Jet Quenching and R_{AA} : Experiment

Heavy Ion Meeting 2012-10, October 06 2012

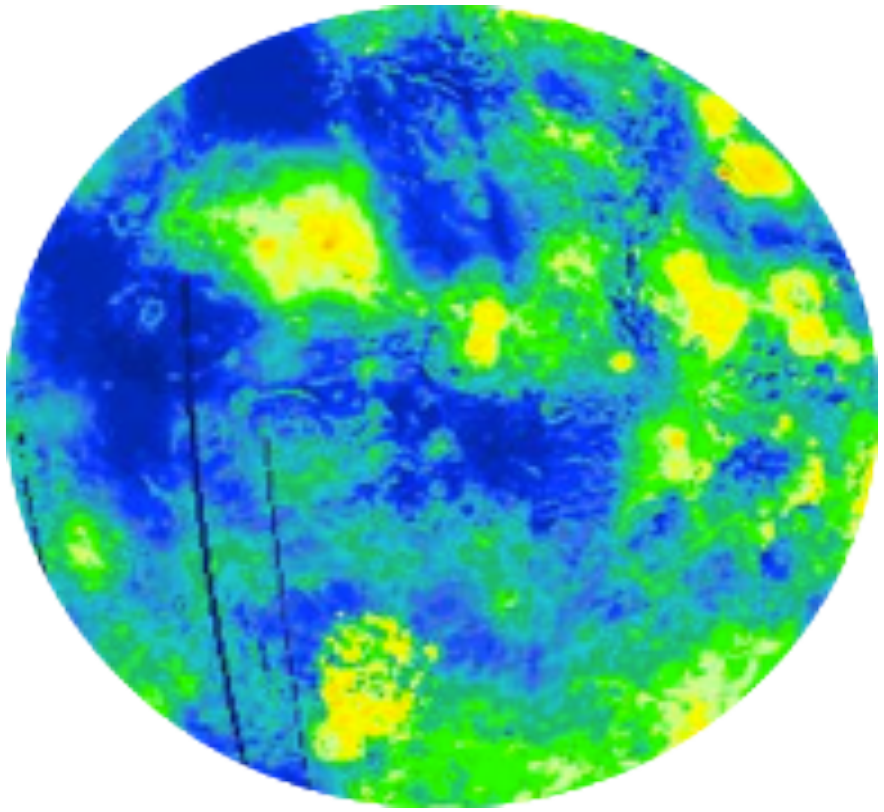
Choi Myeong Hee Literary Museum

Andre Sungho Yoon

(Massachusetts Institute of Technology)*

* Left MIT in June 2012, but all the work presented here were done while I was at MIT.

Jet Quenching = Tomographic Probe of QGP



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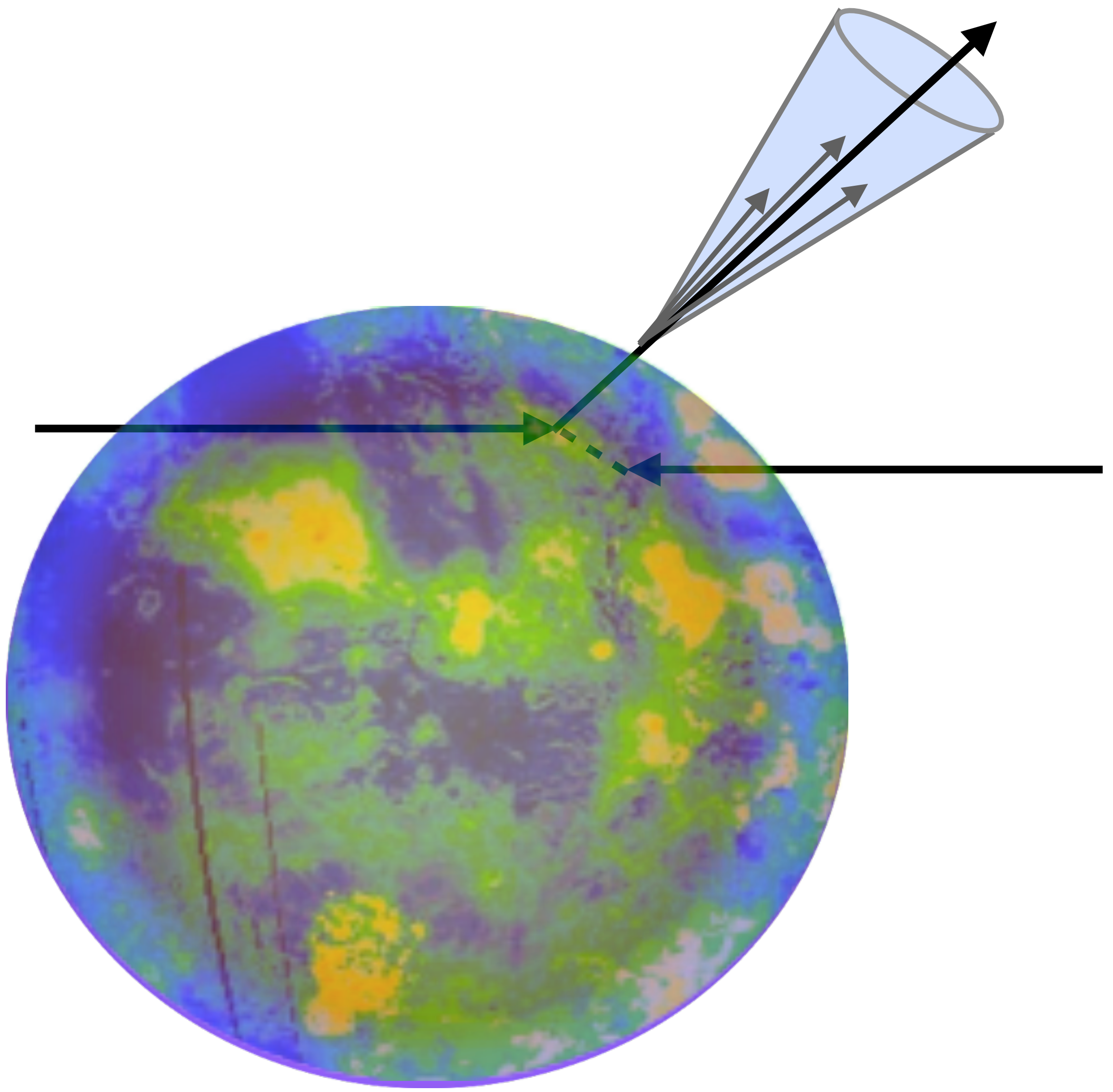

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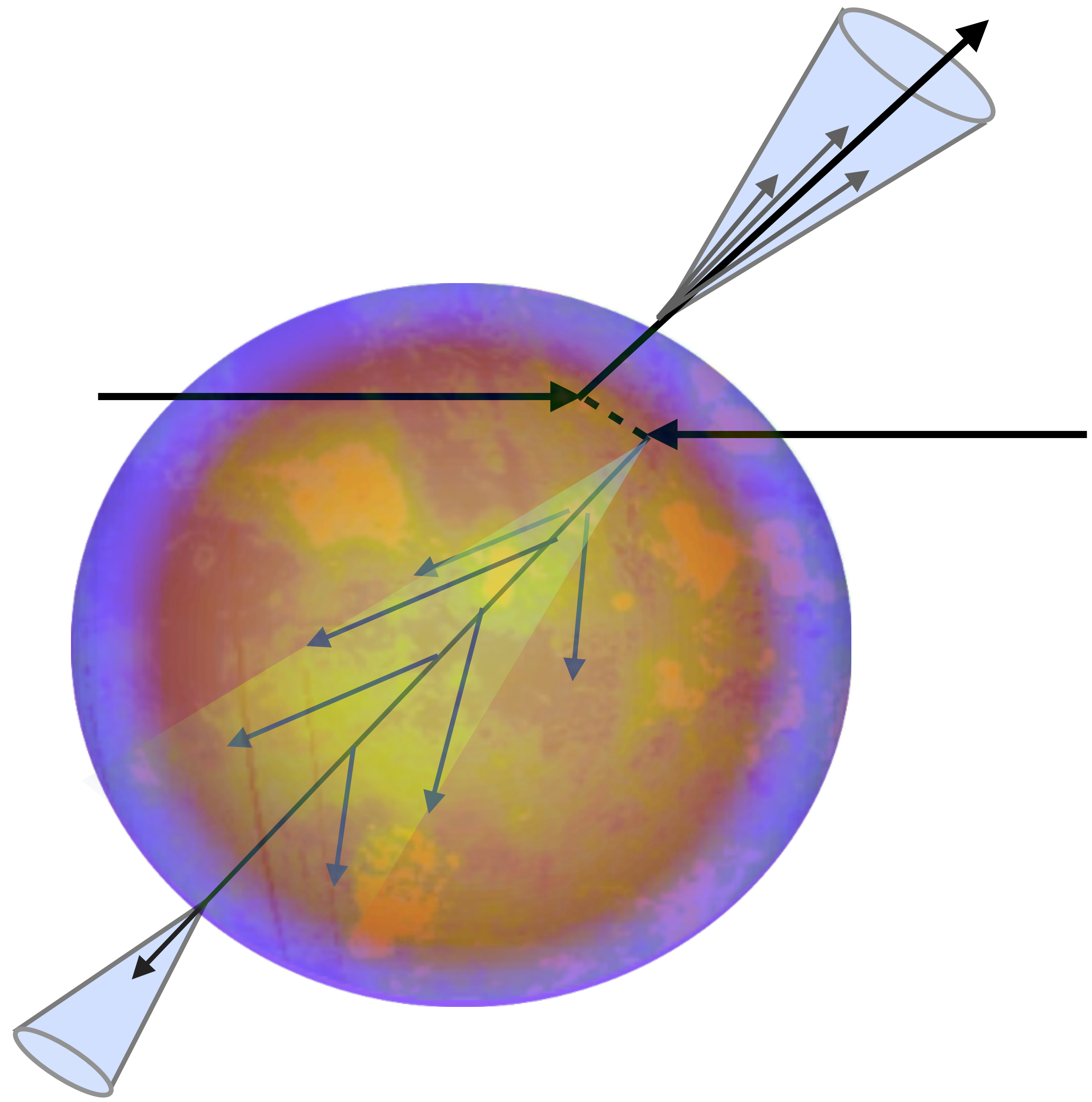

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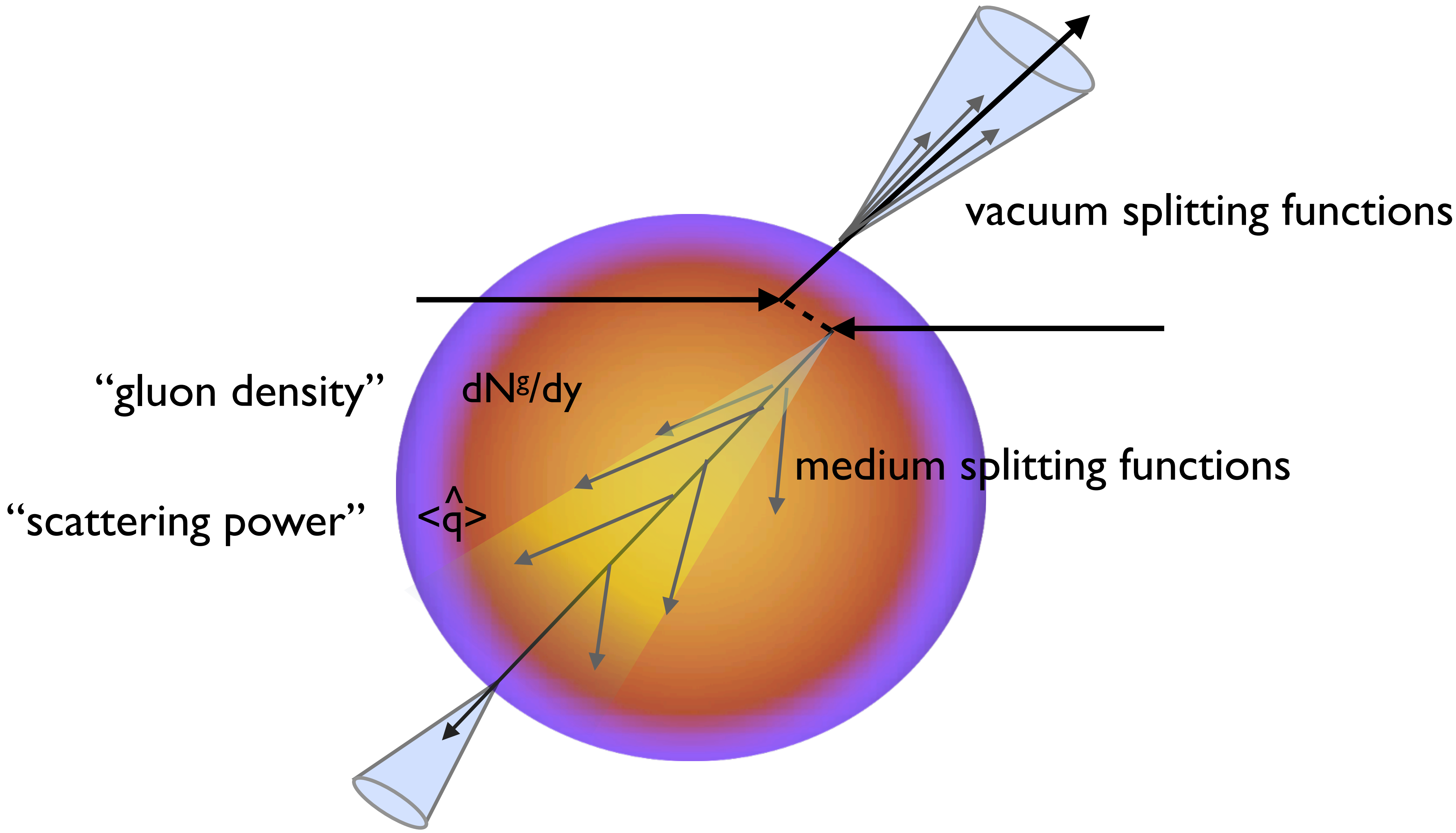

Collisional Energy Loss

Fermi National Accelerator Laboratory

Energy Loss of Energetic Partons in Qu
Possible Extinction of High p_T Jets in Hadr

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Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to

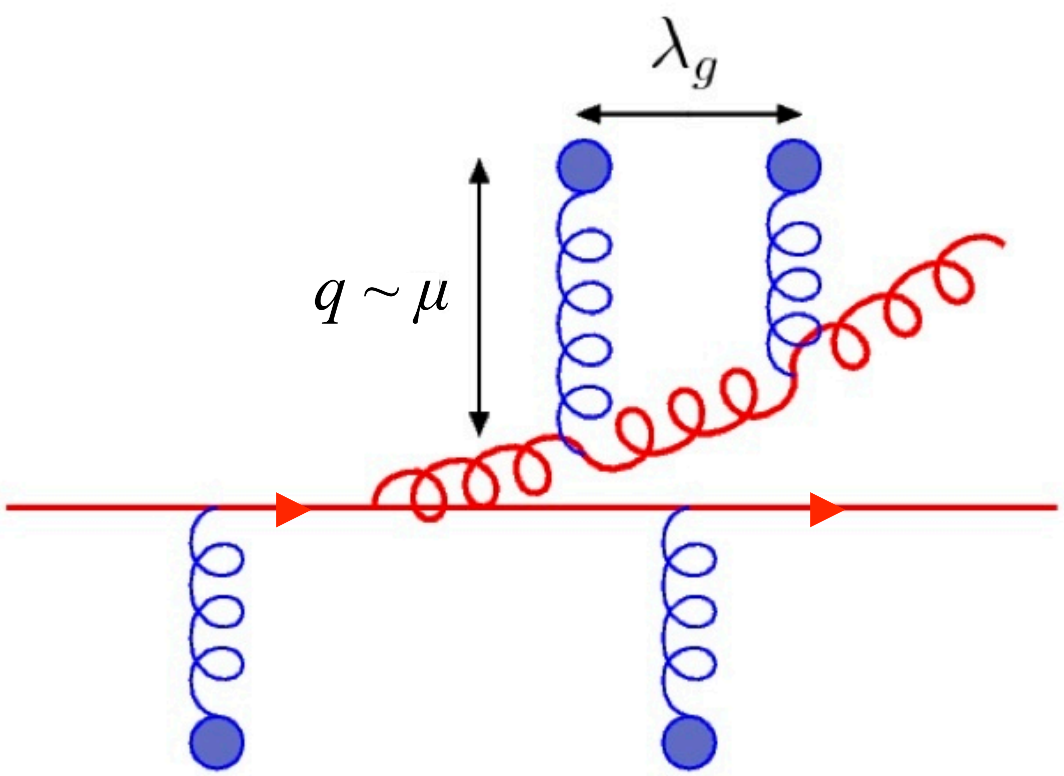
transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

Jet Quenching !!

$$-\frac{dE}{dx} \sim \alpha_s^2 \sqrt{\epsilon} \quad \longrightarrow$$

Hinting that the initial medium (parton) density can be inferred by measuring dE/dx.

Radiative Energy Loss !

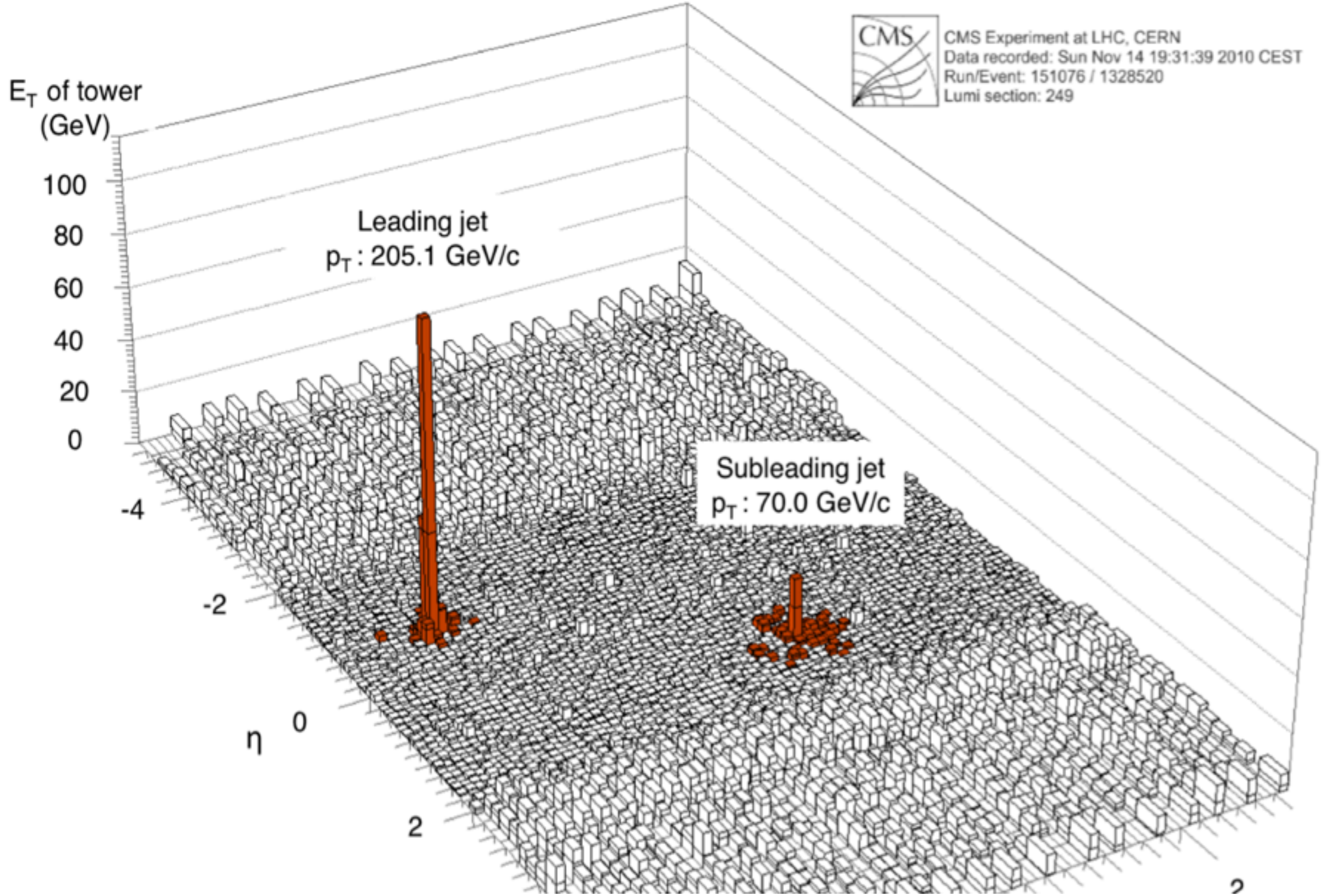


- Gluon radiation induced by multiple scattering of a quark or a gluon traversing the medium (Medium-induced gluon radiation a.k.a Gluon Bremsstrahlung)
- Radiated gluon undergoes multiple coherent scattering and becomes real carrying away a fraction of parent parton energy.
- Medium is characterized by a transport coefficient, q̂ ("stopping power")

$$\hat{q} \equiv \frac{\mu^2}{\lambda} \qquad \omega_c = \frac{1}{2}\hat{q}L^2$$

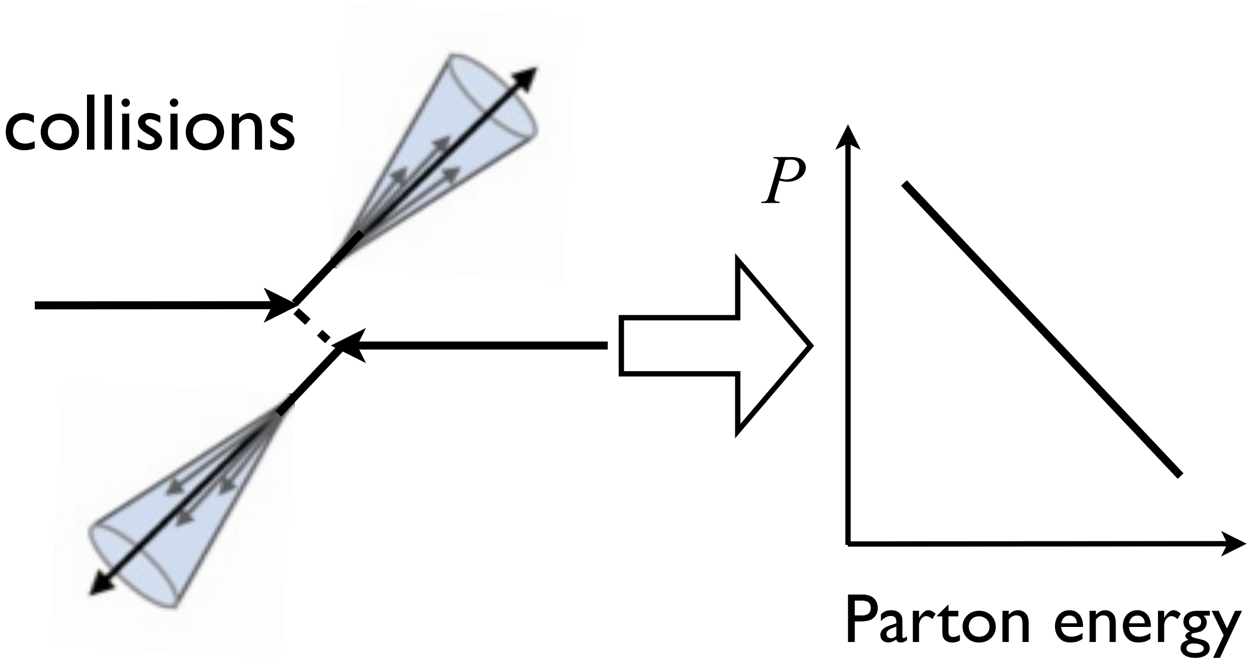
$$\langle \Delta E \rangle = \int_0^{\omega_c} \omega \frac{dI}{d\omega} d\omega \simeq \alpha_{s C_R} \omega_c \propto \alpha_s C_R \hat{q} L^2 \longrightarrow \Delta E \propto L^2 \;\; (dE/dx \propto L)$$

Phenomenological Consequence

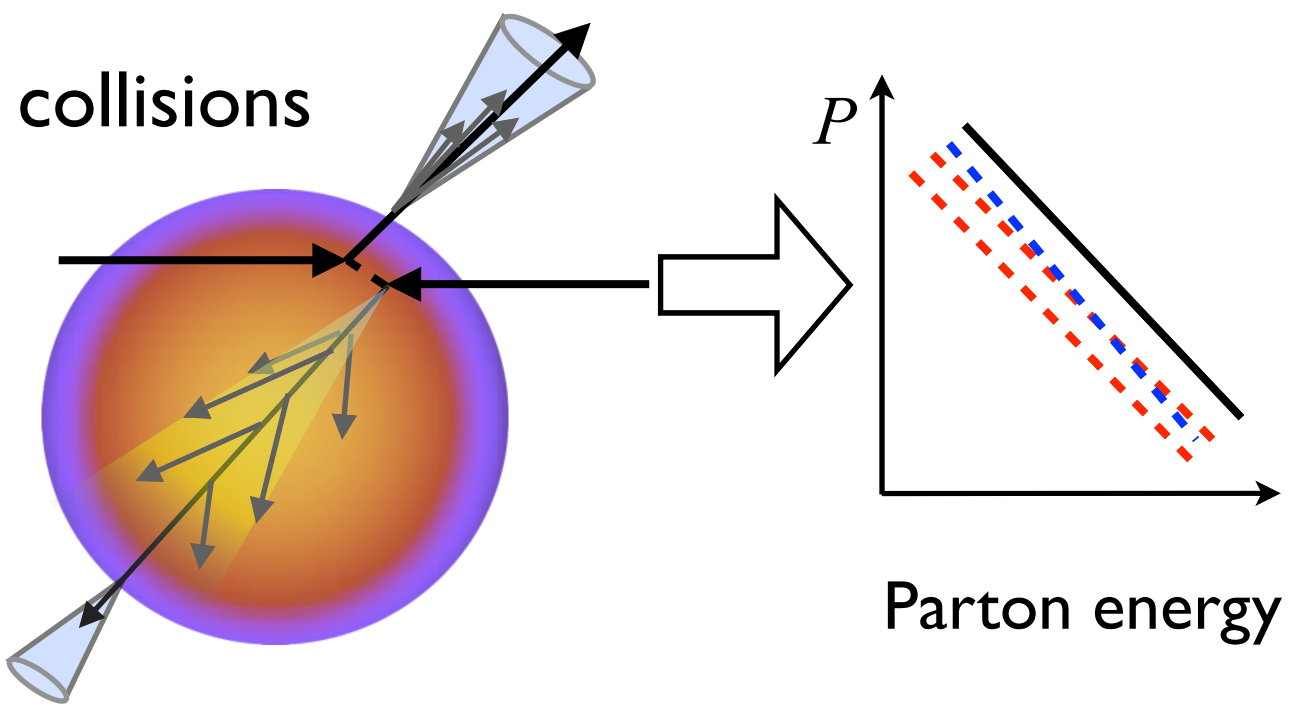


Phenomenological Consequence

pp collisions



HI collisions



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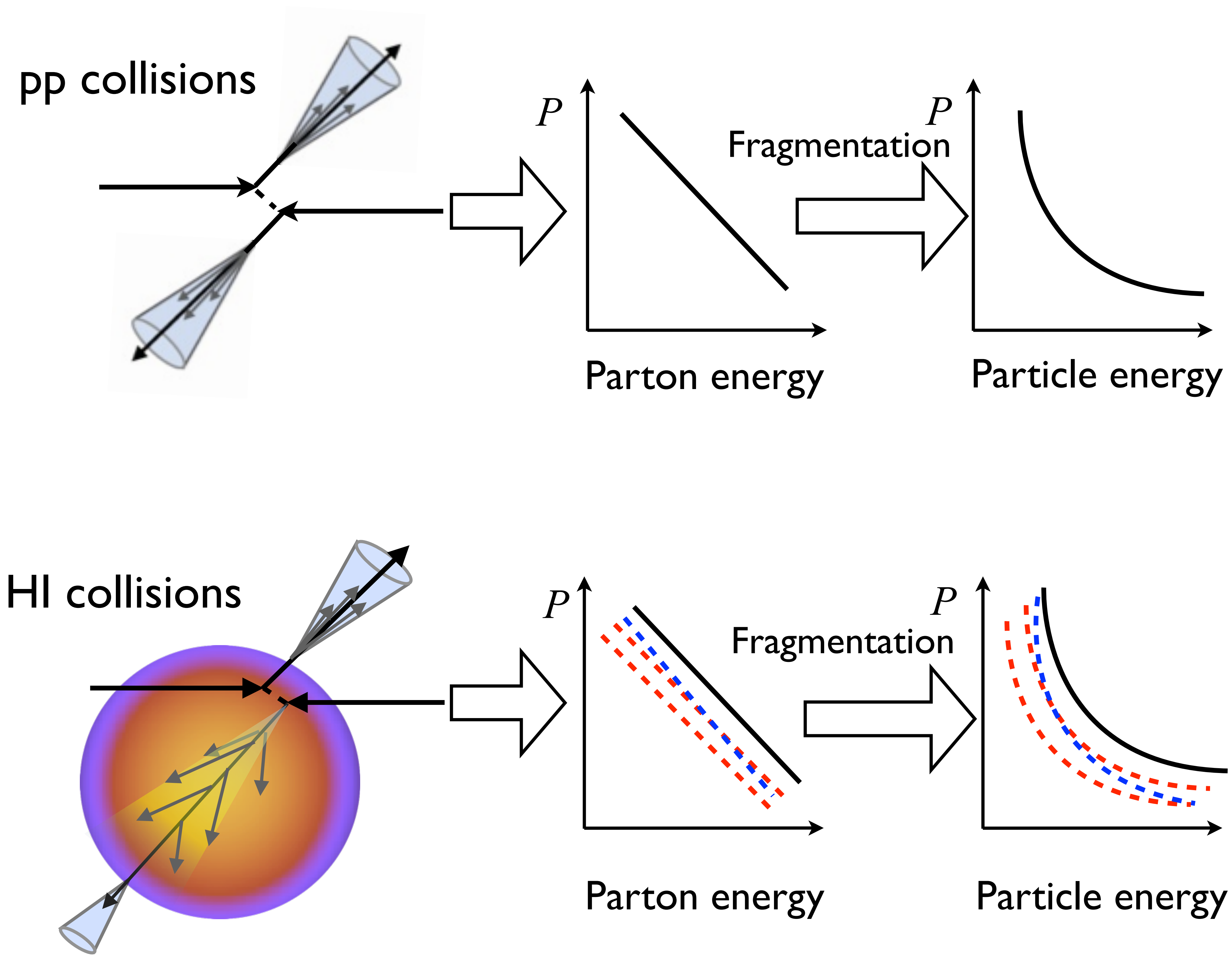

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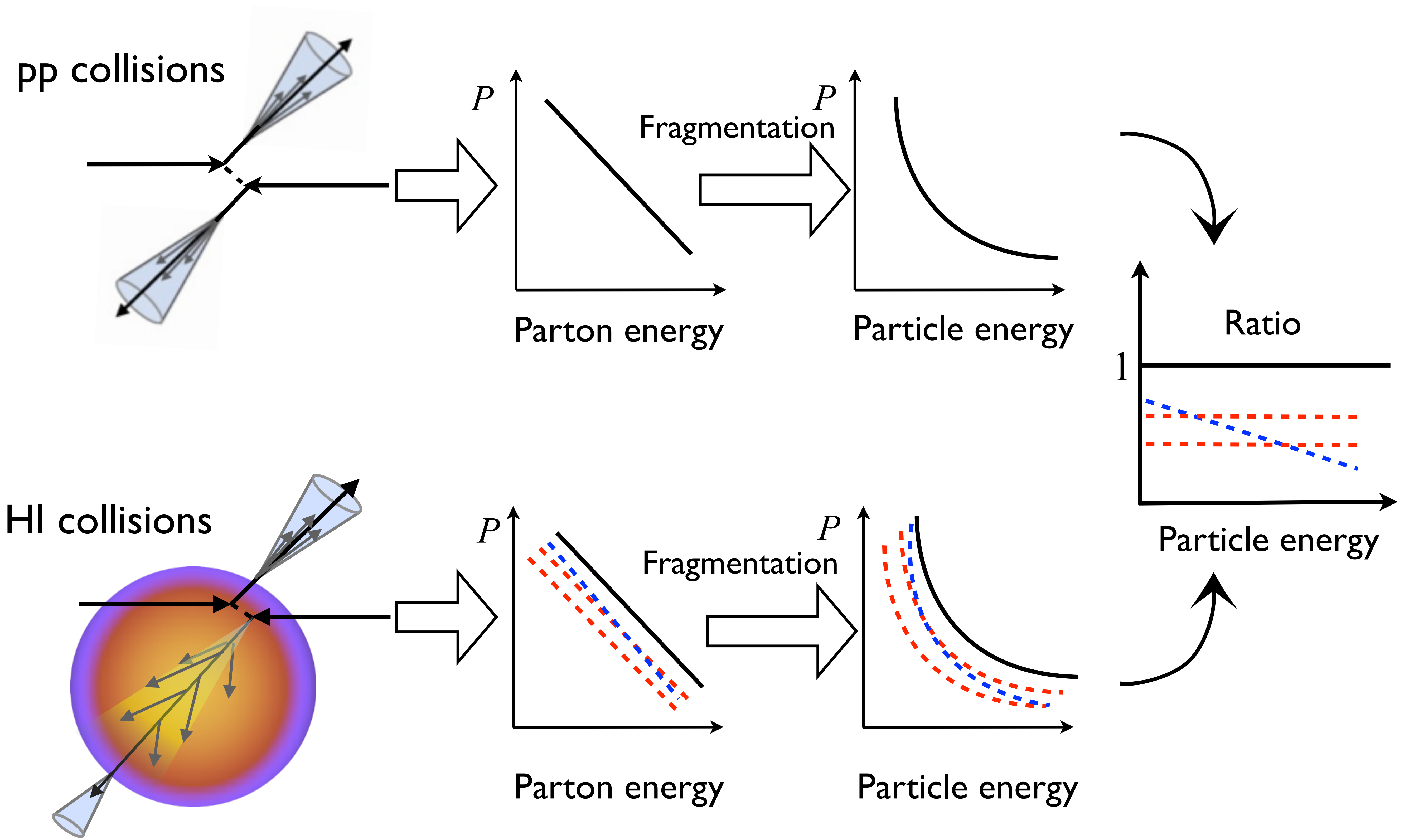


Nuclear Modification Factor R_{AA}

From transverse-momentum spectra measurement in PbPb

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

From Glauber modeling of PbPb collisions

From transverse-momentum spectra measurement in pp

Nuclear Modification Factor R_{AA}

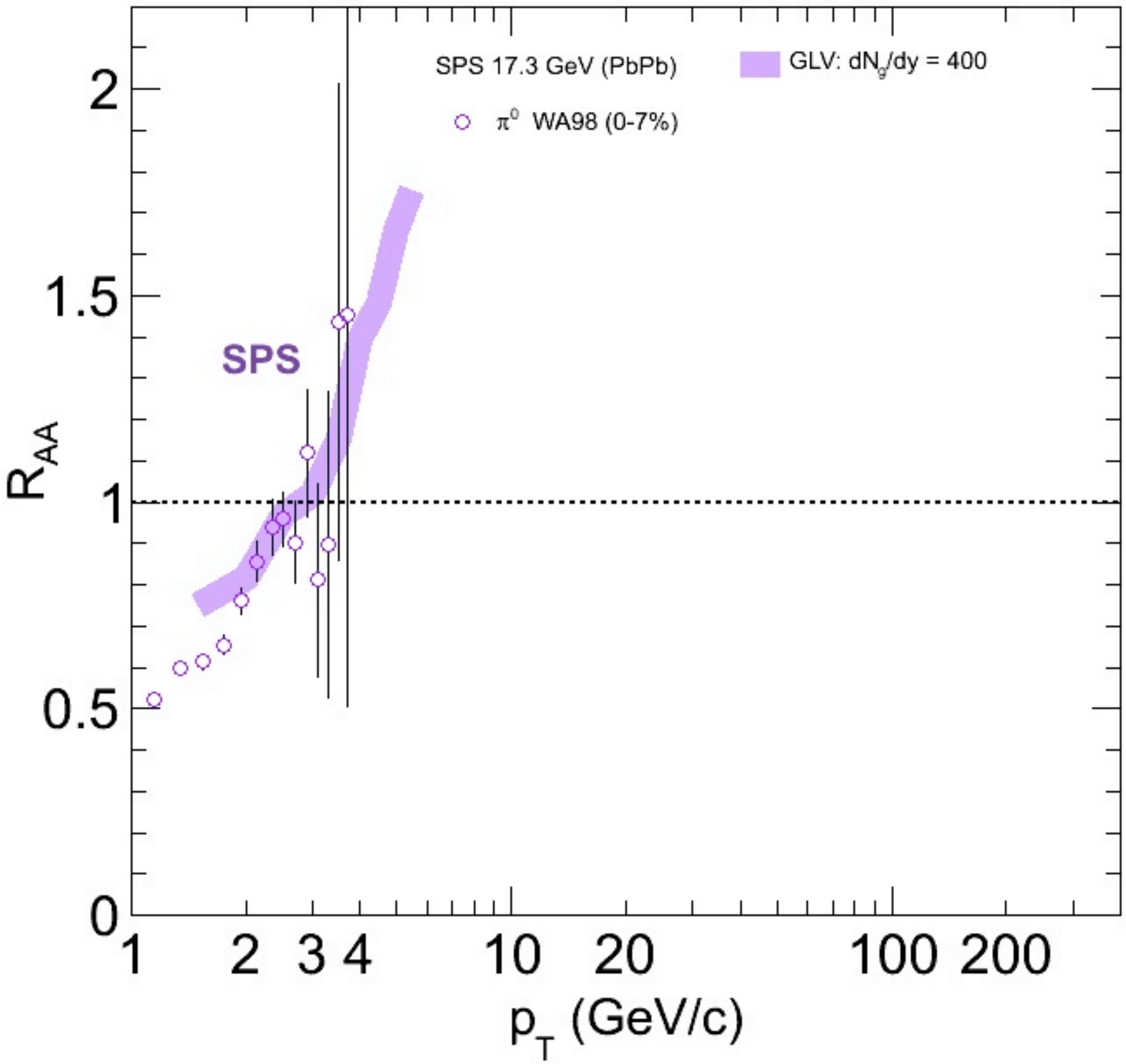
From transverse-momentum spectra measurement in PbPb

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

From Glauber modeling of PbPb collisions

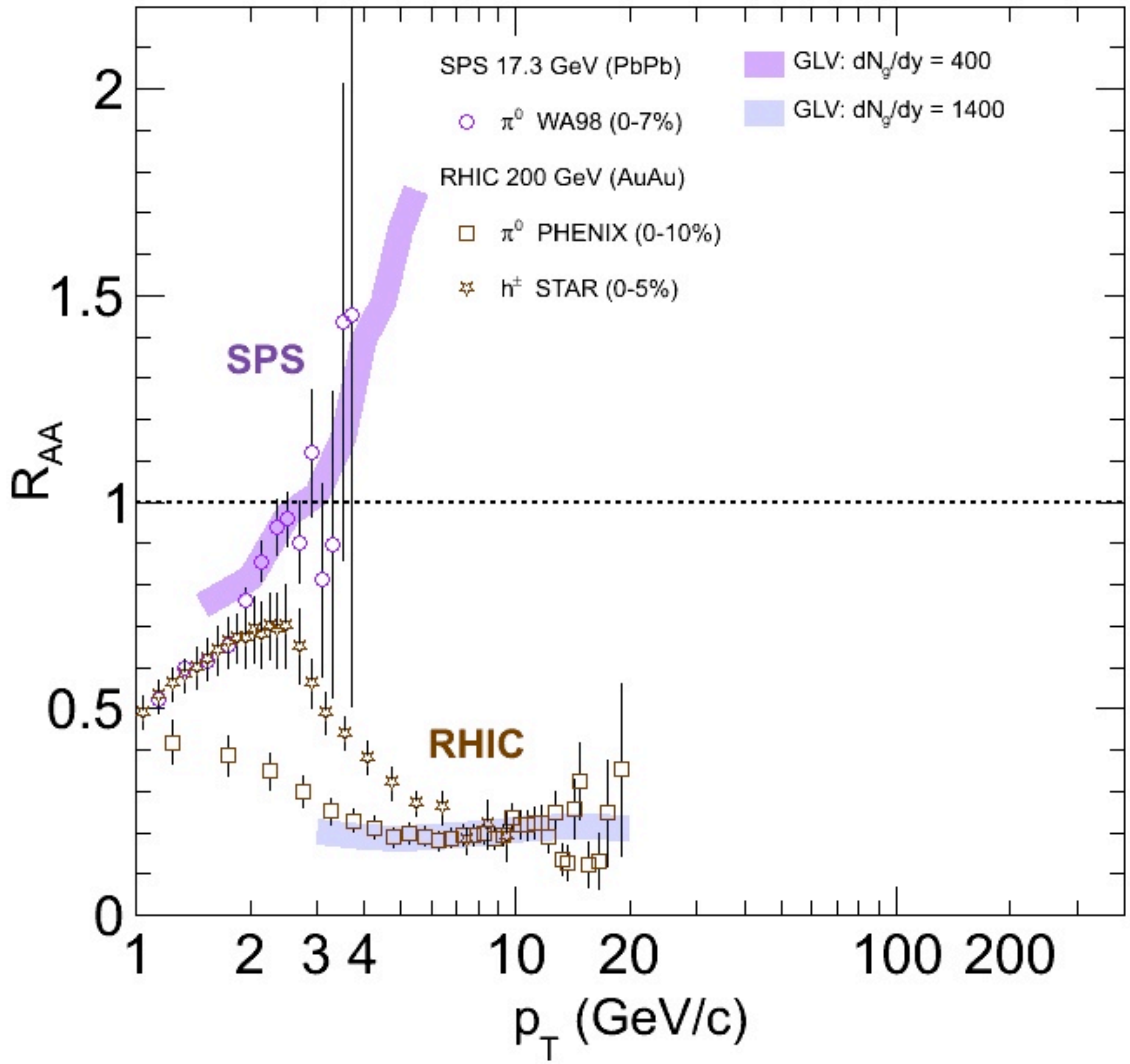
From transverse-momentum spectra measurement in pp

Current State of Knowledge



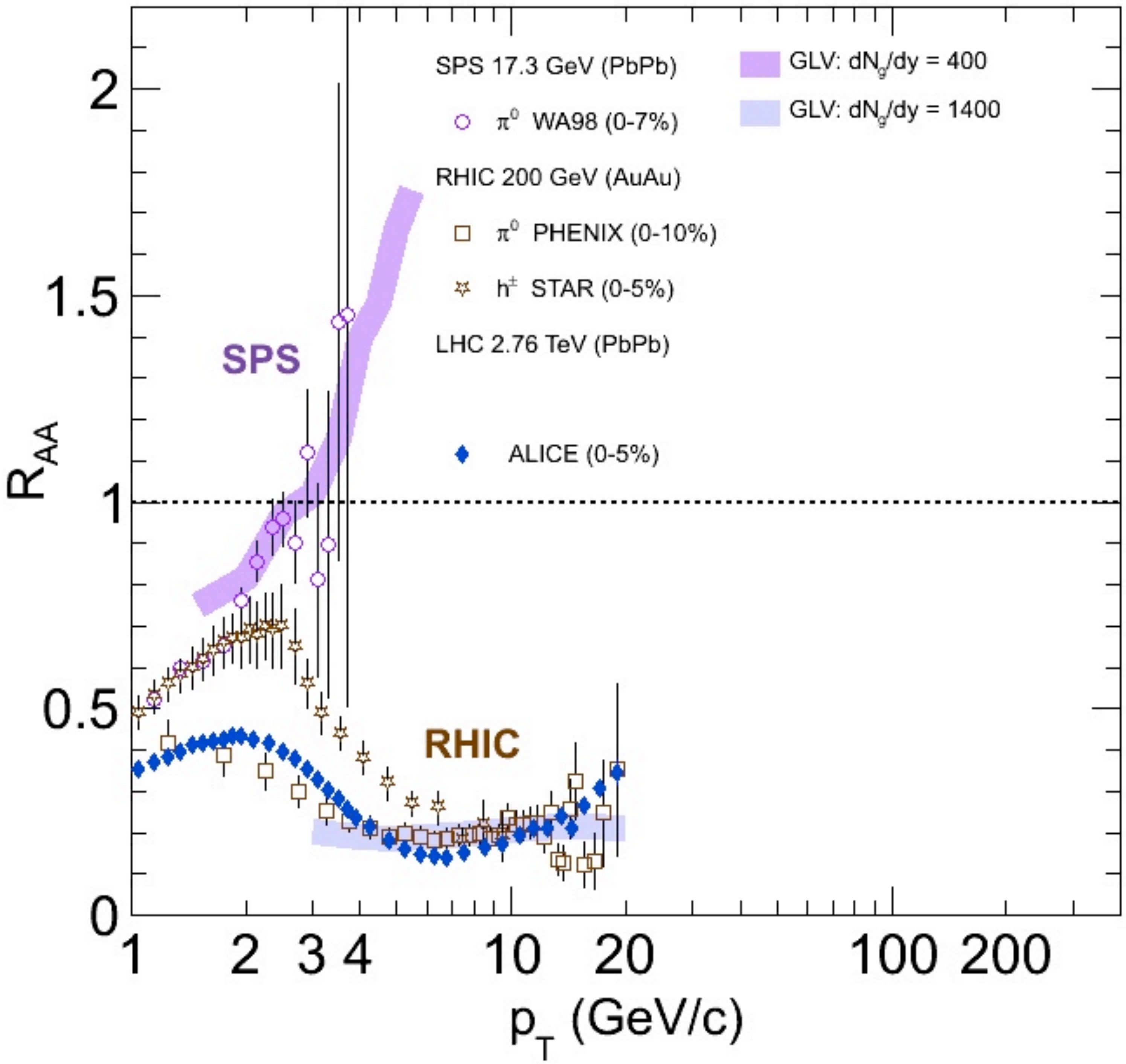
- At SPS, no suppression, but a hint of enhancement ("Cronin Effect")

Current State of Knowledge



- At SPS, no suppression, but a hint of enhancement ("Cronin Effect")
- At RHIC, a factor of 5 suppression above few GeV/c with different species converging above 8 GeV/c

Current State of Knowledge



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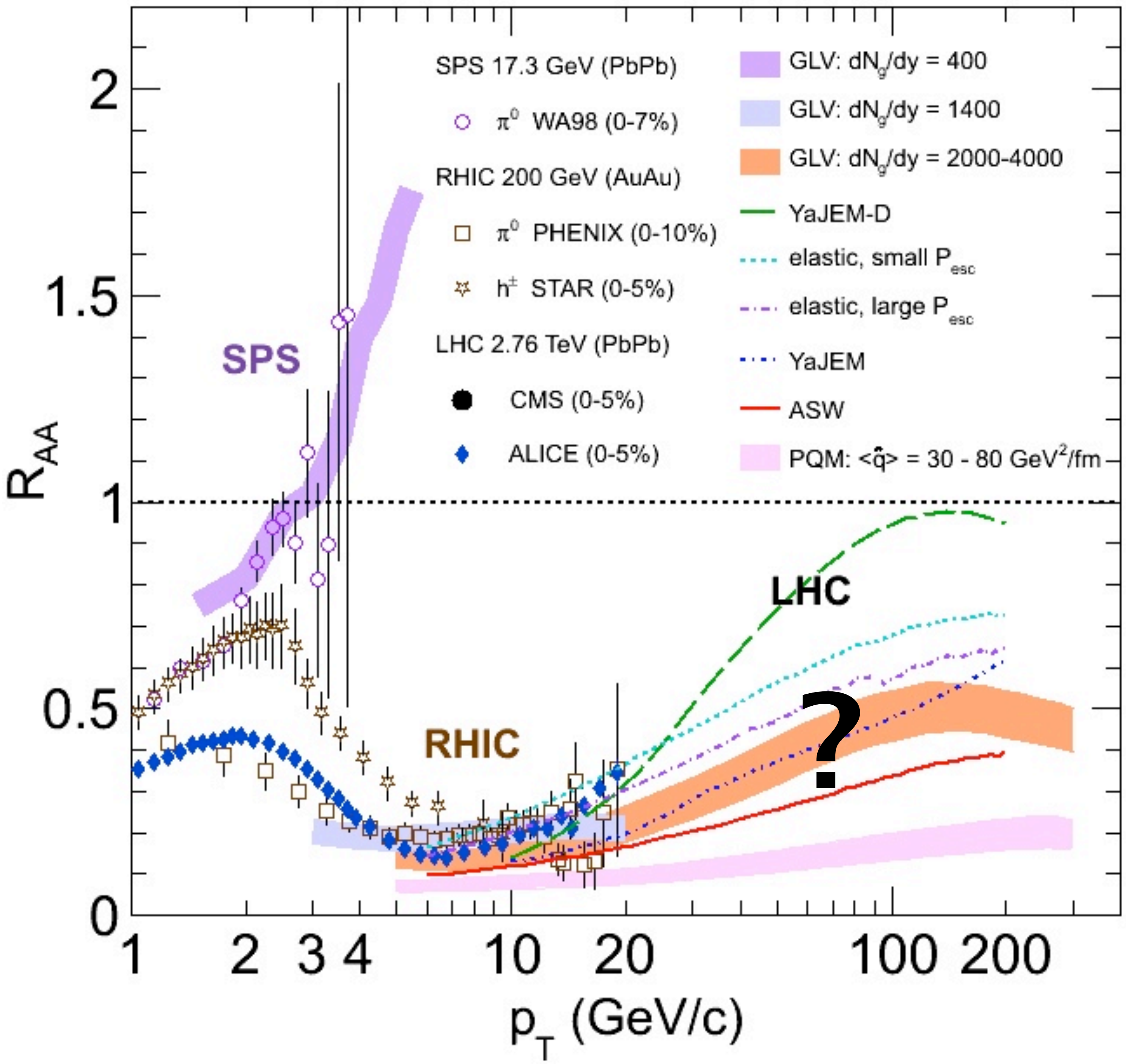
- At LHC, a similar level of suppression with a hint of rising R_{AA} measured by ALICE

Current State of Knowledge



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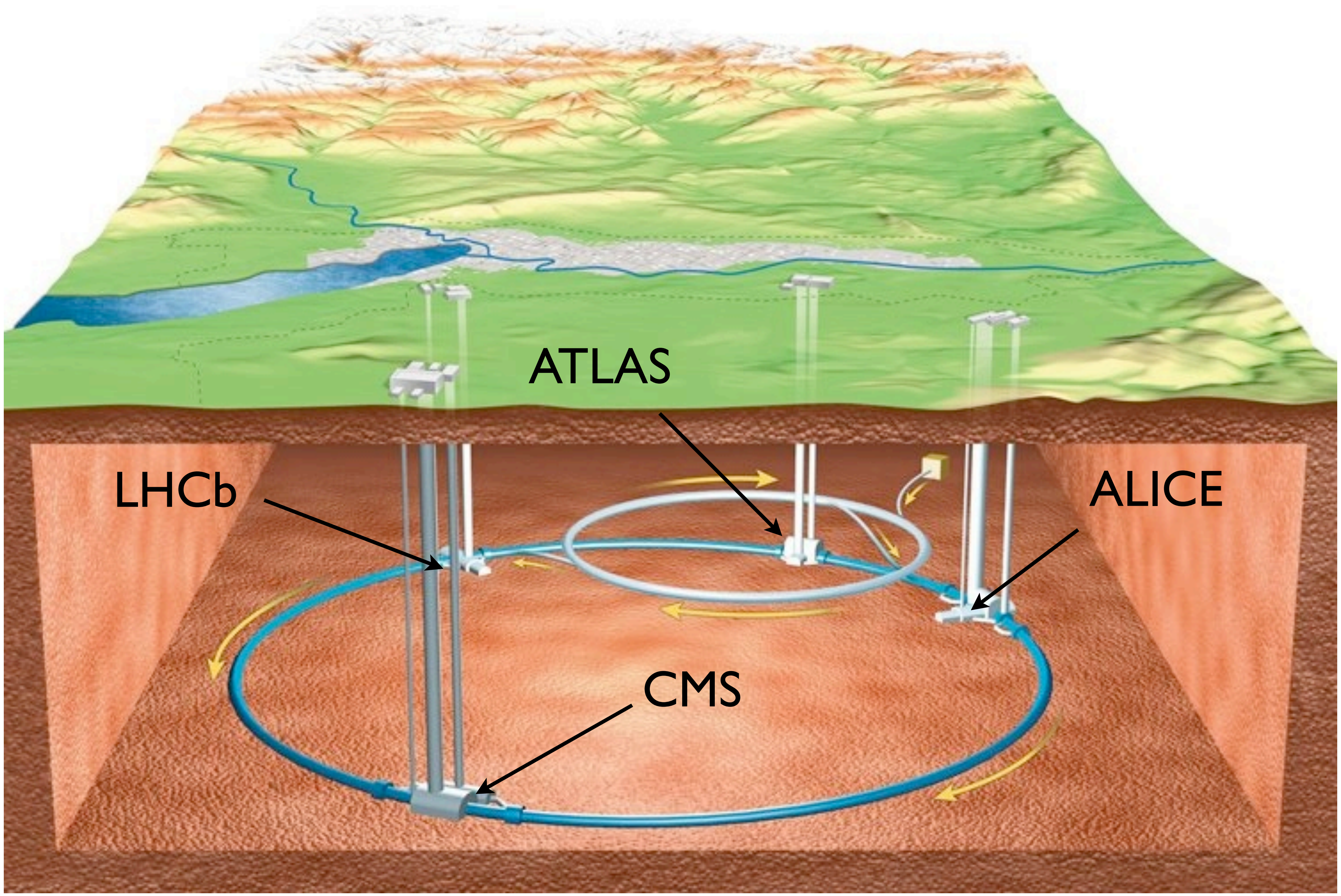
- At RHIC, a factor of 5 suppression above few GeV/c with different species converging above 8 GeV/c
- At LHC, a similar level of suppression with a hint of rising R_{AA} measured by ALICE
- R_{AA} is very sensitive to the details of the quenching parameters at high p_T

Large Hadron Collider (LHC)

Largest energy increase in Heavy Ion Physics

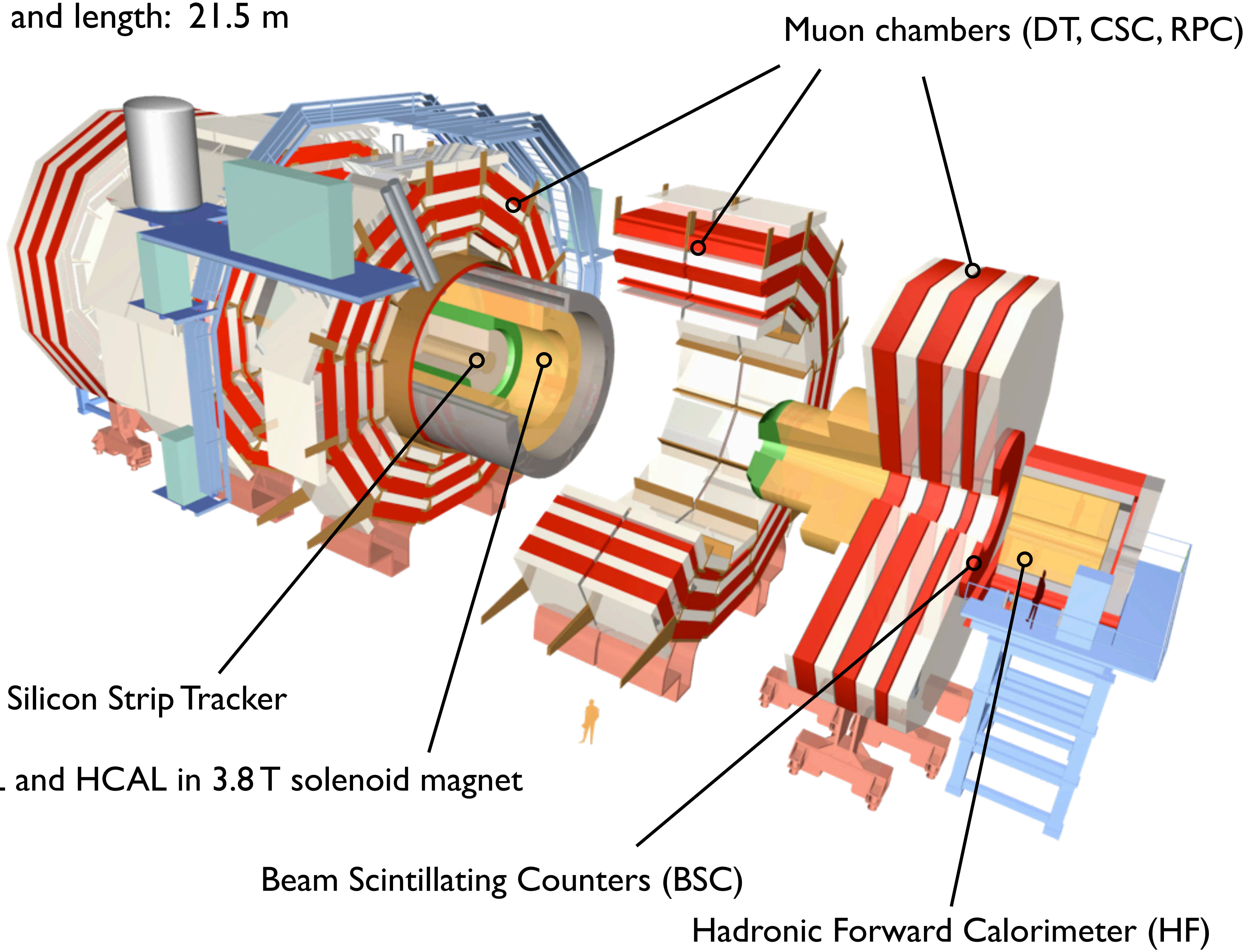
From 0.2 TeV* to 2.76 TeV* (x14 times larger)



* per nucleon pair

Compact Muon Solenoid (CMS) Detector

Weight: 12500 T (c.f. Eiffel tower: 10100 T)
Diameter: 15 m and length: 21.5 m



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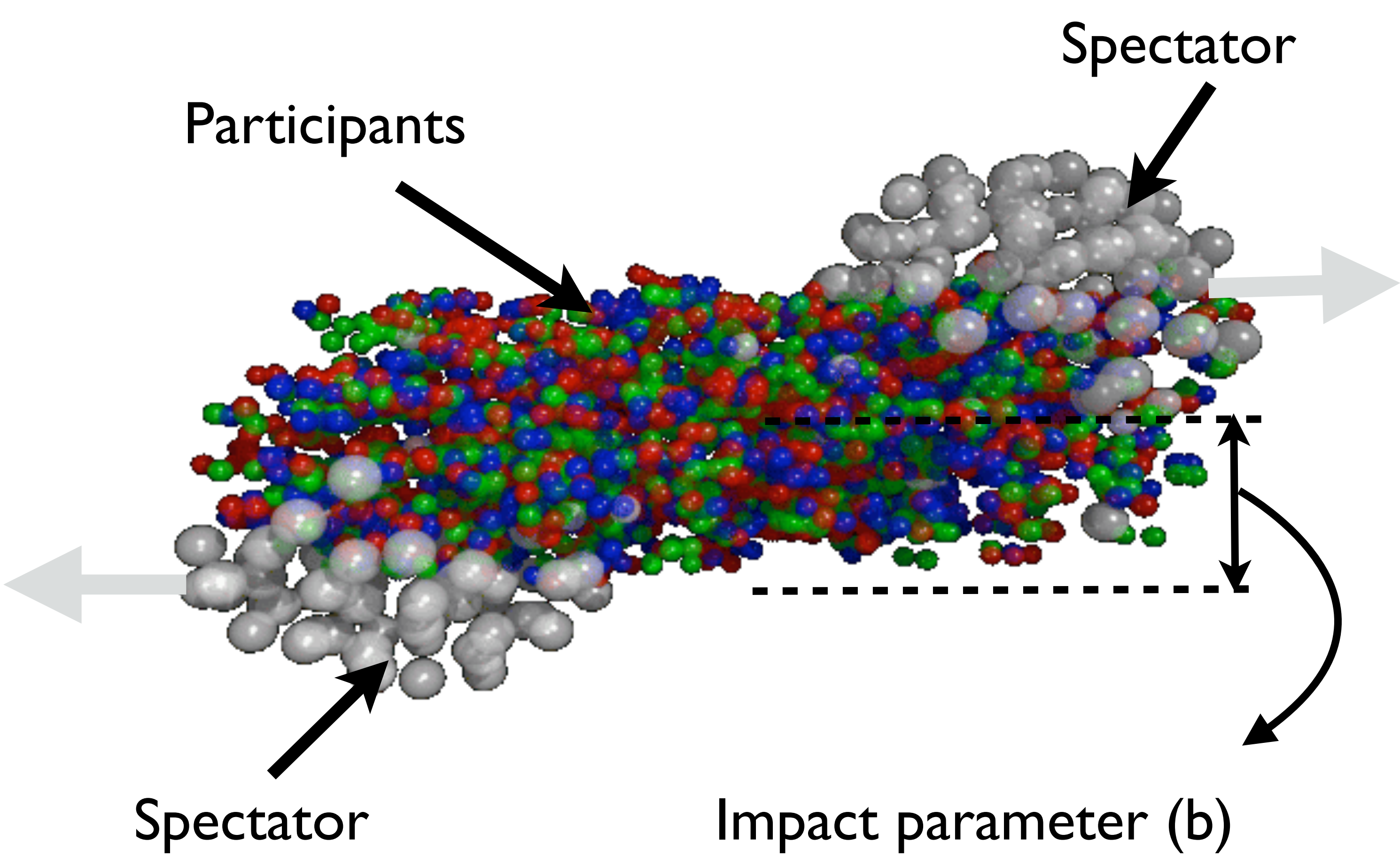
Collision Geometry and Centrality

*UrQMD visualization



Collision Geometry and Centrality

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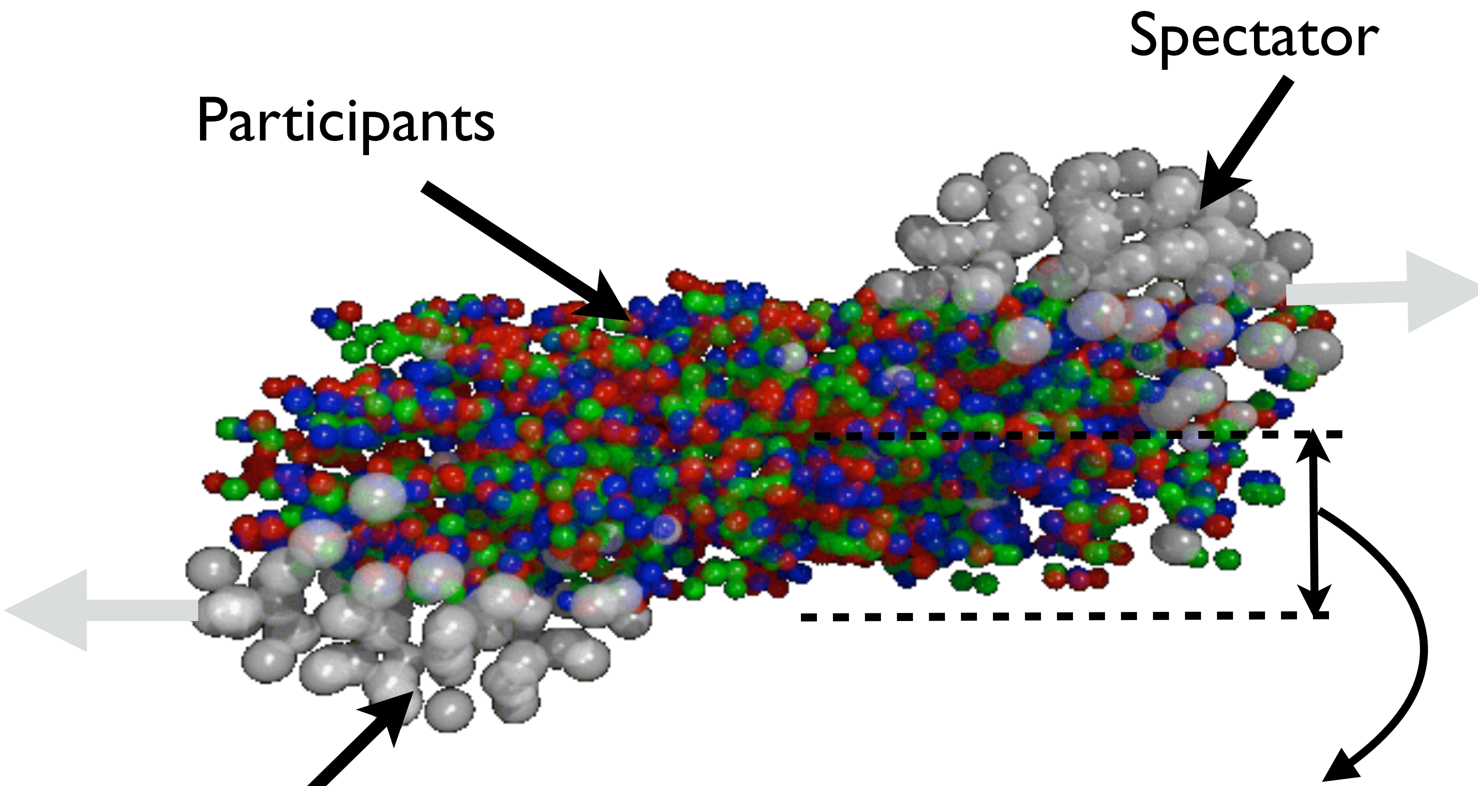

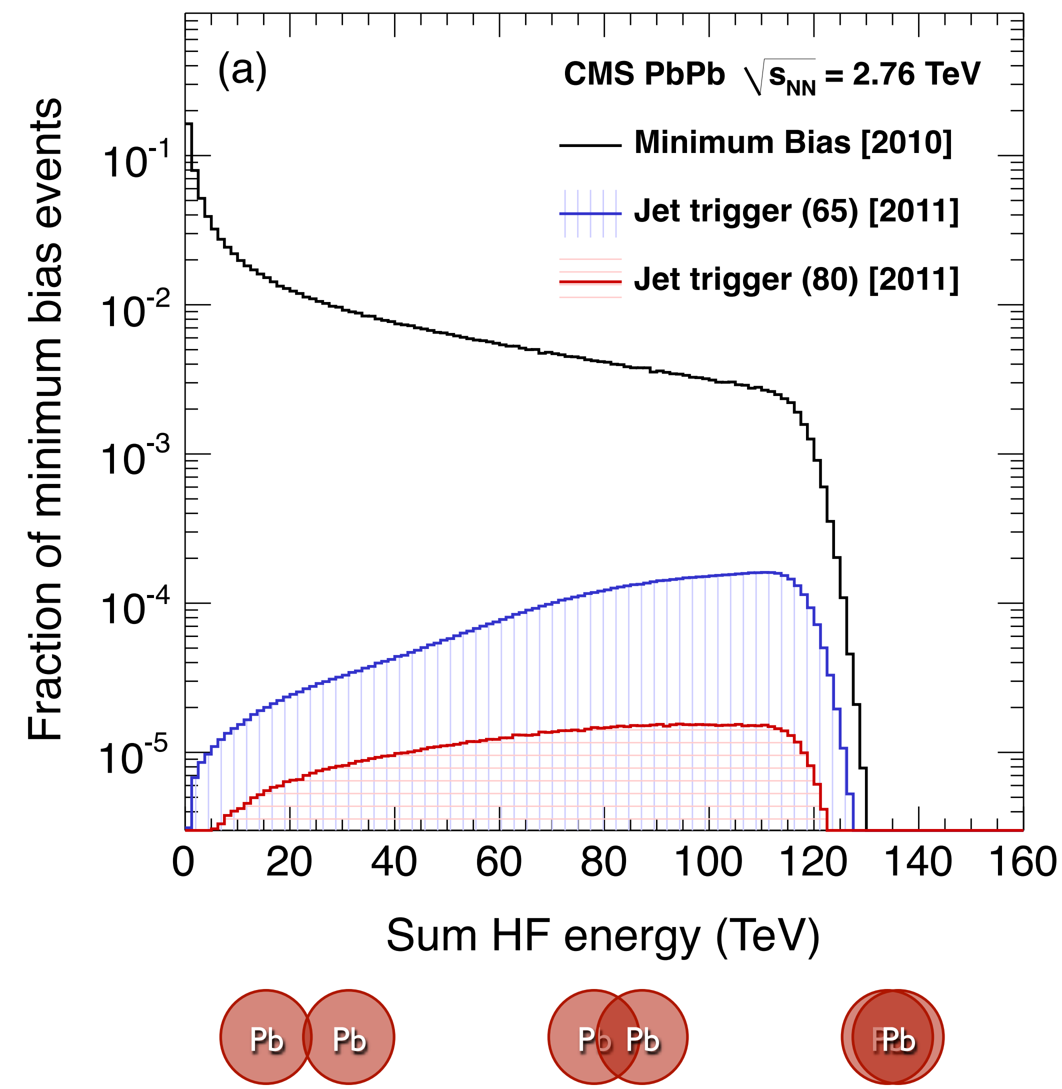

Events are classified by 0-5, 5-10, 10-30, 30-50, 50-70, 70-90% bins in this analysis

$$\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{pp}^{inel}$$

$\langle N_{coll} \rangle$ = average number of inelastic binary collisions

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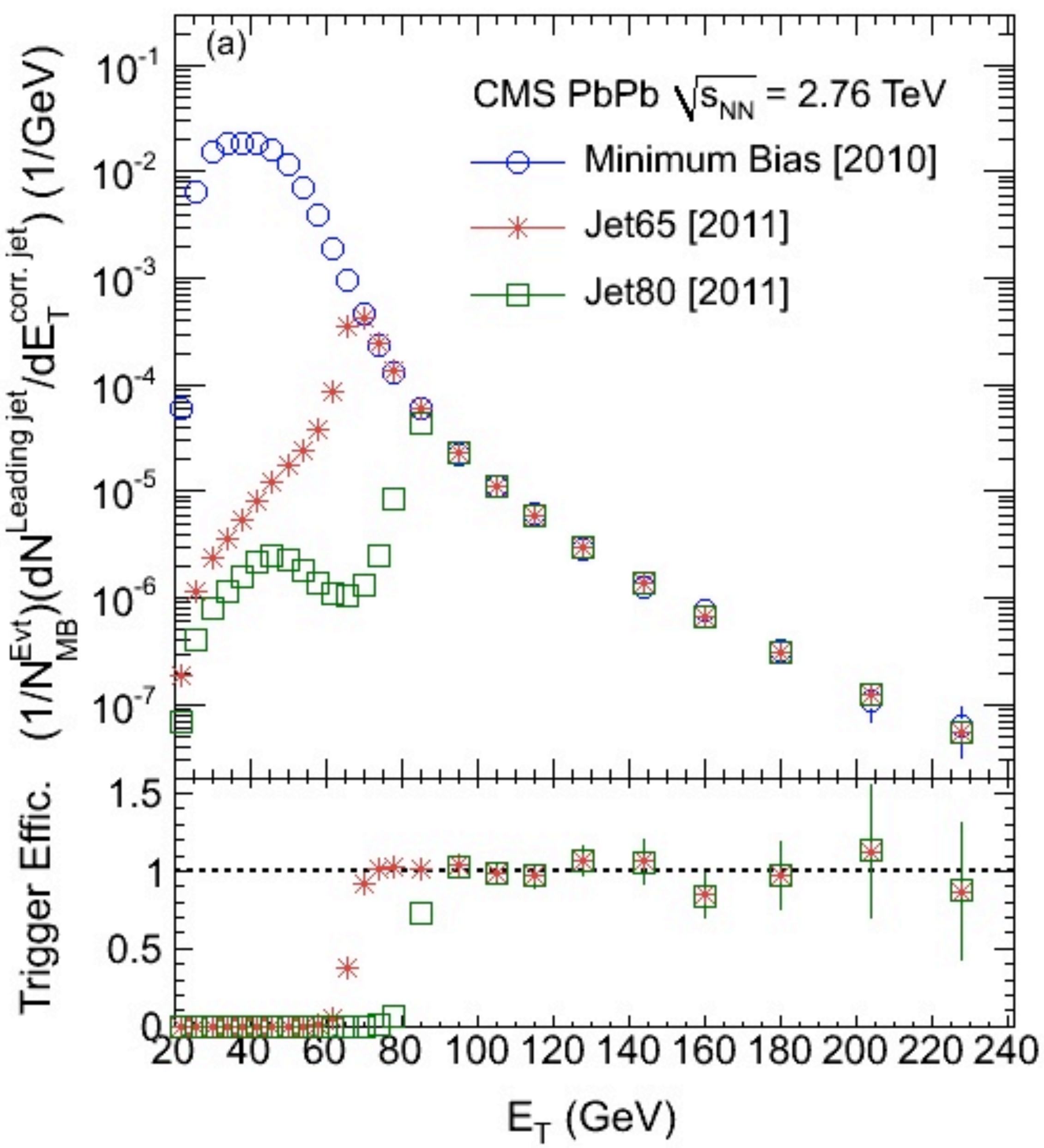
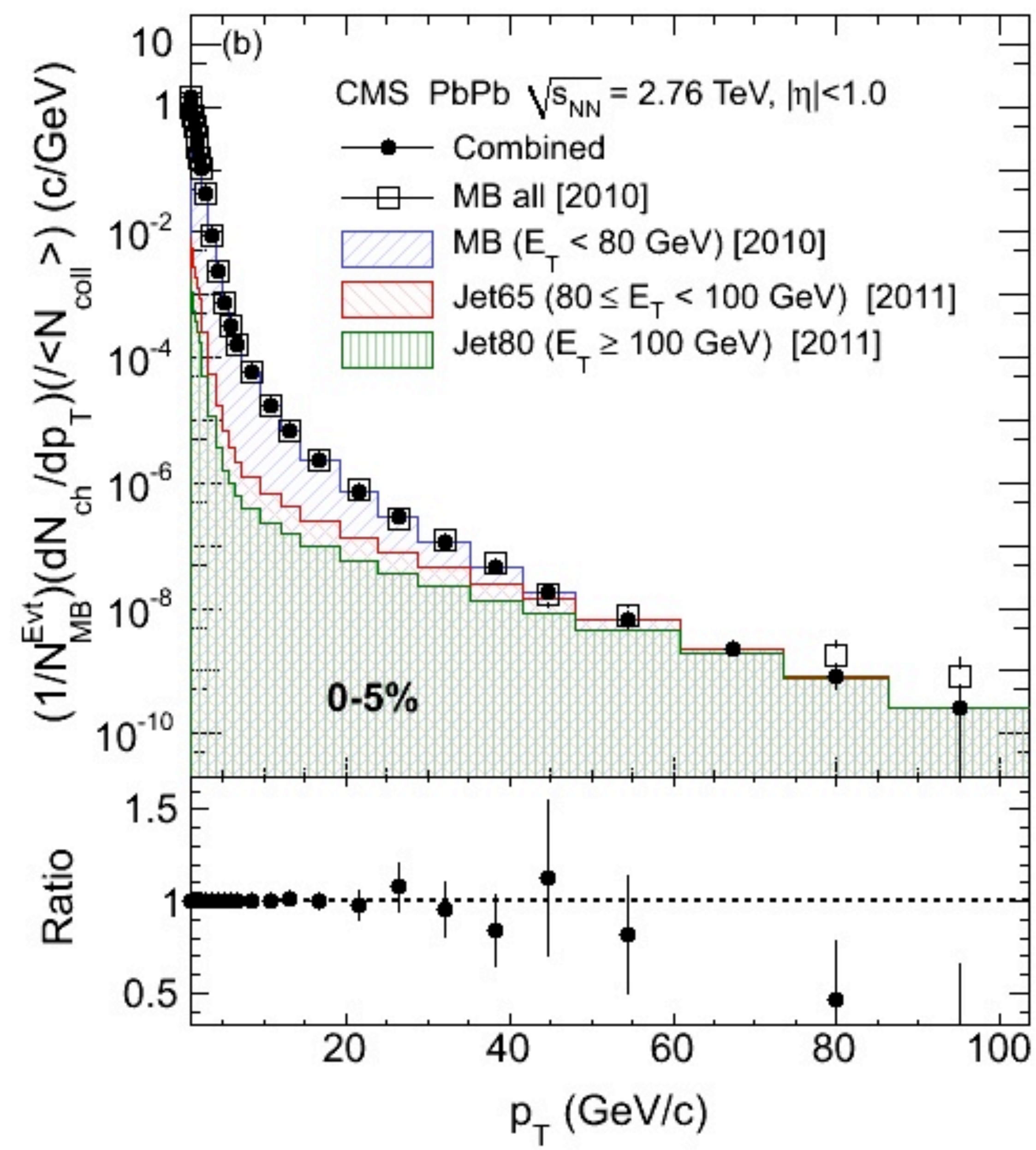
Trigger-Matching

Jet Energy Distribution



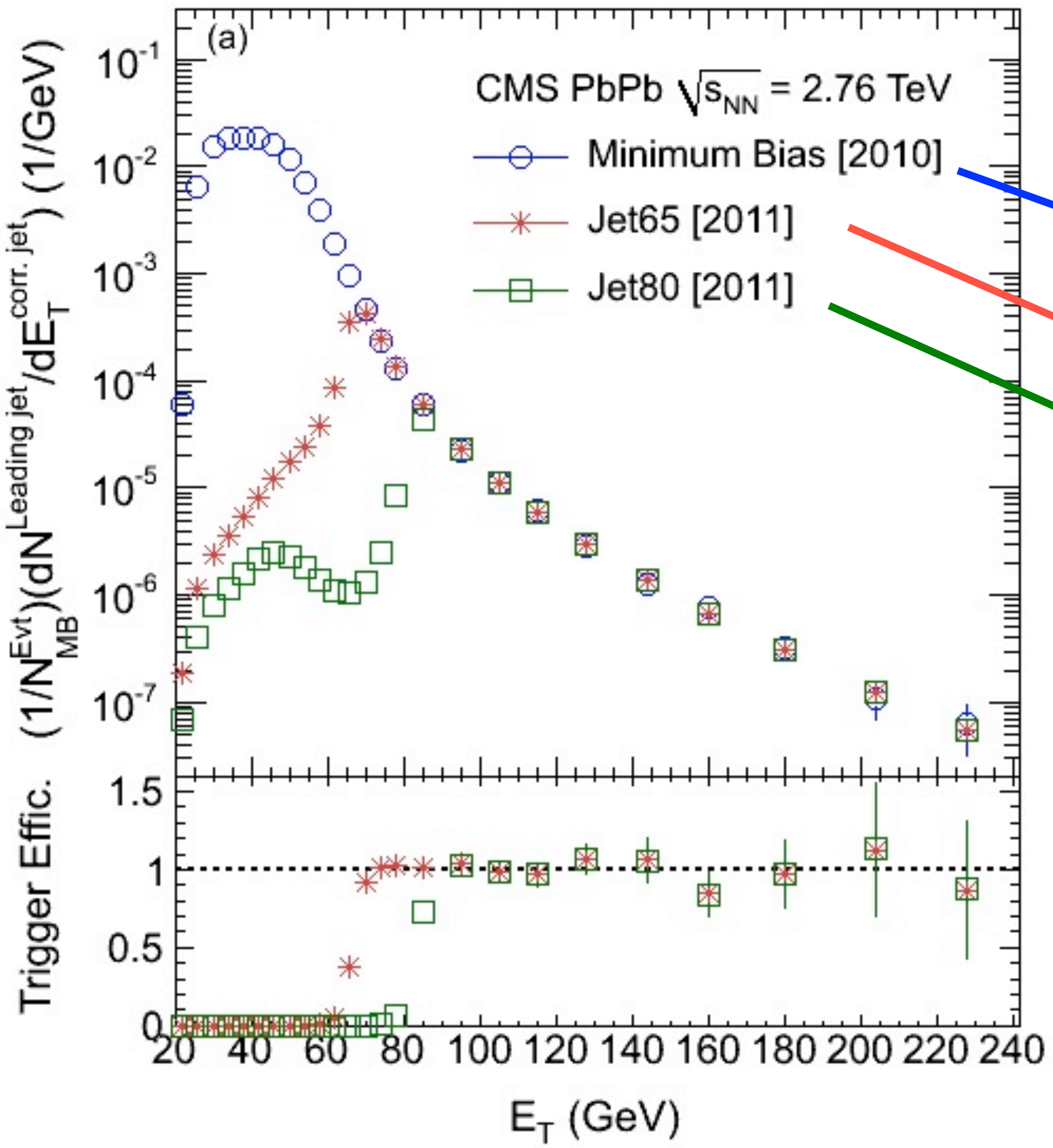
Charged Particle Distribution



Jet triggers are used to enhance p_T reach and have lower fake tracks on average.

Trigger-Matching

Jet Energy Distribution



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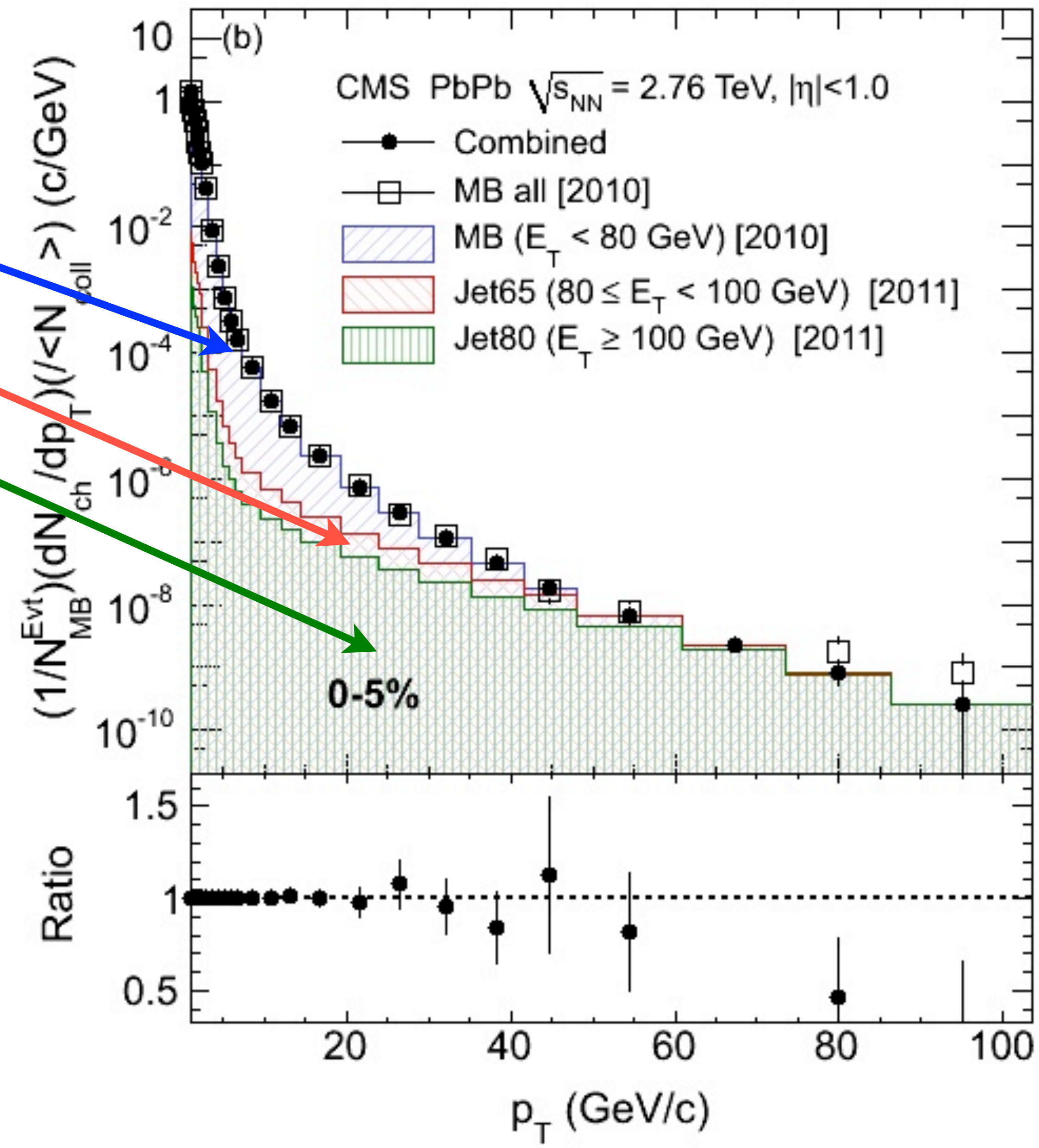

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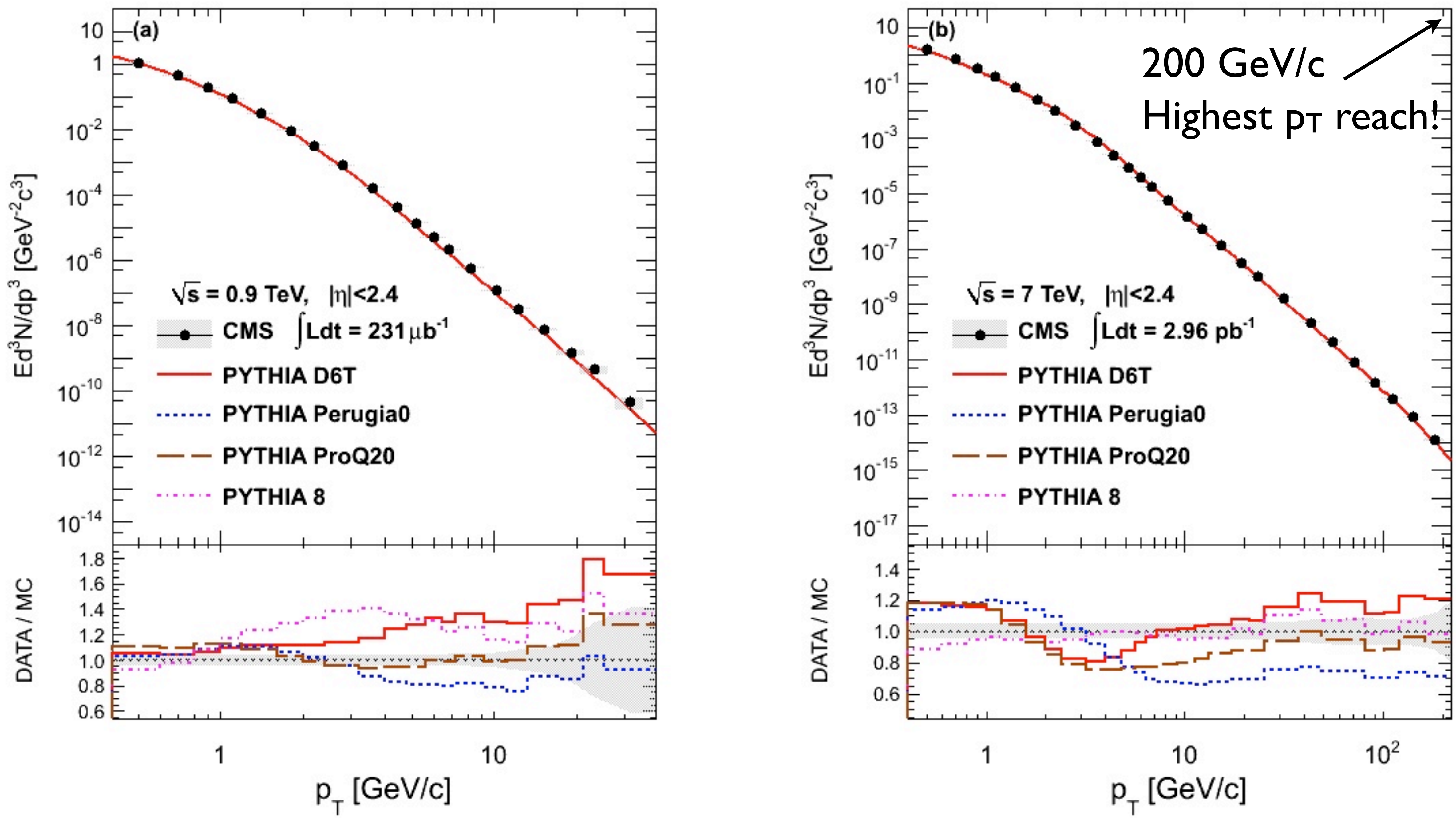
Invariant Yields in 0.9 and 7 TeV pp Collisions

0.9 TeV $|\eta|<2.4$ 7 TeV $|\eta|<2.4$



Measured spectra are in good agreements with the PYTHIA (LO) calculations.

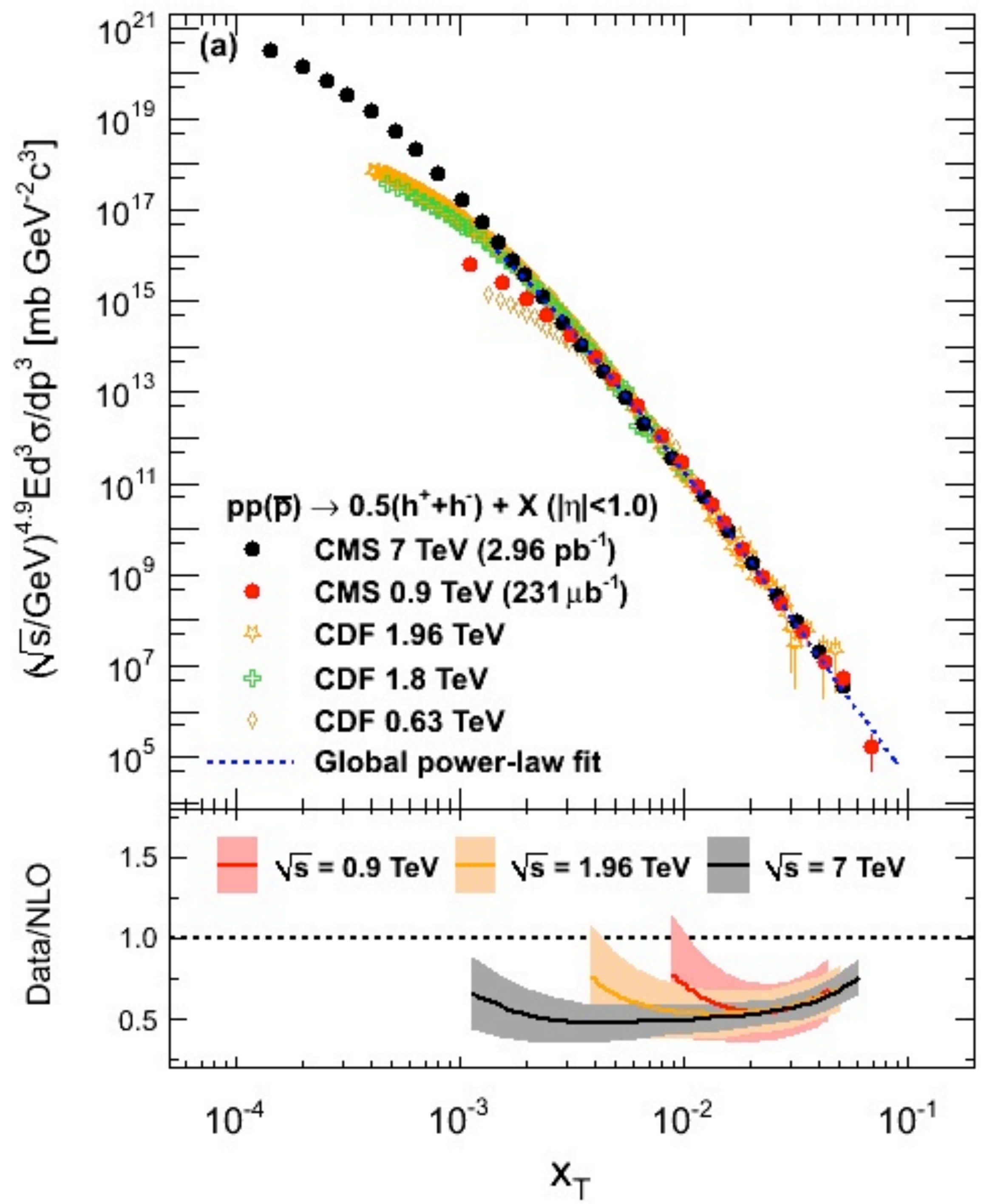
Scaling Behavior of Measured Spectra

- pQCD prediction of hard-processes
- Energy-independent scaling behavior of inclusive spectra with $x_T \equiv 2p_T/\sqrt{s}$

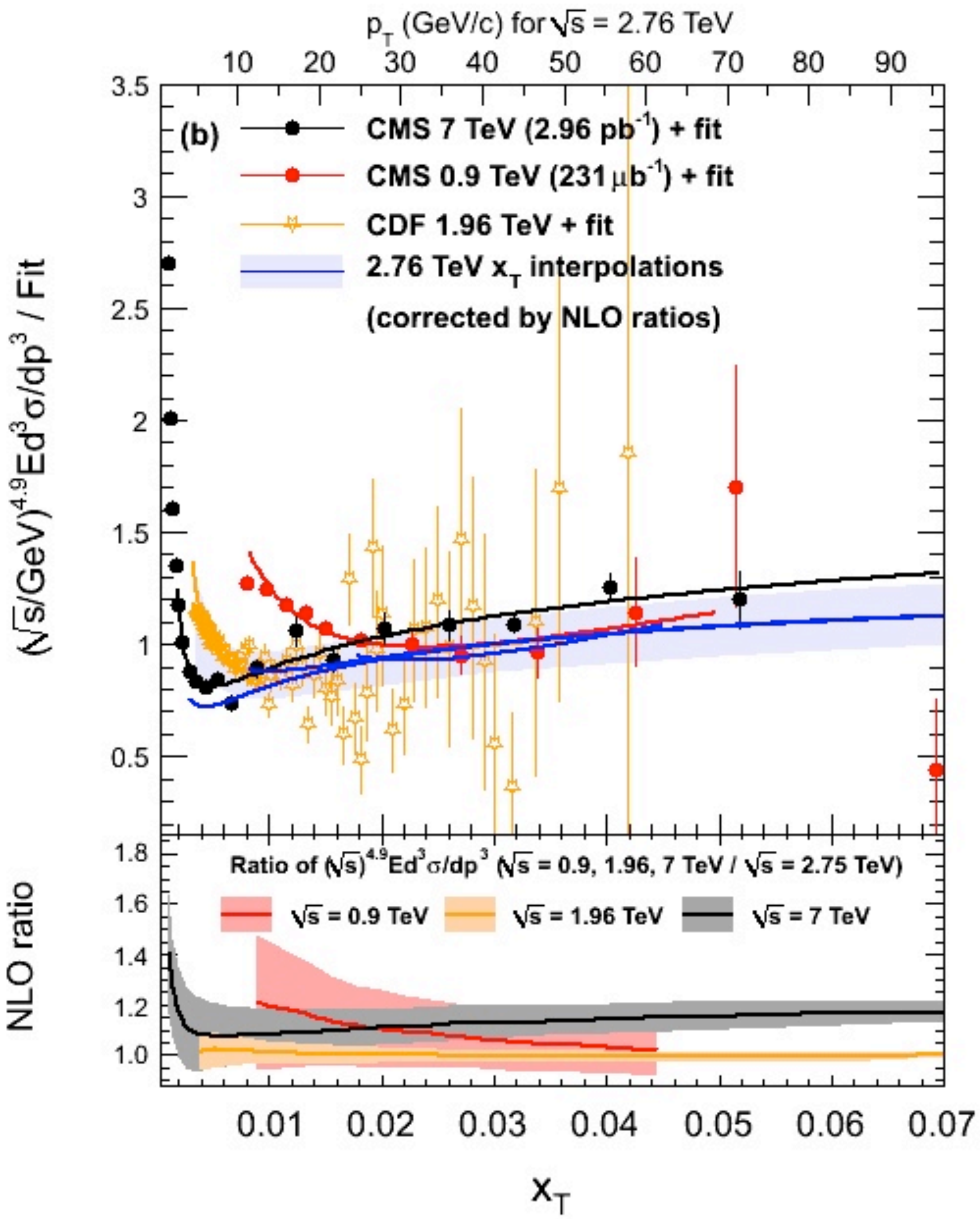
$$E\frac{d^3\sigma}{dp^3} = F(x_T)/p_T^{n(x_T,\sqrt{s})} = F'(x_T)/\sqrt{s}^{n(x_T,\sqrt{s})}$$

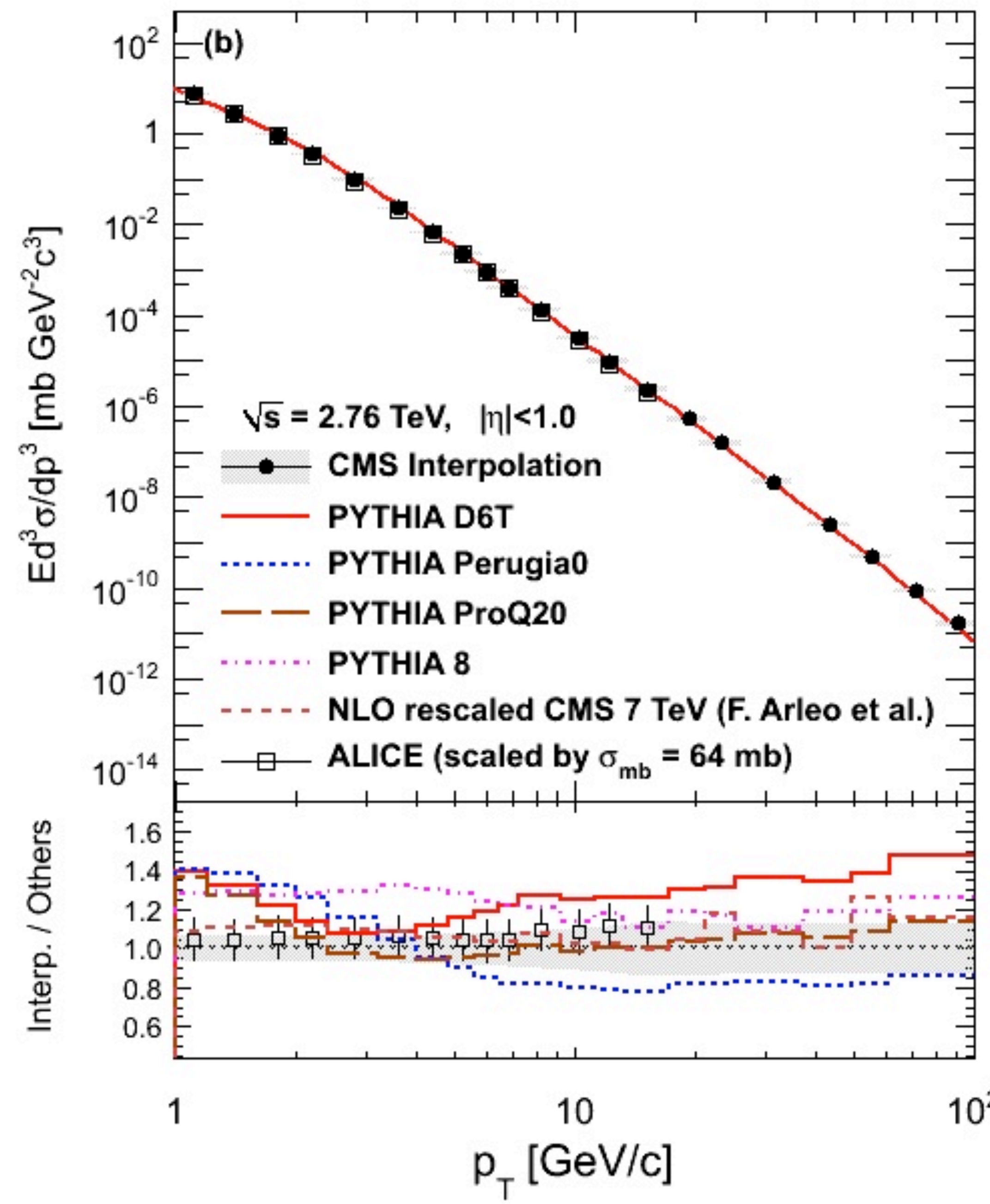
- Not a perfect scaling due to running $\boldsymbol{\alpha}_s(Q)$
- Good scaling behavior over 0.63-7 TeV
- Best global-fit exponent n = 4.9±0.1

$|\eta|<1.0$



Interpolation of 2.76 TeV pp Spectra



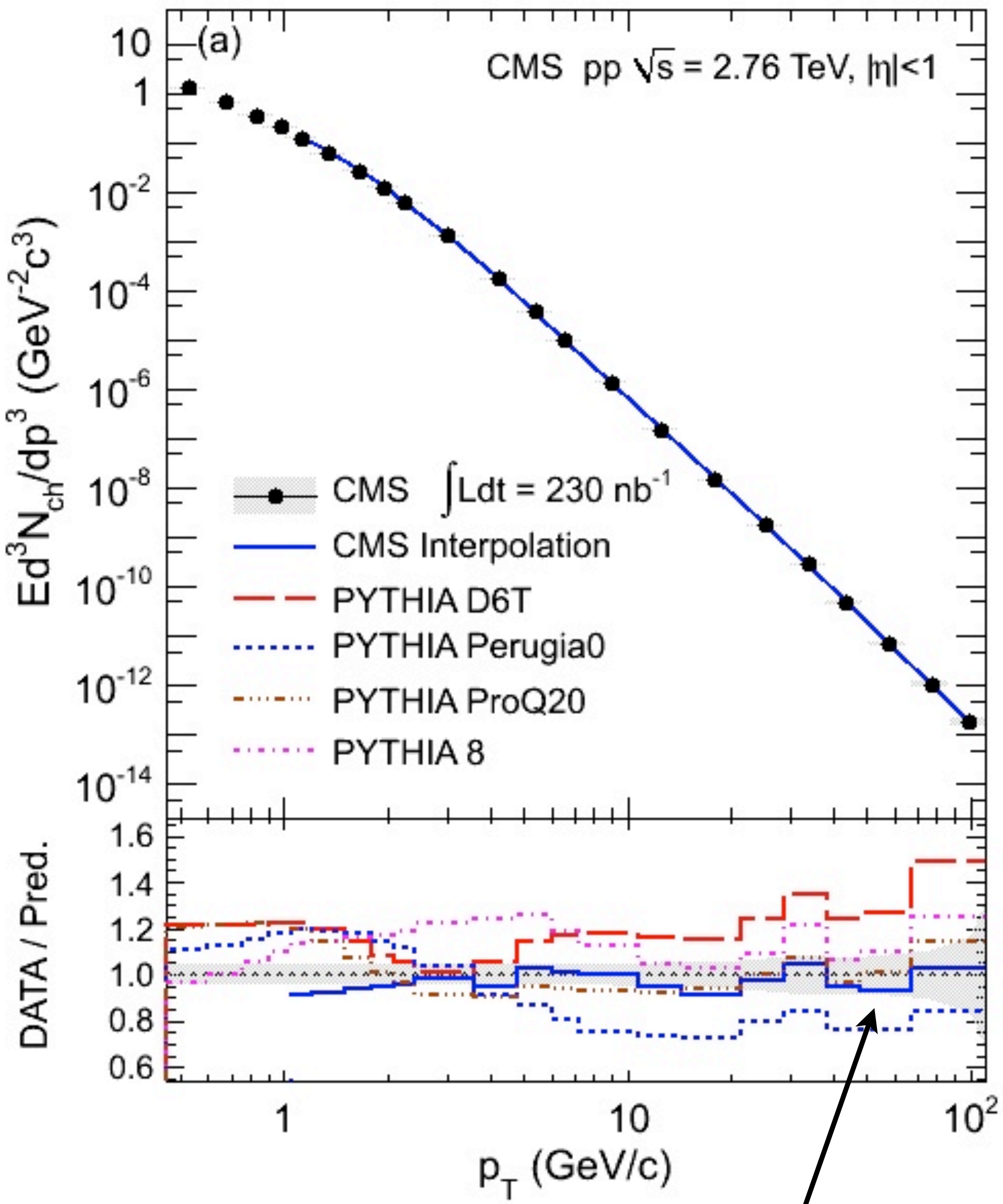


Known x_T scaling violation is corrected based on the NLO calculations.

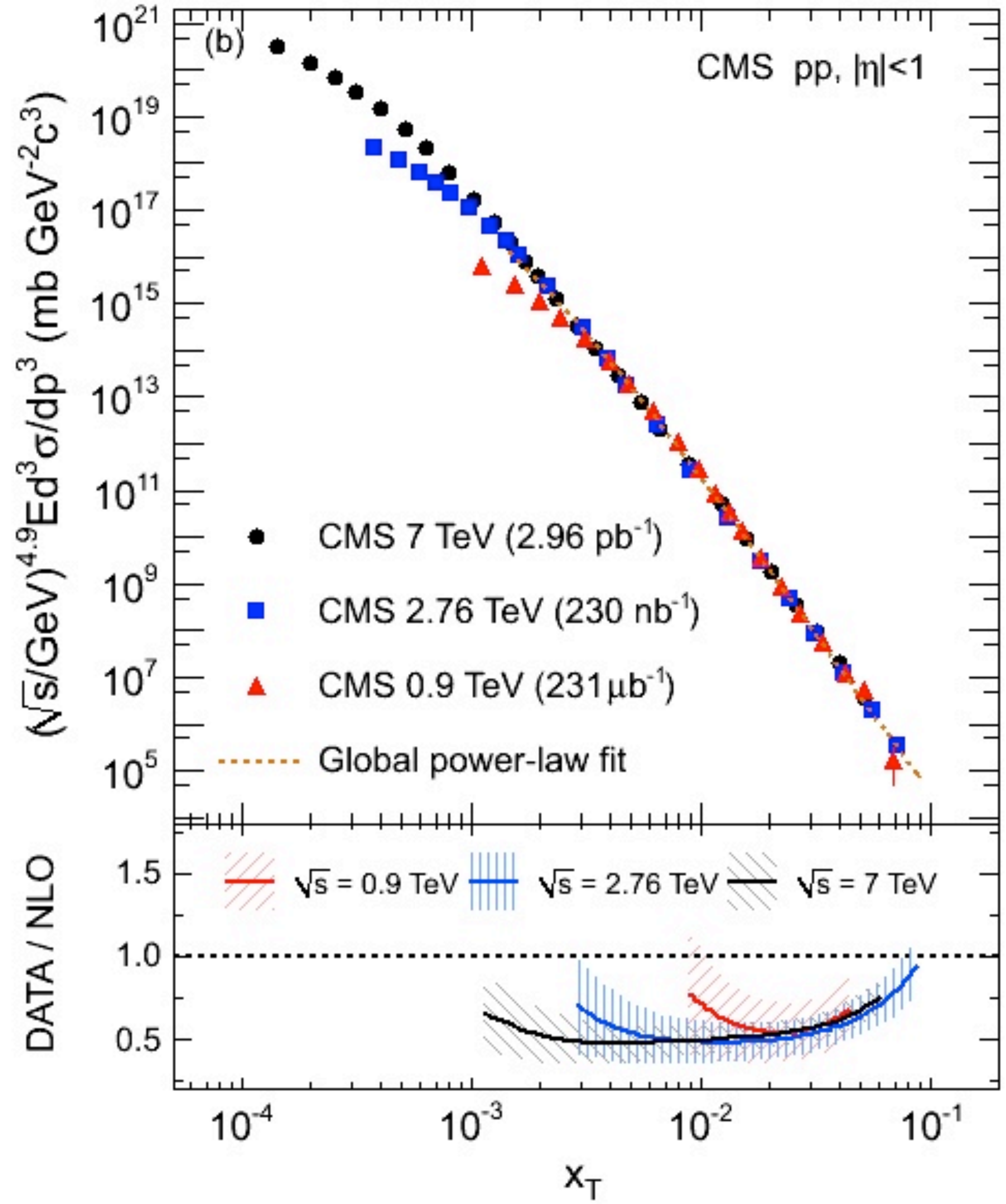
Good agreement with PYTHIA and NLO-rescaled 7 TeV CMS measurement

Invariant Yields in 2.76 TeV pp Collisions

2.76 TeV $|\eta|<1.0$



0.9, 2.76, and 7 TeV $|\eta|<1.0$



Excellent agreement with the interpolated spectra!

x_T scaling based on the CMS only

Summary of pp Spectra Measurements

- Measured high-p_T charged particle spectra are consistent with the pQCD calculations as well as with x_T scaling within the quoted systematic (and theoretical) errors.

- Production of high-p_T charged particle is well understood in the pQCD framework at TeV-scale energy collisions.

<u>High p_T charged particle = "well-calibrated" probe</u>

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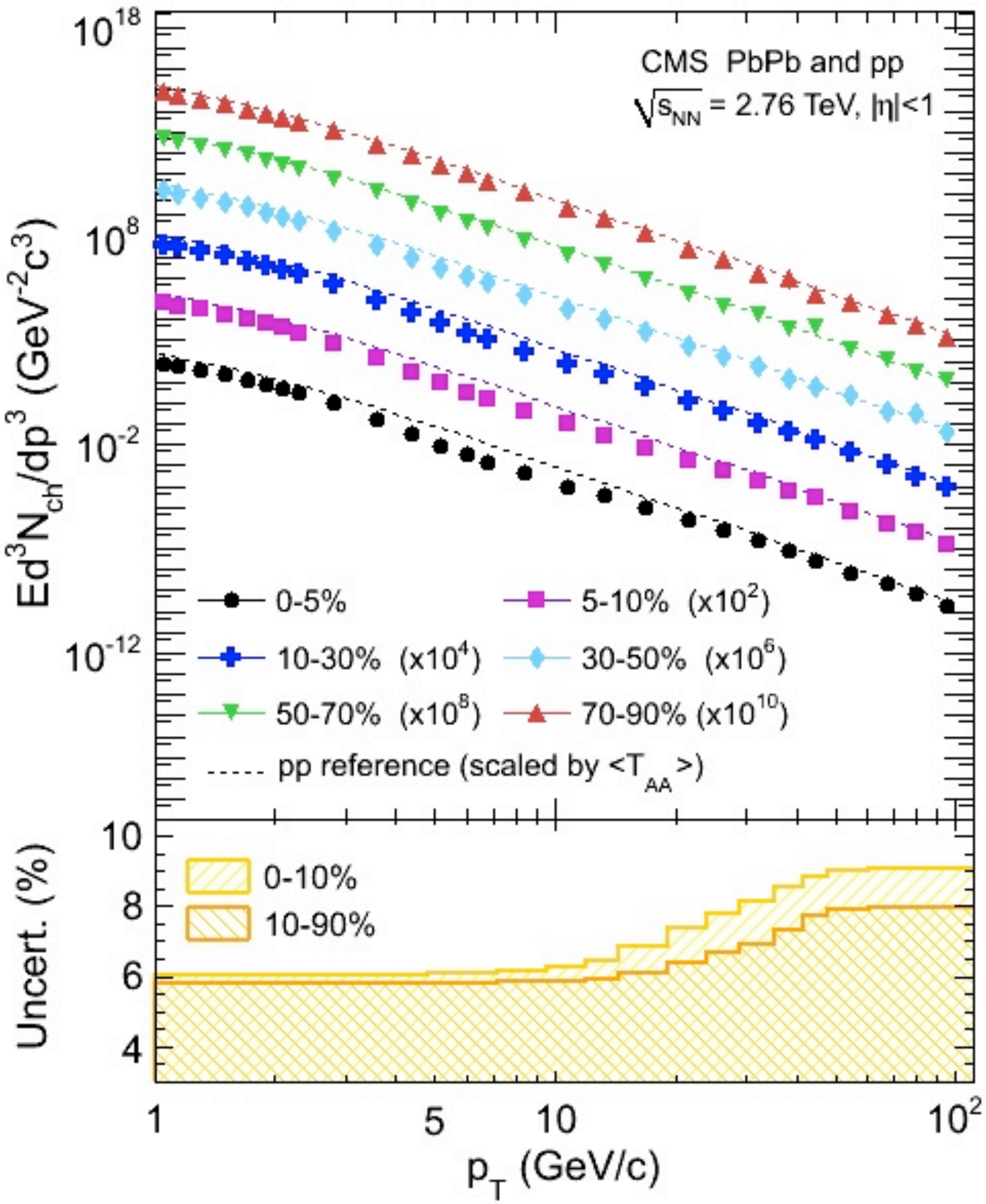
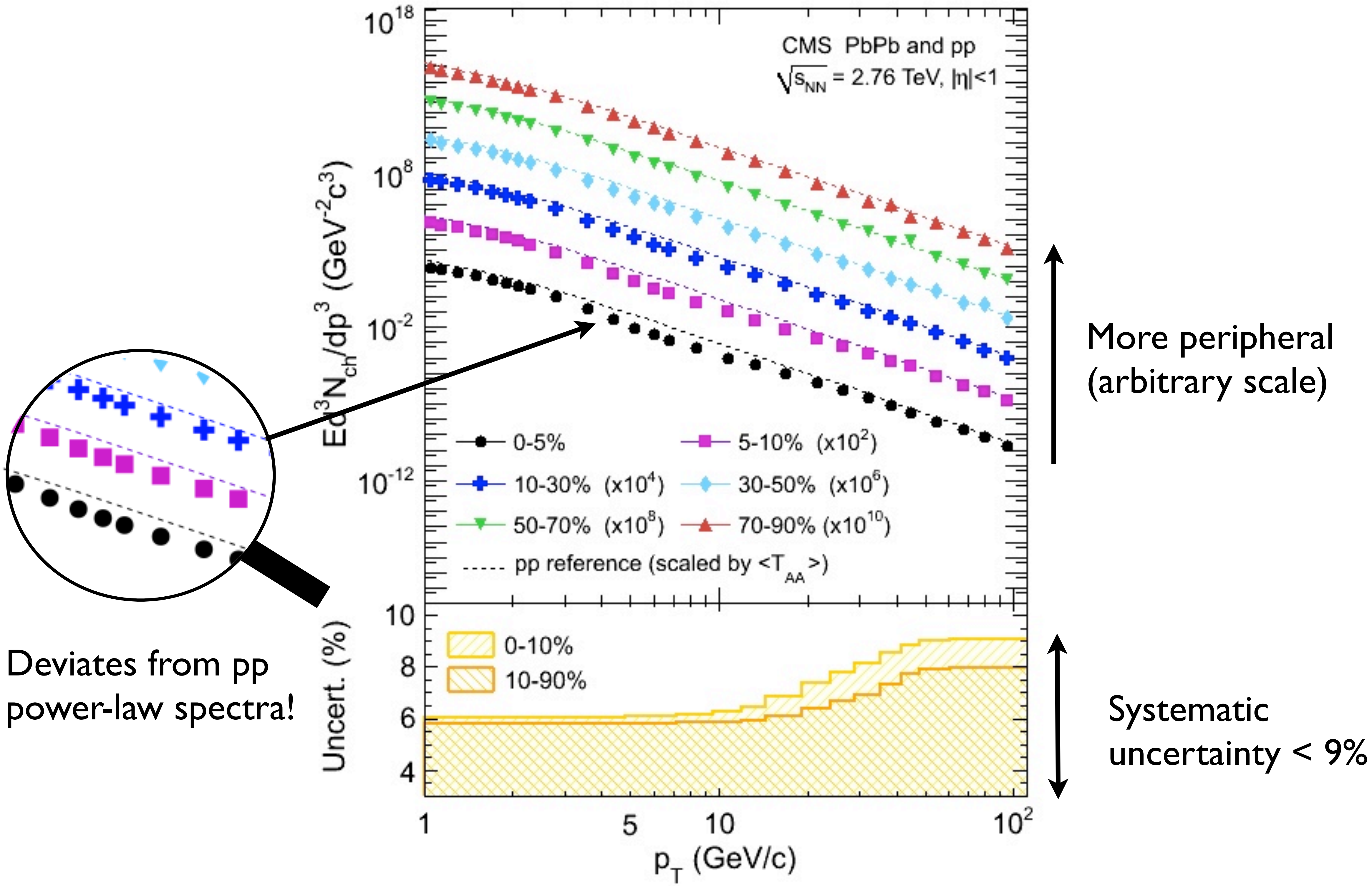


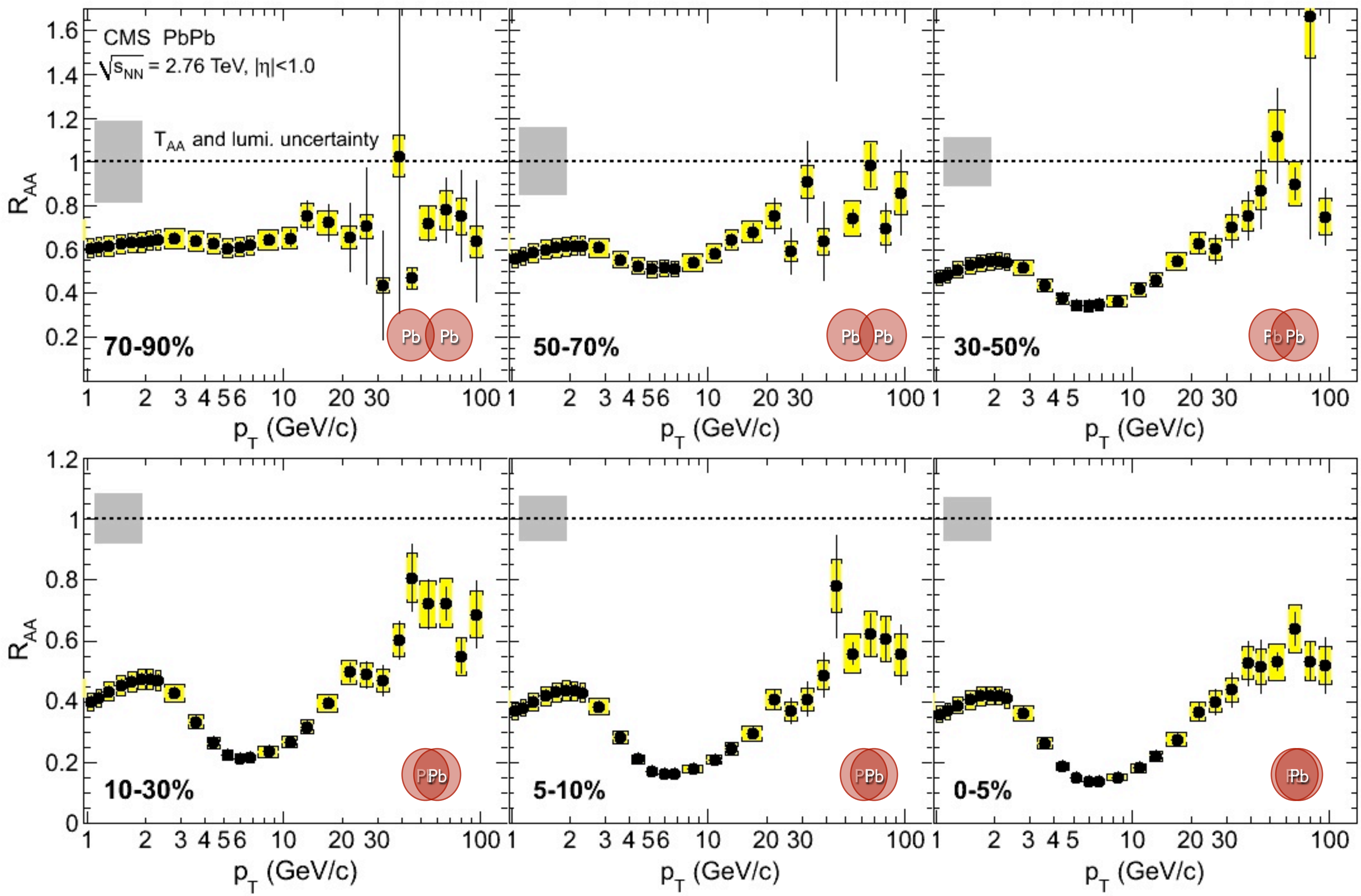
More peripheral (arbitrary scale)

Systematic uncertainty < 9%

Invariant Yields in 2.76 TeV PbPb Collisions

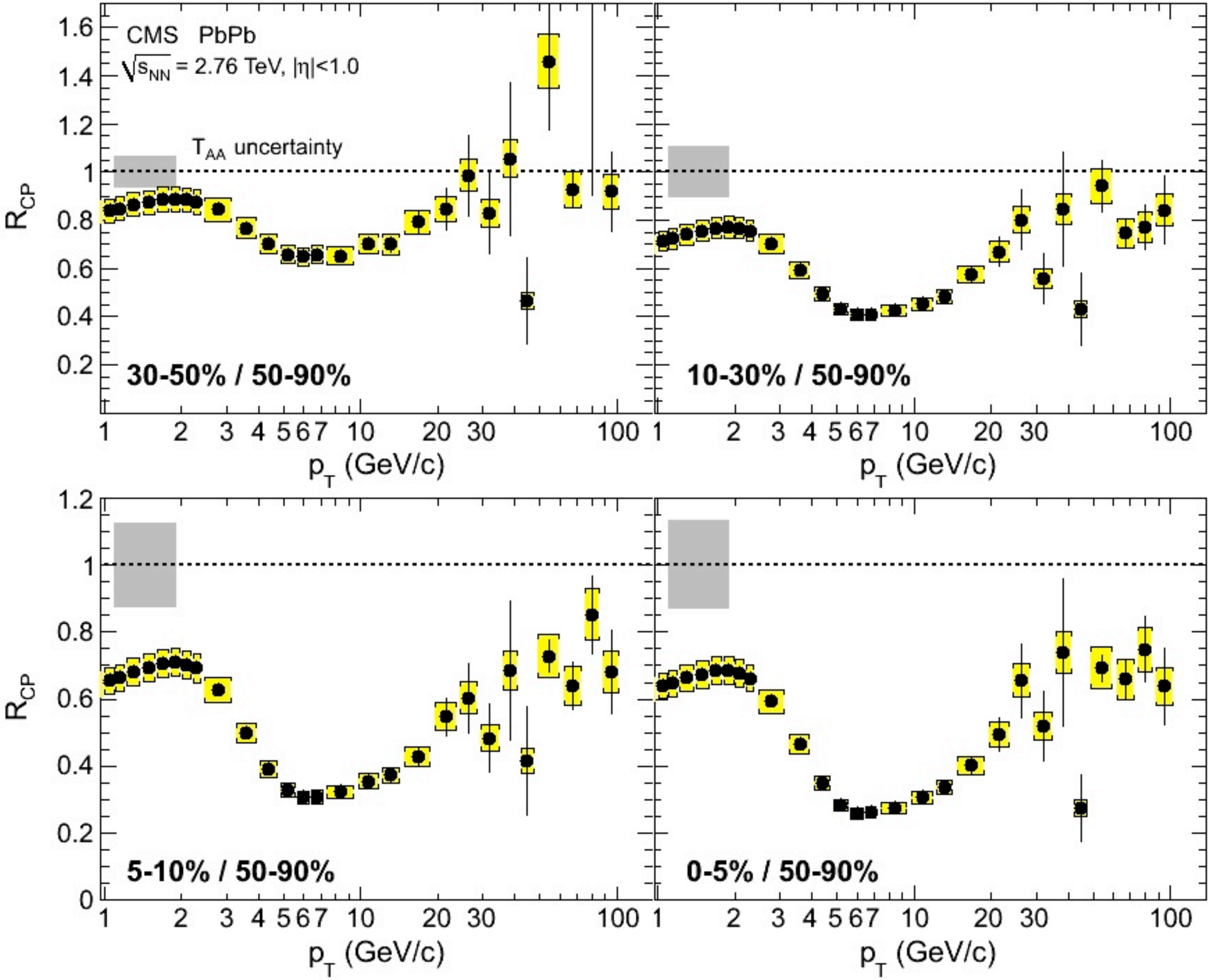


R_{AA}


CMS PbPb
$\sqrt{s_{NN}}$ = 2.76 TeV, |η|<1.0
T_{AA} and lumi. uncertainty
R_{AA}
70-90%
50-70%
30-50%
10-30%
5-10%
0-5%
Pb Pb
p_T (GeV/c)

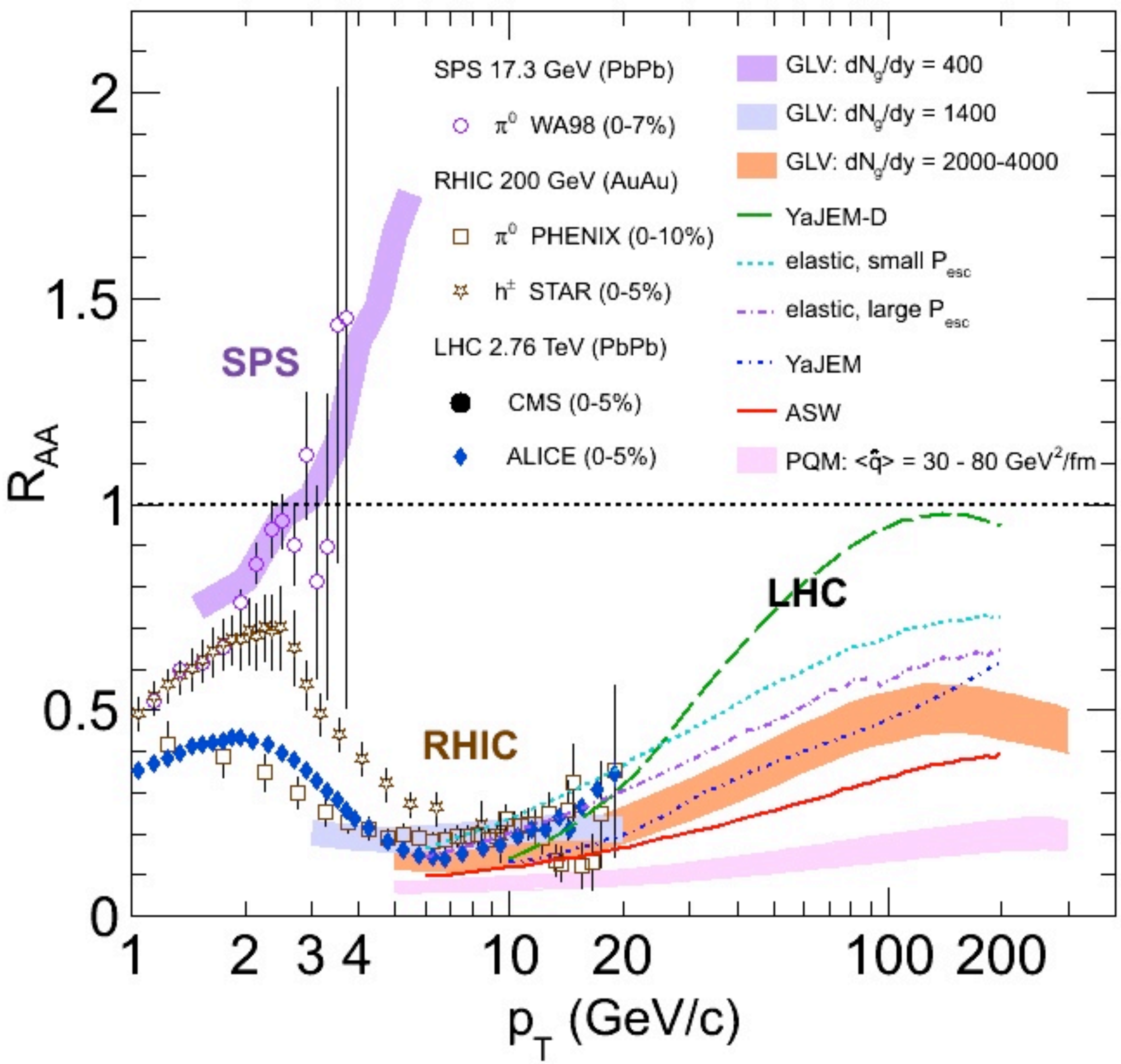
$$R_{CP} \equiv \frac{d^2N_{AA}/dp_T d\eta / N_{coll}(\text{central})}{d^2N_{AA}/dp_T d\eta / N_{coll}(\text{peripheral})}$$

→ Self-calibrating (no dependence on reference spectra)

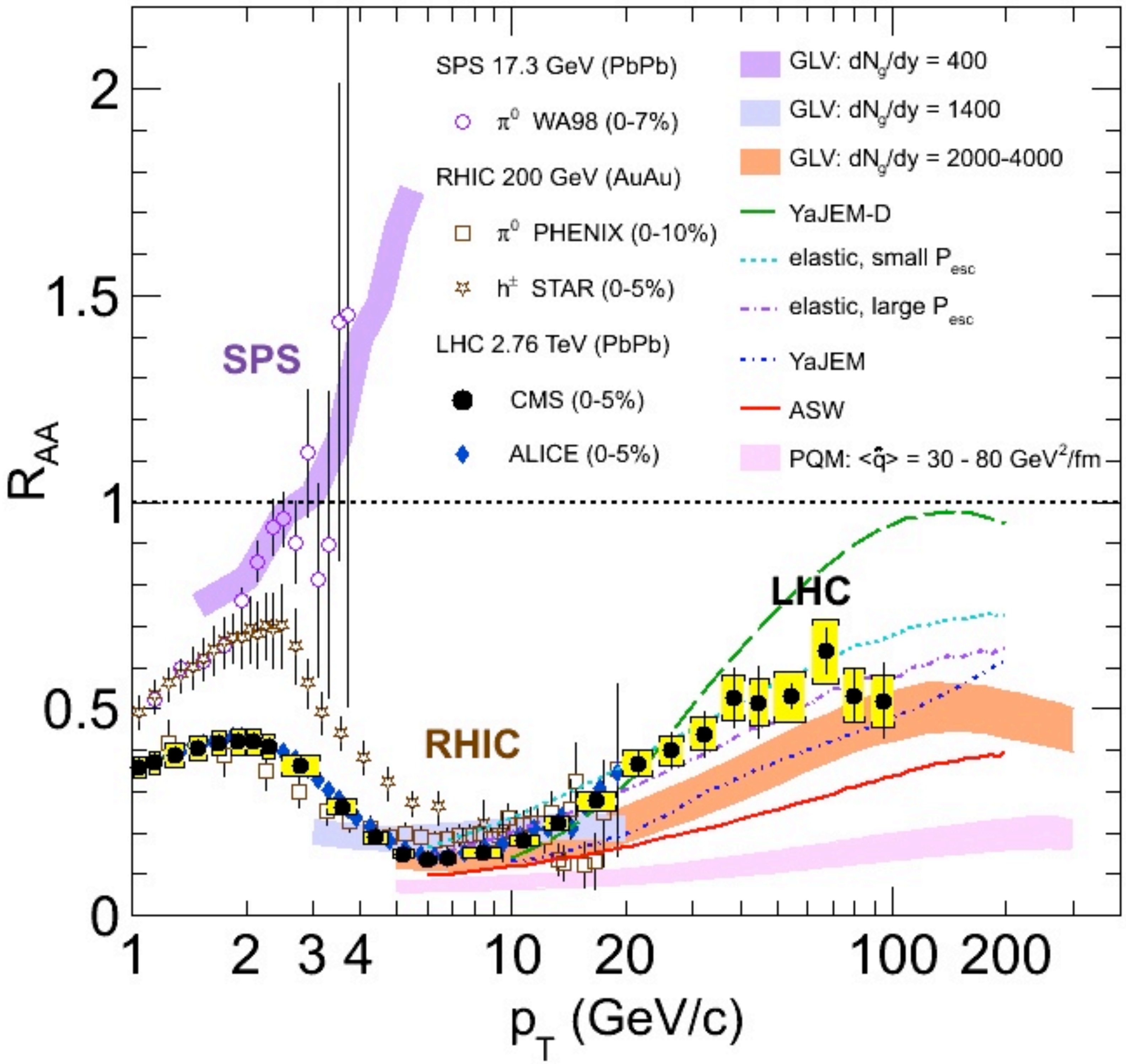


Large suppression and similar shape but suffers from fluctuation in the denominator.

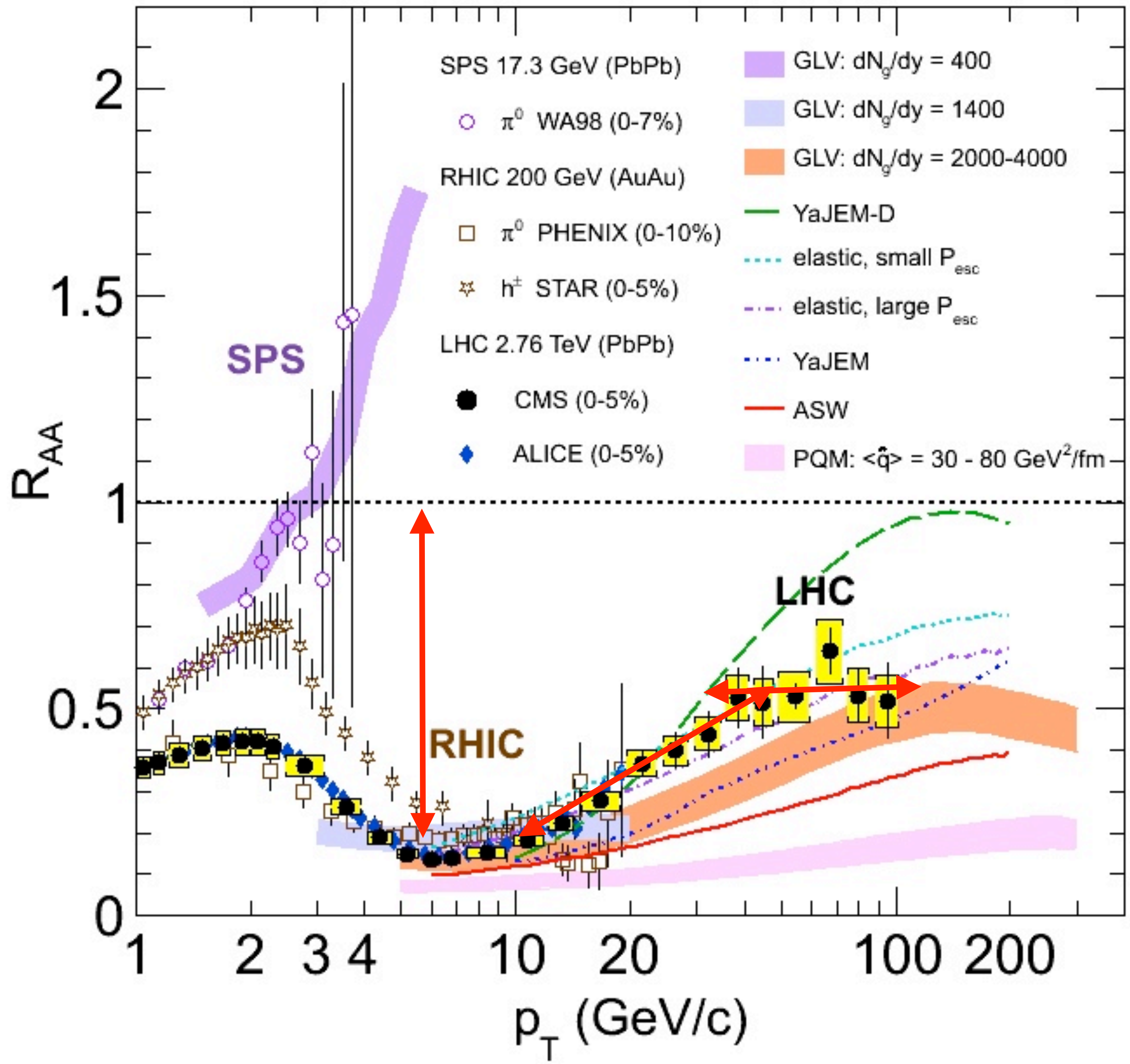
Previous State of Knowledge



Current State of Knowledge

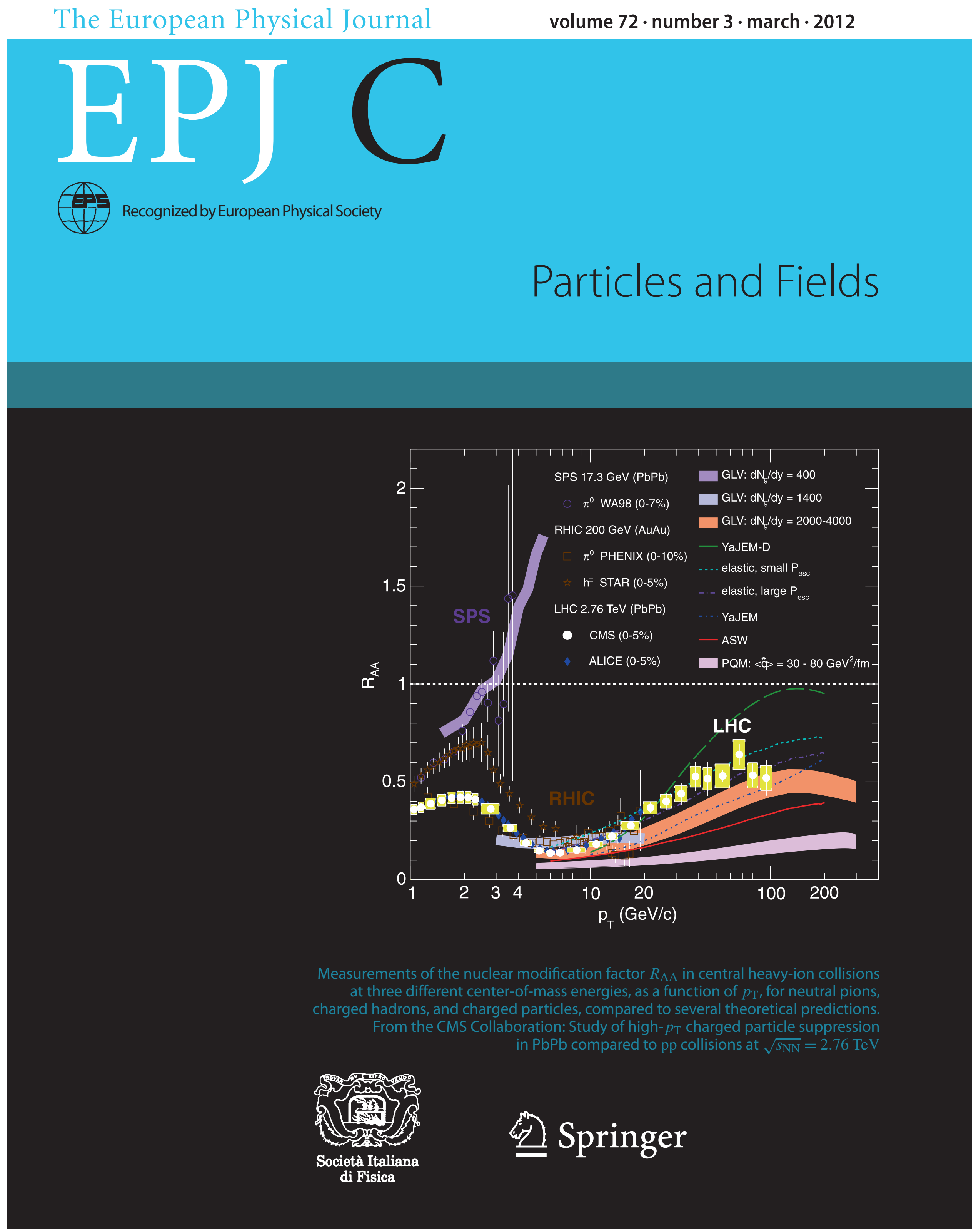


Current State of Knowledge



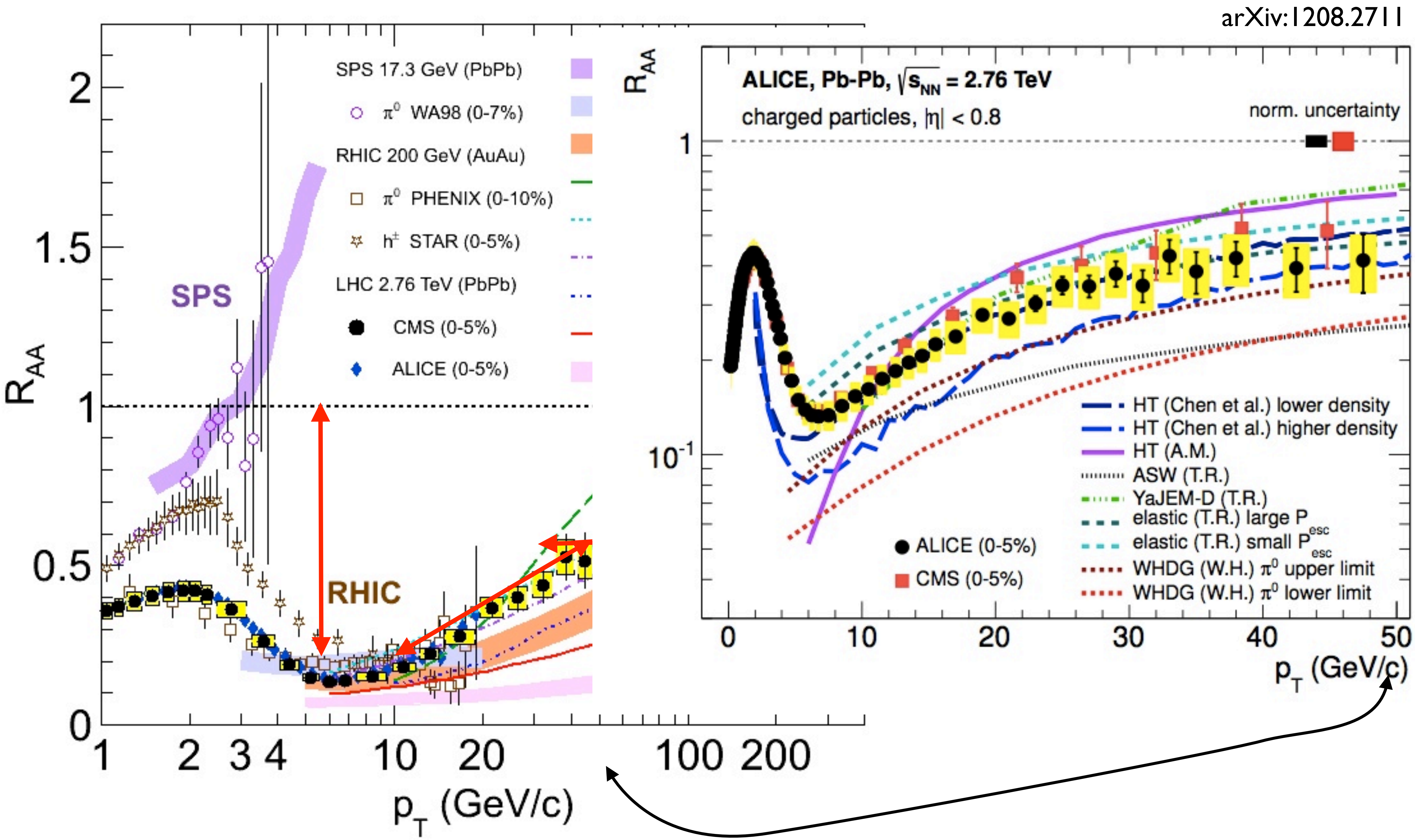
Larger Suppression + Fast Rise + Lebel-Off

Current State of Knowledge



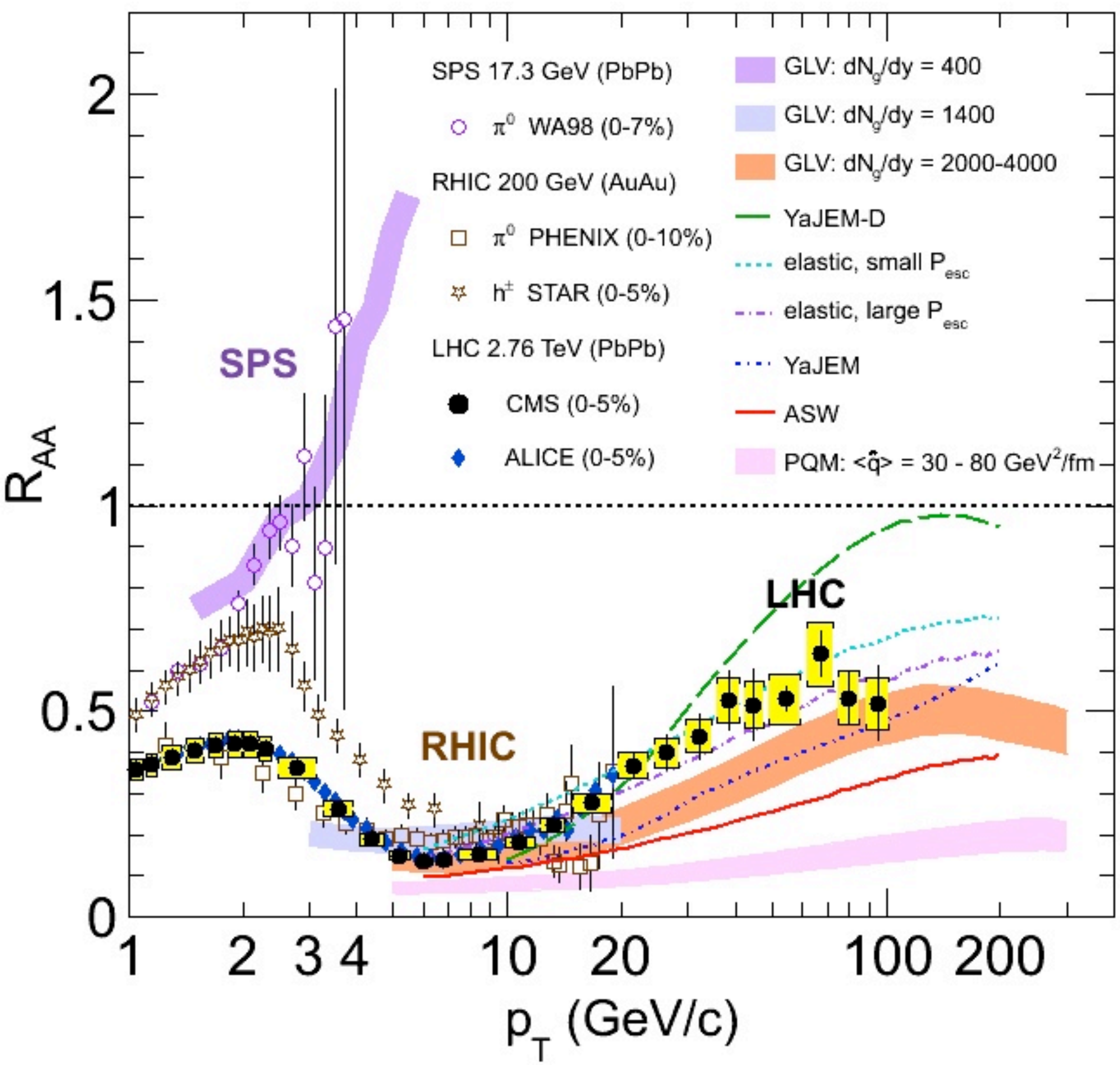
Current State of Knowledge

arXiv:1208.2711



Good to be confirmed by independent measurements!

Different Theoretical Models



GLV: N-well separated color-screened Yukawa potential (i.e., opacity) with dN^g/dy as a free parameter (5.5 TeV)

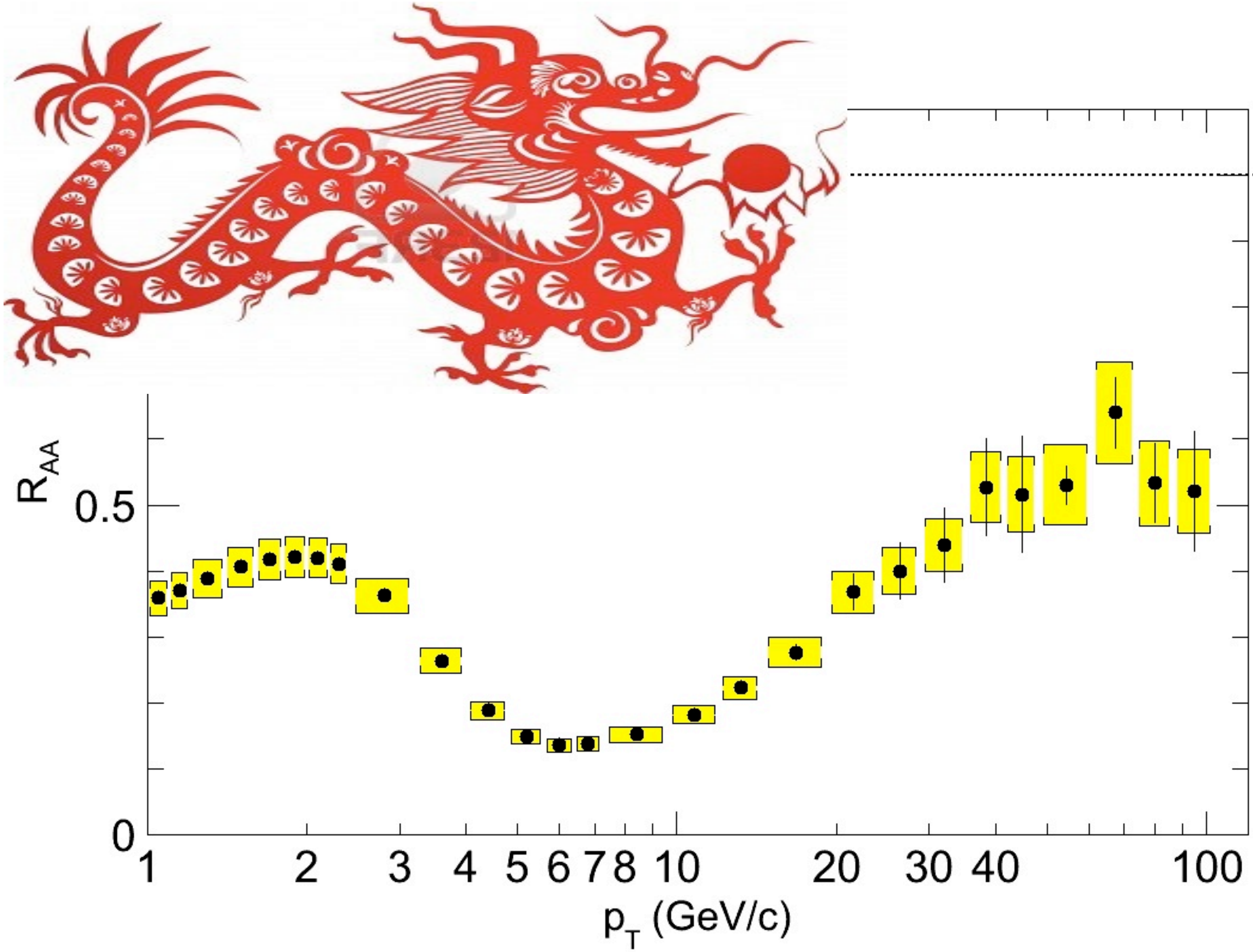
ASW: Multiple soft-scattering approximation with $\hat{q}$ tuned to RHIC measurements

YaJEM(-D): Medium induced radiation implemented via modified splitting probability (D is with dynamic cut-off)

P_{esc}: Phenomenological models for elastic energy loss with escape probability, P_{esc}

PQM: MC calculation of quenching based on the multiple soft-scattering approximation with $\hat{q}$ tuned (5.5 TeV)

Q: Why does the shape look as it is?



Q: Knowing the shape of R_{AA}, can we discern different energy loss models?

Parton Energy Loss Models

1. Constant E-loss: $E' = E - \Delta E$

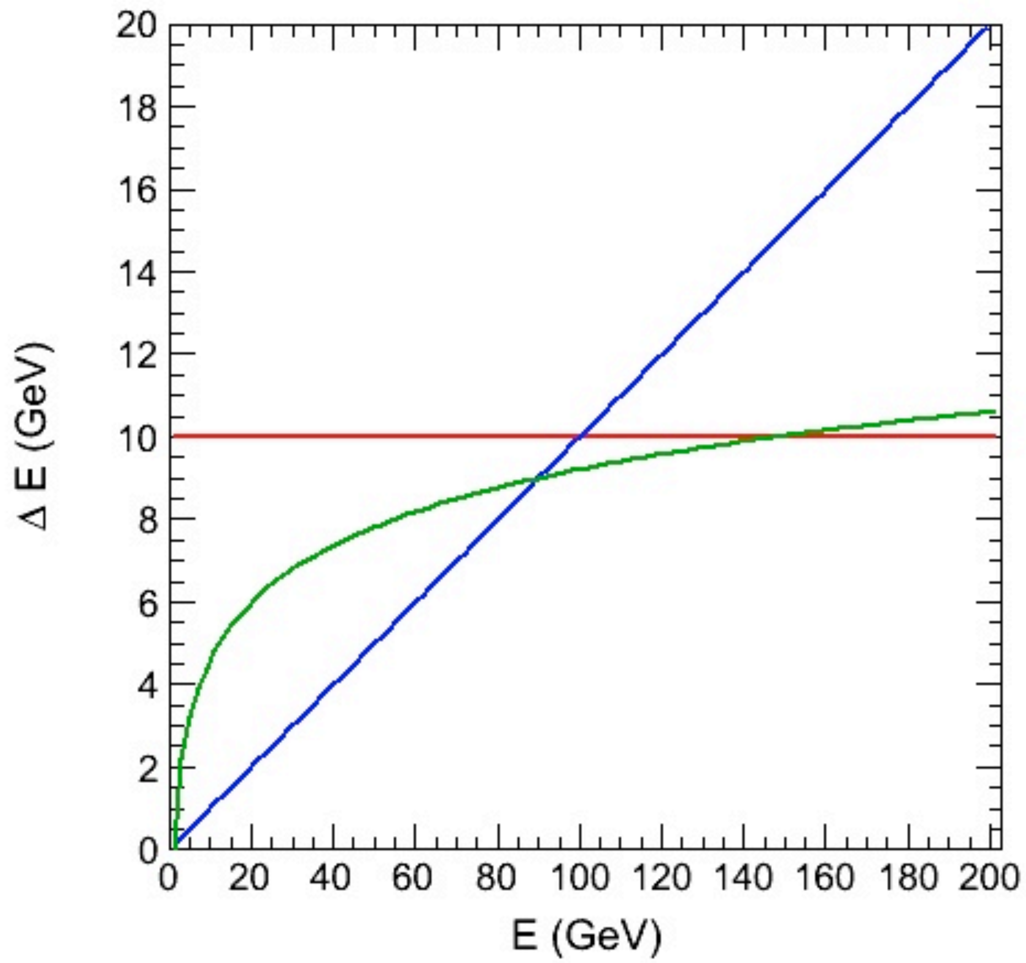
2. Fractional E-loss

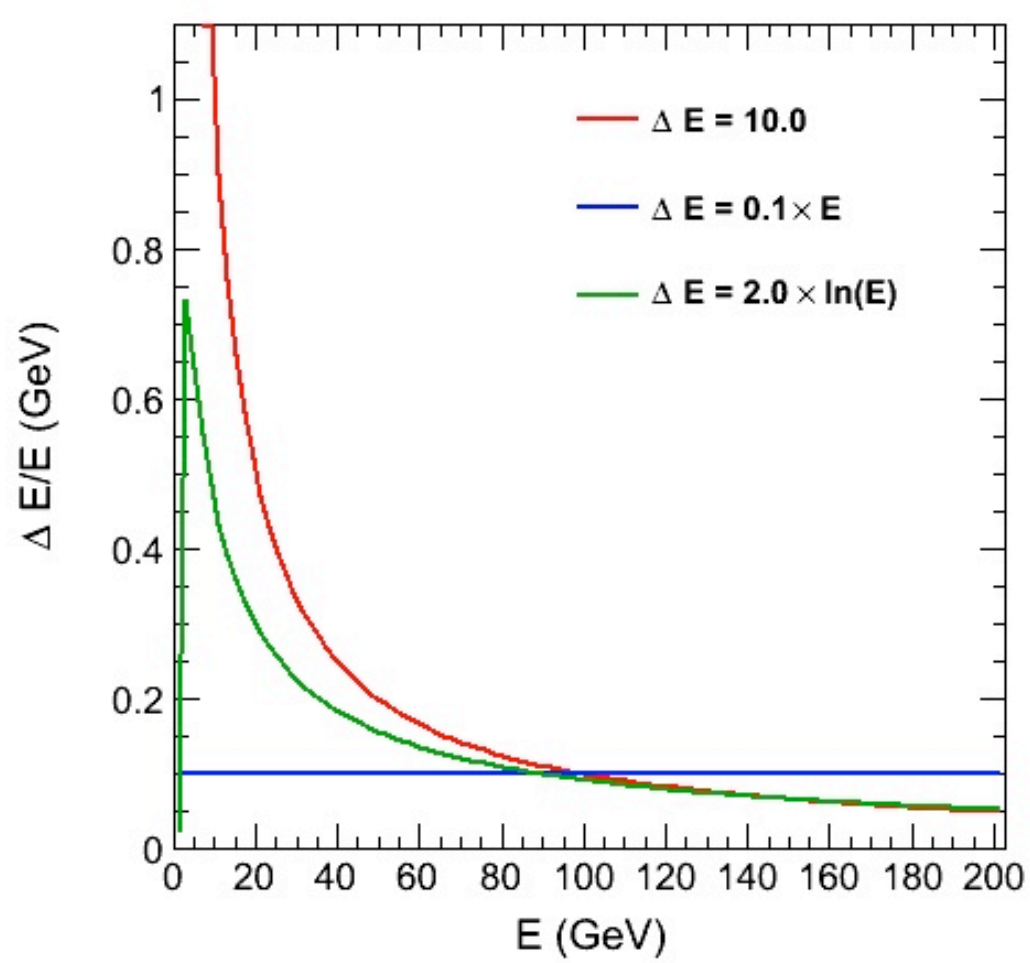
- Constant fraction: $E' = E \times (1-f)$
- E-dependent fraction: $E' = E \times (1 - c \cdot \ln(E)/E)$

$$E' = E \times (1 - c \cdot \ln(E)/E) = E - c \cdot \ln(E) \quad \therefore \quad \Delta E = c \cdot \ln(E)$$

$$\Delta E \approx \frac{C_R \alpha_s}{N(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}$$ GLV model!

Parton Energy Loss Models





Absolute amount of lost energy

Fractional amount of lost energy

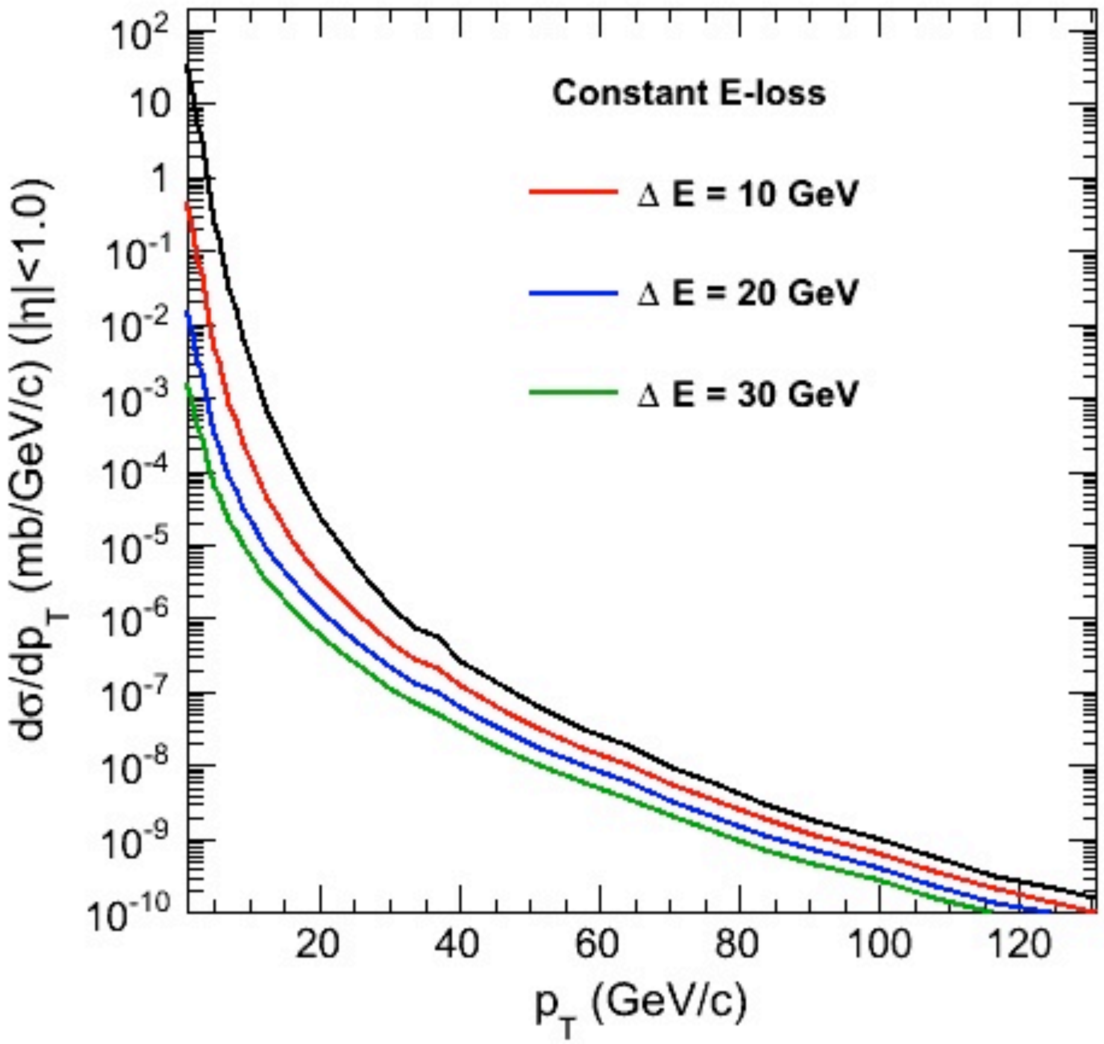
ΔE

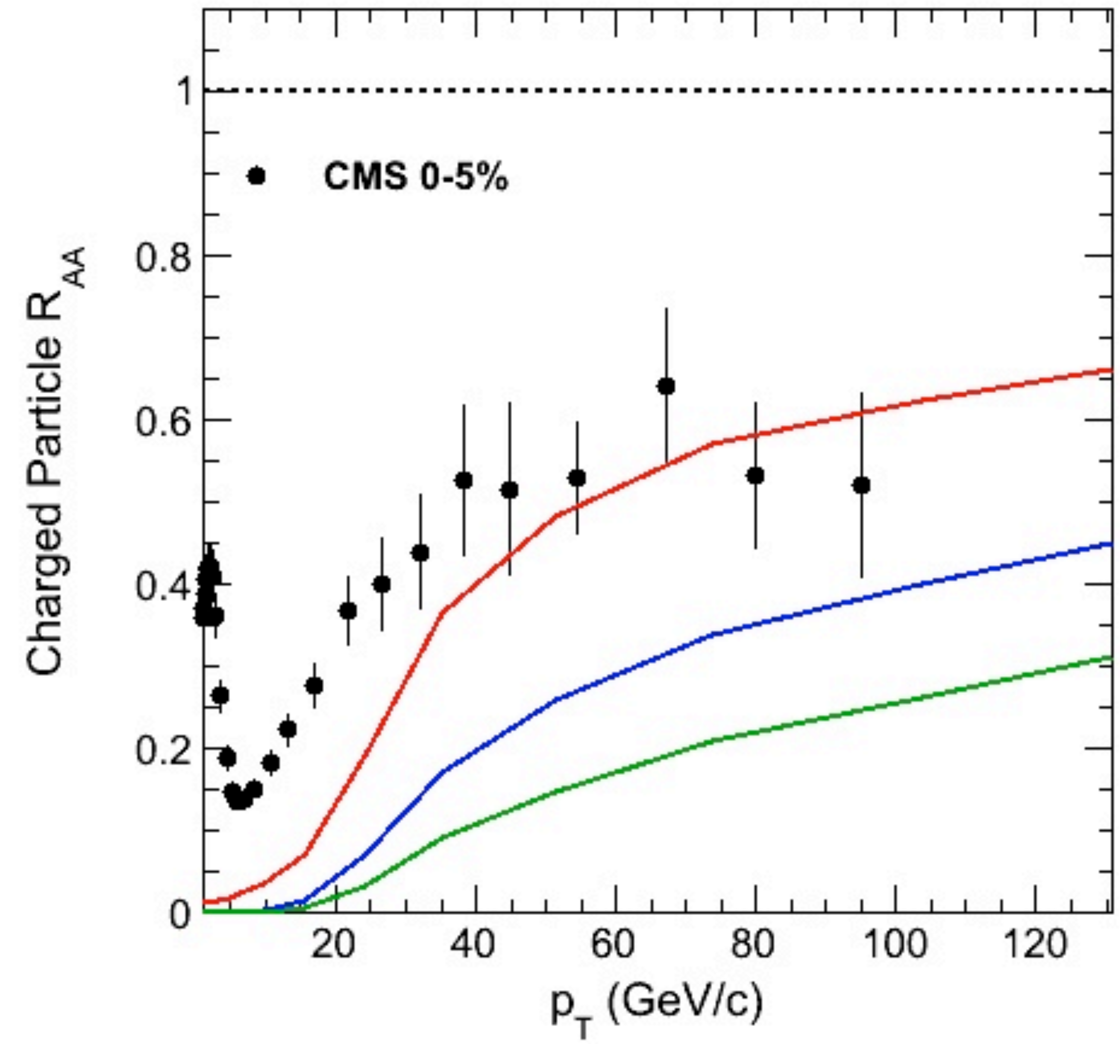
$\Delta E/E$

Constant E-loss

$E' = E - \Delta E$

$\Delta E = 10, 20, 30$



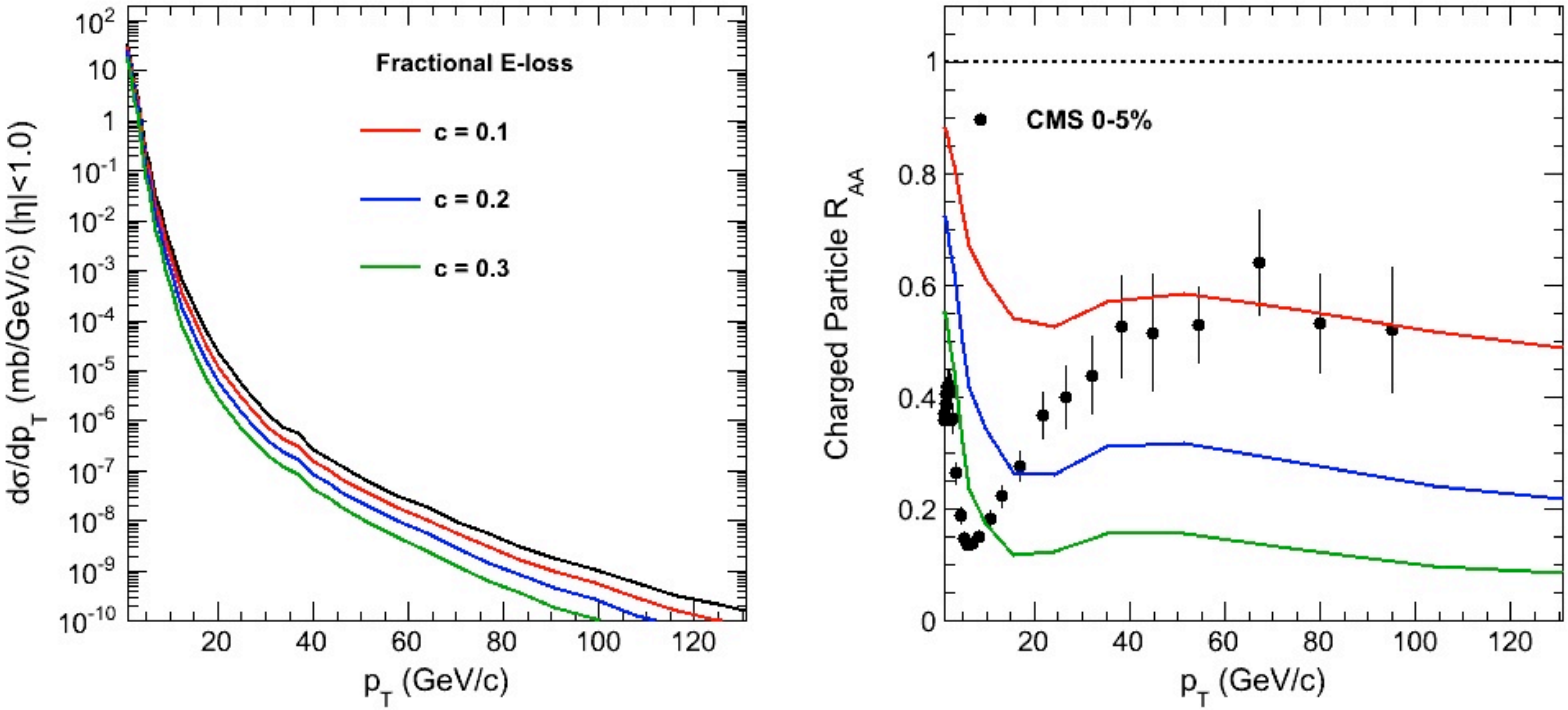


Large fraction of low-p_T parton and therefore charged particles are removed!

Fractional E-loss

$E' = E \times (1-f)$

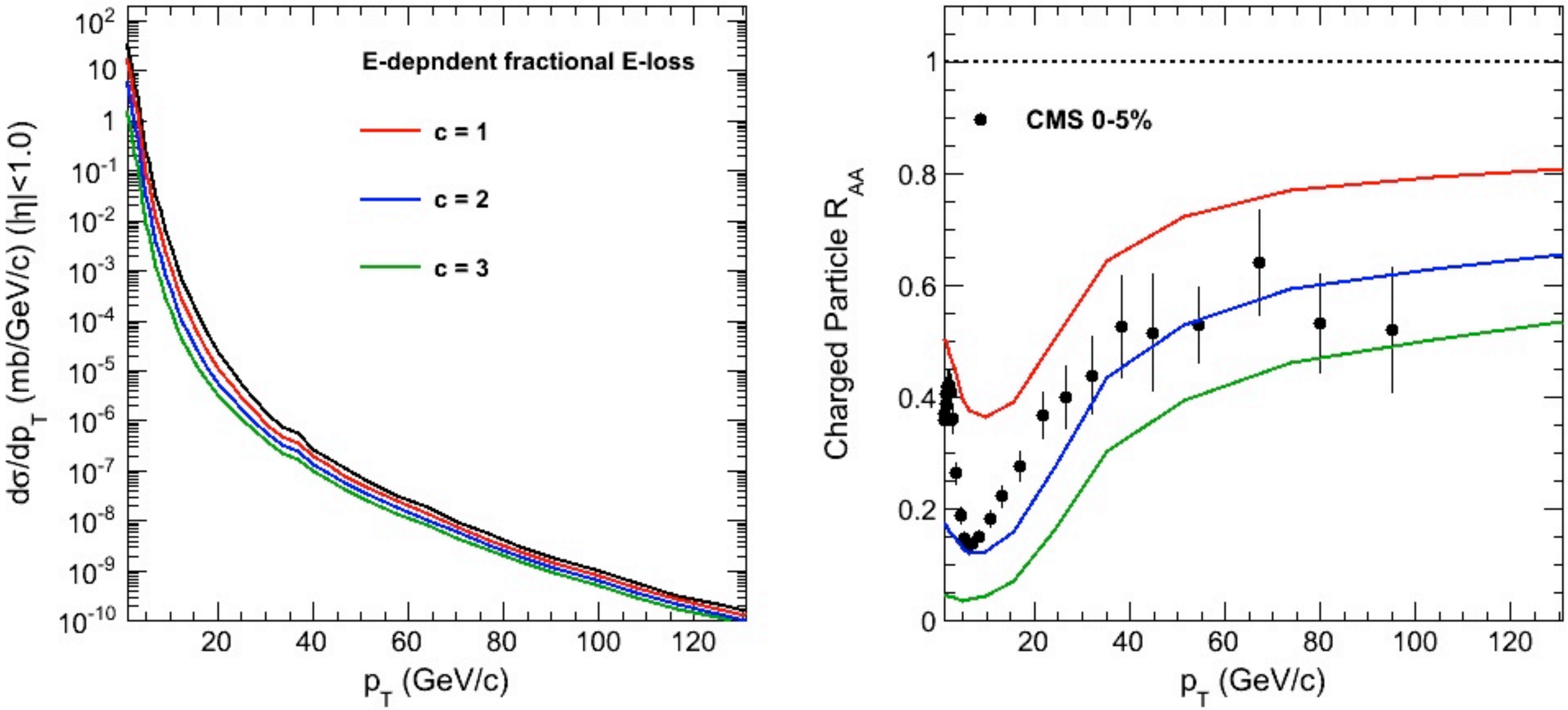
$f = 0.1, 0.2, 0.3$



Increasing fraction of high-p_T parton and therefore charged particles are removed!

Fractional E-loss with logarithmic dependence

$E' = E \times (1 - c \cdot \ln(E)/E)$ c = 1, 2, 3



Good description shape-wise!

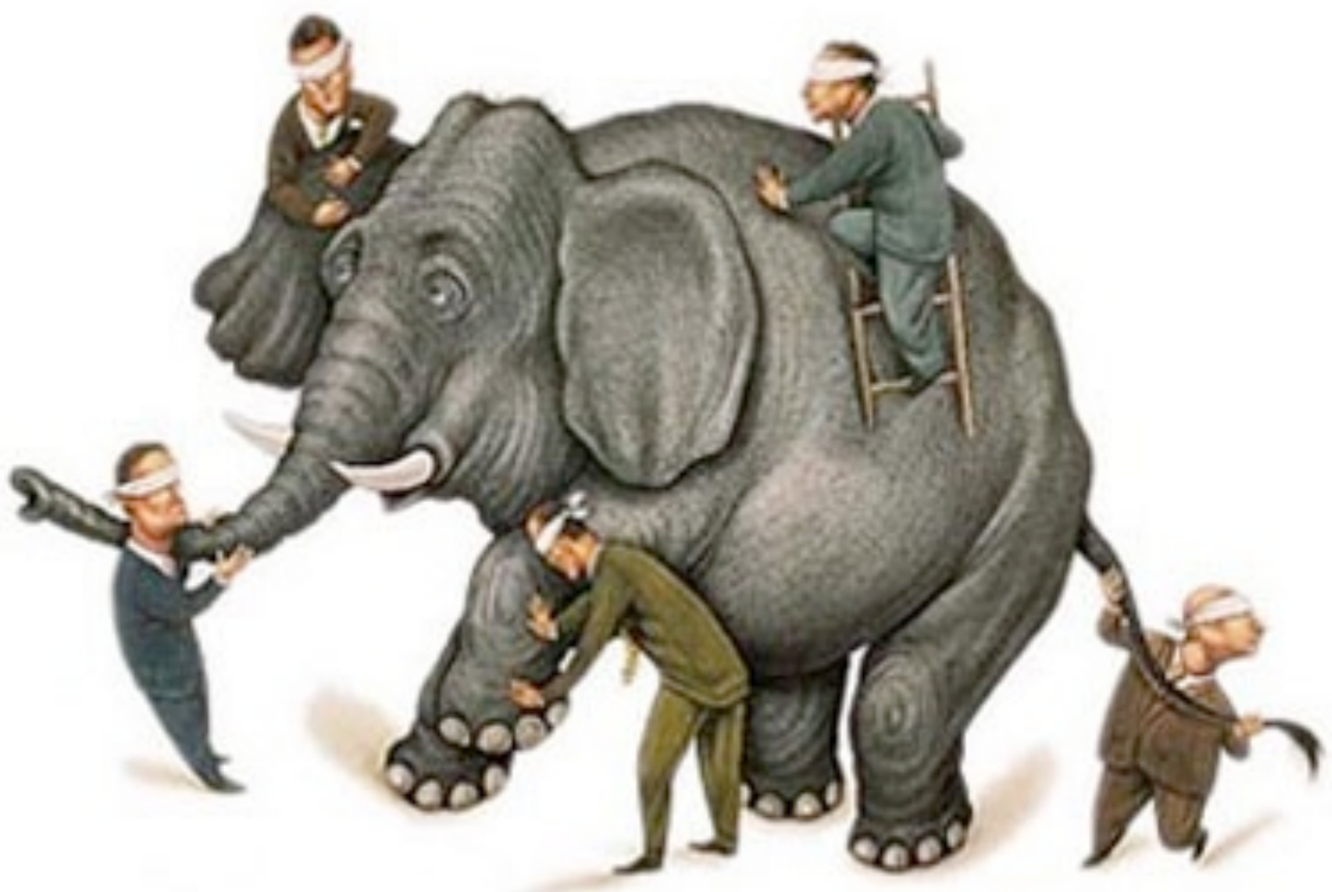
R_{AA} Toy Model Study

1. High-p_T region could be described by different models, which are wildly different toward the low-p_T region.

2. Fractional energy loss with logarithmic energy dependence is highly preferred.

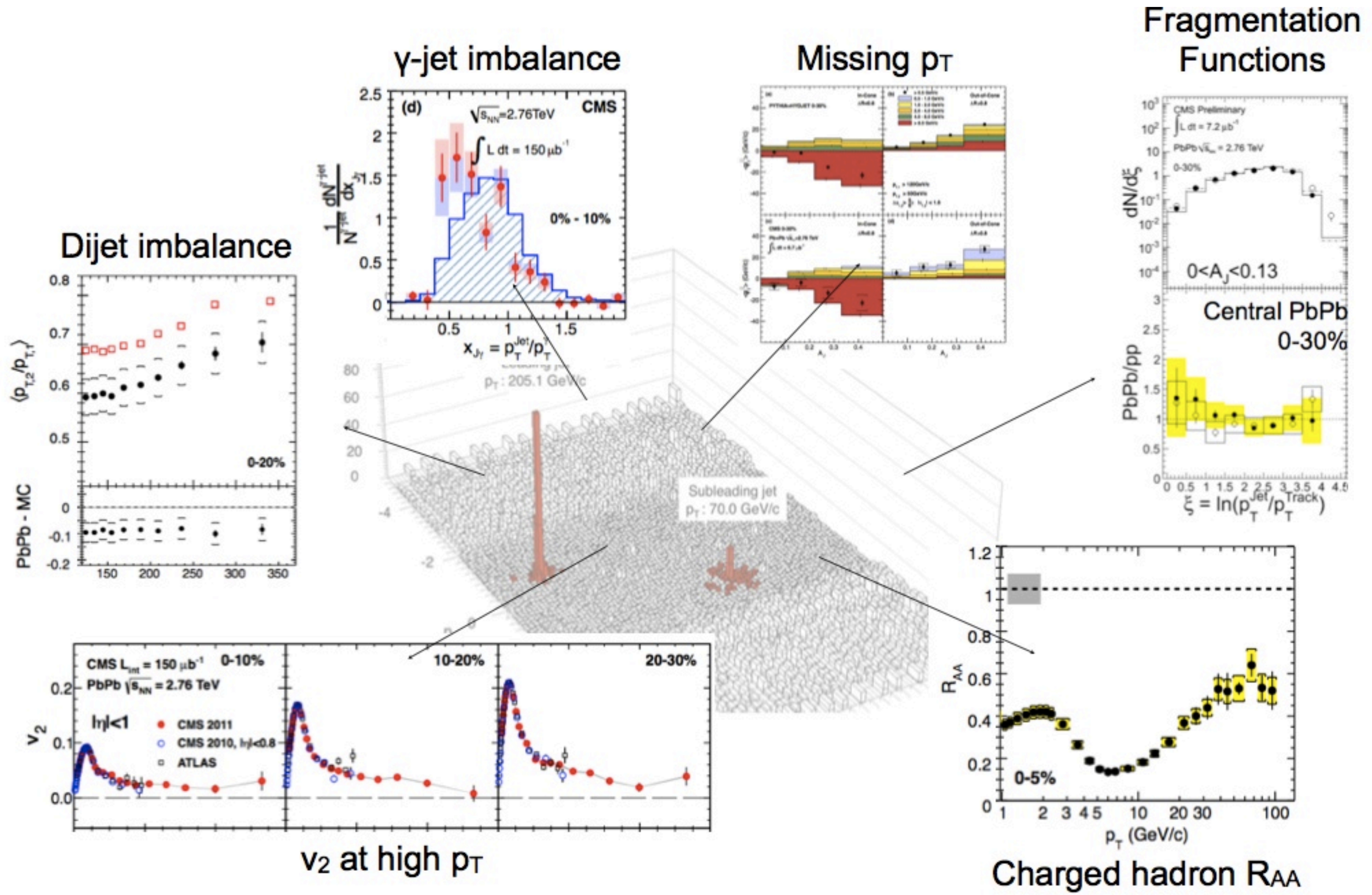
3. Overall magnitude of suppression is yet subject to further studies.

Blind men and An elephant



http://inquiry111westminster.wikispaces.com/

More Jet Quenching Observable...



Summary and Conclusions

1. High p_T charged particle productions → Well understood in pp collisions at TeV-scale energies.

2. Large suppression of high p_T particles in PbPb collisions with characteristic shape → Signature of large final state effect and constraining energy loss models

3. Correlating with other jet quenching observables → further elucidate the detailed mechanism of parton energy loss and medium properties.

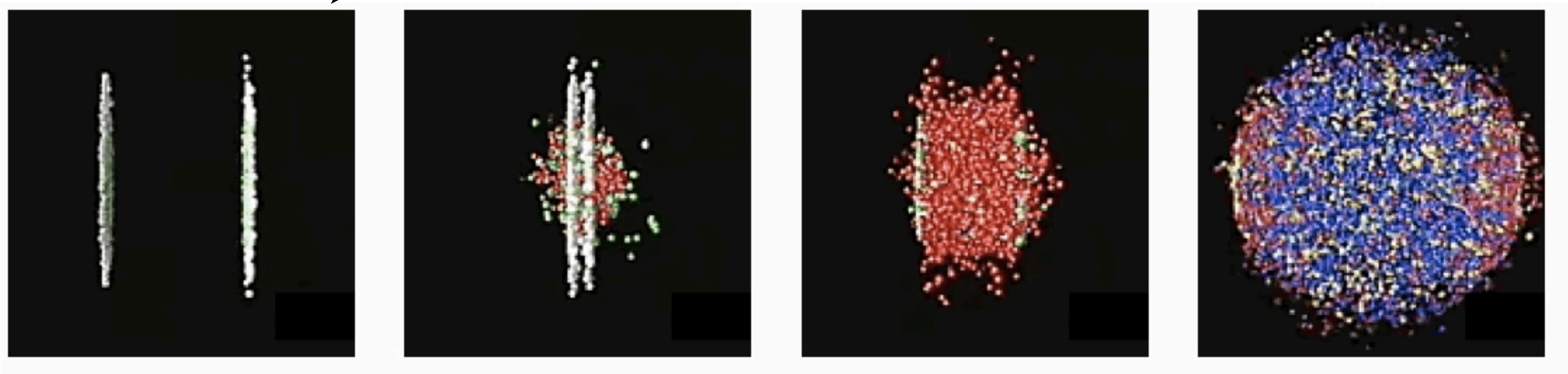
Backup Slides

Heavy Ion Collisions

RHIC

LHC

Time

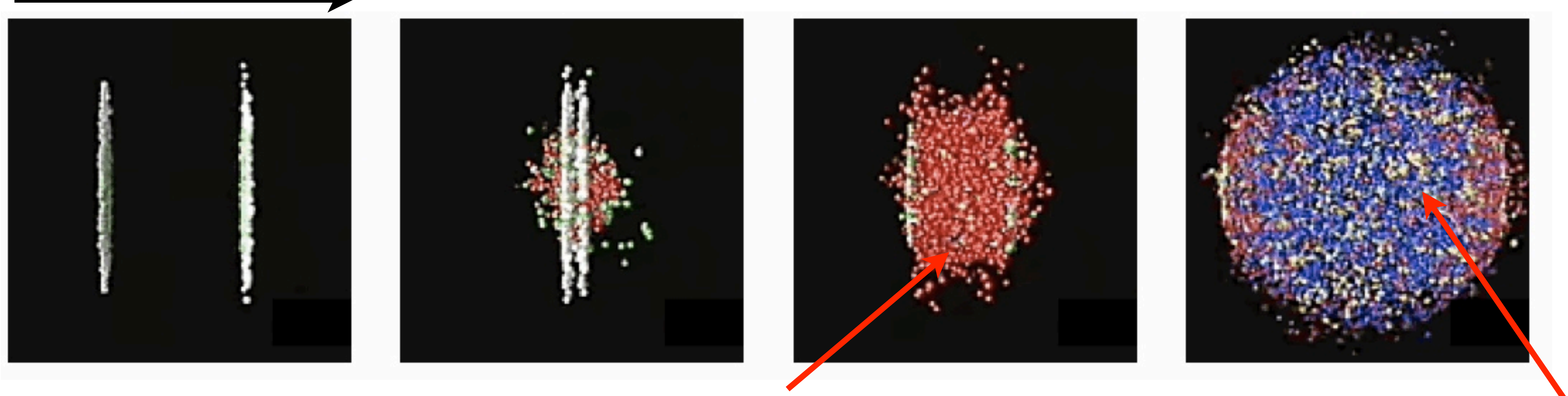


Heavy Ion Collisions

RHIC

LHC

Time →



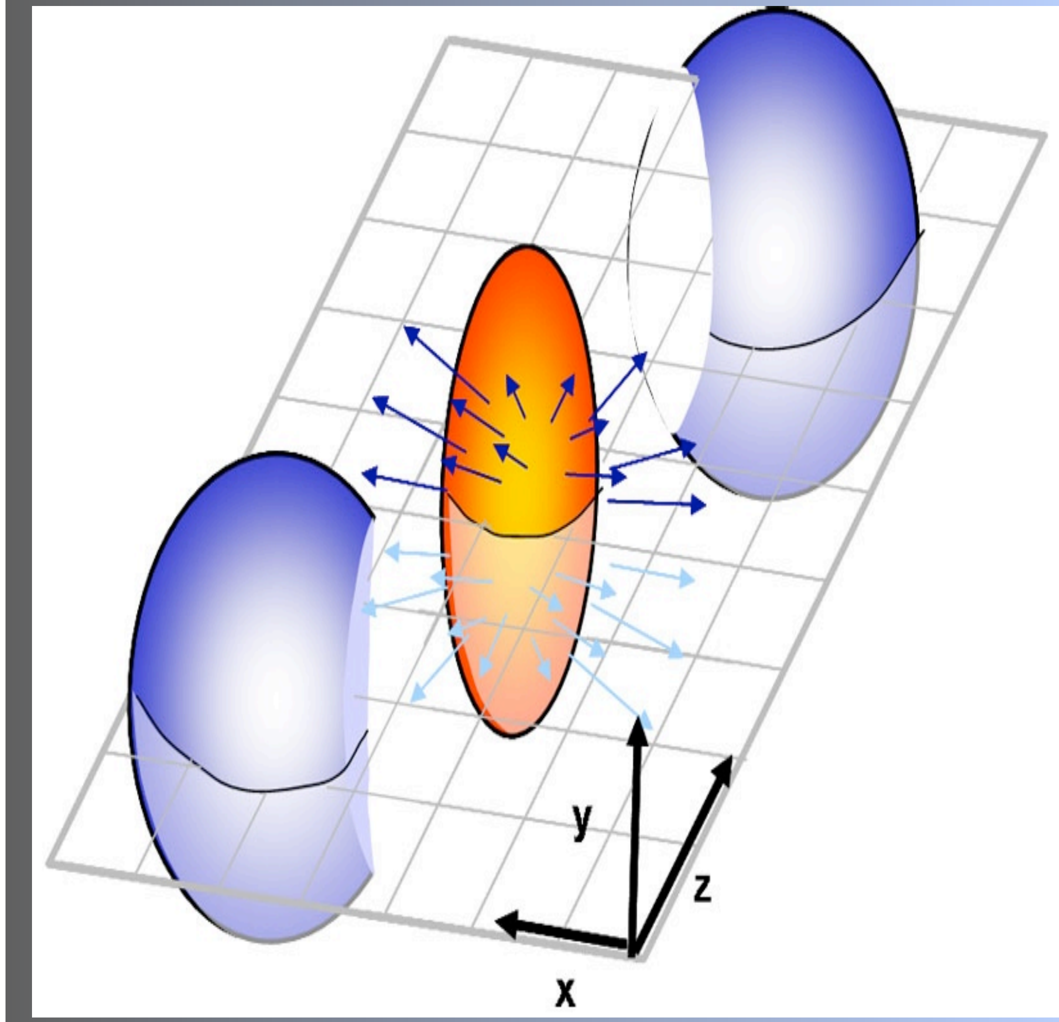
High temperature ← excess of direct photon yield   High energy density ← N_{ch}

Study bulk properties of QCD matter created in Heavy Ion collisions

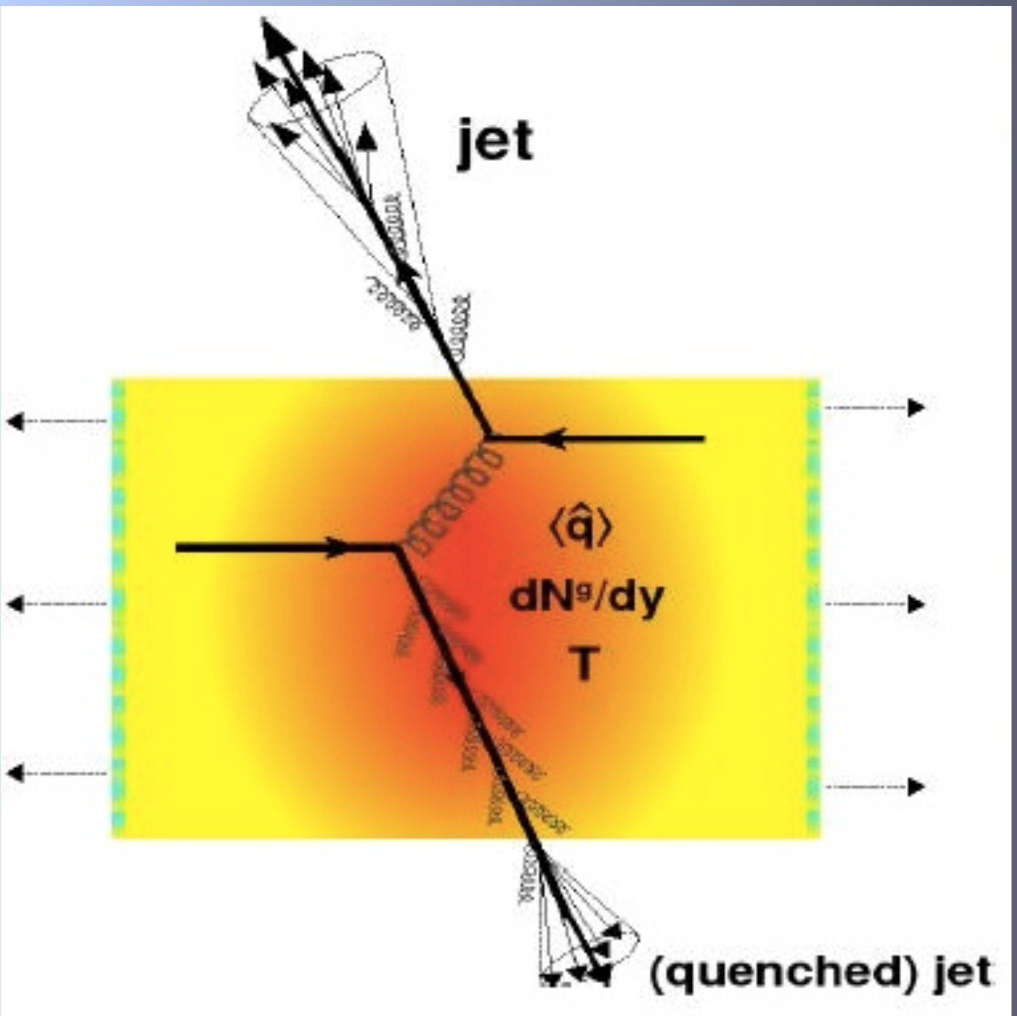
Heavy Ion Collisions

"Two Pillars" of Heavy Ion Physics

Azimuthal anisotropy (v_n)



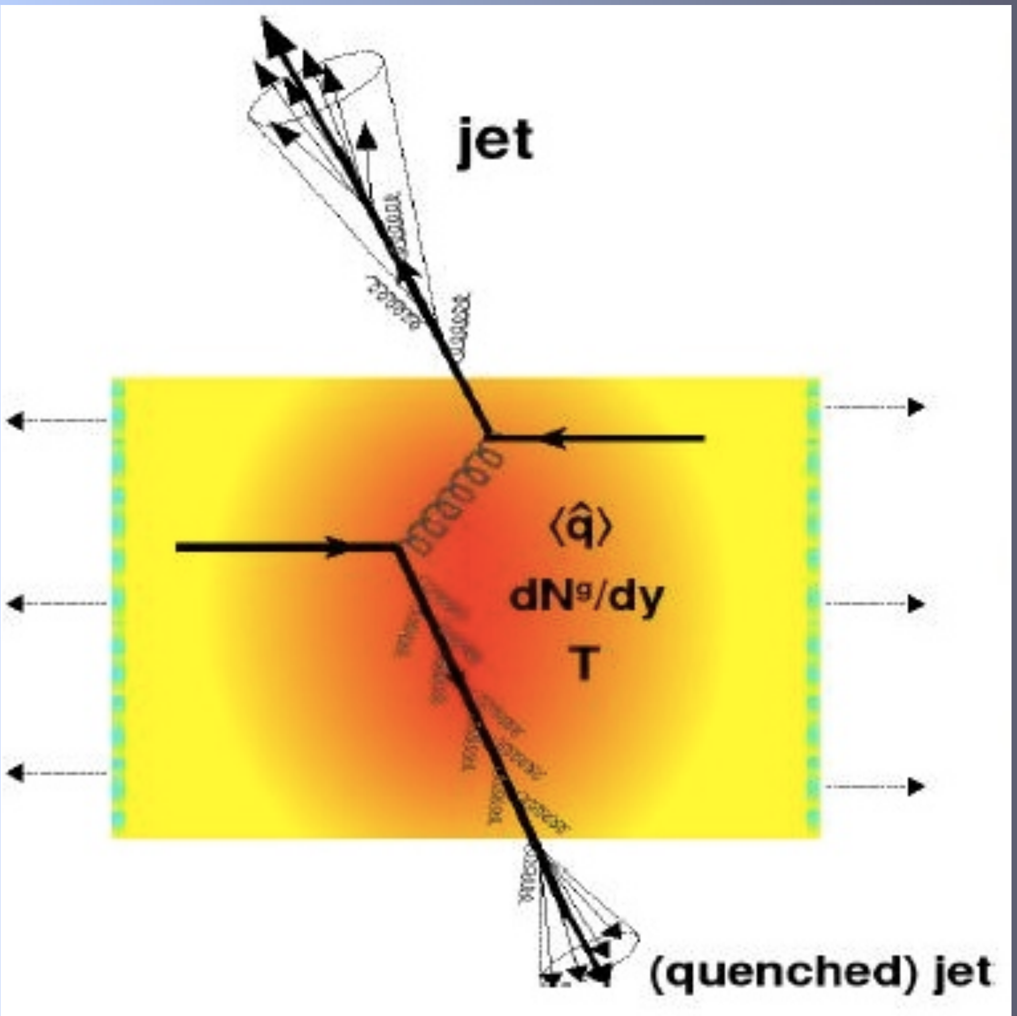
Jet Quenching ($\hat{q}$)



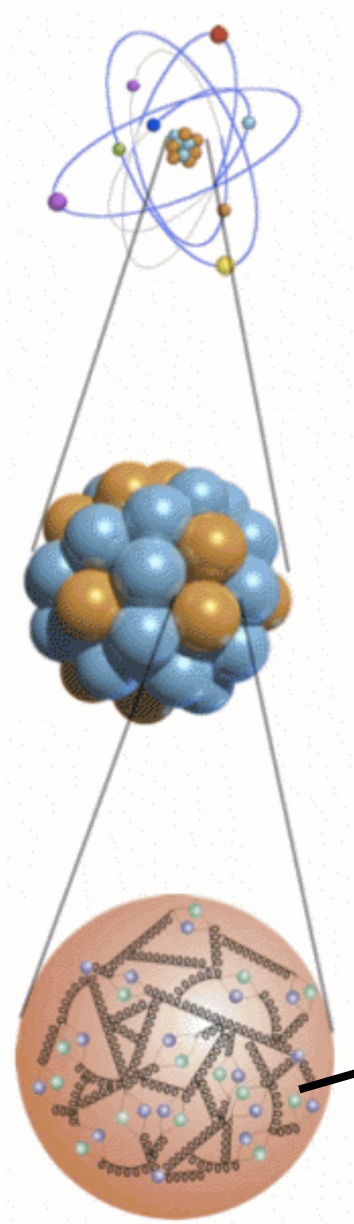
Heavy Ion Collisions

"Two Pillars" of Heavy Ion Physics

Jet Quenching ($\hat{q}$)



What will happen if one puts ordinary matter in extreme conditions of temperature and density?



Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

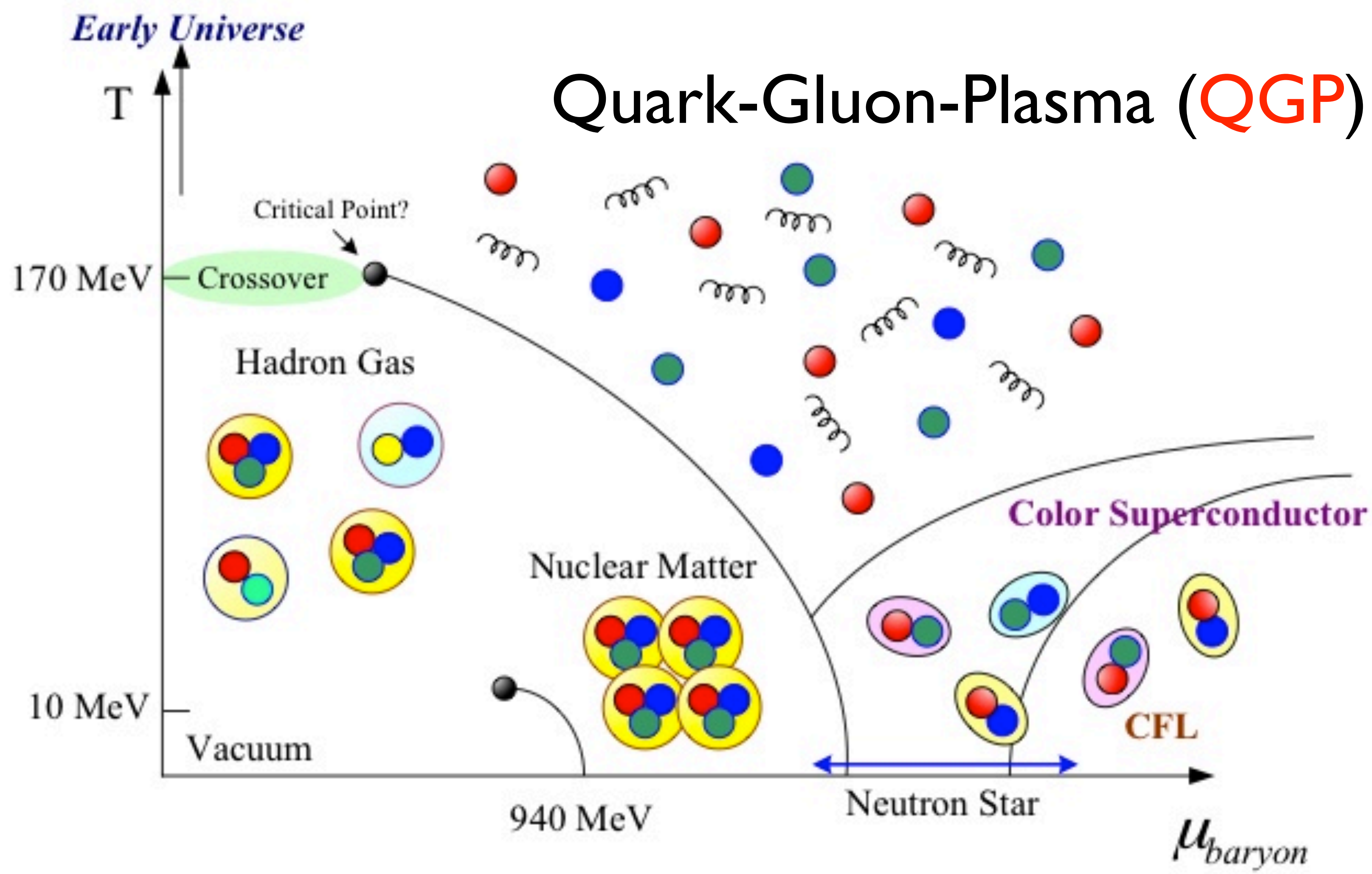
We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

$$\mathscr{L}_{QCD} = -\frac{1}{4} F^{(a)}_{\mu\nu} F^{(a)\mu\nu} + i \sum_q \bar{\psi}_{qi} (\gamma^\mu (D_\mu)^i_j - m_q \delta^i_j) \psi^j_q$$

Relevant degree of freedom:
fundamental building blocks of matter

Quantum ChromoDynamics (QCD)

What will happen if one puts ordinary matter in extreme conditions of temperature and density?

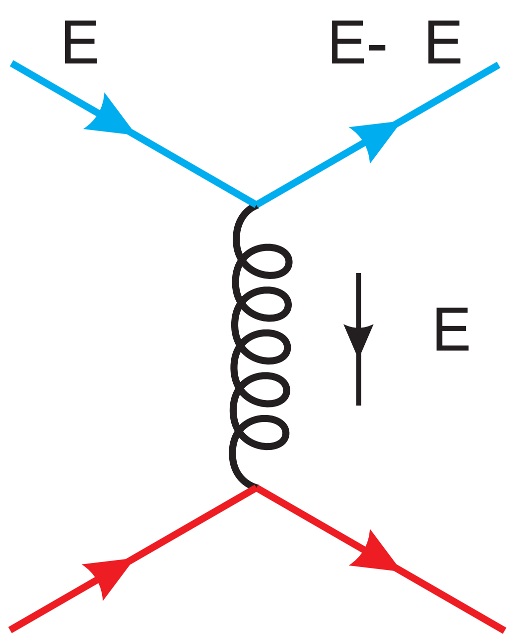


A 'universal' matter phase emerges at sufficiently high temperature.

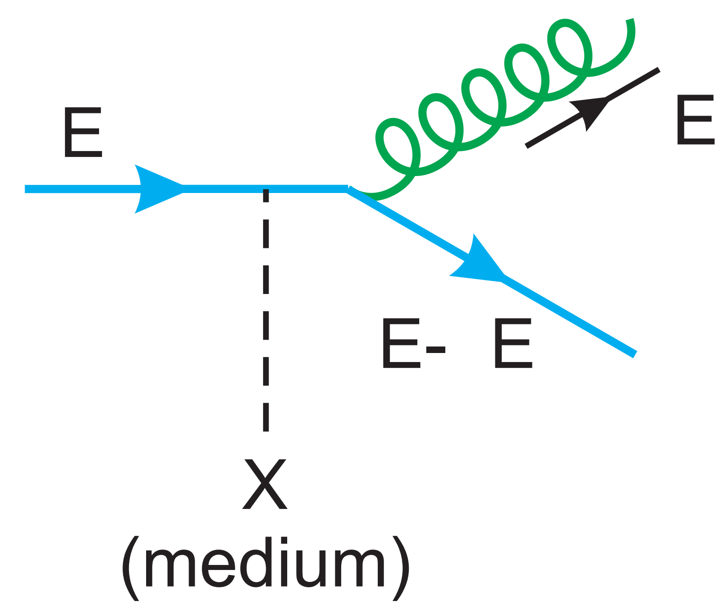
Energy Loss Mechanisms

The total energy loss of a quark or gluon traversing the medium is the sum of the energy losses due to two dominant mechanisms:

$$\Delta E = \Delta E_{\mathrm{coll}} + \Delta E_{\mathrm{rad}}$$



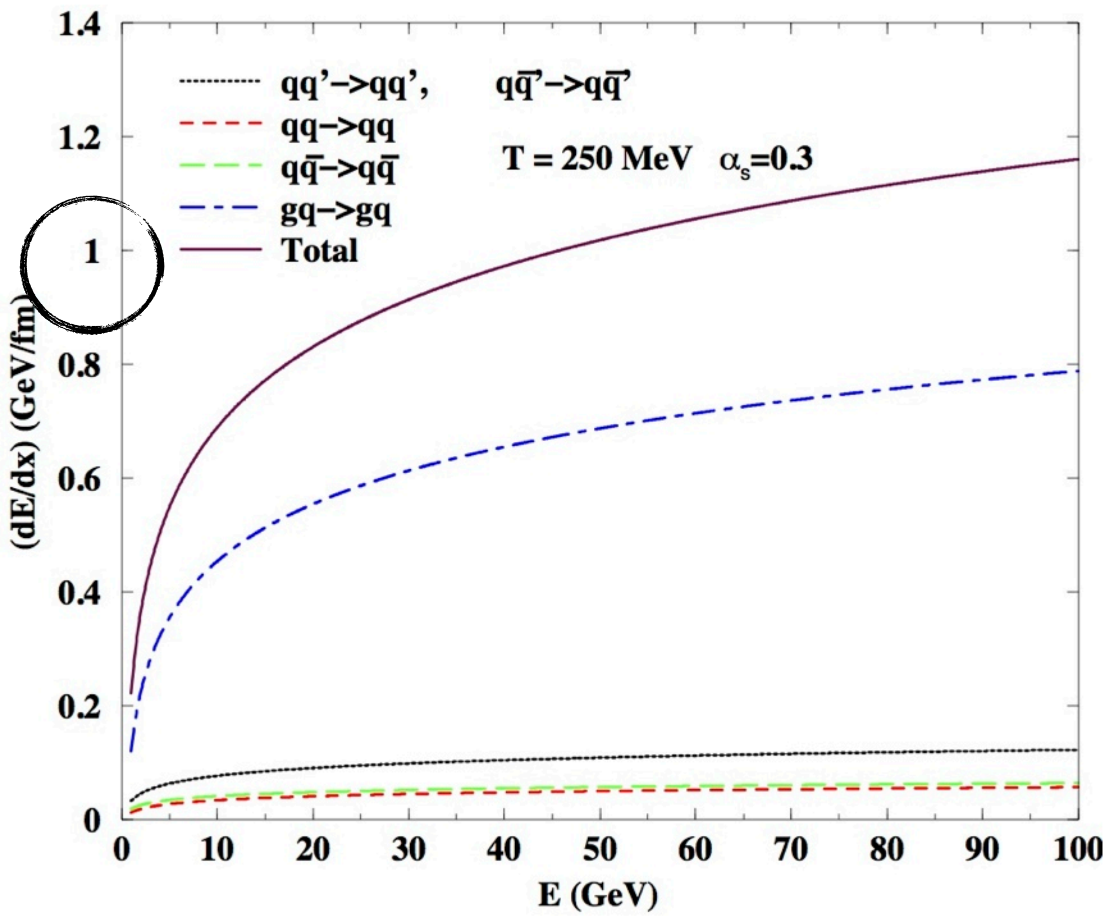
Collisional energy loss

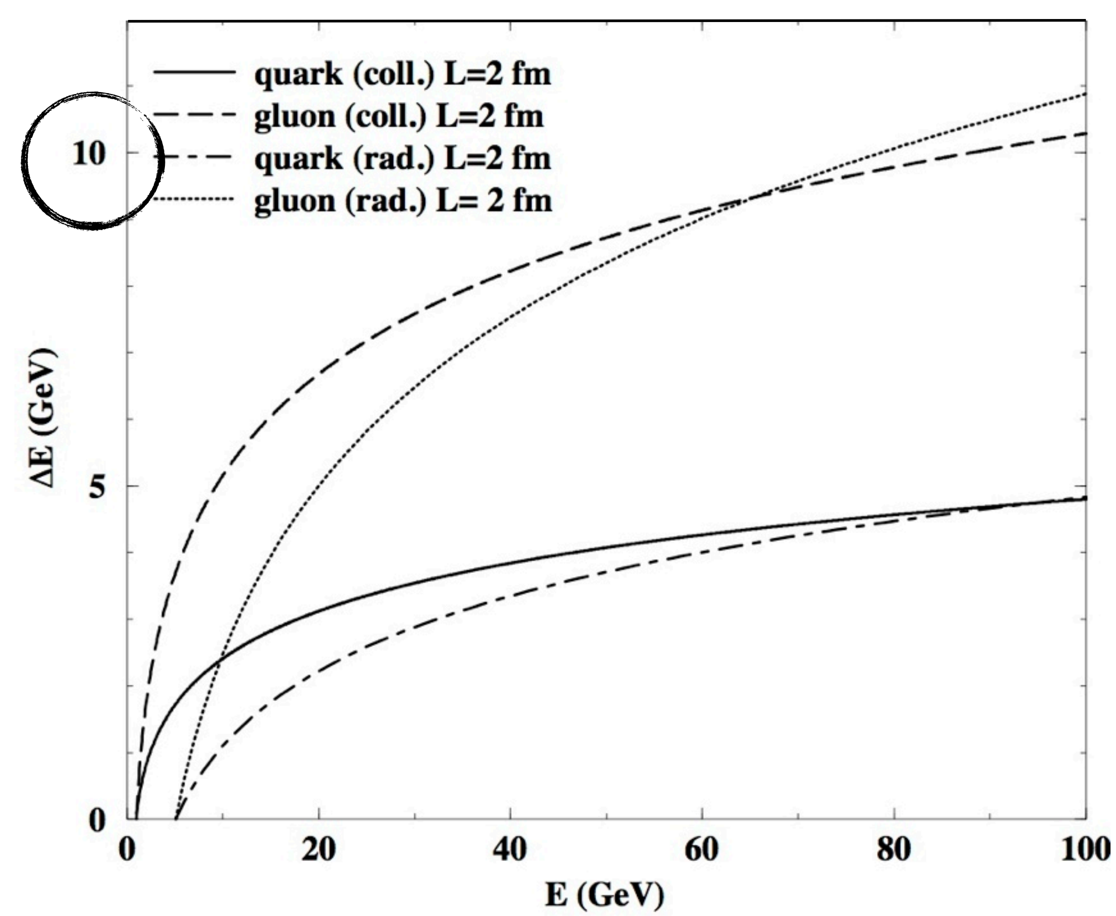


Radiative energy loss

Collisional E-Loss vs Radiative E-Loss

Phys.Rev., D71:094016, 2005





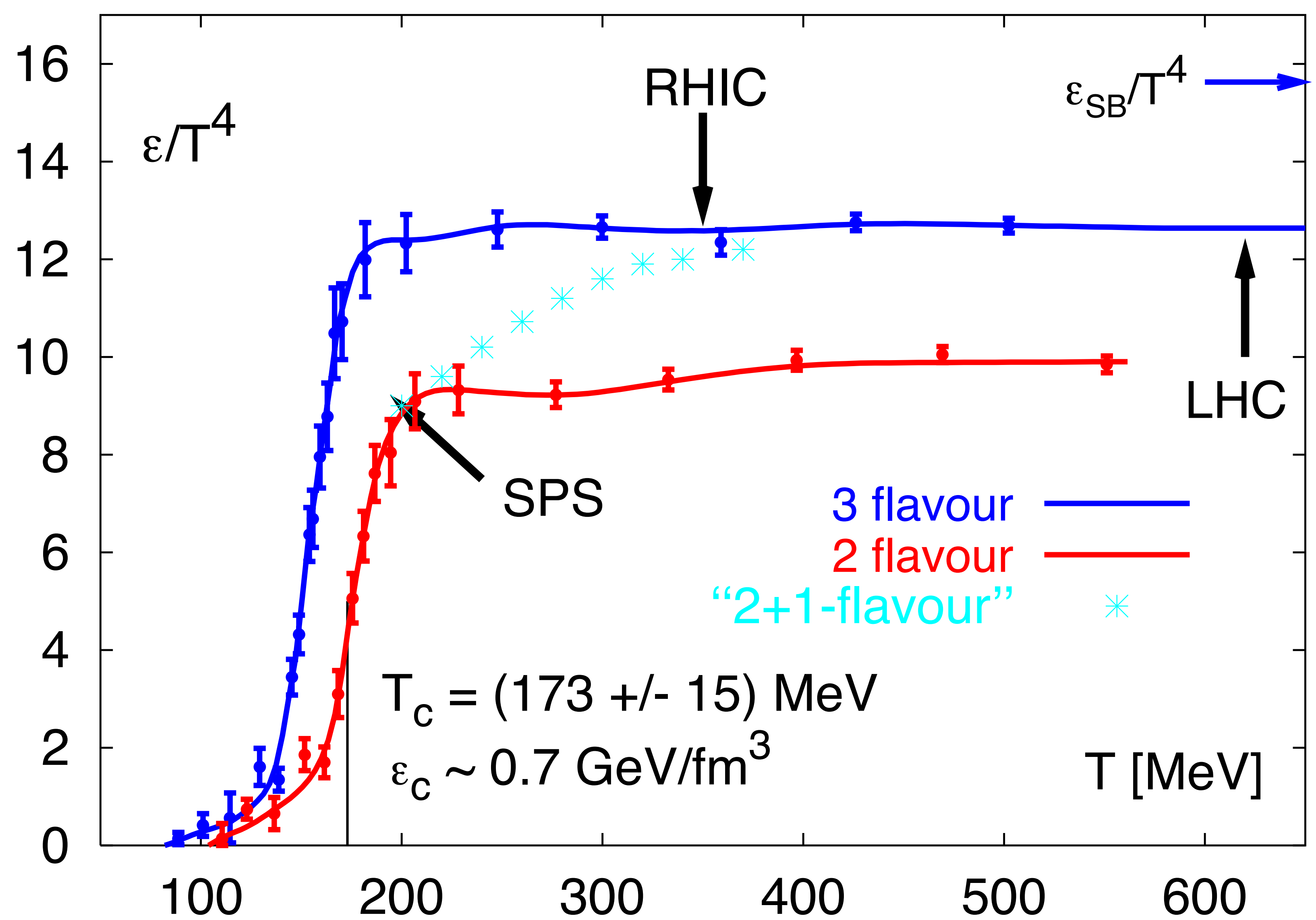
$dE/dx \sim 1$ GeV/fm

$\Delta E \sim$ 5-10 GeV

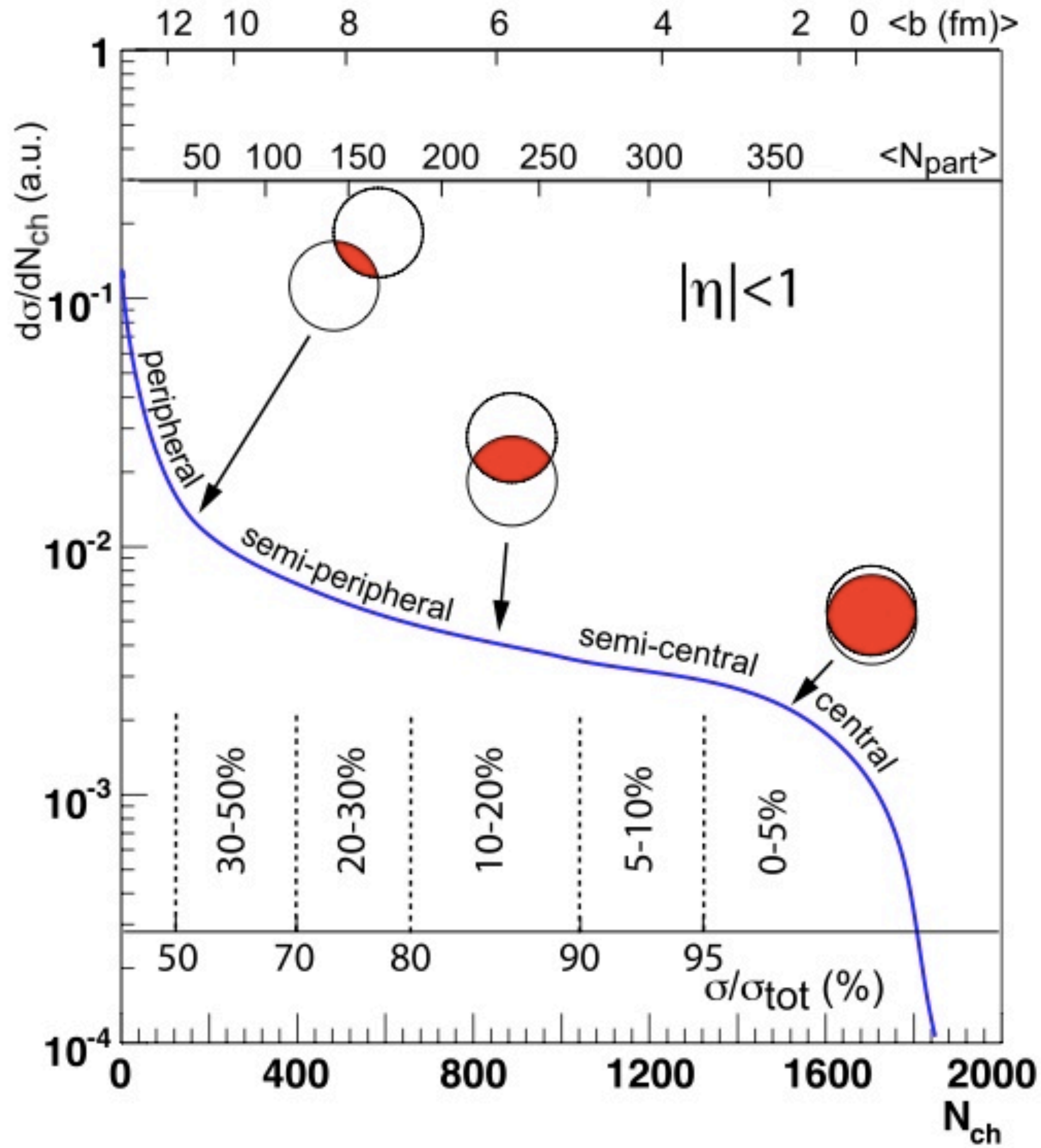
$dE/dx \sim 10$ GeV/fm

$\Delta E \sim$ 50-100 GeV

Dominant source of parton energy loss in medium is the radiative energy loss, caused by the medium induced gluon radiation.

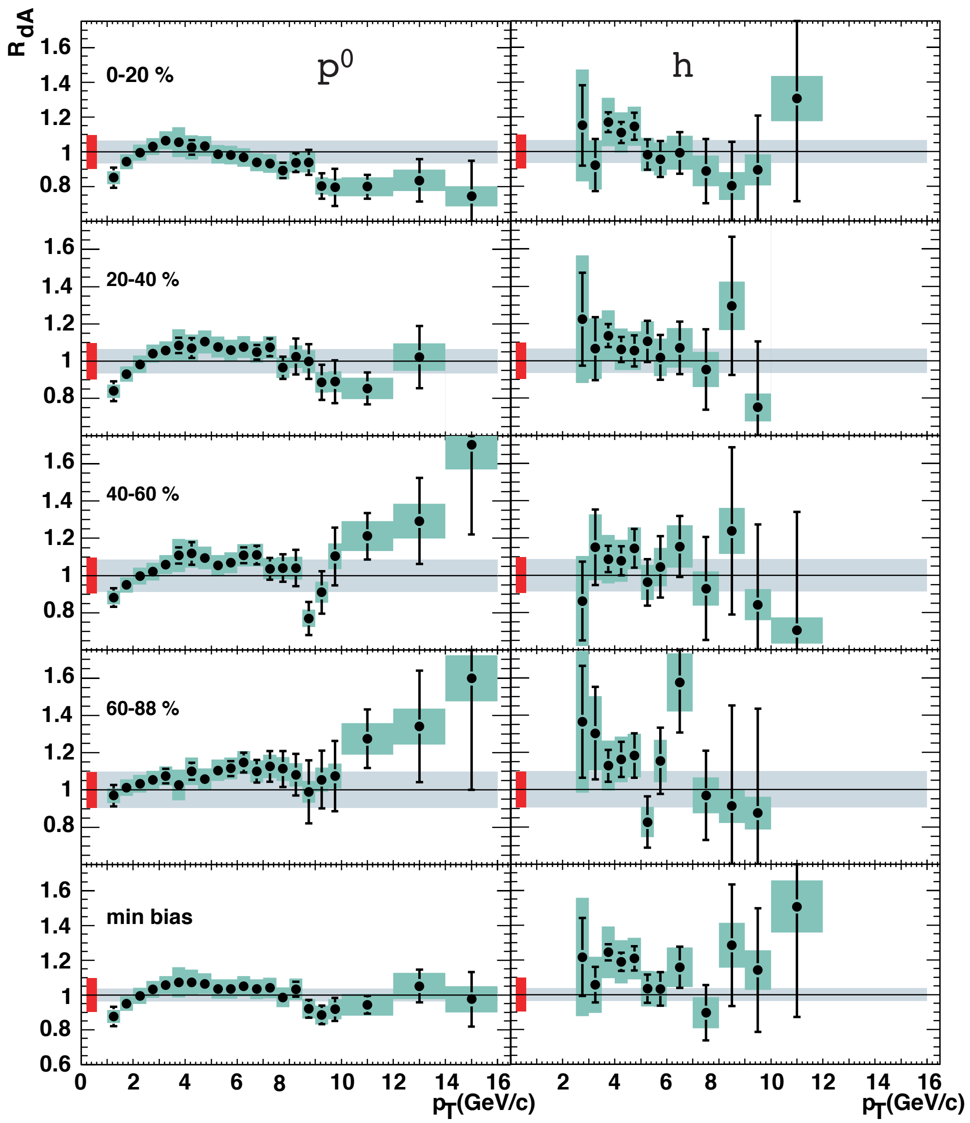


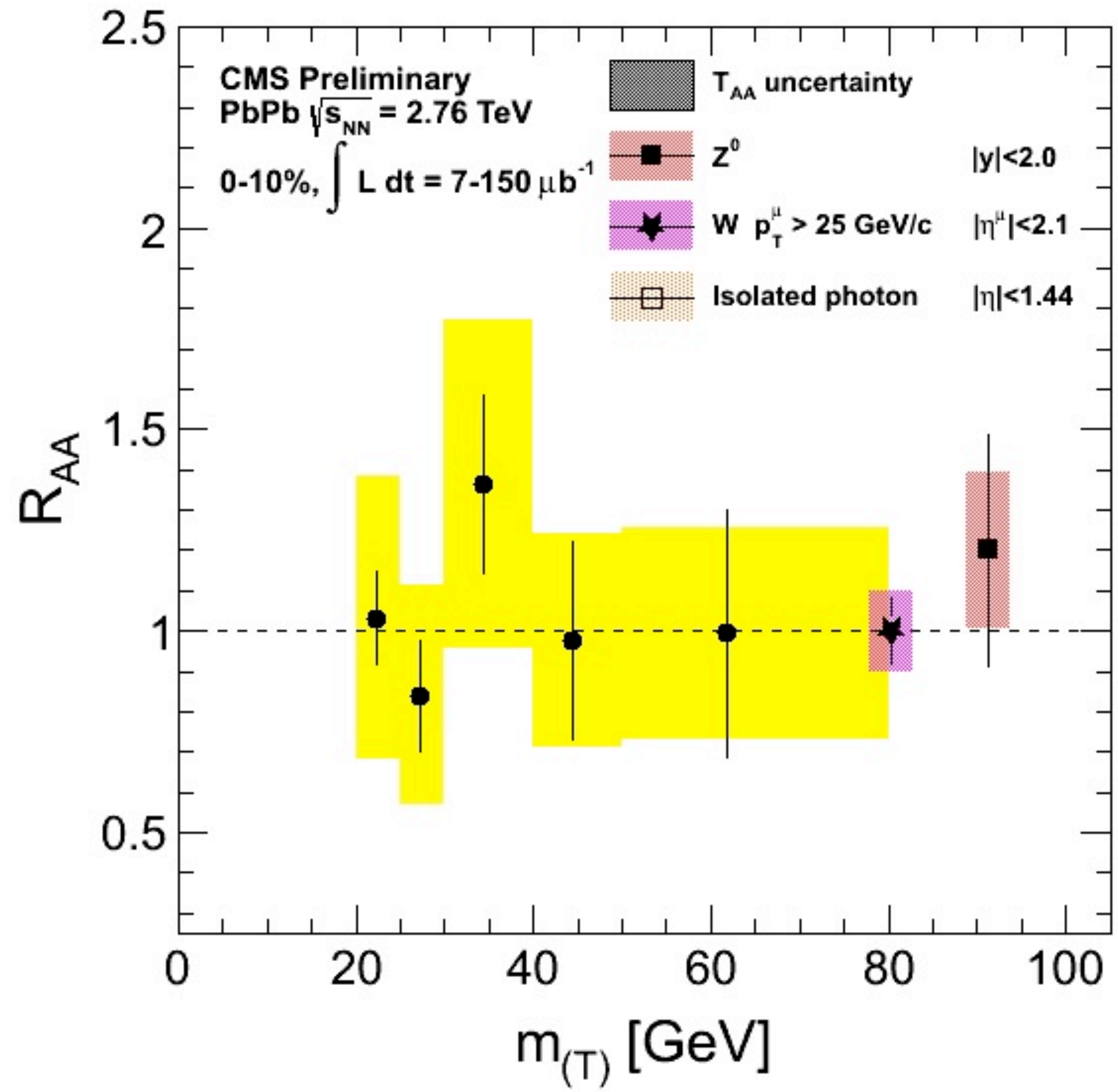
ε/T^4
RHIC
ε_SB/T^4
LHC
SPS
3 flavour
2 flavour
"2+1-flavour"
T_c = (173 +/- 15) MeV
ε_c ~ 0.7 GeV/fm^3
T [MeV]



12 10 8 6 4 2 0 <b (fm)>
50 100 150 200 250 300 350 <N_part>
|η|<1
peripheral
semi-peripheral
semi-central
central
30-50%
20-30%
10-20%
5-10%
0-5%
50 70 80 90 95
σ/σ_tot (%)
dσ/dN_ch (a.u.)
1
10^-1
10^-2
10^-3
10^-4
0 400 800 1200 1600 2000
N_ch

Distinguishing Initial- and Final-State Effects

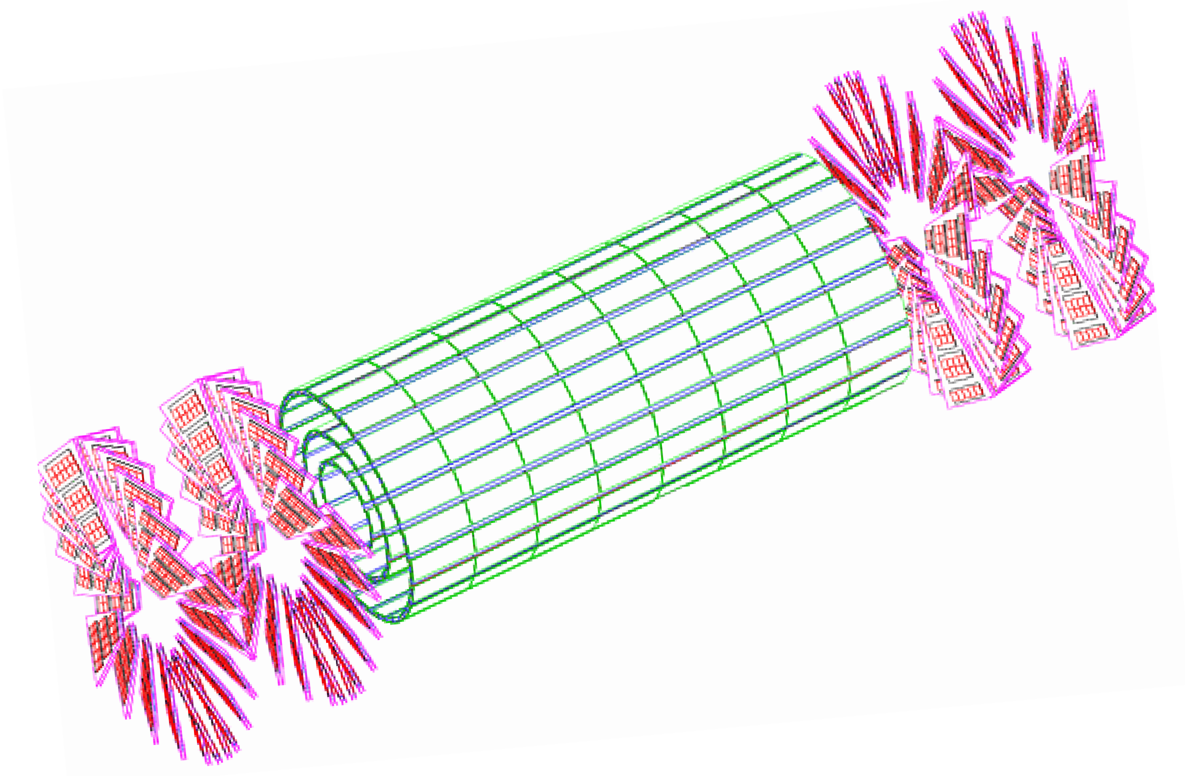




From the experiments with dAu collisions or from the R_{AA} measurements of "color-less" probes, e.g, Z^0, W, and gamma, magnitudes of initial state effect is constrained to be 10-20% at maximum.

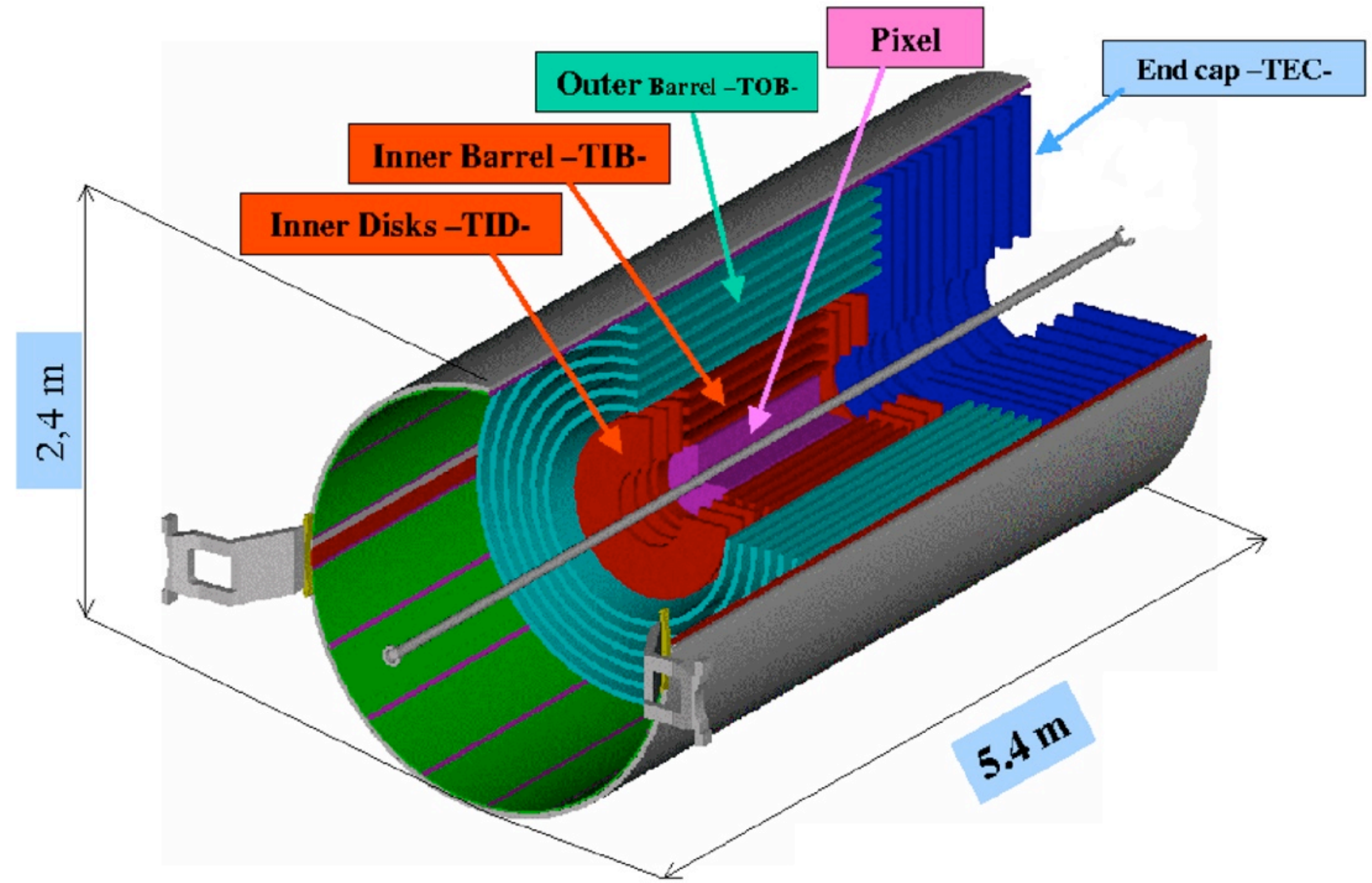
CMS Tracking System

Pixel Detector
(4 < r < 15 cm, ±49 cm from IP)



- 66M pixels
- 100 µm x 150 µm pixel
- 15-20 µm resolution
- up to 3 hits

Silicon Strip Tracker
(25 < r <110 cm, ±280 cm fromIP)

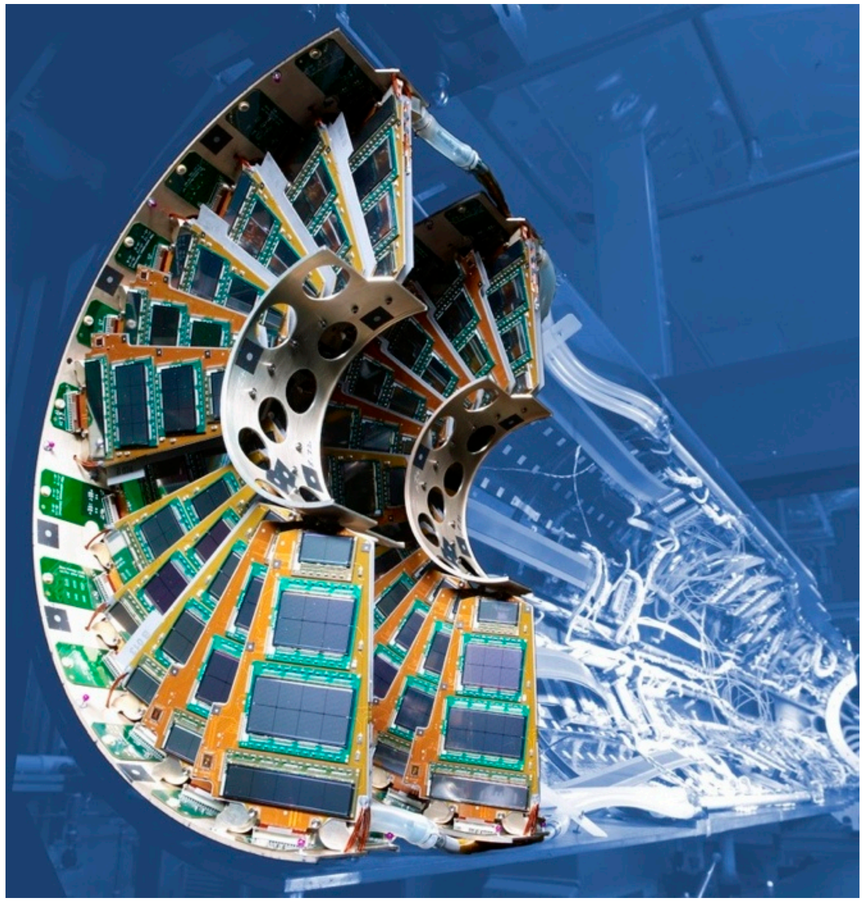


- 10M strip channels
- 10 cm x 80(180) µm pitch
- 30-50 µm resolution
- 8-14 hits (w/o stereo)

Largest silicon detector (200 m^2 by area)

CMS Tracking System

Pixel Detector
(4 < r < 15 cm, ±49 cm from IP)



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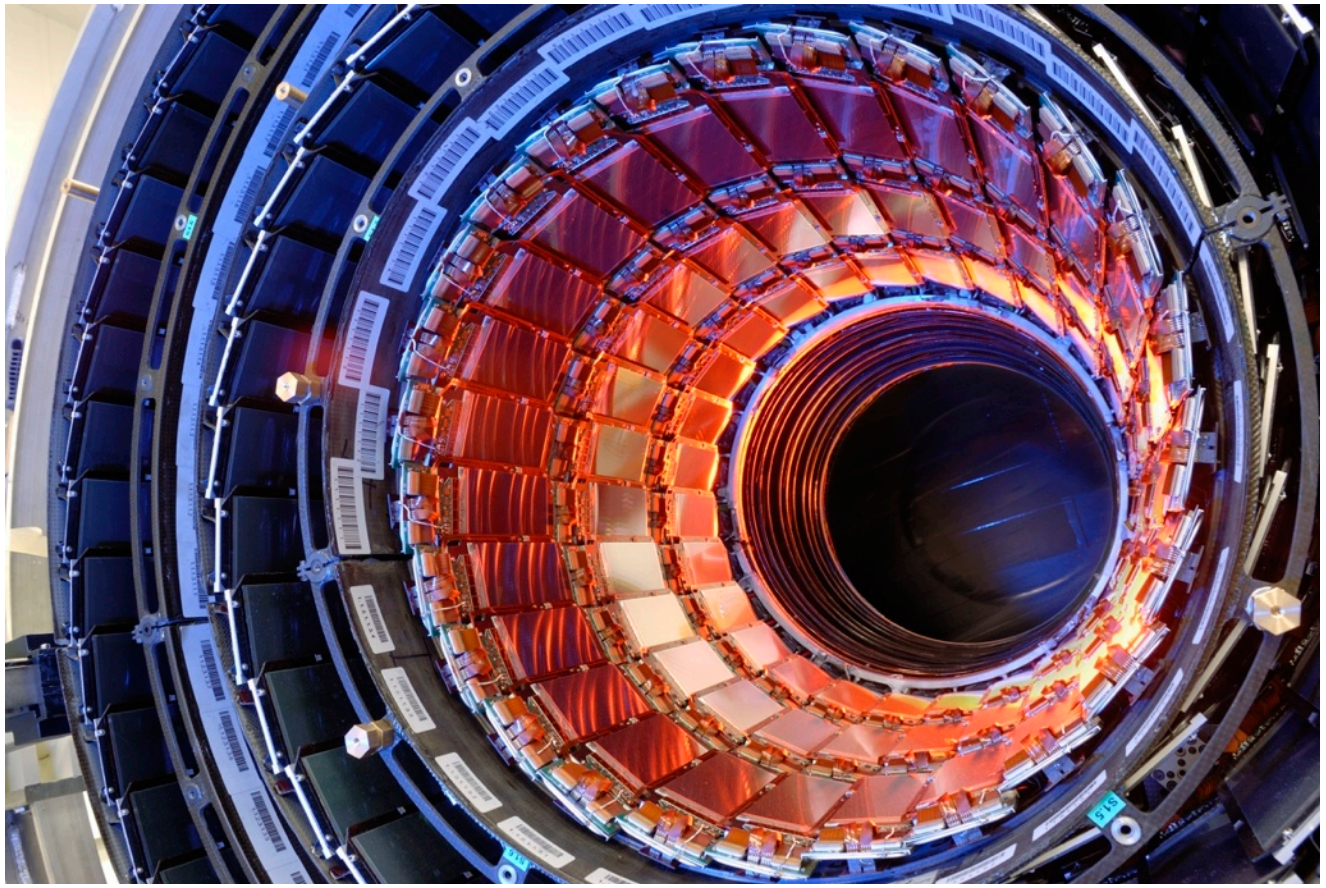
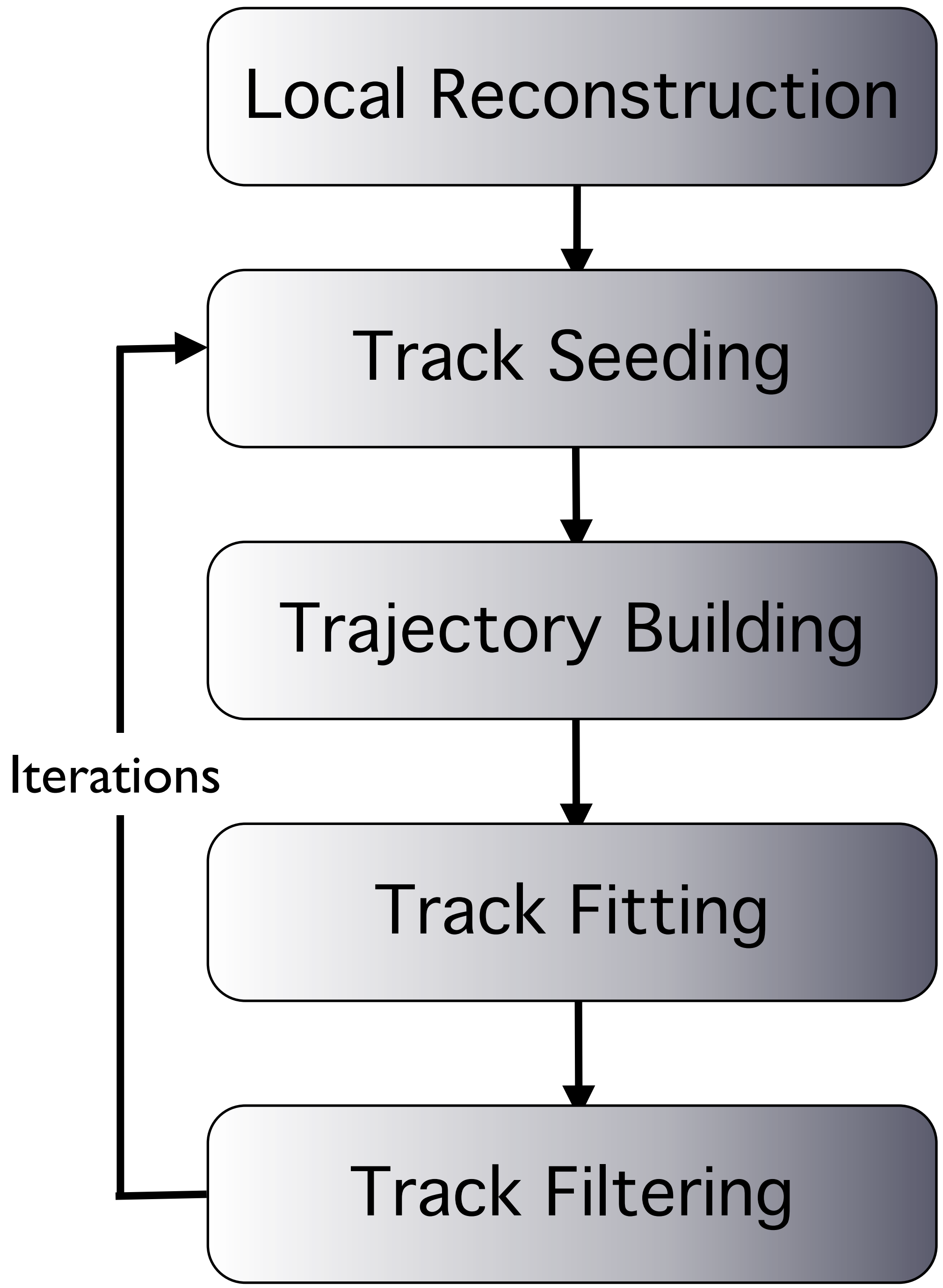


- 10M strip channels
- 10 cm x 80(180) μm pitch
- 30-50 μm resolution
- 8-14 hits (w/o stereo)

Largest silicon detector (200 m^2 by area)

Track Reconstruction in CMS



Default pp Tracking with Modified Selections

- Up to 5 iterations with different seeding layers
- Modified track selections for spectra measurements
- Efficiency ~ 85% and fake ~ 1-2%

Modified Heavy-Ion Tracking

- Minimum p_T cut-off of 0.9 GeV/c
- Up to 3 iterations
- Track quality cuts are tightened
- Uses explicit track-calorimeter matching
- Efficiency ~ 80% and fake ~ 1-5 %

Obtaining Charged Particle Spectra

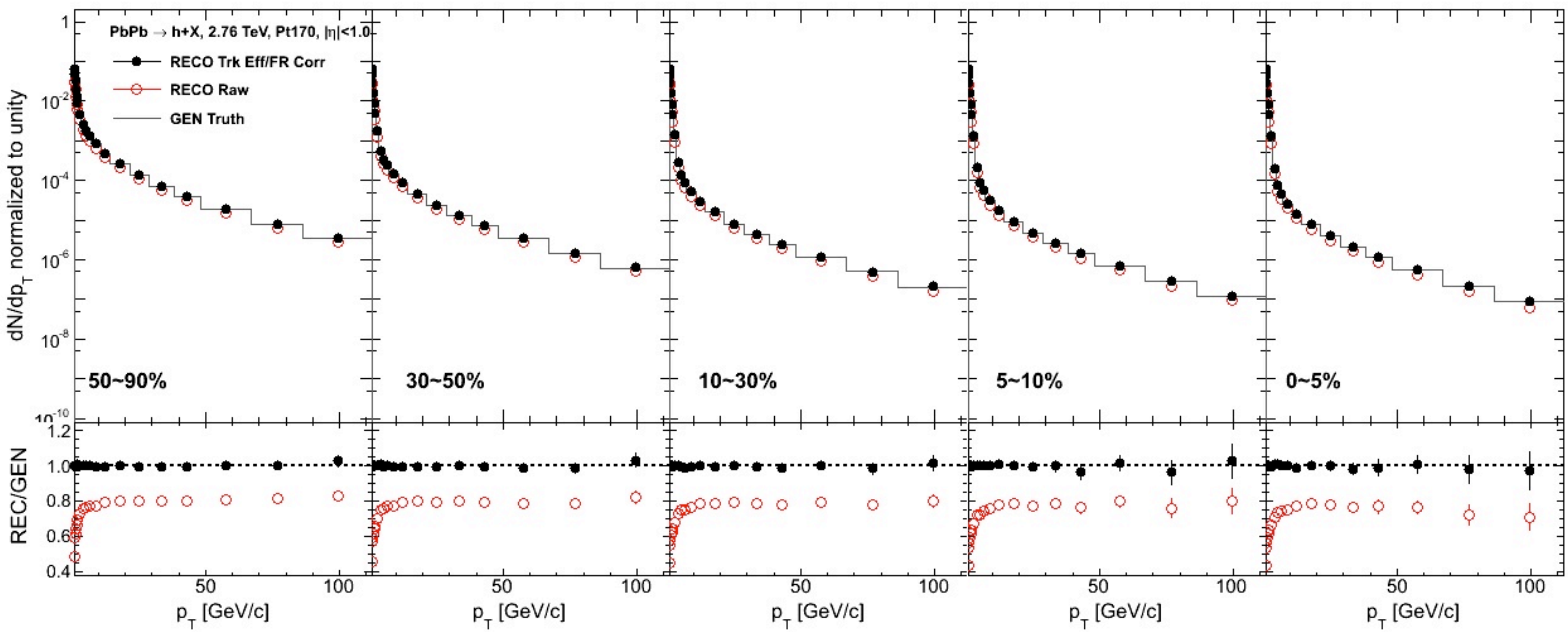
$$E\frac{d^3N_{ch}}{d^3p}(p_T,\eta) = \frac{\sum_{E_T^{jet}} N_{track}^{raw}(E_T^{jet},p_T,\eta)\cdot w_{tr}(p_T,\eta,E_T^{jet})}{2\pi p_T\cdot\delta p_T\cdot\delta\eta\cdot N^{selected}}$$

- Efficiency and Fake
- Secondary fraction
- Multiple reconstruction

- Momentum Resolution
- Binning Correction

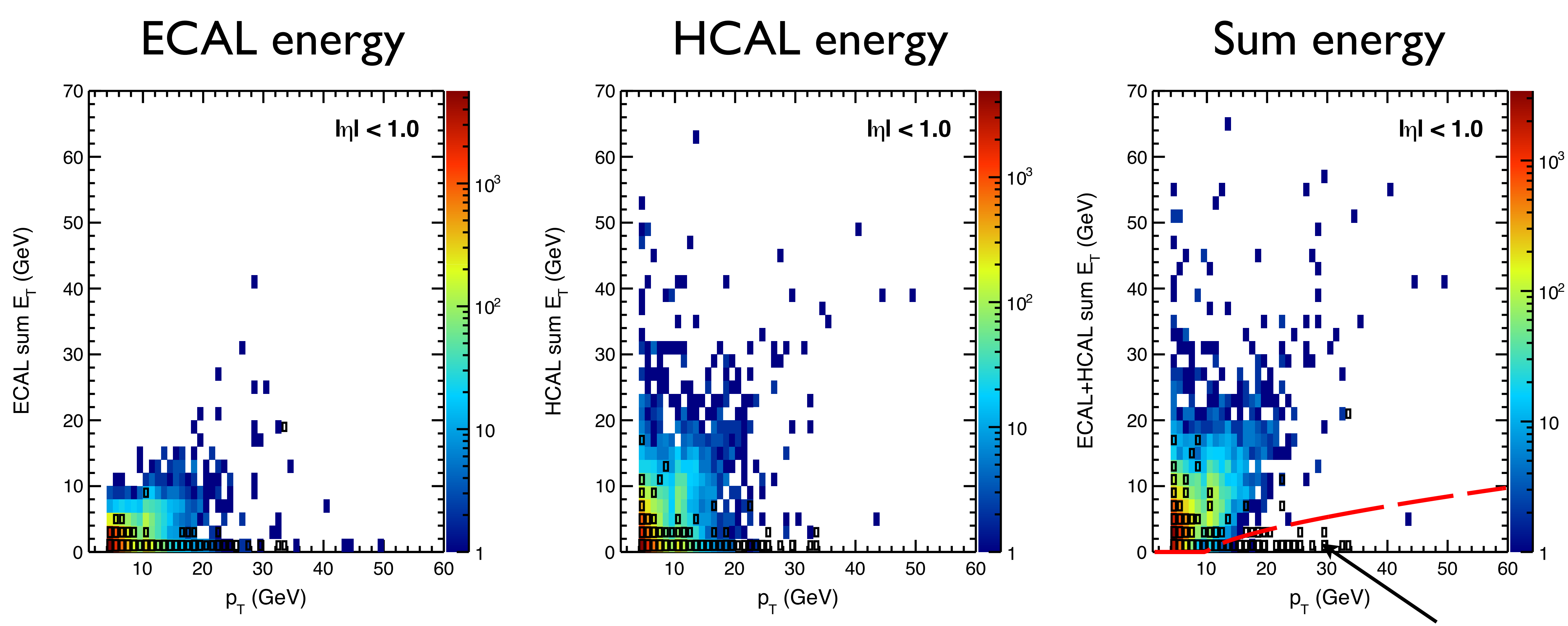
Monte-Carlo (MC) Closure Test

Fully reconstructed and corrected p_T spectra from the PYTHIA QCD sample embedded in HYDJET (PbPb) MC are compared to the "truth" PYTHIA spectra.

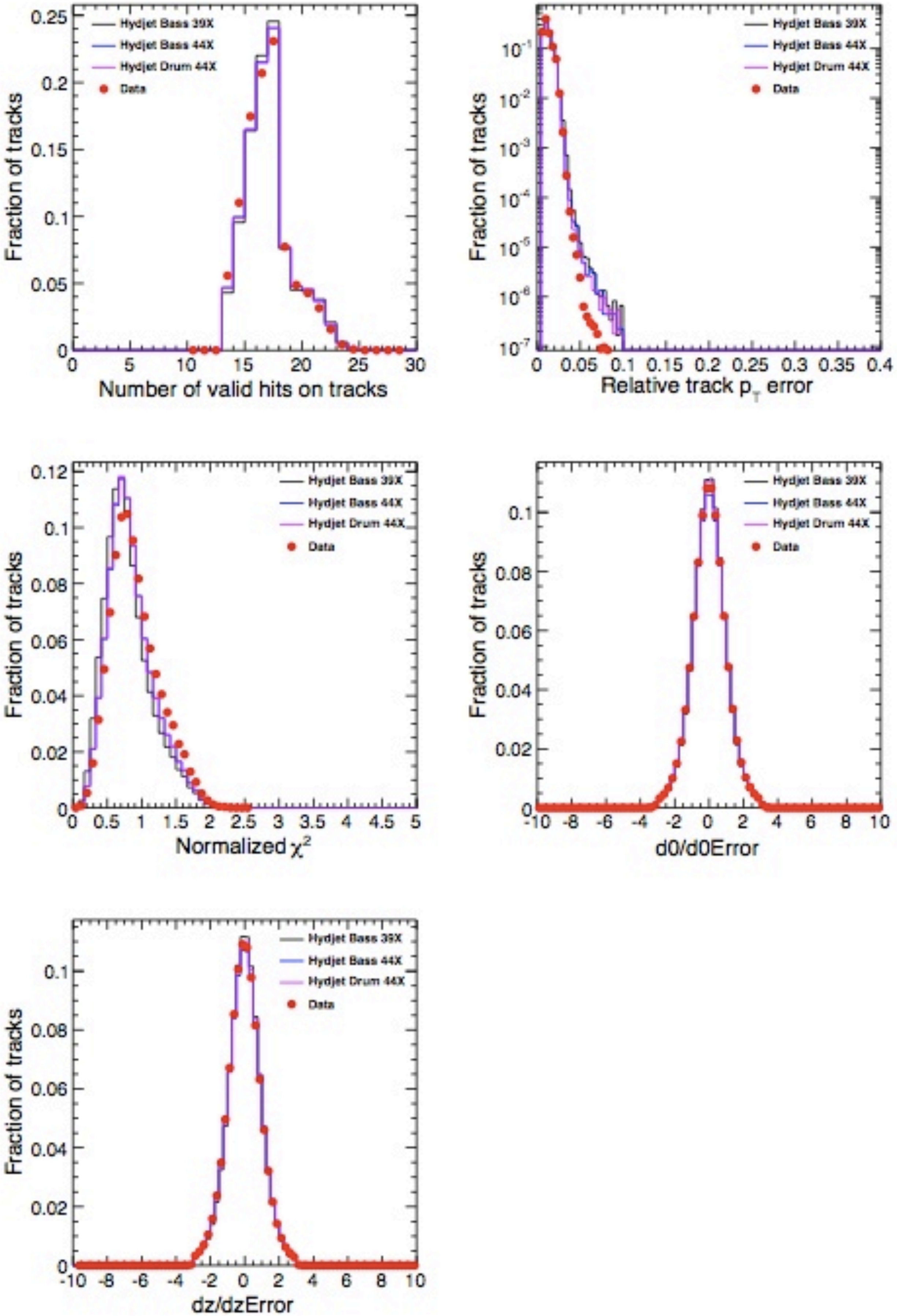


Calorimeter-Track Compatibility

The Idea is to check the calorimeter energy deposits for high-p_T tracks to identify spurious (fake) tracks.

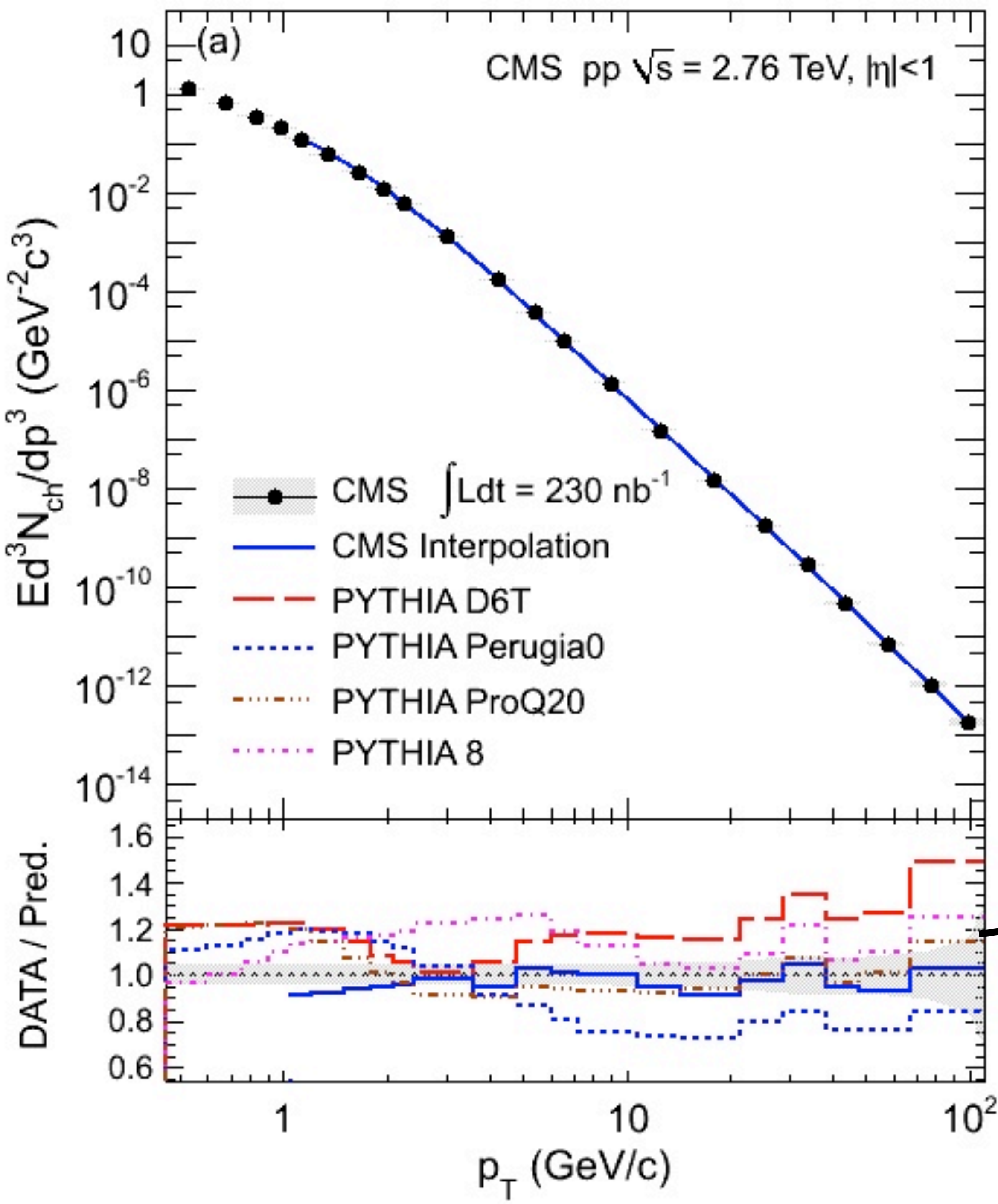


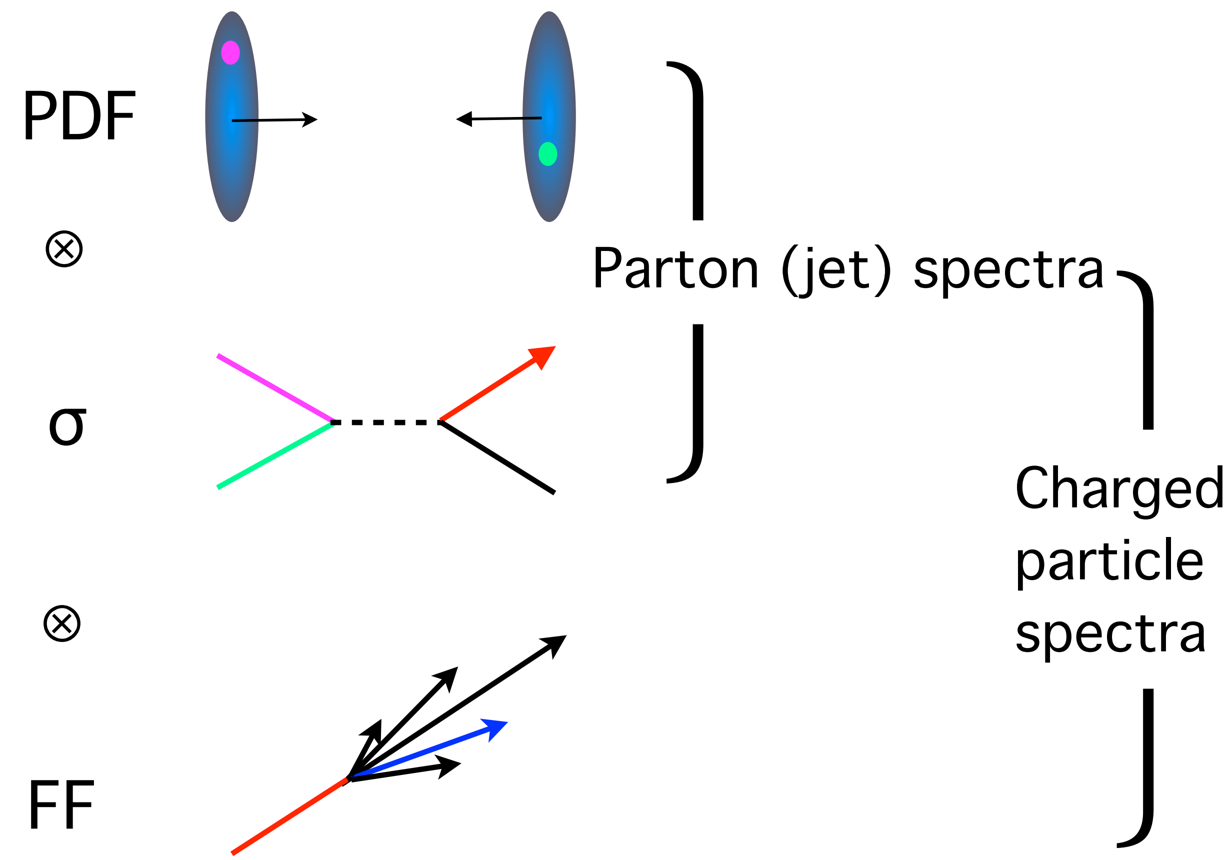
Fake tracks show no sizable energy deposit in the cal.



- ‘Loose’ selections for calorimeter-compatible tracks
  - $N_{hits}^{valid} \geq 10$
  - $\sigma(p_{\mathrm{T}})/p_{\mathrm{T}} \leq 0.1$
  - $(\chi^2/N_{d.o.f})/N_{layers} \leq 0.15$
  - $d_{0,z}/\sqrt{\sigma(d_{0,z}^2)+\sigma(v_{0,z})} \leq 8$
- ‘Tight’ selections for calorimeter-incompatible tracks
  - $N_{hits}^{valid} \geq 13$
  - $\sigma(p_{\mathrm{T}})/p_{\mathrm{T}} \leq 0.05$
  - $(\chi^2/N_{d.o.f})/N_{layers} \leq 0.15$
  - $d_{0,z}/\sqrt{\sigma(d_{0,z}^2)+\sigma(v_{0,z})} \leq 3$

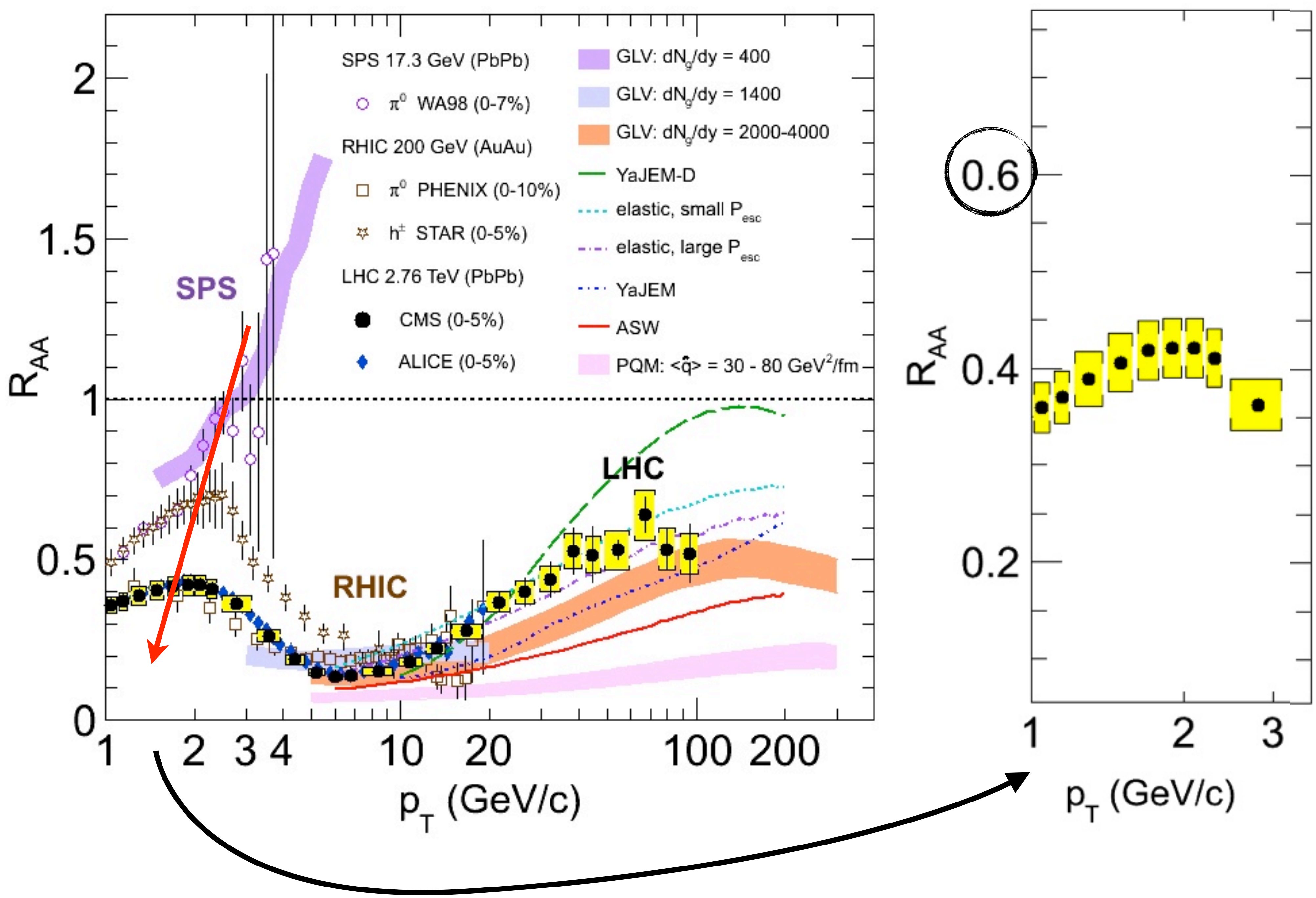
High-p_T Particle Production in pQCD





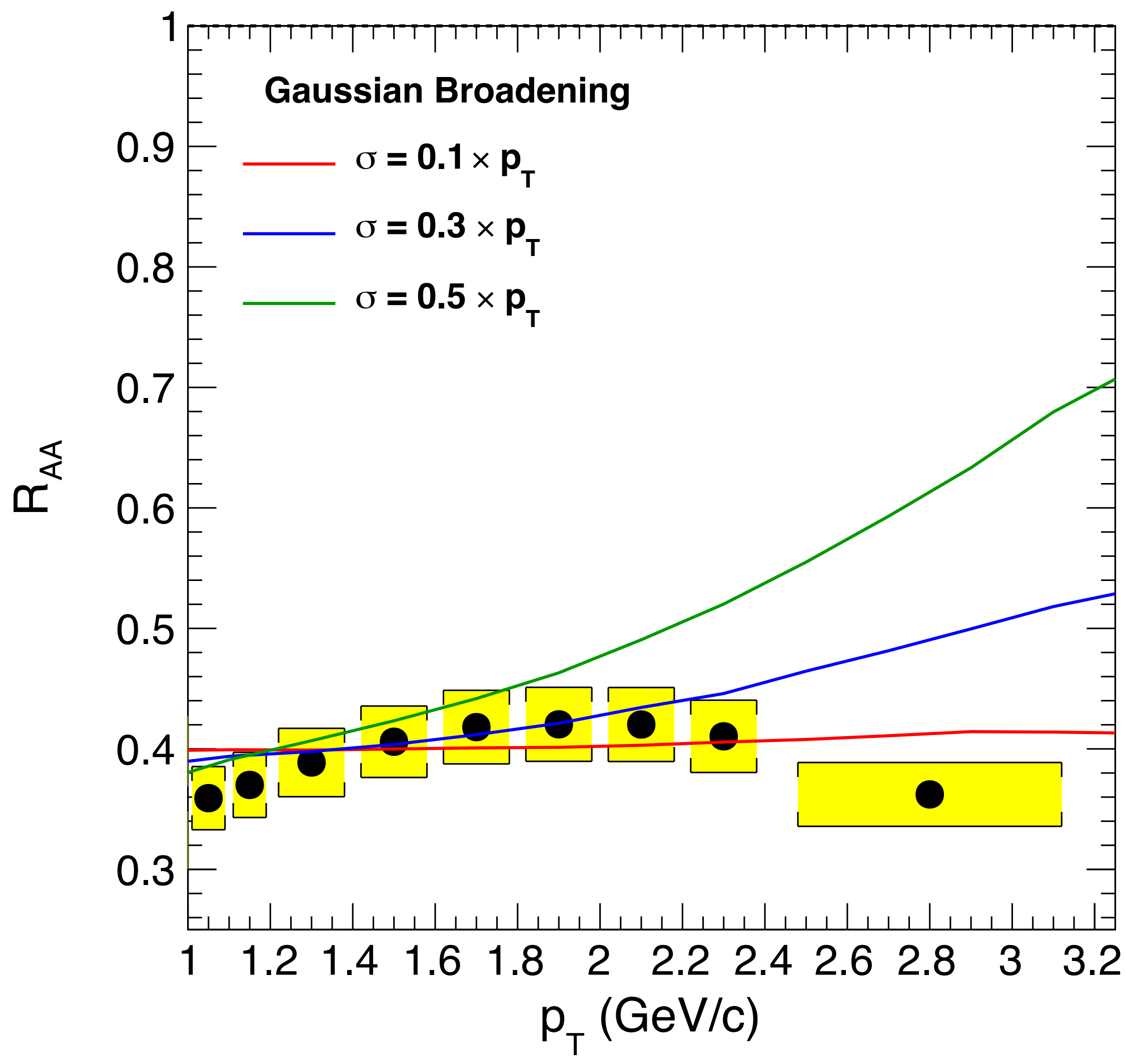
Above 1 GeV/c, PYTHIA ProQ20 describes the measured charged particle spectra within 10%.

Shape of R_{AA} for p_T < 2-3 GeV/c



"Cronin Effect"

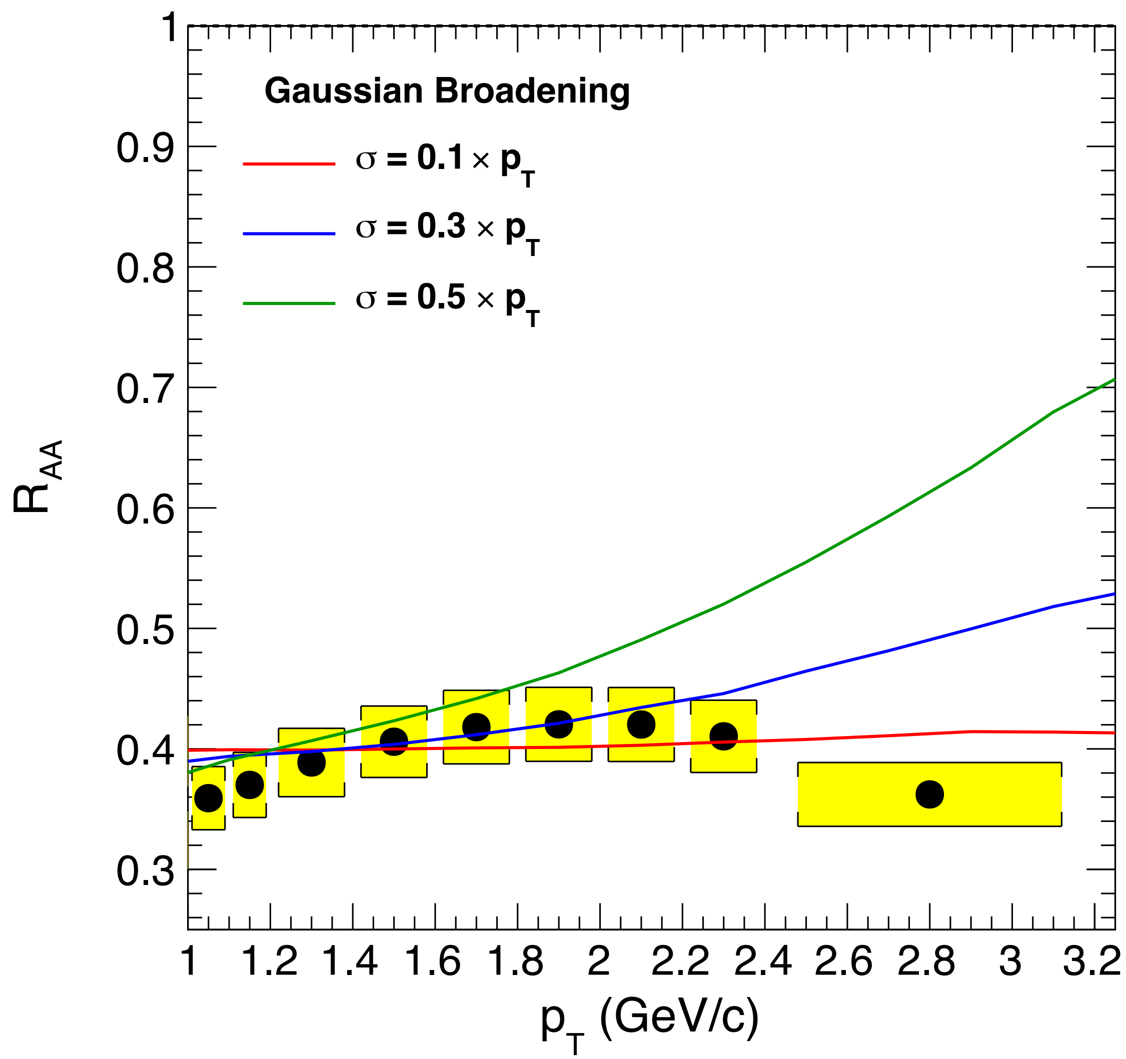
Mimicking Cronin Effect

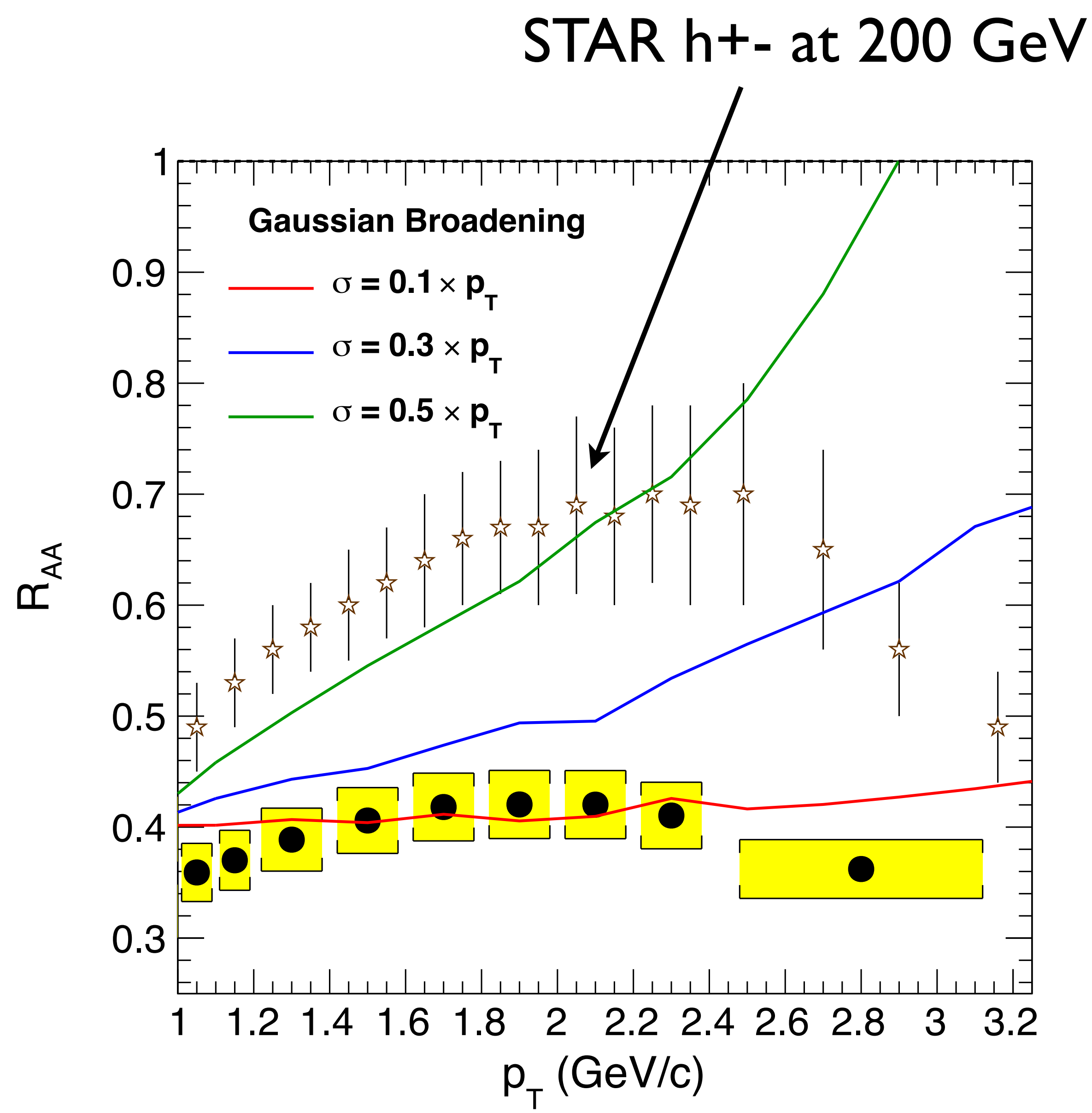


- Apply x% Gaussian broadening to the p_T of produced charged particles, where x = 10, 30, 50.
- Compare the charged particle spectra before and after the broadening. → R_{AA}

The rising trend can be reproduced given the shape of pp spectra with more than 10% of pT broadening. → How about lower energy?

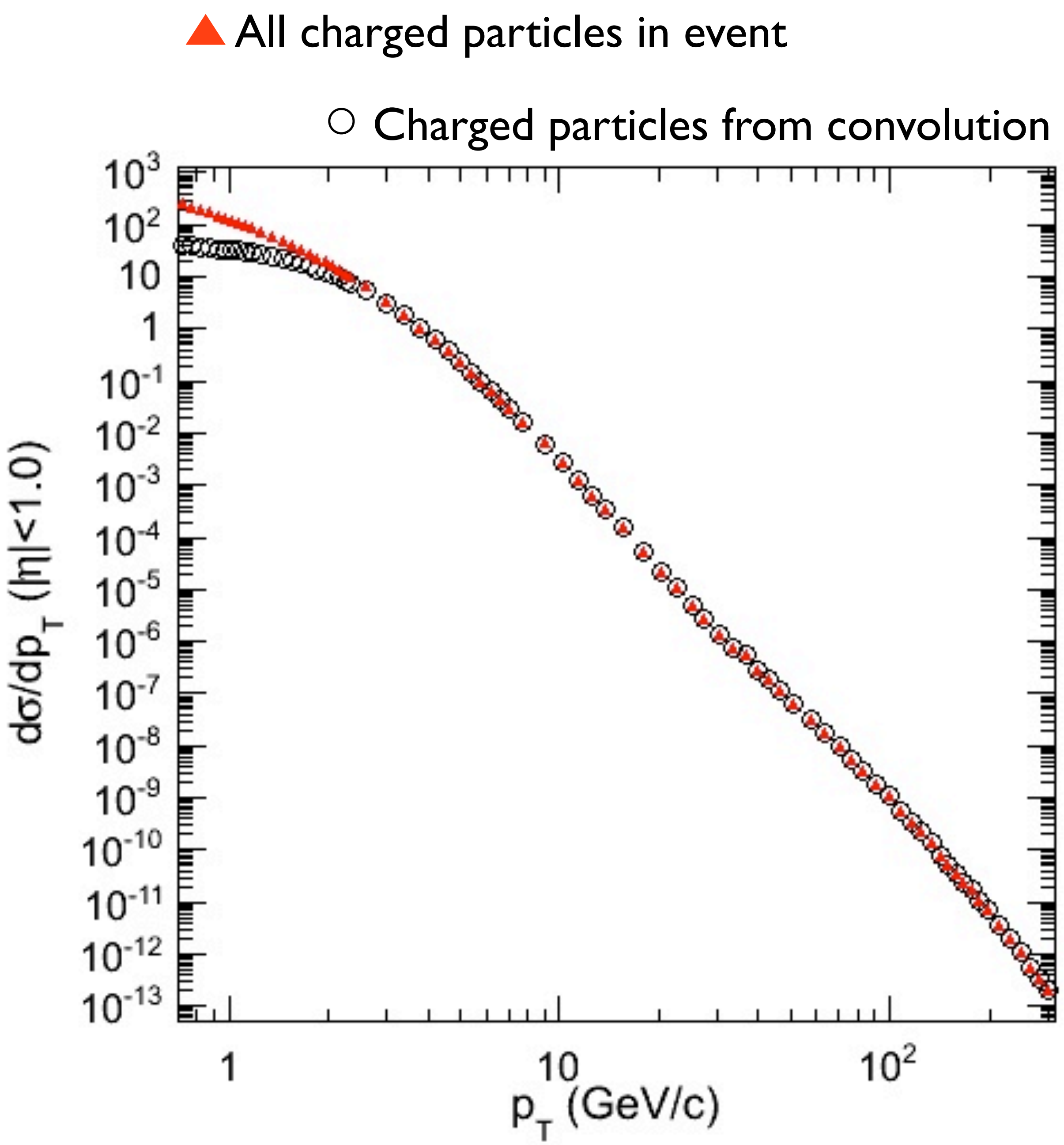
Mimicking Cronin Effect

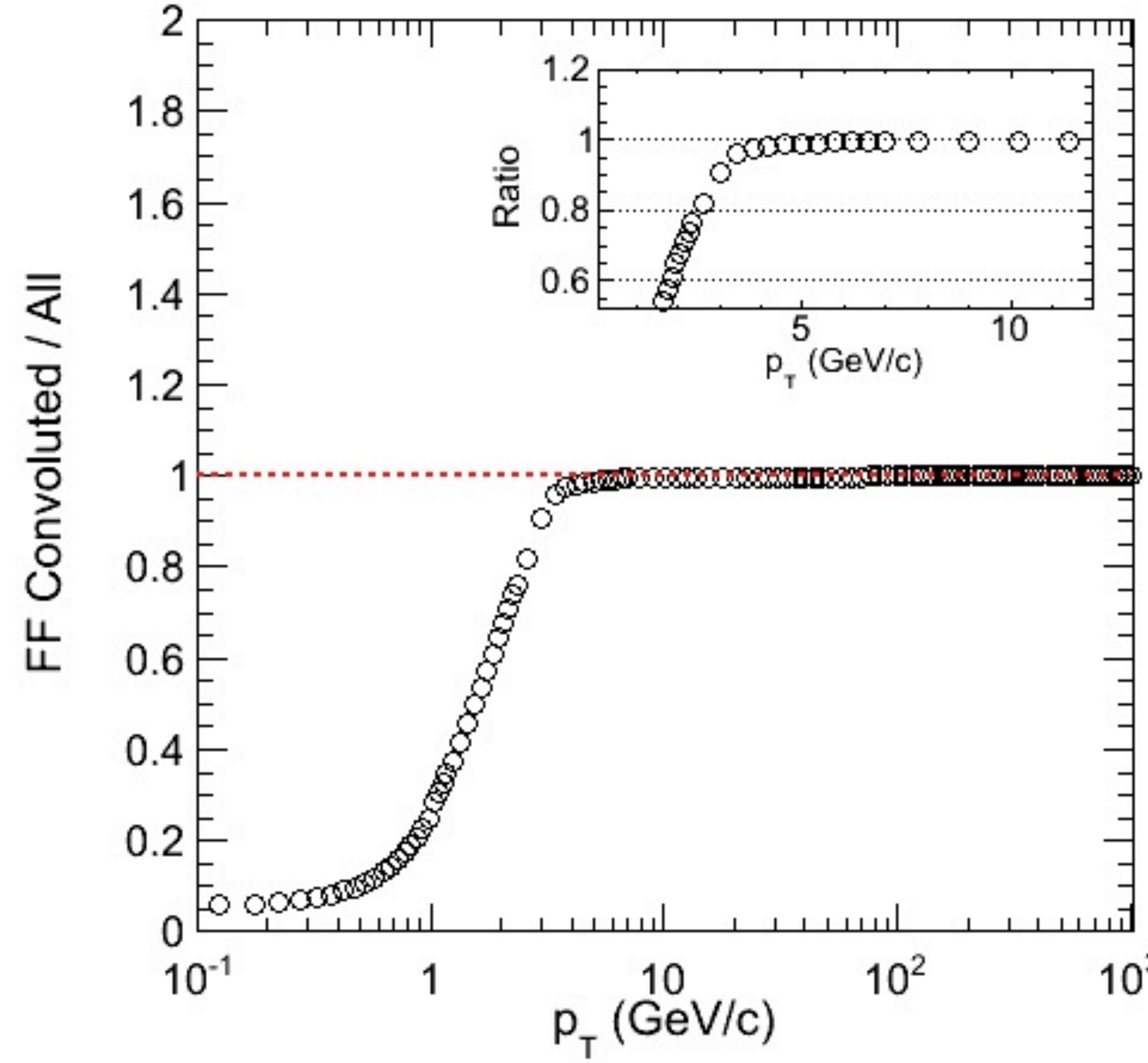




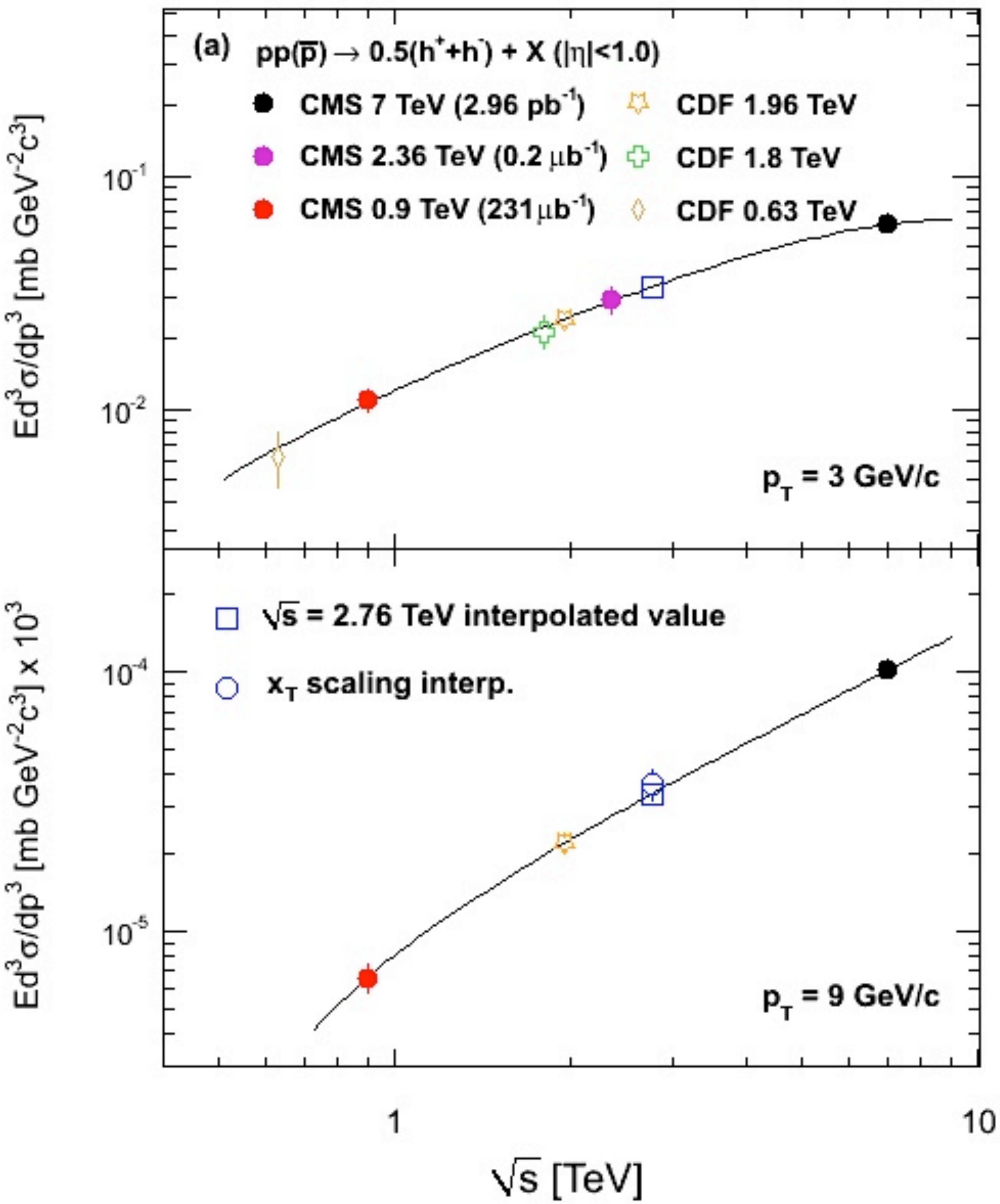
The rising trend can be reproduced given the shape of pp spectra with more than 10% of pT broadening. → How about lower energy?

Convolution Methods





The resulting charged particle spectra reproduces the inclusive charged particle down to 5 GeV/c.

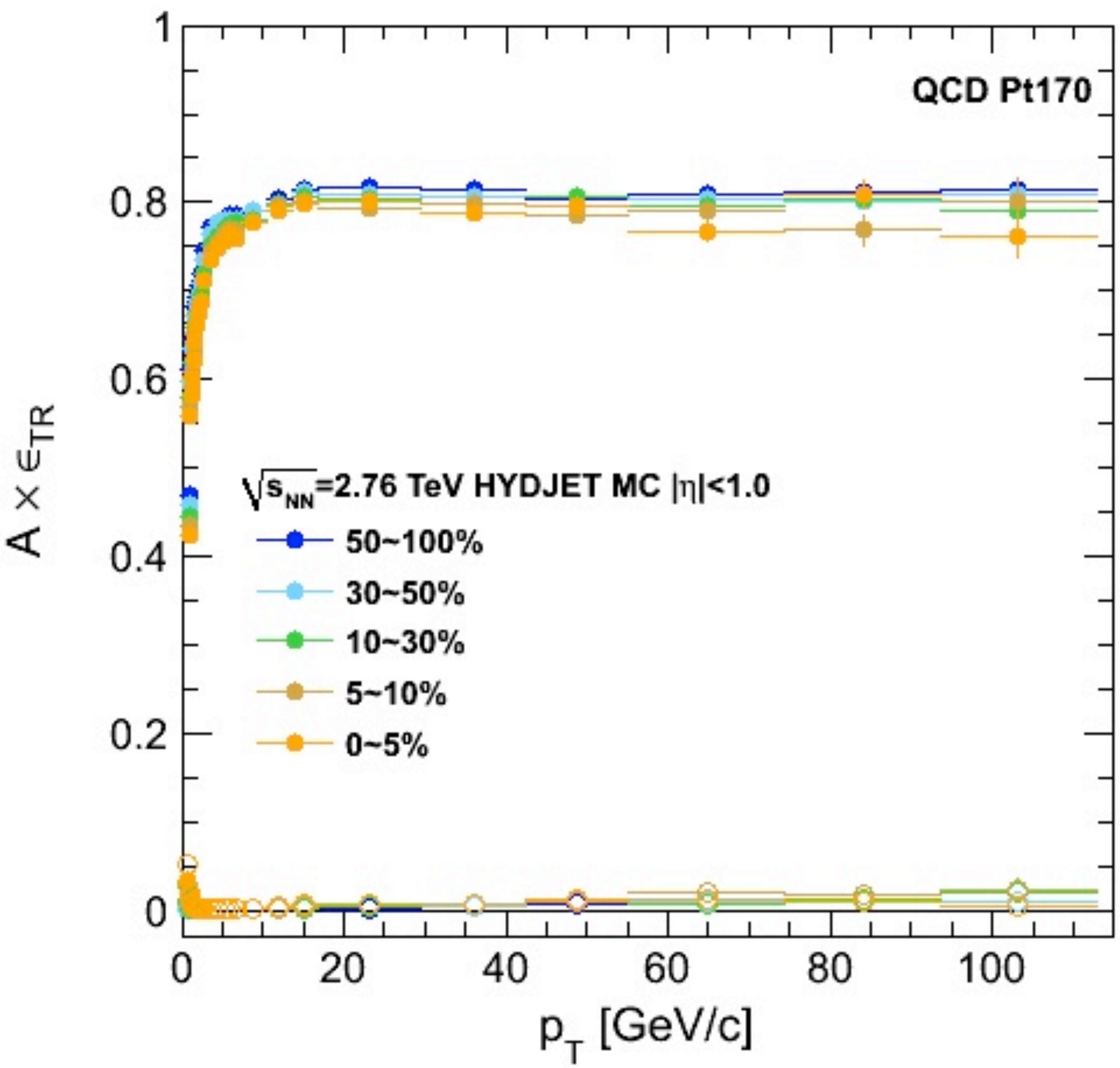


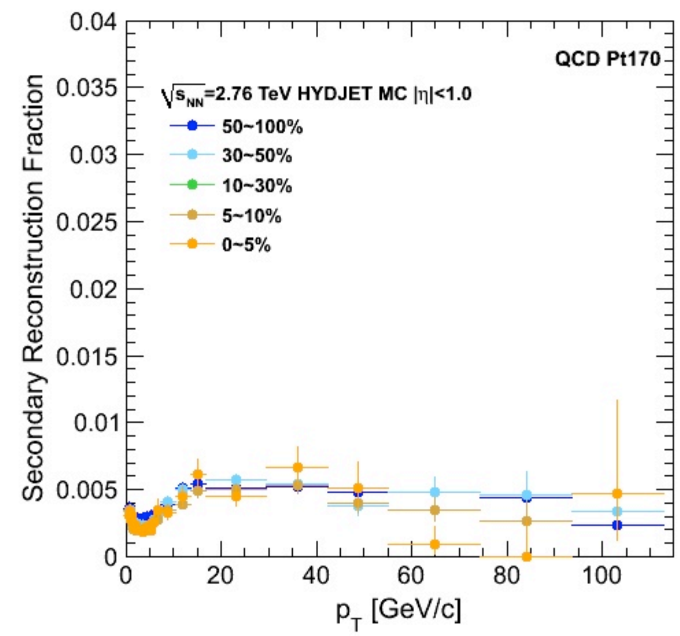
(a)
pp($\overline{p}$) → 0.5(h$^+$+h$^-$) + X (|η|<1.0)
CMS 7 TeV (2.96 pb^{-1})
CMS 2.36 TeV (0.2 μb^{-1})
CMS 0.9 TeV (231μb^{-1})
CDF 1.96 TeV
CDF 1.8 TeV
CDF 0.63 TeV
p_T = 3 GeV/c
$\sqrt{s}$ = 2.76 TeV interpolated value
x_T scaling interp.
p_T = 9 GeV/c
Ed^{3}σ/dp^3 [mb GeV^{-2}c^3]
Ed^{3}σ/dp^3 [mb GeV^{-2}c^3] x 10^3
10^{-1}
10^{-2}
10^{-4}
10^{-5}
1
10
$\sqrt{s}$ [TeV]

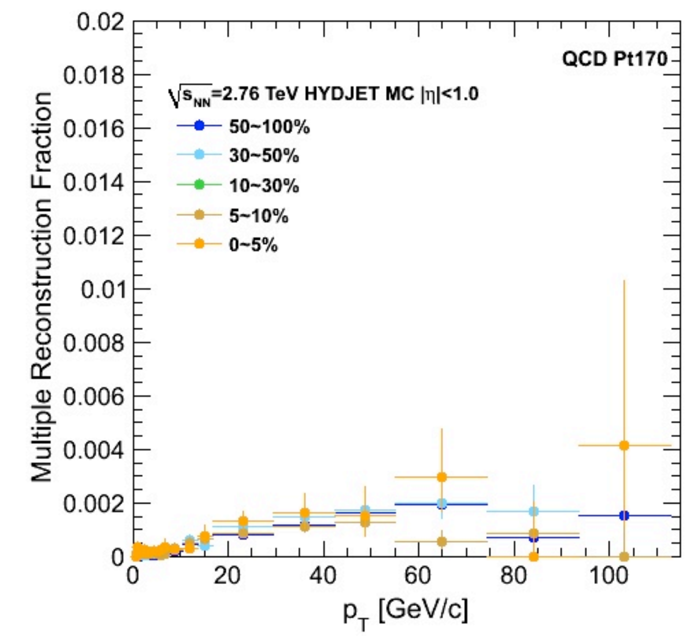
Centrality bin	$\langle N_{\text{part}} \rangle$	r.m.s.	$\langle N_{\text{coll}} \rangle$	r.m.s.	$\langle T_{\text{AA}} \rangle$ (mb^{-1})	r.m.s.
0–5%	381 ± 2	19.2	1660 ± 130	166	25.9 ± 1.06	2.60
5–10%	329 ± 3	22.5	1310 ± 110	168	20.5 ± 0.94	2.62
10–30%	224 ± 4	45.9	745 ± 67	240	11.6 ± 0.67	3.75
30–50%	108 ± 4	27.1	251 ± 28	101	3.92 ± 0.37	1.58
50–70%	42.0 ± 3.5	14.4	62.8 ± 9.4	33.4	0.98 ± 0.14	0.52
70–90%	11.4 ± 1.5	5.73	10.8 ± 2.0	7.29	0.17 ± 0.03	0.11
50–90%	26.7 ± 2.5	18.84	36.9 ± 5.7	35.5	0.58 ± 0.09	0.56

- Uncertainty on N_{coll} value driven by two terms:
  - Trigger and event selection efficiency
  - Glauber parameters

Track Reconstruction Performance





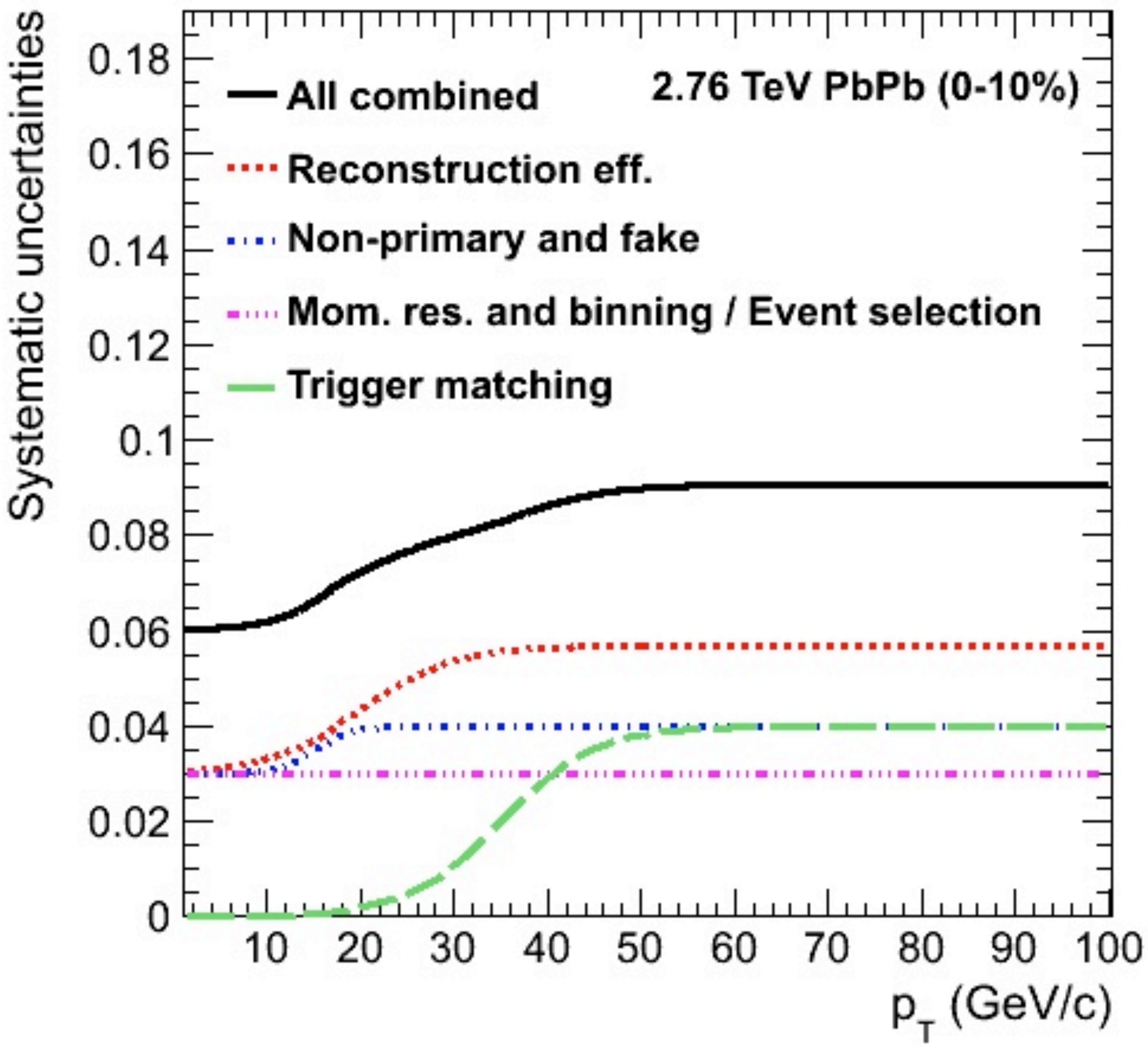


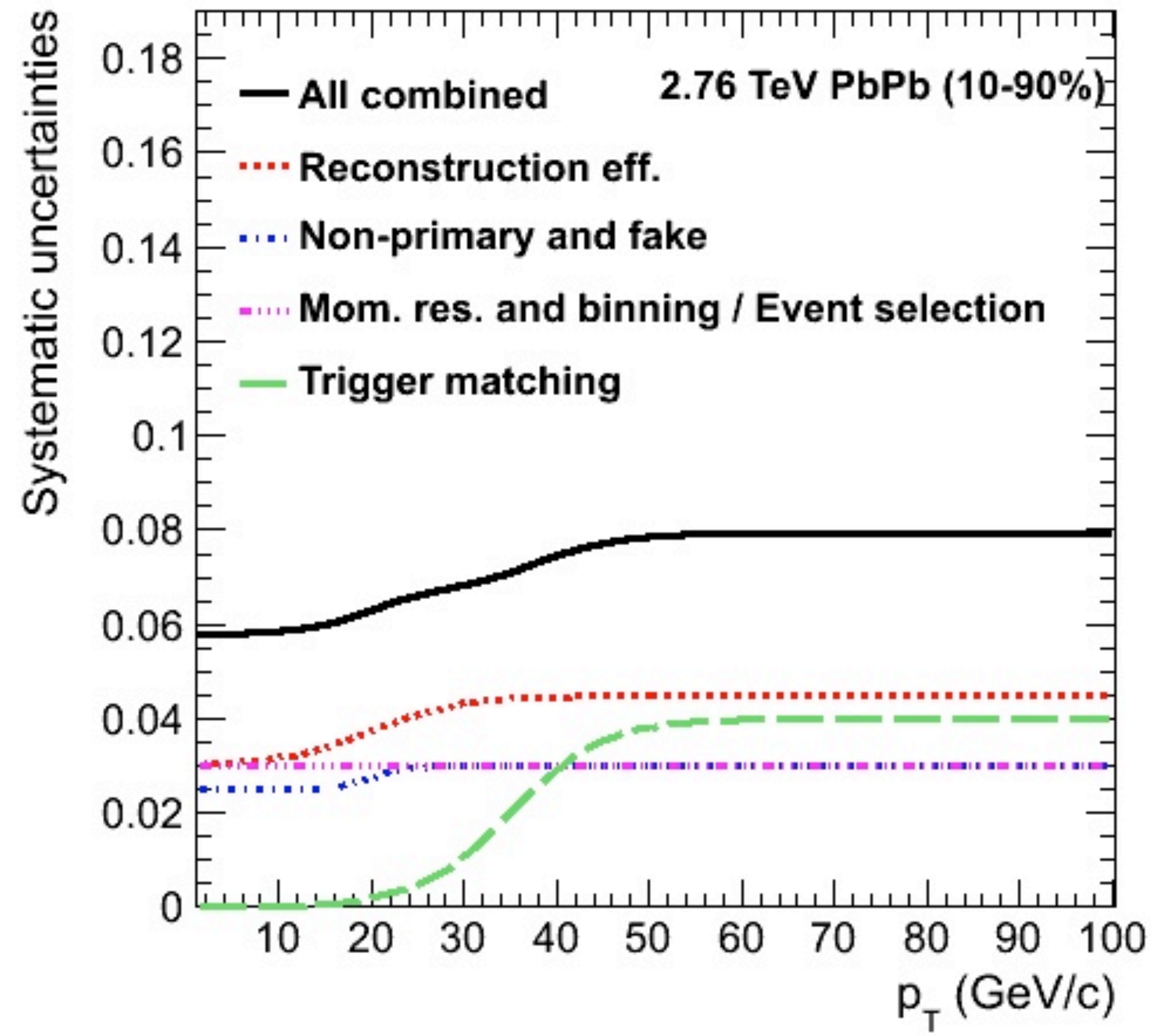
$$w_{tr}(p_T, \eta, E_T^{jet}) = \frac{(1-F)\cdot(1-S)}{A\cdot\varepsilon^{tr}\cdot(1+D)}$$

Systematic Uncertainty

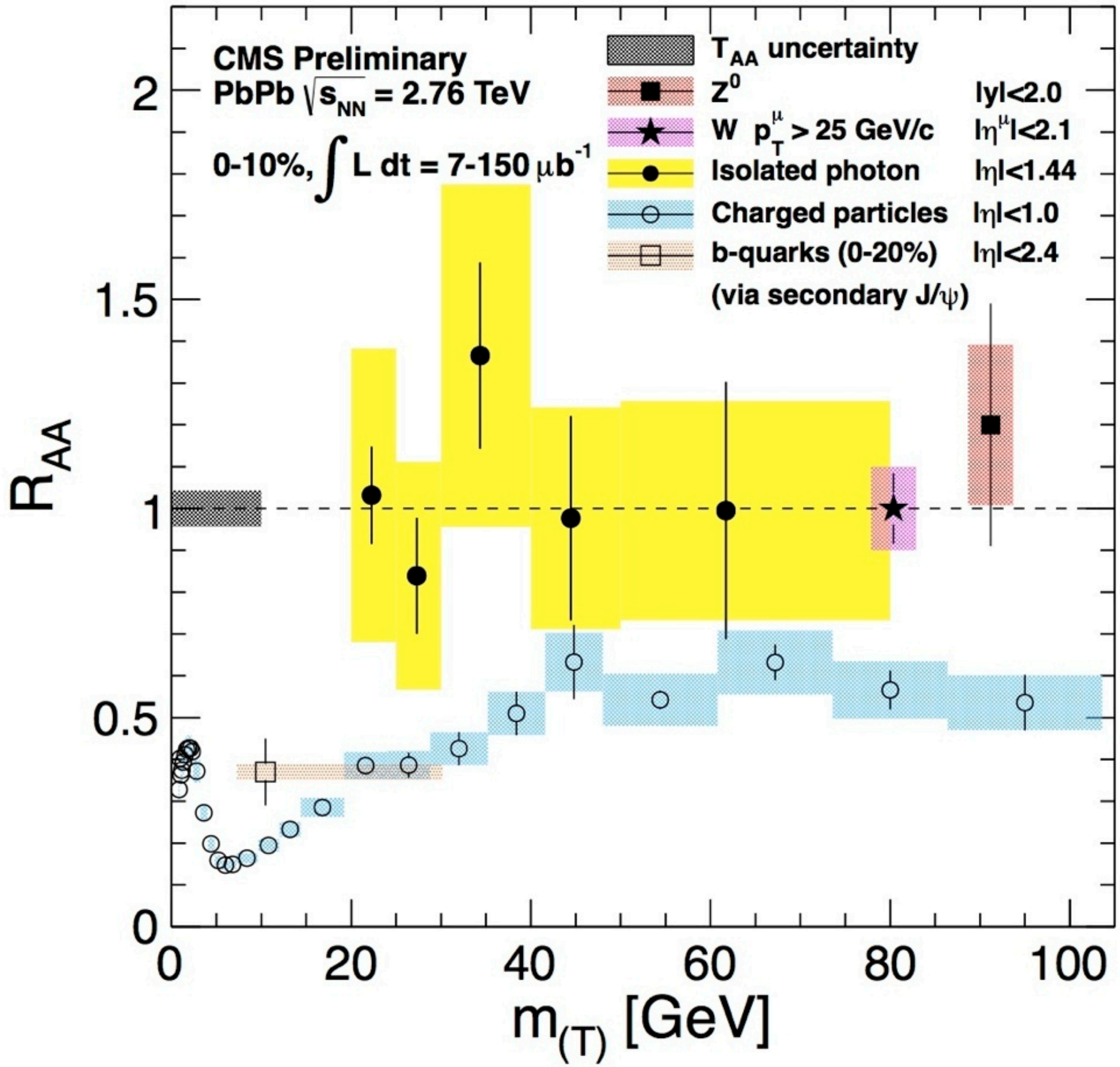
Source	Uncertainty [%]	
	PbPb	pp
Track reconstruction efficiency	3.0–5.7	2.2–3.6
Non-primary and misidentified tracks	2.5–4.0	1.0–3.2
Momentum resolution and binning	3.0	0.3–2.7
Normalization of jet-triggered spectra	0.0–4.0	0.0–6.0
Event selection	3.0	3.5
Pile-up estimation	<0.1	1.2
Total for p_T spectra	5.8–9.1	4.4–9.0
Luminosity	–	6.0
T_{AA} determination	4.1–18.0	–
Total for R_{CP}	6.7–20.0	–
Total for R_{AA}	9.9–23.0	–

Systematic Uncertainty

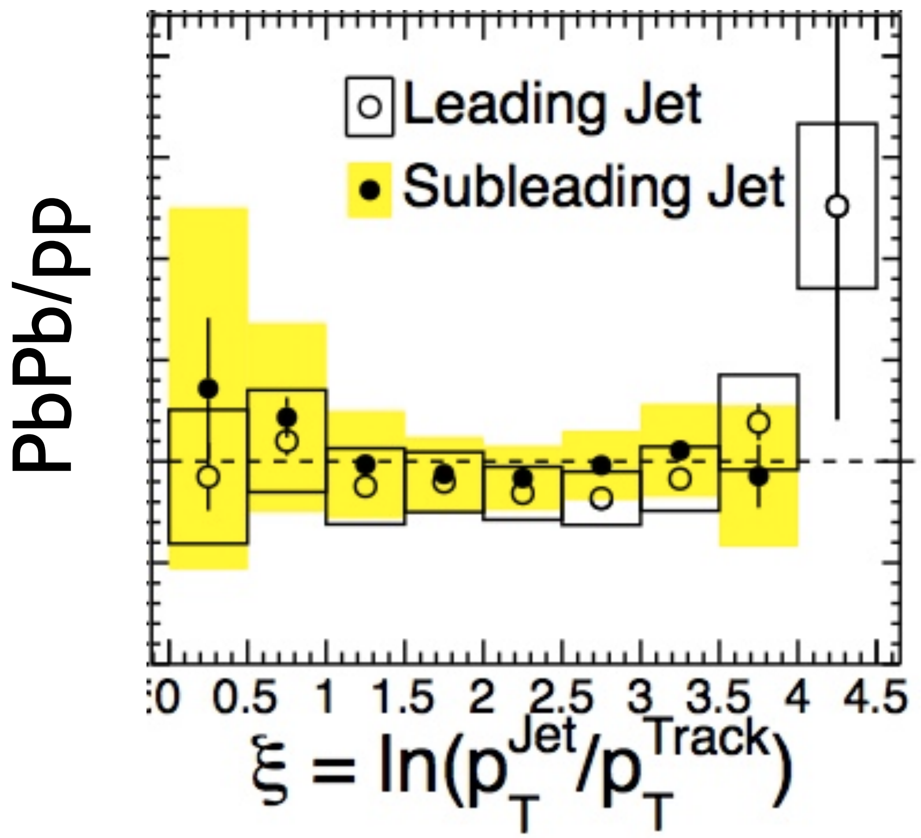


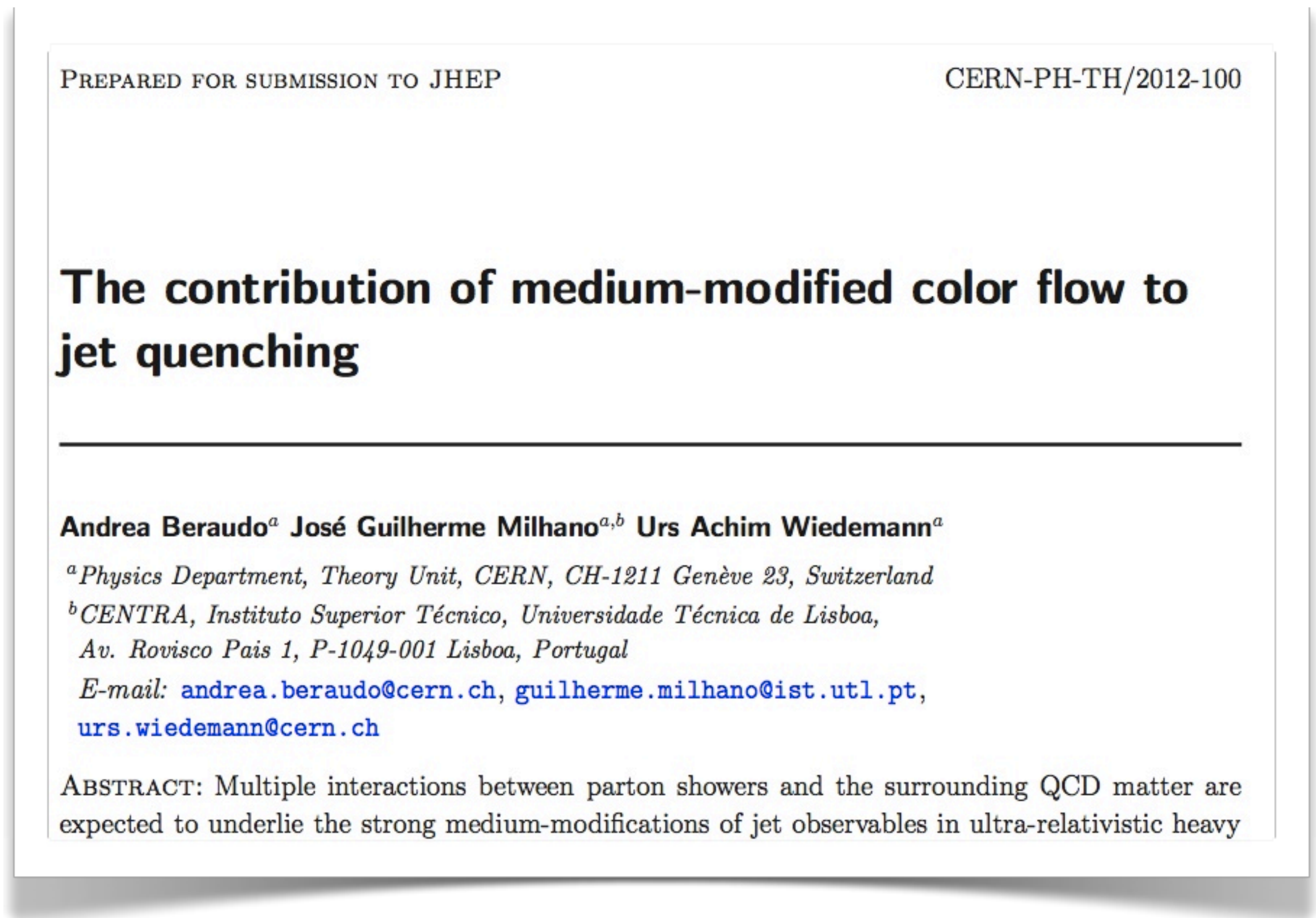


CMS "Perspective" on R_{AA}



Separating Jet Spectrum and Frag. Func. (FF)





Prepared for submission to JHEP CERN-PH-TH/2012-100

The contribution of medium-modified color flow to jet quenching

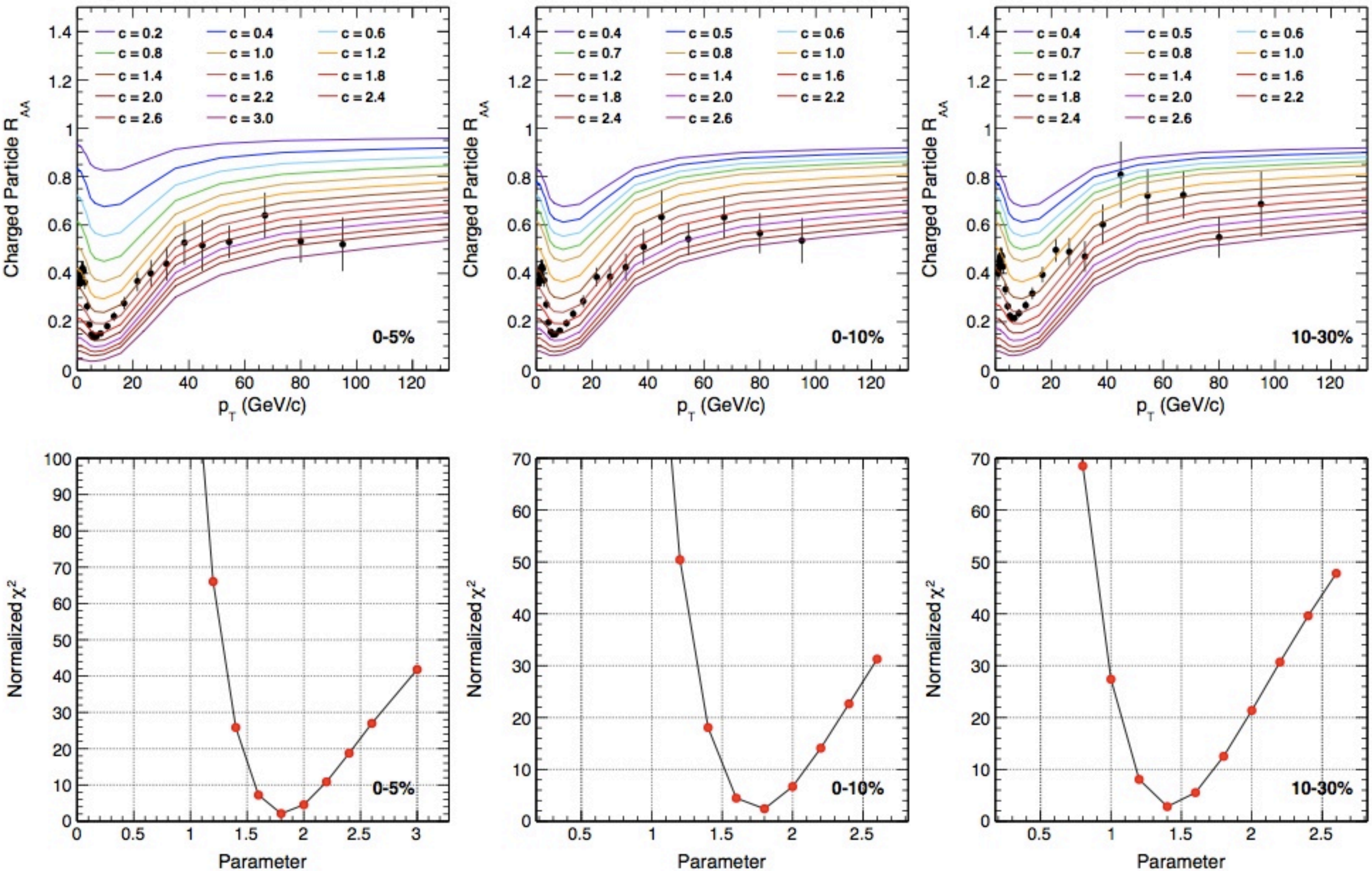
Andrea Beraudo[a] José Guilherme Milhano[a,b] Urs Achim Wiedemann[a]

[a] *Physics Department, Theory Unit, CERN, CH-1211 Genève 23, Switzerland*
[b] *CENTRA, Instituto Superior Técnico, Universidade Técnica de Lisboa, Av. Rovisco Pais 1, P-1049-001 Lisboa, Portugal*
E-mail: andrea.beraudo@cern.ch, guilherme.milhano@ist.utl.pt, urs.wiedemann@cern.ch

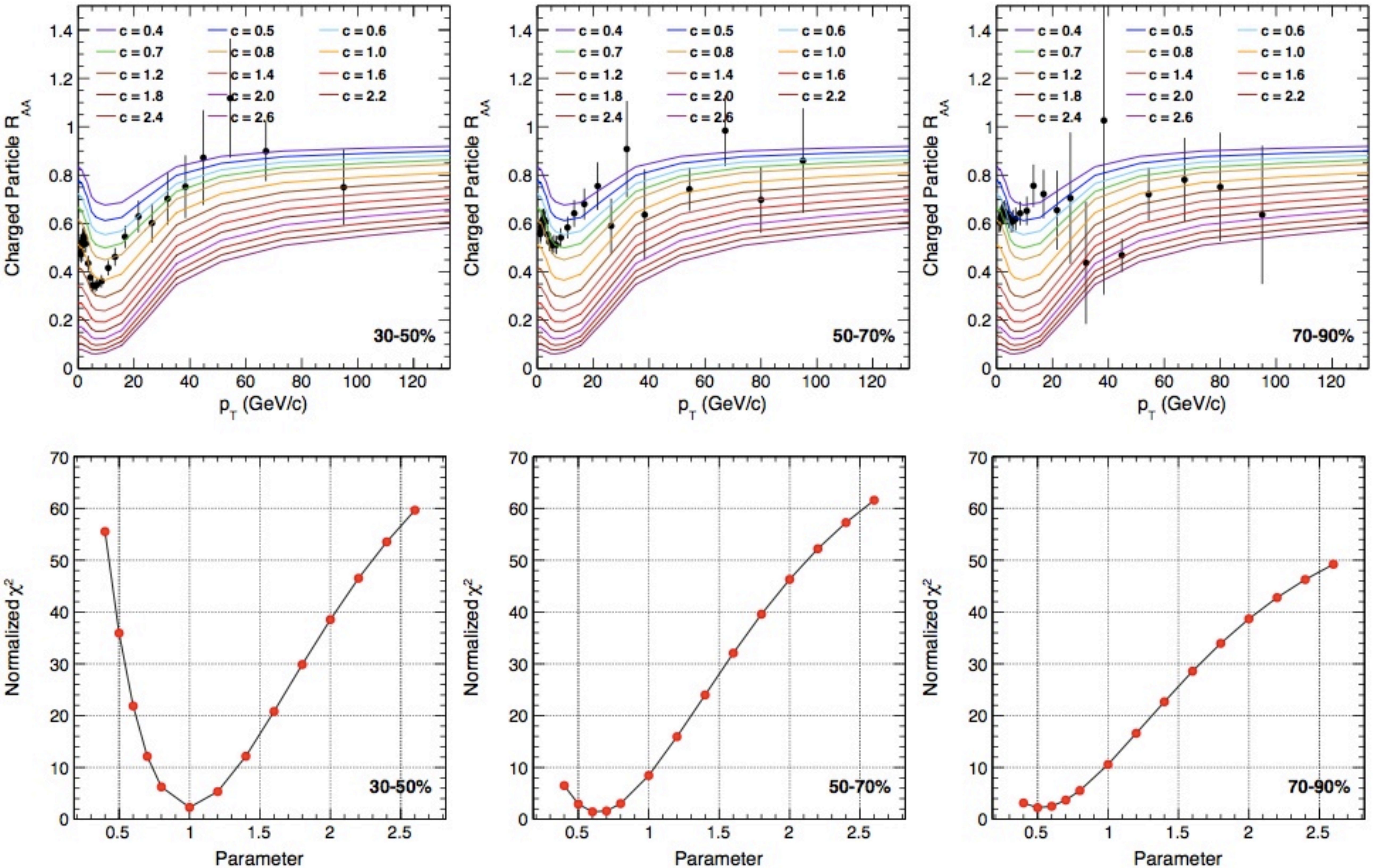
Abstract: Multiple interactions between parton showers and the surrounding QCD matter are expected to underlie the strong medium-modifications of jet observables in ultra-relativistic heavy

"Vacuum-like" Fragmentation Function for high-p_T charged particles

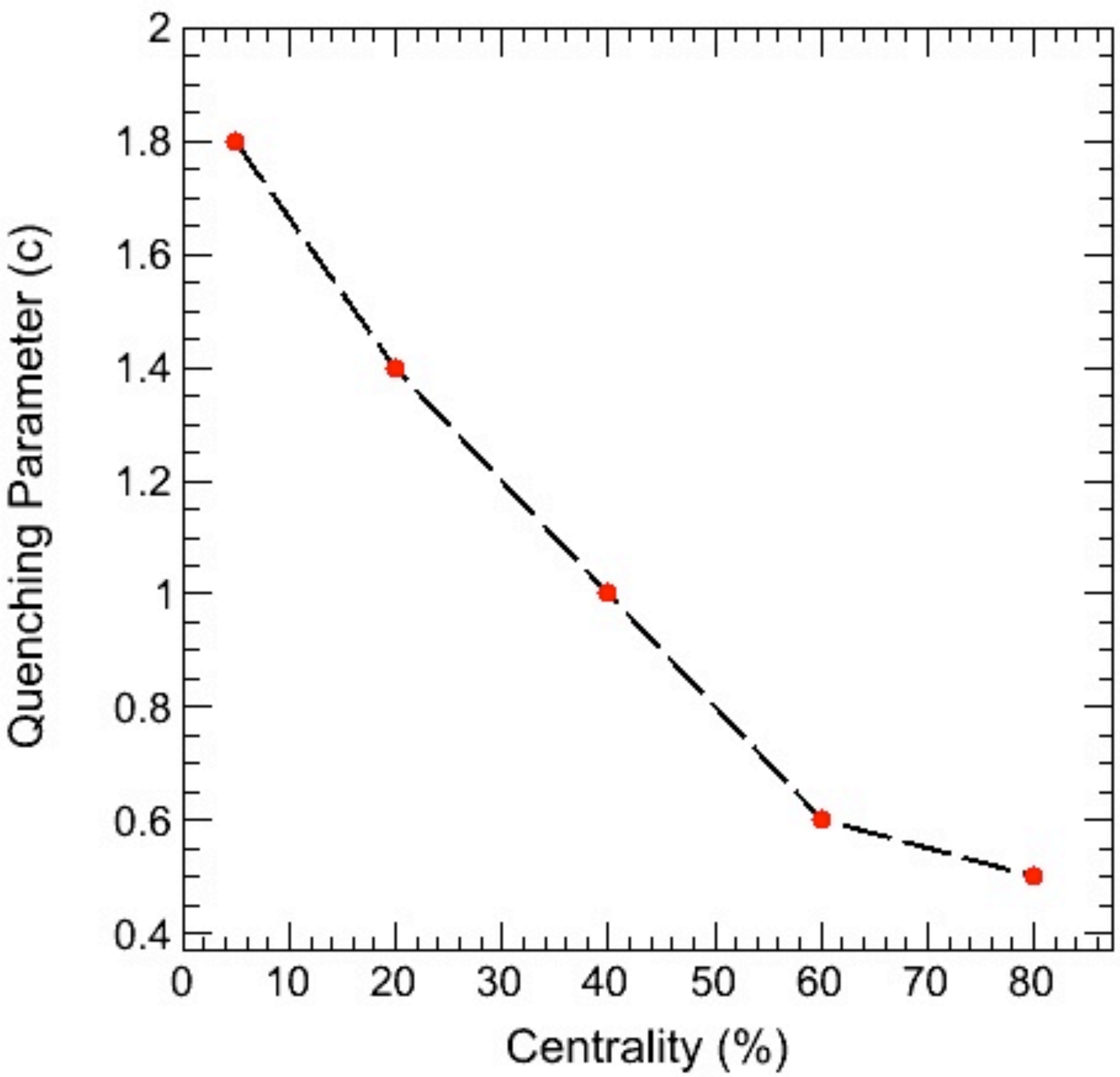
Centrality Dependence

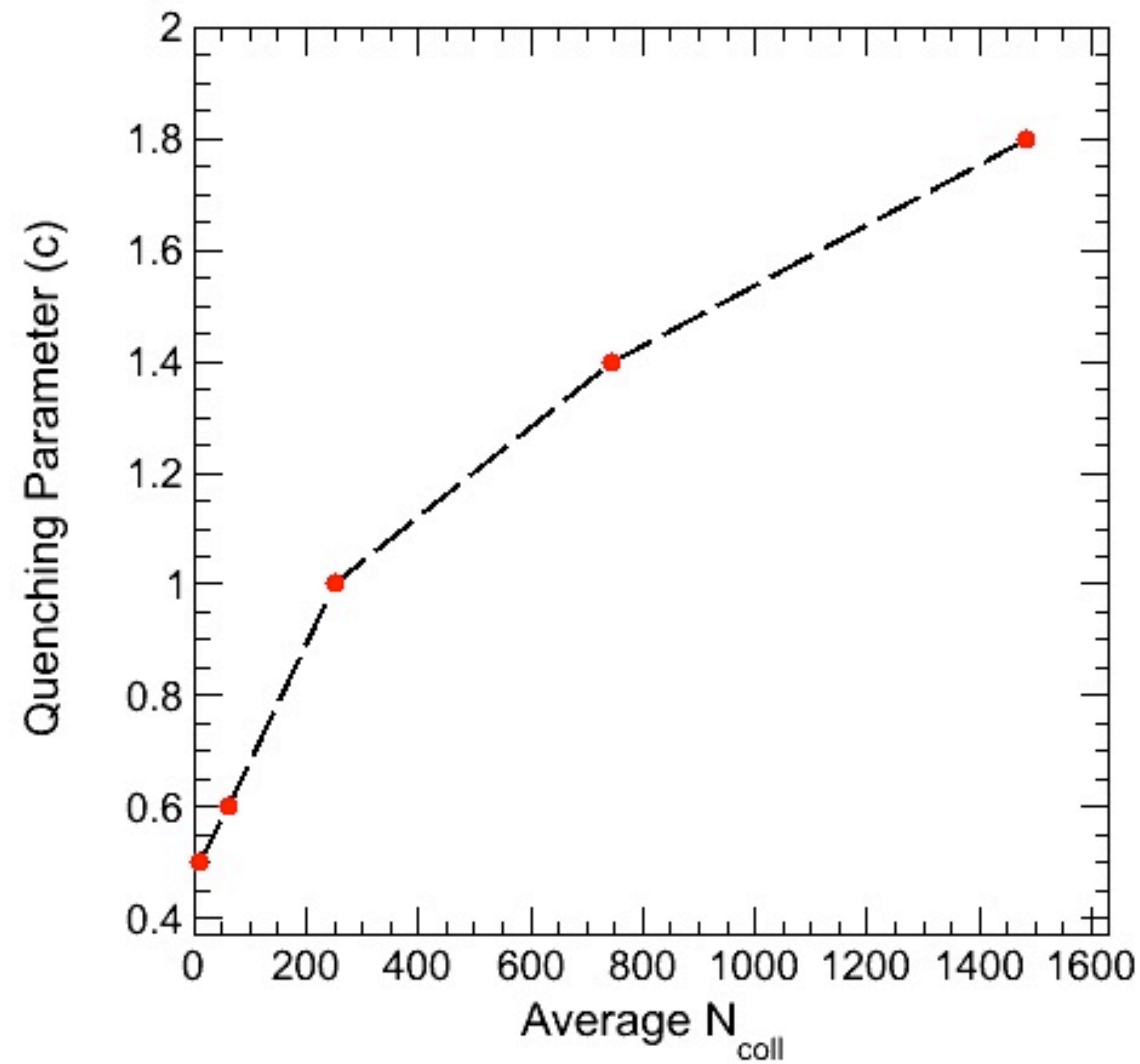


Centrality Dependence



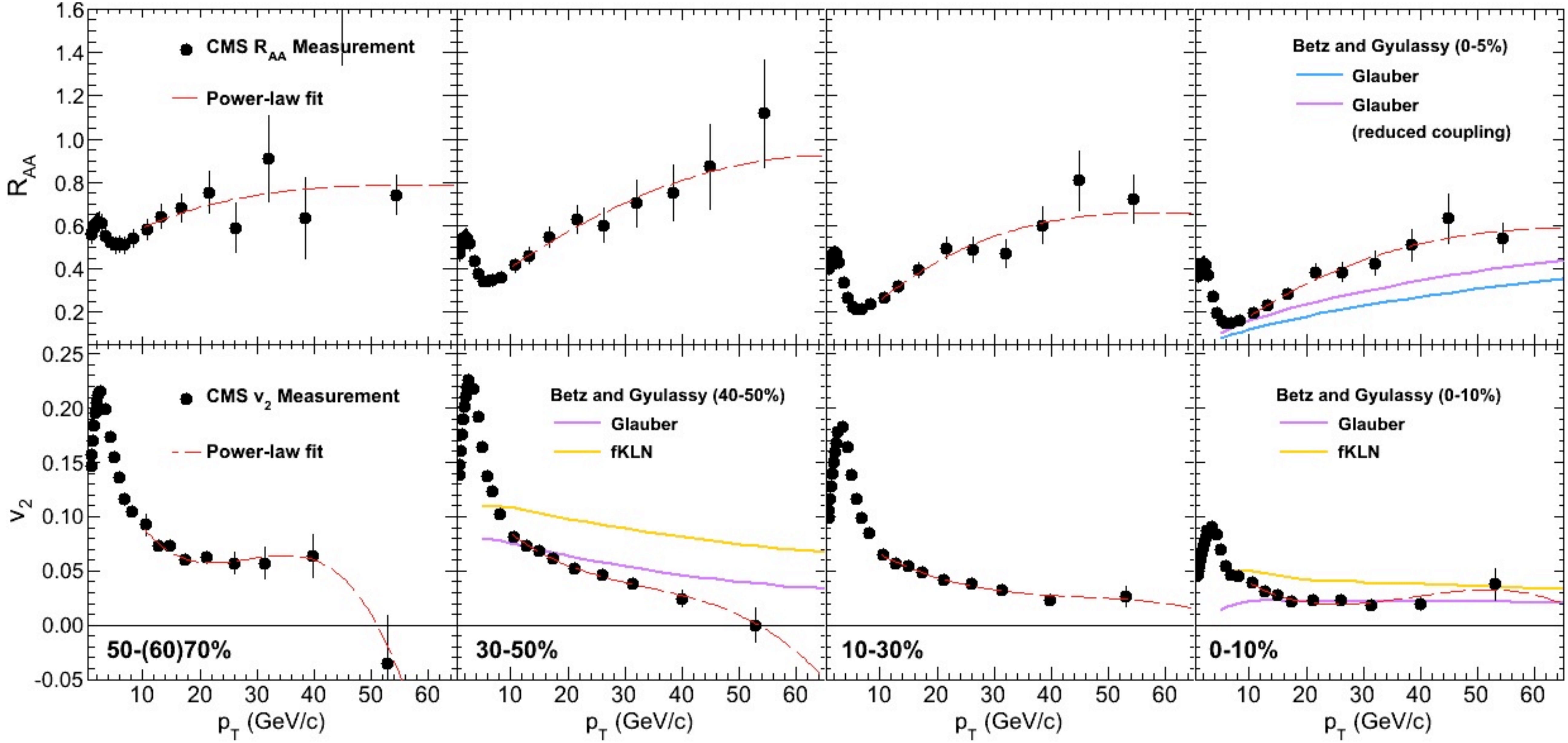
Centrality Dependence





Associating the quenching parameter with average path length <L> in each centrality?

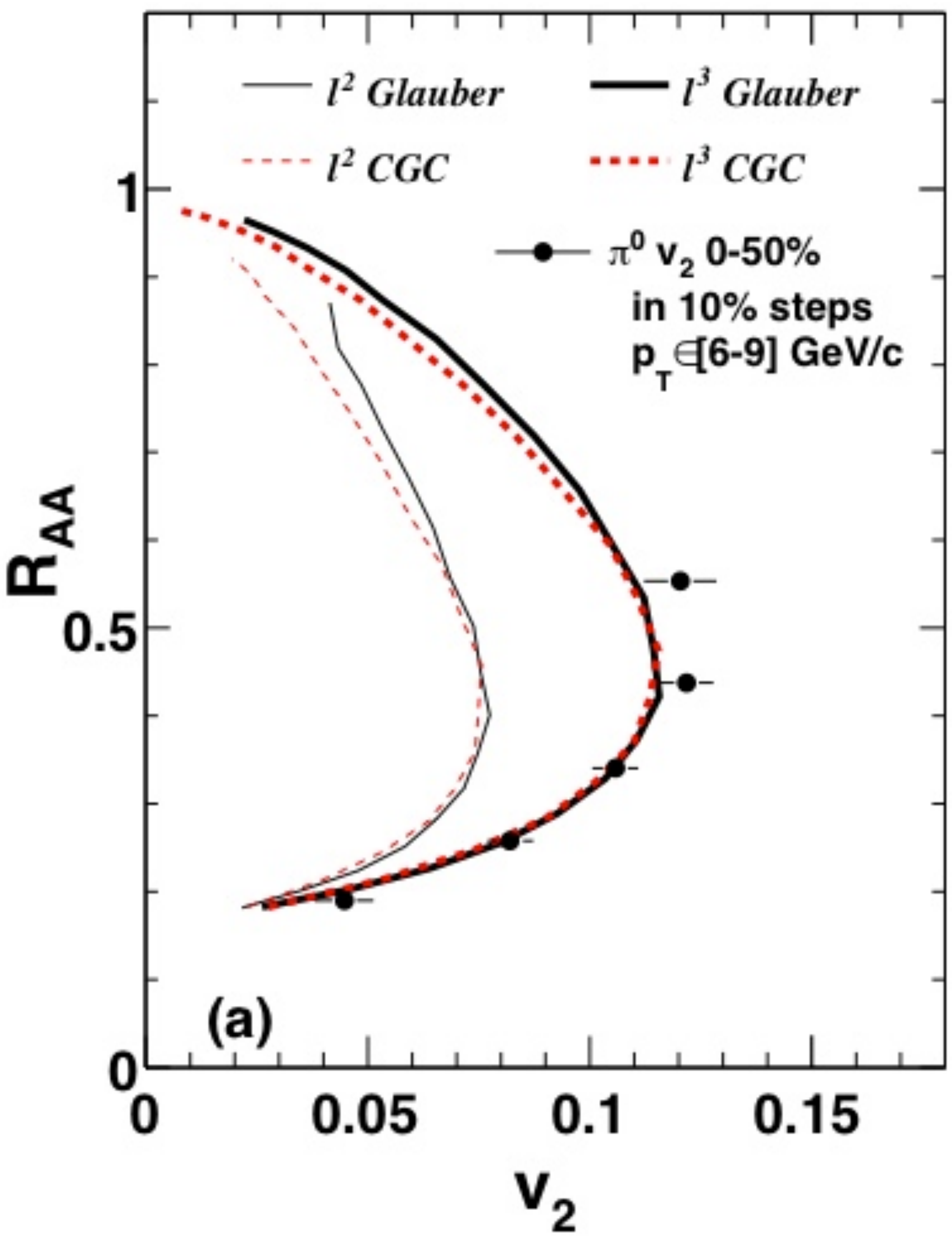
Centrality Dependence

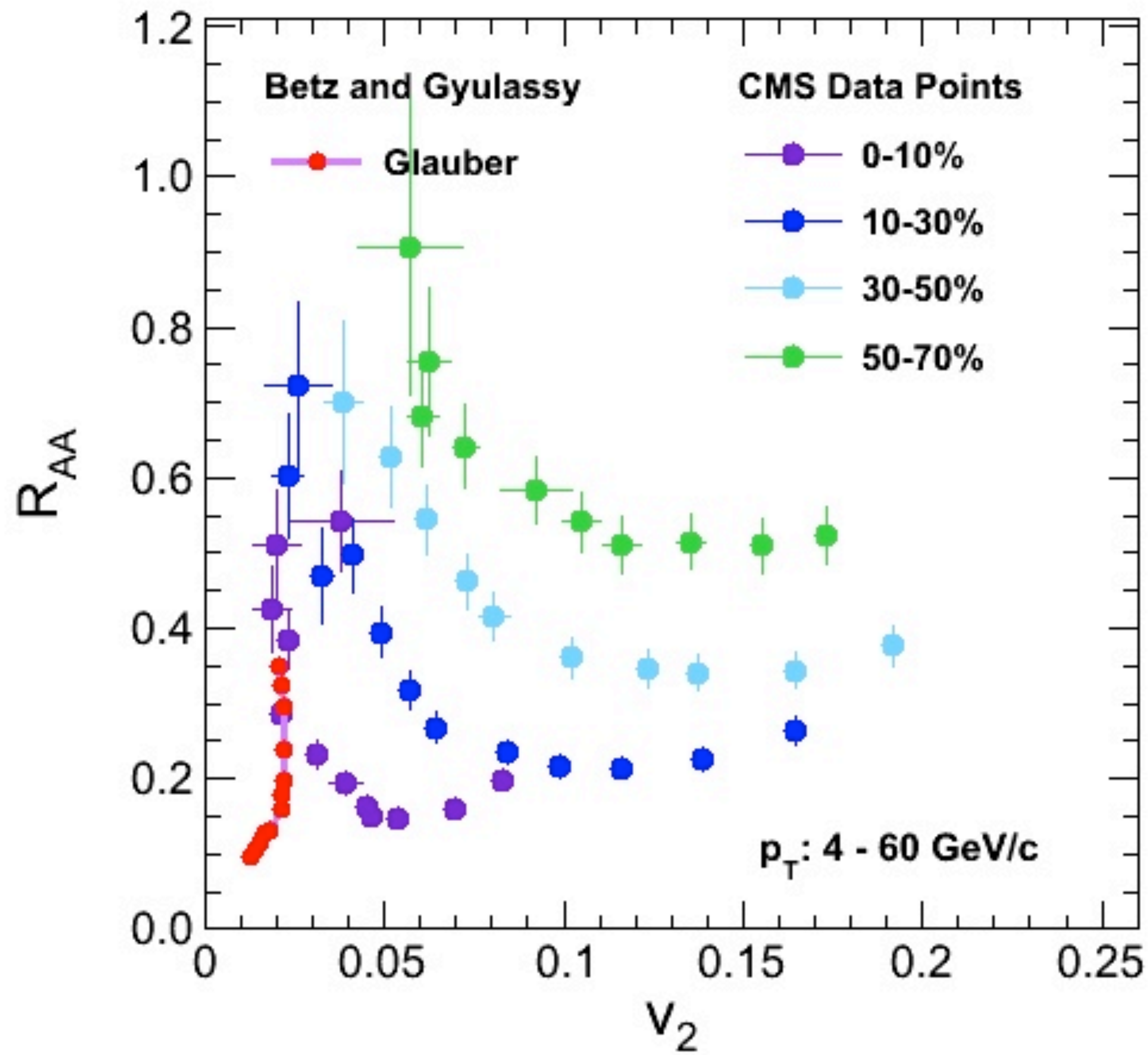


Simultaneous description of R_{AA} and high-pT v_2 ?

High p_T v_2 vs R_{AA}

arXiv:1101.0290





L^2 (QCD) or L^3 (AdS/CFT) ??