theoretical overview of jet quenching

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the study of jets
[reconstructed jets and their high-p_t hadronic content]
in heavy ion collisions aims at their use as probes of
the properties of the hot, dense and coloured matter
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#2 probing the medium

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#1 establishing the probe

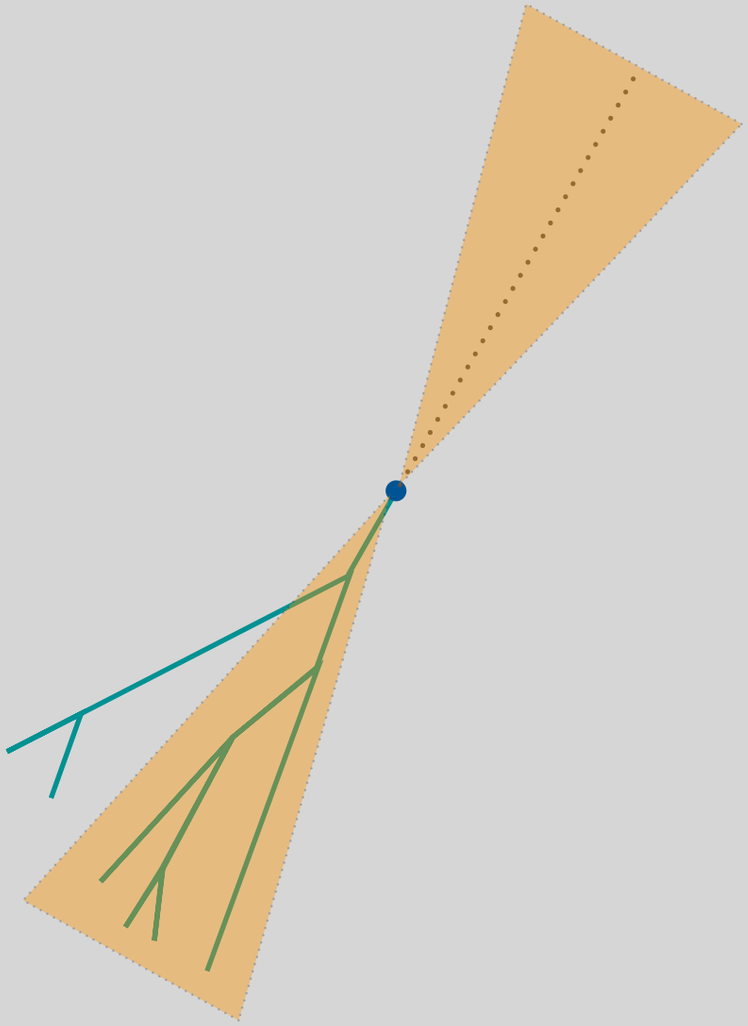
#2 probing the medium

not covered in this talk:

- *heavy quark [mass effects]* **W Horowitz** today 12.15
- *strongly coupled phenomena* **H-U Yee** friday 12.15

#1 establishing the probe

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]

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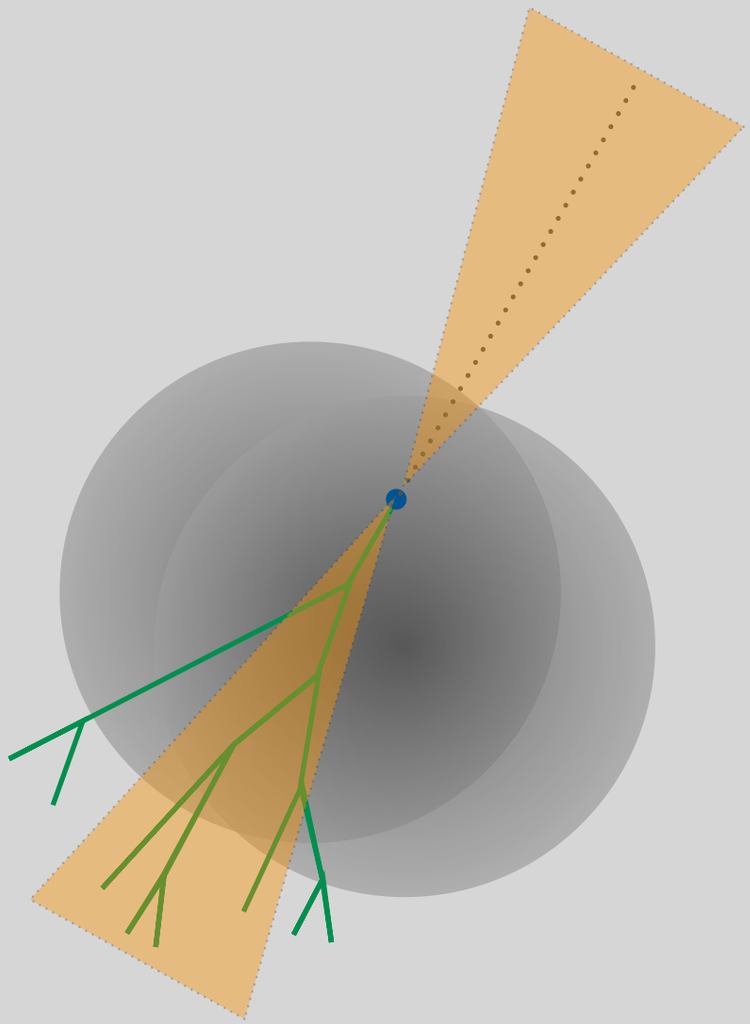

in HIC jets traverse sizable in-medium pathlength

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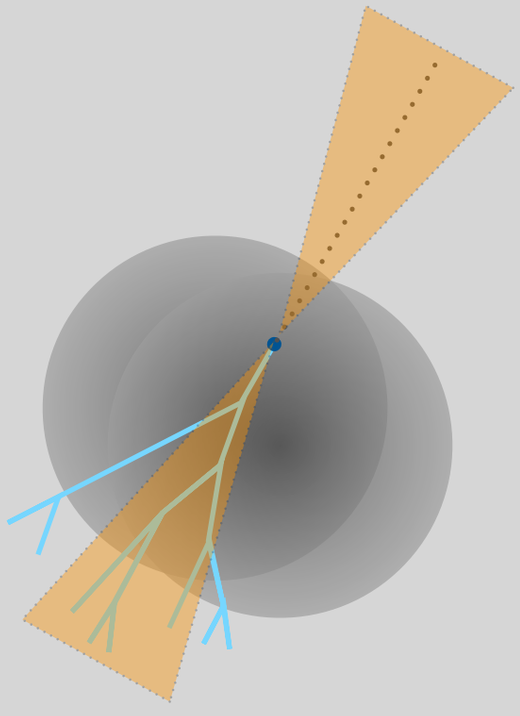
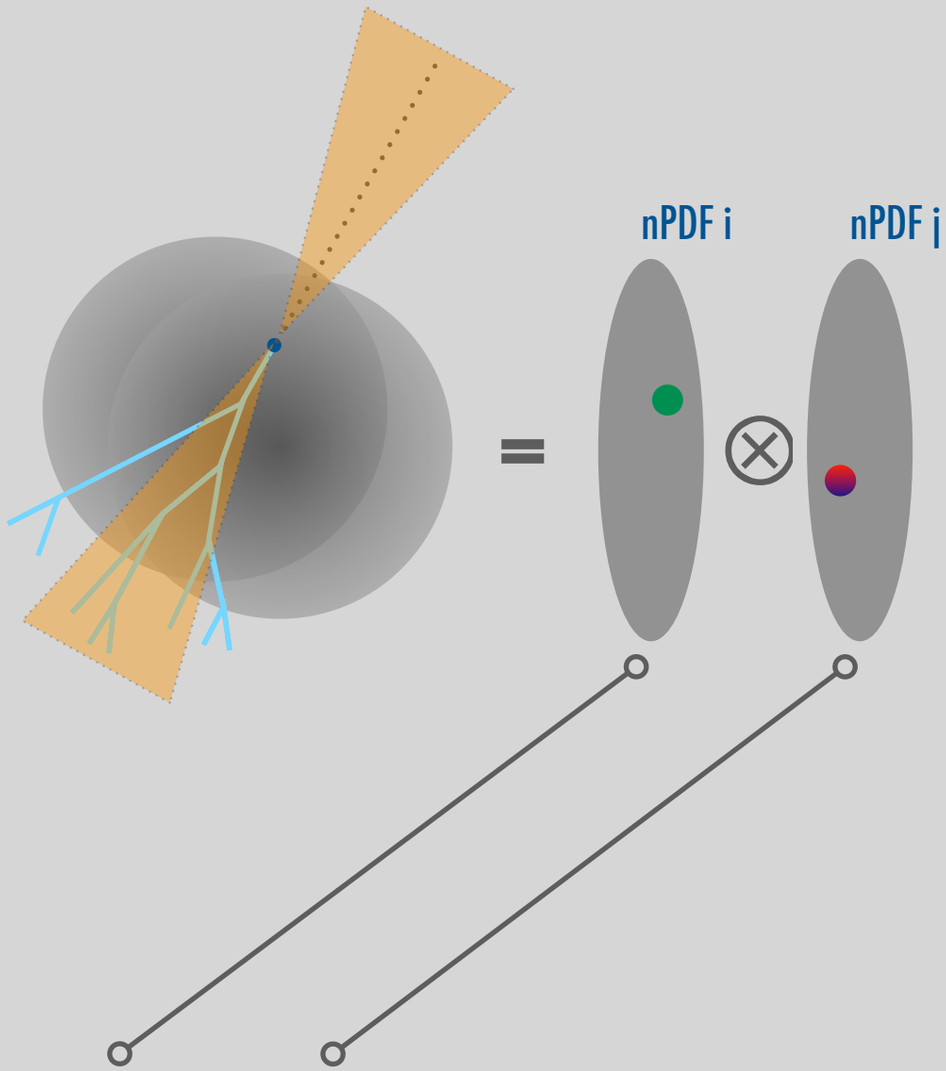


same factorizable structure [challengeable working hypothesis]

jets in heavy ion collisions



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

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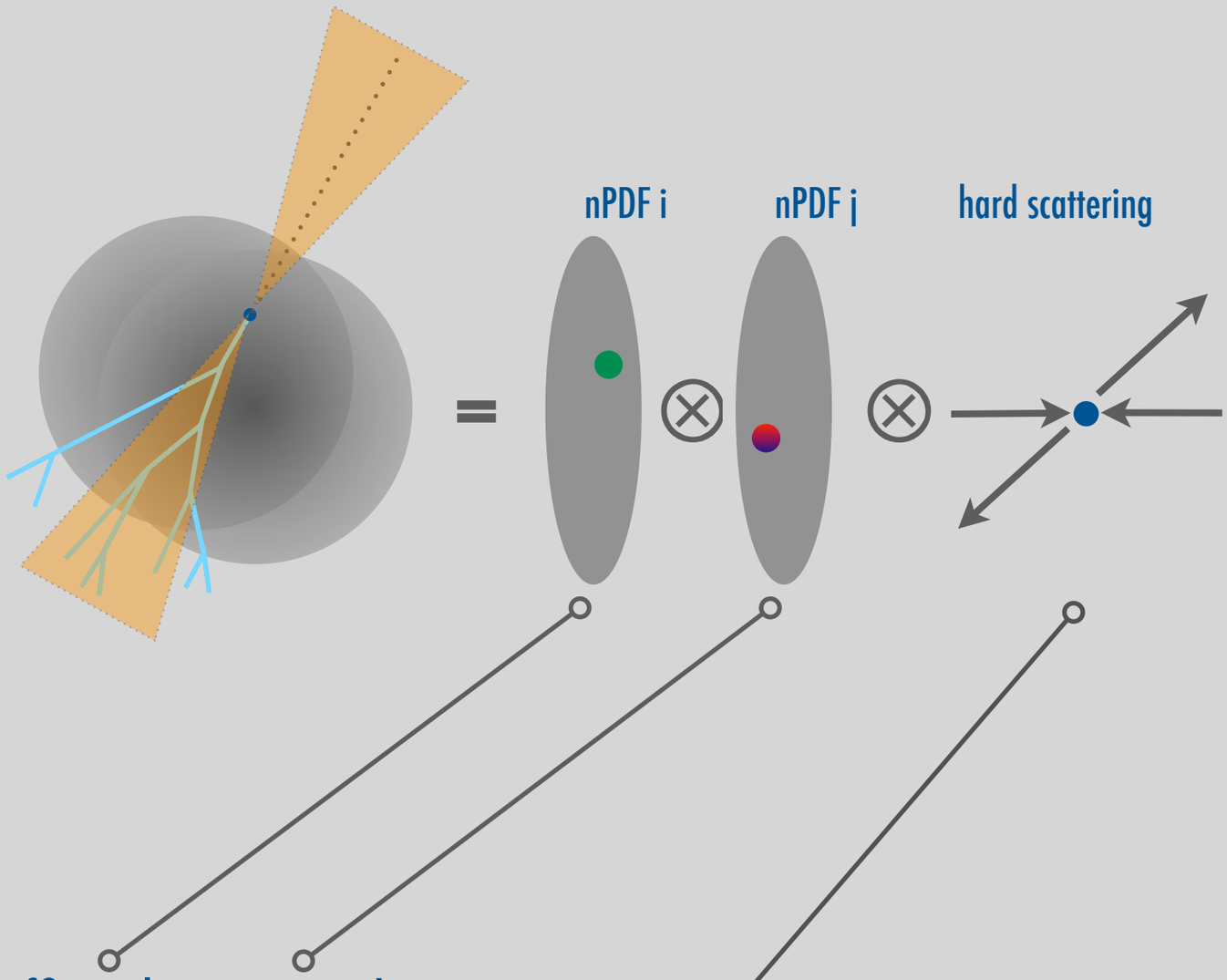

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localized on point like scale oblivious to surrounding matter [calculable to arbitrary pQCD order]

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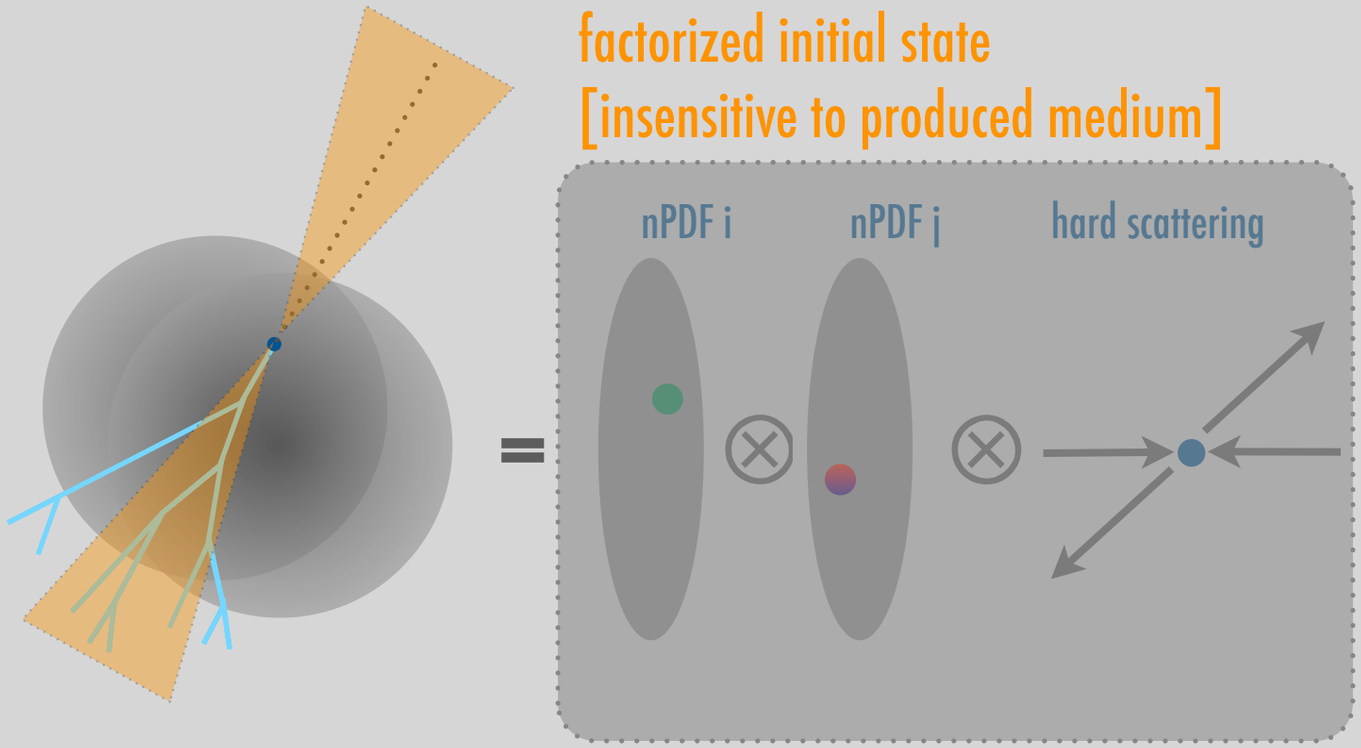

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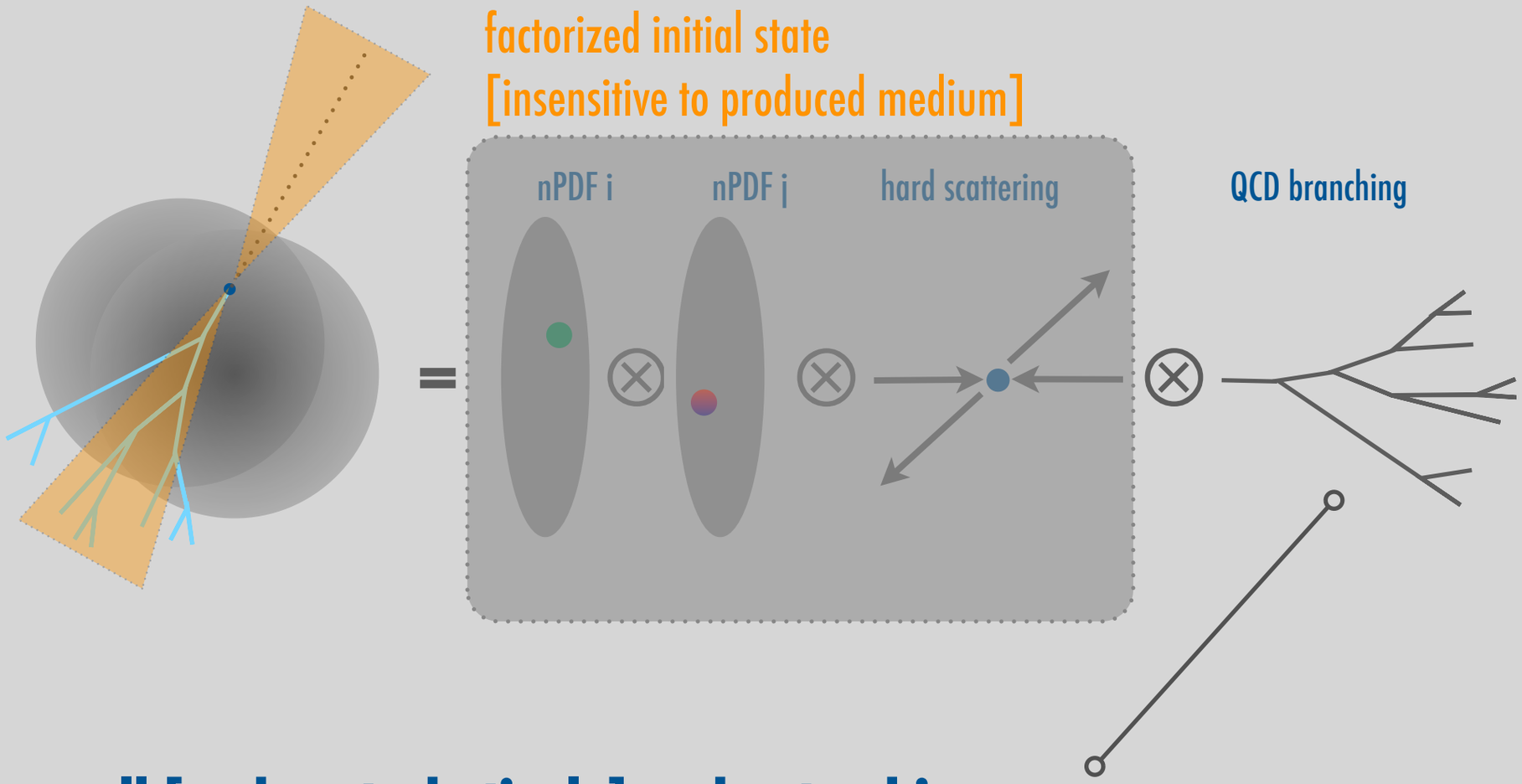

very well [and perturbatively] understood in vacuum

- 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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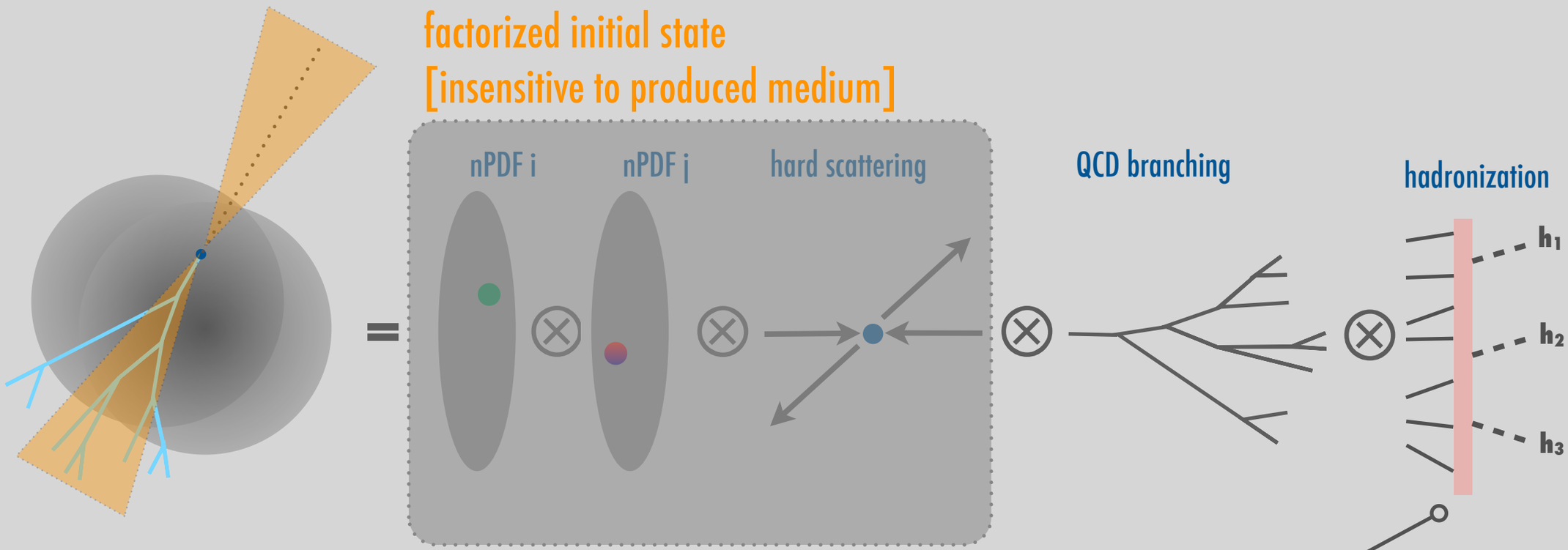


in vacuum

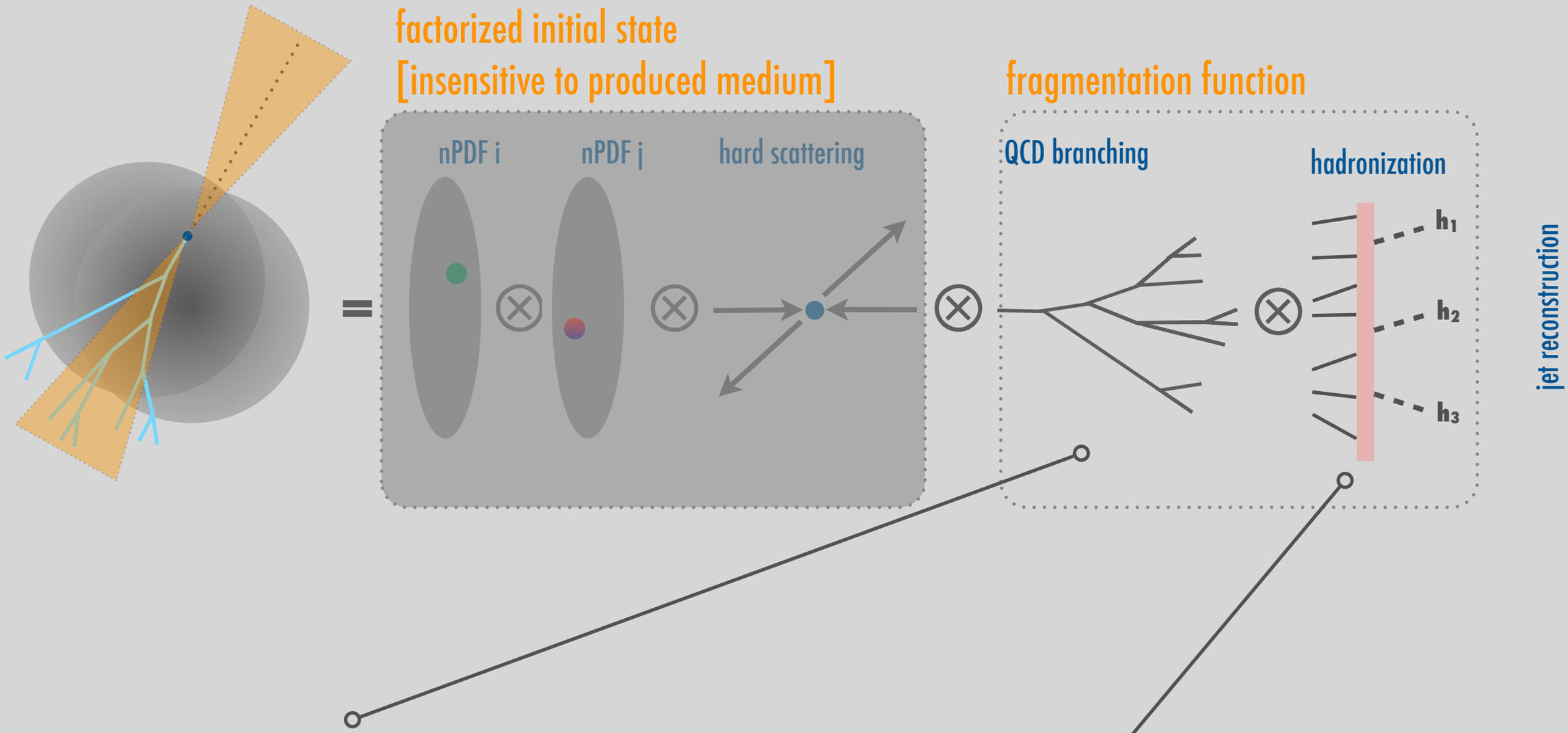
- effective description in MC [Lund strings, clusters, ...]
- FF for specific final state [jet, hadron class/species, ...]

in medium

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

fragmentation outside medium = vacuum FFs ???

jets in heavy ion collisions



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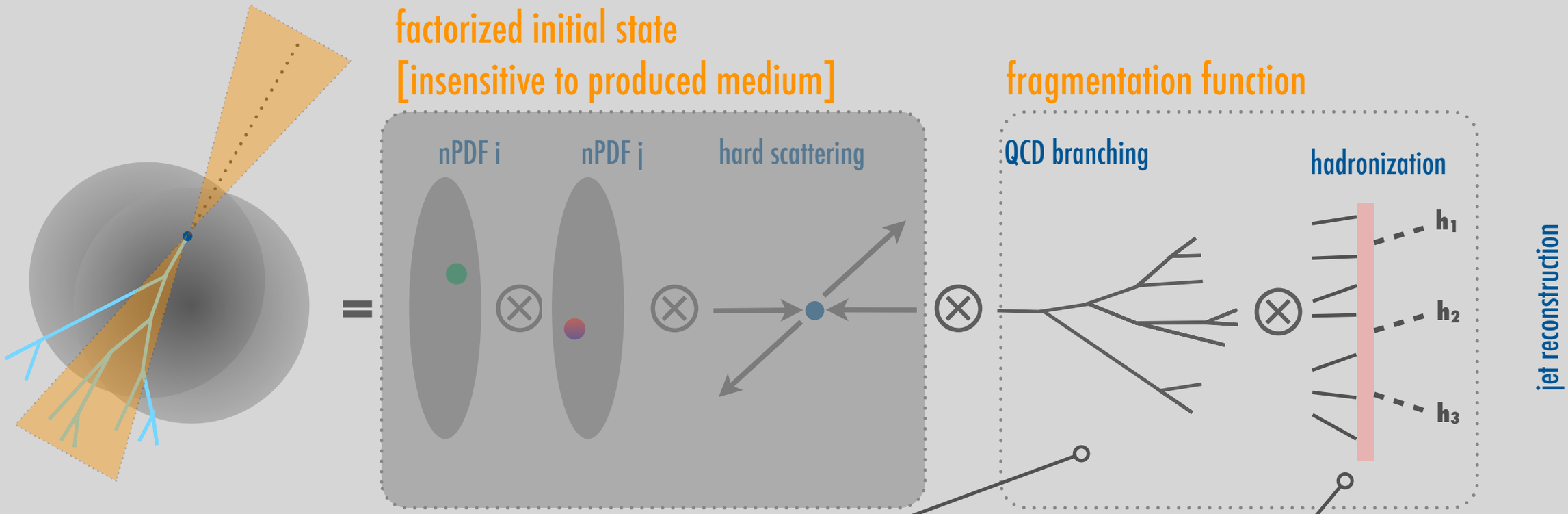

jet quenching ::
observable consequences [in jet and jet-like hadronic observables] of the effect of the medium

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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

medium induced radiation

- single gluon emission understood in 4 classes of pQCD-based formalisms
  - **B**aier-**D**okshitzer-**M**ueller-**P**eigné-**S**chiff–**Z**akharov
  - **G**yulassy-**L**evai-**V**itev
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- all build multiple gluon emission from [ad hoc] iteration of single gluon kernel
  - Poissonian ansatz [BDPMS and GLV]; rate equations [AMY]; medium-modified DGLAP [HT]

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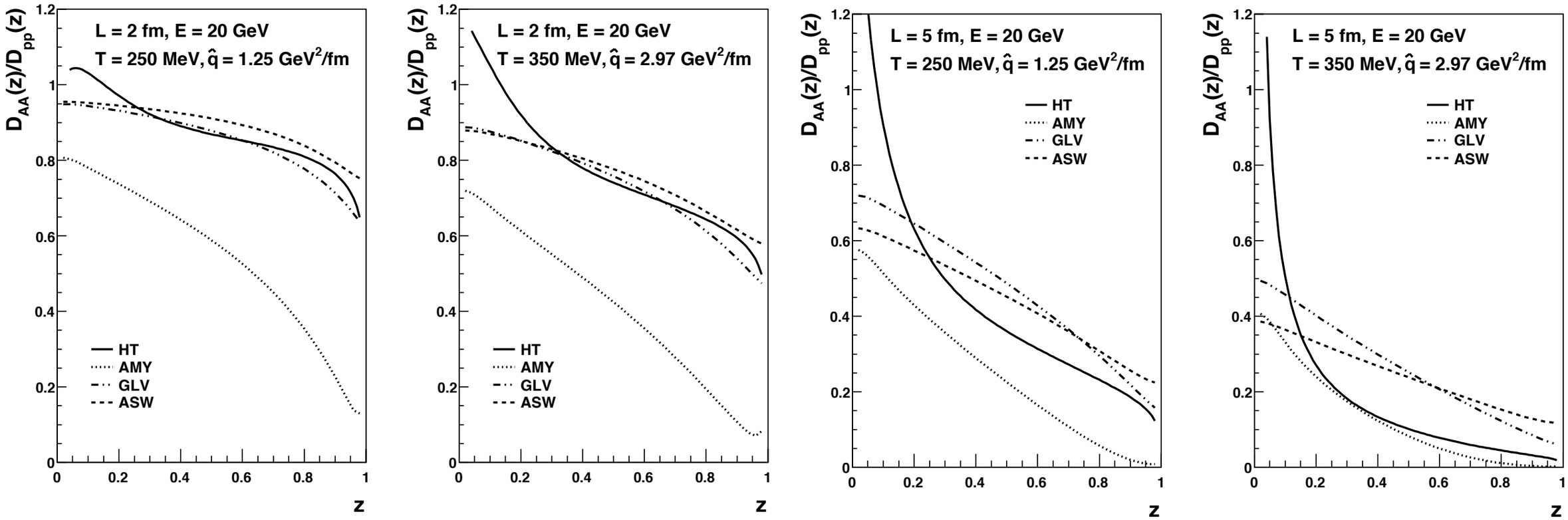
- Monte Carlo implementations [HIJING, Q-PYTHIA/Q-HERWIG, JEWELL, YaJEM, MARTINI]

medium induced radiation

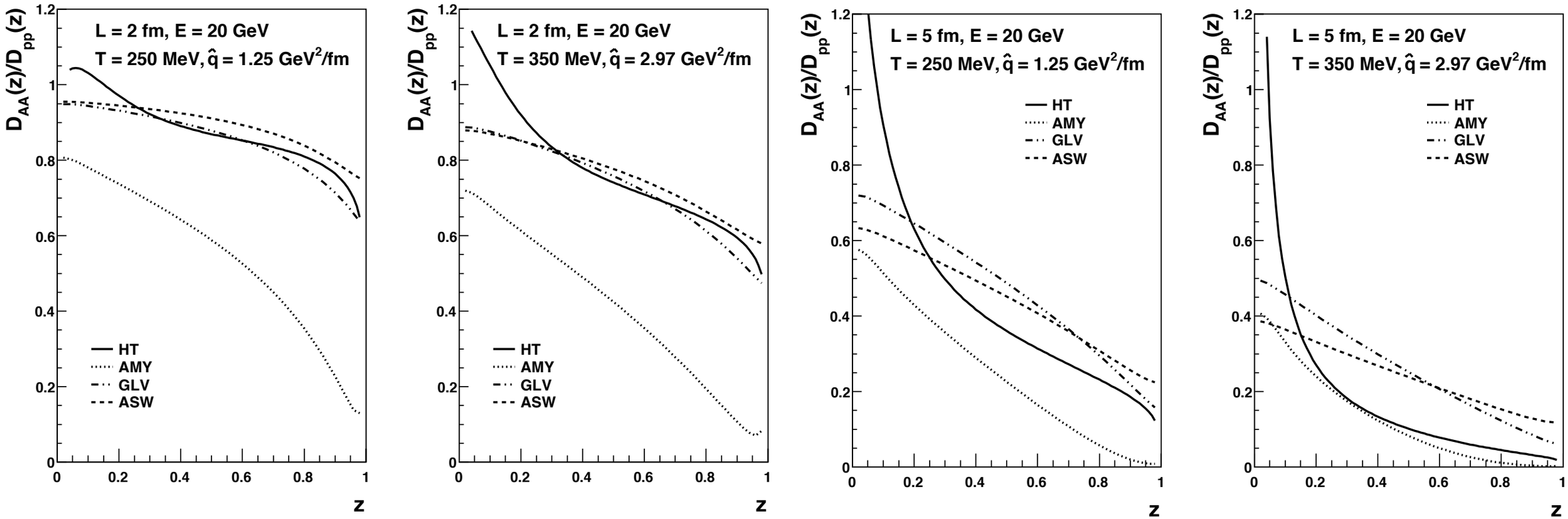


medium modification of quark fragmentation function

Majumder & van Leeuwen [1002.2206]

- systematic comparison in a simple common model medium [the BRICK]
  - large discrepancies [mostly due to necessary extension of formalism beyond strict applicability domain]

medium induced radiation



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none necessarily right or wrong, all incomplete

relaxing approximations

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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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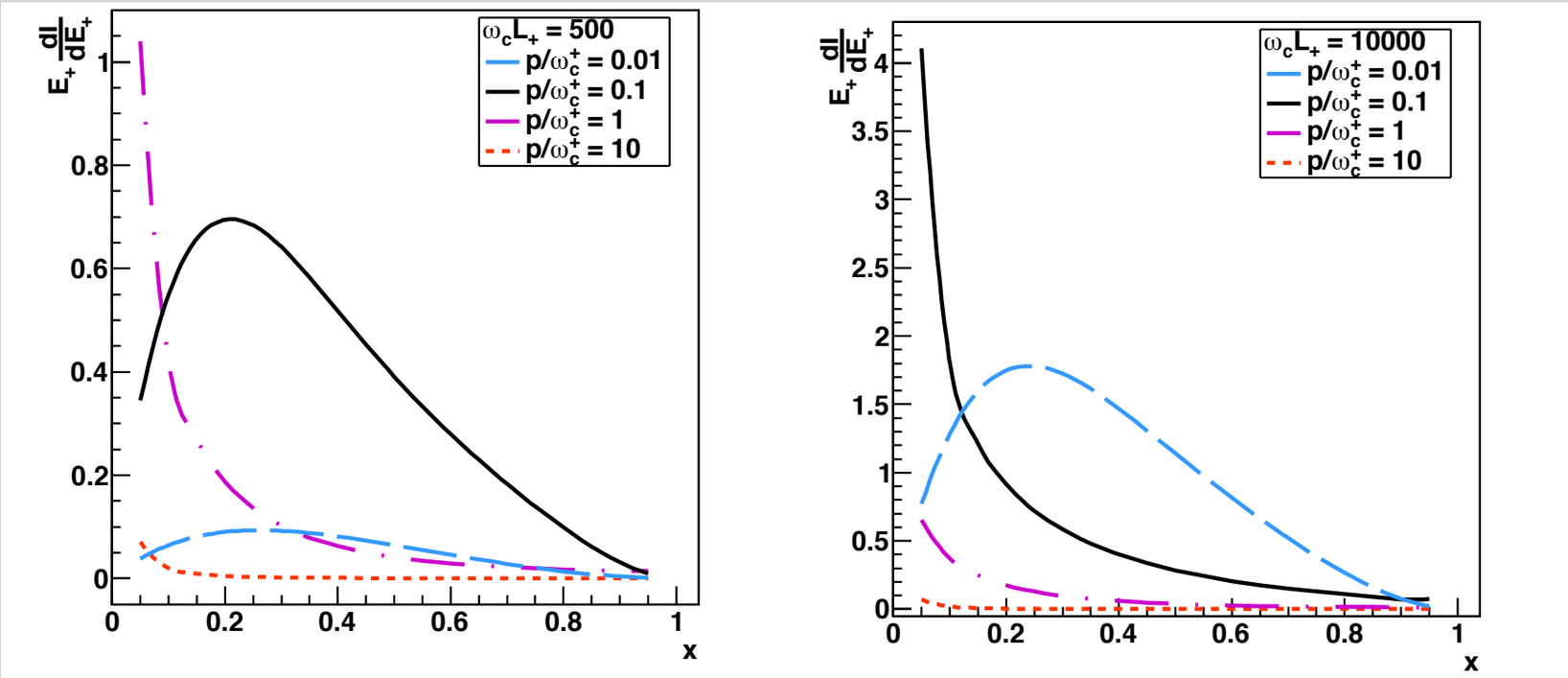
  - ↪ large-x limit computed in path-integral formalism, explicitly in the multiple soft scattering approximation, and small-large x interpolating ansatz

Apolinário, Armesto, Salgado [1204.2929]



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↪ general case computed in SCET

d'Eramo, Liu, Rajagopal [1010.0890]

Ovanesyan & Vitev [1103.1074, 1109.5619]

application for jet quenching pioneered by Adilbi & Majumder [0808.1087]

- promising powerful framework
  - elastic and inelastic [+broadening] energy loss within same formalism
    - same aim in different approach [Zapp, Krauss, Wiedemann [1111.6838]]
  - recoils
- based on scale hierarchy
  - hard scale [$\sim \sqrt{s} \sim \lambda^0$] $\gg$ jet scale [$\sim p_t \sim \lambda^1$] $\gg$ soft radiation scale [$\sim \lambda^2$]
- degrees of freedom
  - collinear modes: $p_c \sim [\lambda^0, \lambda^2, \lambda]$
  - soft modes: $p_s \sim [\lambda^2, \lambda^2, \lambda^2]$
  - Glauber modes [jet-medium interaction]: $q \sim [\lambda^2, \lambda^2, \lambda]$

Ovanesyan fri 16.50 [parallel 7E]

[de]coherence of multiple emissions

- bona fide description of multiple gluon radiation requires understanding of emitters interference pattern

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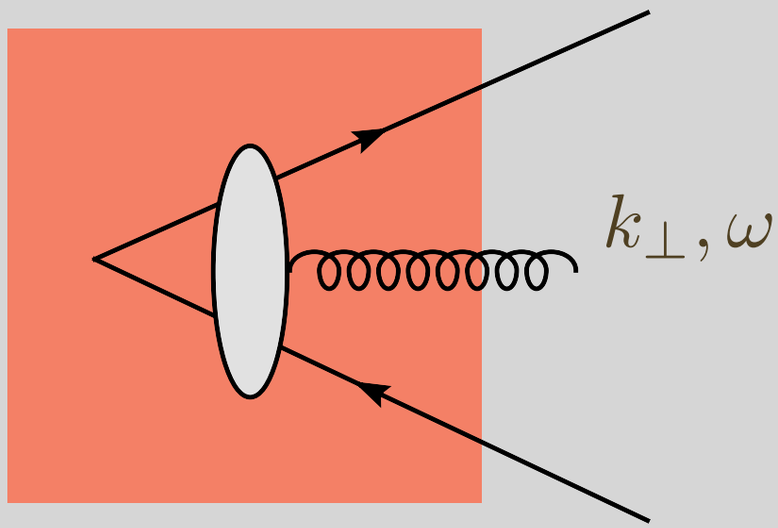

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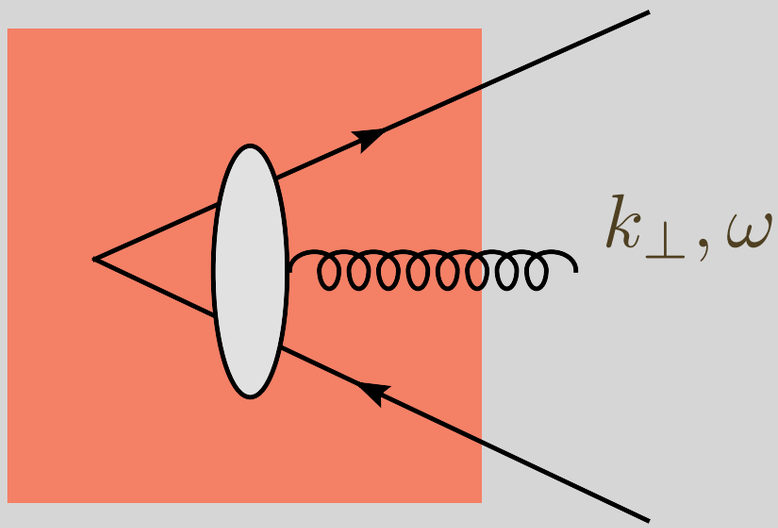

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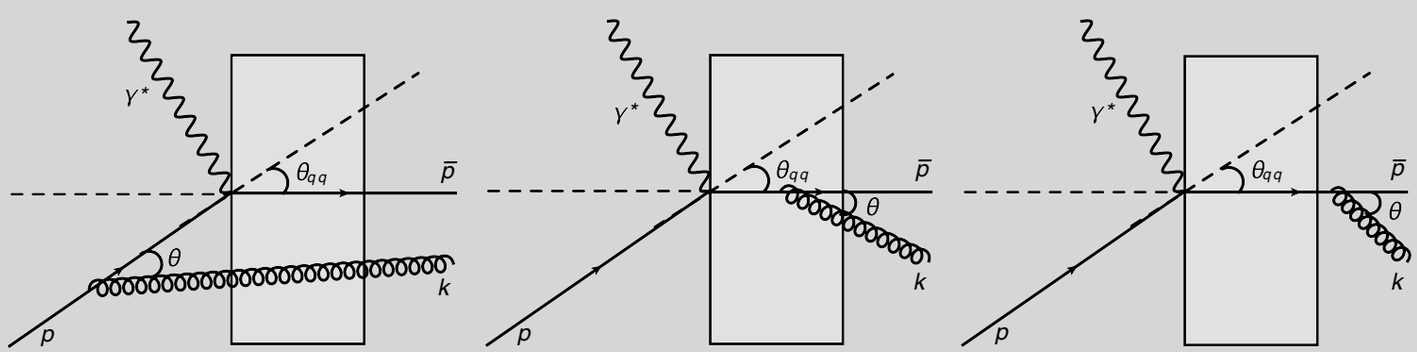
↪ also for initial/final state

Armesto, Ma, Martínez, Mehtar-Tani, Salgado[1207.0984]



a challenge for factorization ???

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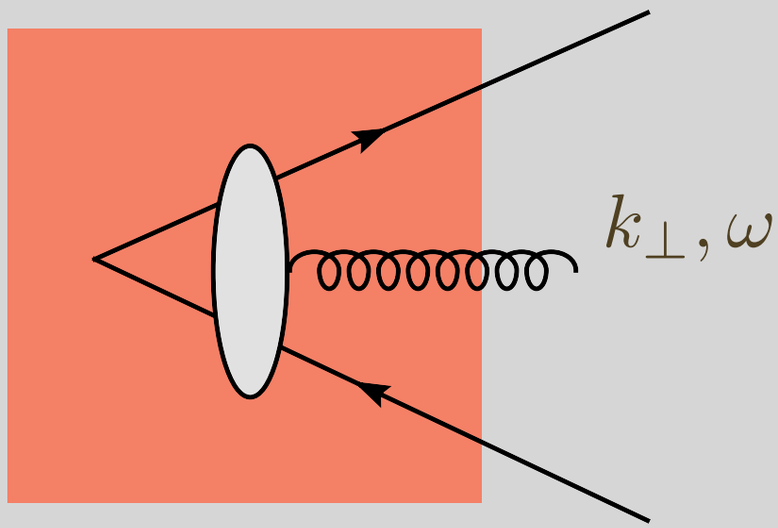

- qqbar colour coherence survival probability

$$\Delta_{\rm med} = 1 - \exp\left\{-\frac{1}{12}\hat{q}\theta^2_{q\bar{q}}t^3\right\}$$

- time scale for decoherence

$$\tau_d \sim \left(\frac{1}{\hat{q}\theta^2_{q\bar{q}}}\right)^{1/3}$$

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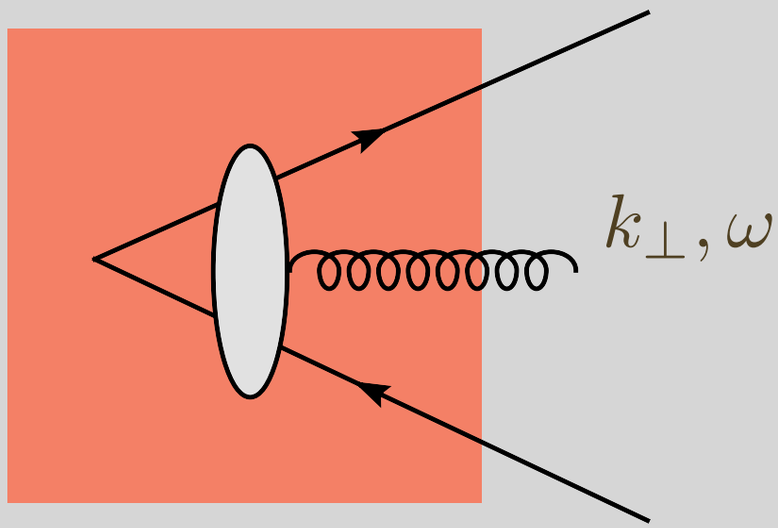

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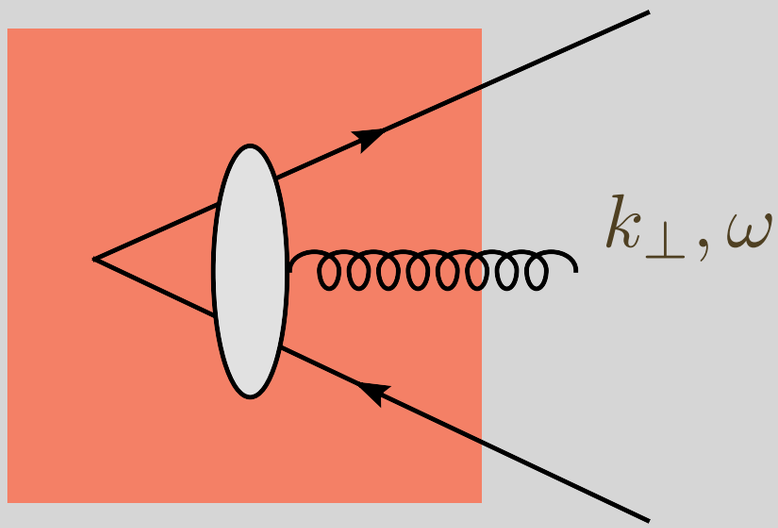

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    - *geometrical separation*

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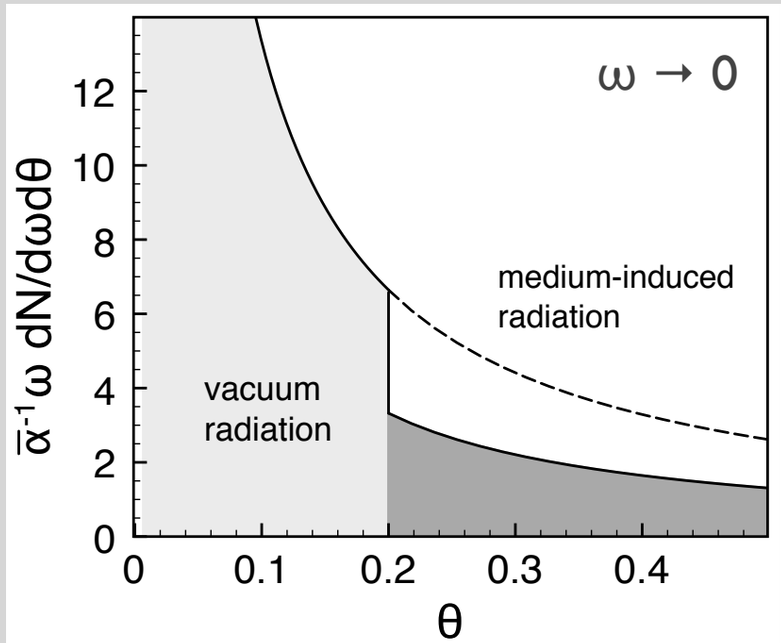

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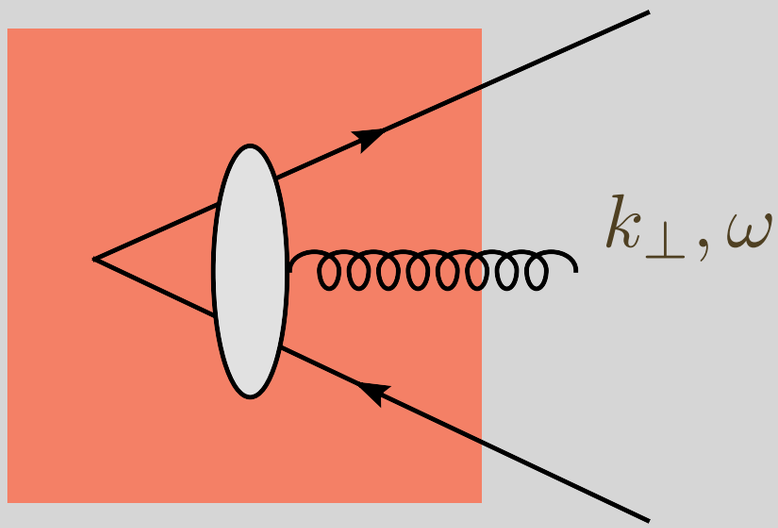

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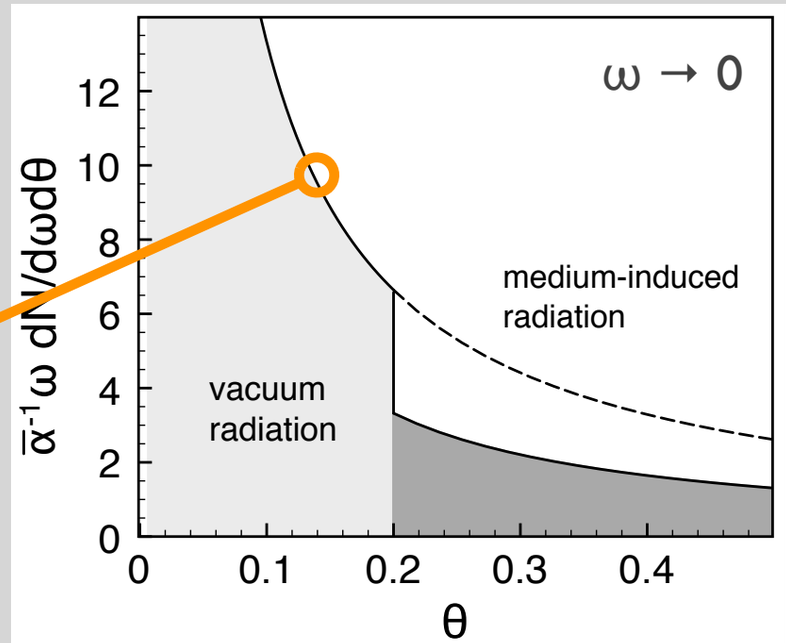
$\Delta_{\rm med} \to 0$ coherence



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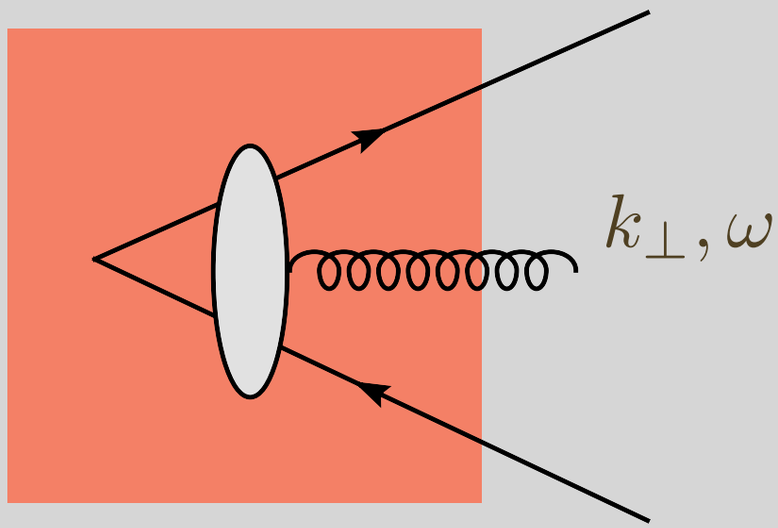

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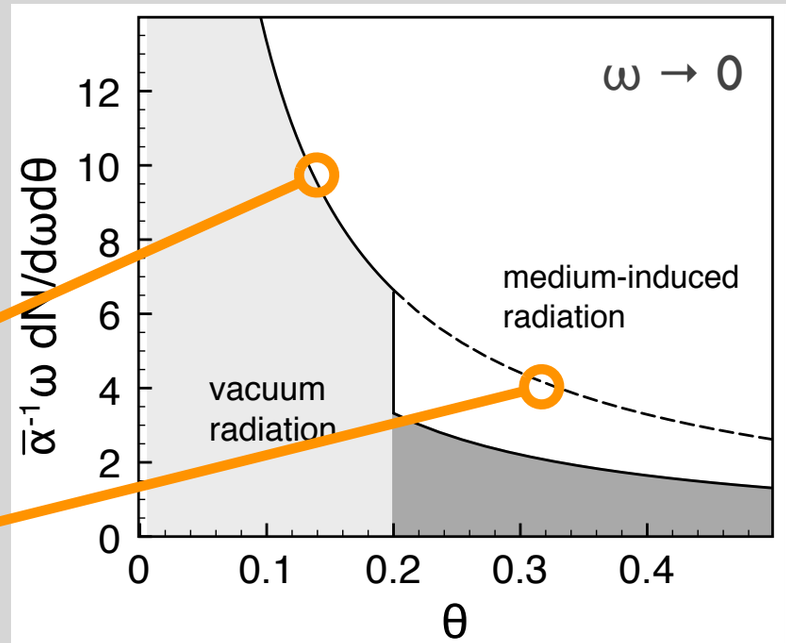

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    - only relevant for emissions during formation time of previous gluon
  - ↪ in the small formation times limit
    - probabilistic decohered branching process via master equation for generating functional

Blaizot, Dominguez, Iancu, Mehtar-Tani [soon]

    - in-medium spitting function

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$$\boldsymbol{k}^{2}_{\rm br}=\sqrt{z(1-z)p^{+}\hat{q}_{\rm eff}}$$

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Dominguez wed 10.10 [parallel 3B]

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$$\boldsymbol{k}^{2}_{\rm br}=\sqrt{z(1-z)p^{+}\hat{q}_{\rm eff}}$$

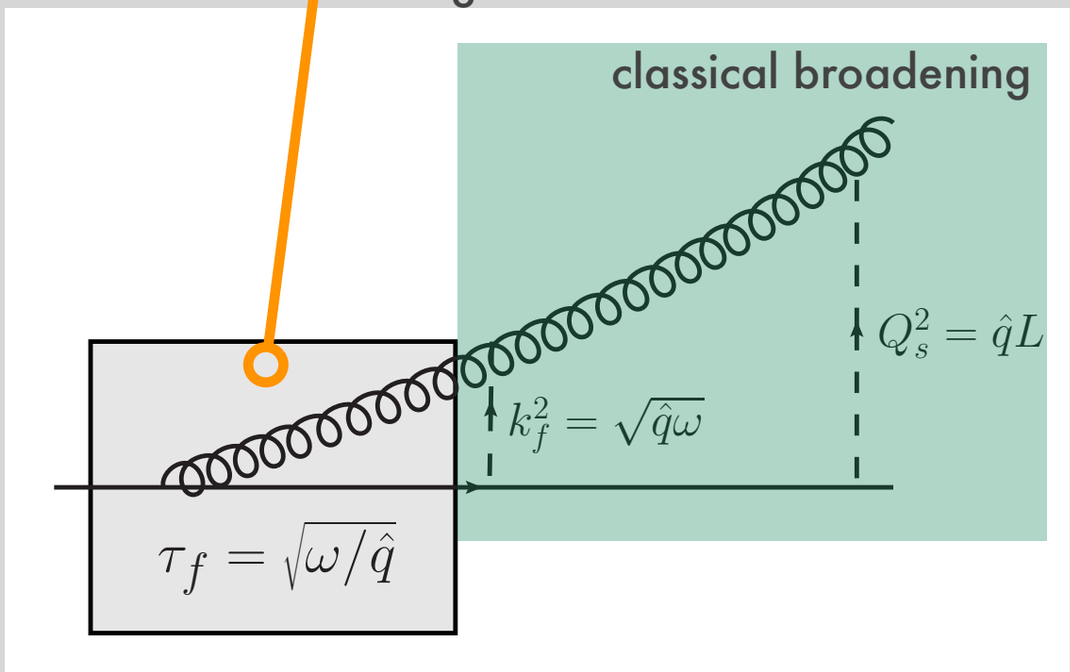
emerging full account of medium effect on QCD coherence

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



AN IMPORTANT LESSON FROM DATA

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

broadening [jet collimation]

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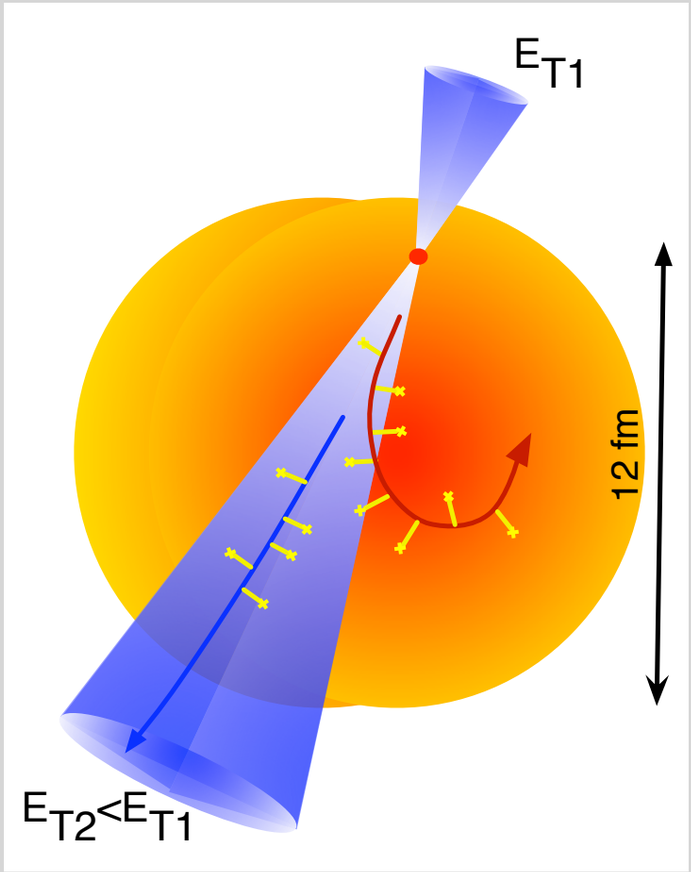
large broadening [beyond quasi-eikonal] is a prominent dynamical mechanism for jet energy loss [dijet asymmetry]

- in-medium formation time for small angle and soft gluons [vacuum] is very short
- democratic broadening is a large effect for soft partons
  - soft radiation decorrelated from jet direction/transported to large angles
  - enhancement of soft fragments outside the jet

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

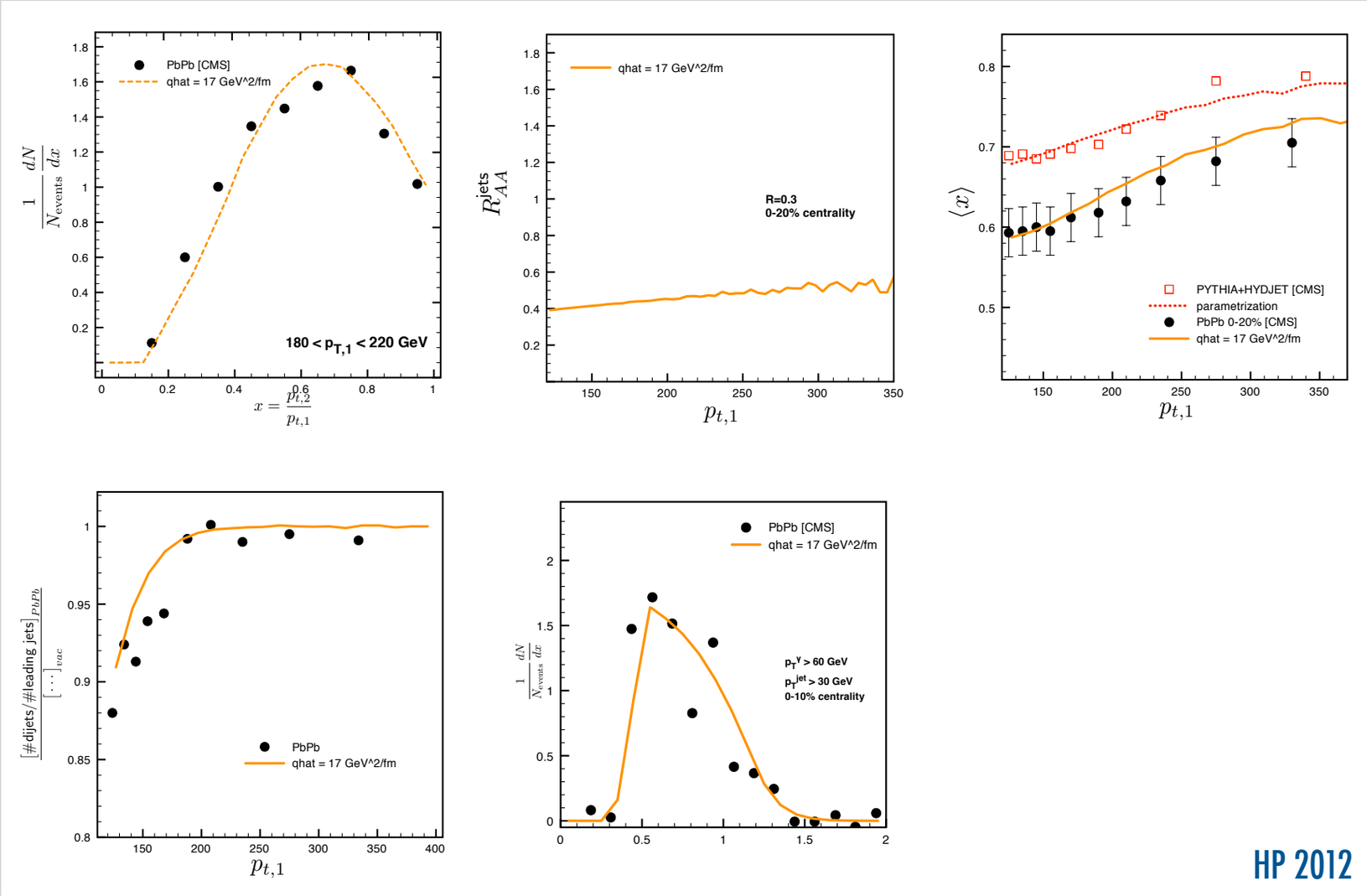
$$\langle k_\perp \rangle \sim \sqrt{\hat{q}L}$$

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



Casalderrey-Solana, Milhano, Wiedemann [1105.1760]
Qin & Muller [1012.5280]

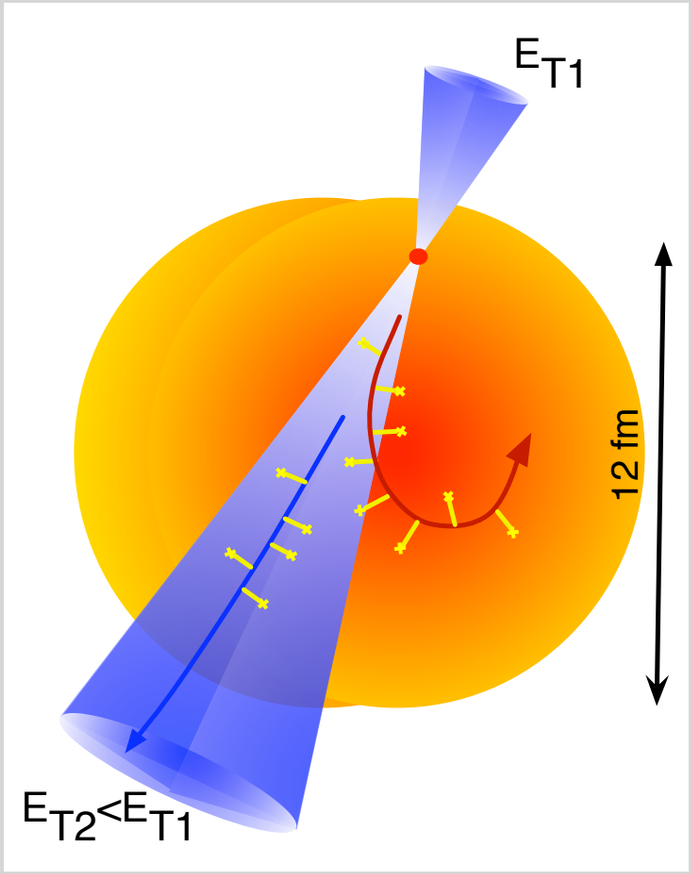
broadening [jet collimation]



HP 2012

Intriguing [given its naivety and caveats] excellent overall account of data

need first principle calculation to support



interplay of branching and hadronization

- colour of all jet components rotated by interaction with medium
  - ↪ colour correlations modified with respect to vacuum case
    - theoretically controllable within a standard framework [opacity expansion]

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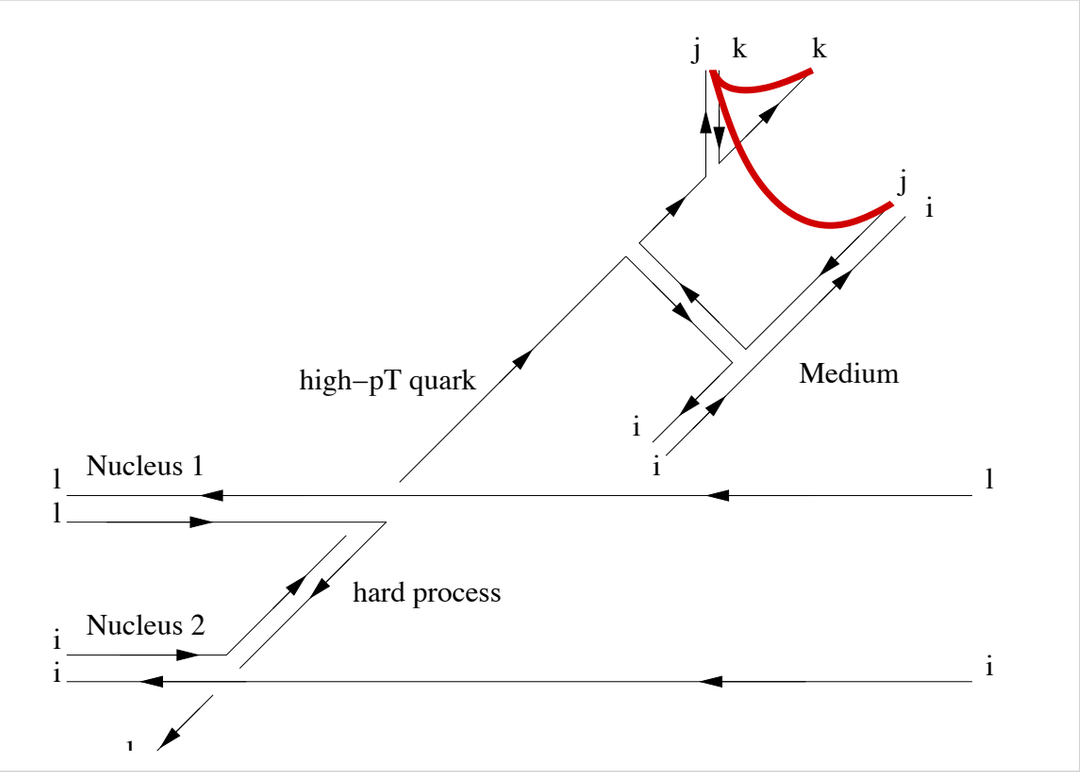

no medium interaction after radiation

- colour properties of hadronizing system vacuum-like
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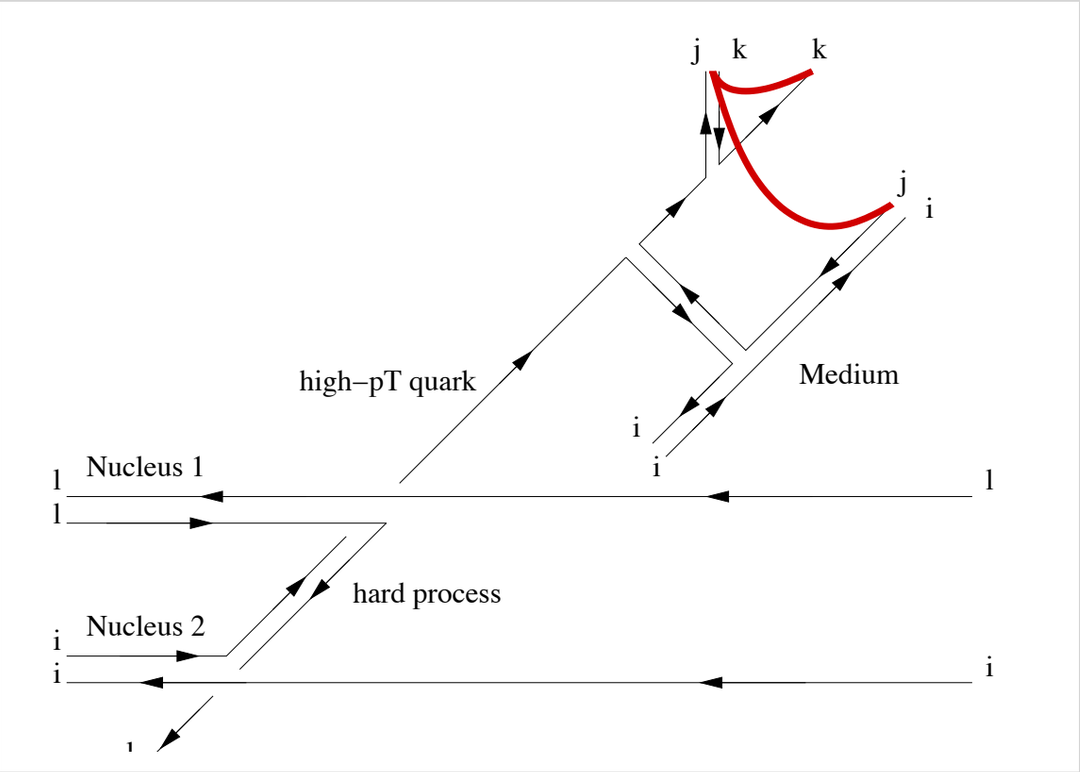

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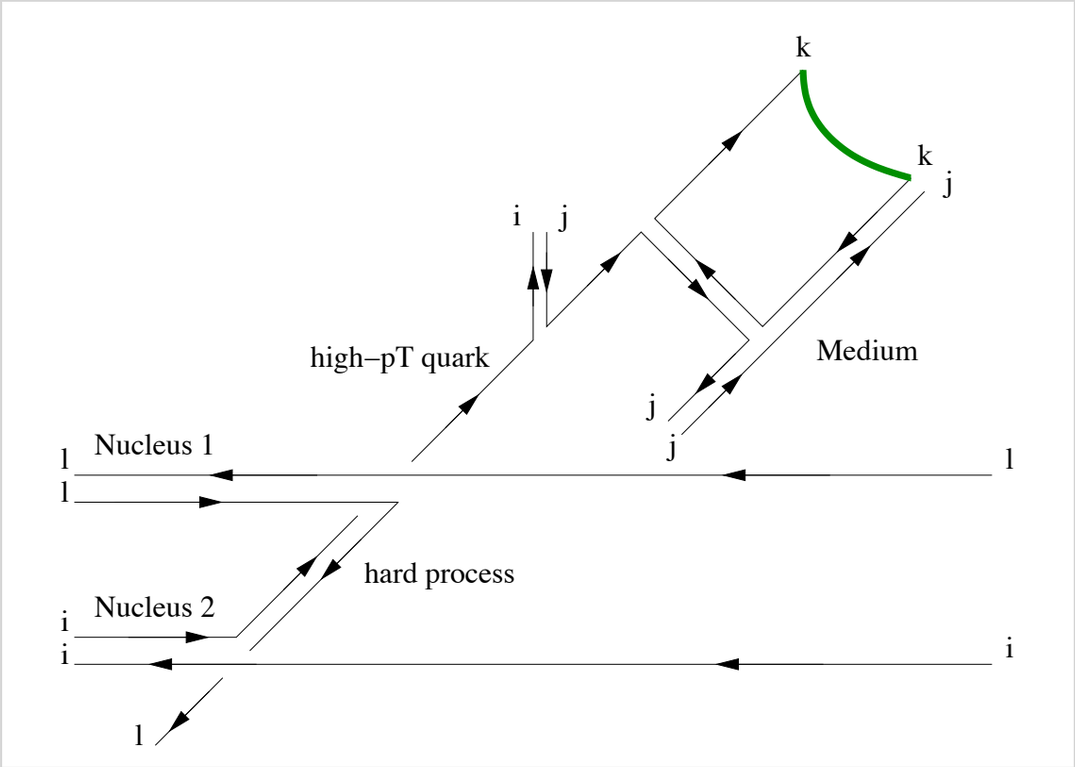

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Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]

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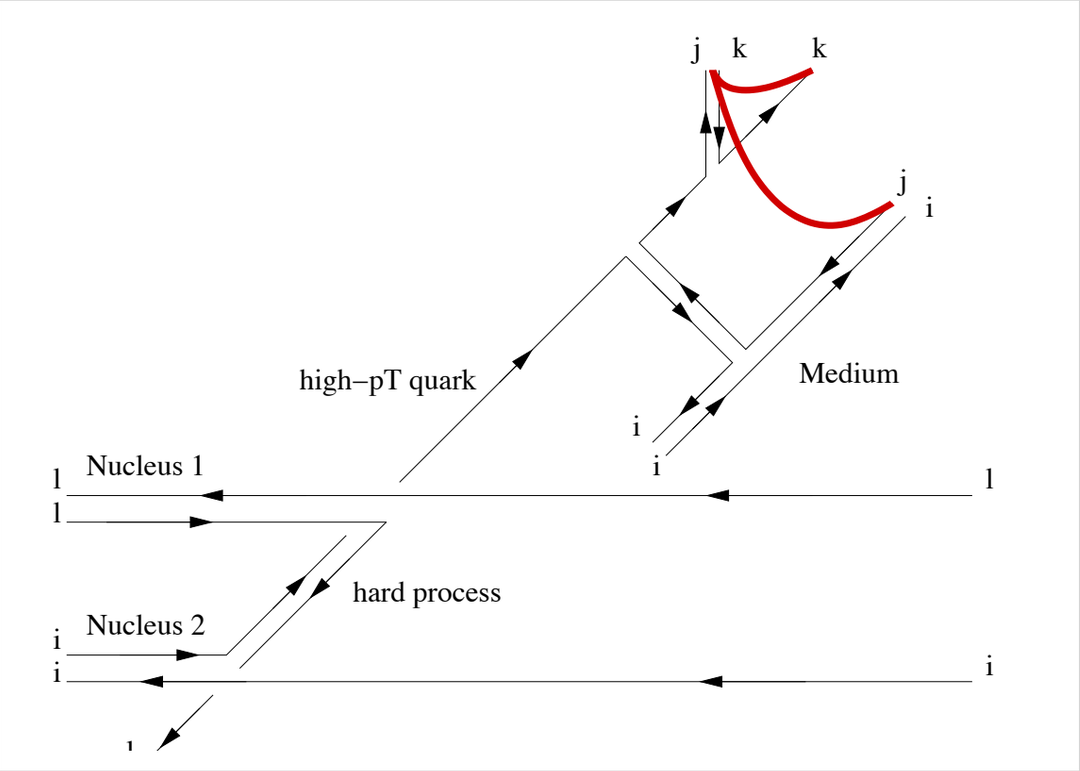

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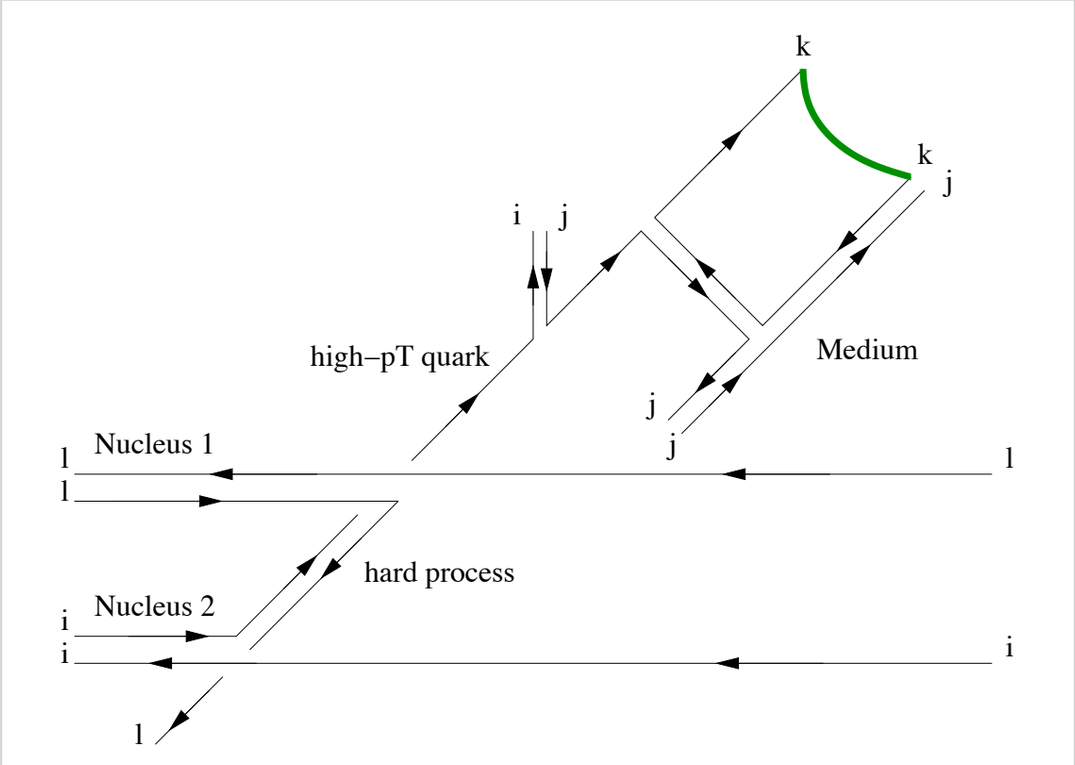

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first steps towards fully colour differential framework

Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]

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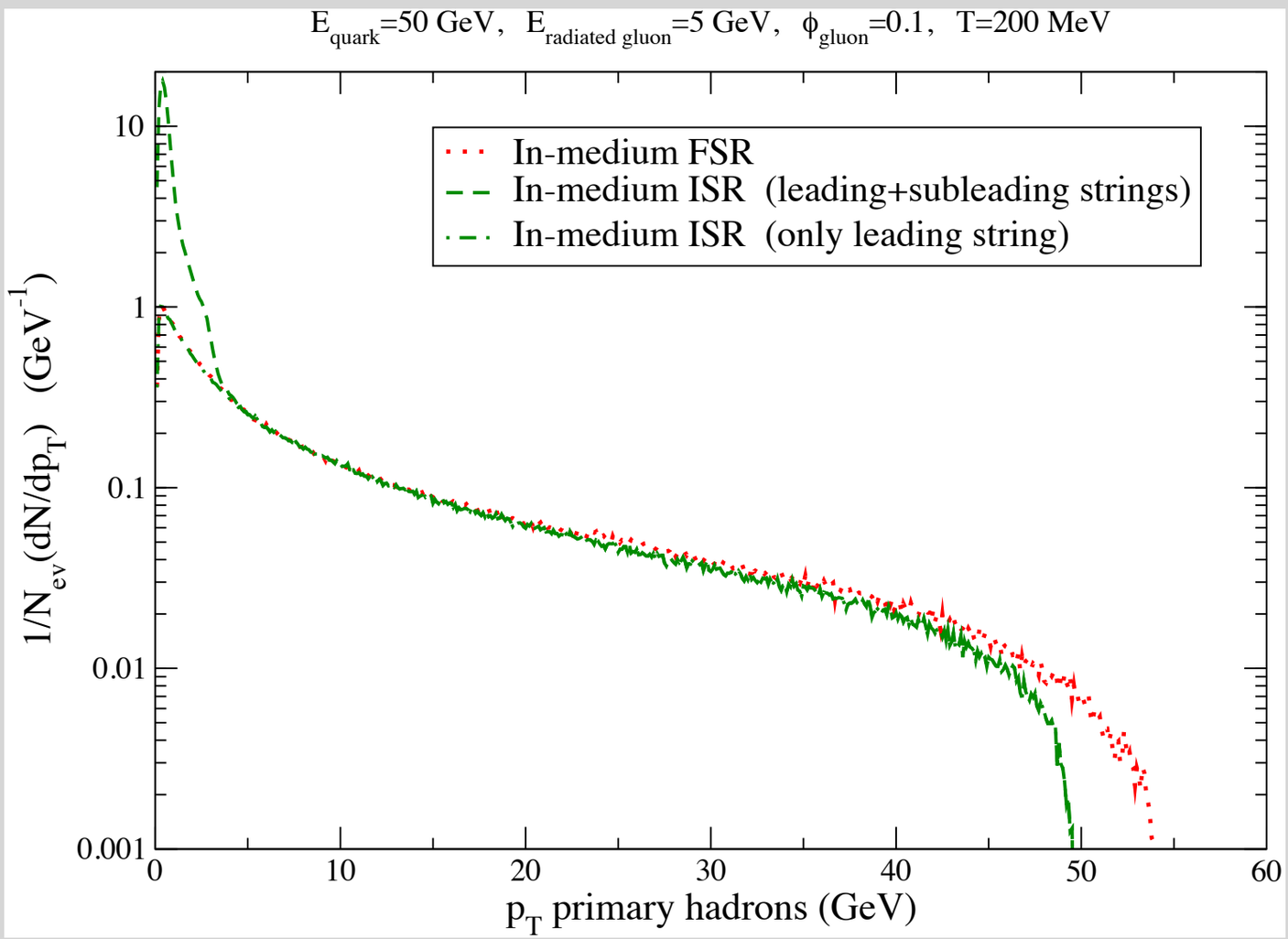

generic [robust] effects:

- softnening of hadronic spectra
- lost hardness recovered as soft multiplicity

- at work even if radiative energy loss kinematically unviable

- survives branching after medium escape

modification of jet hadrochemistry
Aurenche & Zakharov [1109.6819]

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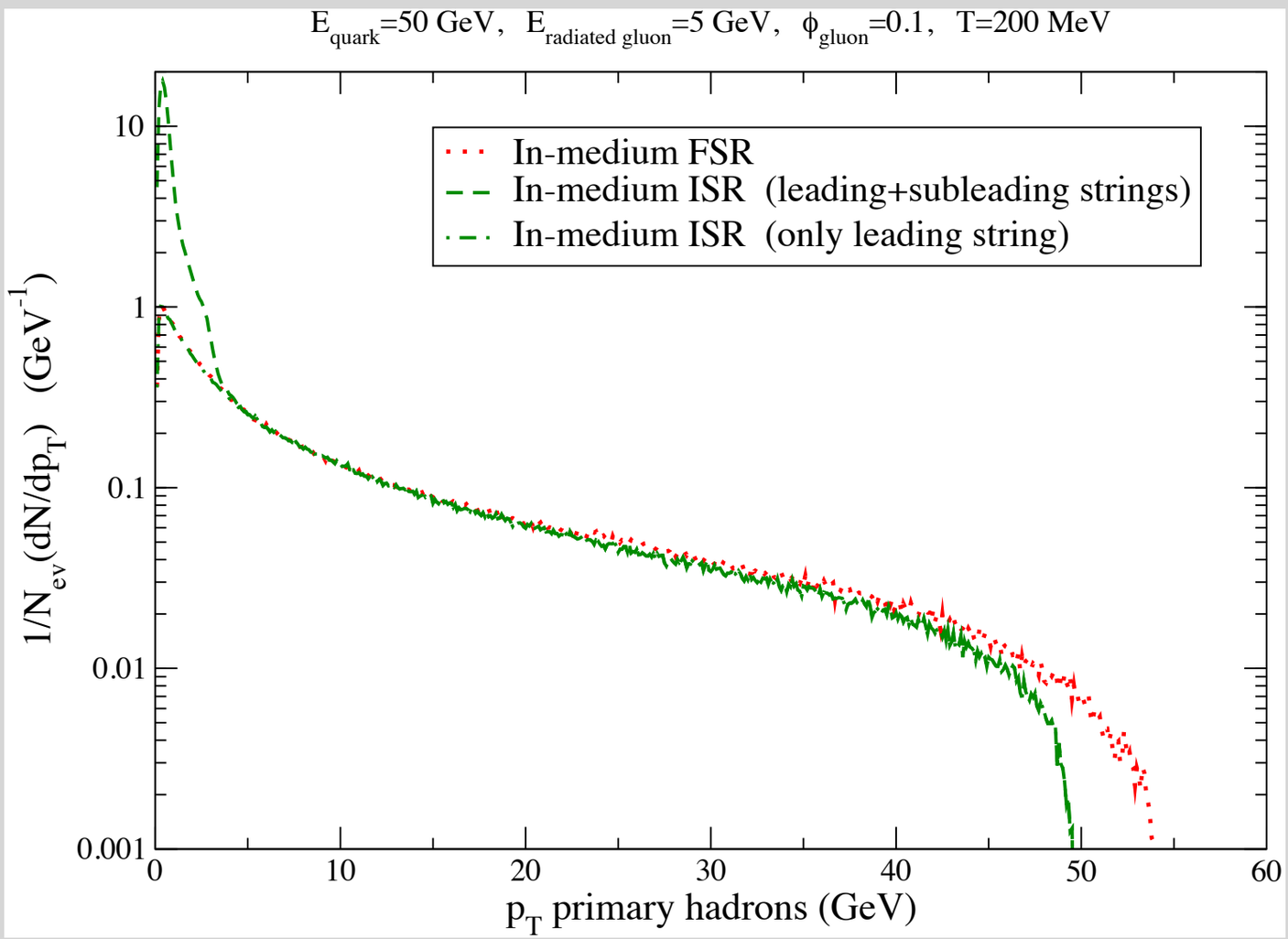

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fragmentation in vacuum NOT the same as using vacuum FFs

life story of an in-medium jet

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  - *hard skeleton defined [3-jet rates, hard frag, ...]*
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most [all?] questions asked, many [most?] being answered

life story of an in-medium jet

very appealing pQCD based overall picture

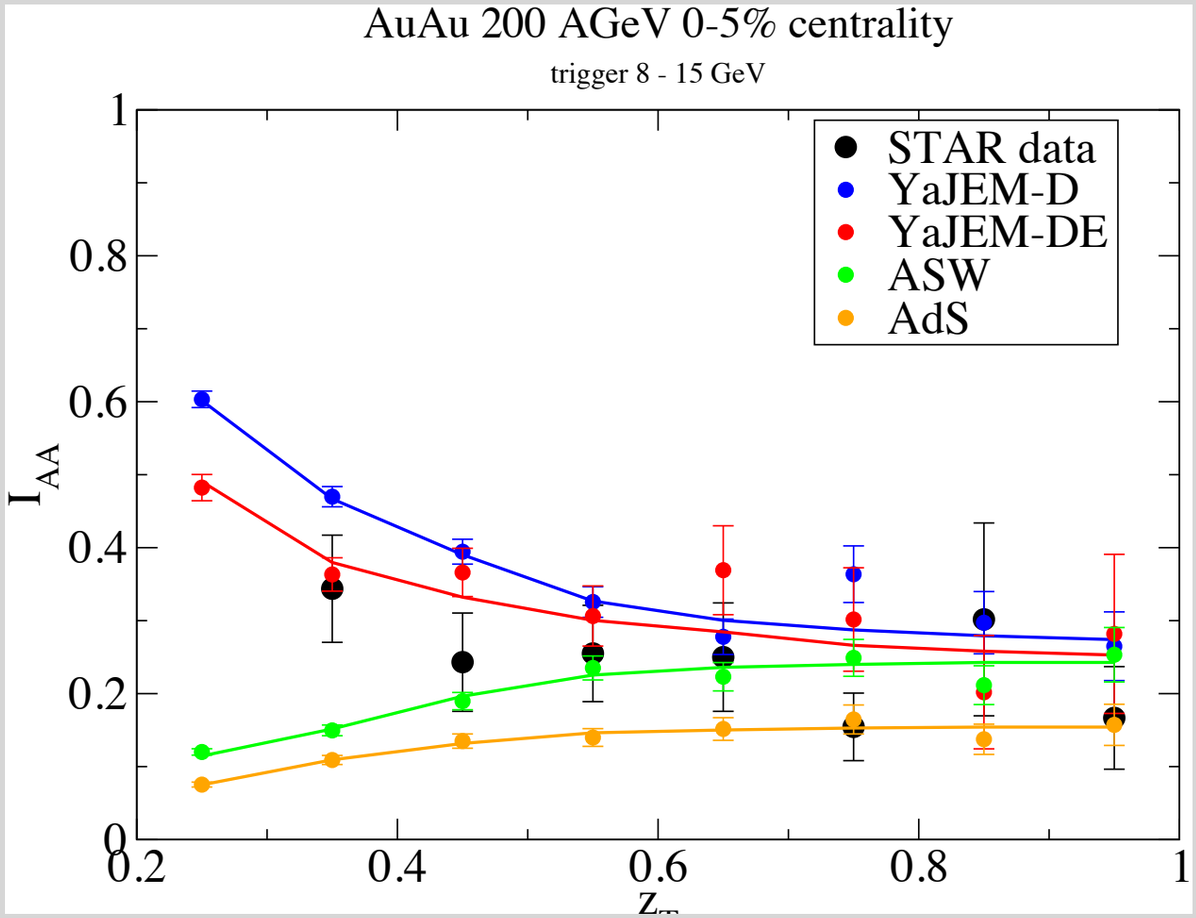
BUT

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

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

the truth is in data [and data is out there]

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



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

Renk [1110.2313,1112.2503,1202.4579]

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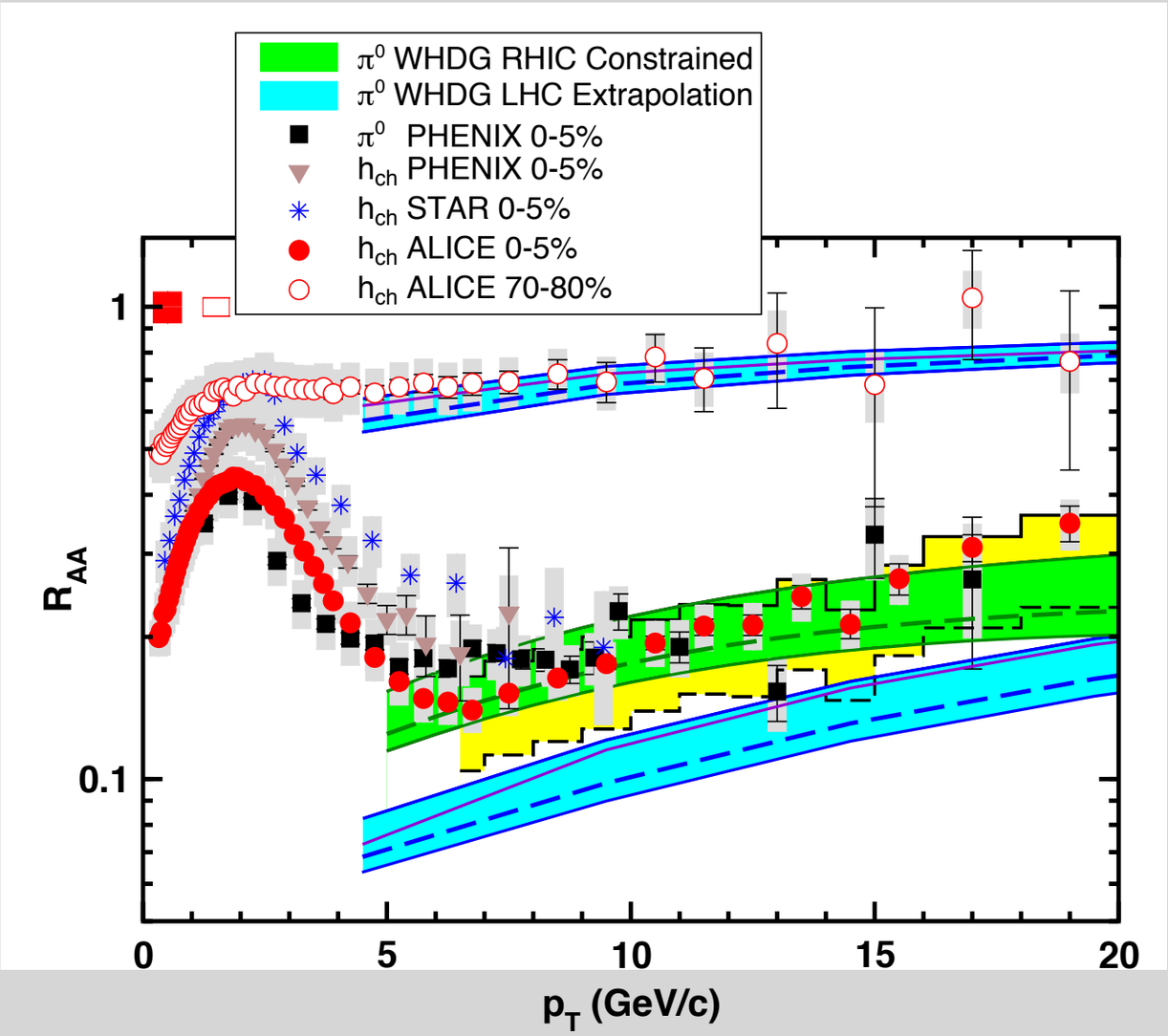
- theory validation [constraining dynamics] requires
  - RHIC to LHC description



Betz today 17.45 [parallel 2B]

Renk wed 8.30 [parallel 3B]

Coleman-Smith thu 14.00 [parallel 5C]

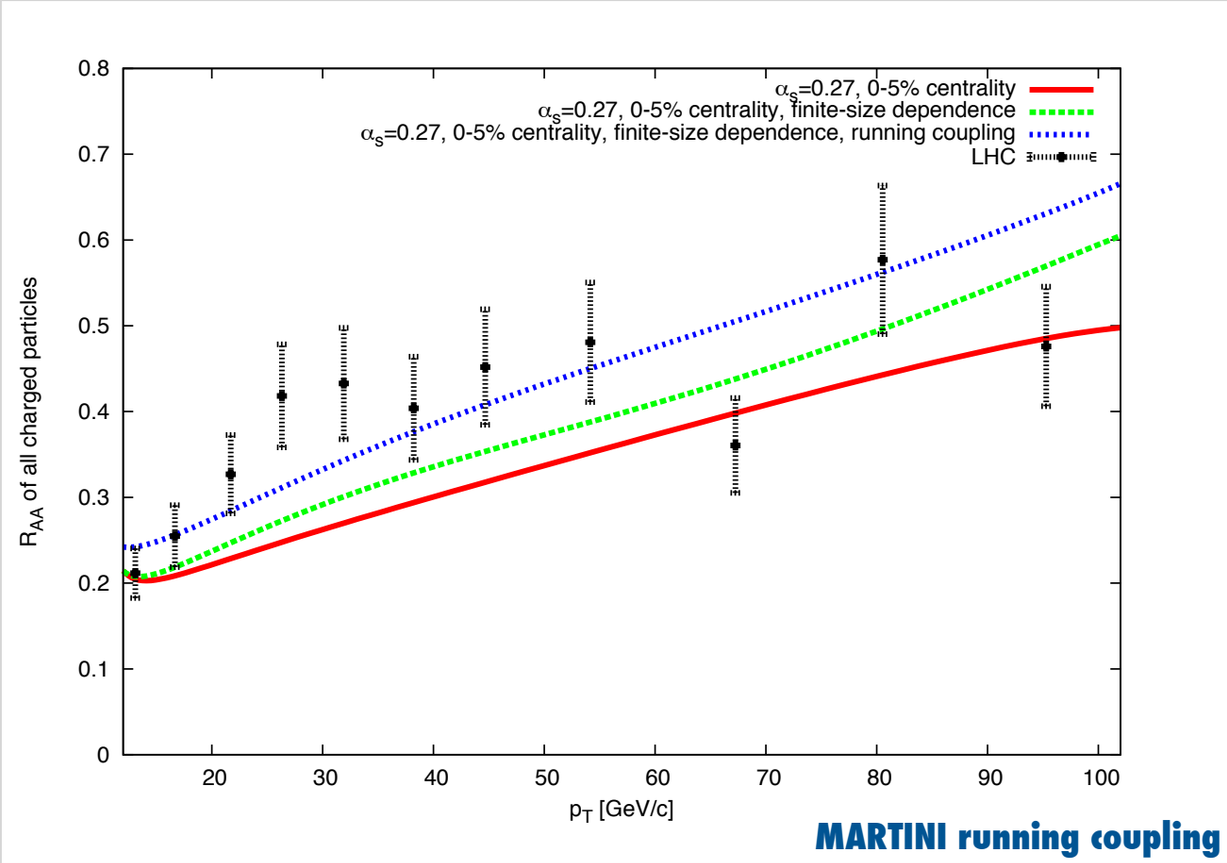
Buzzatti thu 15.50 [parallel 5C]

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

the truth is in data [and data is out there]

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

Vitev today 15.35 [parallel 1B]



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

#2 probing the medium

realistic medium

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

Majumder thu 14.00 [parallel 5D]

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

  - for a weakly coupled medium

Lekaveckas thu 14.20 [parallel 5B]

- 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]

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...*

- *outstanding tasks require structured efforts*
  - *JET collaboartion [US based]; Europe [??]; Asia [??]*

many thanks
to the program committee and IAC
for the privilege of giving this talk

many thanks to
J Albacete, N Armesto, A Beraudo,
J Casalderrey-Solana, L Cunqueiro, S Floerchinger,
K Rajagopal, M Ploskon, G Salam, C Salgado,
P Skands, and U Wiedemann
for extensive feedback