Jet Quenching via Jet Collimation

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CENTRA-IST & CERN PH-TH

[with Jorge Casalderrey-Solana and Urs Wiedemann]

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INSTITUTO SUPERIOR TÉCNICO

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jets [what has the LHC done for us]

- LHC data on full jets in PbPb collisions [previous talks] offers the possibility to probe the QCD dynamics in the presence of a medium
  - ↪ jets are a better proxy for the originating parton than other probes [e.g. leading hadrons]
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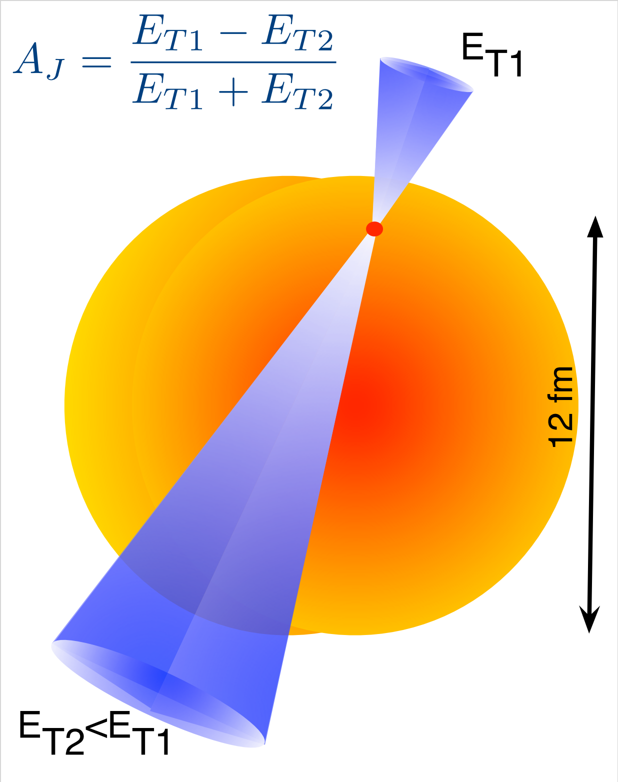
Does available LHC data imply qualitative rethinking/development of fundamental ingredients of ‘Jet Quenching’ ?

measurement of di-jet asymmetry



- *imbalance of jet energy within a cone of radius R* •

	int. luminosity [μb^{-1}]	*R*	E_{T1}^{min} [GeV] *[leading jet]*	E_{T2}^{min} [GeV] [recoiling jet]	$\Delta\phi^{min}$	
ATLAS	1.7	0.4	100	25	$\pi/2$	*1011.6182, PRL (2010)*
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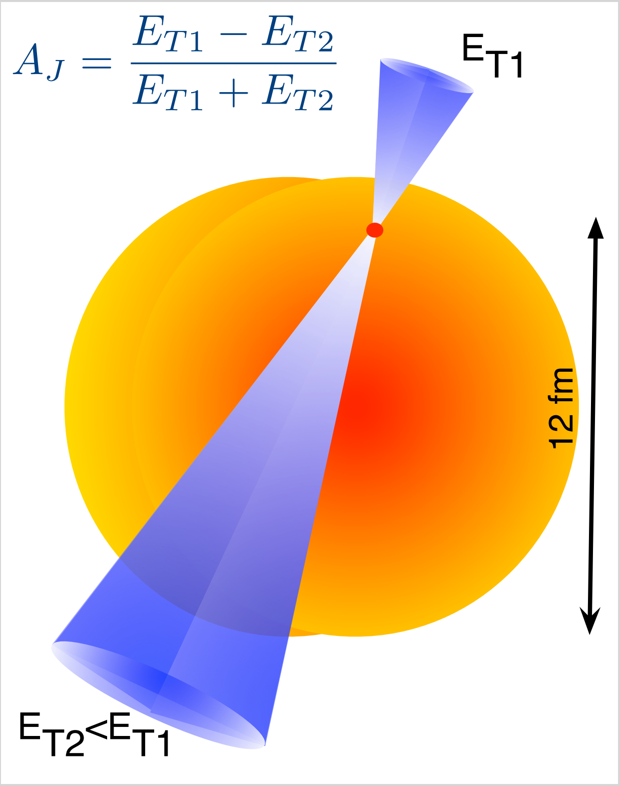

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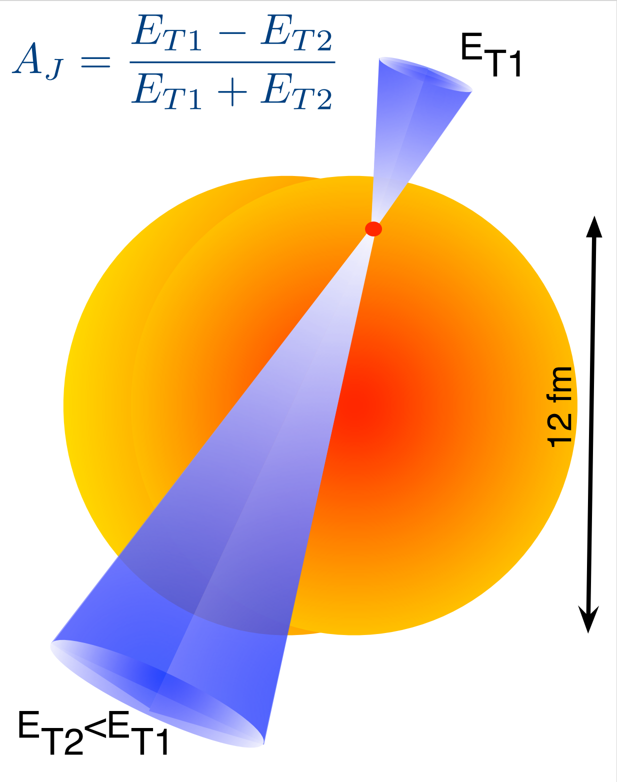

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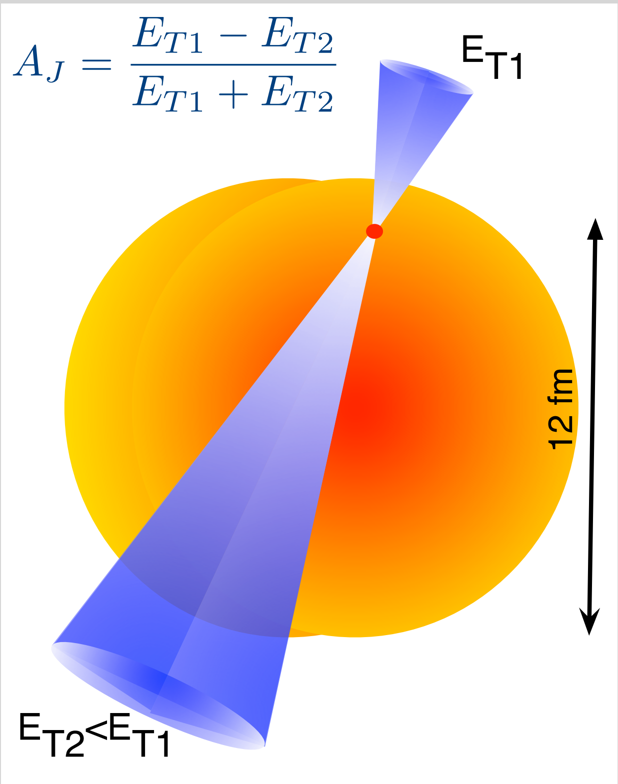

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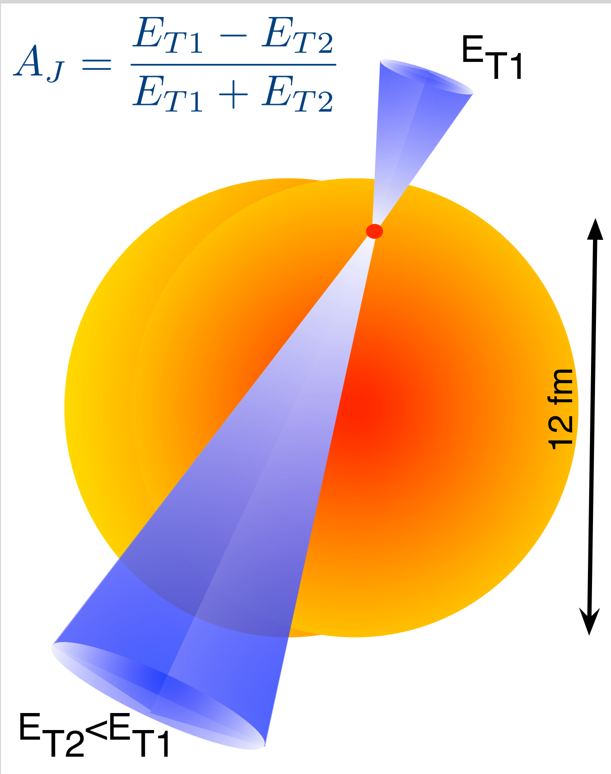

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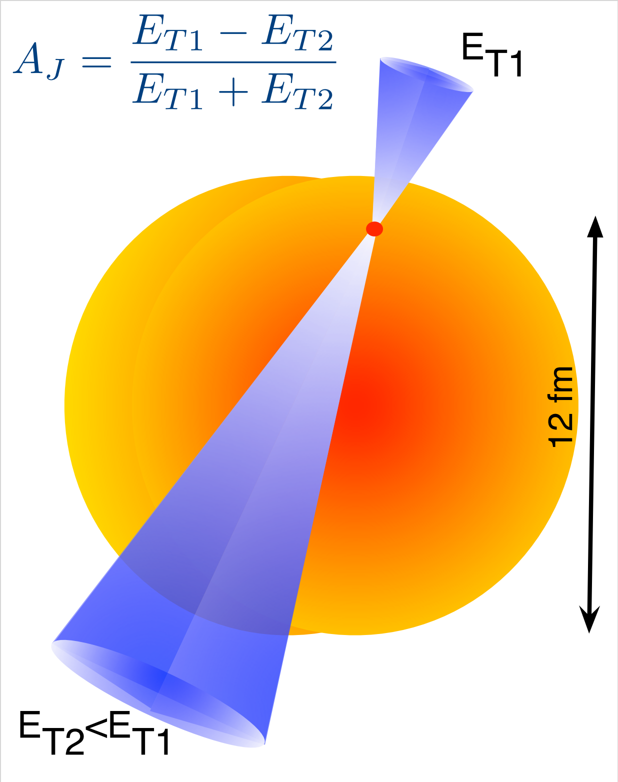

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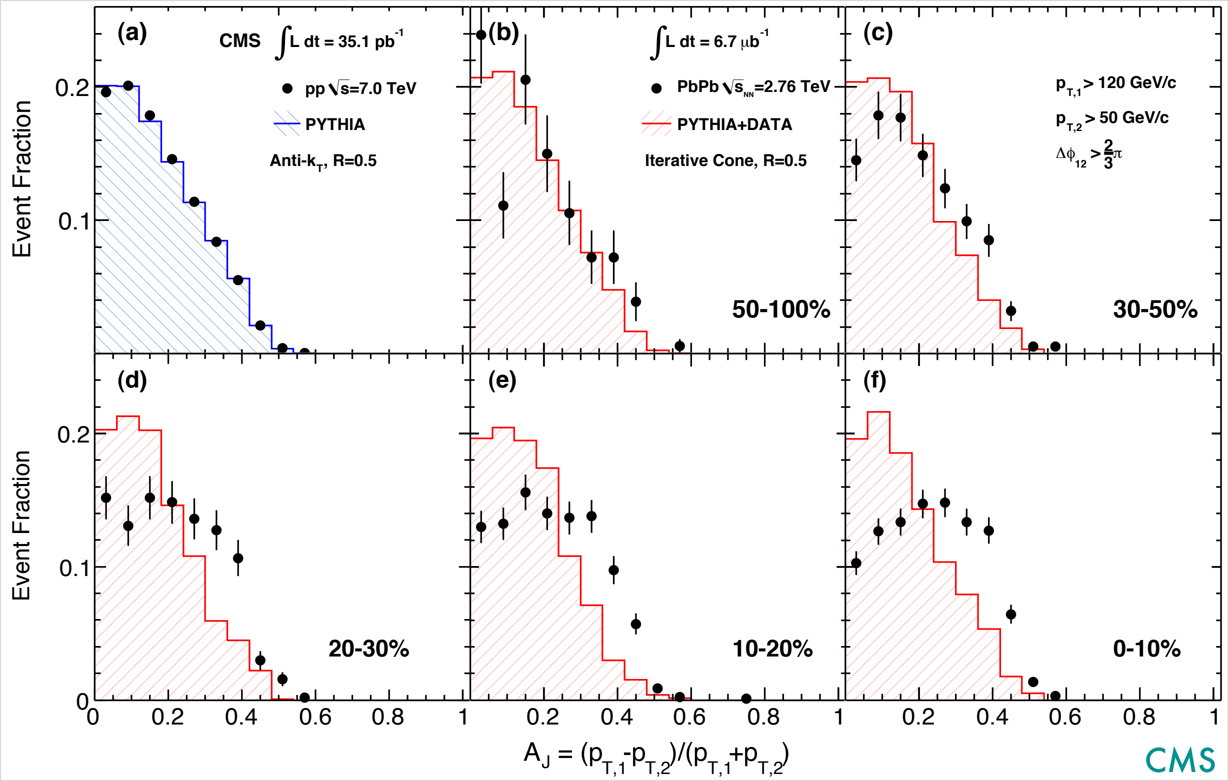
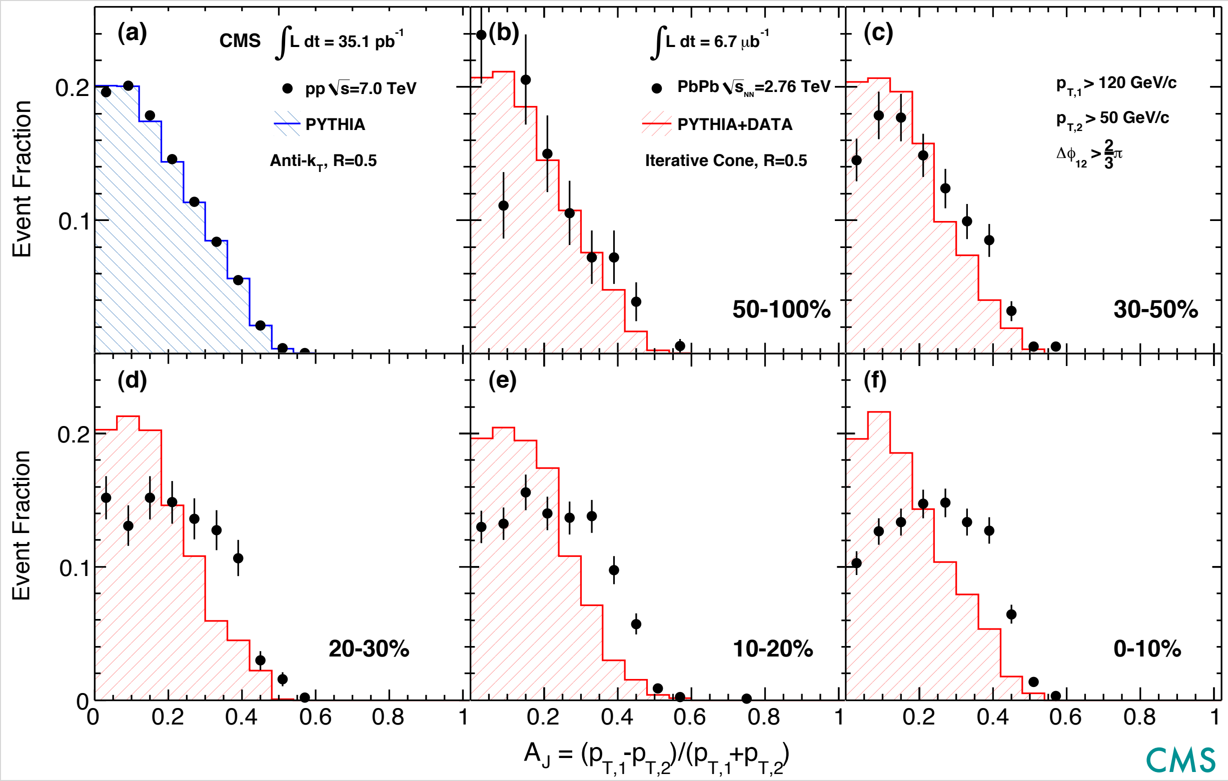
::for the purpose of this talk::
observed asymmetry robust against background issues at [least at] the level of qualitative features

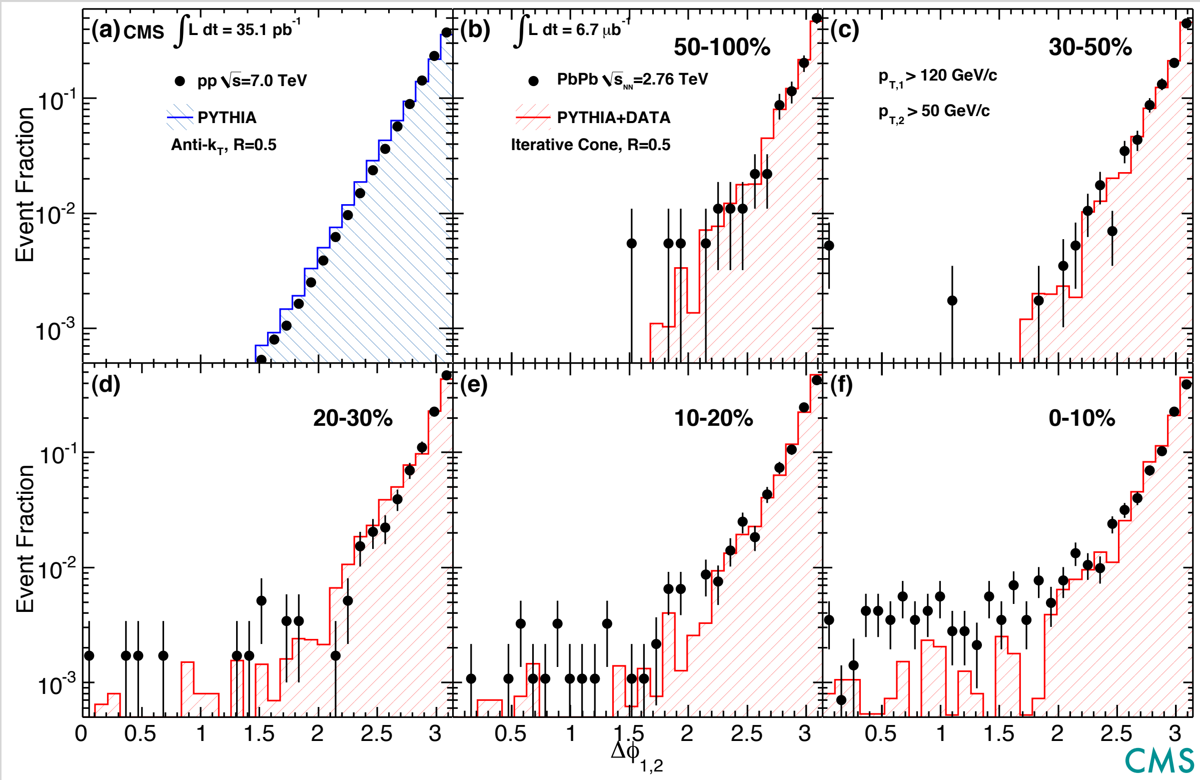
di-jet asymmetry [qualitative features]



- asymmetry increases with centrality
  - ↪ [increased in-medium path length for recoiling jet]

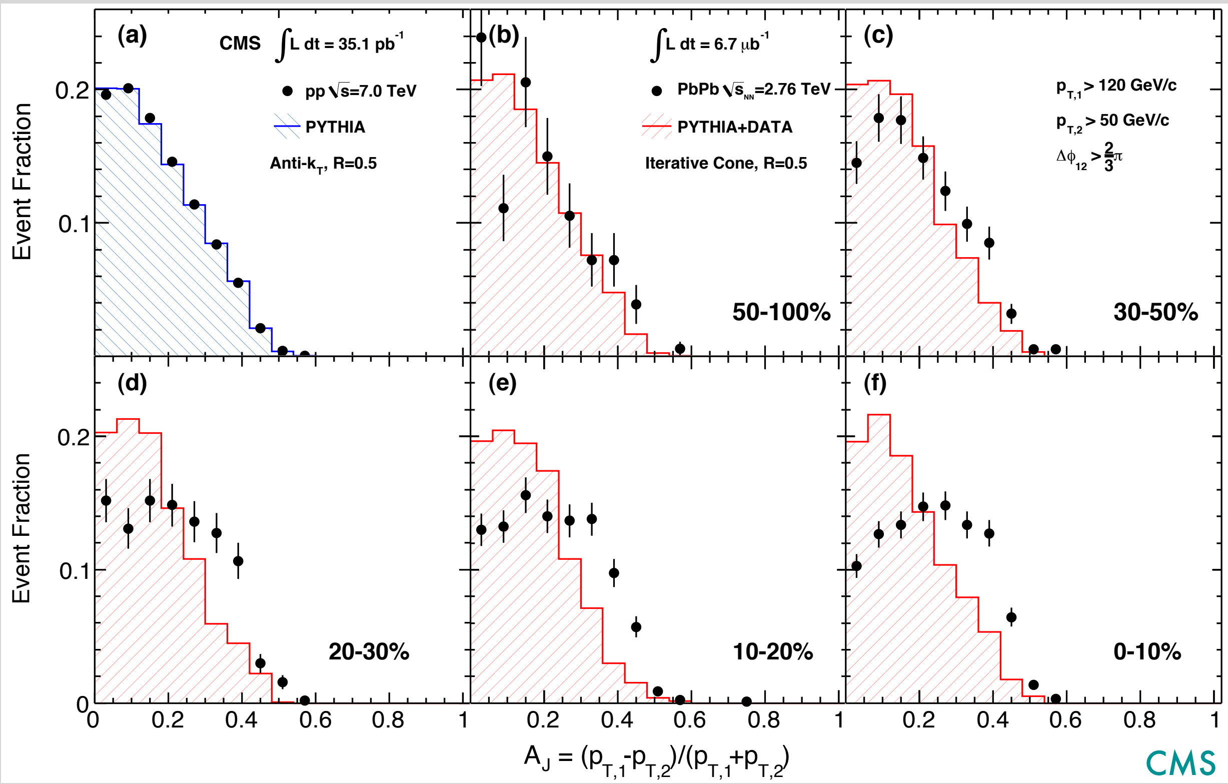
di-jet asymmetry [qualitative features]

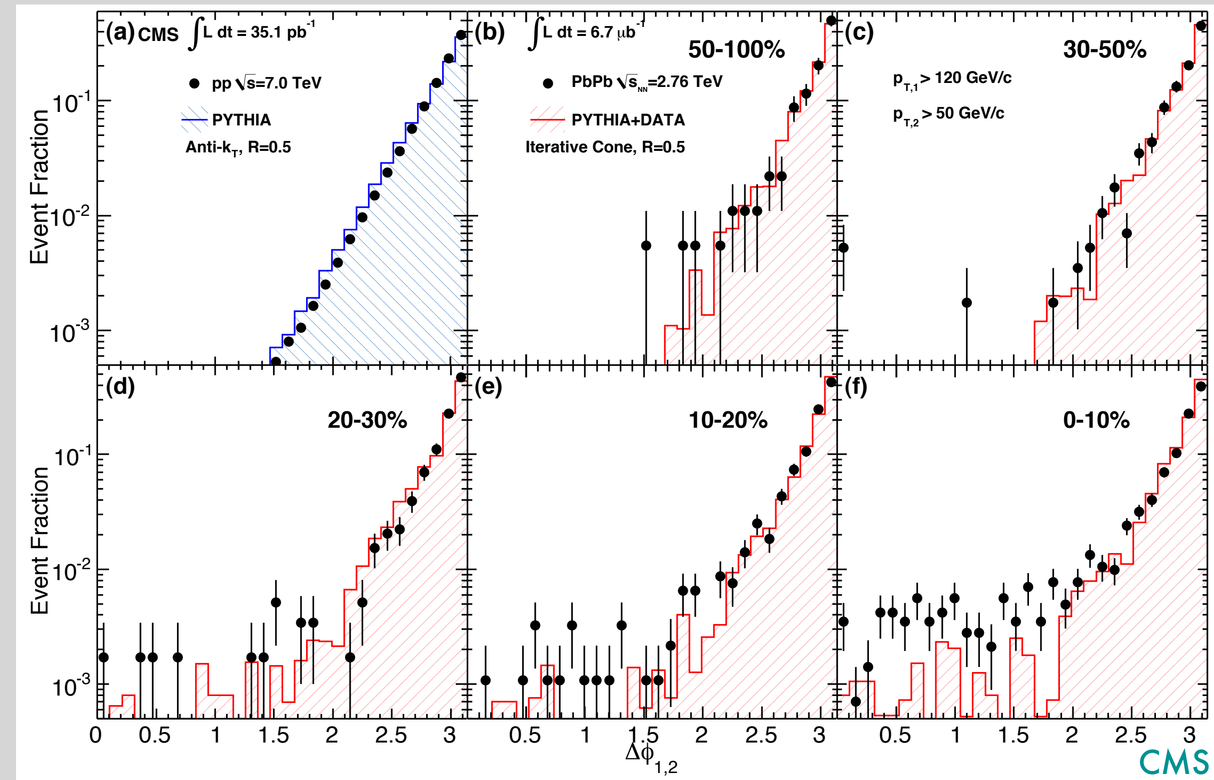




- asymmetry increases with centrality
  - ↪ [increased in-medium path length for recoiling jet]
- very mild centrality dependence for azimuthal distribution and essentially unchanged from pp
  - ↪ [minor medium-induced jet deflection]

di-jet asymmetry [qualitative features]





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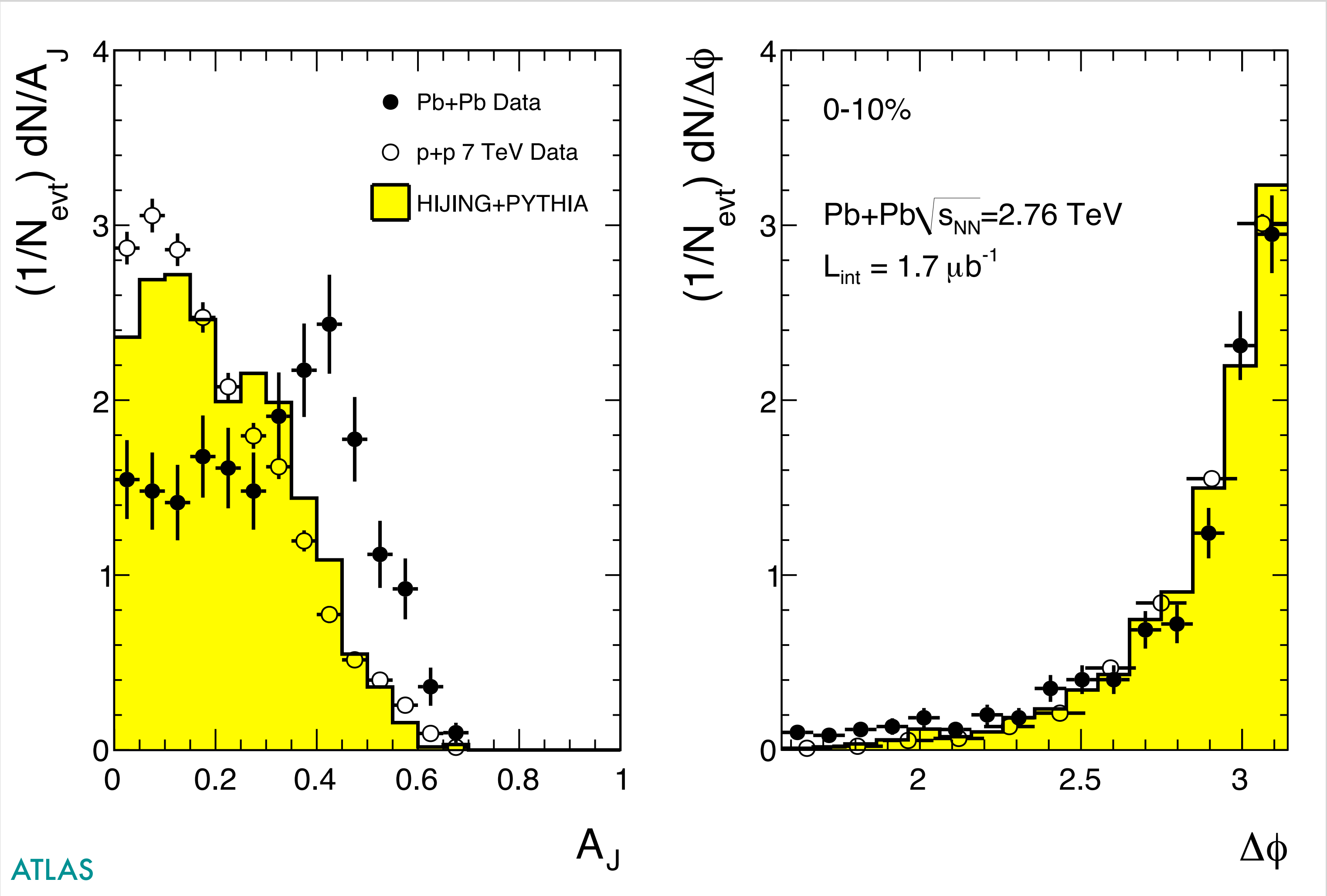
  - [minor medium-induced jet deflection]

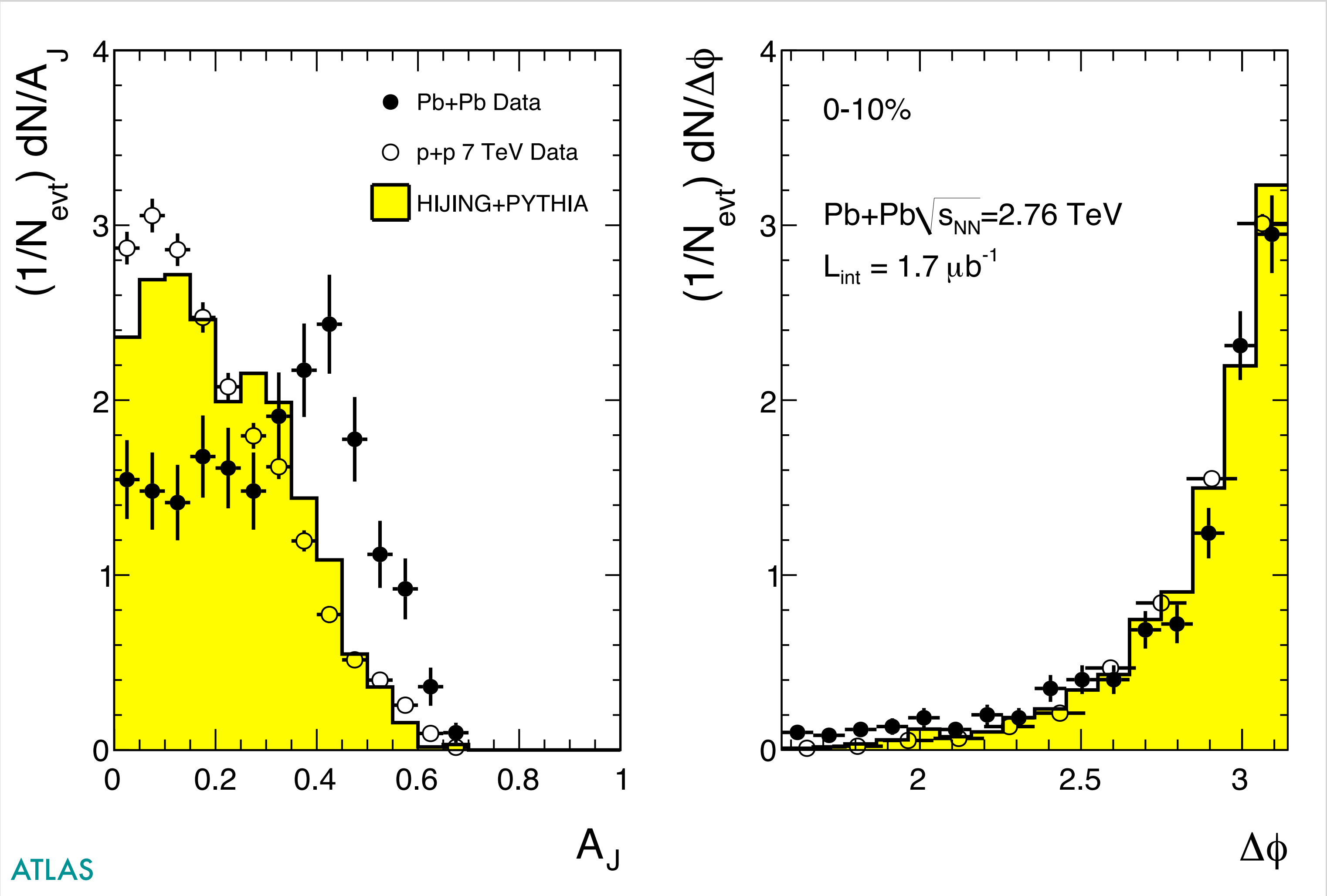
focus on most central events [where the effect is maximal]

most central events



- clear suppression of more symmetric events [$0 < A_J < 0.2$]
- enhancement of events with $A_J \approx 0.4 \div 0.5$
- sharp fall-off at large A_J not entirely physical [focus on not too large A_J]
- very mild modification of the azimuthal angle distribution

most central events



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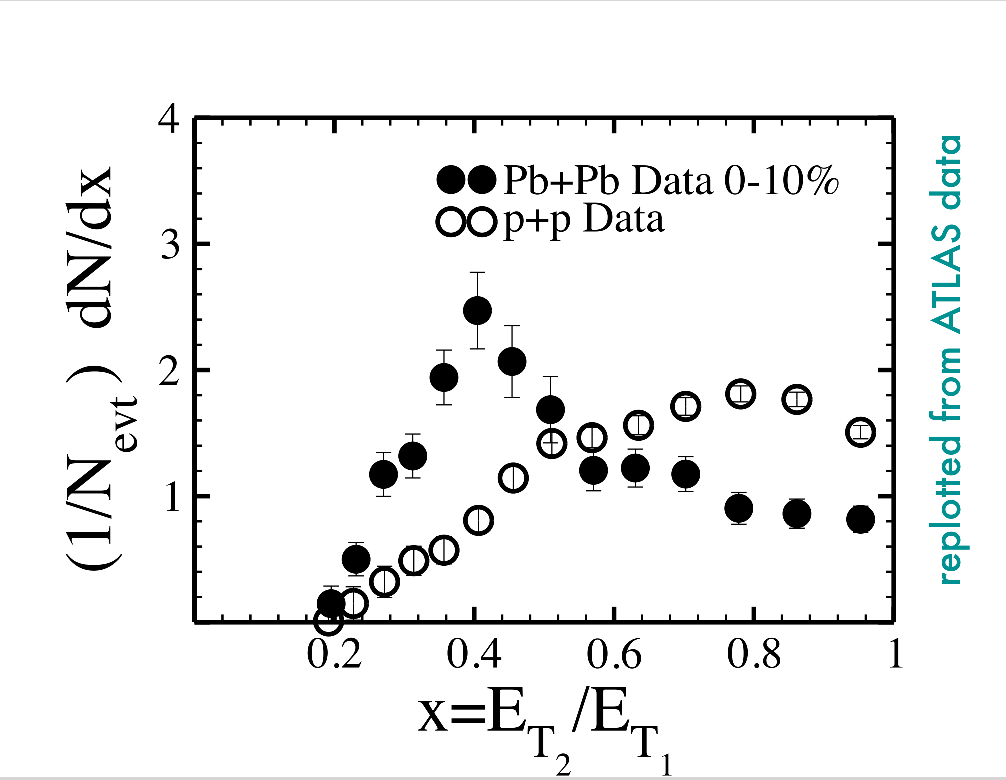
requires medium induced transverse broadening

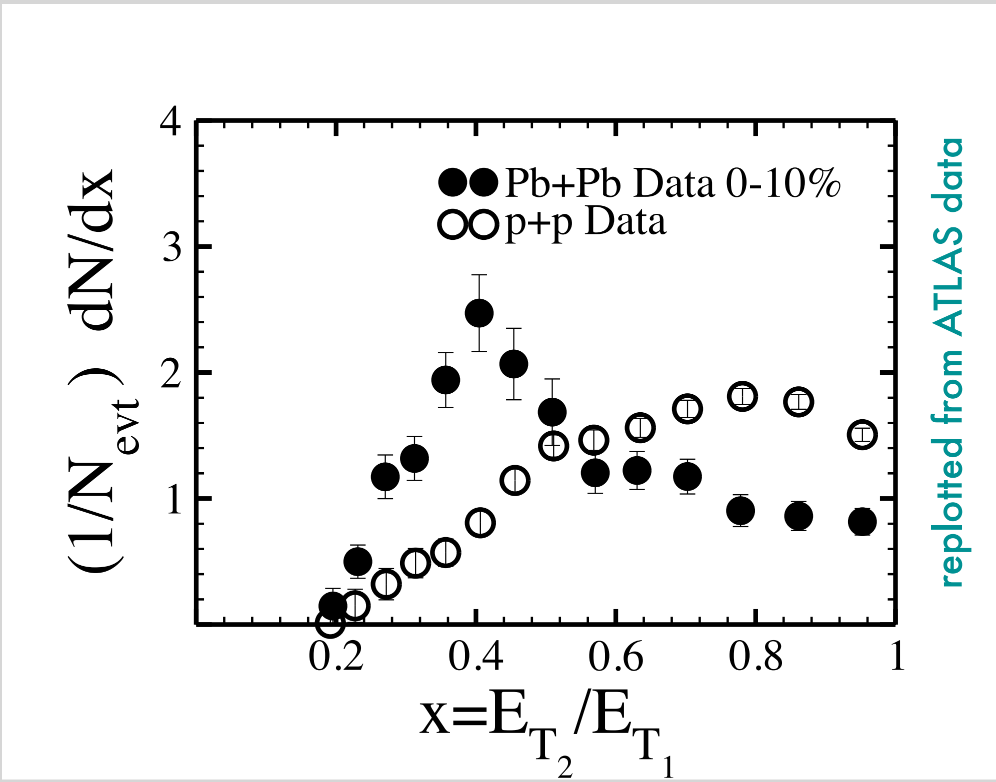
out-of-cone radiation in PbPb



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 recoiling jet]

out-of-cone radiation in PbPb



- pp di-jet events are substantially asymmetric
- significant out of cone radiation

$$\langle x \rangle_{pp} \lesssim \frac{1}{N_{evt}} \int dx\, x \frac{dN}{dx} = 0.67 \text{ [ATLAS]} \div 0.70 \text{ [CMS]}$$

- wide energy distribution

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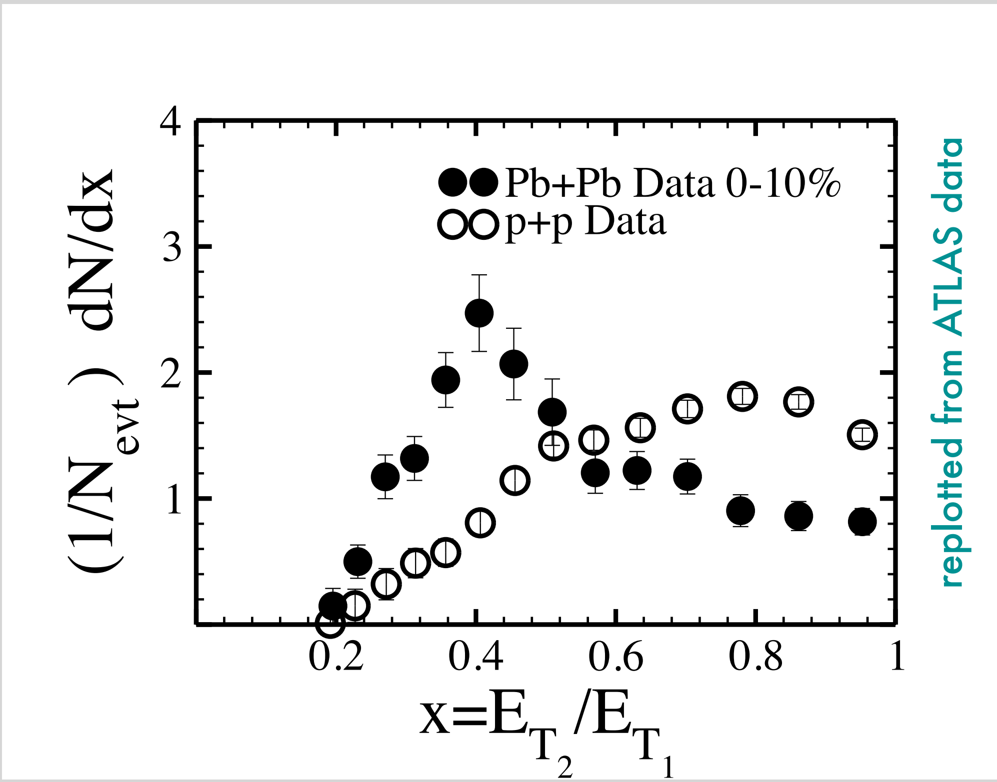

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'moderate' additional out-of cone radiation in PbPb

$$\langle x\rangle_{PbPb} \lesssim 0.54 \text{ [ATLAS]} \div 0.62 \text{ [CMS]} \qquad \langle x\rangle_{pp} - \langle x\rangle_{PbPb} \lesssim 0.12 \text{ [ATLAS]} \div 0.08 \text{ [CMS]}$$

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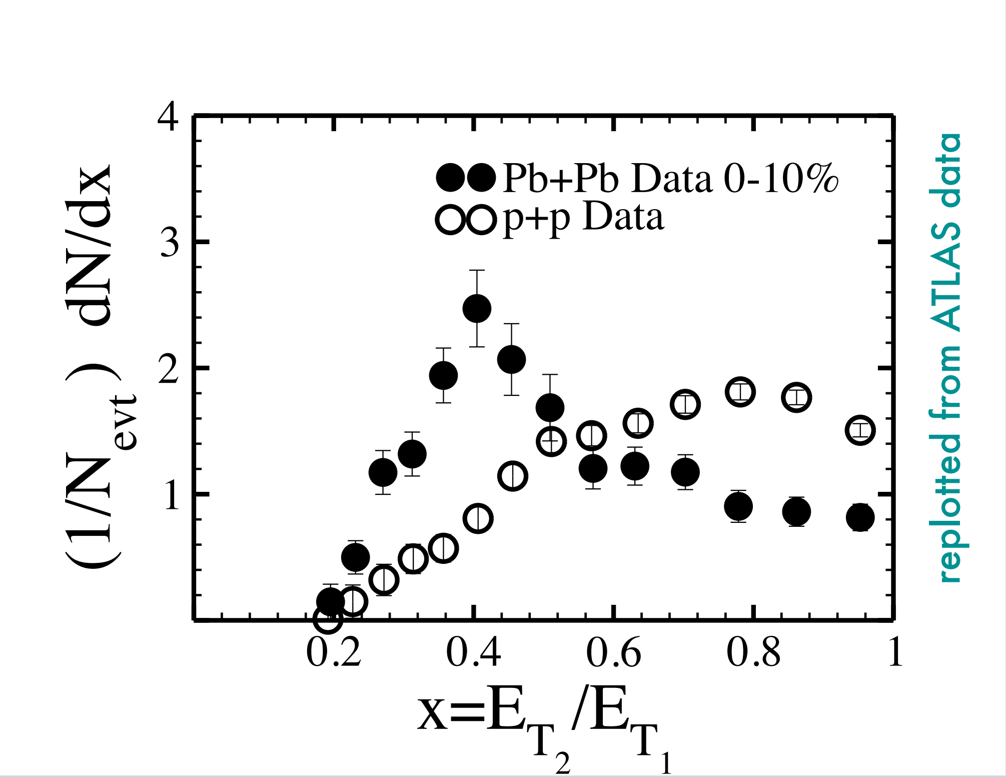

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estimate energy loss

::underestimate::
all jets interact equally

from CDF vacuum jet shape studies

$$\frac{\Delta E}{E_T} > 0.8\,(\langle x \rangle_{pp} - \langle x \rangle_{PbPb}) \text{ [ATLAS]} \div 0.9\,(\cdots) \text{ [CMS]} \sim 0.10 \text{ [ATLAS]} \div 0.07 \text{ [CMS]}$$

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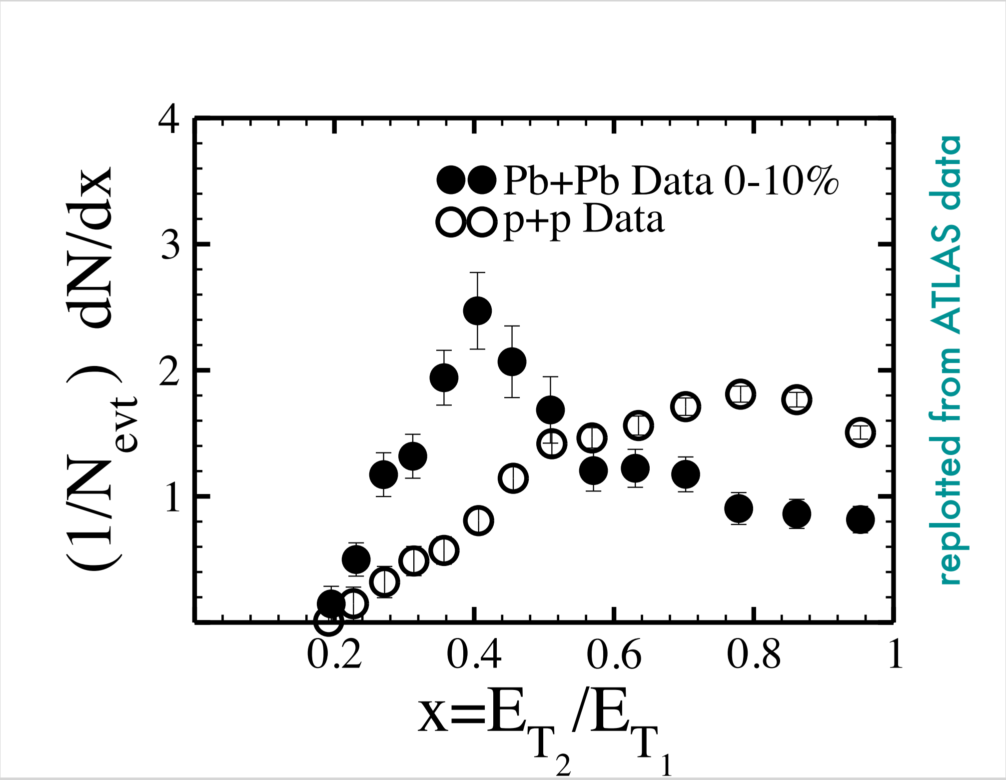

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estimate energy loss

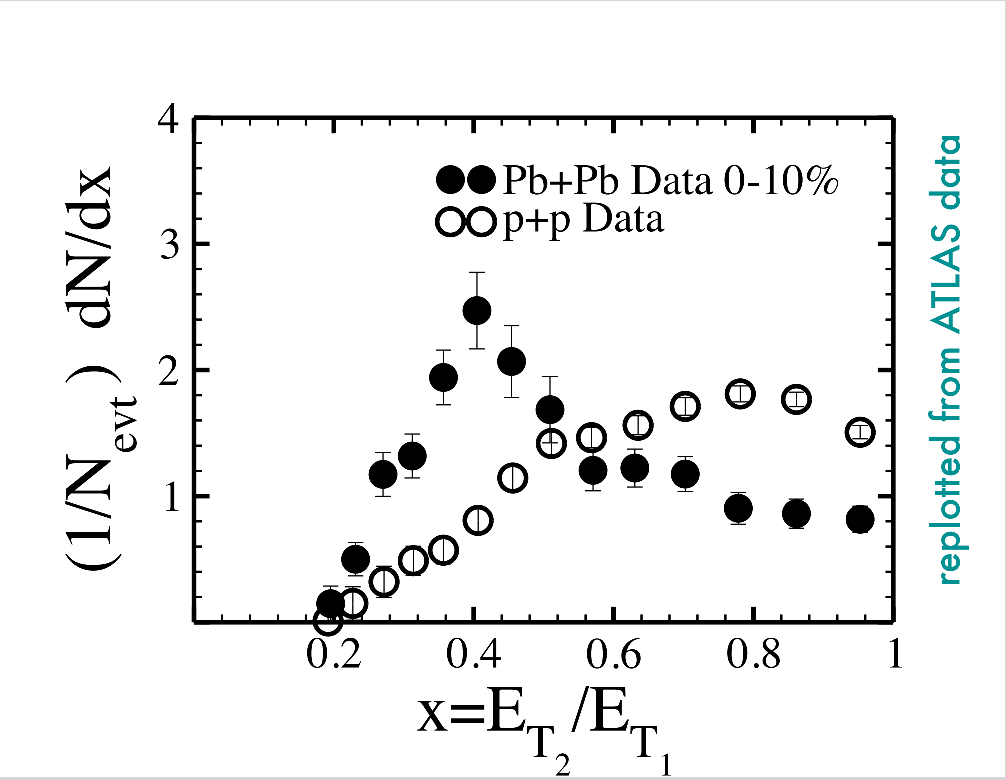
::overestimate::

only fraction (1-α) interact [corona effect]

from ratio at x=1

$$\frac{\Delta E}{E_T} < \frac{\langle x\rangle_{pp} - \langle x\rangle_{PbPb}}{1-\alpha} \sim 0.21\ [\text{ATLAS}] \div 0.15\ [\text{CMS}]$$

out-of-cone radiation in PbPb



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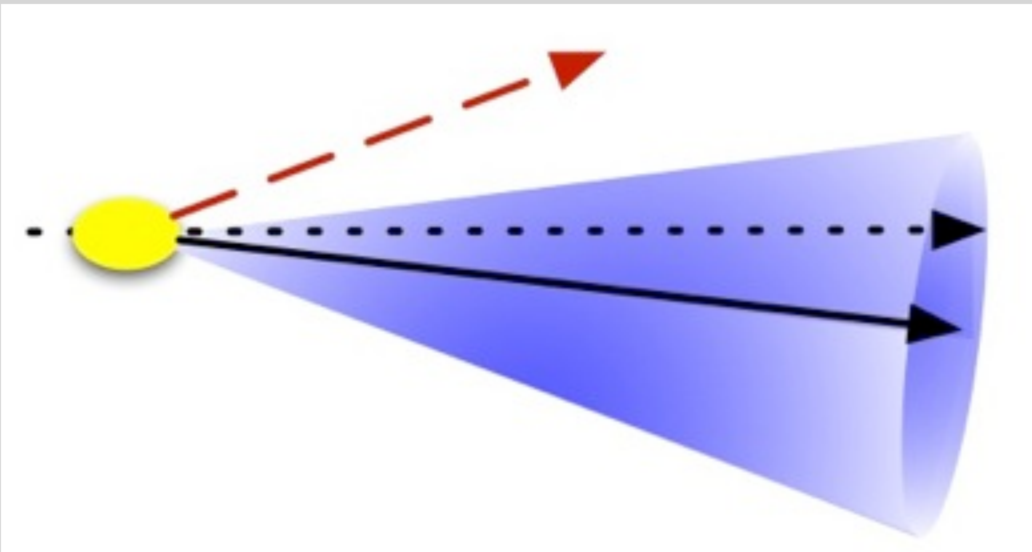
estimate energy loss

$$8.4 \text{ GeV} < \Delta E < 18 \text{ GeV [CMS]} \qquad 10 \text{ GeV} < \Delta E < 21 \text{ GeV [ATLAS]}$$

$$E_T = 120 \text{ GeV [CMS]} \qquad E_T = 100 \text{ GeV [ATLAS]}$$

underlying dynamics



increased large angle medium induced radiation

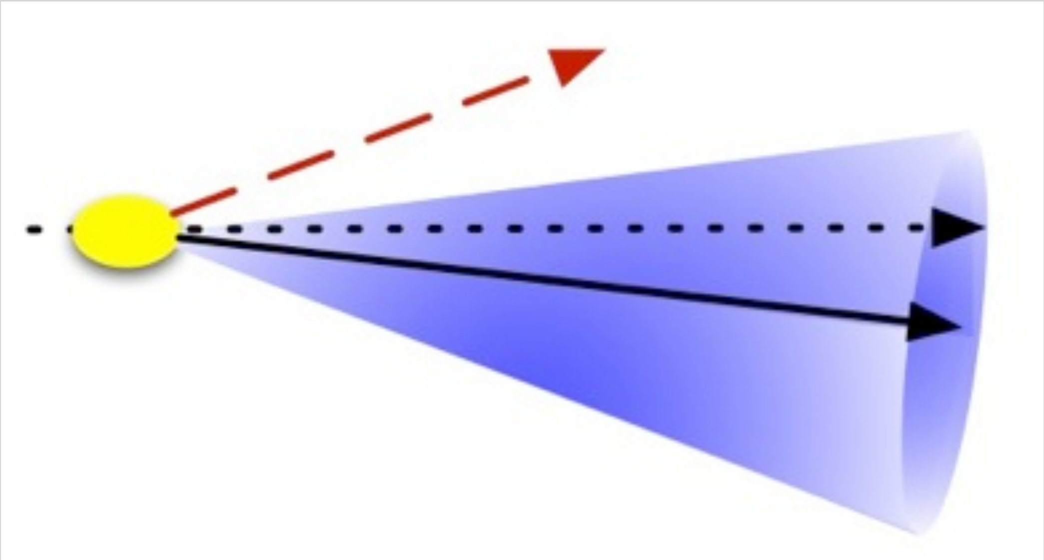
at given fixed angle

$$\tau \sim \frac{1}{\omega\theta^2}$$

:: harder gluons are emitted earlier

:: [semi-]hard gluons deflect jet

underlying dynamics



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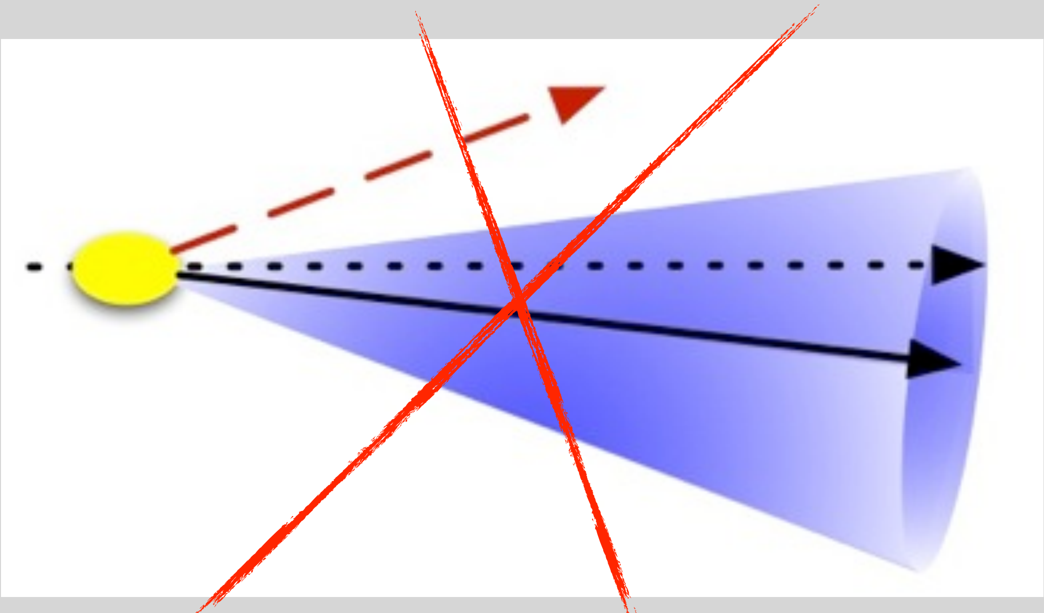

increased large angle medium induced radiation

underlying dynamics must be such that medium effects
LEAD
to significant out of cone radiation
WITHOUT
significant distortion of azimuthal distribution

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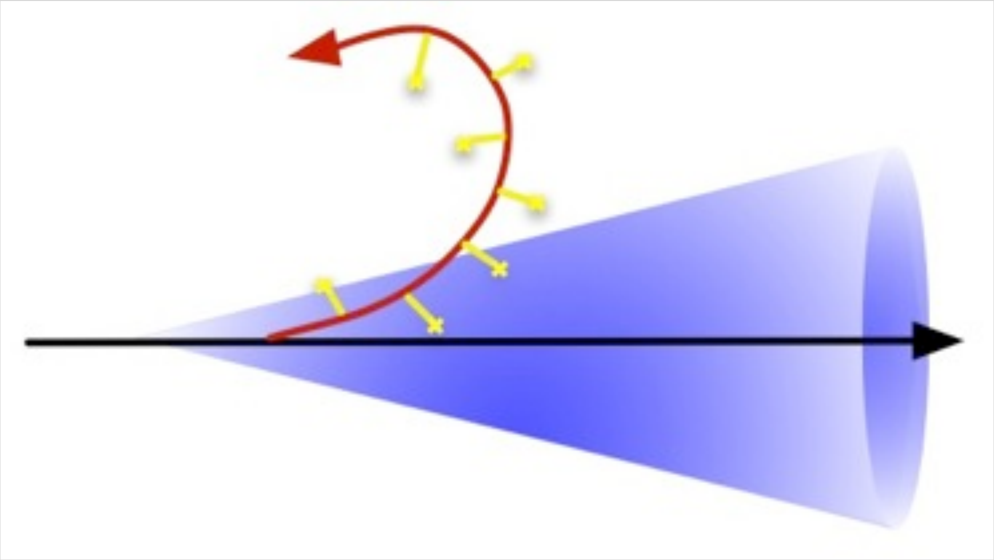
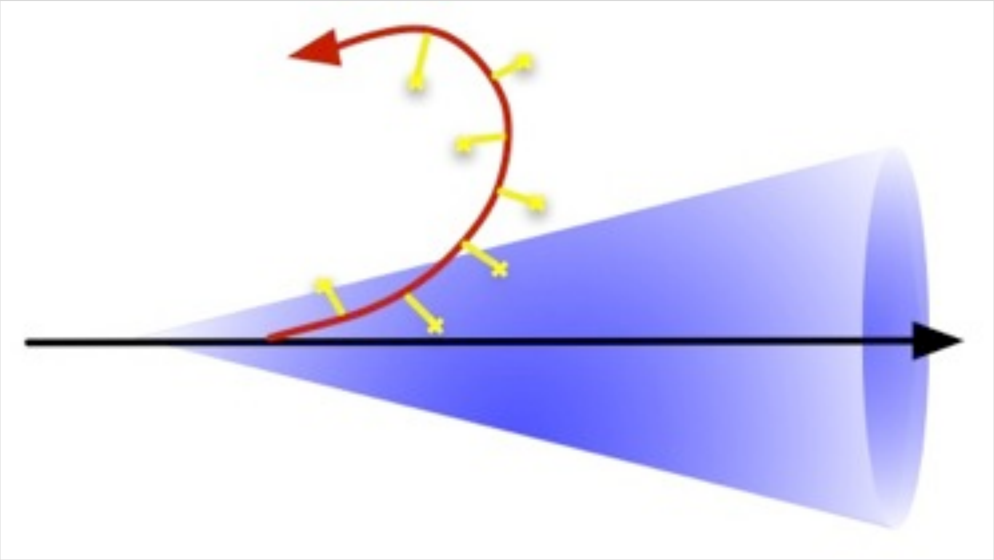


transport of radiated gluons

radiation of soft gluons at small angle

:: no sizeable effect on jet direction

underlying dynamics



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

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

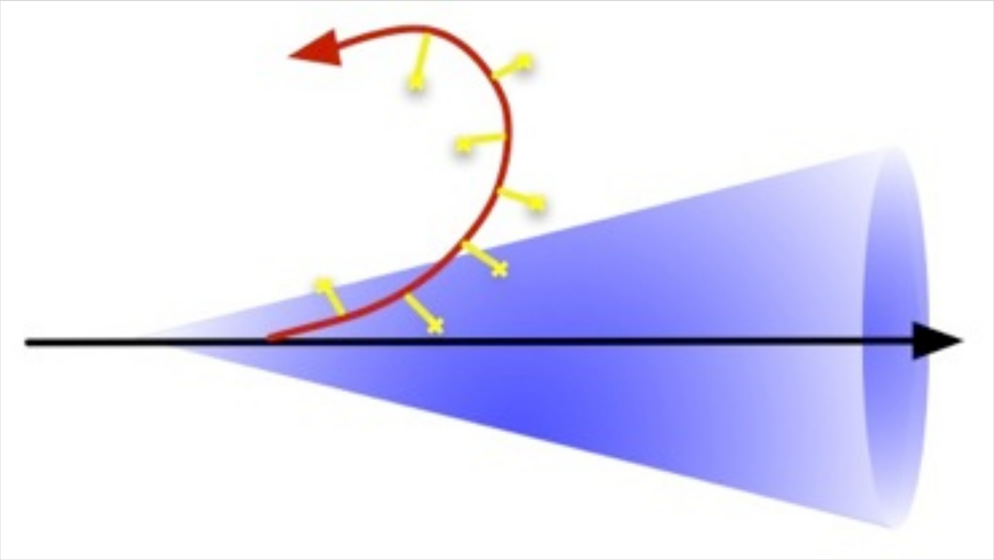
- in the presence of a medium soft modes are formed early

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

- sufficiently soft modes are decorrelated from the jet direction

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

underlying dynamics



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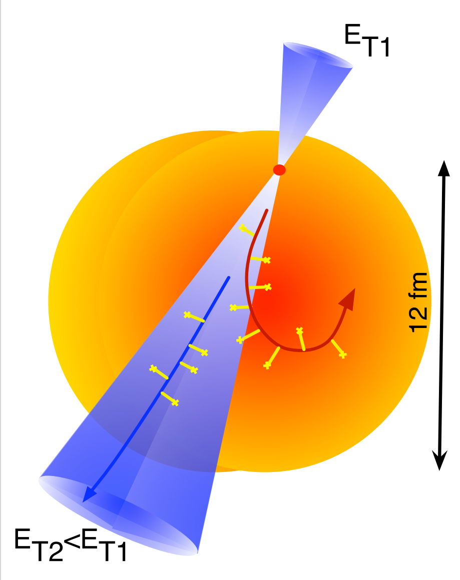


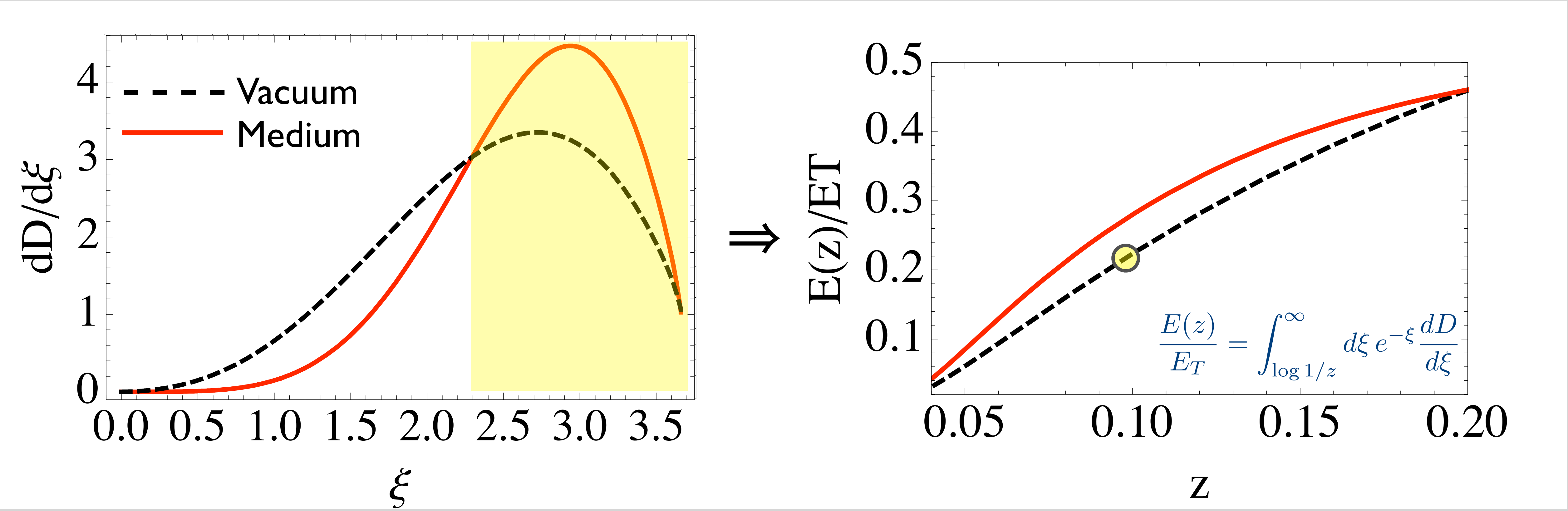
the medium acts as a frequency collimator efficiently trimming away the soft components of the jet

jet [frequency] collimation

- energy carried by soft modes [that can be decorrelated] necessary to account for observed energy loss from jet cone

vac: MLLA

med: medium modified MLLA



jet frequency collimation affects all soft modes in the jet 'wave-function'

:: mechanism effective even if there is no additional medium induced radiation/splittings
[transports vacuum soft gluons out of the jet cone]

:: softening of the spectrum [from medium induced radiation] enhances the effect

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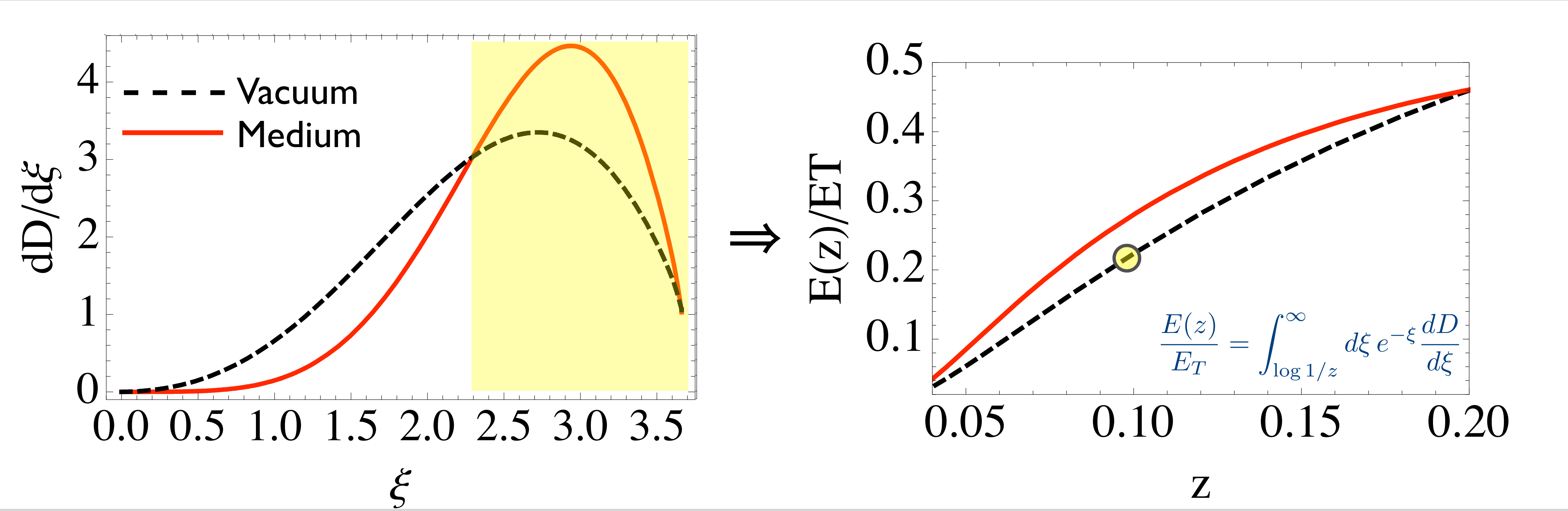

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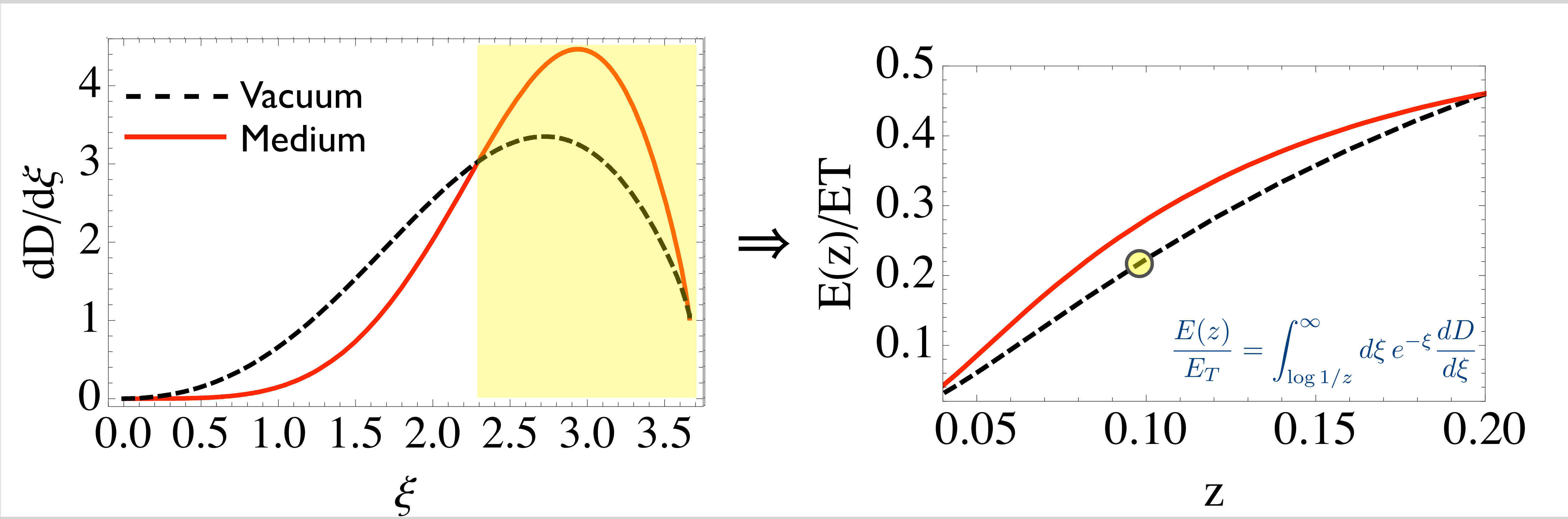

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$$\omega^2 = z^2 E_T^2 \leq \hat{q} L$$

vacuum	$35 \left(\frac{E_T}{E_0}\right)^2 \leq \hat{q}L \leq 85 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$		ATLAS [E_0 = 100 GeV]
medium	$30 \left(\frac{E_T}{E_0}\right)^2$	$60 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$	
vacuum	$24 \left(\frac{E_T}{E_0}\right)^2$	$62 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$	CMS [E_0 = 120 GeV]
medium	$18 \left(\frac{E_T}{E_0}\right)^2$	$40 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$	

(in .vs. out) of cone radiation

- energy lost from cone via jet collimation is soft
  - ↪ [medium strongly enhances soft out-of-cone radiation]
- soft modes can be transported to large angles
- in given asymmetry class, jet collimation leaves hard modes unchanged

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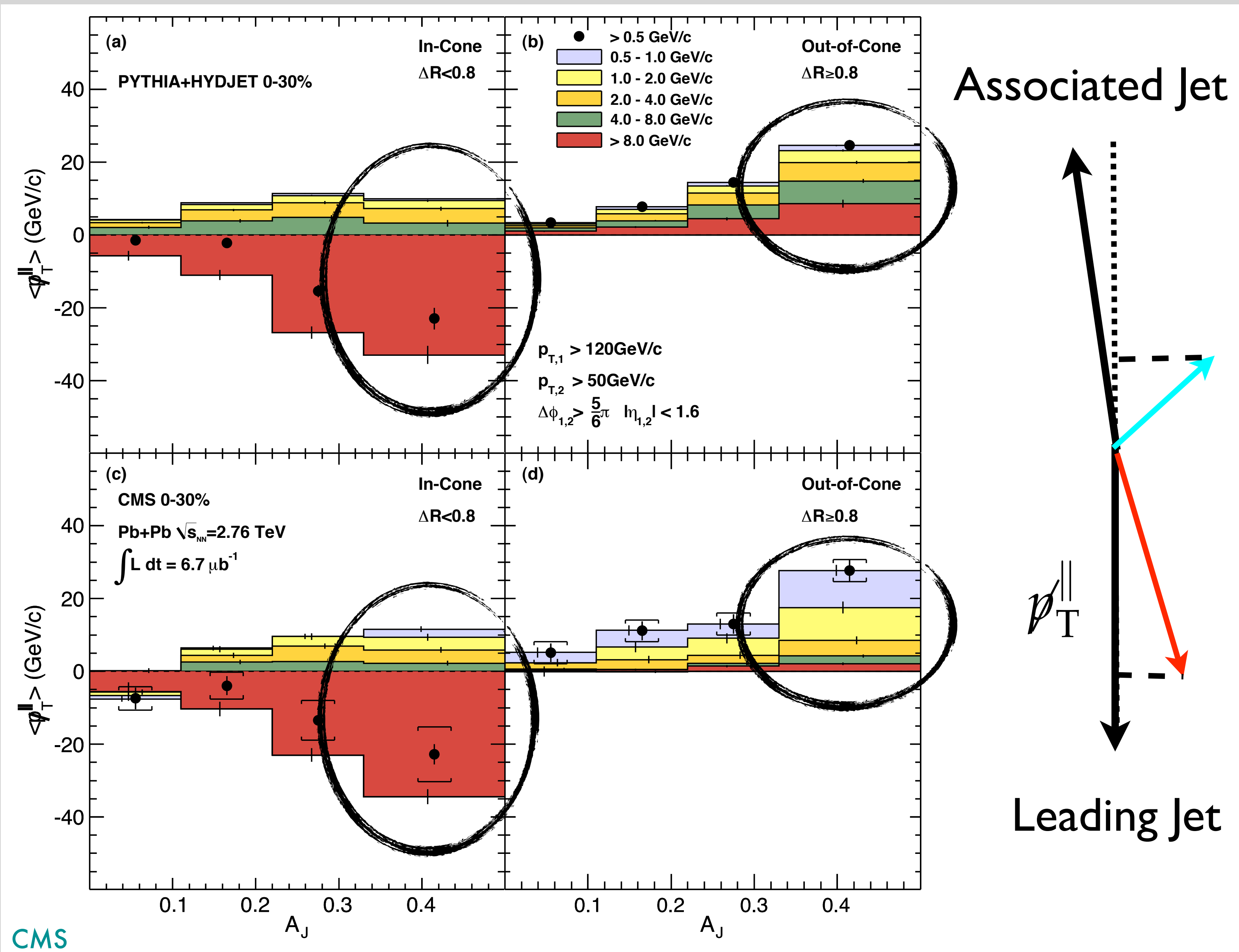
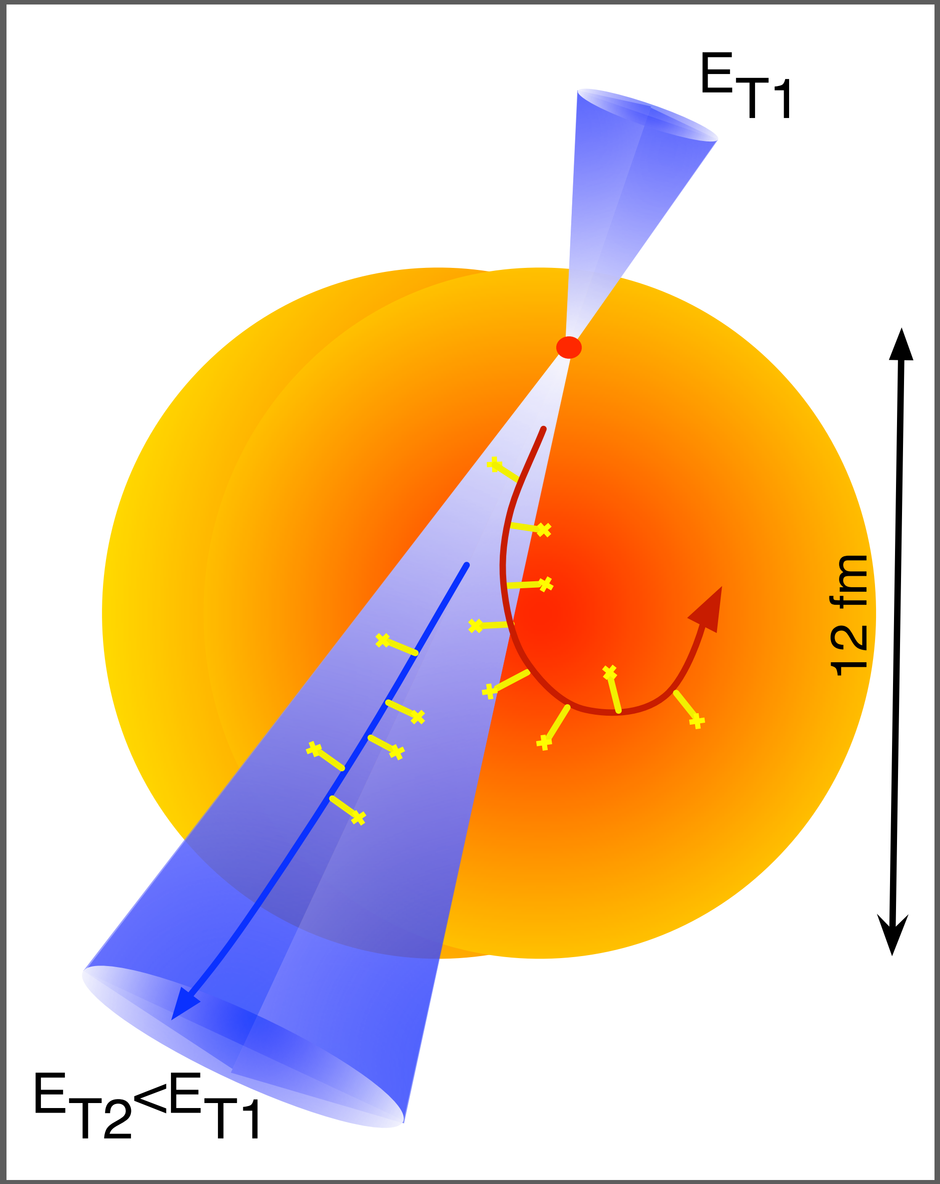


$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\text{Leading Jet}}\right)$$



jet collimation

:: a simple dynamical mechanism
:: consistent with data
:: necessary ingredient for jet quenching theory and related event-generators