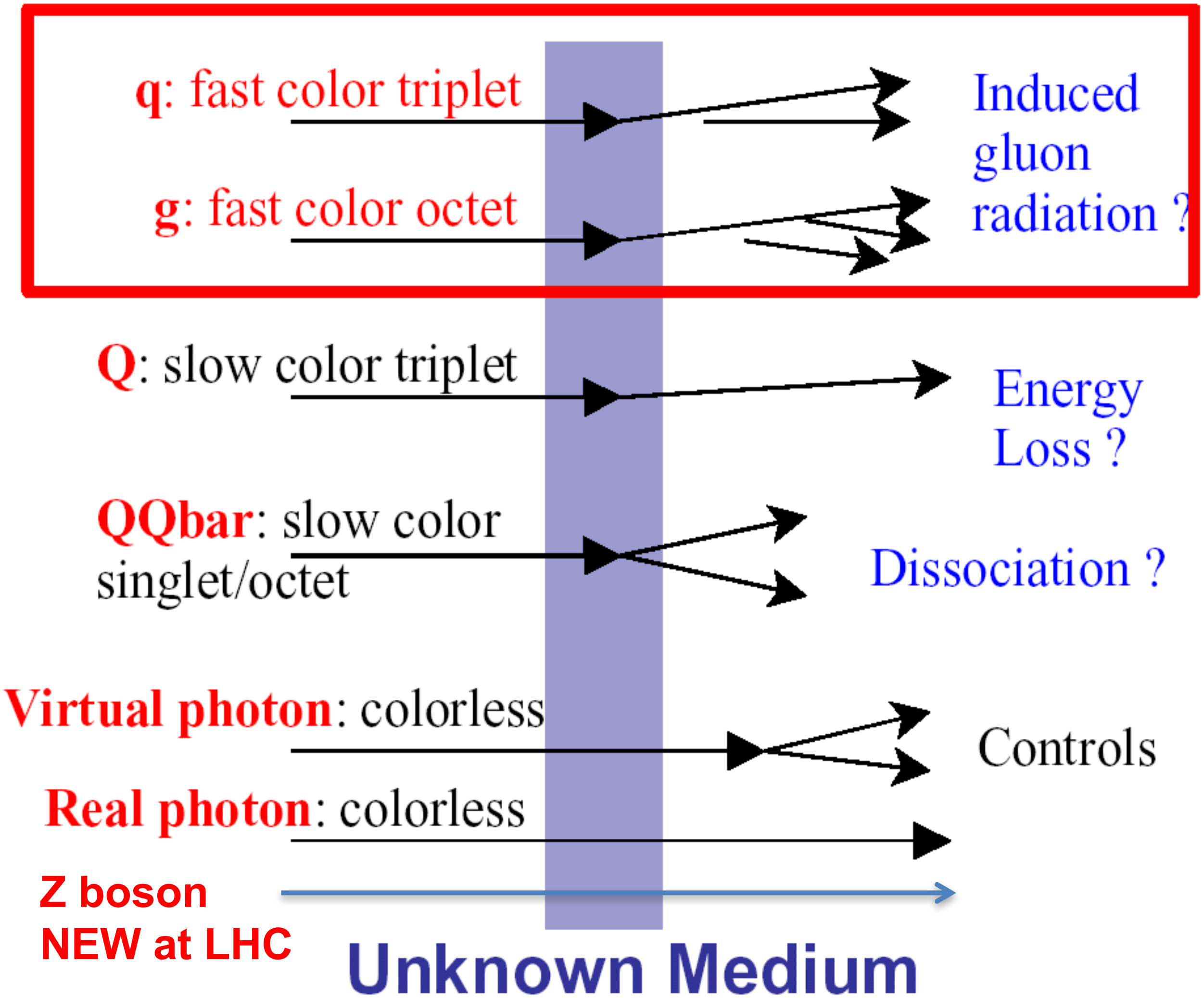
HARD-SCATTERING PROBES

The Probes Gallery:



Jet Suppression

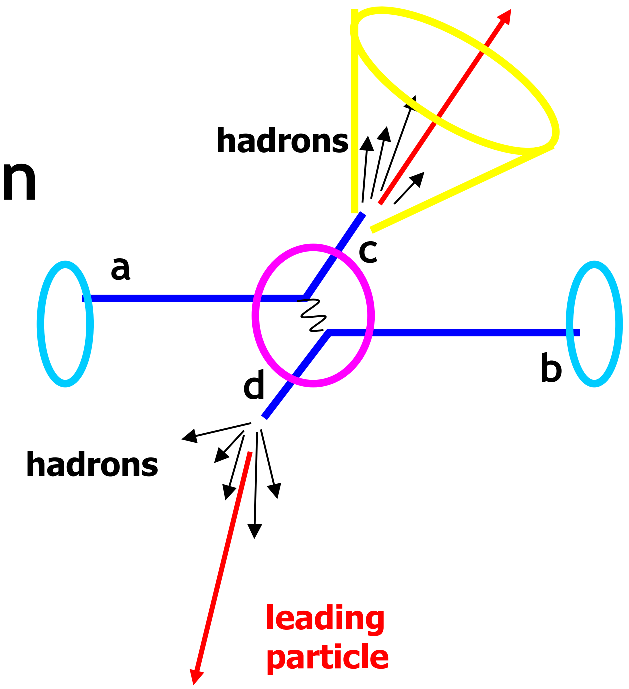
charm/bottom dynamics

J/Ψ & Υ

direct photons
Z bosons
CONTROL

High p_T Particle Production in pp

Jet: A localized collection of hadrons which come from a fragmenting parton



Parton Distribution Functions

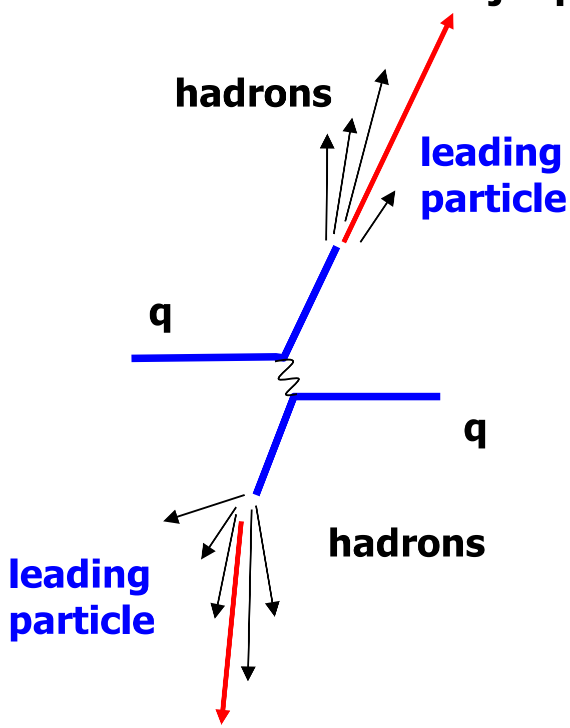
Hard-scattering cross-section

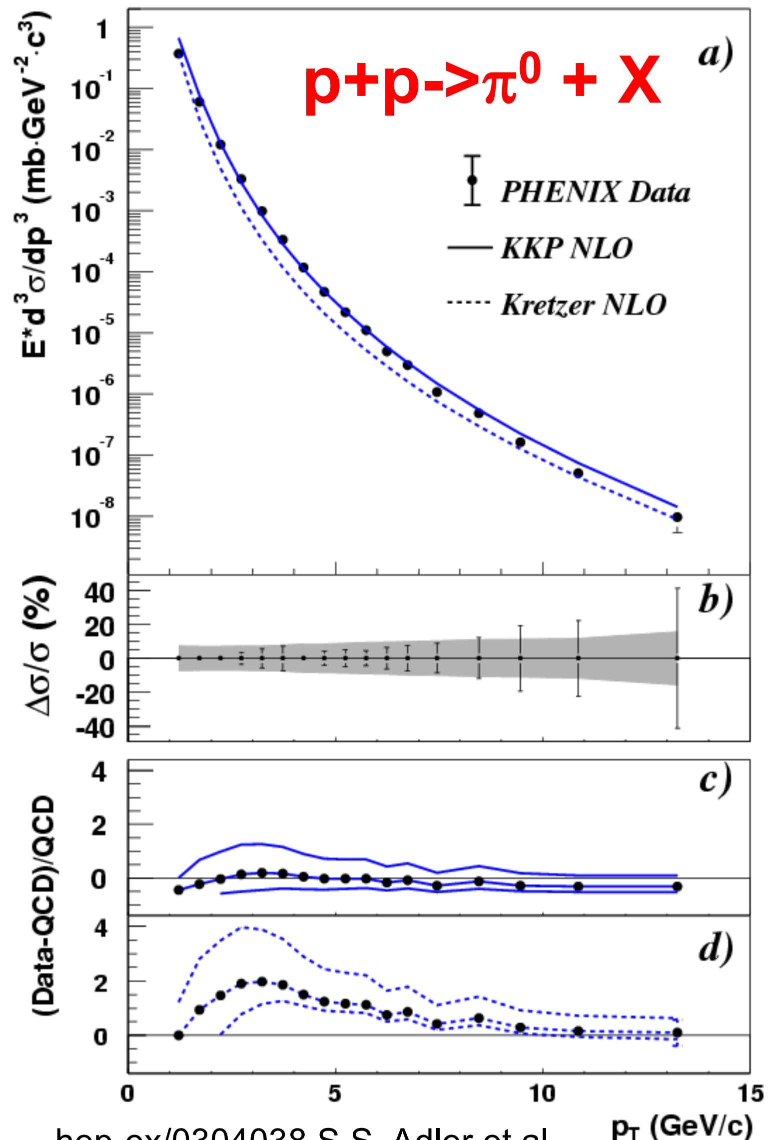
Fragmentation Function

"Collinear factorization"

$$\frac{d\sigma^h_{pp}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \frac{D^0_{h/c}}{\pi z_c}$$

Calibrating the Probe(s)





hep-ex/0304038 S.S. Adler et al.

- Measurement from elementary collisions. Leading particles spectra used as a "proxy" to jets.

High p_T Particle Production in A+A

$$\frac{dN^h_{AB}}{dy d^2 p_T} = ABK \sum_{abcd} \int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b$$

(pQCD context...)

$$\otimes f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2)$$

Parton Distribution Functions

$$\otimes g(\mathbf{k}_a) g(\mathbf{k}_b)$$

Intrinsic k_T , Cronin Effect

$$\otimes S_A(x_a, Q_a^2) S_B(x_b, Q_b^2)$$

Shadowing,

$$\otimes \frac{d\sigma}{d\hat{t}}(ab \to cd)$$

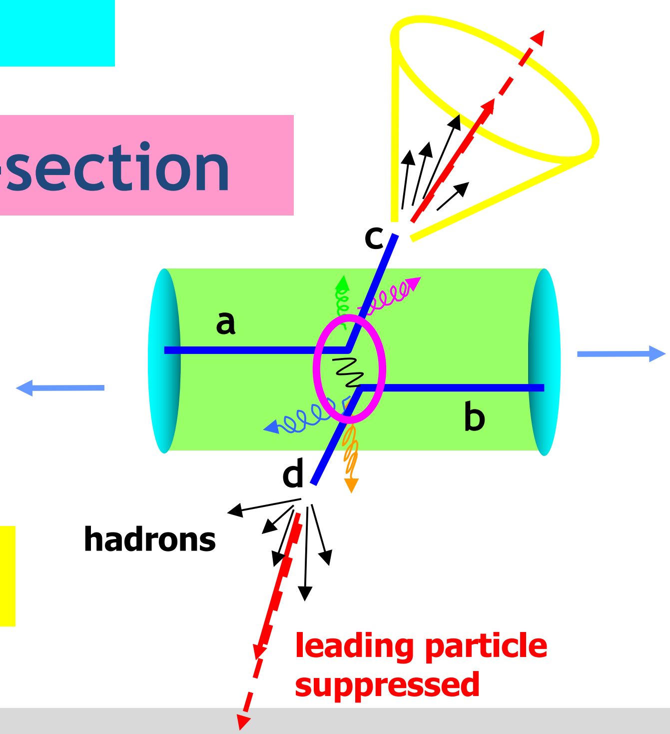
Hard-scattering cross-section

$$\otimes \int_0^1 d\varepsilon P(\varepsilon) \frac{z_c^*}{z_c}$$

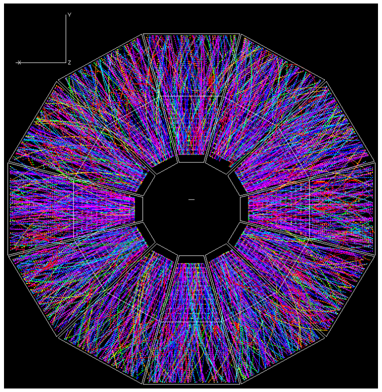
Partonic Energy Loss

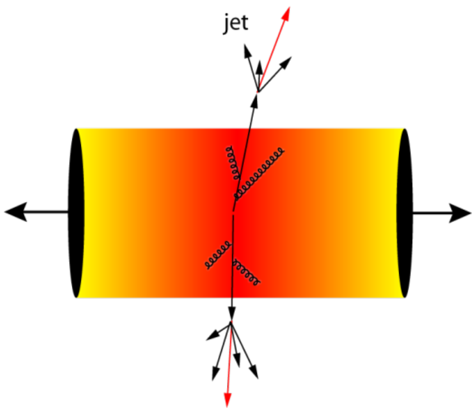
$$\otimes \frac{D^0_{h/c}(z_c^*, Q_c^2)}{\pi z_c}$$

Fragmentation Function



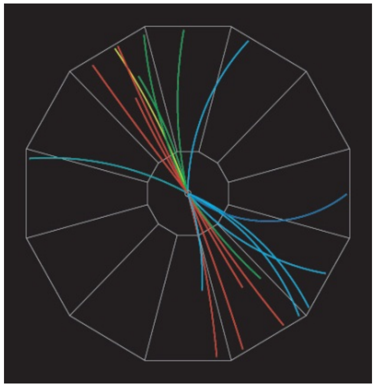
Quantifying the nuclear effect

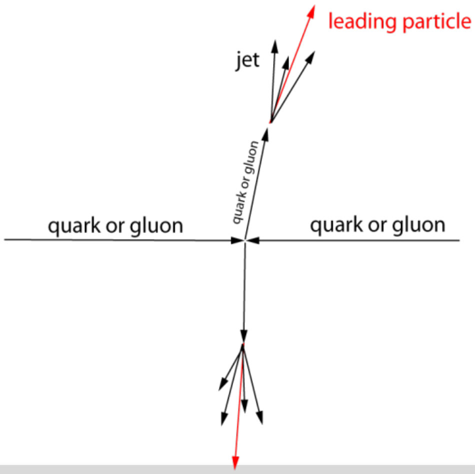




Energy loss depends on
properties of medium
(gluon densities, size, transport coefficients)
properties of "probe"
(color charge, mass)

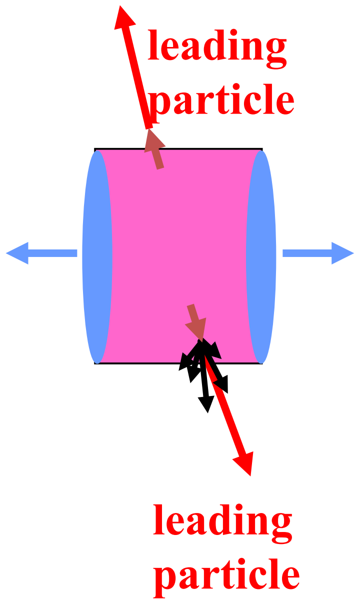
$$R_{AA} = \frac{\text{yield in A+A/number of equivalent p+p collisions}}{\text{yield in p+p}}$$

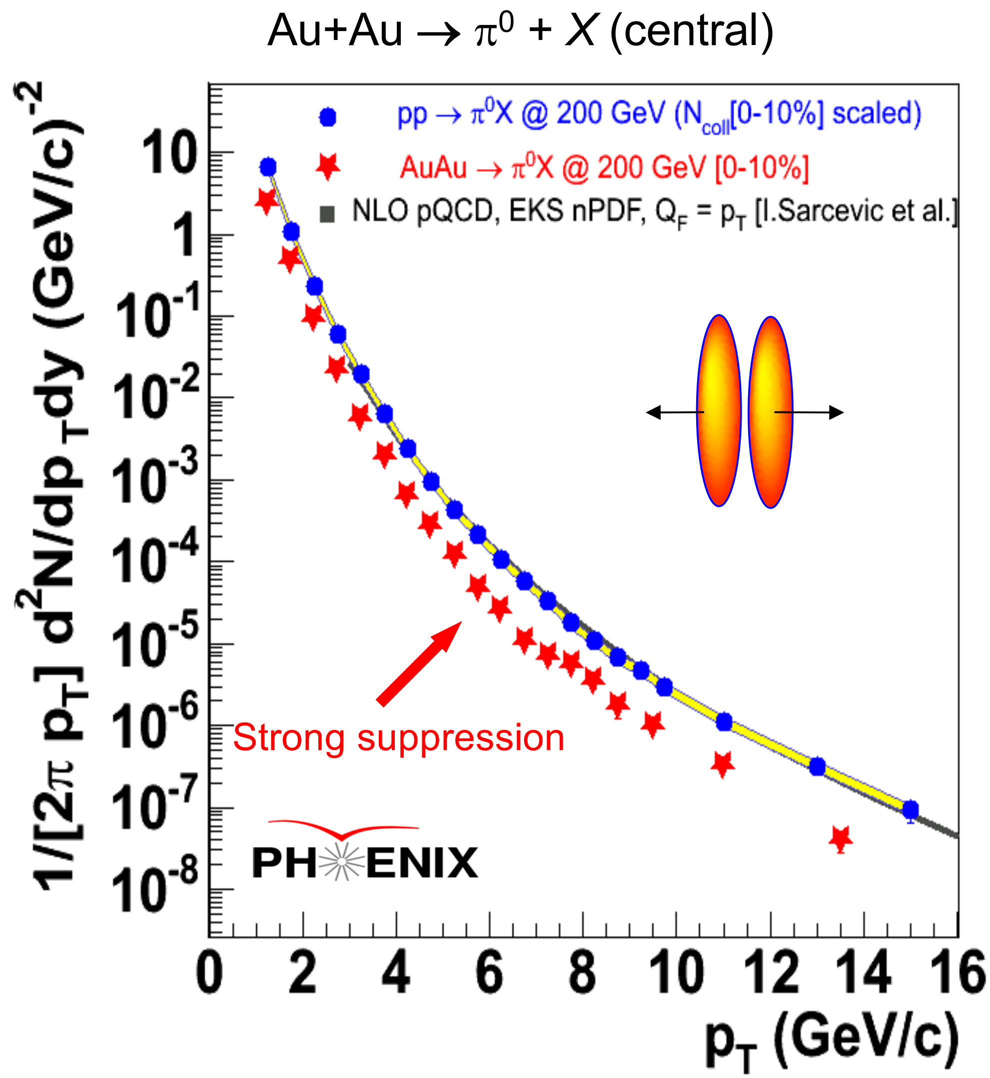




Calibrate the probe and then use it !

- Single-particle spectrum and QCD predictions

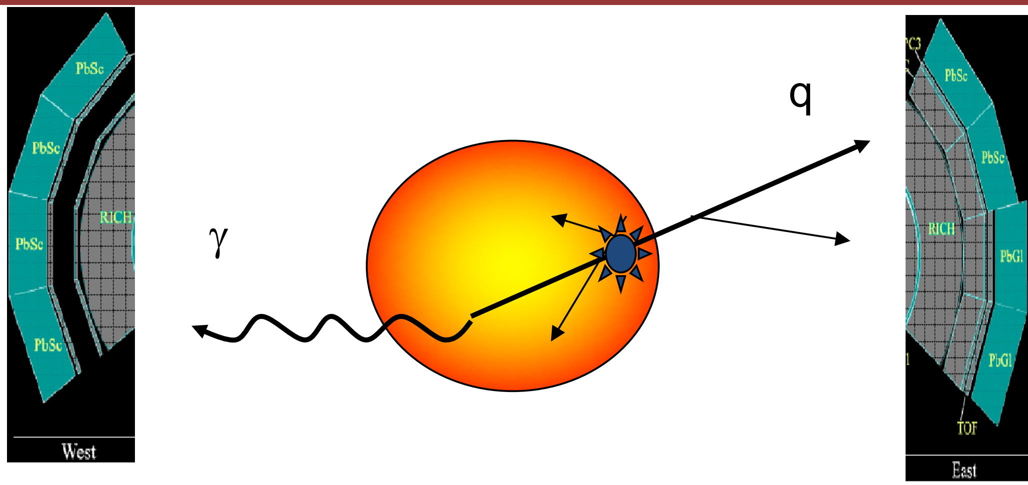




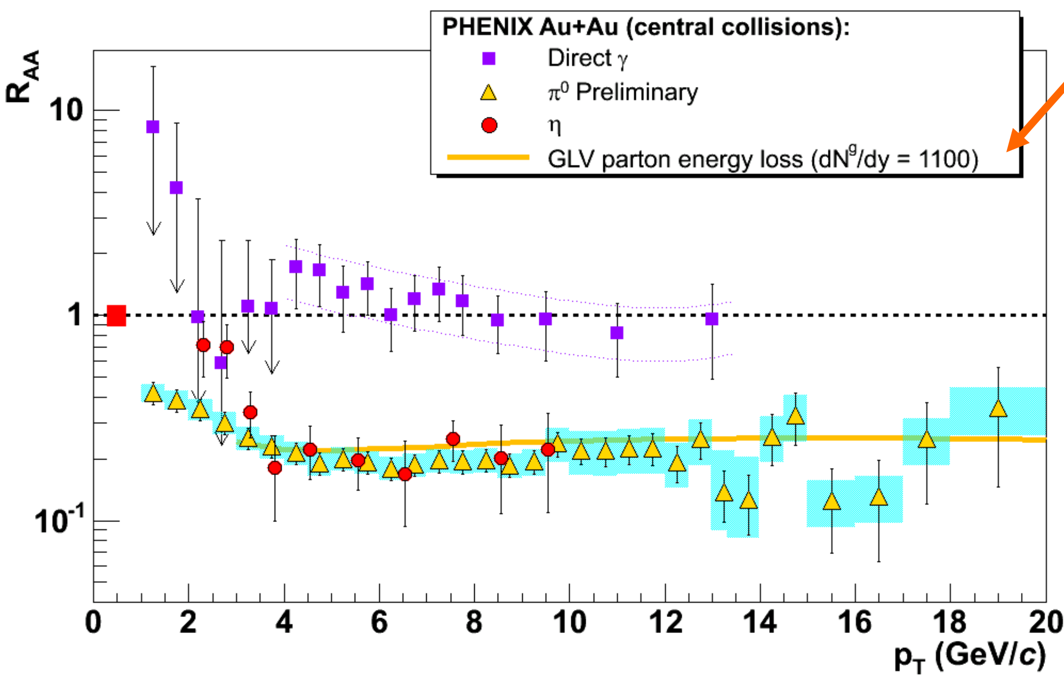
Peripheral spectra agree well with p+p (data & pQCD) scaled by N_{coll}

Central data exhibits suppression!

Control experiment: colorless probe



Confirm that jet quenching is due to energy loss in the medium. Deduce the medium density.

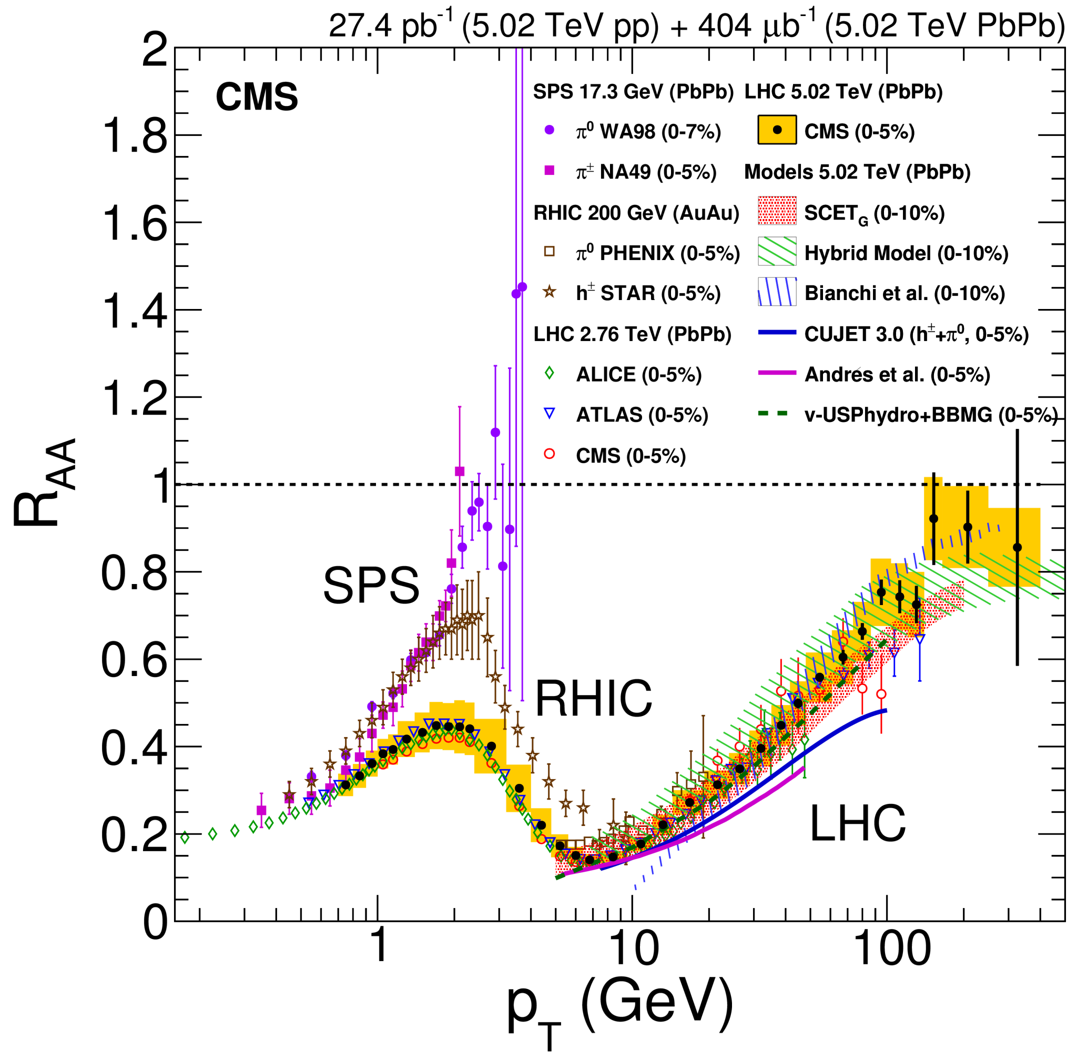


Photons shine !

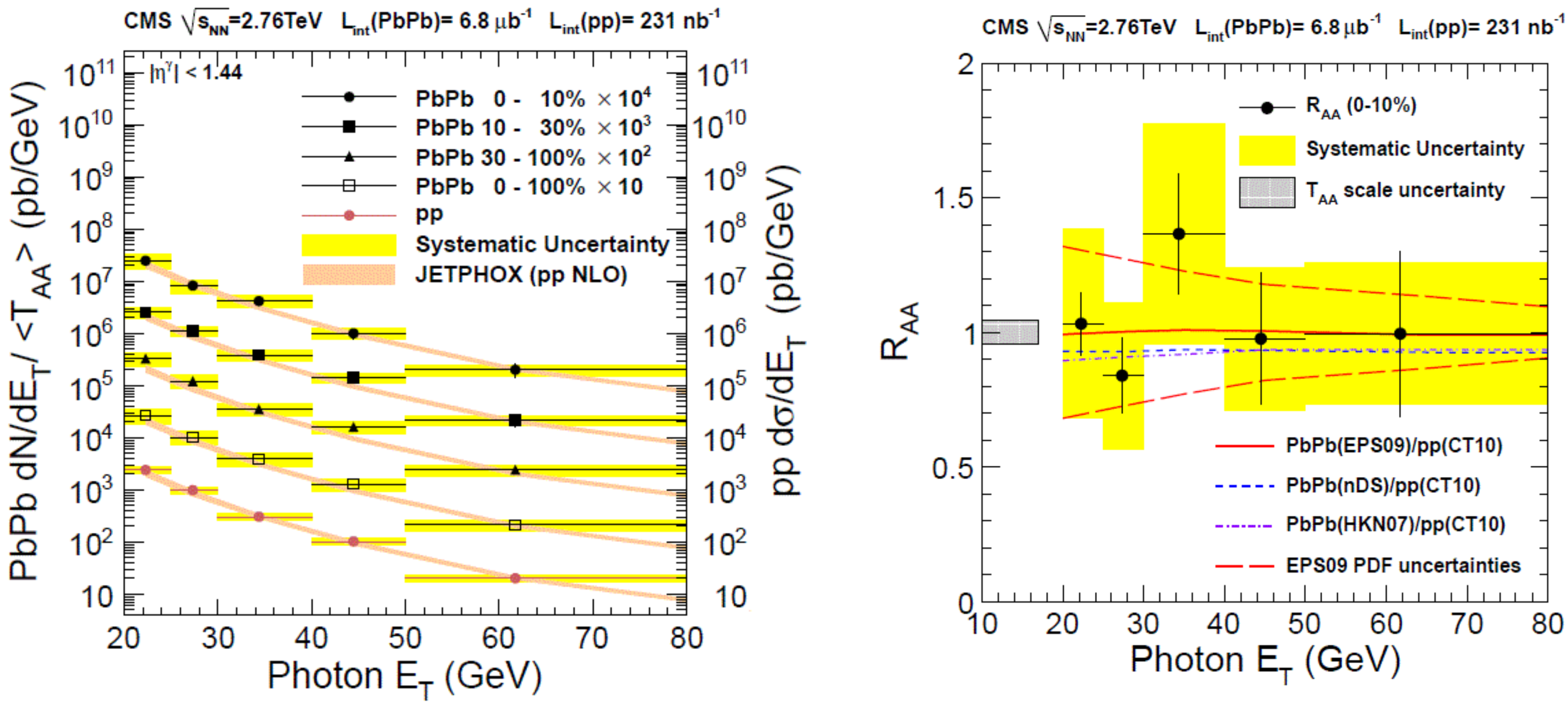
Pions and etas – suppressed !

High p_T charged hadrons: from RHIC to LHC

- Measuring charged tracks up to p_T~400 GeV/c (jet triggers)
- Suppression for p_T> 10 GeV is similar at the much higher energies at the LHC



A colorless probe: isolated high p_T photons at the LHC

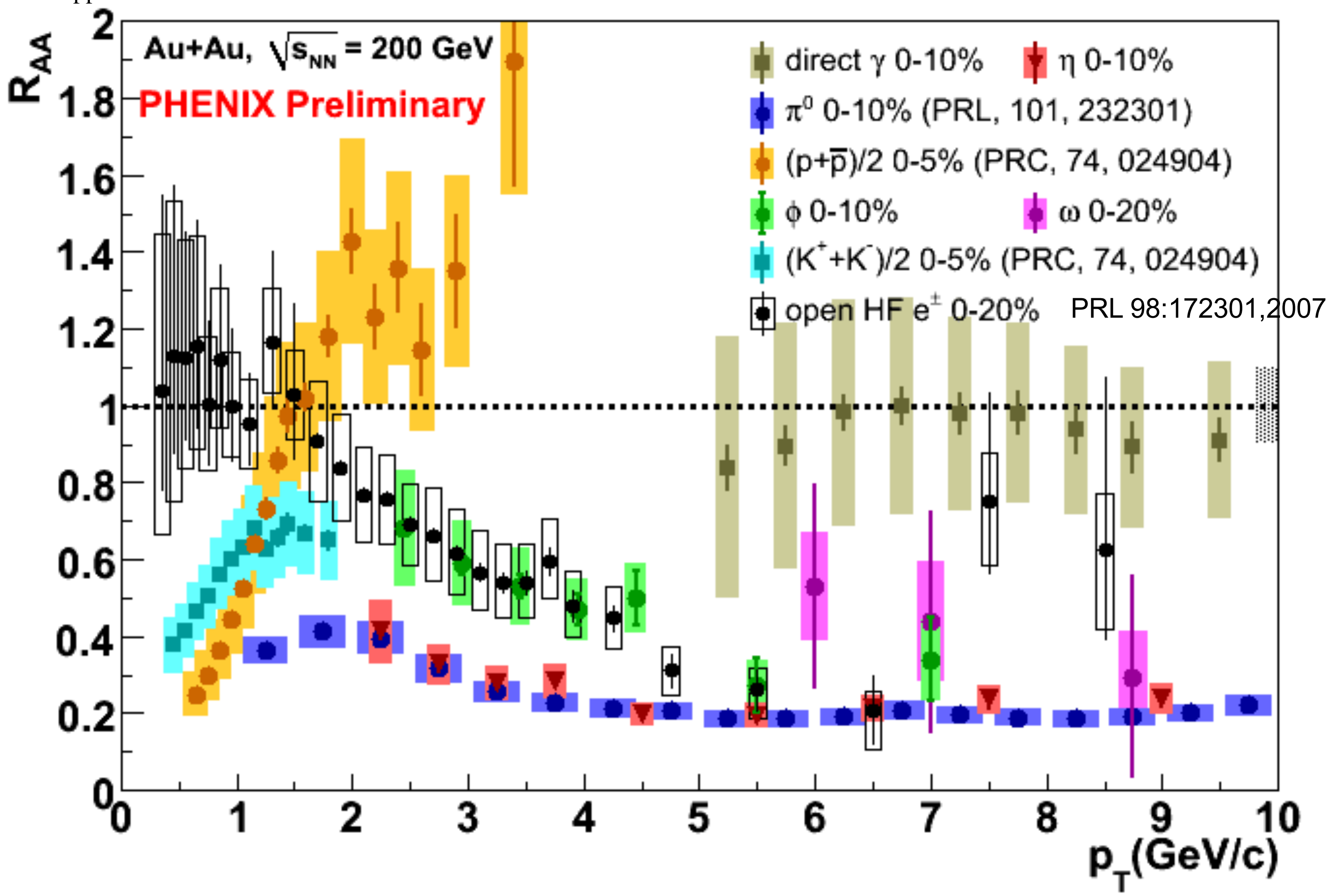


As expected: no nuclear modifications seen

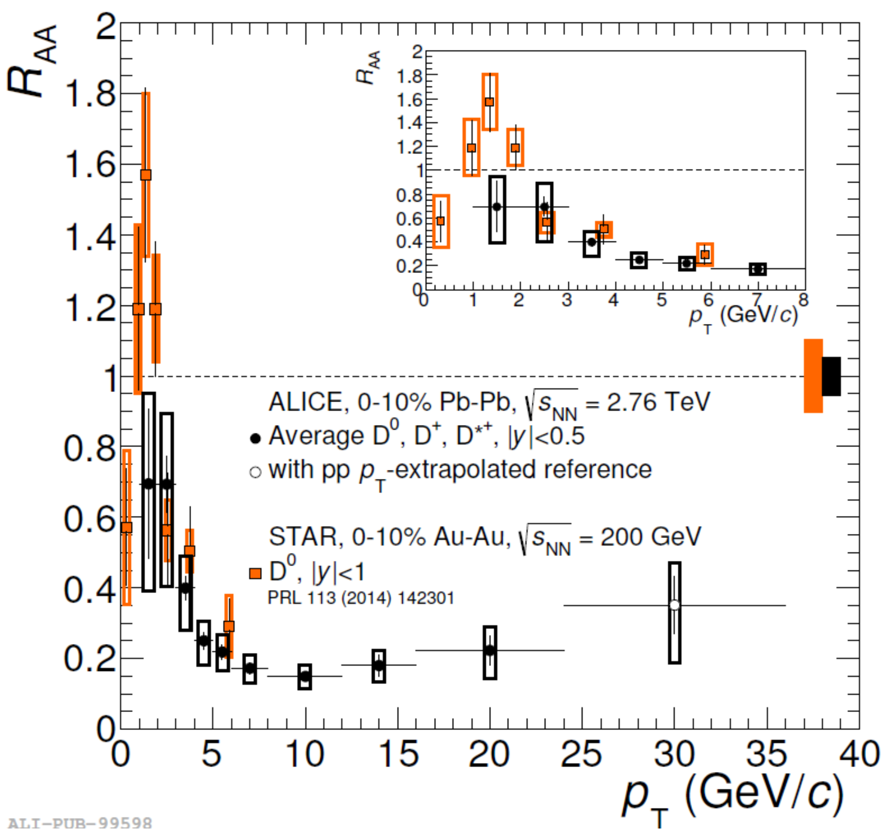
arXiv:1201.3093

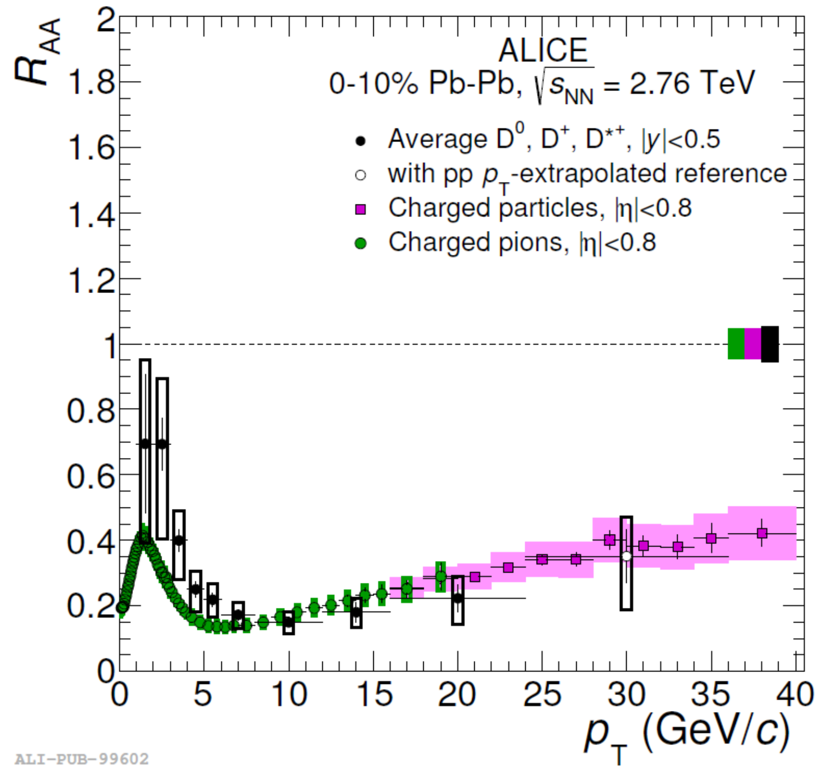
The particle Zoo in PHENIX

$$R_{AA} = \frac{\text{Yield}_{AA}/\langle N_{\text{binary}}\rangle_{AA}}{\text{Yield}_{pp}}$$

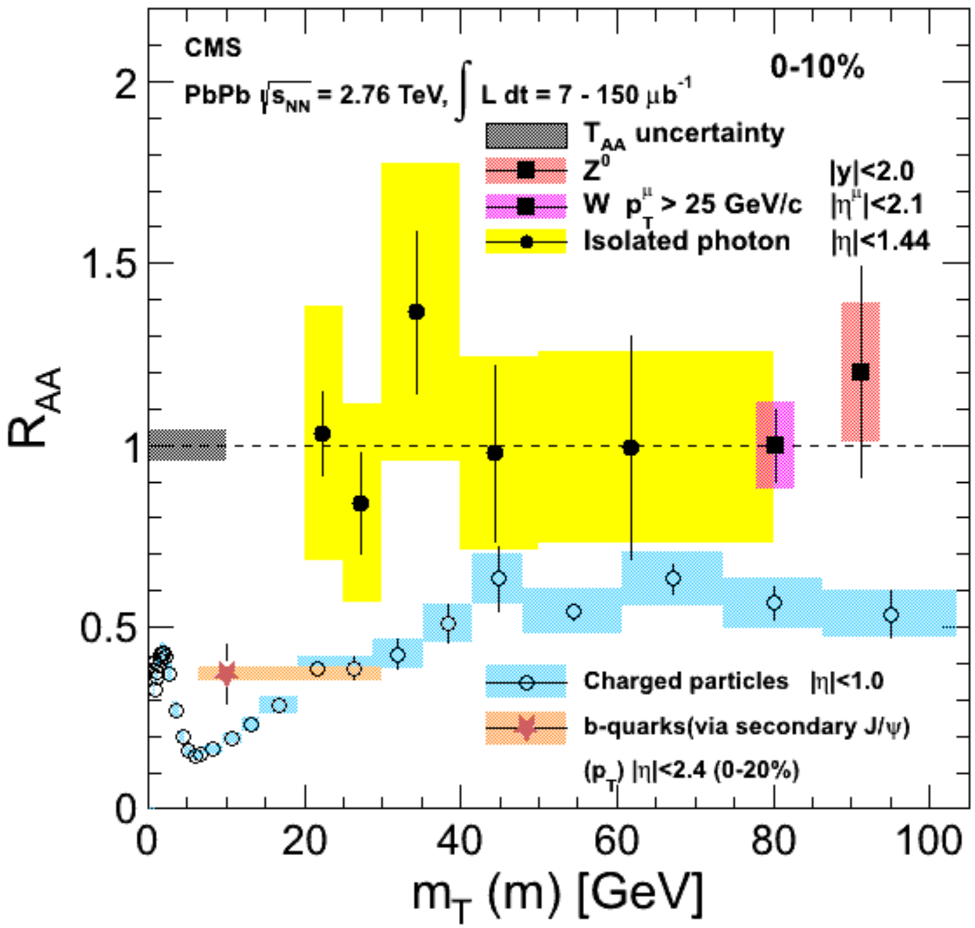


Charmed mesons at RHIC and LHC





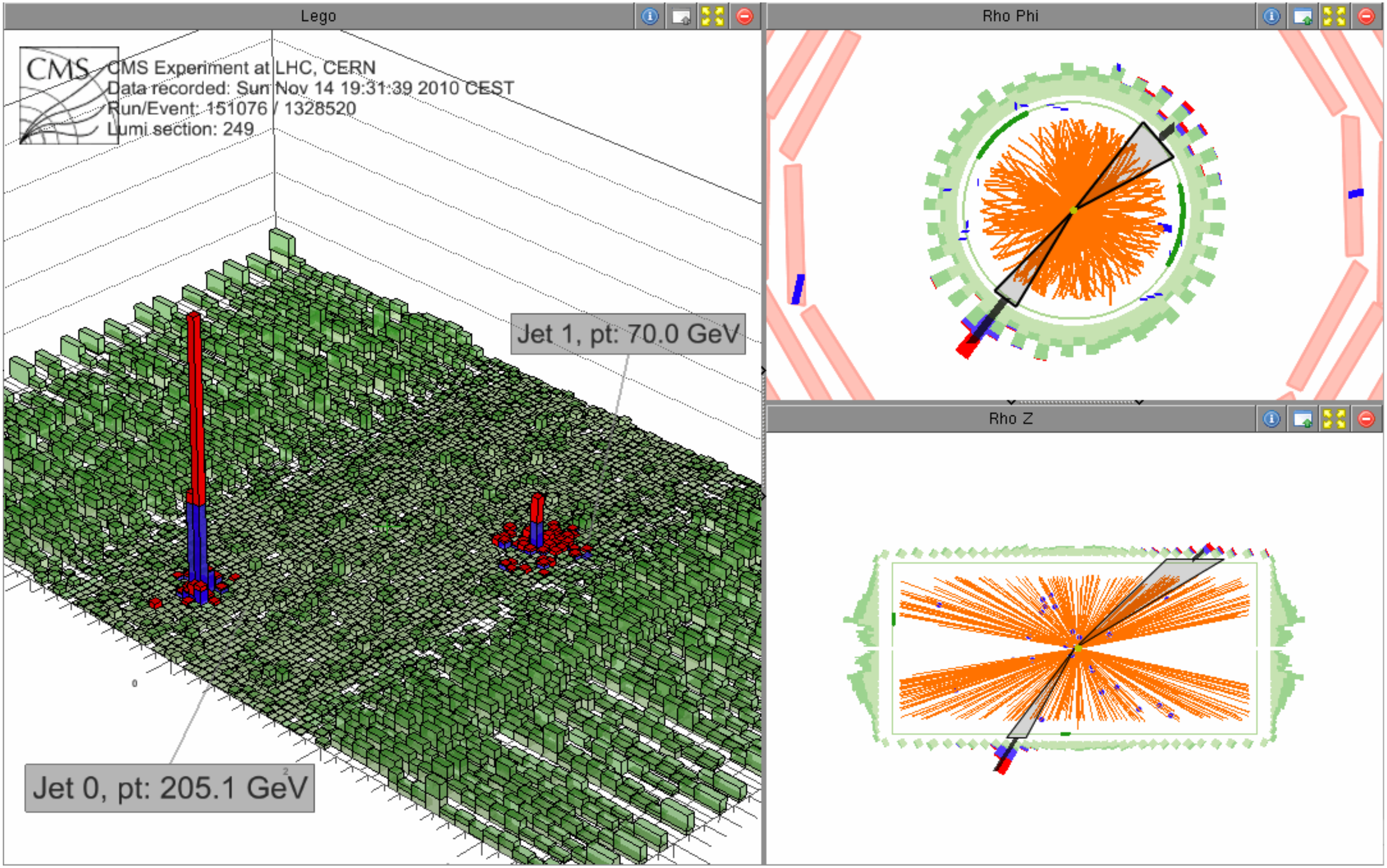
R_{AA} particle Zoo in CMS



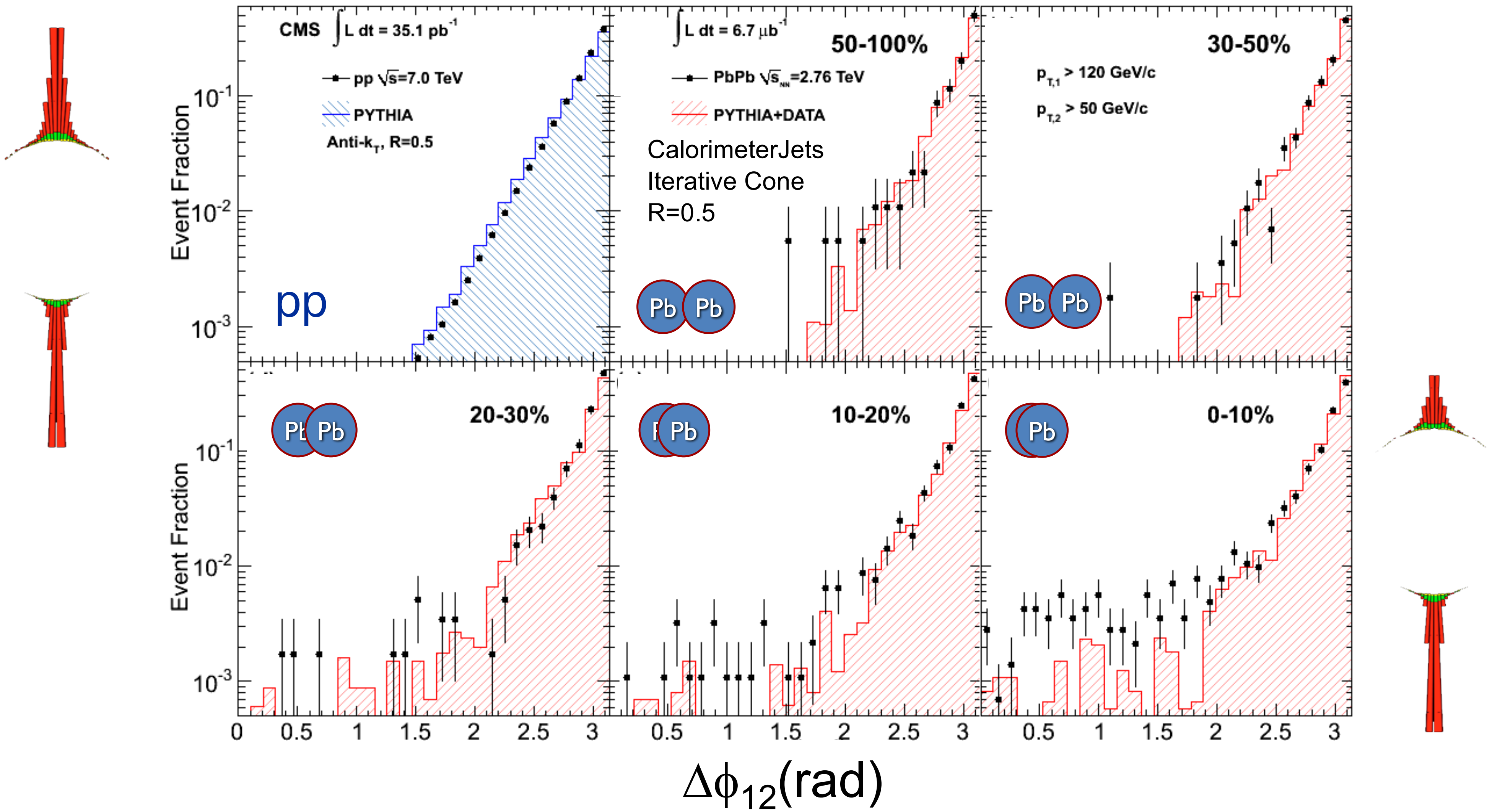
- QGP is transparent to Photons, W and Z bosons NEW colorless probes

- Charged hadrons (light) and heavy quarks (secondary J/Ψ) are suppressed

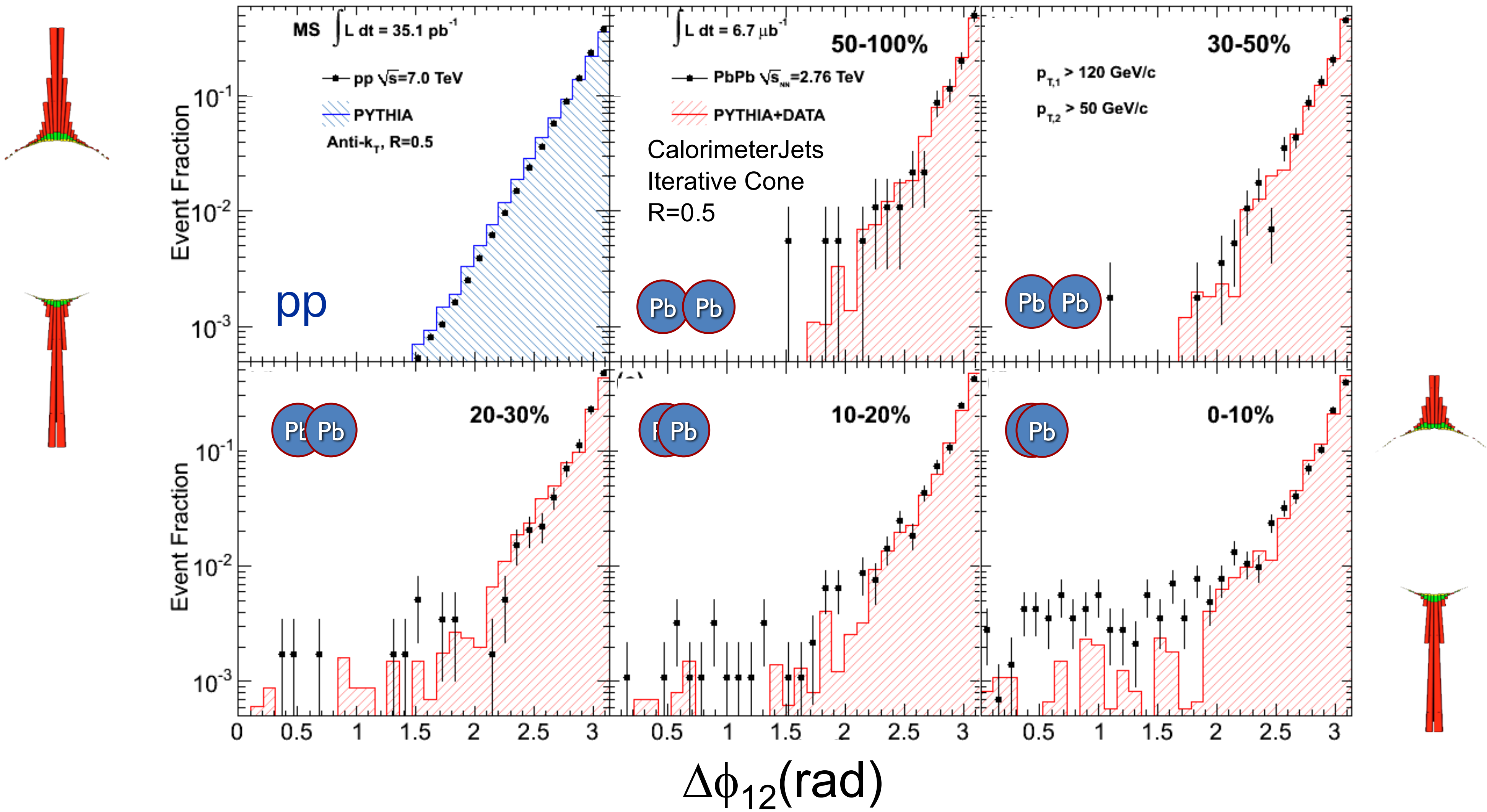
Jet quenching in the CMS detector



Jet Angular Correlation

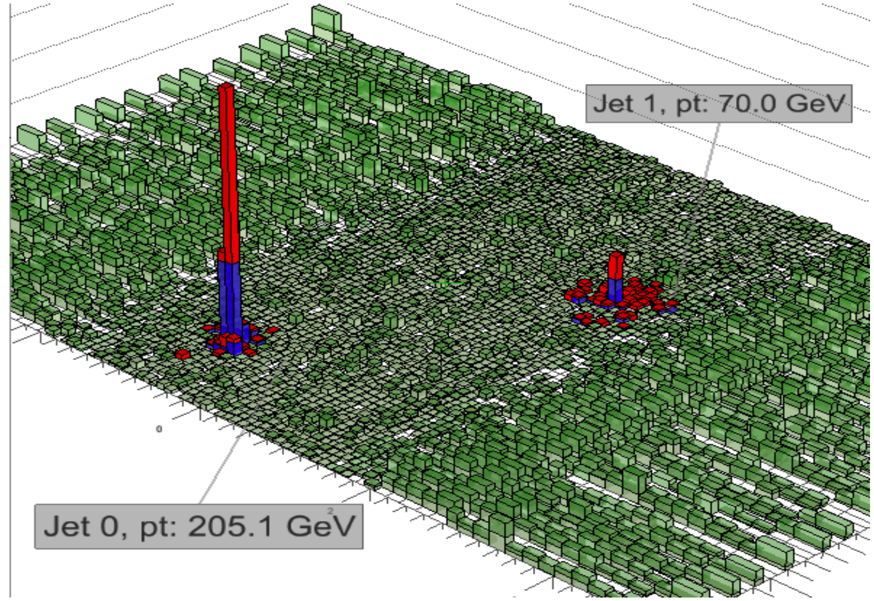


Jet Angular Correlation



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

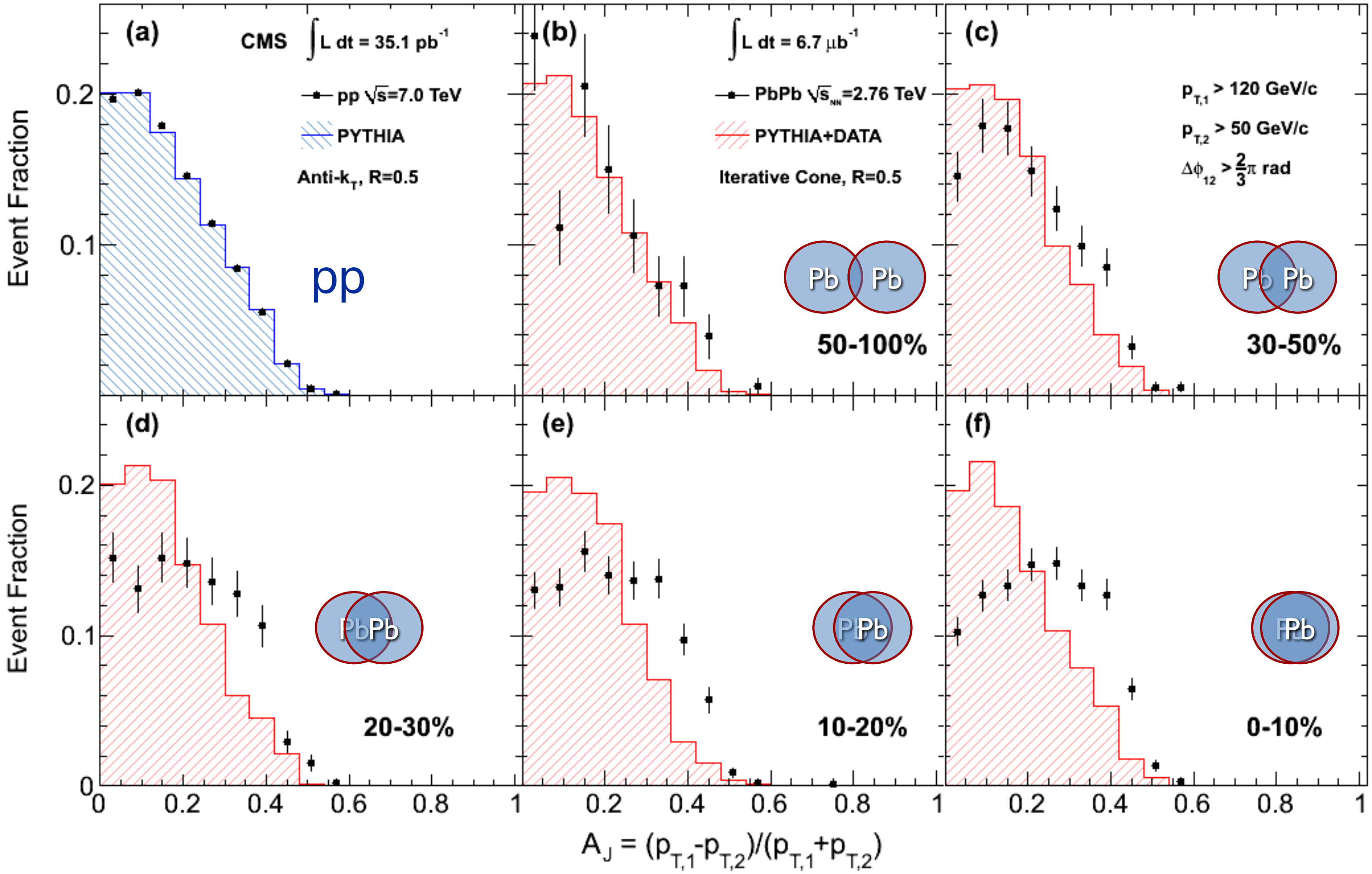
Dijet Asymmetry



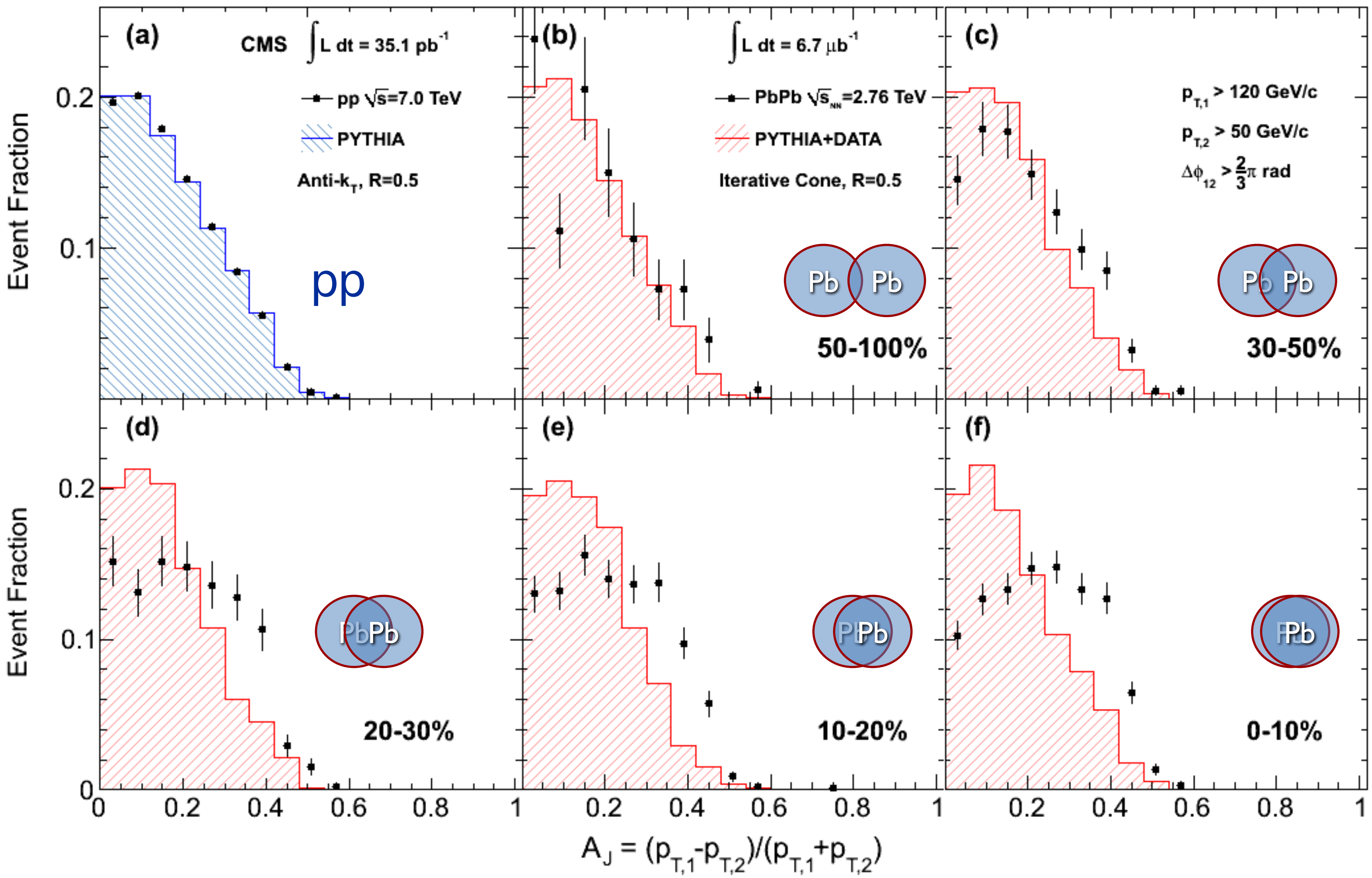
- Dijet selection:
  - $|\eta^{Jet}| < 2$
  - Leading jet $p_{T,1} > 120$GeV/c
  - Subleading jet $p_{T,2} > 50$GeV/c
  - $\Delta\phi_{1,2} > 2\pi/3$
- Quantify dijet energy imbalance by asymmetry ratio:

$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Dijet Energy Imbalance



Dijet Energy Imbalance



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

WHERE DOES THE LOST ENERGY GO ?

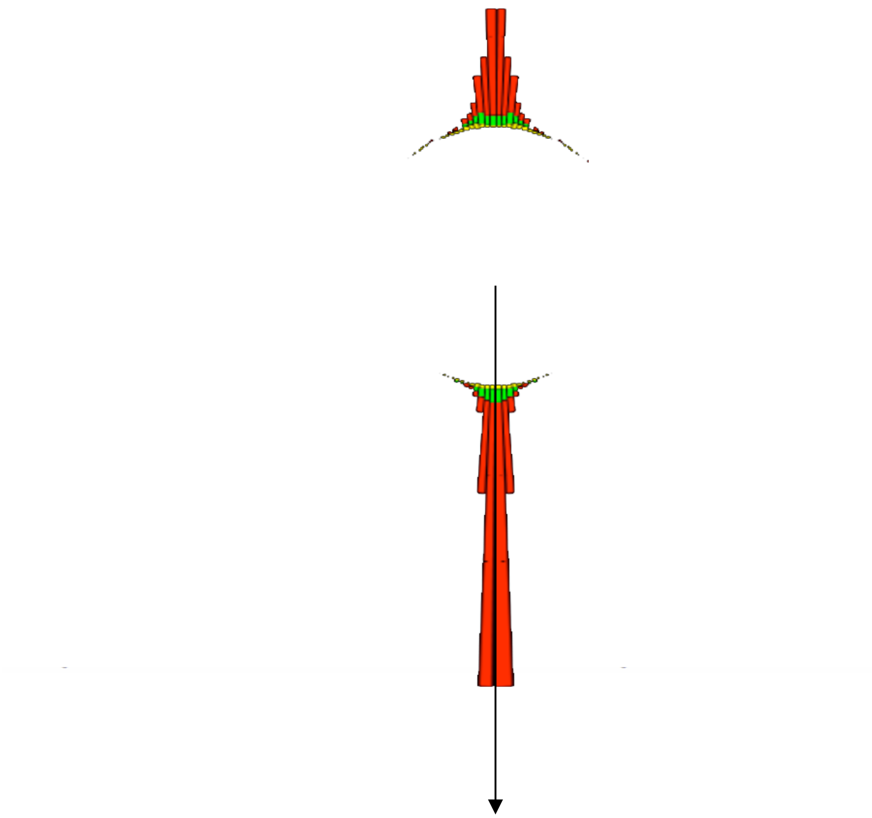
Missing-$p_T^{||}$

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

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

$p_T > 0.5$ GeV/c and

$|\eta| < 2.4$



Leading Jet defines direction

Missing-$p_T^{||}$

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

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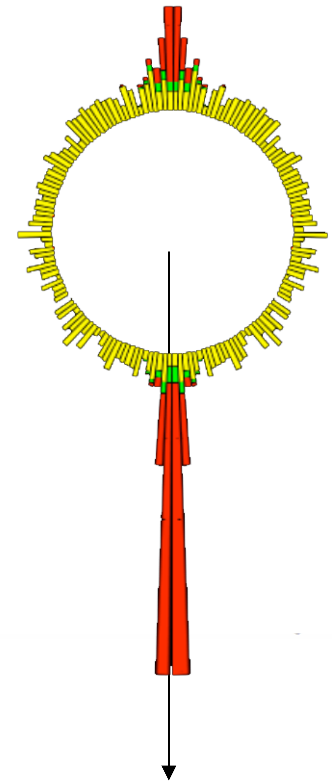
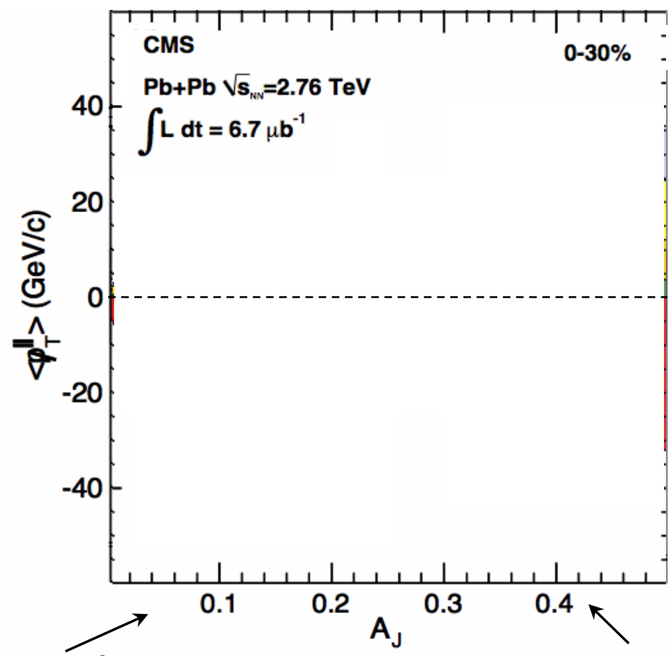


Sum all tracks in the event

Missing-$p_T^{||}$

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

0-30% Central PbPb

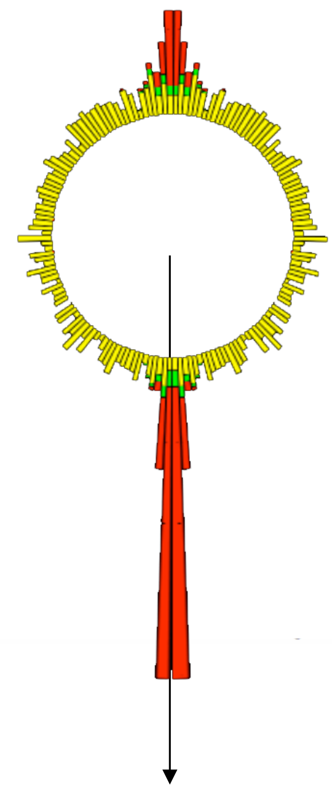


balanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet



Missing-$p_T^{||}$

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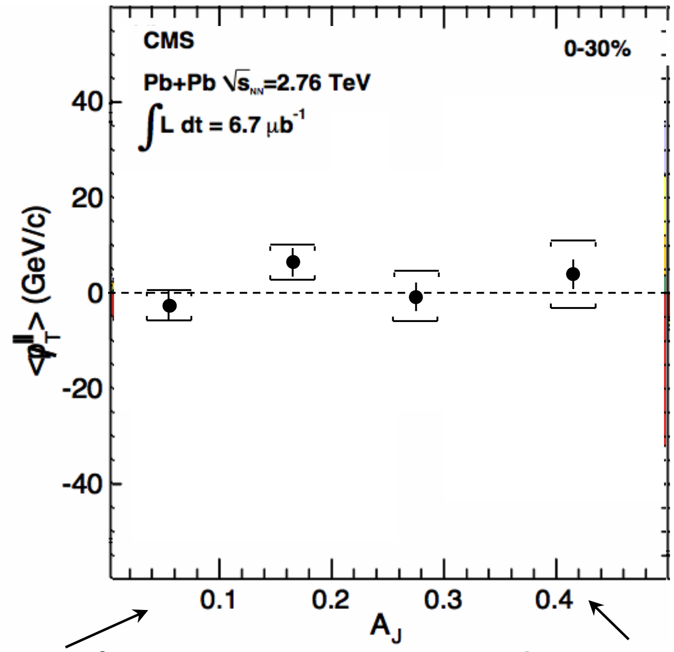
0-30% Central PbPb

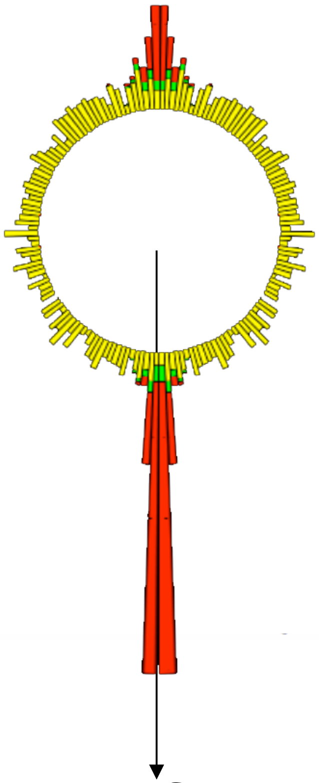


balanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet

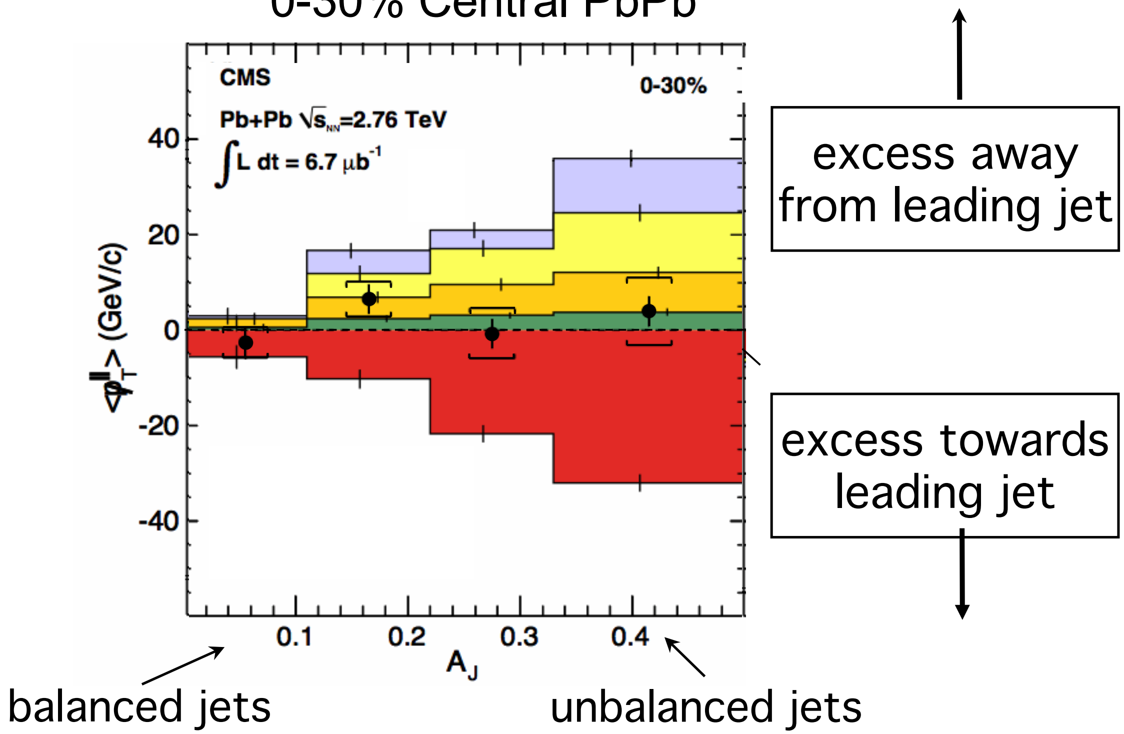


Integrating over the whole event final state the momentum balance is restored

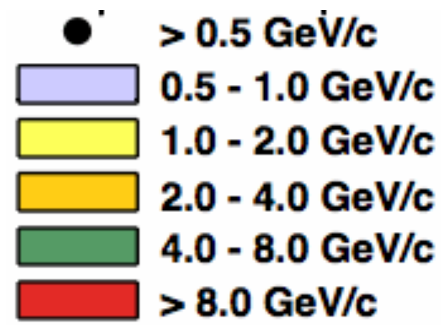
Missing-$p_T^{||}$

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

0-30% Central PbPb



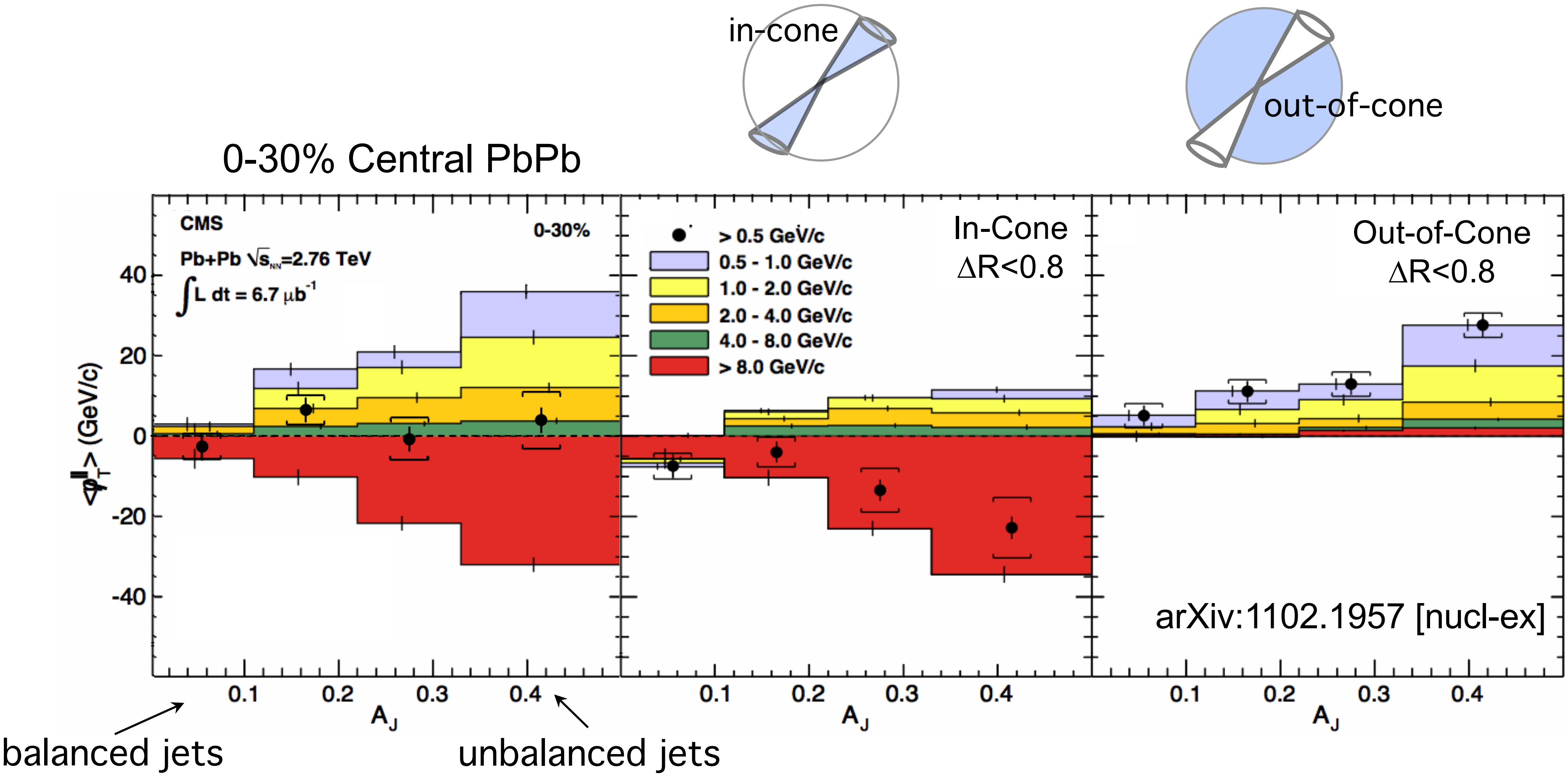
Calculate missing p_T in ranges of track p_T:



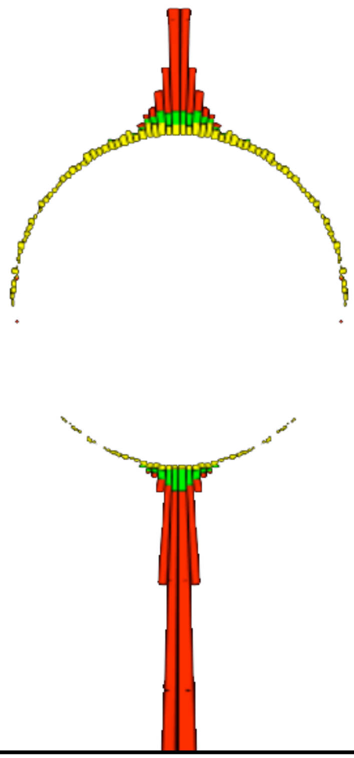
The momentum difference in the dijet is balanced by low p_T particles

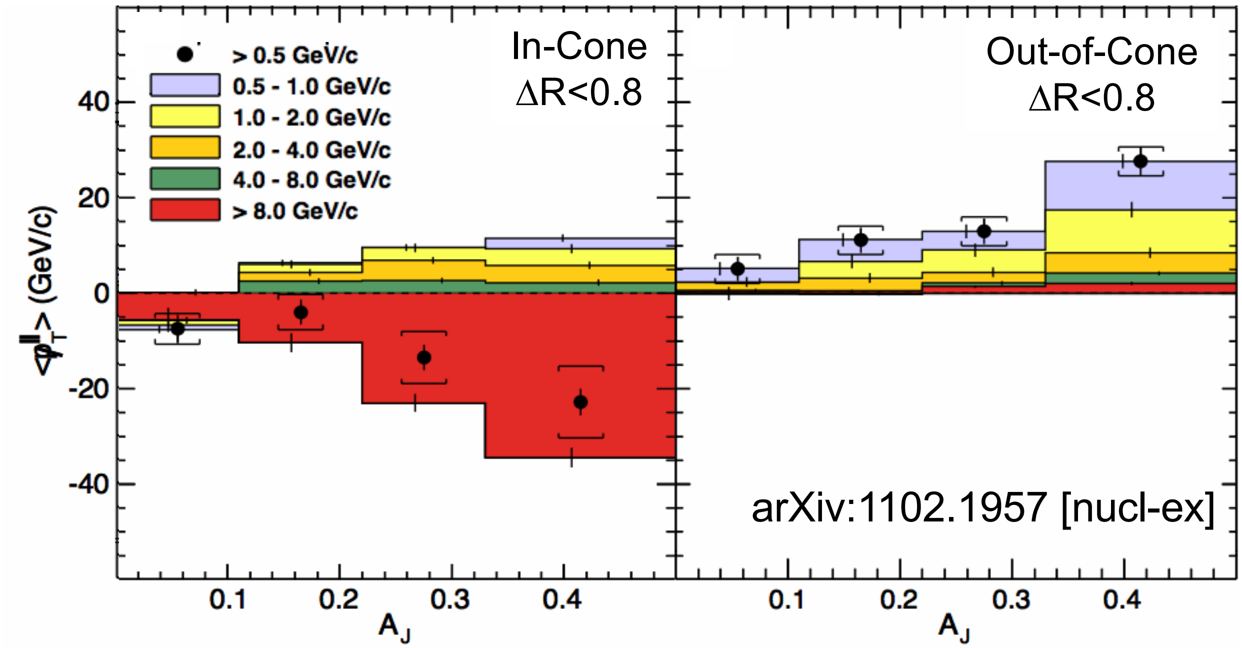
Missing-$p_T^{||}$

0-30% Central PbPb



Missing-$p_T^{||}$

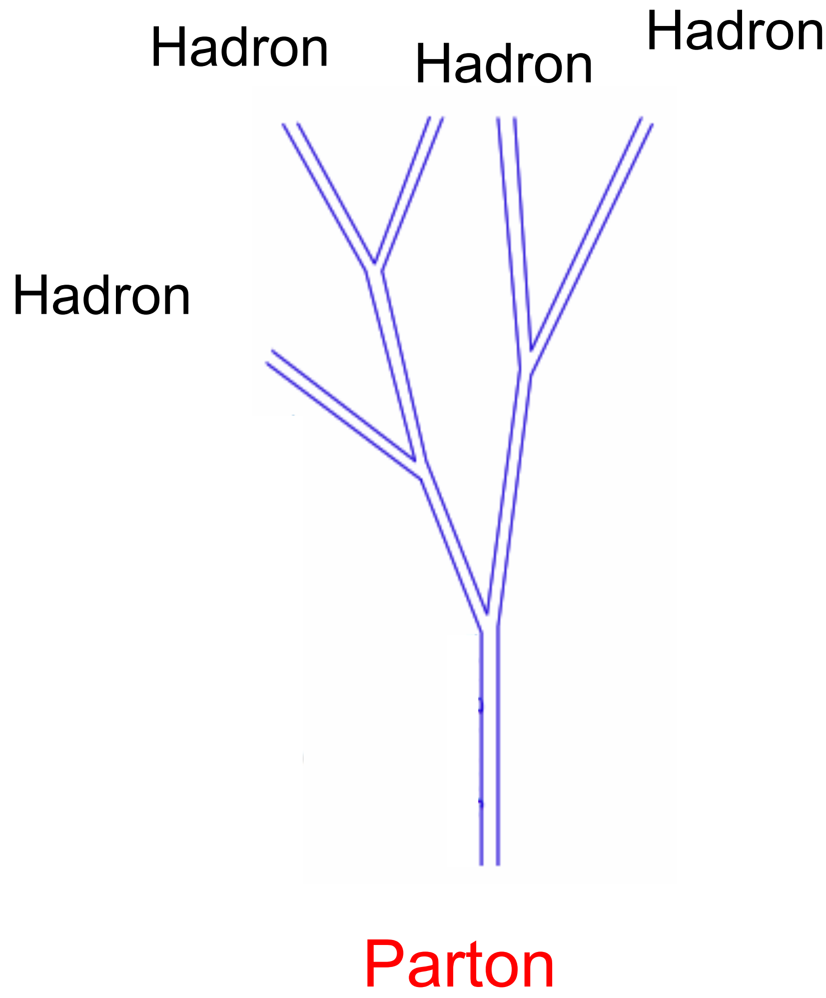




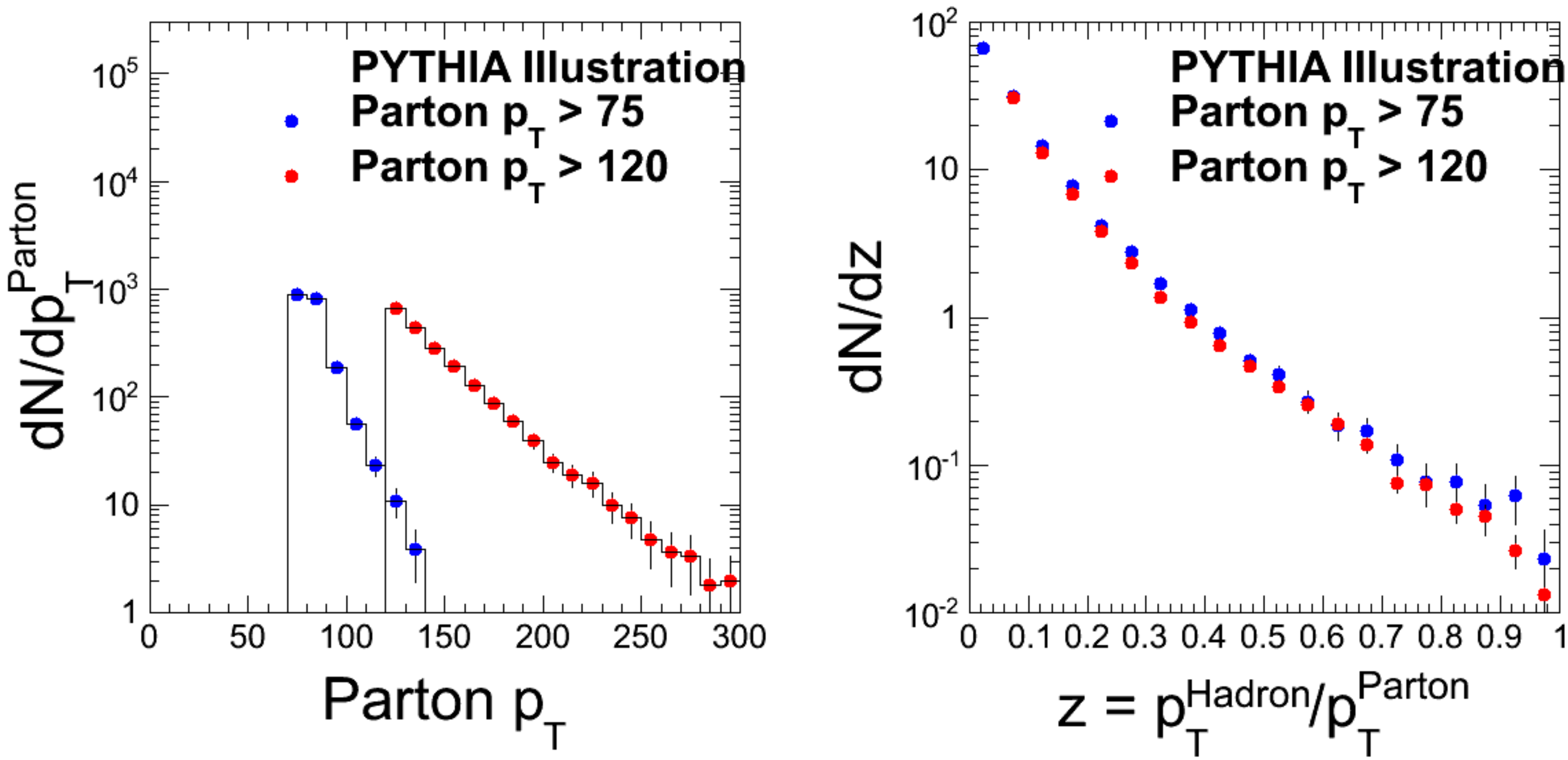
The momentum difference in the dijet is balanced by low p_T particles at large angles relative to the away side jet axis

Parton Fragmentation

Partons fragment to Hadrons

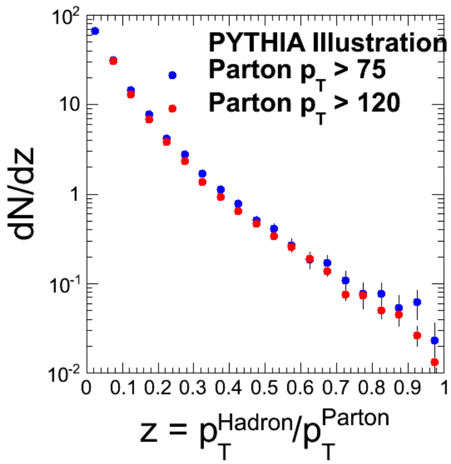


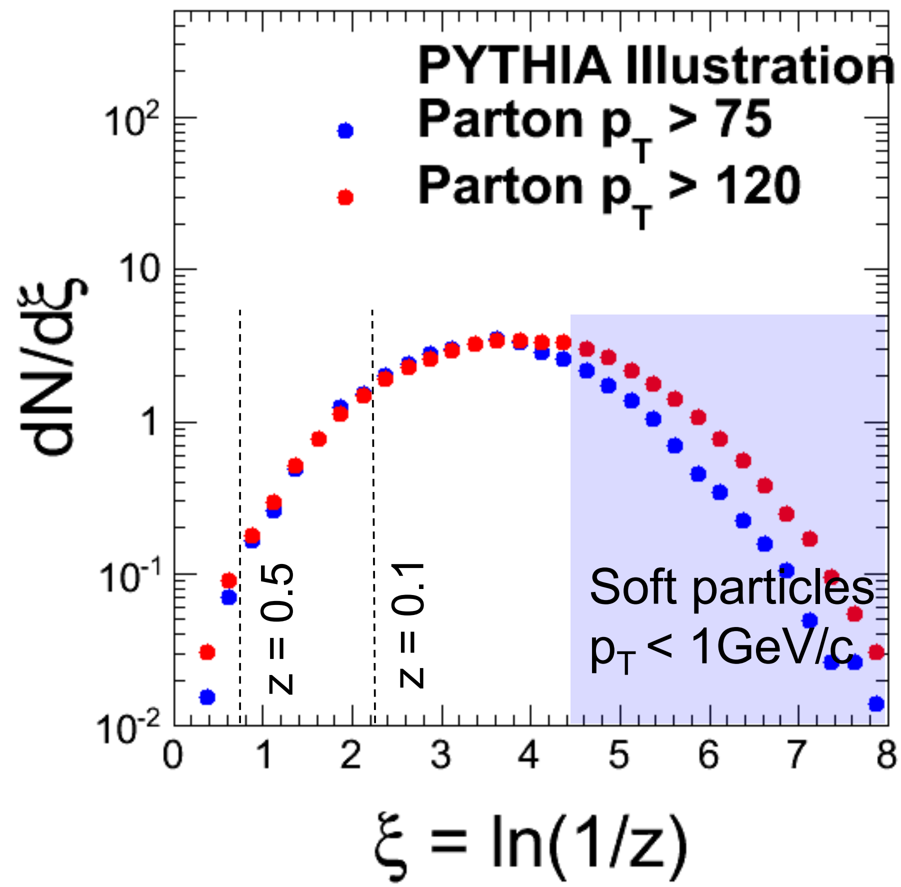
Parton Fragmentation in PYTHIA



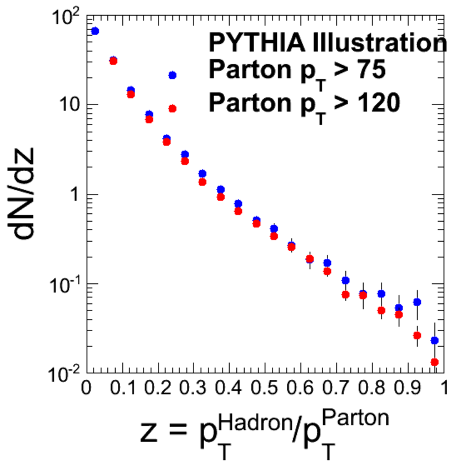
- Momentum Fraction z
  - characteristic of the parton showering process
  - $z=p_T^{hadron}/p_T^{parton}$

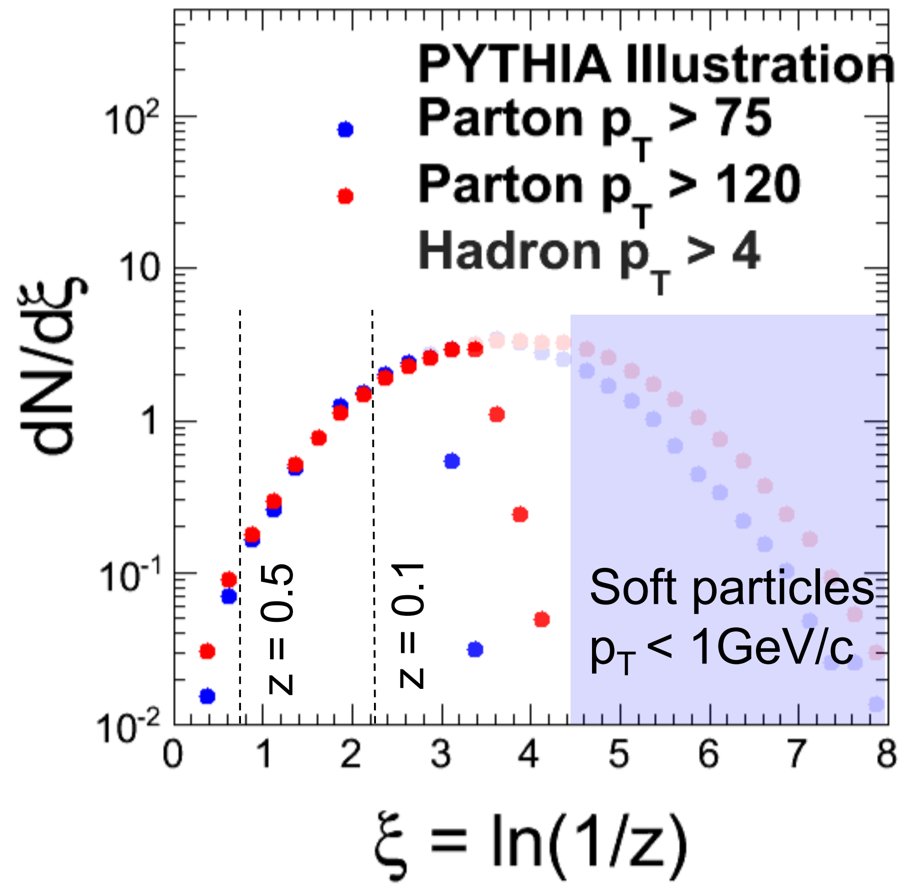
ξ=ln(1/z) Representation

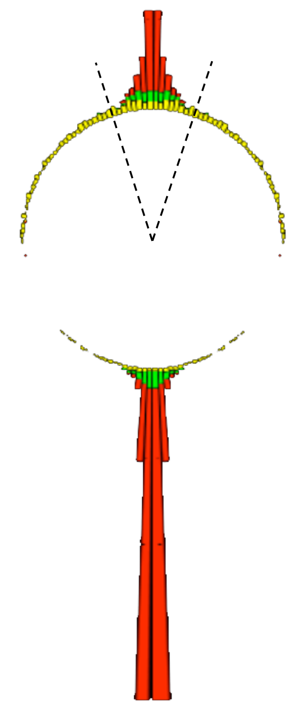




ξ=ln(1/z) Representation

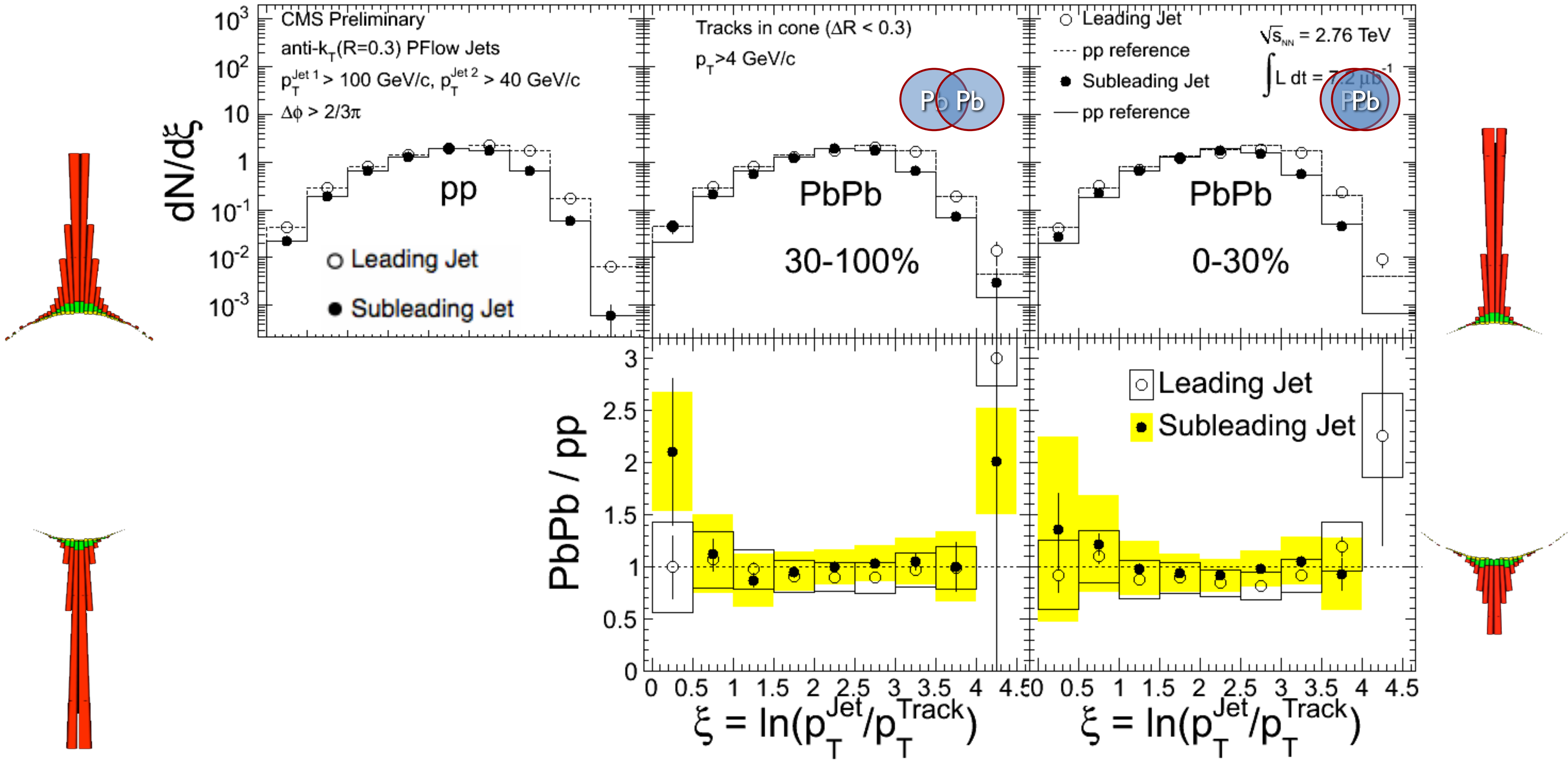






- Eliminate the underlying event contribution, p_T > 4GeV/c
- Select particles in a ΔR=0.3 cone

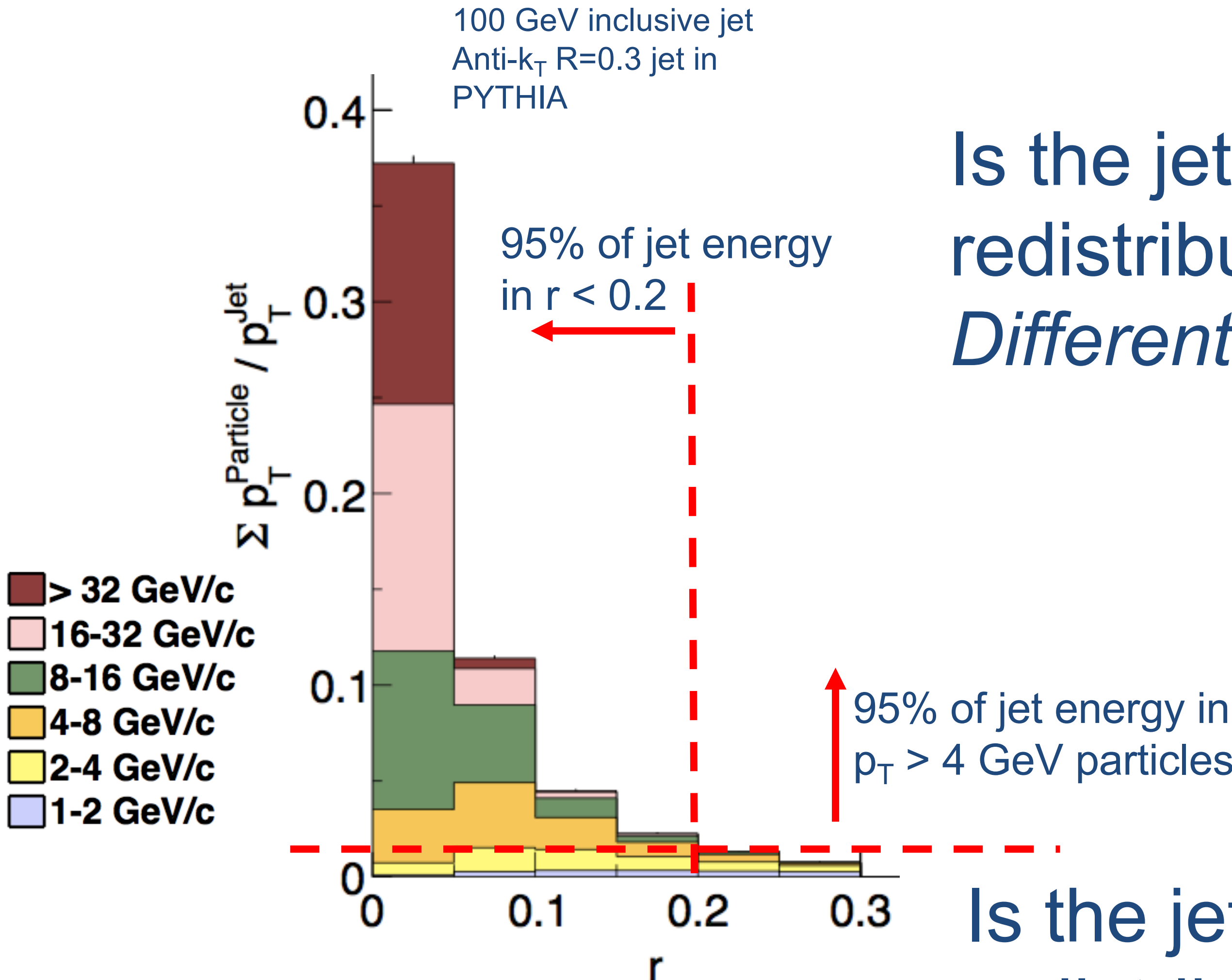
Fragmentation Functions, pp and PbPb



Leading and subleading jet in PbPb fragment like jets of corresponding energy in pp collisions

NOW INCLUDE SOFTER PARTICLES : P_T > 1 GEV/C

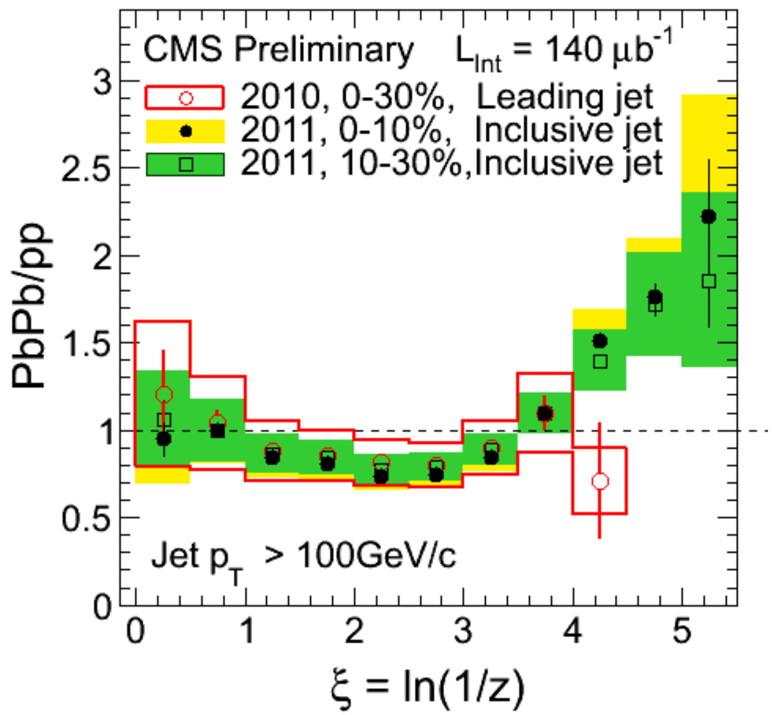
Anatomy of a jet



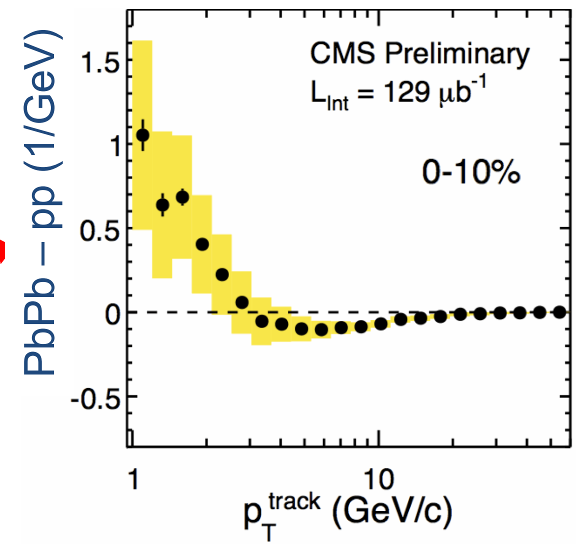
Is the jet energy in PbPb redistributed in radius: *Differential jet-shapes*

Is the jet energy in PbPb redistributed in particle p_T: *Fragmentation functions*

Fragmentation function including soft particles

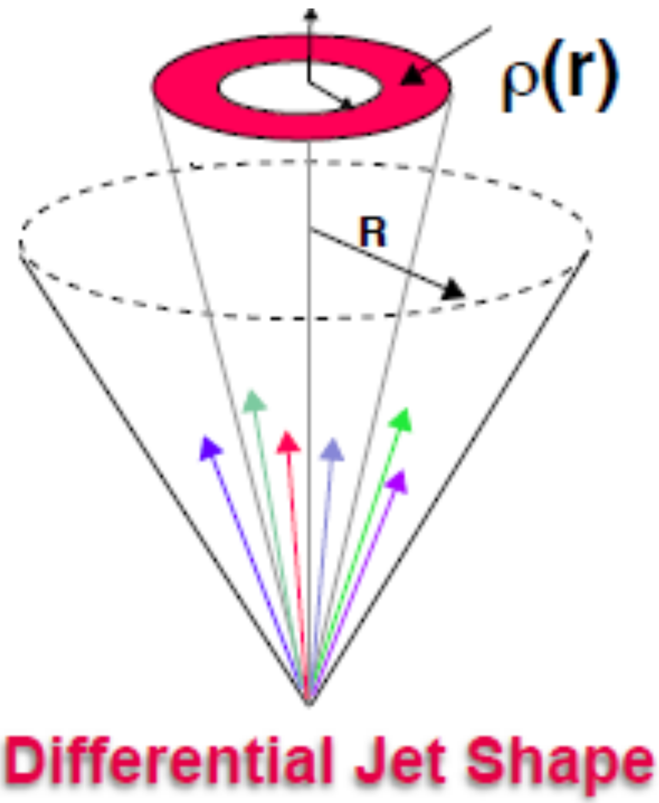


Change from "ξ" to "p_T"



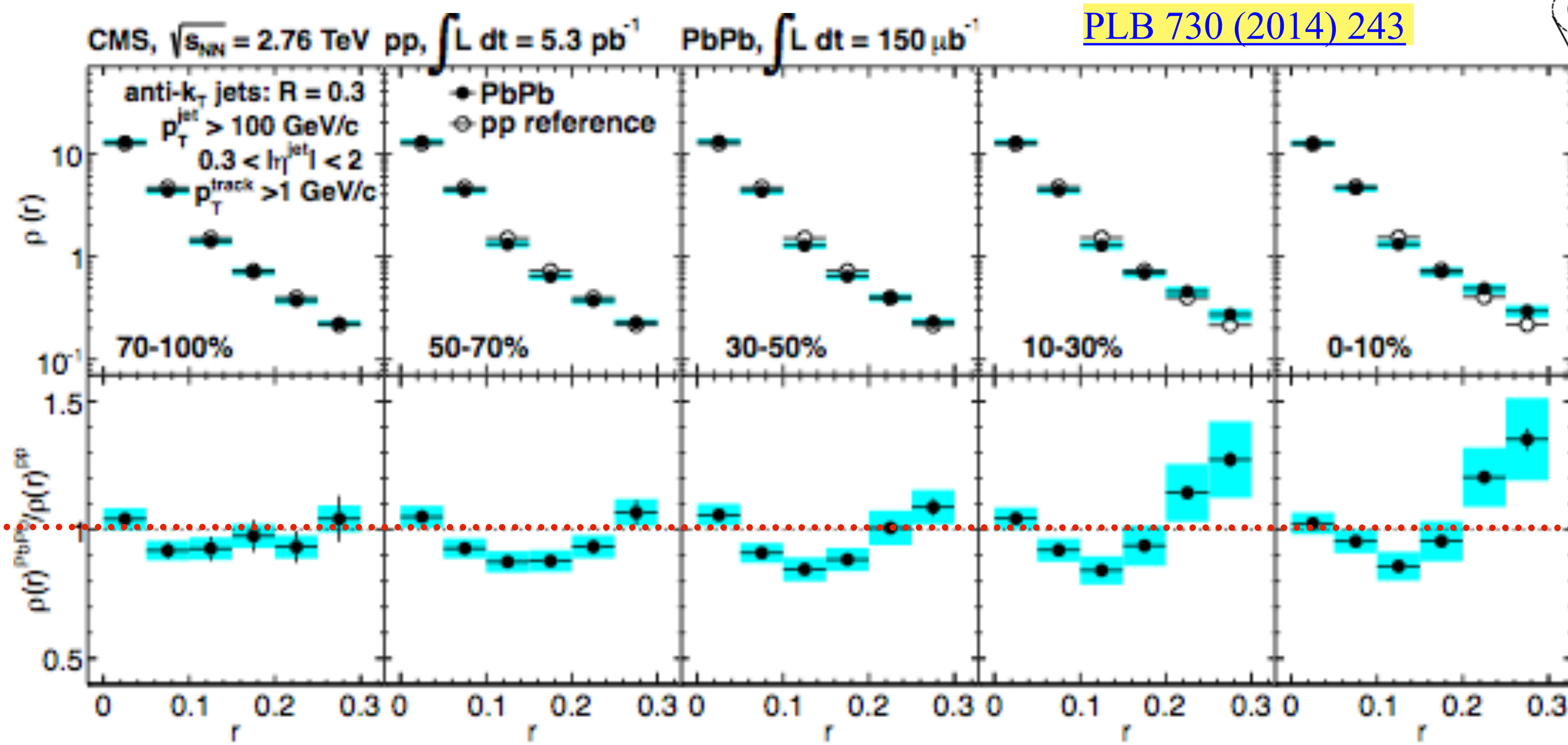
Fragmentation is modified in the medium, a lot more soft particles (1<pt<4 GeV/c) emitted in PbPb collisions

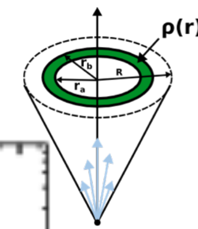
Jet shape



Differential jet shapes

PLB 730 (2014) 243





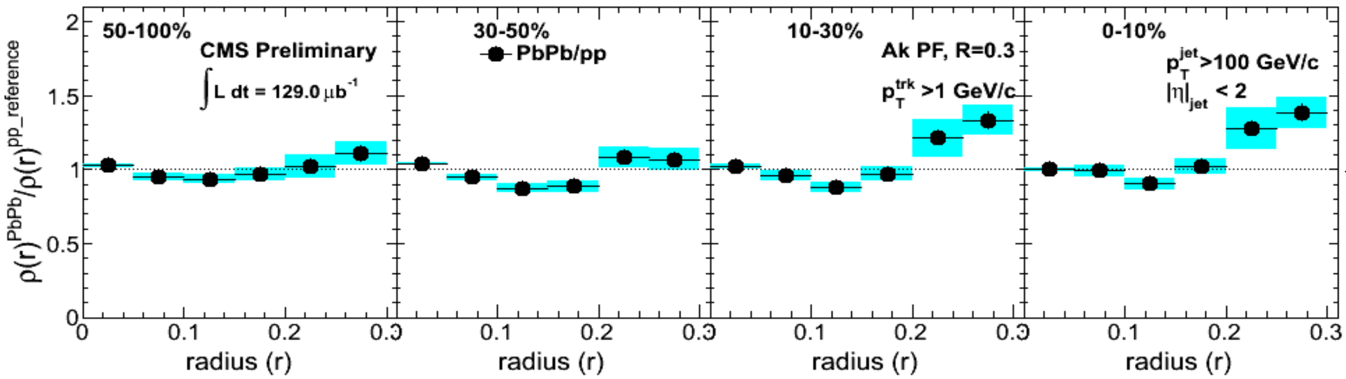
The jet shape is modified in central PbPb collisions

- jet core (r<0.2) is collimated
- broadening in the tails (r>0.2)

Anatomy of a jet

Ratio of PbPb/pp differential jet shapes

CMS-PAS HIN-12-013



No medium effect

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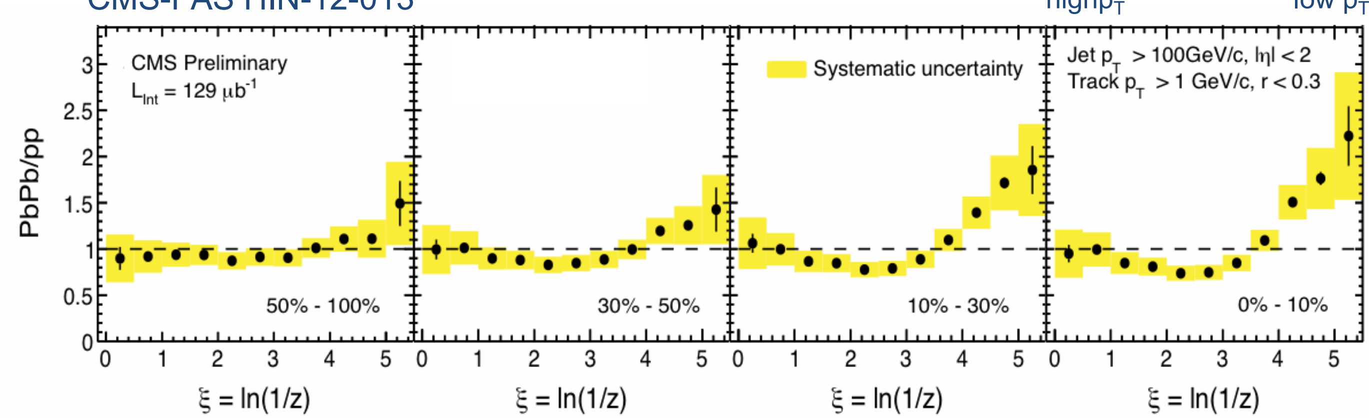
Ratio of PbPb/pp fragmentation functions

CMS-PAS HIN-12-013

high p_T low p_T



No medium effect

Phys. Rev. C 90 (2014) 024908

$z = p_T(\text{track})/p_T(\text{jet})$

Z+jet in PbPb collisions

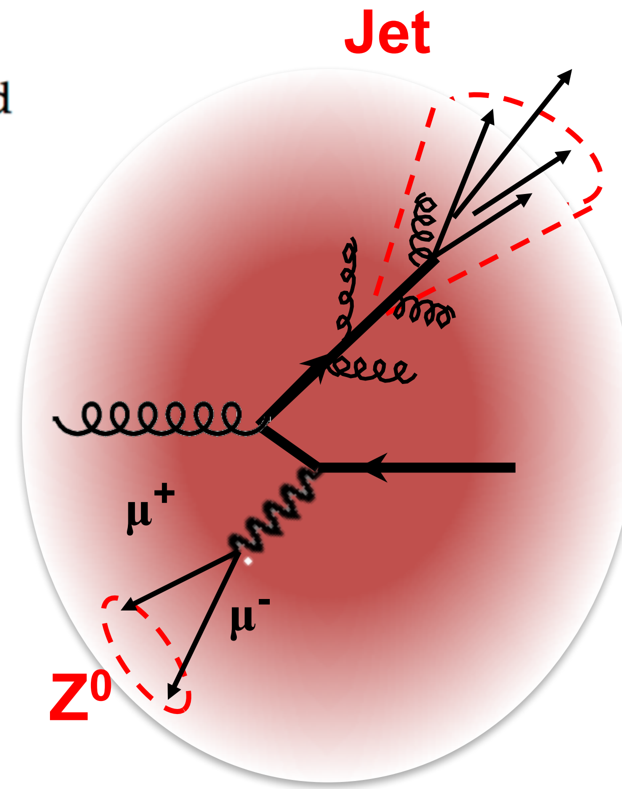
Study of jet quenching with Z+jet correlations in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration*

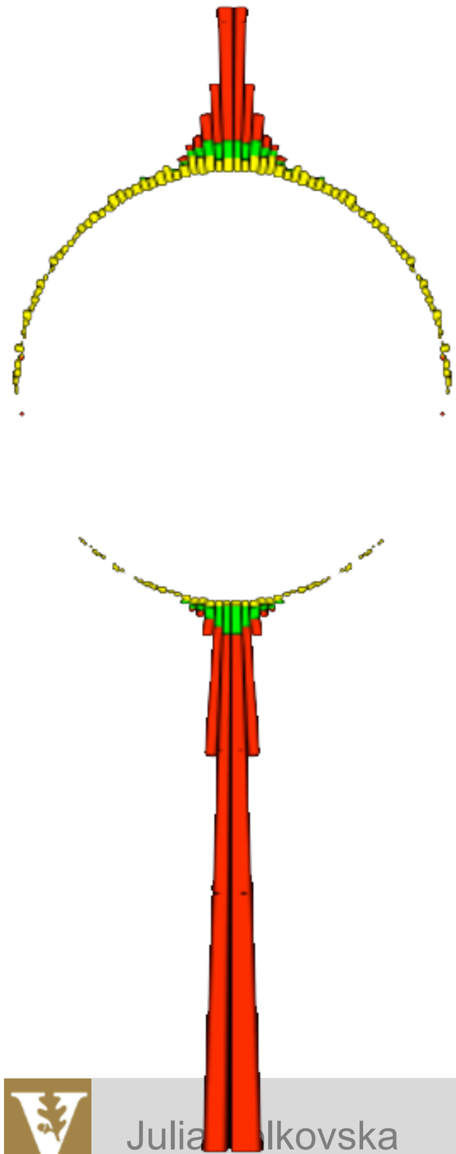
Abstract

The production of jets in association with Z bosons, reconstructed via the $\mu^+\mu^-$ and e^+e^- decay channels, is studied in pp and, for the first time, in PbPb collisions. Both data samples were collected by the CMS experiment at the LHC, at a center-of-mass energy of 5.02 TeV. The PbPb collisions were analyzed in the 0–30% centrality range. The back-to-back azimuthal alignment was studied in both pp and PbPb collisions for Z bosons with transverse momentum $p_T^Z > 60\,\text{GeV}/c$ and a recoiling jet with $p_T^{\text{jet}} > 30\,\text{GeV}/c$. The p_T imbalance, $x_{jZ} = p_T^{\text{jet}}/p_T^Z$, as well as the average number of jet partners per Z, R_{jZ}, were studied in intervals of p_T^Z, in both pp and PbPb collisions. The R_{jZ} is found to be smaller in PbPb than in pp collisions, which suggests that in PbPb collisions a larger fraction of partons, associated with the Z bosons, lose energy and fall below the $30\,\text{GeV}/c$ p_T^{jet} threshold.

Submitted to Physical Review Letters



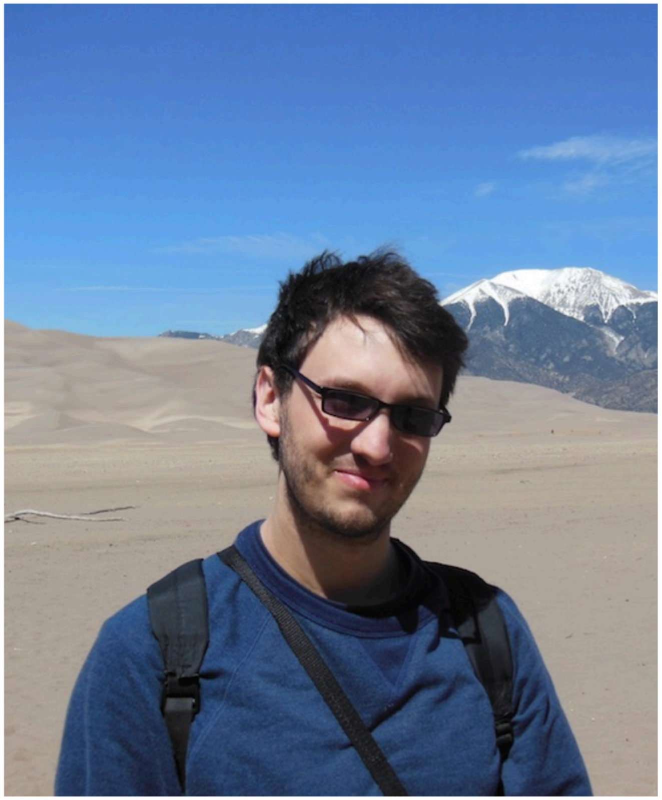
Summary of hard-probe measurements



- R_{AA}<1 for all hadron types; R_{AA} ~1 for EW bosons
- Angular correlation of partons not affected by the medium
  - Constrains the scattering mechanisms
- Large dijet momentum imbalance observed
  - Direct observation of parton energy loss
- Momentum difference in the dijet balanced by low p_T particles at large angles relative to the away side jet
- jet fragmentation and jet shape are modified with excess of soft particles (p_T < 4 GeV/c)
- jet-photon and jet-Z correlations – a new way for precise studies of jet energy loss

How to become a heavy-ion physicist

Javier Orjuela-Koop



How long have you been working in PHENIX and at what institution?
I have been working in PHENIX since January 2013 as a graduate student in Prof. Jamie Nagle's heavy ion group at the University of Colorado Boulder.

What is the focus of your work on the PHENIX experiment?
My work can broadly be described as centered on understanding and controlling event geometry in small systems for various physics applications. Namely, I have studied centrality categorization in d+Au and how it can bias the measurement of centrality-dependent invariant yields; and more recently, the question of collective flow in ^{3}He+Au, d+Au and p+Au. Additionally, I am currently involved in the sPHENIX simulation effort.

Where were you born and what is your education background before your current position?
I was born in Bogota, Colombia at nearly 9000 ft above sea level. I majored in physics and computer engineering at the University of the Andes in 2010 and 2012, respectively.

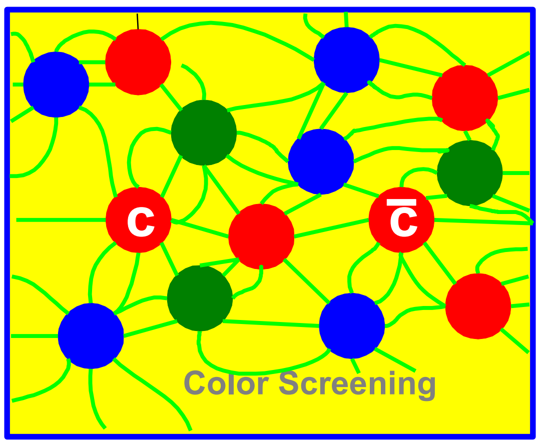
What was the title of your Ph.D. (or tentative title)?
Although I have yet to arrive at a title, my thesis will focus on heavy flavor measurements in small systems with the VTX using data from Run15.

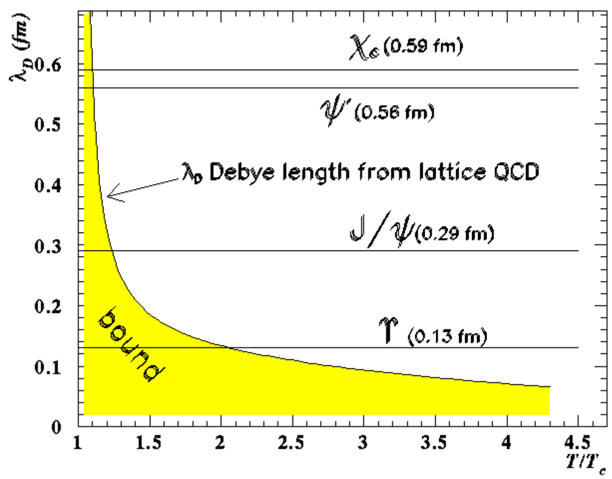
How did you decide to go into heavy ion or spin research?
I first learned of heavy ion physics as a summer student at CERN from people in ALICE, but I didn't have much chance to explore it as an undergraduate. Then, during my first semester at Colorado, I attended a talk by Prof. Nagle on heavy ion physics, PHENIX and the possibilities of sPHENIX. Being interested in both nuclear and particle physics, I found the prospect of high energy nuclear physics quite exciting.

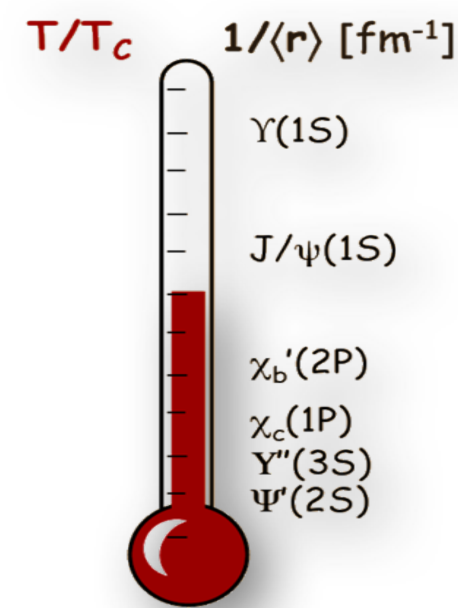
What do you like to do in your spare time?
When I'm not working I really enjoy skiing, painting and playing the guitar. You may also find me at art galleries from time to time.

Color Screening from the QGP

- Debye screening length $\lambda_D \sim 1/T$
- Hadrons with radii greater than ~ λ_D will be dissolved

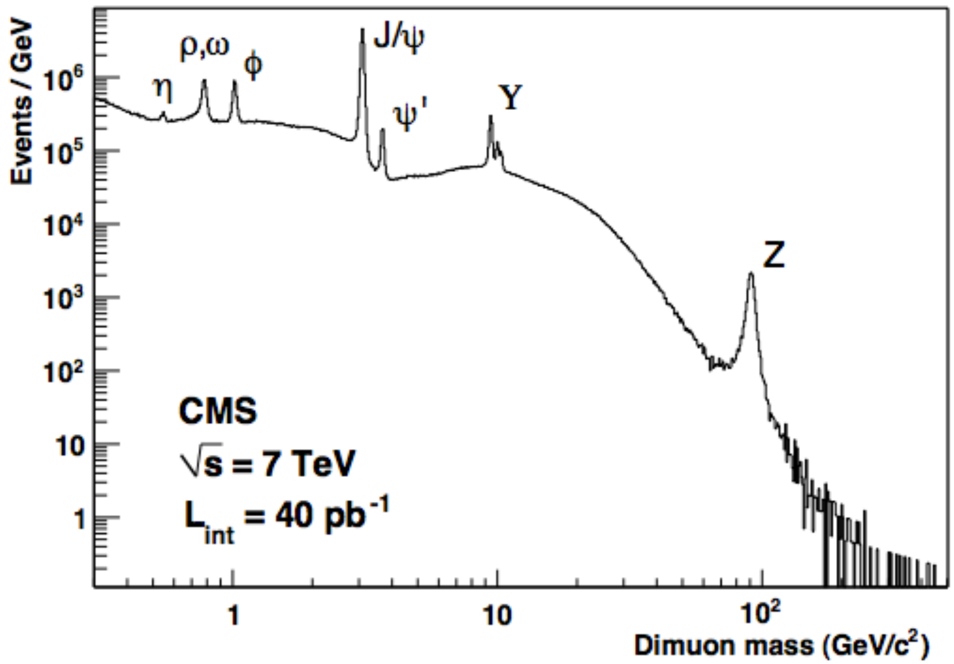




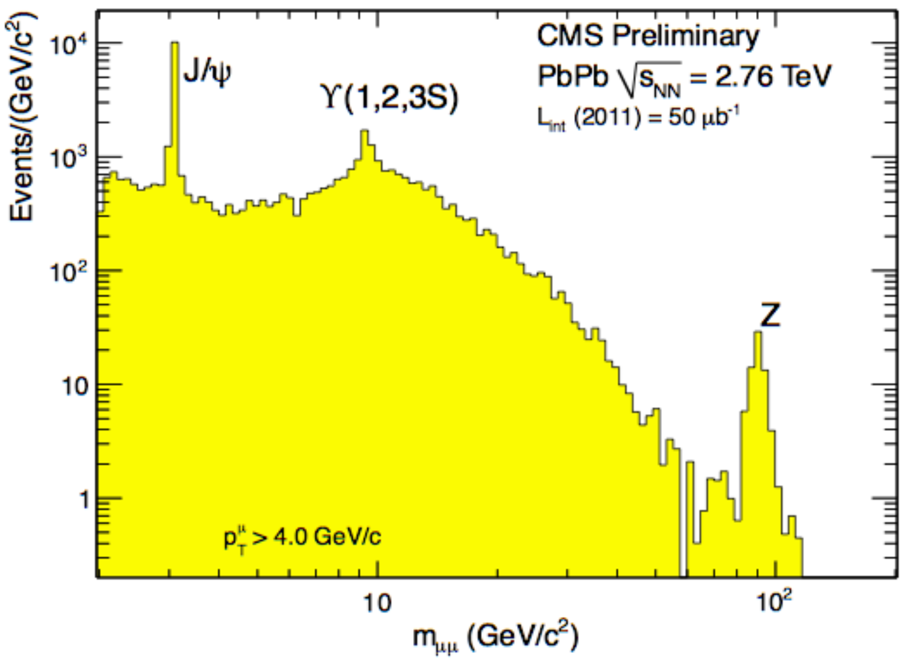


state	J/ψ	χc	ψ′	Υ	χb	Υ′	χb′	Υ″
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

The M in CMS

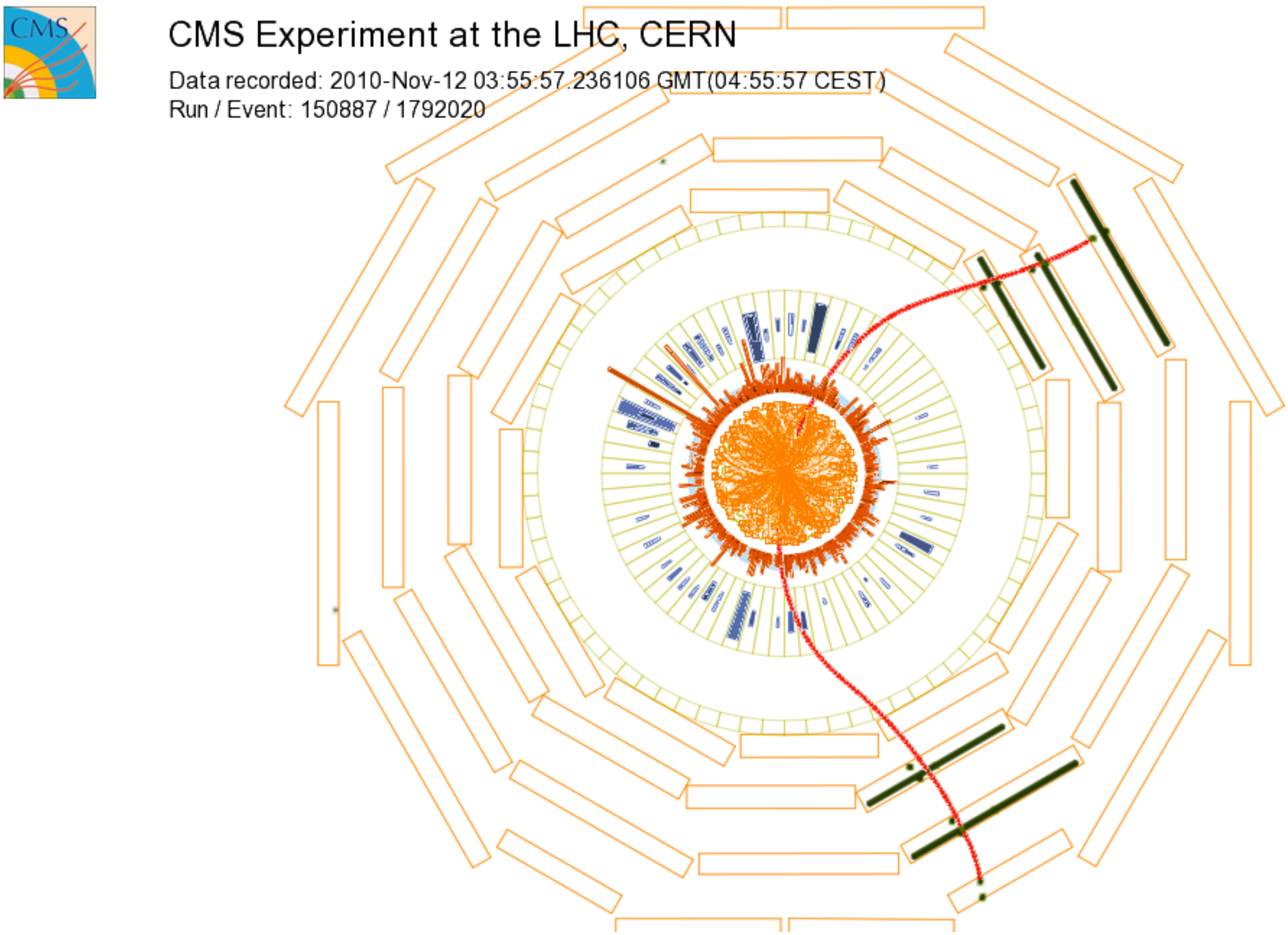


Events / GeV
η
ρ,ω
φ
J/ψ
ψ'
Υ
Z
CMS
√s = 7 TeV
L_int = 40 pb^-1
Dimuon mass (GeV/c²)



Events/(GeV/c²)
J/ψ
Υ(1,2,3S)
Z
CMS Preliminary
PbPb √s_NN = 2.76 TeV
L_int (2011) = 50 μb^-1
p_T^μ > 4.0 GeV/c
m_μμ (GeV/c²)

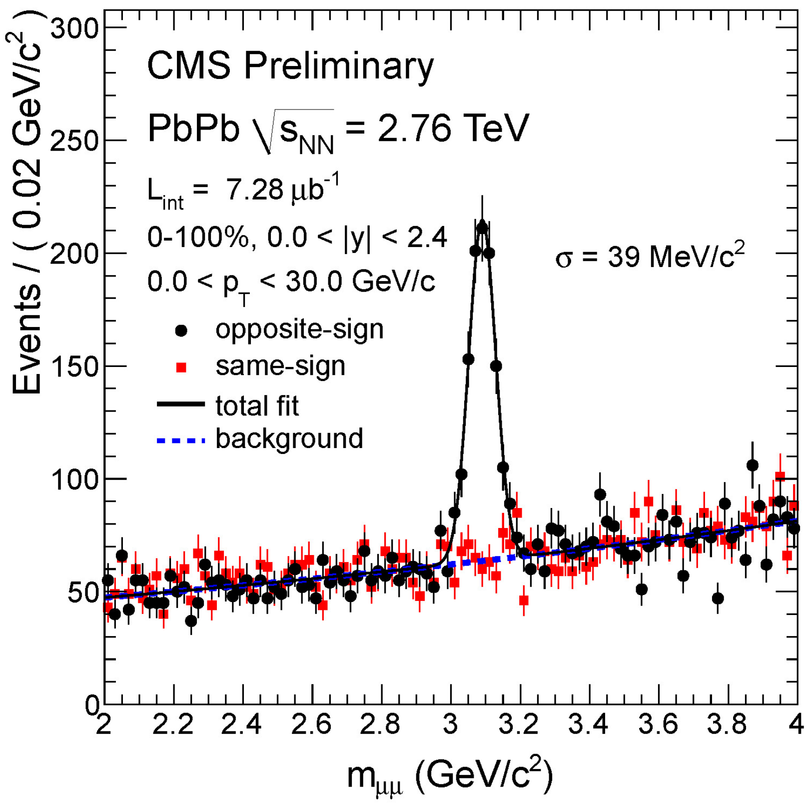
ϒ candidate in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV



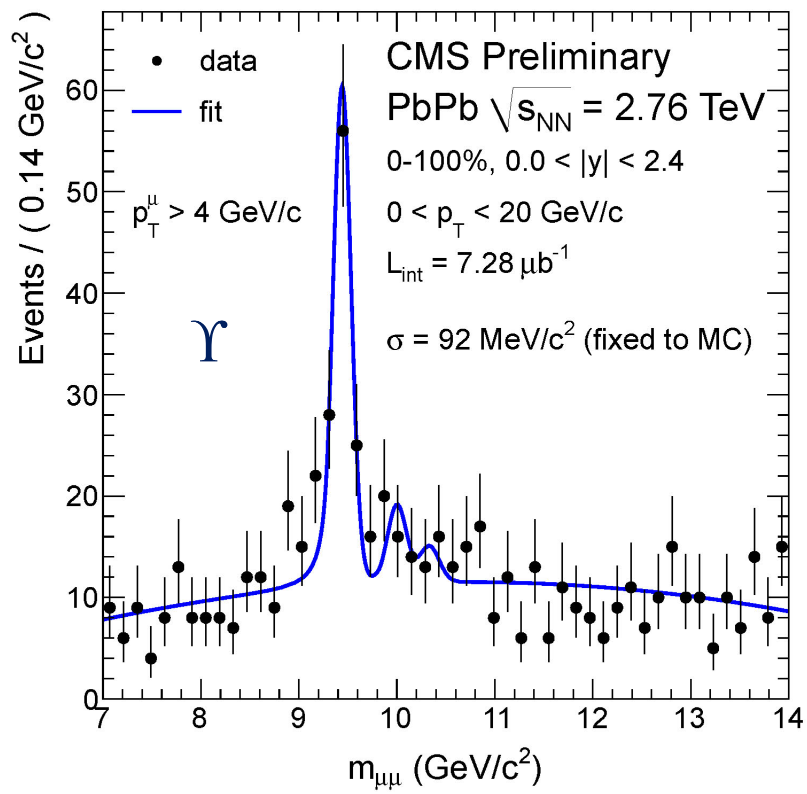
J/ψ and ϒ

- J/ψ and ϒ observed in $\mu^+\mu^-$ channel
- CMS muon acceptance $|\eta|<2.4$, $p_{T\mu}>2\text{-}4$ GeV/c
- Excellent mass resolution ~1%, comparable to pp
- Use displaced vertices to separate prompt J/ψ and B-decays

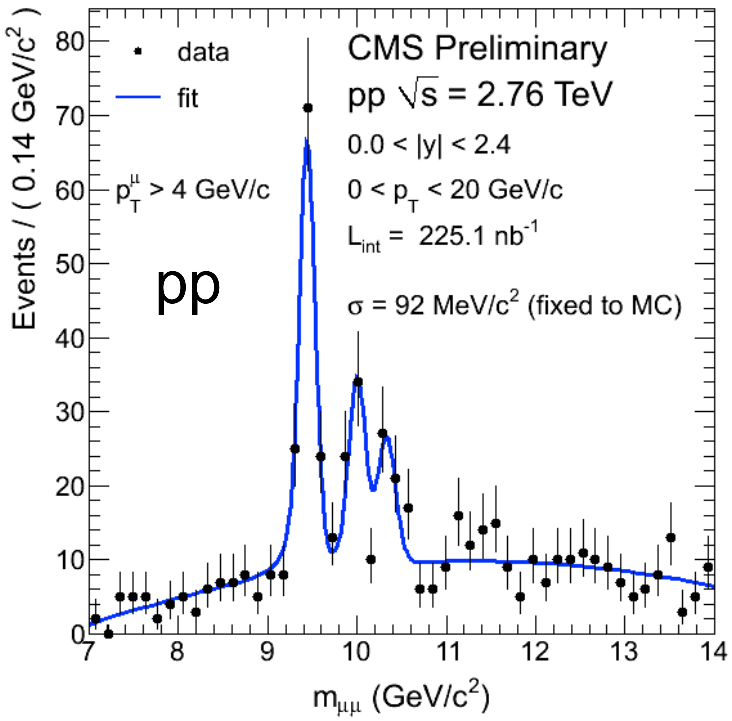
$N_{J/\psi}$ =734±54

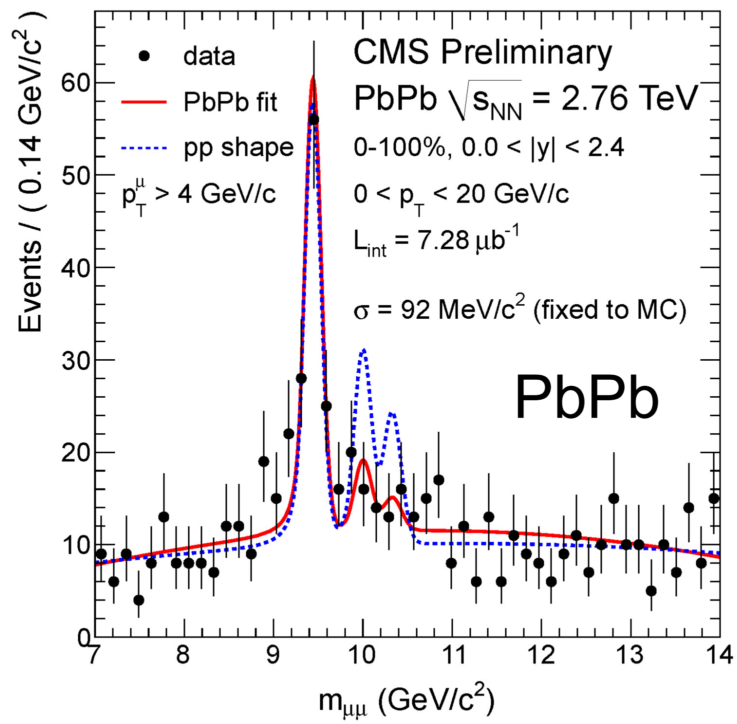


N_{Υ} =86±12



Suppression of excited Υ states





$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Excited states Υ(2S,3S) relative to Υ(1S) are suppressed
- Probability to obtain measured value, or lower, if the real double ratio is unity, has been calculated to be less than 1%