Theoretical overview of high-p_t in heavy ion collisions

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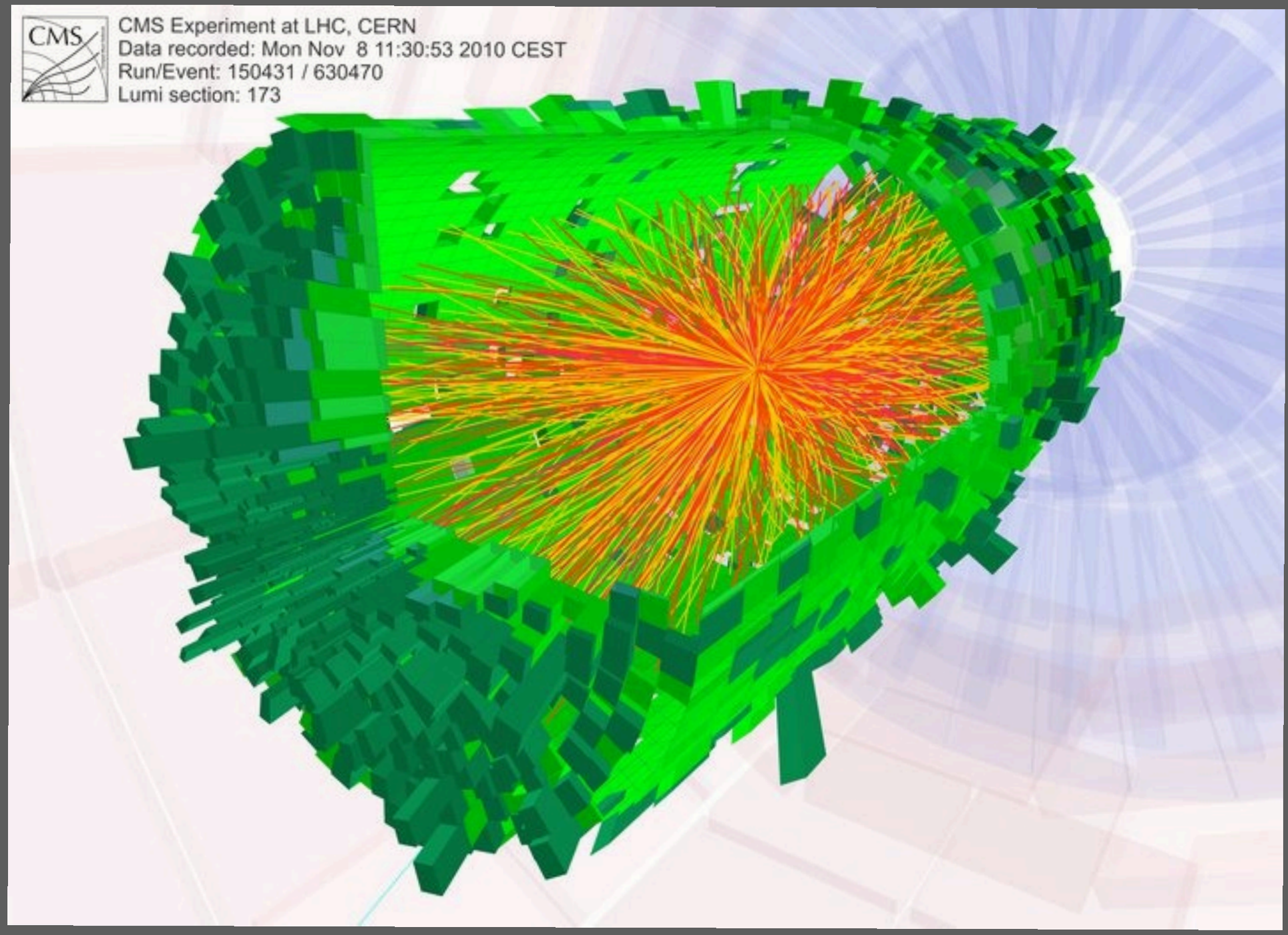
ultra-relativistic heavy ion collisions

- Pb-Pb collisions at $s^{1/2}$ = 2.76 TeV/nucleon pair [ALICE, CMS, ATLAS]
  - ↪ largest jump in energy in collider history [RHIC: $s^{1/2}$ = 200 GeV/nucleon pair]
    - access to an extended kinematic range
    - access to new high-p_t observables [e.g. fully reconstructed jets]
  - ↪ the collision creates a hot and dense QCD medium [the Quark-Gluon Plasma ?]

resulting in

- collective behaviour :: see J.-Y. Ollitrault's talk later in the week
- modified QCD dynamics due to medium presence :: this talk



the main objective of the LHC heavy ion experimental programme is to unveil the properties of the created medium

high-p_t hadron production in HIC

- factorized description of hadron production at high-p_t in heavy ion collisions is a, phenomenological consistent, working assumption

$$\sigma^{AB\to h} \sim f_i^A(x_1, Q^2) \otimes f_j^B(x_2, Q^2) \otimes \sigma^{ij\to k} \otimes D_{k\to h}(z, Q^2)$$

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- scale dependence from DGLAP evolution
- determined from global fits [eA, pA]
- control of nuclear modifications essential [cold nuclear matter effects]

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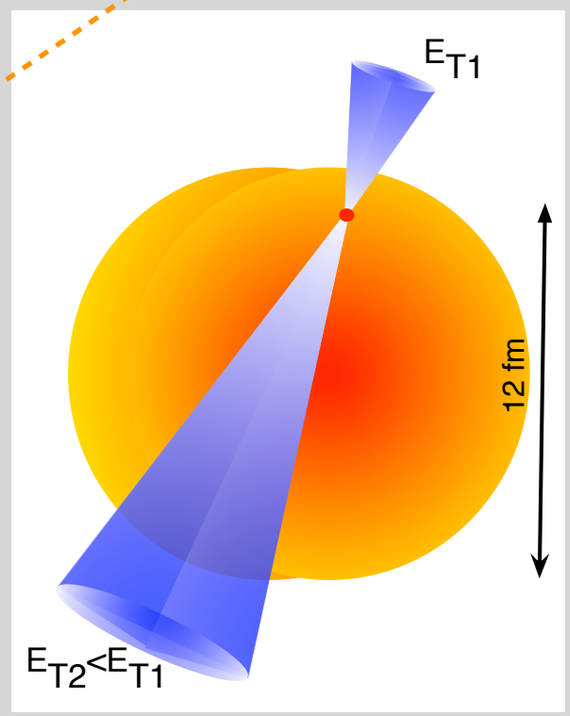
- localized on point-like scale [~ $1/E_T$] and thus oblivious to the surrounding QCD medium



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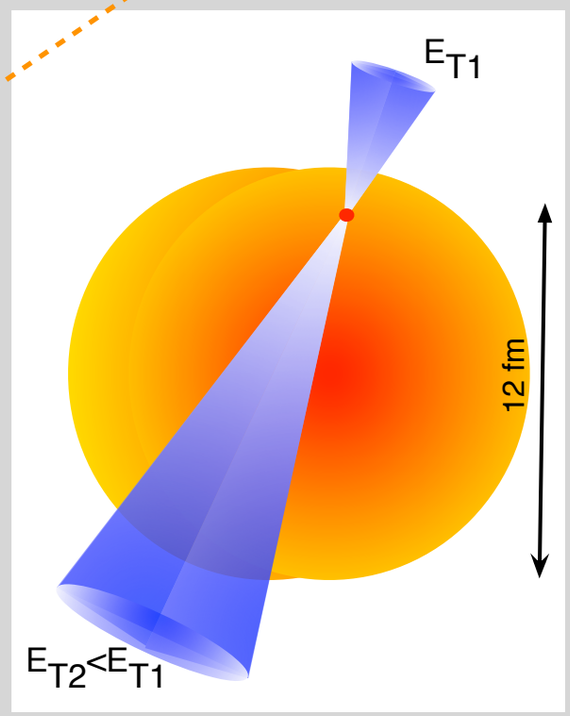

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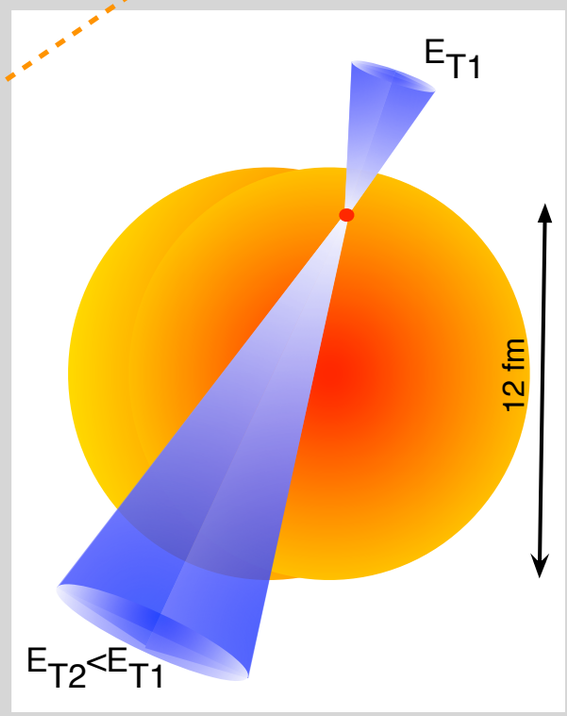

jet quenching :: the modifications effected on the propagating parton, and on its shower, by the QCD medium it traverses

dual role of jet quenching studies

- ultimately jet quenching studies [medium induced modifications of observed properties of high-p_t properties] allow for detailed characterization of produced medium
  - ↪ high-p_t probes are created early
  - ↪ their production mechanism is under good theoretical control
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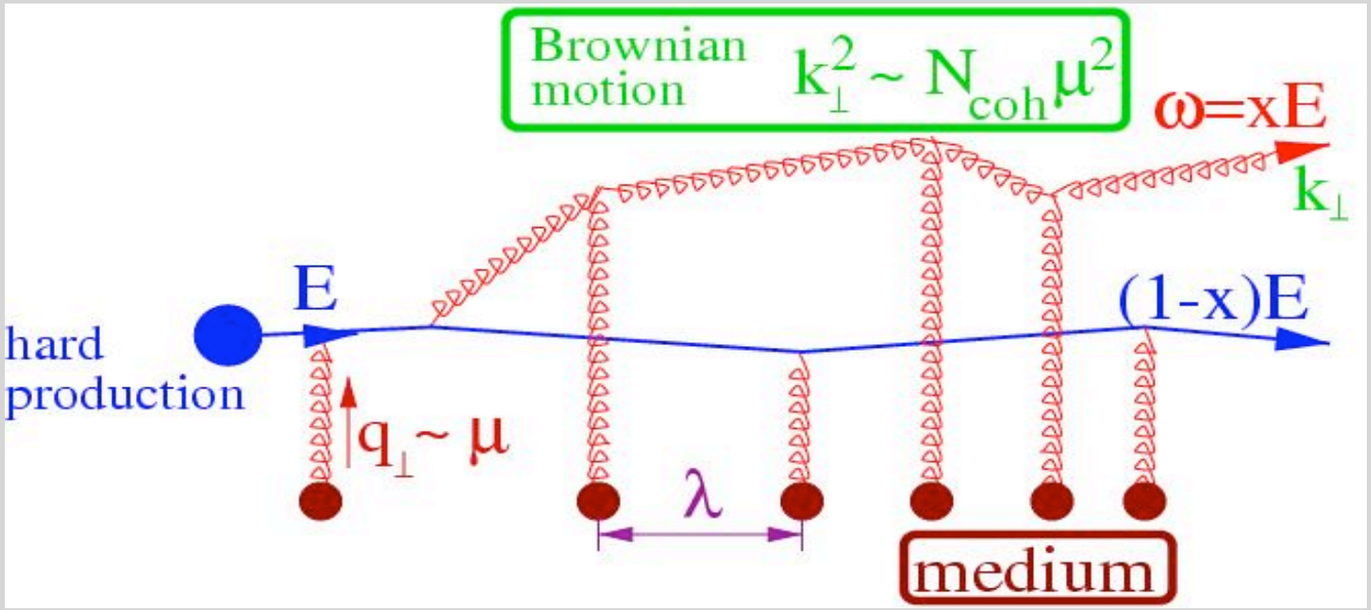
wished full theoretical description of dynamics of in-medium high-p_t parton and its current status [the rest of this talk]

:: disclaimer ::

this talk focus on only those issues for which there has been, in my opinion, significant theoretical and phenomenological progress triggered by LHC heavy ion data.

consequently, many omissions ...

in-medium dynamics of high-p_t parton



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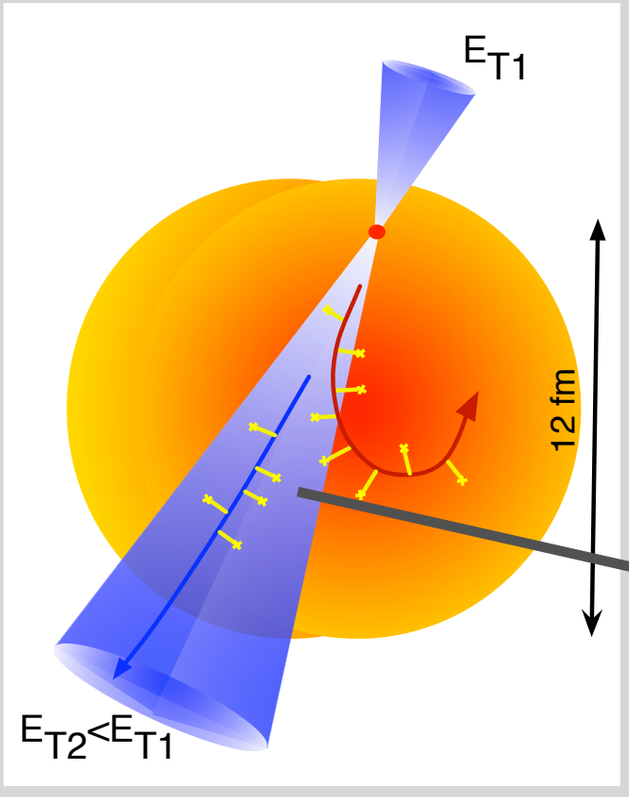

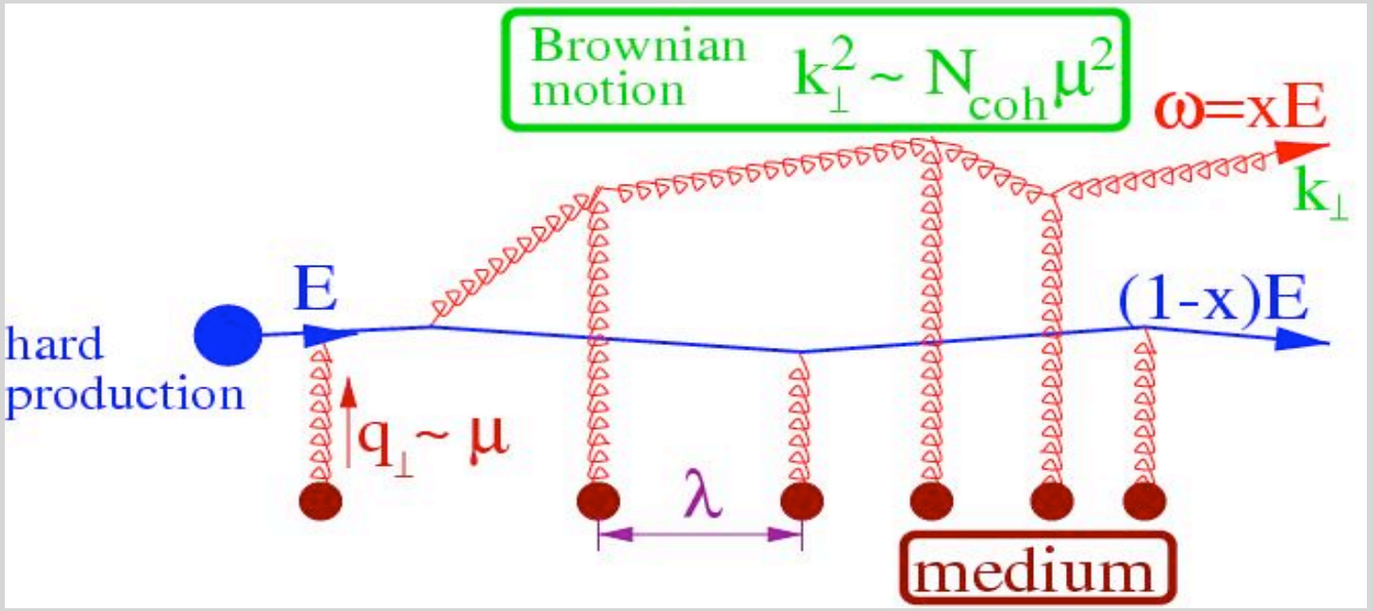

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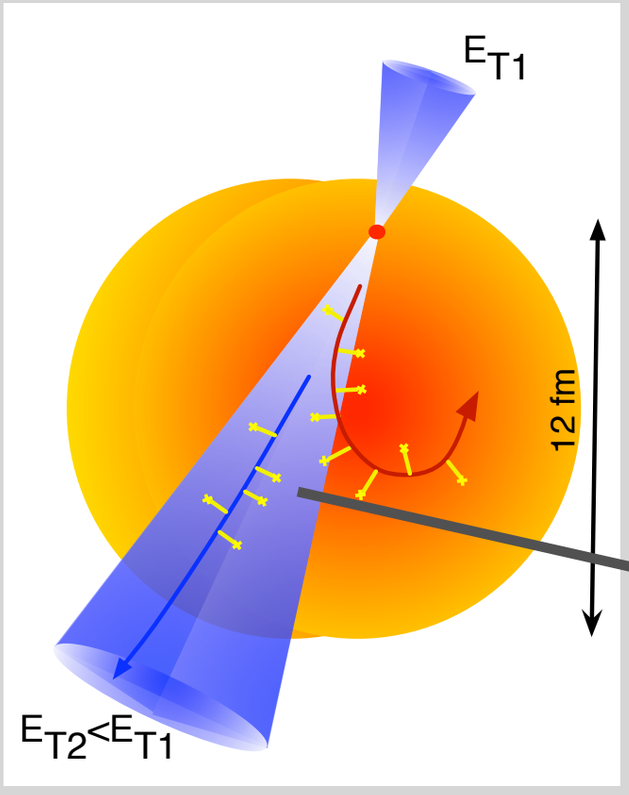

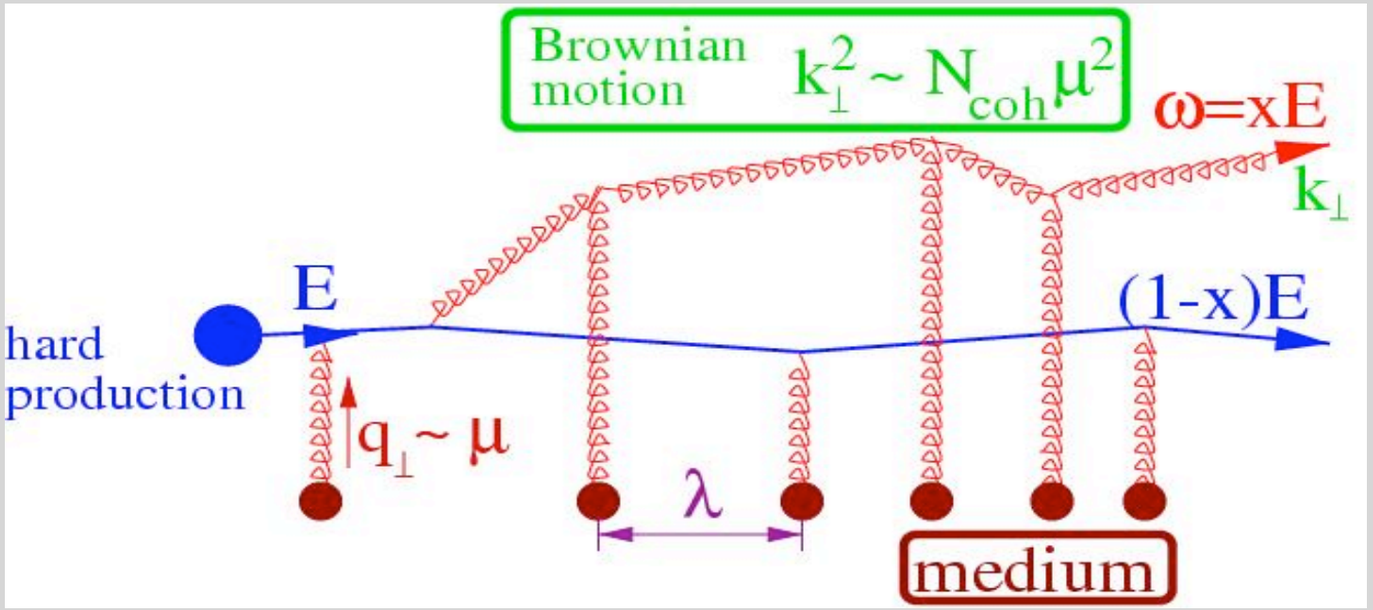

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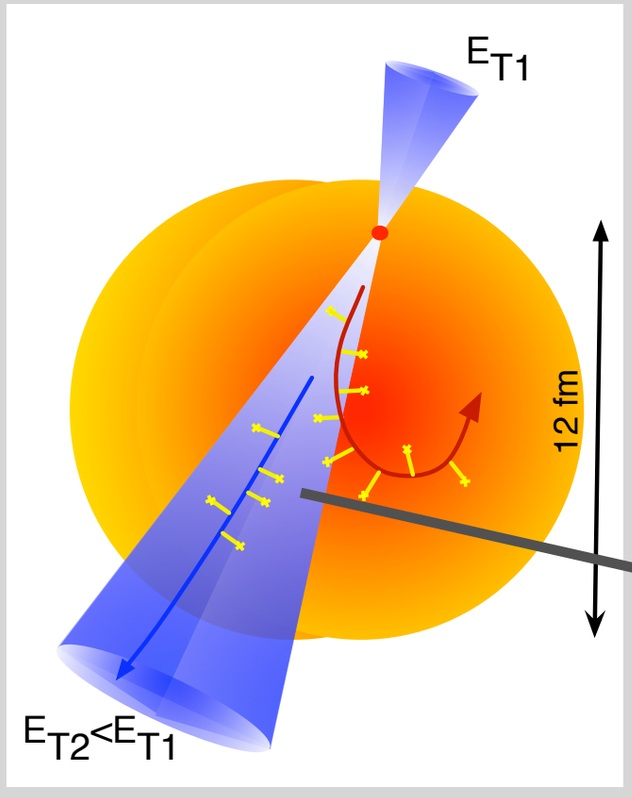

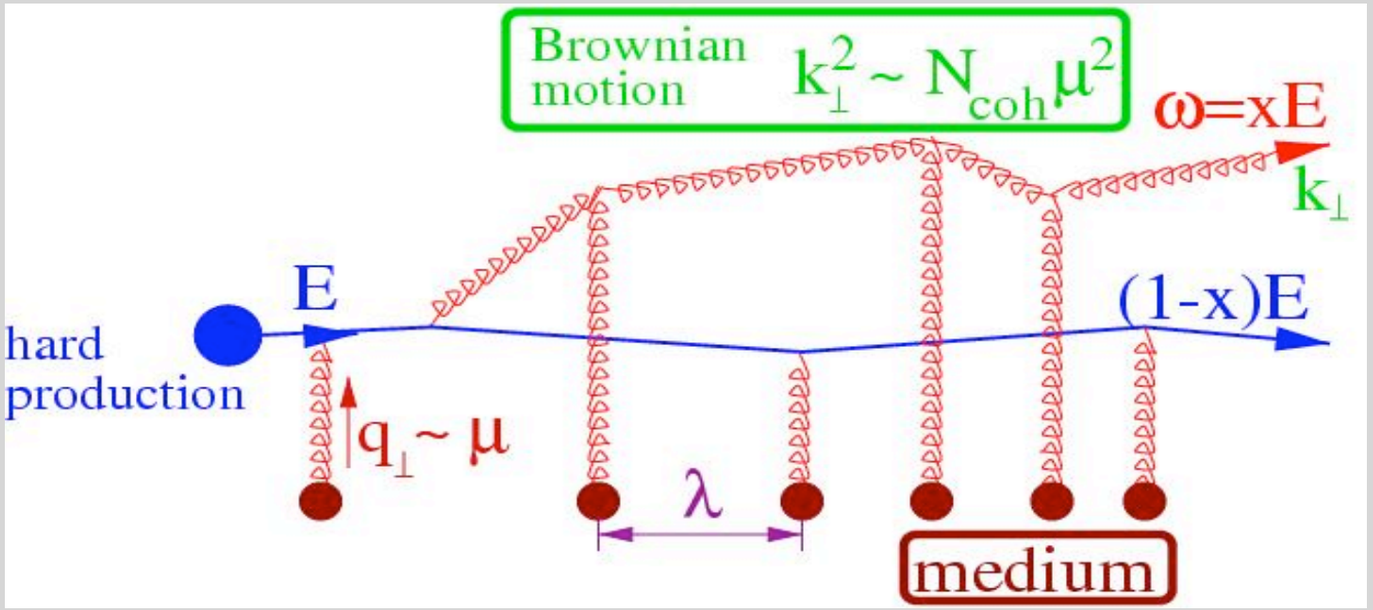

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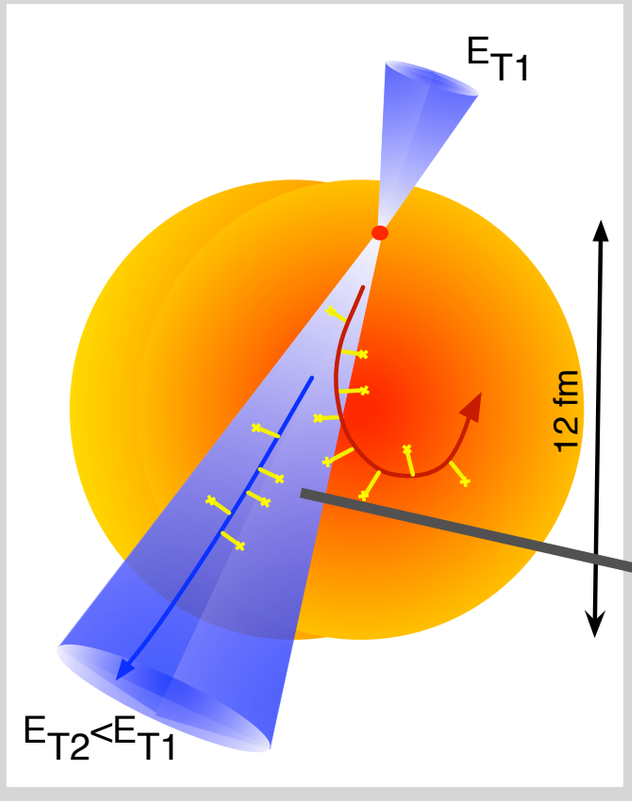

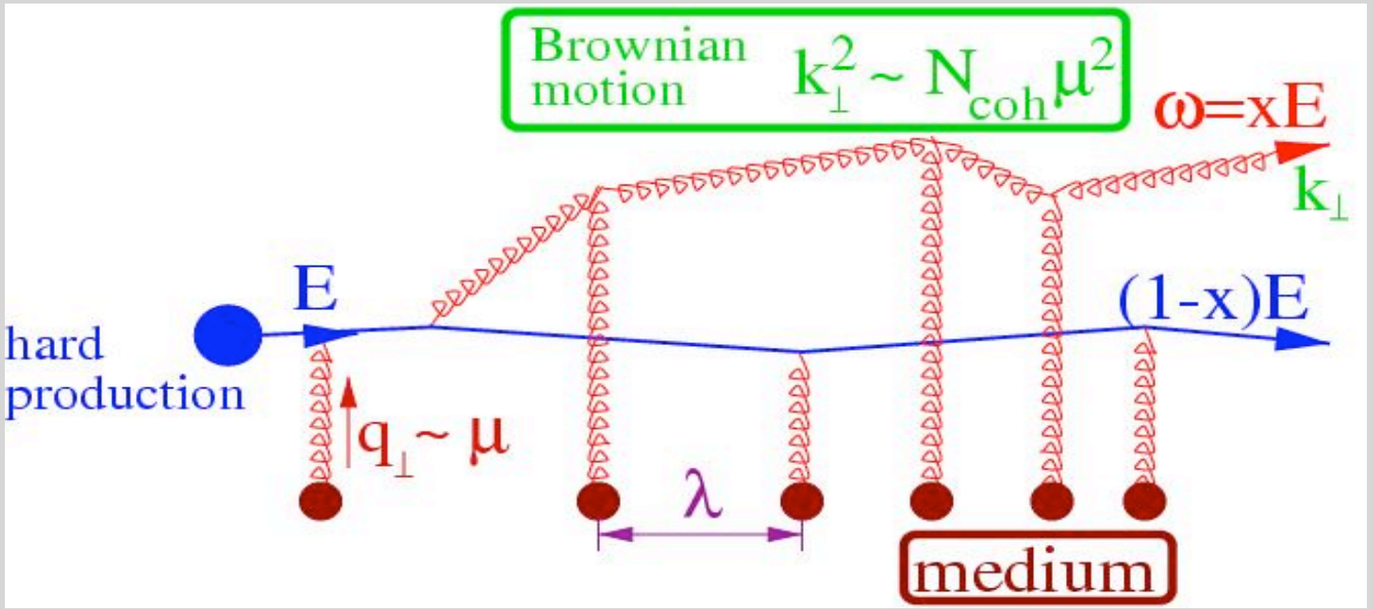

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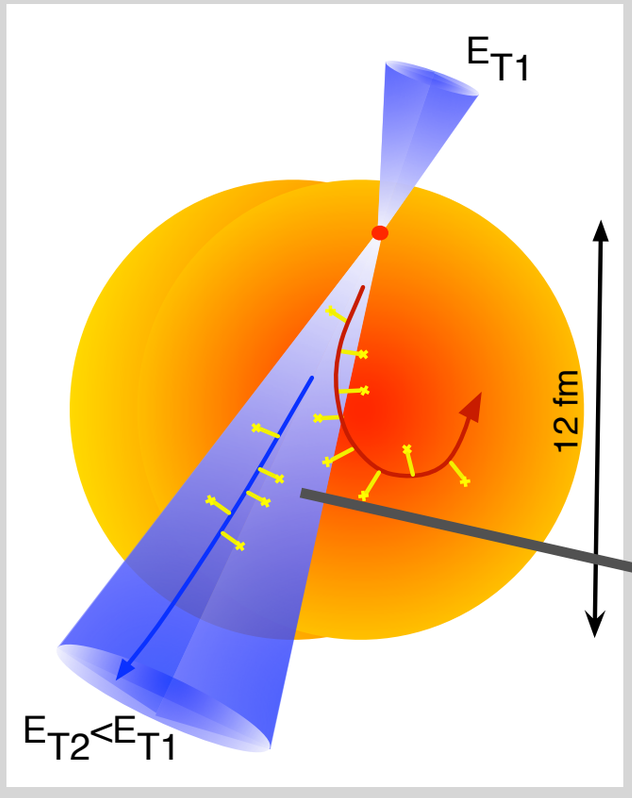

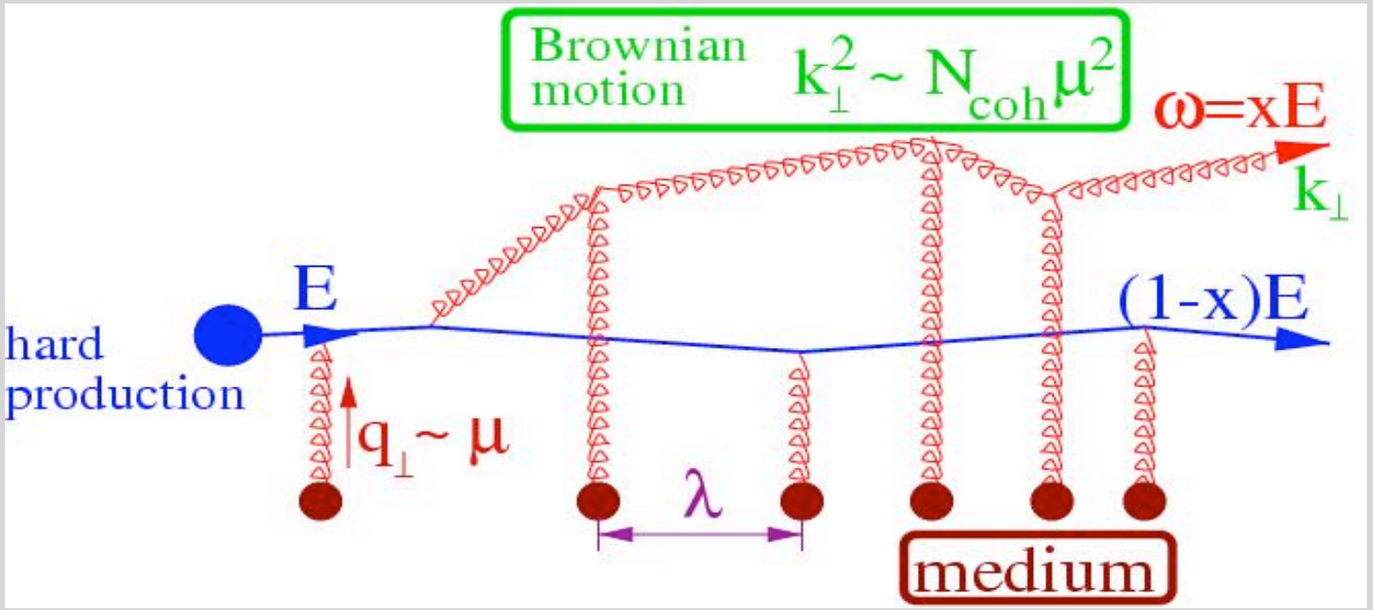

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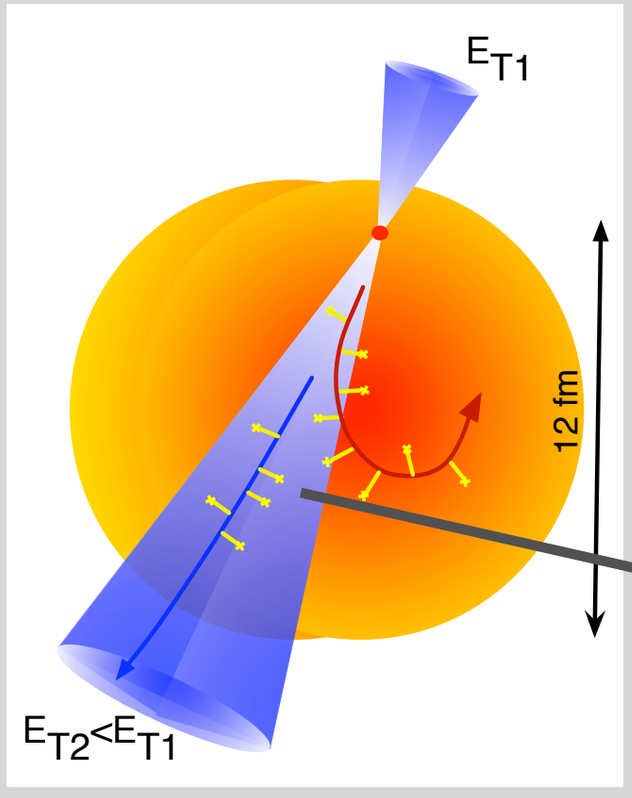

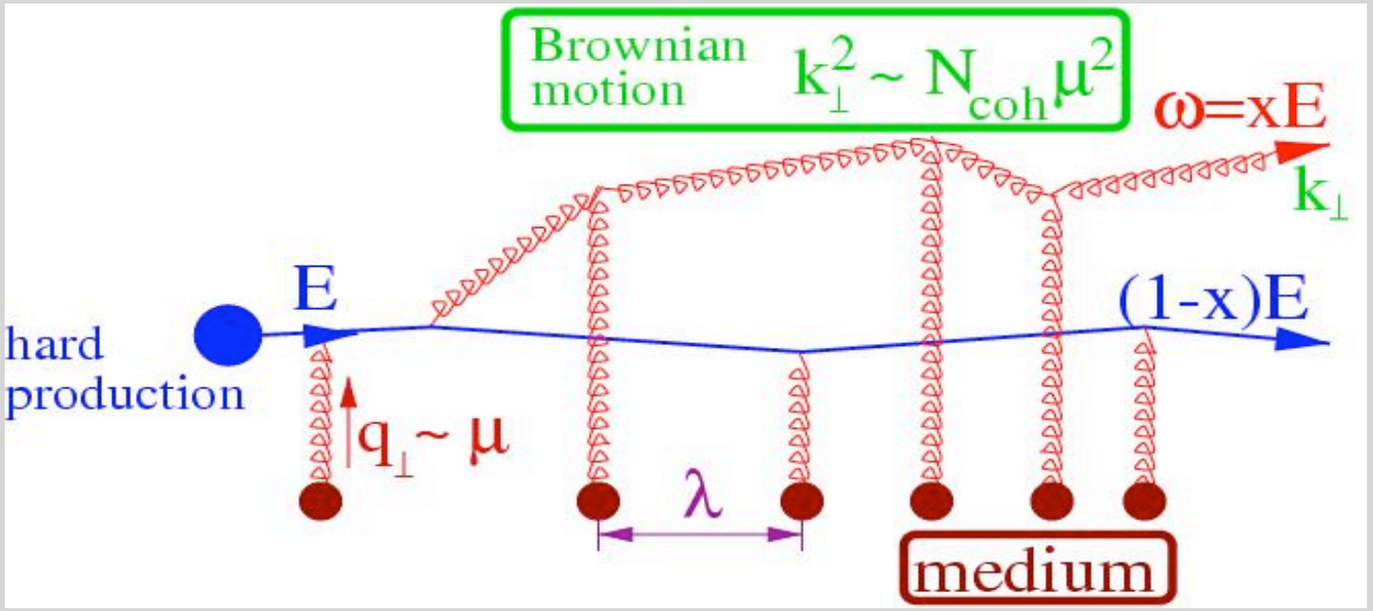

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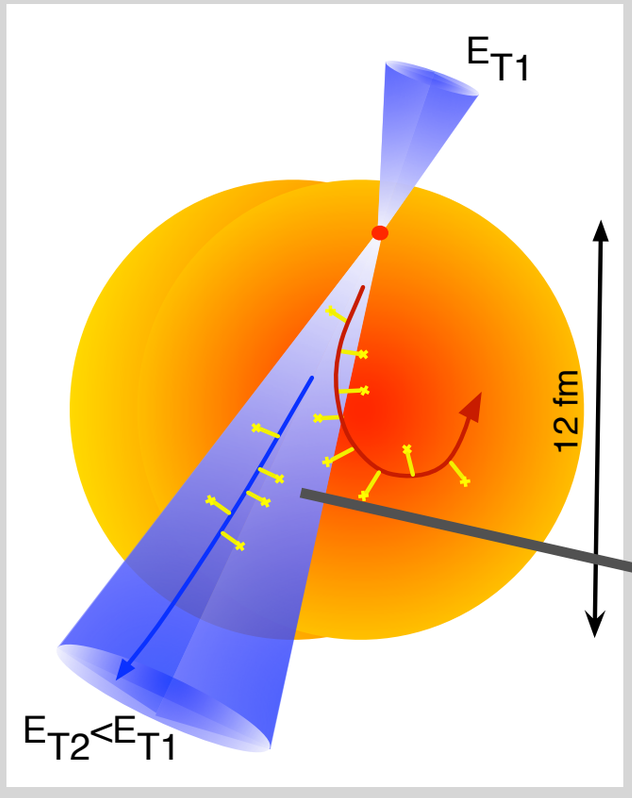

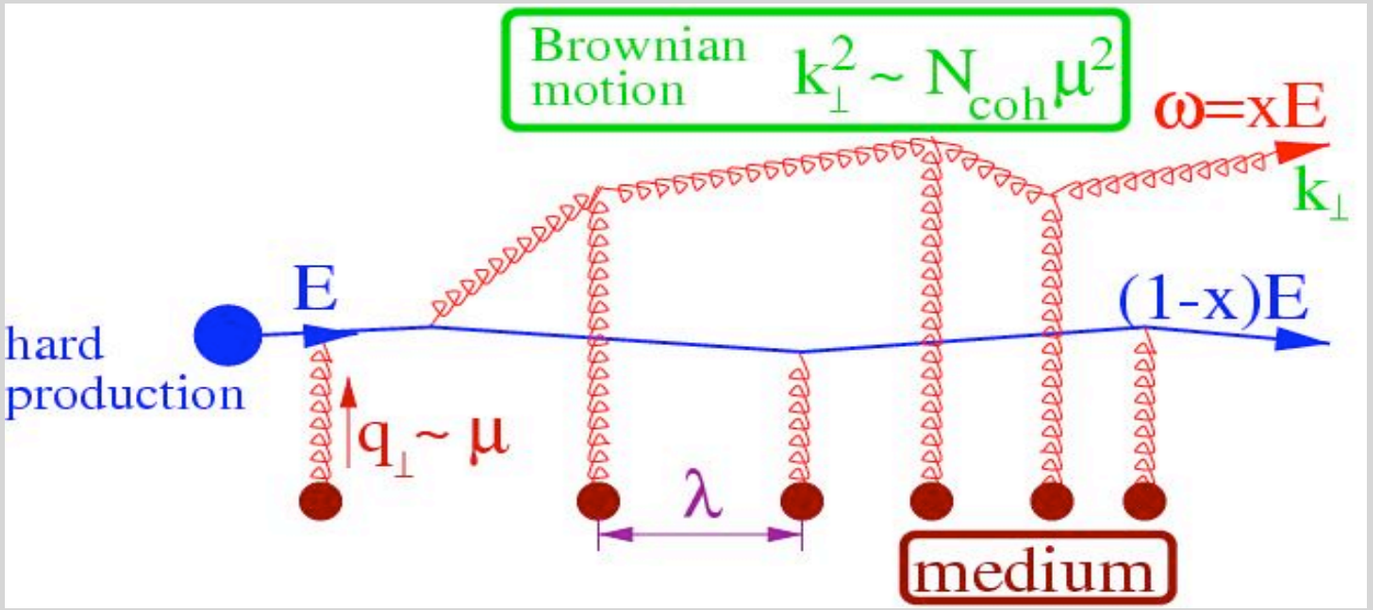

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in general: medium induced parton energy loss and k_t broadnening

abridged to do list [full theory of jet quenching]

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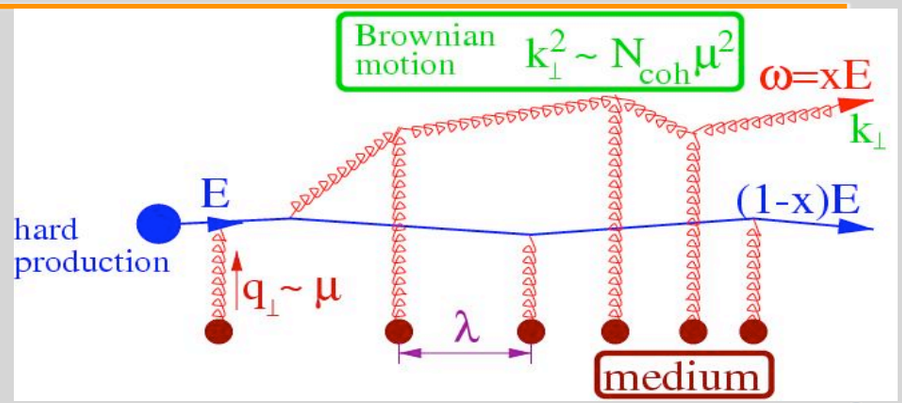
embedding in realistic medium
- hydrodyamical expansion and flow, ...

event generator

parton energy loss

parton energy loss [single emission]



- 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

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

- 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

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

parton energy loss [approaches]

- several pQCD based calculations/frameworks
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for a detailed comparison see 'QGP brick' [arXiv:1106.1106]

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:: none treats parton-medium interactions in rigorous field theoretical terms ::

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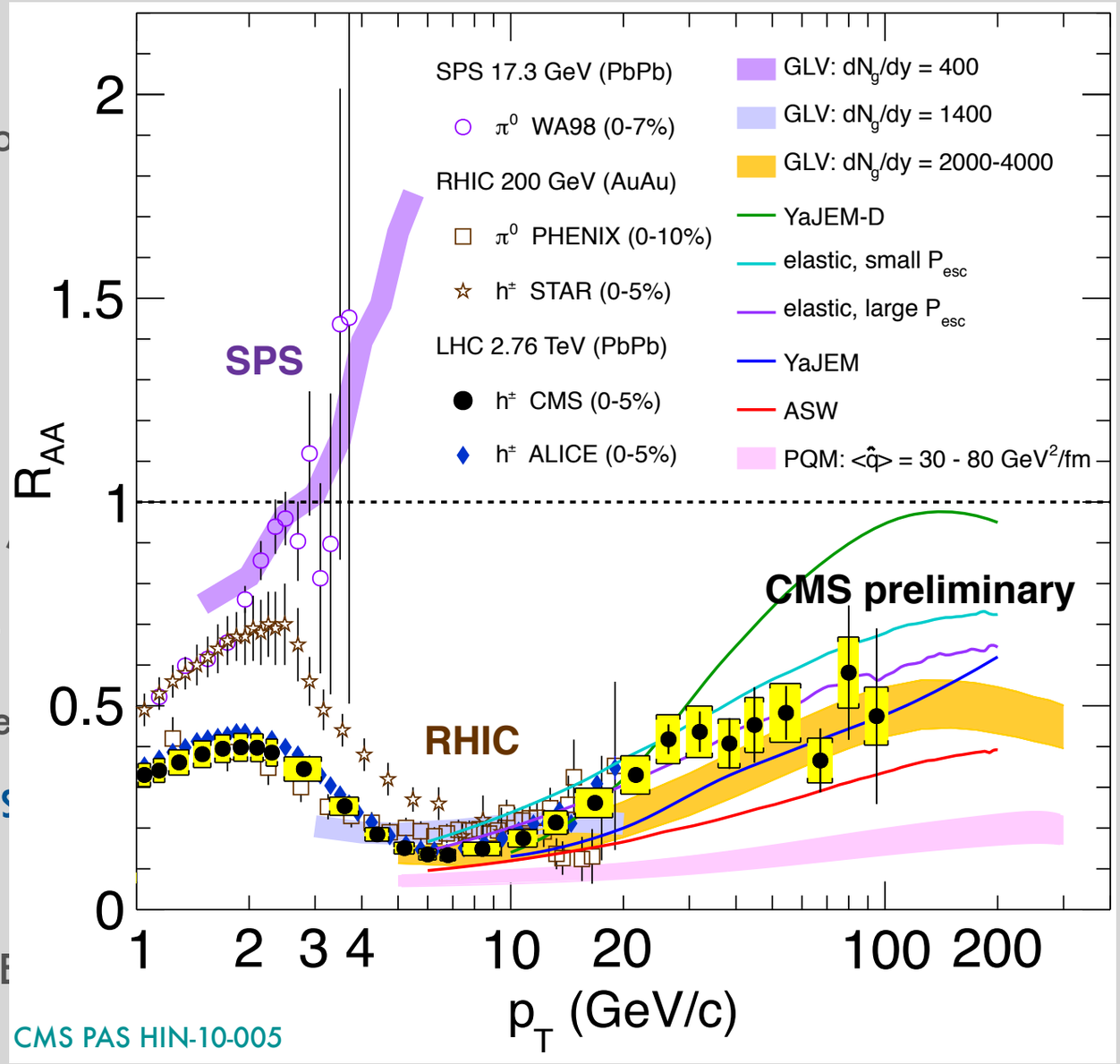

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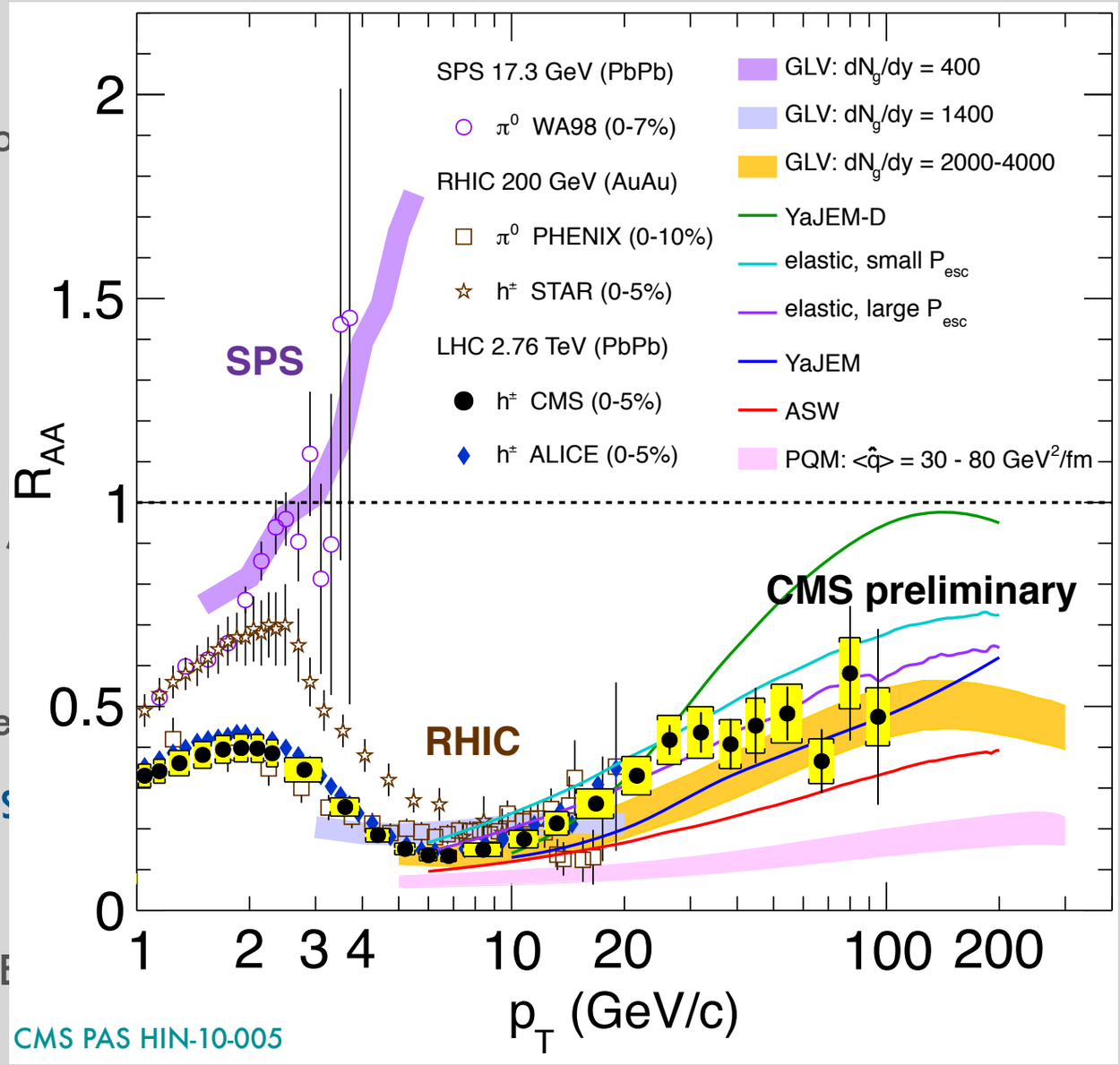

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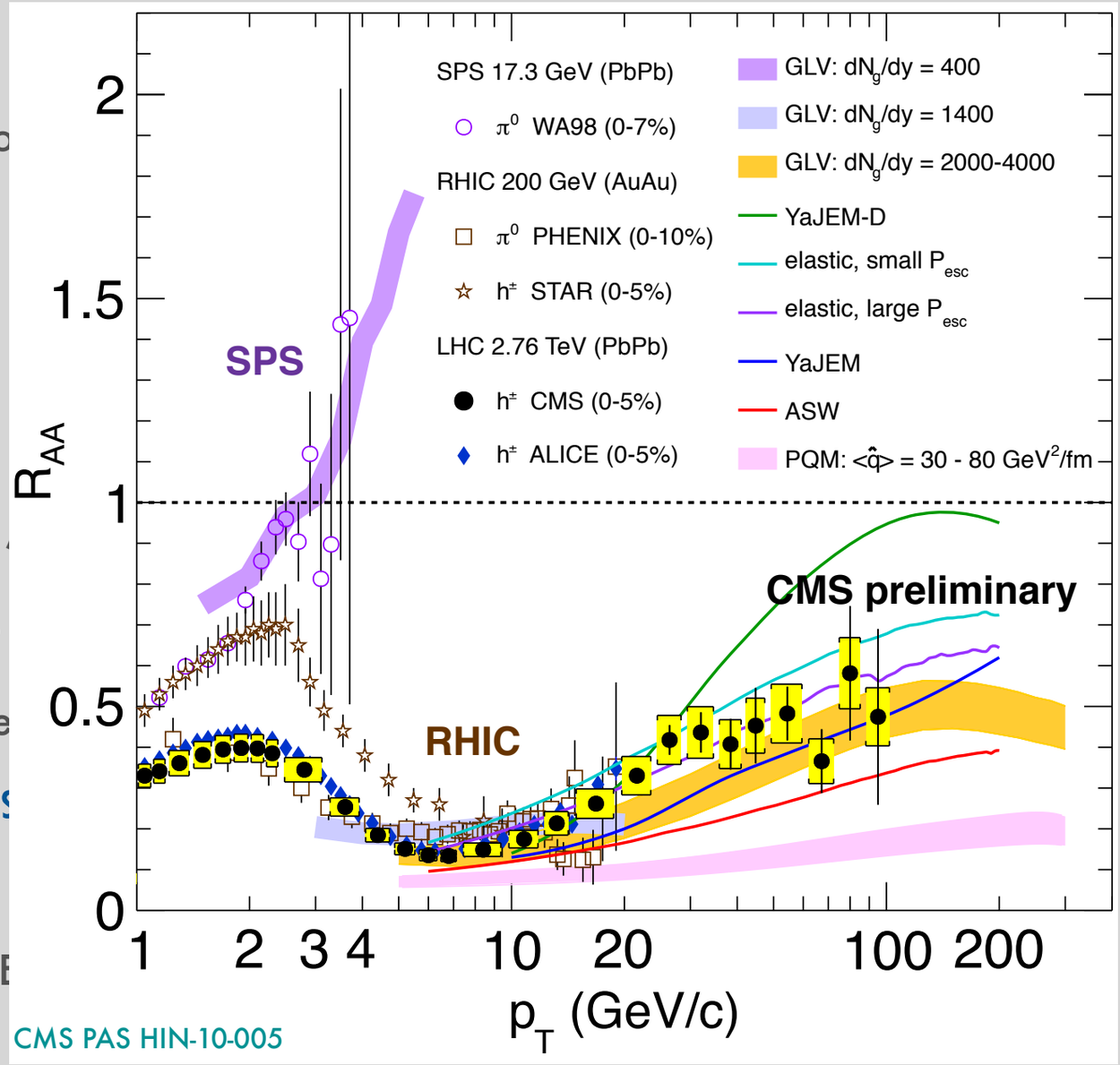
- AdS/CFT based approaches elucidating on the effect of strongly coupled medium



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multiple emissions

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Mehtar-Tani, Salgado, Tywoniuk [2010-11]
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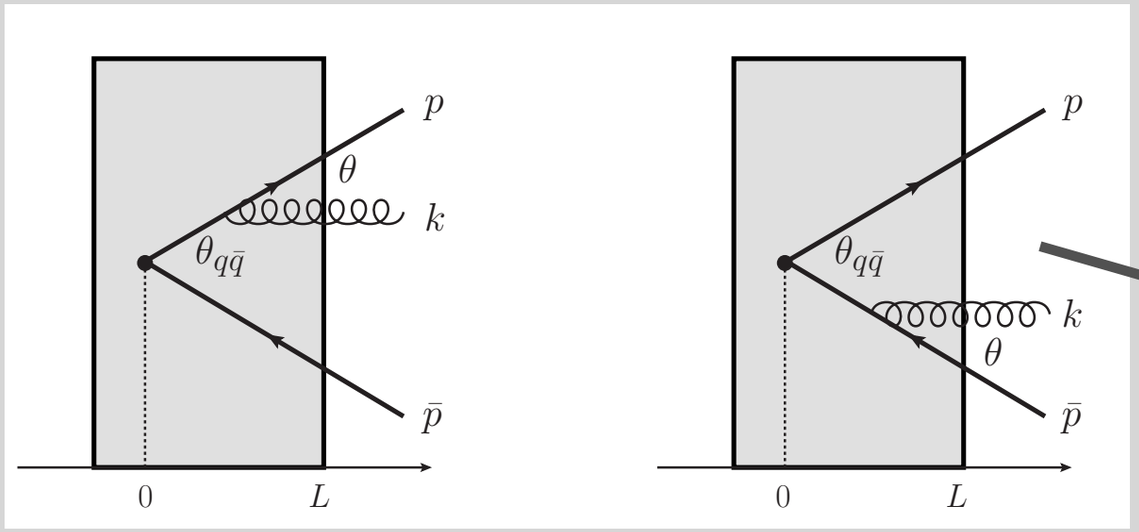
- breakdown of coherence between emitters due to medium momentum transfers and colour exchanges :: no angular ordering

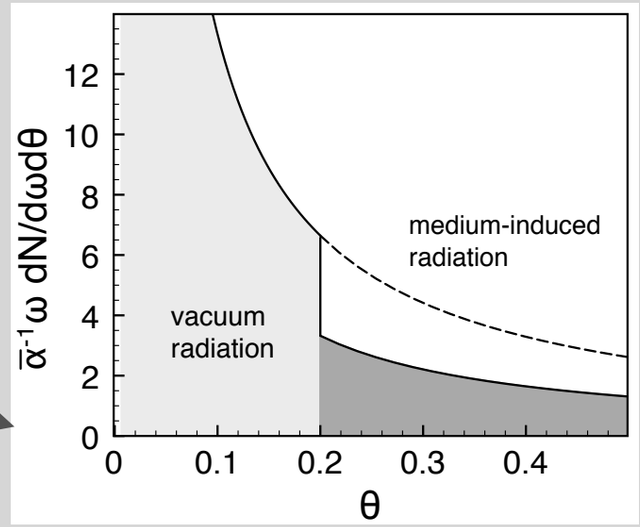
  ↪ medium induced radiation out-of-cone [anti-angular ordering]

  ↪ so far limited to singlet and octet antennas

↪ not yet implemented at monte carlo level



interference



multiple emissions

- rigorous attempts to understand interference between successive emissions

Mehtar-Tani, Salgado, Tywoniuk [2010-11]
Casalderrey-Solana, Iancu [2011]

- breakdown of coherence between emitters due to medium momentum transfers and colour exchanges :: no angular ordering

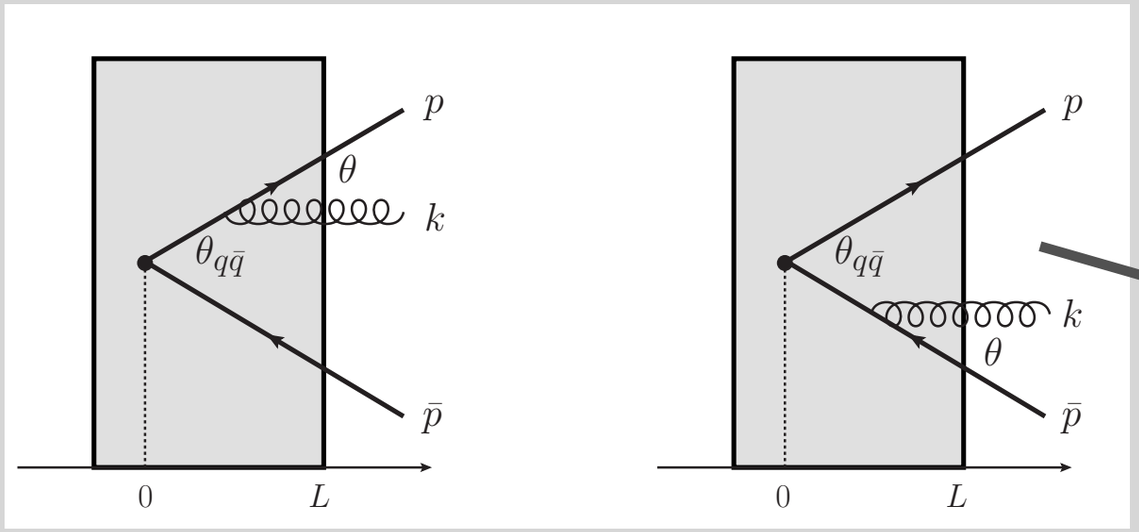
  ↪ medium induced radiation out-of-cone [anti-angular ordering]

  ↪ so far limited to singlet and octet antennas

↪ not yet implemented at monte carlo level

↪ realistic quark-gluon antenna

Abreu, Apolinário, Casalderrey-Solana, Milhano [in progress]



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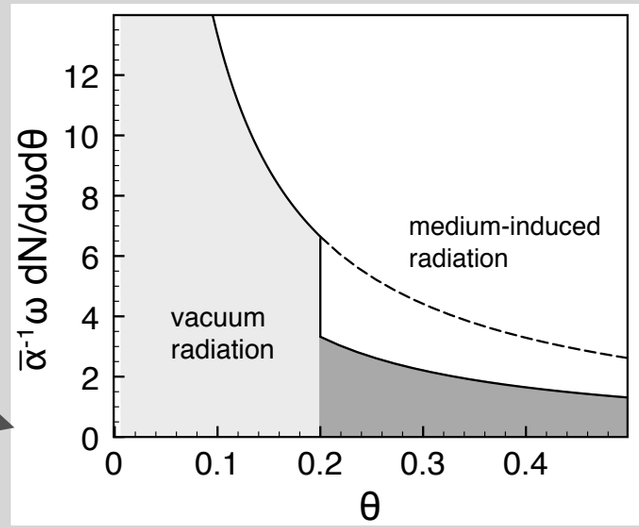

mass effects [heavy quarks]

- massive partons expected theoretically to lose less energy due to veto of radiation at small angle [the dead cone effect]

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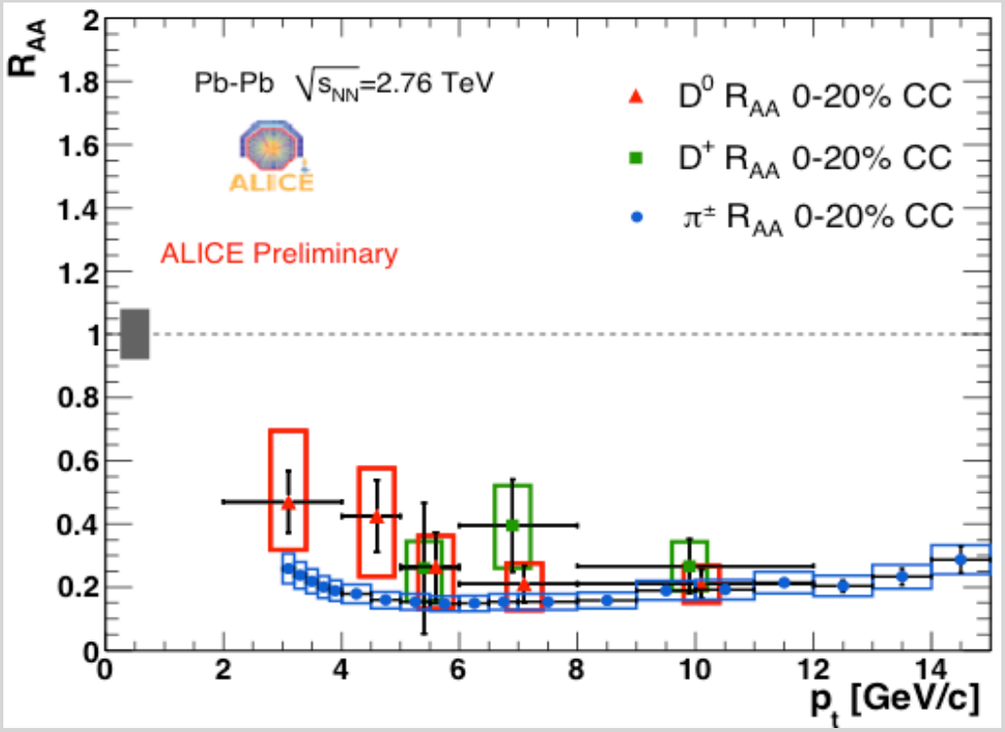

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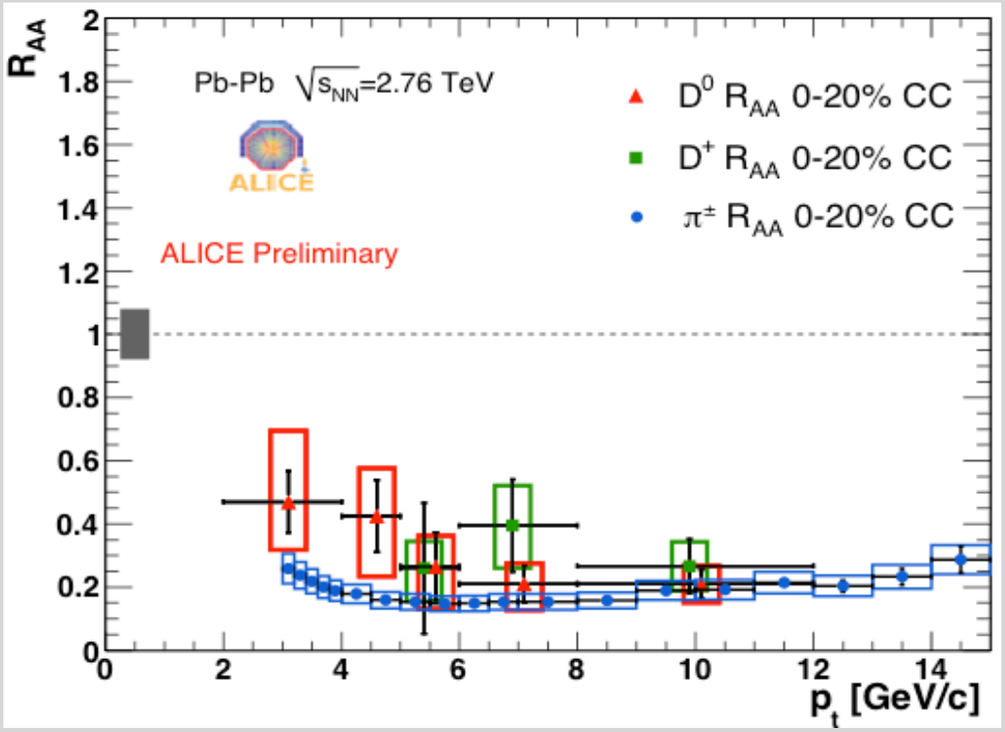

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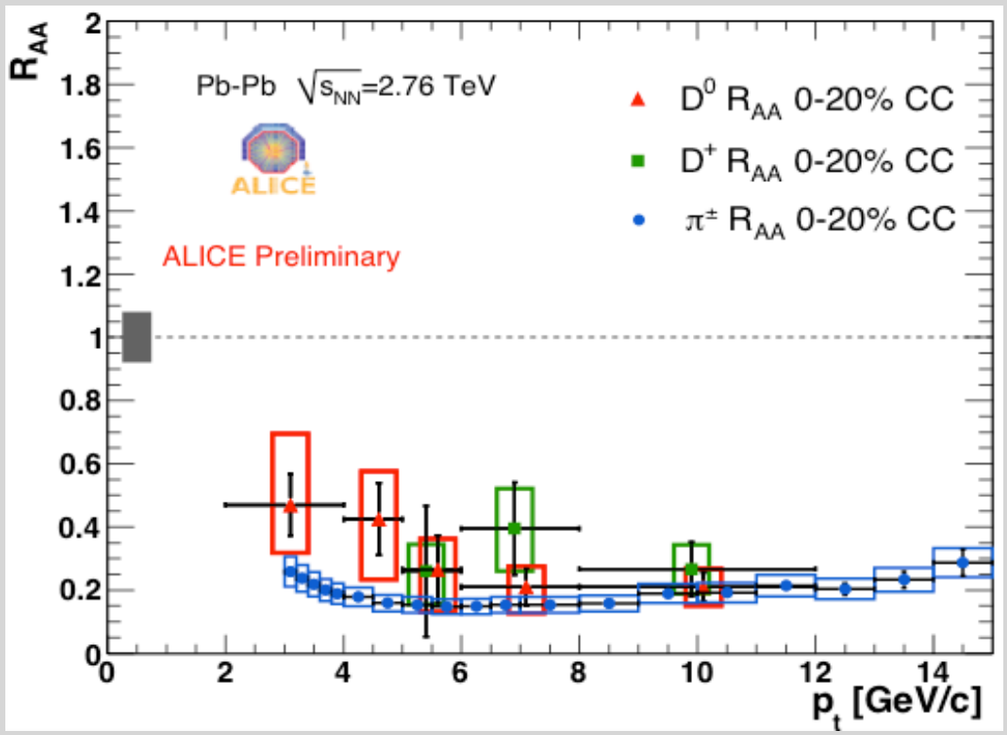
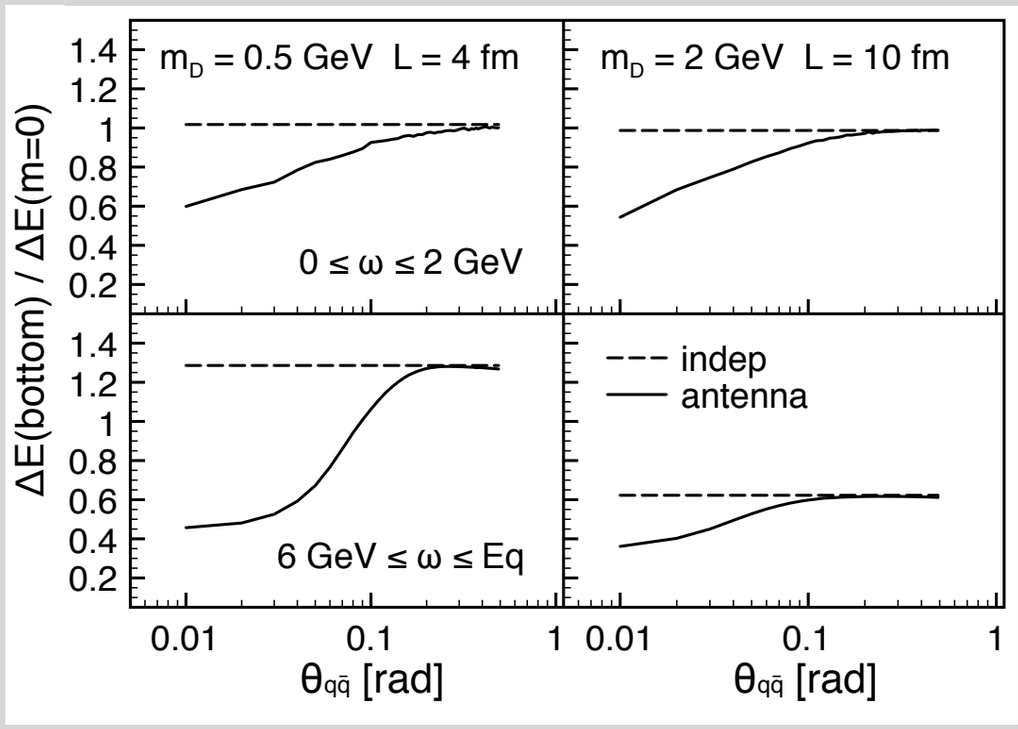
  ↪ calculations generalized for massive case

Armesto, Ma, Mehtar-Tani, Salgado, Tywoniuk [2011]





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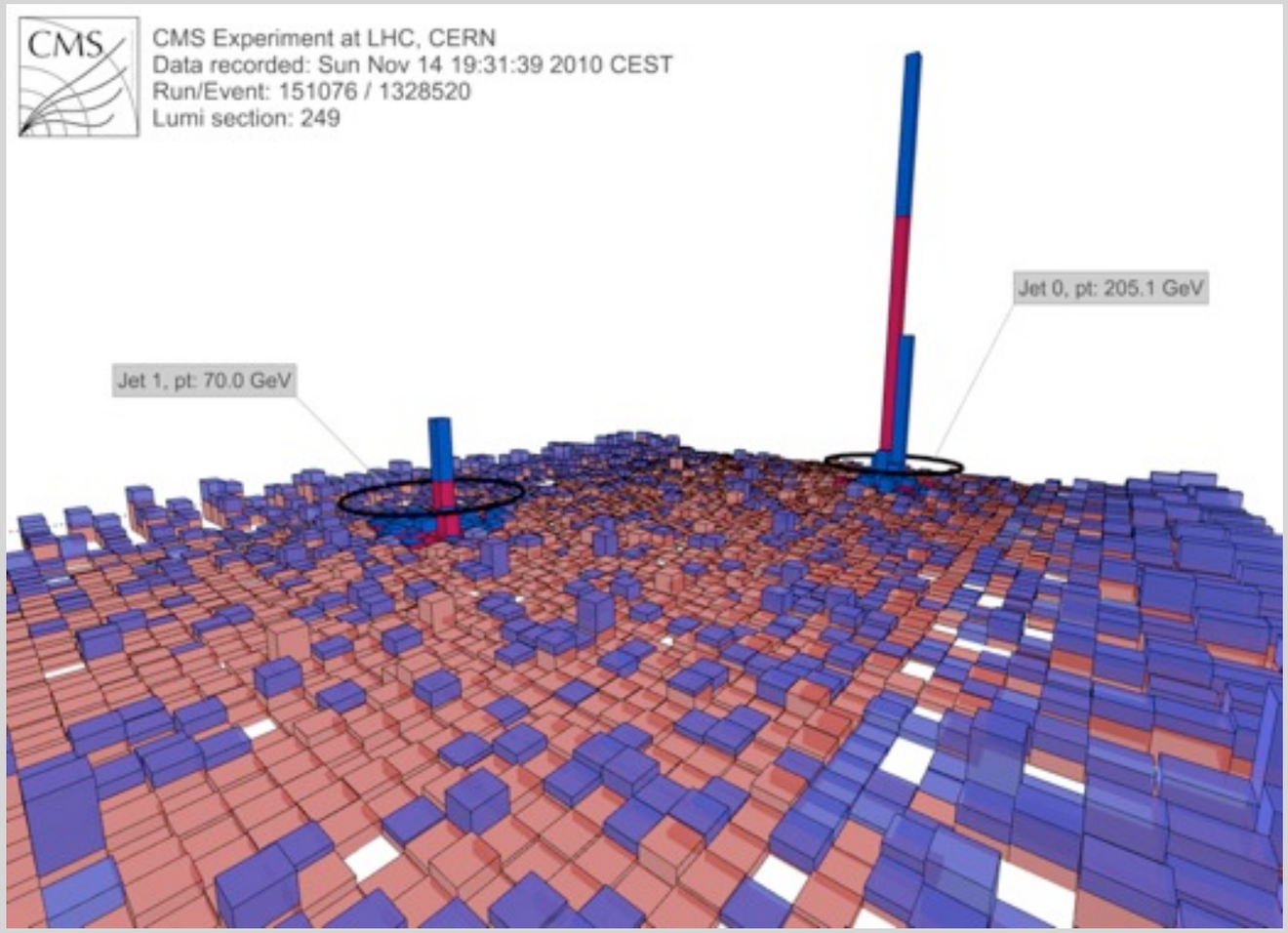
new challenges from data



- jet reconstruction possible in HIC

  Cacciari, Rojo, Salam, Soyez [2010]

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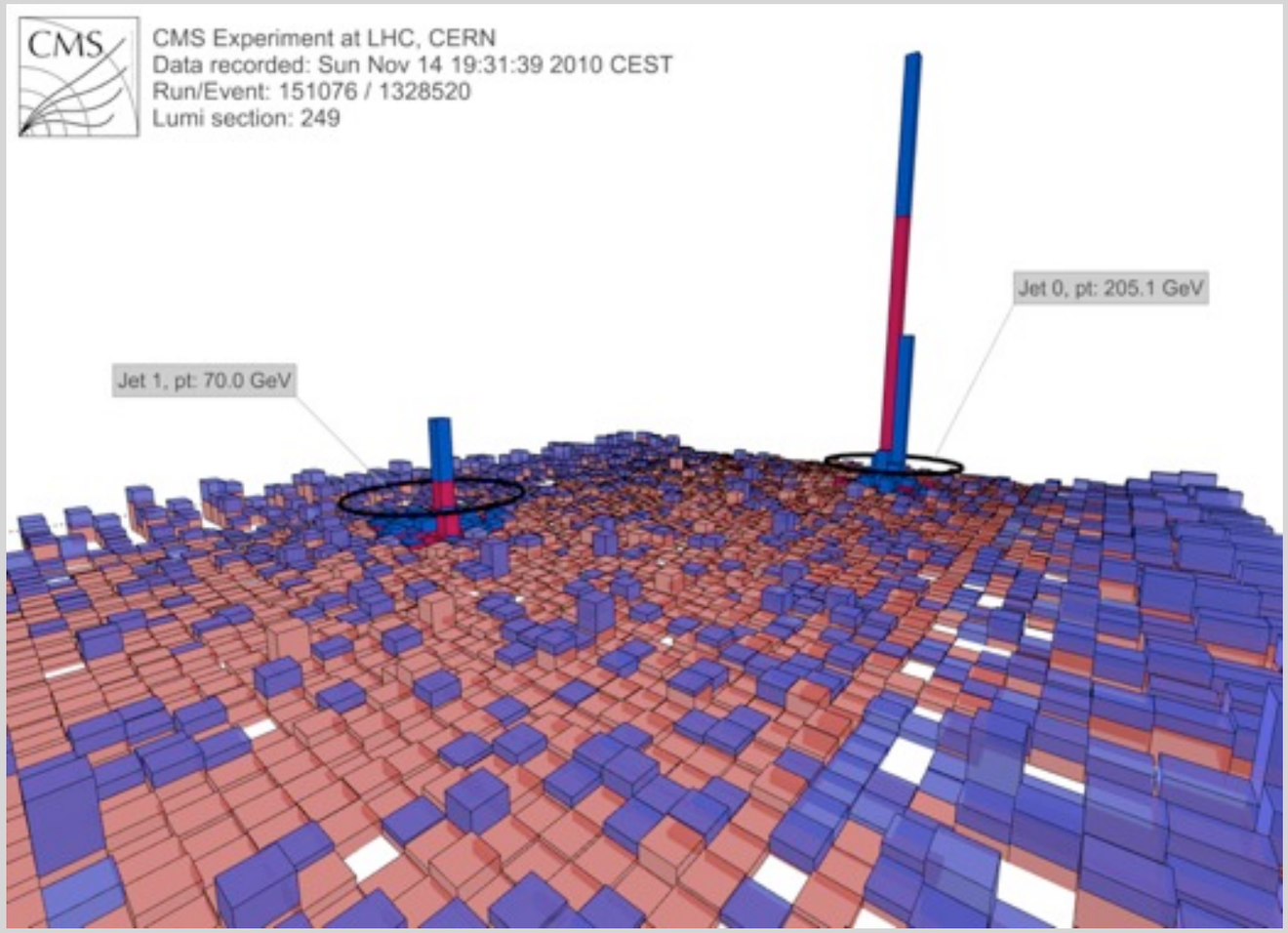

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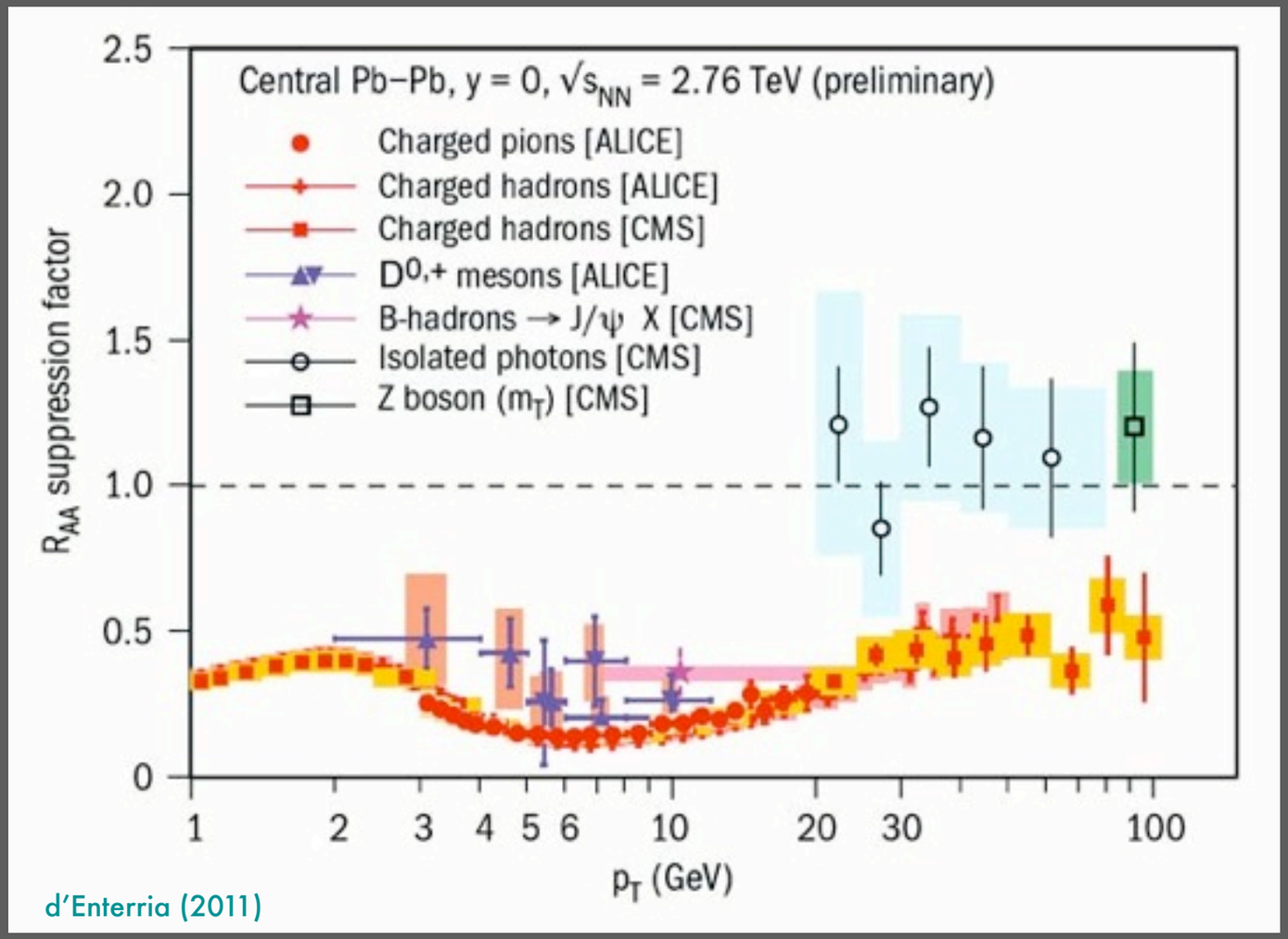
parton energy loss calculations insufficient, by construction, to address fully reconstructed jets

early lessons from LHC data

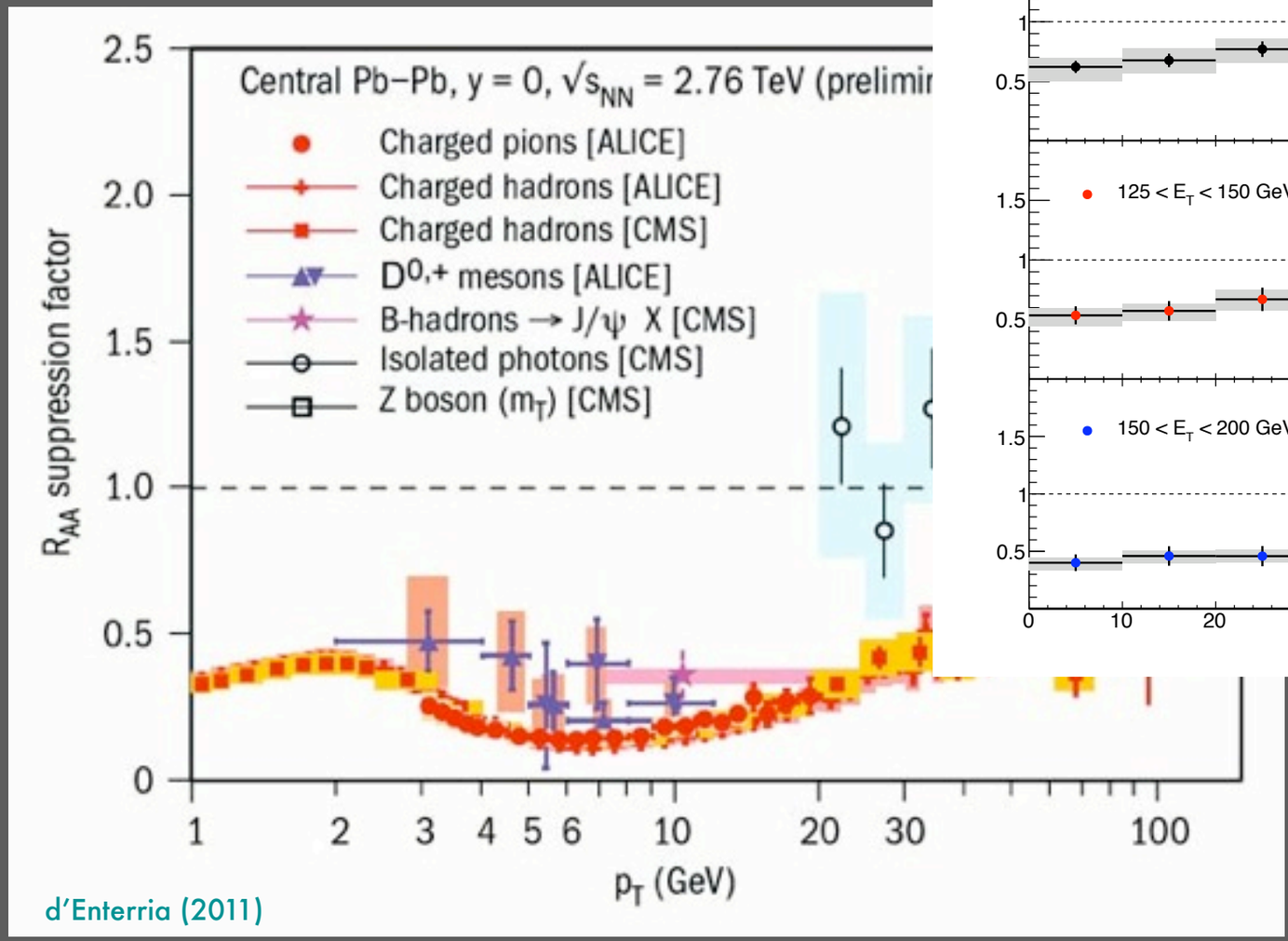


d'Enterria (2011)

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

leading hadron suppression persistent to highest available p_t

early lessons from LHC data



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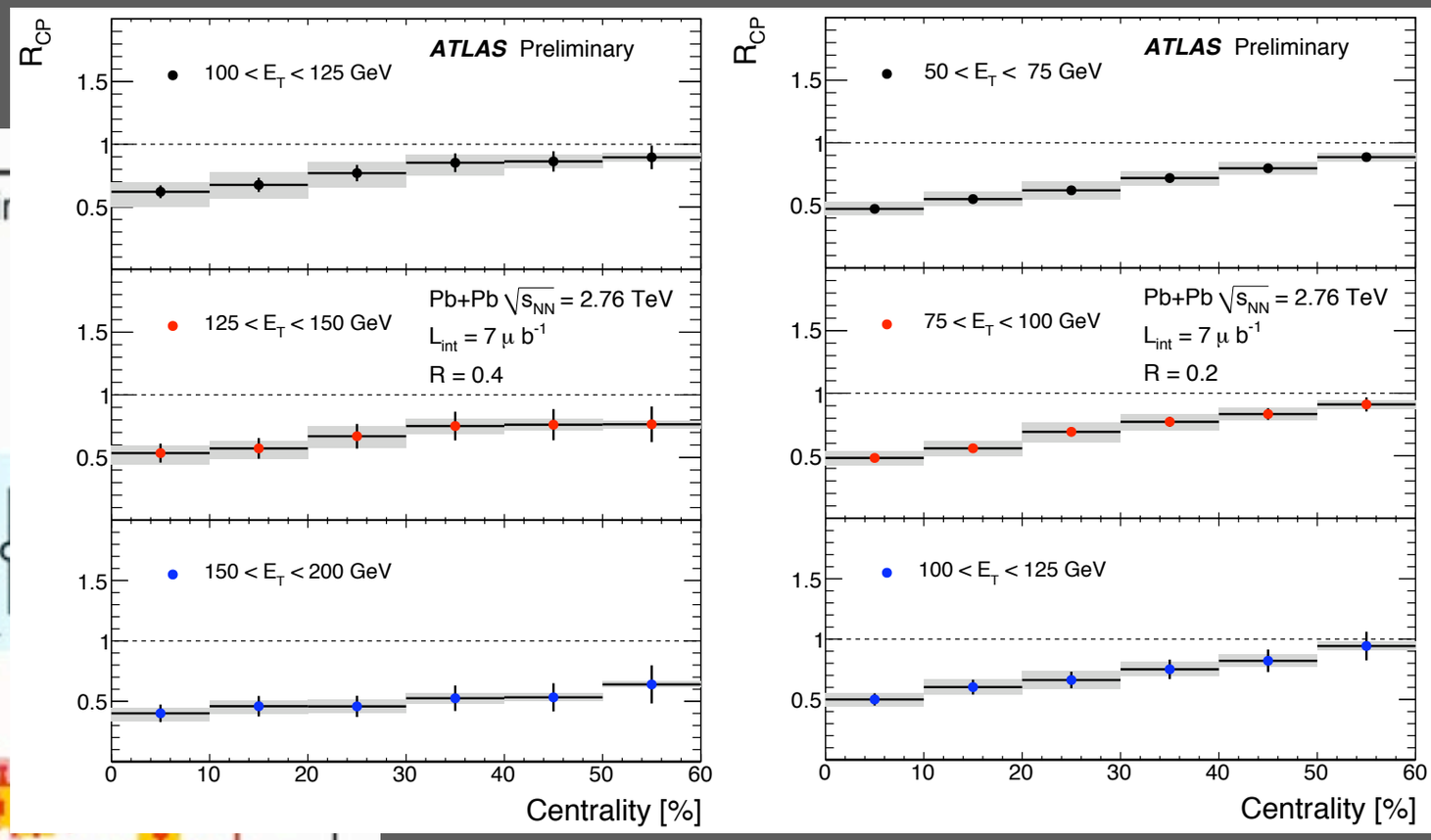

jets also strongly suppressed

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

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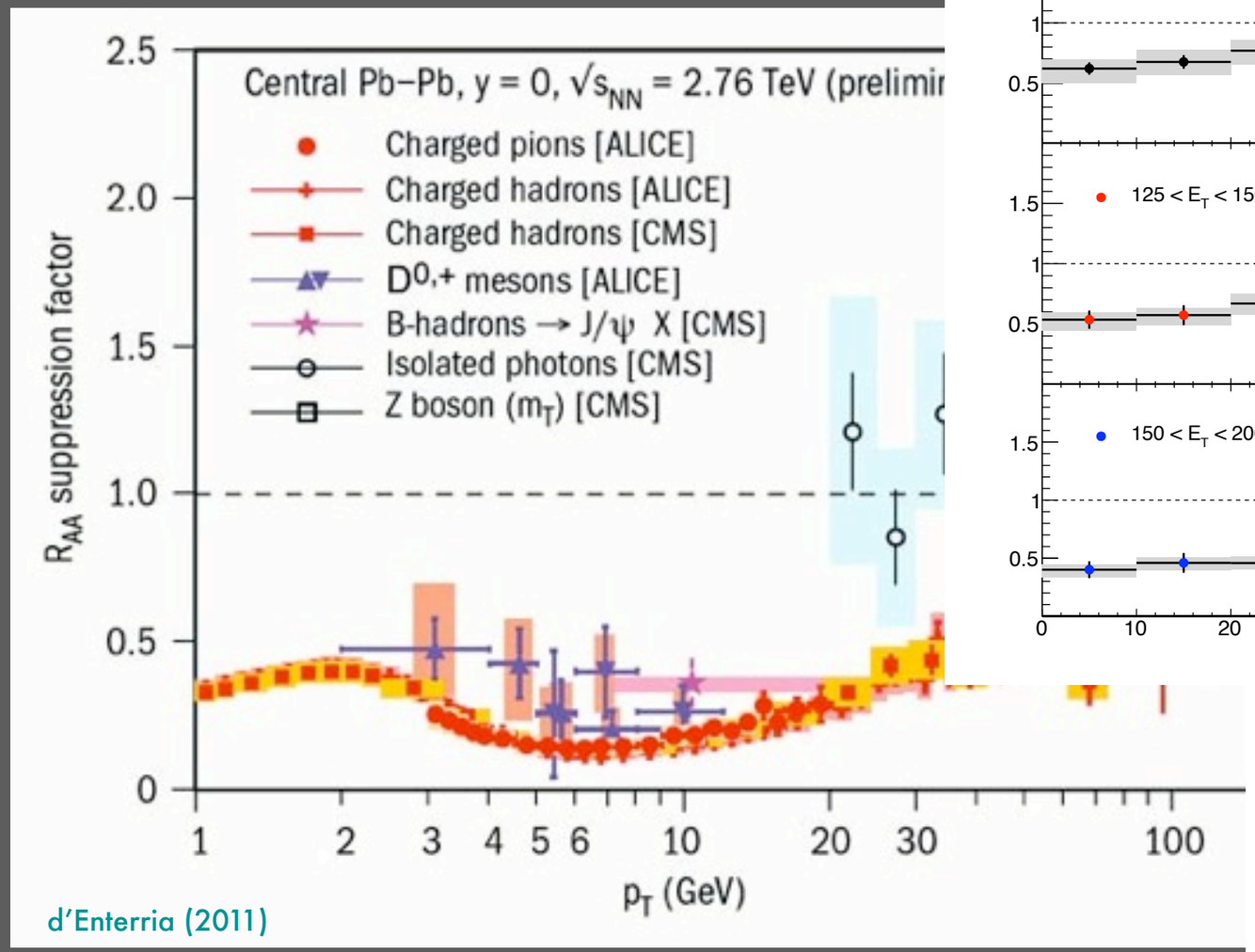

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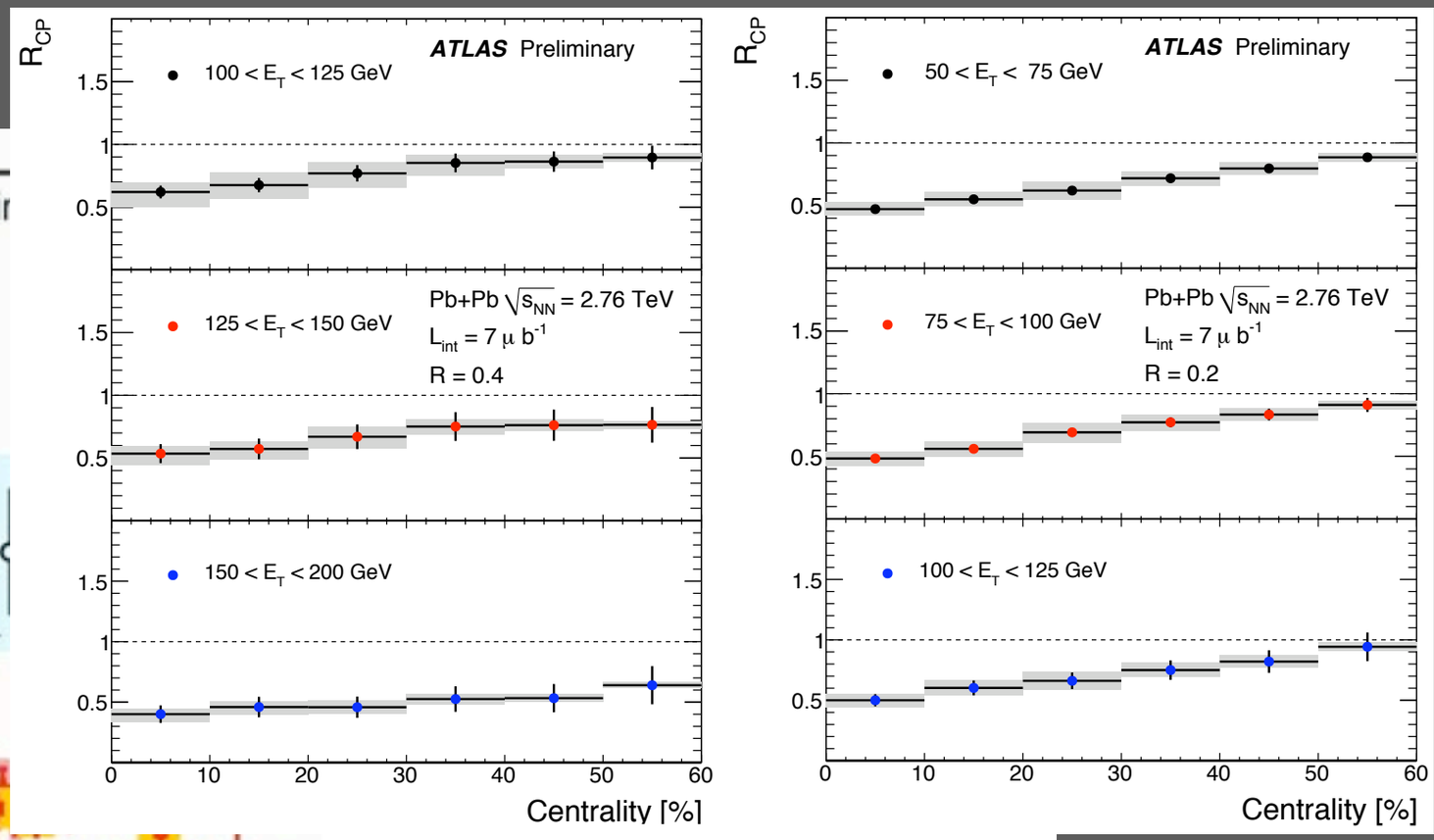
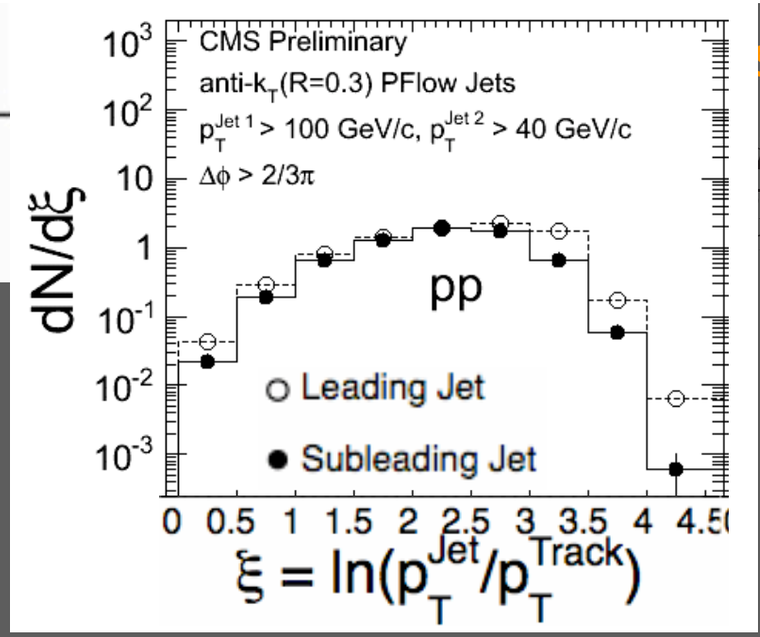


strongly suppressed

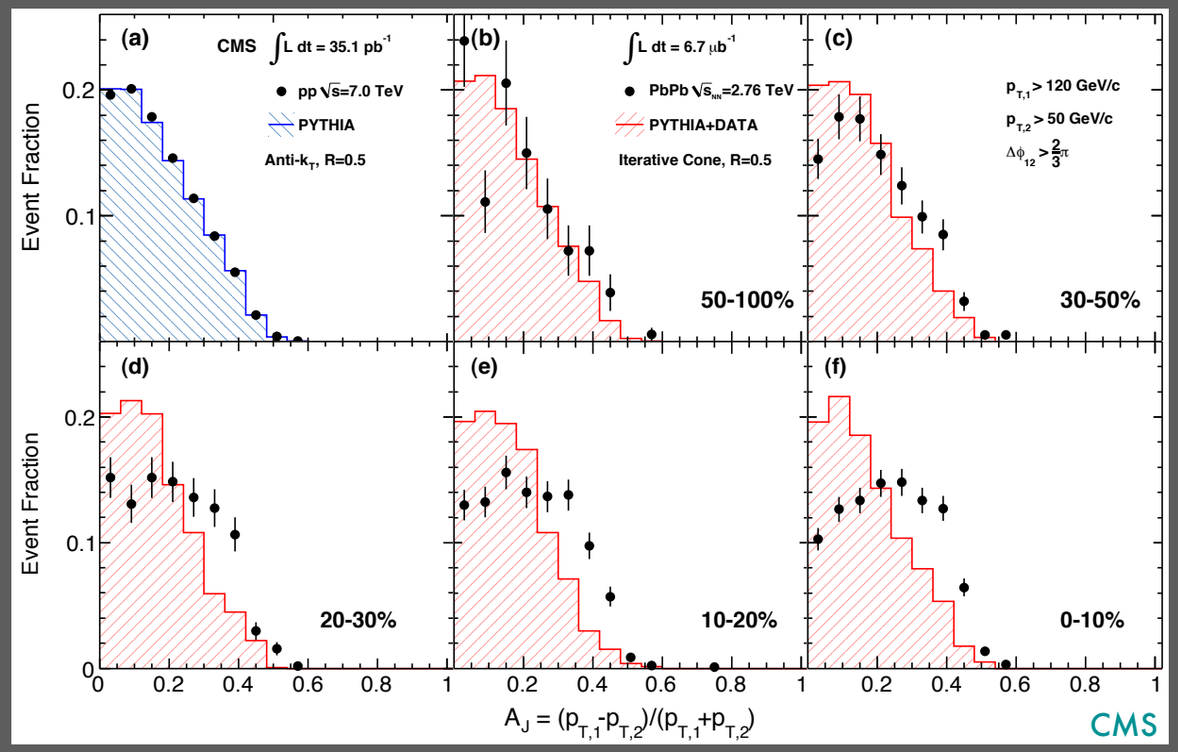
$$\frac{d\eta dp_T}{{}^{P}/d\eta dp_T}$$

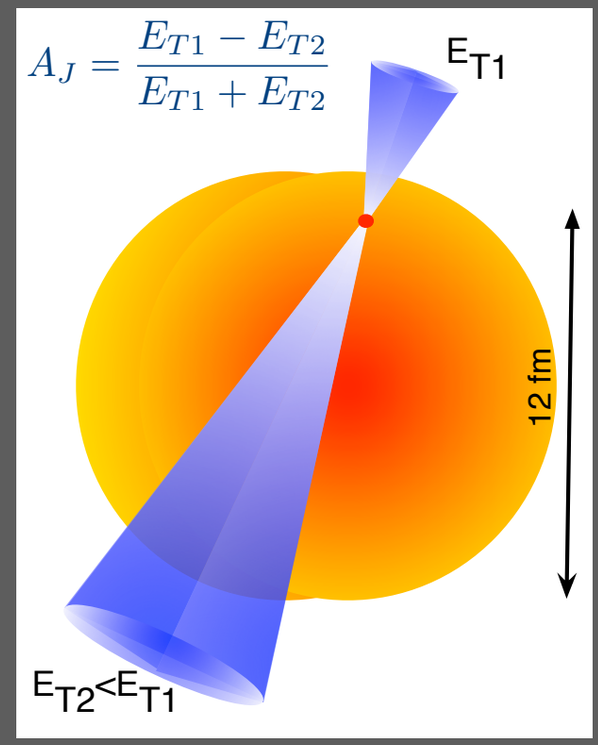


unmodified fragmentation

leading hadron suppression persistent to highest available p_t

early lessons from LHC data
:: di-jet asymmetry

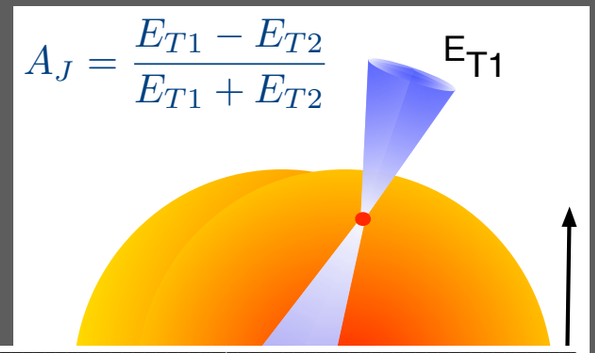


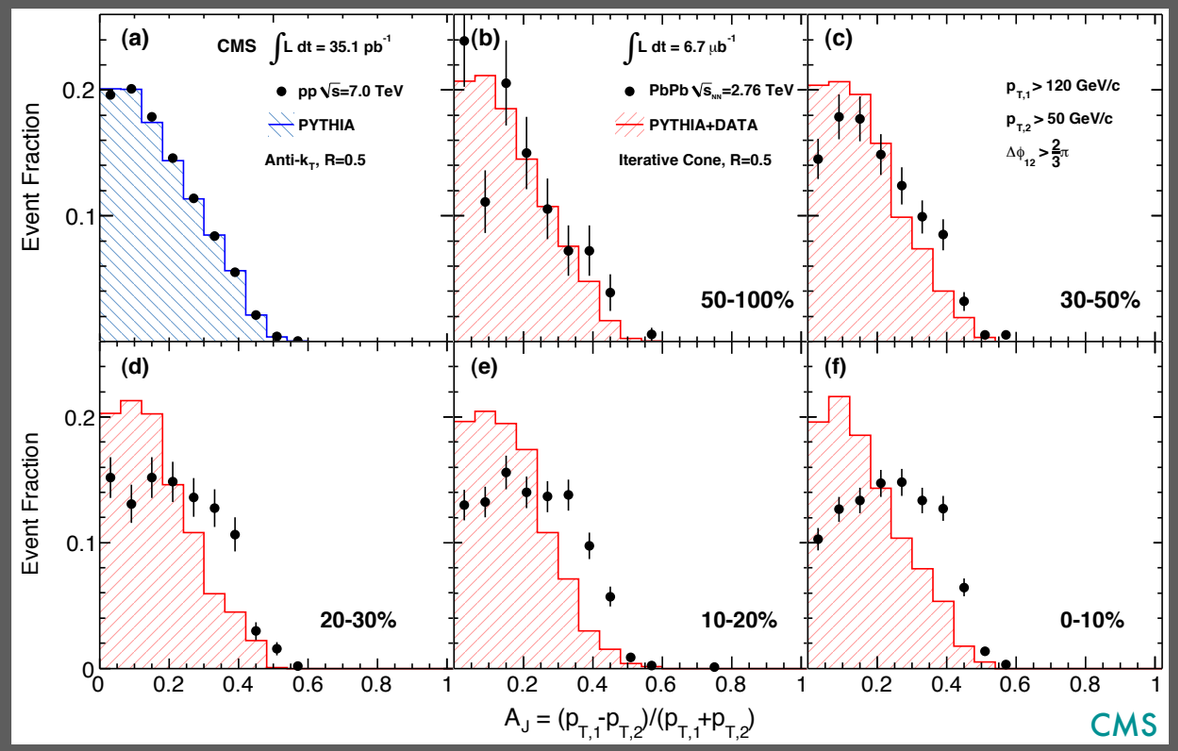


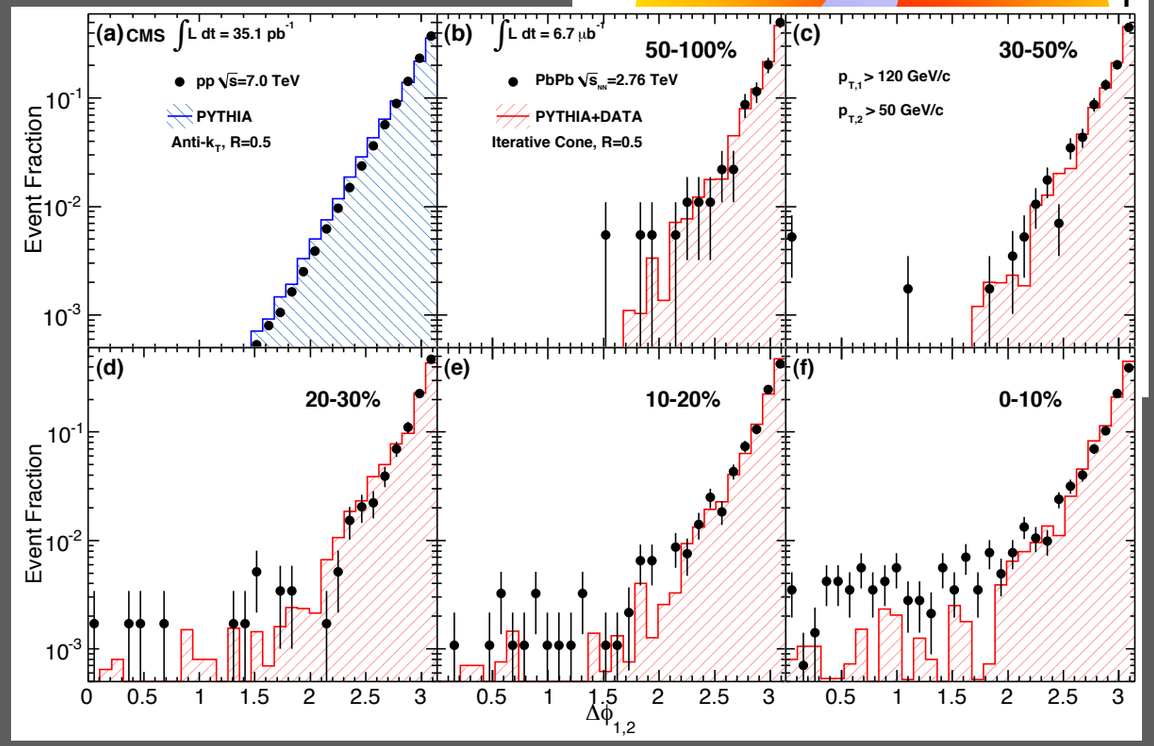
significant enhanced di-jet asymmetry

early lessons from LHC data
:: di-jet asymmetry

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







significant enhanced di-jet asymmetry

without jet deflection

early lessons from LHC data
:: di-jet asymmetry

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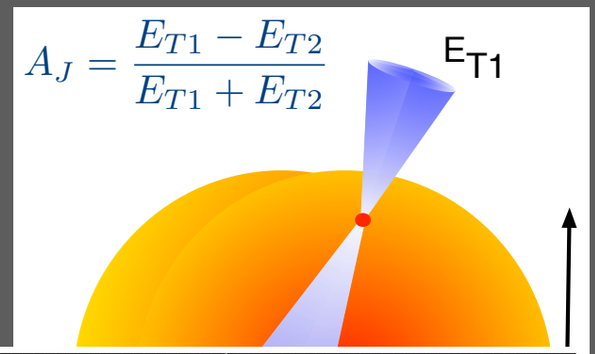
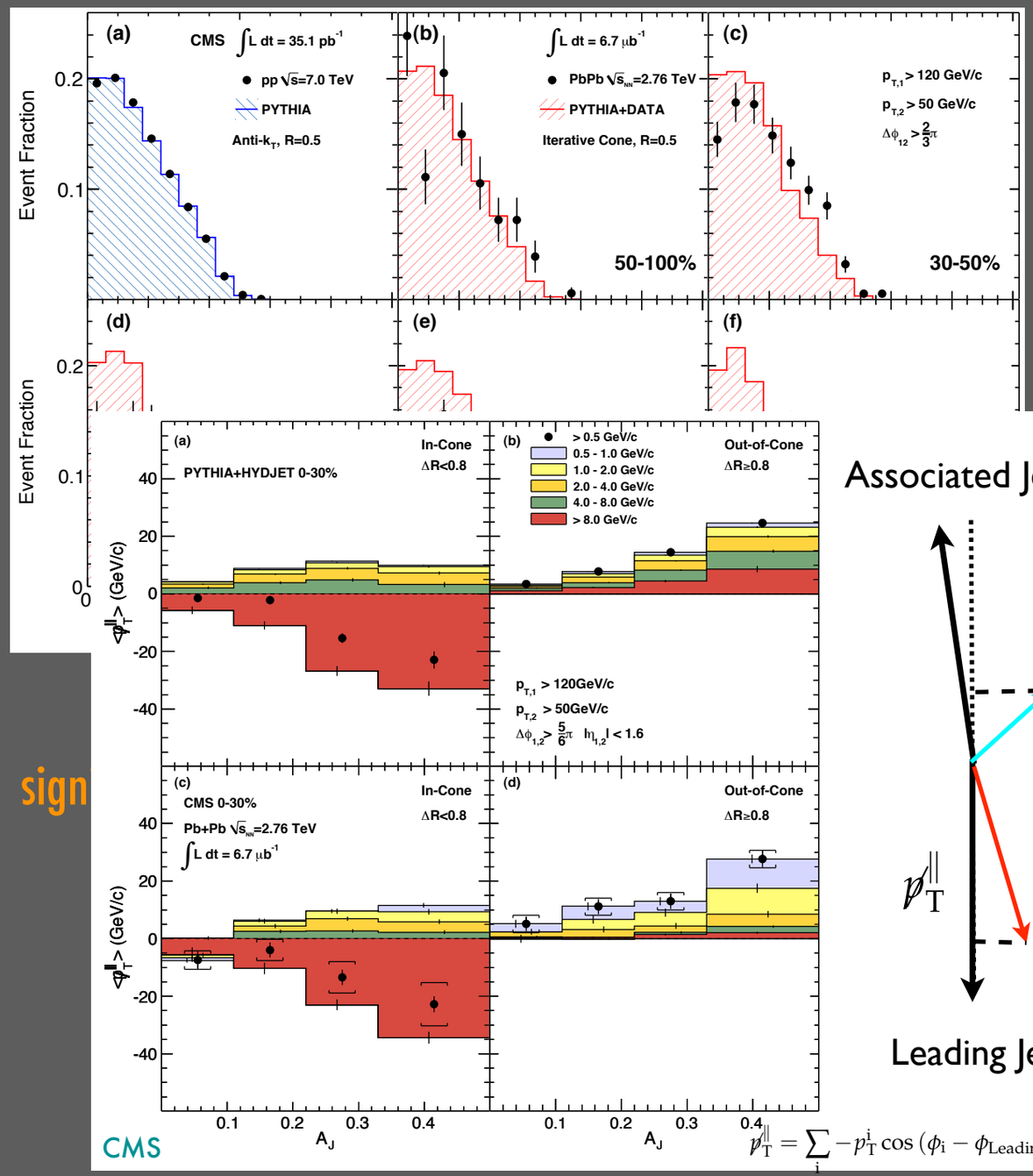
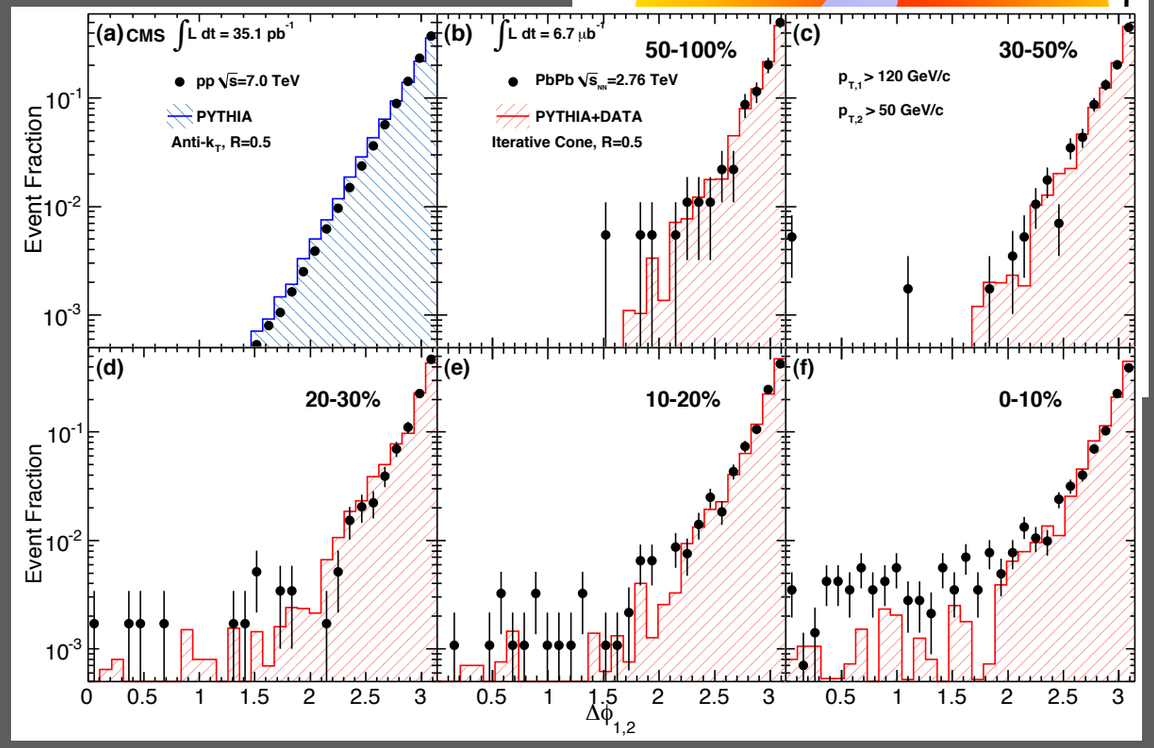






Associated Jet

Leading Jet

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

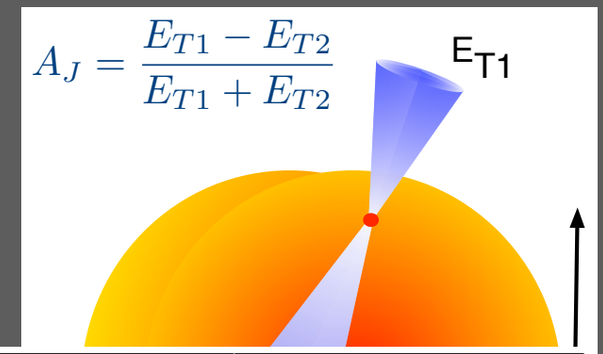
sign

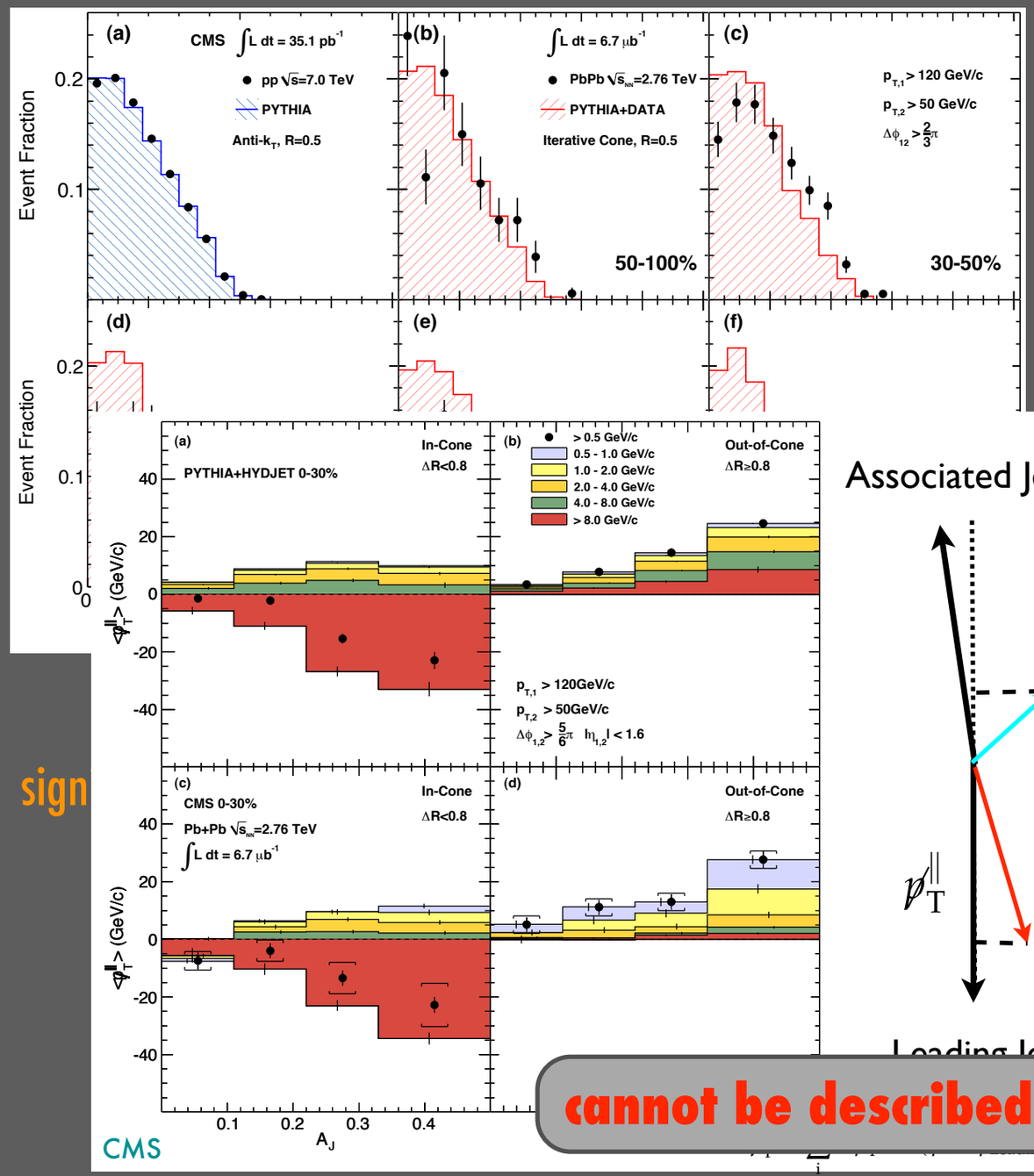
without jet deflection

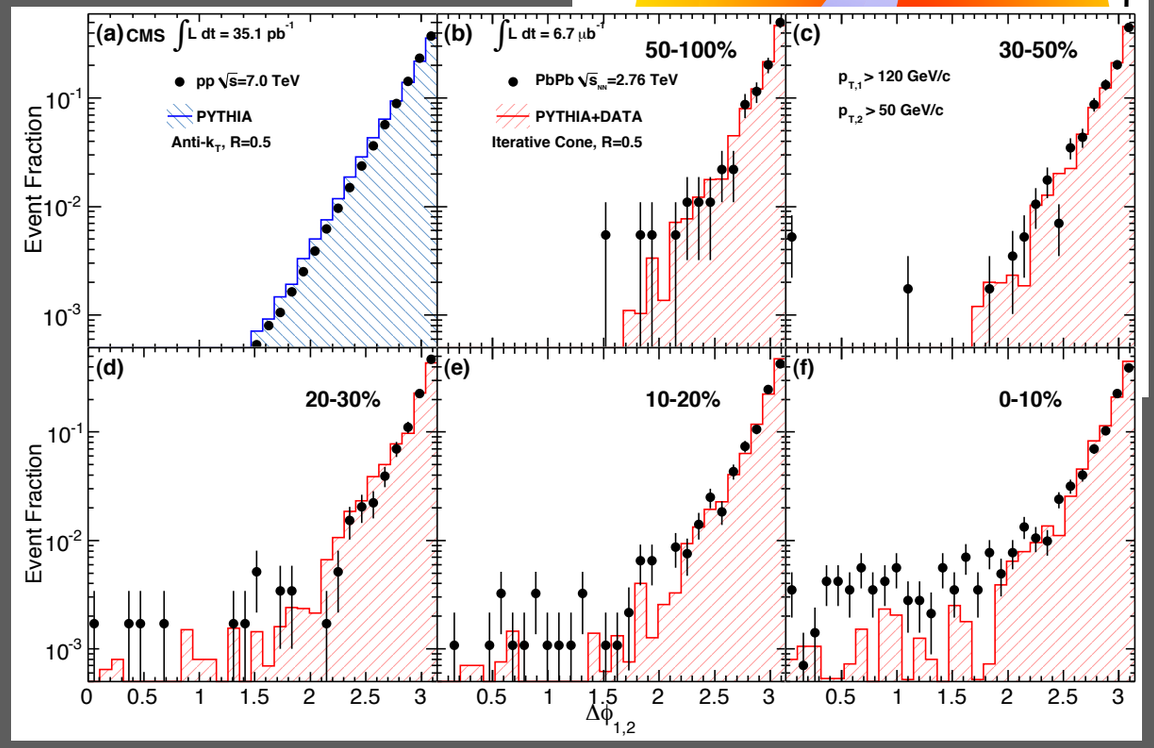
lost energy recovered at large angles as soft particles

early lessons from LHC data
:: di-jet asymmetry

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







sign

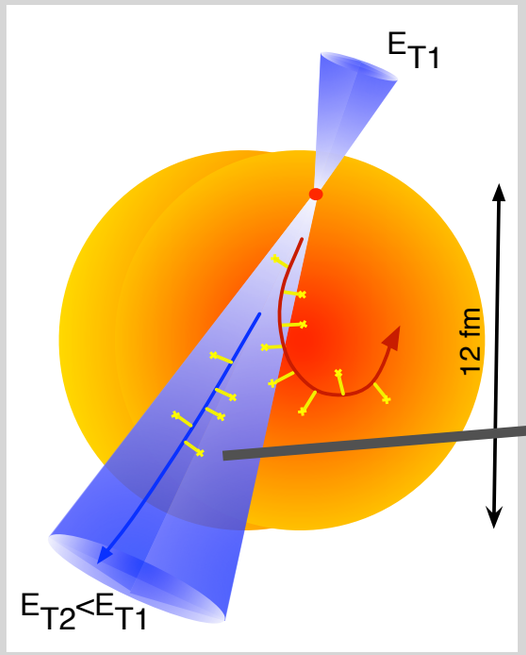
without jet deflection

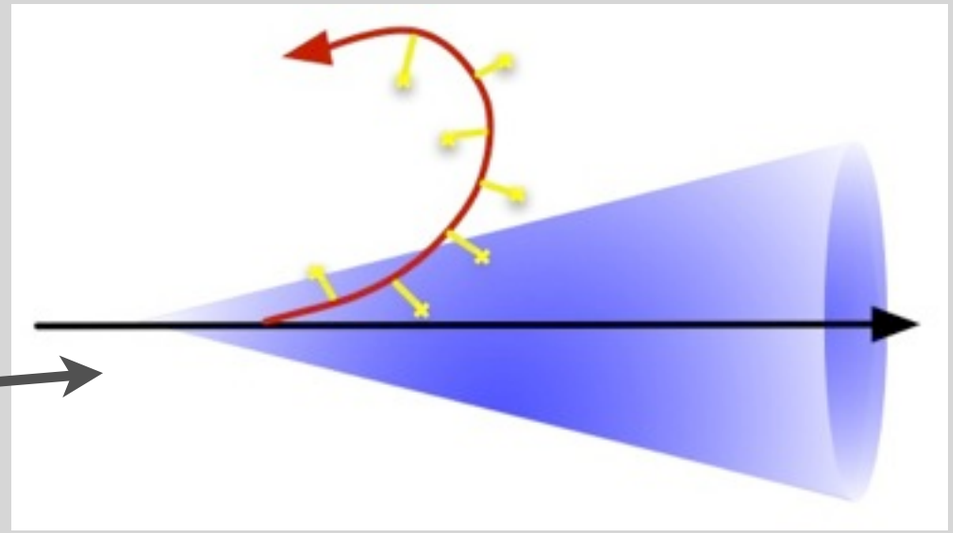
cannot be described by radiative energy loss alone

lost energy recovered at large angles as soft particles

going beyond parton energy loss
:: dynamics of radiated quanta ::

transport of soft quanta away from jet





transport of radiated gluons

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

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

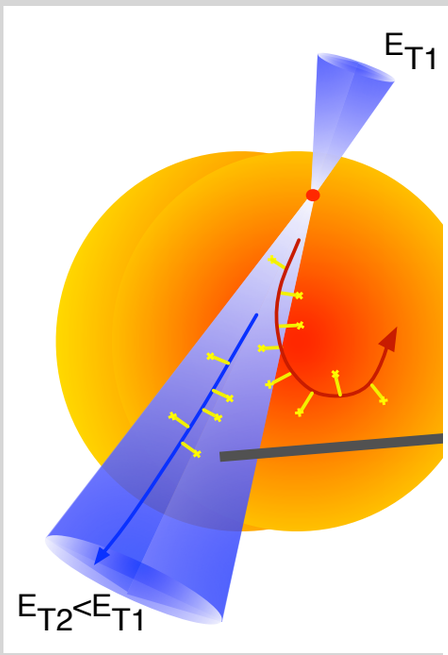
- in the presence of a medium soft modes are formed early

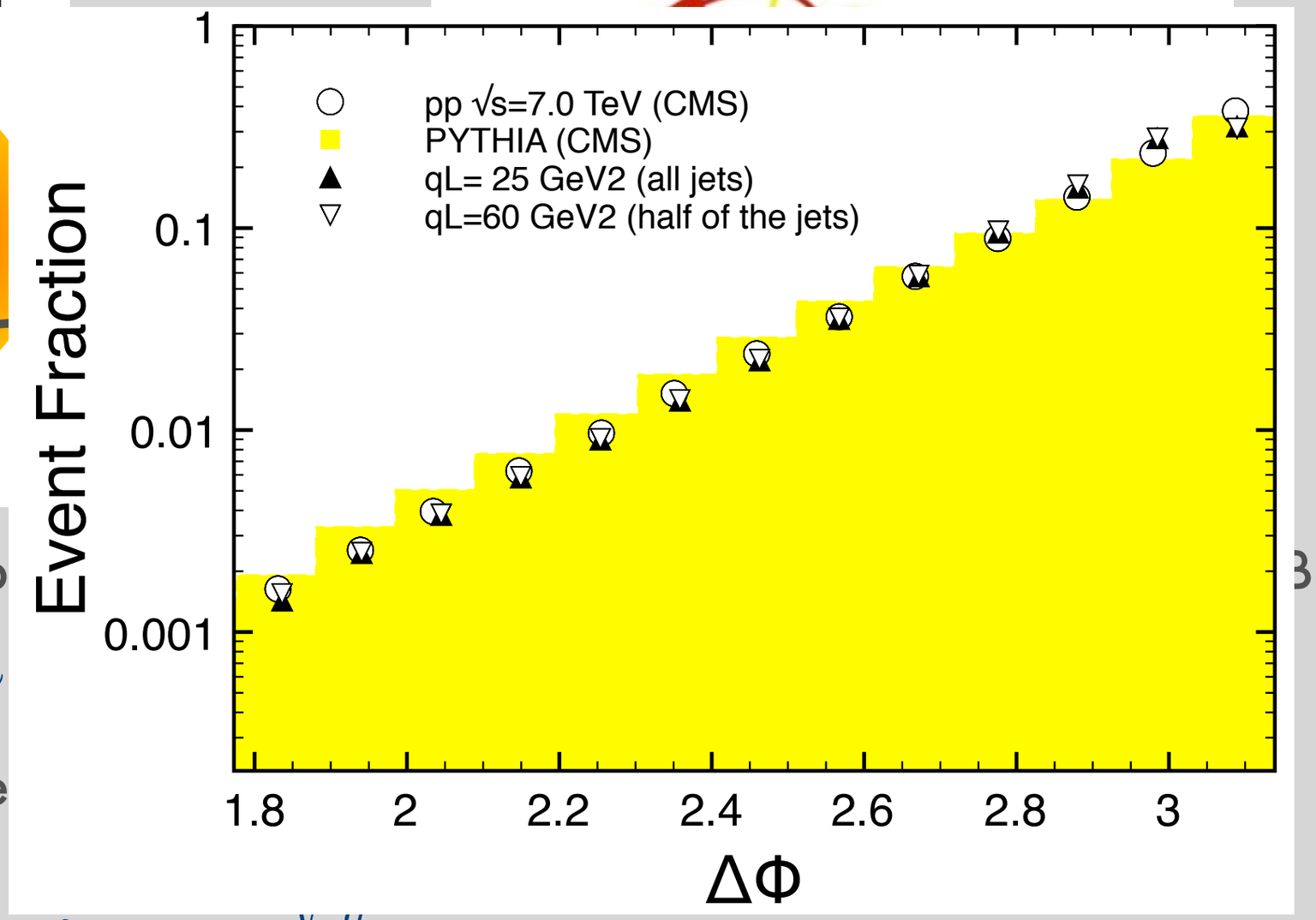
$$\tau \sim \frac{\omega}{k_\perp^2} \underset{\langle k_\perp^2 \rangle \sim \hat{q}\tau}{\longrightarrow} \langle \tau \rangle \sim \sqrt{\frac{\omega}{\hat{q}}}$$

- sufficiently soft modes are completely decorrelated from the jet direction

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

transport of soft quanta away from jet





- all jet comp … Brownian motion]

$$\langle k_\perp \rangle \sim$$

- in the prese…

$$\tau \sim \frac{\omega}{k_\perp^2} \qquad \langle k_\perp^2 \rangle \sim \hat{q}\tau \qquad \sqrt{\quad} \; q$$

- sufficiently soft modes are completely

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

results in jet energy loss with no significant jet deflection
energy is lost by transport of soft components to large angles
efficient even in absence of medium induced radiation

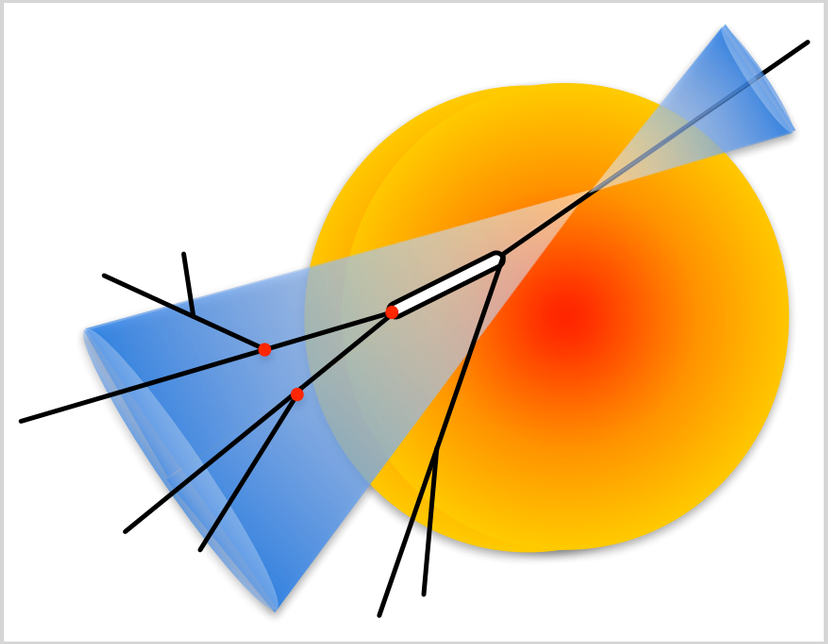
Casalderrey-Solana, Milhano, Wiedemann [2010]
Qin, Muller [2010]
Young, Schenke, Jeon, Gale [2011] :: MARTINI

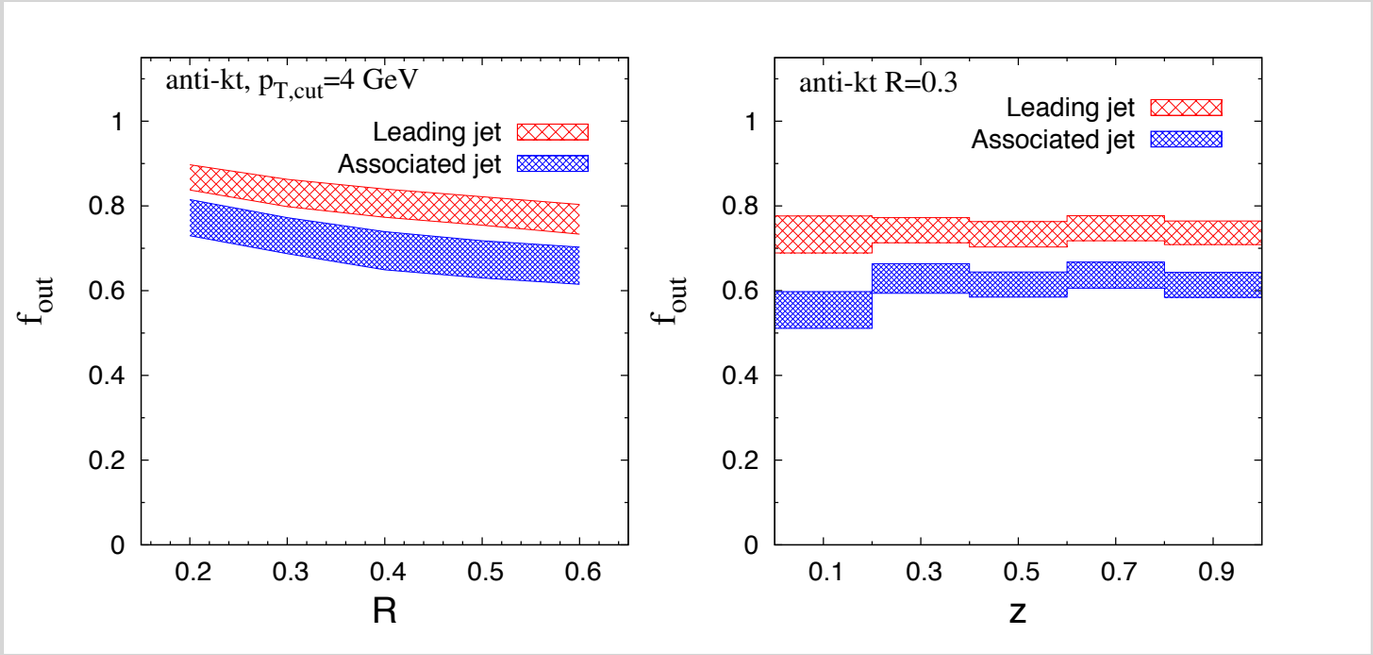
going beyond parton energy loss
:: colour exchanges with medium ::
:: hadronization ::

in and out

- most branchings in parton shower occur outside the medium; hadronization likely to happen outside

Casalderrey-Solana, Milhano, Quiroga-Arias [2011]





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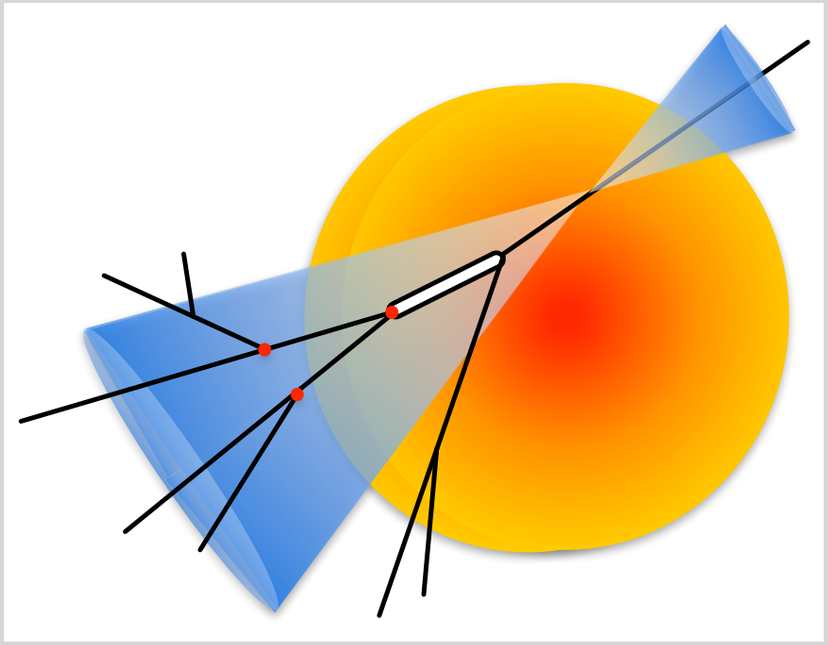

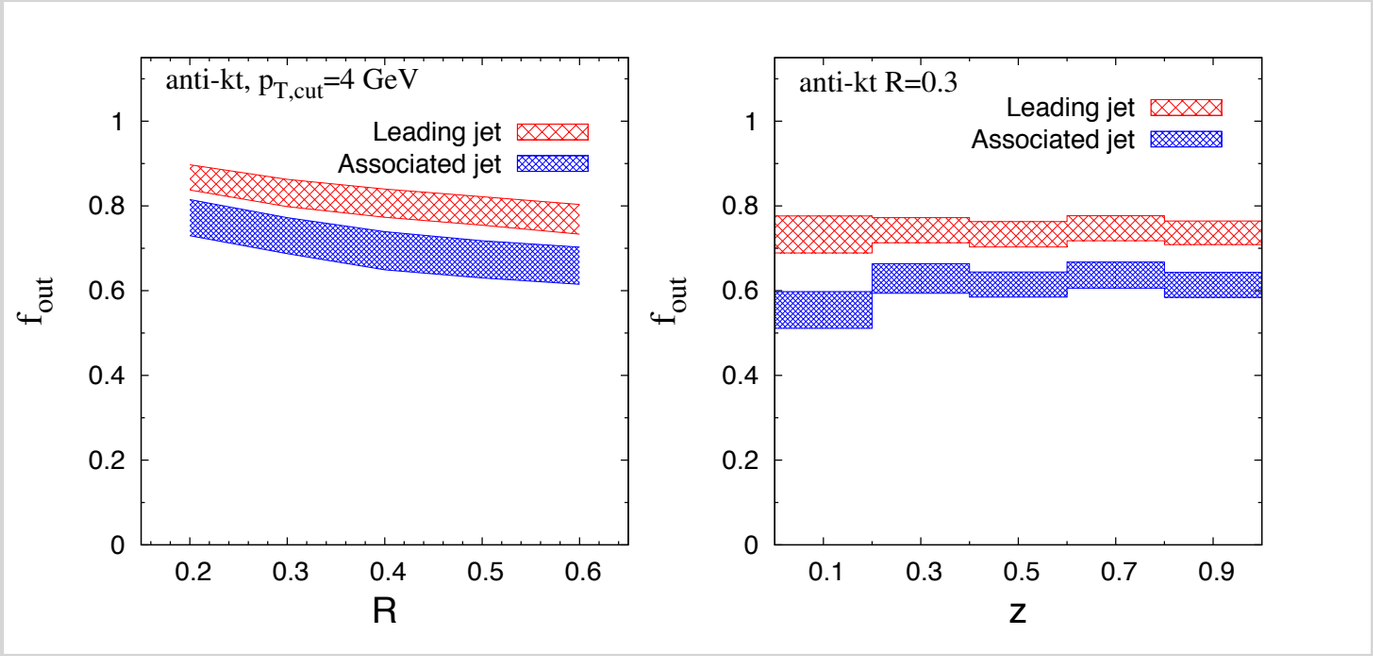

↪ natural explanation for non-modification of jet fragmentation functions

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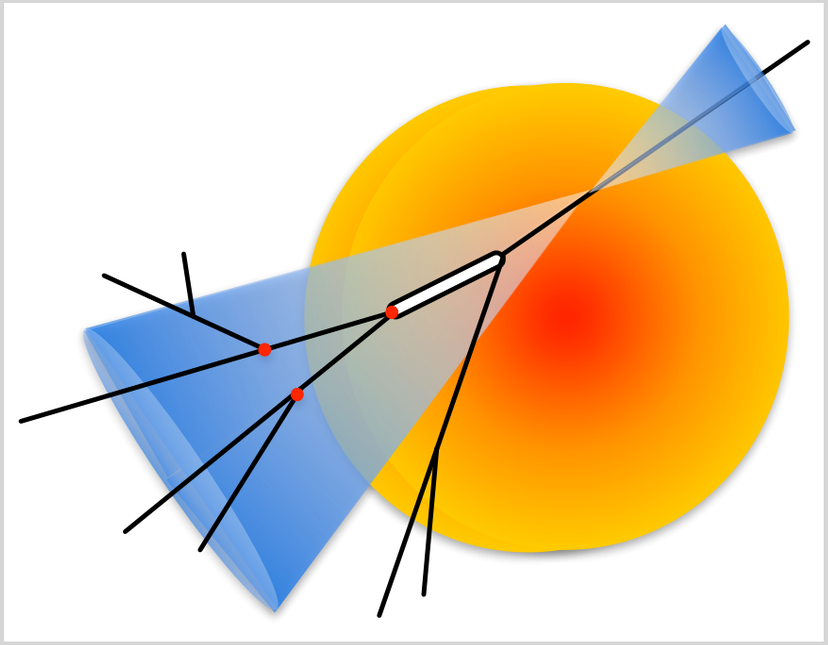

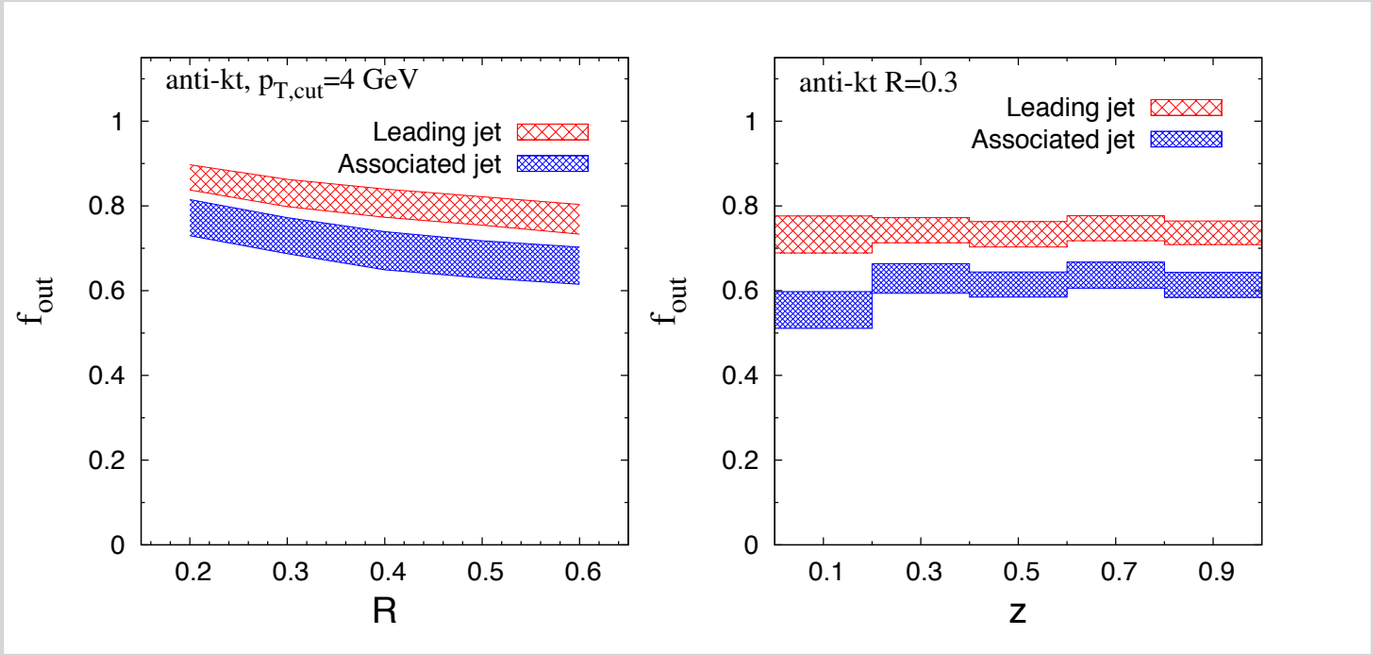

↪ natural explanation for non-modification of jet fragmentation functions

- OR NOT

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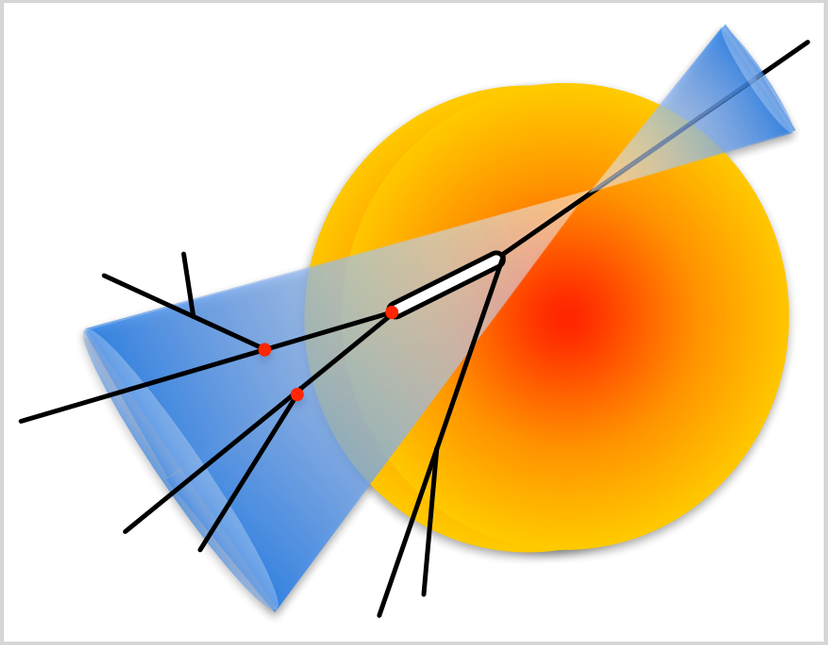
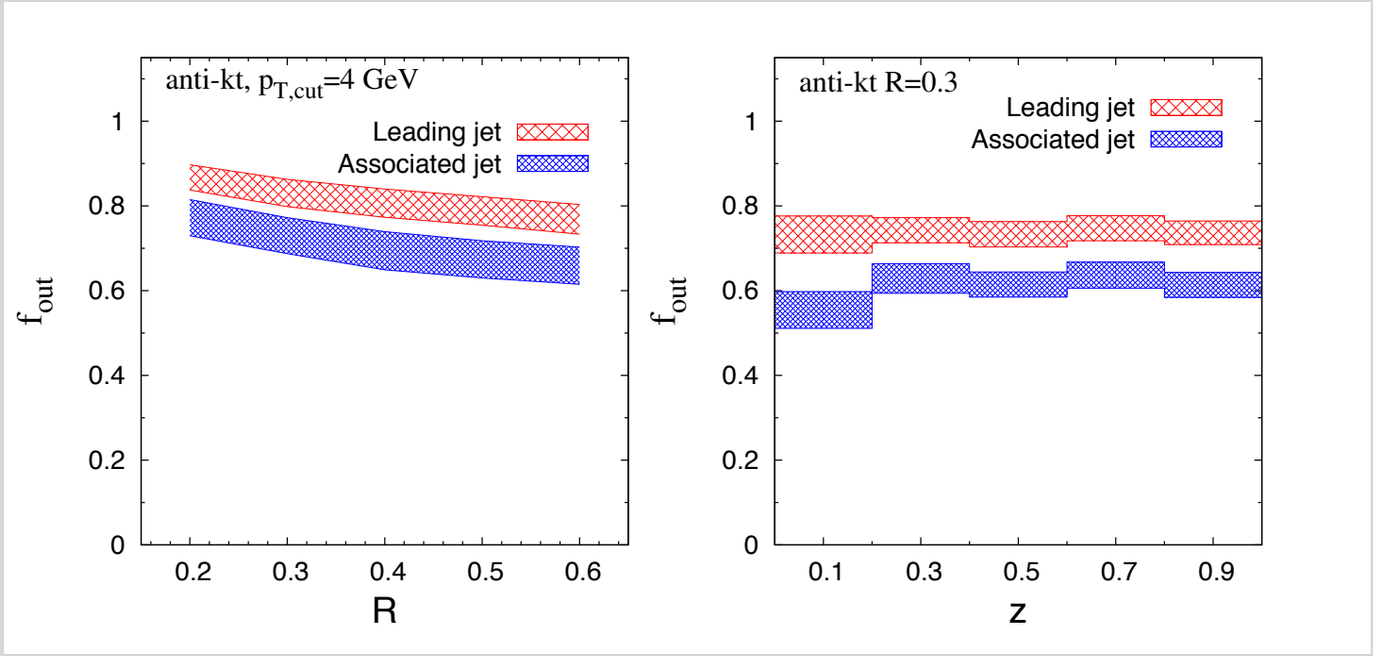




↪ natural explanation for non-modification of jet fragmentation functions

- OR NOT

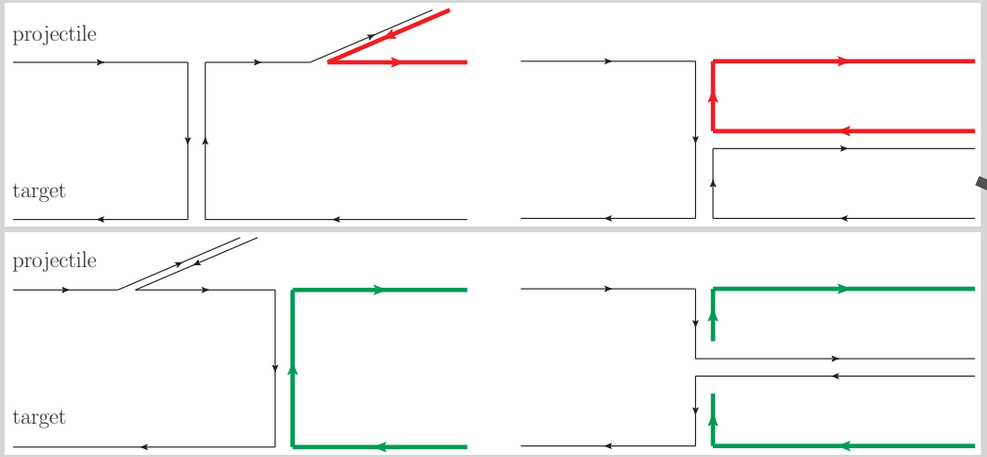
↪ in-medium hadronization, but still with unmodified jet fragmentation within a specific model

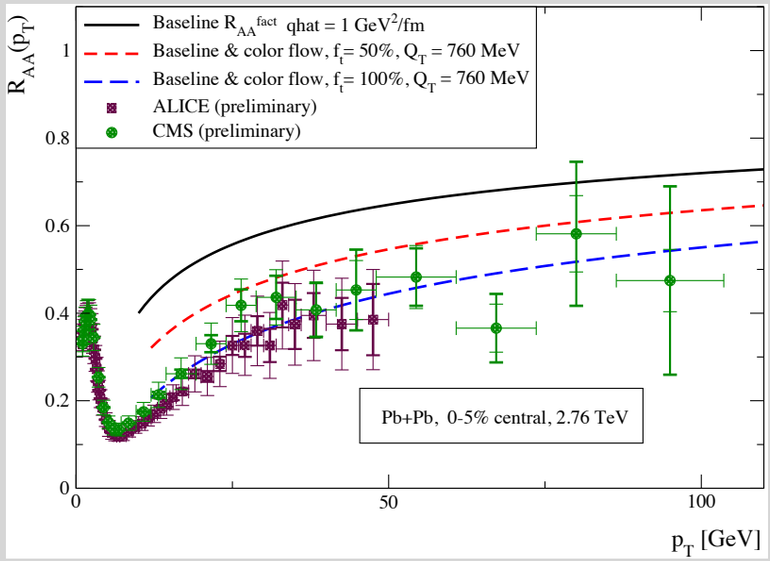
Loshaj,Kharzeev[2011]

colour flow

- colour exchanges between parton and medium can affect hadronization irrespective of where it happens

Beraudo, Milhano, Wiedemann [2011]





↪ colour flow within standard parton energy calculation results in characteristic softening of leading hadron spectra [additional suppression]

↪ further uncertainty in extraction of medium properties

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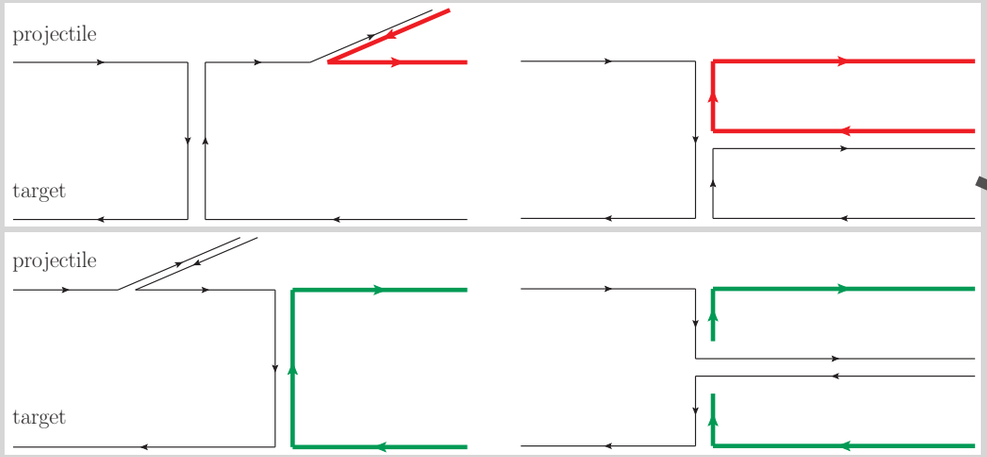

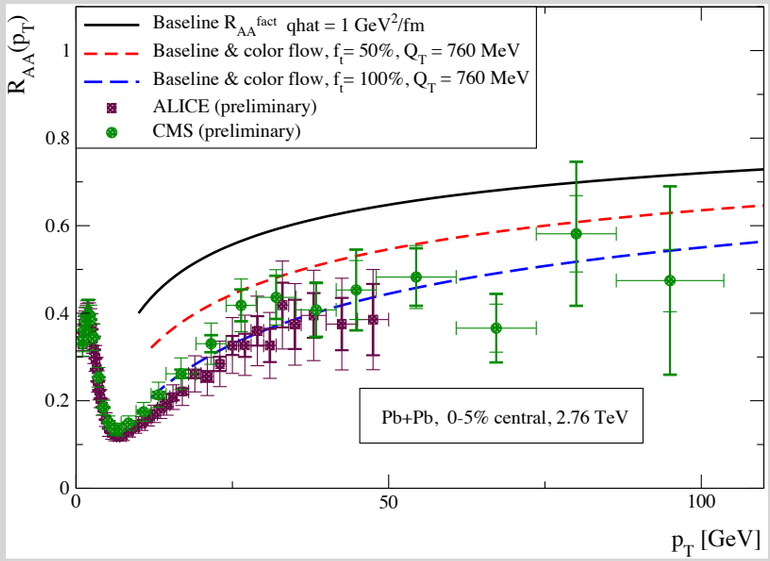

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  - ↪ further uncertainty in extraction of medium properties

- modified jet hadrochemistry

Sapeta, Wiedemann [2008]

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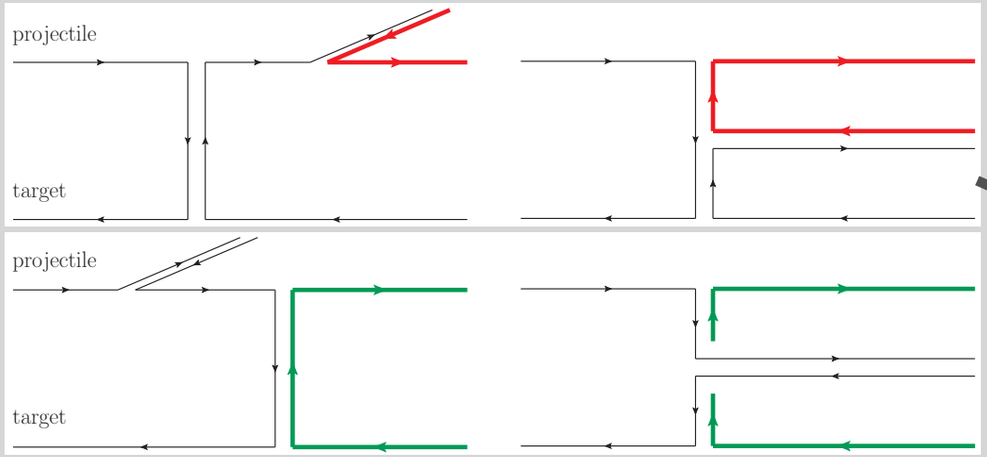

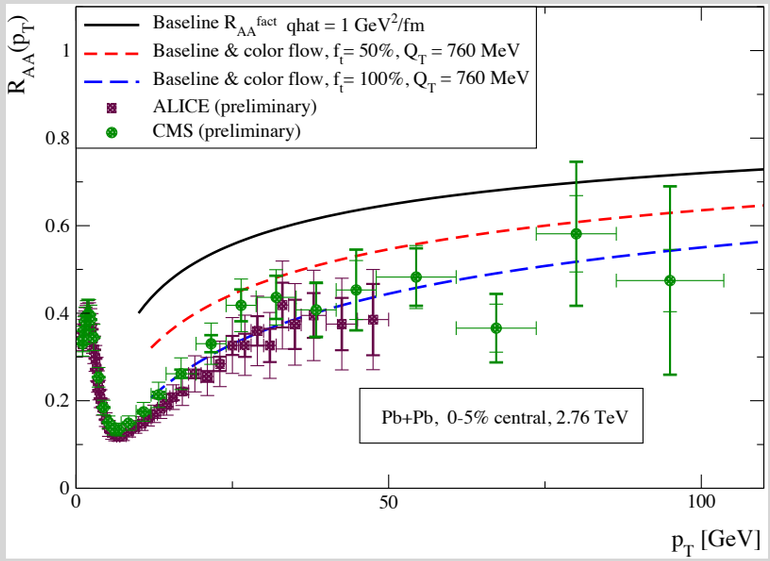

- ↪ colour flow within standard parton energy calculation results in characteristic softening of leading hadron spectra [additional suppression]
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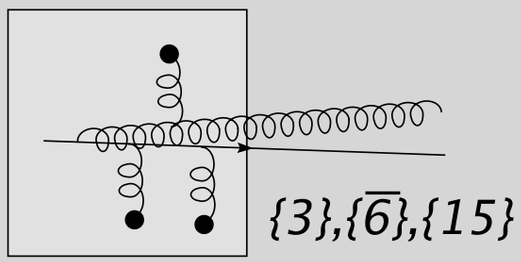
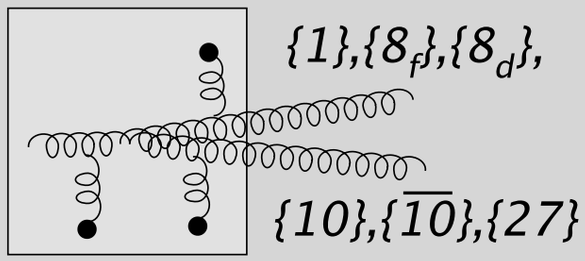
- modified jet hadrochemistry

Sapeta, Wiedemann [2008]

- also, colour exchanges open new 'anomalous' channels for baryon production

Aurenche, Zakharov [2011]





more than ever exp-ph/th crosstalk
essential for significant progress