Is there jet-quenching in pPb?

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IS2013, 8-14 Sep 2013, Illa da Toxa

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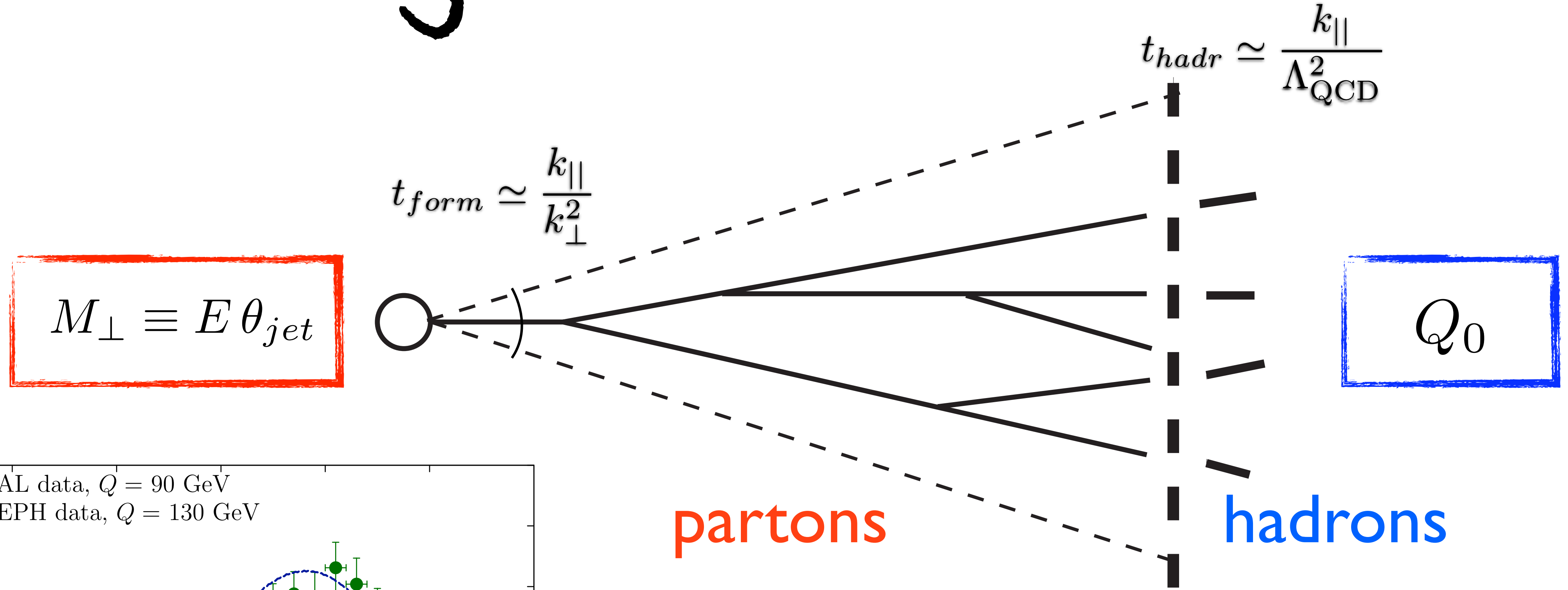
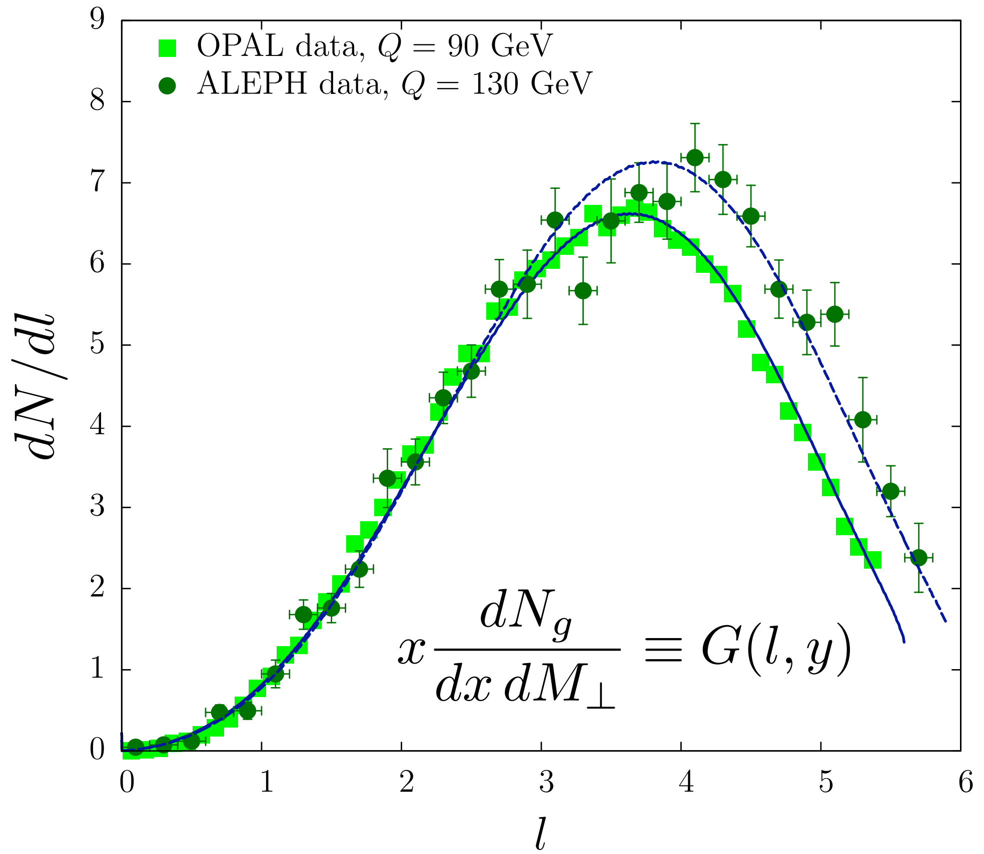
Central question

- how can soft particles from the background "interact strongly" (i.e. give rise to strong flow-effects as described by v_n's) while soft particles from "jet-like" correlations be assumed to be unmodified
- can there by "flow" without "quenching"?

QCD jet in vacuum



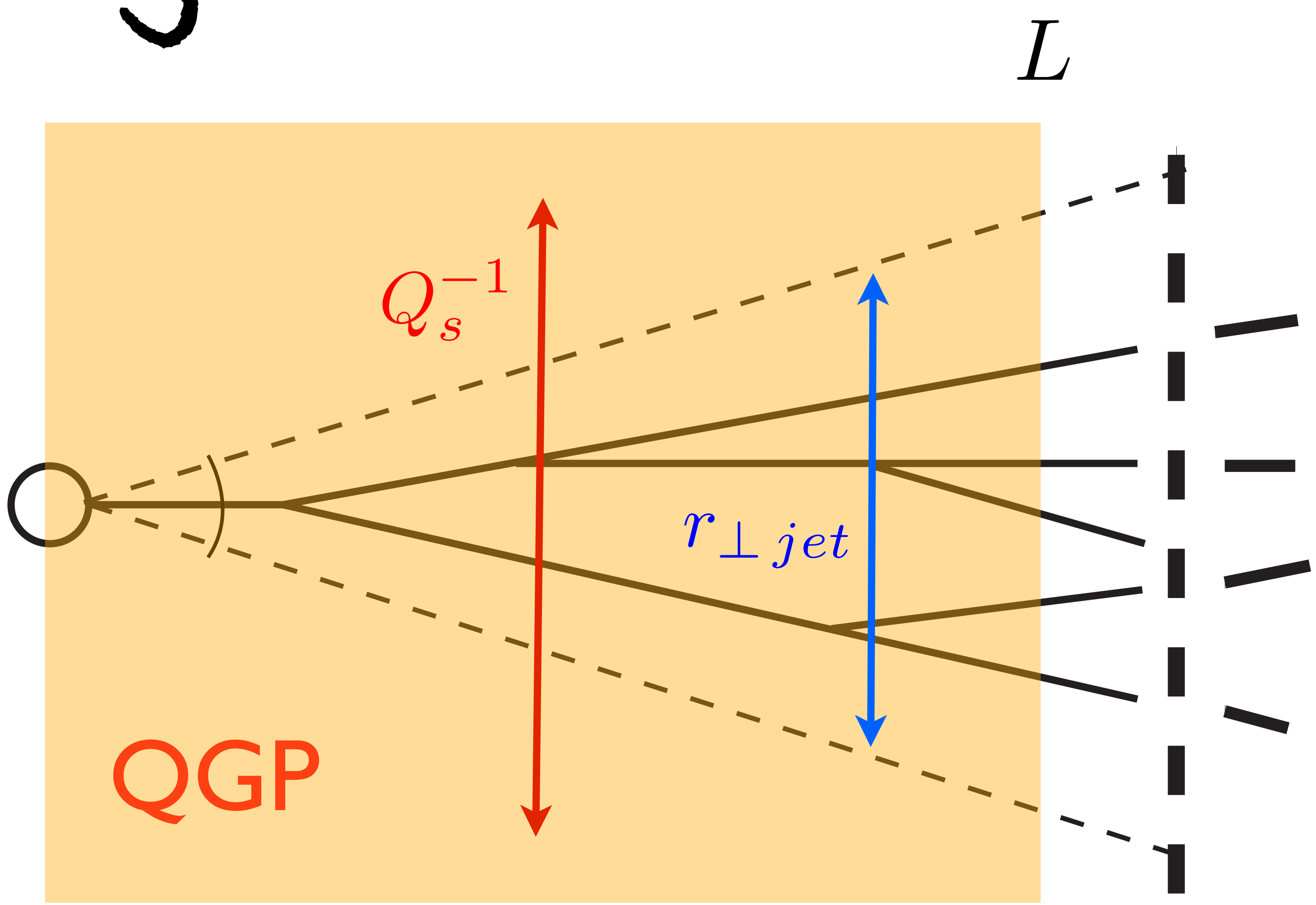


$l = \ln\left(1/x\right) \qquad y = \ln\left(xM_\perp/Q_0\right) \equiv Y - l$

- factorization properties
- jet scales :: perturbative
- angular ordering
- MLLA + LPHD (K factor)
- good description

QCD jet in medium

$M_\perp \equiv E\,\theta_{jet}$



New scales:

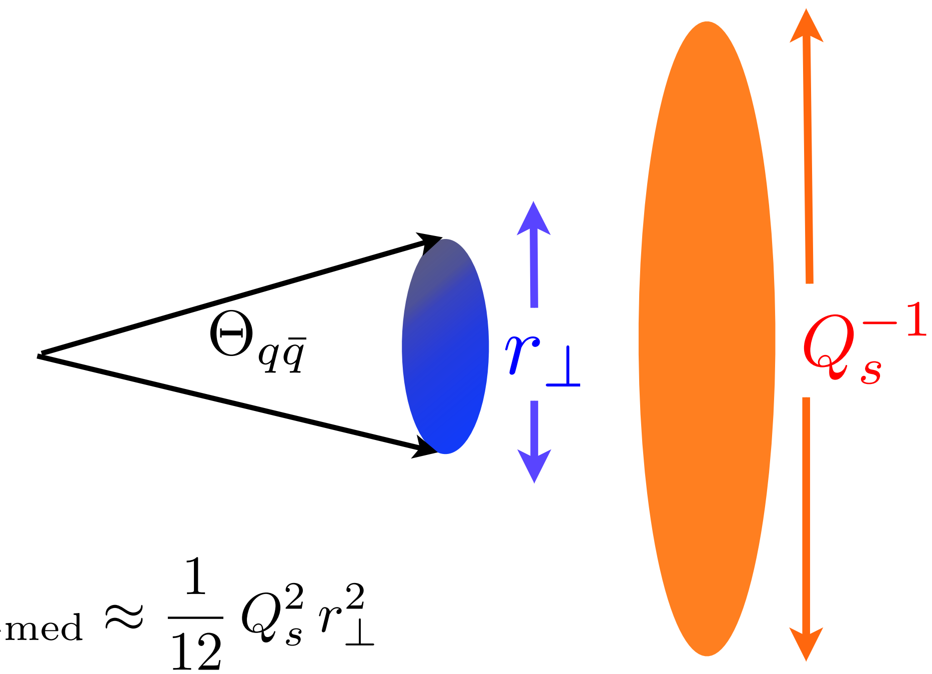
$$M_\perp \equiv E\,\theta_{jet}$$
$$Q_0 \sim \Lambda_{\rm QCD}$$

+

$$Q_s \equiv \sqrt{\hat{q}L} \equiv m_D\,\sqrt{N_{\rm scat}}$$
$$r_{\perp\, jet}^{-1} \equiv (\theta_{jet}L)^{-1}$$

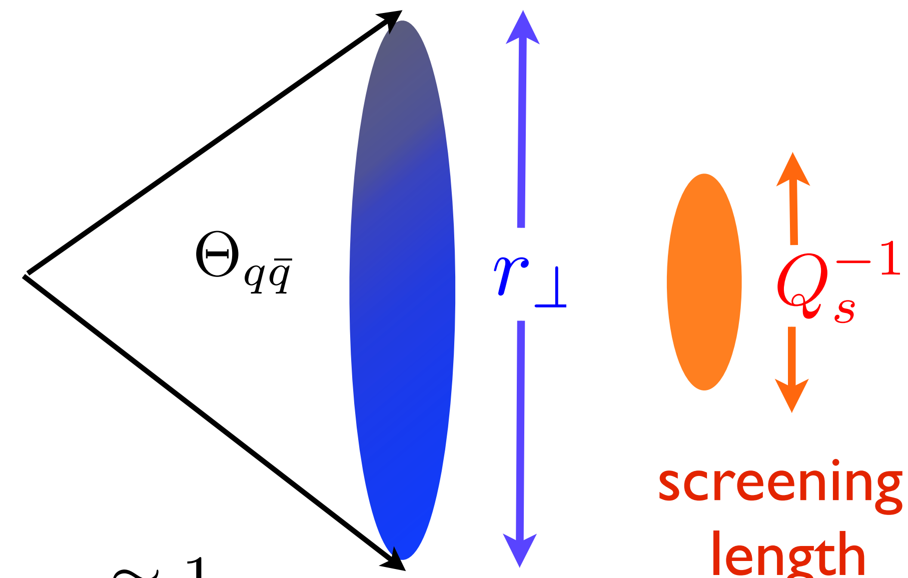
Jet scales in the medium

- $r_\perp < Q_s^{-1}$ (Dipole regime)



$\Delta_{\text{med}} \approx \frac{1}{12} Q_s^2 r_\perp^2$

- $r_\perp > Q_s^{-1}$ (Decoh. regime)



$\Delta_{\text{med}} \approx 1$

$$\Delta_{\text{med}} \approx 1 - \exp[-\frac{1}{12} Q_s^2 r_\perp^2]$$

the decoherence parameter

$$k_\perp < Q_{\text{hard}}$$

$$r_\perp = \theta_{q\bar{q}} L$$

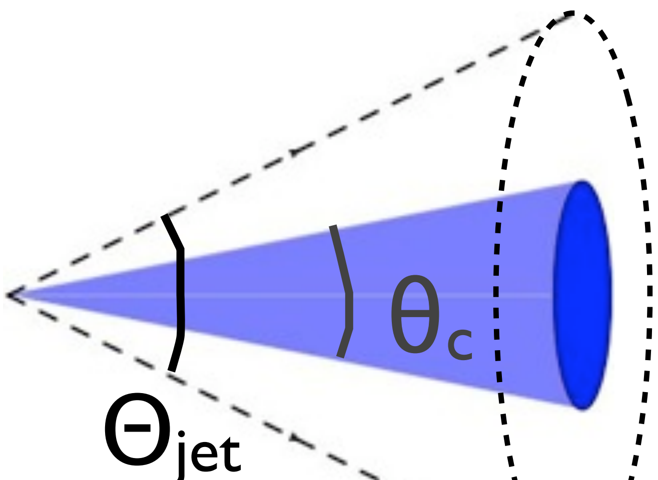
Qs: characteristic momentum scale of the medium

Mehtar-Tani, Salgado, KT 1009.2965; 1102.4317; 1112.5031; 1205.57397
Casalderrrey-Solana, Iancu 1105.1760

Resolved effective charges

$$\Delta_{\rm med} = 1 - e^{-\Theta_{\rm jet}^2/\theta_c^2}$$

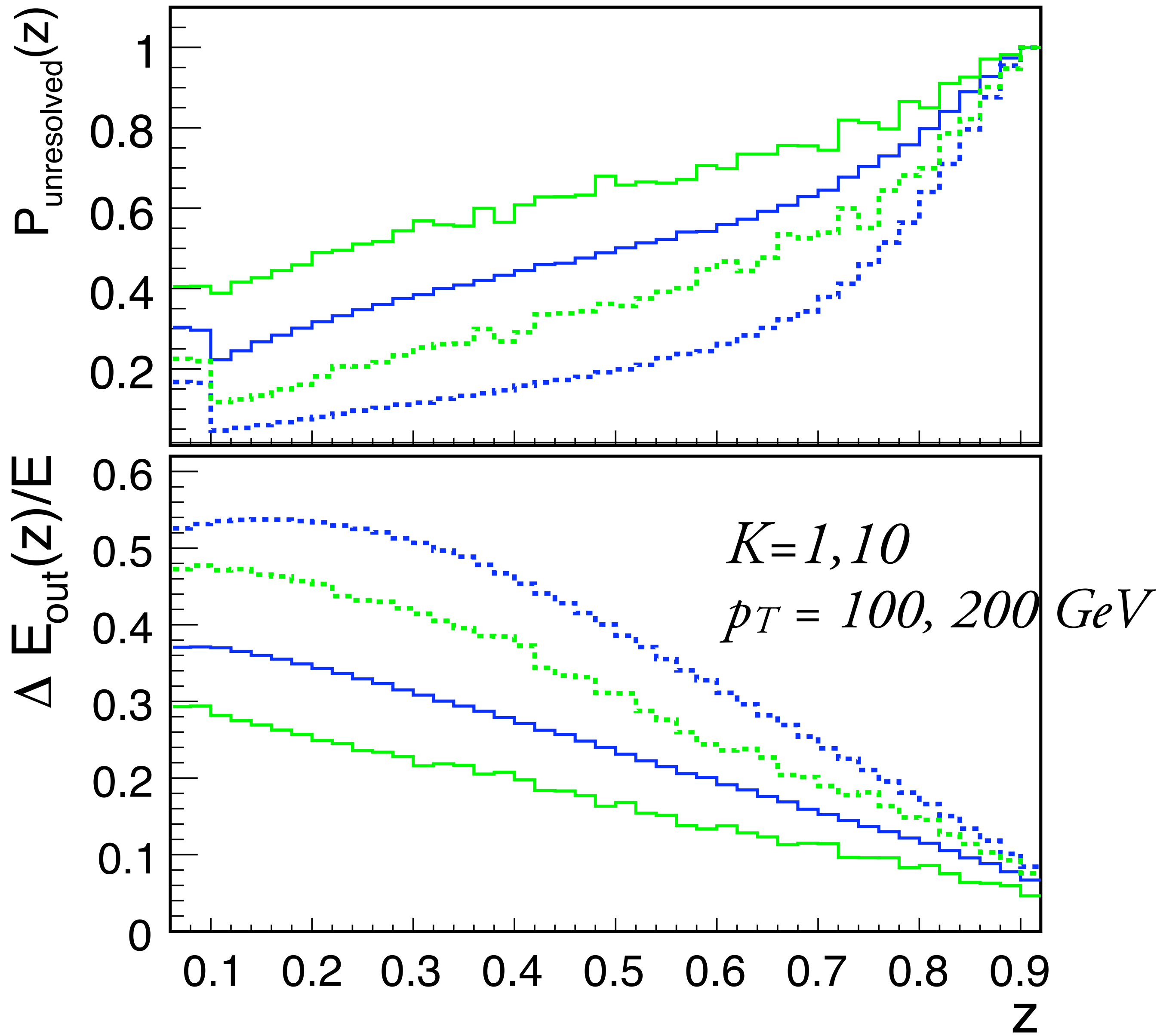
$$\theta_c = 1/\sqrt{\hat{q}L^3}$$



Coherent inner 'core'

- branchings occurring inside the medium with $\theta < \theta_c$
- modes with $\lambda_\perp < Q_s^{-1}$ ($k_\perp > Q_s$)
- $t_f < L \rightarrow Q_s^2 L < \omega < E$
- the core loses energy coherently

Casalderrrey-Solana, Mehtar-Tani, Salgado, KT 1210.7765



:: probability of only finding one leading subjet in the presence of a fragment with mom frac z

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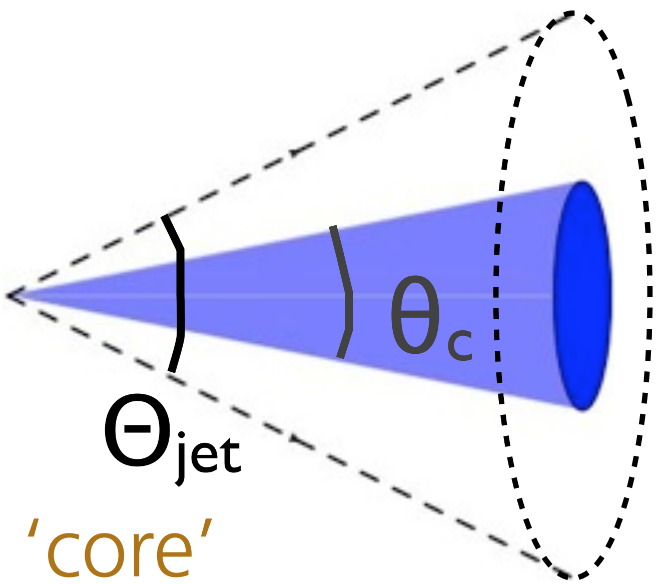

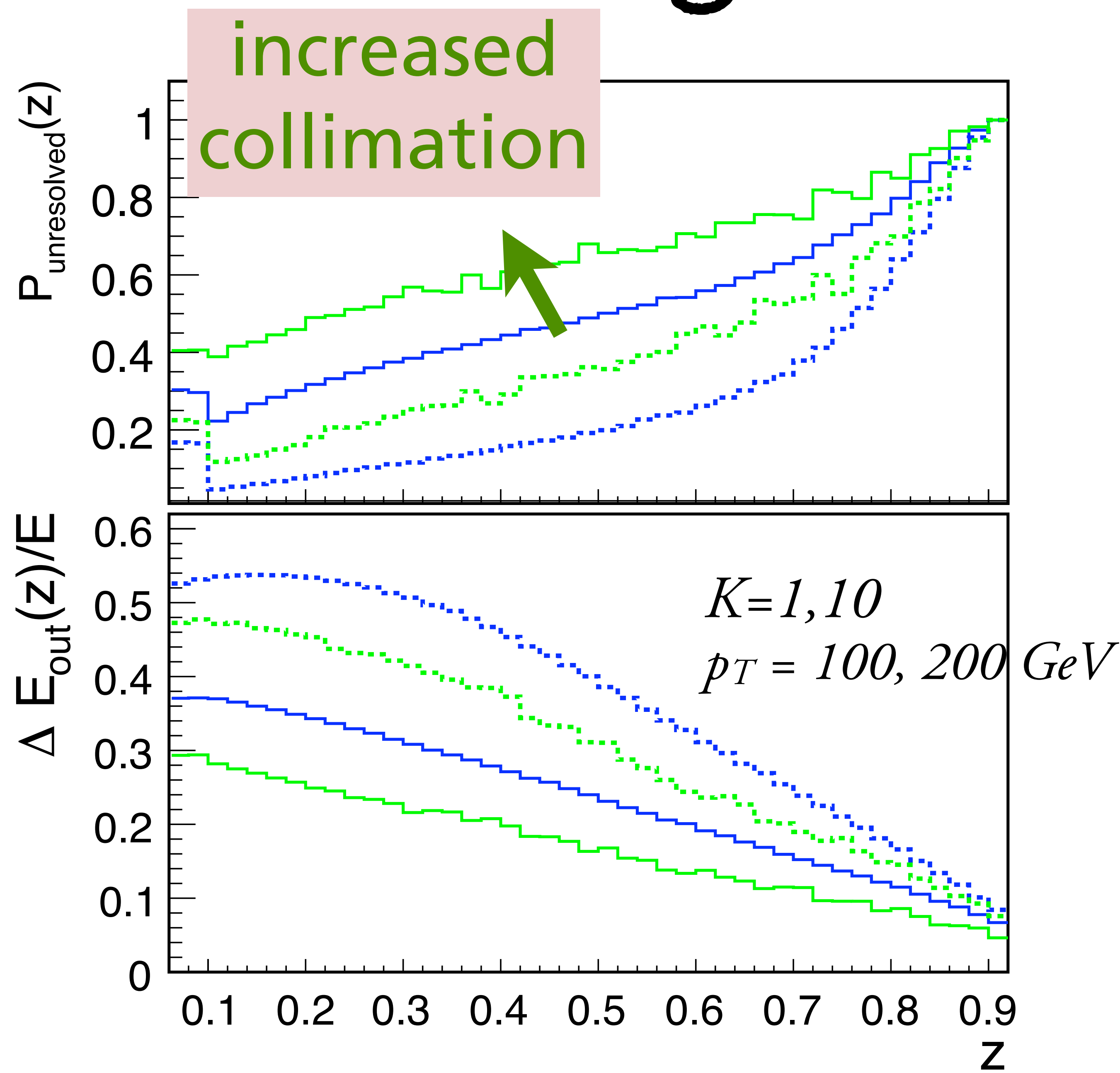

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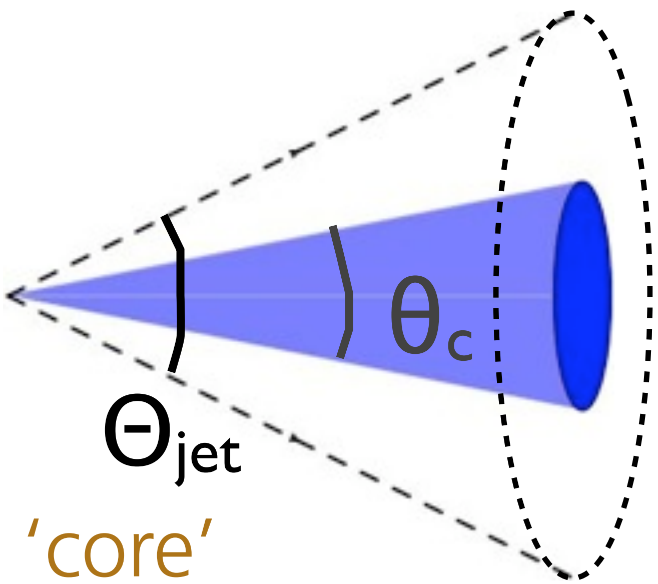

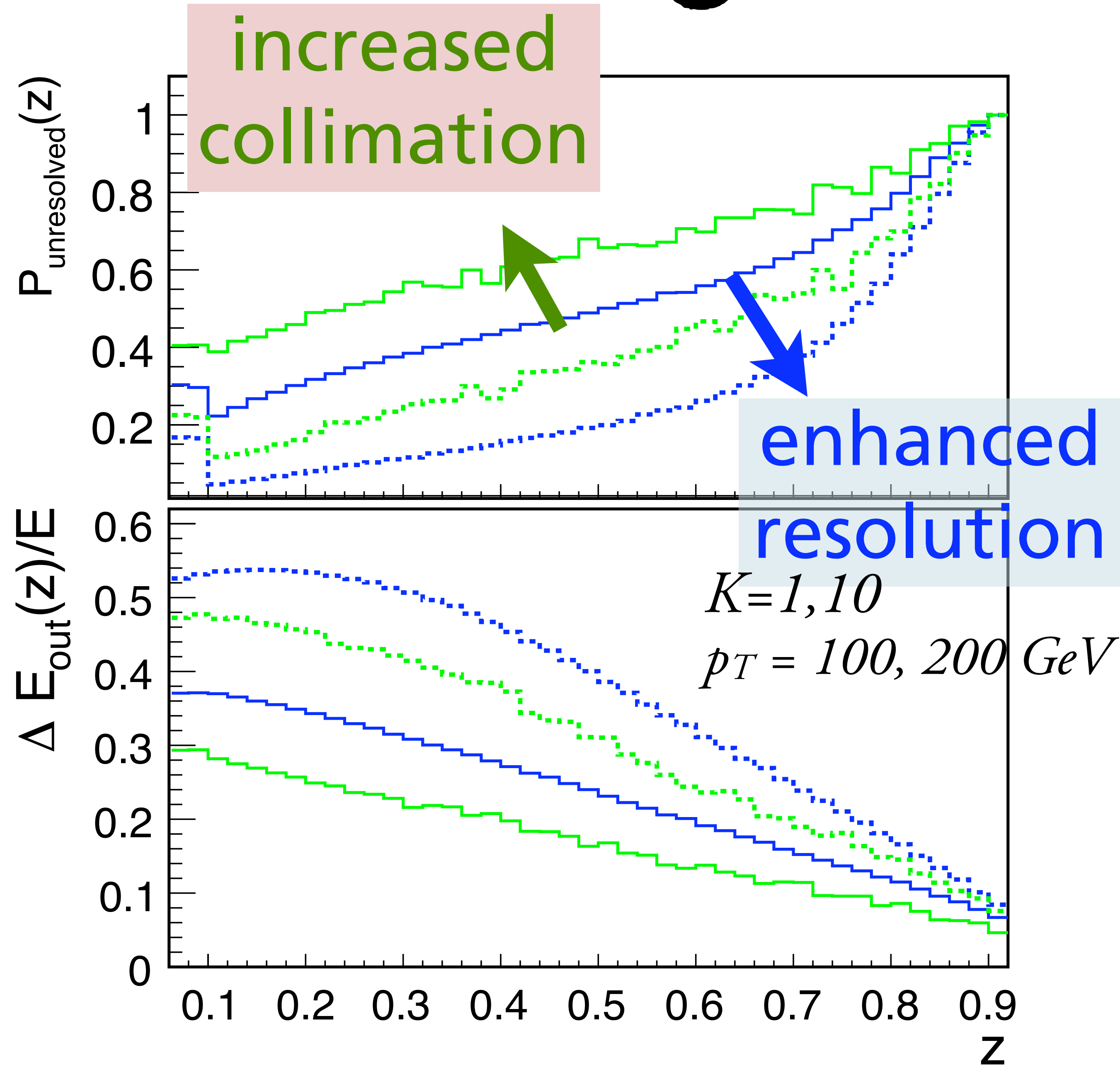

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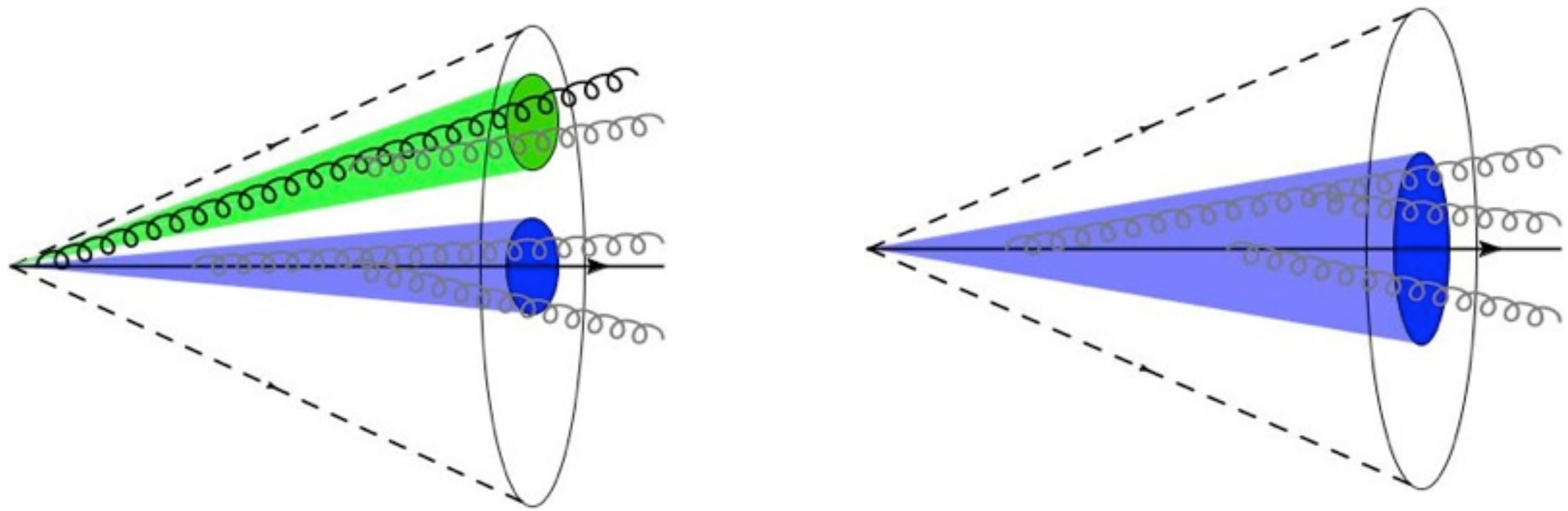
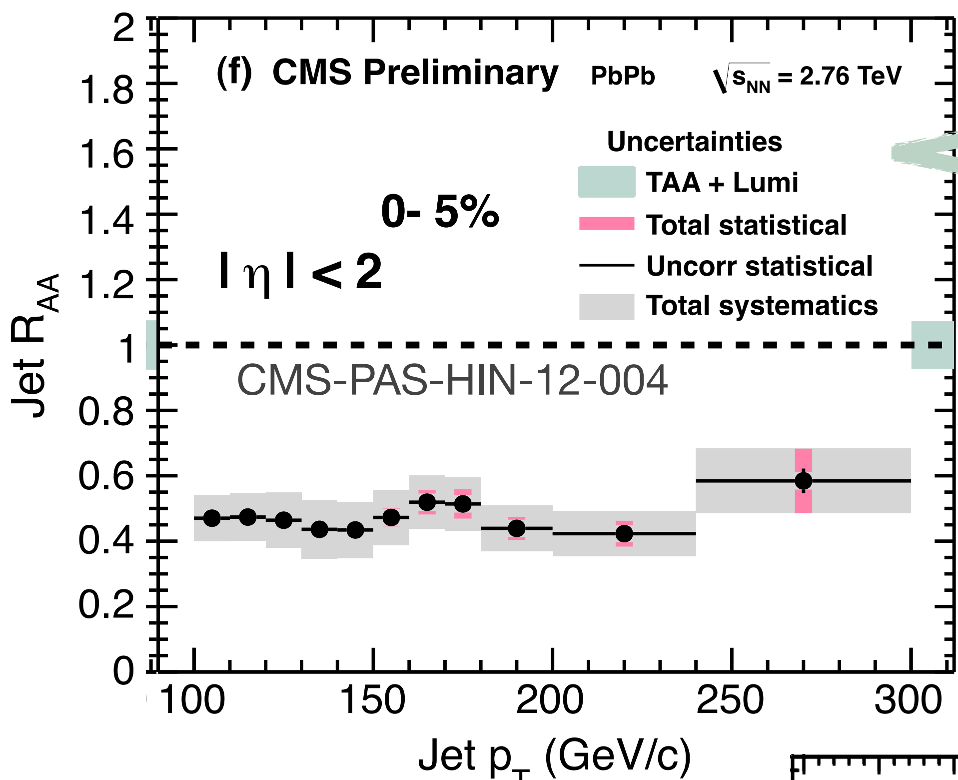
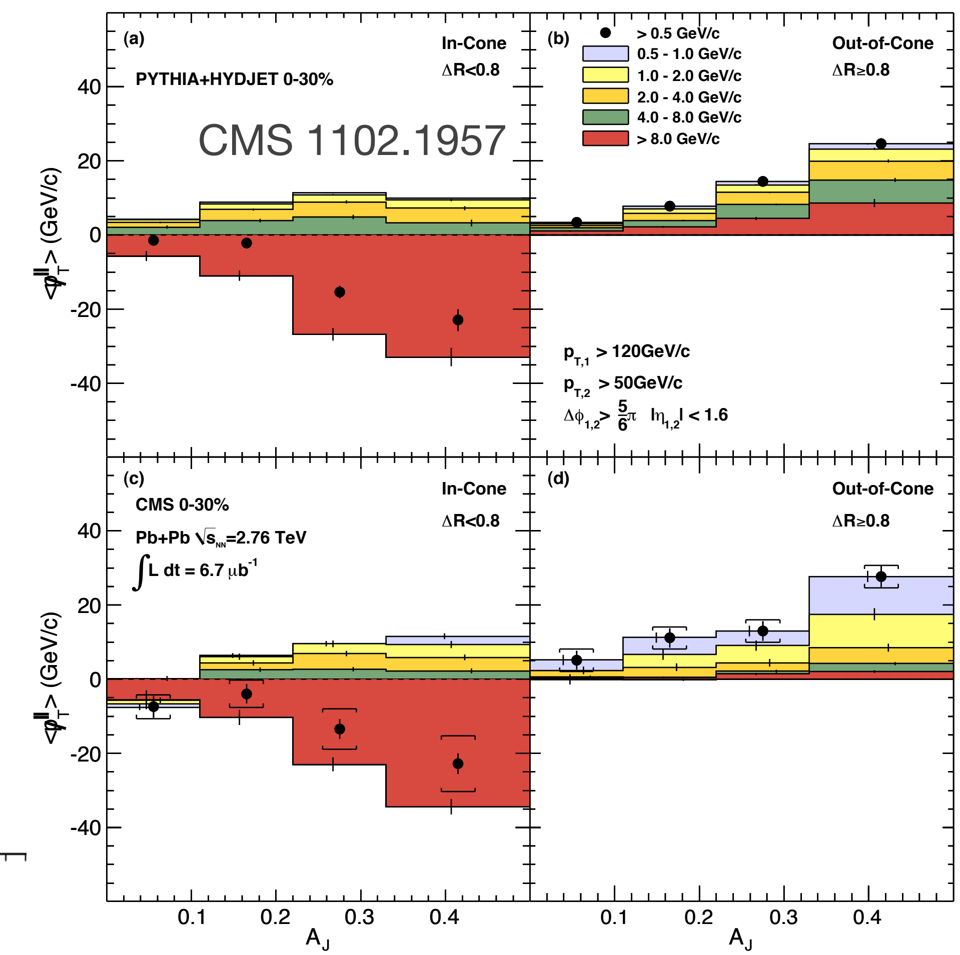


⟶ the objects interacting and radiating in the medium are the resolved subjets (multiparticle states, and not single partons)...

Experimental signatures

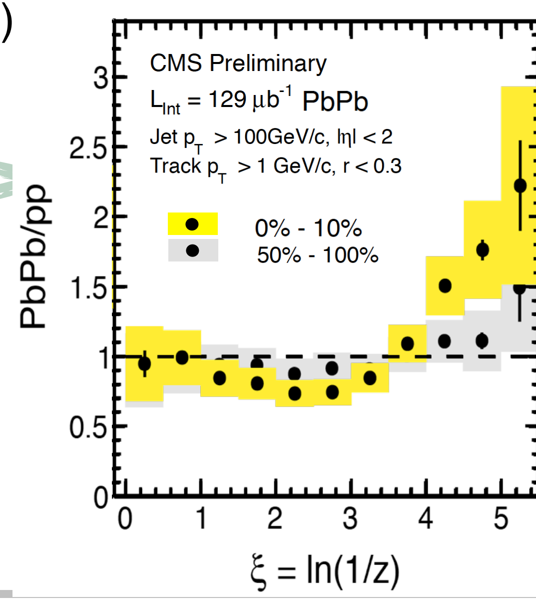


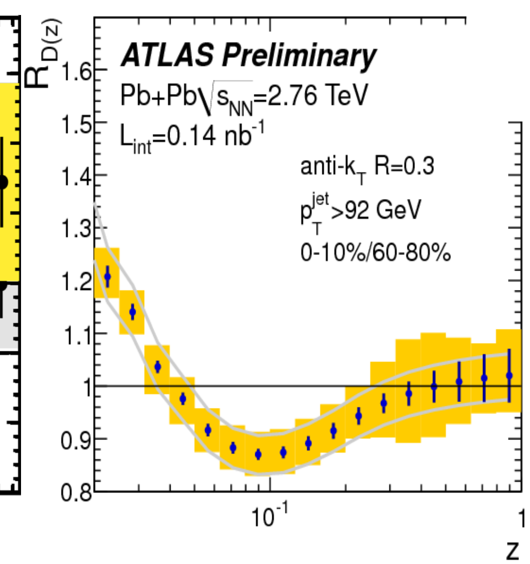
jet rate is suppressed



CMS-PAS-HIN-12-013
ATLAS-CONF-2012-115

dip & softening of the jet long fragmentation function



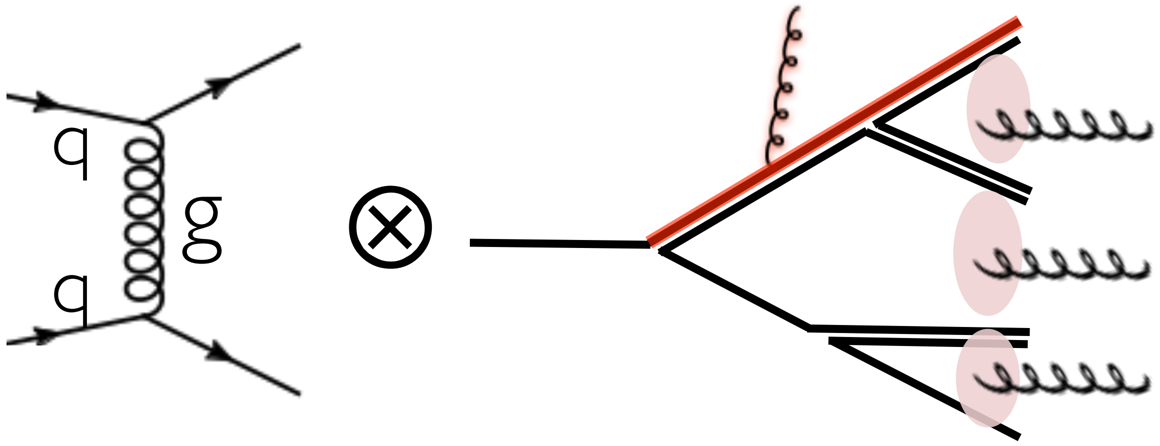


a significant fraction of the jet energy is found at large angles

Factorization of energy loss

Let's assume we have only **one** leading (unresolved) subjet that carries most of the momentum of the full jet :: color transparency.

A "factorization" for leading medium-resolved subjet:



- separation in angles & separation in time :: only the total charge radiates
- allows to separate the treatment of the two different processes

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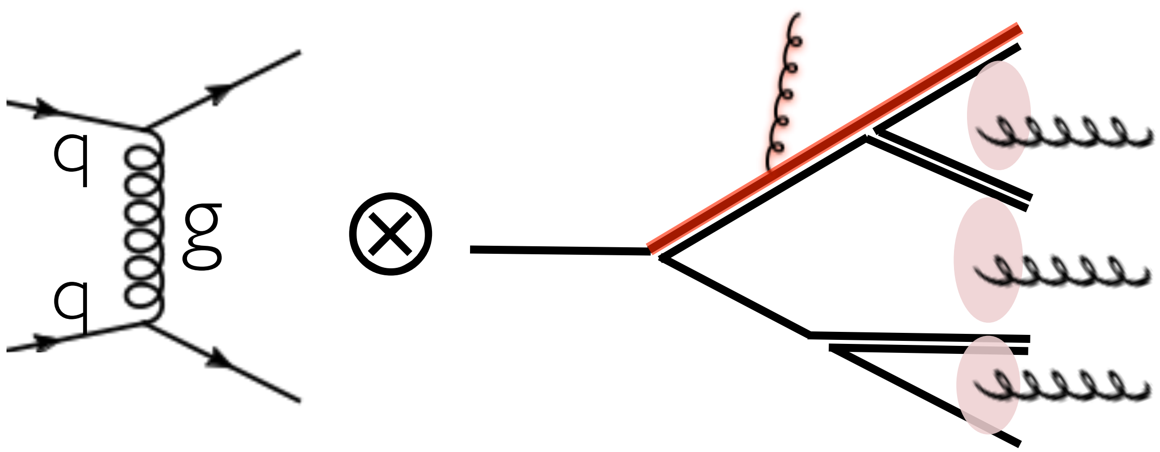

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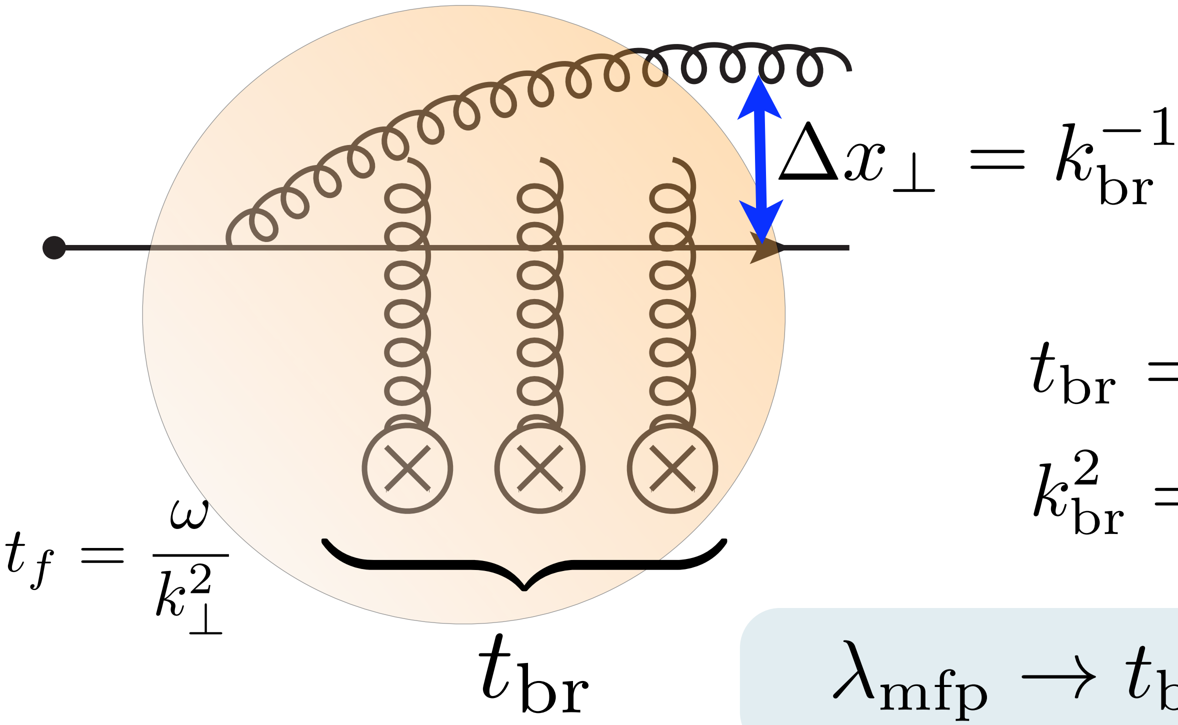
- allows to separate the treatment of the two different processes

jet produced with given p_T, $D_0(x) = \delta(1-x)$ ⇒ *total charge/ancestor particle lose energy* ⇒ vacuum showering (with reduced energy) starts

The 'quenching factor' for jets:

$$Q(p_\perp)^{\text{jet}} = \int_0^1 dz\, D(z,\tau) \frac{d\sigma^{\text{jet,vac}}(p_\perp/z)}{dp_\perp} \bigg/ \frac{d\sigma^{\text{jet,vac}}(p_\perp)}{dp_\perp}$$

Induced radiation



Decoherence :: the virtual gluon fluctuates until it reaches the size $\Delta x_\perp^2 \sim (\tilde{q}\Delta t)^{-1}$ where it can be resolved by the medium.

$$\left.\begin{aligned} t_{\rm br} &= \lambda_{\rm mfp} N_{\rm coh} \\ k_{\rm br}^2 &= \mu^2 N_{\rm coh} \end{aligned}\right\} \qquad \begin{aligned} t_{\rm br} &= \sqrt{\omega/\hat{q}} \\ k_{\rm br}^2 &= \sqrt{\hat{q}\omega} \end{aligned}$$

$\lambda_{\rm mfp} \to t_{\rm br}$ :: Landau-Pomeranchuk-Migdal effect

Bethe-Heitler regime

$$t_{\rm br} \sim \lambda_{\rm mfp}$$

$$\omega_{\rm BH} = \lambda^2 \hat{q} \sim \lambda m_D^2$$

Factorization regime

$$t_{\rm br} \sim L$$

$$\omega_c = \hat{q} L^2$$

LPM regime

$$\omega_{\rm BH} \ll \omega \ll \omega_c$$

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), Arnold, Moore, Yaffe (2001)

The rate-equation

Multiple emission regime

- independent emission
- possible in large media
- very soft radiation at large angles!

$$\omega_{\rm BH} \ll \omega \ll \bar{\alpha}^2 \omega_c$$

$$\theta \gg \theta_{\rm br} \equiv \left(\hat{q}/\omega^3\right)^{1/4}$$

Blaizot, Dominguez, Iancu, Mehtar-Tani 1209.4585

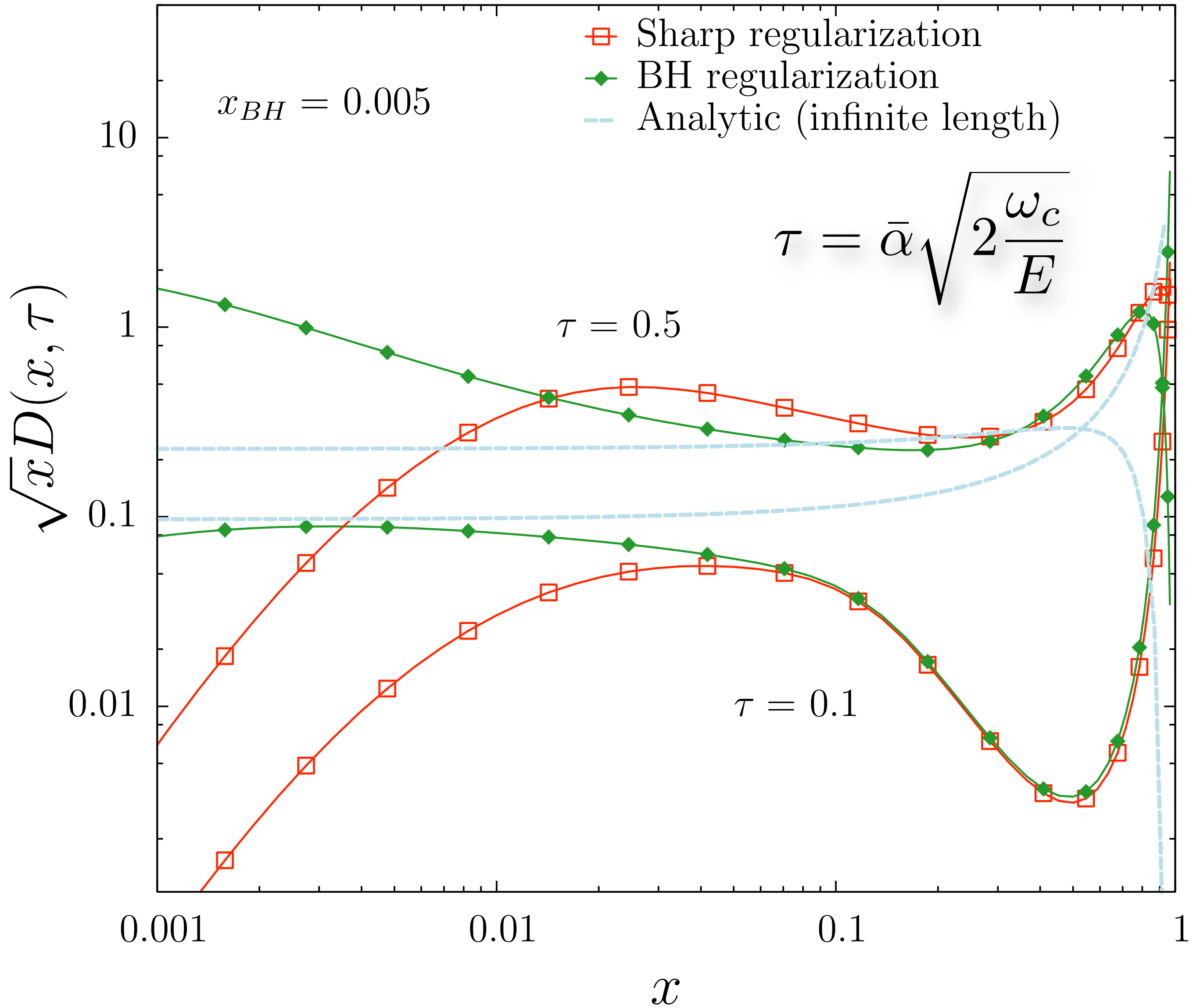
$$\frac{\partial}{\partial \tau} D(x,\tau) = \int_{\mathcal{C}} dz\, \mathcal{F}(z,x;\tau) \left[\sqrt{\frac{z}{x}} D\left(\frac{z}{x},\tau\right) - \frac{z}{\sqrt{x}} D(x,\tau) \right]$$

Jeon, Moore hep-ph/0309332
Baier, Mueller, Schiff, Son hep-ph/0009237
Blaizot, Iancu, Mehtar-Tani 1301.6102

$$\tau = \bar{\alpha}\sqrt{2\frac{\omega_c}{E}}$$

- keeps track of the leading + all the fragments
  - similar to the "quenching weights"
- probabilistic interpretation
- turbulent flow: no intrinsic accumulation of energy
- spectrum is self-replicating :: scaling

Evolution equation



Blaizot, Iancu, Mehtar-Tani arXiv:1301.6102
[...work in progress]

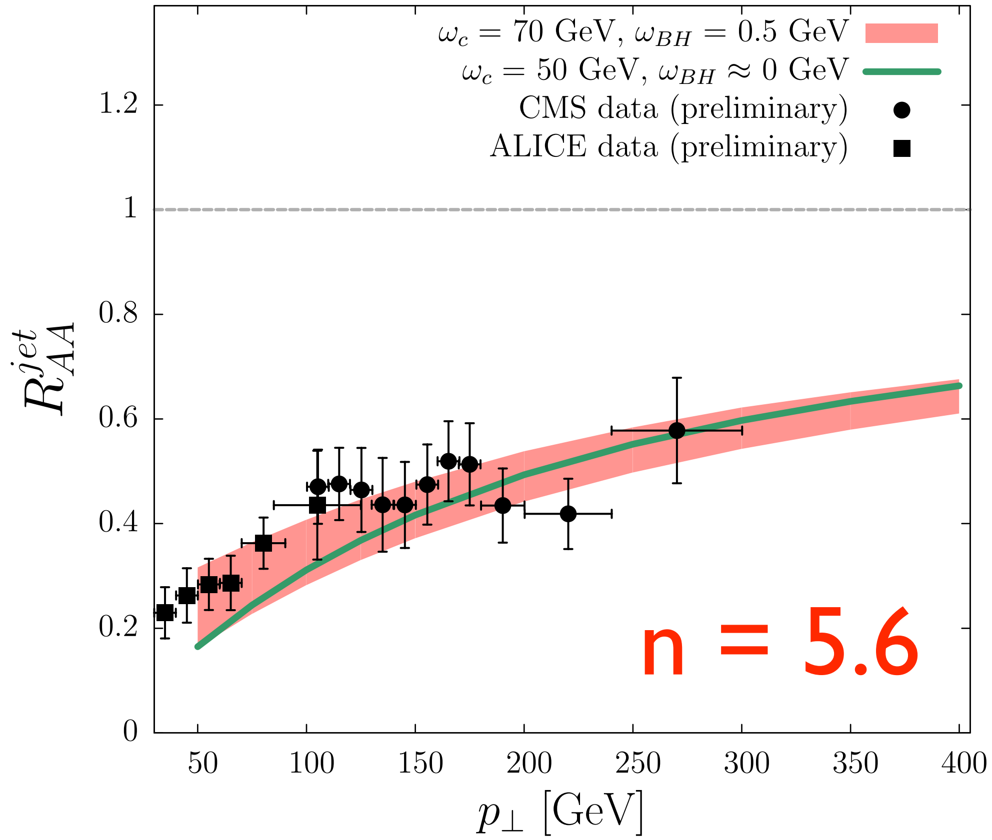
- rapid depletion of leading probe into soft fragments
- finite-size and regularization play a significant role
- slows down the evolution
- important for phenomenological analysis

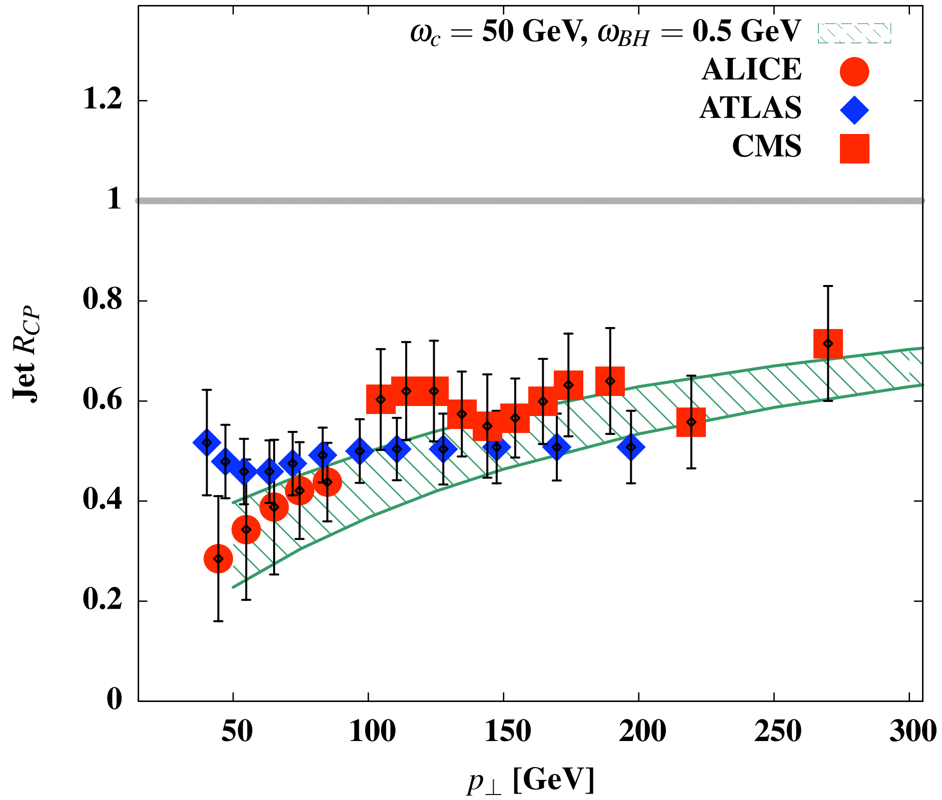
Analytical solution (infinite length):

$$D_0(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} e^{-\pi \frac{\tau^2}{1-x}}$$

Jet suppression

Calculating quenching factor for "leading sub-jet"



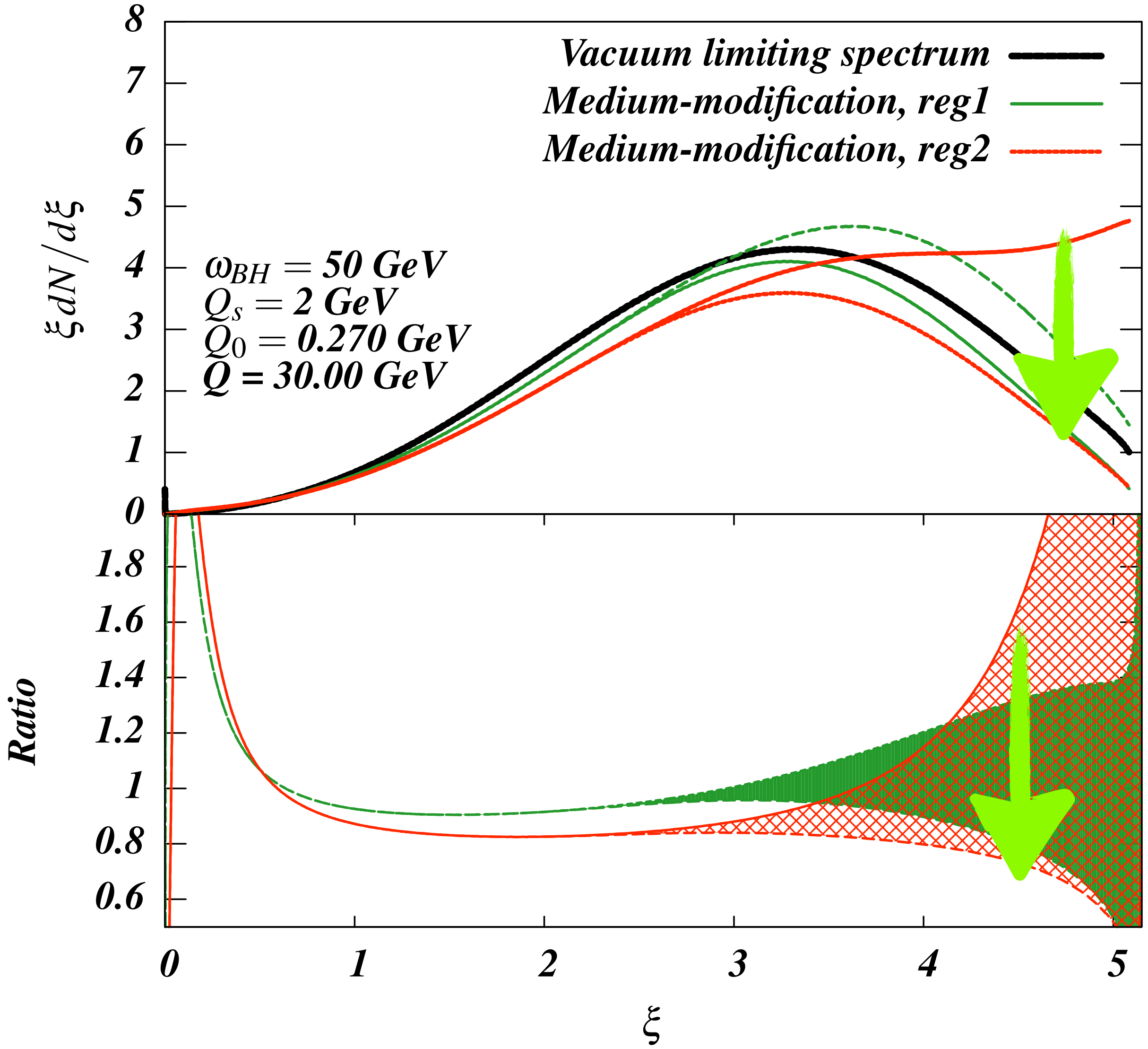


- sensitivity to regularization prescription
- low-p_T sensitive to sub-leading resolved subjets
- baseline: need more realistic collision geometry

$$L \sim 4\,\text{fm}$$

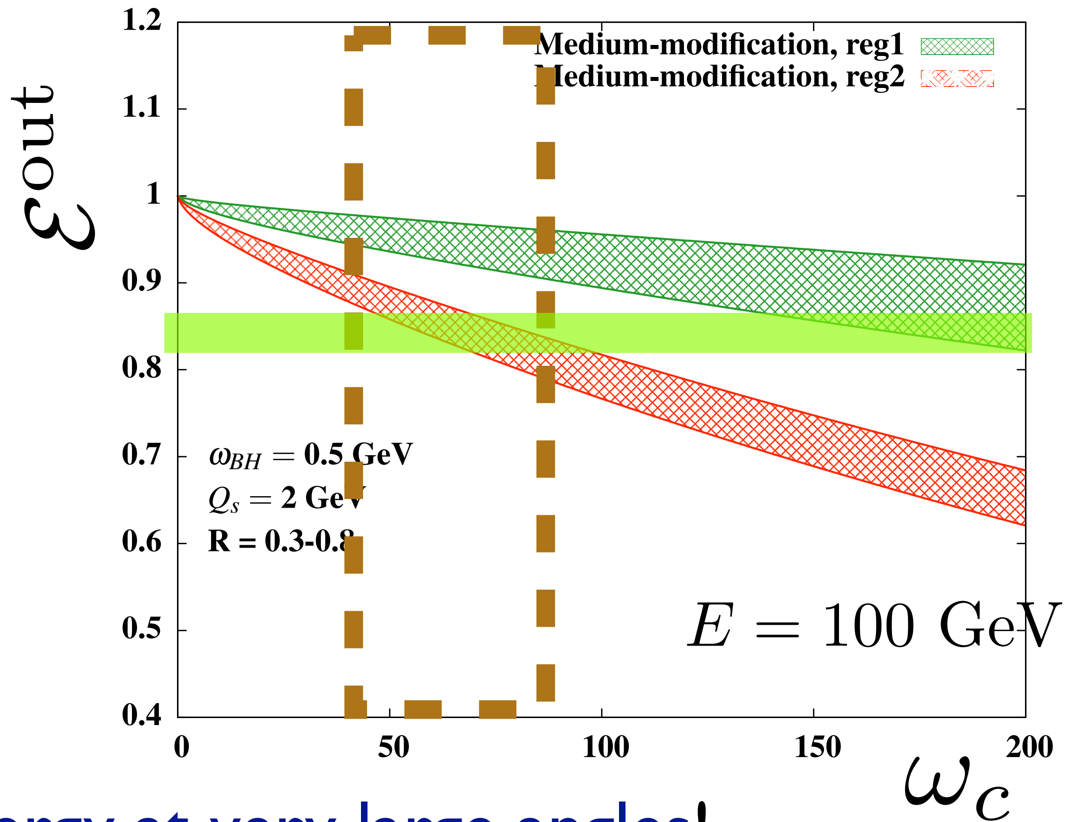
$$\hat{q} \sim 1 - 2\,\frac{\text{GeV}^2}{\text{fm}}$$

Momentum broadening



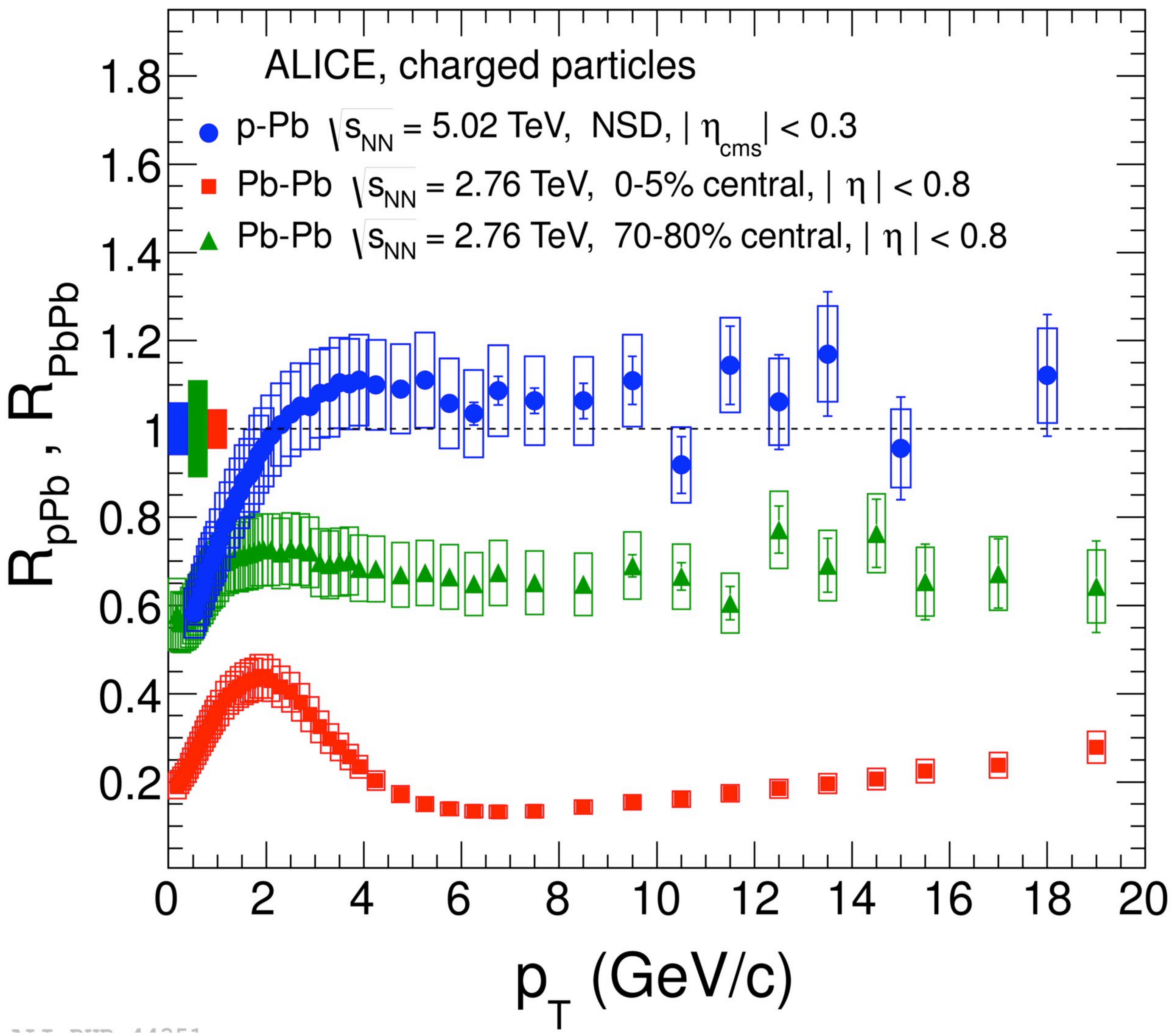
$$D(x, \theta < \Theta_{jet}) = \int^{\Theta_{jet}} \frac{d^2\boldsymbol{k}}{(2\pi)^2} \mathcal{P}(\boldsymbol{k})\, D(x)\,,$$

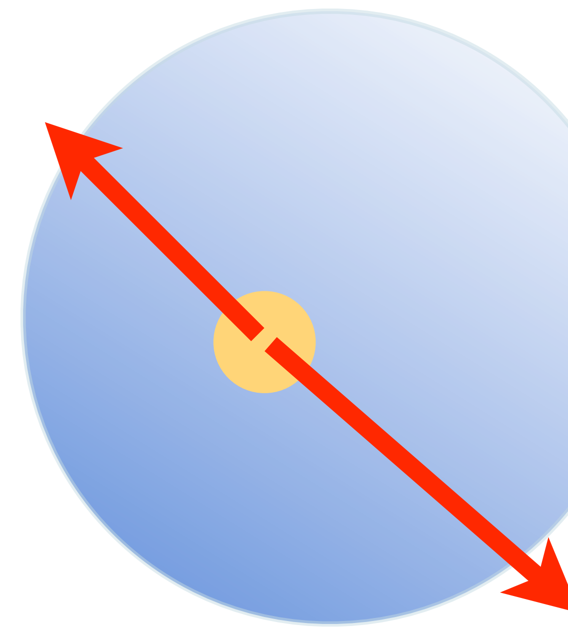
$$\theta \lesssim \theta_c \qquad = \left[1 - \exp\left(-\frac{x^2 M_T^2}{Q_s^2}\right)\right] D(x)$$



- strong sensitivity in the soft sector
- broadening a powerful effect: missing energy at very large angles!

Over to pPb!





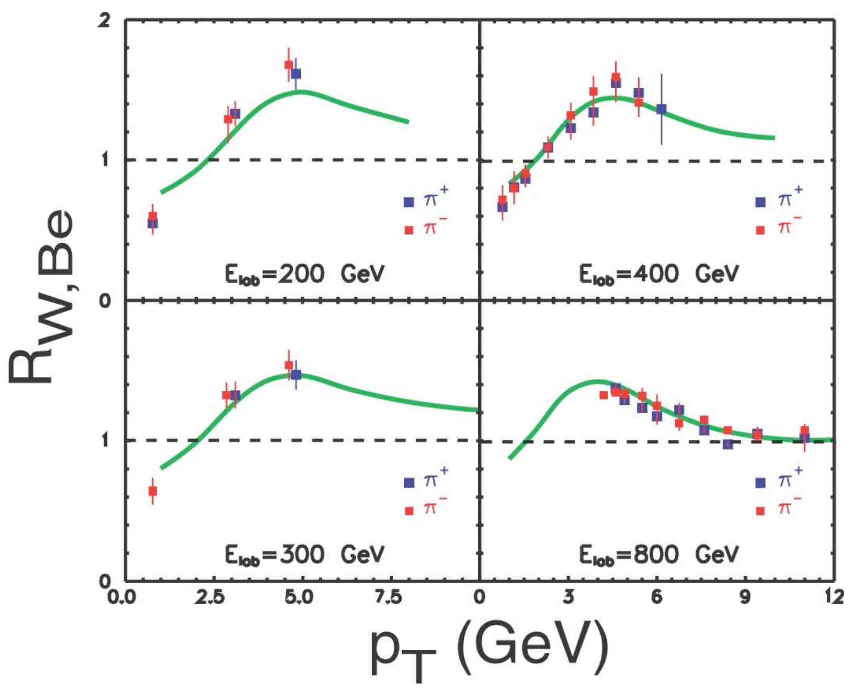
- transverse size of the QGP-"drop" is very small ~ 1fm
- jet-quenching develops over long times

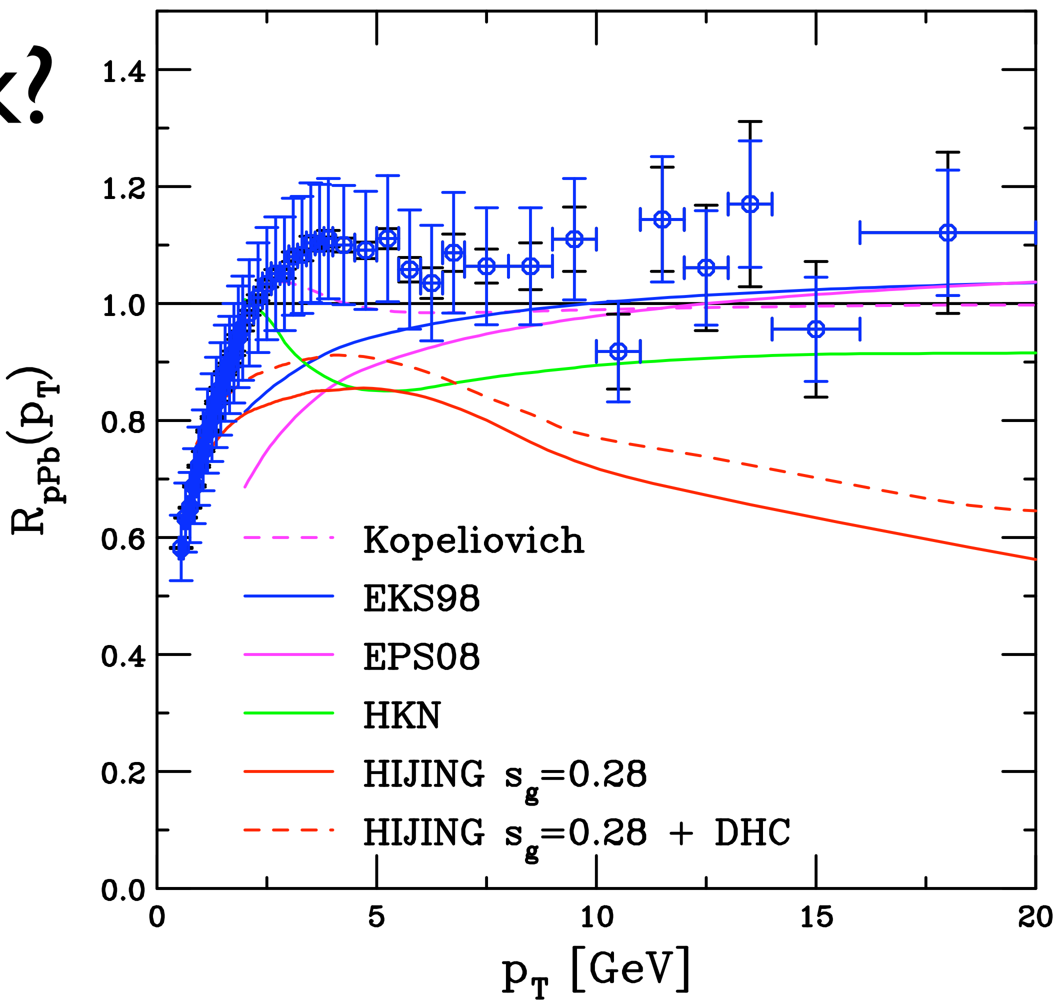
ALICS arXiv:1210.4520

The Cronin effect

What is the origin of the peak?

- anti-shadowing
- low-energy rescattering





Vogt et al., arXiv:1301.3395

Kopeliovich, Nemchik, Schafer, Tarasov PRL 88(2002)232303

Estimating the system size

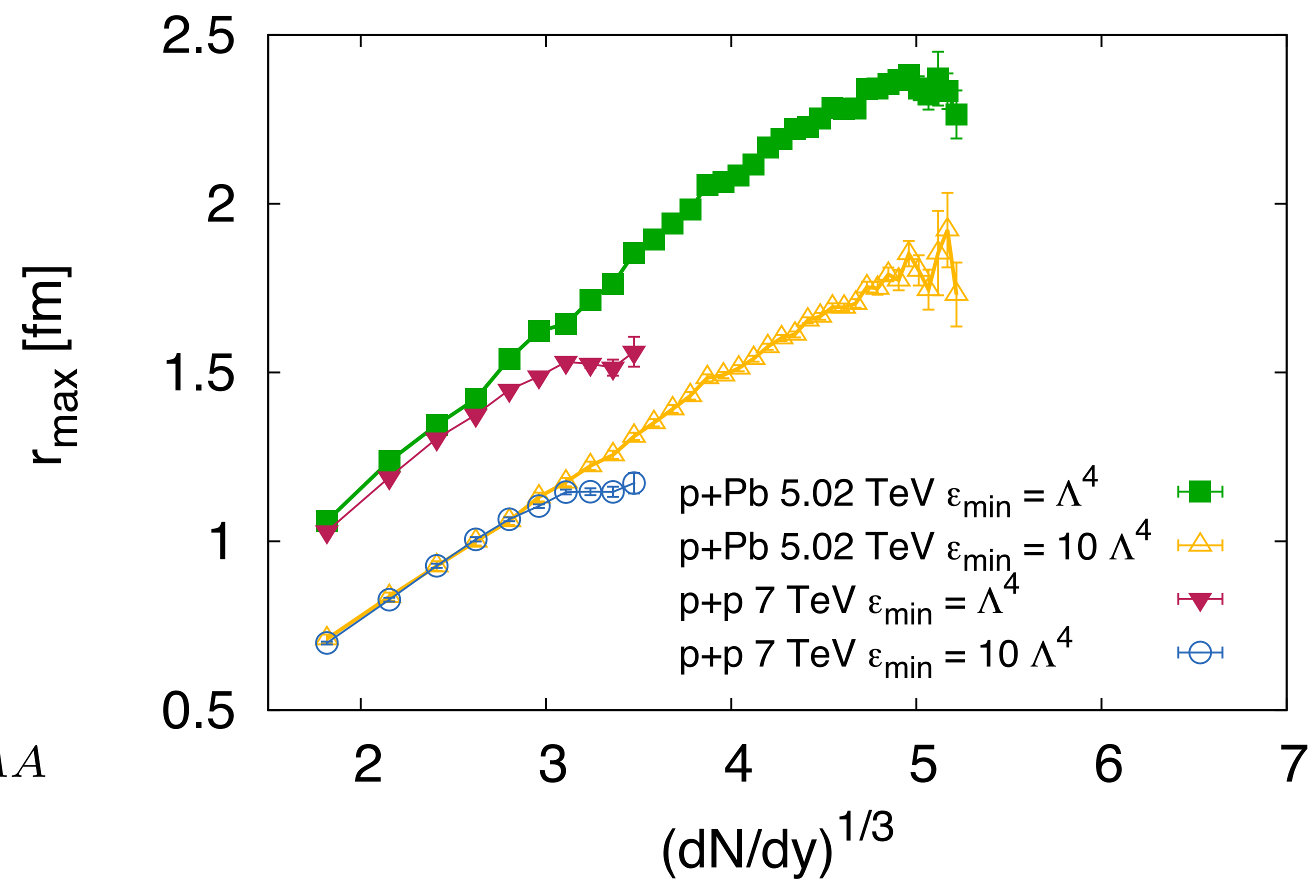
For the most central collisions (η=0):

$$\frac{dN_g}{d\eta} \sim 125 \quad \Rightarrow \frac{dN_{ch}}{d\eta} \sim 225$$

$$L_{pA} \sim 2\,\text{fm} \sim \frac{1}{2} L_{AA}$$

$$\hat{q}_{pA} \sim \frac{1}{7} \hat{q}_{AA}$$

$$\omega_{c,pA} \sim \frac{1}{30}\omega_{c,AA} \qquad Q_{s,pA} \sim \frac{1}{15} Q_{s,AA}$$

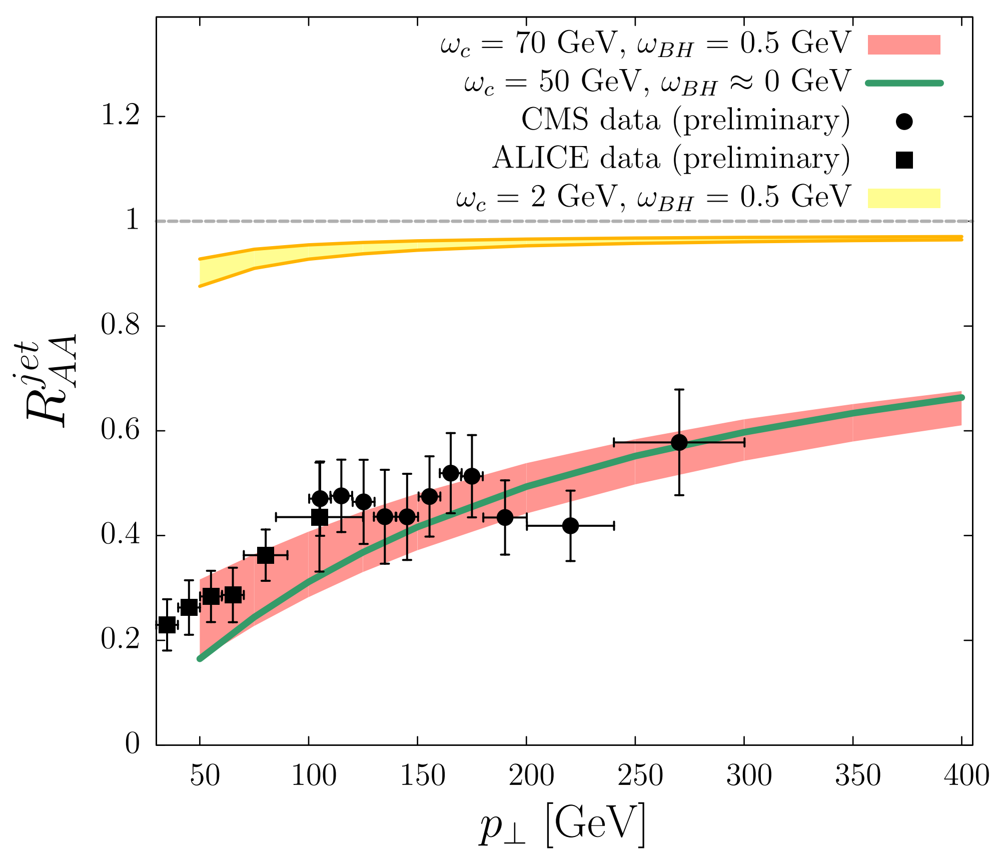


- strongly reduced scales of the medium
- recall jet scale $r_\perp = \theta_{jet} L$ :: dilute regime

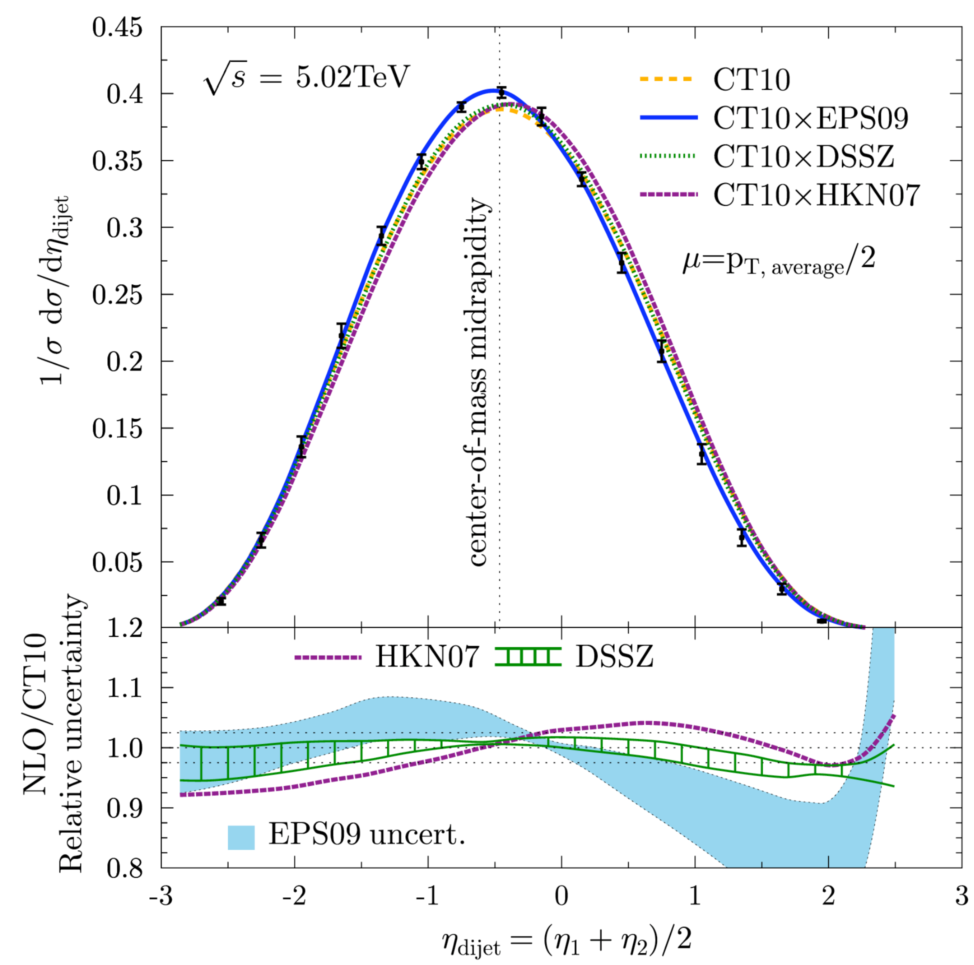
$$\hat{q}_{AA} \propto dN_{ch}/d\eta \sim 1600$$

Bzdak, Schenke, Tribedy, Venugopalan 1304.3403
Gyulassy, Horowitz 1104.4958 , ALICE...

No final-state effects



Eskola, Paukkunen, Salgado, arXiv:1308.6733

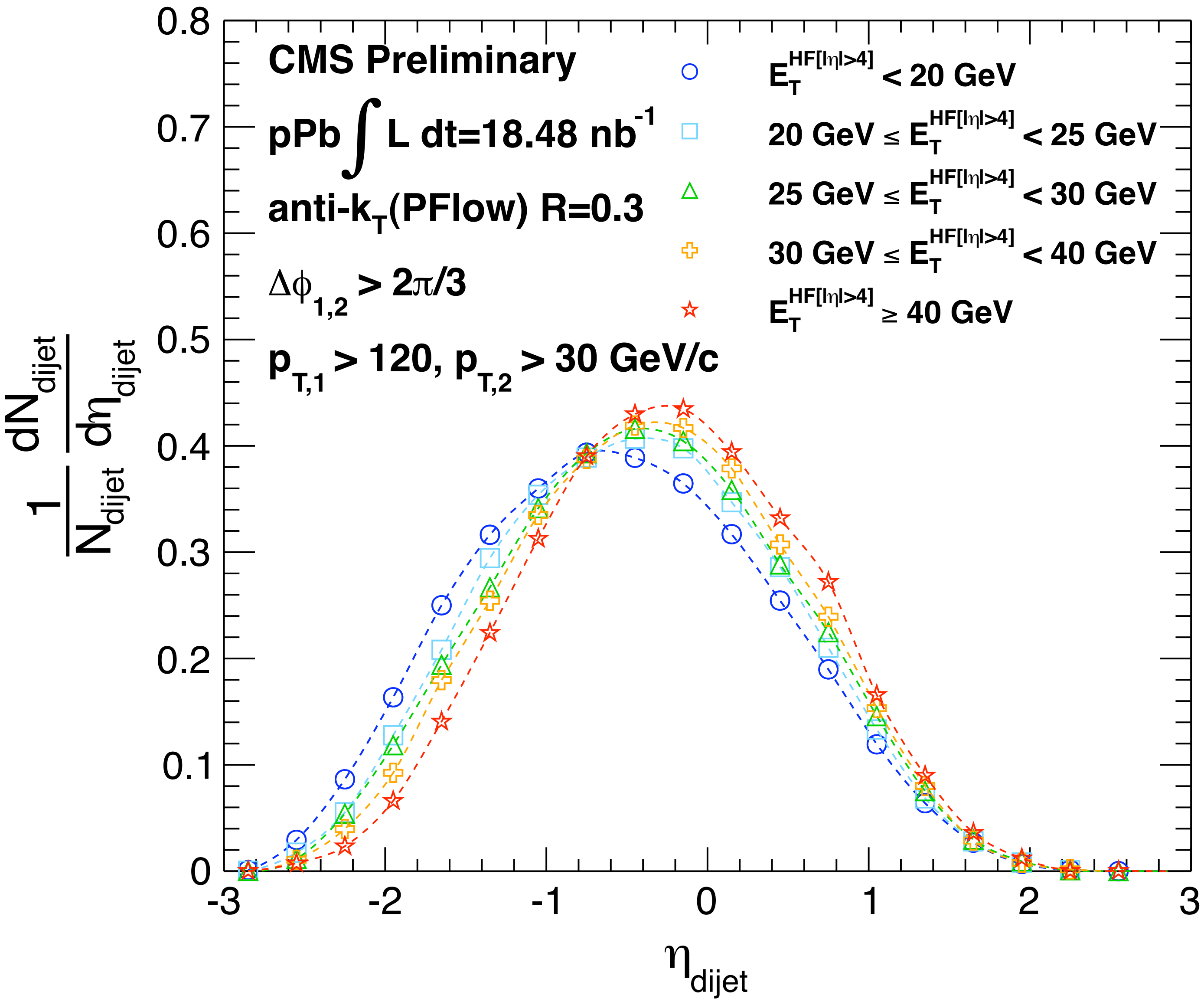


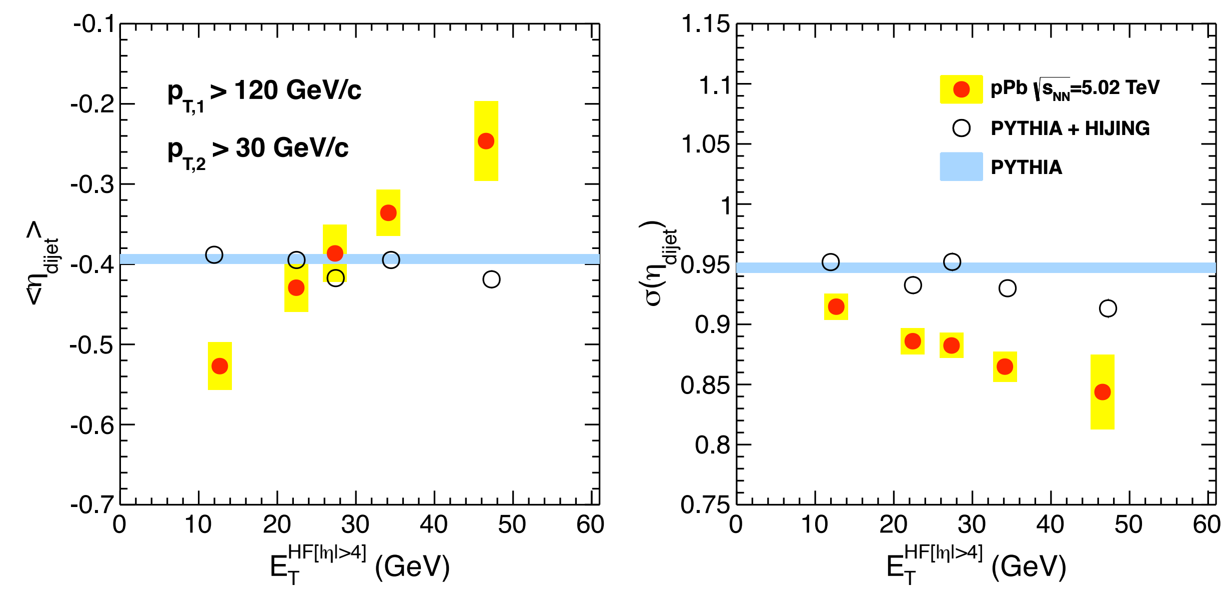
- Excellent situation to extract initial-state effects

also see H. Paukkunen's and J. Qiu's talks yesterday

Dijets vs. centrality

$\eta_{\rm COM} = -0.46$





- strong shift in COM rapidity as f/b activity increases
- narrowing of the distribution
- effect from b-dependent nPDF's is only on %-level

Some ideas

- energy loss in glasma (synchrotron radiation)
  - preliminary results, very short timescales for the effect

Zakharov 0809.0599; Zakharov, Aurenche 1205.6462

- initial-/final-state interferences
  - could be important at large x_F, forward rapidity

Martinez et al. 1308.2186, 1207.0984; Arleo et al. 1006.0818; Kopeliovich

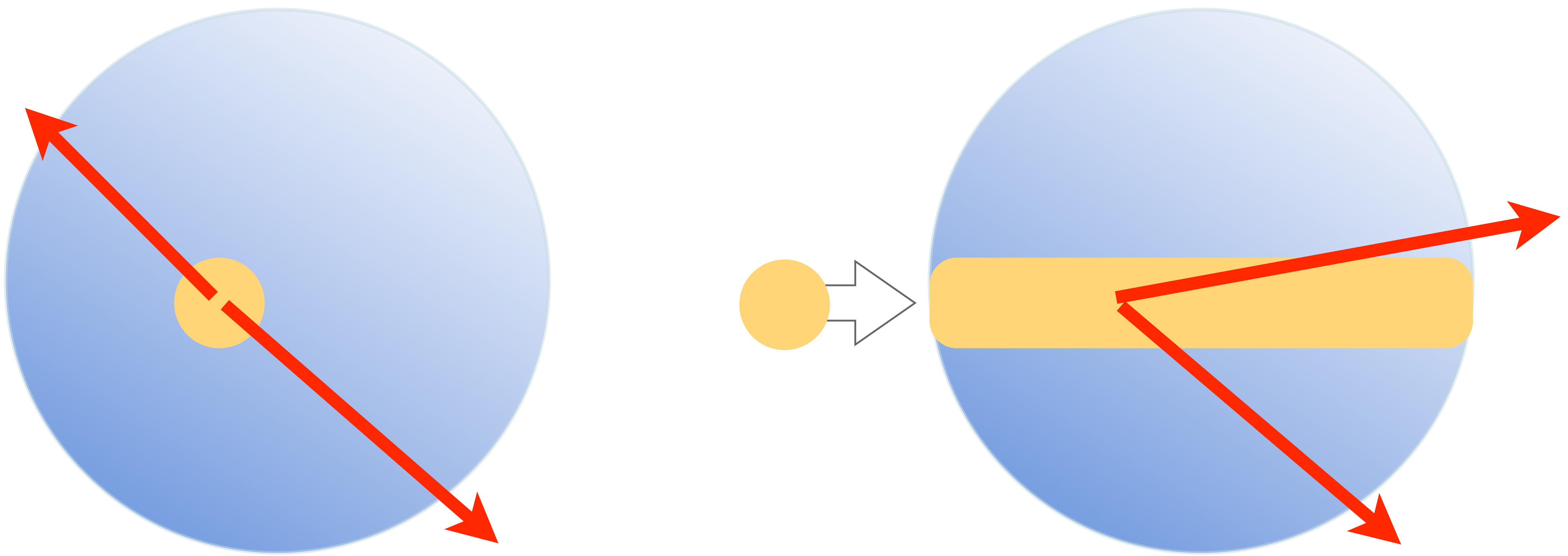
- ... centrality biases (underlying event activity, non-perturbative effects)

Phase-space limitations

- boosted dijet system involves large energy:
  - $E_{jj} = p_{1,\perp}\cosh(\eta_1)+p_{2,\perp}\cosh(\eta_2)$
- demanding large f/b activity biases toward higher activity in proton direction
  - activity in Pb direction is cheap
  - in proton direction, it strongly affects amount of ISR
  - less energy available for hard process
- better centrality selection if HF^{minus} is kept fixed?

also see G. Milhano talk in Trento 2013 and D. Gulhans talk on Friday

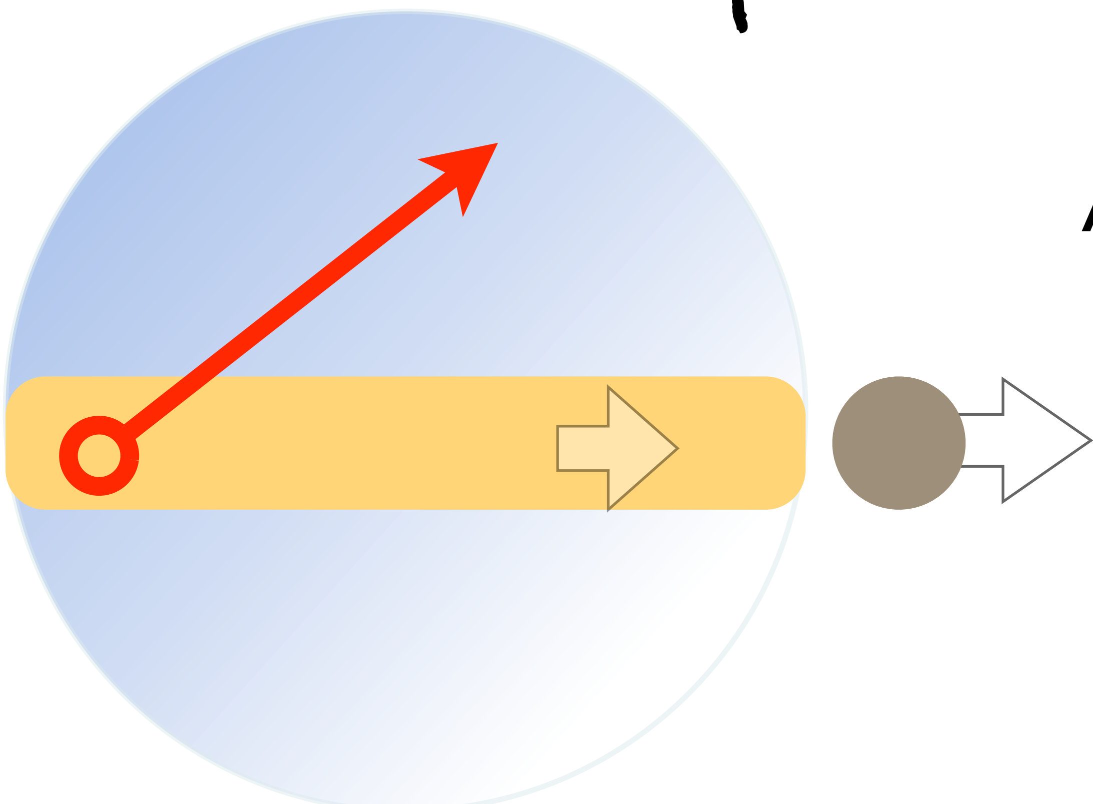
A possible scenario...



mid-rapidity

dense,
off mid-rapidity

"Back-of-the-envelope" model

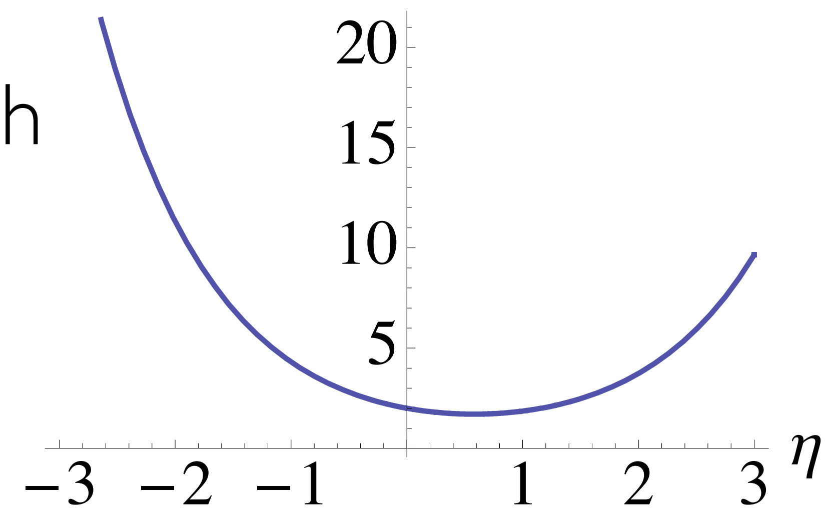


As an example:

$$\eta_{\mathrm{Plasma}} \sim \tanh^{-1}\frac{-4+8\times 1.58}{4+8\times 1.58} = 0.58$$

$$\eta_{\mathrm{binary}} \sim \tanh^{-1}\frac{-4+1.58}{4+1.58} = -0.46$$

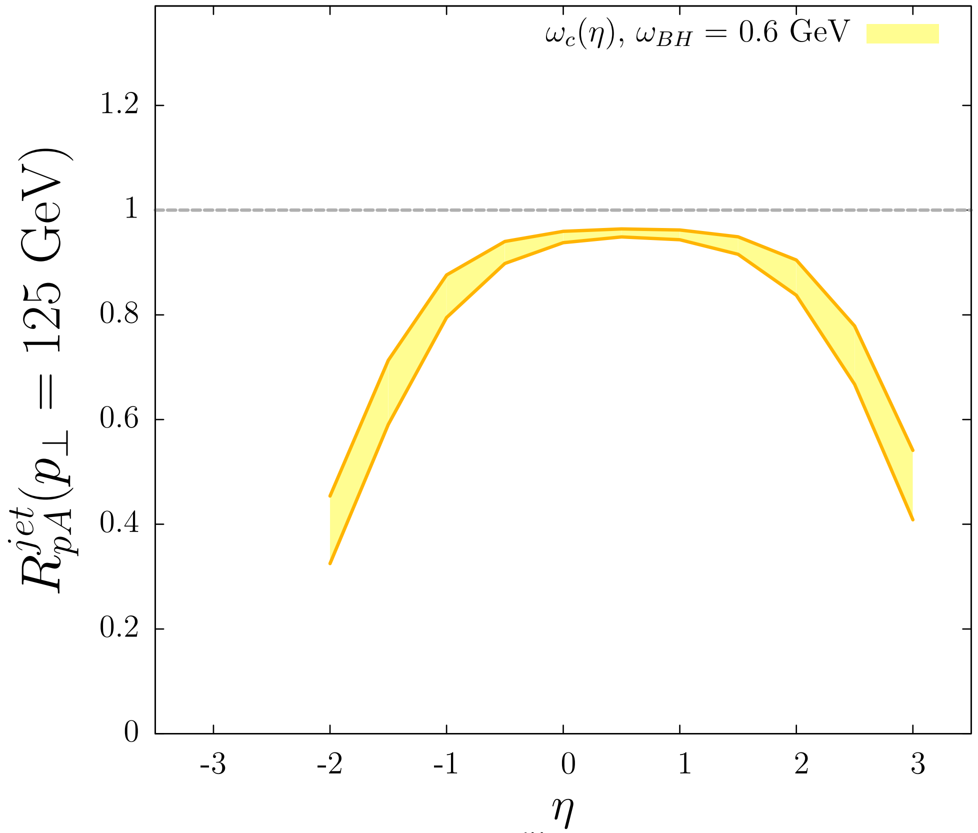
$$L_{\mathrm{eff}}(\eta) = L_0 \cosh\left(\eta - \eta_{\mathrm{Plasma}}\right)$$



No boost-invariance (only z-invariance)! Creating a boosted drop/cylinder of QGP with transverse size L_0, expanding rapidly ($v_{\parallel}$~c).

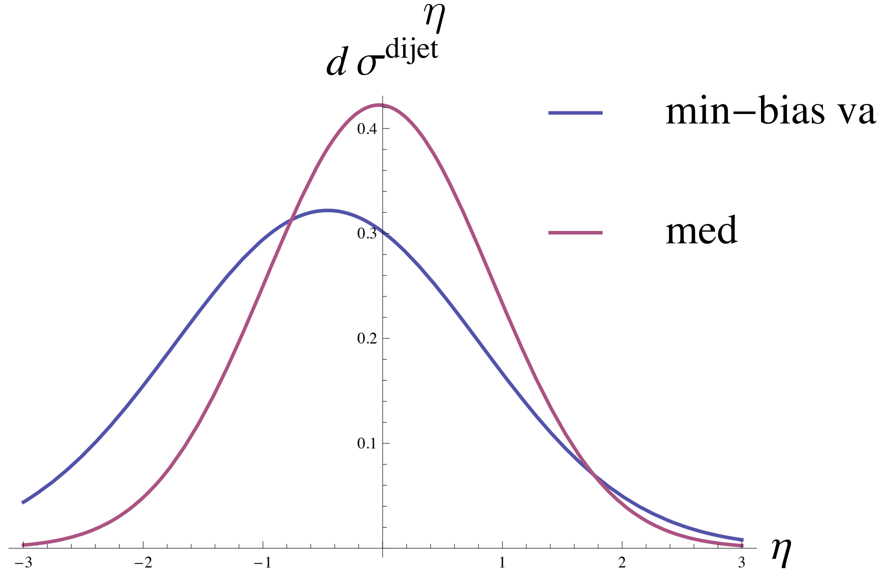
If the dijet system does not move with the flow, it also sees the longitudinal size.

“Back-of-the-envelope” model

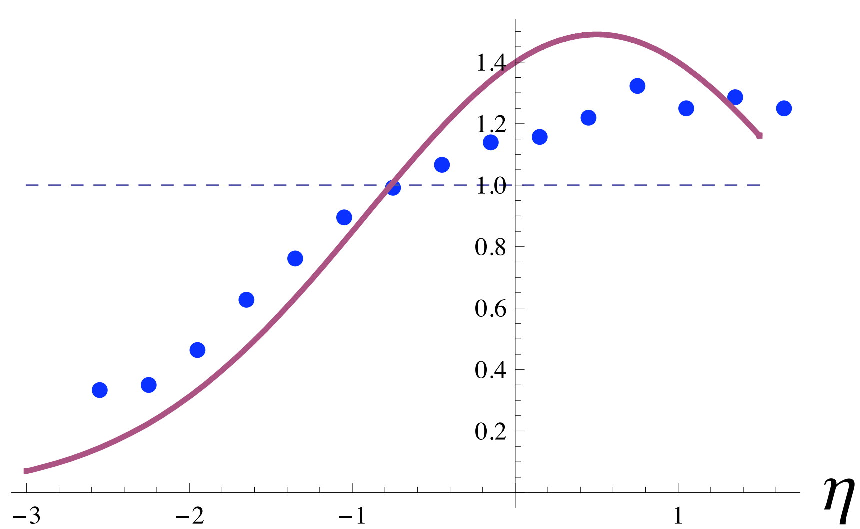


Illustrates possible effects of quenching:

- (artificially) strong rapidity dependence of quenching :: $\omega_c(\eta)$
- AA: many such cylinder-systems at slightly different rapidities
- biases: not present in AA, can we get a better handle on them in pA?



⇒



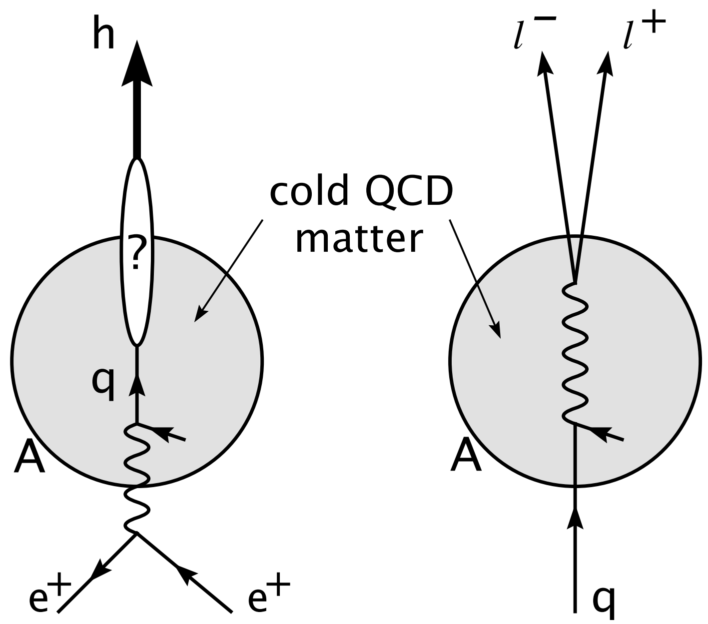
:: blue points are points read off from Guilhermes plot that was read off from the data - just for illustration! ::

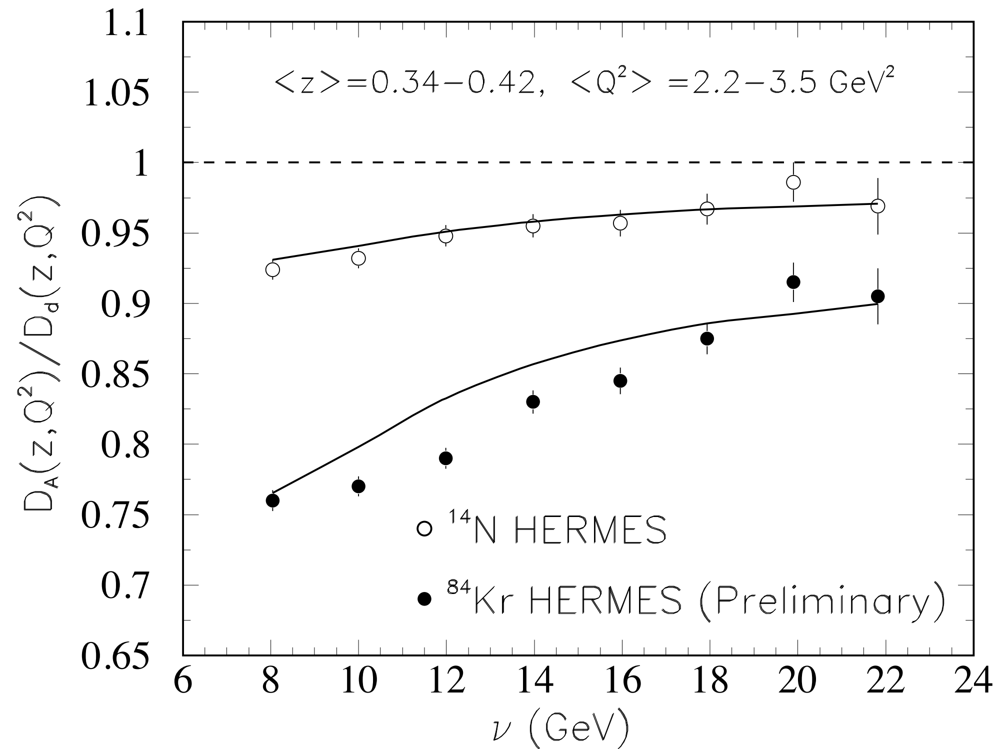
Summary

- jet quenching is a powerful tool to access properties of the hot and dense QGP in AA
  - resolved sub-jets are a consequence of color transparency (pQCD)
- system created in pA is small, typical scales from the medium are small
  - do not resolve nor affect the jet fragmentation much
- getting better control of bias can help constraining models for longitudinal expansion
- so far, no compelling hints of jet quenching effects in pA

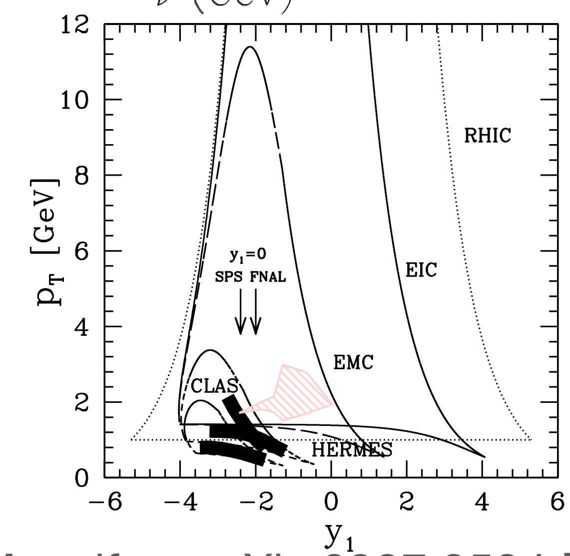
backup

CNM quenching





$$\hat{q}_{\rm cold} \sim \frac{1}{50}\hat{q}_{\rm hot} \sim 0.05\,{\rm GeV}^2/{\rm fm}$$



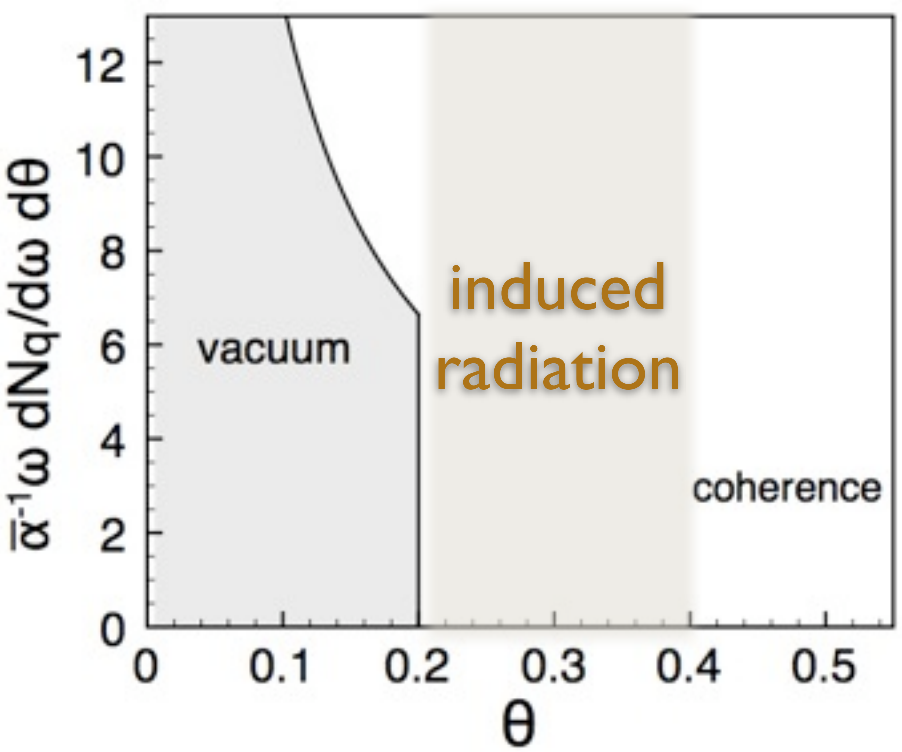
- extremely small density but system of similar size as PbPb
- no effect at RHIC

Accardi, Arleo, Brooks, D'Enterria, Muccifora arXiv:0907.3534 [nucl-th]
Wang, Wang PRL 89(2002)162301

Antiangular component

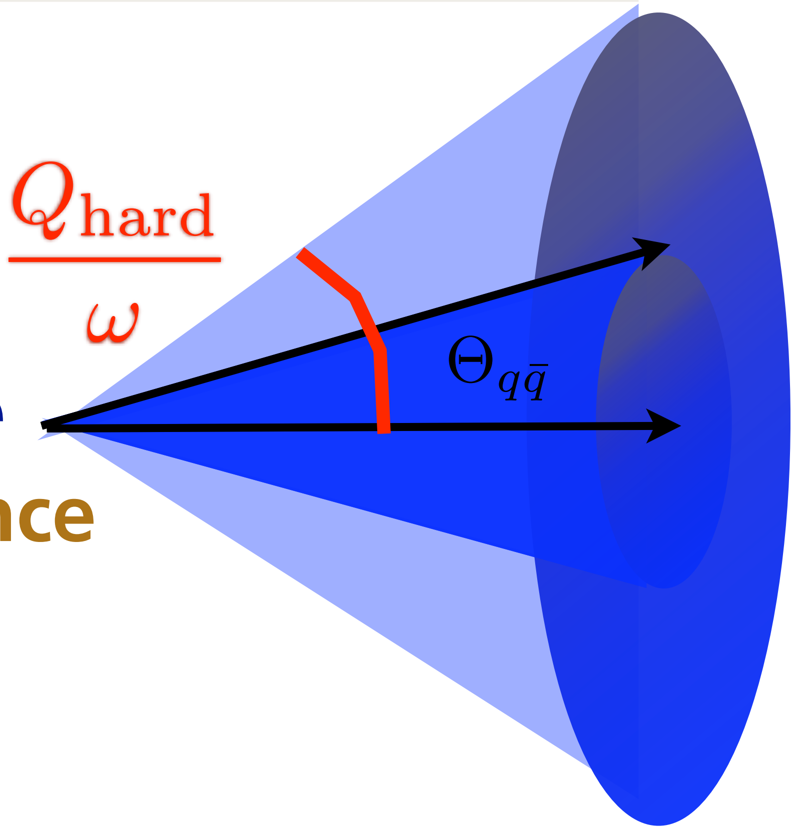
$$dN^{\mathrm{tot}}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\; d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{q\bar q}) + \Delta_{\mathrm{med}}\,\Theta(\cos\theta_{q\bar q} - \cos\theta)\right] \; .$$

$k_\perp < Q_{\mathrm{hard}}$ DLA accuracy (a=0) :: affects only 2nd emission



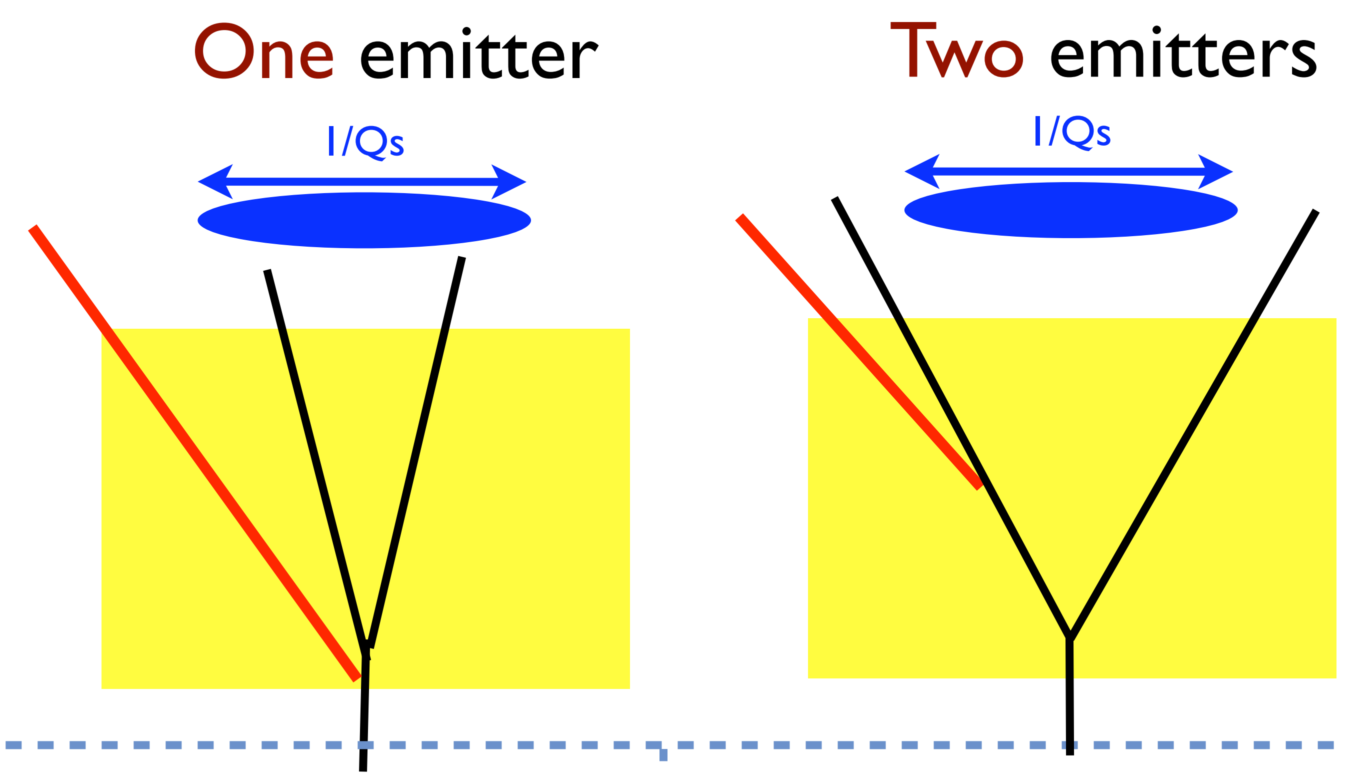
$\Delta_{\mathrm{med}} \to 0$ **Coherence**

$\Delta_{\mathrm{med}} \to 1$ **Decoherence**



$$Q_{\rm hard} = \max\left(r_\perp^{-1}, Q_s\right)$$

$$k_\perp < Q_{\rm hard}$$



	One emitter	Two emitters
vacuum coherence (at large angles)	weak AAO, $\propto \Delta_{\rm med} < 1$	AO completely broken, radiation up to $k_\perp \sim Q_s$
"medium-induced"	radiation as total charge	radiation as independent charges

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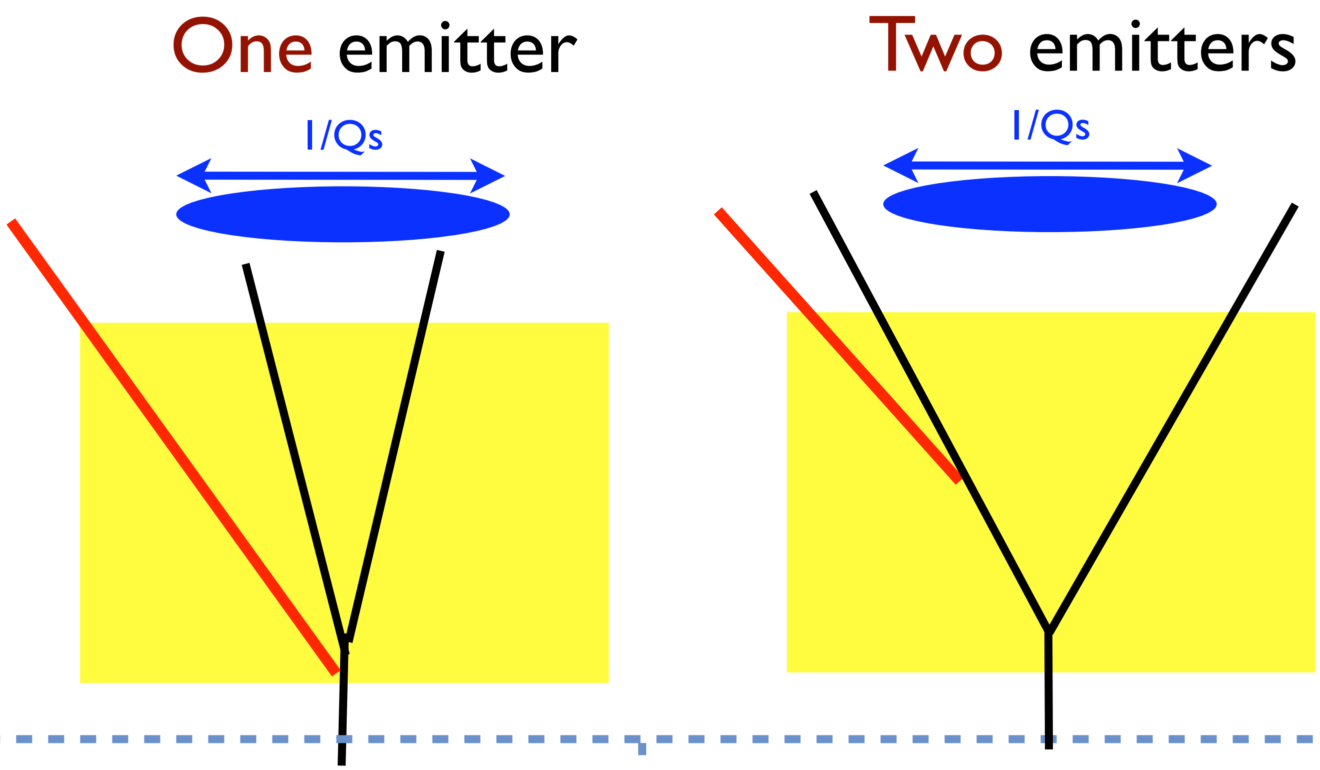

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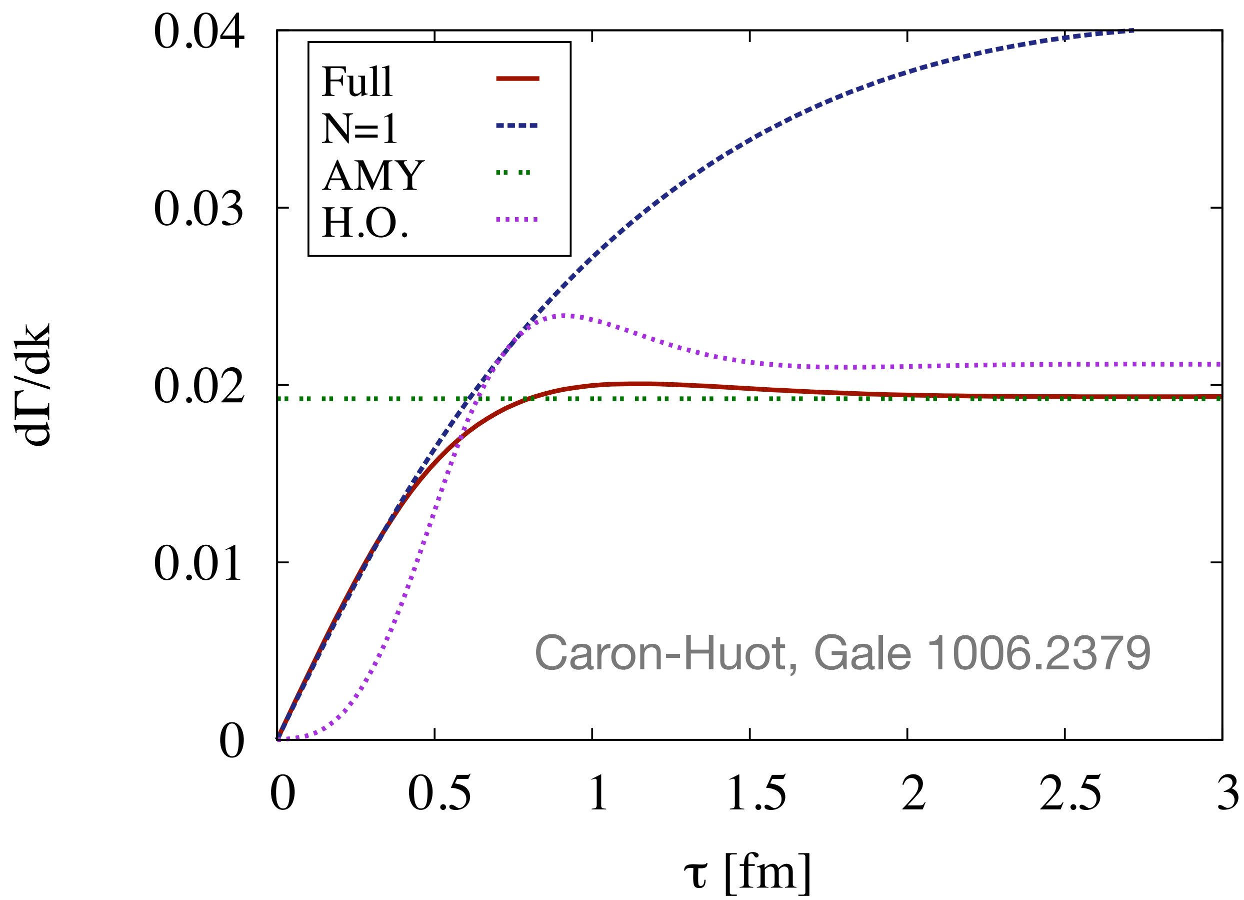
→ importance of medium-resolved sub-jets!

Finite-size effects



- including finite-size effects in the 'harmonic oscillator' approximation
- could be improved by including the full rate or interpolate between N=1 and HO

$$z\frac{dI^{\text{ind}}}{dz} = \frac{\alpha_s}{2\pi} z P_{gg}(z) \, \ln \left| \cos(1+i)\sqrt{\frac{\hat{q}_{\text{eff}} L^2}{z(1-z)p^+}} \right| \quad \Rightarrow \quad z\frac{dI^{\text{ind}}}{dz\, dL}$$

$$k_{\text{br}}^2 = \sqrt{z(1-z)p_0^+ \hat{q}_{\text{eff}}} \qquad \hat{q}_{\text{eff}} = \hat{q}\Big[(1-z)N_c - zC_R\Big]$$

Regularization

$$\frac{d^2\mathcal{P}}{dz d\tau} = \frac{1}{2}\frac{\mathcal{F}(z,x;\tau)}{\sqrt{x}}$$

$$x_c = \omega_c/p_0^+ \qquad \tau \equiv \bar{\alpha}\sqrt{2x_c}$$

$$\mathcal{F}(z,x;\tau) = \tilde{P}_{gg}(z)\mathcal{K}(z)\frac{\sinh\sigma(z,x;\tau) - \sin\sigma(z,x;\tau)}{\cosh\sigma(z,x;\tau) + \cos\sigma(z,x;\tau)}$$

$$\sigma(z,x;\tau) = \frac{\mathcal{K}(z)}{\bar{\alpha}\sqrt{x}}\tau$$

$$\tilde{P}_{gg}(z) = \frac{\left(1 - z(1-z)\right)^2}{[z(1-z)]_{\epsilon_1}}$$

$$\mathcal{K}(z) = \sqrt{\frac{1-z(1-z)}{[z(1-z)]_{\epsilon_2}}}$$

$$t_{\rm br} \sim \lambda_{\rm mfp} \Rightarrow \omega_{\rm BH} = \lambda_{\rm mfp}^2\hat{q} \sim m_D^2\lambda_{\rm mfp}$$

$$k_\perp \sim k_{\rm br} < \omega$$

$$\Downarrow$$

$$\omega < \hat{q}^{1/3}$$

$$\lambda_{\rm mfp} > 1/m_D \Rightarrow \omega_{\rm BH} > \hat{q}^{1/3}$$

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reg1: $\frac{1}{(1-z)_\epsilon} = \frac{\xi(\xi - x)}{(\xi - x + x_{\rm BH})^2}$ 'strong'

reg2: $\frac{1}{(1-z)_\epsilon} = \frac{\xi}{\xi - x + x_{\rm BH}}$ 'smooth'

$x_{\rm BH} = \omega_{\rm BH}/E$
$\xi = x/z$

→ apply it only to the medium $\mathcal{K}$