[very brief]
Comments on Jet Quenching

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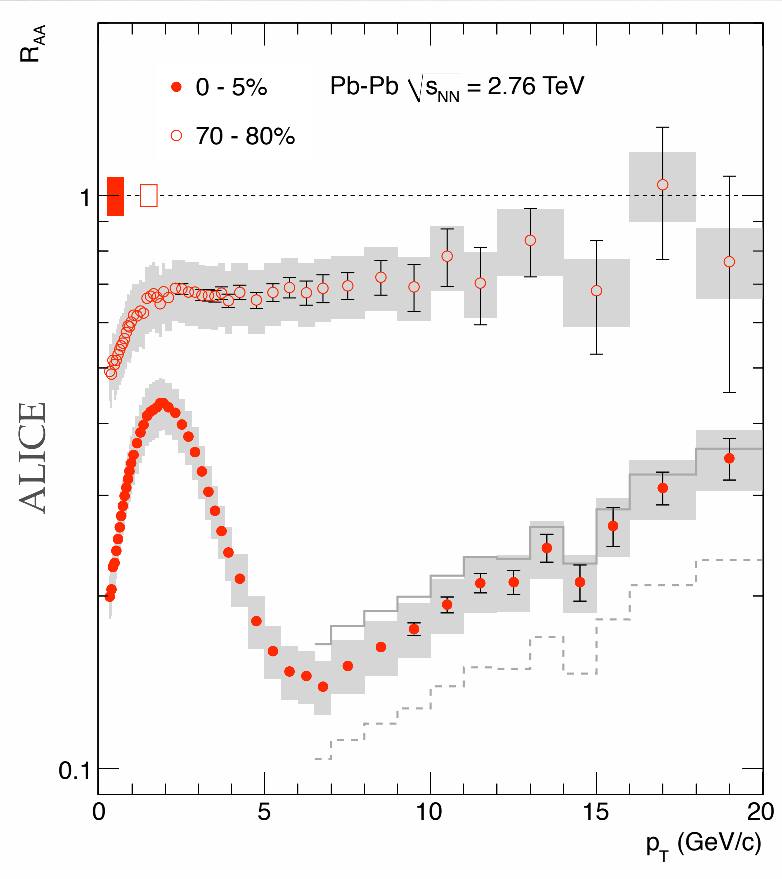
HI at the LHC: a first assessment, LPCC day, CERN, 4 March 2011

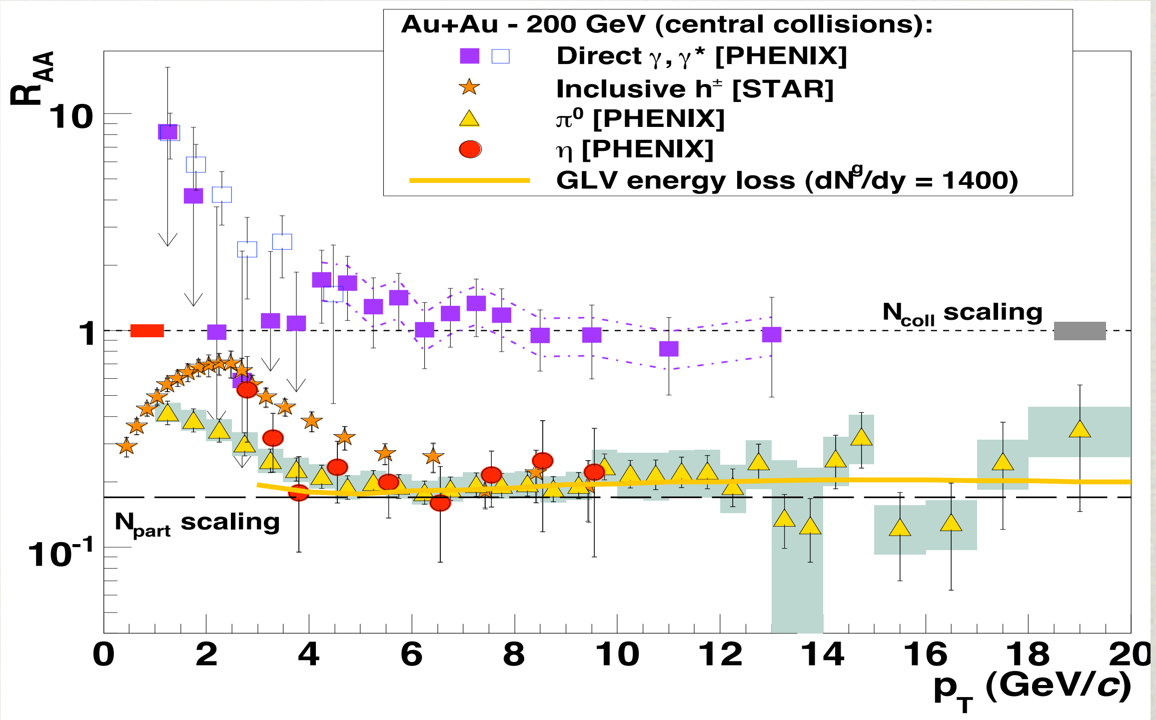
:: leading particle energy loss ['same' as RHIC]

- centrality dependent suppression in leading hadron spectra [R_{AA}]



$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

d'Enterria (2009)

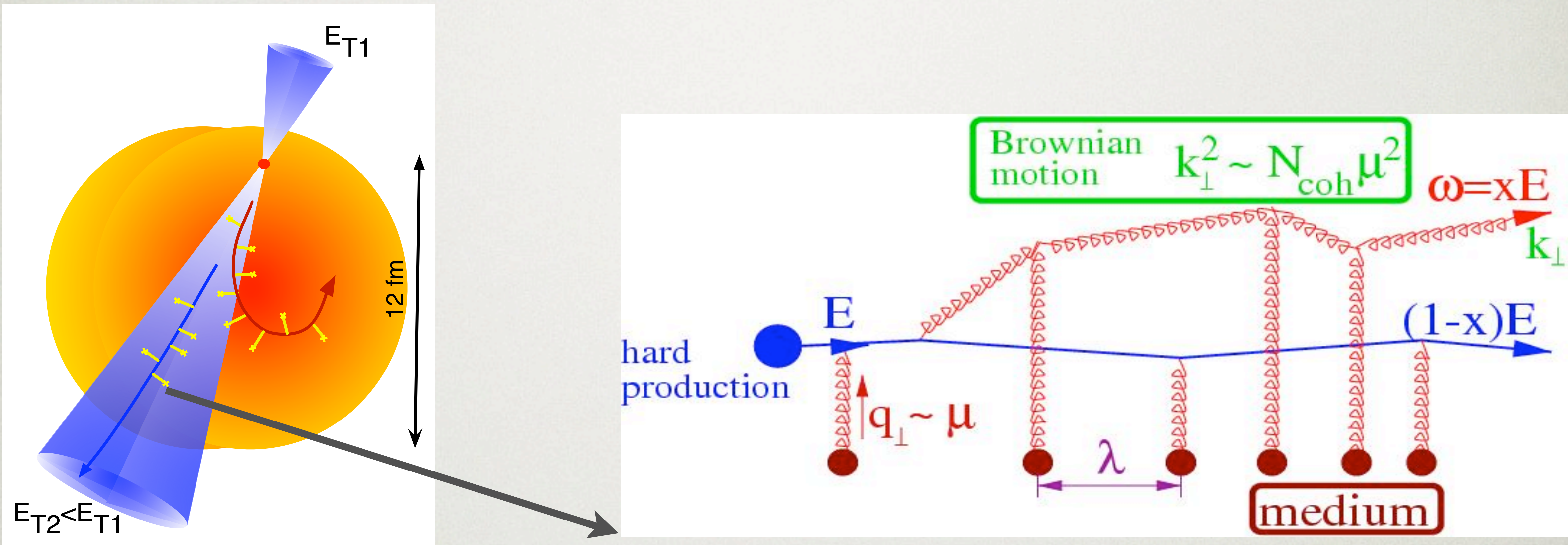


- ... and unsuppressed photons

:: evidence for longitudinal softening of leading parton ::

:: very sketchy theory primer

- parton traversing the medium

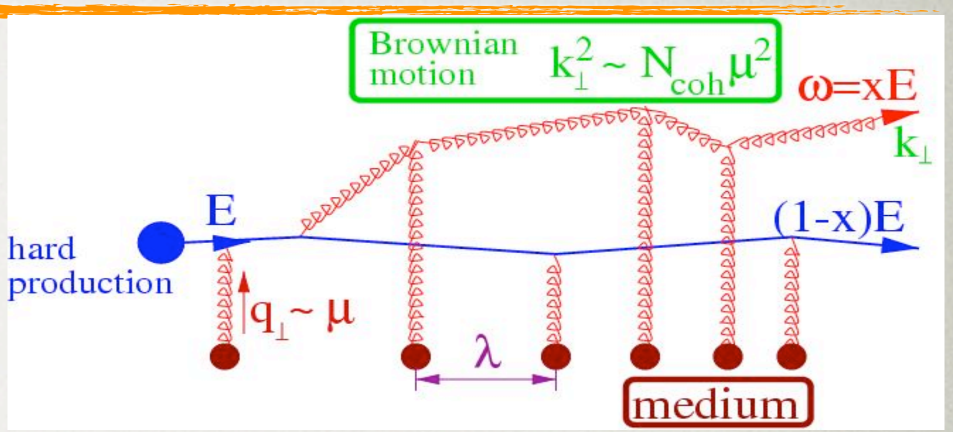


- medium characterized by BDMPS transport coefficient

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

- how much energy is lost ?

:: very sketchy theory primer



- 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

- number of coherent scatterings

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

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

- gluon energy distribution

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

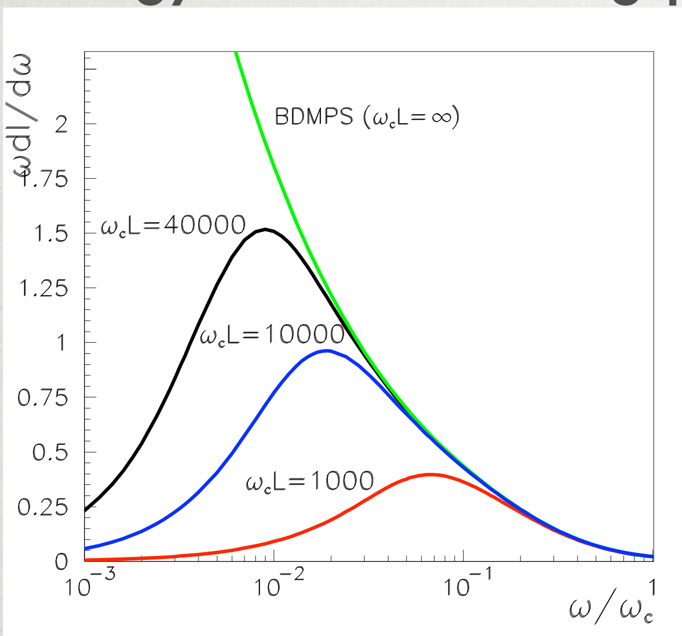
non-abelian LPM

- average energy loss

$$\Delta E = \int_0^L dz \int_0^{\omega_c} \omega d\omega \frac{dI_{med}}{d\omega dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2$$

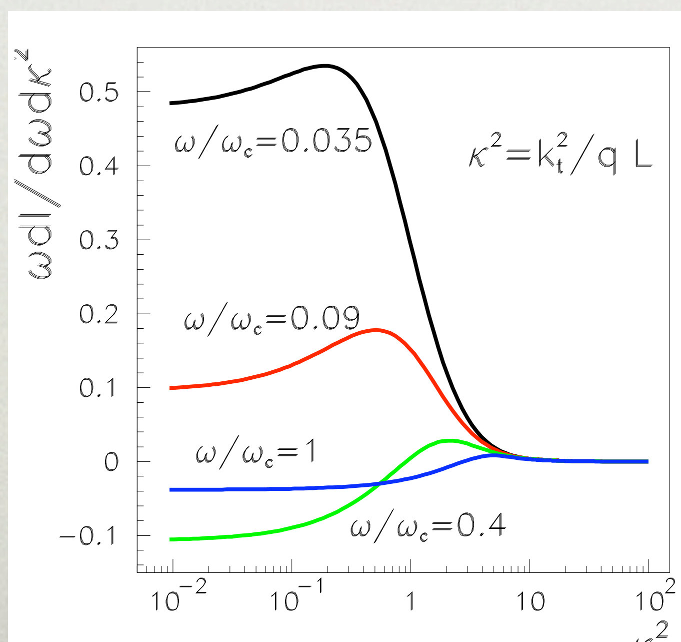
:: very sketchy theory primer

- estimates supported by QCD calculations [and MC implementations]
  - energy loss of leading parton → longitudinal softening

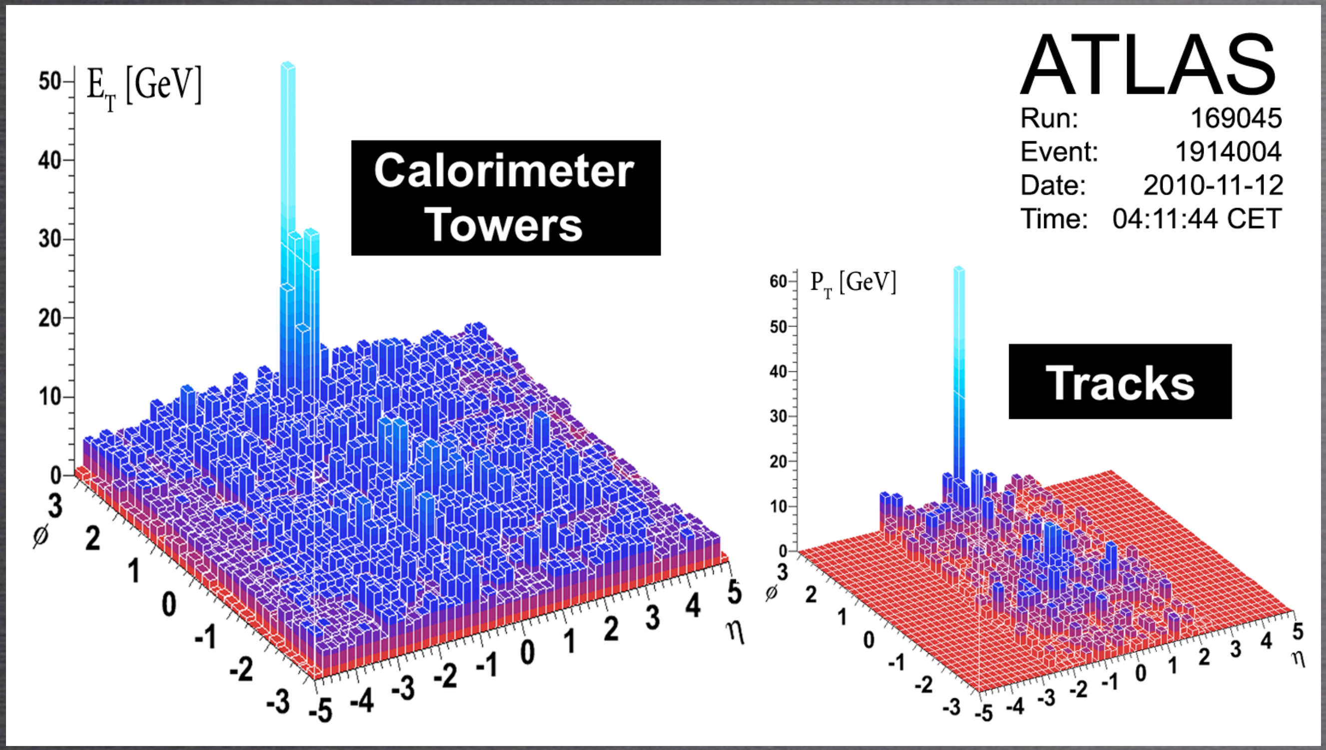


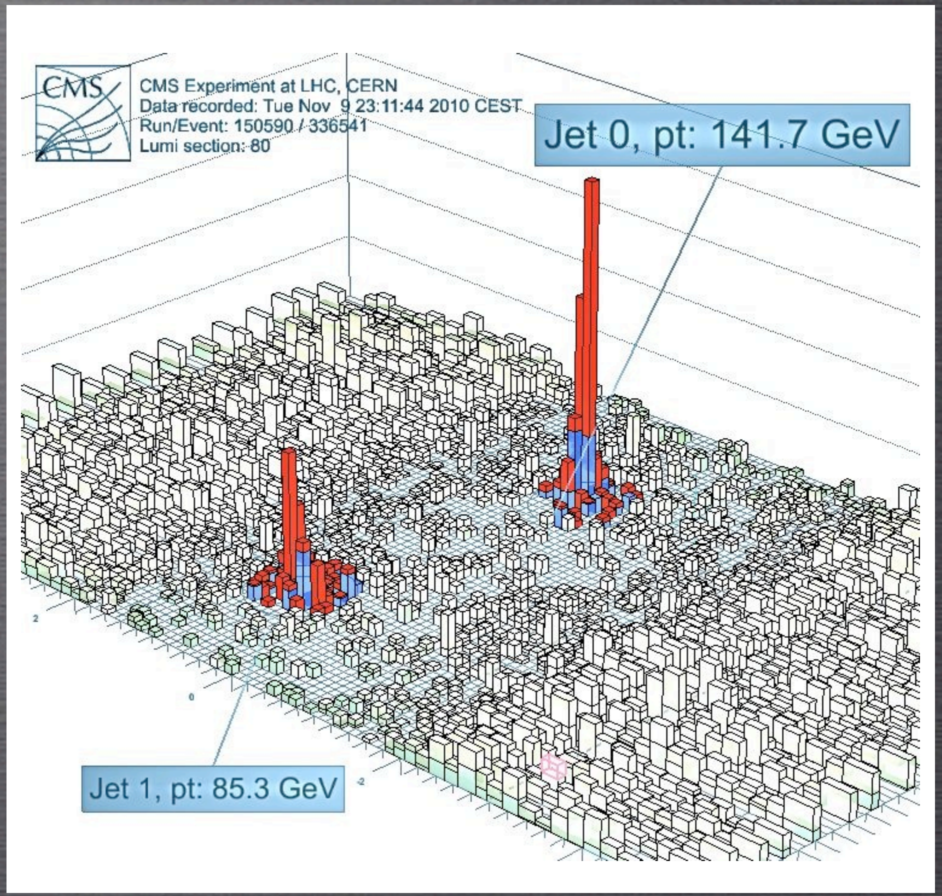
→ $\hat{q}L^2$

  - k_t broadening



→ $\hat{q}L$

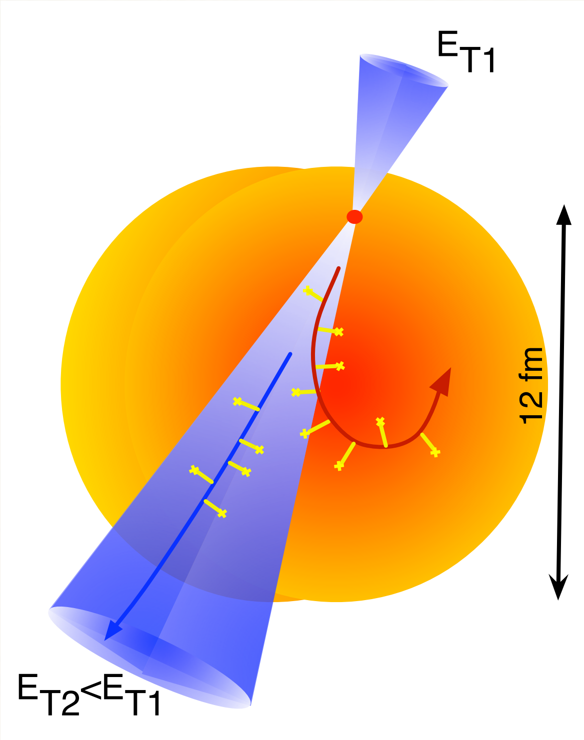




what does LHC data teach us so far?
[calorimetric jets + reconstruction algorithms]
constrained dynamics?

:: di-jet asymmetry

- jet energy within a cone R=0.4 [ATLAS] (R=0.5 [CMS]) with
  - E_{T1} > 100 GeV (120 GeV) [leading jet]
  - E_{T1} > E_{T2} > 25 GeV (50 GeV) [recoiling jet] with azimuthal separation Δϕ > π/2 (2/3 π)



- energy asymmetry

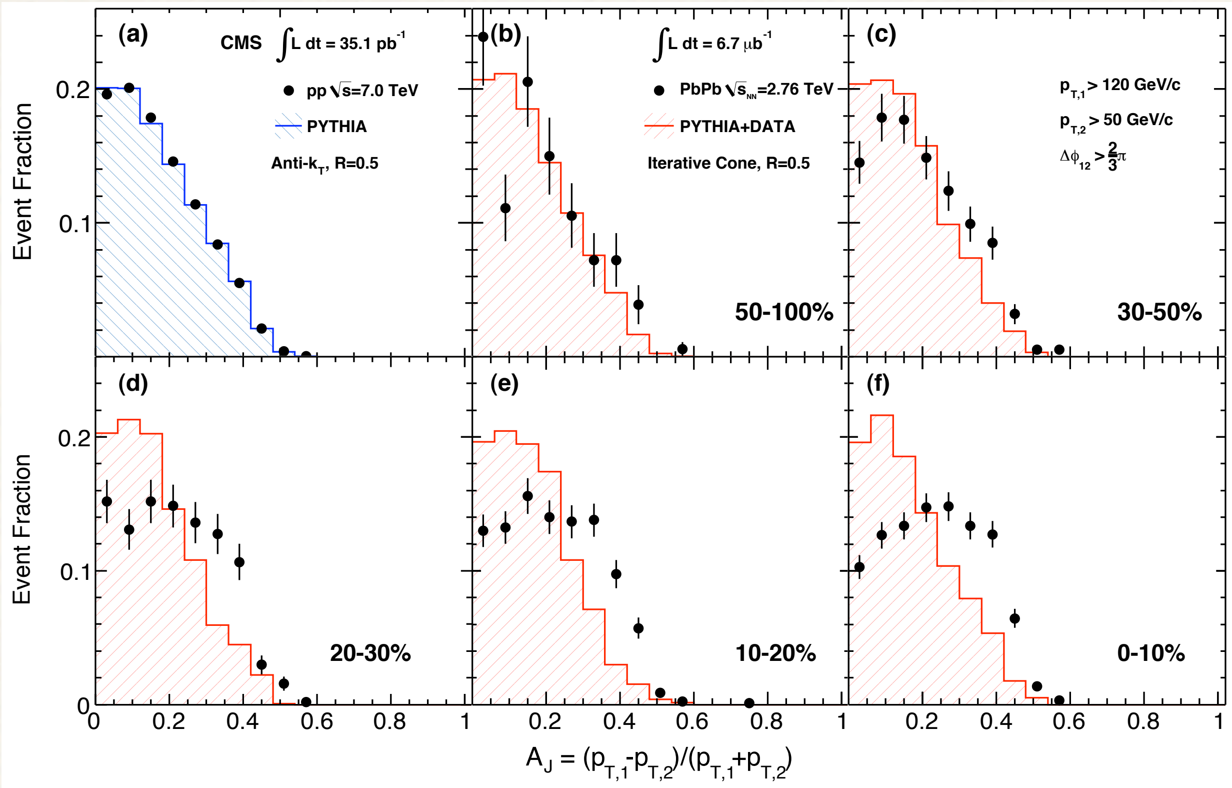
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

- jet finding in high multiplicity environment is challenging
  - [c.f. Gavin's talk]

:: di-jet asymmetry

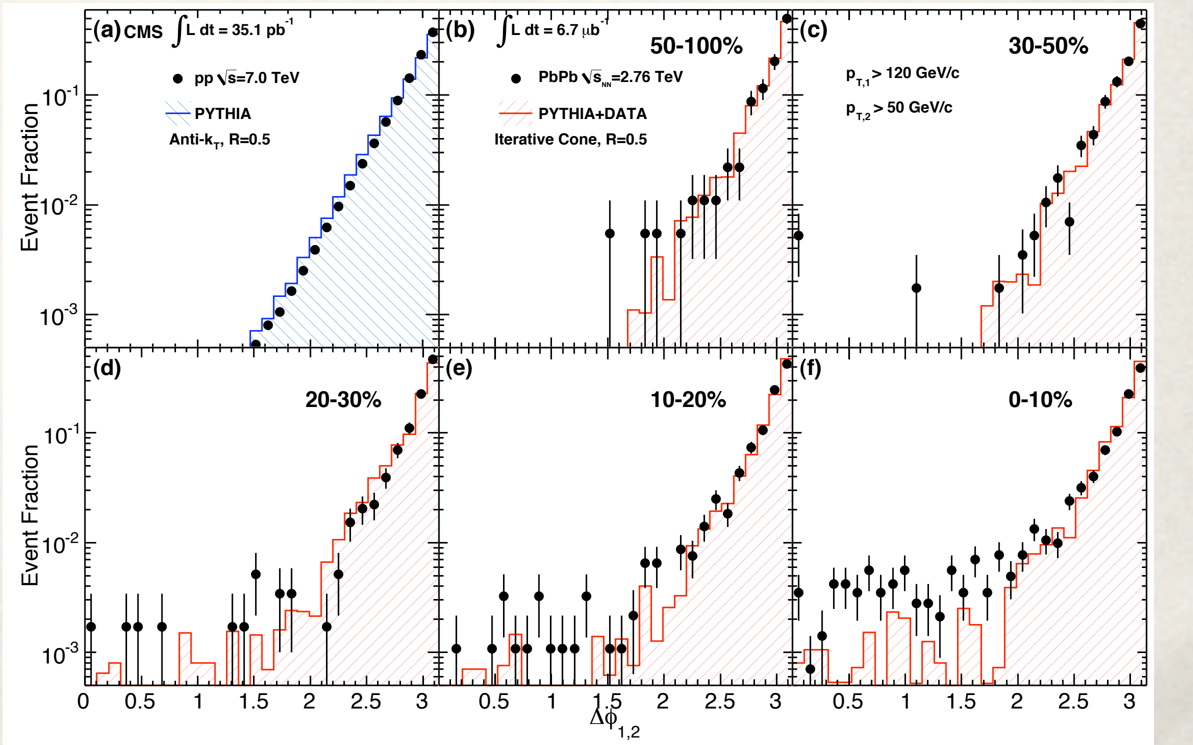
↪ energy asymmetry grows with centrality

CMS

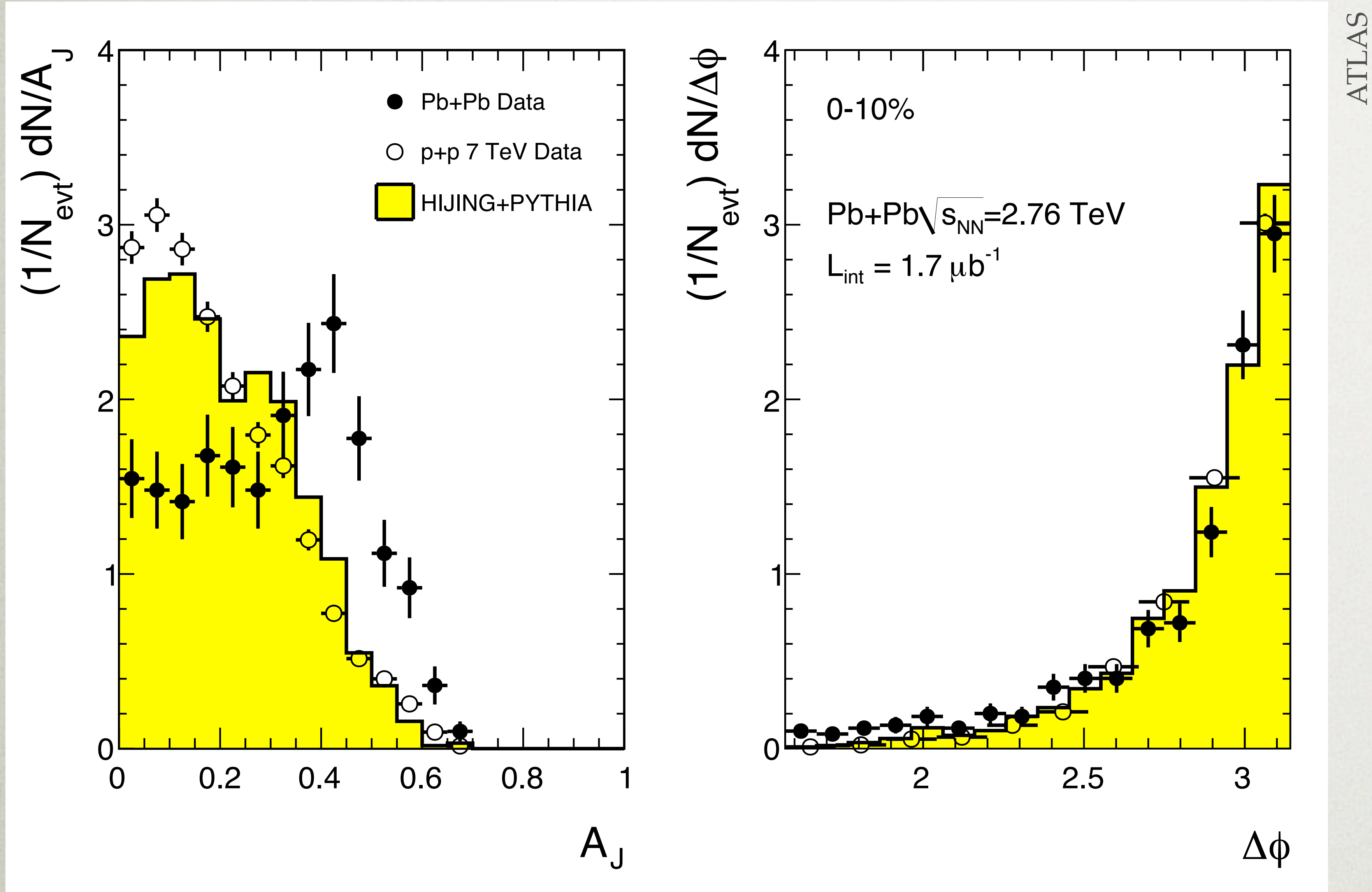


↪ very mild dependence for azimuthal distribution [also *unchanged* from pp]

CMS



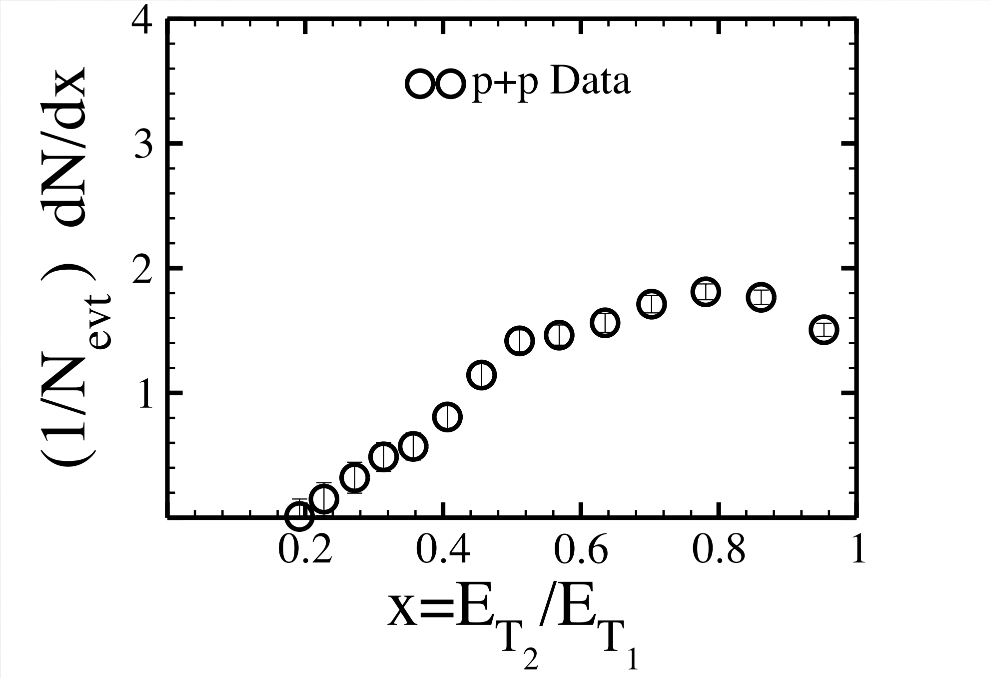
:: most central events



- clear suppression of more symmetric events [$0 < A_J < 0.2$]
- enhancement of events with $A_J \approx 0.5$
- very mild modification of the azimuthal angle distribution

:: few observations [pp]

- pp jets are asymmetric



E_{T1} good approximation to E_{tot}
[data sample biased to leading jets with 'little' energy loss]

$x= E_{T2}/E_{T1}$
[fractional energy in associated jet]

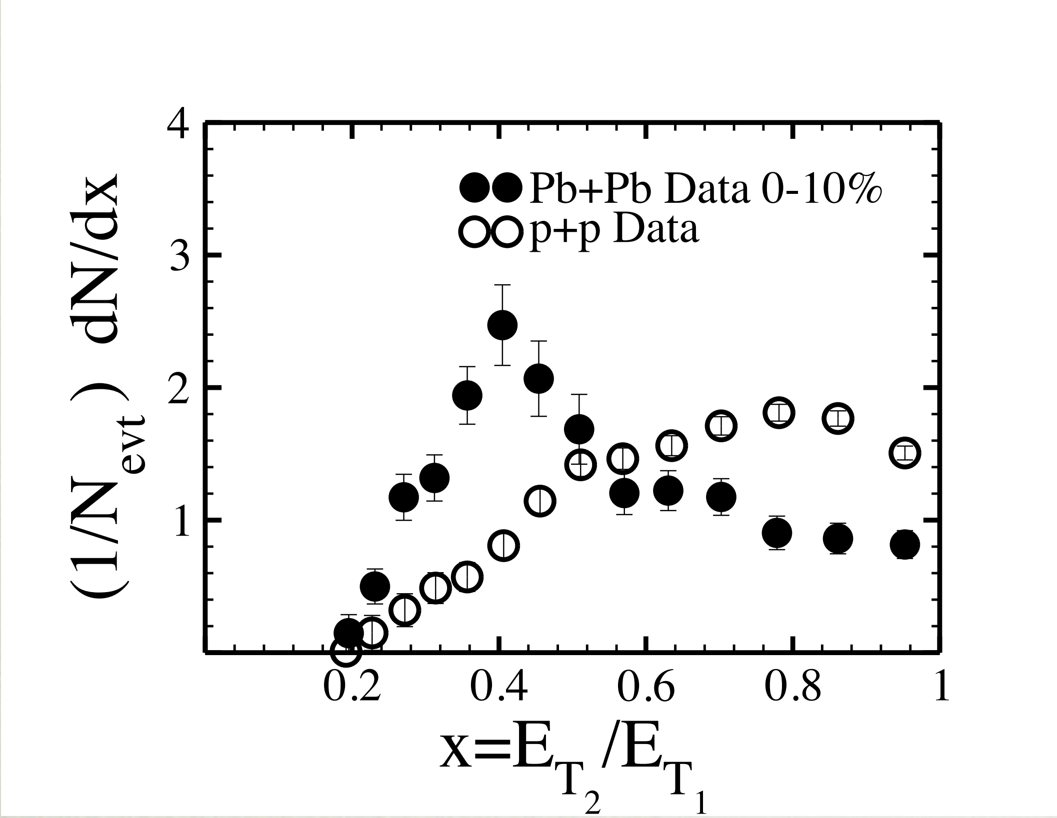
- significant out of cone radiation [average fractional in associated jet]

$$\langle x \rangle_{pp} \leq \frac{1}{N_{evt}} \int dx\, x \frac{dN}{dx} = 0.67$$

- wide energy distribution

:: out-of-cone radiation in PbPb

- ‘moderate’ additional out-of cone radiation in PbPb



$$\langle x \rangle_{PbPb} \leq \frac{1}{N_{evt}} \int dx\, x \frac{dN}{dx} = 0.54$$

$$\langle x \rangle_{pp} - \langle x \rangle_{PbPb} \simeq 0.13$$

↪ estimate energy loss

- [underestimate] all jets interact equally $\frac{\langle E \rangle}{E_T} > 0.1$

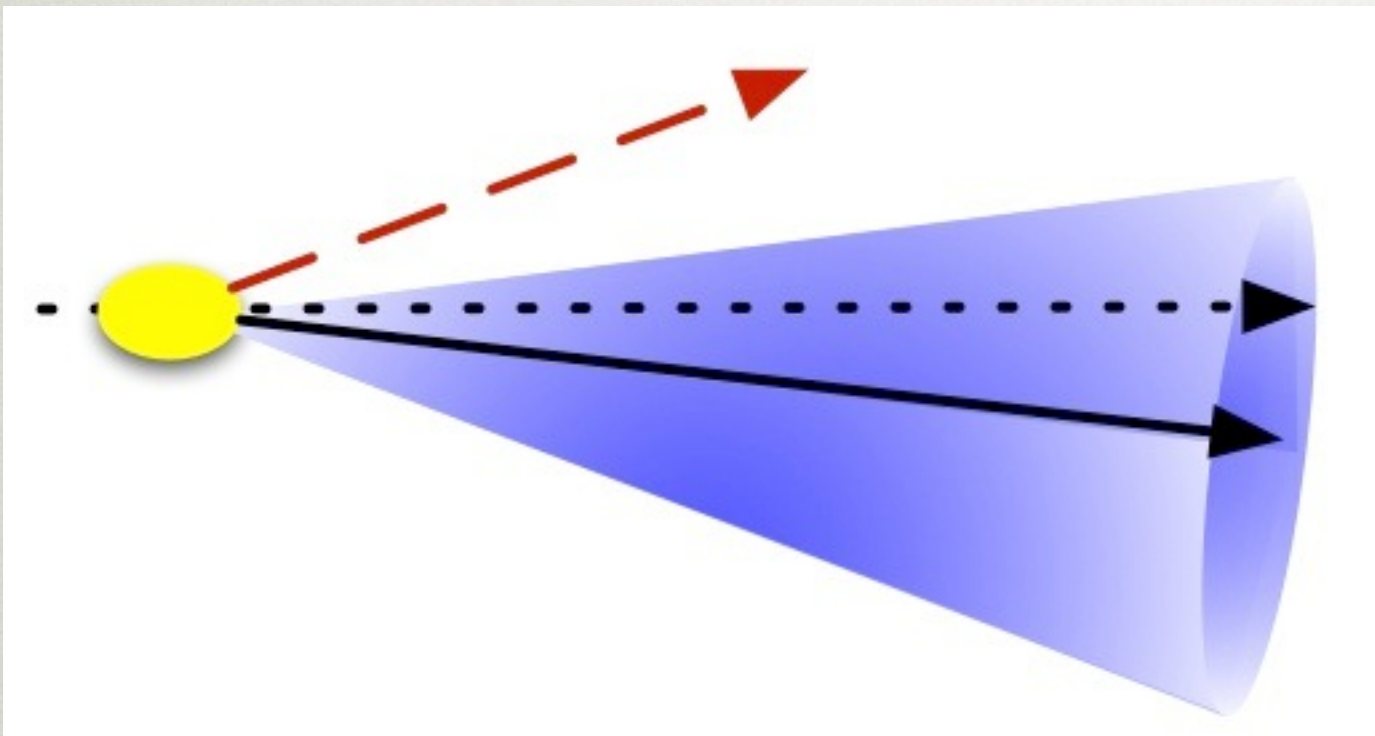
$\alpha < 0.5$

- [overestimate] only fraction (1-α) interact [corona effect] $\frac{\langle E \rangle}{E_T} < 0.2$

:: requires medium induced transverse broadening ::

:: out-of-cone emission

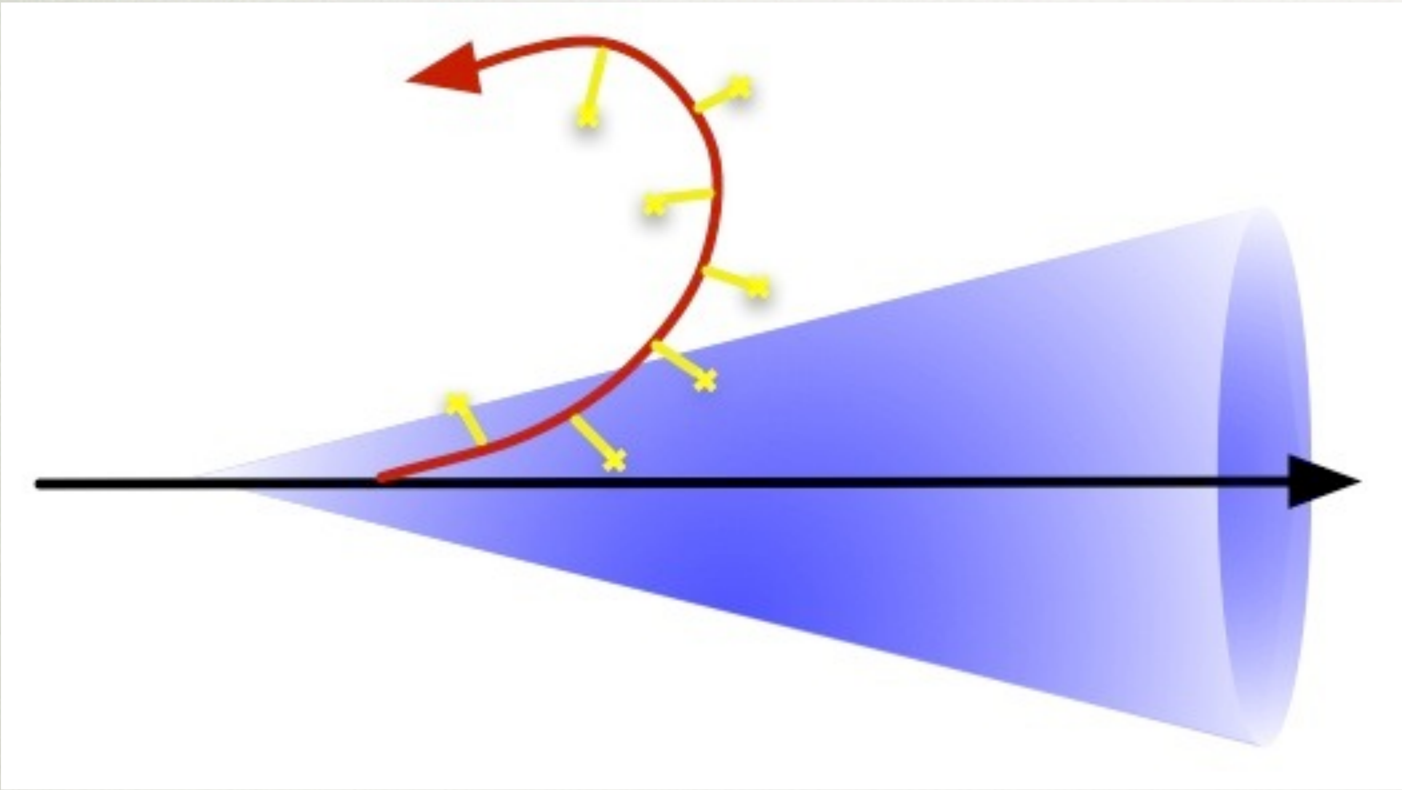
- large angle *medium induced* hardish radiation ?



deflects recoiling jet → sizeable modification of azimuthal distribution

:: out-of-cone emission

- transport of radiated gluons



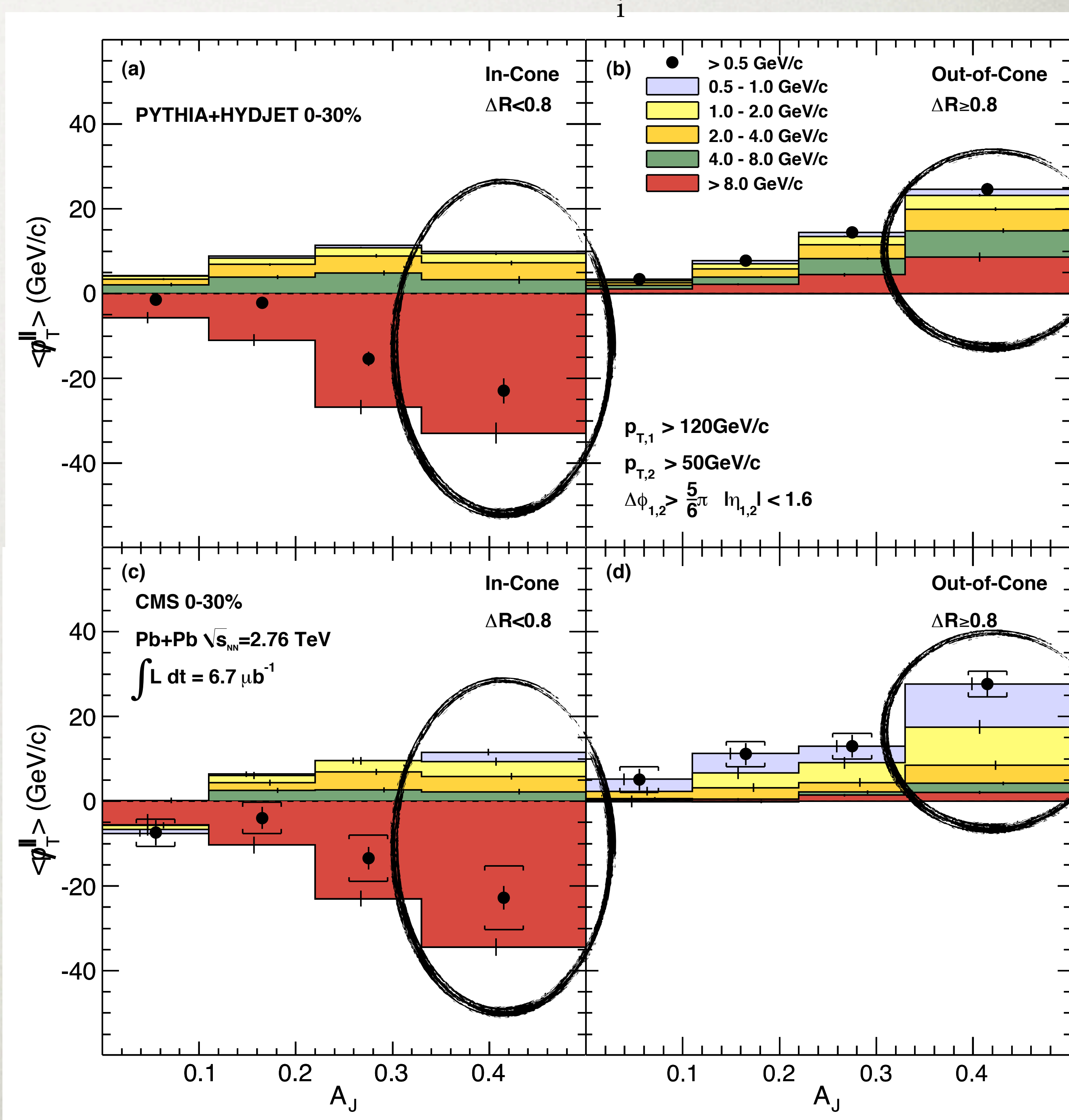
- very effective for softer components

the medium acts as a frequency collimator efficiently trimming away the soft components of the jet

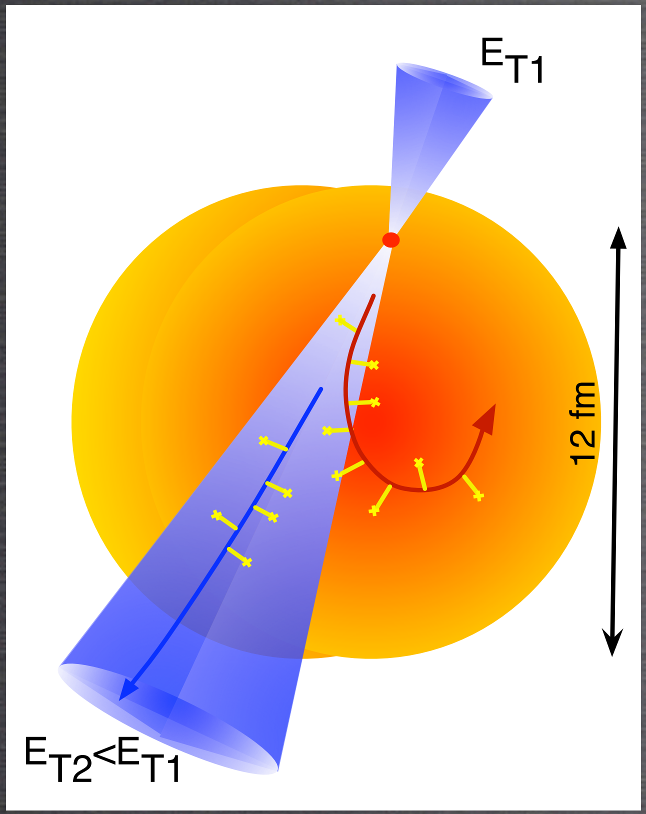
:: (in .vs. out) of cone radiation

- no missing transverse momentum [CMS] :: who is where?

$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{Leading Jet}}\right)$$



- given A_J achieved in PbPb by out-of-cone radiation of extra *soft* modes
  - ↪ medium strongly enhances out-of-cone *soft* radiation
- mild softening of in-cone radiation pattern



a simple underlying dynamical mechanism ?

[beyond and before any specific formal implementation]

:: enhanced asymmetry
:: unchanged azimuthal distribution
:: small in-cone effect
:: increase of out-of-cone soft radiation

:: jet collimation

[with Jorge Casalderrey-Solana and Urs Wiedemann]

arXiv:1012.0745 [hep-ph], J Phys G (2011)

- all jet components accumulate an average transverse momentum [Brownian motion]

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

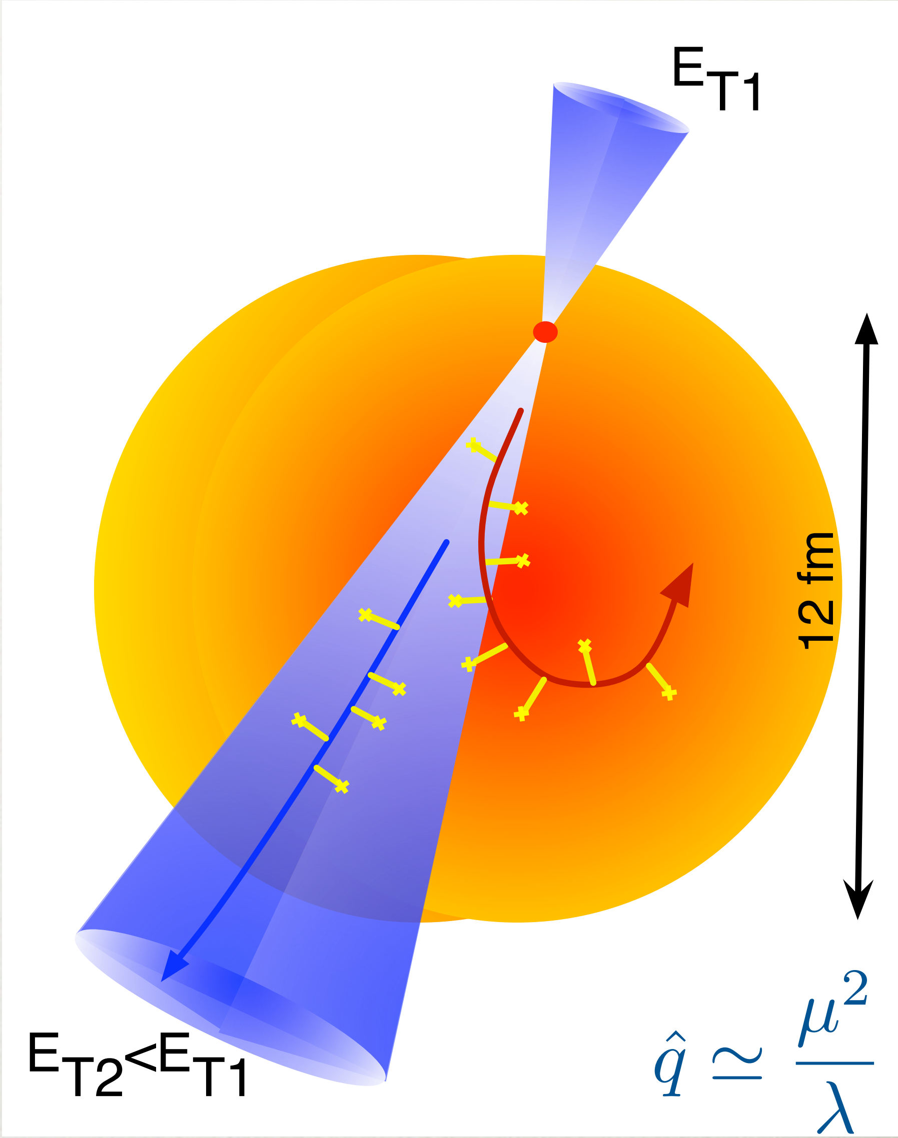
- soft modes are formed early

$$\tau \sim \frac{\omega}{k_\perp^2} \quad \xrightarrow[\langle k_\perp^2 \rangle \sim \hat{q}\tau]{} \langle \tau \rangle \sim \sqrt{\frac{\omega}{\hat{q}}}$$

- sufficiently soft modes are decorrelated from the jet direction

$$\omega \leq \sqrt{\hat{q}L}$$

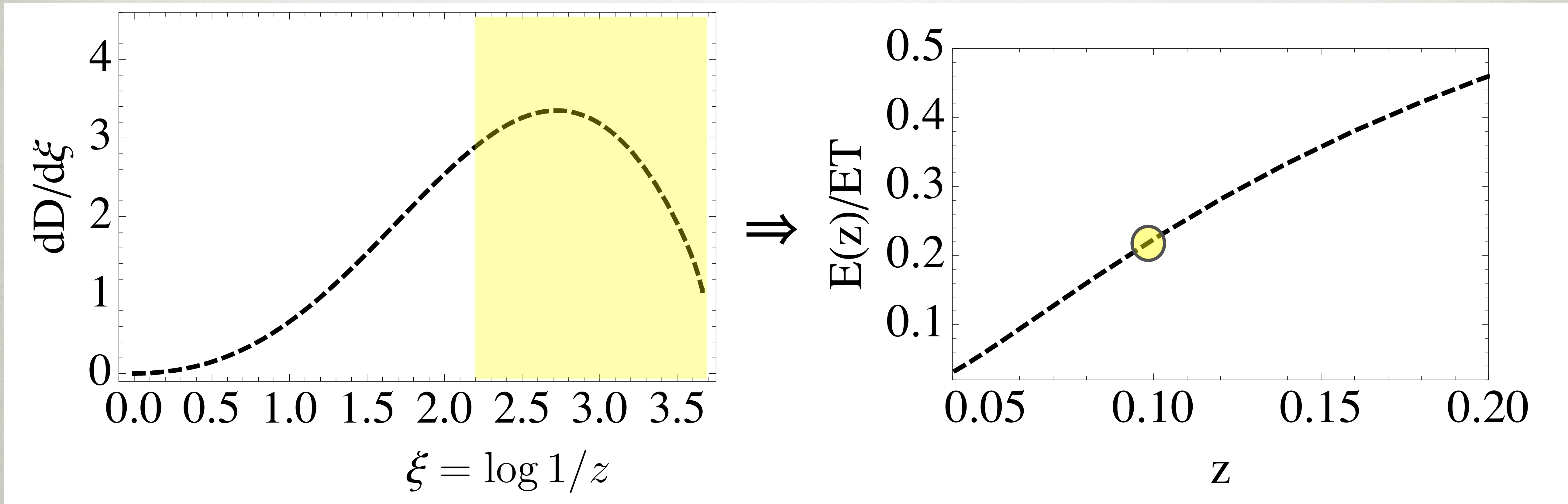
↪ [the medium filters out soft components of the jet 'wave-function']



the mechanism does not require further splitting [but it is further enhanced by it]

:: energy fraction in soft components

- parton distribution within [vacuum MLLA] jet [evolved to $Q_0 = 1$ GeV]

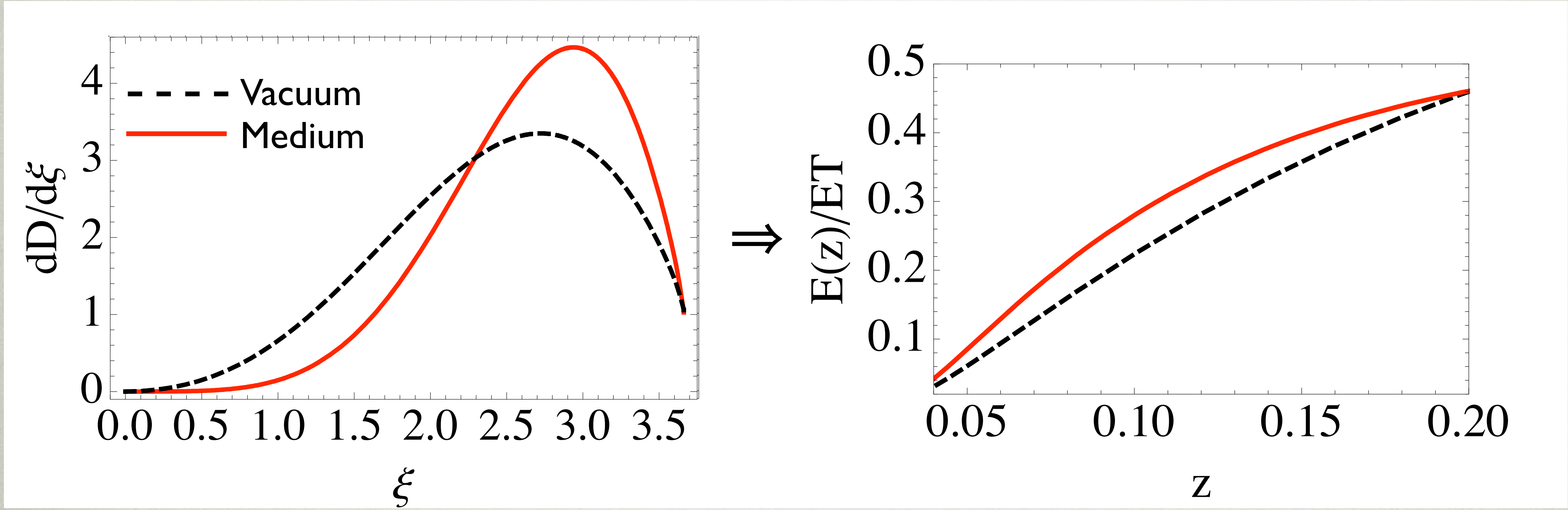


- significant amount of energy stored in soft modes

$$\frac{E(z)}{E_T} = \int_{\log 1/z}^{\infty} d\xi \, e^{-\xi} \frac{dD}{d\xi}$$

:: energy fraction in soft components

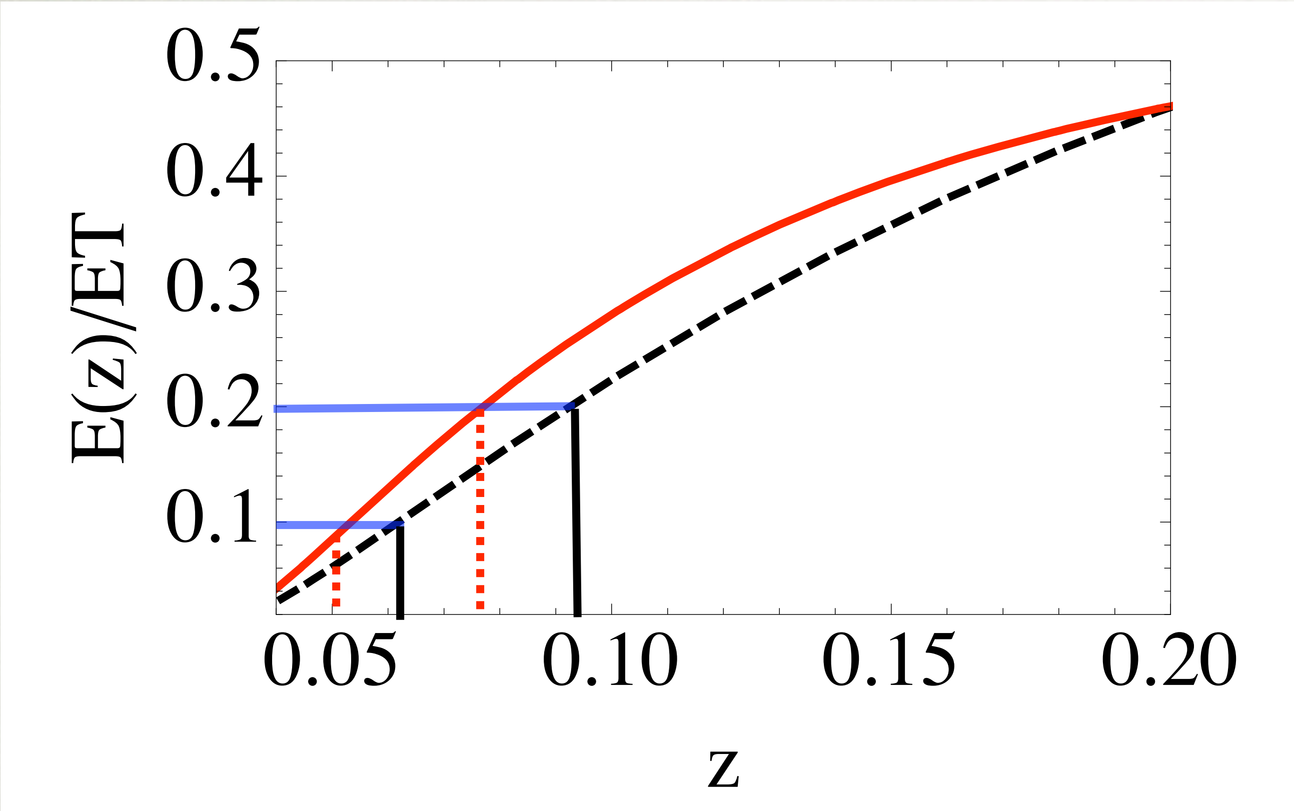
- medium effects [medium modified MLLA :: Borghini/Wiedemann] further soften parton distribution [medium induced gluon radiation]



- larger energy fraction stored in soft modes
  - ↪ further mechanisms for early radiation of soft modes [Mehtar-Tani, Salgado, Tywoniuk 2010-2011]

:: an estimate of qhat

- use estimates for out-of-cone energy loss



partons with energy

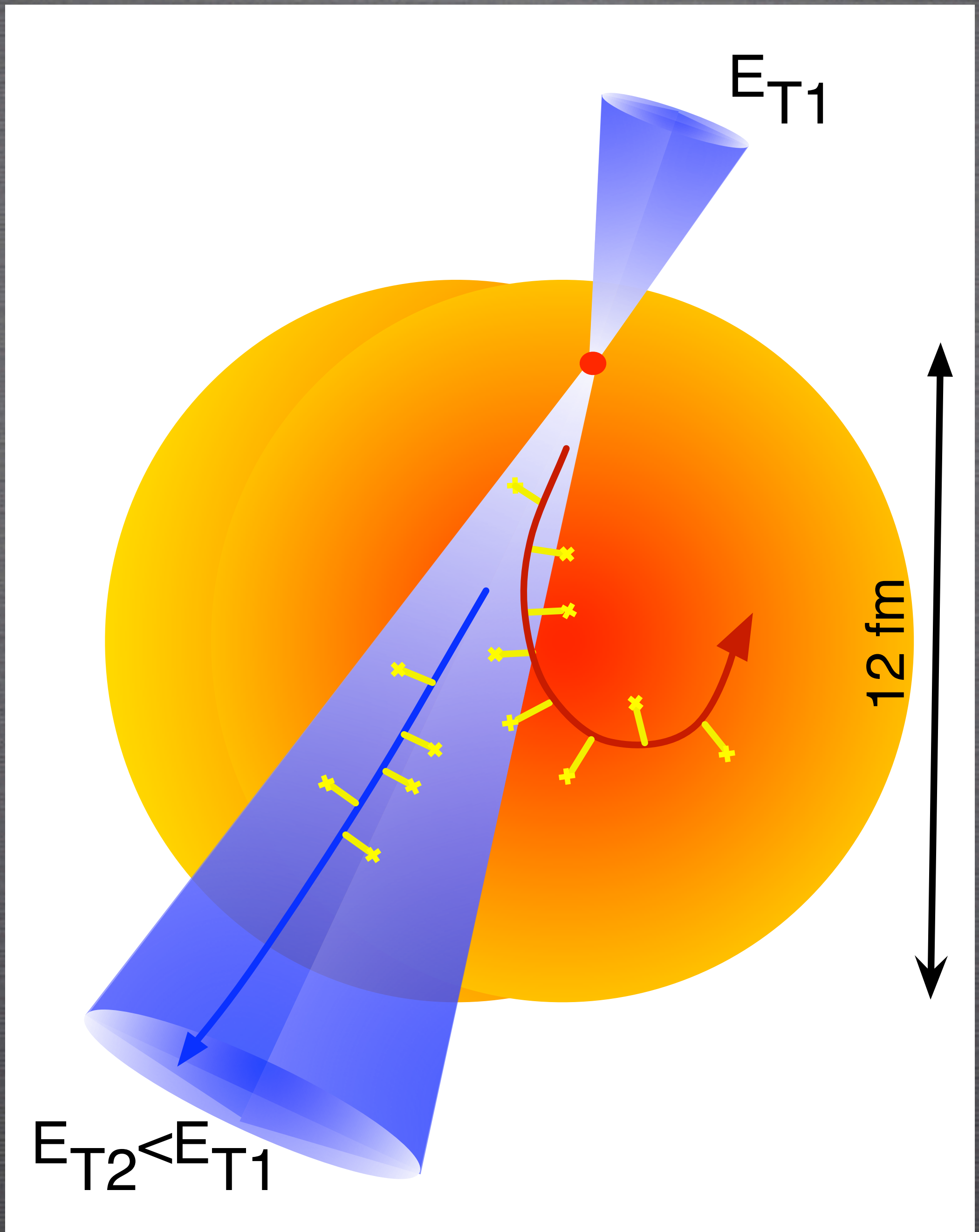
$$\omega^2 = z^2 E_T^2 \leq \hat{q} L$$

are decorrelated from the jet

$$35 \left(\frac{E_T}{E_0}\right)^2 \leq \hat{q}L \leq 85 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$$ [vacuum distribution :: MLLA]

$$30 \left(\frac{E_T}{E_0}\right)^2 \leq \hat{q}L \leq 60 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$$ [medium modified distribution]

E_0 = 100 GeV



jet frequency collimation is a natural mechanism to explain existing data