# jets in heavy ion collisions
# :: from theory to phenomenology

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the study of jets
[reconstructed jets and their high-$p_t$ hadronic content]
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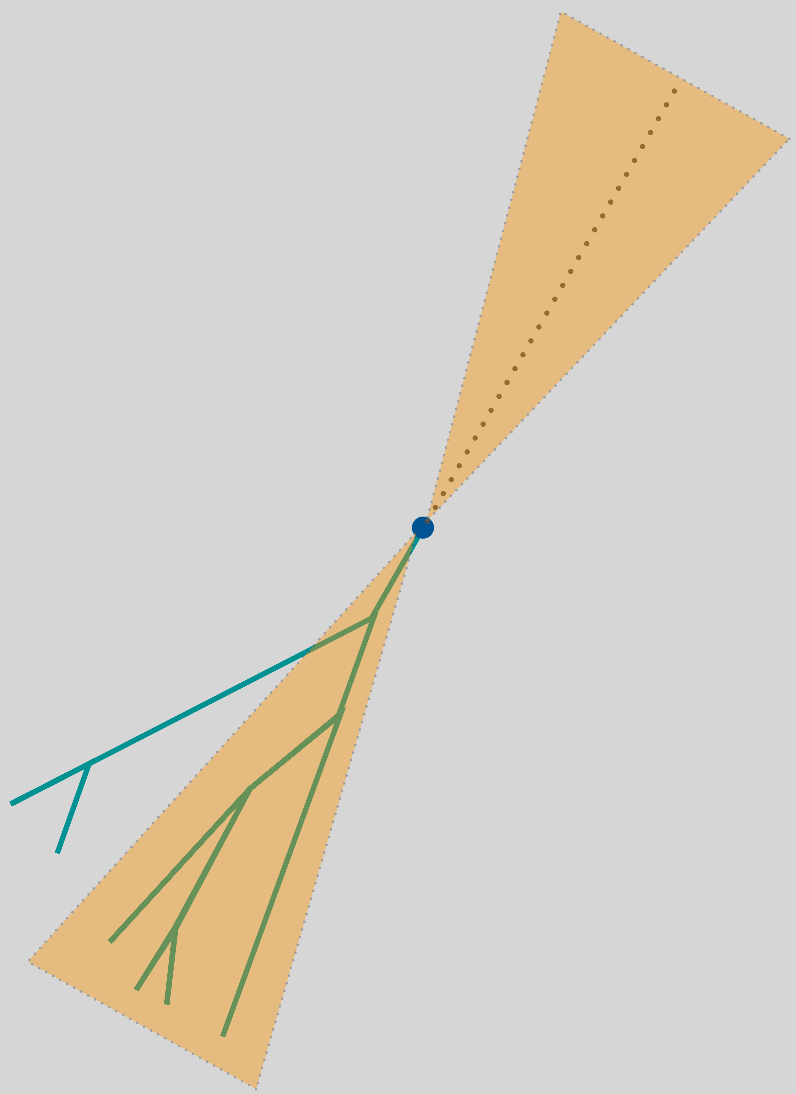
#1 establishing the probe

#2 probing the medium

# jets in heavy ion collisions



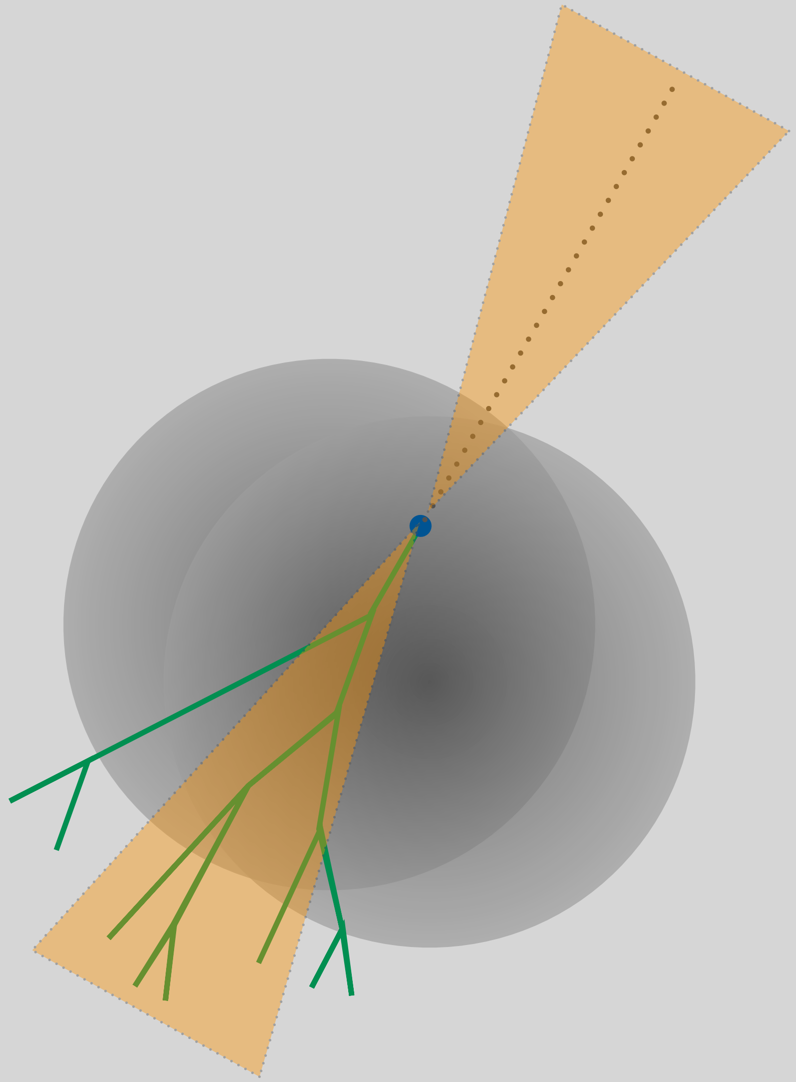
vacuum jets under overall excellent theoretical control

- factorization of initial and final state

*jet :: collimated spray of hadrons resulting from the QCD branching of a hard [high-$p_t$] parton and subsequent hadronization of fragments and grouped according to given procedure [jet algorithm] and for given defining parameters [eg, jet radius]*

# jets in heavy ion collisions

in HIC jets traverse sizable in-medium pathlength



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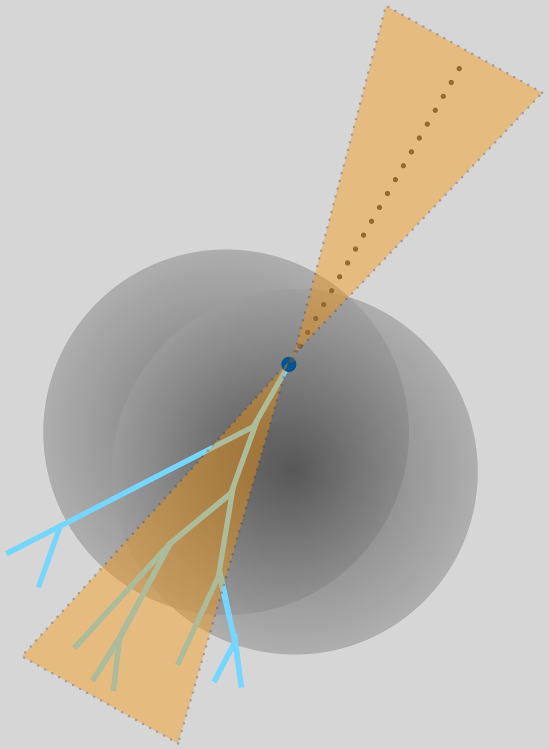

same factorizable structure [challengeable working hypothesis]

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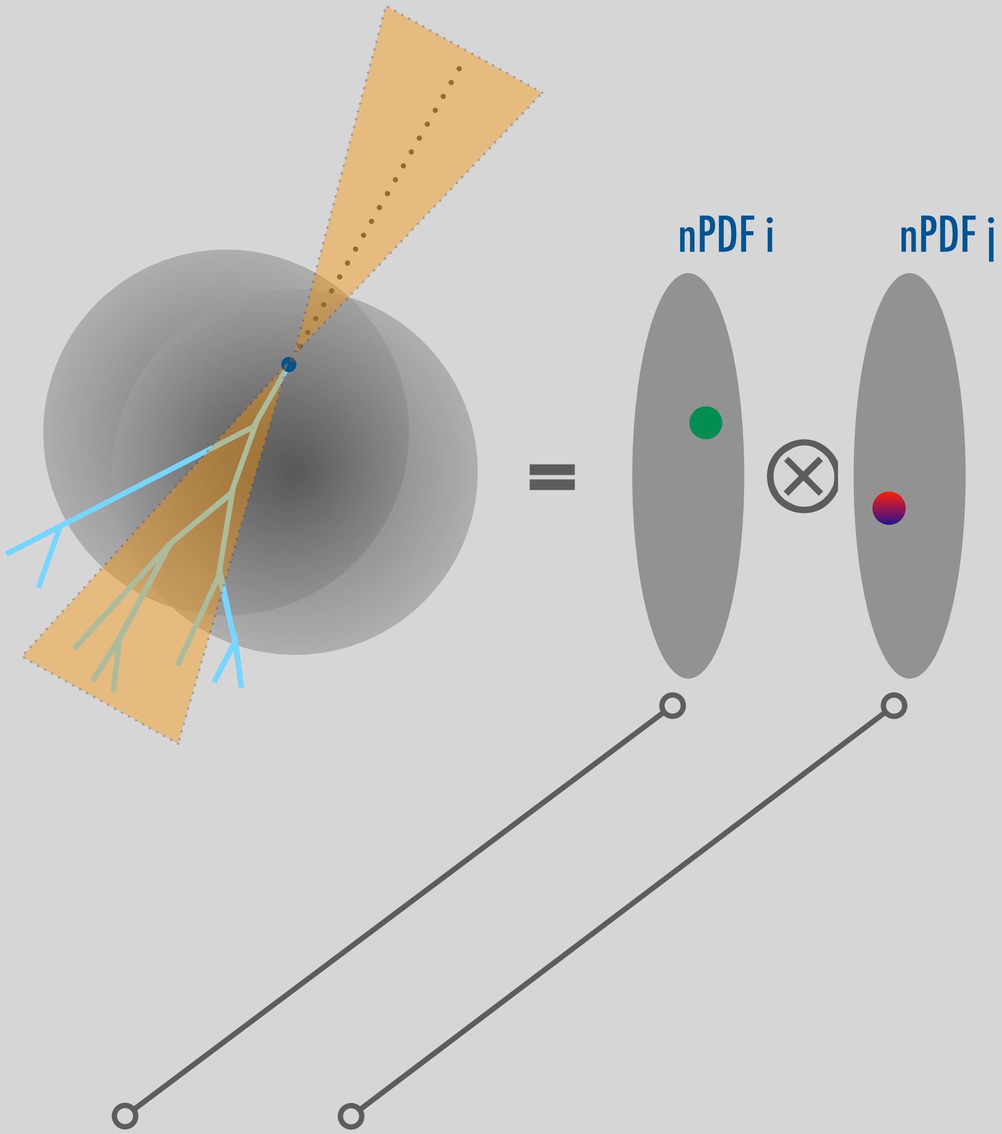


sufficiently constrained in relevant kinematical domain [further improvement from future pA data]

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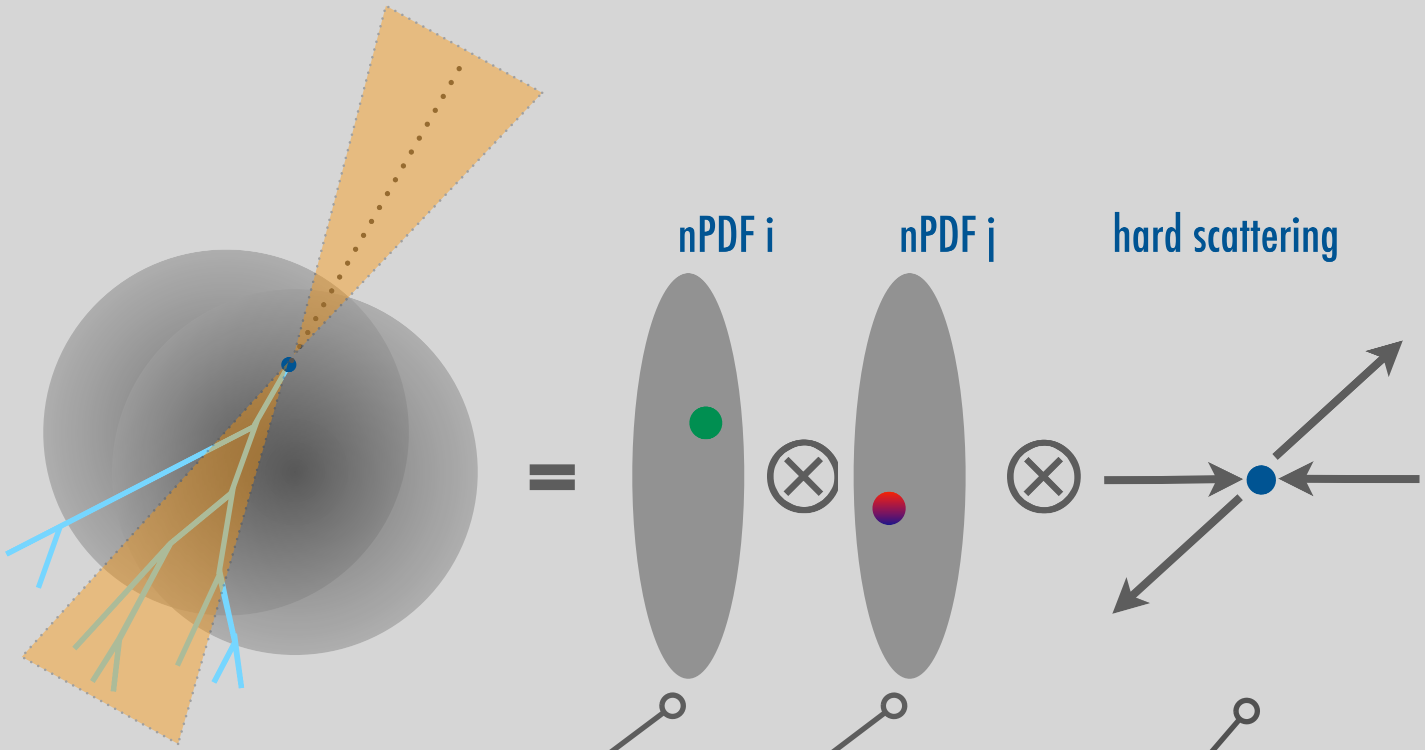


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localized on point like scale
oblivious to surrounding matter
[calculable to arbitrary pQCD order]

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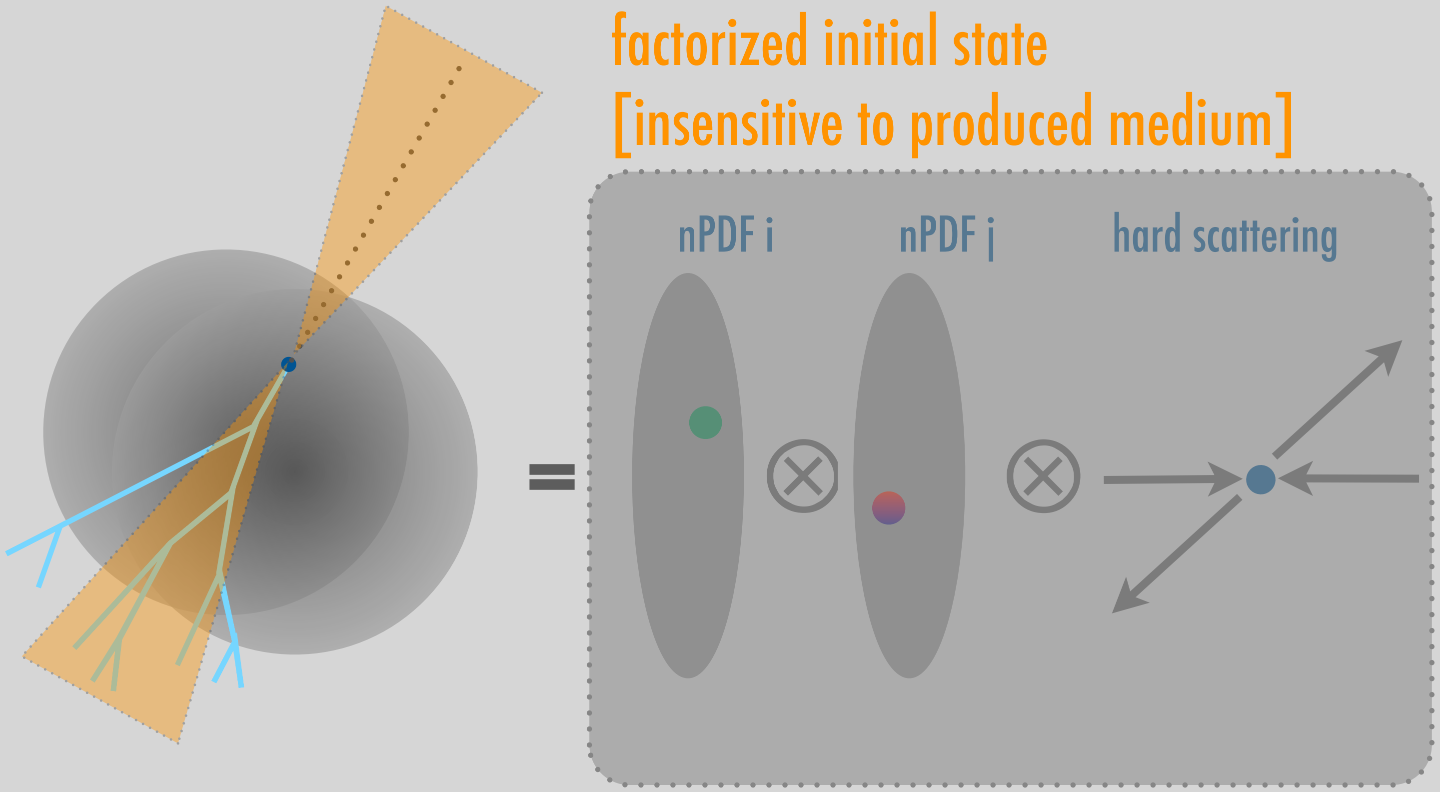

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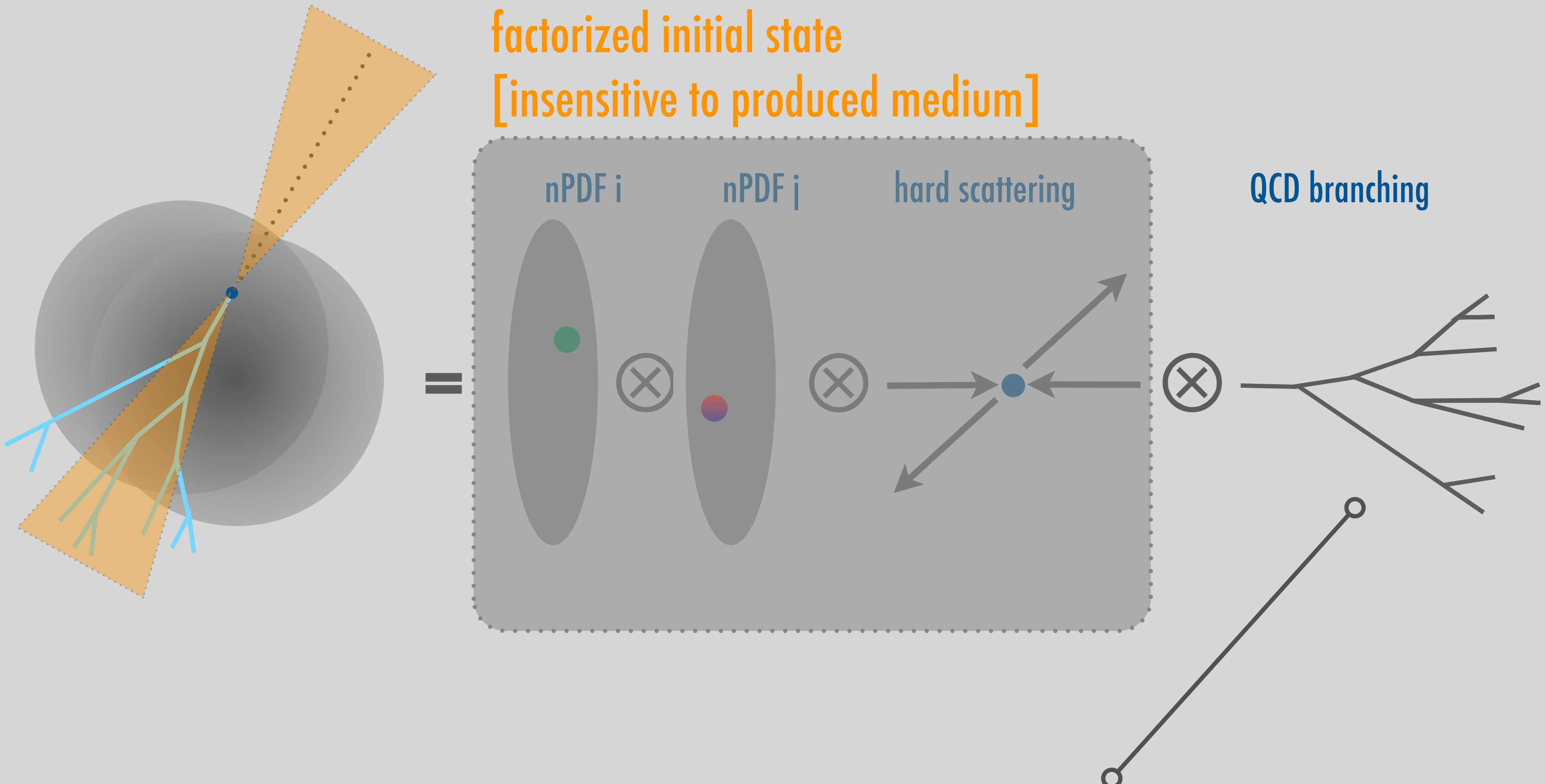


**very well [and perturbatively] understood in vacuum**

- coherence between successive splittings leads to angular ordering
- faithfully implemented in MC generators

**medium modified**

- induced radiation [radiative energy loss]
- broadening of all partons traversing medium
- energy/momentum transfer to medium [elastic energy loss]
- strong modification of coherence properties
- modification of colour correlations

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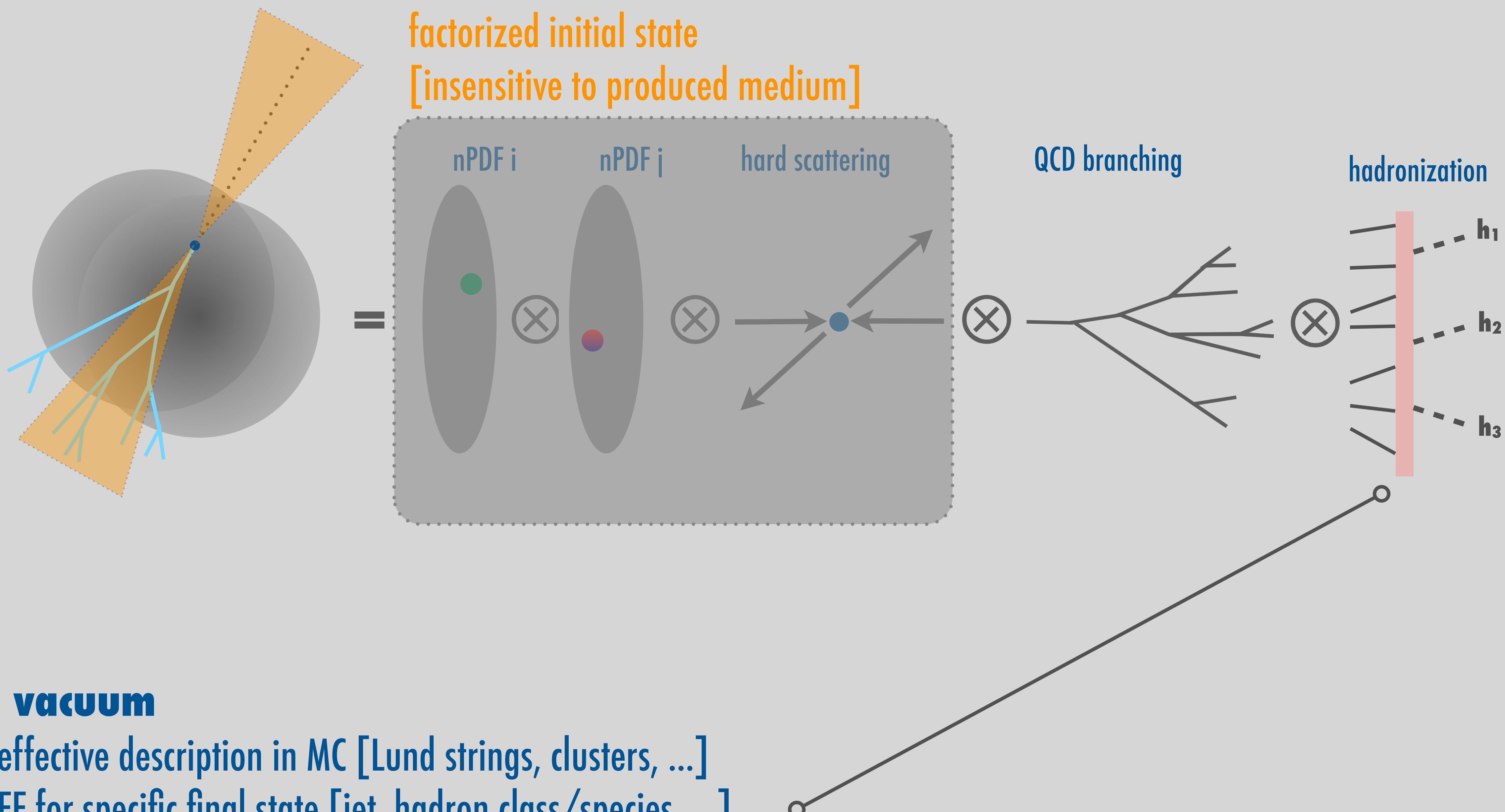


**in vacuum**

- effective description in MC [Lund strings, clusters, ...]
- FF for specific final state [jet, hadron class/species, ...]

**in medium**

- time delayed [high enough $p_t$] thus outside medium
- colour correlations of hadronizing system changed

**fragmentation outside medium = vacuum FFs ???**

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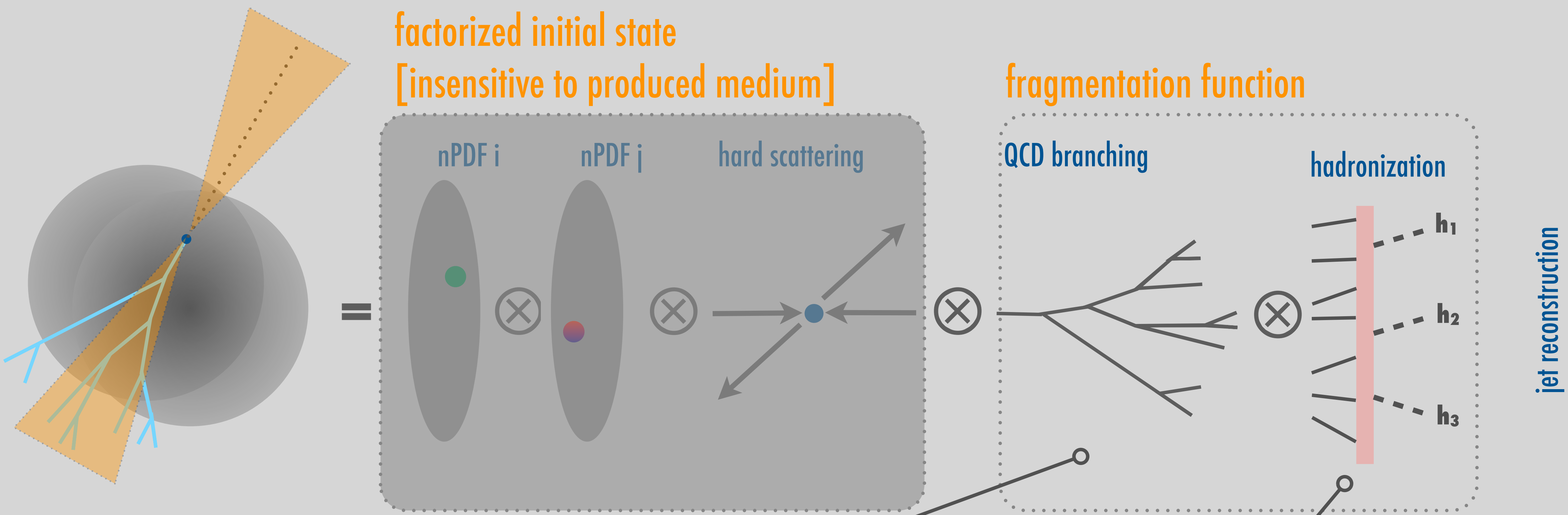


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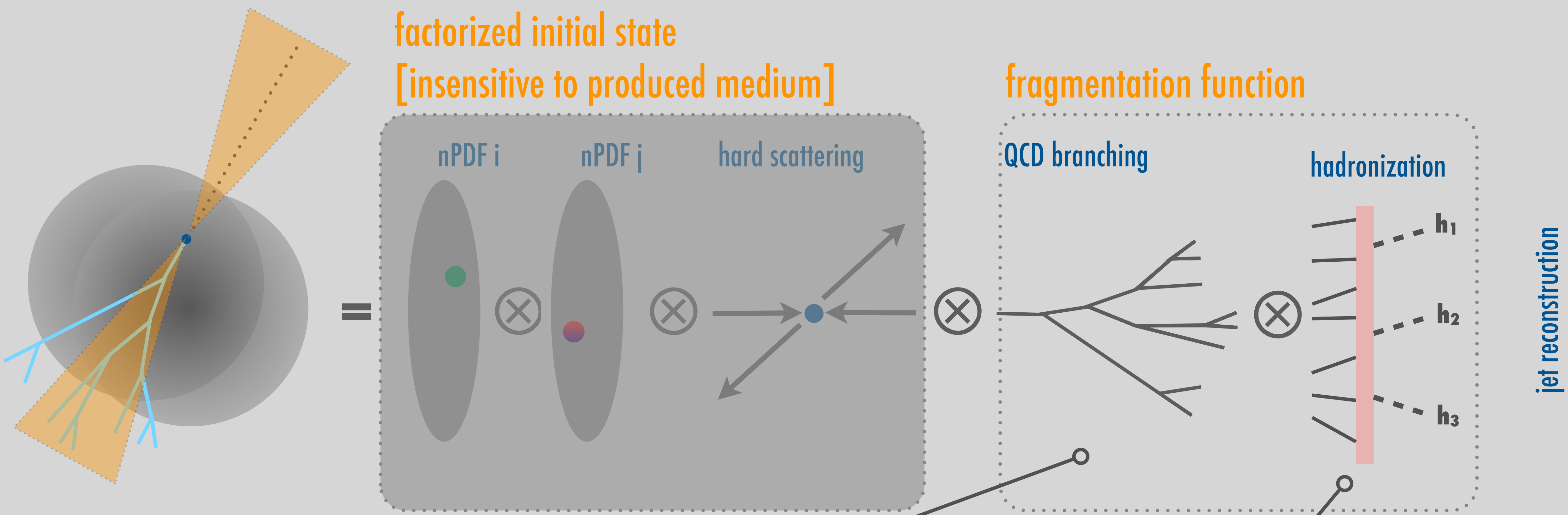


**jet quenching ::**
**observable consequences [in jet and jet-like hadronic observables] of the effect of the medium**

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to establish quenched jets
[their hadron 'jet-like' and full jet observables]
as medium probes requires a full theoretical account of

- *QCD branching*
- *effect on hadronization [if any]*

in the presence of a generic medium

and

a detailed assessment of the sensitivity of observables
to specific medium effects

**:: probe ::**
*physical object/process under strict theoretical control for which a definite relationship between its observable properties and those of the probed system can be established*

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**soft components at large angles**
**[double counting ?]**

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**most [all?] questions asked, many [most?] being answered**

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- energy of radiated gluon assumed [not in AMY] much smaller than that of emitter [$x=\omega/E \ll 1$] but emission spectrum computed for all allowed phase space with violation of energy-momentum conservation cured by explicit cut-offs

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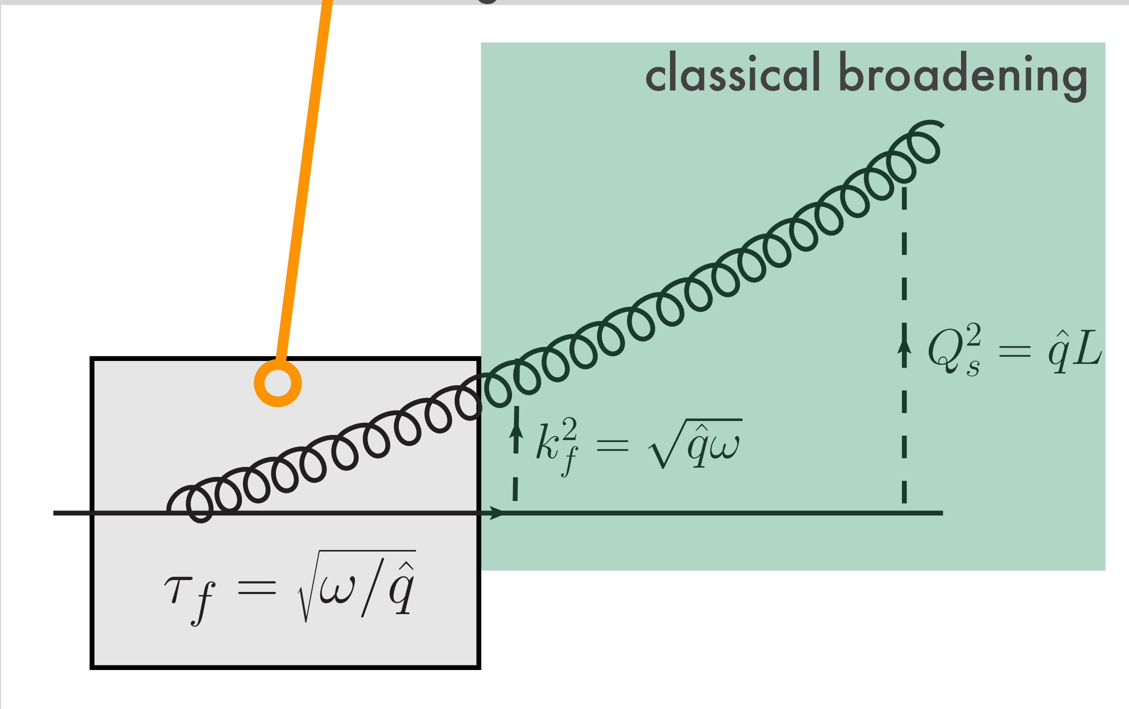
# broadening



- medium induced radiation off a single quark in a dense medium **BDMPS-Z** revisited

$$\mathcal{R}_q^{\rm med} \approx 4\omega \int_0^L dt' \int \frac{d^2\boldsymbol{k}'}{(2\pi)^2} \mathcal{P}(\boldsymbol{k}-\boldsymbol{k}', L-t') \sin\left(\frac{\boldsymbol{k}'^2}{2k_{\rm f}^2}\right) e^{-\frac{\boldsymbol{k}'^2}{2k_{\rm f}^2}}$$

quantum emission/broadening
during formation time

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large broadening [beyond quasi-eikonal] is a prominent dynamical mechanism for jet energy loss [dijet asymmetry]

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- in-medium formation time for small angle and soft gluons [vacuum] is very short
- democratic broadening is a large effect for soft partons
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  - enhancement of soft fragments outside the jet

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

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

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

Casalderrey-Solana, Milhano, Wiedemann [1105.1760]
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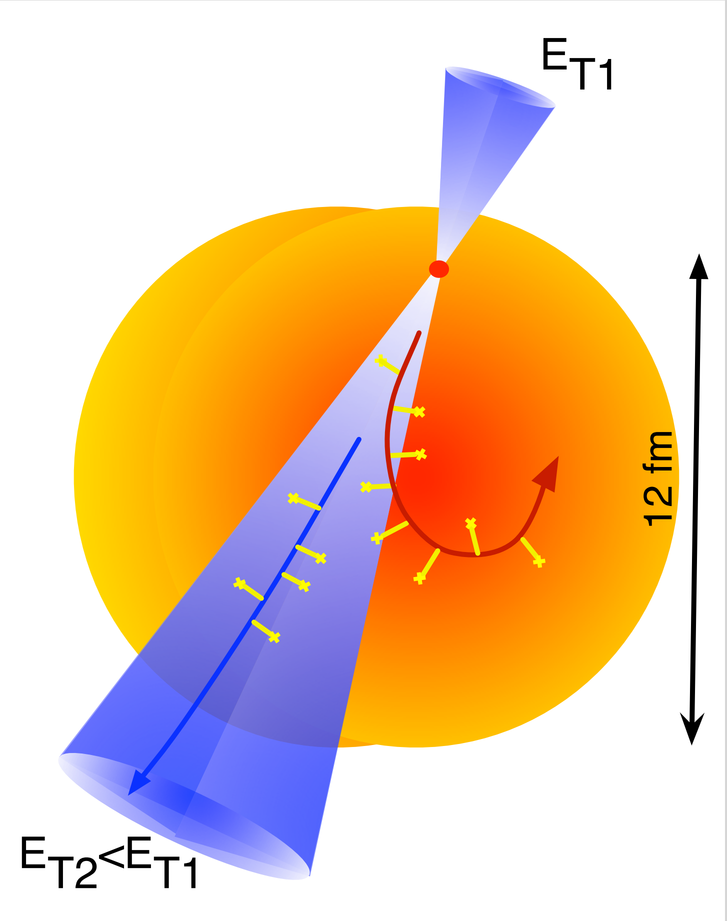


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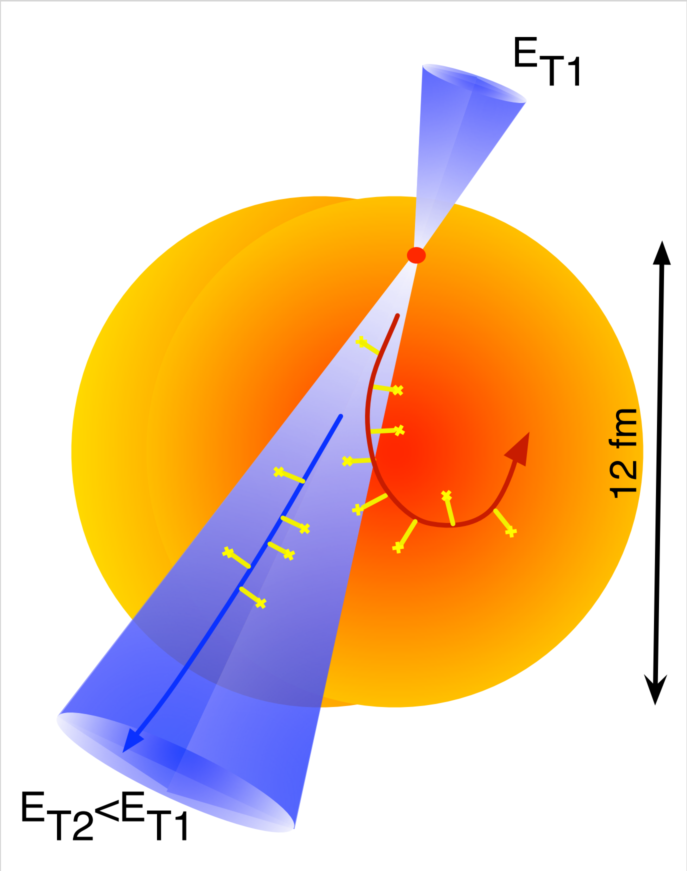


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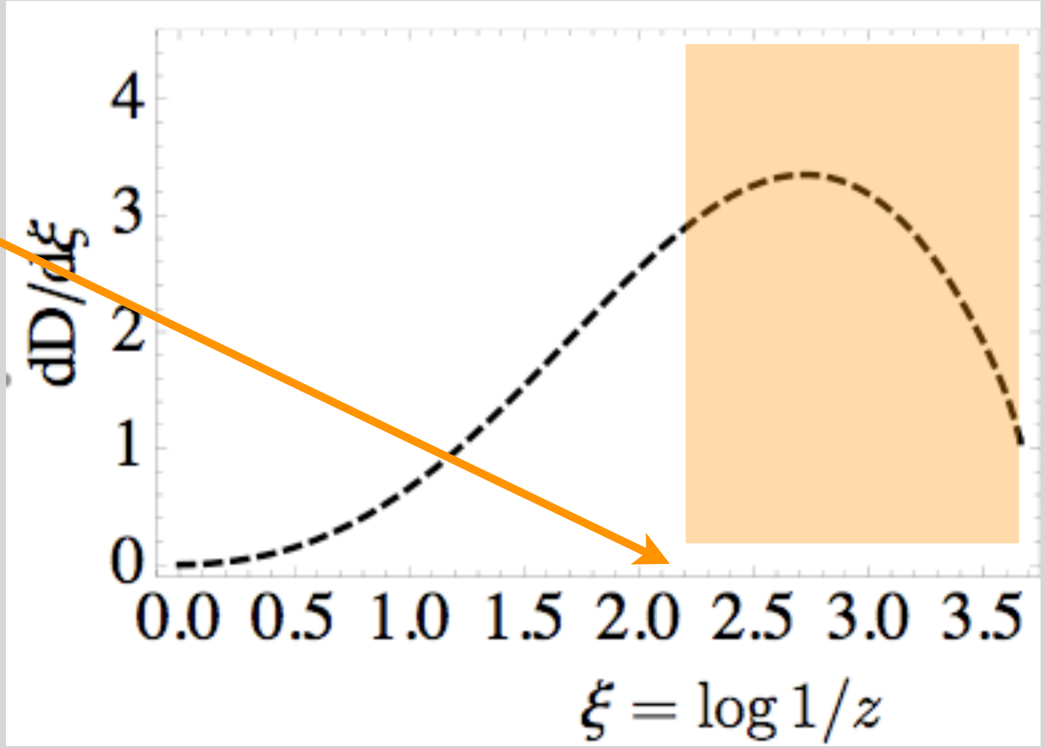

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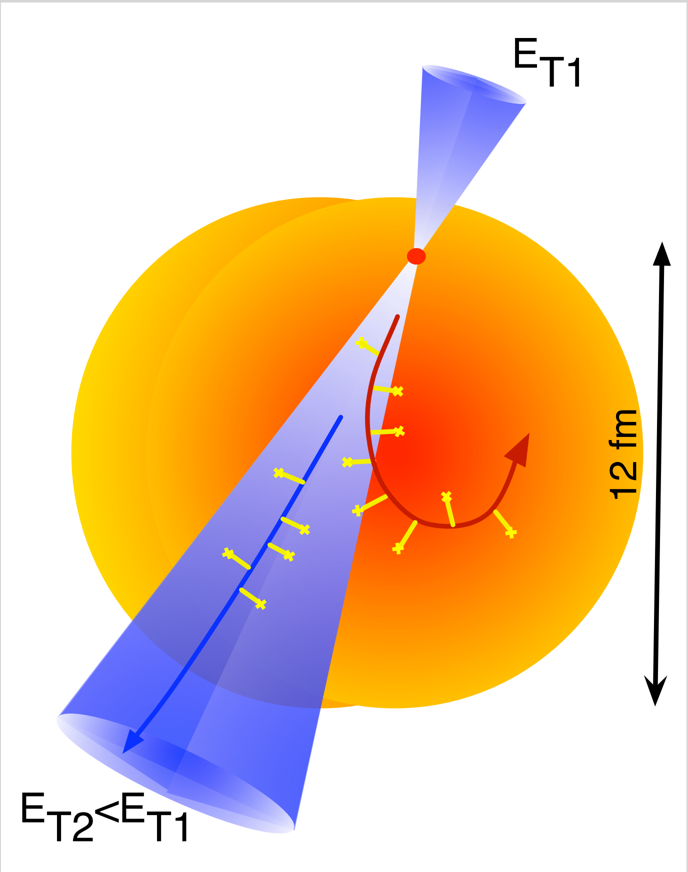


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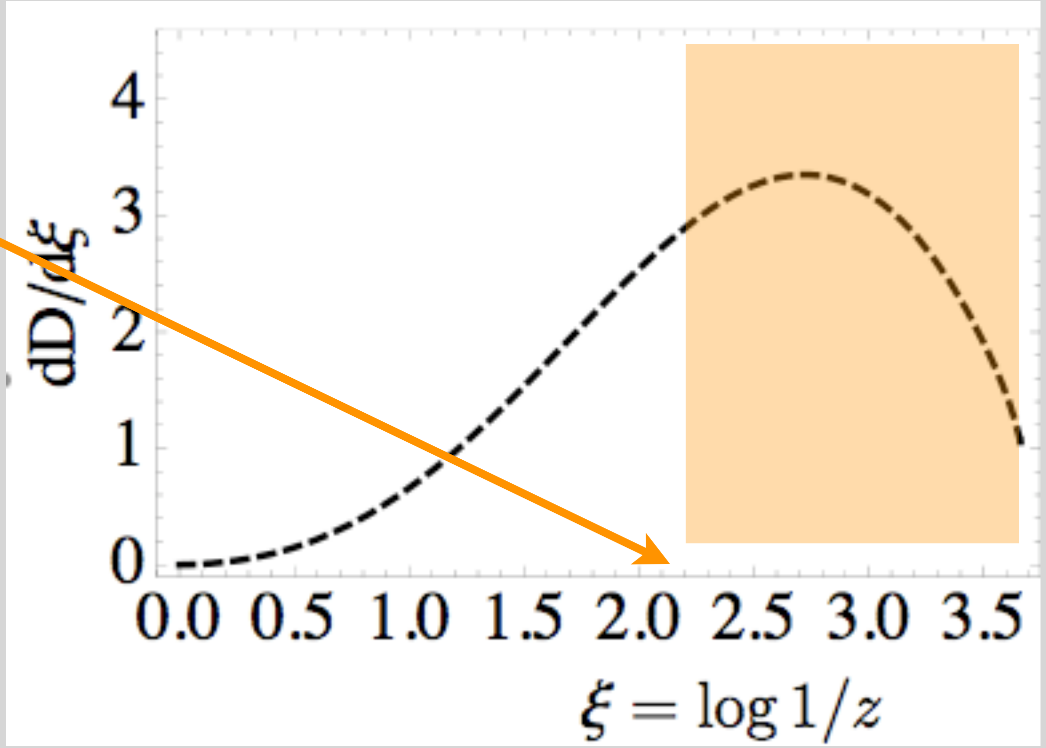


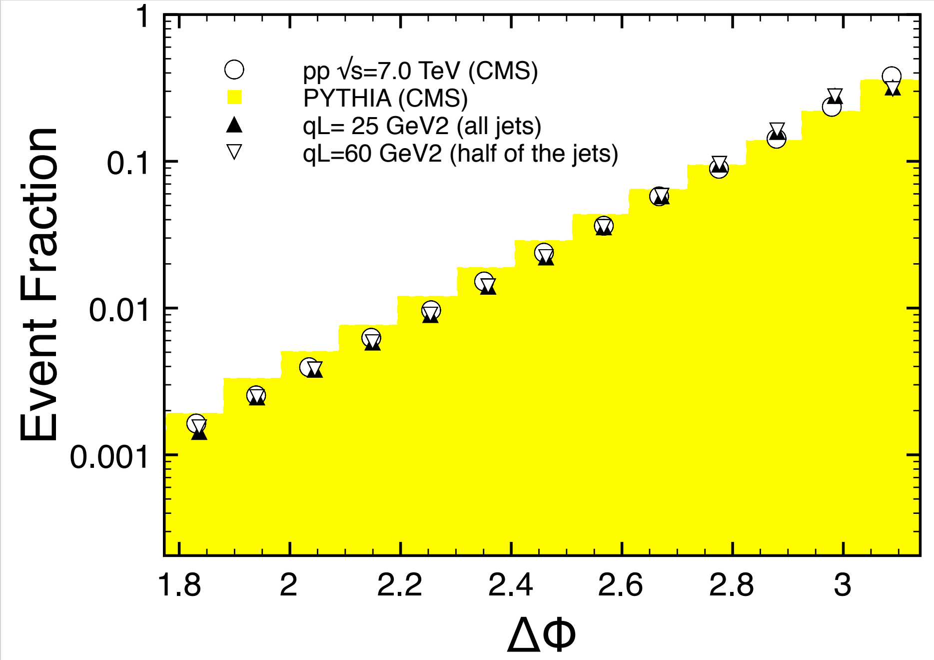


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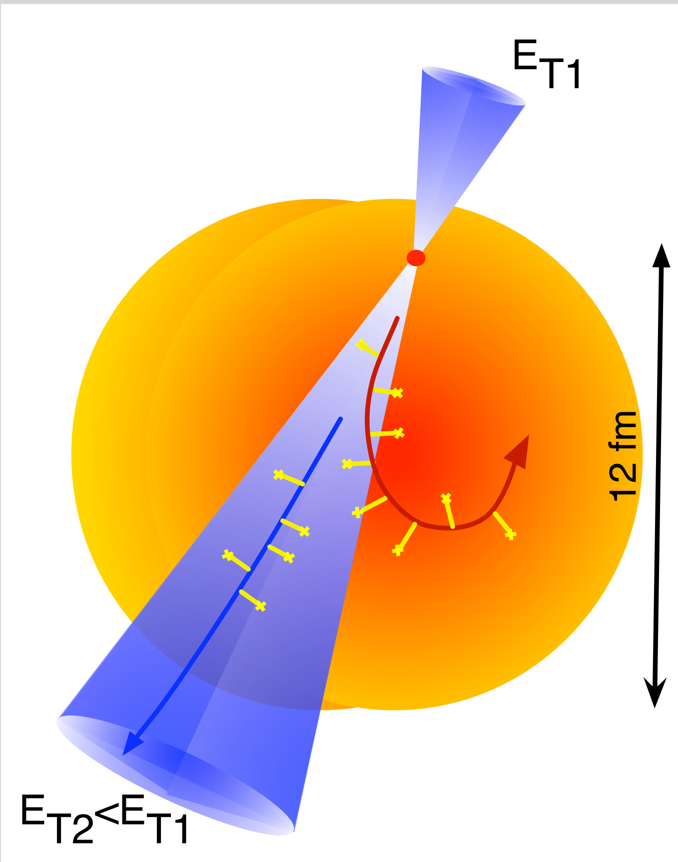


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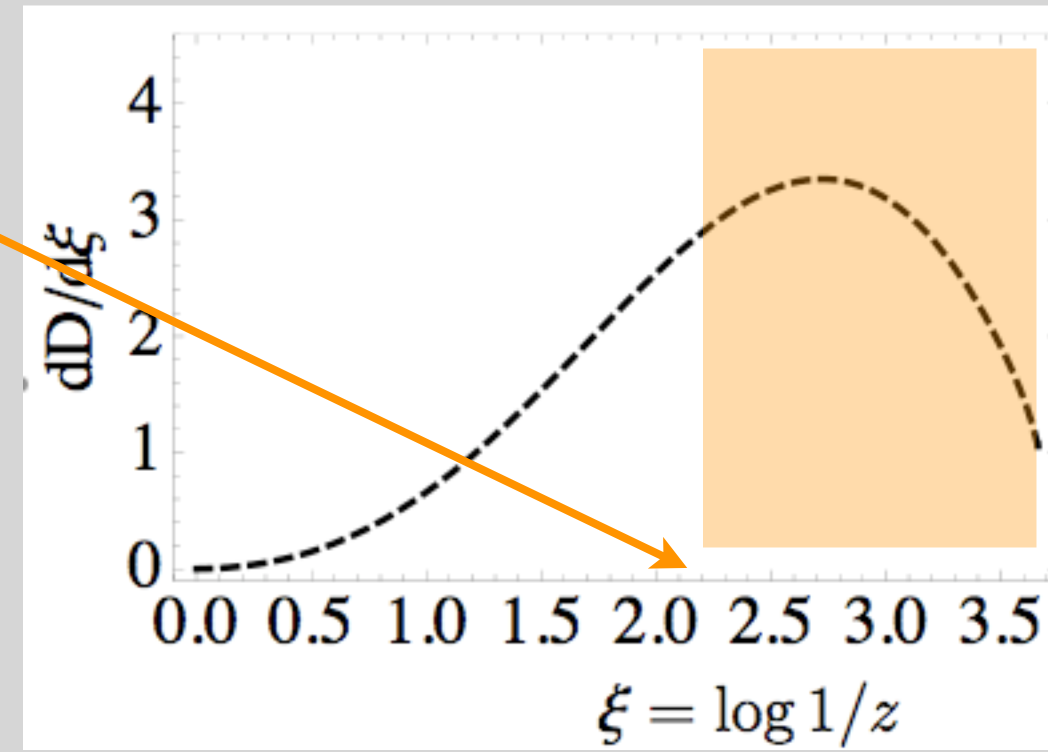


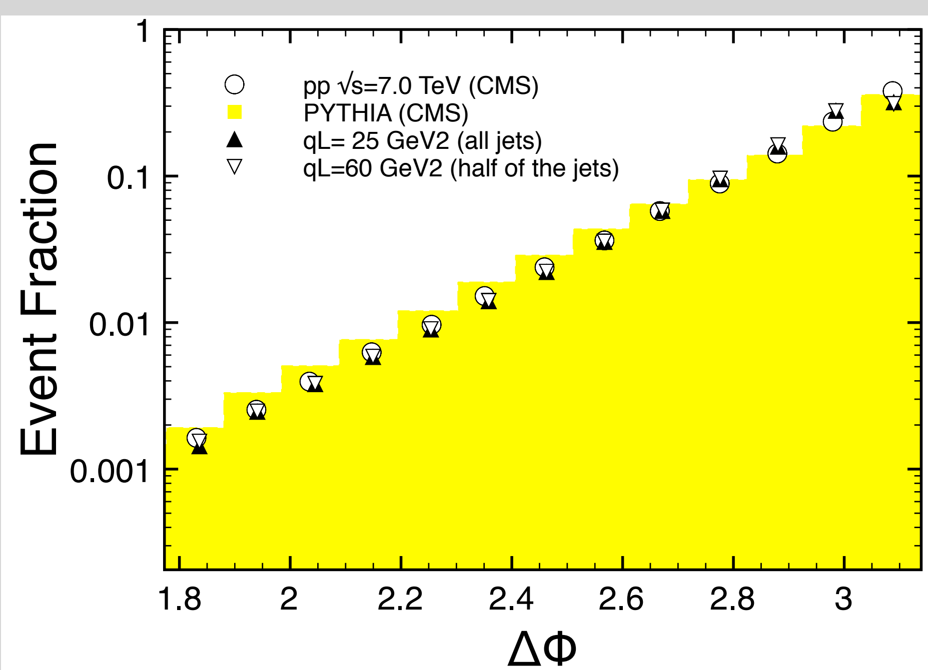


good qualitative description of average medium induced asymmetry

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- geometry
  - path length fluctuations with realistic nuclear profile
  - all distances density weighed and account for $1/\tau$ expansion

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  - ↪ additional medium induced gluons from Gaussian distributed 'BDMPS' formula
    - path length dependent
    - event-by-event with [independent] Poissonian assumption

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  - ↪ vacuum baseline from data [CMS]

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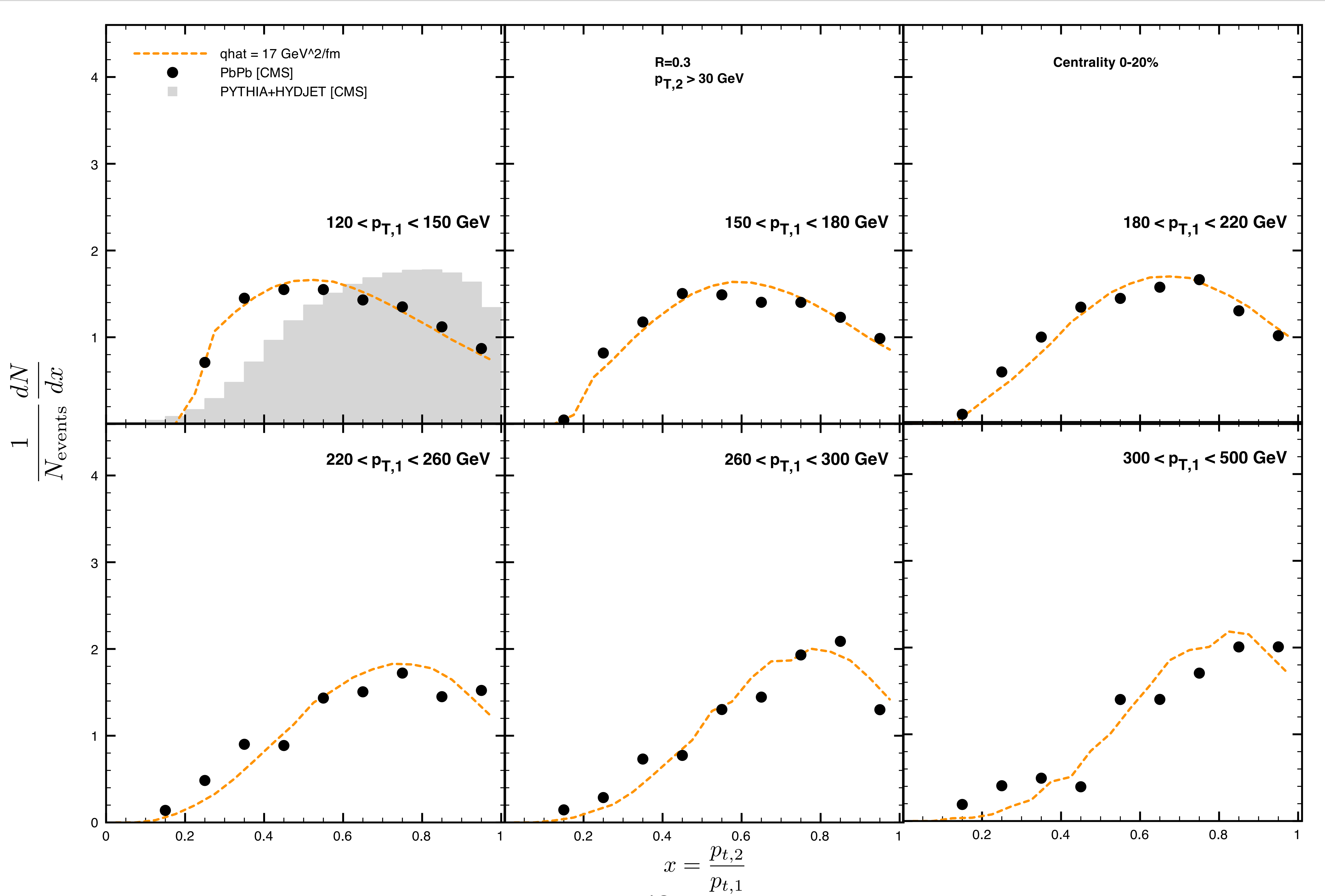
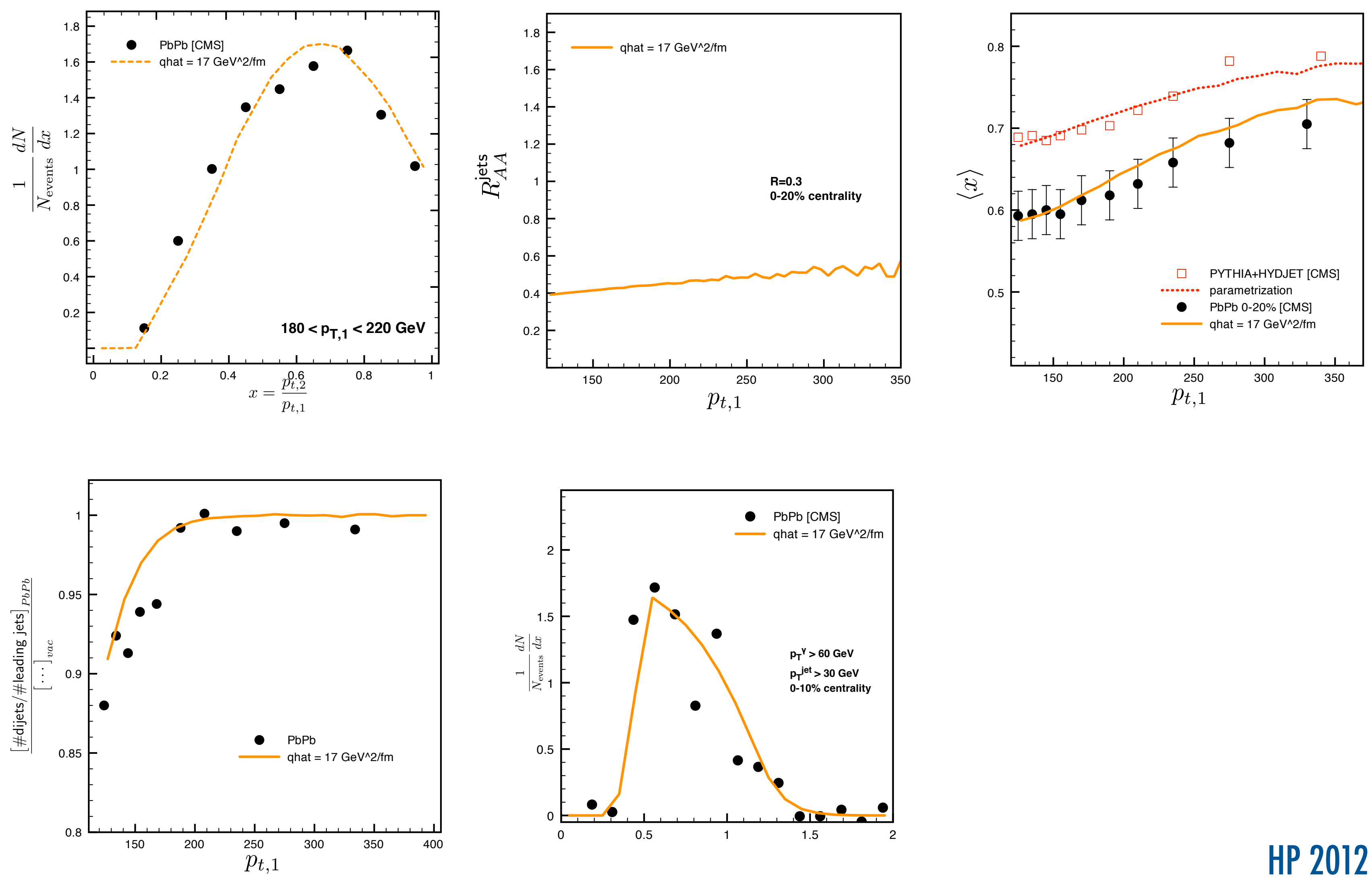
[$\alpha_s$ = 0.3]

# energy dependence of dijet imbalance



# broadening [jet collimation]






HP 2012

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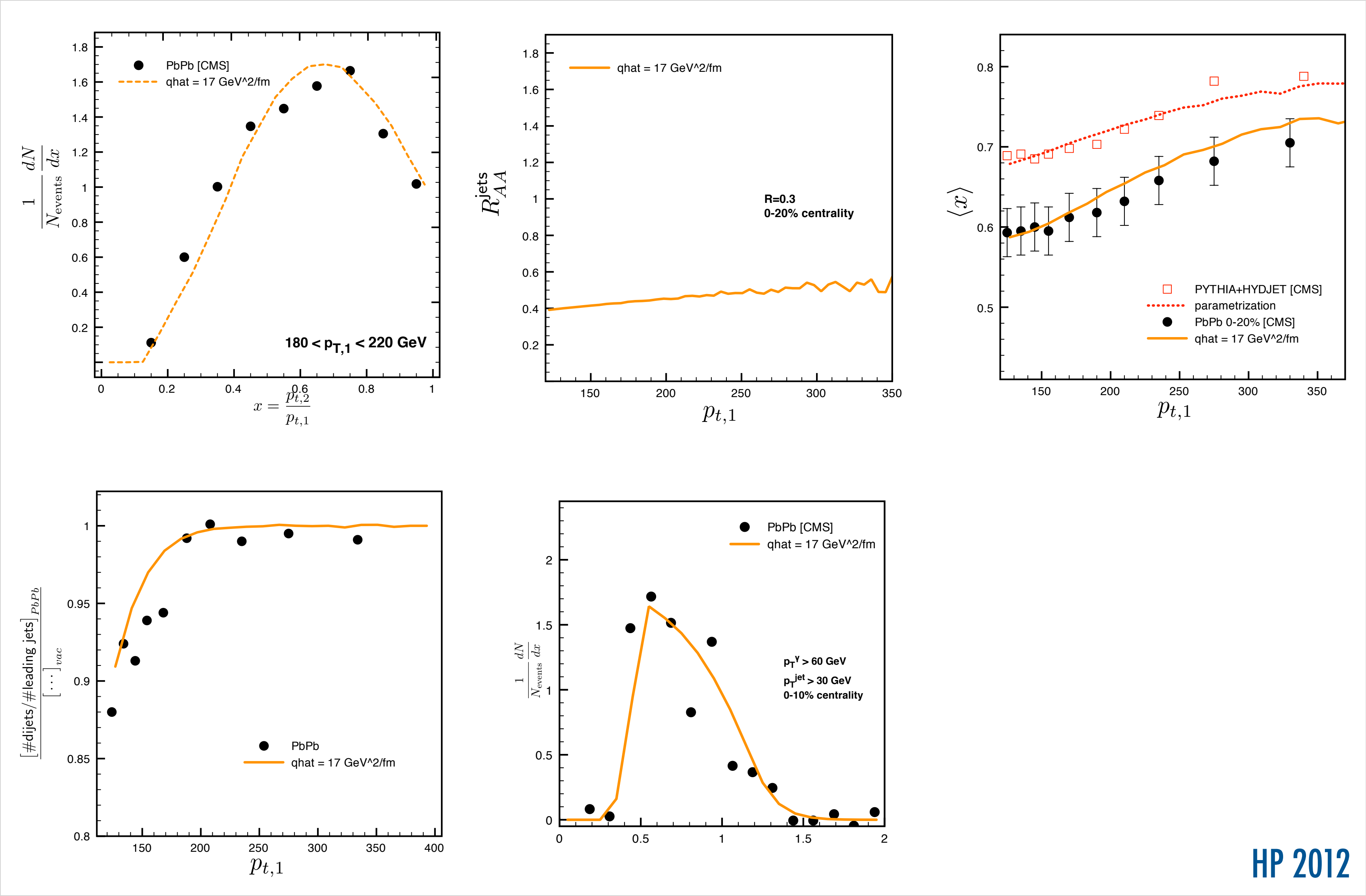


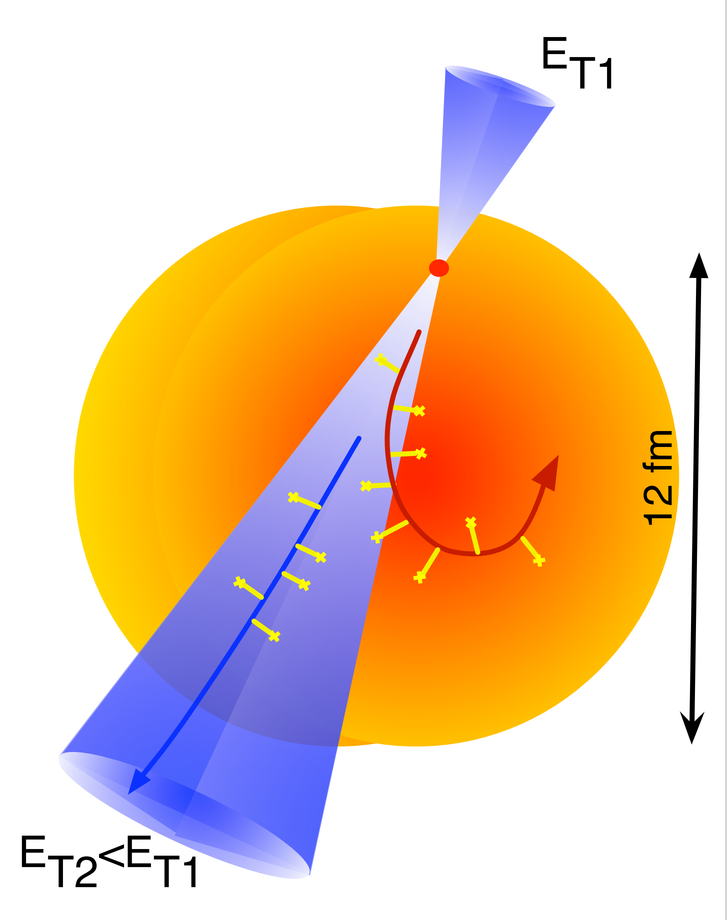

# color flow and hadronization

- hadronization is effectively accounted for by
  - ↪ [analytically] defining universal fragmentation functions [the probability of a given final state – hadron, jet – to arise from the showering and subsequent hadronization of fragments]
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  **color correlations between final state partons [+ kinematics] determine hadronic output**

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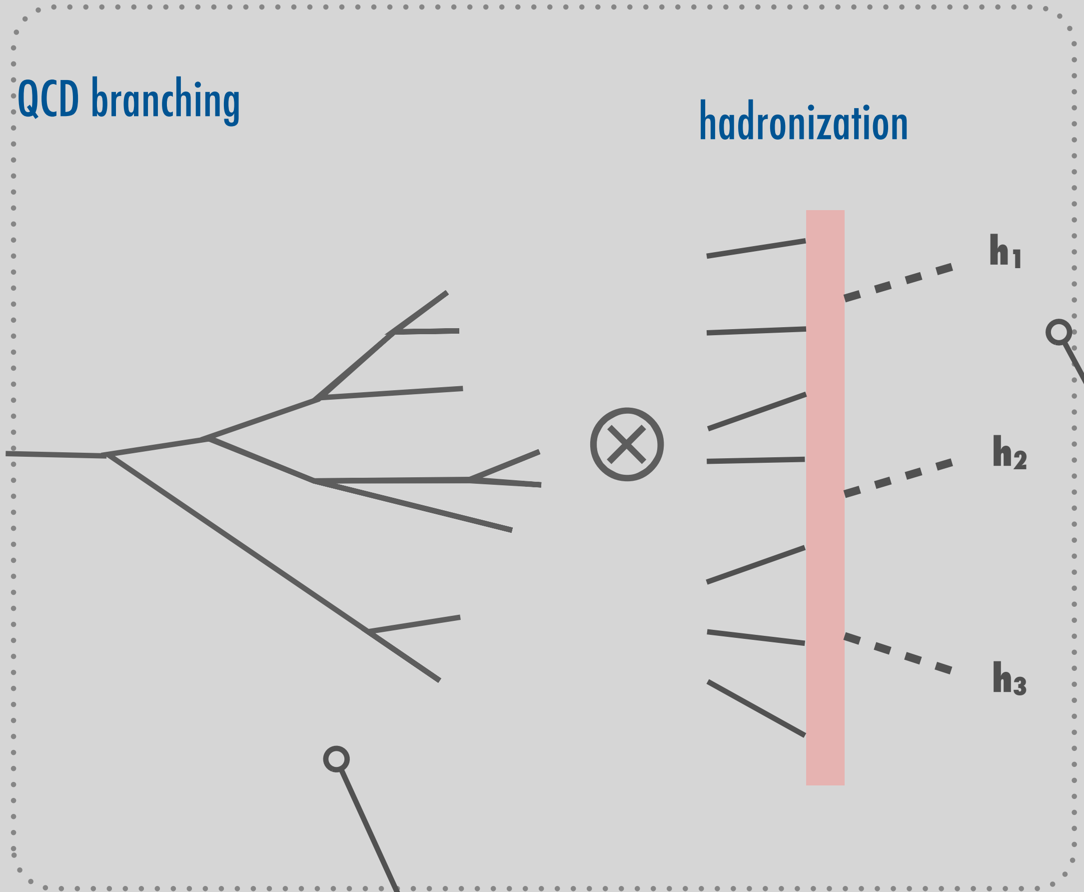


**color correlations of hadronizing system changed**

- surviving medium effect irrespectively of where hadronization takes place

**interactions with medium**

- energy/momentum exchanges
- modification of color correlations

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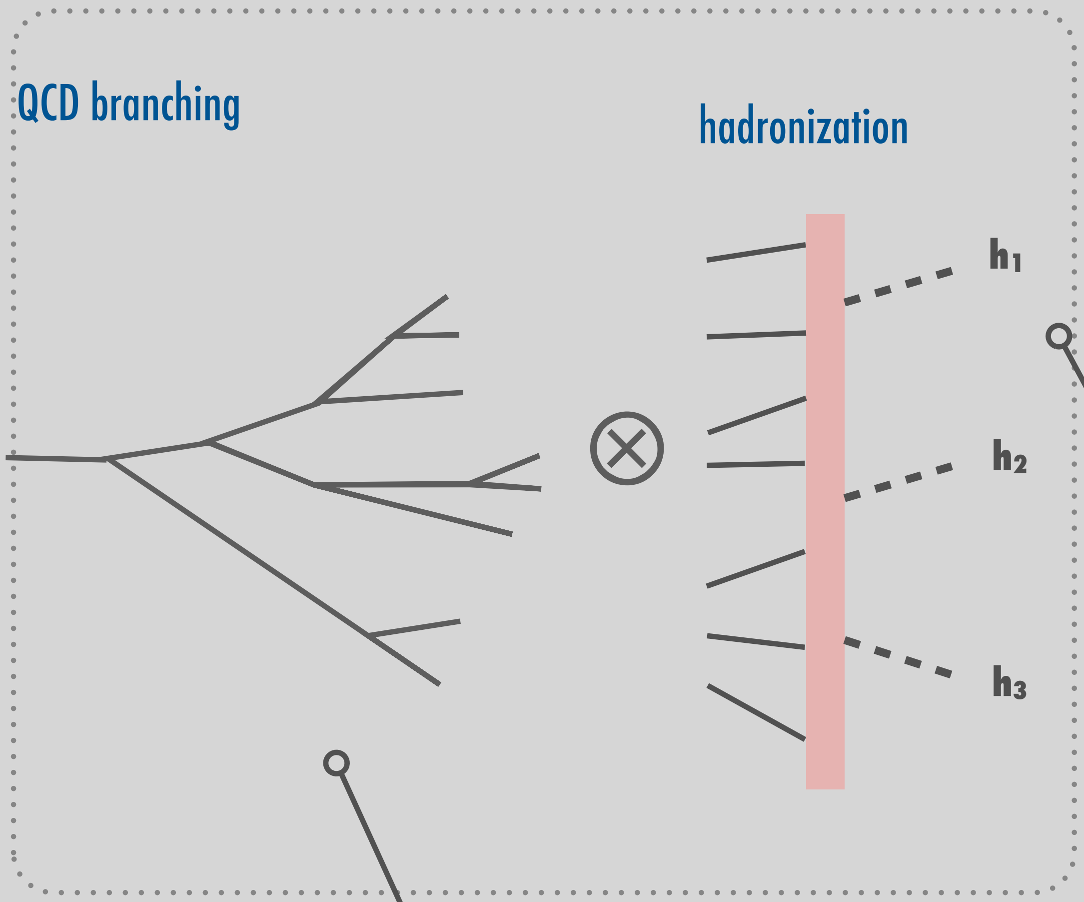


**standard energy loss calculations**
- amplitudes squared at partonic level
- color information LOST

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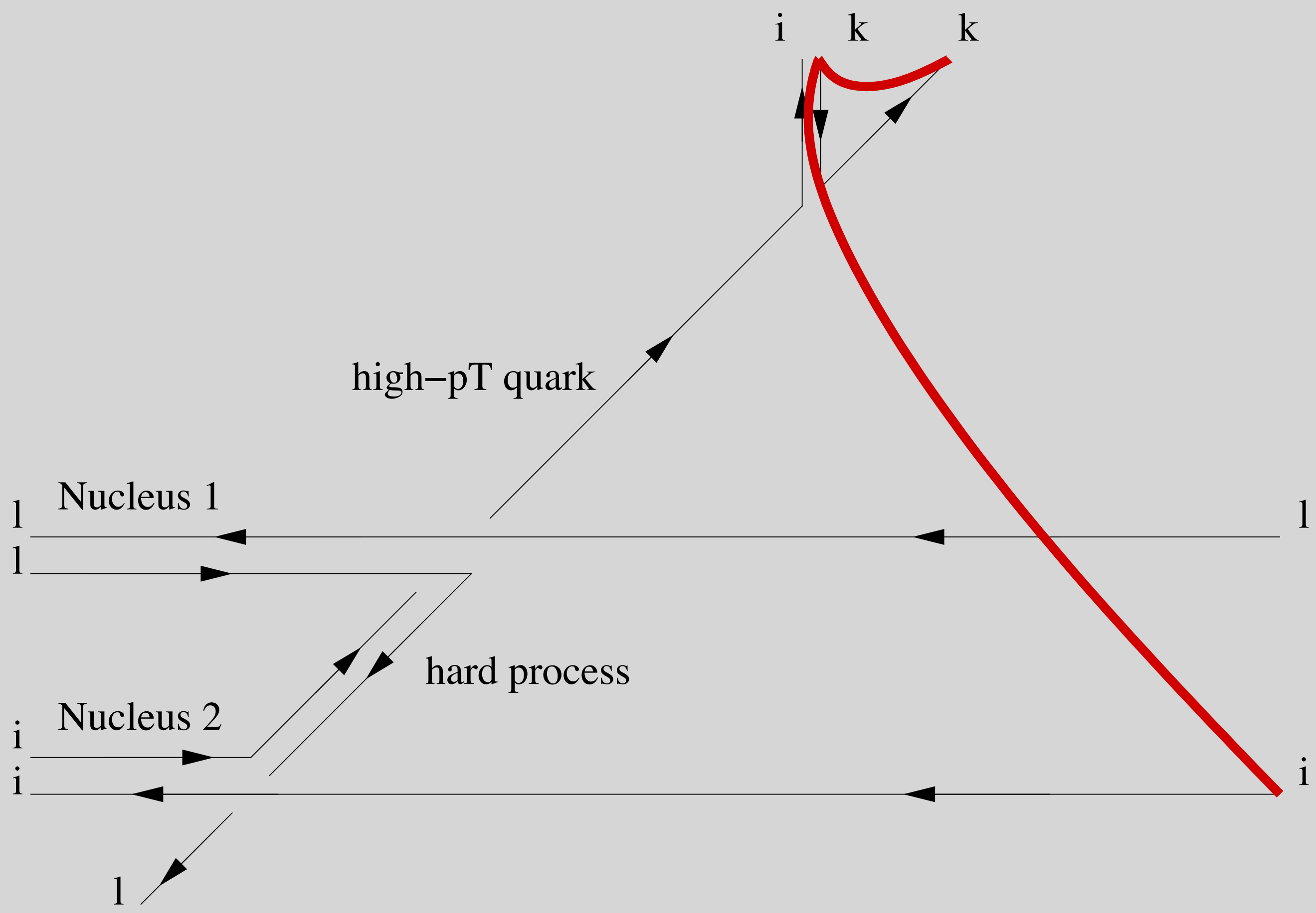
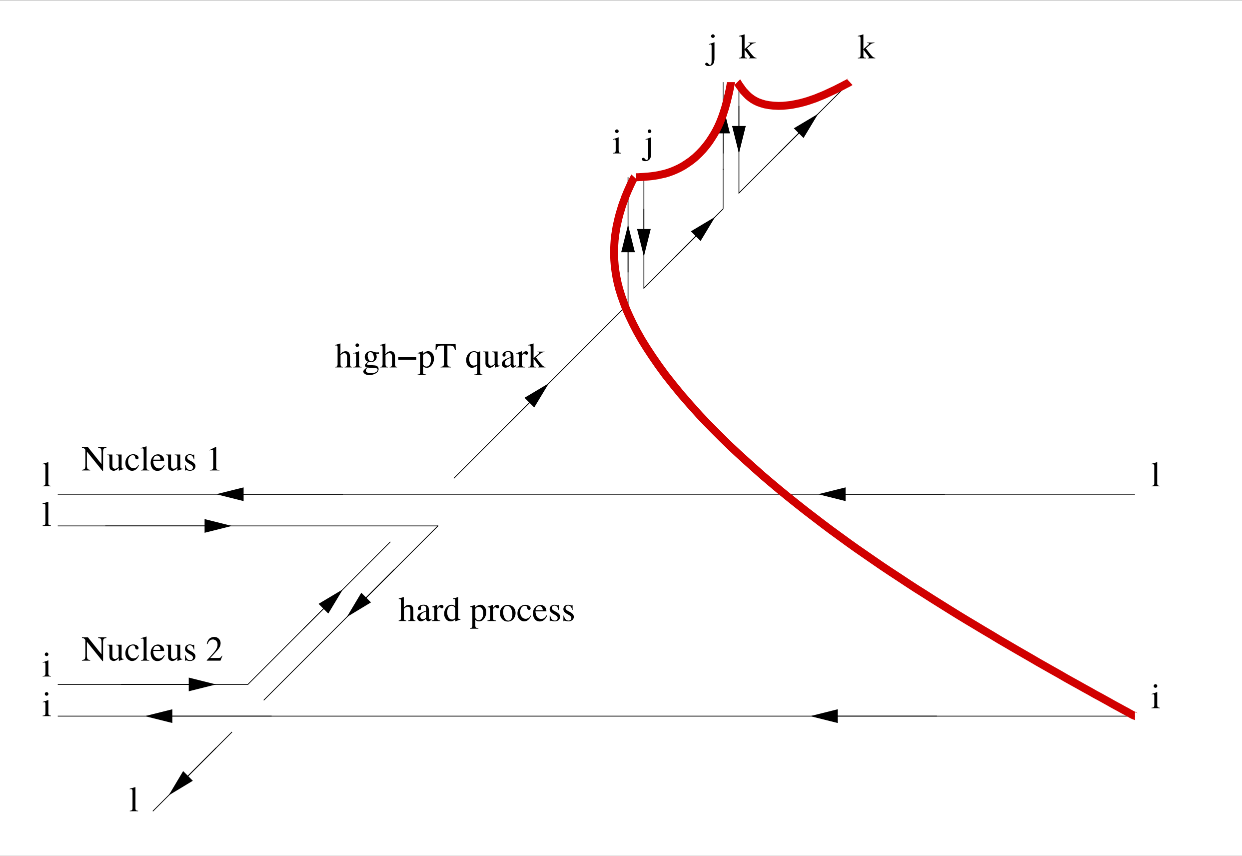
- Lund [PYTHIA] strings in the following
  - ↪ same conclusions from clustering [HERWIG]

# color flow in the vacuum



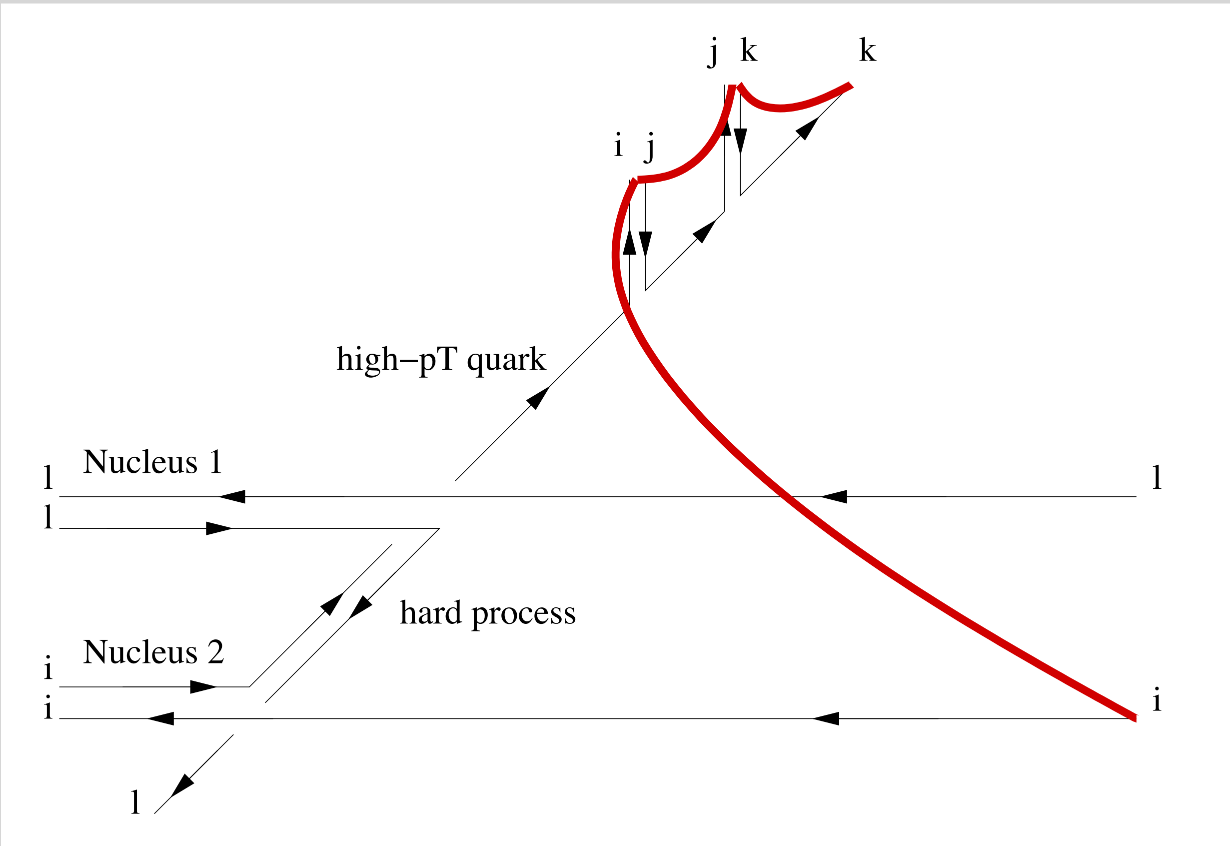

- ‘string’ extends from high-$p_t$, through gluon ‘kink’, to low-$p_t$ beam remnant
- multiplicity and distribution of hadrons resulting from ‘string’ depends essentially on the ‘string length’ [separation of endpoints in momentum space]
- final-state quark and radiated gluon always part of same string
- only correlation is between primary parton and ‘beam remnant’

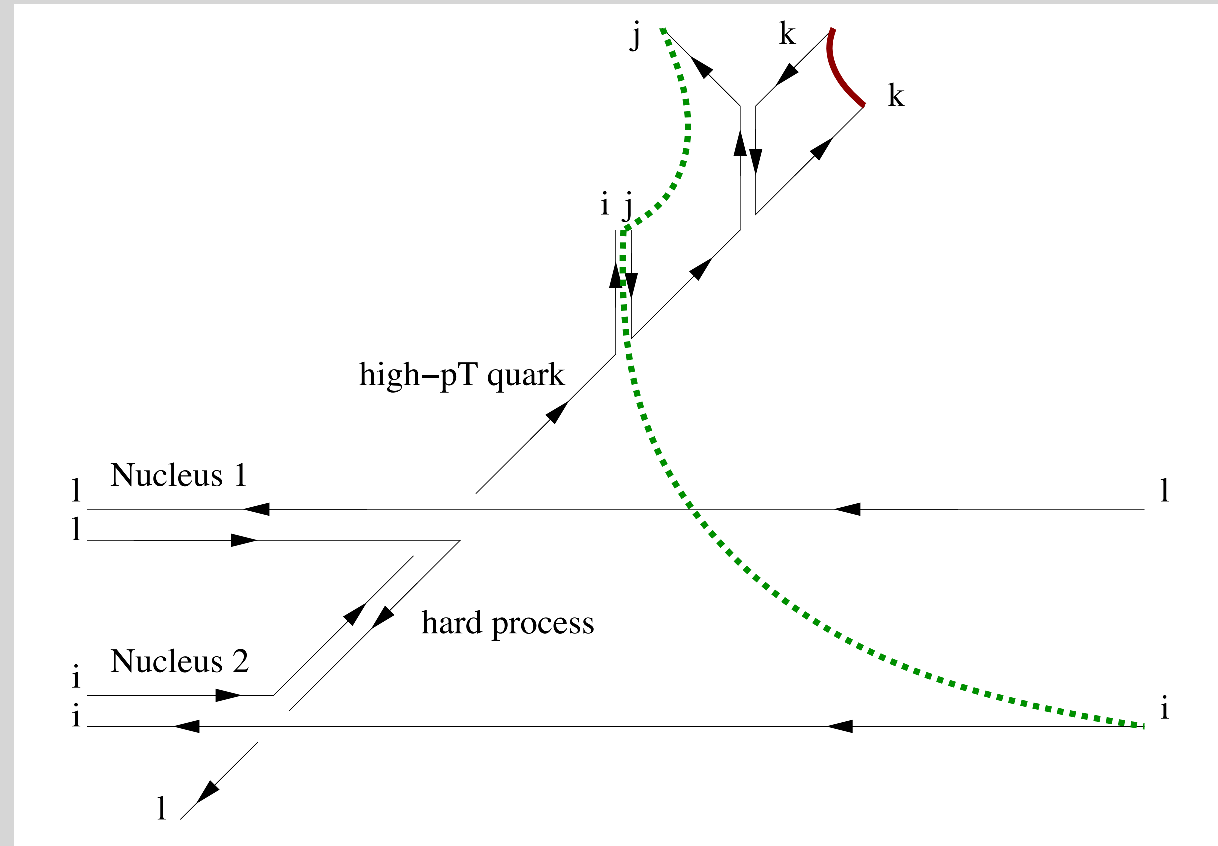
# color flow in the vacuum




- most radiated gluons color-connected with projectile fragment

# color flow in the vacuum




- most radiated gluons color-connected with projectile fragment
- only g → qqbar can break color connection
  - ↪ splitting with no soft enhancement [~ $z^2 + (1\text{-}z)^2$]

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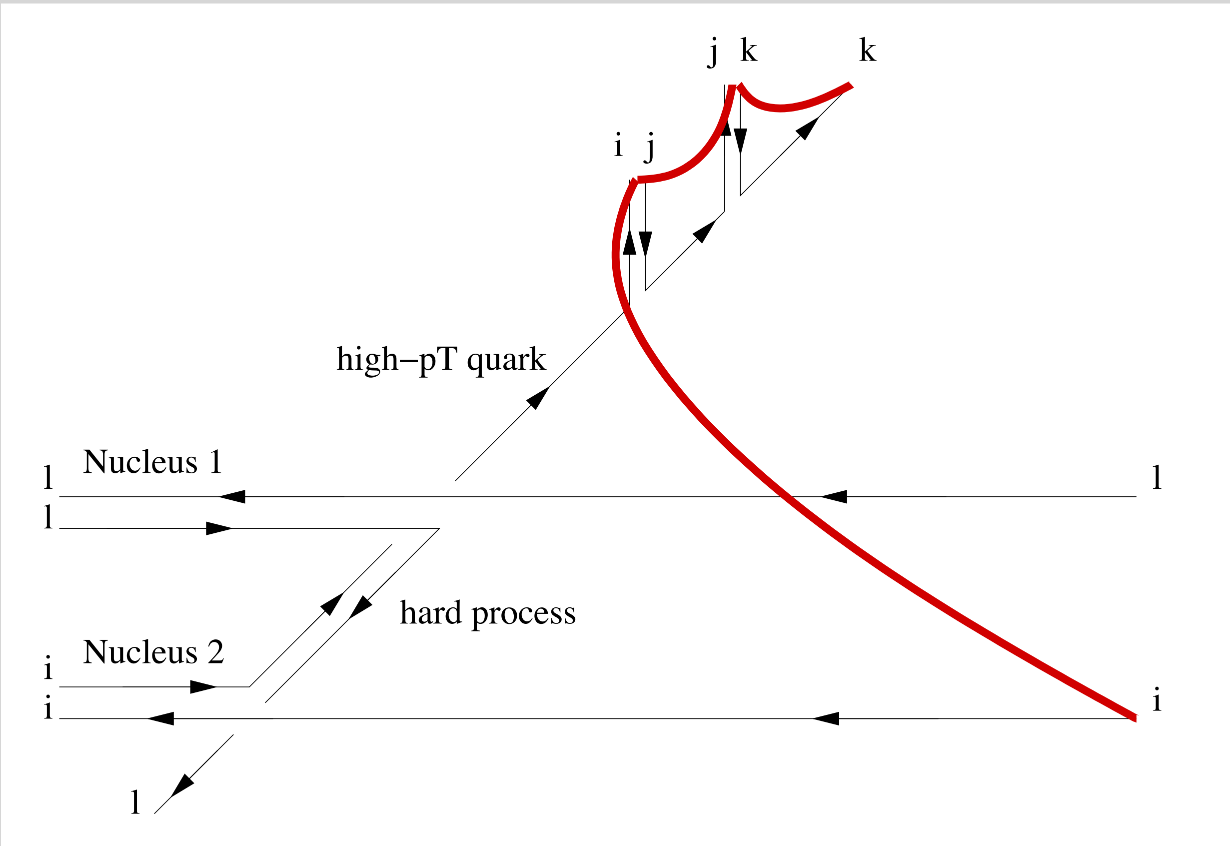
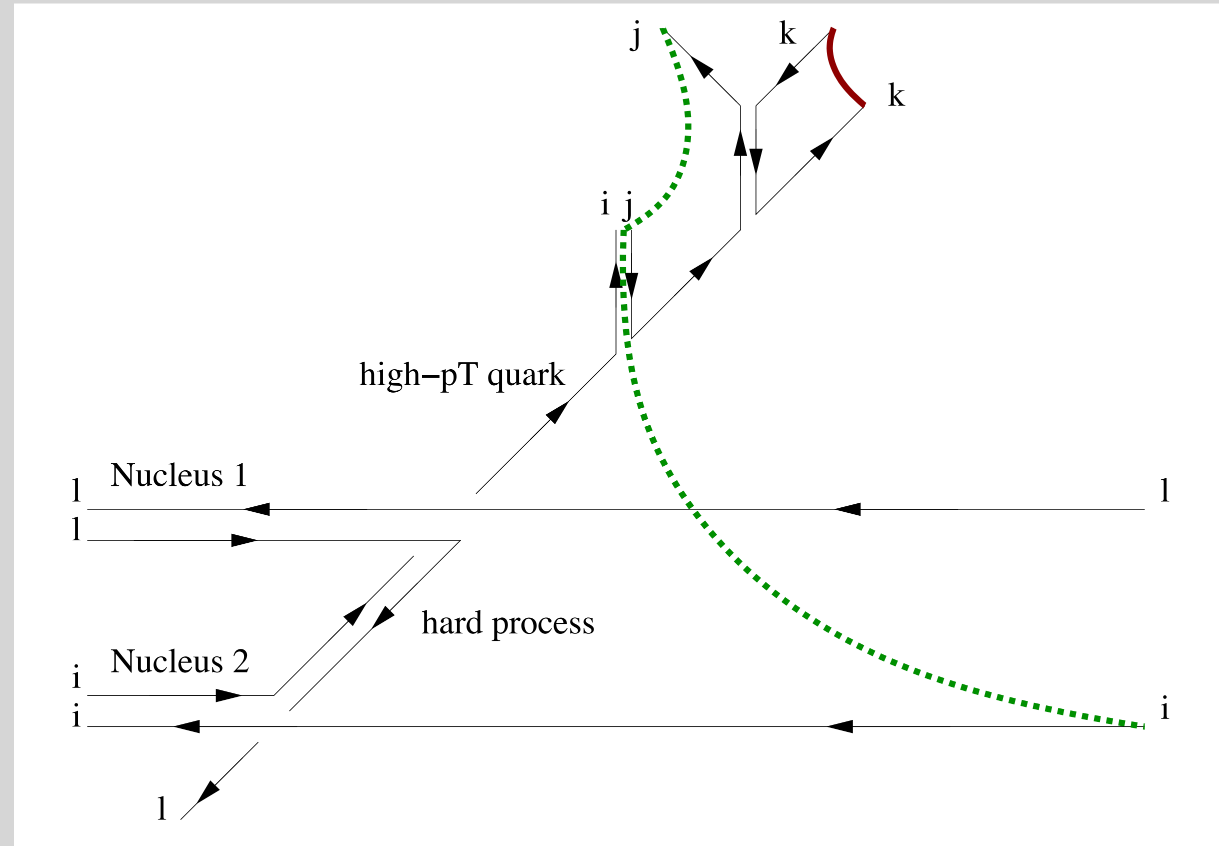
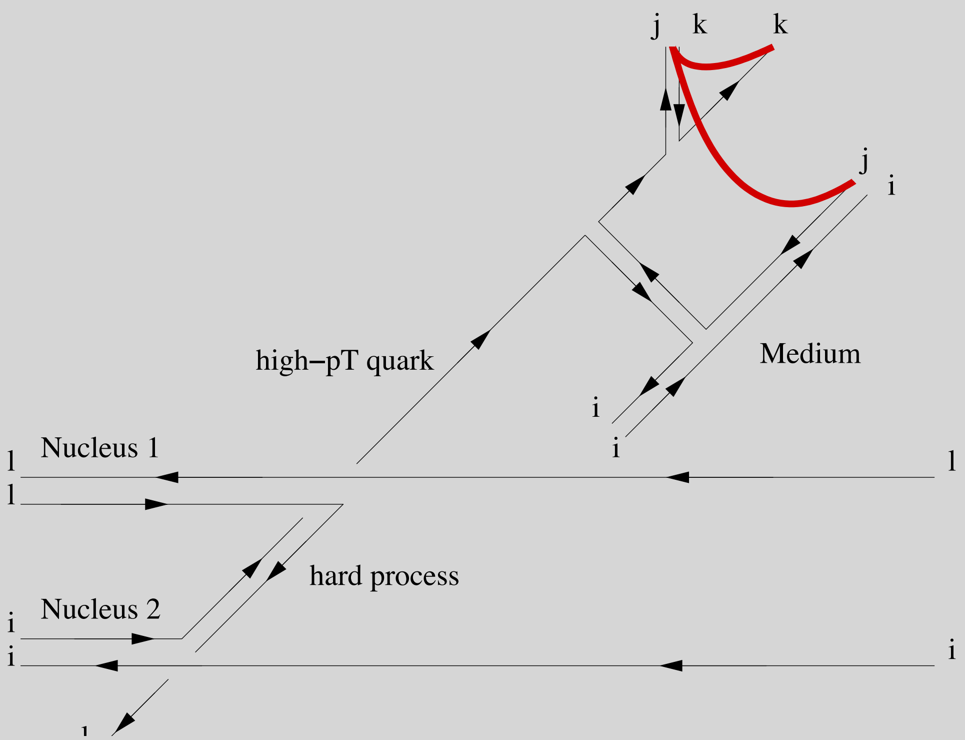


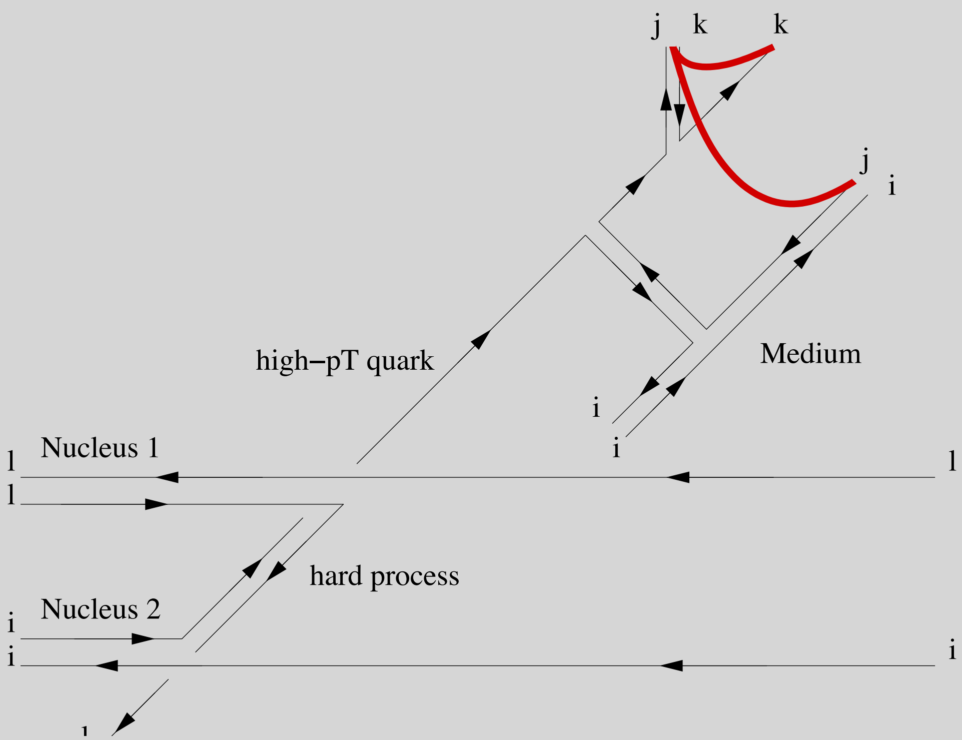

- most radiated gluons color-connected with projectile fragment
- only g → qqbar can break color connection
  - ↪ splitting with no soft enhancement [~ $z^2 + (1\text{-}z)^2$]
    - compare with g → gg [~ $(1\text{-}z)/z + z/(1\text{-}z) + z(1\text{-}z)$]

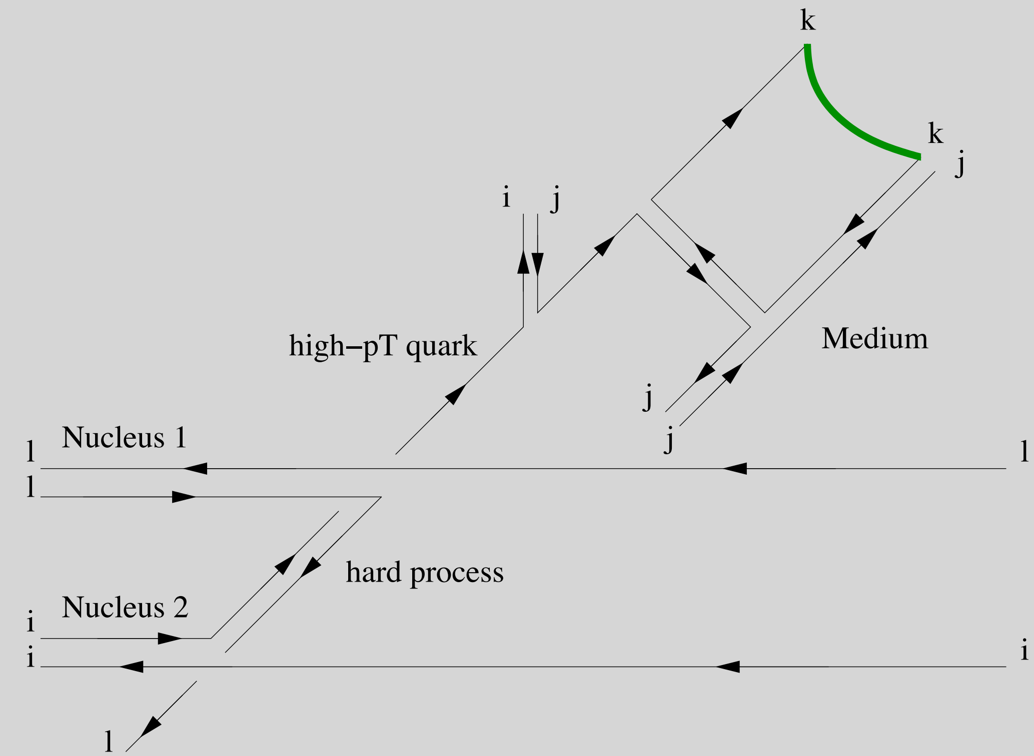
# color flow in the medium




- medium interaction prior to gluon emission
  - ↪ 'vacuum like' string from high to low [thermal] $p_t$ and including the gluon

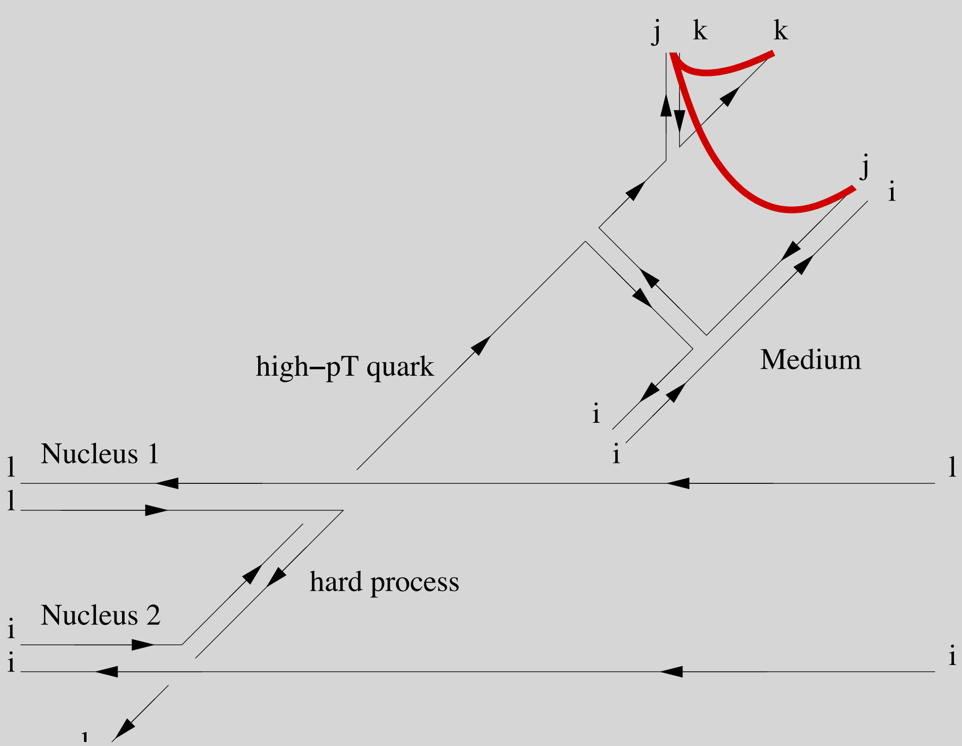
# color flow in the medium

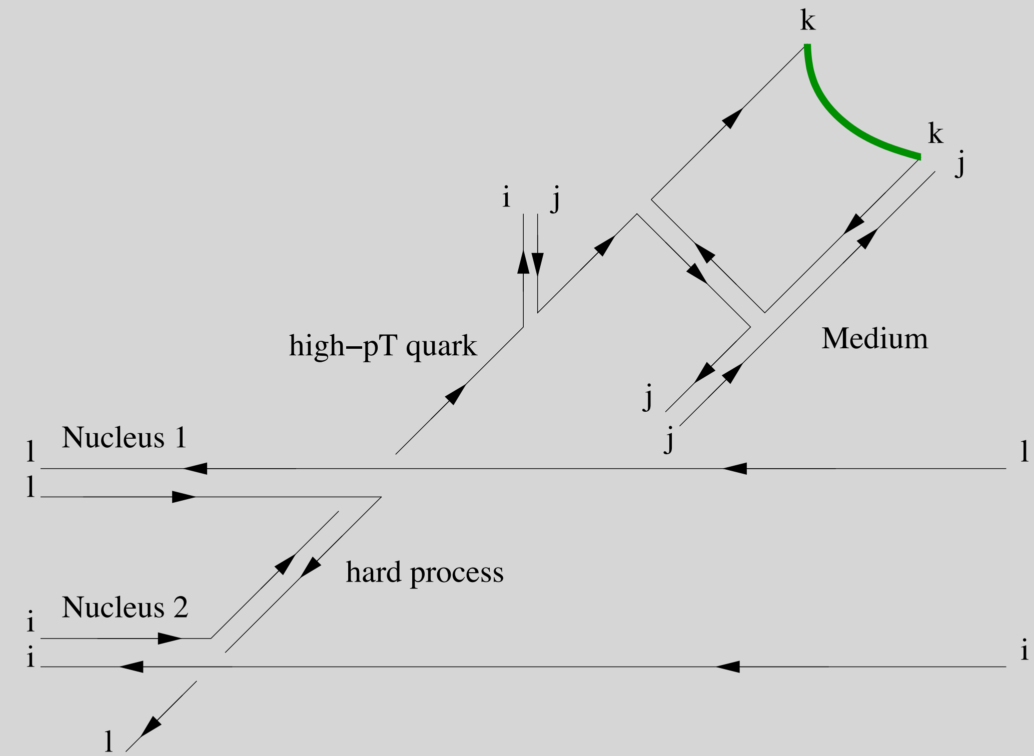



- medium interaction prior to gluon emission
  - ↪ 'vacuum like' string from high to low [thermal] $p_t$ and including the gluon
- medium interaction after gluon emission
  - ↪ gluon NOT in the leading parton string and thus decohered

# color flow in the medium

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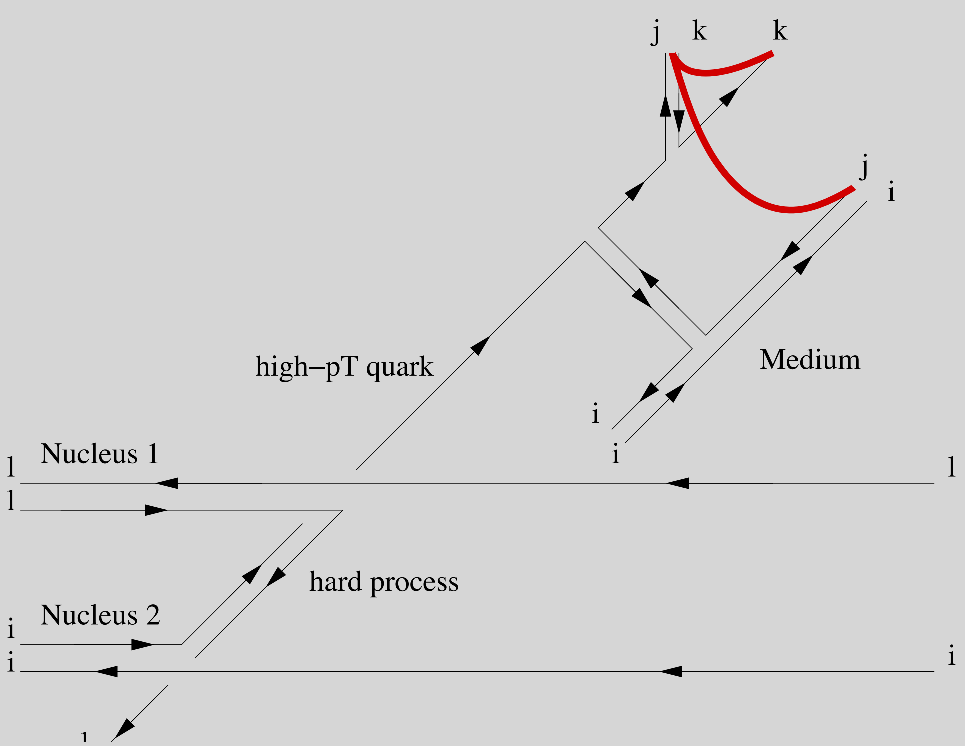
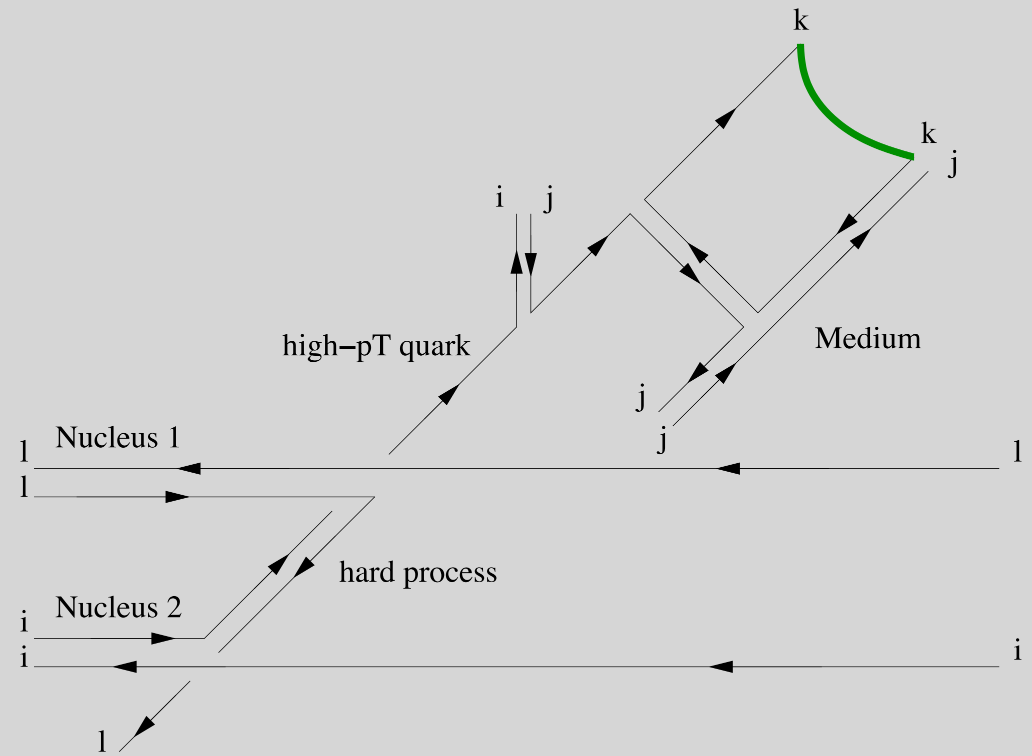
- medium interaction with gluon contributes to both channels

# color flow in the medium




- medium interaction prior to gluon emission
  - ↪ 'vacuum like' string from high to low [thermal] $p_t$ and including the gluon
- medium interaction after gluon emission
  - ↪ gluon NOT in the leading parton string and thus decohered
- medium interaction with gluon contributes to both channels
- obvious overlap with decoherence [antenna] calculations
  - colour differential antenna Beraudo, Milhano, Salgado

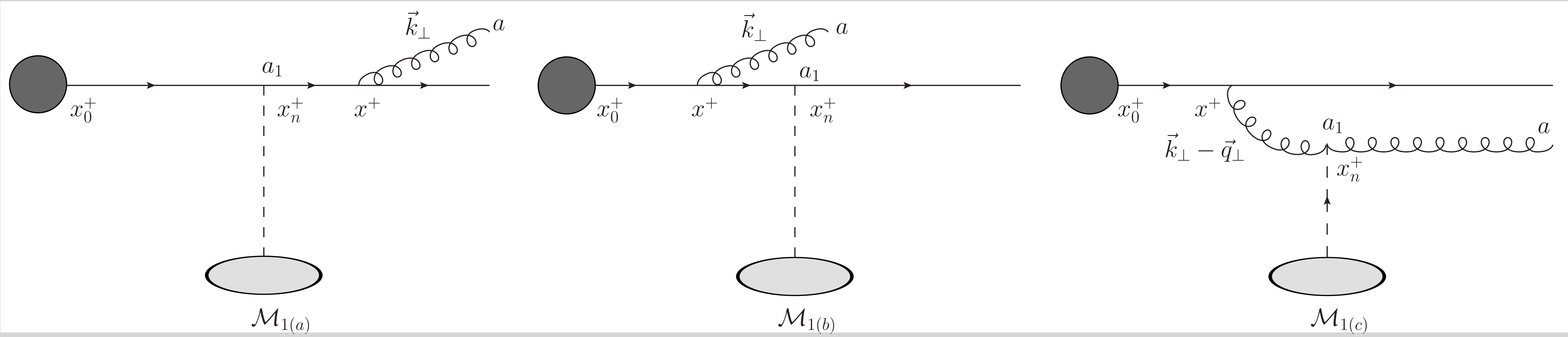
the existence of color modified channels

[those in which the emitted gluon is decohered]

leads to softnening of hadronic spectra

irrespectively of the strength of radiative energy loss

# N=1 opacity [colour inclusive]




$$\left\langle |\mathcal{M}_0 + \mathcal{M}_1 + \mathcal{M}_2^{\rm cont} + ...|^2 \right\rangle = |\mathcal{M}_0|^2 + \left\langle |\mathcal{M}_1|^2 \right\rangle + 2{\rm Re} \left\langle \mathcal{M}_2^{\rm cont} \mathcal{M}_0^* \right\rangle + ...$$

$$k^+ \frac{dI^{\rm med}}{dk^+\, d\mathbf{k}} = \zeta \frac{\alpha_s C_R}{\pi^2} \left\langle \left( (\mathbf{K_0} - \mathbf{K_1})^2 - \mathbf{K_0}^2 + \mathbf{K_1}^2 \right) \mathcal{T_I} \right\rangle$$

$$\mathbf{K_0} \equiv \mathbf{k}/\mathbf{k}^2$$

$$\mathbf{K_1} \equiv (\mathbf{k} - \mathbf{q})/(\mathbf{k} - \mathbf{q})^2$$

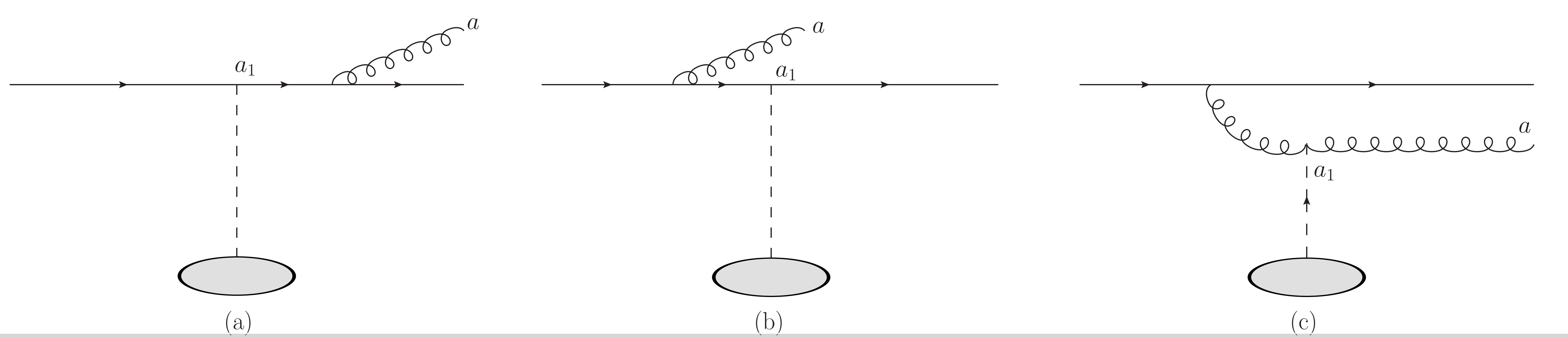
$$\mathcal{T_I} = \left( 1 - \frac{\sin\left(\omega_1^- L^+\right)}{\omega_1^- L^+} \right) = \begin{cases} 1 & \text{for} \quad 1/\omega_1^- \ll L^+ \\ 0 & \text{for} \quad 1/\omega_1^- \gg L^+ \end{cases}$$

- medium modifications only for quanta of sufficiently short formation time

$$1/\omega_1^- \equiv 2k^+ / \left(\mathbf{k} - \mathbf{q}\right)^2 \ll L^+$$

# colour differentially

- in the large $N_c$ limit it is straightforward to identify distinct colour channels which do not interfere




$$\mathcal{M}_0 + \mathcal{M}_1 + \mathcal{M}_2^{\text{cont}} = \mathcal{M}^{aa_1} + \mathcal{M}^{a_1 a} + \mathcal{M}^a$$

$$\mathcal{M}_1 = \mathcal{M}^{aa_1} + \mathcal{M}^{a_1 a}$$

$$\mathcal{M}_0 + \mathcal{M}_2^{\text{cont}} = \mathcal{M}^a$$

contact terms

- two distinct colour channels: 'vac like' $aa_1$ [FSR] & 'medium modified' $a_1 a$ [ISR]
- contact terms 'subtract' from no interaction case to preserve probability

# N=1 result

$$\langle |\mathcal{M}_1^{aa_1}|^2\rangle \sim \left\langle (\boldsymbol{K}_0-\boldsymbol{K}_1)^2+\boldsymbol{K}_1^2+2\boldsymbol{K}_1\cdot(\boldsymbol{K}_0-\boldsymbol{K}_1)\frac{\sin[\overline{\omega}_1 L^+]}{\overline{\omega}_1 L^+}\right\rangle$$

$$\langle |\mathcal{M}_1^{a_1 a}|^2\rangle \sim 2\left(1-\frac{\sin[\overline{\omega}_0 L^+]}{\overline{\omega}_0 L^+}\right)\boldsymbol{K}_0^2+2\left\langle\left(1-\frac{\sin[\overline{\omega}_1 L^+]}{\overline{\omega}_1 L^+}\right)\boldsymbol{K}_1^2\right\rangle$$
$$-\left\langle 2\left(1-\frac{\sin[\overline{\omega}_0 L^+]}{\overline{\omega}_0 L^+}-\frac{\sin[\overline{\omega}_1 L^+]}{\overline{\omega}_1 L^+}+\frac{\sin[(\overline{\omega}_1-\overline{\omega}_0)L^+]}{(\overline{\omega}_1-\overline{\omega}_0)L^+}\right)\boldsymbol{K}_0\cdot\boldsymbol{K}_1\right\rangle$$

$$2\mathrm{Re}\,\langle\mathcal{M}_2\mathcal{M}_0^*\rangle \sim -\boldsymbol{K}_0^2-2\left(1-\frac{\sin[\overline{\omega}_0 L^+]}{\overline{\omega}_0 L^+}\right)\boldsymbol{K}_0^2$$
$$-2\left\langle\left(\frac{\sin[\overline{\omega}_0 L^+]}{\overline{\omega}_0 L^+}-\frac{\sin[(\overline{\omega}_1-\overline{\omega}_0)L^+]}{(\overline{\omega}_1-\overline{\omega}_0)L^+}\right)\boldsymbol{K}_0\cdot\boldsymbol{K}_1\right\rangle$$

dependence on two distinct formation times [only one in the colour inclusive case]

$$k^+\frac{dI^{\mathrm{med}}}{dk^+\,dk_g}=C_R\,\frac{\alpha_s}{\pi^2}\,\frac{L^+}{\lambda_{\mathrm{el}}^+}\left\langle\left((\boldsymbol{K}_0-\boldsymbol{K}_1)^2-\boldsymbol{K}_0^2+\boldsymbol{K}_1^2\right)\left(1-\frac{\sin[\overline{\omega}_1 L^+]}{\overline{\omega}_1 L^+}\right)\right\rangle$$

# formation times

- additional formation time becomes relevant [final state gluon]

$$1/\omega_0^- \equiv 2k^+/\mathbf{k}^2$$

- look at phenomenologically most relevant limit
  - ↪ there is parton energy loss and final state gluon has short formation time

$$1/\omega_1^-\,, 1/\omega_0^- \ll L^+$$

$$k^+ \frac{dI^{\rm med}}{dk^+ d\boldsymbol{k}_g}\bigg|_{aa_1} \underset{\varpi_i L^+\to\infty}{\sim} \frac{C_F}{2}\frac{\alpha_s}{\pi^2}\frac{L^+}{\lambda_g^+}\left\langle(\boldsymbol{K}_0-\boldsymbol{K}_1)^2+\boldsymbol{K}_1^2\right\rangle\,,$$

$$k^+ \frac{dI^{\rm med}}{dk^+ d\boldsymbol{k}_g}\bigg|_{a_1 a} \underset{\varpi_i L^+\to\infty}{\sim} \frac{\alpha_s}{\pi^2}\left[\frac{L^+}{\lambda_g^+}\left(\frac{C_F}{2}\right)\left(\left\langle(\boldsymbol{K}_0-\boldsymbol{K}_1)^2\right\rangle+\left\langle\boldsymbol{K}_1^2\right\rangle\right)+\frac{L^+}{\lambda_q^+}C_F\boldsymbol{K}_0^2\right]$$

$$k^+ \frac{dI^{\rm med}}{dk^+ d\boldsymbol{k}_g}\bigg|_{a} \underset{\varpi_i L^+\to\infty}{\sim} \frac{C_F}{2}\frac{\alpha_s}{\pi^2}\frac{L^+}{\lambda_g^+}(-3\boldsymbol{K}_0^2)\,.$$

medium modified channel [gluon decohered]
accounts for more than half the cases

# a curious kinematic window

$$1/\omega_0^- \ll L^+ \ll 1/\omega_1^-$$

$$k^+ \frac{dI^{\rm med}}{dk^+ d\boldsymbol{k}_g}\bigg|_{aa_1} \underset{\overline{\omega}_1 L^+ \to 0}{\overset{\overline{\omega}_0 L^+ \to \infty}{\sim}} \frac{L^+}{\lambda_q^+} C_F \frac{\alpha_s}{\pi^2} \boldsymbol{K}_0^2 \,,$$

$$k^+ \frac{dI^{\rm med}}{dk^+ d\boldsymbol{k}_g}\bigg|_{a_1 a} \underset{\overline{\omega}_1 L^+ \to 0}{\overset{\overline{\omega}_0 L^+ \to \infty}{\sim}} 2\frac{L^+}{\lambda_q^+} C_F \frac{\alpha_s}{\pi^2} \boldsymbol{K}_0^2 \,,$$

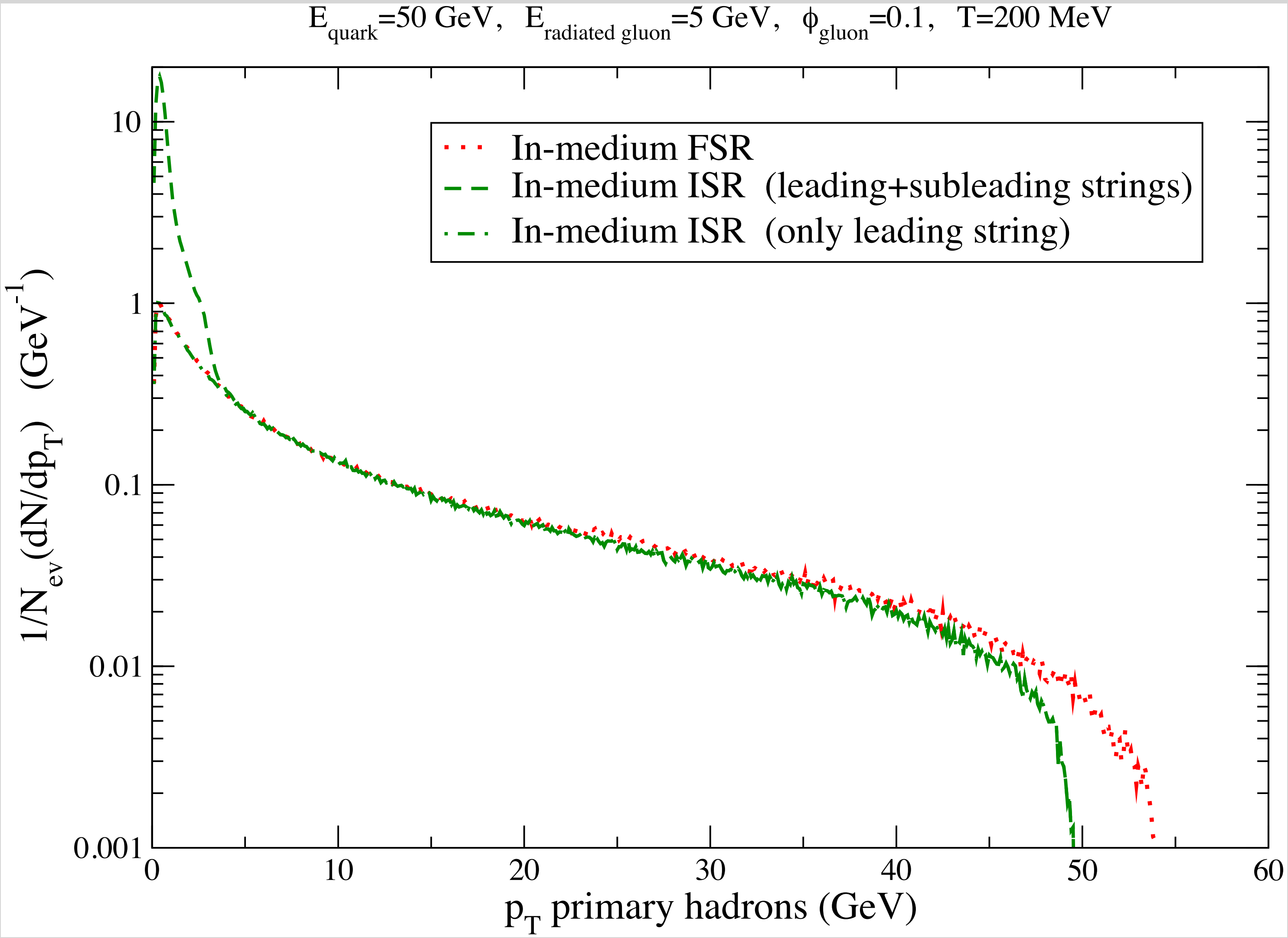
$$k^+ \frac{dI^{\rm med}}{dk^+ d\boldsymbol{k}_g}\bigg|_{a} \underset{\overline{\omega}_1 L^+ \to 0}{\overset{\overline{\omega}_0 L^+ \to \infty}{\sim}} -3\frac{L^+}{\lambda_q^+} C_F \frac{\alpha_s}{\pi^2} \boldsymbol{K}_0^2 \,.$$

- color inclusive medium-induced radiation vanishes

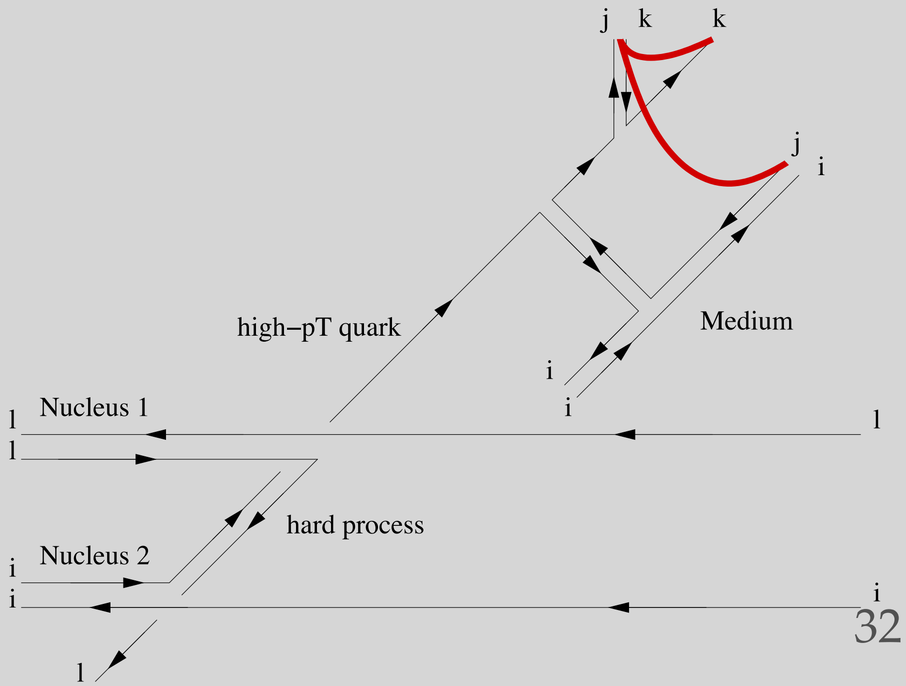
- HOWEVER, 2/3 of medium induced gluons [compensated by depletion of vacuum radiation] are in a color modified channel

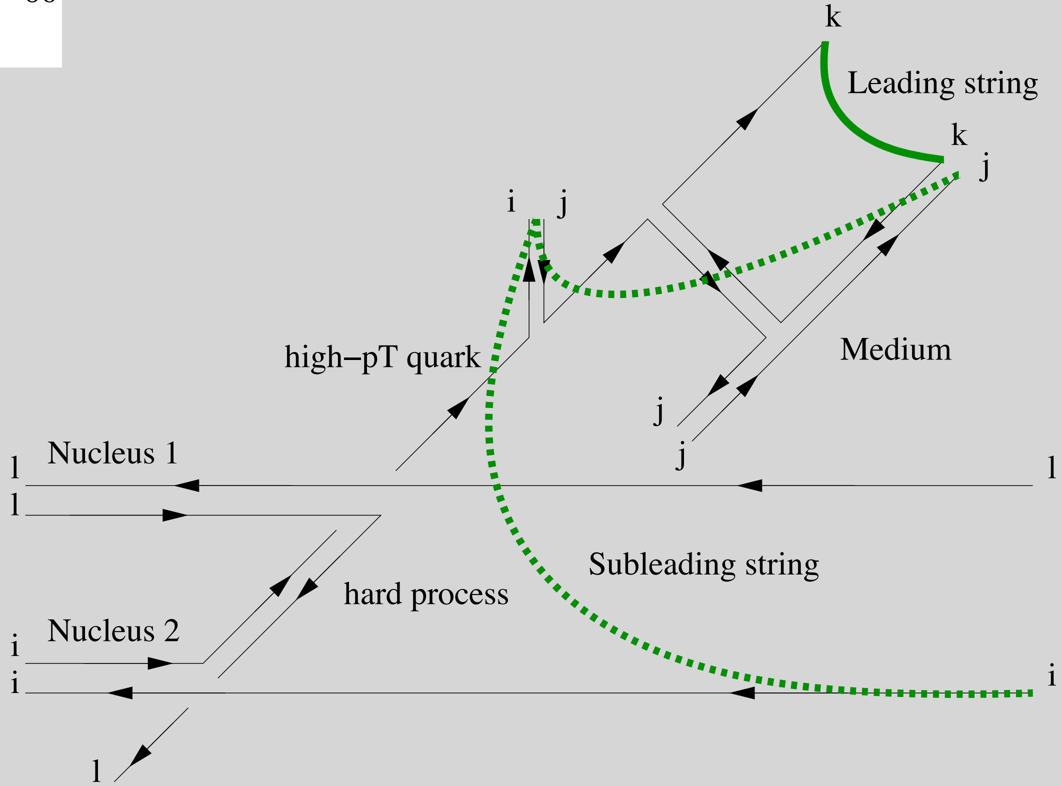
  ↪ resulting hadrons will be softened...

# hadronizing parton showers with medmod flow



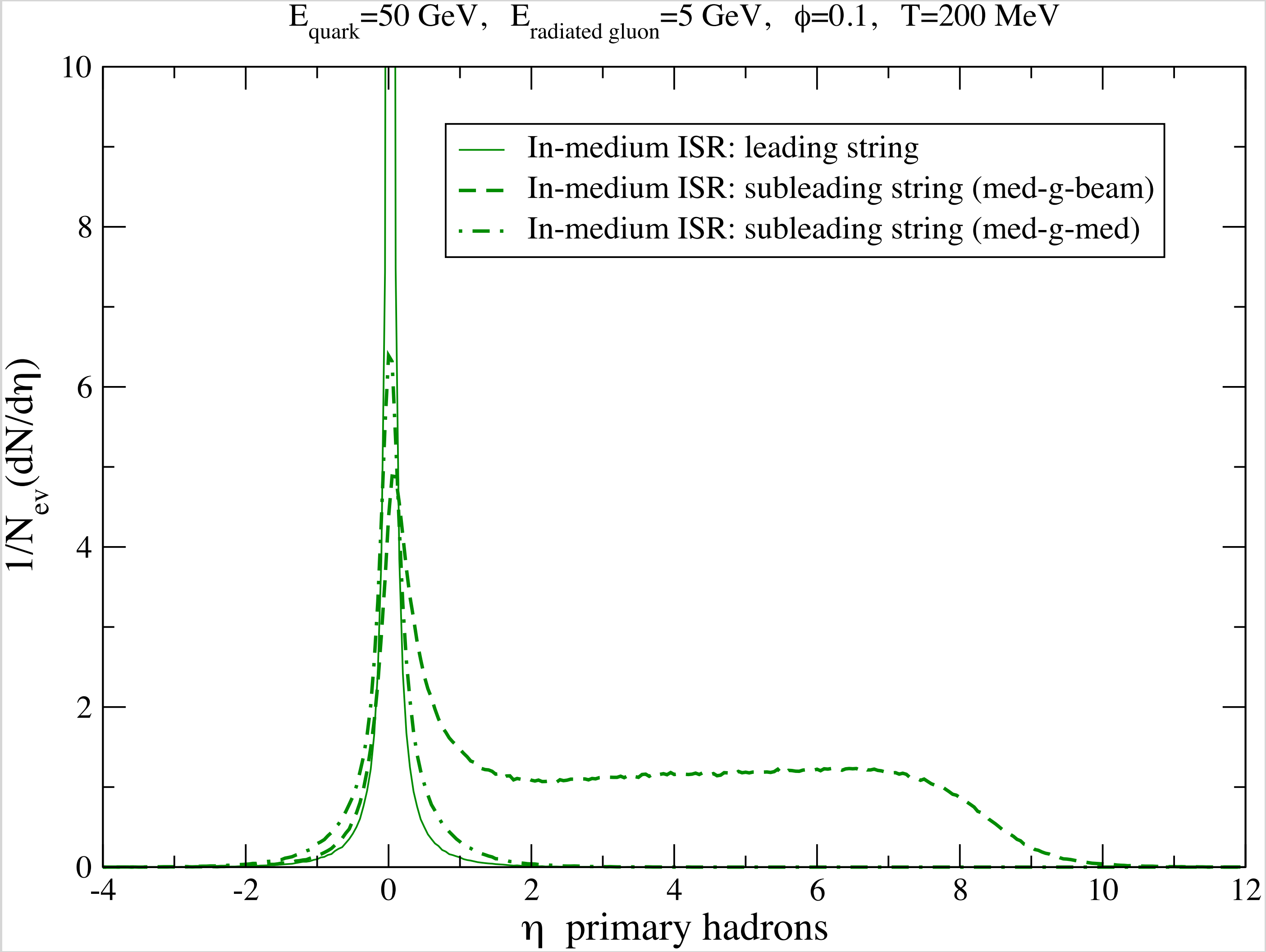

- medium modified channel [ISR] leads to softer spectrum
- 'missing' content recovered from sub-leading string at very low $p_t$ and with high multiplicity
- unmodified in wide range [FF]



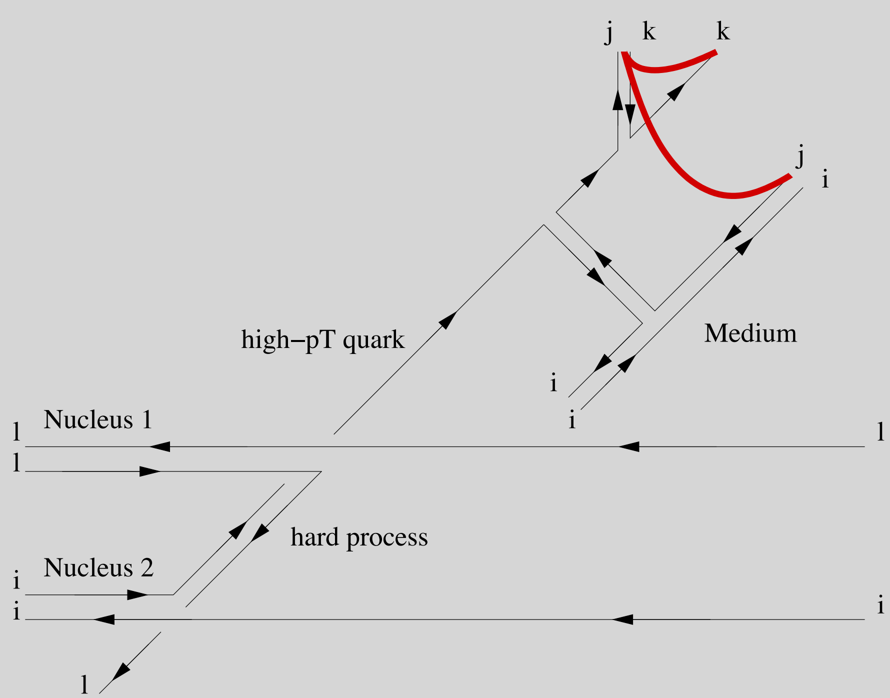



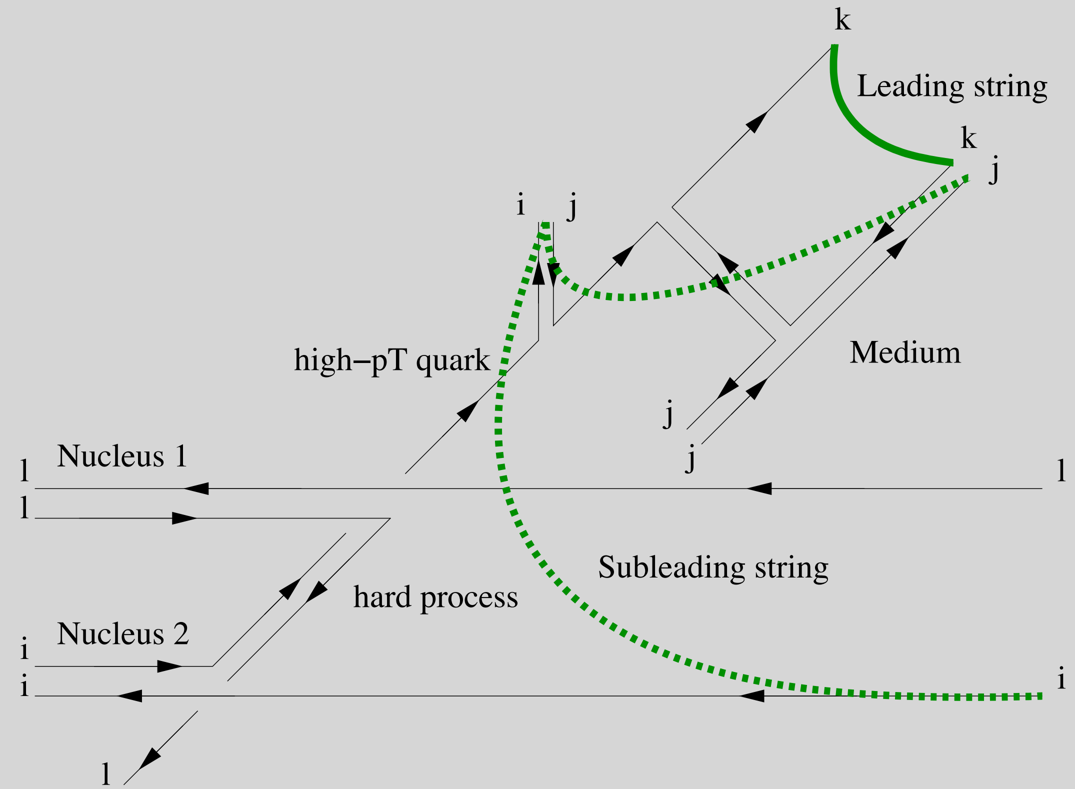
# hadronizing parton showers with medmod flow





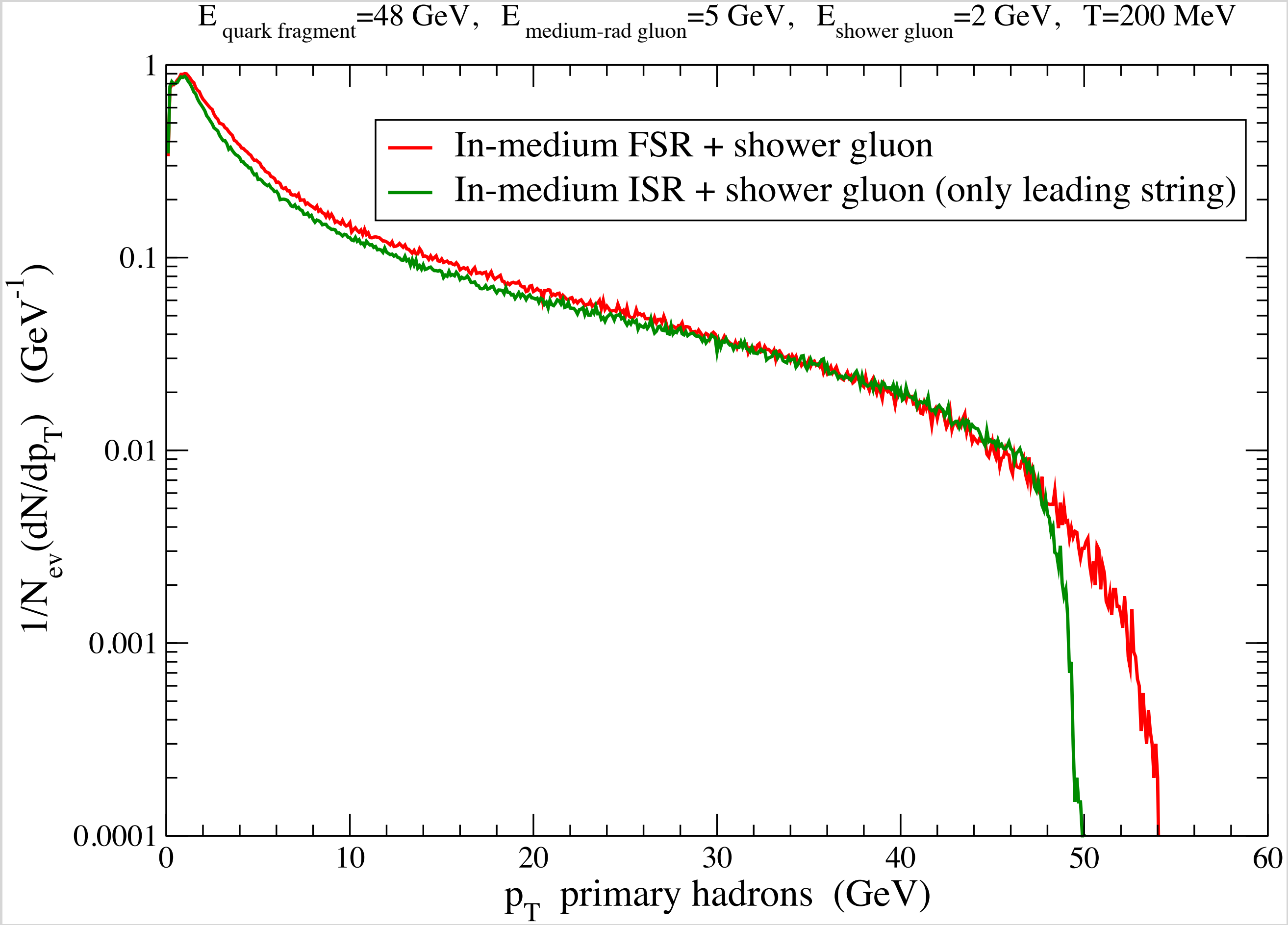

- hadrons from subleading string distributed in wide rapidity range

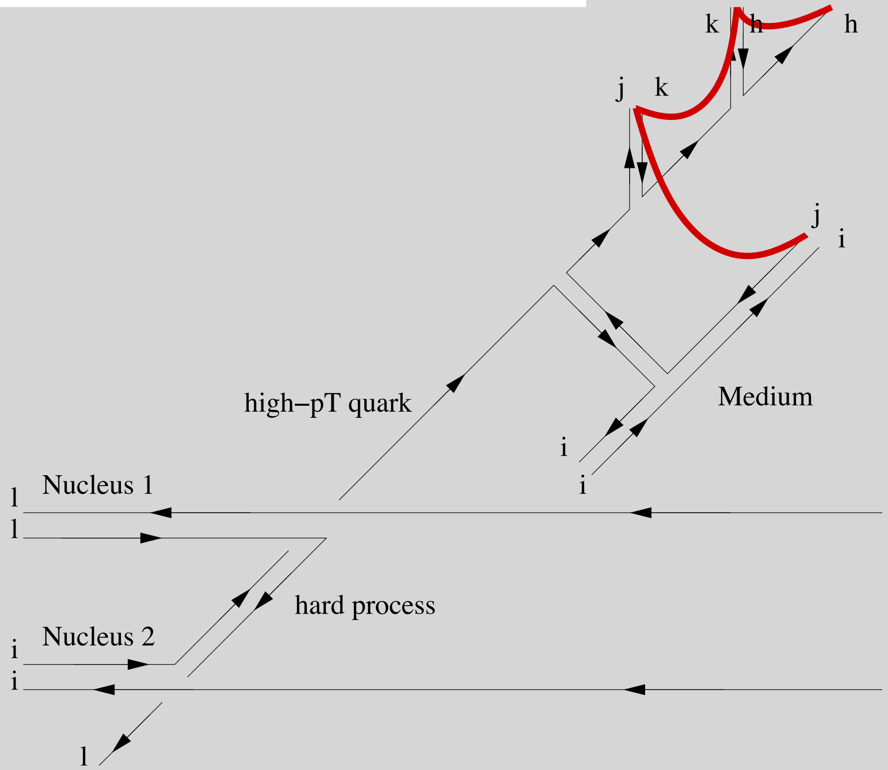


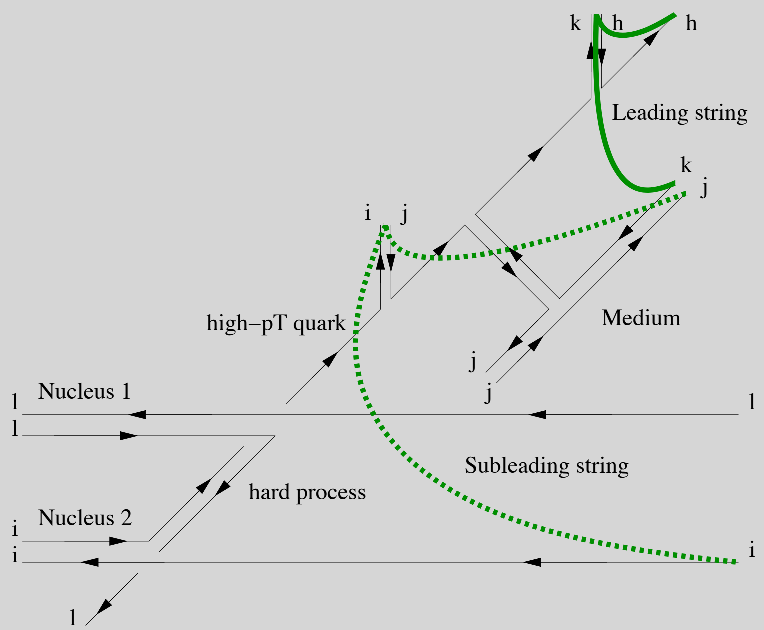



# further emissions outside





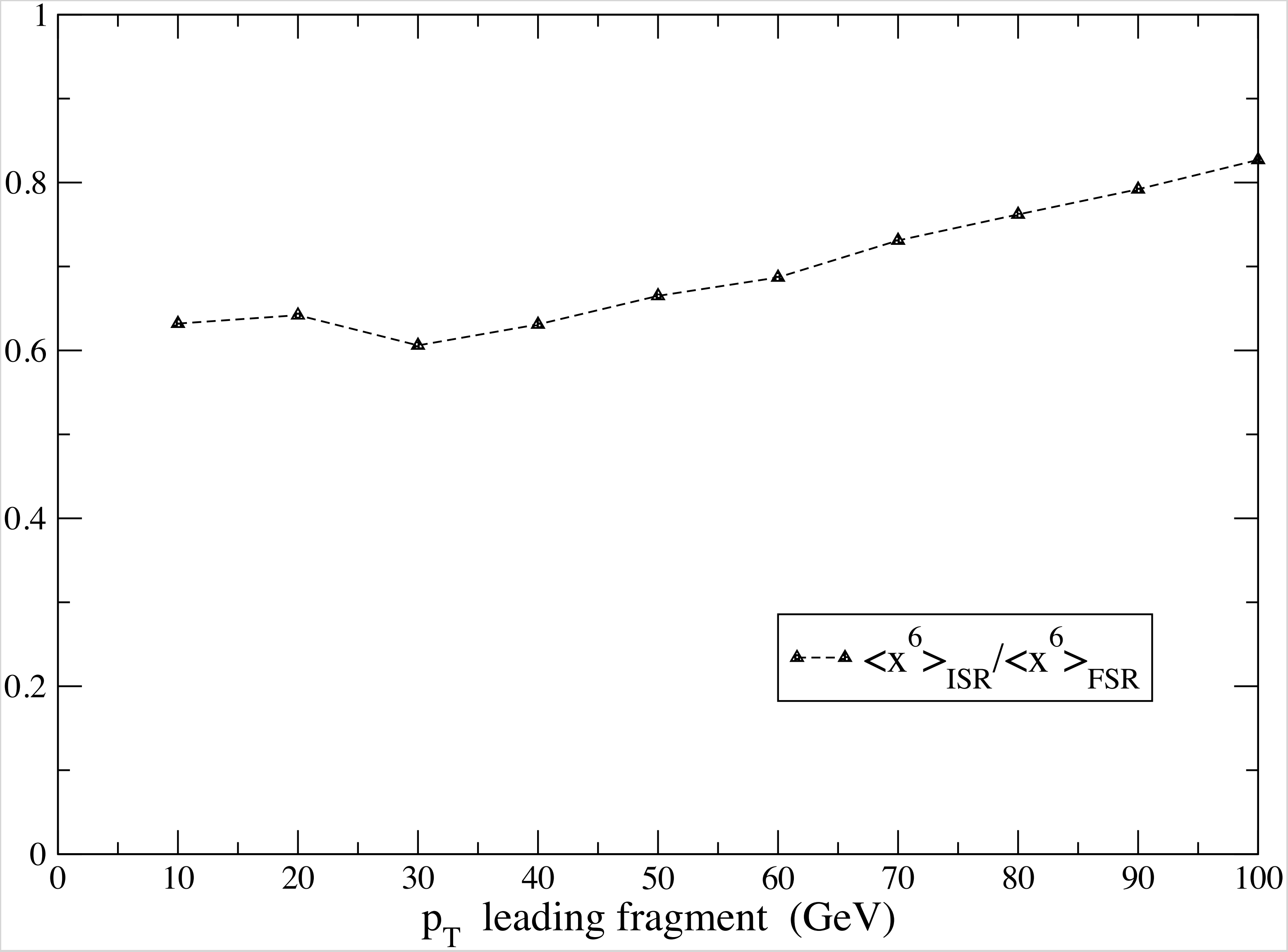



# single hadron spectra



- single hadron spectra sensitive to the hard tail of the fragmentation function
  - ↪ FF convoluted with steeply falling spectra, thus sensitive to higher moments
  - ↪ for same parton energy loss, colour connections can be significant source of suppression [contribution to $R_{AA}$]



*very appealing pQCD based overall picture*

**BUT**

*can we confidently exclude a conceptually different scenario in which strong jet-medium coupling effects drag energy from all jet 'propagators' and 'vertices' remain pQCD like ???*

Can Gulhan, Casalderrey-Solana, Milhano, Pablos, Rajagopal

# are there quasi-particles ?



- do hard probes have finite mean free paths?
  - ↪ all pQCD based approaches assume so
  - ↪ in AdS/CFT [strong coupling] constructions
    - heavy quarks propagate without mean free path :: lost energy goes into Mach cone and wake
    - light quarks/jets propagate towards thermalization :: no collinear structure [hedgehog jets]

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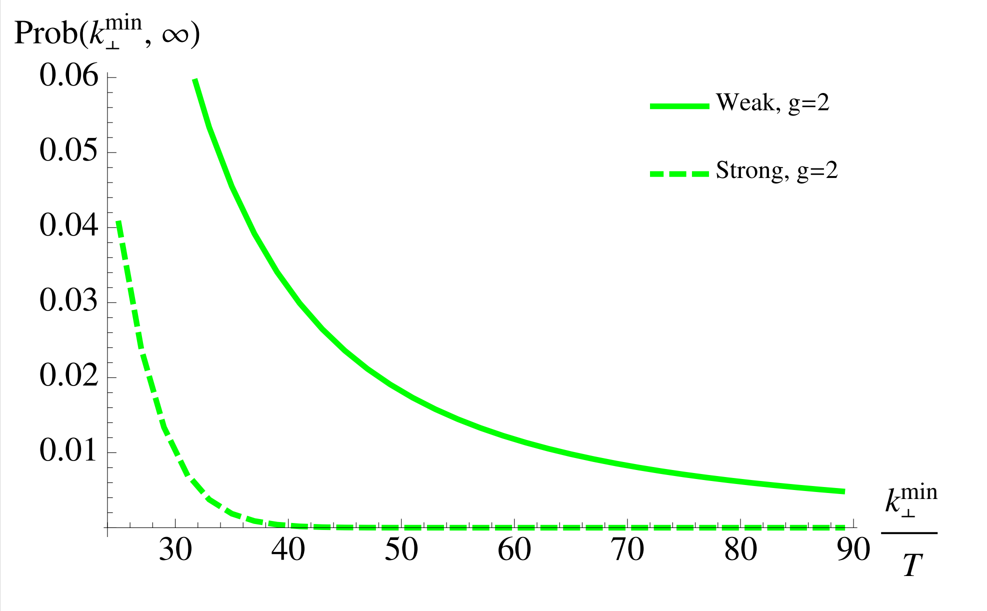
- probability of large broadening larger for pQCD [$\sim 1/k_t^4$] than for strong coupled [gaussian]
  - ↪ rare but measurable events

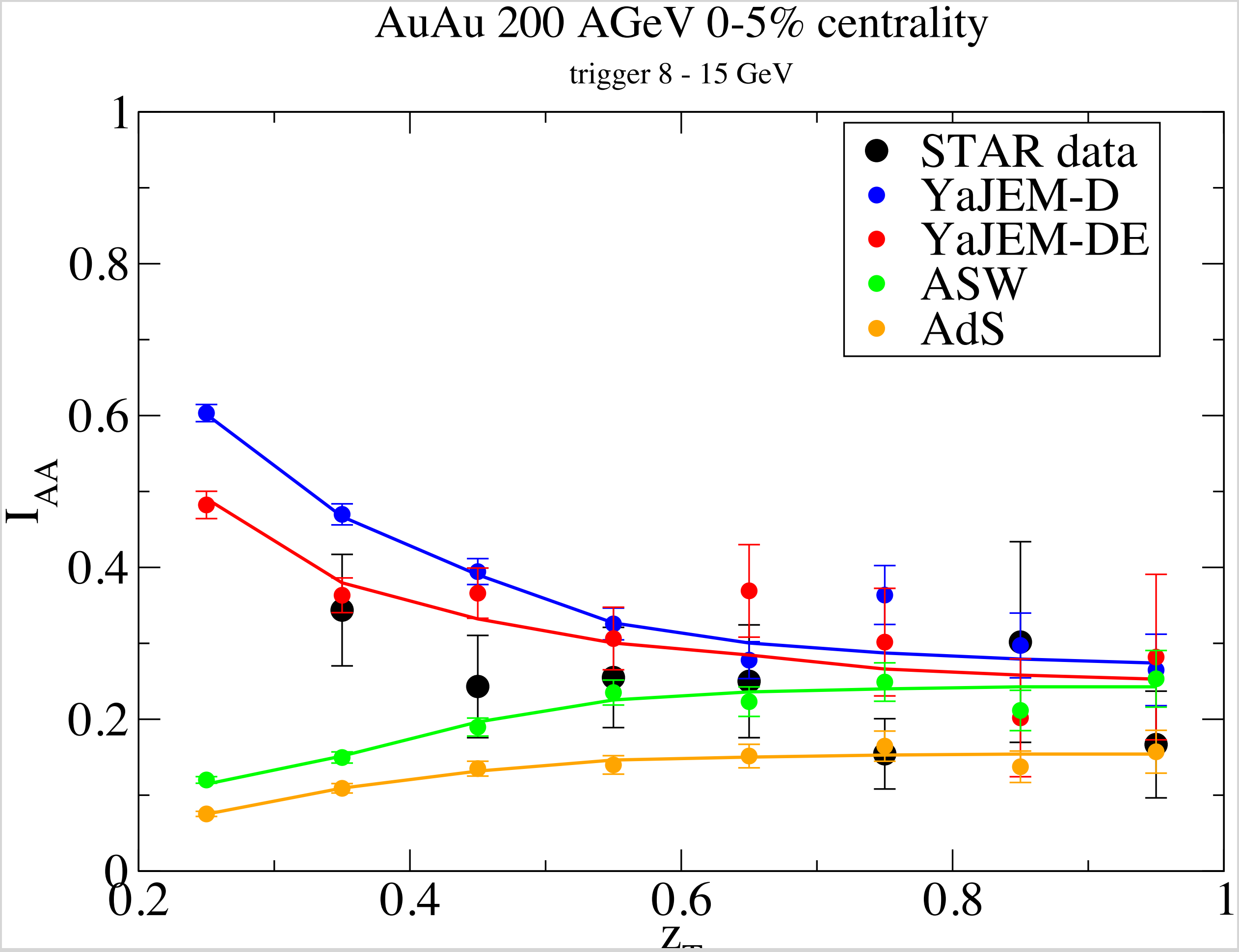



Eramo, Lekaveckas, Liu, Rajagopal [1211.1922]

# the truth is in data



- theory validation [constraining dynamics] requires
  - ↪ multi-observable description [$R_{AA}$, $I_{AA}$ (jets, hadrons), jet asym, shapes, FFs, ...]
    - understand specific biases [pathlength, etc.] and sensitivities to dynamical mechanisms



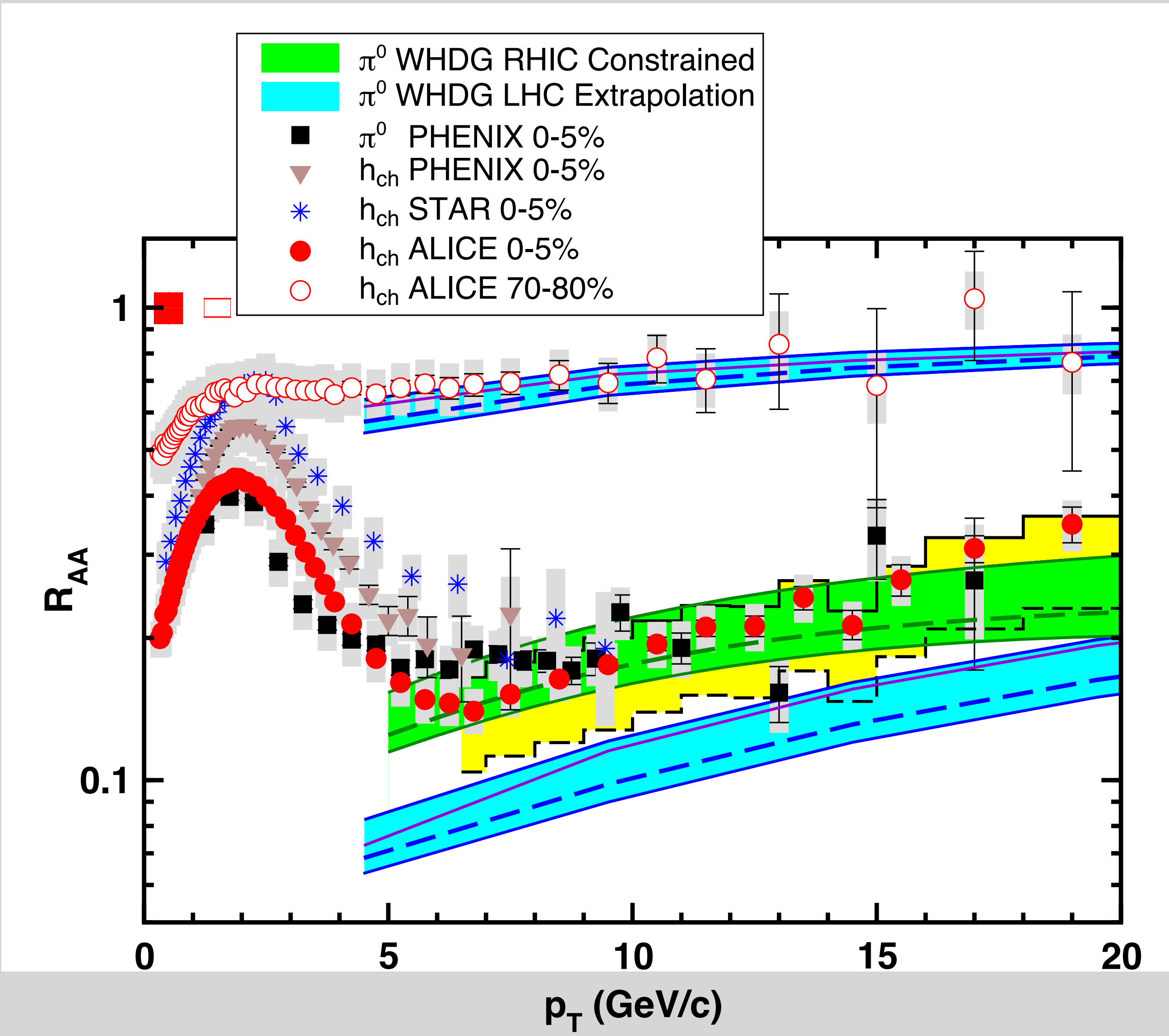

**sensitivity of $I_{AA}$ to weight of elastic energy loss**

Renk [1110.2313,1112.2503,1202.4579.1212.0646]

# consistency



- theory validation [constraining dynamics] requires
  - ↪ RHIC to LHC description

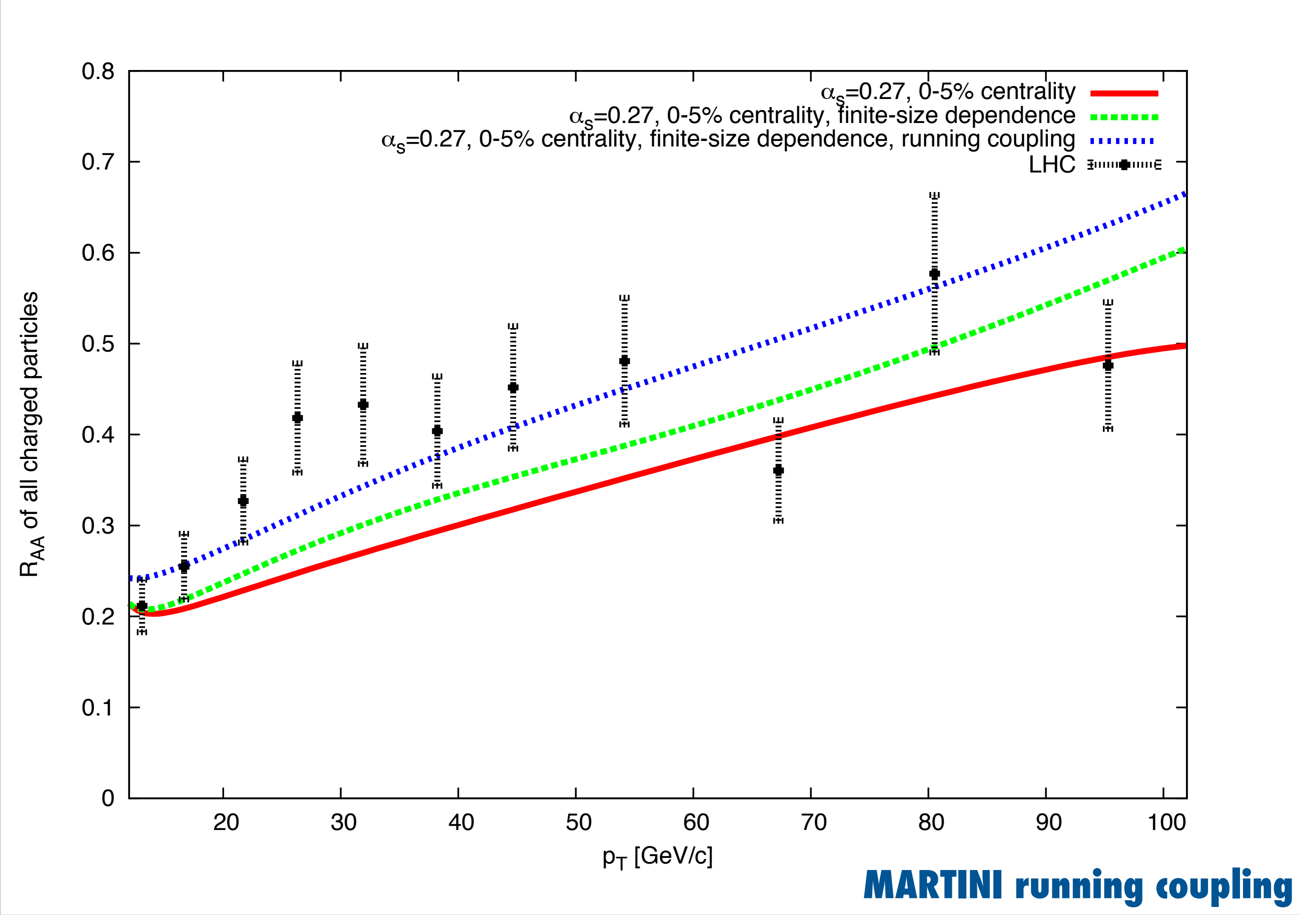



Gyulassi, Horowitz [1104.4958]
Betz, Gyulassi [1201.0281]

# consistency



- theory validation [constraining dynamics] requires
  - ↪ ...
  - ↪ assessment of importance of NLO corrections




  - ↪ jet reconstruction [as in exp]
  - ↪ response of calculables to background
  - ↪ detector response [exp unfold/ph fold :: we need to decide]

Cacciari, Salam, Soyez, Quiroga [1209.6086]
Apolinário, Armesto, Cunqueiro [1211.1161]

# outlook

- in just over ten years jet quenching has gone from ‘an idea’ to a robust experimental reality
- recent efforts have established a clear pathway to conclude [soon] the ‘establish the probe’ programme
- recent efforts have readied the necessary [embedding] tools for realistic medium probing

- pA as complementary baseline [CNM]

- time to think hard about ‘new’ observables
  - direct sensitivity to formation times
  - sensitivity to different time and spacial scales
  - isolation of ‘pure’ sample of strongly modified jets

# IS2013

**International Conference on the Initial Stages in High-Energy Nuclear Collisions**

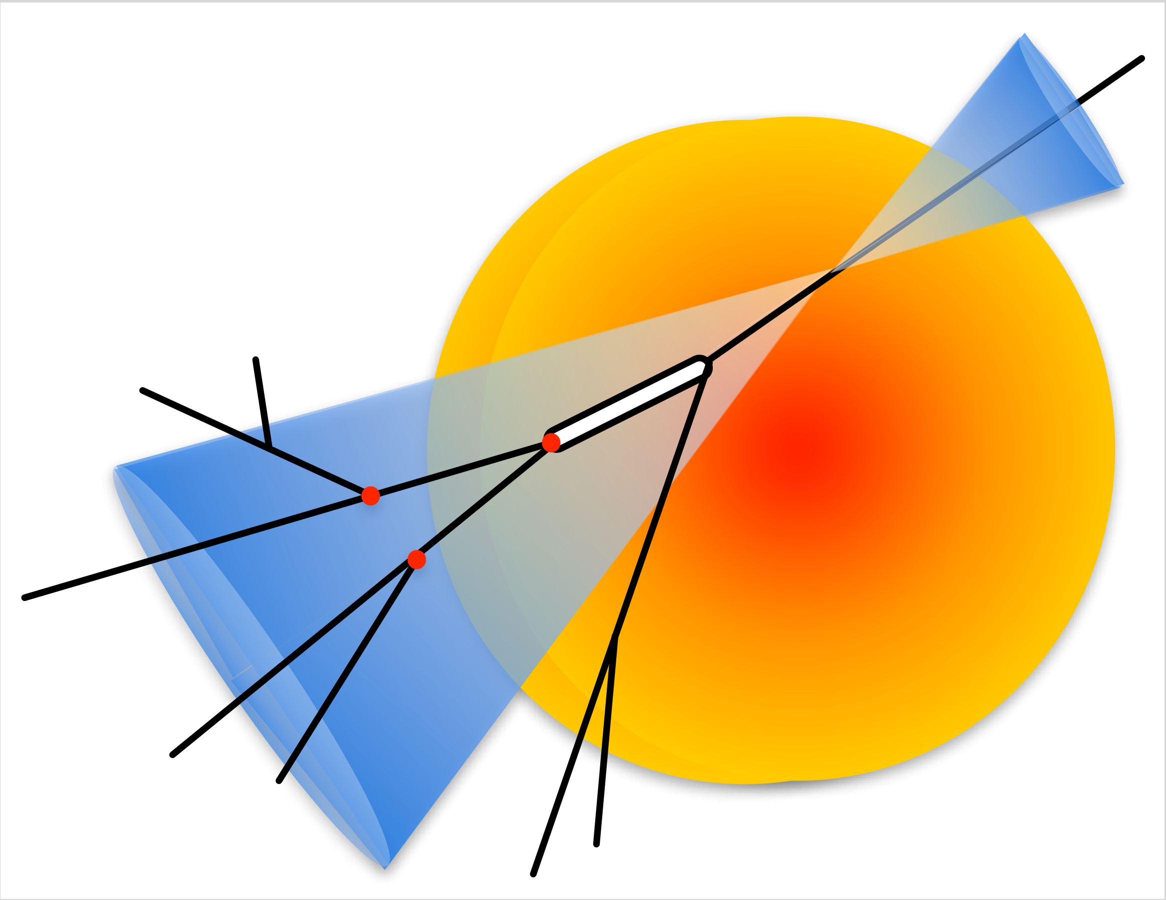
## 8-14 September, Illa da Toxa (Galicia-Spain)

Abstract submission is open - send your abstracts before the **deadline July 7th 2013**

http://igfae.usc.es/is2013/

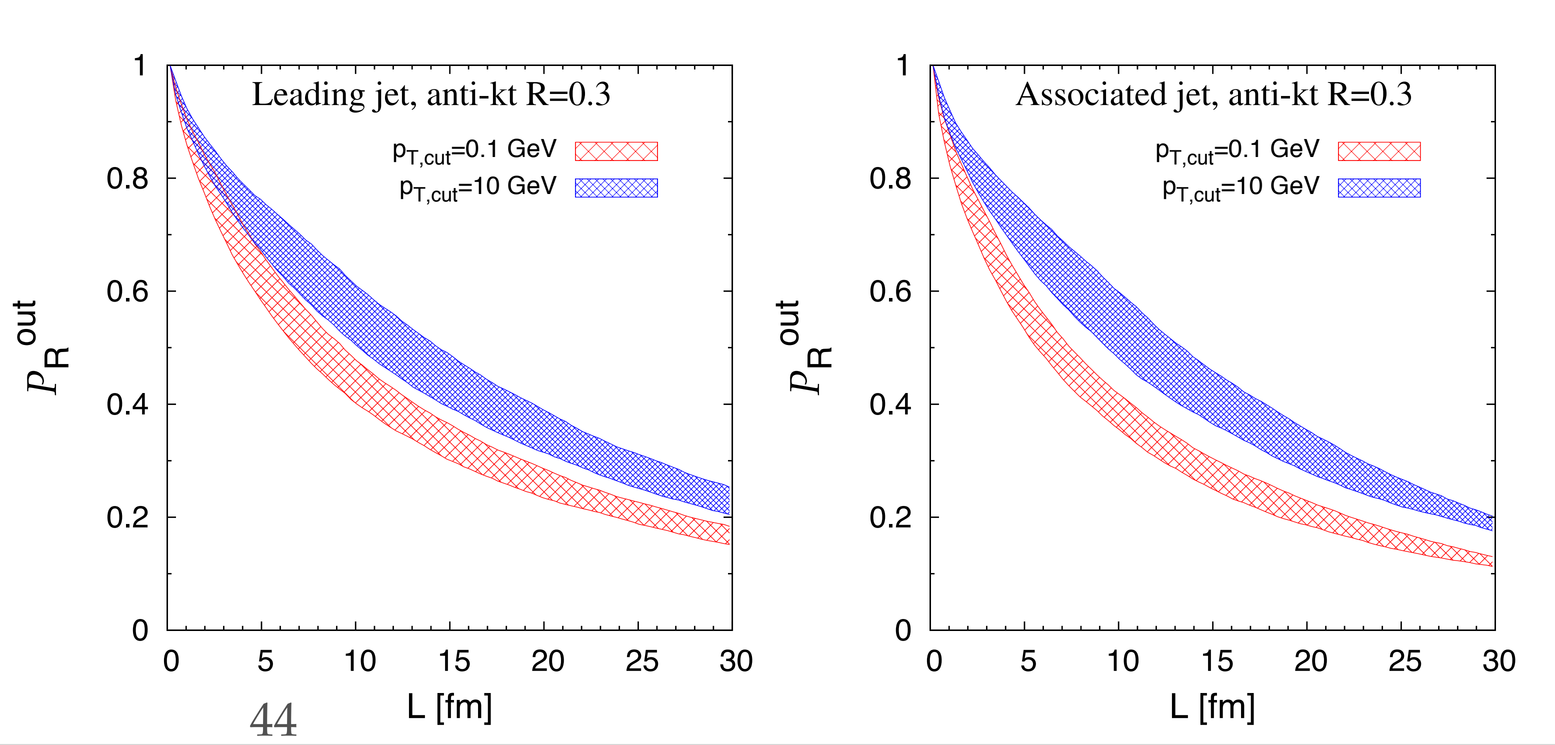
# BACKUPS

# where does hadronization happen ?



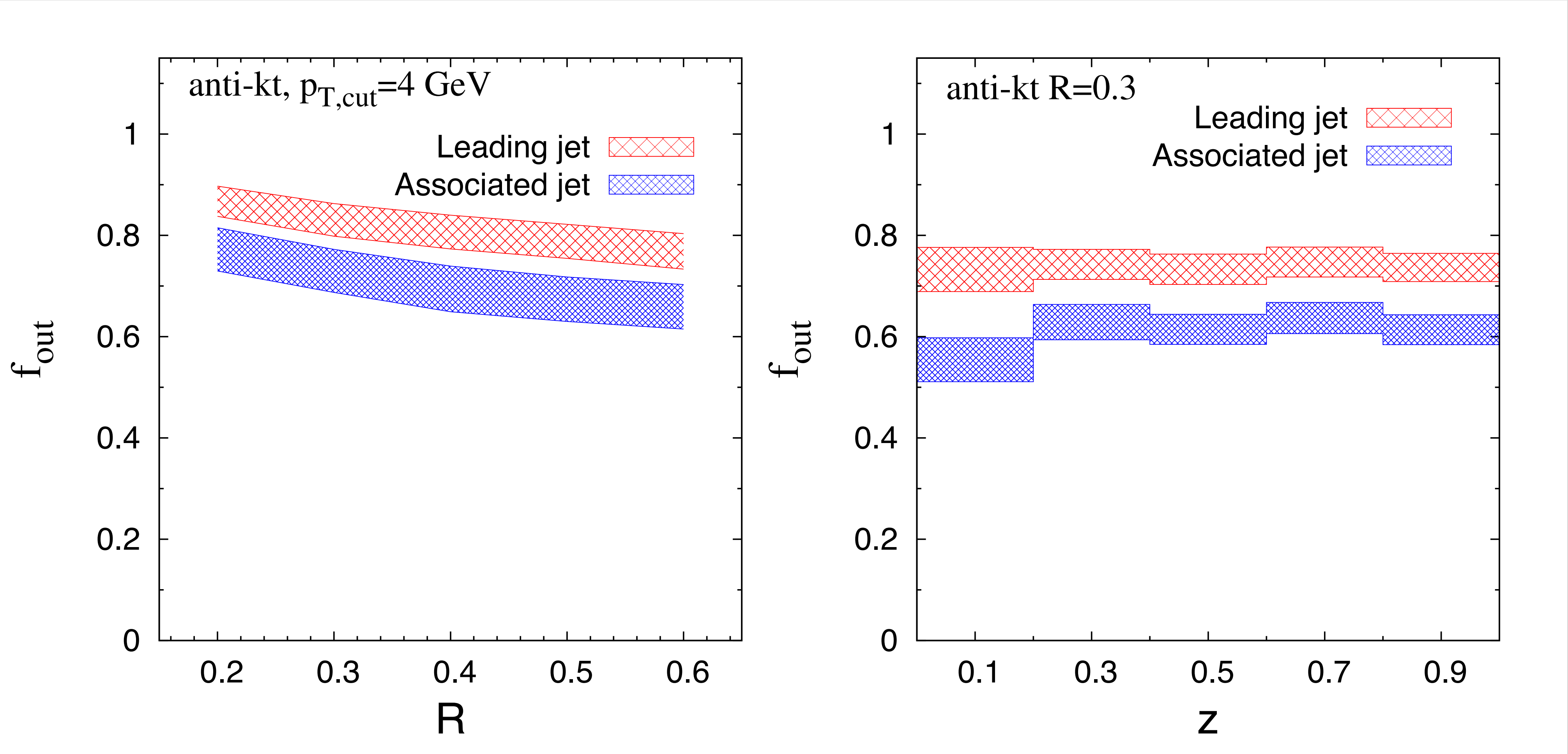
- unmodified parton shower, embedded in semi-realistic collision geometry
  - ↪ large fraction of splittings in history of fragments in reconstructed jet occur outside the medium
  - ↪ hadronization, which follows last splittings, is arguably outside [and more so for high-$p_t$ fragments]

$$\tau_f = 2\frac{E}{Q^2} \qquad \tau_S = \sum_{i=1}^{n} \tau_f(i)$$

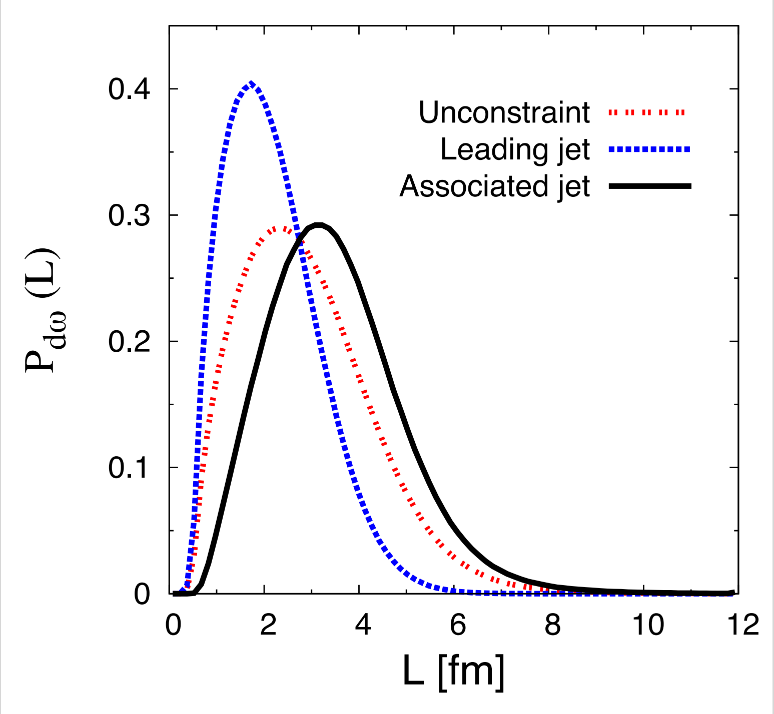



Casalderrey-Solana, Milhano, Quiroga-Arias [1111.0310]

# where does hadronization happen ?

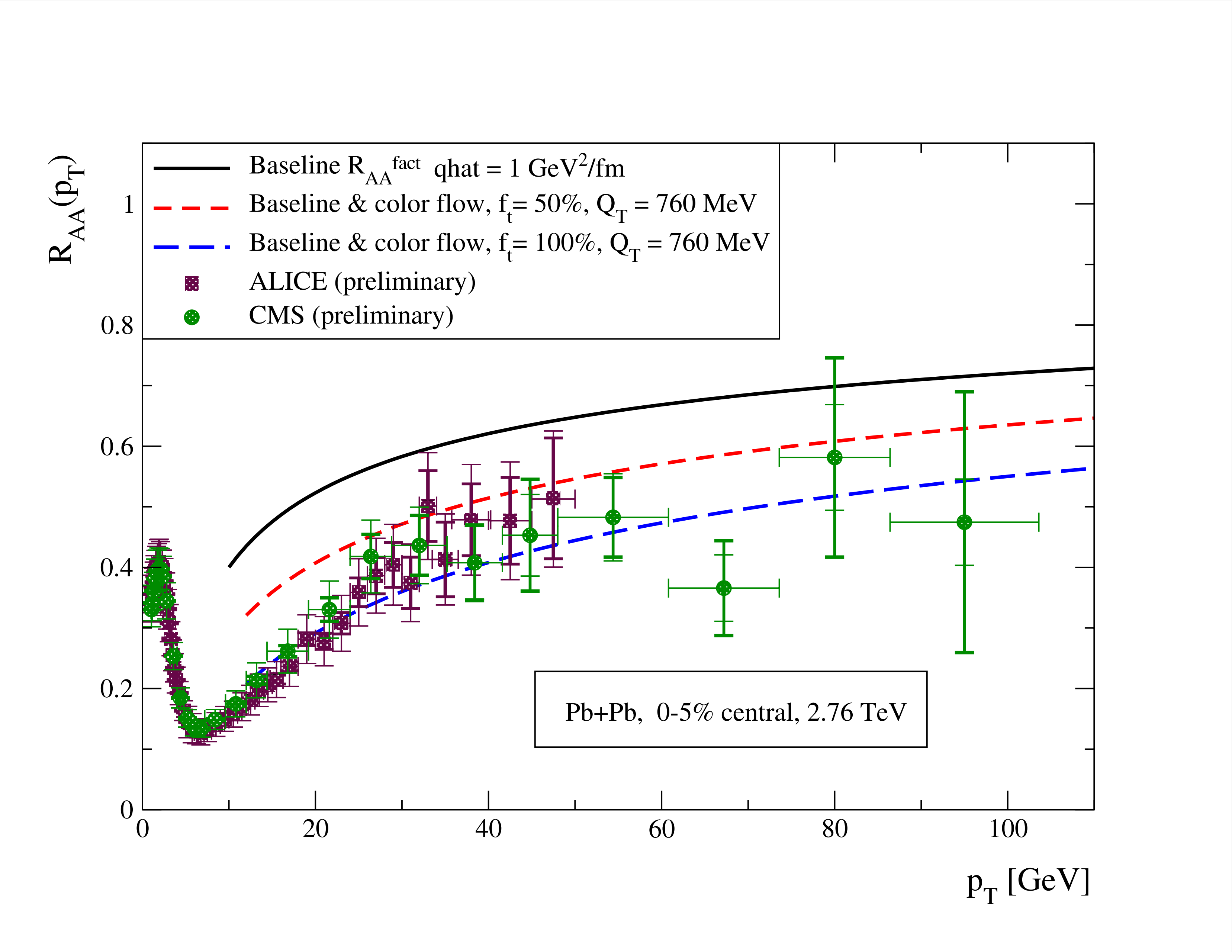



- mild dependence on jet reconstruction radius
- mild dependence on fragment momentum fraction
- induced radiation can/will shift splittings to earlier times



# illustration






- data to guide the eye
  - ↪ ASW RHIC computation with low qhat

# #2 probing the medium

meaningful determination of medium properties

requires embedding of faithful jet dynamics

in realistic medium description

[partly constrained elsewhere]

# realistic medium



- establish relationship between properties of realistic medium and parameters effecting jet quenching
  - first principle [SU(2) lattice] computation of

Majumder [1202.5295]

$$\hat{q} = \frac{4\pi^2\alpha_s}{N_c}\int\frac{dy^- d^2y_\perp d^2k_\perp}{(2\pi)^3} e^{i\frac{k_\perp^2 y^-}{2q^-} - ik_\perp\cdot y_\perp} \left\langle P \right| \mathbf{Tr}\left[F_\perp^{a\,+\mu}(y^-, y_\perp)U^\dagger(\infty^-, y_\perp; 0^-, y_\perp)\right.$$
$$\left. T^\dagger(\infty^-, \vec{\infty}_\perp; \infty^-, y_\perp)T(\infty^-, \infty_\perp; \infty^-, 0_\perp U(\infty^-, 0_\perp; 0^-, 0_\perp)F^{b\,+}_{\perp,\mu}\right]\left| P \right\rangle$$

  - for a weakly coupled medium

Eramo, Lekaveckas, Liu, Rajagopal [1211.1922]

- full embedding of probe in dynamical hydro medium [Monte Carlo]
  - most complete effort :: MARTINI + MUSIC
    - hard partons from Pythia
    - McGill-AMY for radiative and elastic
    - 3+1 hydro medium

**MC efforts reviewed by**
K Zapp [QM2011]