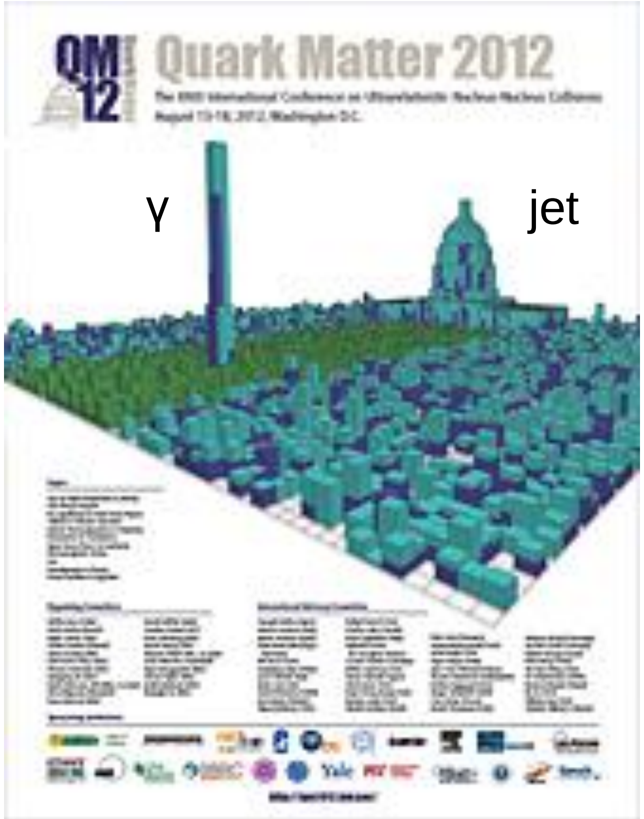
Hard Probes

with focus on LHC data



Yen-Jie Lee (CERN)

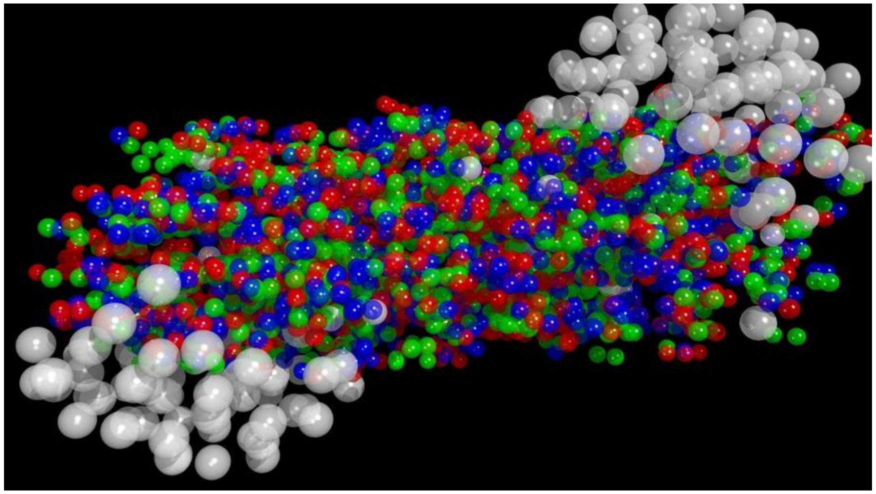
Probe the medium

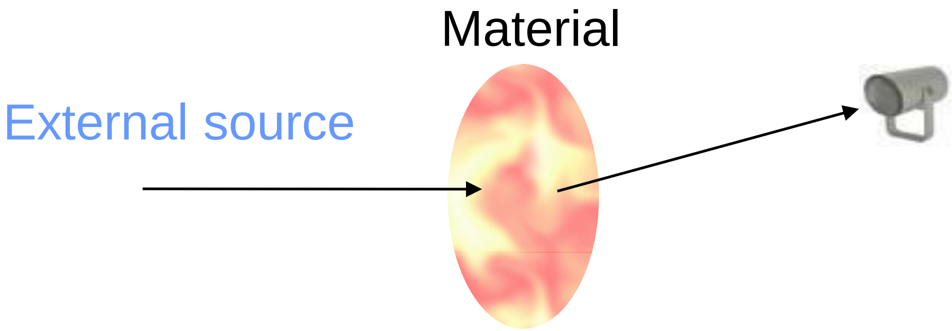
- Goal:

  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.

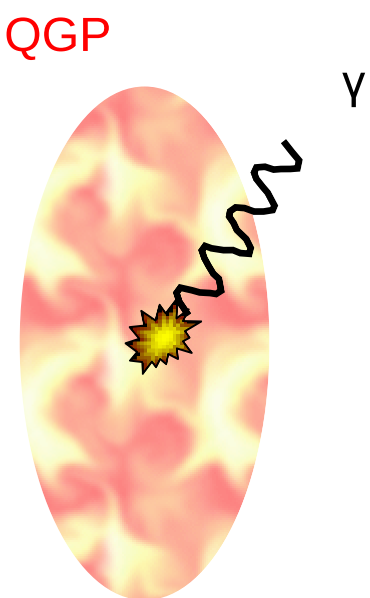




Three types of hard probes

Electroweak probes

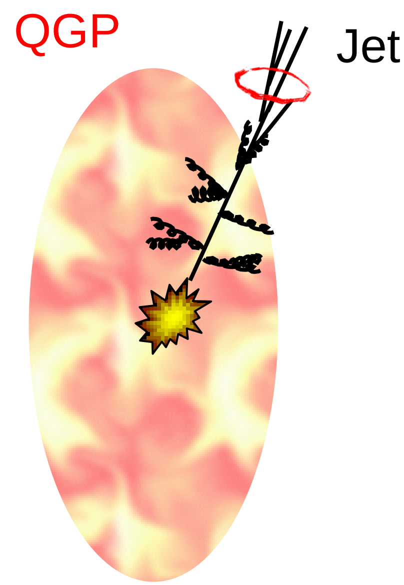
W/Z bosons, high p_T γ



Probe the initial state

Quarks and gluons

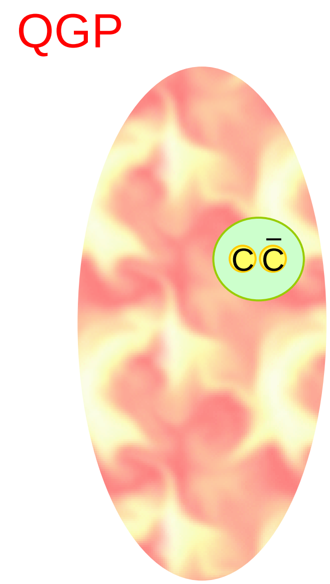
Jets



Probe the opacity of QGP

Quarkonium

J/ψ, Υ family



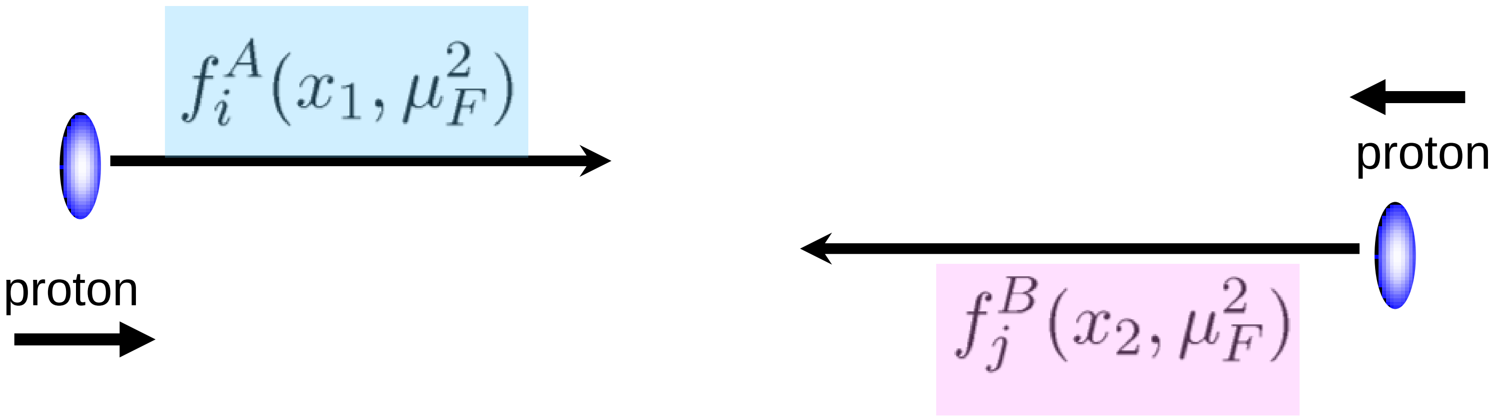
Sensitive to
the temperature of QGP

Factorization

Factorization

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

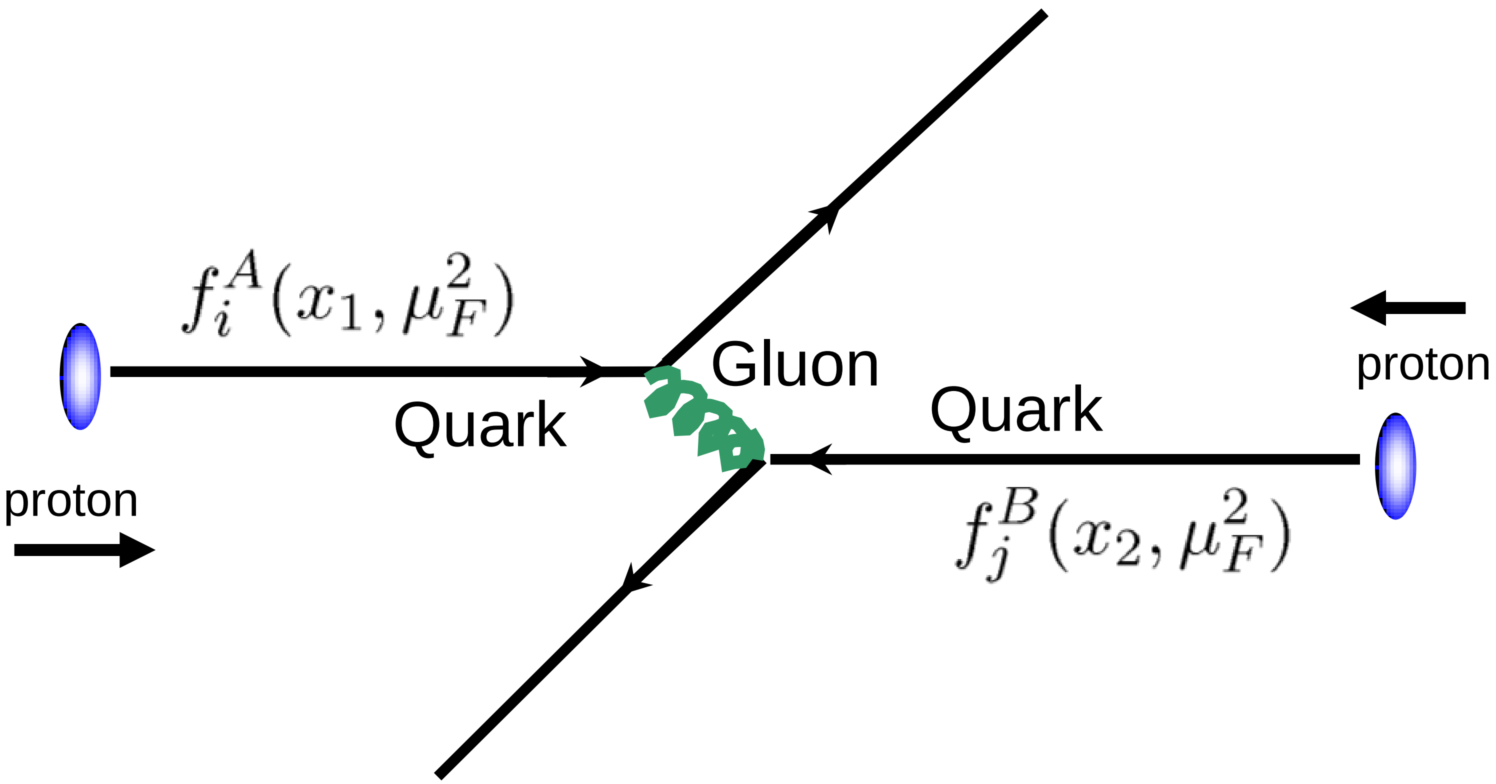
Parton Distribution Function (PDF)



Factorization

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

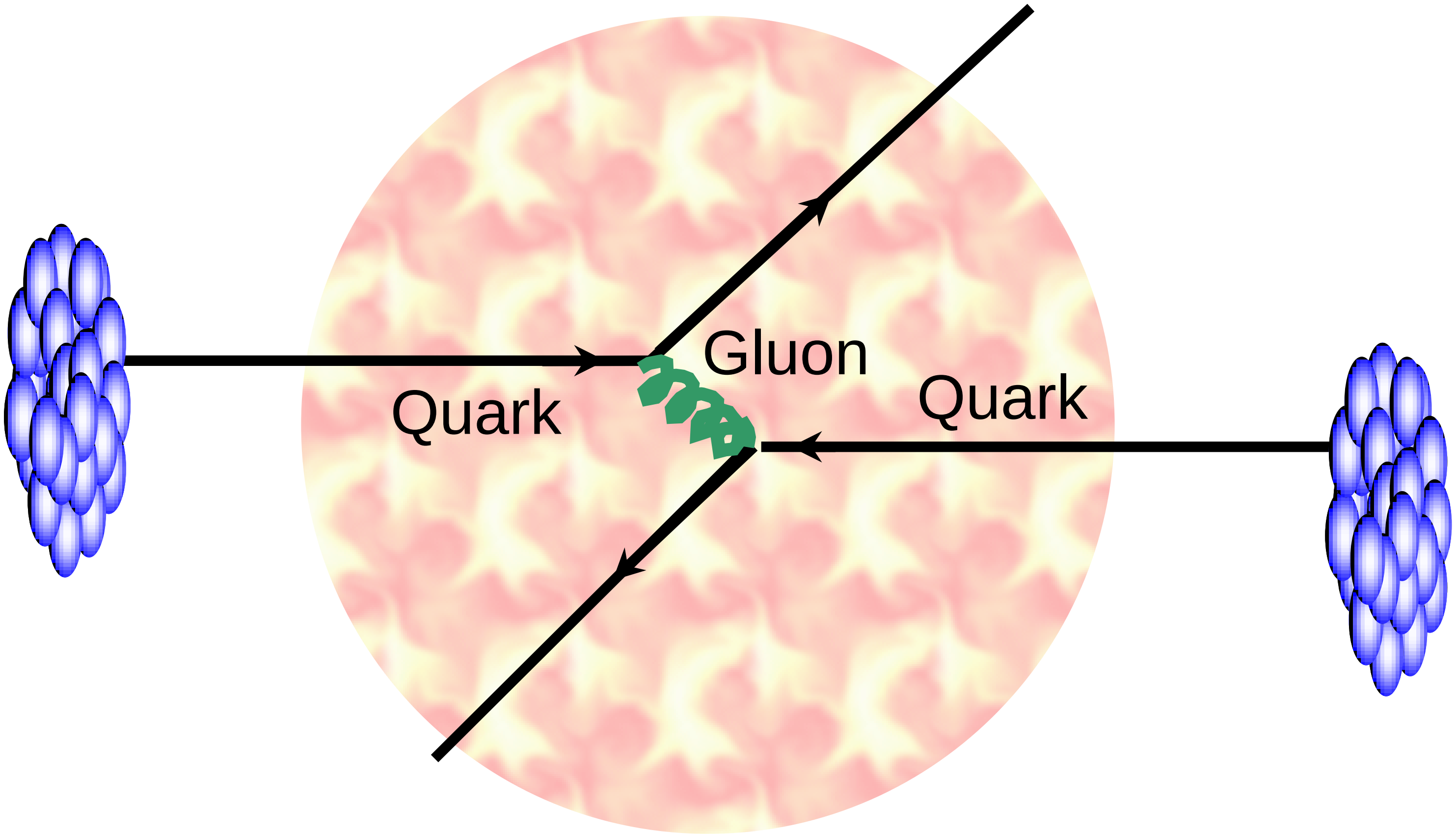
Parton Distribution Function (PDF)   Cross-section of 2→2 process



Factorization

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

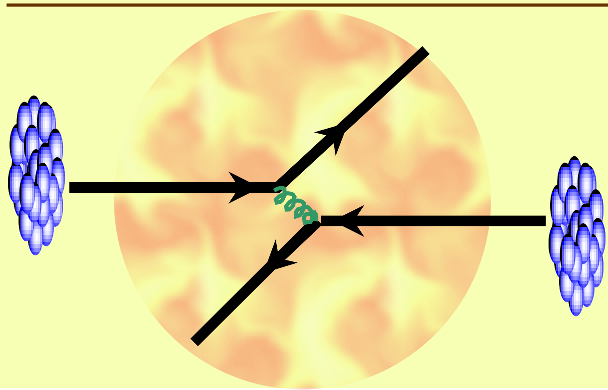
Nuclear Parton Distribution Function (nPDF)   Cross-section of 2→2 process



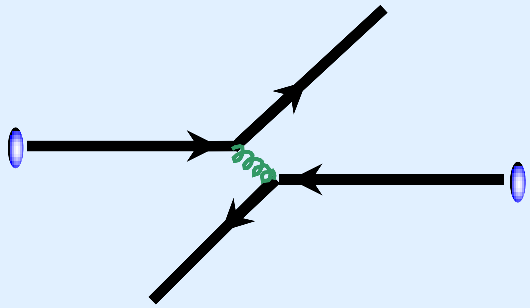
How do we extract the medium effect in PbPb collisions?

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

PbPb measurements



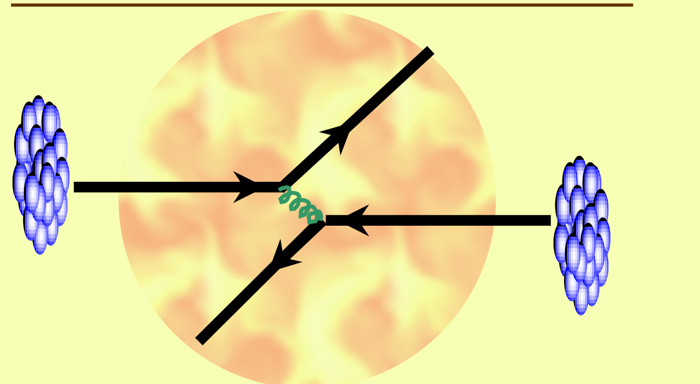
pp reference



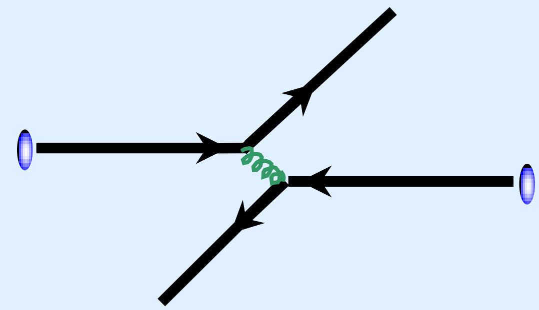
How do we extract the medium effect in PbPb collisions?

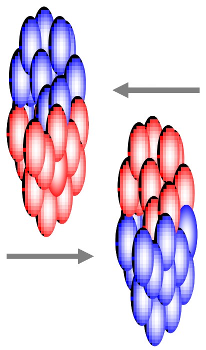
One typical way is to compare PbPb data to pp reference measurement

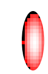
PbPb measurements

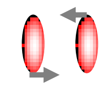


pp reference

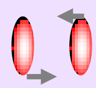


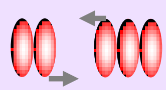


N_{part} → Number of participating nucleons 

N_{coll} → Number of binary scatterings 

Example:

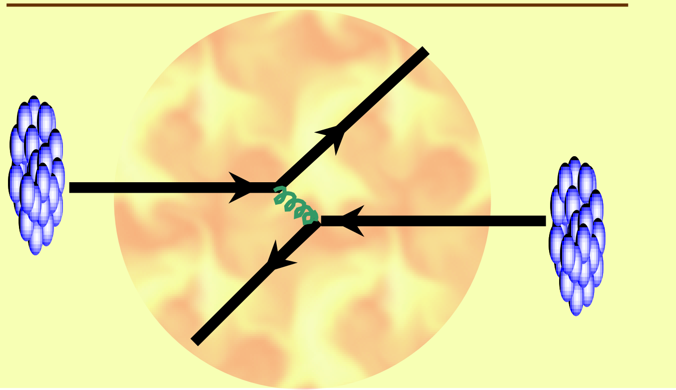
 $N_{part} = 2$ $N_{coll} = 1$

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

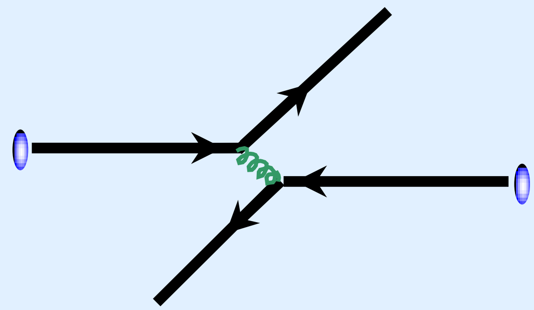
How do we extract the medium effect in PbPb collisions?

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

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)

$N_{coll} \rightarrow$ Averaged number of binary scattering

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

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

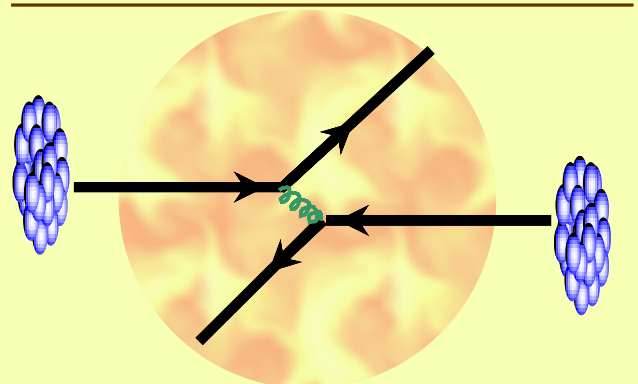
"NN equivalent integrated luminosity per AA collision"

Reduces the uncertainty from pp inclusive cross-section

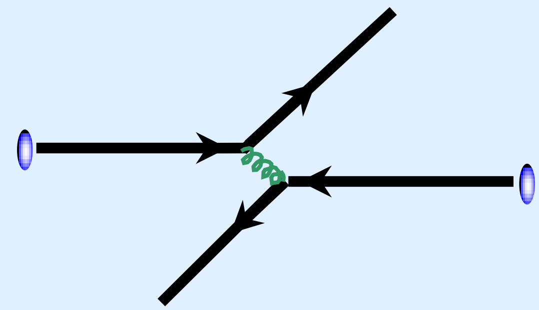
How do we extract the medium effect in PbPb collisions?

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

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

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

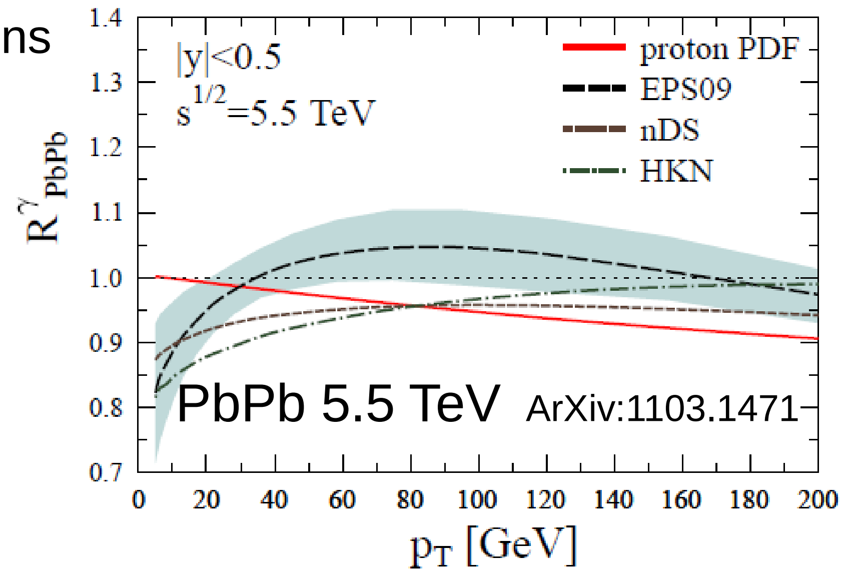
Is the nuclear PDF modified with respect to nucleon PDF?

⟶ Motivates the studies of electroweak probes

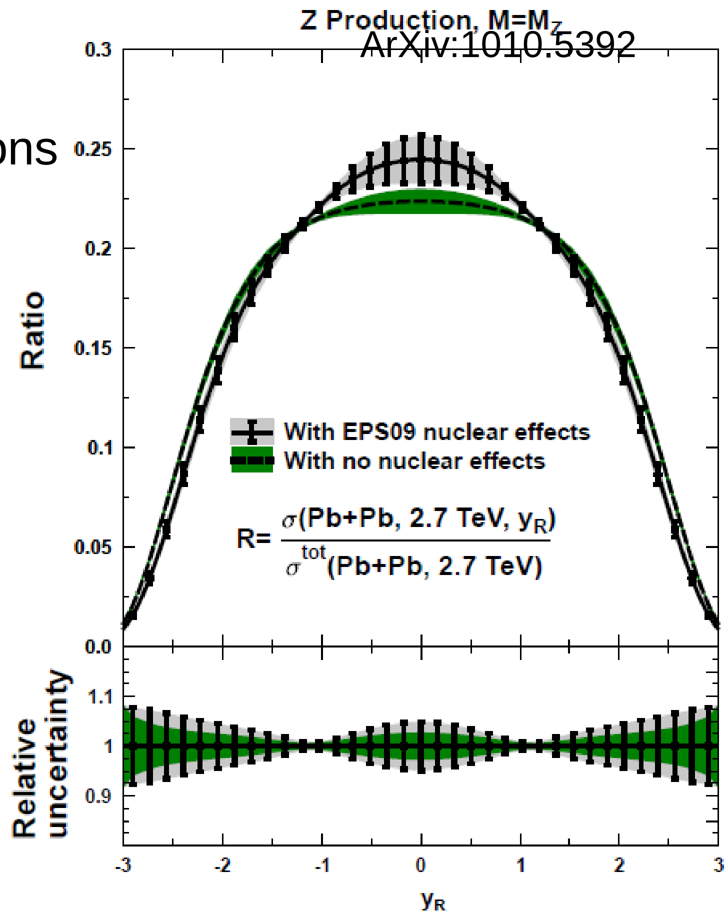
Electroweak probes

- 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

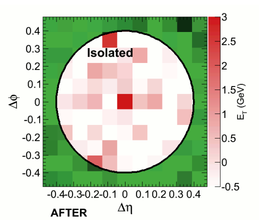
- Ideally: LO photons from hard scattering

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

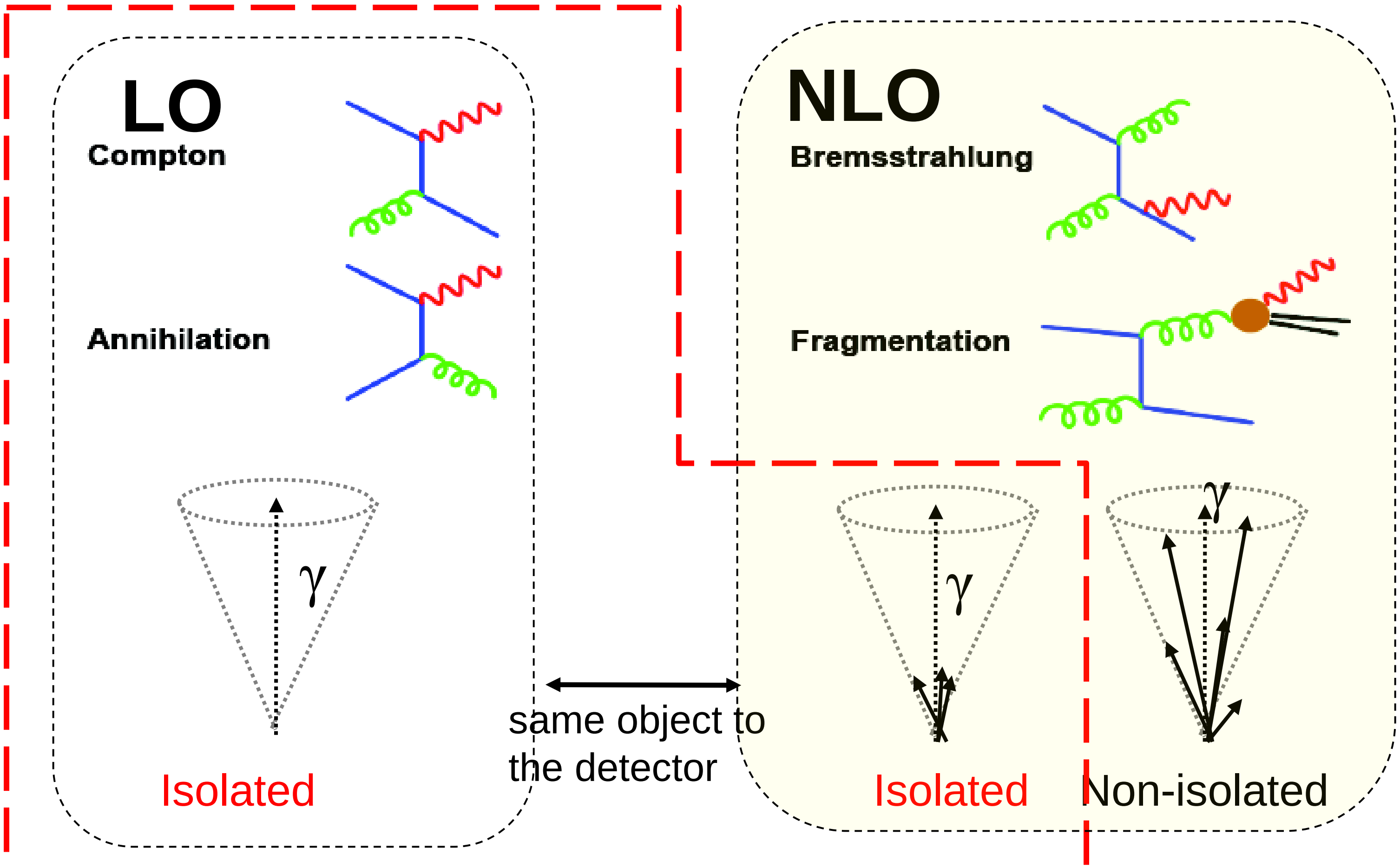
- Need a consistent definition between measurements and theoretical calculations

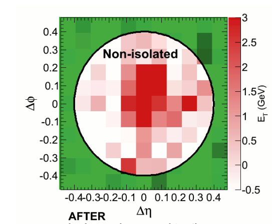
Isolated high p_T photons

- 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



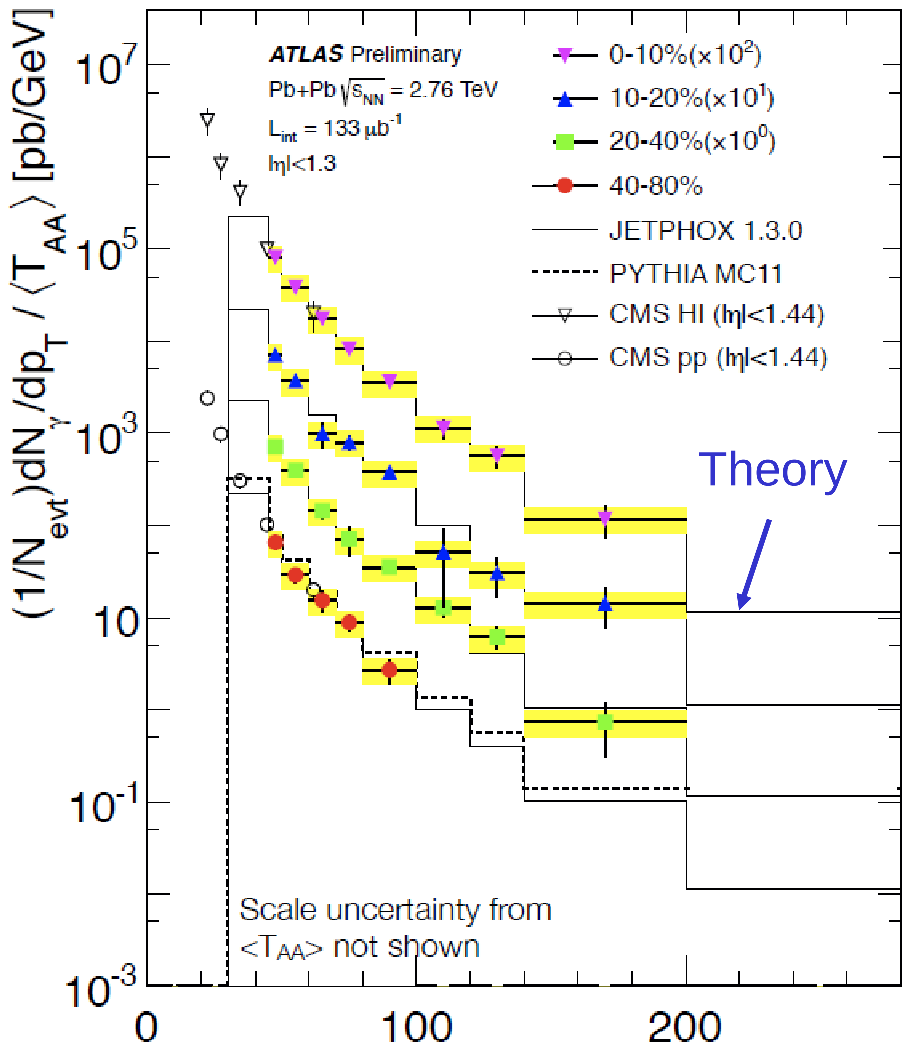
Isolated



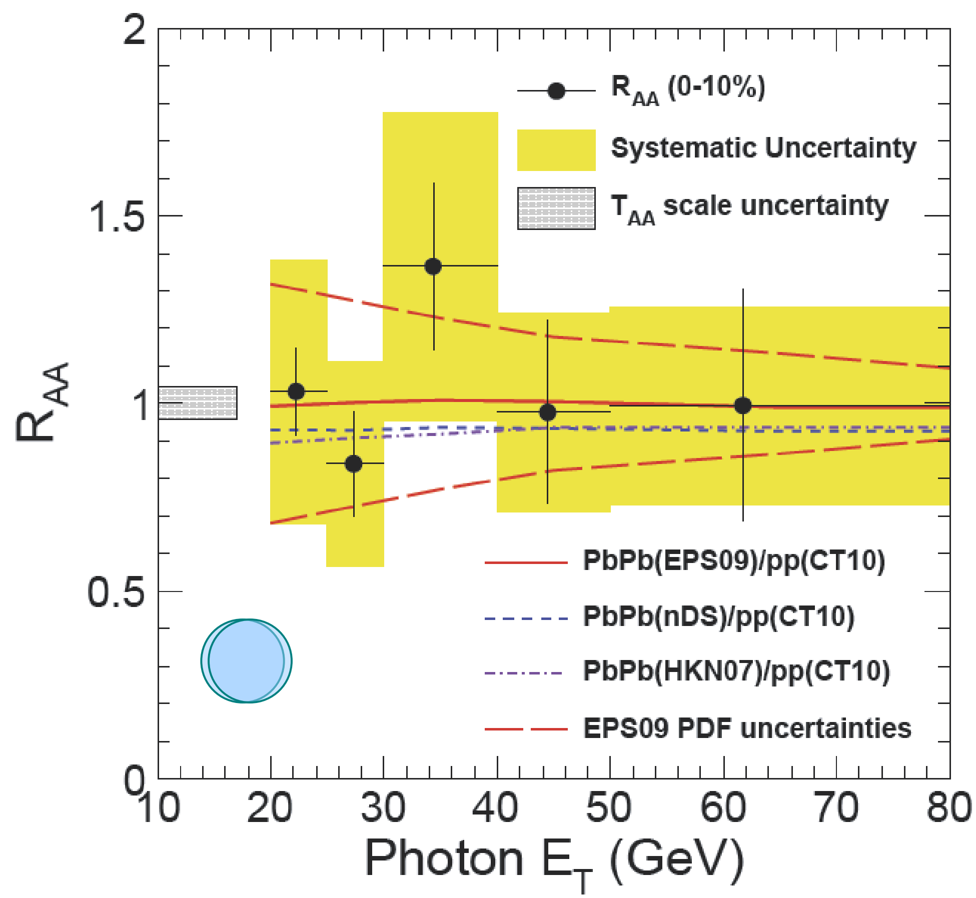


Non-isolated

Isolated photon R_{AA}

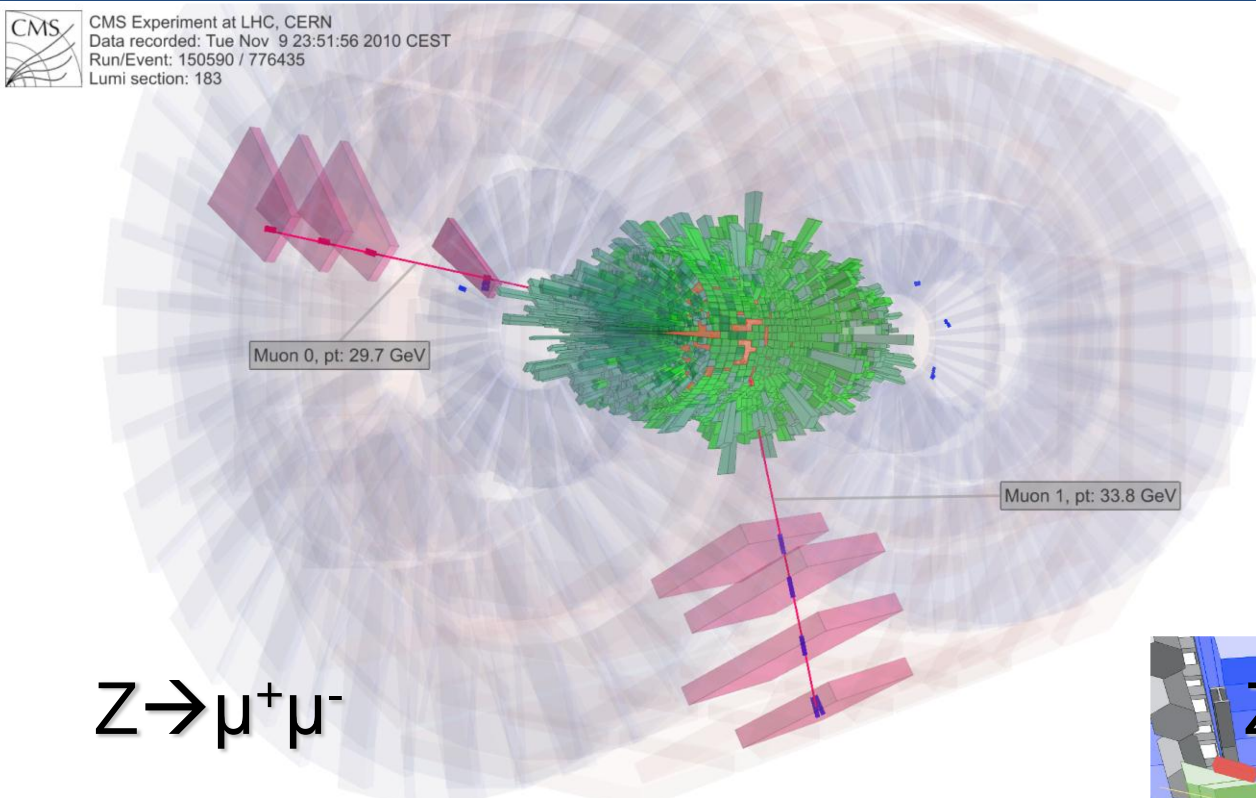


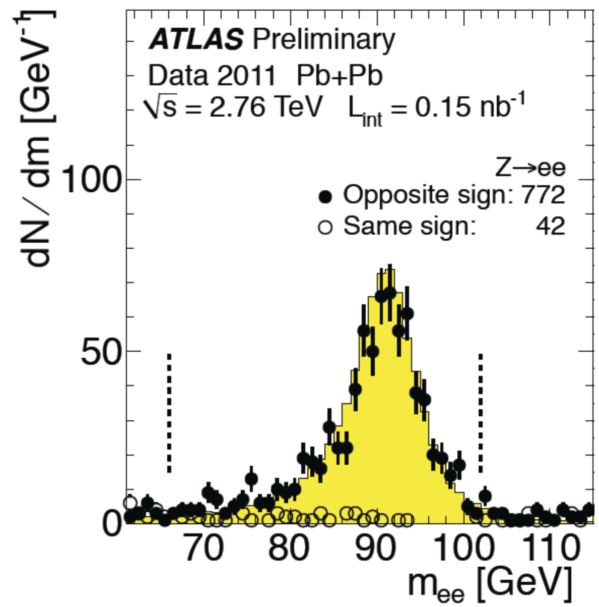
0-10% PbPb compared to pp

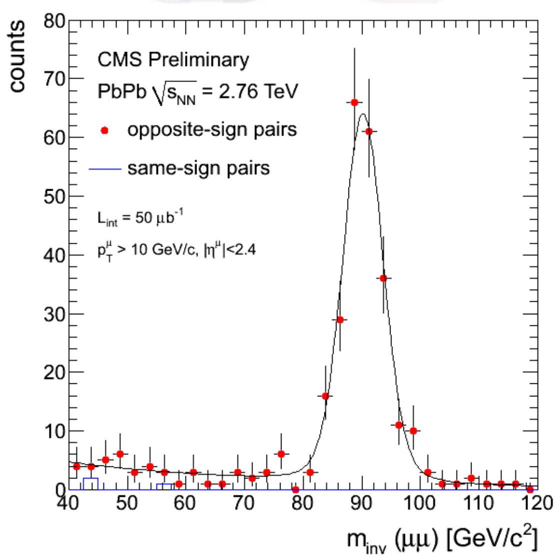


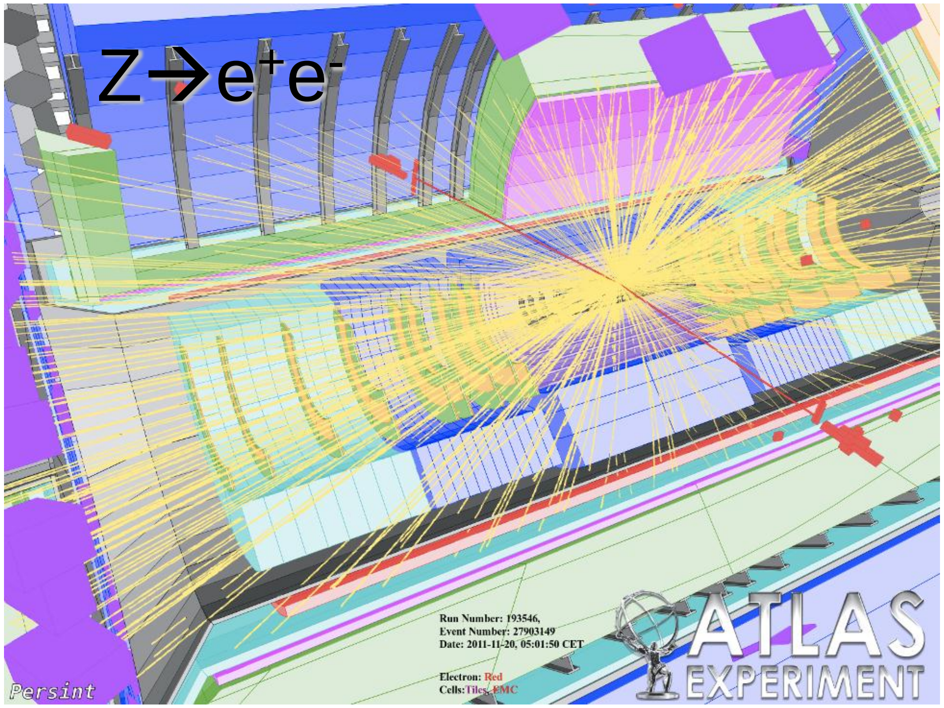
- No modification of the photons as expected!

Z boson production in PbPb collisions



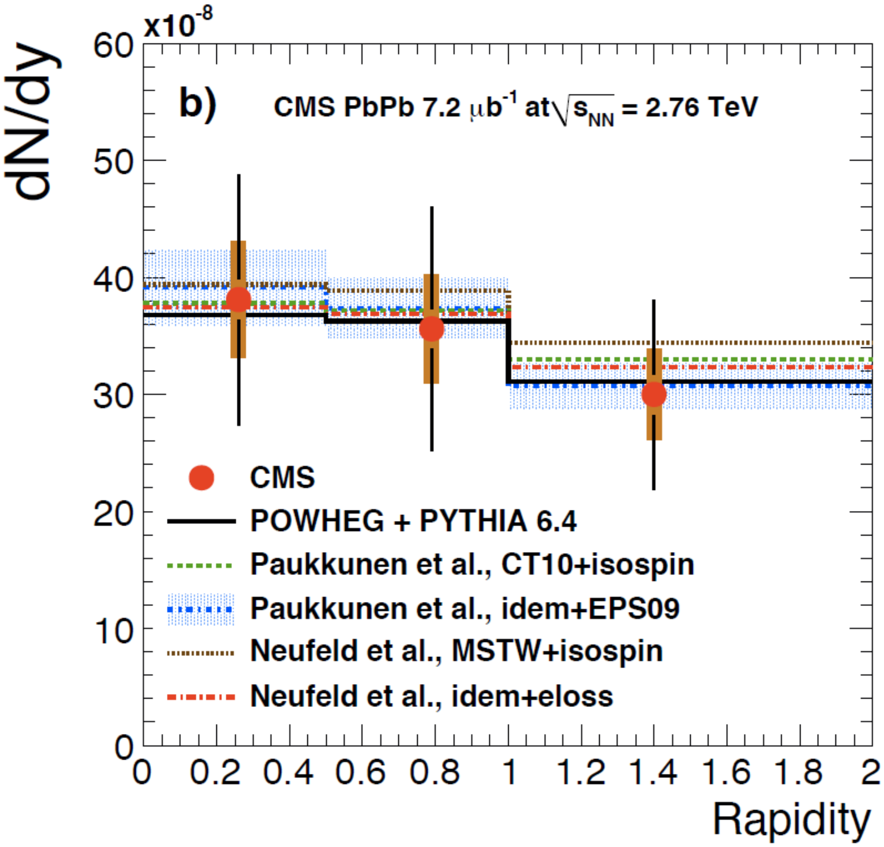


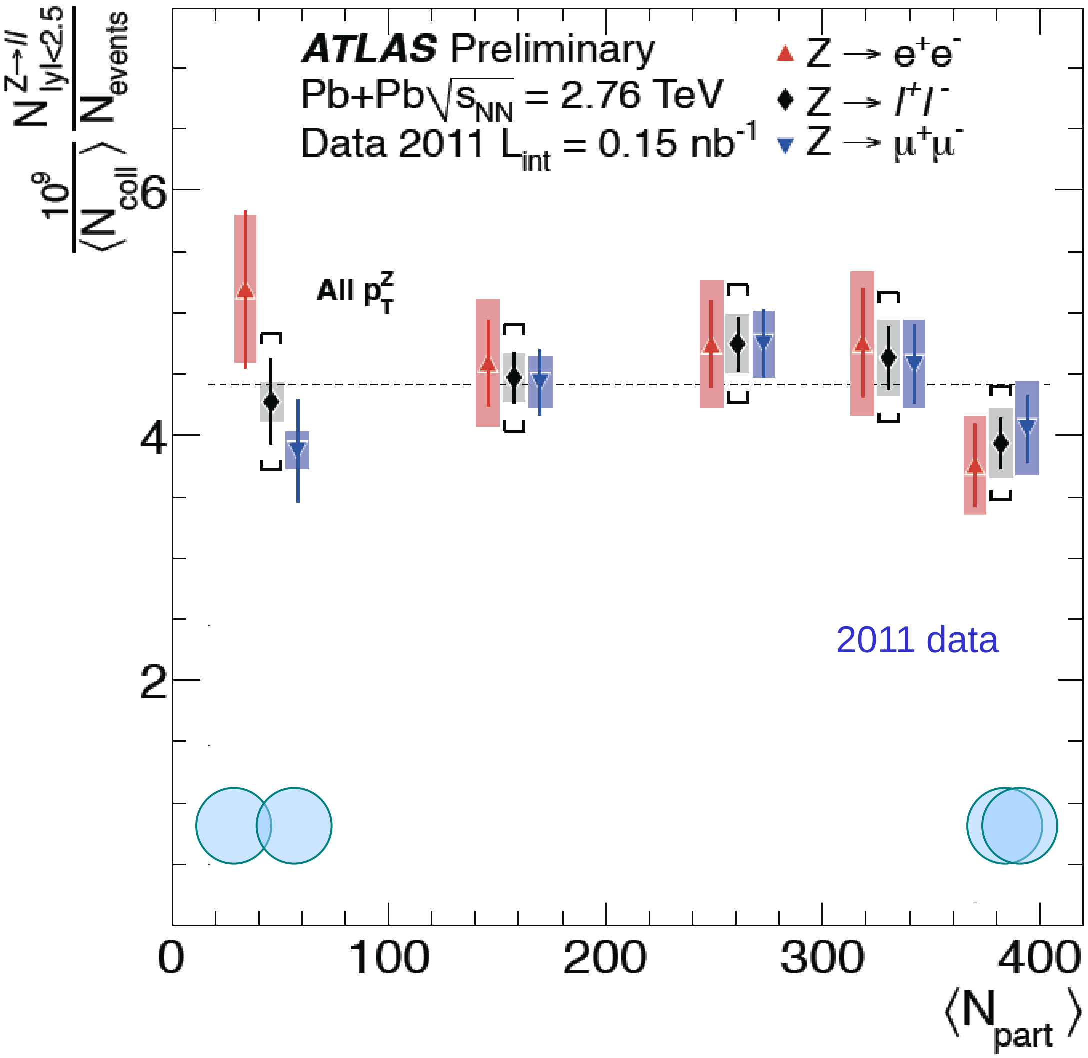




Z boson production in PbPb collisions

2010 data



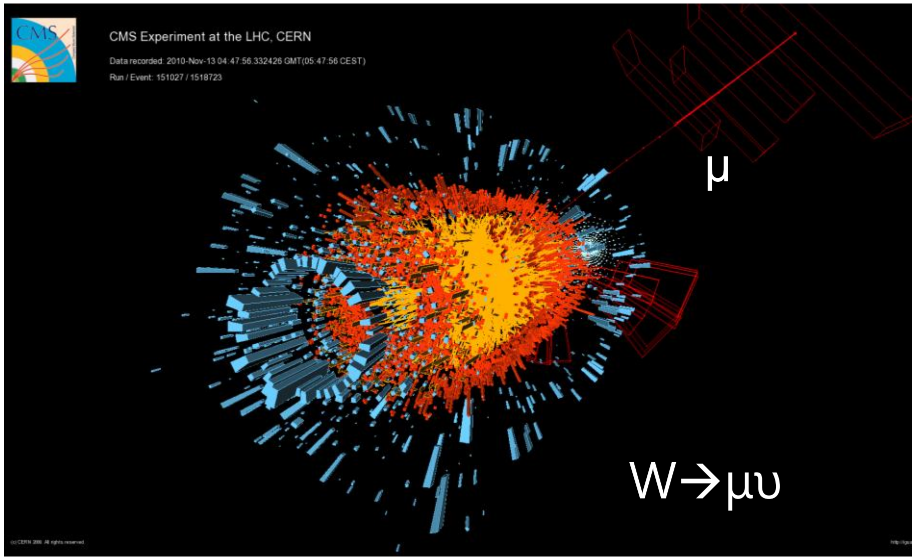


2011 data

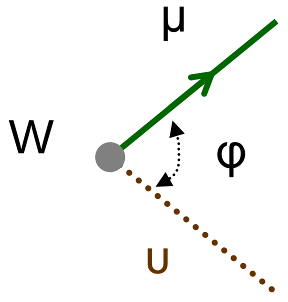
- No modification is found with respect to the pp reference

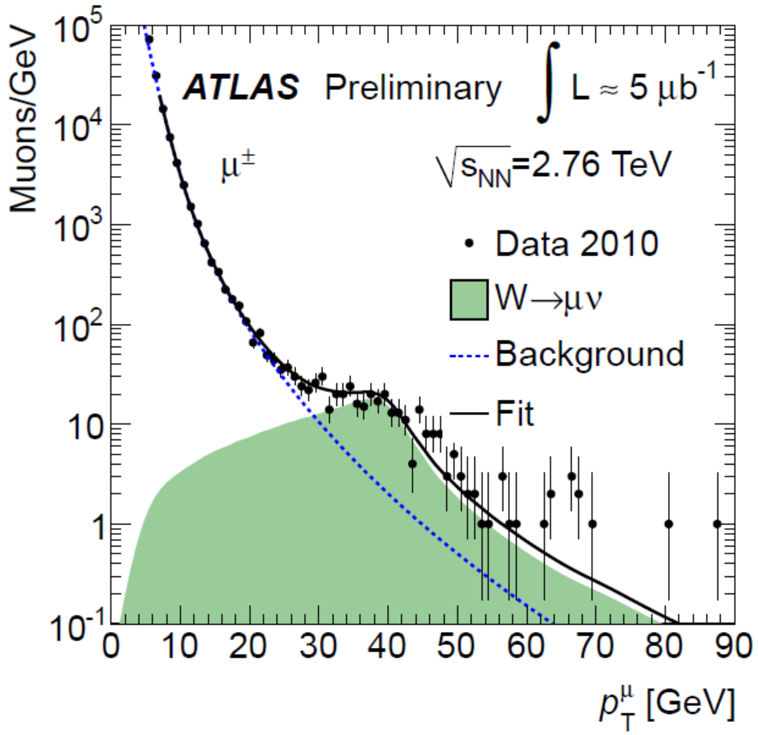
- Normalized yield is not varying as a function of centrality

W boson

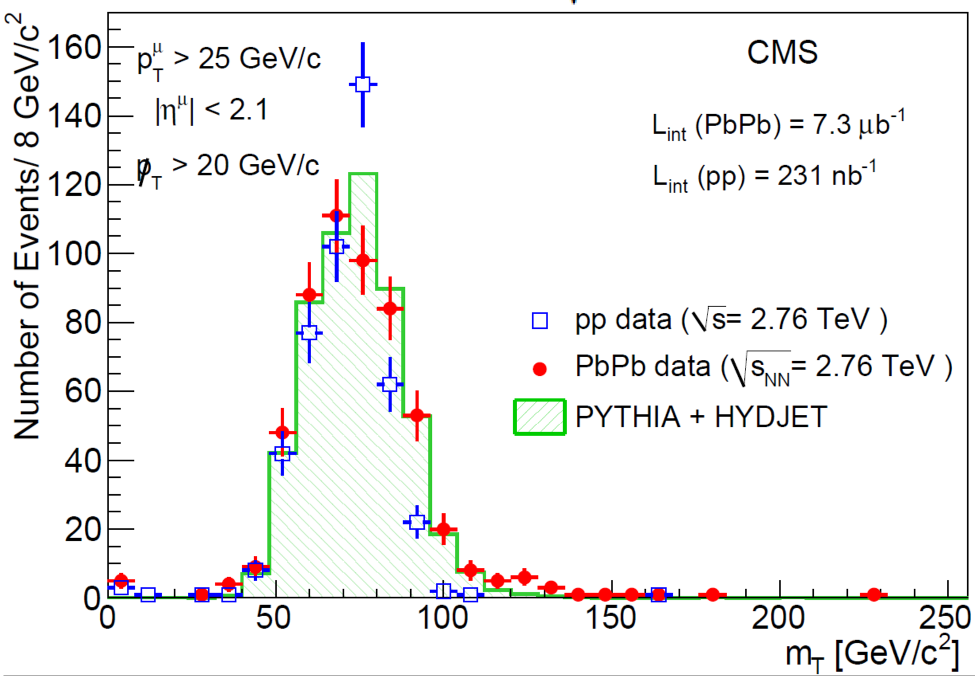


W→μυ Single high p_T μ + Missing p_T



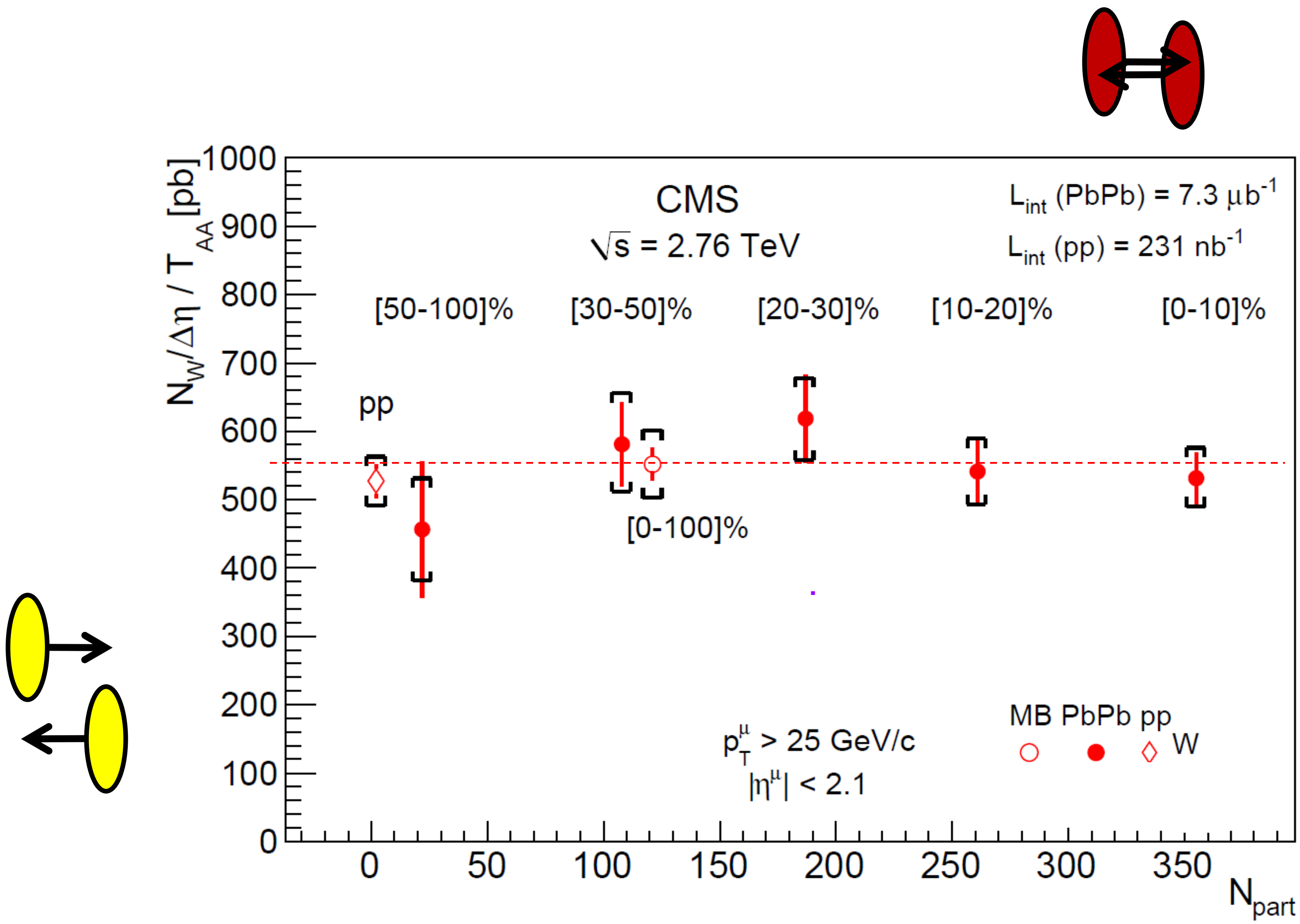


Transverse mass $m_T = \sqrt{2p_T^{\mu}\not{p}_T(1-\cos\phi)}$



W boson R_{AA}

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



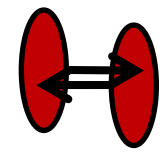
- Normalized yield is not varying as a function of centrality

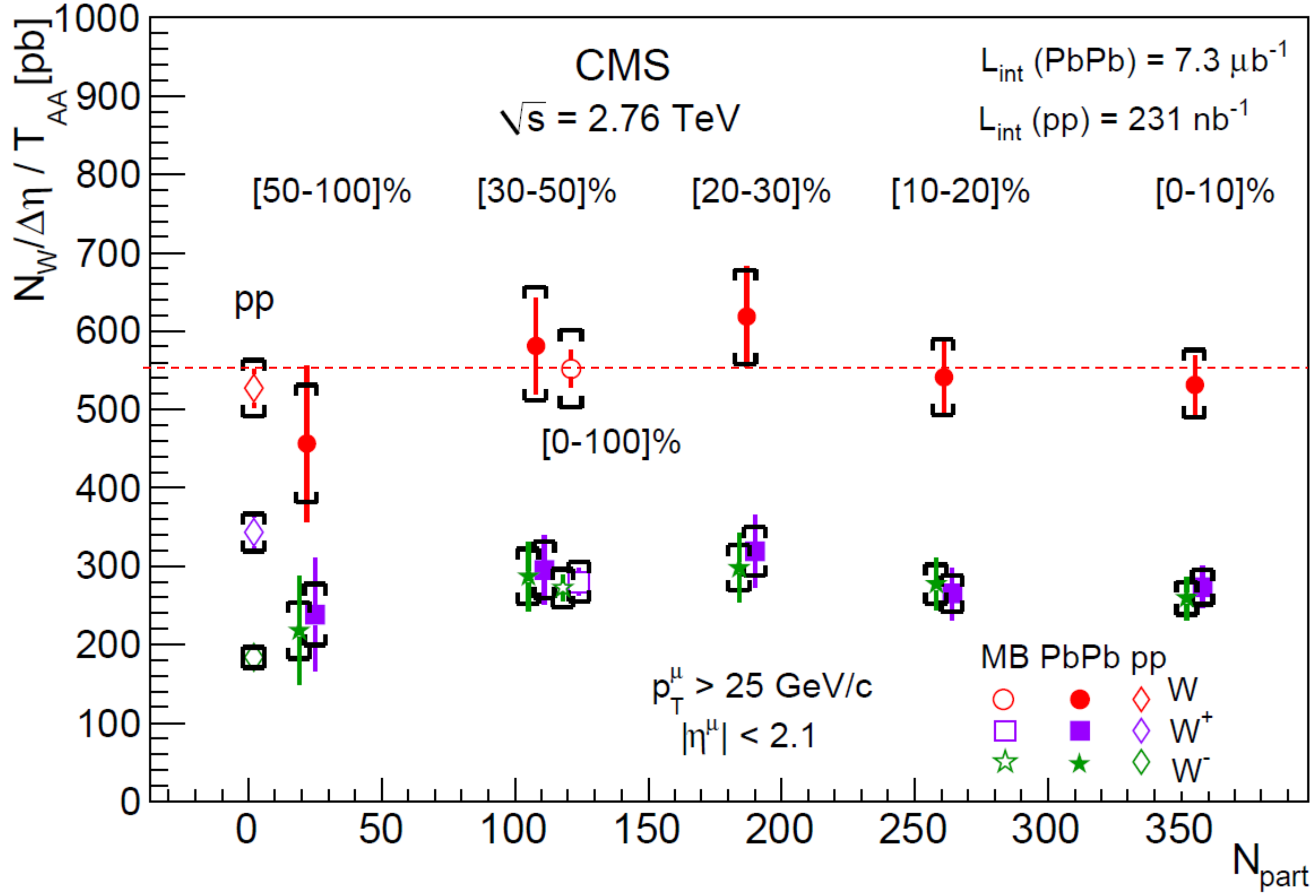
W boson R_{AA}

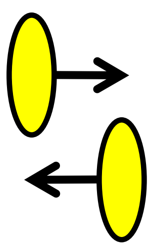
$R_{AA}(W) = 1.04 \pm 0.07 \pm 0.12$

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

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



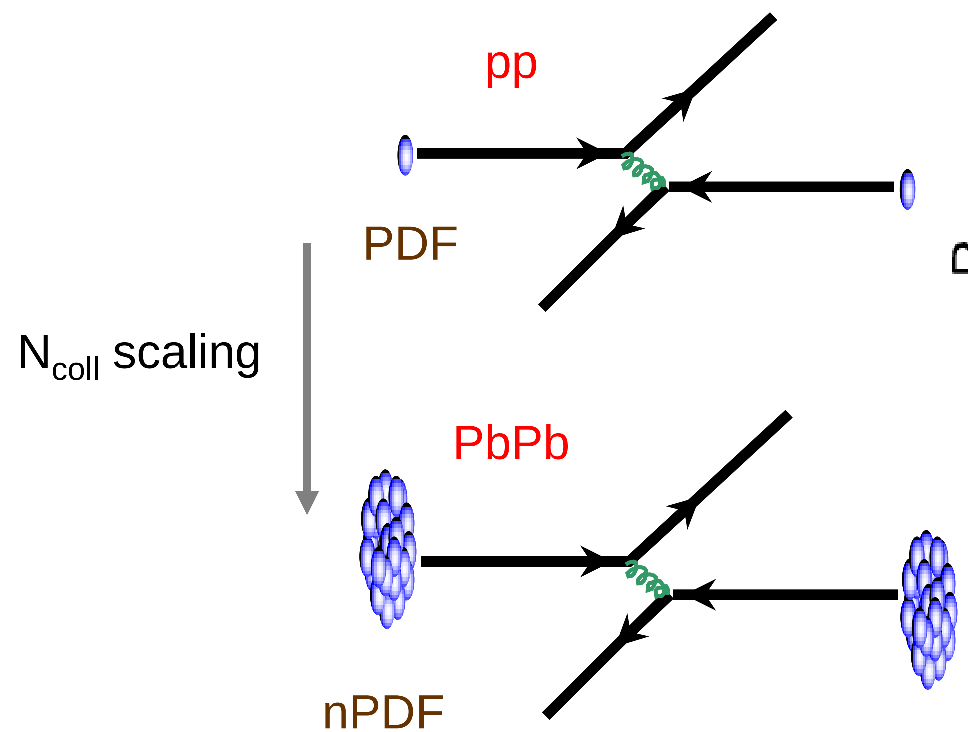


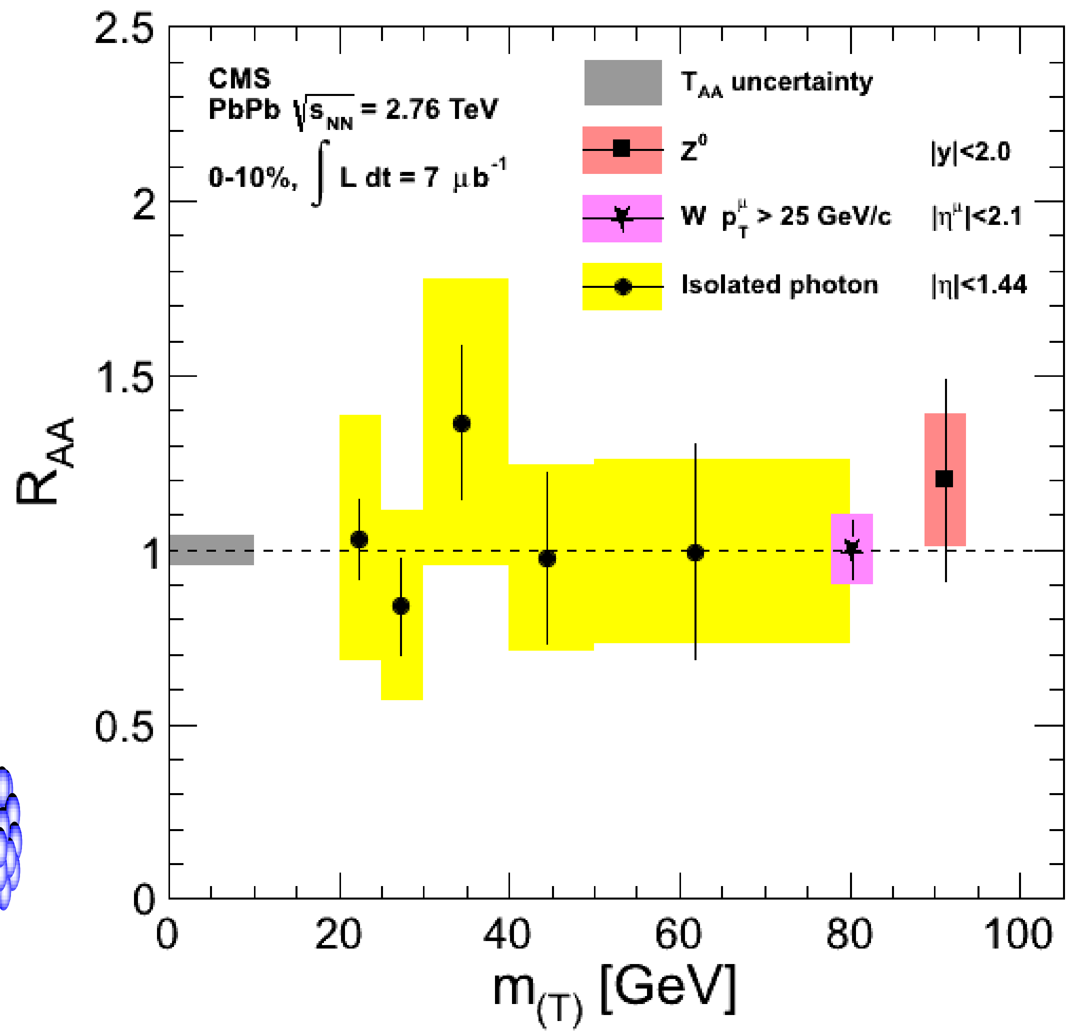


- Isospin effect is seen if we differentiate W^{+} and W^{-}

Summary of electroweak probes

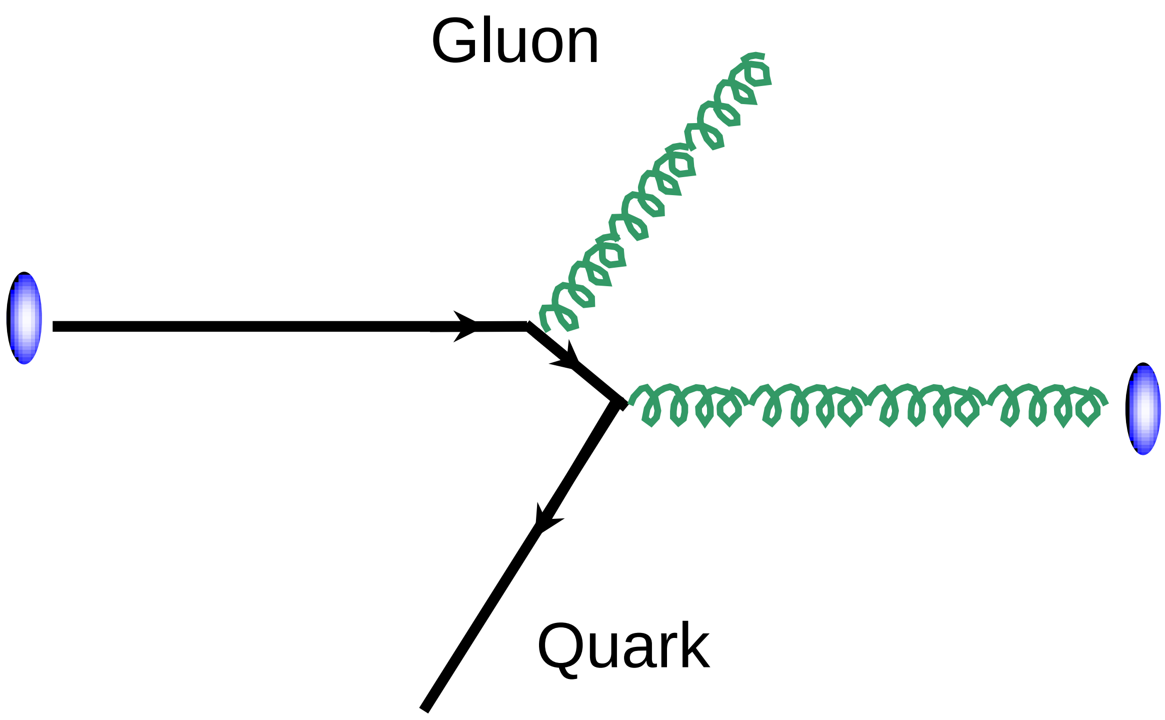
- Electroweak probes are unmodified
- Confirmed N_{coll} scaling of hard scattering
- Constraint nuclear Parton Distribution Function





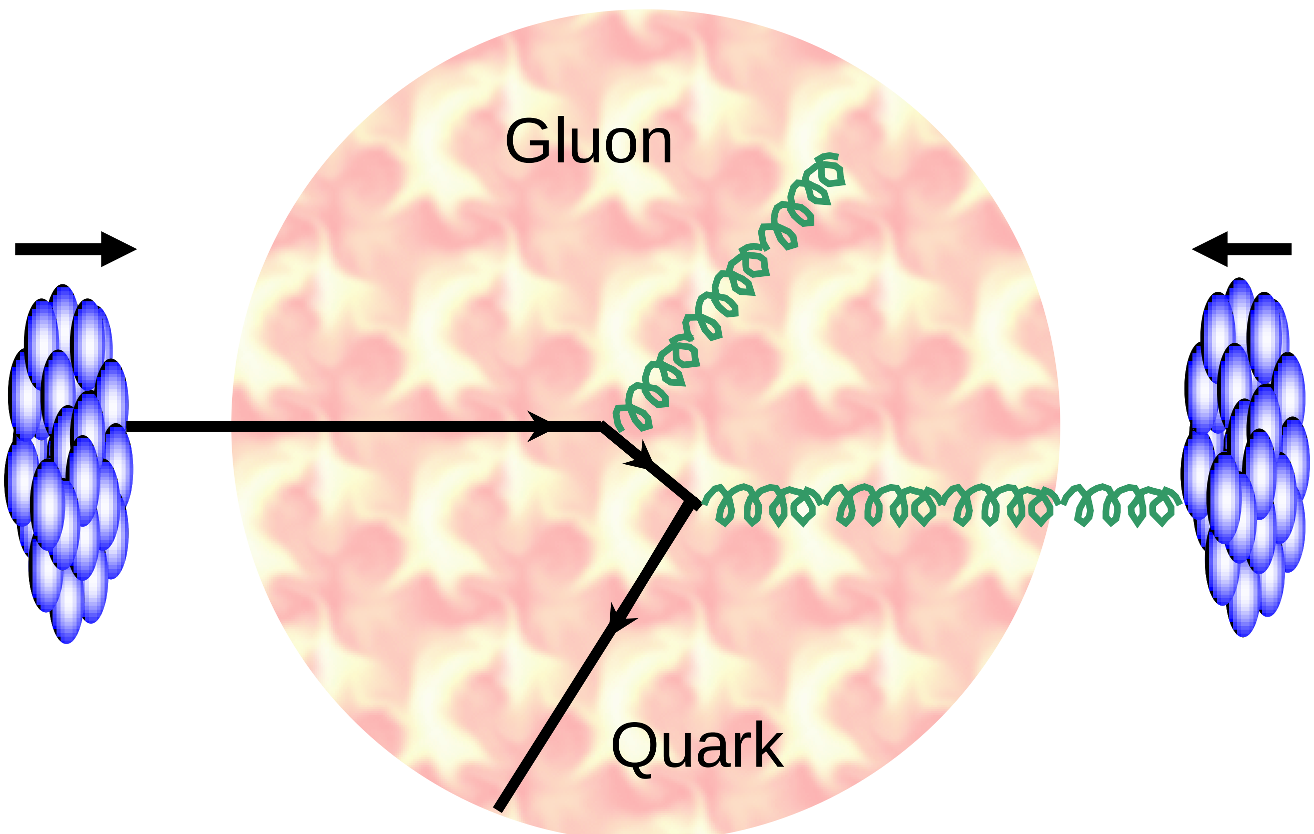
How about quarks and gluons?

Quarks and gluons in pp collisions

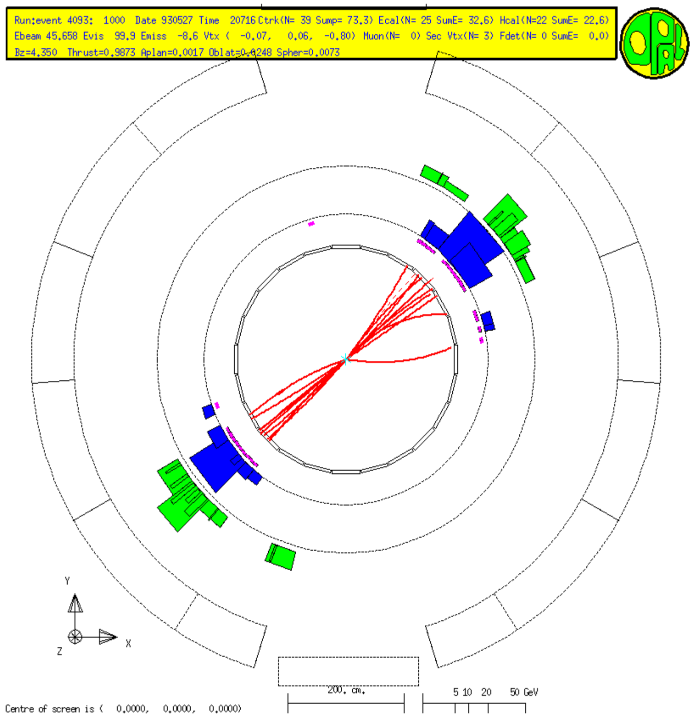


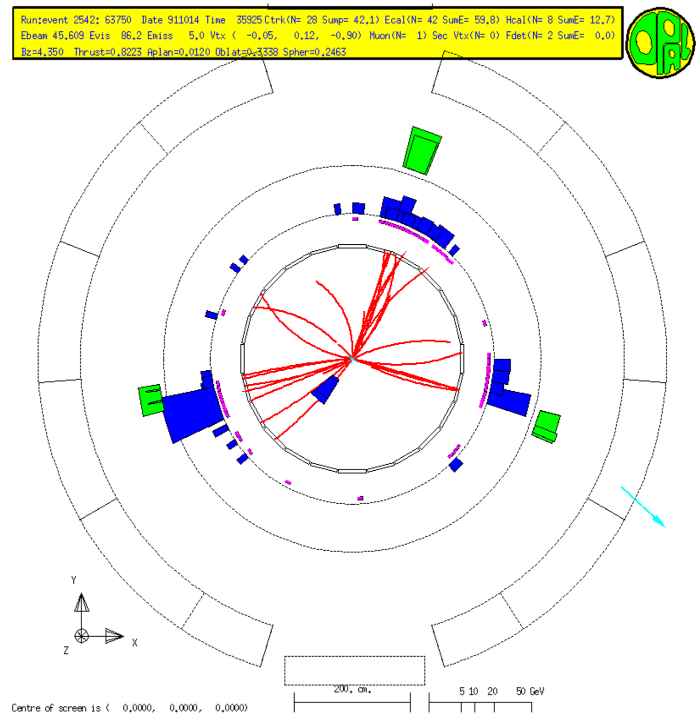
How about quarks and gluons?

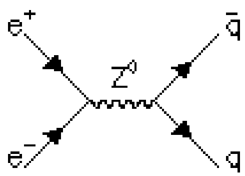
Want to measure quarks and gluons which carry color charge and see how they interact with QGP

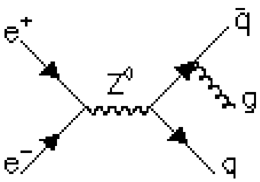


Quarks and gluons







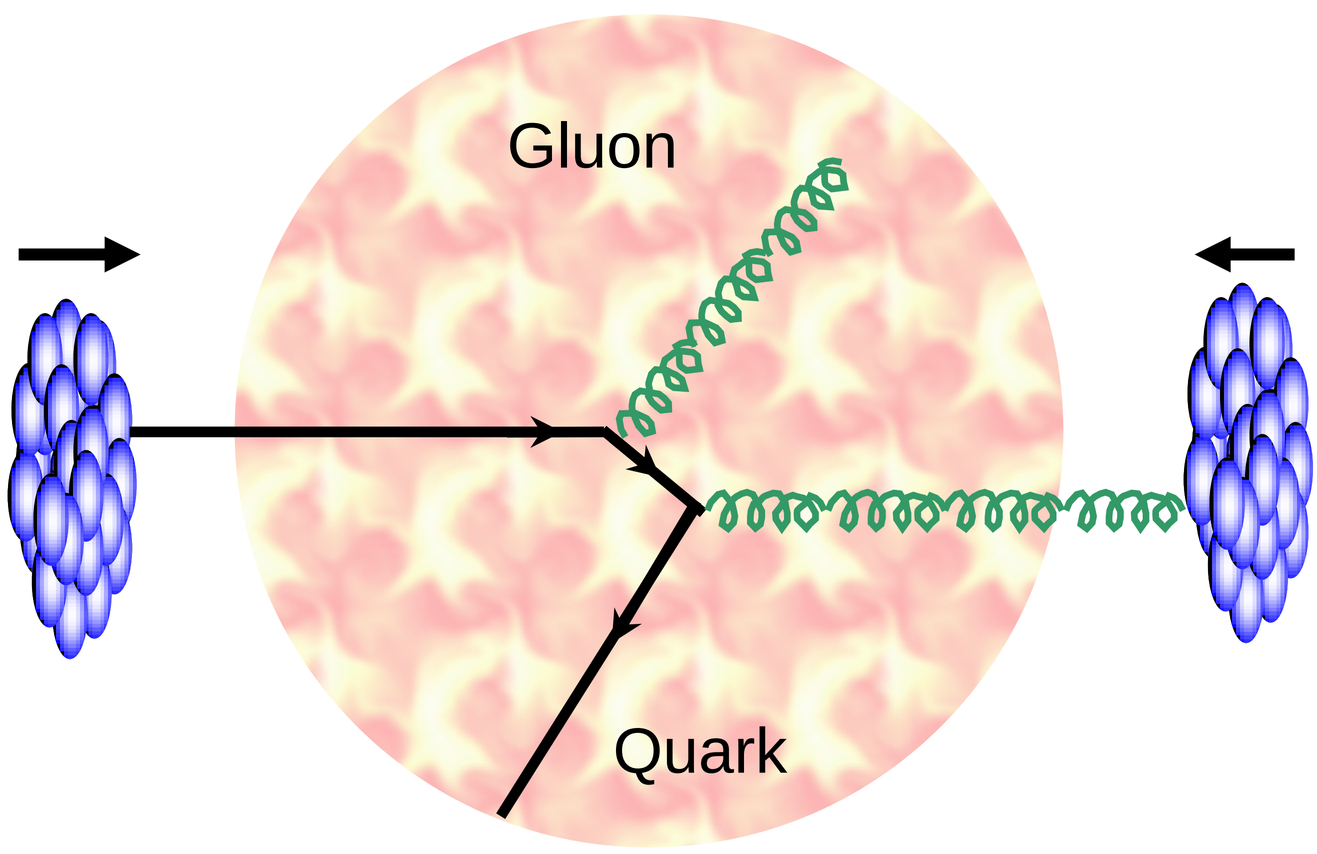


Color confinement:

Quarks and gluons → groups of hadrons

How about quarks and gluons?

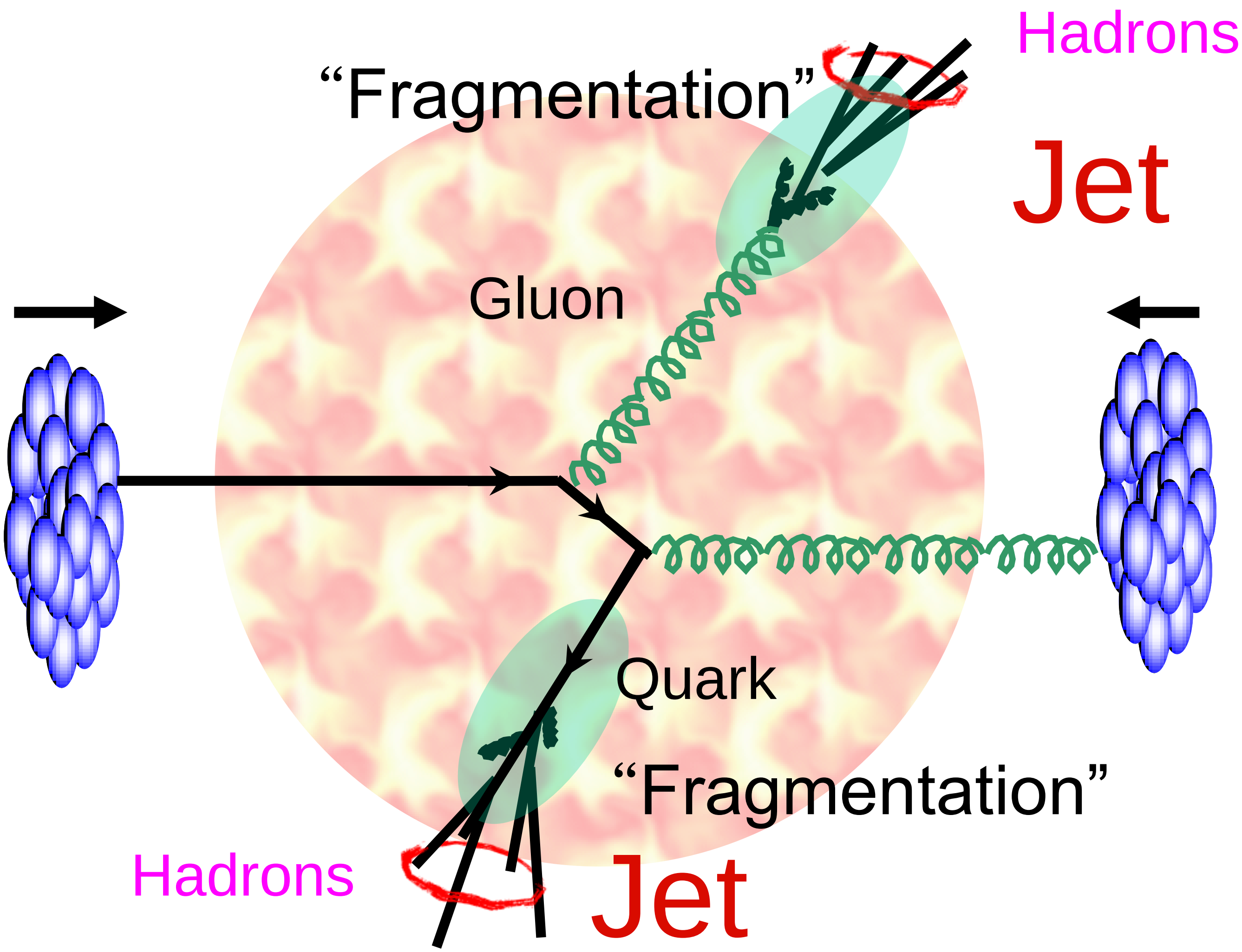
Want to measure quarks and gluons which carry color charge and see how they interact with QGP



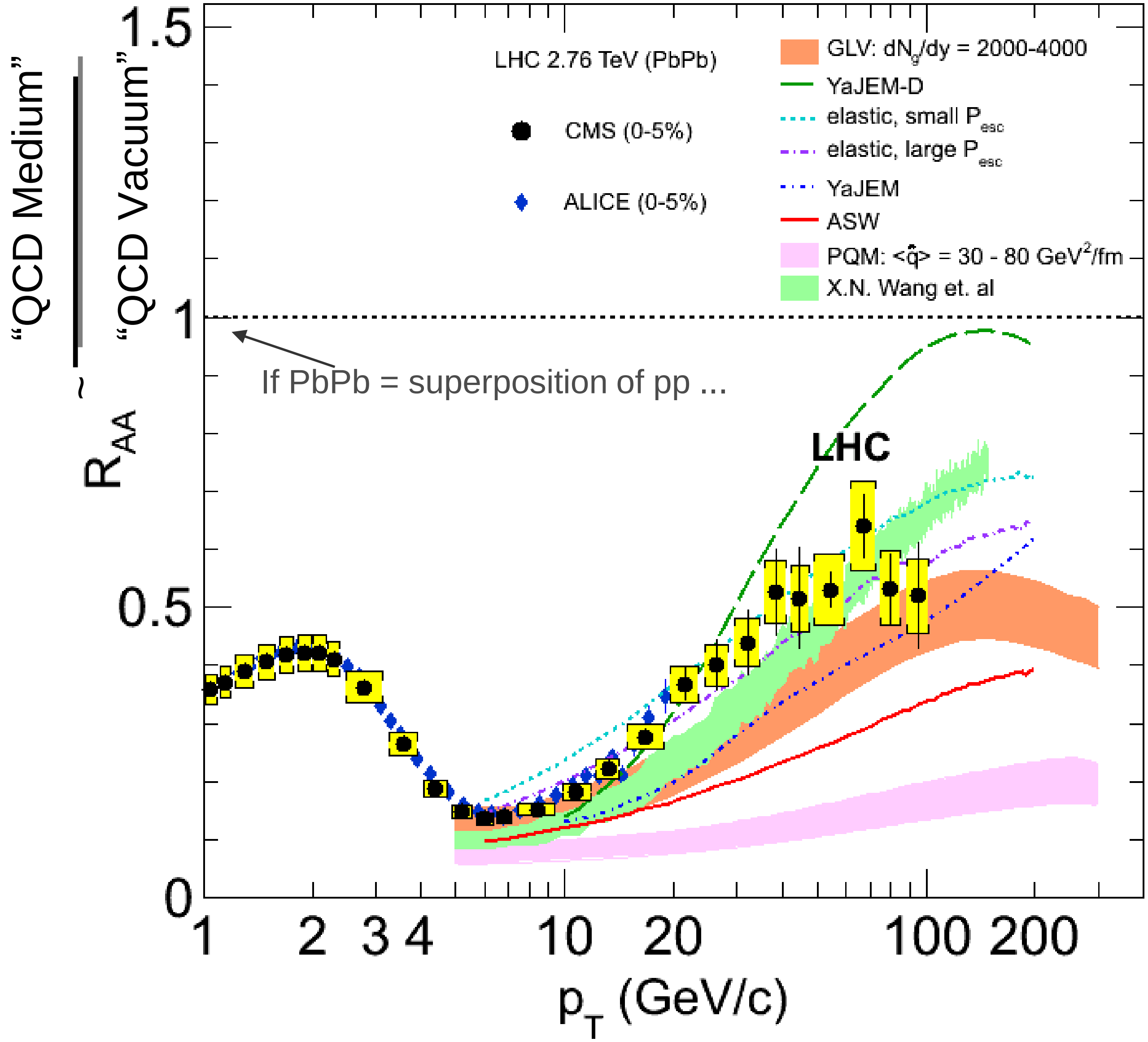
How about out going quarks and gluons?

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

→ Practically: measure hadrons and jets

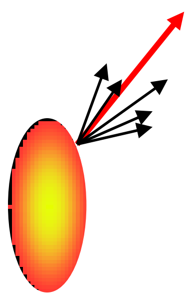


An easier measurement: charged particle R_{AA}



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

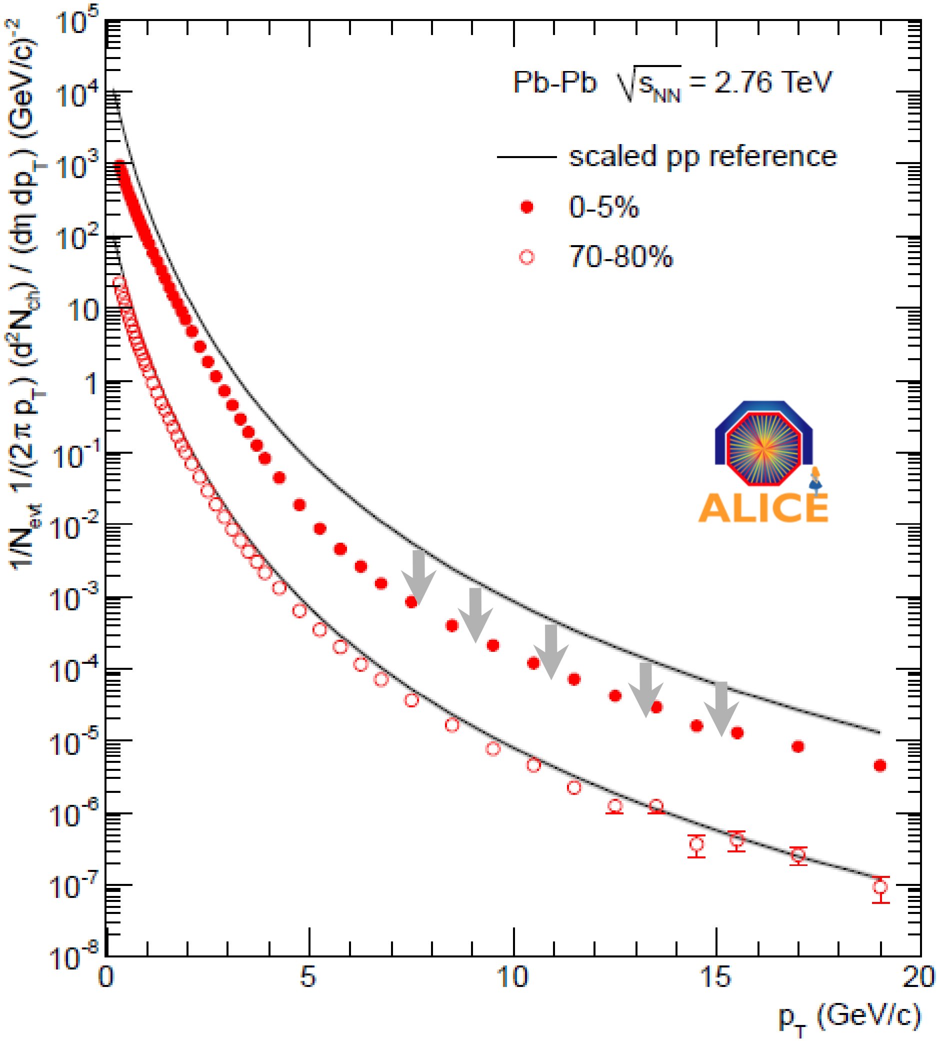
N_{coll} validate by photons W/Z bosons



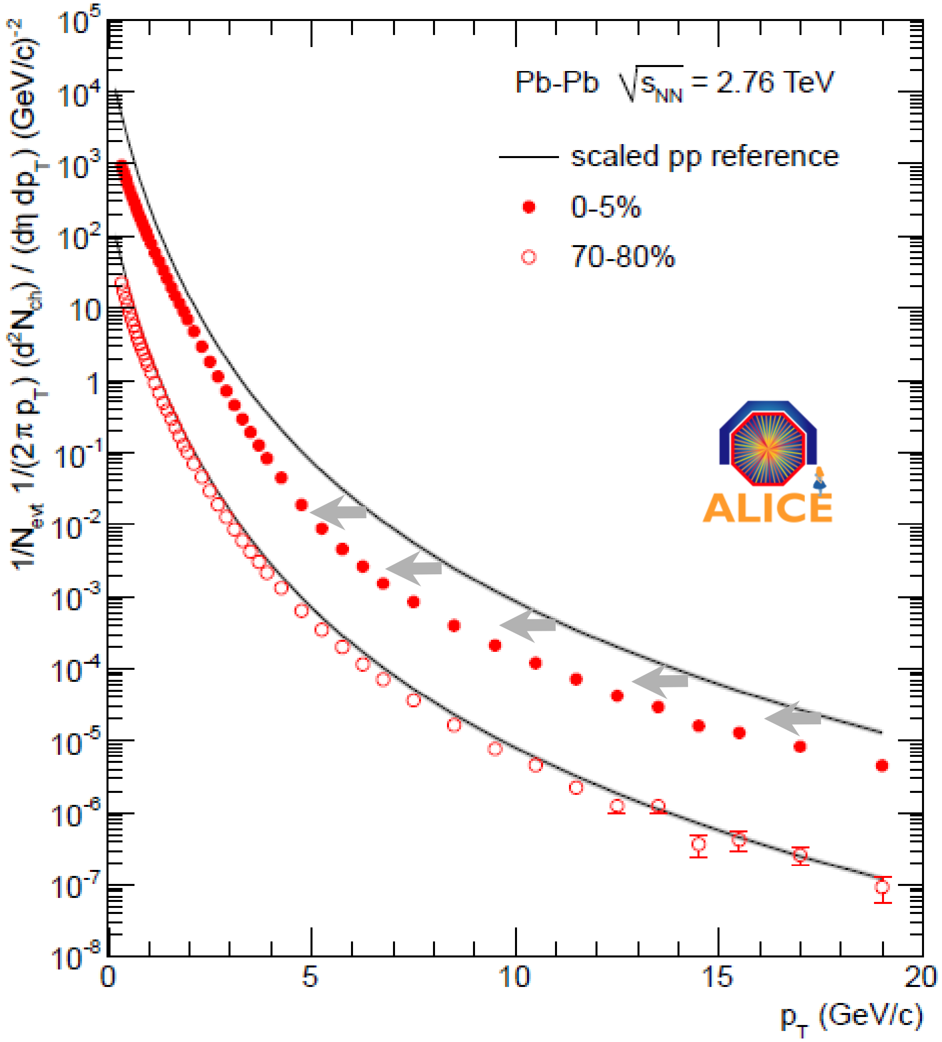
Provide constraints on the parton energy loss models

Charged particle spectra

Absorption?



Energy loss?

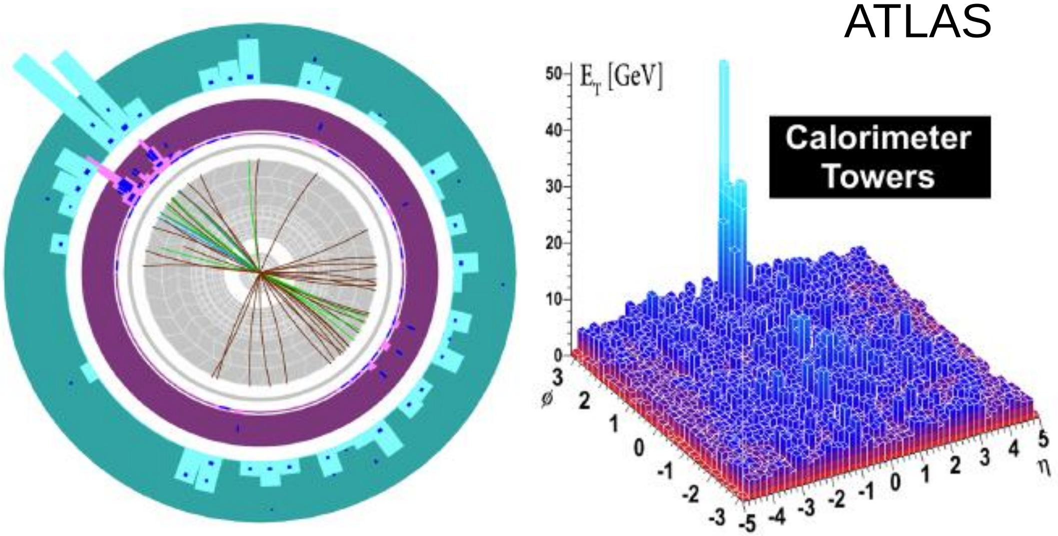


Single hadron spectra itself do not provide details of the underlying mechanism

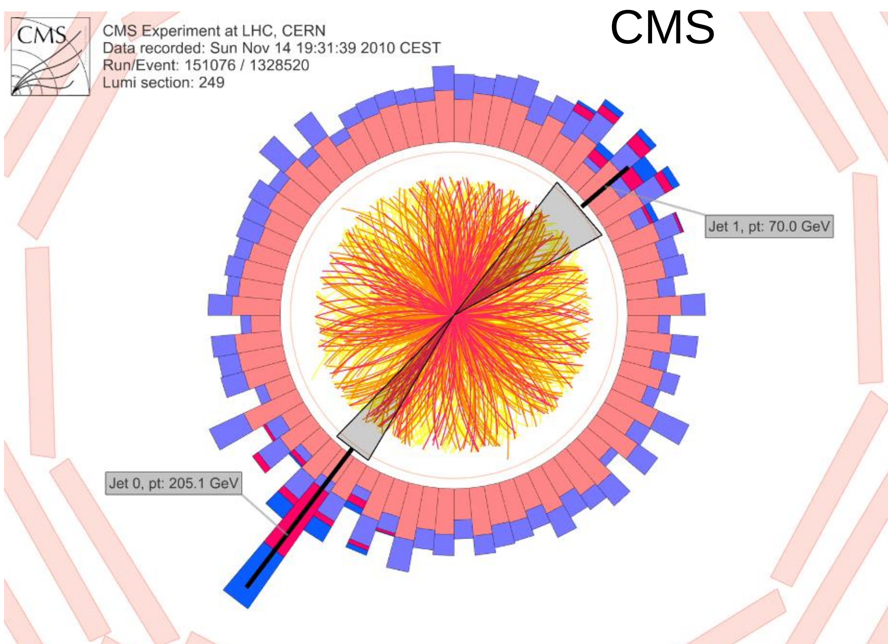
→ Need direct jet reconstruction and correlation studies

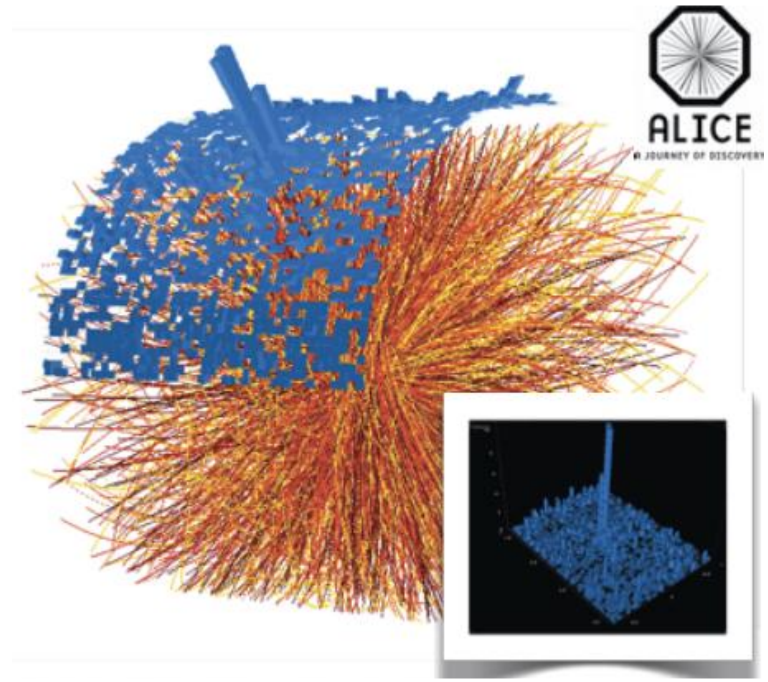
Jet events in PbPb collisions at LHC

ATLAS



CMS

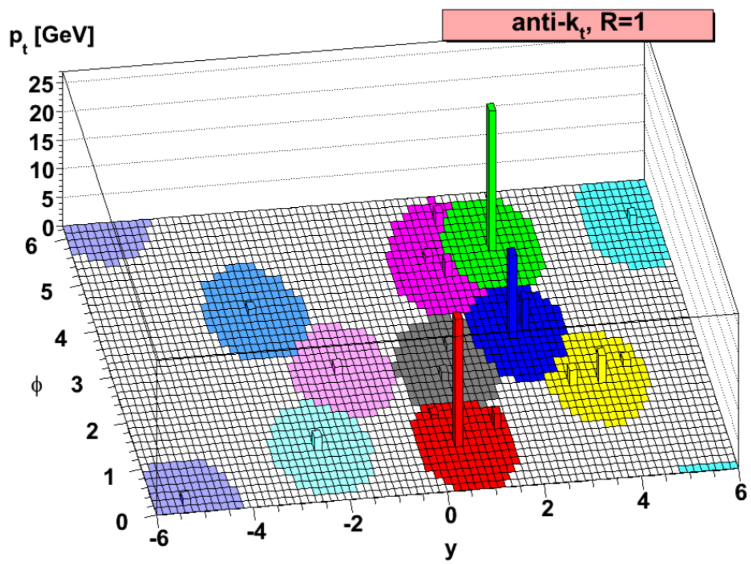




Jet reconstruction

Need rules to group the hadrons

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

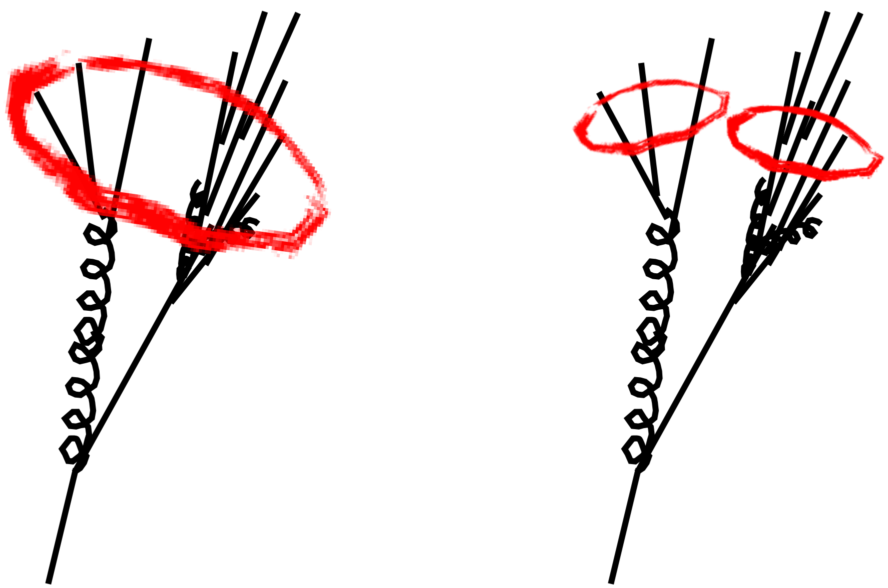


Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

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

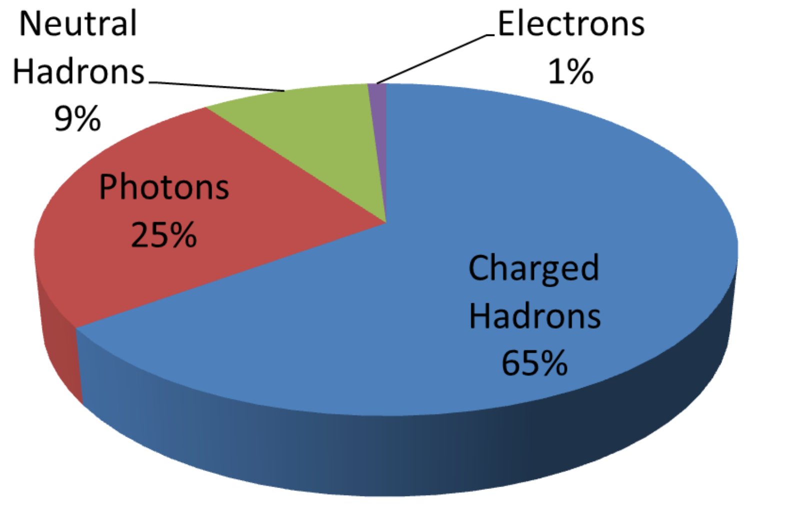
Jet composition

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

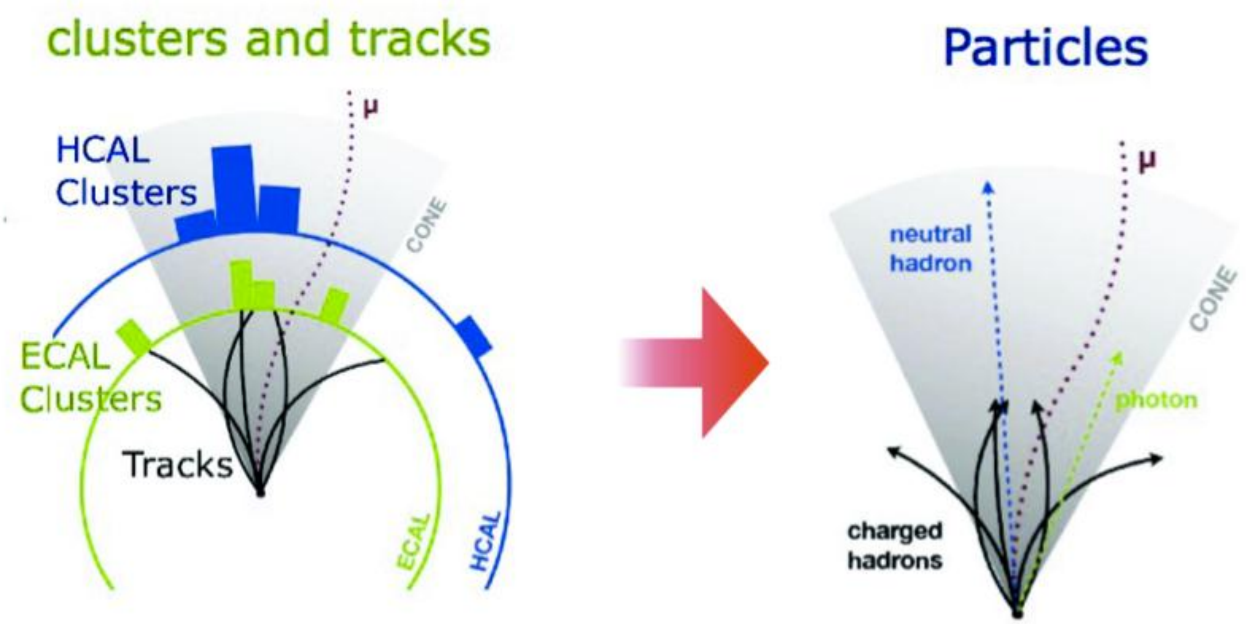
Measure the known part

Correct the rest by MC simulation

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



A typical high p_T jet



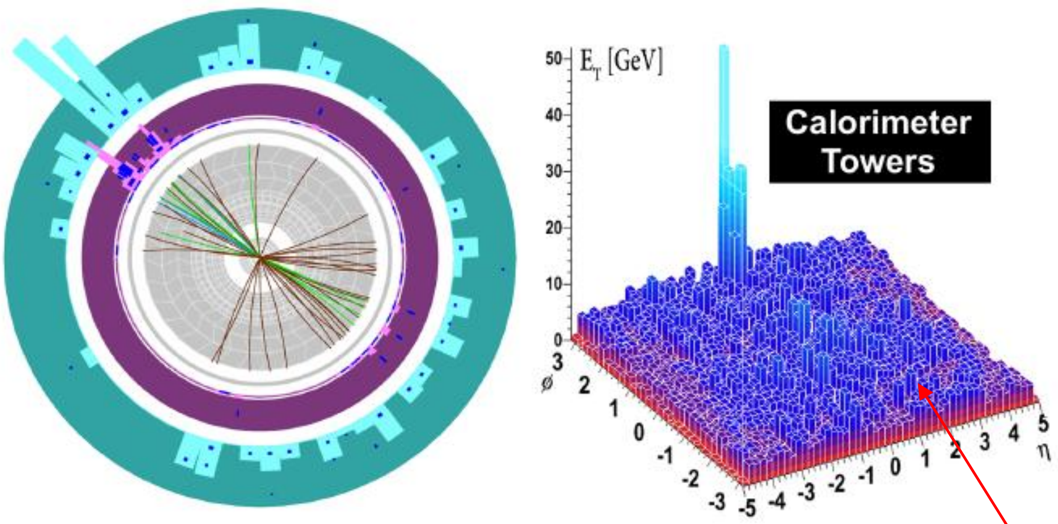
Goal:

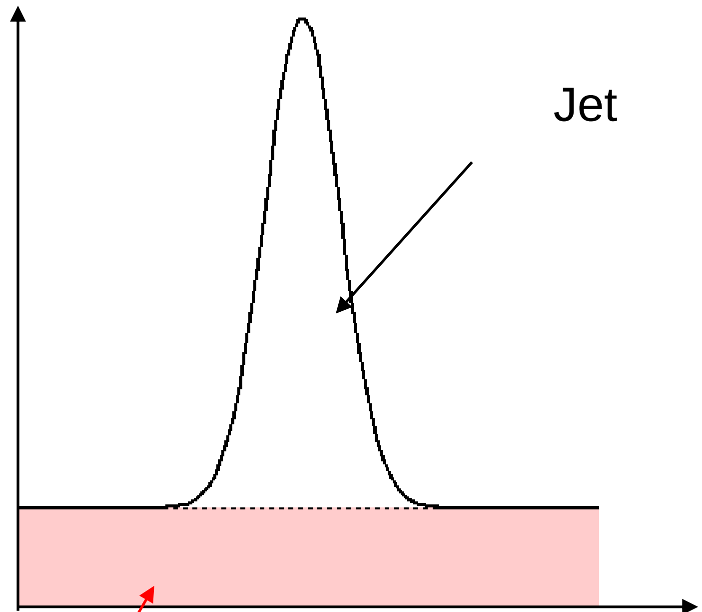
- Make use of the redundancy of measurements from calorimeter and tracker
- Improve the sensitivity to low p_T particles in jet
→Reduce the dependence on MC

(ex: PYTHIA)

Underlying event background

ATLAS



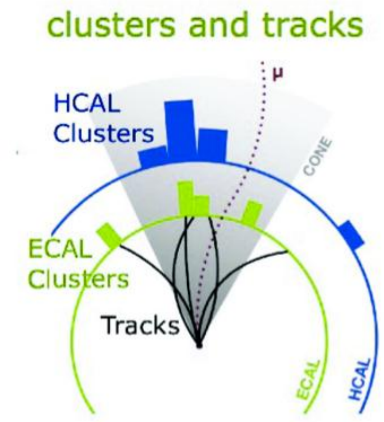


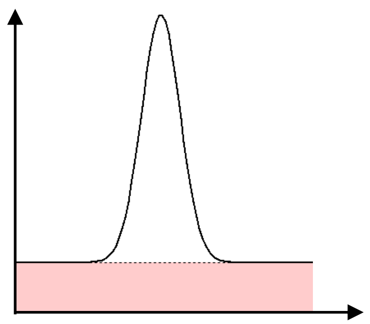
Multiple parton interaction

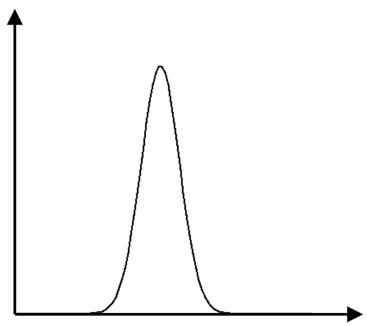
Large underlying event from soft scattering

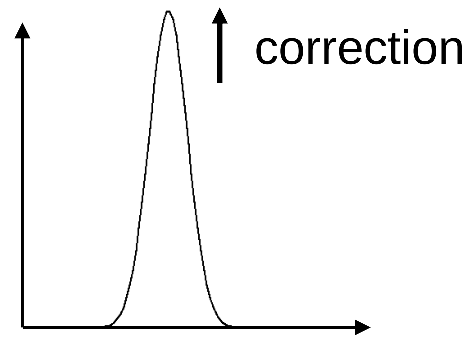
Need background subtraction

Summary of jet reconstruction









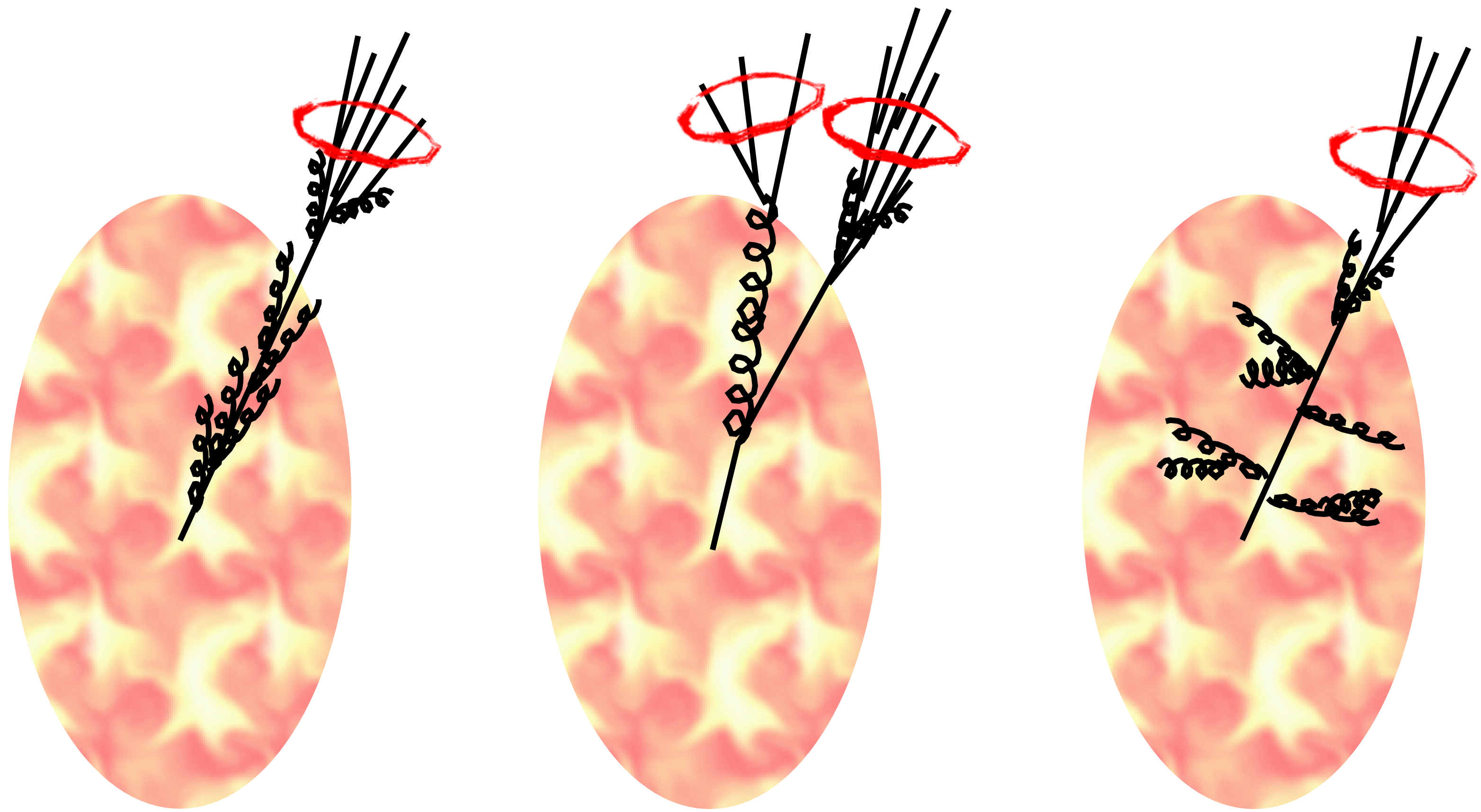
Raw jet energy → Background subtraction → Jet energy correction → Jet energy

Background subtraction: Remove underlying events contribution

Jet energy correction: MC Simulation PYTHIA

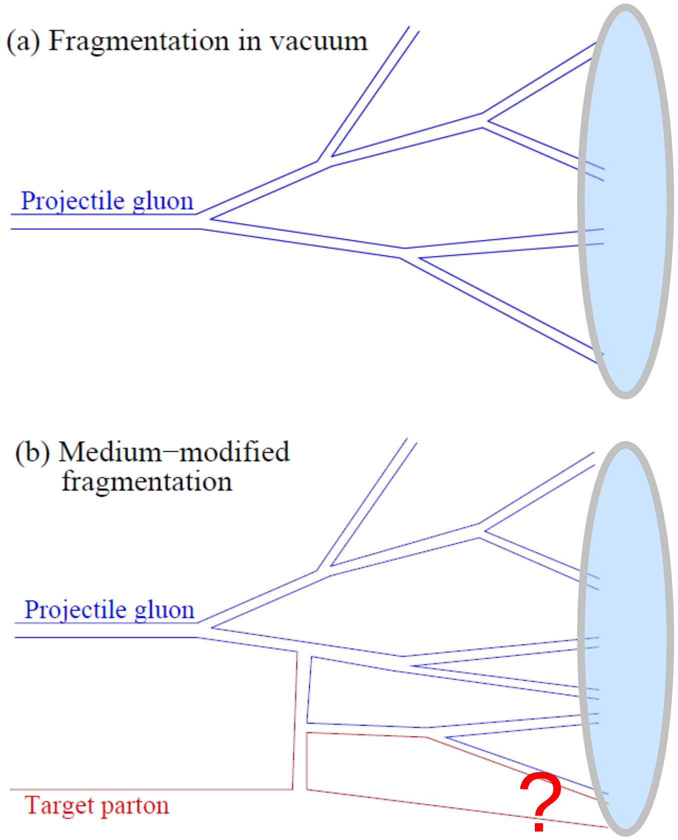
Three possible scenarios

To explain the suppression of high p_T particles



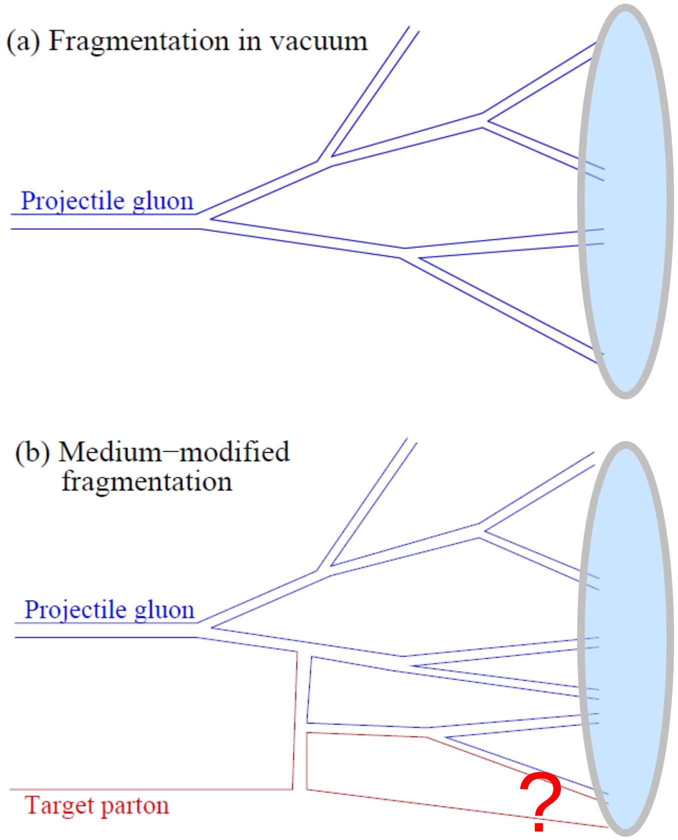
Soft collinear radiation	Hard radiation	Large angle soft radiation "QGP heating"
GLV + others	PYTHIA inspired models Modified splitting functions	AdS/CFT

Jet fragmentation function



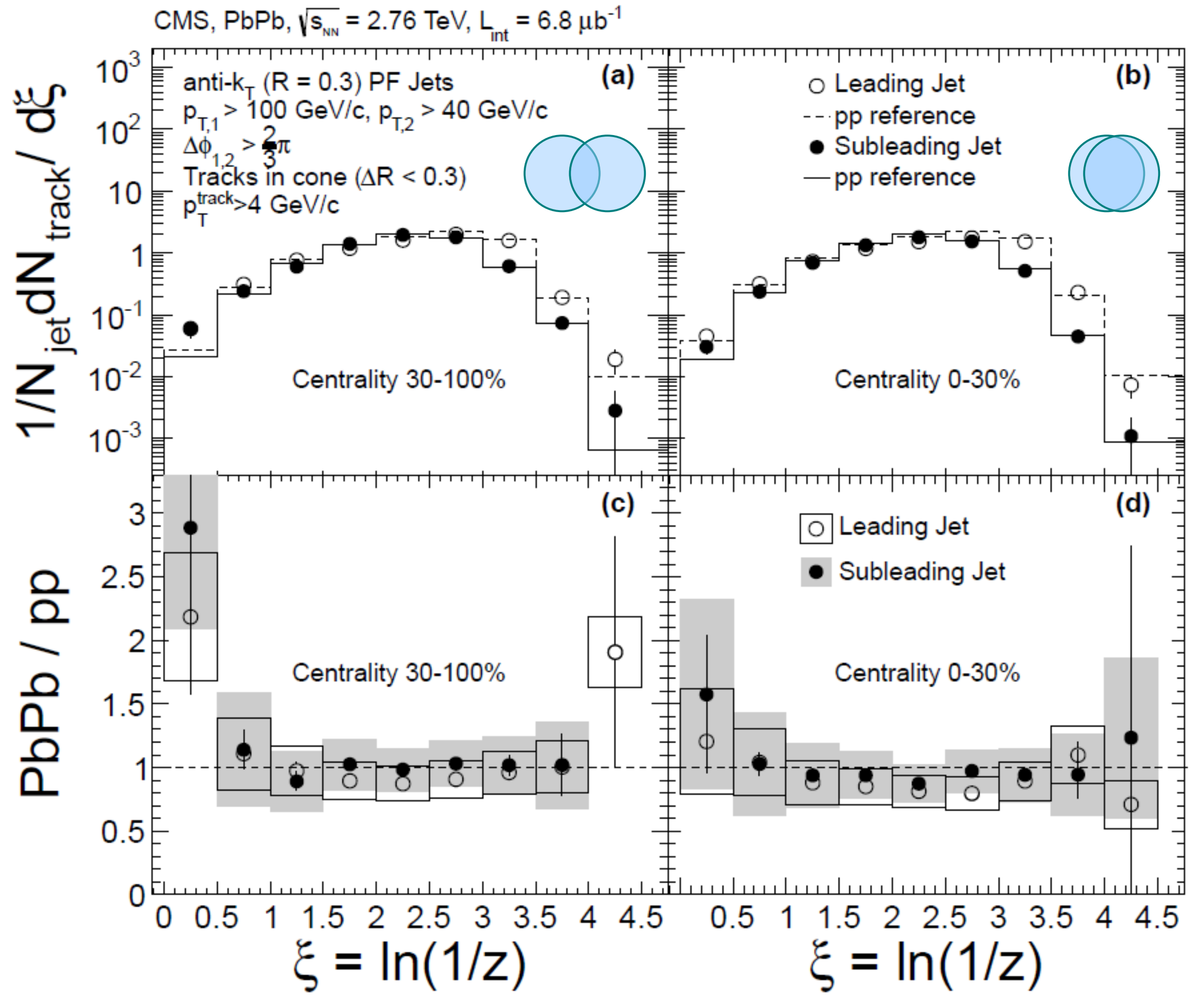
$$\xi = -\ln z = -\ln \frac{p_T^{track}}{p_T^{jet}}$$

Jet fragmentation function



$$\xi = -\ln z = -\ln \frac{p_T^{track}}{p_T^{jet}}$$

Select Tracks in $\Delta R=0.3$ cone $p_T > 4$ GeV/c



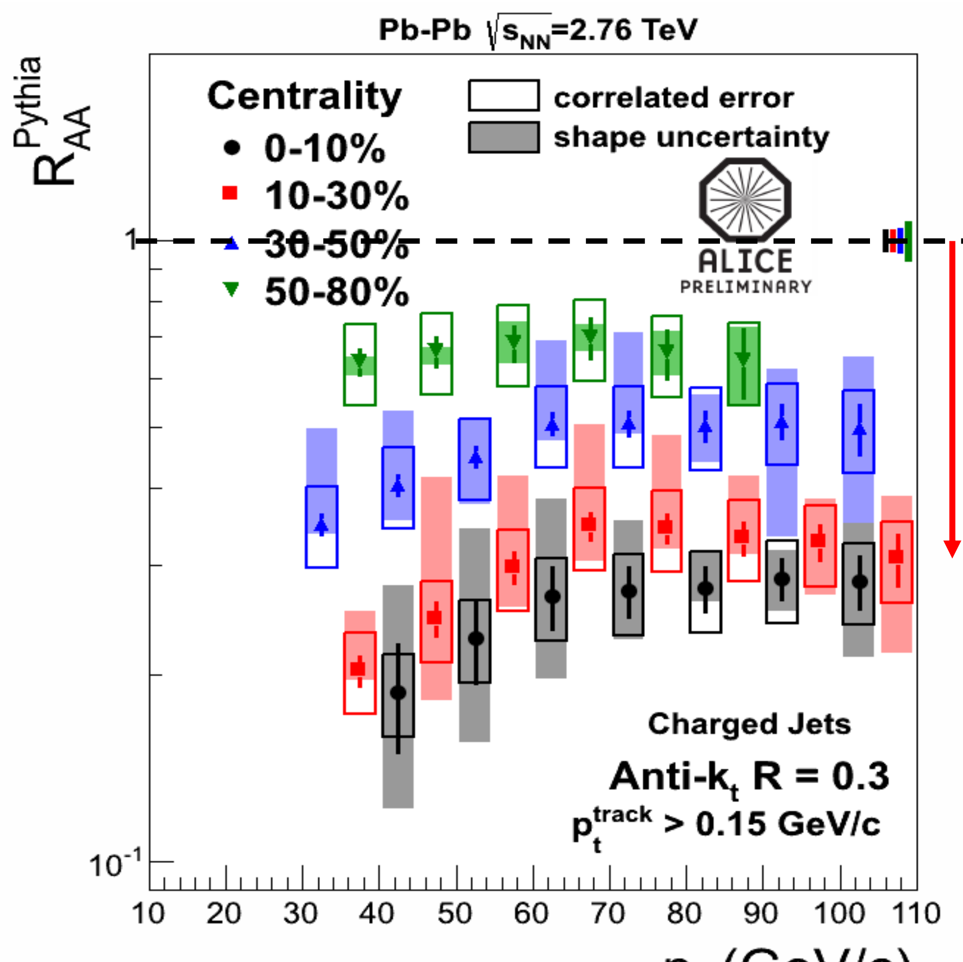
Fragmentation pattern of the “hard part” in PbPb collision is consistent with pp

Justify the use of PYTHIA for jet energy correction

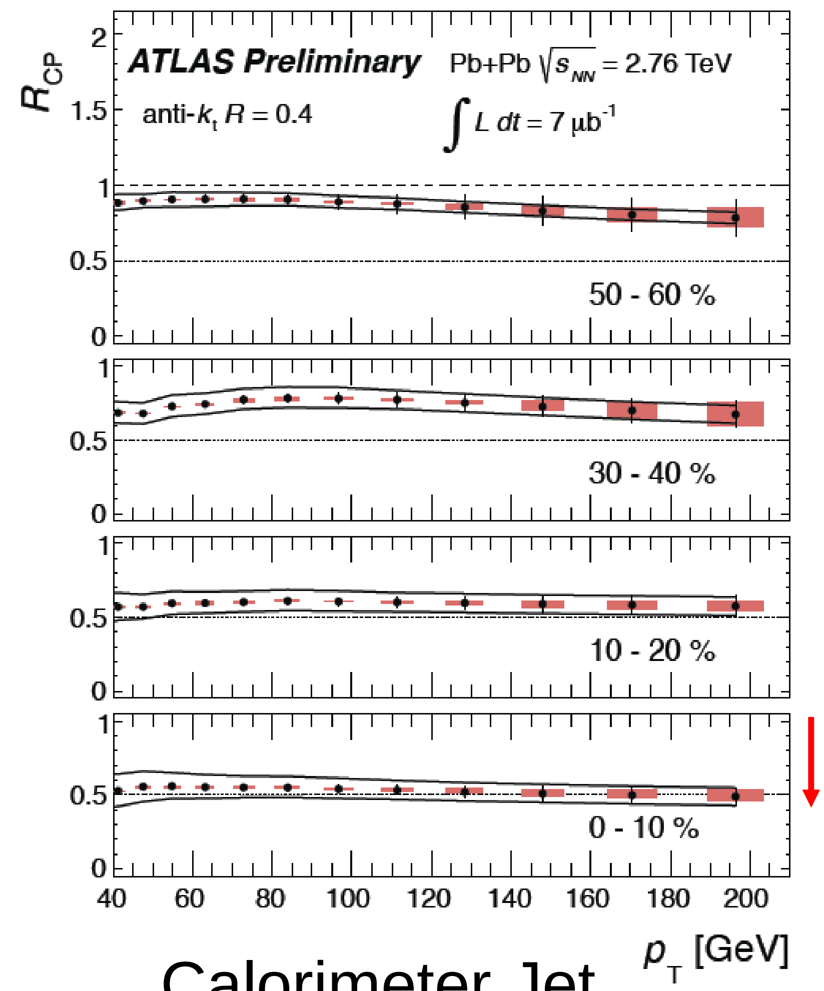
Inclusive jet R_{AA}, R_{CP}

Compare PbPb to PYTHIA (pp generator)

R_{CP}: Compare  to



Track Jet



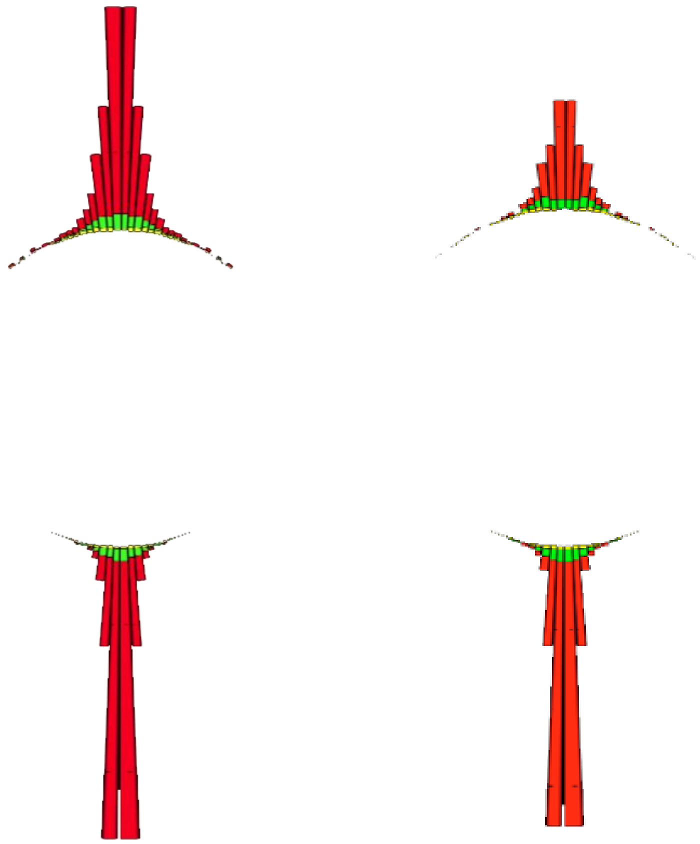
Calorimeter Jet

Strong suppression of inclusive high p_T jets!

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

Correlation study: Di-jet imbalance

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

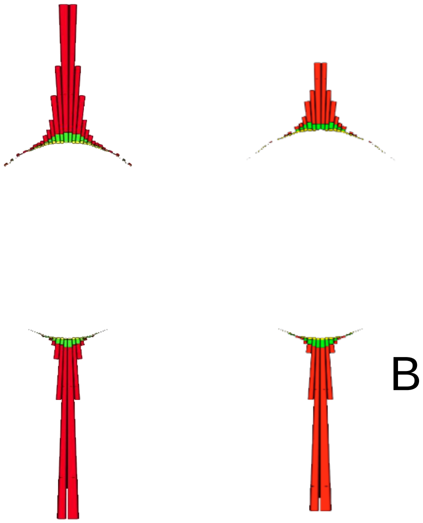


Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)

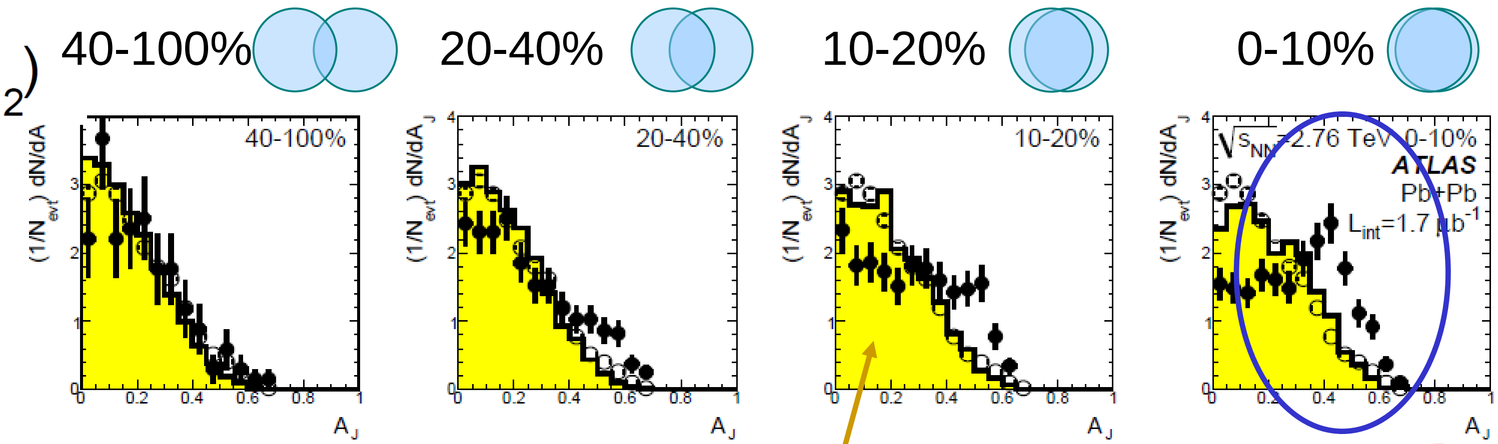
Correlation study: Di-jet imbalance

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



Small A_J (Balanced dijet)

Large A_J (Un-balanced dijet)



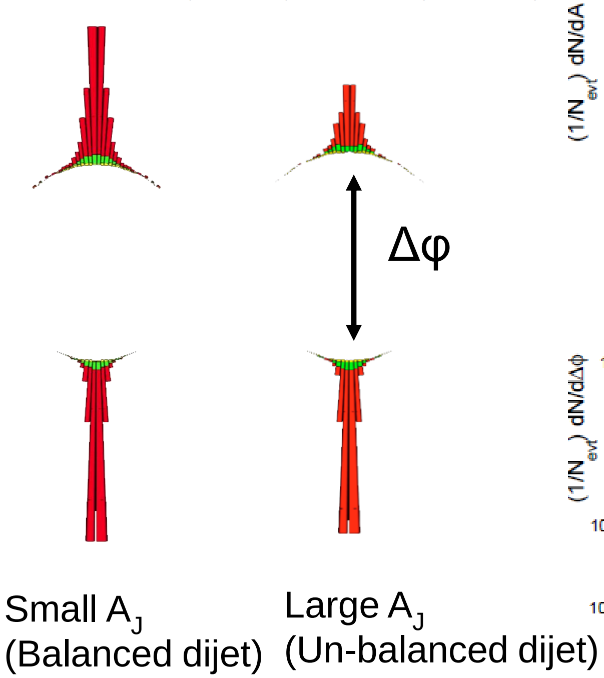
← Balanced dijet → Asymmetric dijet

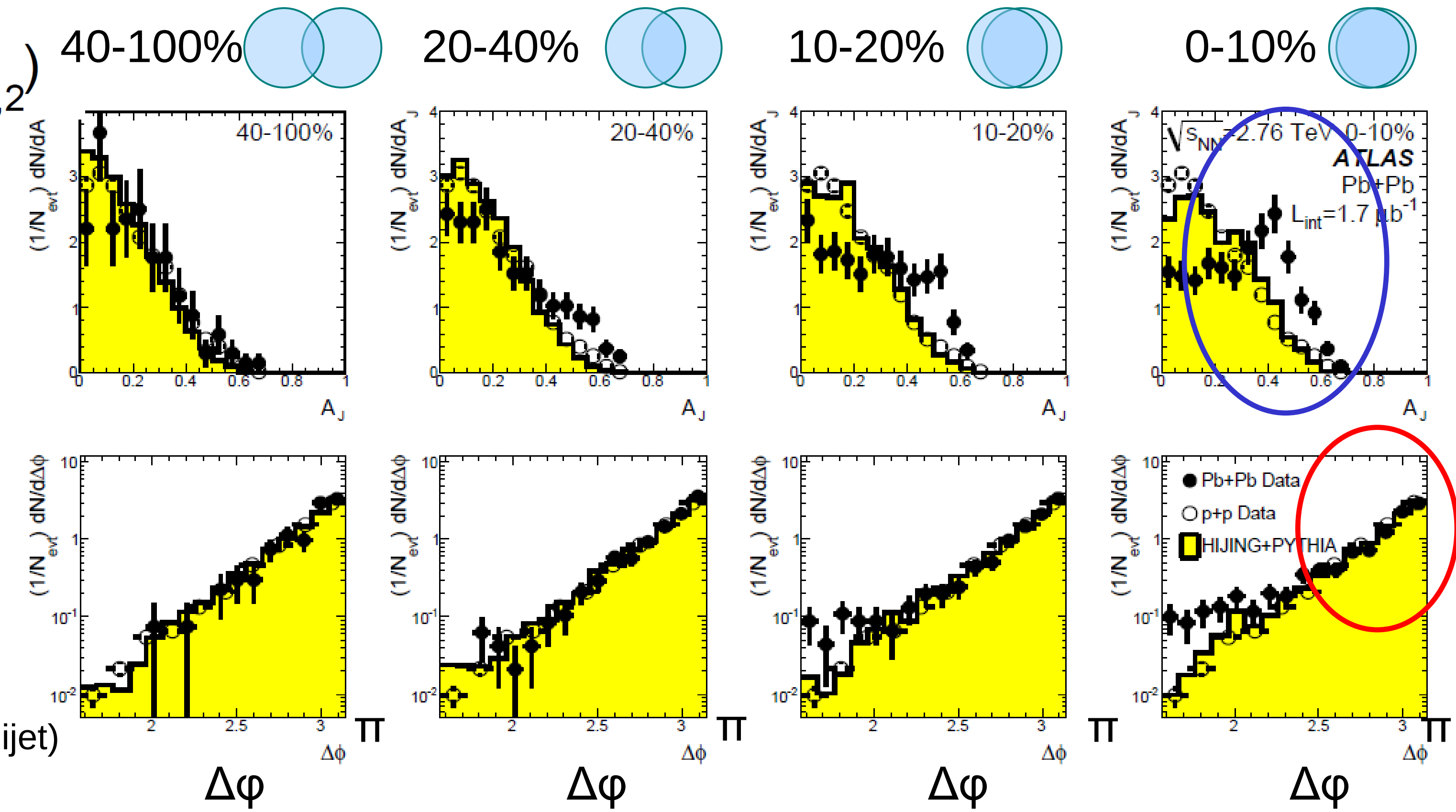
pp reference

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

Correlation study: Di-jet imbalance

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





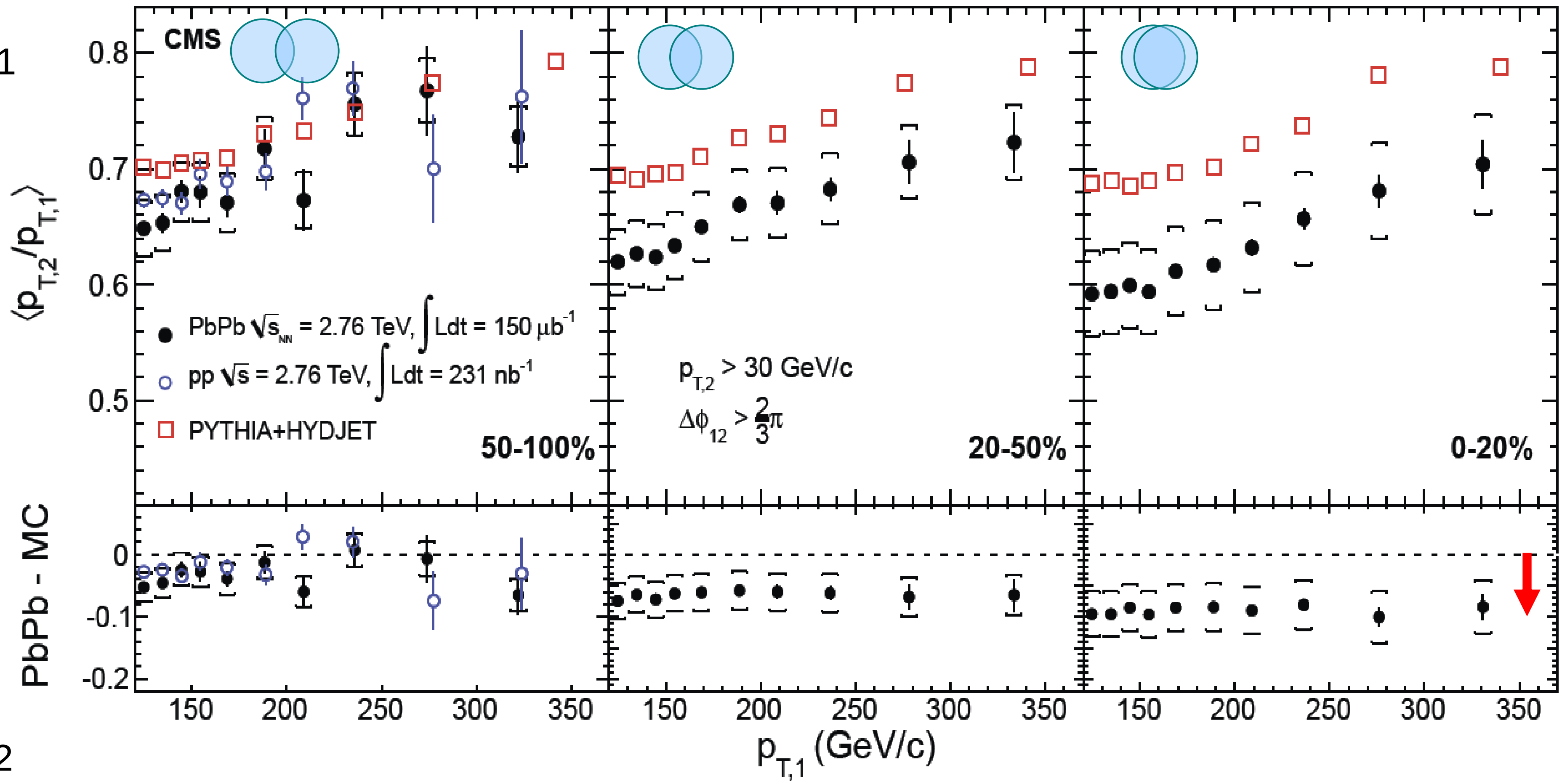
Parton energy loss is observed as a pronounced energy imbalance in central PbPb collisions

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

Leading jet and subleading jet p_T ratio

p_{T1}

p_{T2}

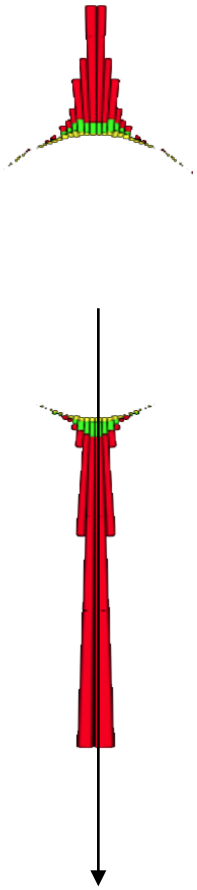


The shift in $<p_{T2}/p_{T1}>$ increases monotonically with collision centrality, and is largely independent of the leading jet p_T.

Where does the energy go?

- Suppression of high p_T jets
- Large dijet energy (momentum) imbalance

Jets lose energy when passing through the medium



ΔE_T ~ O(10) GeV,
~10% shift in <dijet p_T ratio>

Where does the energy go?

Missing-$p_T^{||}$

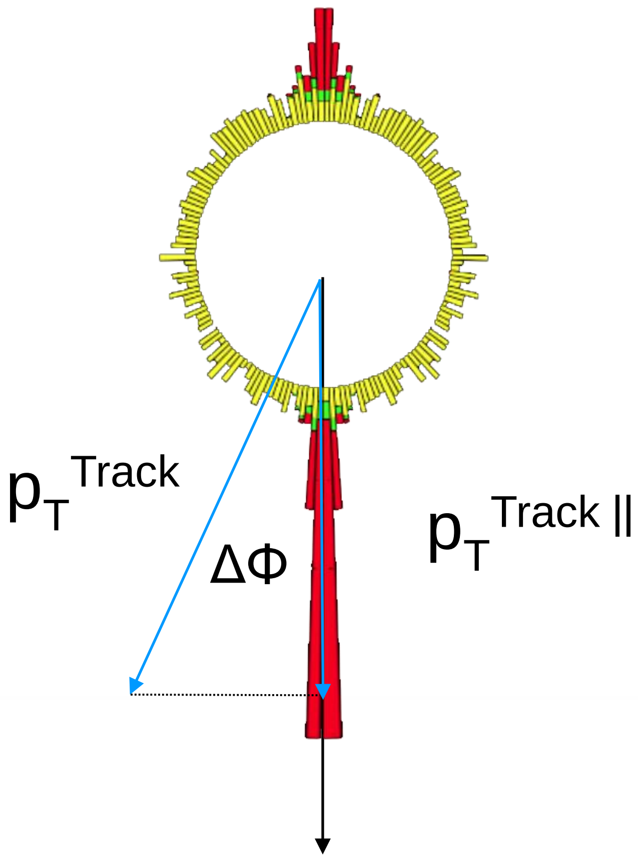
Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

Where does the energy go?

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

$p_T > 0.5$ GeV/c and
$|\eta| < 2.4$

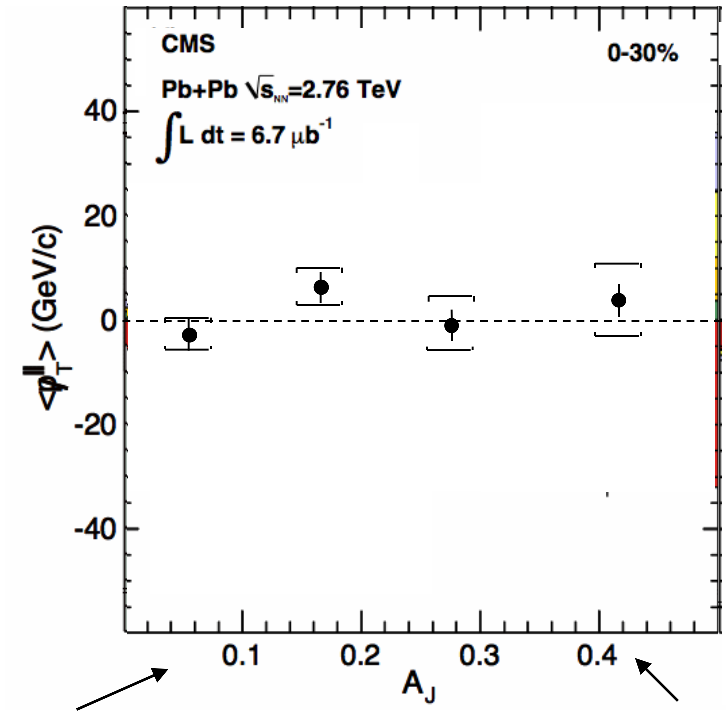
Underlying events cancels



Sum over all tracks in the event

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



balanced jets

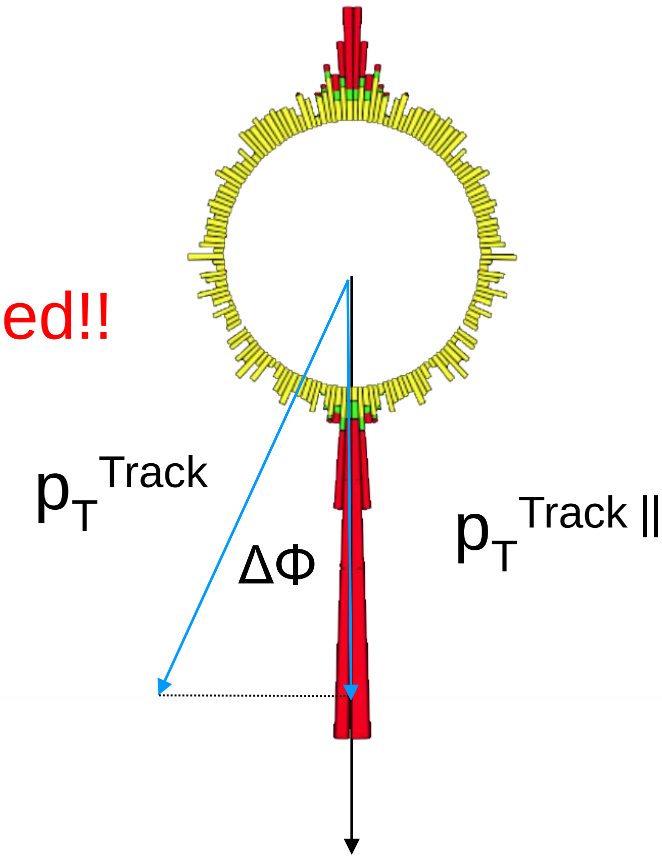
unbalanced jets

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

excess away from leading jet

Balanced!!

excess towards leading jet



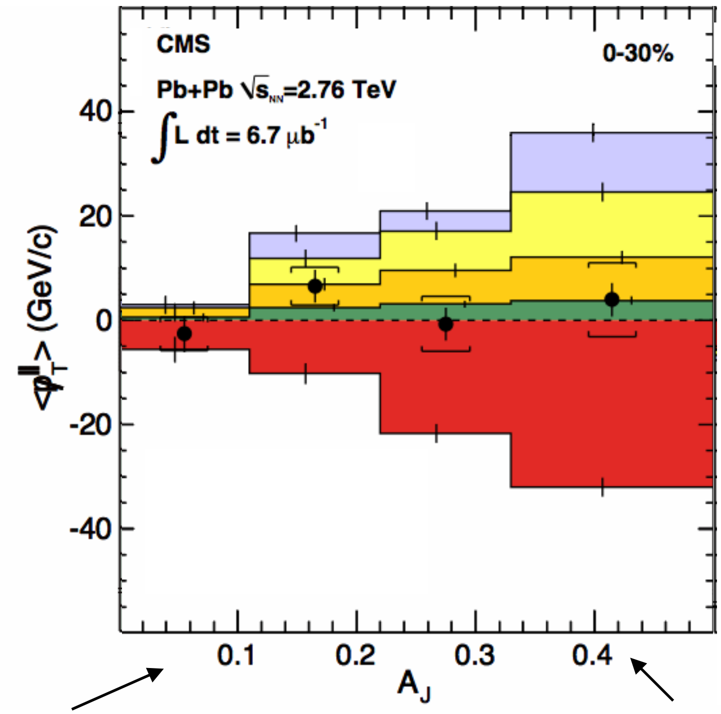
Integrating over the whole event final state

the dijet momentum balance is restored

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



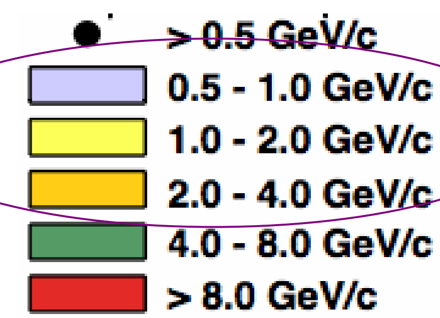
balanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet

Calculate missing p_T in ranges of track p_T:



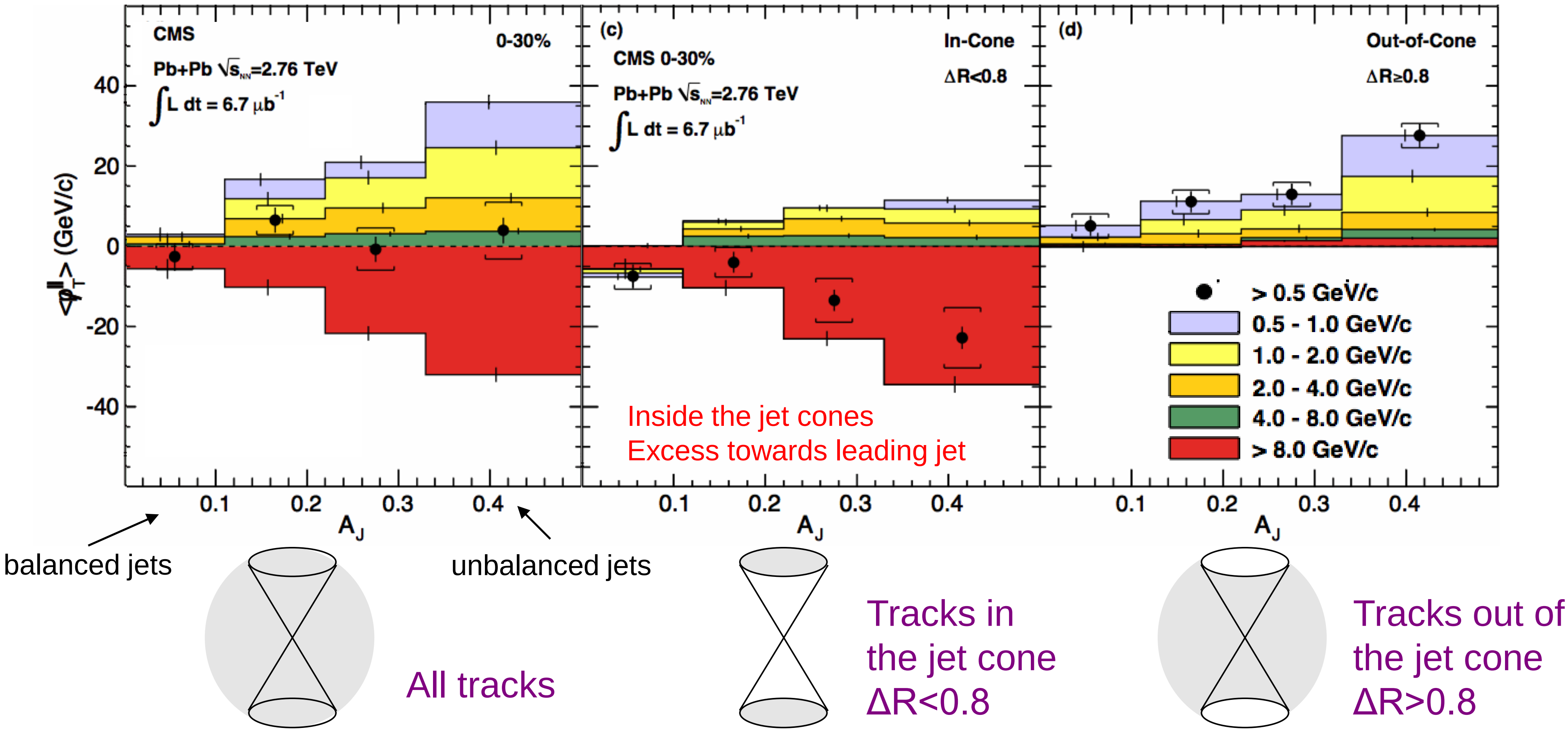
The momentum difference in the dijet is balanced by low p_T particles

Missing-$p_T^{||}$

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

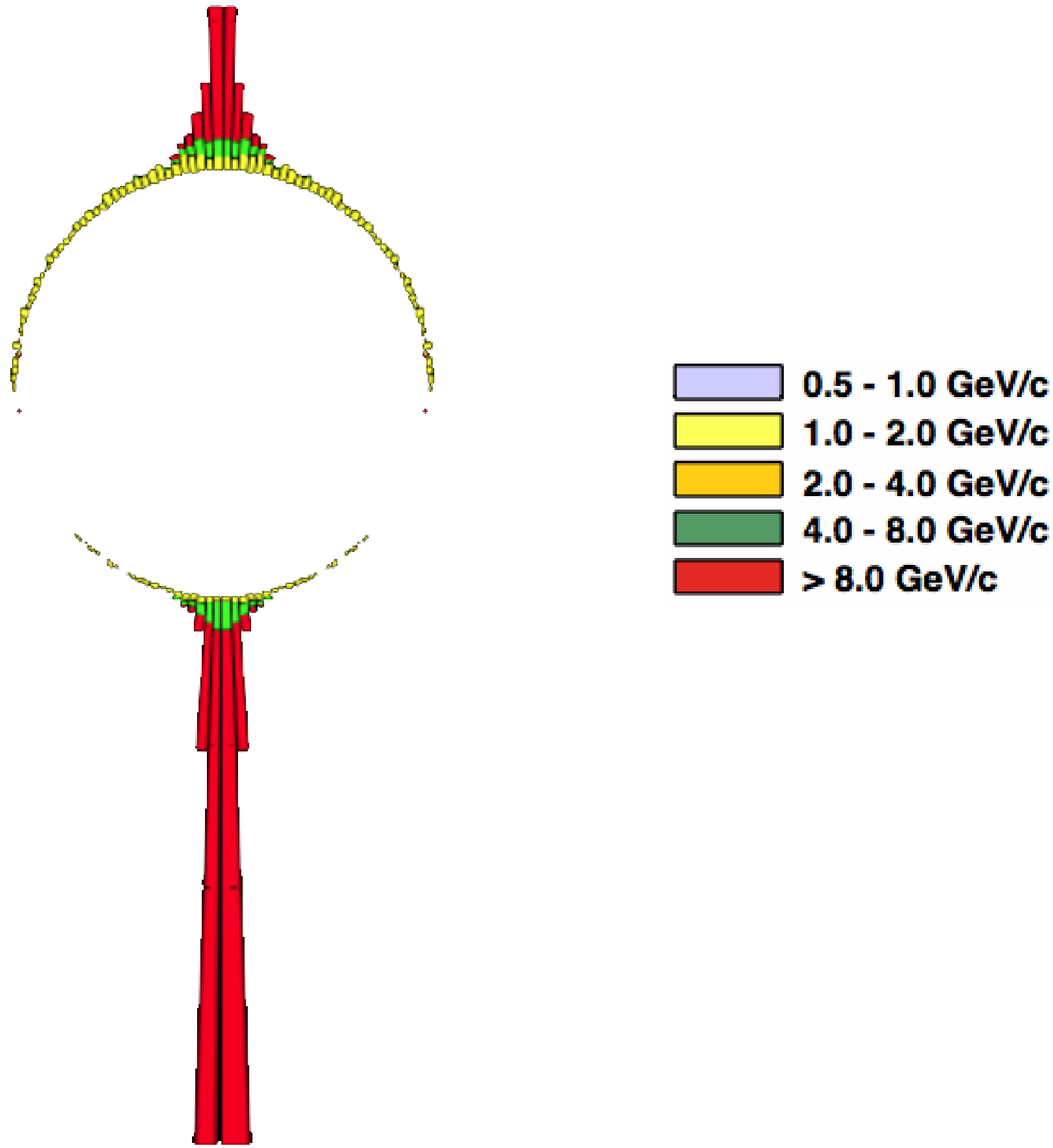
0-30% Central PbPb

Out of the jet cones
Excess towards sub-leading jet



The momentum difference in the dijet is
balanced by low p_T particles outside the jet cone

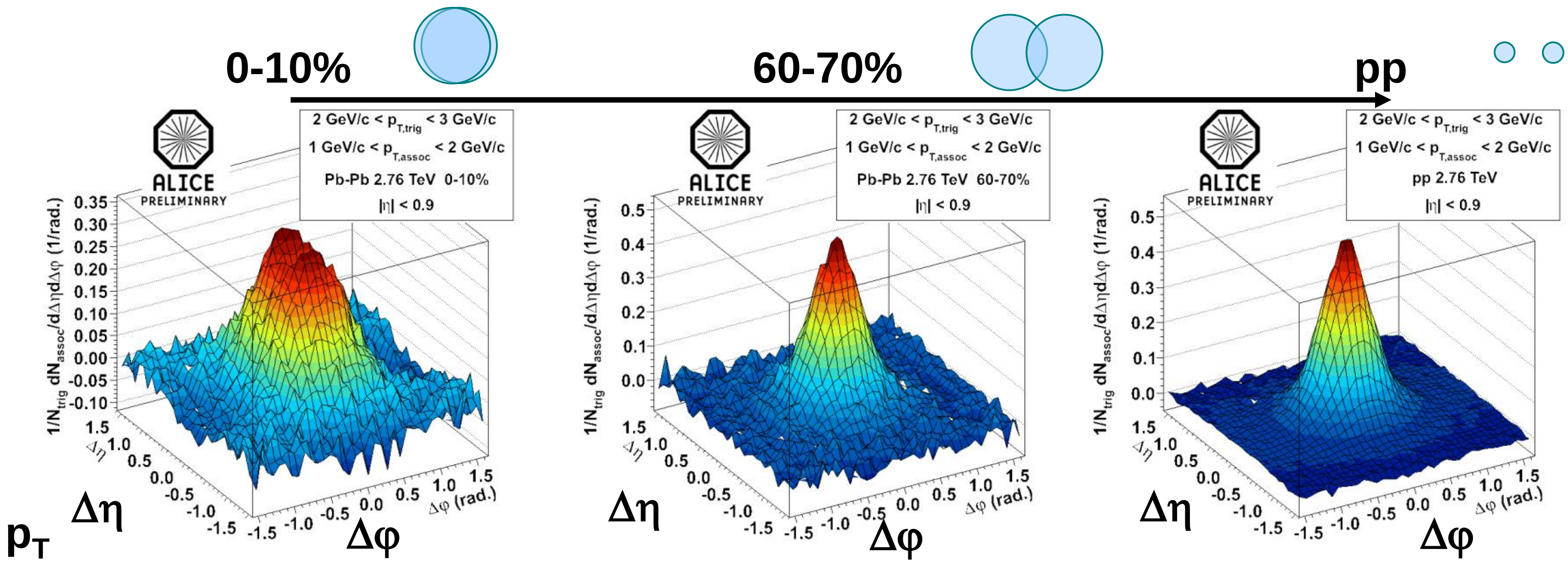
High p_T jet in PbPb collisions



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

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

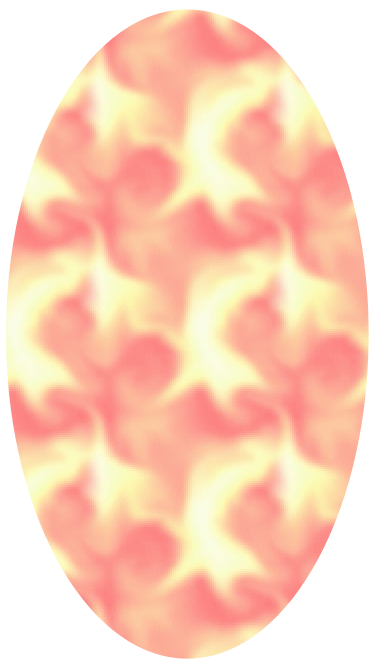


→Motivates jet shape analysis and fragmentation function with low p_T particles

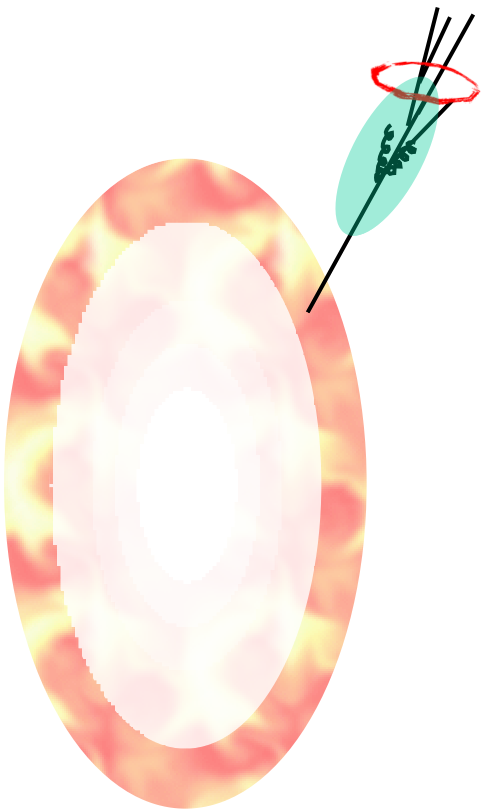
→ Look at low p_T reconstructed jet

Problem 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



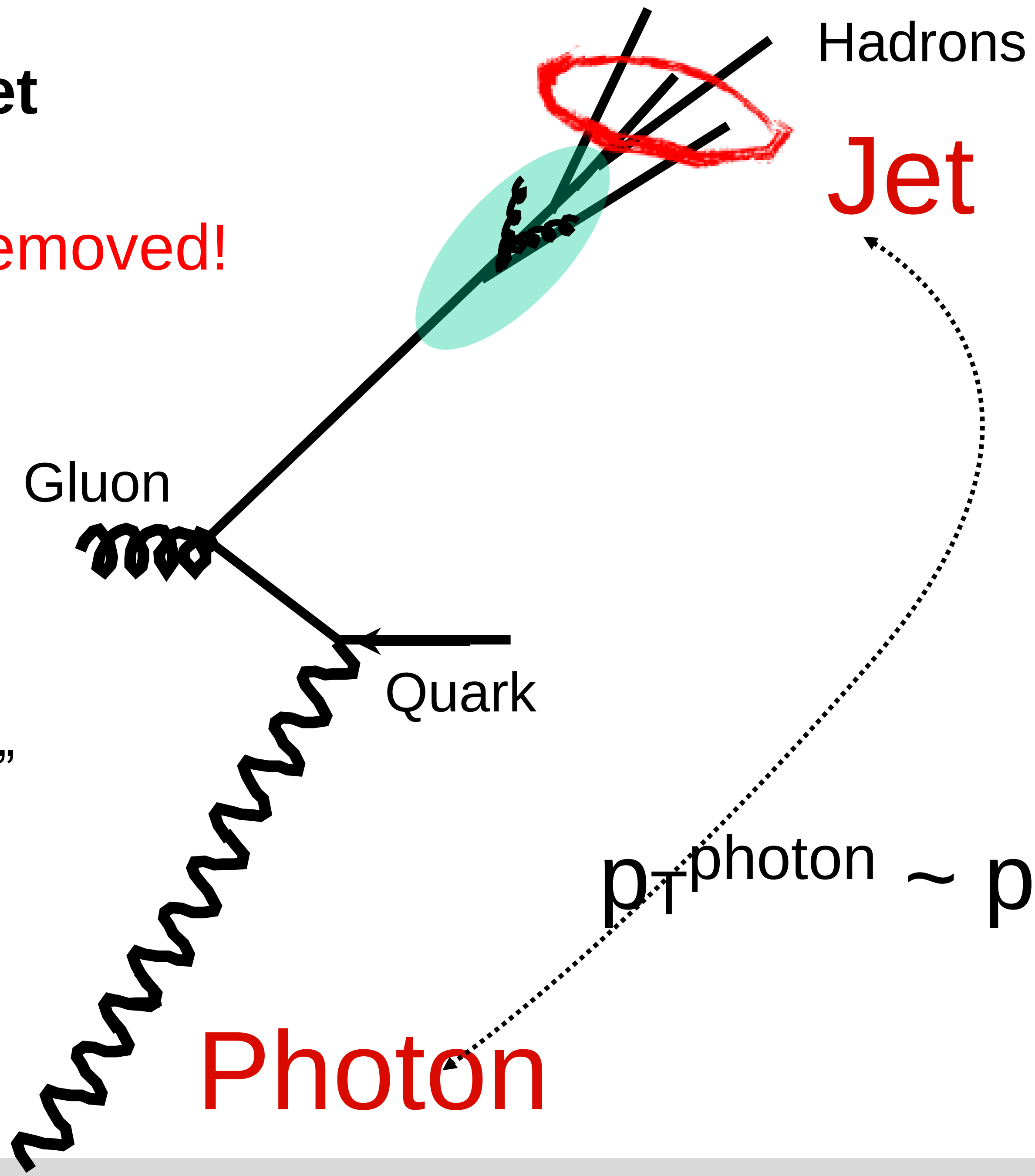
High p_T leading jet
Triggered sample

How about correlate photons and jets?

photon+jet

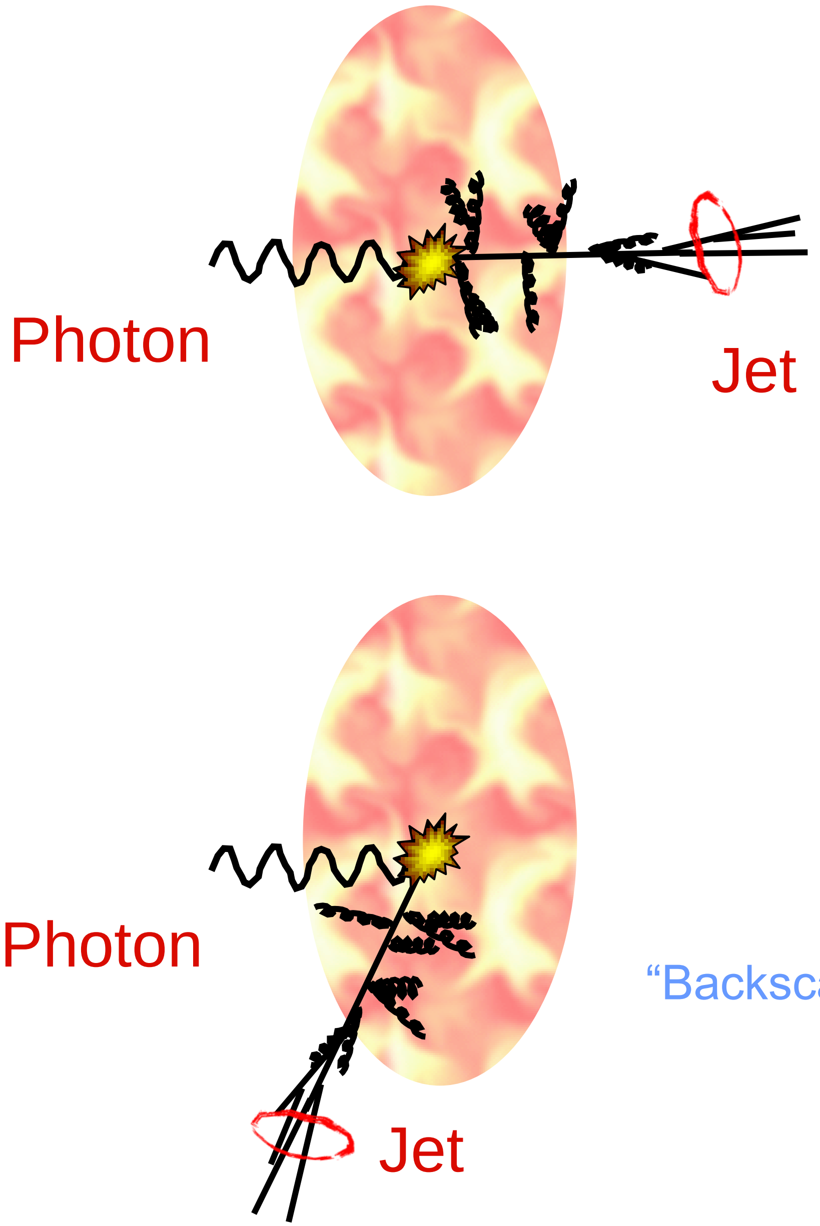
Surface bias is removed!

“quark-gluon compton scattering”



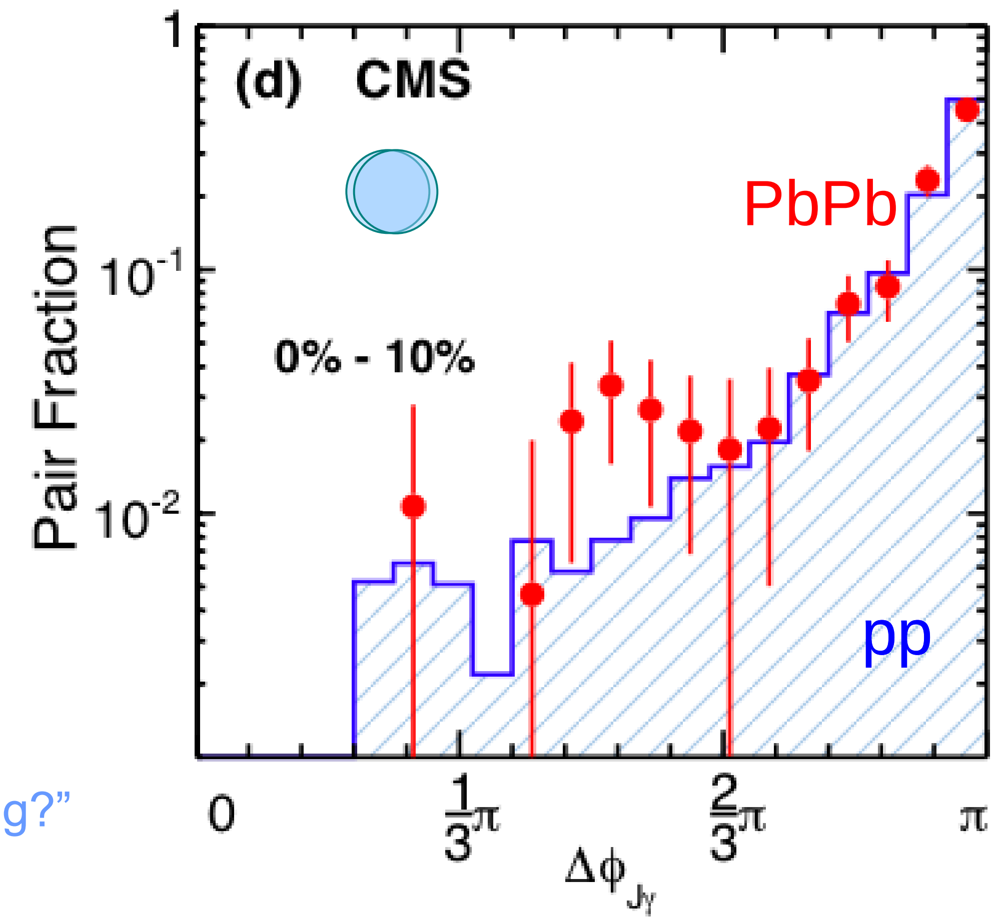
$p_T^{photon} \sim p_T^{Jet}$

Photon jet angular correlation



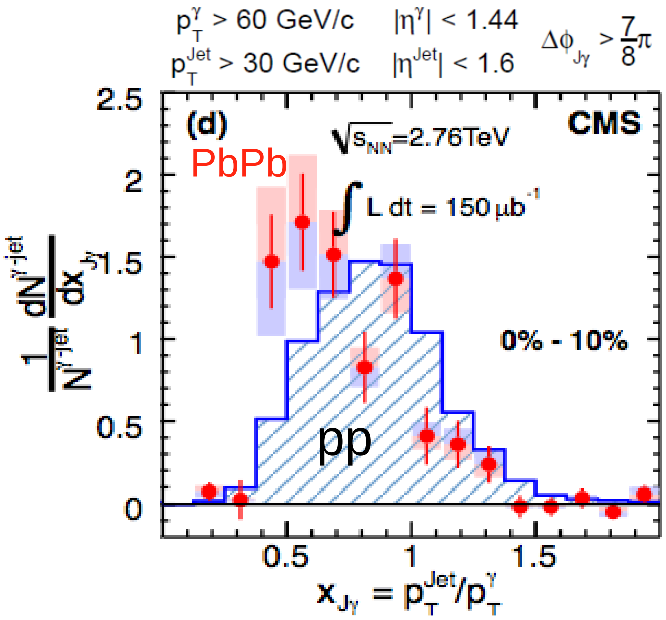
"Backscattering?"

"QGP Rutherfold experiment"



Azimuthal angle between photon and jet

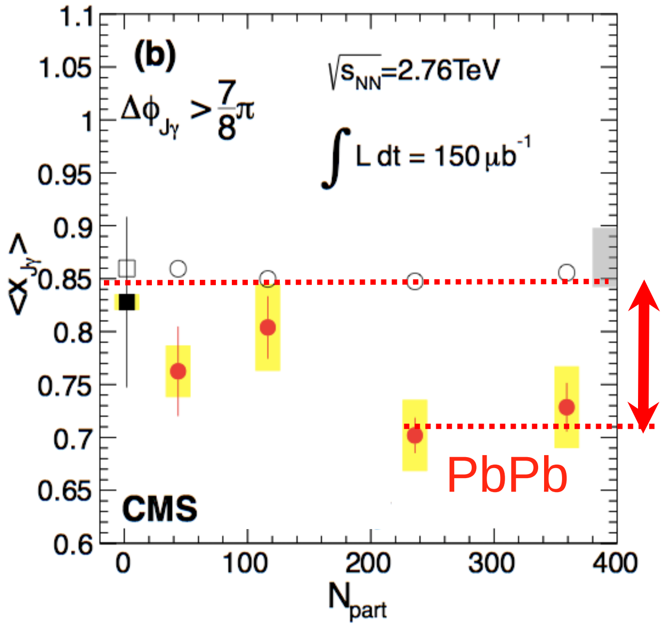
Photon-jet momentum balance



Compare photon-jet momentum balance

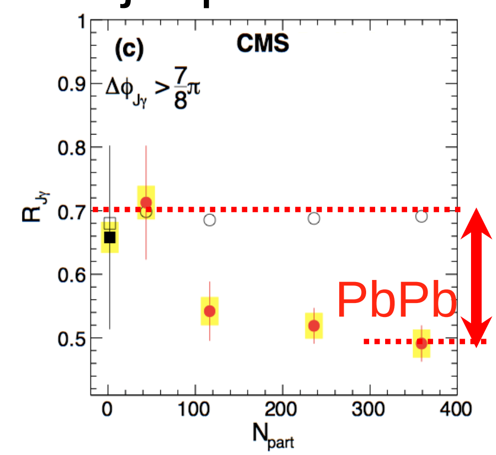
$x_{jg} = p_T^{Jet}/p_T^{photon}$

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



Open Charm & Beauty

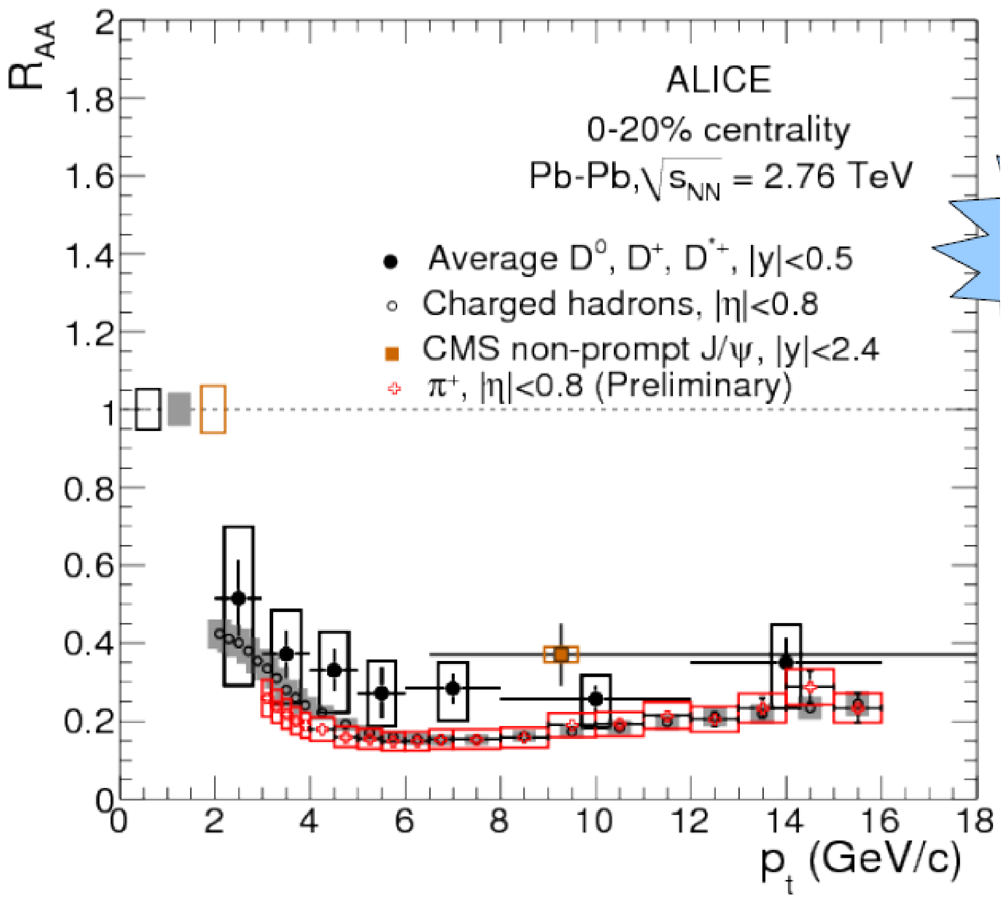
Color factor → $\Delta E_g > \Delta E_q$

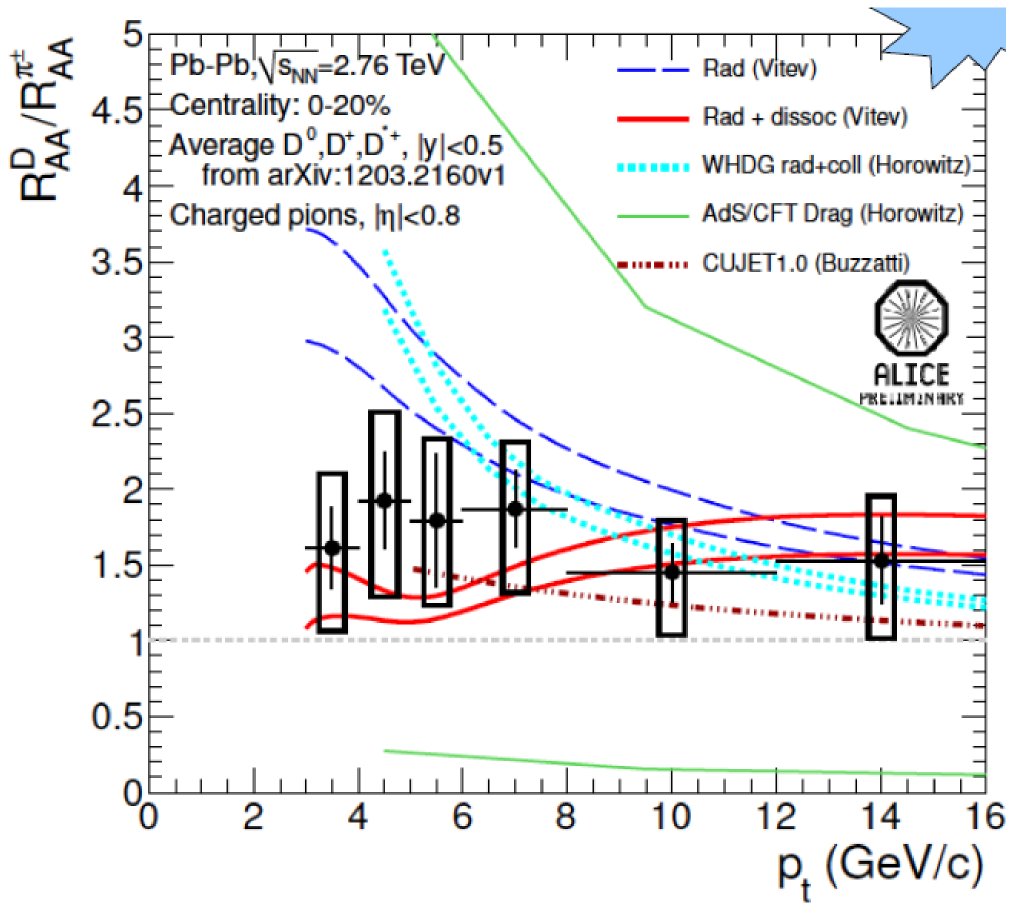
Dead cone effect → $\Delta E_q > \Delta E_Q$

$\Delta E_g > \Delta E_c > \Delta E_b$

Meson R_{AA}: π< D < B

Jet R_{AA}: g < uds < c < b





Motivates B meson, and b-jet measurements

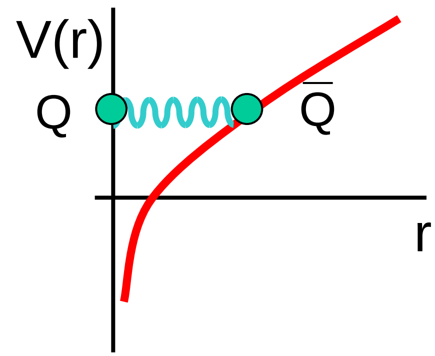
How about the temperature of QGP?

How about the temperature of QGP?

One interesting tool is the quarkonium states!

→ Bound state of heavy Q-Qbar pair

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

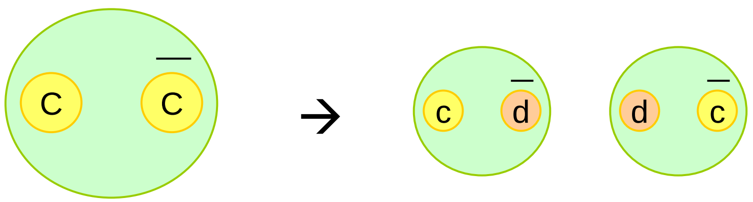


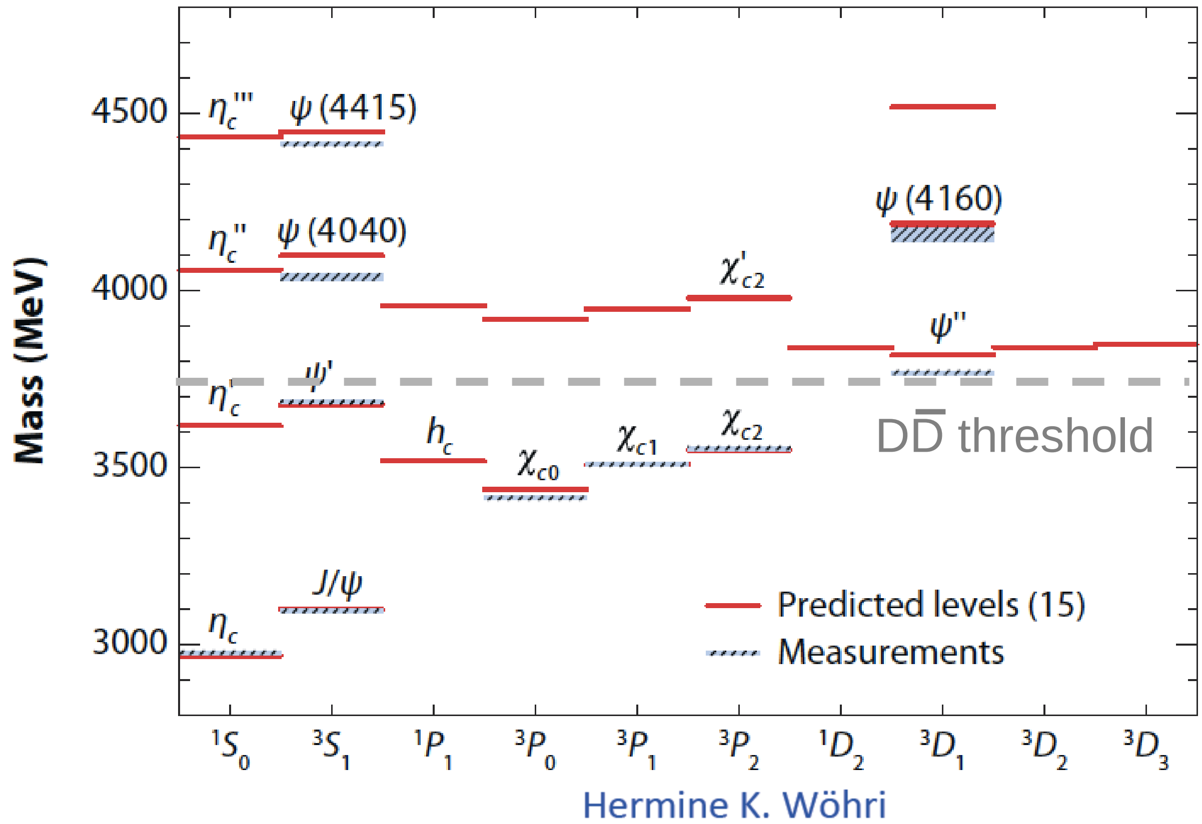
Charmonium $c\bar{c}$: J/ψ
Bottomonium $b\bar{b}$:Y

The states can be described by non-relativistic Schrödinger Eq

Above $D\bar{D}$ ($B\bar{B}$) threshold:

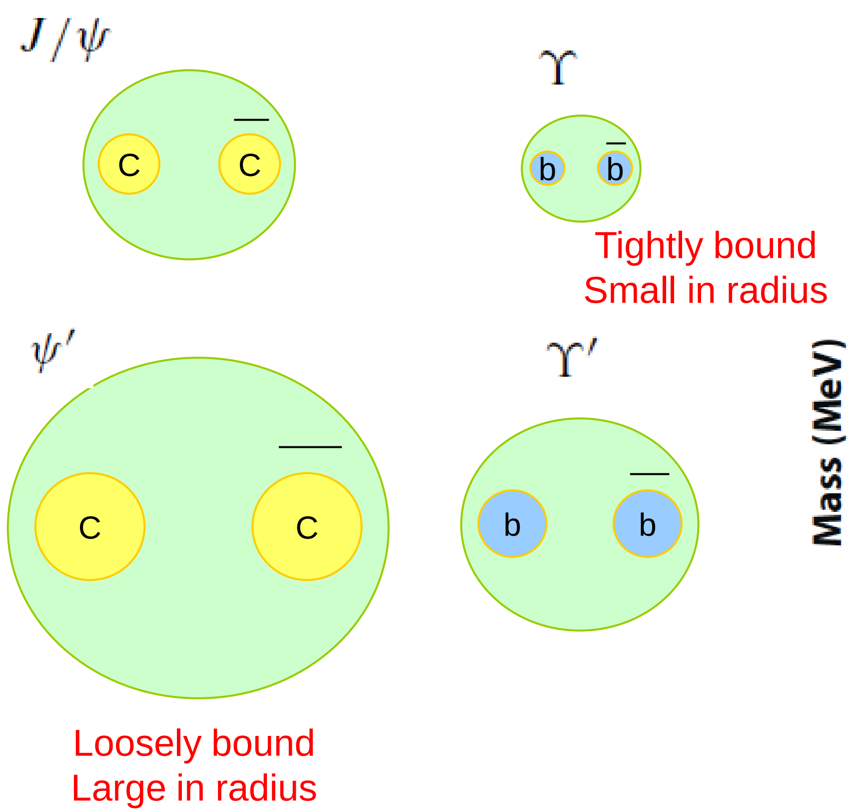
→Dissociate via strong interaction into open-charm(beauty)

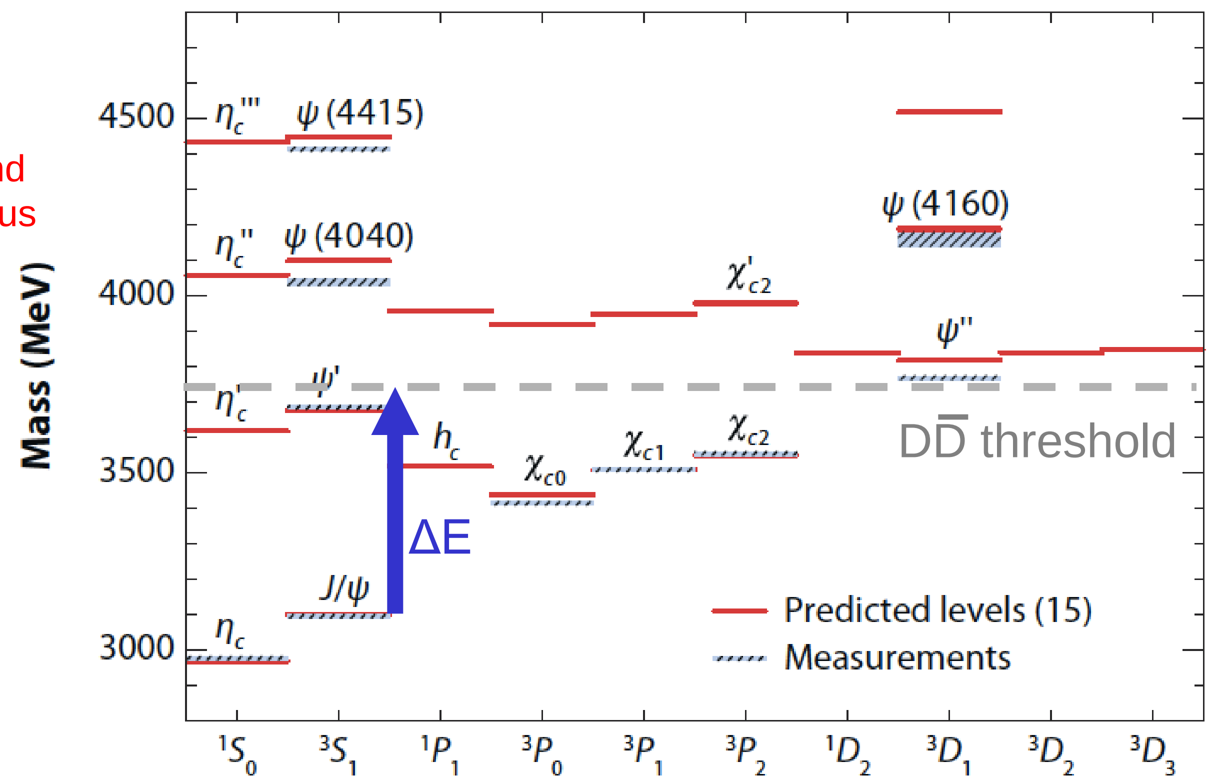




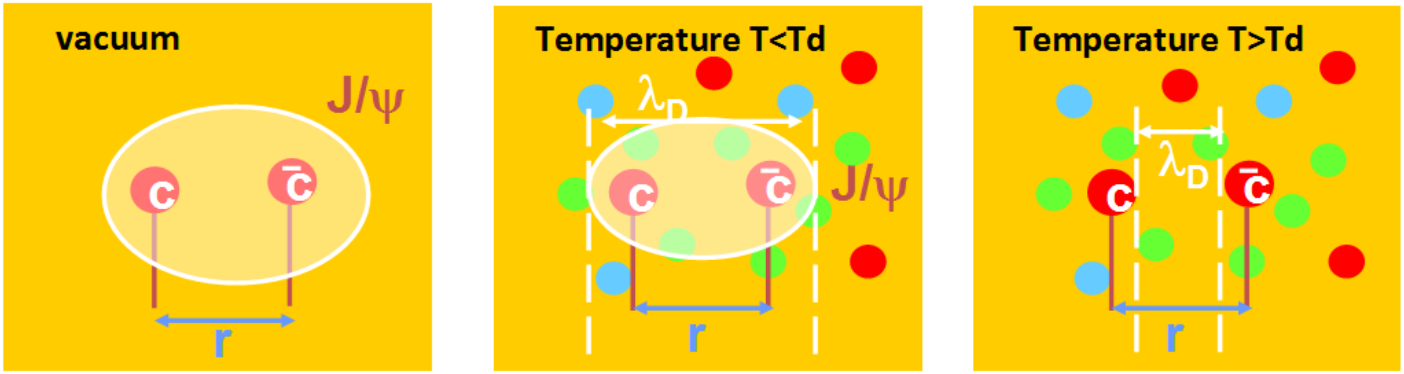
Quarkonia as a tool to probe the QGP

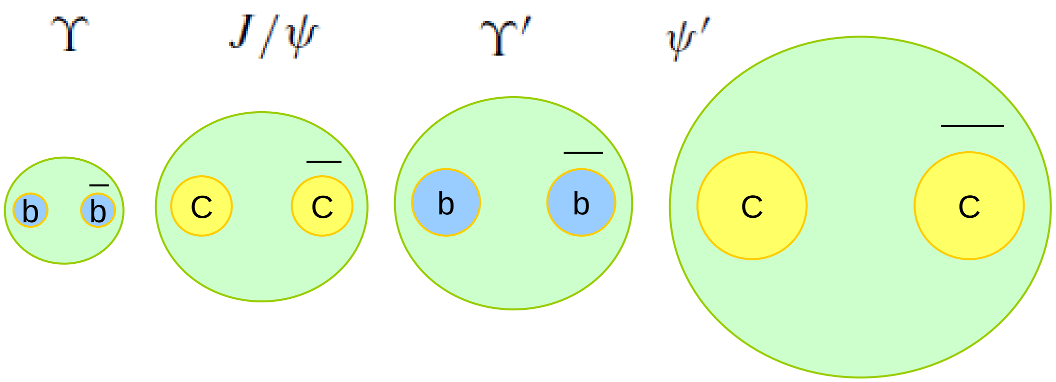
State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
Mass (GeV)	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
r_0 (fm)	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78





Quarkonia as a tool to probe the QGP

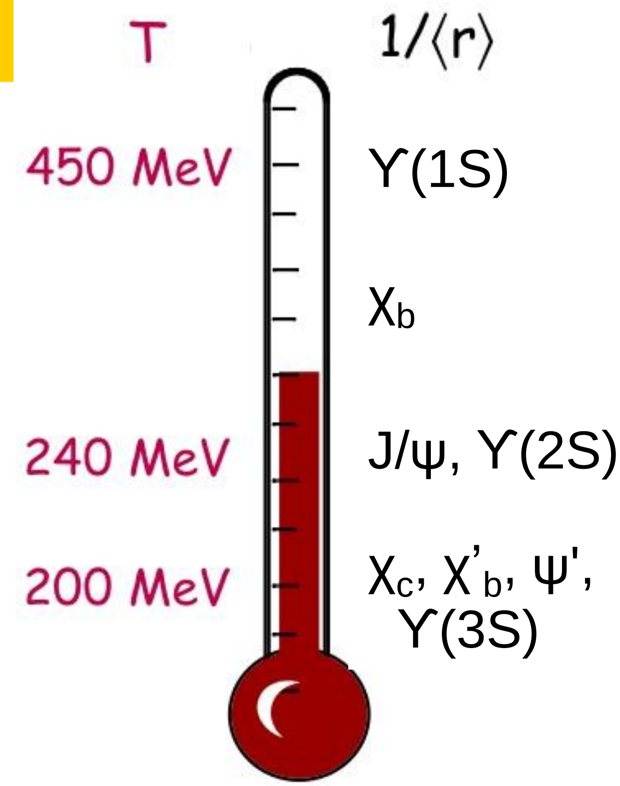




Different states have different binding energies
Loosely bound states melt first!

Successive suppression of individual states provides a "thermometer" of the QGP

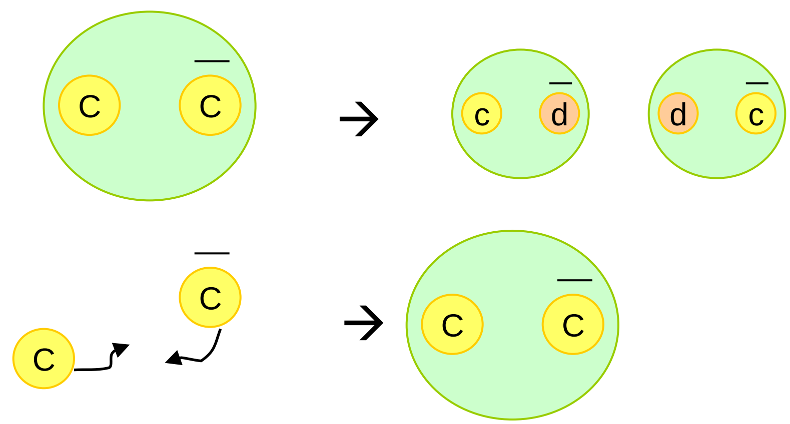
Matsui & Satz, PLB168 (1986) 415



Mocsy, EPJC61 (2009) 705
BNL workshop in June

Actually the story is not that simple

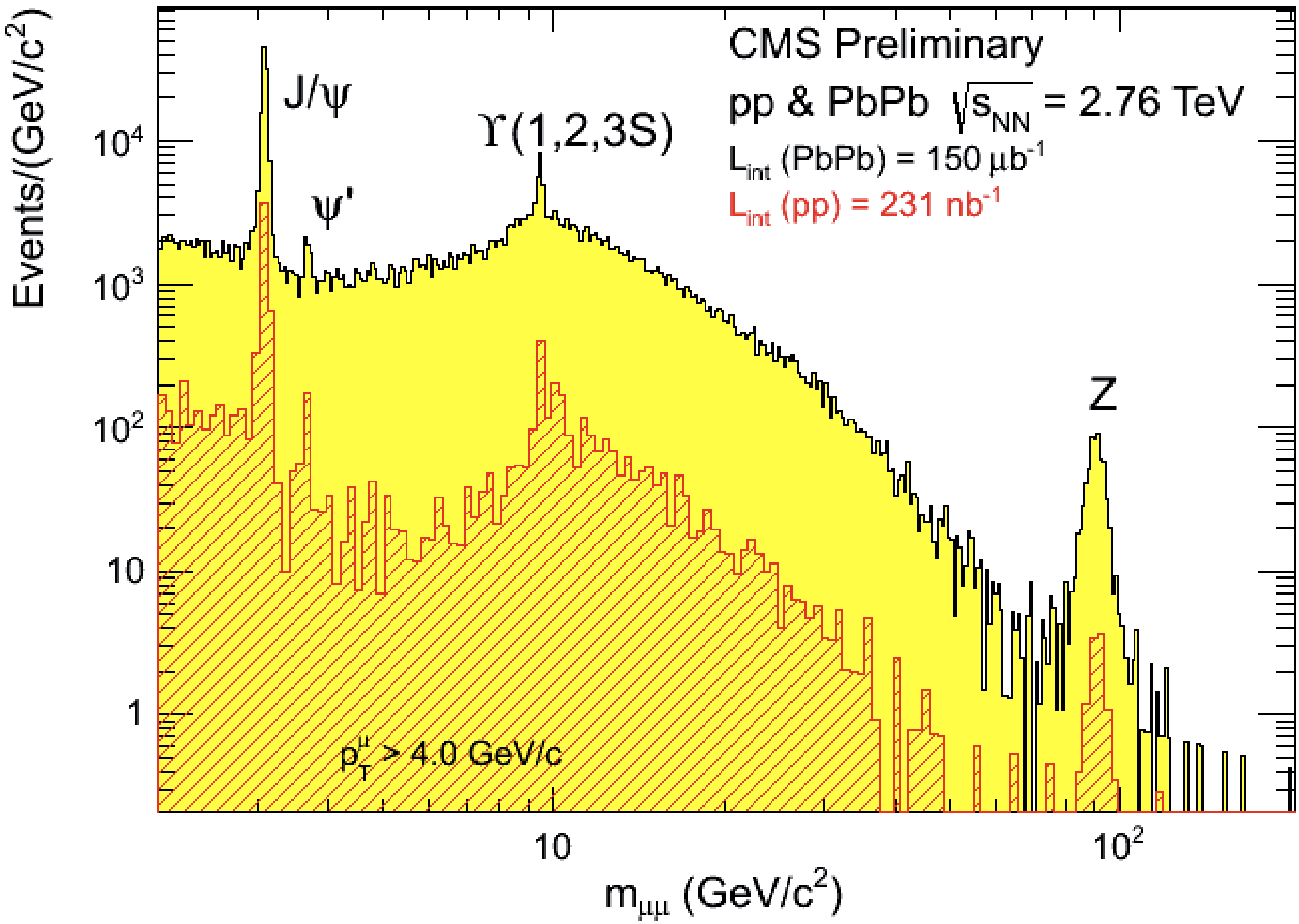
- Cold effects: (no thermalization)
  - Shadowing effect (nPDF vs. PDF)
  - Nuclear absorption (multiple scattering of QQbar wihin nucleus)
  - Hadronic comover (dissociation in dense hadonic medium)
  - …
- Hot effects: (thermalized)
  - Sequential suppression in QGP
  - Recombination
- …



Reconstruction of quarkonium states

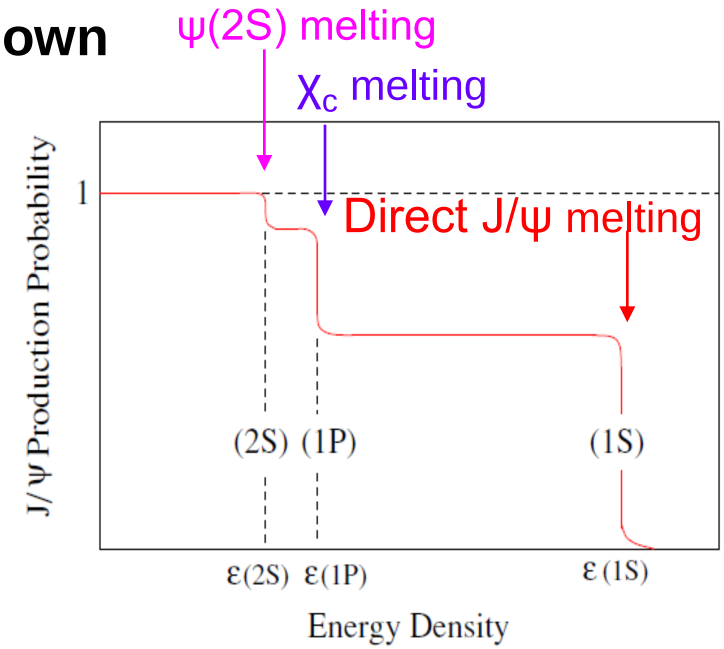
Quarkonium states can be reconstructed via di-lepton

For instance, dimuon channel: J/ψ→ee,μμ Υ(1,2,3S)→ee,μμ

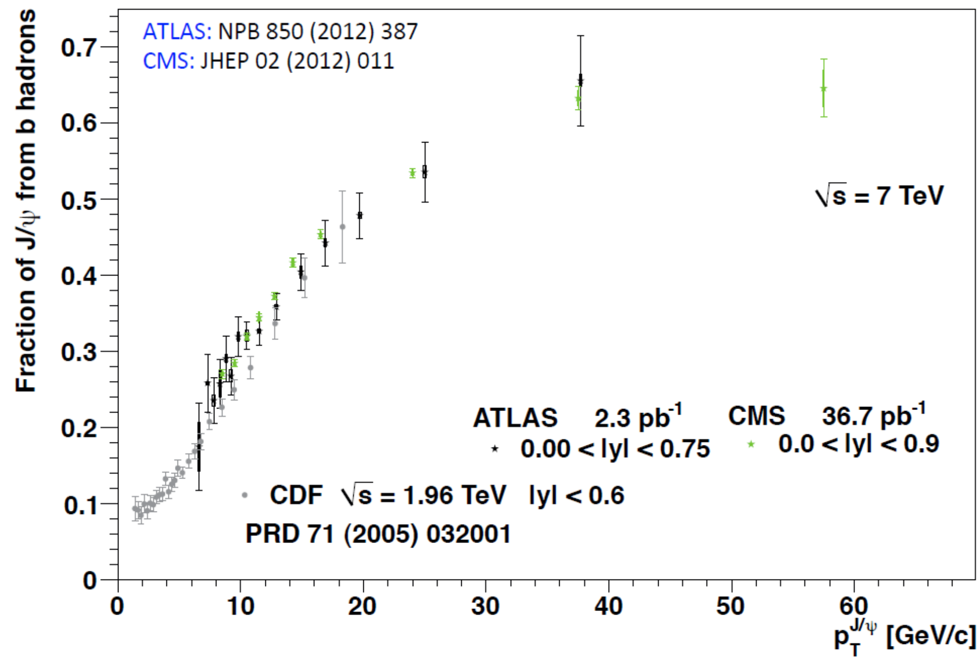


Quarkonium production

- **Observed quarkonium = Direct production + feed-down**

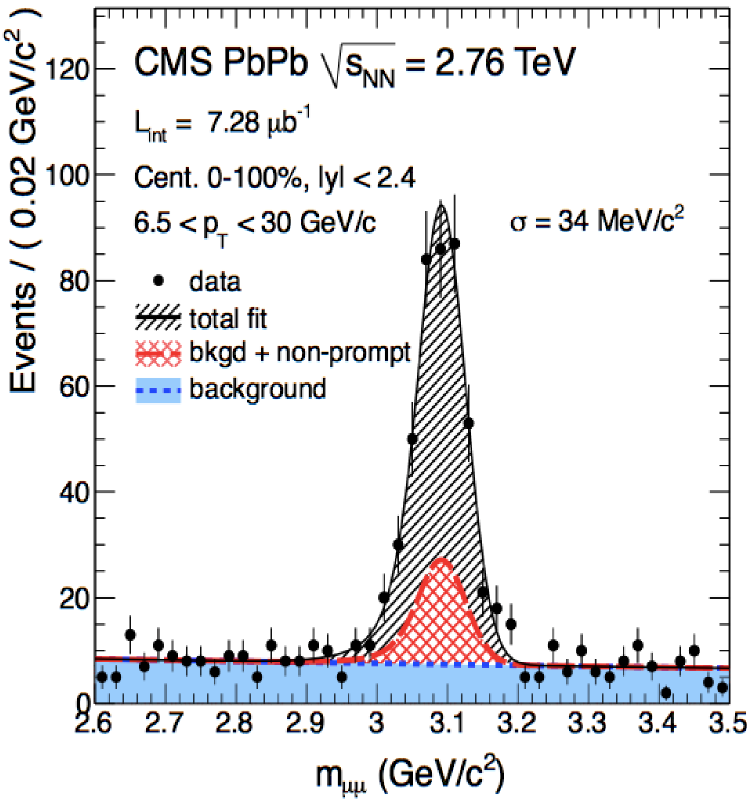


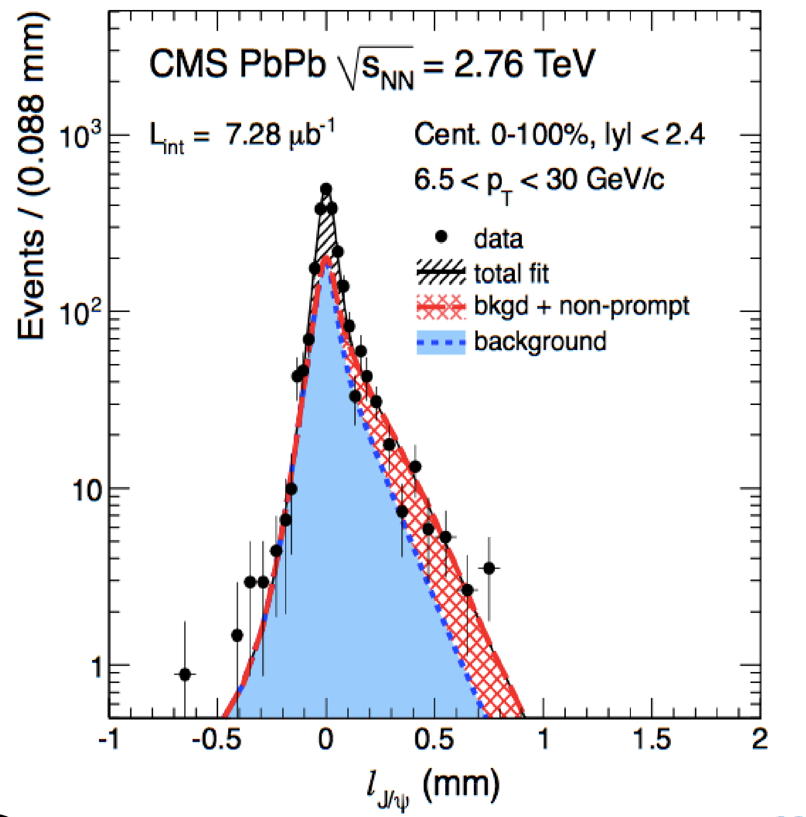
- J/ψ production:
  - Prompt J/ψ
    - Direct production from hard scattering of partons
    - Feed-down from higher charmonium states
      - At low p_T, ~ 15% from χ_c
      - 5-10% from ψ(2S)
      - Feed-down fraction is J/ψ p_T dependent
  - Non-prompt J/ψ
    - B decays → can be separated based on displaced vertex
    - J/ψ p_T dependent

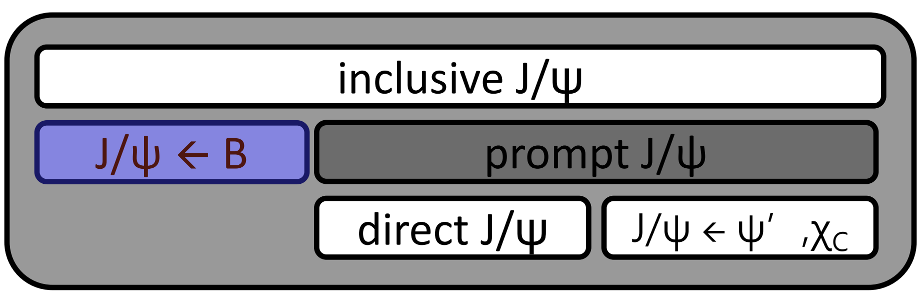


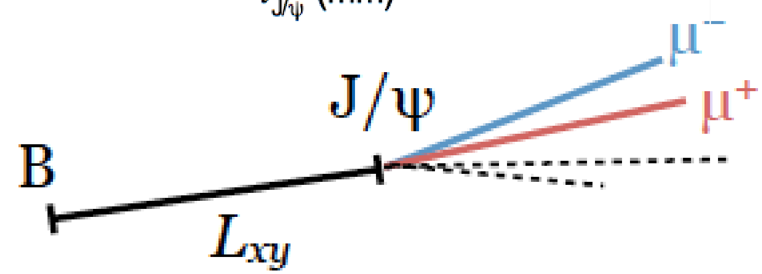
- Υ production:
  - ~50% of the Υ(1S) are directly produced (measurement from CDF)

Prompt and non-prompt J/ ψ



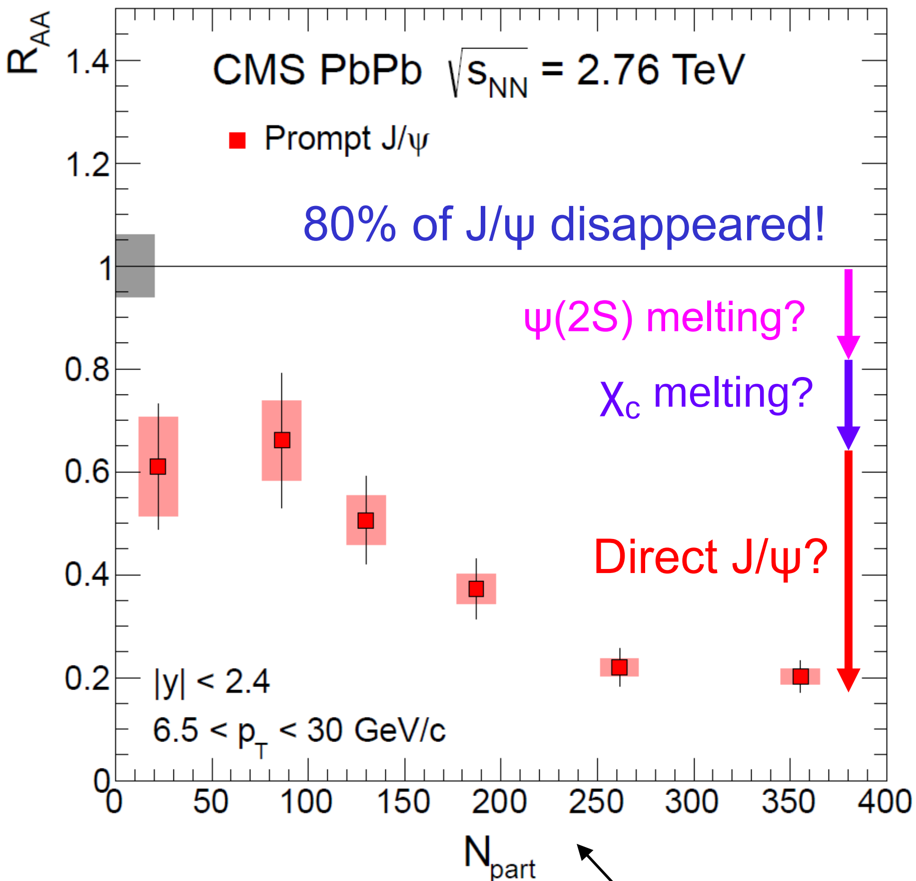




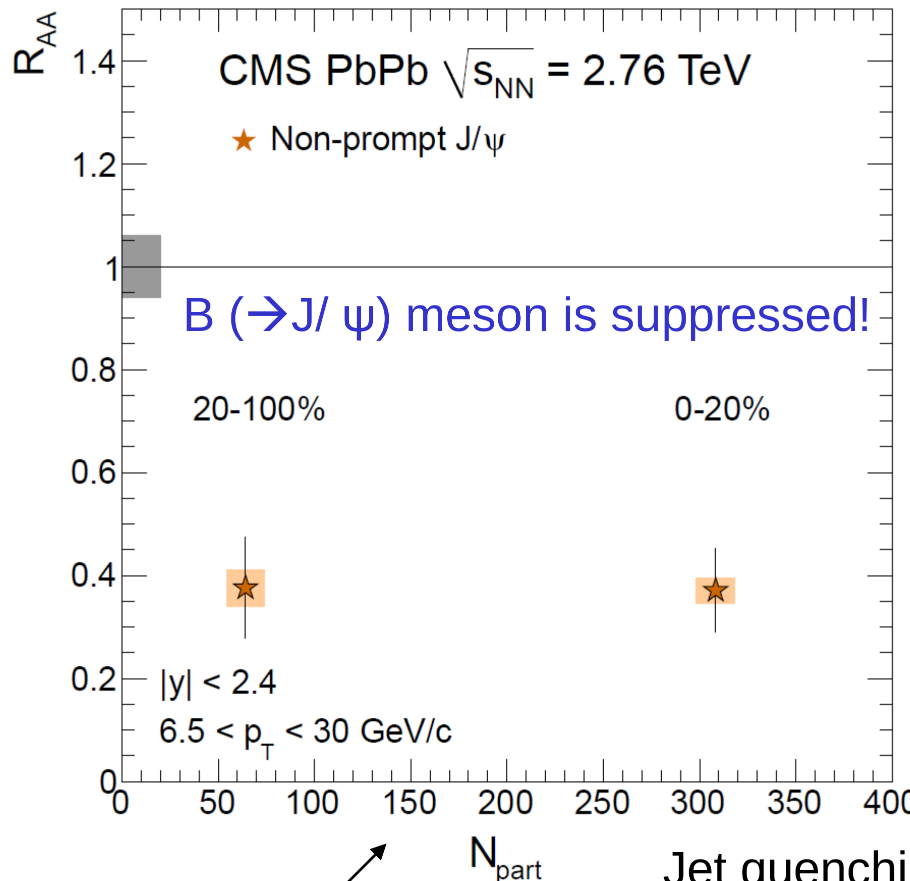


J/ ψ R_{AA}

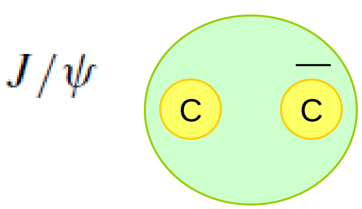
Prompt

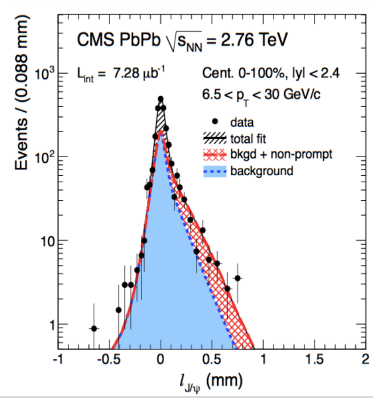


Non-prompt



Jet quenching

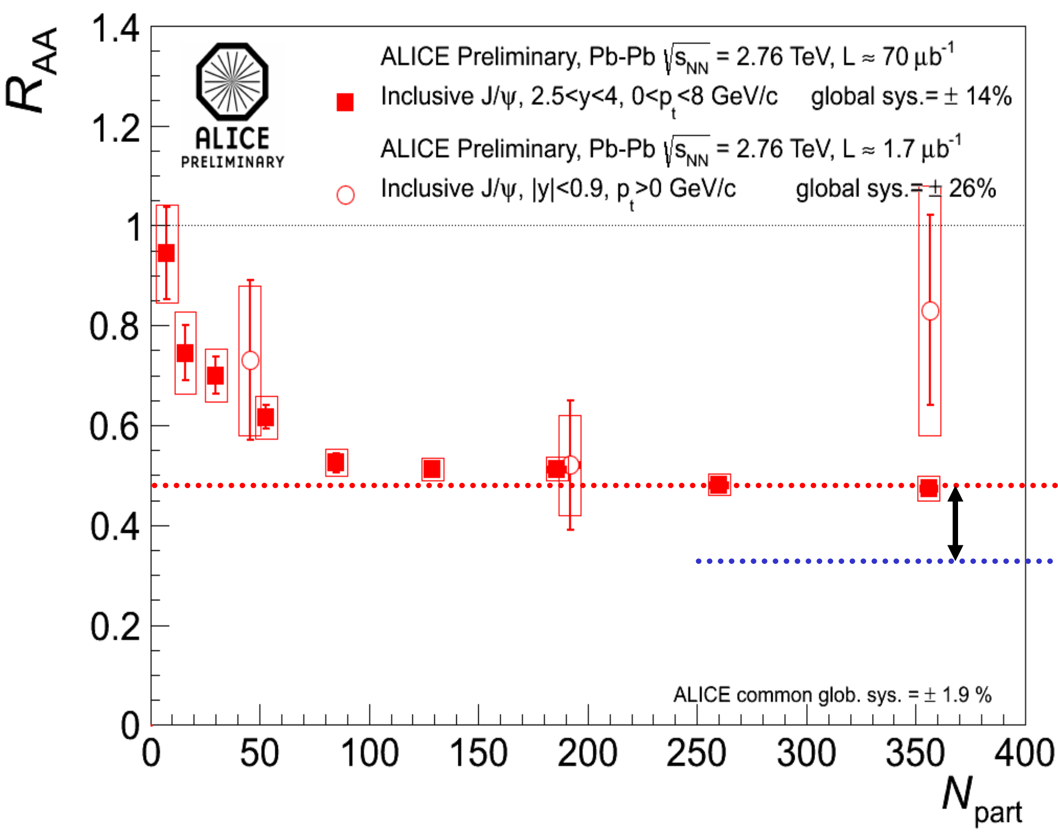




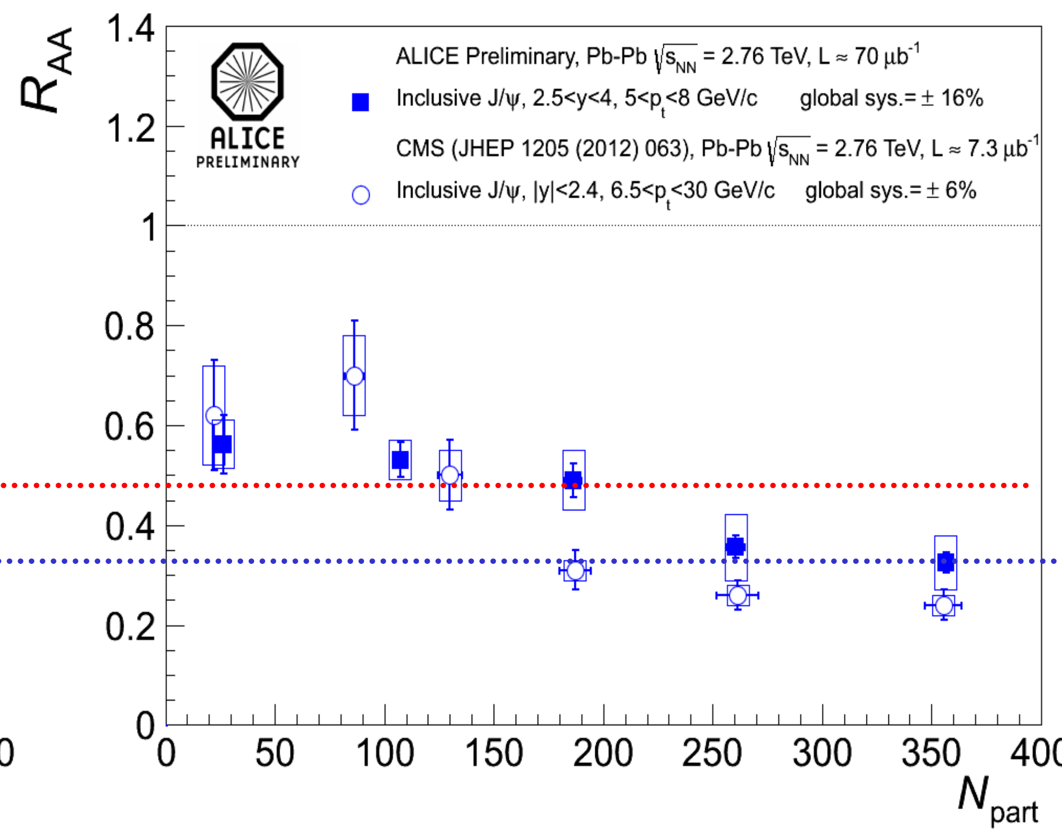
Low p_T J/ ψ R_{AA}

Low p_T J/ψ: More sensitive to recombination of c and cbar in QGP

0 < J/ψ p_T < 8 GeV/c



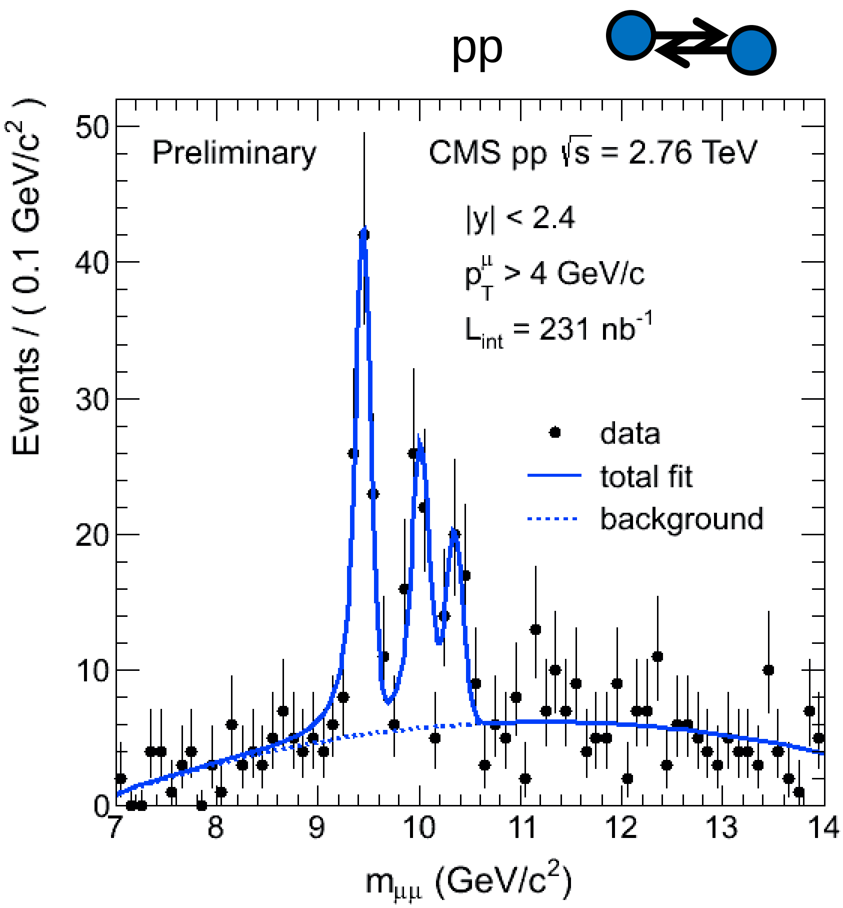
5 < J/ψ p_T < 8 GeV/c

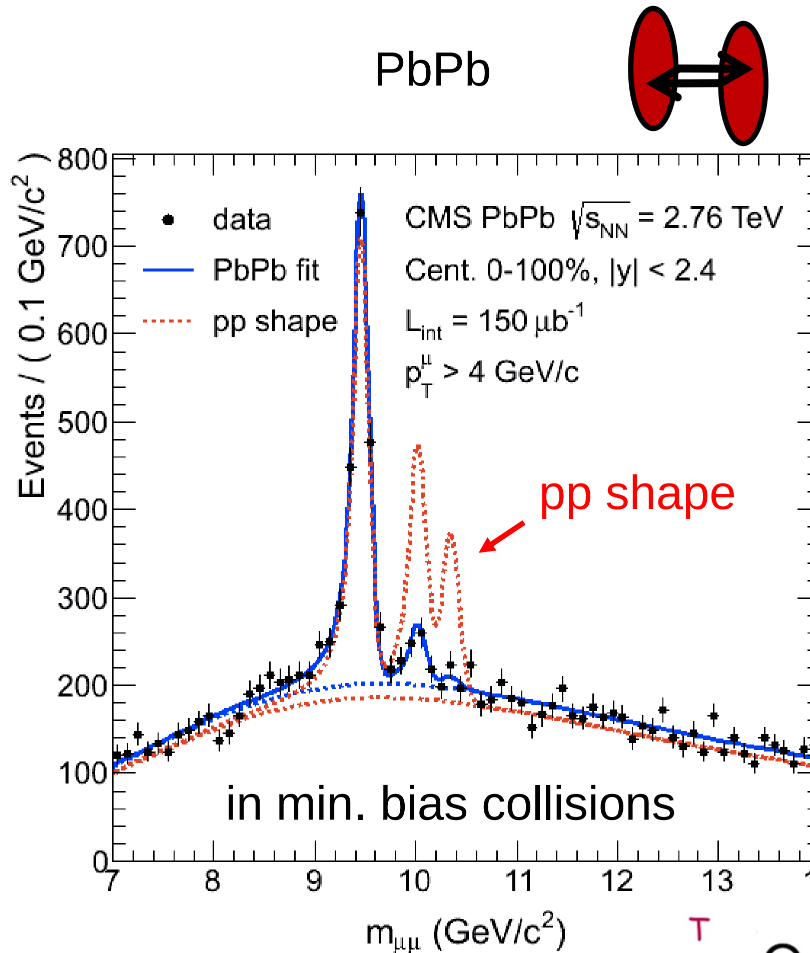


Size of the suppression is p_T dependent!

Recombination?

Upsilon family

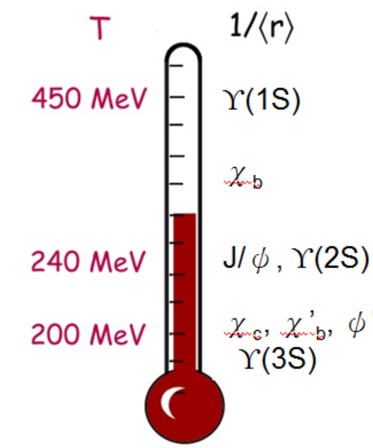




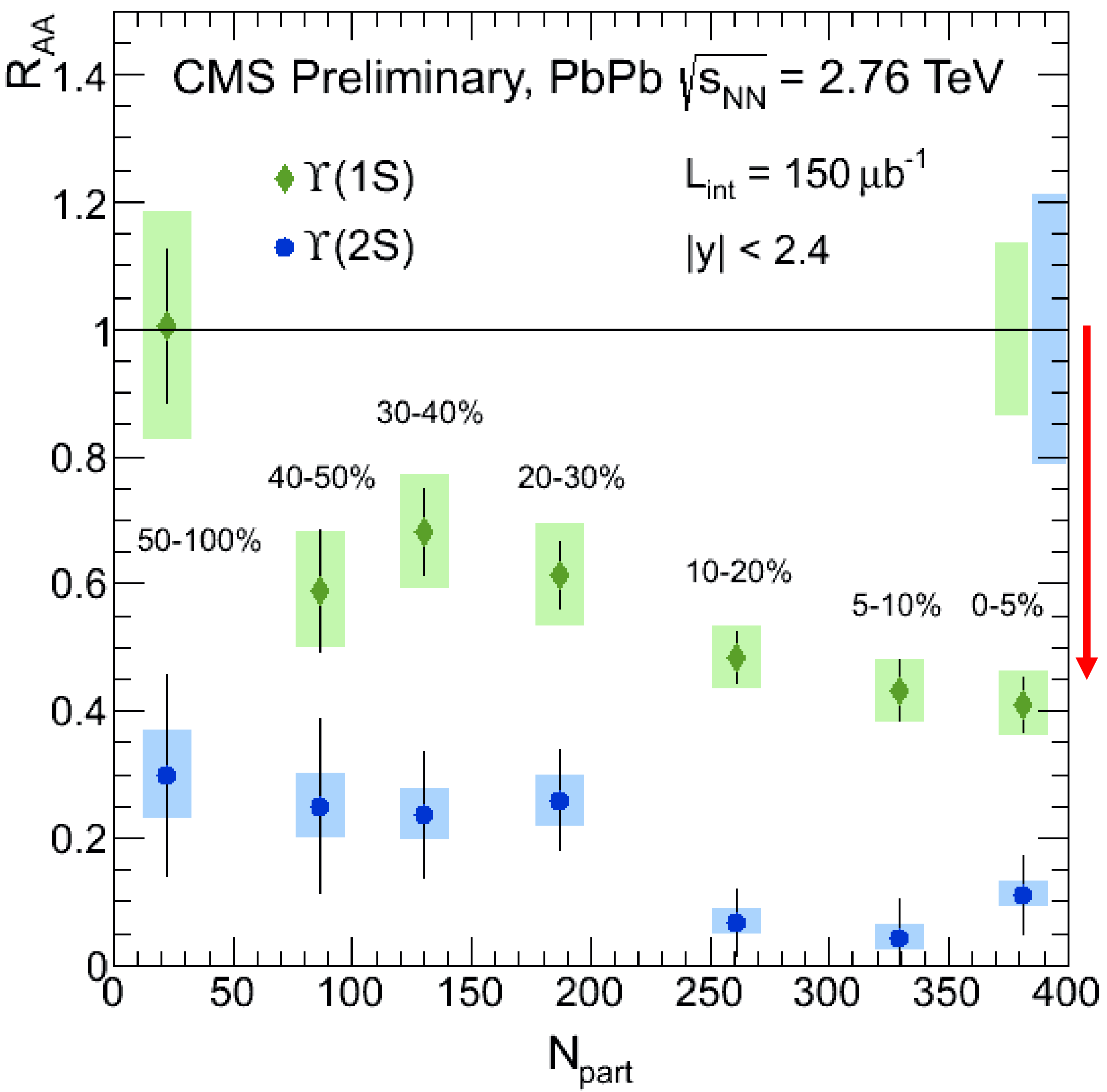
$$\frac{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb}}{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp}} = 0.21 \pm 0.7 \pm 0.02$$

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

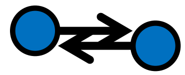
Upsilon suppression!

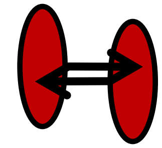


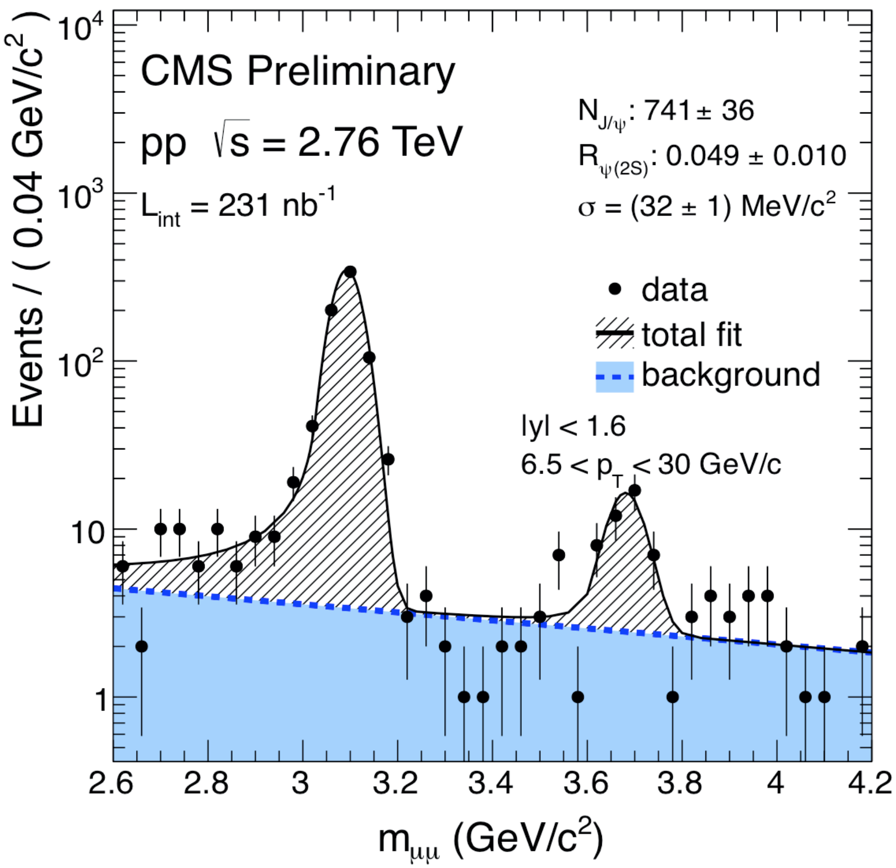
Upsilon suppression

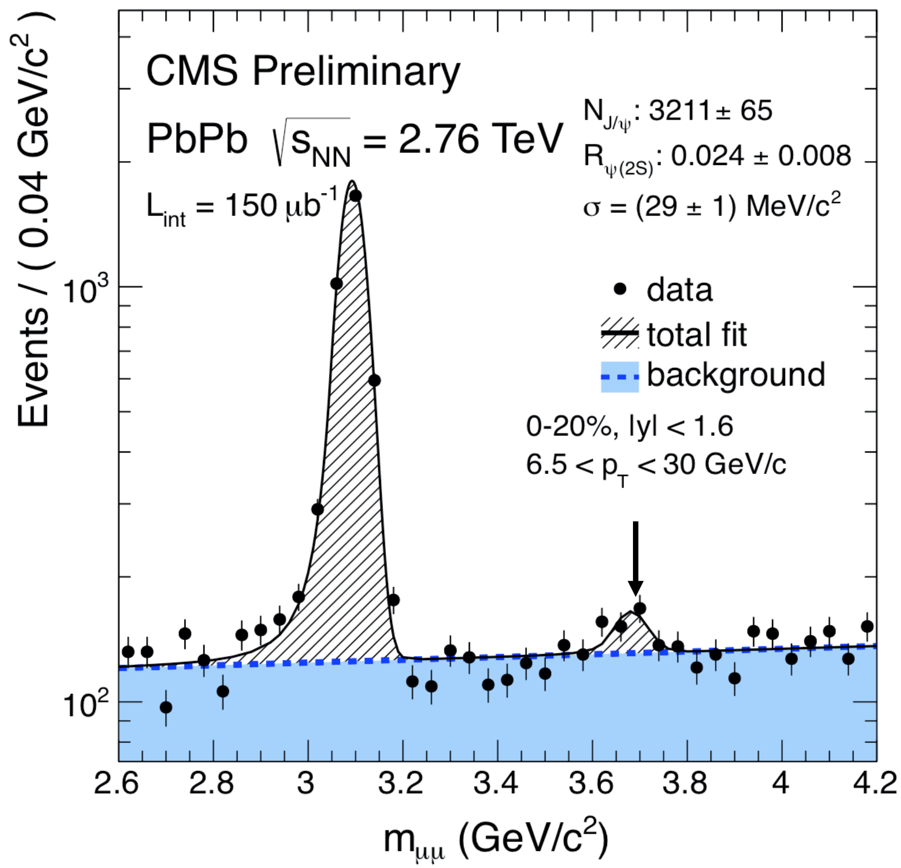


ψ(2S) suppression

pp 

PbPb 





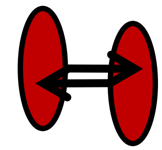
High p_T ψ(2S) suppression

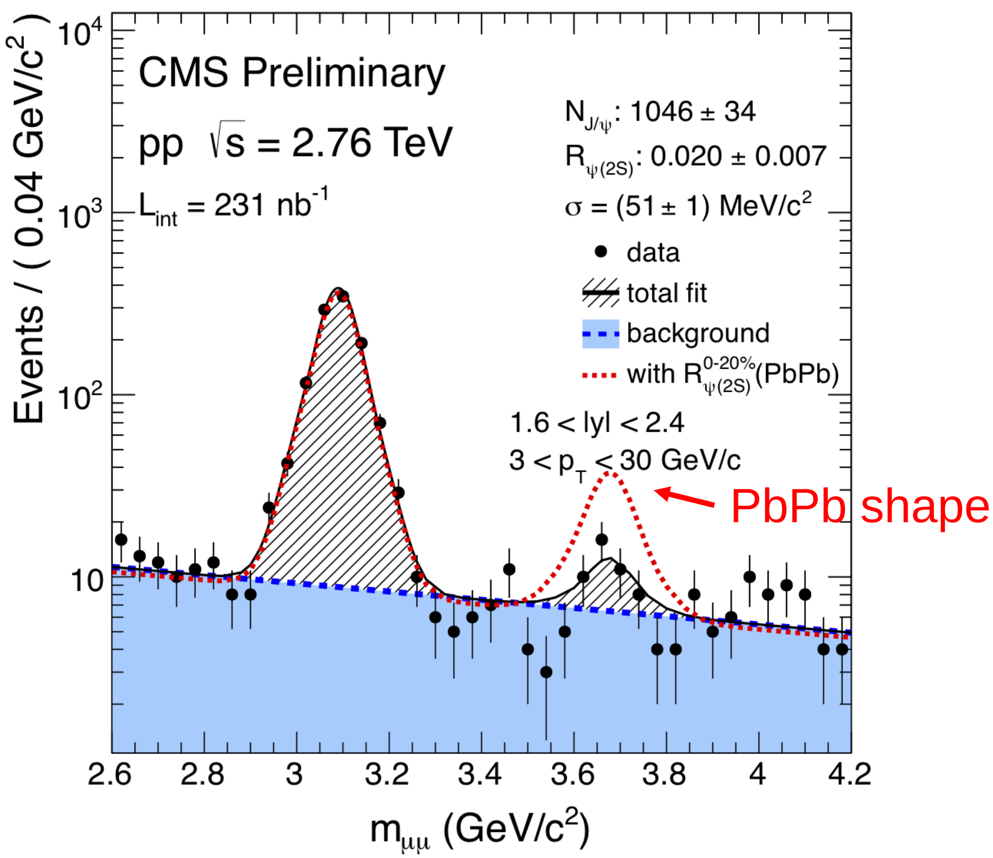
|y|<1.6, 6.5<pT<30 GeV/c

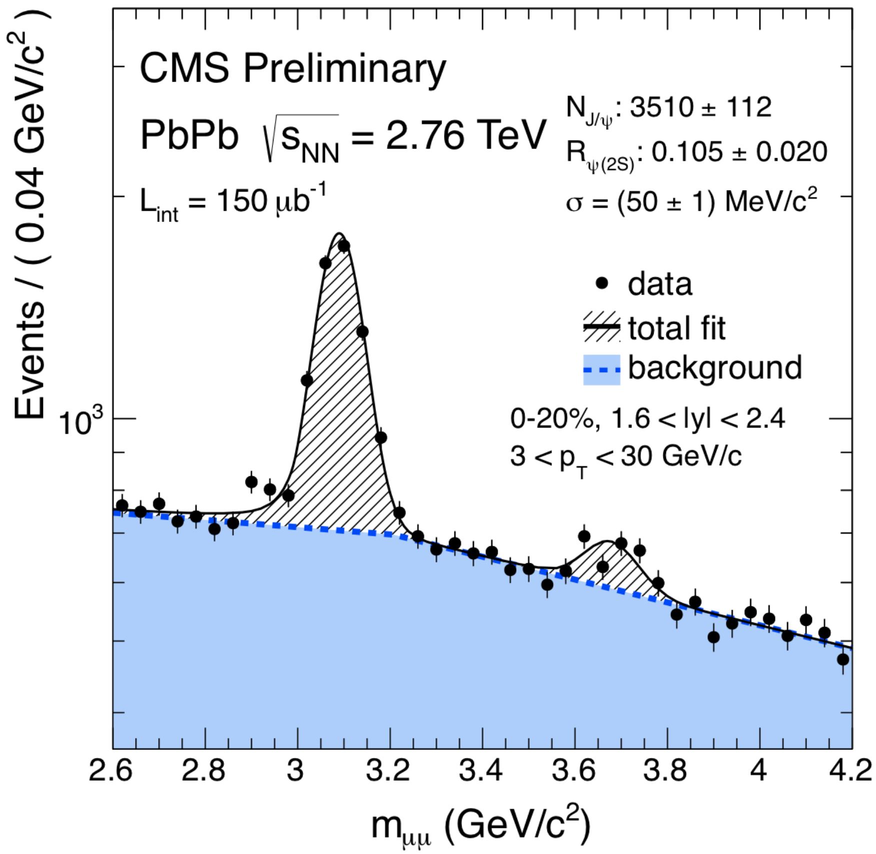
ψ(2S) enhancement??

Things look good so far, but…

pp 

PbPb 



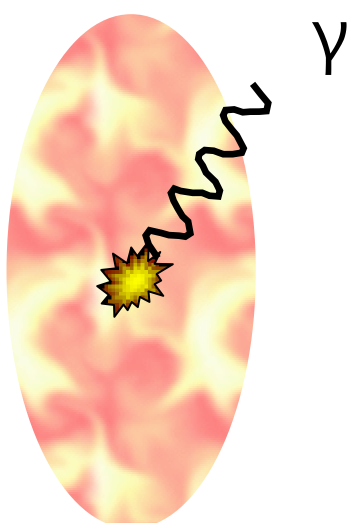


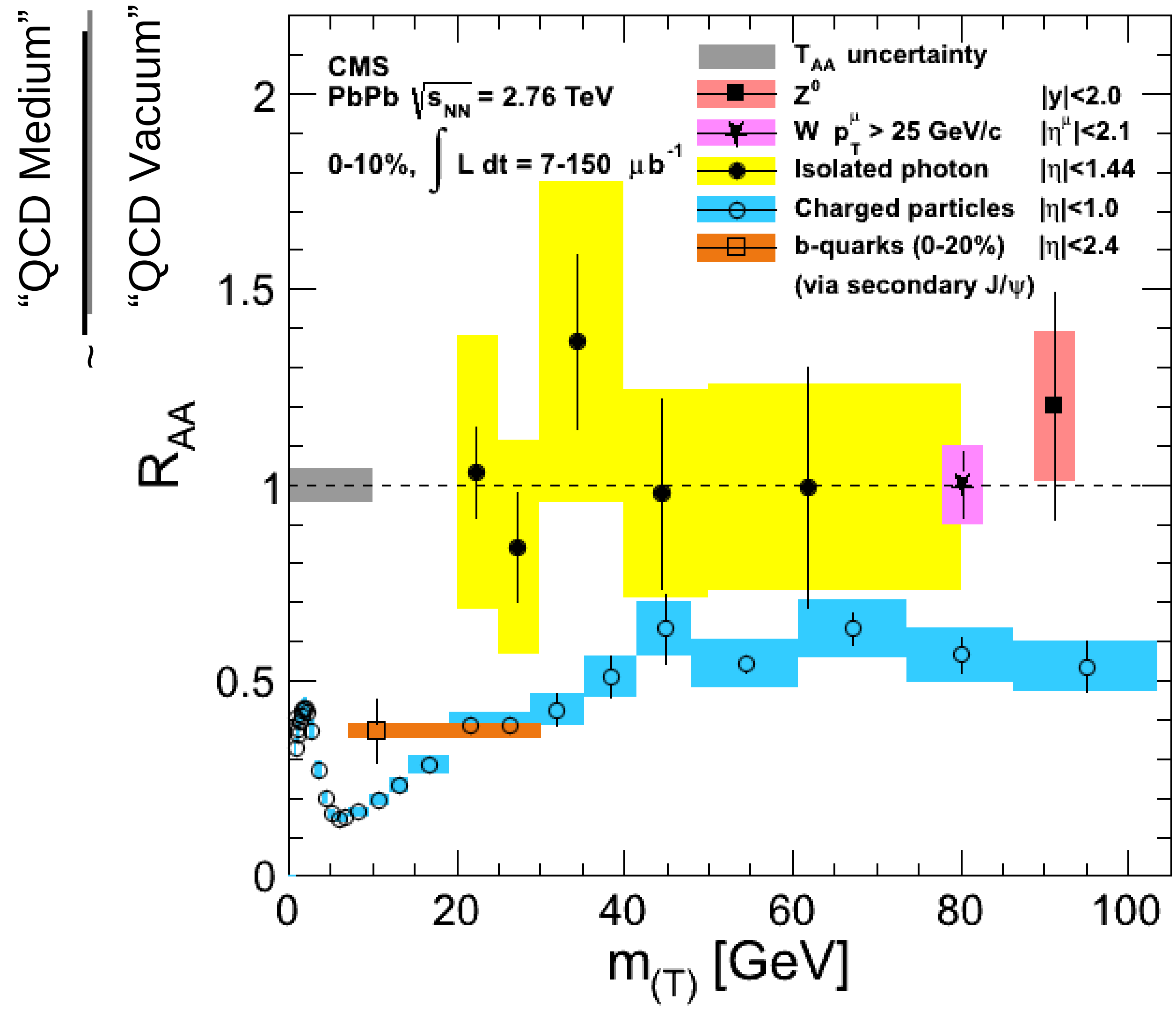
Low pT ψ(2S) 1.6<|y|<2.4, 3<p_T<30 GeV/c

Recombination?
Statistical fluctuation?
→ Need more pp data and results from ALICE & ATLAS

Summary (1/3)

1. Photons, W and Z bosons are not affected, which is different from charged particles and jets.

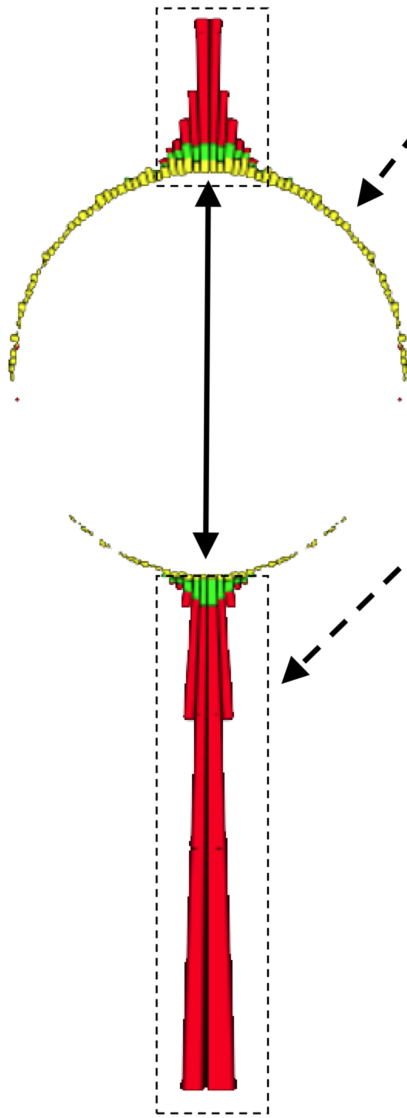




Summary (2/3)

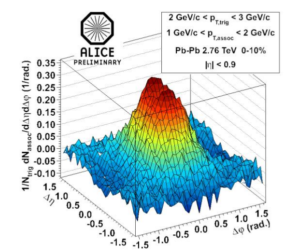
2. High p_T jet suppression
→ΔR = 0.2 — 0.5 doesn't capture all the radiated energy

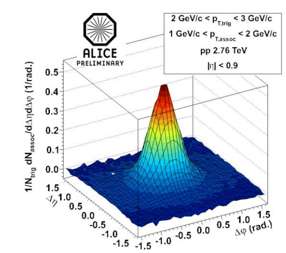
5. p_T difference found at low p_T particles far away from the jets



3. Large average dijet p_T imbalance

6. "Hard part" of the partons fragment as in vacuum





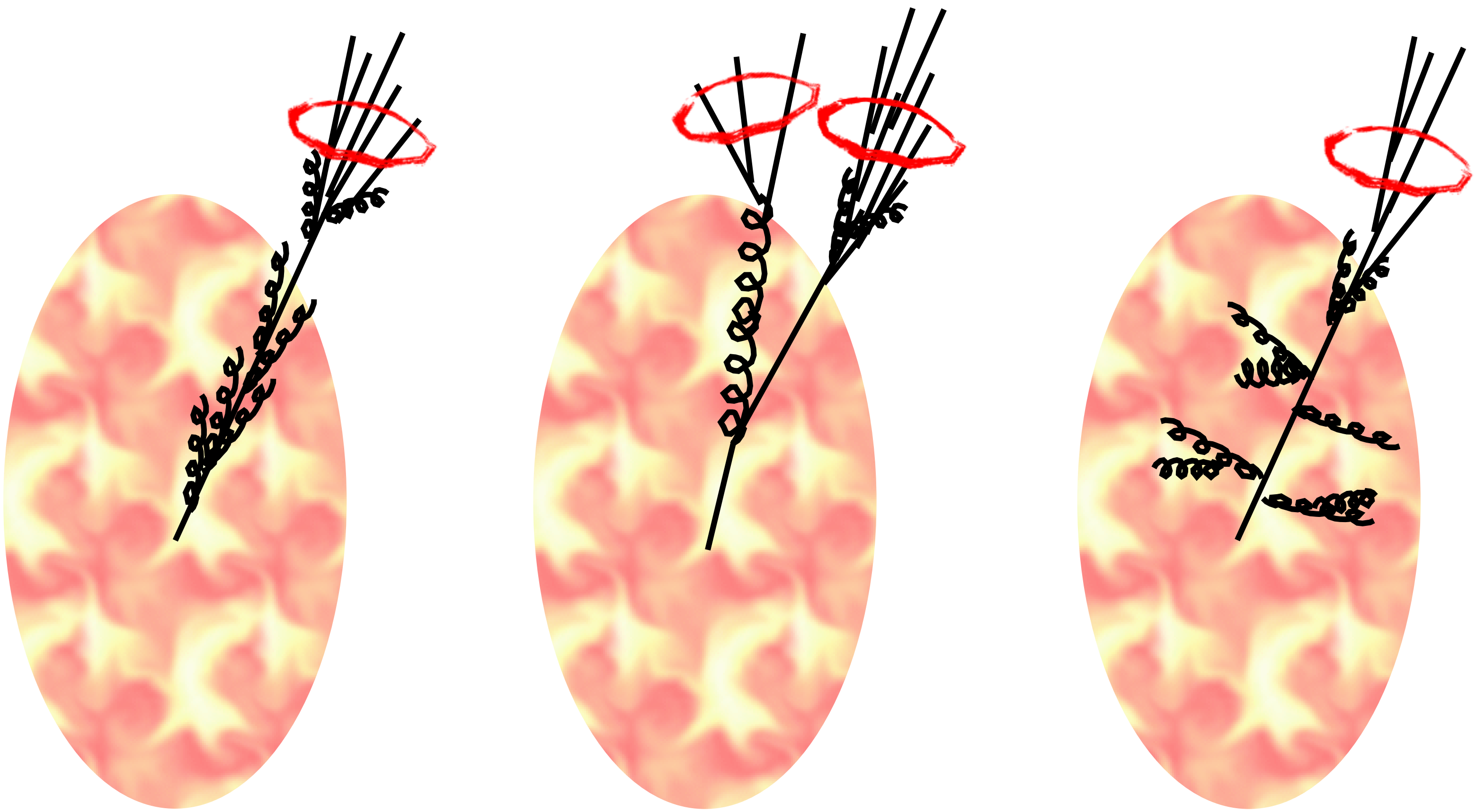
4. Angular correlation of jets not largely modified

7. Jet shape "broadening" seen in low p_T two particle correlation

8. Large photon-jet p_T imbalance > dijet p_T imbalance

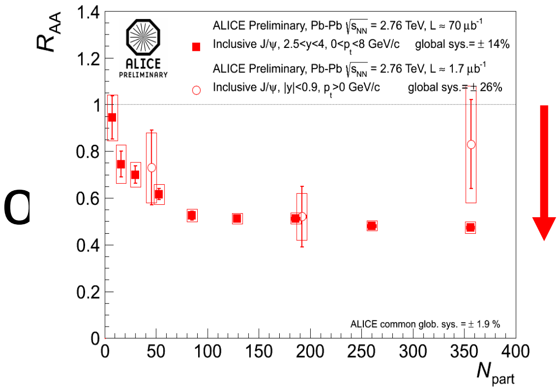
Three possible scenarios

To explain the suppression of high p_T particles



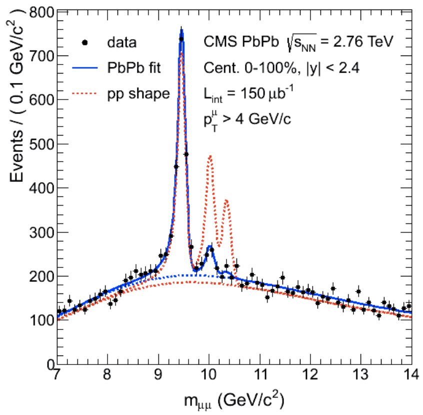
Soft collinear radiation	Hard radiation	Large angle soft radiation "QGP heating"
GLV + others	PYTHIA inspired models Modified splitting functions	AdS/CFT

Summary (3/3)



9. Large J/ψ suppression in central events

→ Indirect evidence of high p_T ψ (2S), χ_c suppressio

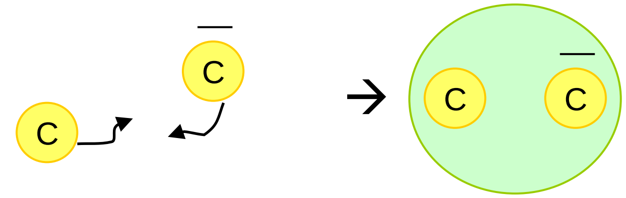


10. Indications of suppression of excited Υ States in Pb-Pb Collisions!

11. R_{AA} (low p_T J/ψ) > R_{AA} (high p_T J/ψ)

Enhancement of ψ(2S) / J/ψ ratio at low p_T

Recombination?



Expect a lot of new results in this conference!!!

Acknowledgement & other lectures

I would like to thank

Gabor Veres, Gunther Roland, Hermine Woehri, Raphael Granier de Cassagnac, Camelia Mironov, Matthew Nguyen, Guilherme Milhano and Yetkin Yilmaz

for the useful discussions

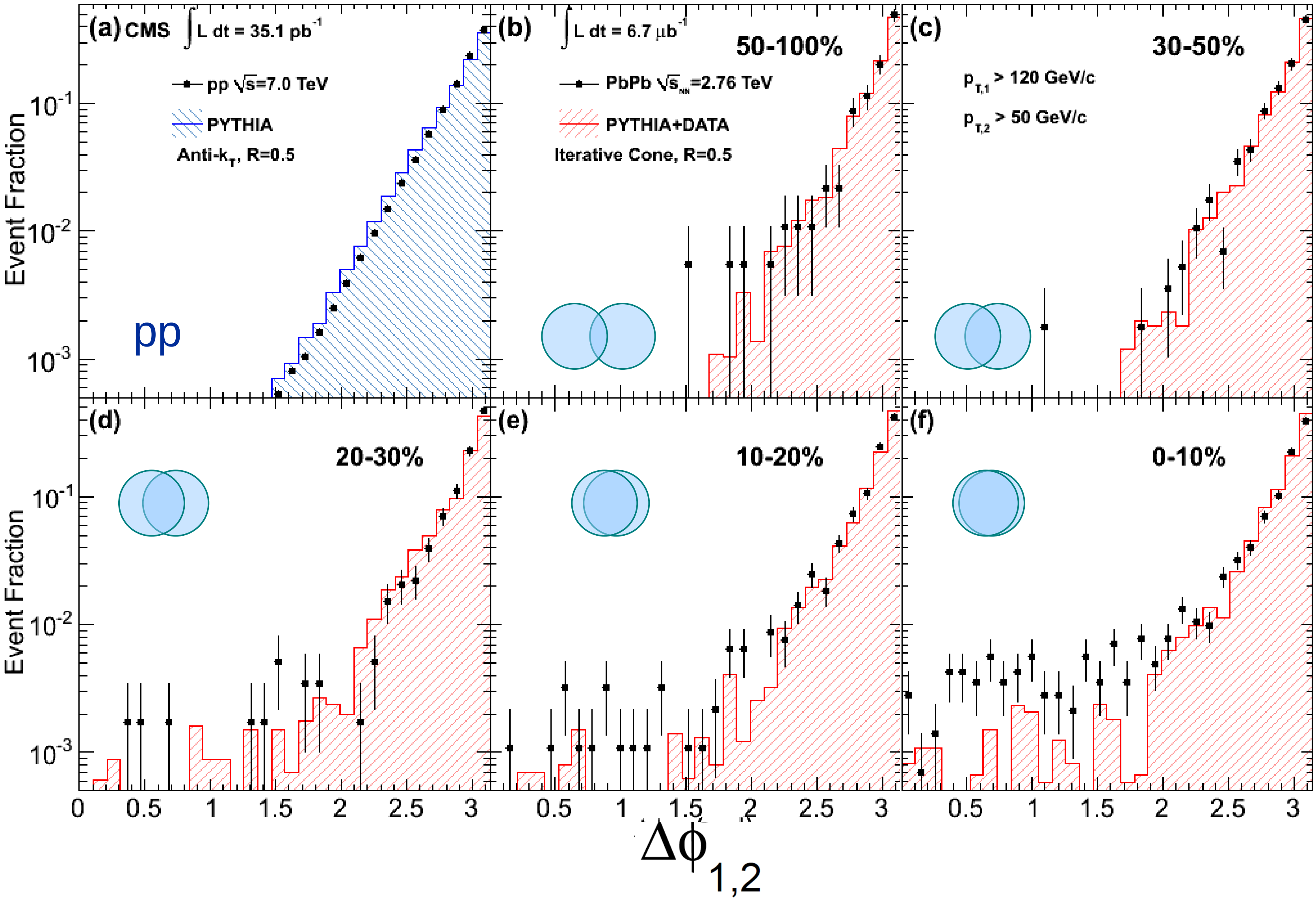
And nice results from ALICE, ATLAS and CMS collaboration

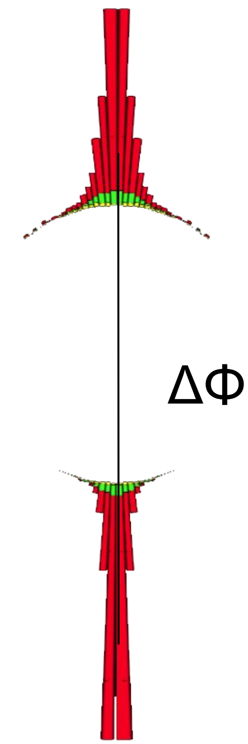
- HP2012 student lectures (video!)
  - Quarkonium Experiment (Hermine K. Wöhri)
  - Quarkonium Theory (Elena G. Ferreiro)
  - Jet Quenching (Guilherme Milhano, Mateusz Ploskon)

Expect a lot of new results in this conference!!!

Backup slides

Di-jet angular correlation



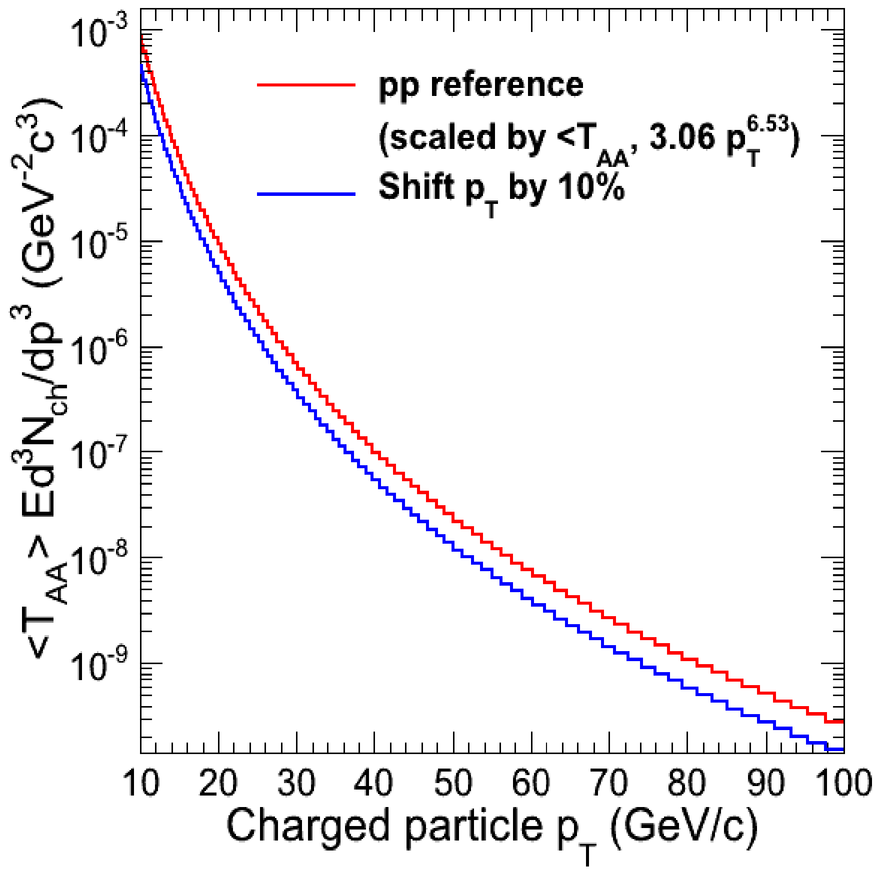


The propagation of high p_T partons in a dense medium does not lead to a visible angular decorrelation.

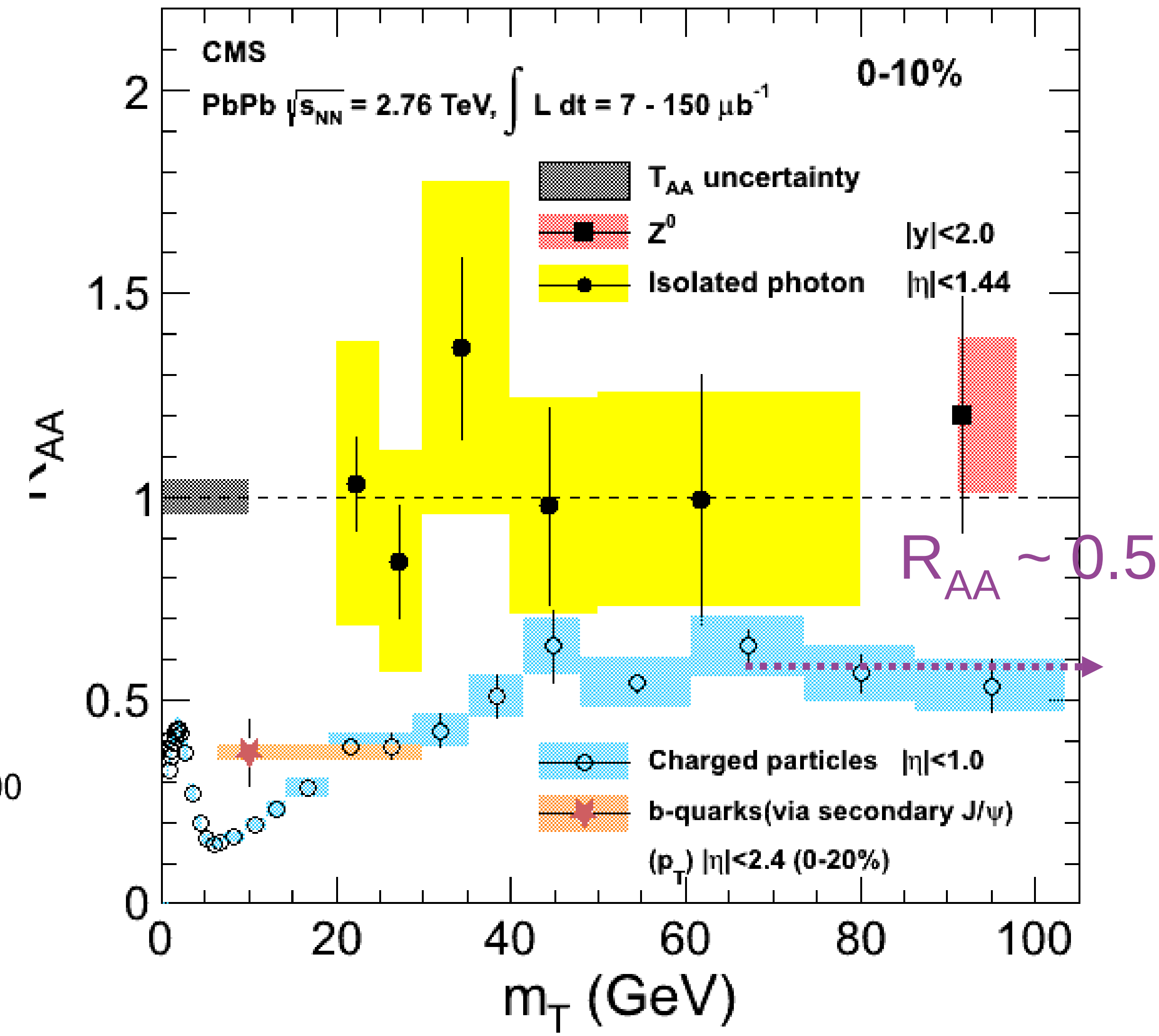
Phys. Rev. C 84, 024906 (2011)

Scaling the charged particle p_T spectrum

Scale p_T by 10%



$$\frac{\text{Shifted reference}}{\text{pp reference}} \sim 0.5$$



Consistent picture obtained from dijet momentum balance results and charged particle R_{AA} analysis

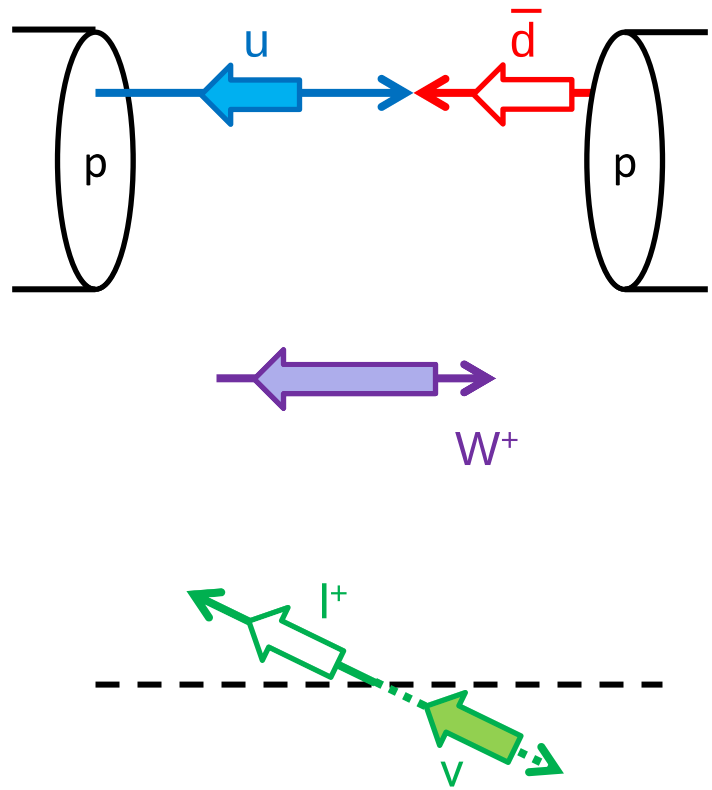
Centrality	b mean (fm)	b RMS (fm)	N_{part} mean	N_{part} RMS	N_{coll} mean	N_{coll} RMS
0–10%	3.4 ± 0.1	1.2	355 ± 3	33	1484 ± 120	241
10–20%	6.0 ± 0.2	0.8	261 ± 4	30	927 ± 82	183
20–30%	7.8 ± 0.2	0.6	187 ± 5	23	562 ± 53	124
30–50%	9.9 ± 0.3	0.8	108 ± 5	27	251 ± 28	101
50–100%	13.6 ± 0.4	1.6	22 ± 2	19	30 ± 5	35

Charge asymmetry

@LO: $u\bar{d} \rightarrow W^+$ & $\bar{u}d \rightarrow W^-$

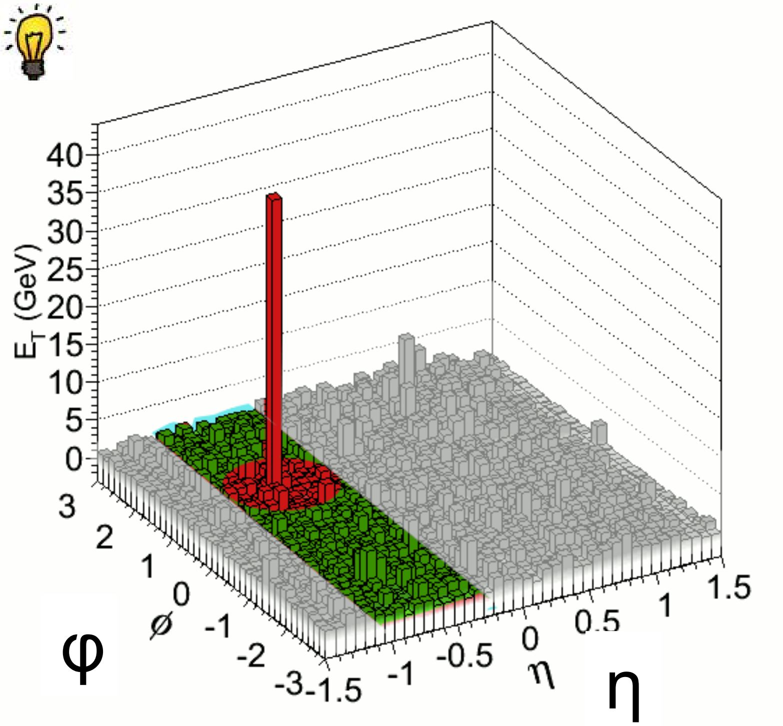
- Less W^+ and more W^- in PbPb than in pp (*isospin* effect)
  - Cancels for $W^+ + W^-$
- W boosted towards the valence quark (higher rapidity)
- Spin conservation → μ^+ (μ^-) boosted back to (away from) midrapidity

→ A strong acceptance difference (not heavy-ion specific)



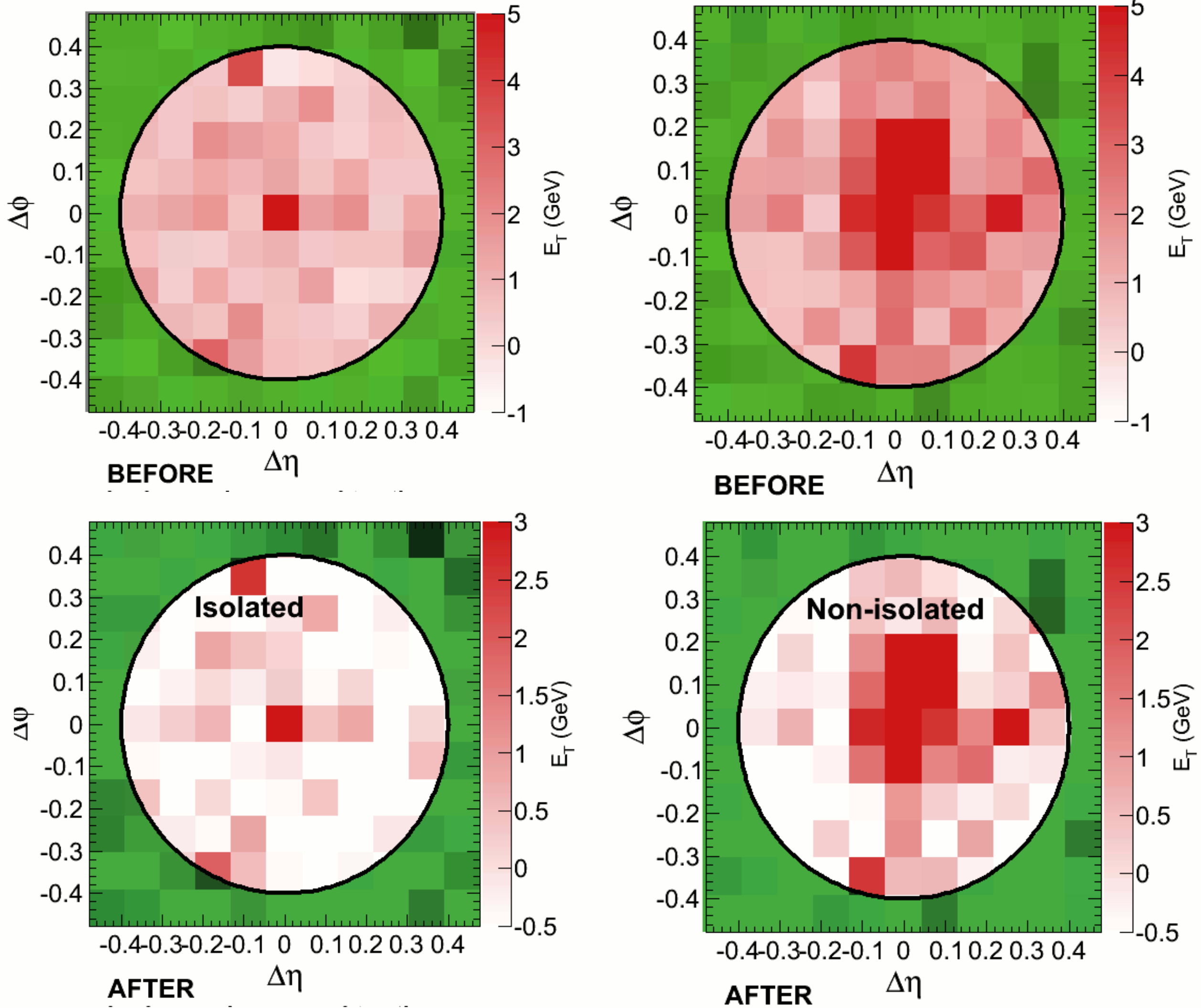
Background subtraction

- Background subtracted isolation by using the mean E_T per unit area in the η strip and remove the underlying event contribution inside the isolation cone

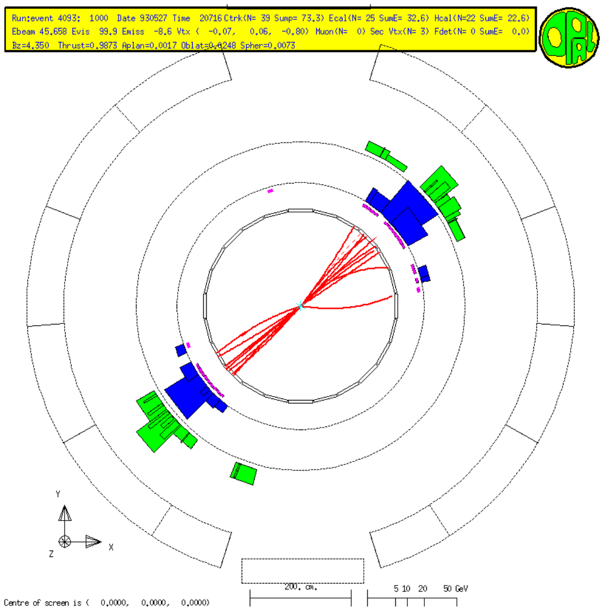


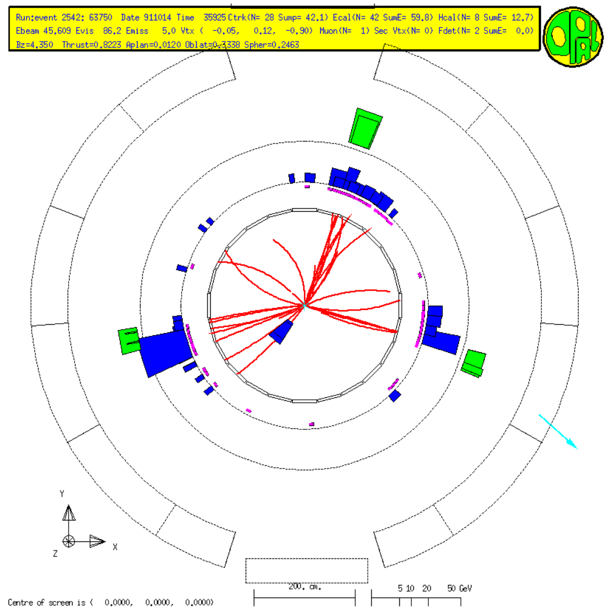
Isolated photon

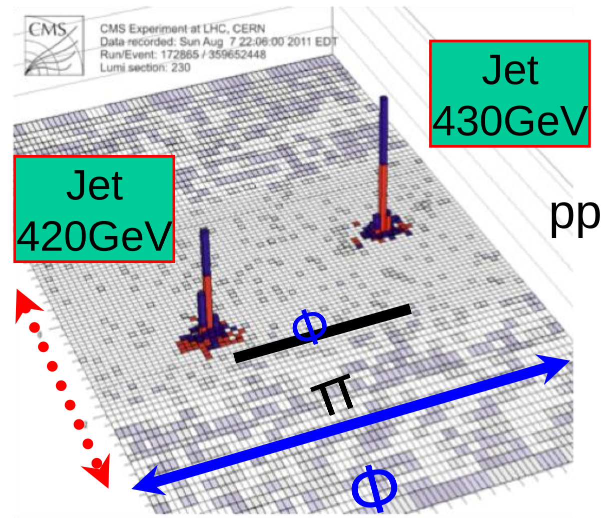
Photon candidate from jet

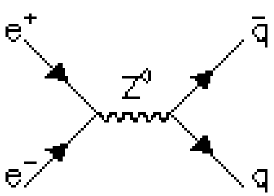


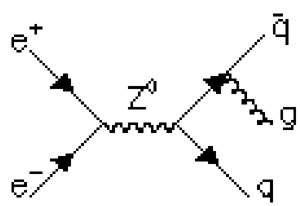
Quarks and gluons

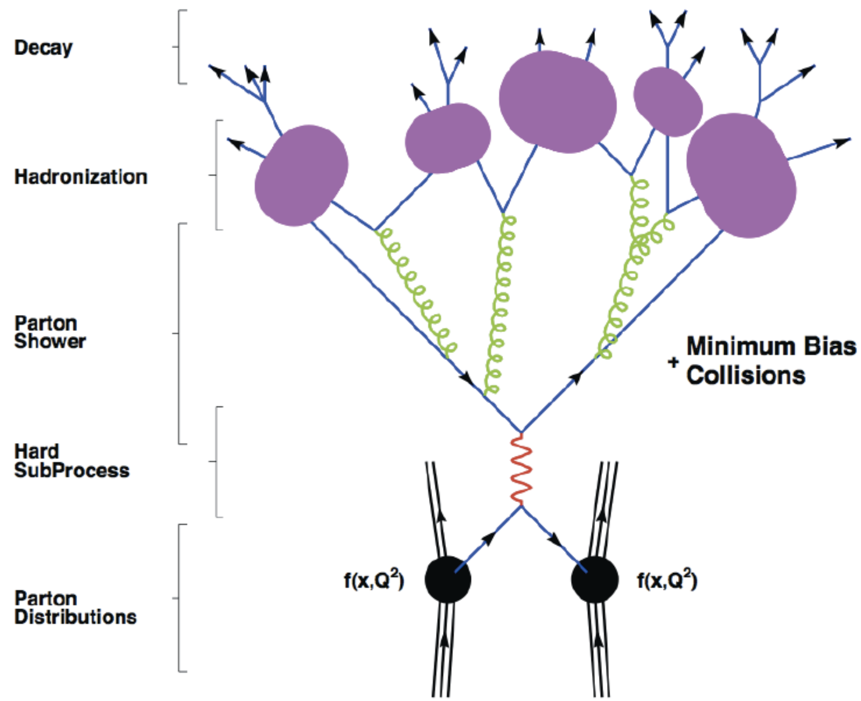








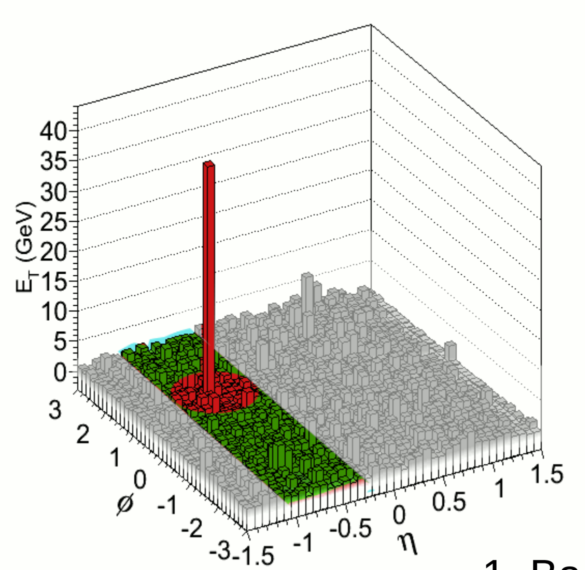


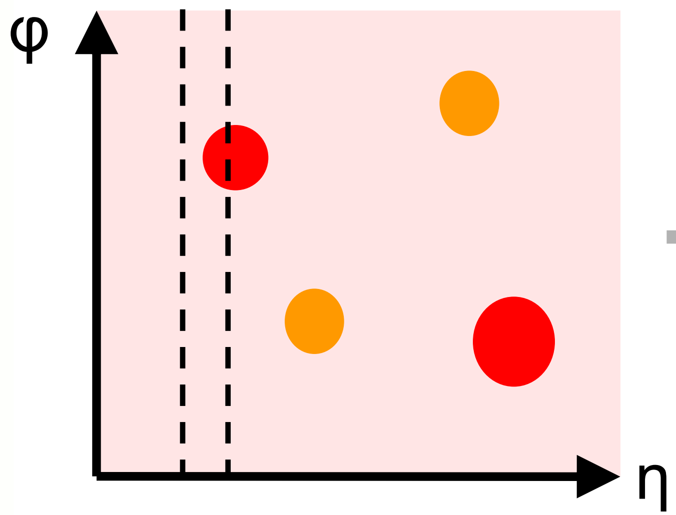


Color confinement:

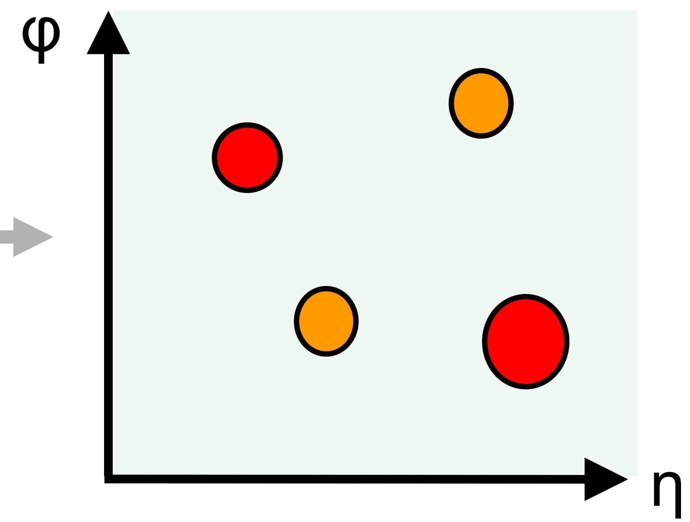
Quarks and gluons → groups of hadrons

Background subtraction



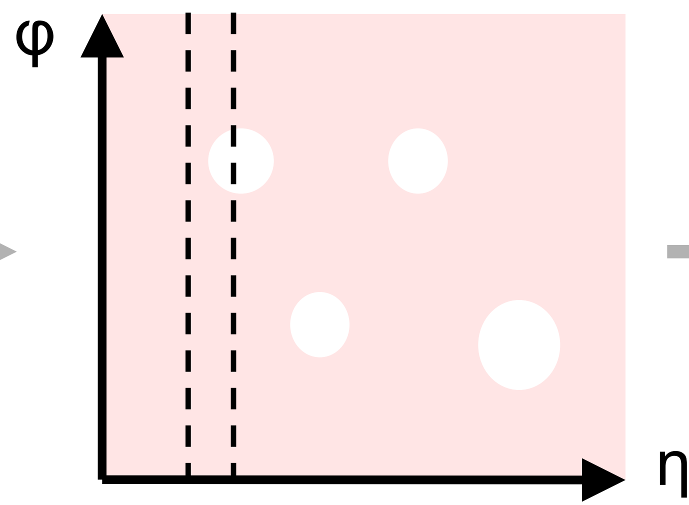


1. Background energy per tower calculated in strips of η. Pedestal subtraction

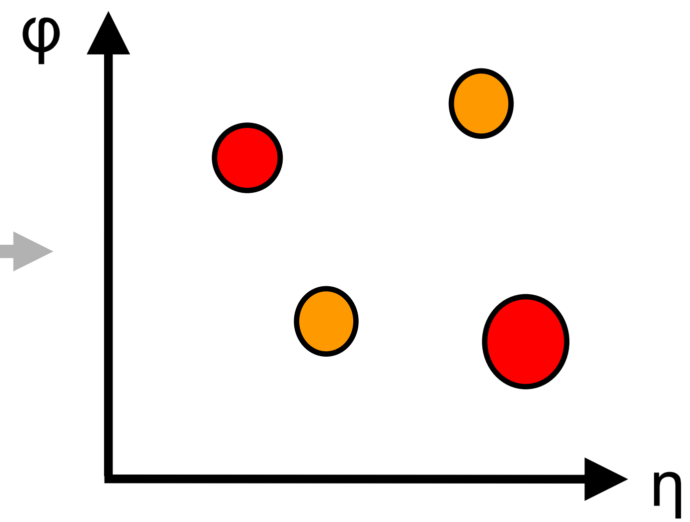


2. Run anti k_T algorithm on background subtracted towers

CMS as a example:



3. Exclude reconstructed jets
Recalculate the background energy



4. Run anti k_T algorithm on background subtracted towers to get final jets