New developments in medium modifications of jets

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CENTRA-IST & CERN PH-TH

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jet quenching

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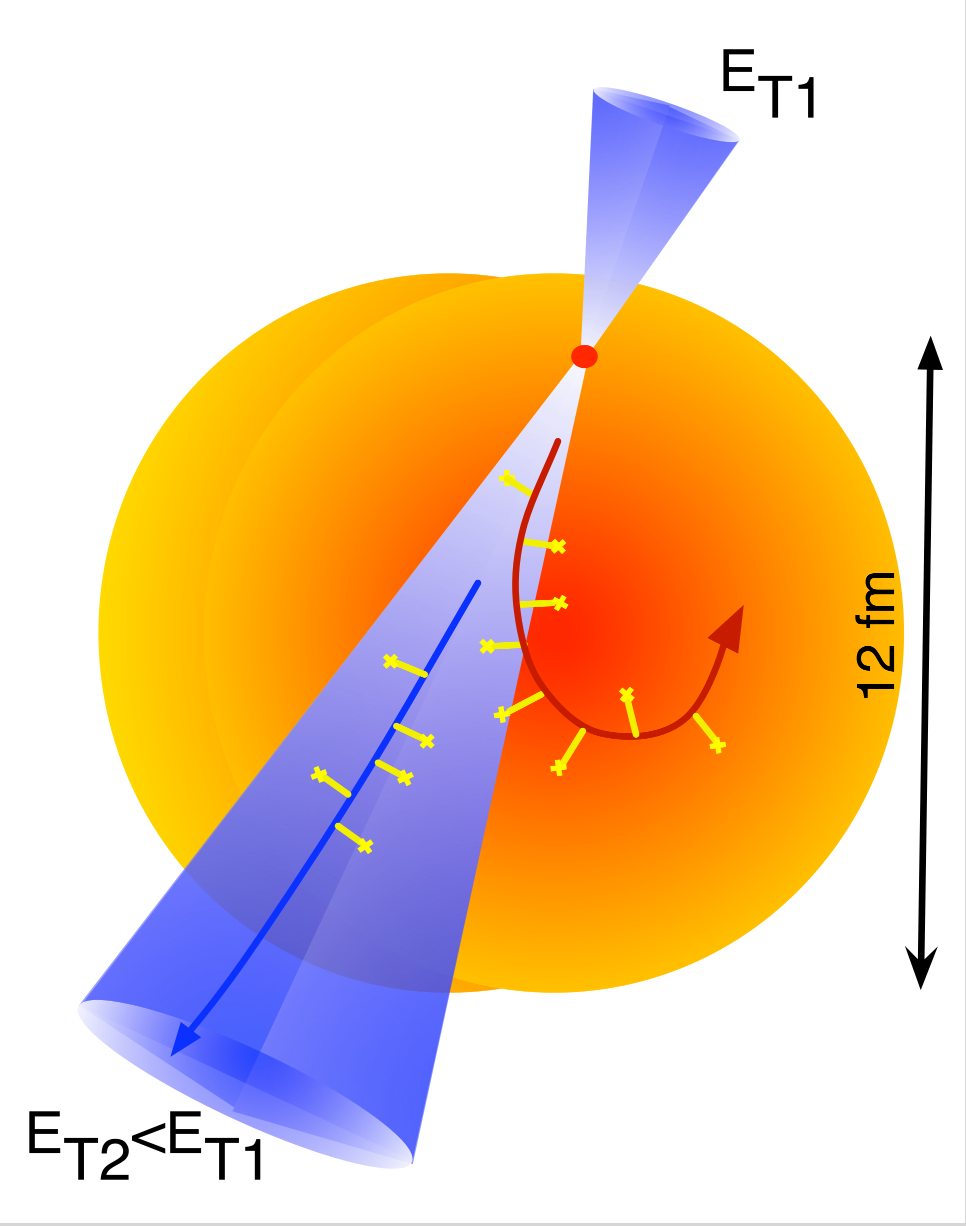

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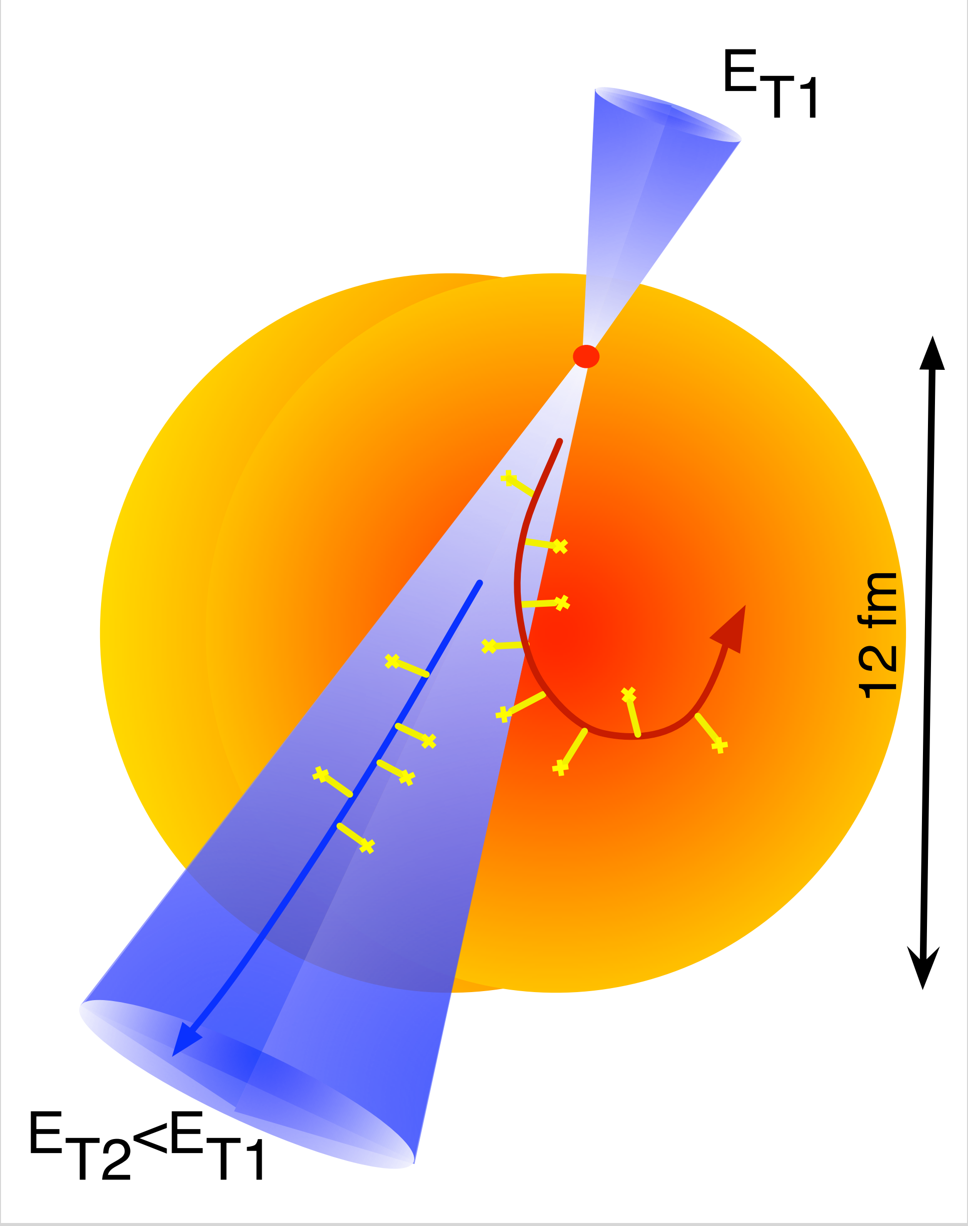
  [a long QCD time to interact]



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$\hookrightarrow$ enhanced and softened radiation :: leading parton energy loss

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    BDMPS and related frameworks

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  - ↪ modified coherence properties :: towards in-medium jet calculus

    Mehtar-Tani, Salgado, Tywoniuk (2010-11)/ Casalderrey-Solana, Iancu (2011)
    Abreu, Apolinário, Casalderrey-Solana, JGM (in preparation)

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    Casalderrey-Solana, JGM, Wiedemann (2011) :: this talk

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    Casalderrey-Solana, JGM, Wiedemann (2011) :: this talk

  - ↪ colour transfers with medium

    Beraudo, JGM, Wiedemann (2011 + in preparation) :: this talk

a trivial remark

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BUT...

role of jets as powerful detailed probes of medium properties will only
come to full fruition once dynamics is under full theoretical control

jet quenching [b. LHC]

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- most information on jet quenching NOT from jets

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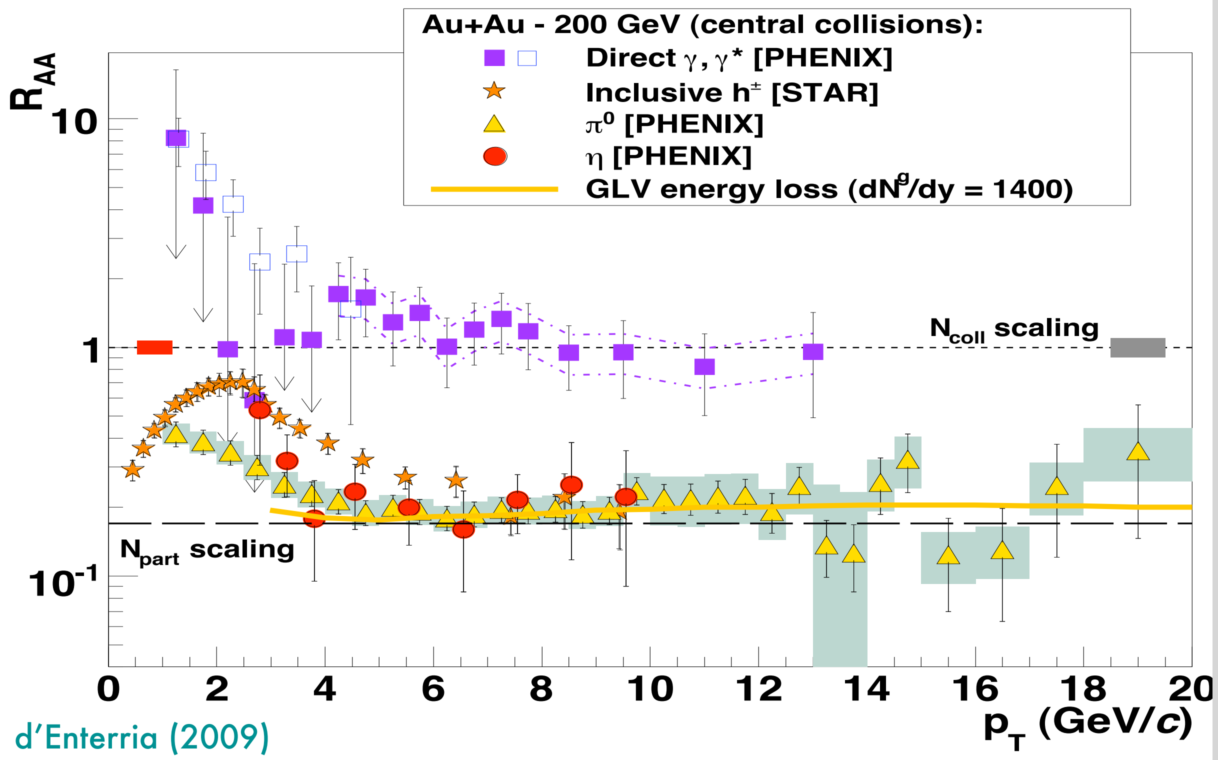
  - ↪ centrality dependent suppression of leading hadron spectra + unsupressed photons



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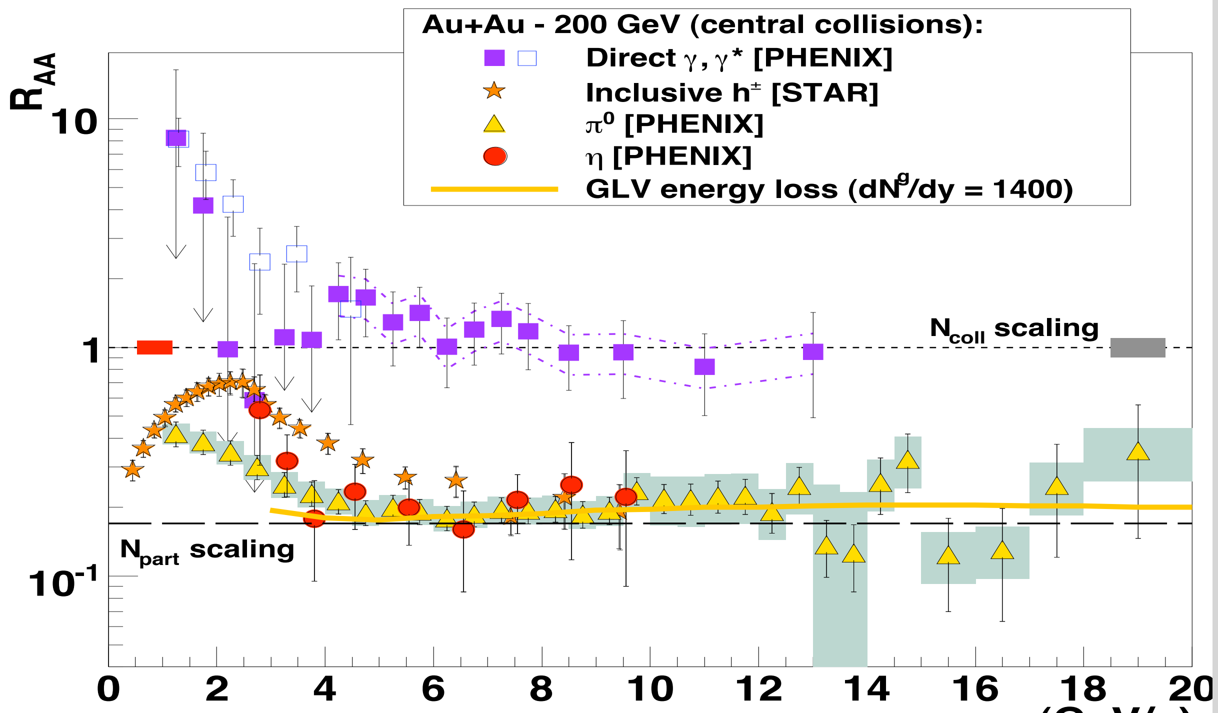

d'Enterria (2009)

  - ↪ suppression of back-to-back di-hadrons in AuAu but not in dAu

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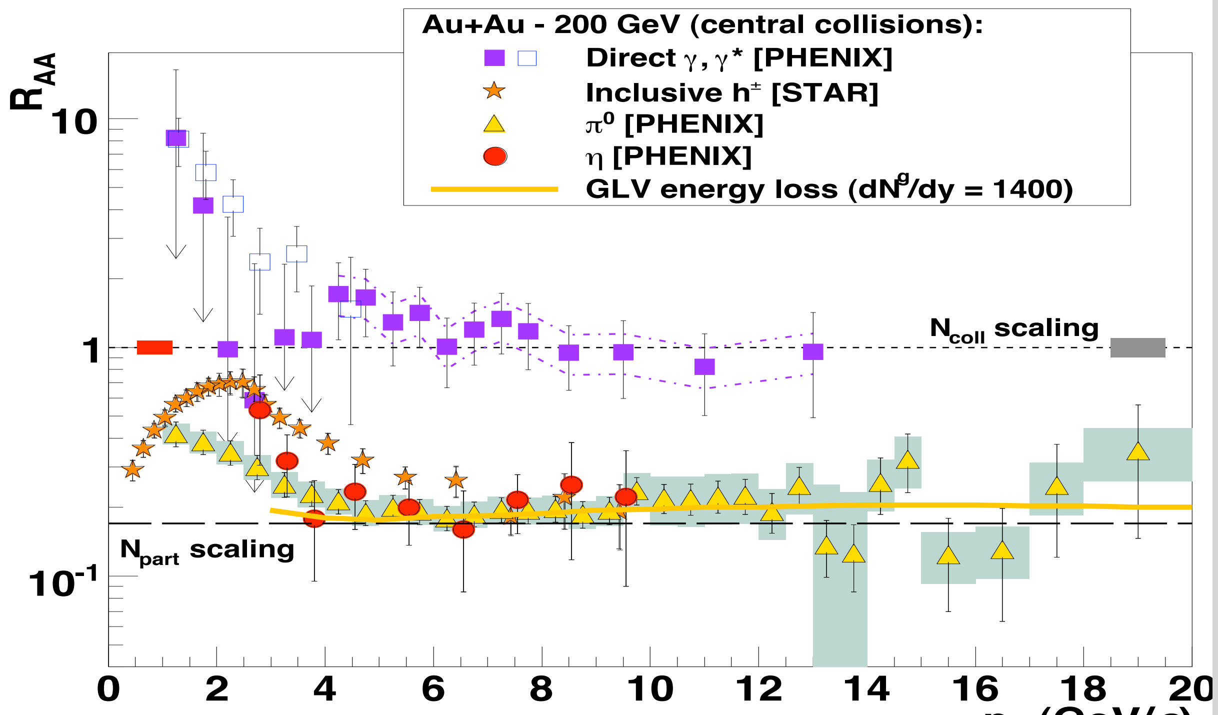

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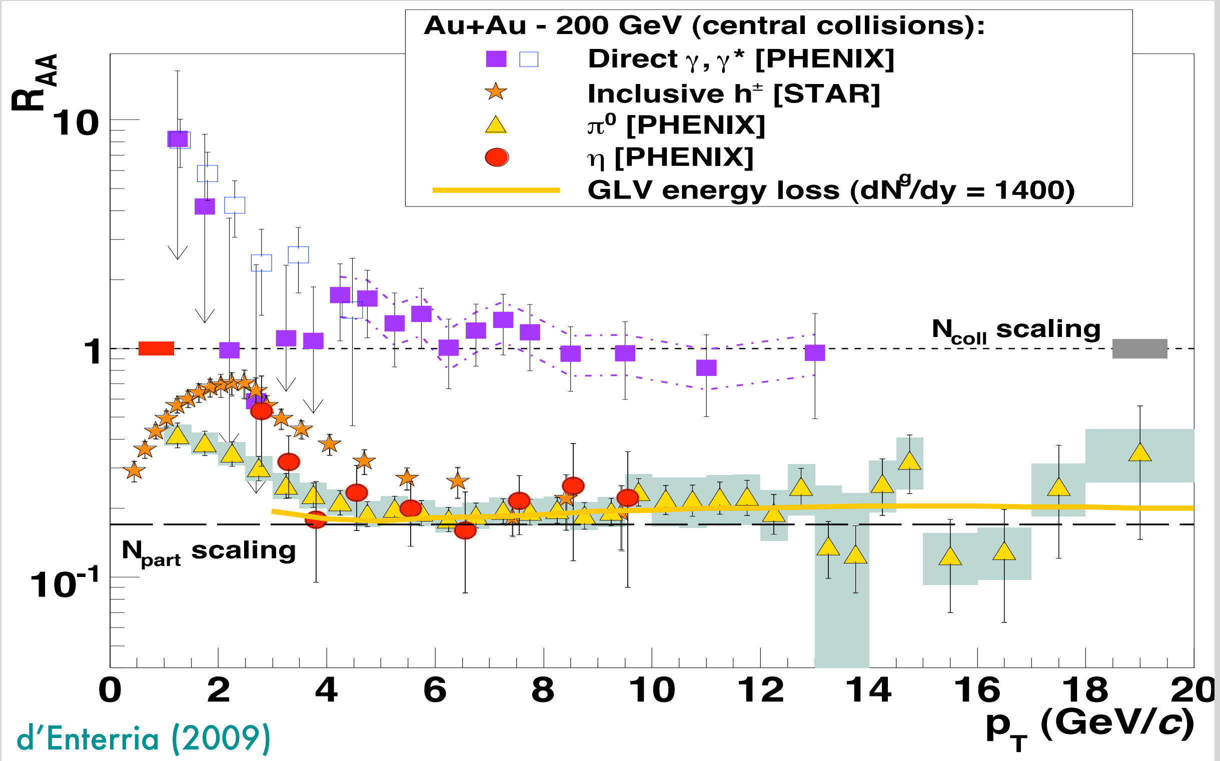

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↪ background subtraction for calorimetric jet measurements very challenging at RHIC

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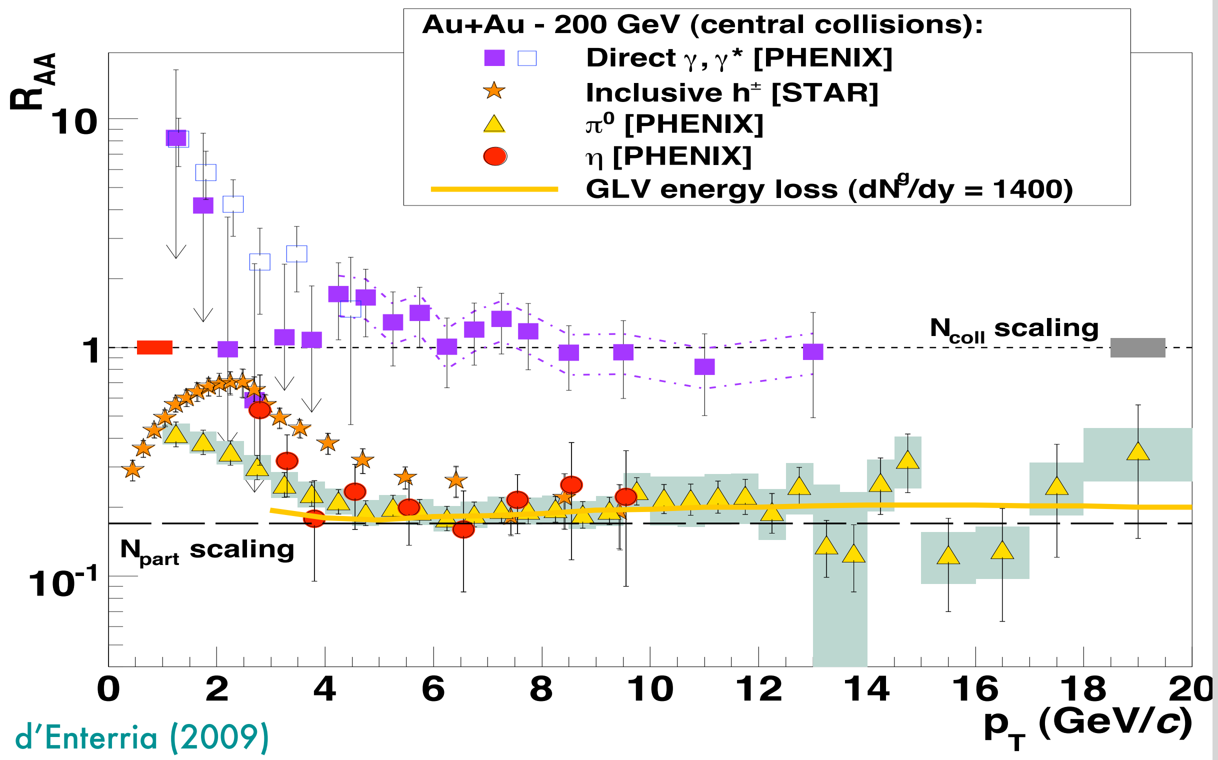

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  - ↪ background subtraction for calorimetric jet measurements very challenging at RHIC

The medium created in HIC is very opaque to energetic partons traversing it
[no strict constraints on underlying dynamics]

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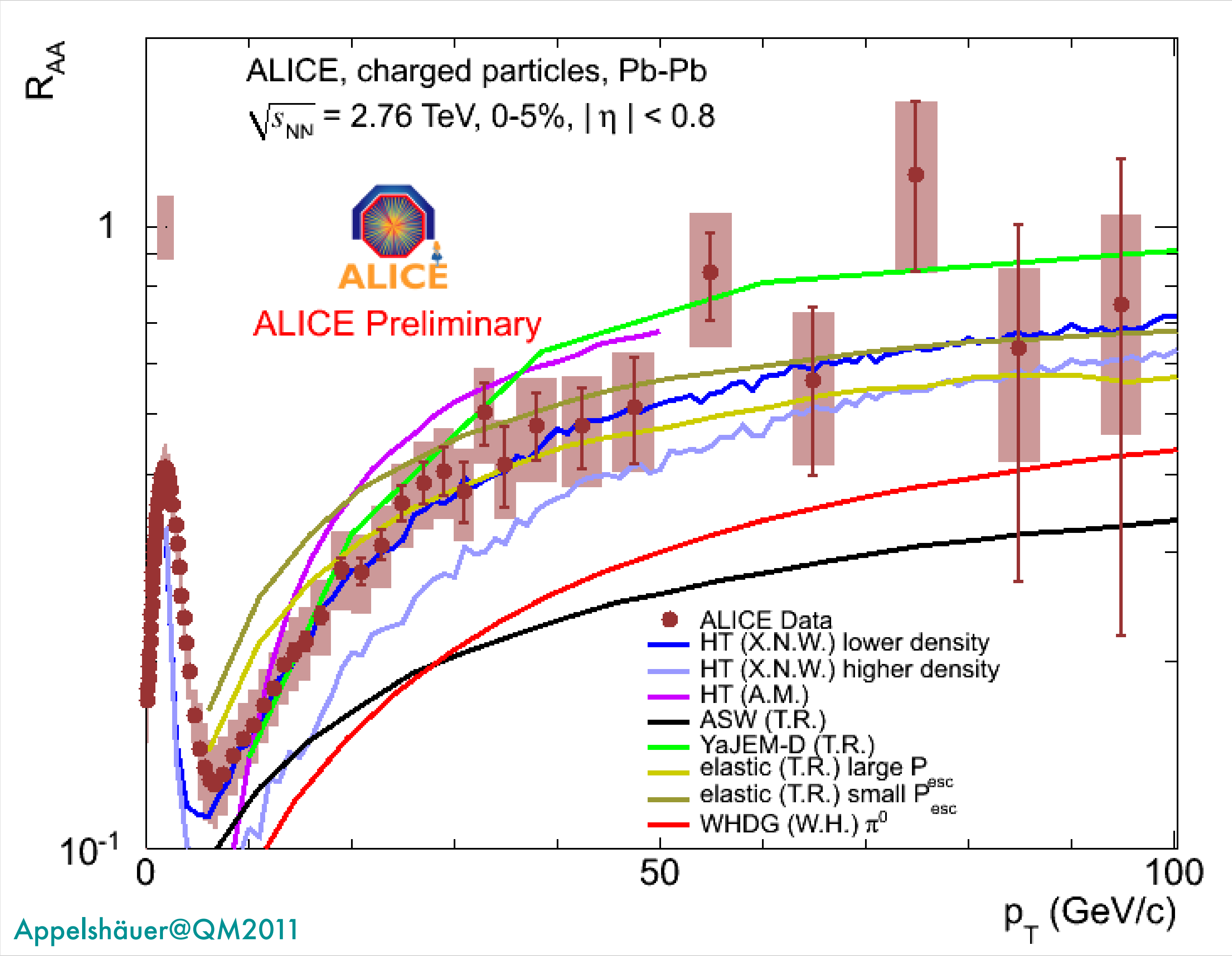

:: already a challenge for theoretical models

jet quenching [1 a. LHC]

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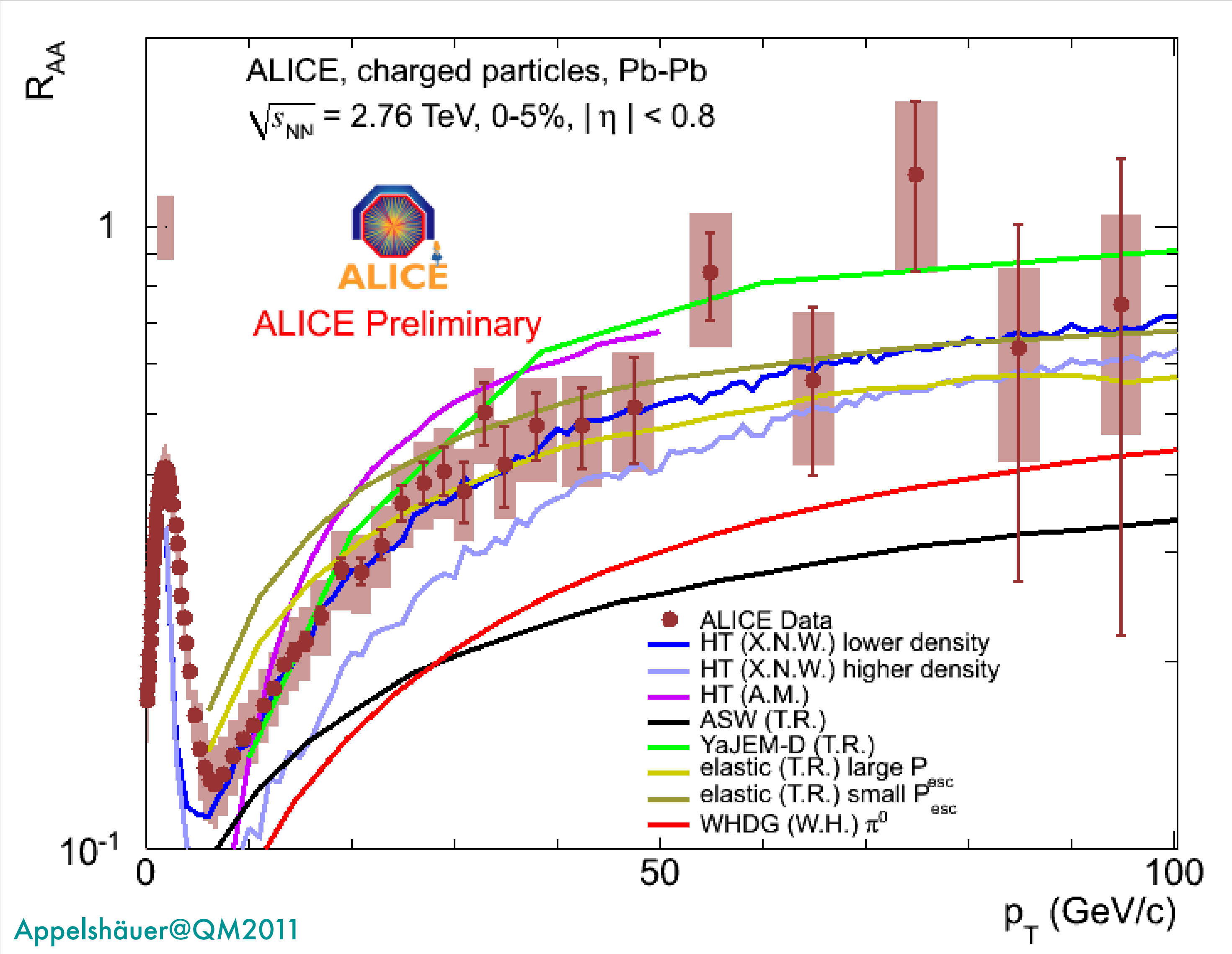


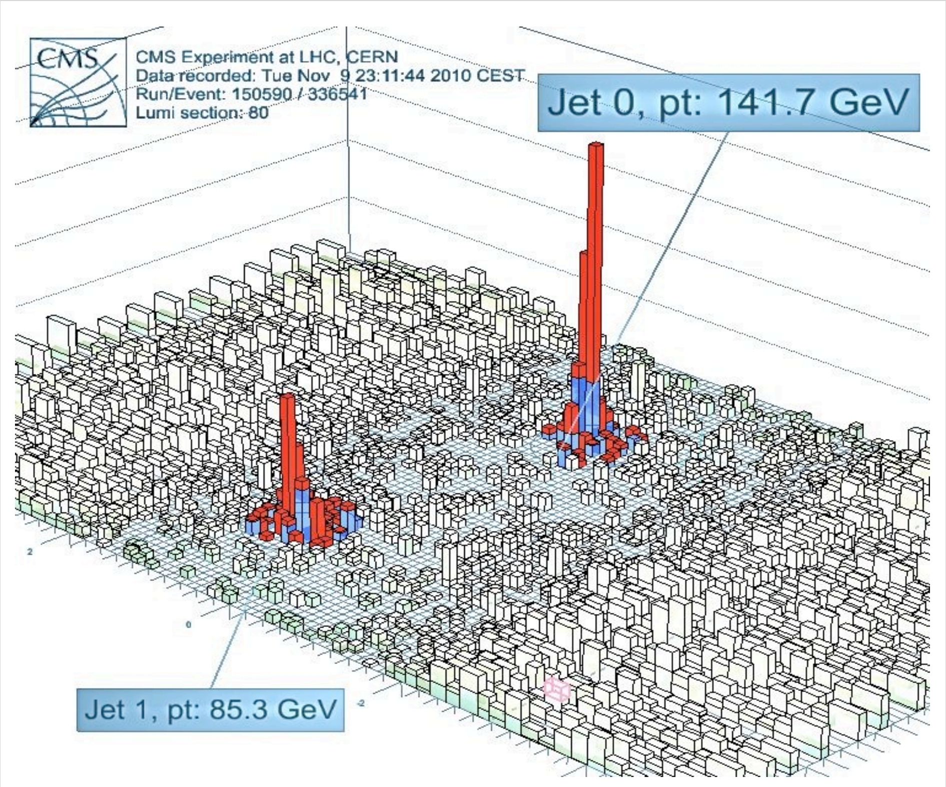
:: already a challenge for theoretical models

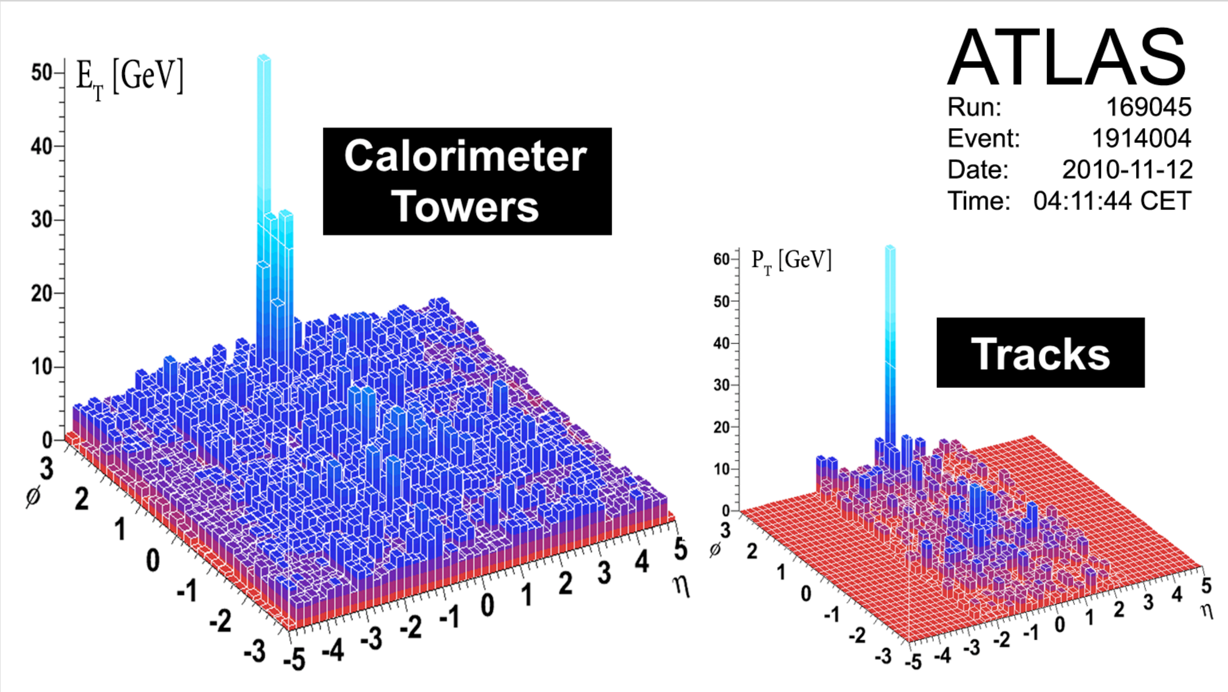
- but that is not ALL [Dr Seuss, The Cat in the Hat] ...

jet quenching [1 a. LHC]

—o fully reconstructed calorimetric jets...

↪ better proxy for original parton; a wealth of information encoded in substructure





—o jet identification above large and fluctuating background performed on systematic basis

↪ concerns raised [Cacciari, Salam, Soyez :: 1101.2878] that background fluctuations can significantly affect measurements

↪ extensive tests carried out by ATLAS, CMS and ALICE

the big question

the big question

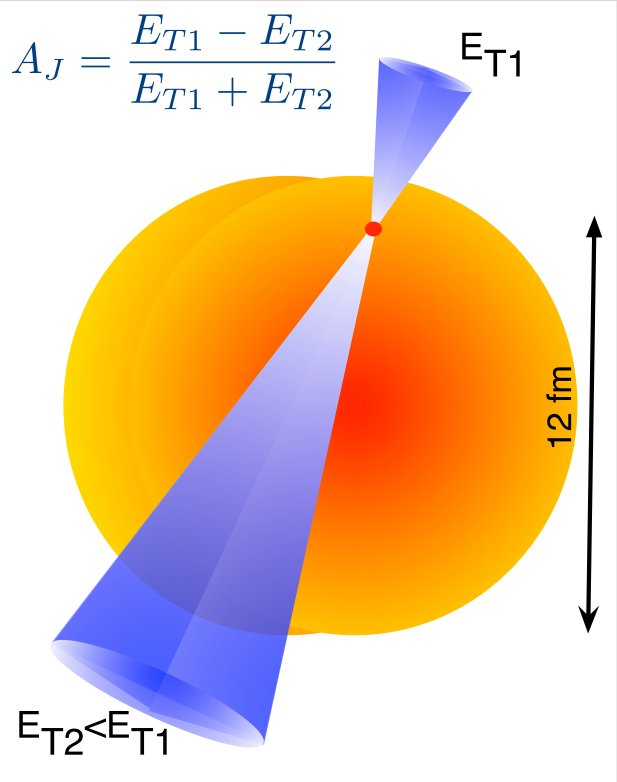
Does available LHC data imply qualitative rethinking/development of fundamental ingredients of 'Jet Quenching' ?

Jet energy loss via Jet collimation

arXiv:1012.0745 + arXiv:1107.1964

[with Jorge Casalderrey-Solana and Urs Wiedemann]

measurement of di-jet asymmetry



imbalance of jet energy within a cone of radius R for 'back-to-back' di-jets

	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)*
CMS	6.7	0.5	120	50	$2\pi/3$	*1102.1957*

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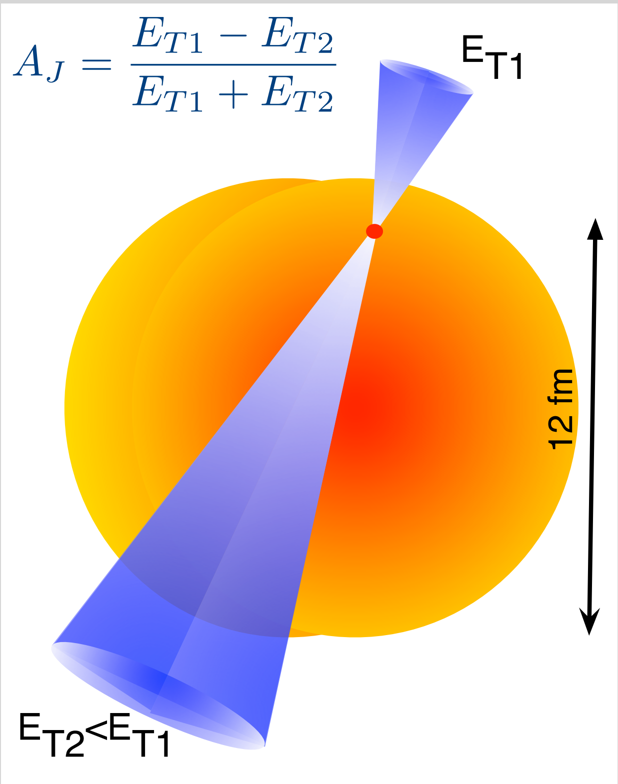

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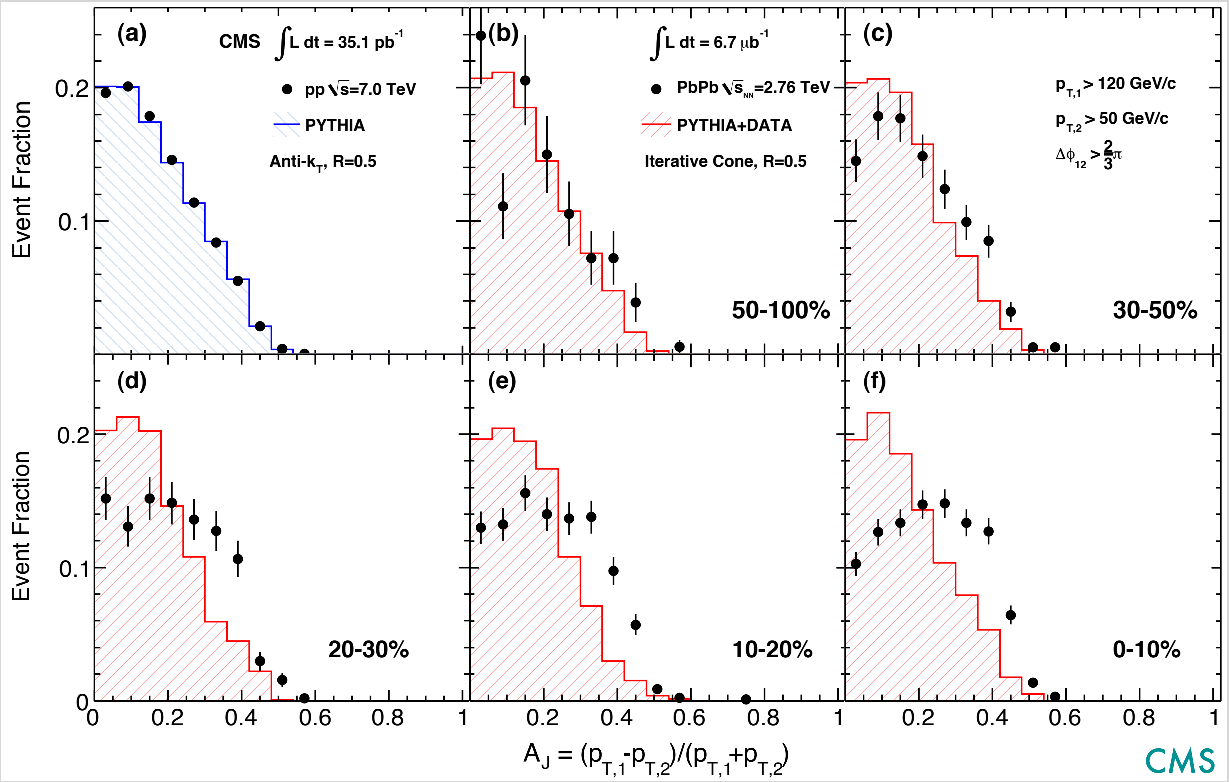
::for the purpose of this talk::

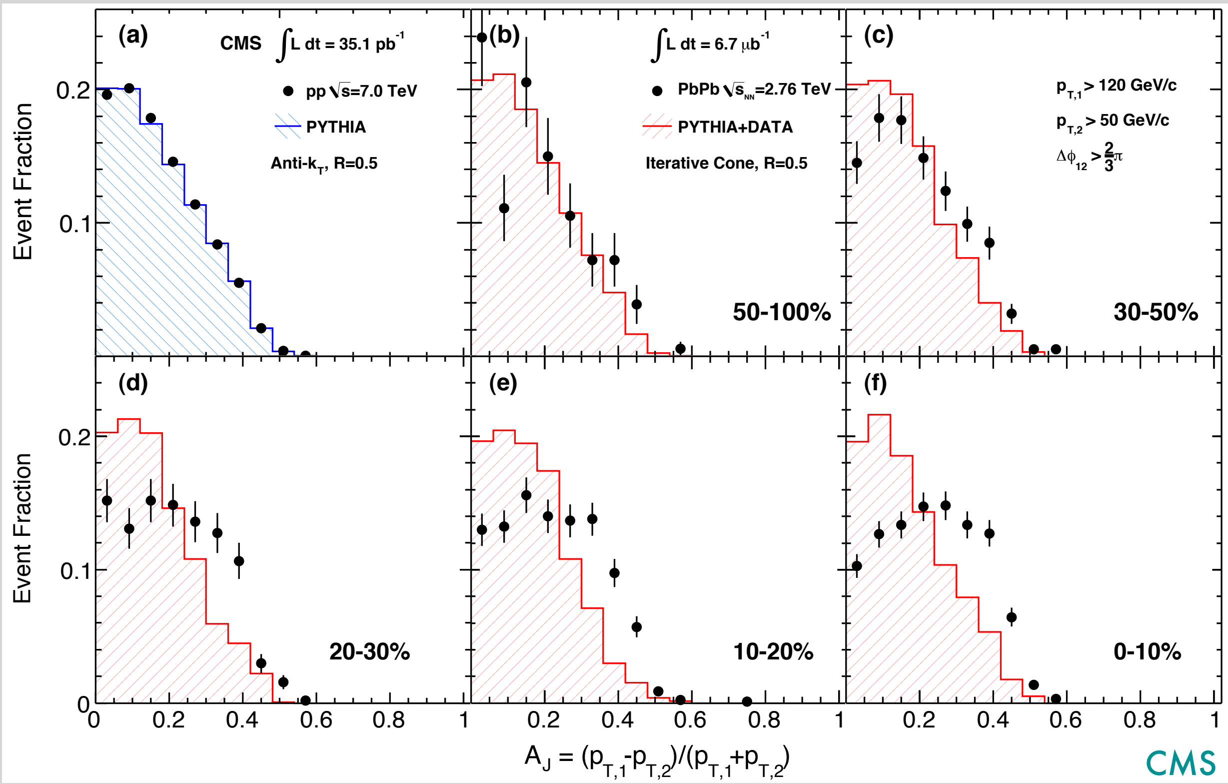
observed asymmetry robust against background issues and CMS/ATLAS differences at [least at] the level of qualitative features

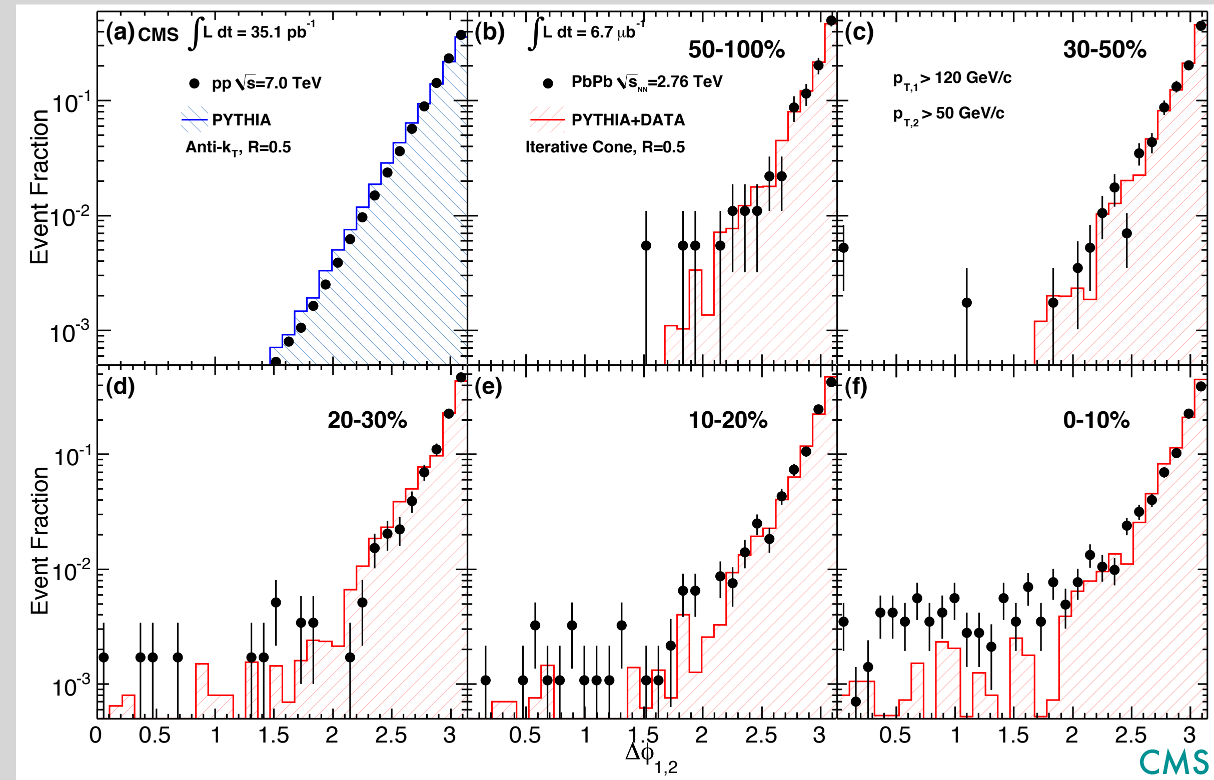
di-jet asymmetry [qualitative features]



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

di-jet asymmetry [qualitative features]





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  - ↪ [minor medium-induced jet deflection]

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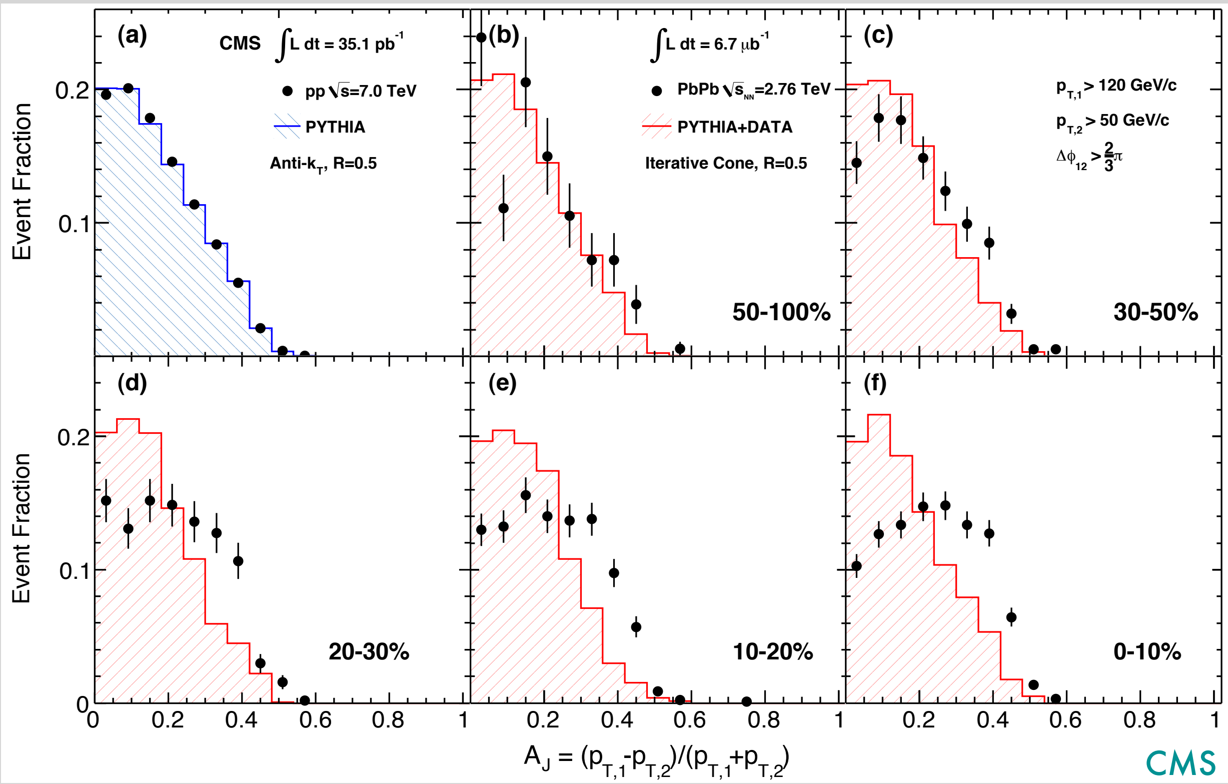

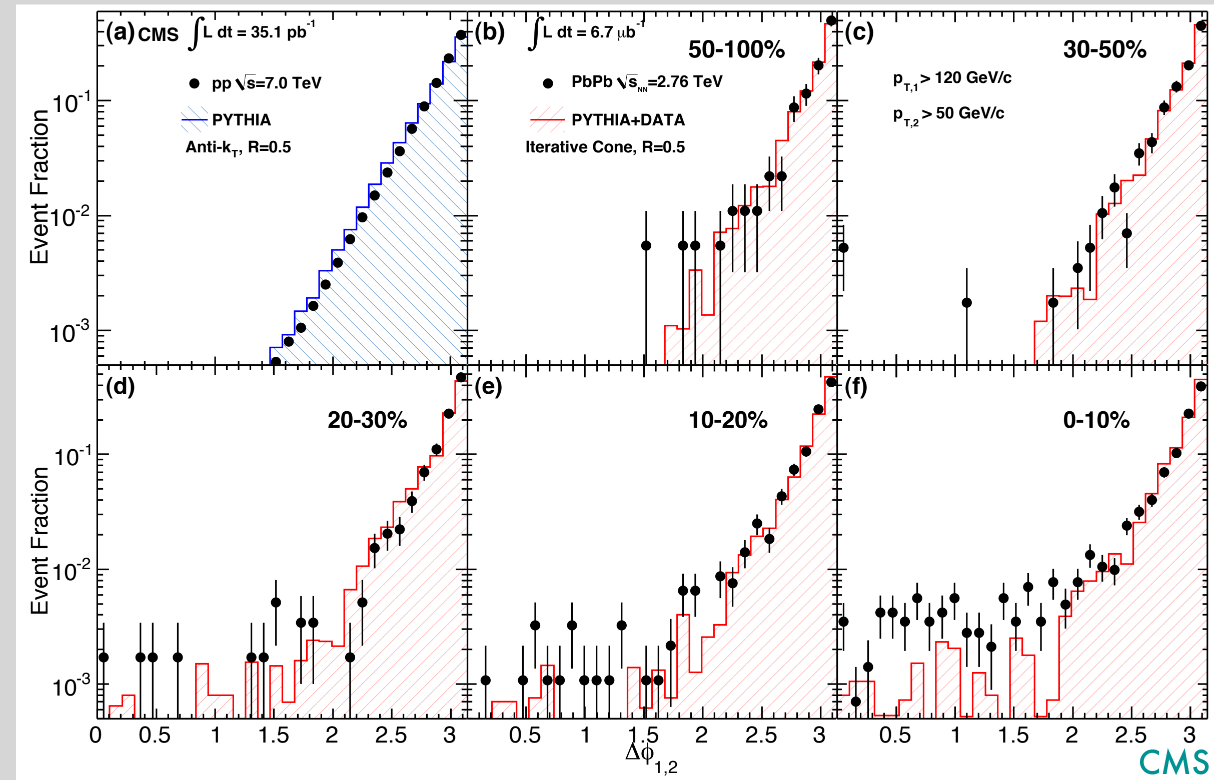

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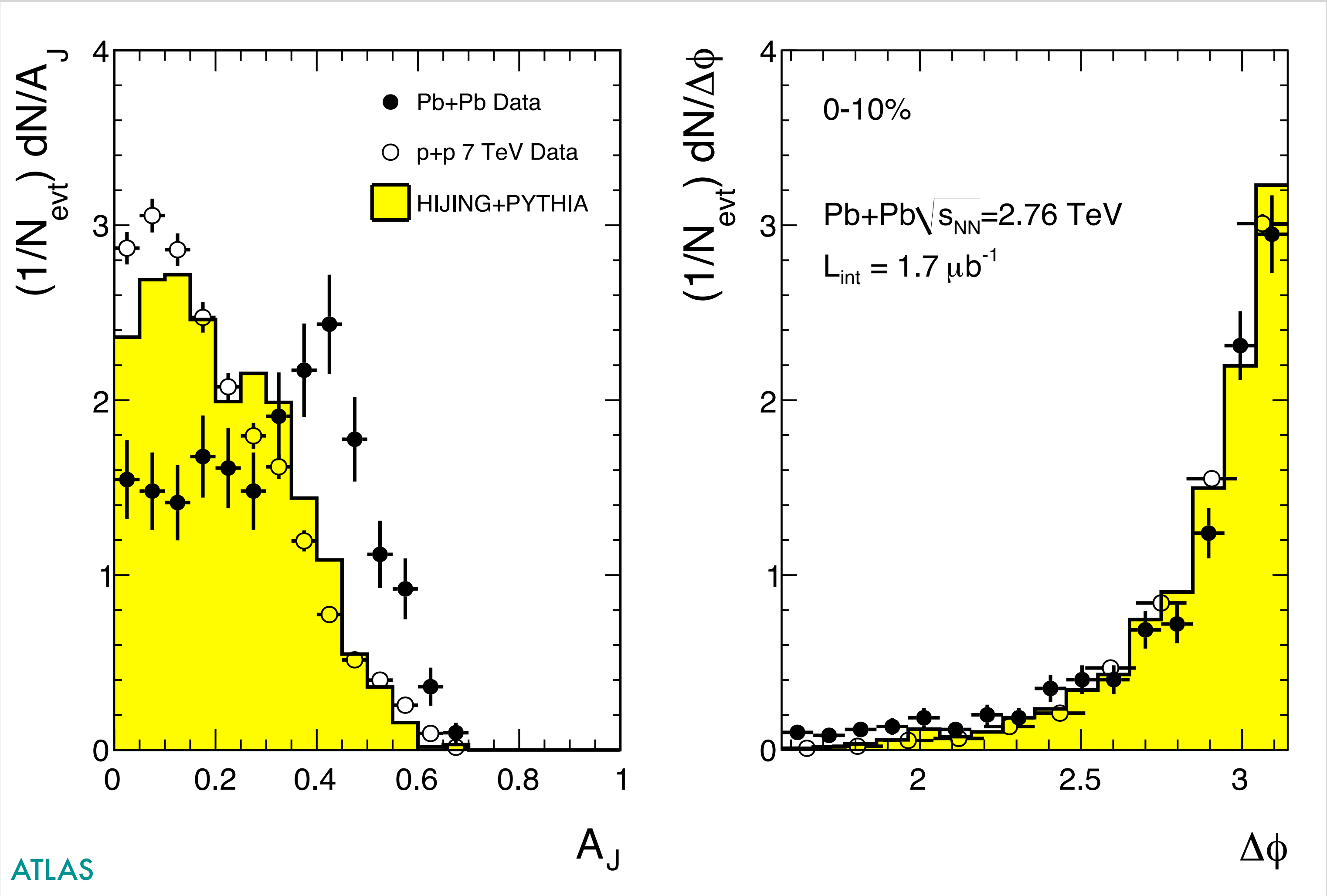
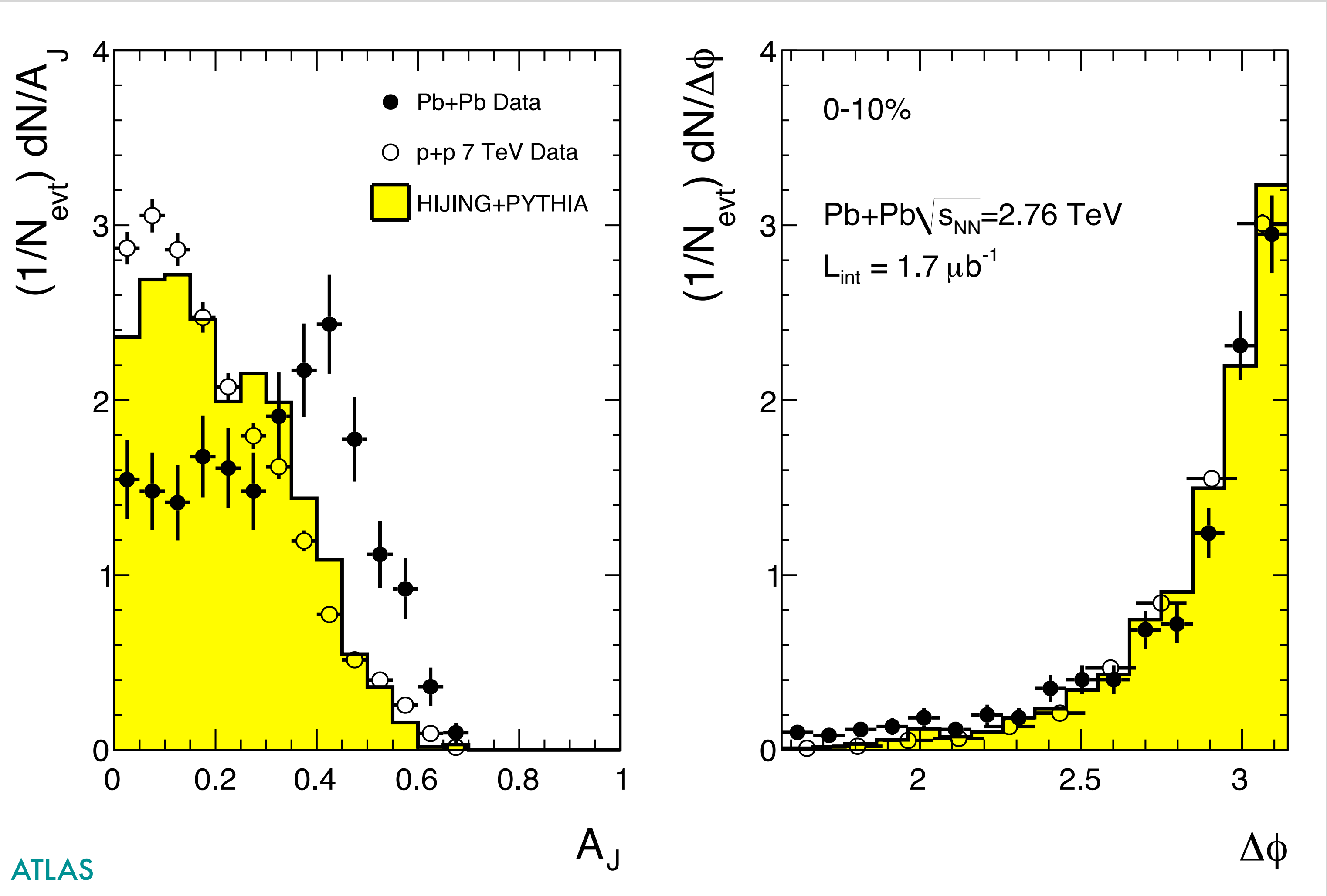
focus on most central events [where the effect is maximal]

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 physical
- very mild modification of the azimuthal angle distribution

most central events



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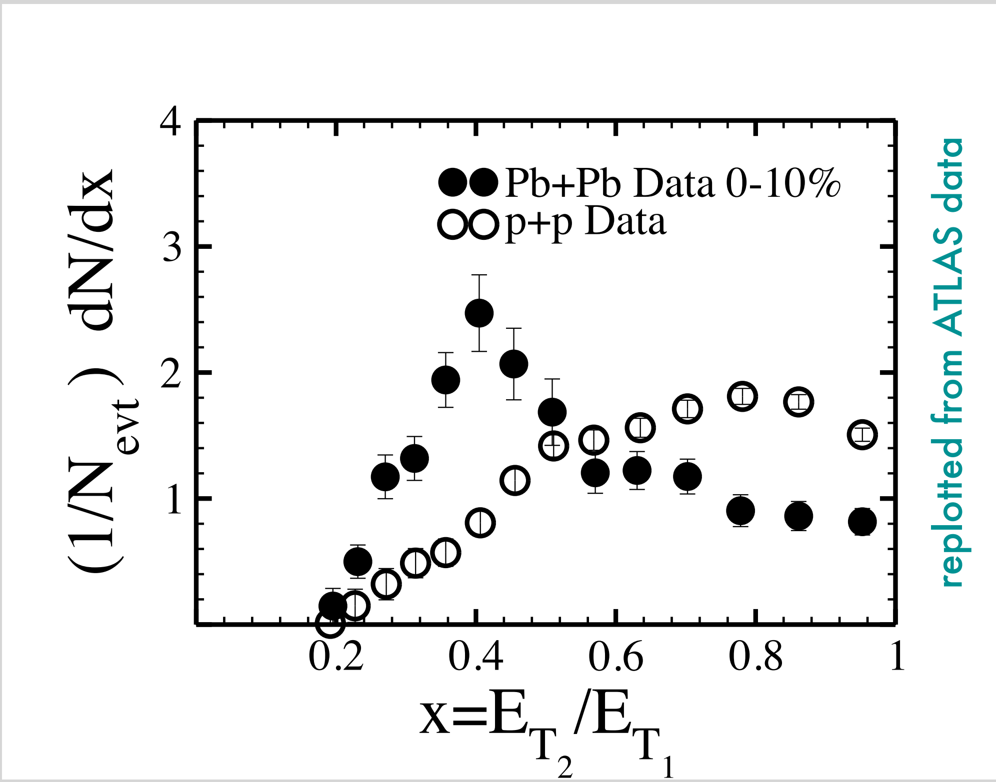
requires medium induced transverse broadening with no deflection of jet

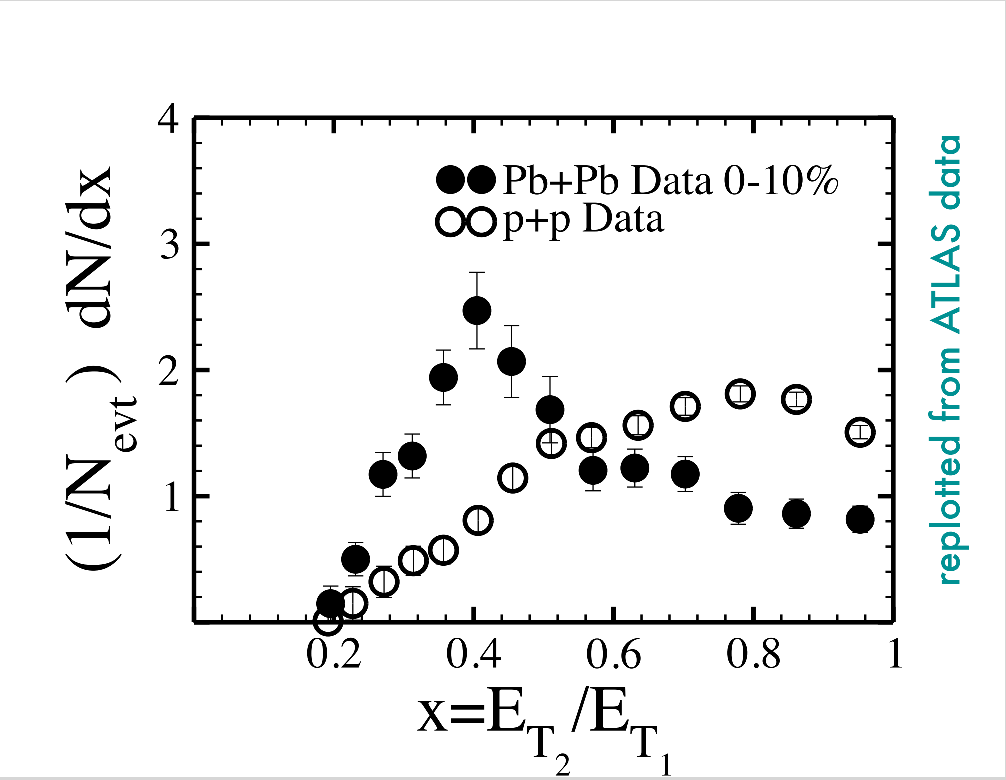
out-of-cone radiation [jet energy loss] in PbPb



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 [jet energy loss] 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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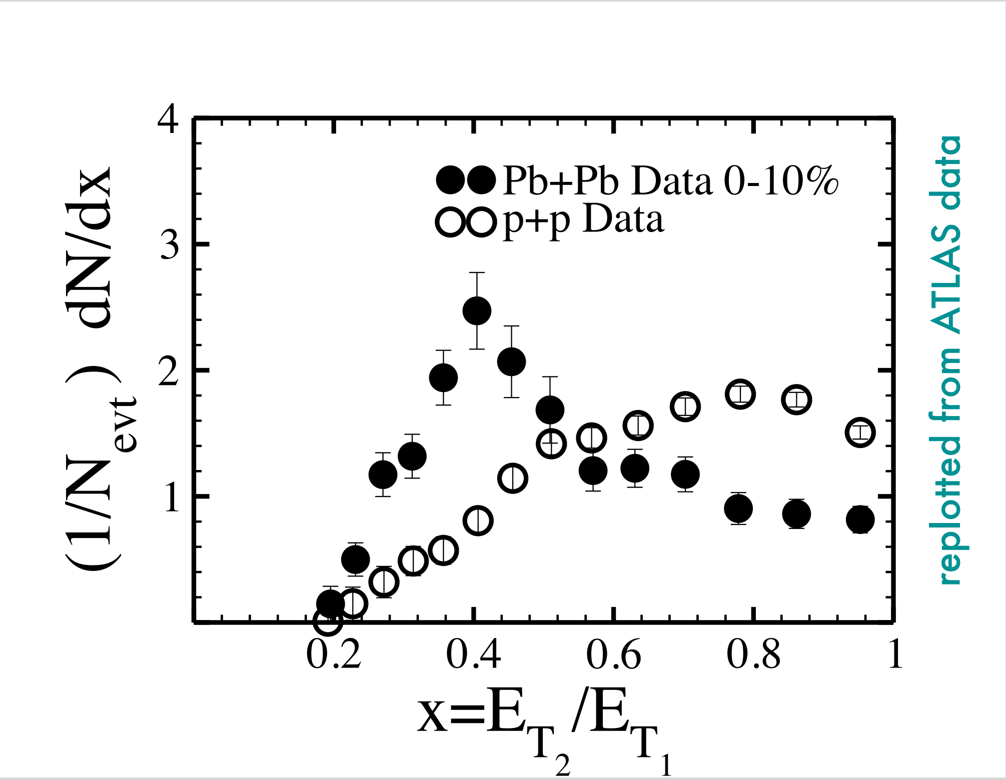

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$$\langle x \rangle_{PbPb} \lesssim 0.54 \text{ [ATLAS]} \div 0.62 \text{ [CMS]} \qquad \langle x \rangle_{pp} - \langle x \rangle_{PbPb} \lesssim 0.12 \text{ [ATLAS]} \div 0.08 \text{ [CMS]}$$

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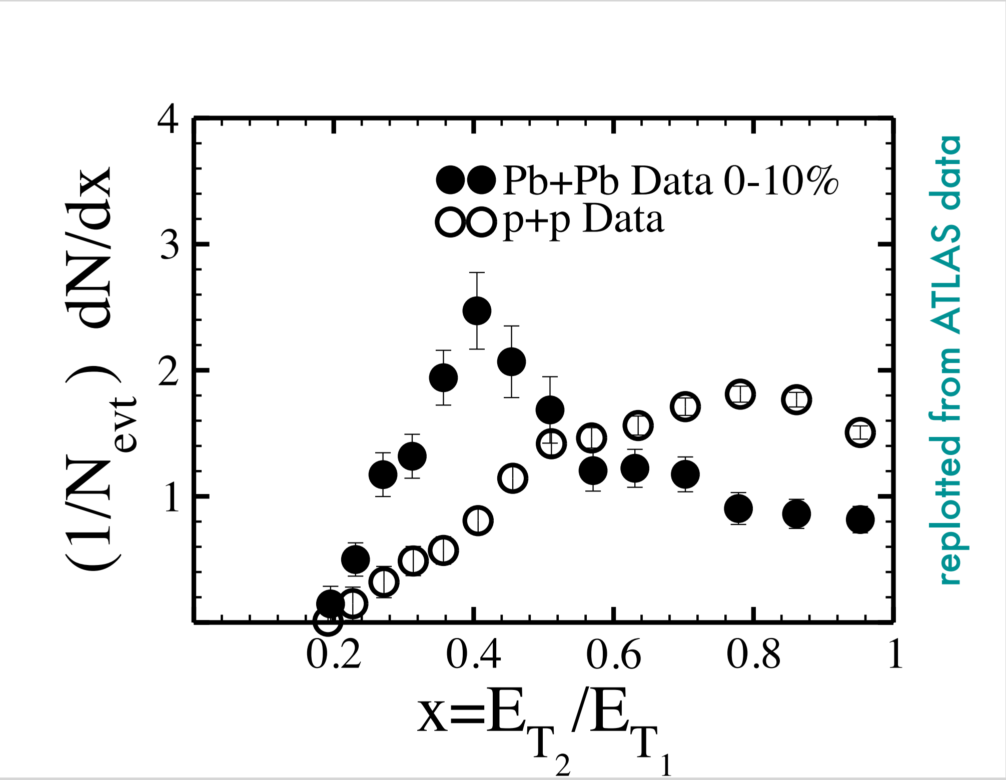

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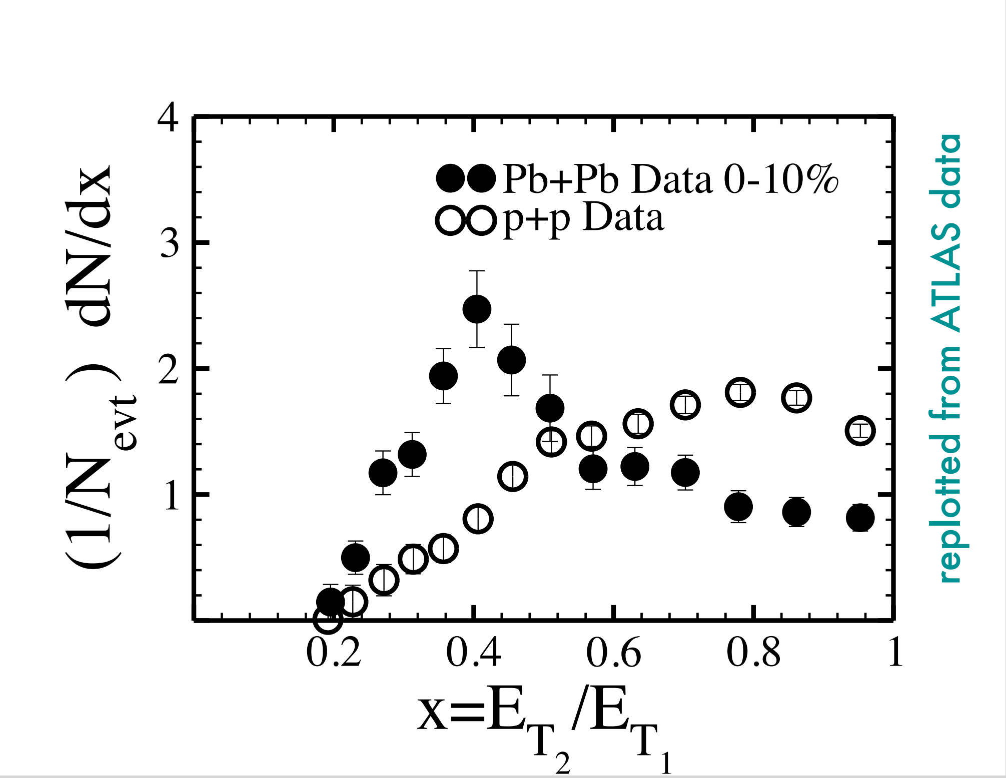
estimate energy loss

::underestimate::
all jets interact equally

from CDF vacuum jet shape studies

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

out-of-cone radiation [jet energy loss] in PbPb



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estimate energy loss

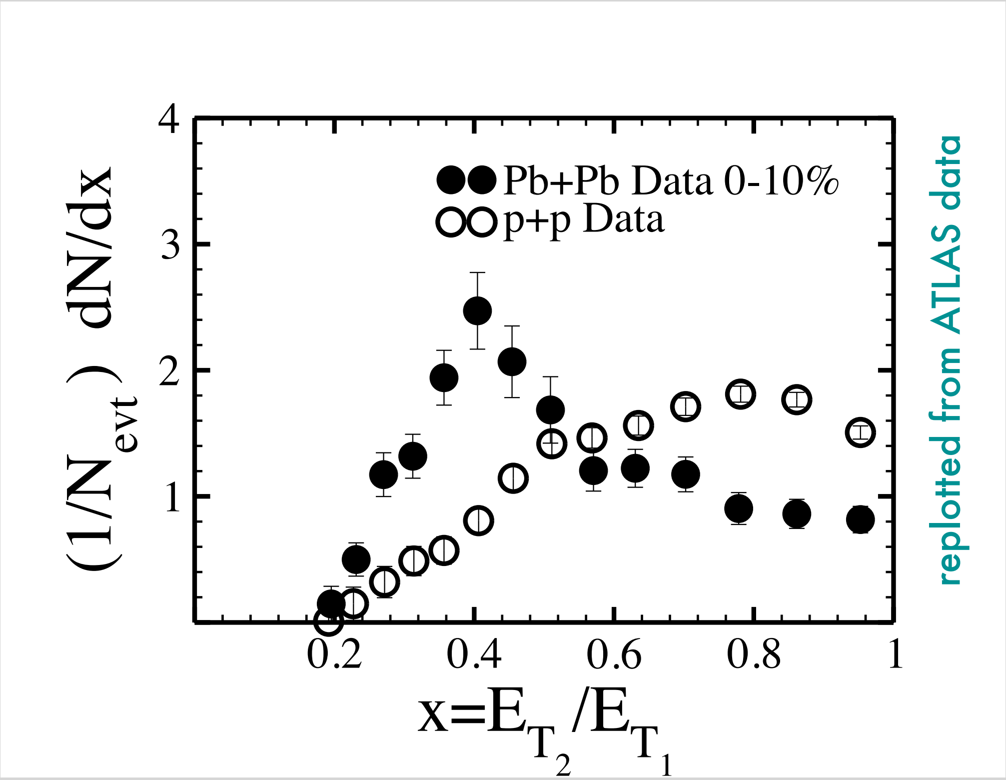
::overestimate::

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 [jet energy loss] in PbPb



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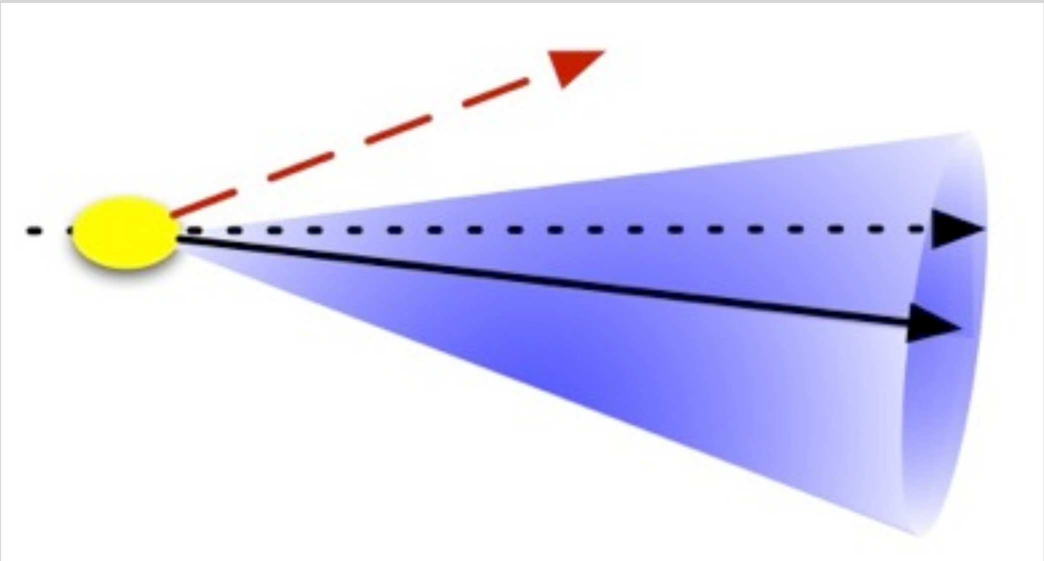
estimate energy loss

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

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

underlying dynamics



increased large angle medium induced radiation

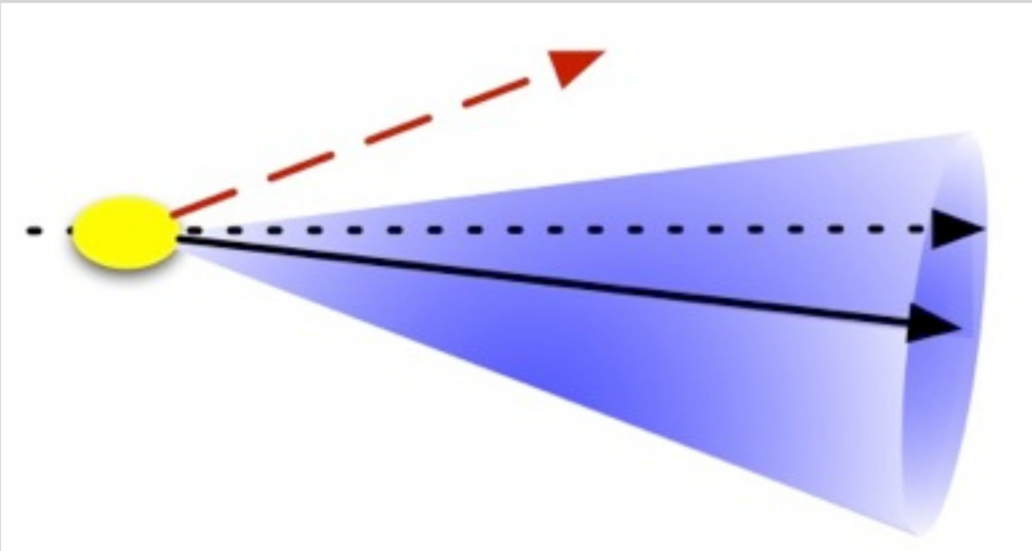
at given fixed angle

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

:: harder gluons are emitted earlier

:: [semi-]hard gluons deflect jet

underlying dynamics



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sizeable out-of-cone radiation implies sizeable modification of azimuthal distribution

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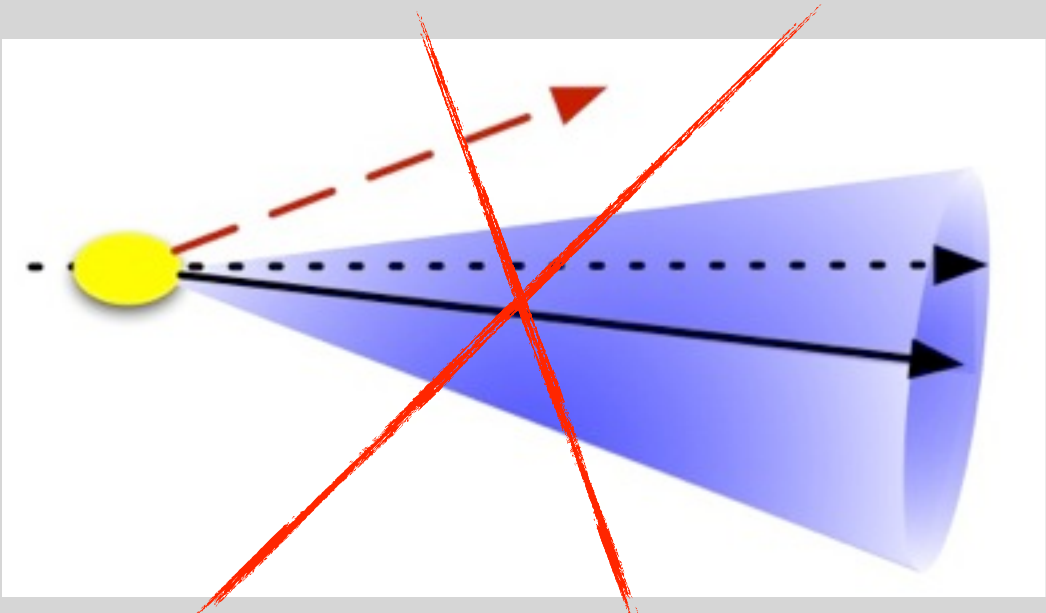

increased large angle medium induced radiation

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

at given fixed angle

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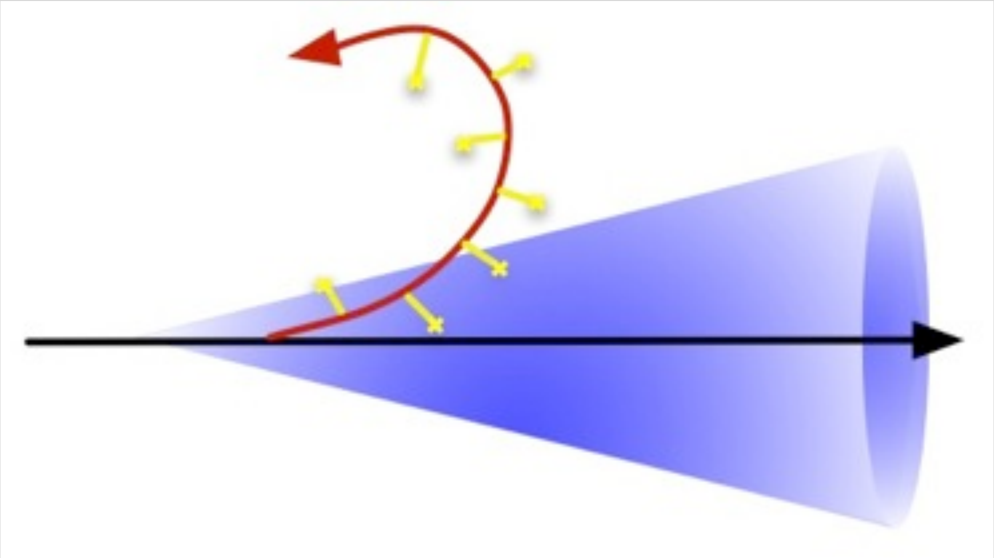
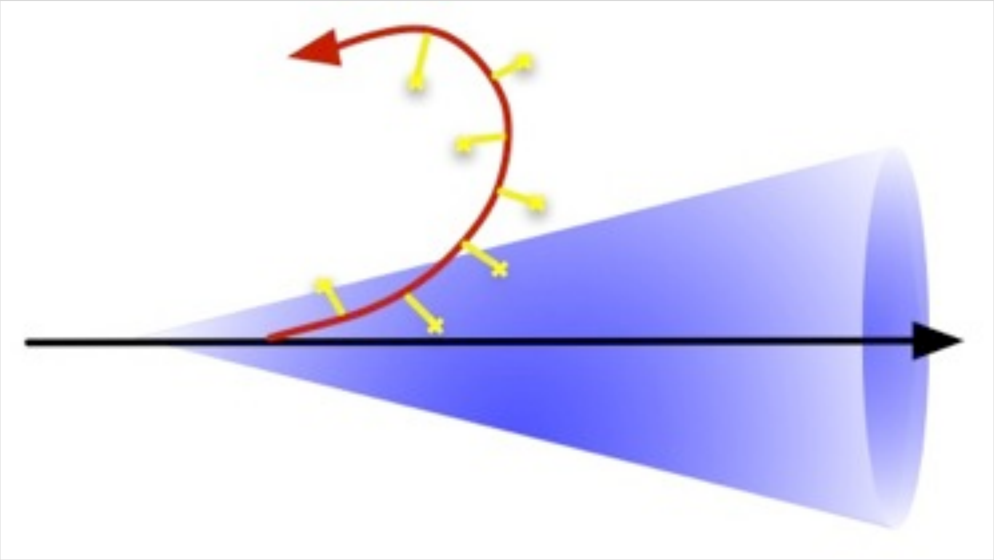


transport of radiated gluons

radiation of soft gluons at small angle

:: no sizeable effect on jet direction [see later]

underlying dynamics



transport of radiated gluons

radiation of soft gluons at small angle

:: no sizeable effect on jet direction [see later]

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

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

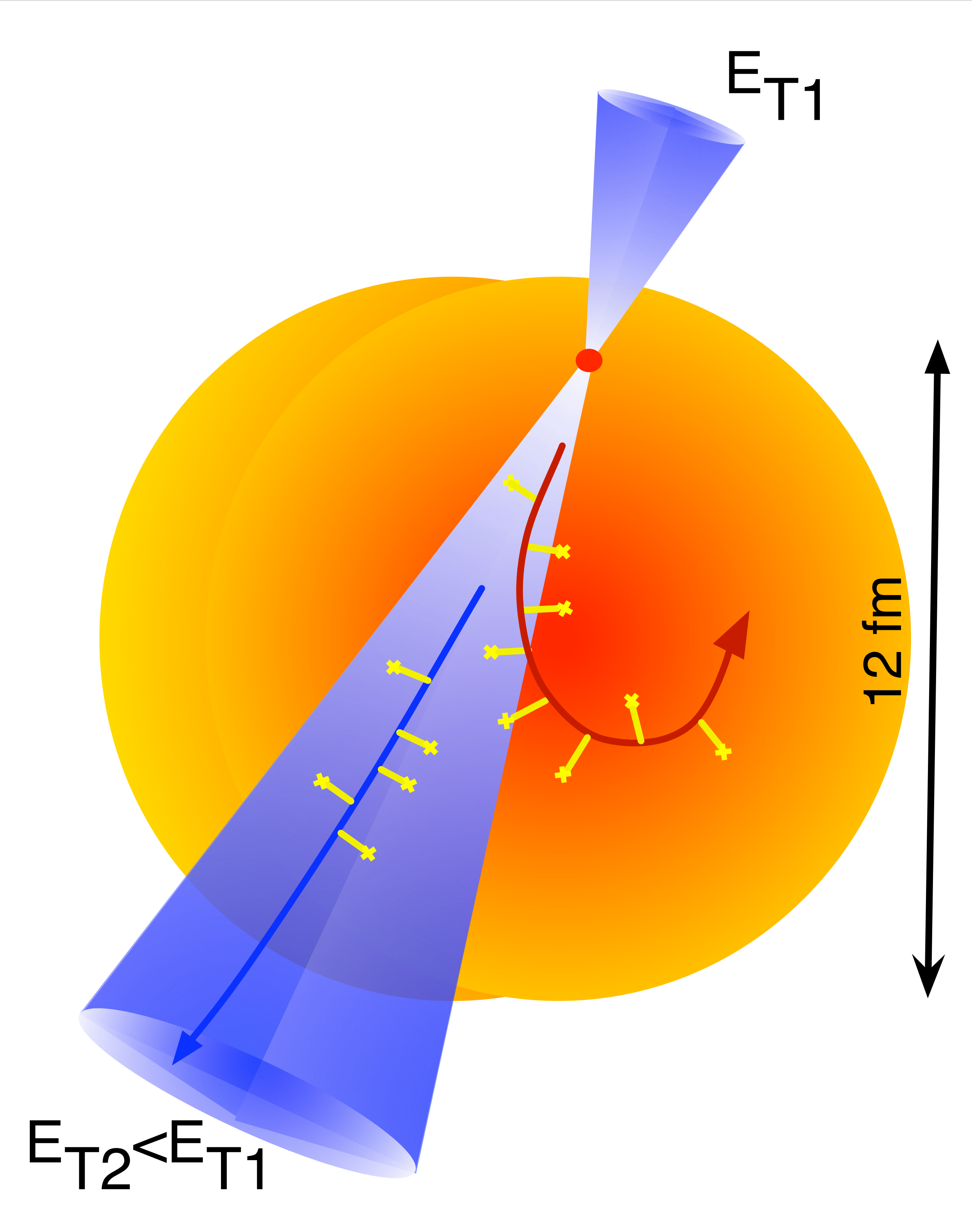
- in the presence of a medium soft modes are formed early

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

- sufficiently soft modes are completely decorrelated from the jet direction

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

jet collimation



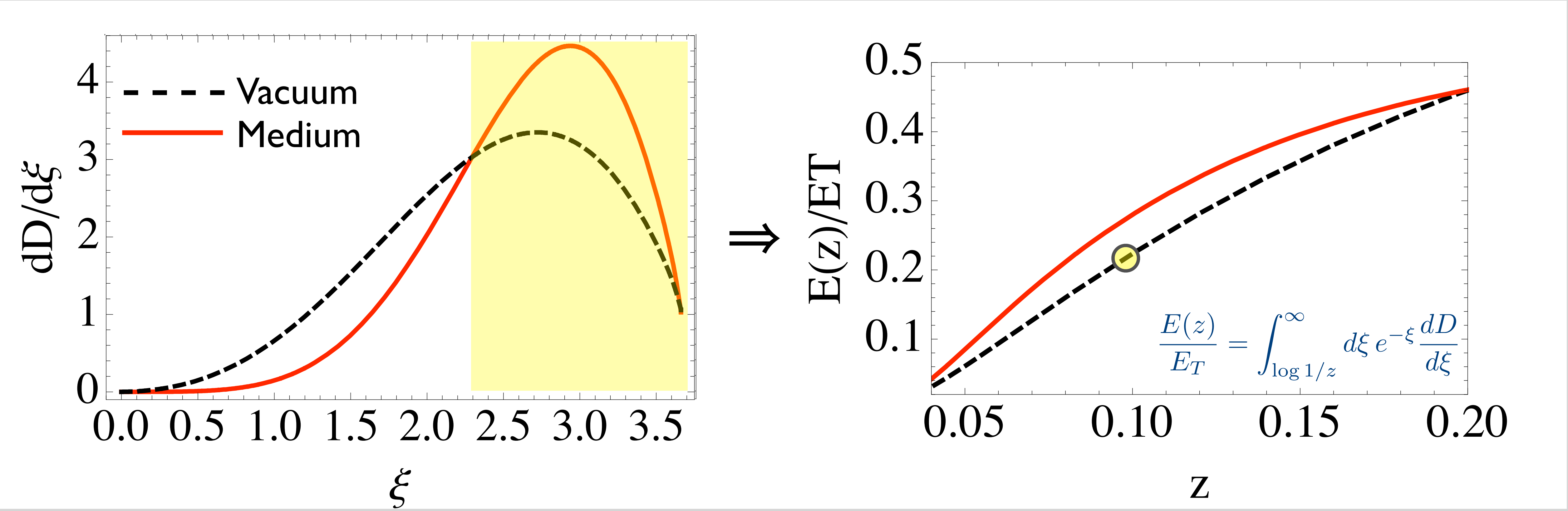
the medium acts as a frequency collimator efficiently trimming away the soft components of the jet

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

jet [frequency] collimation

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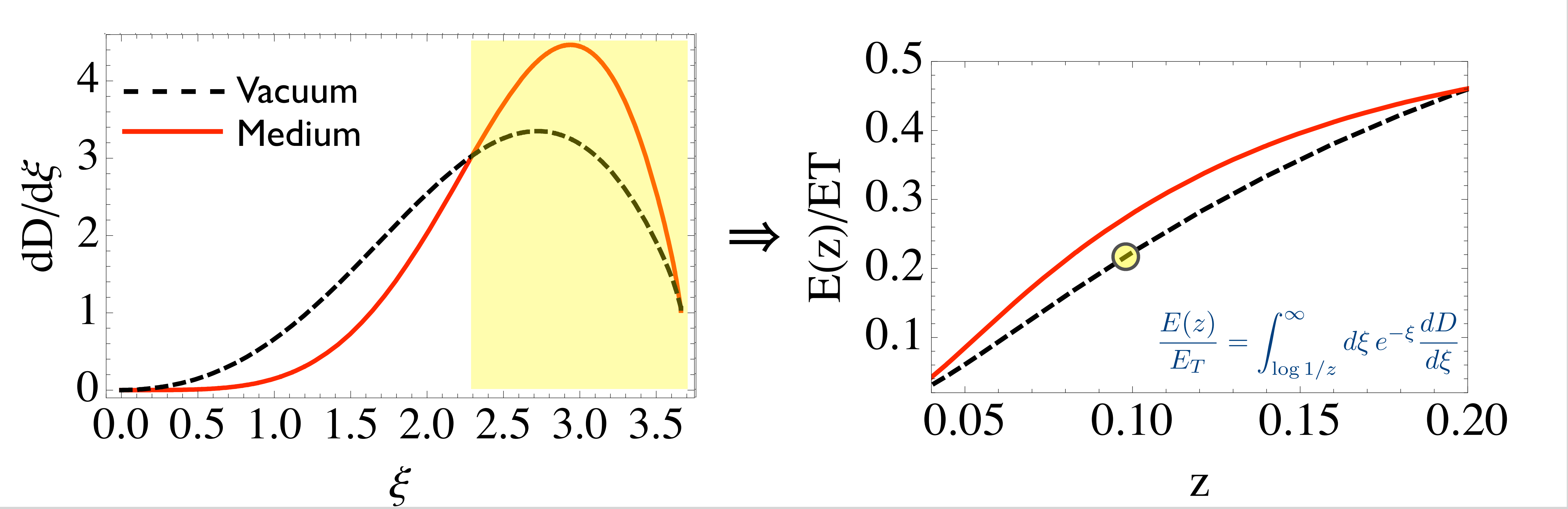

↪ if jet collimation is the sole medium effect [or with additional medium induced softening], transport coefficient needed to account for asymmetry can be estimated from earlier energy loss bounds

jet [frequency] collimation

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

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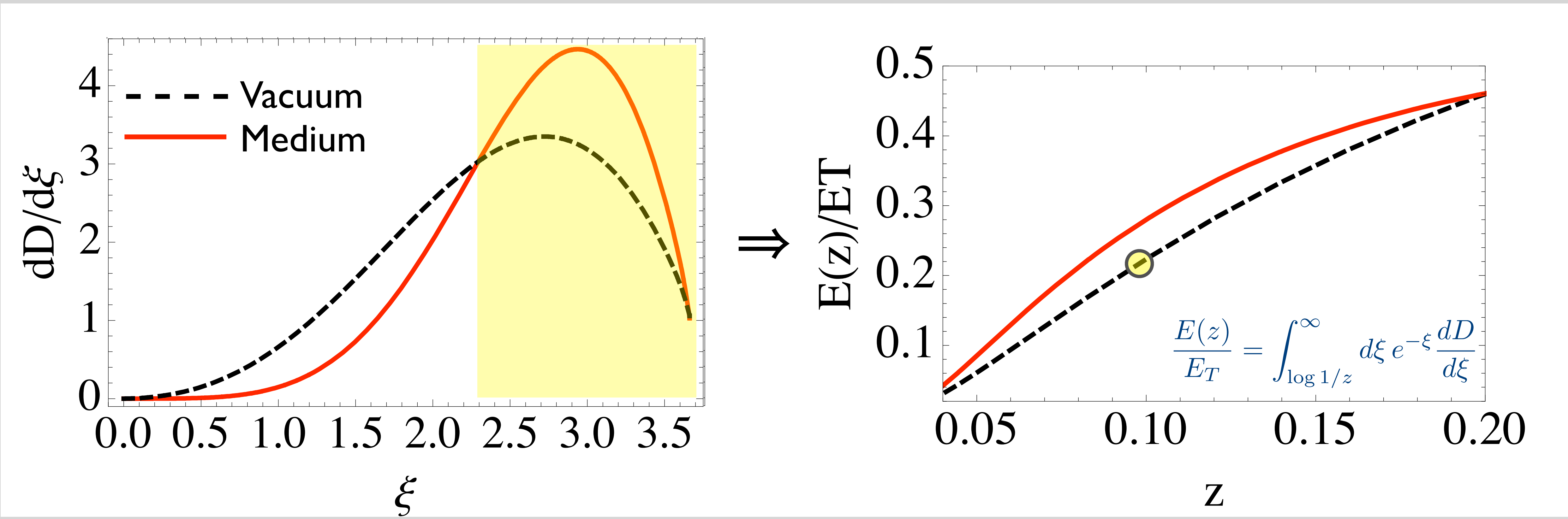

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$$\omega^2 = z^2 E_T^2 \leq \hat{q} L$$

ATLAS [E_0 = 100 GeV]

vacuum $\quad 35 \left(\frac{E_T}{E_0}\right)^2 \leq \hat{q}L \leq 85 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$

medium $\quad 30 \left(\frac{E_T}{E_0}\right)^2 \quad\quad 60 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$

CMS [E_0 = 120 GeV]

vacuum $\quad 24 \left(\frac{E_T}{E_0}\right)^2 \quad\quad 62 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$

medium $\quad 18 \left(\frac{E_T}{E_0}\right)^2 \quad\quad 40 \left(\frac{E_T}{E_0}\right)^2 \mathrm{GeV}^2$

(in .vs. out) of cone radiation

- energy lost from cone via jet collimation is soft
  - $\hookrightarrow$ [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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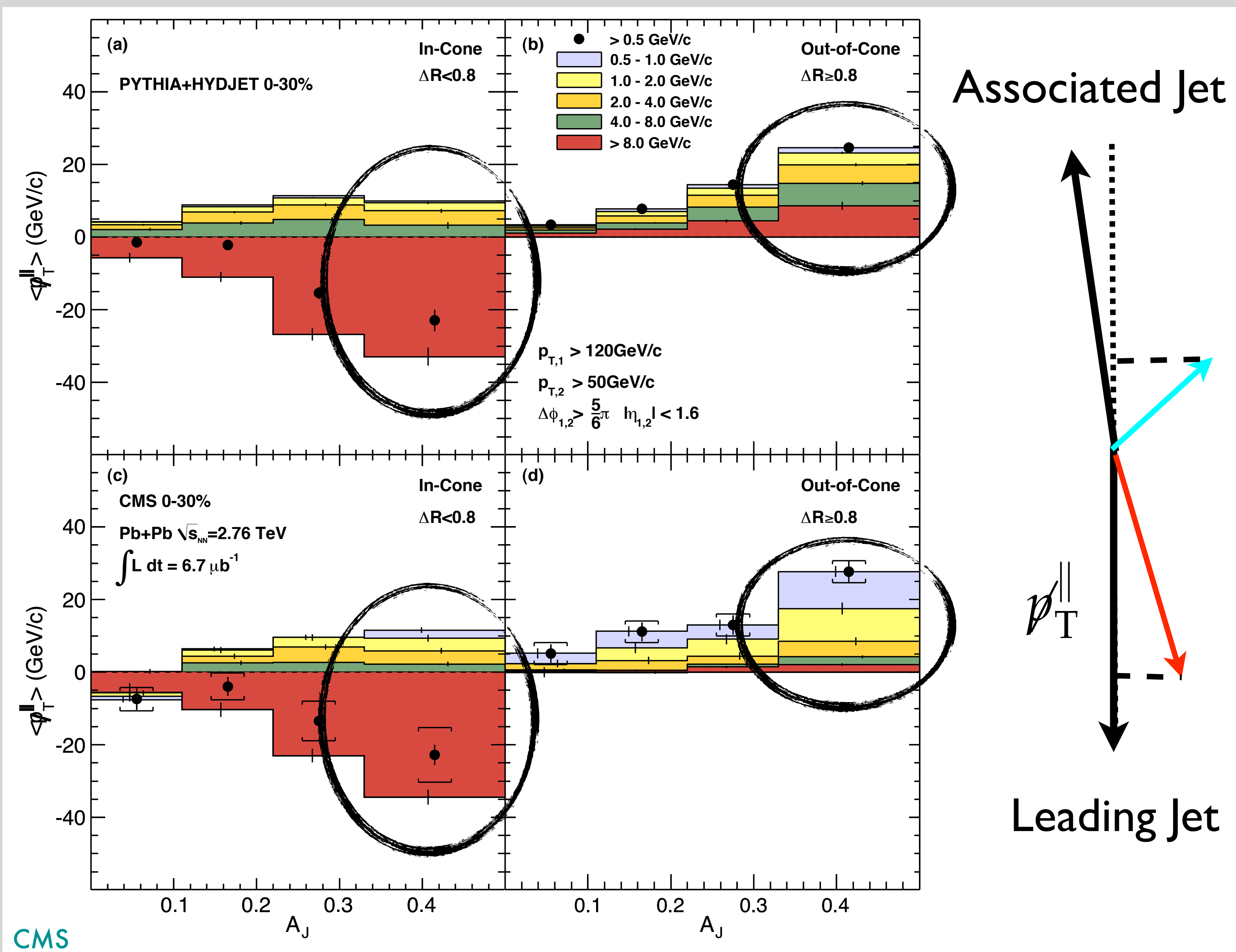
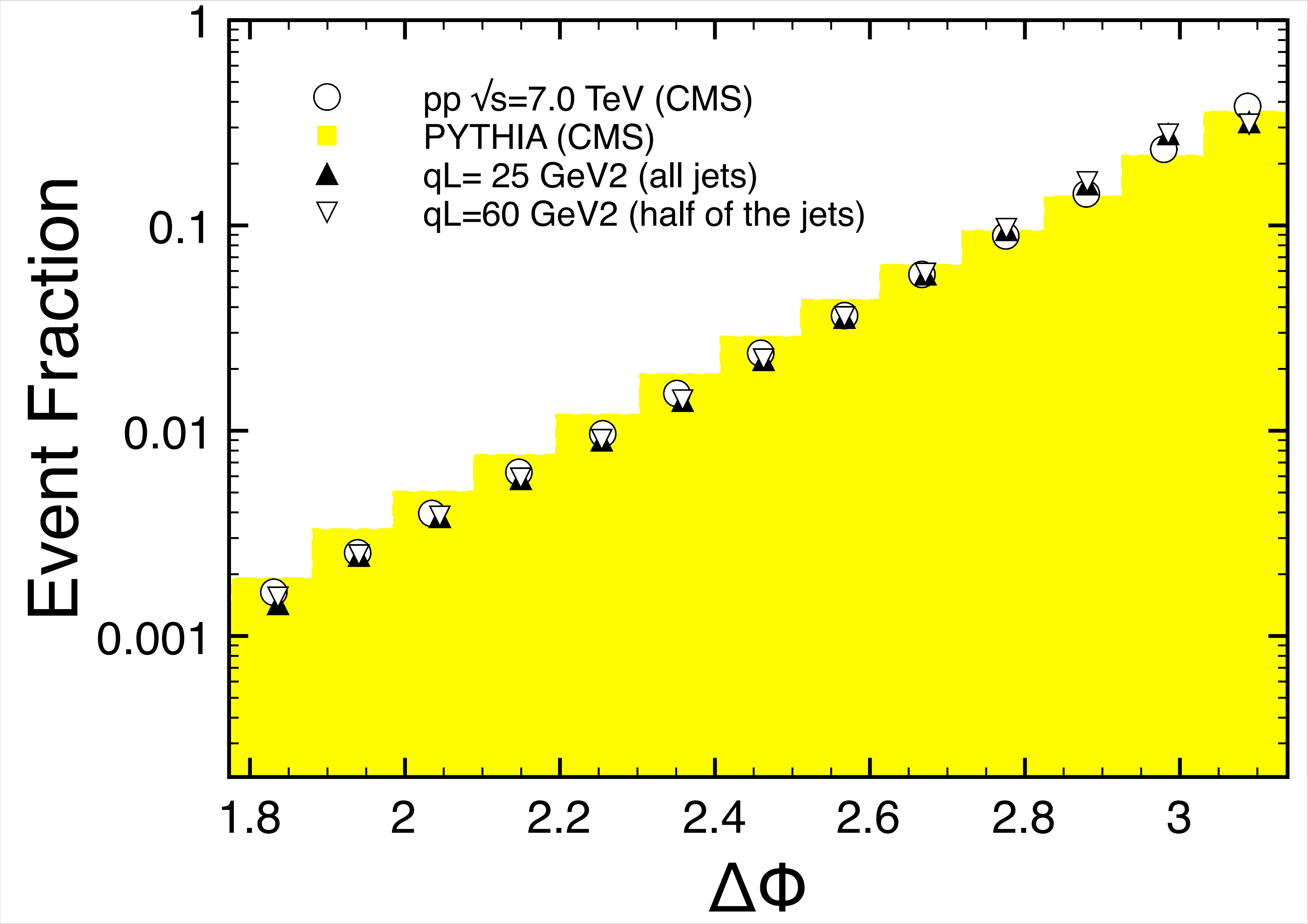


$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\text{Leading Jet}}\right)$$

effect on azimuthal distribution

- smear transverse momentum corresponding to each angle [from reference proton-proton distribution] $p_T = \langle E_{T_2} \rangle \sin(\pi - \Phi)$ with gaussian weight of average squared momentum $\hat{q}L$.



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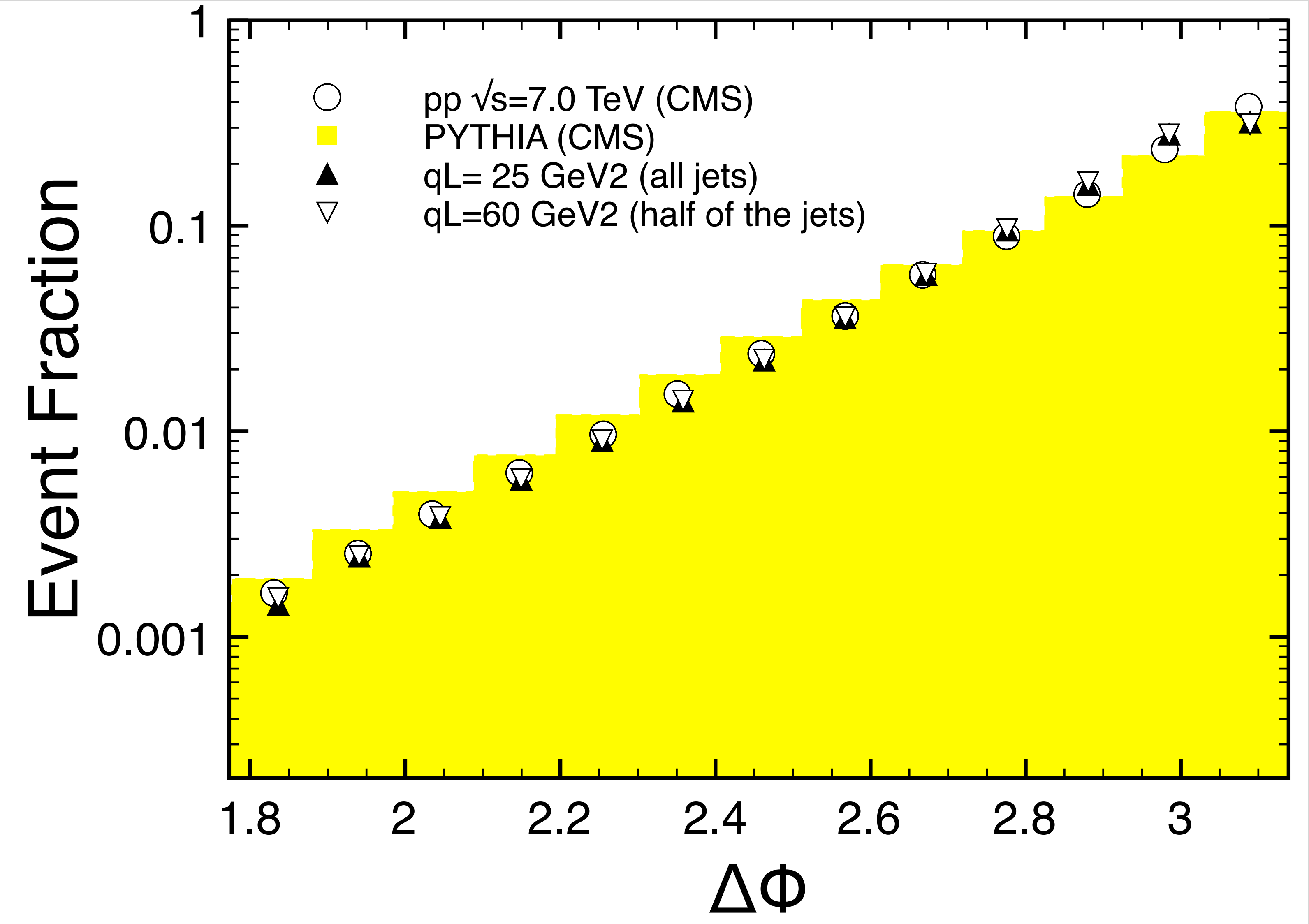

for estimated values of qL jet collimation DOES NOT result in sizeable effect for azimuthal distribution

in-medium colour flow

arXiv:1107.1080 + in preparation

[with Andrea Beraudo and Urs Wiedemann]

colour flow and hadronization

colour flow and hadronization

- R_{AA} models based factorization of parton energy loss and fragmentation

$$d\sigma_{\rm med}^{AA\to h+X} = \sum_f d\sigma_{\rm vac}^{AA\to f+X} \otimes \langle P(\Delta E)\rangle_{AA} \otimes D_{\rm vac}^{f\to h}(z)$$

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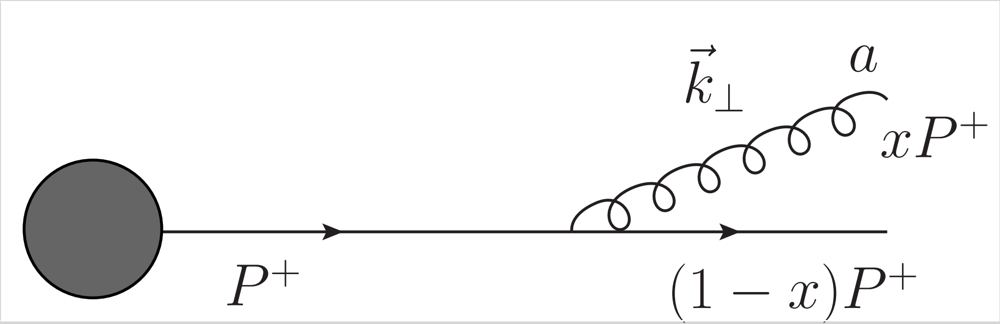
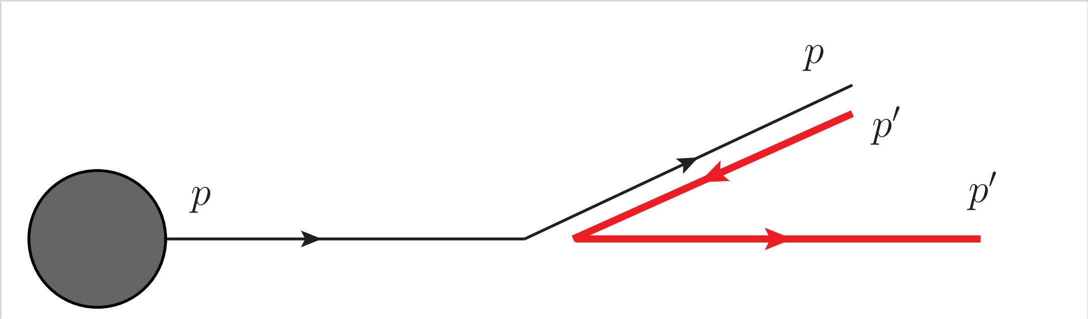
- proof of principle calculation in large N_c and N=1 order in opacity

colour flow [vacuum]

- colour flow in vacuum branching





↪ colour singlet cluster giving rise to leading hadron

$$p^+_{cluster} = \left(1 - \frac{x}{2}\right) p^+_{parton} \qquad M^2_{inv} = \frac{k_t^2}{2x(1-x)}$$

colour flow [in-medium]

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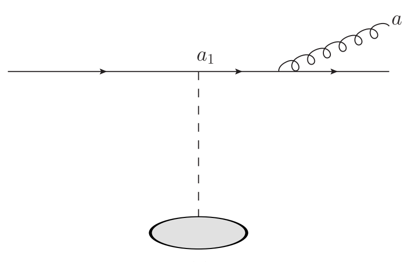
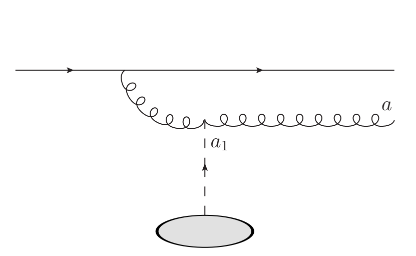
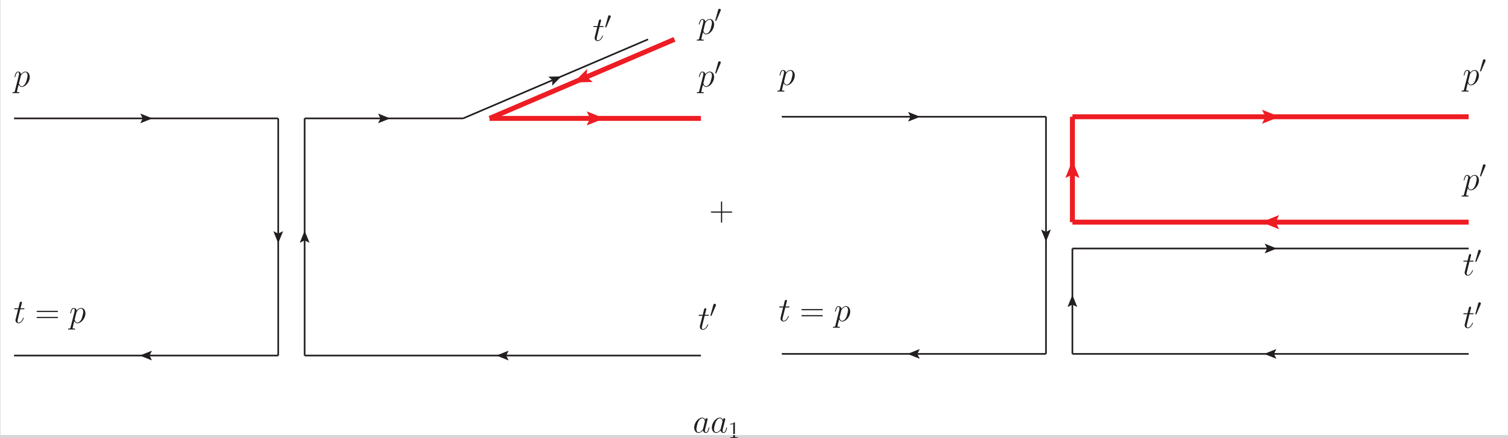
- vacuum like



(a)



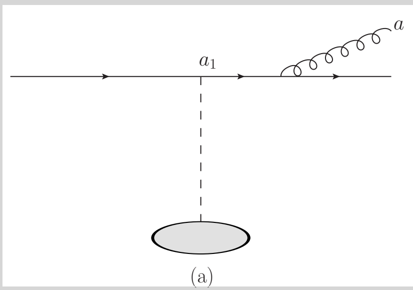
(c)



$$p^+_{cluster} = \left(1 - \frac{x}{2}\right) p^+_{parton} \qquad M^2_{inv} \approx \frac{k_t^2}{2x}$$

colour flow [in-medium]

vacuum like



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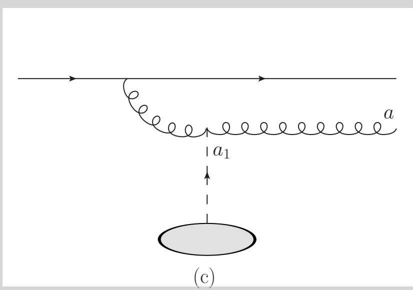

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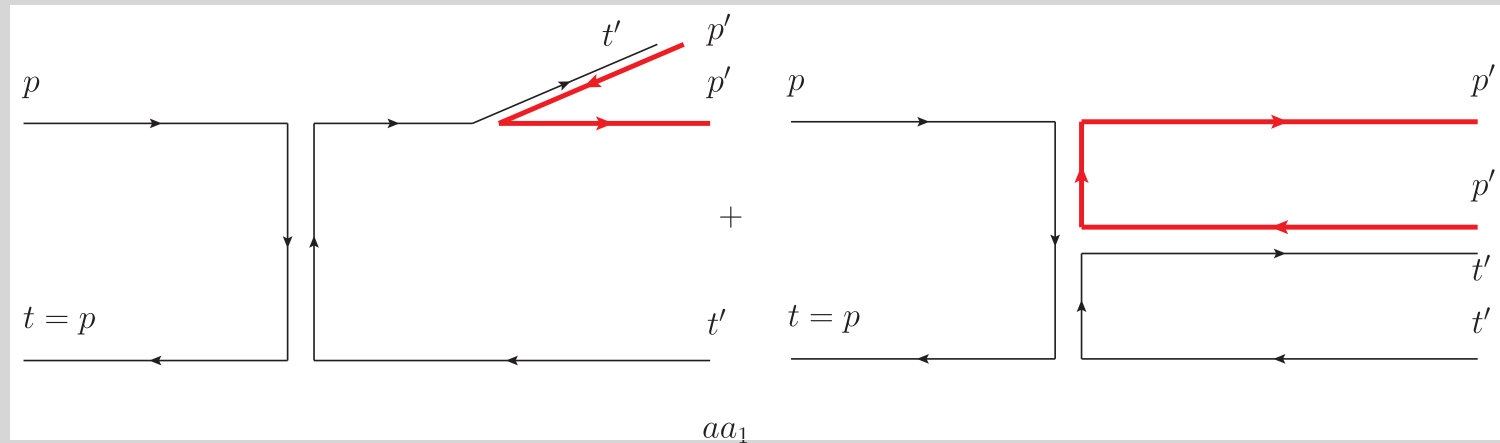

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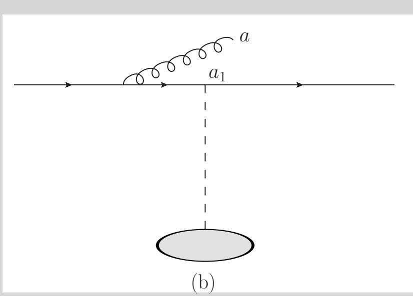
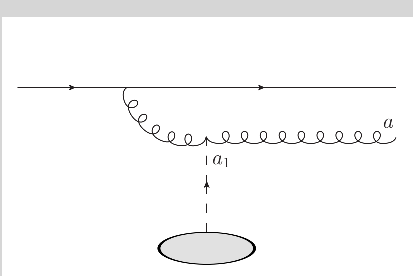
medium modified colour flow



(b)



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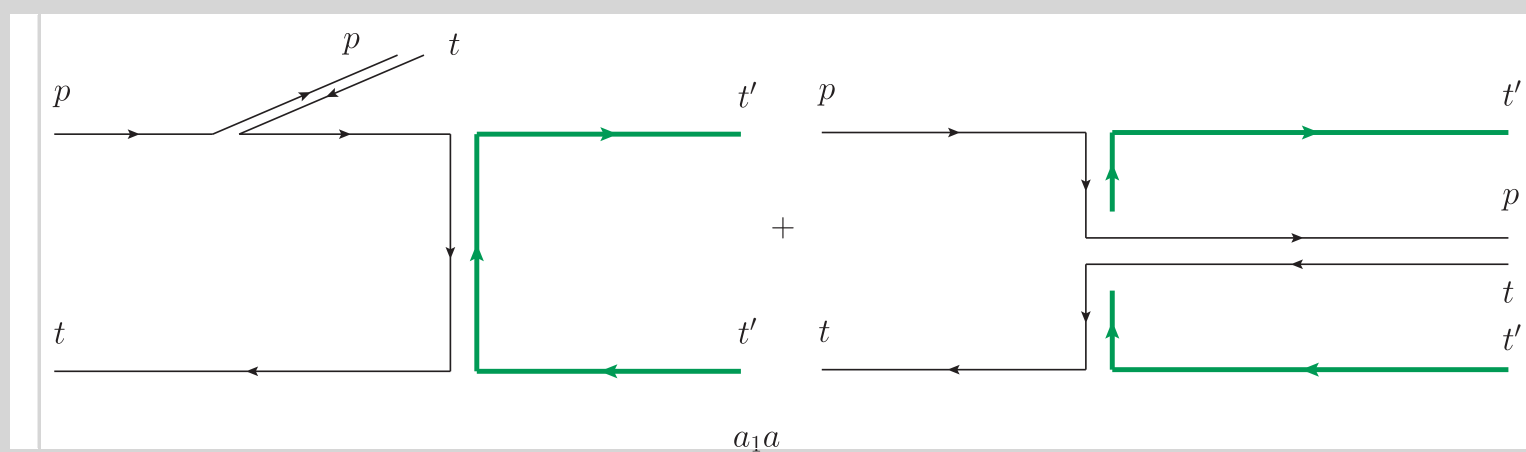

$$p^+_{cluster} = (1 - x) p^+_{parton} \qquad M^2_{inv} \approx 2(1 - x) p^+_{parton} \frac{t_t^2}{2t^+}$$

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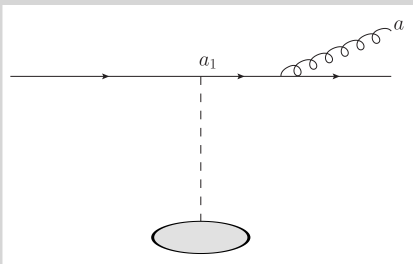

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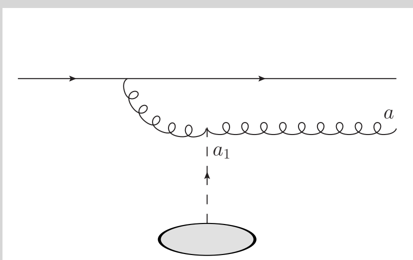

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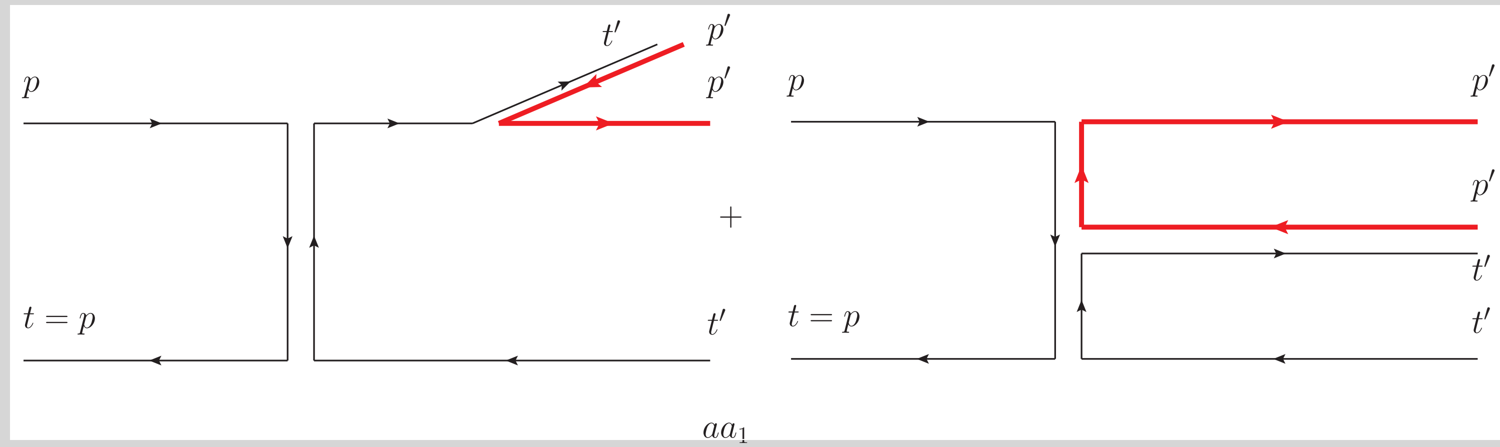

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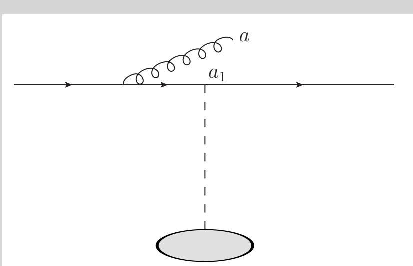

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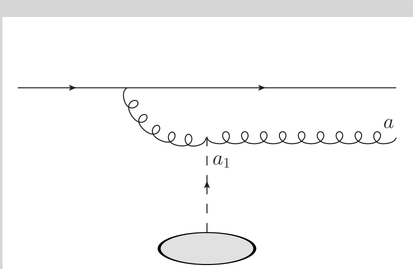

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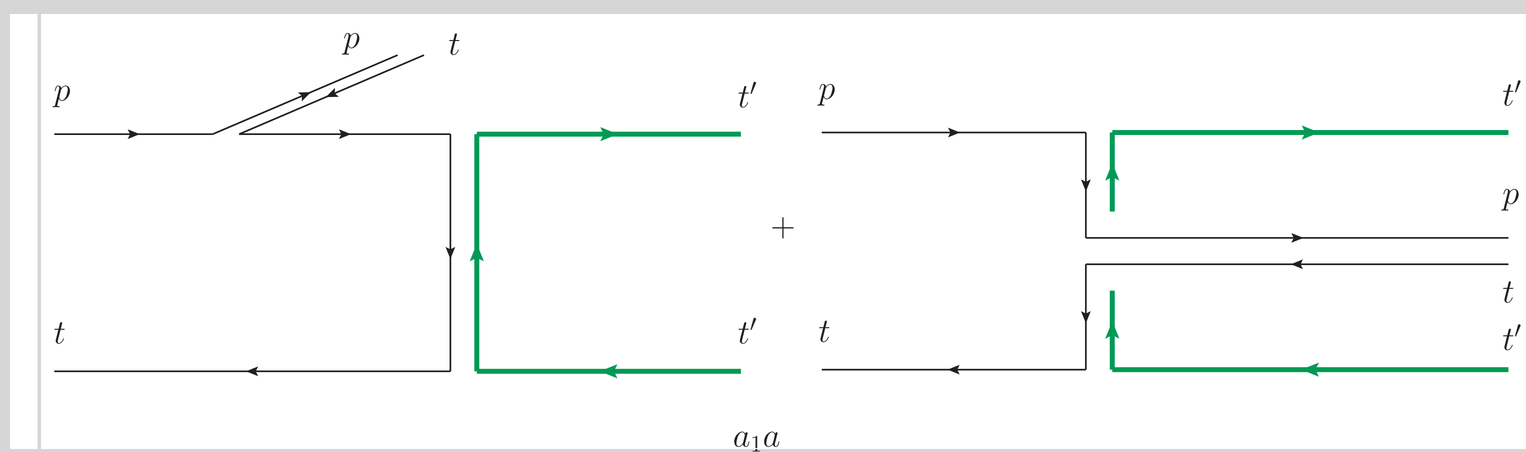

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medium modified clusters have less energy and larger invariant mass [higher splitting probability]

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- clusters of large invariant mass (> 4 GeV) decay [HERWIG]

$$C \longrightarrow XY$$

$$p_X^+ = (1 - \frac{Q_0}{M_C})p^+_{parton} + \frac{Q_0}{M_C}t^+$$

$$Q_0 = 600\,\mathrm{GeV}\ \ (\mathrm{HERWIG})$$

$$M_C \approx \sqrt{p^+_{parton}T}$$

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- with general quenched partonic spectrum

$$\frac{dN}{dp^+_{parton}} = \frac{c}{(dp^+_{parton})^n}$$

$$\frac{dN}{dp^+_{cluster}} > (1 - f^{modcolour}) \frac{c}{(dp^+_{cluster})^n}$$

vacuum-like colour flow

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$$\frac{dN}{dp_{parton}^+} = \frac{c}{(dp_{parton}^+)^n}$$

$$F_{sup}(p_X^+) = \frac{2\left(1 + Q_0/\sqrt{p_X^+ T}\right)^{1-n}}{\left(2 + Q_0/\sqrt{p_X^+ T}\right)}$$

$$\frac{dN}{dp_{cluster}^+} > (1 - f^{modcolour})\frac{c}{(dp_{cluster}^+)^n}$$

vacuum-like colour flow

$$\frac{dN}{dp_X^+} = f^{modcolour}\,F_{sup}(p_X^+)\frac{c}{(dp_X^+)^n}$$

medium modified colour flow

as an illustration

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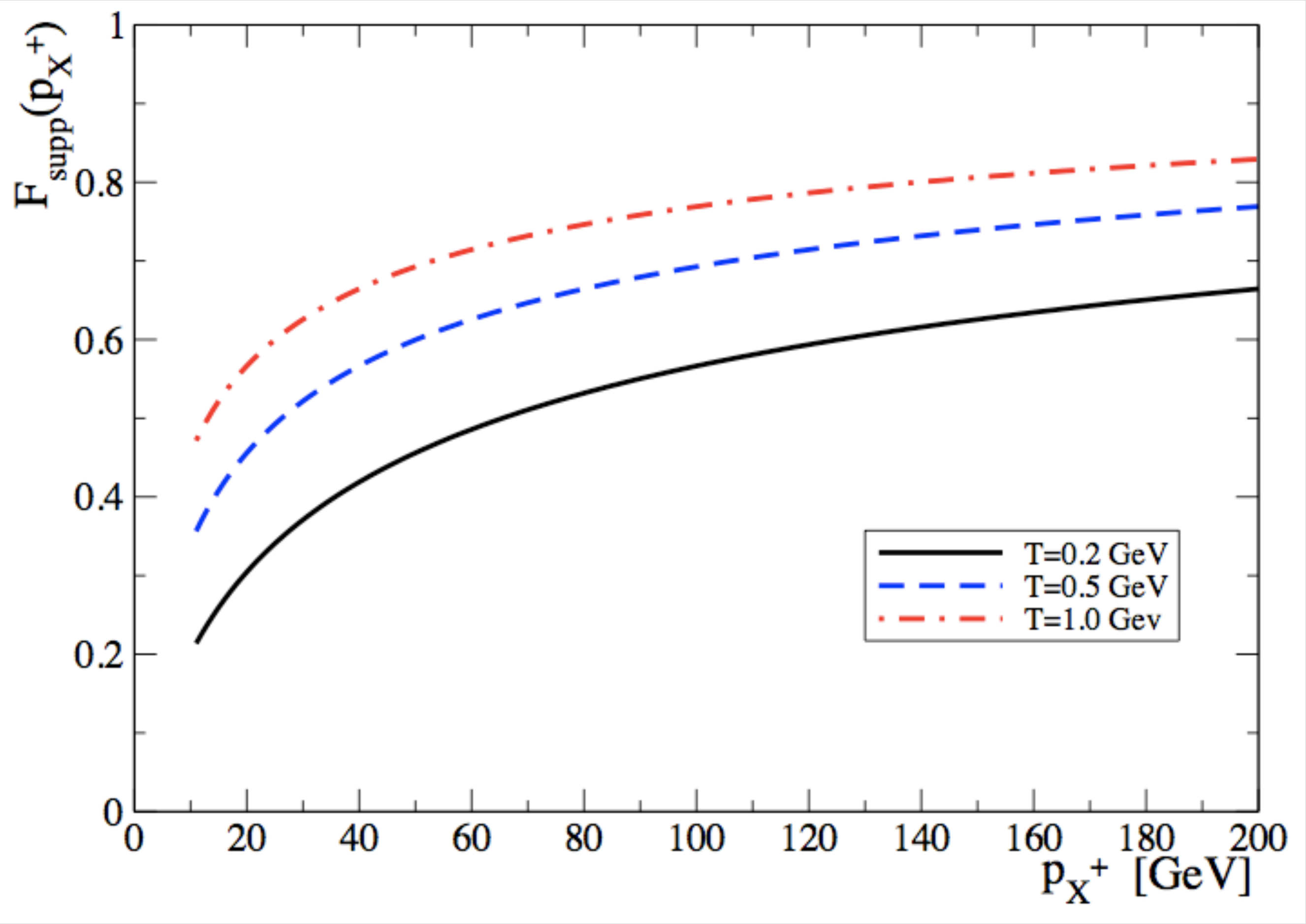

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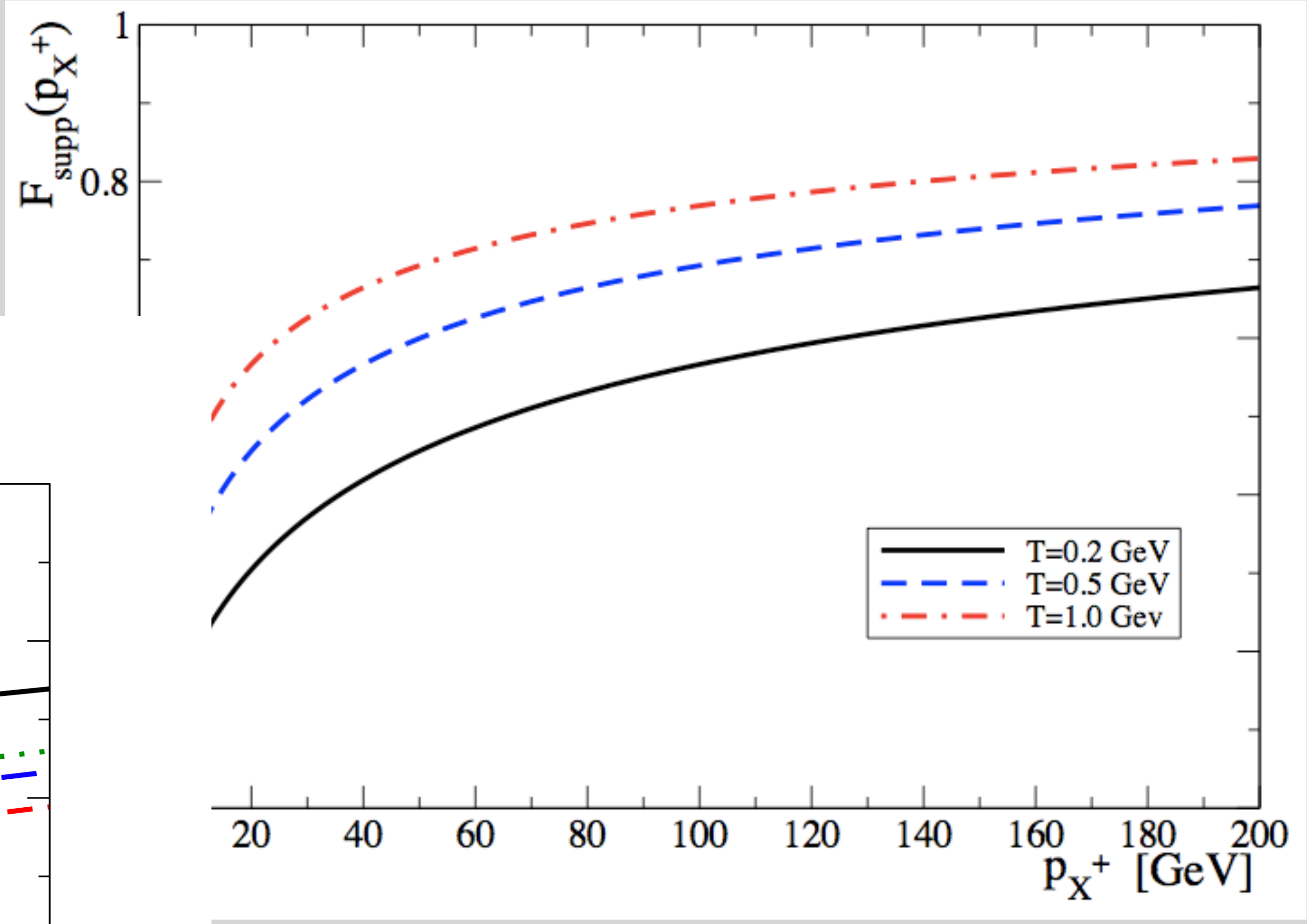

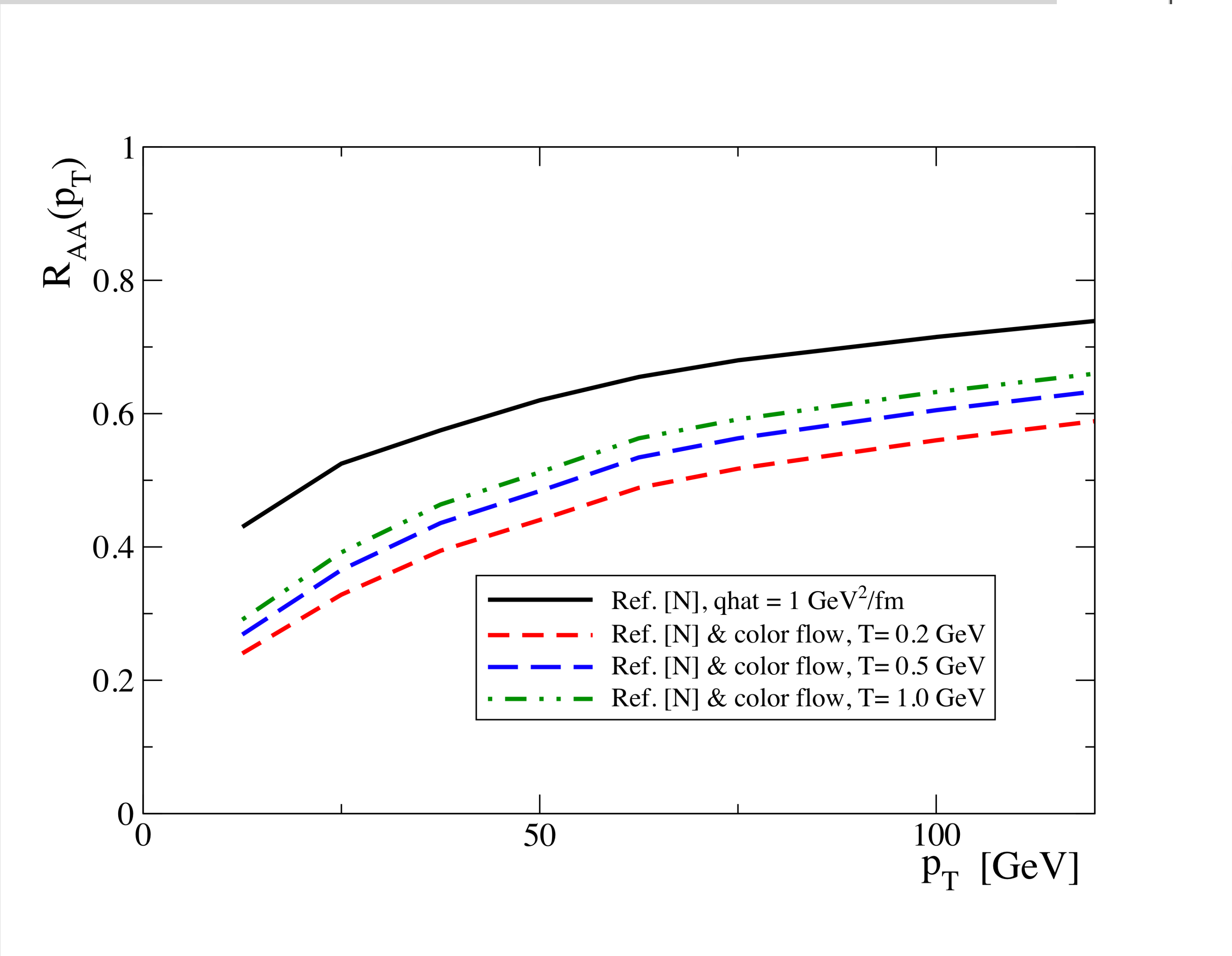

$$R_{AA}(p_t) \approx (1 - f^{modcolour}) R_{AA}^{fact}(p_t) + f^{modcolour} F_{sup}(p_t) R_{AA}^{fact}$$

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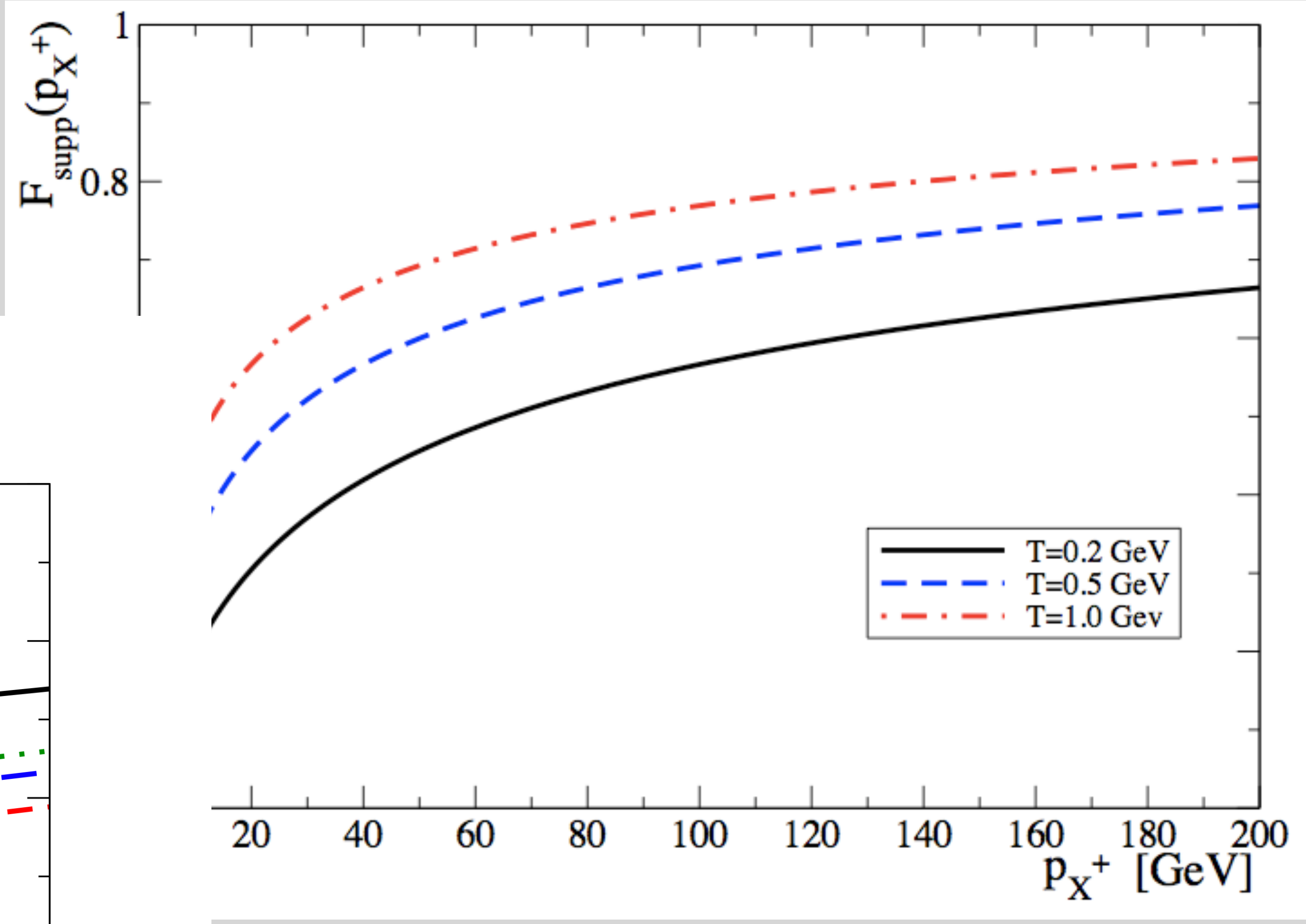

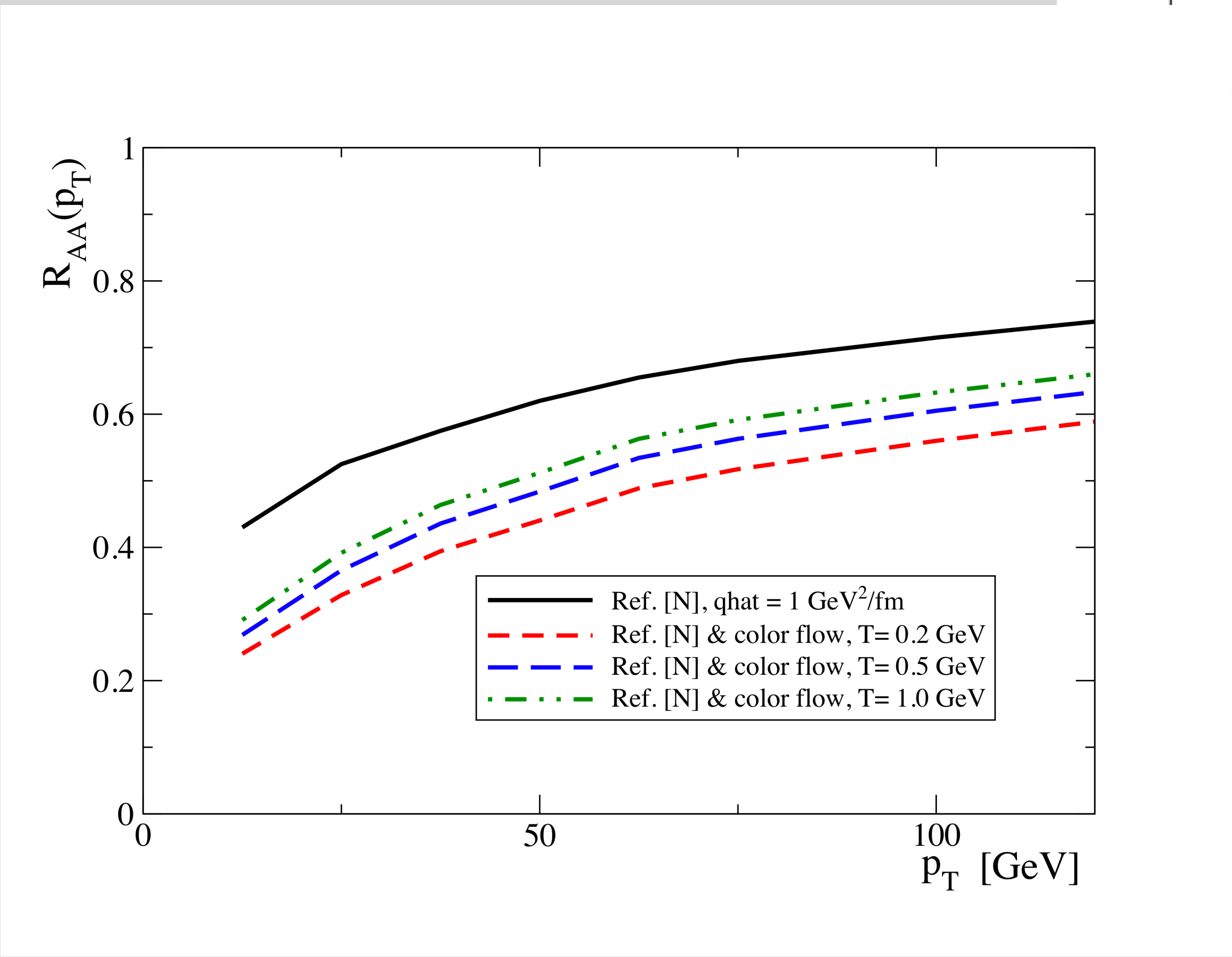

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colour flow effects on hadronization persistent at 100 GeV ?

Thank you