A new era for jet studies in ultra-relativistic heavy-ion collisions

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TÉCNICO LISBOA

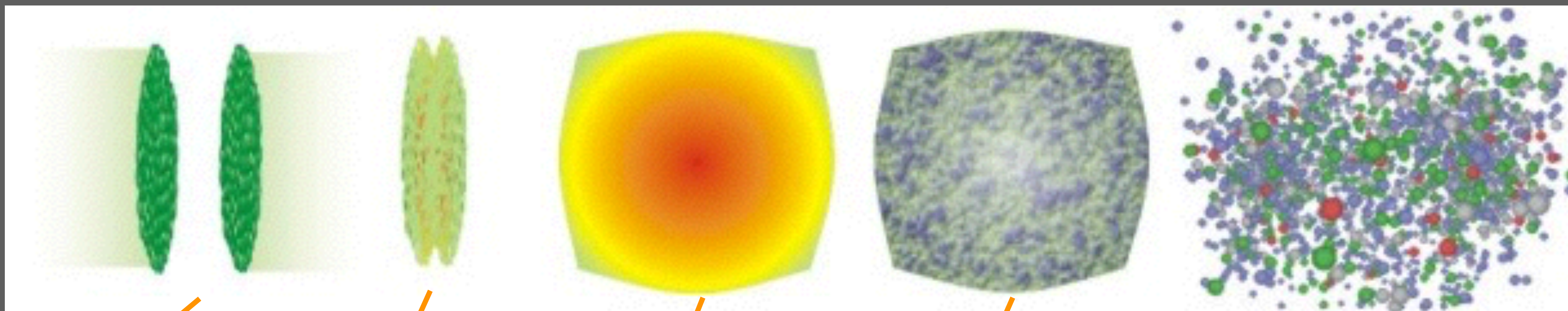
EuNPC2015, Groningen, 3rd September 2015

~ 0.1 fm/c

~1 fm/c
[~10^{-24} s]

~ 10 fm/c

time



colliding [cold] nuclei
[initial condition]

pre-equilibrium
[collision]

Quark Gluon Plasma
[hot, dense and coloured]
[equilibrated/thermalized]
hydrodynamic expansion

hadronization

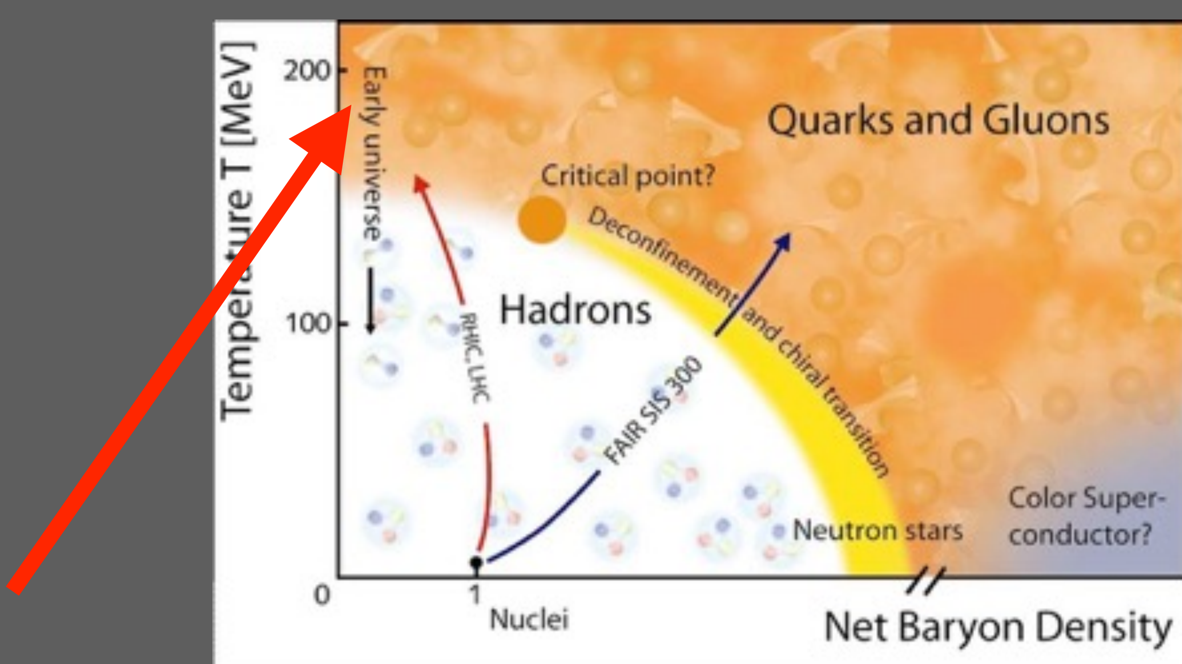
hadrons
[back to cold nuclear matter]

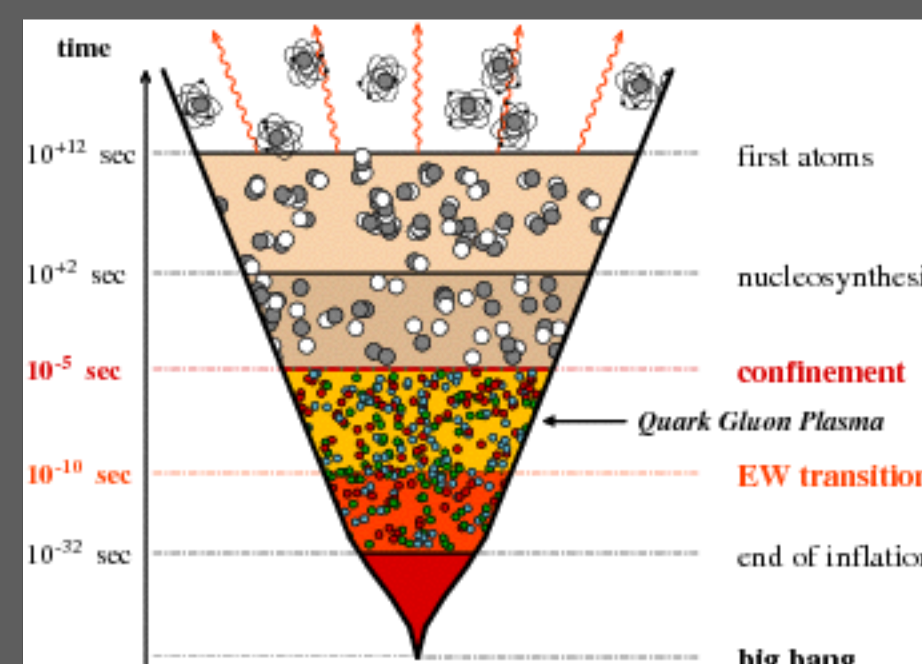
from nuclei to QGP :: a heavy ion collision

quark gluon plasma

- *an almost perfect liquid [the most perfect ever observed] of fundamental degrees of freedom [quarks and gluons] :: direct manifestation of collective behaviour in a fundamental non-abelian Quantum Field Theory [QCD]*

- *a unique, experimentally accessible and theoretically tractable, opportunity to further the understanding of nuclear matter in a novel regime [deconfined, yet strongly interacting, quarks and gluons] also of critical importance in the early history of the Universe*





quark gluon plasma

- *'discovered' and confirmed at the SPS, RHIC and LHC*

- *current focus on understanding of dynamics and precise measurement of properties :: must rely on self-generated probes [short-lived QGP]*

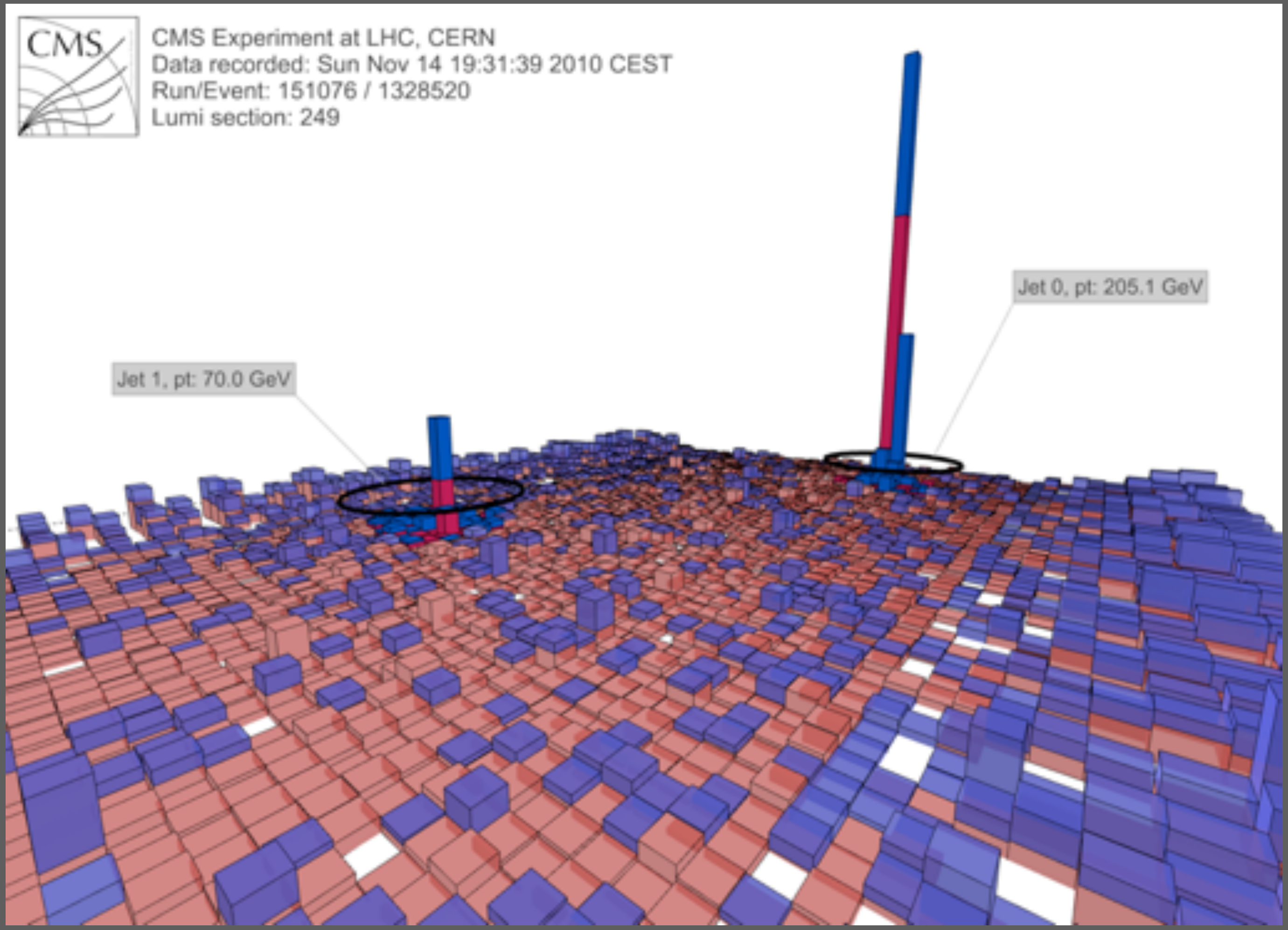
- *broadly two sets of handles*
  - *bulk [collective] observables :: flows, correlations, ...*
  - *hard probes [detailed microscopic probes]*
    - *EW [non-interacting benchmark]*
    - *quarkonia/heavy flavour*
    - *jets*

B Schenke Wed 11.00
K Redlich Wed 12.00
M van Leeuwen Mon 10.00
S Masciocchi Tue 12.00
M van Leeuwen + this talk

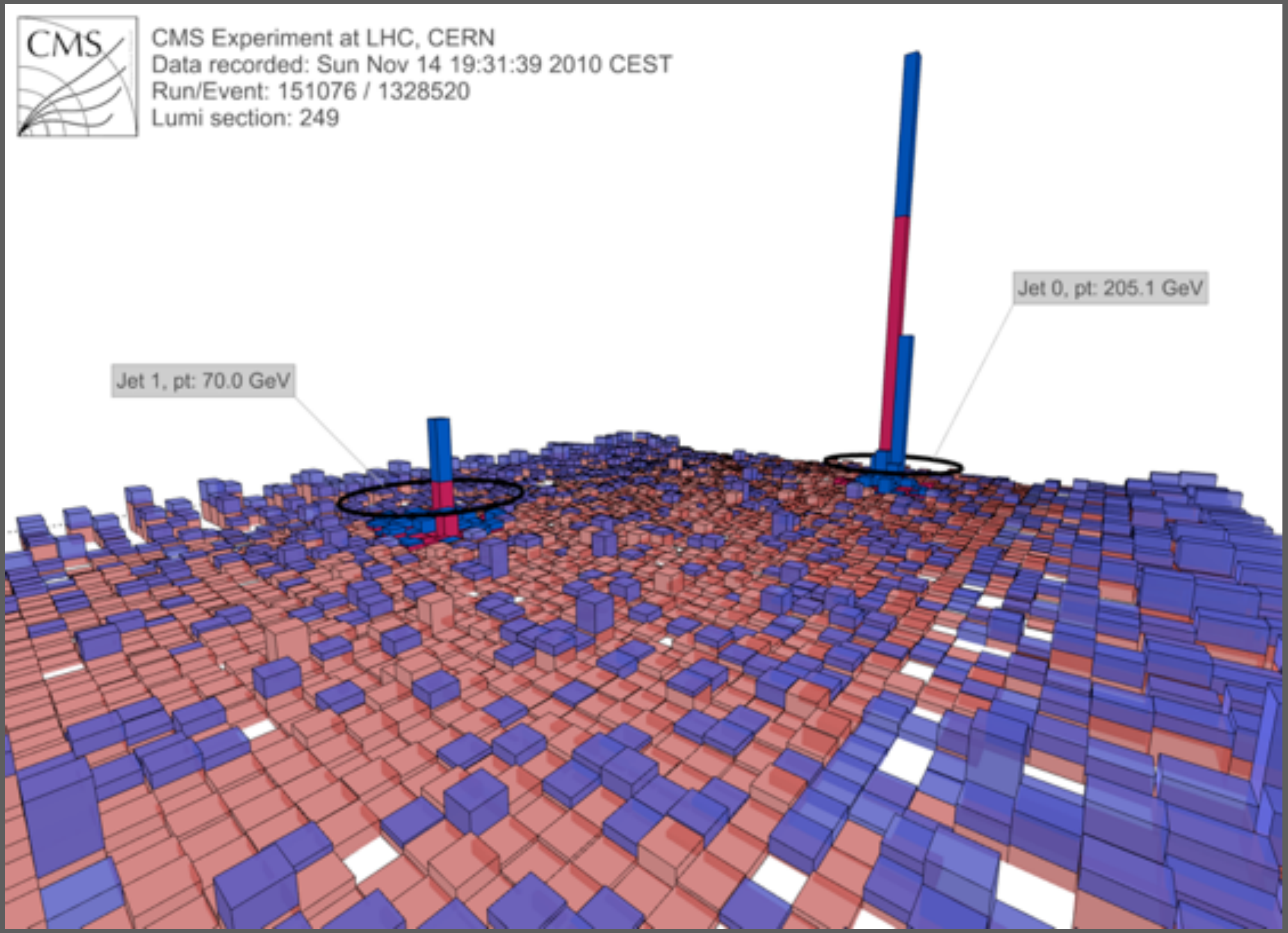
focus here on few key theoretical ideas

jet definition

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 infra-red and collinear safe procedure [jet algorithm] and for given defining parameters [eg, jet radius]



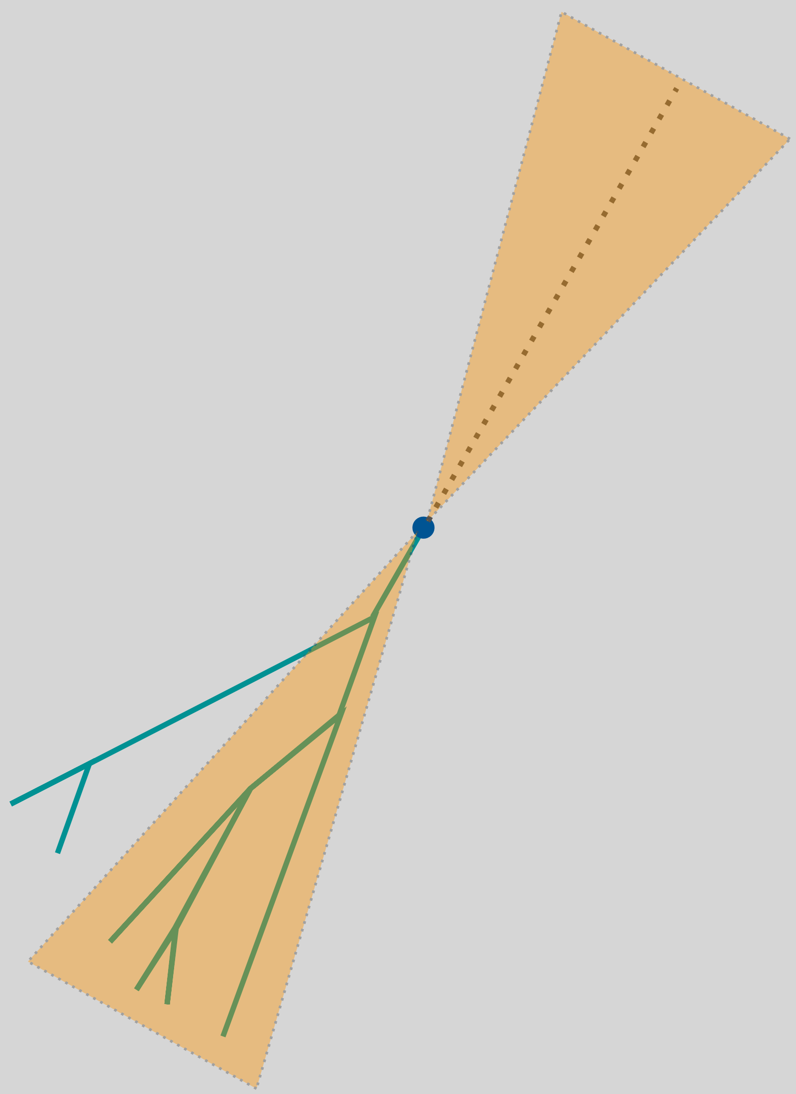
jets in heavy ion collisions



- major accomplished experimental challenge
    - jets can be systematically reconstructed above large [100 GeV in jet catchment area] and fluctuating [up to 20 GeV] background
- jets are very well understood in vacuum and modified [jet quenching] by the QGP they traverse
- jets are multi-scale probes [wealth of observables/properties sensitive to different QGP scales]

in-medium jet dynamics

jets in vacuum



vacuum jets under overall excellent theoretical control

- reliable baseline and template for inclusion of medium effects
- factorization of initial and final state

$$\sigma^{h_1 h_2 \to X}(p_1, p_2) = f_i^{h_1}(x_1, Q^2) \otimes f_j^{h_2}(x_2, Q^2) \otimes \sigma^{i\, j \to k}(x_1 p_1, x_2 p_2, Q^2) \otimes D_{k \to X}(z, Q^2)$$

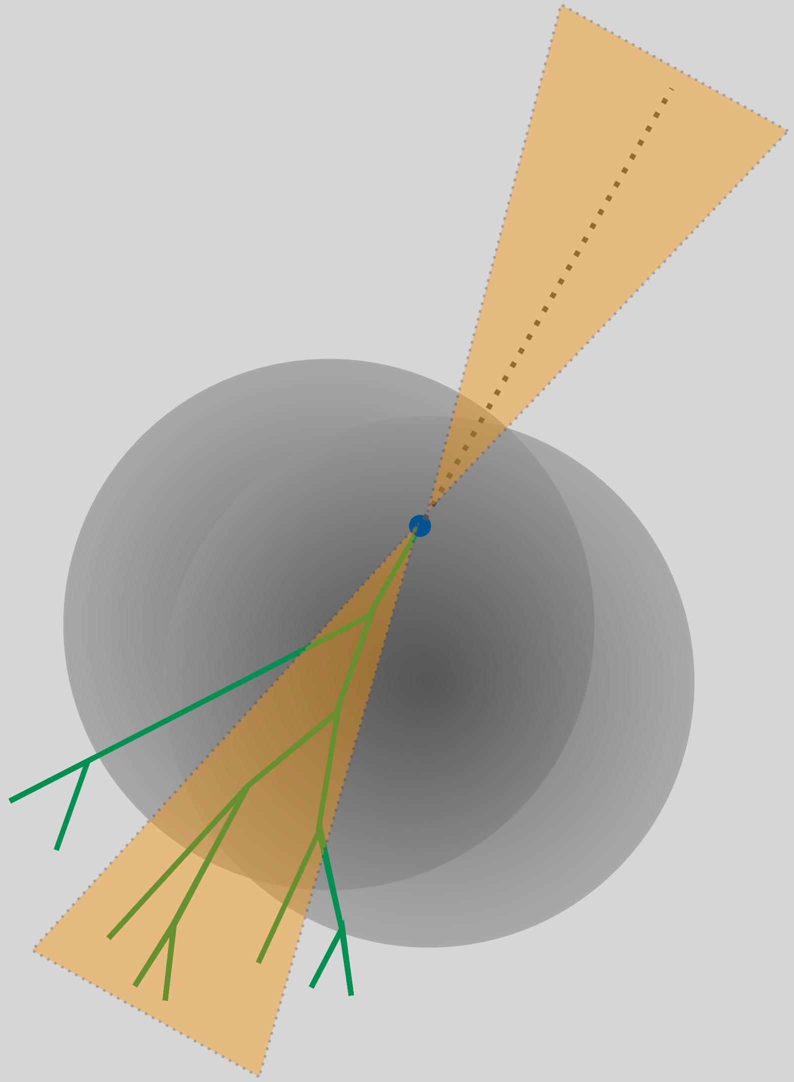
- branching pattern dictated by Altarelli-Parisi splitting functions

$$dw^{k \to l+m} = \frac{\alpha_s}{4\pi} \frac{d^2 k_\perp}{k_\perp^2} \, dz \, P_{lk}(z)$$

- AND coherence [interference] between emitters :: angular ordering [MLLA]

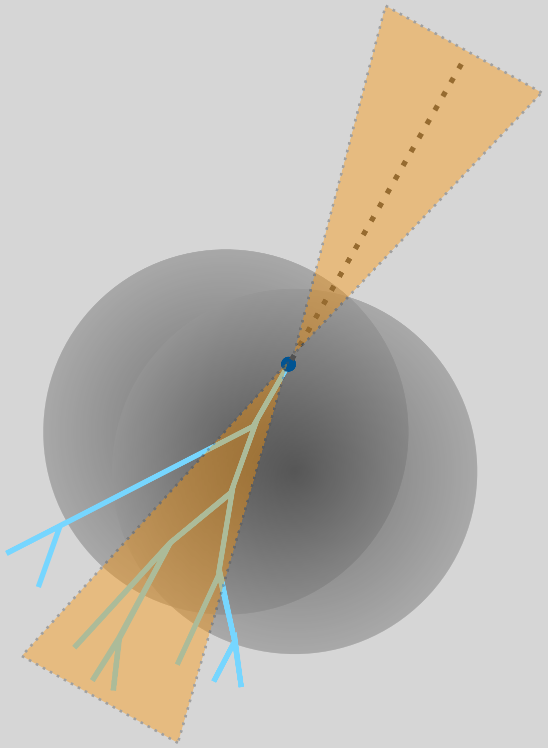
$$\frac{\partial}{\partial \log Q} D_i(x, Q) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_s(k_\perp^2)}{2\pi} \hat{P}_{ji}(z) D_j(x/z, zQ)$$

jets in heavy ion collisions



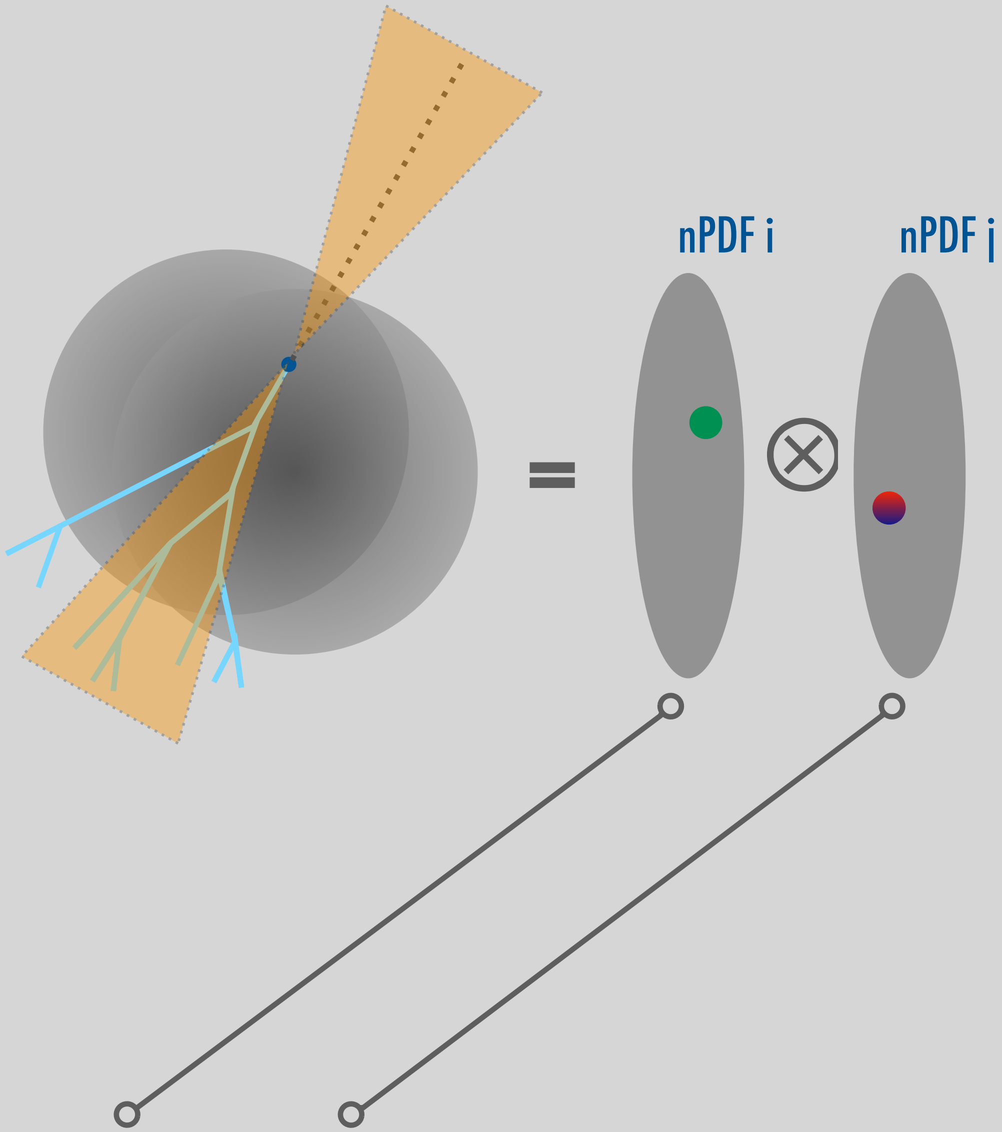
in HIC jets traverse sizable in-medium pathlength

jets in heavy ion collisions



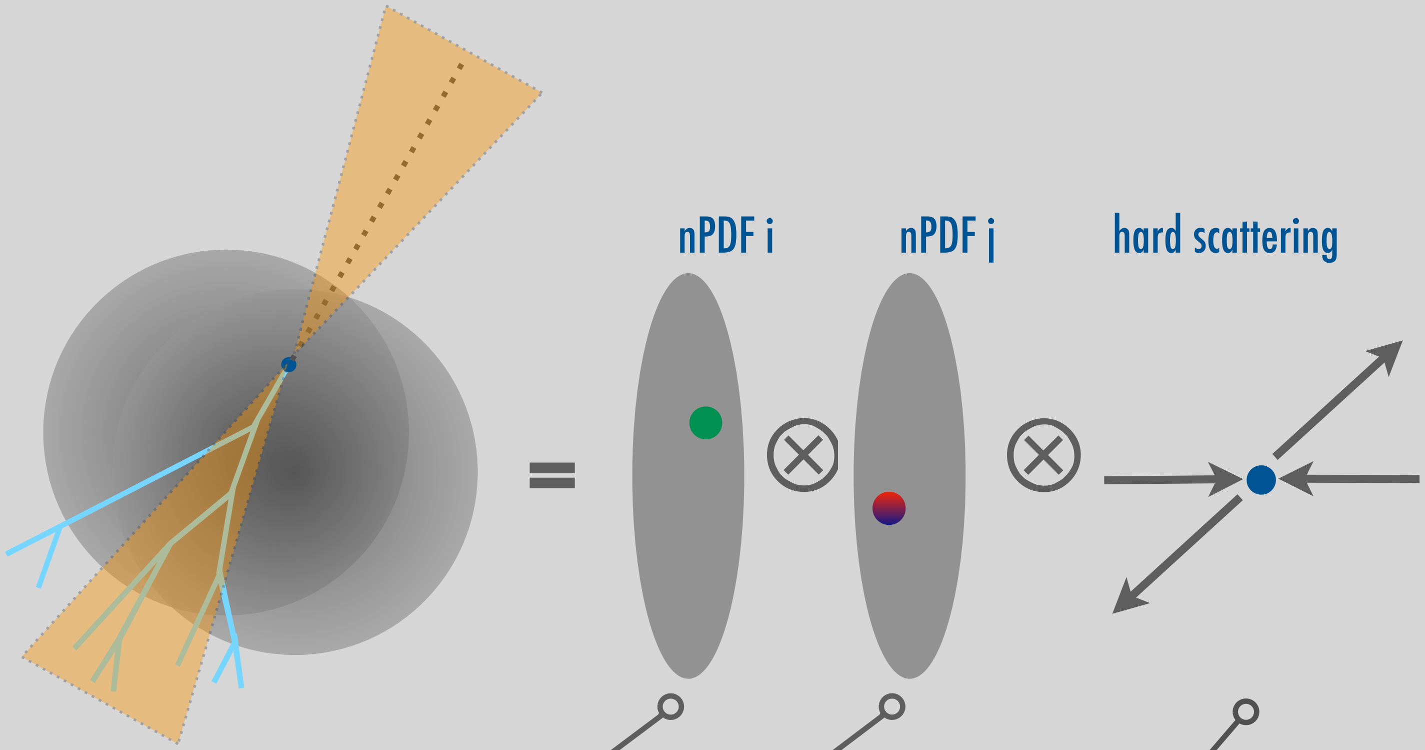
same factorizable structure [challengeable working hypothesis]

jets in heavy ion collisions



sufficiently constrained in
relevant kinematical domain

jets in heavy ion collisions

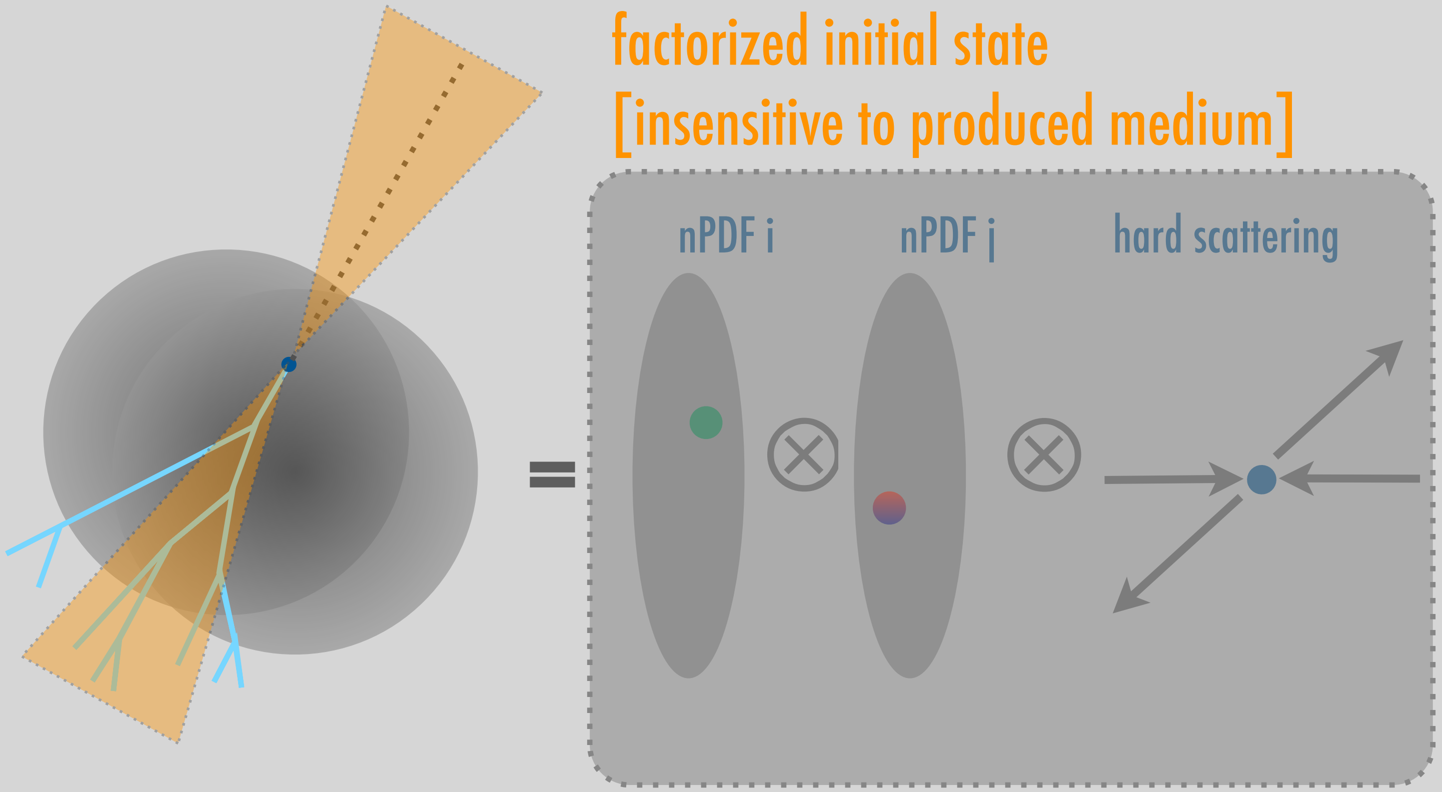


sufficiently constrained in
relevant kinematical domain

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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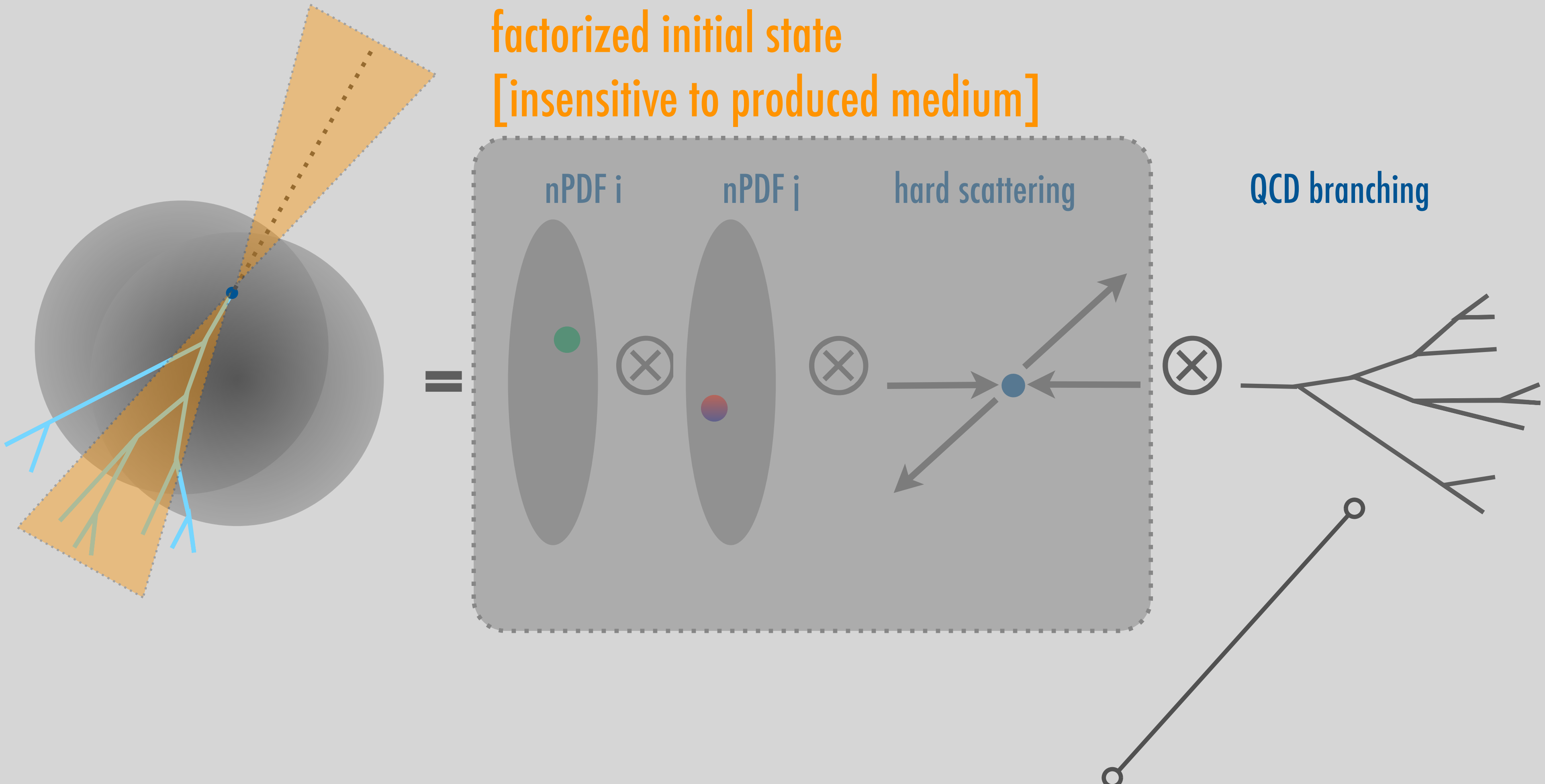


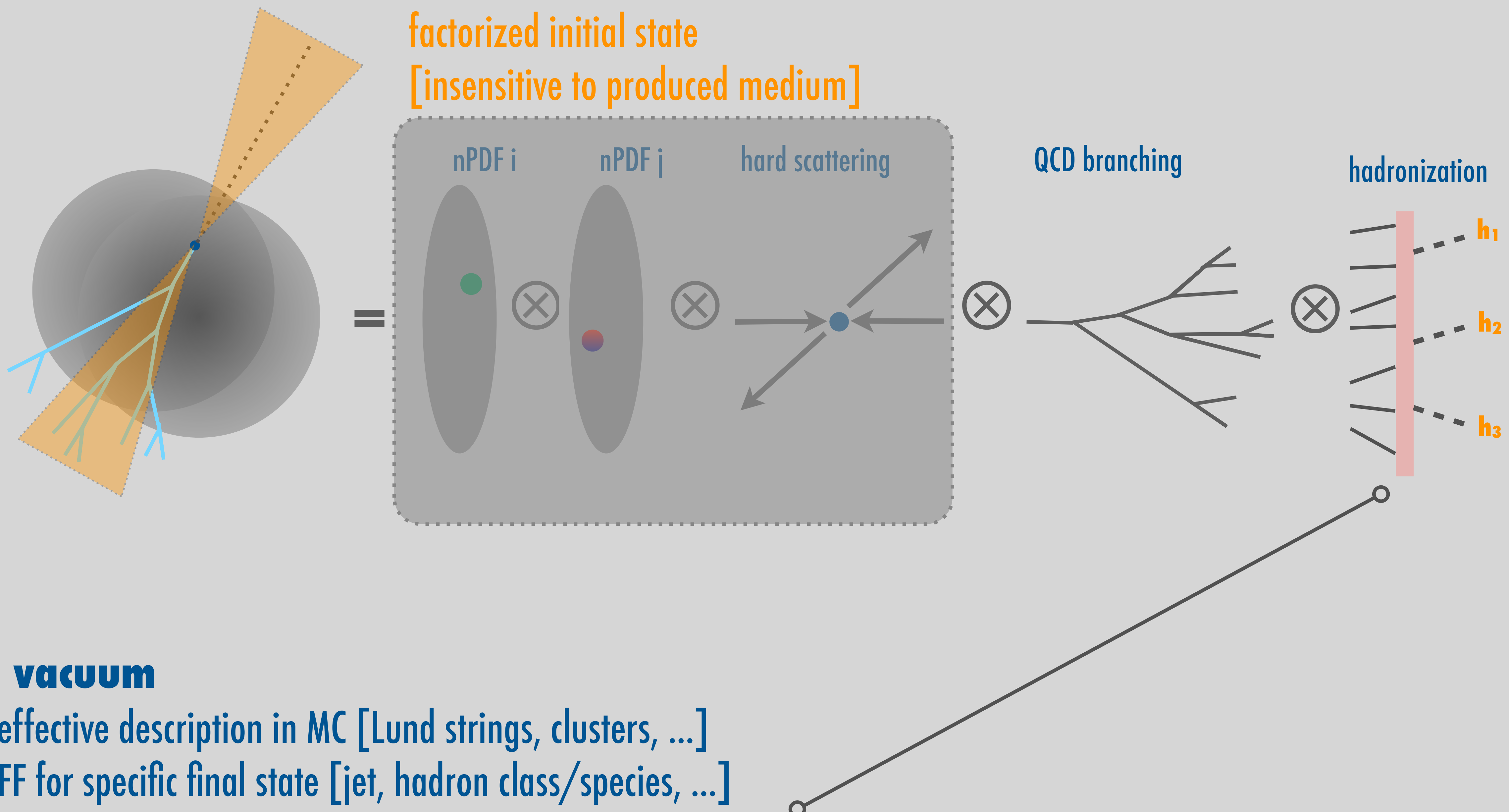
very well [and perturbatively] understood in vacuum

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

medium modified

- induced radiation
- 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

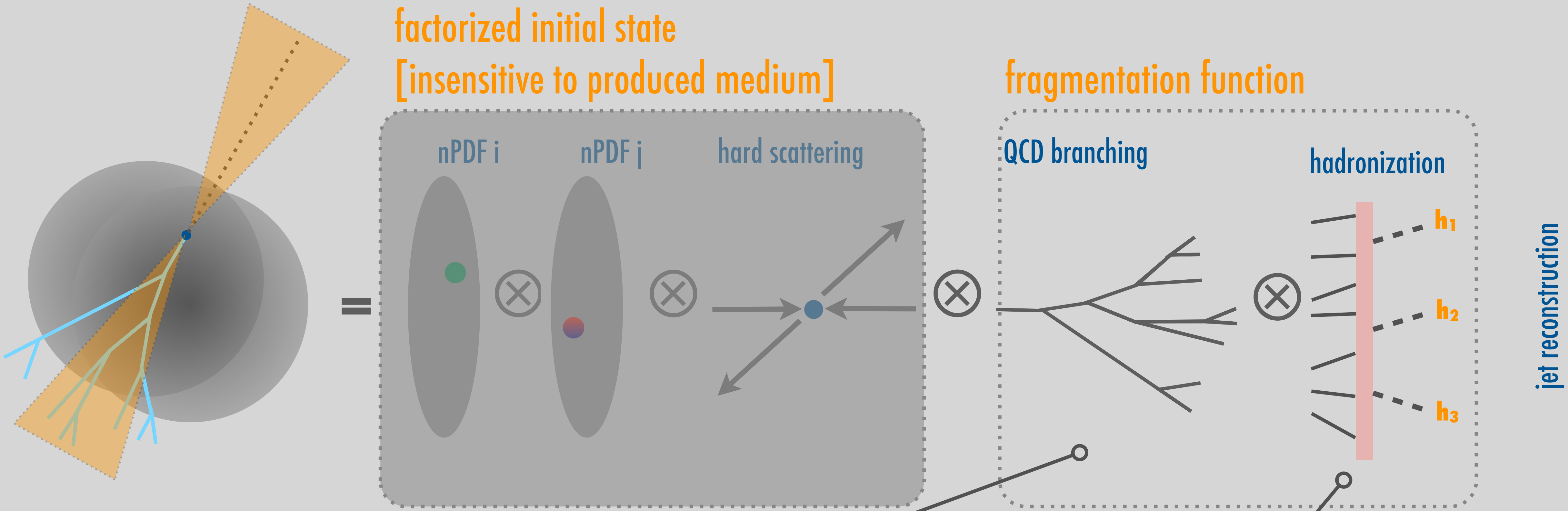
- effective description in MC [Lund strings, clusters, ...]
- FF for specific final state [jet, hadron class/species, ...]

in medium

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

fragmentation outside medium = vacuum FFs ???
[however, many jet observables largely insensitive to hadronization]

jets in heavy ion collisions



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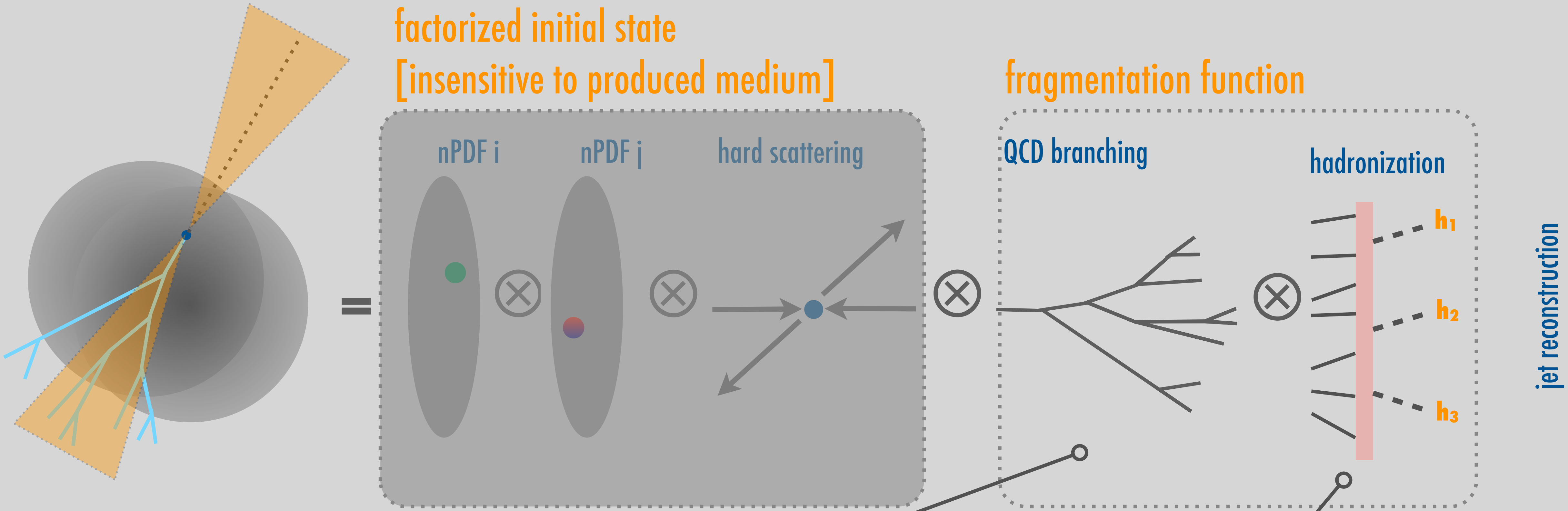

jet quenching ::
observable consequences [in jet and jet-like hadronic observables] of the effect of the medium

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to establish quenched jets
as medium probes requires a full theoretical account of

- *QCD branching*
- *effect on hadronization [for hadrons]*

in the presence of a generic medium

and

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

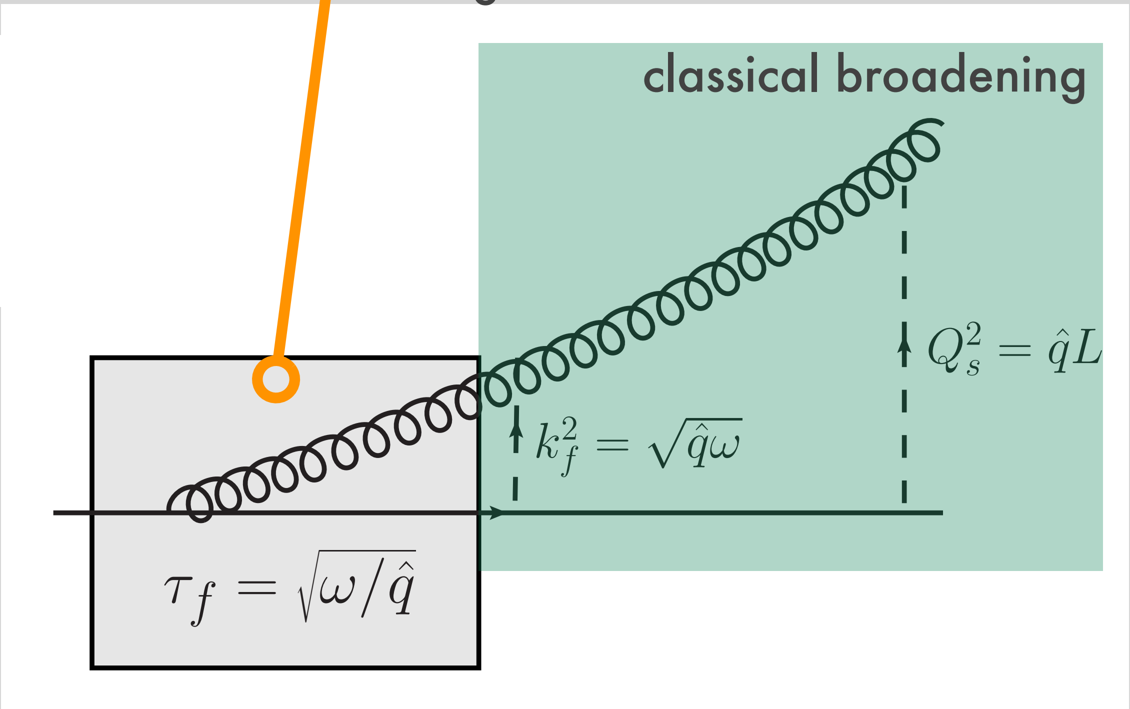
:: probe ::
physical object/process/observable under strict theoretical control for which a definite relationship between its properties and those of the probed system can be established

medium induced radiation and broadening

- interaction with QGP leads to enhanced splitting probability [more emissions] for each jet component [parton]
- classical [Brownian] broadening of all partons
  - understood within several perturbative approaches

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

quantum emission/broadening during formation time



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

large broadening

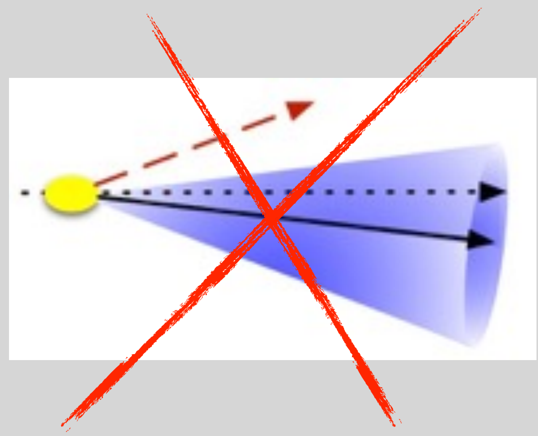
- in-medium formation time for small angle and soft gluons [vacuum] is very short
- democratic broadening is a large effect for soft partons
  - soft radiation decorrelated from jet direction/transported to large angles without disturbing back-to-back correlation
  - enhancement of soft fragments outside the jet
  - jet energy depletion driven by away transport of soft fragments NOT by rare out-of-cone semi-hard splitting

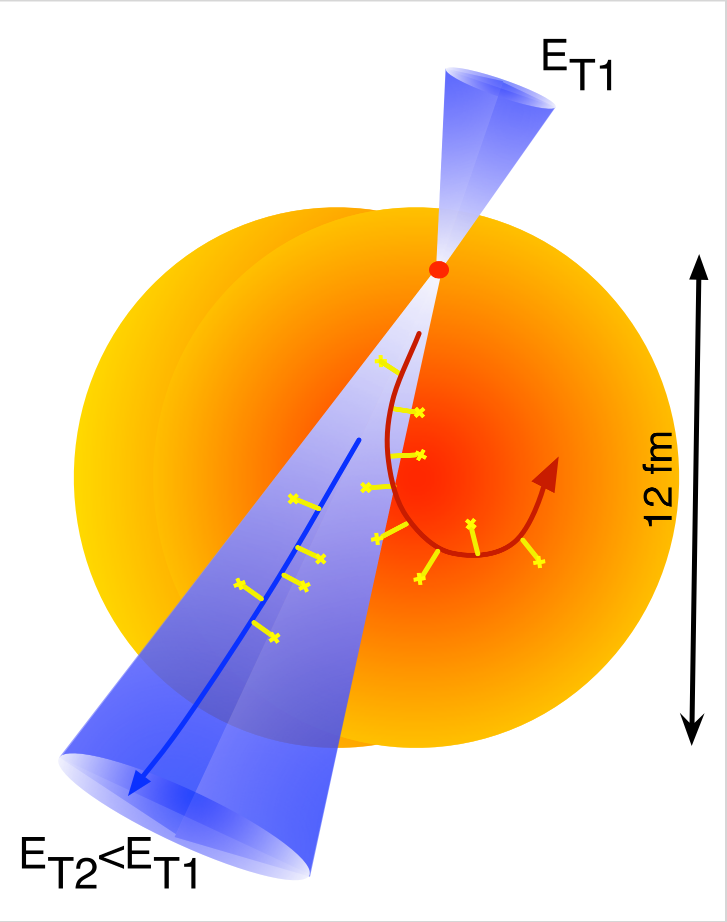
$$\tau \sim \frac{\omega}{k_\perp^2} \xrightarrow[\langle k_\perp^2 \rangle \sim \hat{q}\tau]{} \langle \tau \rangle \sim \sqrt{\frac{\omega}{\hat{q}}}$$

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

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

an important lesson learnt from dijet asymmetry data





Casalderrey-Solana, Milhano, Wiedemann

multiple emissions :: vacuum antennas

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

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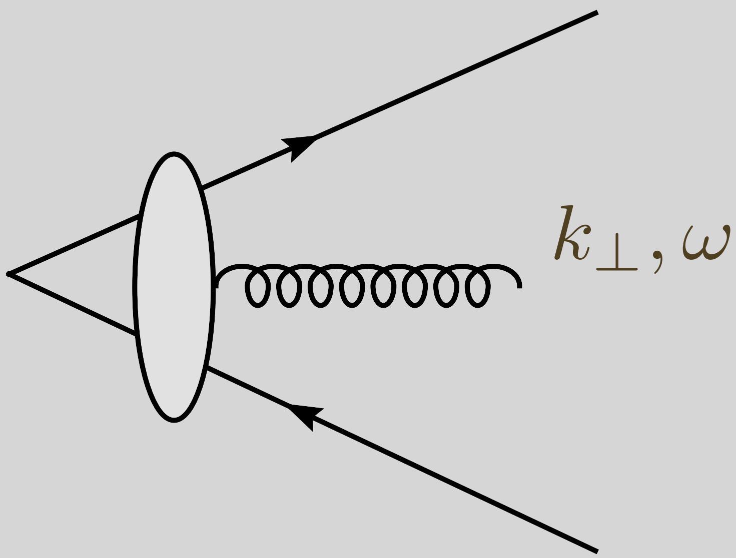
  - ⟶ qqbar antenna [radiation much softer than both emitters] as a TH lab



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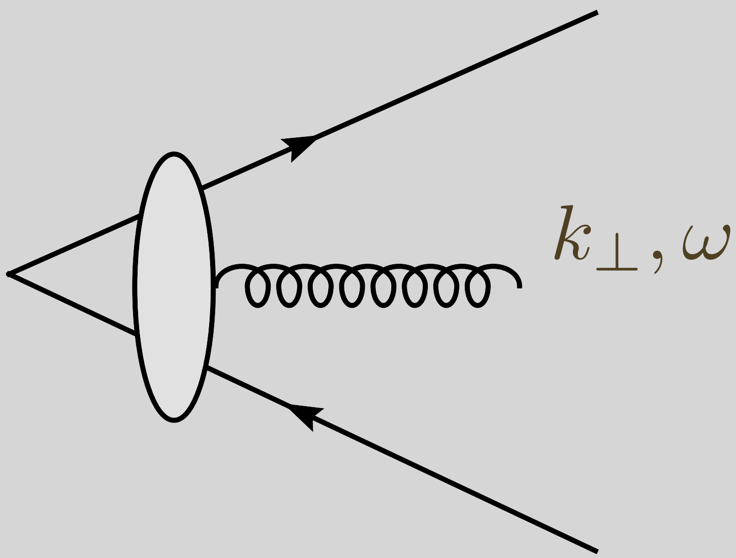

::vacuum::

- transverse separation at formation time

$$r_\perp \sim \theta_{q\bar{q}} \tau_f \sim \frac{\theta_{q\bar{q}}}{\theta^2 \omega}$$

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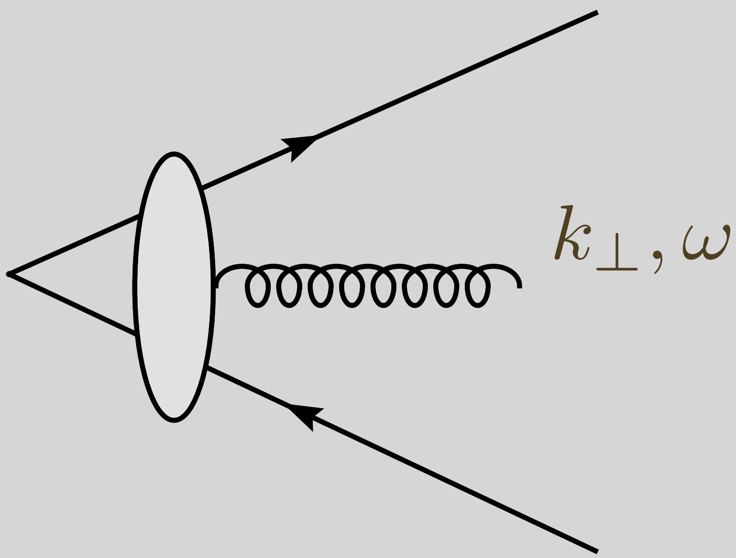

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- wavelength of emitted gluon

$$\lambda_\perp \sim \frac{1}{k_\perp} \sim \frac{1}{\omega\theta}$$

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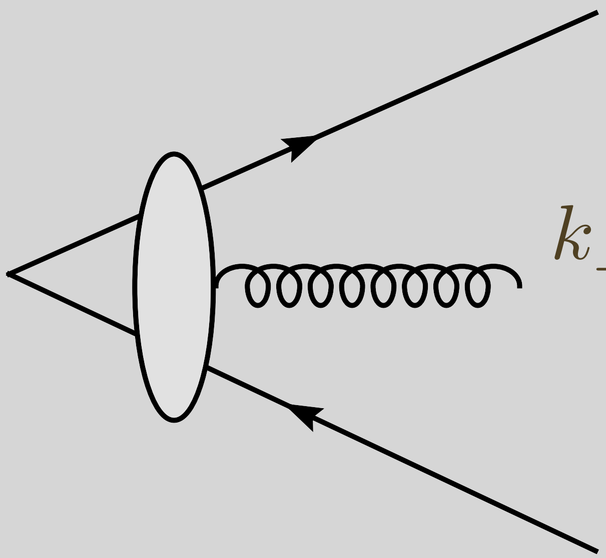

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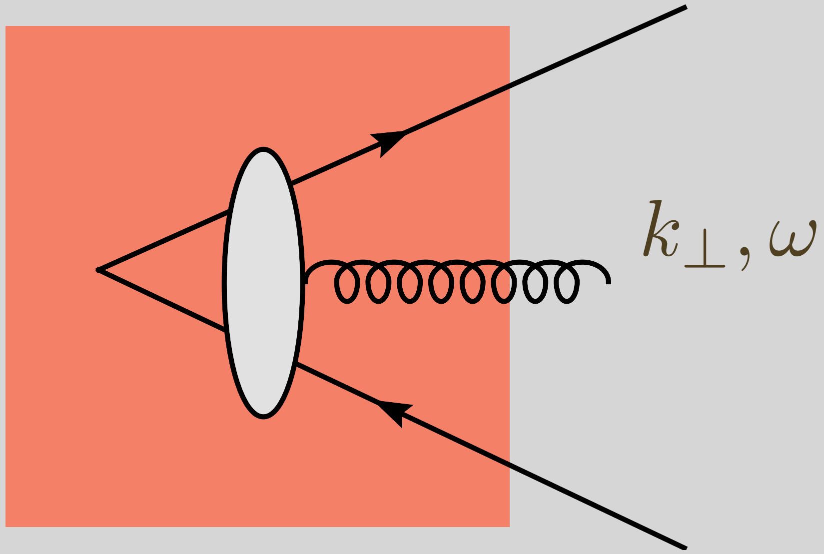
$$\lambda_\perp \sim \frac{1}{k_\perp} \sim \frac{1}{\omega\theta}$$

for $\lambda_\perp > r_\perp$ emitted gluon cannot resolve emitters, thus emitted coherently from total colour charge

large angle radiation suppressed :: angular ordering

medium antennas



MAJOR EFFORT
Mehtar-Tani, Salgado, Tywoniuk
Casalderrey-Solana & Iancu
Blaizot, Dominguez, Iancu, Mehtar-Tani
Mehtar-Tani, Milhano, Tywoniuk [review]

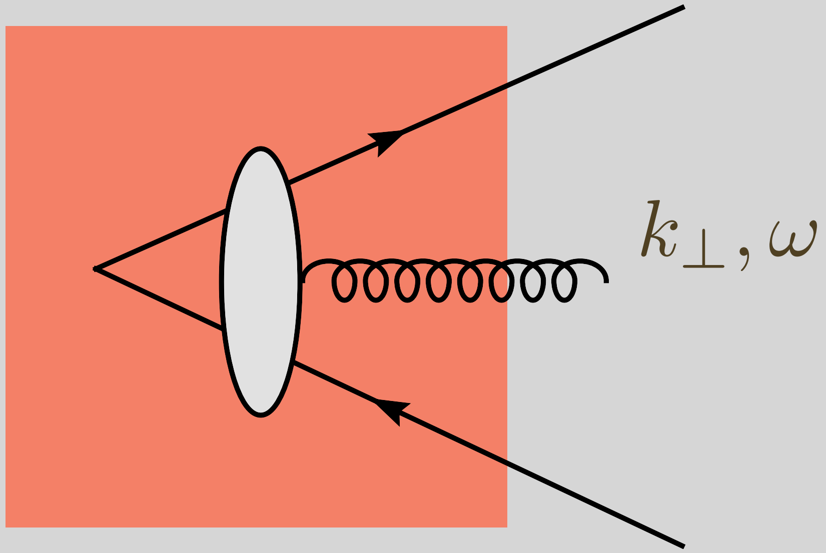
- new medium induced colour decorrelation scale

$$\Lambda_{med} \sim \frac{1}{k_\perp} \sim \frac{1}{\sqrt{\hat{q}L}}$$

- such that decorrelation driven by timescale

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

[de]coherence of multiple emissions



- qqbar colour coherence survival probability

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

- time scale for decoherence

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

- total decoherence when $L > \tau_d$

⟶ colour decoherence opens up phase space for emission

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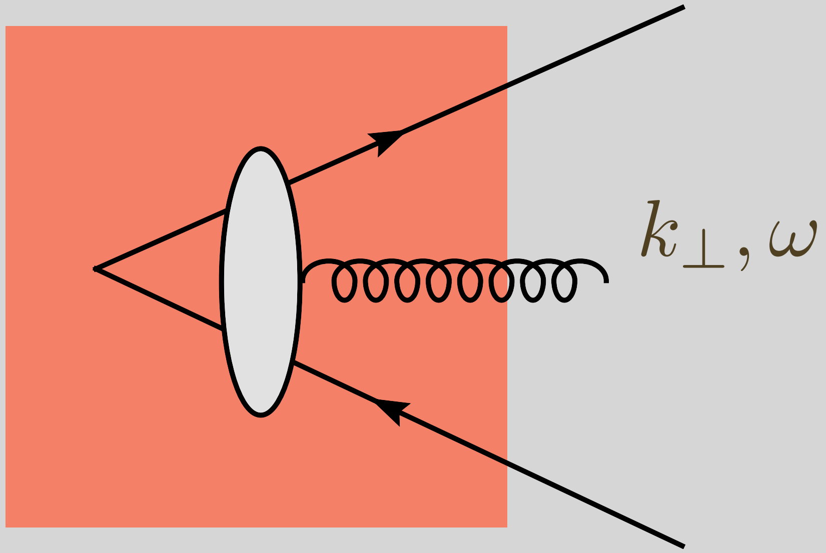

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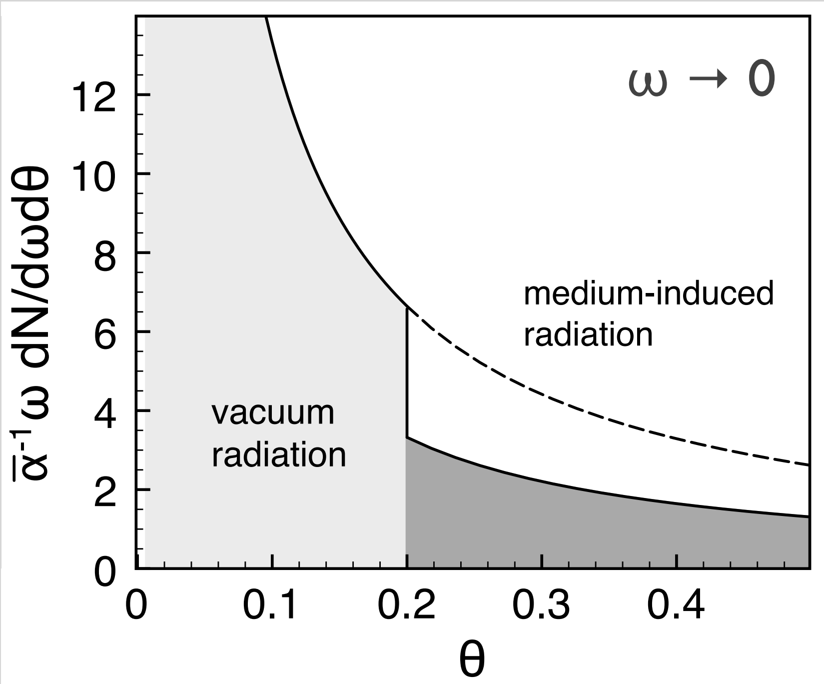
- large angle radiation [anti-angular ordering]
  - *geometrical separation [in soft limit]*

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



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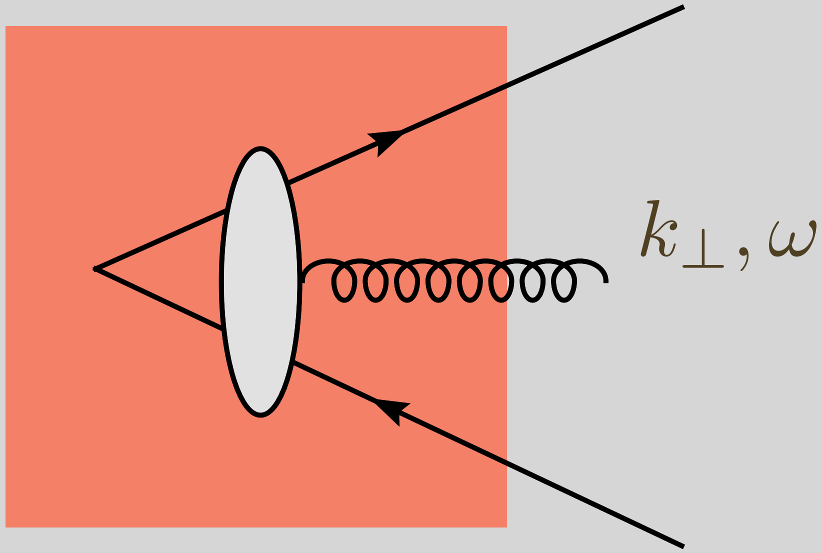

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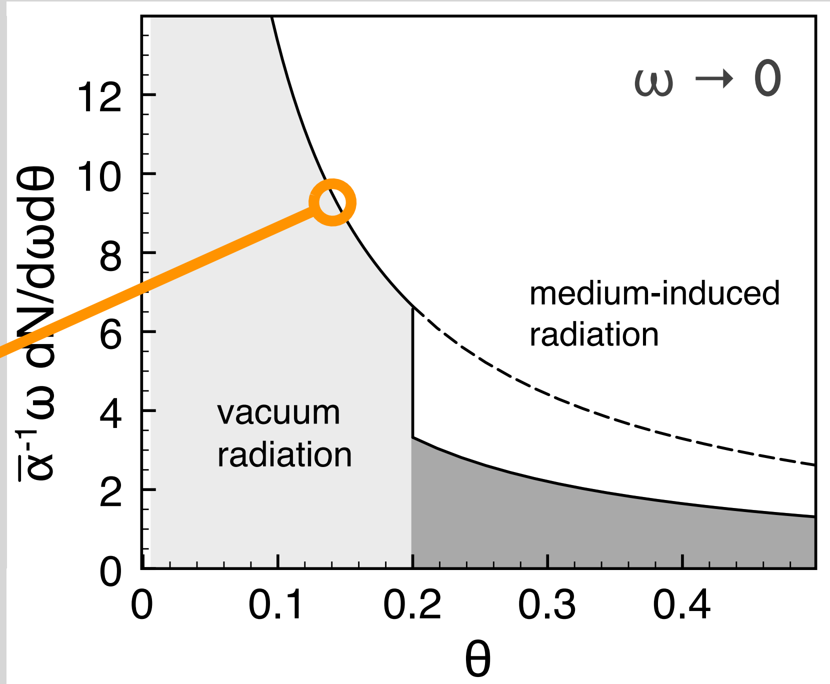
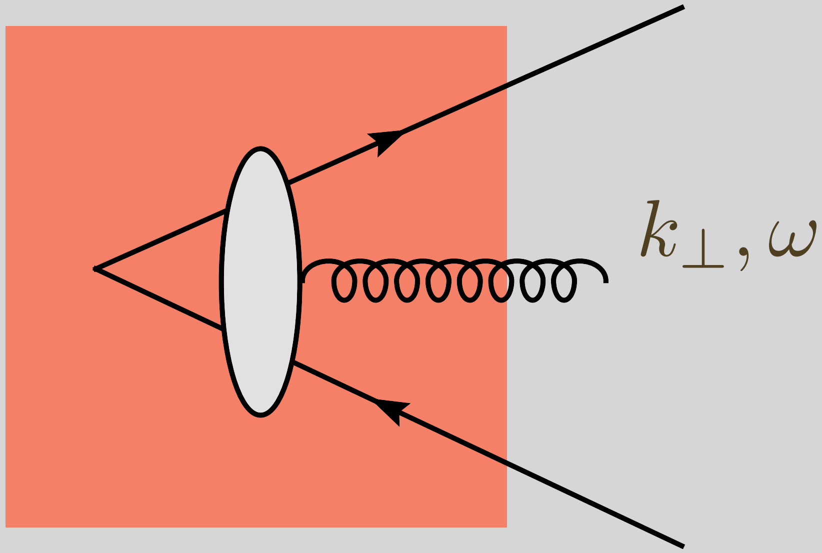
$\Delta_{\rm med} \to 0$ coherence



[de]coherence of multiple emissions



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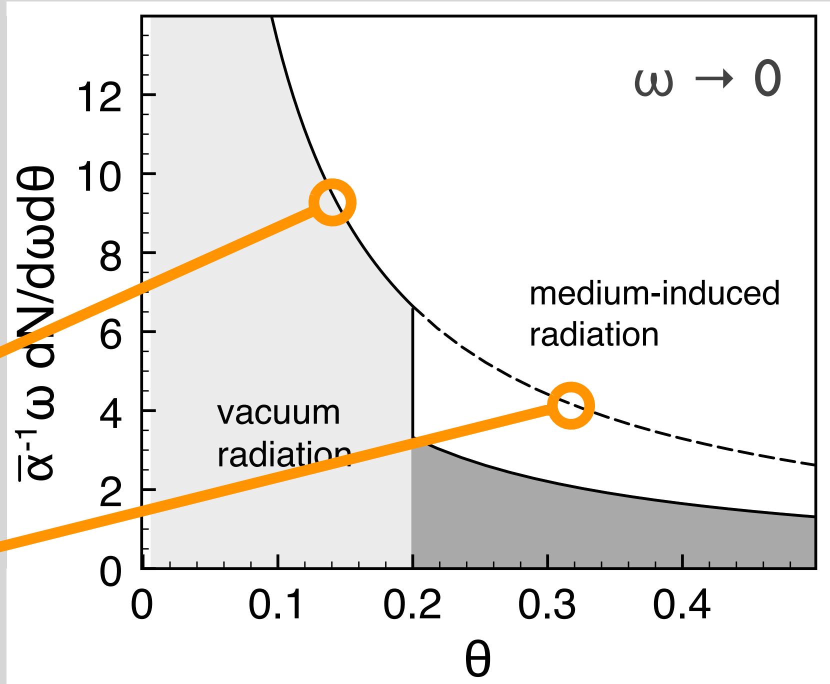
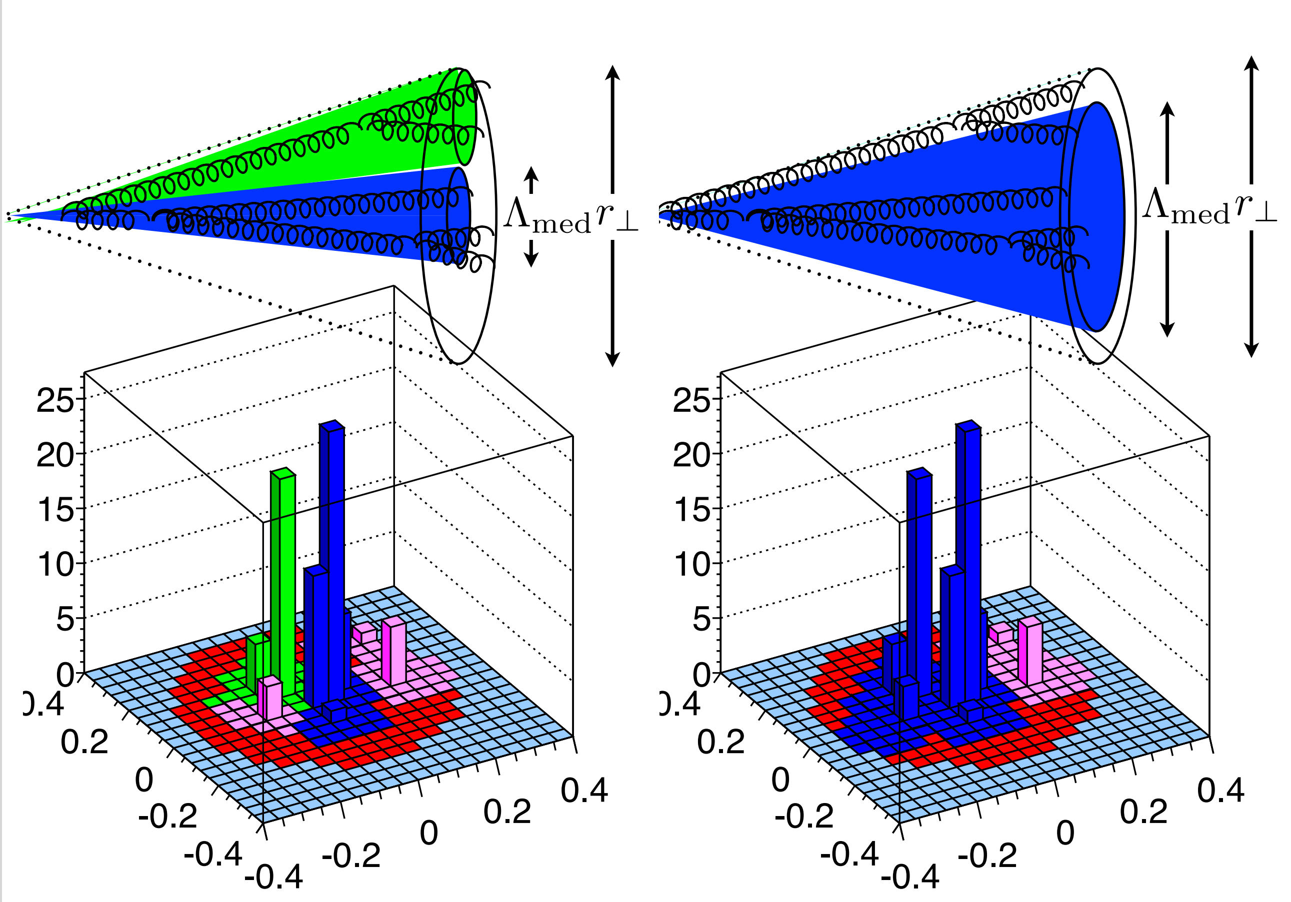
$\Delta_{med} \to 0$ coherence

$\Delta_{med} \to 1$ decoherence



from antennas to jets

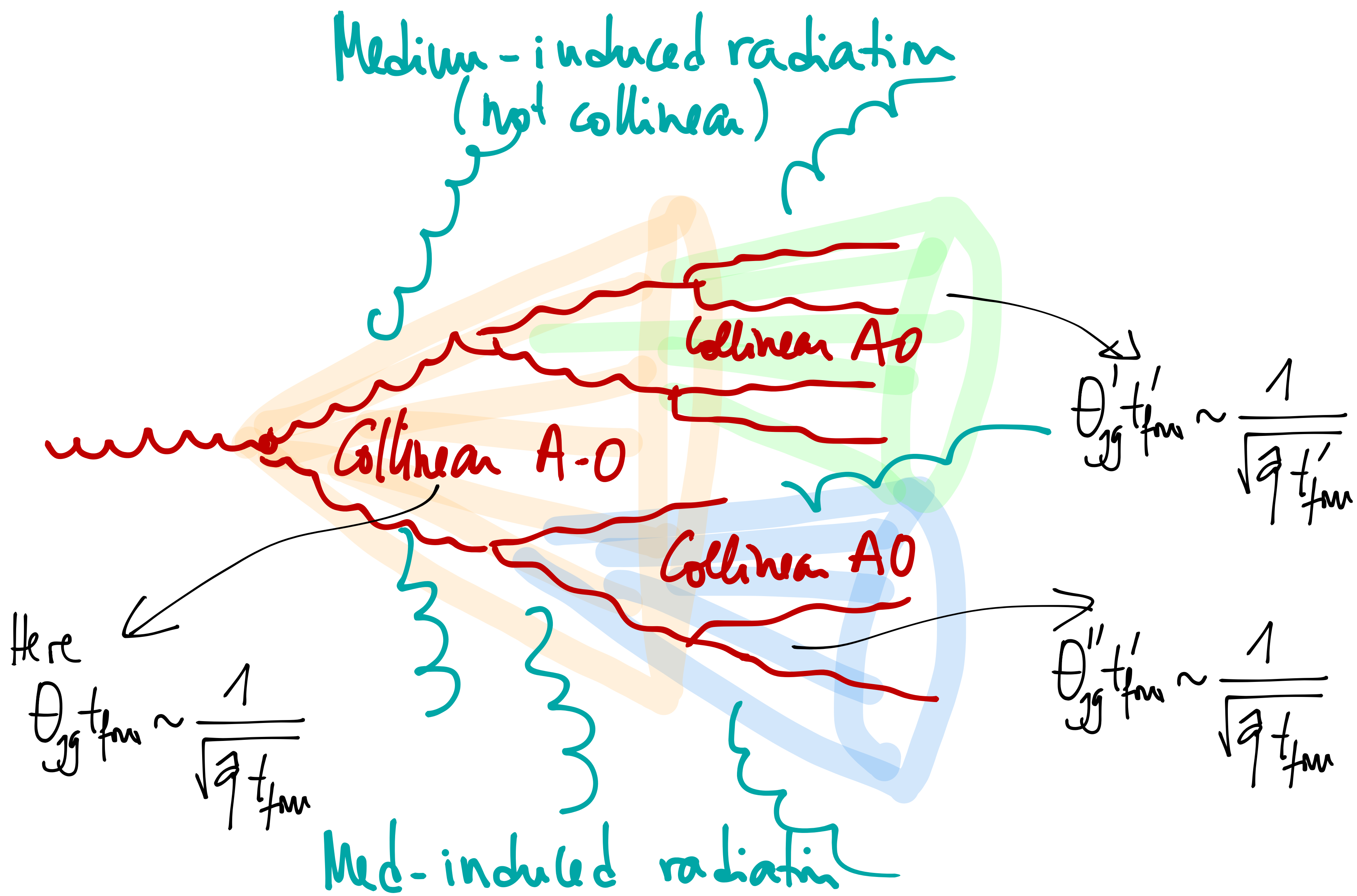
Casalderrey, Mehtar-Tani, Salgado, Tywoniuk



- $r_t < \Lambda_{med}$ :: antenna unresolved by medium :: vacuum like
- $r_t > \Lambda_{med}$ :: medium probes antenna :: strong suppression of interference :: independent radiation from each constituent

- in-medium jet dynamics driven by number of resolved charges

from antennas to jets

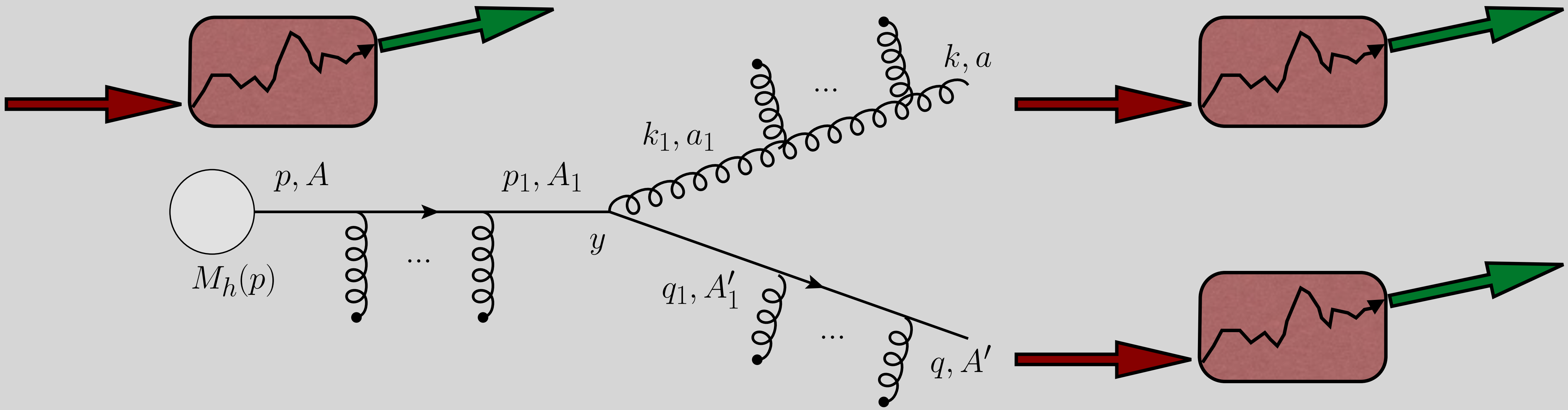


Salgado

beyond antennas [full in-medium jet calculus]

Apolinário, Armesto, Milhano, Salgado
Blaizot, Dominguez, Iancu, Mehtar-Tani

- compute in-medium splitting vertices for arbitrary momentum fraction of radiation



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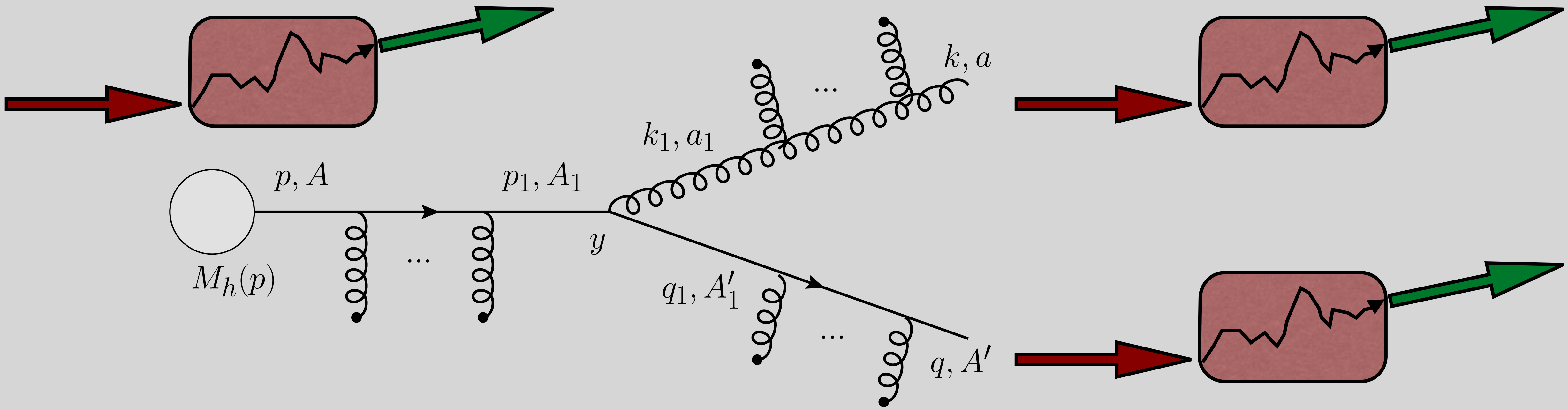

- general decoherence features survive [just more complicated]

- in short formation time limit [equivalently infinite medium] full evolution equation derived :: not valid close to medium edge

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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  - *broadening [large for very soft]*
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  - *E-p transfer to medium*

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  - E-p transfer to medium
- after medium escape
  - vacuum branching
  - hadronization of colour modified system

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  - *vacuum branching*
  - *hadronization of colour modified system*

soft components at large angles

life story of an in-medium jet

very appealing pQCD based overall picture

BUT

the QGP is strongly coupled and its collective behaviour [flows] suggestive of the non-existence of scattering centres [quasi-particles]

still, parton branching is a perturbative process

are there quasi-particles ?

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

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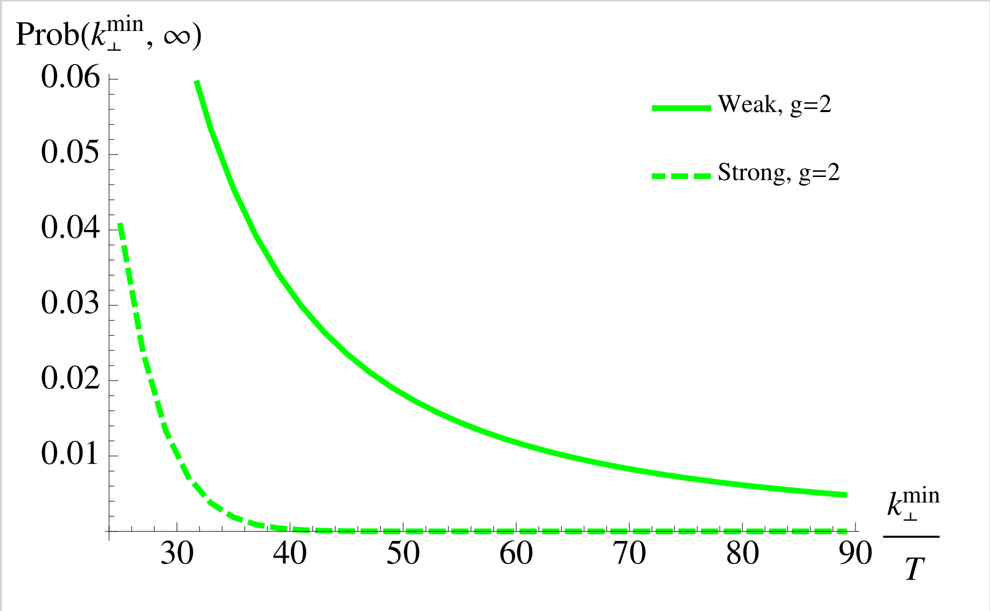
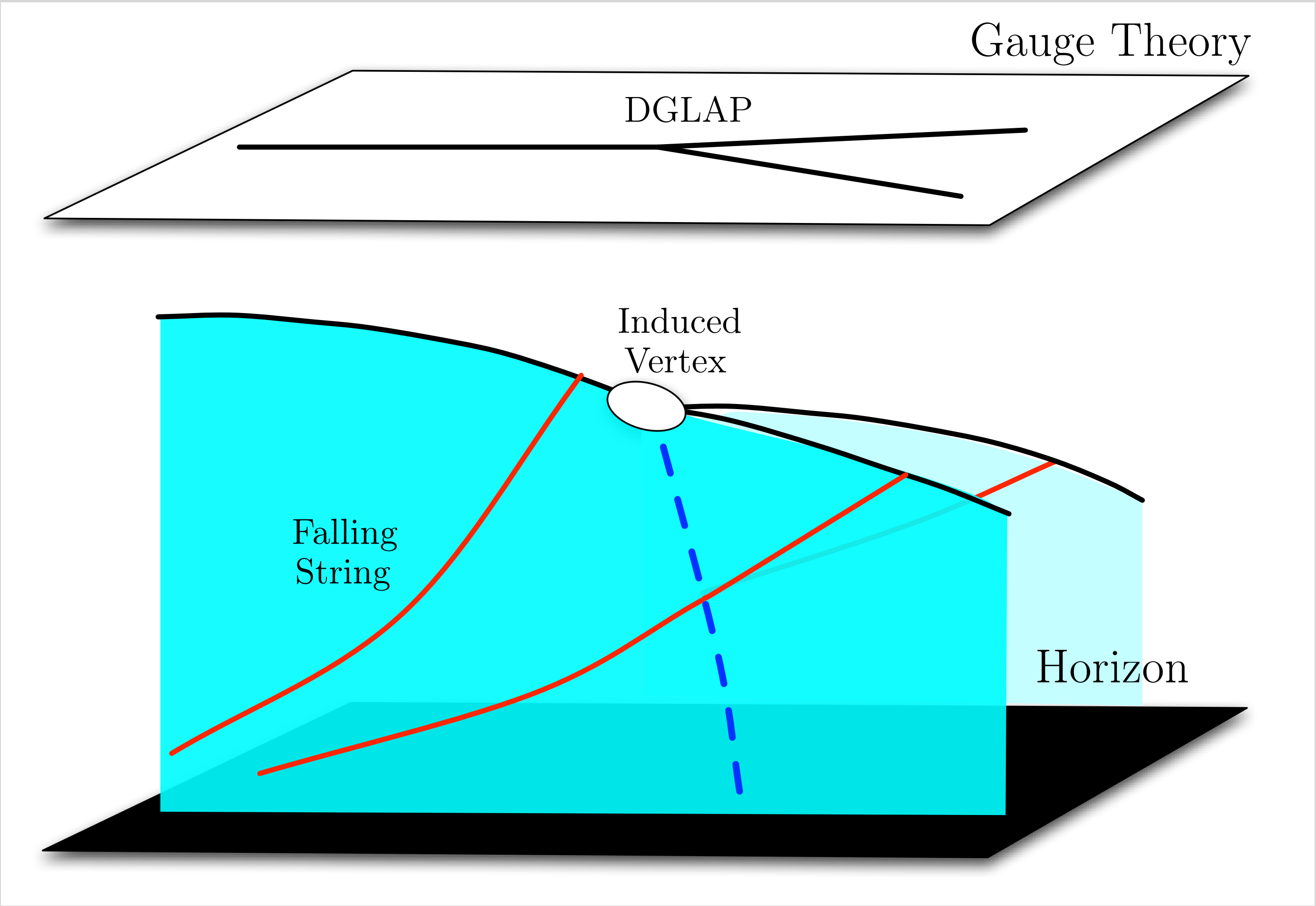
- probability of large broadening larger for pQCD [$\sim 1/k_t^4$] than for strong coupled [gaussian]
  - ⟶ rare, yet unmeasured, but measurable events



Eramo, Lekaveckas, Liu, Rajagopal [1211.1922]

hybrid strong/weak coupling model

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



$$\left.\frac{dE}{dx}\right|_{\text{strongly coupled}} = -\frac{4}{\pi} E_{\text{in}} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}, \qquad x_{\text{stop}} = \frac{1}{2\kappa_{\text{sc}}} \frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

single free parameter
[accounts for QCD/N=4 SYM differences]

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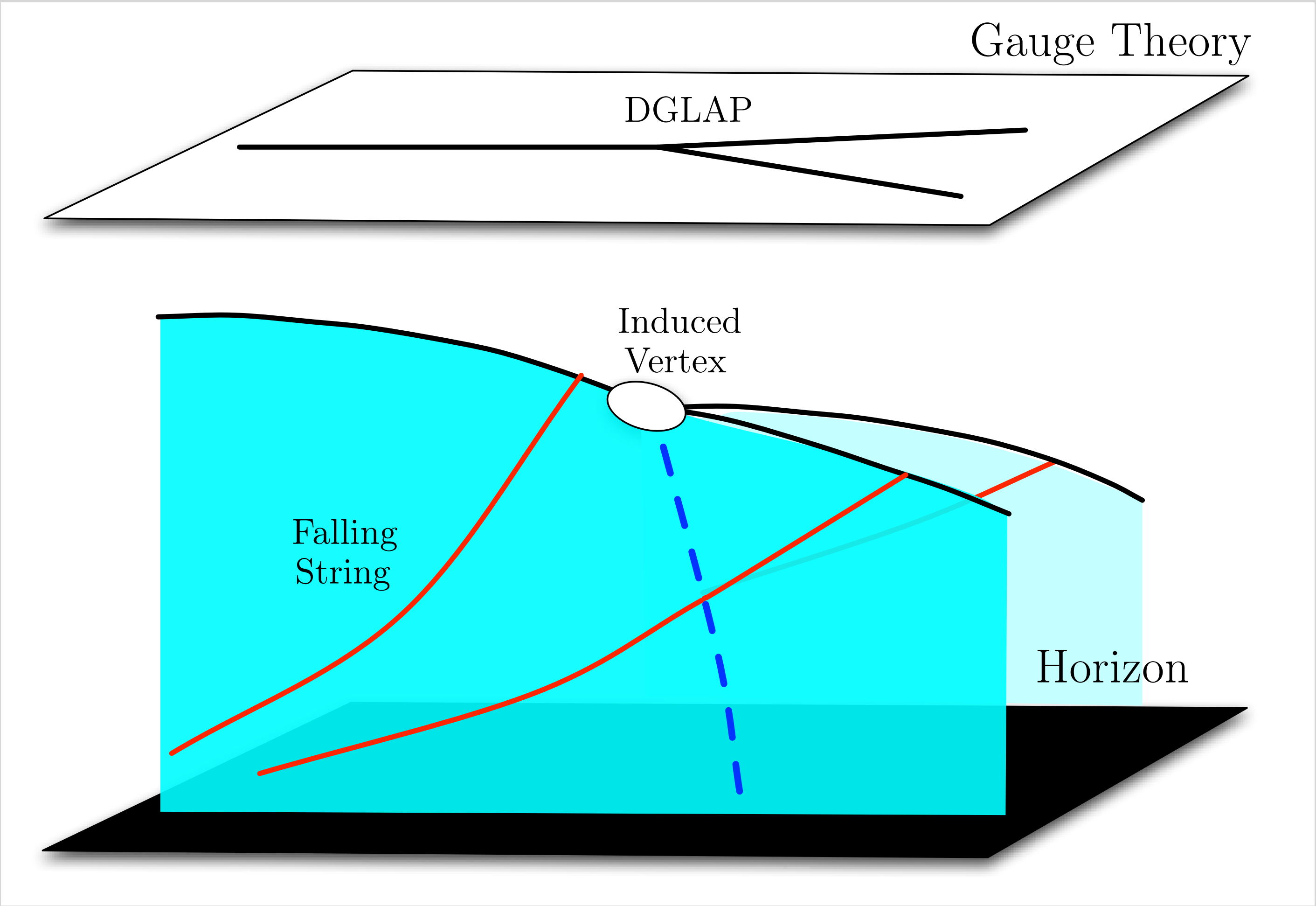

- vacuum jets [no medium induced radiation] where each parton loses energy non-perturbatively [as given by a holographic AdS-CFT calculation]

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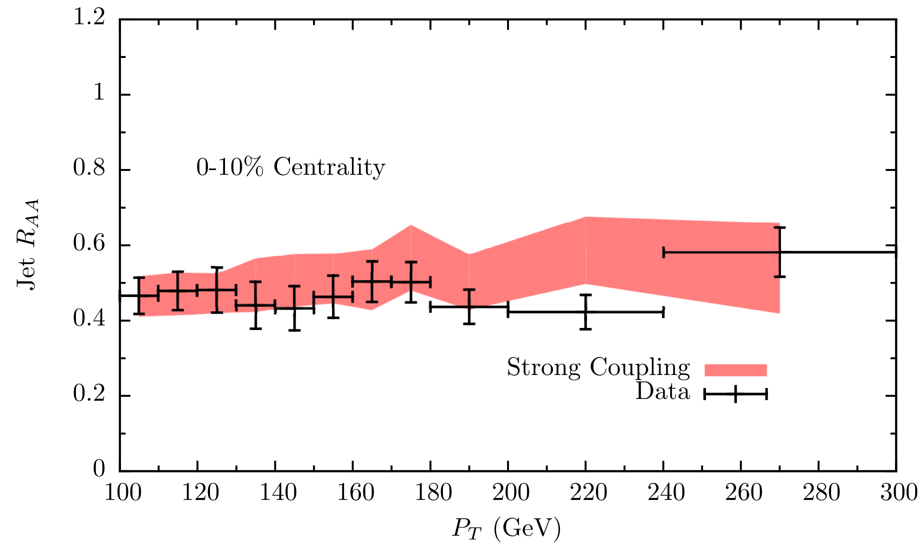
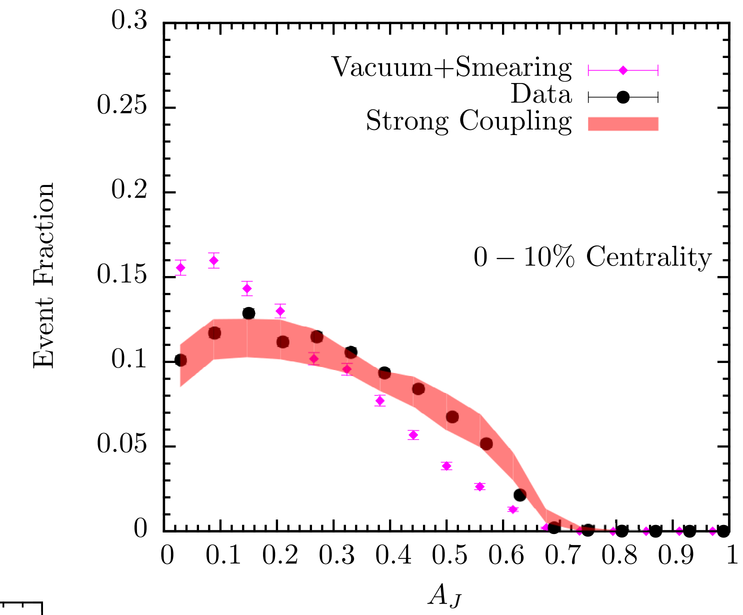
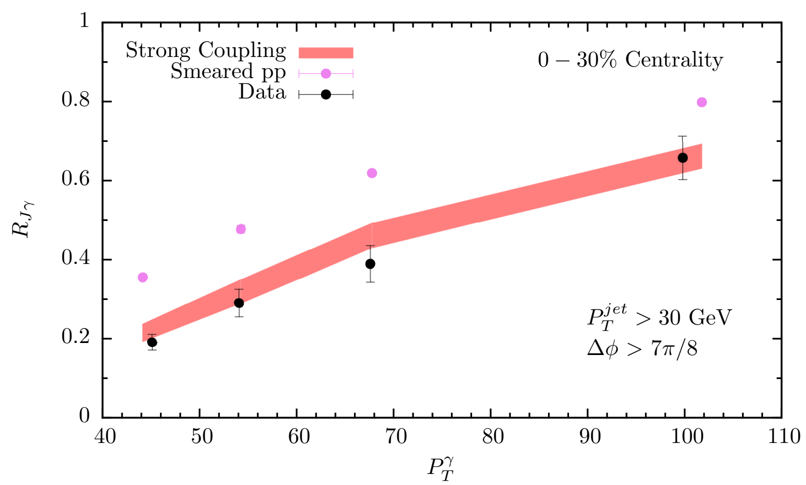




5 observables
and centrality dependence
all described with
single parameter

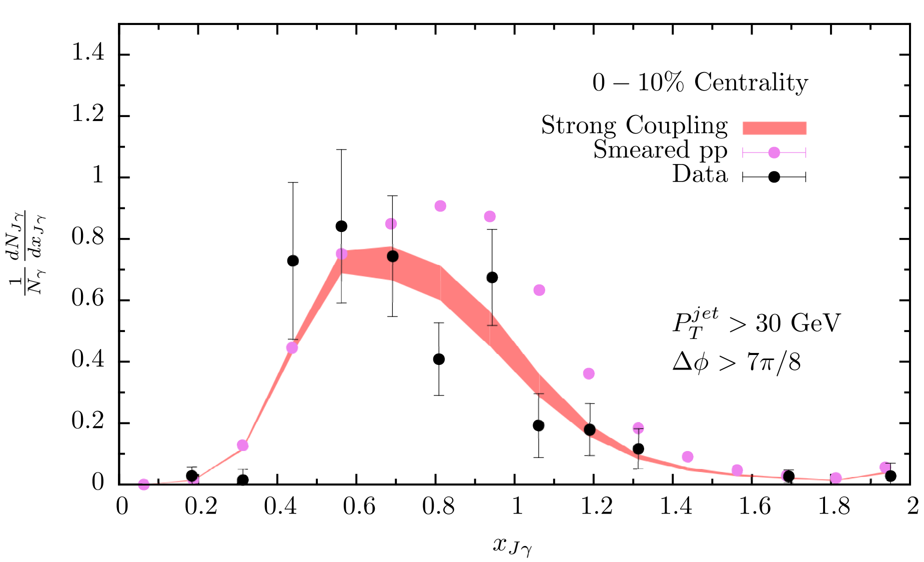


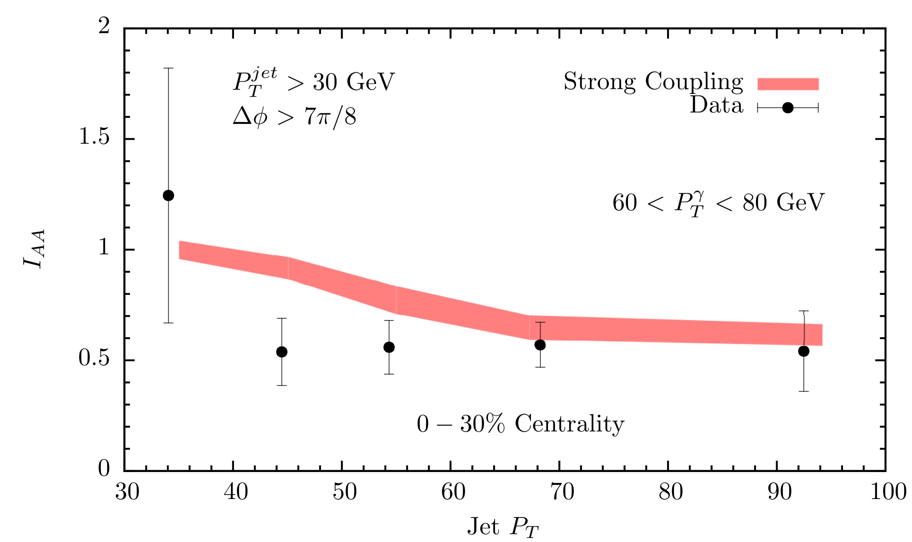
Bands in all plots correspond to

$$0.32 < \kappa_{sc} < 0.41$$

$\mathcal{O}(1)$ as expected.

$$x_{stop}^{QCD} \sim (2-3) x_{stop}^{\mathcal{N}=4}$$

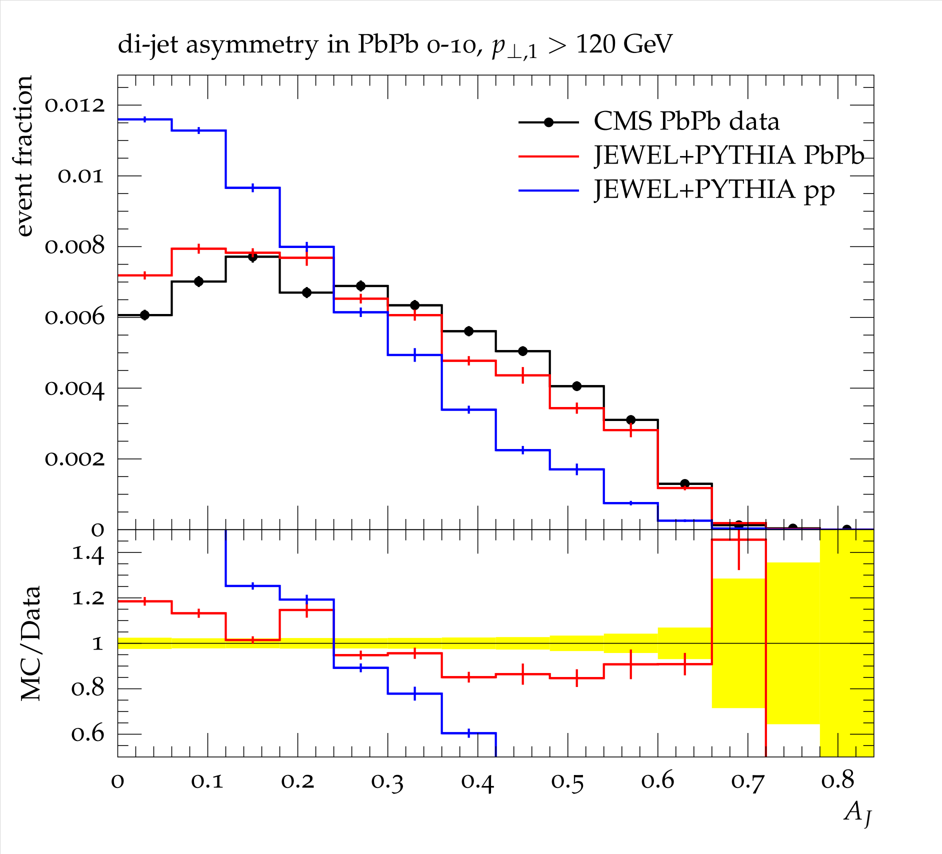


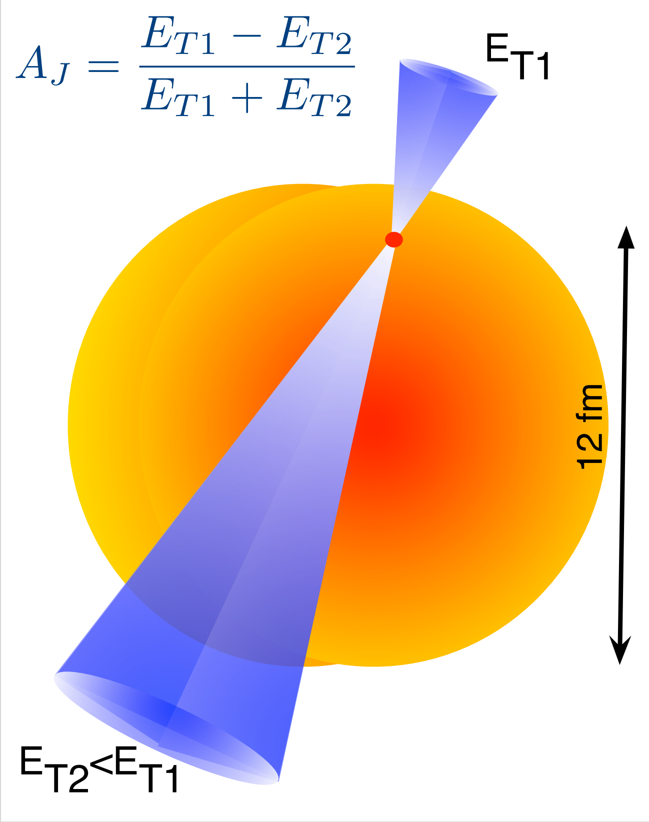


understanding sensitivity
[a non-trivial example towards a new era]

dijet asymmetry

Milhano, Zapp

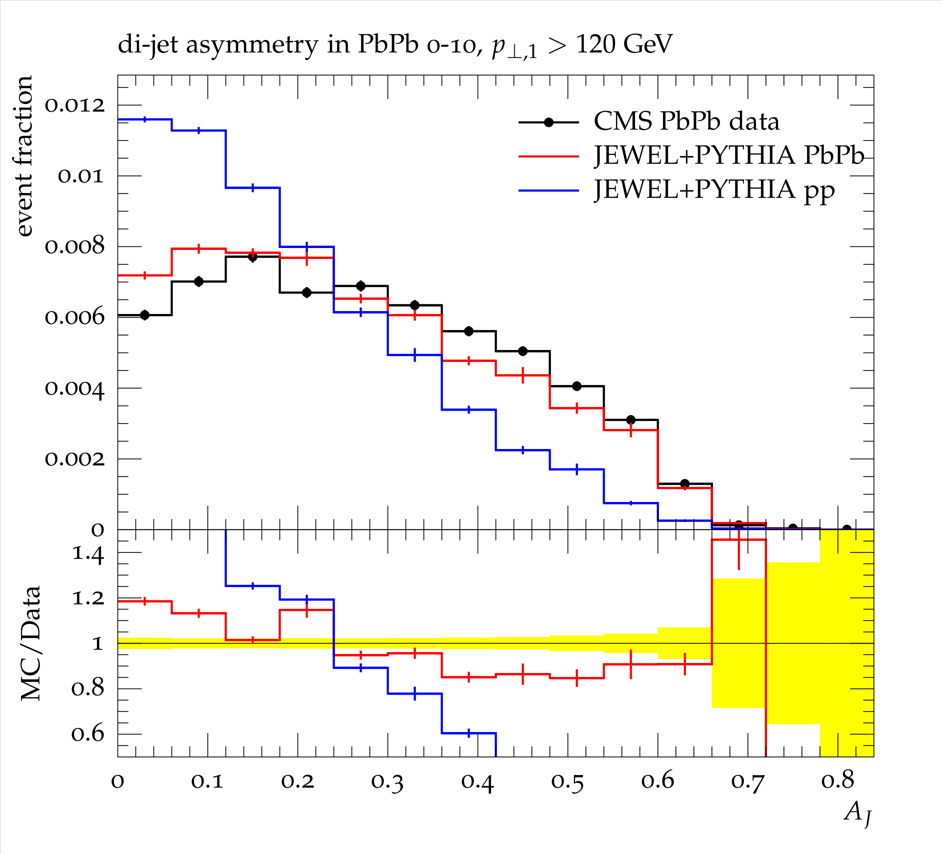




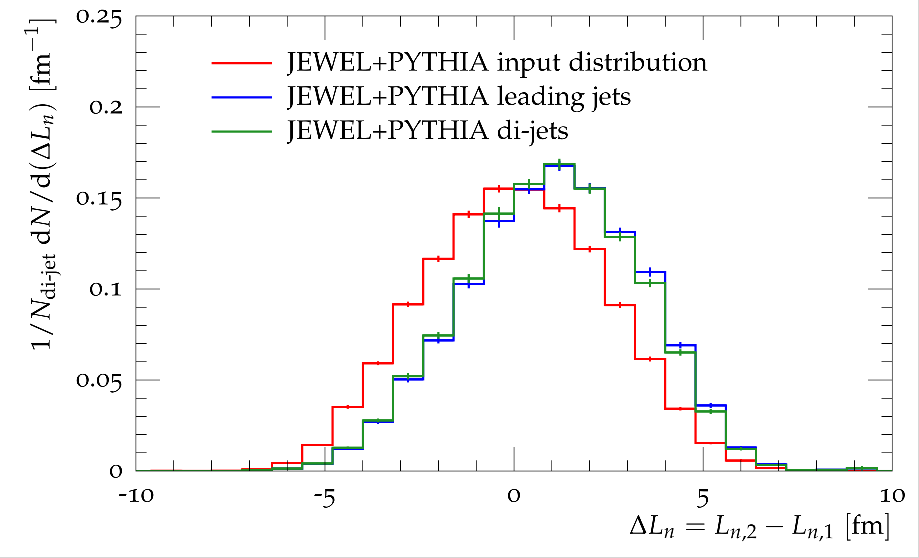
imbalance of jet energy within a cone of radius R for 'back-to-back' di-jets

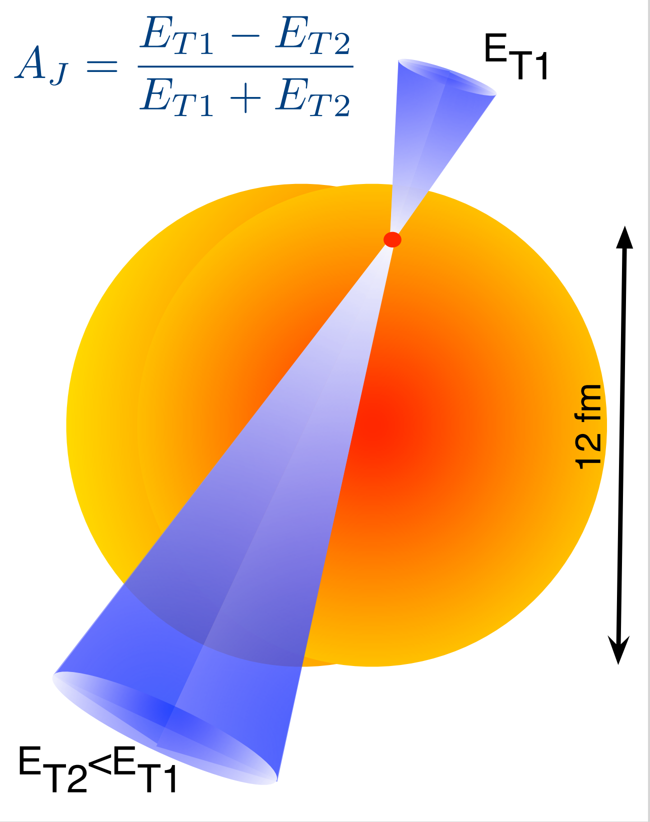
dijet asymmetry

Milhano, Zapp



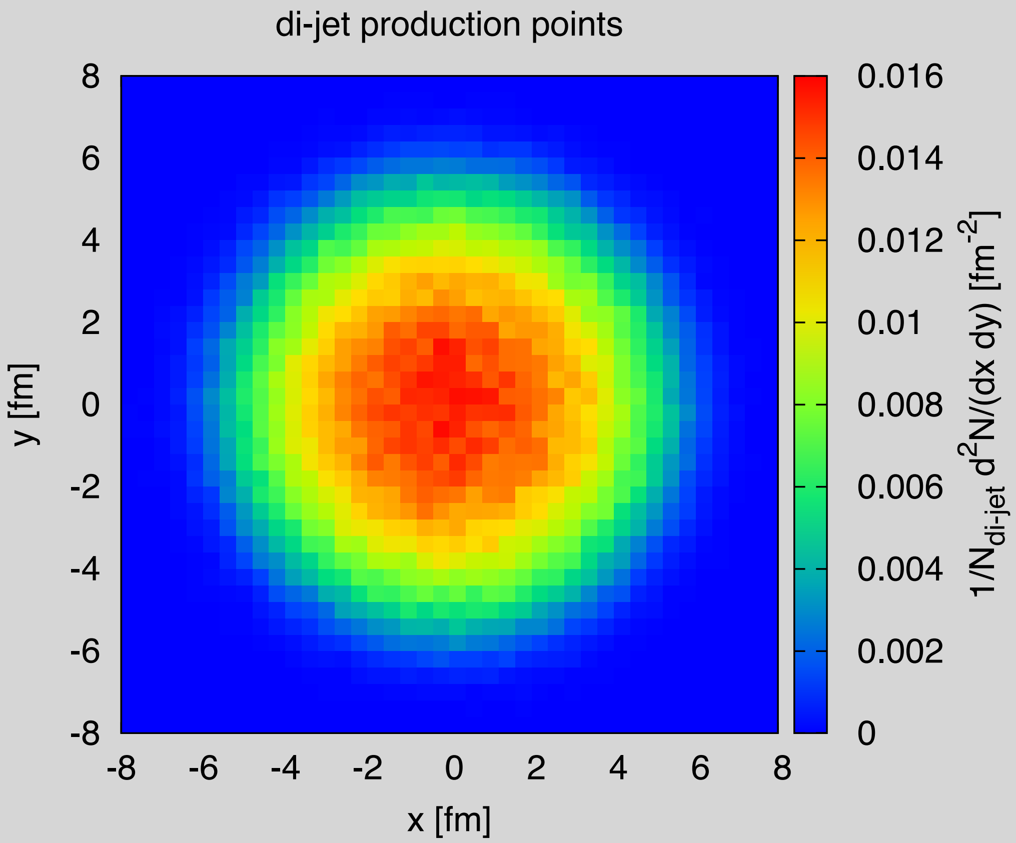
- most naive guess :: medium-induced asymmetry is sensitive to difference in traversed QGP by leading and recoiling jets





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

a sanity check



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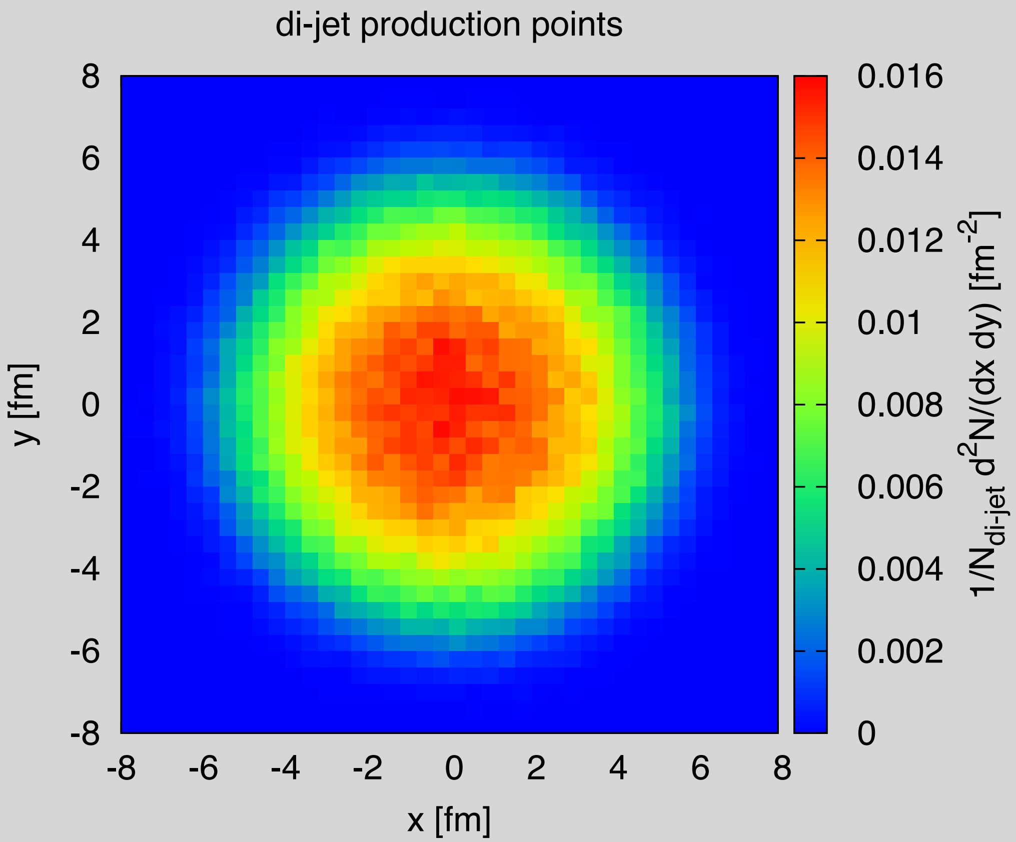
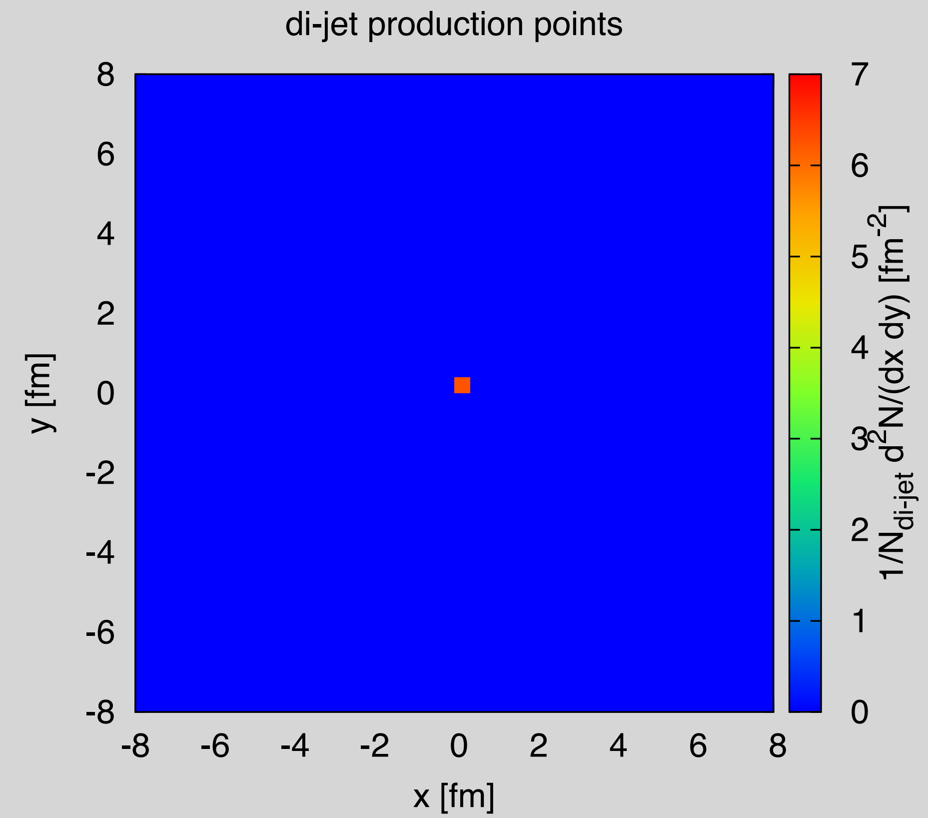
Milhano, Zapp





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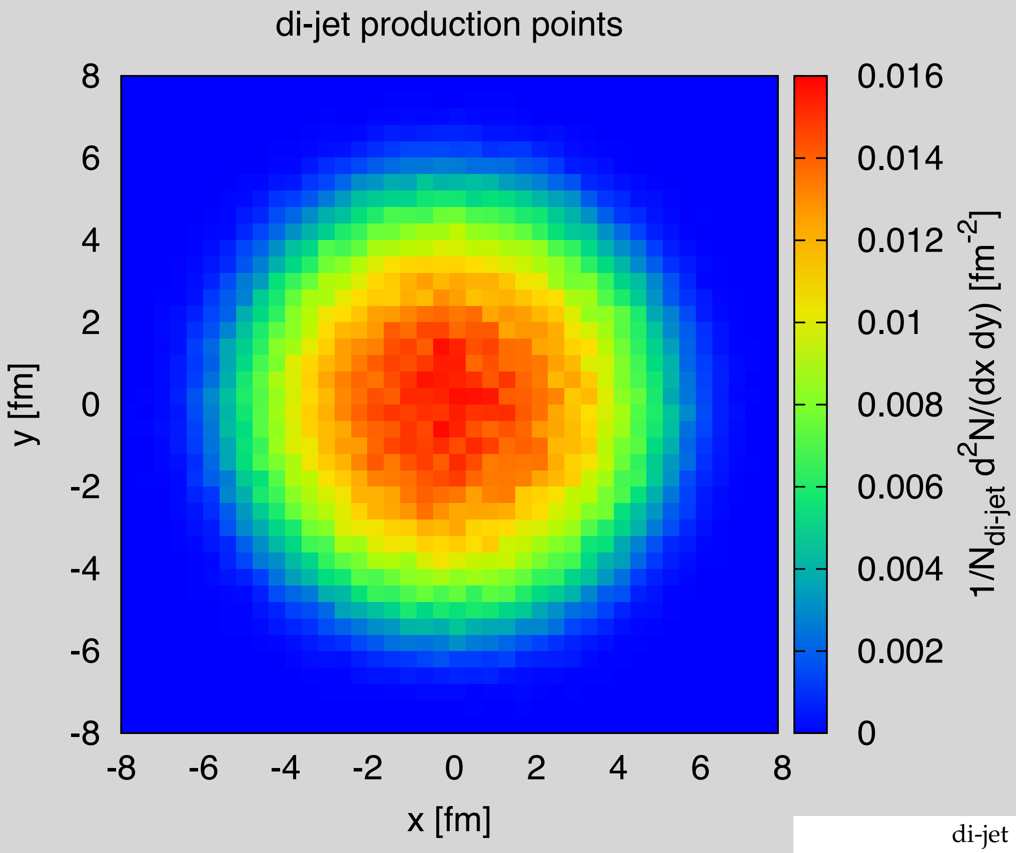

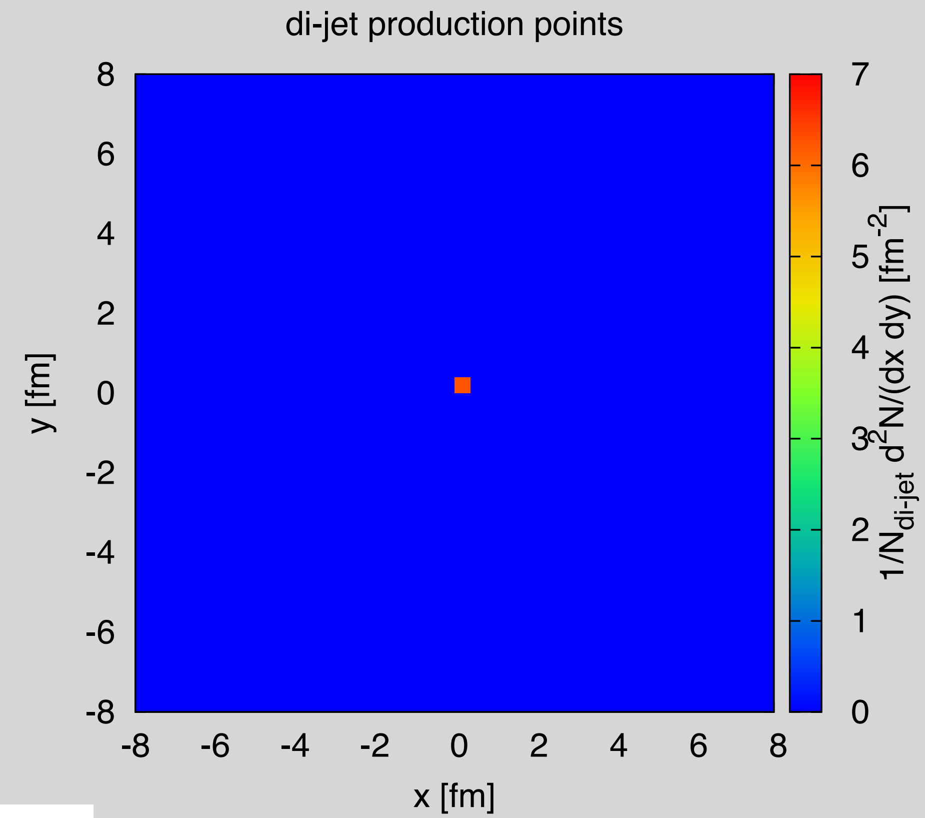

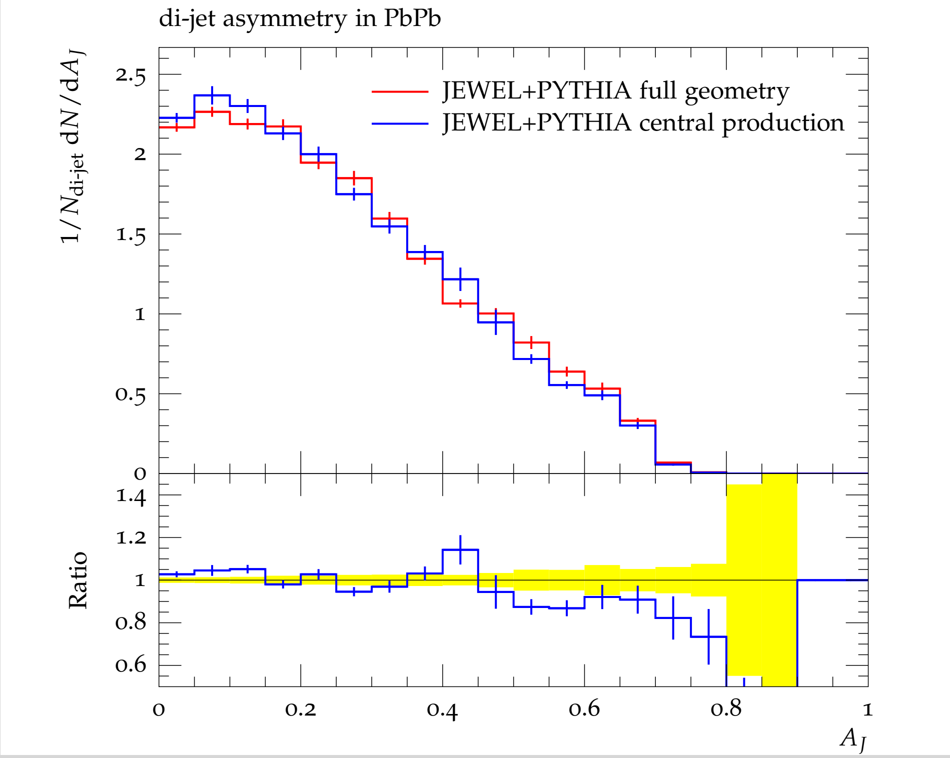

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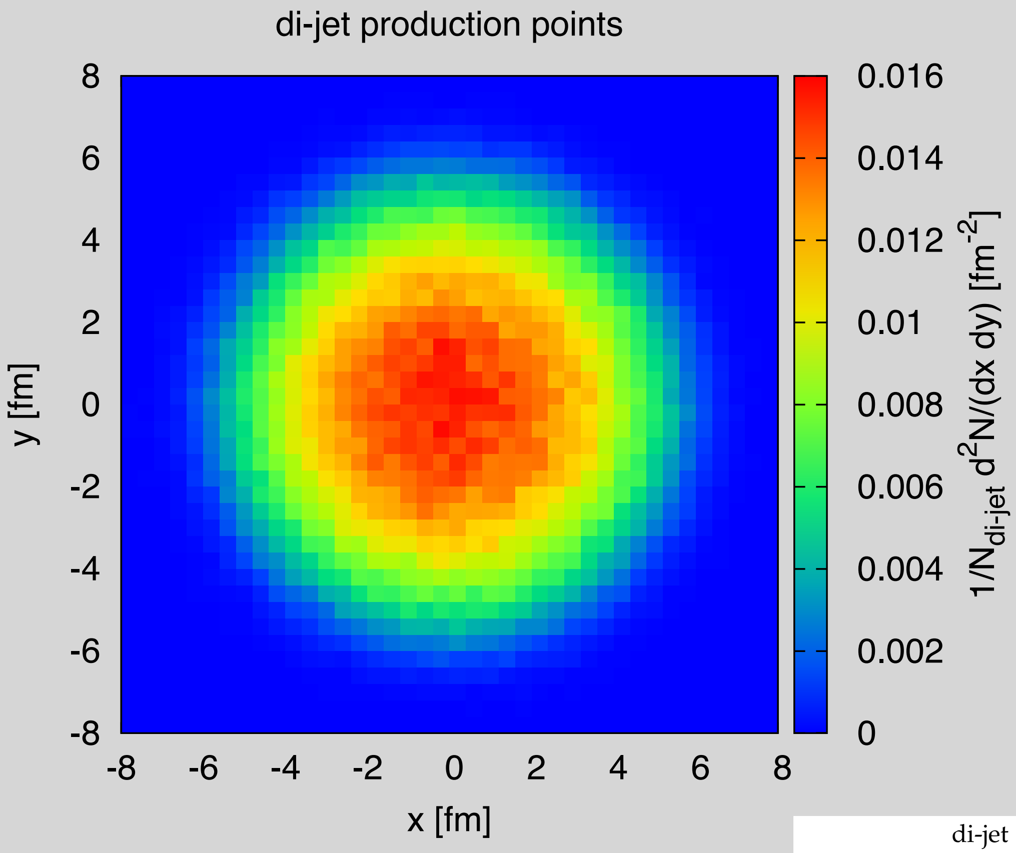
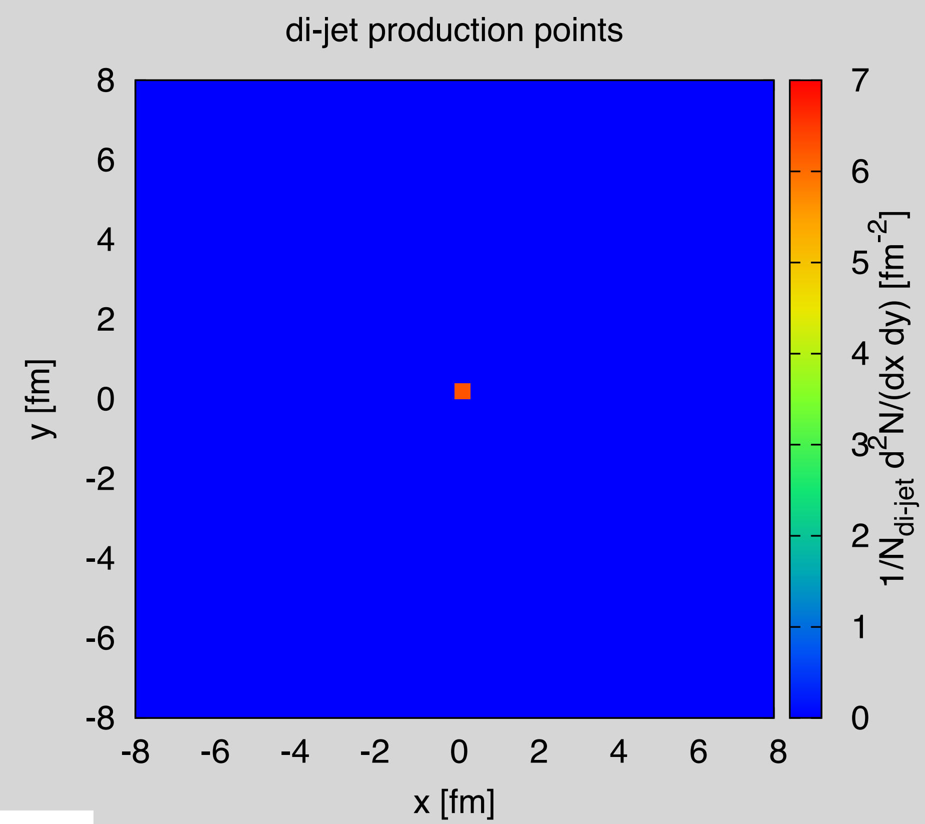
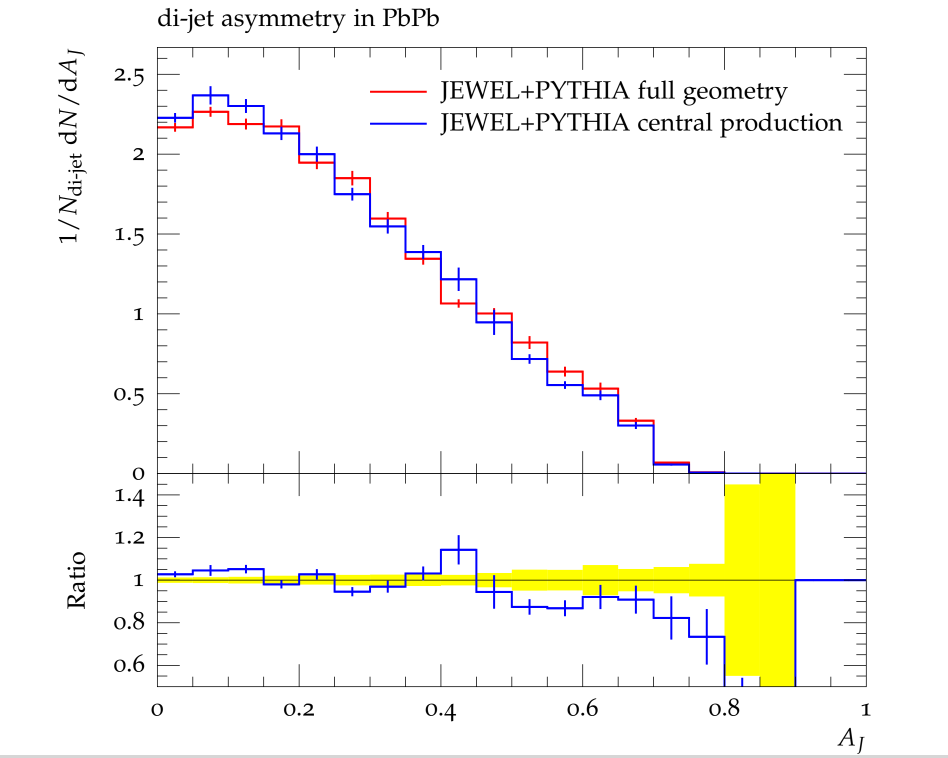
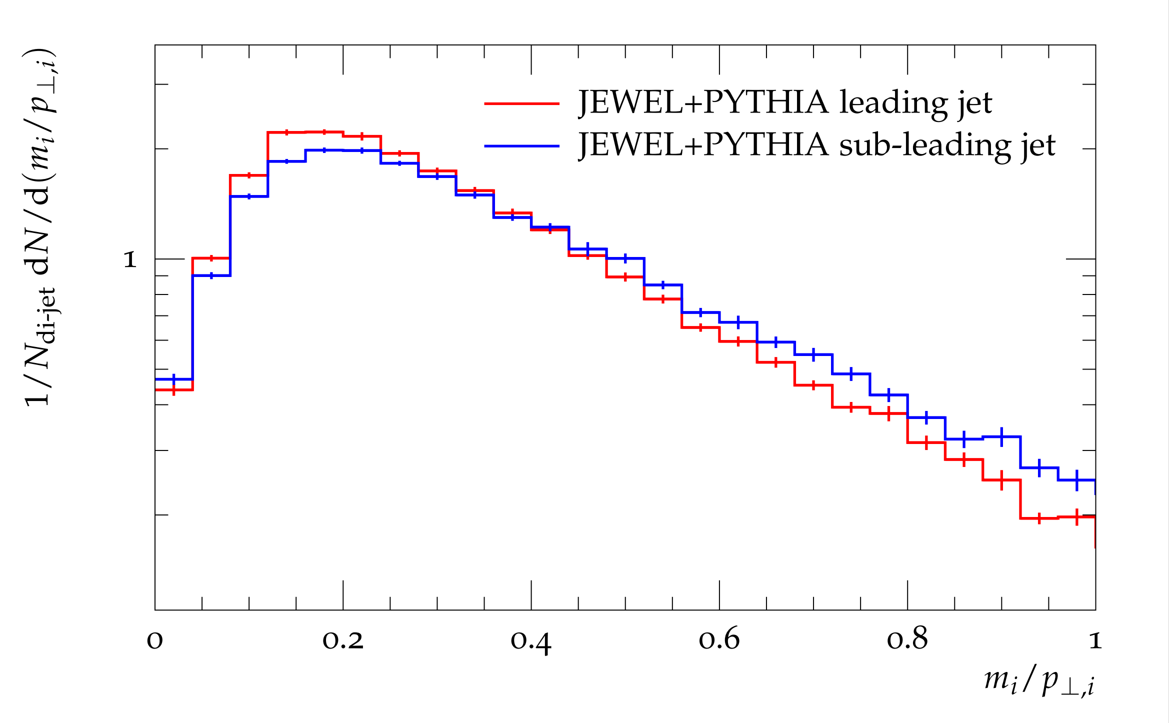


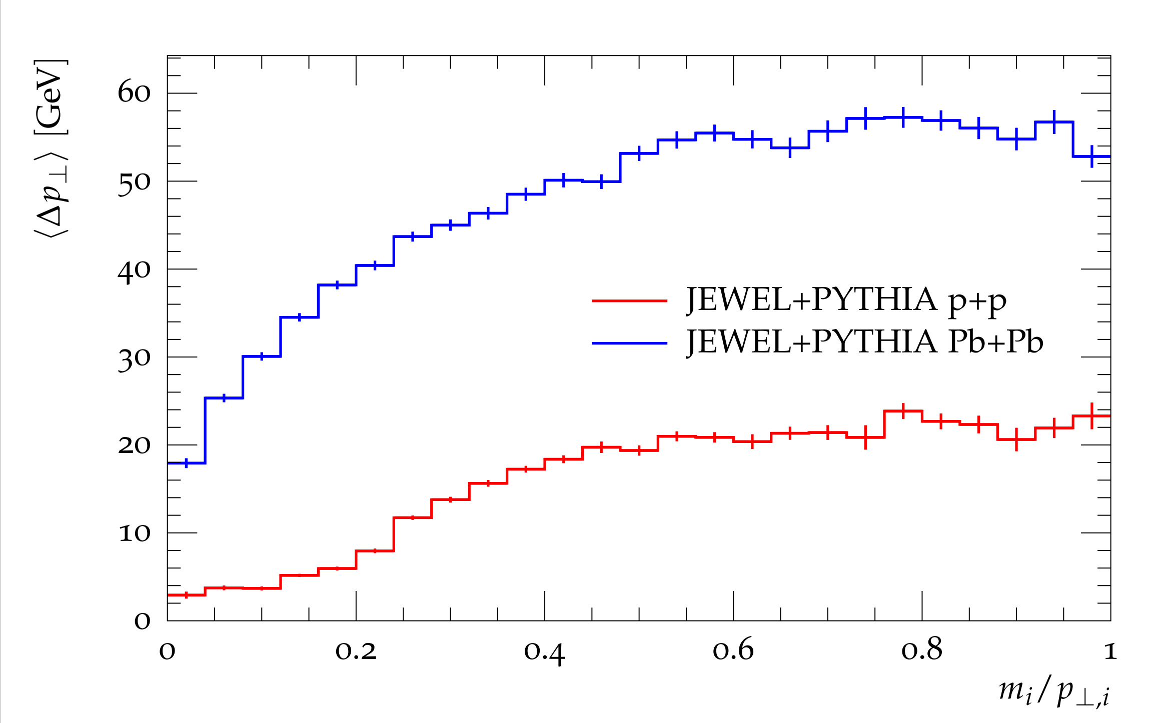




asymmetry is not driven by path-length differences

what then?





- asymmetry is driven by fragmentation fluctuations [how many constituents in a jet] which are mostly due to vacuum-like fragmenation

- direct sensitivity to ‘number of emitters’
  - much more interesting than the naive guess

outlook

- *in just over ten years jet studies in heavy ion collisions have gone from 'an idea' to a robust experimental reality*
- *recent efforts have established a clear pathway to reliably compute jet dynamics in QGP*

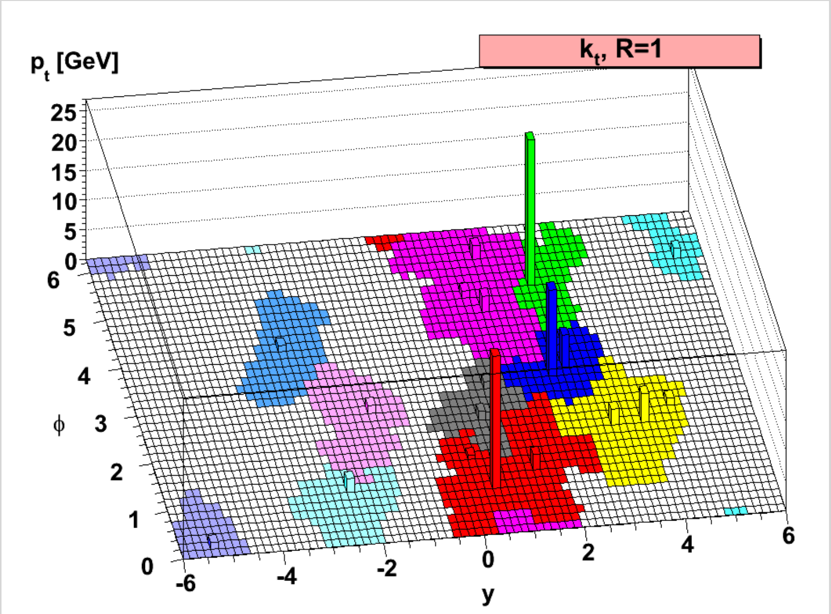
- *detailed probing programme in its beginnings*
  - *time to think hard about 'new' observables [measurable and calculable]*
  - *direct sensitivity to formation times*
  - *sensitivity to different time and spacial scales*
  - *isolation of 'pure' sample of strongly modified jets where*

backups

jets in vacuum [recombination algorithms]

$$d_{ij} = \min\left(p_{ti}^{2p}, p_{tj}^{2p}\right) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

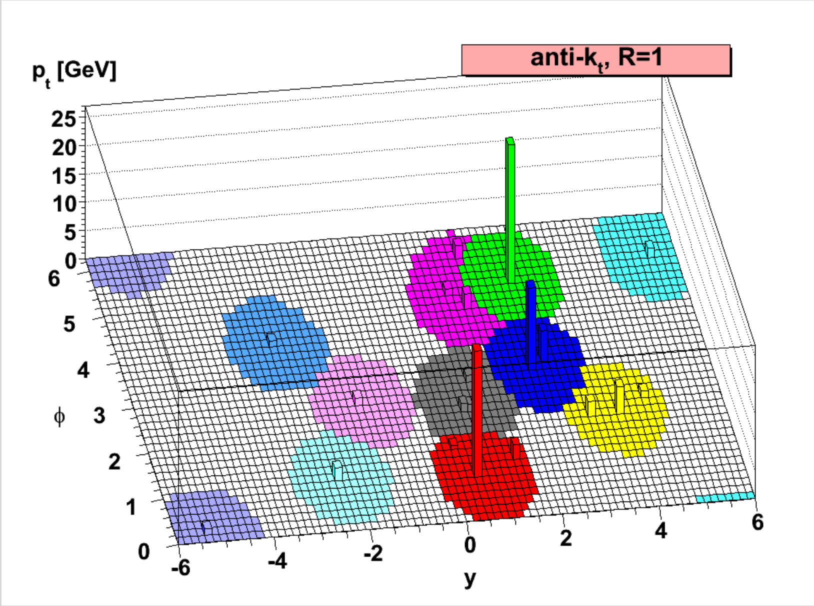


p = 1

:: k_t [from soft to hard] ::

:: preserves information on shower structure ::

Cacciari, Salam, Soyez [0802.1189]



p = -1

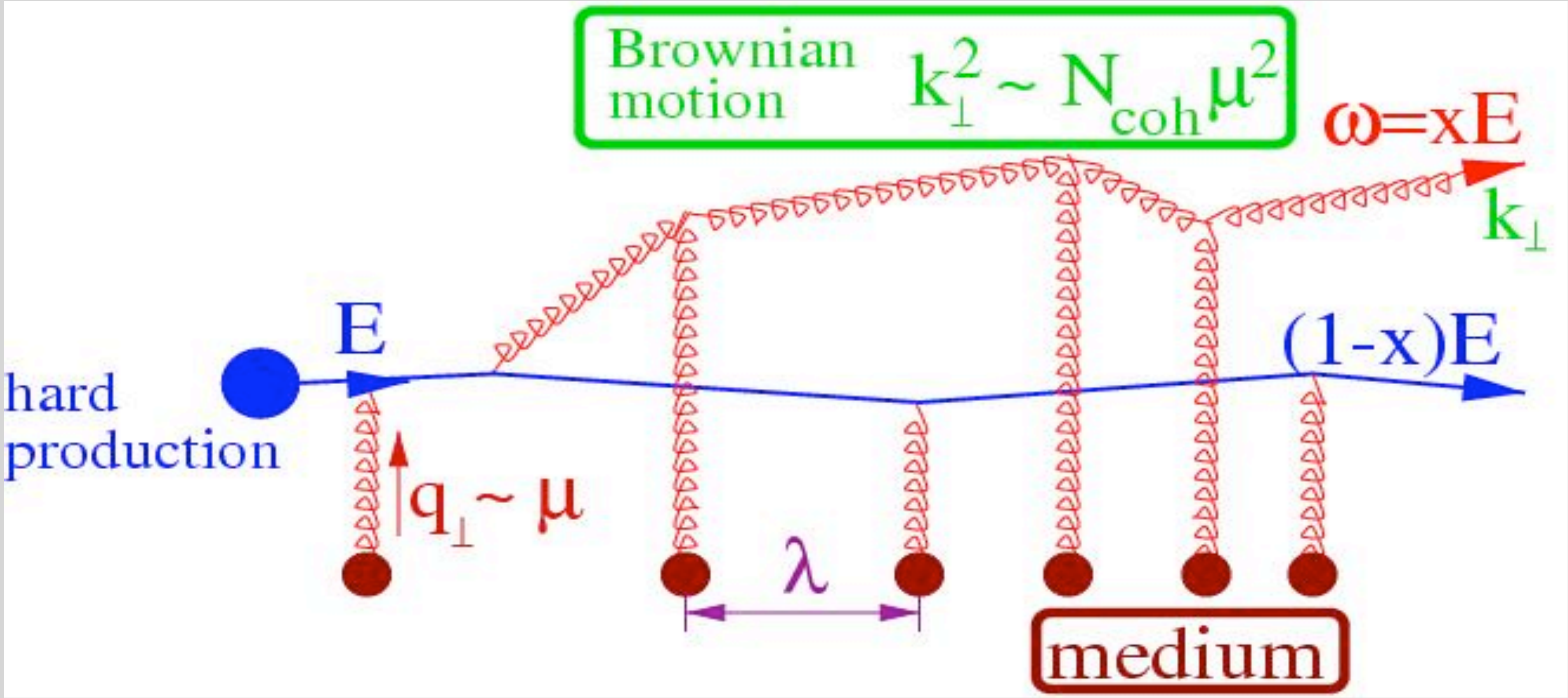
:: anti-k_t [from hard to soft] ::

:: robustness in large background situations ::

additional handle [yet to be explored in heavy ions]

:: different jet definitions [recombination sequence] yield different jet populations

single emission [BDMPS-Z]



$$\hat{q}(t) \equiv \alpha_s n(t) \int_{|\boldsymbol{q}|<q^*} d\boldsymbol{q}^2 \; \boldsymbol{q}^2 \gamma(\boldsymbol{q}^2)$$

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

medium induced radiation

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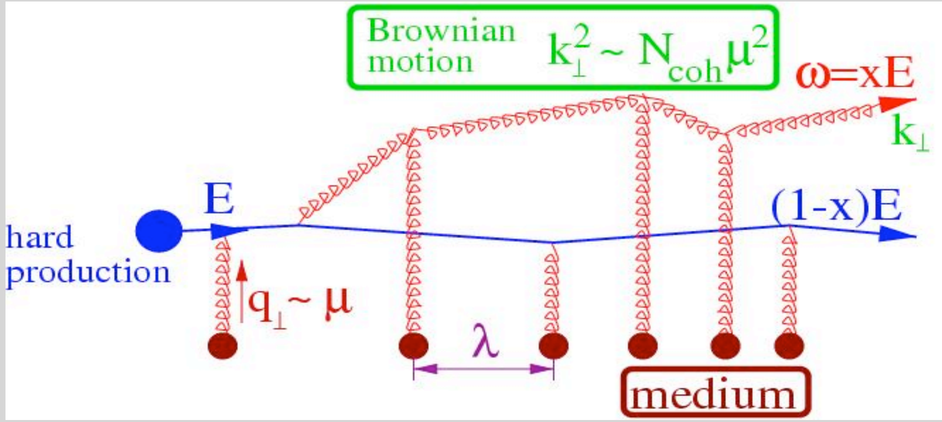
- Monte Carlo implementations [HIJING, Q-PYTHIA/Q-HERWIG, JEWELL, YaJEM, MARTINI]

single emission [BDMPS-Z]



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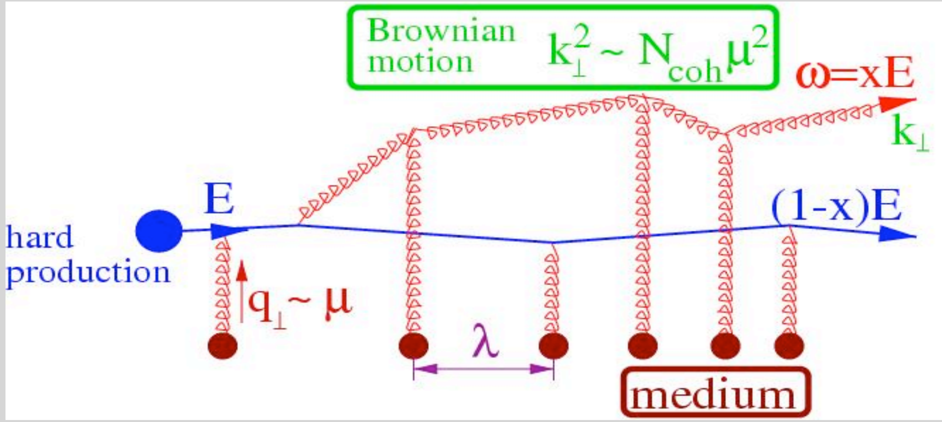
single emission [BDMPS-Z]

- Brownian motion

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



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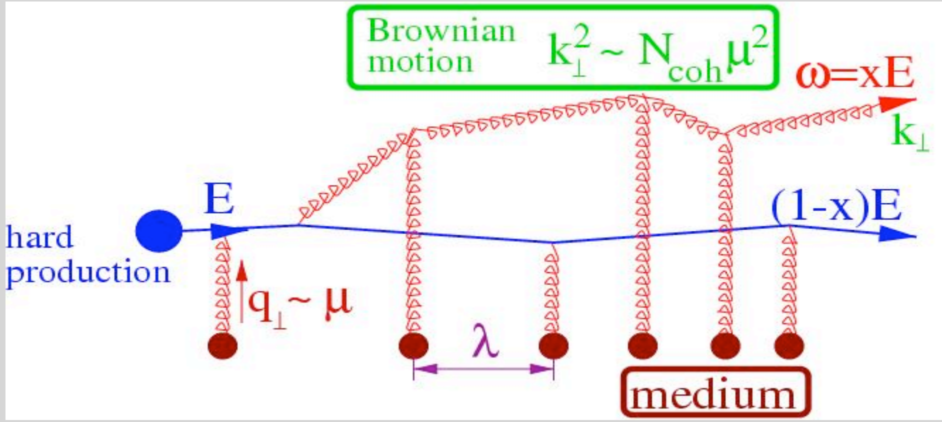

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ω_c → characteristic gluon energy

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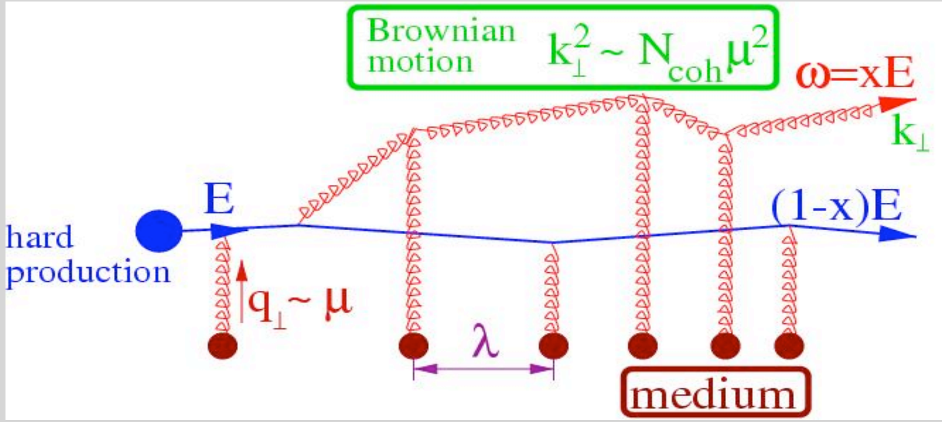

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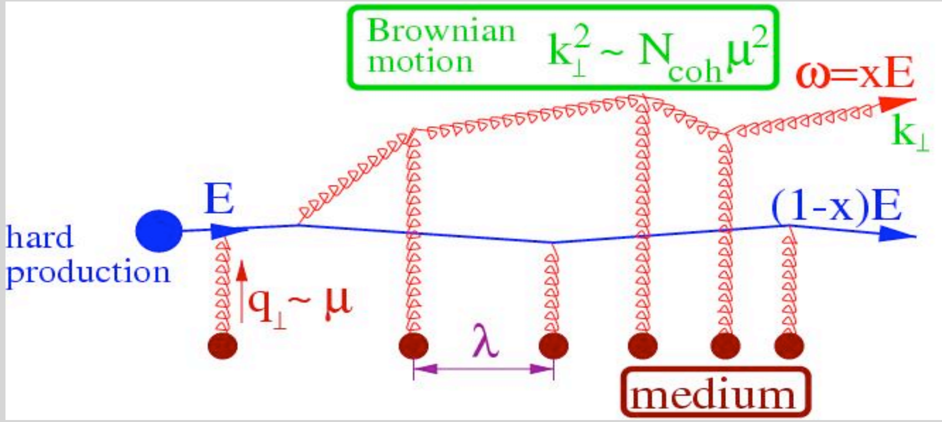
$$k_\perp^2 \sim \hat{q}\, t_{coh}$$

- number of coherent scatterings

$$N_{coh} \sim \frac{t_{coh}}{\lambda}$$

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

single emission [BDMPS-Z]



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- gluon energy distribution

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

ω → non-abelian LPM

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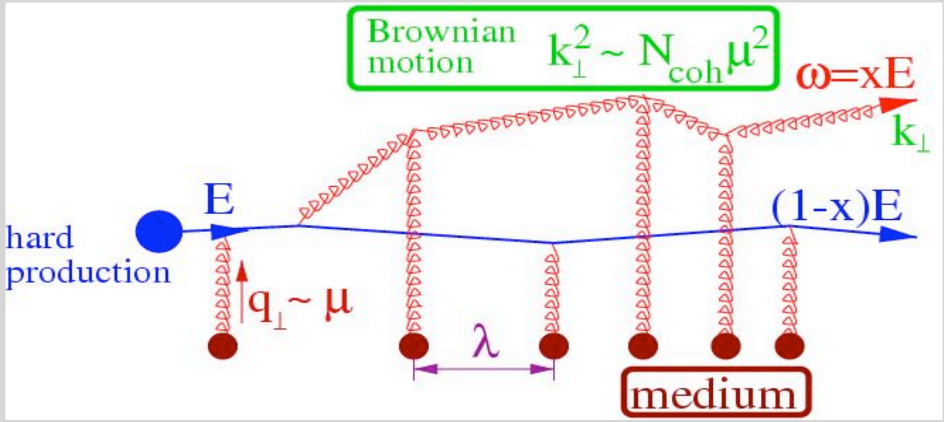

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- average energy loss

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

beyond back the envelope [path-integral]

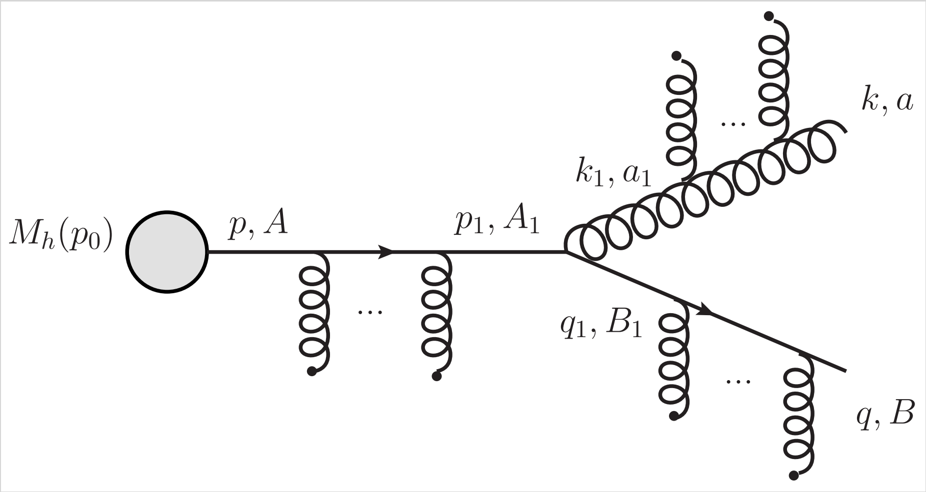
- eikonal trajectory of parton propagating in medium

$$W_{\alpha_f\alpha_i}(x_{f+},x_{i+};\mathbf{r}(\xi)) = \mathcal{P}\exp\left\{ig\int_{x_{i+}}^{x_{f+}} d\xi A_-(\xi,\mathbf{r}(\xi))\right\}$$

- off[but close to]-eikonal trajectory

$$G_{\alpha_f\alpha_i}(x_{f+},\mathbf{x}_f;x_{i+},\mathbf{x}_i|p_+) = \int_{\mathbf{r}(x_{i+})=\mathbf{x}_i}^{\mathbf{r}(x_{f+})=\mathbf{x}_f} \mathcal{D}\mathbf{r}(\xi)\exp\left\{\frac{ip_+}{2}\int_{x_{i+}}^{x_{f+}} d\xi\left(\frac{d\mathbf{r}}{d\xi}\right)^2\right\} W_{\alpha_f\alpha_i}(x_{f+},x_{i+};\mathbf{r}(\xi))$$

- observables computed from medium averages of Gs [from medium field 2-pt correlators]



- BDMPS: quark eikonal, gluon soft and [slightly] off-eikonal

large broadening [a lesson from data]

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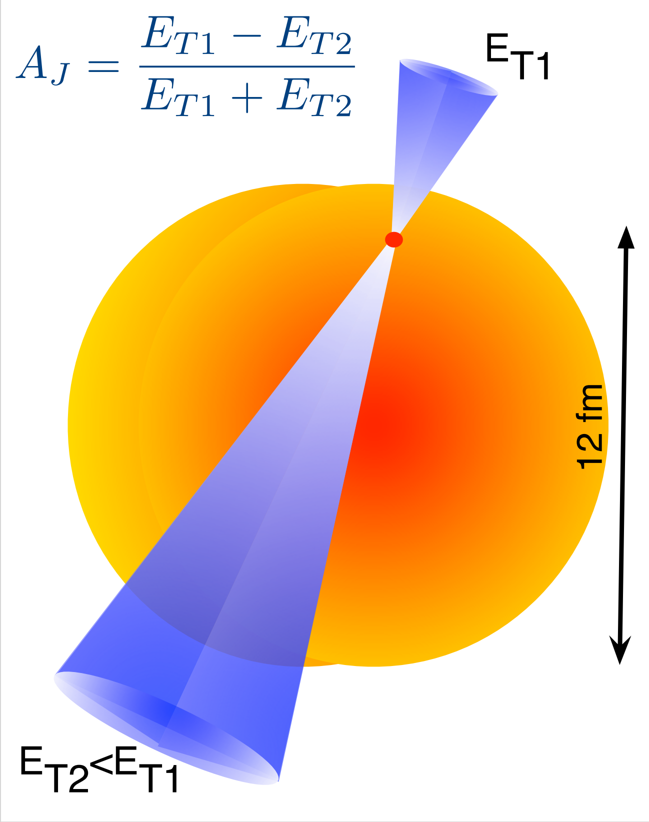
imbalance of jet energy within a cone of radius R for 'back-to-back' di-jets



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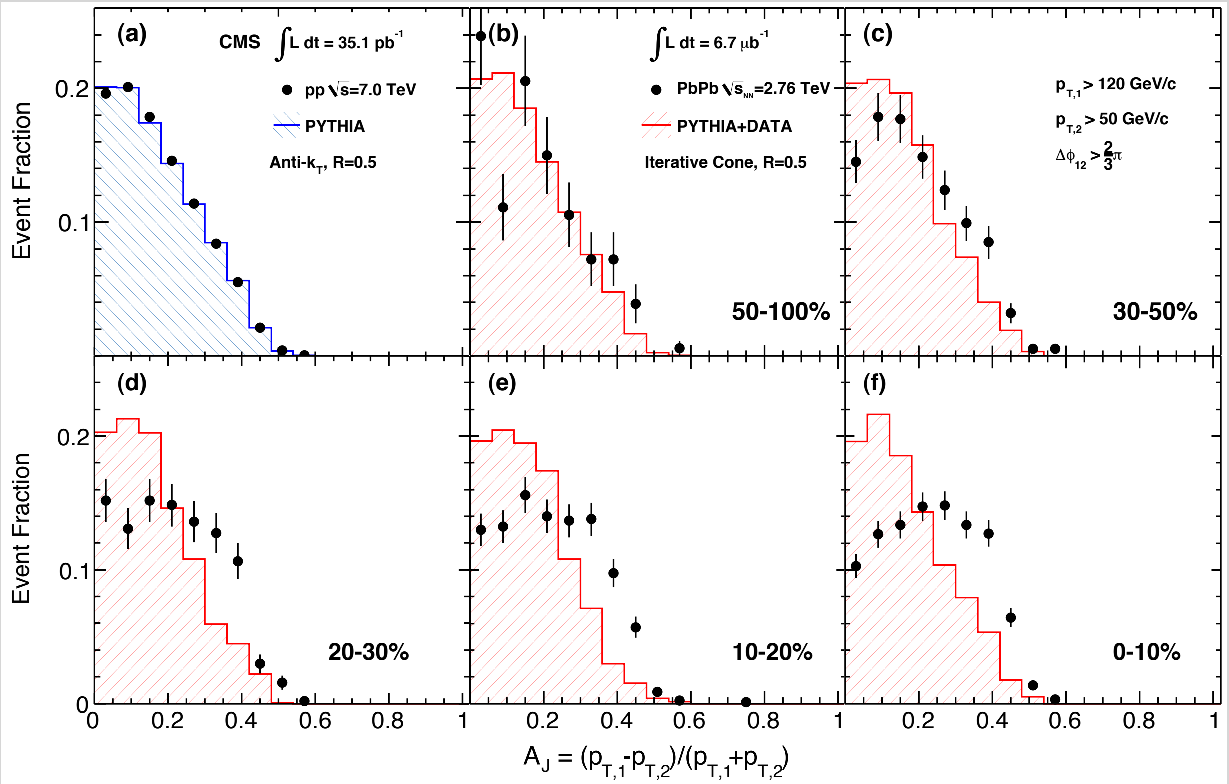

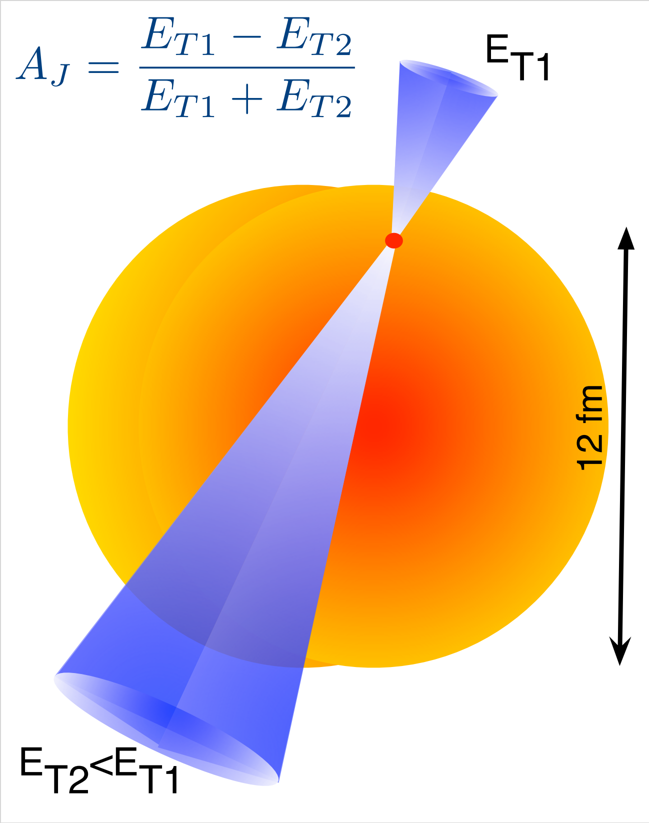

- significant enhancement of asymmetry

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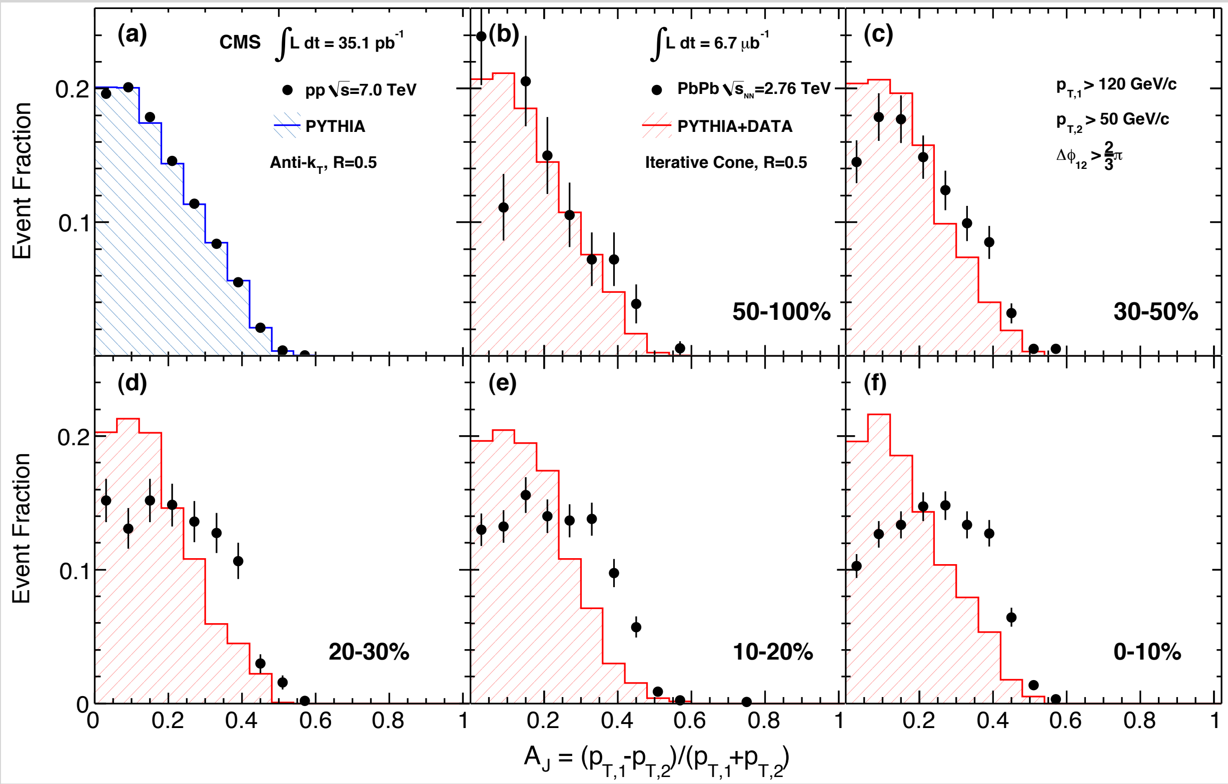
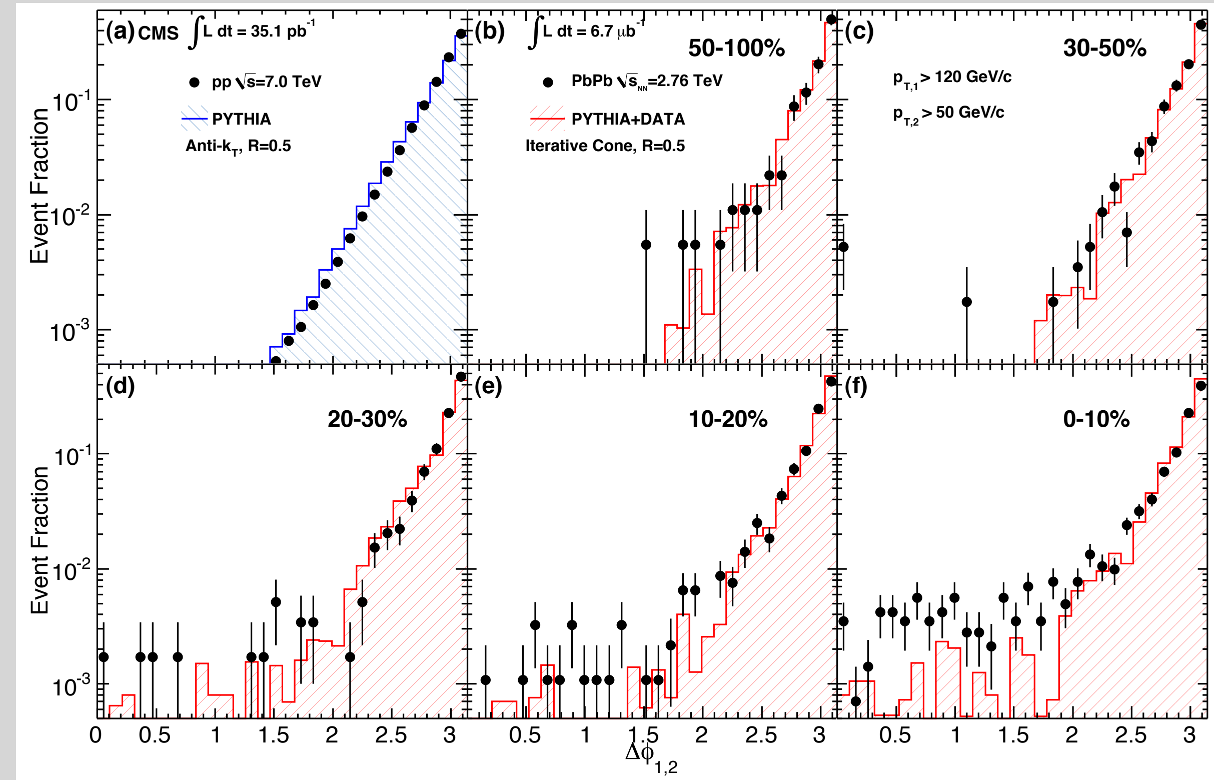
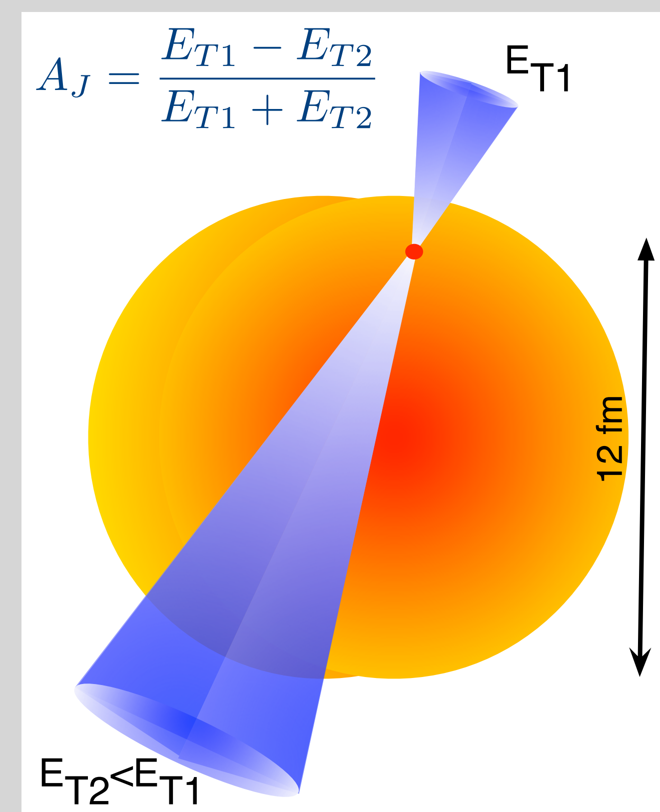
large broadening [a lesson from data]



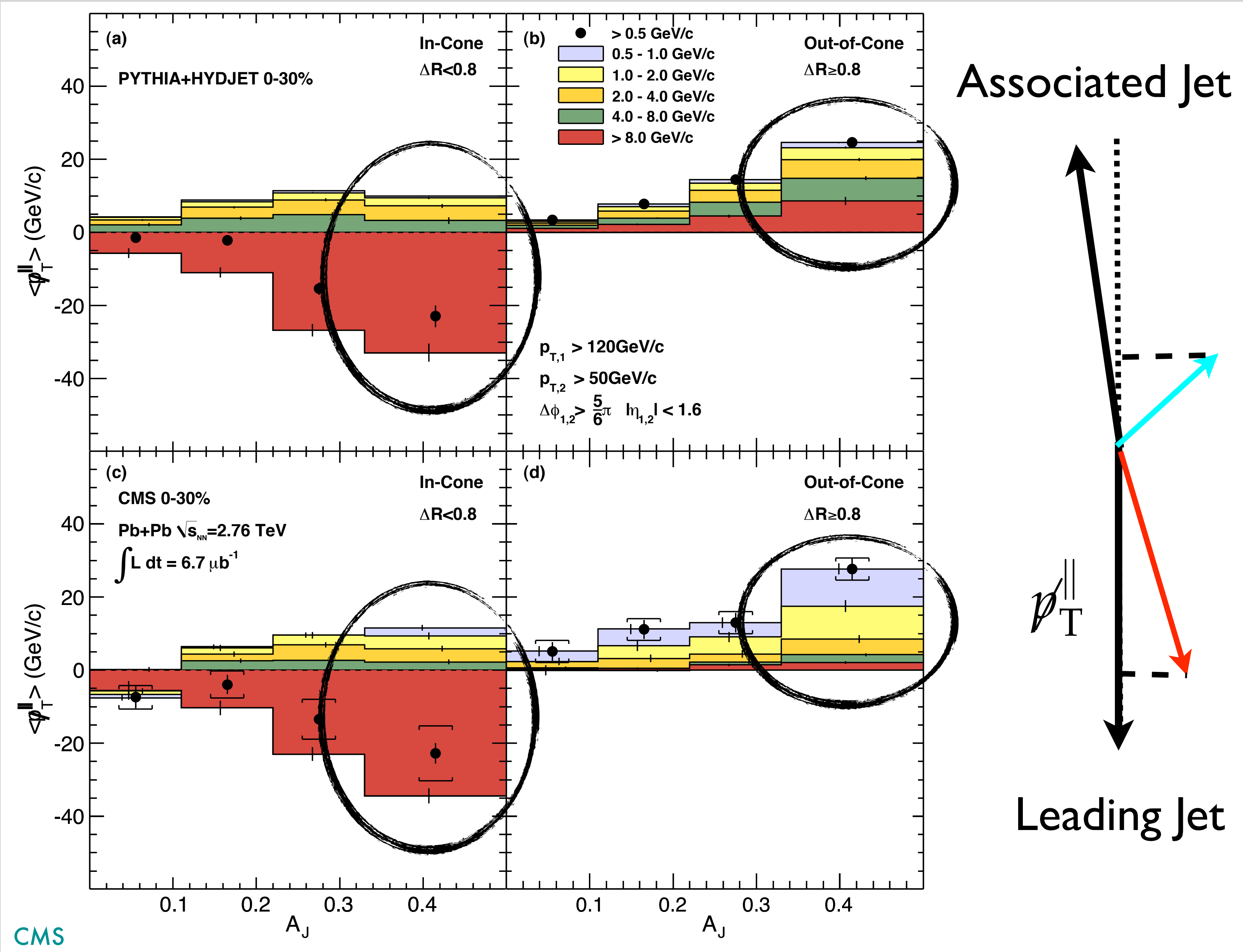




- significant enhancement of asymmetry
- no disturbance of azimuthal distribution

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

large broadening [a lesson from data]



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

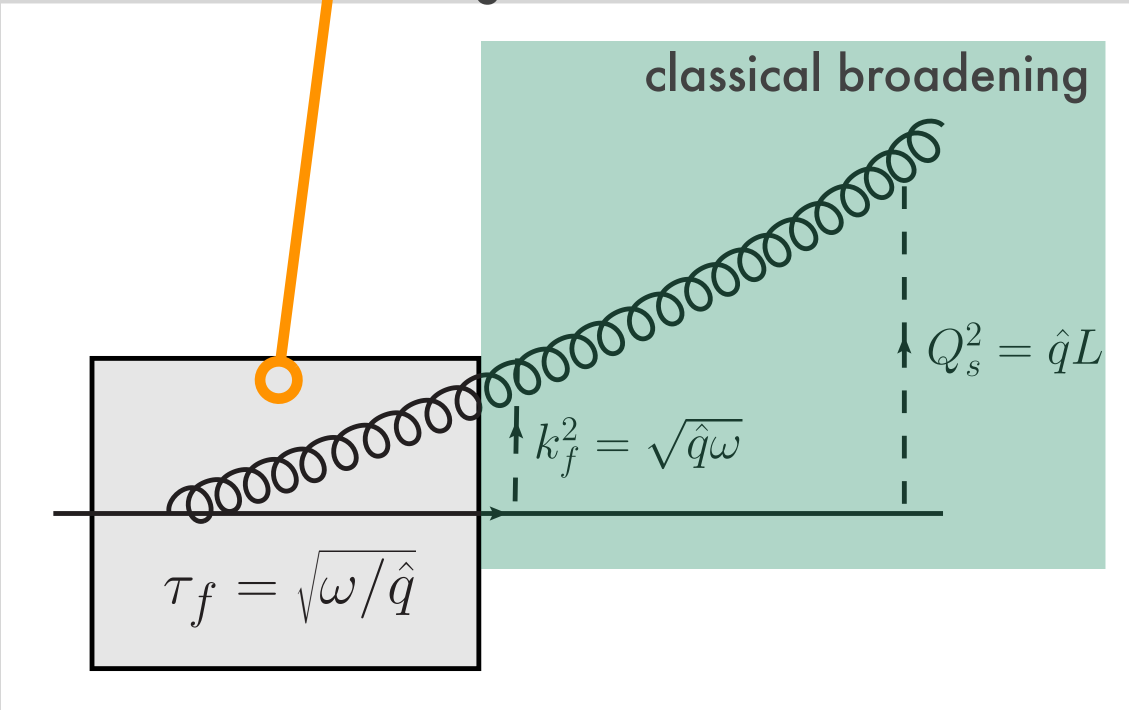
- energy lost from jet cone recovered in soft fragments at large angles

large broadening

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

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

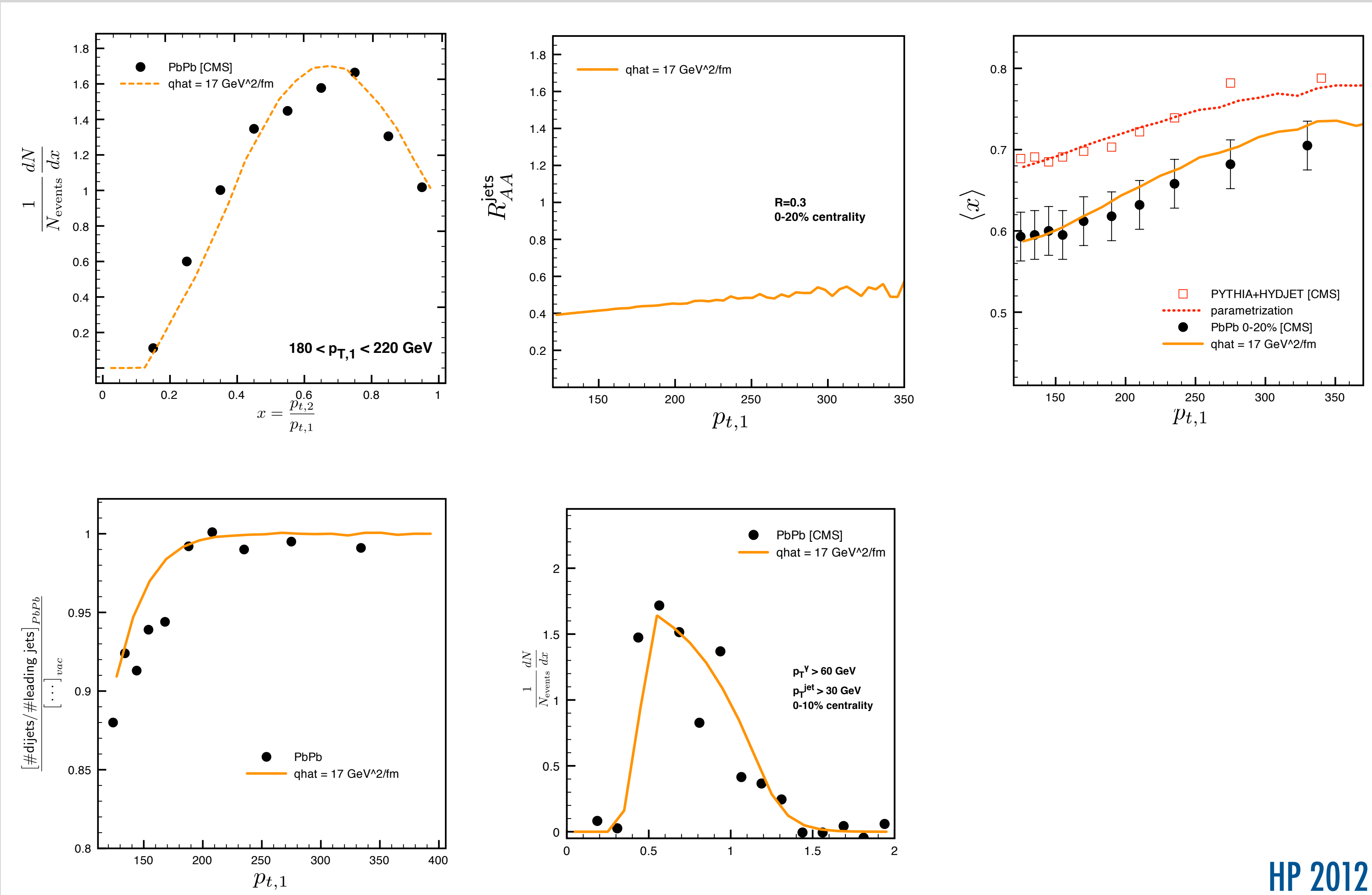
quantum emission/broadening during formation time



AN IMPORTANT LESSON FROM DATA

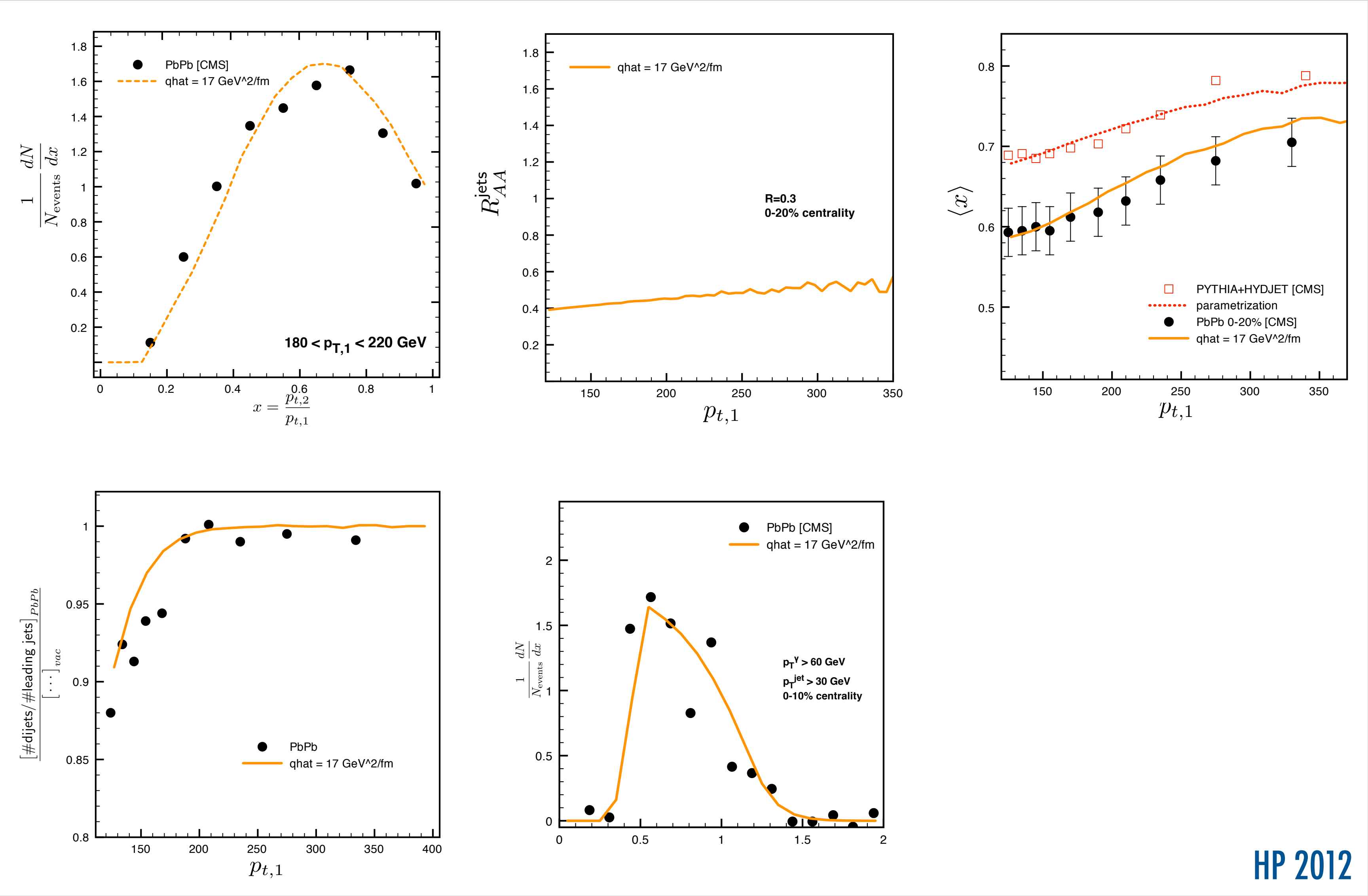
large broadening [beyond quasi-eikonal] is a prominent dynamical mechanism for jet energy loss [dijet asymmetry]

large broadening



very reasonable phenomenological approach that remains unsubstantiated by a first principle calculation

large broadening



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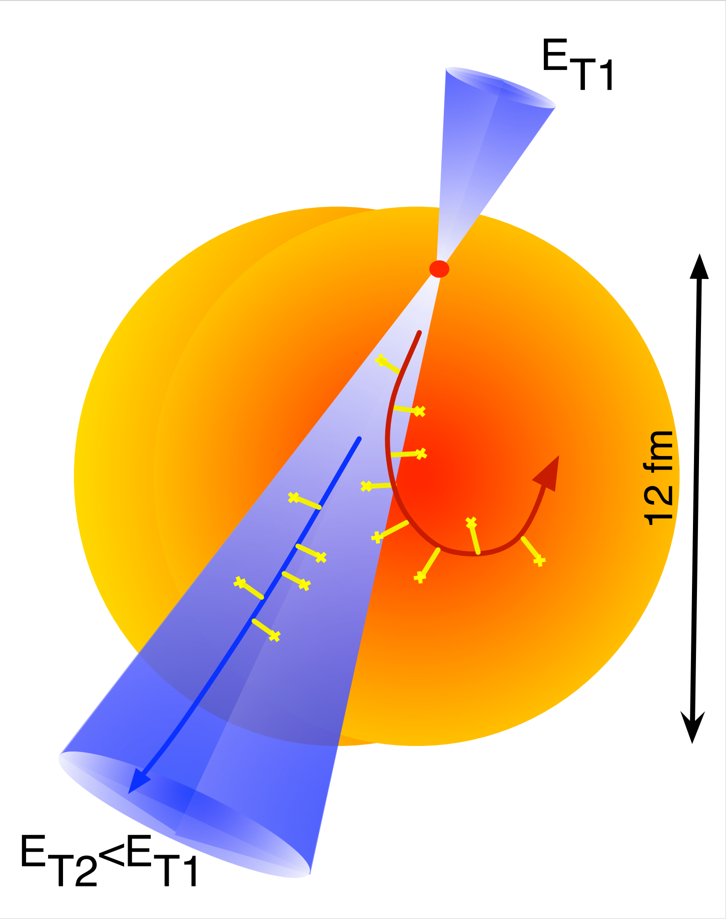

interplay of branching and hadronization

—o 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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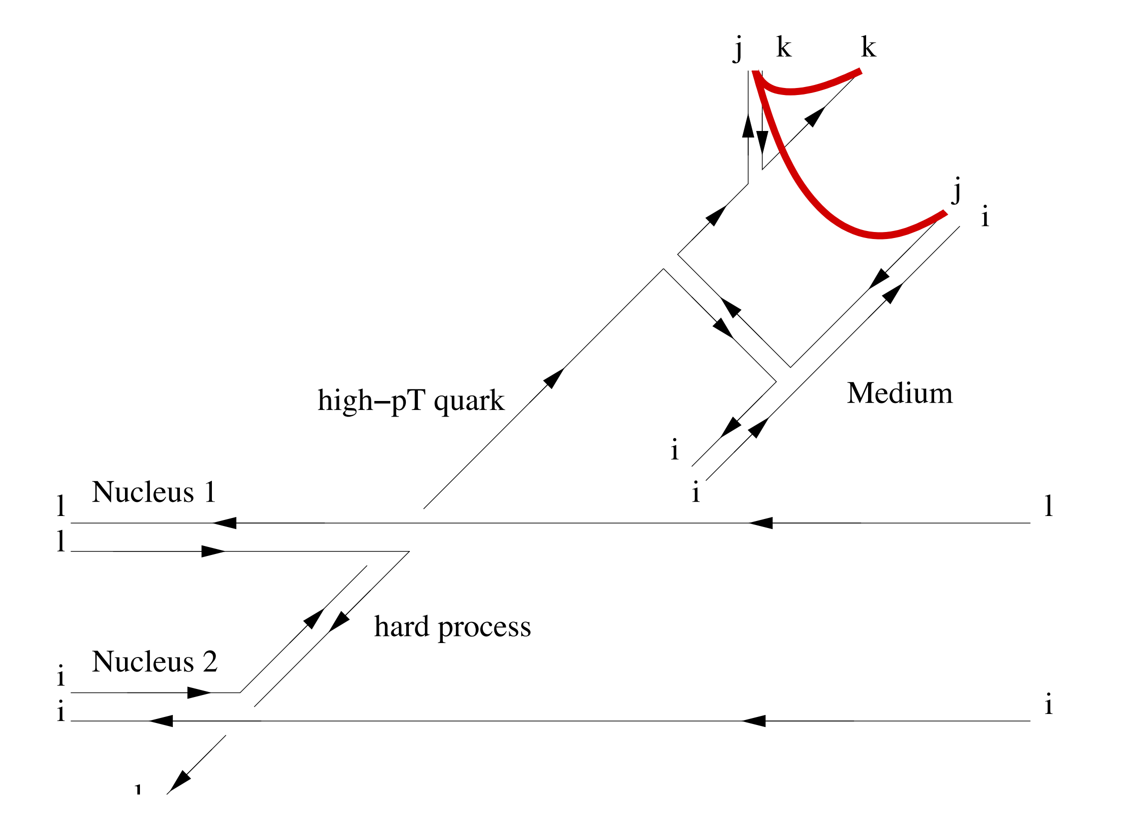

no medium interaction after radiation

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

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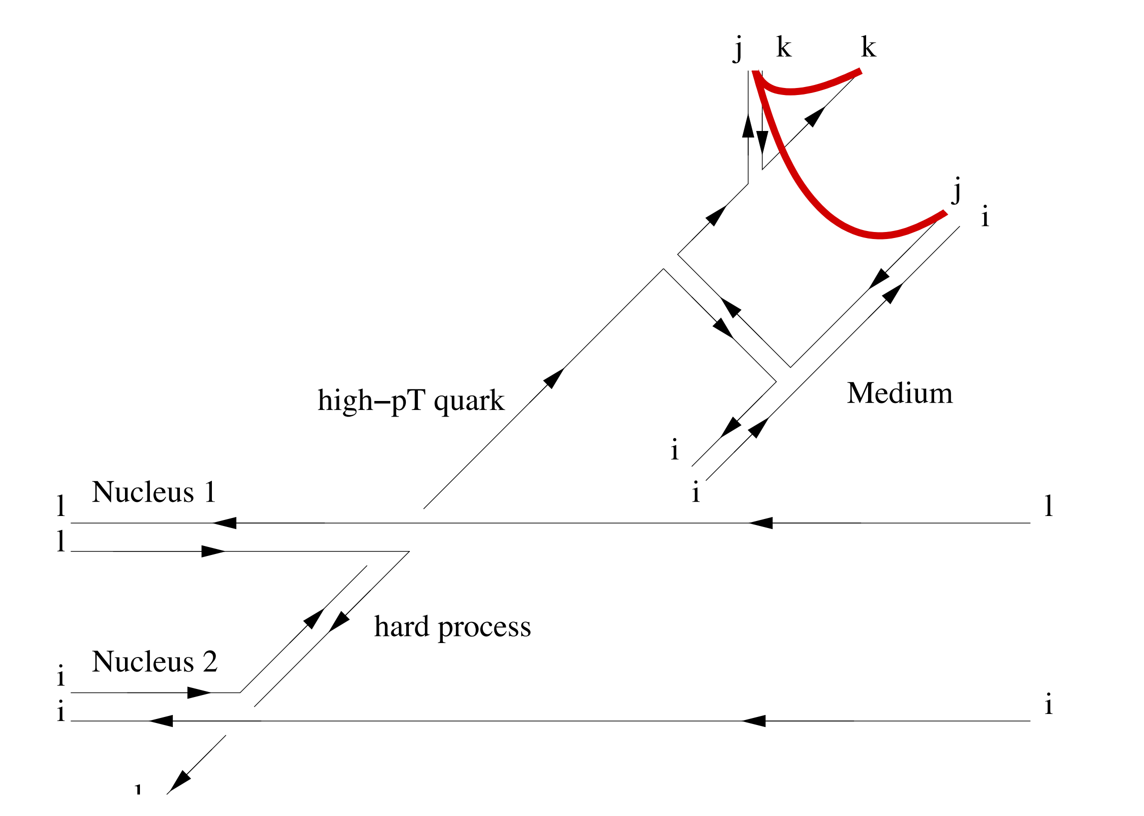

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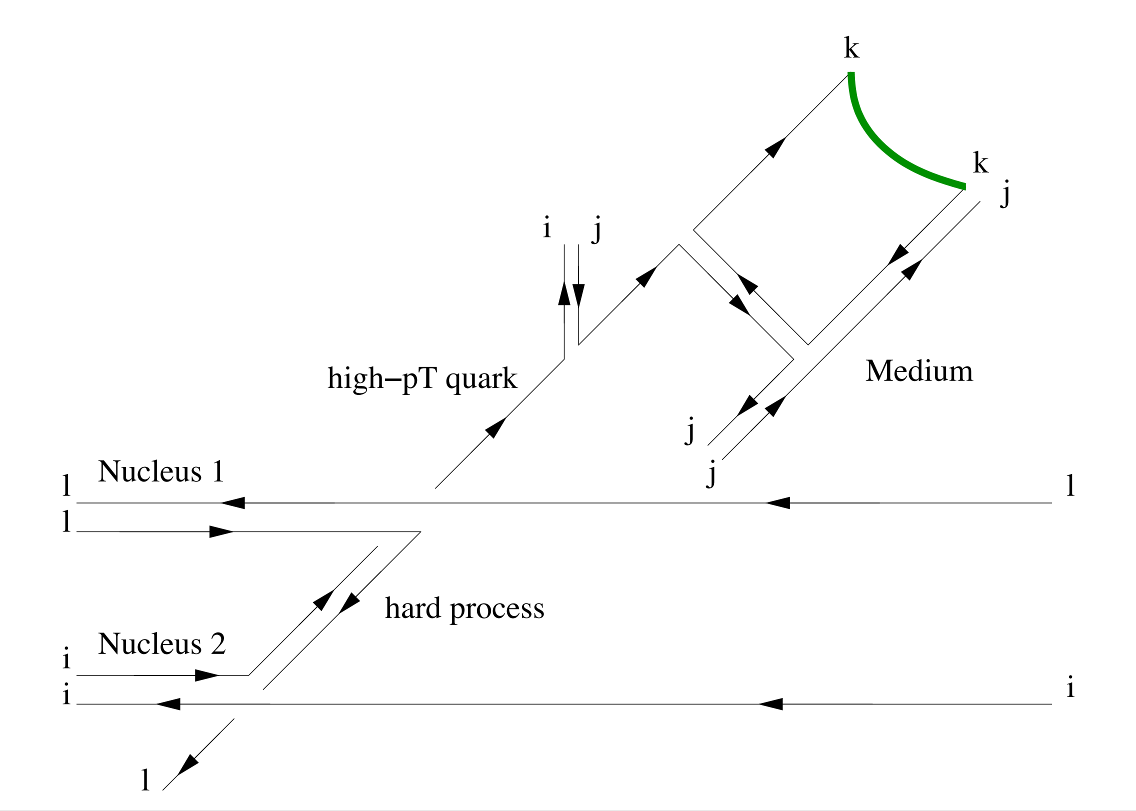

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Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]

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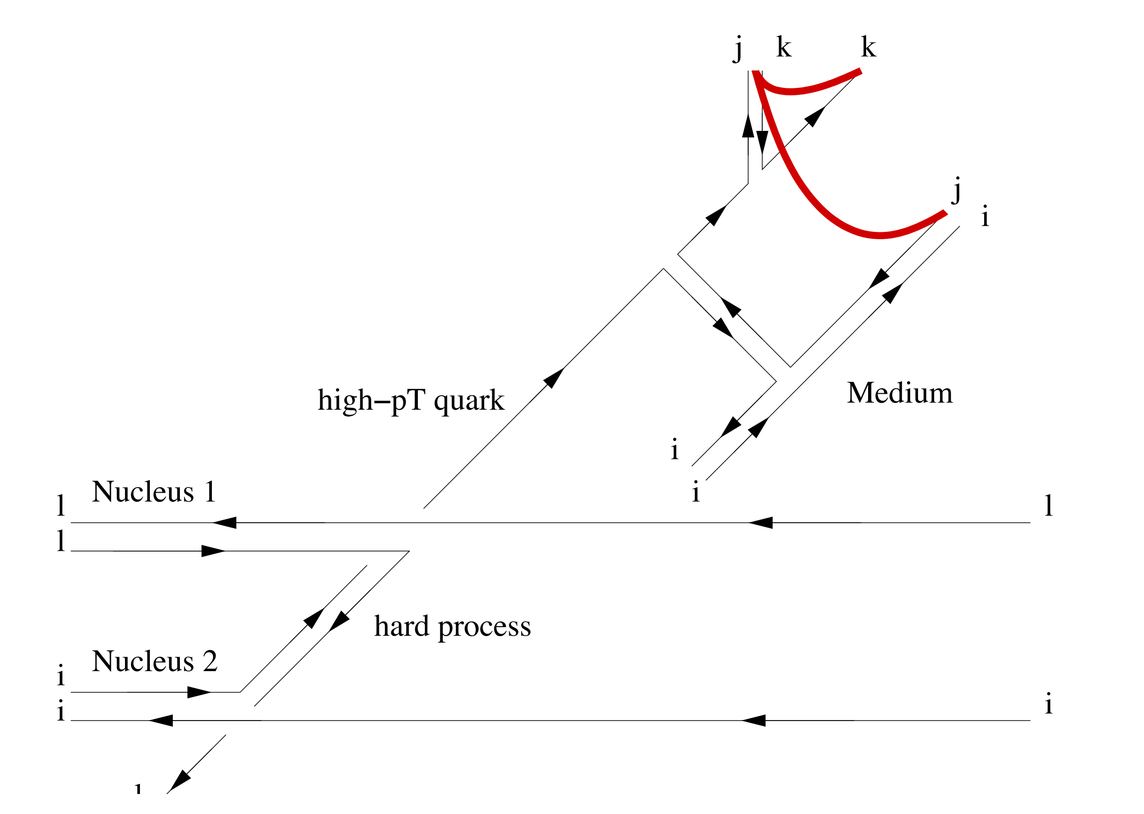

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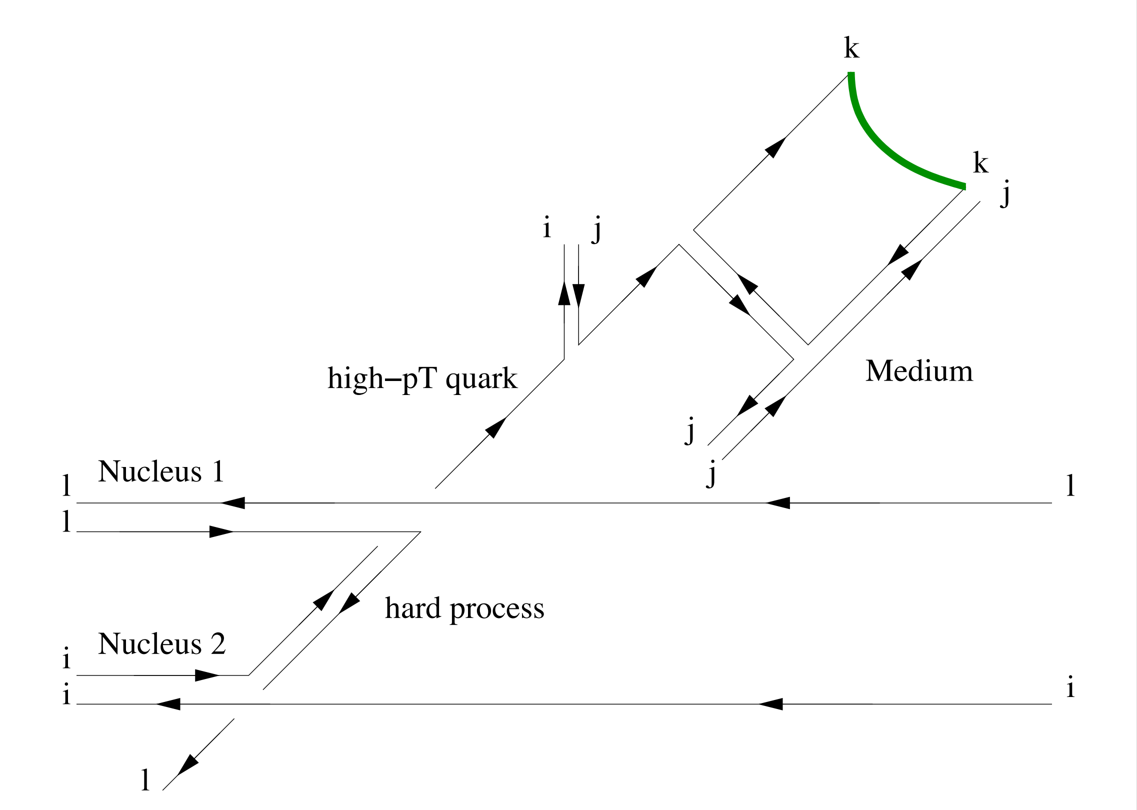

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first steps towards fully colour differential framework

Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]

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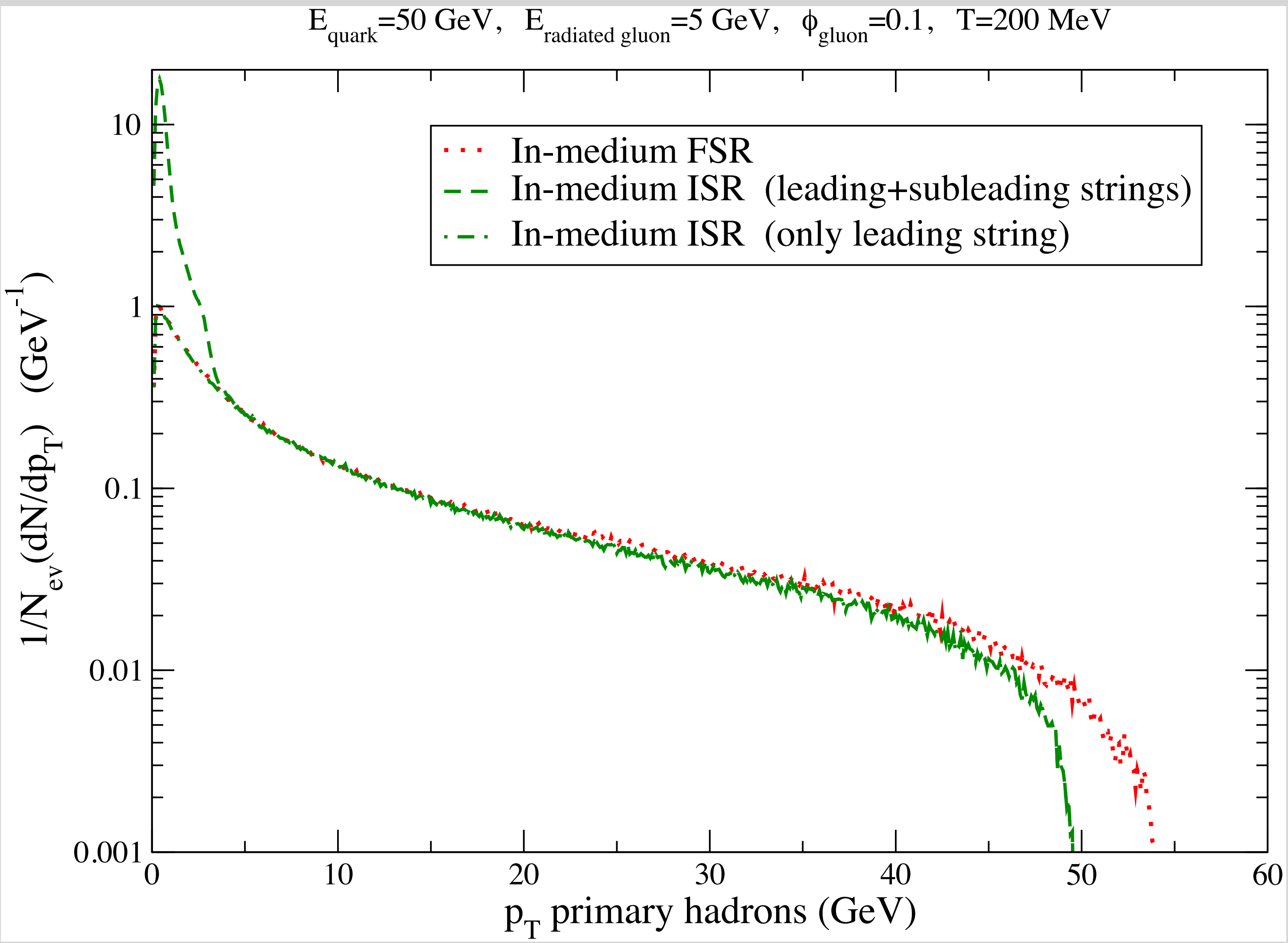
↪ essential input for realistic hadronization schemes



generic [robust] effects:

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

- at work even if radiative energy loss kinematically unviable

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modification of jet hadrochemistry

Aurenche & Zakharov [1109.6819]

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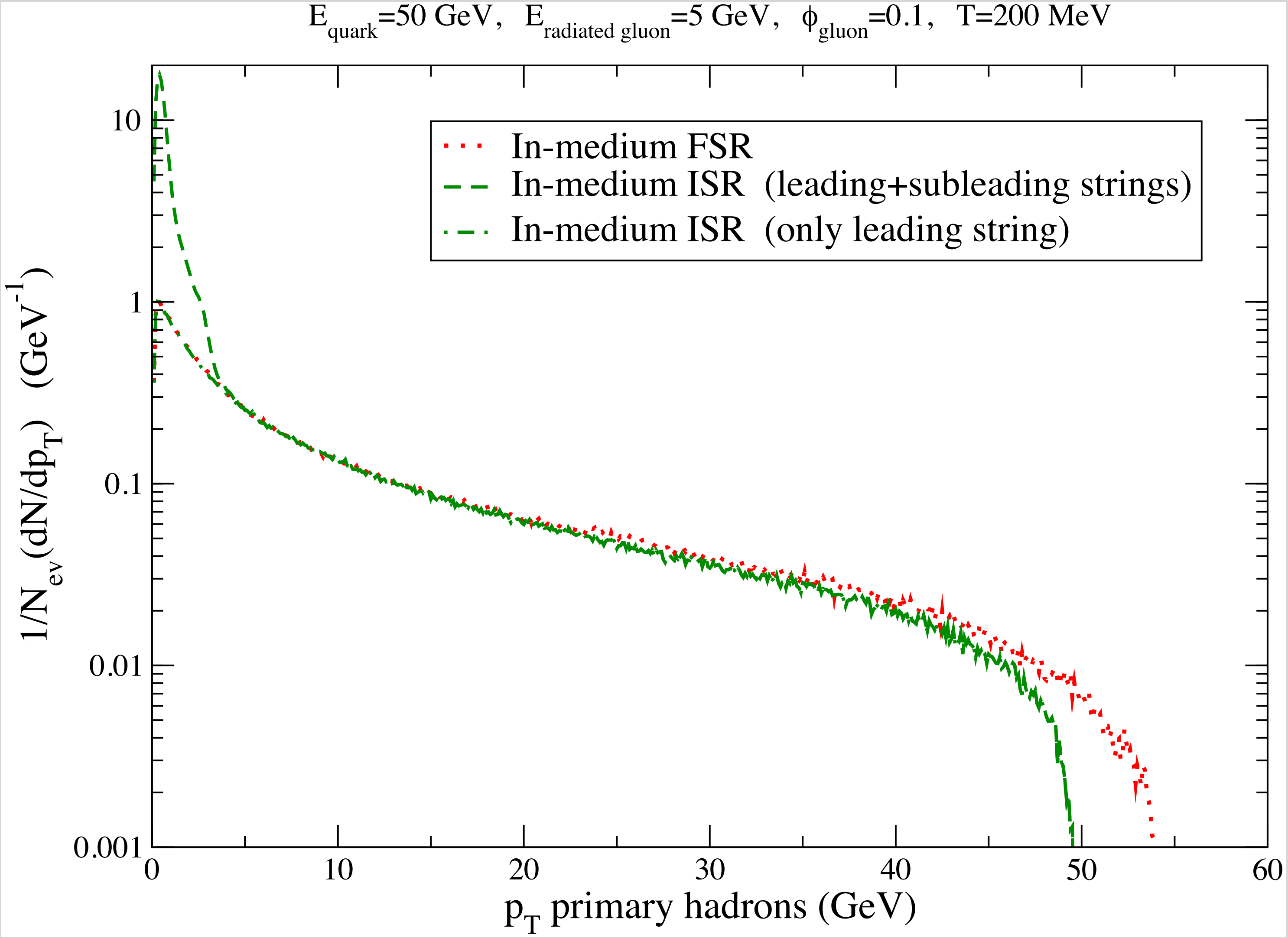

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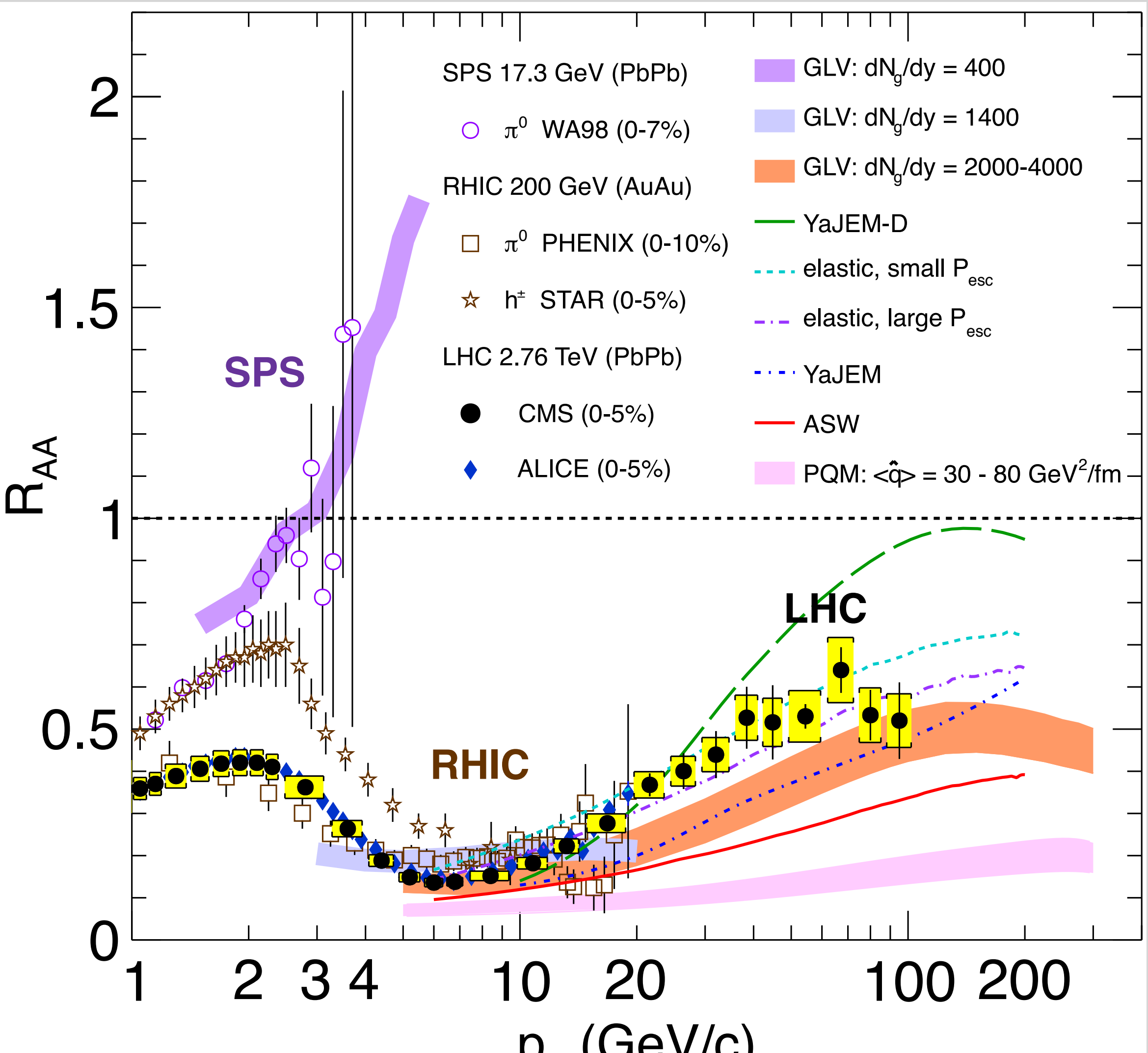
fragmentation in vacuum NOT the same as using vacuum FFs

sensitivity :: hadron spectra



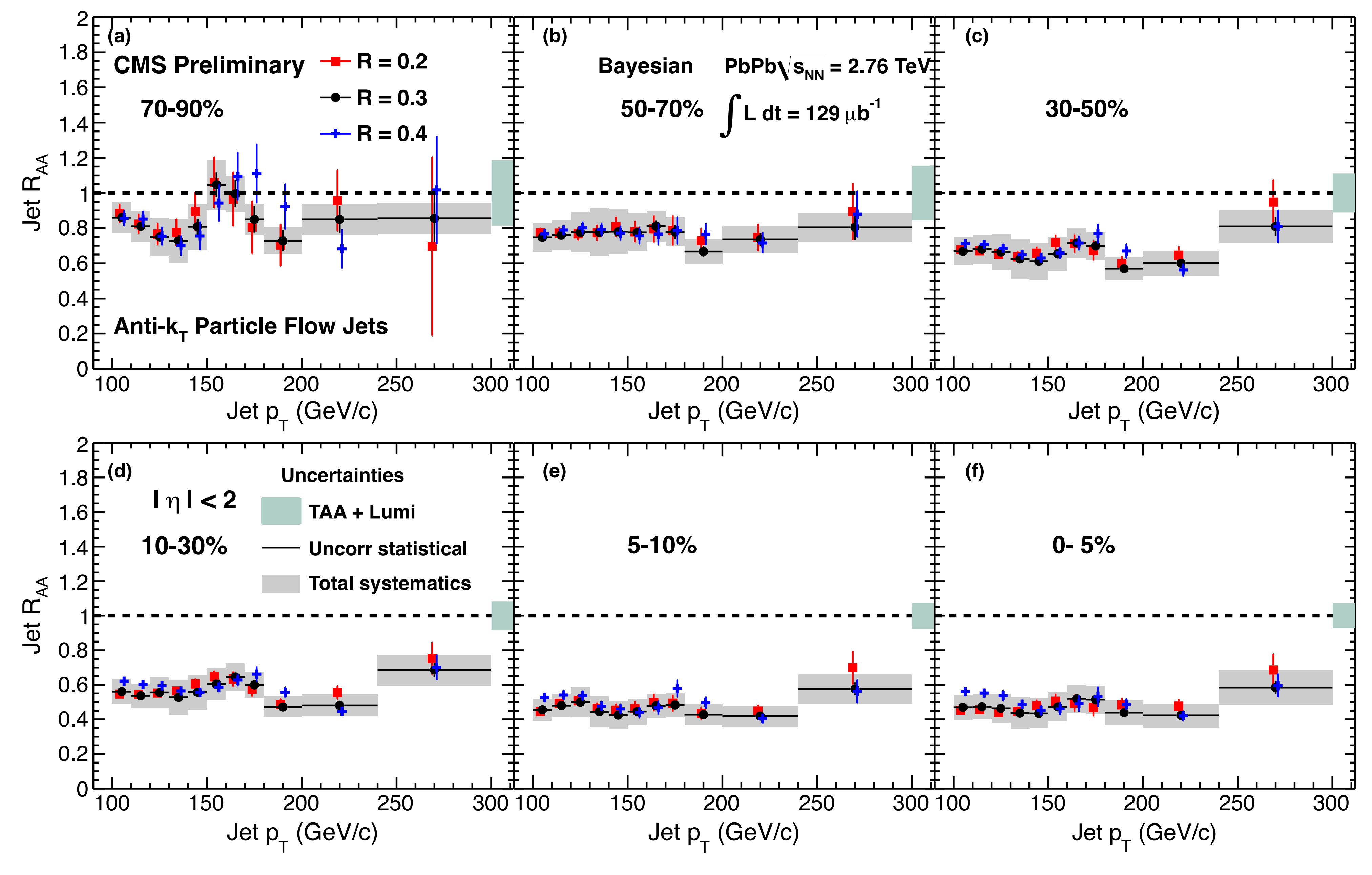
[CMS] 1202.2554

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

- clear and strong suppression of all hadronic yields
  - ↪ photons/Z^0 unsupressed
  - ↪ centrality [path-length] dependence

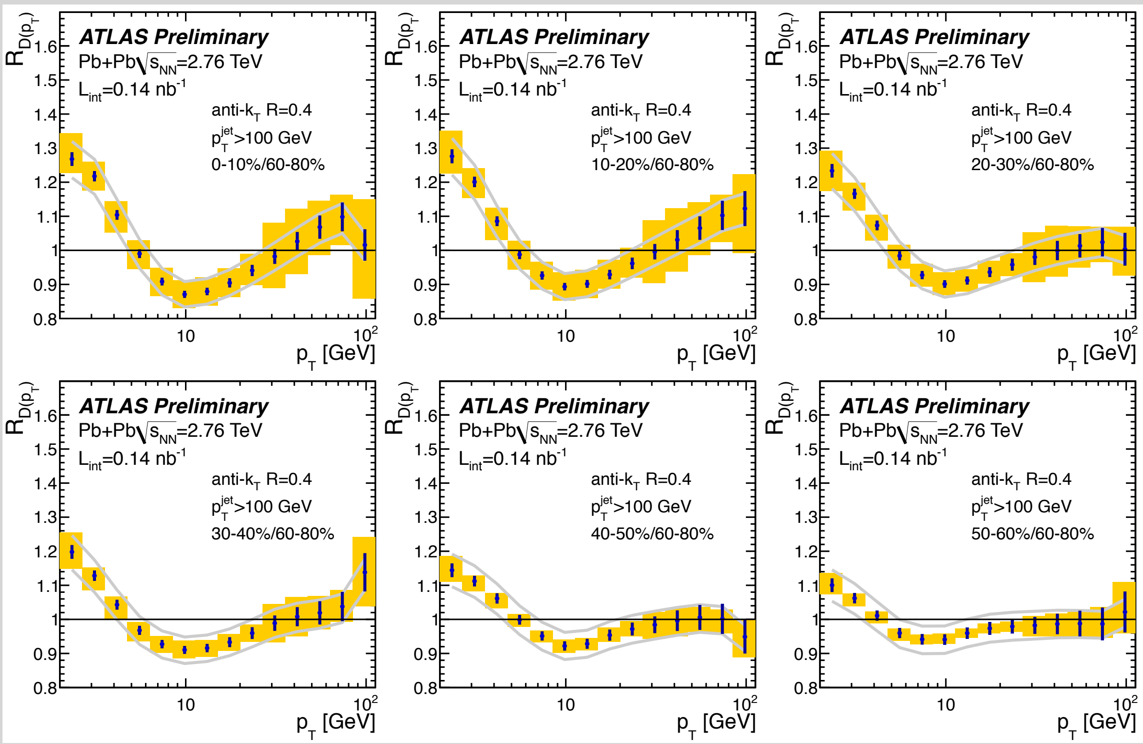
- sensitive to induced radiation, also to hadronization modifications, but NOT to broadening

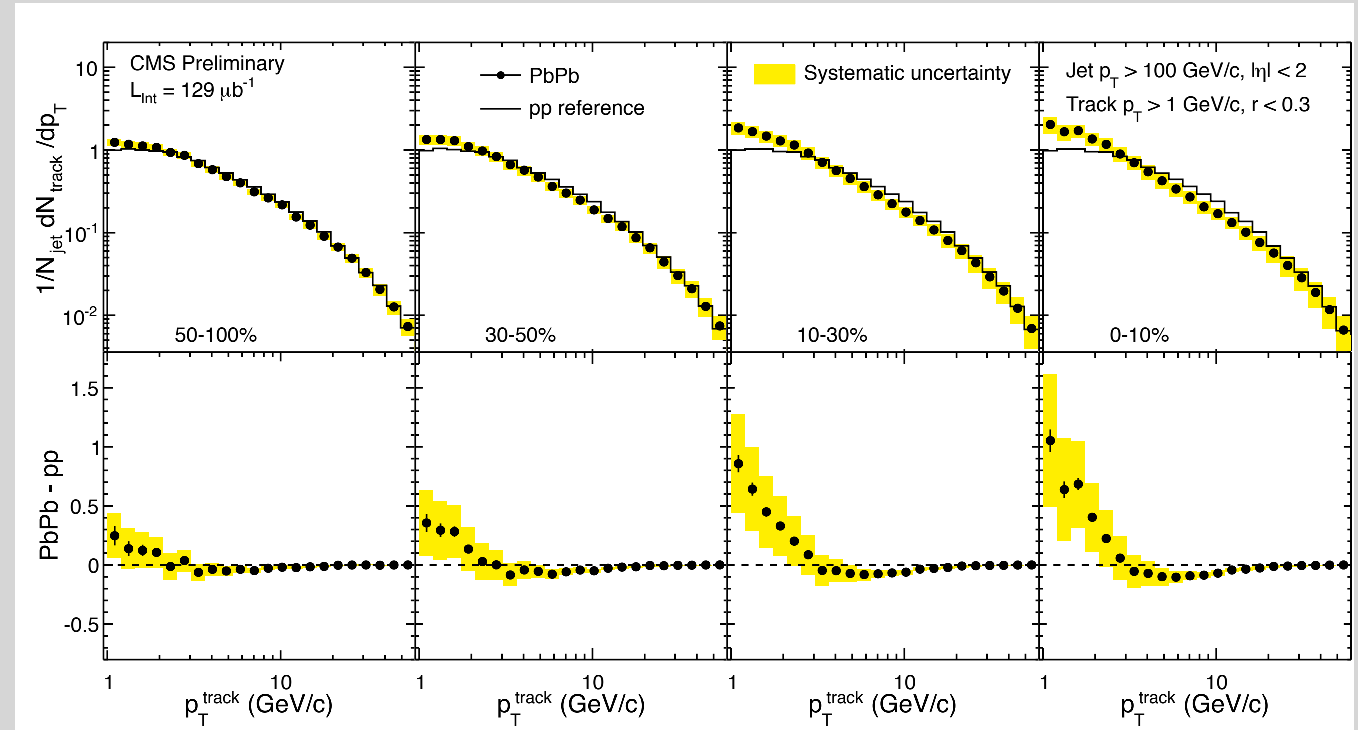
sensitivity :: jet R_{AA}



- just counts fraction of unmodified jets [steeply falling jet spectrum]
- [recall] dijet asymmetry sensitive to broadening, same for photon jet [advantage of known initial energy, but statically limited]

sensitivity :: fragmentation functions





- sensitivity to medium-induced radiation, broadening, hadronization
  - ↪ remarkably similar to vacuum jets [most branching occurs after medium escape; branching within unresolved systems also vacuum like]