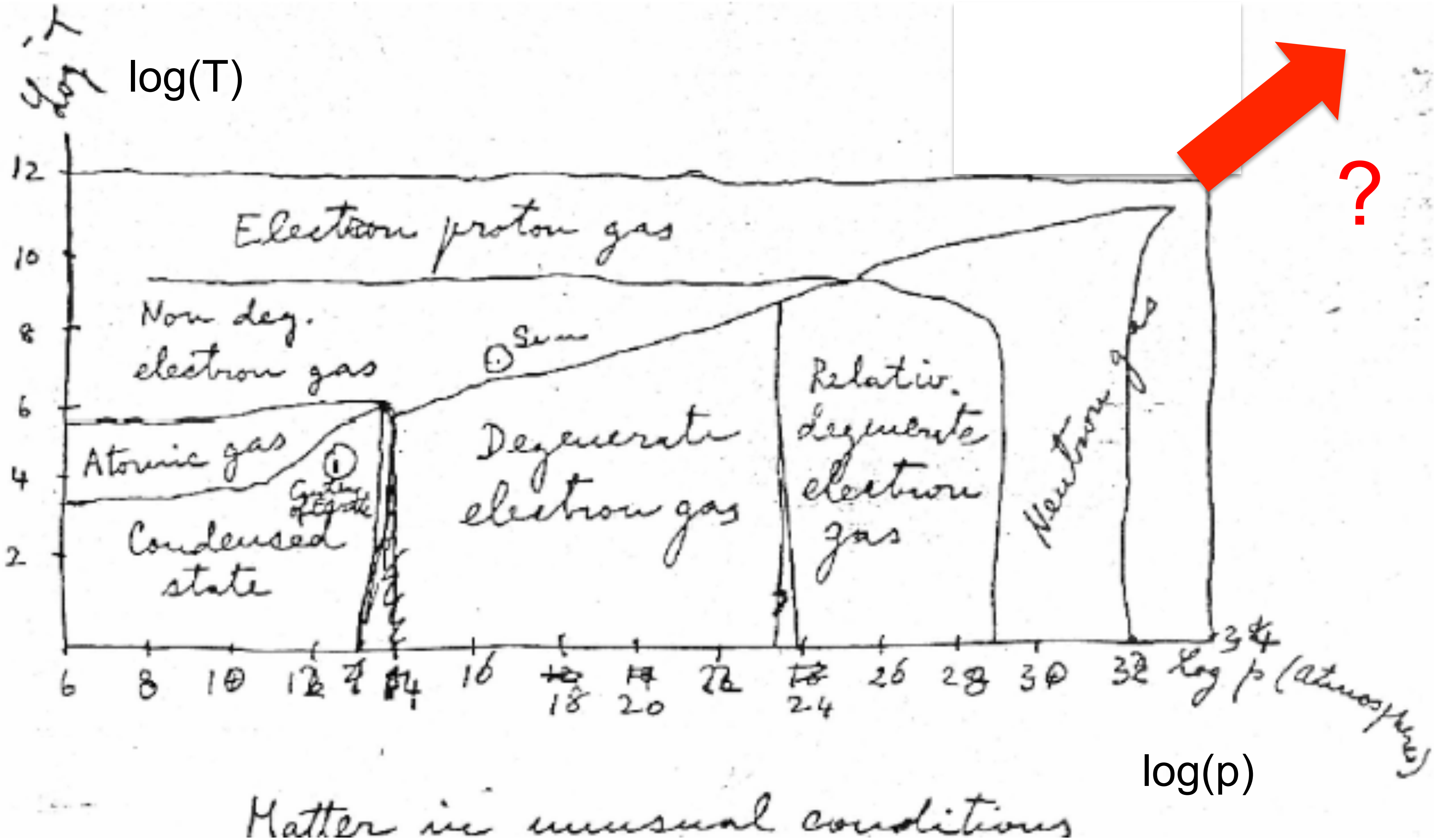
Heavy Ion Physics at the LHC

LISHEP 2015

Manaus, Brazil

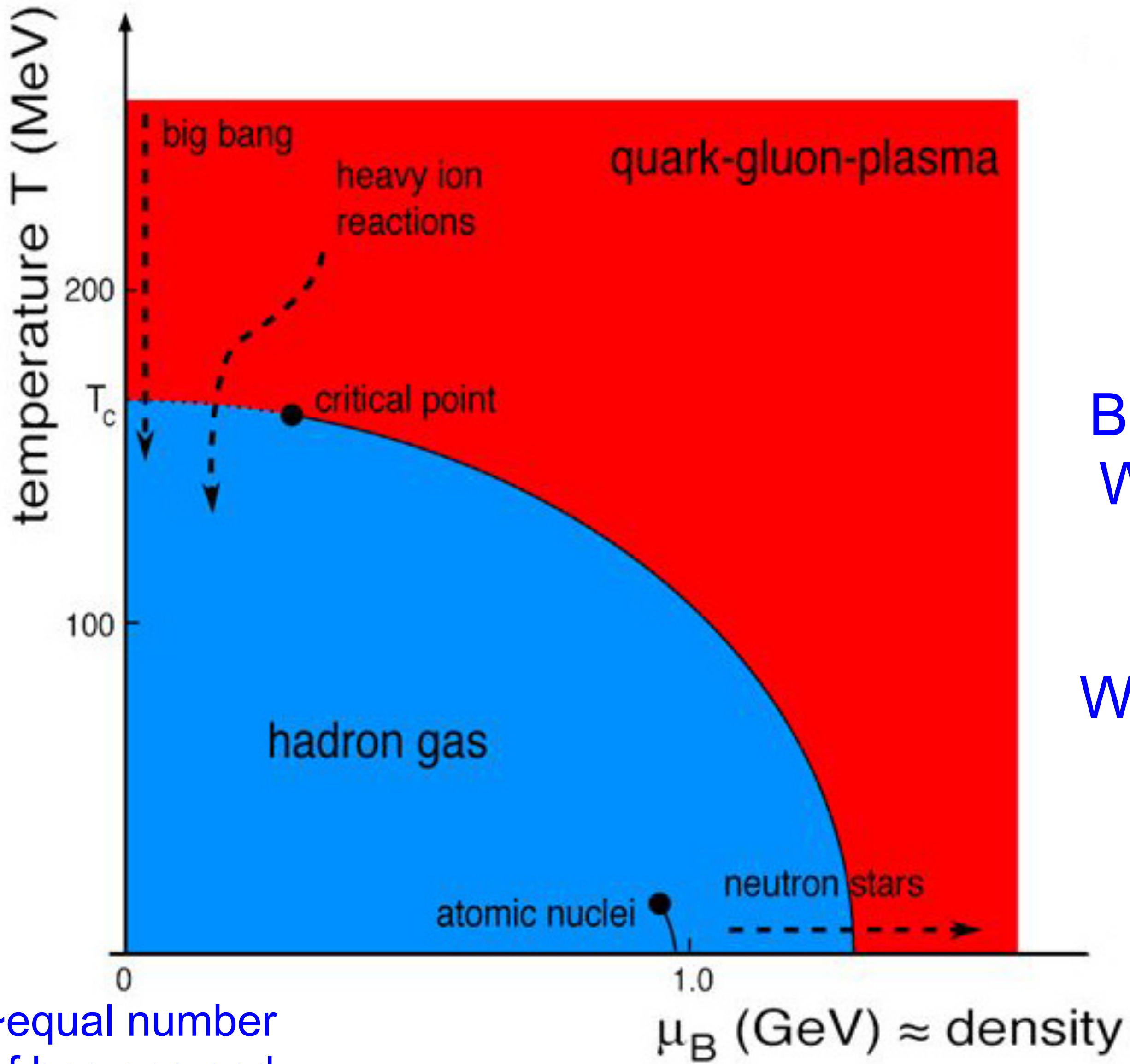
Bolek Wyslouch

Enrico Fermi's lectures on statistical physics ~1953



Matter in very unusual conditions!

Phase diagram of quark and gluon matter



~equal number of baryons and anti-baryons

dominated by baryons

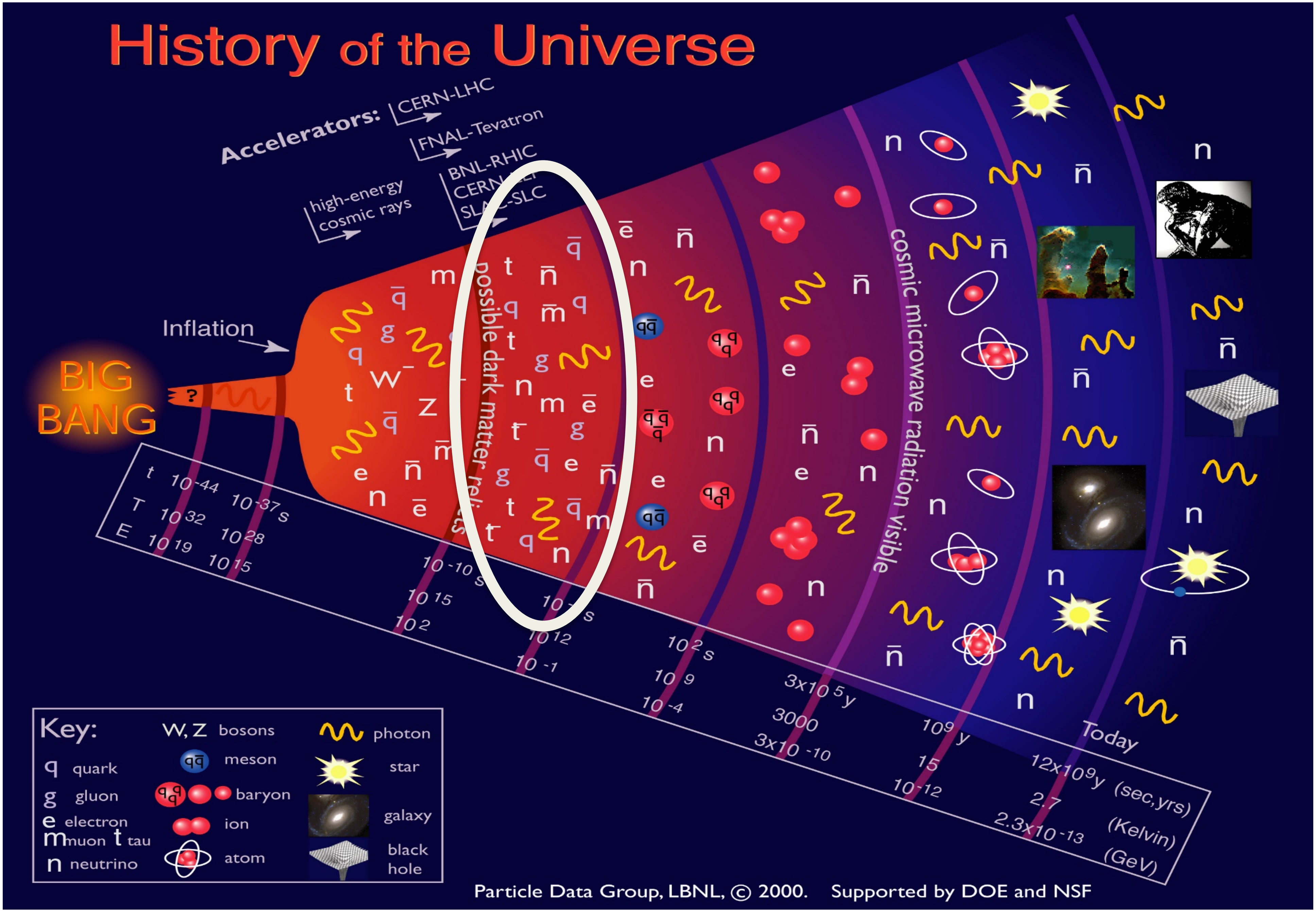
1 eV ~ 12000 K

100 MeV ~ 1.2 10^{12} K

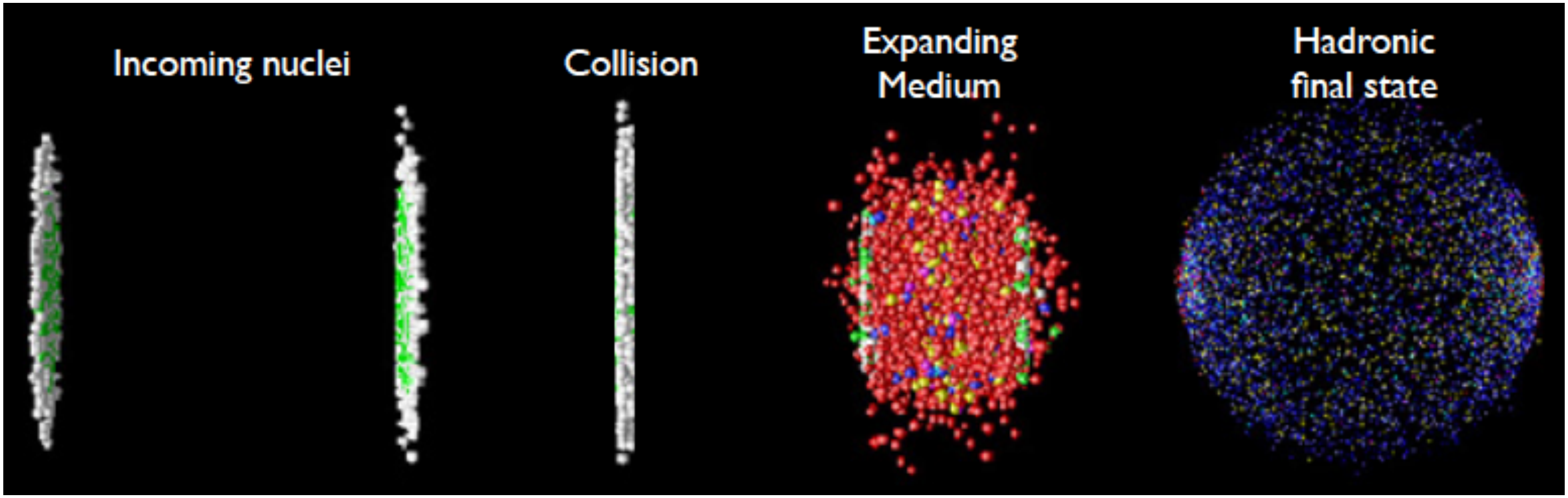
Big questions of our field: What is the nature of the phase transition?

What are the properties of the melted phase?

Quarks and Gluons in the Universe

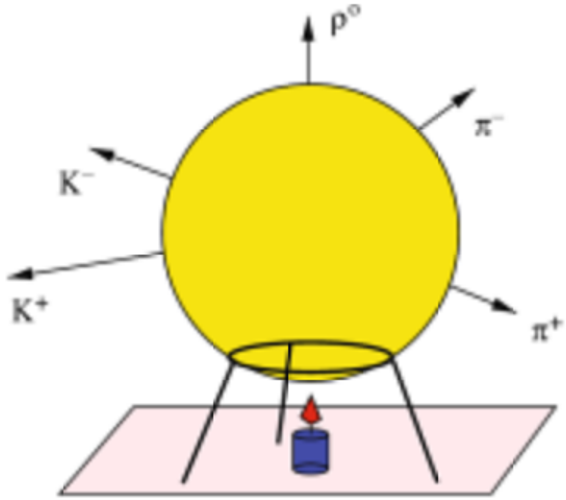


Stages of the heavy ion collision

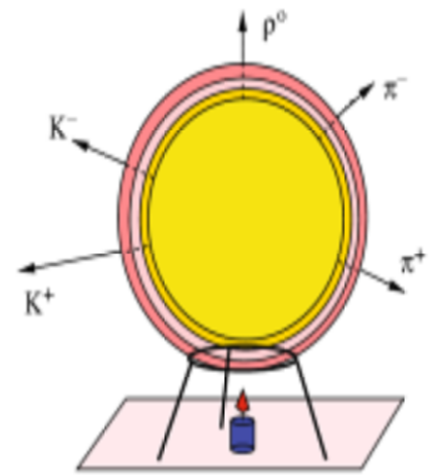


- Initial state: parton distributions inside nuclei
- Hot and dense, expanding medium: energy density
- Final state: fragmentation of partons into hadrons, experimental detection

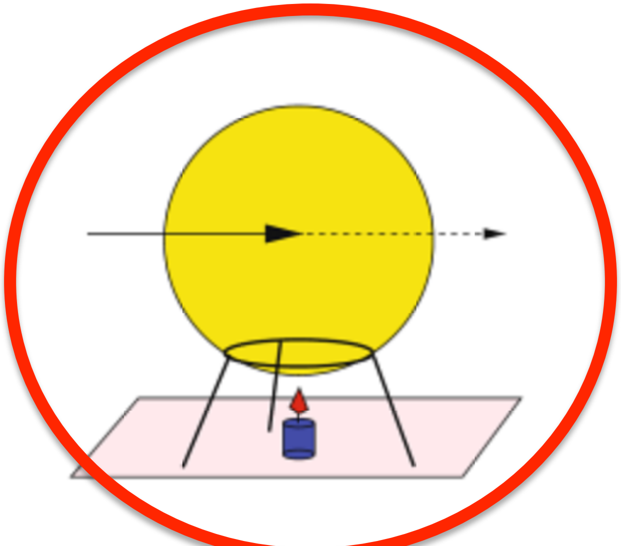
Techniques to study the plasma



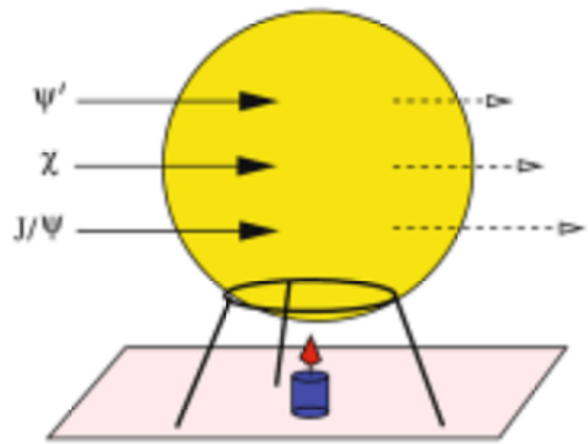
Radiation of hadrons



Azimuthal asymmetry and radial expansion

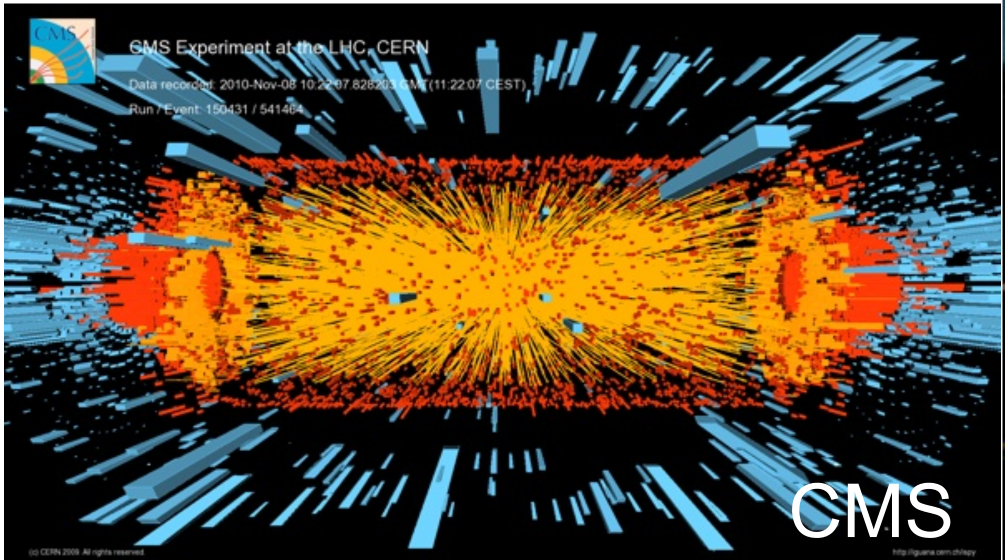


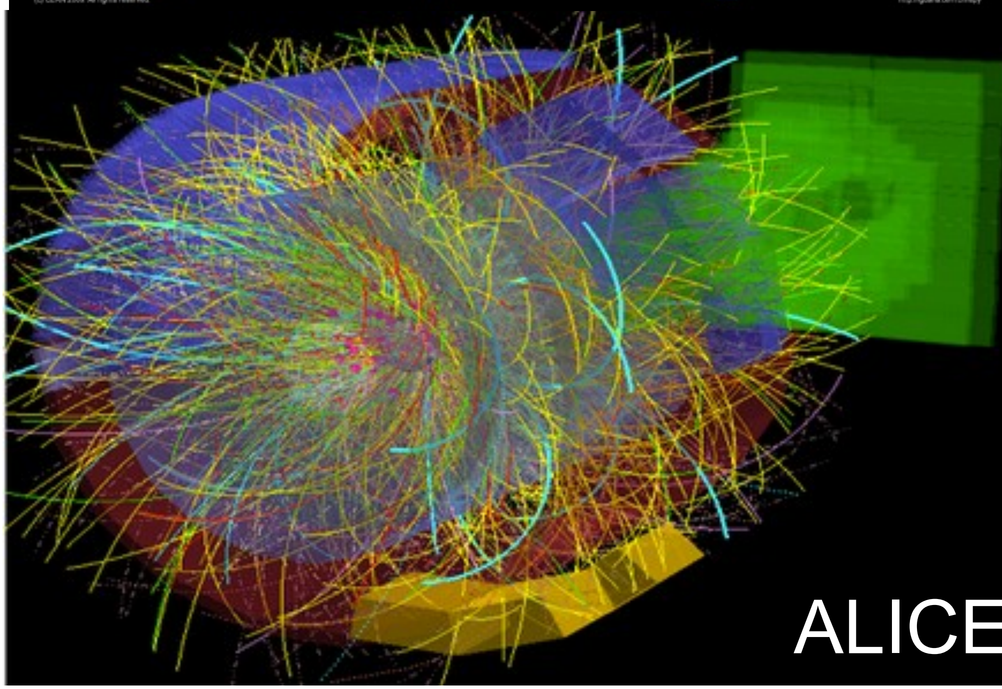
Energy loss by quarks, gluons and other particles

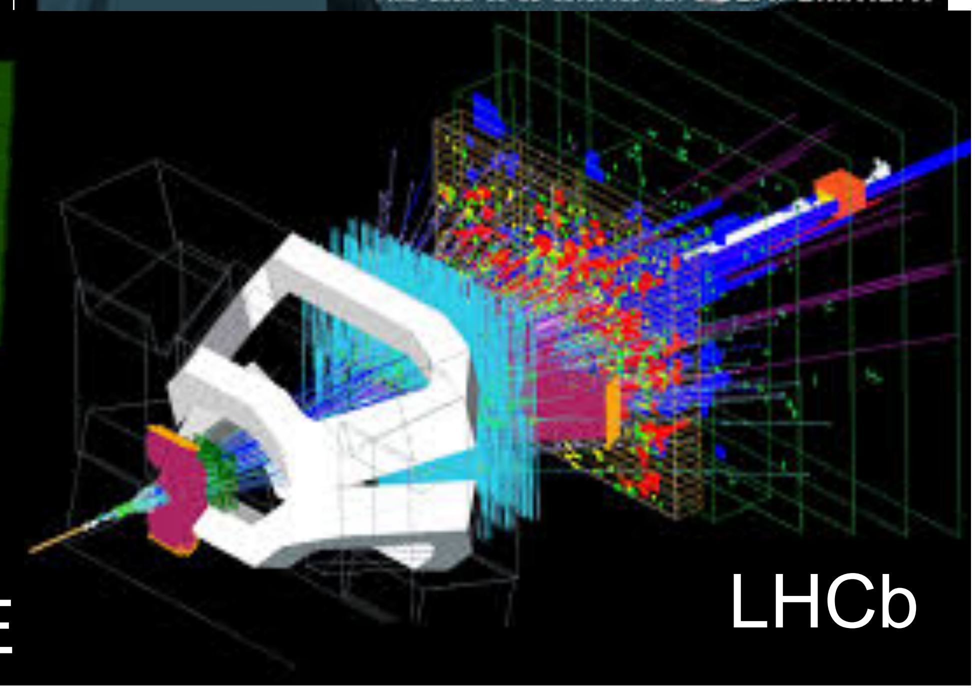


Suppression of quarkonia

Heavy Ion Experiments at the LHC

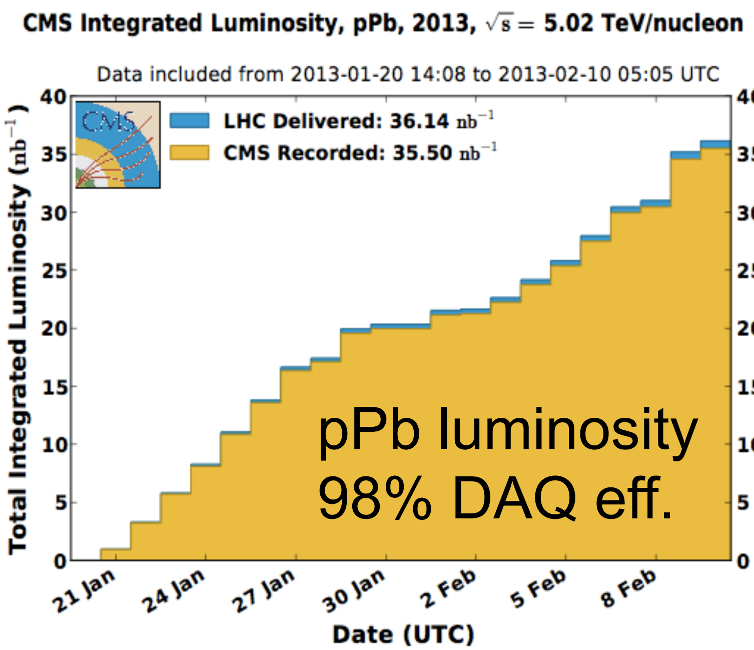






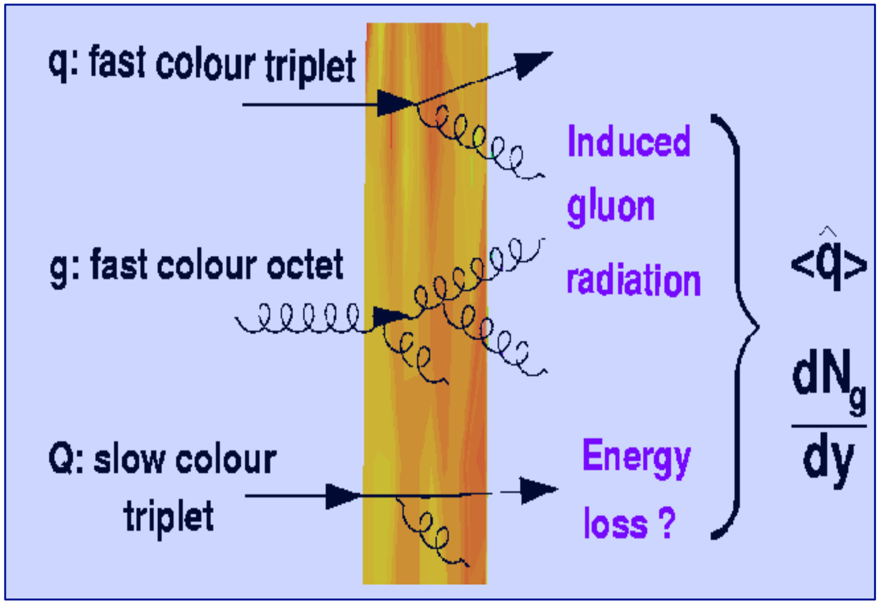
HI-oriented runs: past and future

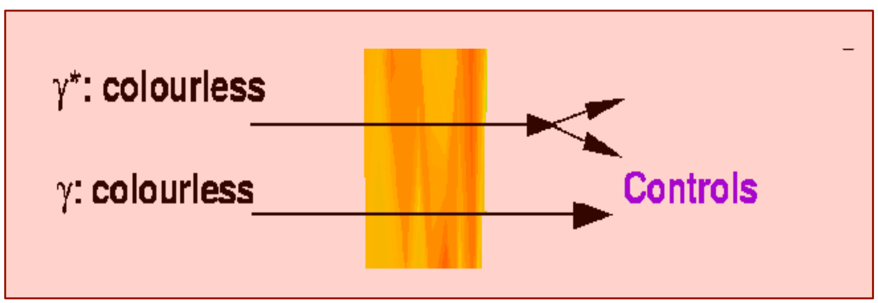
Period	Species	Energy	Lumi
Dec. 2010	Pb+Pb	2.76 TeV	7 μb^{-1}
Dec. 2011	Pb+Pb	2.76 TeV	150 μb^{-1}
Mar. 2011	p+p	2.76 TeV	230 nb^{-1}
Jan. 2013	p+Pb	5.02 TeV	35 nb^{-1}
Feb. 2013	p+p	2.76 TeV	5.4 pb^{-1}
Nov 2015	*Pb+Pb*	*~5 TeV*	*~0.8 nb^{-1}*
?	*p+p*	*~5 TeV*	*?*
Nov 2016	*p+Pb*	*?*	*?*



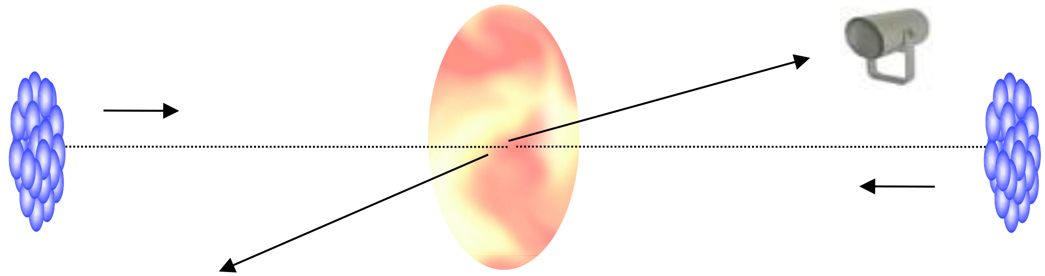
- Same N_{coll} scaled luminosities for pp, pPb, PbPb
  - (as many Z's and W's, modulo the $\sqrt{s}$ dependence)

Focus on hard probes in nuclear collisions





Hot and dense medium



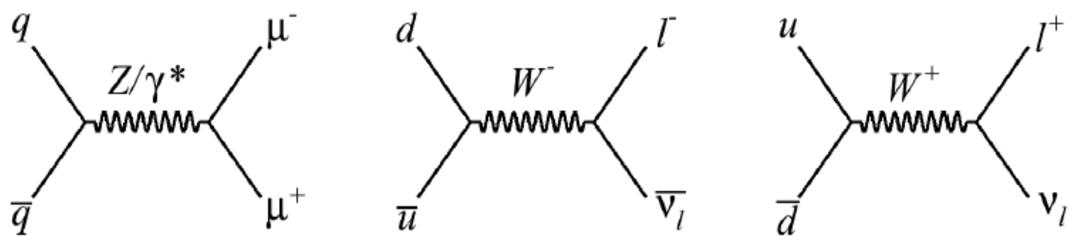
Jets, Quarkonia : originated from the hard scattered partons which carry color charges and interact with the medium. Probe the medium

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

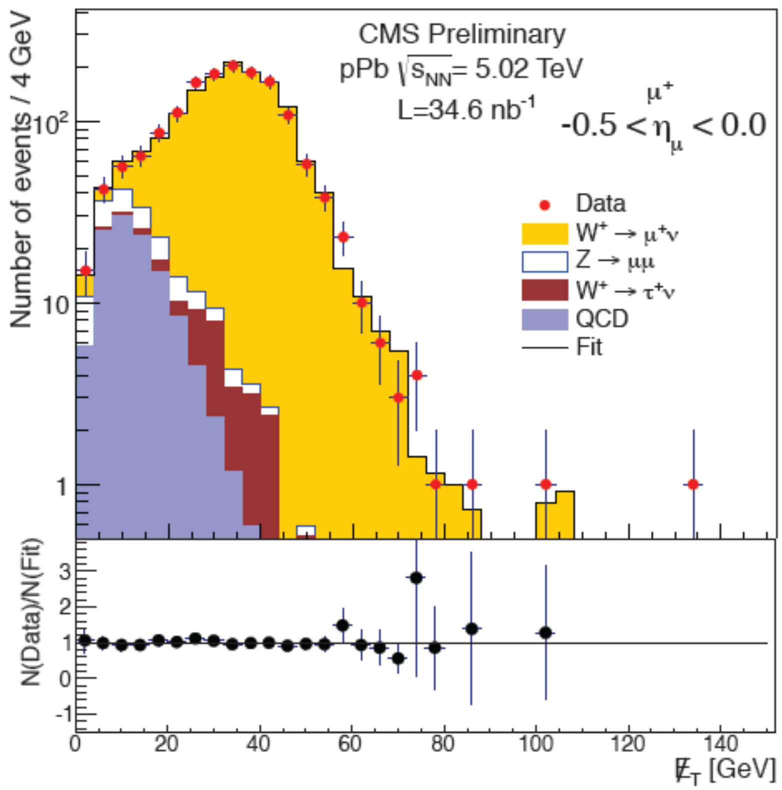
pA collisions: information about nPDF, helps disentangle different physics effects

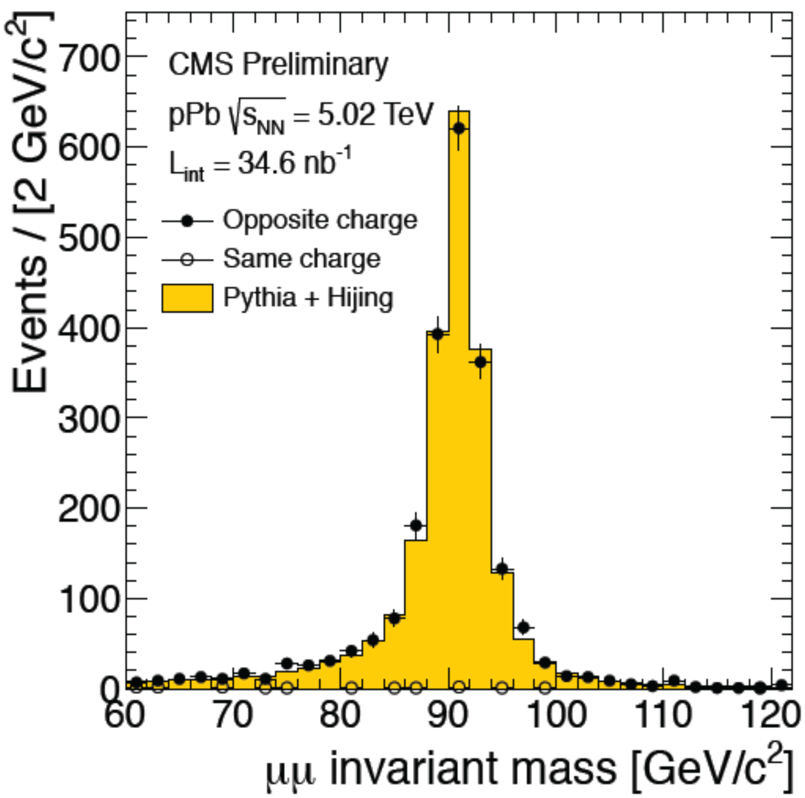
Electroweak bosons in PbPb & pPb

- Standard candles: Z^0 and $W^{\pm}$ unmodified in PbPb
- pPb providing an opportunity to probe (valence) q and (sea) $\bar{q}$ nPDF



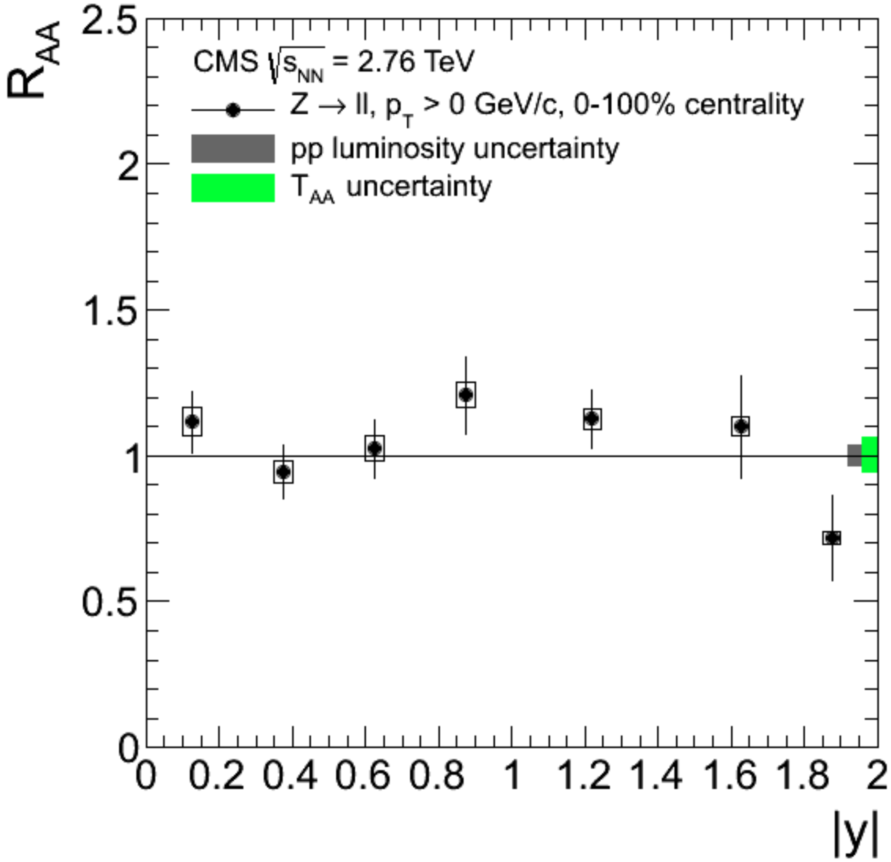
W

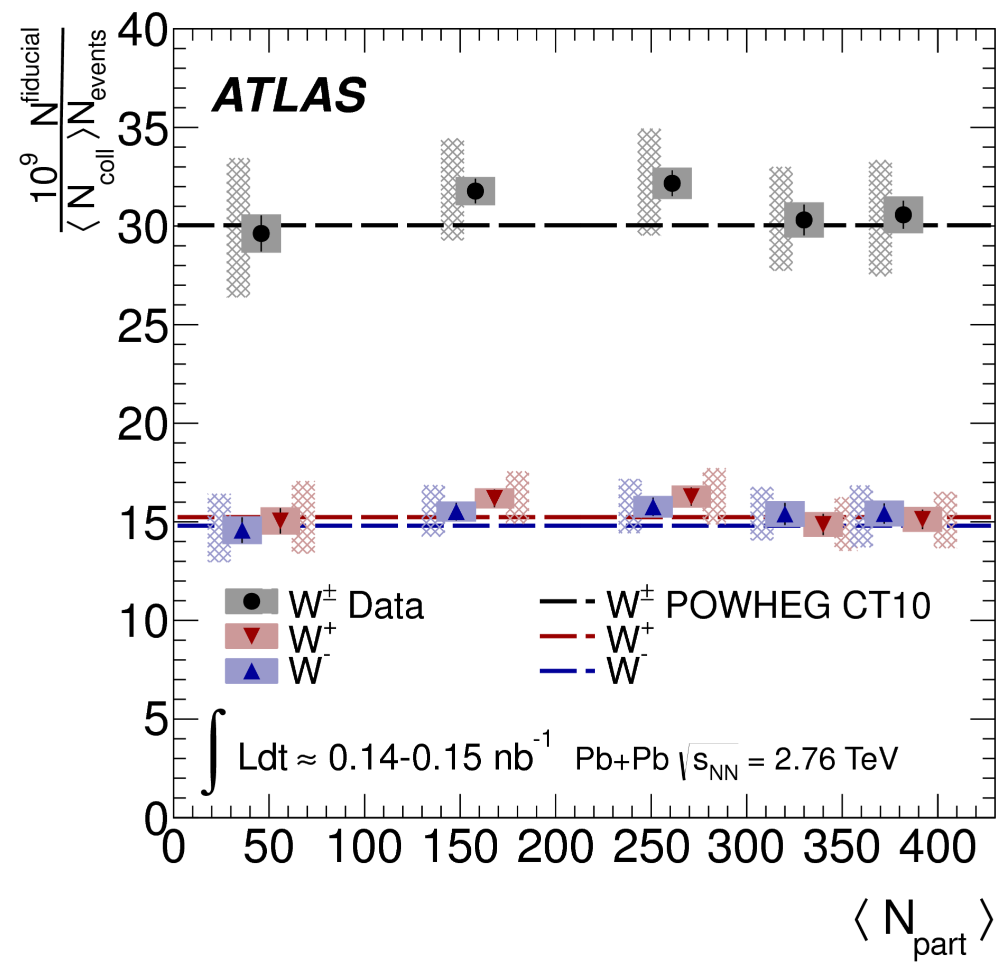




Z

Z and W in PbPb collisions

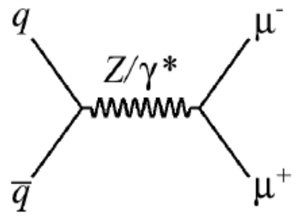


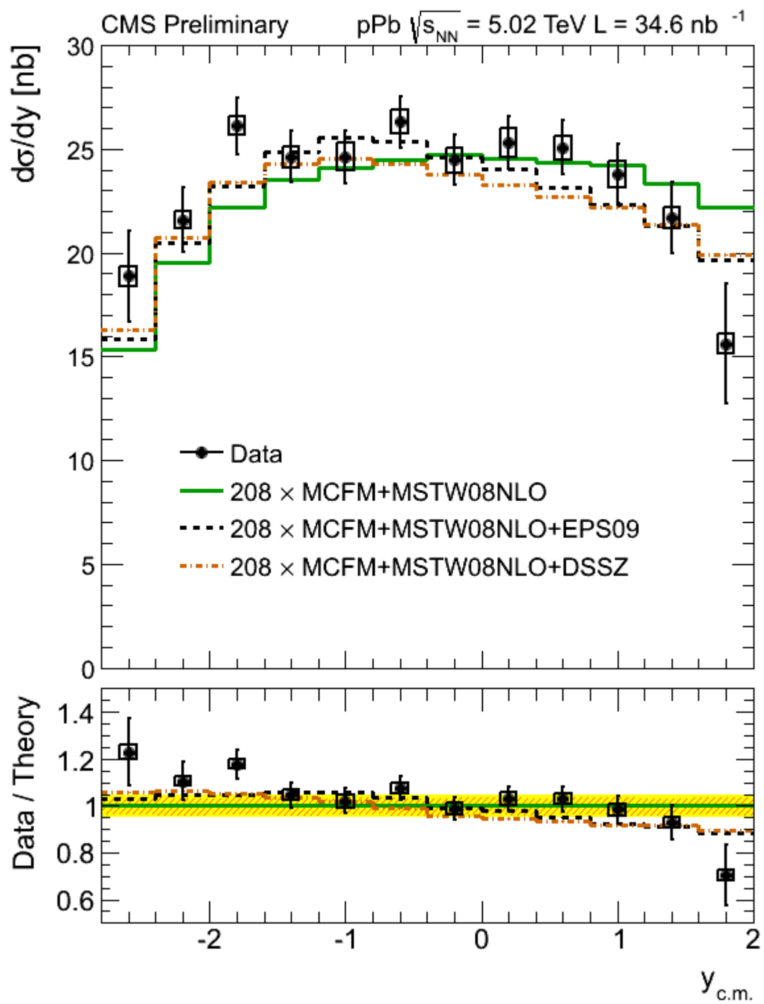


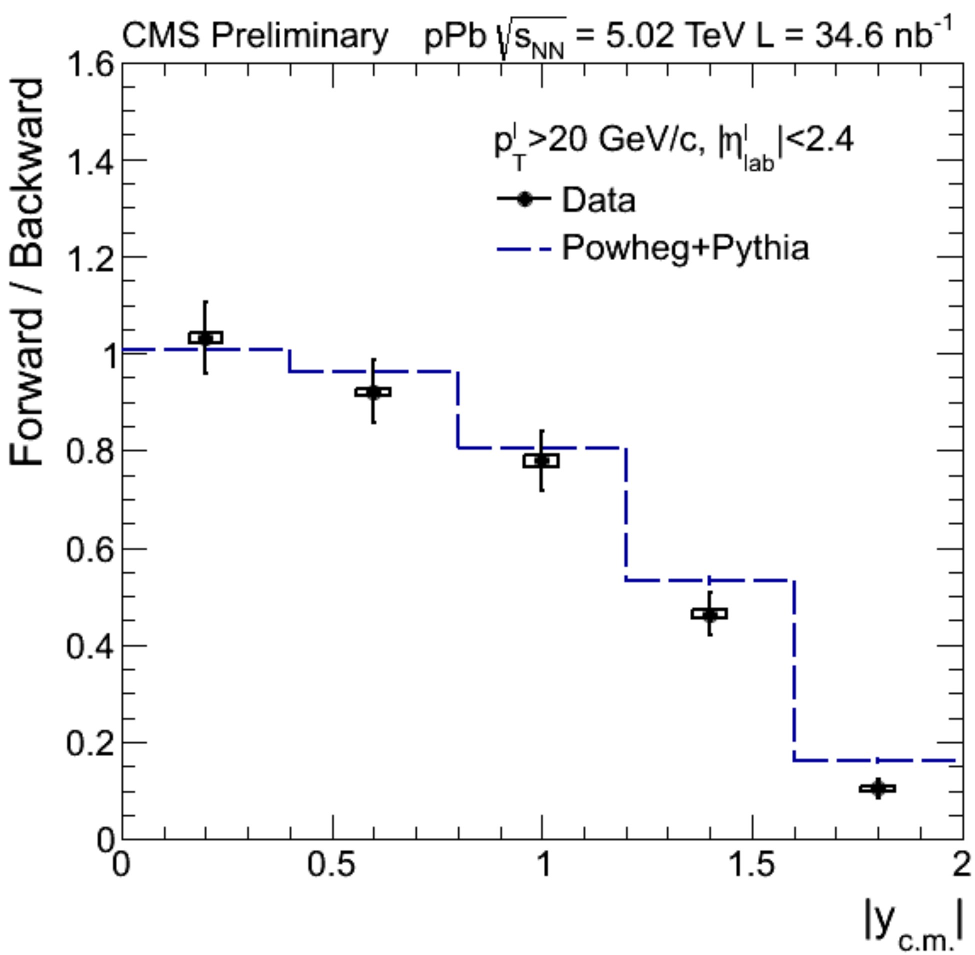
- RAA: ratio of PbPb to proton-proton: ~1 to within 10%, no effect of the final state
- Some modifications expected due to nuclear PDF

Z in pPb

- Z → μμ+ee showing a nuclear effect
  - maybe a hint of forward/backward asymmetry

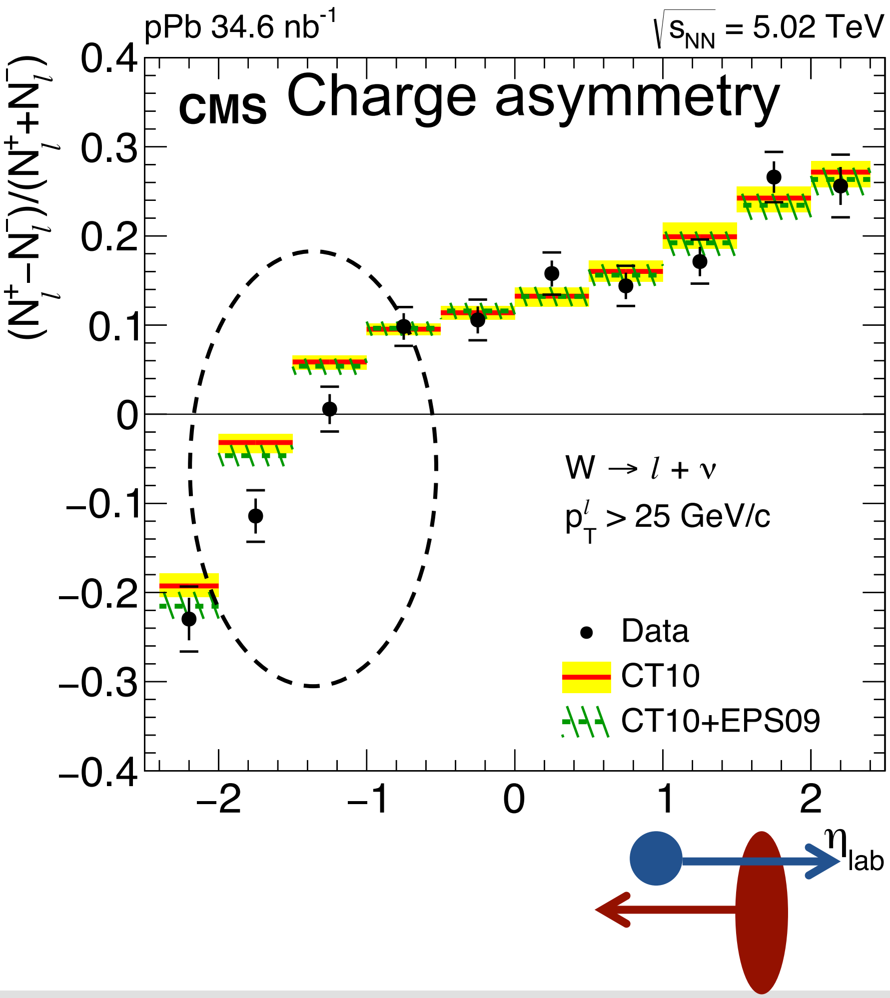


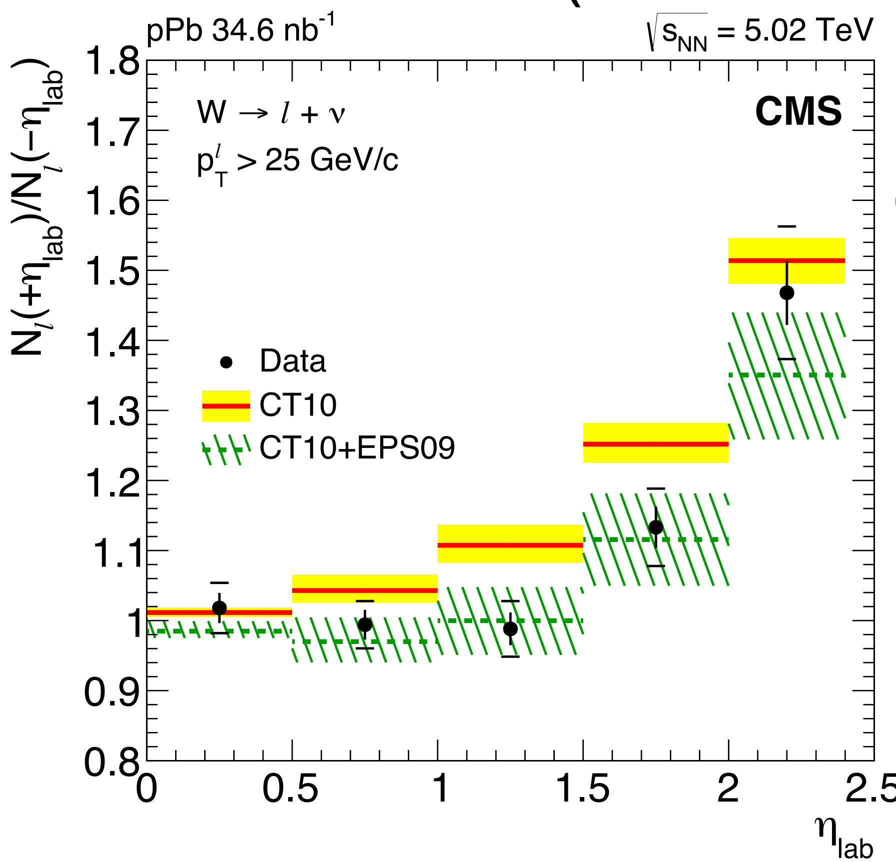




W^+ and W^- in pPb

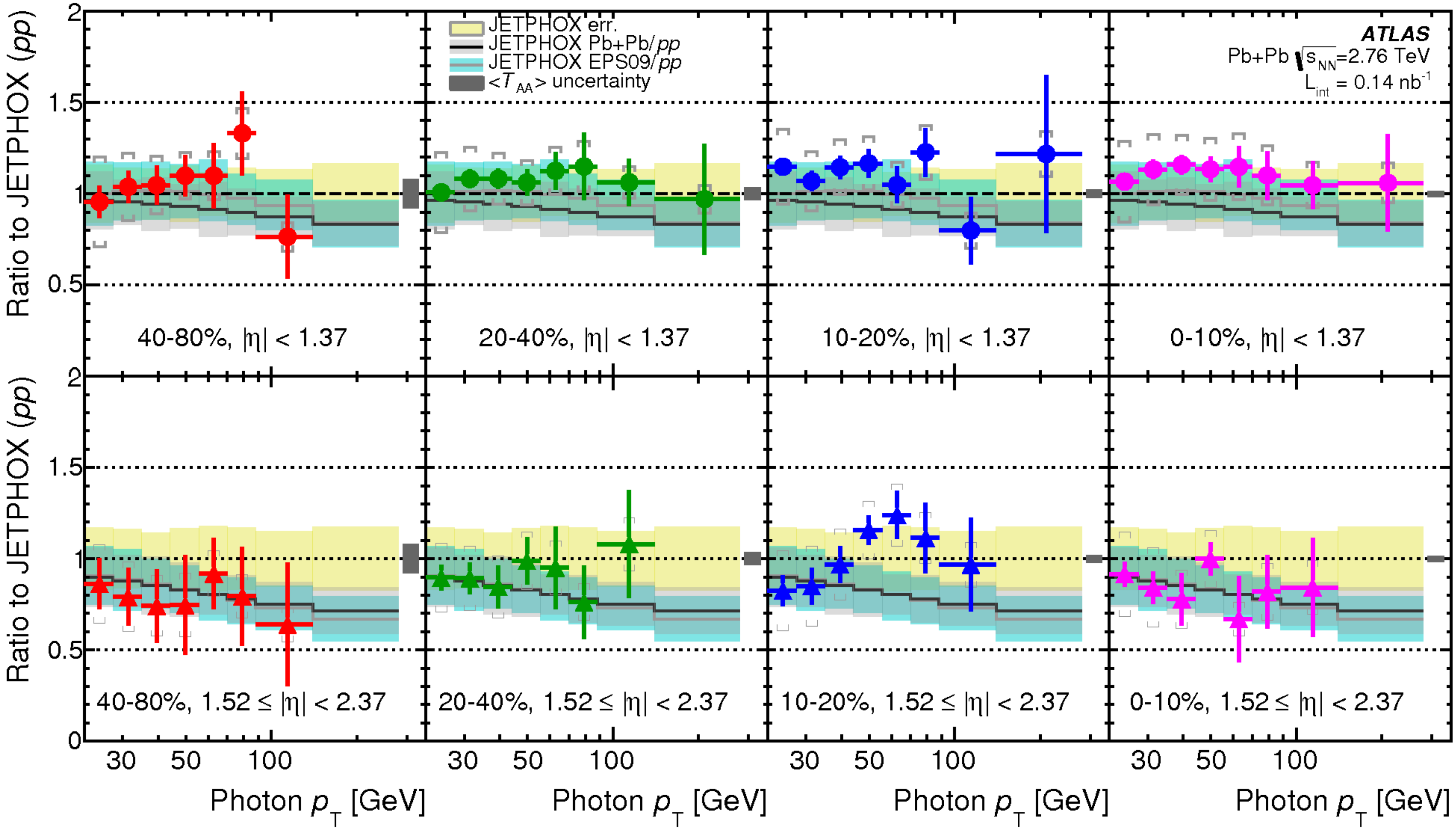
- ≈ 21000 W → μ & 16000 W → e
  - Showing small deviations from unmodified PDFs
  - A hint of a different u/d modification? (not in EPS09)





Forward/ Backward (in lab)

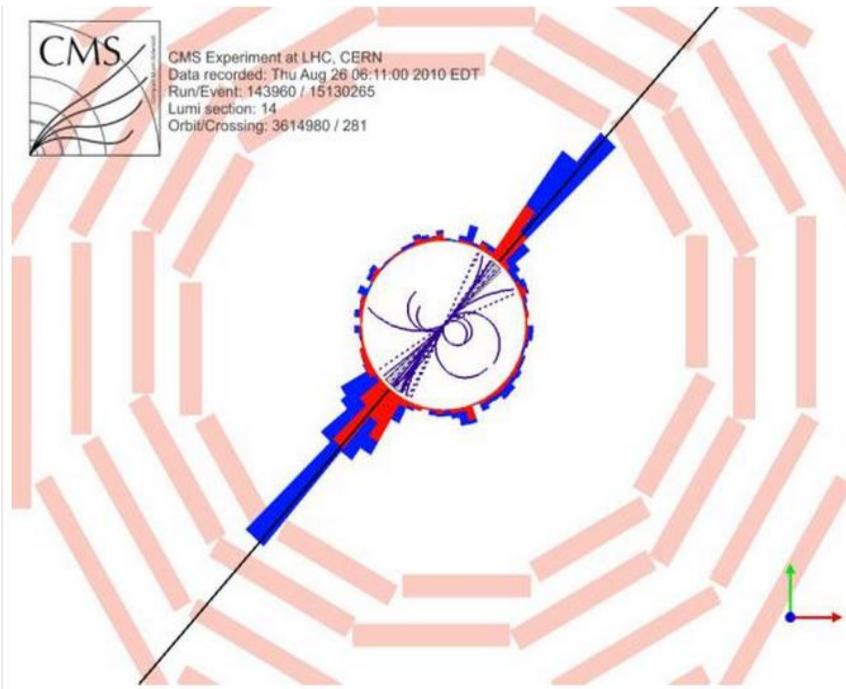
High Energy Photons in PbPb



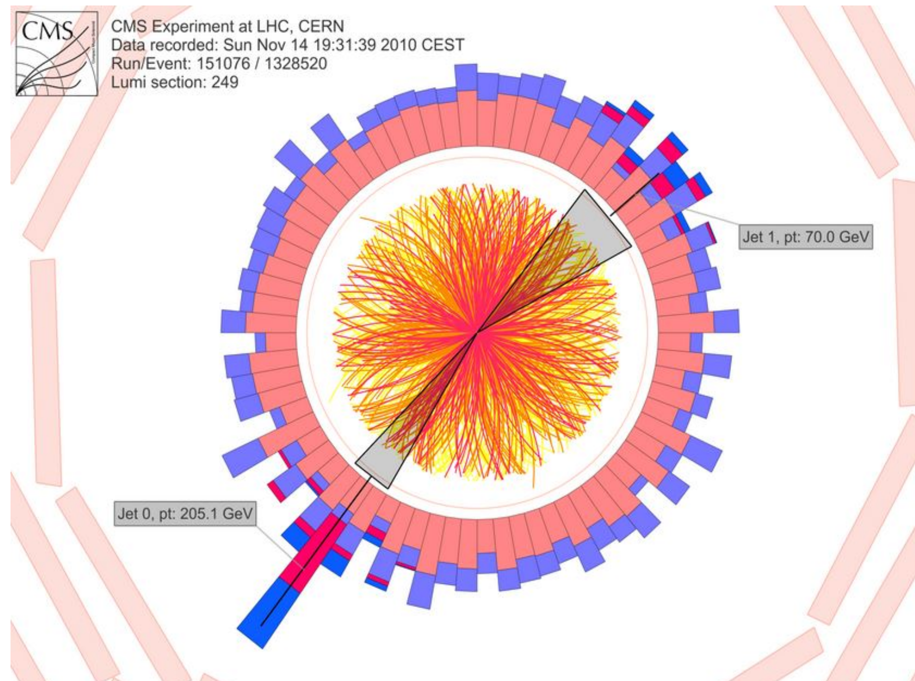
- Ratio of PbPb to simulation: consistent with no effects due to final state

Probe plasma with energetic quarks and gluons

Quark-gluon plasma is incredibly strongly interacting – It can slow down and even stop very high energy quarks and gluons passing through it



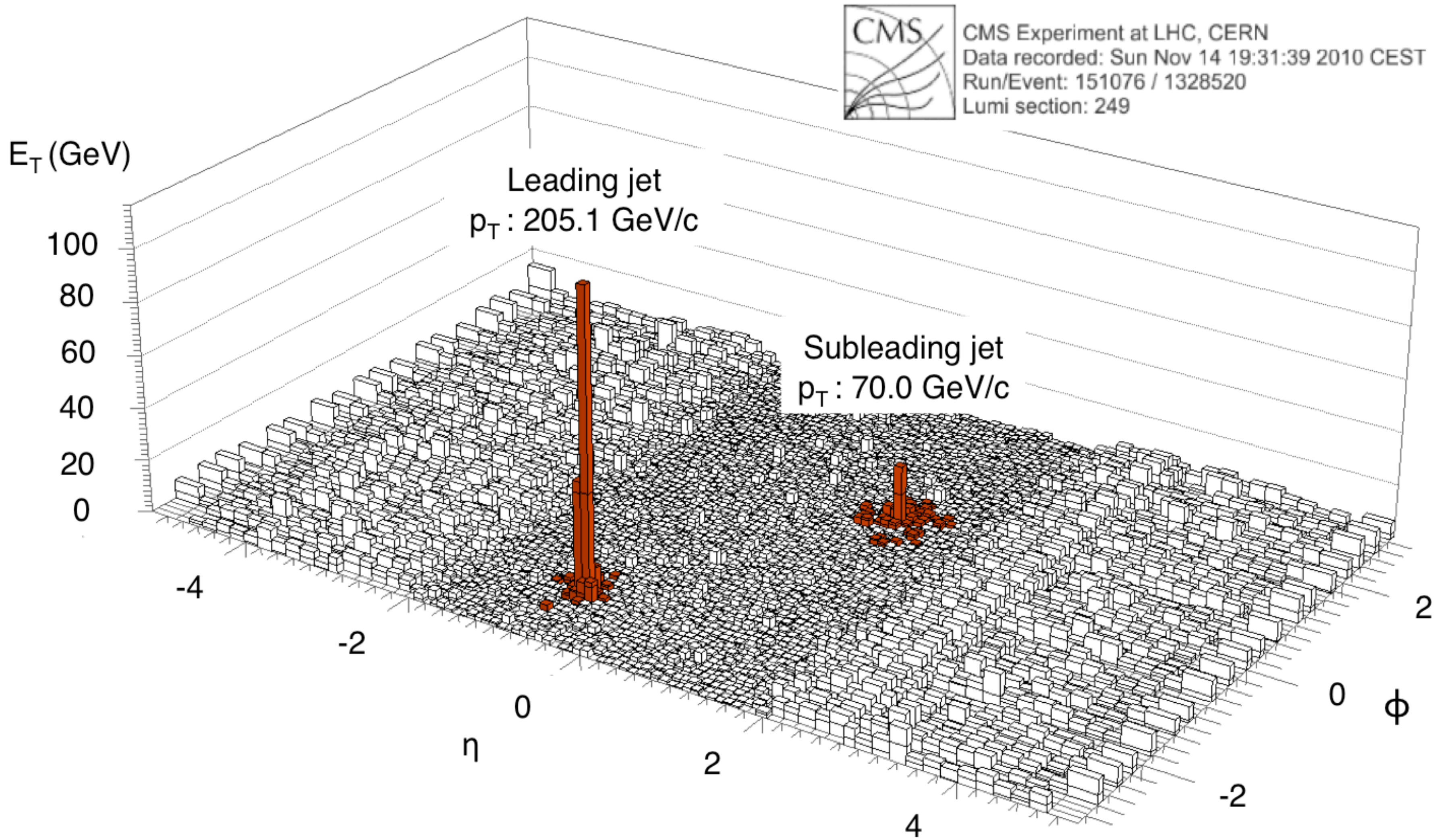
P + P



Pb + Pb

PRC 84 (2011) 024906

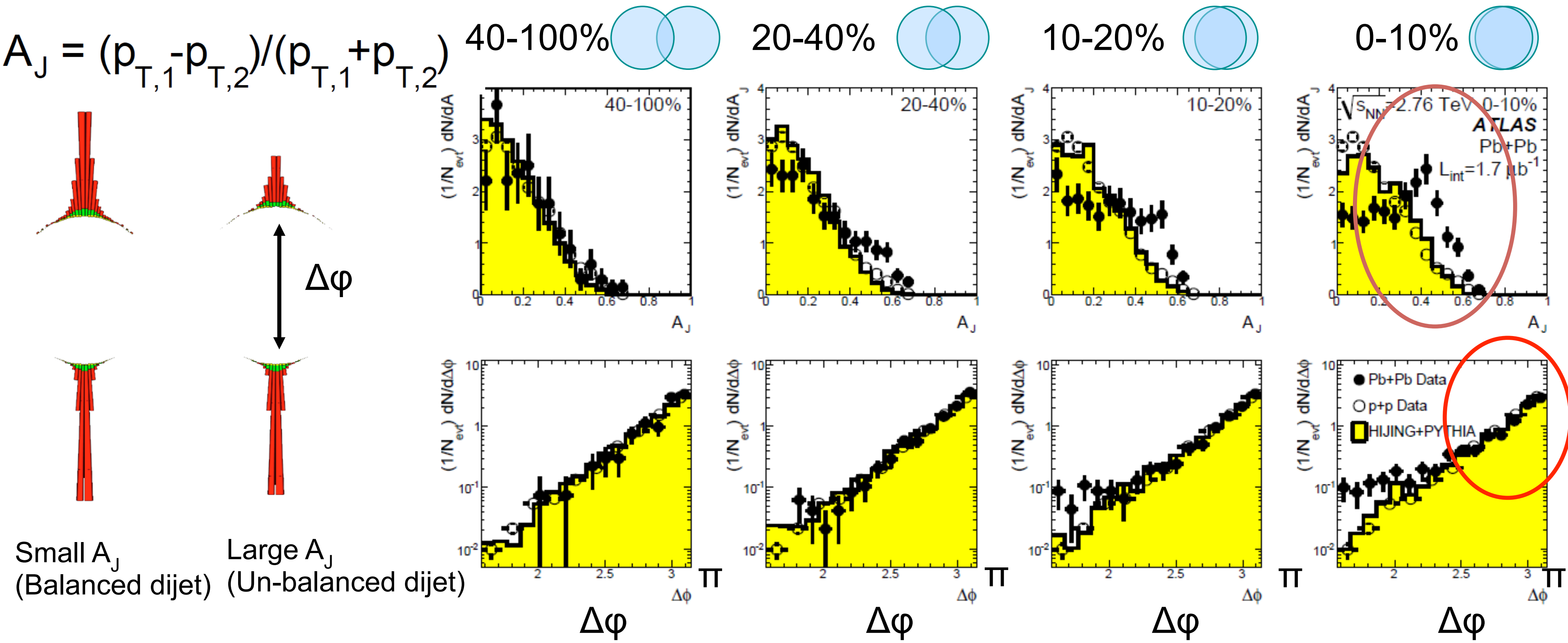
Jet quenching in PbPb



Large jet quenching at the LHC gives rise to asymmetric dijets in central collisions

Correlation study: Di-jet imbalance in ATLAS

$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$



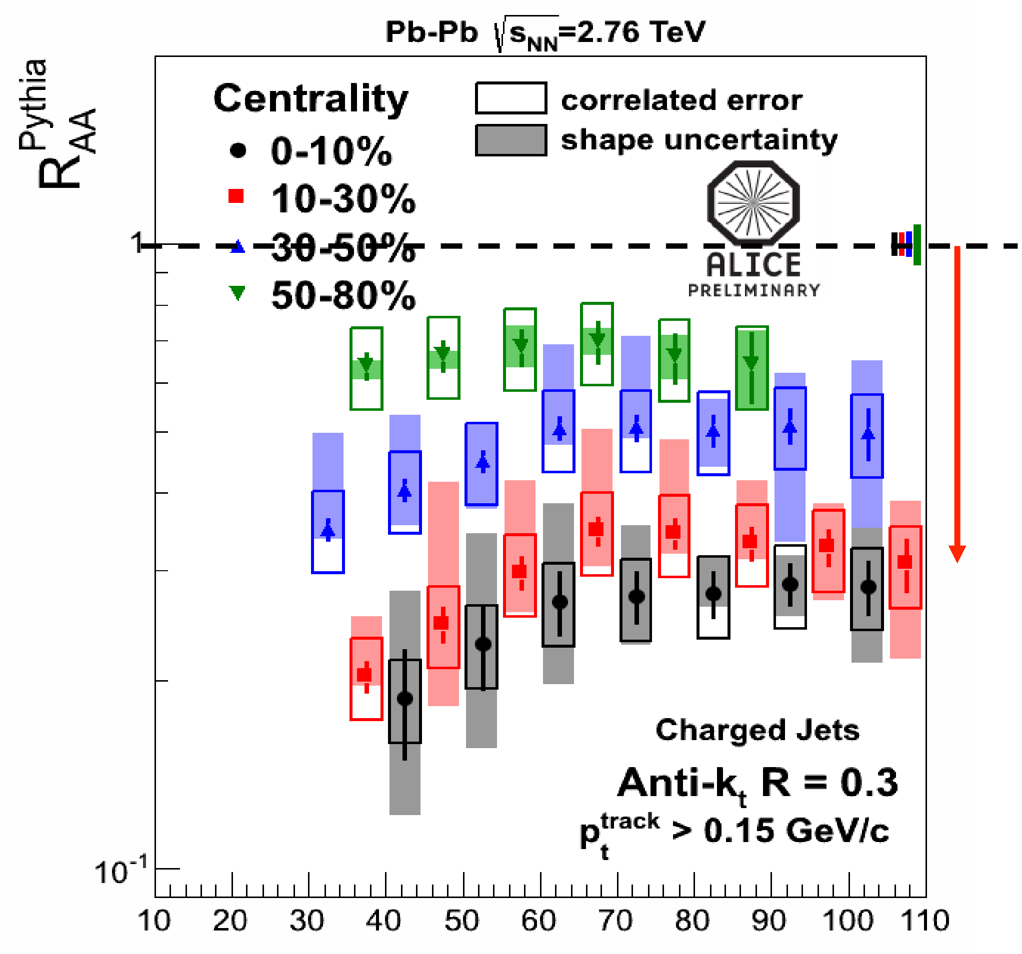
Parton energy loss is observed as a pronounced energy imbalance in central PbPb collisions

No apparent modification in the dijet Δφ distribution (Dijet pairs are still back-to-back in azimuthal angle)

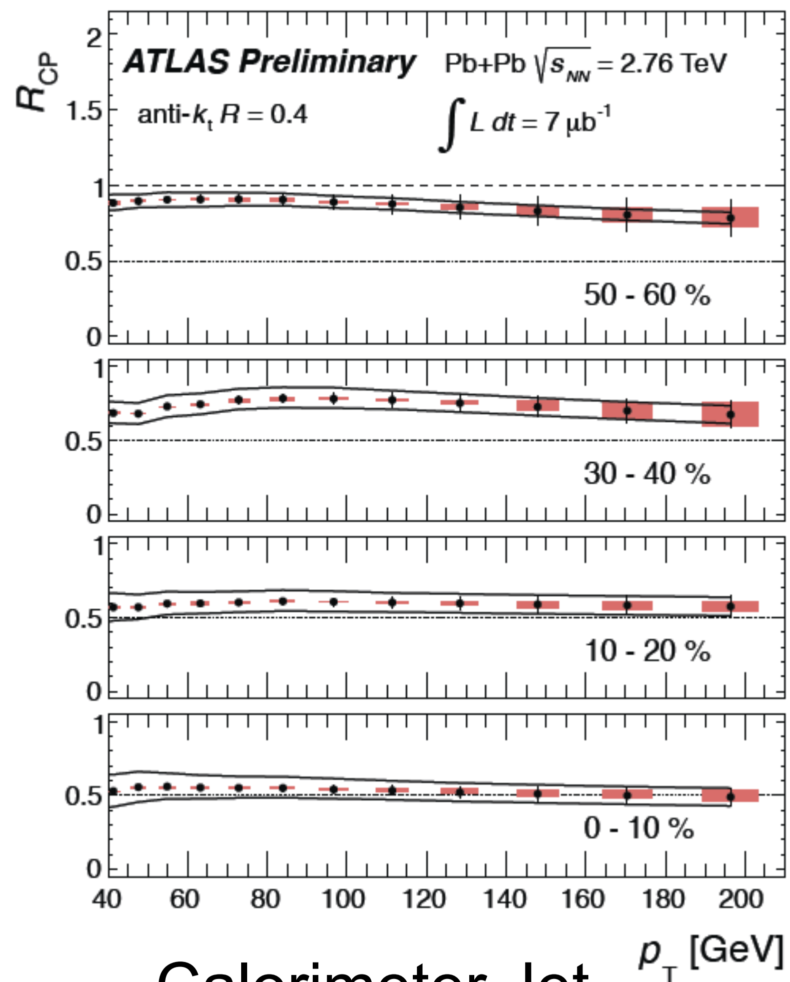
Inclusive jet R_{AA}, R_{CP}

Compare PbPb to PYTHIA (pp generator)

R_{CP}: Compare to



Track Jet

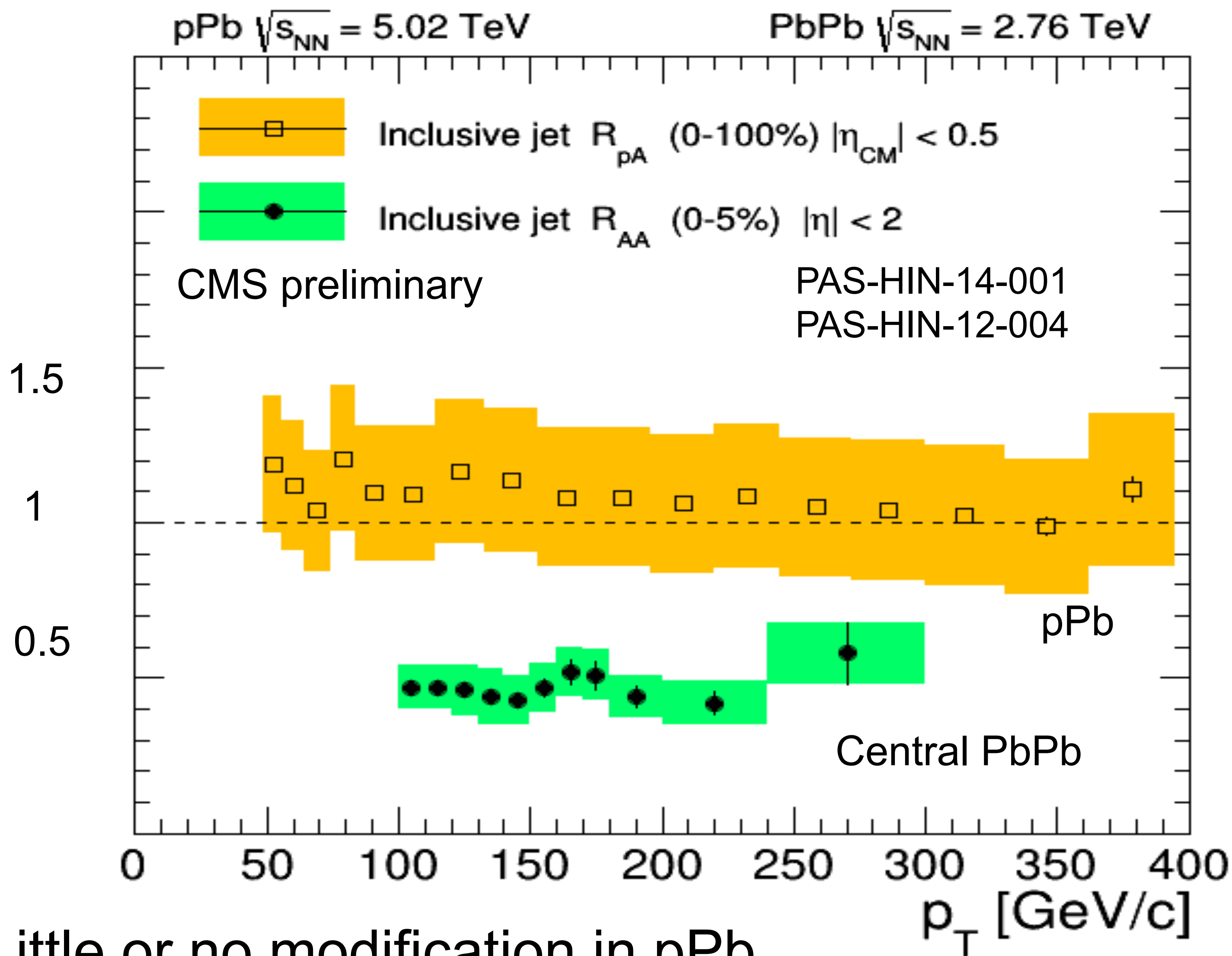


Calorimeter Jet

Strong suppression of inclusive high p_T jets!

A cone of R=0.3, 0.4 doesn't catch all the radiated energy

Jets in PbPb & pPb

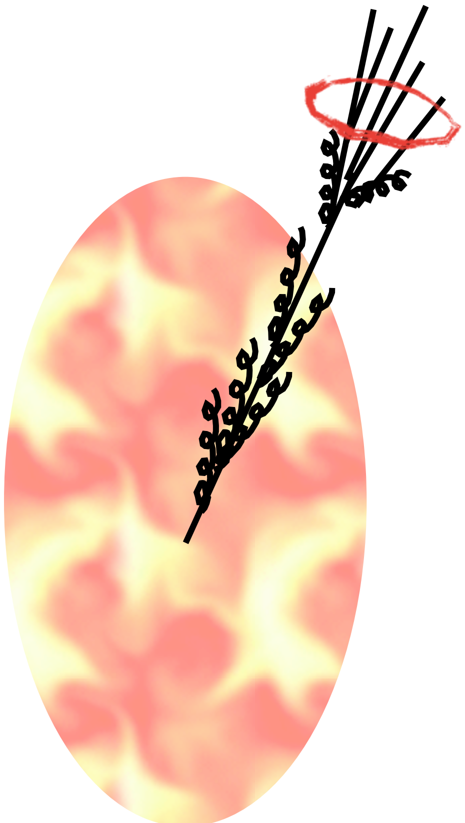


- Little or no modification in pPb
- Strong suppression in PbPb
- No strong flavor dependence

$$R_{AA} = \frac{ions}{protons}$$

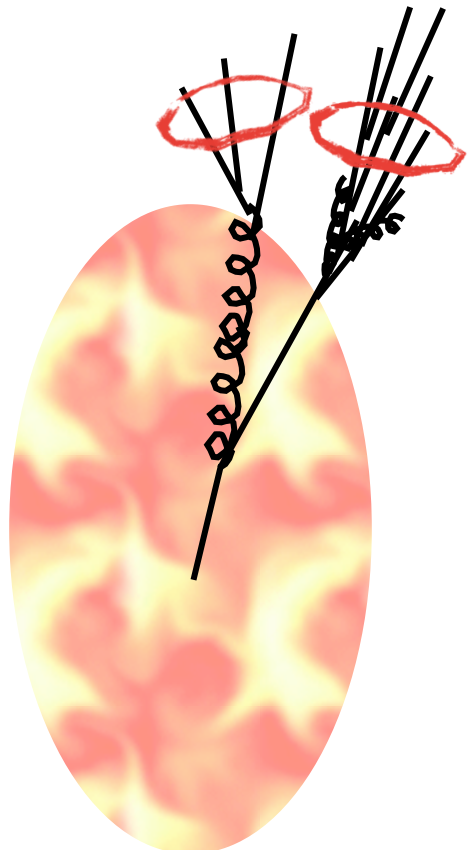
Three possible scenarios

To explain the suppression of high p_T particles



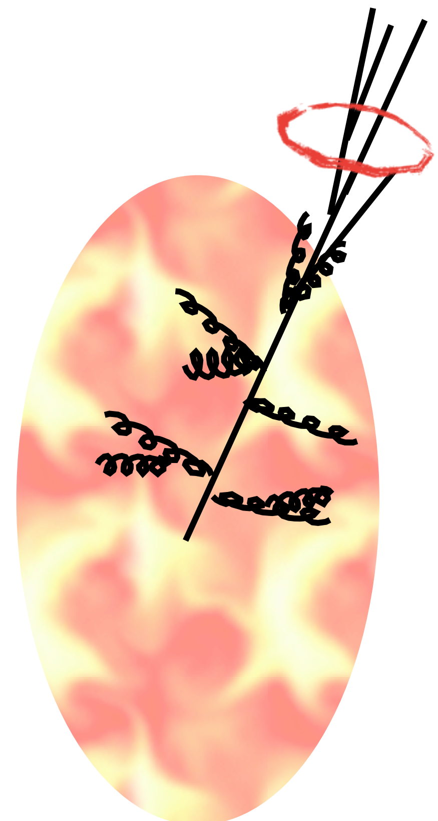
Soft collinear radiation

GLV + others



Hard radiation

PYTHIA inspired models
Modified splitting functions



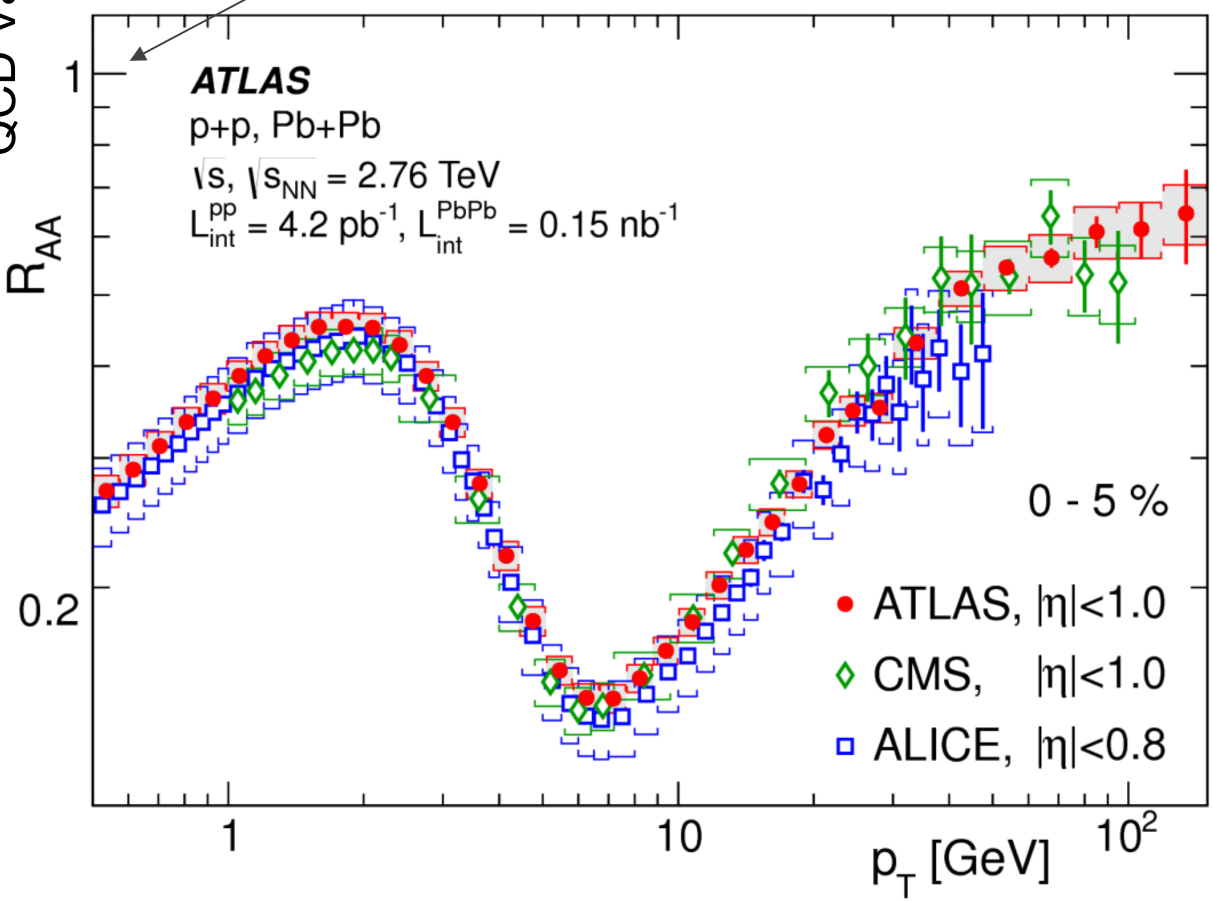
Large angle soft radiation
"QGP heating"

AdS/CFT

Charged particle R_{AA}

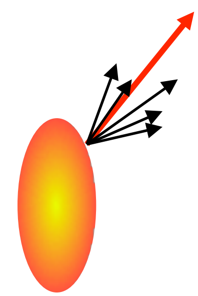
"QCD Medium" ~ "QCD Vacuum"

If PbPb = superposition of pp ...



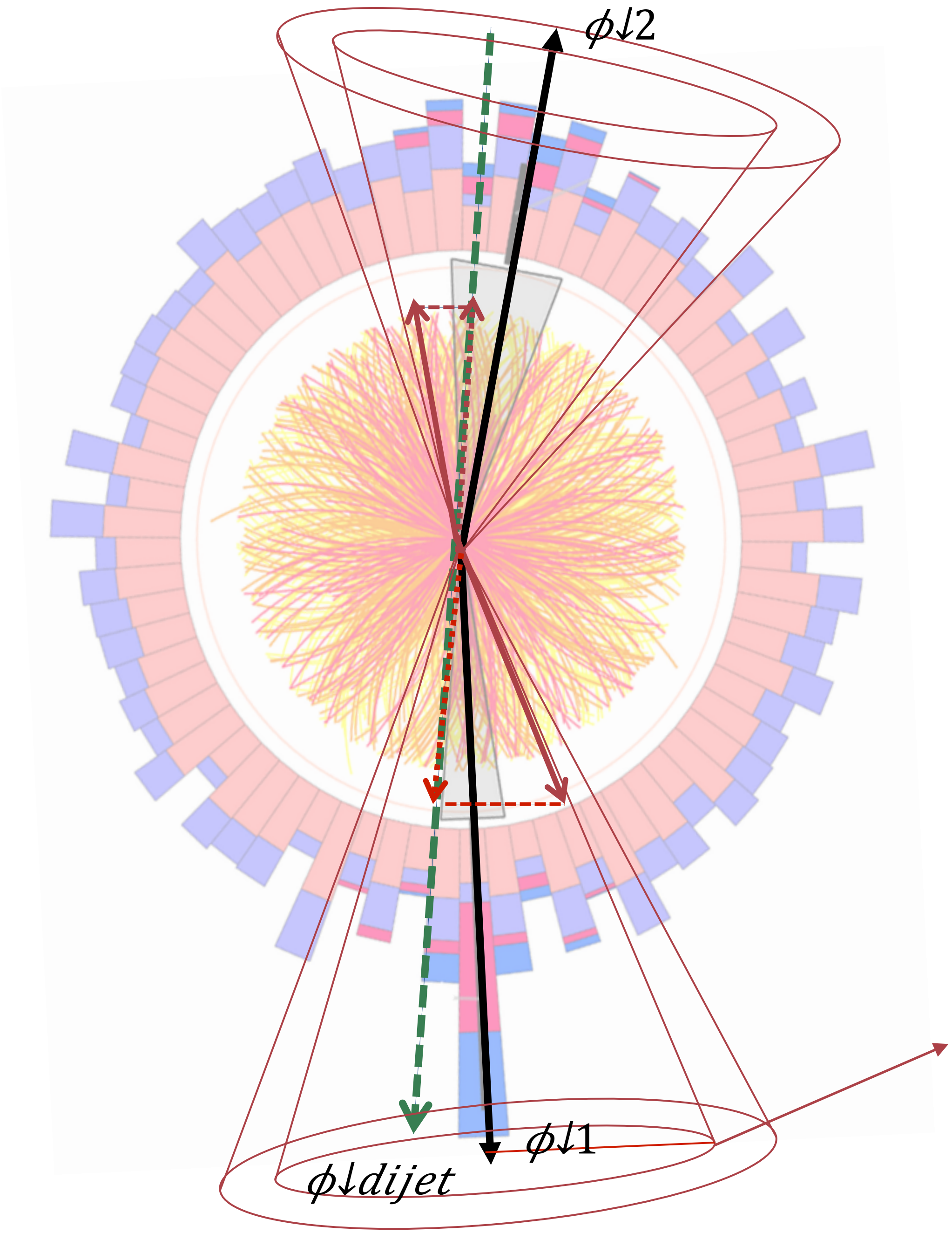
$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T\, d\eta}{d^2 \sigma_{pp}/dp_T\, d\eta}$$

N_{coll} validate by photons W/Z bosons



Provide constraints on the parton energy loss models

Momentum flow with respect to the dijet



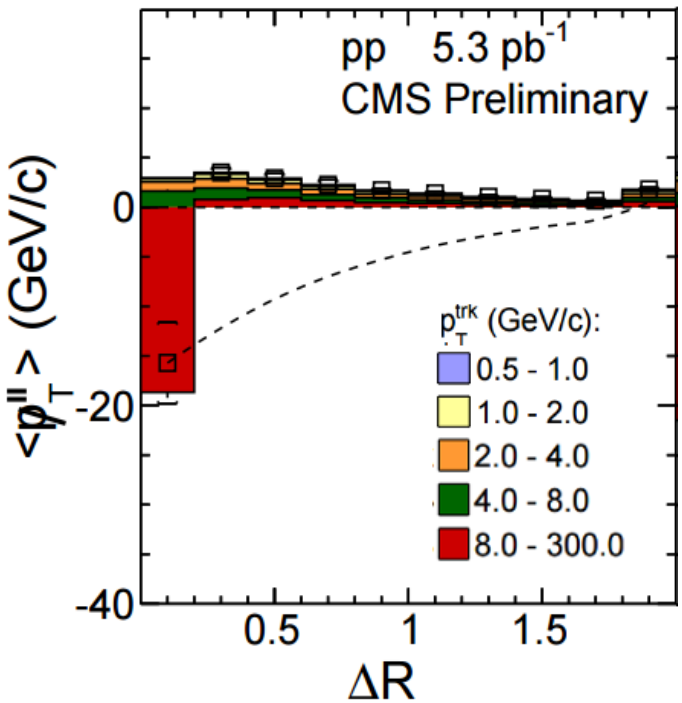
- Project and sum transverse momenta of charged particles that fall in slices of around each jet

$$p_T^{||} = \left(\sum_i -p_T^i \cos\left(\phi_i - \phi_{dijet}\right) \right) \Big|_{R_{down} < \Delta R < R_{up}}$$

- Make scan of the event by increasing

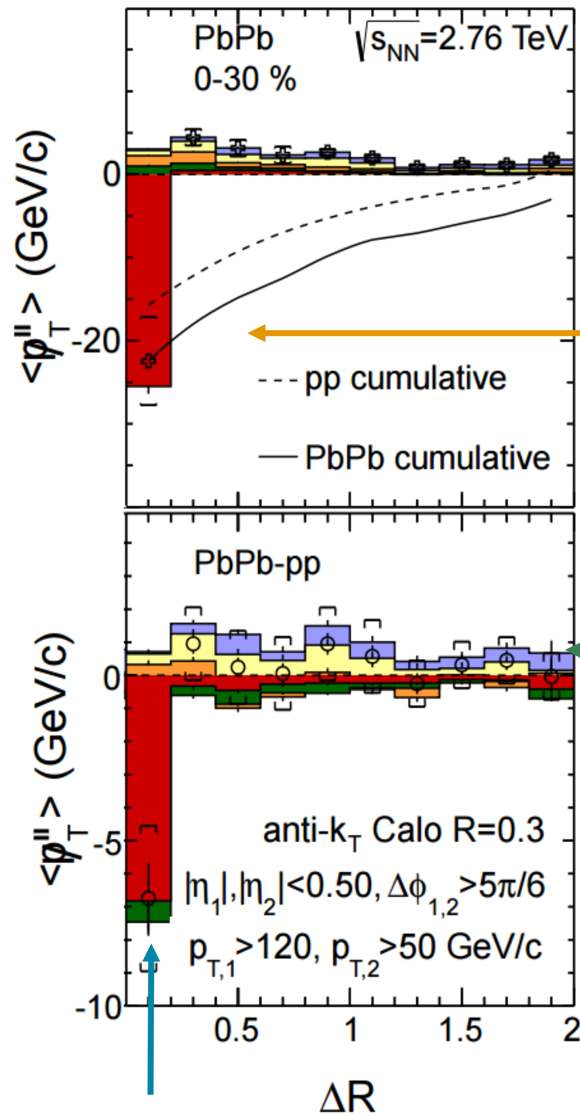
$$\Delta R = \sqrt{\Delta\phi^2_{Trk,jet} + \Delta\eta^2_{Trk,jet}}$$

Momentum flow with respect to the dijet



Characteristics of the distribution:

- In-cone imbalance (<0.2)
- Small balancing contributions on subleading jet side which extend up to large angles
- Cumulative curve shows the rate of recovery of balance

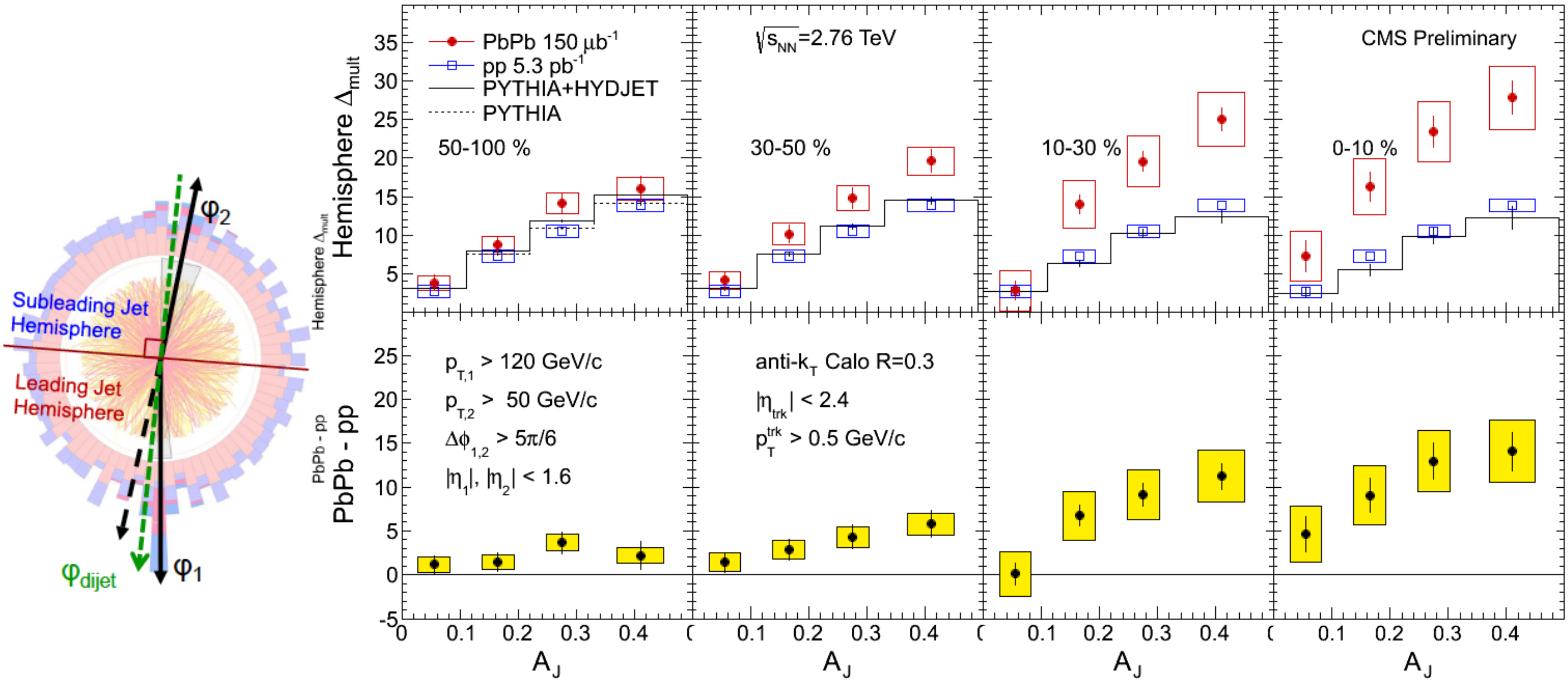


Shape of energy flow is similar in PbPb and pp

Excess of soft particles with p_T < 2 GeV

Larger dijet imbalance in PbPb

Counting particles in dijet events



Compare two hemispheres:

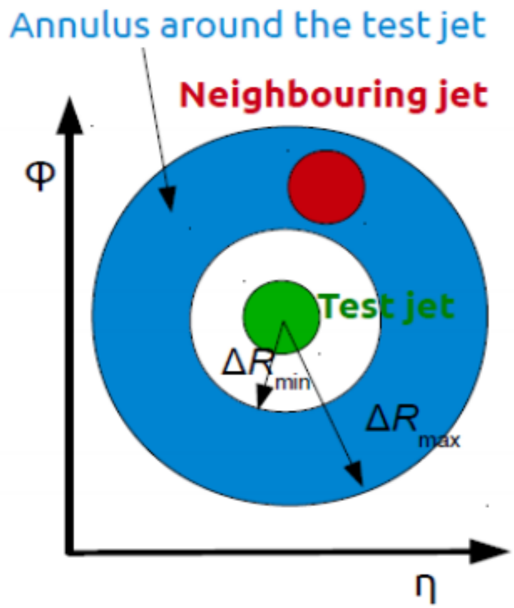
For large A_J and central Pb-Pb collisions there are about 14 extra particles with p_T>0.5 GeV/c in the subleading jet hemisphere

Explicit third jet counting: ATLAS

- Count the number of neighboring jets near a test jet at a fixed energy for both test and neighboring jets

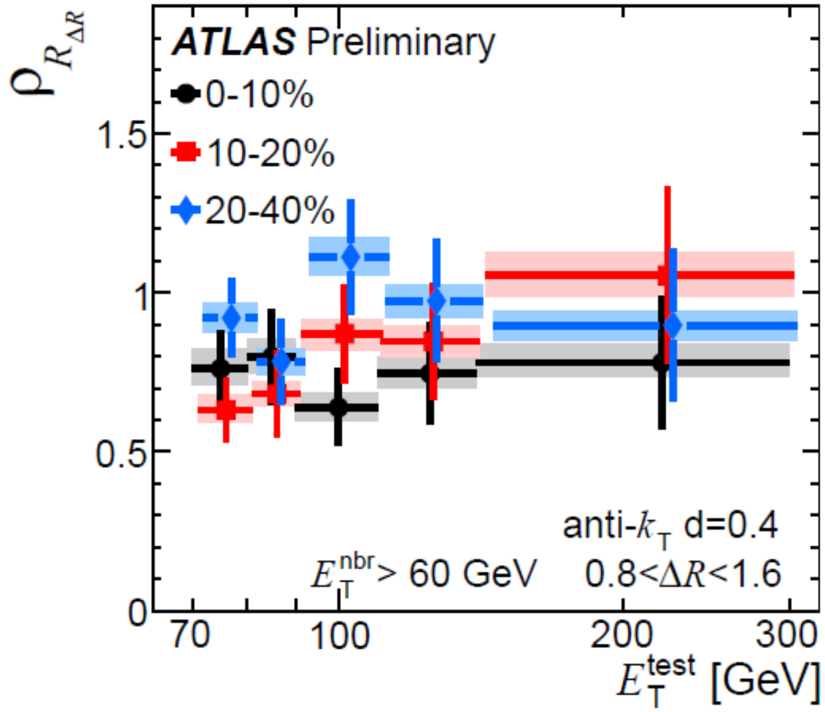
$$R_{\Delta R} = \frac{1}{\mathrm{d}N_{\mathrm{jet}}^{\mathrm{test}}/\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}} \sum_{i=1}^{N_{\mathrm{jet}}^{\mathrm{test}}} \frac{\mathrm{d}N_{\mathrm{jet},i}^{\mathrm{nbr}}}{\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}}(E_{\mathrm{T}}^{\mathrm{test}}, E_{\mathrm{T,min}}^{\mathrm{nbr}}, \Delta R)$$

- Take the ratio with respect to the most peripheral bin to obtain $\rho_{\Delta R}$

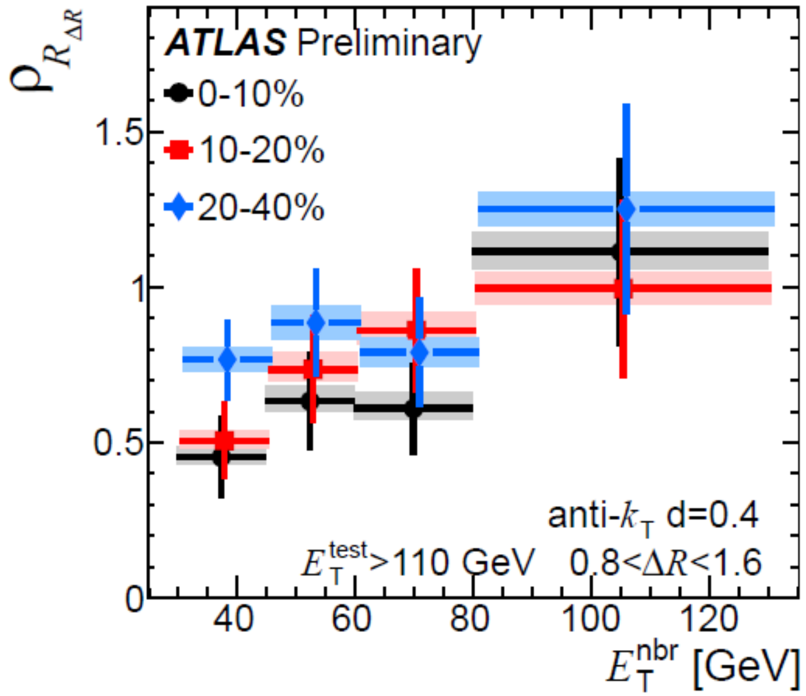


Energy sharing on the subleading side

- Finding a high energy third jet reduces the quenching on subleading jet as well as on the third jet itself

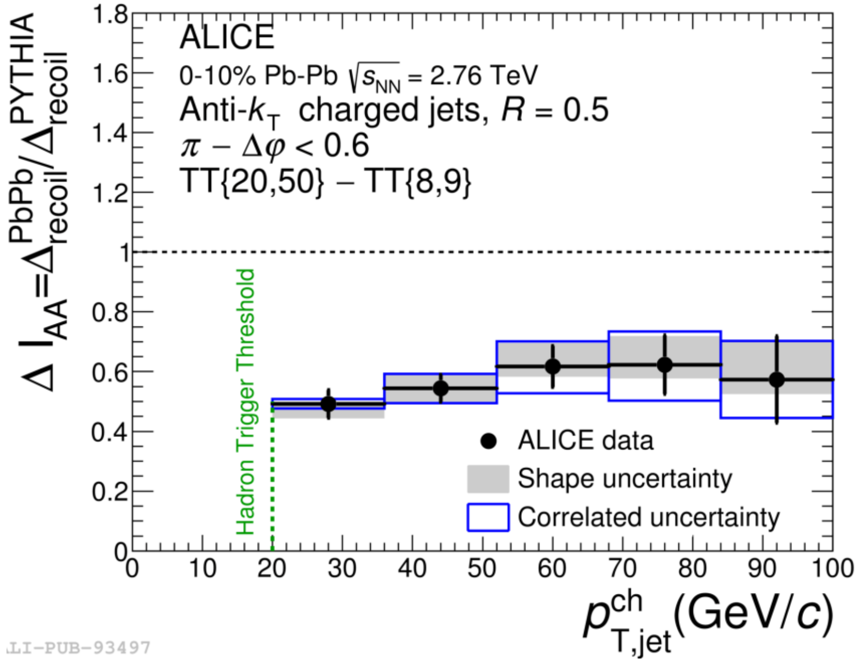


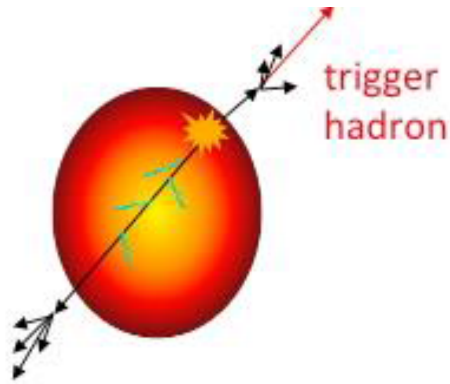
The suppression in the number neighboring jets decrease slightly as test jet energy gets larger



The suppression in the number neighboring jets decrease more significantly as neighboring jet energy gets larger

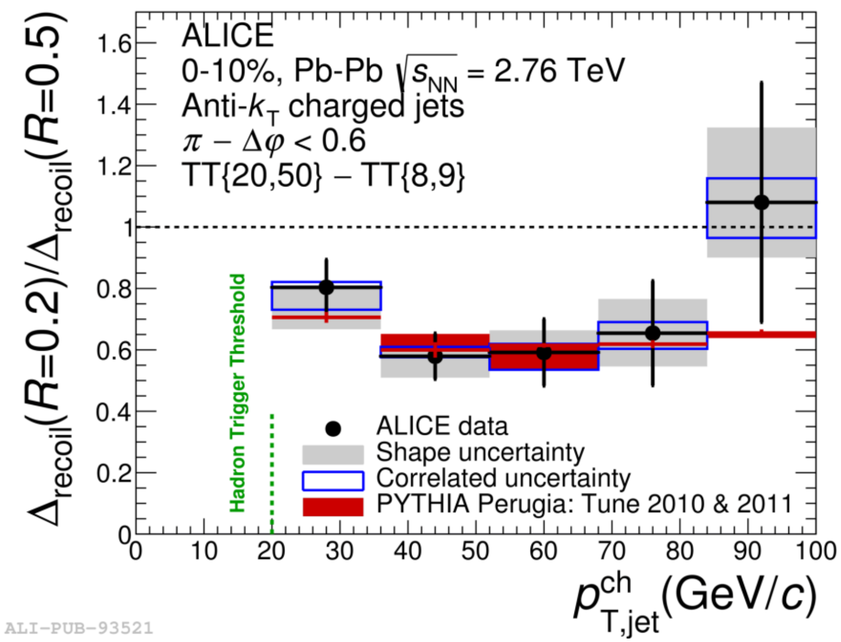
Semi inclusive charged jet recoil in PbPb: ALICE





Number of jets per trigger charged hadron

$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_T}\bigg|_{p_{T,trig} \in TT_{Sig}} - \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_T}\bigg|_{p_{T,trig} \in TT_{Ref}}$$

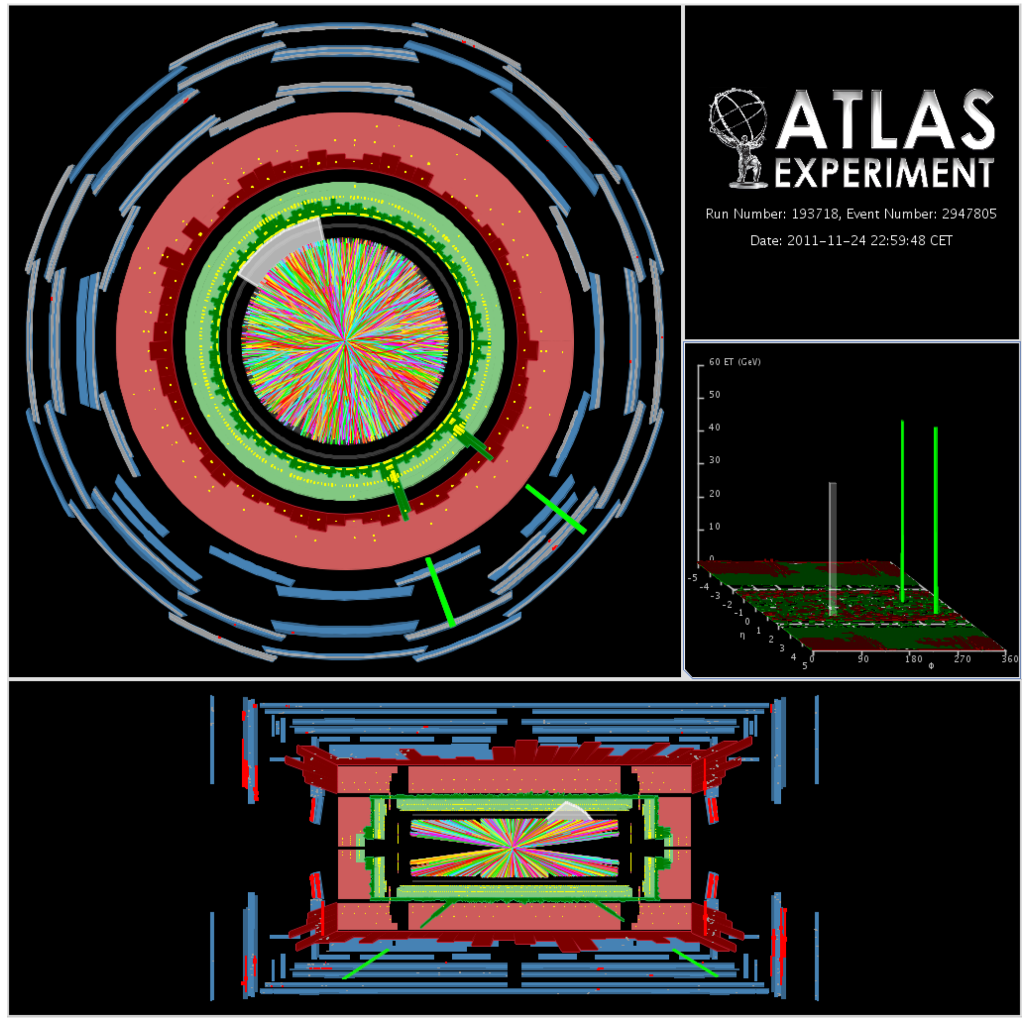


Jet suppression confirmed

Comparing suppression for different recoil jet ratio there is very little intra-jet modifications compared to pp

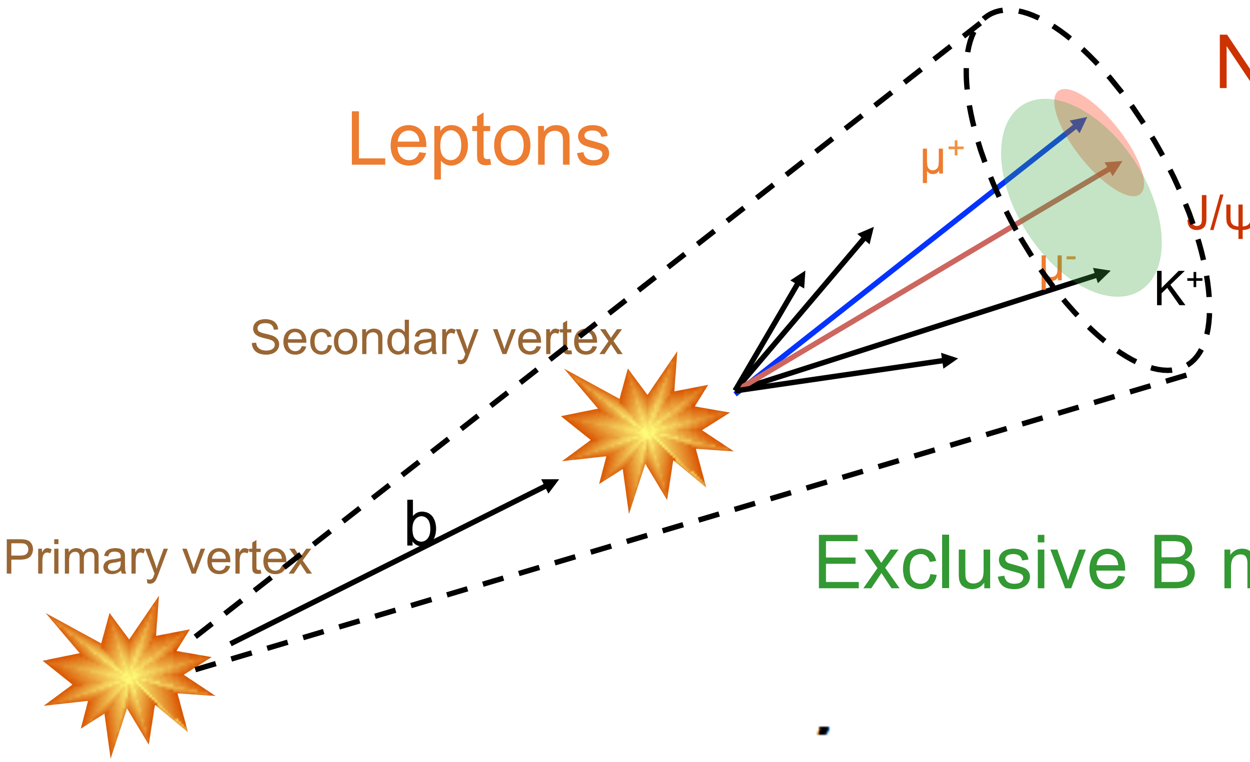
Near future for jet physics

- Z+jet channel

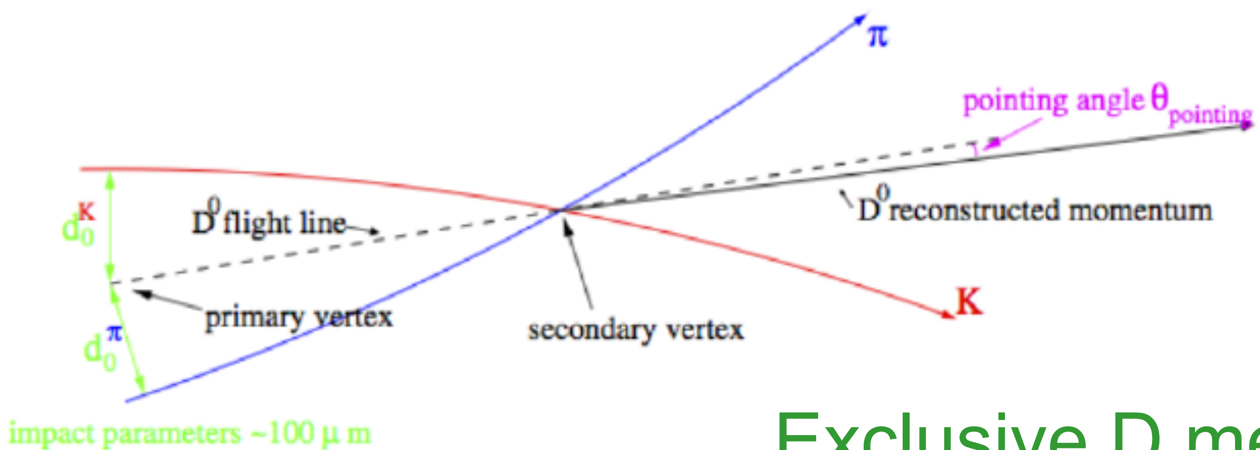


Heavy flavor production experimentally accessible by all four LHC experiments!

Non-prompt J/ψ

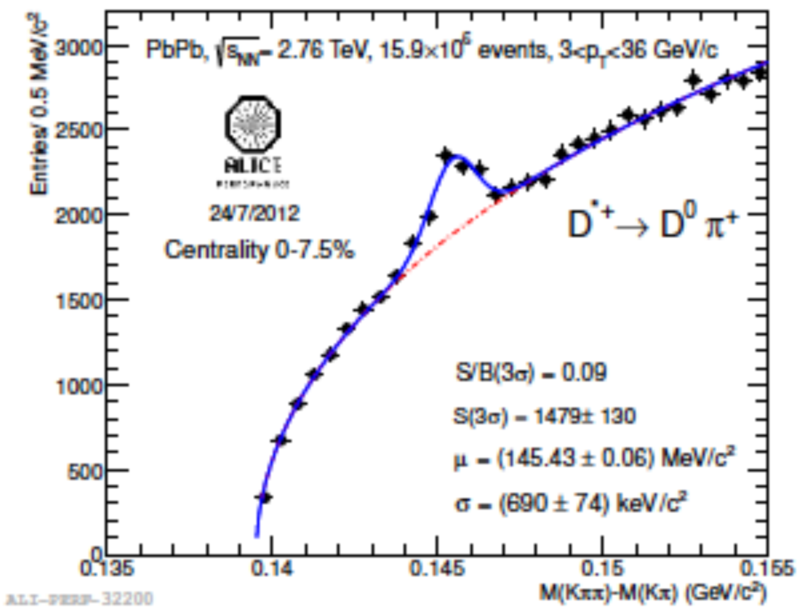


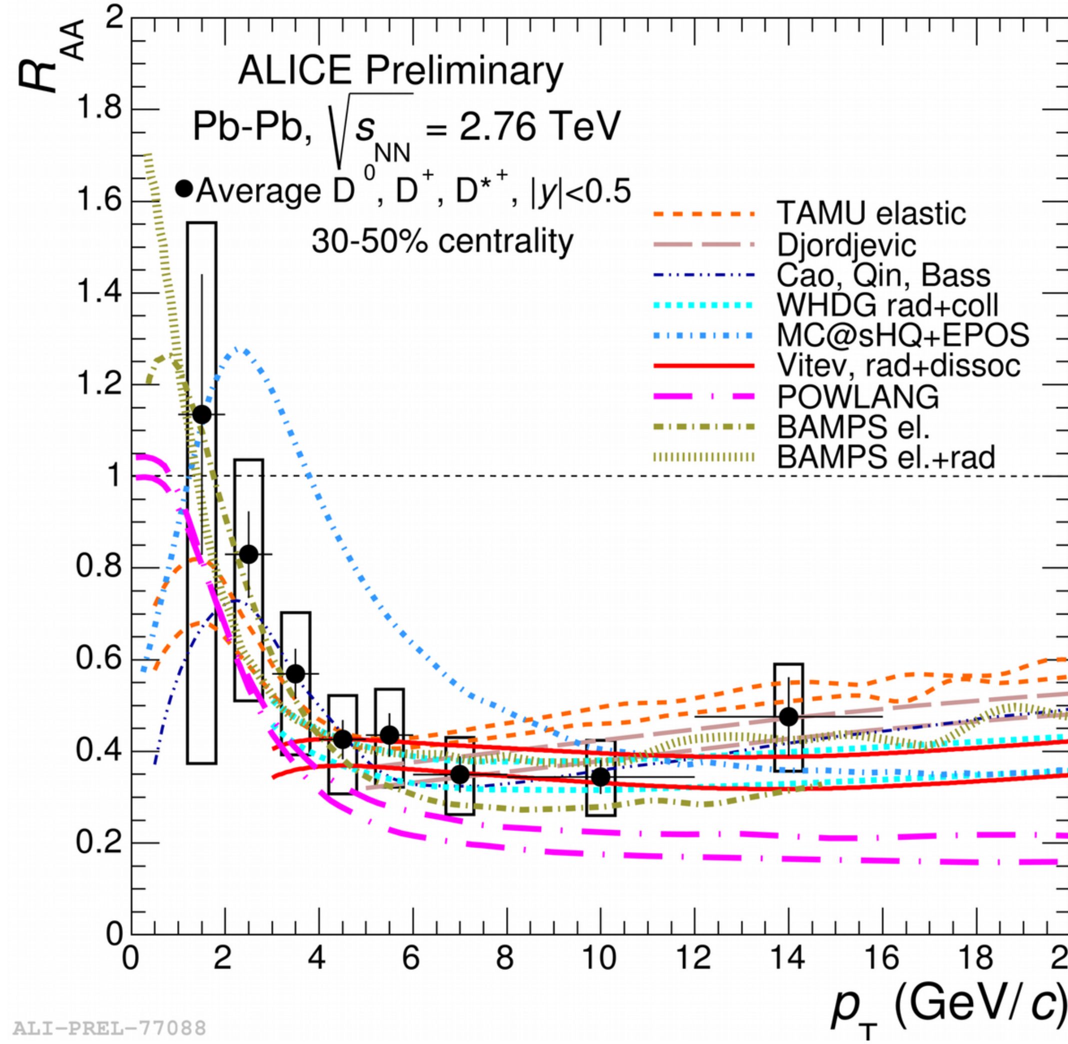
Exclusive B meson decays



Exclusive D meson decays

D meson suppression in PbPb ALICE



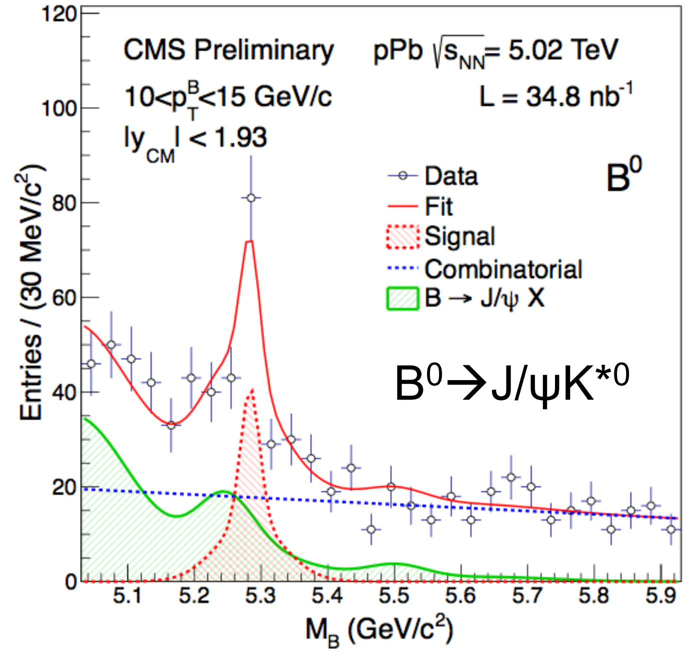


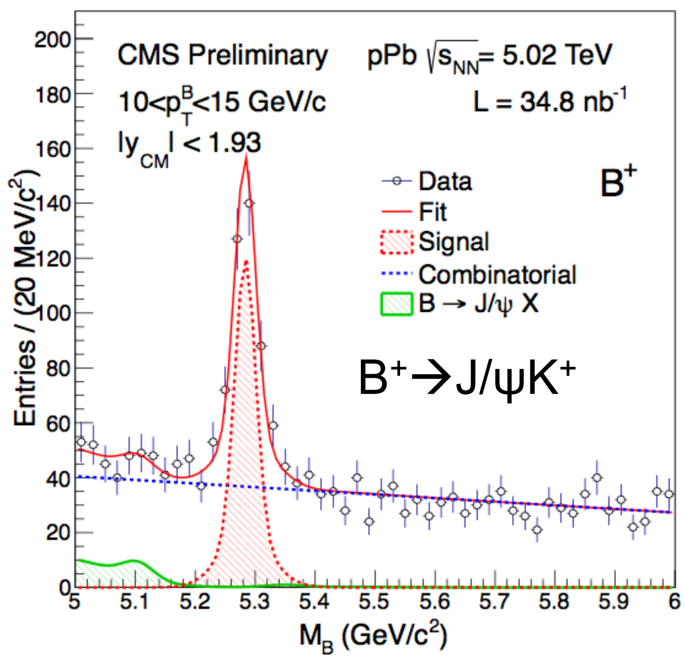
B meson production in pPb

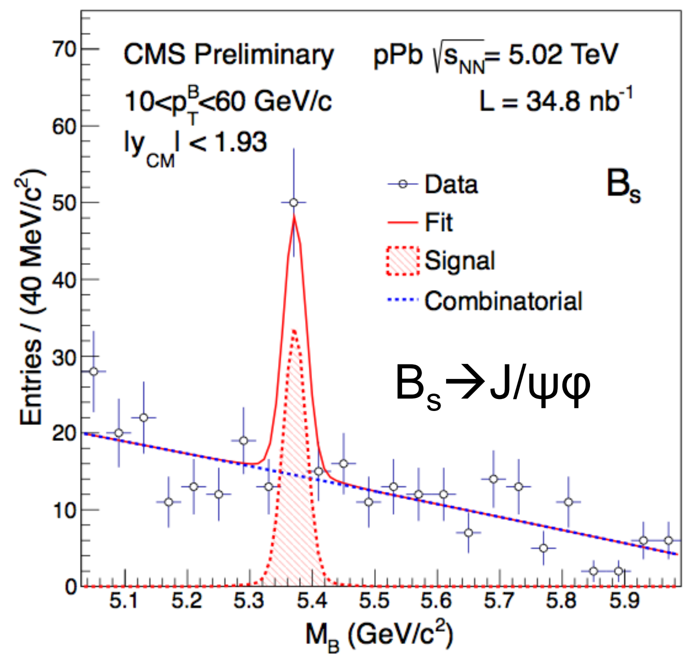
Three component fit for signal extraction:

- Signal
- Combinatorial background from J/ψ-track(s)
- Non-prompt component from other B-meson decays that form peaking structures (e.g. in B^+ analysis, bkg from $B^0 \rightarrow J/\psi\ K^{0*}$)

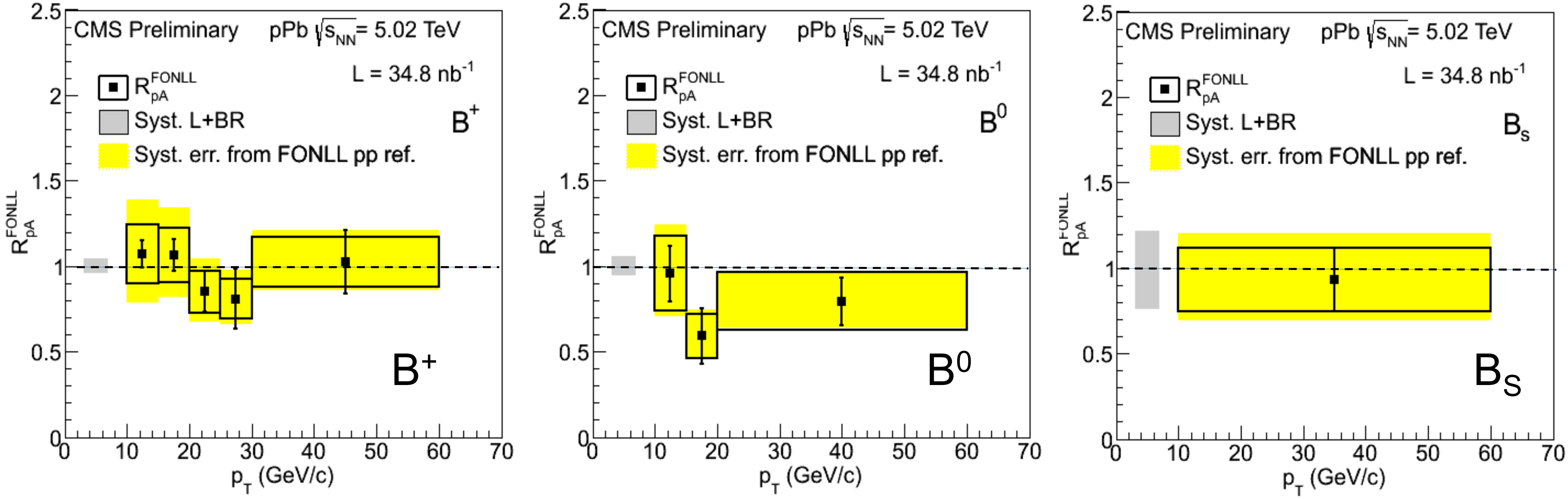
Fully reconstructed B meson signal in nuclear collisions!





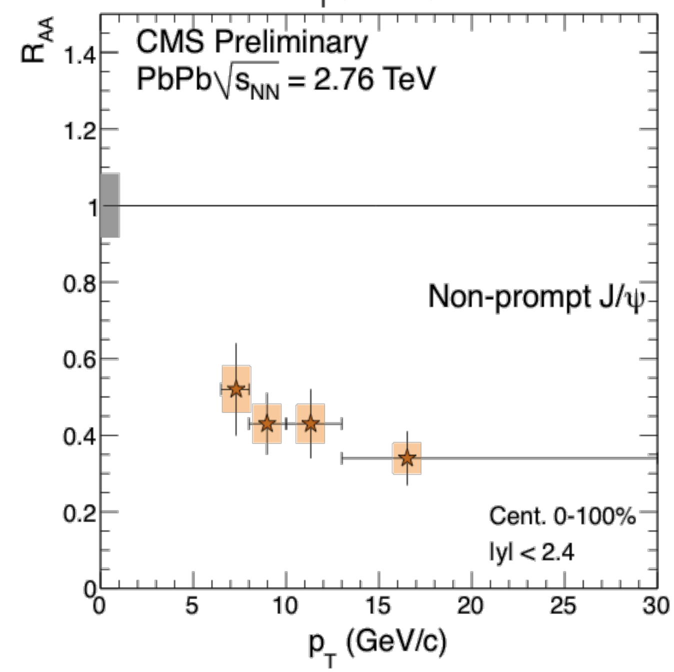


R_{pA} & R_{AA} for B mesons: pA and AA



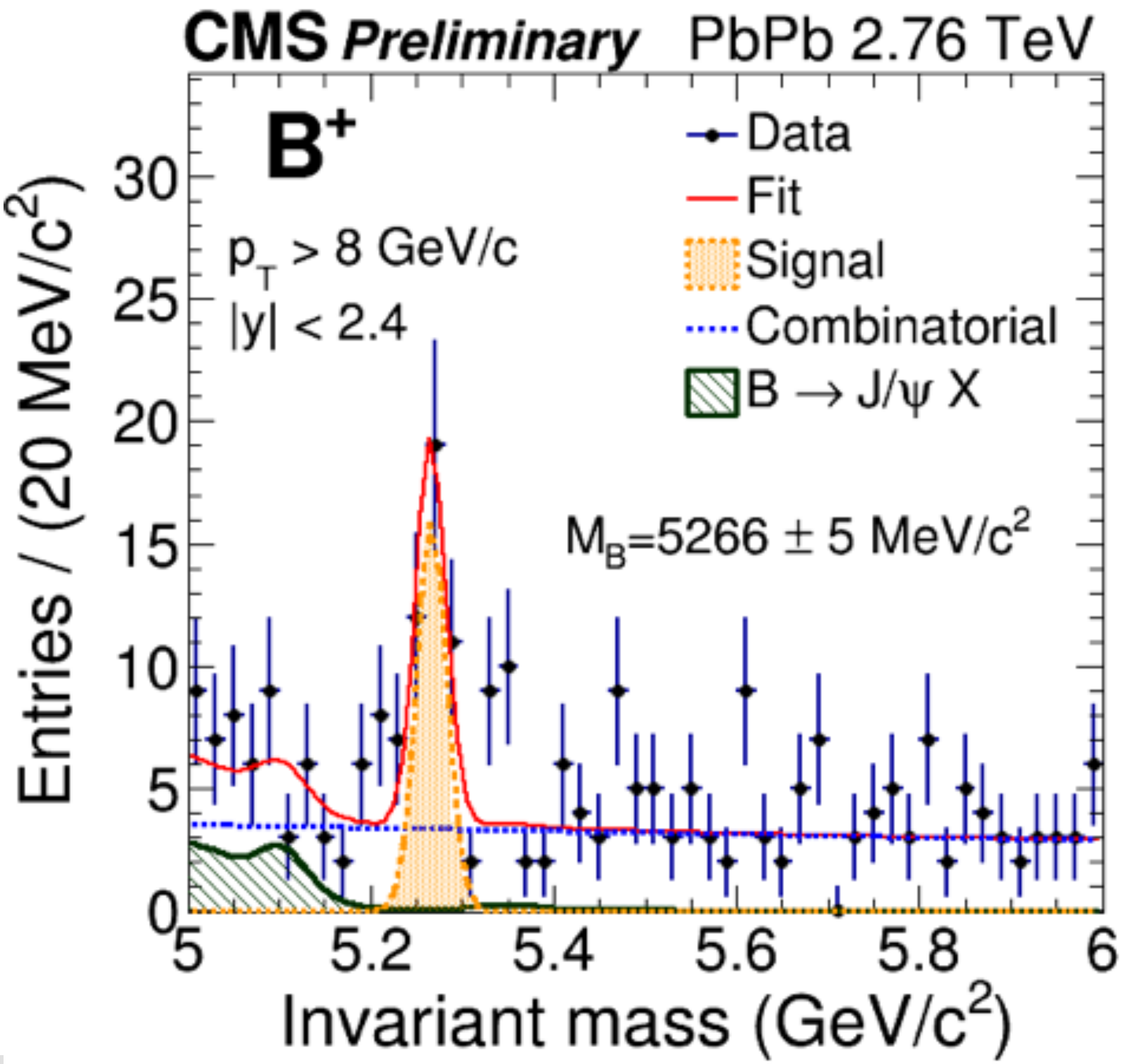
pPb exclusive B decays (p_T(B) > 10 GeV)
($B^+ \to J/\psi\ K^+$, $B^0 \to J/\psi\ K^*$, $B_S \to J/\psi\ \varphi$)
Showing no modification
(large uncertainty, incl. the FONLL ref)

PbPb, inclusive B → J/ψ X ($p_T(\psi)$ > 6.5 GeV)
Showing strong suppression

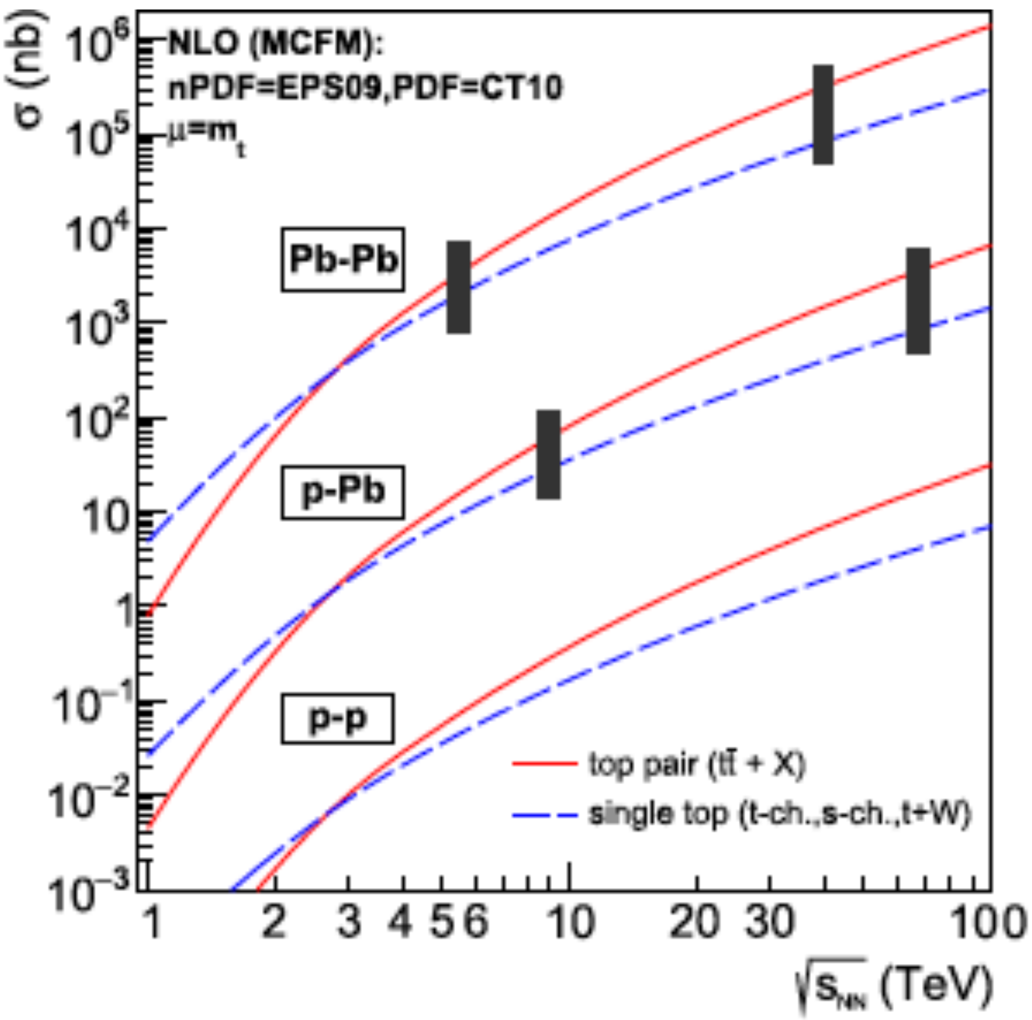


Near term promise

- B-mesons can be reconstructed in PbPb



Interesting new channels for 2015 and beyond



- Top quark production in pPb and PbPb
  - Handle on nPDFs
  - Rates are small but should be measurable

Summary

- LHC experiments collected extensive data in nuclear collisions: PbPb, pPb
- The first discoveries of strong jet quenching, strong flow, quarkonia suppression are now quantified and made more precise
- I have shown examples of measurements that help us understand the behavior of the hot nuclear matter, in particular jet quenching
- There are exciting prospects for the physics with much higher luminosities expected later this year. Heavy flavor and jet physics are examples but there will be many more