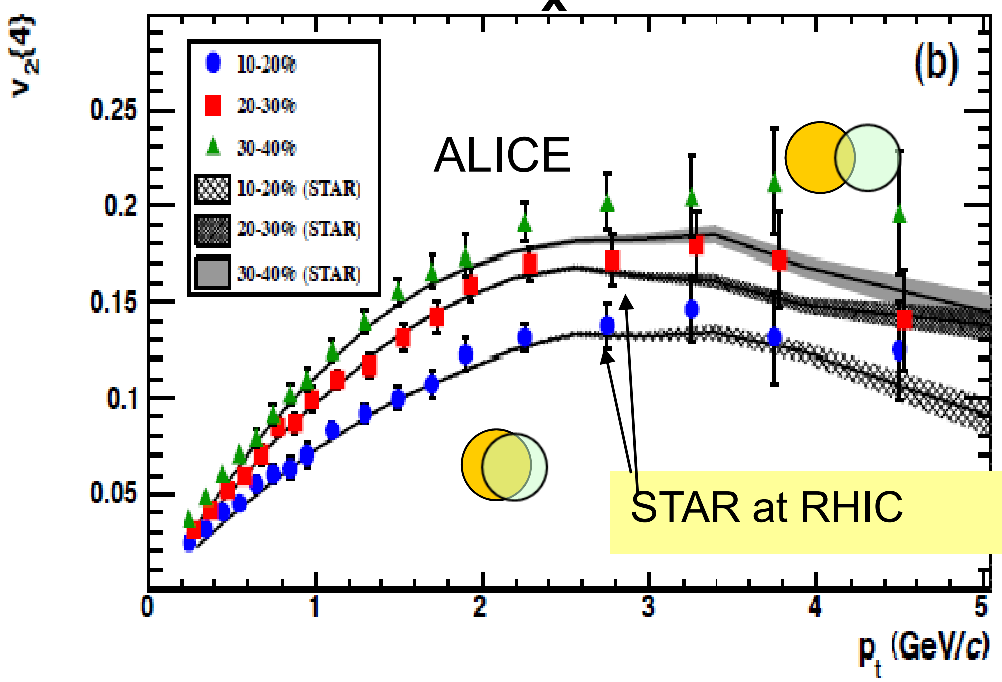
INTERATIONS
(hydrodynamics?)

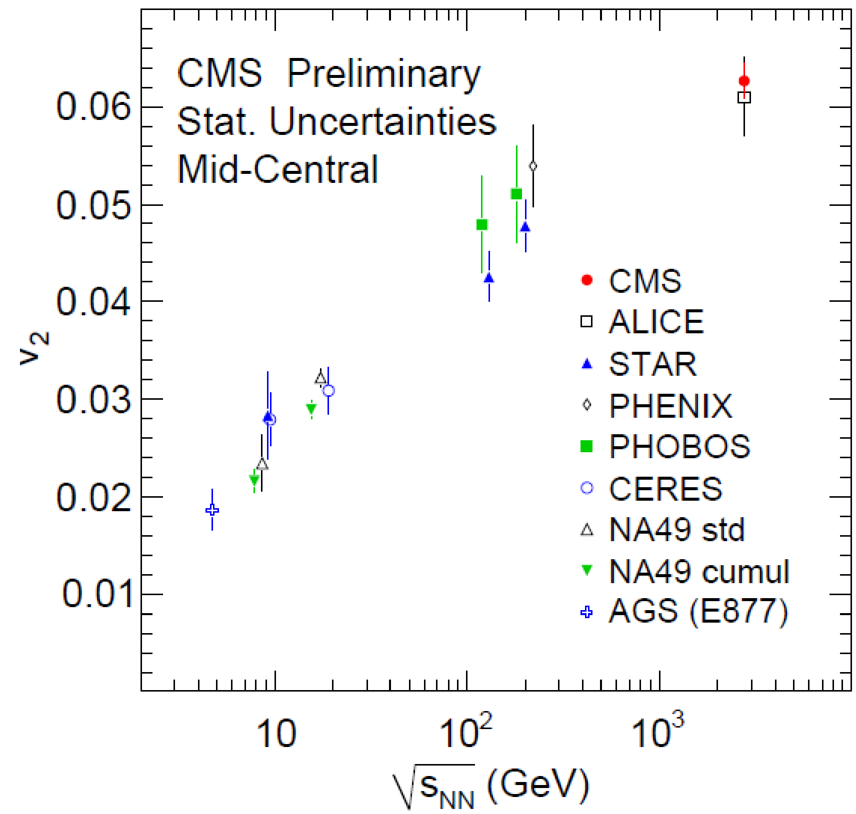
Final momentum anisotropy



$$\varphi = \arctan \frac{p_y}{px}$$

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

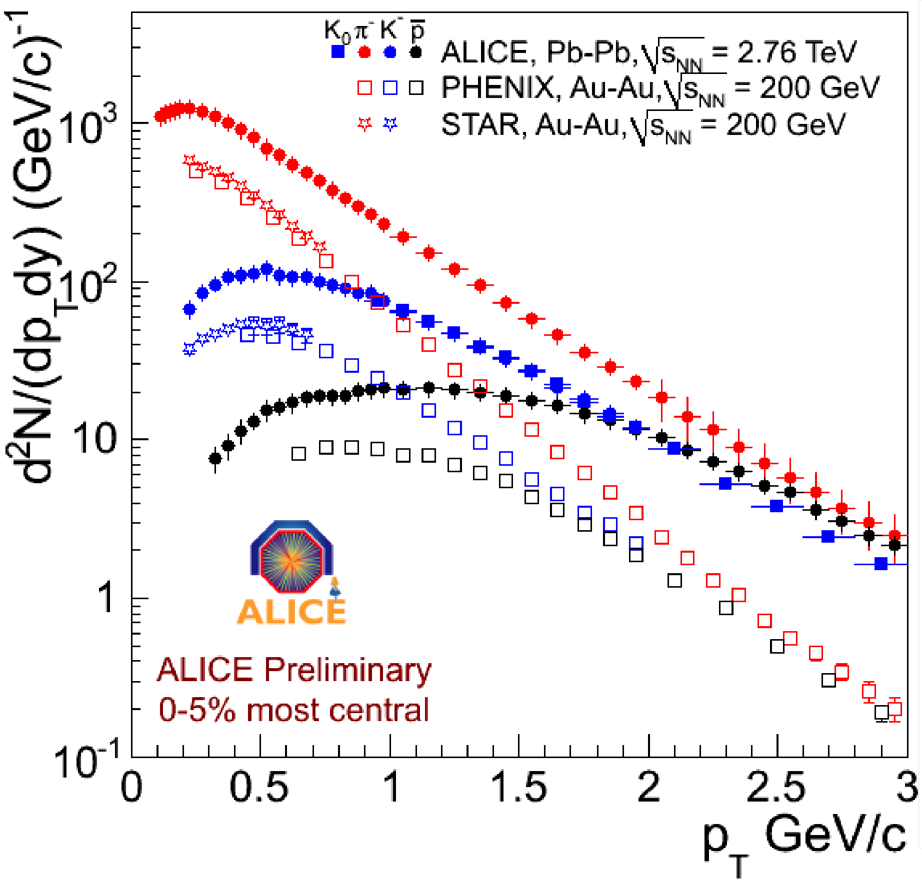


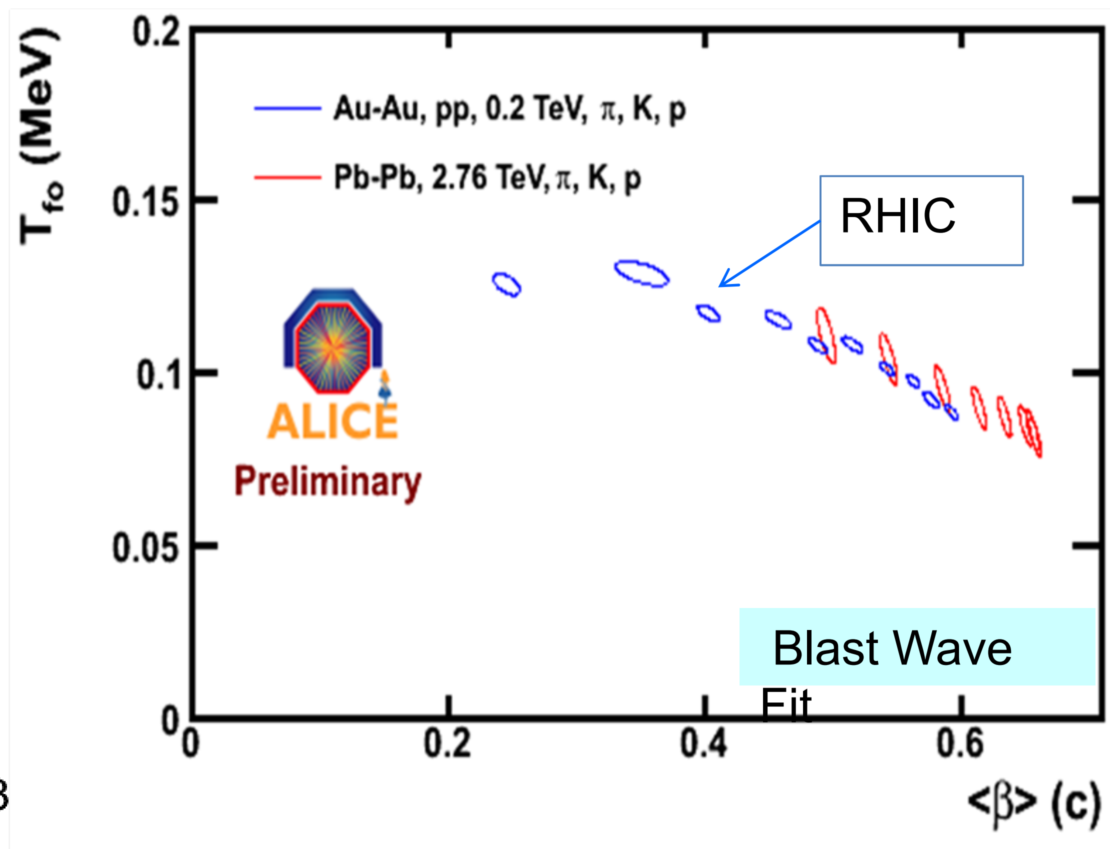


Some increase compared to RHIC: higher p_T overall
Hydrodynamics similar

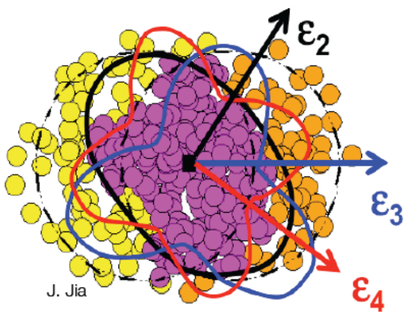
Radial expansion (radial flow)

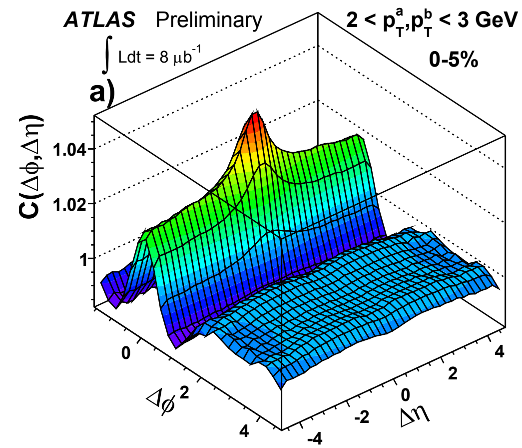
- By comparing momenta of particles with different masses one can estimate speed of expansion of the fireball: up to $\beta \approx 0.66$
- Particle ID is essential here..

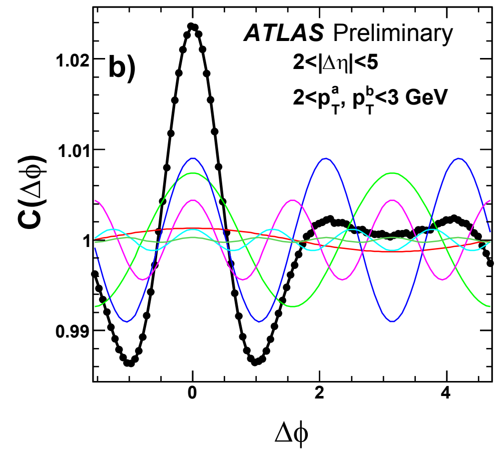


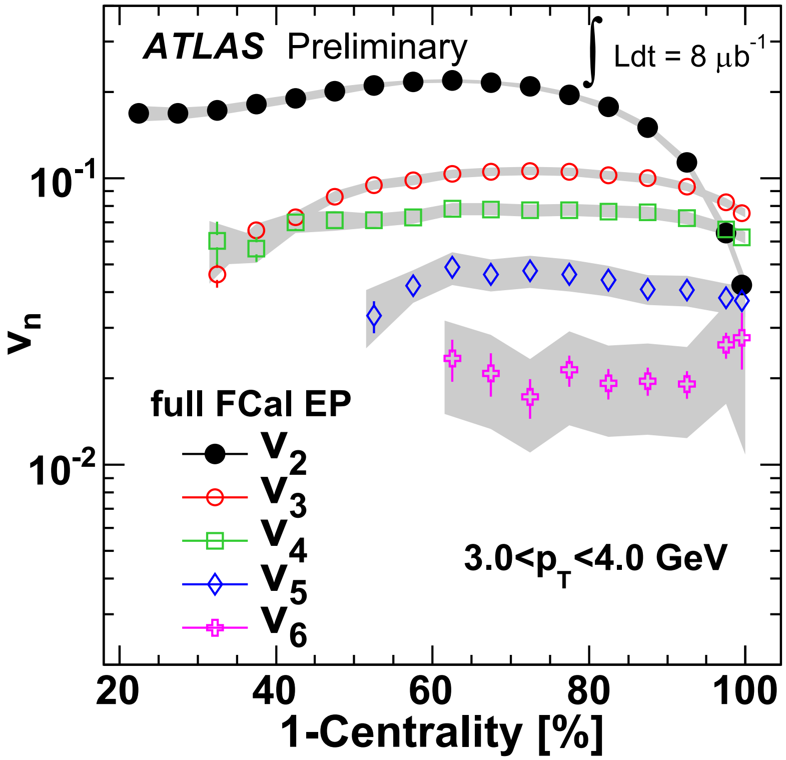


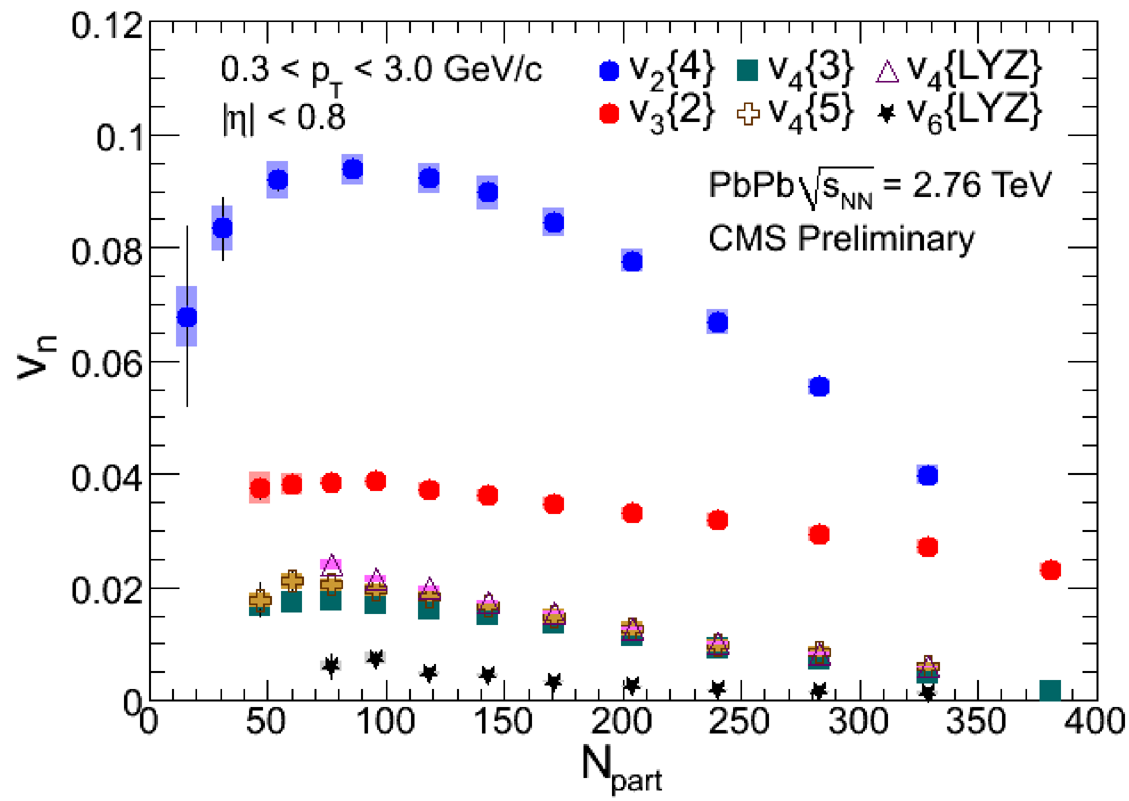
Higher harmonics: fluctuations of initial state









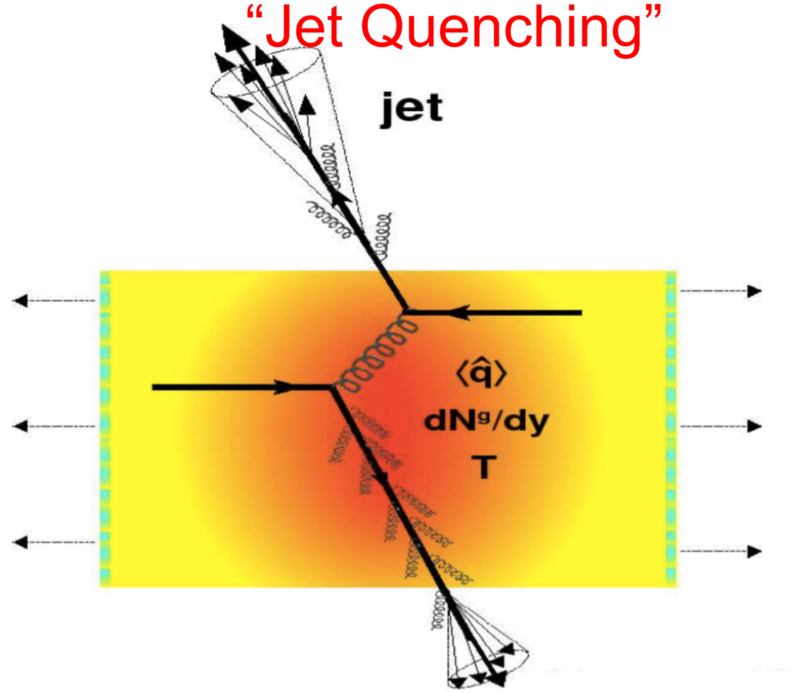


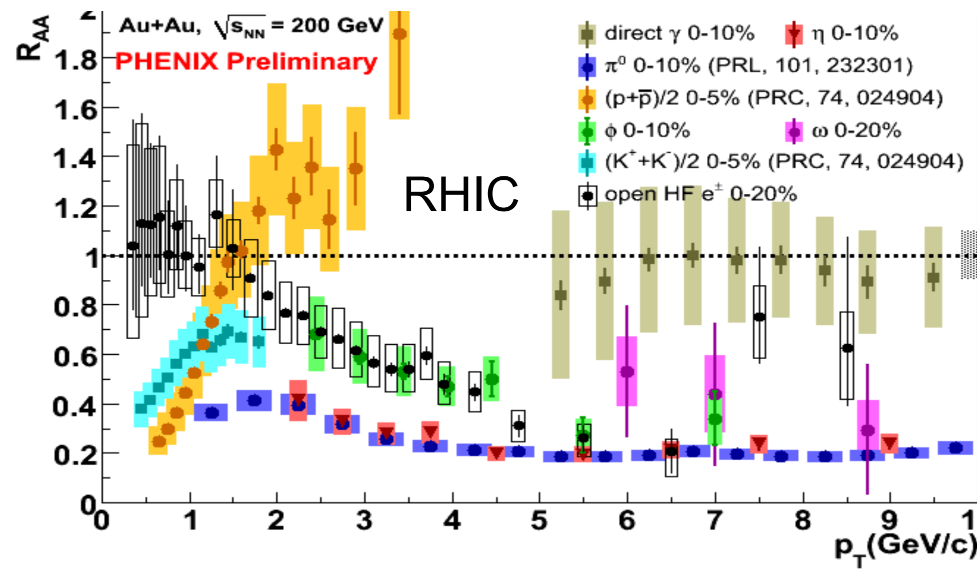
Jet "quenching" in heavy ion collisions

- Single particle spectra
  - Compare to pp: R_{AA}
- Study different particles
  - Colorless: Photon, Z, W colorless
  - Colored: Charged particles, π^0, b-quarks
- Identify full jets
  - Jet energy spectra
  - Dijet energy asymmetry
  - Jet fragmentation
  - *γ-jet, Z-jet*

- Study as a function of p_T, centrality

Parton probes the QCD medium:
"Jet Quenching"

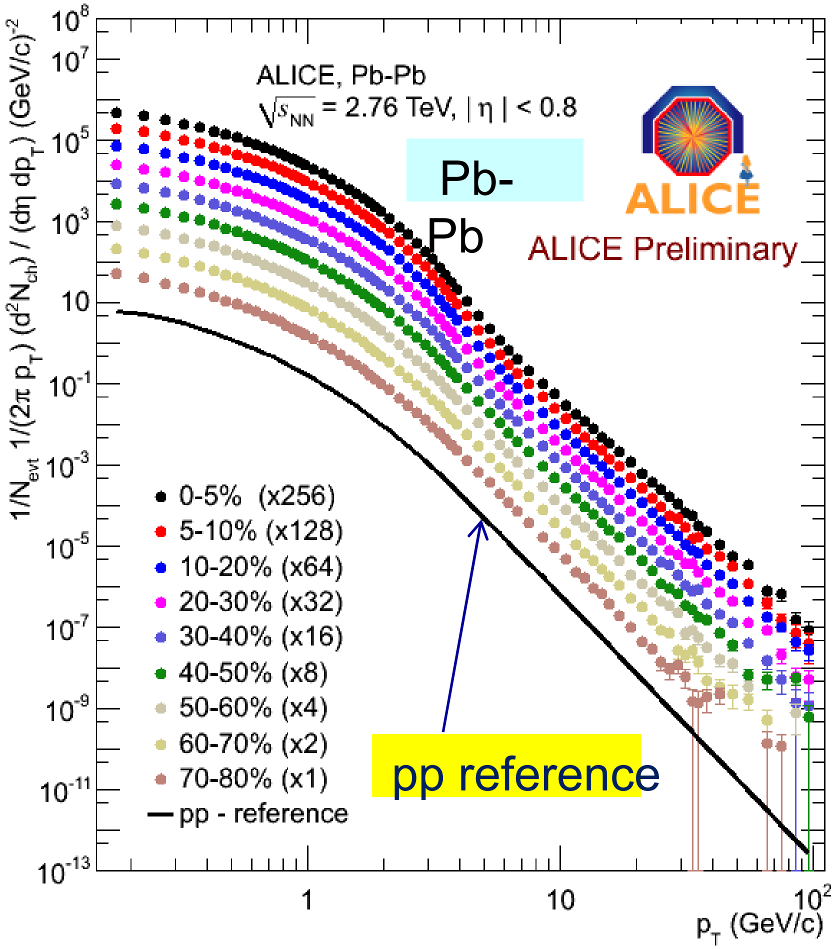




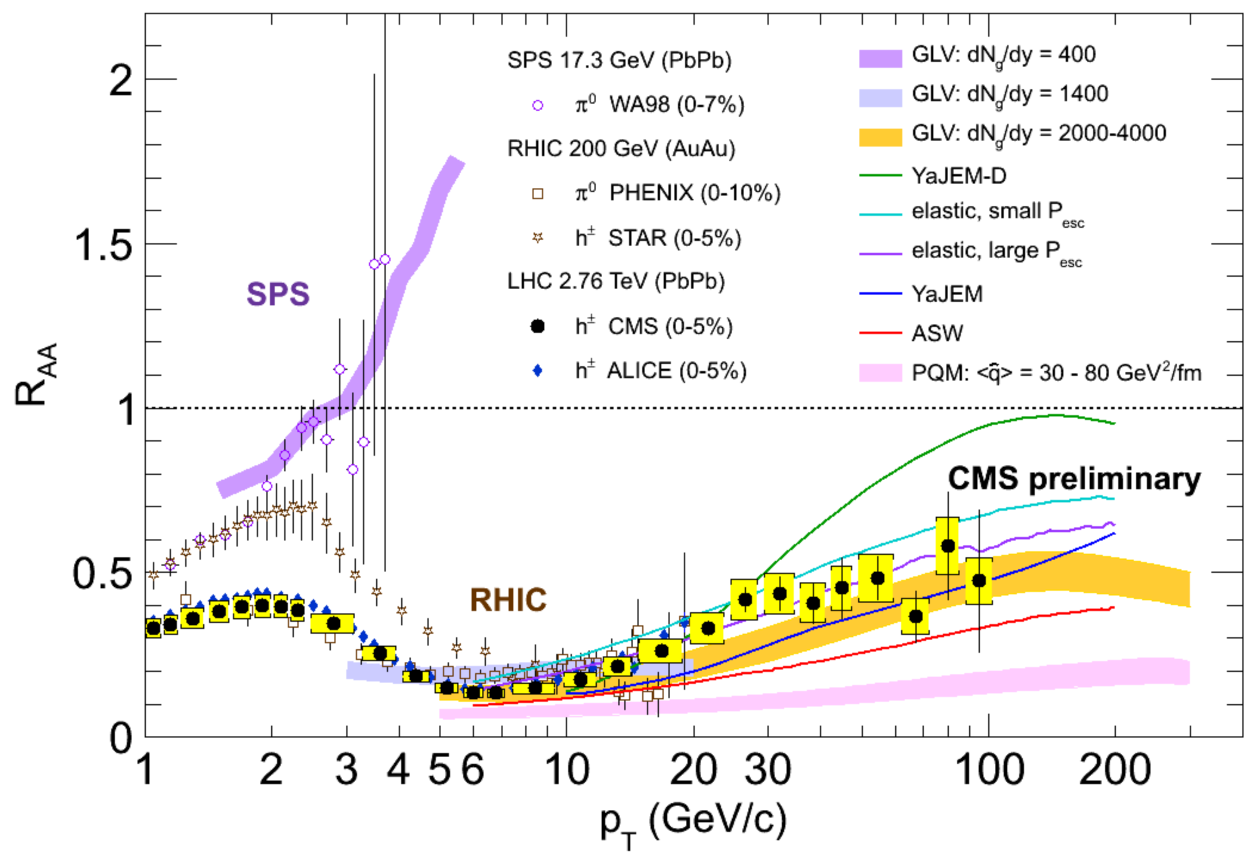
Jet quenching via hadron suppression

$$R_{AA} = \frac{\#(\text{particles observed in AA collision per N-N (binary) collision})}{\#(\text{particles observed per p-p collision})}$$

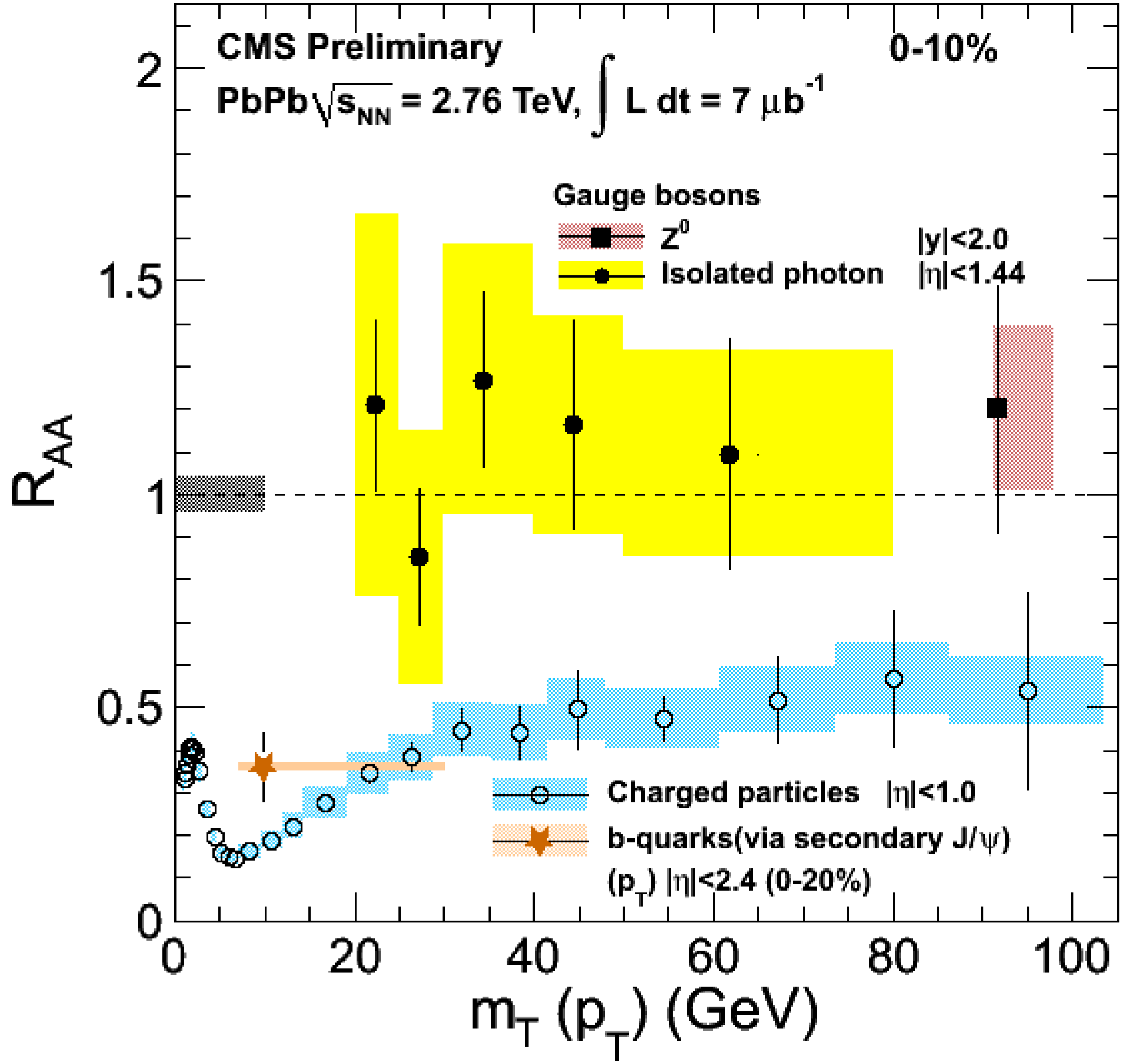
Cross-section



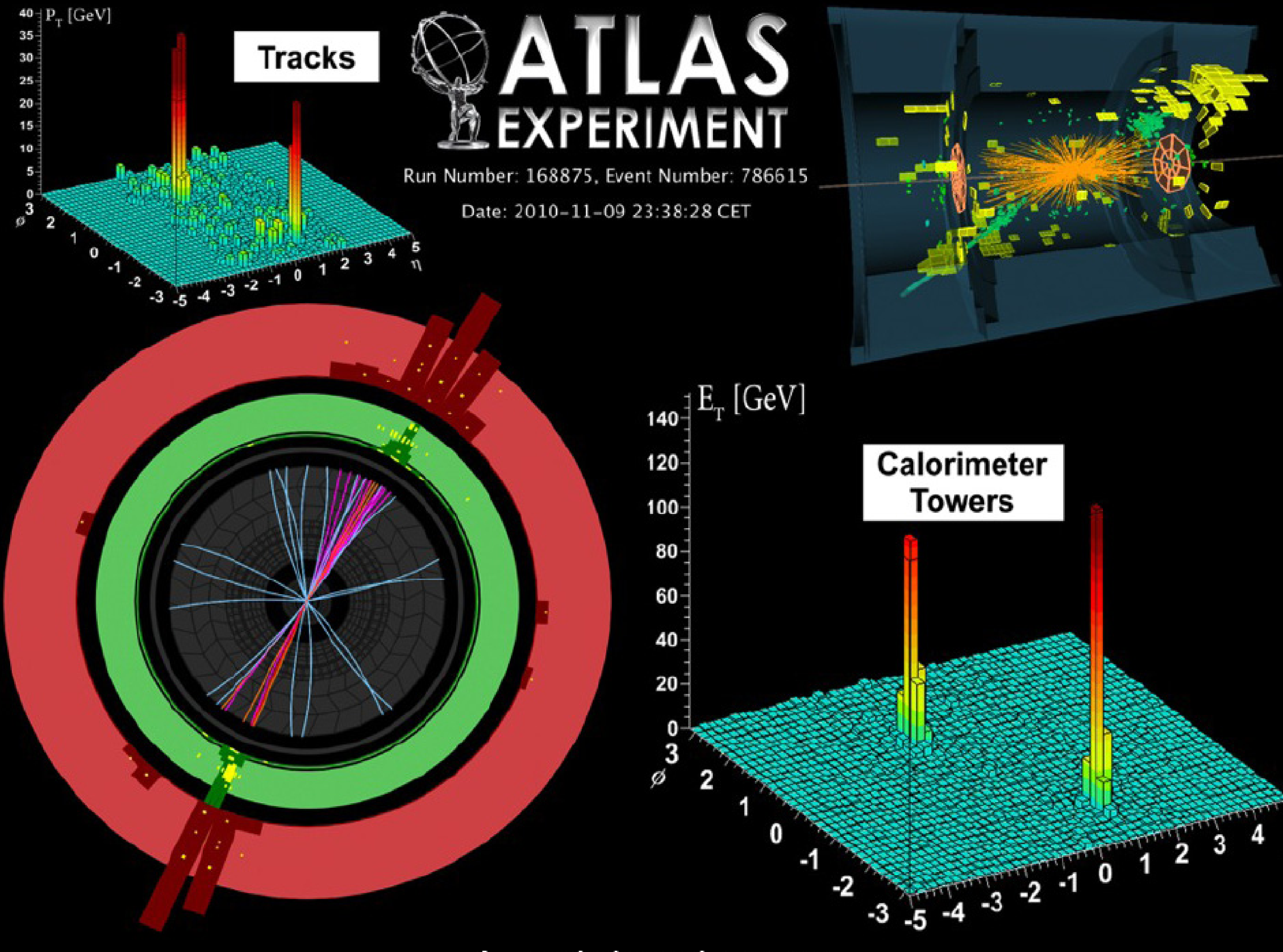
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$



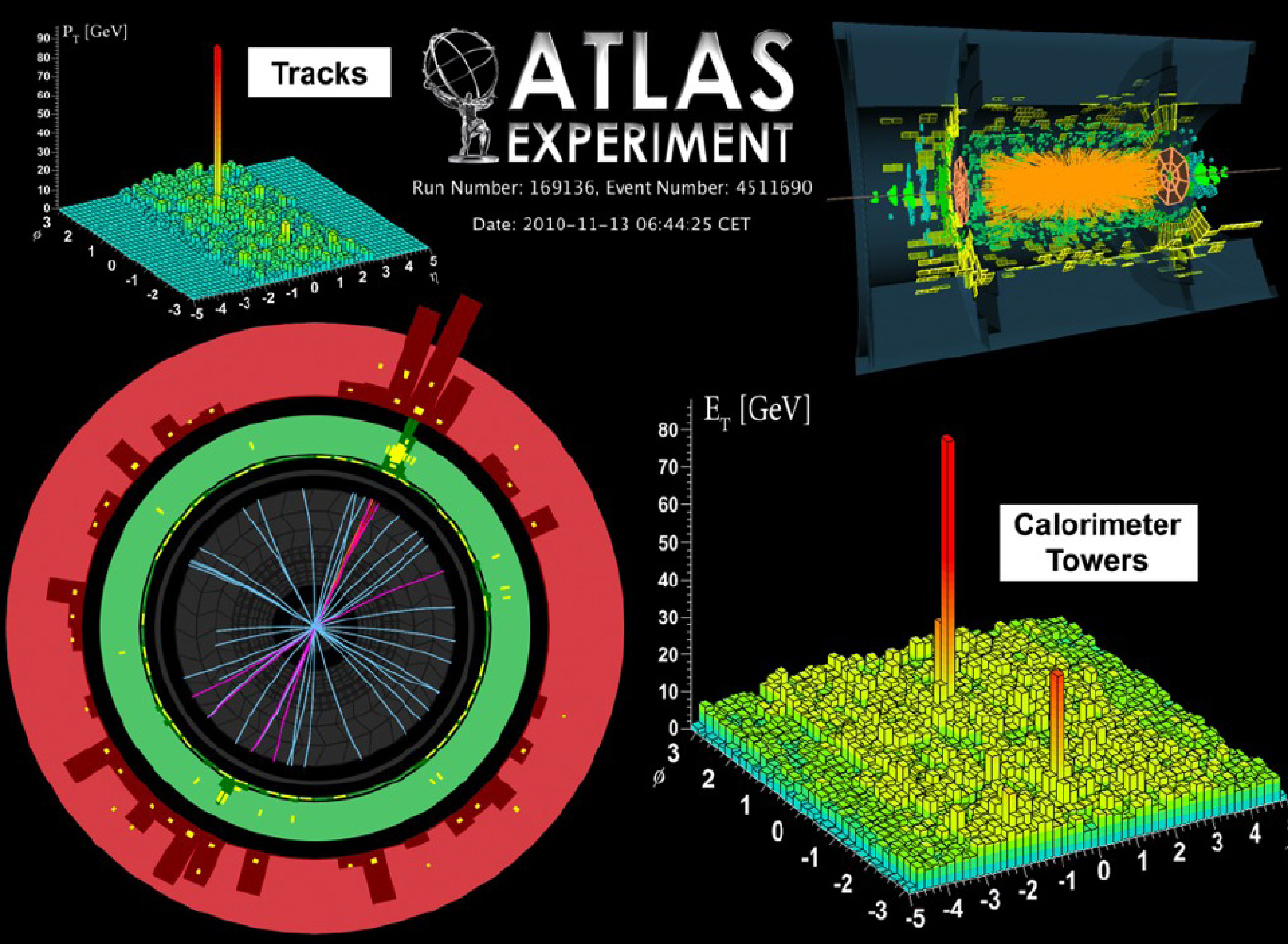
R_{AA} for multiple particle types



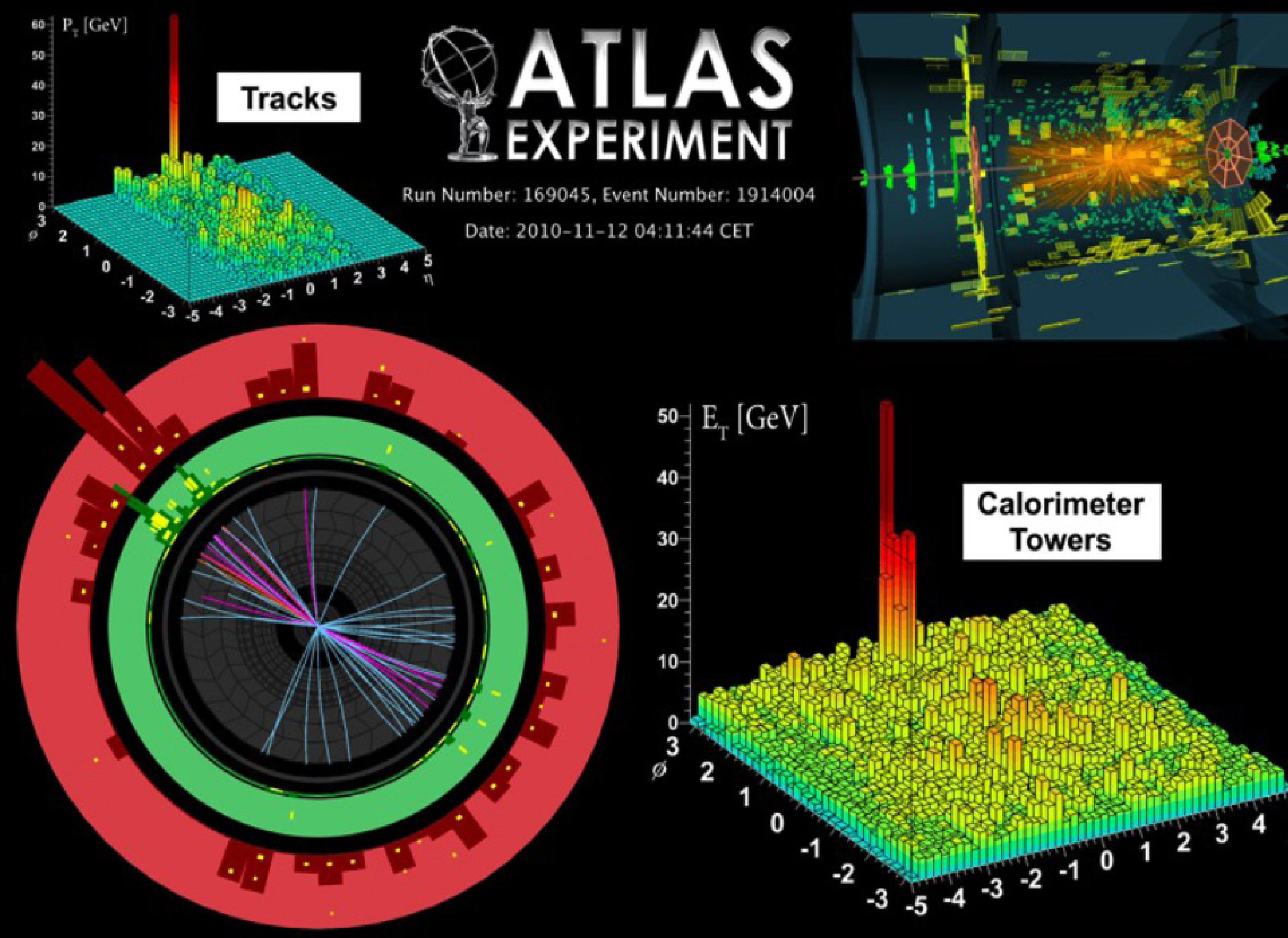
- Colorless particles are not quenched
- Colored particles are strongly quenched



A peripheral event

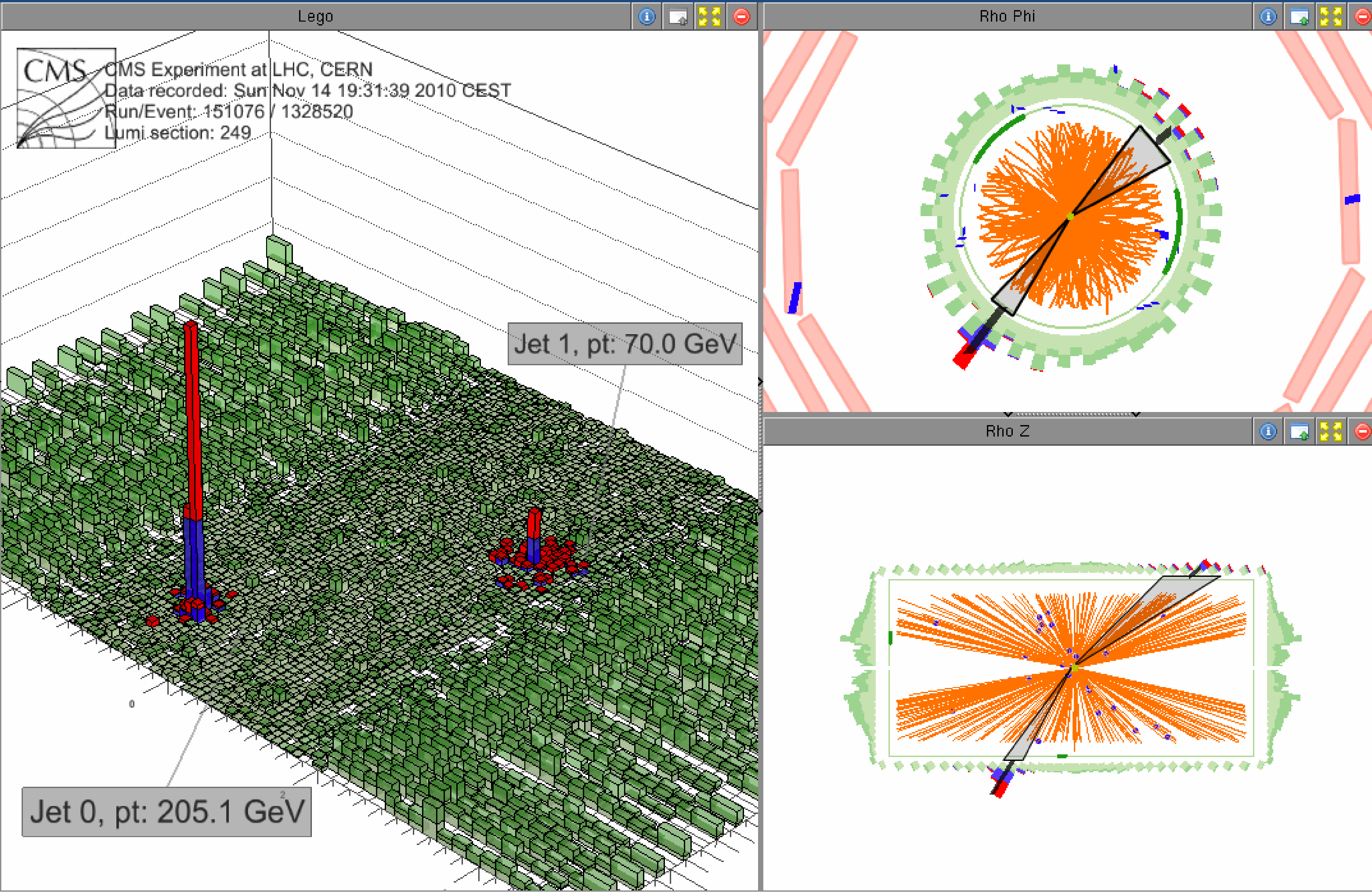


A more central event



A very central event

Jets in the CMS detector

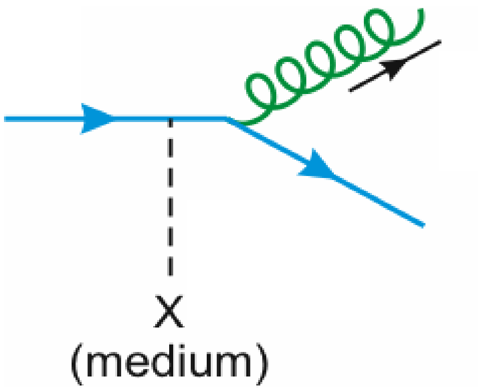


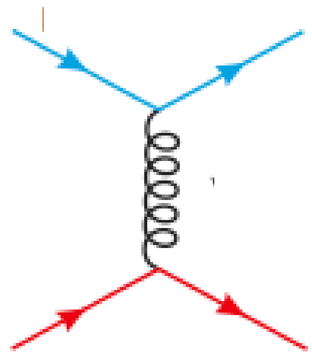
Parton energy loss

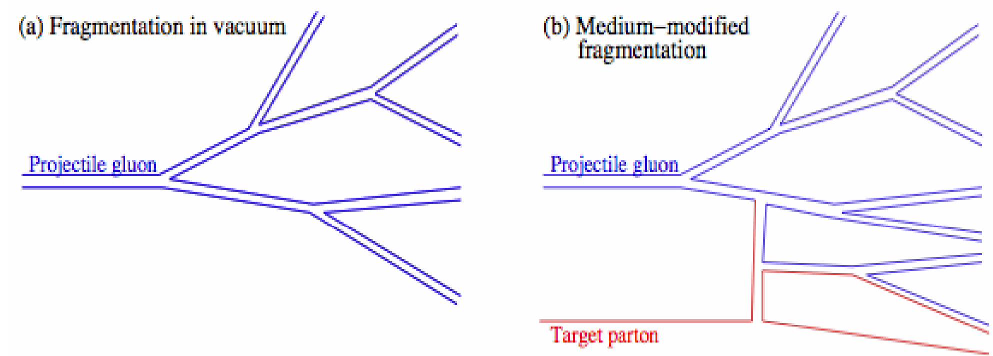
- Key ingredients of parton energy loss calculations:

Parton propagation in the nuclear medium
Radiative- Collisional-energy loss

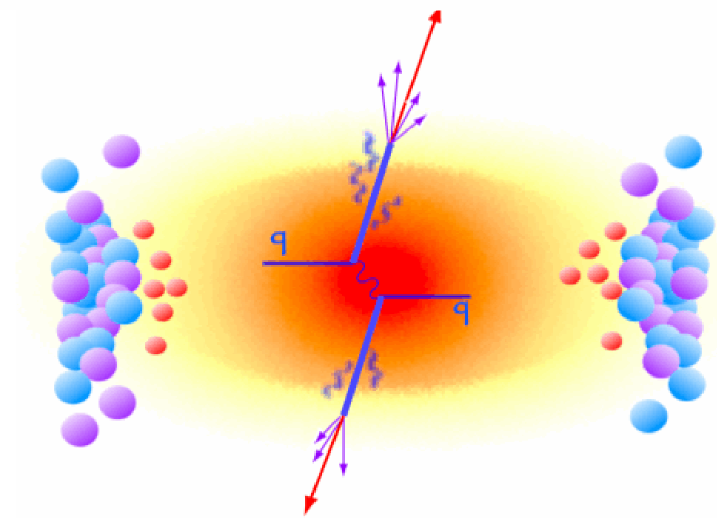
Parton Showering
(Fragmentation)



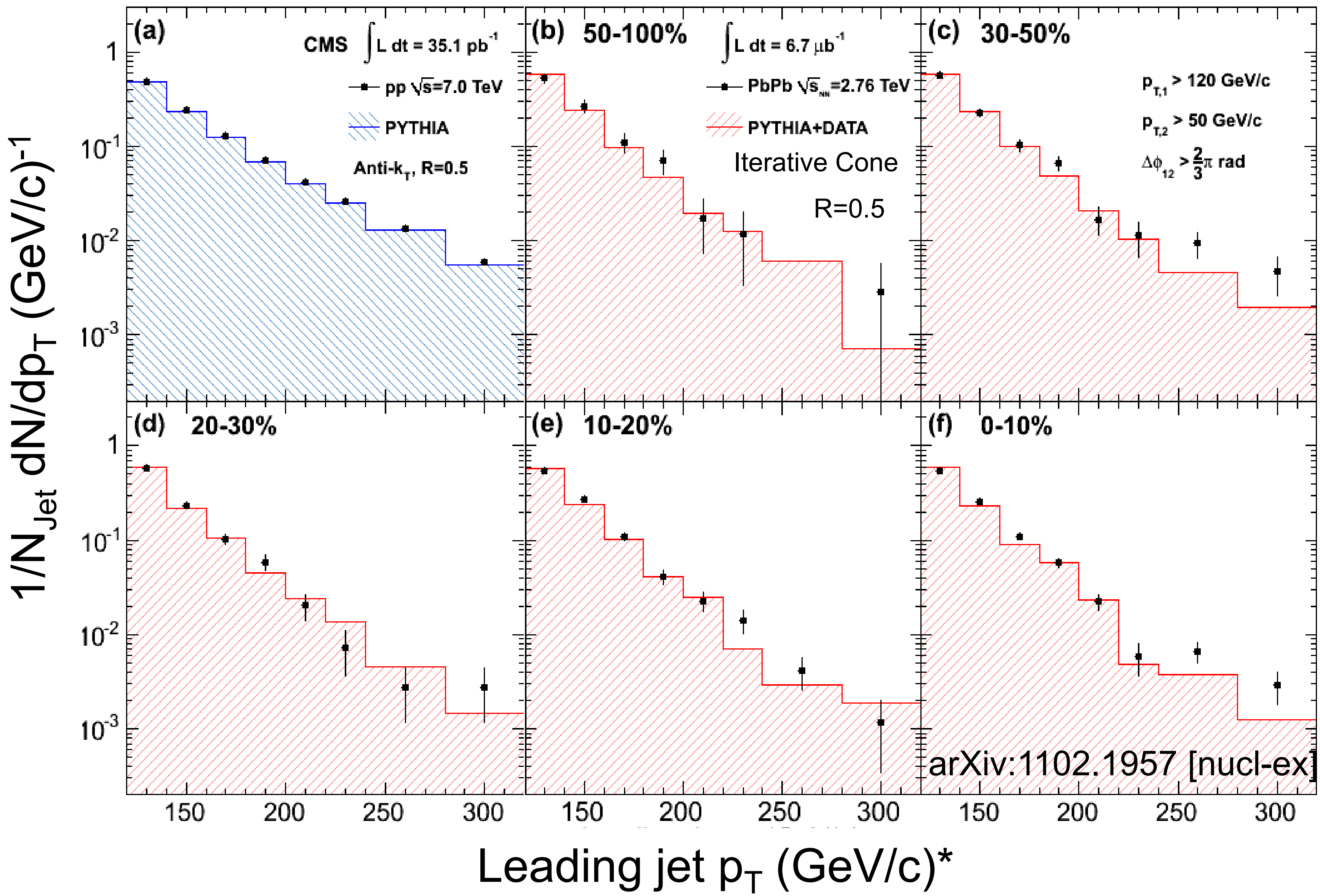




- Components sensitive to
  - medium properties
  - where and when the process happens
- Reconstructed dijets
  - full final state of hard scatterings
  - study the individual components contributing to the parton energy loss



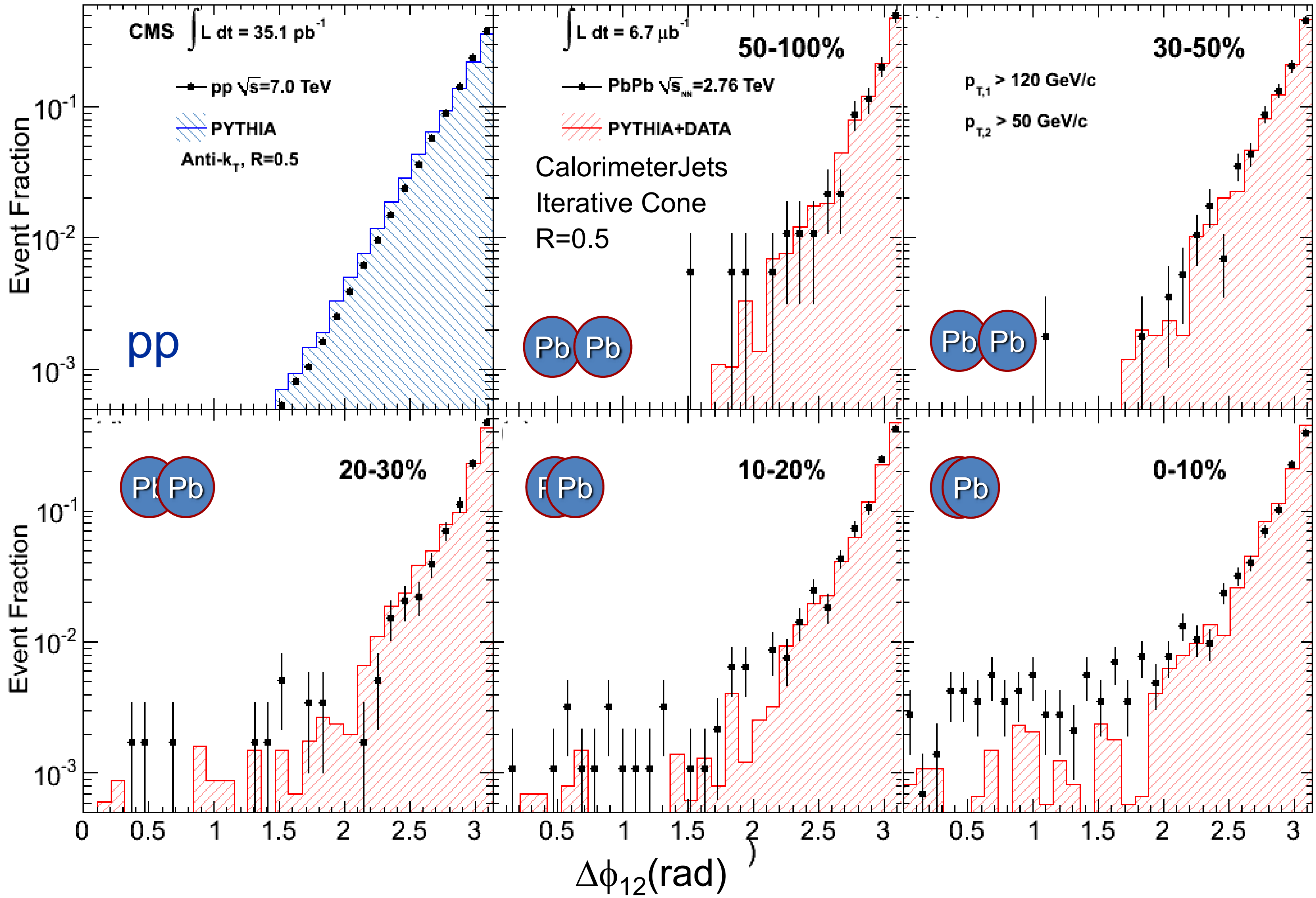
Jet spectra in PbPb and pp reference



Large data sample, reach to very high jet p_T

*Uncorrected for p_T resolution

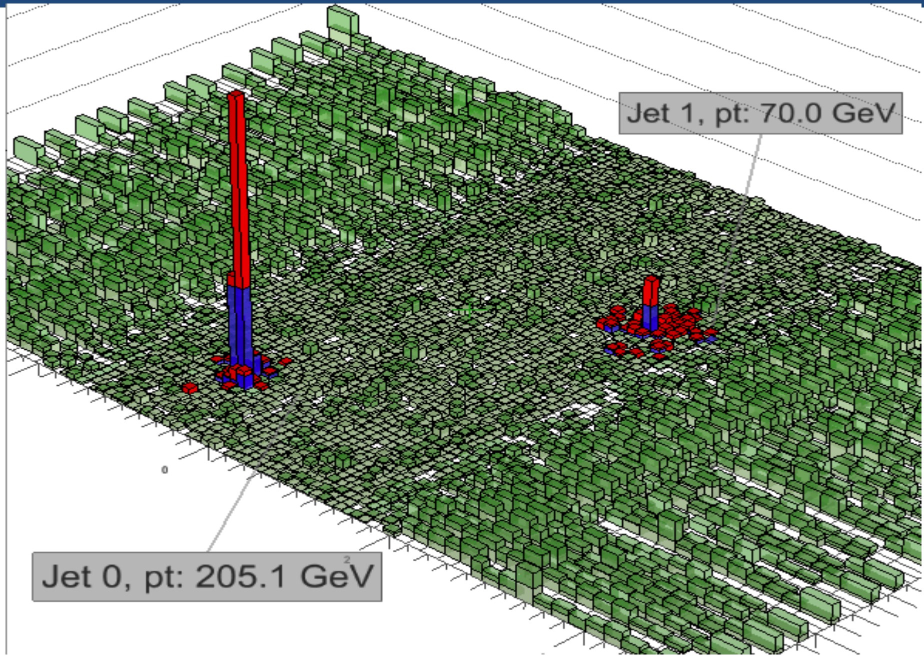
Jet angular correlation



The propagation of high p_T partons in a dense nuclear medium does not lead to a visible angular decorrelation

Dijet asymmetry

- Dijet selection:
  - $|\eta^{Jet}| < 2$
  - Leading jet $p_{T,1} > 120GeV/c$
  - Subleading jet $p_{T,2} > 50GeV/c$
  - $\Delta\phi_{1,2} > 2\pi/3$

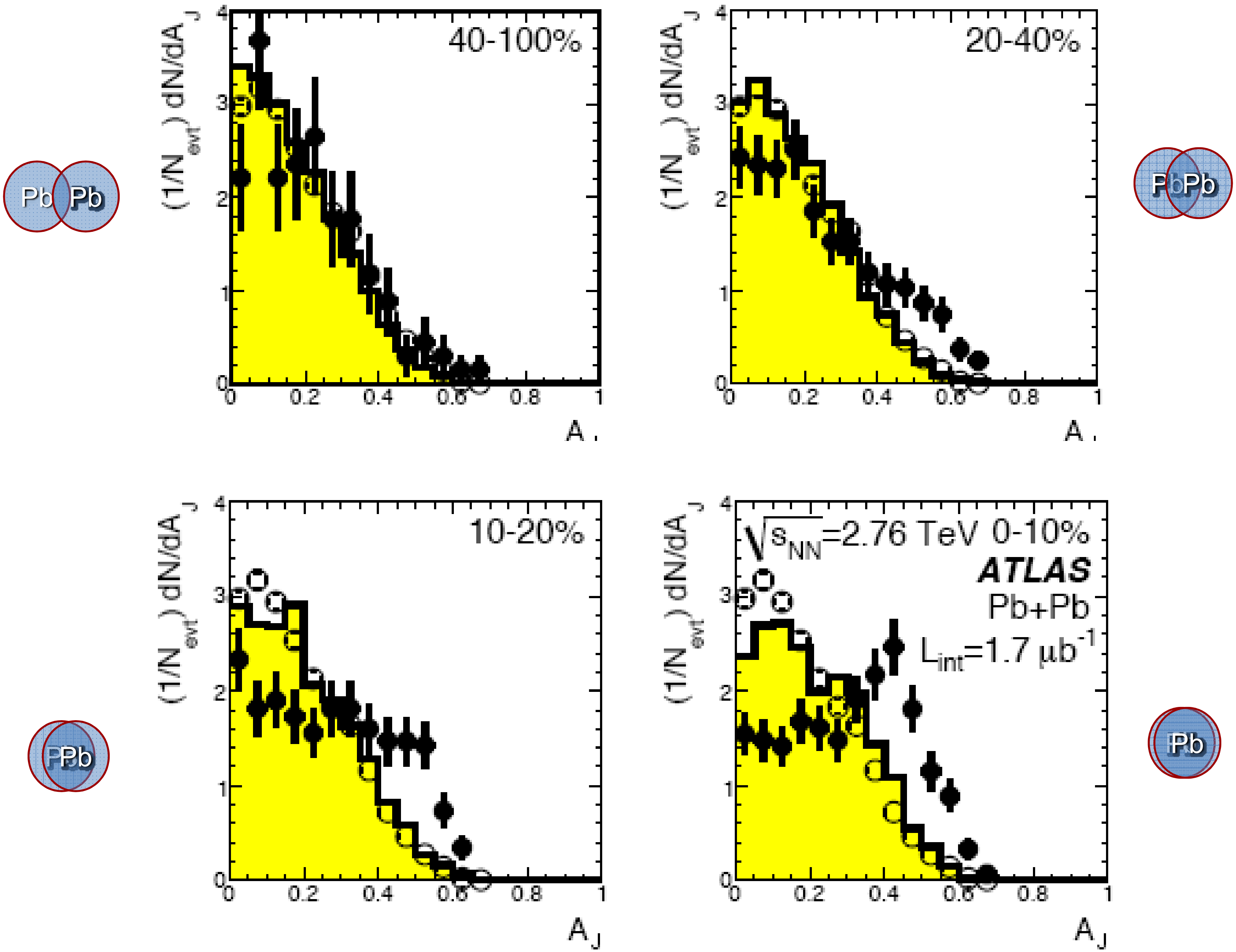


- Quantify dijet energy imbalance by asymmetry ratio:

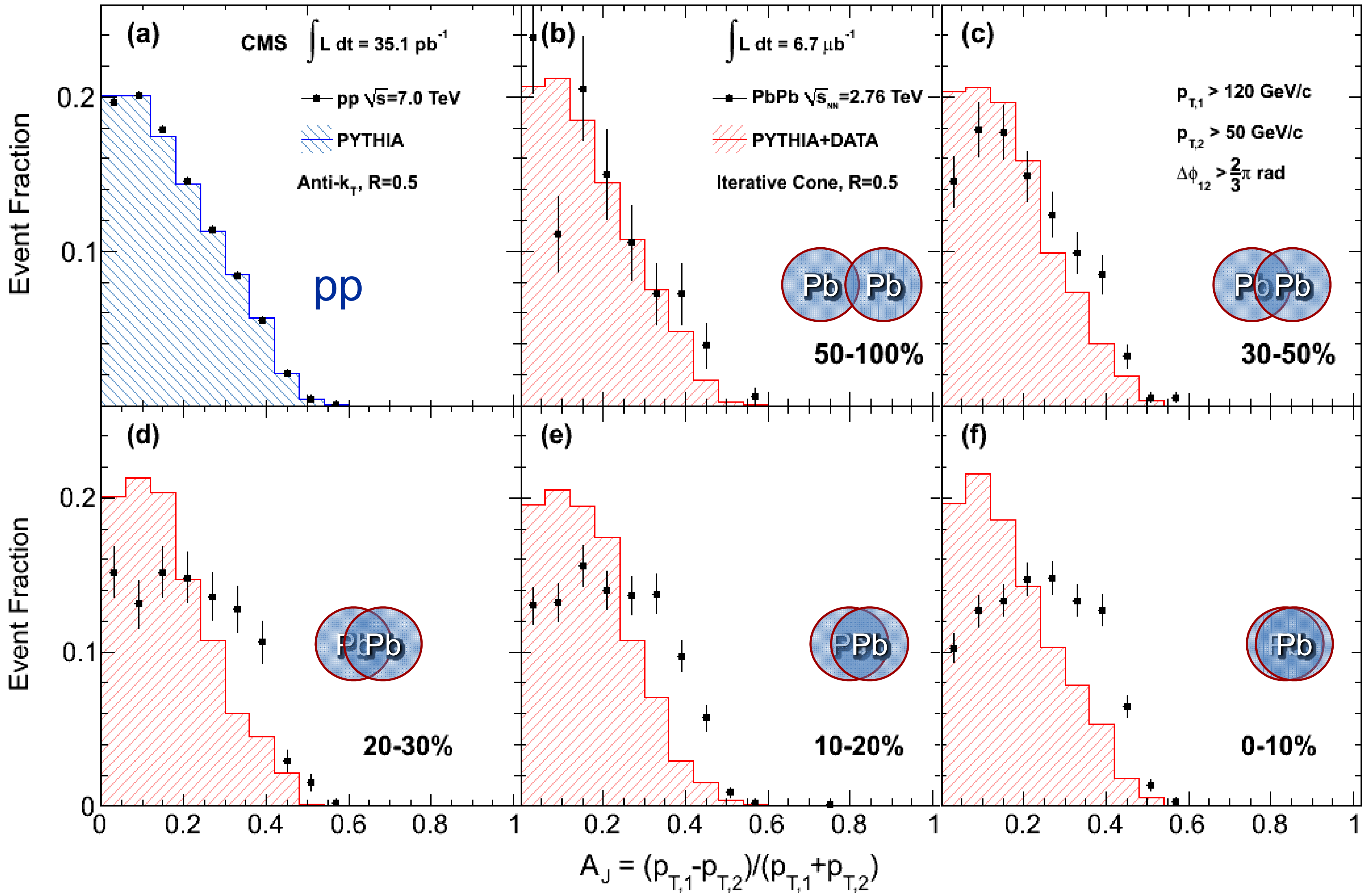
$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- Removes uncertainties in overall jet energy scale

Dijet energy imbalance: ATLAS



Dijet energy imbalance: CMS



Parton energy loss is observed as a pronounced energy imbalance in central PbPb

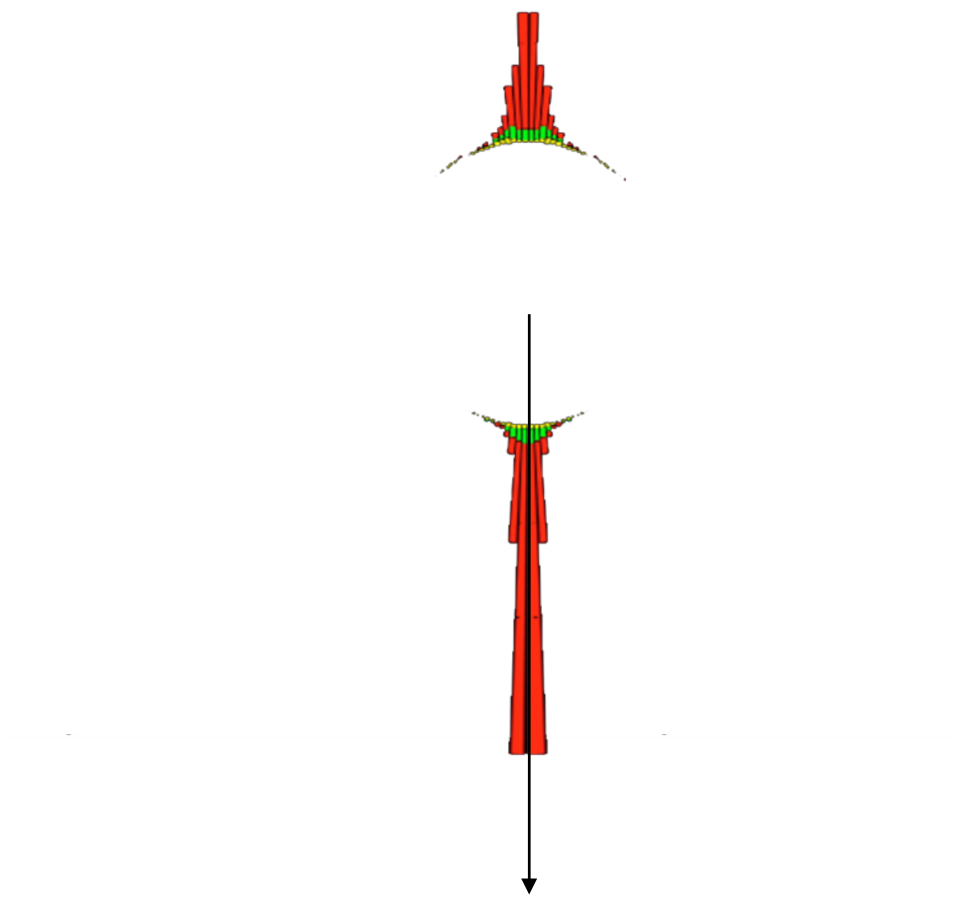
Missing-$p_T^{||}$

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

Calculate projection of p_T on leading jet axis and average over selected tracks with

$p_T > 0.5$ GeV/c and

$|\eta| < 2.4$



Leading Jet defines direction

Missing-$p_T^{||}$

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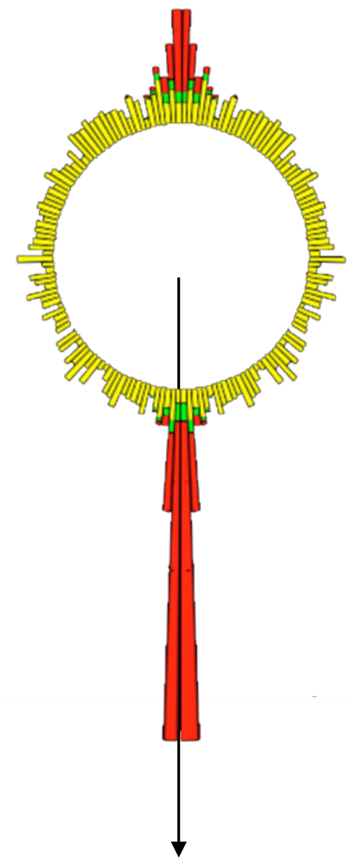
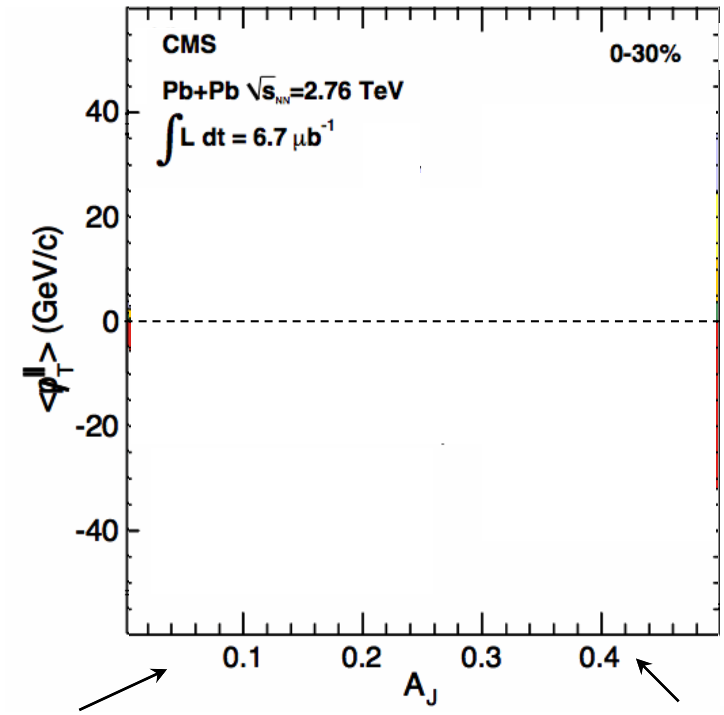


Sum all tracks in the event

Missing $p_T^{||}$: $$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

0-30% Central PbPb

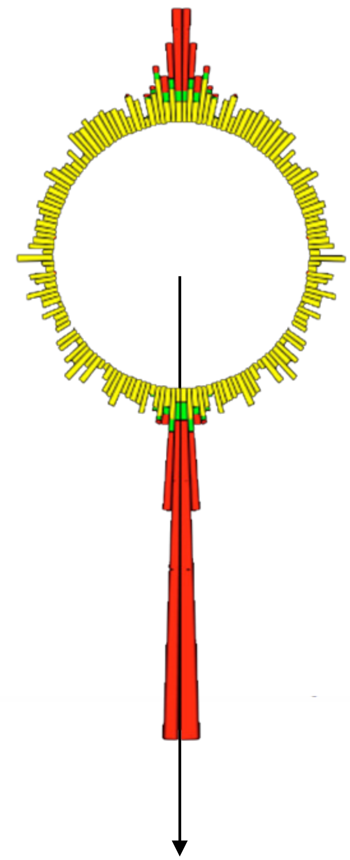


balanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet



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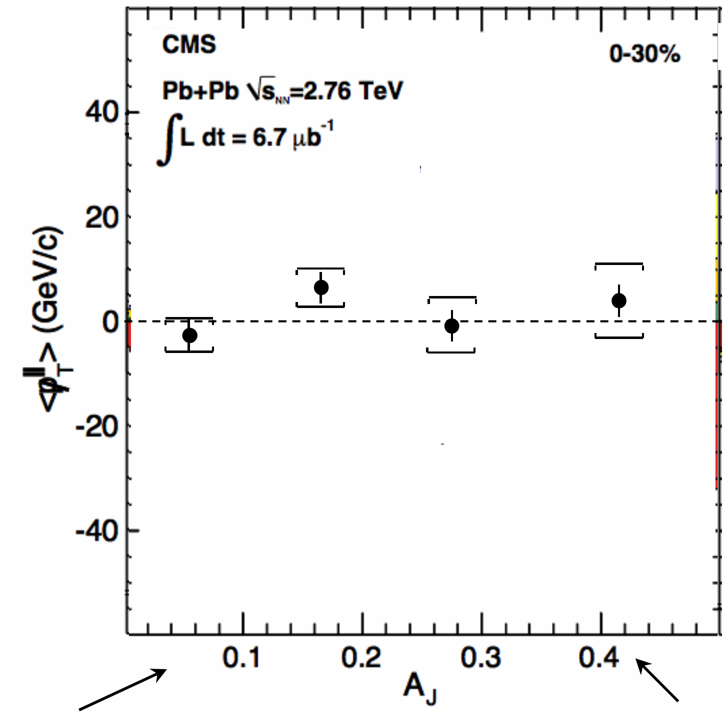

balanced jets

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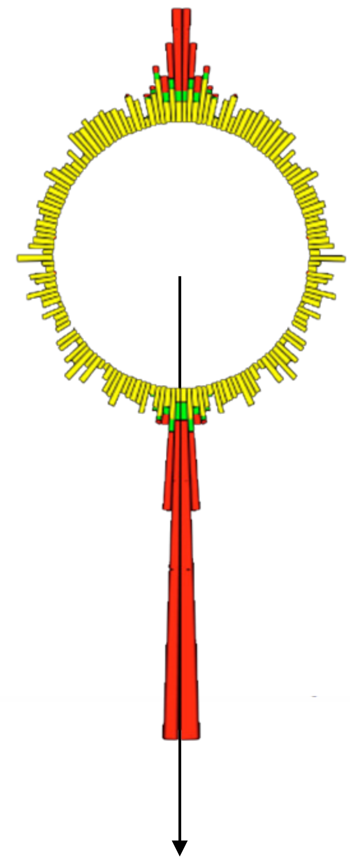
excess away from leading jet

excess towards leading jet

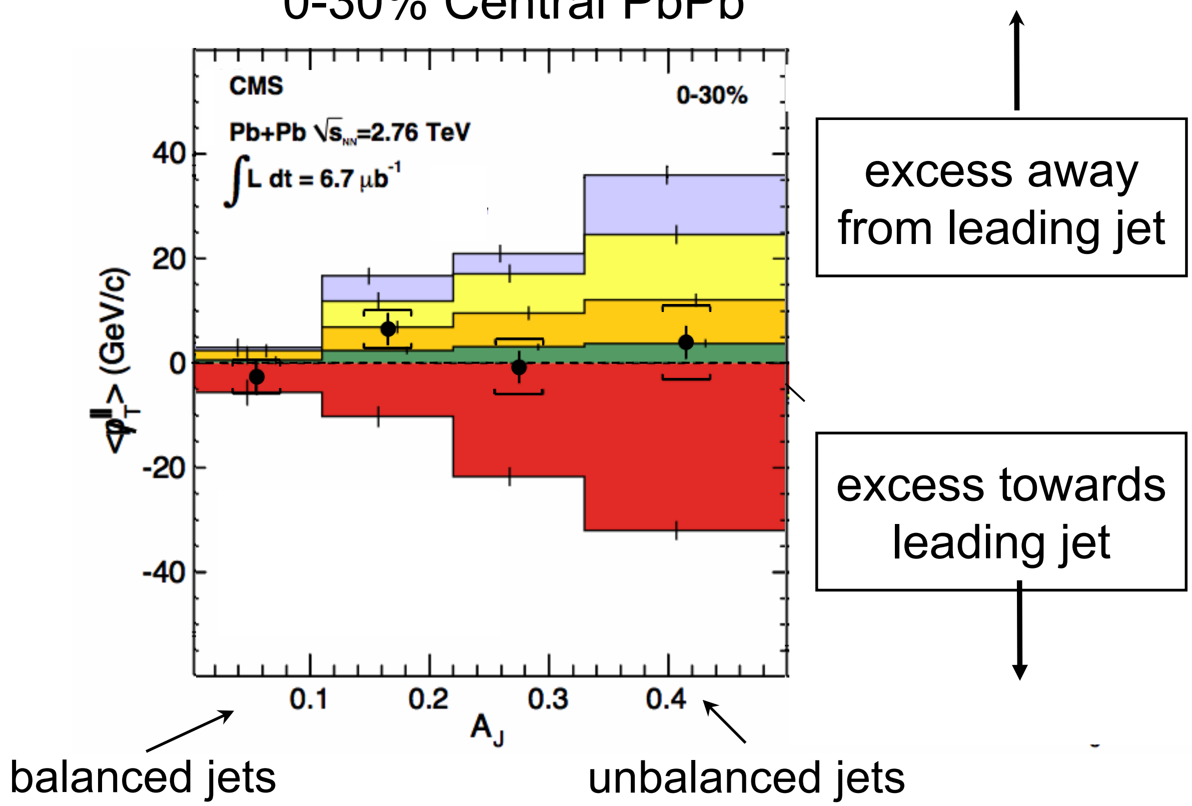


Momentum balance is restored by integrating over event final state

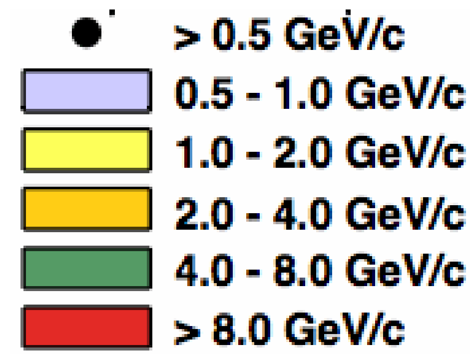
Missing-$p_T^{||}$

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

0-30% Central PbPb

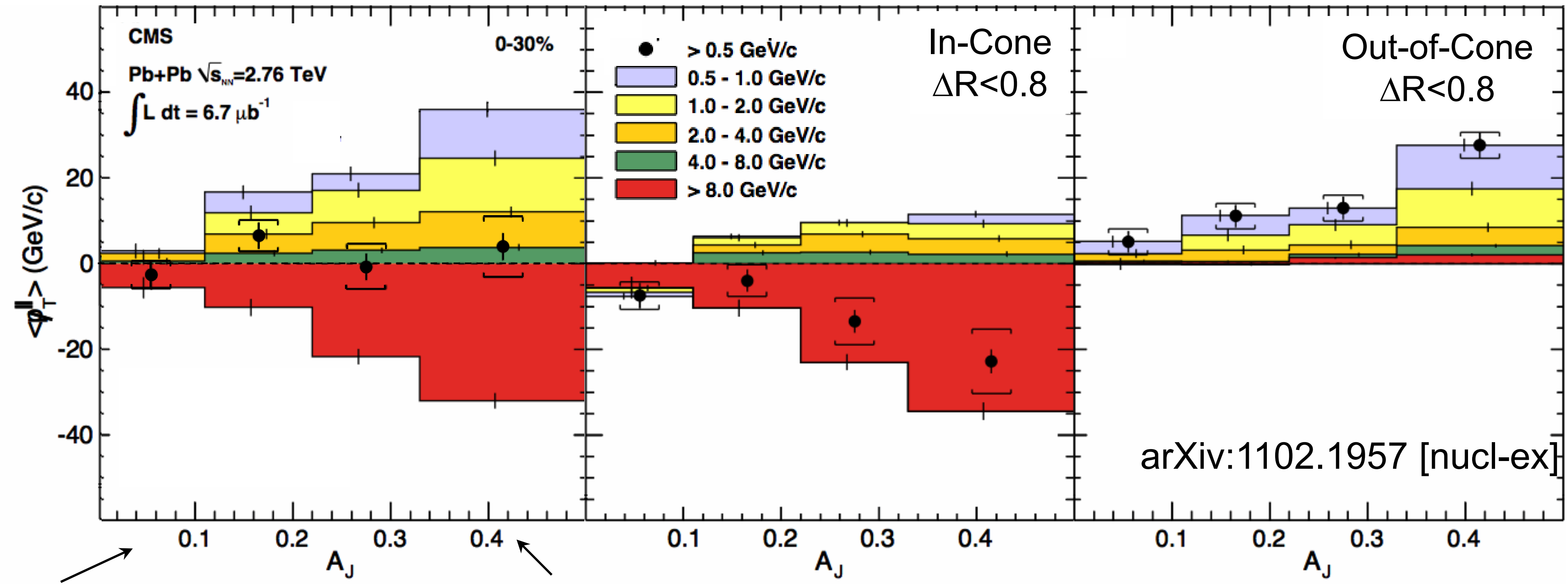


Calculate missing p_T in ranges of track p_T:



Missing-$p_T^{||}$

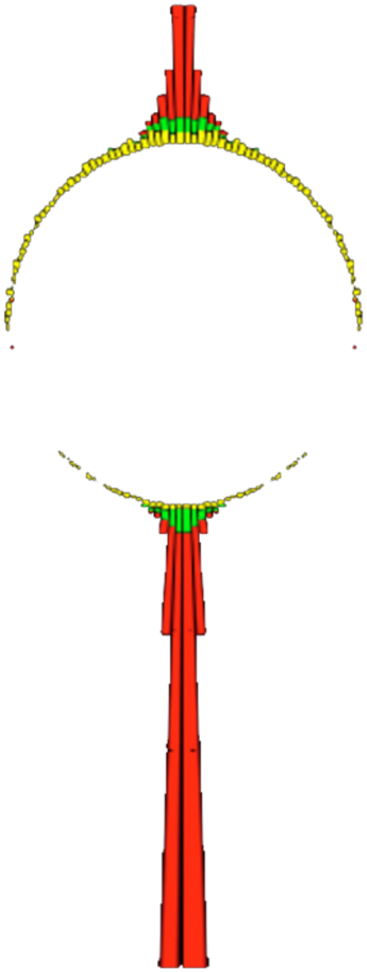
0-30% Central PbPb



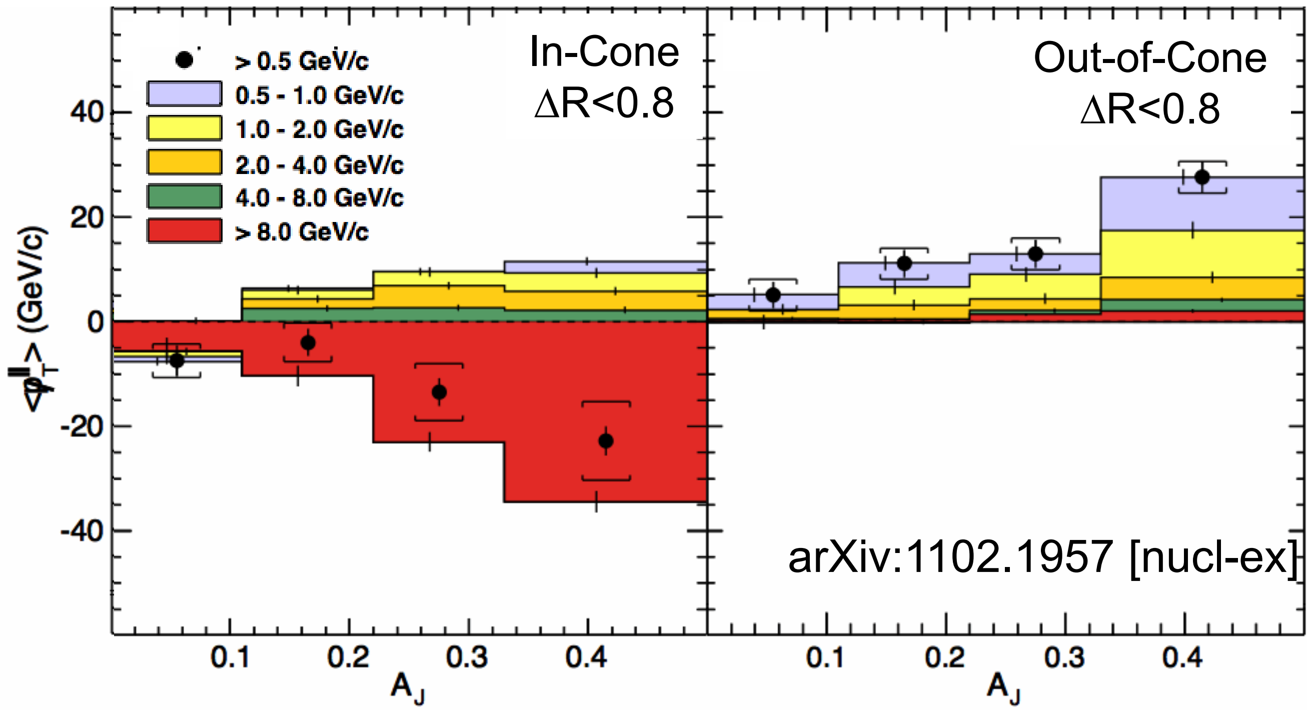
balanced jets unbalanced jets

The momentum difference in the dijet is balanced by low p_T particles at large angles to the jet axis

Missing-$p_T^{||}$

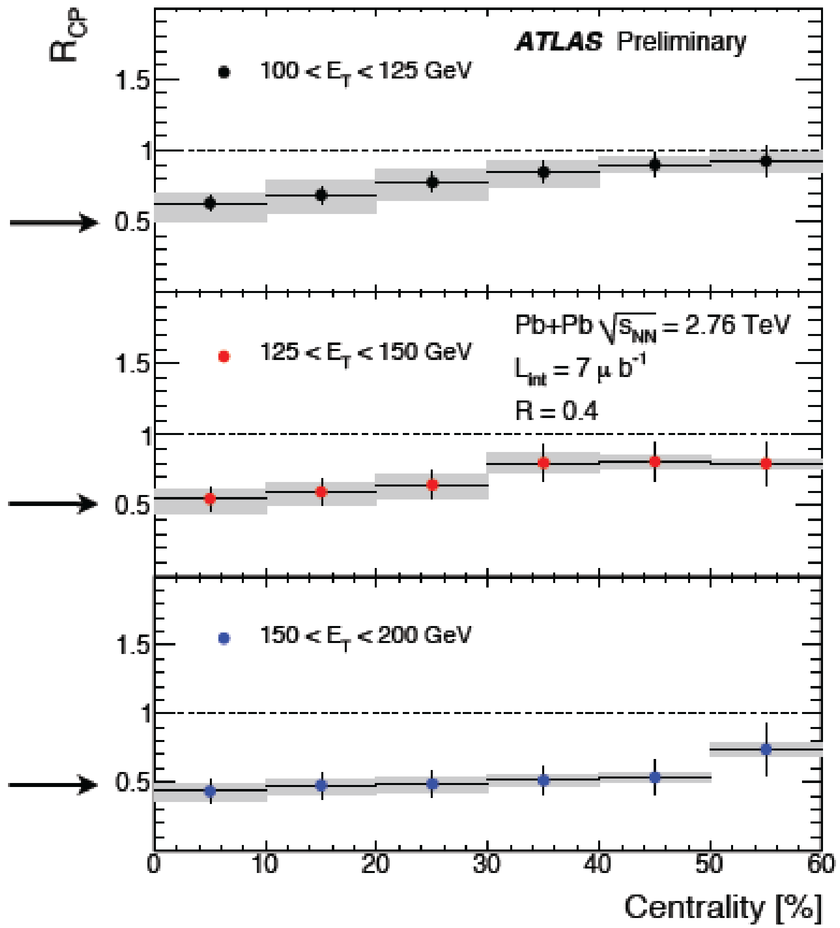


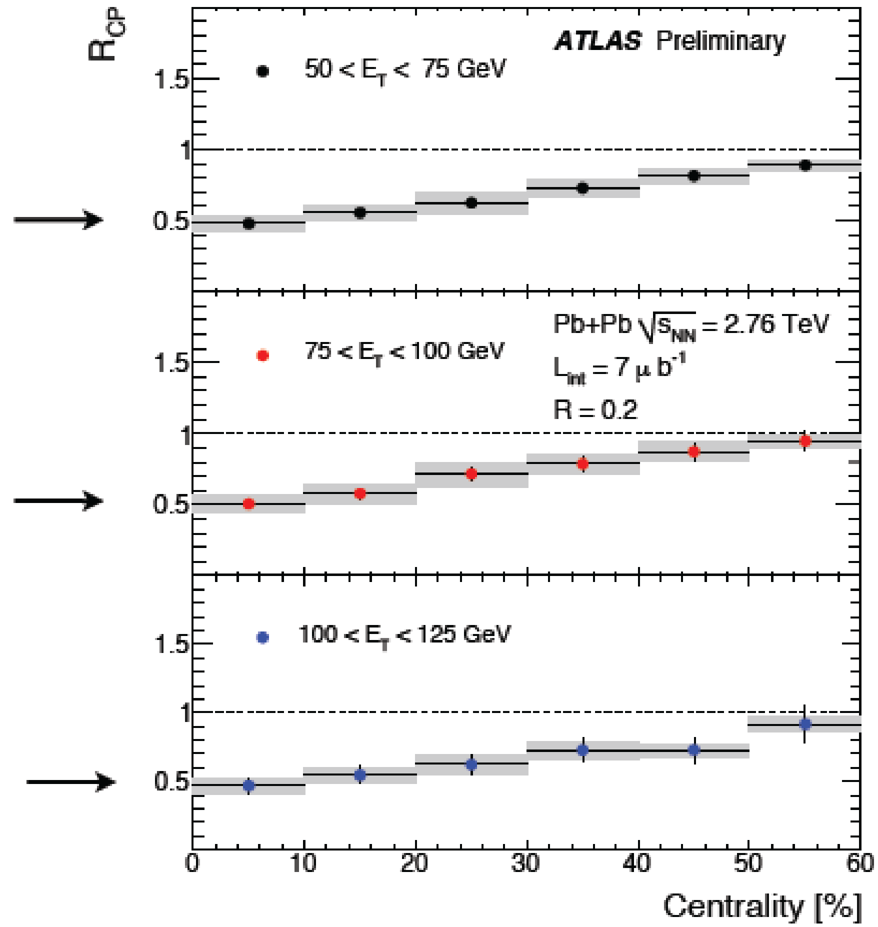
in-cone
out-of-cone



> 0.5 GeV/c
0.5 - 1.0 GeV/c
1.0 - 2.0 GeV/c
2.0 - 4.0 GeV/c
4.0 - 8.0 GeV/c
> 8.0 GeV/c
In-Cone
ΔR<0.8
Out-of-Cone
ΔR<0.8
arXiv:1102.1957 [nucl-ex]
$<p_T^{||}>$ (GeV/c)
40
20
0
-20
-40
0.1
0.2
0.3
0.4
A_J

Jet rates: fewer in central collisions





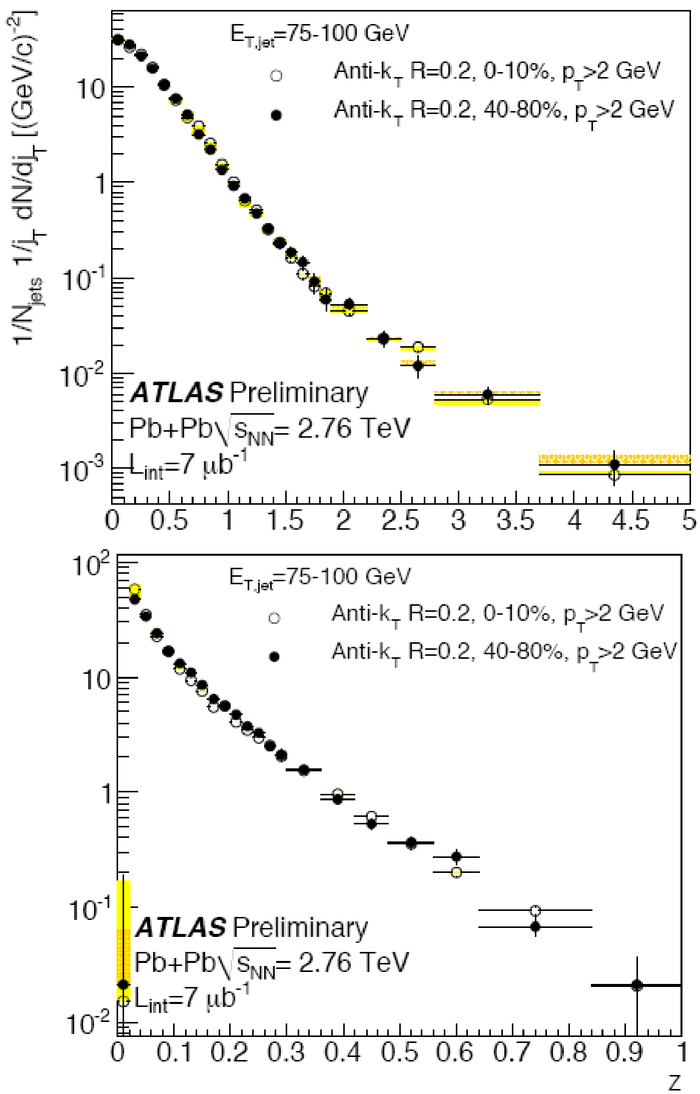
Suppression characterized by central/peripheral ratio (pinned on 60-80%)

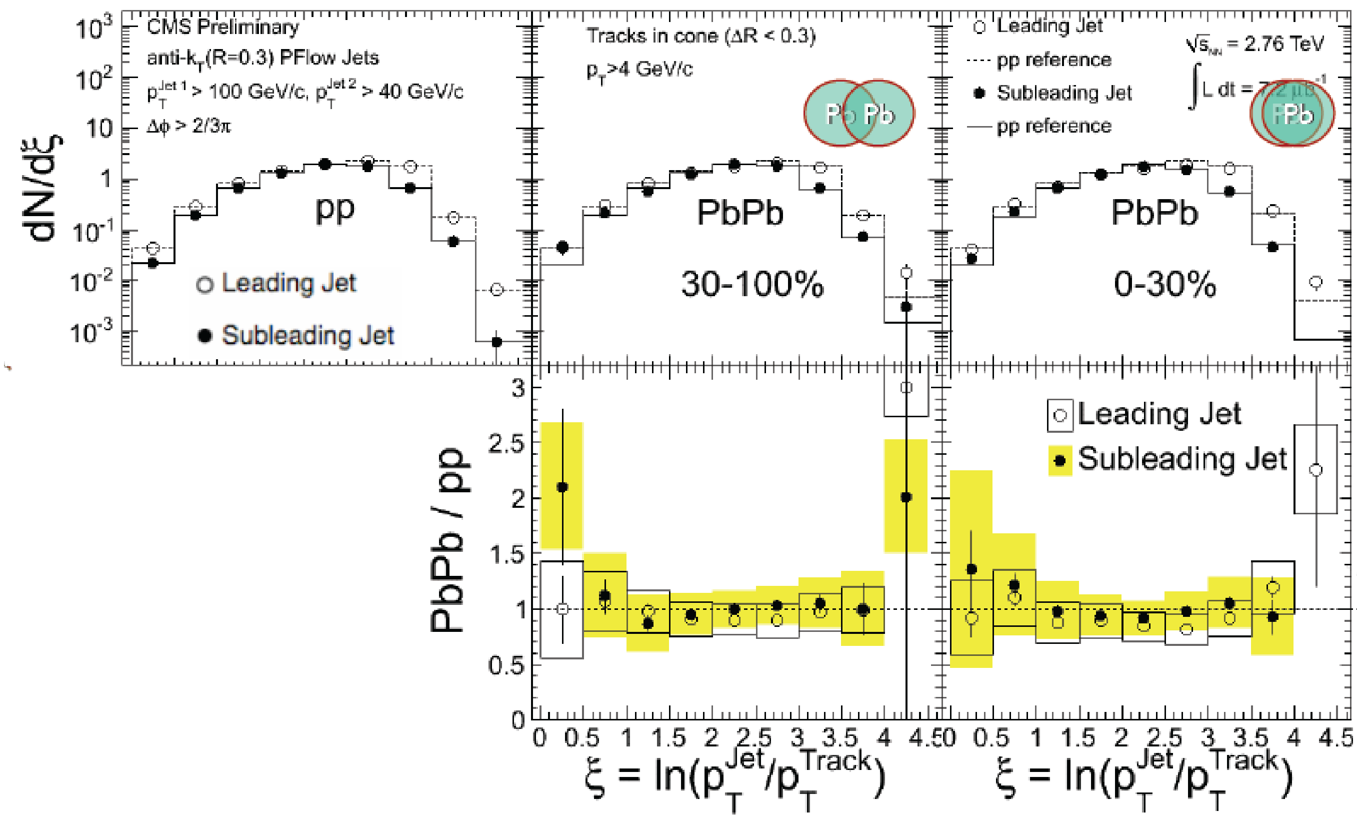
$$R_{CP} = \frac{\frac{1}{N_{\text{coll}}^{\,cent}} E \frac{d^3N^{cent}}{dp^3}}{\frac{1}{N_{\text{coll}}^{\,periph}} E \frac{d^3N^{periph}}{dp^3}}.$$

tends to ~0.5 in central bin

Fragmentation function

- Studies by ATLAS and CMS indicate that jets "look" like normal pp jets but with different energy: partons lose energy in the medium but the jets fragment in vacuum





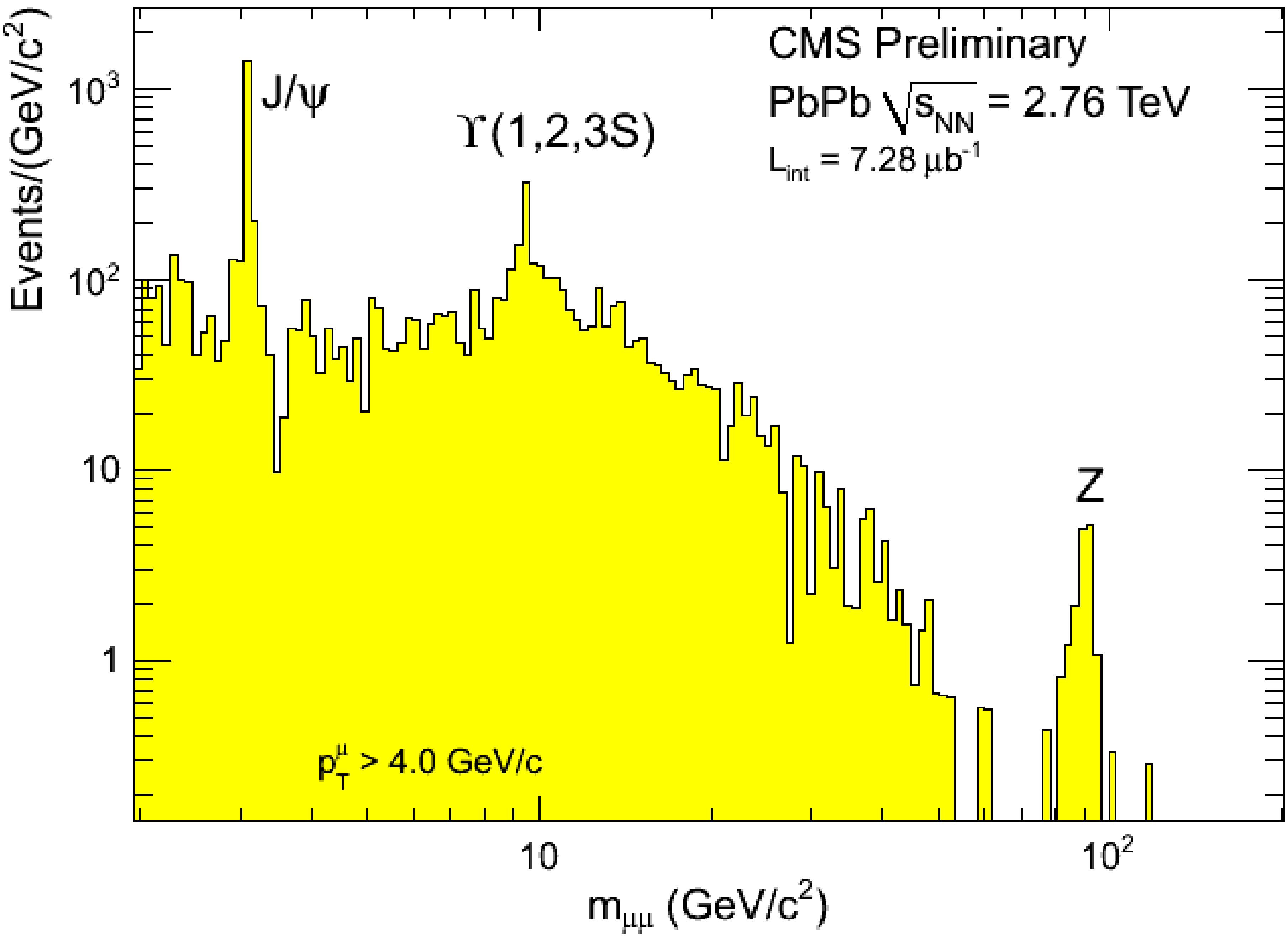
Longitudinal and transverse momentum distributions inside jet cone

Jet "quenching" in HI: what have we learned so far?

- Effects are huge: tens of GeV are lost by partons as they traverse hot medium (ATLAS, CMS)
- Particle spectra are consistent with RHIC observations (ALICE)
- The deposited energy leads to the production of many low p_T particles, distributed in wide range of angles, away from the jet axis (CMS)
- The jets seem to fragment like jets produced in the vacuum (CMS)

- Most of theoretical work done to interpret RHIC results needs to be reworked: we expected modifications to fragmentation functions
- We can do these measurements because jet energies are higher but also because we have large acceptance, hermetic detectors

Compact Muon Solenoid: $\mu^+\mu^-$ invariant mass



Quarkonia in heavy ion collisions

- Good candidates to probe the QGP in HIC
  - Large masses and (dominantly) produced at the early stage of the collision via hard-scattering of gluons
  - Strongly bound resonances

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

State	Υ (1S)	χ_b (1P)	Υ' (2S)	χ'_b (2P)	Υ'' (3S)
m (GeV/c^2)	9.46	9.99	10.02	10.26	10.36
r_0 (fm)	0.28	0.44	0.56	0.68	0.78

decreasing binding energy

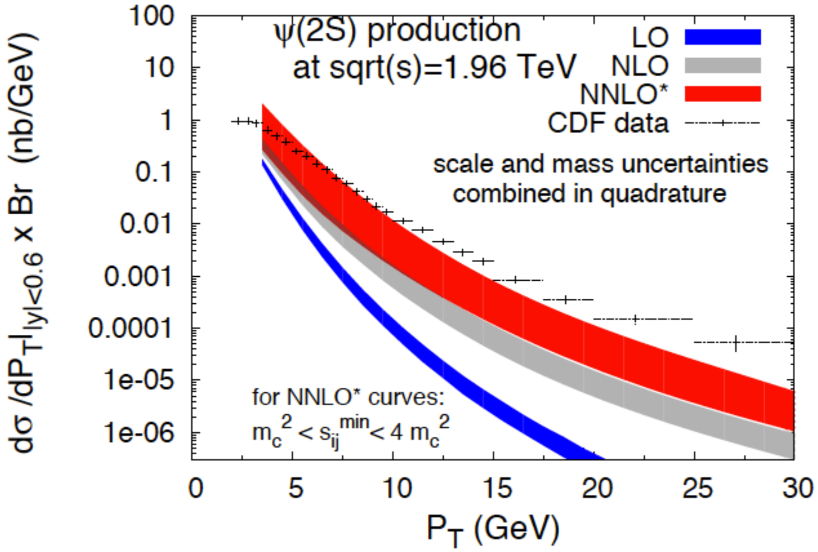
The start : quarkonia should melt in the QGP

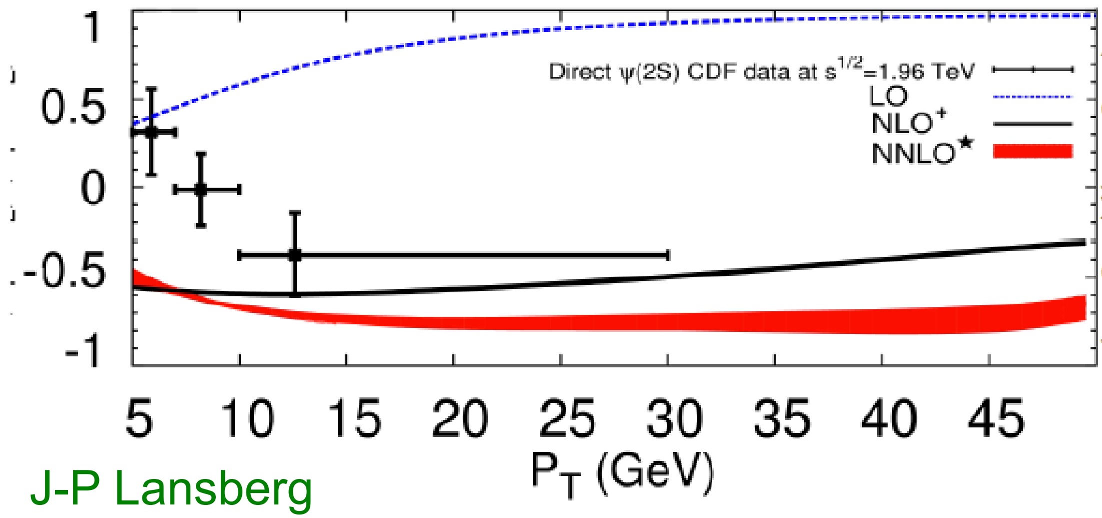
T. Matsui & H. Satz PLB178, 416 (1986)

Color Screening

Complex production of quarkonia in hadron collisions

- Production mechanism not completely understood





J-P Lansberg

The NNLO* is not a complete NNLO → possibility of (large) uncanceled logs !
If NNLO* ≈ NLO, problem with polarization

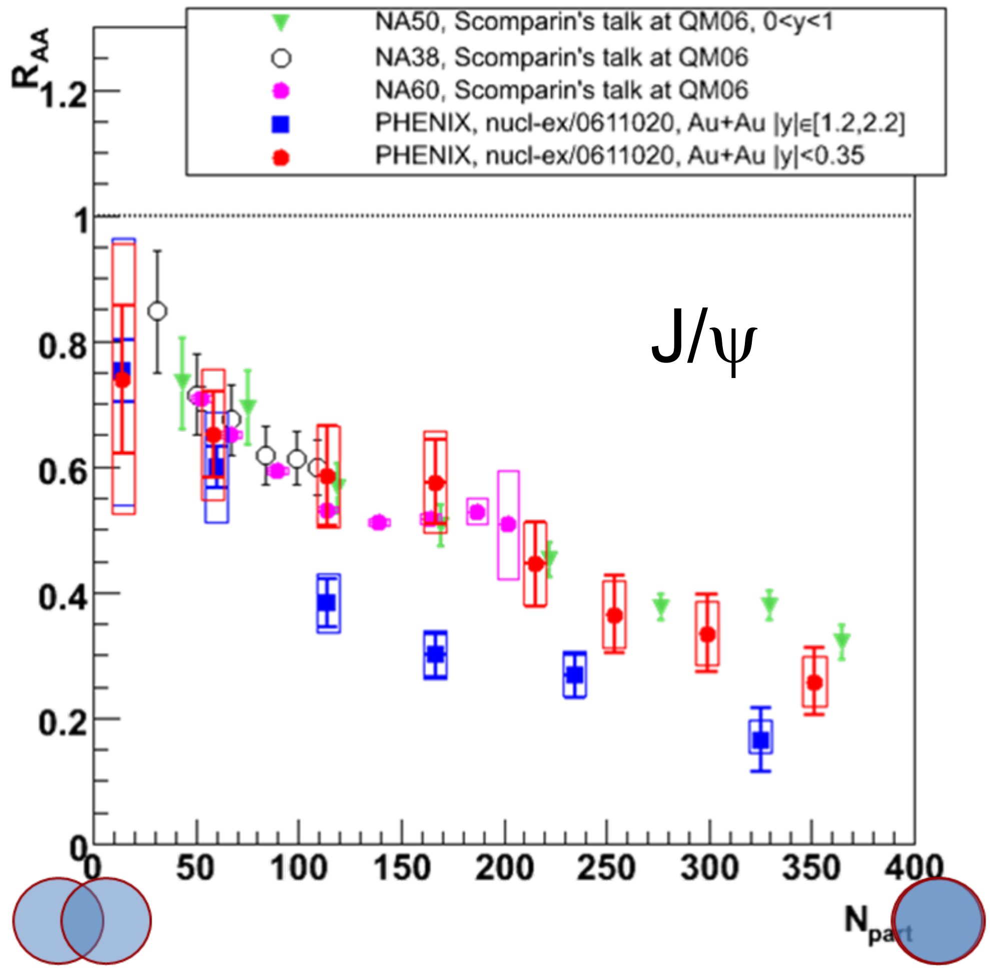
- Many effects altering production in nuclear reactions
  - In pA, cold nuclear matter (CNM) effects
    - Extensively studied at the SPS and RHIC
    - But different at the LHC ?
  - In AA, hot medium effects

J/ψ suppression puzzles

- No increase of the suppression with local density

  R_{AA} (|y|<0.35) > R_{AA} (1.2<|y|<2.2)
- Similar suppression at SPS and RHIC energies

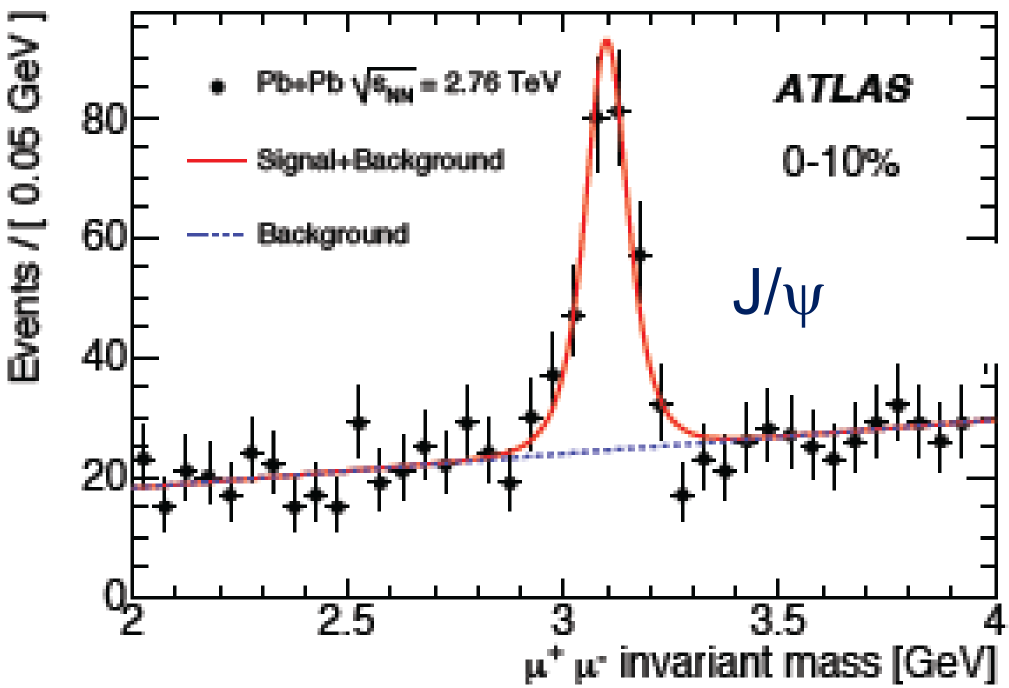
  R_{AA} (RHIC, |y|<0.35) ≈ R_{AA} (SPS)

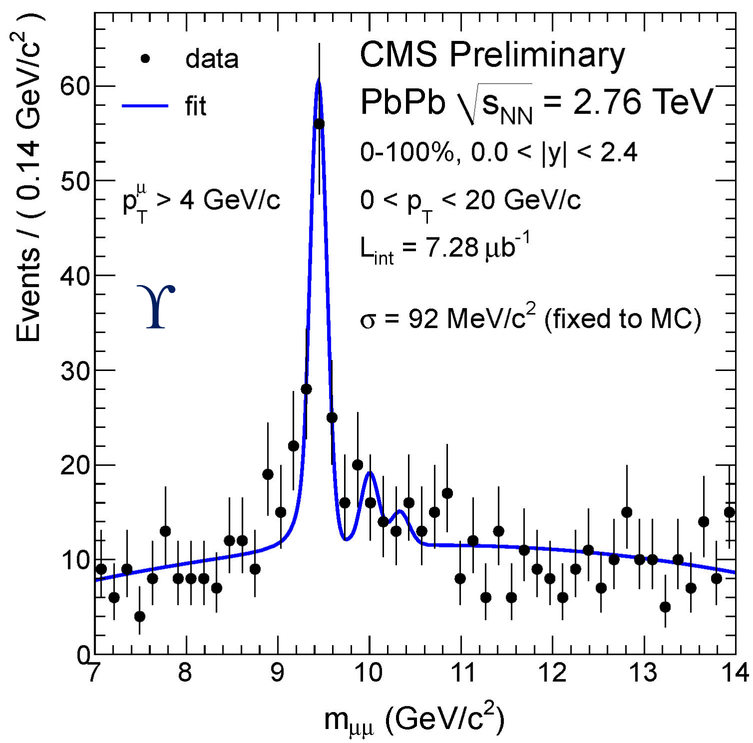


- Possible ingredients
  - –Suppression (gluon diss.)
  - –Sequential melting
  - –Gluon saturation / shadowing
  - –Regeneration
  - –Some combination of all

J/ψ and ϒ at LHC

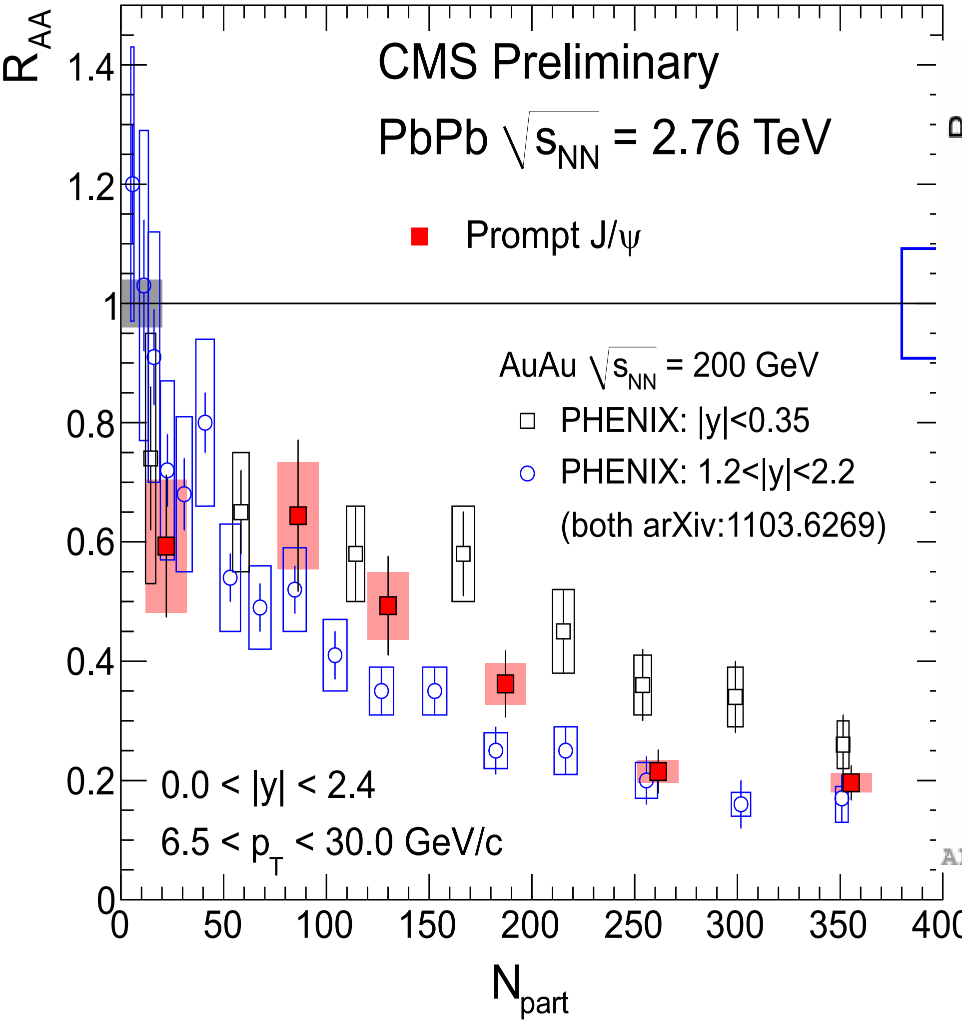
- J/ψ observed by all experiments: compare suppression with lower energies
  - ALICE: low p_T, forward
  - CMS/ATLAS: high p_T central
- ϒ reported by CMS, look for all three bound states

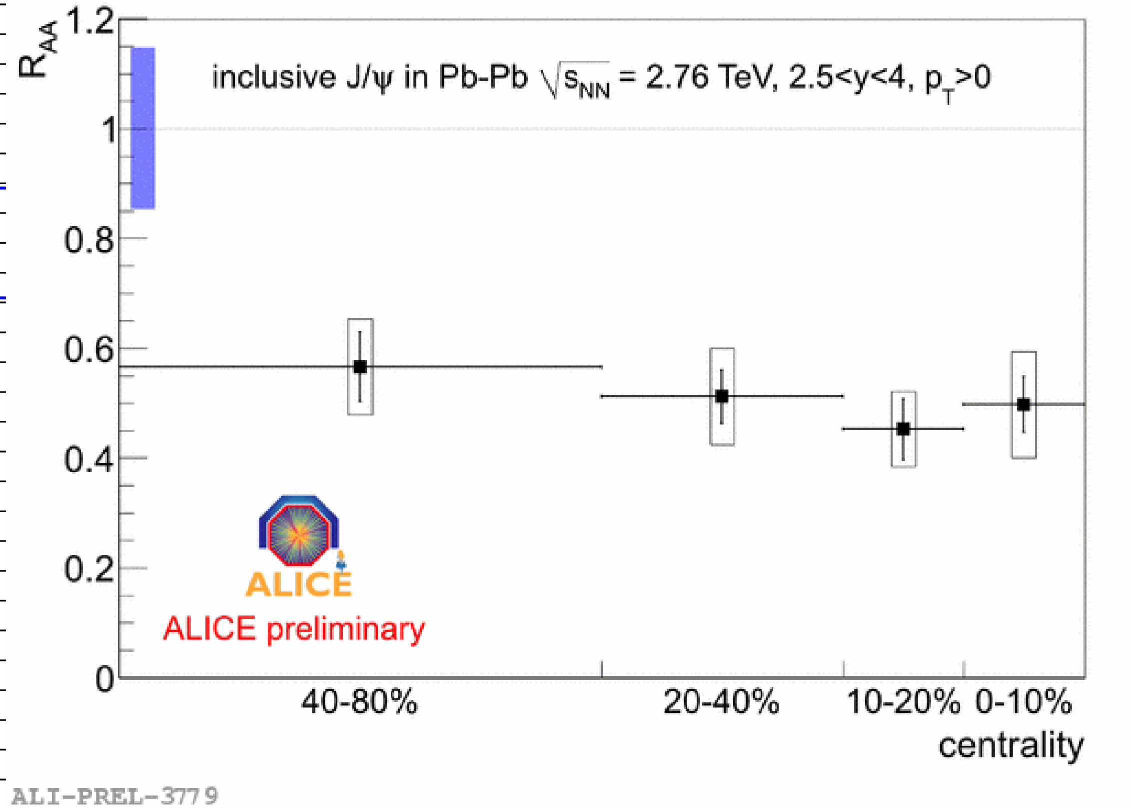




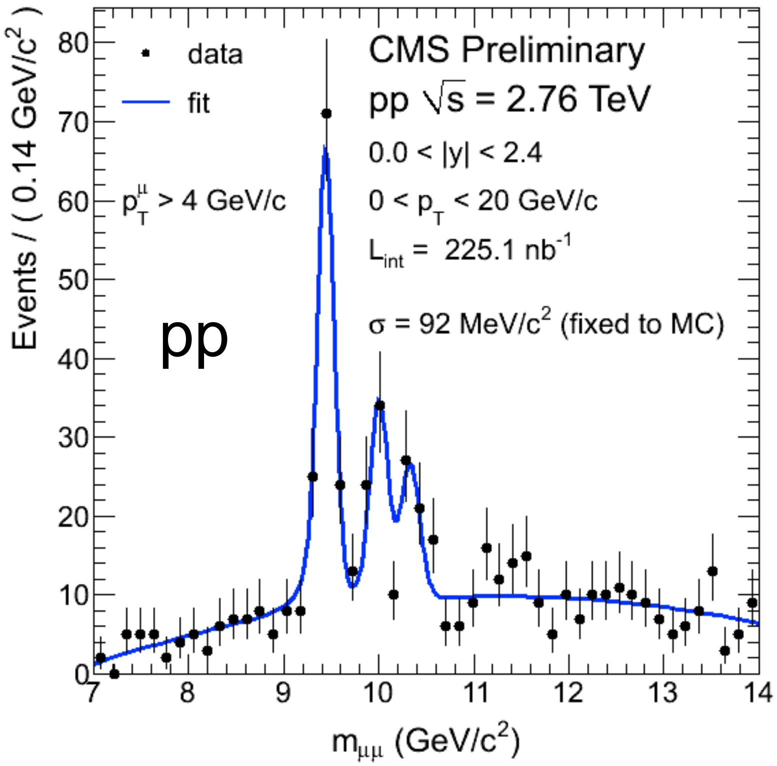
Suppression of J/ψ

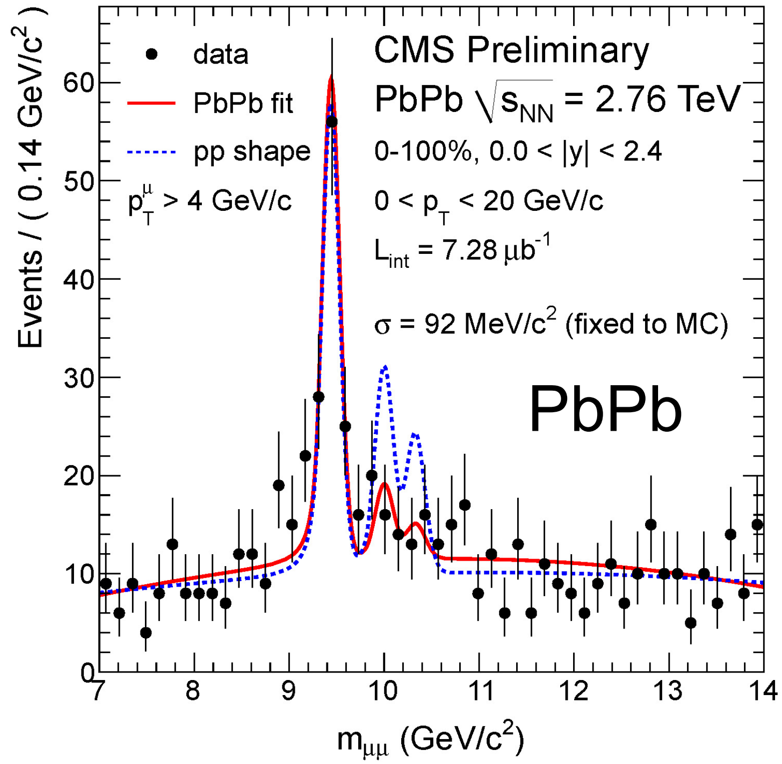
- ATLAS and CMS: comparable to RHIC but at high p_T
- ALICE: smaller suppression
- p_T and coverage differences…

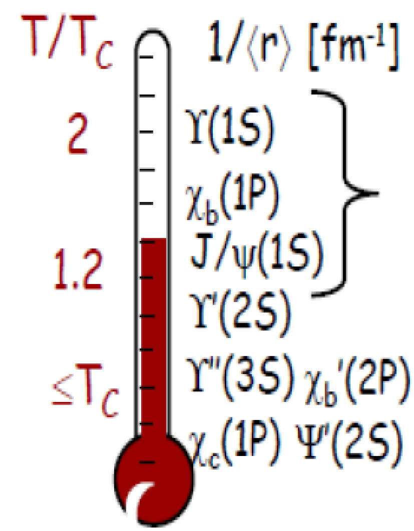




Suppression of excited Υ states





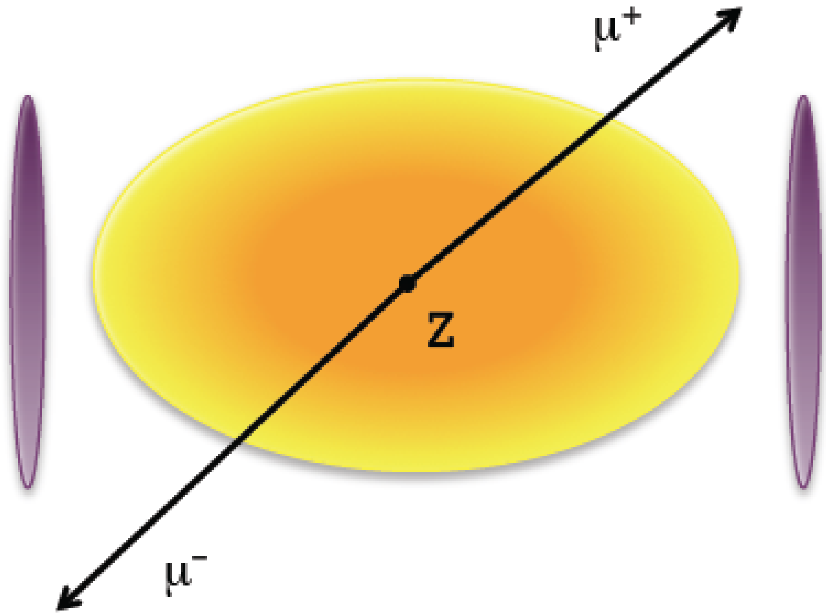


$$\Upsilon(2S+3S)/\Upsilon(1S)\Big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\Big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

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

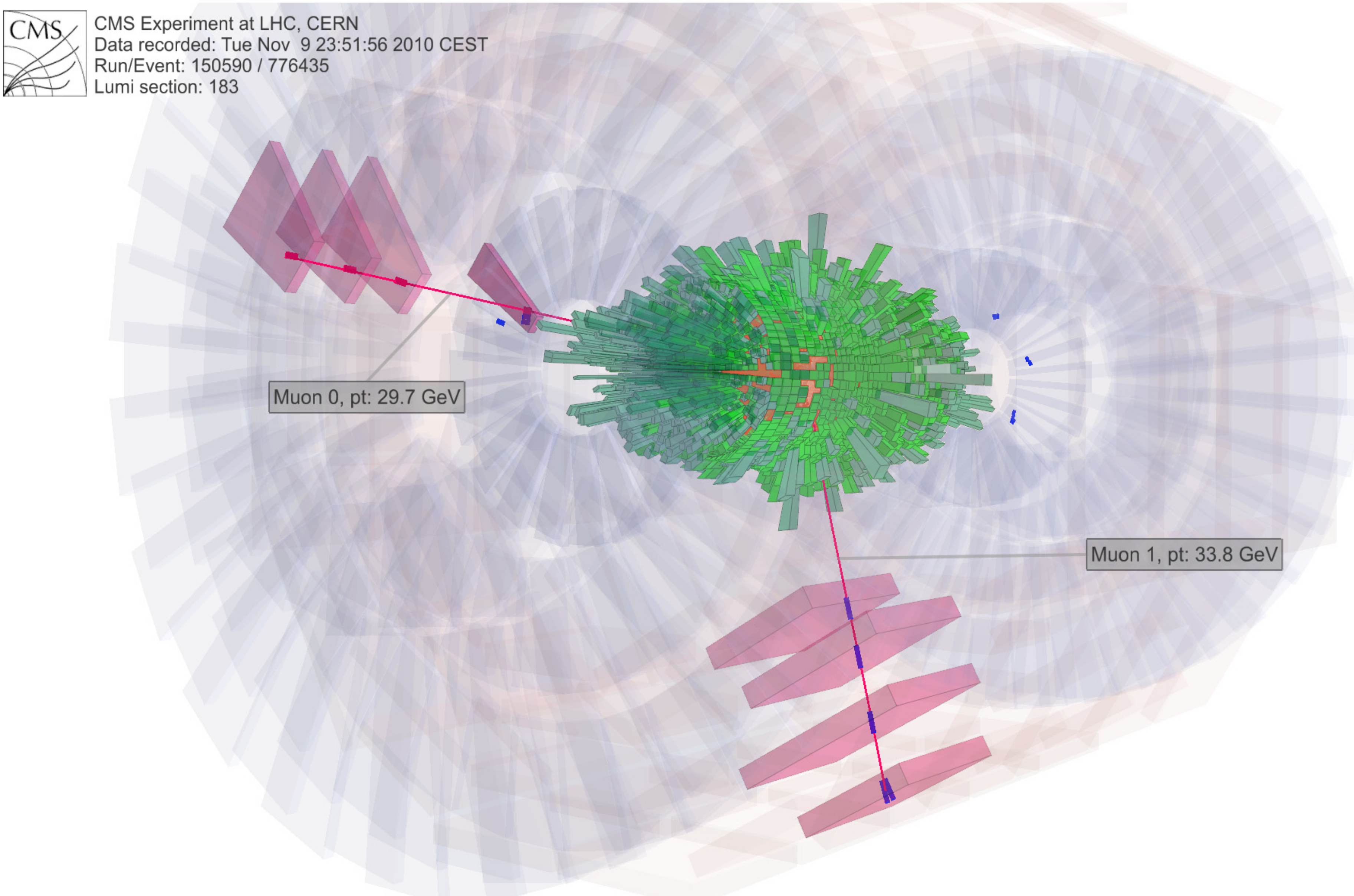
- Excited states Υ(2S,3S) relative to Υ(1S) are suppressed
- Probability to obtain measured value, or lower, if the real double ratio is unity, has been calculated to be less than 1%

Z bosons

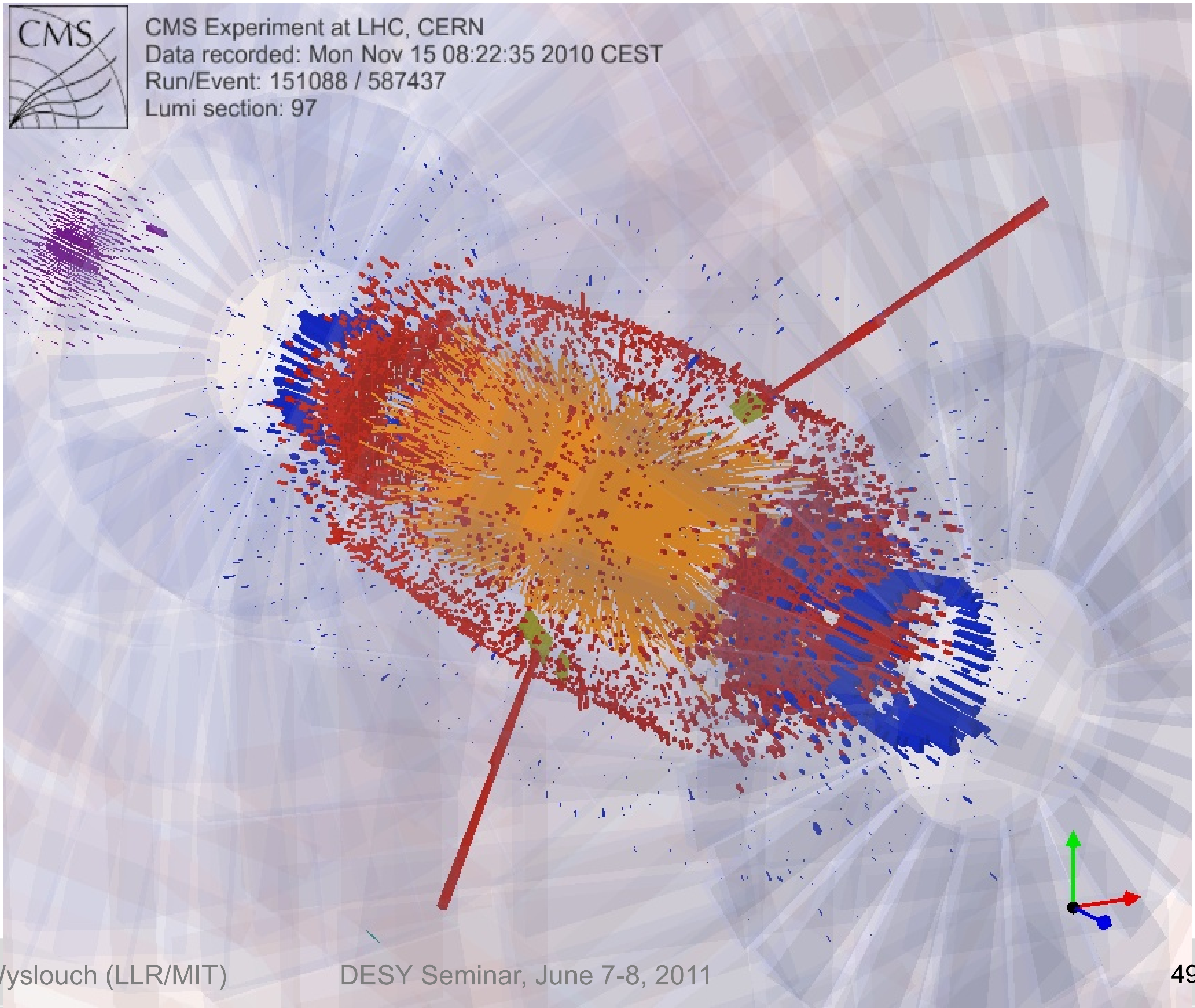


- Z$\rightarrow \ell^+ \ell^-$ signal is essentially unaffected by the strongly interacting medium produced in heavy ion collisions
- Z production is a reference for processes modified by the medium such as quarkonia production, jets via Z-jet process
- Precise measurement of Z production in heavy ion collisions can help to constrain nuclear parton distribution functions

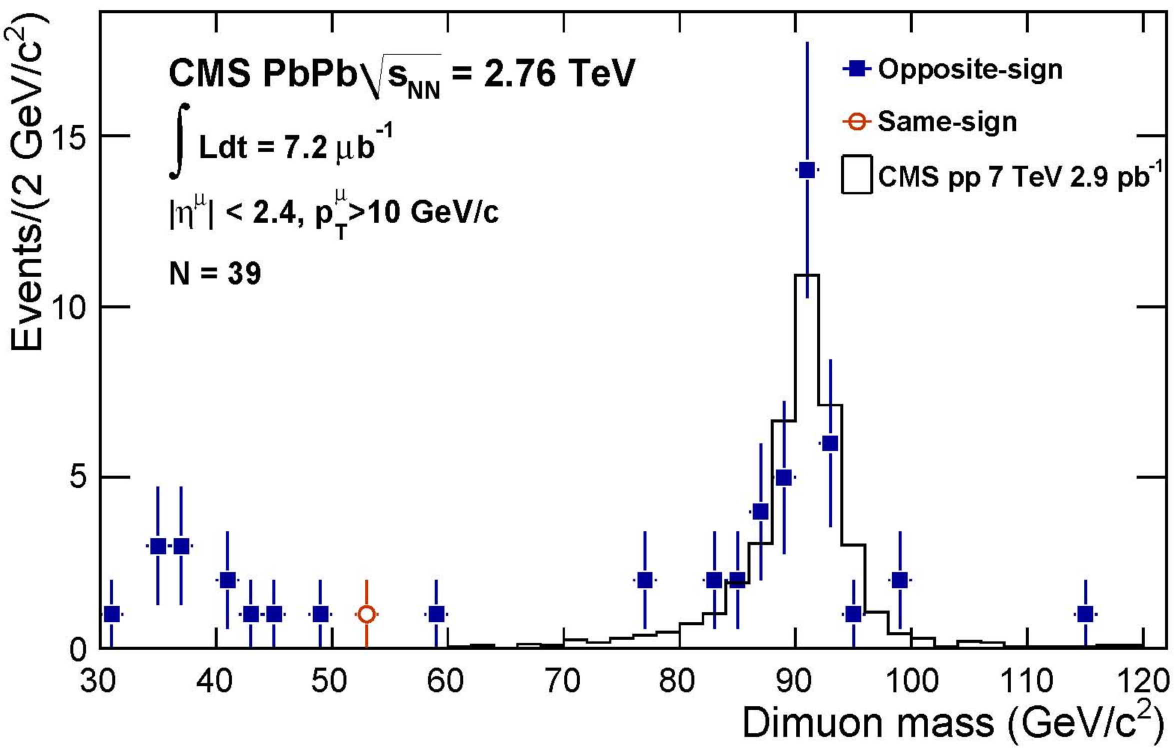
Our first $Z^0 \rightarrow \mu^+\mu^-$ candidate

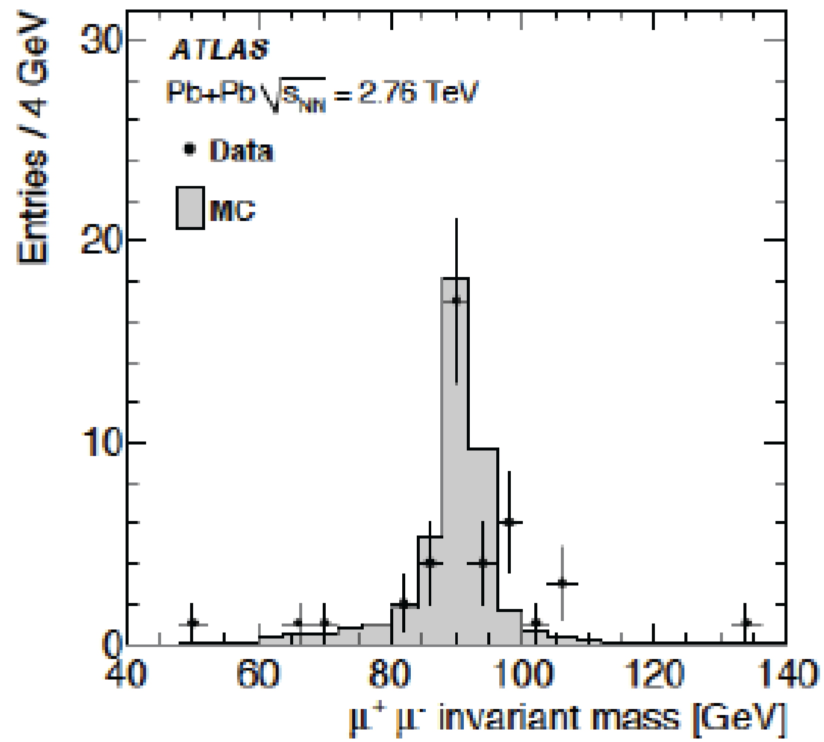


$Z^0 \rightarrow e^+e^-$ candidate



$Z^0 \rightarrow \mu^+\mu^-$

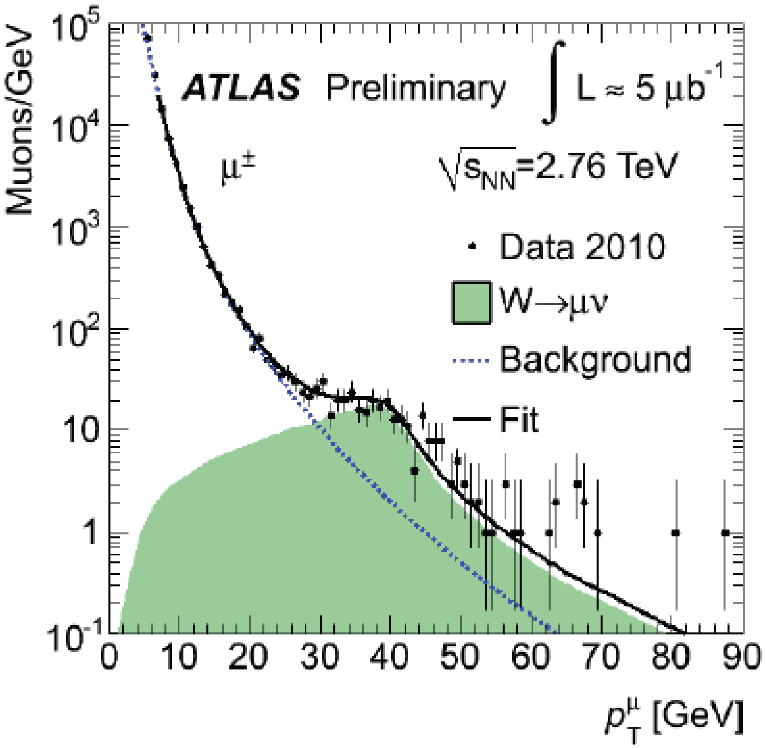


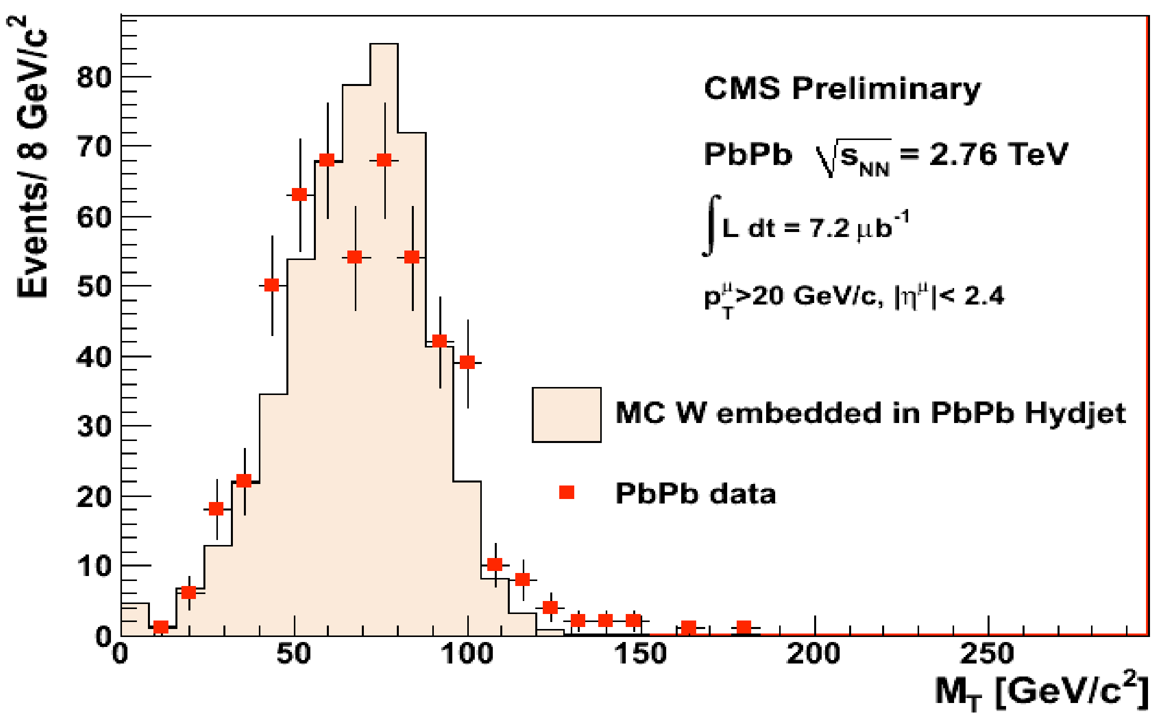


- Excellent agreement with pp data and MC

$W \rightarrow \mu\nu$

- W bosons are not expected to interact with the hot medium
- W detection is more difficult than Z
  - ATLAS: muon spectra, template
  - CMS: muon spectra, M_T

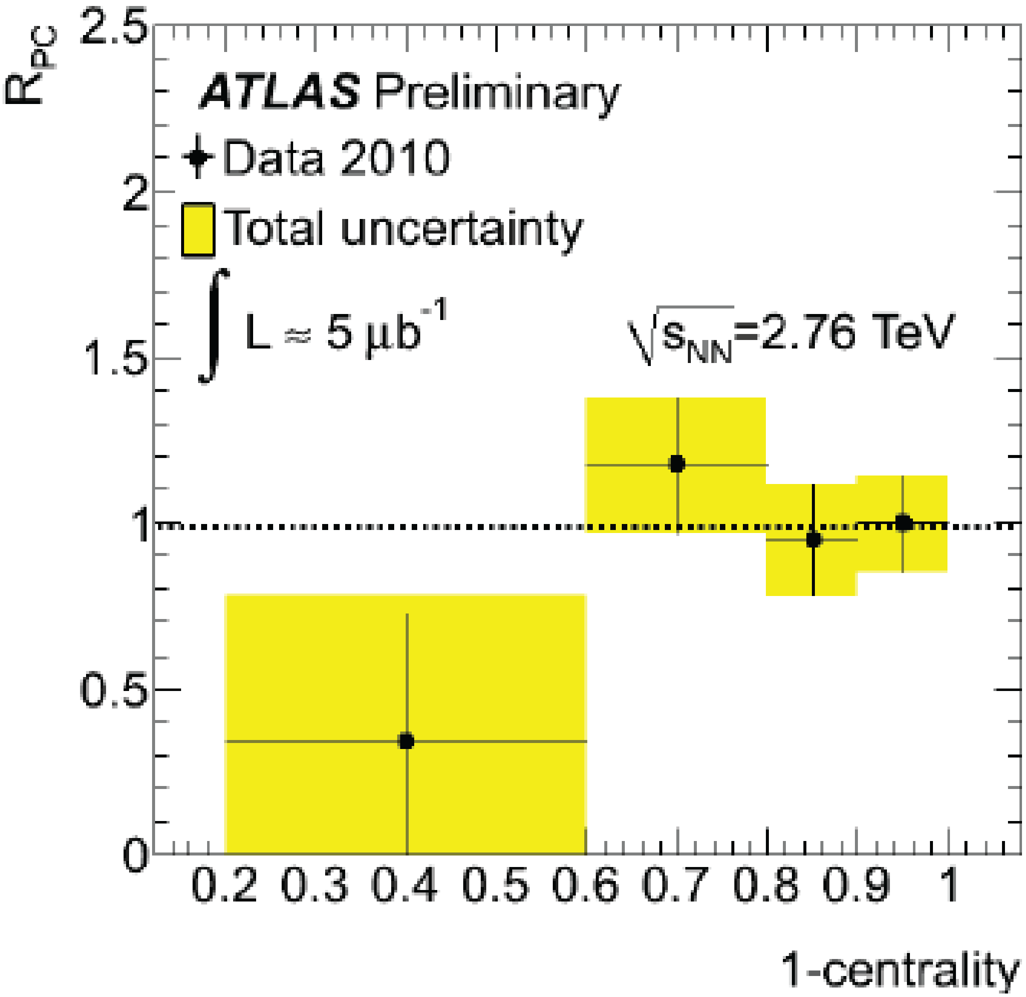


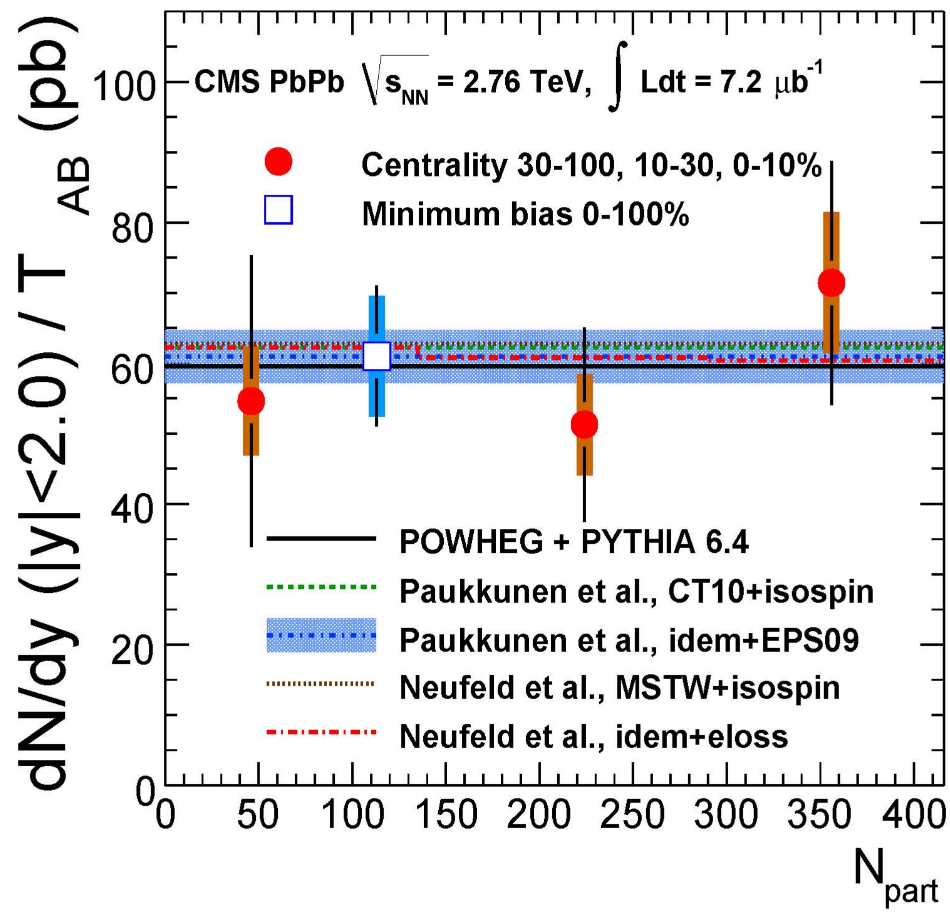


$$M_T = \sqrt{2 p_{T\mu} p_{T\nu} (1 - \cos\phi_{\mu\nu})}$$

W & Z yield do not depend on centrality

- Consistent with other colorless probes





$$\frac{dN_{AA}}{dy}\Big/ T_{AB} = R_{AA}\cdot\frac{d\sigma_{pp}}{dy}$$

Prospects for the near future

- Next HI run at LHC: November 14, 2011
  - About 5-8 times higher luminosity of PbPb collisions
  - Detailed studies of jets and quarkonia
  - Test of pPb acceleration
- 2012 run:
  - More statistics of PbPb OR pPb?

Summary

- During the first LHC Heavy Ion run LHC experiments collected ~9μb^{-1} PbPb collisions at energy 14 times higher than at RHIC
- Hot, dense and fast expanding medium
  - Strong elliptic and radial flow
  - Transverse energy density approaching 2 TeV per unit rapidity
- Production of colored probes strongly affected by hot medium
  - Modified particle spectra, R_{AA}
  - Measurements include identified particles, b-quarks
  - Jet quenching, parton energy distributed over large rapidity
- Colorless probes not affected by medium
  - Photons, Z, W
- Interesting patterns of quarkonium production
  - J/ψ suppressed at high p_T, enhanced at low p_T (compared to RHIC)
  - Suppression of excited Υ states