jet quenching
theoretical and experimental aspects

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jets in vacuum

Ellis, Stirling, Webber, *QCD and Collider Physics*, CUP (1996)

Dokshitzer, Khoze, Mueller, Troyan, *Basics of Perturbative QCD*, Ed. Frontieres (1991)

Salam, *Towards Jetography*, arXiv:0906.1833 [hep-ph]

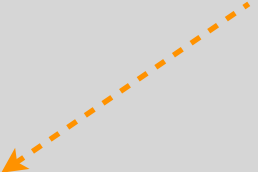# hard scattering processes in hadronic collisions

the cross section for the production of a back-to-back pair of hard partons in a hadronic collision can be written

$$\sigma^{AB \to kl} \sim f_i^A(x_1, \mu_F^2) \otimes f_j^B(x_2, \mu_F^2) \otimes \hat{\sigma}^{ij \to kl}(p_1 = x_1 P_1, p_2 = x_2 P_2, \alpha_s(\mu_R^2), Q^2/\mu_F^2, Q^2/\mu_R^2)$$

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- high-p_t processes result from interaction between parton constituents [quarks and gluons] of the incoming hadrons
- parton content of hadrons described by parton distribution functions [PDFs]
    - non-perturbative objects
    - scale [Q^2] dependence driven [perturbatively] by DGLAP evolution
    - universal, determined from global data fits

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- partonic cross section
  - ◉ does not depend on the details of the hadronic wave functions [factorization]
  - ◉ only involves high momentum transfers [short distance and time scales]; all low momentum scales in the PDFs
  - ◉ can be calculated to any order in perturbation theory

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$$\sigma^{AB \to kl} \sim f_i^A(x_1, Q^2) \otimes f_j^B(x_2, Q^2) \otimes \hat{\sigma}^{ij \to kl}(p_1, p_2, \alpha_s(Q^2)) + \mathcal{O}(1/Q^2)$$

hard scattering processes in hadronic collisions

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- ○ what is factorized into the PDFs depends on the perturbative order to which partonic cross-section is calculated [must be done consistently :: always be suspicious of calculations that mix perturbative orders – most likely they do not make sense]

- ○ in principle three momentum scales [of the same order] are involved
  - ↪ factorization scale μ$_F$ [separation between long- and short-distance physics] at which PDFs are evaluated
  - ↪ renormalization scale μ$_R$ at which the coupling is calculated
  - ↪ hard scale Q^2 that characterizes parton-parton scattering

- ○ the relation between these scales is fixed by higher order calculations :: to all orders the cross section does not depend on μ$_F$ and μ$_R$

- ○ a standard approximation is to take [at LO] μ$_F$ = μ$_R$ = Q^2 :: their relative variation [by a factor 2, say] estimates theoretical uncertainty

$$\sigma^{AB \rightarrow kl} \sim f_i^A(x_1, Q^2) \otimes f_j^B(x_2, Q^2) \otimes \hat{\sigma}^{ij \rightarrow kl}(p_1, p_2, \alpha_s(Q^2)) + \mathcal{O}(1/Q^2)$$

branching of hard parton

outgoing [virtual] high-p_t parton relaxes virtuality down to hadronization scale by branching

    branching independent of parton's previous history [i.e. it also factorizes]

$$\sigma^{AB \longrightarrow X} \sim f_i^A(x_1, Q^2) \otimes f_j^B(x_2, Q^2) \otimes \hat{\sigma}_{ij \to k} \otimes D_{k \to X}(z, Q^2)$$

- fragmentation function [generic]
  - probability distribution for parton k to result in 'state' X carrying fraction z of parton's momentum
  - encodes [perturbative] branching and [non-perturbative] hadronization
  - in principle depends on separate scale μ_{frag} [set here to Q^2]

- X=parton
  - fragmentation function only includes parton branching
  - [perturbative] DGLAP-like evolution towards lower Q^2

- X=hadrons [or jets]
  - fragmentation function includes hadronization
  - constrained from global fits to data [since factorizable and universal] with evolution still driven by DGLAP [analogous to PDFs]
  - different in MC event generators
    ➡ evolution [branching] down to hadronization scale followed by hadronization prescription [Lund strings, cluster, local parton-hadron duality]

[perturbative] partonic branching

$$t\frac{\partial}{\partial t}D_i(x,t) \sum_j \int_x^1 \frac{dz}{z}\frac{\alpha_s}{2\pi}P_{ji}(z)D_j(x/z,t)$$

evolution of the momentum fraction distribution of partons produced from original parton i
resums multiple branchings to leading logarithmic order $O[(\alpha_s \log Q^2)^n]$

parton splitting function :: probability of parton i to come from splitting of parton j

P_{qq} 1−z   z P_{qg} 1−z   z P_{gq} 1−z   z P_{gg} 1−z   z

probabilistic interpretation clearer from integral formulation [also useful for numerical MC implementation]

$$D(x,t) = \Delta(t)D(x,t_0) + \Delta(t)\int_{t_0}^t \frac{dt_1}{t_1}\frac{1}{\Delta(t_1)}\int \frac{dz}{z}\,P(z)D\left(\frac{x}{z},t_1\right)$$

$$\Delta(t) = \exp\left[-\int_{t_0}^t \frac{dt'}{t'}\int dz \frac{\alpha_s(t',z)}{2\pi}P(z,t')\right]$$
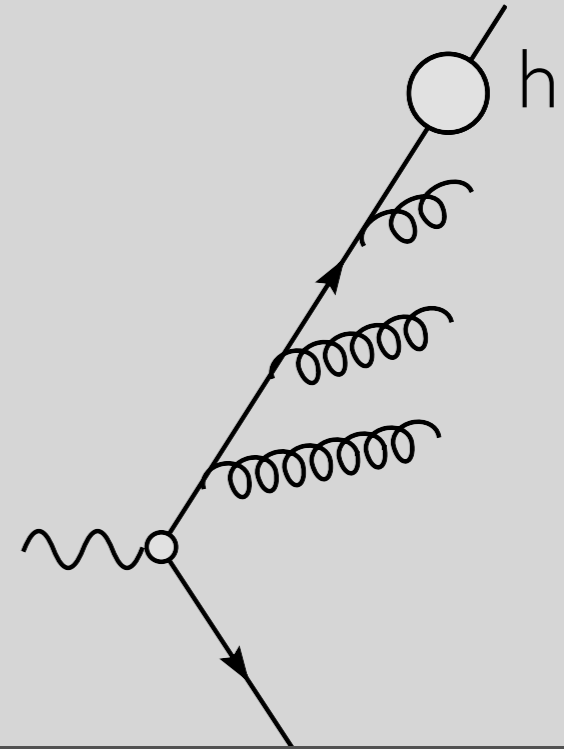
Sudakov form factor
• probability of no resolvable splitting between scales t_0 and t

branching + hadronization [pathway #1]

include hadronization in the definition of fragmentation functions

- scale evolution still DGLAP-like driven [as before]
- hadronization not understood from first principles
  - ⦿ non-perturbative information in evolution initial conditions
  - ⦿ constrained from data global fit

$$\frac{1}{\sigma_{tot}}\frac{d\sigma^\pi}{dz}$$

$zD_i^{\pi^+}(z)$
$Q^2 = 10\ \text{GeV}^2$

$u + \bar{u}$
$\bar{u}$
$s + \bar{s}$

gluon
$c + \bar{c}$

THIS FIT / KRE

THIS FIT / AKK

D_Σ

THIS FIT
KRE
AKK

(data - theory)/theory

TPC
SLD
ALEPH
DELPHI
OPAL

not fitted

[de Florian, Sassot, Stratmann 2007]
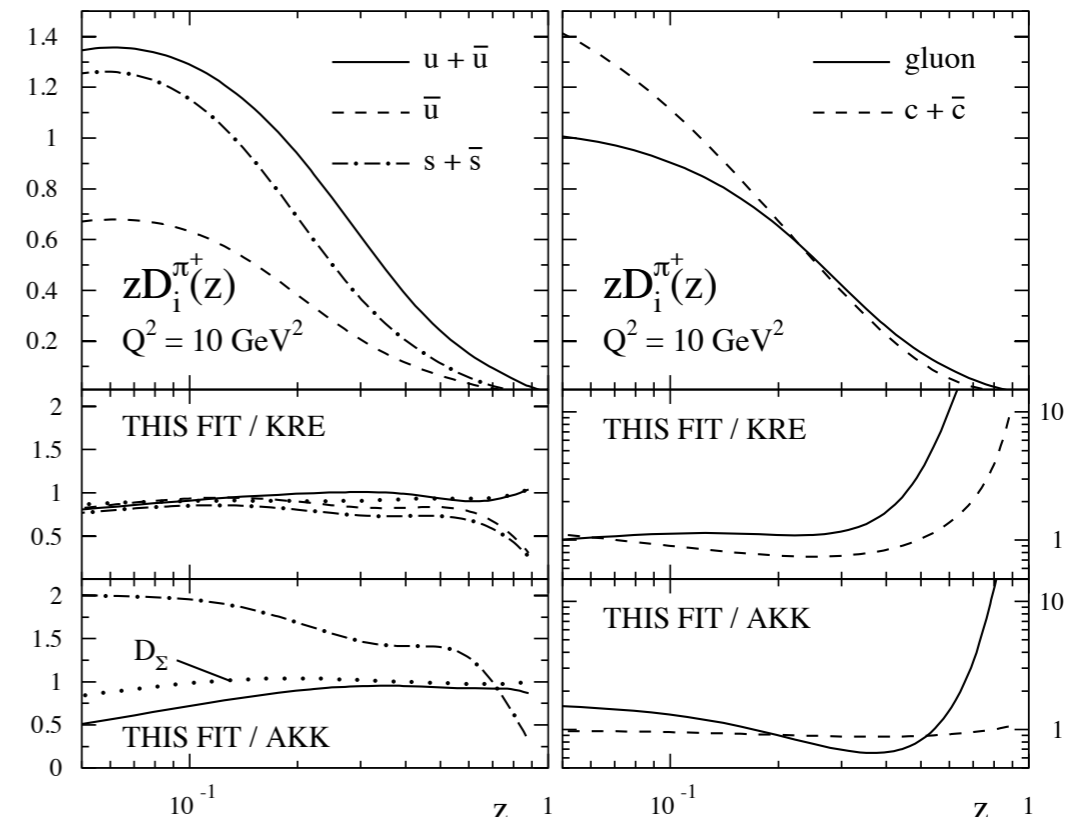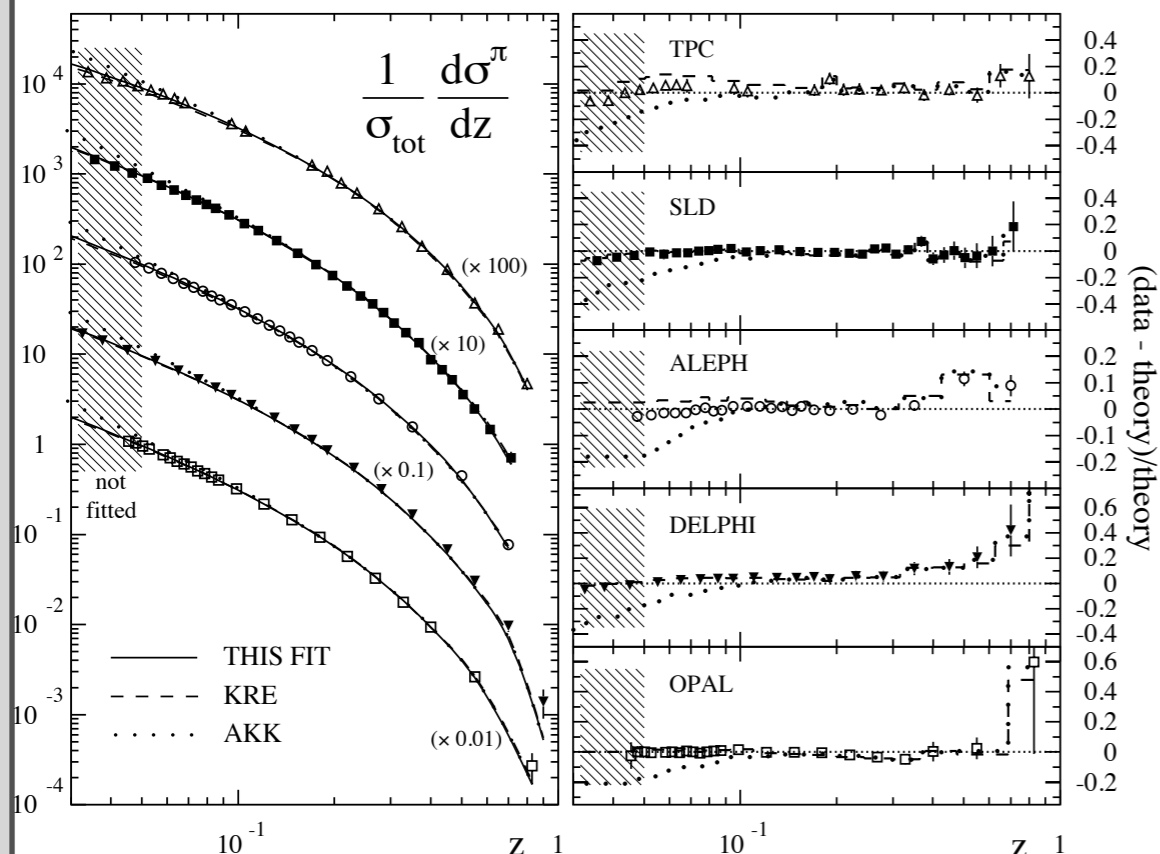
branching + hadronization [pathway #2]

Monte Carlo event generators [PYTHIA, HERWIG] proceed differently

- probabilistic implementation of evolution [parton shower] with the Sudakov form factors
  - down to hadronization scale [~ 1 GeV]

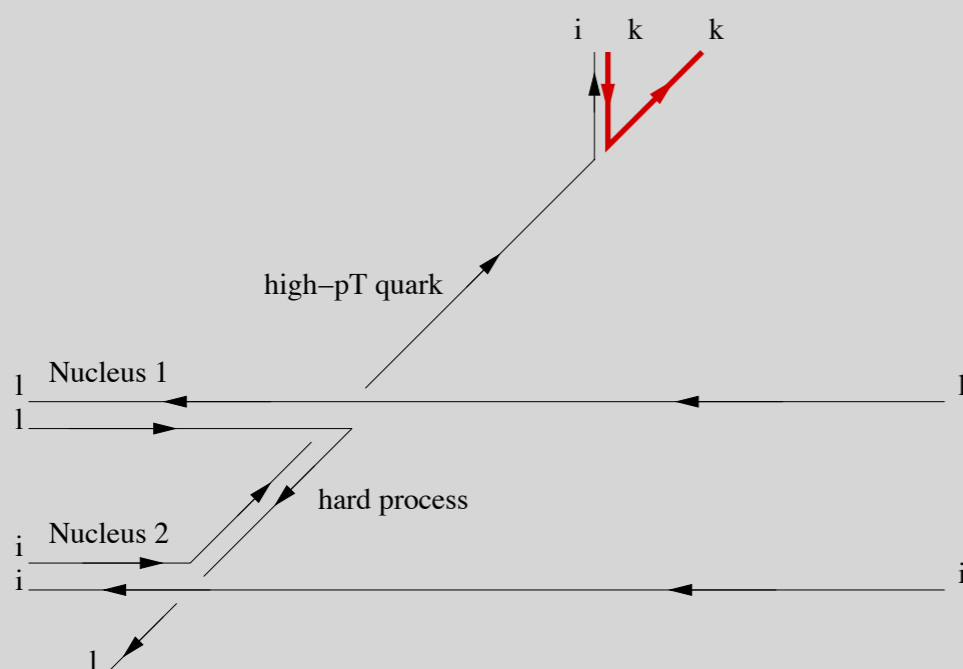$$\Delta(t) = \exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int dz\frac{\alpha_s(t',z)}{2\pi}P(z,t')\right]$$

- identification of colour singlet objects [strings, clusters]
  - colour information tracked to $1/N_c$ accuracy [gluon = quark–antiquark pair]
  - hadronization by string-breaking/cluster decay
    - long strings/large mass clusters lead to increased and softer multiplicity
    - tuned to data :: 'reproduces' data extracted fragmentation functions
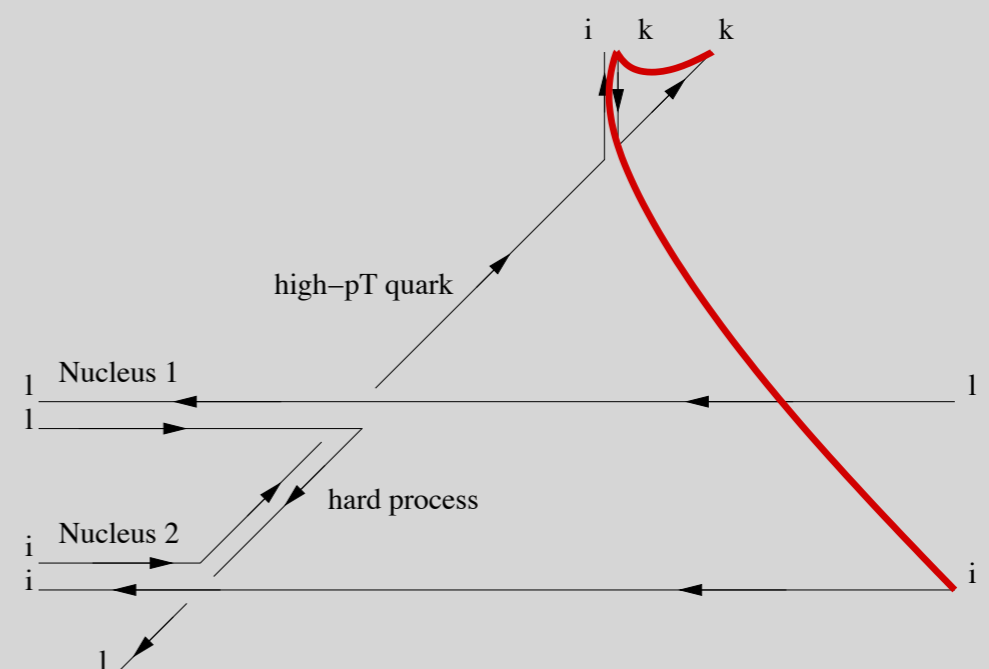
coherent branching

so far we have assumed that successive branchings are independent
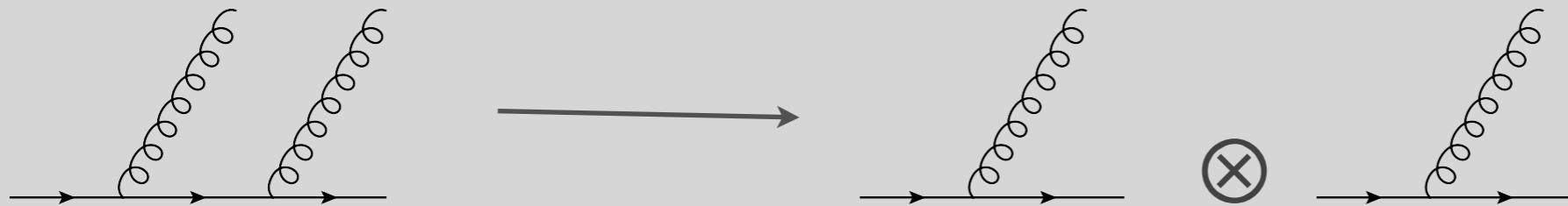
however, interferences play an important role
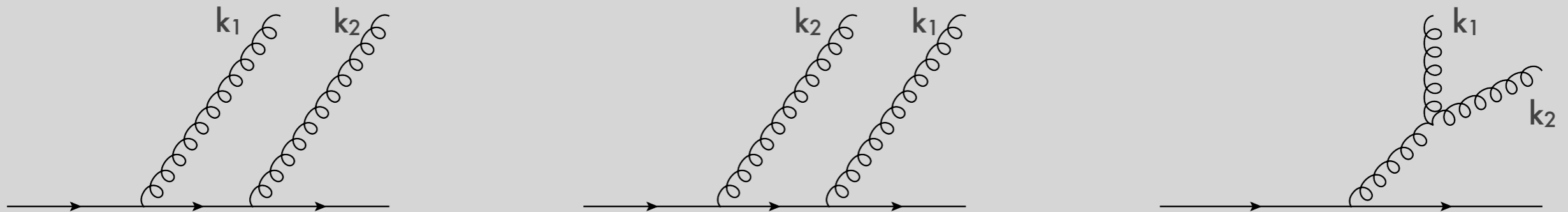
● coherence between successive splittings results in suppression of radiation of 2nd gluon at angles larger than 1st emission angle :: angular ordering

 ◉large angle 2nd gluon emissions cannot resolve quark and gluon separately :: emitted as if from initial quark

 ◉gluon emission is colinearly singular :: dominated by strong hierarchy in emission angles

 ◉not the full story [also need energy-momentum conservation for full description] but qualitatively right
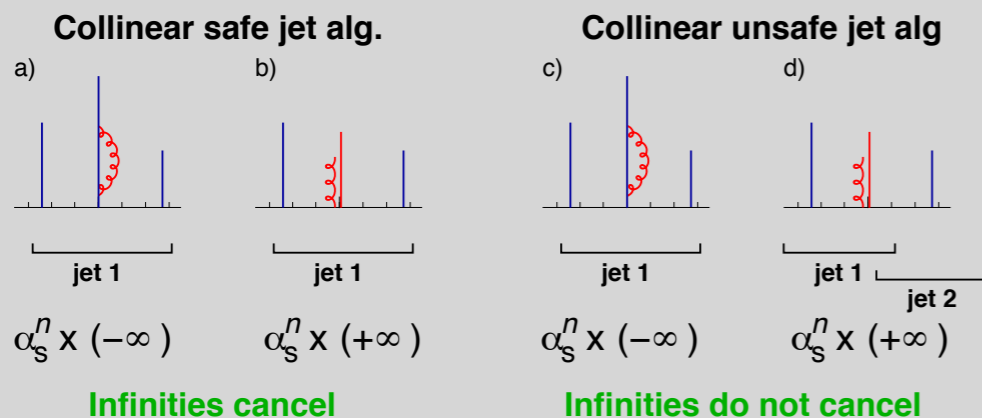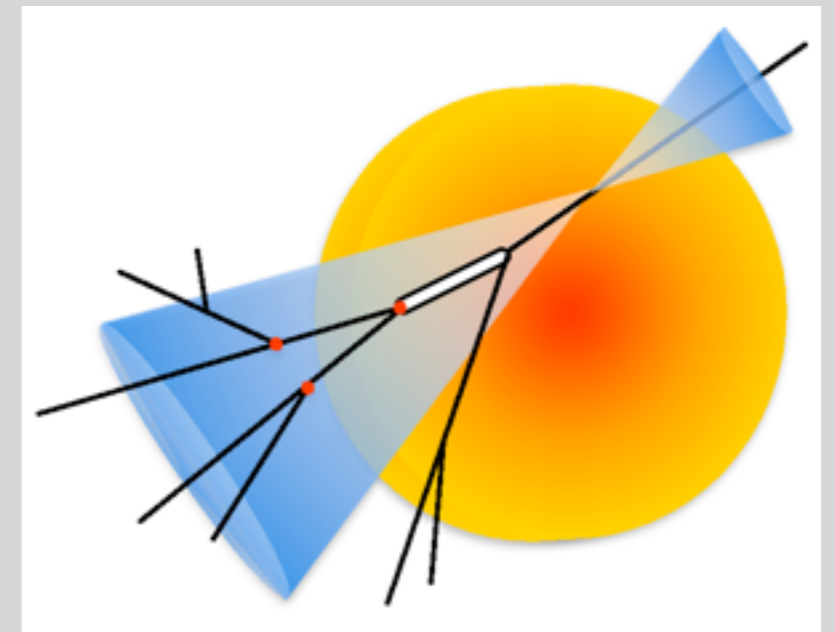
jet definition

the collimated spray of particles that results from the branching of the original hard parton and subsequent hadronization of the fragments

in order to **define** a jet, a set of rules on how to group particles into a jet and how to assign a momentum to the jet must be specified

:: properties of a good jet definition ::

- the same for experimental analysis, analytical partonic calculations and Monte Carlo simulations
- collinear safe [the emission of a collinear gluon does not change what is identified as a jet]
- IR safe [the emission of a soft gluon does not change the jet]
- is not sensitive to hadronization details

Collinear safe jet alg.

a)   b)

jet 1   jet 1

$\alpha_s^n \times (-\infty)$ $\alpha_s^n \times (+\infty)$

Infinities cancel

Collinear unsafe jet alg

c)   d)

jet 1   jet 1 ⌐ jet 2

$\alpha_s^n \times (-\infty)$ $\alpha_s^n \times (+\infty)$

Infinities do not cancel

jet   jet   jet   jet   jet

soft divergence

(a)   W   (b)   W   (c)   W

[Salam 2009]
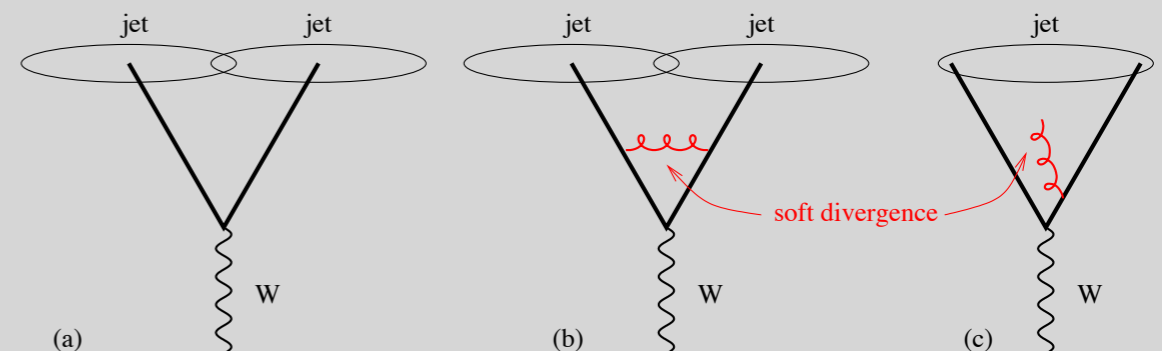
jet resolution scale

the jet definition is completed by specifying a resolution scale [jet size]

$\Delta\eta$

$\Delta\phi$
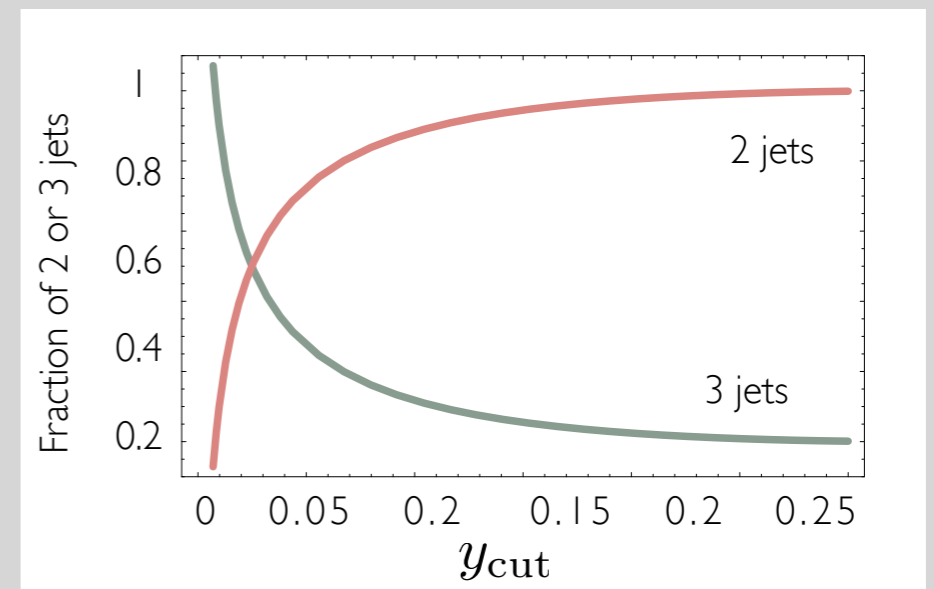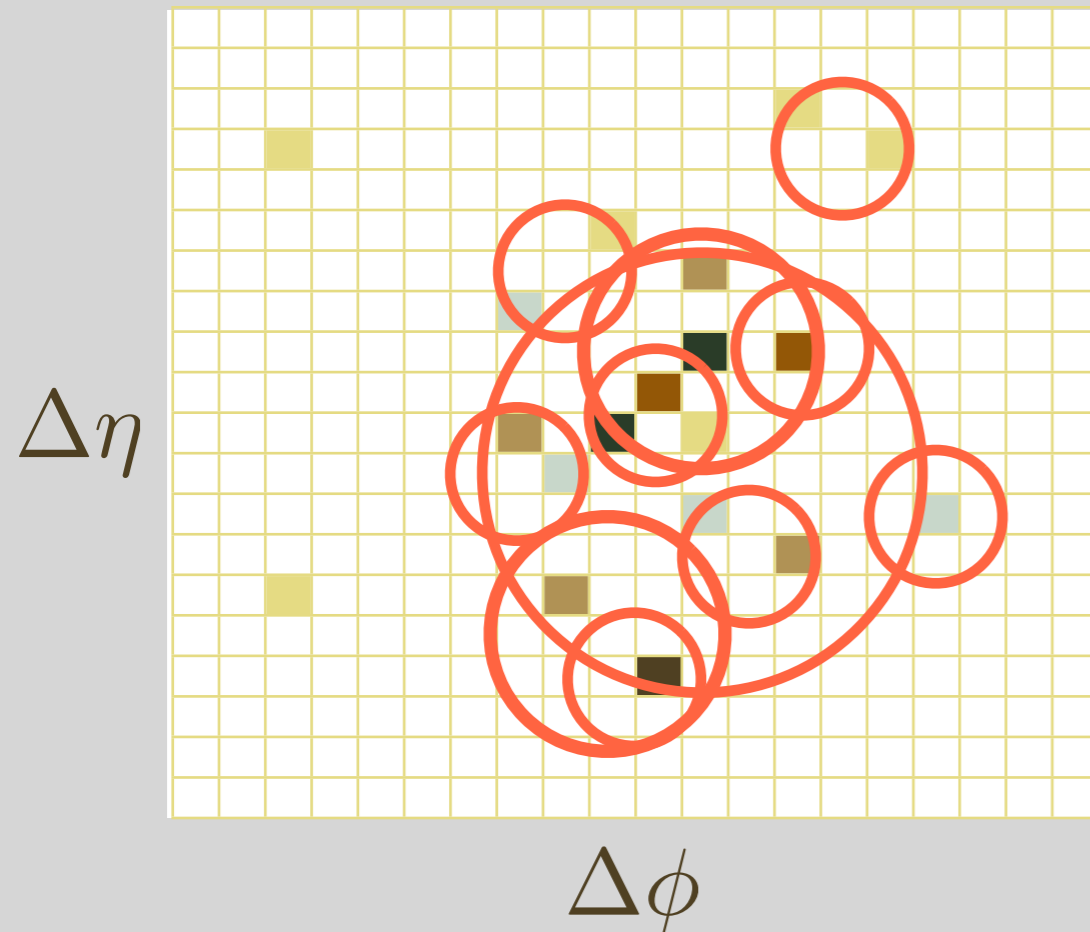
different jet sizes result in a different number of jets

anti-k$_t$ jets

most commonly used [at present] jet algorithm [also in HIC]

— define distance measures [R= 'jet cone radius]

$$d_{ij} = \min(1/p_{ti}^2, 1/p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2} \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = 1/p_{ti}^2$$

— sequentially recombine particles:

```
1.  compute all d_ij and d_iB
2.  find the minimum of the d_ij and d_iB
3.  if it is a d_ij, recombine i and j into a single new particle and return to step 1.
4.  otherwise, if it is a d_iB, declare i to a [final state] jet, and remove it from the list
5.  stop when no particles remain
```

↪ *jet grows around hard seeds*
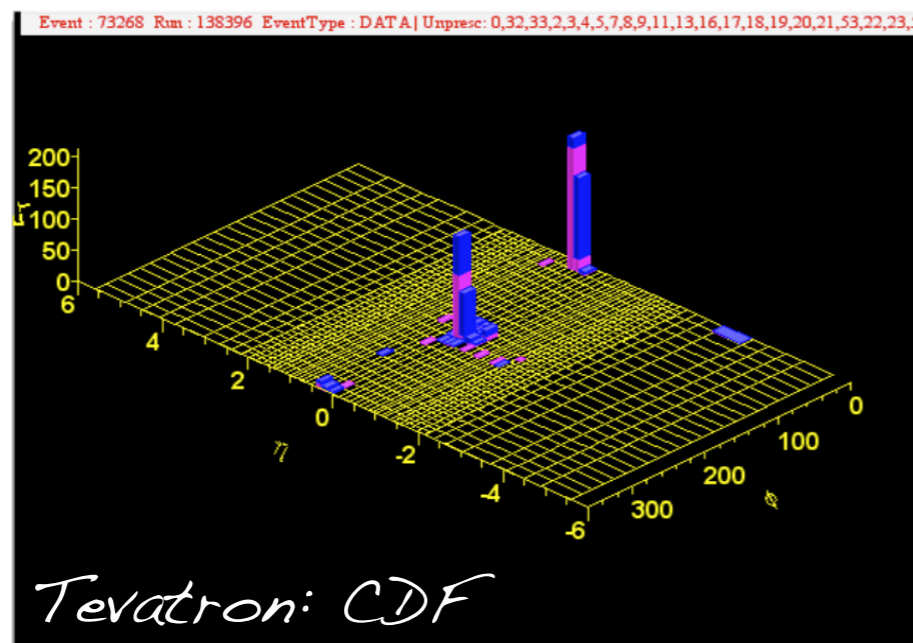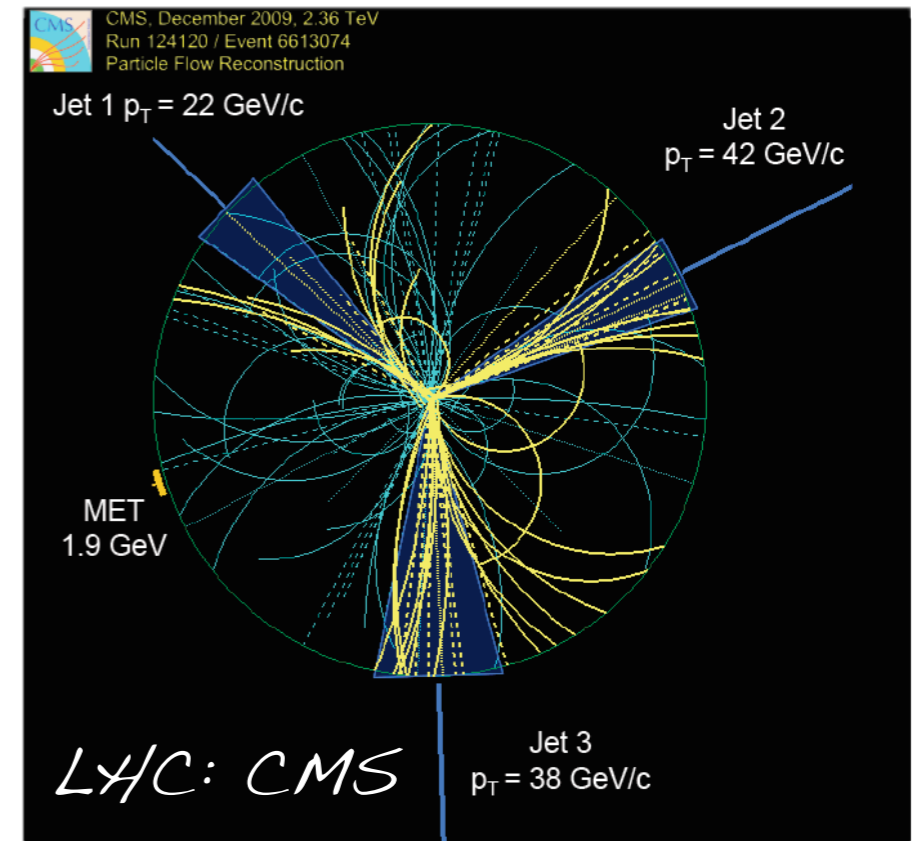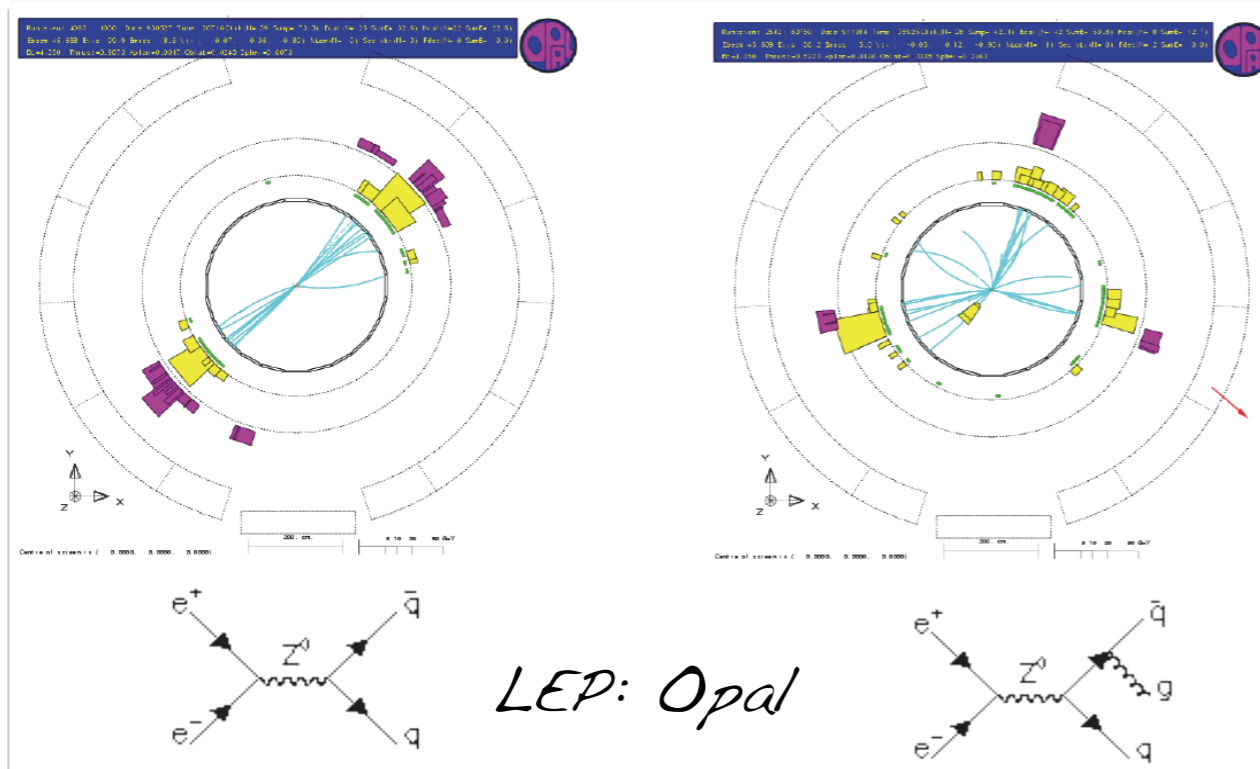↪ *collinear branchings clustered at the beginning*
↪ *gives circular hard jets*

Jets

- experimental aspects

Mateusz Ploskon

Jets in collider experiments

LEP: Opal

CMS, December 2009, 2.36 TeV
Run 124120 / Event 6613074
Particle Flow Reconstruction

Jet 1 p_T = 22 GeV/c

Jet 2
p_T = 42 GeV/c

MET
1.9 GeV

LHC: CMS

Jet 3
p_T = 38 GeV/c

Tevatron: CDF
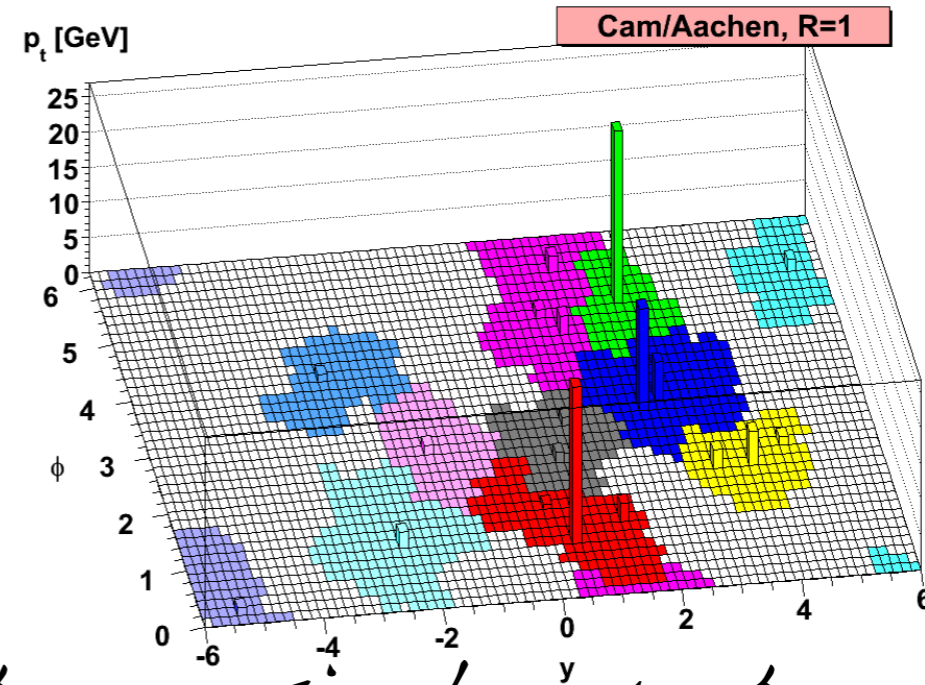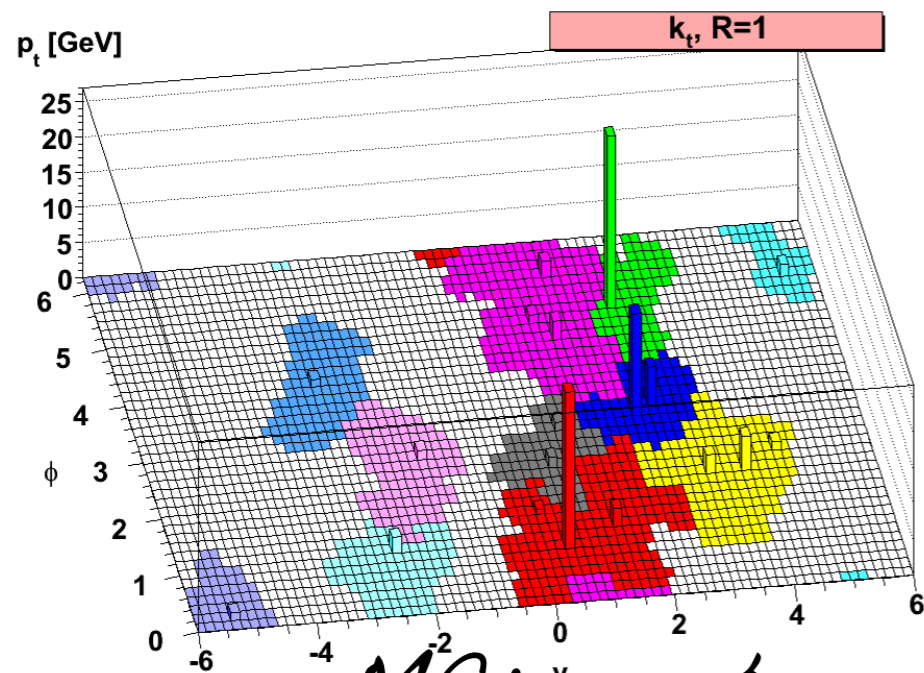

xy plane

STAR TPC Event Display

RHIC: Star
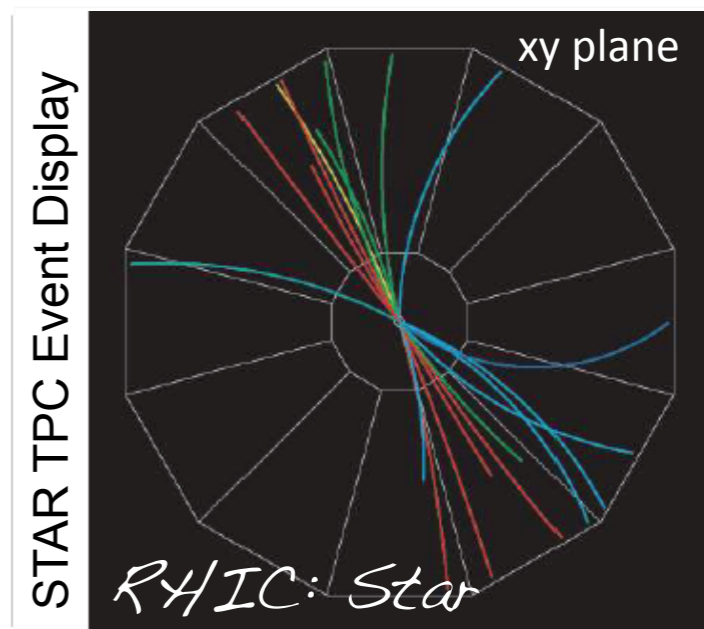
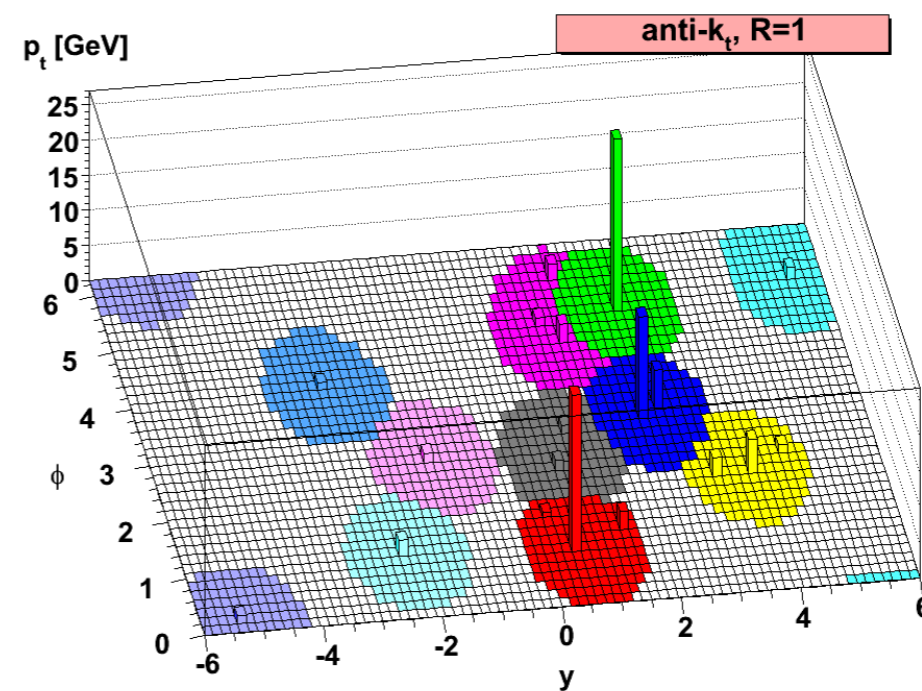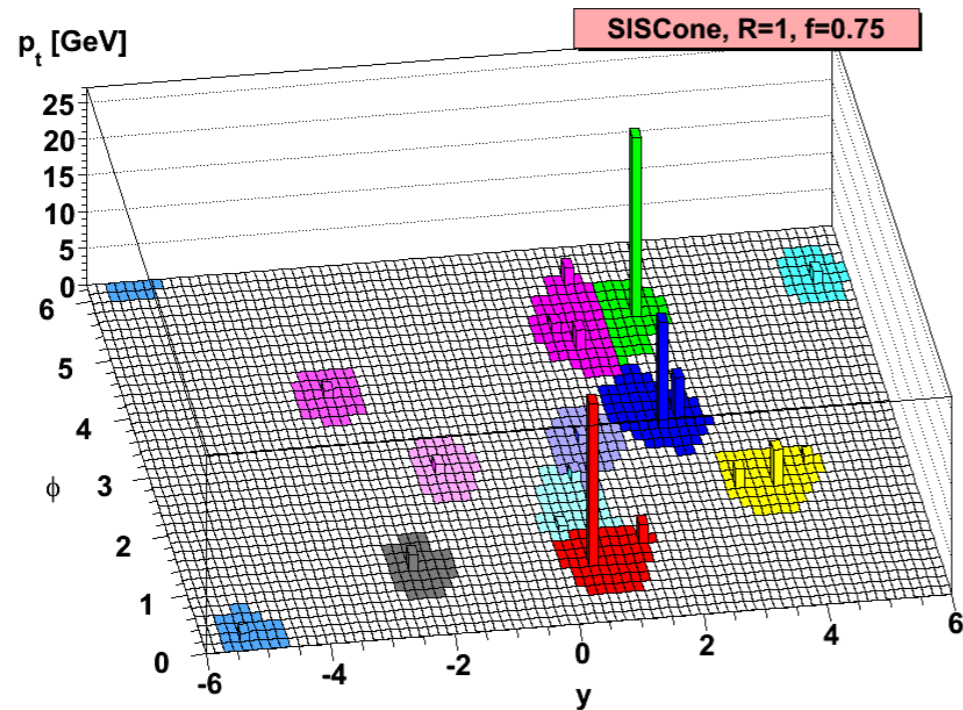# Optimum jet finder algorithm

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;

2. Simple to implement in the theoretical calculation;

3. Defined at any order of perturbation theory;

4. Yields finite cross section at any order of perturbation theory;

5. Yields a cross section that is relatively insensitive to hadronization.
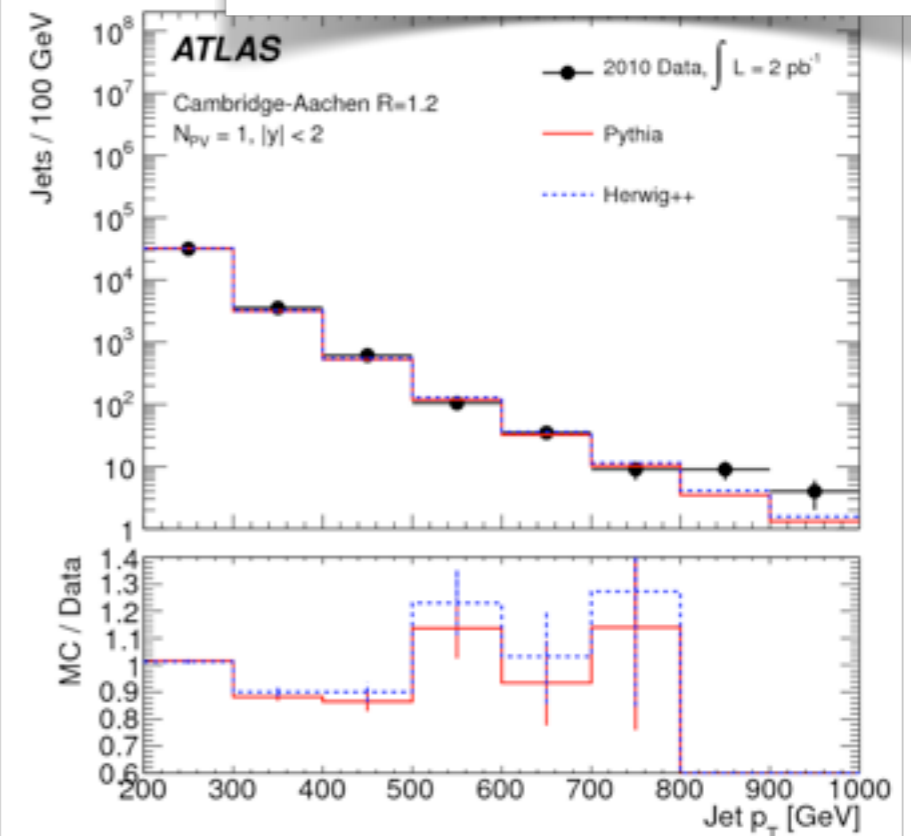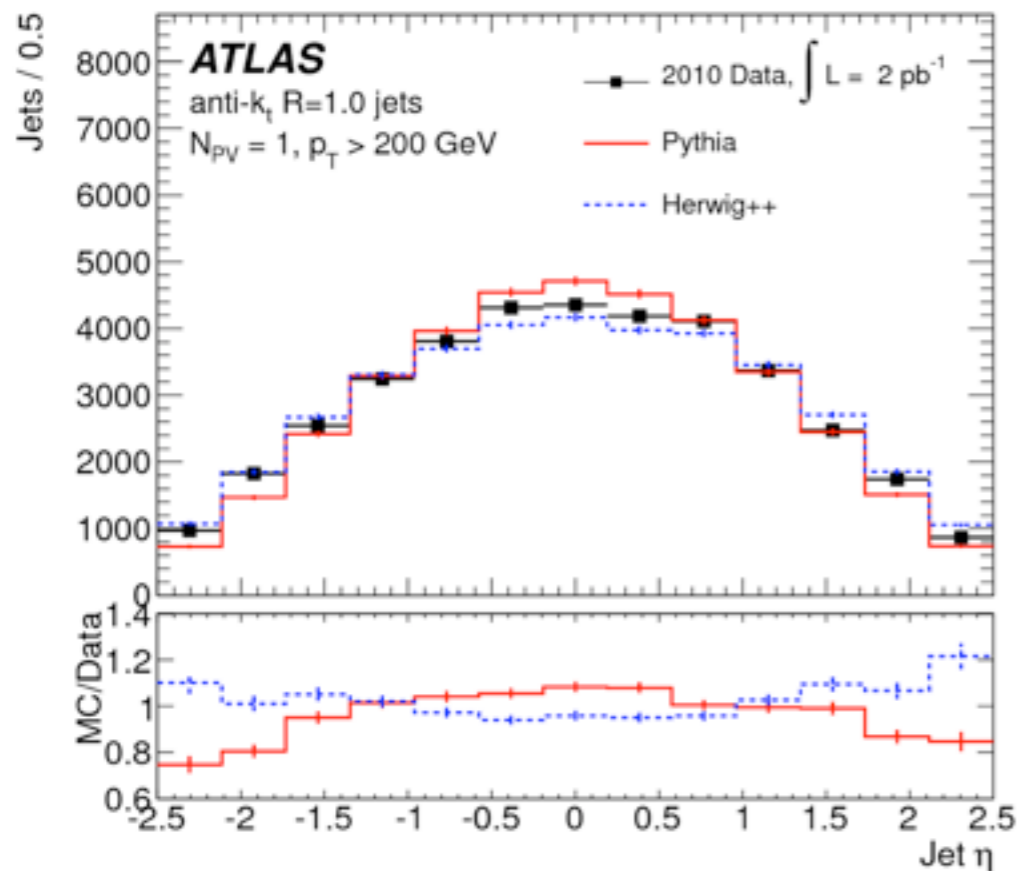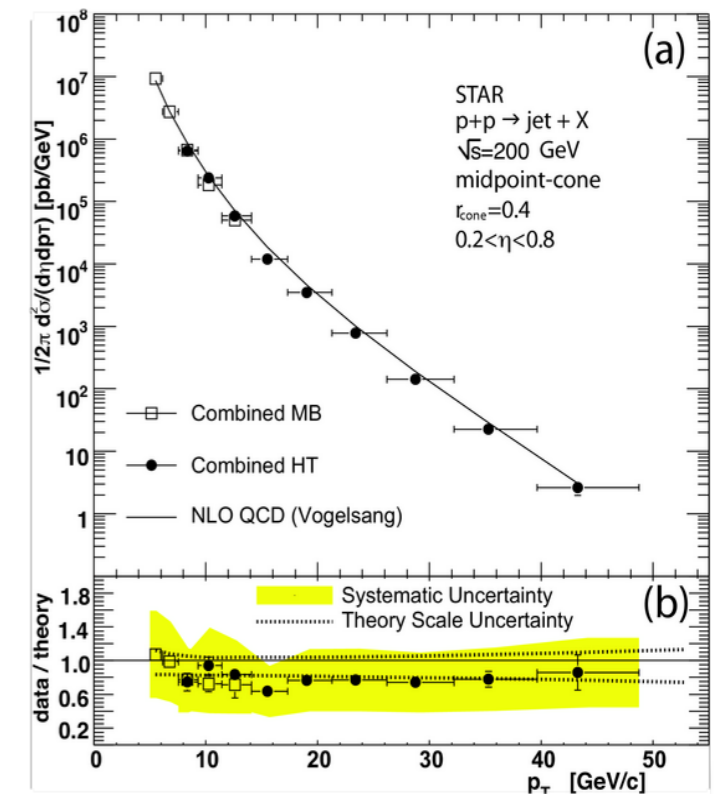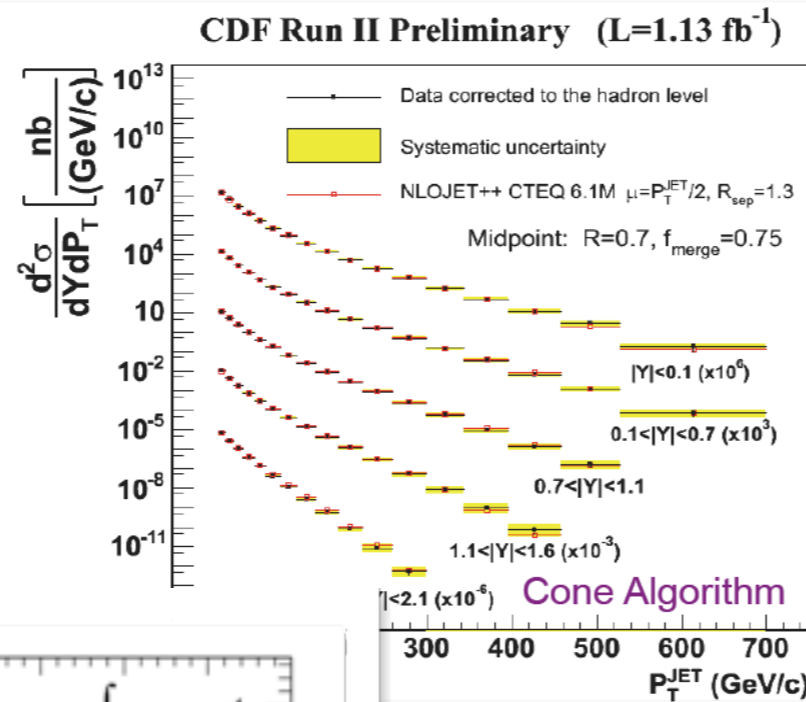
Tevatron 1990

Jet finding – jet finders

MC: proton-proton – single event

Cacciari, Salam, Soyez, arXiv:0802.1189

Jets in collider experiments

Jets are fairly well known by now... and well described by theory and MC

CDF Run II Preliminary (L=1.13 fb⁻¹)

$\frac{d^2\sigma}{dYdP_T}\left[\frac{nb}{(GeV/c)}\right]$

- Data corrected to the hadron level
- Systematic uncertainty
- NLOJET++ CTEQ 6.1M $\mu=P_T^{JET}/2$, $R_{sep}=1.3$

Midpoint: R=0.7, f_{merge}=0.75

|Y|<0.1 (x10⁶)
0.1<|Y|<0.7 (x10³)
0.7<|Y|<1.1
1.1<|Y|<1.6 (x10⁻³)
|Y|<2.1 (x10⁻⁶)

Cone Algorithm

P_T^{JET} (GeV/c)

(a)

STAR
p+p → jet + X
√s=200 GeV
midpoint-cone
r_{cone}=0.4
0.2<η<0.8

$1/2\pi\, d\sigma/(d\eta dp_T)$ [pb/GeV]

- Combined MB
- Combined HT
- NLO QCD (Vogelsang)

(b)
data / theory

Systematic Uncertainty
Theory Scale Uncertainty

p_T [GeV/c]

ATLAS
anti-k_t R=1.0 jets
N_{PV} = 1, p_T > 200 GeV

- 2010 Data, ∫ L = 2 pb⁻¹
- Pythia
- Herwig++

Jets / 0.5

MC/Data

Jet η

ATLAS
Cambridge-Aachen R=1.2
N_{PV} = 1, |y| < 2

- 2010 Data, ∫ L = 2 pb⁻¹
- Pythia
- Herwig++

Jets / 100 GeV

MC / Data

Jet p_T [GeV]

Particle Flow Jet Reconstruction

JET composition

$$C(p_T^{raw}, \eta) = C_{MCtruth}(p_T^{raw}, \eta) \times C_{Residual}(p_T^{raw} \cdot C_{MCtruth}(p_T^{raw}, \eta),$$

The overall jet energy corre... ... ...d its uncertainty is shown in Fig. 1 of ... for fixed jet p_T values ... ...ic ...ALO jets require a much ...arger c... compared to the track-base... ...ms. ...n the region beyond the tracker cover... are ...n agreement within the ... ...inties. ...g...e ... shows th... correc... the...r uncertainty as a functio... ... ...ixed η values. ...he systematic un... over...ll calibration factor is the ... ...ture of the relative scale and th... un...ertainties. Figure 14 shows th... ...ned uncertainty of the jet energy sca... fun...tion of jet p_T while Fig. 15 shows the same quantity as a function o... η.

A Typical Jet

25% photons

15% neutral hadrons

65 % charged hadrons

1-2% electrons
(conversions)

Measure a jet?

Need to have control over all components

Measure or know "

the [unknown] rest from DATA + MC

Correction Factor

3

2.5

- Calorimeter jets
- Jet-Plus-Track jets
- Particle Flow jets

CMS Preliminary

$\sqrt{s}$ = 7 TeV

anti-k_T R = 0.5

p_T = 50 GeV

Correction Factor

3

2.5

- Calorimeter jets
- Jet-Plus-Track jets
- Particle Flow jets

CMS P...

$\sqrt{s}$ =

anti-k

p_T =

cs event generation

detector

At Hadronic Colliders, quarks & gluons produced, evolves (parton shower, hadronisation) to become jets

In a cone around the initial parton: high density of hadrons

LHC calorimeters cannot separate all the incoming hadrons

Use dedicated calibration schemes (based on simulation in ATLAS)

Use tracking system to identify charged hadrons (Particle Flow in CMS)

Decay

Hadronization

Parton Shower

Hard SubProcess

Parton Distributions

Minimum Bias Collisions

$f(x,Q^2)$ $f(x,Q^2)$

"calorimeter jet"

CH

FH

EM

hadrons

γ

"particle jet"

π K

"parton jet"

q g

p p

$\bar{q}$

A Jet Detector

Primary sub-detectors: Silicon tracker, ECAL, HCAL, muon chambers

Key:
— Muon
— Electron
— Charged Hadron (e.g. Pion)
-- Neutral Hadron (e.g. Neutron)
-- Photon

4T

2T

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

Transverse slice through CMS

D. Barney, CERN, February 2004

Improvements in jet reconstruction on detector level => Particle flow
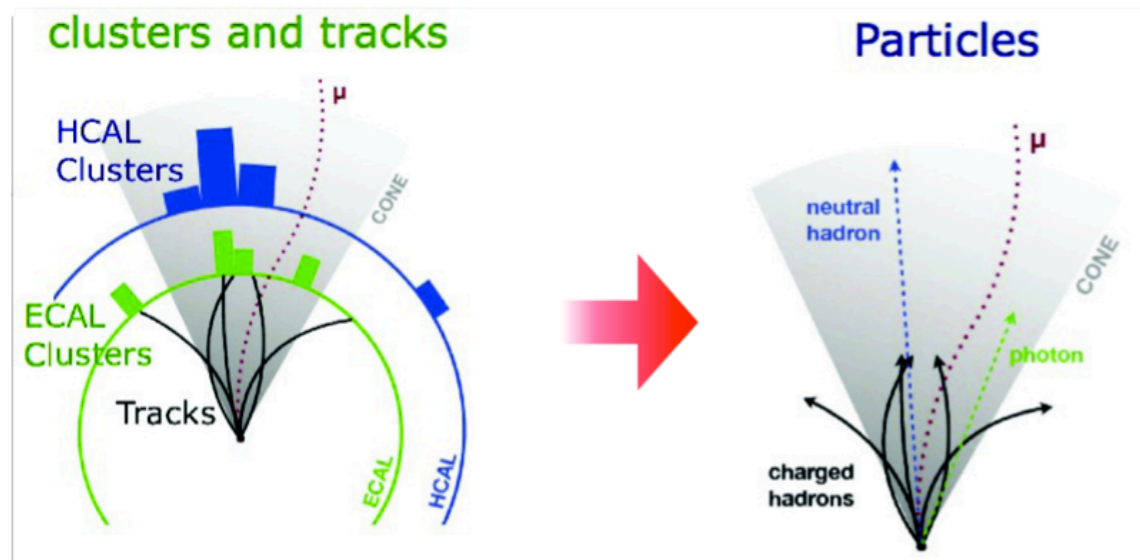
Purely calorimeter jet vs. Particle Flow jet

Better response w.r.t. calorimeter measurement => smaller jet-energy corrections

Mean of Gaussian fit to

$$\frac{Reco\ p_T - Gen\ p_T}{Gen\ p_T}$$

PF reconstructs > 95% of the jet p_T

CMS Preliminary

PYTHIA

Jet Response

Particle-Flow Jets

Calo-Jets

$0 < |\eta| < 1.5$

p_T (GeV/c)

Barrel: $|\eta| < 1.5$

Generator-level
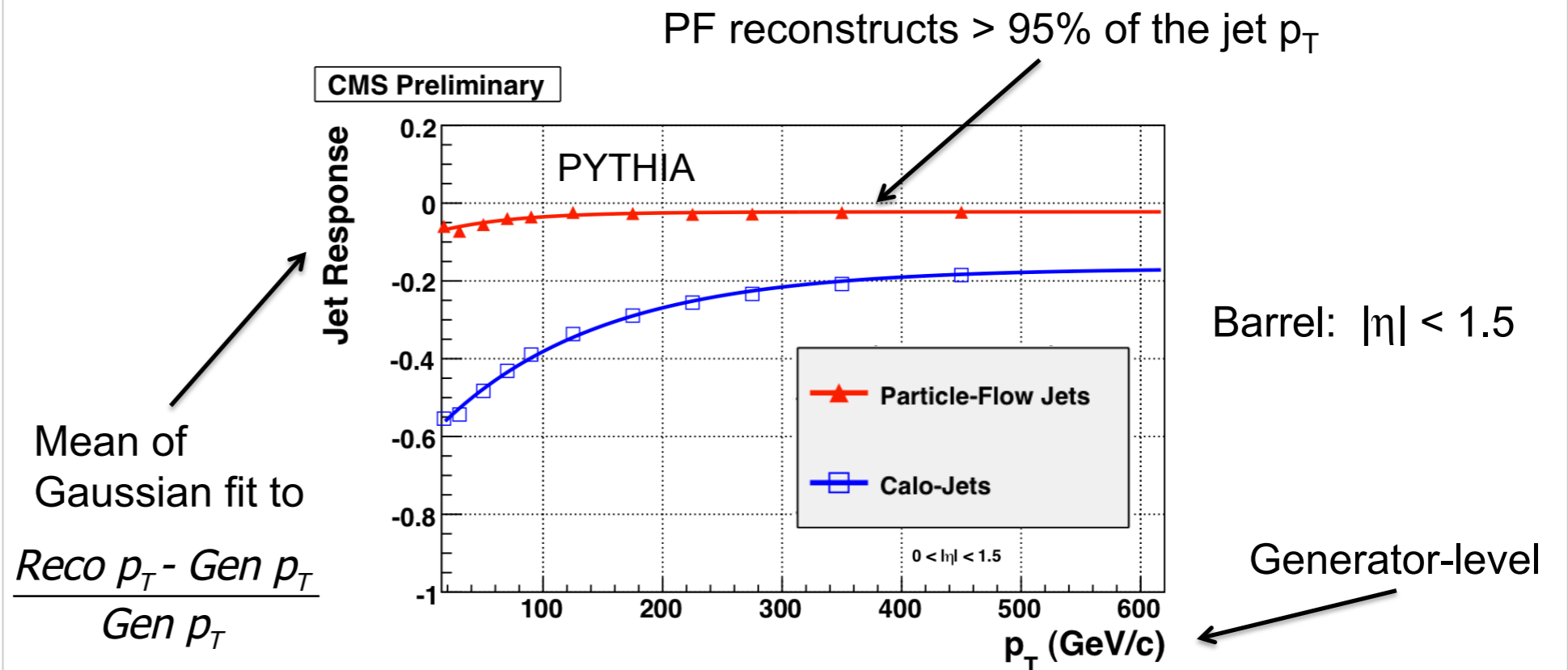
Jet: energy scale & resolution

Bias == Scale
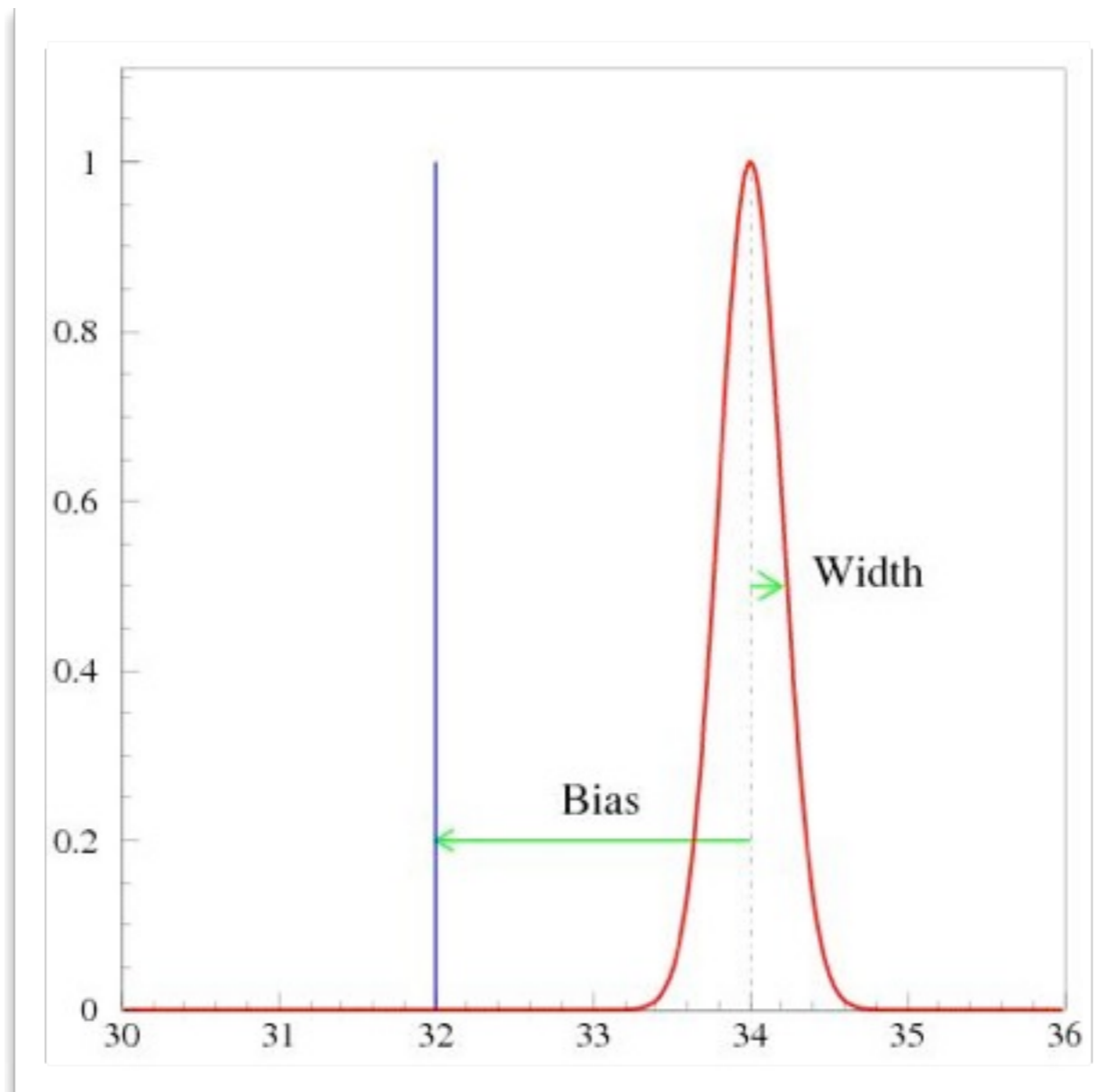
Width == Resolution

Control over the two crucial in p-p and AA collisions

JET: From Measured to *meaningful* ...

Jet Calibration: Factorized Approach

$$\text{Response} = \frac{\text{Reco Jet } p_\text{T}}{\text{True Jet } p_\text{T}}$$

Physics Object

Underlying event!

Raw Jet $\times$ Offset Correction (pile up) $\times$ Relative Response (vs. η) $\times$ Absolute Response (vs. p_T) $=$ Calibrated Jet
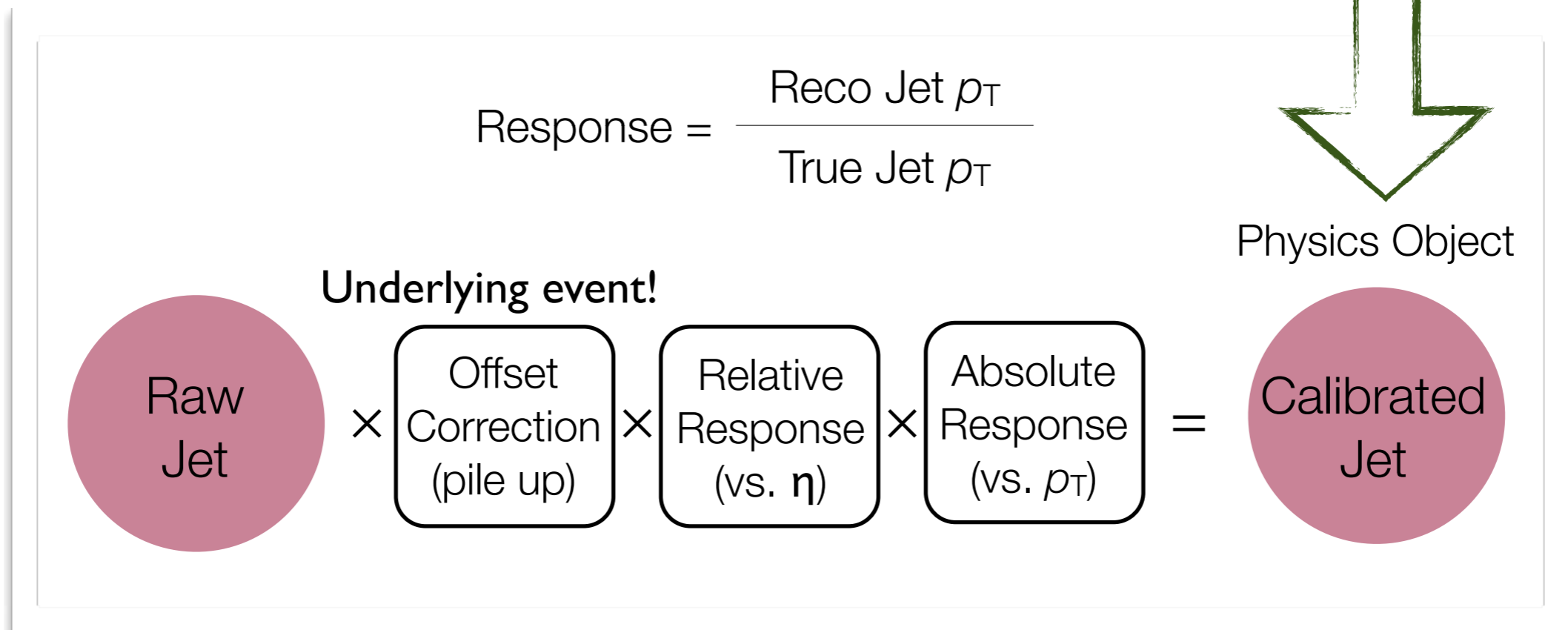
This is an experimental enterprise!
It is a substantial effort...

ATLAS Linearit

Jet Resolution Measurement
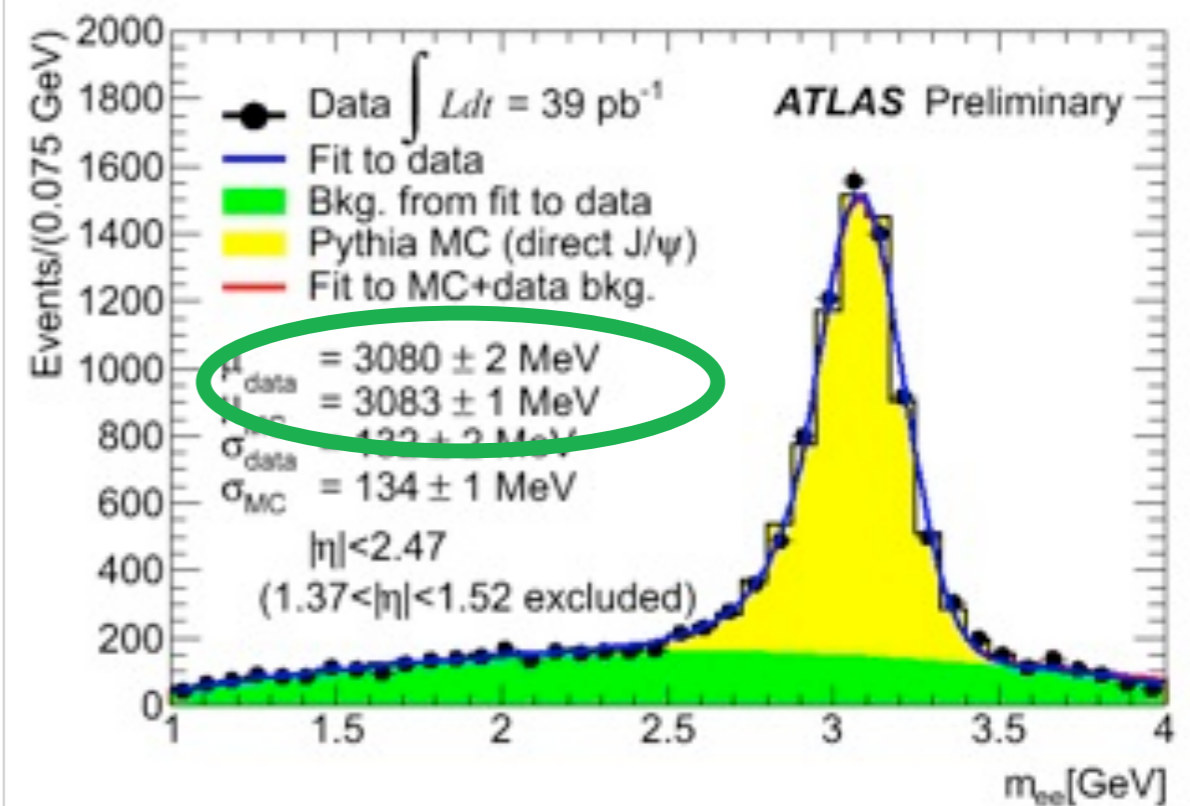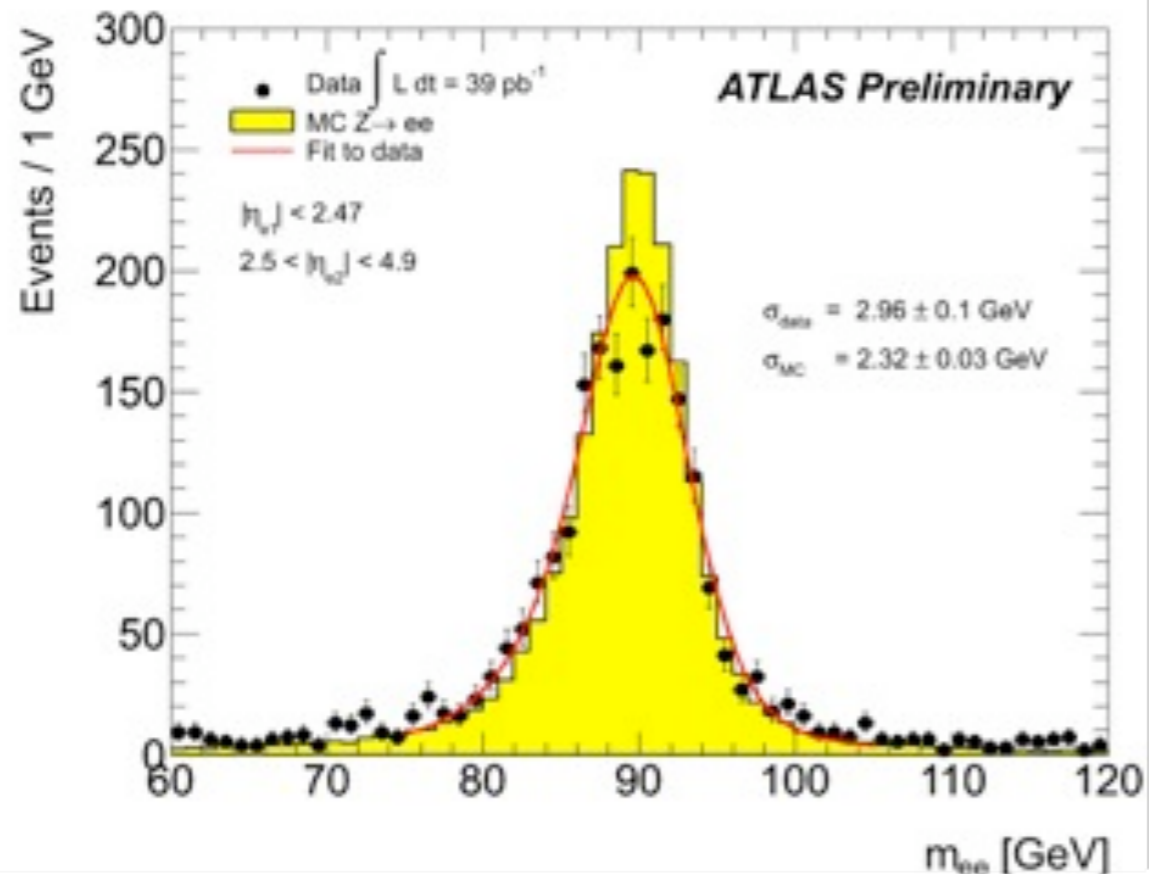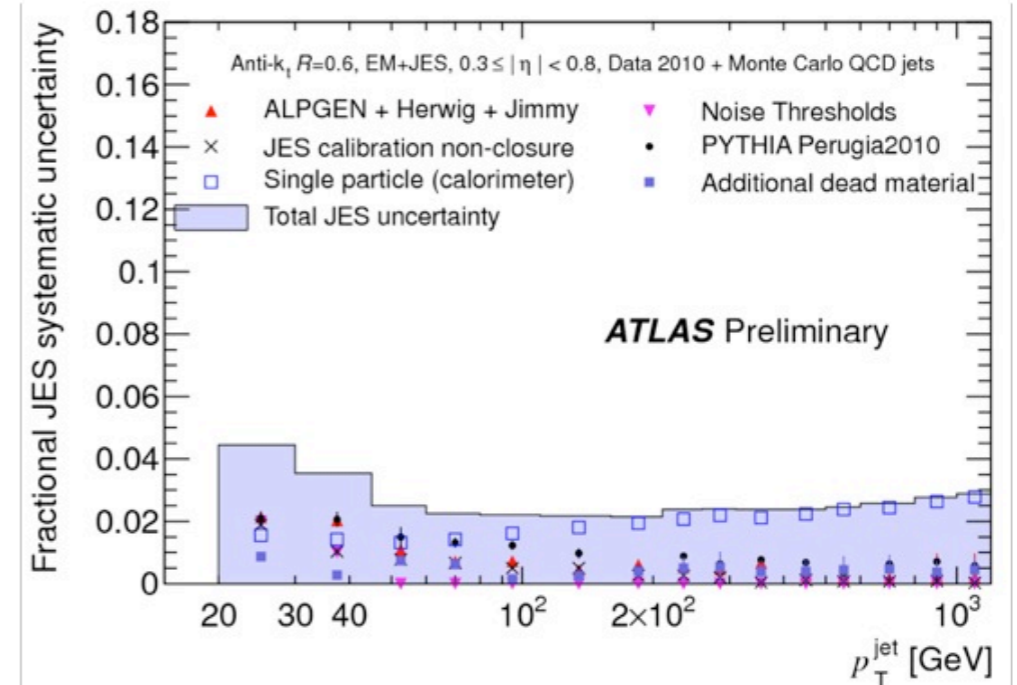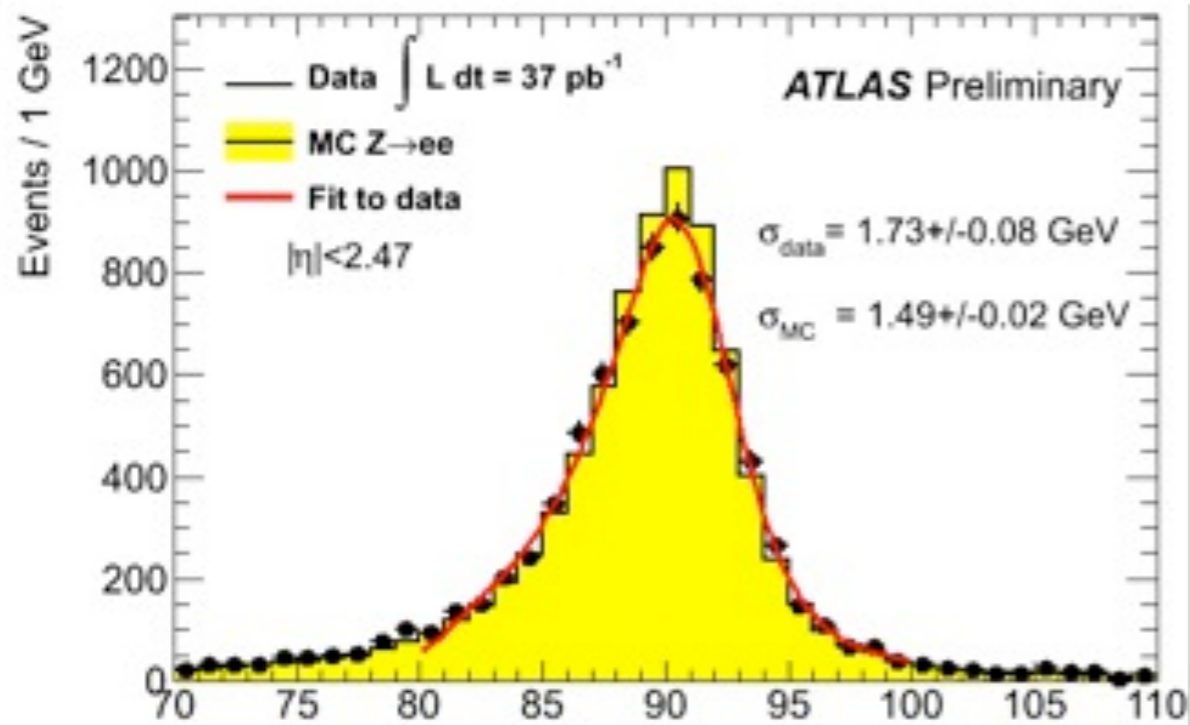
Jet energy resolution

An example: proton-proton collisions

$$\mathcal{A} = \frac{p_{\mathrm{T}}^{\mathrm{Jet1}} - p_{\mathrm{T}}^{\mathrm{Jet2}}}{p_{\mathrm{T}}^{\mathrm{Jet1}} + p_{\mathrm{T}}^{\mathrm{Jet2}}} \longrightarrow \frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}} = \sqrt{2}\,\sigma_{\mathcal{A}}$$

$\sqrt{s}=7$ TeV, L=35.9 pb^{-1} **CMS preliminary 2010**

total systematic uncertainty — **CaloJets**
MC truth (c-term added) — (Anti-k$_{\mathrm{T}}$ R=0.5)
MC truth — $0 < |\eta| \le 0.5$
data

Calorimeter Jets

JME-10-014

jet p$_{\mathrm{T}}$ resolution

p$_{\mathrm{T}}$ [GeV]

$\sqrt{s}=7$ TeV, L=35.9 pb^{-1} **CMS preliminary 2010**

total systematic uncertainty — **PFJets**
MC truth (c-term added) — (Anti-k$_{\mathrm{T}}$ R=0.5)
MC truth — $0 < |\eta| \le 0.5$
data

Particle Flow Jets

jet p$_{\mathrm{T}}$ resolution

p$_{\mathrm{T}}$ [GeV]
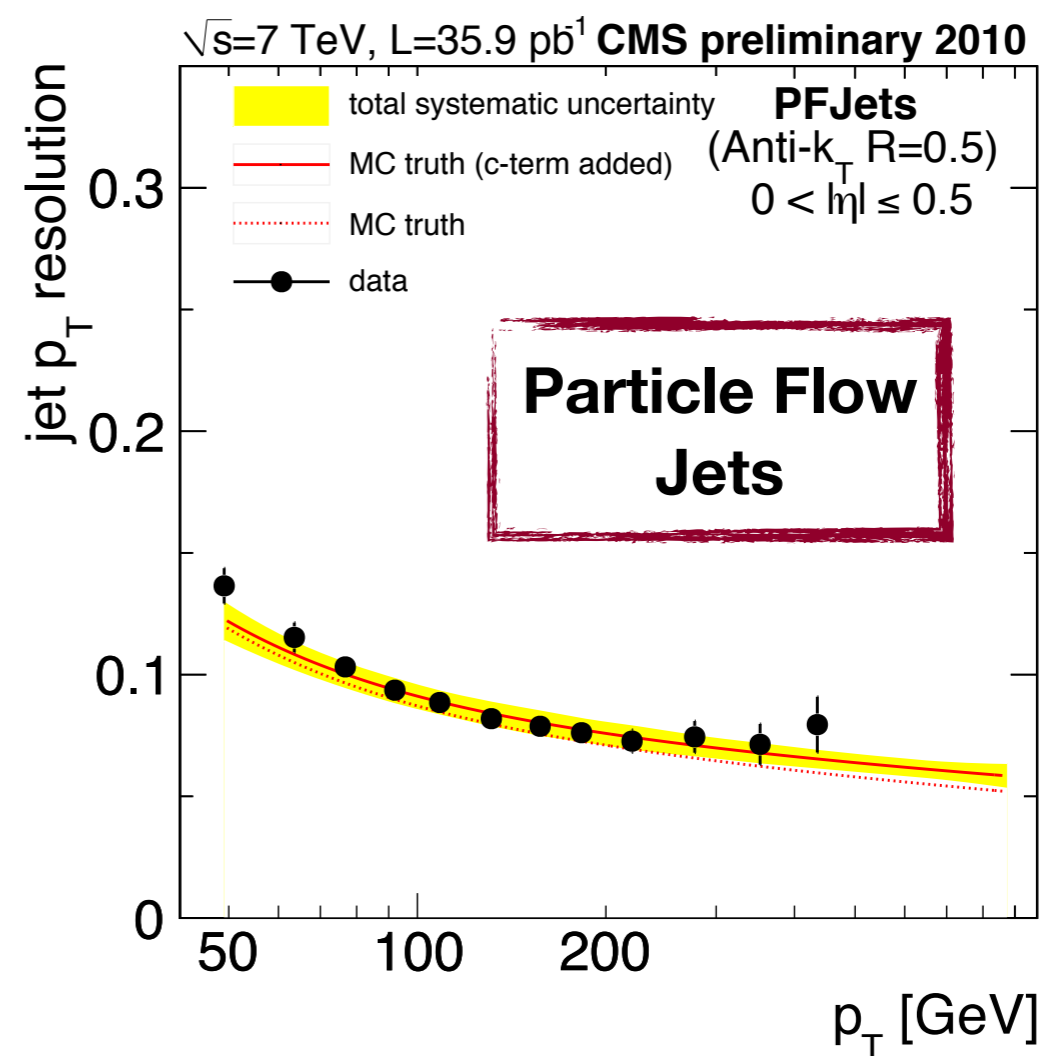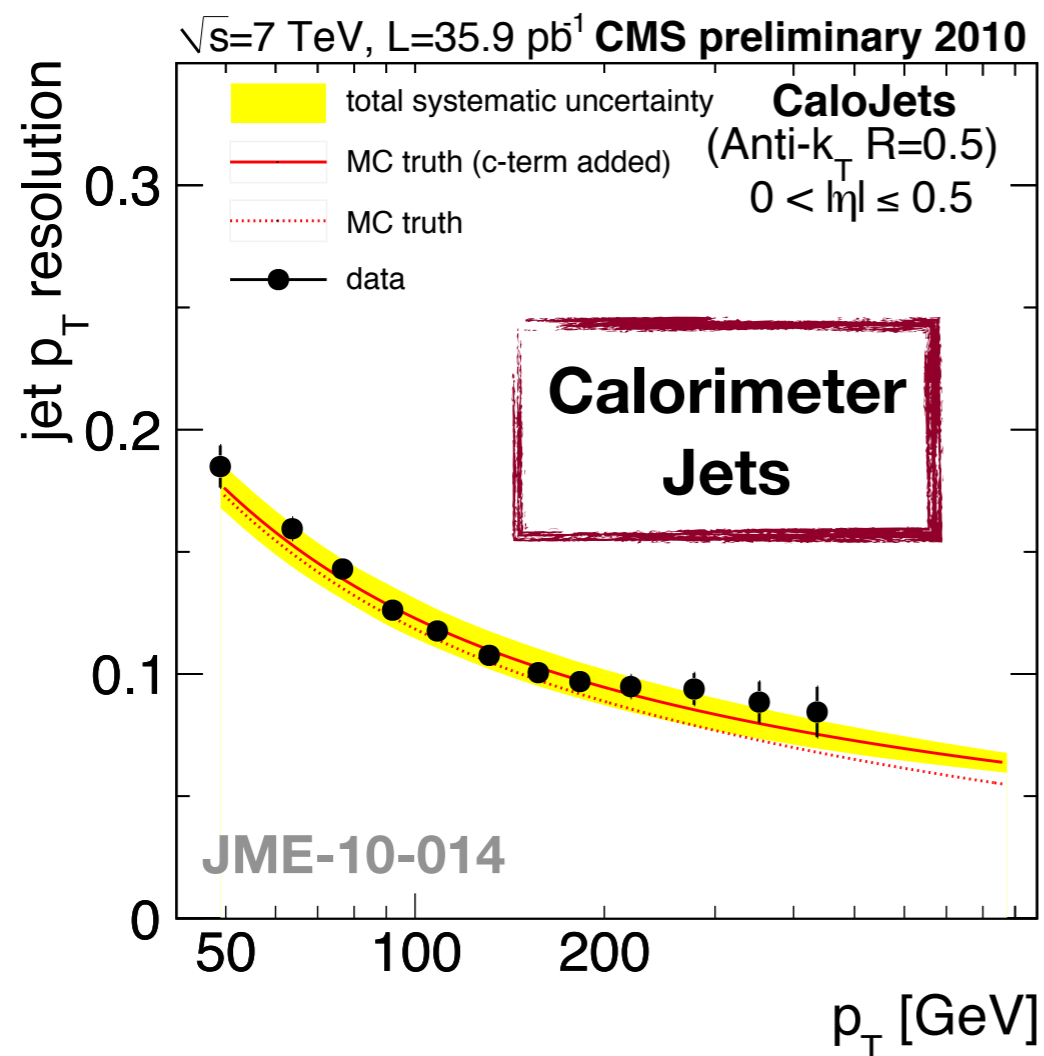
jet-medium interactions

Casalderrey-Solana, Salgado, Introductory lectures on jet quenching, arXiv:0712.3443 [hep-ph]

JGM, *High-p$_t$ in heavy ion collisions: an abridged overview,*arXiv:1202.0646 [hep-ph]

high-p_t processes in heavy ion collisions

- factorized description of hadron production at high-p_t in heavy ion collisions is a, phenomenological consistent, working assumption

$$\sigma^{AB \to h} \sim f_i^A(x_1, Q^2) \otimes f_j^B(x_2, Q^2) \otimes \sigma^{ij \to k} \otimes D_{k \to h}(z, Q^2)$$

high-pₜ processes in heavy ion collisions

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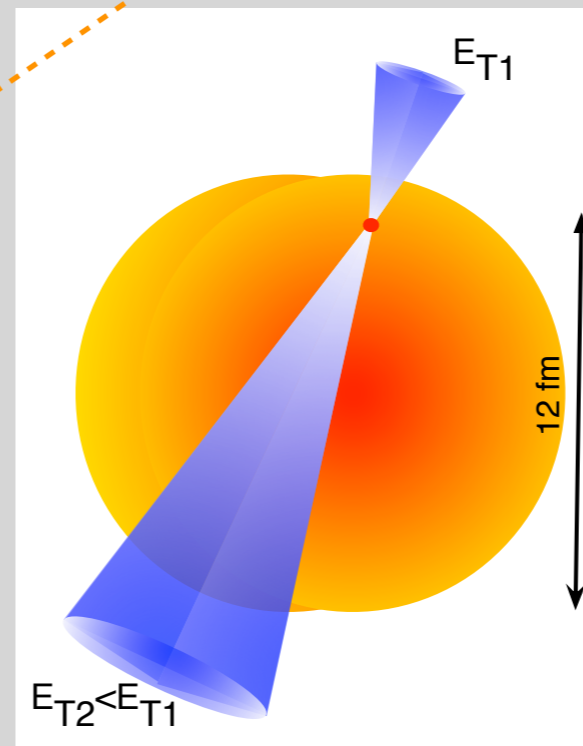
PDFs [initial state]
- universal, non-perturbative
- scale dependence from DGLAP evolution
- determined from global fits [eA, pA]
- control of nuclear modifications essential
  [cold nuclear matter effects]

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E_{T1}

12 fm

$E_{T2} < E_{T1}$

hard partonic collision process [pQCD]
  - localized on point-like scale [~ 1/E$_T$]
    and thus oblivious to the surrounding
    QCD medium

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jet quenching :: the modifications effected on the propagating parton, and on its shower, by the QCD medium it traverses

dual role of jet quenching studies

dual role of jet quenching studies

- ultimately jet quenching studies [medium induced modifications of observed properties of high-p_t properties] allow for detailed characterization of produced medium

    ↪ high-p_t probes are created early

    ↪ their production mechanism is under good theoretical control

    ↪ they can traverse a significant in-medium path length

    ↪ the observable consequences of probe-medium interactions encode detailed information on medium properties

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what can conceivably happen to a jet that develops in the presence of a hot, dense and coloured medium?

jet-medium interactions [jet quenching]

induced radiation
- medium transfers momentum to jet components
  - :: increases splitting probability and broadens radiation
  - :: finite quark mass vetos small angle radiation [dead cone]
- medium disturbs coherence between successive splittings
  - :: modified angular pattern

K.Tywoniuk [Tue 12.15]

A.Beraudo[Tue 11.45]

dynamics of emitted quanta
- transverse transport of all jet components

color exchanges with medium
- modified colour flow in the jet
  - :: affects hadronization irrespectively of where it occurs

medium response to jet propagation
- recoil, ...

T.Renk [Tue 9.00]

modelling
- piecewise description
- first principle probabilistic or effective formulation for Monte Carlo implementation
- embedding in medium

observables

○ jet quenching without jets

↪ hadronic spectra [R_{AA}, correlations, etc...]

↪ in principle very sensitive to hadronization effects

○ jet quenching with reconstructed jets

↪ in principle less sensitive to hadronization details

↪ mechanisms irrelevant for parton energy loss may play significant role

• a gluon radiated from the hard parton is energy lost for that parton, but not necessarily so for that parton's jet
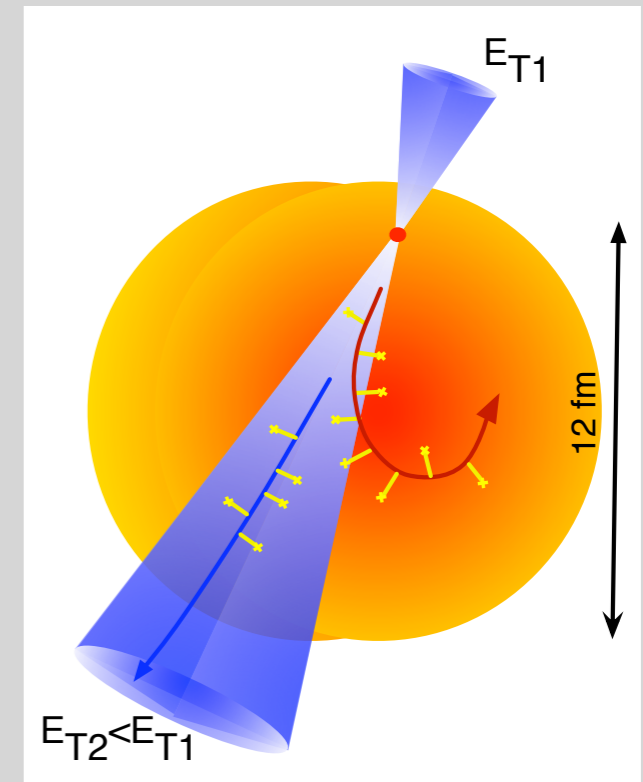
parton energy loss [schematic]

Brownian motion

$$\langle k_\perp^2 \rangle \sim \hat{q}L$$

accumulated phase

$$\left\langle \frac{k_\perp^2 L}{\omega} \right\rangle \sim \frac{\hat{q}L^2}{\omega} \sim \frac{\omega_c}{\omega}$$

characteristic gluon energy

$$\hat{q} \simeq \frac{\mu^2}{\lambda}$$

number of coherent scatterings

$$N_{coh} \sim \frac{t_{coh}}{\lambda} \qquad t_{coh} \sim \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

$$k_\perp^2 \sim \hat{q}\, t_{coh}$$

1 parameter medium definition

gluon energy distribution

$$\omega \frac{dI_{med}}{d\omega dz} \sim \frac{1}{N_{coh}} \omega \frac{dI_1}{d\omega dz} \sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$$

non-abelian LPM

average energy loss
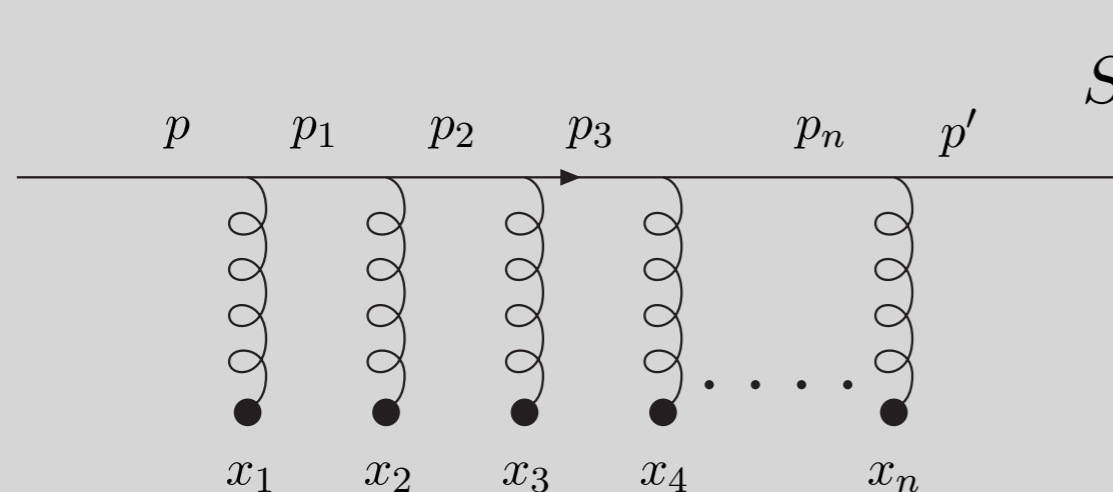
$$\Delta E = \int_0^L dz \int_0^{\omega_c} \omega d\omega \frac{dI_{med}}{d\omega dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q}L^2$$
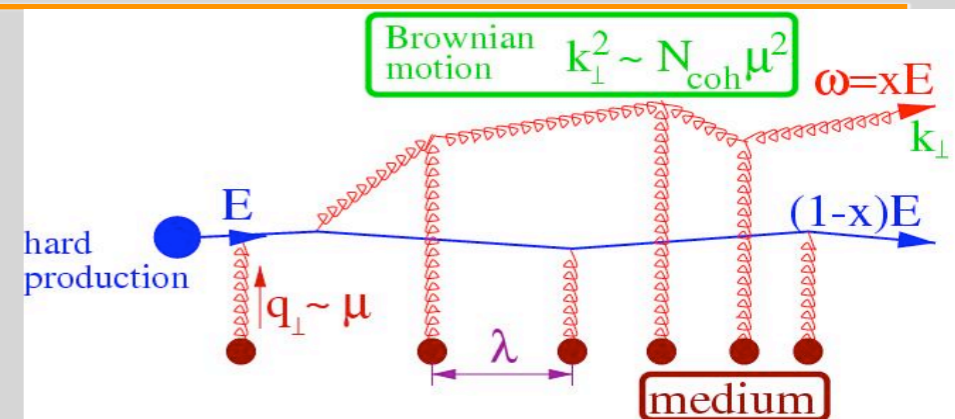
in-medium parton propagation

medium as set of static localized scattering centres

$$S_1(p', p) = \int d^4x \; e^{i(p'-p)\cdot x} \; \bar{u}(p') \; igA_\mu^a(x)T^a\gamma^\mu \; u(p)$$

$$W(\mathbf{x}) = \mathcal{P}\exp\left[ig\int dx_+ A_-(x_+, \mathbf{x})\right]$$

eikonal propagation [parton energy much larger than medium kicks]
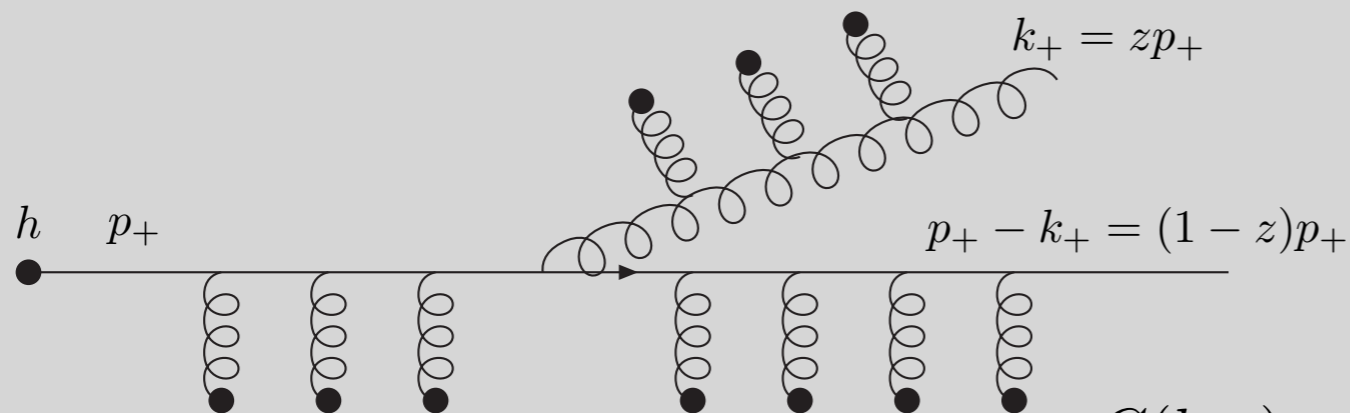
$$G(b, a) = \int \mathcal{D}\mathbf{r}(x_+) \exp\left\{i\frac{p_+}{2}\int dx_+ \left[\frac{d\mathbf{r}}{dx^+}\right]^2\right\} W(\mathbf{r})$$

beyond, but close to, eikonal propagation [allow for transverse brownian motion] of radiated gluon

single gluon emission [BDMPS]

building block for parton energy loss calculation [modified splitting kernel]
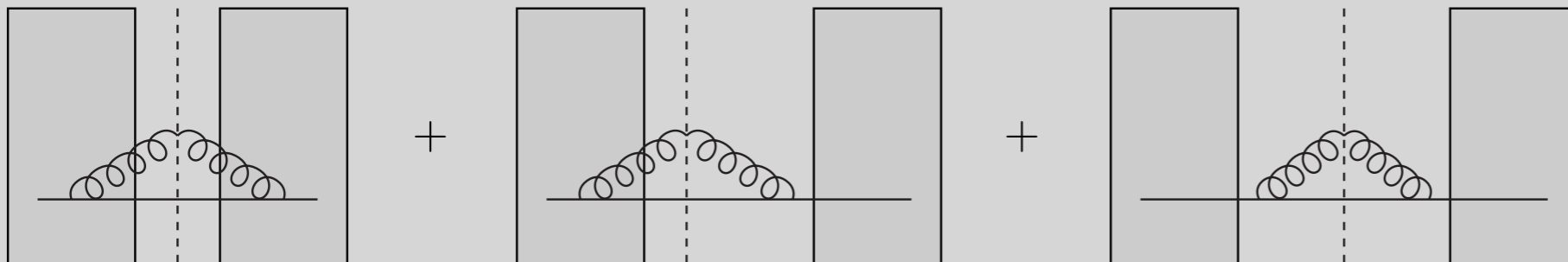
$$\langle |\mathcal{M}_{a \to bc}|^2 \rangle = \frac{g^2}{N^2 - 1} 2\mathrm{Re}\left[\frac{1}{k_+^2} \int_{x_{0+}}^{L_+} dx_+ \int_{x_+}^{L_+} d\bar{x}_+ \int d\mathbf{x} d\bar{\mathbf{x}} \; e^{i\mathbf{k}_\perp (\mathbf{x} - \bar{\mathbf{x}})} \times \right.$$

$$\left\langle W_{aa_1}(\mathbf{0}, x_{0+}, x_+) T^{c_1}_{a_1 b_1} \frac{\partial}{\partial \mathbf{y}} G_{c_1 c}(\mathbf{y} = 0, x_+; \mathbf{x}, L_+) W_{b_1 b}(\mathbf{0}, x_+, L_+) \times \right.$$

$$W^\dagger_{b\bar{b}_1}(\mathbf{0}, \bar{x}_+, L_+) \frac{\partial}{\partial \bar{\mathbf{y}}} G_{c\bar{c}_1}(\bar{\mathbf{x}}, L_+; \bar{\mathbf{y}} = 0, \bar{x}_+) T^{\bar{c}_1}_{\bar{b}_1 \bar{a}_1} W^\dagger_{\bar{a}_1 a}(\mathbf{0}, x_{0+}, \bar{x}_+) \Big\rangle -$$

$$-\frac{2}{k_+} \frac{\mathbf{k}_\perp}{k_\perp^2} \int_{x_{0+}}^{L_+} dx_+ \int d\mathbf{x} e^{i\mathbf{k}_\perp \mathbf{x}} \Big\langle W_{aa_1}(\mathbf{0}, x_{0+}, x_+) T^{c_1}_{a_1 b_1} \times$$

$$\left. \frac{\partial}{\partial \mathbf{y}} G_{c_1 c}(\mathbf{y} = 0, x_+; \mathbf{x}, L_+) \times W_{b_1 b}(\mathbf{0}, x_+, L_+) T^{c_1}_{b\bar{a}_1} W^\dagger_{\bar{a}_1 a}(\mathbf{0}, x_{0+}, L_+) \Big\rangle \right] +$$

$$+ \frac{4g^2 C_R}{k_\perp^2}$$

medium averages

local in longitudinal space [scattering centres are independent, no colour in between them], only 2-point field correlator is relevant

$$\frac{1}{N}\text{Tr}\langle W^\dagger(\mathbf{x}_\perp)W(\mathbf{y}_\perp)\rangle = \frac{1}{N}\text{Tr}\Big\langle \exp\{-ig\int dx_+ A^\dagger_-(x_+,\mathbf{x}_\perp)\} \times$$

$$\times \exp\{ig\int dx_+ A_-(x_+,\mathbf{y}_\perp)\}\Big\rangle$$

expand Wilson lines, perform colour algebra, etc.

$$\frac{1}{N}\text{Tr}\langle W^\dagger(\mathbf{x}_\perp)W(\mathbf{y}_\perp)\rangle \simeq \exp\left\{-\frac{C_F}{2}\int dx_+ n(x_+)\sigma(\mathbf{y}_\perp - \mathbf{x}_\perp)\right\}$$

$$k_+\frac{dI}{dk_+ d^2\mathbf{k}_\perp} = \frac{\alpha_S C_R}{(2\pi)^2 k_+}2\text{Re}\int_{x_{0+}}^{L_+} dx_+ \int d^2\mathbf{x}\; e^{-i\mathbf{k}_\perp\cdot\mathbf{x}} \times$$

$$\times\left[\frac{1}{k_+}\int_{x_+}^{L_+} d\bar{x}_+\; e^{-\frac{1}{2}\int_{x_+}^{L_+} d\xi n(\xi)\sigma(\mathbf{x})}\frac{\partial}{\partial\mathbf{y}}\cdot\frac{\partial}{\partial\mathbf{x}}\mathcal{K}(\mathbf{y}=0,x_+;\mathbf{x},\bar{x}_+) - \right.$$

$$\left. -2\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\cdot\frac{\partial}{\partial\mathbf{y}}\mathcal{K}(\mathbf{y}=0,x_+;\mathbf{x},L_+)\right] + \frac{\alpha_S C_R}{\pi^2}\frac{1}{\mathbf{k}_\perp^2}$$

$$\mathcal{K}\left(\mathbf{r}(x_+),x_+;\mathbf{r}(\bar{x}_+),\bar{x}_+\right) = \int \mathcal{D}\mathbf{r}\exp\left[\int_{x_+}^{\bar{x}_+} d\xi\left(i\frac{p_+}{2}\dot{\mathbf{r}}^2 - \frac{1}{2}n(\xi)\sigma(\mathbf{r})\right)\right]$$

numerics

↪ energy loss of leading parton → longitudinal softening

$$\hat{q}L^2$$
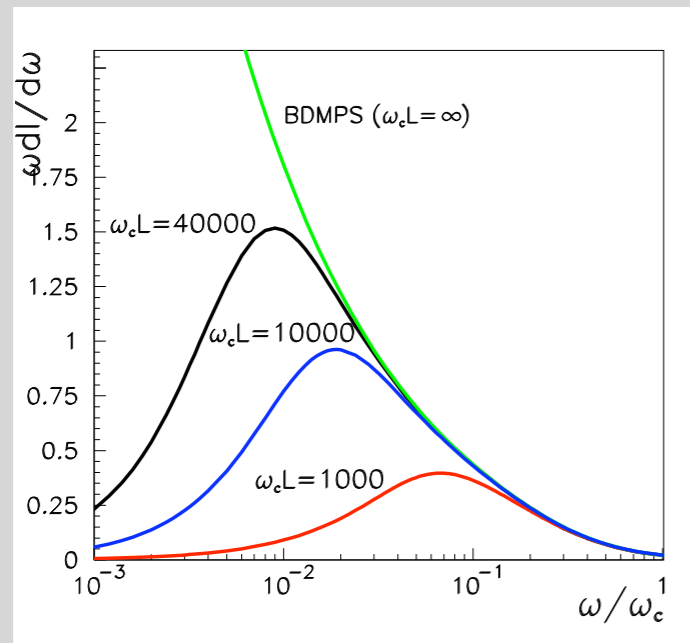
↪ k_t broadening
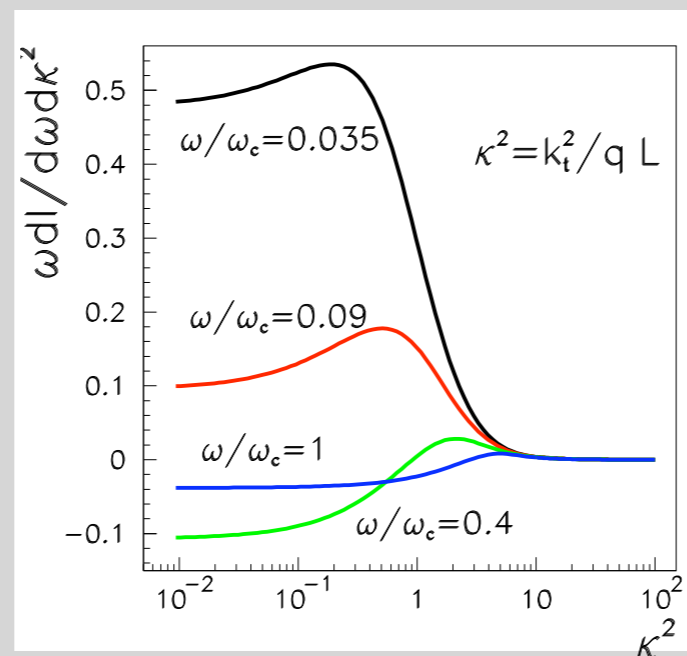
opacity expansions

- it is often useful to perform calculation in the opacity expansion [GLV]

  ↪ this is an expansion on [medium extent/elastic mean free path]

  ↪ in practical terms it corresponds to allowing for a finite total number of medium interactions

  ↪ N=1 opacity is then

(a)   (b)   (c)
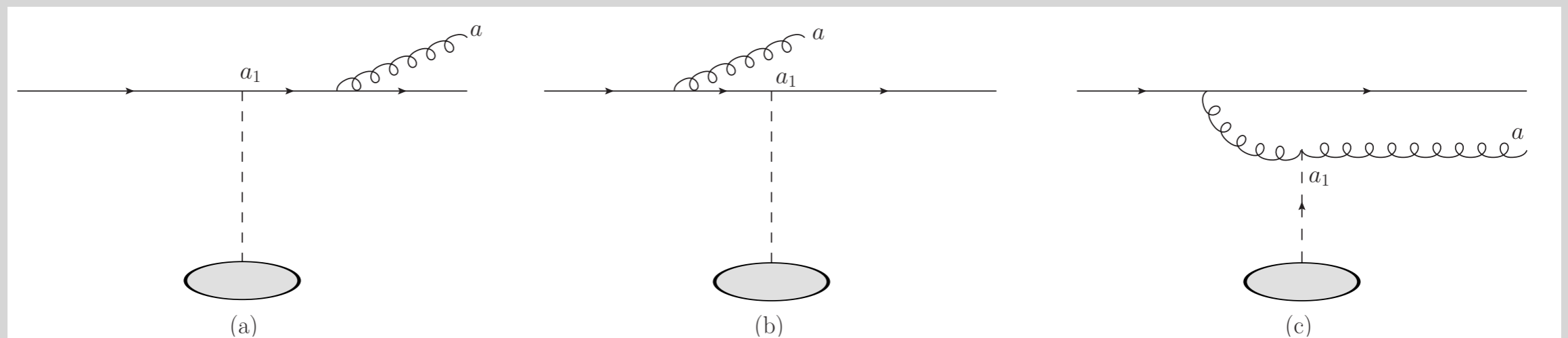
  ↪ much simpler framework

  ↪ captures essential features

a whole lot left to say…

Heavy-ion collisions
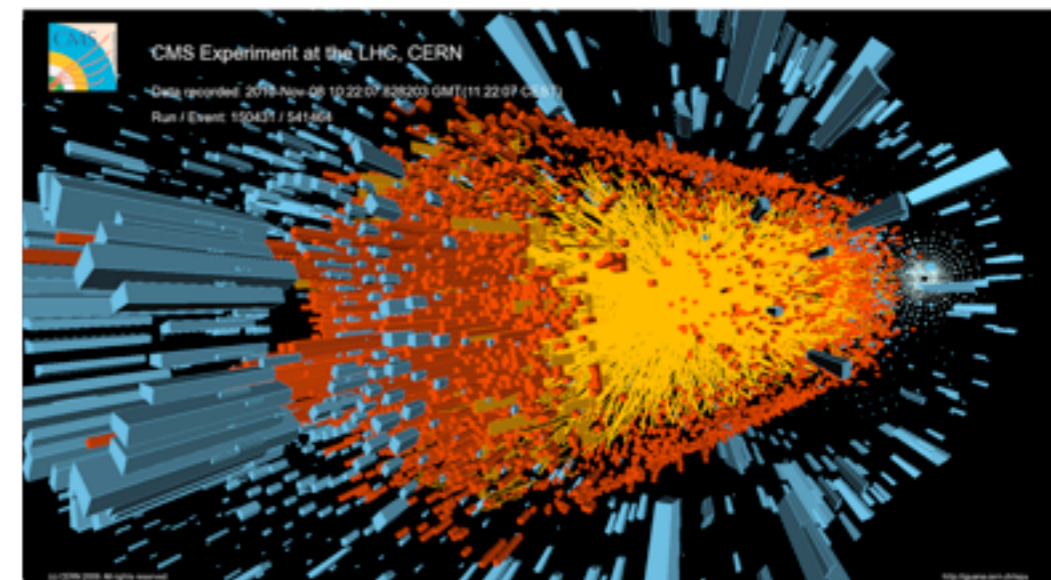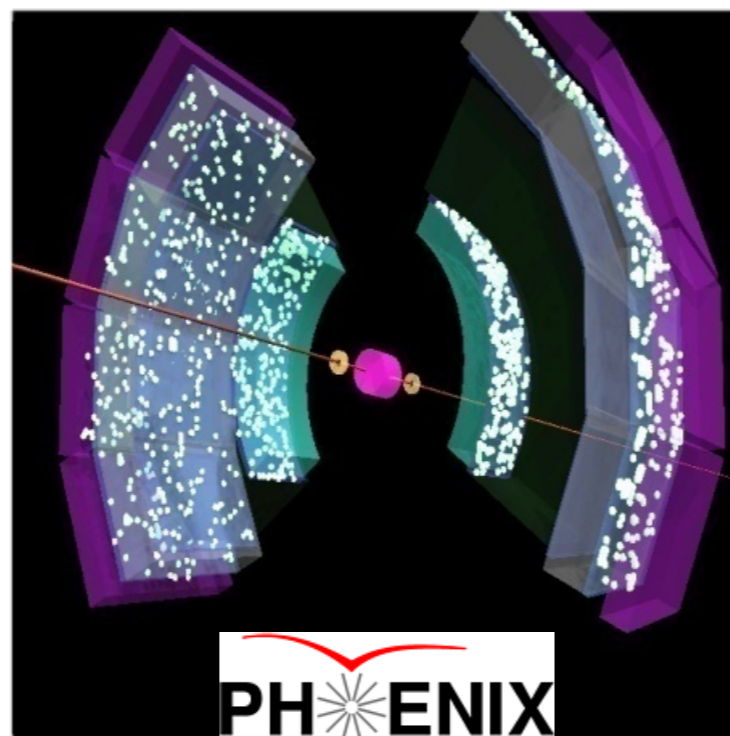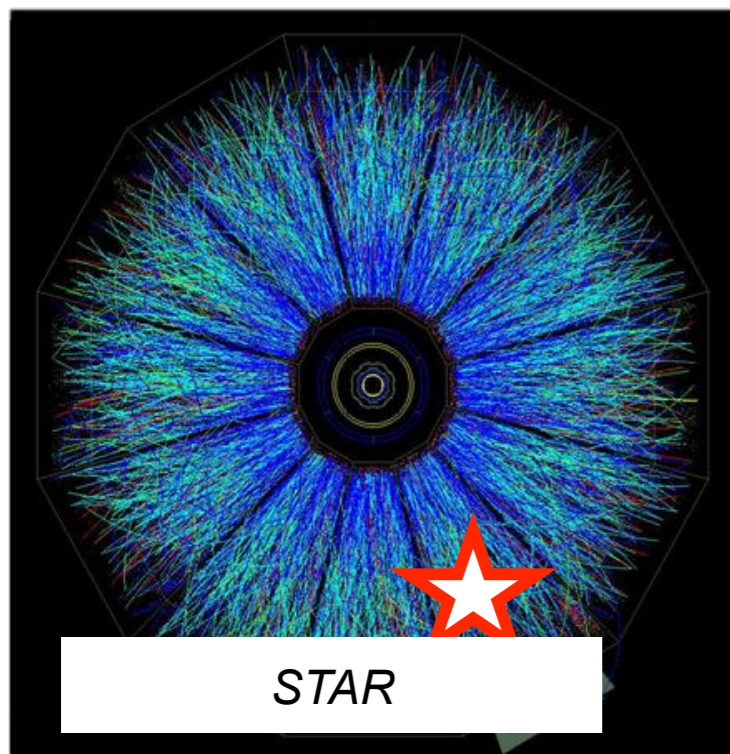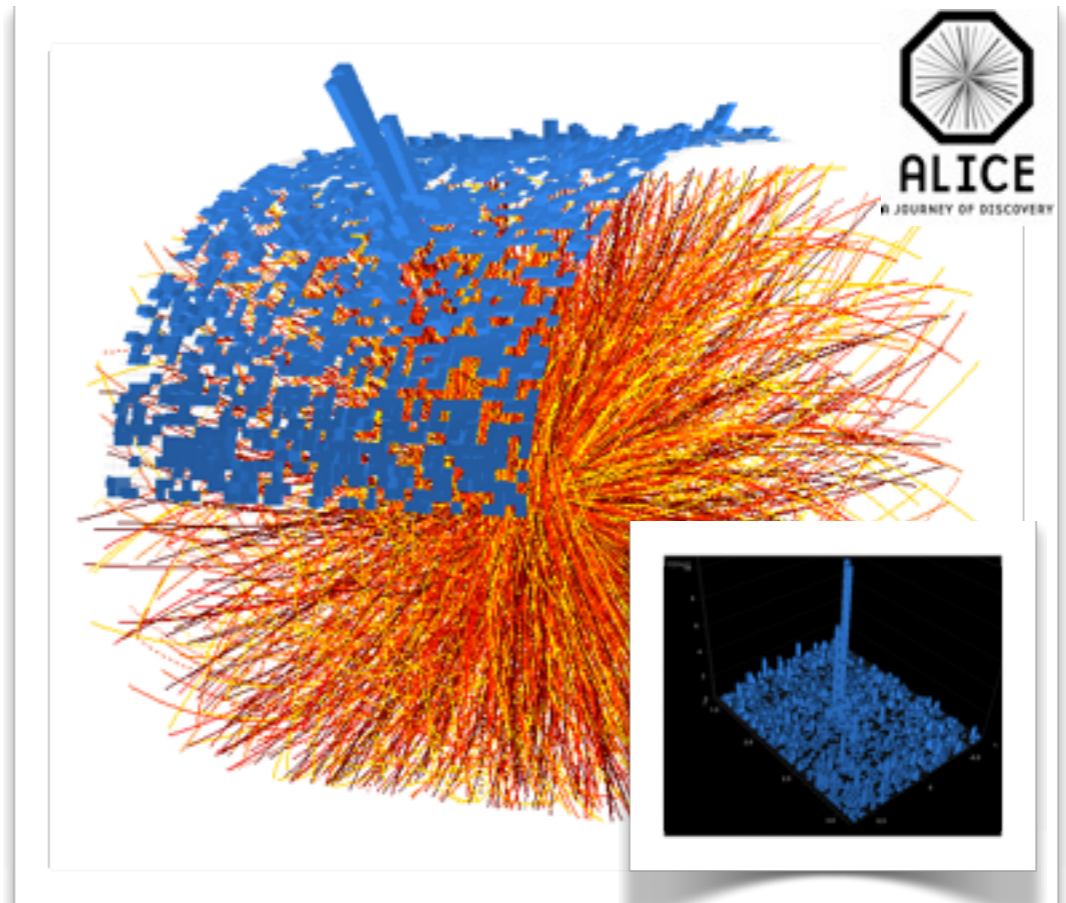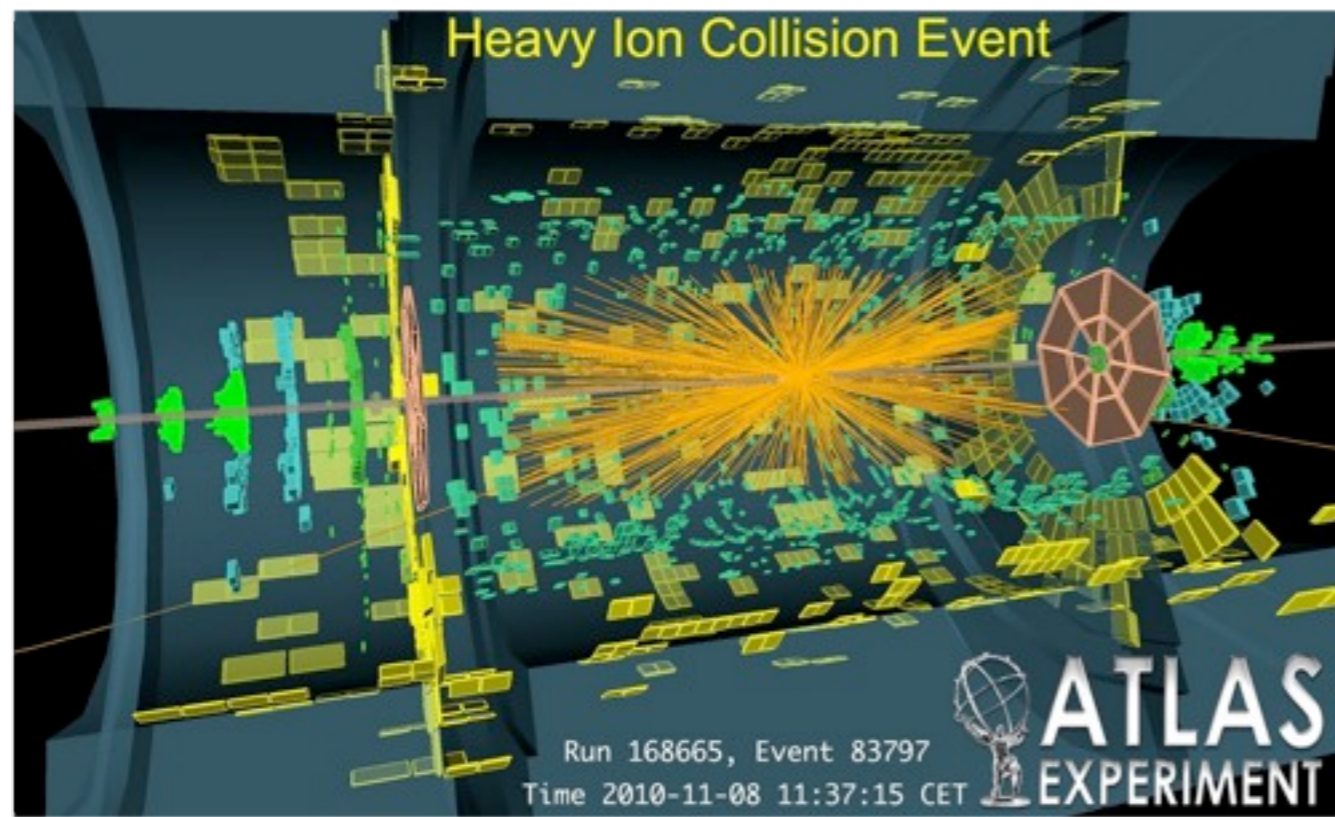
Energy density:
RHIC to LHC

LHC > 2.5 x RHIC

... within a volume (per nucleon)
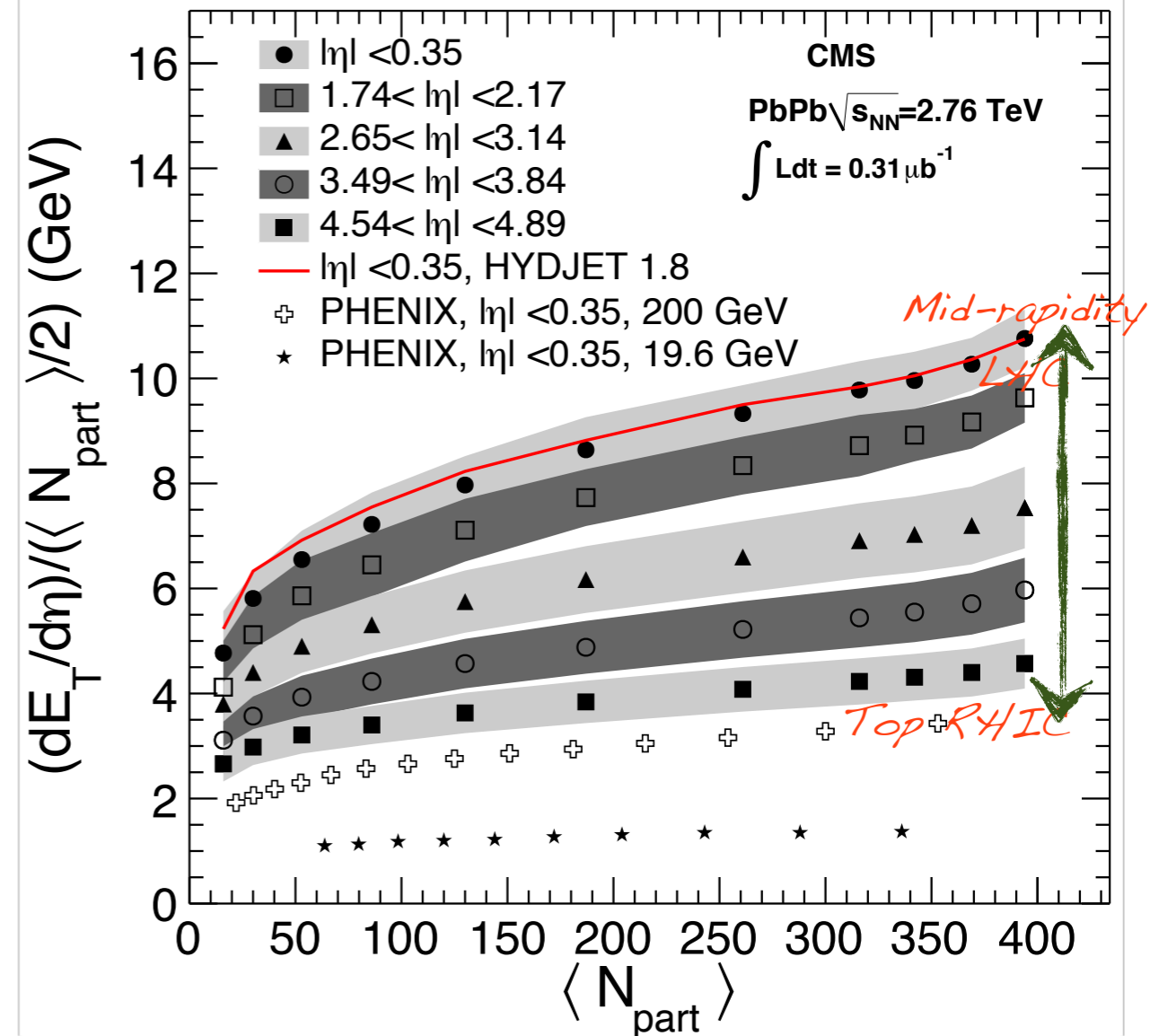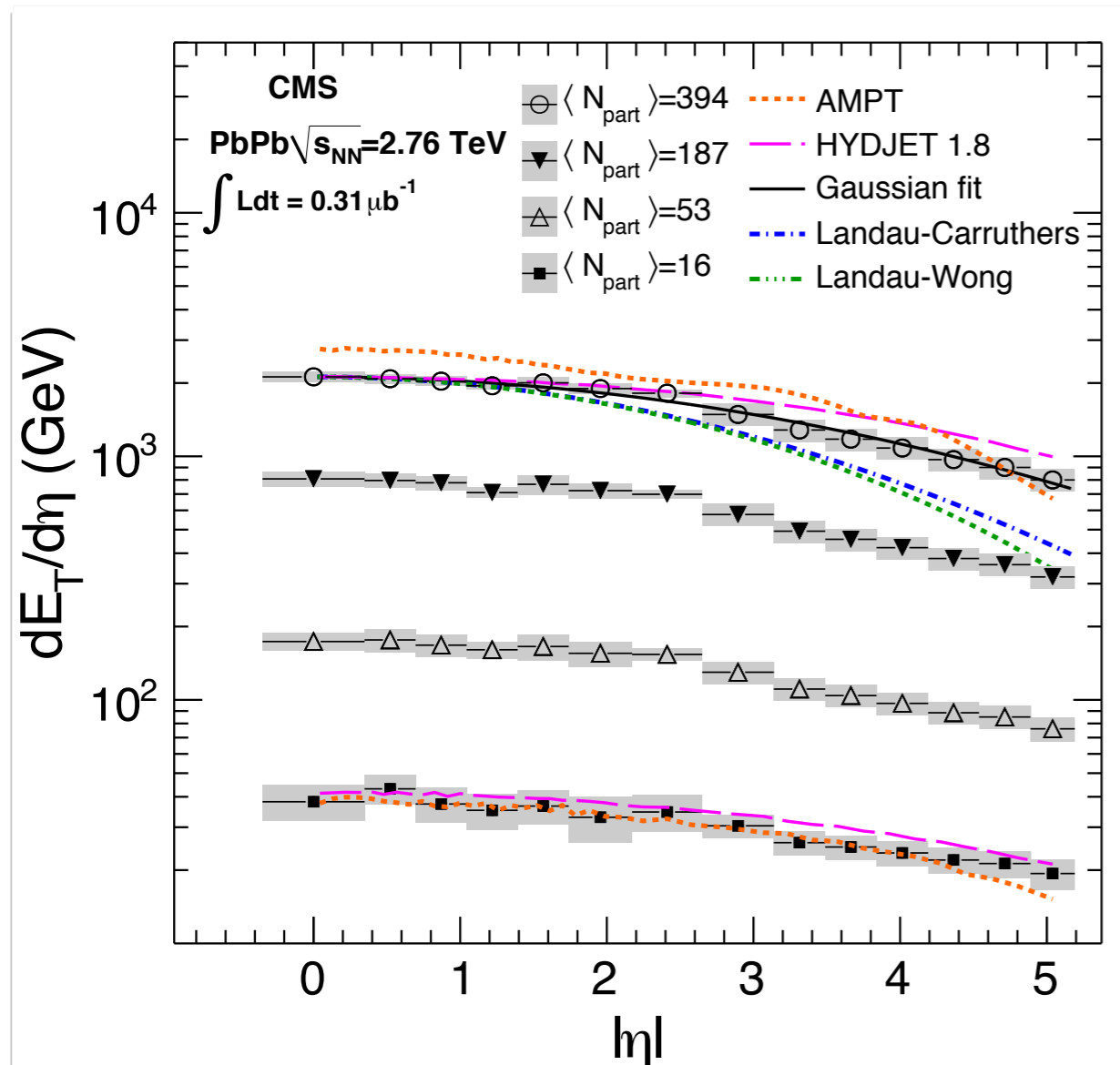
Hadron production in heavy-ion collisions

A slight digression...

RHIC vs LHC
(LHC: higher mean pT - more flow)
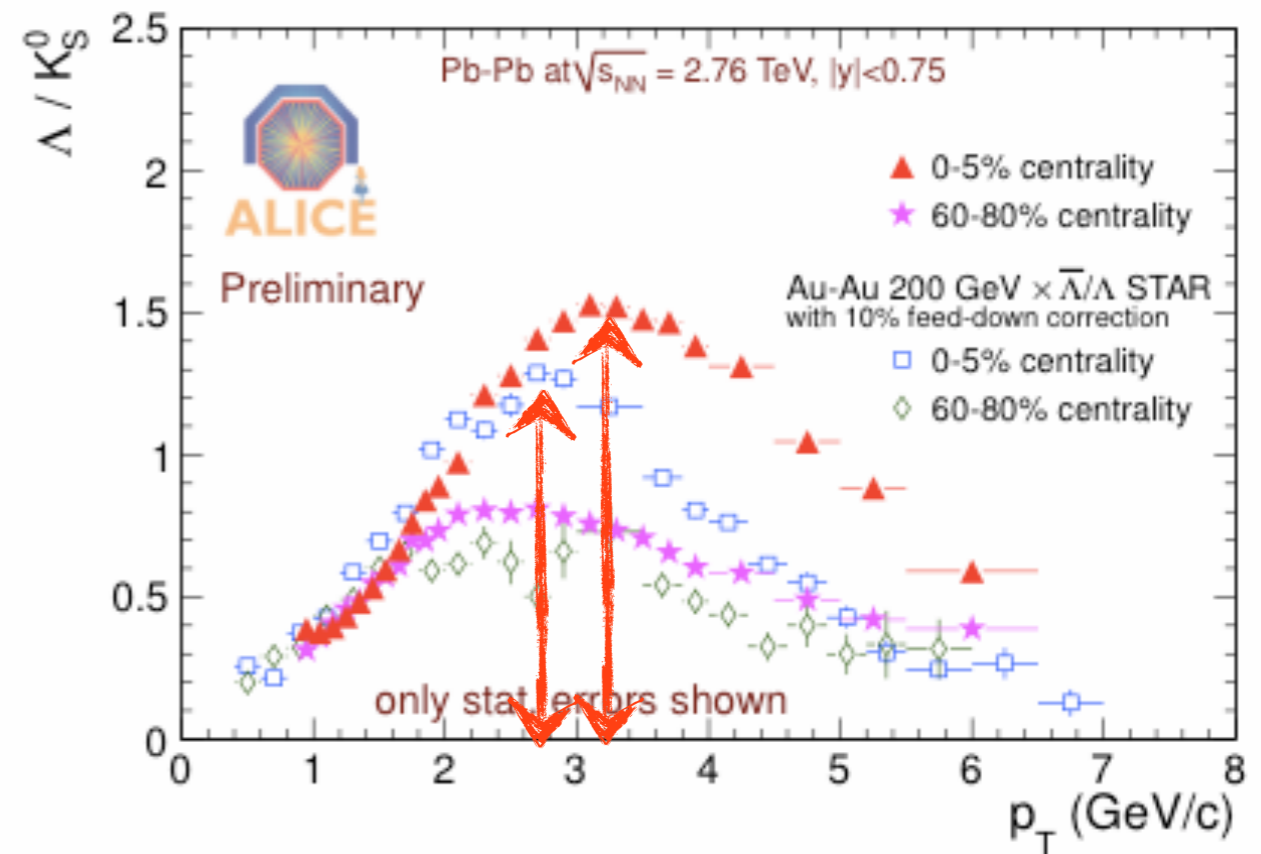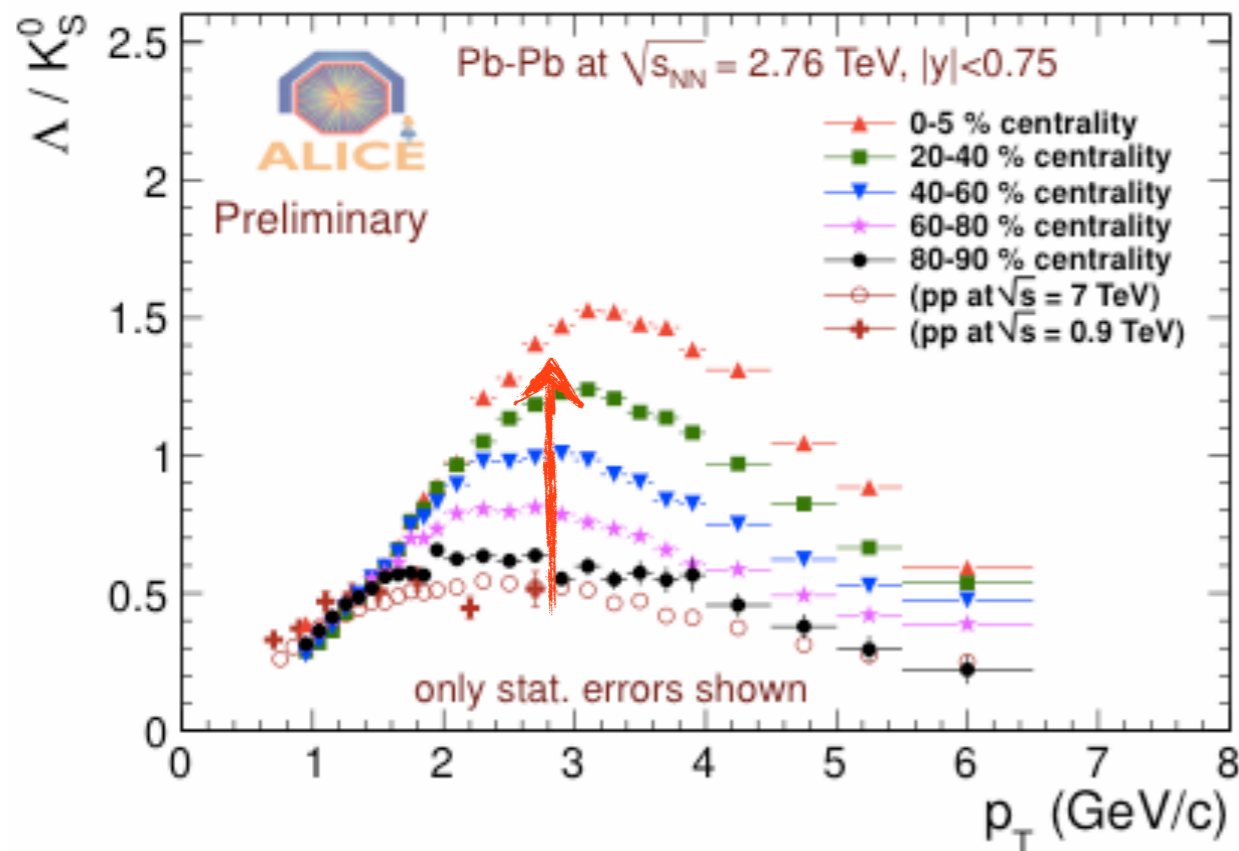
Much more baryons than mesons in central collisions as compared to proton-proton (coalescence/recombination? bulk+jet?)

LHC similar to RHIC
Maximum at slightly higher-pT

bulk, jets, medium and pᴛ:
arbitrary regions
and INFORMAL Language

bulk, jets, medium and p_T:
arbitrary regions
and INFORMAL Language

Λ / K_S^0

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, |y|<0.75

▲ 0-5% centrality
★ 60-80% centrality

Au-Au 200 GeV × $\overline{\Lambda}/\Lambda$ STAR
with 10% feed-down correction
□ 0-5% centrality
◇ 60-80% centrality

ALICE

Preliminary

only stat. errors shown

p_T (GeV/c)

"soft"
-bulk
thermal

<0.75
% centrality
40 % centrality
60 % centrality
80 % centrality
90 % centrality
at $\sqrt{s}$ = 7 TeV)
at $\sqrt{s}$ = 0.9 TeV)

p_T (GeV/c)

bulk, jets, medium and p_T:
arbitrary regions
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at √s = 7 TeV)
at √s = 0.9 TeV)

p_T (GeV/c)

bulk, jets, medium and p_T: arbitrary regions and INFORMAL Language

"soft" -bulk thermal

"soft+hard" jet-medium "intermediate"

hard jet dominated
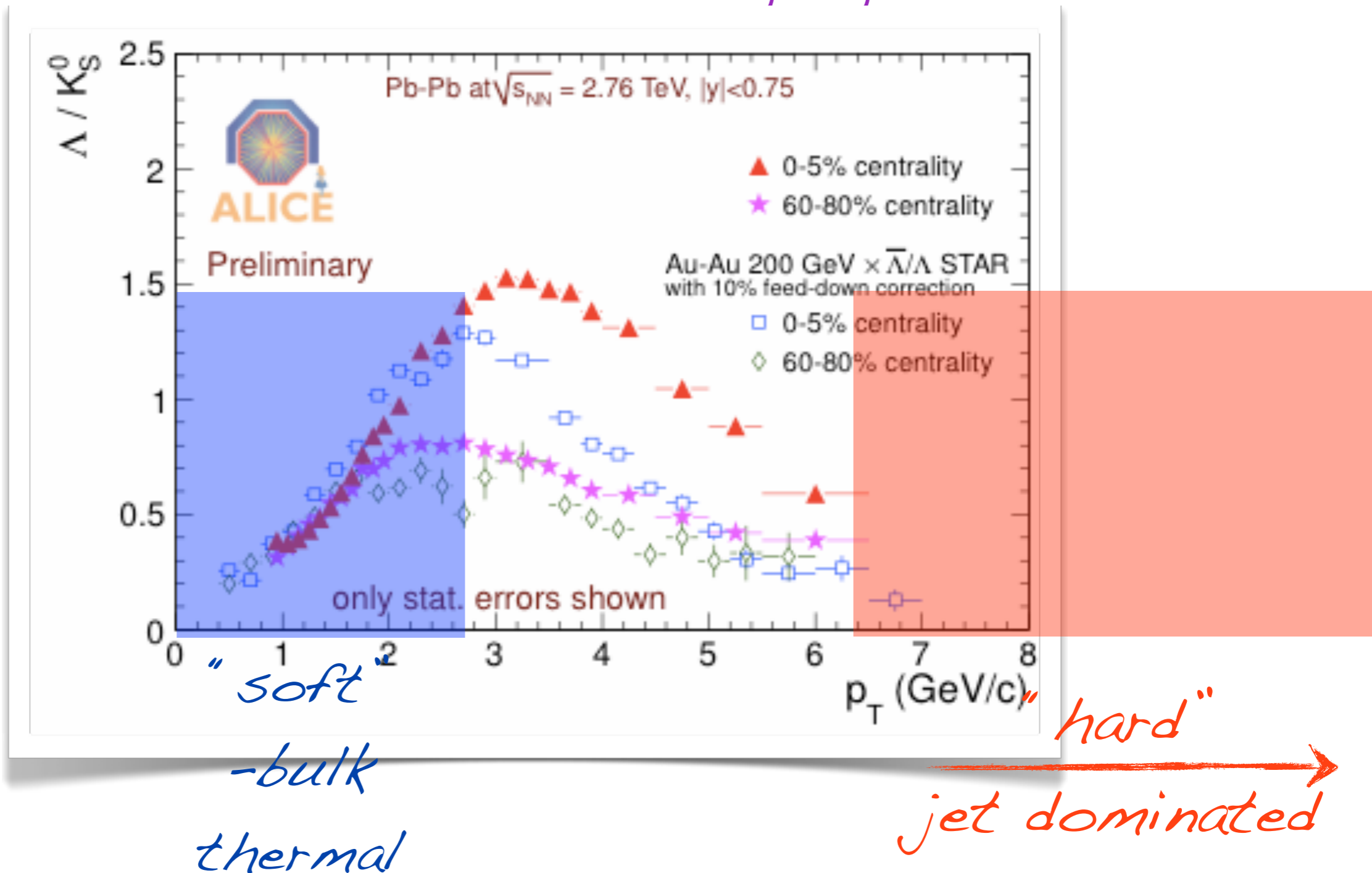
Hadronization of bulk+hard
– parton coalescence

Fries, Muller et al
Hwa, Yang et al

fragmenting parton:
$p_h = z\,p,\ z < 1$

recombining partons:
$p_1 + p_2 = p_h$

PHENIX proton/π ratio

- proton/π^+
- proton/π^0
- Duke
- Oregon
- TAMU w/ shower
- TAMU no shower

R. Belmont, QM09
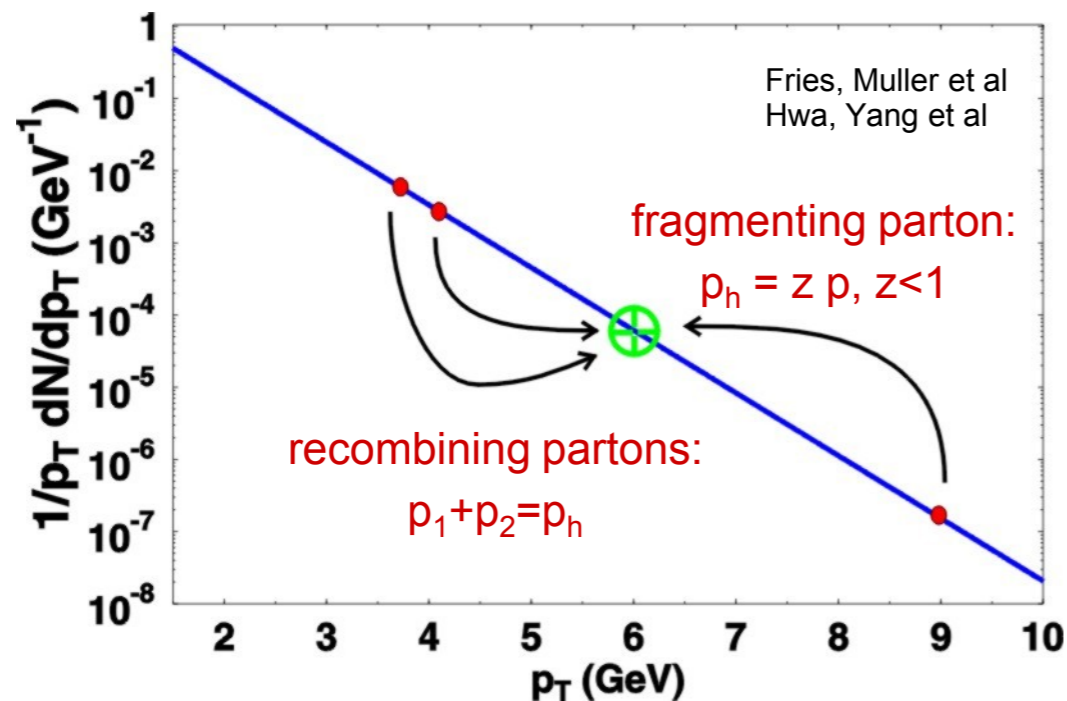
Recombination of
thermal ('bulk') partons
produces baryons at larger p_T
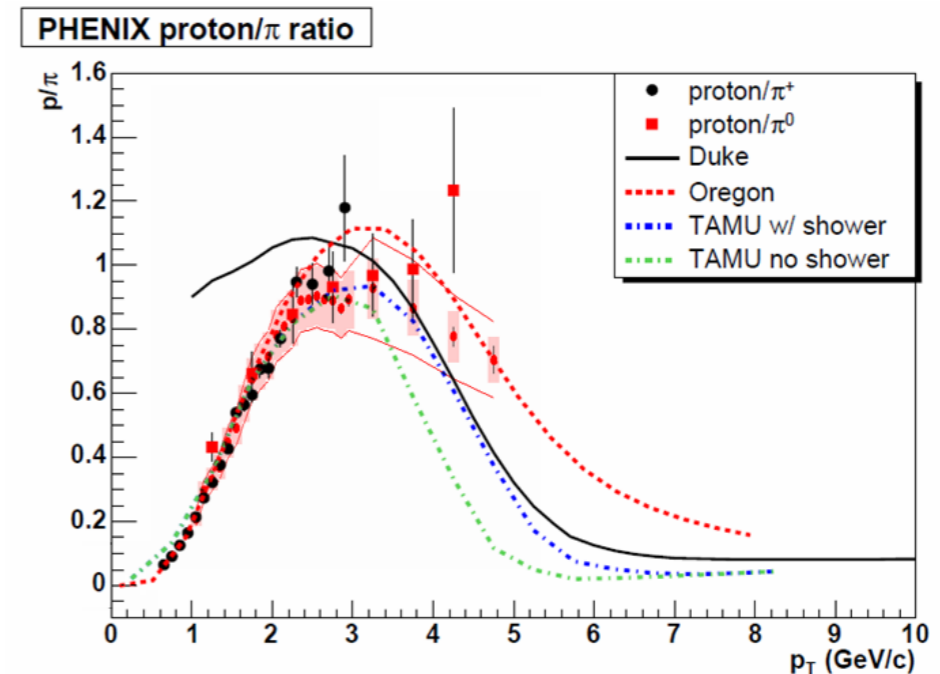
Recombination enhances
baryon/meson ratio

Note also: v_2 scaling

Meson
$p_T = 2\,p_{T,parton}$

Baryon
$p_T = 3\,p_{T,parton}$

Hot matter

The probes

q: fast color triplet

g: fast color octet

Induced gluon radiation ?

Q: slow color triplet

Energy Loss ?

QQbar: slow color singlet/octet

Dissociation ?

Virtual photon: colorless

Real photon: colorless

Controls

Unknown Medium
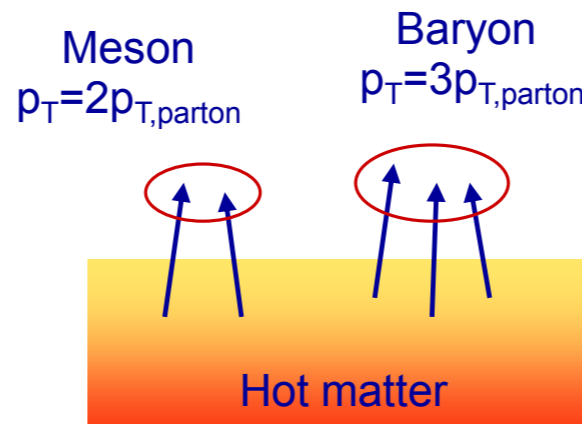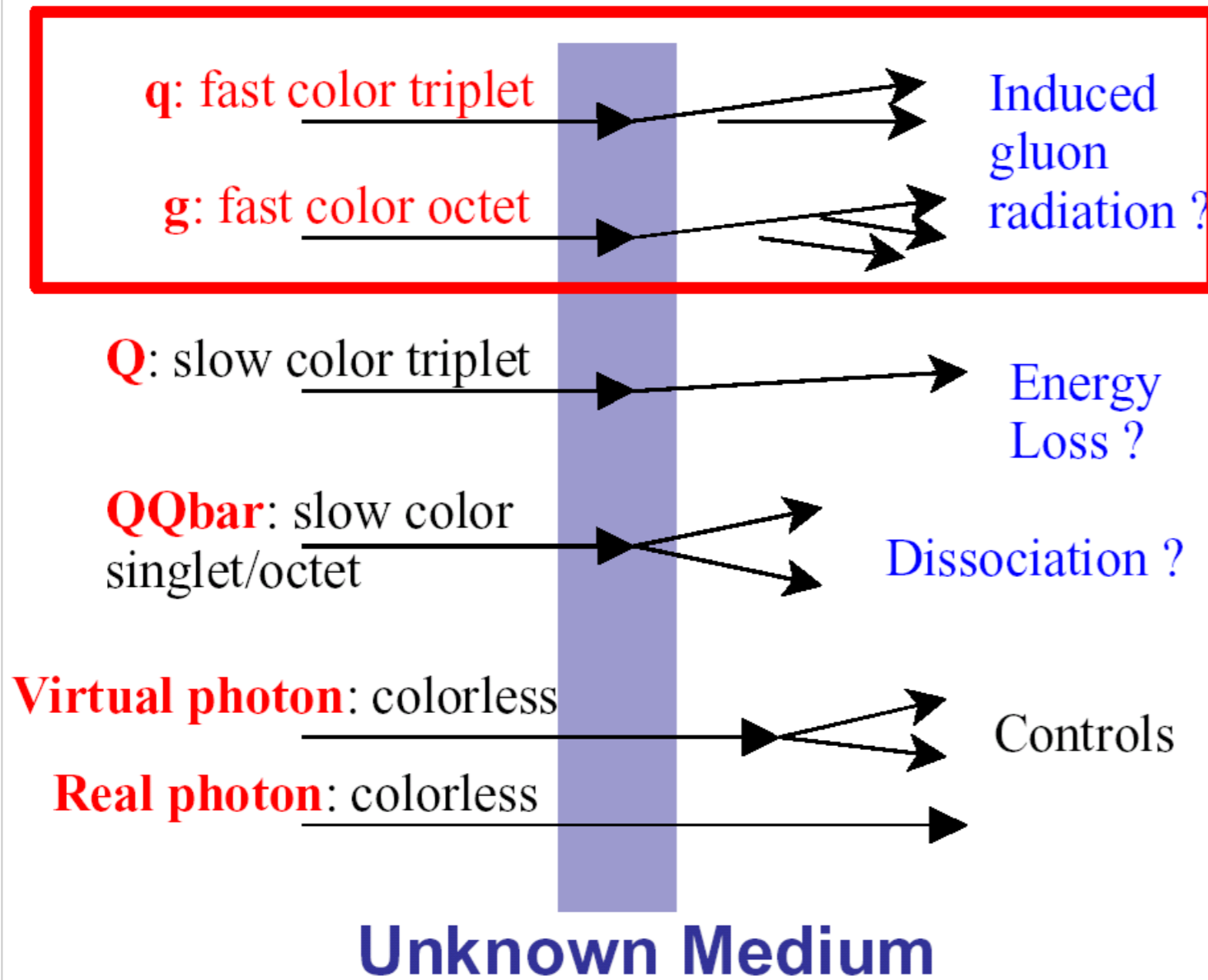
jet suppression (quenching)

charm/bottom dynamics

J/ψ & Υ

color-less particles

Jets in heavy-ion collisions
RHIC & LHC

STAR: Au+Au at 0.2 TeV

~220 GeV   ~220 GeV

CMS: Pb+Pb at 2.76 TeV
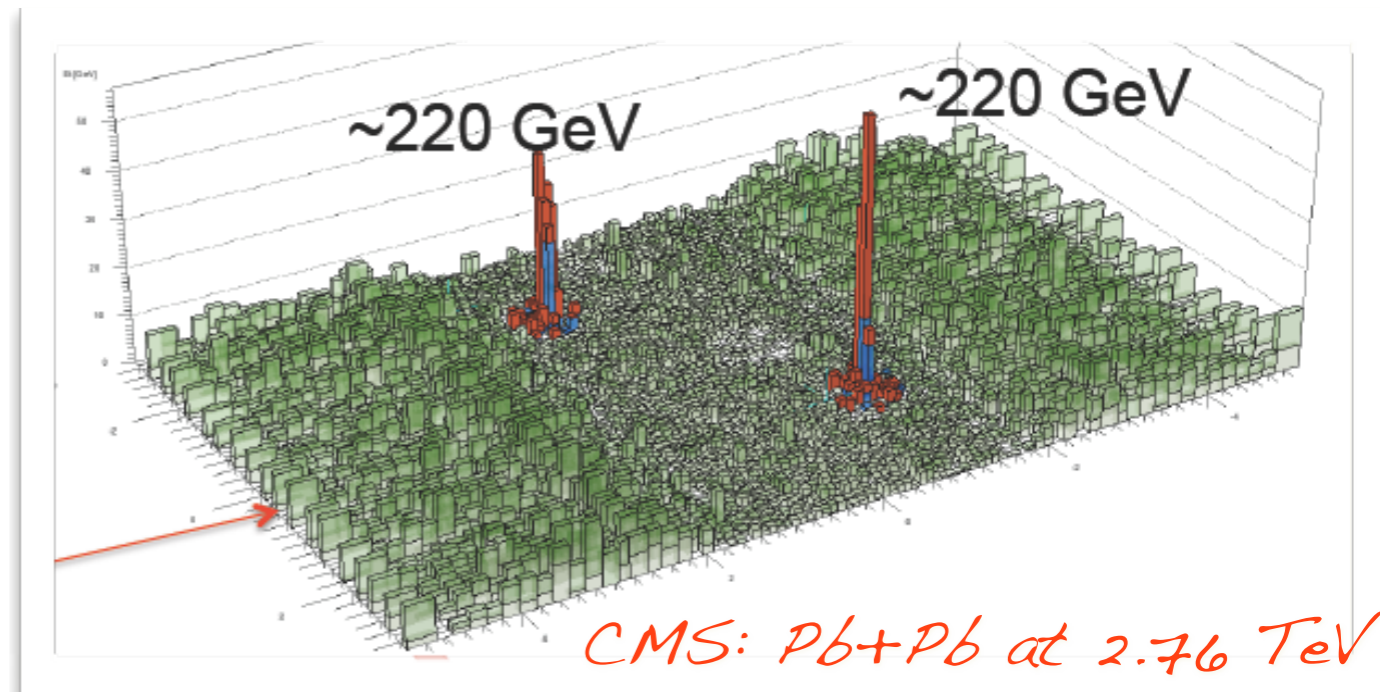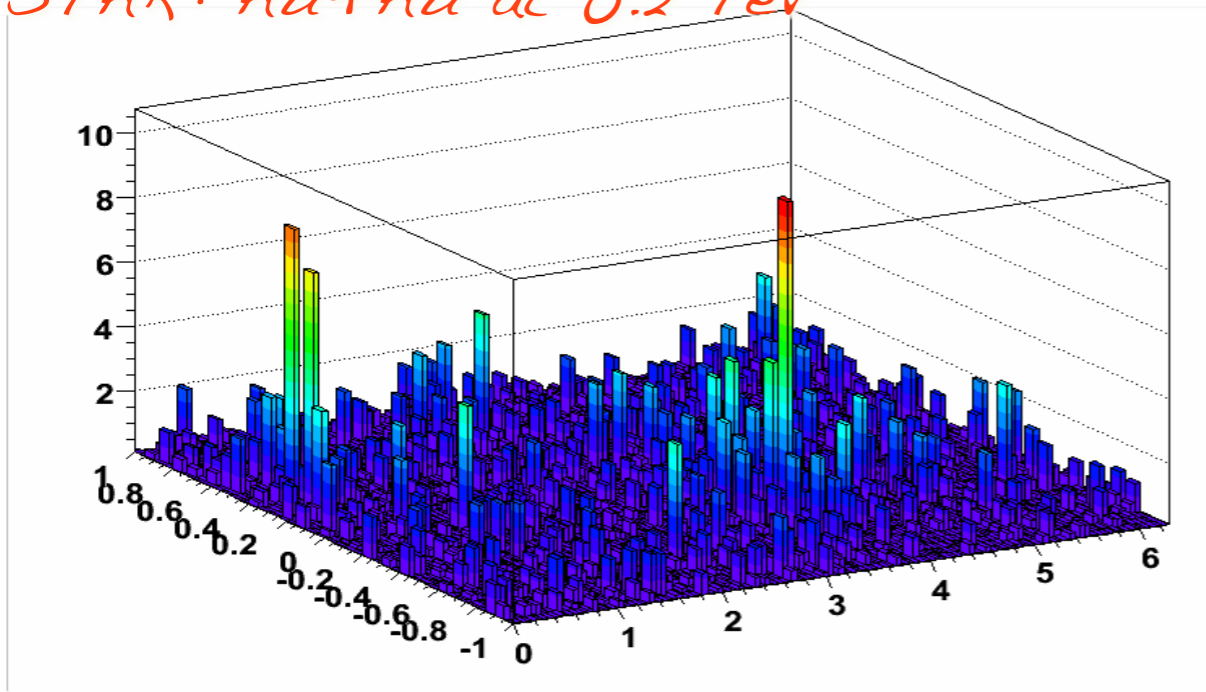
LHC + RHIC: QCD evolution of jet quenching ?

Vary energy of the jet:

LHC: Vary the scale with which QGP is probed (a la DIS)

Compare and contrast RHIC and LHC

Jets in heavy-ion collisions RHIC & LHC

Jets in heavy-ion environment – few experimental notes:

- large combinatorial backgrounds (especially at RHIC)

- energy within an event varies from point to point ("fluctuations")

- a plus for LHC is larger kinematic reach – abundance of high-energy jets (higher-p_T measurements less affected by backgrounds)

=> various approaches among experiments for background suppression AND/OR jet energy-resolution corrections

- is there an optimal jet definition for heavy-ion collisions (?)

=> use multiple jet algorithms (?); sub-jets (?); filtering (?)

- jets are reported on the particle (generator) level – hadronization corrections (to the "parton" jet) in HI collisions impossible

Jets in heavy-ion collisions RHIC & LHC

LHC

RHIC

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"Easier" (than full jet reconstruction) exercise: Jet-quenching via leading hadrons

Inclusive hadron production

Measured as a function of collision centrality

Loss of measured yield in central A-A

Di-hadron correlations

Rates of recoil ("away-side") hadrons suppressed
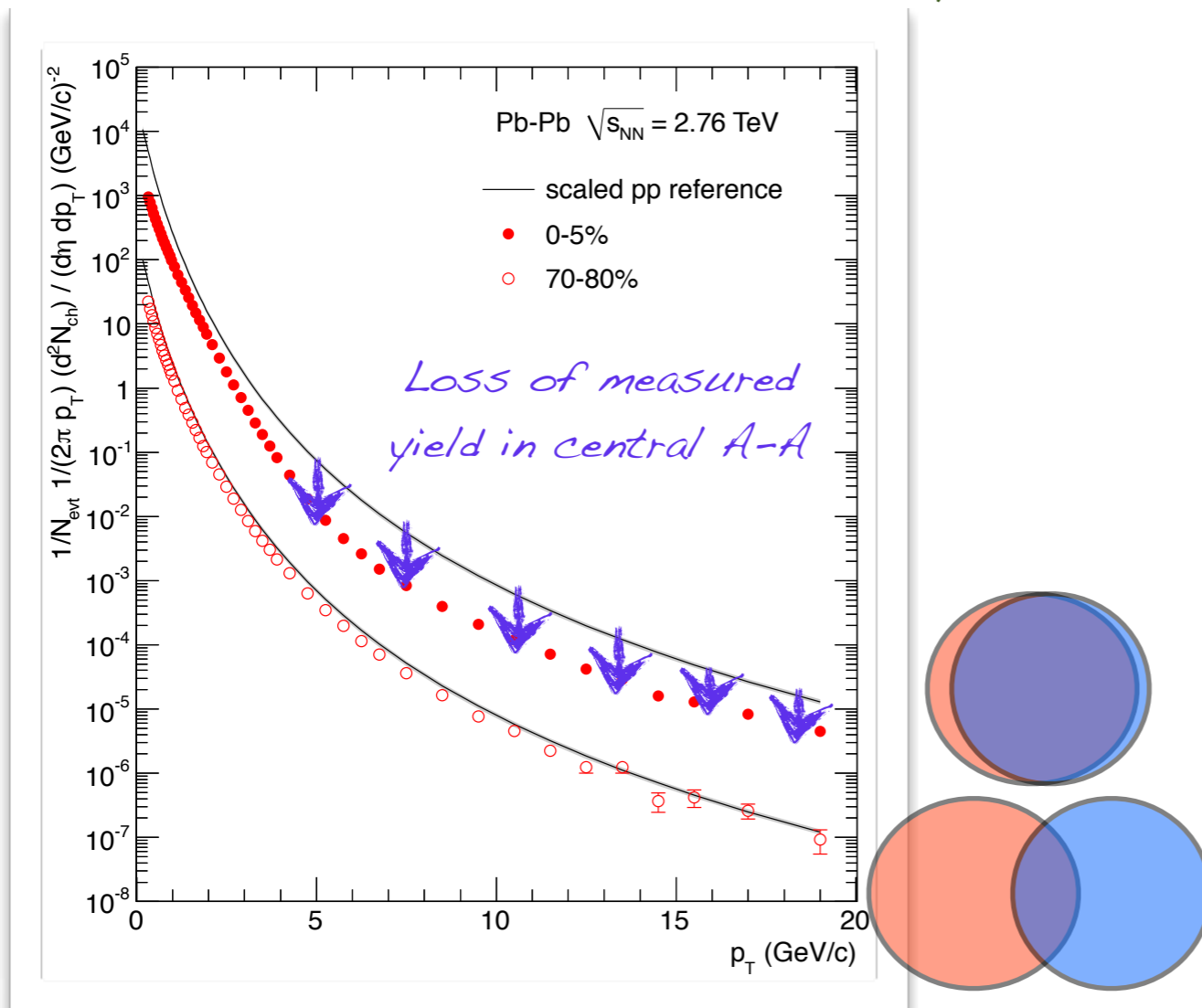
Note on correlations: interesting tool to study the "intermediate"-p_T region – jets vs flow and recombination
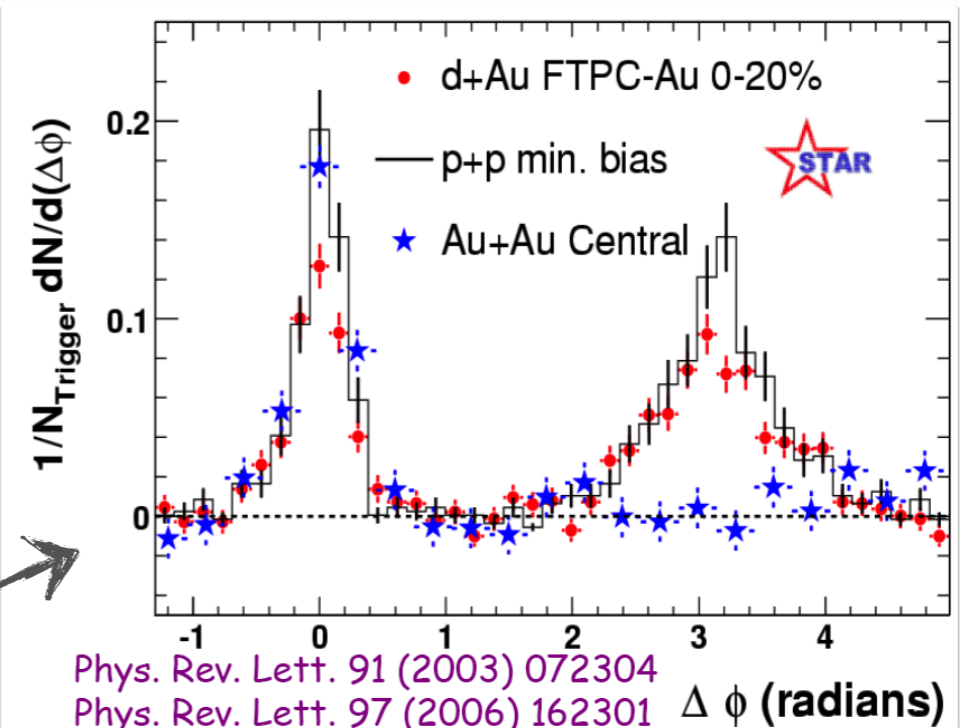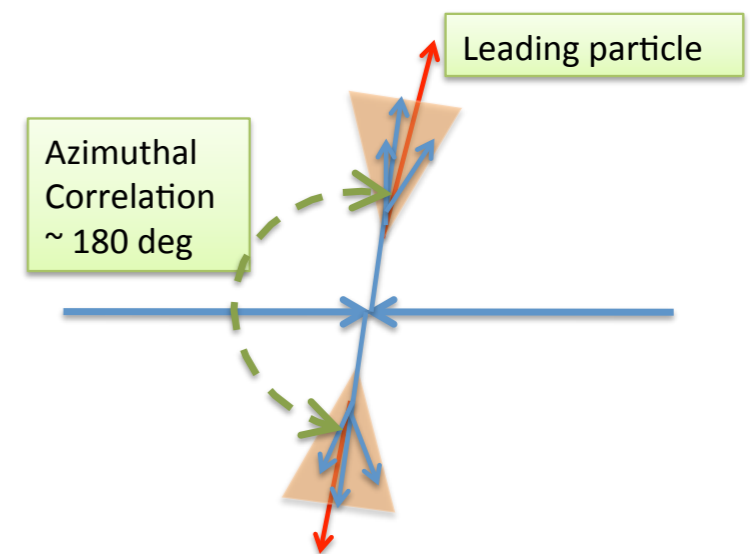
Hadron suppression

Nuclear modification factor:

$$R_{AA} = \frac{\#(particles\ observed\ in\ AA\ collision\ per\ N\text{-}N\ (binary)\ collision)}{\#(particles\ observed\ per\ p\text{-}p\ collision)}$$
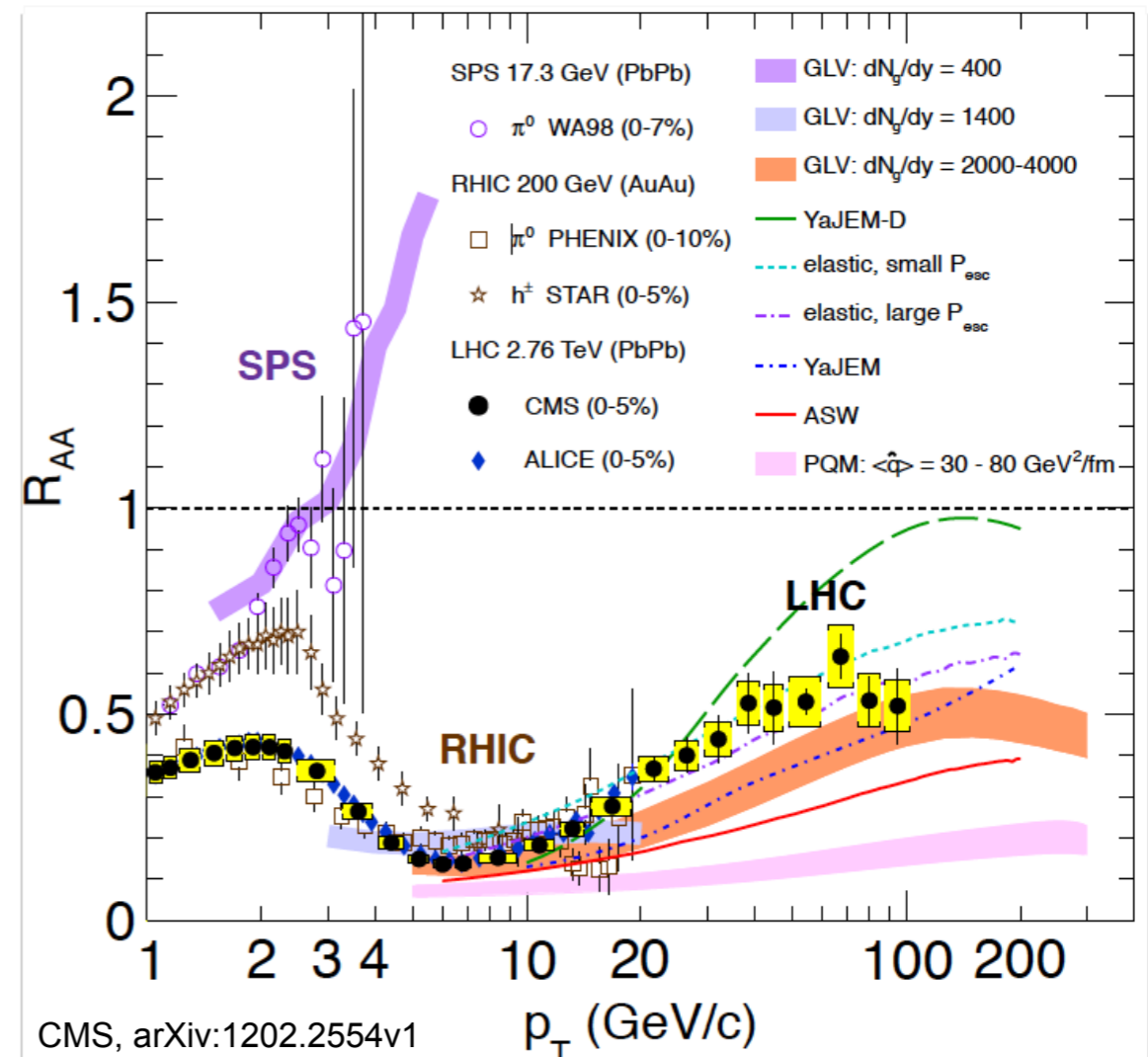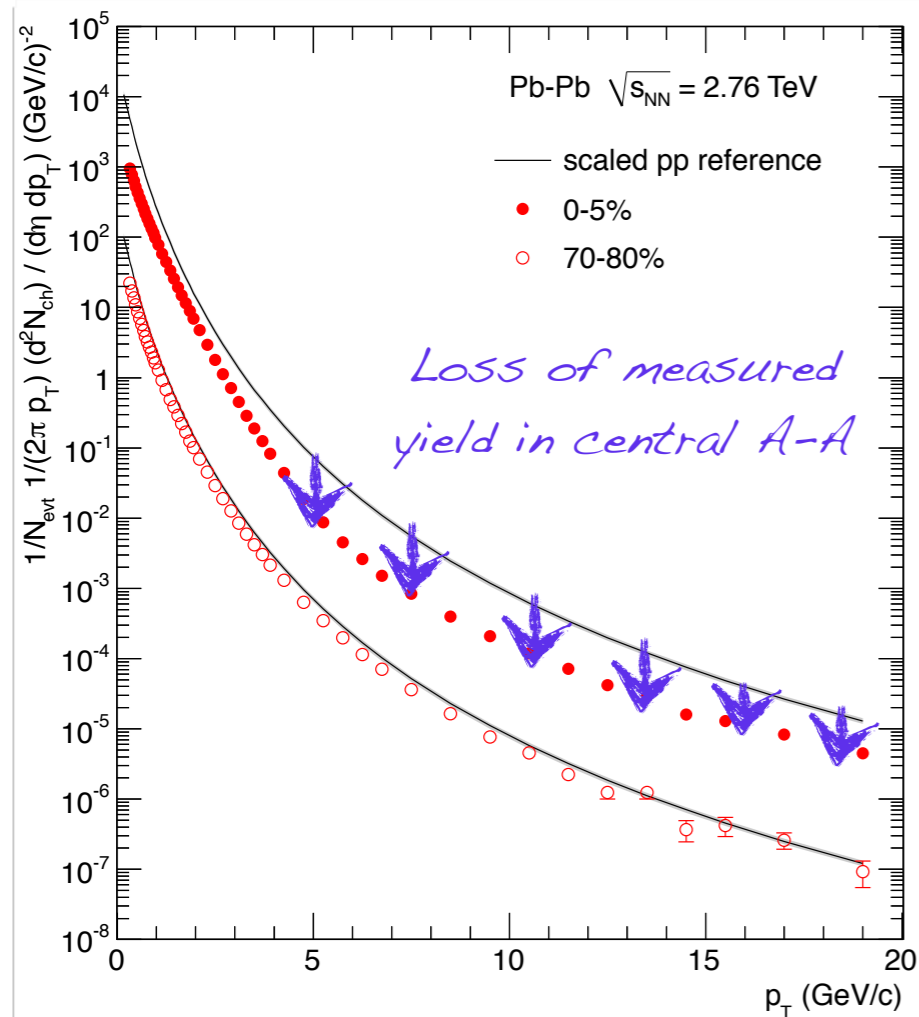
"No effect" case is for $R_{AA} = 1$ at high pT where hard processes dominate

R_{AA} for different particle type

Is parton energy loss different for gluons, light-quarks and heavy-quarks?

Expectation: $\Delta E_g > \Delta E_{light-q} > \Delta E_{heavy-q}$

Casimir (color factor)
- gluons "glue" better to the medium than quarks

"Dead-cone" effect: mass of the parent quark

=> radiation for angles $\theta < m/E$

is suppressed

=> $R_{AA}^{pions} < R_{AA}^{D-mesons} < R_{AA}^{B-mesons}$

RAA for different particle type

Discussion based on LHC results
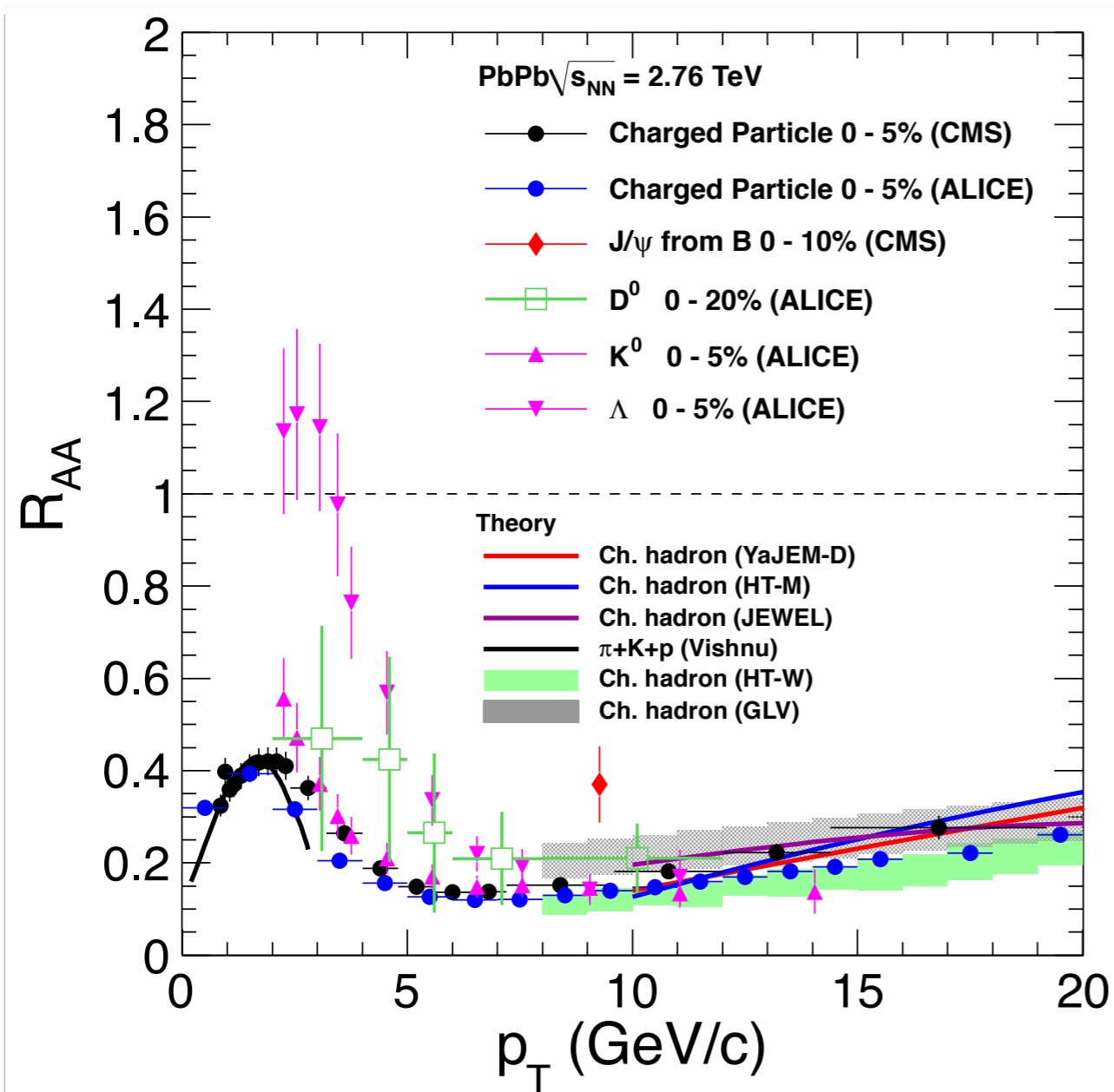
Similar suppression for heavier-q (strange, charm) and gluons (large elastic e-loss; less dep. on mass?; color factor? - small effect?)

J/ψ from B-decays - dead cone effect?

Lambda vs K0 RAA below 7 GeV - manifestation of flow (?)

Rise towards higher pT's:
1) Harder partonic spectrum (as compared to RHIC)
2) Weak dependence of [pQCD] e-loss on parton energy

Not shown but measured:
Photons and Z's not suppressed -> quenching is a final state effect

So, why bother with full jet reconstruction in heavy-ion collisions?

R_{AA} and correlations of leading hadrons provide constraints on density of the medium (qhat), however do not tell us about the *parton* energy loss and its dynamics; leading hadrons are biased towards jets that interact little or not at all with the medium

30 GeV/c pi0 Trigger

qPythia MODEL!

$Et^{\pi} > 30 GeV$
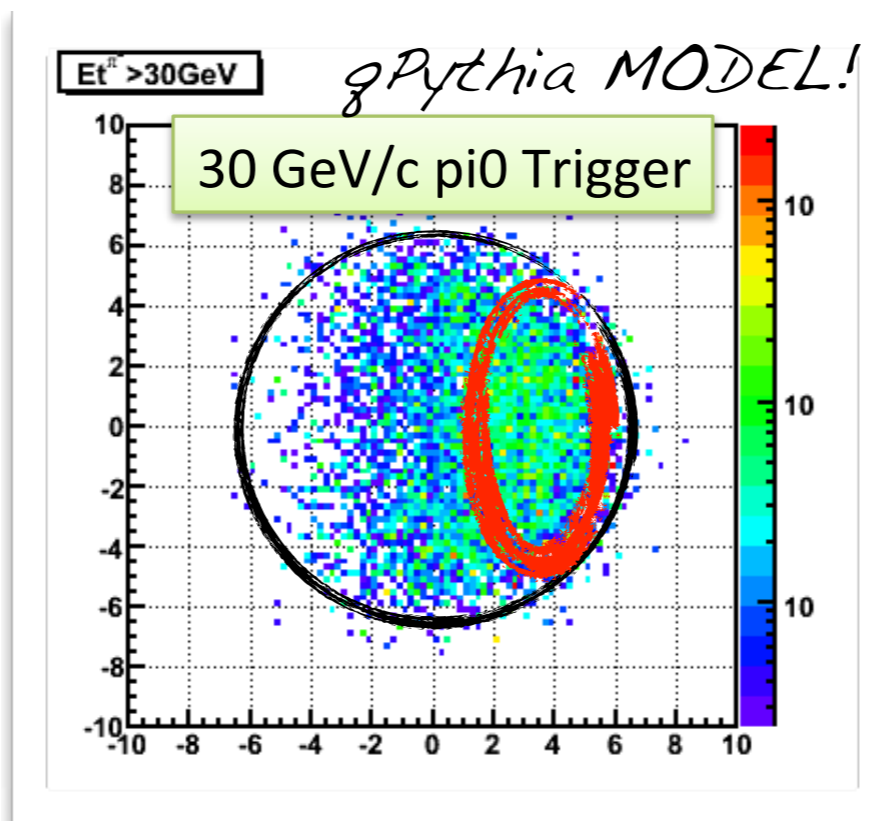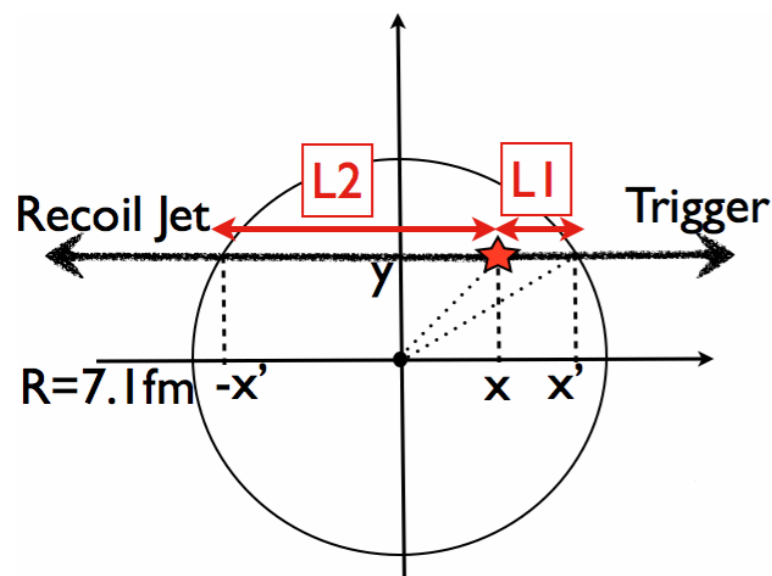
So called **surface bias**: requesting a high-pT particle selects a population of jets close to surface of the medium - these jets interact only little (or not at all) with the medium

=> full jet reconstruction premise: integrate over the hadronic degrees of freedom; better access to the parton energy scale; dynamics of the jet quenching (?); other promising observables: gamma-jet correlations

HI jet finding:
dealing with the background energy

50GeV jets + minbias + ghosts
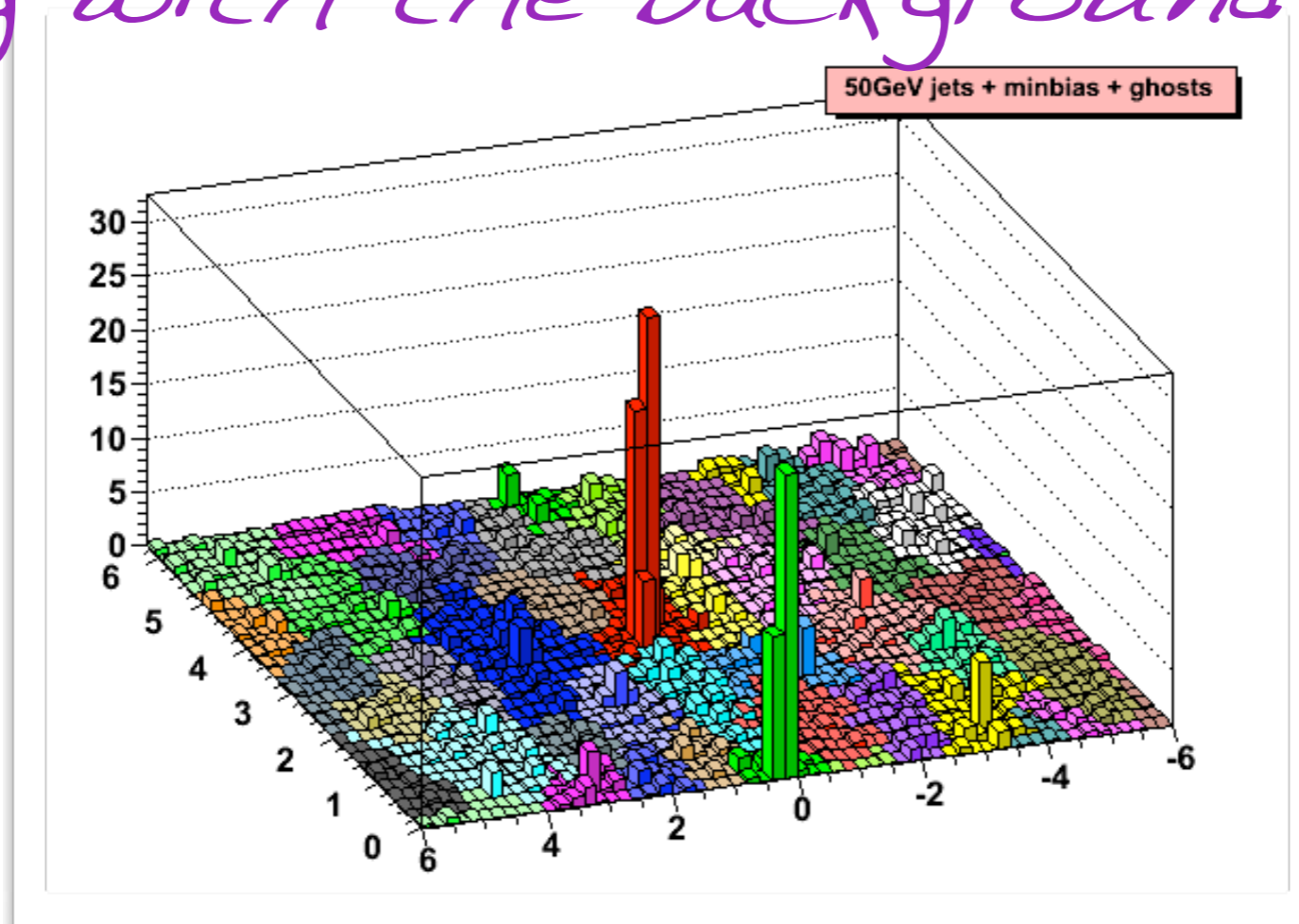
A single event: all particles clustered ("assigned") to a jet
Many of these objects are simply background
Energy of the signal jets overestimated due to background energy
=> several possibilities to subtract the average background and/or
suppress the background particles [and background jets]

HI jet finding: treatment of the background

$$\rho = median\left(\frac{p_T^{jet,i}}{A_i^{jet}}\right)$$

Method 1

FastJet k_t (p_t^{min} = 0.15 GeV/c)
Fit: (-3.3±0.3) GeV/c + (0.0623±0.0002) GeV/c × N_{input}^{raw}

Pb-Pb $\sqrt{s}$ = 2.76 TeV

50GeV jets + minbias + ghosts
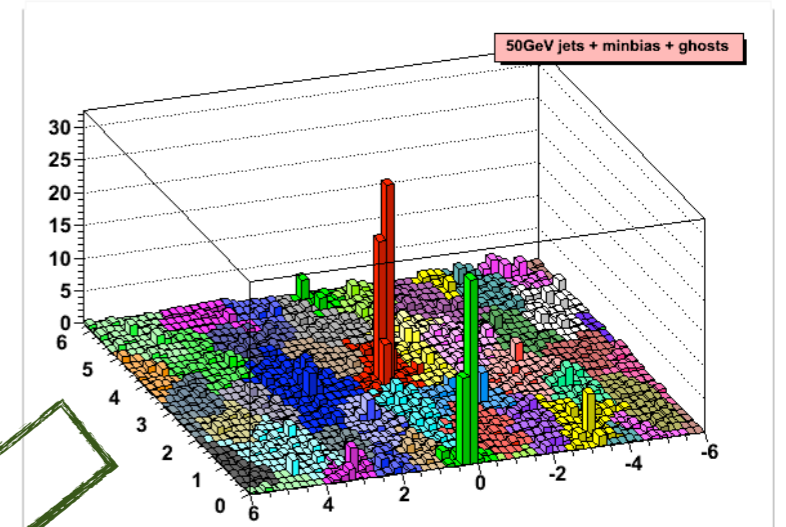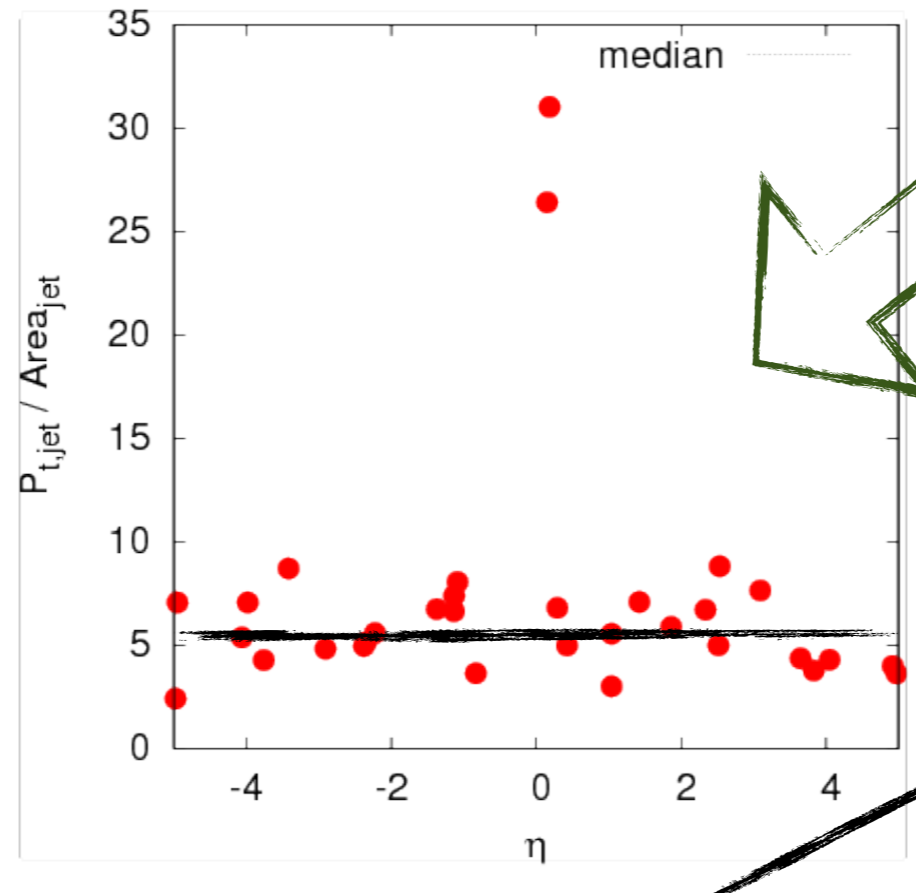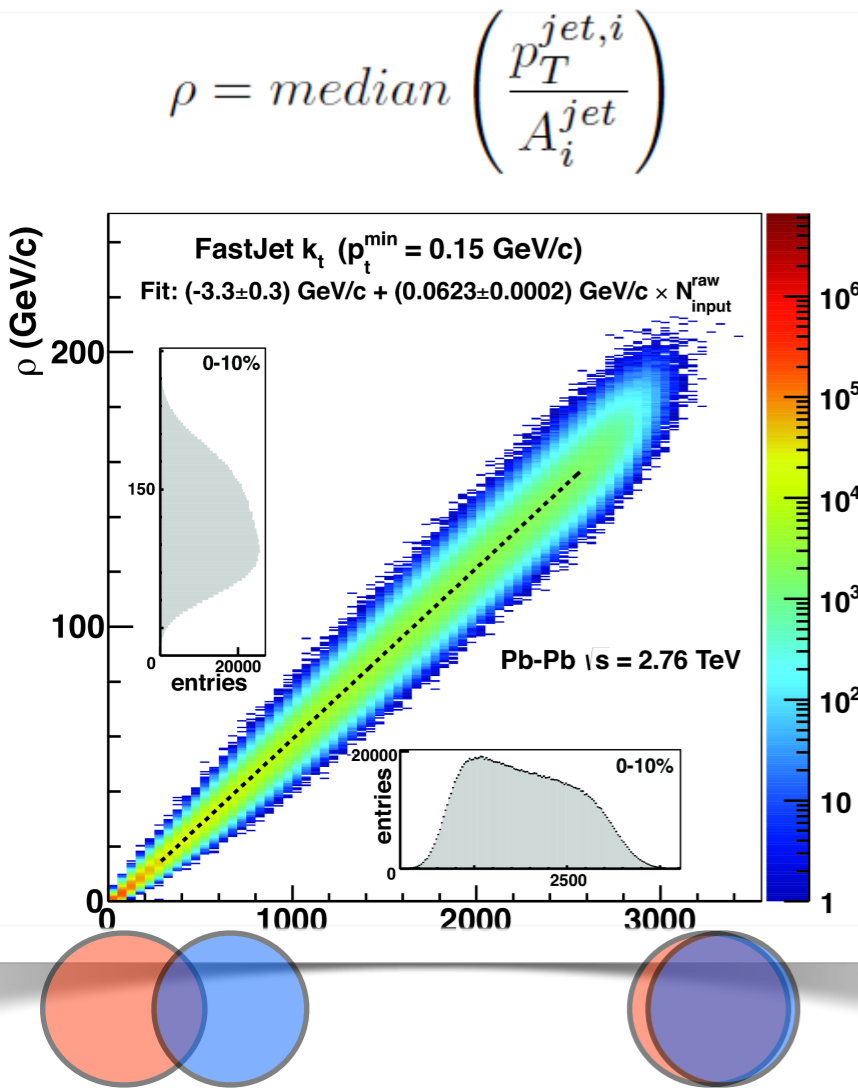
average background energy density

$$p_T = p_T^{raw} - \rho \times Area_{jet}$$

Must correct for remaining residual energy resolution
- magnitude of the correction is related to the background fluctuations
- jet Area : small R (area) - smaller correction

Jet reconstruction in HI collisions:
Background fluctuations: characterized
by δp_T; spectrum before corrections

LHC2010 Pb-Pb $\sqrt{s}$=2.76 TeV

0-10% centrality
RC Pb+Pb anti-k_t

▲ R=0.2 σ=4.47
▼ R=0.3 σ=7.15
● R=0.4 σ=10.18

$p_T^{track} > 0.15$ GeV/c

ALICE PERFORMANCE
15/03/2012

probability density

δp_+^{ch} (GeV/c)
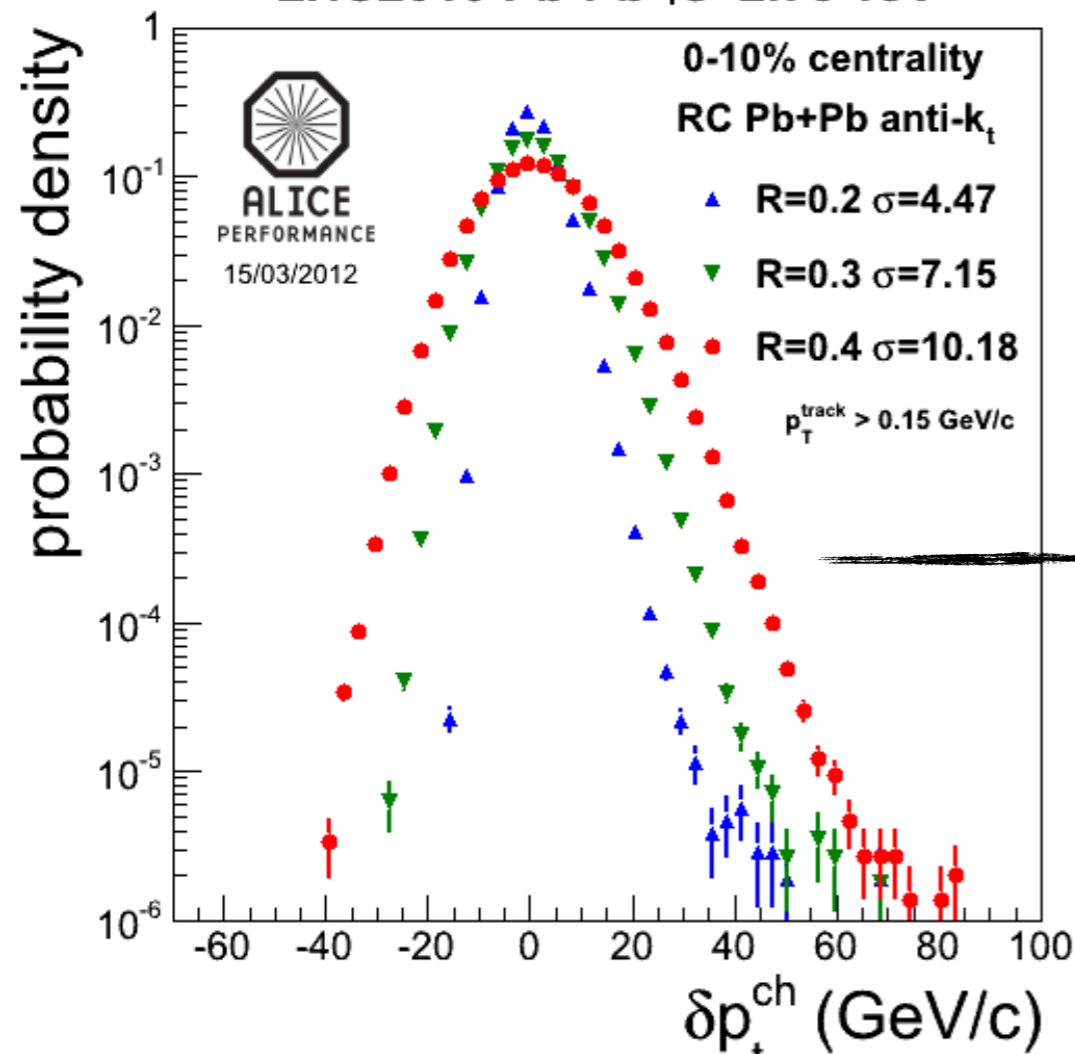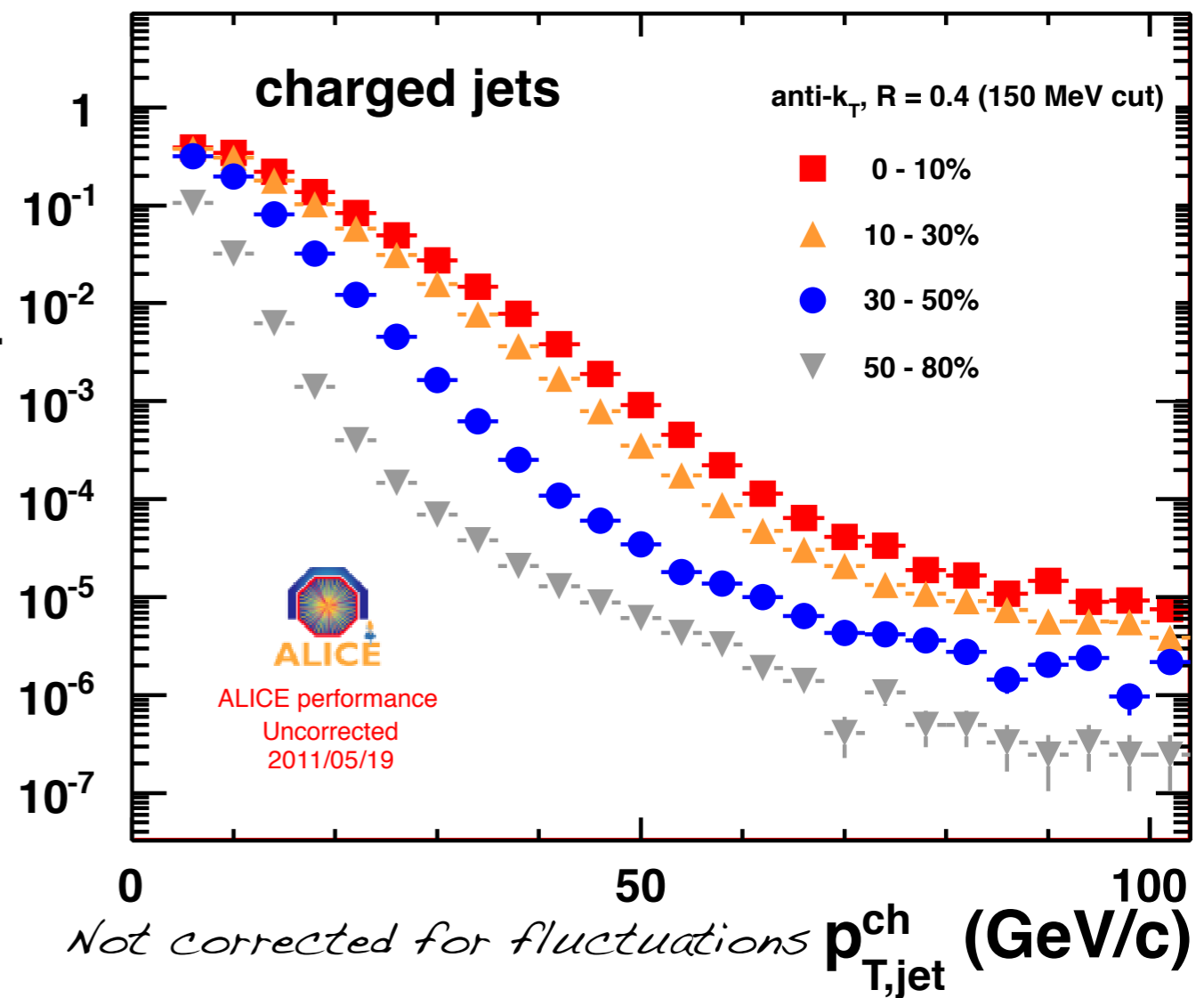
Energy resolution function: δp_T

LHC2010 Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

charged jets

anti-k_T, R = 0.4 (150 MeV cut)

■ 0 - 10%
▲ 10 - 30%
● 30 - 50%
▼ 50 - 80%

$\frac{1}{N_{evt}} dN/dp_T d\eta$ (c/GeV)

ALICE performance
Uncorrected
2011/05/19

Not corrected for fluctuations $p_{T,jet}^{ch}$ (GeV/c)

Background corrections
in Atlas

- Reconstruction algorithm anti-k_t (0.2, 0.4).

- Input: calorimeter towers 0.1 x 0.1 ($\Delta\eta$ x $\Delta\varphi$).

- Event-by-event background subtraction: $E_{Tsub}^{cell} = E_T^{cell} - \rho^{layer}(\eta) \times A^{cell}$

➡ Anti-k_t reconstruction prior to a background subtraction.

➡ Underlying event estimated for each longitudinal layer and η slice separately.

- We exclude jets with $D = E_{T\,tower}^{max}/\langle E_{T\,tower}\rangle > 4$ to avoid biasing subtraction from jets but no jet rejection based on *D*.

- Iteration step to exclude jets with E_T > 50 GeV from background estimation. Jets corrected for flow contribution.
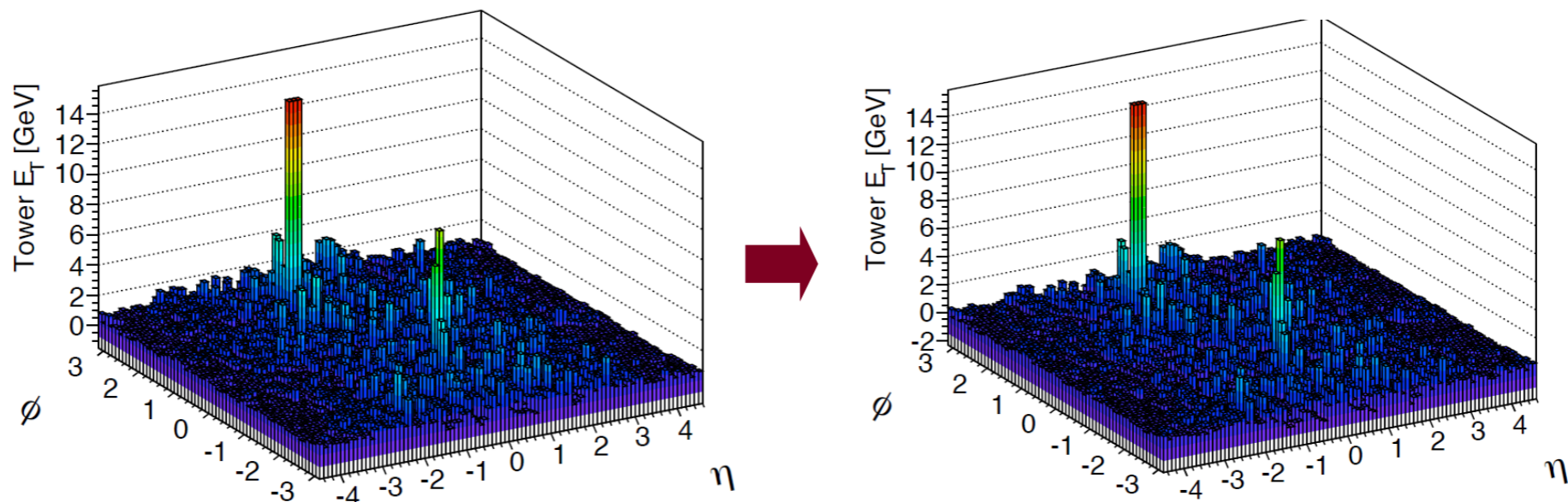
Background subtraction / jet energy corrections (CMS)

PF pseudo-tower

0.087 (barrel)

γ h^0 $h^{+/-}$
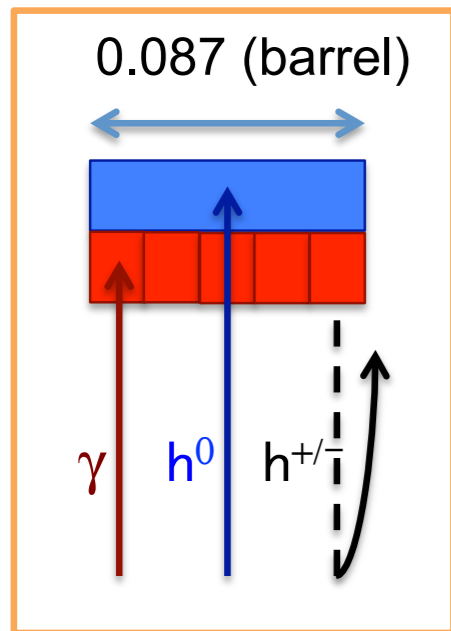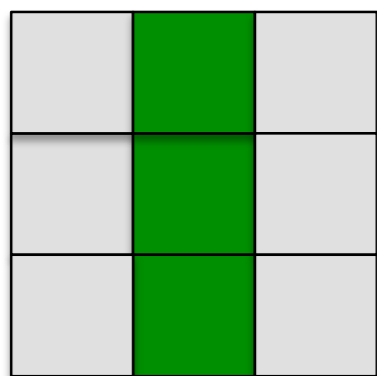
η strip

0.087 (barrel)

a) Event-by-event subtraction of the heavy-ion background

- Reconstructed particles towered into an (η,φ) grid according to HCAL cell dimensions

- Mean tower energy and dispersion are calculated for each η strip
- Same iterative background subtraction applied in [0], described in [1]
- Random cone studies: good agreement between background fluctuations in data and HYDJET simulations
- The effect of quenching on the energy scale is constrained using the jet associated charged particle spectra

b) Jet energy corrections (JEC) based on GEANT simulation of PYTHIA jets

c) Validation of the BG subtraction + JEC for PYTHIA jets embedded in HYDJET

[0] CMS, arXiv:1102.1957
[1] Kodolova et al., EPJC 50 (2007) 117

discussion of measurements

Text

Jet R Central-Peripheral

R_{CP} : similar as R_{AA}, but denominator are not yields from proton-proton but from peripheral heavy-ion collisions
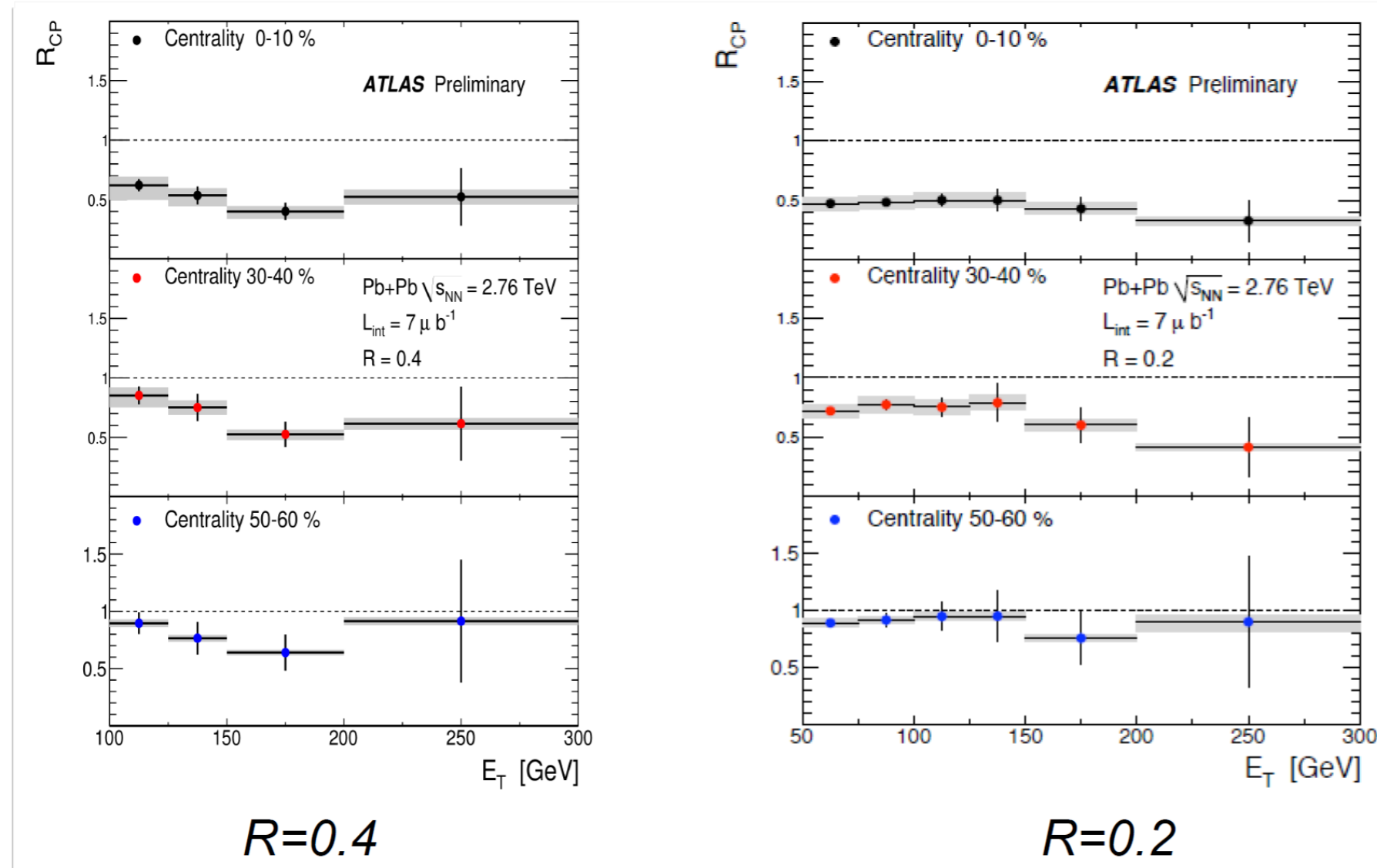
Flat! – in contrast to R_{AA} of hadrons

$R_{CP} \sim 0.5$ => suppression – jets loose energy in most central events
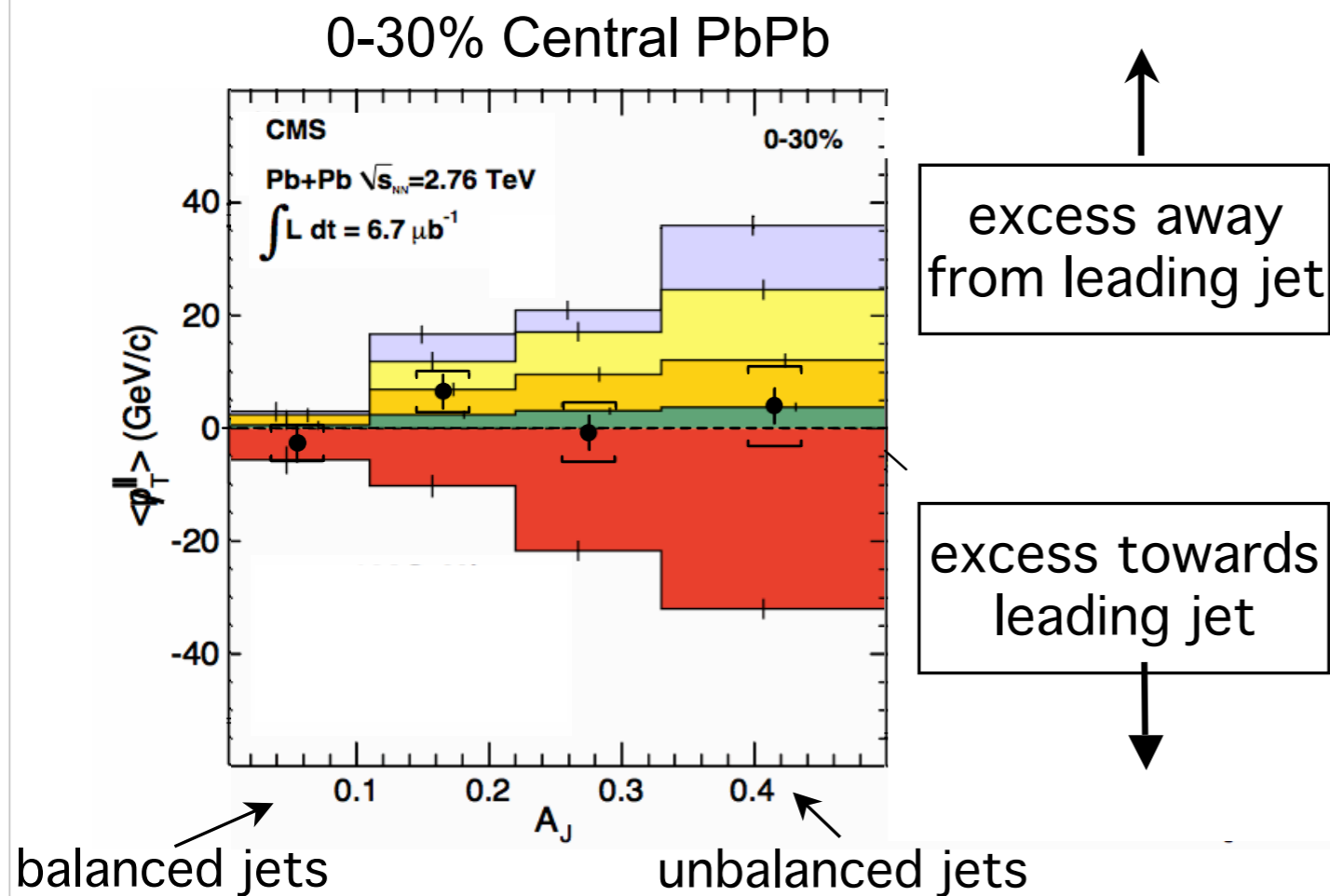– the radiation is not captured within the jet cone (R)

LHC: Di-jet asymmetry
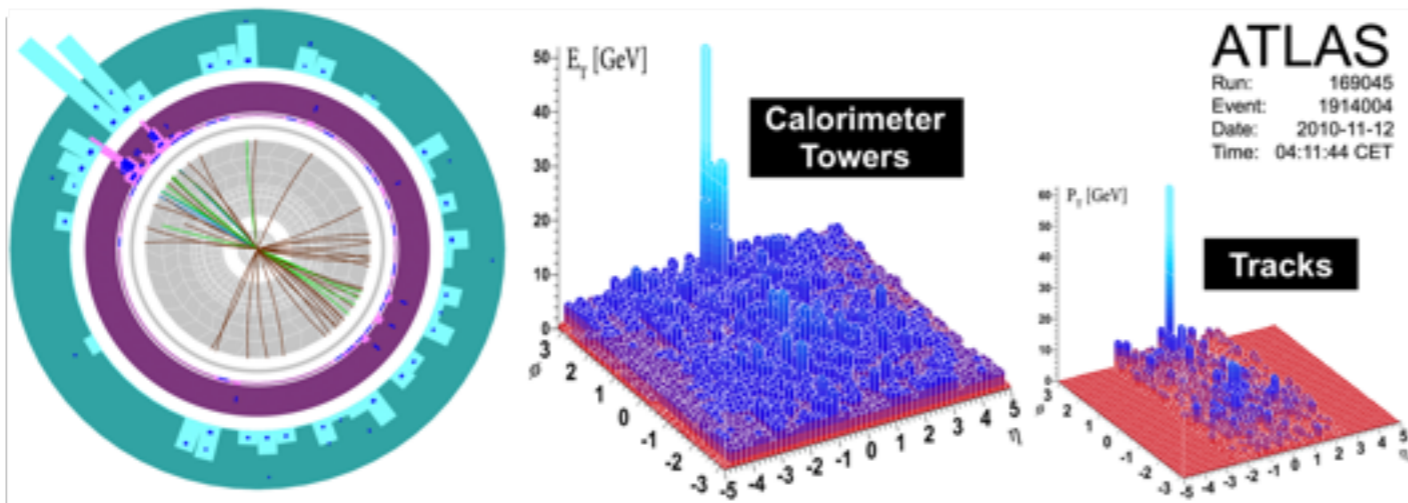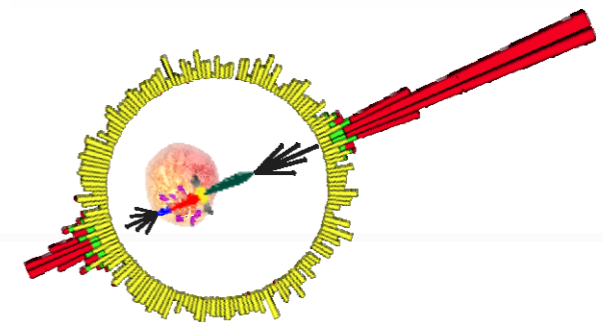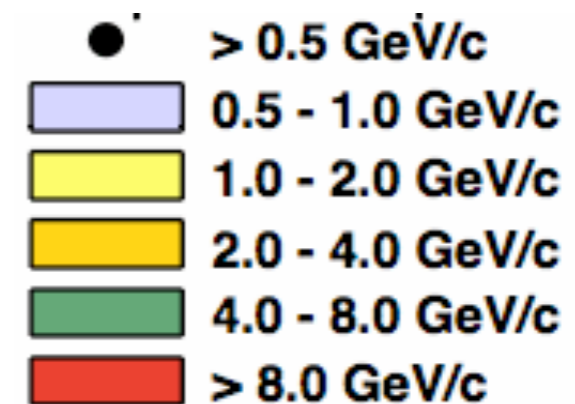

$$A_J \equiv \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$
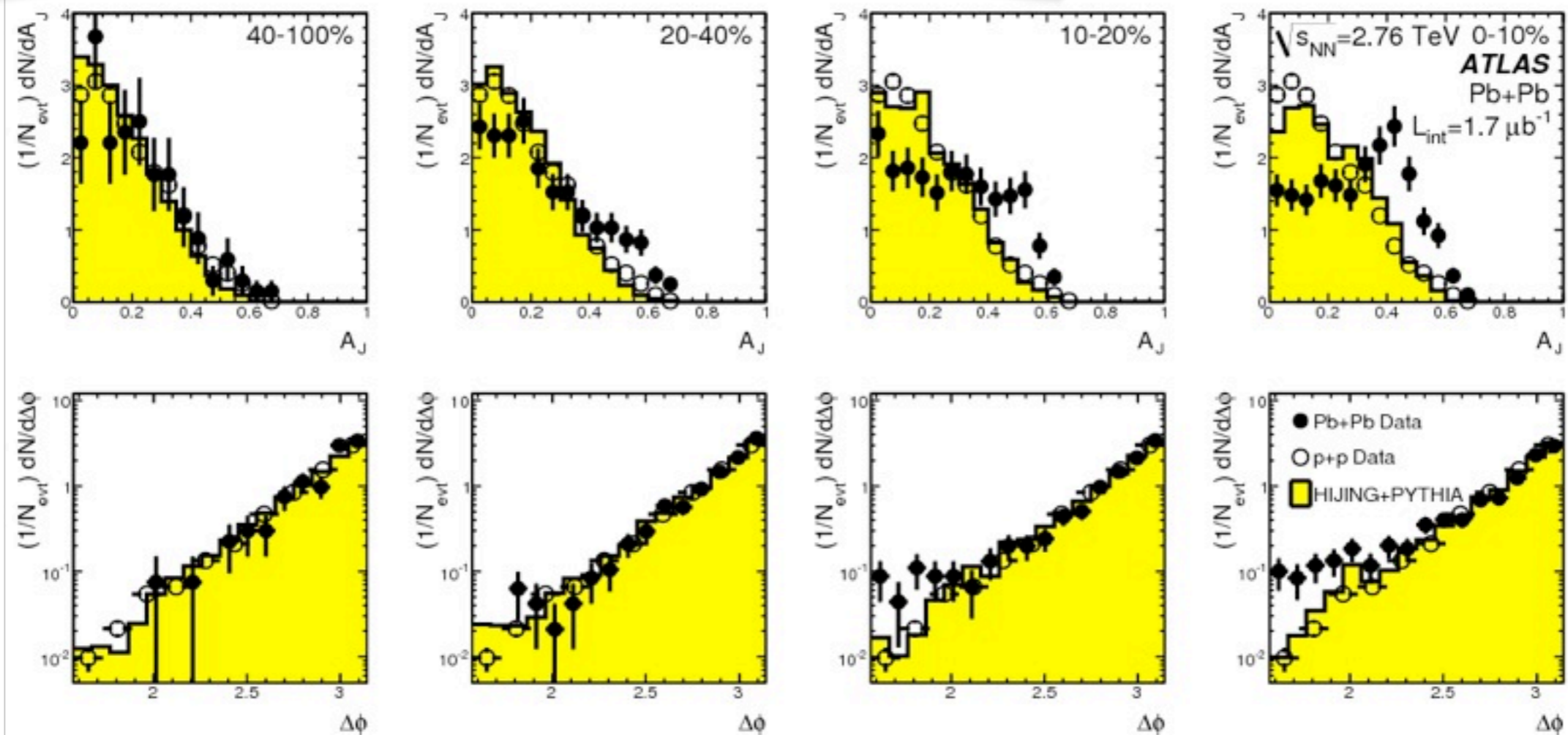
di-jet asymmetry: where does the energy go?

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

0-30% Central PbPb

CMS

Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV

$\int L\, dt = 6.7\ \mu b^{-1}$

0-30%

excess away from leading jet

Calculate missing p_T in ranges of track p_T:

- ● > 0.5 GeV/c
- 0.5 - 1.0 GeV/c
- 1.0 - 2.0 GeV/c
- 2.0 - 4.0 GeV/c
- 4.0 - 8.0 GeV/c
- > 8.0 GeV/c

excess towards leading jet

balanced jets   unbalanced jets

The momentum difference balanced by low-pT particles

di-jet asymmetry: where does the energy go?

In-cone / out-of-cone

0-30% Central PbPb

CMS
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV
$\int$ L dt = 6.7 μb^{-1}

0-30%

> 0.5 GeV/c
0.5 - 1.0 GeV/c
1.0 - 2.0 GeV/c
2.0 - 4.0 GeV/c
4.0 - 8.0 GeV/c
> 8.0 GeV/c

In-Cone
$\Delta R < 0.8$

Out-of-Cone
$\Delta R < 0.8$

arXiv:1102.1957 [nucl-ex]

$\langle \not{p}_T^{\parallel} \rangle$ (GeV/c)

balanced jets   unbalanced jets
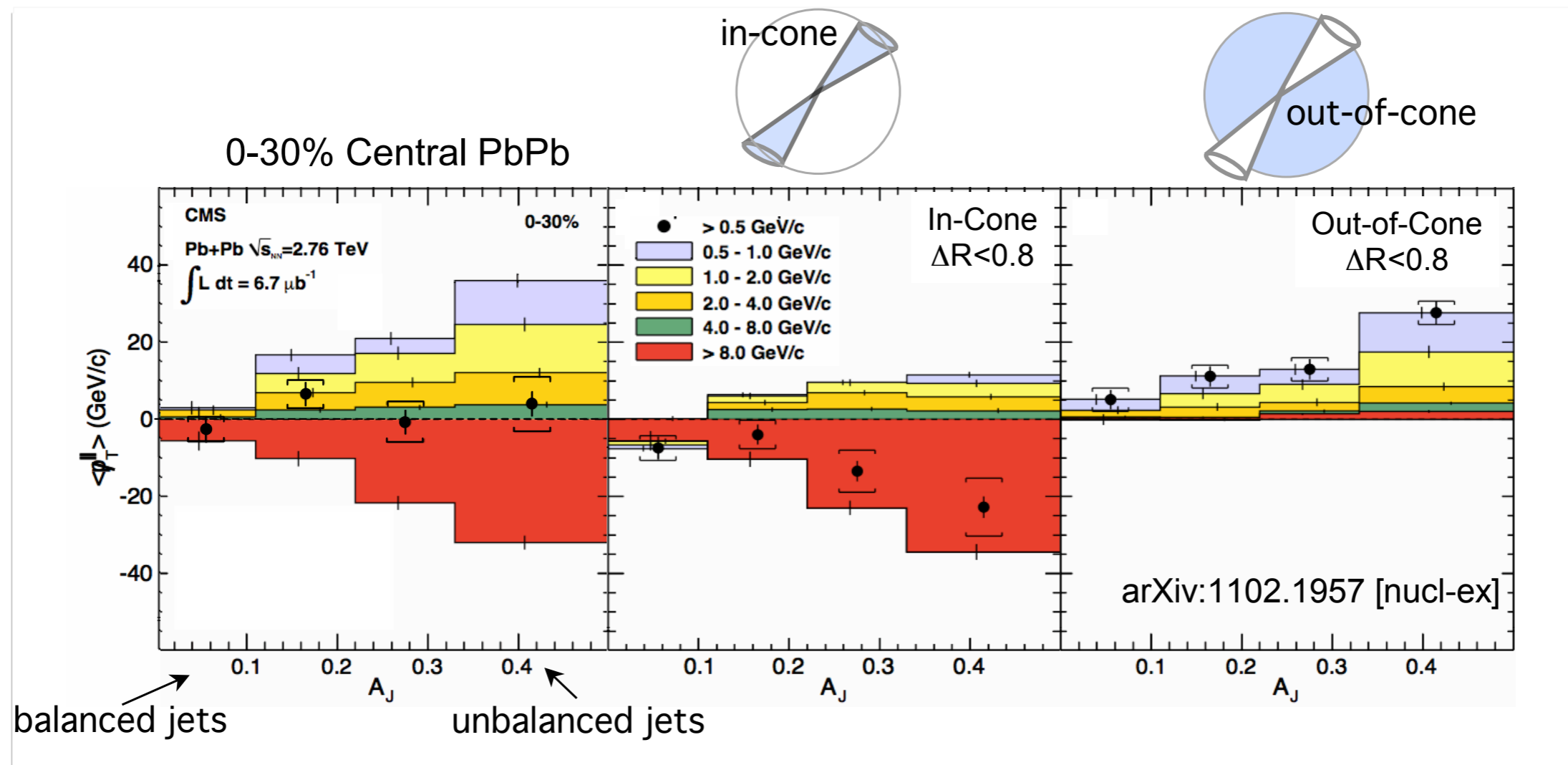
The low-pT particles "balancing" the lost energy appear at large angles wrt recoil jet
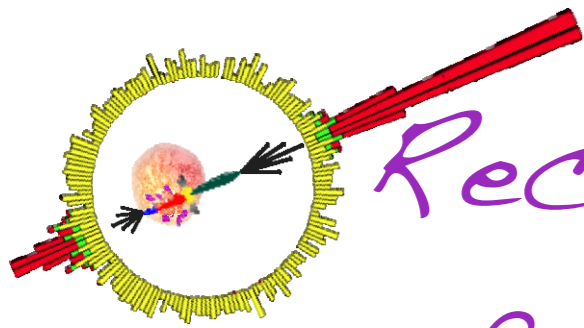
Recoil jet (2) energy-loss as a function of trigger jet (1) p_T

$p_{T,2} > 30$ GeV/c

CMS

$\langle p_{T,2}/p_{T,1}\rangle$

- PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $\int Ldt = 150$ μb^{-1}
- pp $\sqrt{s} = 2.76$ TeV, $\int Ldt = 231$ nb^{-1}
- PYTHIA+HYDJET

$p_{T,2} > 30$ GeV/c

$\Delta\phi_{12} > \frac{2}{3}\pi$

50-100%   20-50%   0-20%

Vacuum reference

Data in PbPb

PbPb − MC

$p_{T,1}$ (GeV/c)
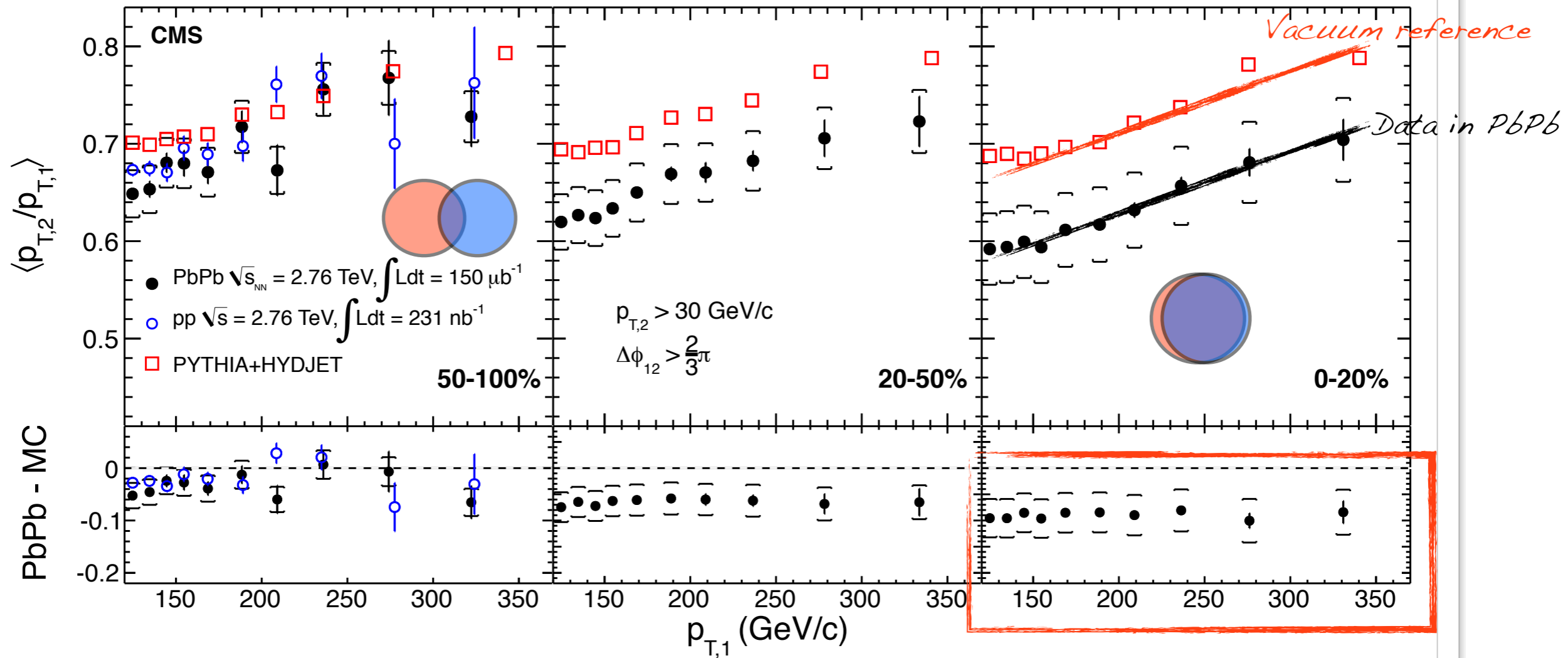
Ratio follows the PYTHIA+HYDJET reference with the same rate – constant offset over 200 GeV in p_T

Modified jet fragmentation
- an expectation from jet quenching

$$\xi = ln(E_{jet}/p_{hadron})$$

LEP Data Shown

$\frac{dN^h}{d\xi}(\xi,\tau)$

■ OPAL, $\sqrt{s}$=192–209 GeV
— in vacuum, E_{jet}=100 GeV
-- in medium, E_{jet}=100 GeV

Jet quenching

"hump-back plateau"

p_T^{hadron}~2 GeV

$\xi=ln(E_{Jet}/p_{hadron})$
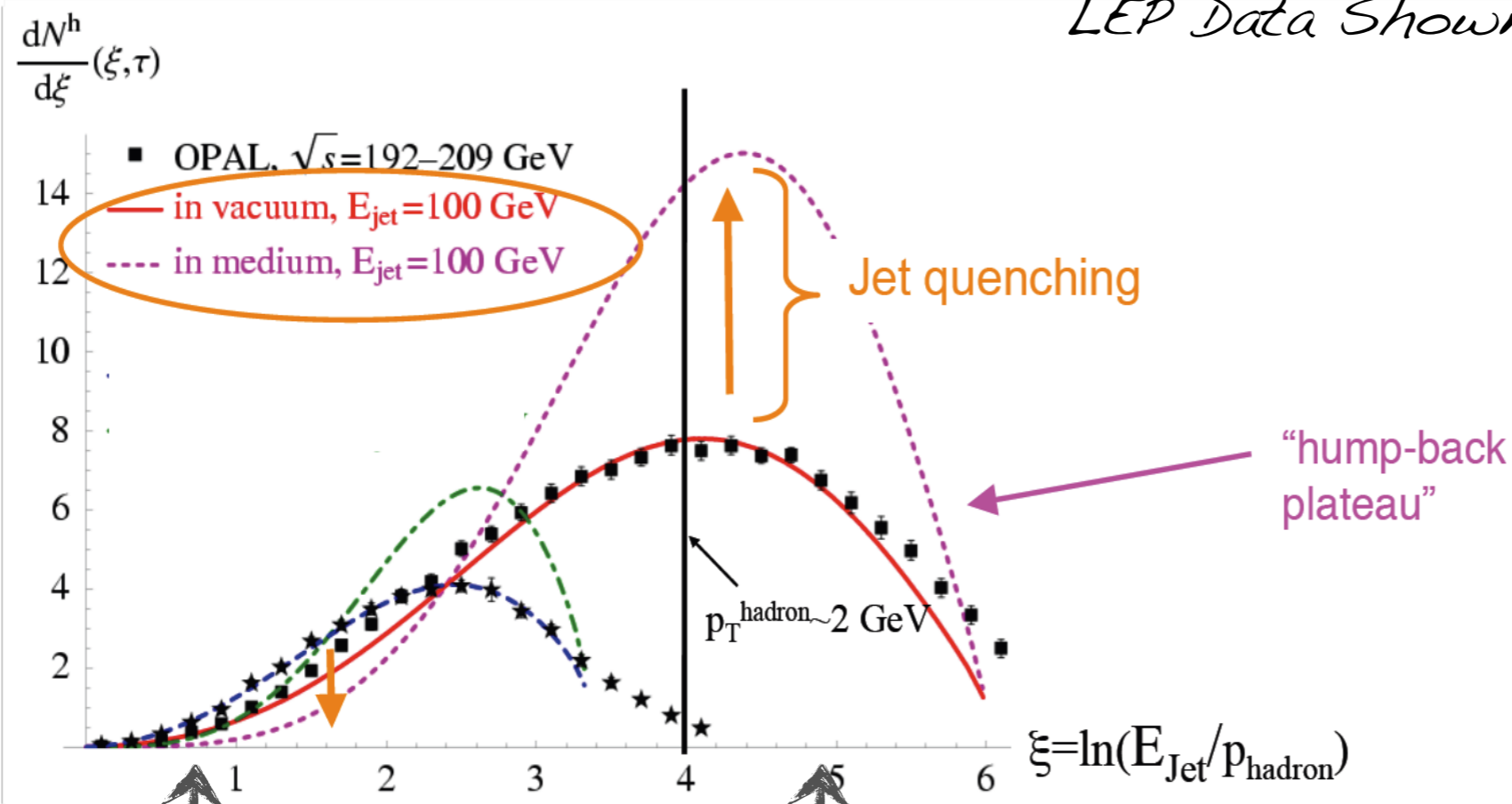
High momentum hadrons

Low momentum hadrons

Jet vector

projection

hadron
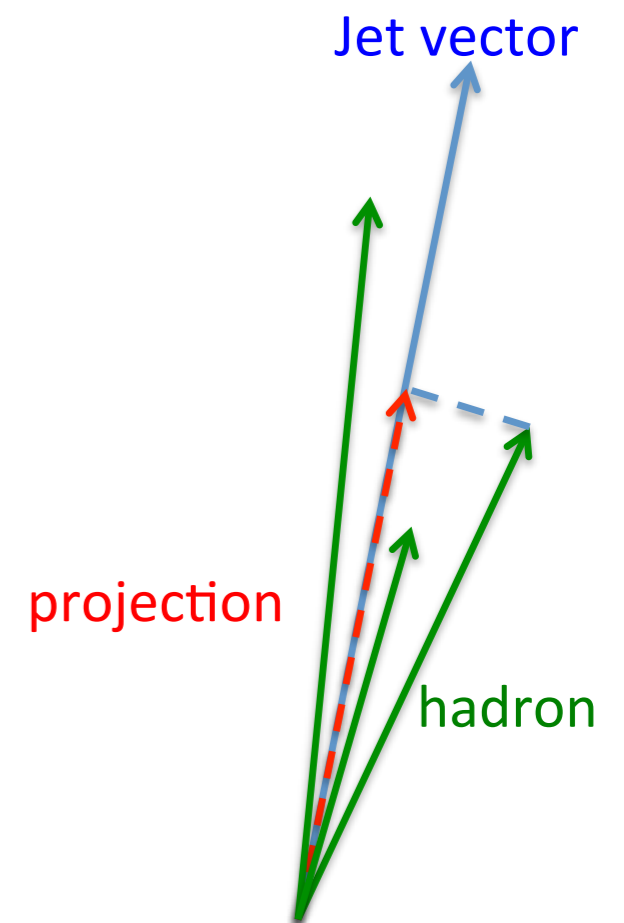
Jet fragmentation in Heavy-ion collisions
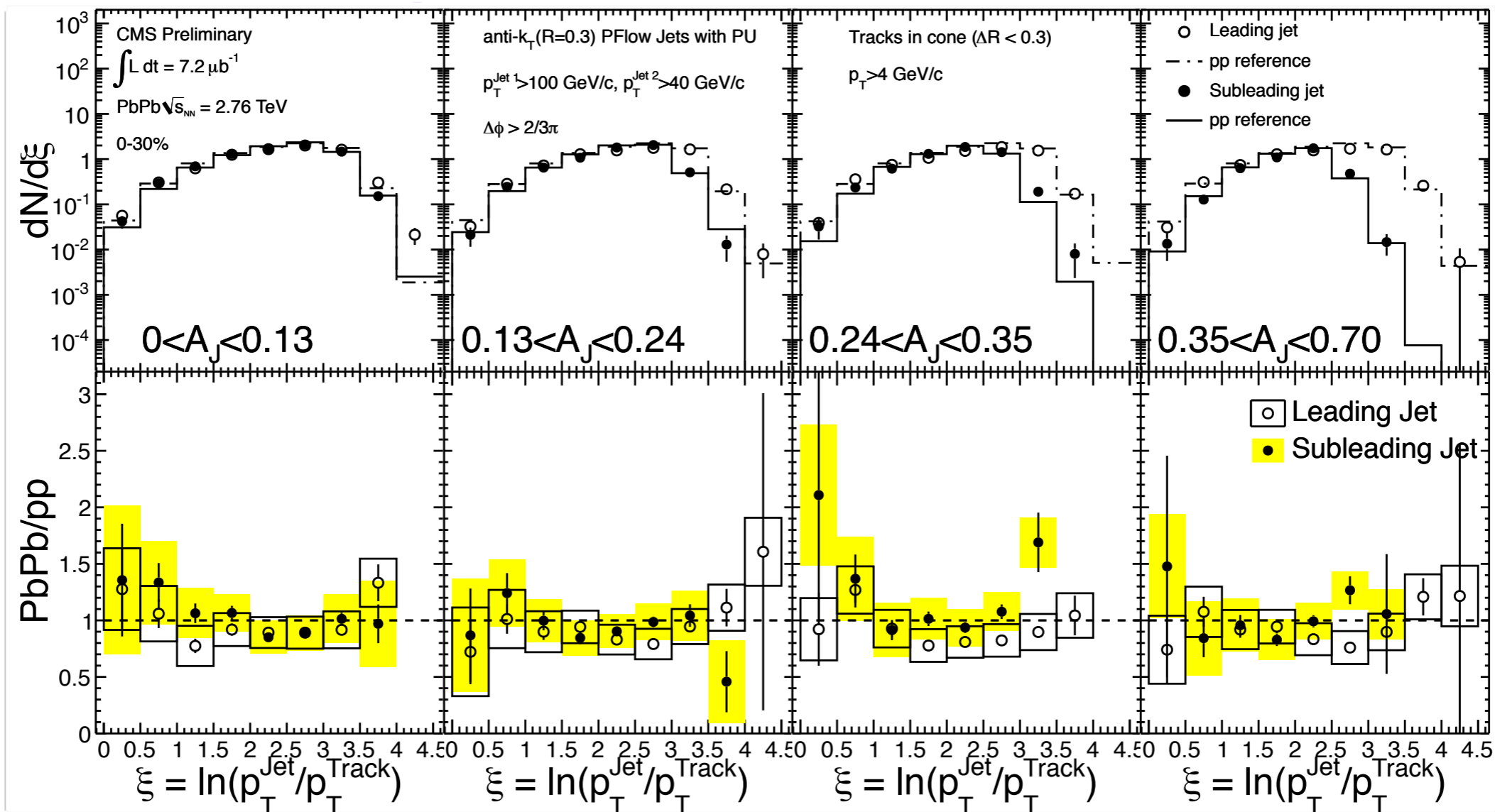
CMS observation: Fragmentation of jets that lost energy consistent with jet fragmentation in proton-proton (vacuum) - similar observations by ATLAS
- a question: is the particle composition of the jet modified?

Photon$_{(\Delta E = 0)}$-jet$_{(\Delta E > 0)}$
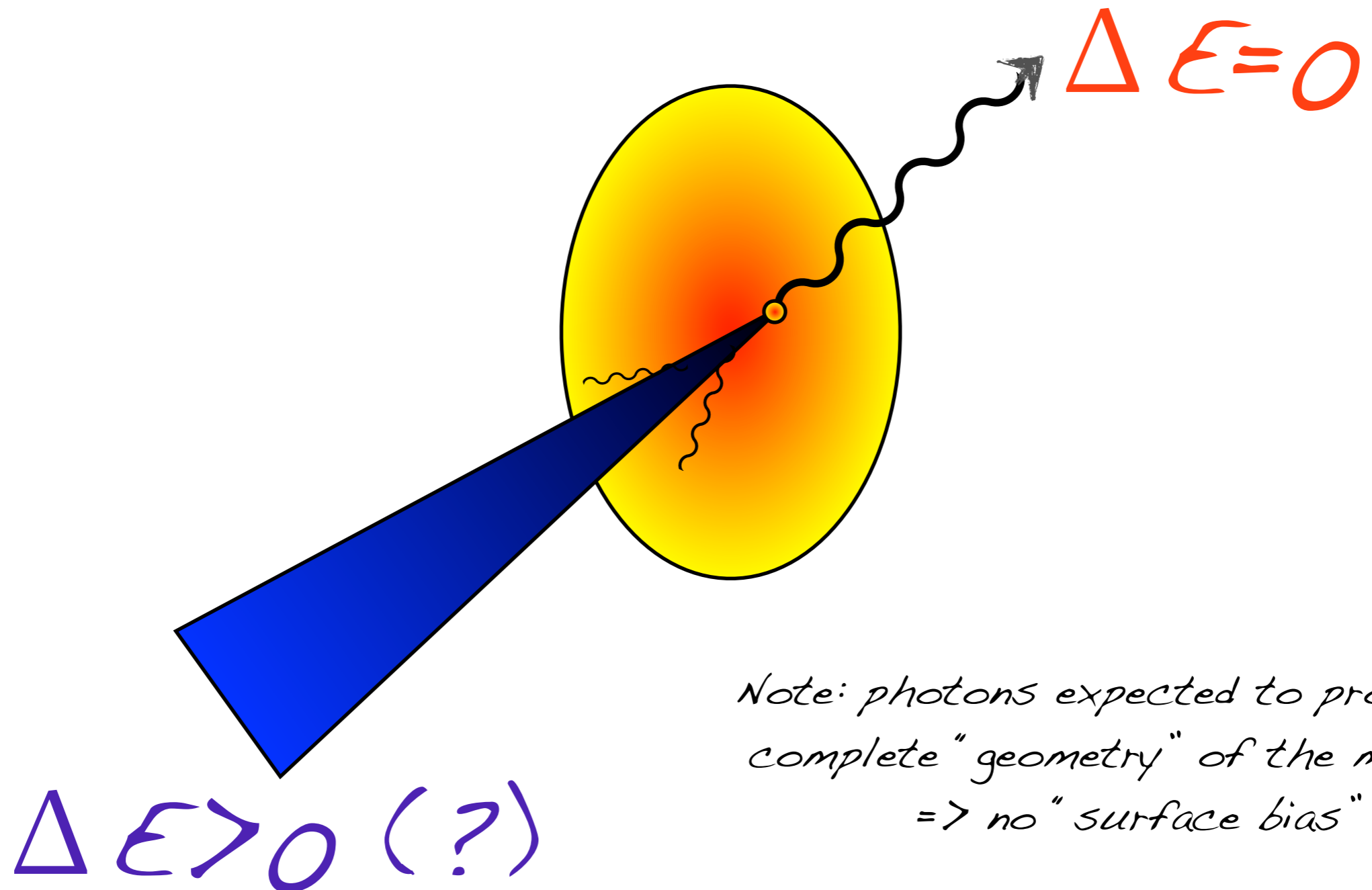
(a) PbPb Data
PYTHIA + HYDJET
pp Data

50% - 100%

Pair Fraction

$\Delta\phi_{J\gamma}$

(d)

PbPb Data
PYTHIA + HYDJET
pp Data
PYTHIA

$\sigma(\Delta\phi_{J\gamma})$

$p_T^\gamma > 60$ GeV/c $|\eta^\gamma| < 1.44$

$p_T^{Jet} > 30$ GeV/c $|\eta^{Jet}| < 1.6$

N_{part}

Pair Fraction

0% -
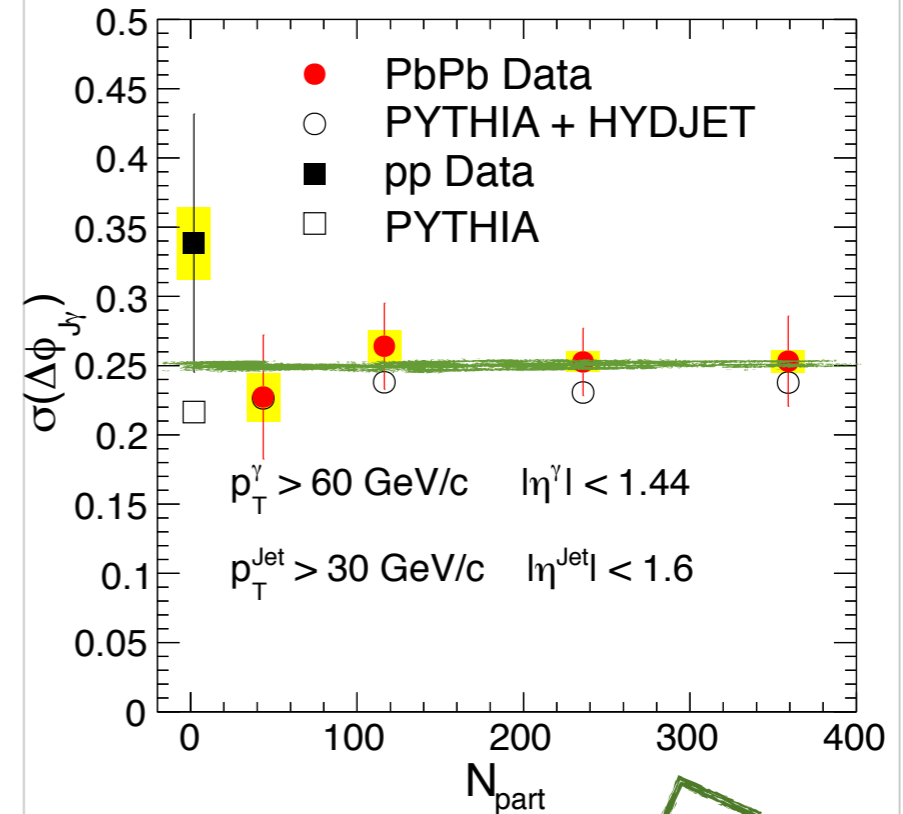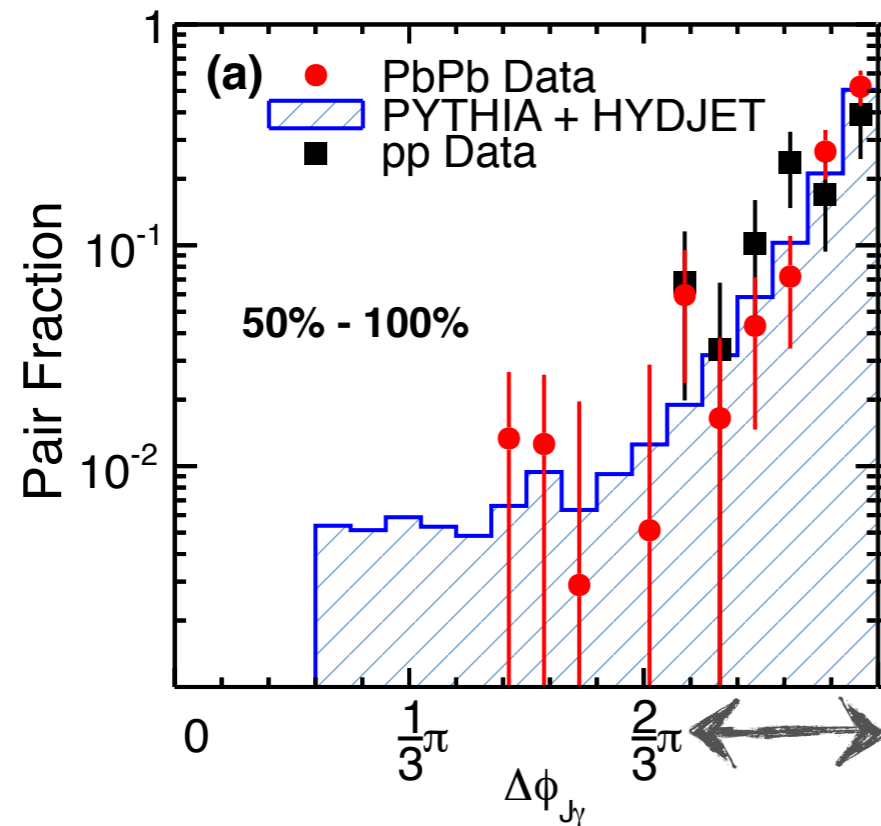
$Fit \quad \dfrac{1}{N_{J\gamma}} \dfrac{\mathrm{d}N_{J\gamma}}{\mathrm{d}\Delta\phi_{J\gamma}} = \dfrac{\mathrm{e}^{(\Delta\phi - \pi)/\sigma}}{(1 - \mathrm{e}^{-\pi/\sigma})\,\sigma}$

$Range: \Delta\phi > 2\pi/3$

"Width" consistent with vacuum

$Photon_{\langle\Delta E=0\rangle}-jet_{\langle\Delta E>0\rangle}$

The asymmetry ratio $x_{J\gamma} = p_T^{Jet}/p_T^\gamma$ is used to quantify the photon+jet momentum imbalance.

peripheral events

central events
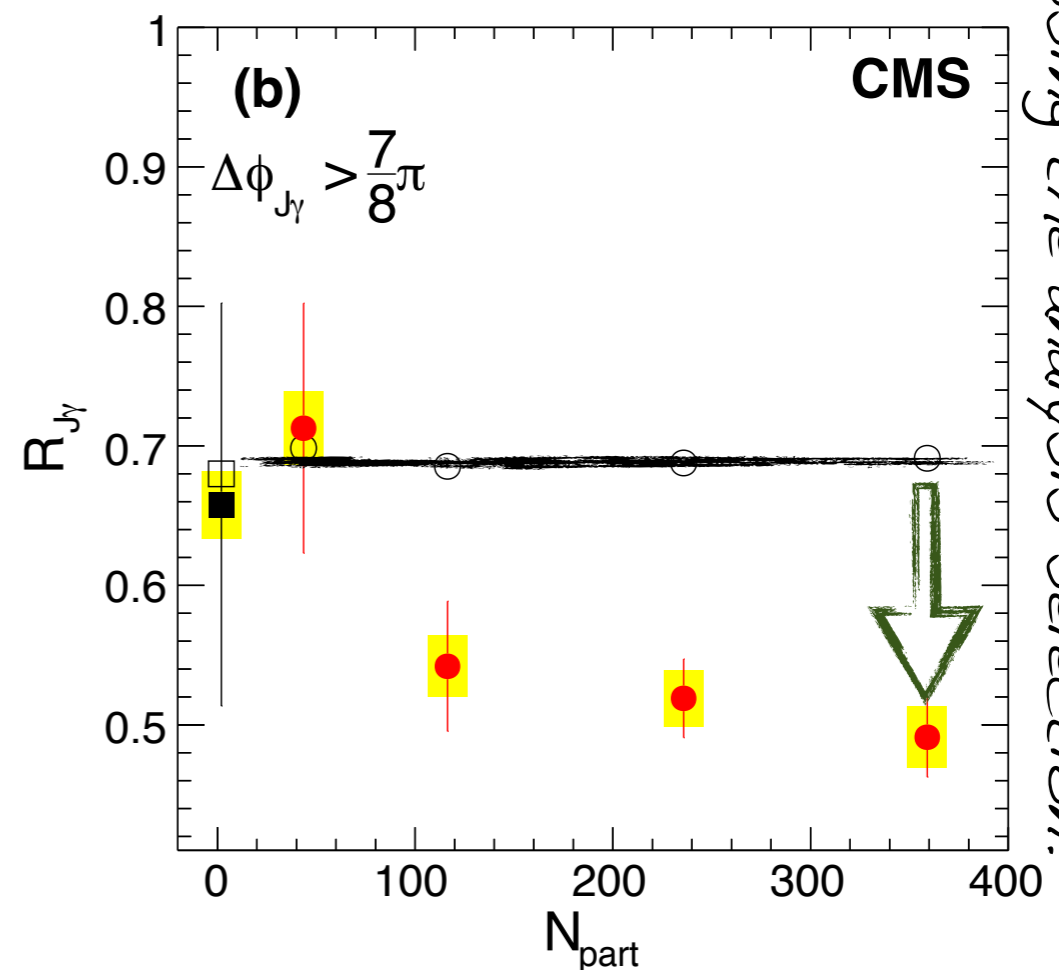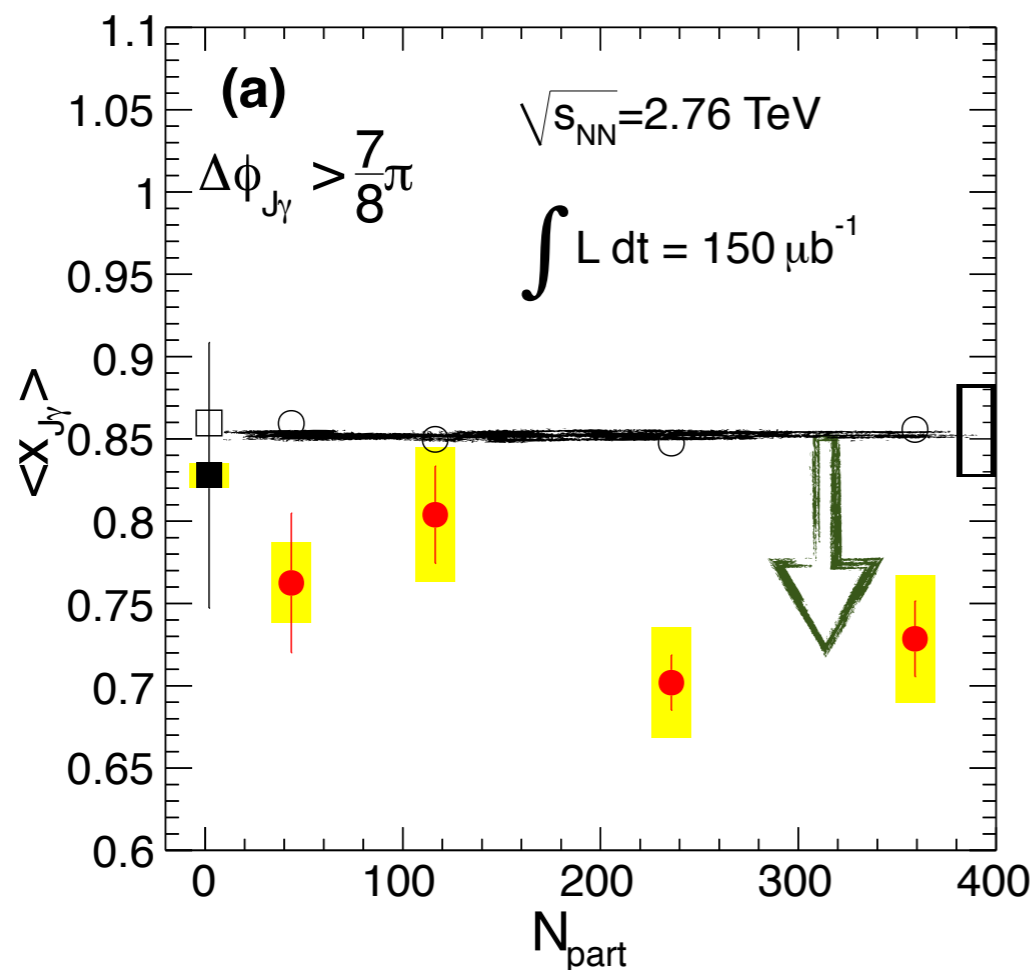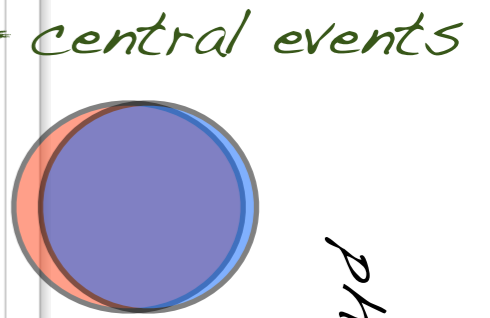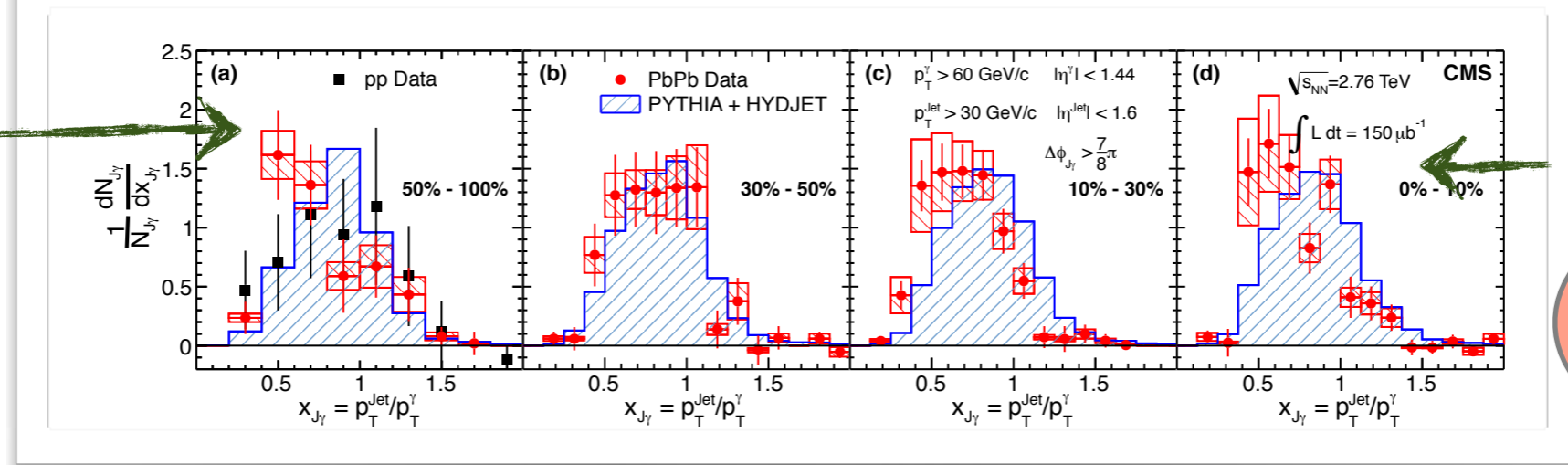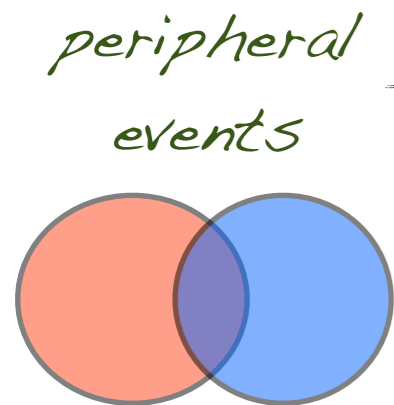

$R_{J\gamma}$ ~ the fraction of isolated photons that have an associated jet passing the analysis selection.

Thanks!

- For graphics/slides from: P. Govoni, M. Nguyen, T. Hemmick, P. Jacobs, M. van Leeuwen, J. Putschke, C. Roland, M. Rybář, I. Wingerter

- For the material by collaborations: ALICE, ATLAS, CMS, PHENIX, STAR

Nuclear geometry – Glauber model and hard processes

Normalized nuclear density r(b,z):
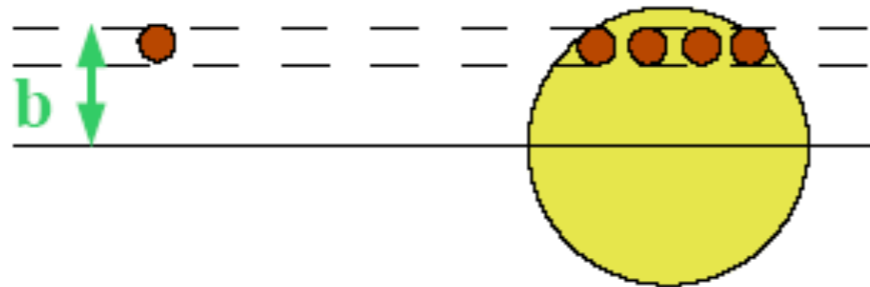
$$\int dz\, db\, \rho(b,z) = 1$$

Nuclear thickness function

$$T_A(b) = \int_{-\infty}^{\infty} dz\, \rho(b,z)$$

Inelastic cross section for p+A:

$$\sigma_{pA}^{inel} = \int d\vec{b}\left(1 - \left[1 - T_A(b)\sigma_{NN}^{inel}\right]^A\right)$$

Glauber scaling: hard processes with large momentum transfer
  • short coherence length $\Rightarrow$ successive NN collisions independent
  • p+A is incoherent superposition of N+N collisions

$$\sigma_{pA}^{hard} \approx A\sigma_{NN}^{hard} \int d\vec{b}\, T_A(\vec{b}) = A\sigma_{NN}^{hard}$$

Glauber scaling of hard processes
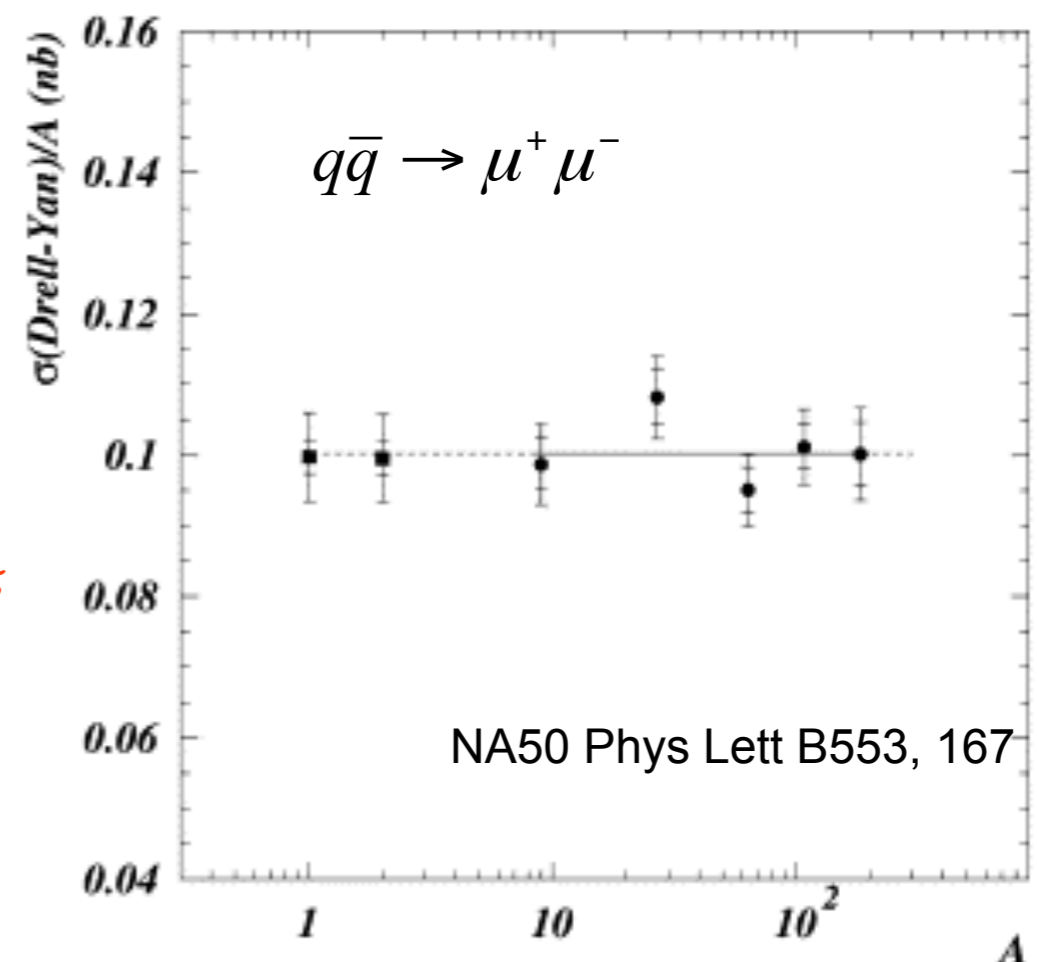
Glauber scaling: $\sigma^{hard}_{pA} = A\sigma^{hard}_{NN}$

σ_{inel} for 7 GeV muons on nuclei
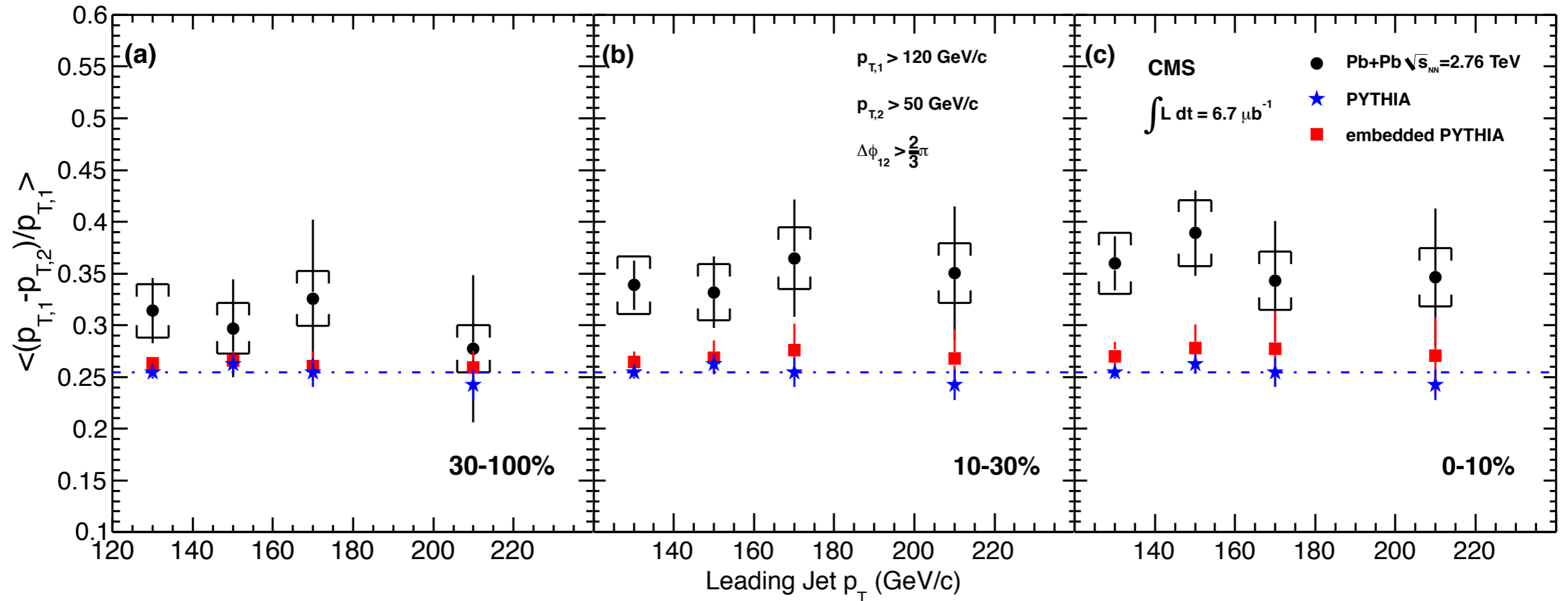
M.May et al, Phys Rev Lett 35, 407 (1975)

$\sigma_{Drell-Yan}/A$ in p+A at SPS

PRELIMINARY
μ – p Inelastic
$0.3 < q^2 < 3.5$
$E_{in} = 7\ 2$ GeV

$A^{1.00}$

$A^{1.00}$

Pb

$A^{0.91}$

Cu

Yield/Nucleus

Al

C

Photoabsorption

D

p

10   100   A ⟶

A

$A^{1.00}$
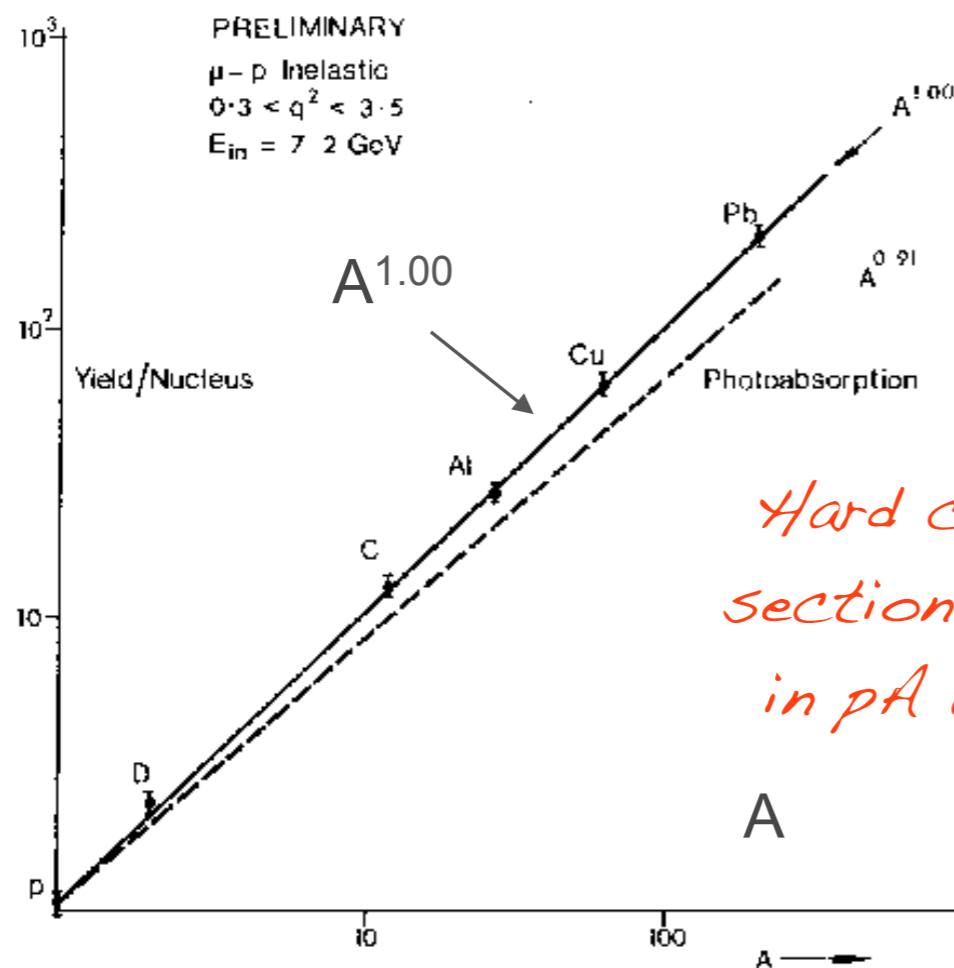
Hard cross-section scales in pA as $A^{1.0}$

$q\bar{q} \rightarrow \mu^+\mu^-$

$\sigma(Drell-Yan)/A$ (nb)

NA50 Phys Lett B553, 167

Di-jet asymmetry

The fractional imbalance:
- grows with collision centrality and reaches a much larger value than in PYTHIA or PYTHIA+DATA
- clearly visible even for the highest-p_T jets observed in the data set
- the $p_{T,1}$ dependence of the excess imbalance is compatible with either a constant difference or a constant fraction of $p_{T,1}$.

Jet-hadron coincidences

Figure 1. The Gaussian widths of the awayside jet peaks in Au–Au (triangles) and p–p (circles) indicate broadening of the awayside jet in Au–Au.
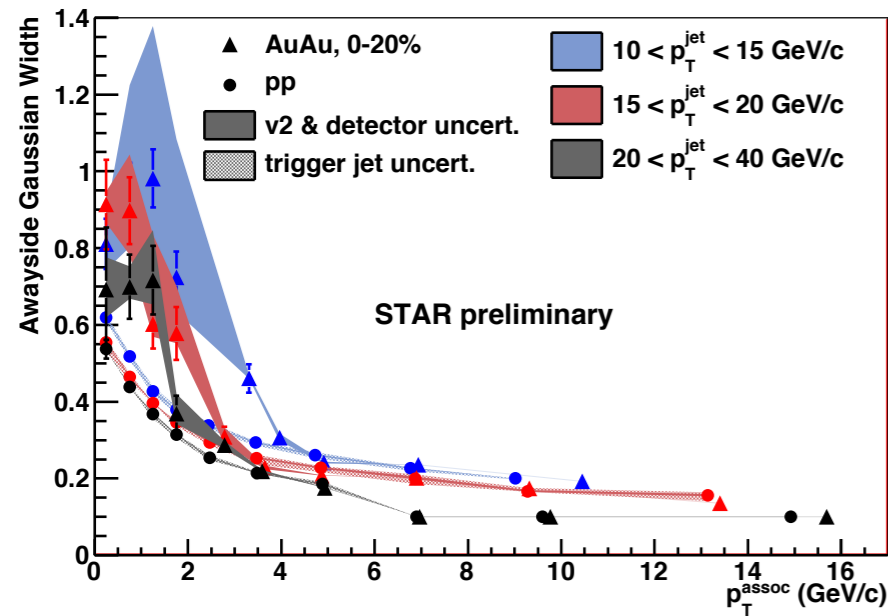
Broadening & softening of the recoil jet at RHIC
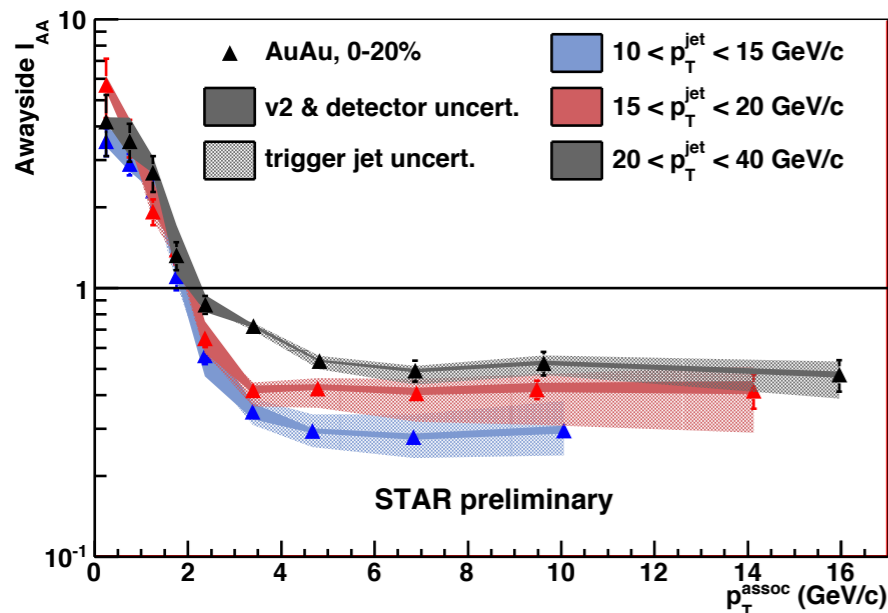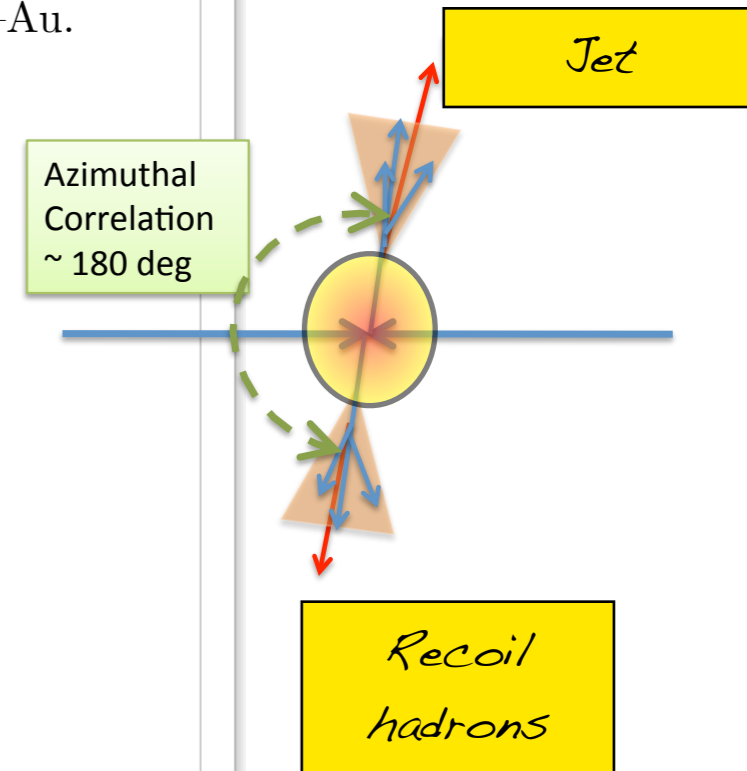
STAR @ RHIC
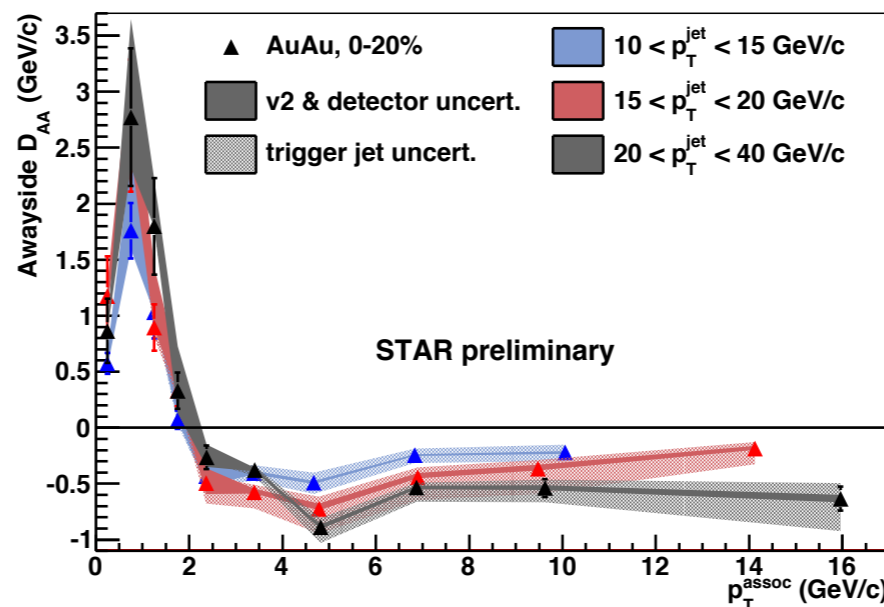
Figure 2. The awayside I_{AA} (left) and D_{AA} (right) indicate a softening of the awayside jet for three reconstructed jet energy ranges. The awayside D_{AA} shows that high-p_T^{assoc} suppression is compensated for by low-p_T^{assoc} enhancement.
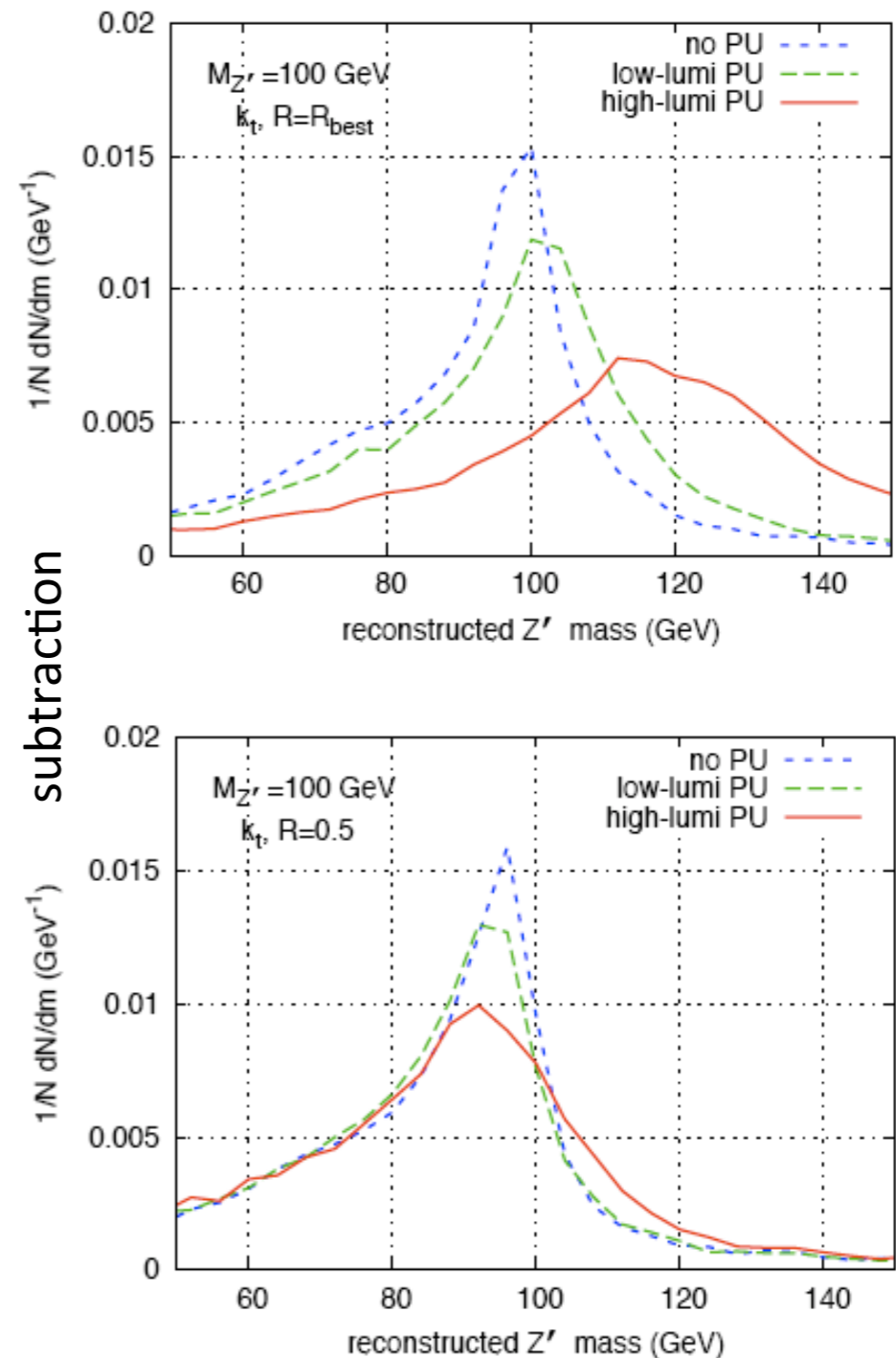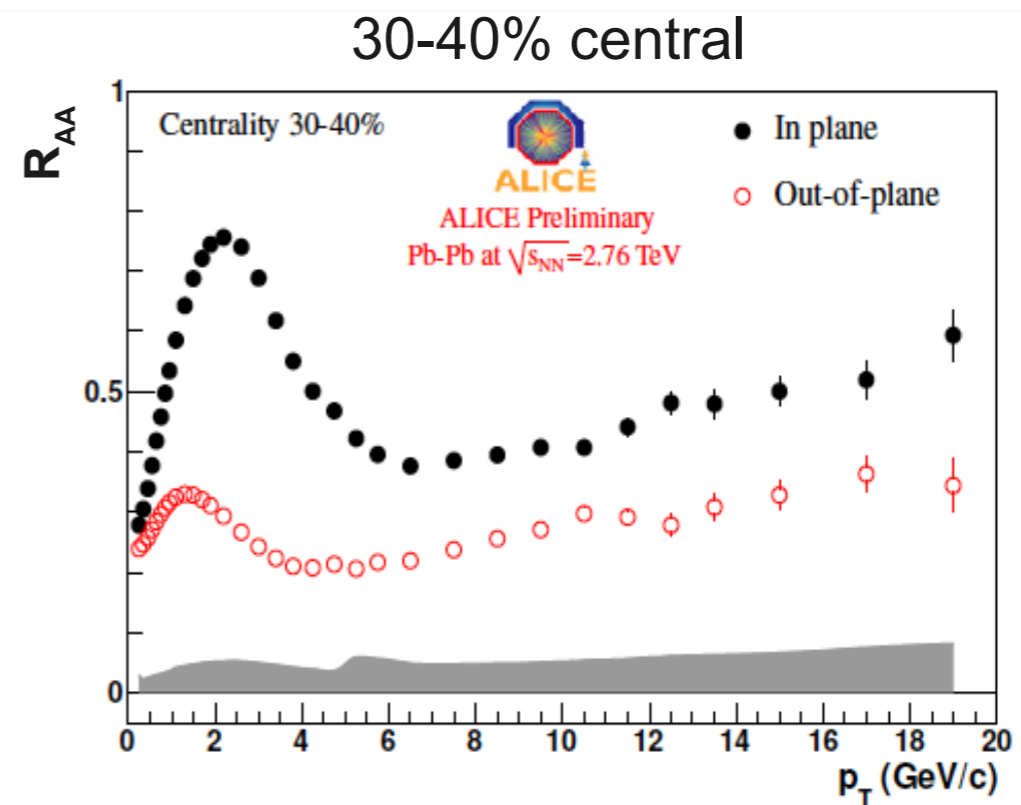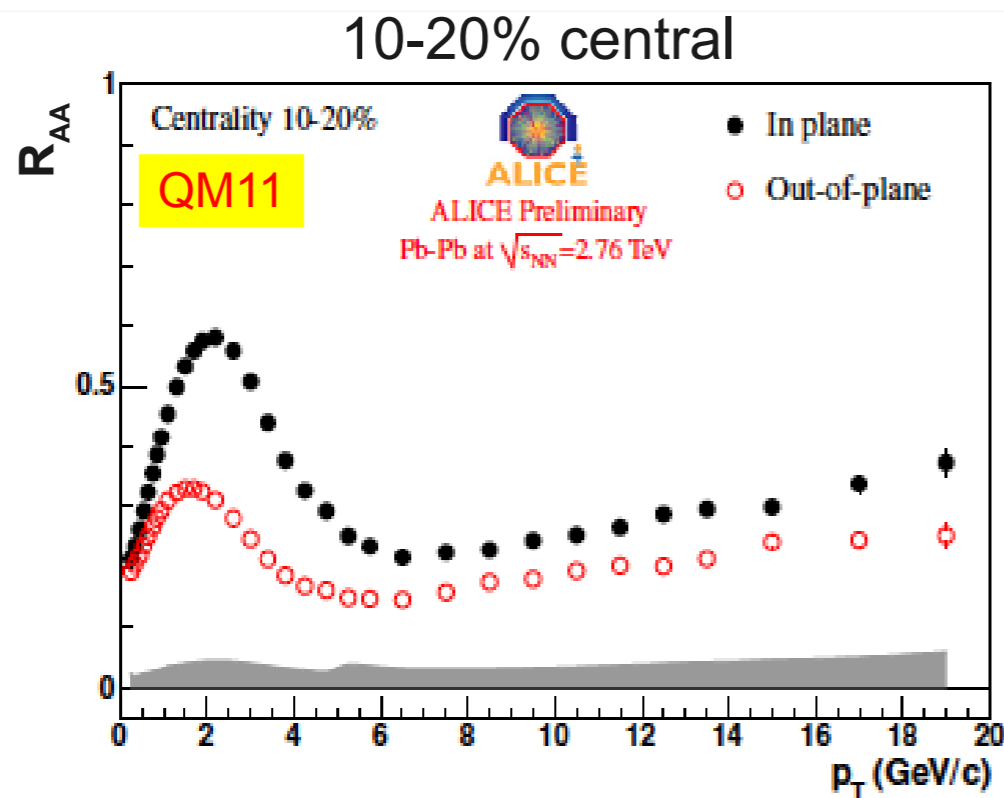
Background subtraction

$$p_T^{jet} = p_T^{cluster} - \rho \times Area$$

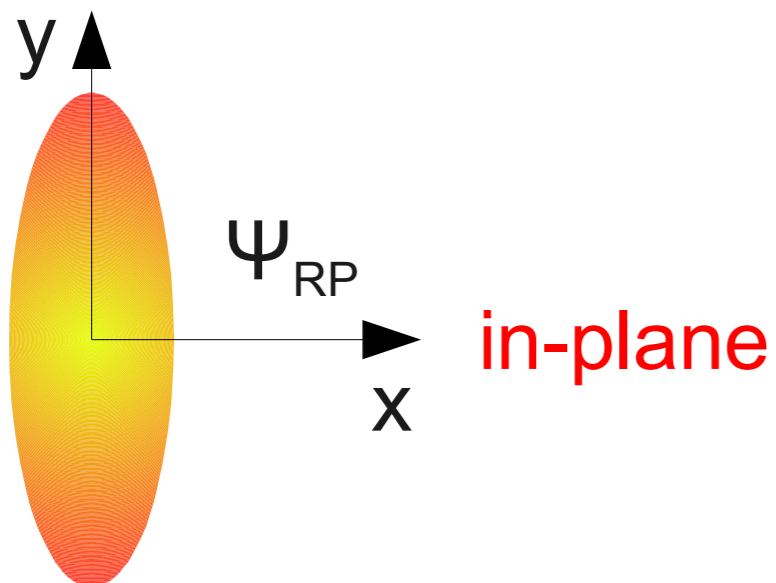$$p_T^{jet} = p_T^{true} \otimes \delta\rho$$

- ρ: median pT per unit area of the diffuse background in an event – measured using background *"jets"* as found by kT algorithm

- A: area of the jet – measured using number of artificially injected infinitely soft particles of finite *"size"* into an event that are clustered into the jet

- δρ: uncertainty due to noise fluctuations – non-uniformity of the event background

M. Cacciari, G. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]
M. Cacciari, G.Salam Phys.Lett.B659:119-126,2008. e-Print: arXiv:0707.1378 [hep-ph]

RAA wrt reaction plane

Suppression out-of-plane stronger <= longer in-medium path length - significant effect even at 20 GeV/c
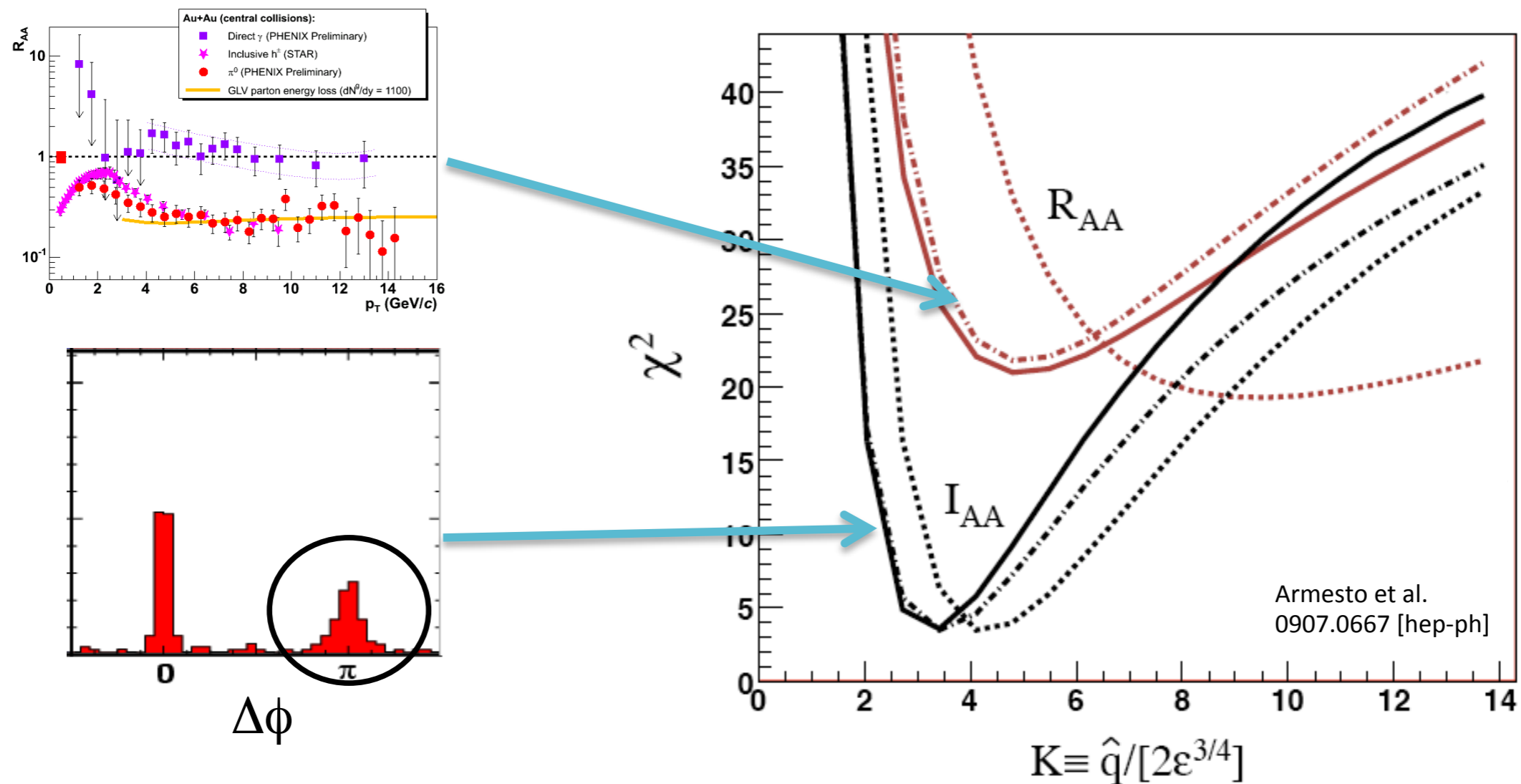**=> Path length dependence of energy loss** ?
Additional constraints to energy loss models (?)
   - **similar** information from v2 at high p_T

$$R_{AA}(\varphi) = R_{AA}\big(1 + 2v_2\cos2(\varphi-\psi)\big)$$

High-p_T hadrons: quantitative analysis

Model calculation: ASW quenching weights, detailed geometry
Simultaneous fit to data.

Armesto et al.
0907.0667 [hep-ph]

Reasonably self-consistent fit of independent observables
Main limitation is the accuracy of the theory...