Jetting through the Quark Soup

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https://indico.ihep.ac.cn/event/7841/timetable/#all

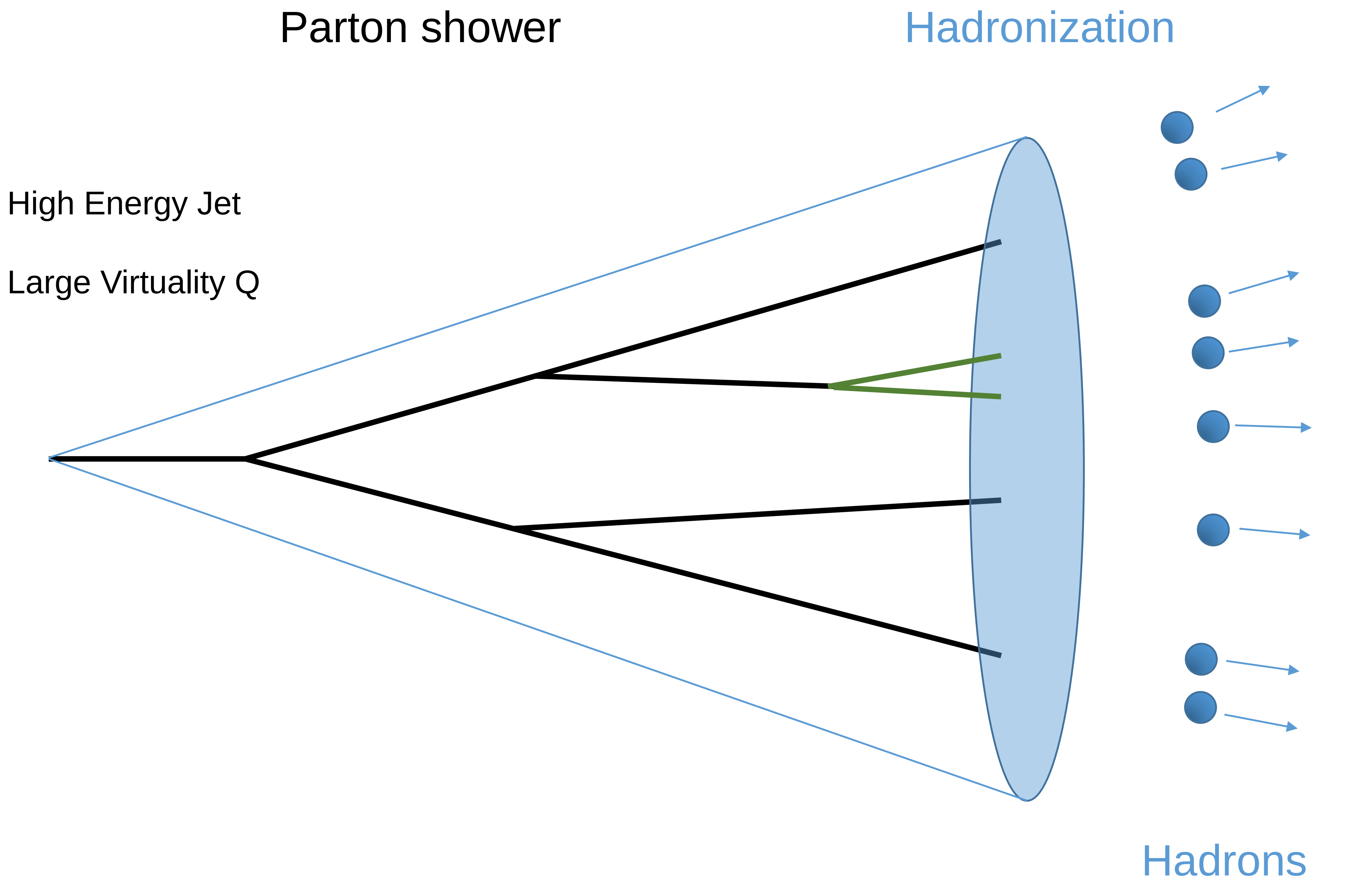
Outline

- Lecture 1
  Why do we study relativistic heavy ion collisions?
- Lecture 2
  How do we measure jets in heavy ion collisions?
- Lecture 3
  Parton energy loss and its parton flavor dependence
- Lecture 4
  Modification of jet substructure and medium response
- Lecture 5
  Open questions and future direction

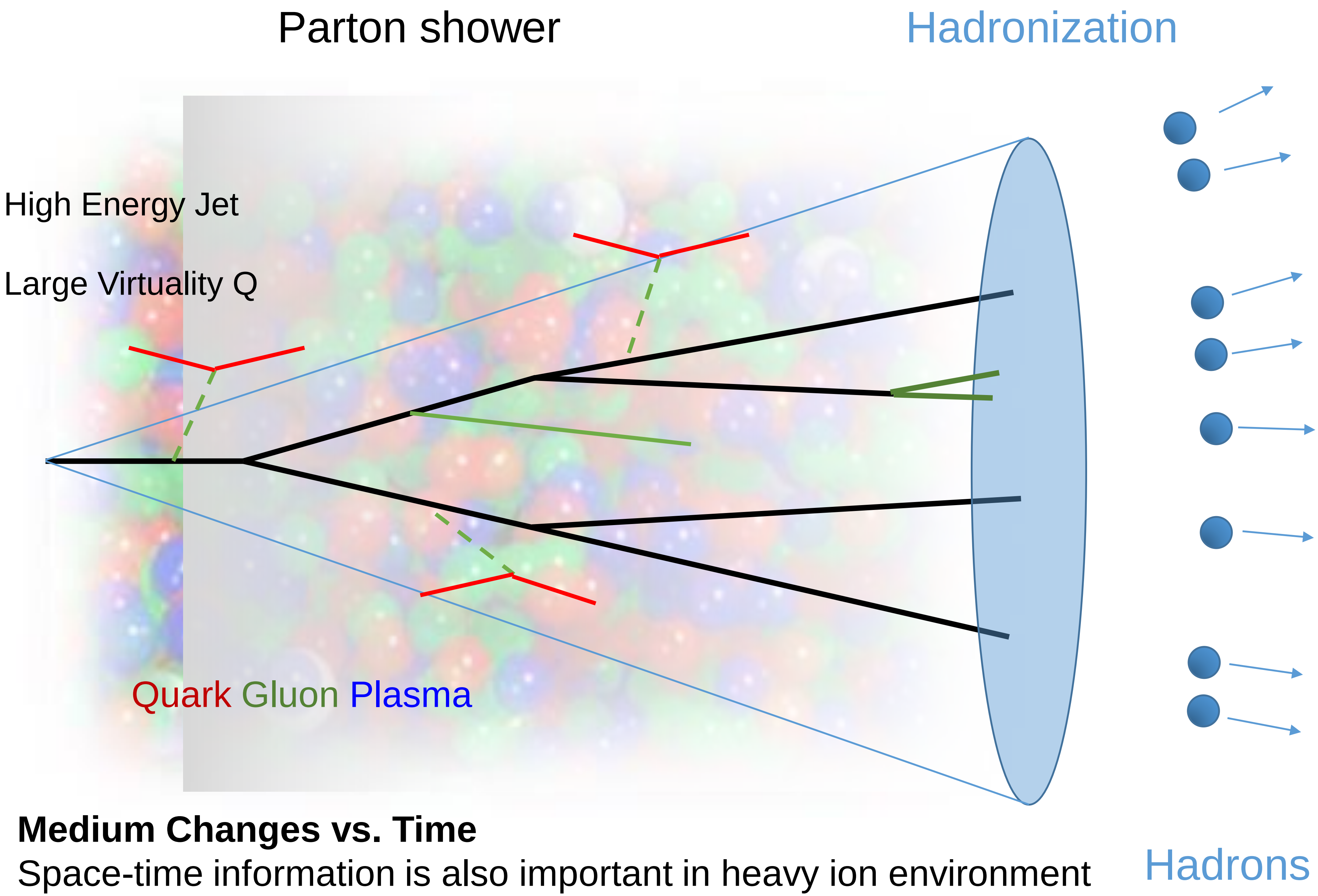
Lecture 3

Parton energy loss and its parton flavor dependence

Parton Cascade in Vacuum



Parton Cascade in the Quark Soup



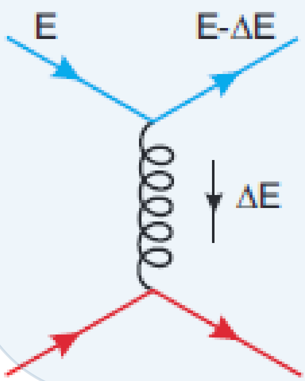
Medium Changes vs. Time
Space-time information is also important in heavy ion environment

Extraction of the medium properties

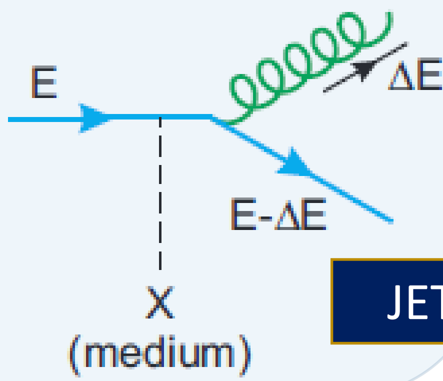
- **The main difficulty:** we don't know how to describe the interaction between the hard scattered parton and QGP (a multi-scale problem)
- **Two theoretical approaches:**
  (neither of them are the full stories and both of them are effective descriptions in proper regimes)

Perturbative QCD
Weak coupling limit

Collisional energy loss

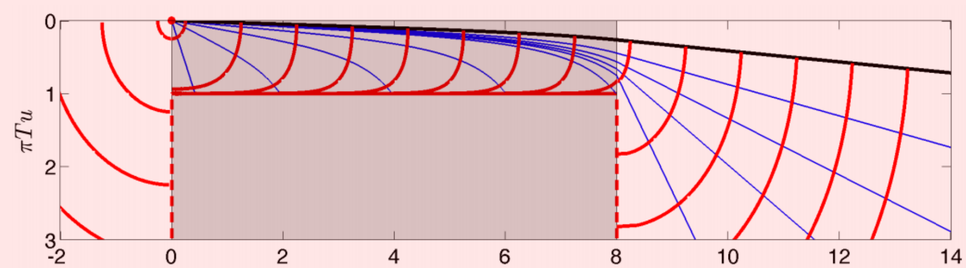


Radiative energy loss



Holographic calculation
Strong coupling limit

AdS/CFT "drag force"



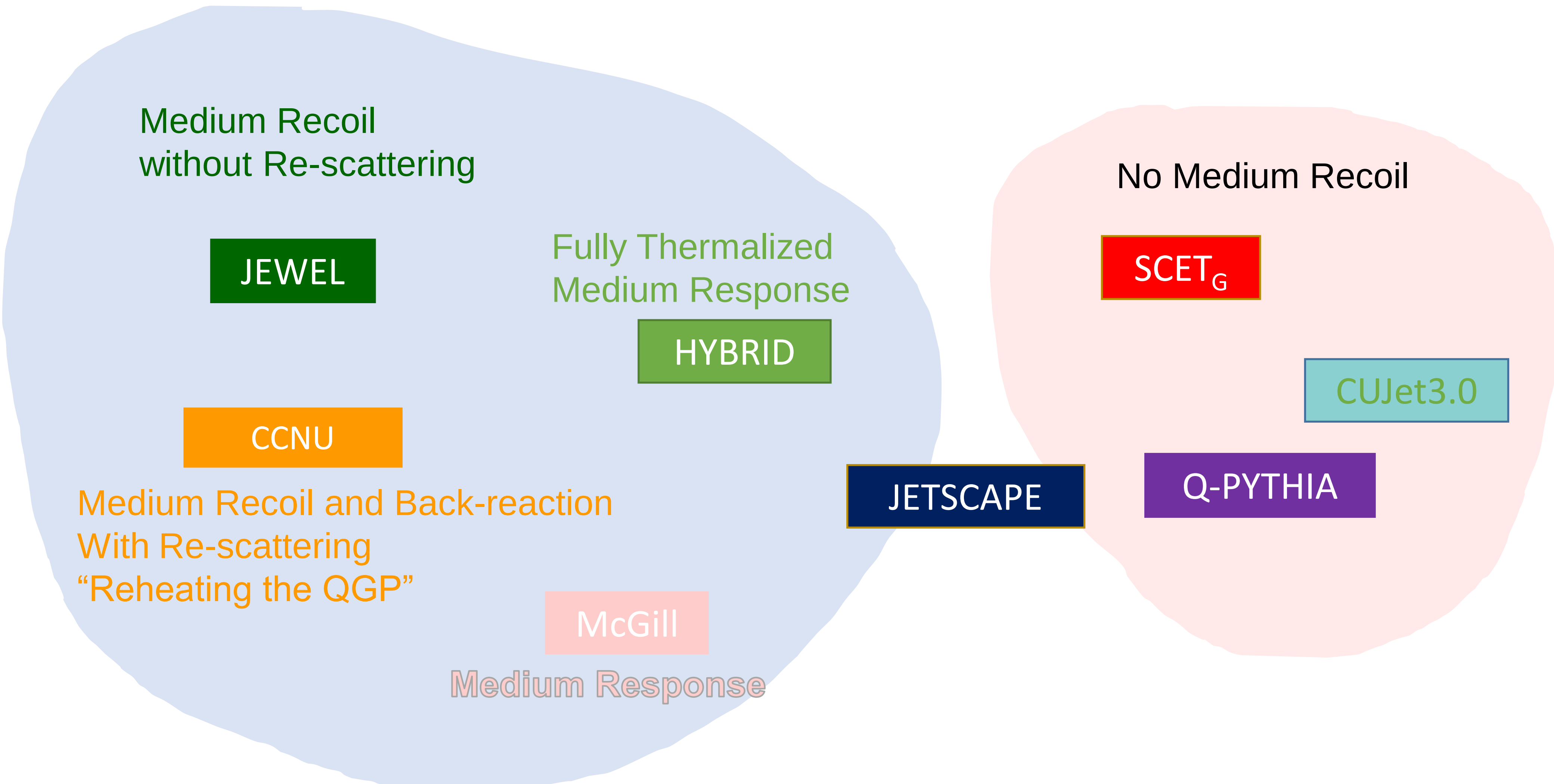
JETSCAPE

JEWEL | CUJet3.0 | CCNU | HYBRID

Q-PYTHIA | $SCET_G$ | McGill

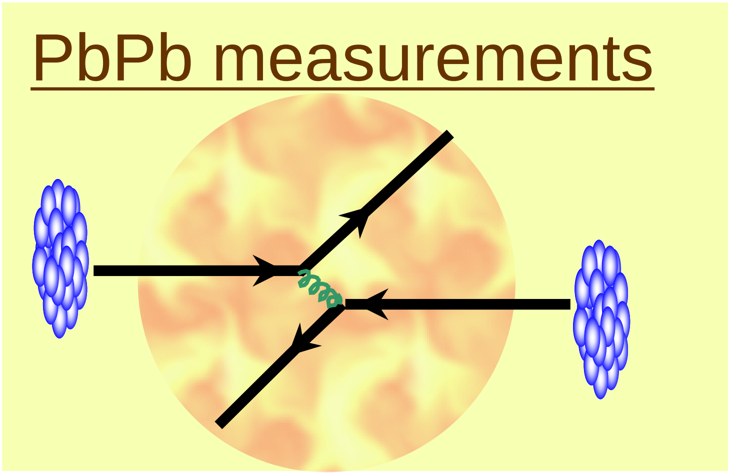
Medium Response

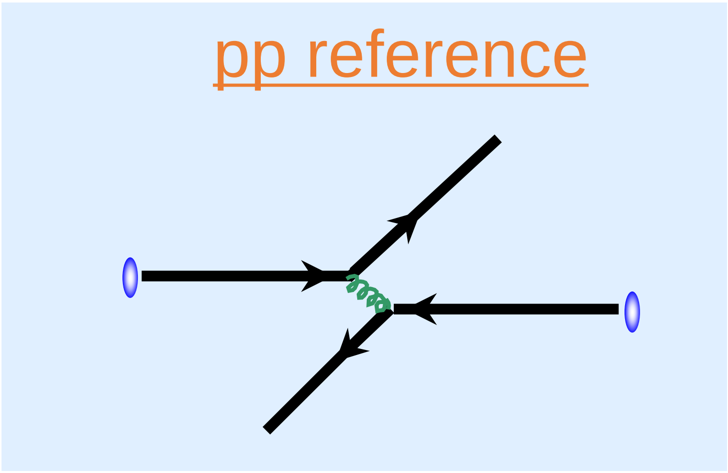
We also don't know **how much** the medium response (recoil) plays a role in the description of the jet quenching observables and how to describe it correctly



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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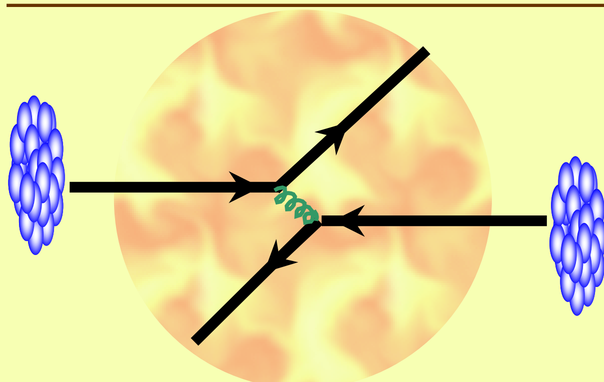
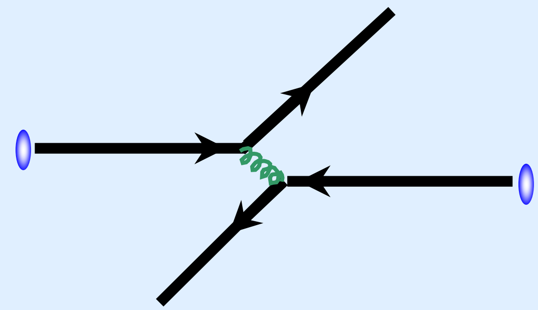
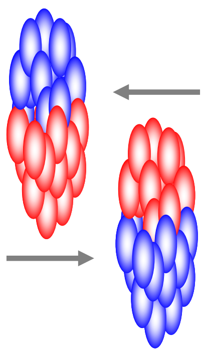
PbPb measurements



pp reference

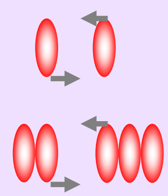




N_{part} → Number of participating nucleons

N_{coll} → Number of binary scatterings

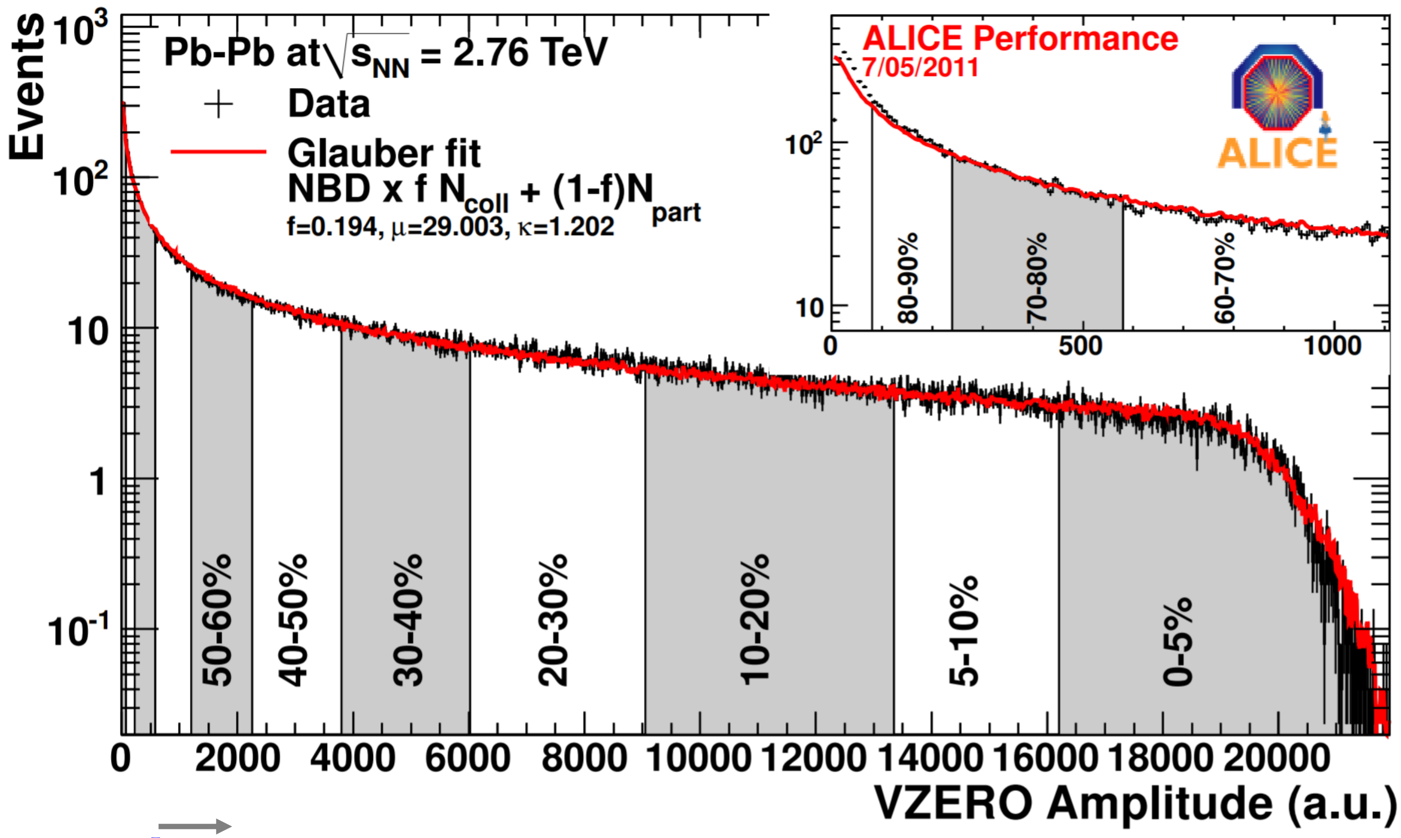
Example:

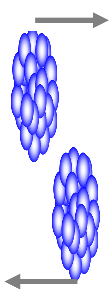


$N_{part} = 2$ $N_{coll} = 1$

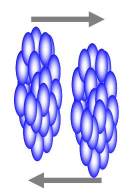
$N_{part} = 5$ $N_{coll} = 6$

Centrality





"Peripheral"
Large impact parameter



"Head-on"
Small impact parameter

- We can not (yet) control the impact parameter of the colliding ions
- Instead, we make use of the **ASSUMPTION:** strong correlation between impact parameter and energy measured in the large rapidity region to classify the events into centrality classes

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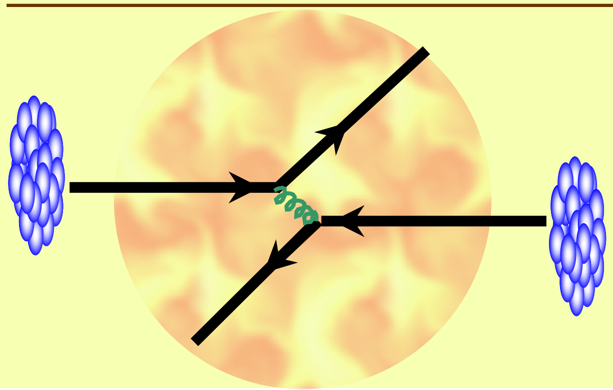
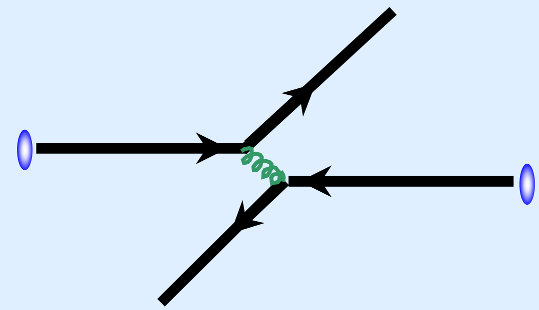
PbPb measurements



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)

$N_{coll} \rightarrow$ Averaged number of binary scattering from a Glauber model calculation

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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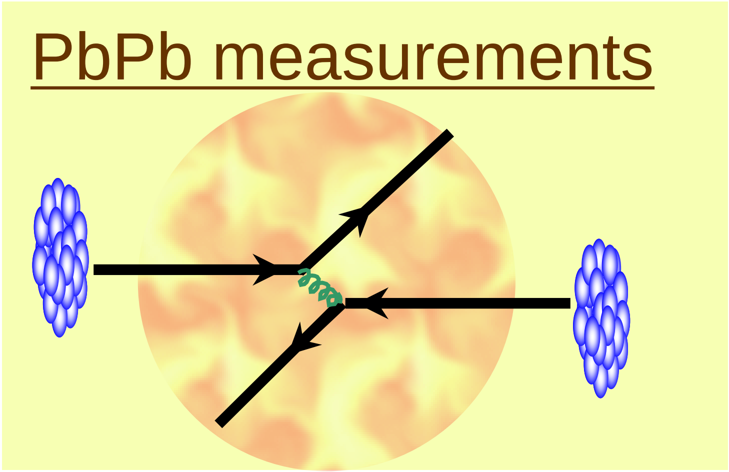

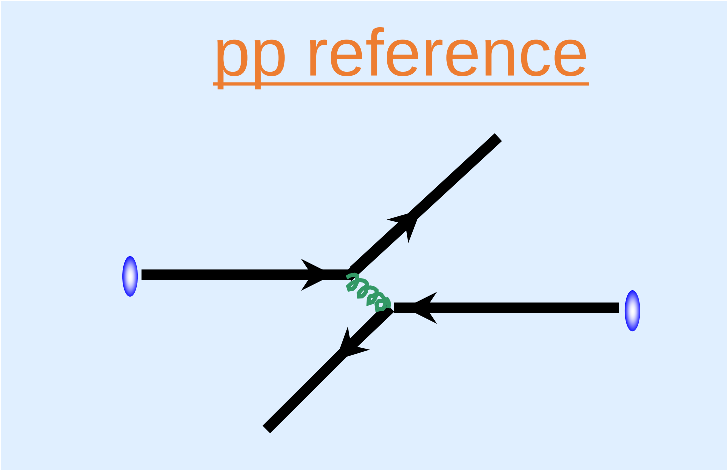

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Questions: How do we know the Glauber model calculation of N_{coll} is correct?

How do we extract the medium effect in PbPb collisions?

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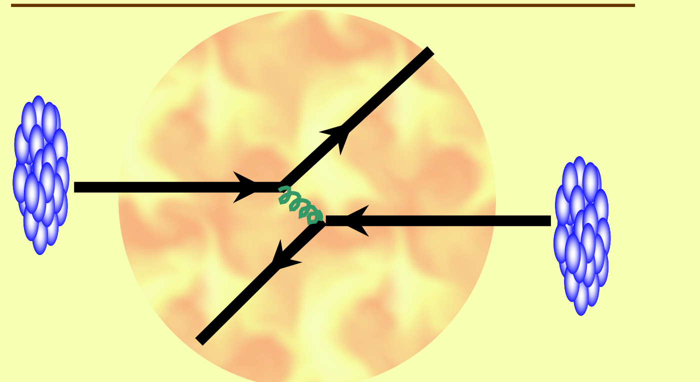
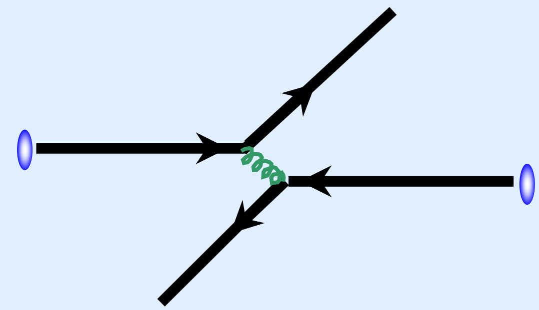
PbPb measurements



pp reference



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

→ Motivates the studies of electroweak probes

Nuclear Modification Factors (R_{AA})

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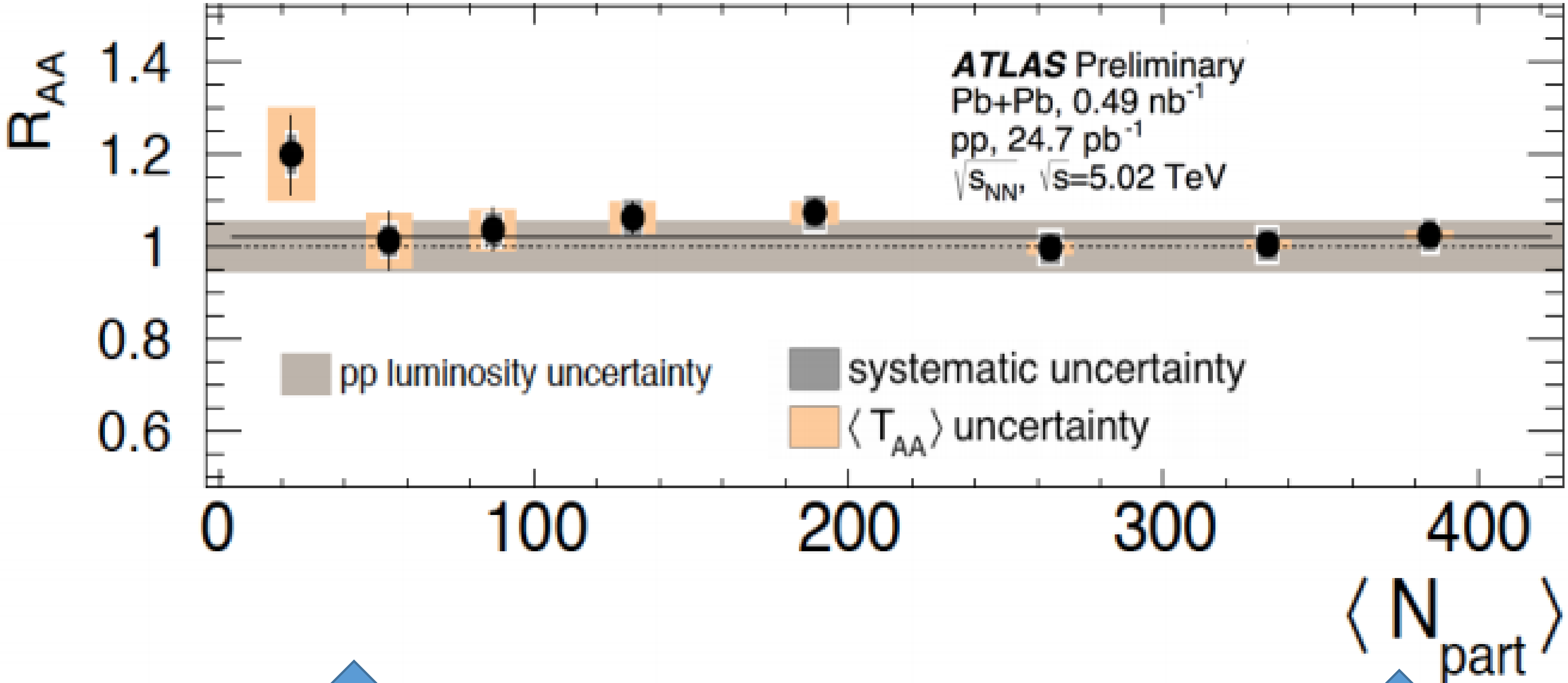
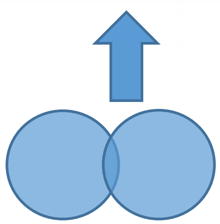
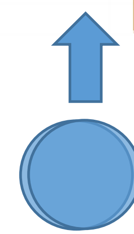
Z boson R_{AA} (PbPb at 5 TeV)



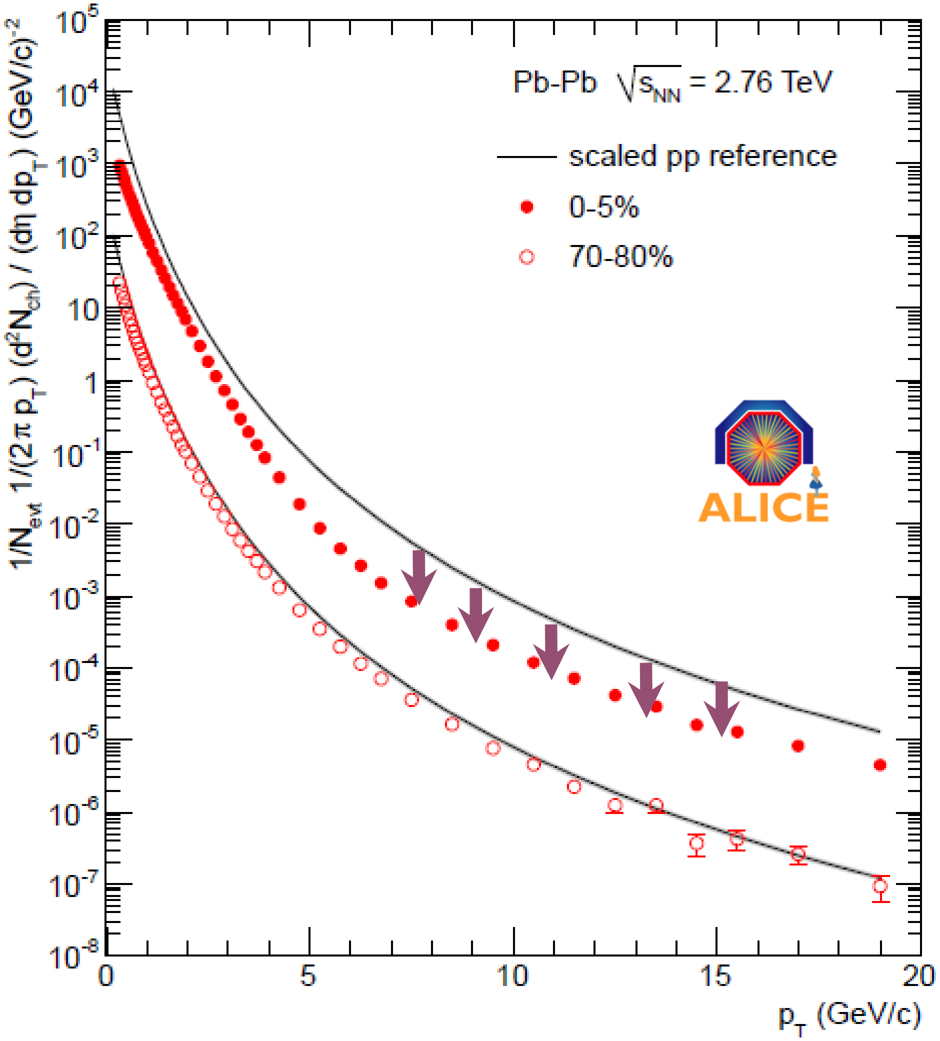




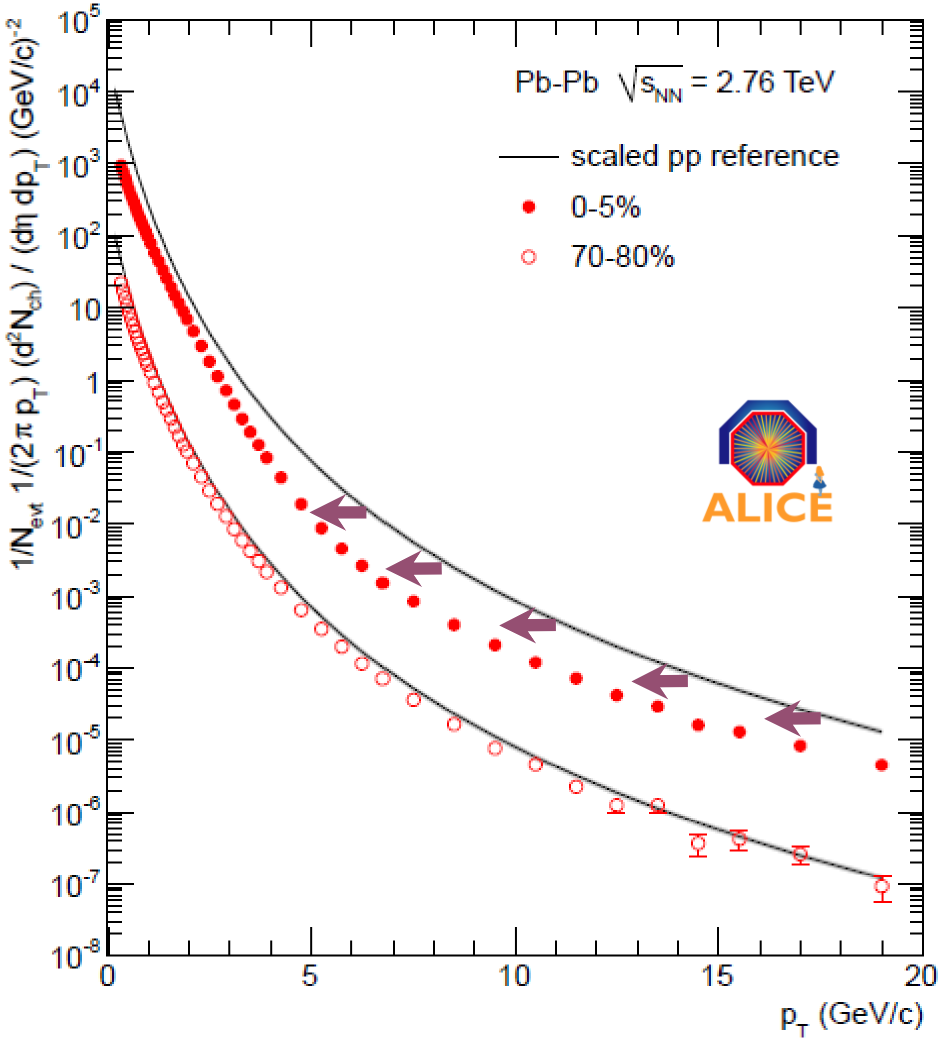
No significant modification of colorless probes in PbPb collisions

Charged Particle Spectra

Absorption?

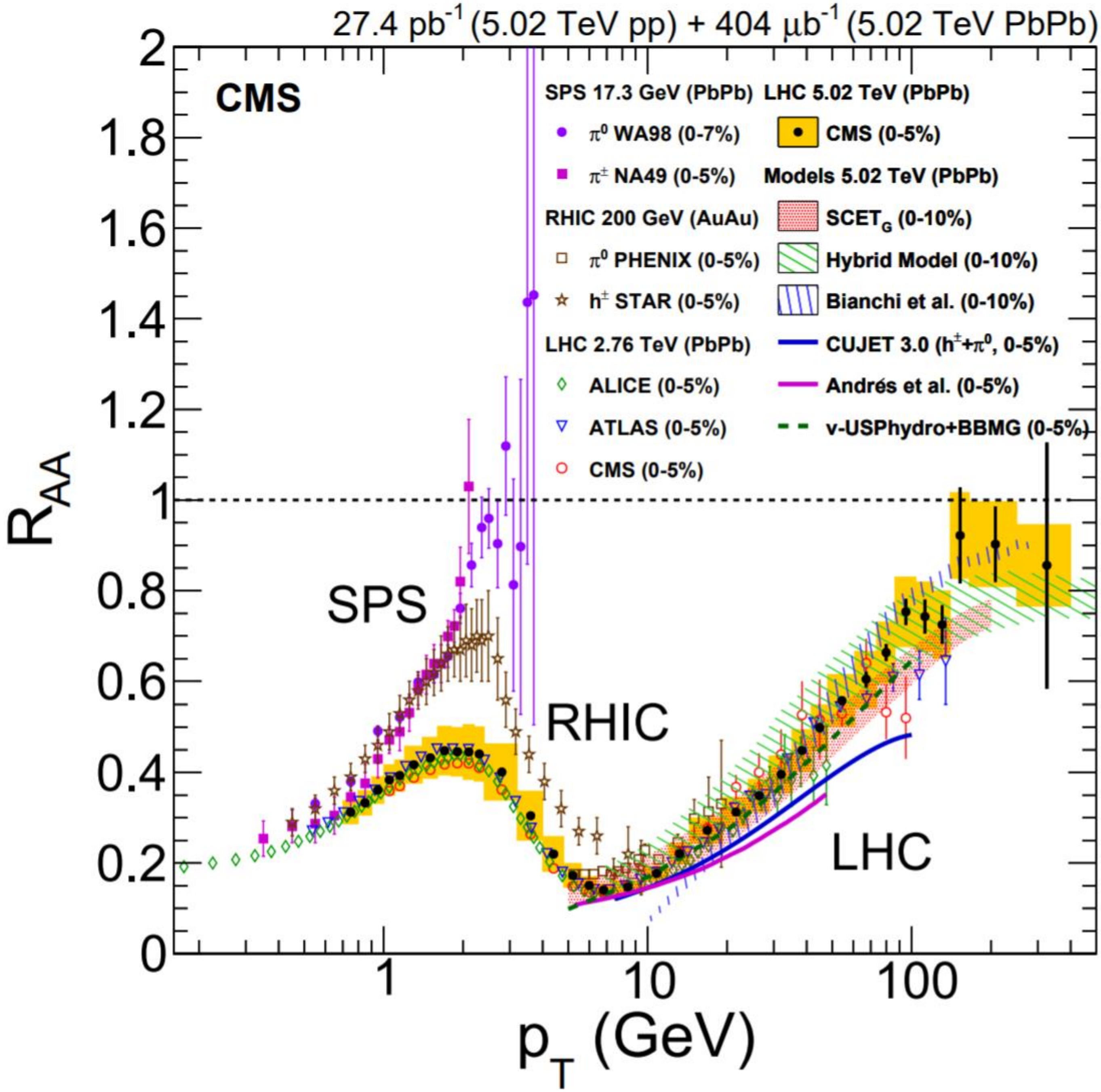


Energy loss?



Beautiful measurement from ALICE in charged particle transverse momentum spectra

Jet Quenching without Jet

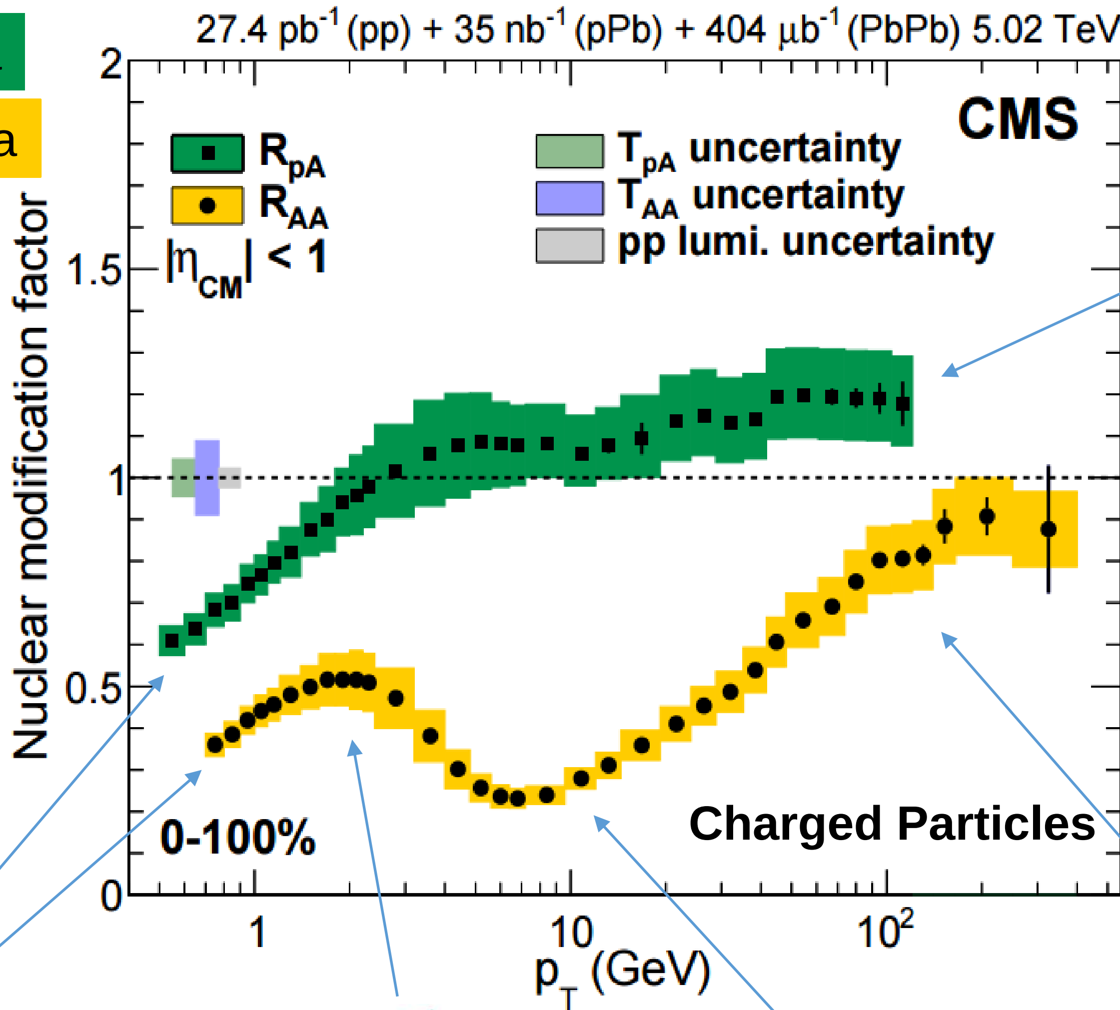


Charged particle R_{AA} in head-on collisions

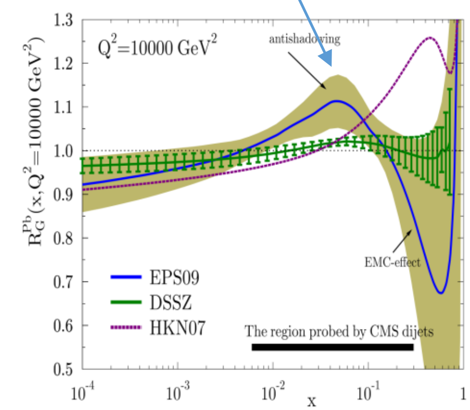
Jet Quenching without Jet

R_{pA} from pPb data

R_{AA} from PbPb data

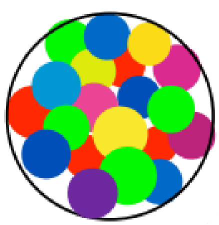


Anti-shadowing for intermediate x partons

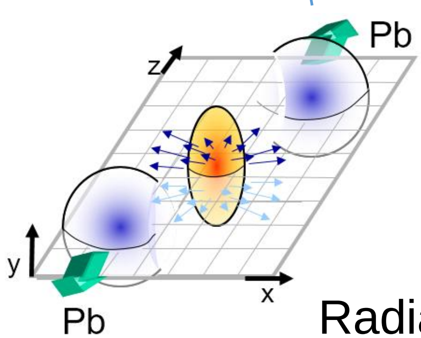


QGP become more transparent to very high p_T particles

Gluon saturation

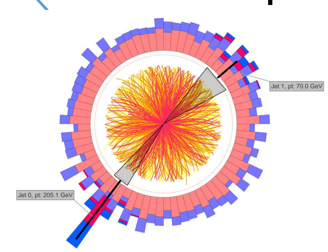


Shadowing



Radial flow

Jet quenching



Charged Particle R_{AA} vs. Theory

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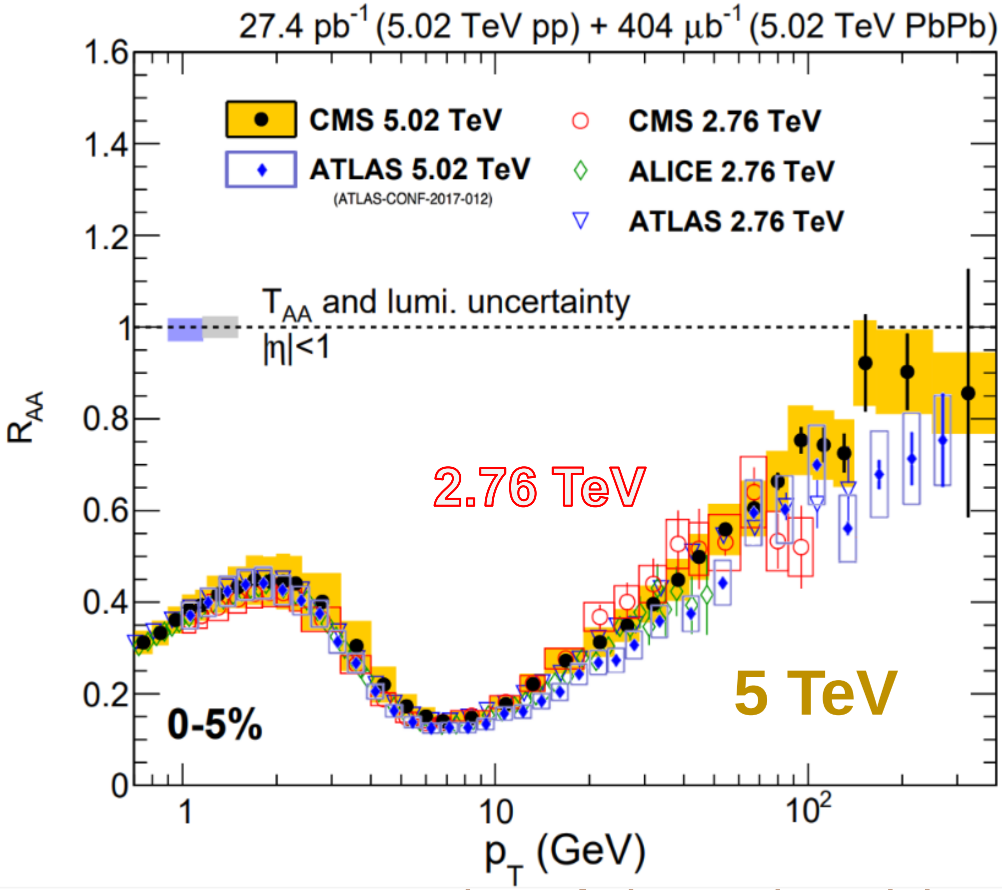

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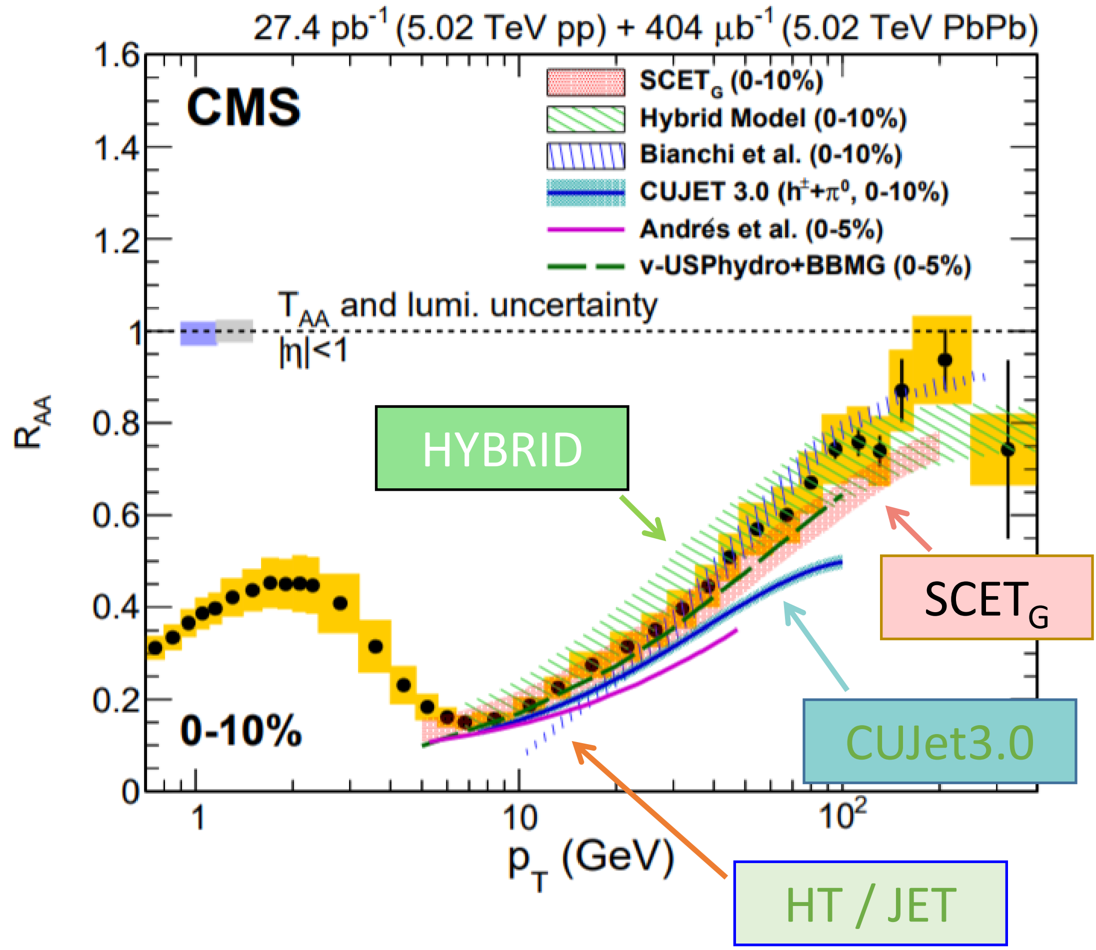
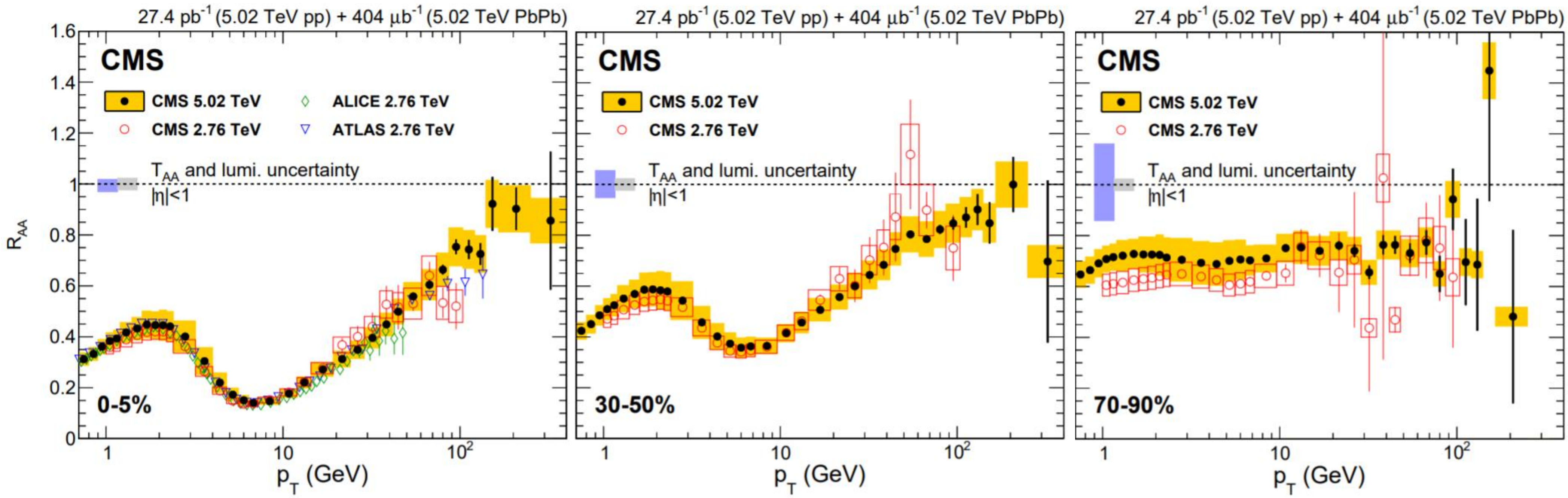


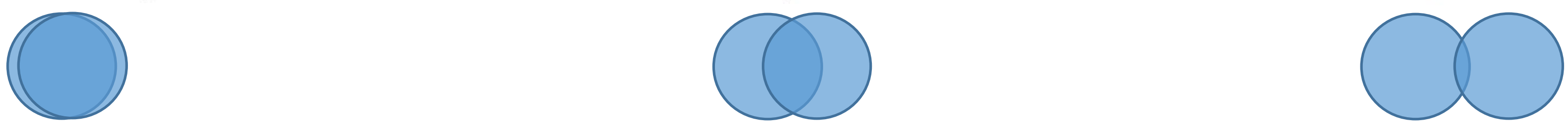
- Strong suppression of charged particles (up to a factor of 6) in PbPb
- Almost no suppression at very high p_T compared to **pp reference** (p_T~400 GeV)
- Similar charged particle R_{AA} in PbPb at **5 TeV** compared to 2.76 TeV

- General trend described by both **pQCD** and **Hybrid** models
- Description of the R_{AA} over the whole p_T range is still challenging

Centrality Dependence

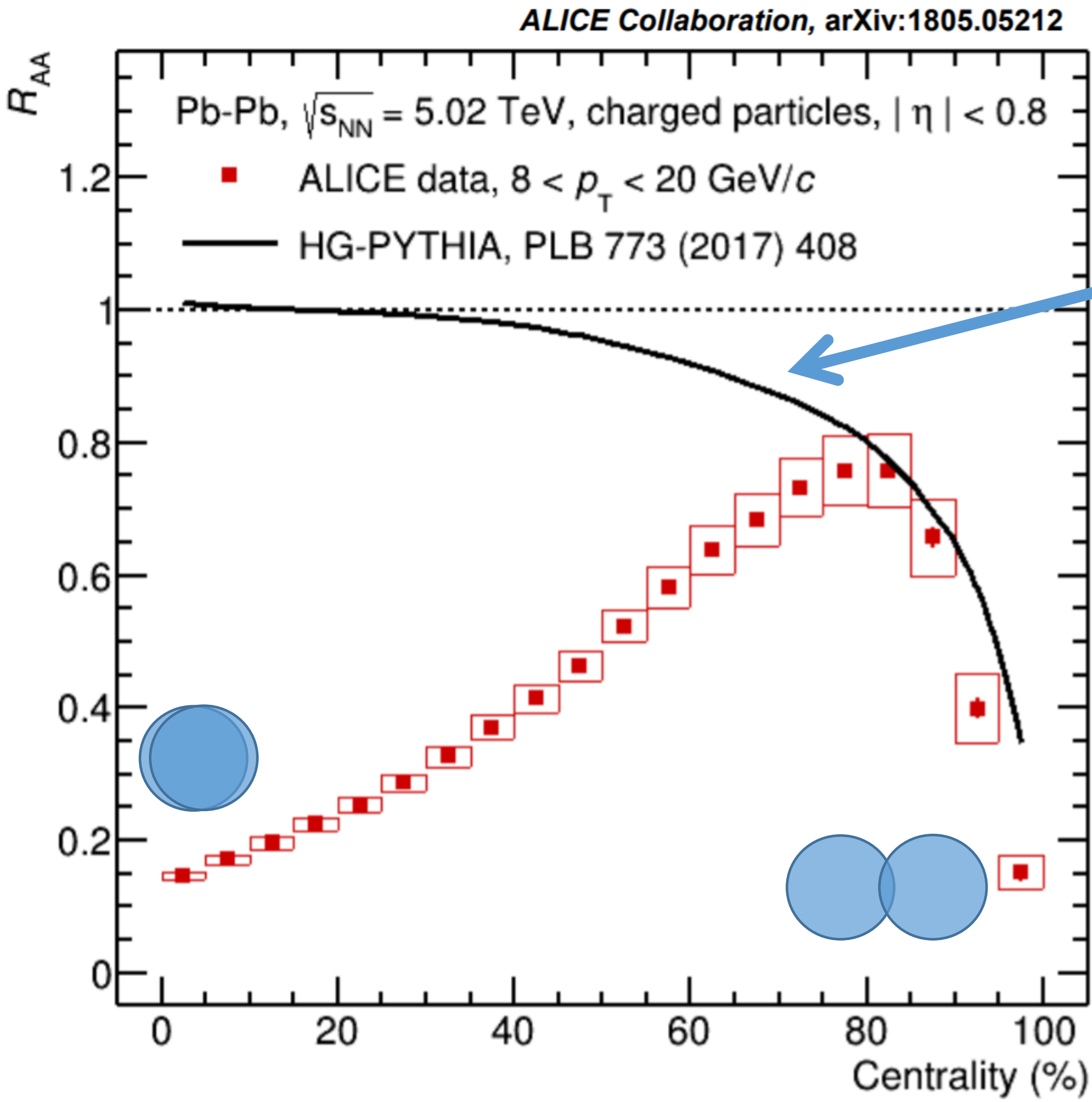
0-5% 30-50% 70-90%





- Less suppression observed in peripheral event when compared to head-on collisions
- Still sizable apparent suppression in 70-90% ??
    - Sometimes interpreted as “cold nuclear matter effects”

Centrality Selection Bias



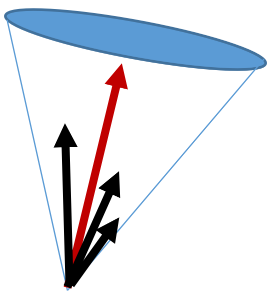
Incoherent superposition of many PYTHIA events (nucleon-nucleon collision) according to the # of multi-parton interaction in HIJING generator

- Selection bias plays a very important role in peripheral events
- Very important input to the interpretation of the peripheral data.

Lessons from Charged Particle R_{AA}

- High p_T charged particle suppression played an important role for the discovery of jet quenching at RHIC

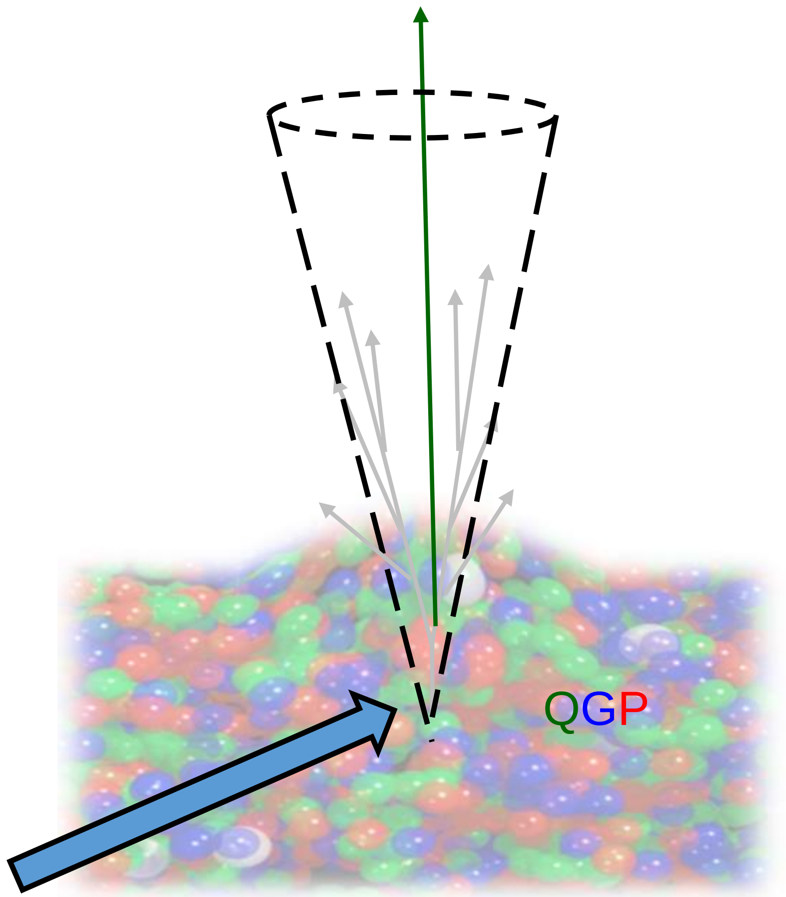
- This hadron-based observable is sensitive to the leading fragment of the jet from hard scattered parton



- Interpretation of the result complicated by:
  - Need of hadronization in theoretical calculation
  - Leave the freedom (ambiguity) to explain the observed suppression by:
    (1) Modified parton-to-particle fragmentation in QGP
    (2) Modified parton momentum due to energy loss
    (3) Modification of hadronization process in QGP

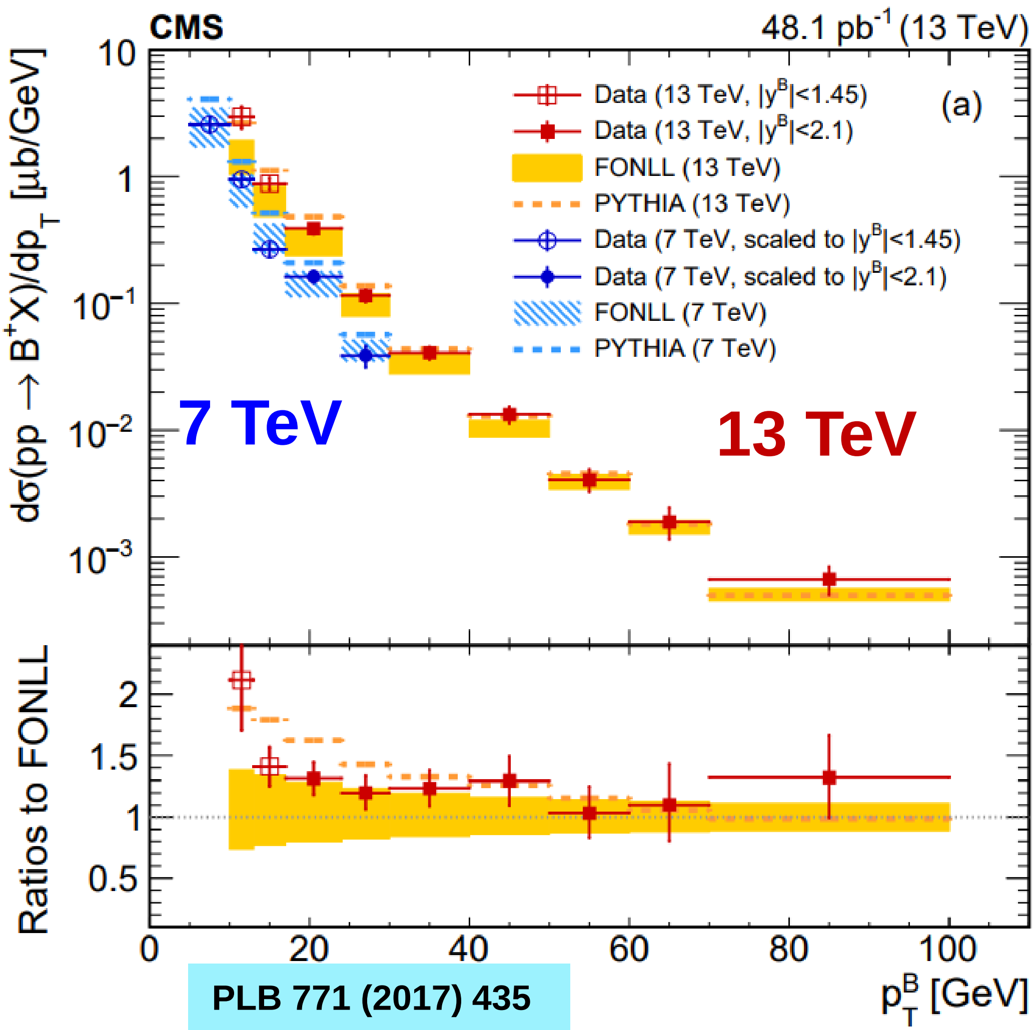
Motivate the analyses with jet reconstruction

Jet Quenching



Do heavy quarks lose less energy than the light quarks or gluons?

Results from pp @ 5, 7 and 13 TeV



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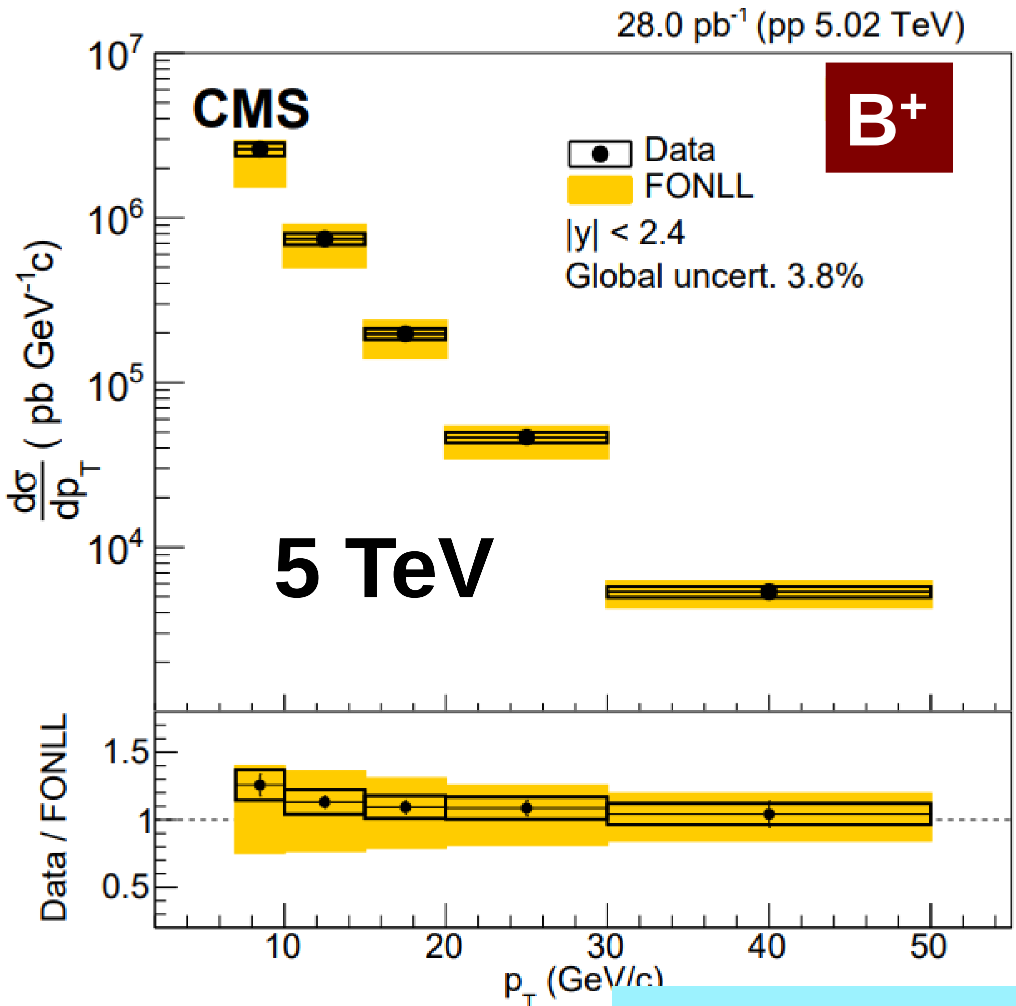

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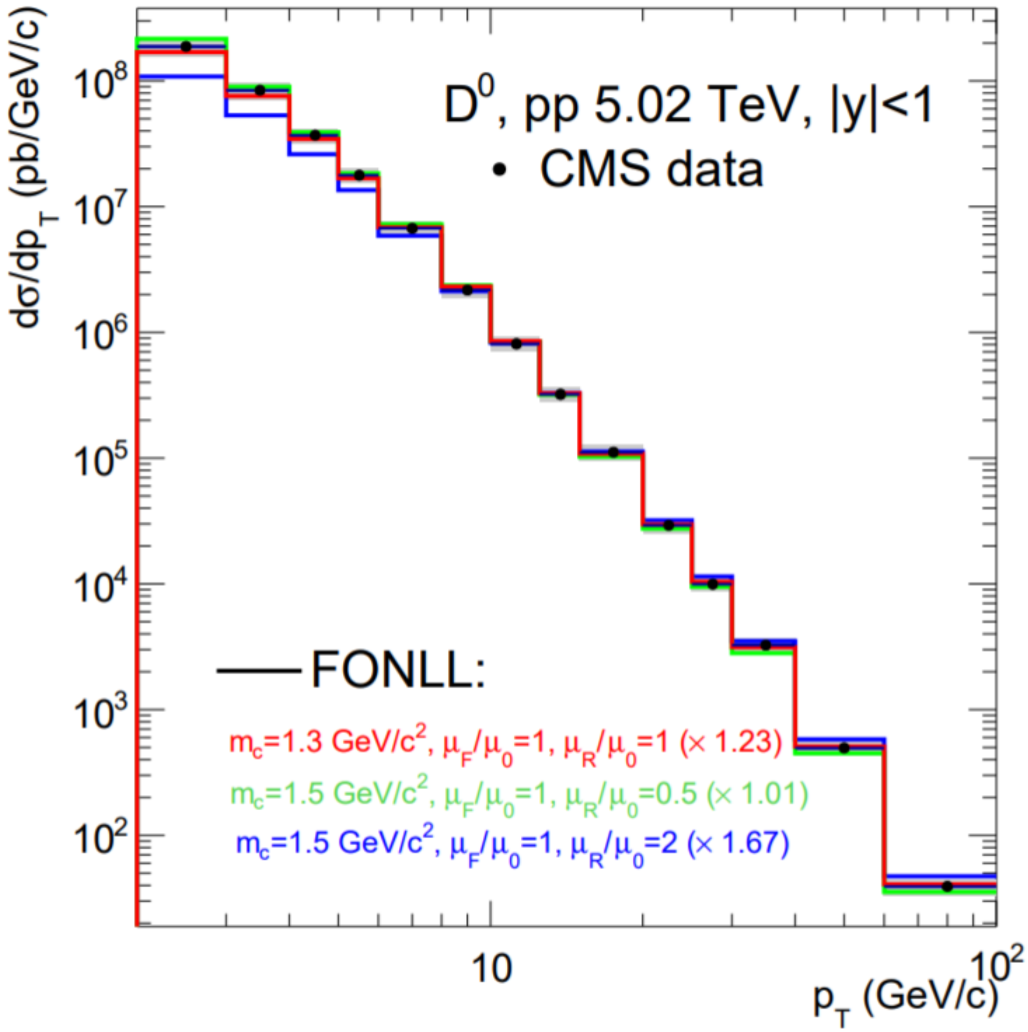
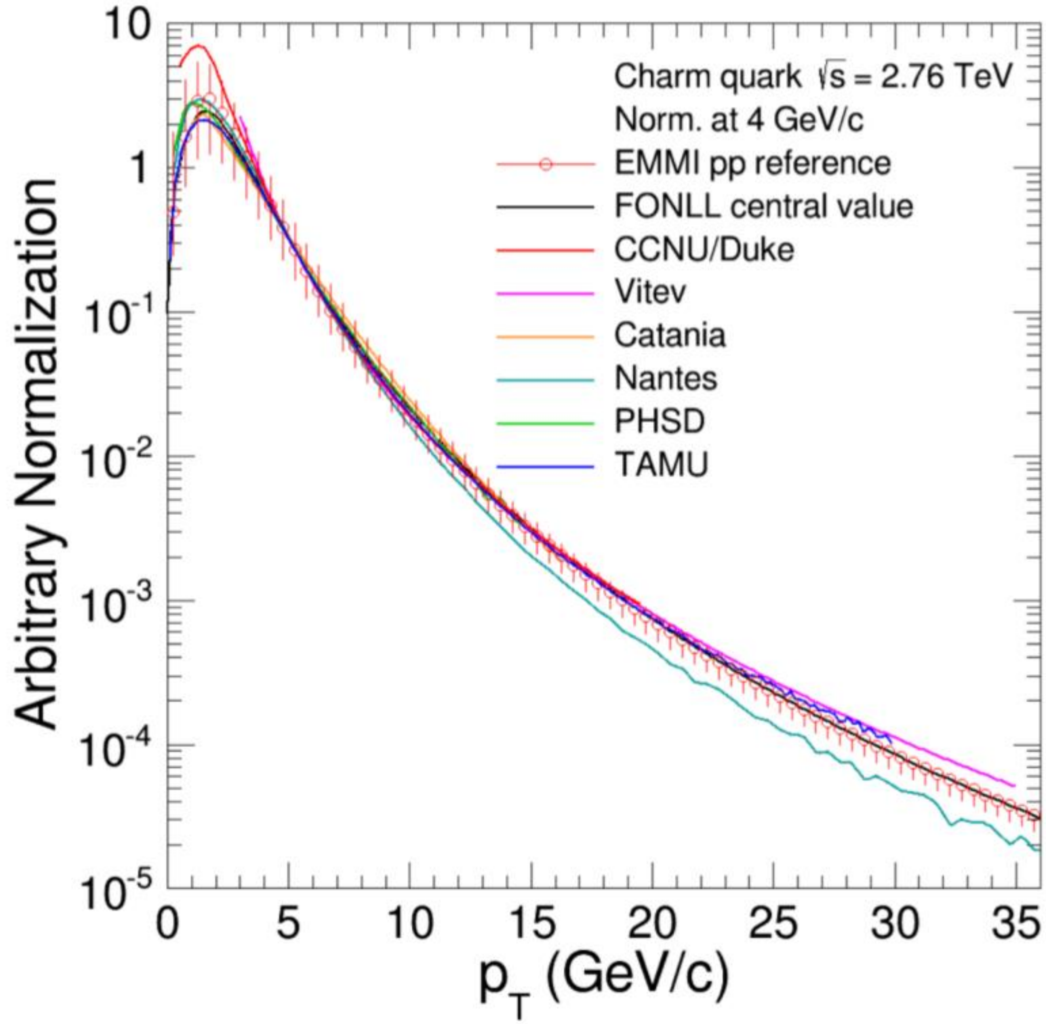
- pp at **5**, **7** and **13 TeV** are in agreement with FONLL within the quoted uncertainties
- PYTHIA doesn't give a perfect description of the B^+ p_T spectra

Initial Charm Quark p_T Spectra

D^0 p_T spectra vs. FONLL calculations



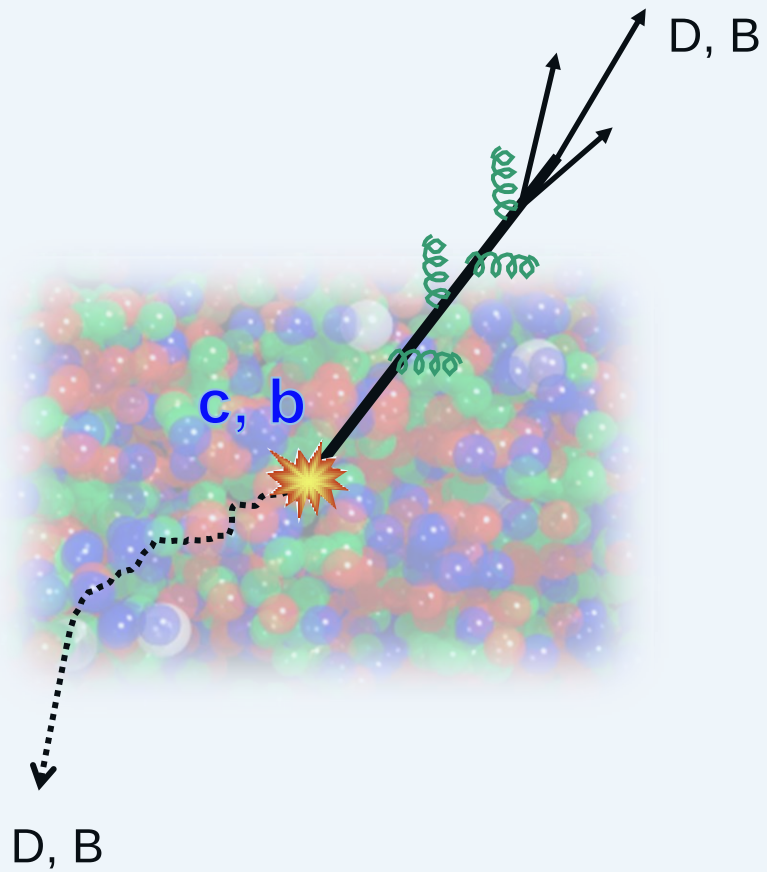
Charm quark p_T spectra used in various groups



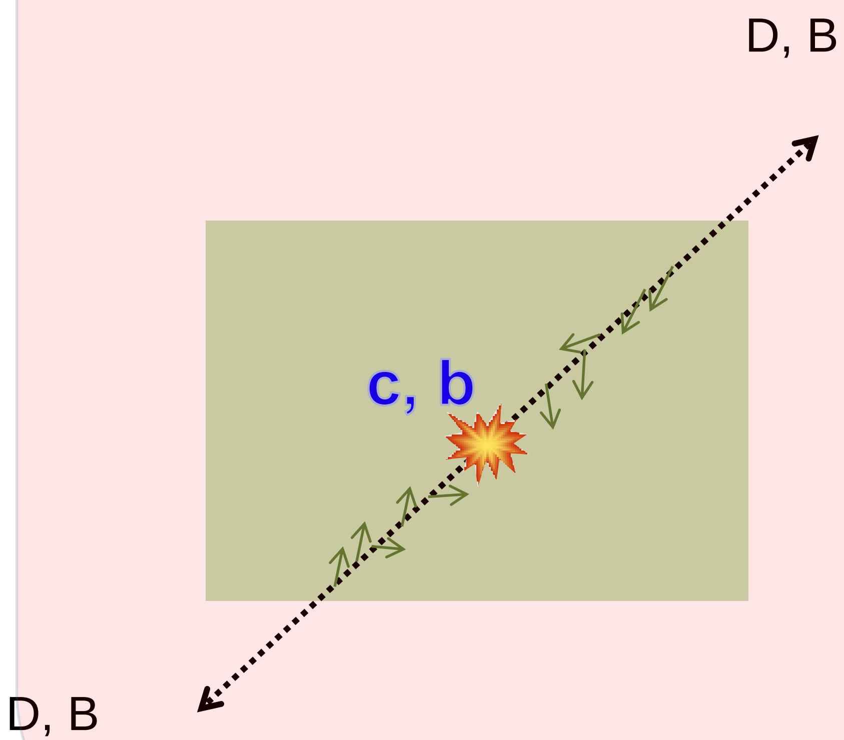
- pp data could be used to extract charm quark spectra by varying the parameters used in FONLL calculations (charm quark mass, factorization scales)

Weak Coupling vs. Strong Coupling Limit

Perturbative QCD
Weak coupling limit



Holographic calculation
Strong coupling limit



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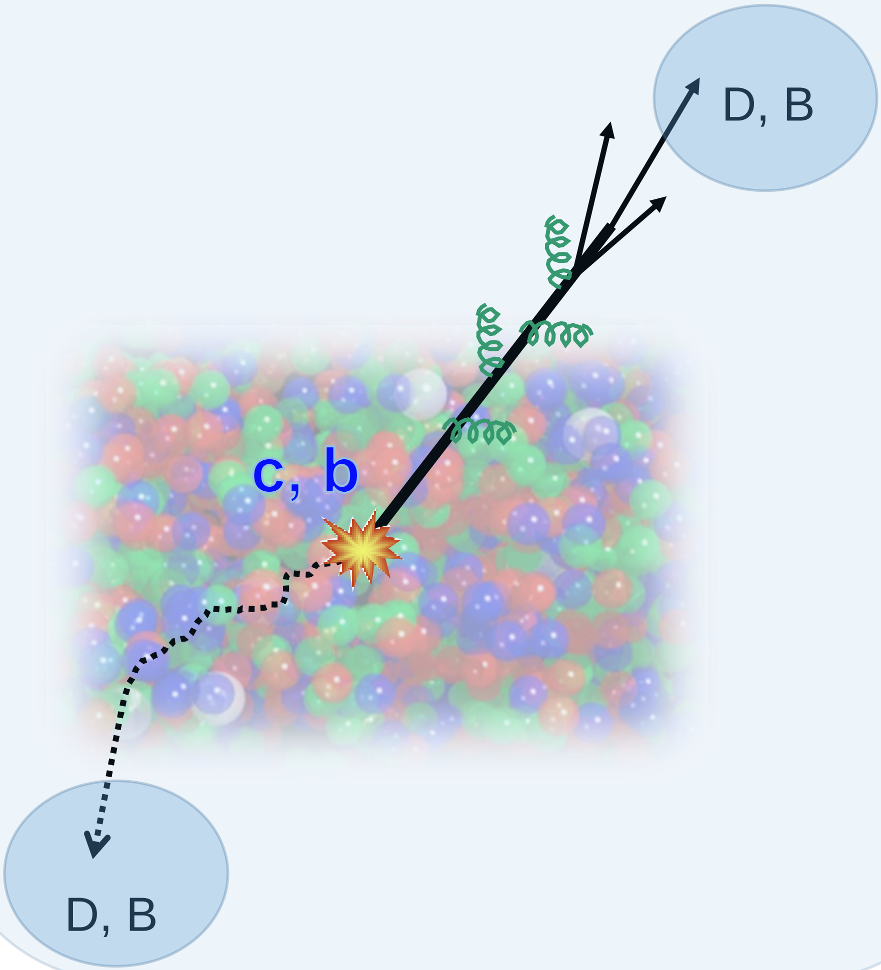
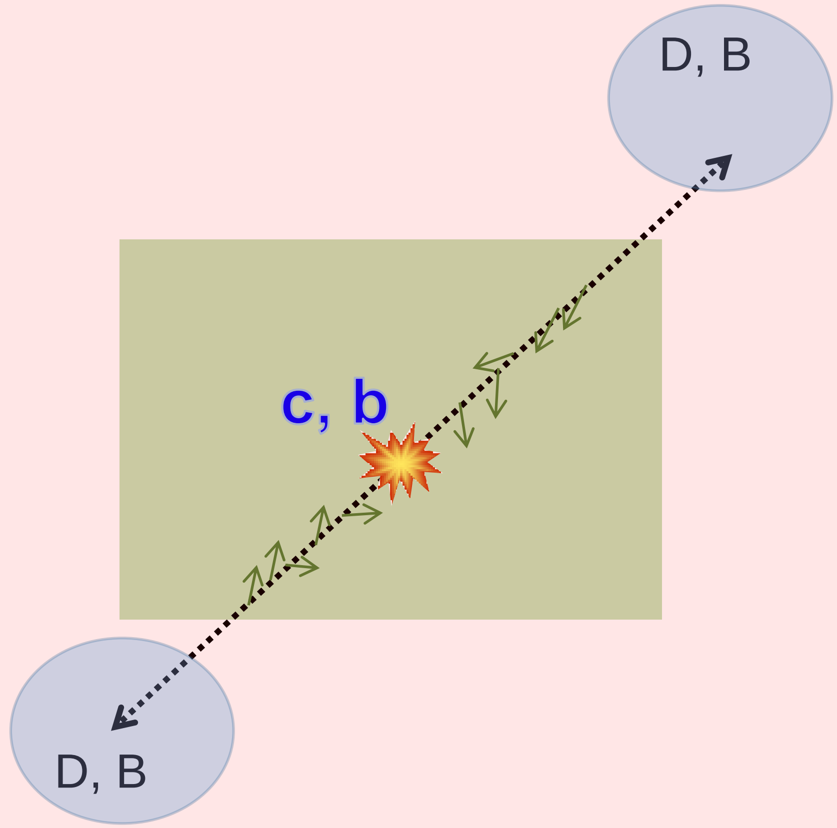
Perturbative QCD
Weak coupling limit

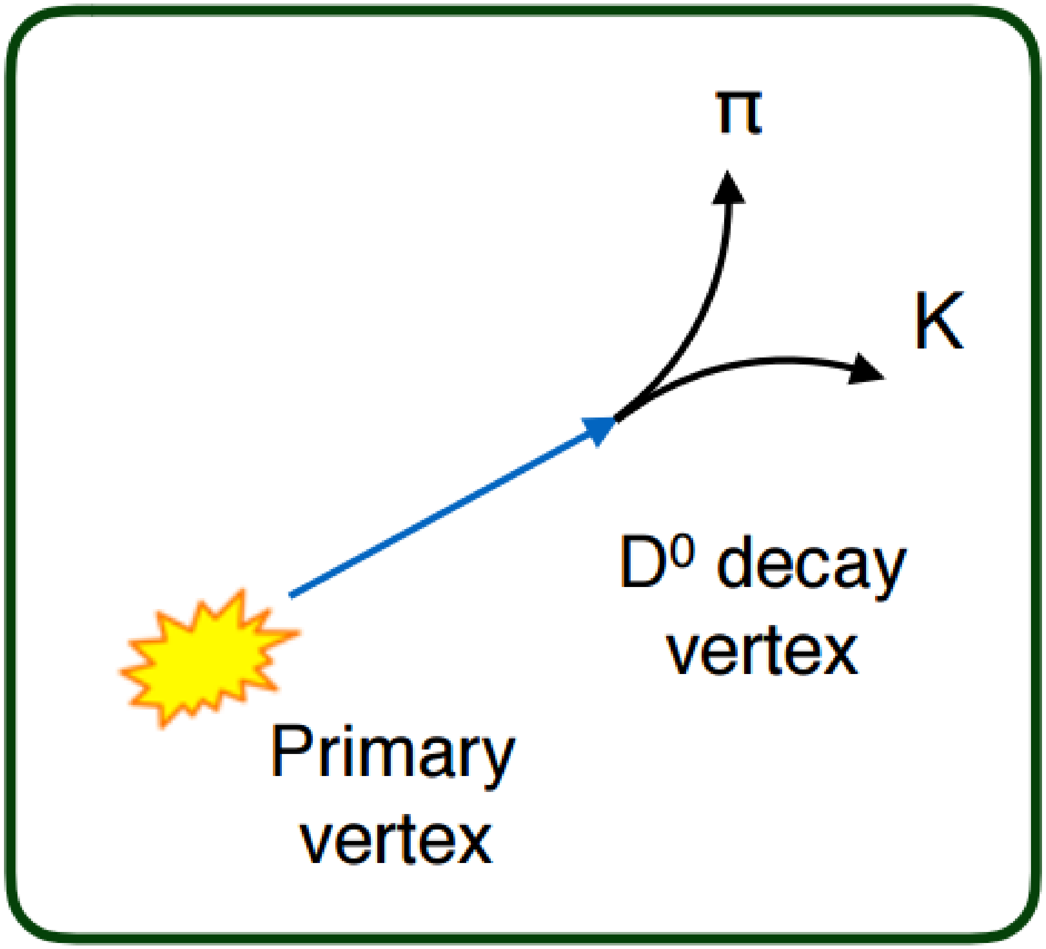


Holographic calculation
Strong coupling limit

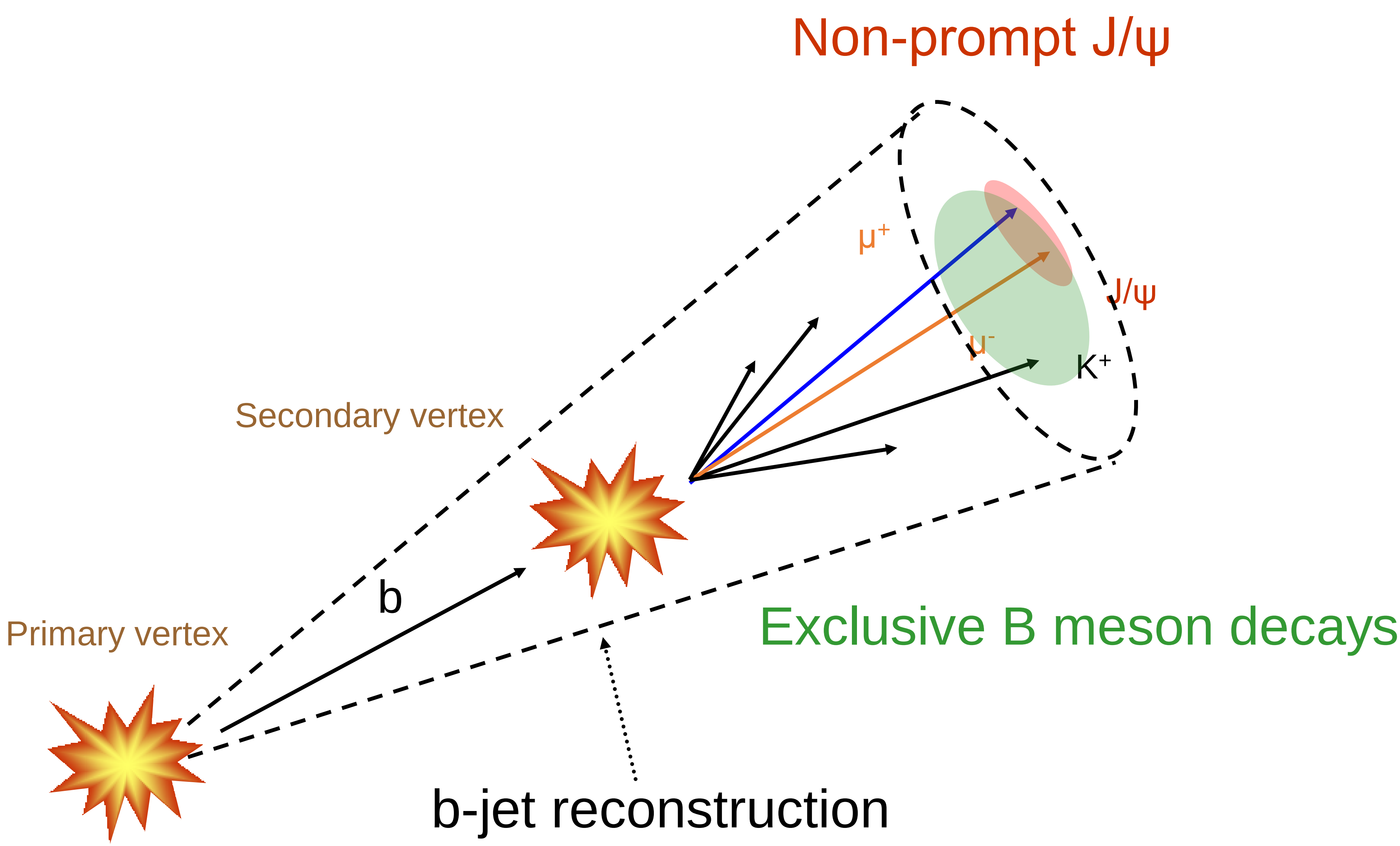


Moreover, we still need to quantify the role of hadronization for open heavy flavor mesons

Measurement of Charm Quark



Measurement of Beauty Quark



Requirement: flexible trigger system, muon / electron detection, secondary vertex reconstruction, jet reconstruction

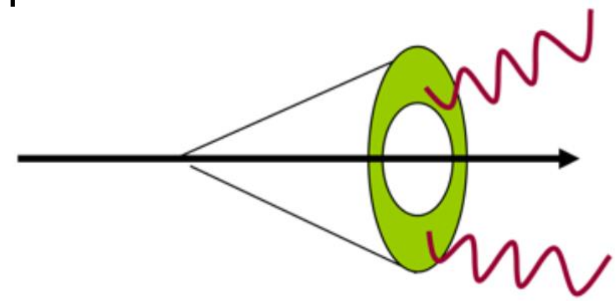
Flavor Dependence of Parton Energy Loss

Radiative Energy loss:

$$<\Delta E> \sim \alpha_s C_R \, q \, L^2$$

C_R=3 for gluons and 4/3 for quarks

Forward radiation suppressed in heavy quarks due to kinematics



- Color charge: E_{loss} in gluons > E_{loss} in quarks
- Kinematics: "Dead cone effect": E_{loss} in quarks > E_{loss} in heavy quarks (radiation suppressed in the (mass-dependent) forward direction **θ< M/E**)

Low momentum

E_{loss} in QGP:

gluons > quarks > heavy quarks

(M/E large, Dead cone effect)

High momentum

E_{loss} in QGP:

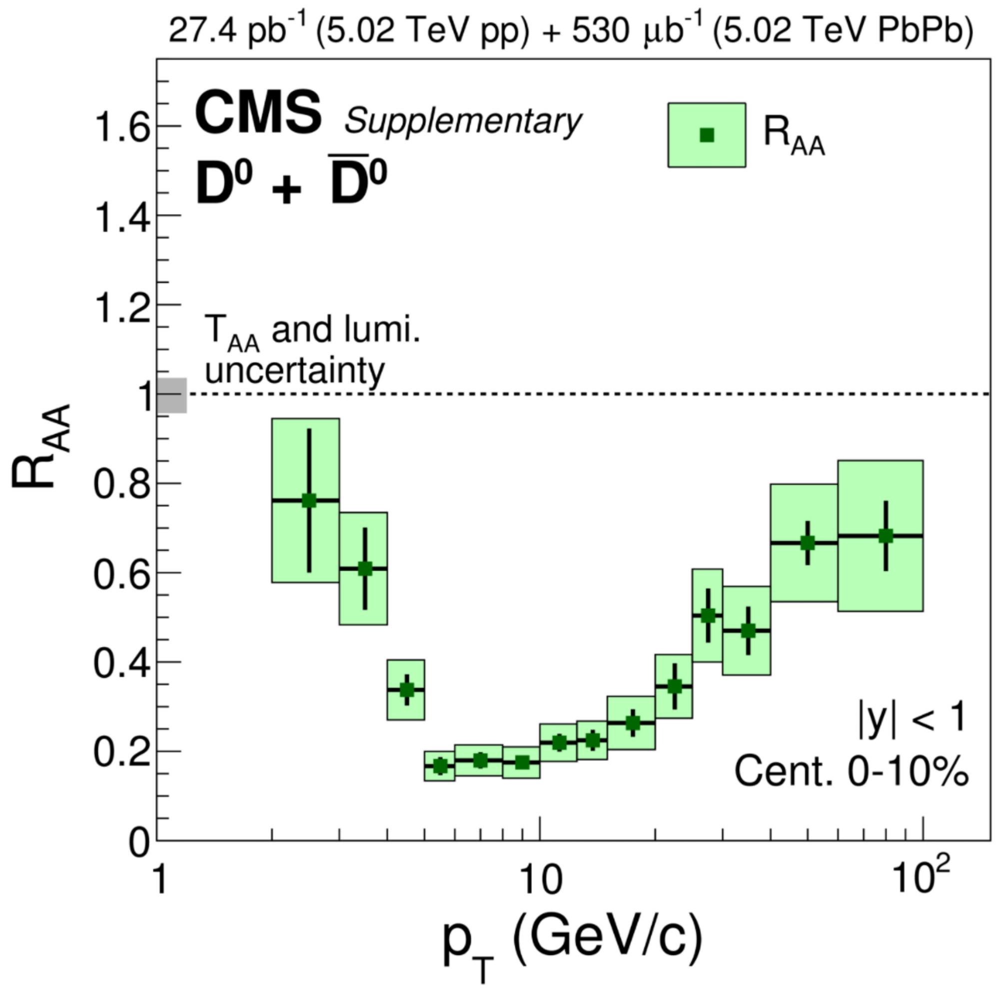
gluons > quarks = heavy quarks

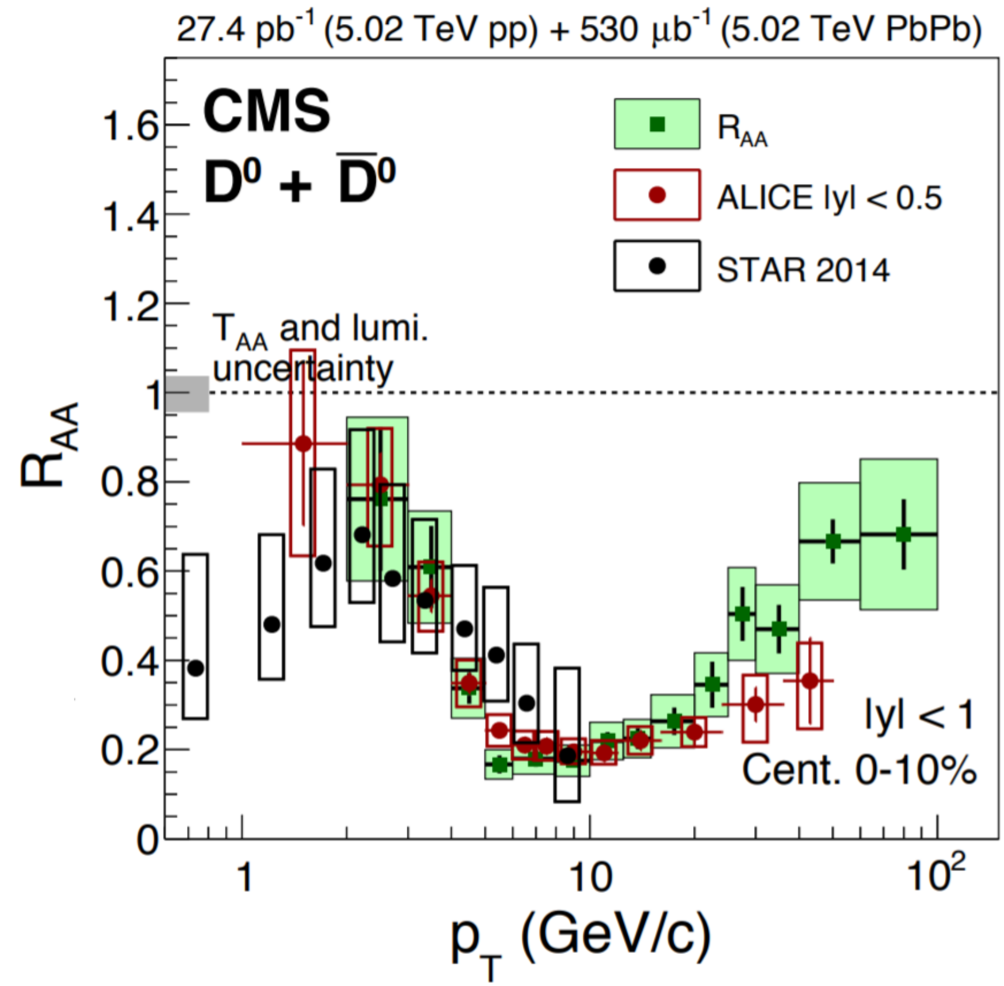
(M/E small, No dead cone effect)

Parton Energy (E)

Prompt D^0 R_{AA} in PbPb at 5.02 TeV

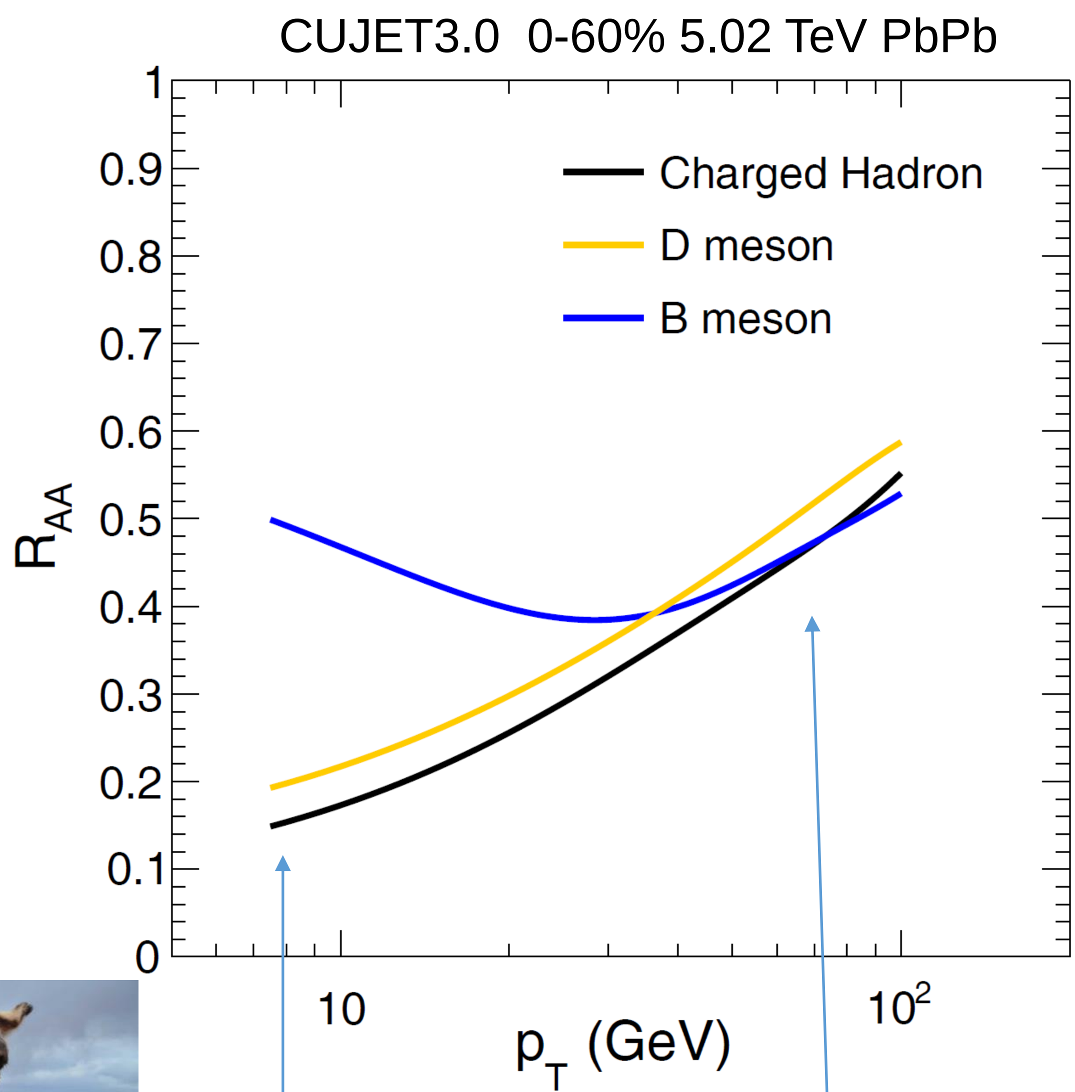
PbPb 0-10%





- D^0 production is strongly suppressed
- Strongest suppression around D^0 p_T = 5-8 GeV

Have We Observed the Dead-Cone Effect?

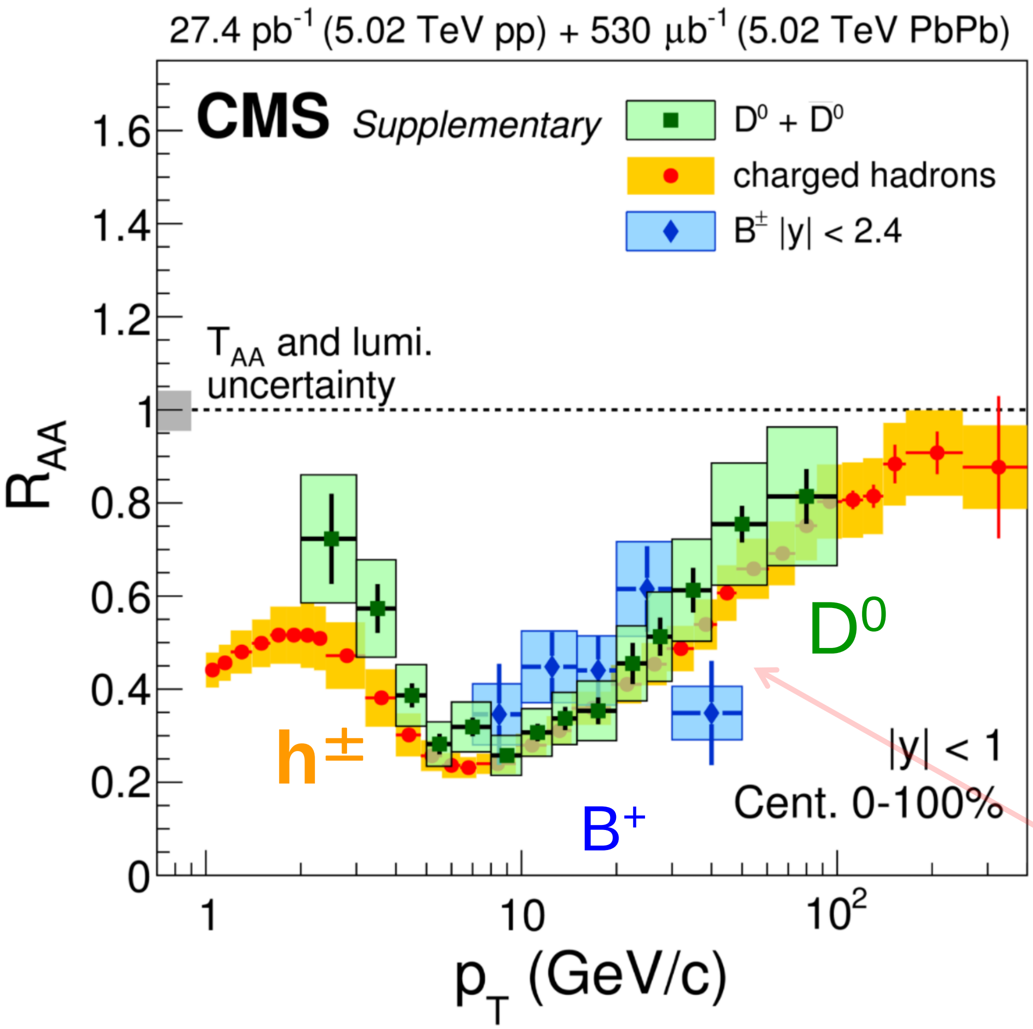


Mass effect
(Dead cone)

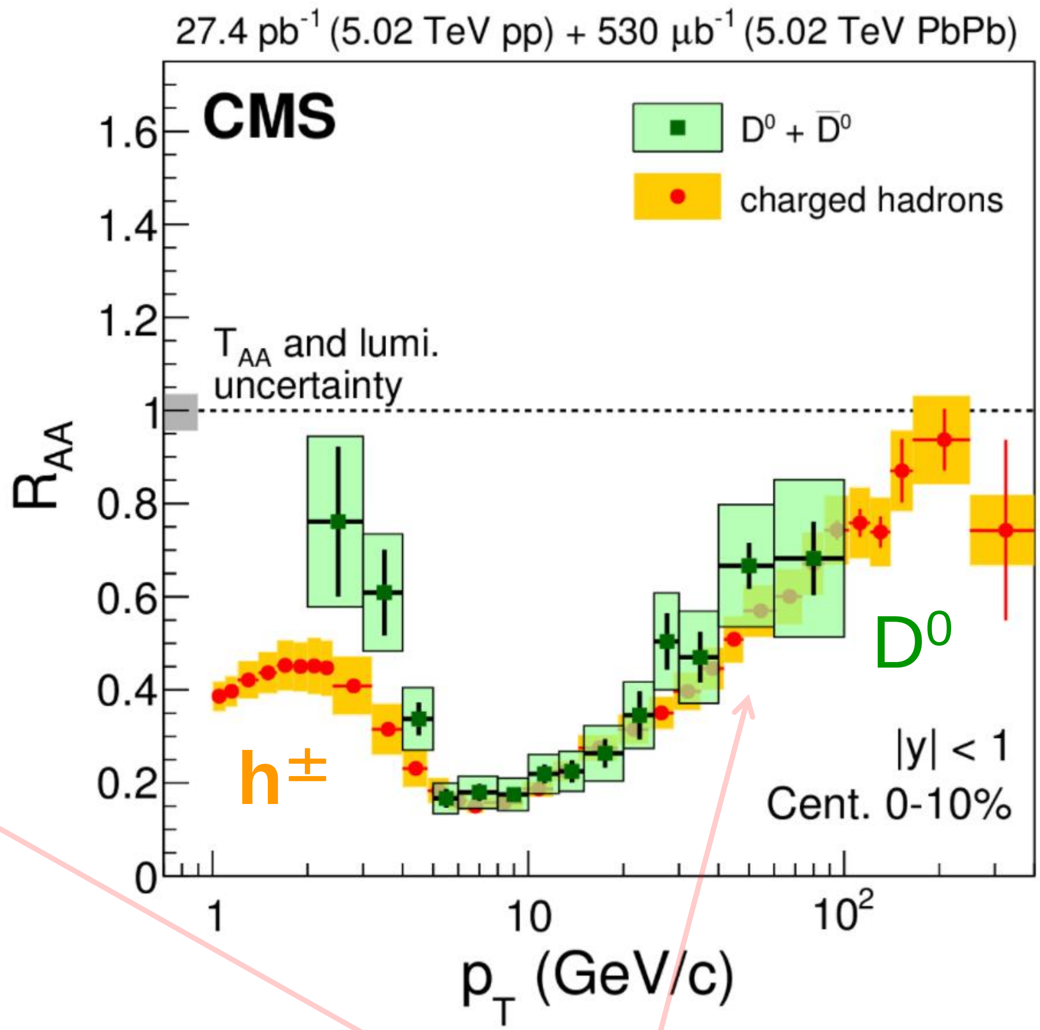
Dead cone
goes away

D^0, B^+ and $h^{\pm}$ R_{AA} in PbPb at 5.02 TeV

PbPb 0-100%



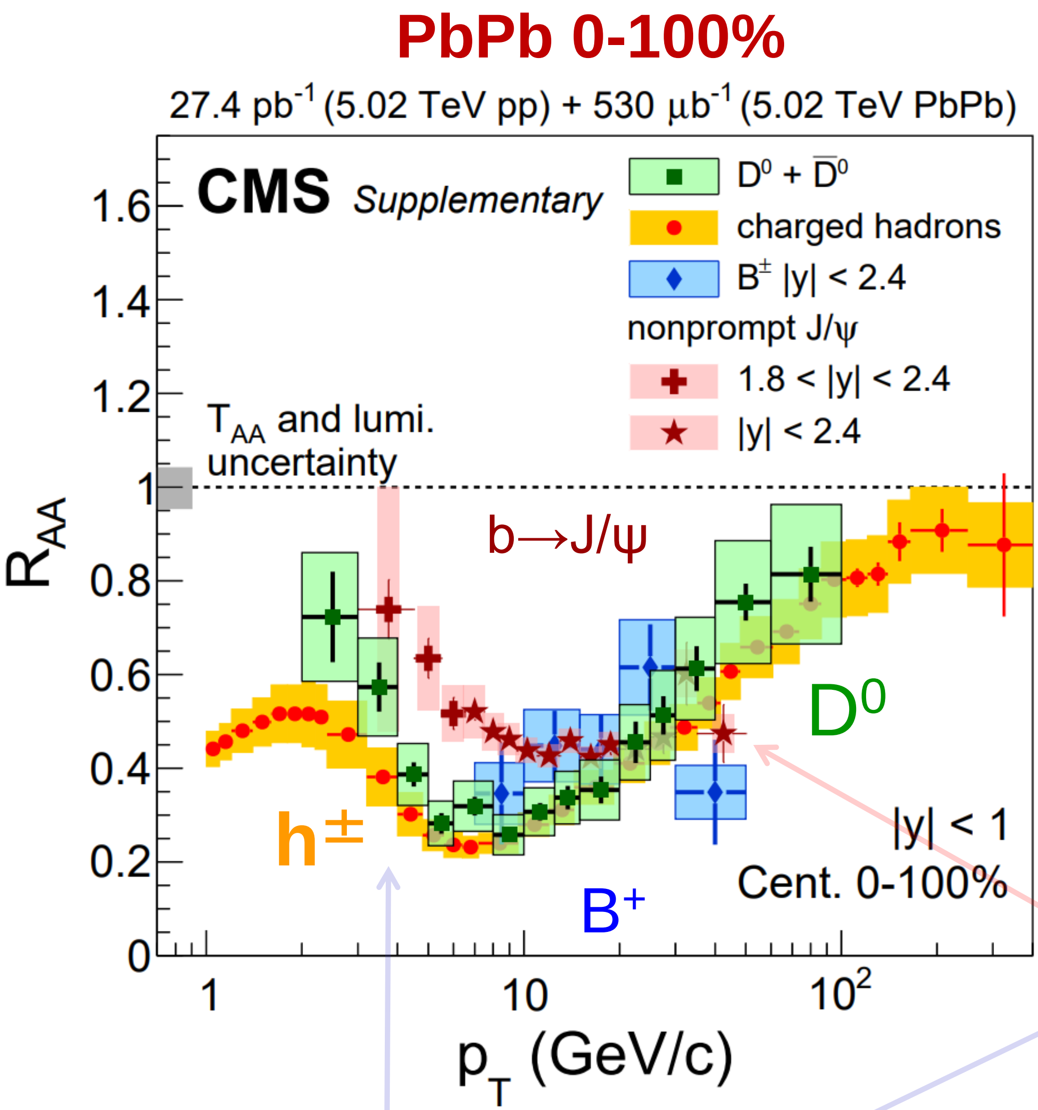
PbPb 0-10%

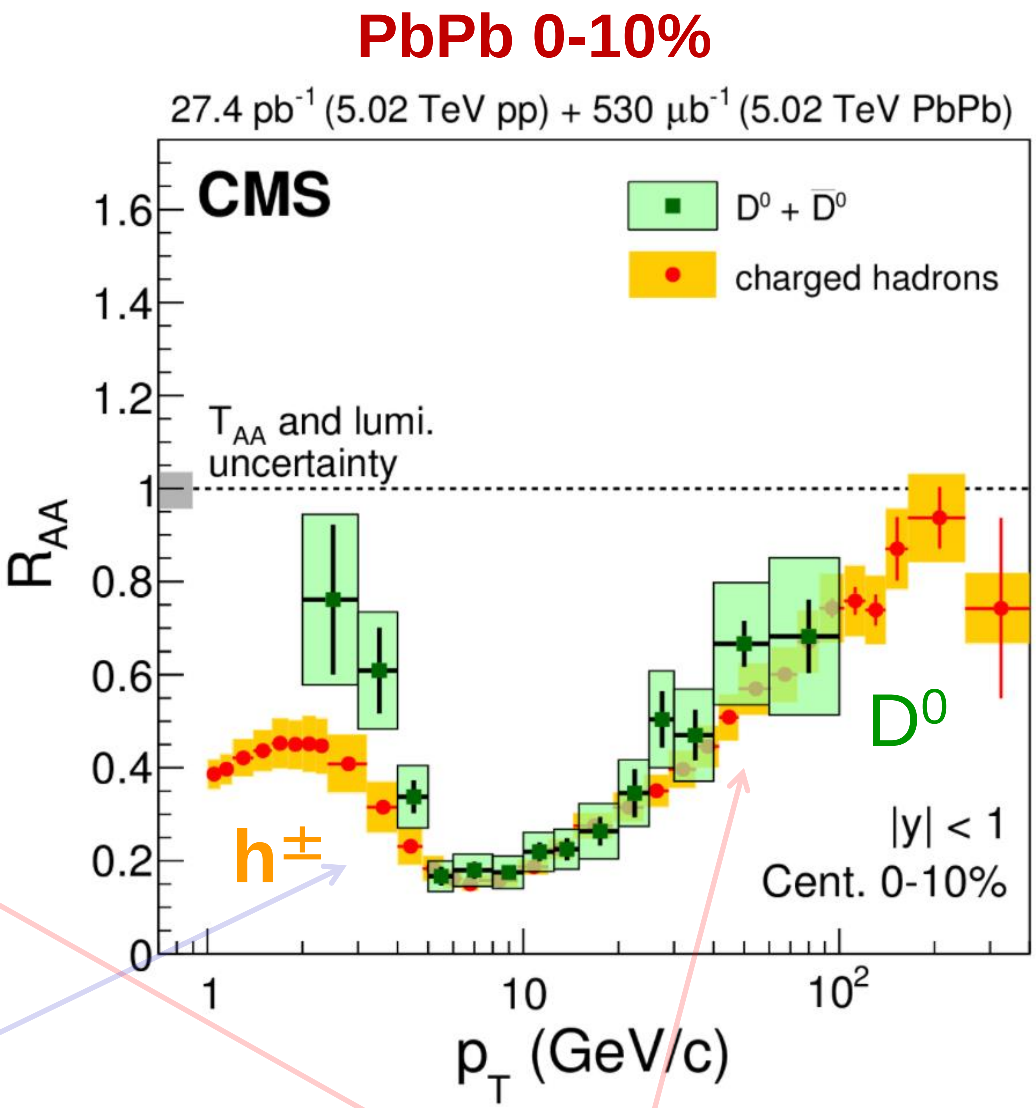


Charged particle R_{AA} JHEP 04 (2017) 039
B meson R_{AA} arXiv:1705.04727 PRL 119 (2017) 152301

R_{AA} at high p_T: No significant meson flavor dependence observed yet
$B^+ \sim D^0 \sim h^{\pm}$

D^0, B^+ and $h^{\pm}$ R_{AA} in PbPb at 5.02 TeV





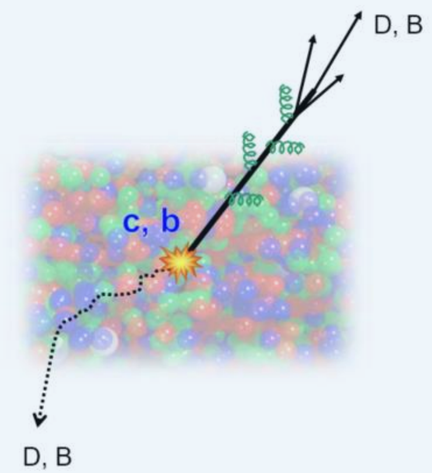
R_{AA} at low p_T: meson flavor dependent
b→J/ψ > D^0 ≥ $h^{\pm}$

b→J/ψ CMS-PAS-HIN-16-025

R_{AA} at high p_T: No significant meson flavor dependence observed yet
B^+ ~ D^0 ~ $h^{\pm}$

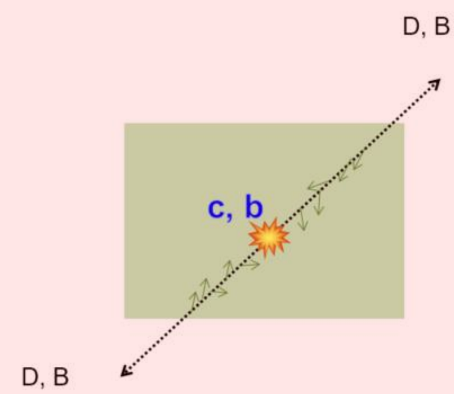
What is the Mechanism of HQ-Medium Interaction?

pQCD (Weak Coupling Limit)



PHSD (Parton-Hadron-String Dynamics model[2])
S.Cao et al. (Linearized Boltzmann transport model + hydro) arXiv:1605.06447v1
M. Djordjevic (QCD medium of finite size with dynamical scattering centers with collisional and radiative energy loss) Phys. Rev. C 92 (Aug, 2015) 024918
CUJET3.0 (jet quenching model based on DGLV opacity expansion theory) JHEP 02 (2016) 169
I.Vitev (Jet propagation in matter, soft-collinear effective theory with Glauber gluons (SCETG)) Phys. Rev. D 93 (Apr, 2016)

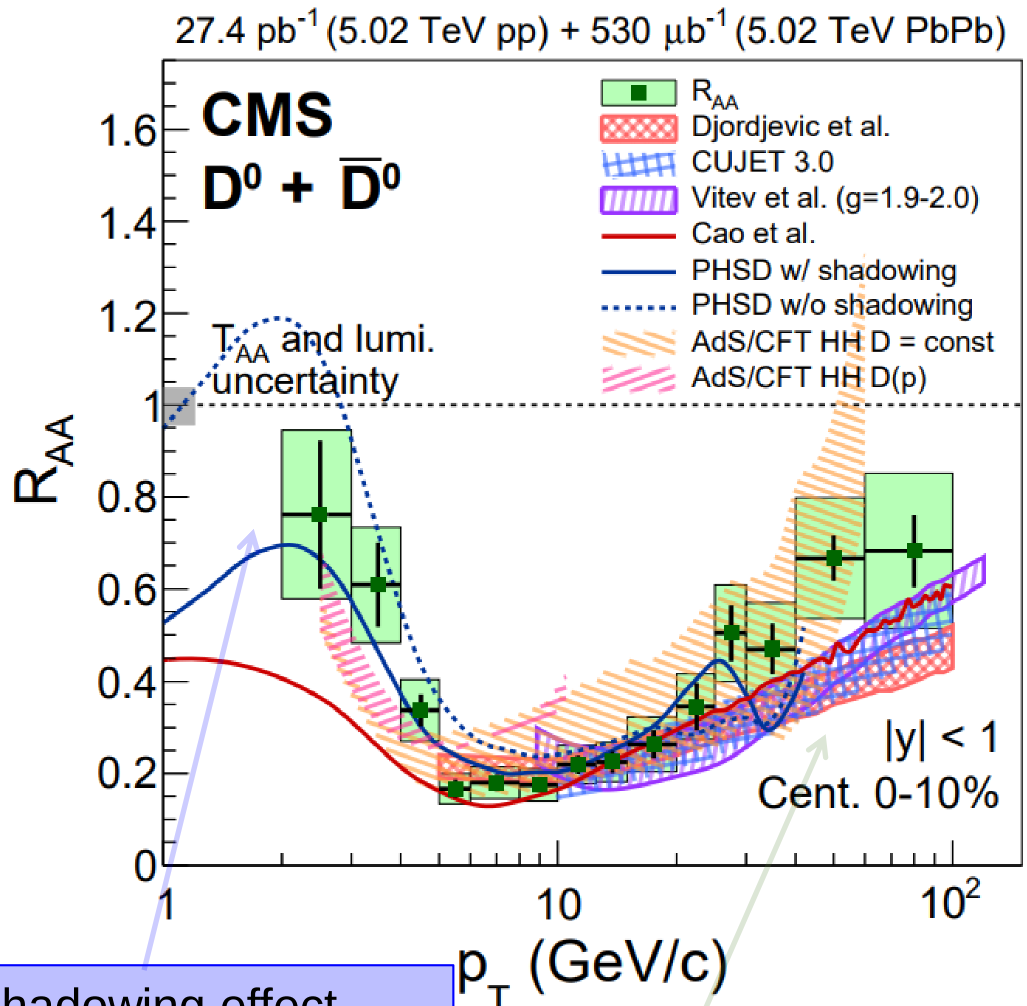
AdS/CFT (Strong Coupling Limit)



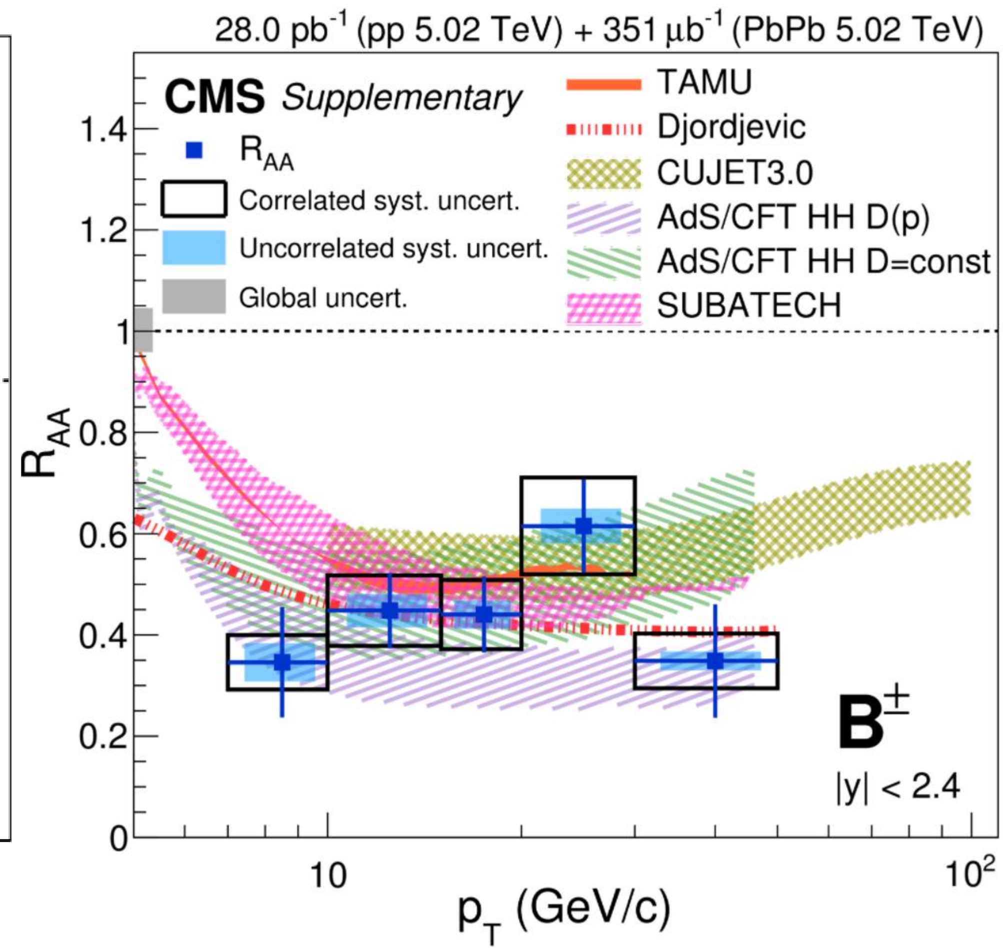
AdS/CFT Nucl. Part. Phys. Proc. 289-290 (2017) 233-236 , arXiv 1703.05845
Hybrid model: Ads/CFT drag + PYTHIA, JHEP 1410 (2014) 019 arXiv: 1405.3864

D^0 R_{AA} vs. Theory

D^0 RAA



PbPb 0-10%



Shadowing effect important at low D^0 p_T

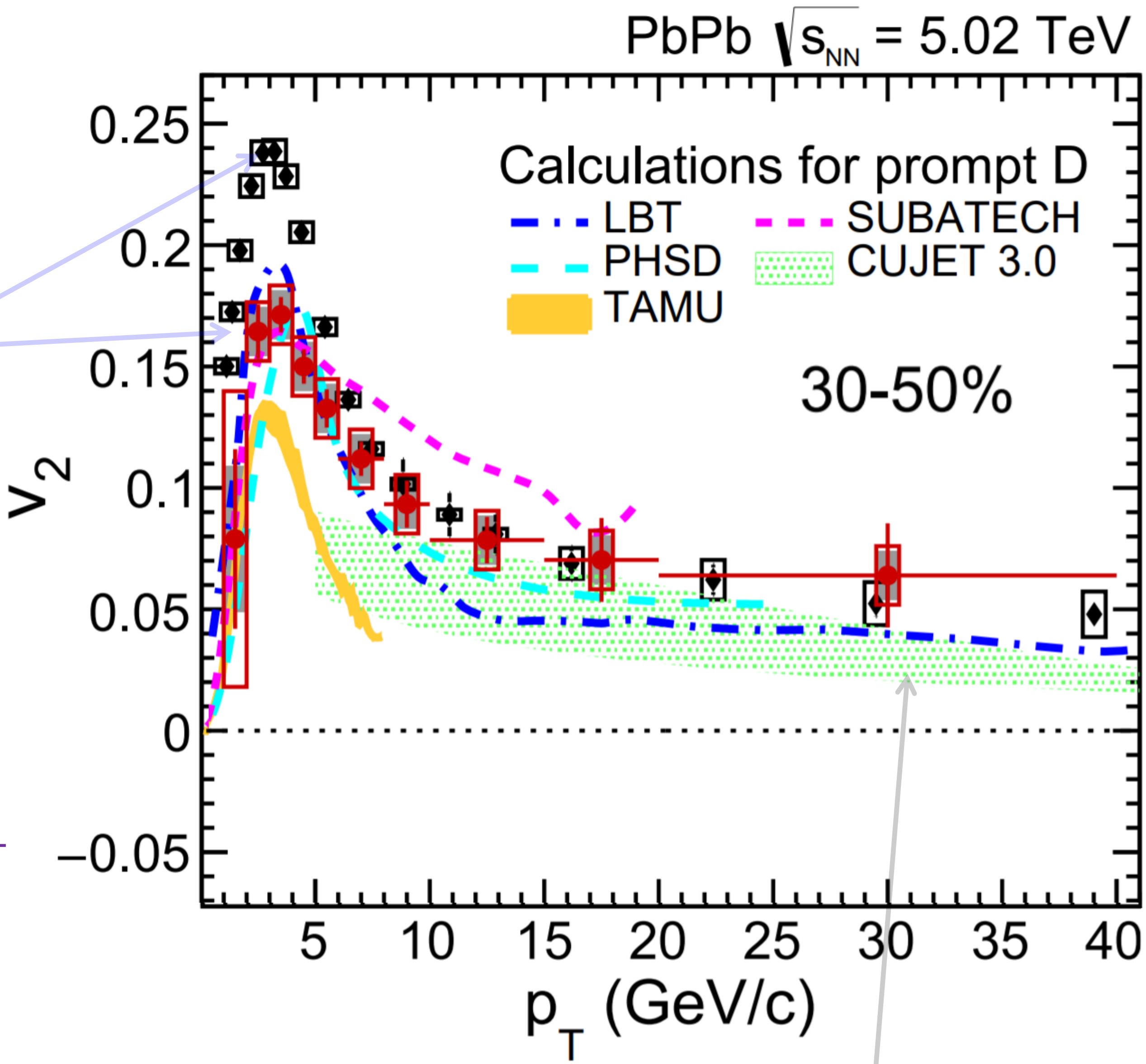
Predictions before data capture the **rising trend** of the D^0 R_{AA}

Predictions including mass effects describe both D^0 and B^+ R_{AA} !!

Data agrees with both **pQCD** and **AdS/CFT** based calculations

D^0 v_2 in PbPb at 5.02 TeV

- Significant v_2 signal over a very wide D^0 p_T interval
- Clear difference between **$h^\pm$ an D^0 v_2 at low p_T**
- Model calculations describe the trend of the v_2 as a function of p_T
- However, none of the model predictions match the data over the whole p_T range
- Is this an indication that charm quarks flow with light flavor?



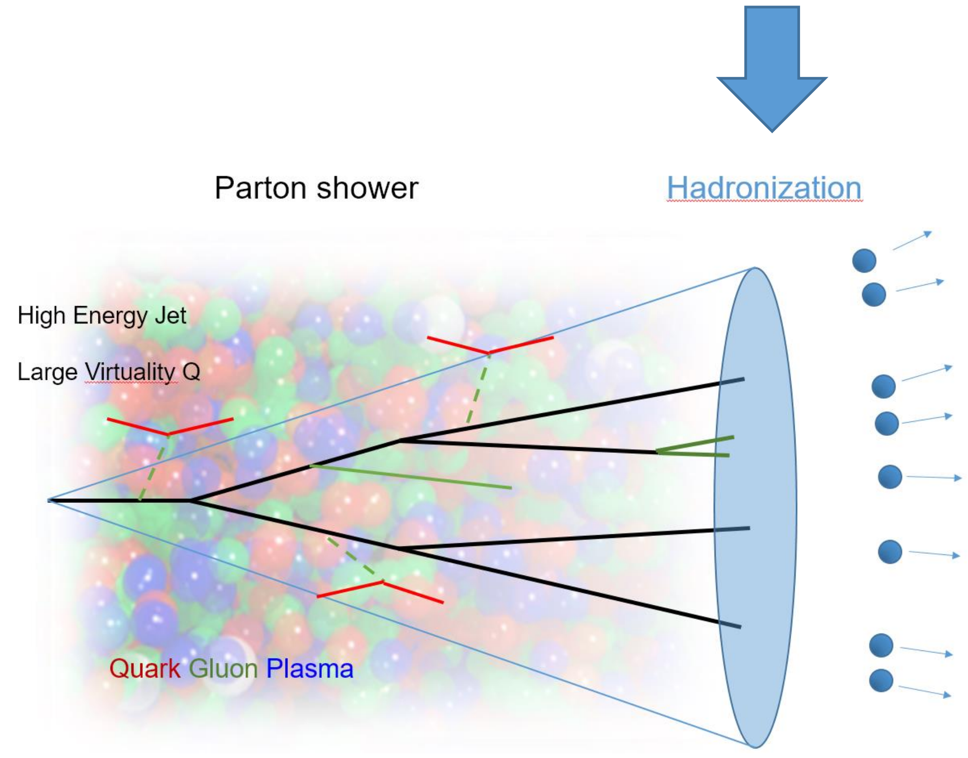
- High p_T: Sensitive to path length dependence of energy loss: **D^0 ~ $h^\pm$**

Hadronization

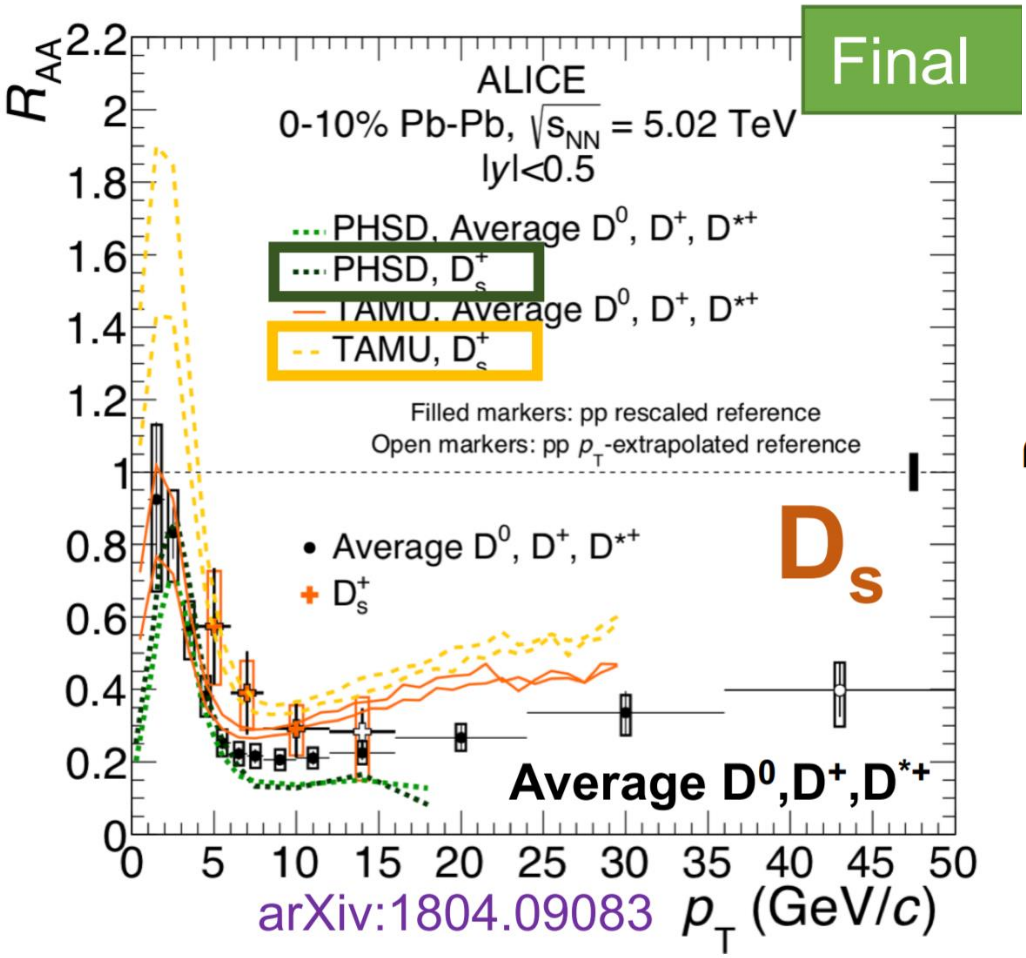
Can we see modification of hadronization process in heavy ion collisions with heavy flavor particles?

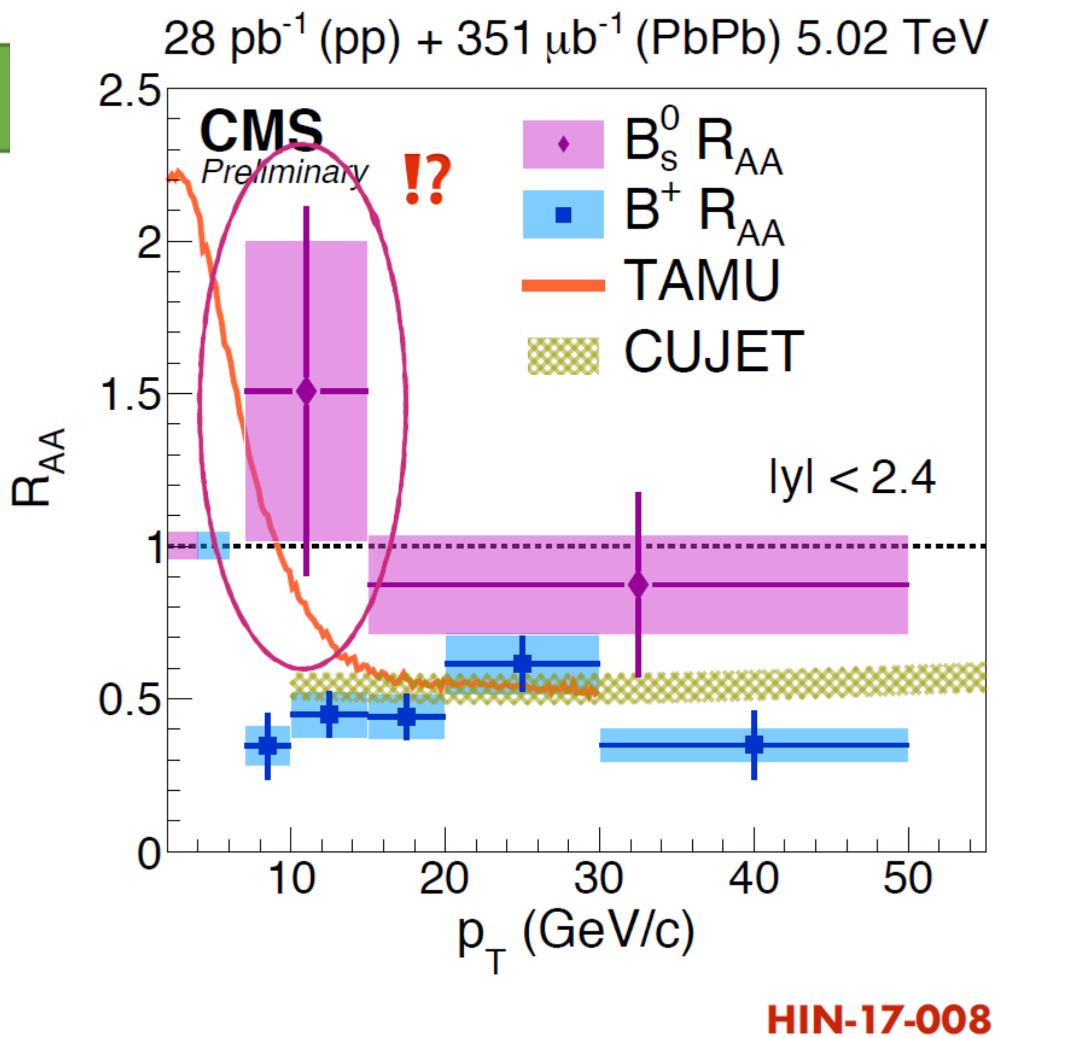
We know that strange quarks are enhanced in the quark soup…

Will we see enhancement of D_s (or B_s) mesons compared to D^0 and B^+ mesons?



Hadronization





D_s vs. D

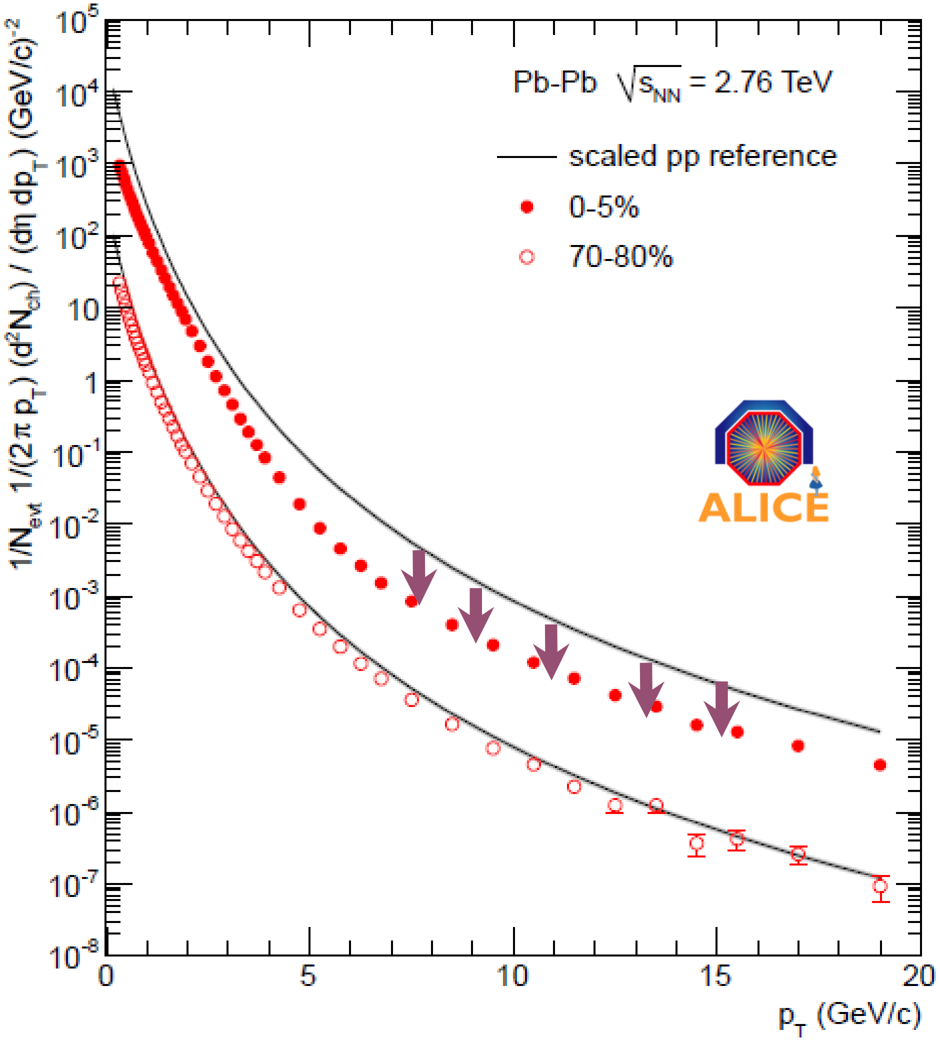
B_s vs. B^+

Lessons from the heavy flavor mesons

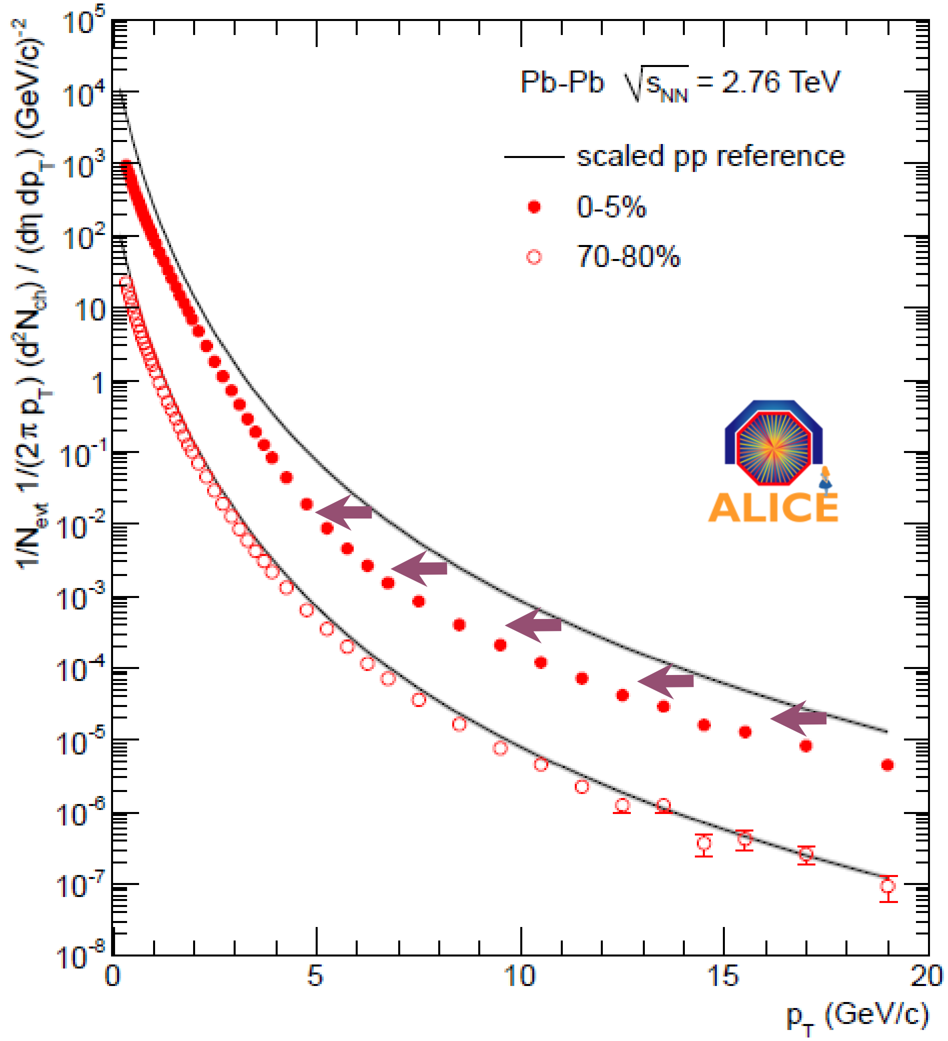
- **What we learned from here:**
  - Hadrons are strongly suppressed in PbPb collisions. The amount of suppression depends on the hadron flavor in the intermediate p_T range.
  - Difference between D, B and charged hadrons disappears at high p_T.
  - These results are consistent with expectation on the parton flavor dependence of in-medium energy loss.
  - We see hint of modified hadronization process based on D_s vs. D^0 and B_s vs. B^+
- **What we still don't know too much:**
  - Details still doesn't work: the slopes of the models (R_{AA} vs p_T) seems to be different from data.
  - How large is the role of recombination and modifications due to hadronization process?
  - Mechanism: Both strongly coupled and weakly coupled approach are consistent with data.

Charged Particle Spectra

Absorption?



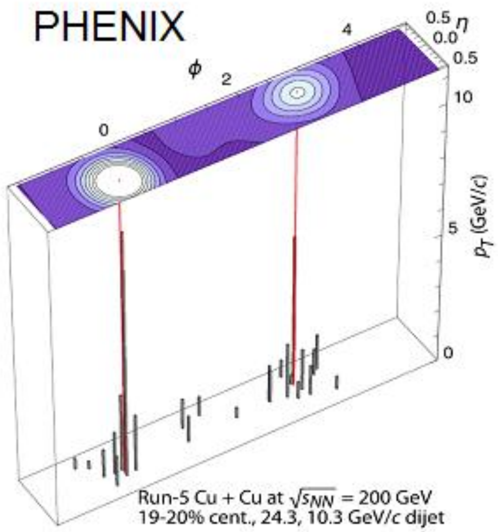
Energy loss?

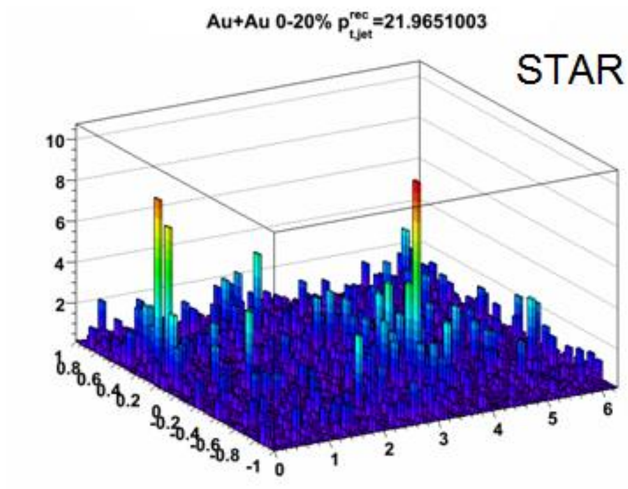


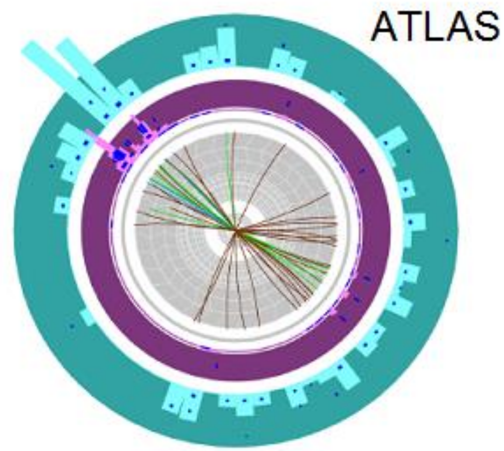
Single hadron spectra itself do not provide details of the underlying mechanism

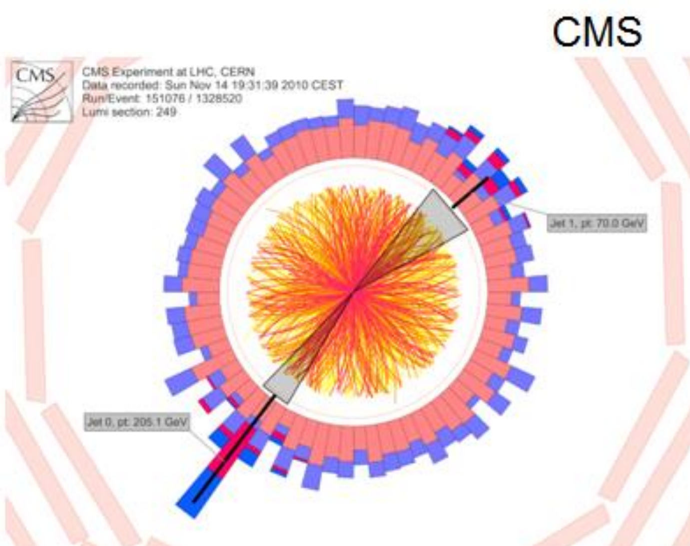
→ Need direct jet reconstruction and correlation studies!

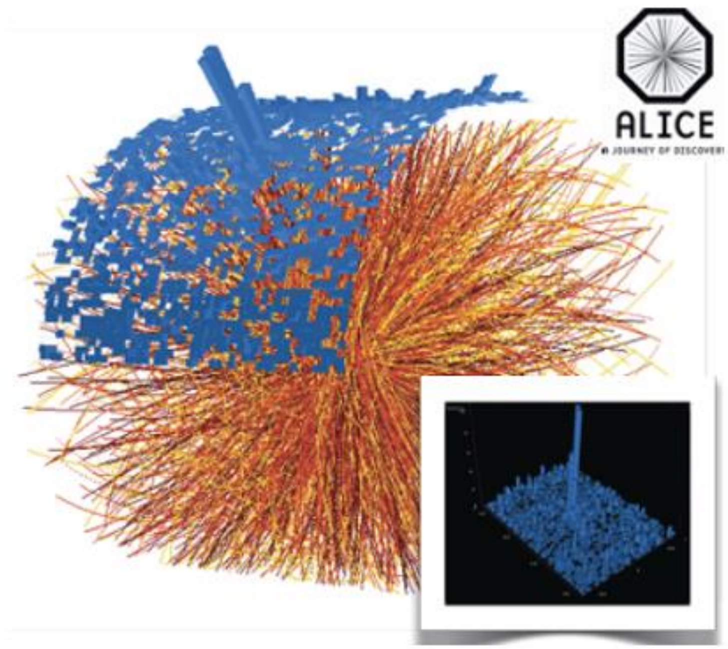
Jet Events in Heavy Ion Collisions









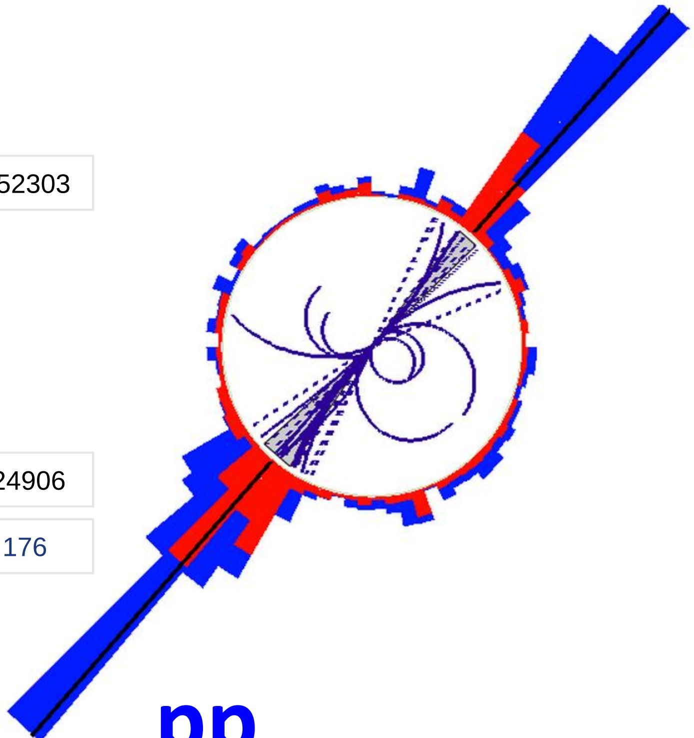


Probe the QGP with High Energy Quarks and Gluons

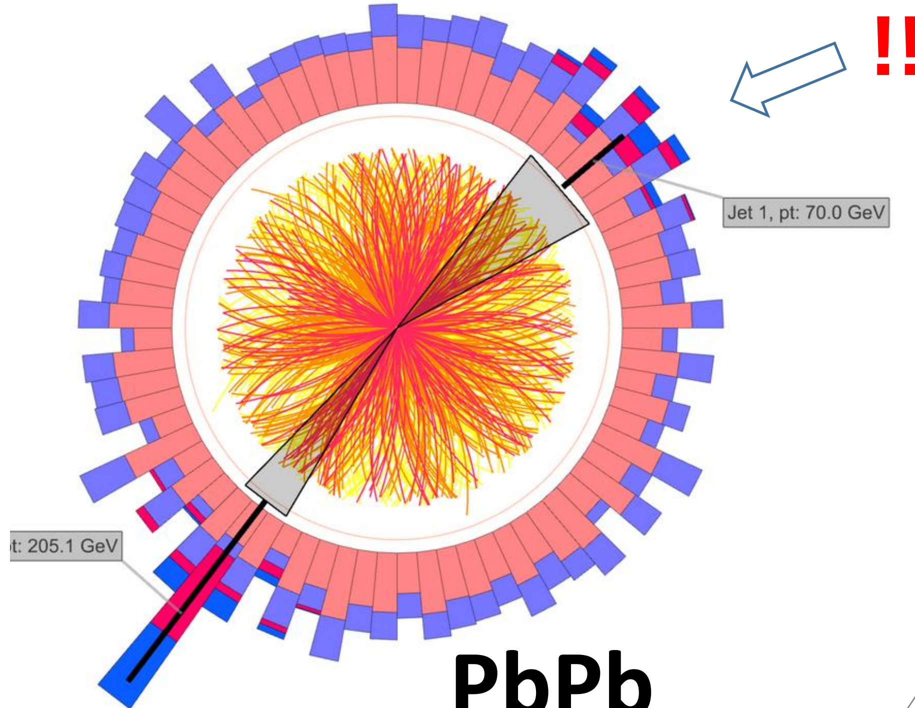
PRL 105 (2010) 252303

PRC 84 (2011) 024906

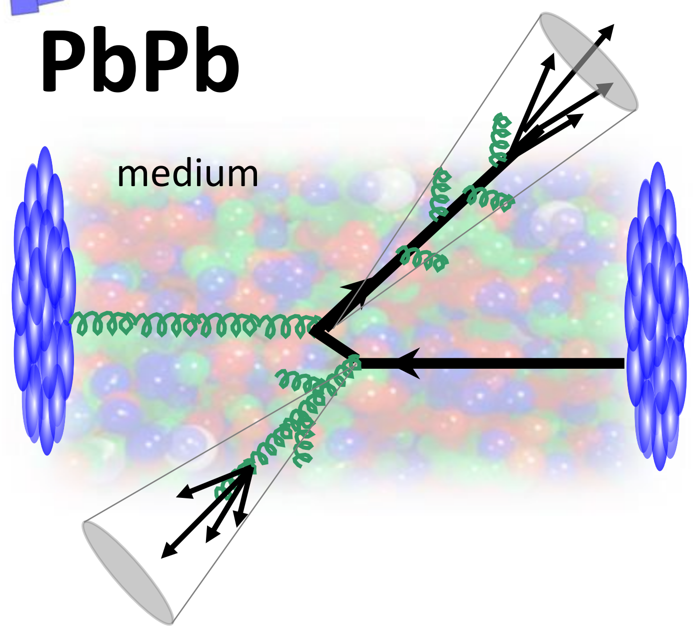
PLB 712 (2012) 176



pp



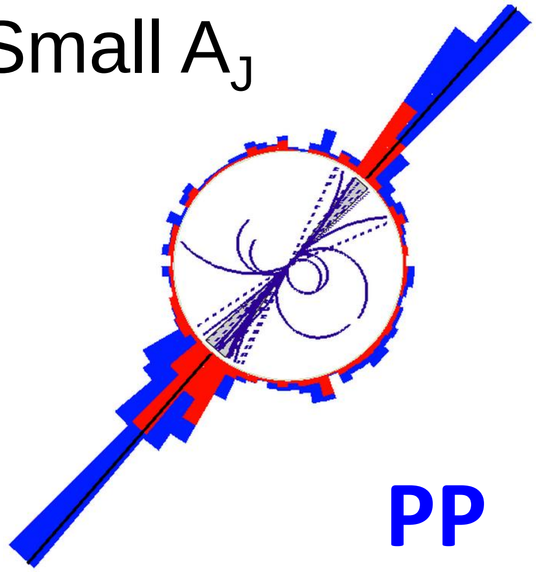
PbPb



- Asymmetric dijets observed more frequently in PbPb collisions
- The stopping power (dE/dx) of the Quark Soup is **Incredibly Strong**

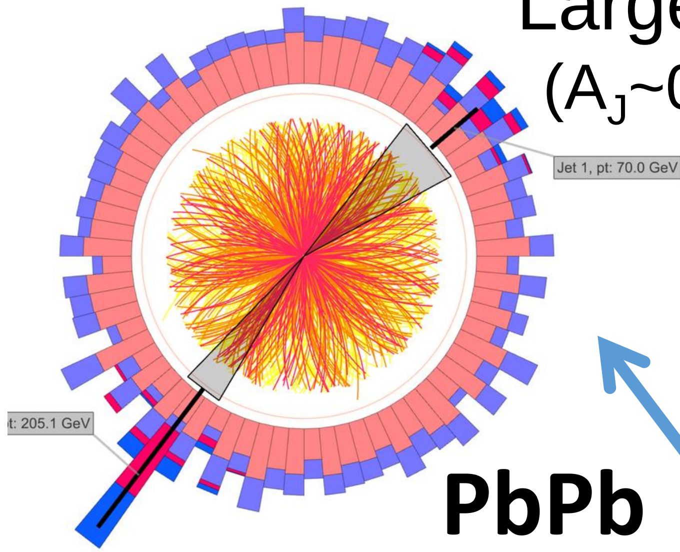
Probe the QGP with Dijets

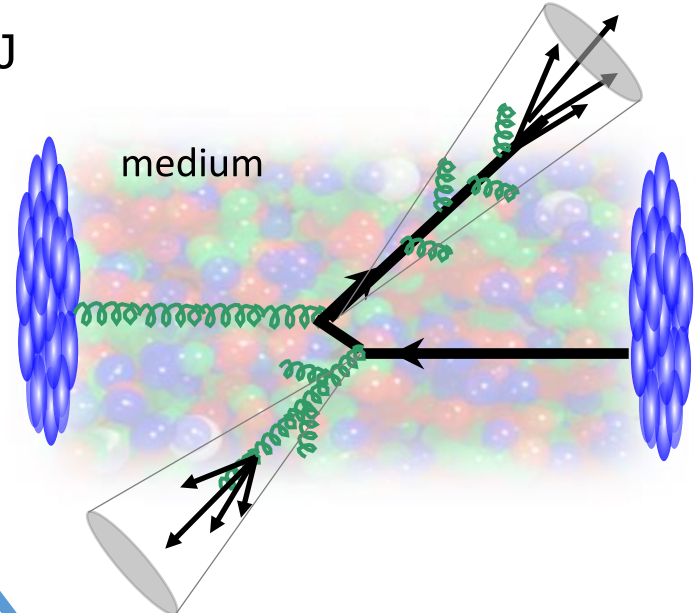
Small A_J

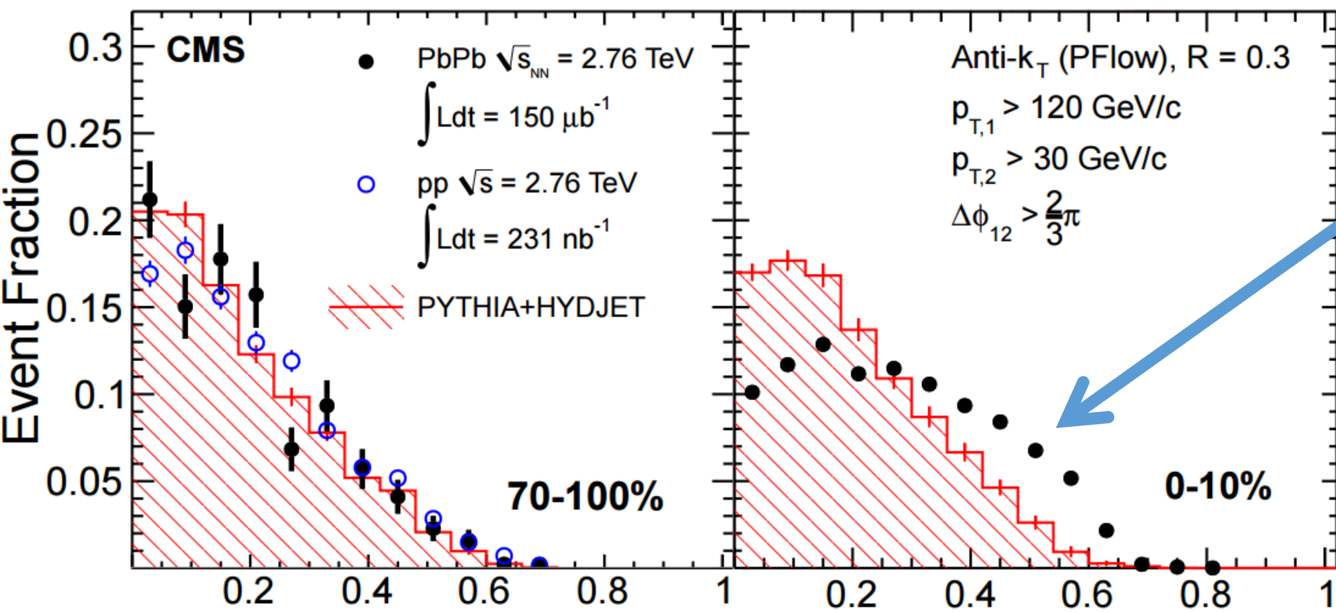


Large A_J

(A_J~0.5)







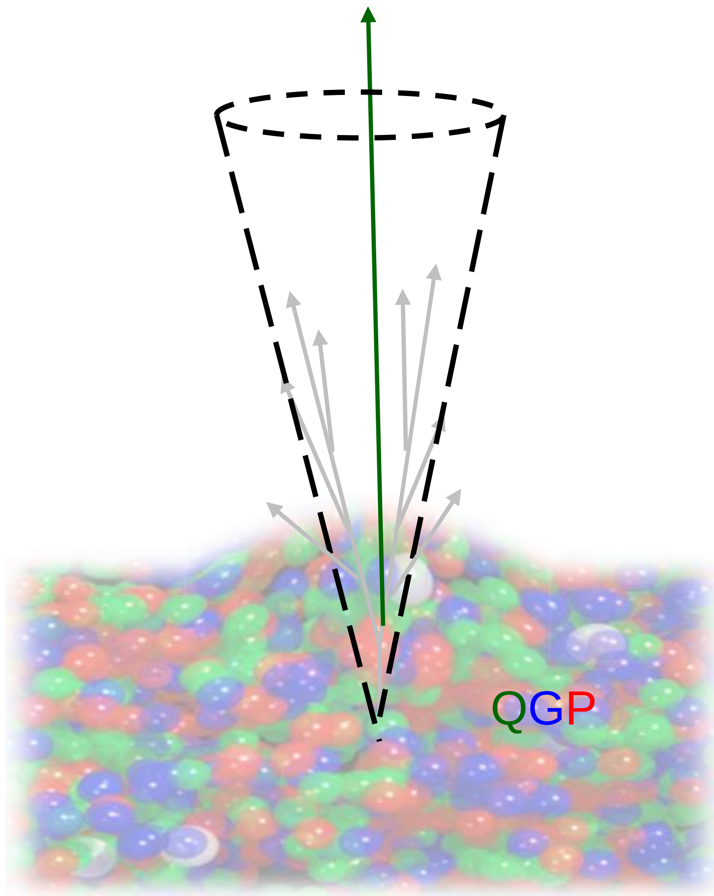
$$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$$

Increased rate of asymmetric dijets in central PbPb collisions

Parton energy loss

Jet Quenching

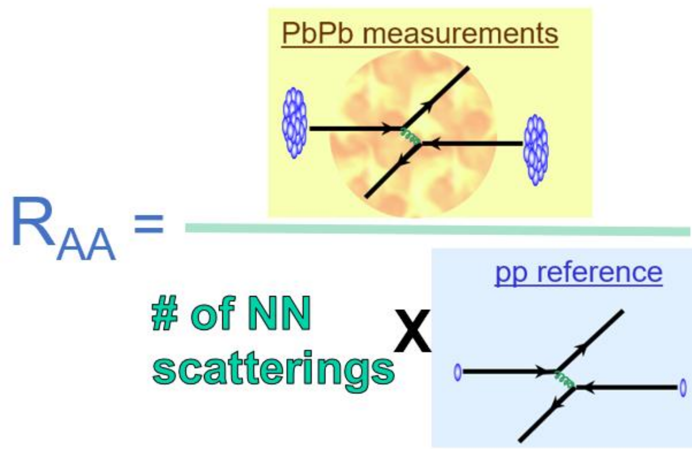
What is the mechanism of jet quenching?



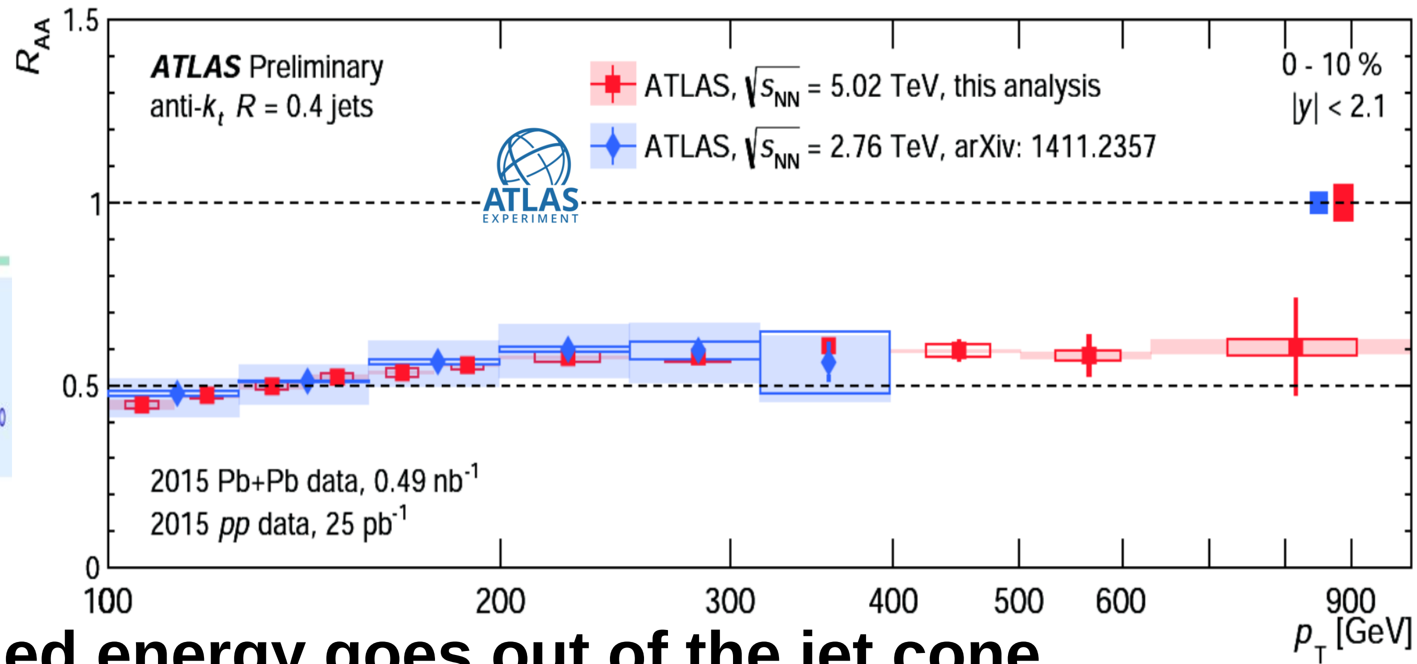
- We see huge suppression of the hadrons
- Can I recover the quenched energy by jet reconstruction?
  i.e., can we cluster the energy back?!

Jet R_{AA} up to p_T ~ 1 TeV

Can we capture all the quenched energy by jet reconstruction?



Anti-k_T R=0.4 Jet R_{AA} in 2.76 and 5.02 TeV



- Jet R_{AA} < 1 : **quenched energy goes out of the jet cone**
  - Similar results from the STAR measurement on the h-jet at RHIC
- Significant jet suppression at high p_T (up to ~ **1 TeV**!)
  - If the suppression is purely due to energy loss

    → Energy transported out of the cone is **O(100) GeV!**

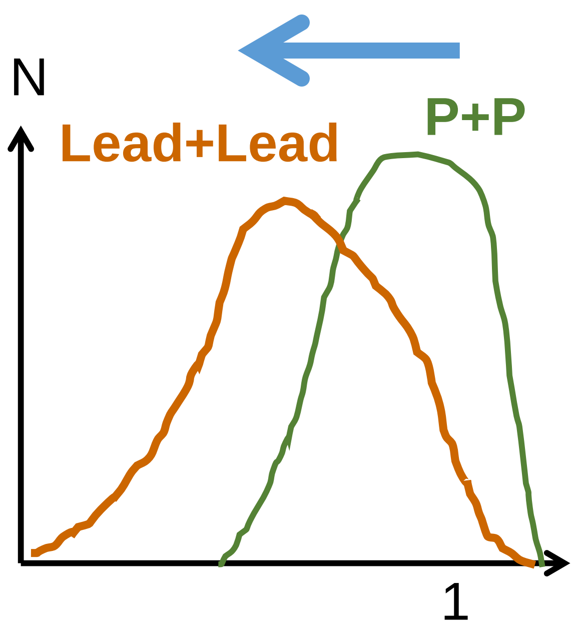
What is the fraction of parton energy going out of the jet cone?

Measurement of Absolute Energy Loss in QGP

Boson-Jet correlation

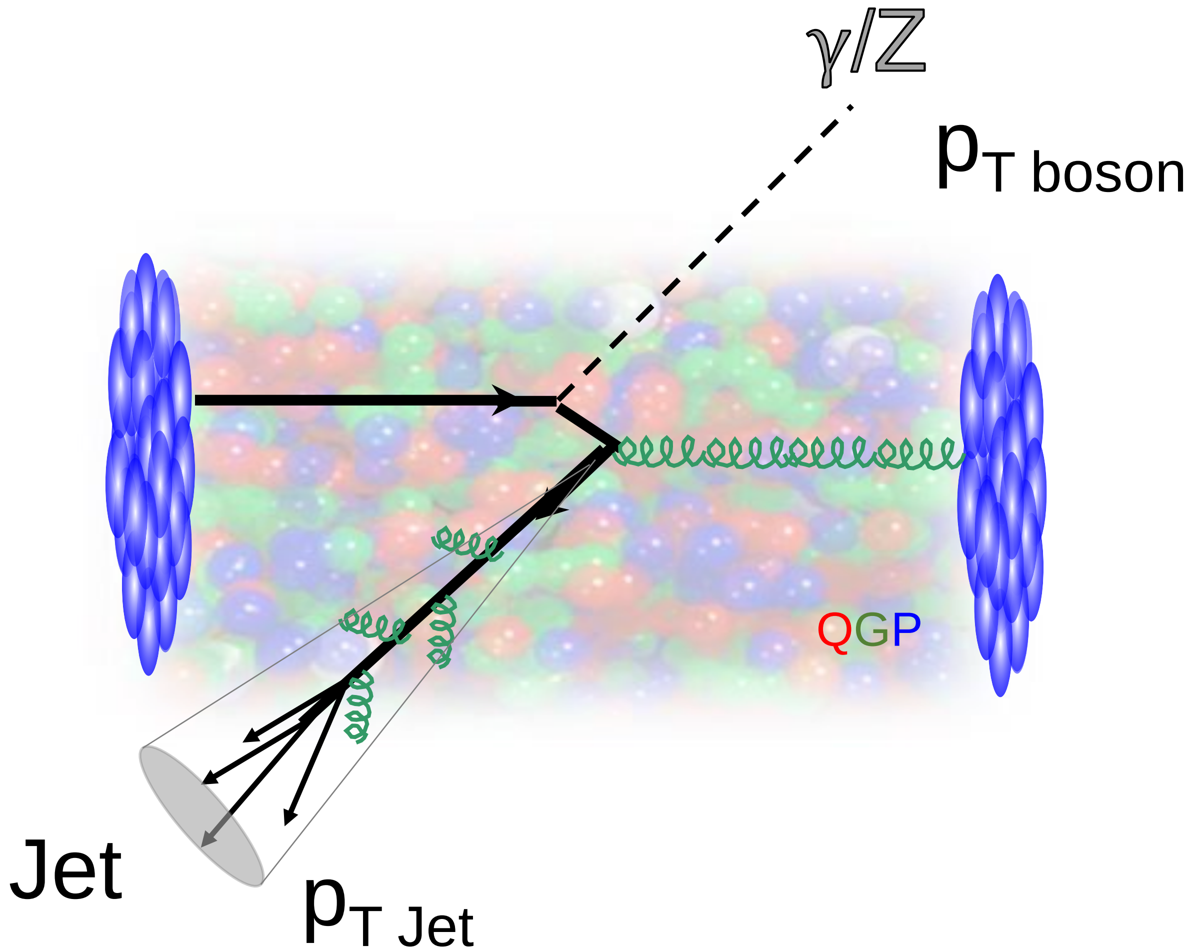
Momentum conservation
in the transverse direction

Jet quenching



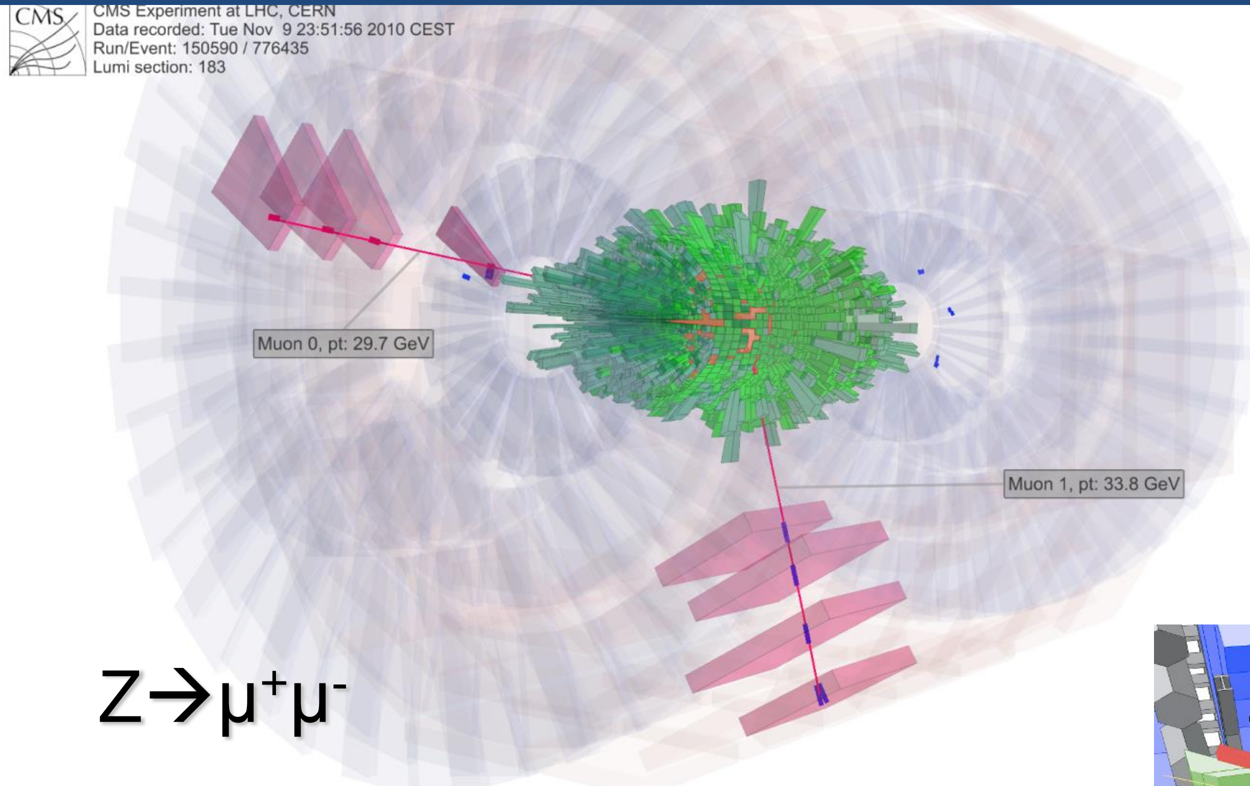
$x = p_{T\,Jet} / p_{T\,boson}$

Colorless objects: photons, electroweak bosons are unmodified

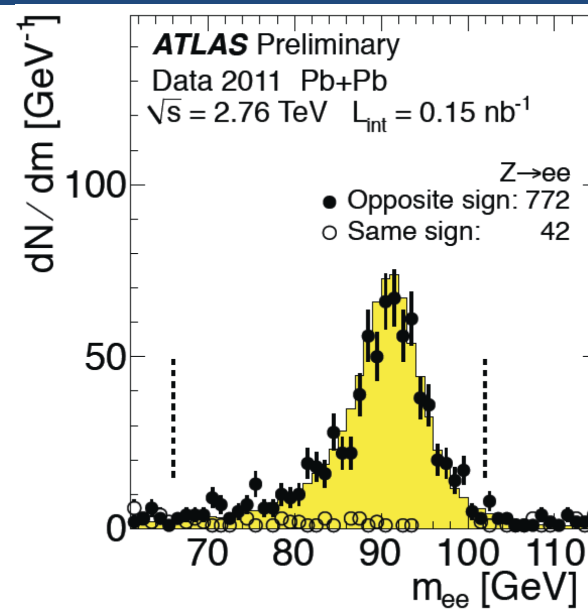


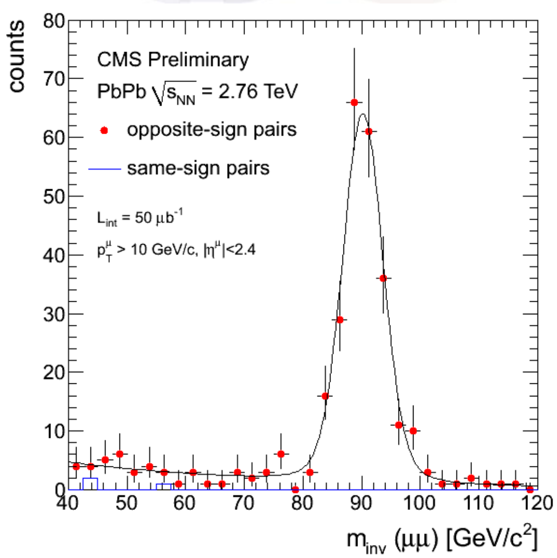
Ratio of the boson and jet momenta

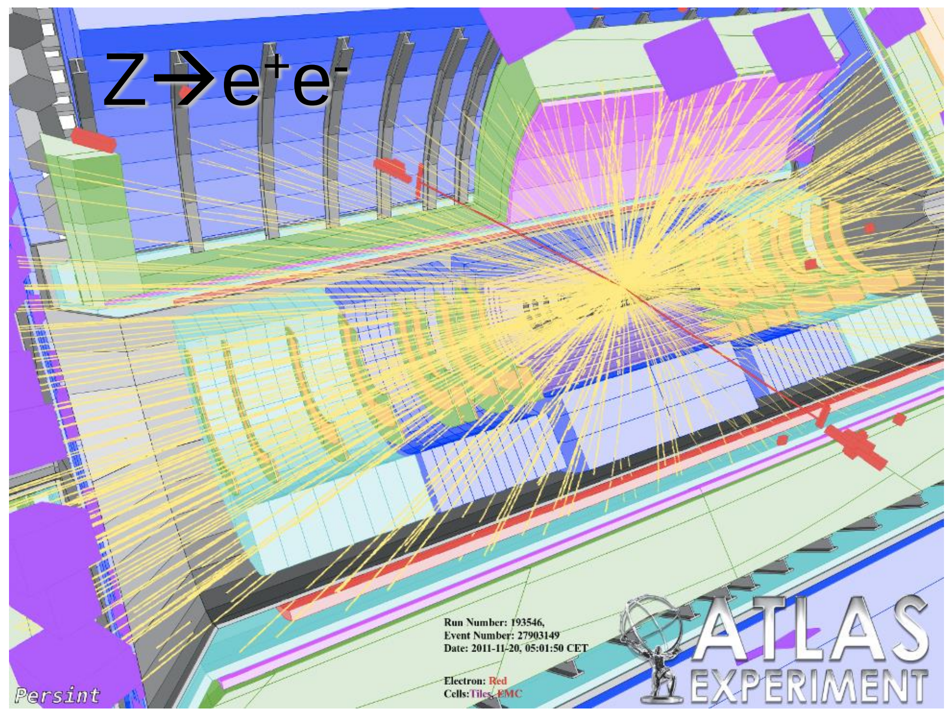
Z boson production in PbPb collisions



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



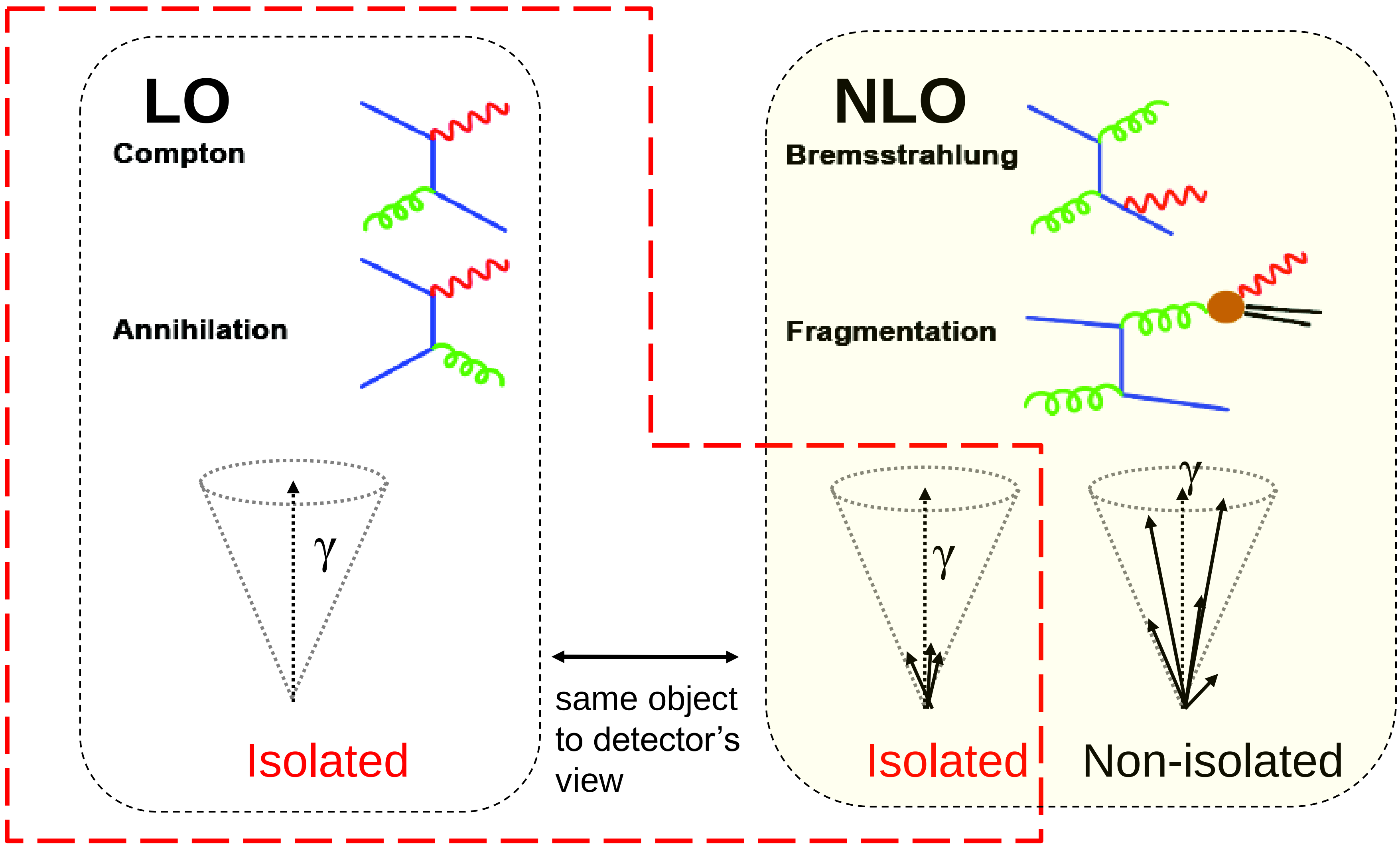




$Z \rightarrow e^+e^-$

Isolated high p_T photons

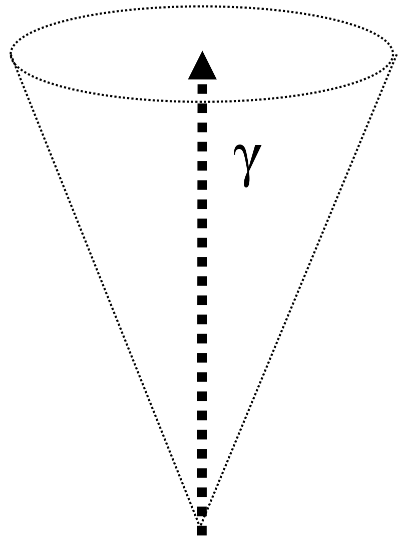
- Ideal: Direct photon from hard scattering
- Real world: Background from the decay and fragmentation photons.
- Solution: Measurement of the isolated photons

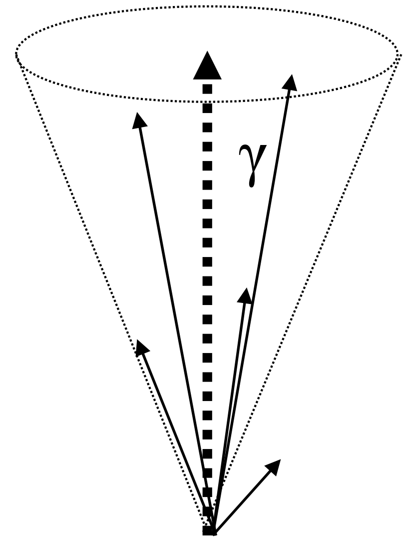


Photon isolation in PbPb

Generator level
$\Delta R<0.4$, $\Sigma E_T^{IsoCone} < 5$ GeV
with only particles from the same hard scattering

Particles from the same hard scattering



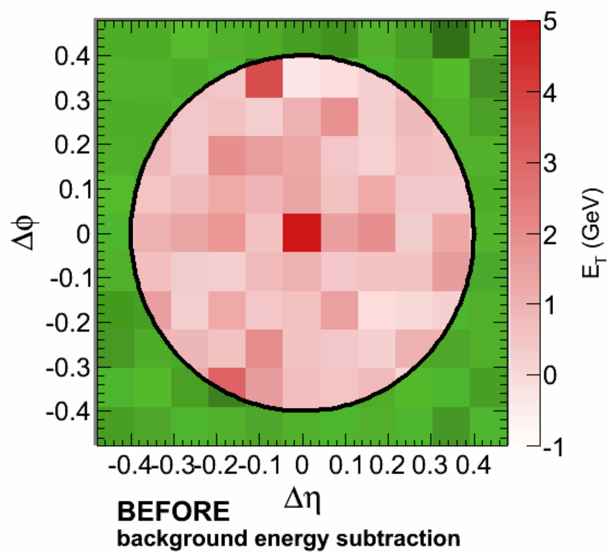


CMS Experiment

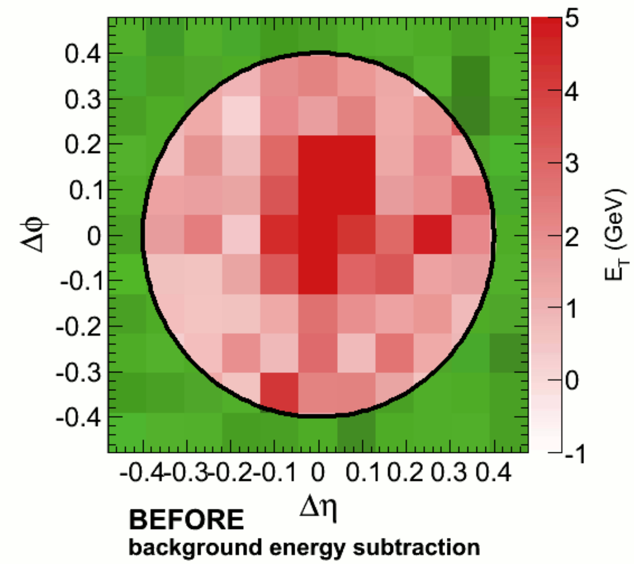
Sum E_T (p_T) from Calorimeter and tracker

Contribution from underlying event

Isolated photon



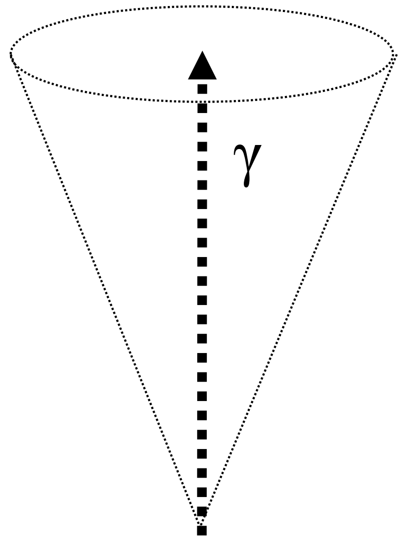
Photon candidate from jet

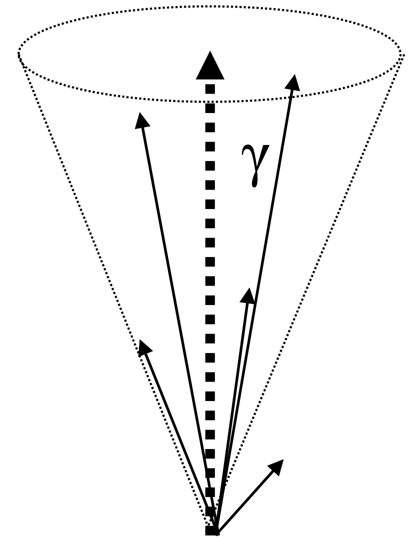


Background subtracted isolation in PbPb

Generator level
$\Delta R<0.4$, $\Sigma E_T^{IsoCone} < 5$ GeV
with only particles from the same hard scattering

Particles from the same hard scattering

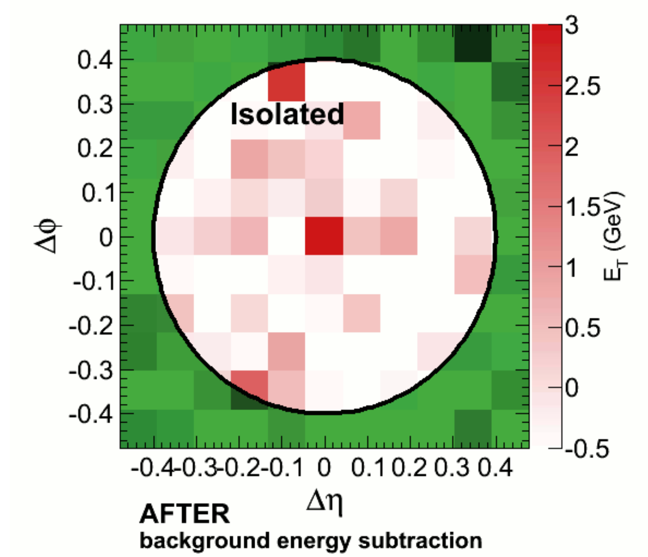




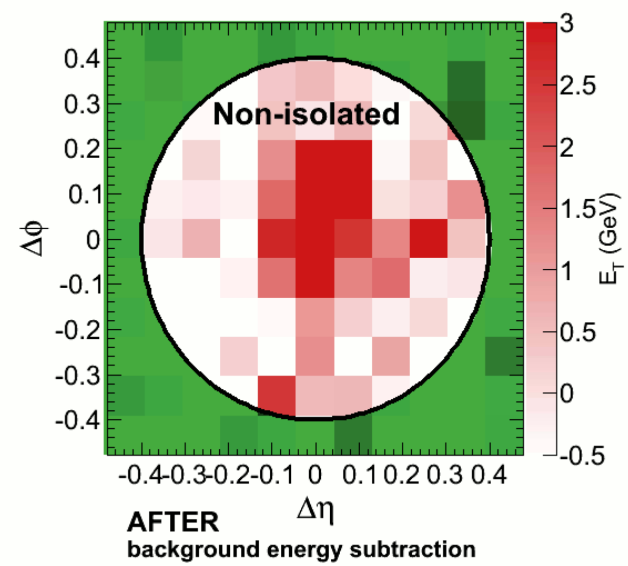
CMS Experiment

Sum E_T (p_T) from Calorimeter and tracker < 5 GeV with background subtracted

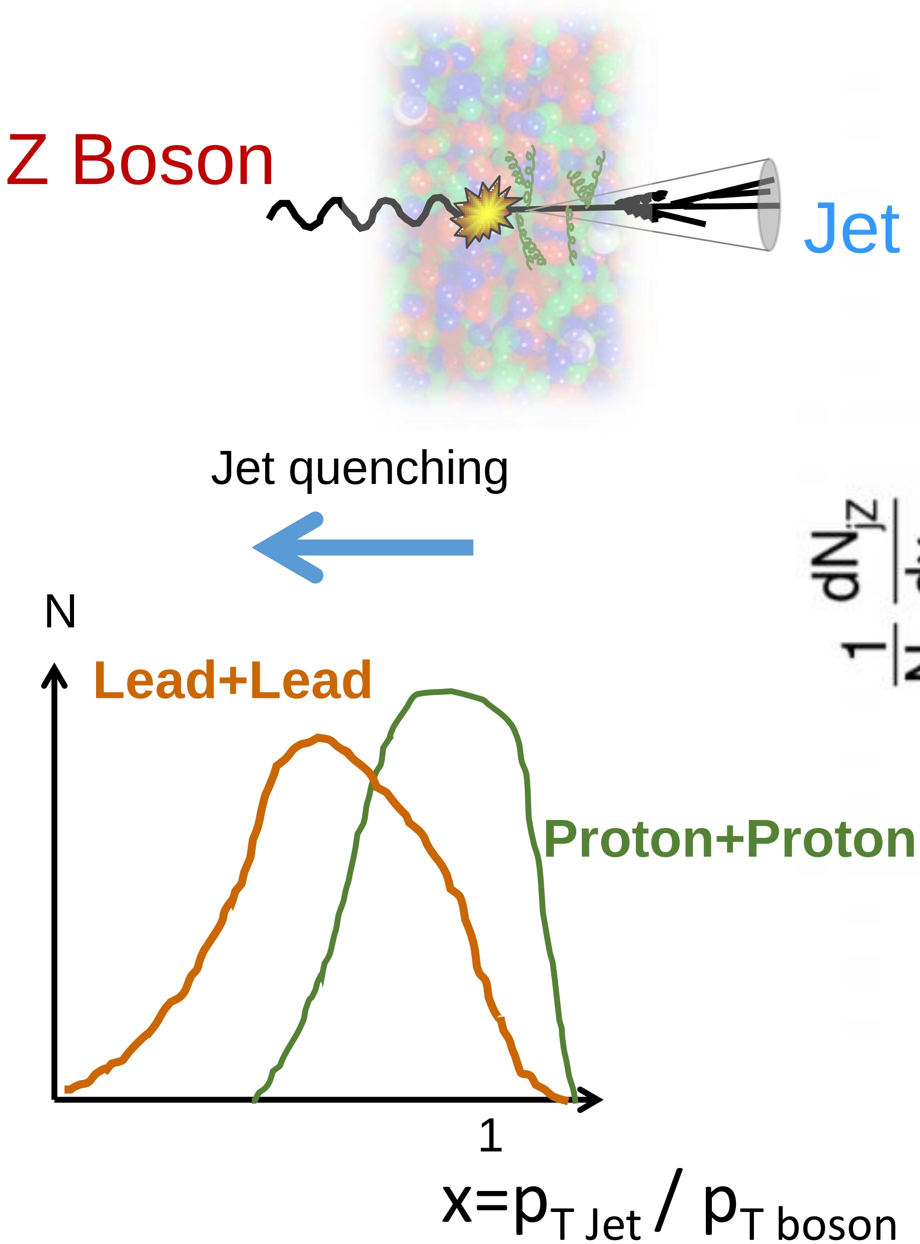
Isolated photon



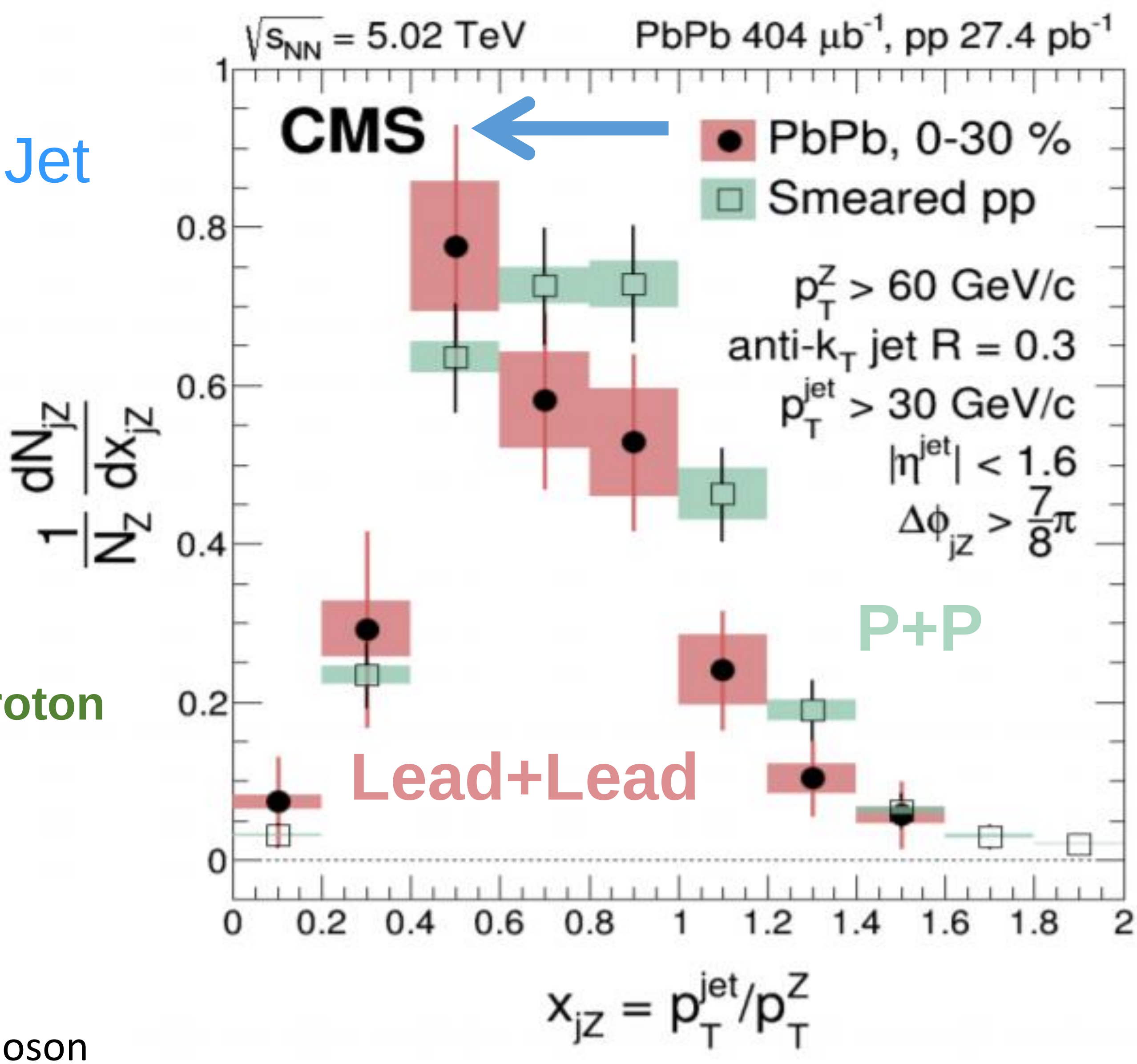
Photon candidate from jet



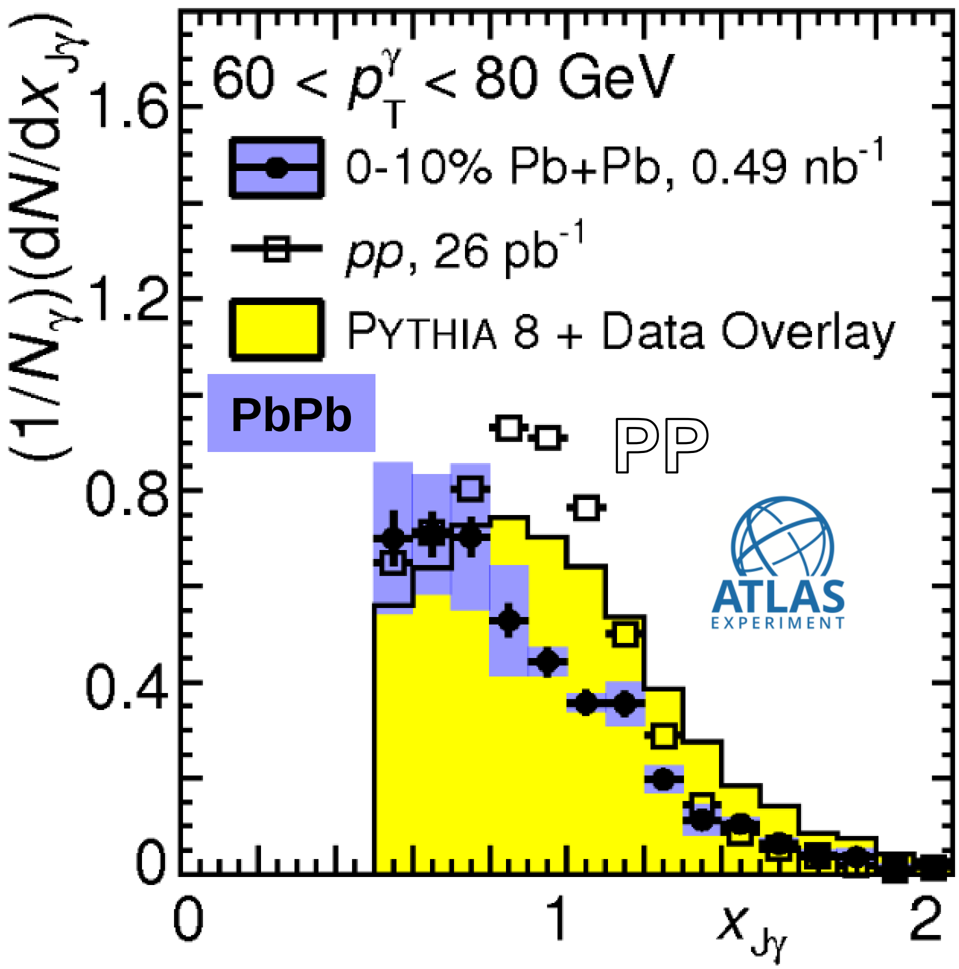
Boson-Jet Correlation in PbPb at 5.02 TeV

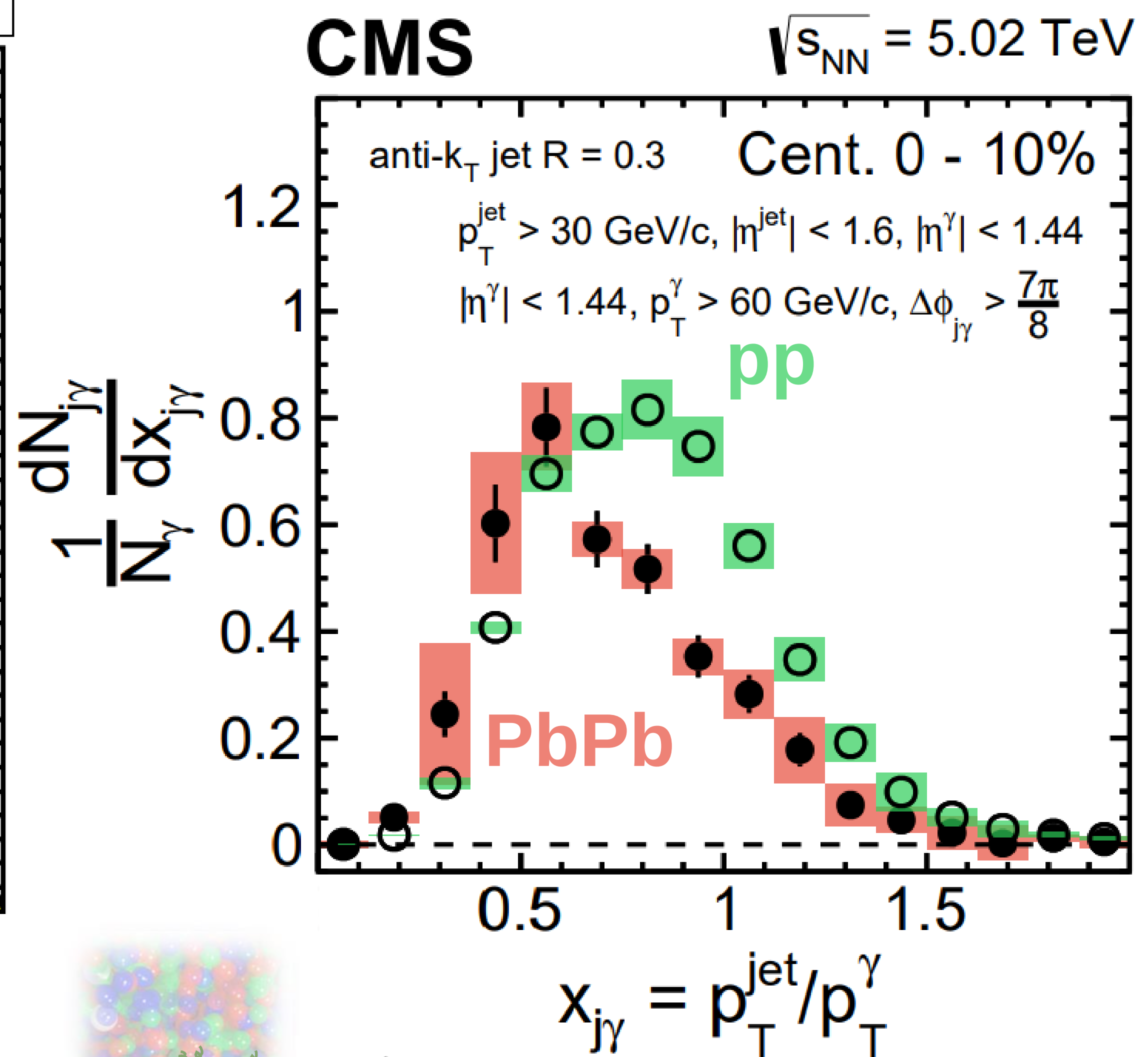


PRL cover page (2017)



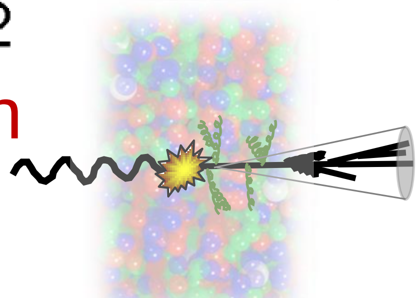
Absolute Energy Loss with γ+Jet at 5 TeV





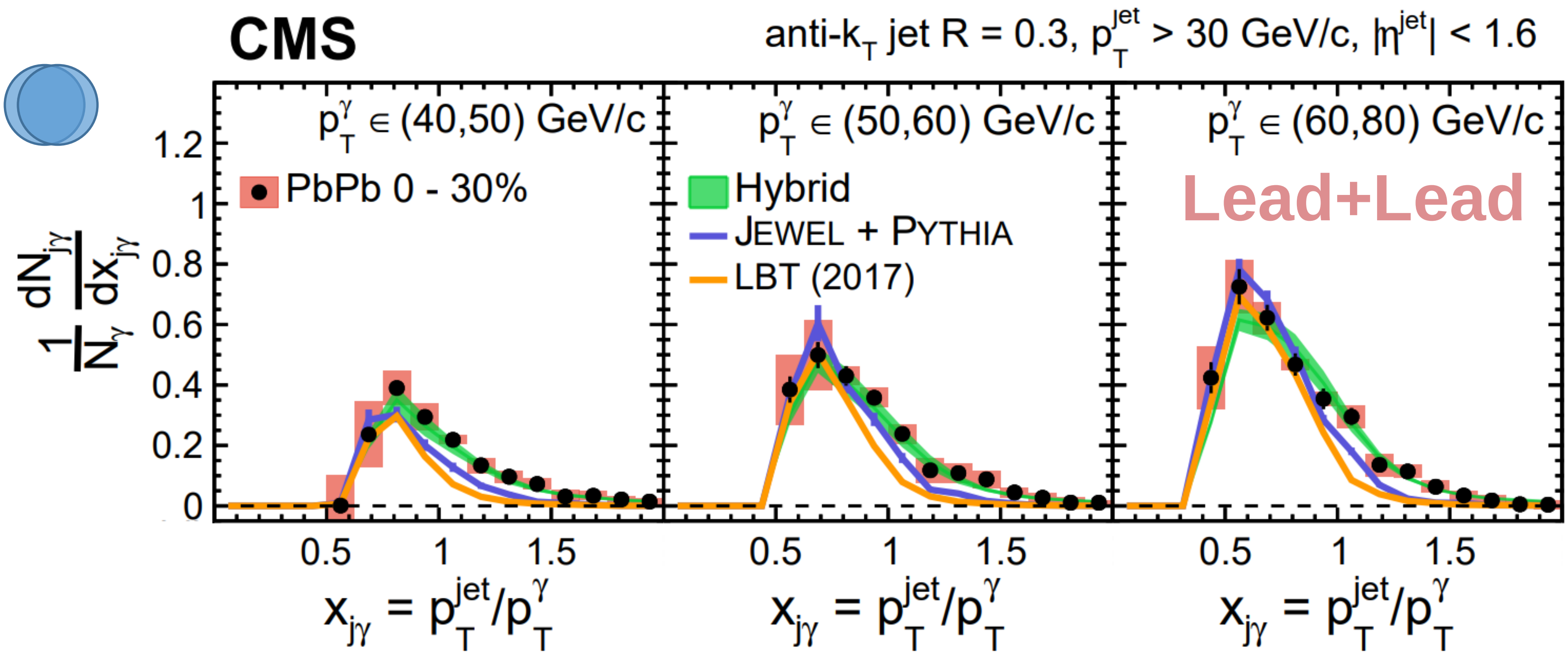
arXiv: 1711.09738
Submitted to PLB

$x_{J\gamma} = p_T^{\ Jet} / p_T^{\ \gamma}$



Fraction of the jet energy out of cone (R=0.3) **~ 14%±4%**

Data vs. Theoretical Predictions

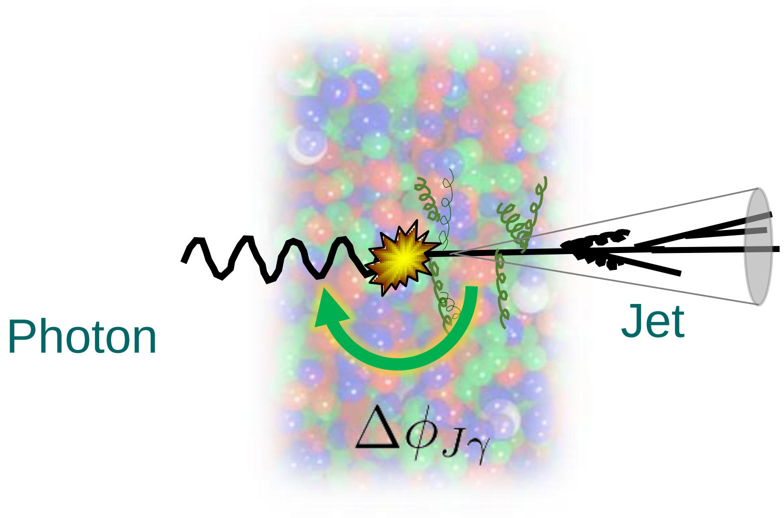


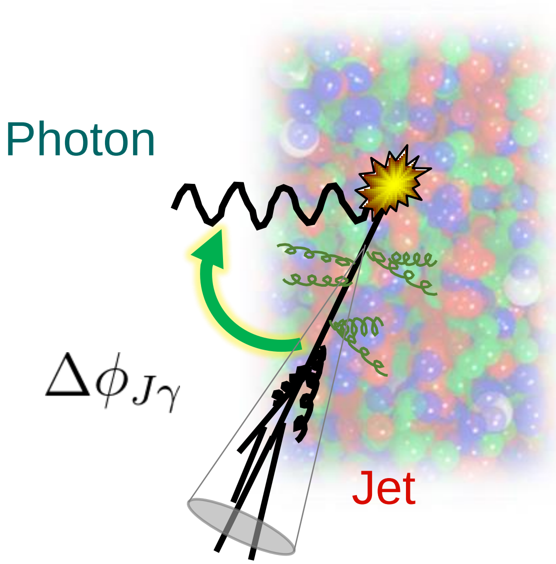
Photon p_T 40-50 GeV/c 50-60 GeV/c 60-80 GeV/c

- JEWEL: pQCD 2 to 2 scattering extrapolated to infrared region and medium recoil
- LBT: pQCD Transport model with medium recoil and thermalization of the quenched energy
- Hybrid Model: PYTHIA8 + AdS/CFT drag force

CMS-PAS-HIN-16-002 (2017)

“QGP Rutherford experiment”

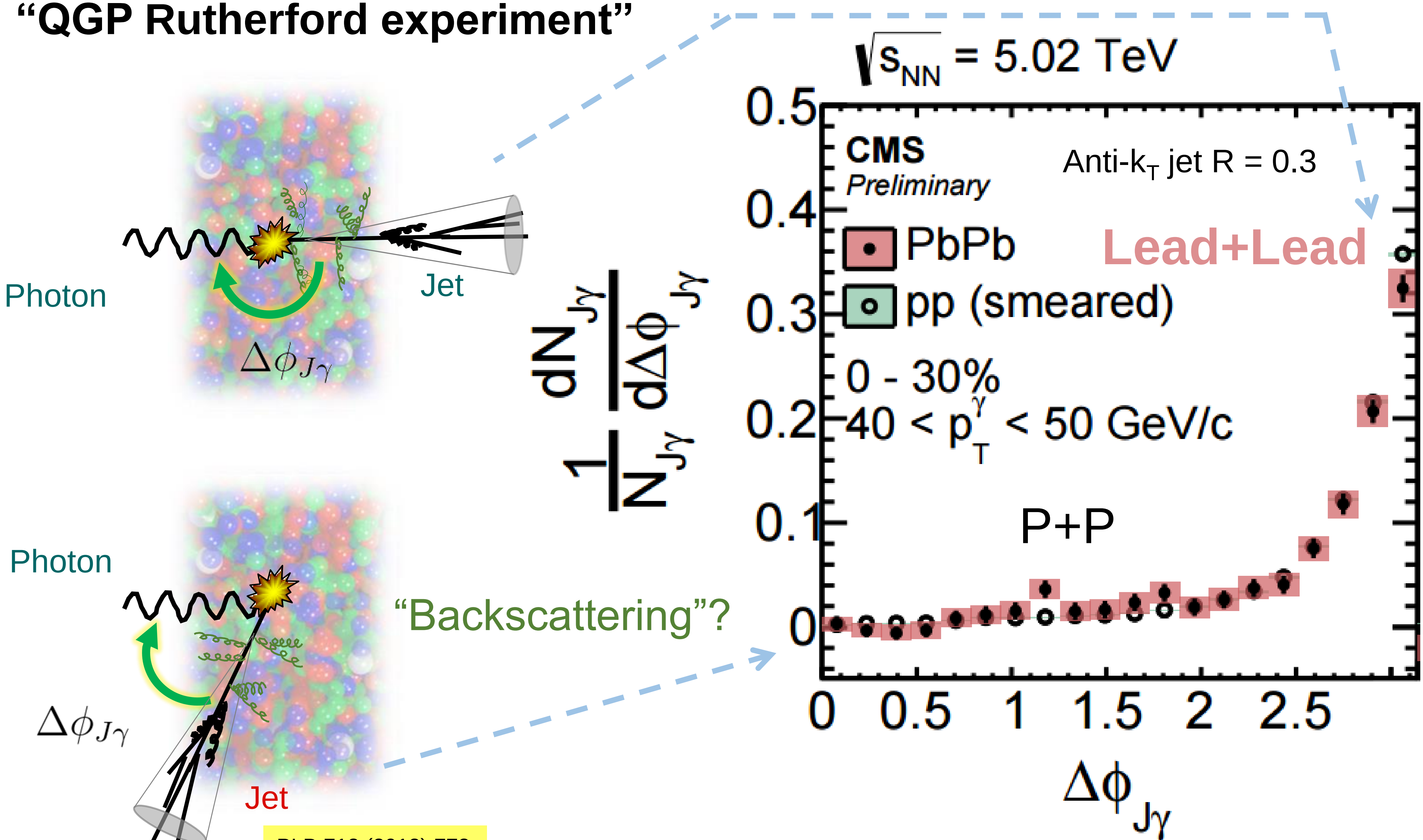




“Backscattering”?

Search for Quasi-Particles in the QGP

“QGP Rutherford experiment”



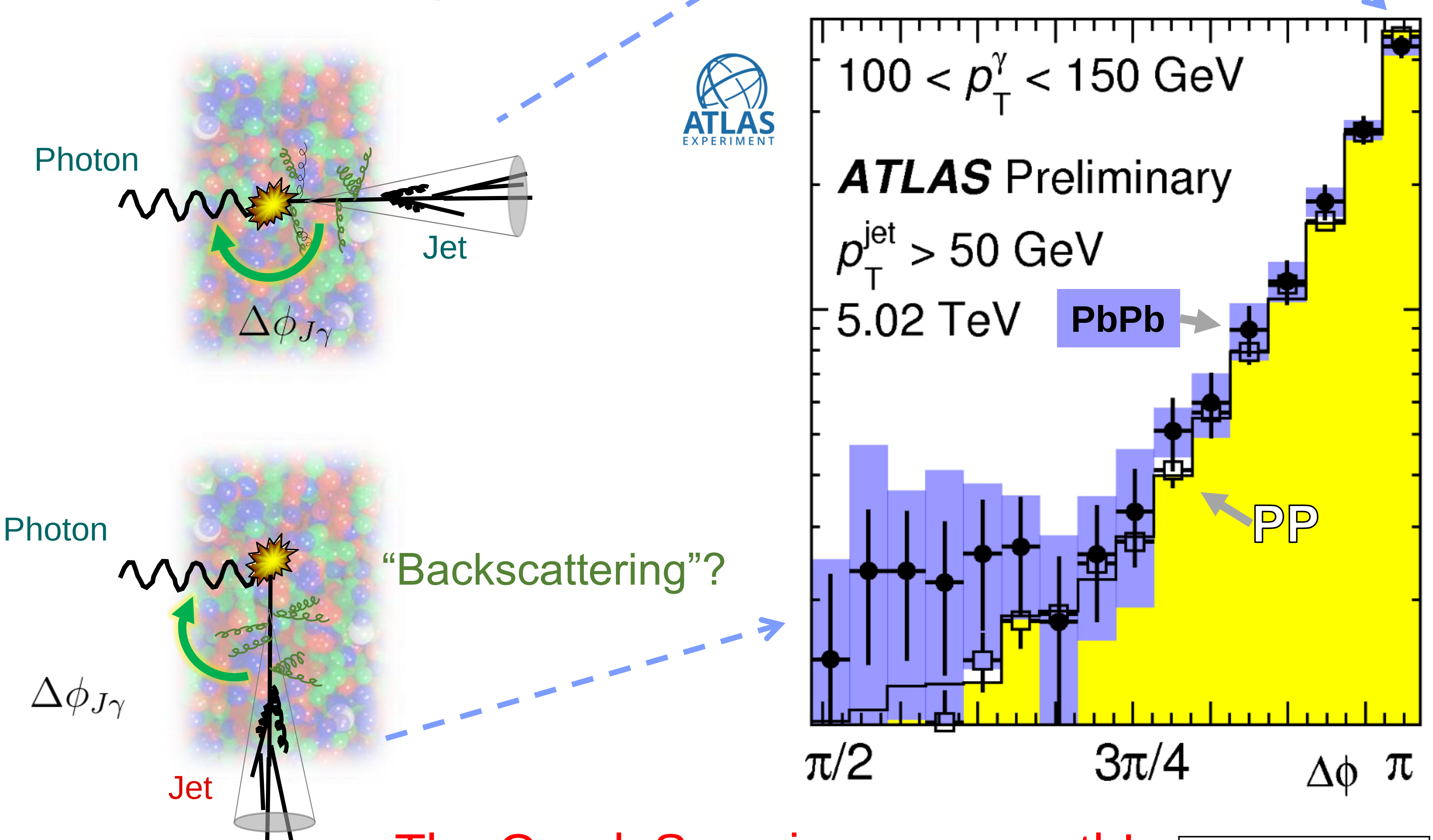
PLB 718 (2013) 773

CMS-PAS-HIN-16-002 (2017)

The Quark Soup is very smooth!

Search for Quasi-Particles in the QGP

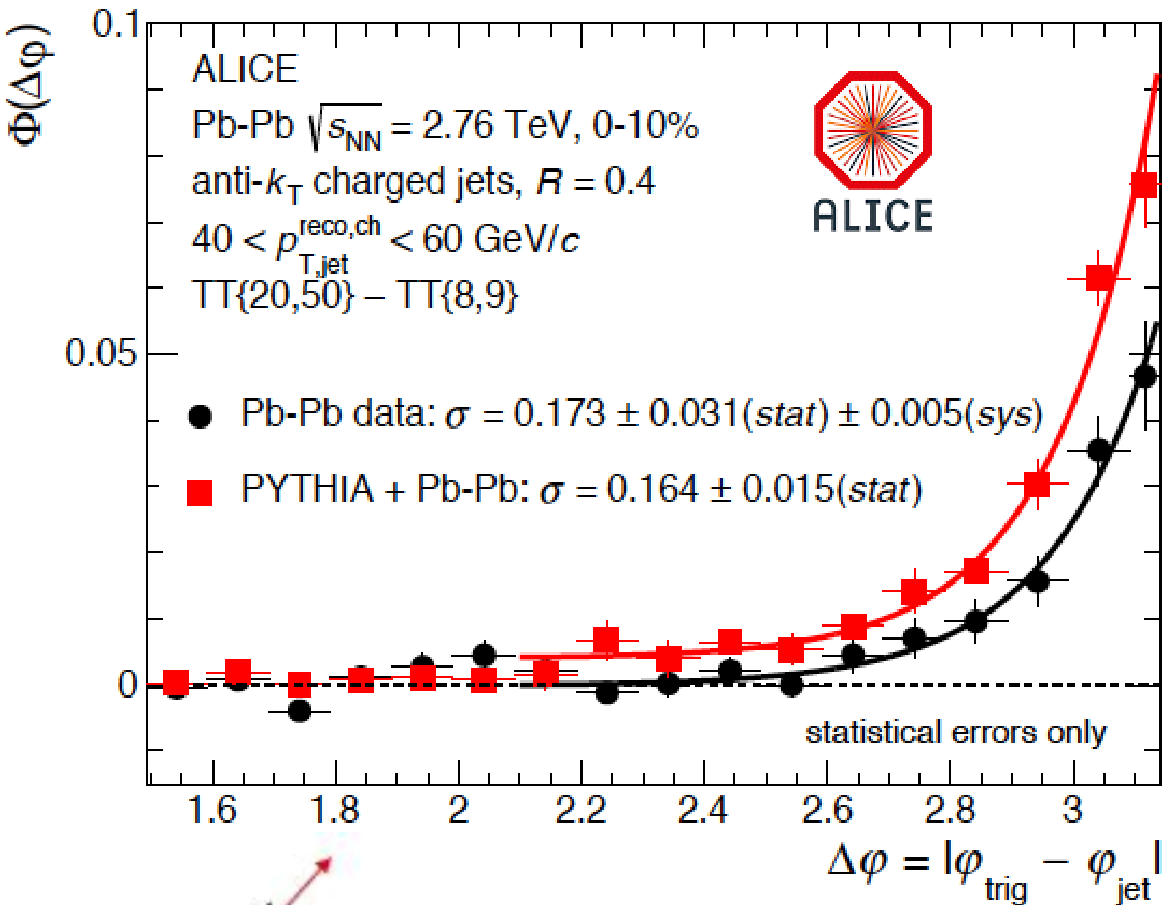
“QGP Rutherford experiment”

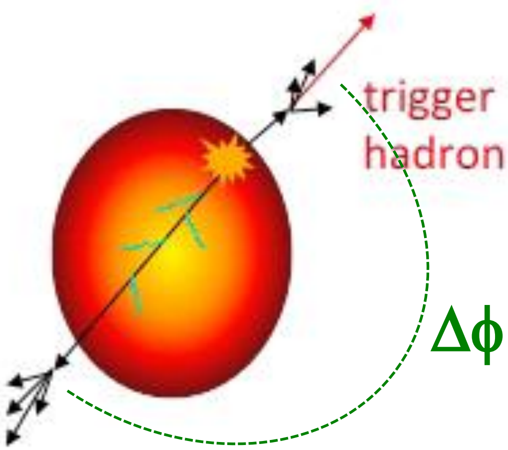


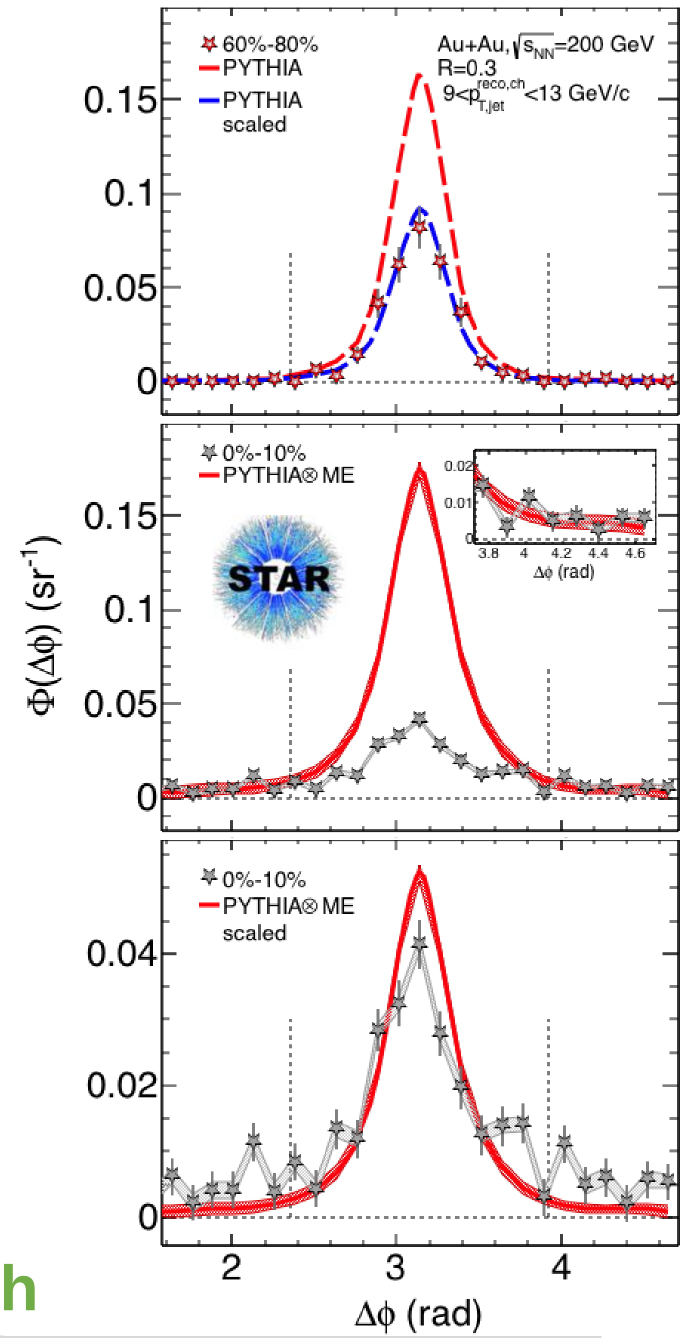
The Quark Soup is very smooth!

ATLAS-CONF-2016-110

Hadron-Jet Angular Correlation



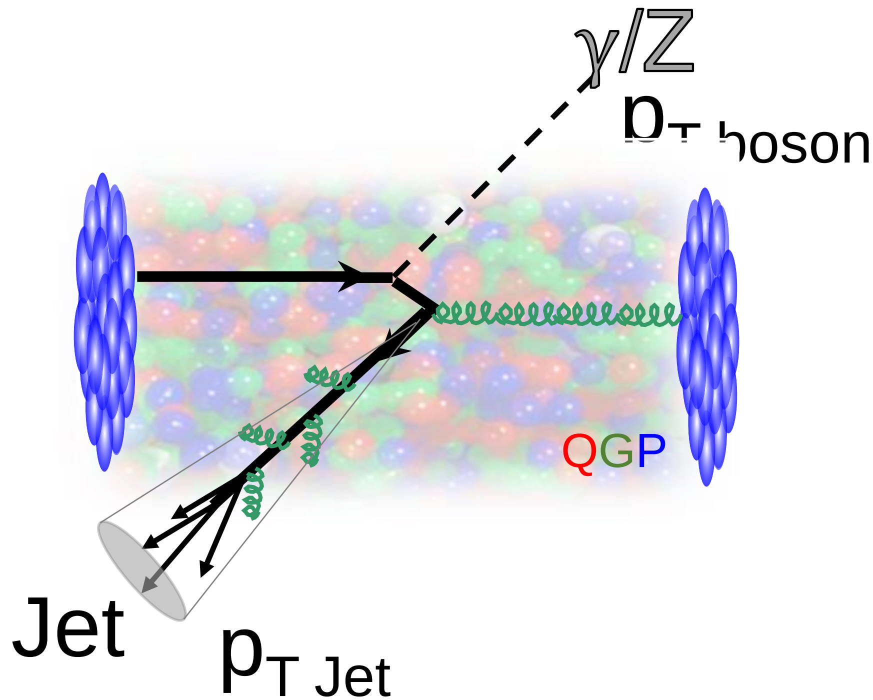




No significant broadening

QGP probed looks **smooth**

What do we learn from those measurements?



- Hard scattered quarks and gluons are losing energy:
  - Quenched energy going out of the jet cone, can not be recovered by jet reconstruction
- No significant modification of azimuthal angle correlation between X+jet
- Mechanism: Both pQCD based and Ads/CFT drag based models are consistent with data.
- Can we make more progress by looking at the modification of jet substructure?