jet quenching:
towards medium probing

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Physics Colloquium, BNL, 11th December 2012

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
created in the collisions

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#1 establishing the probe

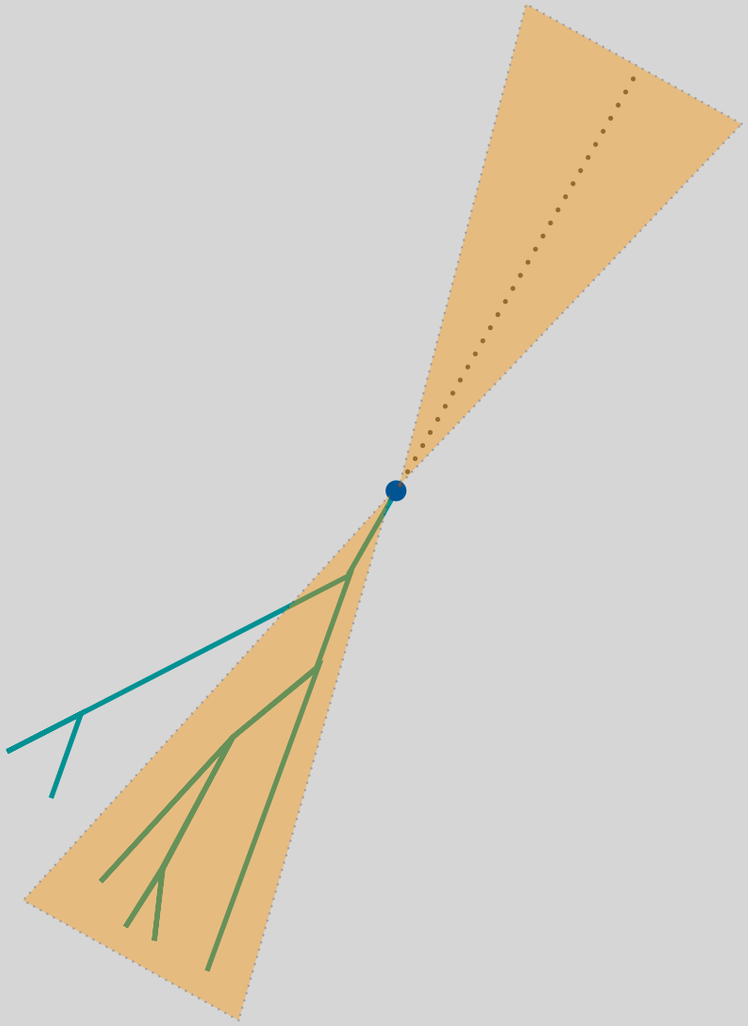
#2 probing the medium

not covered in this talk:

- *mass effects [heavy quarks]*
- *strongly coupled approaches*

#1 establishing the probe

jets in heavy ion collisions

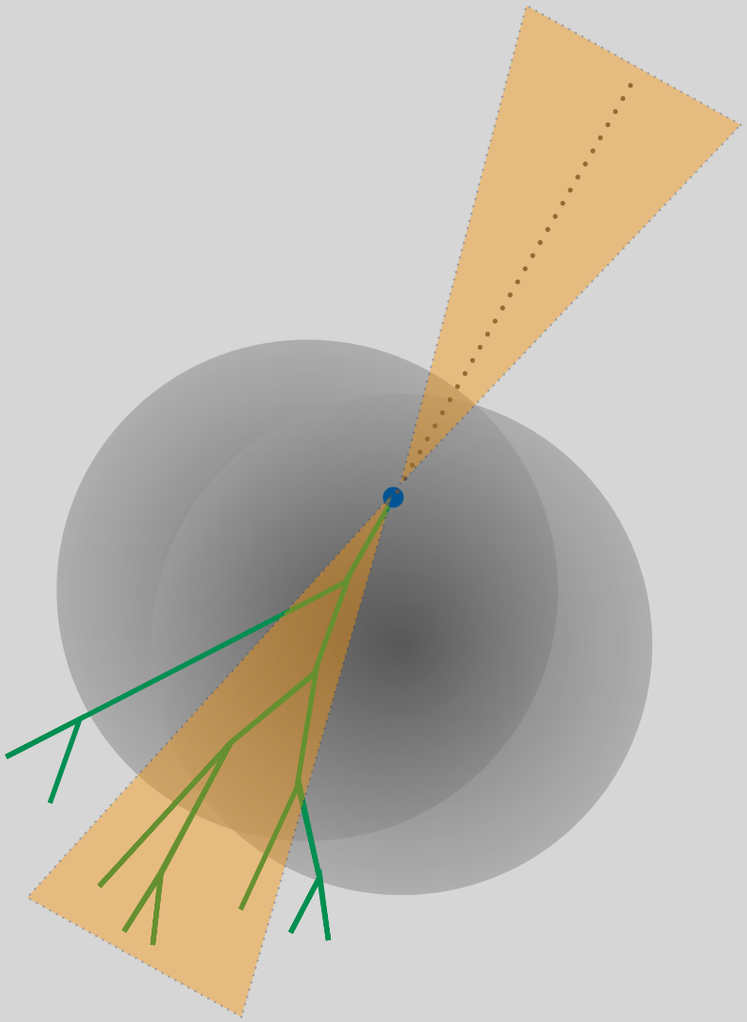


vacuum jets under overall excellent theoretical control

- reliable baseline and template for inclusion of medium effects
- 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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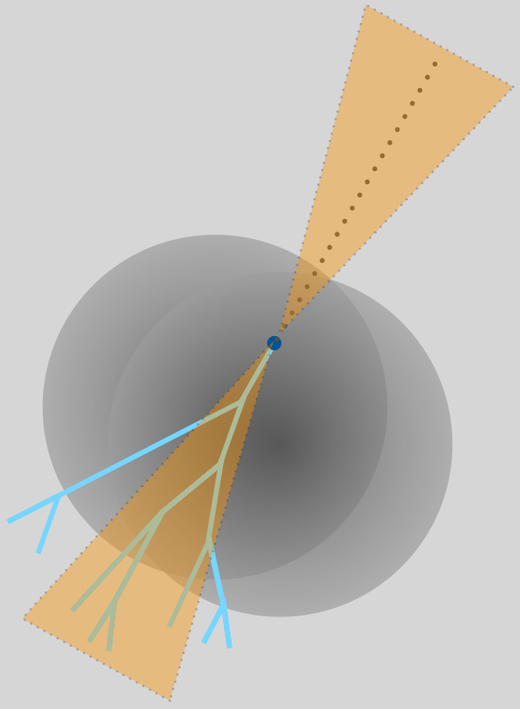
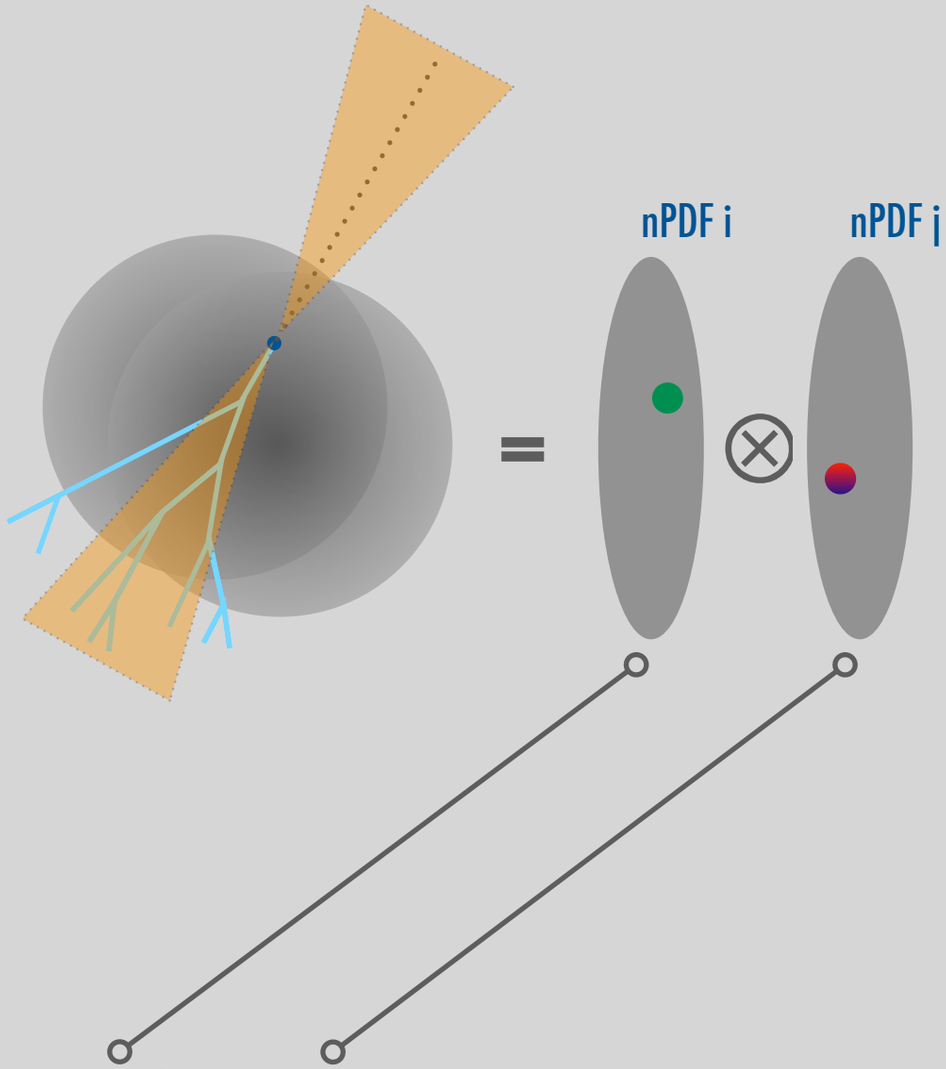


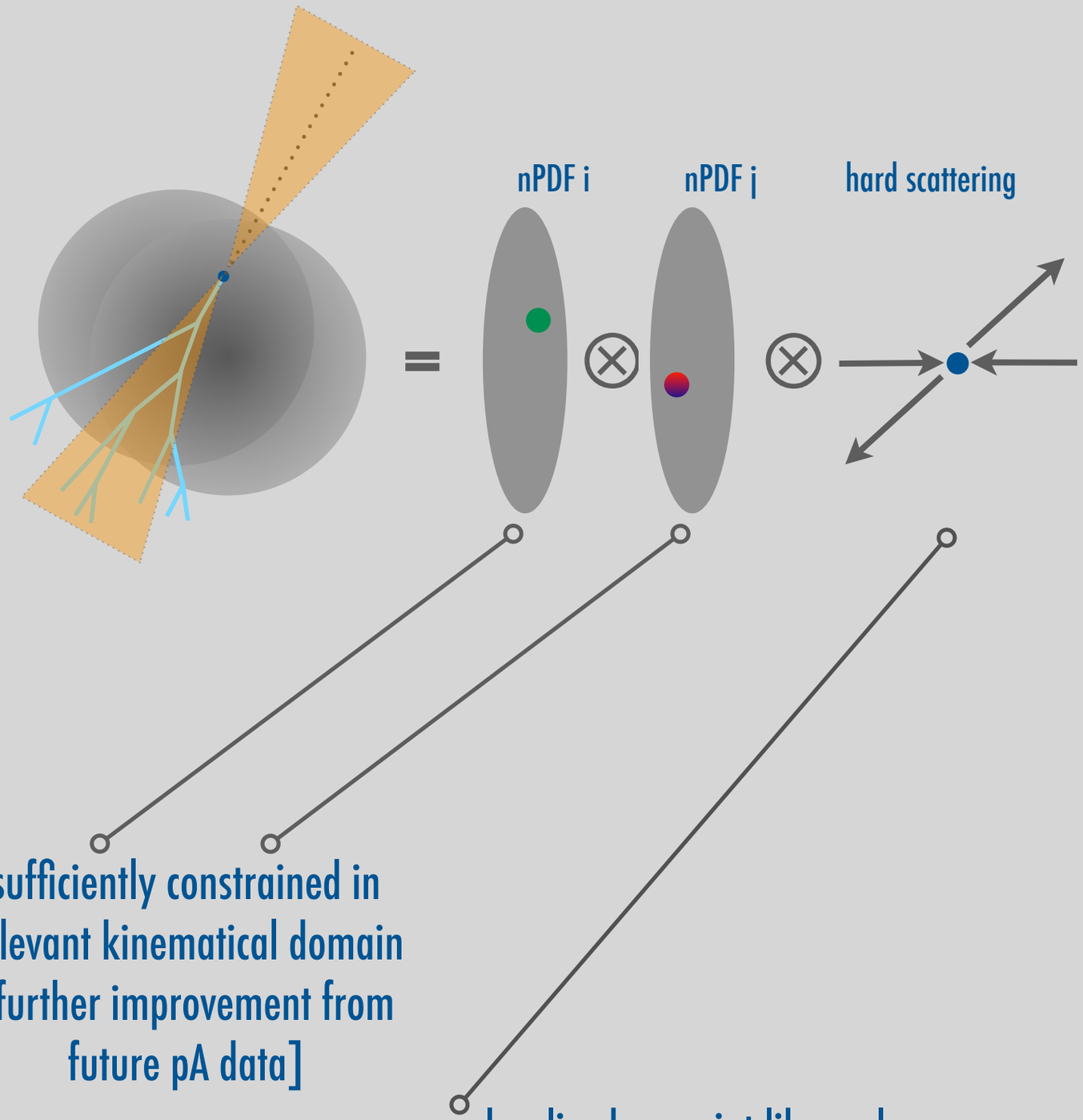
same factorizable structure [challengeable working hypothesis]

jets in heavy ion collisions



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

jets in heavy ion collisions



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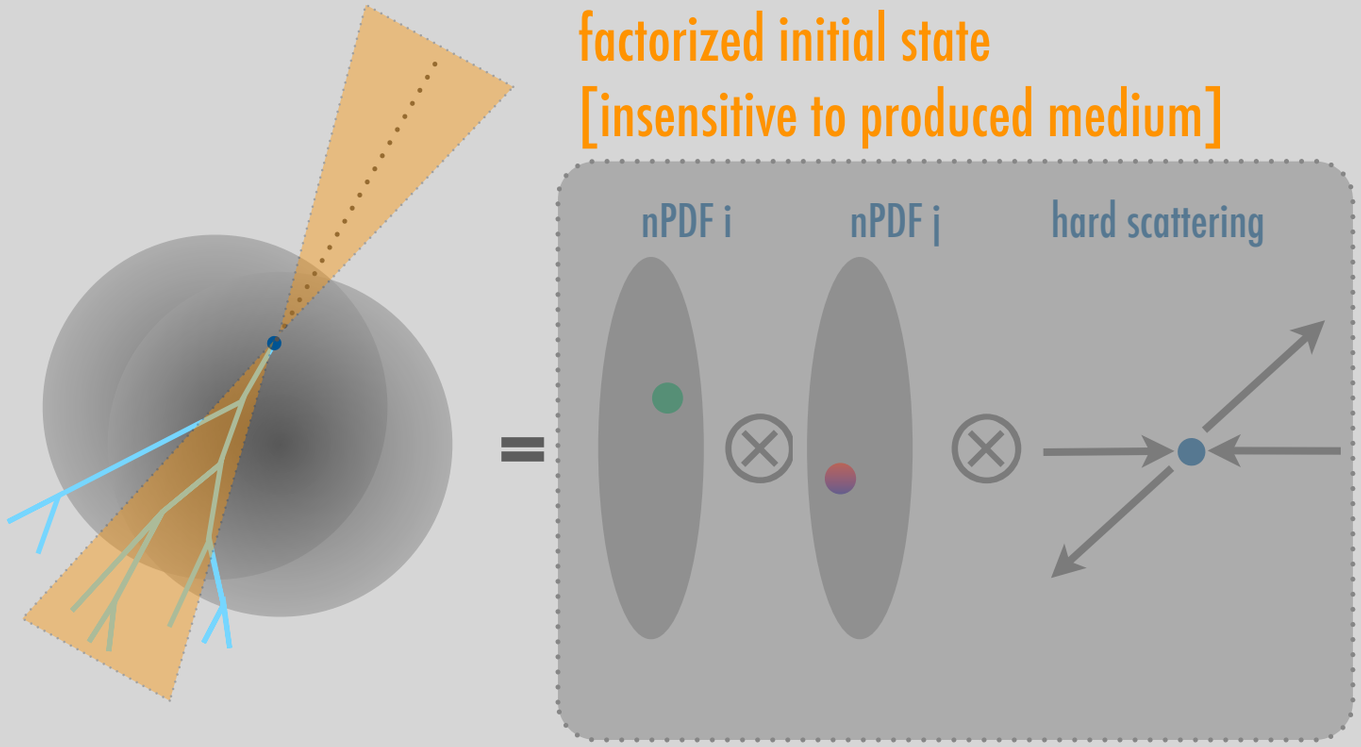

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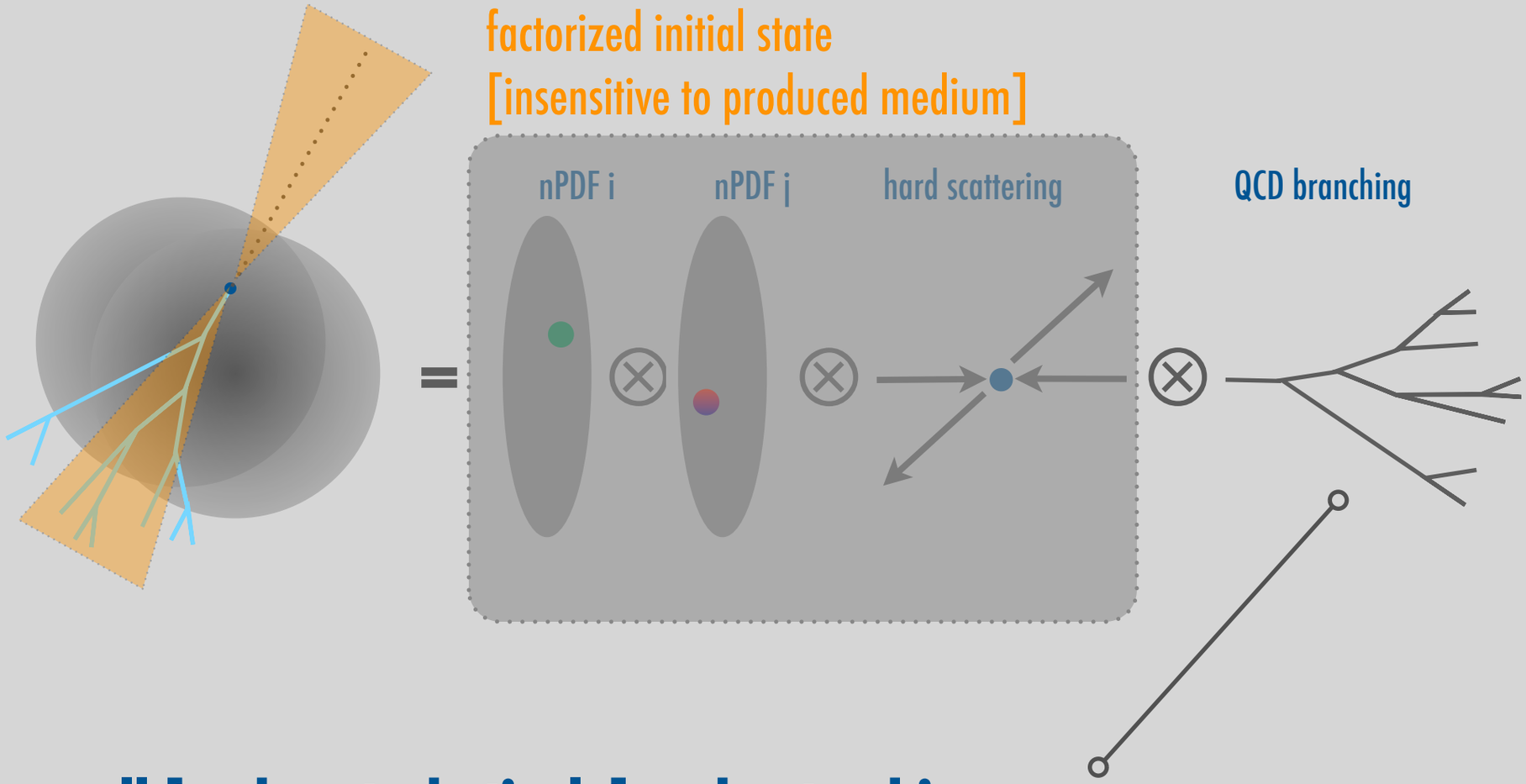


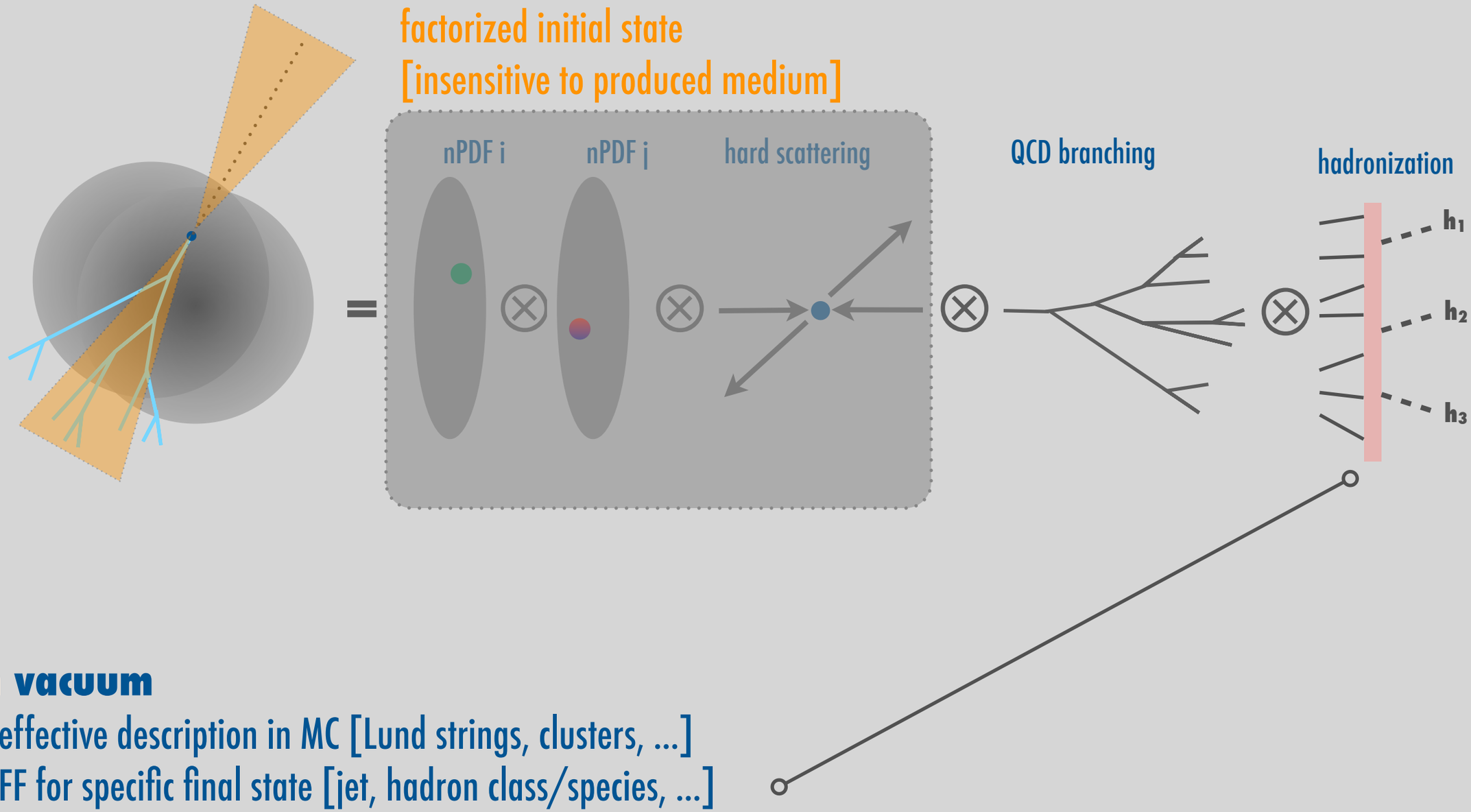
very well [and perturbatively] understood in vacuum

- 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

jets in heavy ion collisions



in vacuum

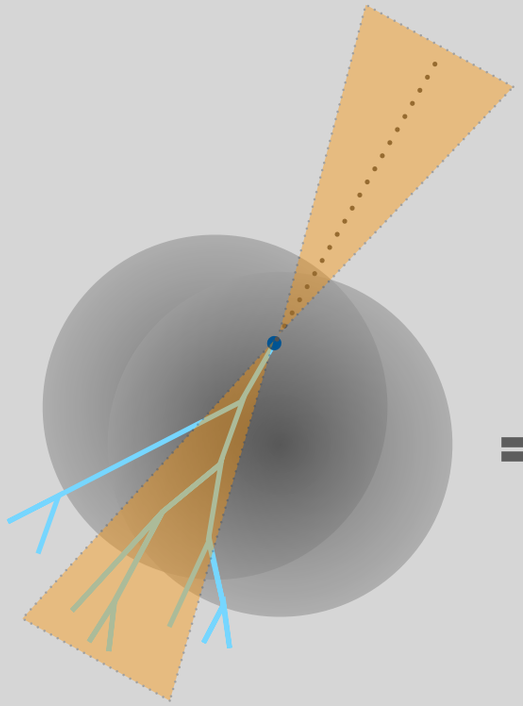
- effective description in MC [Lund strings, clusters, ...]
- FF for specific final state [jet, hadron class/species, ...]

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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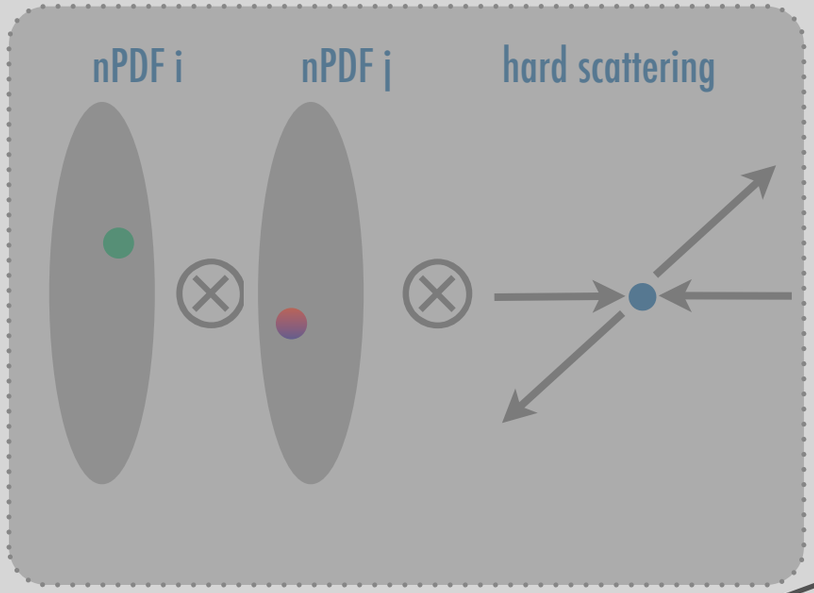
factorized initial state
[insensitive to produced medium]



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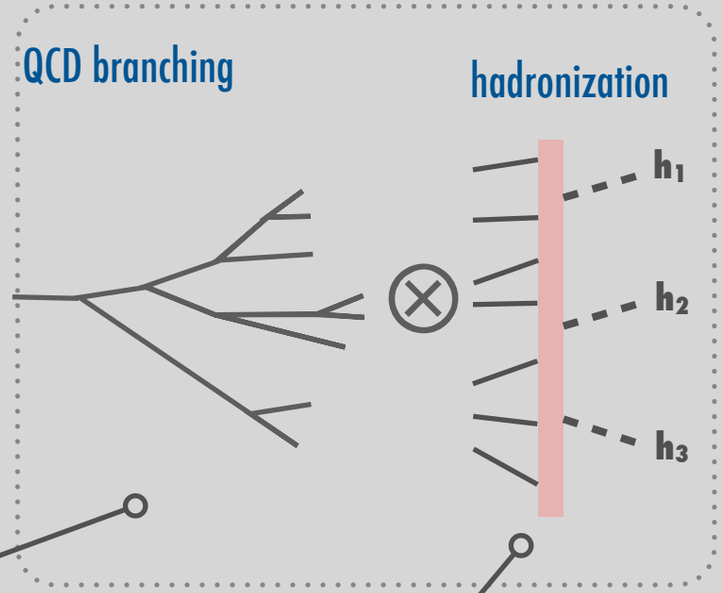
fragmentation function



jet reconstruction

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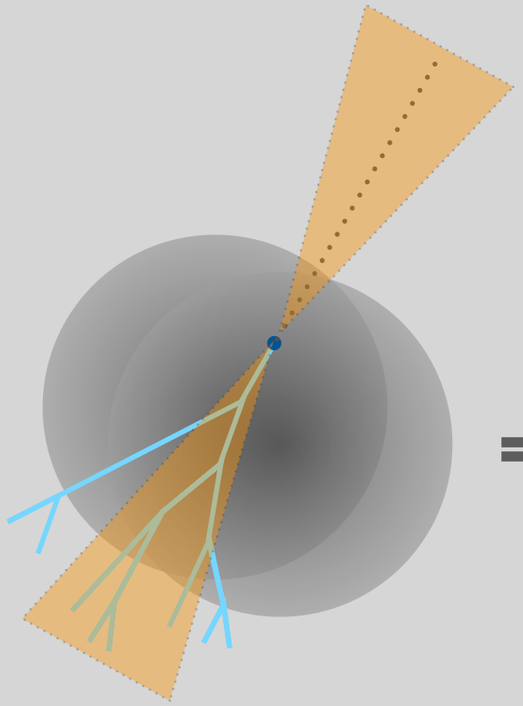

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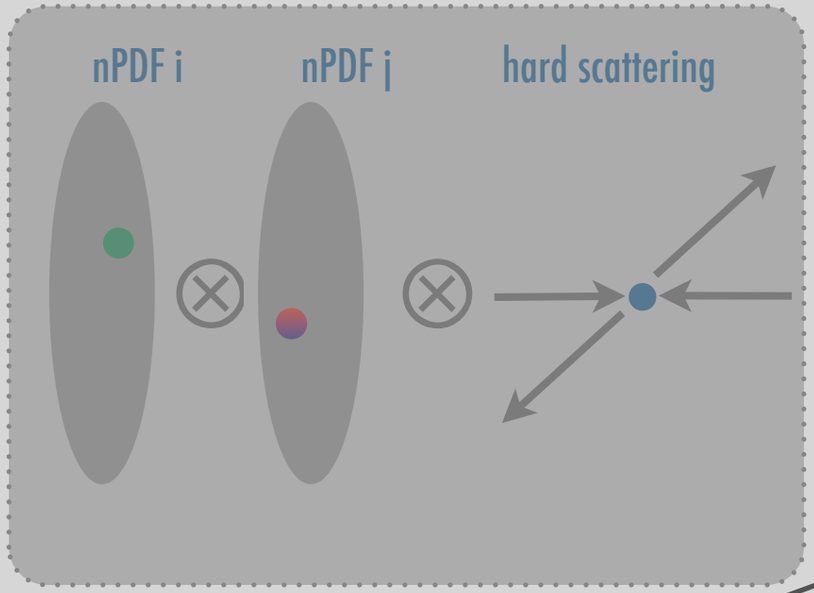

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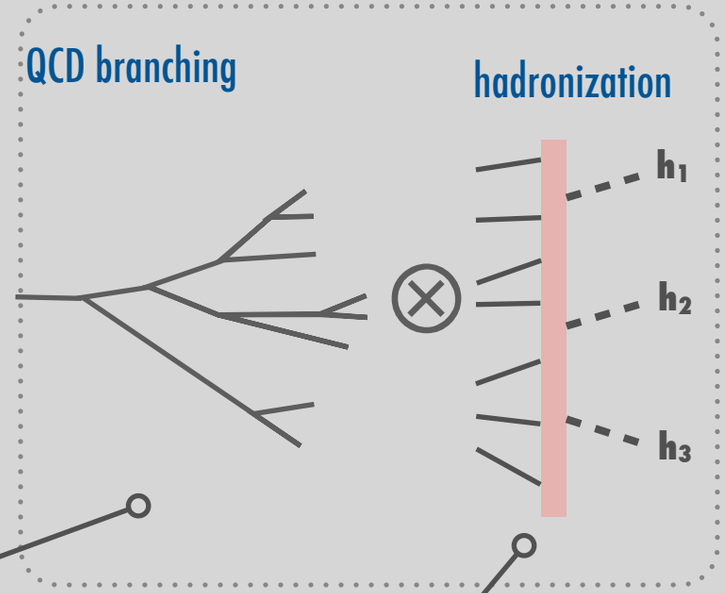

jet reconstruction

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]*

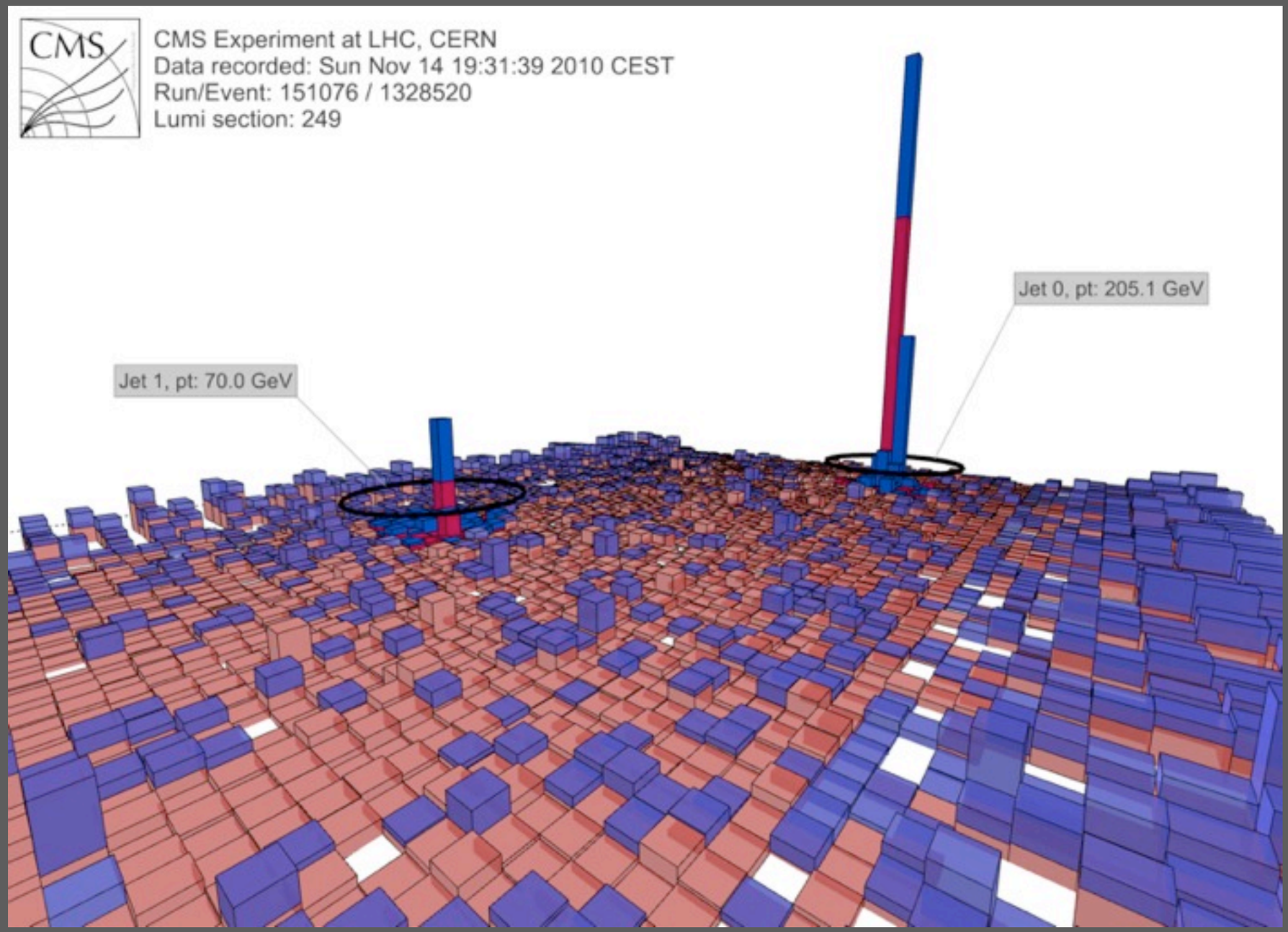
in the presence of a generic medium

and

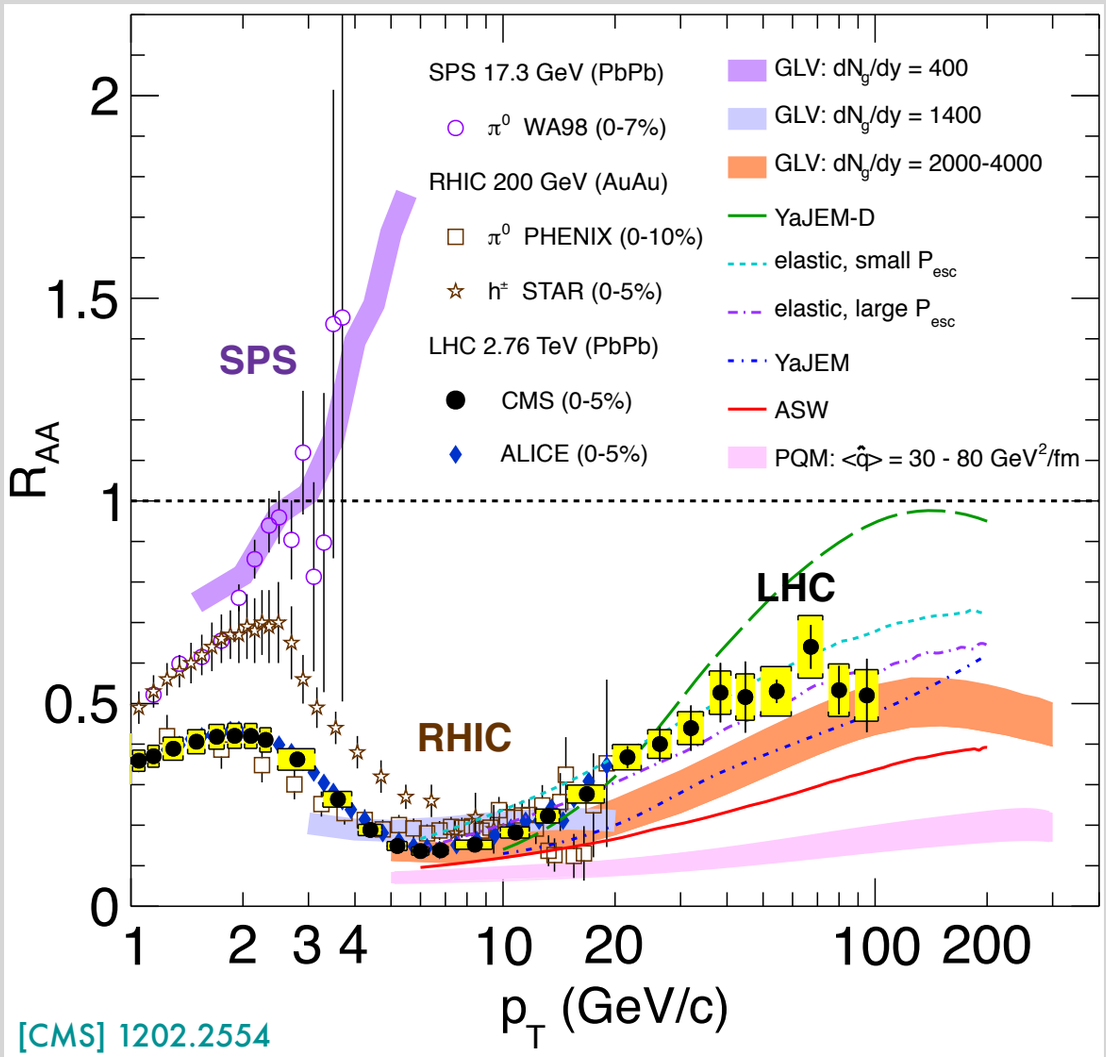
a detailed assessment of the sensitivity of observables
to specific medium effects

:: 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

observation of jet quenching



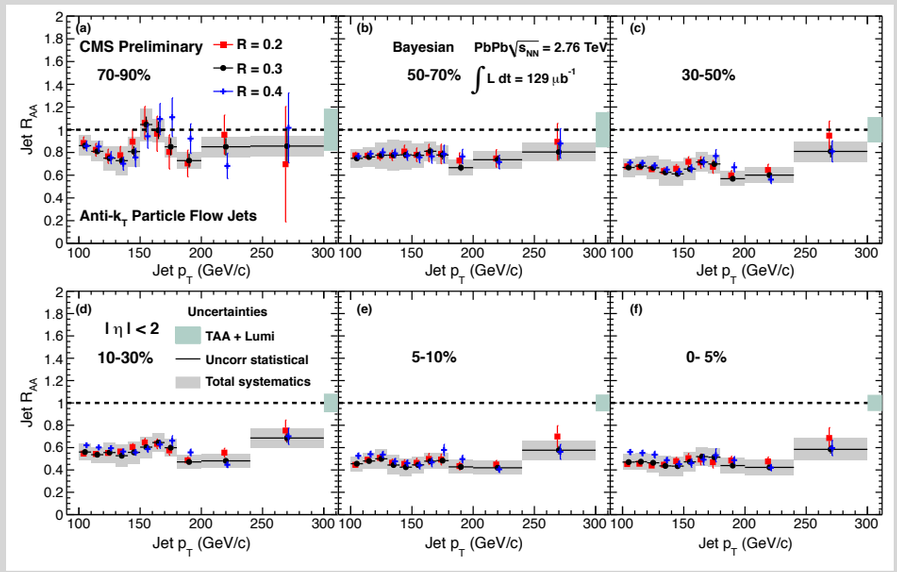
hadron spectra



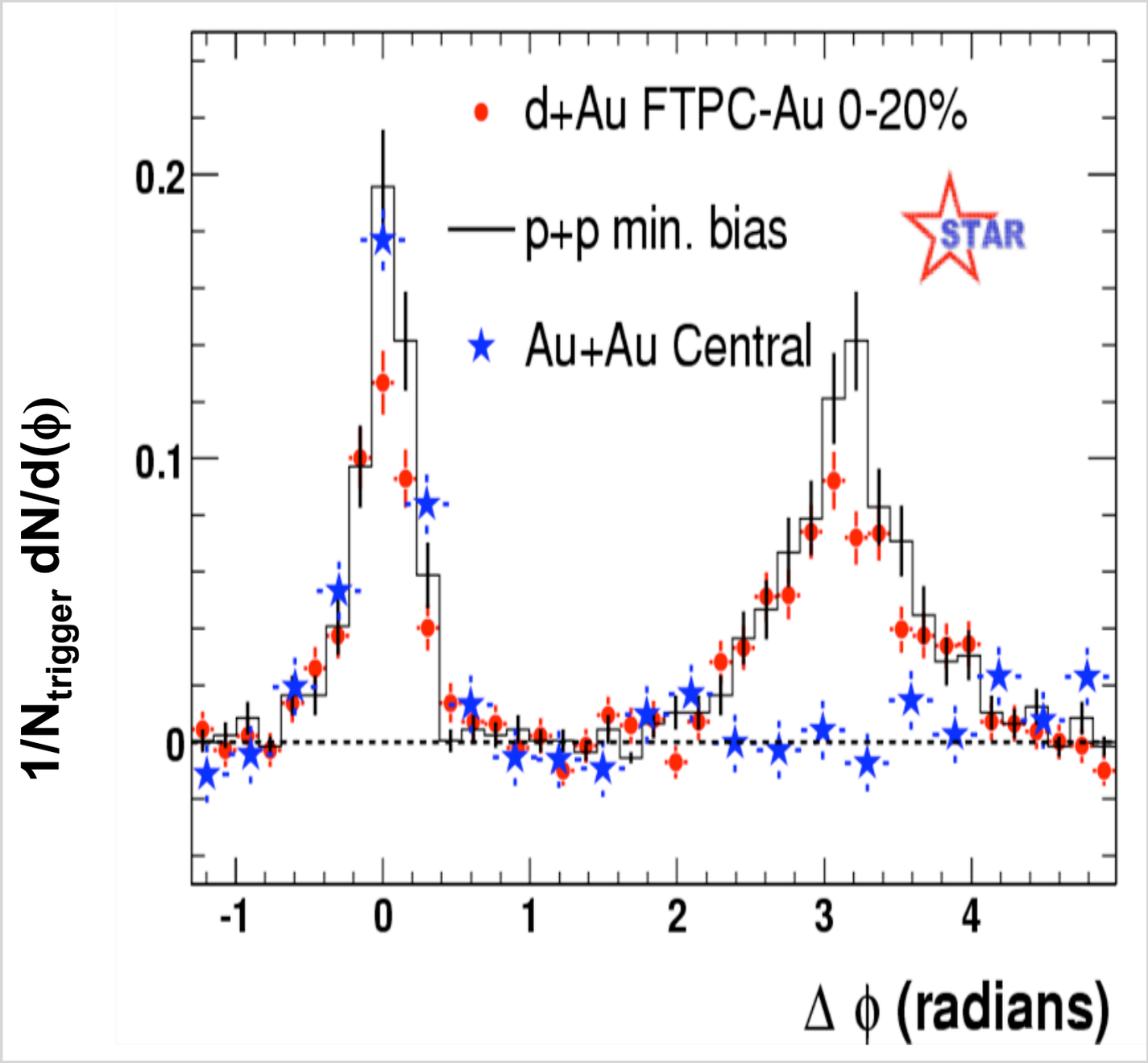
[CMS] 1202.2554

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{\mathrm{ch}}^{AA}/d\eta dp_T}{\langle N_{\mathrm{coll}}\rangle\,(1/N_{evt}^{pp})\, d^2N_{\mathrm{ch}}^{pp}/d\eta dp_T}$$

- clear and strong suppression of all hadronic yields
  - ↪ persistent to high-p_t
  - ↪ no apparent strong rising trend
  - ↪ photons/Z^0 unsupressed
  - ↪ centrality dependence
- jet suppression

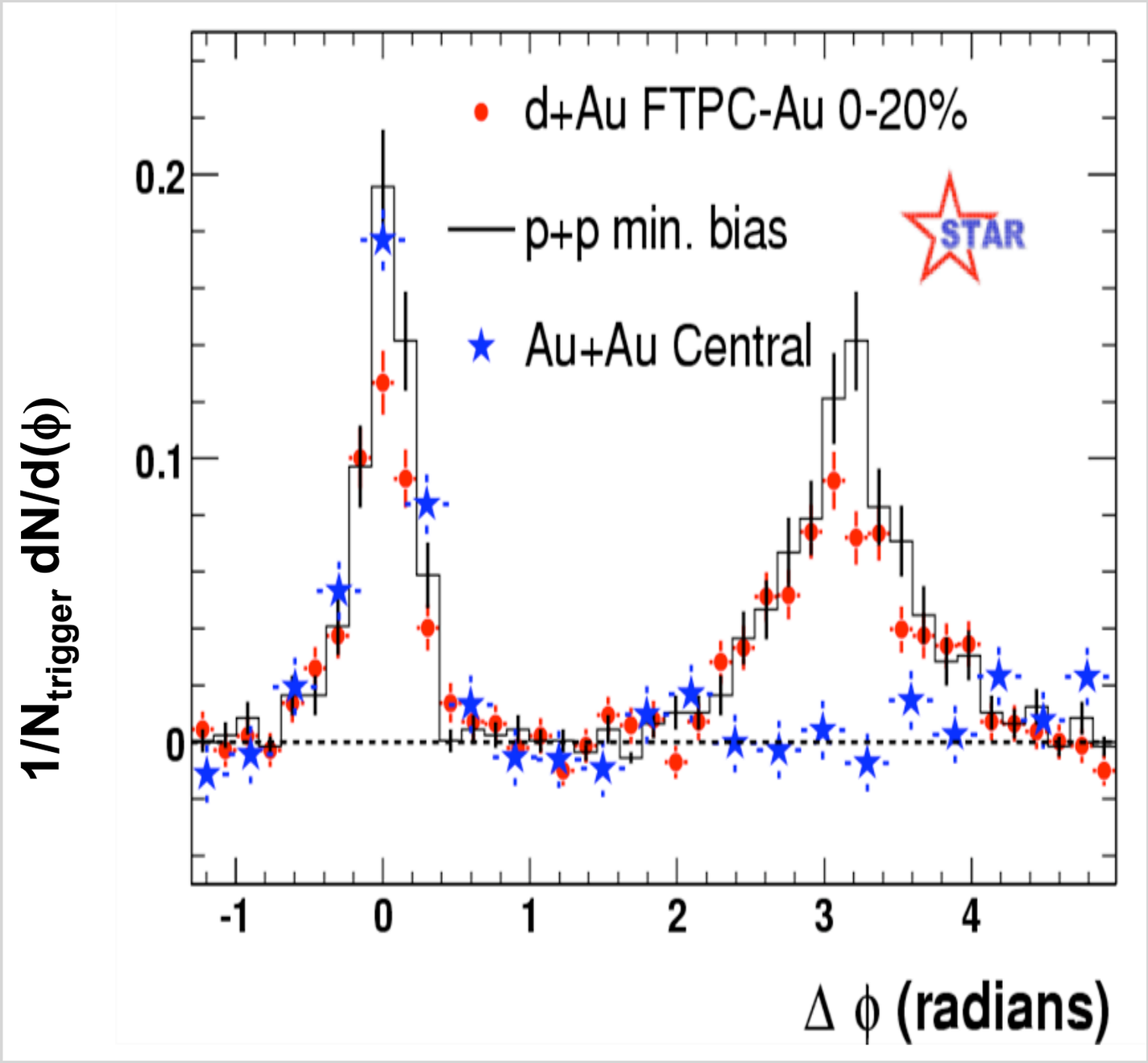


correlations



- suppression of back-to-back hadrons in AA
- but not in dA

correlations

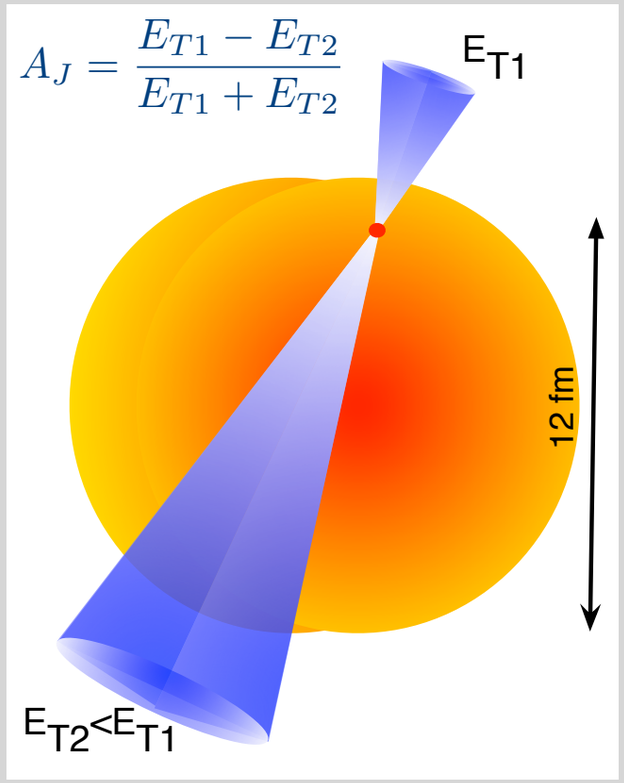


- suppression of back-to-back hadrons in AA
- but not in dA

hadronic observables intrinsically sensitive to hadronization and oblivious to broadening effects on radiation

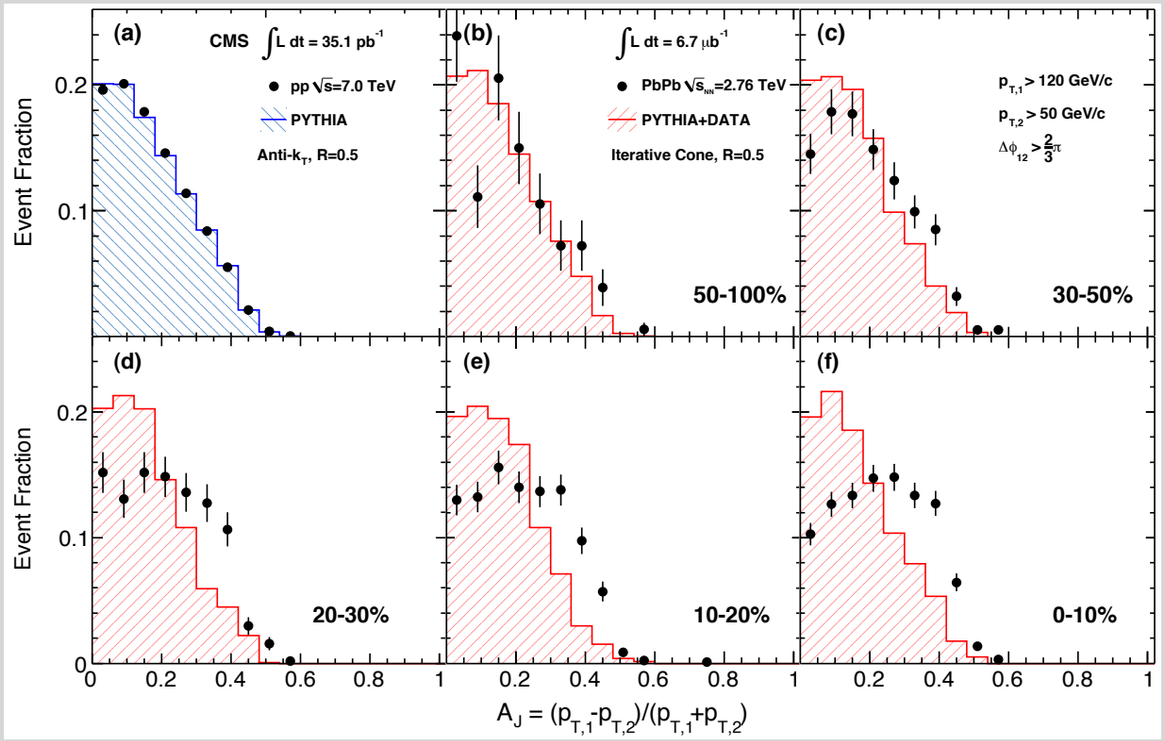
dijet asymmetry

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$



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

dijet asymmetry



- significant enhancement of asymmetry

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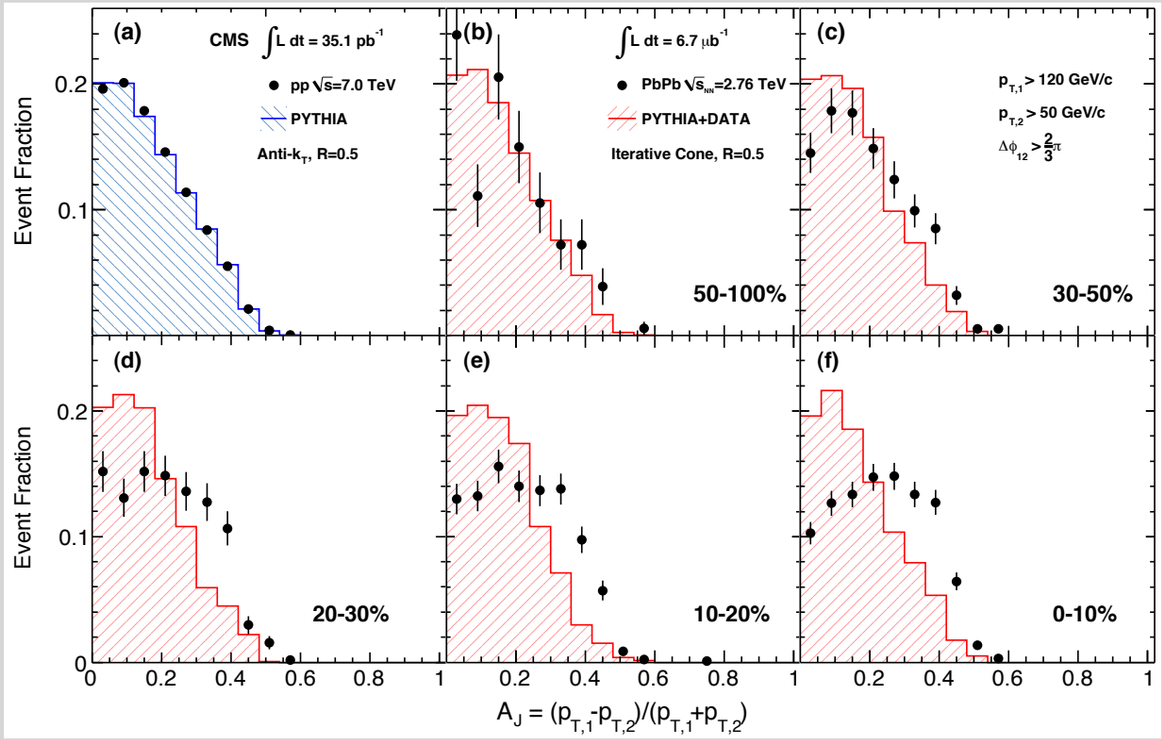
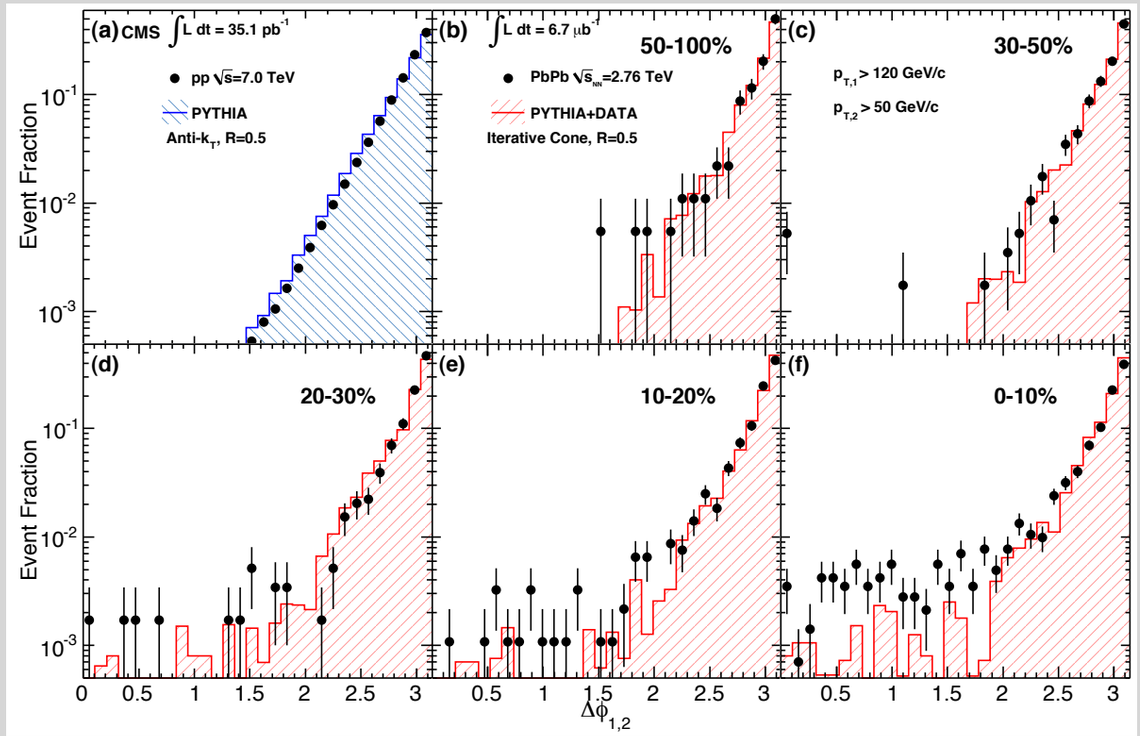
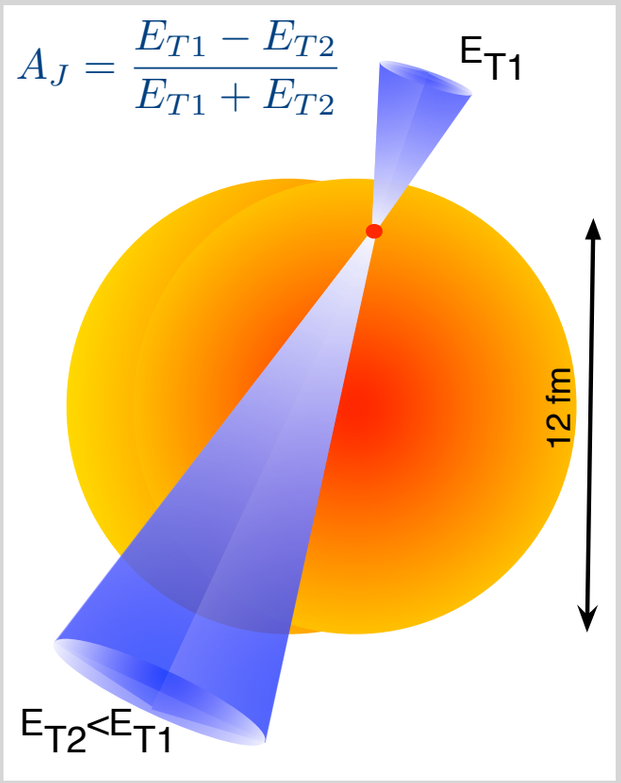




- significant enhancement of asymmetry
- no disturbance of azimuthal distribution

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



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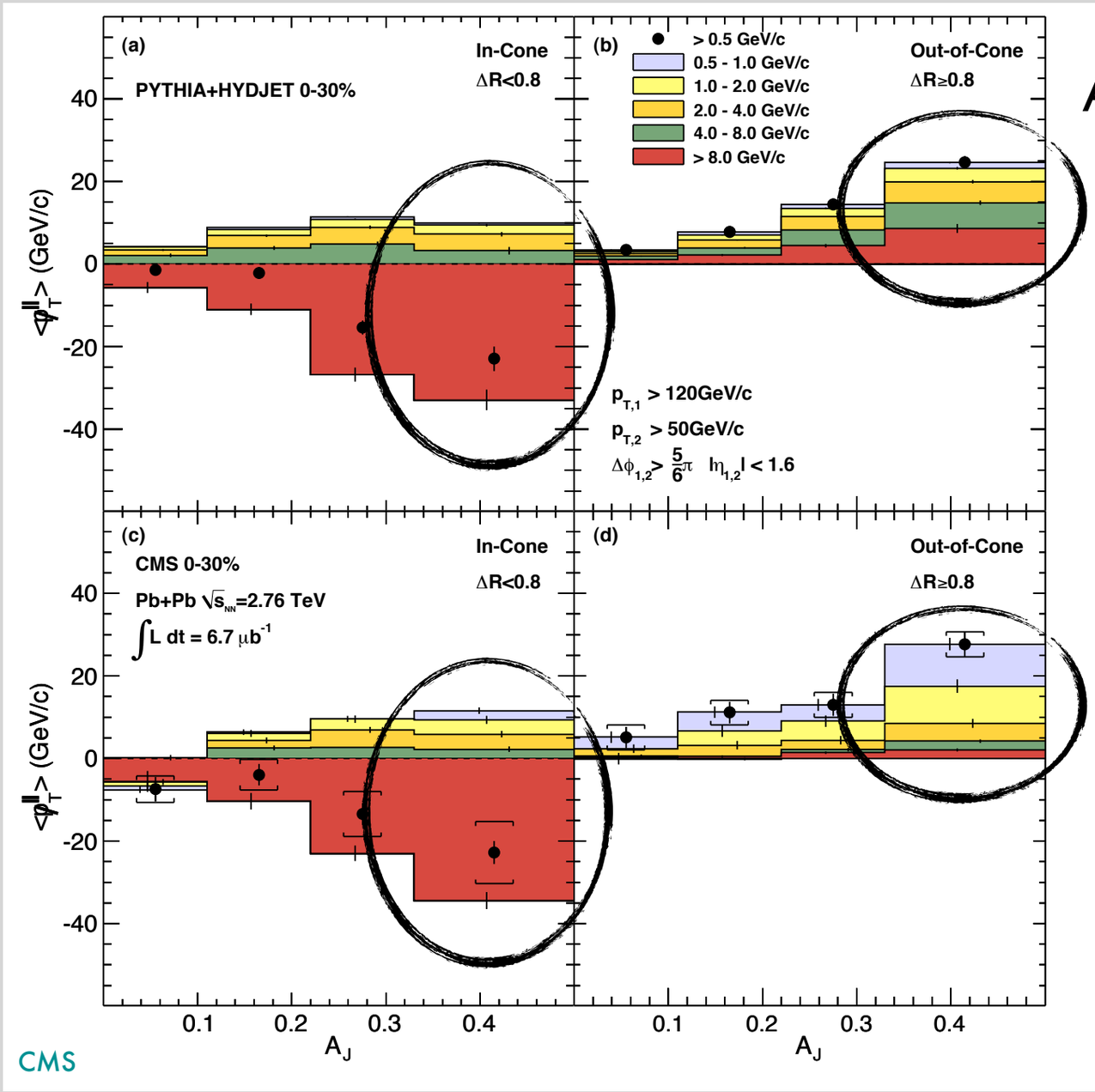
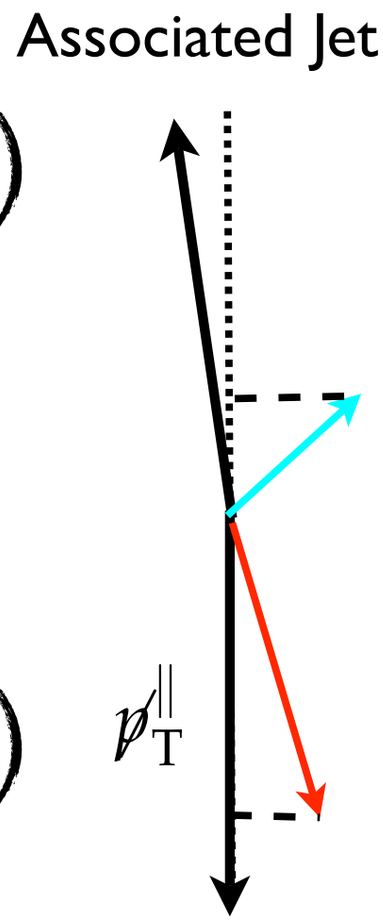
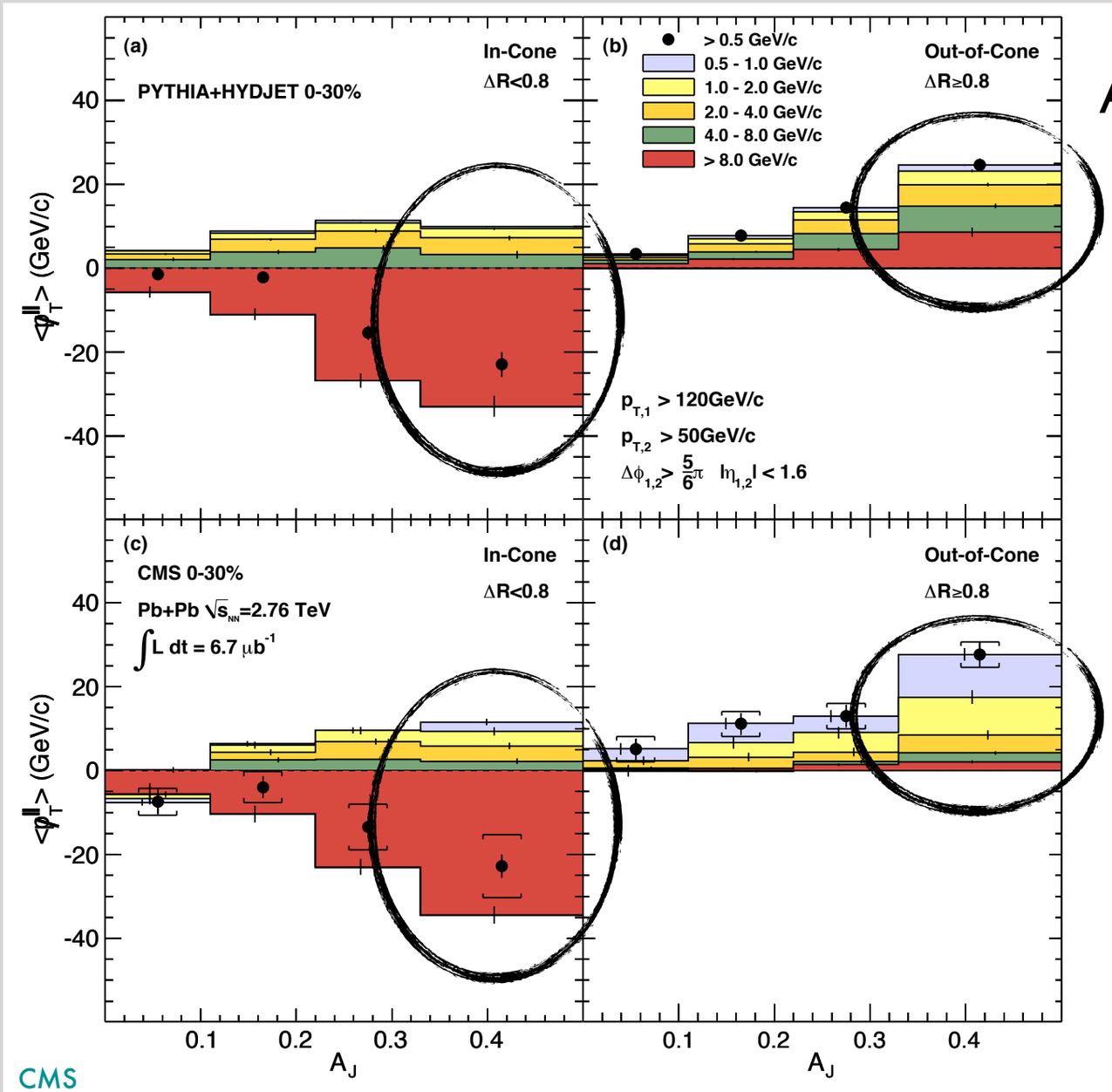


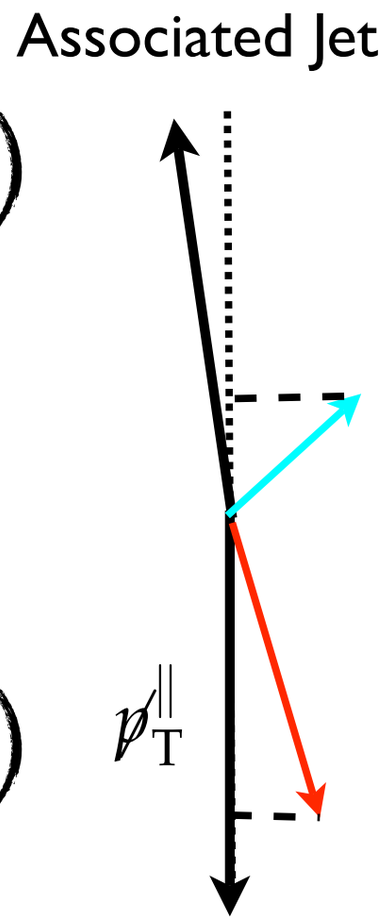


$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{Leading Jet}}\right)$$

- energy lost from jet cone recovered in soft fragments at large angles

dijet asymmetry





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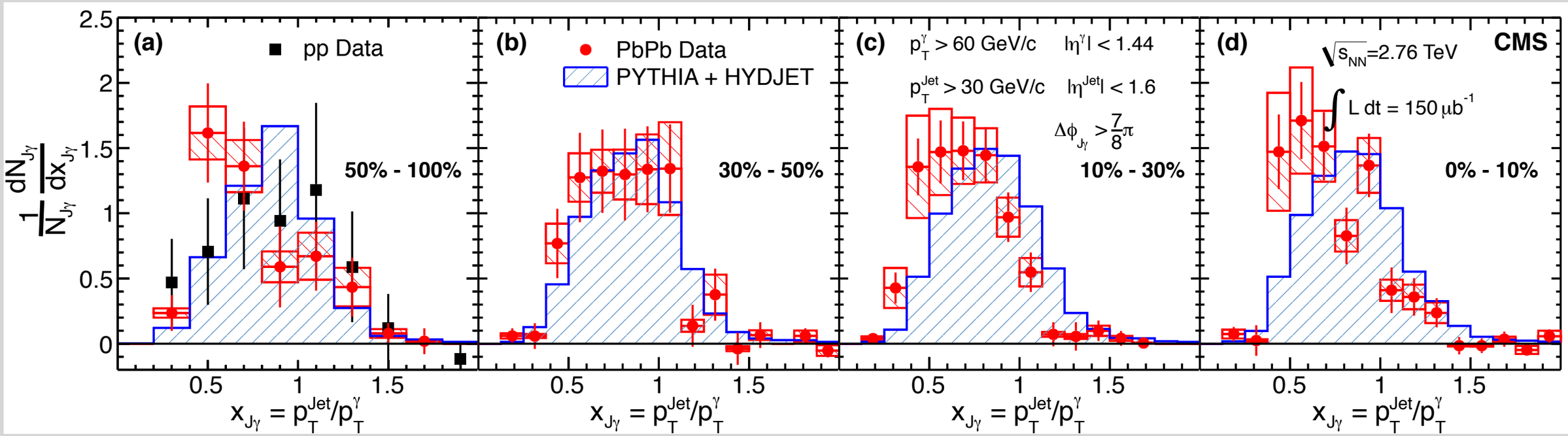
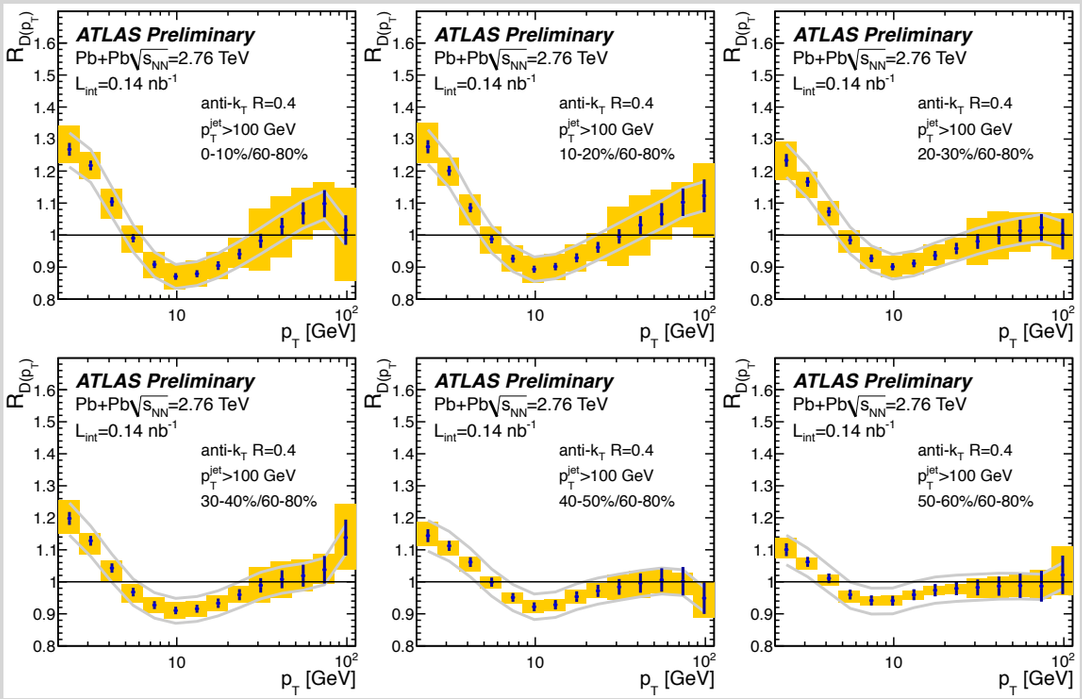
direct sensitivity to broadening

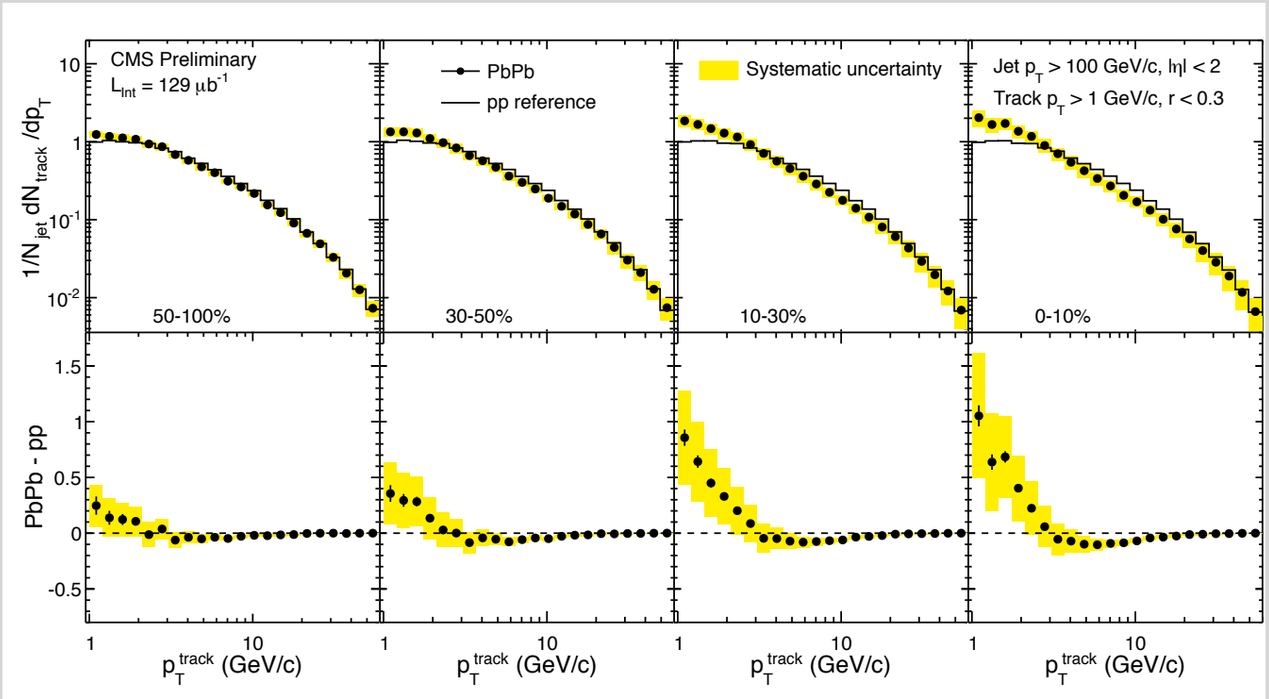
photon-jet correlations



- analogous to dijet case
  - ↪ azimuthal distribution unmodified
  - ↪ knowledge of initial parton energy [obvious advantage]
  - ↪ energy lever-arm [very] limited by statistics

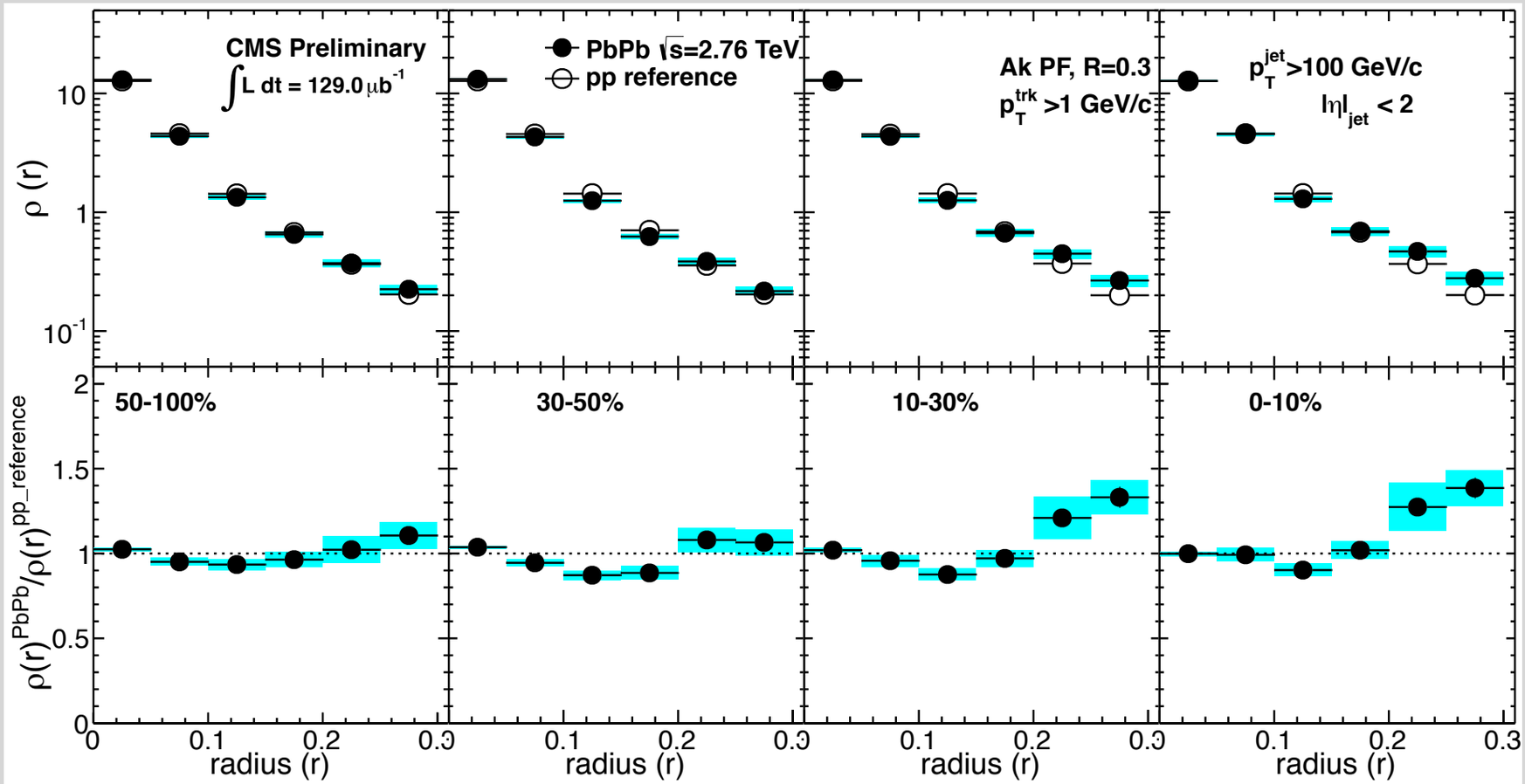
fragmentation functions





- FF modified by loss of intermediate p_t fragment reconverted into several low p_t fragments
  - ↪ [personal view] major caveat for phenomenological interpretation: jets with same *final* energy are compared
  - ↪ very wide binning: all jets above 100 GeV

jet shapes



- most salient: excess for larger radii [of soft fragments]
  - ↪ consistent with FF results
  - ↪ same caveats as FF

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
  - ↪ **A**rnold-**M**oore-**Y**affe
  - ↪ **H**igher-**T**wist [Guo and Wang]

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- differ in modeling of the medium and some kinematic assumptions [most shared]

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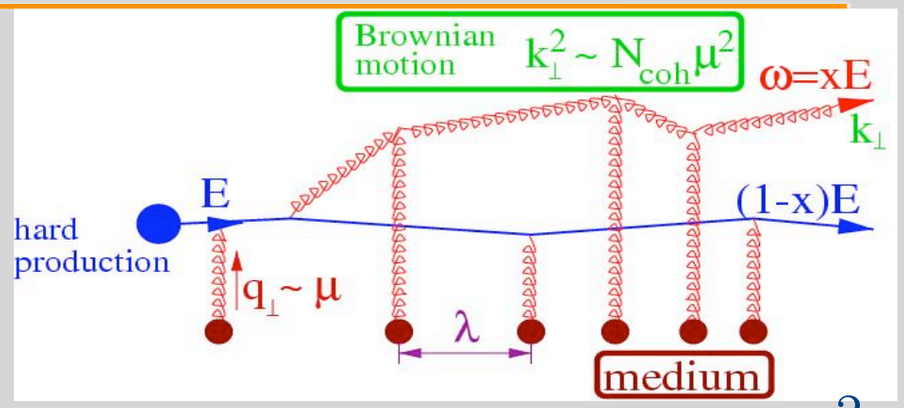
- Monte Carlo implementations [HIJING, Q-PYTHIA/Q-HERWIG, JEWELL, YaJEM, MARTINI]

medium induced radiation [BDMPS-Z]



$$\hat{q} \simeq \frac{\mu^2}{\lambda}$$

- Brownian motion

$$\langle k_\perp^2 \rangle \sim \hat{q} L$$

- accumulated phase

$$\left\langle \frac{k_\perp^2 L}{\omega} \right\rangle \sim \frac{\hat{q} L^2}{\omega} \sim \frac{\omega_c}{\omega}$$

characteristic gluon energy

- number of coherent scatterings

$$N_{coh} \sim \frac{t_{coh}}{\lambda} \qquad t_{coh} \sim \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

$$k_\perp^2 \sim \hat{q}\, t_{coh}$$

- gluon energy distribution

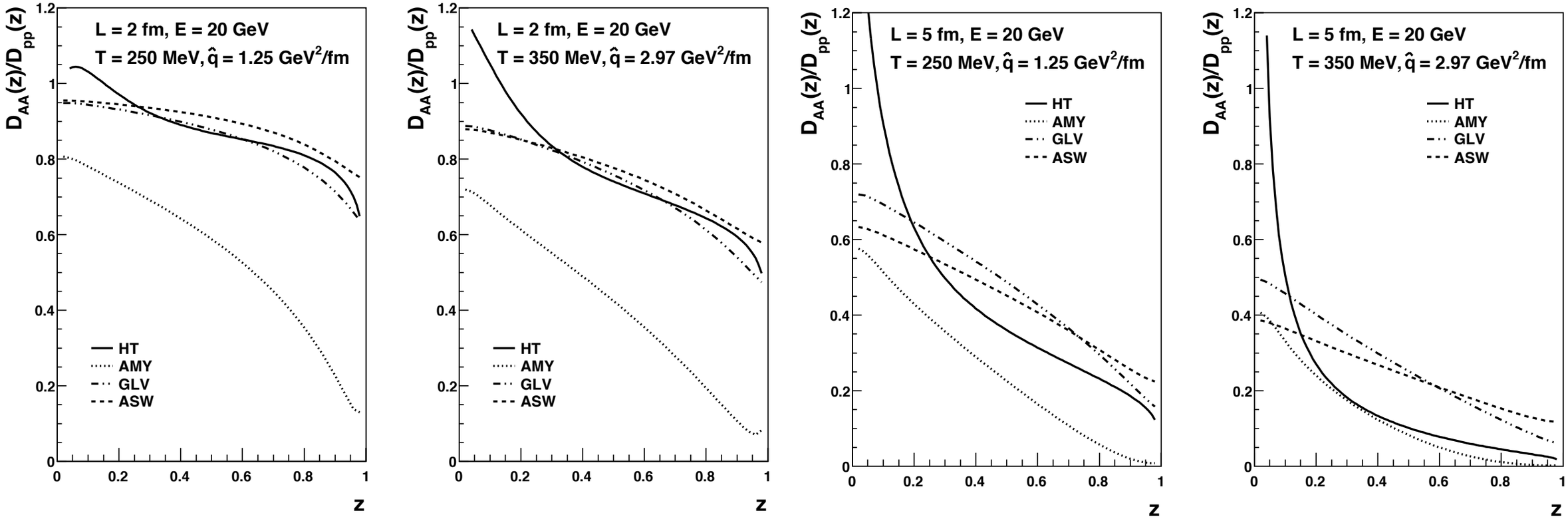
$$\omega \frac{dI_{med}}{d\omega dz} \sim \frac{1}{N_{coh}} \omega \frac{dI_1}{d\omega dz} \sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$$

non-abelian LPM

- average energy loss

$$\Delta E = \int_0^L dz \int_0^{\omega_c} \omega d\omega \frac{dI_{med}}{d\omega dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2$$

medium induced radiation

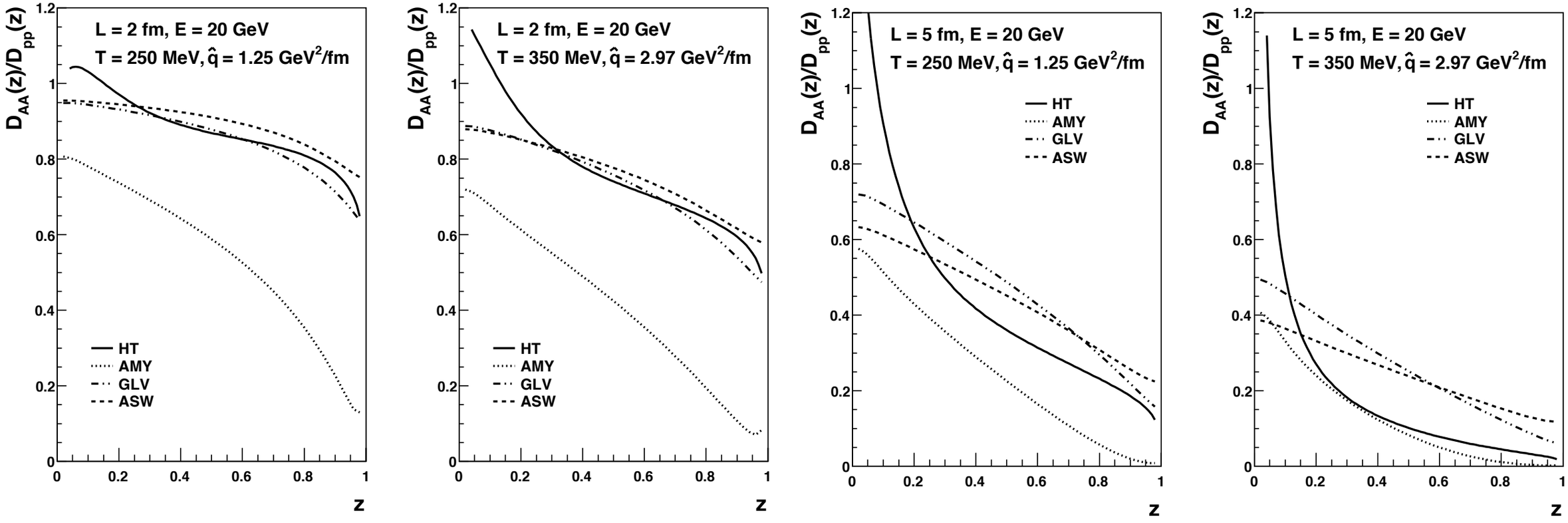


medium modification of quark fragmentation function

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

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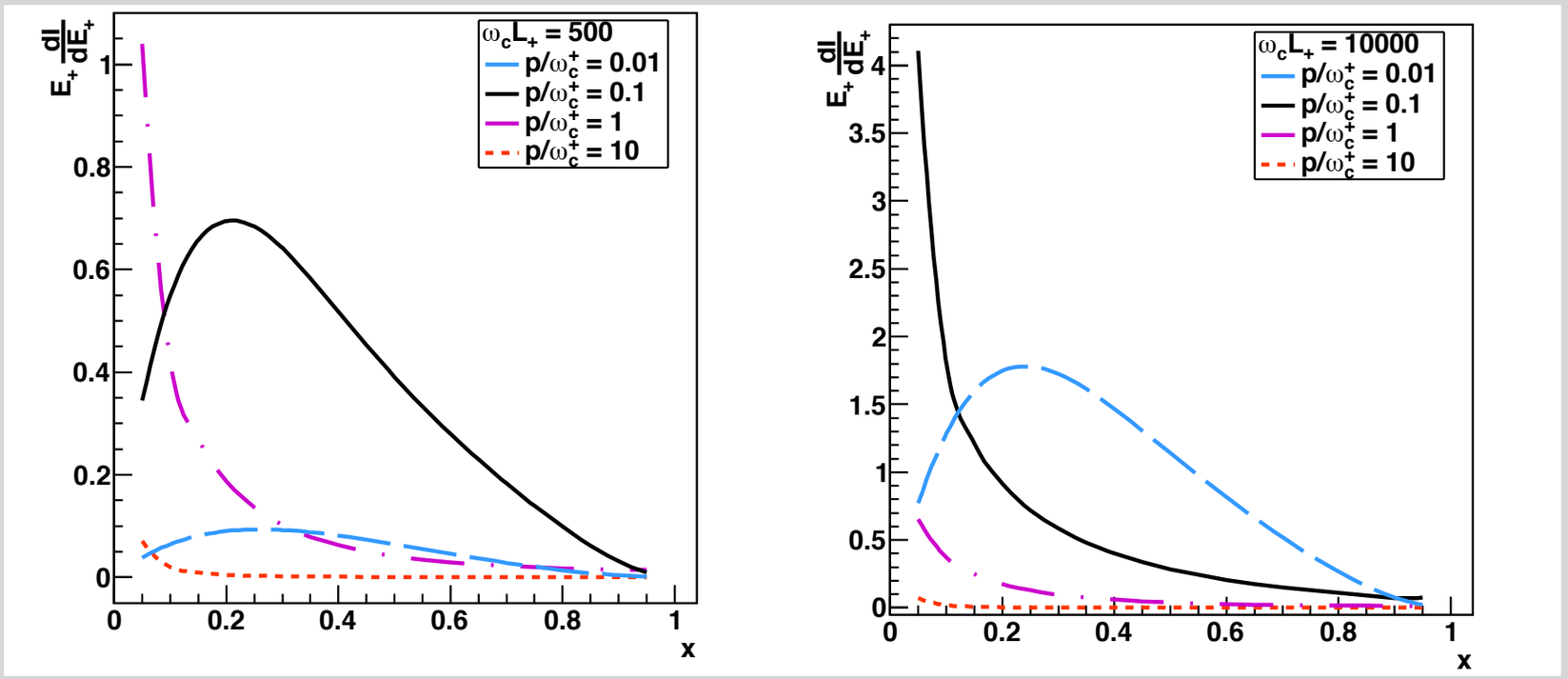
- energy of radiated gluon assumed [not in AMY] much smaller than that of emitter [$x=\omega/E \ll 1$] but emission spectrum computed for all allowed phase space with violation of energy-momentum conservation cured by explicit cut-offs

  - 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 [1006.1367]

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: $p_c \sim [\lambda^0, \lambda^2, \boldsymbol{\lambda}]$
  - soft modes: $p_s \sim [\lambda^2, \lambda^2, \boldsymbol{\lambda^2}]$
  - Glauber modes [jet-medium interaction]: $q \sim [\lambda^2, \lambda^2, \boldsymbol{\lambda}]$

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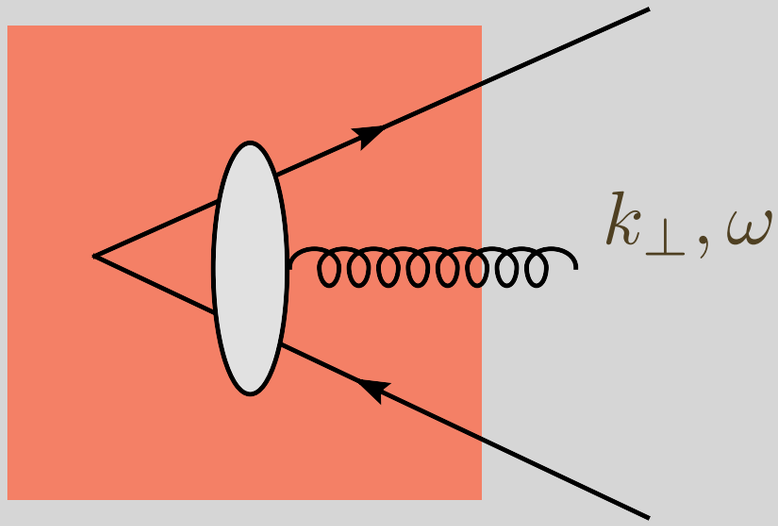

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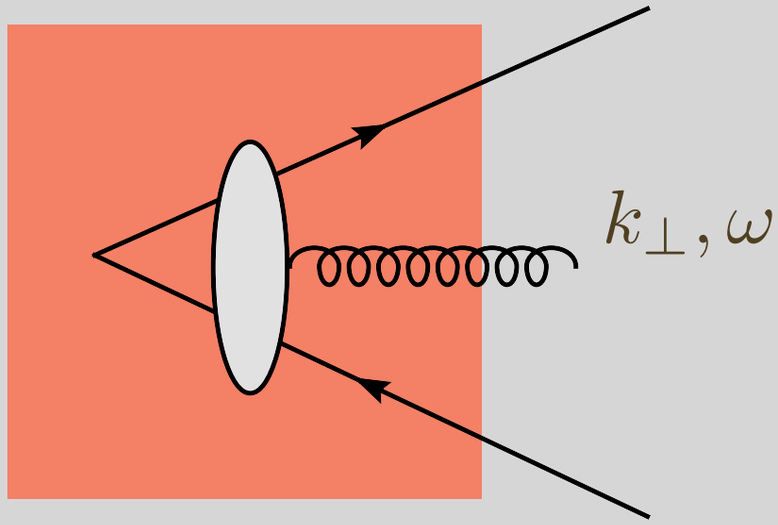

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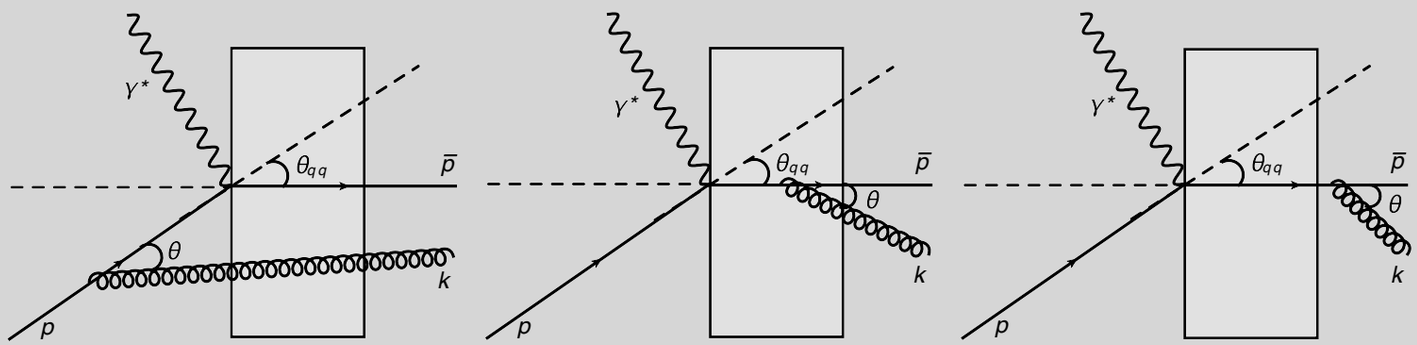
↪ also for initial/final state

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



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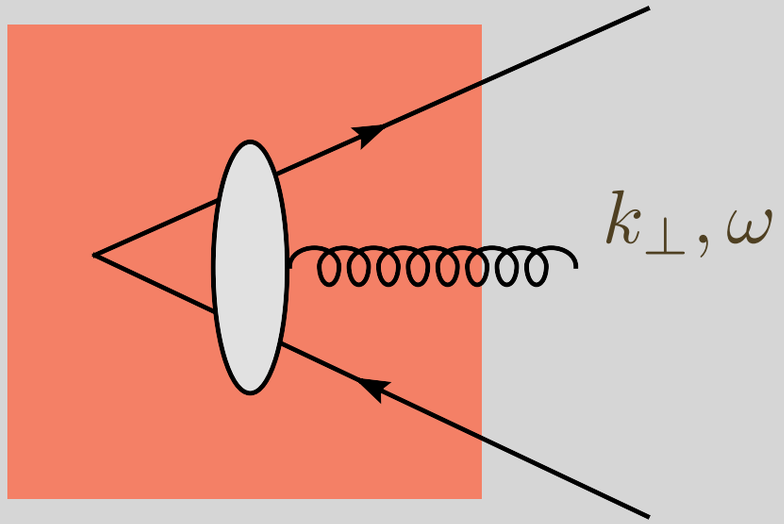

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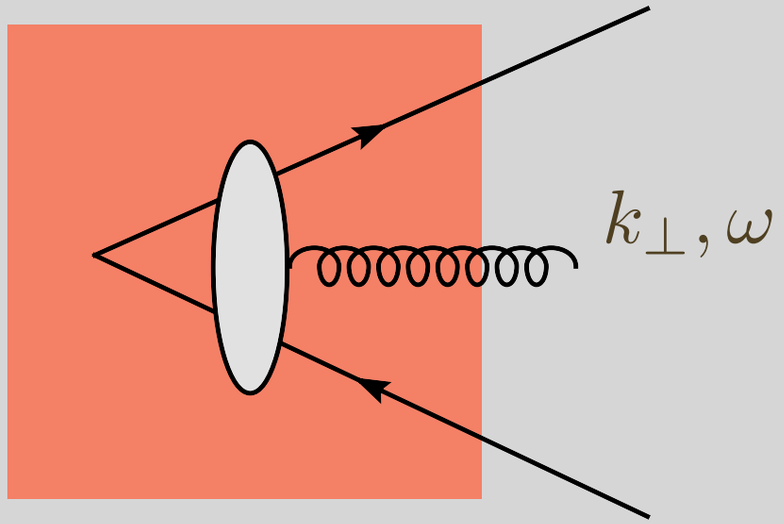

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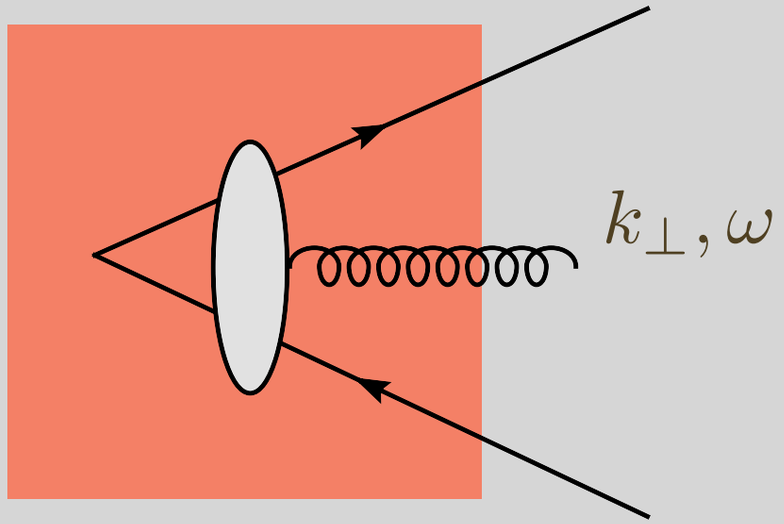

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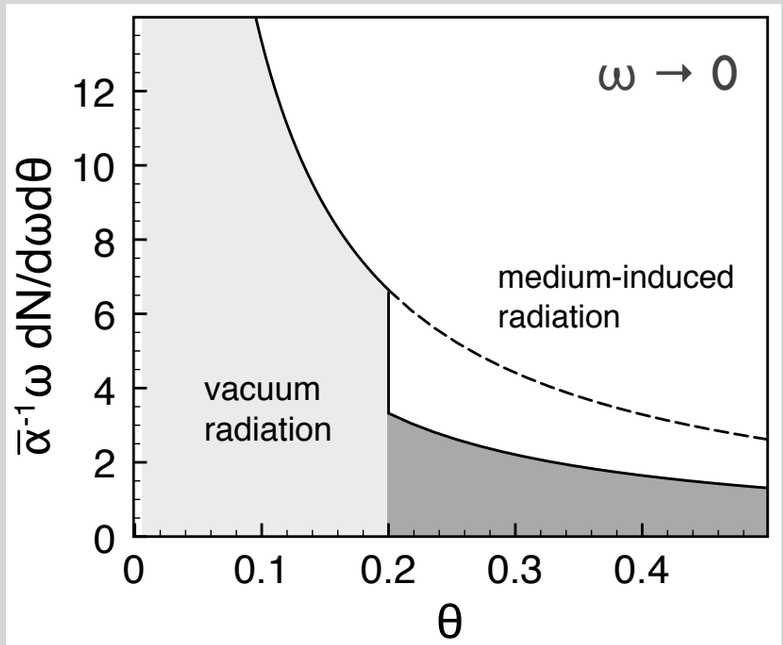

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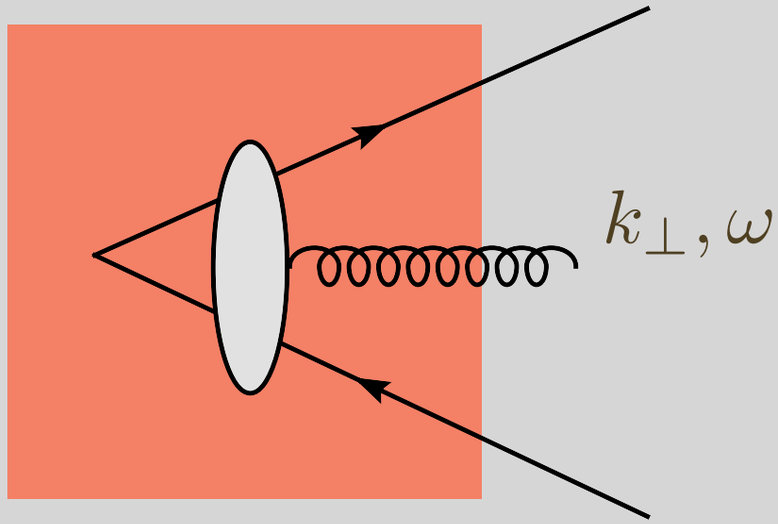

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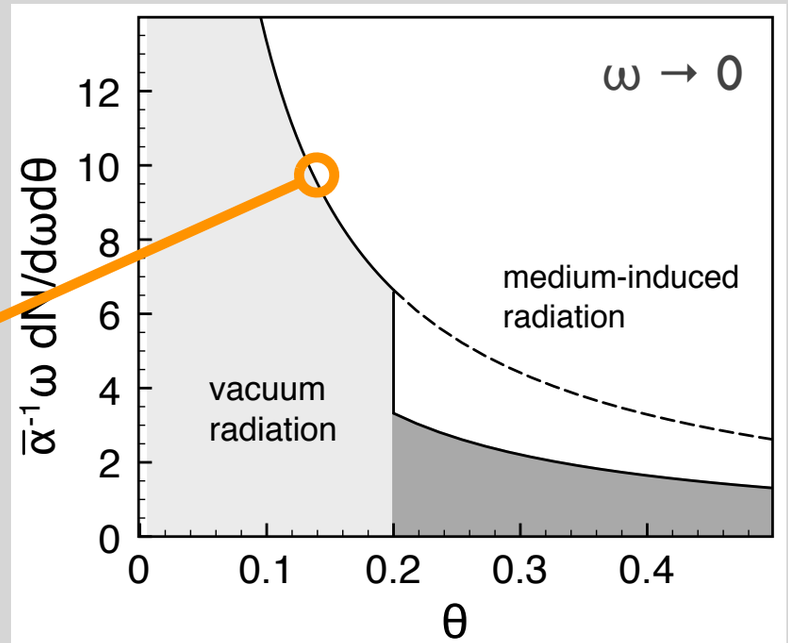

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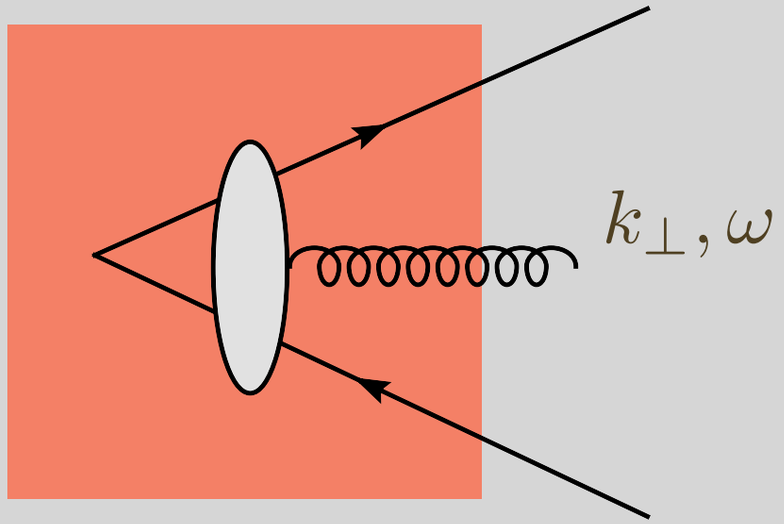

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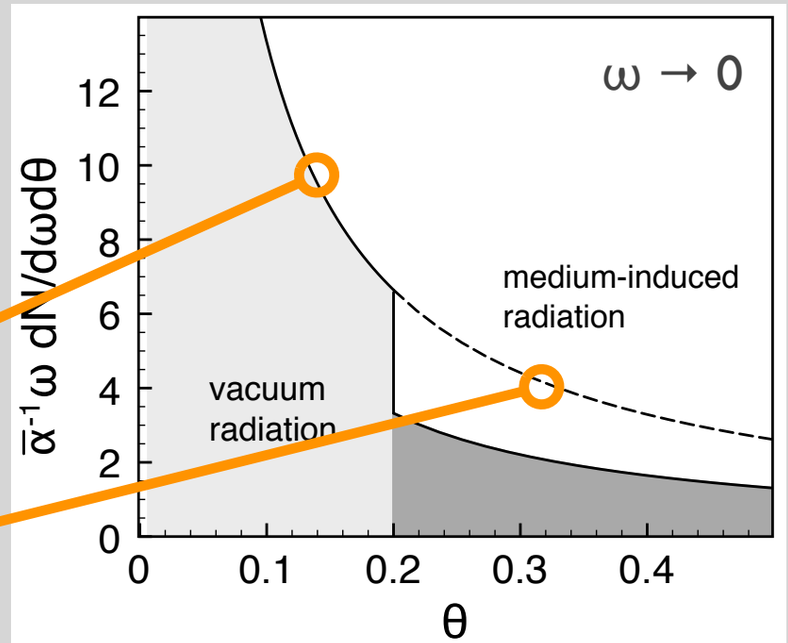

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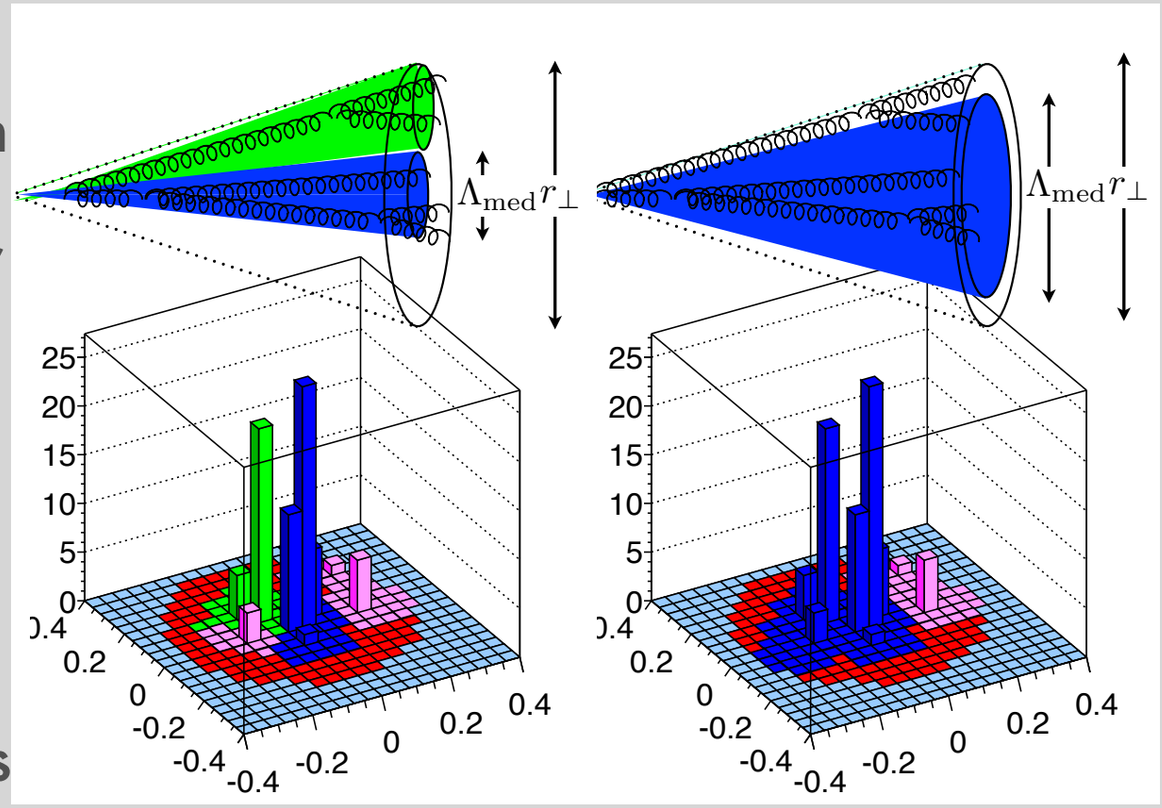

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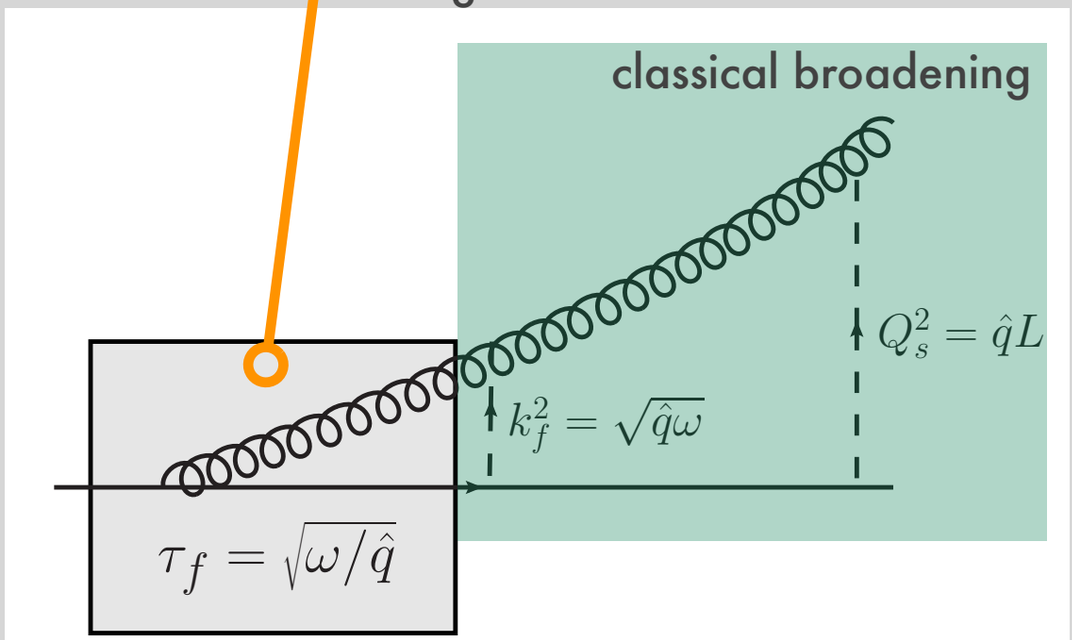
emerging full account of medium effect on QCD coherence

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



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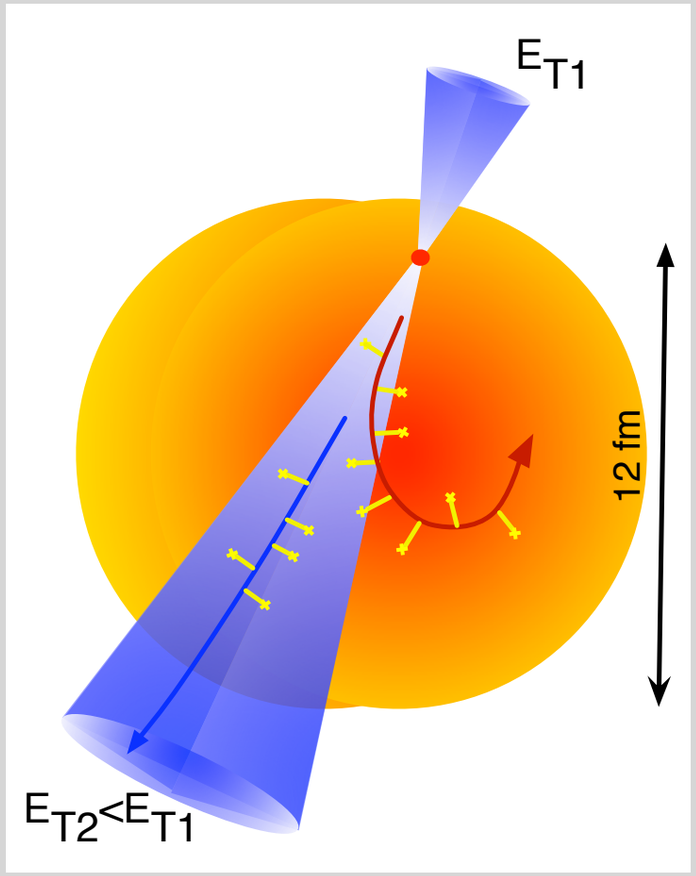

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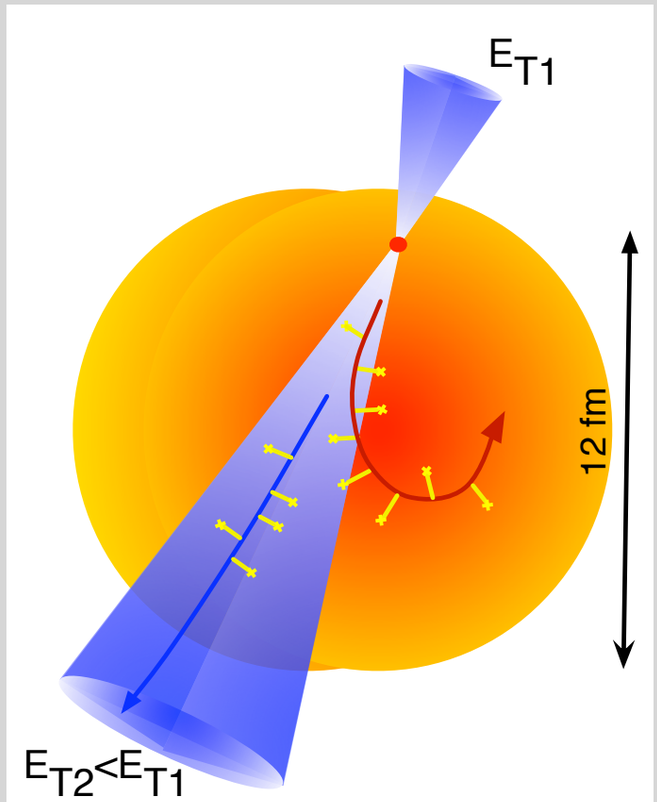

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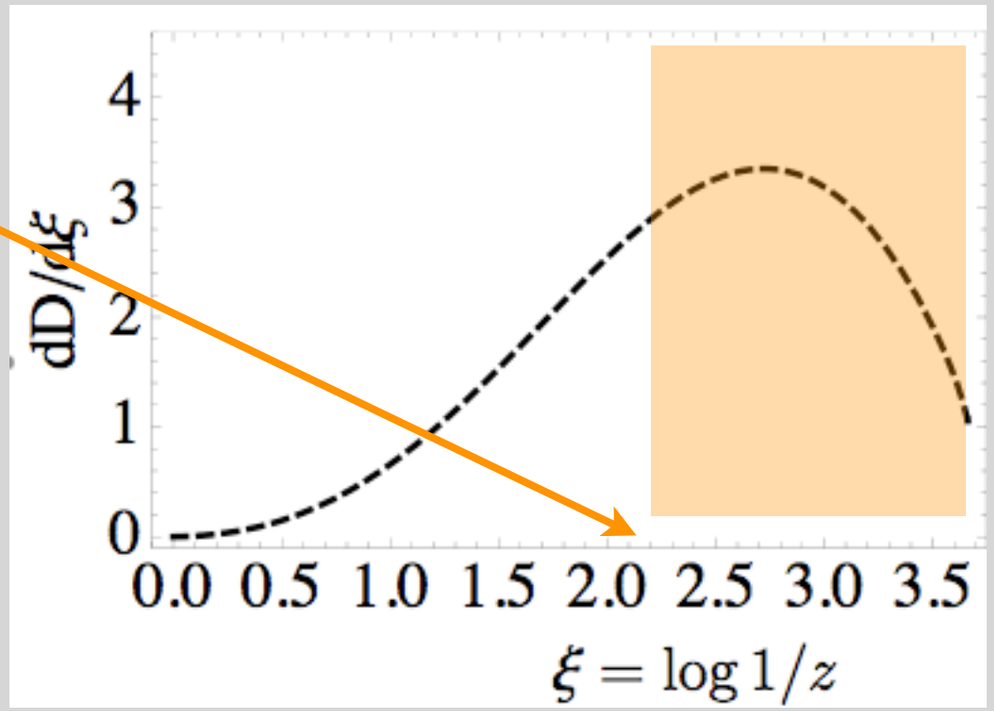

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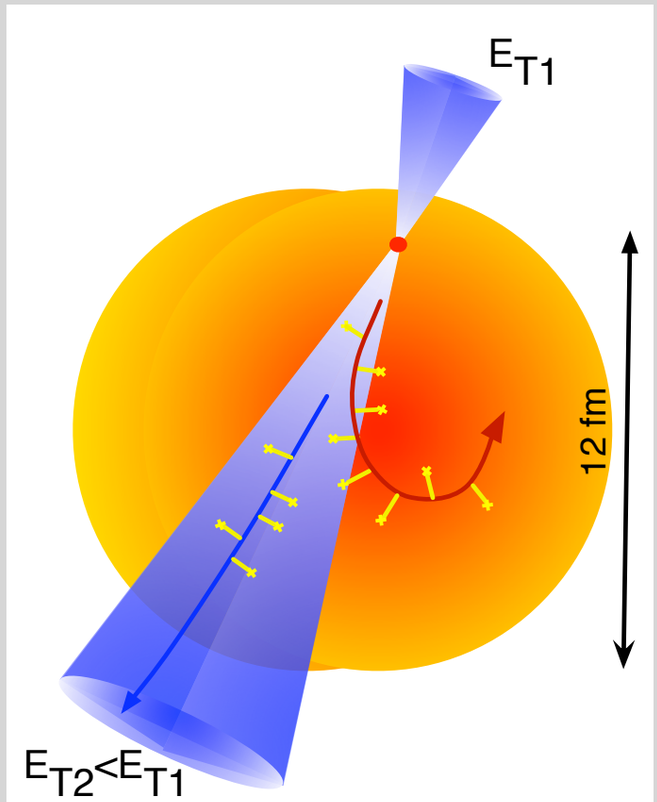

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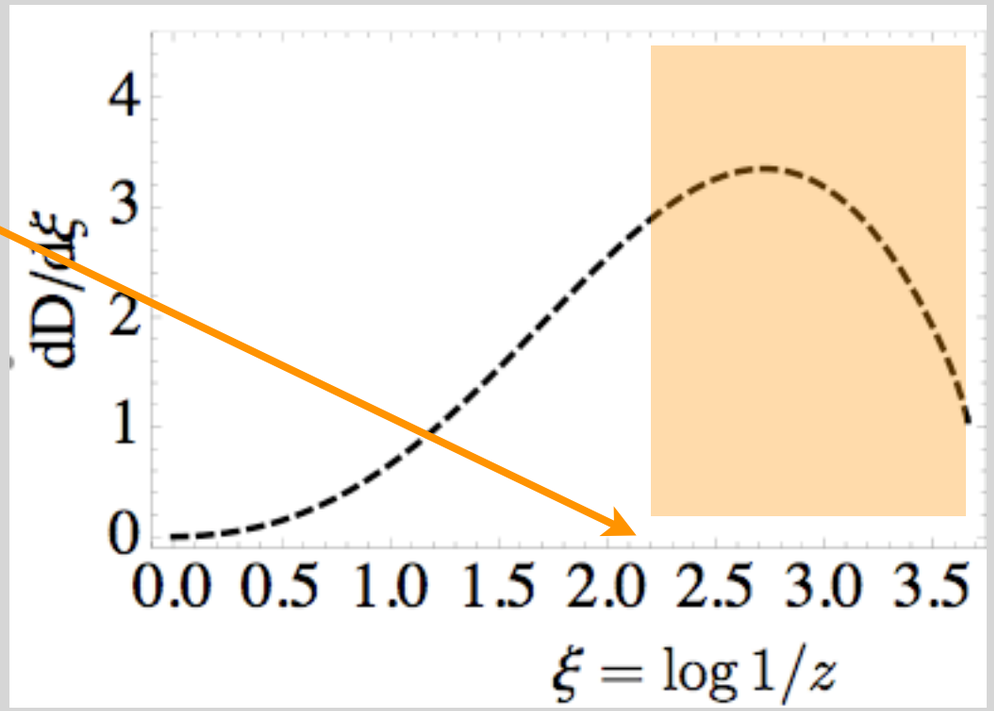

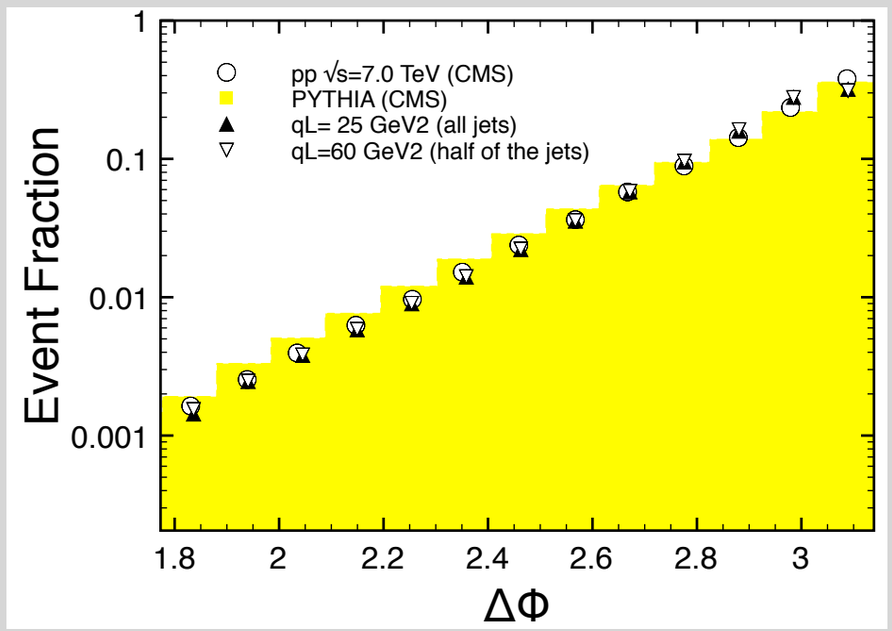

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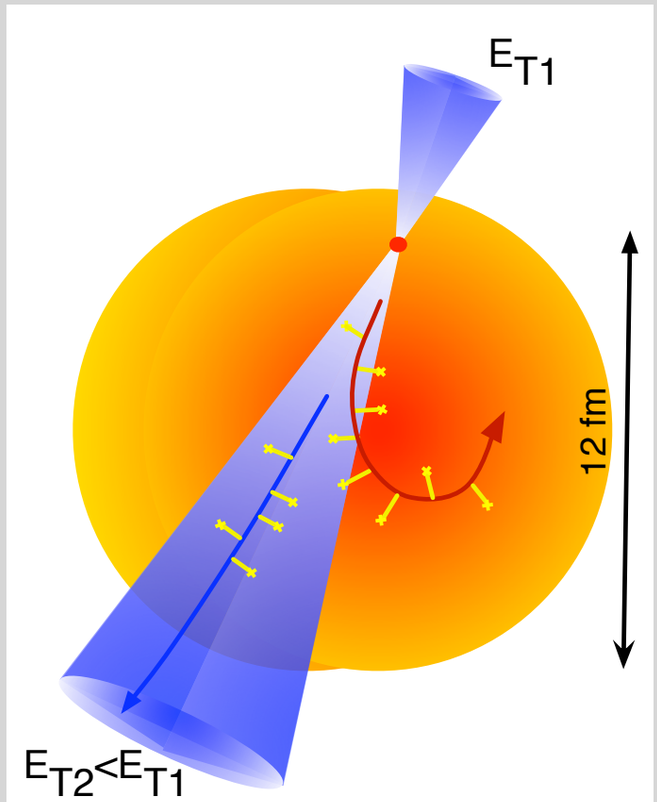

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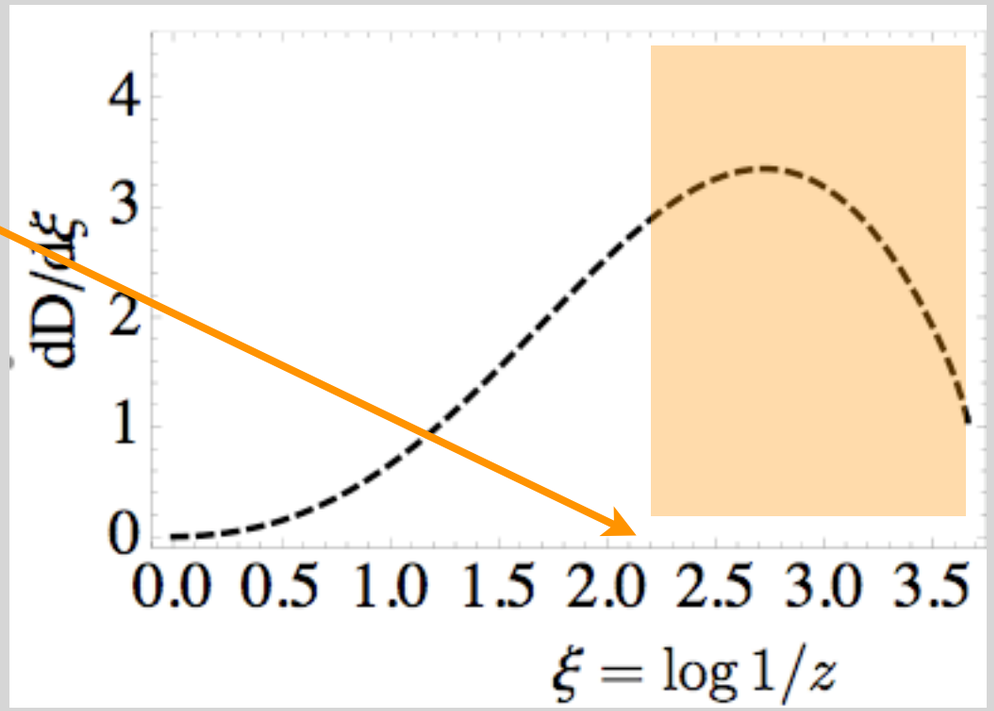

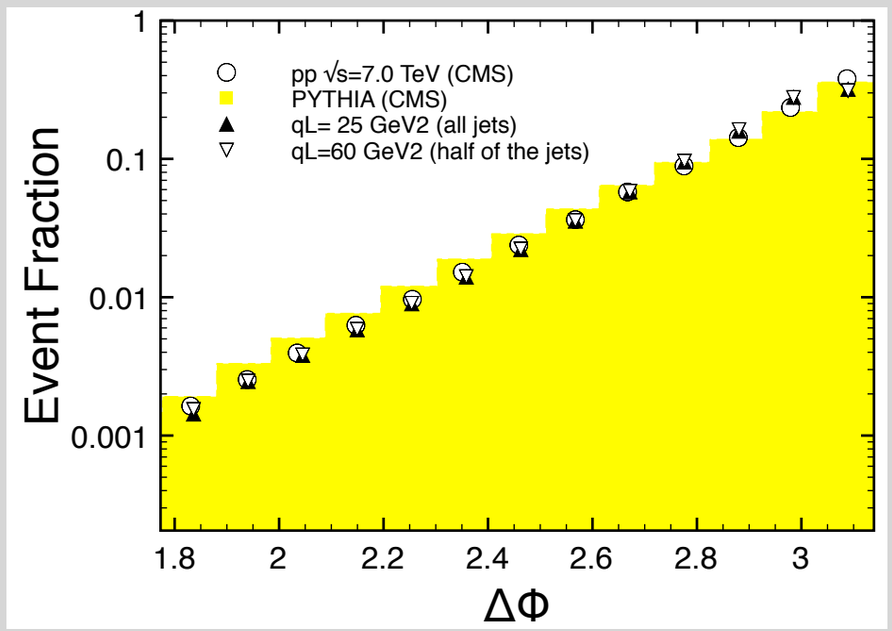

good qualitative description of average medium induced asymmetry

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

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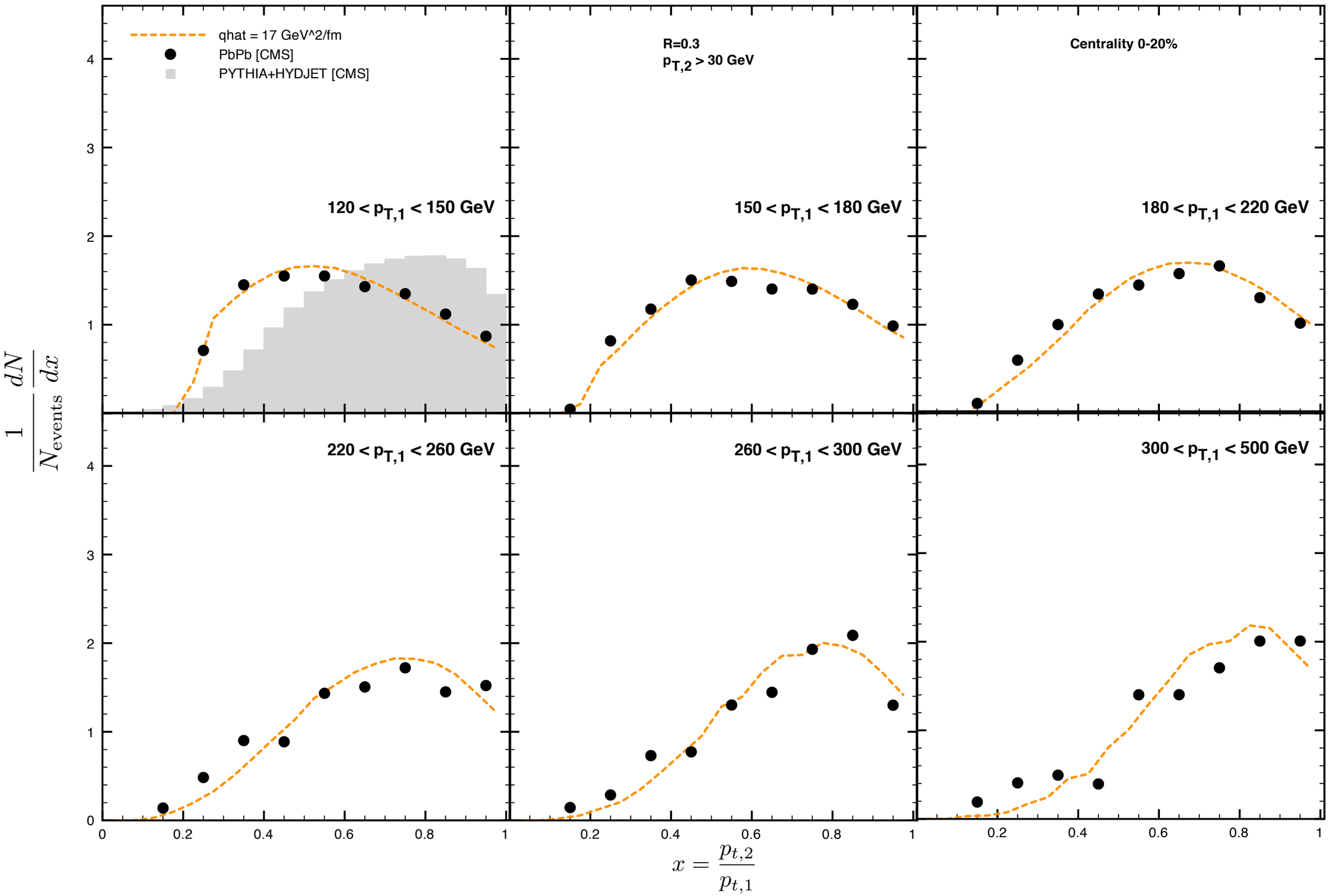
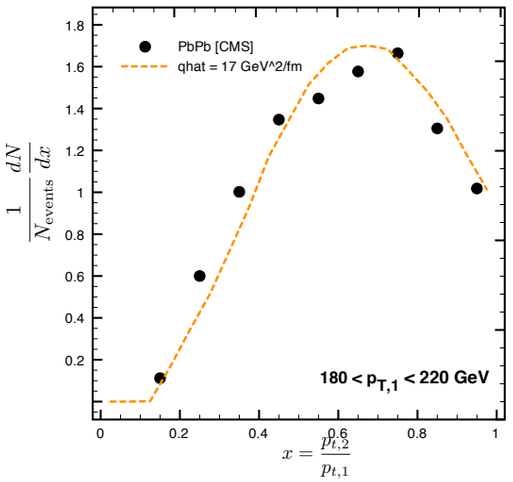
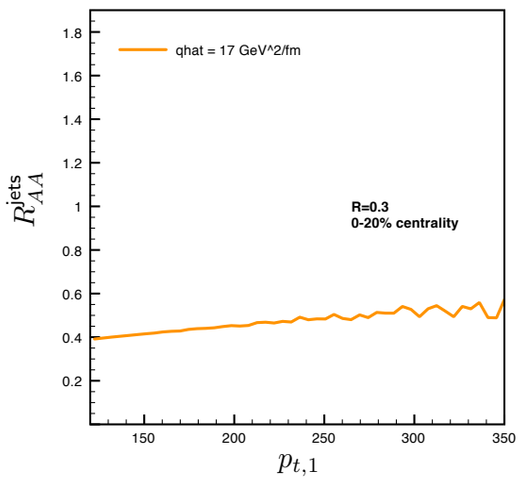
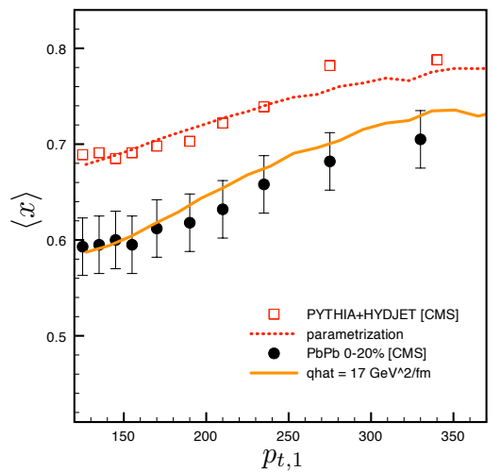
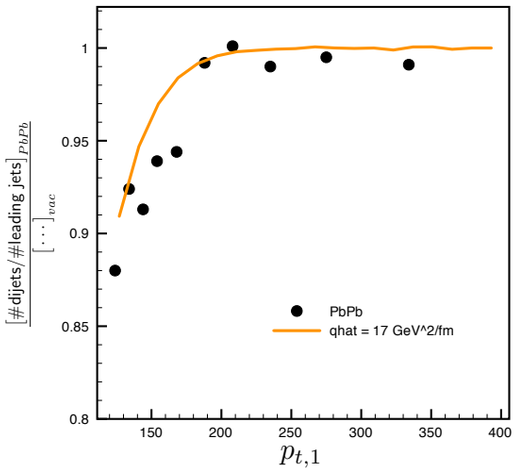


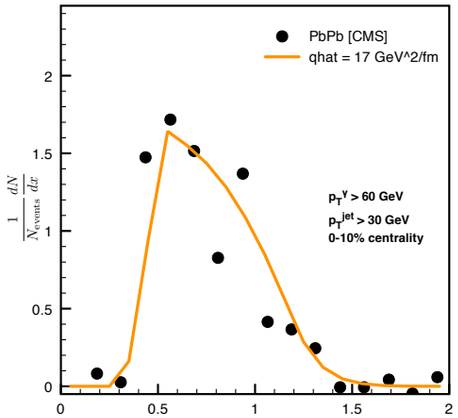
broadening [jet collimation]







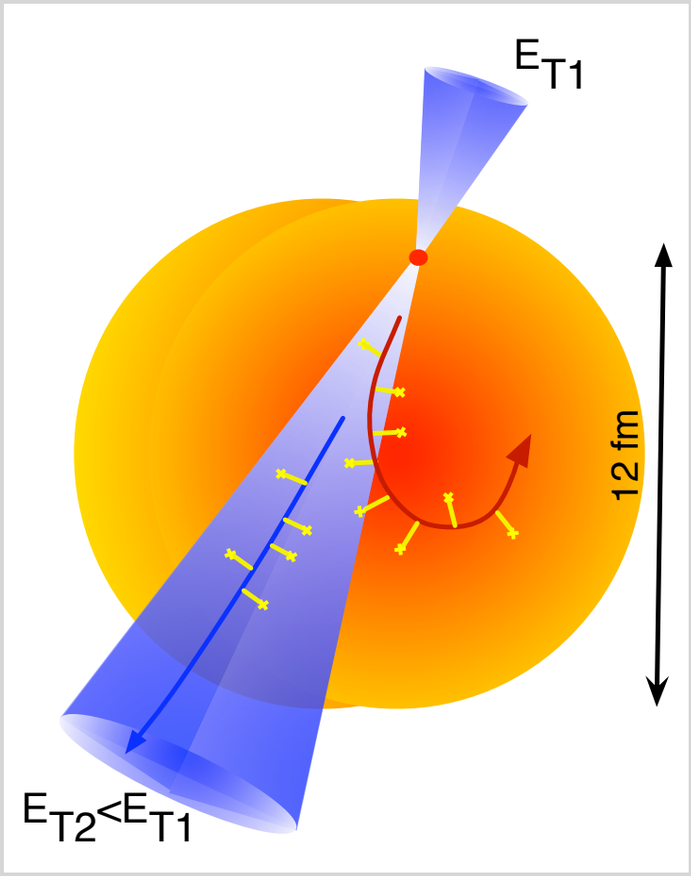




HP 2012

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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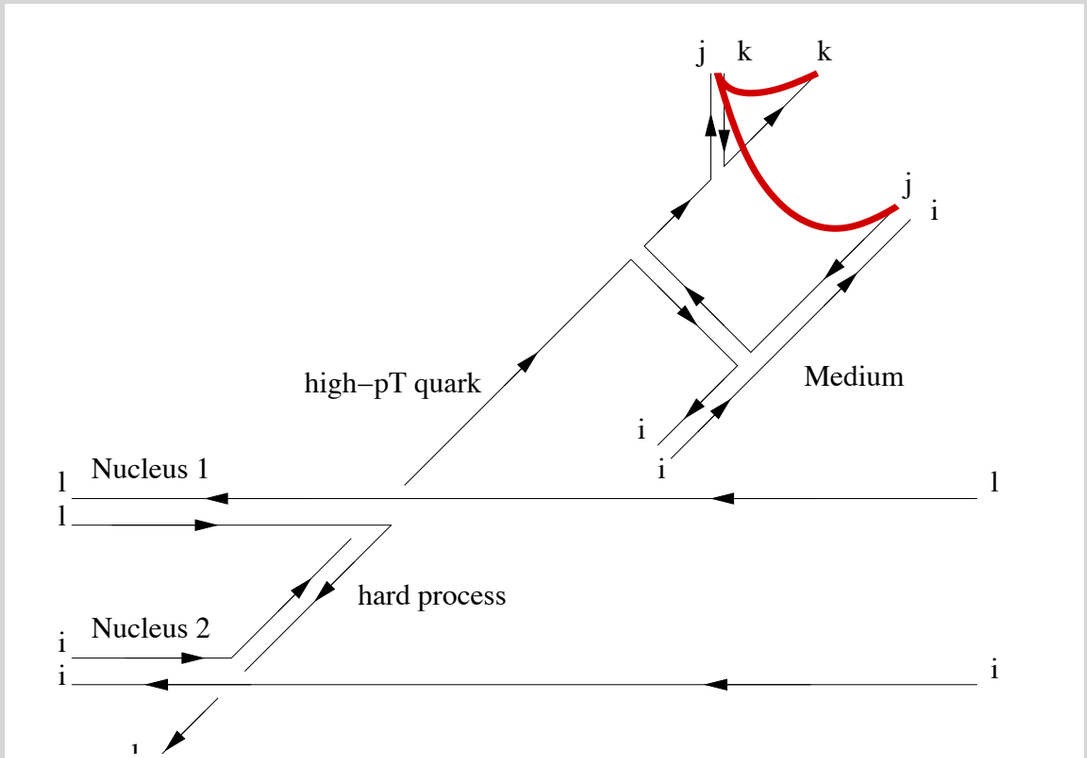

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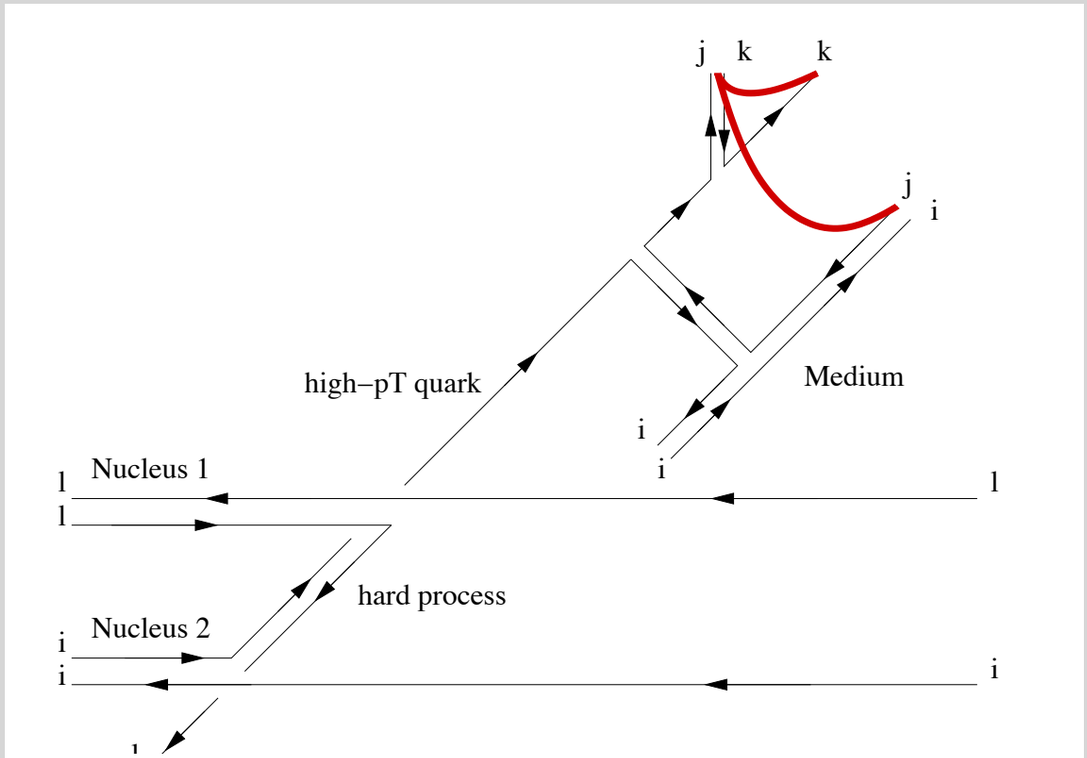

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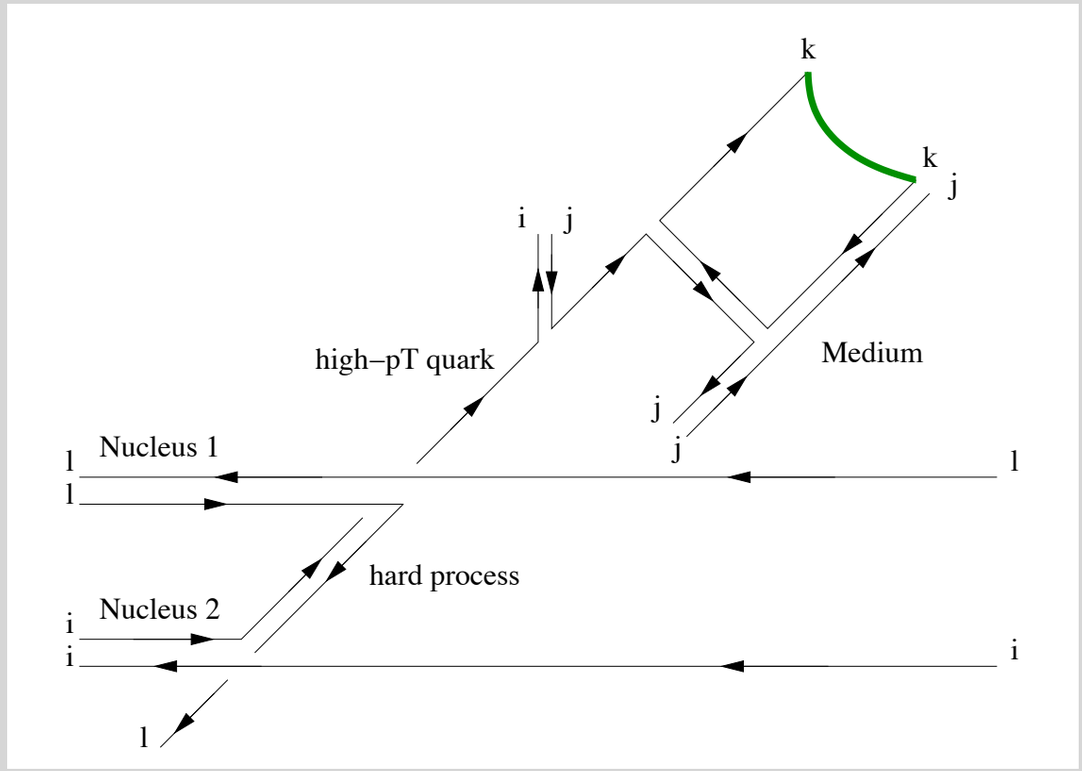

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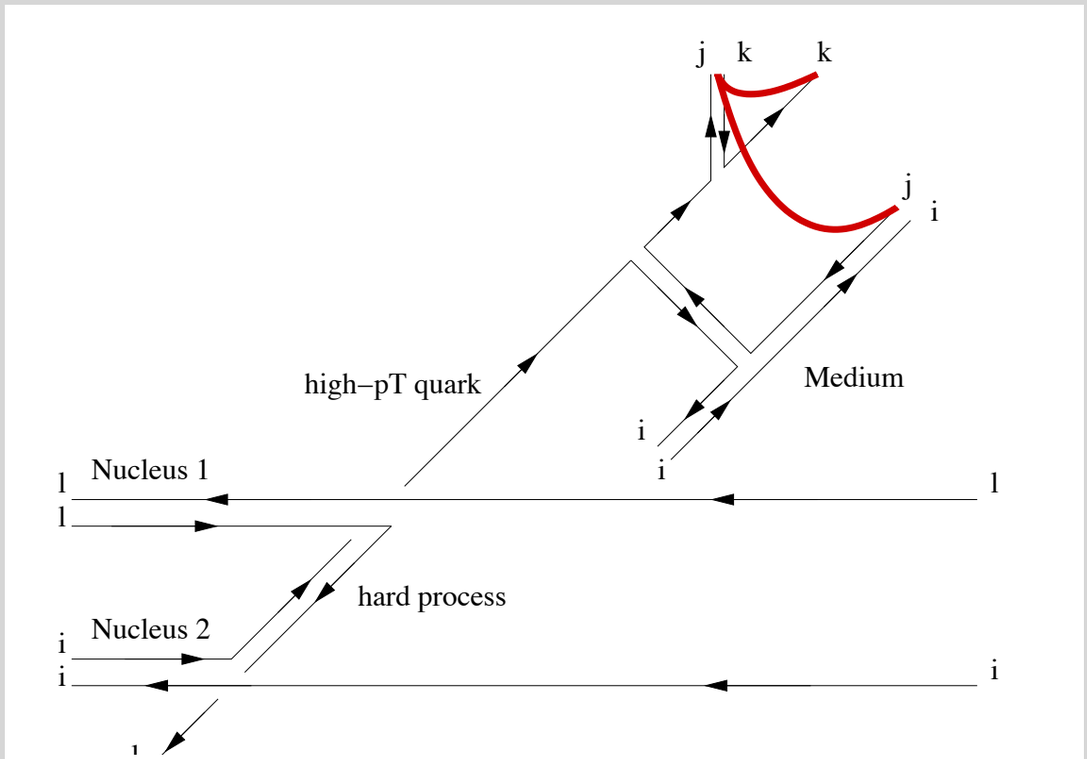

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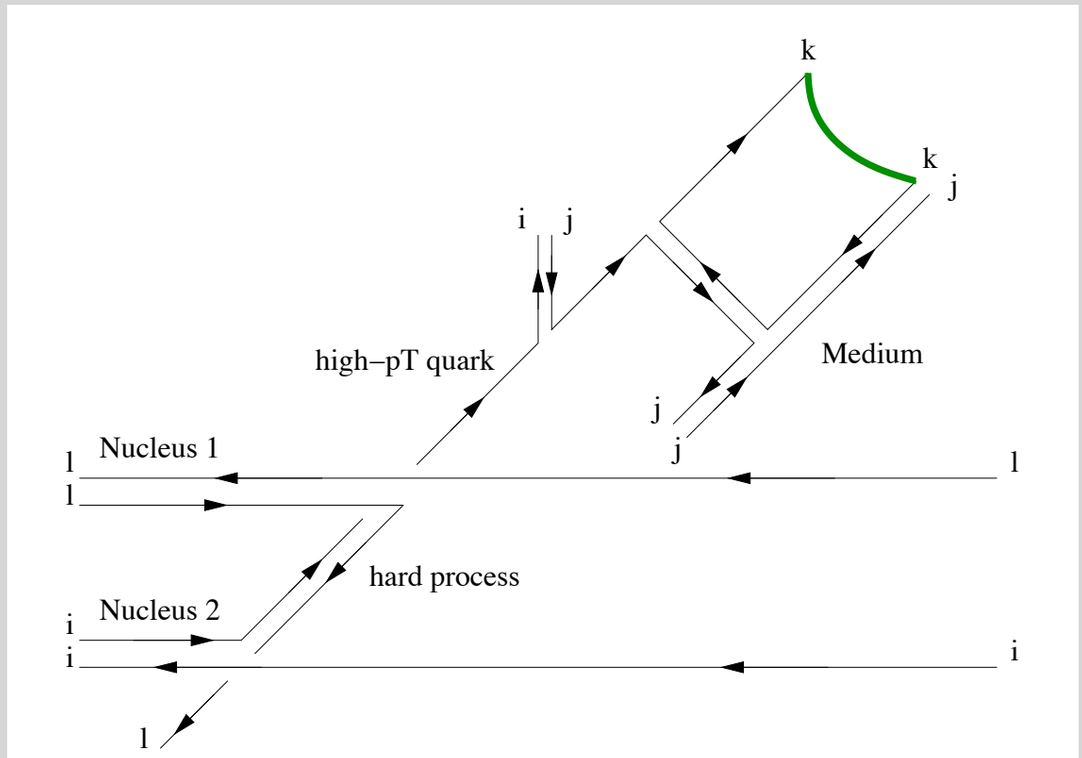

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first steps towards fully colour differential framework

Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]

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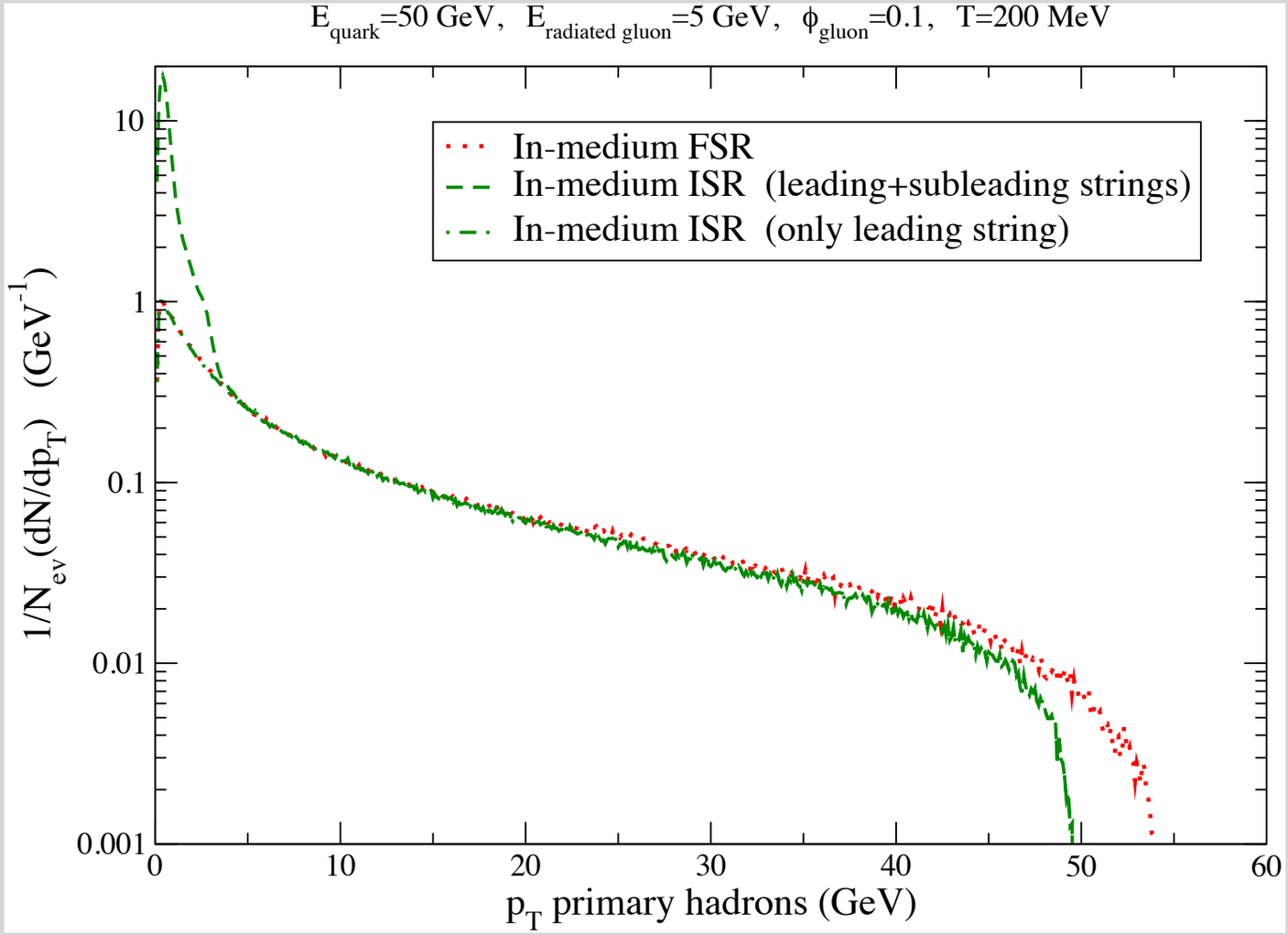

generic [robust] effects:

- softening of hadronic spectra
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- at work even if radiative energy loss kinematically unviable
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modification of jet hadrochemistry
Aurenche & Zakharov [1109.6819]

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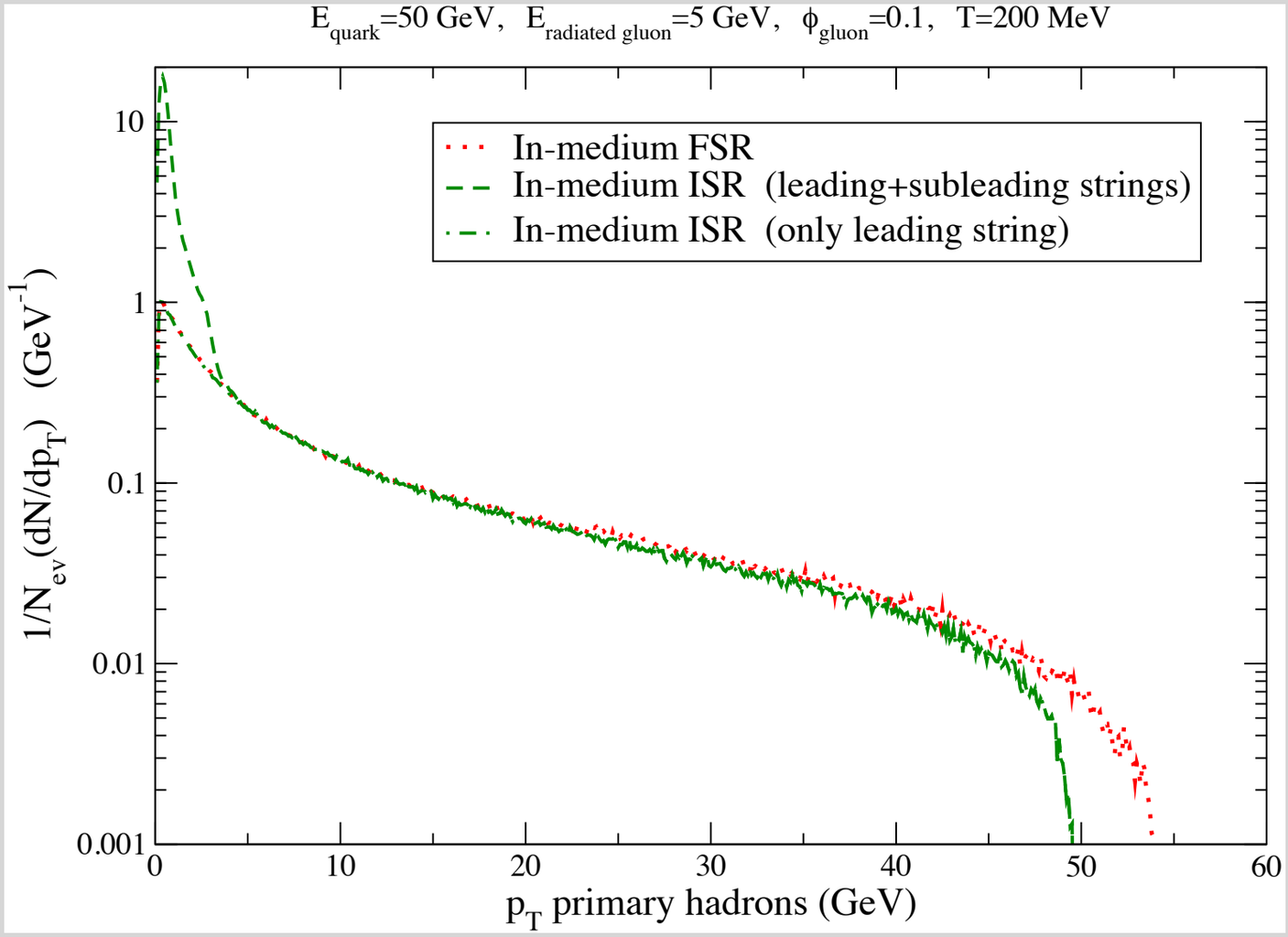

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fragmentation in vacuum NOT the same as using vacuum FFs

life story of an in-medium jet

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  - *hard skeleton defined [3-jet rates, hard frag, ...]*
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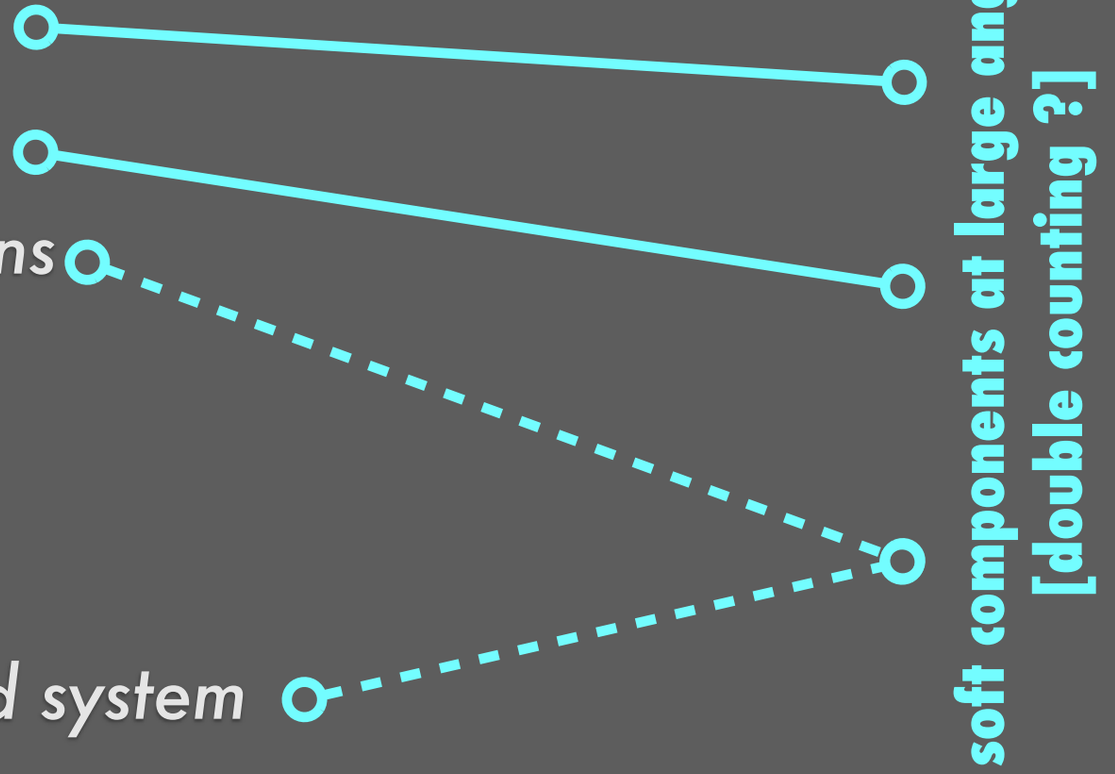

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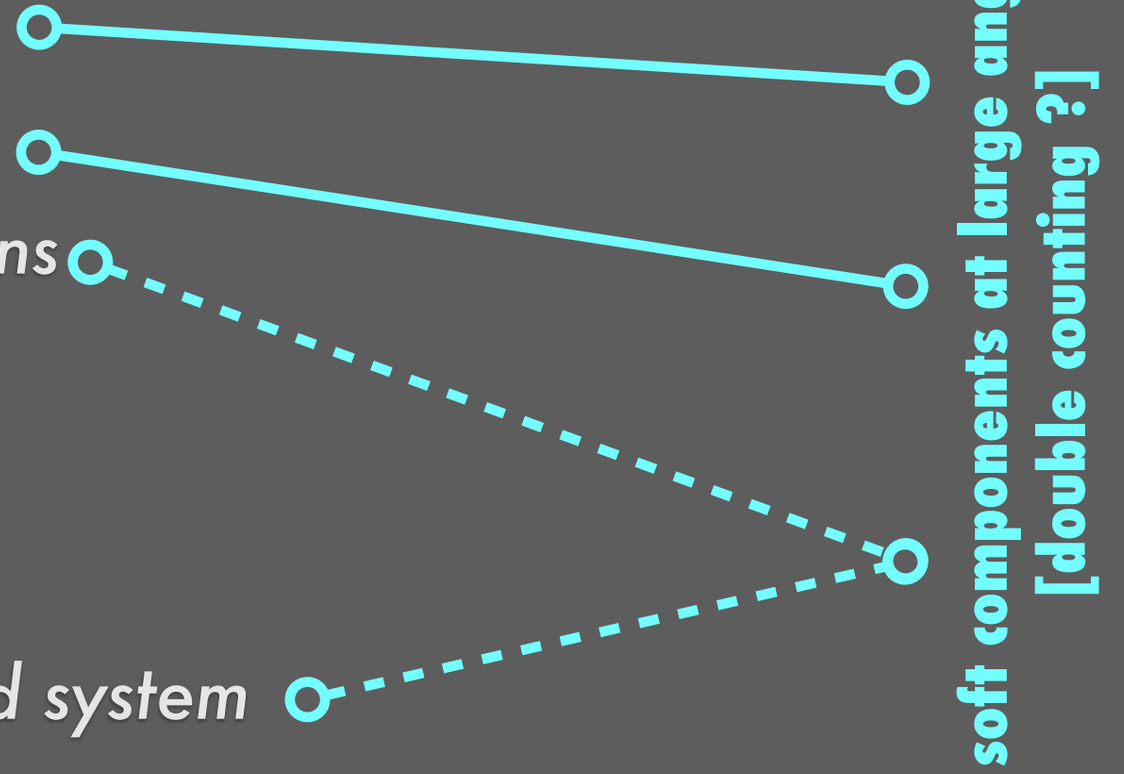

most [all?] questions asked, many [most?] being answered

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 from all jet 'propagators' and 'vertices' remain pQCD like ???

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

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

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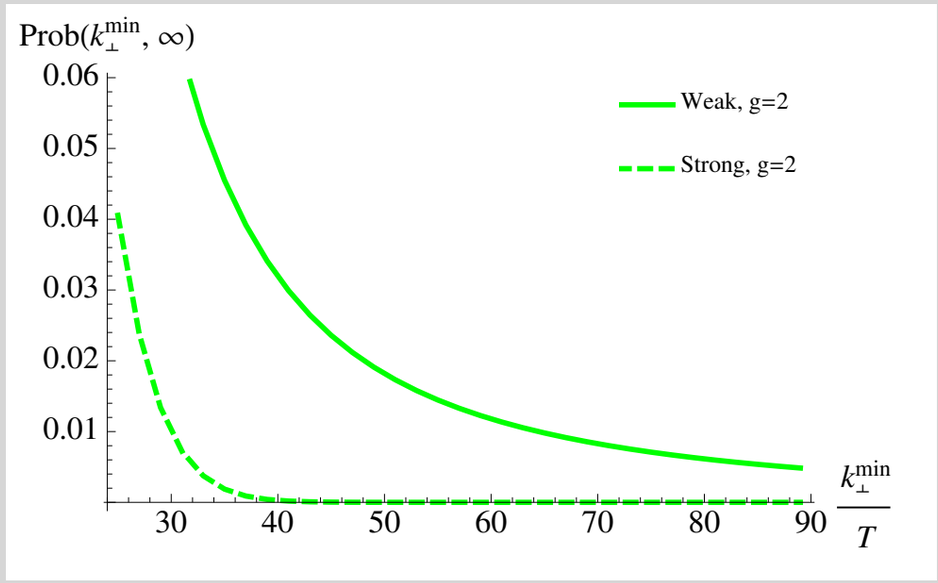
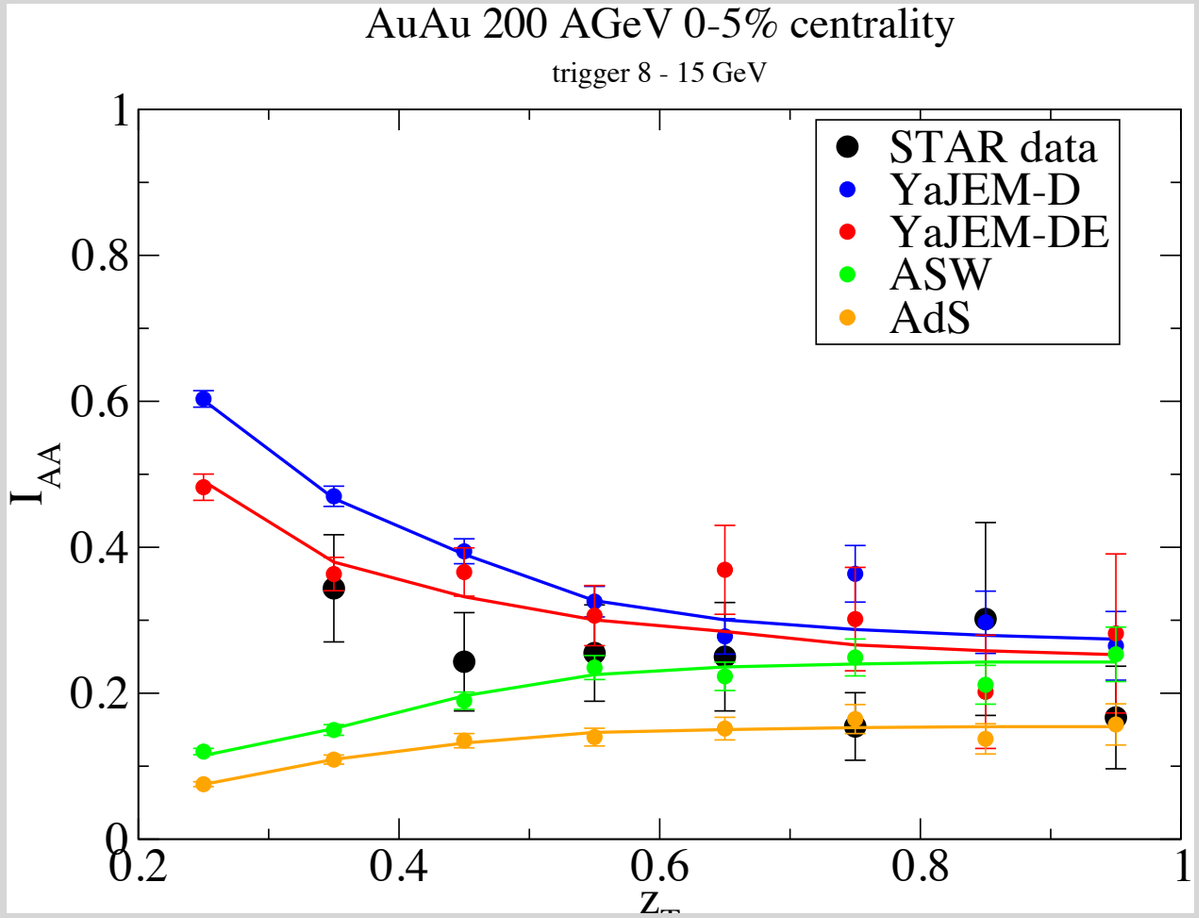
- probability of large broadening larger for pQCD [~$1/k_t^4$] than for strong coupled [gaussian]
  - ↪ rare but measurable events



Eramo, Lekaveckas, Liu, Rajagopal [1211.1922]

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 [pathlength, etc.] and sensitivities to dynamical mechanisms

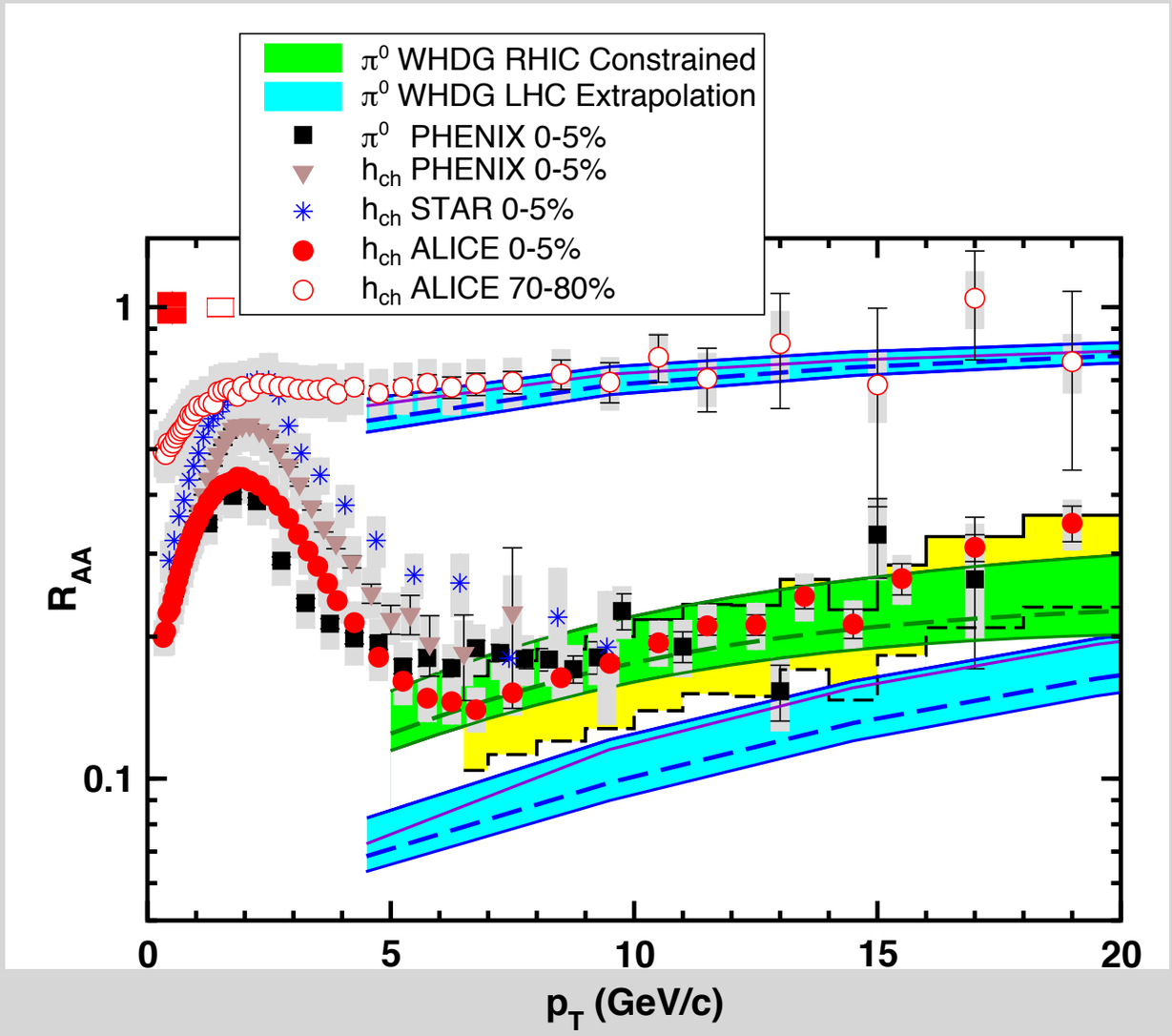


sensitivity of I_{AA} to weight of elastic energy loss

Renk [1110.2313,1112.2503,1202.4579.1212.0646]

consistency

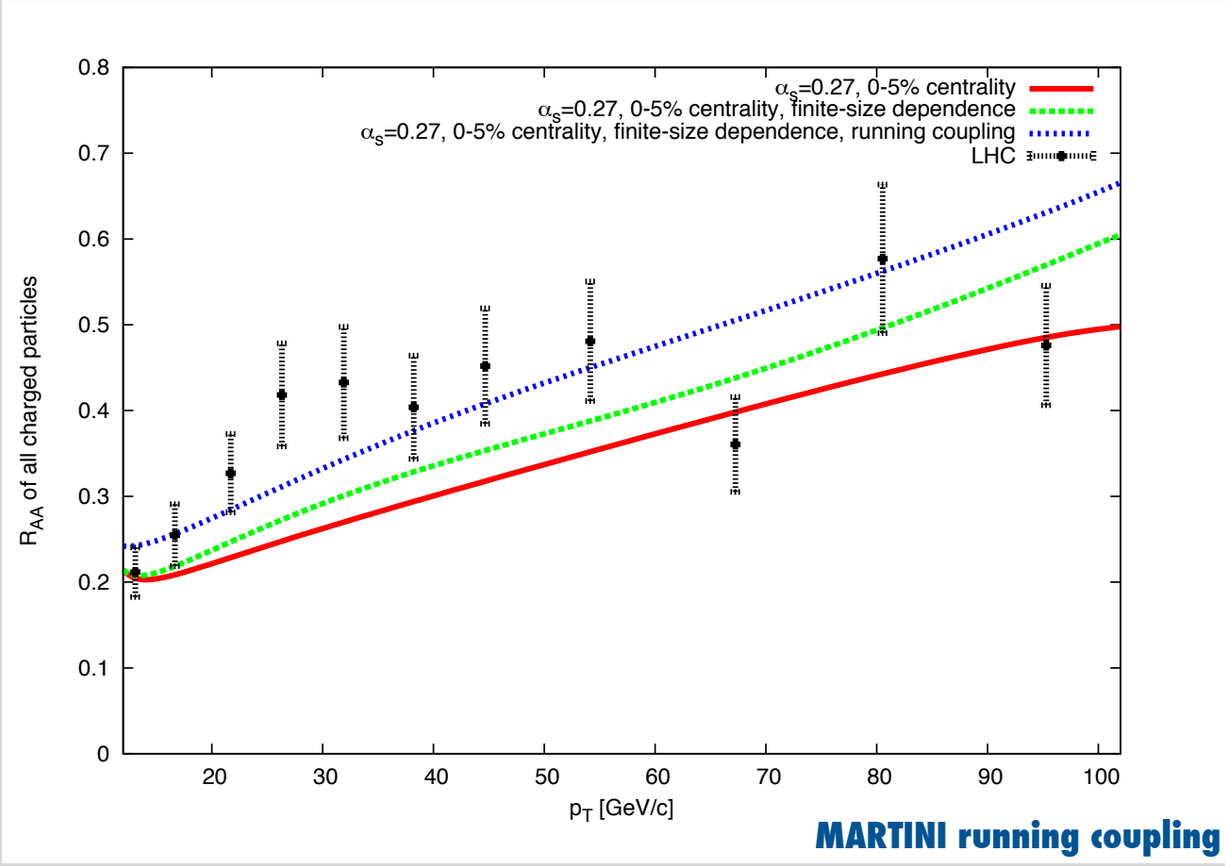
- theory validation [constraining dynamics] requires
  - ↪ RHIC to LHC description



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

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

- ↪ detector response [exp unfold/ph fold :: we need to decide]

#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]

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

  - ↪ for a weakly coupled medium

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]

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*