jet quenching

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CENTRA-IST (Lisbon) & CERN PH-TH

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heavy ion collisions at the LHC

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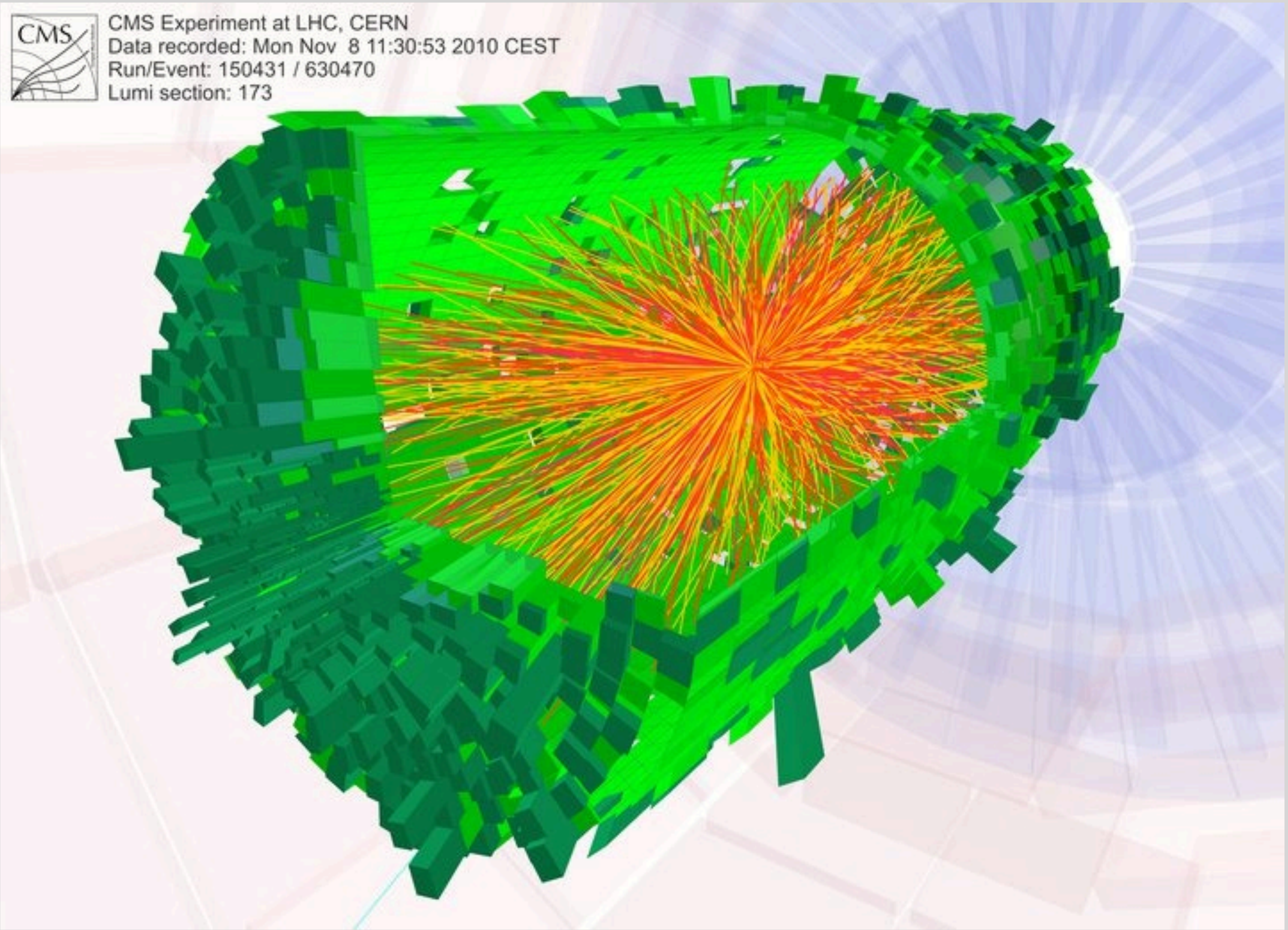
    - $\sim$ 380 nucleons participate in the collision
    - $\sim$ 1600 charged particles in mid-rapidity

heavy ion collisions at the LHC



why?

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    - to a large extend still unchartered land
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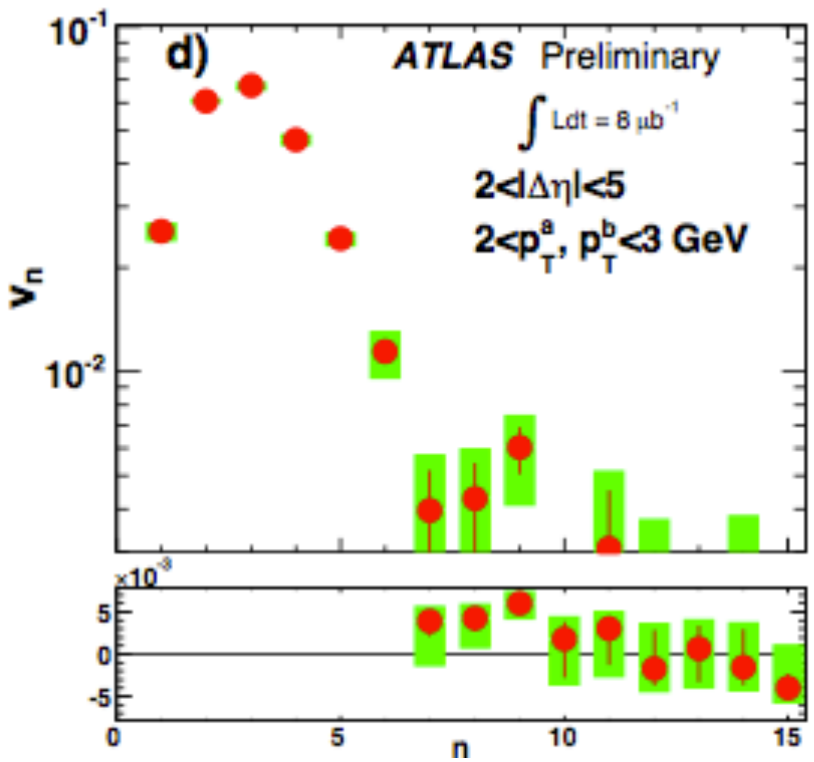
the main objective of the LHC heavy ion experimental programme is to unveil the properties of this medium

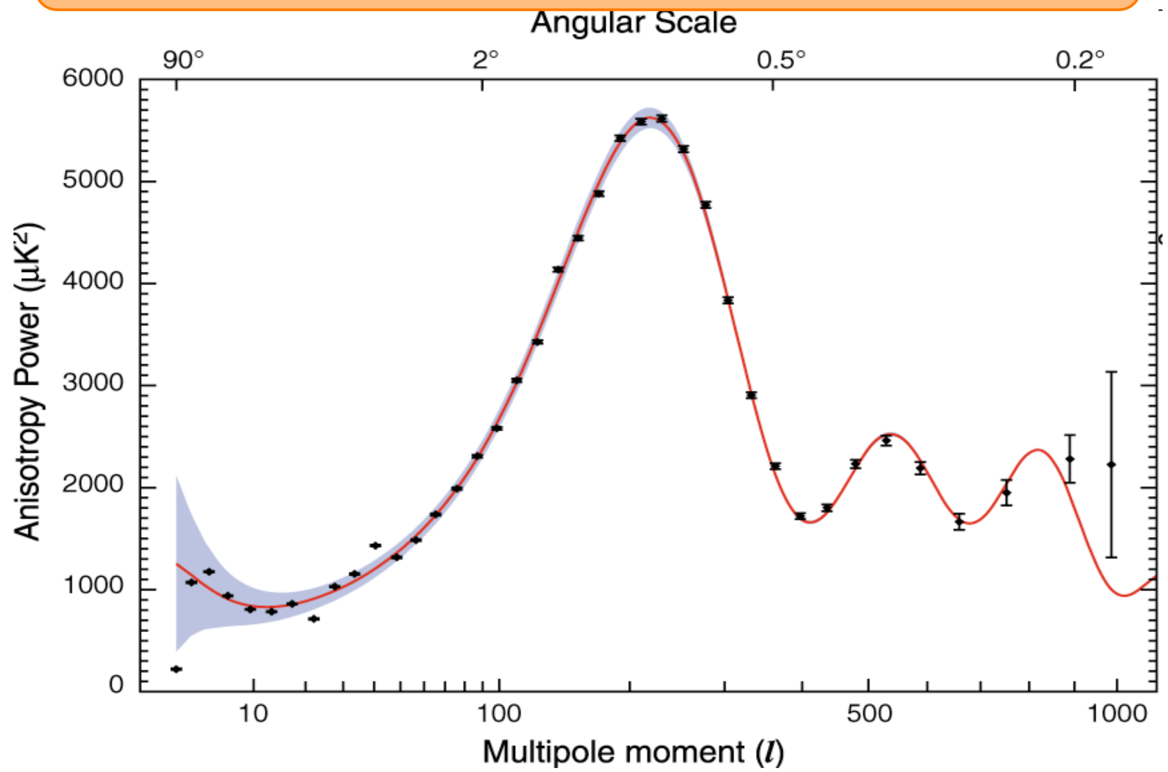
Little Bangs versus Big Bang

Hydro evolution of fluctuating initial condition reveals matter properties

$\eta/s = 0.08^{+\dots}_{-\dots}$

$\Omega_b = 0.044^{+0.04}_{-0.04} \quad \Omega_\Lambda = 0.73^{+0.04}_{-0.04} \dots$





- Uncertainties in initial conditions
- Many observables

$$v_n(p_T),\ n = 1,\dots,10$$

- Many small events

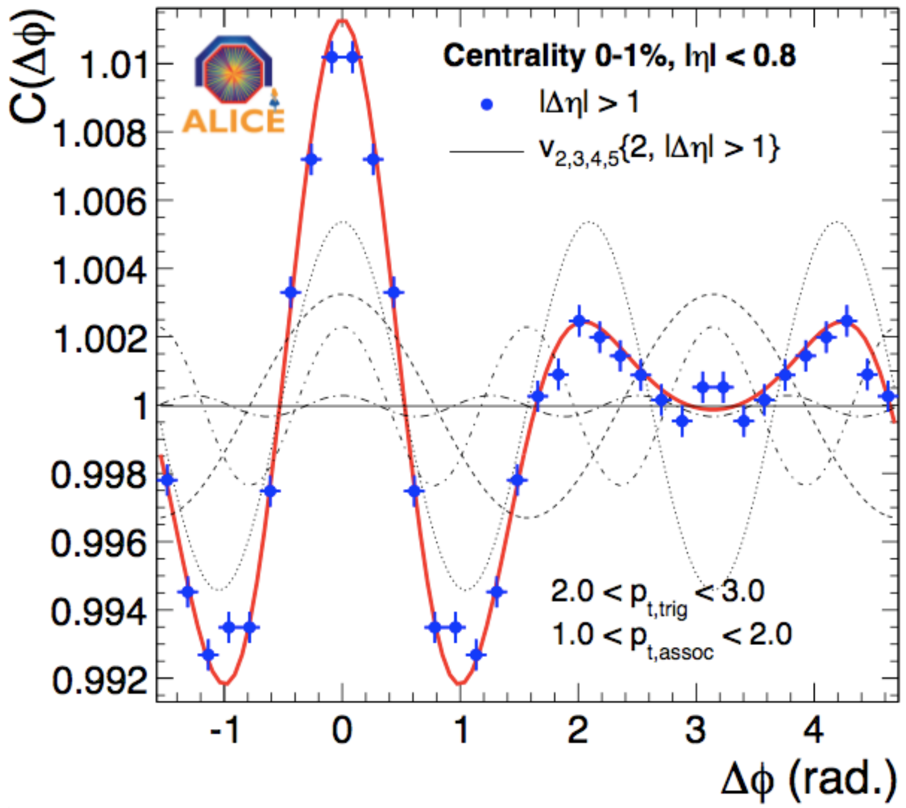
- Uncertainties in initial condition
- Many observables

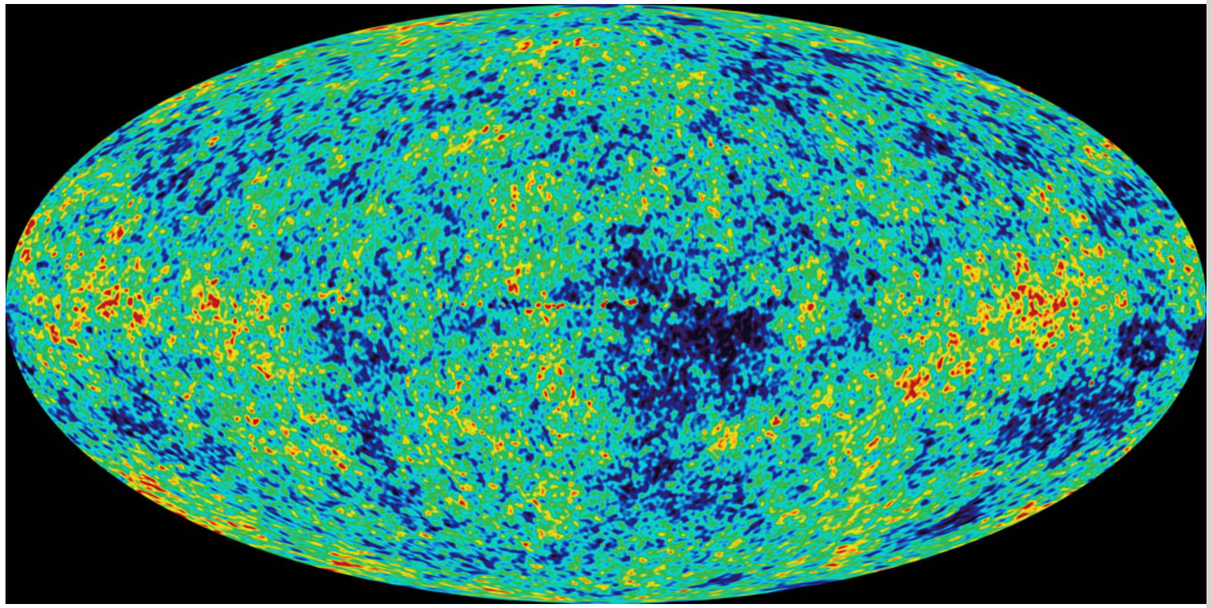
$$c_l,\ l = 1,\dots,1000$$

- One big event
  (additional uncertainty: cosmic variance)

U Wiedemann, QM2012

Little Bangs versus Big Bang





- Fluctuation analyzed since 2009
  ~ 100 % uncertainty on η/s
- Improved measurements upcoming (future RHIC & LHC running)
- Parameter not yet listed in PDG

(Note: feasibility of analysis method fully established, see rhs …)

- After more than a decade of analysis and measurements,
  ~1 % accuracy on key parameter
- Improved measurements upcoming (PLANCK, …)
- Parameter listed in PDG

U Wiedemann, QM2012

Quenchings & Suppressions

• Light hadrons $\pi, K, p, \Lambda, ...$	**fast**, propagation close to eikonal	fragile	formed late	$\tau_{had} \approx \frac{1}{Q_{had}} \frac{p_T}{Q_{had}}$
• Heavy flavors $D^0, D^+, D^{*+}, ...$	**slow** up to medium p_T random walk?	Carry robust tag	formed earlier	$\tau_{D/B} \approx \frac{1}{M_{D/B}} \frac{p_T}{M_{D/B}}$
• Quarkonia $J/\psi, \psi', \Upsilon(1s), \Upsilon(2s)...$	**slow** but not static	Robust up to T_{diss}	formed early (endogamously) or late (exogamously)	
• Jets	**fast**, propagation close to eikonal	from fragile to robust	Forms throughout medium evolution	

Hard probes: - initiated at $\tau_{init} \approx 1/Q_{hard} << 1\,fm$

- propagate up to $\tau_{final} \approx 10\,fm$

⇒ Hard probes challenge picture of a plasma that does not carry quasi-particle excitations.

U Wiedemann, QM2012

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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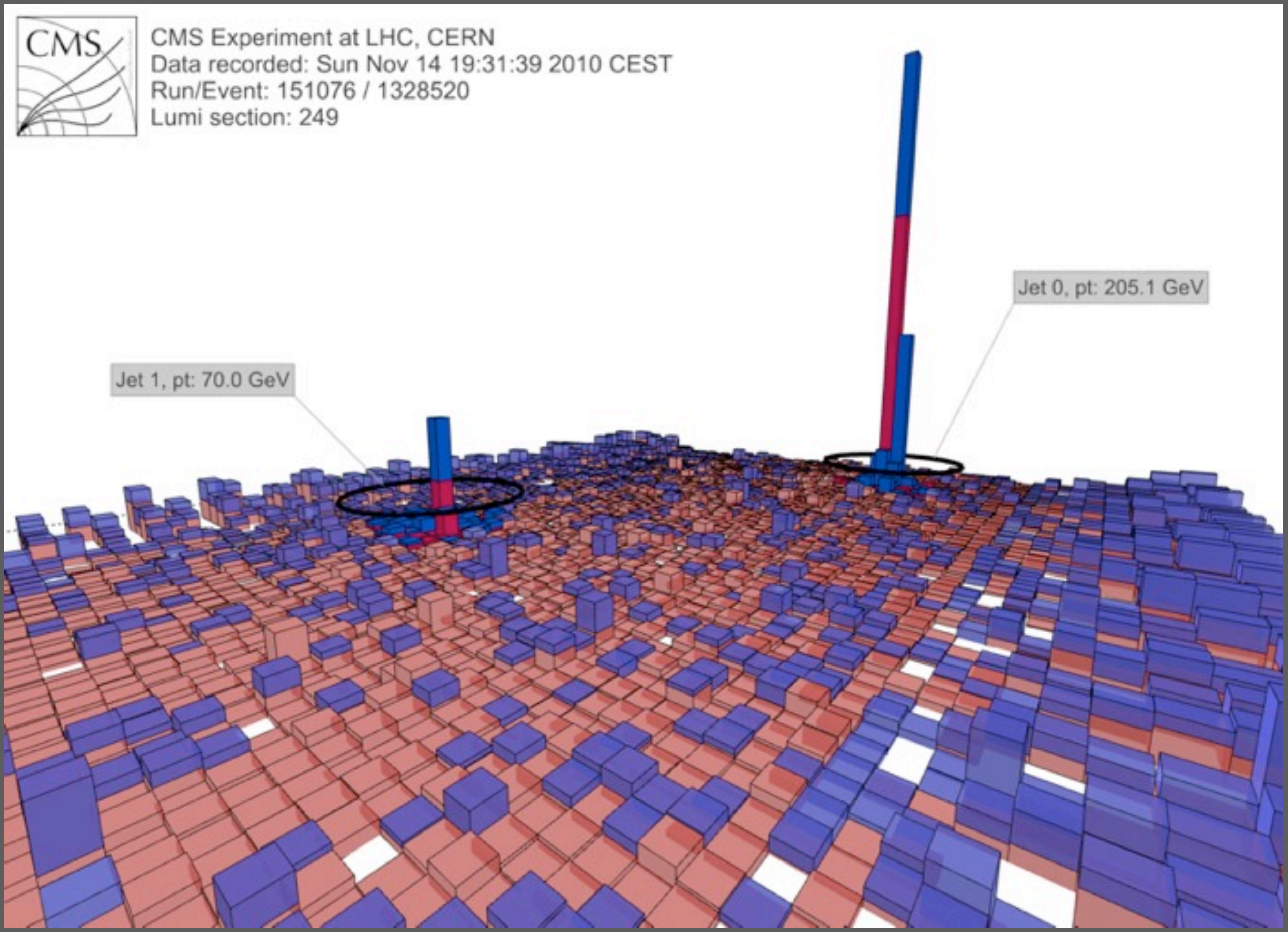
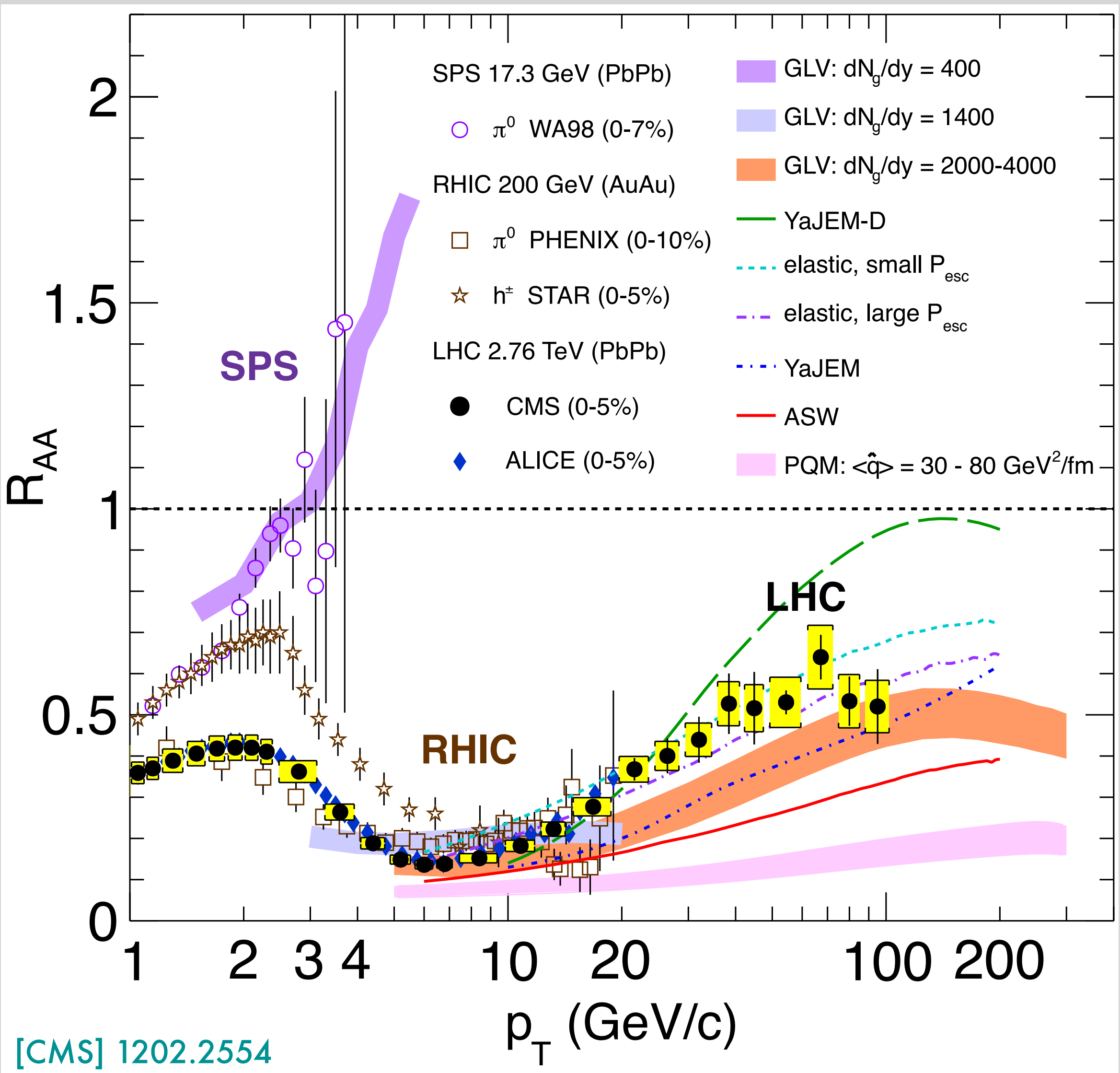
#1 establishing the probe

#2 probing the medium

observation of jet quenching

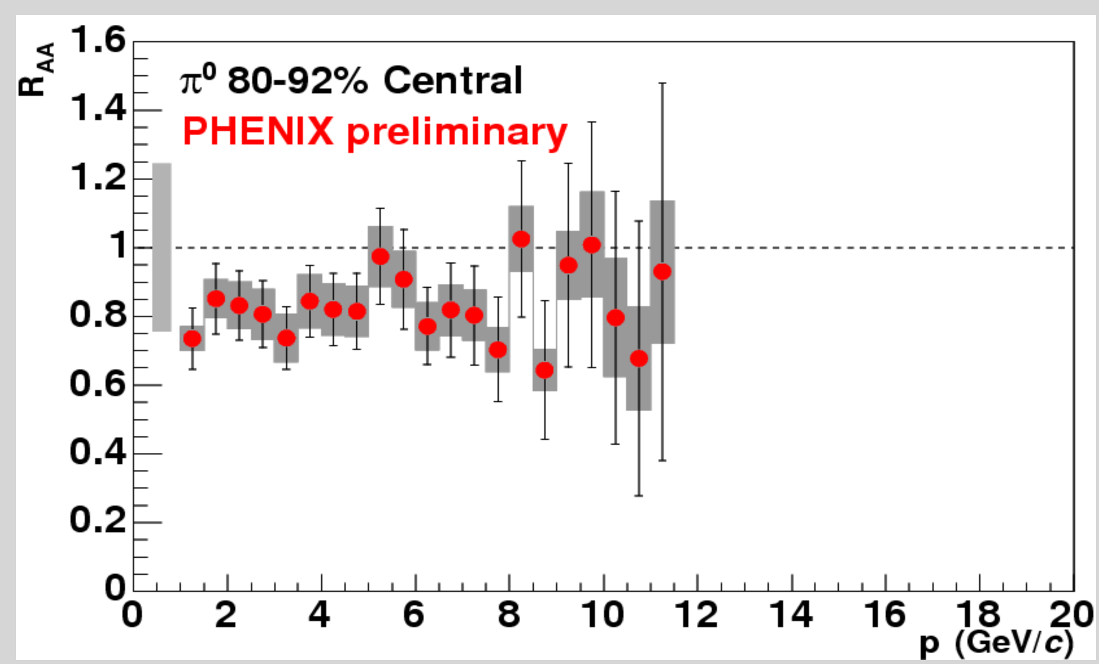


hadron spectra



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

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



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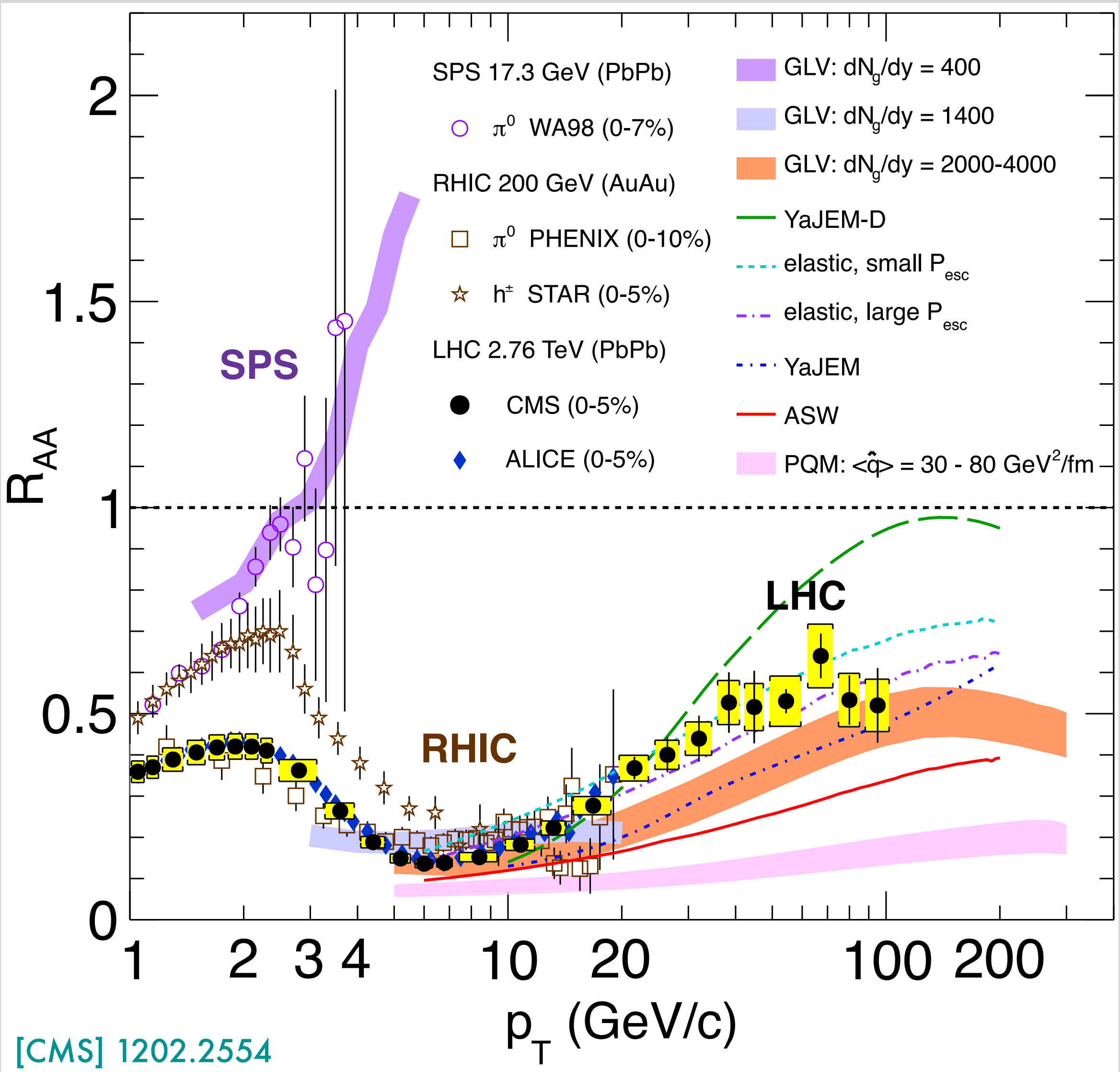

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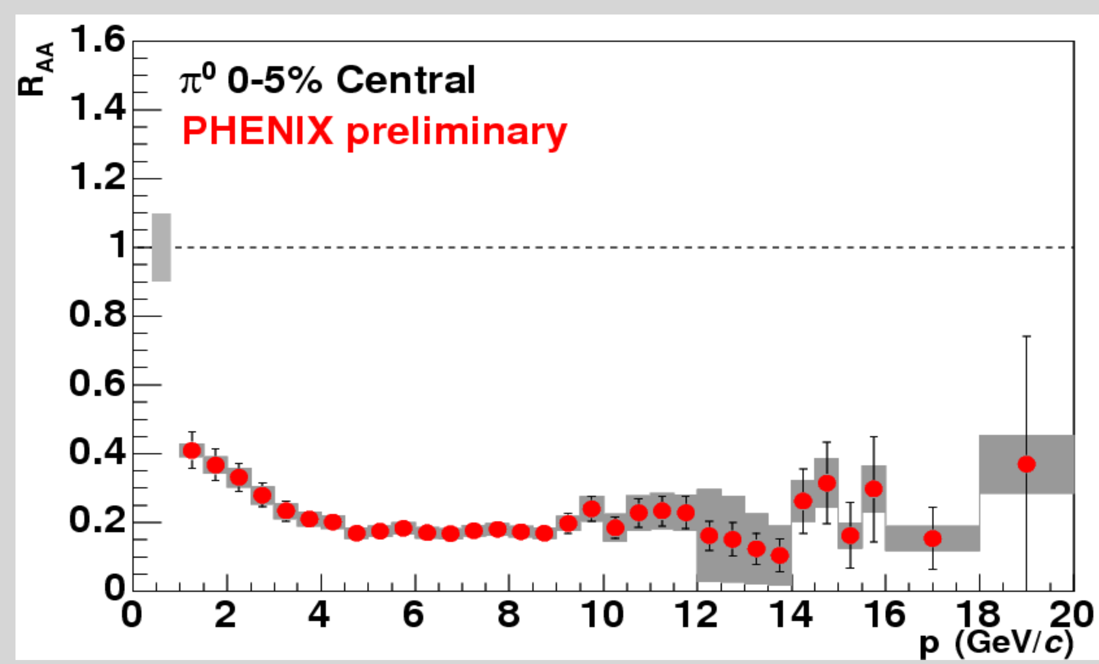
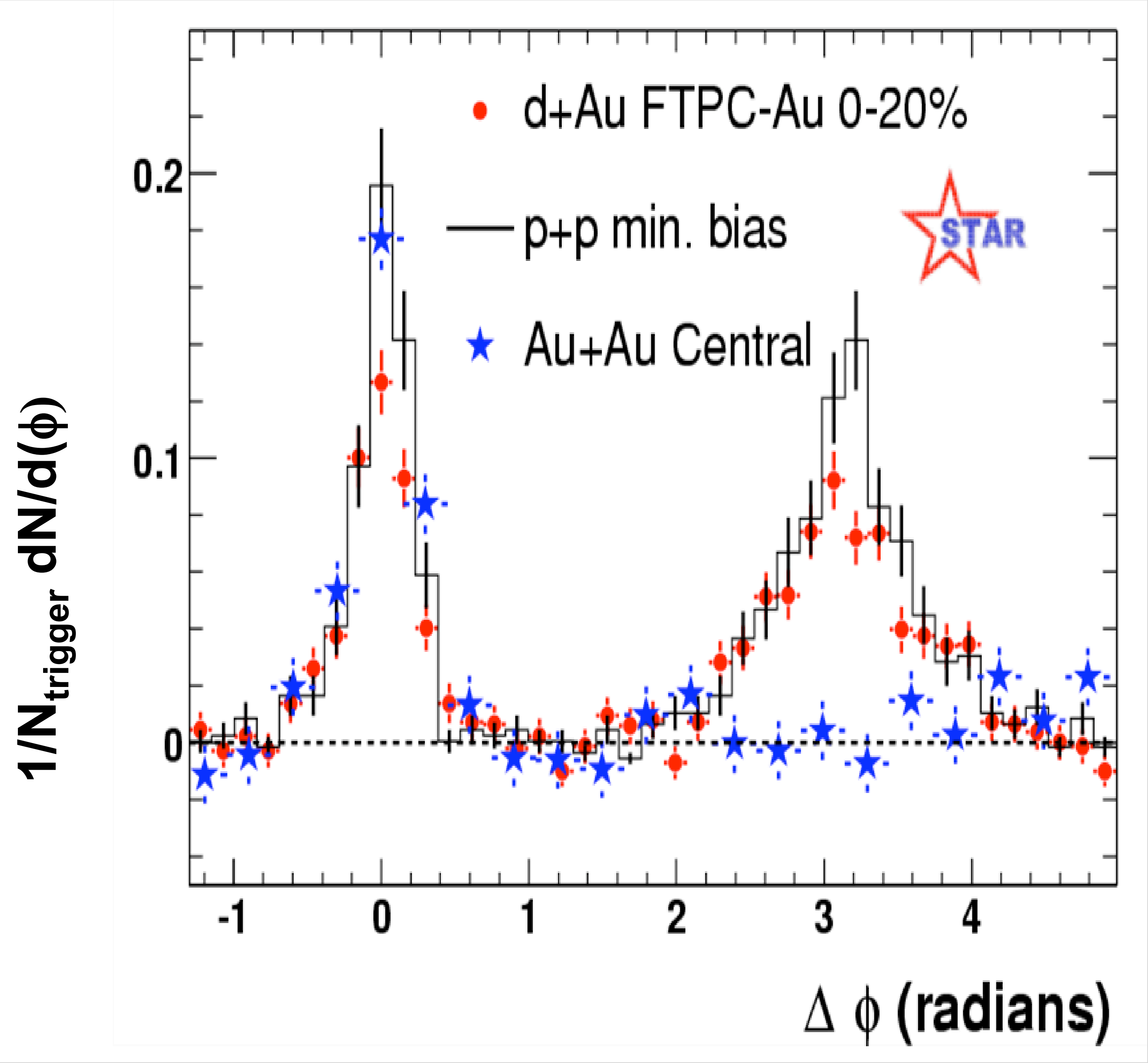


correlations



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

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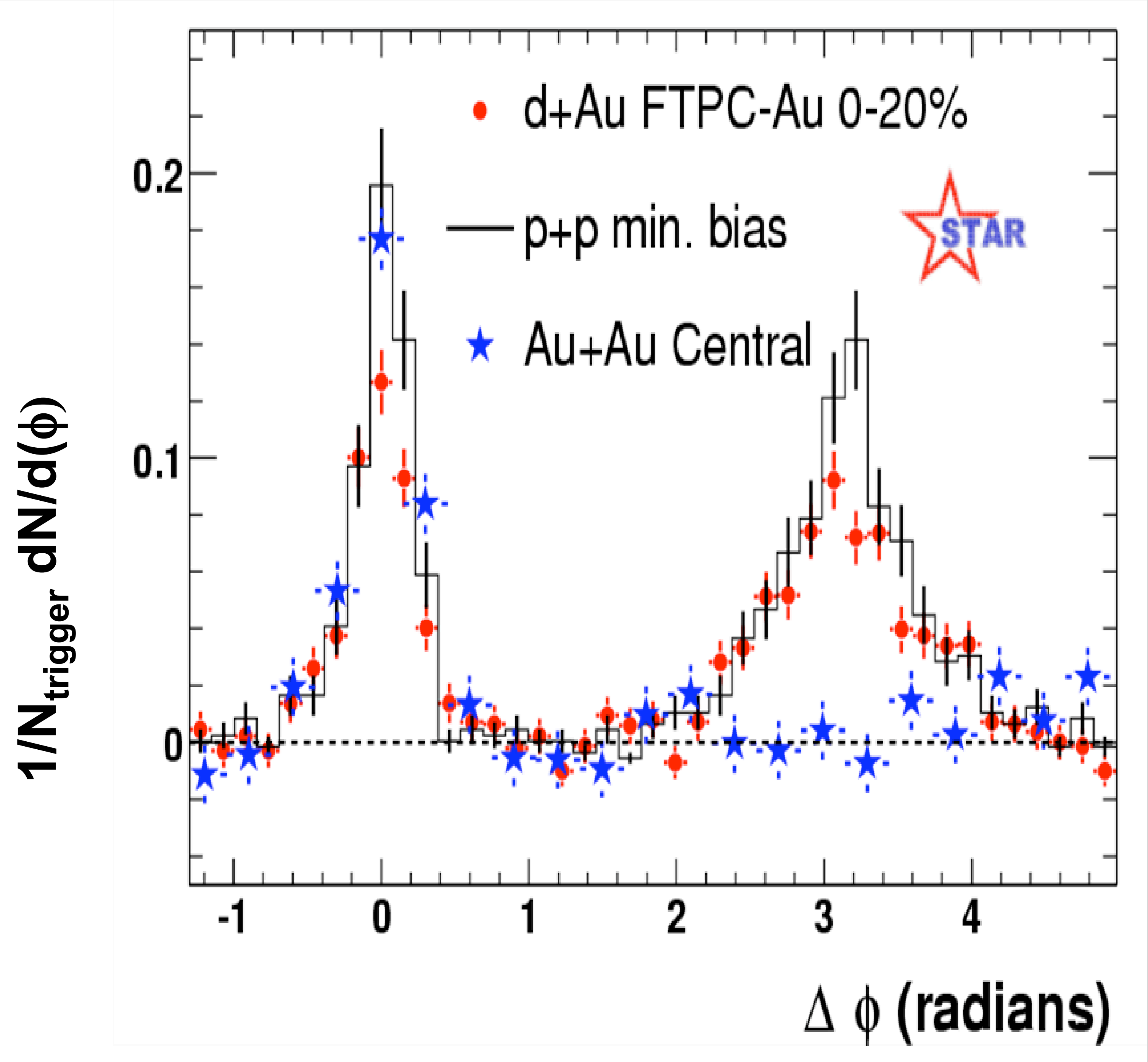

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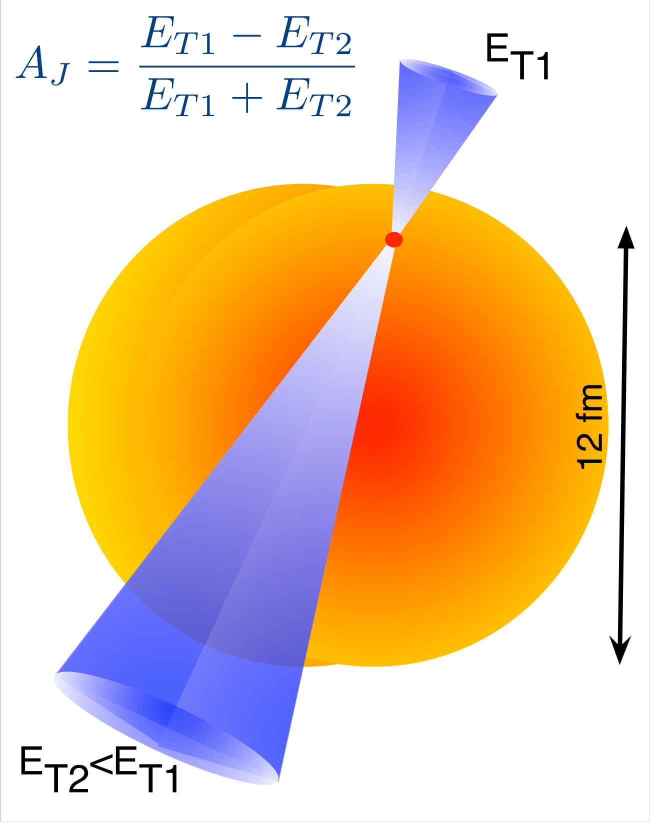
hadronic observables intrinsically sensitive to hadronization and oblivious to broadening effects on radiation

dijet asymmetry

dijet asymmetry

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



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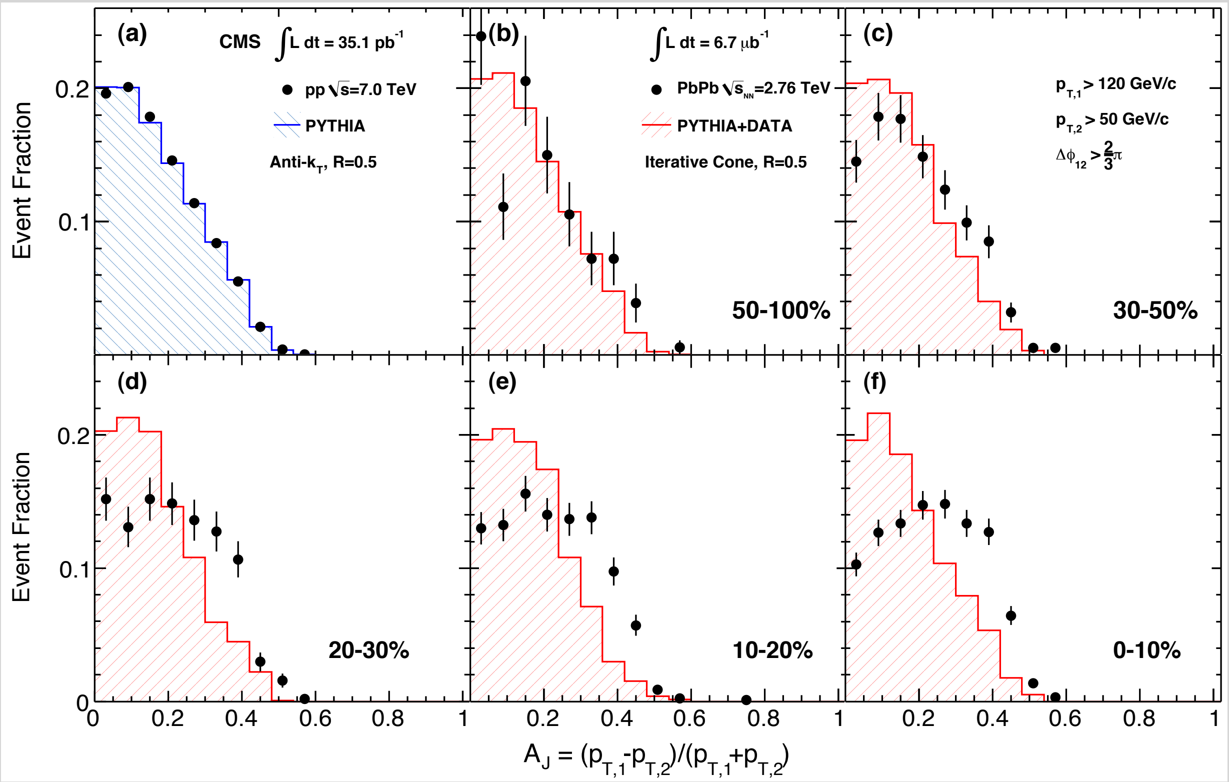

- significant enhancement of asymmetry

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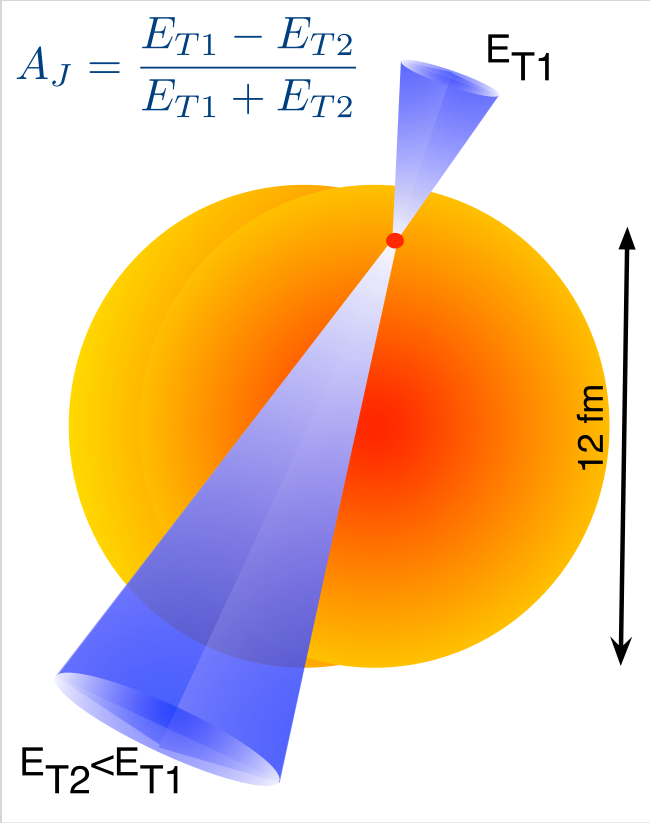

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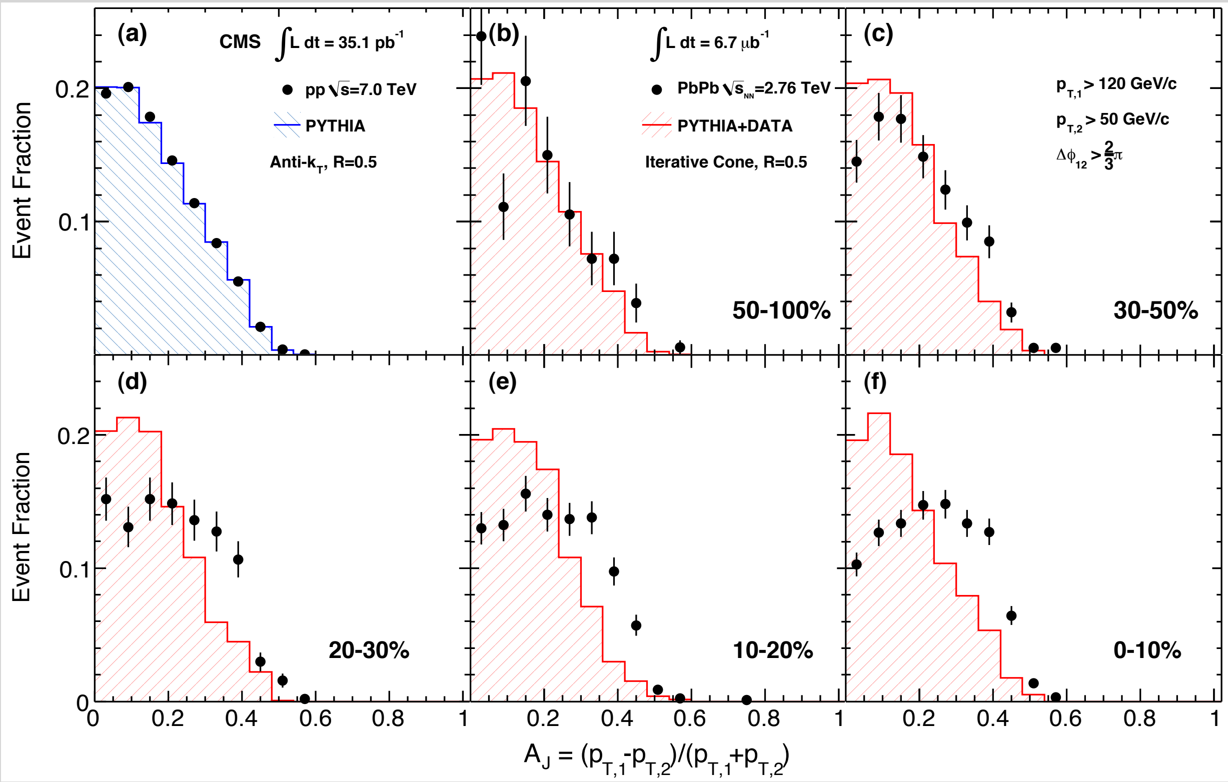

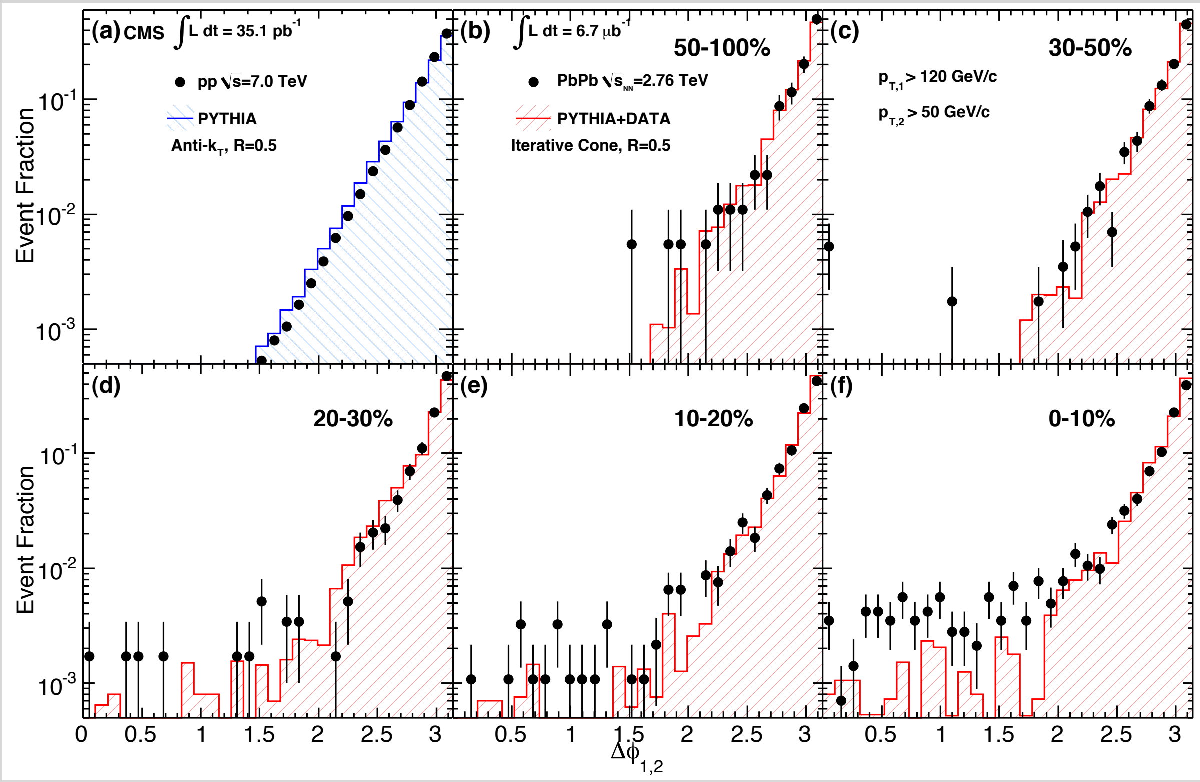

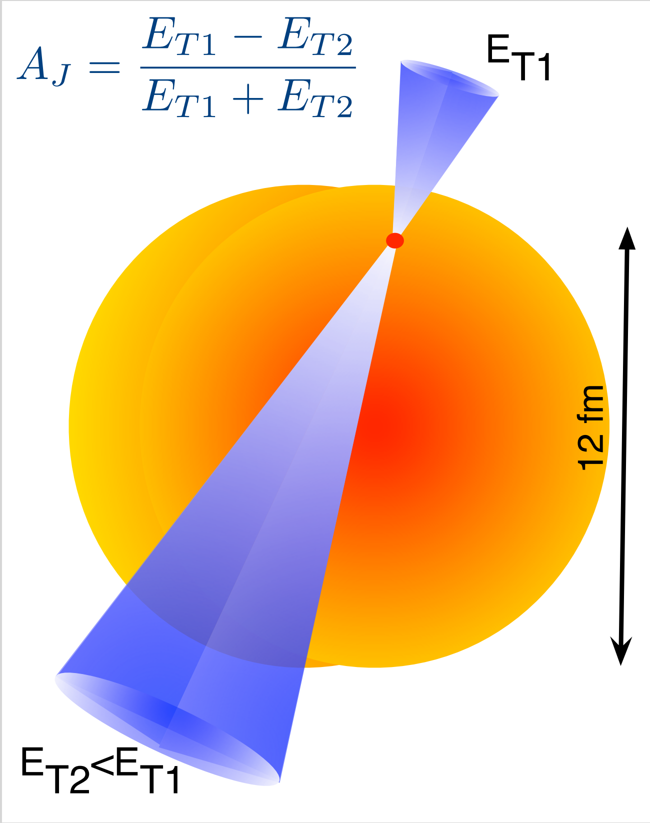

- significant enhancement of asymmetry
- no disturbance of azimuthal distribution

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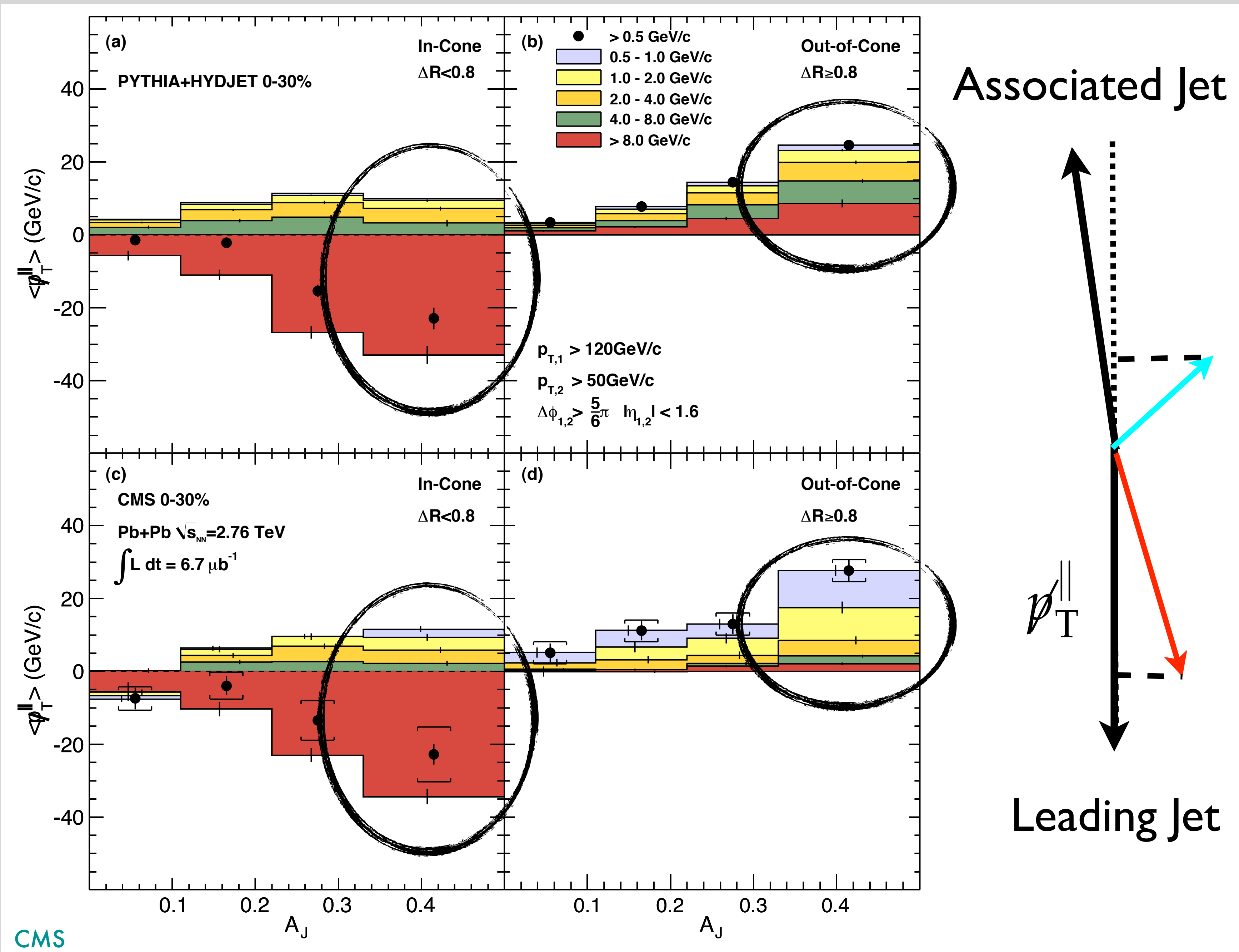

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

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

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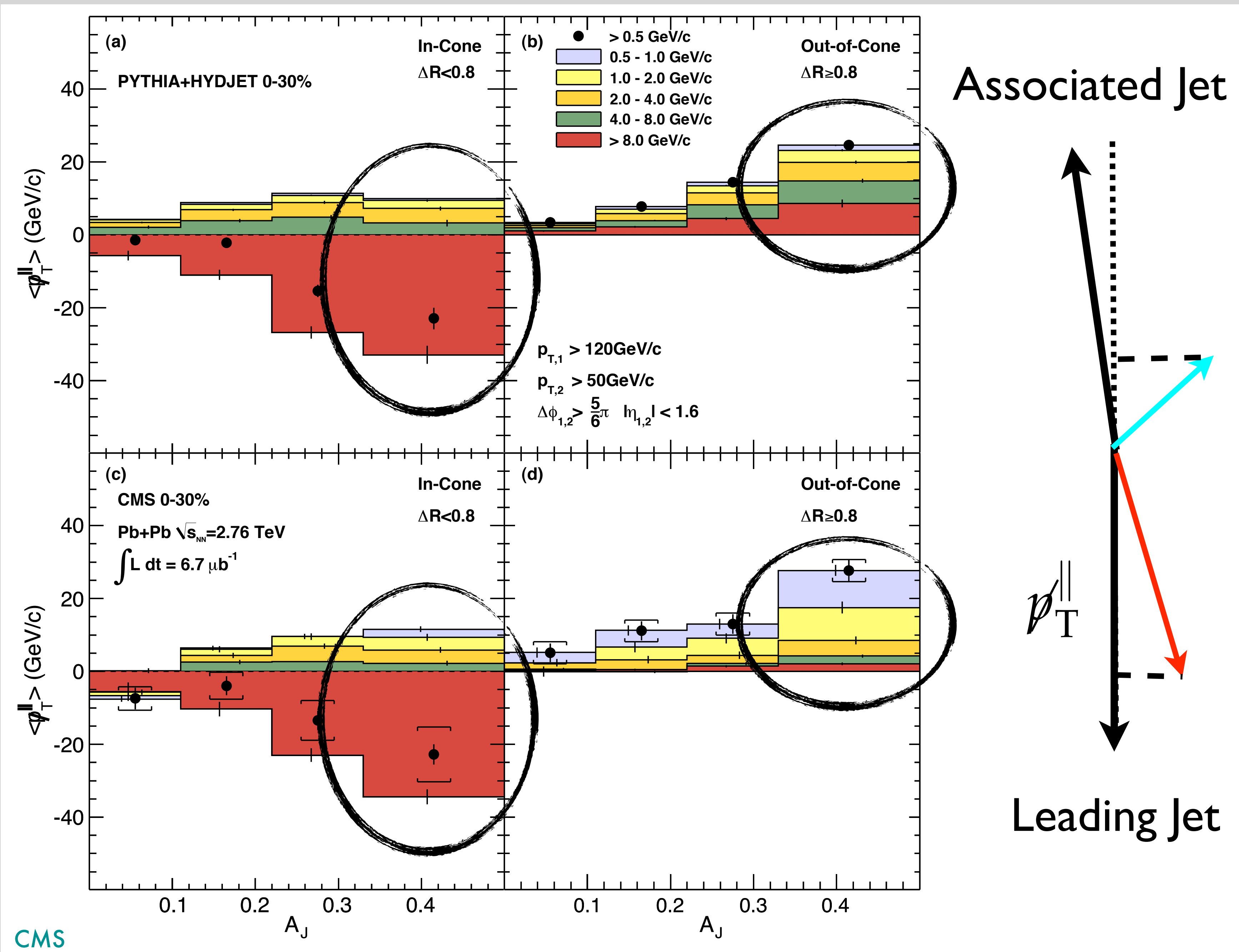

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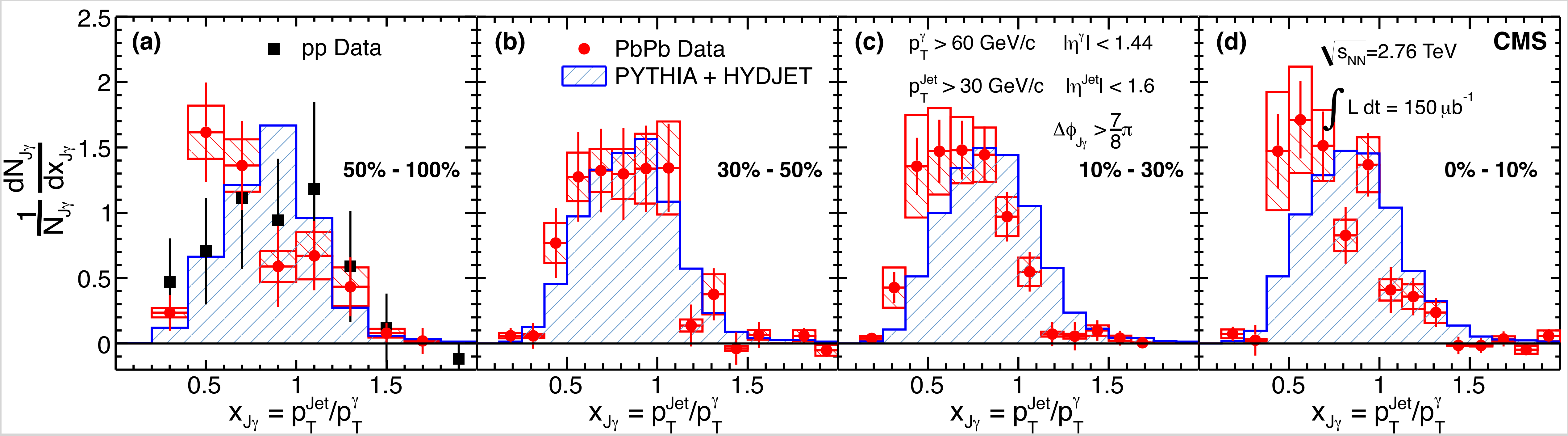
direct sensitivity to broadening

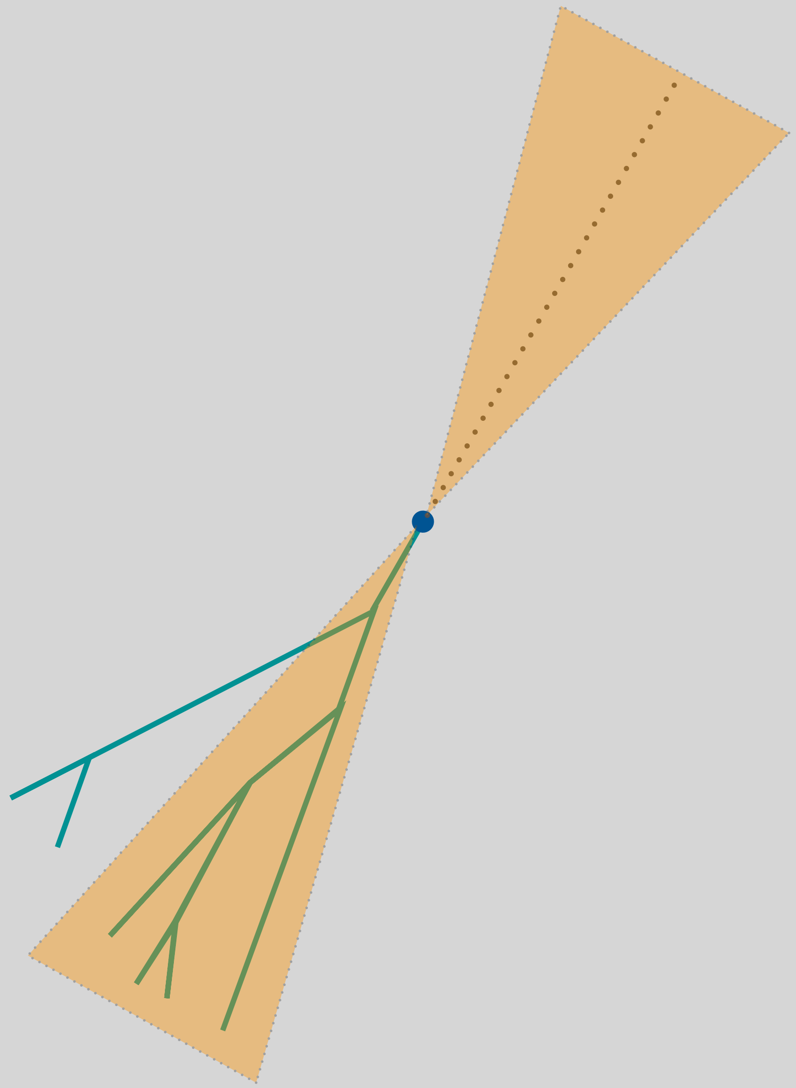
photon-jet correlations



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

#1 establishing the probe

jets in heavy ion collisions

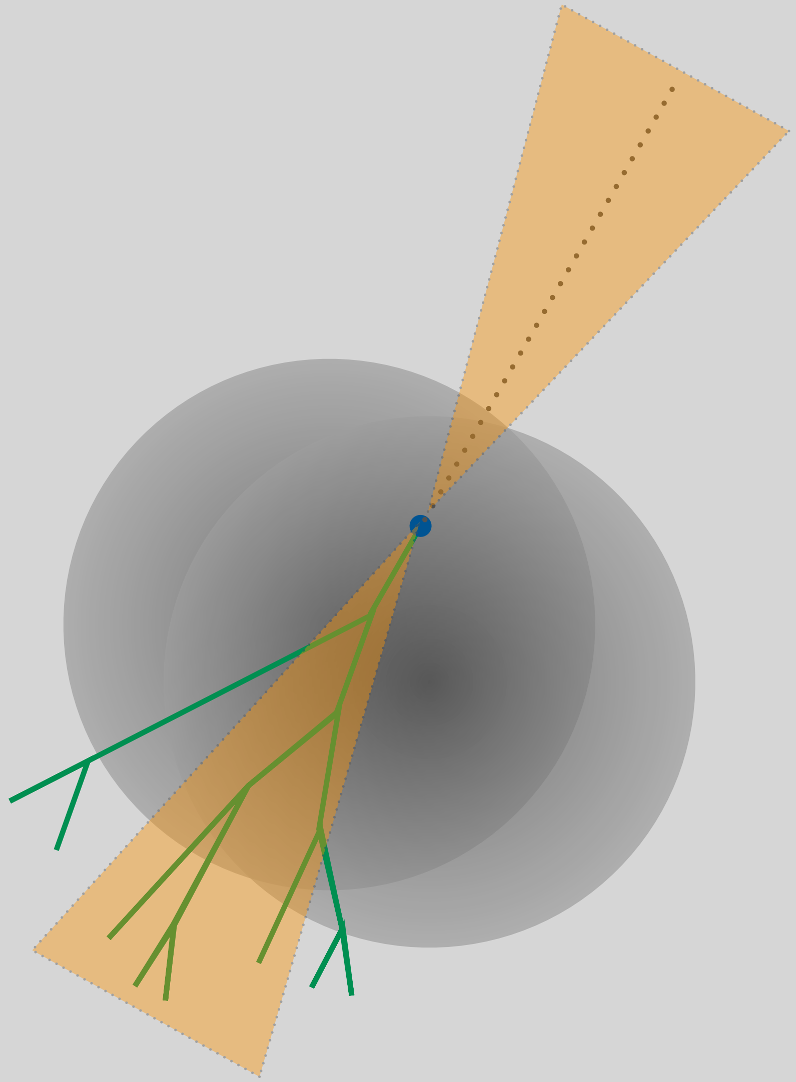


vacuum jets under overall excellent theoretical control

- 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]

jets in heavy ion collisions



in HIC jets traverse sizable in-medium pathlength

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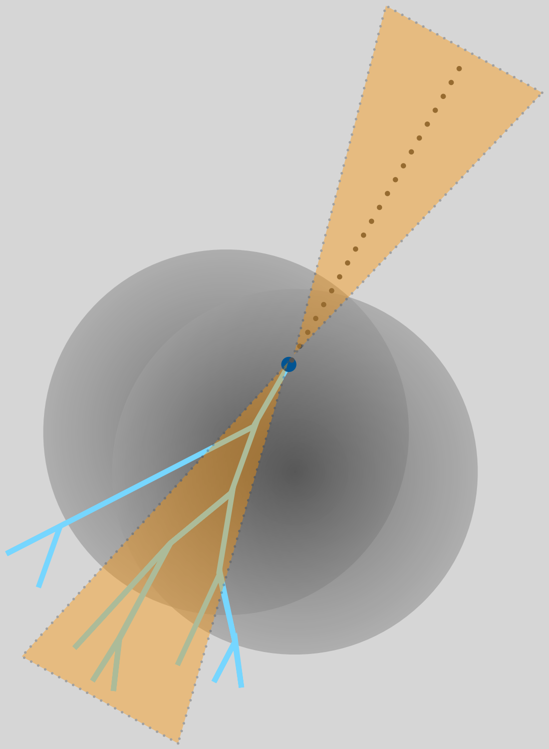
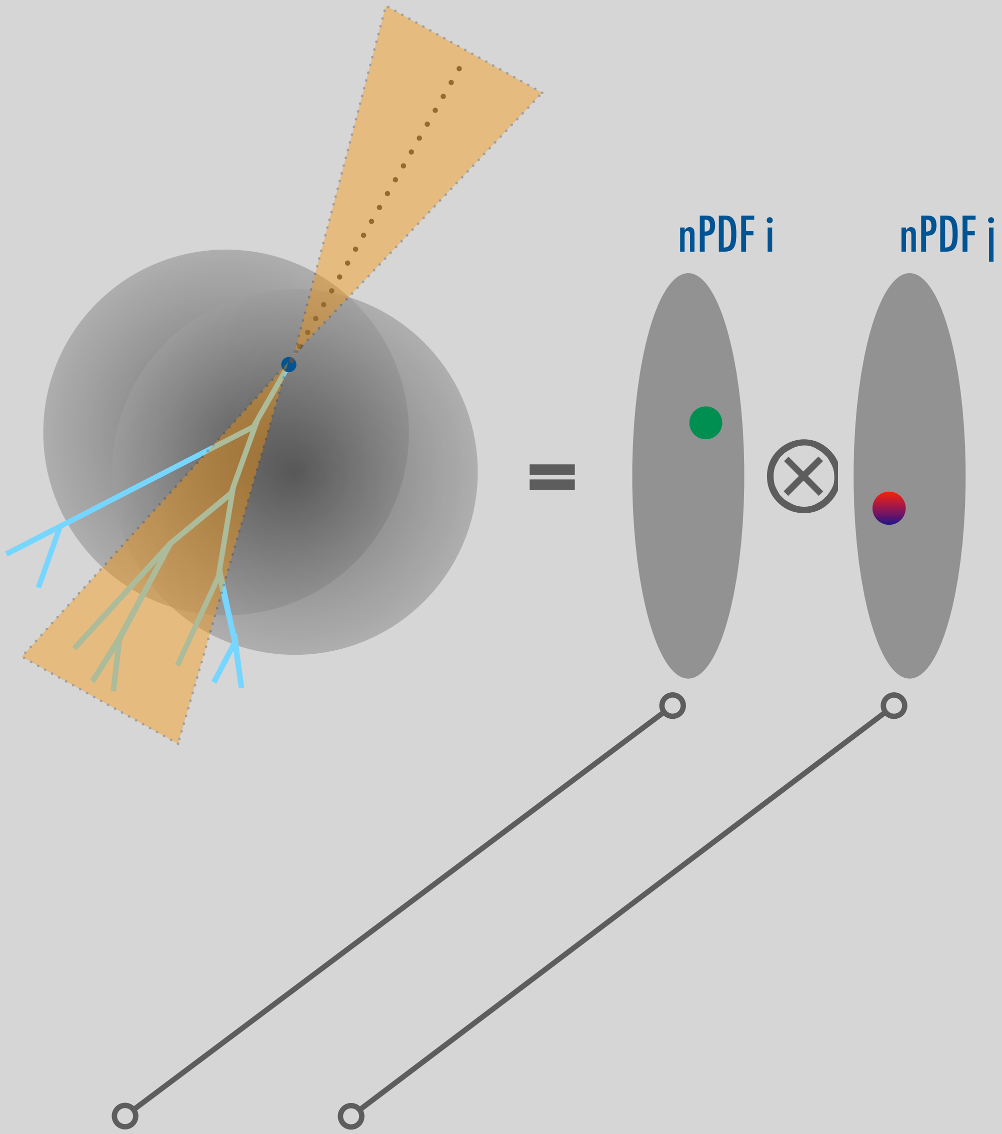


same factorizable structure [challengeable working hypothesis]

jets in heavy ion collisions



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

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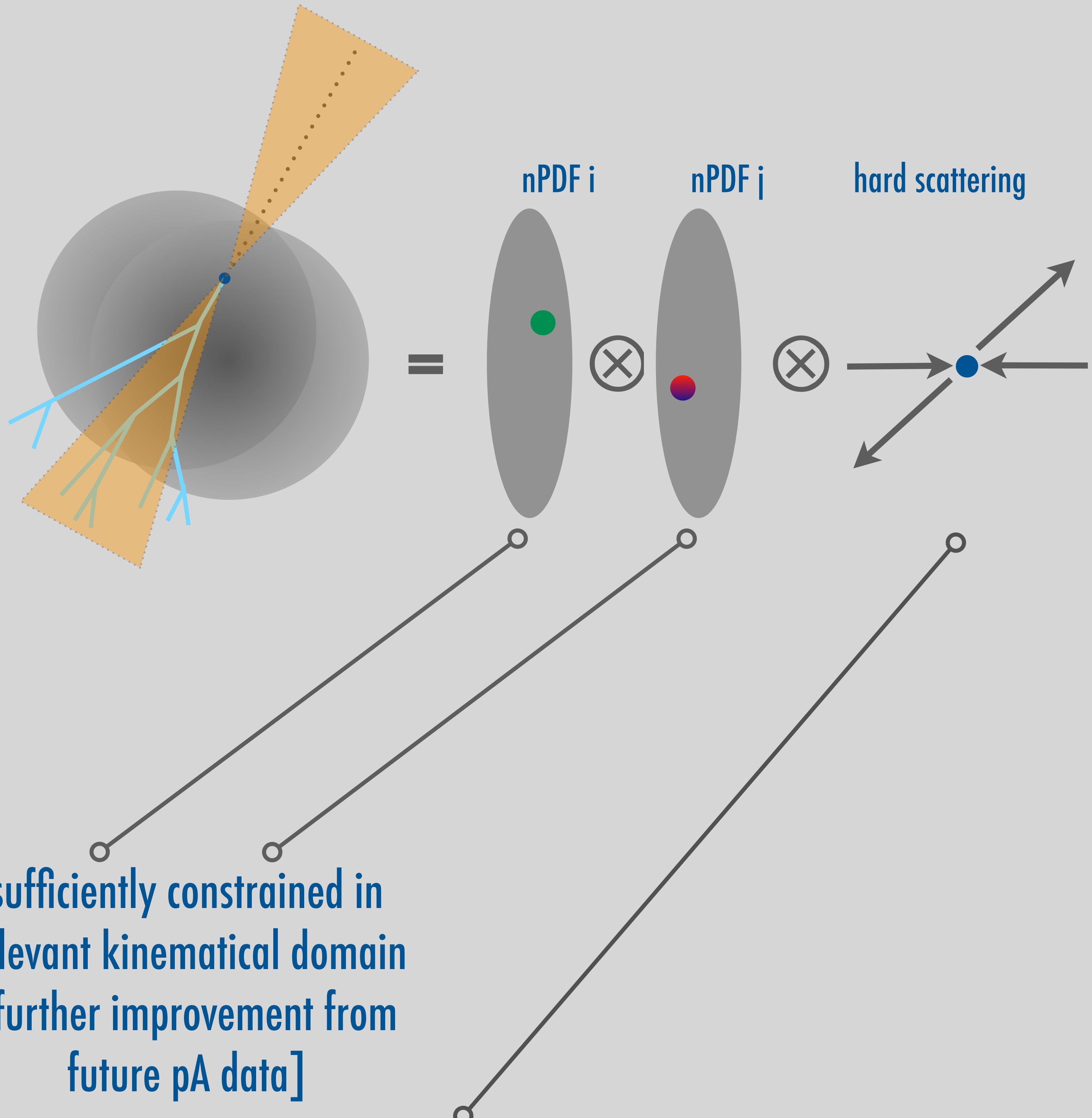
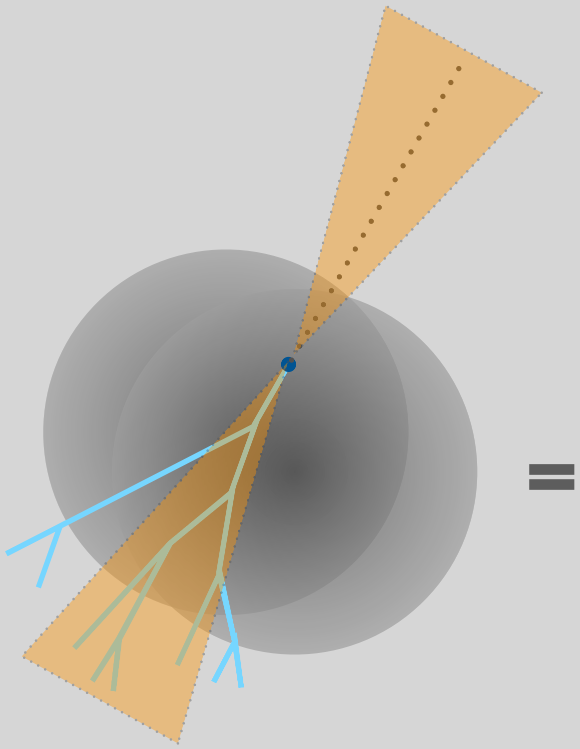


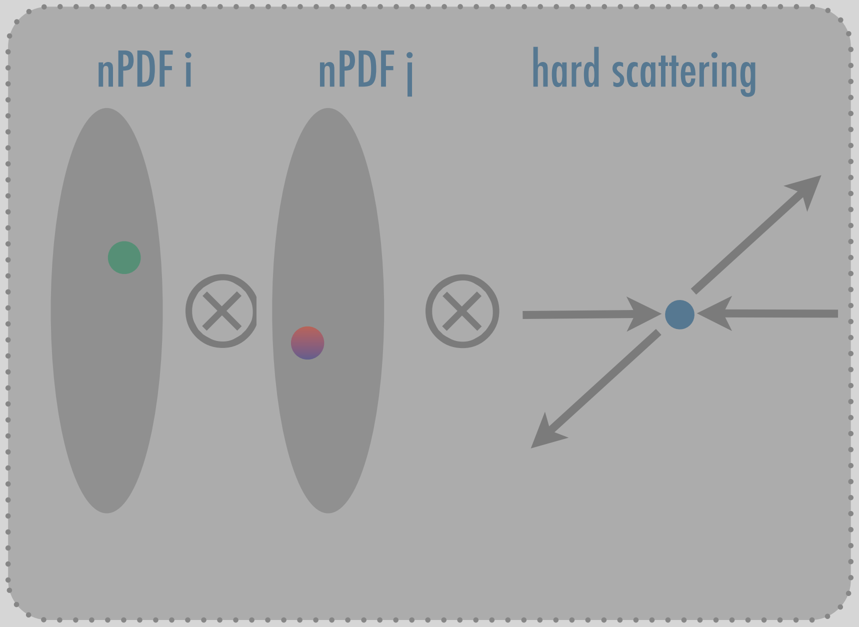
sufficiently constrained in relevant kinematical domain
[further improvement from future pA data]

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

jets in heavy ion collisions



factorized initial state
[insensitive to produced medium]



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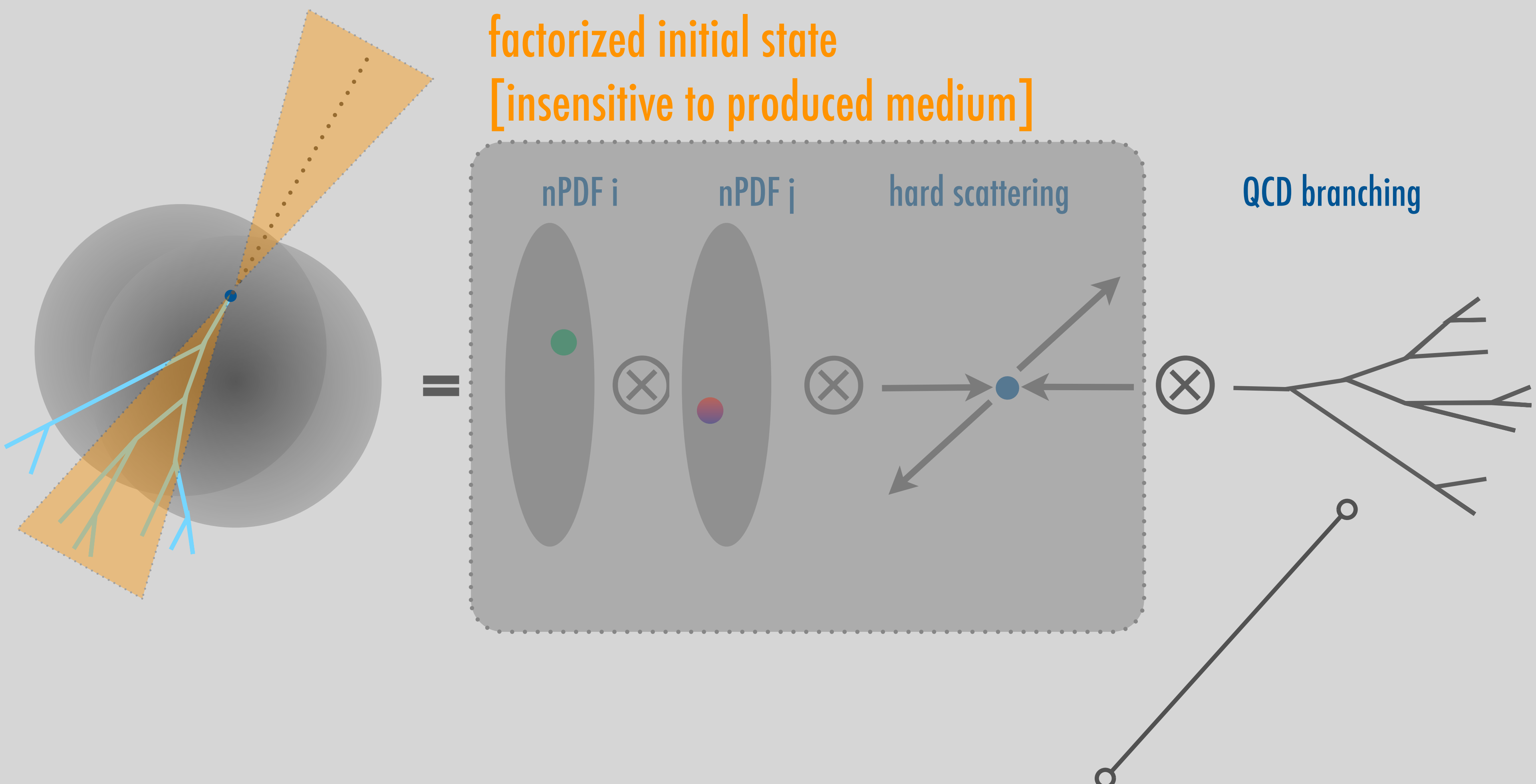

very well [and perturbatively] understood in vacuum

- 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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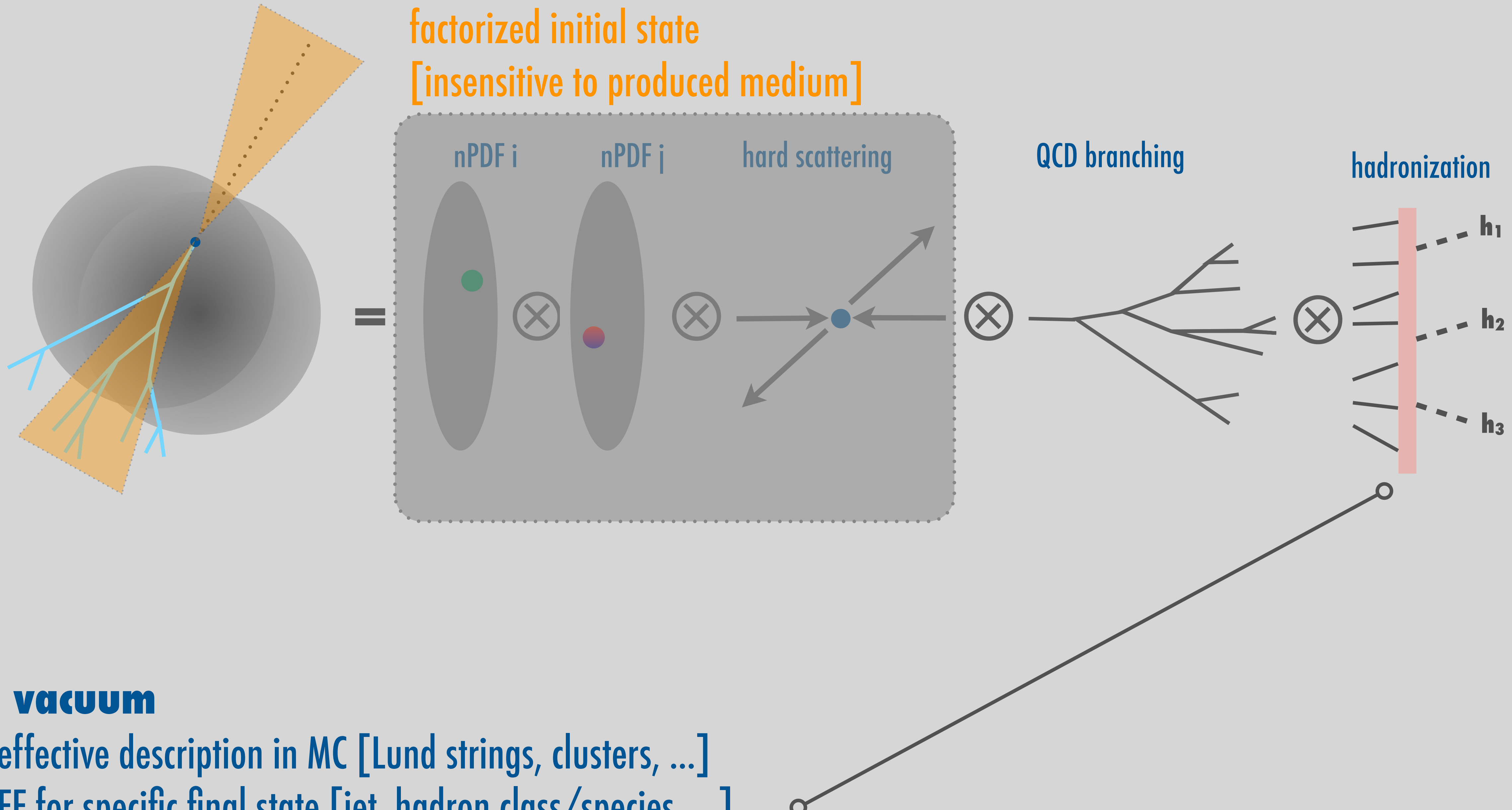


in vacuum

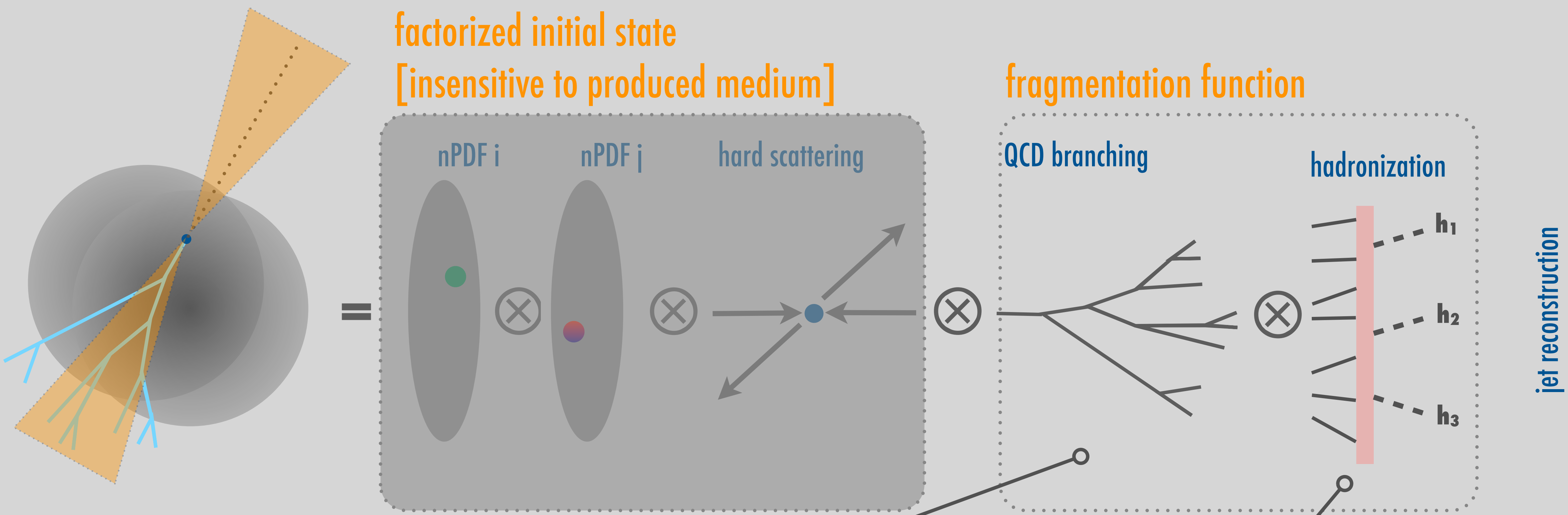
- effective description in MC [Lund strings, clusters, ...]
- FF for specific final state [jet, hadron class/species, ...]

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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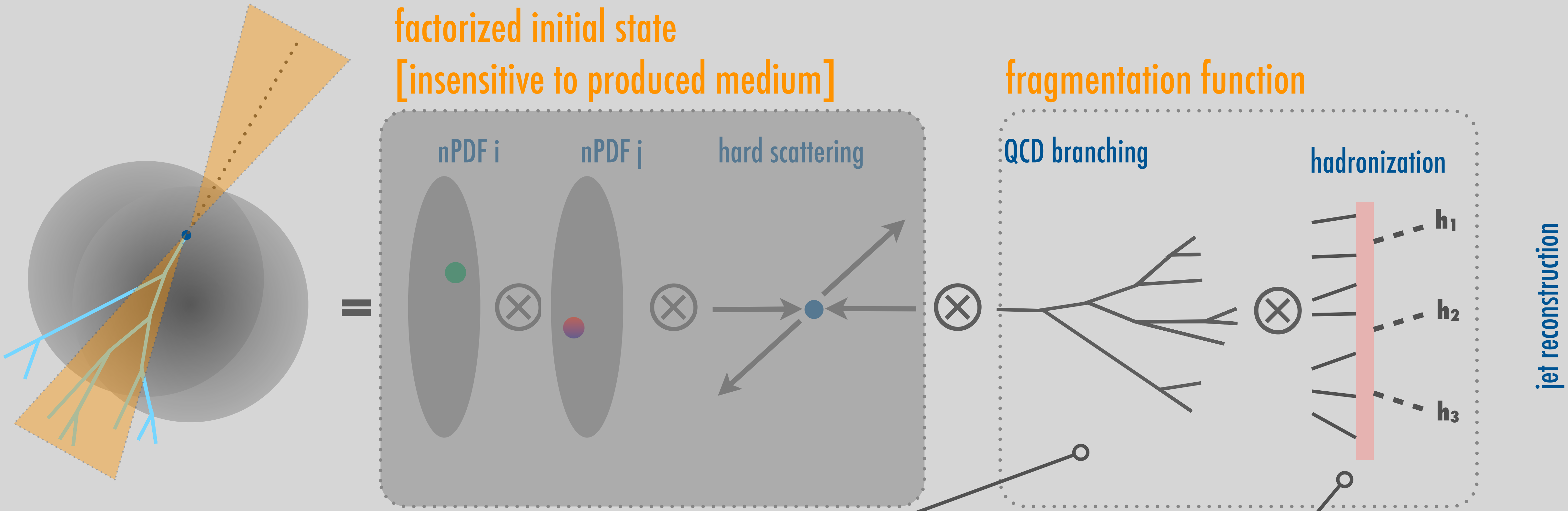

jet quenching ::
observable consequences [in jet and jet-like hadronic observables] of the effect of the medium

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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

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- single gluon emission understood in 4 classes of pQCD-based formalisms
  - ↪ **B**aier-**D**okshitzer-**M**ueller-**P**eigné-**S**chiff−**Z**akharov
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  - ↪ **H**igher-**T**wist [Guo and Wang]

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  - Poissonian ansatz [BDPMS and GLV]; rate equations [AMY]; medium-modified DGLAP [HT]

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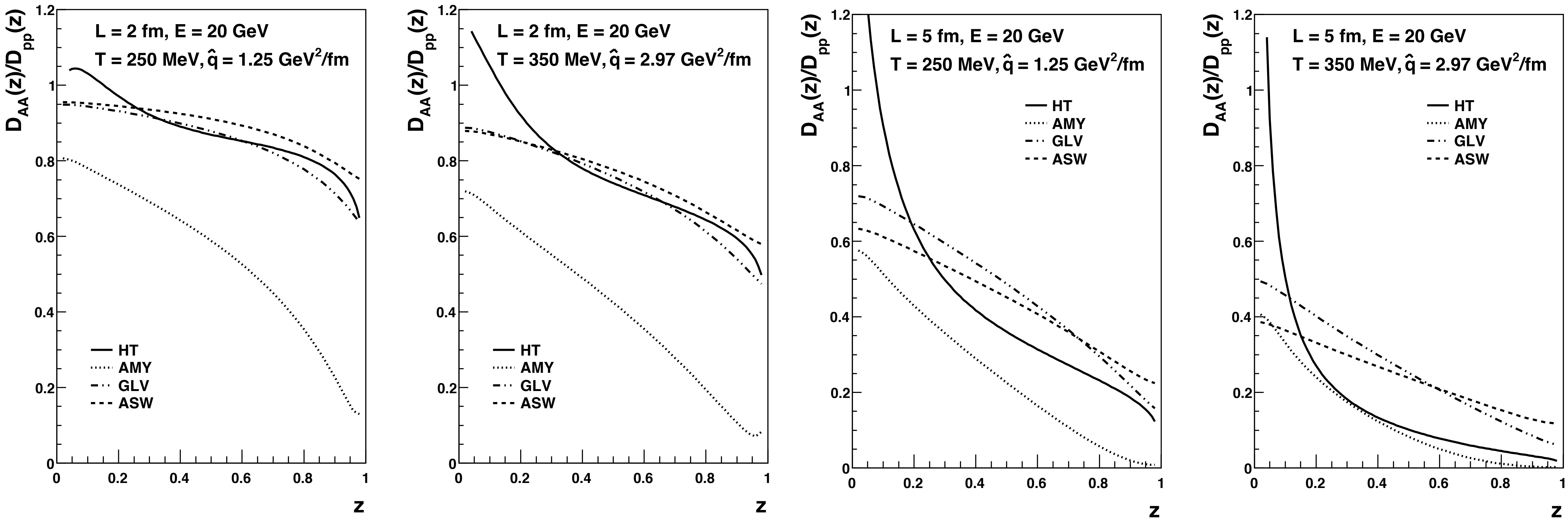
- Monte Carlo implementations [HIJING, Q-PYTHIA/Q-HERWIG, JEWELL, YaJEM, MARTINI]

medium induced radiation

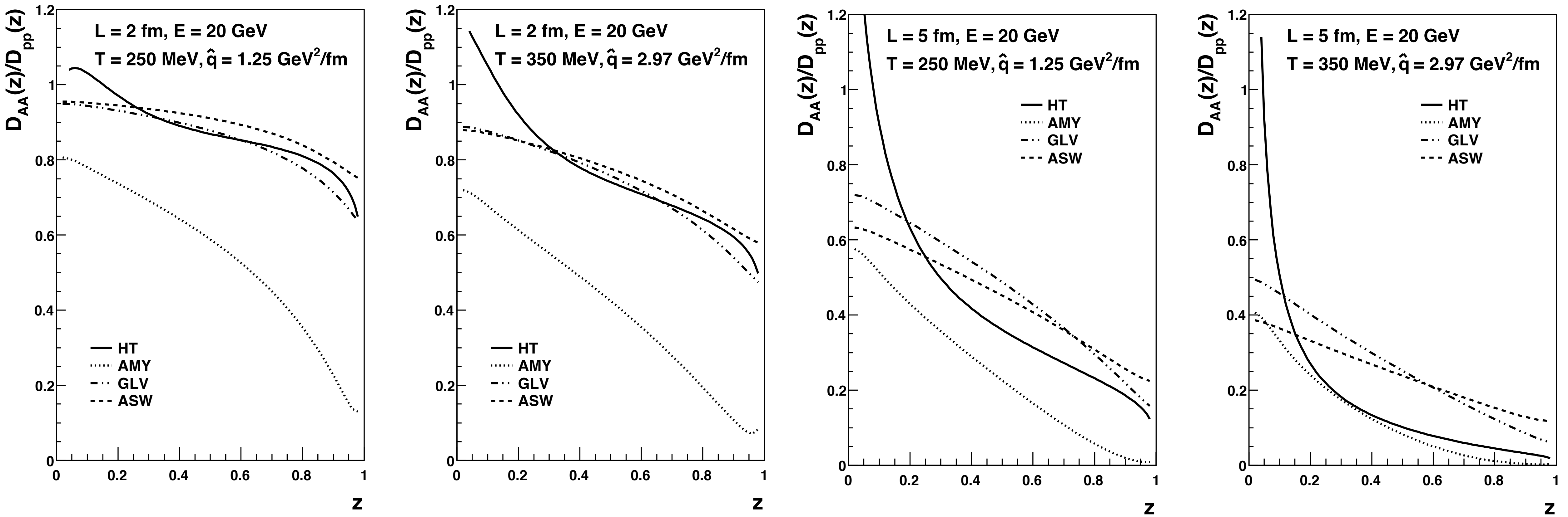


medium modification of quark fragmentation function

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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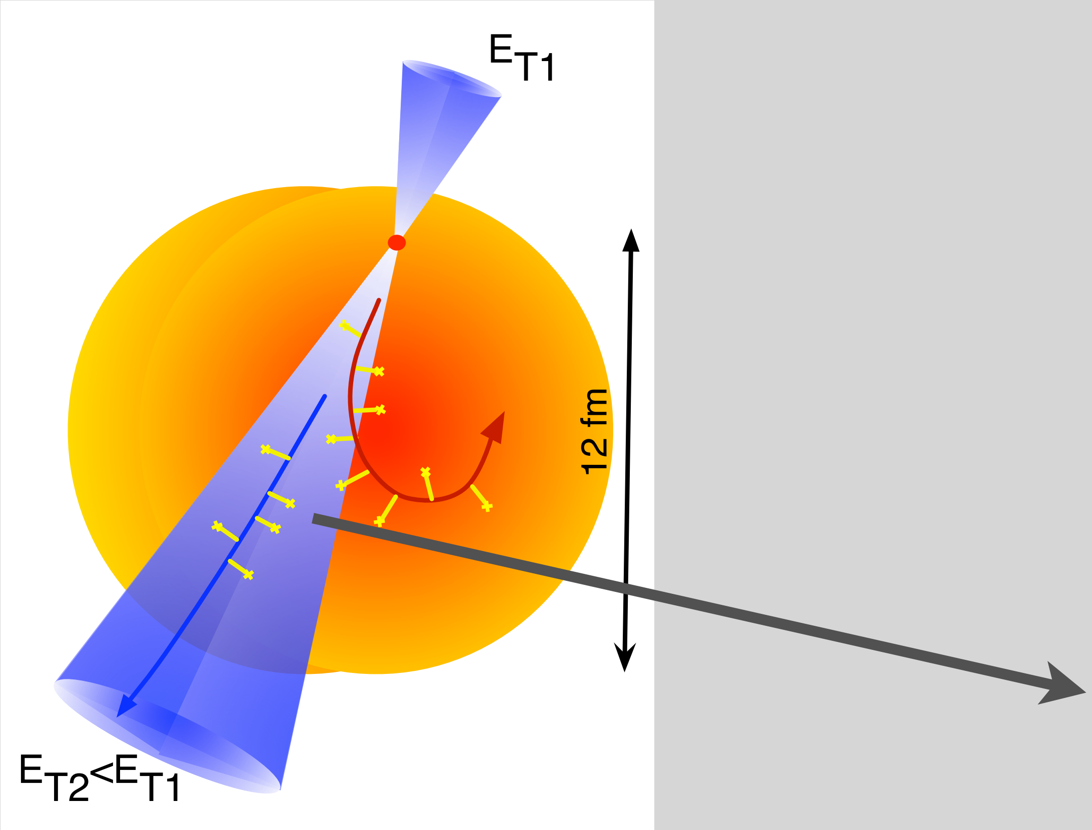
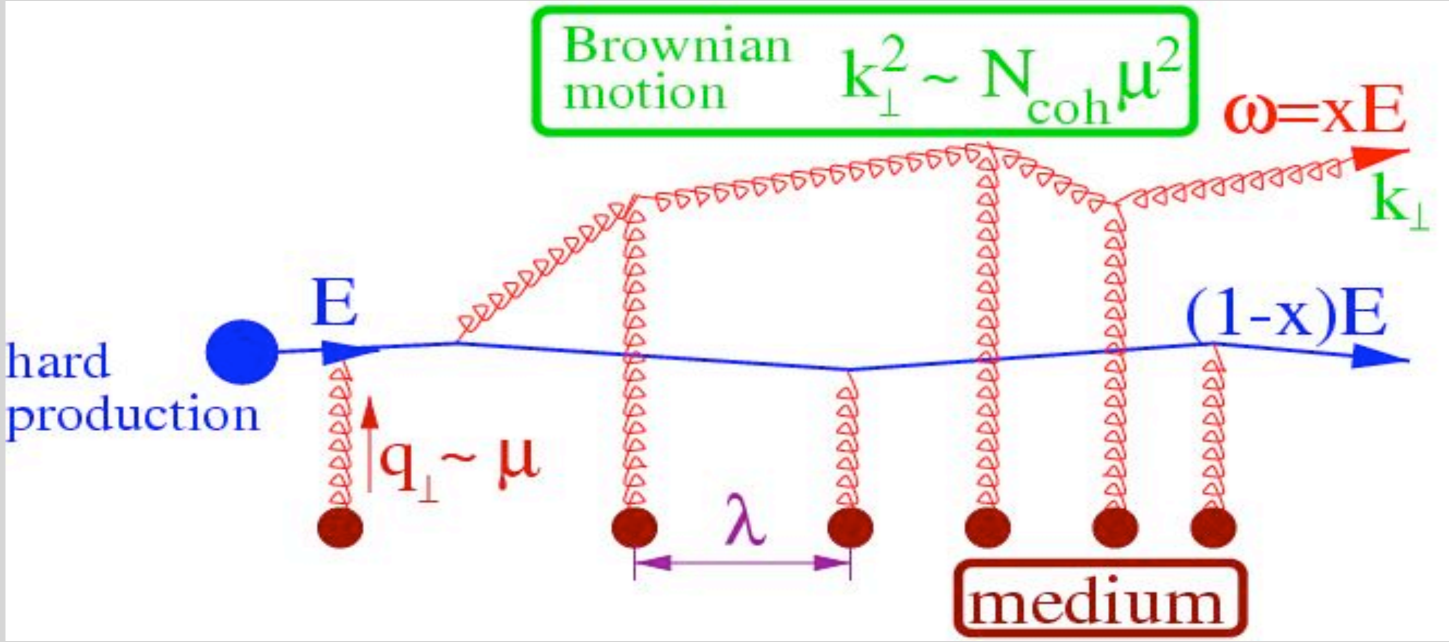
none necessarily right or wrong, all incomplete

in-medium dynamics





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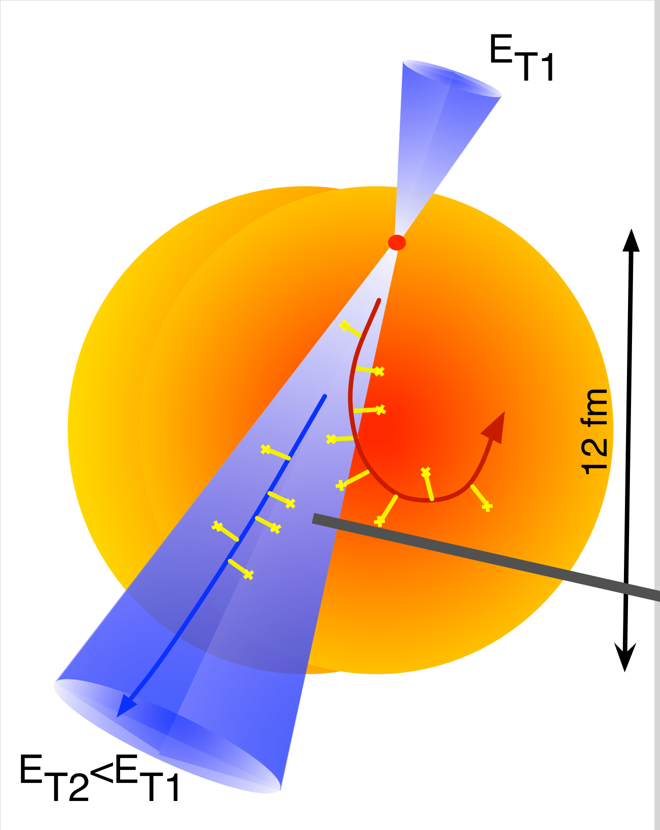

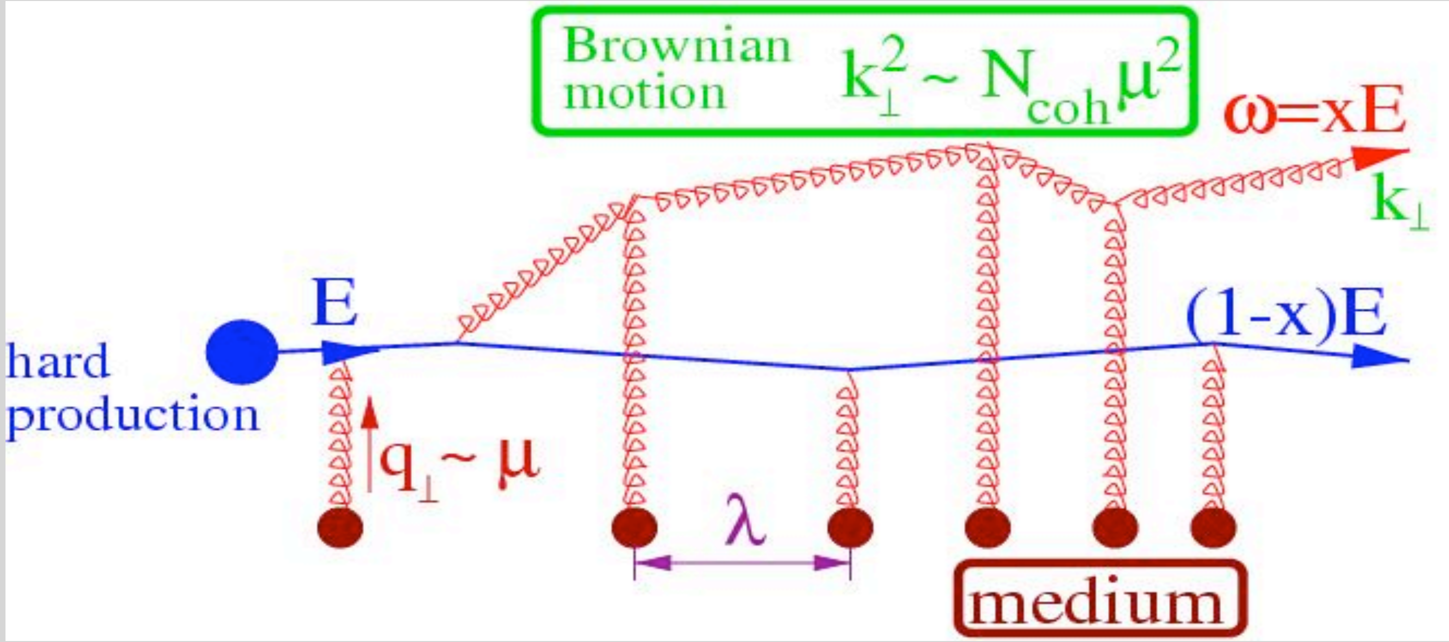

- enhanced and softened radiation :: parton energy loss

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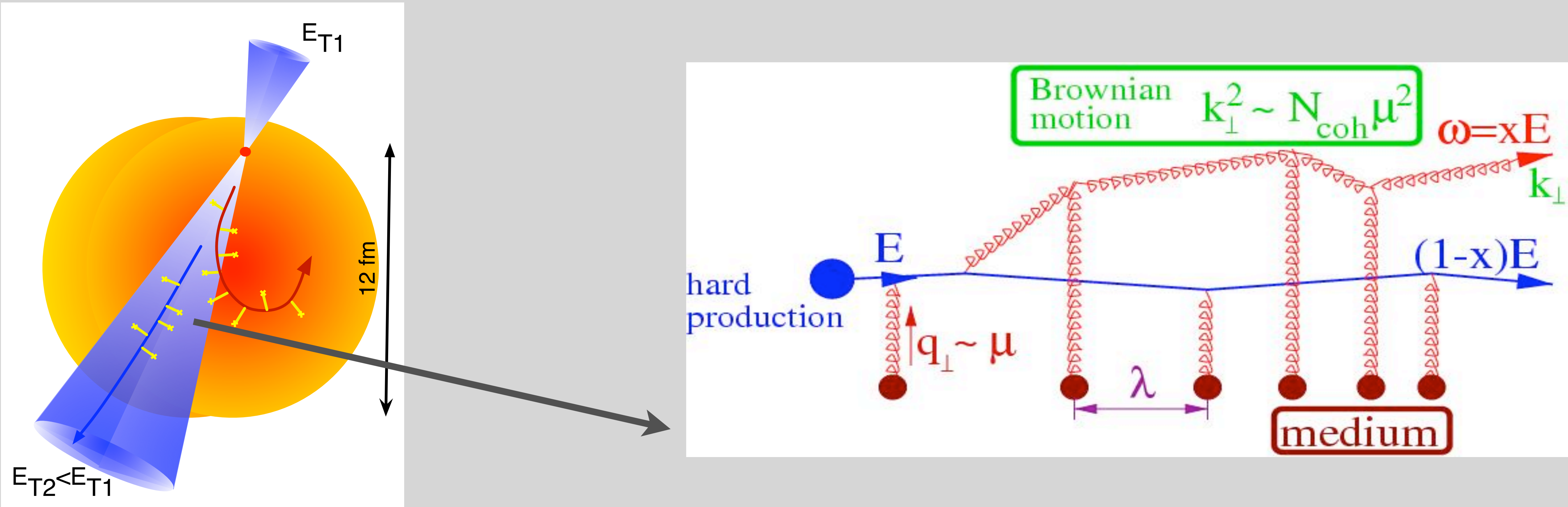

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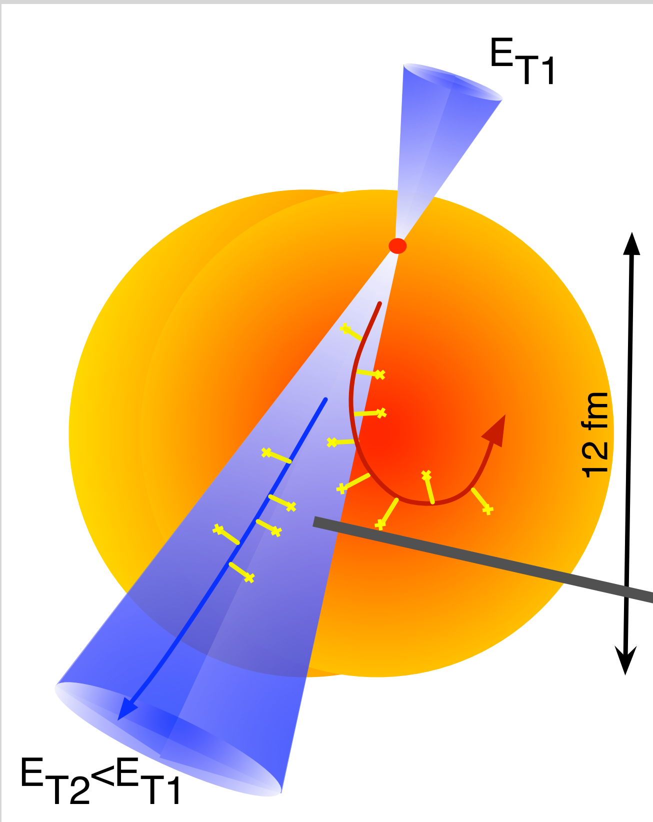

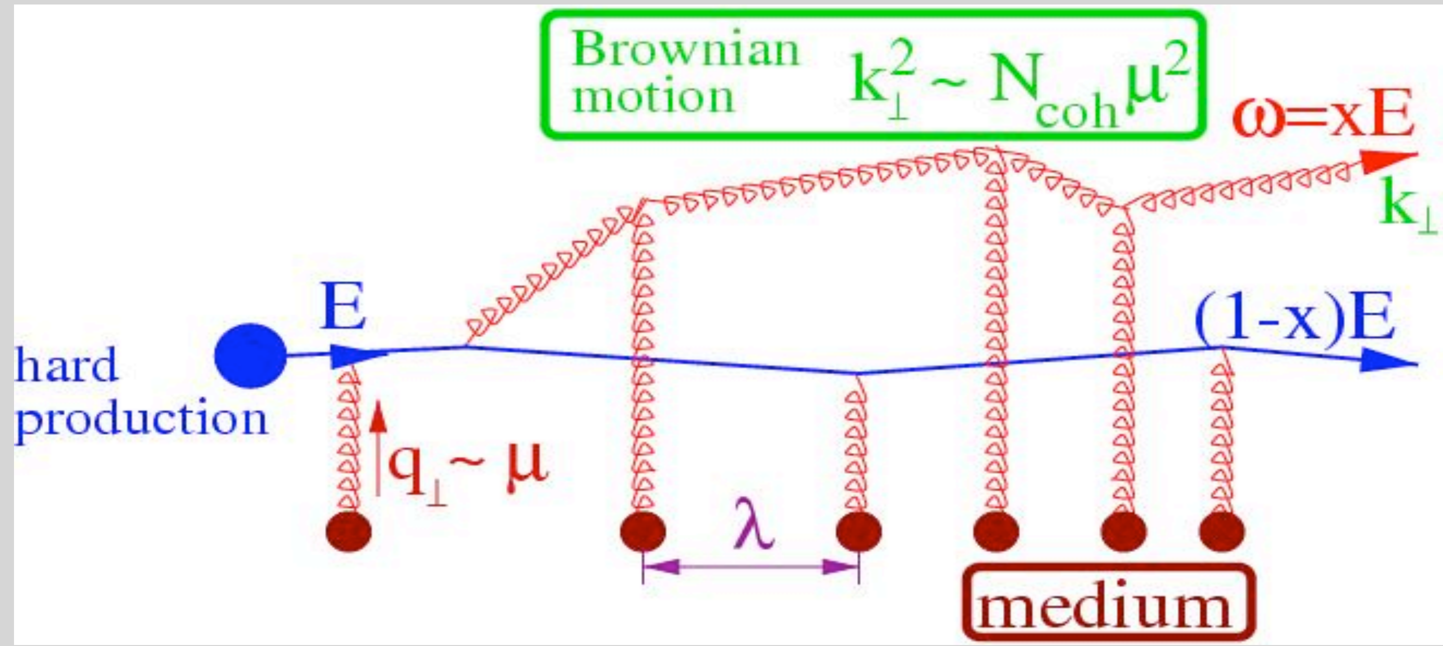

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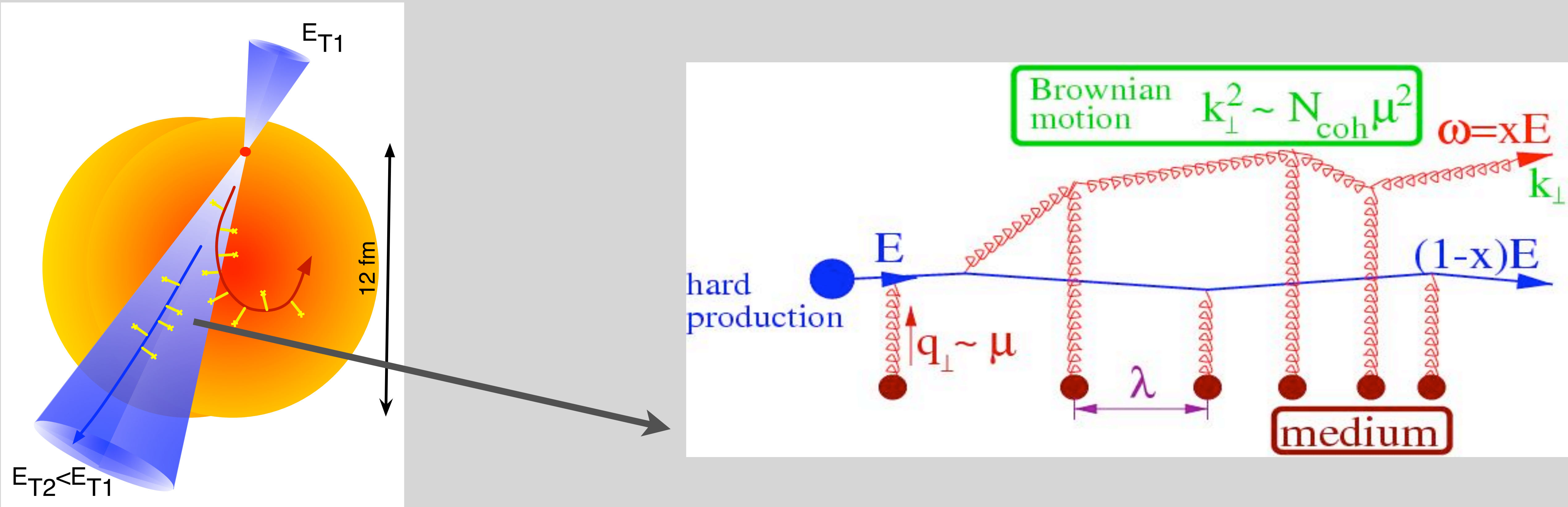

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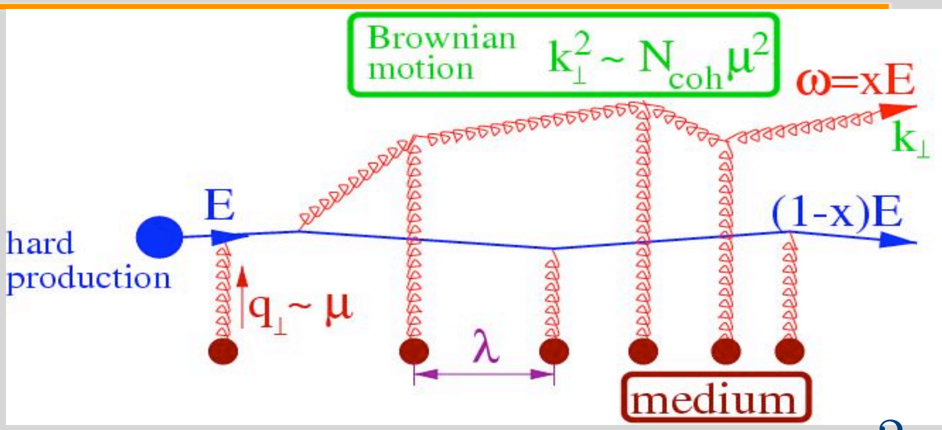
- transverse momentum transfers with medium :: k_t broadening

parton energy loss [BDMPS-Z]



- 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

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

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

- number of coherent scatterings

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

- 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

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

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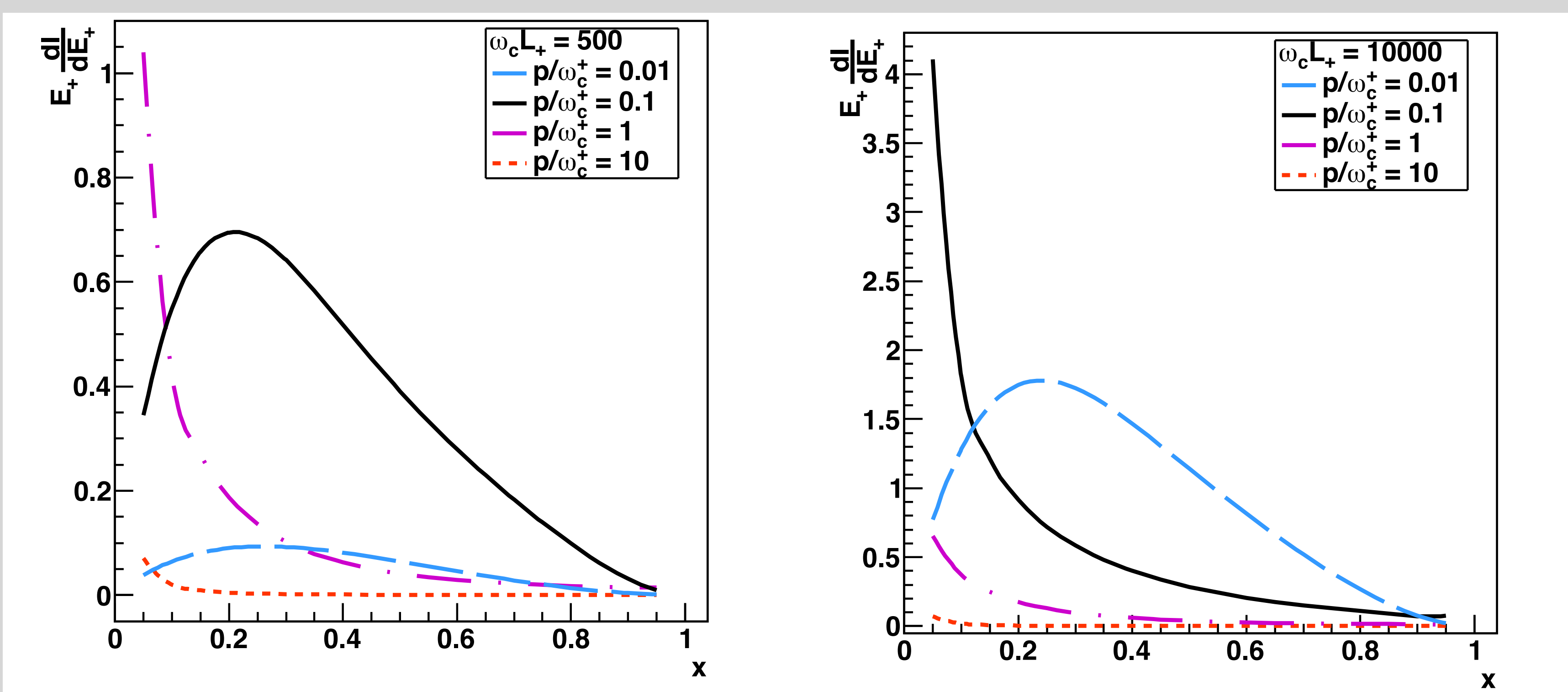
  ↪ large-x limit computed in path-integral formalism, explicitly in the multiple soft scattering approximation, and small-large x interpolating ansatz

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

[de]coherence of multiple emissions

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

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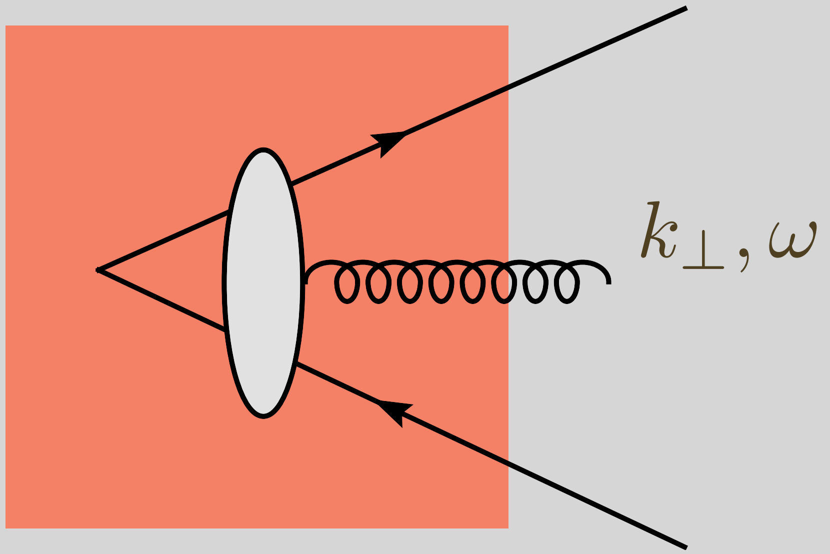

MAJOR EFFORT

Mehtar-Tani, Salgado, Tywoniuk [1009.2965 ... 1205.5739]

Casalderrey-Solana & Iancu [1105.1760]

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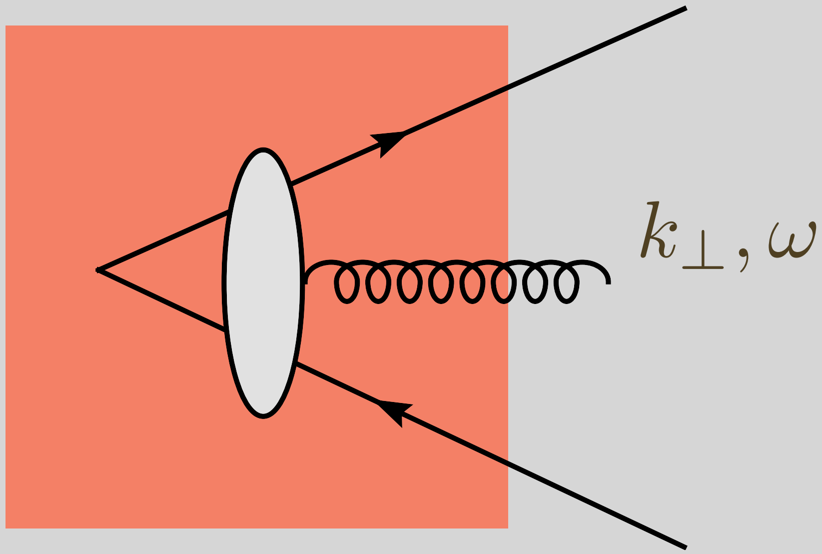
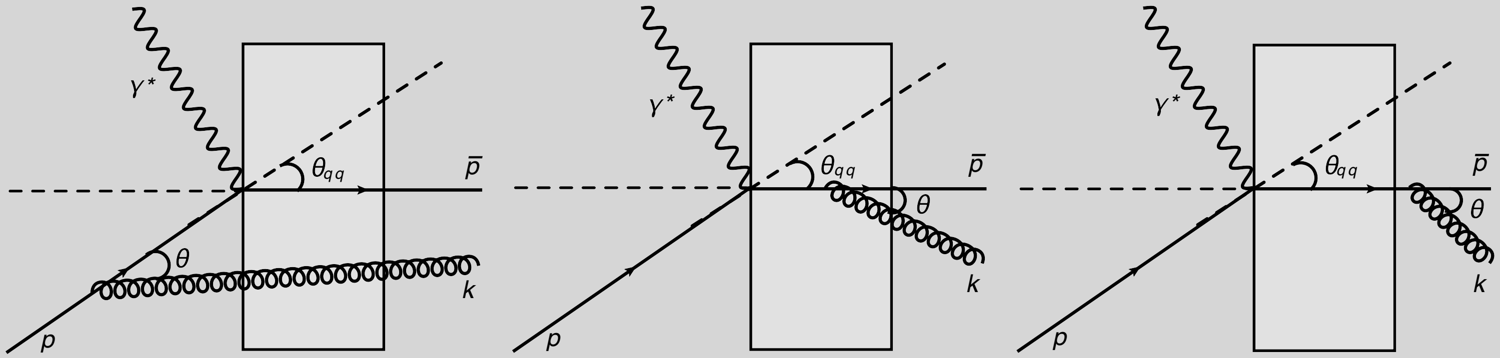


MAJOR EFFORT

Mehtar-Tani, Salgado, Tywoniuk [1009.2965 ... 1205.5739]
Casalderrey-Solana & Iancu [1105.1760]

  - also for initial/final state

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



a challenge for factorization ???

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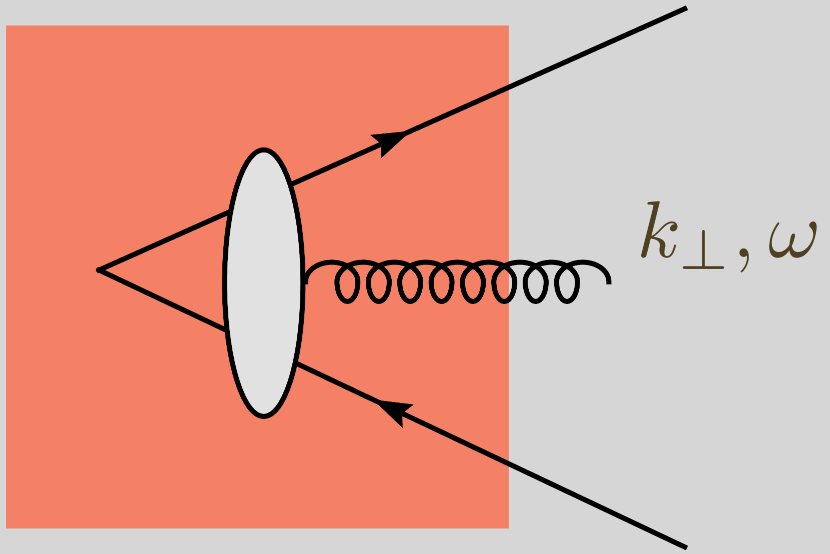

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$$\Delta_{\rm med} = 1 - \exp\left\{ -\frac{1}{12}\hat{q}\theta^2_{q\bar{q}}t^3 \right\}$$

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

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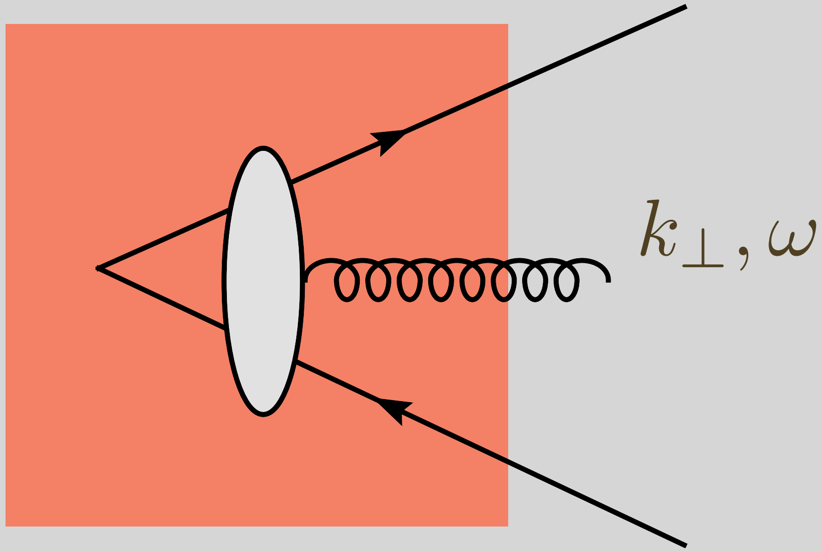

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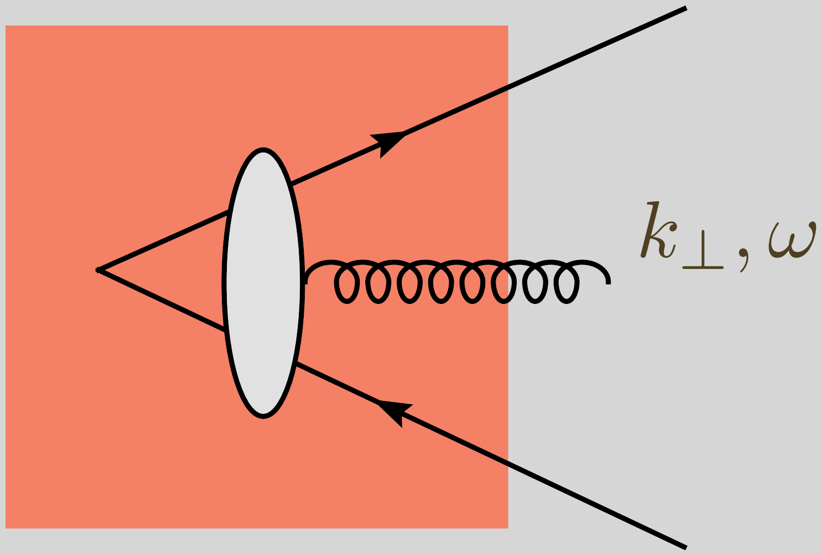

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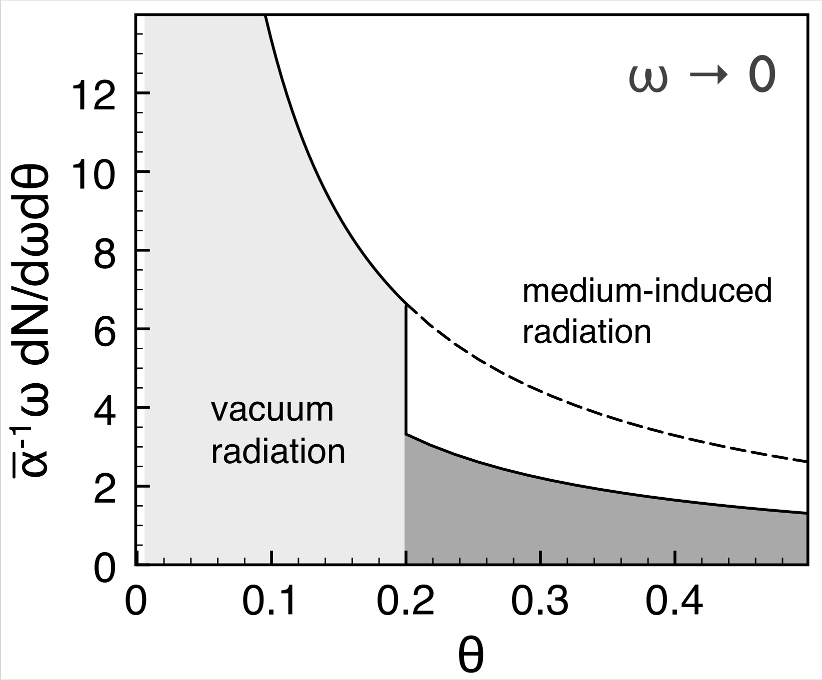

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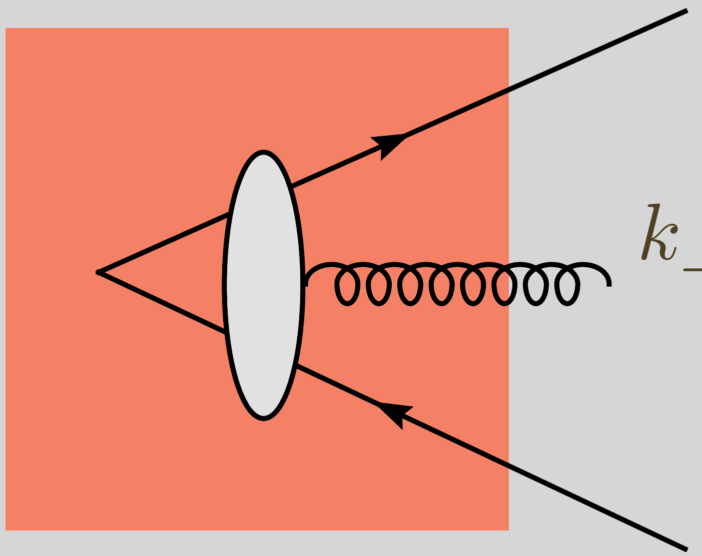

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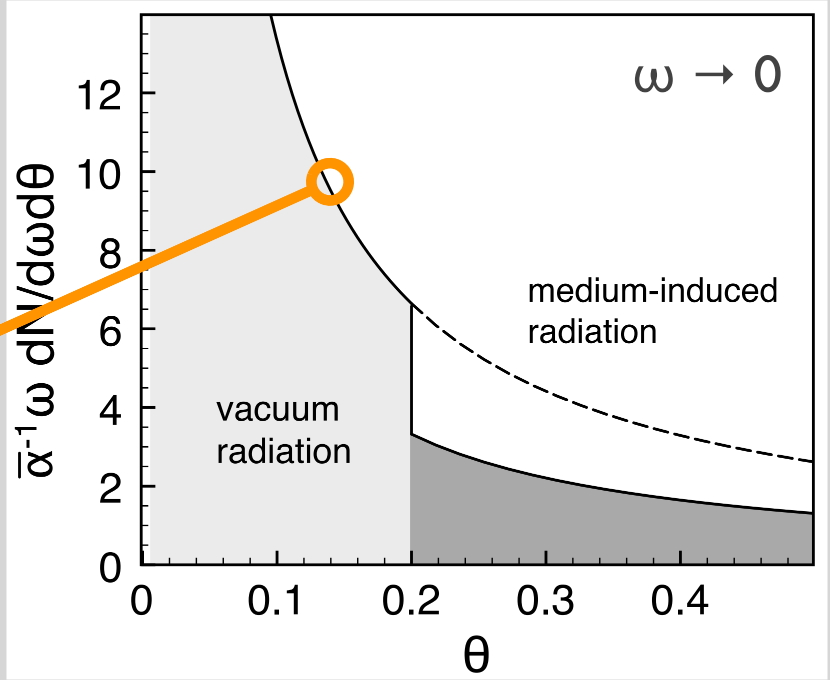

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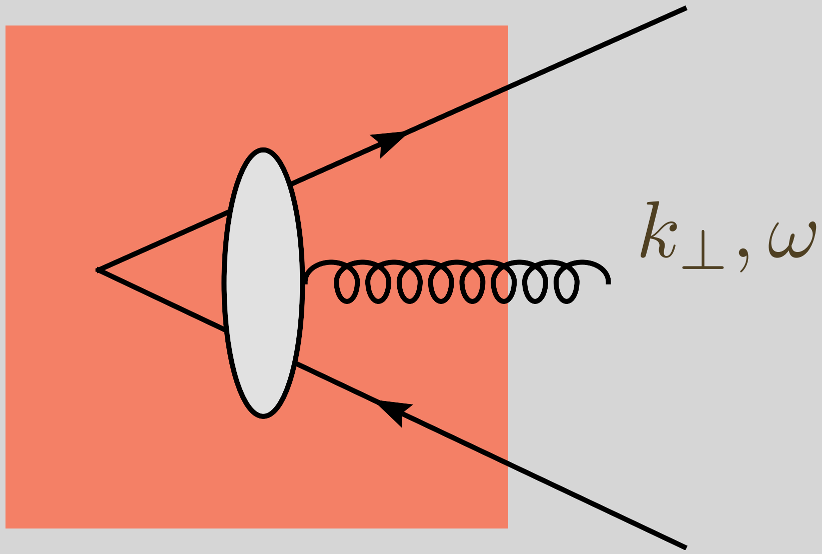

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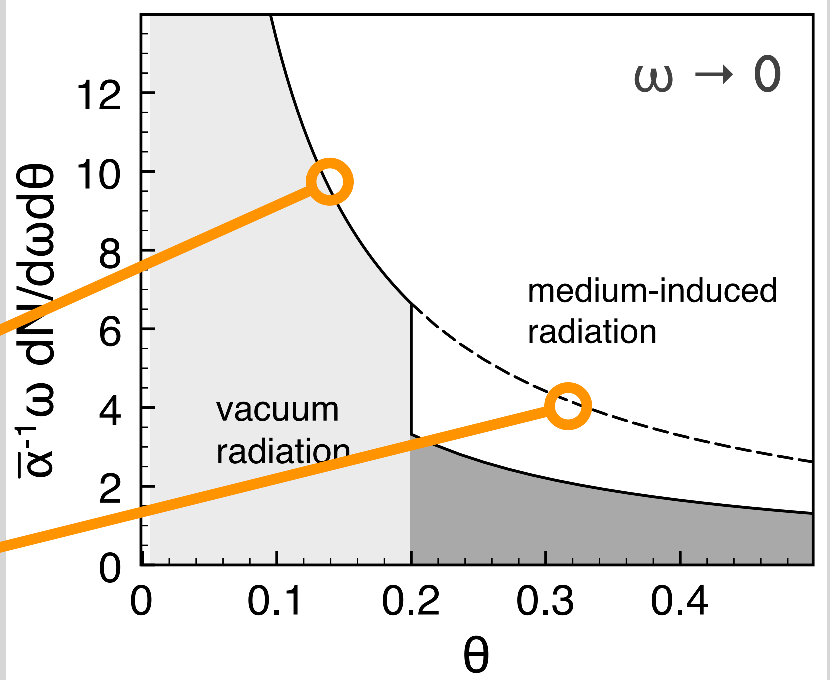


transport of soft radiation away from jet

[probing broadening]

A. Casalderrey-Solana, JGM, U. Wiedemann

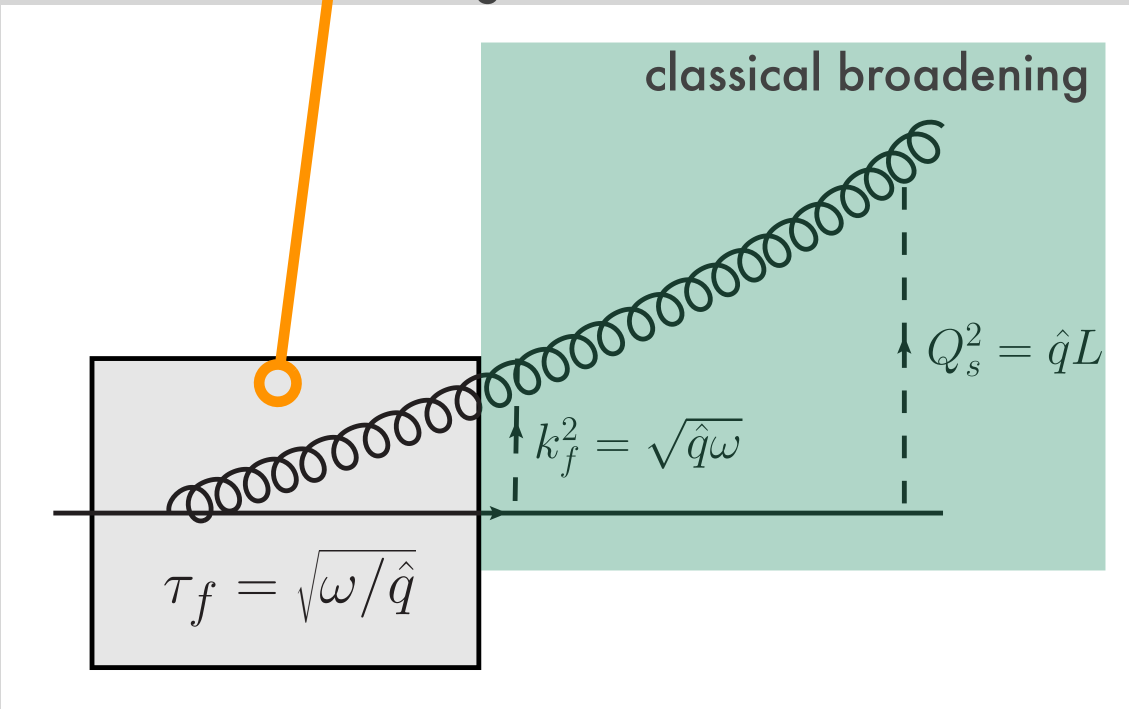
[1012.0745 &1107.1964 & in progress]

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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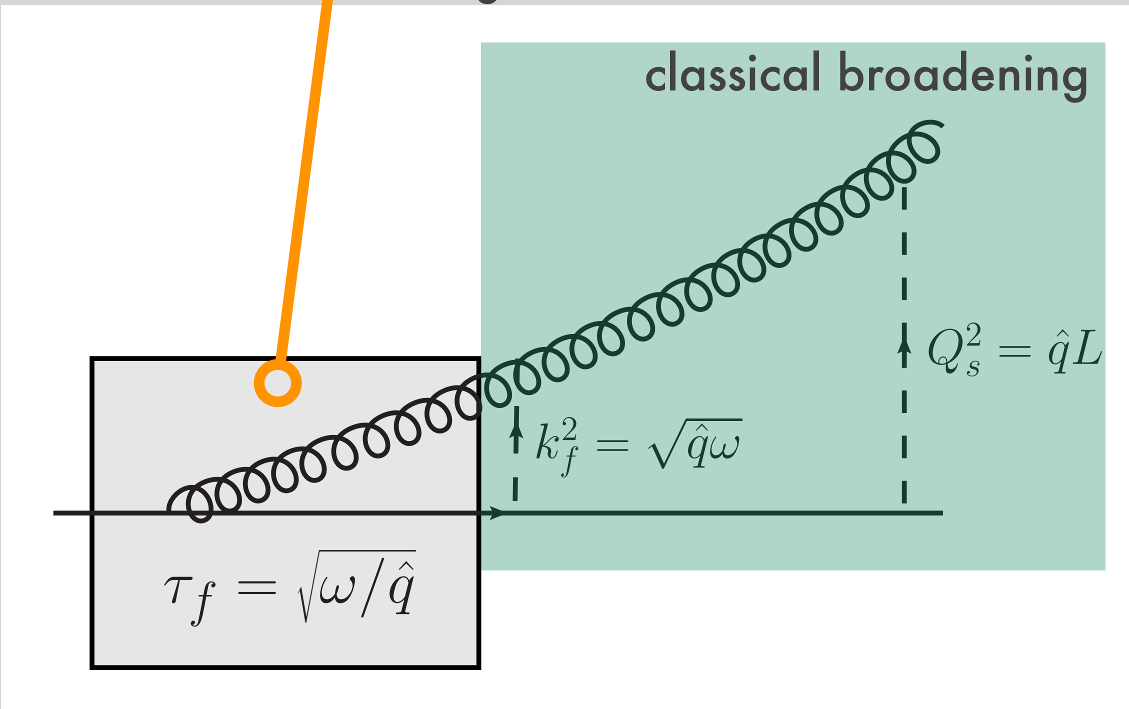
AN IMPORTANT LESSON FROM DATA

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



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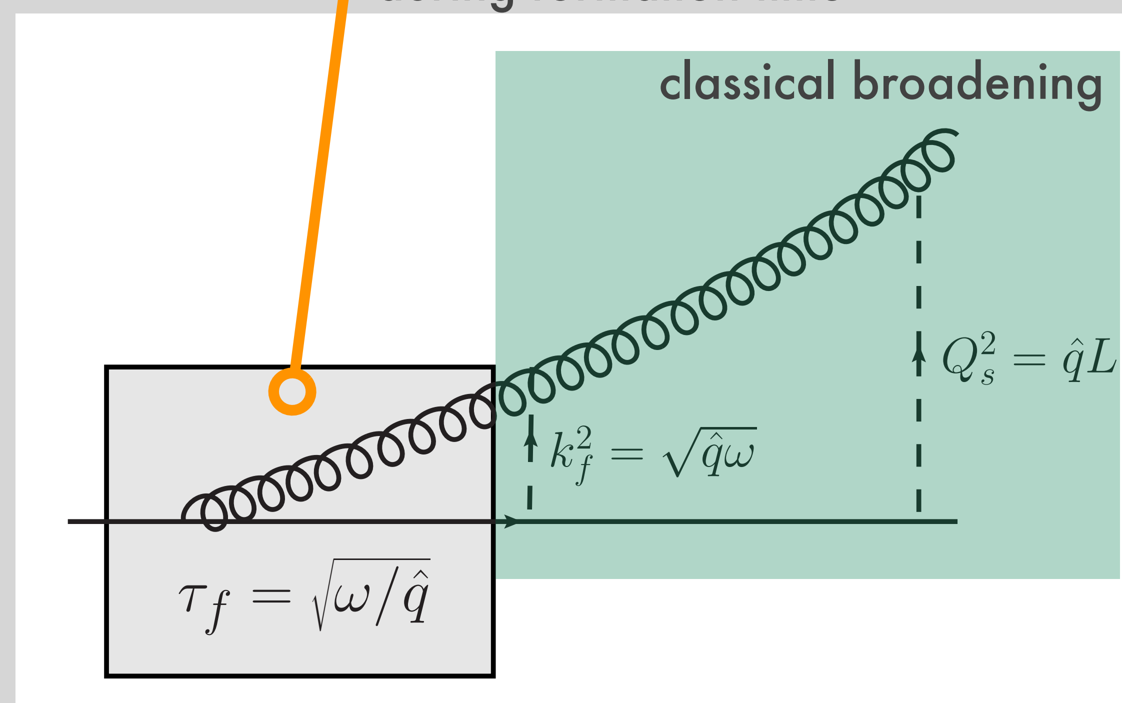

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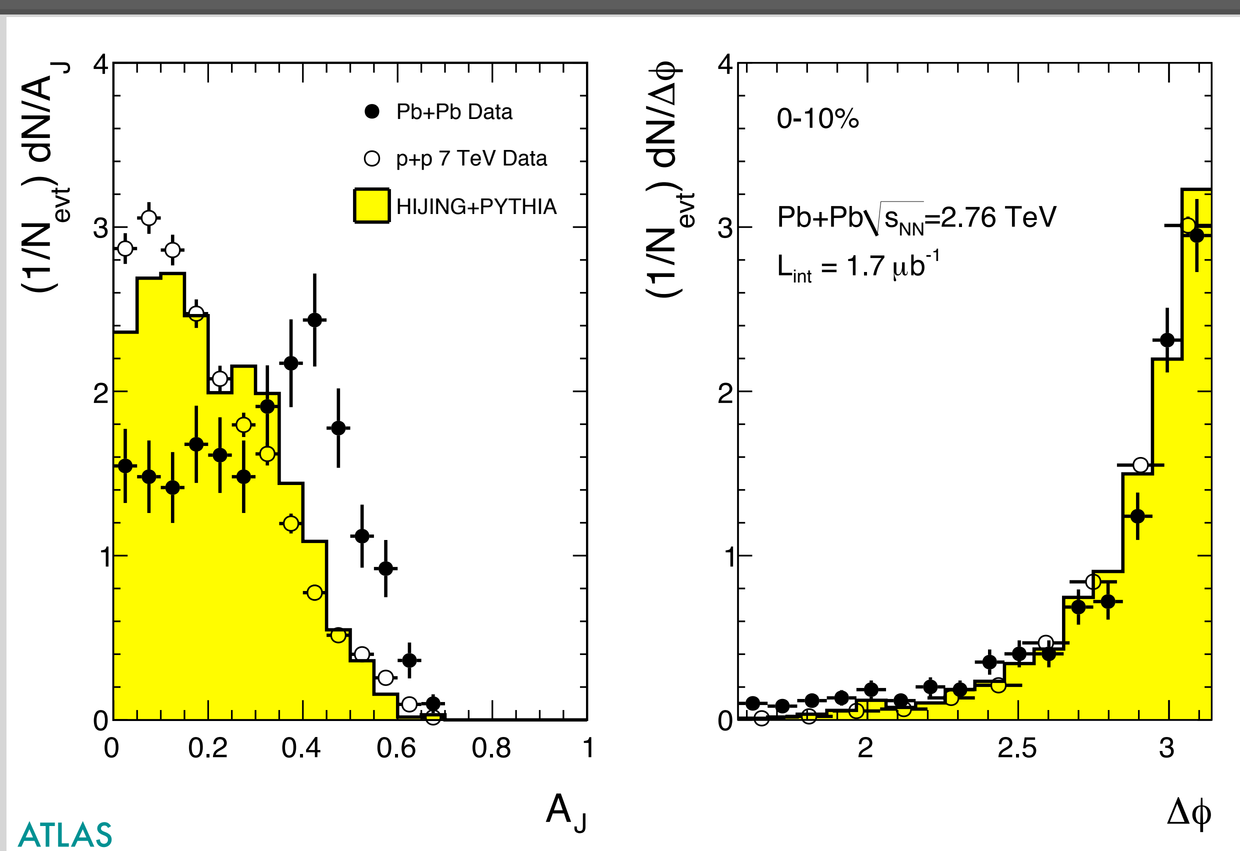

broadening [jet collimation]

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- in-medium formation time for small angle and soft gluons [vacuum] is very short

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

- democratic broadening is a large effect for soft partons

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

  - soft radiation decorrelated from jet direction/transported to large angles

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

  - enhancement of soft fragments outside the jet

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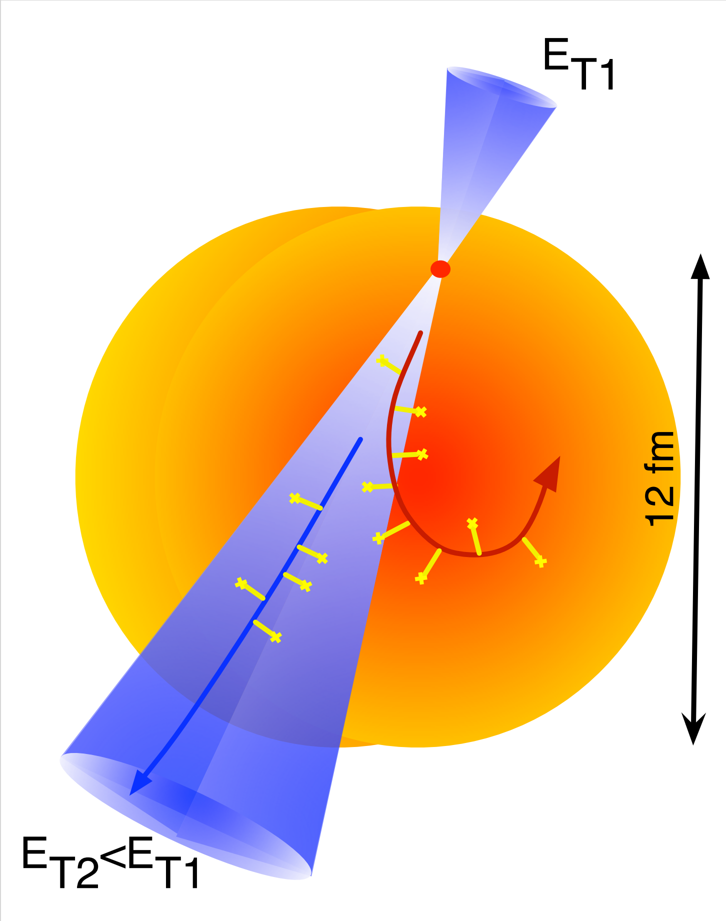
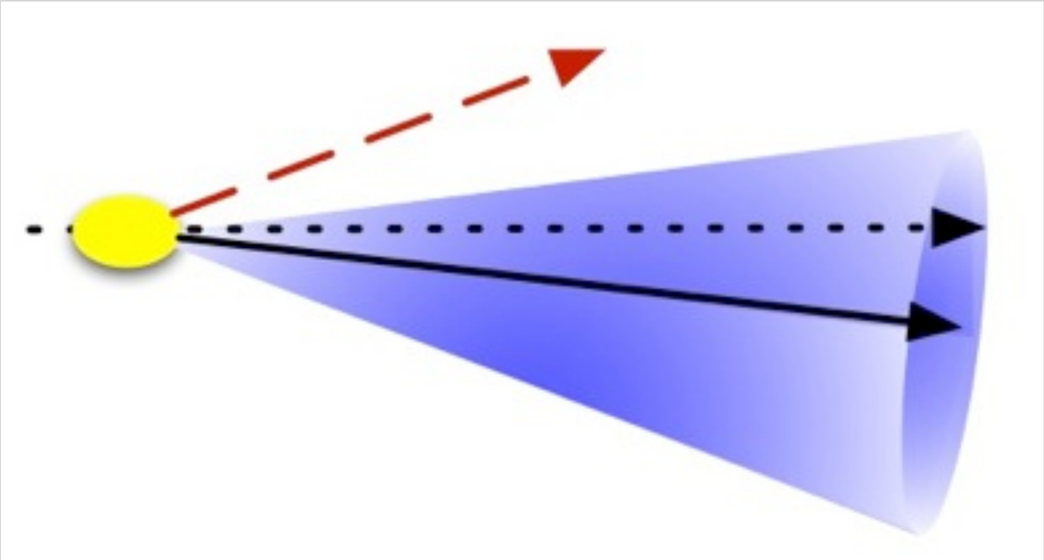


underlying dynamics



increased large angle medium induced radiation

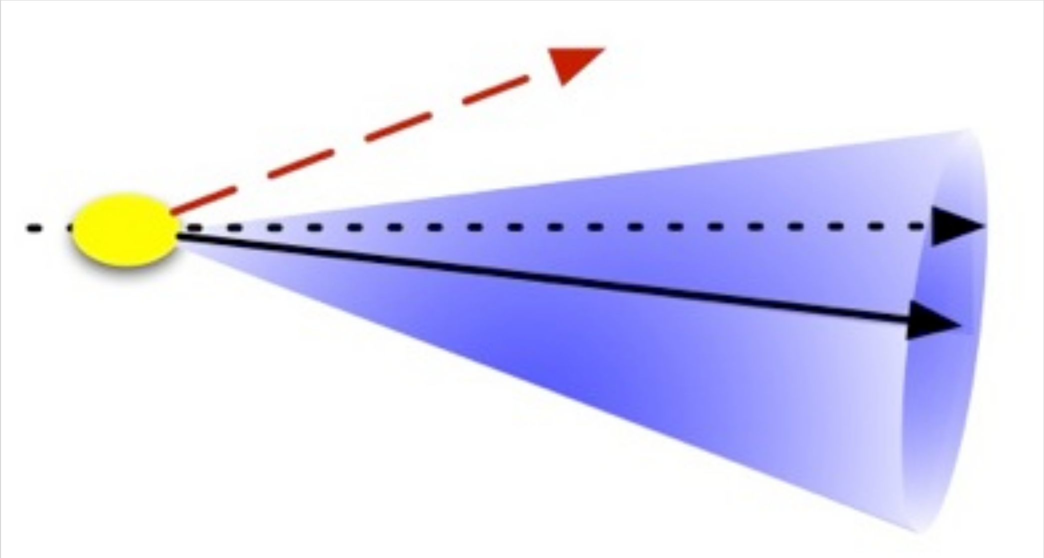
at given fixed angle

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

:: harder gluons are emitted earlier

:: [semi-]hard gluons deflect jet

underlying dynamics



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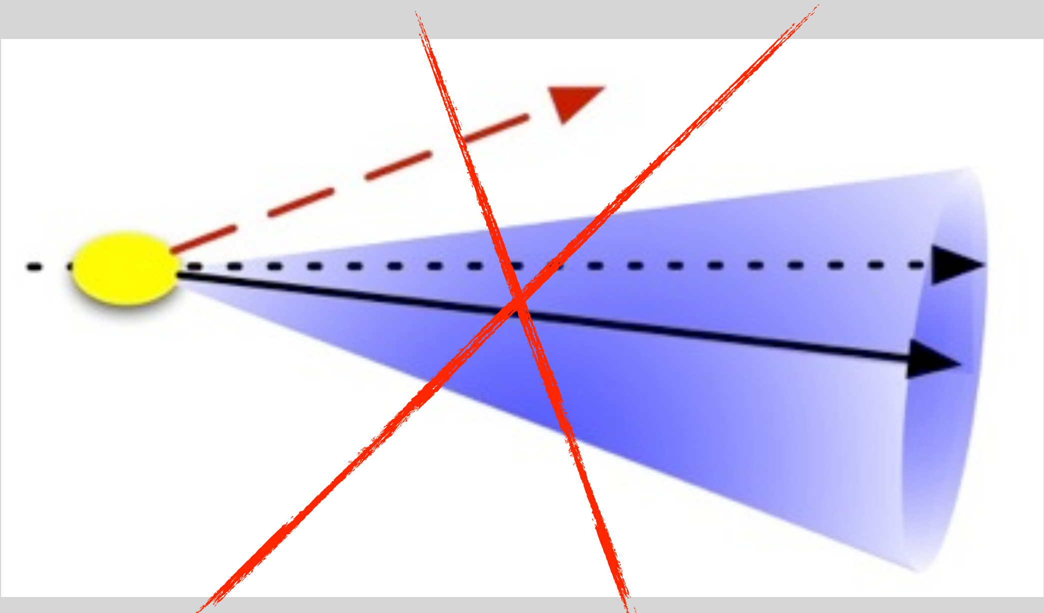

increased large angle medium induced radiation

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

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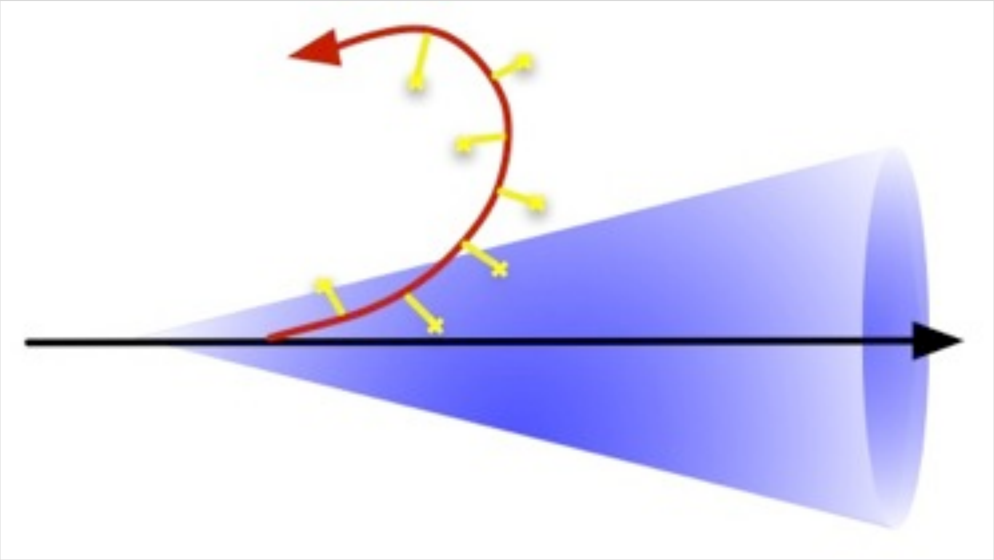
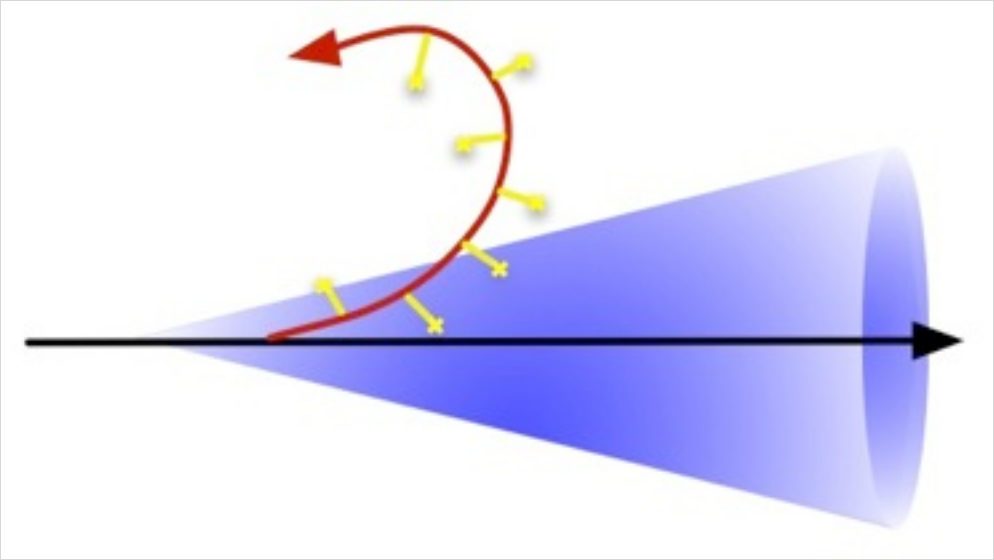


transport of radiated gluons

radiation of soft gluons at small angle

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

underlying dynamics



transport of radiated gluons

radiation of soft gluons at small angle

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

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

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

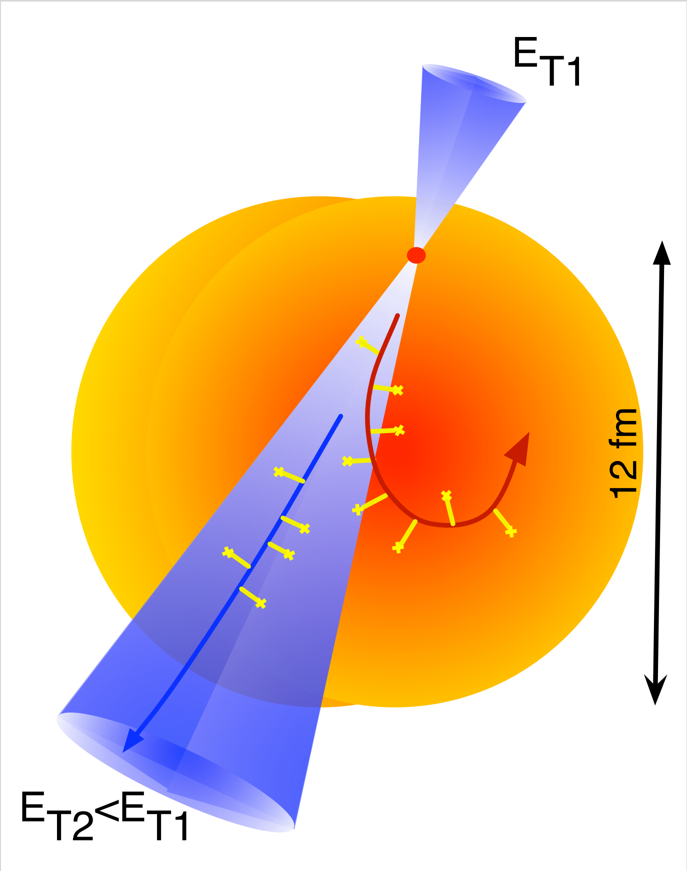
- in the presence of a medium soft modes are formed early

$$\tau \sim \frac{\omega}{k_\perp^2} \underset{\langle k_\perp^2 \rangle \sim \hat{q}\tau}{\longrightarrow} \langle \tau \rangle \sim \sqrt{\frac{\omega}{\hat{q}}}$$

- sufficiently soft modes are completely decorrelated from the jet direction

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

jet collimation [circa 2010]



- sufficiently soft modes decorrelated [lost] from jet

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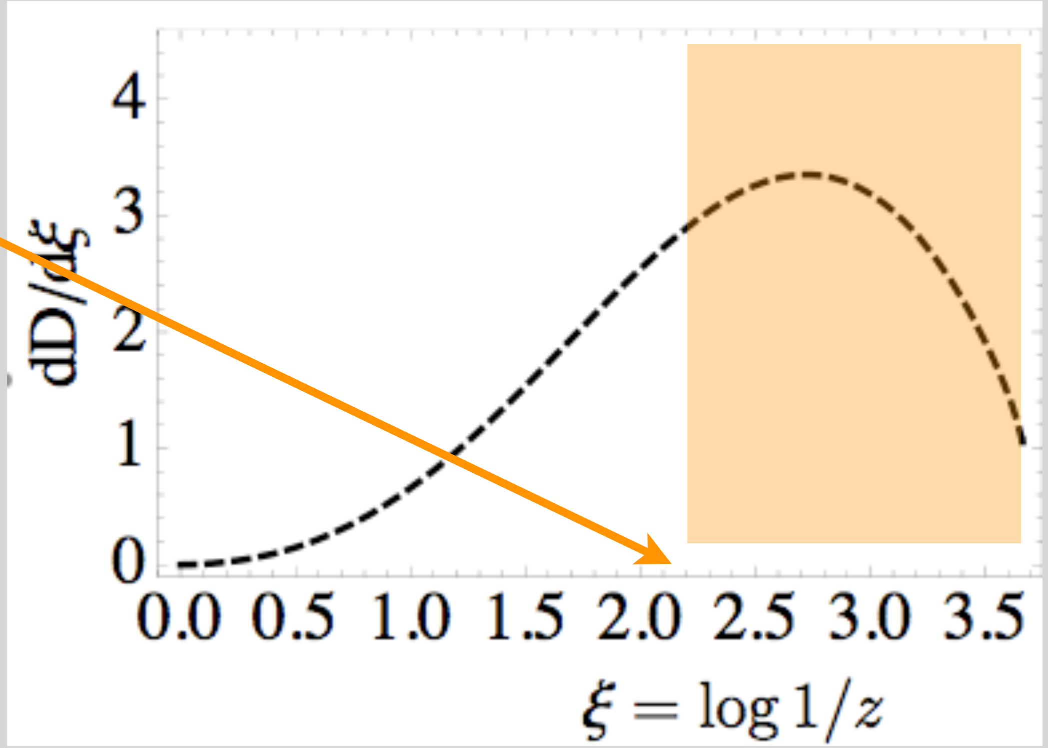

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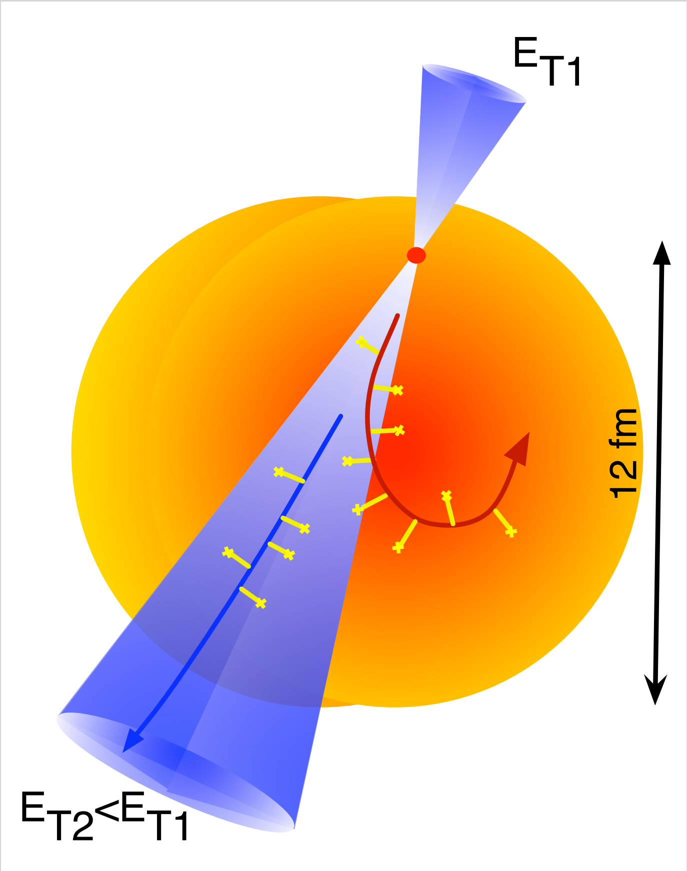

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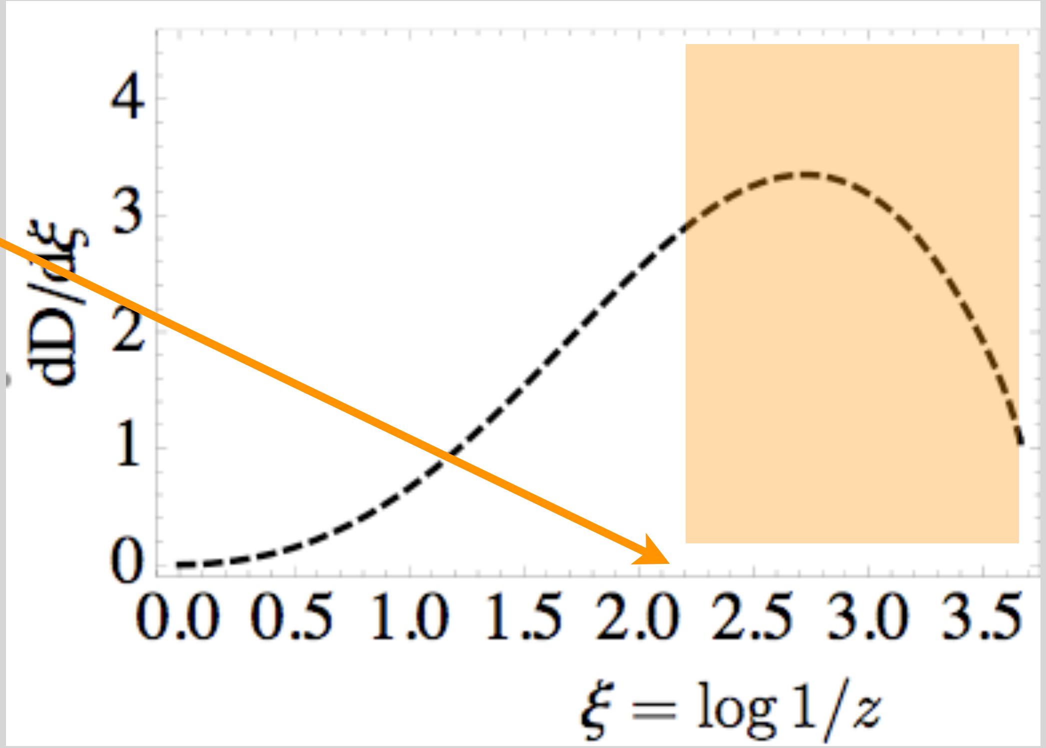
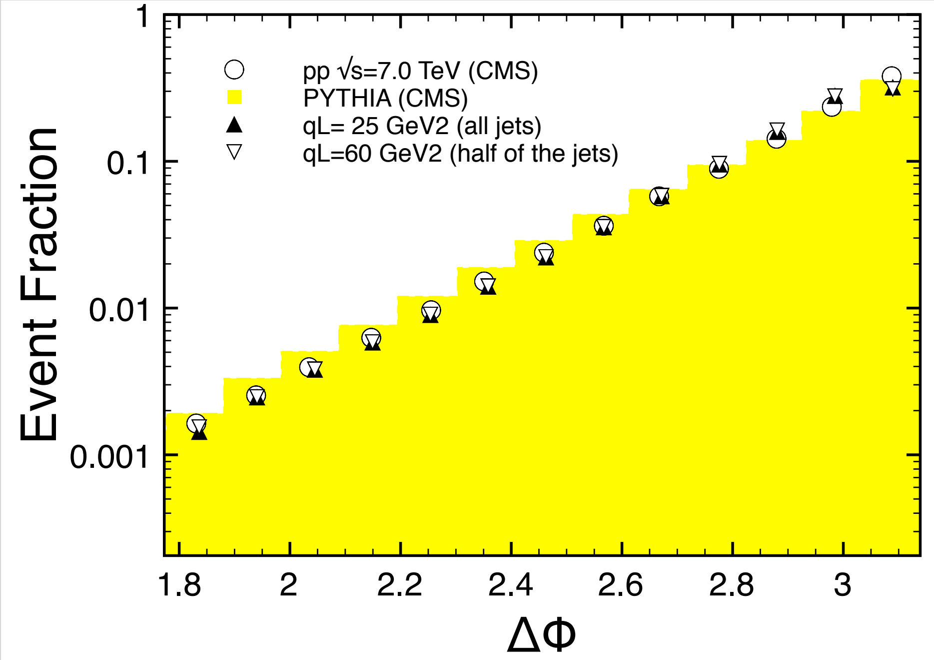
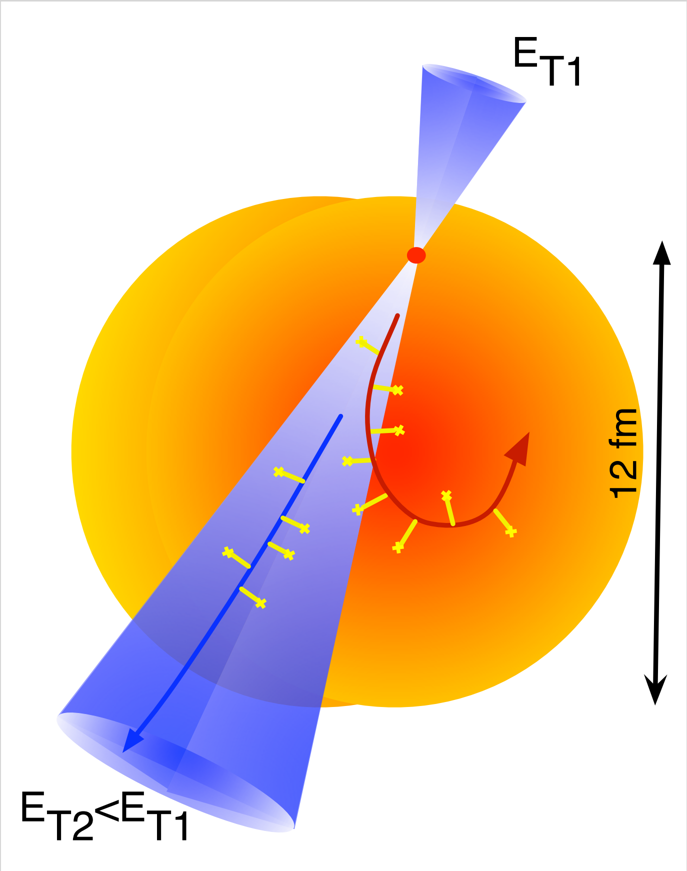




- does not disturb azimuthal correlation

jet collimation [circa 2010]



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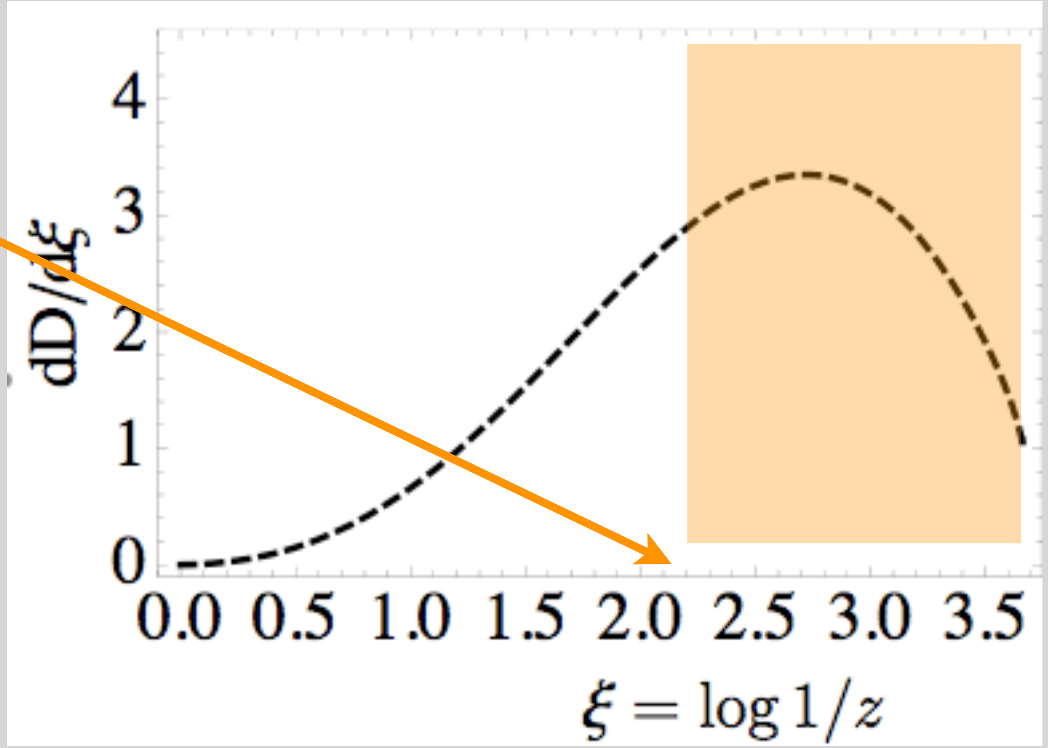

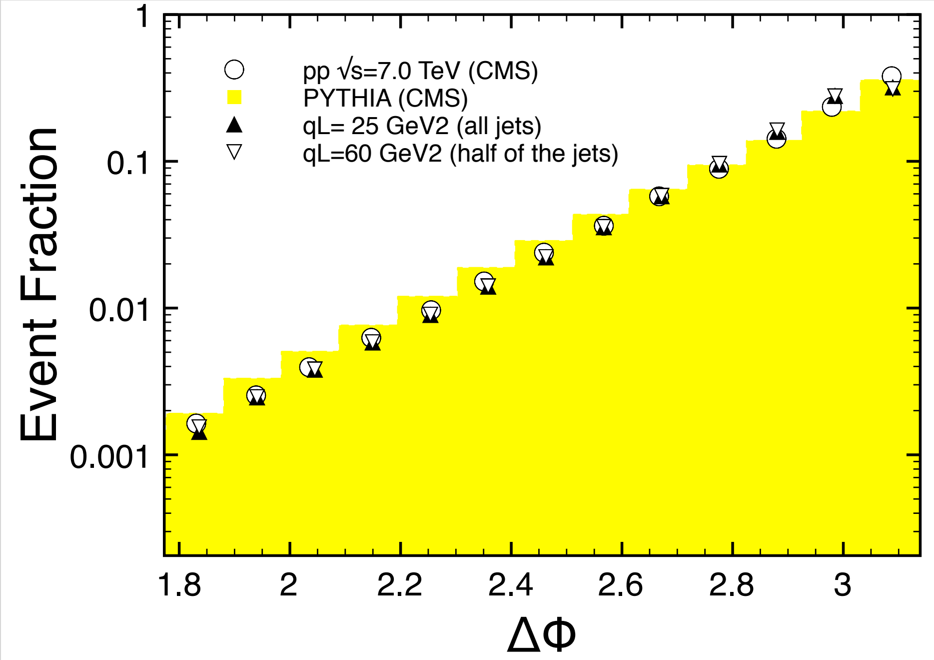

good qualitative description of average medium induced asymmetry

- does not disturb azimuthal correlation

improvements [2012]

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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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α_s [= 0.3]

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  - ↪ vacuum baseline from data [CMS]

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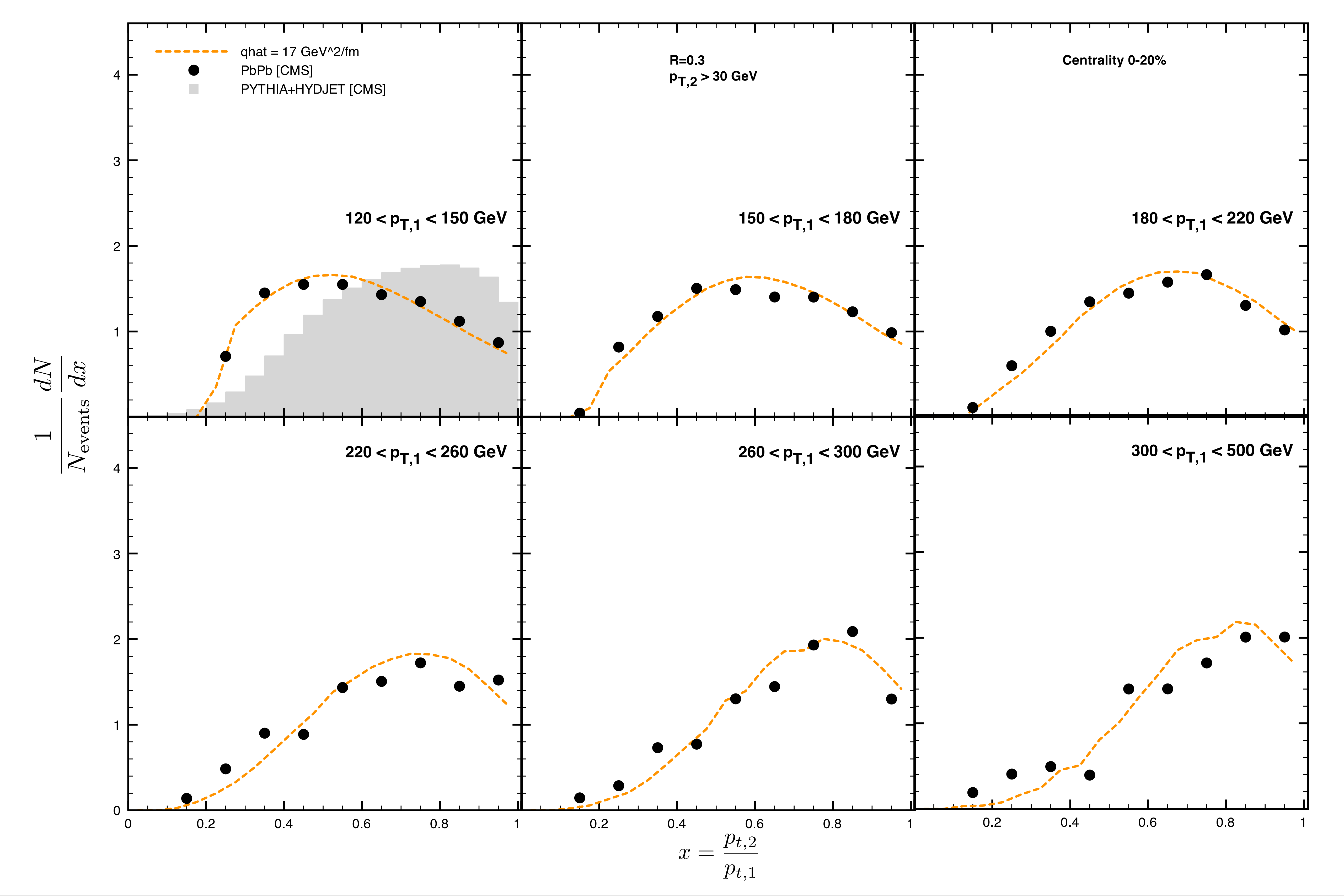
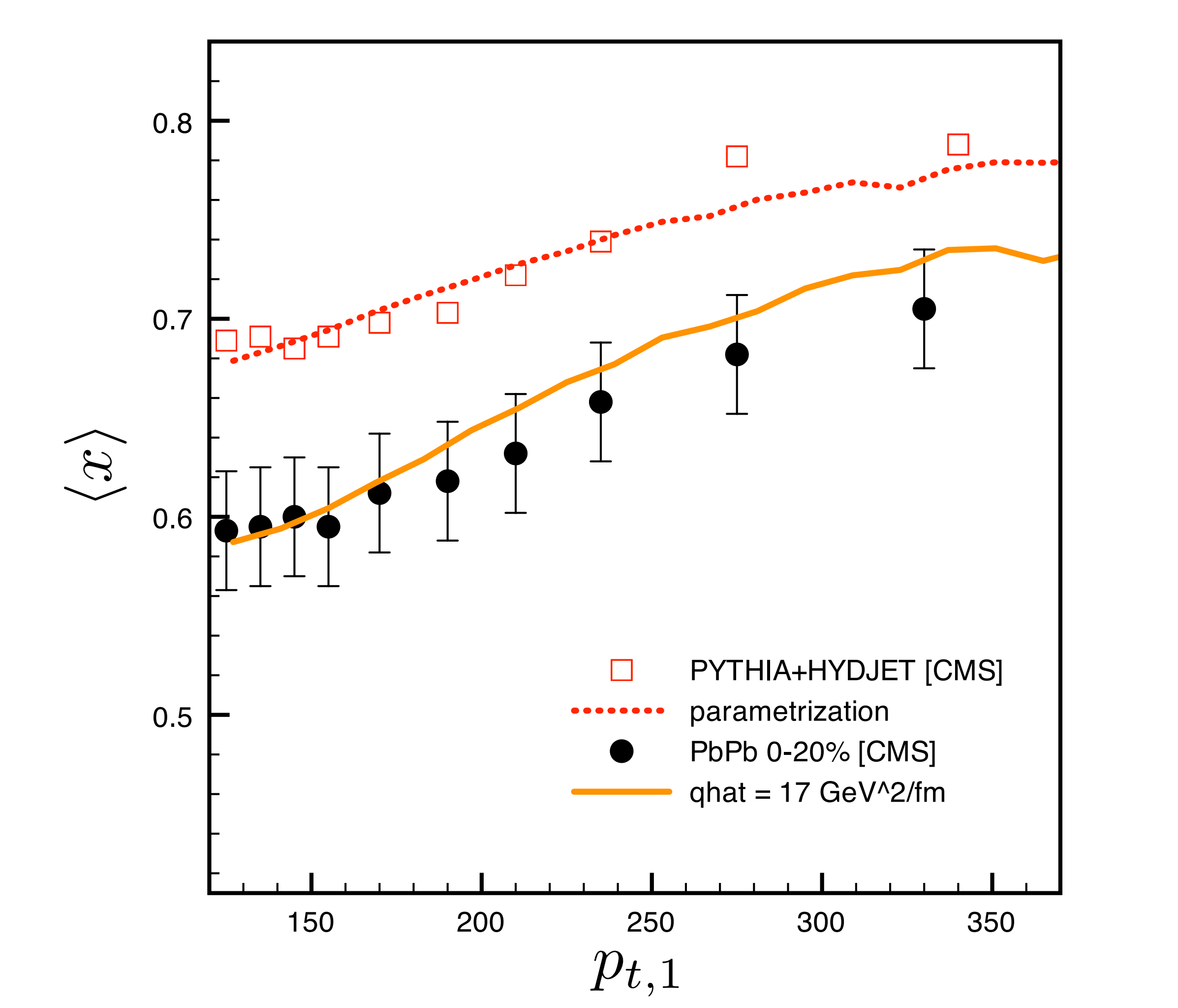
α_s [= 0.3]

energy dependence of dijet imbalance



average imbalance



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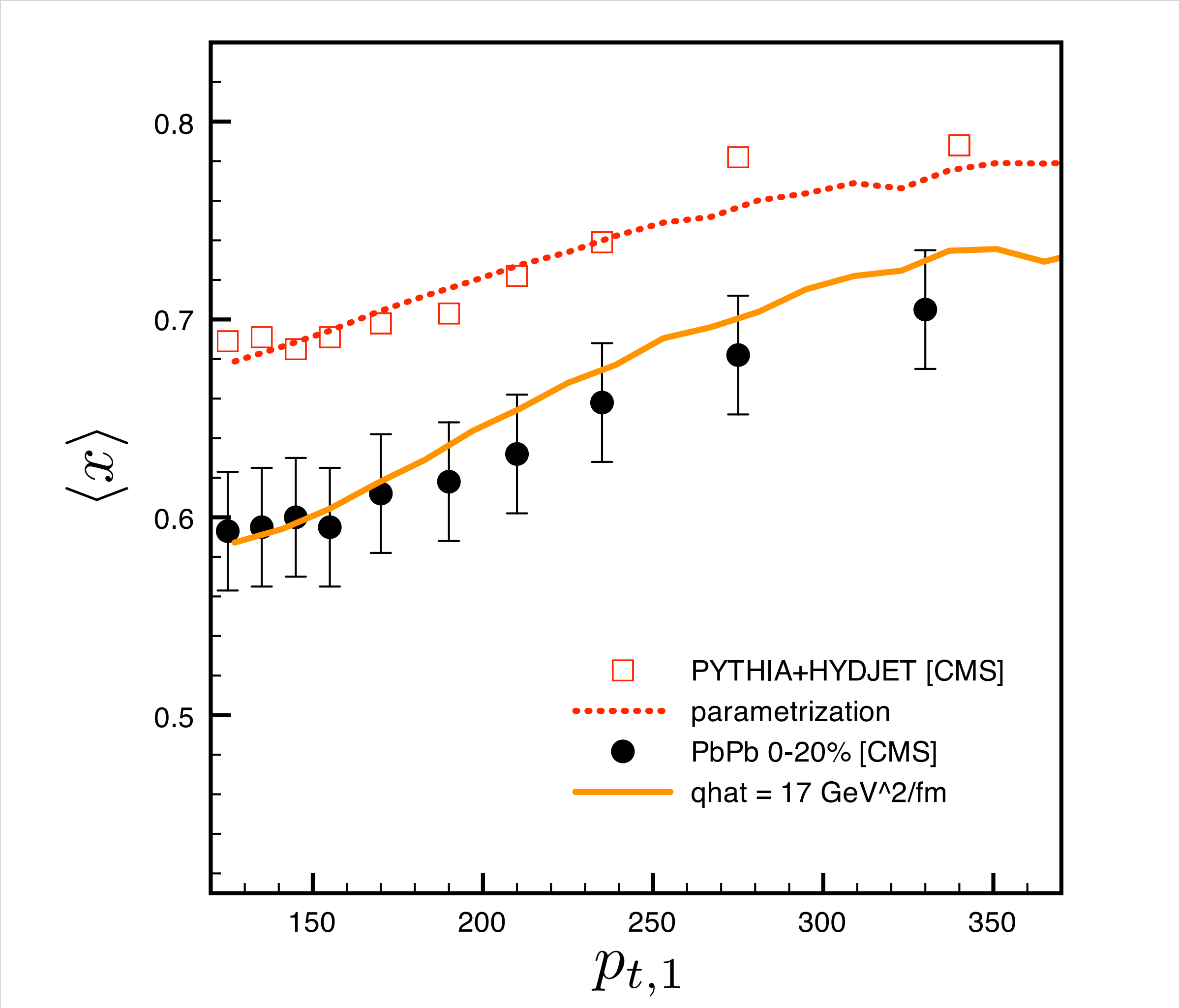
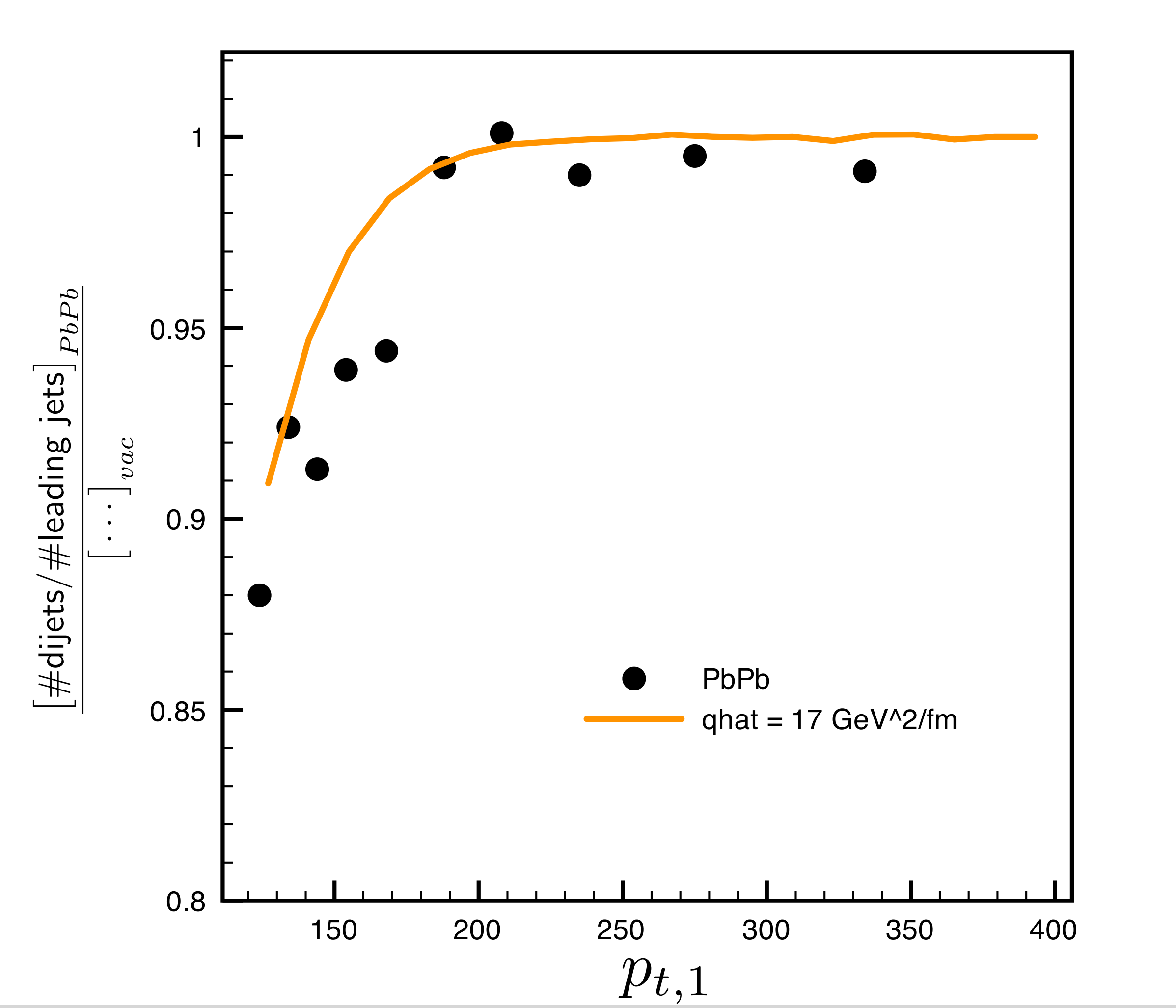
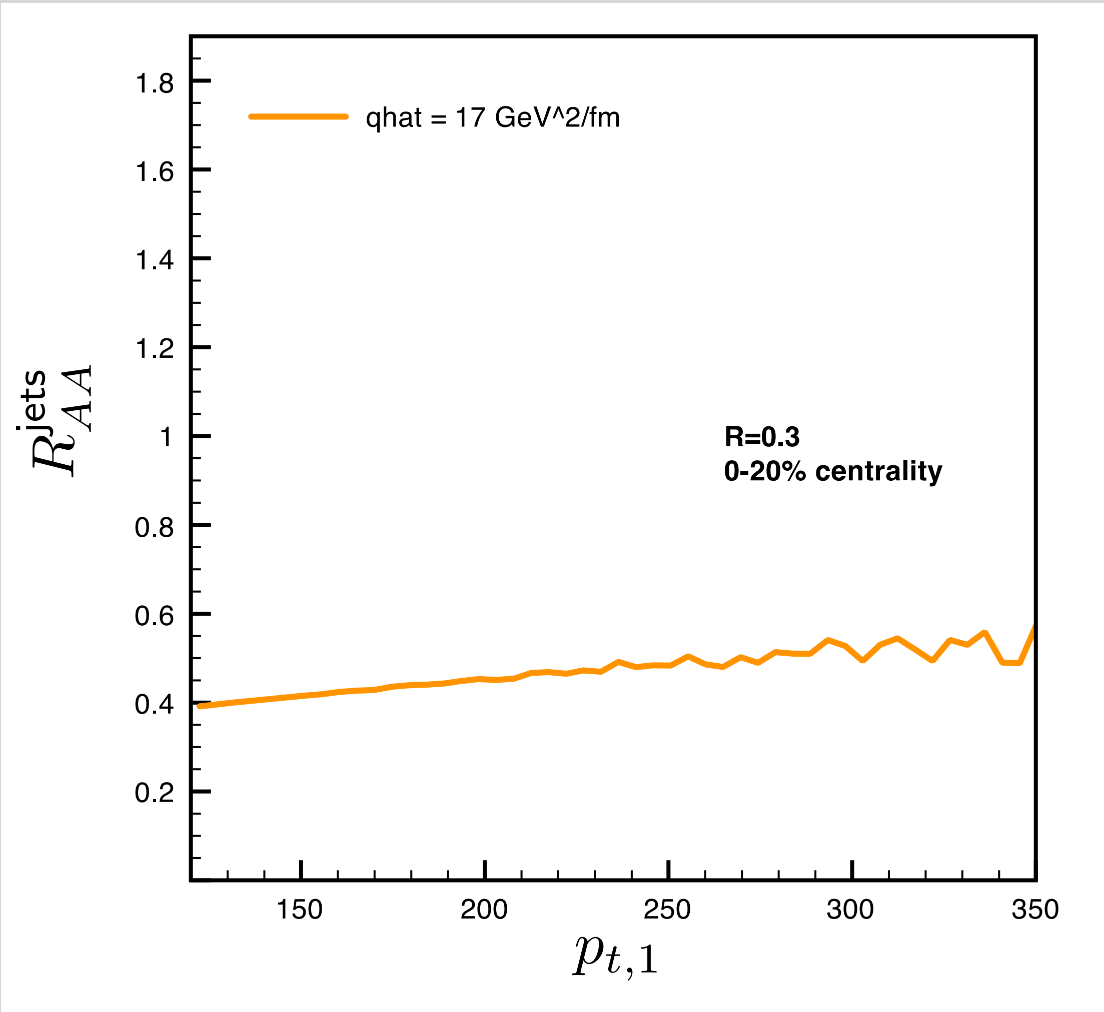
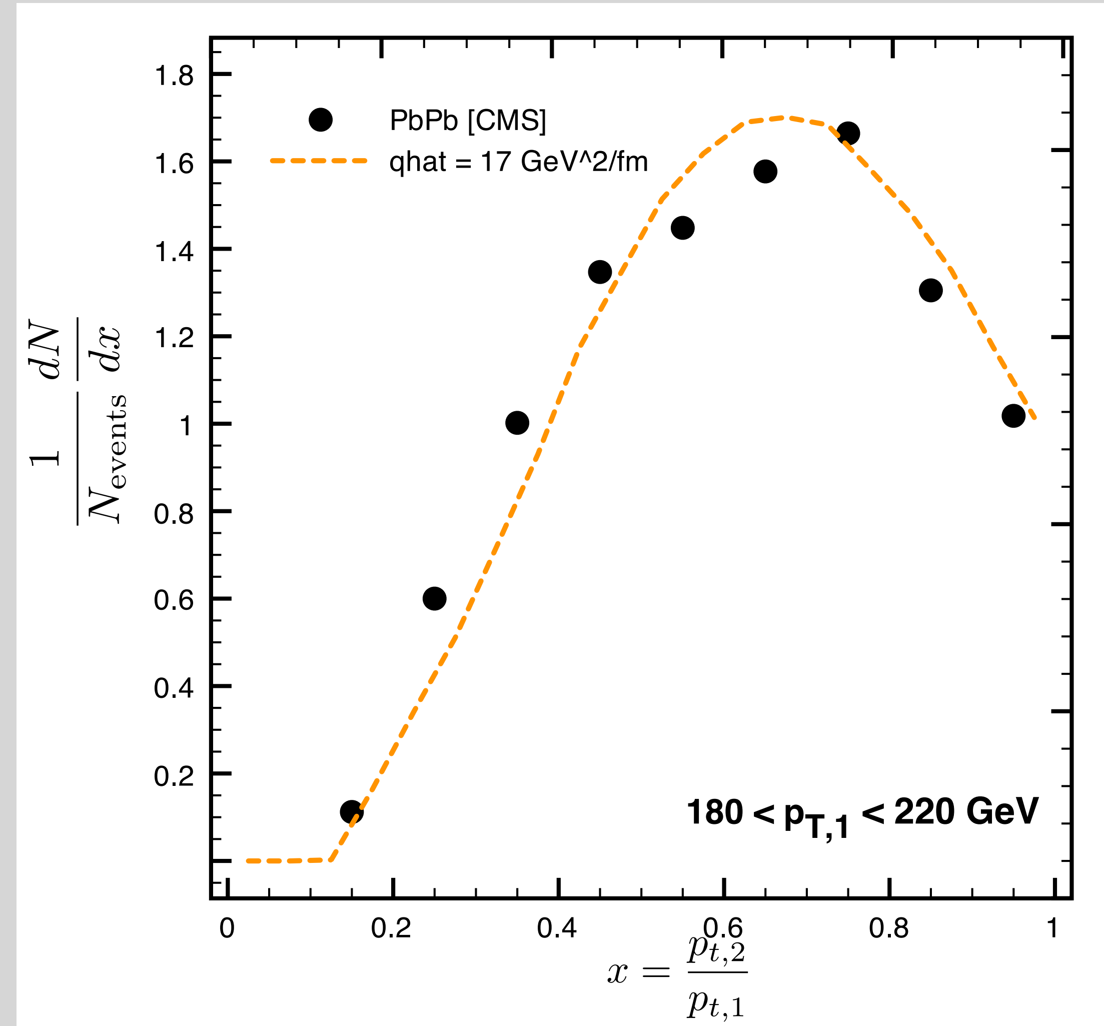


must also account for fraction of jets quenched beyond reconstruction cut



R_{AA}





- dijet imbalance sensitive to transverse dynamics
- R_{AA} [very] sensitive to path-length [longitudinal] fluctuations
- constrains energy loss relation to broadening
- leading and recoiling jet probe different path-length ranges

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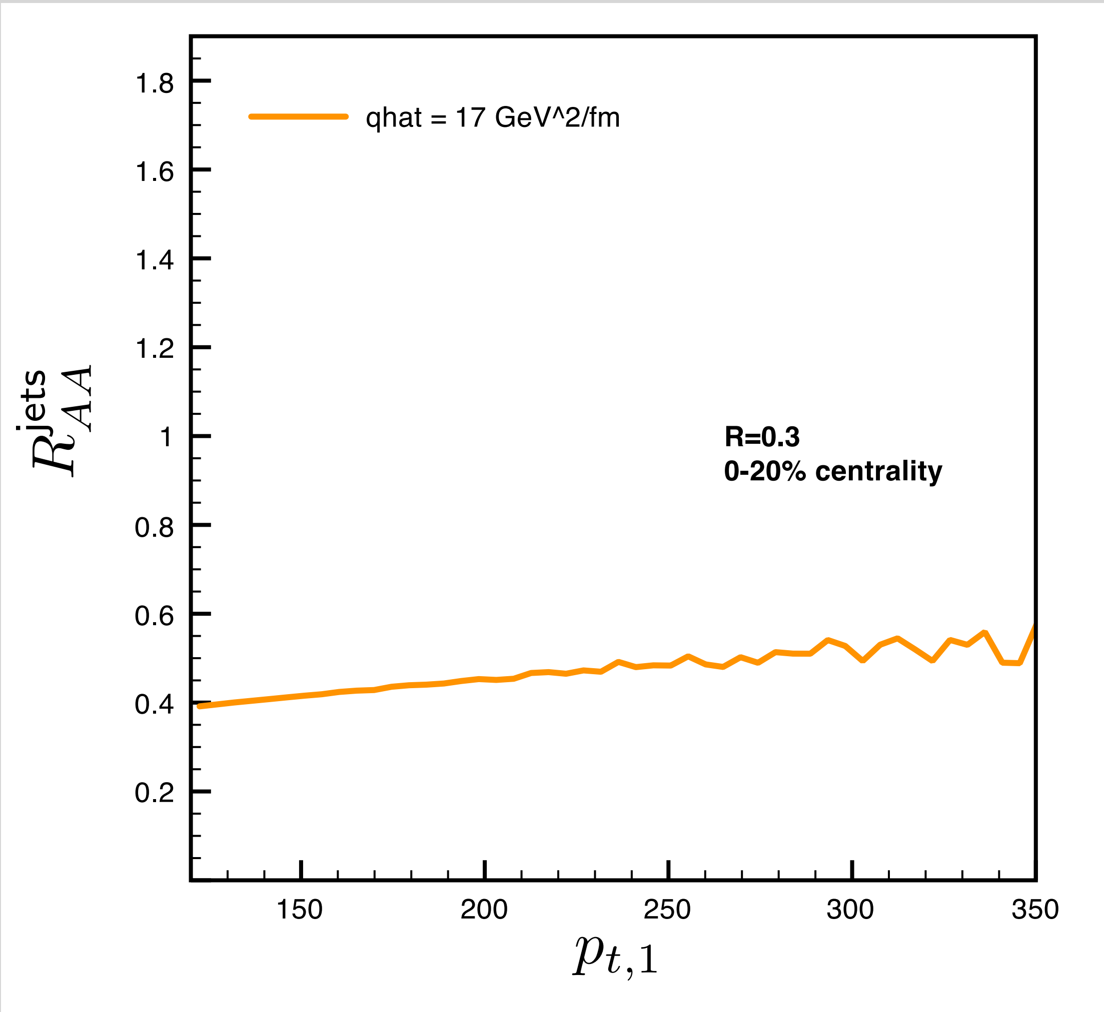

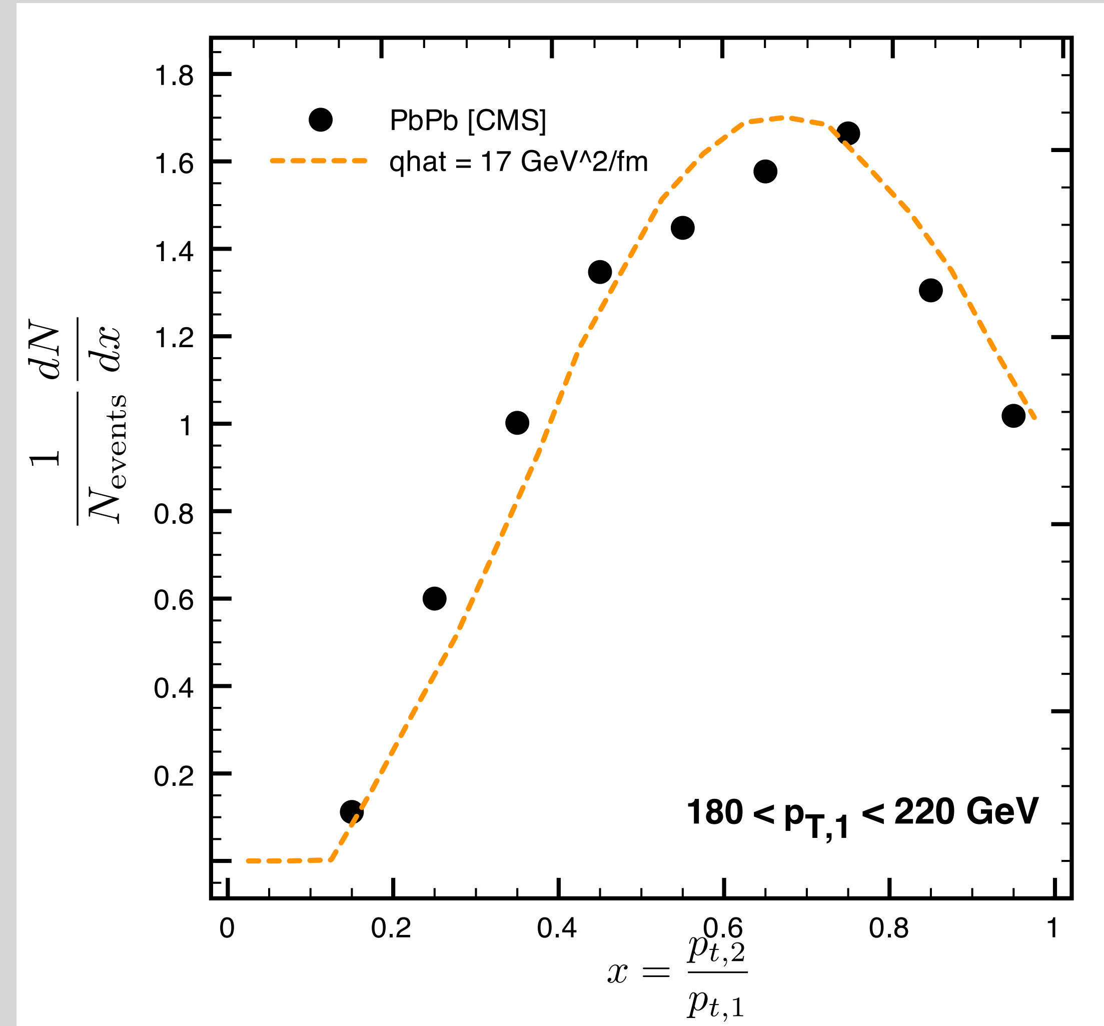

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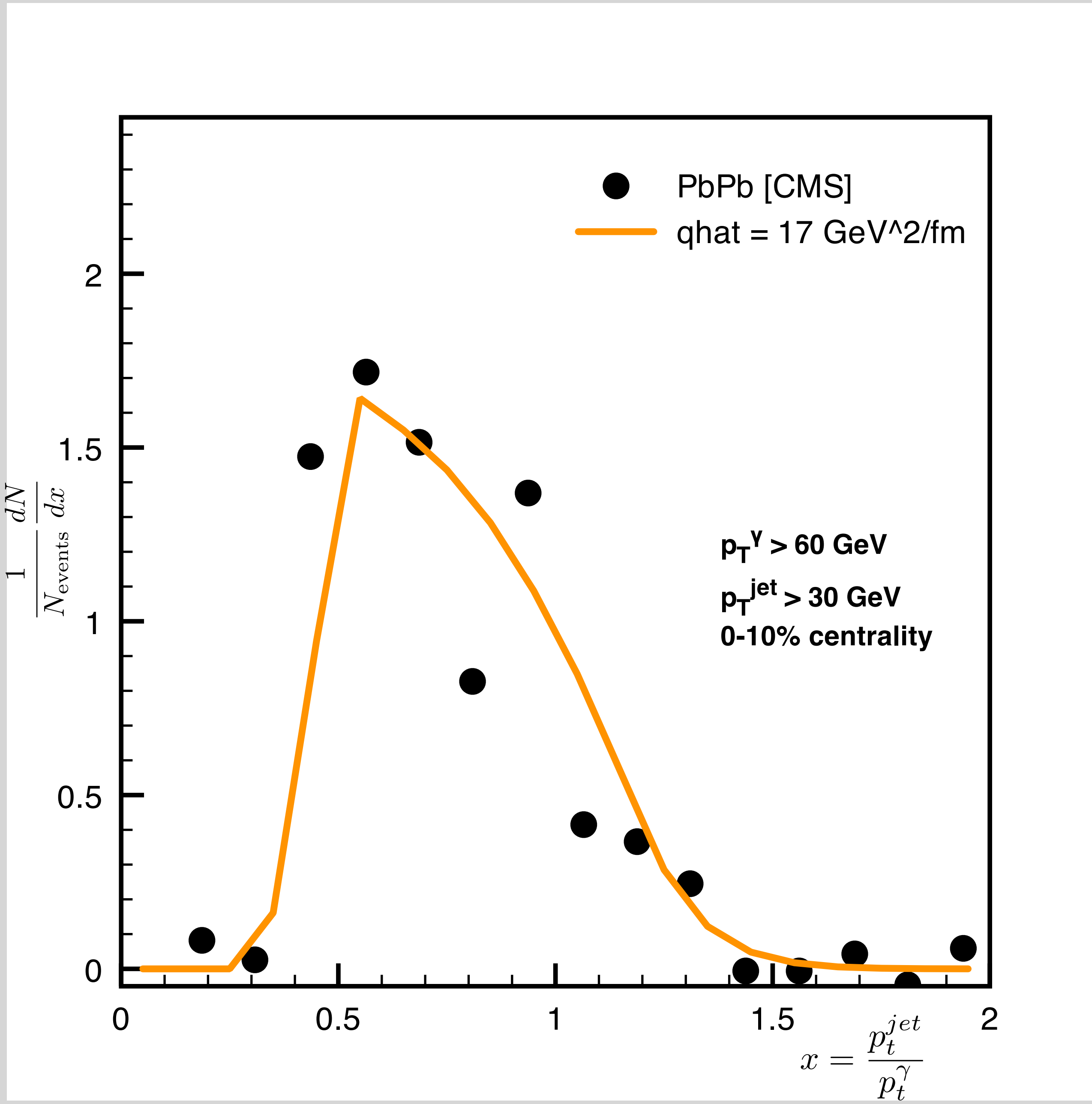
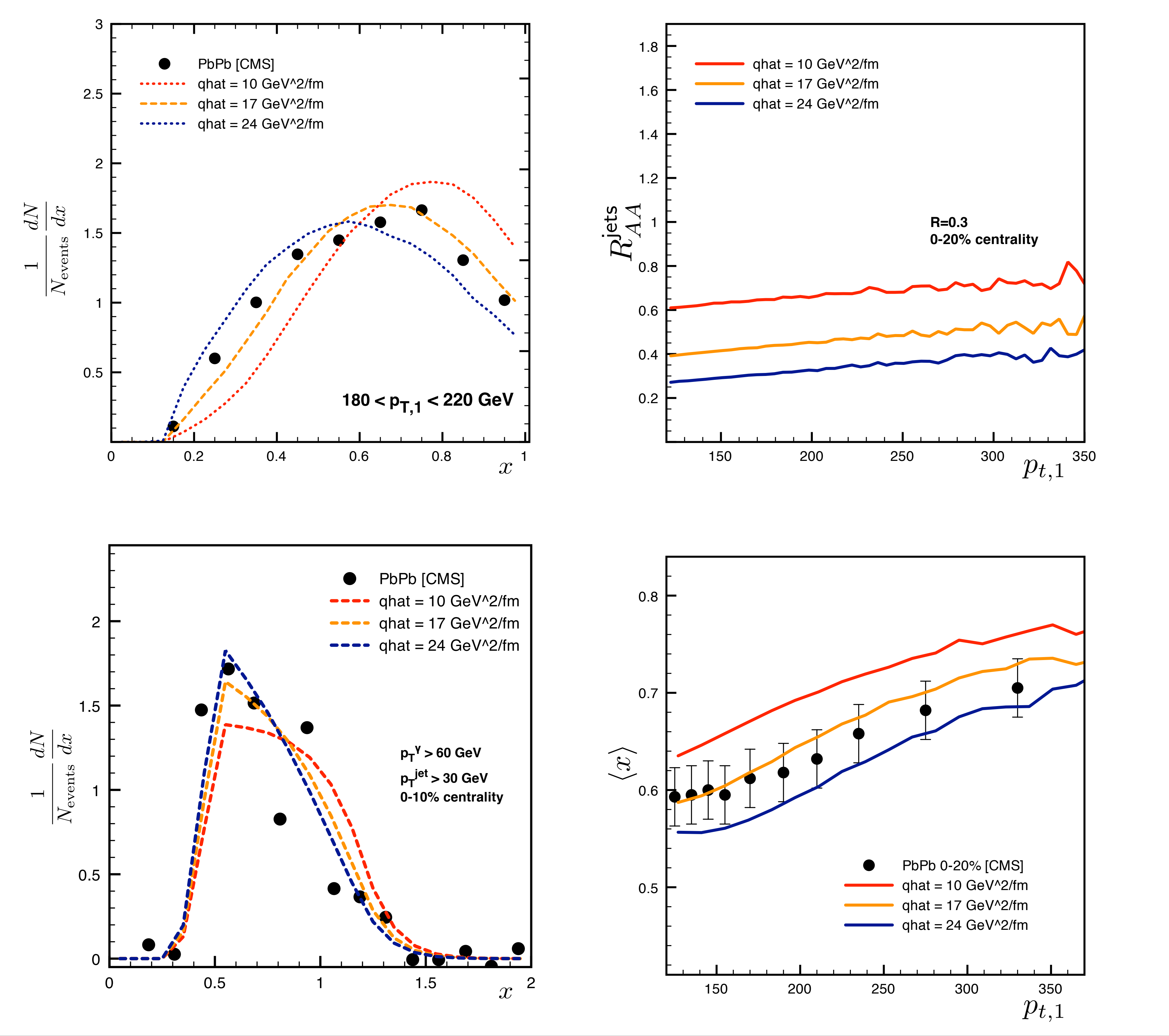
together provide tight constraint on underlying dynamics

γ-jet



- quark jets, otherwise same set-up

qhat dependence



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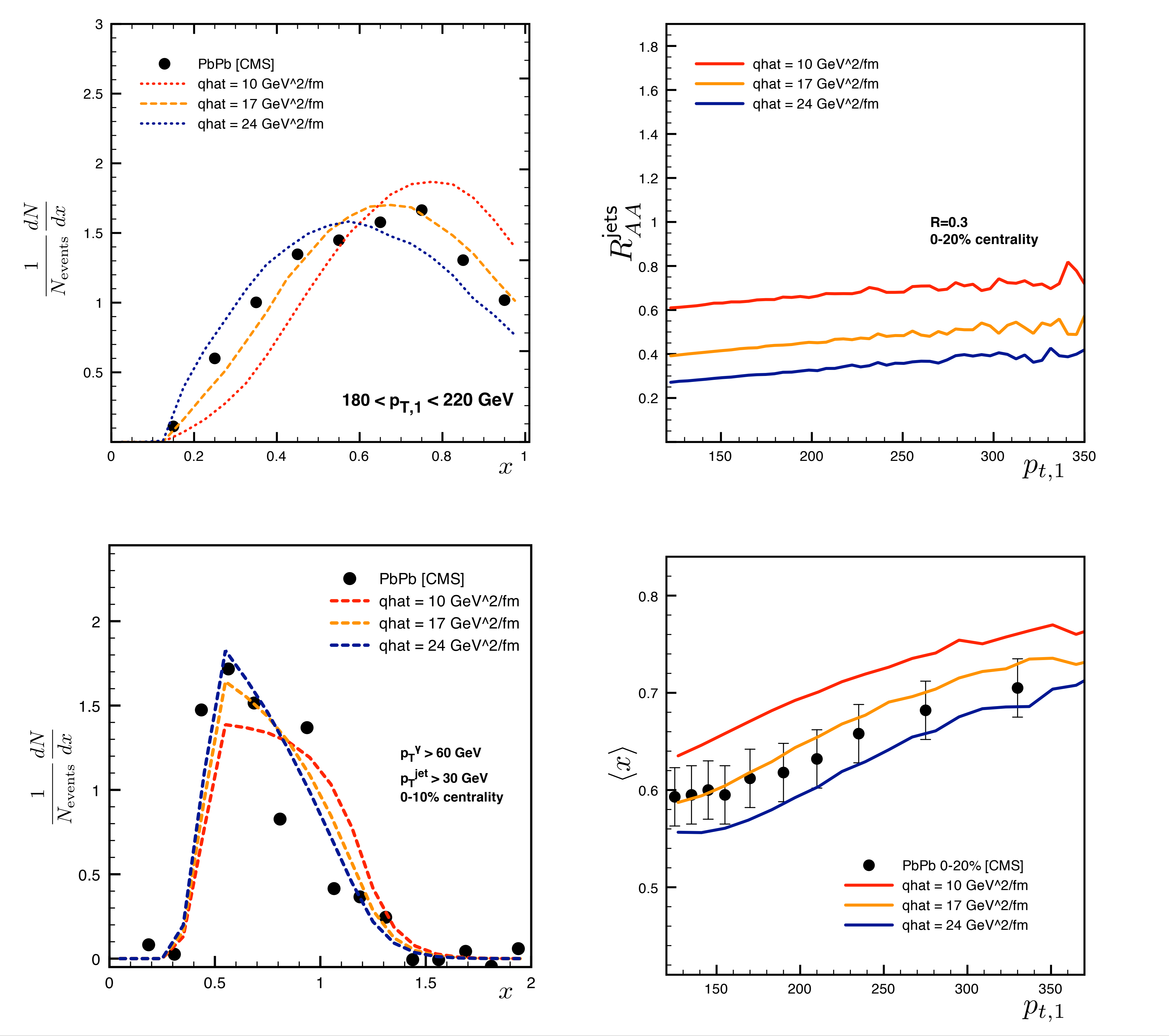

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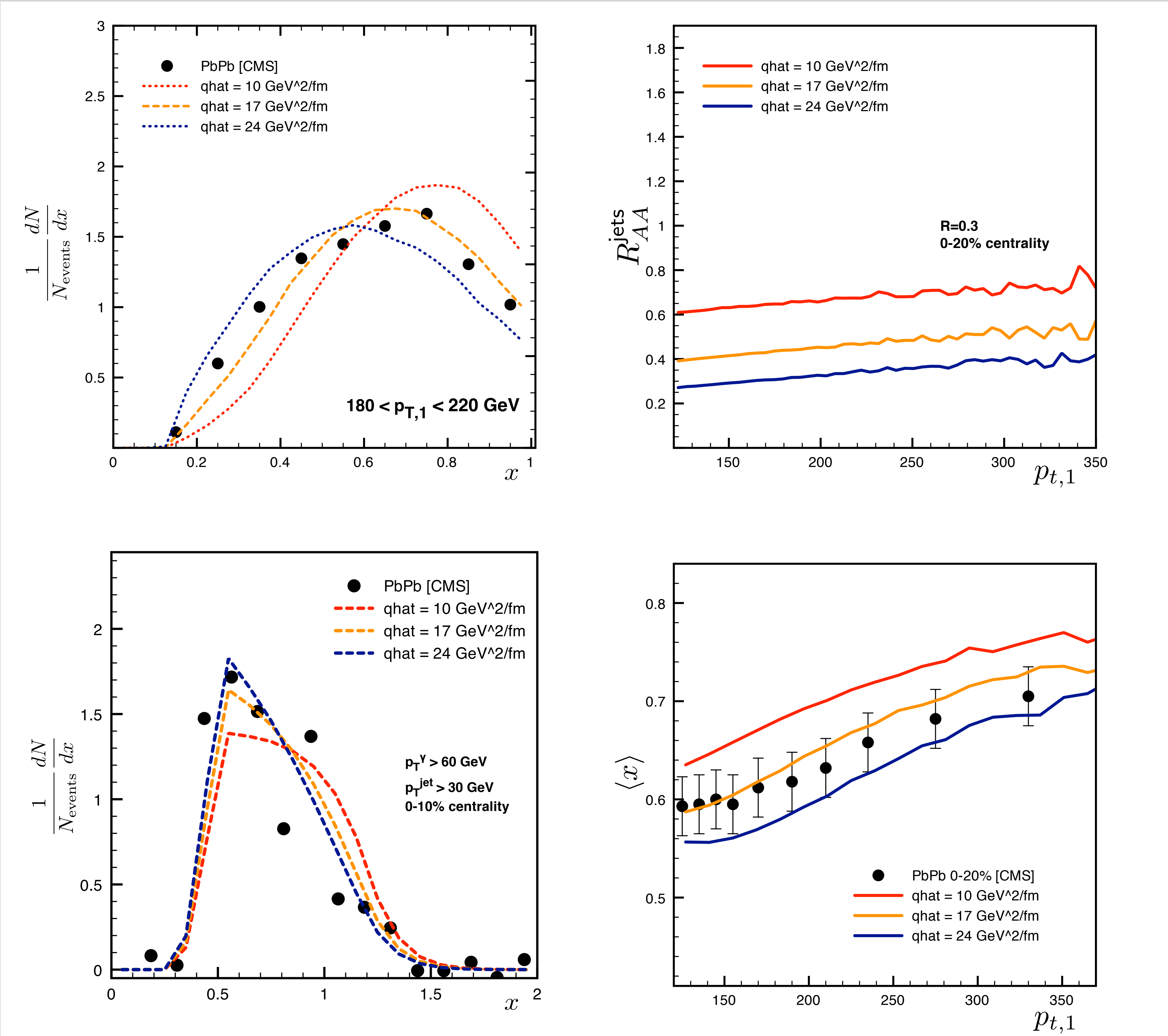
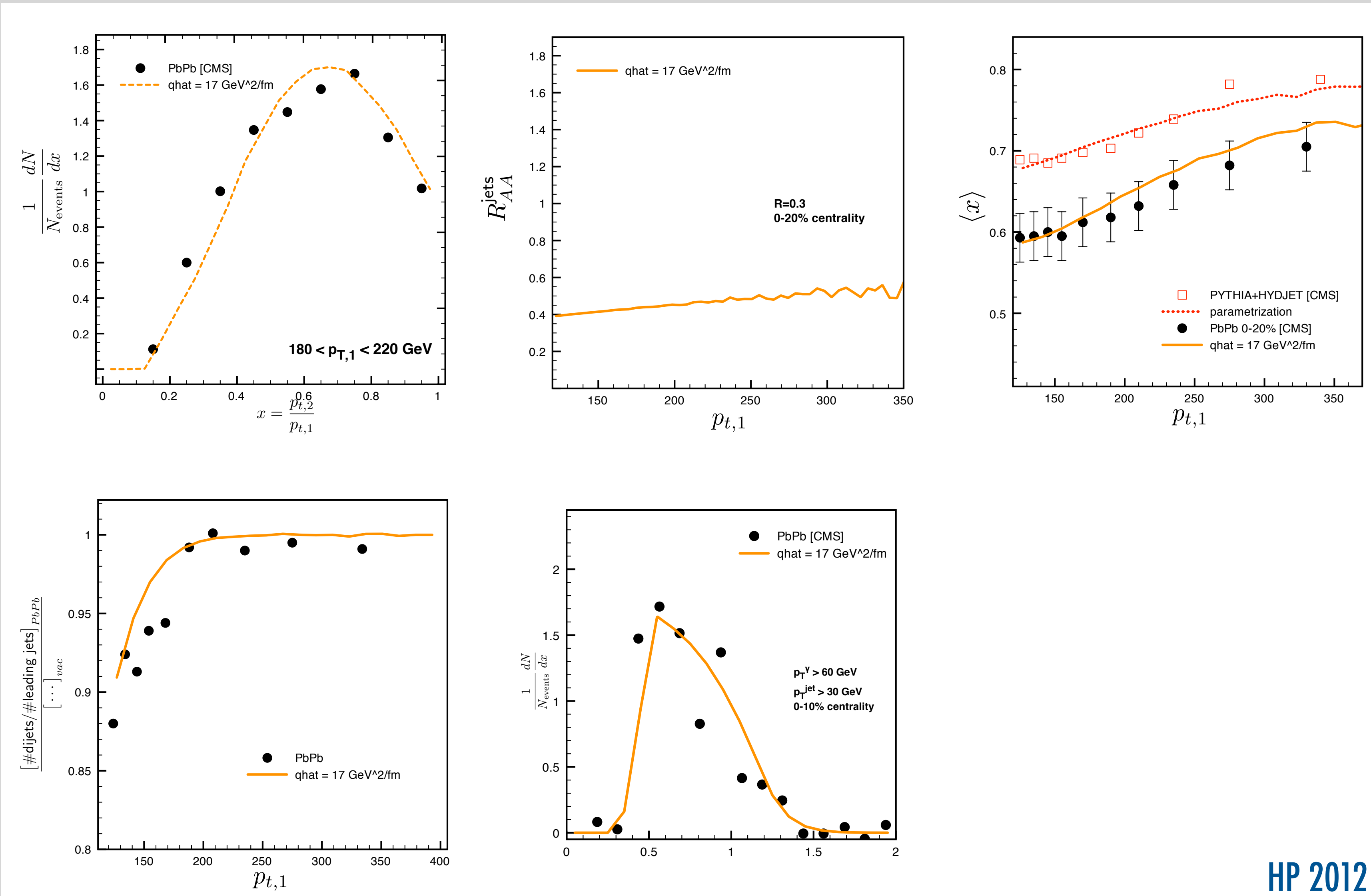
qhat dependence



very sensitive to changes of qhat

weak sensitivity to qhat variation in γ-jet

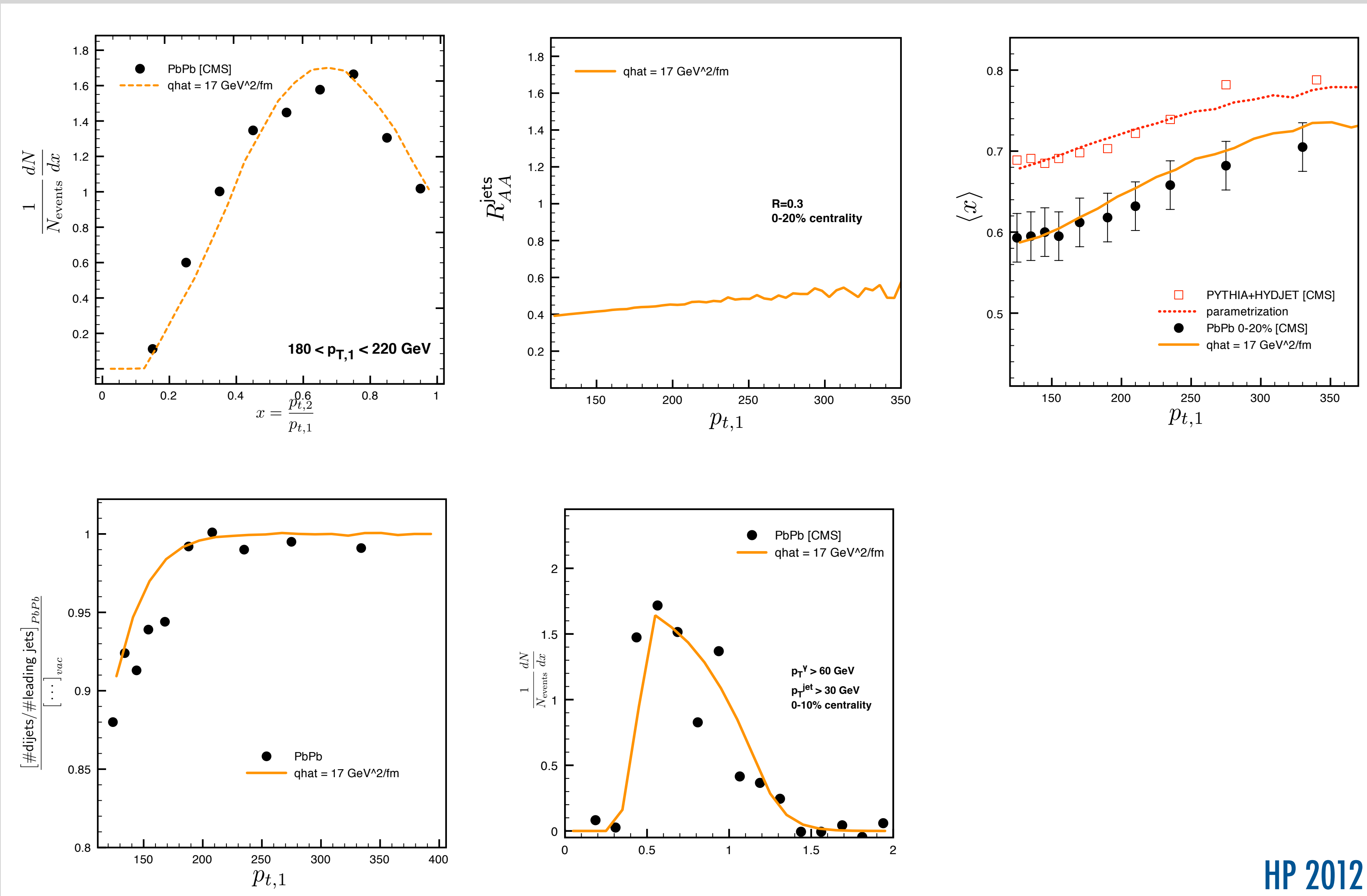
broadening [jet collimation]

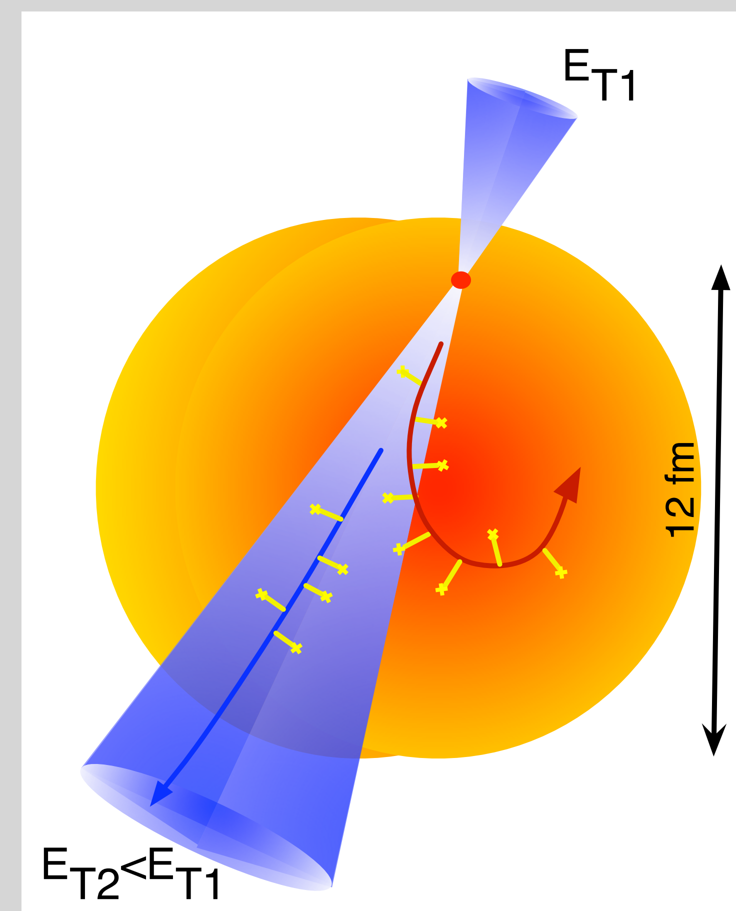


Intriguing [given its naivety and caveats] excellent overall account of data

need first principle calculation to support

broadening [jet collimation]





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consistent multi-observable description

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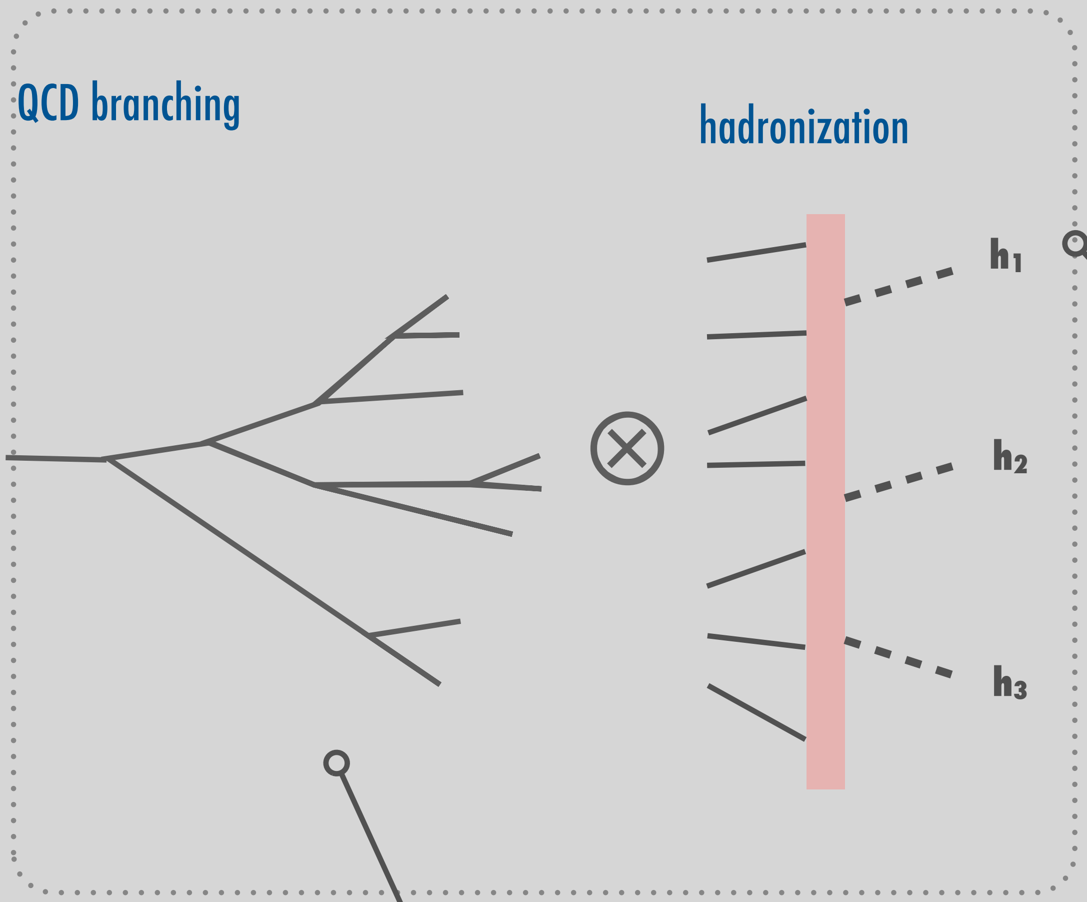
may be sufficiently simple to allow for reliable extraction
of medium properties

jets in heavy ion collisions



in medium

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

fragmentation outside medium = vacuum FFs ???

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

contribution of colour flow to jet quenching

[hadronization interface]

A. Beraudo, JGM, U. Wiedemann

[1109.5025 &1204.4342]

interplay of branching and hadronization

—o colour of all jet components rotated by interaction with medium

↪ colour correlations modified with respect to vacuum case

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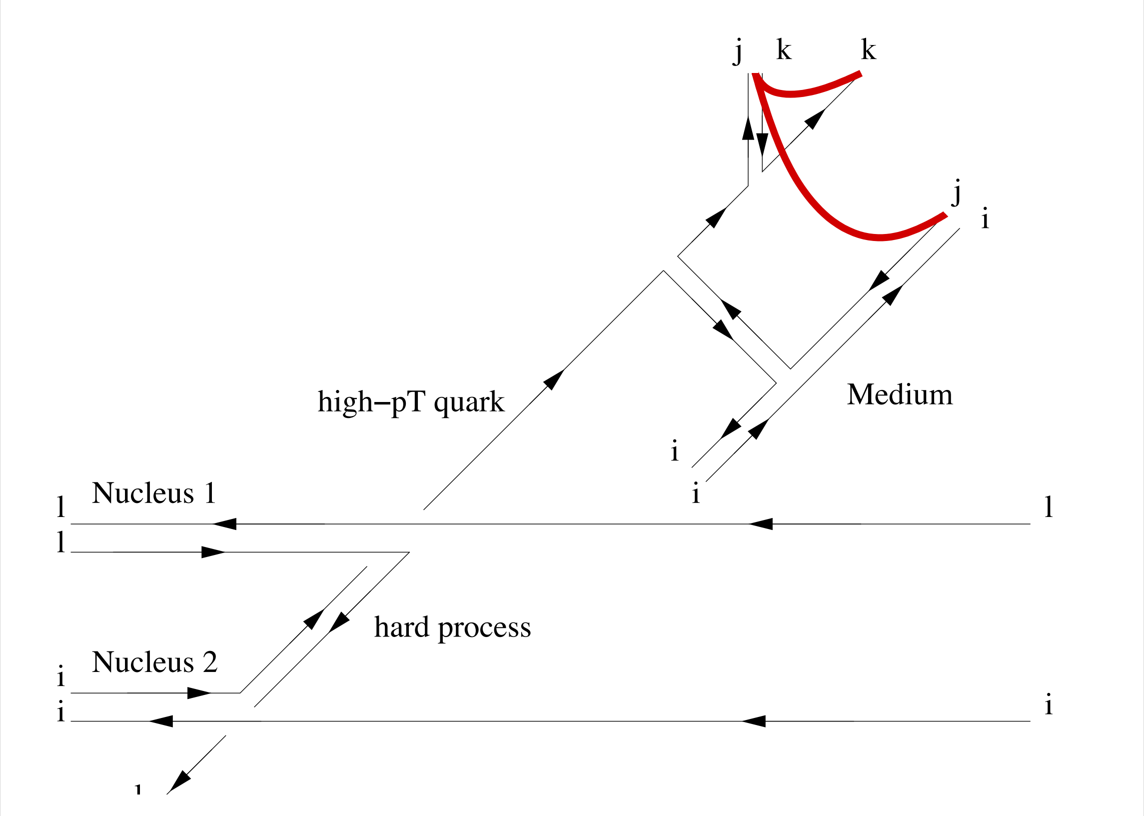

no medium interaction after radiation

- colour properties of hadronizing system vacuum-like
- radiated gluon belongs to system

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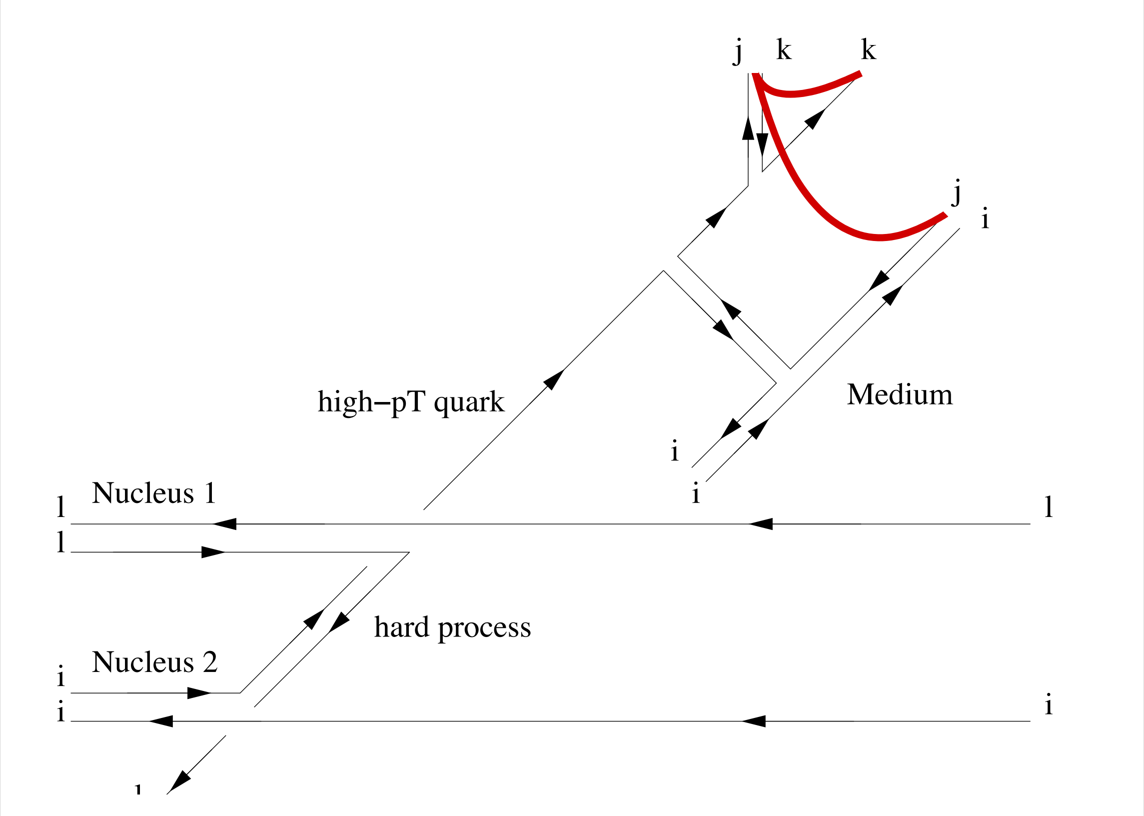

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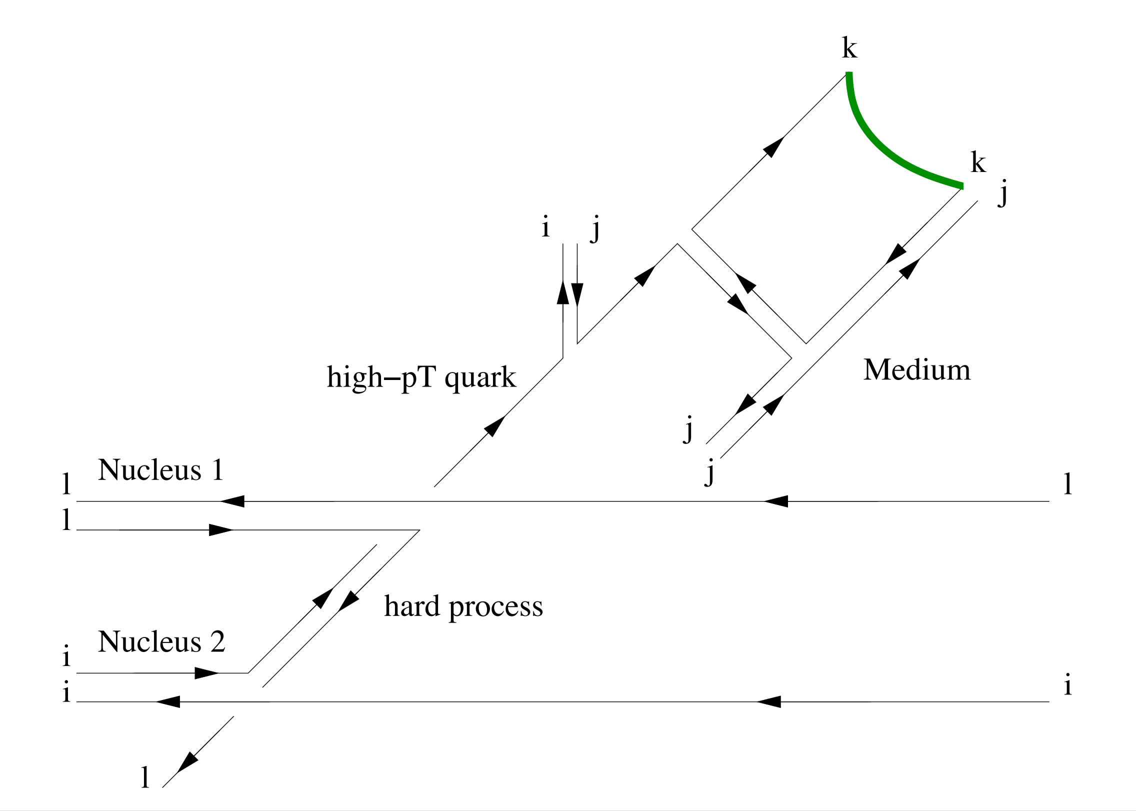

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Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]

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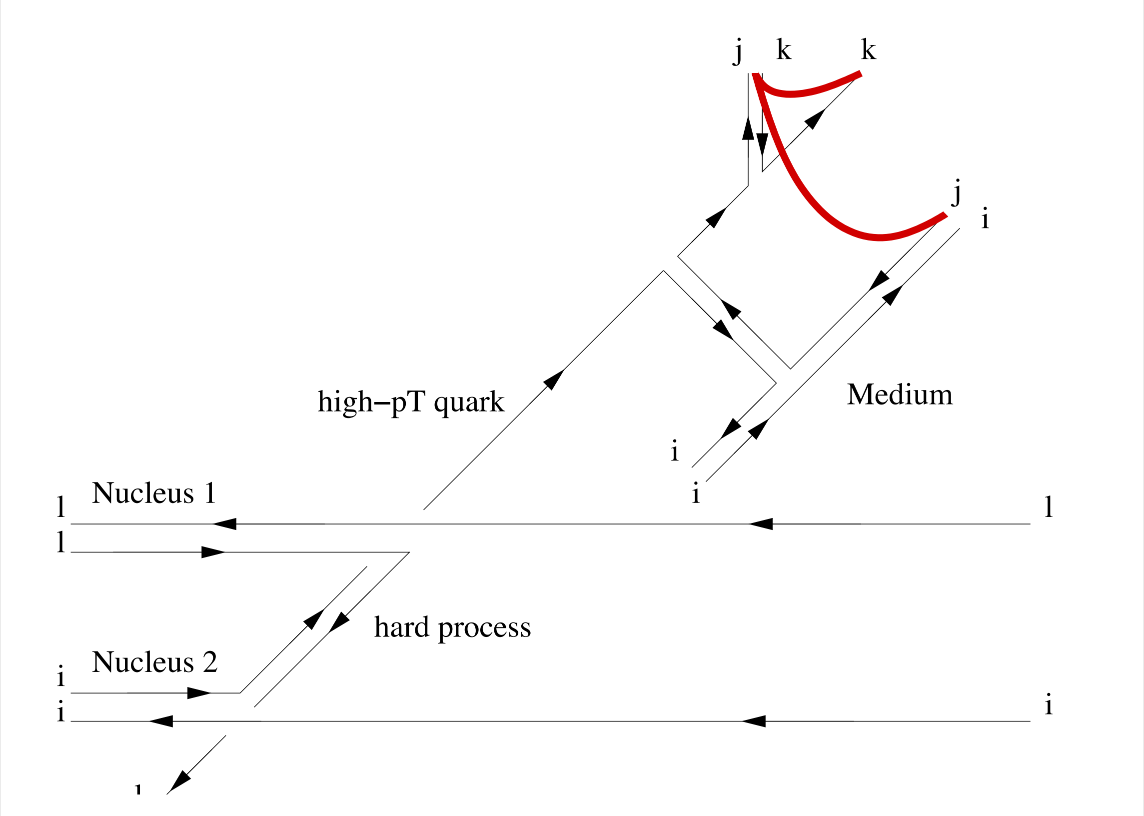

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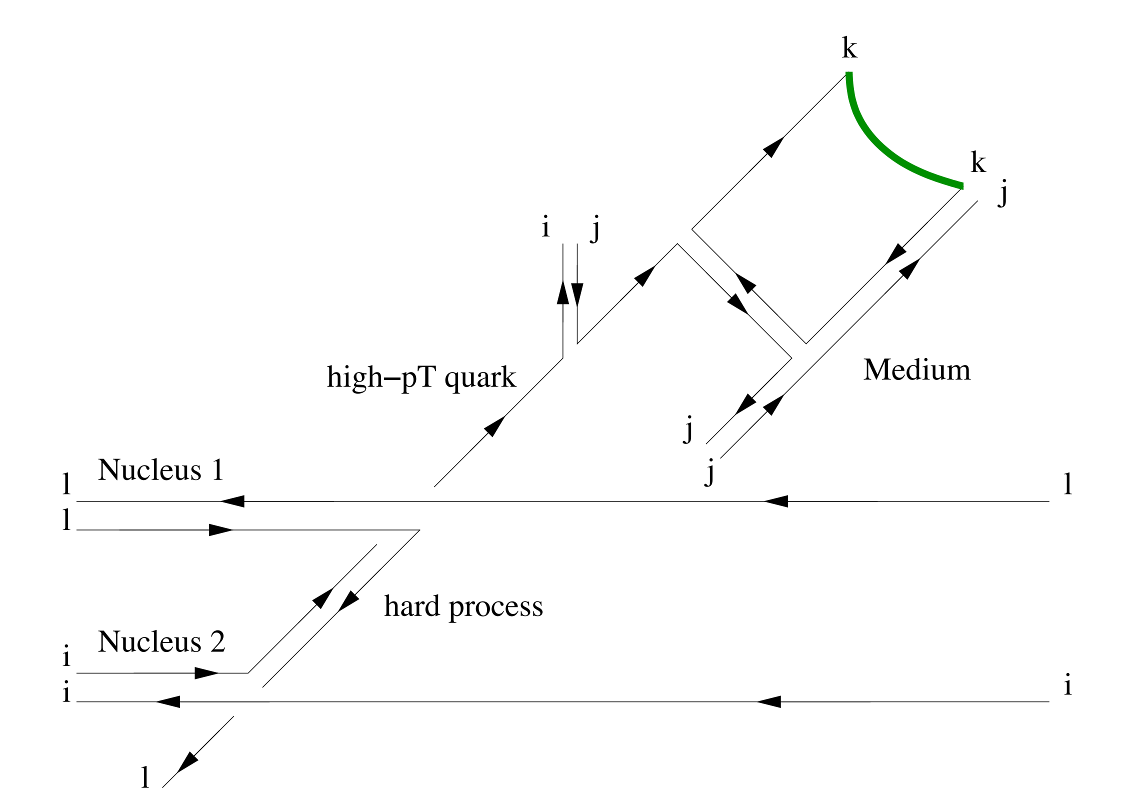

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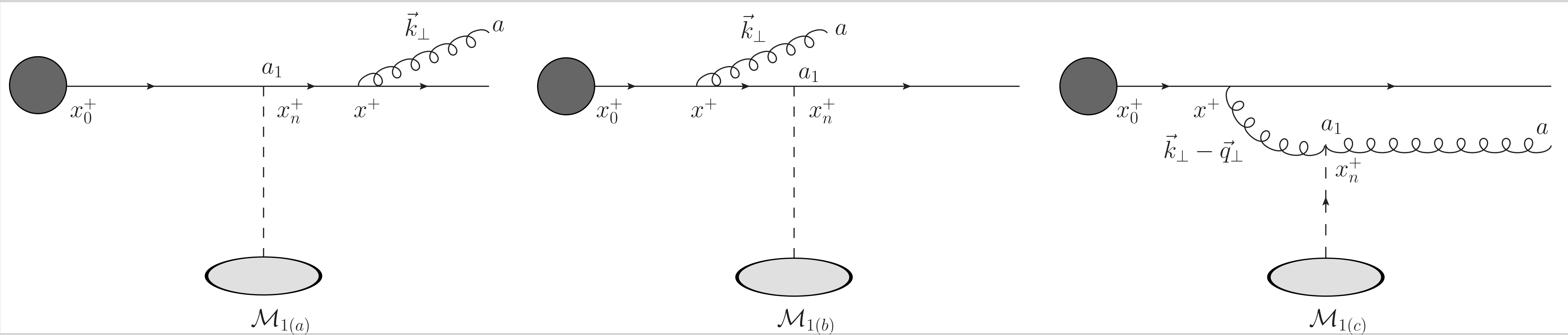
first steps towards fully colour differential framework

Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]

N=1 opacity [colour inclusive]



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

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

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

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

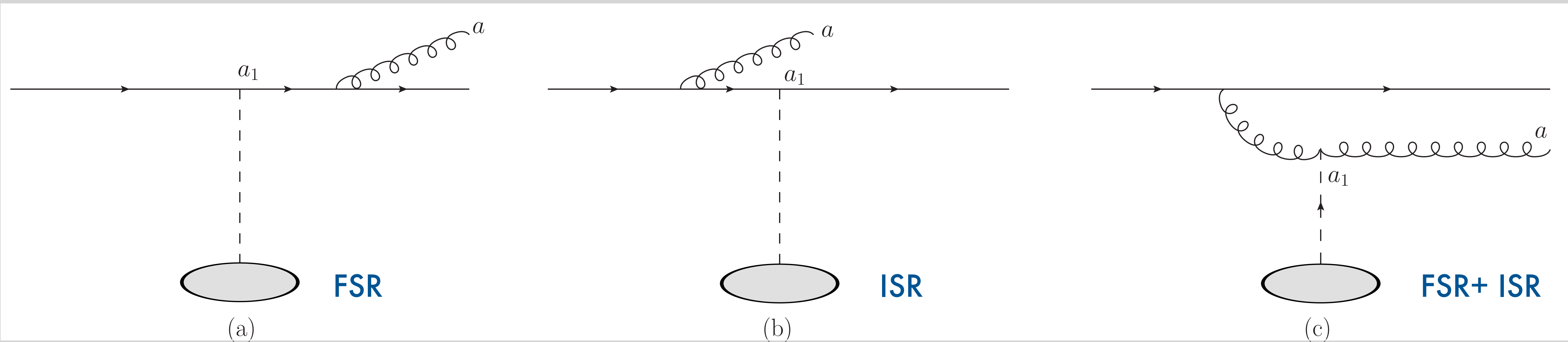
$$\mathcal{T_I} = \left(1 - \frac{\sin\left(\omega_1^-\, L^+\right)}{\omega_1^-\, L^+} \right) = \begin{cases} 1 & \text{for} \quad 1/\omega_1^- \ll L^+ \\ 0 & \text{for} \quad 1/\omega_1^- \gg L^+ \end{cases}$$

- 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_1a [ISR]
- contact terms 'subtract' from no interaction case to preserve probability

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

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

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

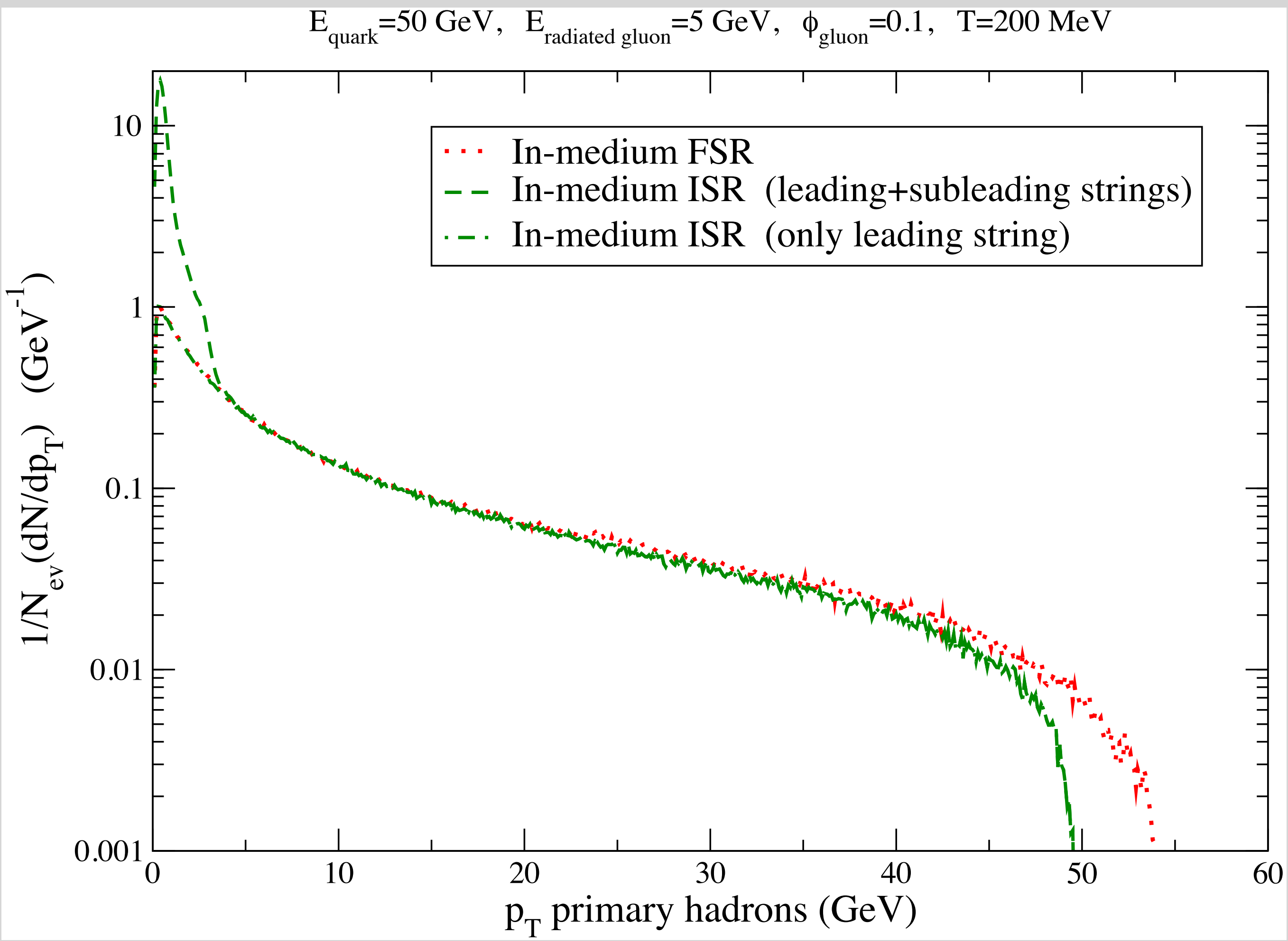
$$k^+ \frac{dI^{\rm med}}{dk^+ d\boldsymbol{k}_g}\bigg|_{a_1 a} \underset{\varpi_i L^+\to\infty}{\sim} \frac{\alpha_s}{\pi^2}\left[\frac{L^+}{\lambda_g^+}\left(\frac{C_F}{2}\right)\left(\left\langle(\boldsymbol{K}_0-\boldsymbol{K}_1)^2\right\rangle+\left\langle\boldsymbol{K}_1^2\right\rangle\right) +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

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

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

interplay of branching and hadronization

- colour correlations modified with respect to vacuum case
  - ↪ essential input for realistic hadronization schemes

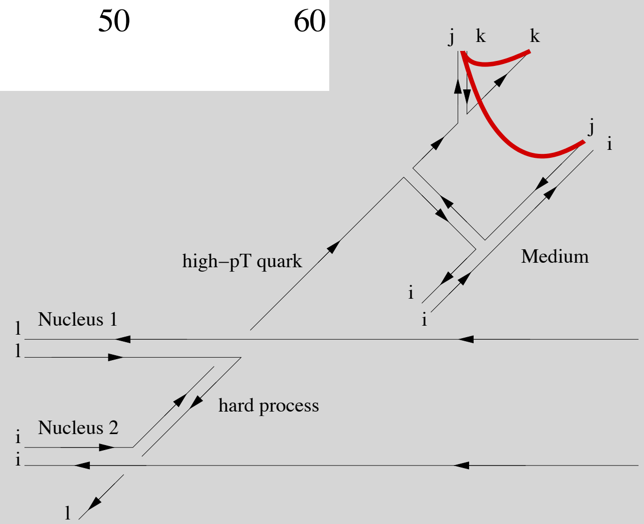


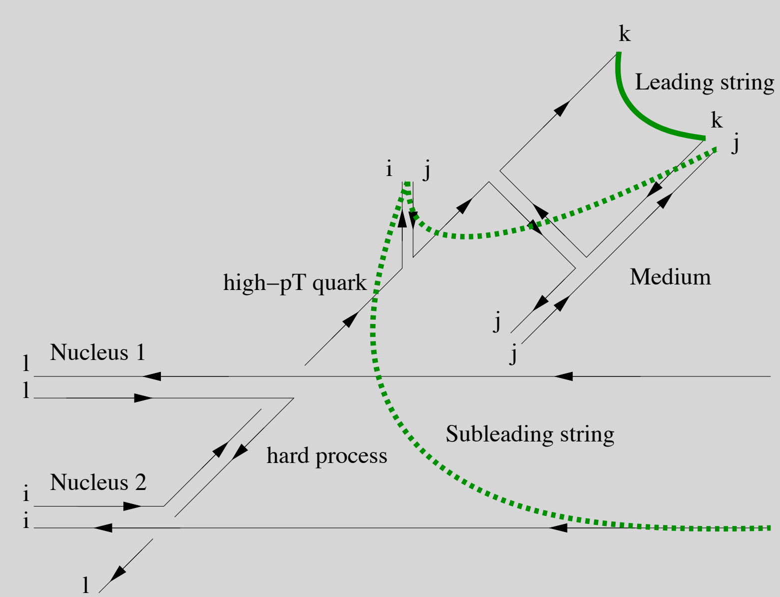
generic [robust] effects:

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

- at work even if radiative energy loss kinematically unviable

- survives branching after medium escape





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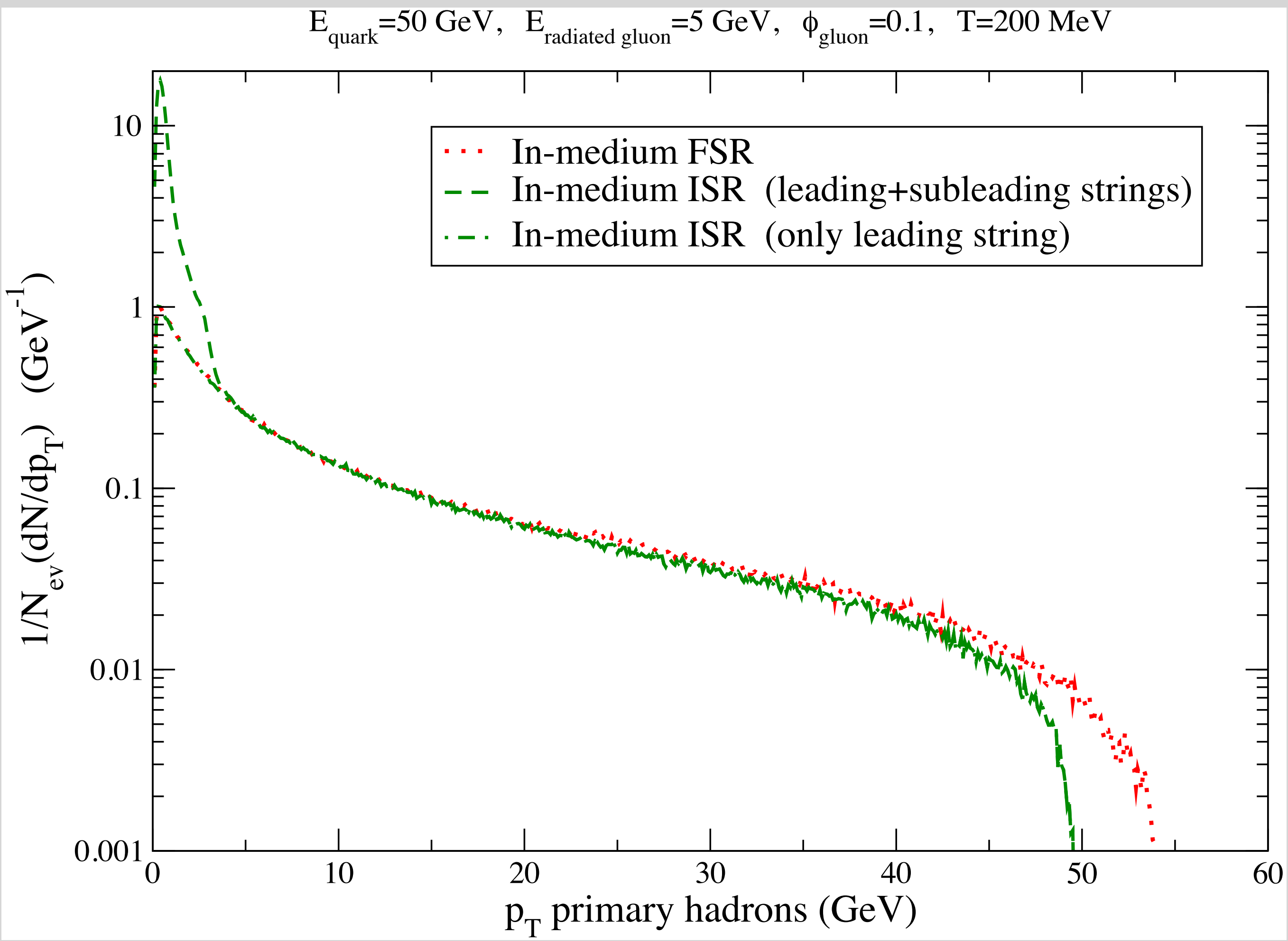

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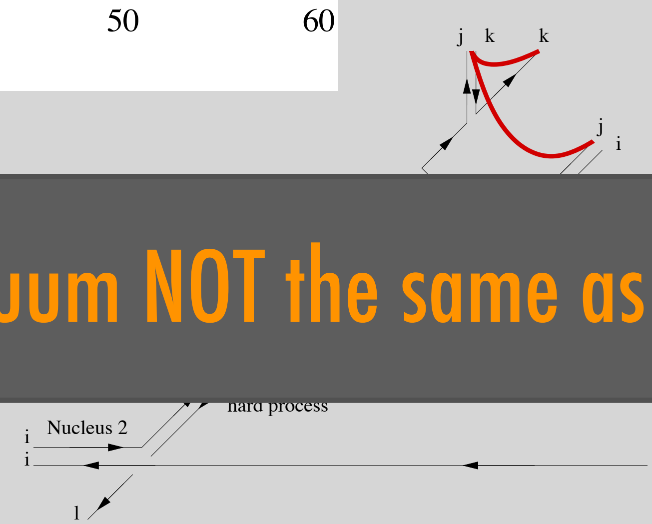
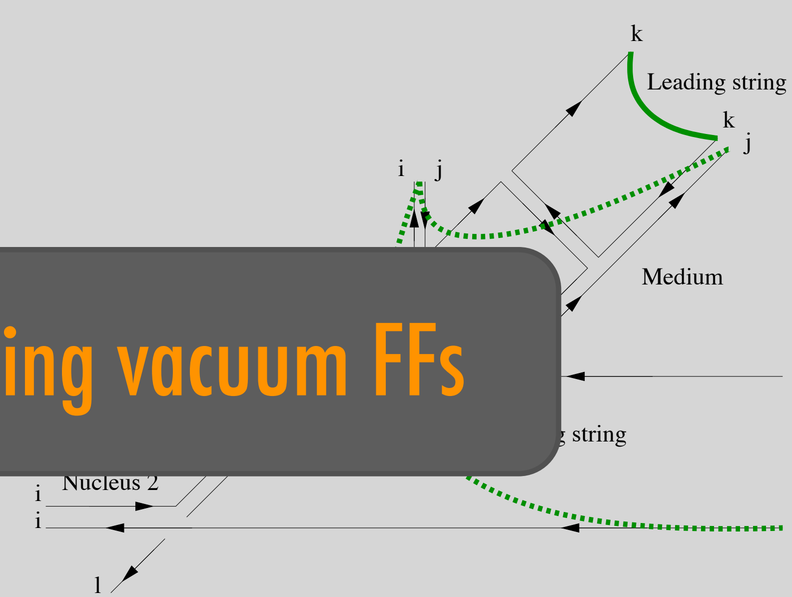
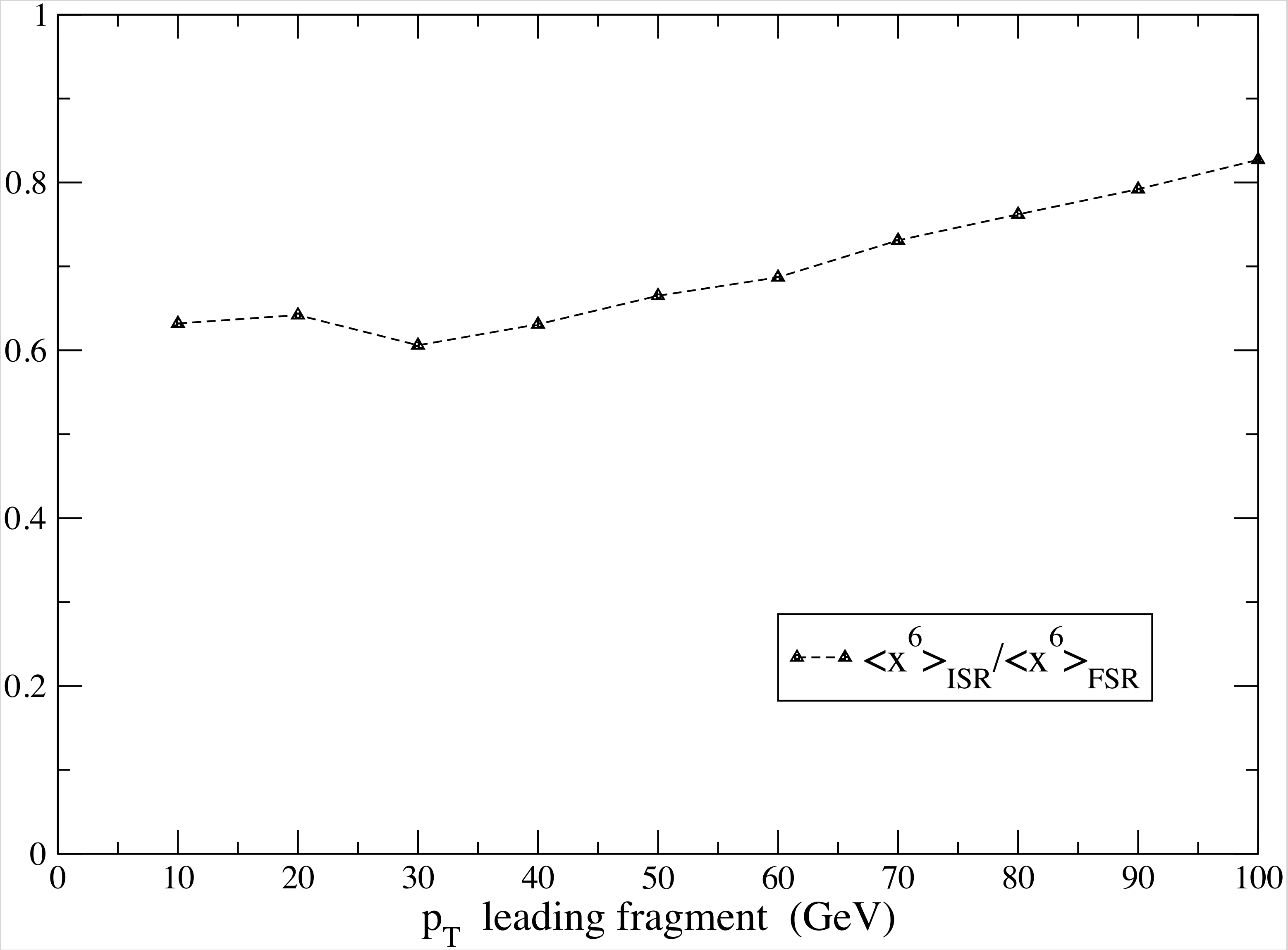




fragmentation in vacuum NOT the same as using vacuum FFs

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 hadron R_{AA}]



colour flow is a non-negotiable ingredient for jet-quenching studies that can be addressed perturbatively and provides input for non-perturbative hadronization prescriptions

it results in softening of hadronic spectra, increased soft multiplicity, fragmentation patterns unmodified over wide range, ...

life story of an in-medium jet

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- *prior to medium formation [$\tau^{med} \sim 0.1$ fm]*
    - *hard skeleton defined [3-jet rates, hard frag, ...]*
    - *effect of Glasma ?*

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soft components at large angles
[double counting ?]

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[double counting ?]

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

life story of an in-medium jet

very appealing pQCD based overall picture

BUT

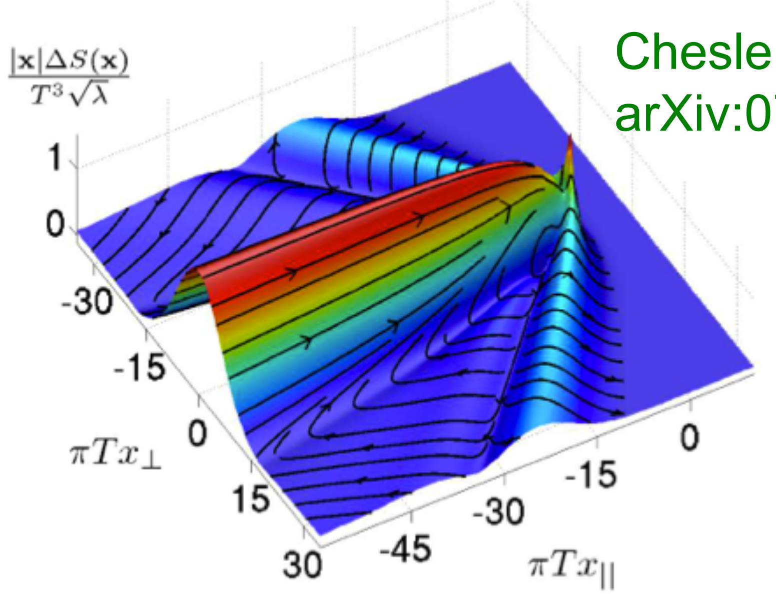
can we confidently exclude a conceptually different scenario in which strong jet-medium coupling effects drag energy loss on all jet ‘propagators’ and ‘vertices’ remain pQCD like ???

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

Probes propagating in a perfect liquid

Do hard probes have a finite mean free path?

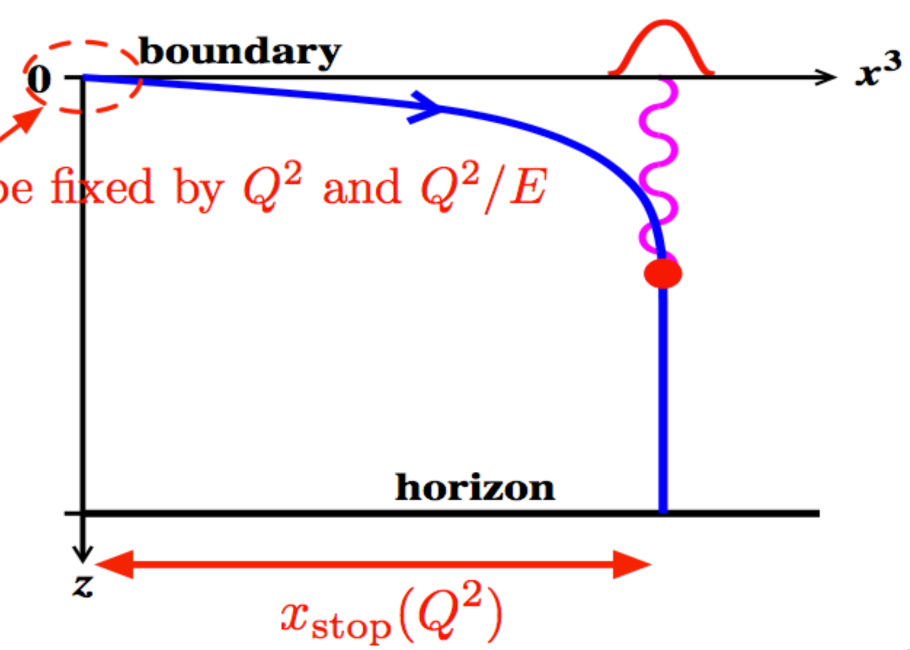
AdS/CFT view



Chesler, Yaffe
arXiv:0712.0050

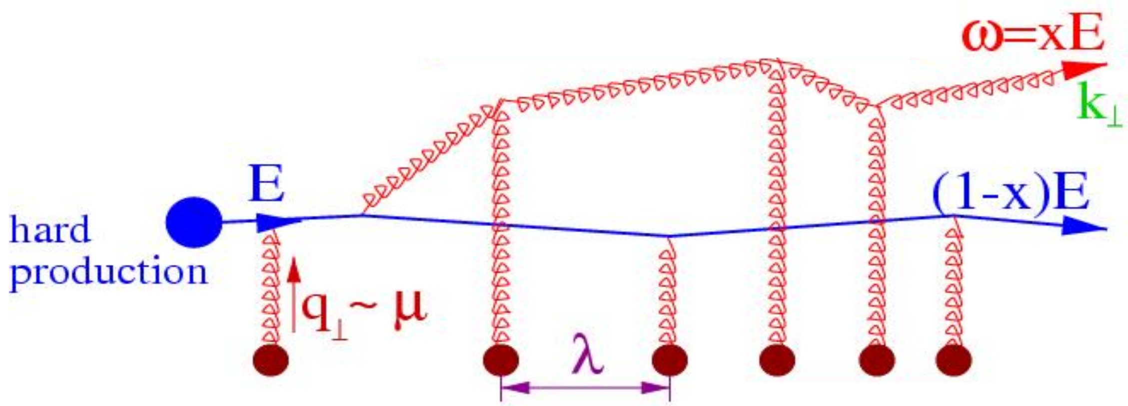
Heavy quarks propagate without mean free path
-> Lost momentum goes into Mach cone and wake

Light partons/jets propagate towards thermalization
(no collinear structure emerges, jet=hedgehog)



talk by W. Horowitz

If λ_{mfp} is finite



Energy moved to softer scales via elastic (aka collisional) and inelastic (aka radiative) mechanisms

Fragmentation broader but collinear dynamics present.

talk by G. Milhano

Collinear structure can also result from evolution outside the medium
=> Need to understand formation times

#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

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

  - ↪ for a weakly coupled medium

- 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
    - jet reclustering
  - direct sensitivity to resolution scales
  - …