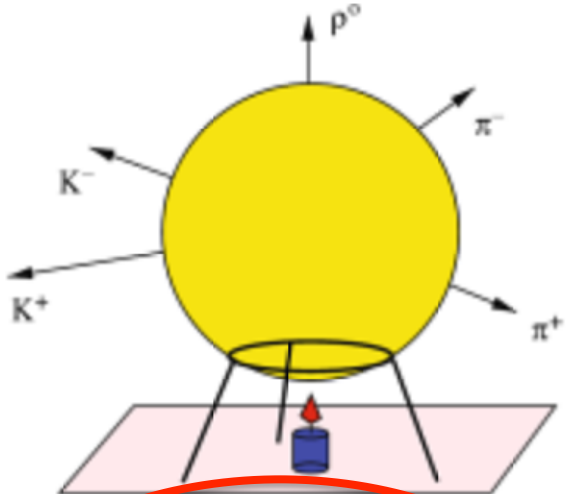
LHC Heavy Ion Physics
Lecture 5: Jets, W, Z, photons

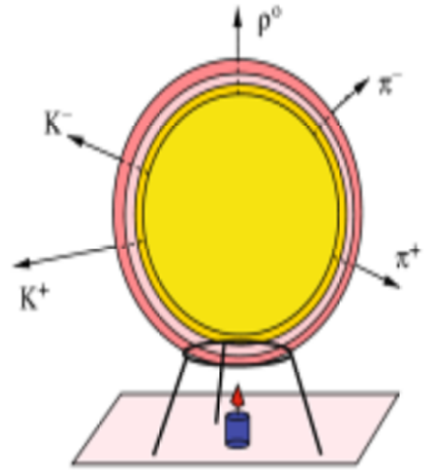
HUGS 2015

Bolek Wyslouch

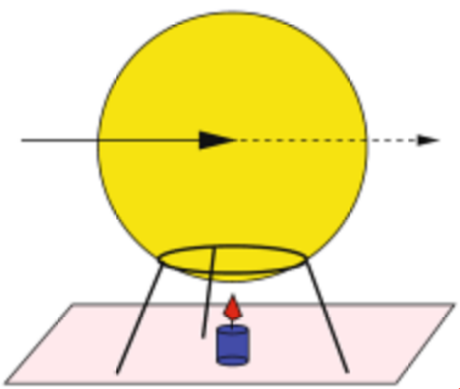
Techniques to study the plasma



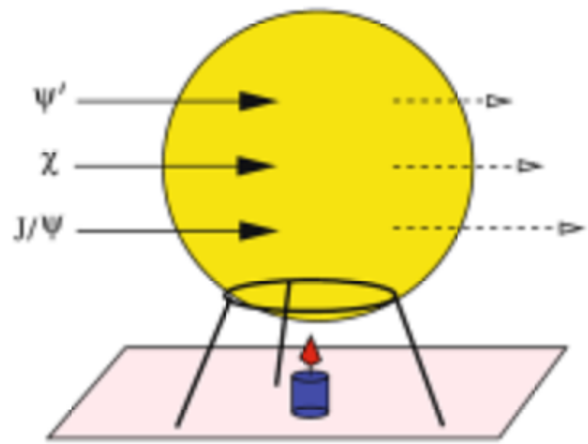
Radiation of hadrons



Azimuthal asymmetry and radial expansion



Energy loss by quarks, gluons and other particles

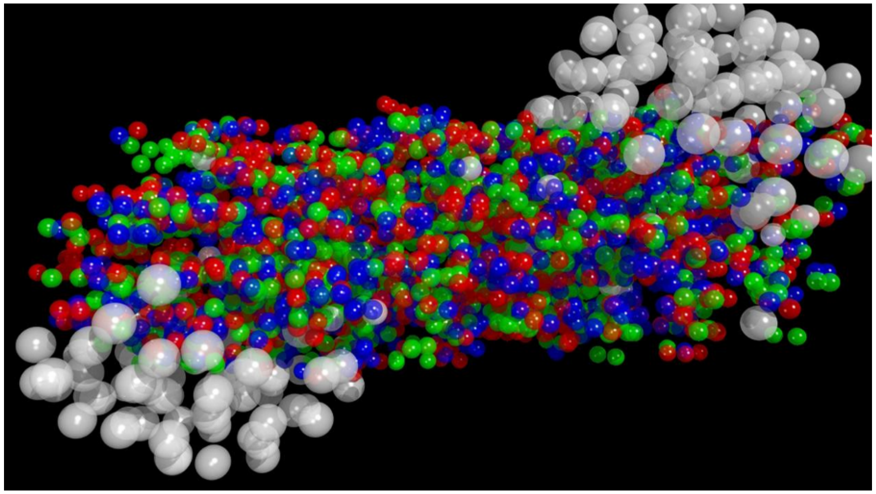


Suppression of quarkonia

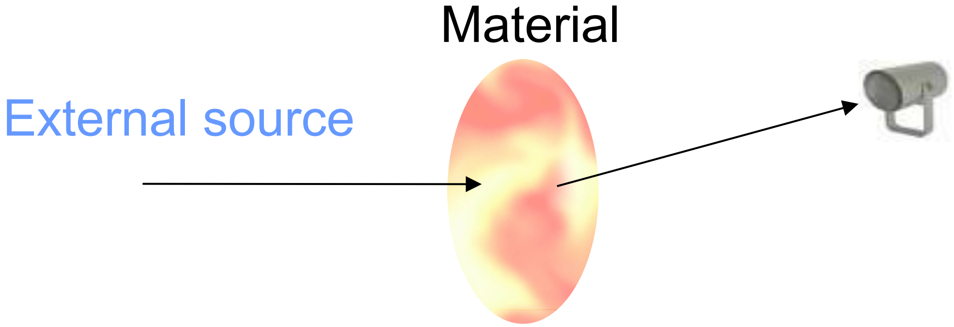
Energy loss by quarks, gluons and other particles

- Equivalent of x-ray of the plasma, the loss of energy can tell us about the density, composition and the microscopic structure of the plasma
- We use probes created during the elementary collisions between the initial quarks and gluons
  - Large transverse momentum quarks or gluons appearing as jets
  - Particles that do not interact strongly can be used as a reference: Z, W, photon

Probe the medium



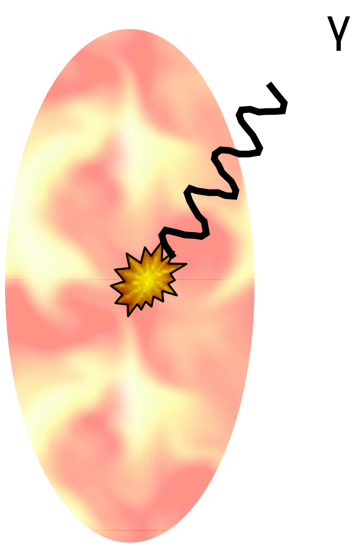
- Goal:
  Understand the property of QGP
- Problem: the lifetime of QGP is so short (O(fm/c)) such that it is not feasible to probe it with an external source.
- Solution: Take the advantage of the large cross-sections of high p_T jets, γ/W/Z, quarkonia at the LHC energy, use hard probes produced with the collision.



Three types of hard probes

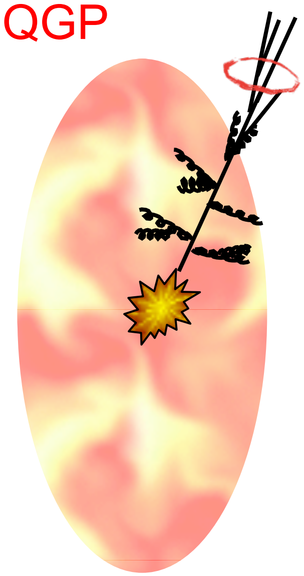
Electroweak probes	Quarks and gluons	Quarkonium
W/Z bosons, high p_T γ	Jets	J/ψ, Υ family

QGP



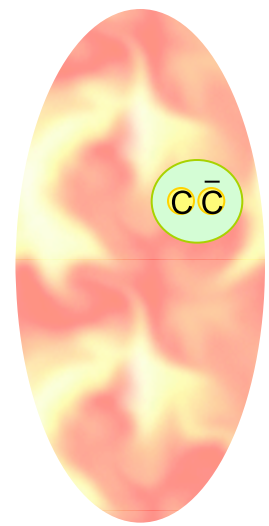
Probe the initial state

QGP



Probe the opacity of QGP

QGP



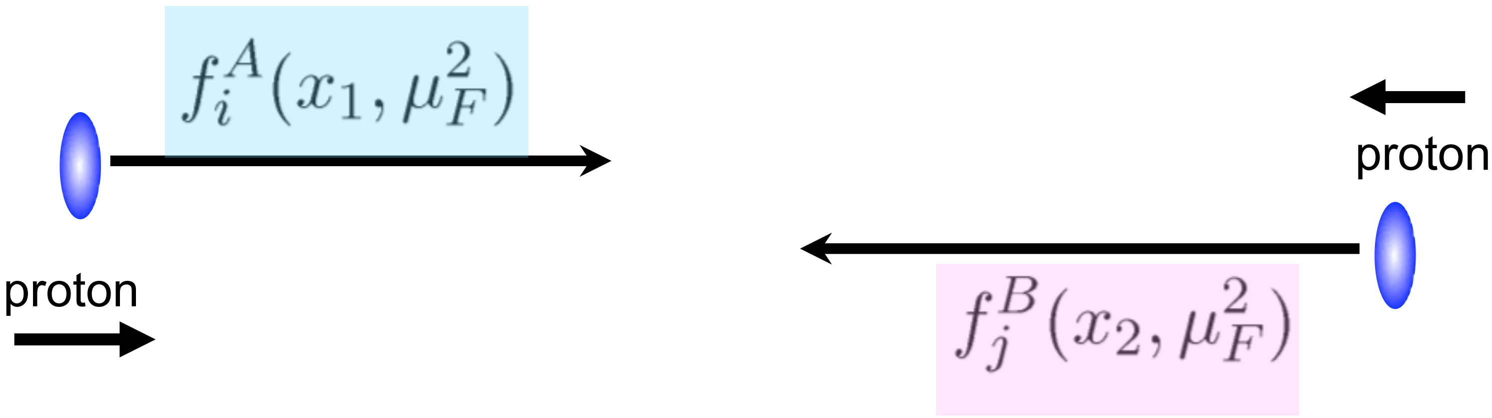
Sensitive to
the temperature of QGP

Factorization

Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

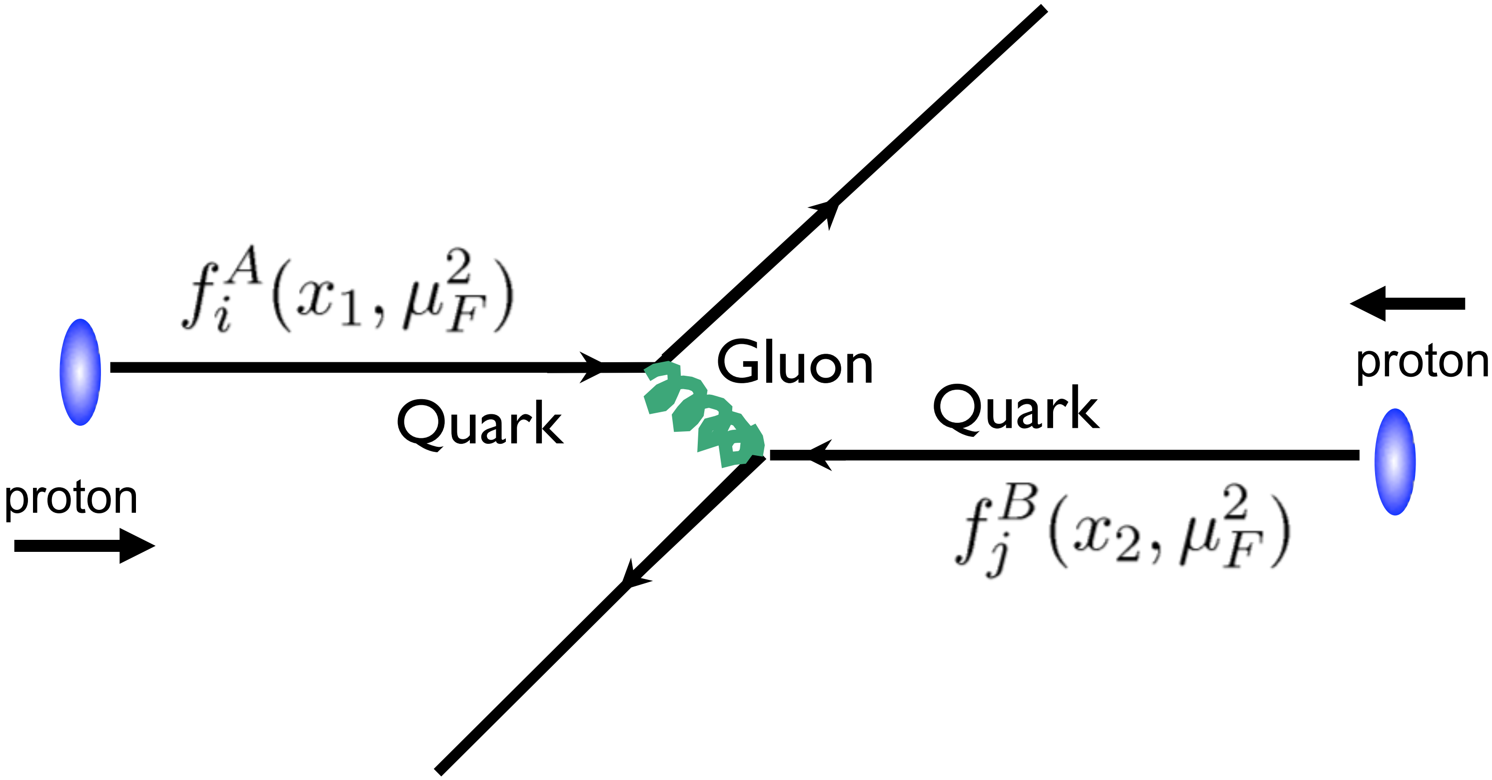
Parton Distribution Function (PDF)



Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

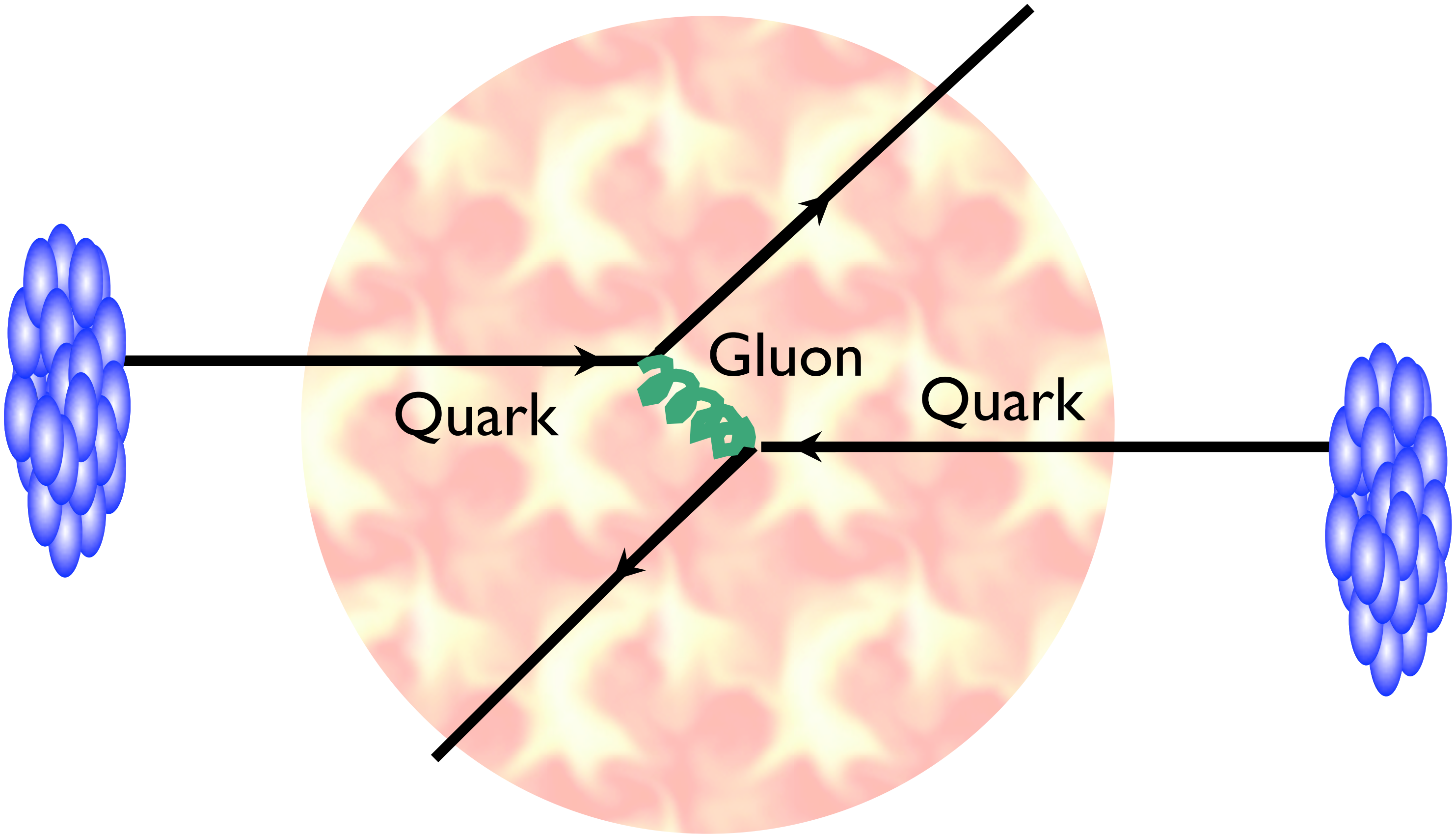
Parton Distribution Function (PDF)   Cross-section of 2→2 process



Factorization

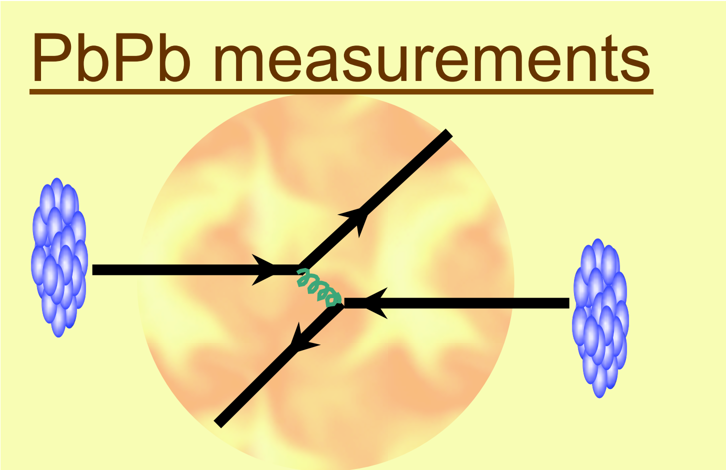
$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

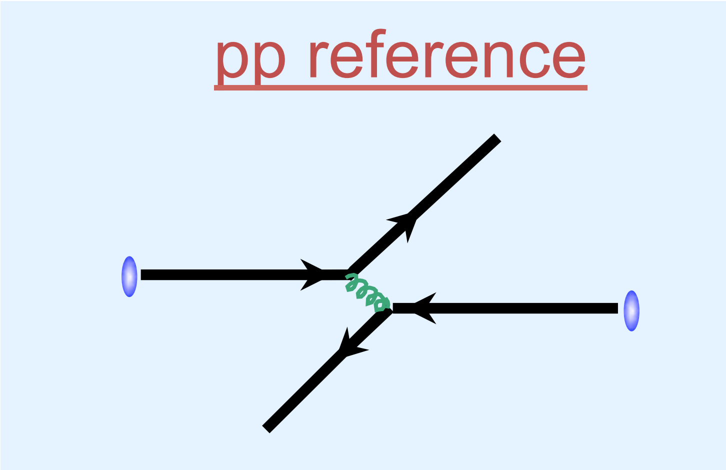
Nuclear Parton Distribution Function (nPDF)   Cross-section of 2→2 process



How do we extract the medium effect in PbPb collisions?

One typical way is to compare PbPb data to pp reference measurement





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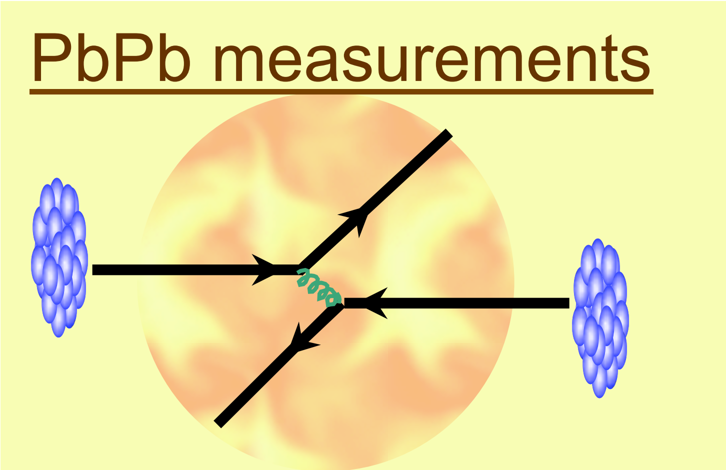
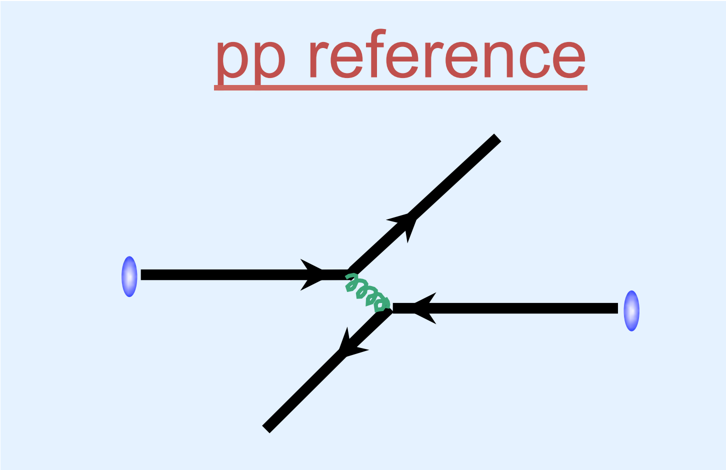
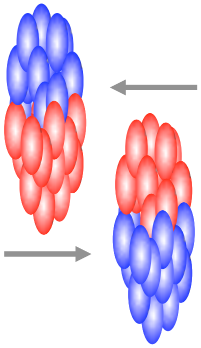
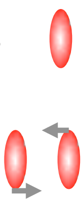




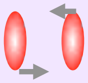


N_{part} → Number of participating nucleons

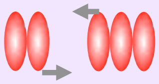
N_{coll} → Number of binary scatterings



Example:



$N_{part} = 2$ $N_{coll} = 1$



$N_{part} = 5$ $N_{coll} = 6$

How do we extract the medium effect in PbPb collisions?

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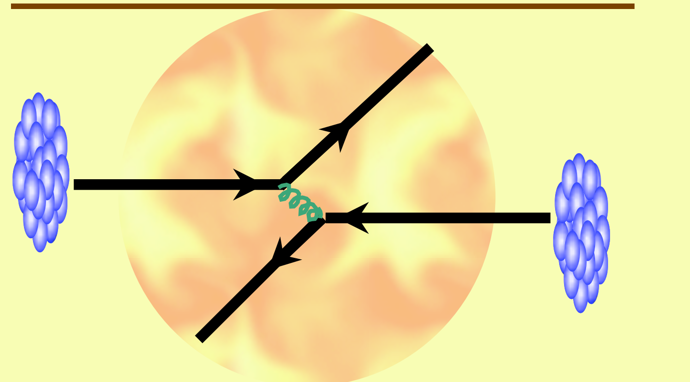
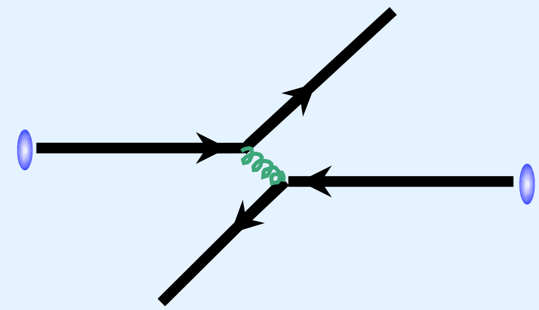
PbPb measurements



pp reference



'Nuclear modification factors'

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

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

N_{coll} → Averaged number of binary scattering

Can also be written as $1/T_{AA}$

$$T_{AA} = \frac{N_{coll}}{\sigma_{pp}^{inel}}$$

"NN equivalent integrated luminosity per AA collision"

Reduces the uncertainty from pp inclusive cross-section

How do we extract the medium effect in PbPb collisions?

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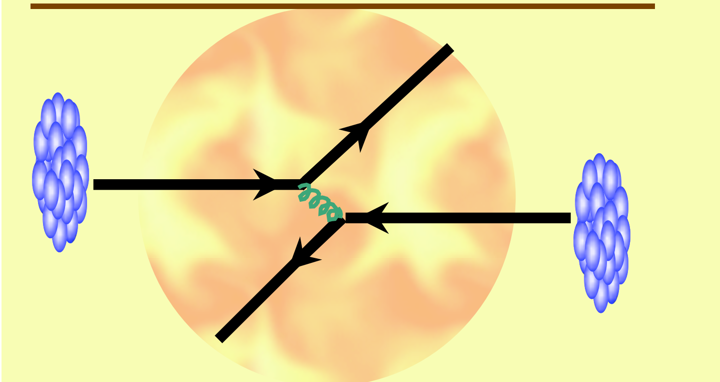
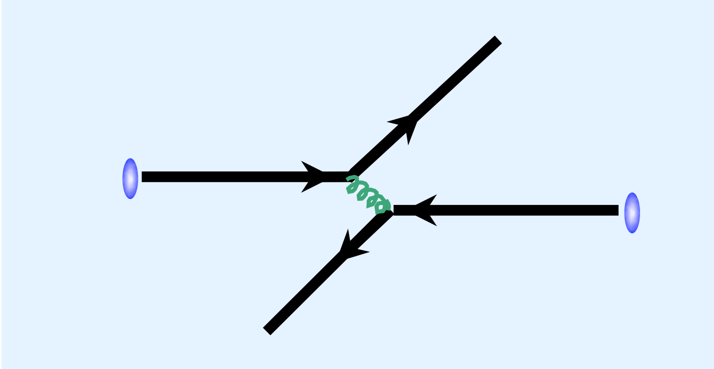
PbPb measurements



pp reference



'Nuclear modification factors'

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N_{coll} → Averaged number of binary scattering

Questions: How do we know the Glauber model calculation of N_{coll} is correct?

Is the nuclear PDF modified with respect to nucleon PDF?

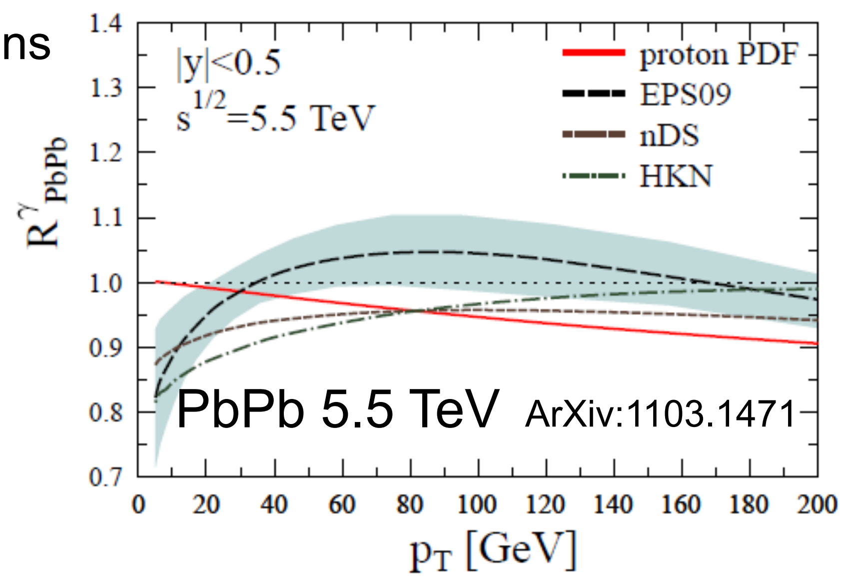
→ Motivates the studies of electroweak probes

Electroweak probes

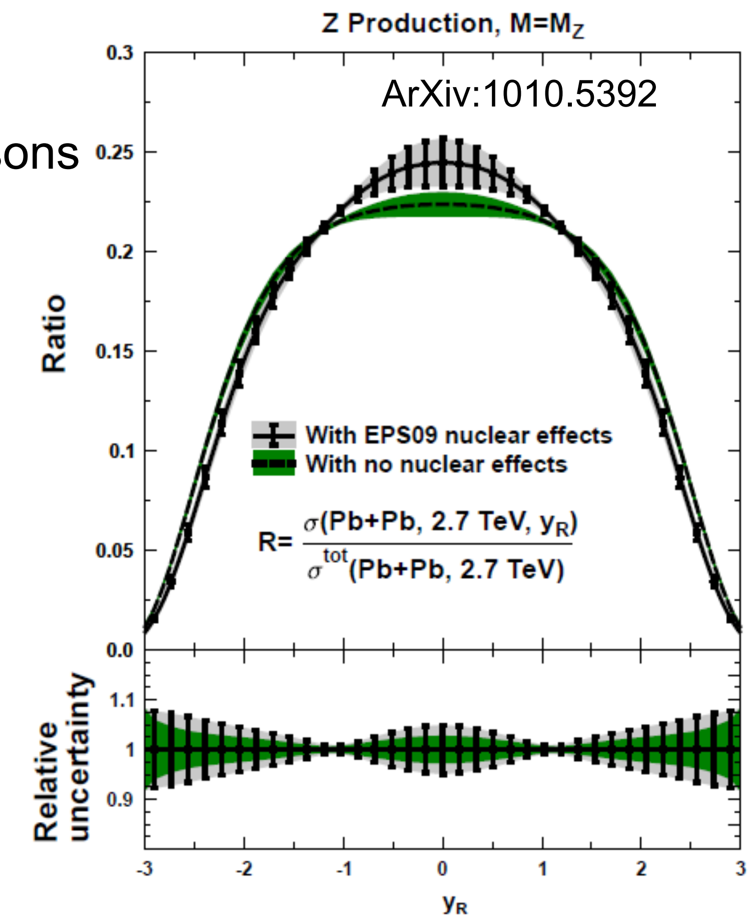
- High p_T Photons, W and Z bosons:

  - Colorless → Not affected by the QGP
  - Good theoretical control
  - Check the validity of N_{coll} calculation (ex. from Glauber Model) nucl-ex/0701025v1
  - Constraint the nuclear parton distribution function (nPDF)

Photons



Z bosons



Photons

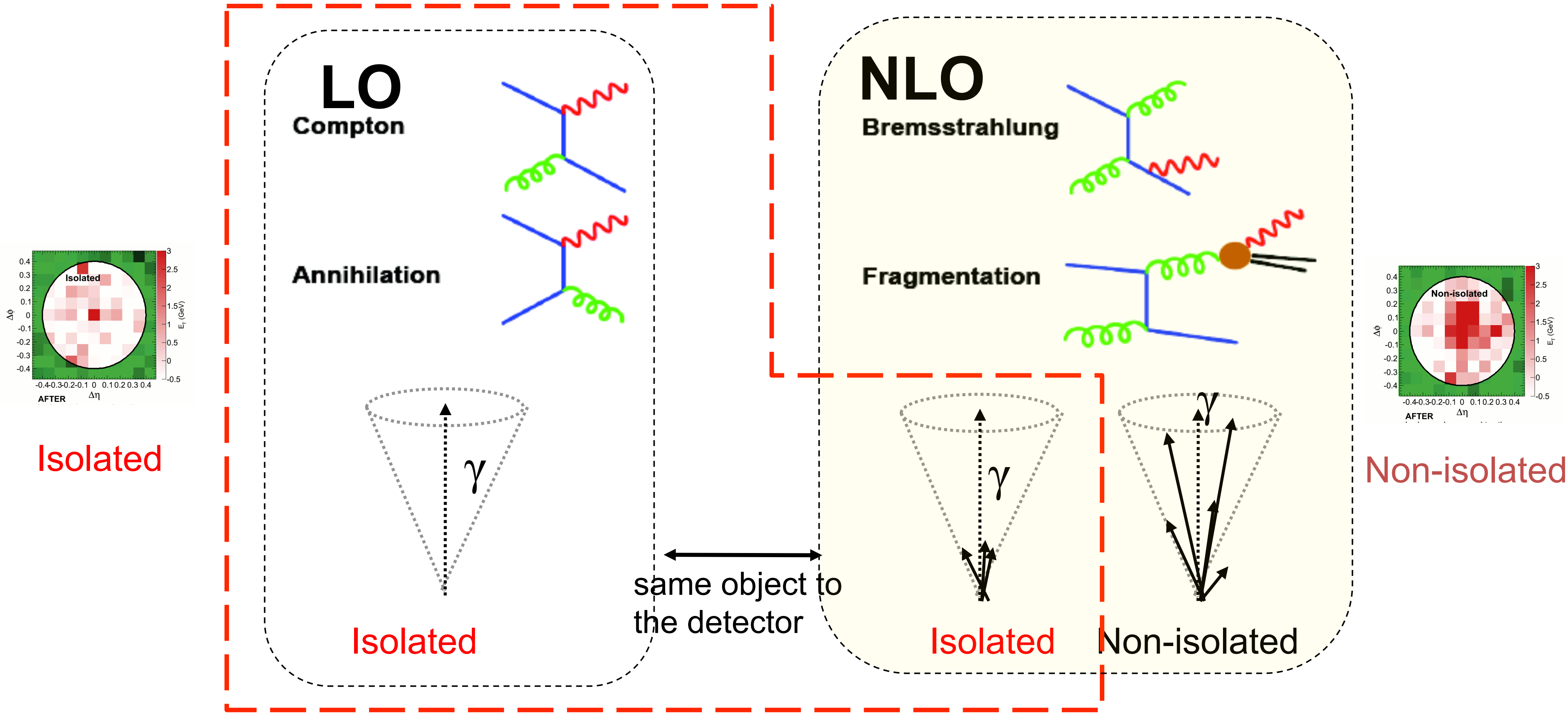
- Ideally: LO photons from hard scattering

- Real world:
  huge background from the decay and fragmentation photons

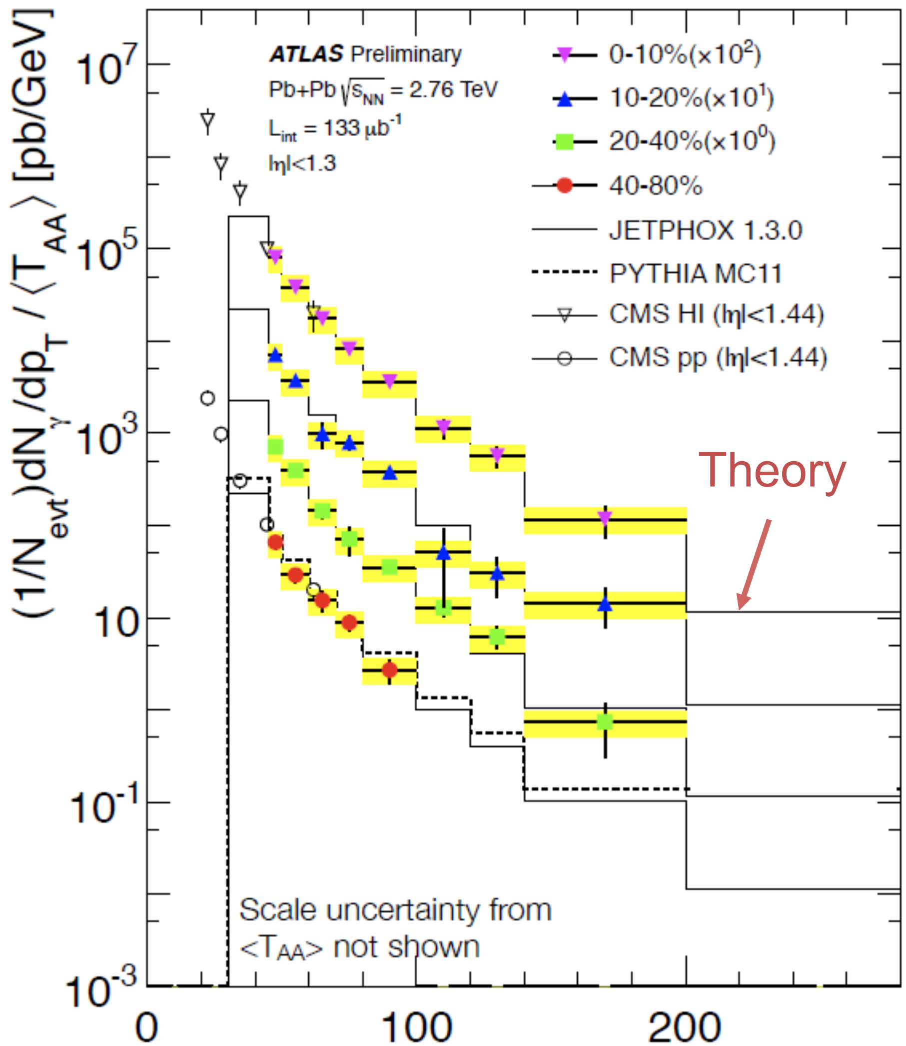
- Need a consistent definition between measurements and theoretical calculations

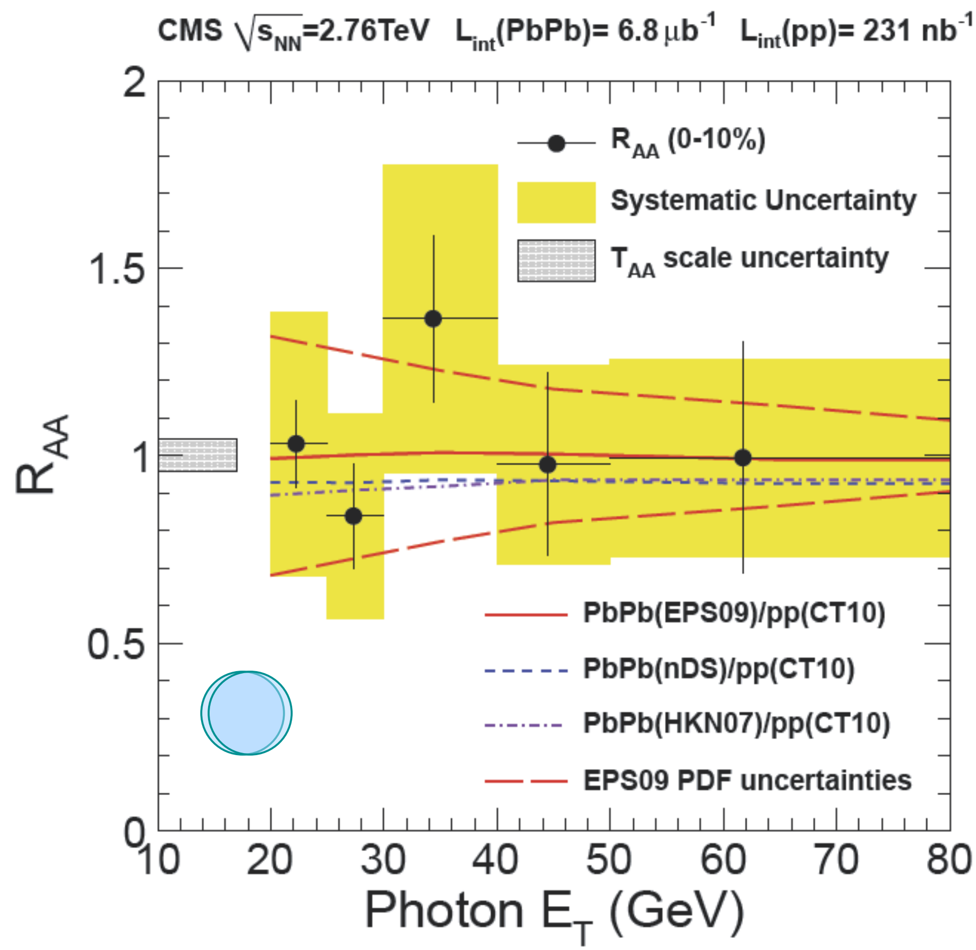
Isolated high p_T photons

- Solution: measurement of the isolated photons
- Decay photons from hadrons in jets such as π^0, $\eta \rightarrow \gamma\ \gamma$ are largely suppressed
- UE subtracted isolation variables are developed



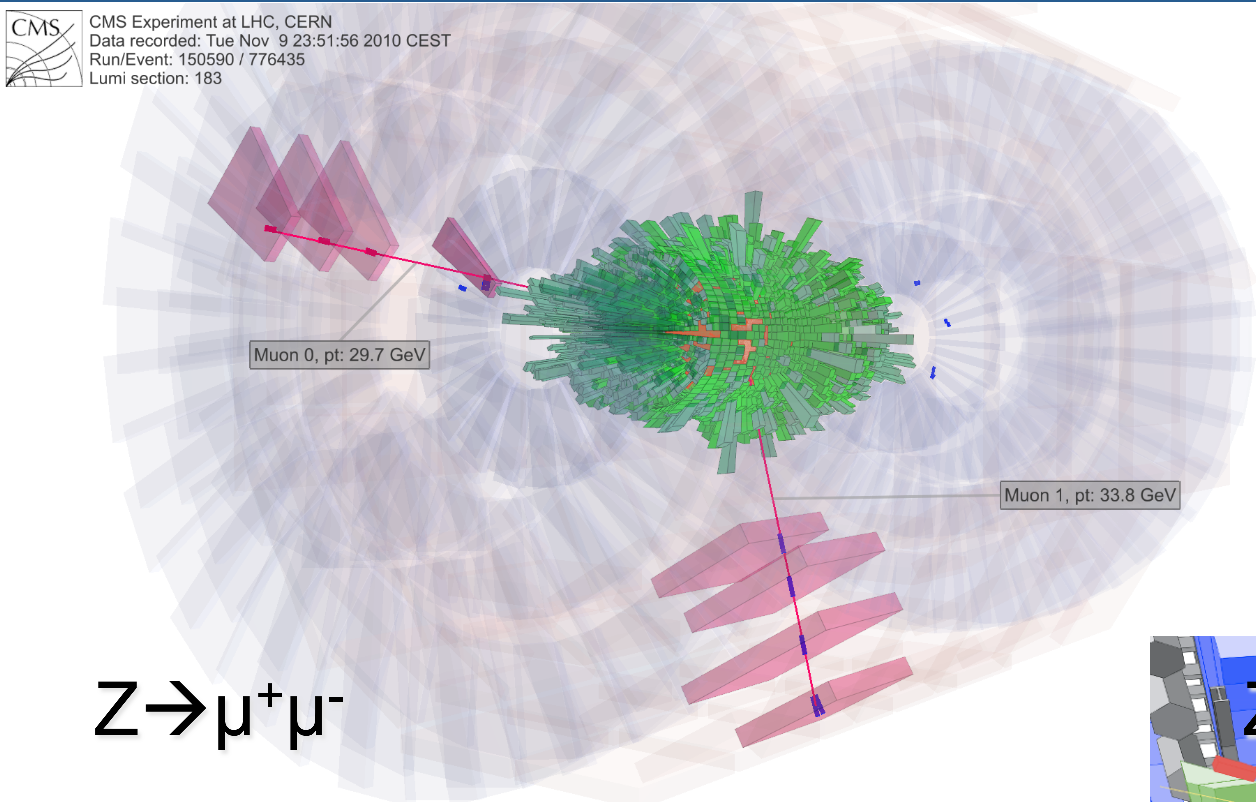
Isolated photon R_{AA}

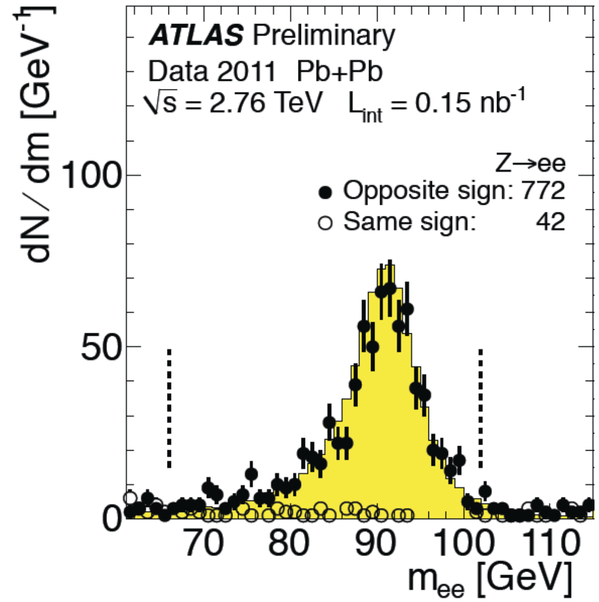




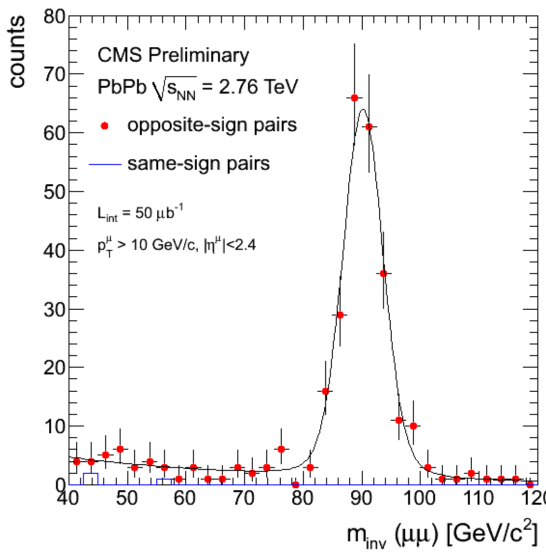
- No modification of the photons as expected!

Z boson production in PbPb collisions

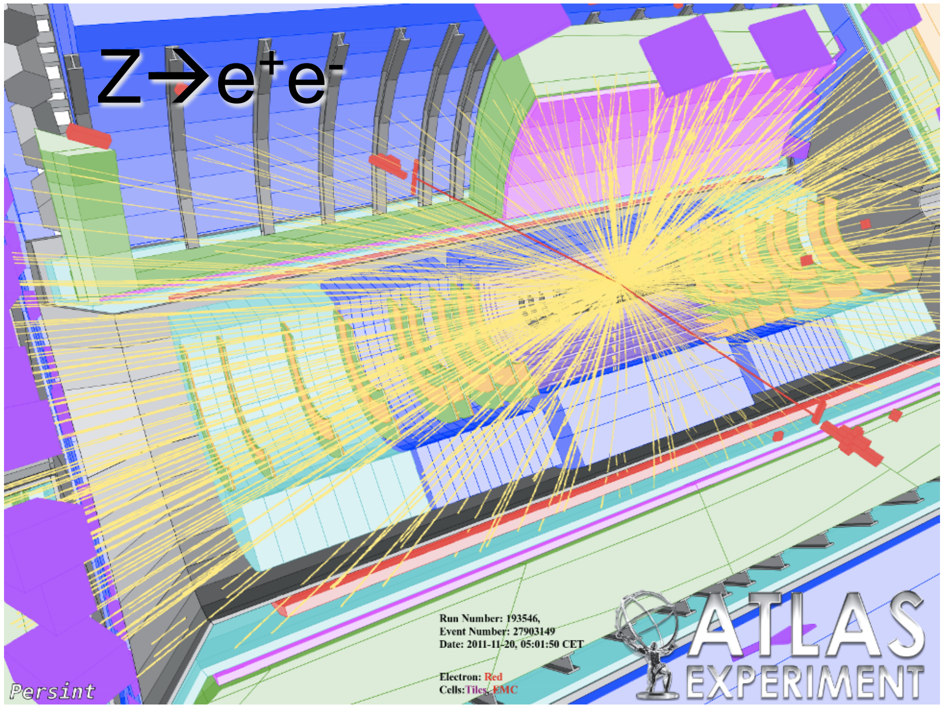




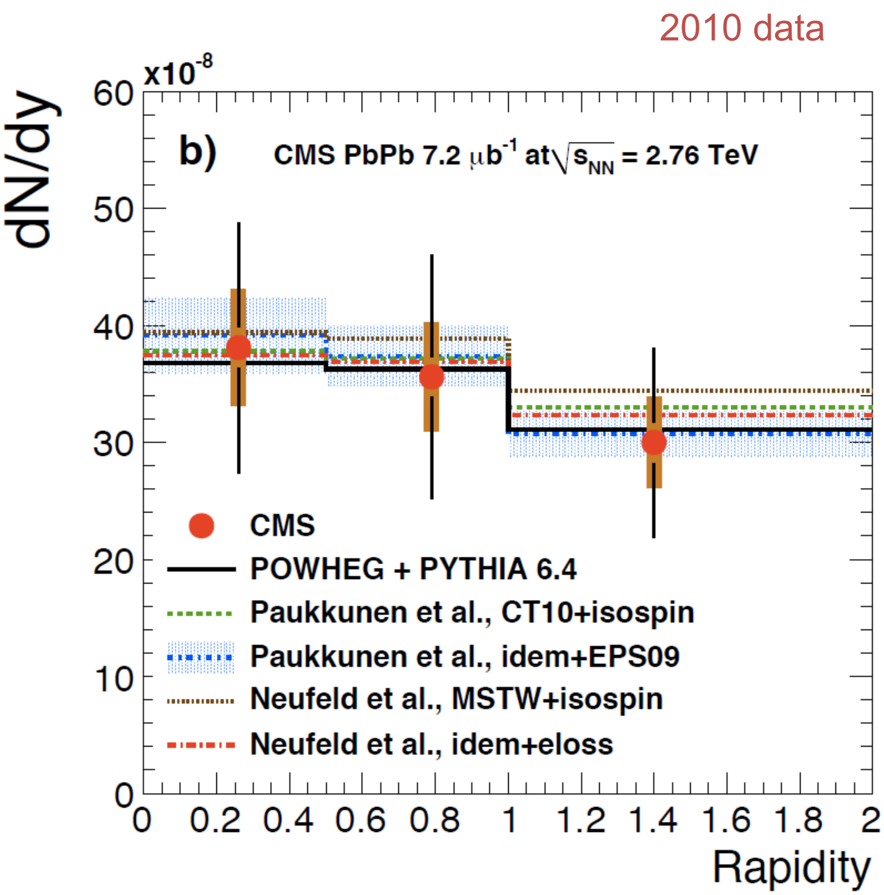
$Z \rightarrow \mu^+\mu^-$

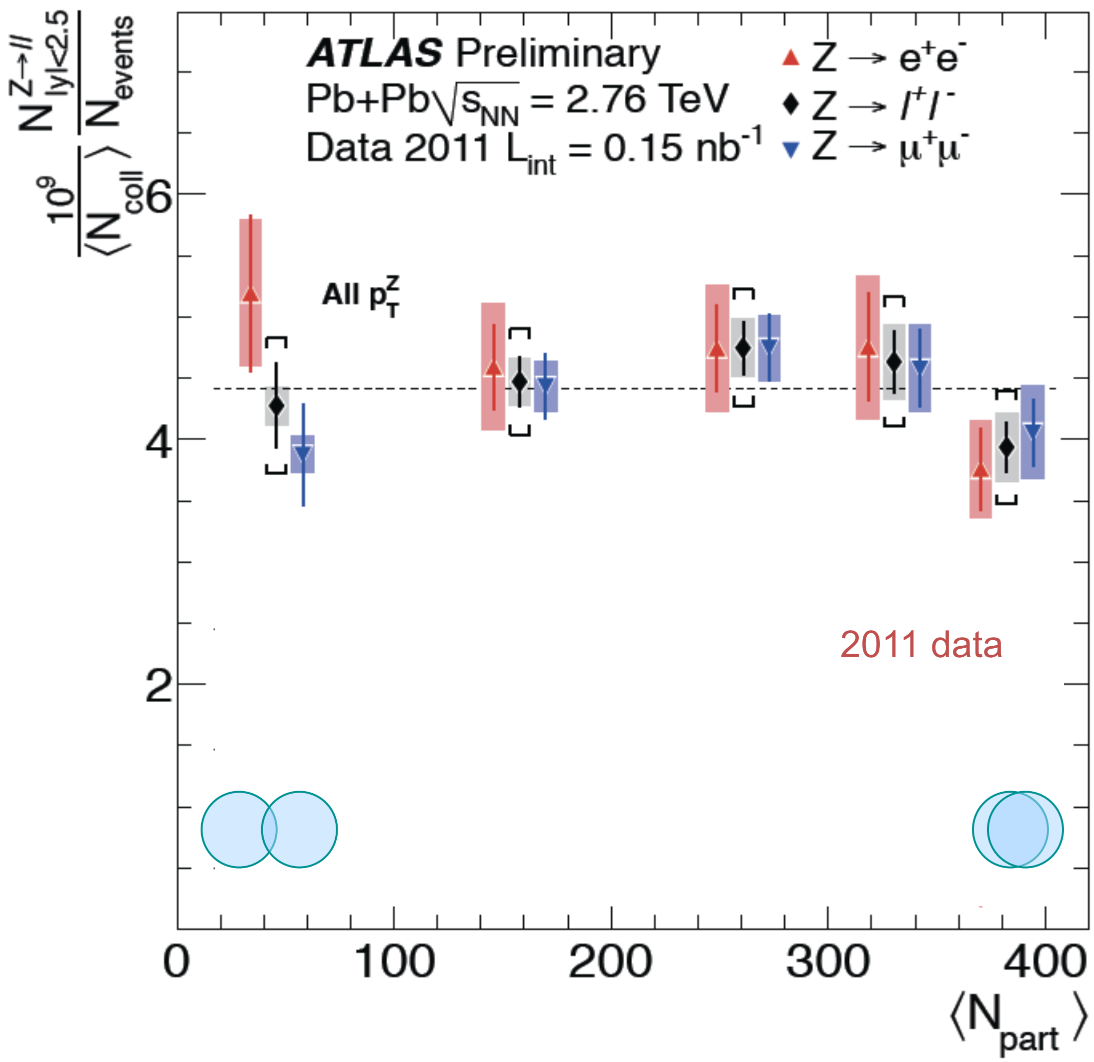


$Z \rightarrow e^+e^-$



Z boson production in PbPb collisions

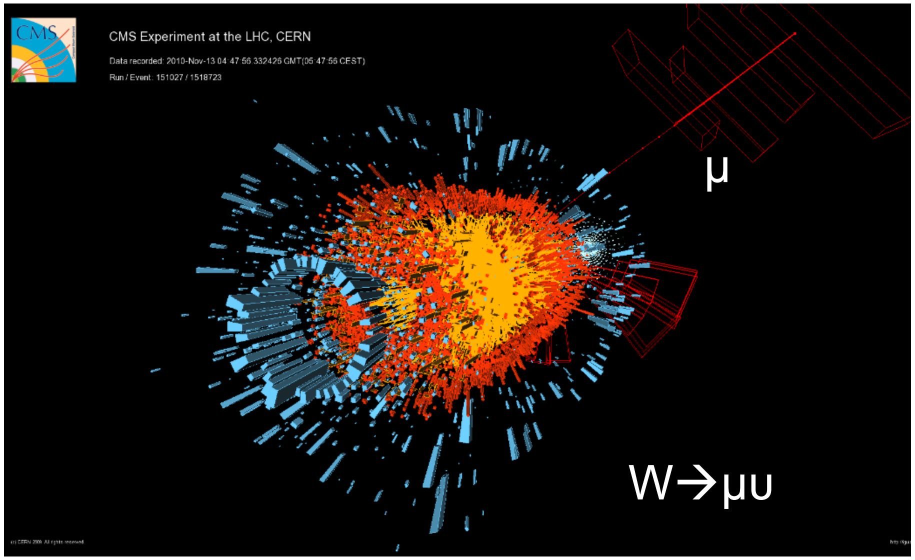




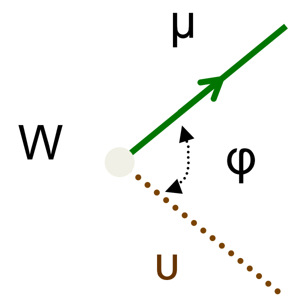
- No modification is found with respect to the pp reference

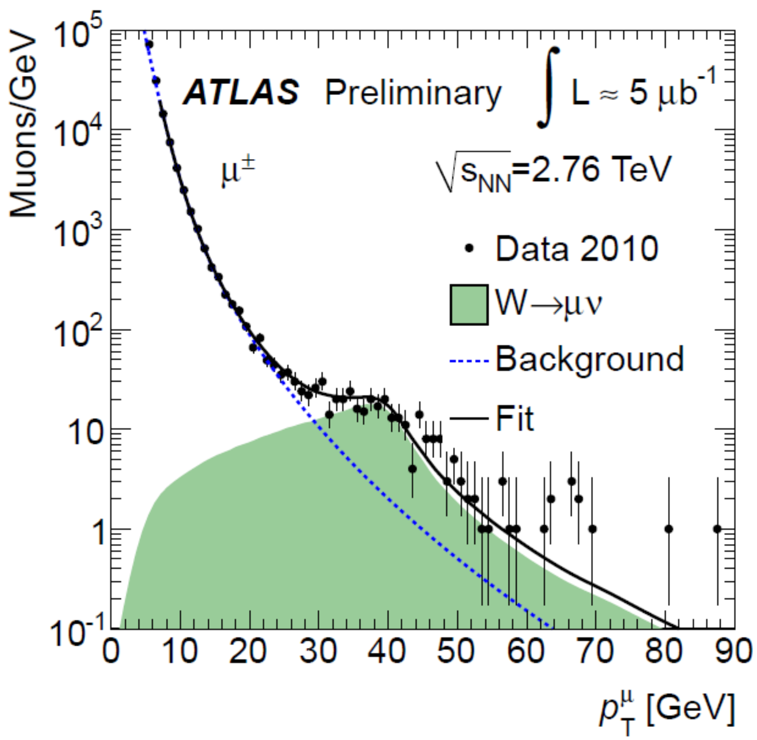
- Normalized yield is not varying as a function of centrality

W boson

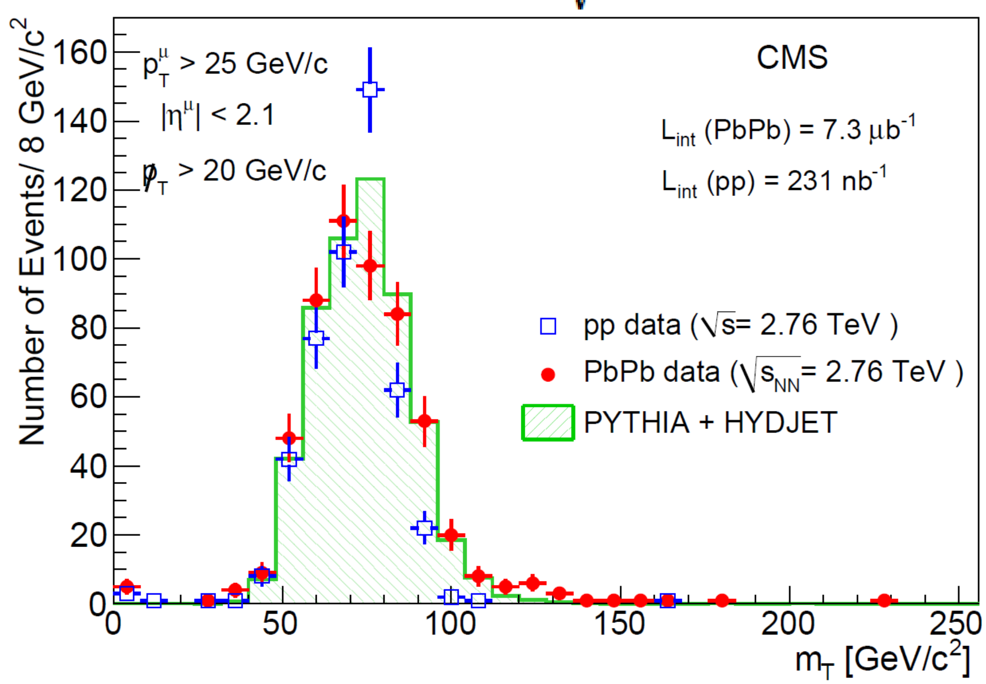


W→μυ   Single high p_T μ + Missing p_T



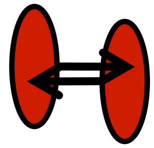


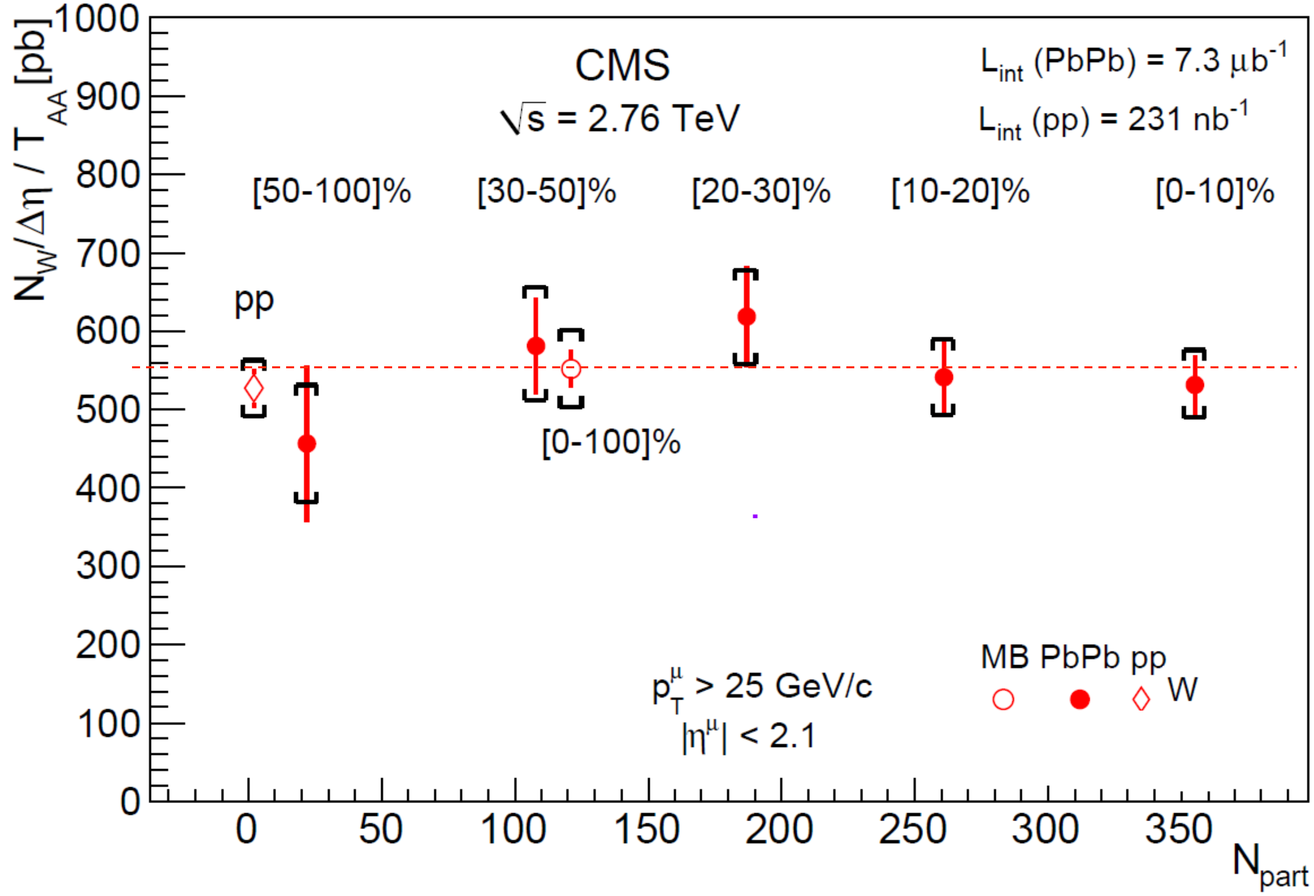
Transverse mass $m_T = \sqrt{2 p_T^\mu \not{p}_T (1 - \cos\phi)}$

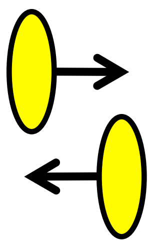


W boson R_{AA}

$R_{AA}(W) = 1.04 \pm 0.07 \pm 0.12$







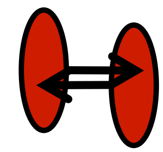
- Normalized yield is not varying as a function of centrality

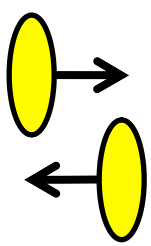
W boson R_{AA}

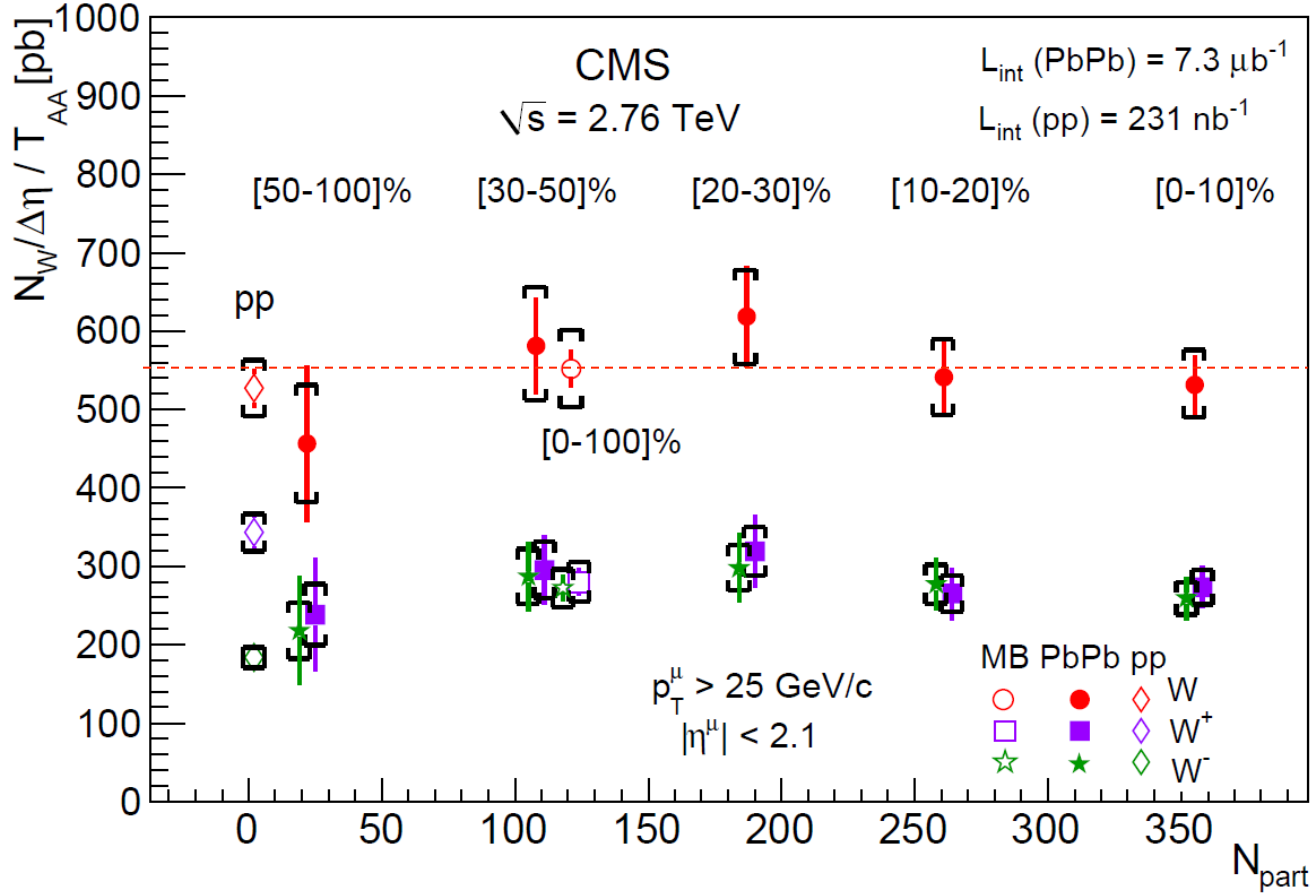
$R_{AA}(W) = 1.04 \pm 0.07 \pm 0.12$

$R_{AA}(W^{+}) = 0.82 \pm 0.07 \pm 0.09$

$R_{AA}(W^{-}) = 1.46 \pm 0.14 \pm 0.16$



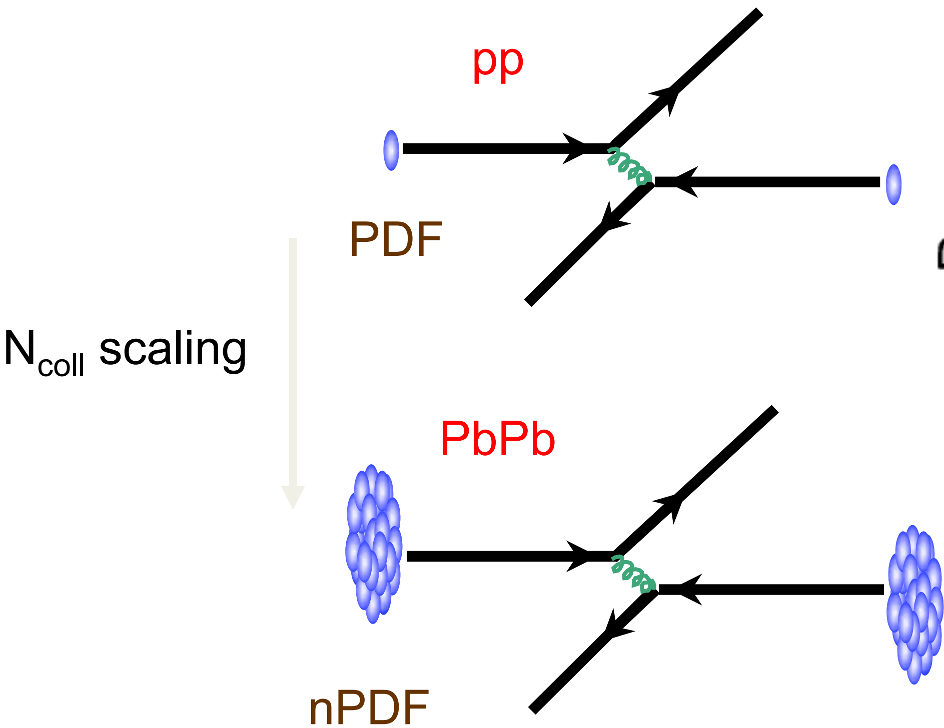


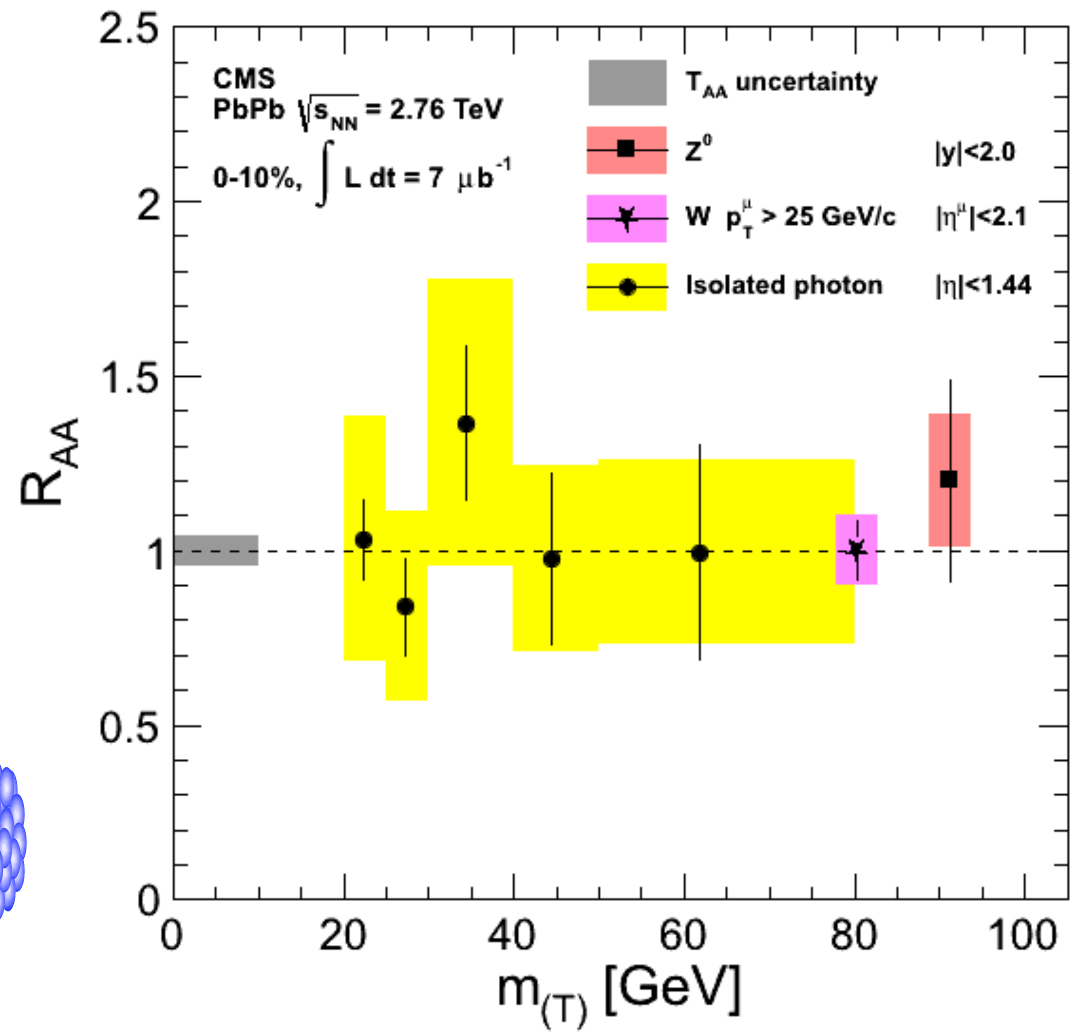


- Isospin effect is seen if we differentiate W^{+} and W^{-}

Summary of electroweak probes

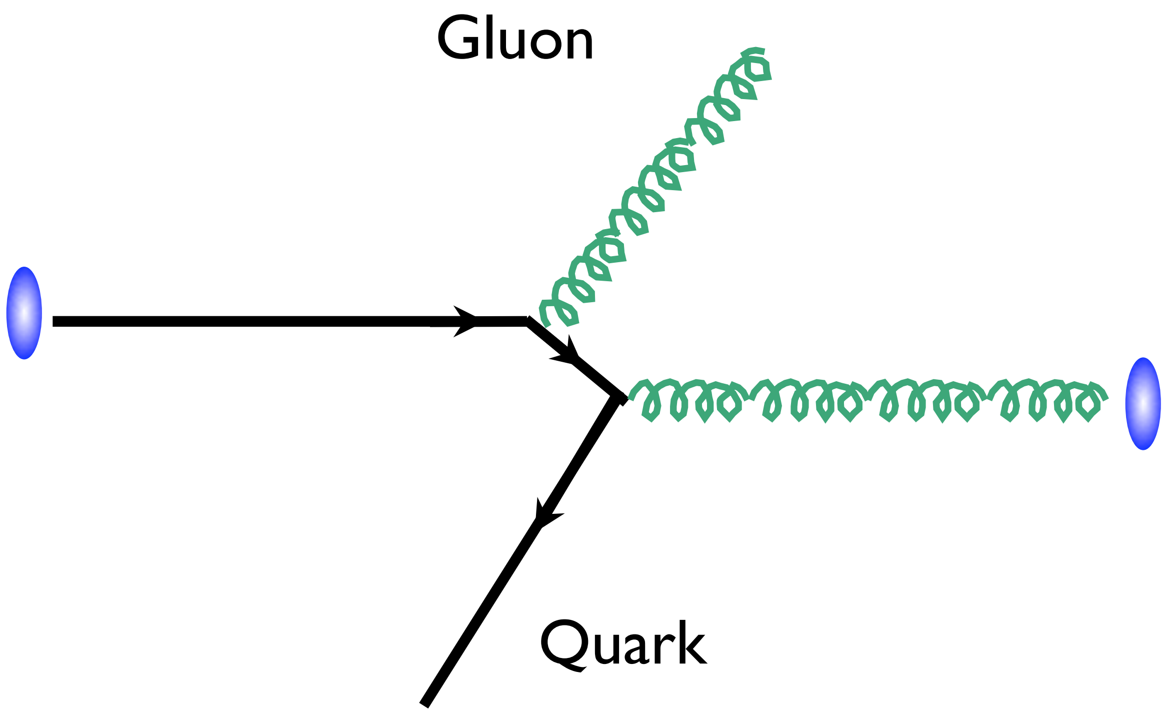
- Electroweak probes are unmodified
- Confirmed N_{coll} scaling of hard scattering
- Constraint nuclear Parton Distribution Function





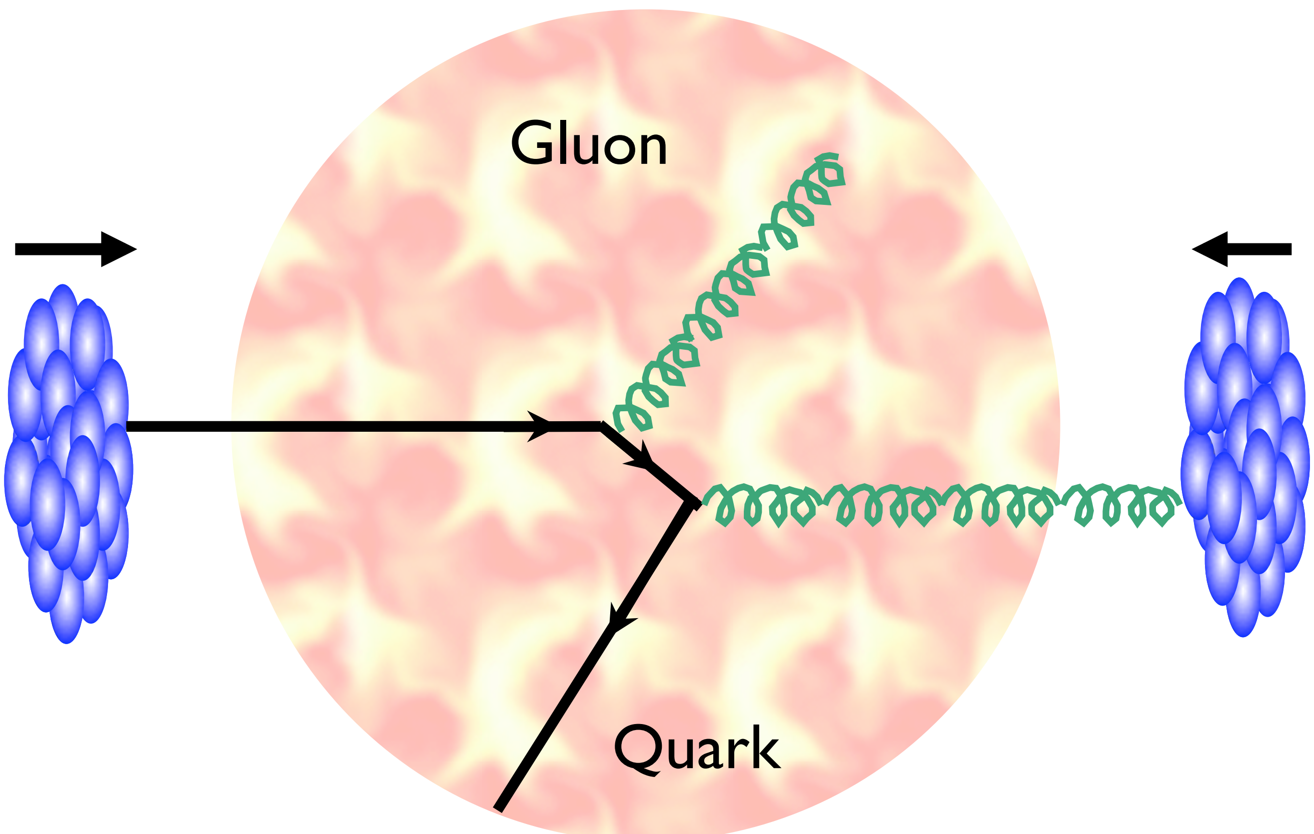
How about quarks and gluons?

- Quarks and gluons in pp collisions

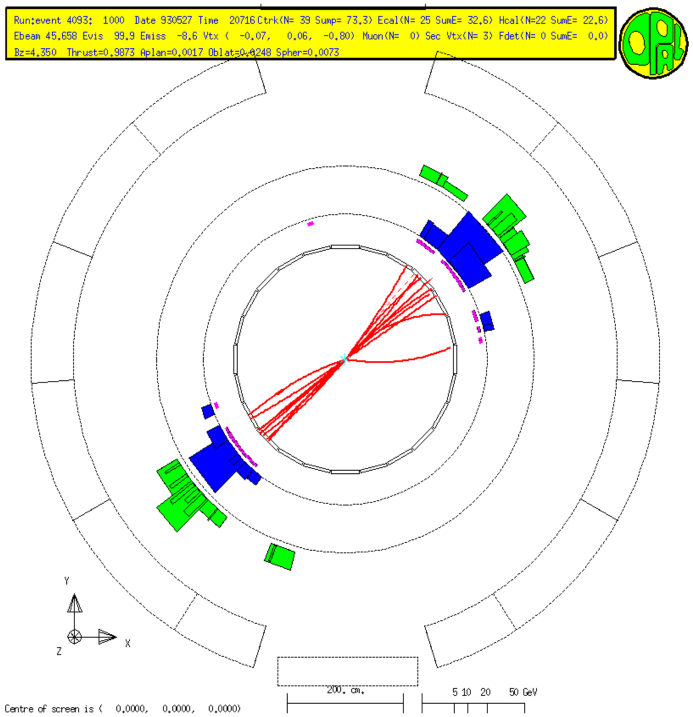


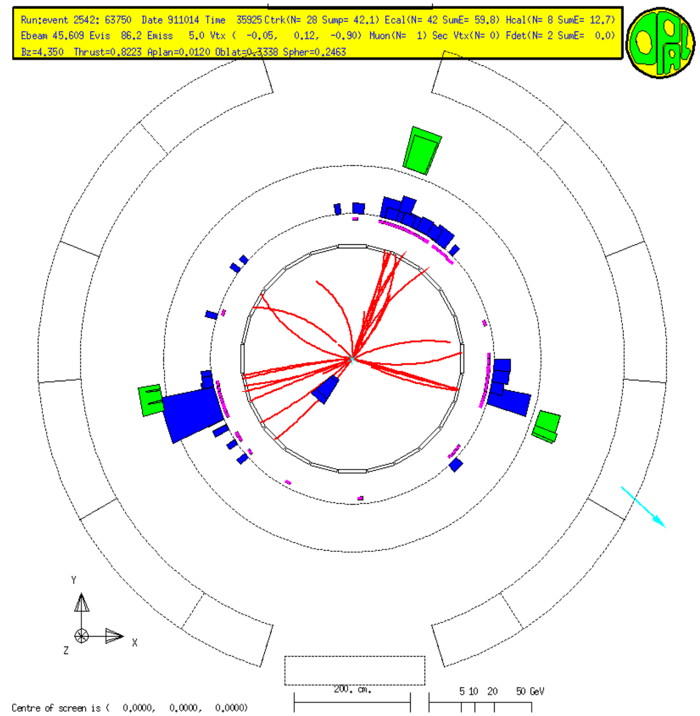
How about quarks and gluons?

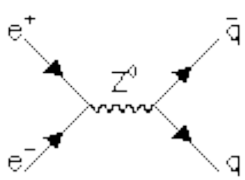
- Want to measure quarks and gluons which carry color charge and see how they interact with QGP

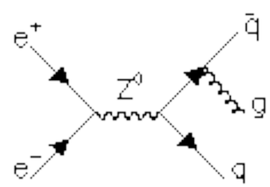


Quarks and gluons







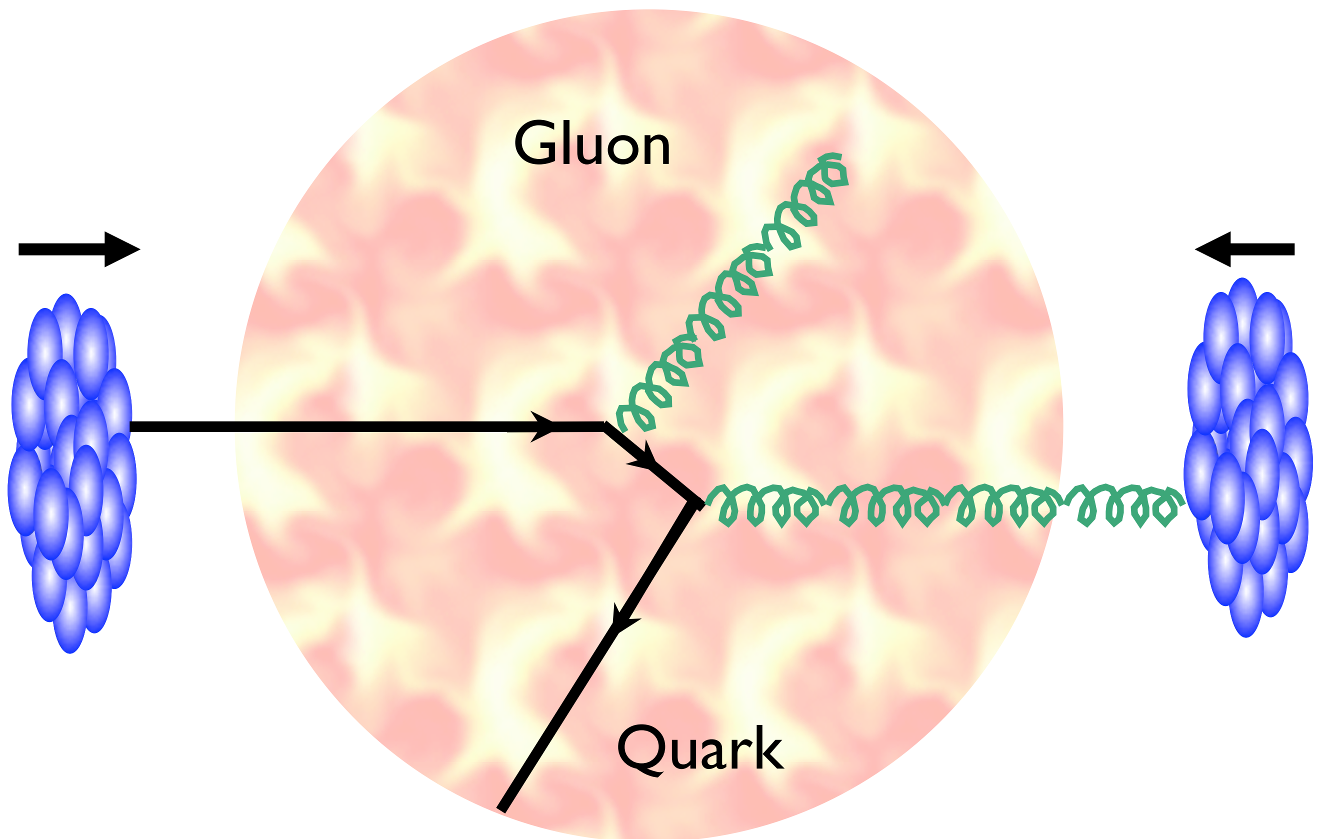


Color confinement:

Quarks and gluons → groups of hadrons

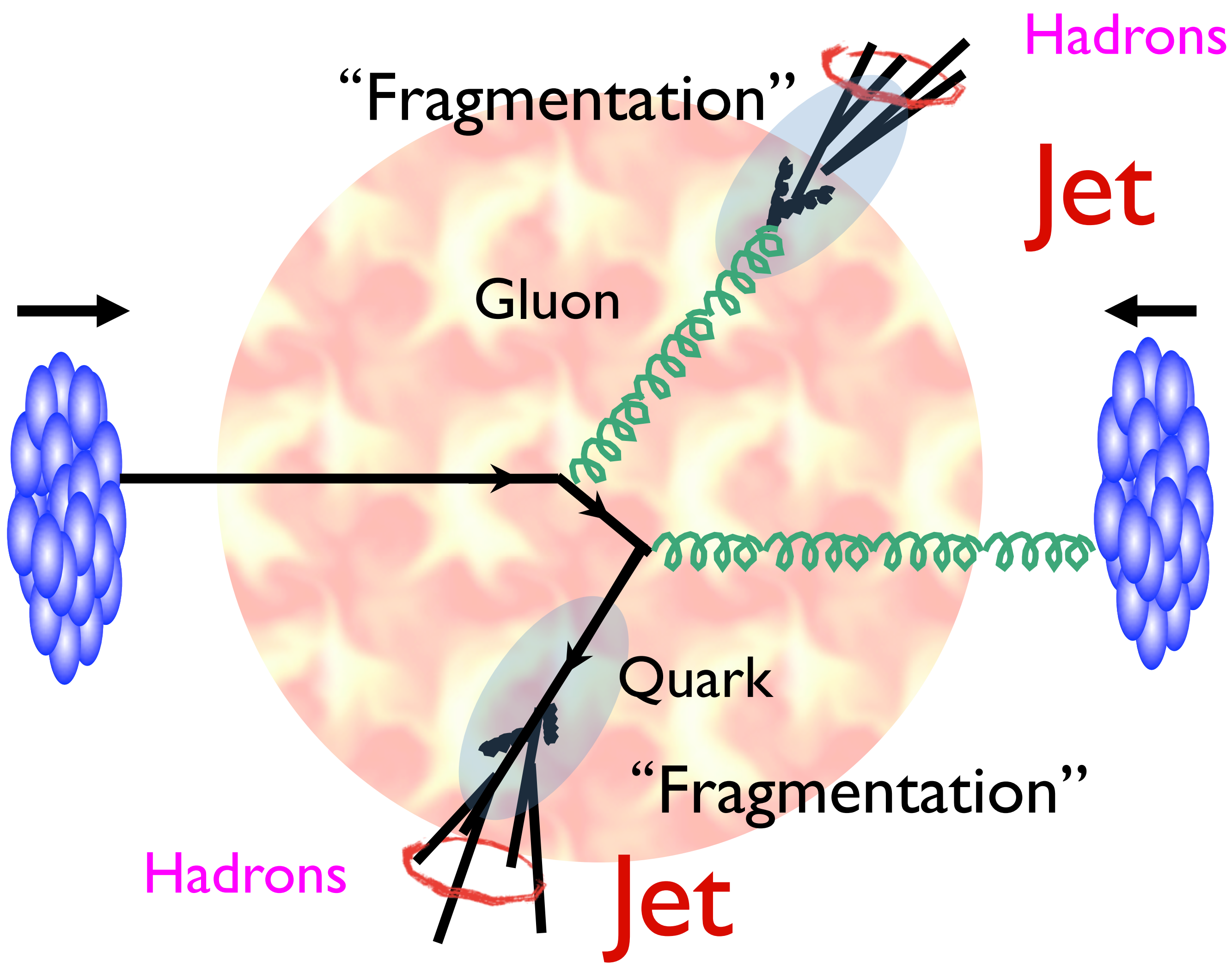
How about quarks and gluons?

- Want to measure quarks and gluons which carry color charge and see how they interact with QGP

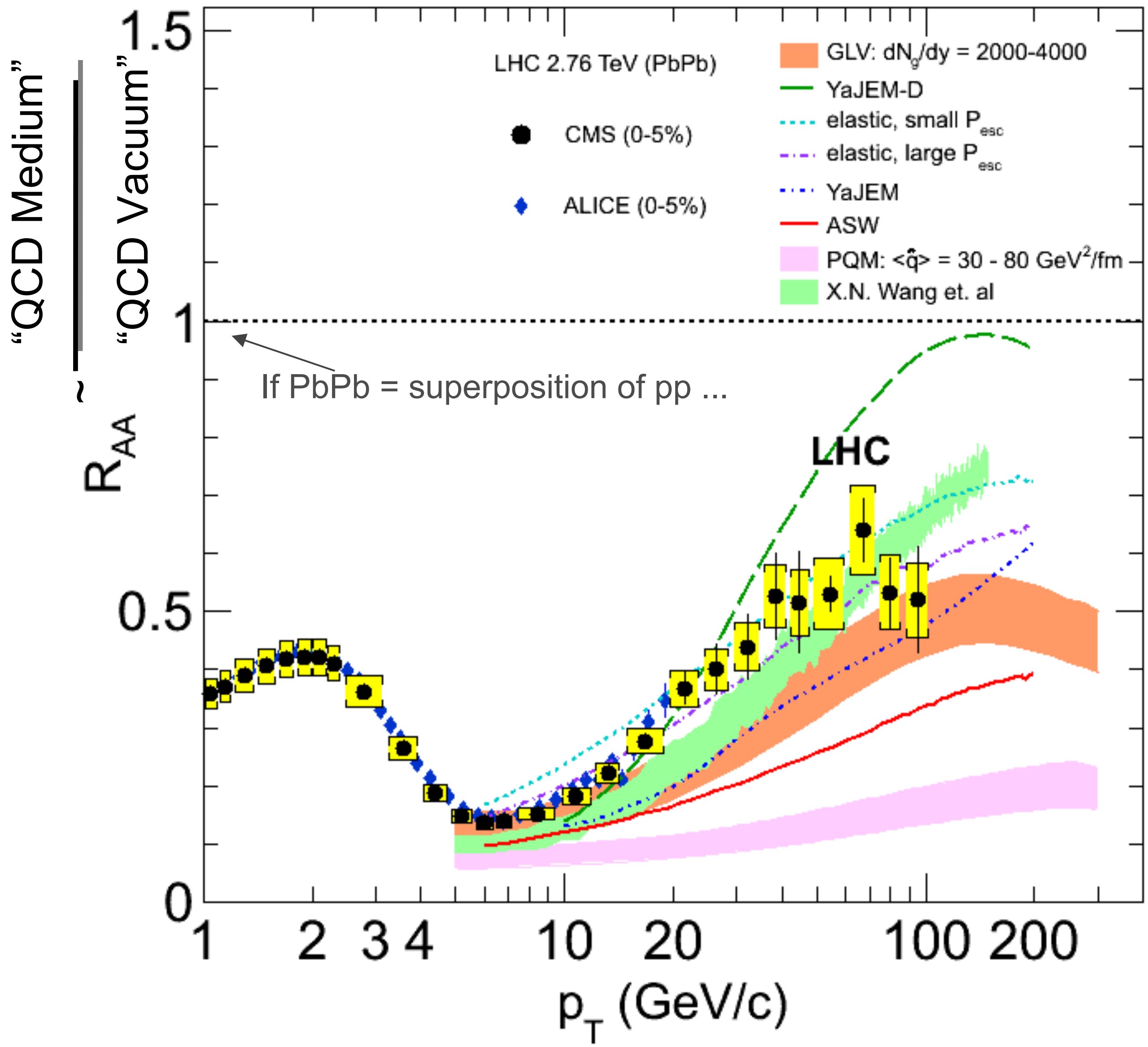


How about out going quarks and gluons?

- Want to measure quarks and gluons which carry color charge and see how they interact with QGP
- → Practically: measure hadrons and jets

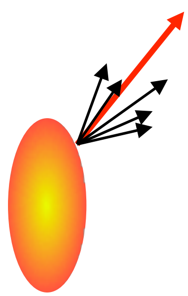


An easier measurement: charged particle R_{AA}



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

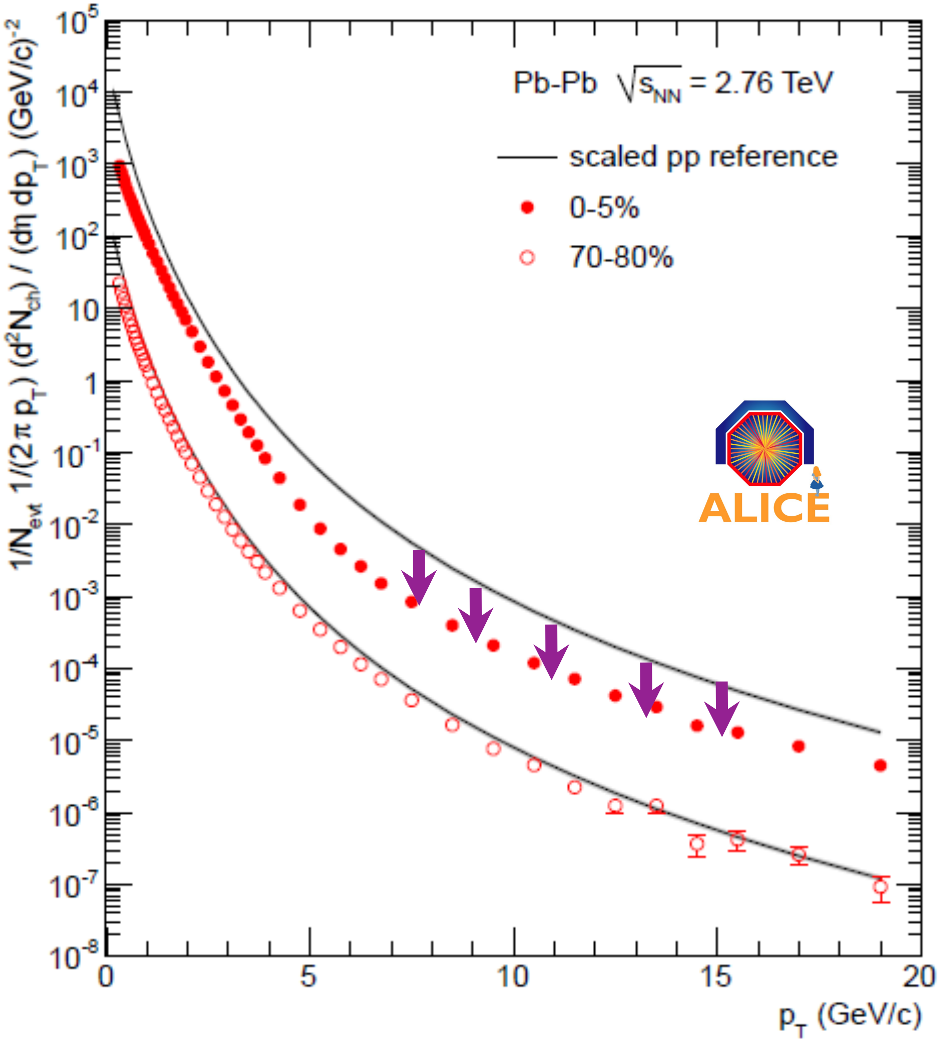
N_{coll} validate by photons W/Z bosons



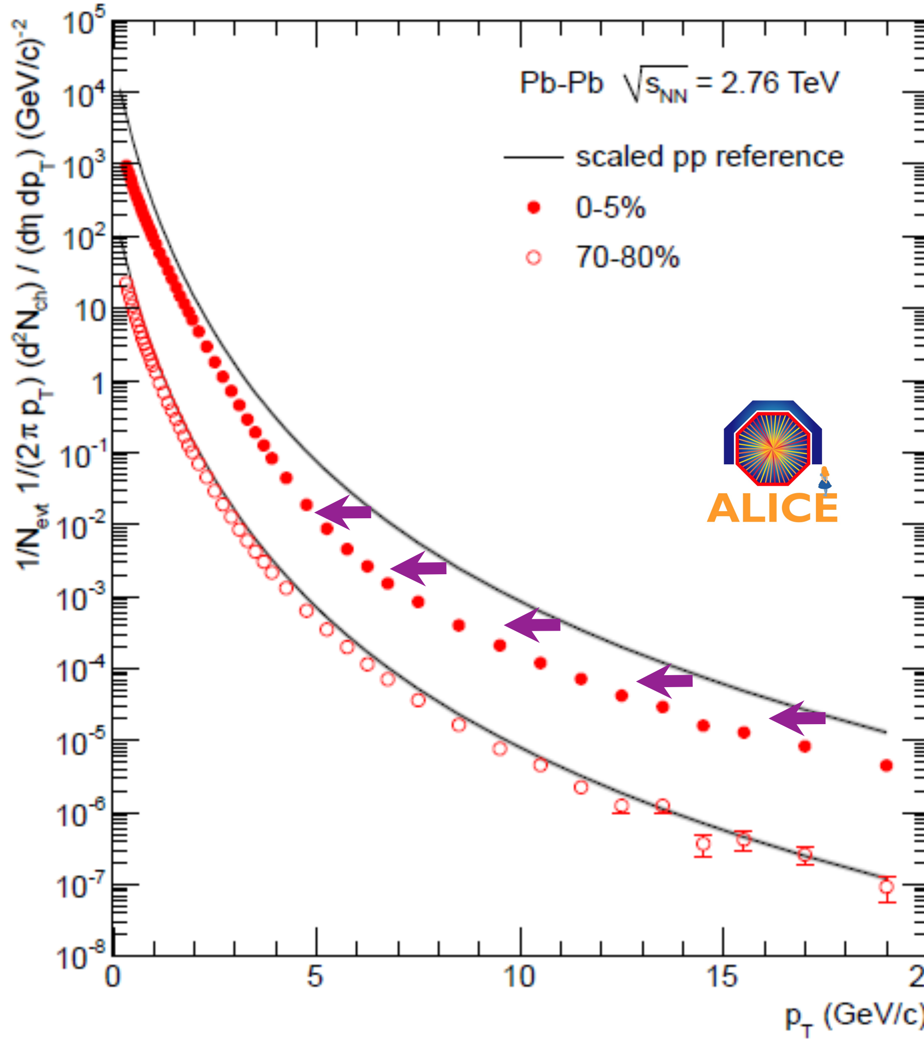
Provide constraints on the parton energy loss models

Charged particle spectra

Absorption?



Energy loss?

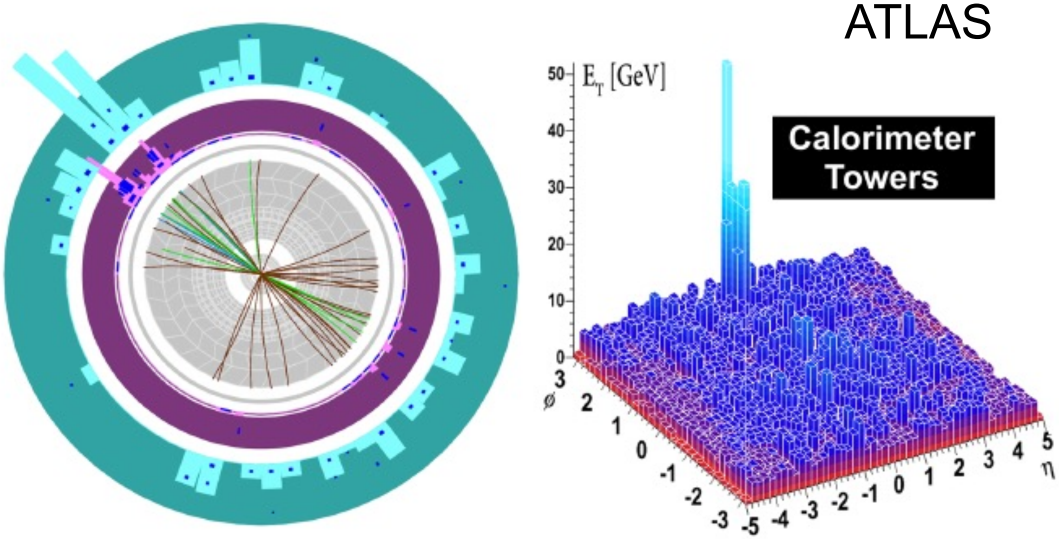


Single hadron spectra itself do not provide details of the underlying mechanism

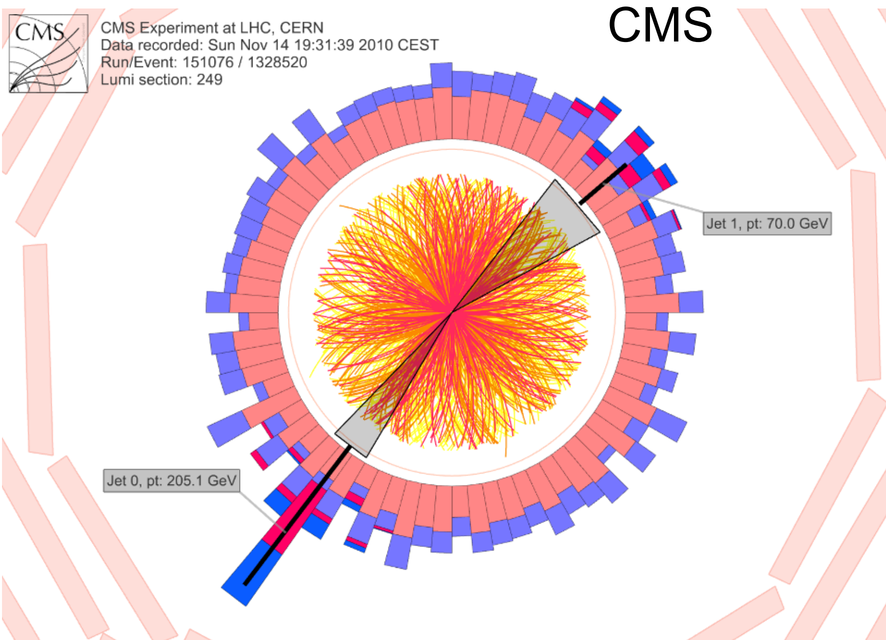
→ Need direct jet reconstruction and correlation studies

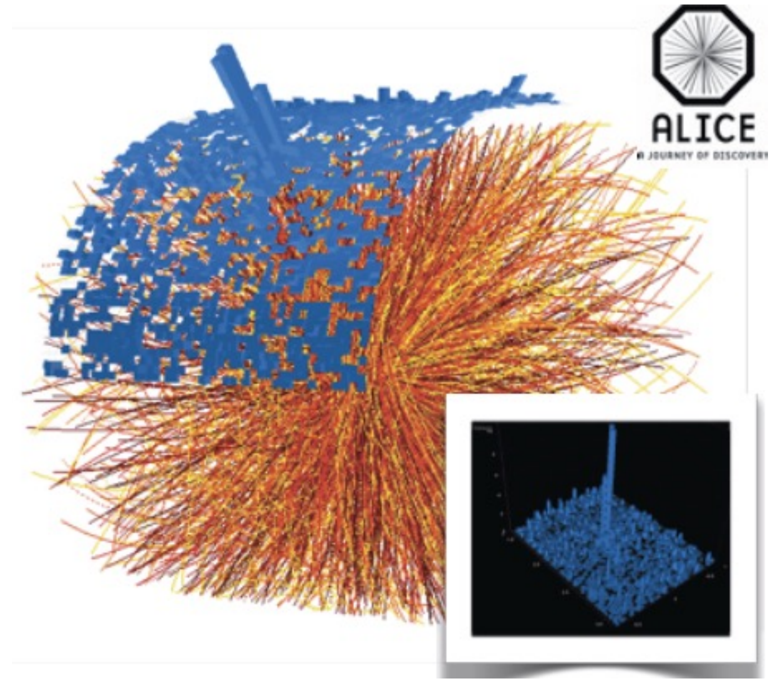
Jet events in PbPb collisions at LHC

ATLAS



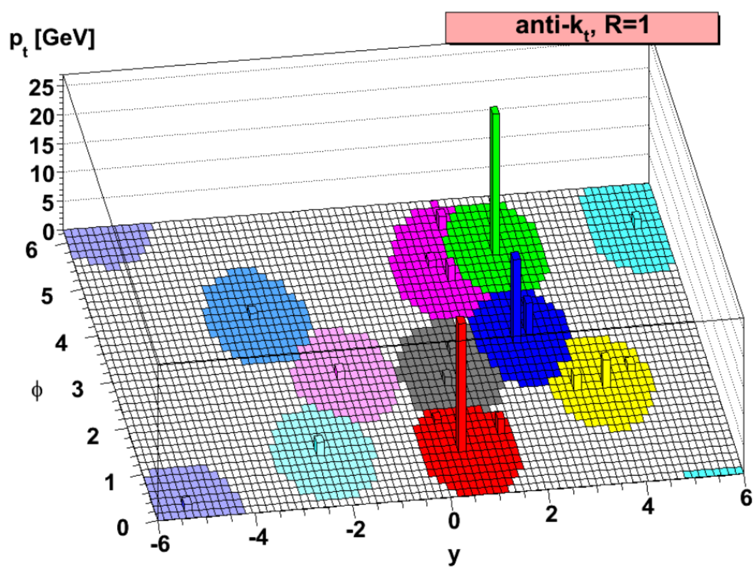
CMS





Need rules to group the hadrons

A popular algorithm is anti-k_T algorithm
Used in ALICE, ATLAS and CMS analyses

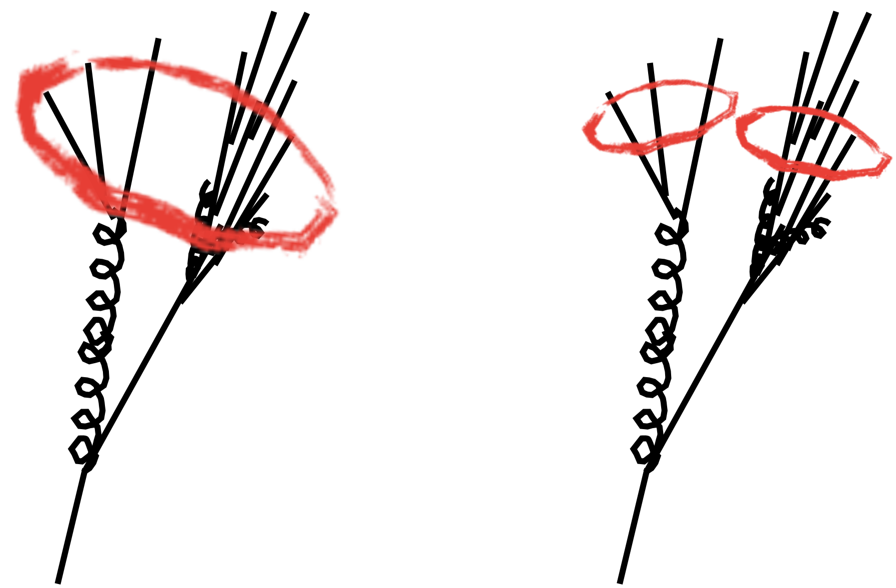


Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

Radius parameter: decide the resolution scale

Large radius parameter

Small radius parameter
→ jet spliting



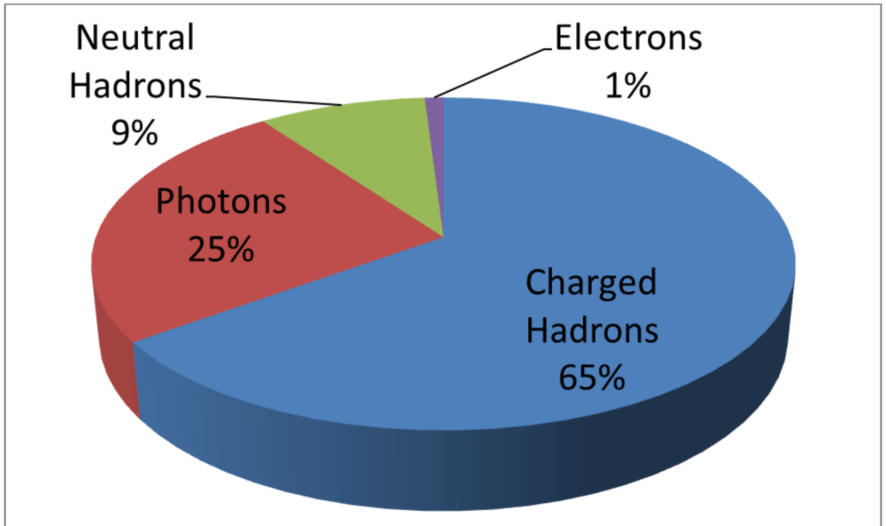
ΔR = 0.2, 0.3, 0.4, 0.5 are used in LHC analyses

Jet composition

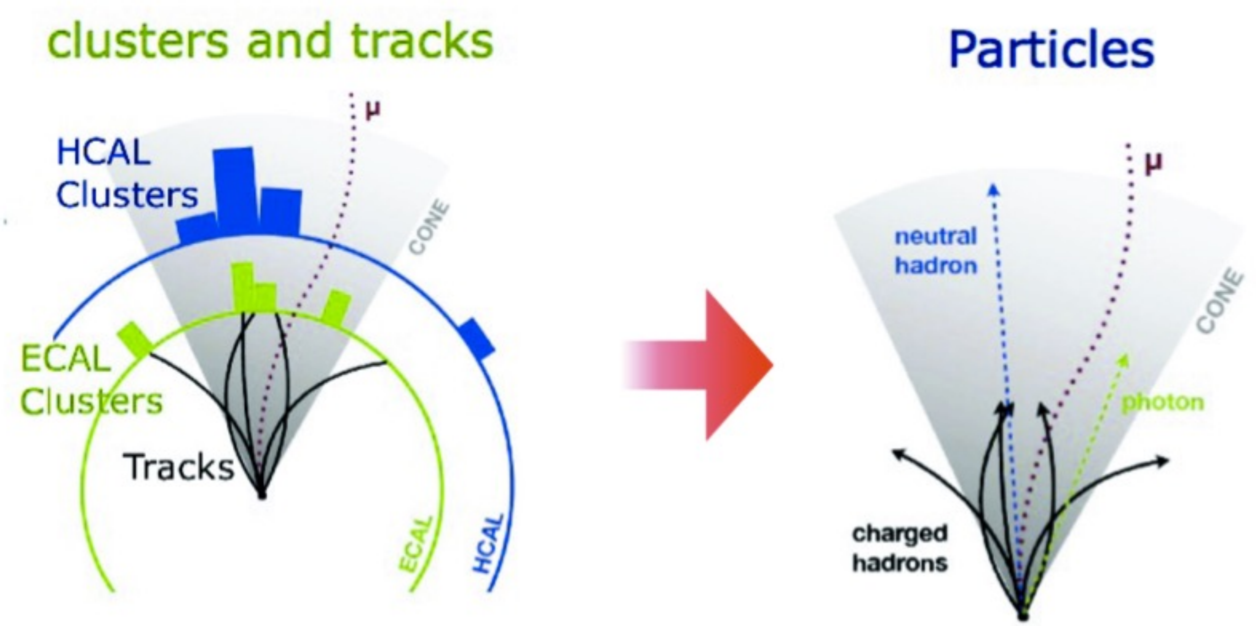
On average, charged hadrons carry 65% of the jet momentum

Measure the known part
Correct the rest by MC simulation

Optimize the use of calorimeter and tracker
Example: “Particle Flow” in CMS



A typical high p_T jet



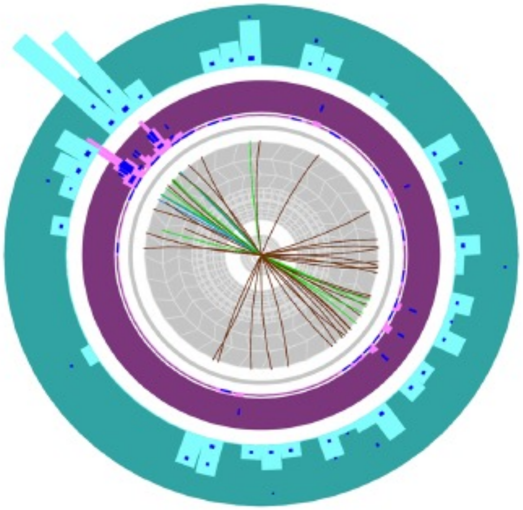
Goal:

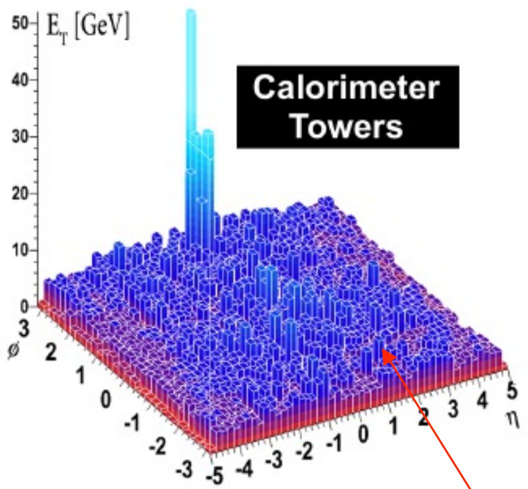
- Make use of the redundancy of measurements from calorimeter and tracker
- Improve the sensitivity to low p_T particles in jet
→Reduce the dependence on MC

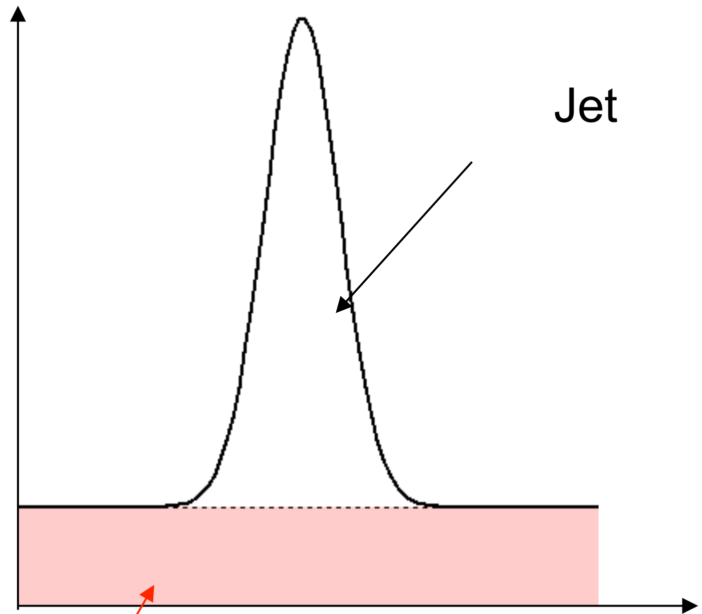
(ex: PYTHIA)

Underlying event background

ATLAS





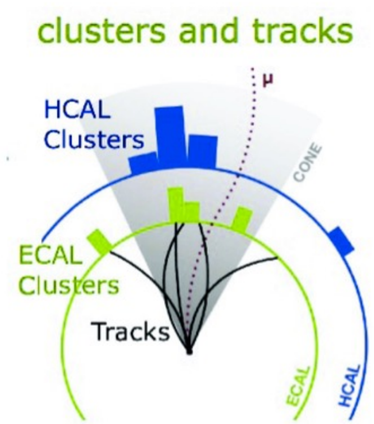


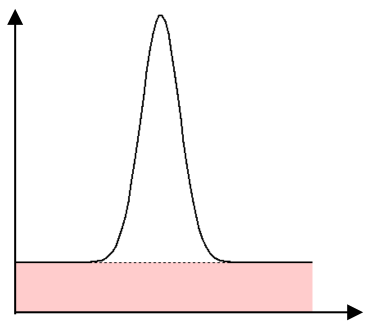
Multiple parton interaction

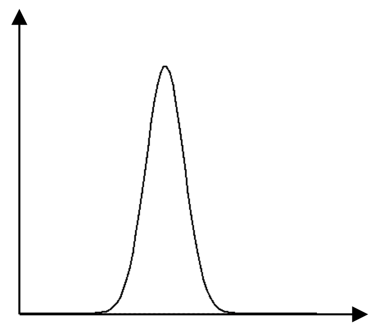
Large underlying event from soft scattering

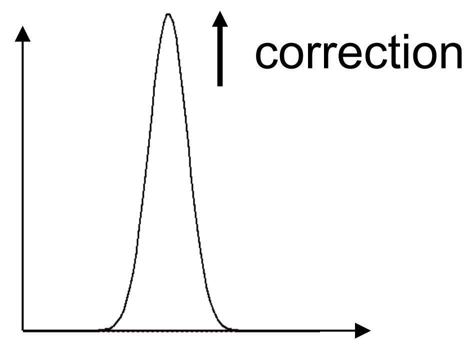
Need background subtraction

Summary of jet reconstruction









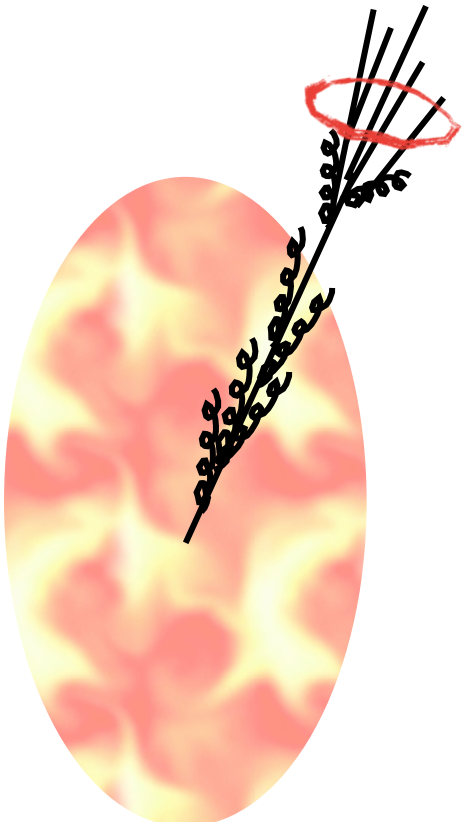
Raw jet energy → Background subtraction → Jet energy correction → Jet energy

Background subtraction: Remove underlying events contribution

Jet energy correction: MC Simulation PYTHIA

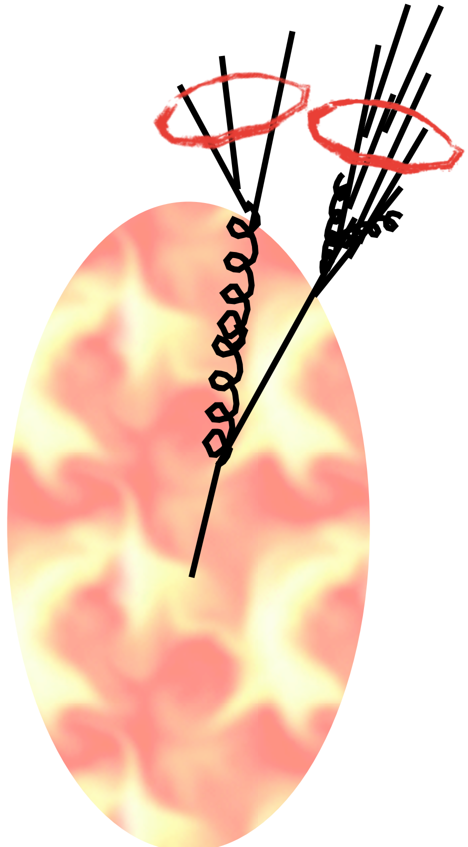
Three possible scenarios

To explain the suppression of high p_T particles



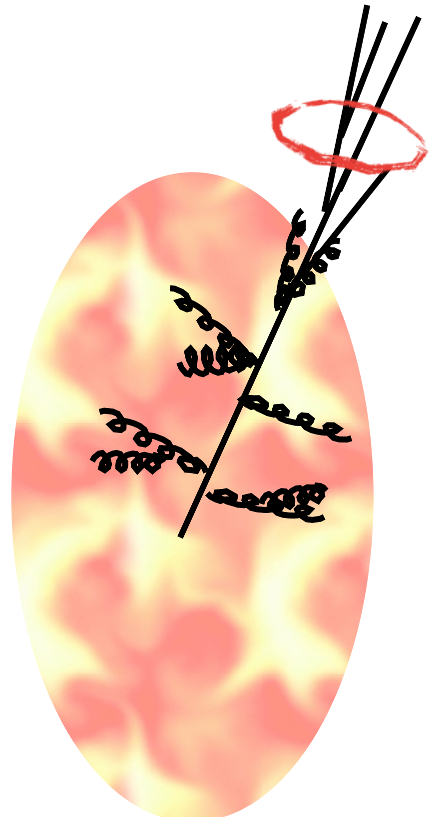
Soft collinear radiation

GLV + others



Hard radiation

PYTHIA inspired models
Modified splitting functions

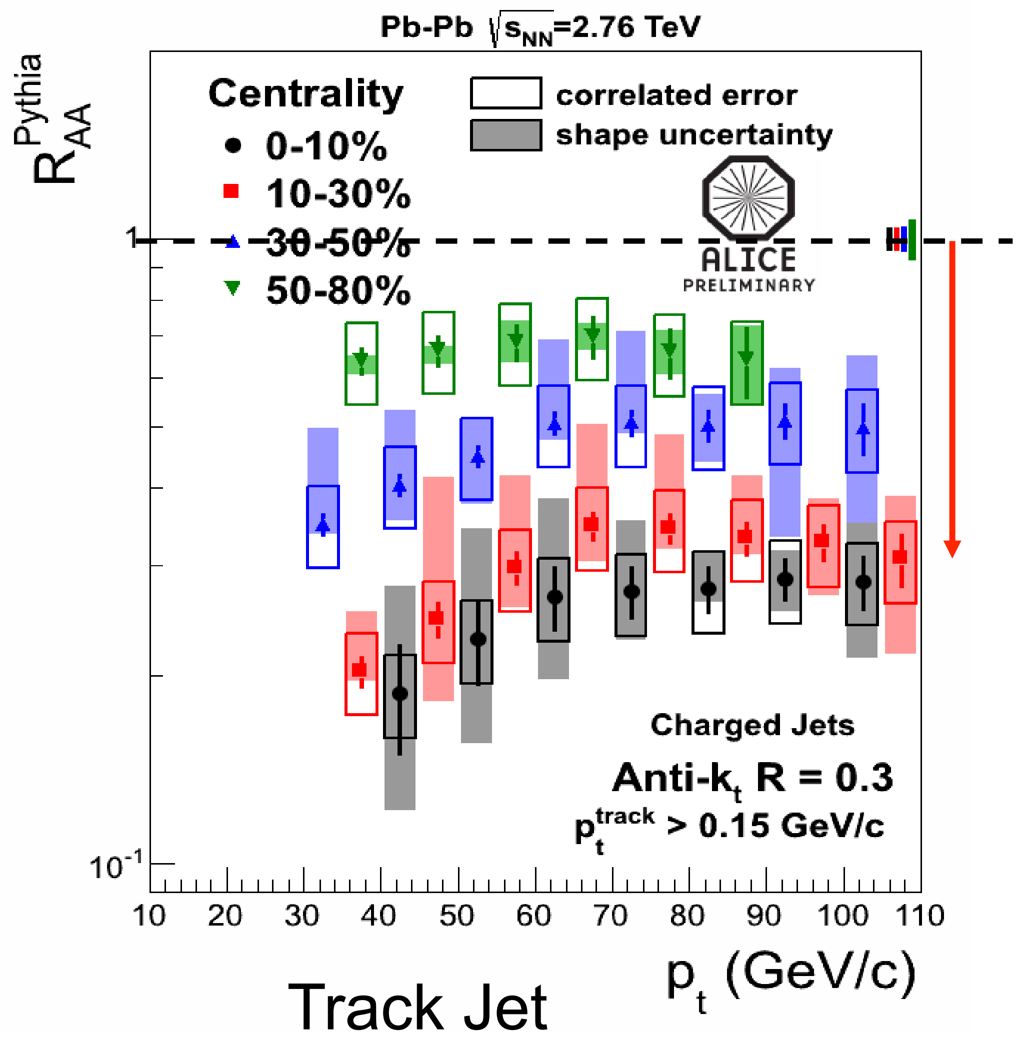


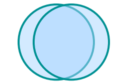
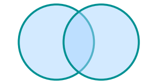
Large angle soft radiation
"QGP heating"

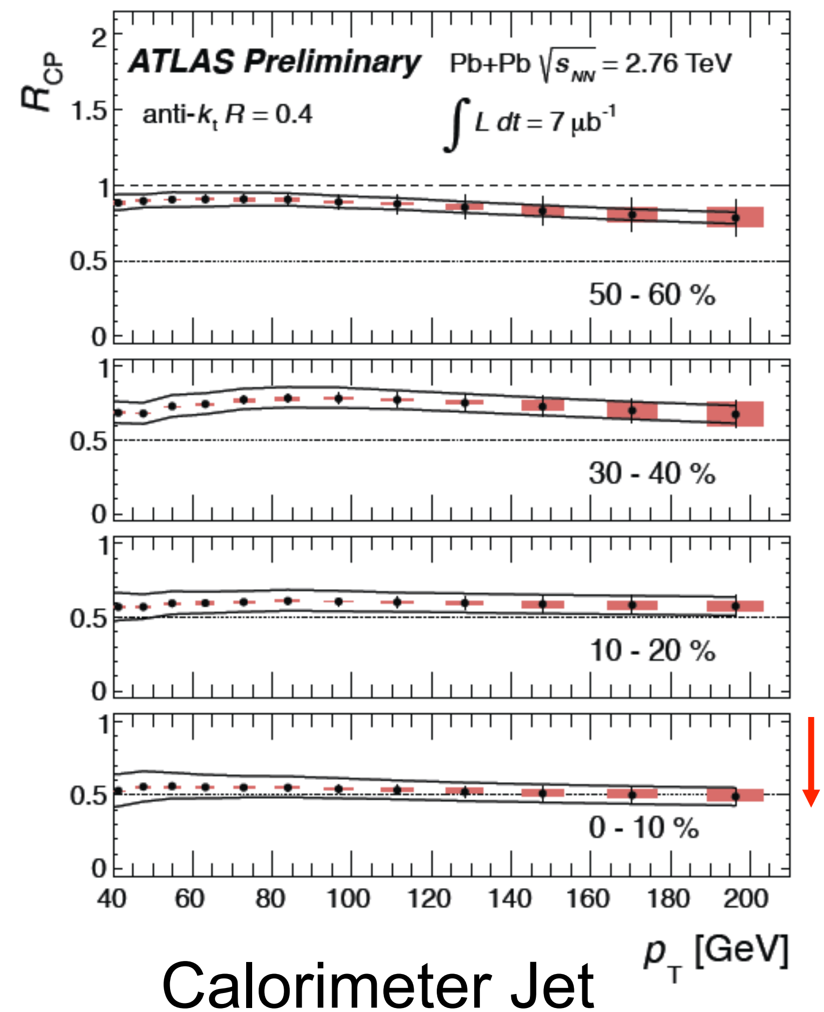
AdS/CFT

Inclusive jet R_{AA}, R_{CP}

Compare PbPb to PYTHIA (pp generator)



R_{CP}: Compare  to 

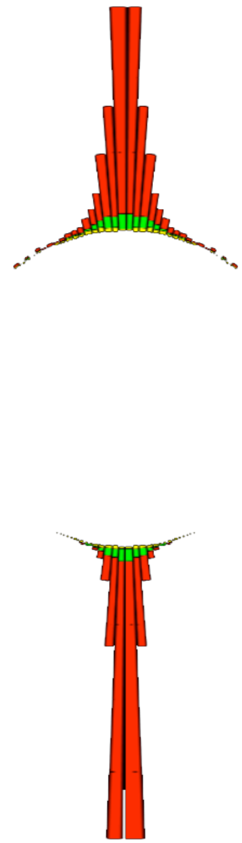


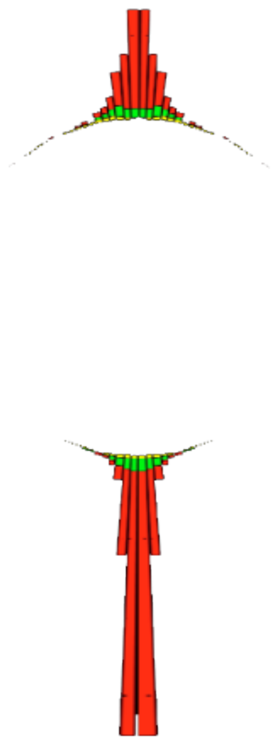
Strong suppression of inclusive high p_T jets!

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

Correlation study: Di-jet imbalance

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



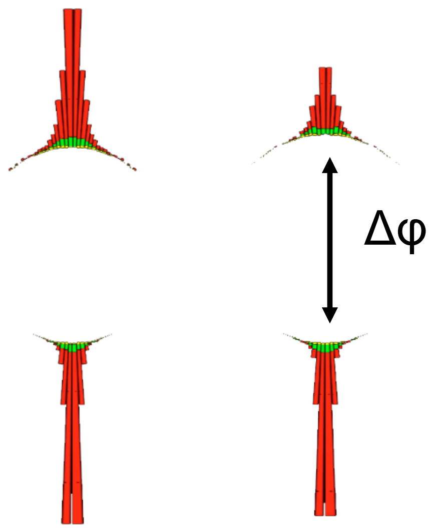


Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)

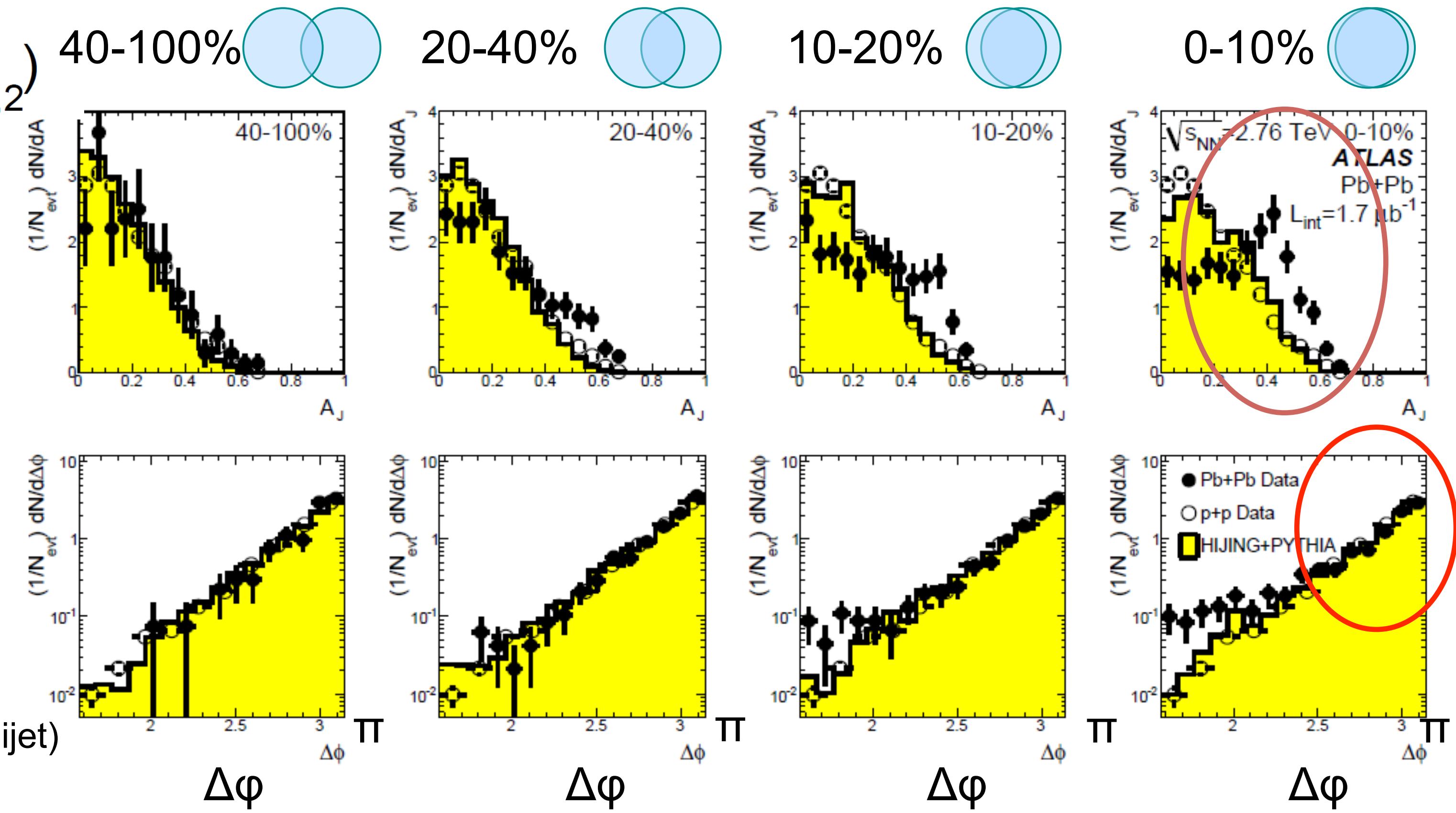
Correlation study: Di-jet imbalance

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



Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)



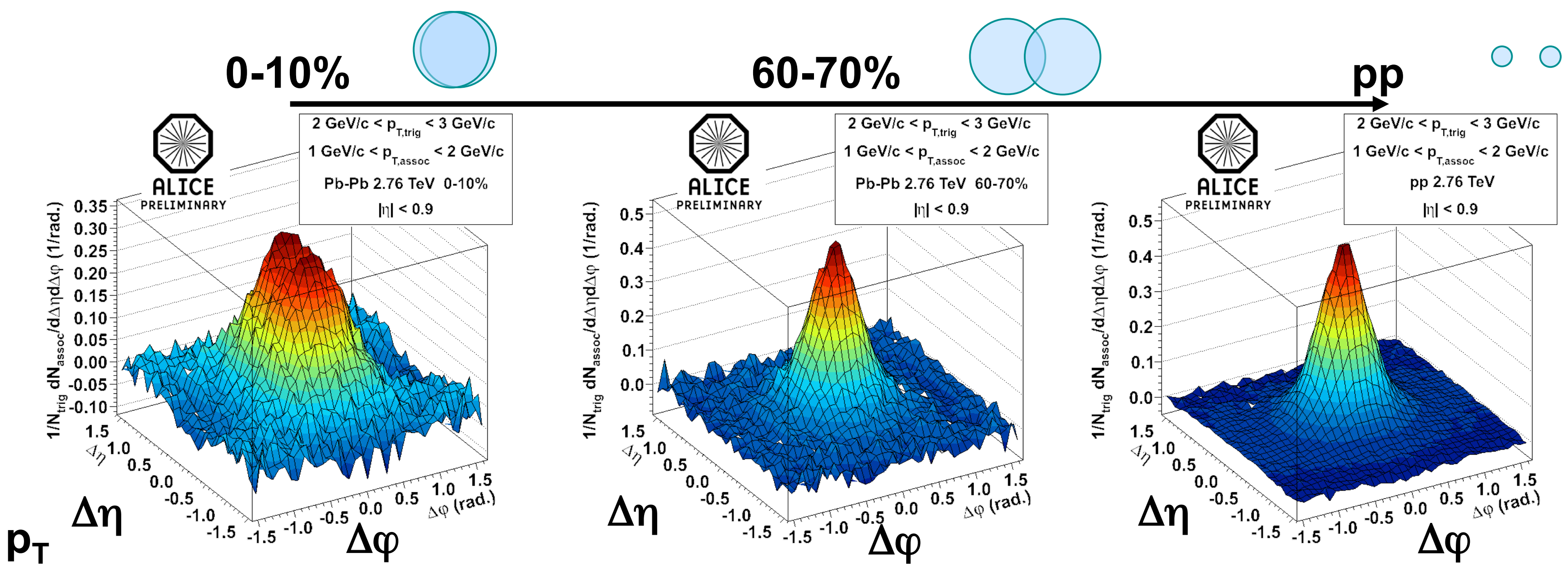
Parton energy loss is observed as a pronounced energy imbalance in central PbPb collisions

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

Low p_T jets in PbPb collisions

Two particle correlation from ALICE:
Jet like near side correlation with background subtraction
Strong centrality dependence, widening of the angular correlation

$2 < p_{T,trig} < 3$
$1 < p_{T,assoc} < 2$

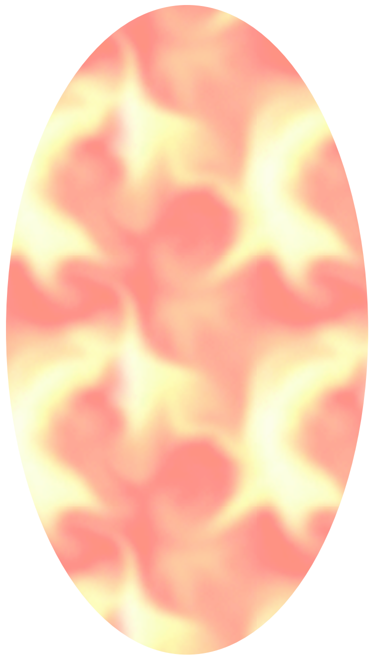


→Motivates jet shape analysis and fragmentation function with low p_T particles

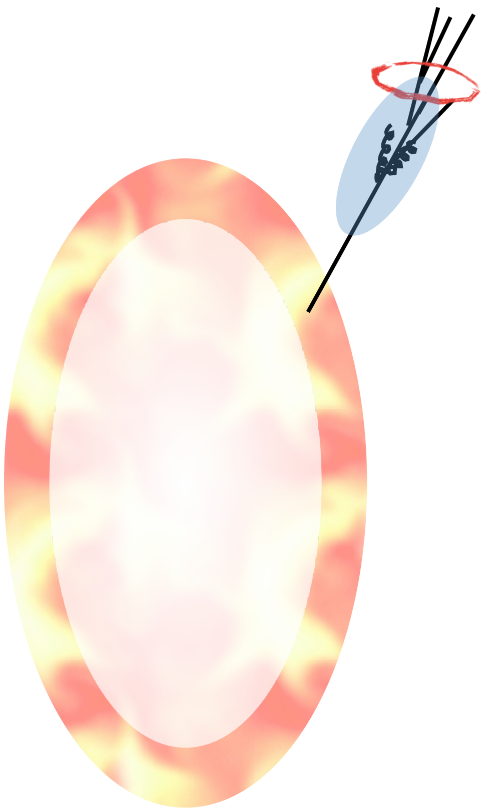
→ Look at low p_T reconstructed jet

Challenge of jet as a trigger: surface bias

- Selection on a high p_T leading jet (charged particle) may bias the position of the hard scattering in the QGP



All hard collisions
Can happen in any place in the QGP

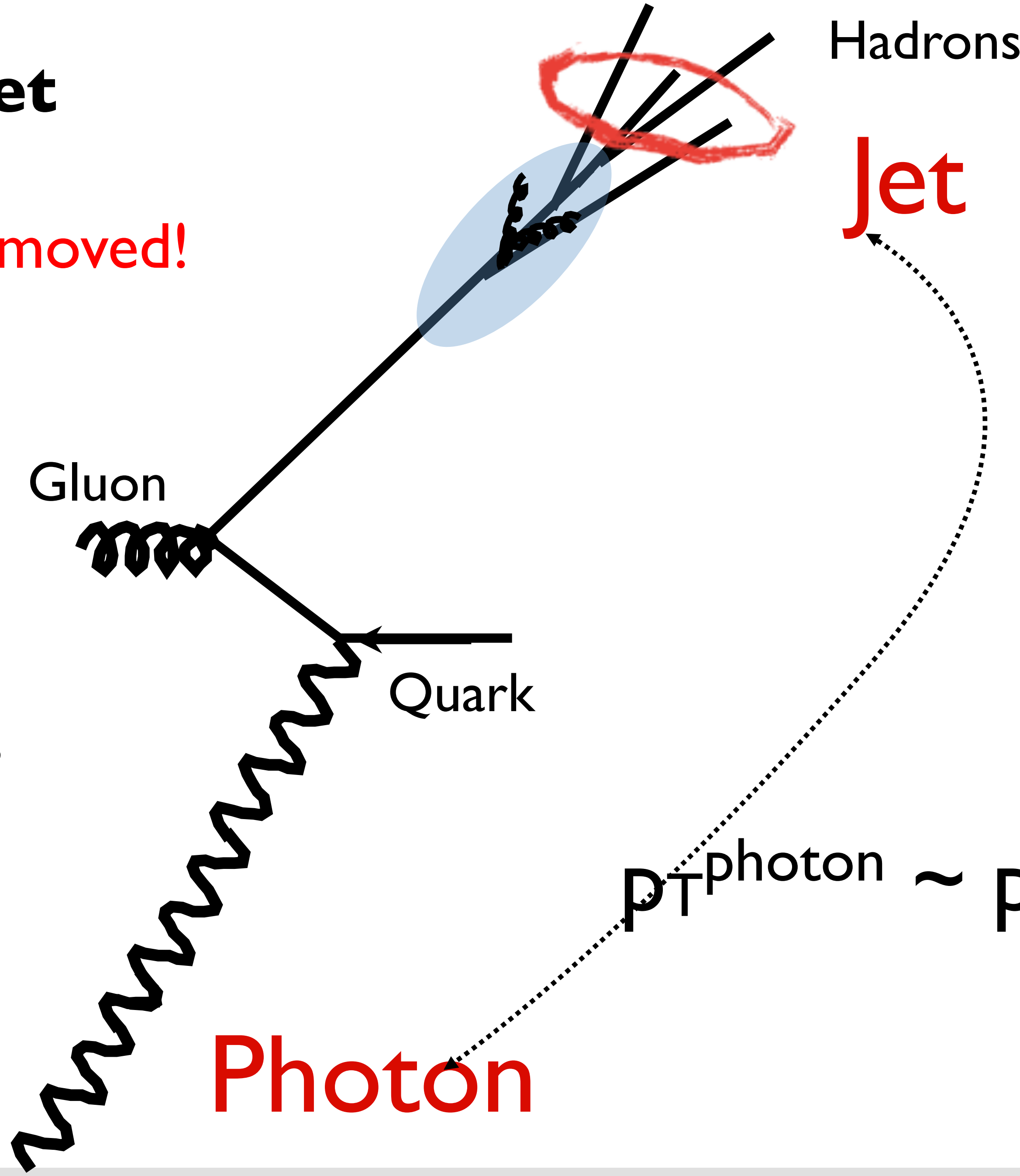


High p_T leading jet
Triggered sample

How about correlate photons and jets?

photon+jet

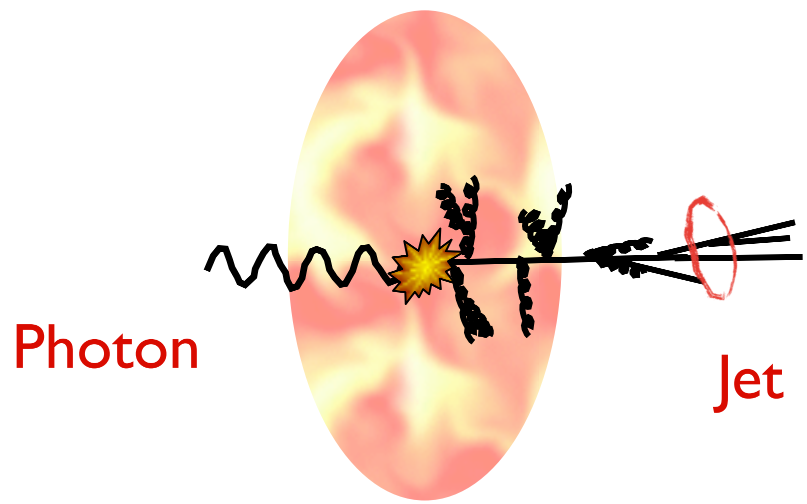
Surface bias is removed!

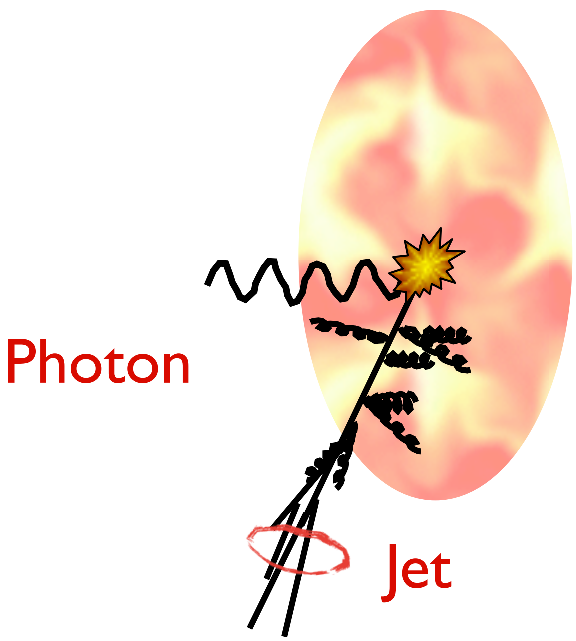


"quark-gluon compton scattering"

$p_T^{photon} \sim p_T^{Jet}$

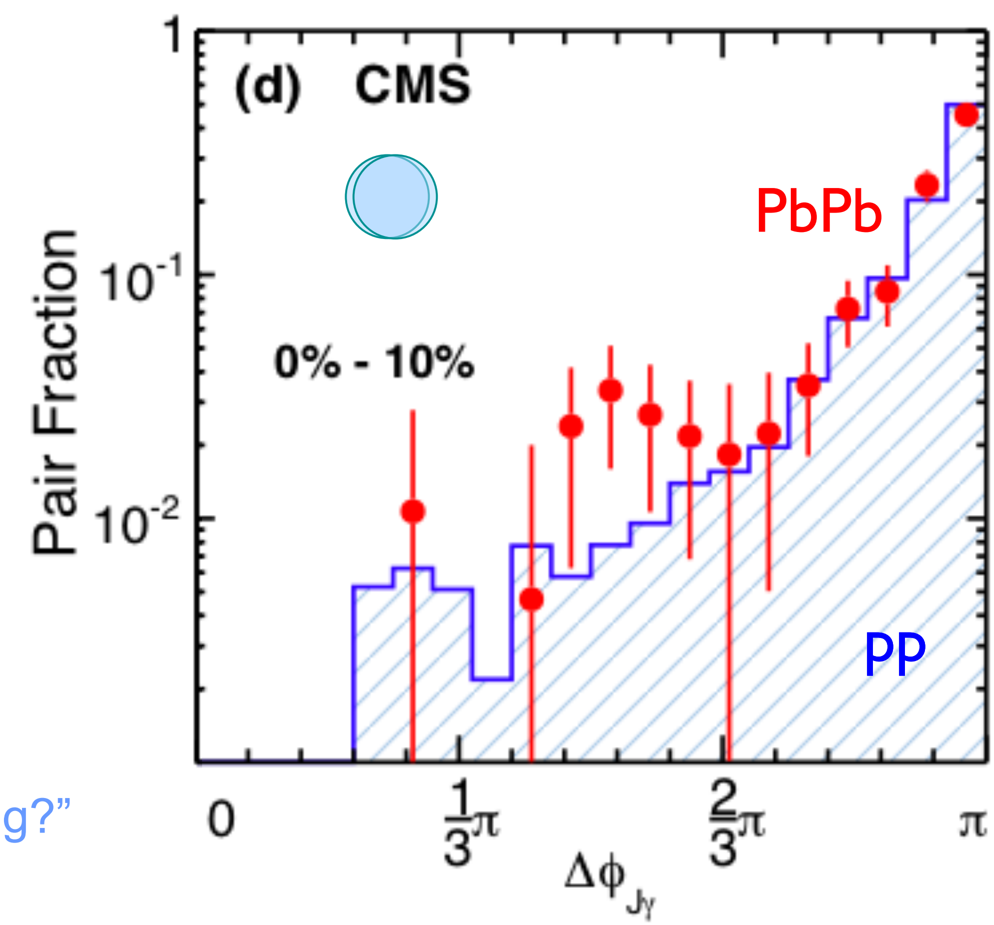
Photon jet angular correlation





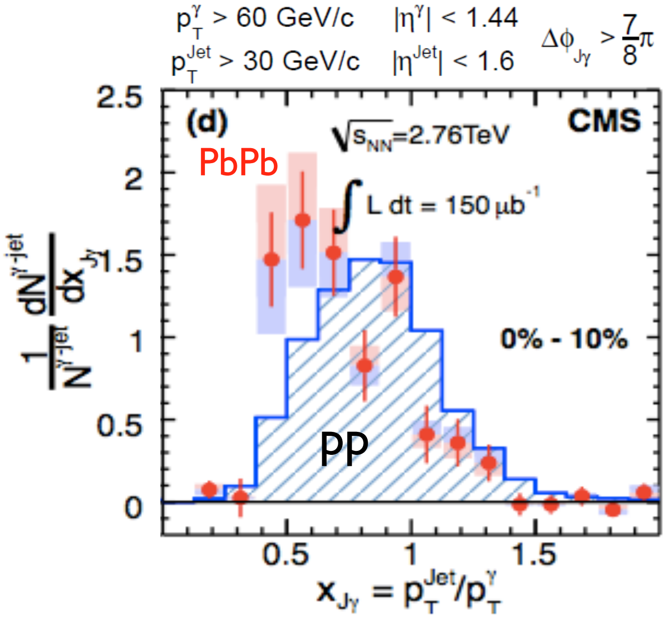
"Backscattering?"

"QGP Rutherfold experiment"



Azimuthal angle between photon and jet

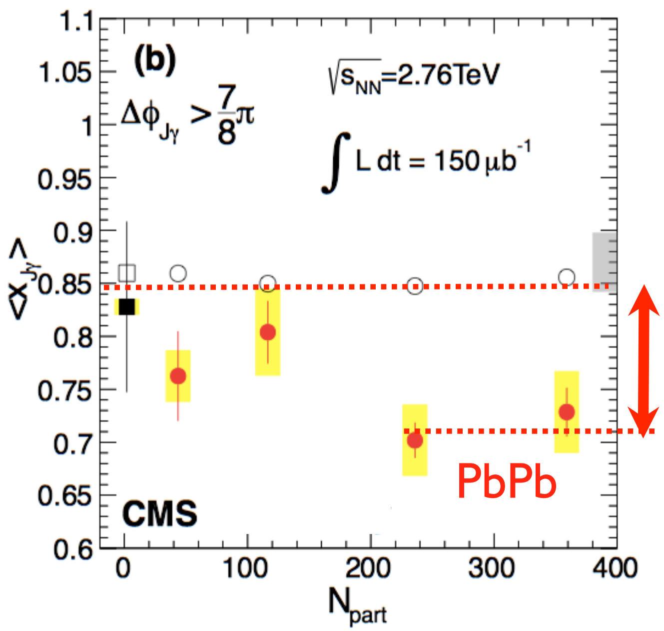
Photon-jet momentum balance



Compare photon-jet momentum balance

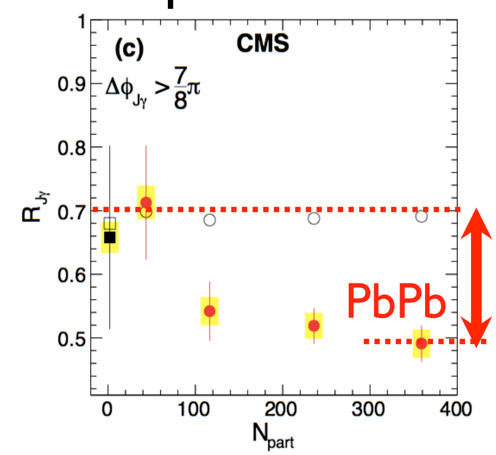
$x_{jg} = p_T^{Jet}/p_T^{photon}$

in **vacuum** (pp collision) to the **QGP** (PbPb collision)



Quarks lose about 15% of their initial energy

In addition, 20% of photons lose their jet partner



Summary

- Quarks and gluons lose a lot of energy traversing the hot nuclear medium: huge effect!
- It is transparent to W, Z, γ
- Detailed theoretical studies of “where the energy goes” and details of energy loss models are work in progress