Nuclear modification factors in PbPb and pPb collisions

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Lazar Markovic on behalf of the Discussion Group E

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PbPb

Motivation

1) Measure spectra of charged particles in $|\eta|<1$ at $\sqrt{s}$ = 5.02 TeV per NN pair for :
   a) *pp* collisions
   b) *PbPb* collisions
2) Study nuclear modification factors R_{AA} and R_{pA}
3) Compare $R_{AA/pA}$ factors to models and previous experimental results

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Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS collaboration

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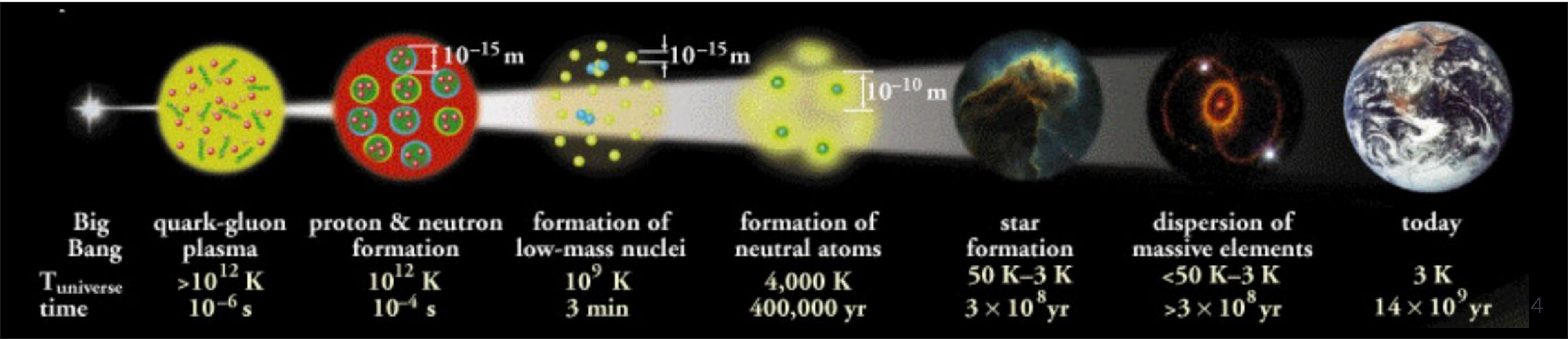
ABSTRACT: The spectra of charged particles produced within the pseudorapidity window $|\eta| < 1$ at $\sqrt{s_{NN}} = 5.02$ TeV are measured using 404 μb^{-1} of PbPb and 27.4 pb^{-1} of pp data collected by the CMS detector at the LHC in 2015. The spectra are presented over the transverse momentum ranges spanning $0.5 < p_T < 400$ GeV in pp and $0.7 < p_T < 400$ GeV in PbPb collisions. The corresponding nuclear modification factor, R_{AA}, is measured in bins of collision centrality. The R_{AA} in the 5% most central collisions shows a maximal suppression by a factor of 7–8 in the p_T region of 6–9 GeV. This dip is followed by an increase, which continues up to the highest p_T measured, and approaches unity in the vicinity of $p_T = 200$ GeV. The R_{AA} is compared to theoretical predictions and earlier experimental results at lower collision energies. The newly measured pp spectrum is combined with the pPb spectrum previously published by the CMS collaboration to construct the pPb nuclear modification factor, R_{pA}, up to 120 GeV. For $p_T > 20$ GeV, R_{pA} exhibits weak momentum dependence and shows a moderate enhancement above unity.

Analysis Strategy

Introduction

- **Quark Gluon Plasma (QGP)**
  - Deconfined nuclear matter (gluons and quarks are “free”)
  - Our universe up to a microsecond after the Big Bang
  - Cannot be probe directly - we need generated particles in QGP

The charged-particle transverse momentum (p_T) spectrum used



Introduction

- **Nuclear modification factor**

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll} \rangle dN^{pp}/dp_T} = \frac{dN^{AA}/dp_T}{T_{AA}\, d\sigma^{pp}/dp_T},$$

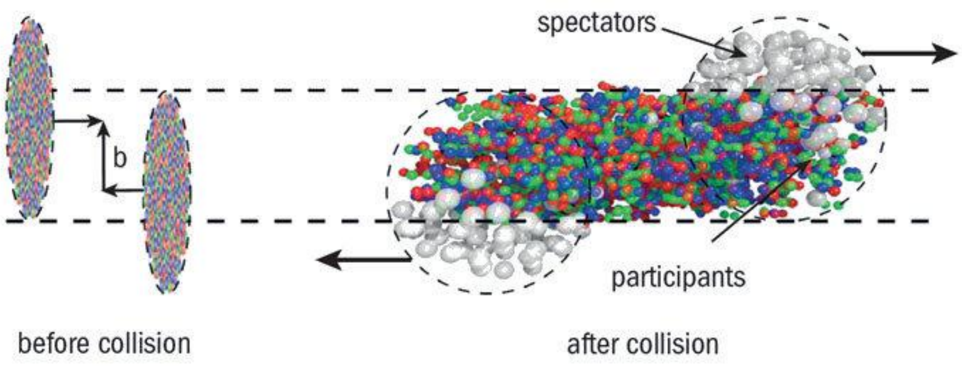
- Number of particles from AA collisions
- Average number of binary nucleon-nucleon collisions
- Nuclear overlap function
- Number of particles from *pp* collisions

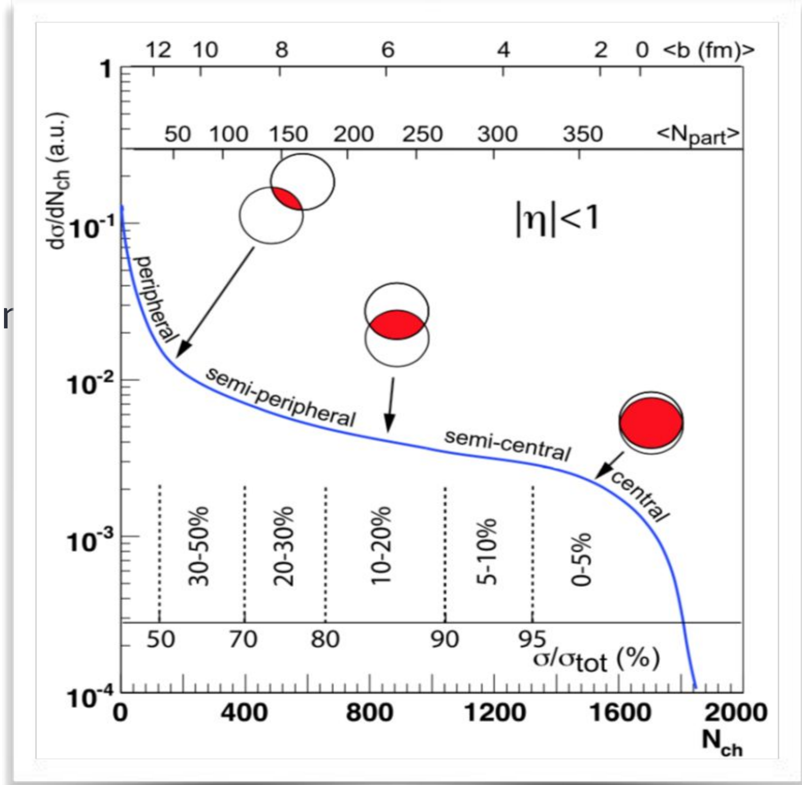
  - $R_{AA}>1$: Increased particle production in ion collision
  - $R_{AA}<1$: Particle production suppressed in ion collision, hint for medium

Introduction

Centrality of nucleus-nucleus collision

- The properties of QGP are given by **centrality**
- Higher particle **multiplicity** (N_{ch}) for central collision
- **Centrality classes**: percentiles of the total cross section



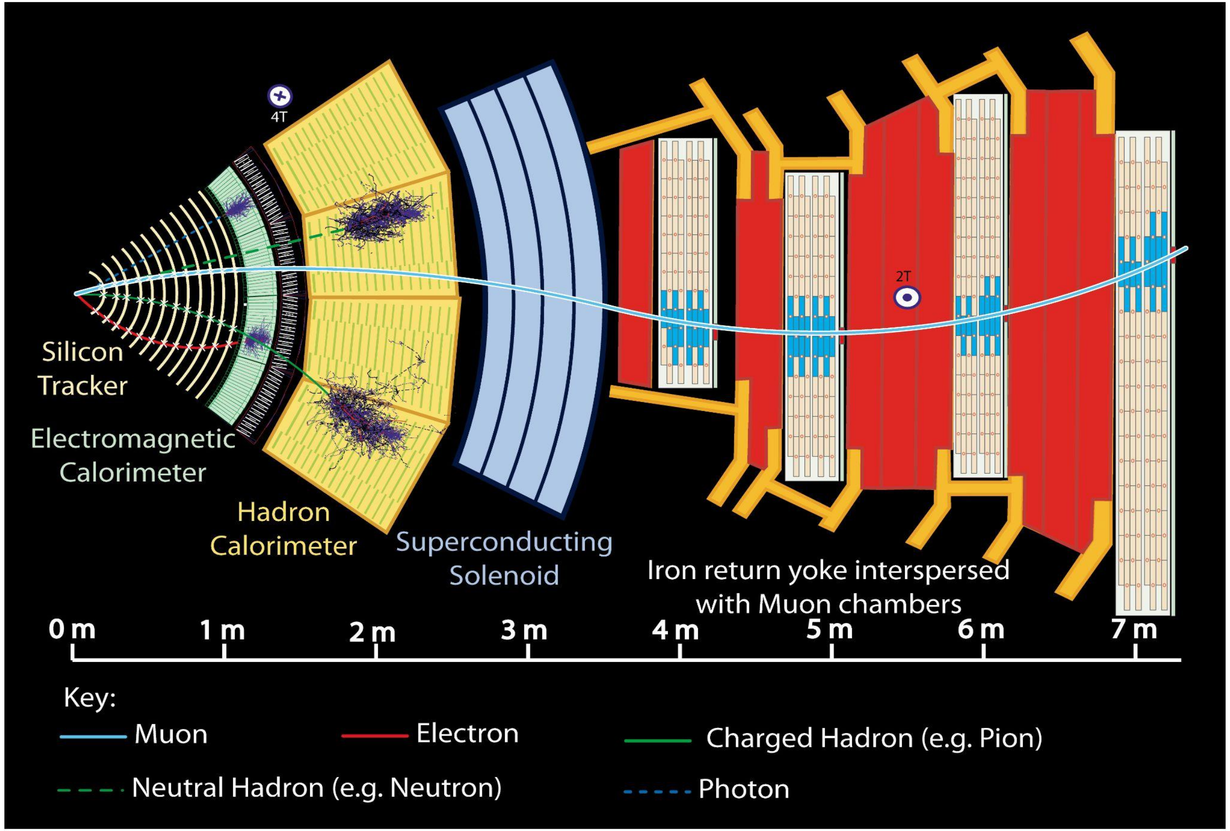


CMS detector

22 m long!
15 m in diameter!
14,000 tones!
Records 40 million events in each second!

- Silicon Tracker
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Superconducting Solenoid
- Muon Tracker

Particle detectability:
Interact with detector: e,μ,γ,q
Escape from detector: ν,DM,...
Decay of various particles, e.g: τ, Z, W, Higgs



Triggers and event selection

- **Jet** (nominal) and **track** (alternative) triggers with different E_T and p_T thresholds are used:

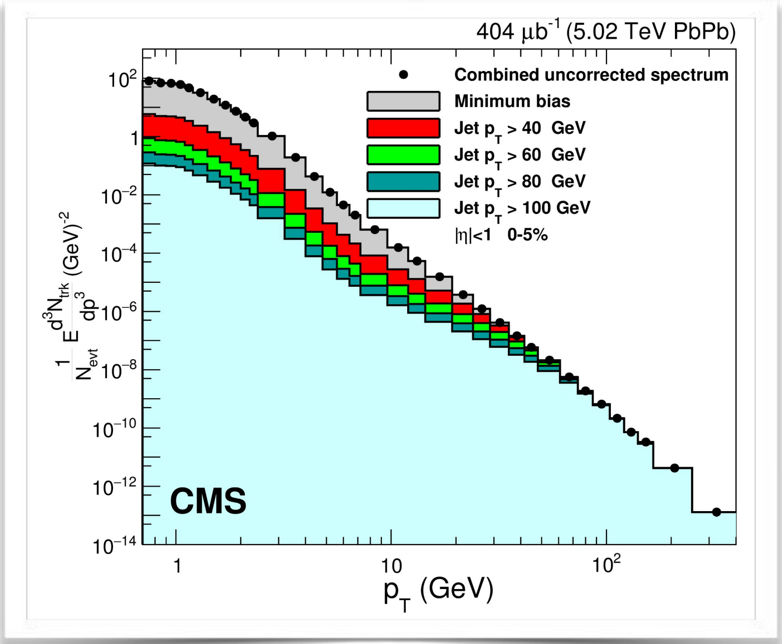
Collision system/trigger	L1 thresholds [GeV]	HLT thresholds [GeV]
pp		
Jet triggers	28, 40, 48	40, 60, 80
Track triggers	MB, 28, 40, 48	12, 24, 34, 45, 53
PbPb		
Jet triggers	28, 44, 56	40, 60, 80, 100
Track triggers	MB, 16, 24	12, 18, 24, 34

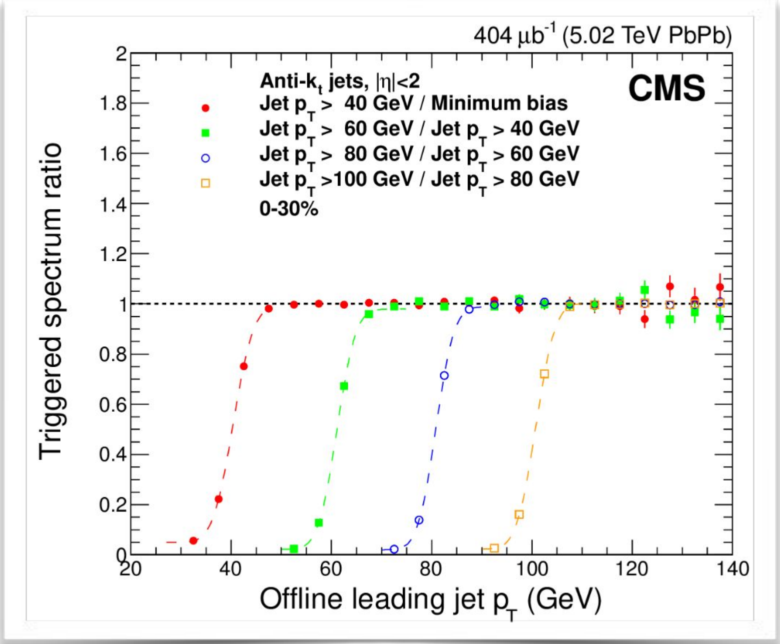
- Primary charged particles (**PCP**) are required to have a mean proper lifetime τ **> 1 cm**
- Daughters of secondary decays are also considered as PCP if the mother particle had τ **< 1 cm**
- Selection criteria on track reconstruction can be found in the backup

The E_T decomposition in the HF calorimeter is used to determine the collision centrality!

Combination of data from different triggers

- **Combine** data recorded by the MB and jet **triggers** → obtain charged particle spectra
- Ratio of number of events in the two triggered sets of data is used as a **weighting factor**





Systematic uncertainties

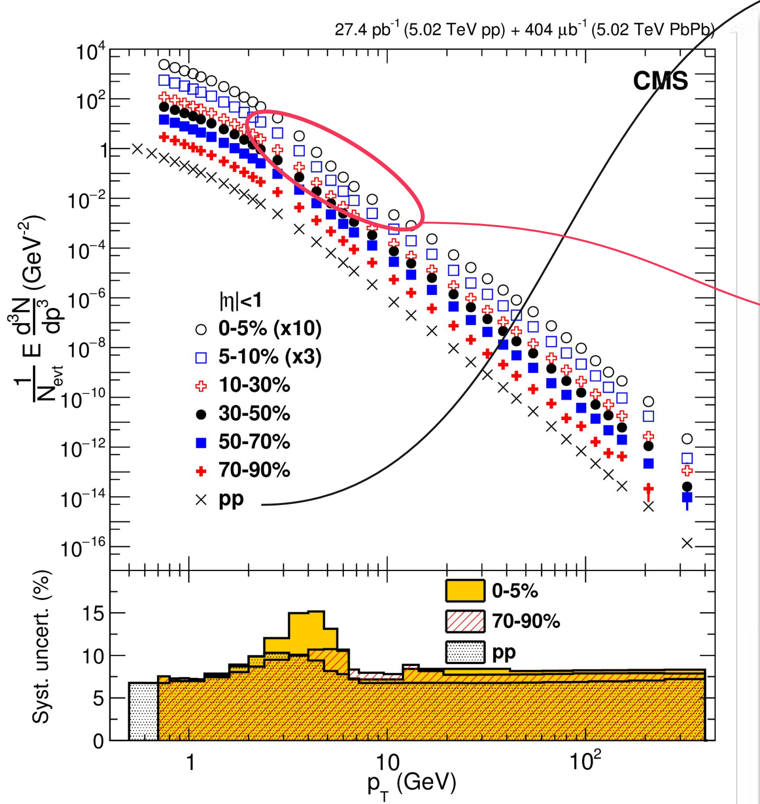
Leading uncertainties

- Particle species composition:
  - Due to differences between the MC generators
- MC/data tracking efficiency difference:
  - Due to difference between track reconstruction efficiency in *pp* data and simulation

Sources	Uncertainty [%]		
	pp	PbPb	R_{AA}
Particle species composition	1–8	1.0–13.5	1.5–15.5
MC/data tracking efficiency difference	4	4–5	2.0–6.5
Tracking correction procedure	1	1–4	1.5–4.0
PbPb track selection	—	4	4
Pileup	3	<1	3
Fraction of misreconstructed tracks	<3	<1.5	<3
Trigger combination	<1	1	1
Momentum resolution	1	1	1
Event selection correction	<1	—	<1
Combined uncertainty	7–10	7–15	7.0–17.5
Glauber model uncertainty (T_{AA})	—	—	1.8–16.1
Integrated luminosity	2.3	—	2.3

Results

RESULTS



Number of charged particles per event per p_T bin

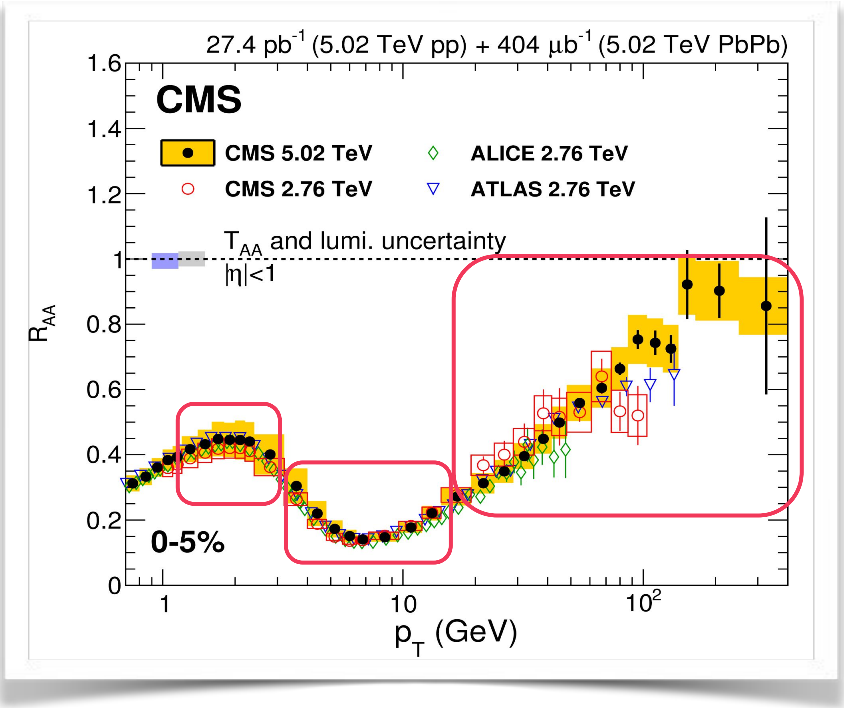
- The pp spectrum is measured as a **differential cross section**
  - Scaled by inverse of 70 mb (70 mb ≅ total inelastic xs)

In pp : power law @ > 5 GeV.
In PbPb : apparent modifications.

These distributions will be the ingredients to compute the R_{AA}.

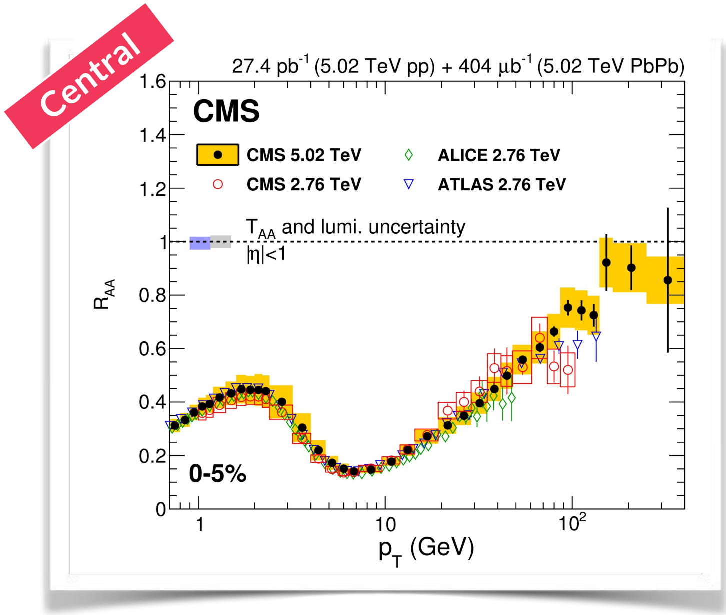
$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle dN^{pp}/dp_T} = \frac{dN^{AA}/dp_T}{T_{AA}\, d\sigma^{pp}/dp_T}$$

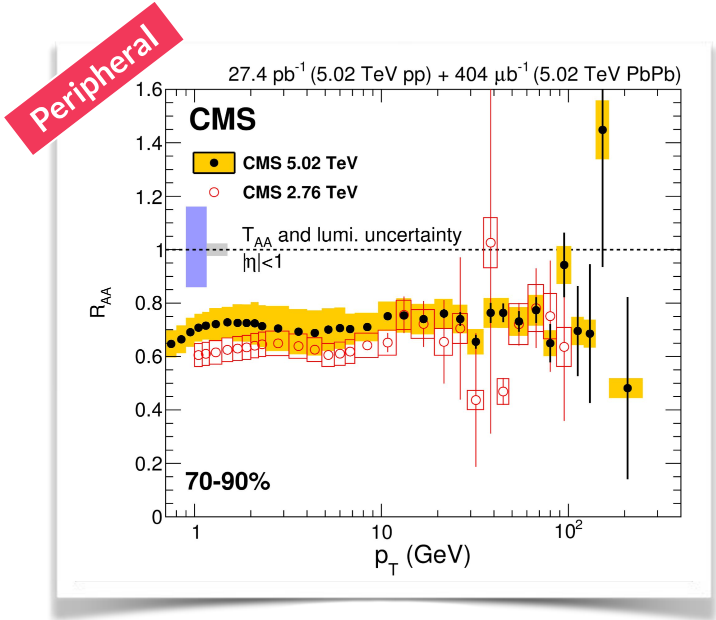
Charged particle R_{AA} for central collisions



- Characteristic suppression **pattern** over most of the **p_T** range is observed
  - Local peak at ~ 2 GeV
  - Dip at ~ 7 GeV
  - Suppression weakens as p_T increases
- Different collision **energies** do not produce significant difference of R_{AA}

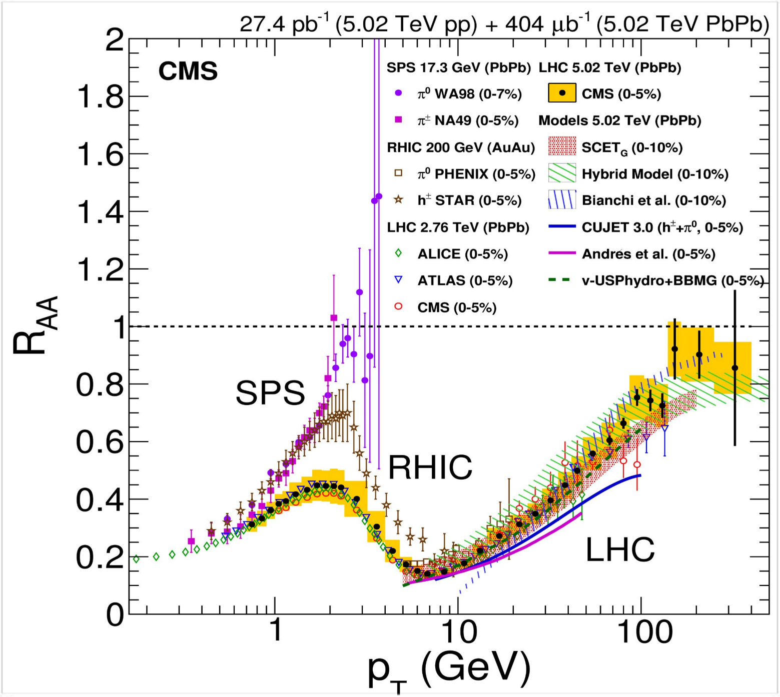
Charged particle R_{AA} in centrality regions





- R_{AA} pattern is **centrality** dependent:
    - Competition between nuclear PDF, radial flow, parton energy loss, and the Cronin effects
- Peripheral: Weaker medium effects

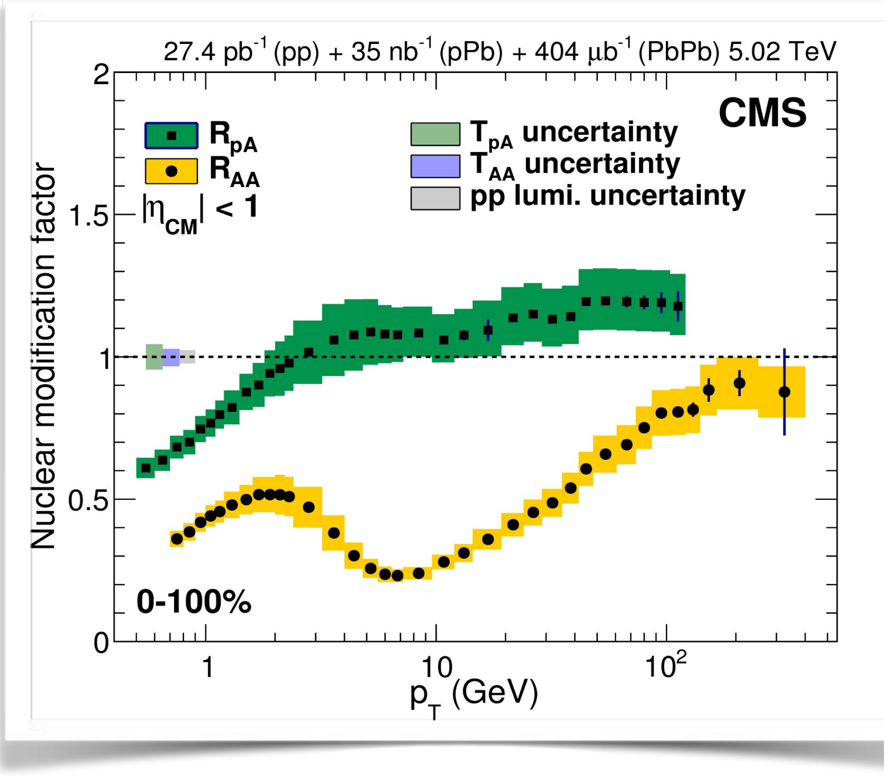
R_{AA} comparison for different collision energies



LHC **consistent** regardless of collision **energy**

- Low p_T hadrons (0.5-10 GeV):
  - Higher suppression for larger collision energy
- High p_T (10-150 GeV):
  - Similar R_{AA} despite different collision energy
- **Similar R_{AA}** pattern across the board
- Agreement of data with models within uncertainty

PbPb vs pPb



pPb collisions

- No suppression for tracks with p_T 2-150 GeV
    - **Is there QGP in pPb?**
- Weak momentum dependence for particles with p_T>10 GeV
- **R_{pA} above 1 (enhancement)**
    - Due to Cronin effect

Conclusions

- Nuclear modification factor measured with charged particles in PbPb collisions recorded by CMS at 5.02 TeV
  - Suppression of factor of 7–8 around p_T = 7 GeV
- R_{PbPb} centrality and p_T dependence observed
  - Lower suppression for peripheral collisions
- No significant R_{AA} changes for different collision energies
- R_{pPb} measured
  - No hints for QGP in pPb collisions

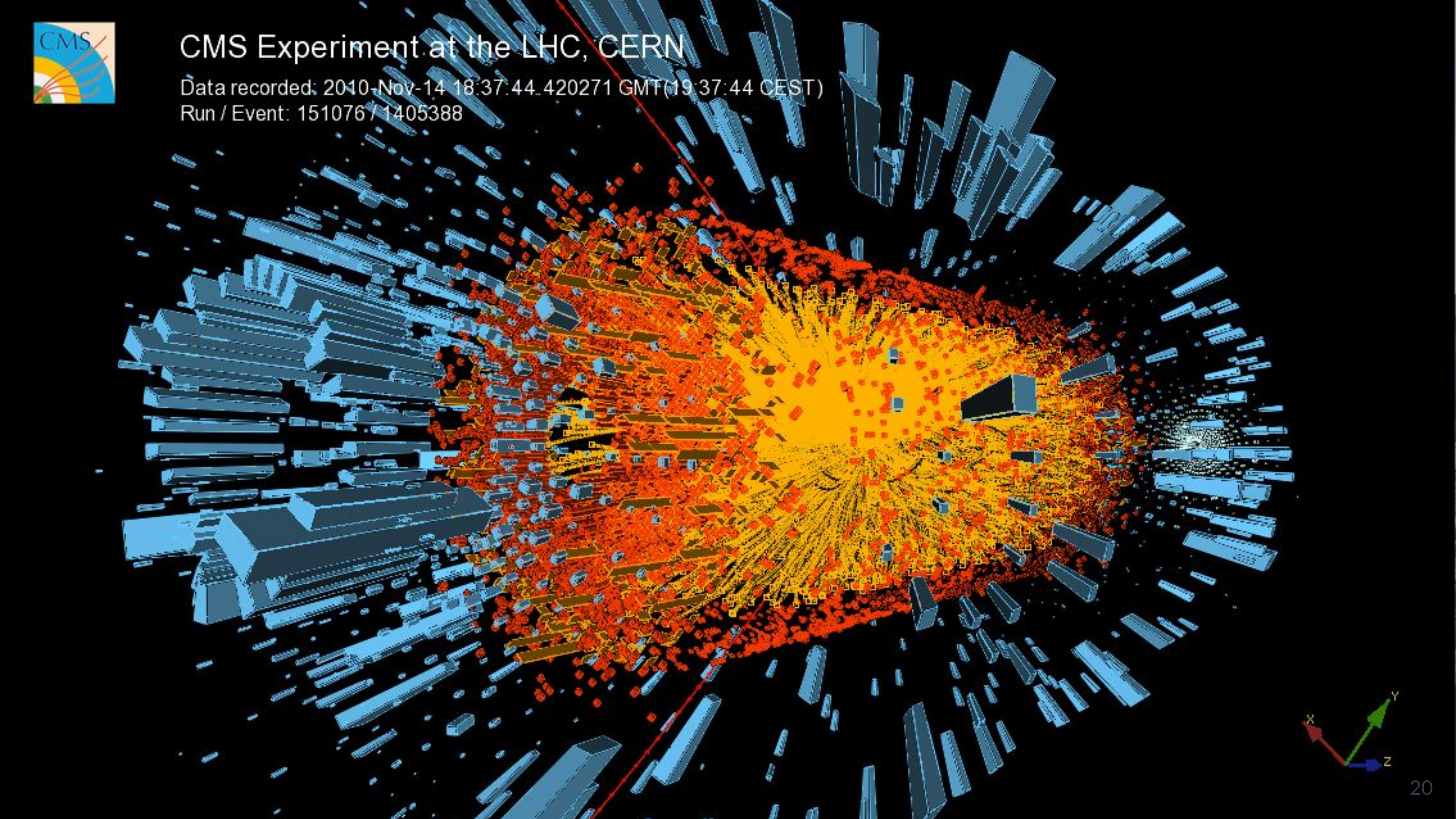
Thanks for your attention!

Discussion Group E

Stefio Yosse Andrean, Sweta Baradia, Olexiy Dvornikov, Sagar Hazra, Jieun Hong, Niamat Ullah Khan, Elham Khazaie, Lazar Marković, Dang Bao Nhi Nguyen, Lukáš Novotný, Laura Pereira Sánchez, Dinesh Kumar Singha, Shusaku Tsumua, Vismaya V S, Chu Want, Chaochen Yuan.

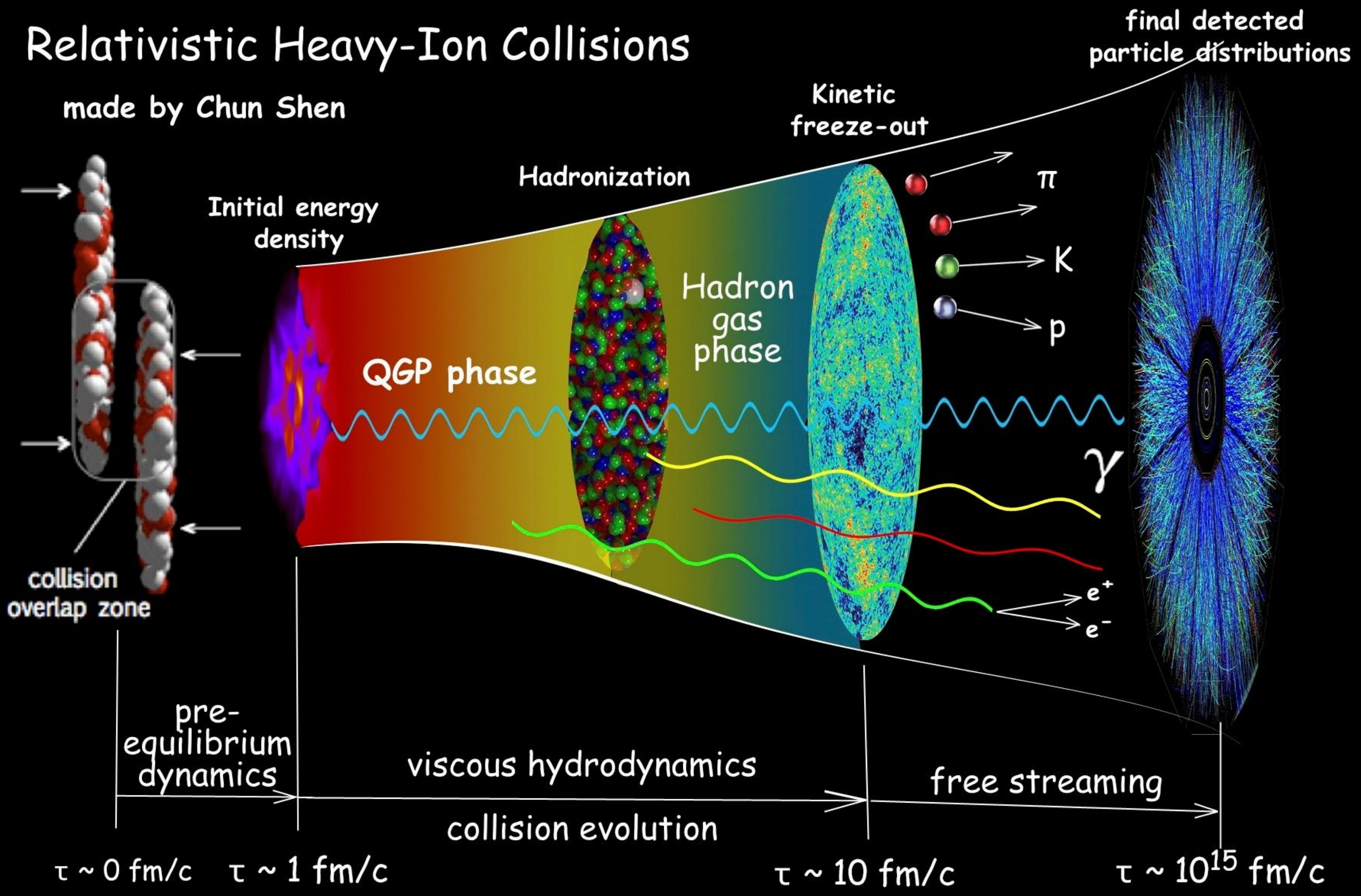
Any comments or questions?

Back-up slides

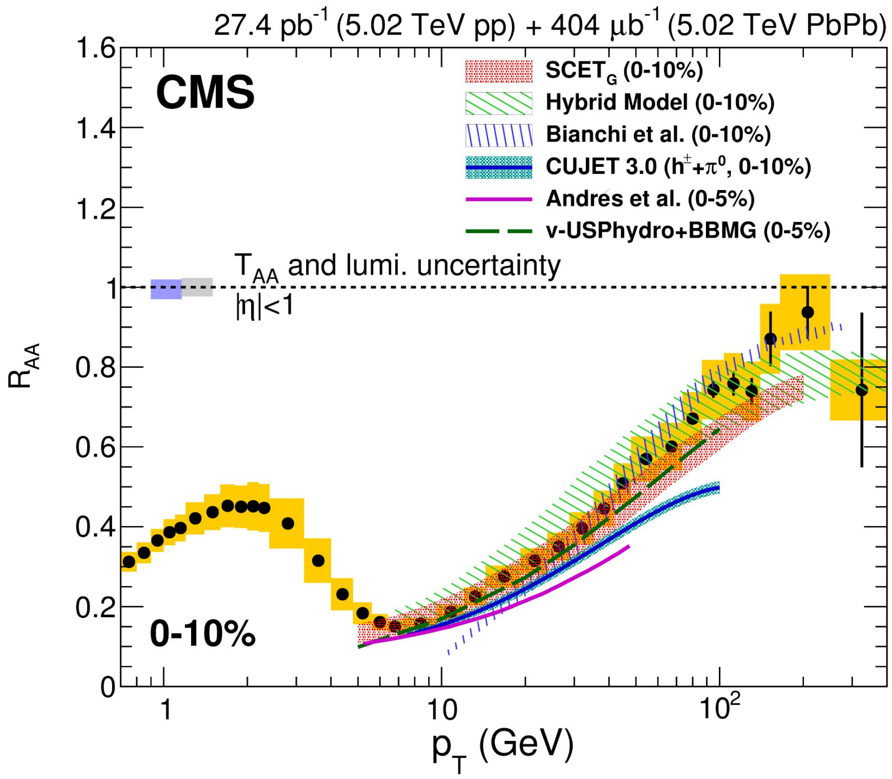

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-14 18:37:44.420271 GMT(19:37:44 CEST)
Run / Event: 151076 / 1405388
X
Y
Z

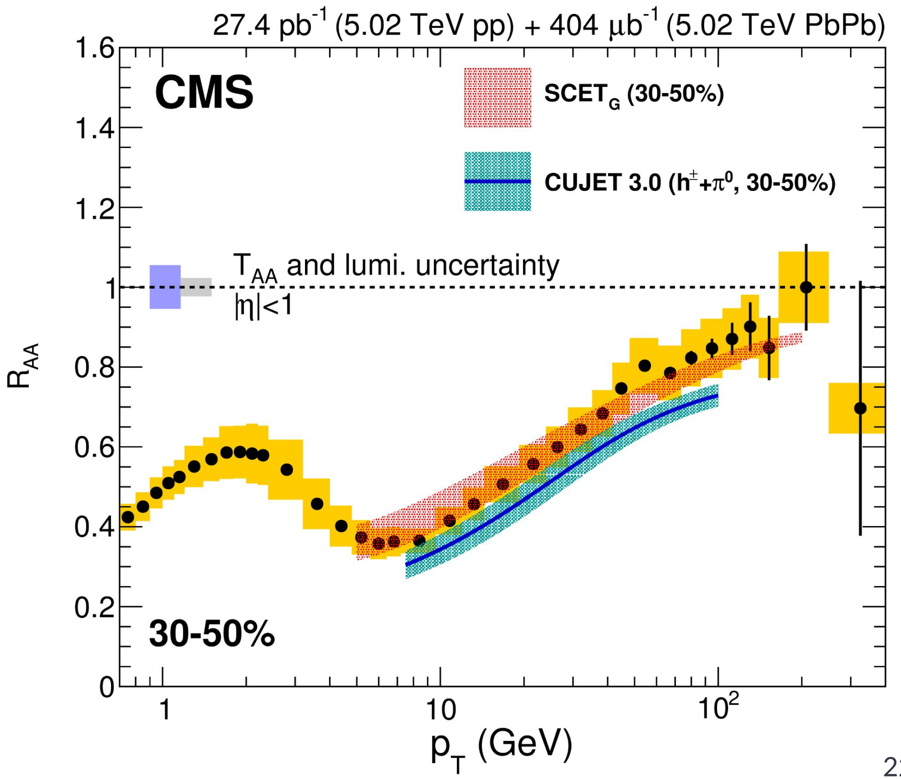
Relativistic Heavy-Ion Collisions

made by Chun Shen

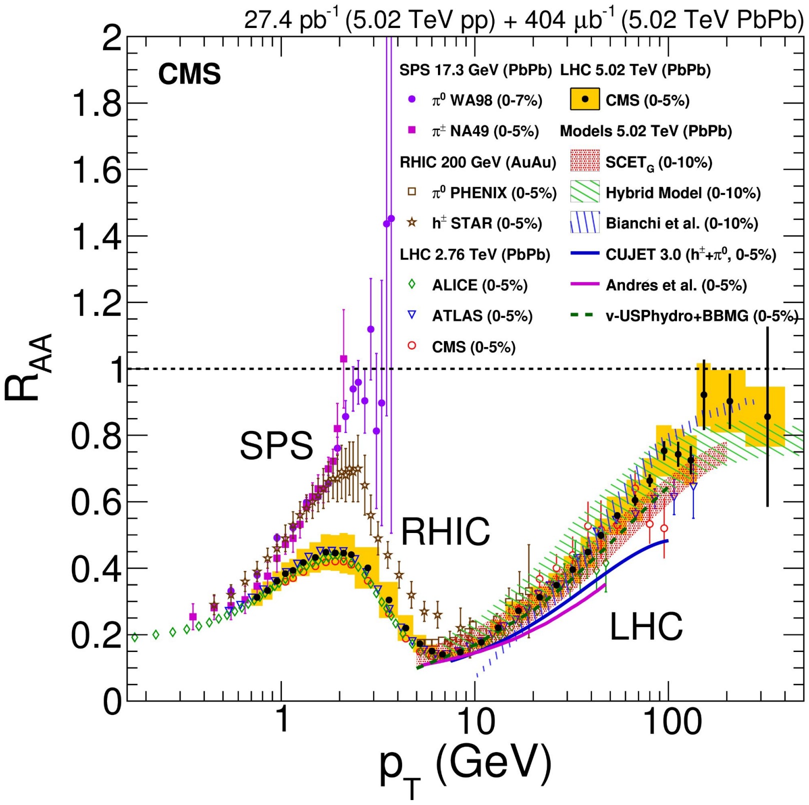


Data vs Model comparisons





R_{AA} comparison for different collision energies



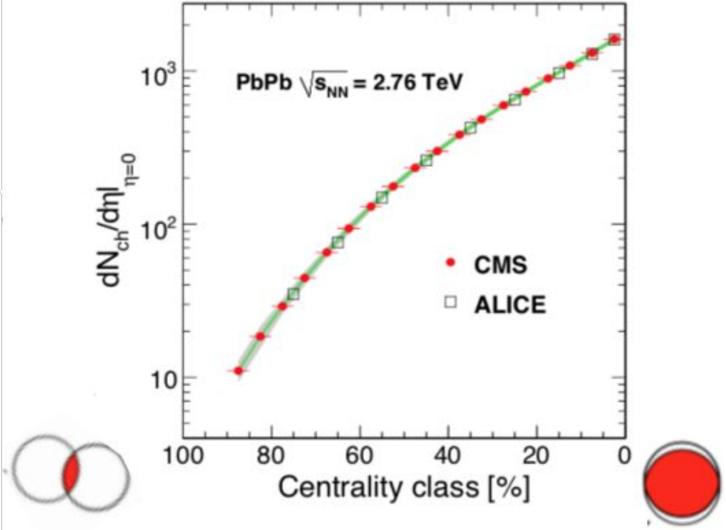
- LHC experiments consistent regardless of collision energy
- **Low p_T hadrons (0.5-10 GeV):**
  - Higher suppression for larger collision energy
- **High p_T (10-150 GeV):**
  - Charged particle spectra is flattened
  - Energy loss increases
  - Resulting in similar R_{AA} despite different collision energy
- **R_{AA} pattern similar across the board**
- Agreement of data with models within uncertainty

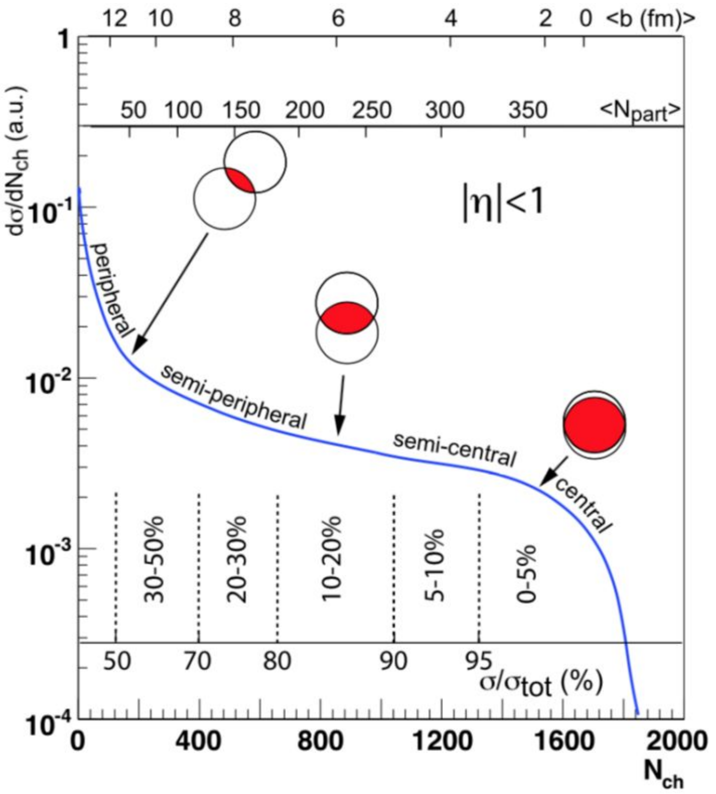
Centrality of nucleus-nucleus collision

- Centrality measured by transverse energy

$$\frac{dE_T}{d\eta} \approx \langle m_T \rangle \frac{3}{2} \frac{dN_{ch}}{d\eta}$$

- Transverse energy measured by calorimeters





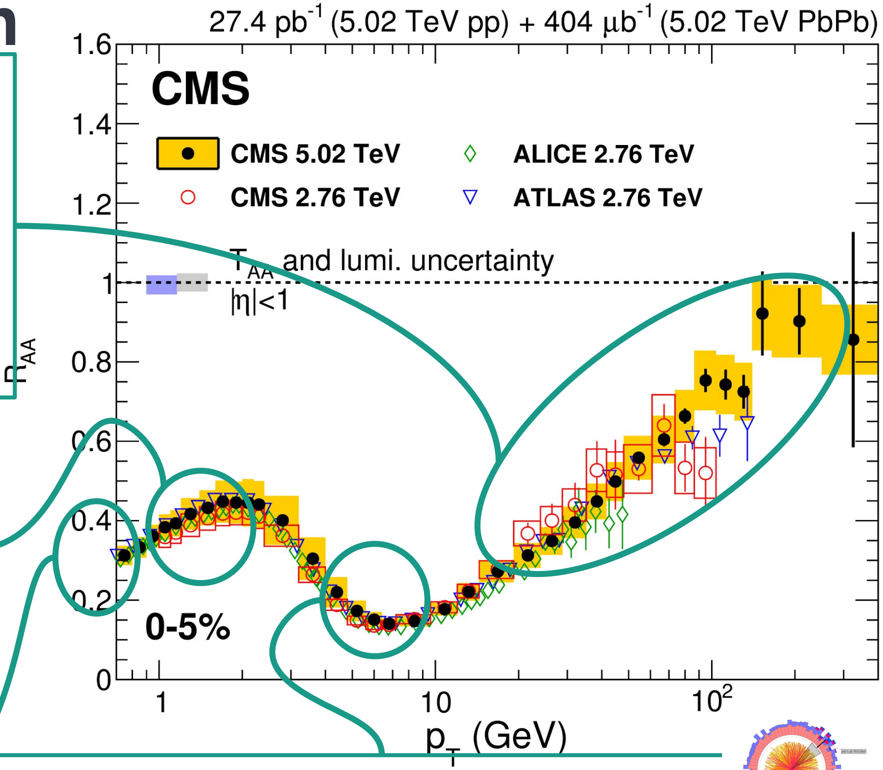
RAA shape description

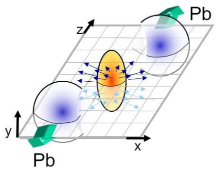
Colinear gluon emission

- Clearly described by theories 
- Travelling particle emits gluons that cannot be distinguished from the particle

Color transparency

- Quark dipole do not quickly form hadron (is colorless)



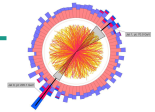


Radial flow and Cronin effect

- **Cronin**: multiple scattering of particle before the medium is fully created
- **Radial flow**: QGP expansion speed
- **Antishadowing**: due to the PDF shape

Gluon shadowing

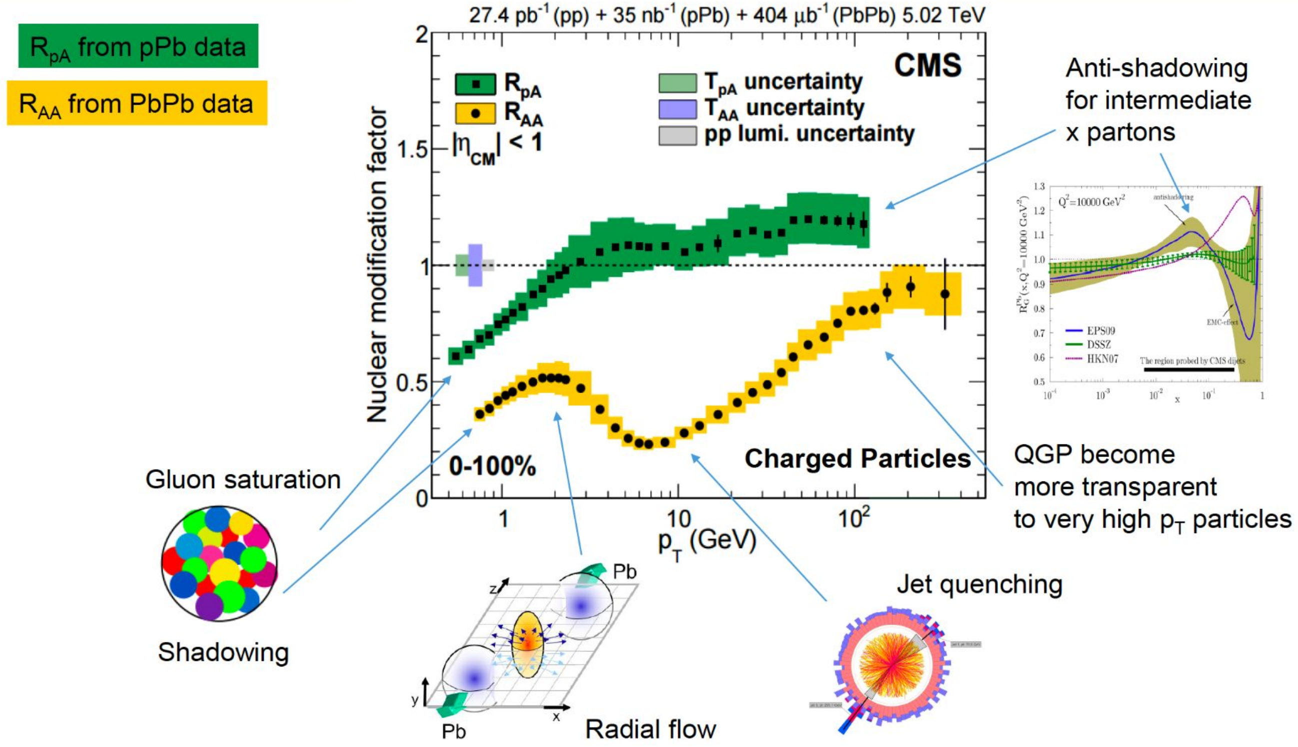
- Non-linear PDF behaviour for small Bjorken x
- The PDF of nucleon shielded by other nucleons' PDF



Energy loss

- Largest energy losses around 6-10 GeV
- Interaction of particles with medium

RAA shape description

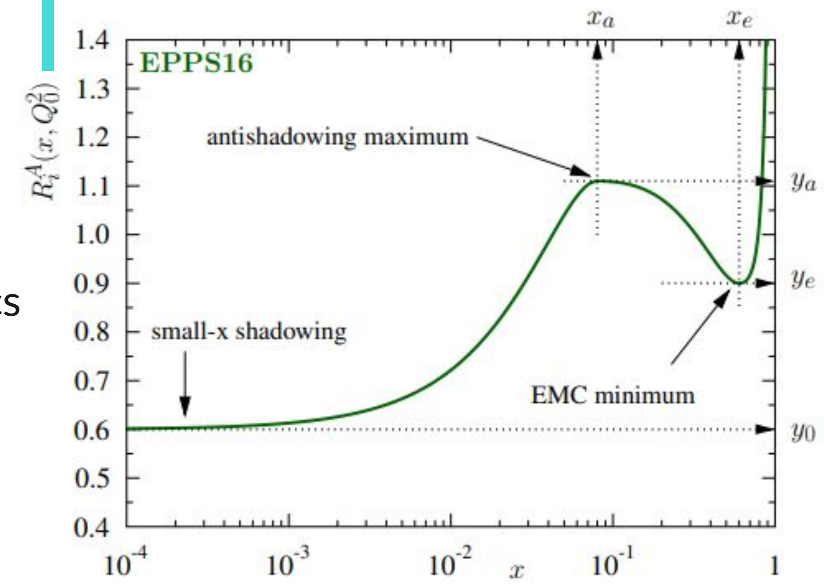


From Prof. Yen-Jie Lee's Heavy Ion Lecture 2

Nuclear PDF

- Known from nuclear DIS measurements
- Bjorken x: fraction of nucleon's momentum carried by struck parton
- Small x
  - Gluons must saturate -> non-linear dynamics
  - Visible in R_{AA} plot for very low p_T region
- Larger x
  - Small enhancement
  - Known as antishadowing

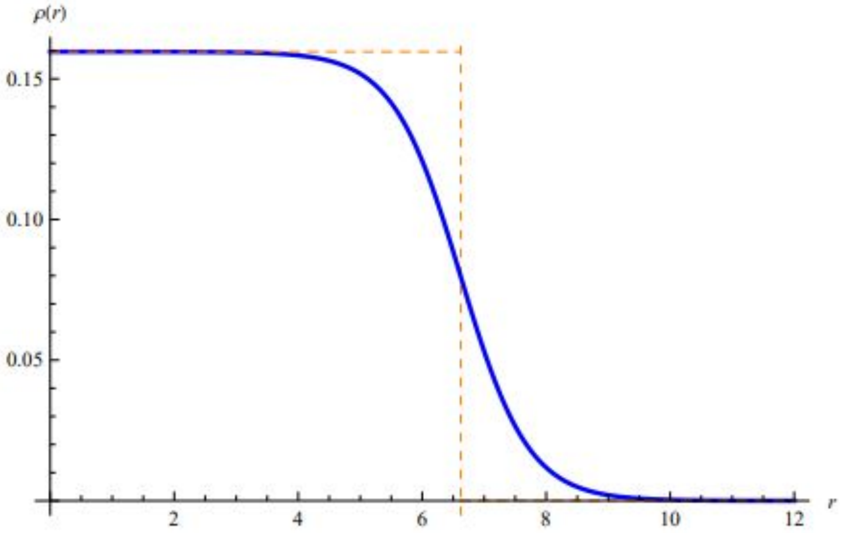
Ratio of nuclear PDF to free proton PDF



Glauber model

- Modelling the size of ions
- Nuclear charge density described
  by Woods-Saxon distribution

$$\rho(r) = \frac{\rho_0}{1 + exp[(r-R)/a]}$$



  - Assuming spherical nucleus
    with surface thickness a and expected radius R

$$T_A(\vec{s}) = \int \rho_A(\vec{s}, z)\, \mathrm{d}z$$

- The nuclear overlap function

$$T_{\mathrm{AB}}(b) = \int T_A(\vec{s}) \cdot T_B(\vec{s} - \vec{b}) \mathrm{d}^2 s$$

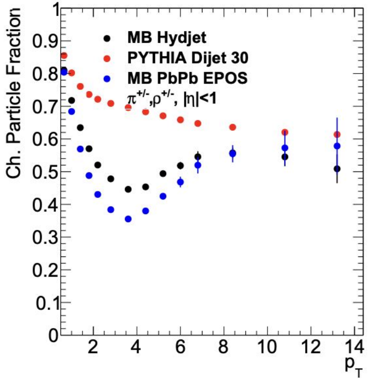
- Number nucleon-nucleon collisions

$$N_{\mathrm{coll}}(b) = T_{\mathrm{AB}}(b) \cdot \sigma_{\mathrm{inel}}^{\mathrm{nn}}$$

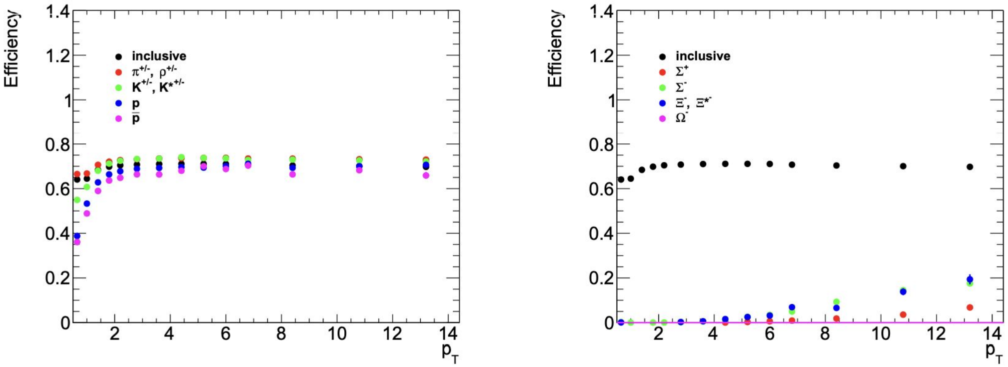
Systematic uncertainties (I)

1. Particle species composition
   Due to the different simulation tools :

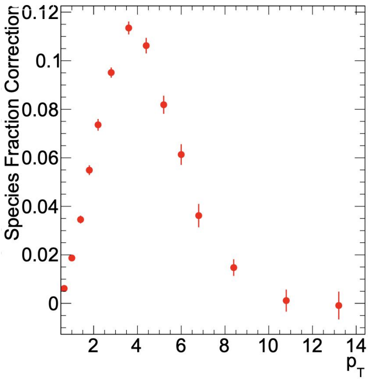
   PYTHIA8 ,HYDIJET and EPOS.
   This uncertainty has a strong p_T dependence :
   p_T< 1.5 GeV : 1% (pp and PbPb)
   p_T =3.0GeV : 8%(pp) / 13.5% (PbPb)



Different fraction of pythia and EPOS



Tracking efficiencies for different particle species.



The magnitude of correction in pbpb

Systematic uncertainties (II)

2. MC/data tracking efficiency difference :
   Due to the difference of track reconstruction efficiency in pp data and pp simulation

   Studied by the comparison of simulated / data events of D^* meson decay

Systematic uncertainties (III)

3. Tracking correction procedure:

   Due to the error of track reconstruction

   The main source is the fact that the tracking efficiency only approximately factorizes into single-variable functions

4. PbPb track selection:

   Due to the difference of the track selection criteria between PbPb and pp data

Systematic uncertainties (IV)

5. Pileup:

   Due to the difference between the selected primary vertices and single vertex spectrum.

   3% uncertainty in the pp spectrum is propagated to RAA

6. Fraction of mis-reconstructed tracks:

   To account for possible differences in the mis-reconstruction fraction between simulated and data events.

   3% in pp and less than 1.5% in PbPb.

Systematic uncertainties (V)

7. Trigger combination:

   Rely on the calculation of overlaps in the leading jet spectra between different triggers.(<1%)

8. Momentum resolution:

   Finite resolution of the track reconstruction is evaluated using simulated events.(Pt dependency, overall 1%)

9. Event selection correction:

   Estimate the bias by evaluating event selection efficiency based on zero-bias data. The corresponding systematics is also evaluated using simulated events.

Systematic uncertainties (VI)

Centrality	$\langle N_{\text{coll}} \rangle$	T_{AA} [mb^{-1}]
0–5%	1820^{+130}_{-140}	$26.0^{+0.5}_{-0.8}$
5–10%	1430^{+100}_{-110}	$20.5^{+0.4}_{-0.6}$
10–30%	805^{+55}_{-58}	$11.5^{+0.3}_{-0.4}$
30–50%	267^{+20}_{-20}	$3.82^{+0.21}_{-0.21}$
50–70%	$65.4^{+7.0}_{-6.6}$	$0.934^{+0.096}_{-0.089}$
70–90%	$10.7^{+1.7}_{-1.5}$	$0.152^{+0.024}_{-0.021}$
0–10%	1630^{+120}_{-120}	$23.2^{+0.4}_{-0.7}$
0–100%	393^{+27}_{-28}	$5.61^{+0.16}_{-0.19}$

10. Glauber model uncertainty:

    The systematic uncertainty in the Glauber model normalization factor (TAA) ranges from 1.8% (in the 0–5% centrality bin) to 16.1% (in the 70–90% centrality bin).

11. Integrated luminosity:

    The uncertainty in the integrated luminosity for pp collisions is 2.3%. For the PbPb analysis, no luminosity information is used as per-event yields are measured.

Previous measurements

- RHIC (2005):
  - Suppression in R_{AA} ~ 5 → strong medium effect
  - Measurement limit: p_T < 25 GeV, COM energy ≤ 200 GeV
- LHC – first PbPb run (2012-2015)
  - Suppression in R_{AA} ~ 7 in region p_T = 5 - 10 GeV
  - Suppression in R_{AA} ~ 2 in region p_T = 40 - 100 GeV
  - Measurement limit: $p_T \leq$ 150 GeV, COM energy = 2.76 TeV
- LHC – first heavy ion data-taking of Run-2 (end of 2015)
  - Measurement limit: COM energy = 5.02 TeV
  - Proton-proton data at same energy were also taken

=> Can direct compare AA data and pp data.

Triggers

- HLT anti-k_T algorithm for clustering with R=0.4
- Triggers with thresholds on the jet energy from 40 to 100 GeV were employed.
- High -level jet-trigger containing calorimeter cluster |eta| < 5.1 in case of pp collisions

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PbPb		
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Track triggers	MB, 16, 24	12, 18, 24, 34

Tracks

- Events are required to have at least one reconstructed primary interaction vertex with at least two associated tracks.
- In pp collisions, the events are also required to have at least 25% of the tracks passing a tight track-quality selection requirement [24].
- In PbPb collisions, the shapes of the clusters in the pixel detector are required to be compatible with those expected from particles produced by a PbPb collision.
- To decrease the likelihood of counting nonprimary charged particles originating from 2° decay products, a selection requirement of $< 3\sigma$ is applied on the significance of distance of closest approach to at least one primary vertex in the event, for both collision systems.

Tracks

- Primary charged particles are required to have a mean proper lifetime > 1 cm.
- The daughters of 2° decays are considered 1° only if the mother particle had a mean proper lifetime < 1 cm.

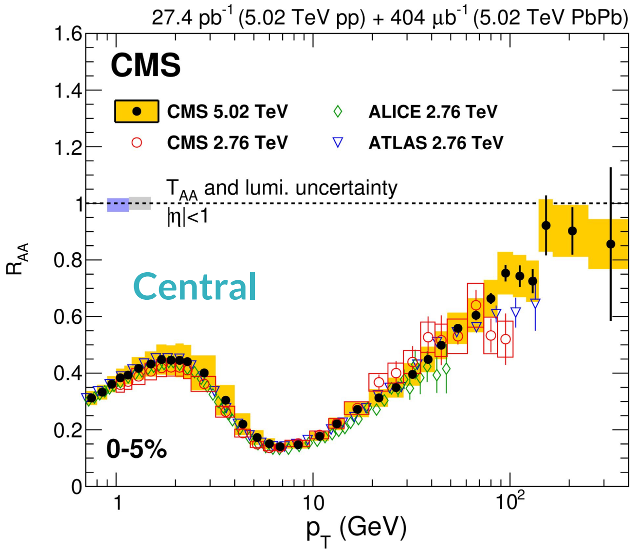
$\lvert\eta\rvert$	< 1
Rel p_T uncert.	< 10% (PbPb) & < 30% (pp)
No. of hits (PbPb)	≥ 11
χ^2 (PbPb)	< 0.15

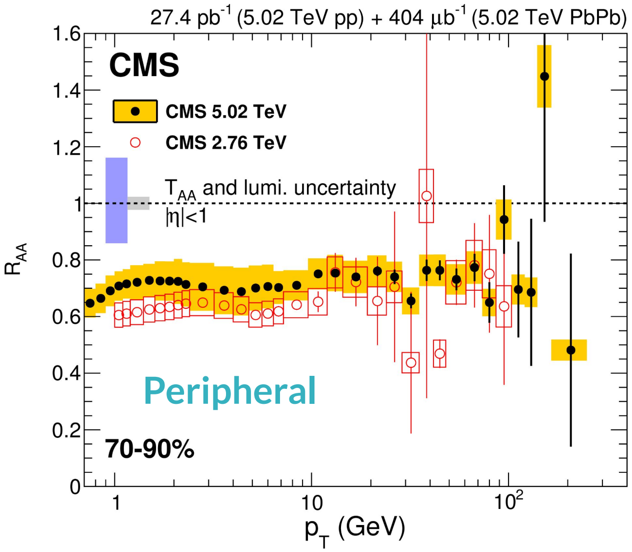
- A selection based on the relationship of a track to calorimeter energy deposits along its trajectory is applied in order to curtail the contribution of mis-reconstructed tracks with very high p_T.

Questions

- How do you measure centrality from Et with forward calorimeter?
- Minimum bias threshold used for the trigger?
- Why only |eta| < 1.0 is used?
    - Due to the almond shape of the QGP, there are more particle density in the central direction.
- Jet is required with |eta|<2.0?
    - This is for trigger combination. They use weighting schemes to avoid double counting.
- Why only charged particles?
    - Two reasons: isolated neutral particles (mainly photons) can easily pass the medium without interaction. And it is easier to detect charged particles, more information about tracks can be extracted.
- Why collision energy difference does not affect R_{AA}?
    - Collision energy affect Raa, but not dominant for 2.76TeV vs 5.02TeV. STAR AuAu Raa is larger, SPS is even larger. This means that denser medium is created in the higher energetic collisions
- Why SPS pi+- R_{AA} differ from LHC charged particle R_{AA}?
    - It is not matter of usage pions for RAA calculation, the energy is the reason.
- What is going on at low pT RAA comparing different collision energy?

Charged particle R_{AA} in centrality regions





- R_{AA} pattern **disappears** for lower centrality
  - Higher centrality: competition between nuclear PDF, radial flow, parton energy loss, and the Cronin effects
- Peripheral collisions: Effects of medium (if exists) are not dominant