Selected Topics in the Theory of Heavy Ion Collisions

Lecture 3

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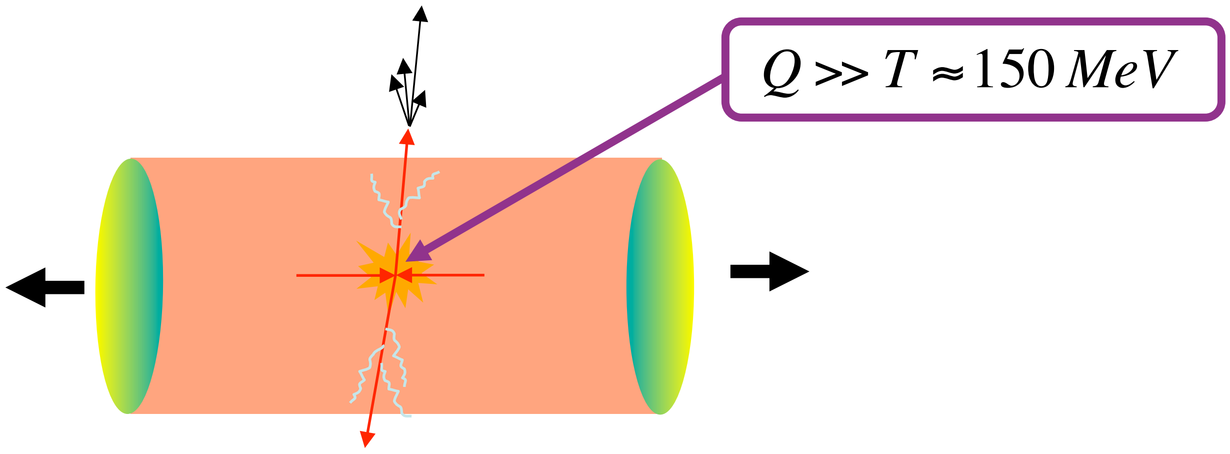
IV.1. Hard Probes

Heavy Ion Collisions produce auto-generated probes at high $\sqrt{s_{NN}}$



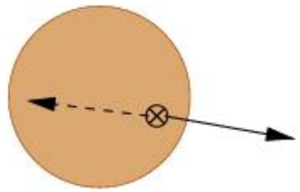
Q: How sensitive are such 'hard probes'?

IV.2.Bjorken’s original estimate and its correction

Bjorken 1982: consider jet in p+p collision, hard parton interacts with underlying event ⇨ collisional energy loss

$$dE_{coll}/dL \approx 10\,GeV/fm$$ (error in estimate!)

Bjorken conjectured monojet phenomenon in proton-proton

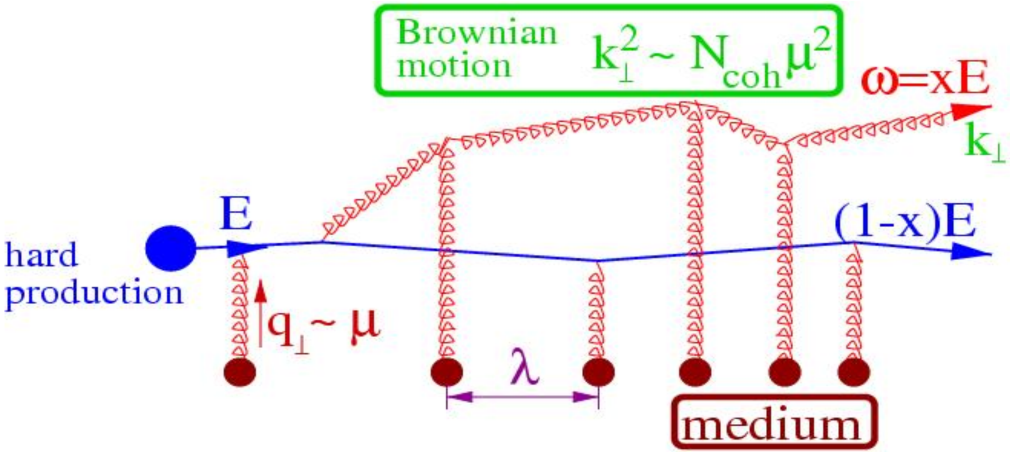


But: radiative energy loss expected to dominate

(4.1) $$\Delta E_{rad} \approx \alpha_s \hat{q} L^2$$ Baier Dokshitzer Mueller Peigne Schiff 1995

- p+p: $L \approx 0.5\ fm, \quad \Delta E_{rad} \approx 100\ MeV$ Negligible !
- A+A: $L \approx 5\ fm, \quad \Delta E_{rad} \approx 10\,GeV$ Monojet phenomenon! Observed at RHIC

IV.3. Parton energy loss - a simple estimate



Medium characterized by transport coefficient:

$$\hat{q} \equiv \frac{\mu^2}{\lambda} \propto n_{density}$$

- How much energy is lost ?

(4.2) Phase accumulated in medium: $\left\langle k_T^2 \Delta z \big/ 2\omega \right\rangle \approx \frac{\hat{q}L^2}{2\omega} = \frac{\omega_c}{\omega}$ Characteristic gluon energy

(4.3) Number of coherent scatterings: $N_{coh} \approx \frac{t_{coh}}{\lambda}$, where $t_{coh} \approx \frac{2\omega}{k_T^2} \approx \sqrt{\omega/\hat{q}}$

$k_T^2 \approx \hat{q}\, t_{coh}$

(4.4) Gluon energy distribution: $\omega \frac{dI_{med}}{d\omega\, dz} \approx \frac{1}{N_{coh}} \omega \frac{dI_1}{d\omega\, dz} \approx \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$

(4.1) Average energy loss $\Delta E = \int_0^L dz \int_0^{\omega_c} d\omega\, \omega \frac{dI_{med}}{d\omega\, dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2$

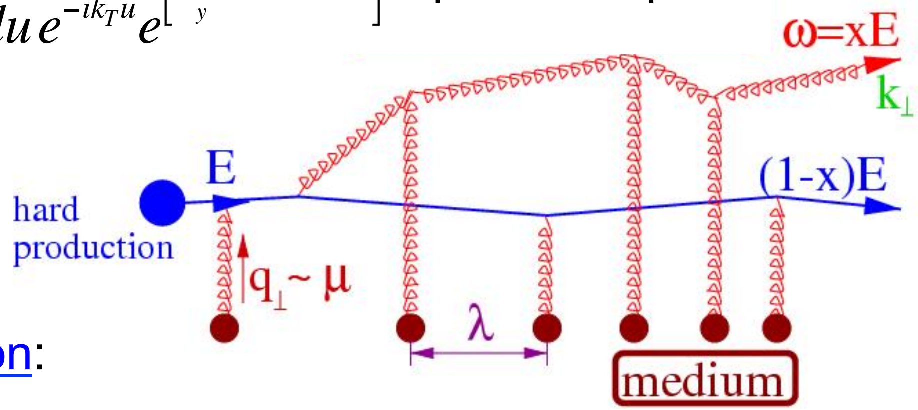
IV.4. Medium-modified Final State Parton Shower

Wang, Gyulassy (1994); Baier, Dokshitzer, Mueller, Peigne, Schiff (1996); Zakharov (1997); Wiedemann (2000); Gyulassy, Levai, Vitev (2000); Wang ...

Radiation off produced parton

$$\frac{dI}{d\ln\omega\, dk_T} = \frac{\alpha_s C_R}{(2\pi)^2\omega^2} 2\,\mathrm{Re}\int_0^\infty dy \int_y^\infty d\bar{y} \int du\, e^{-ik_T u} e^{\left[-\int_y^\infty d\xi\, n(\xi)\sigma(u)\right]}$$

(4.5) $$\times \frac{\partial}{\partial u} \cdot \frac{\partial}{\partial s} K(s=0, y; u, y \mid \omega)$$



Target average includes Brownian motion:

$$K(s,y;u,\bar{y} \mid \omega) = \int_{s=r(y)}^{u=r(\bar{y})} Dr \exp\left[i \int_y^{\bar{y}} d\xi \left\{ \left(\omega \dot{r}^2/2\right) - n(\xi)\sigma(r) \right\} \right] \xrightarrow{\omega\to\infty} e^{-v(s)}$$

Two approximation schemes:

1. Harmonic oscillator approximation:

(4.6) $$n(\xi)\sigma(r) \approx \hat{q}(\xi)\, r^2$$

BDMPS transport coefficient

$$\left\langle Tr\left[W^{A+}(0)W^{A}(r)\right]\right\rangle = \exp\left[-\tfrac{1}{4}\hat{q}L_{long}r^2\right]$$

2. Opacity expansion in powers of

(4.7) $$\left(\alpha_s \int_0^L d\xi\, n(\xi)\sigma_{el}\right)^n$$

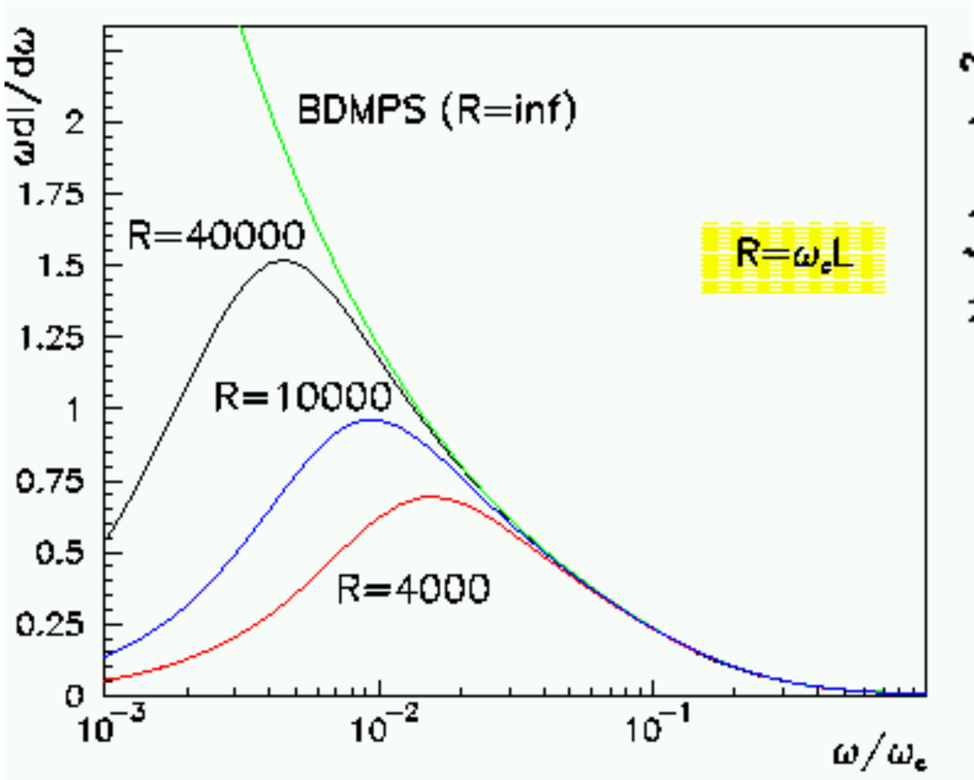
U.A.Wiedemann

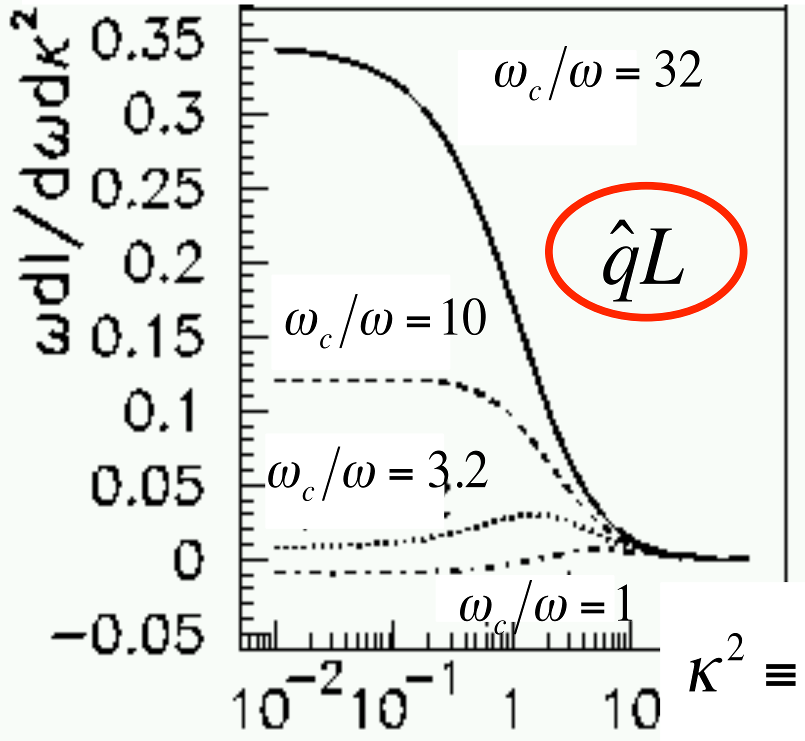
IV.5. Medium-induced gluon energy distribution

Consistent with estimate (4.1), spectrum is indeed determined by $\omega_c = \hat{q}L^2/2$

Transverse momentum distribution is consistent with Brownian motion

Salgado,Wiedemann PRD68:014008 (2003)





$$\kappa^2 \equiv \frac{k_T^2}{\hat{q}L}$$

U.A.Wiedemann

IV.6. Opacity Expansion - zeroth order

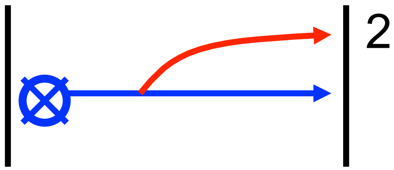
To understand in more detail the physics contained in

(4.5)
$$\frac{dI}{d\ln\omega\, dk_T} = \frac{\alpha_s C_R}{(2\pi)^2\omega^2} 2\mathrm{Re}\int_0^\infty dy \int_y^\infty d\bar{y} \int du\, e^{-ik_T u} e^{\left[-\int_y^\infty d\xi\, n(\xi) v(u)\right]} \times \frac{\partial}{\partial u}\cdot\frac{\partial}{\partial s} K(s=0,y;u,y\,|\,\omega)$$

We expand this expression in **'opacity'** (=density of scattering centers times dipole cross section)

(4.8)
$$K(\underline{s},y;\underline{u},\bar{y}) = K_0(s;u) - \int d\underline{r}\, d\xi\, K_0(\underline{s},y;\underline{r},\xi)\, n(\xi)\,\sigma(\underline{r})\, K_0(\underline{r},\xi;\underline{u},\bar{y}) + \ldots$$

To zeroth order, there is no medium (vaccum case), and one finds:

(4.9)
$$\omega\frac{dI^{(0)}}{d\omega\, dk_T} = \frac{\alpha_s C_F}{\pi^2} H(k_T) =$$  $$, \qquad H(k_T) = \frac{1}{k_T^2}$$

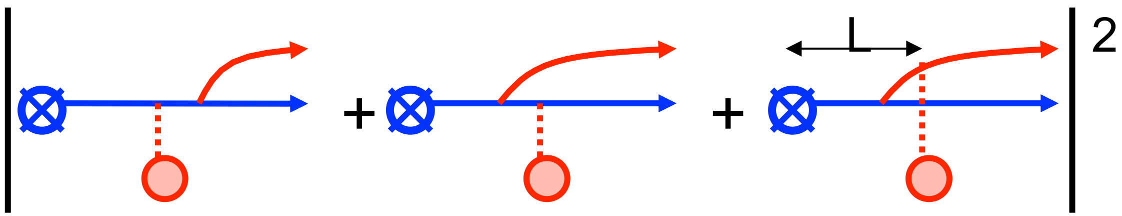
So, in the vacuum, the gluon energy distribution displays the dominant $1/\underline{k}^2$ piece of the DGLAP parton shower.

U.A.Wiedemann

IV.7. Opacity Expansion - up to 1st order

To first order in opacity, there is a generally complicate interference between vacuum radiation and medium-induced radiation.

(4.10) $$\omega \frac{dI^{(1)}}{d\omega\, dk_T} =$$

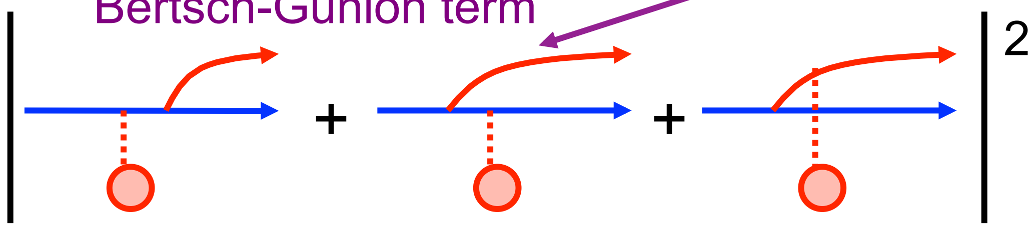


In the parton cascade limit $L \to \infty$, we identify three contributions:

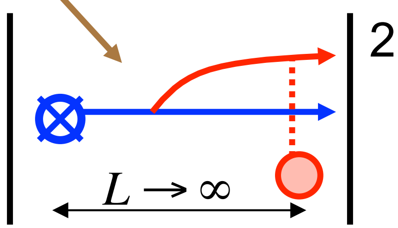
1. **Probability conservation** of medium-independent vacuum terms.
2. **Transverse phase space** redistribution of vacuum piece.
3. **Medium-induced gluon radiation** of quark coming from minus infinity

(4.11) $$\lim_{\substack{nL=const\\ L\to\infty}} \omega \frac{dI^{(1)}}{d\omega\, dk_T} = -w_1 H(k_T) + nL \int_{q_T} dq_T \left[R(q_T, k_T) + H(q_T + k_T) \right]$$

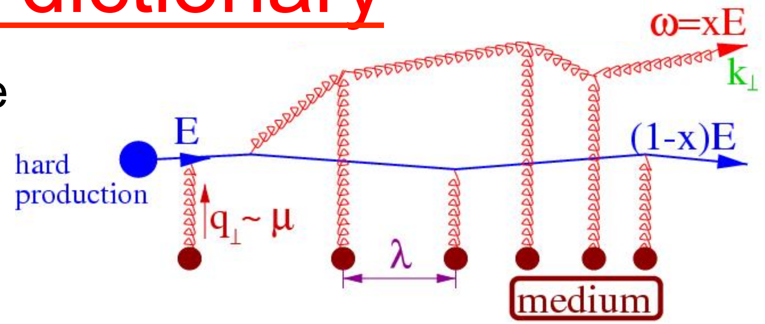
Bertsch-Gunion term



Rescattering of vacuum term



IV.8. BDMPS – dictionary

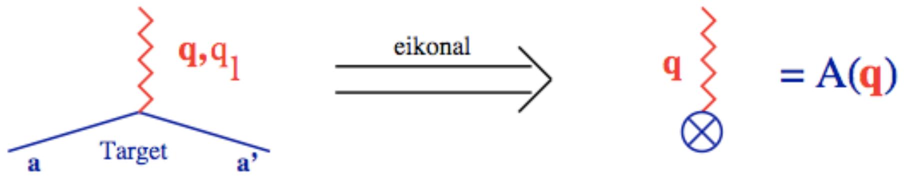


BDMPS-Z calculates in the kinematic regime

$$E >> \omega >> |k_T|,|q_T| >> \Lambda_{QCD}$$

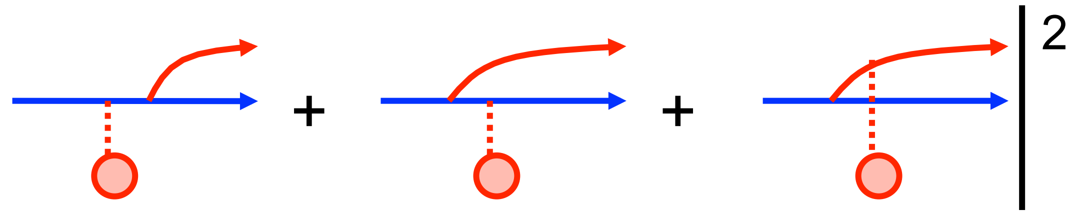
Elastic cross section in this limit

(4.12)



Inelastic cross section for one-fold incoherent scattering

(4.13) $\frac{1}{\omega}|A(q)|^2 R(k,q) =$



Inelastic cross section for multiple scattering

(4.14)

$$\propto \left(\prod_i |A(q_i)|^2\right) R\left(k + \sum_{i=2} q_i, q_1\right) \qquad \propto \left(\prod_i |A(q_i)|^2\right) R\left(k, \sum_i q_i\right)$$

Incoherent limit **Coherent limit**

IV.9. Example: N=2 opacity

$$\frac{dI(N=2)}{d\ln\omega\, dk_T} = \frac{\alpha_s C_R}{\pi^2} \int dq_1\left(\left|A(q_1)\right|^2 - \sigma_{el}\delta(q_1)\right) \int dq_2\left(\left|A(q_2)\right|^2 - \sigma_{el}\delta(q_2)\right)$$

(4.15)

$$\times\left[\frac{(nL)^2}{2} \underbrace{R(k+q_1;q_2)}_{\text{Incoherent}} - n^2 \frac{1-\cos LQ_1}{Q_1^2}\left\{\underbrace{R(k+q_1;q_2)}_{\text{Incoherent}} - \underbrace{R(k;q_1+q_2)}_{\text{Coherent}}\right\}\right]$$

Formation times

(4.16)

$$\tau_{f,n} = \frac{1}{Q_n} = \frac{2\omega}{\left(k_T + \sum_{i=1}^{n} q_i\right)^2}$$

define interpolation scale between totally coherent and incoherent limit

(4.17)

$$n^2 \frac{1-\cos LQ_1}{Q_1^2} \longrightarrow \begin{cases} 0 & ,L > \tau_{f1} \\ n^2 L^2/2 & ,L < \tau_{f1} \end{cases}$$

Formally, determine totally coherent and incoherent limiting cases by taking $L \to 0$ or $L \to \infty$ for $nL = fix$

IV.10. Main take-home message

- In high-energy limit, the medium-induced splitting a -> b+c, i.e., **medium-induced gluon radiation**) is regarded as the **most efficient mechanism to degrade energy of partonic projectile a**.
  It is more efficient than collisional mechanism a+b -> a' +b'

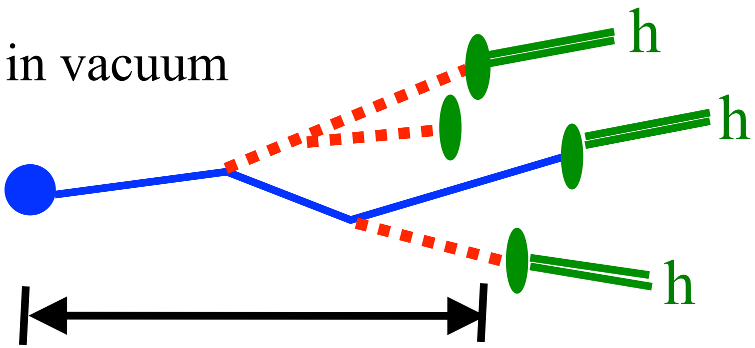
- Medium-induced gluon radiation has two 'classical' limiting cases:
  - incoherent limit: radiation = incoherent sum of radiation from all independent scattering centers
  - coherent limit: all scattering centers act coherently, as if radiation occurs from one scattering center with q = sum of the q_i

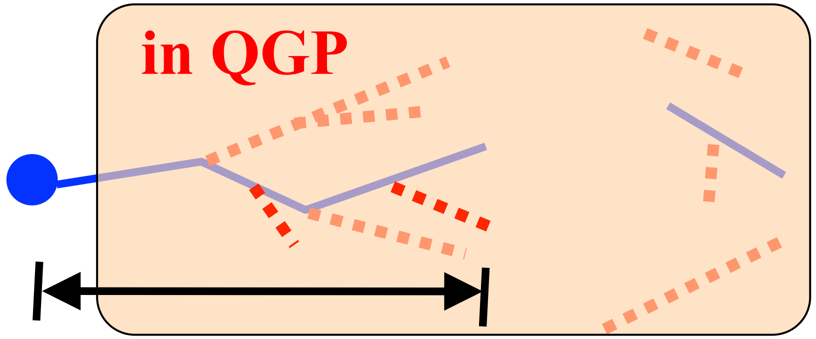
- The **interpolating scale** between coherent and incoherent limits is set by the **gluon formation time**

- Medium-induced quantum interference leads to characteristic parametric dependencies of medium-induced gluon radiation, in particular

$$\omega \frac{dI_{med}}{d\omega} \approx \alpha_s \sqrt{\frac{\omega_c}{\omega}}, \quad \omega_c = \hat{q} L^2 / 2 \qquad \left\langle k_T^2 \right\rangle \propto \hat{q}\, L \qquad \Delta E \propto \hat{q}\, L^2$$

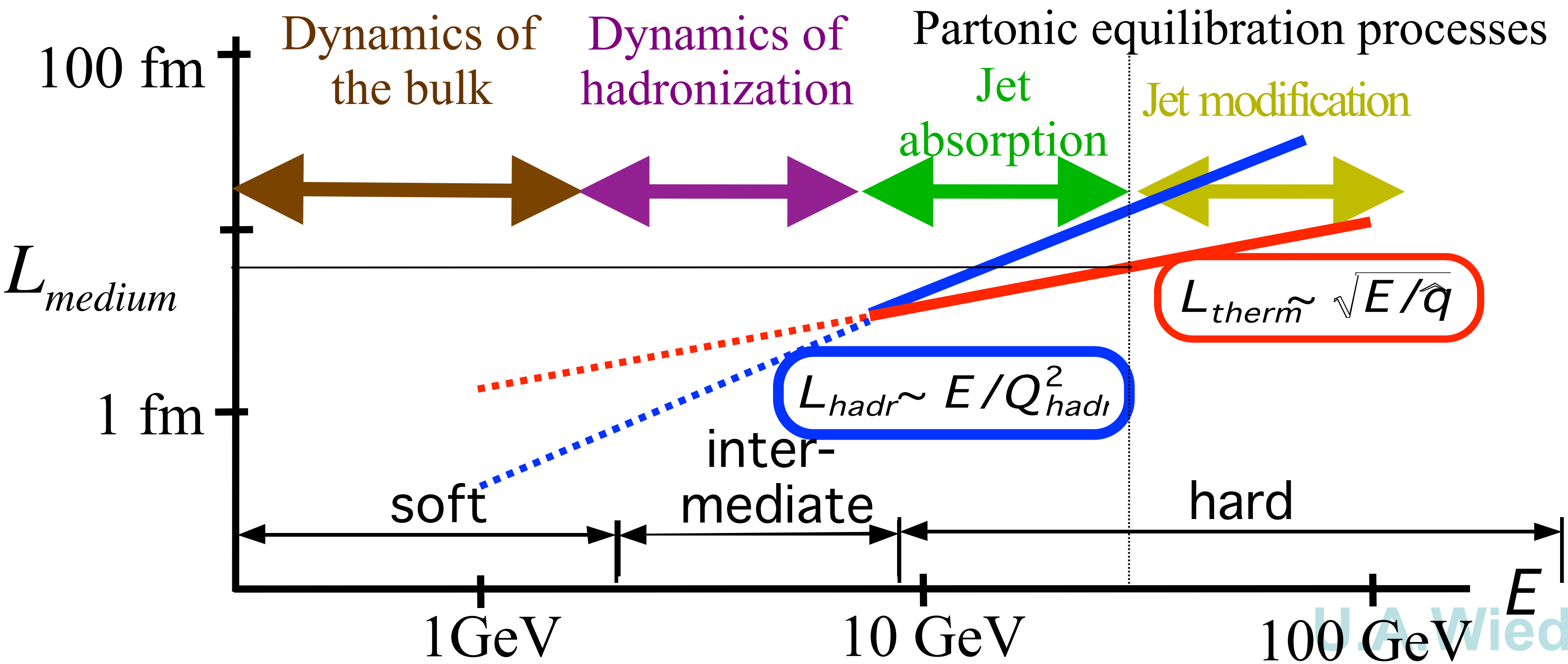
IV.11. Estimating Time scales for parton E-loss



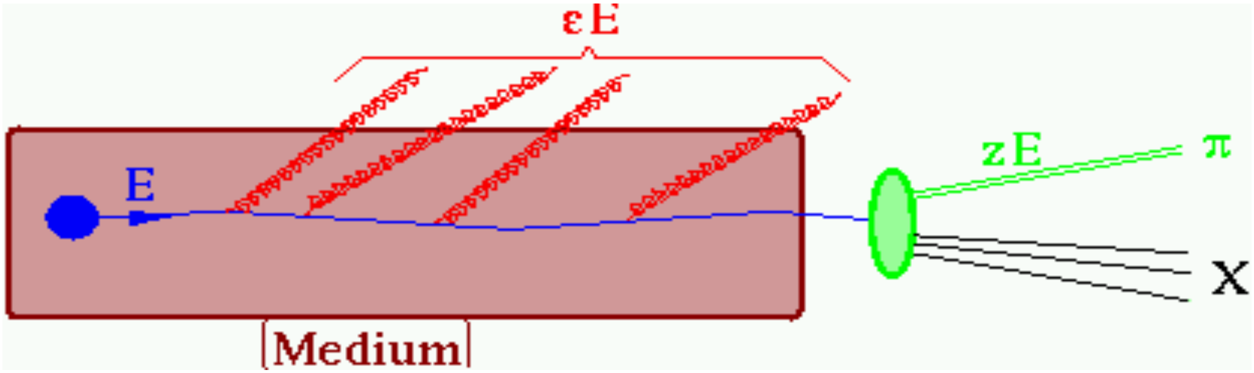


$$L_{hadr} = const \frac{E}{Q^2}$$

$$\Delta E \approx E \approx \alpha_s \hat{q} L_{therm}^2$$



IV.12. "Jet"-quenching of High p_T Hadron Spectra

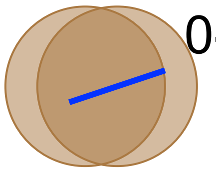


$$R_{AA}(p_T,\eta) = \frac{dN^{AA}/dp_T d\eta}{n_{coll}\, dN^{NN}/dp_T d\eta}$$

$R_{AA}(p_T) = 1.0$ no suppression

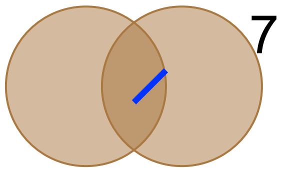
$R_{AA}(p_T) = 0.2$ factor 5 suppression

Centrality dependence:



0-5%

L large

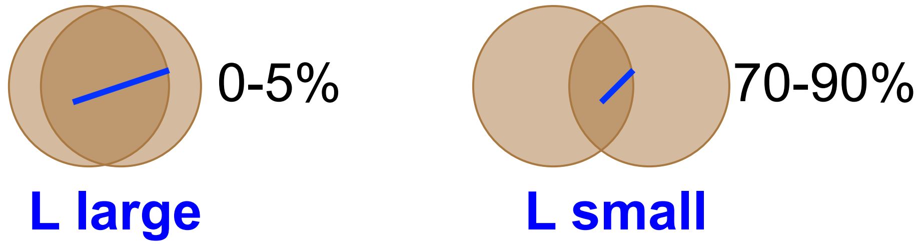


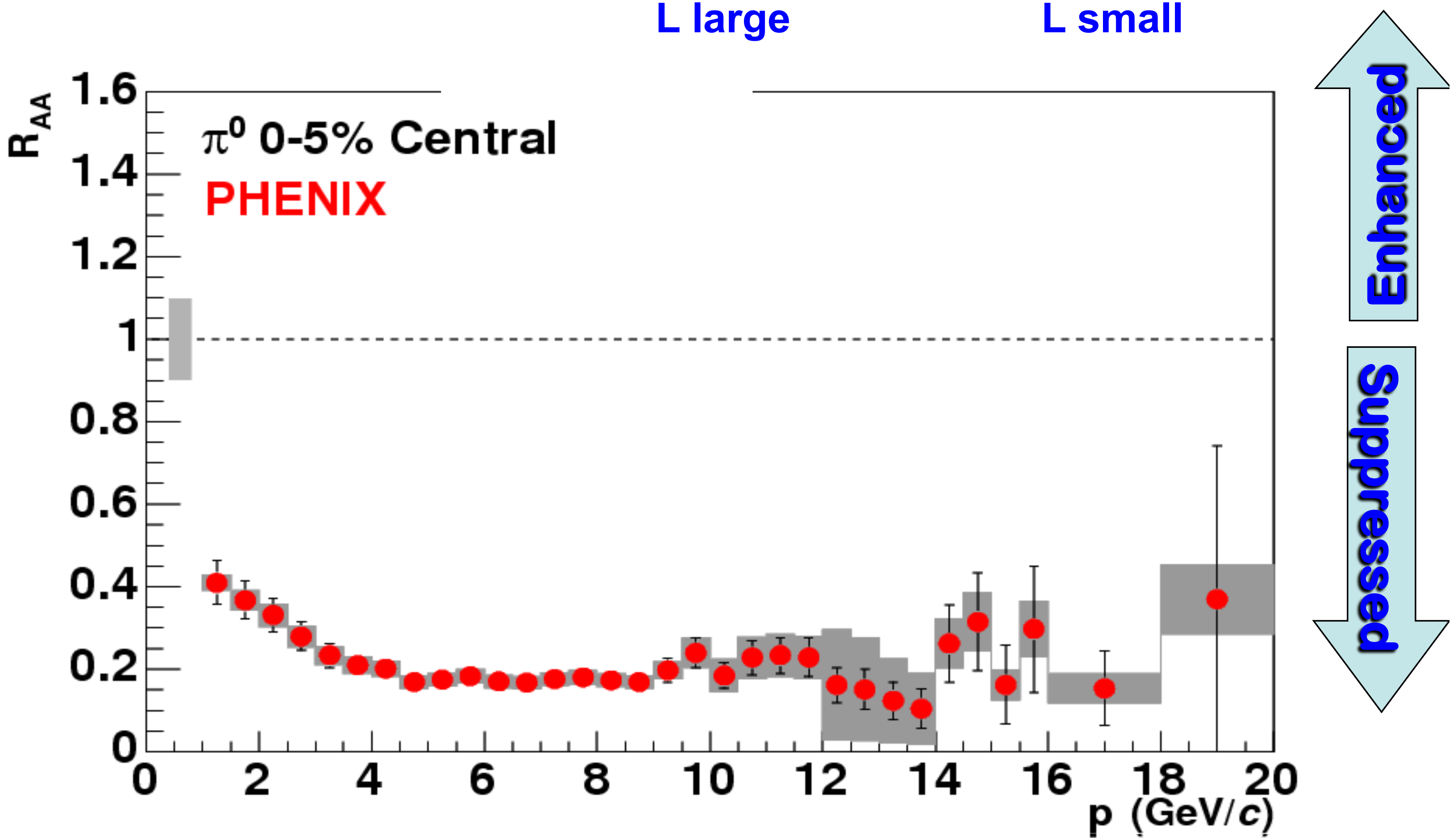
70-90%

L small

IV.13. Suppression at high p_T at RHIC

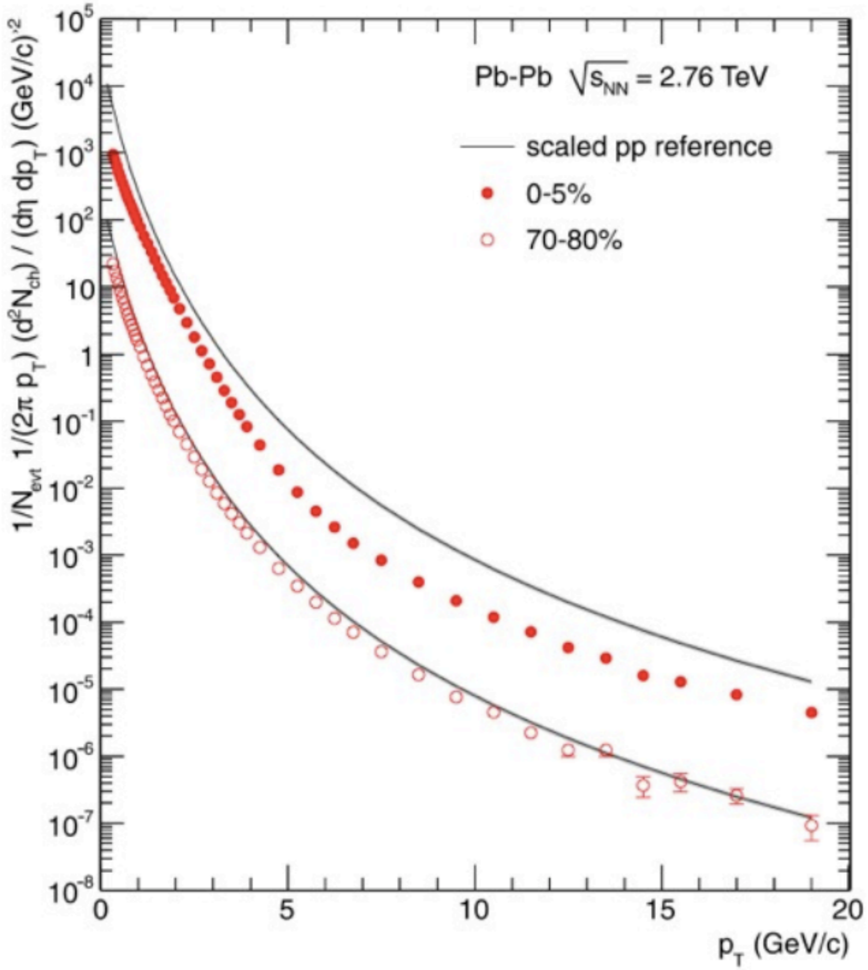
Centrality dependence:





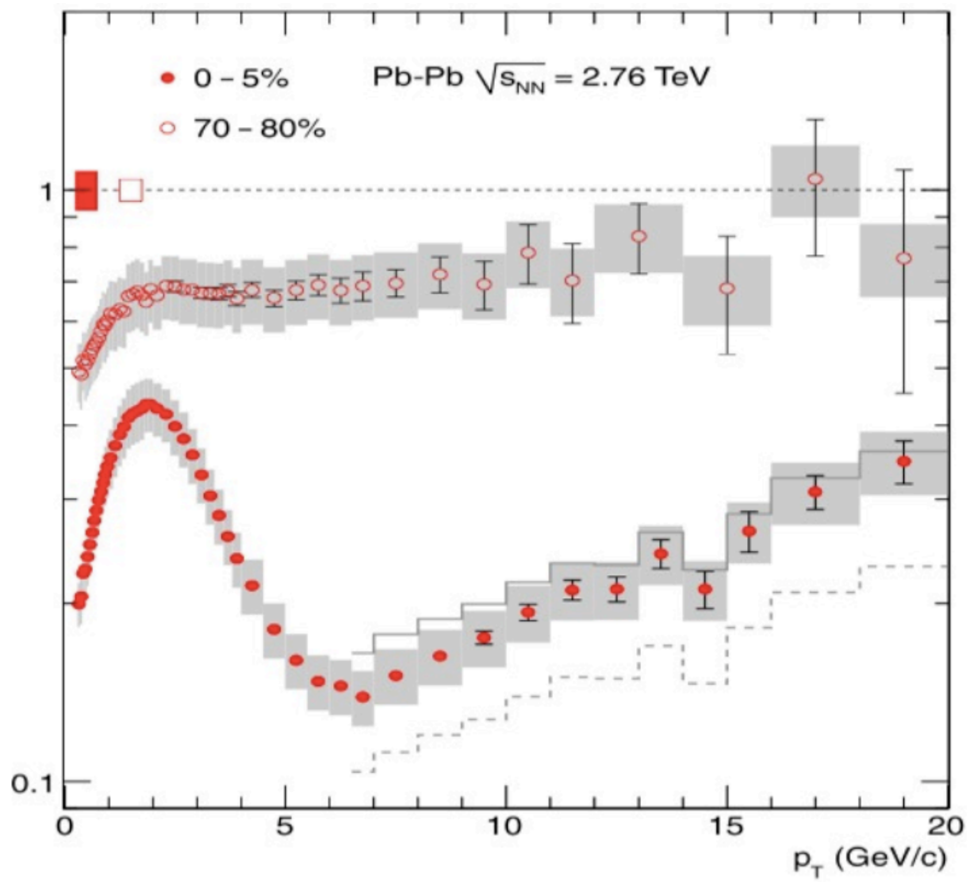
IV.14. Suppression persists to highest p_T

- Spectra in AA and pp-reference



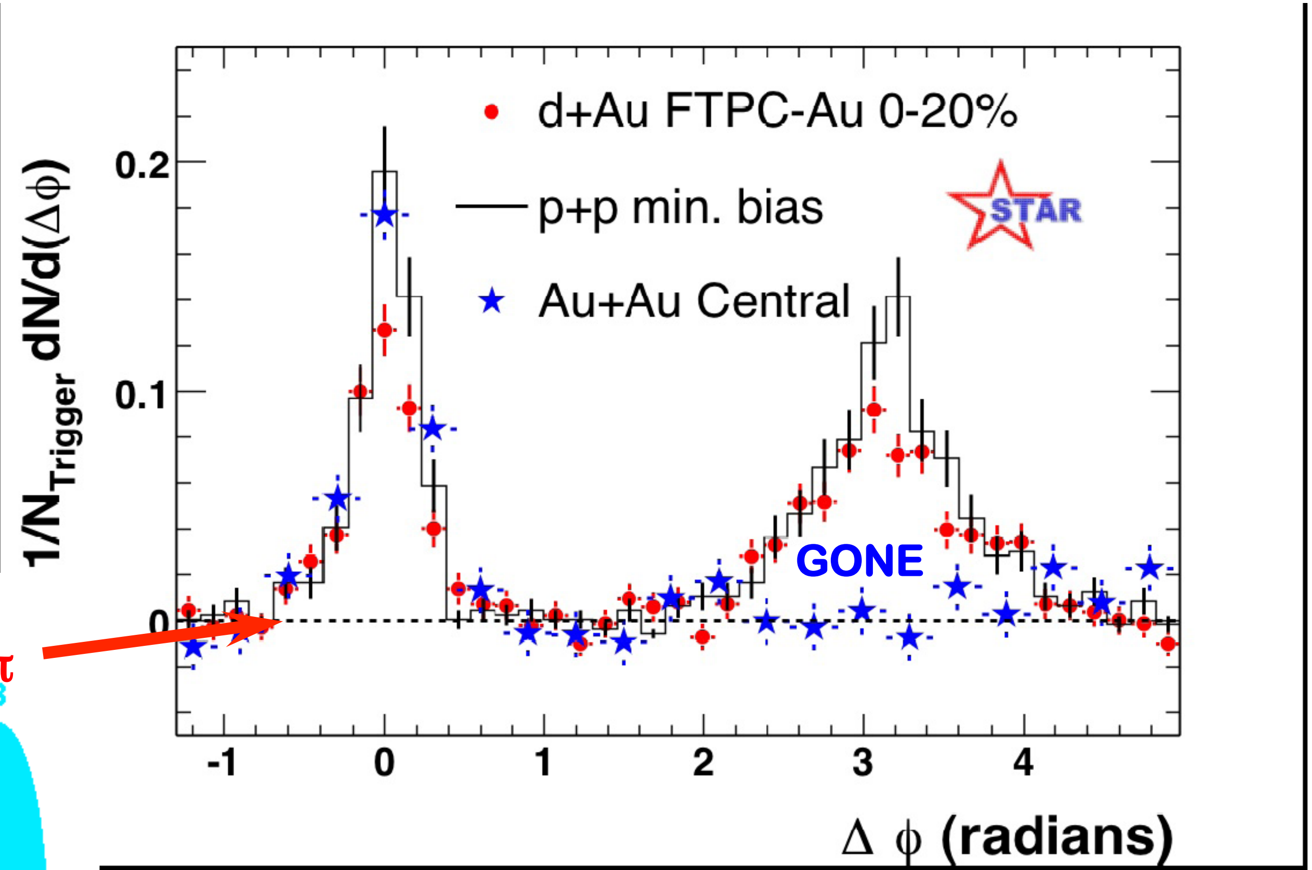
- Nuclear modification factor shows pt-dependence

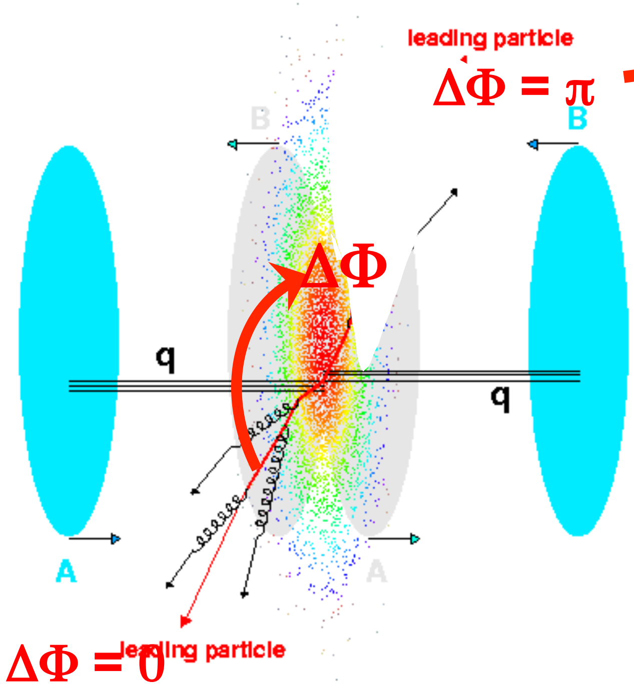
ALICE, PLB 696 (2011) 30



IV.15. The Matter is Opaque at RHIC

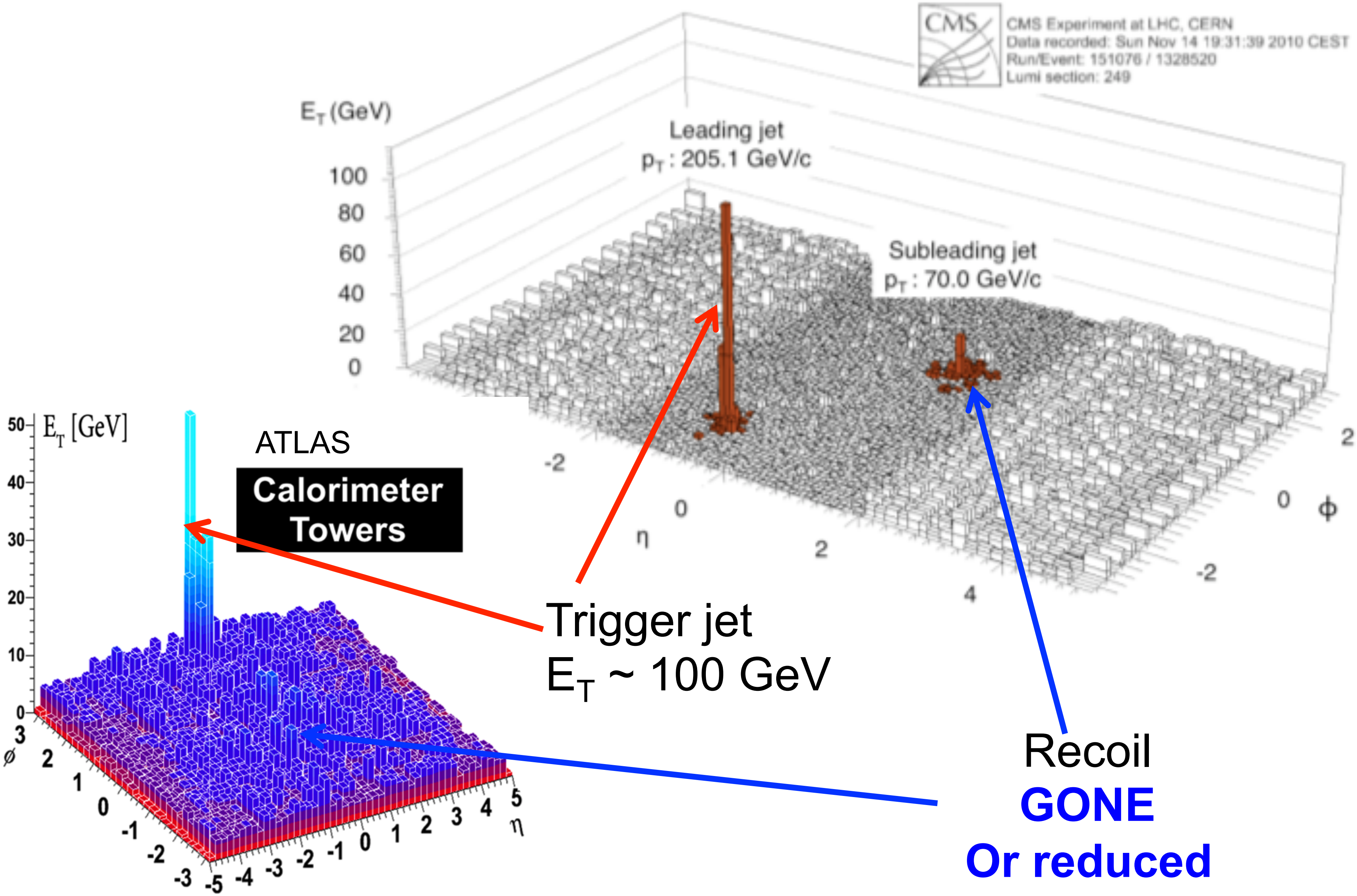
- STAR azimuthal correlation function shows ~ complete absence of "away-side" (high-pt) particle





✦ Partner in hard scatter is ***completely absorbed*** in the dense medium

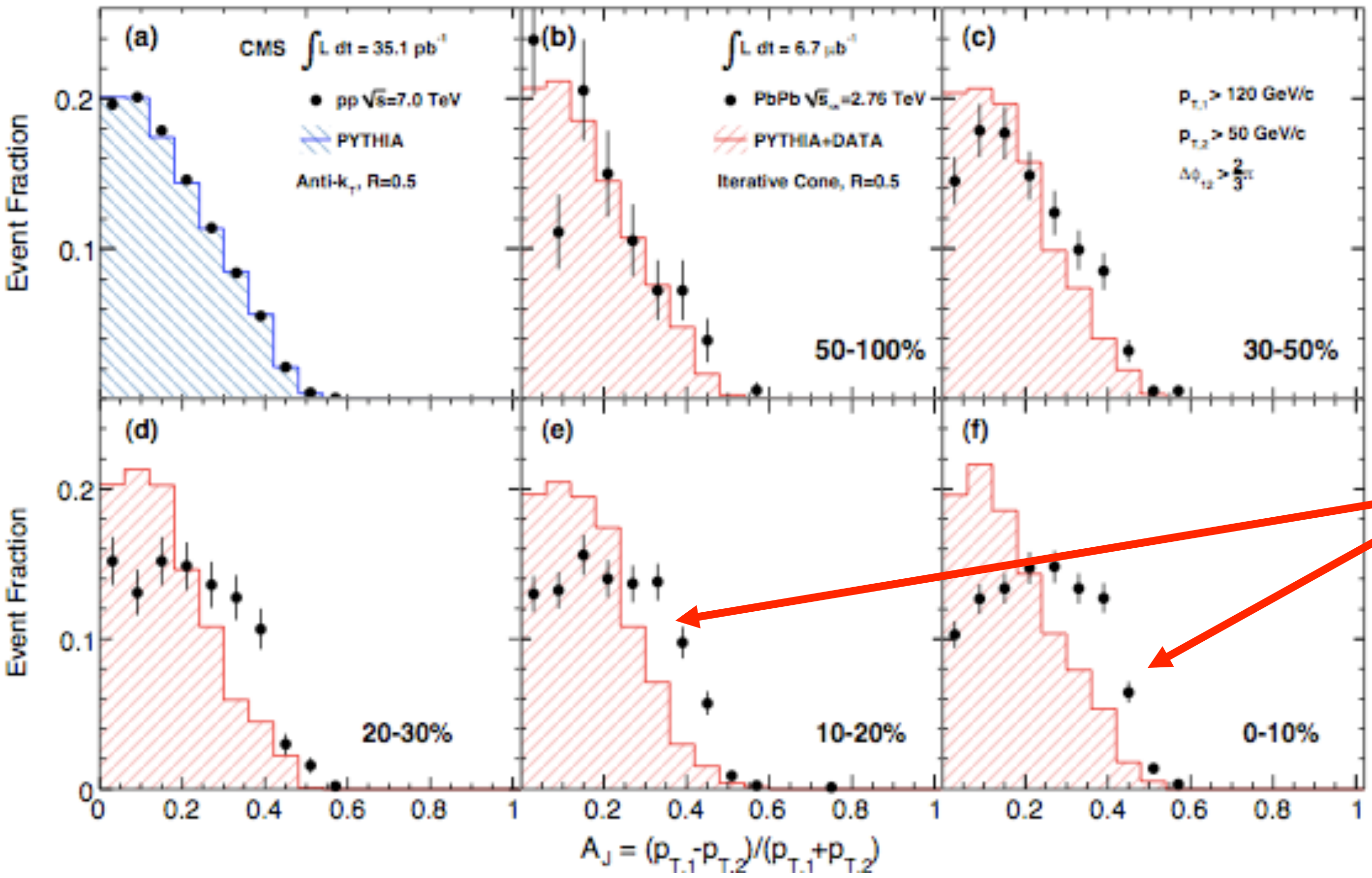
IV.16. Dijet asymmetries at LHC

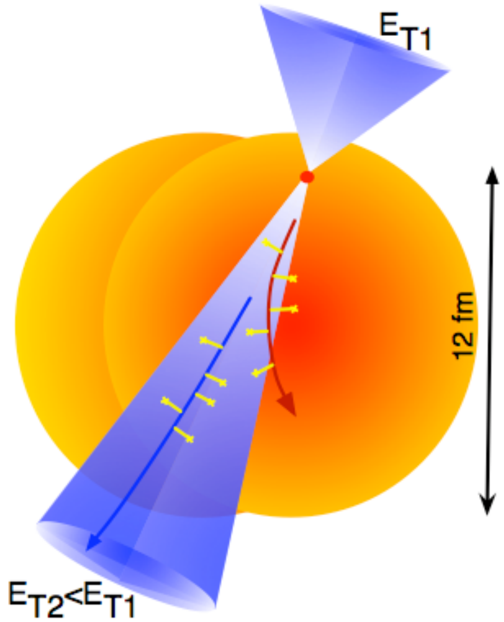


IV.17. Dijet asymmetry

$$A_J = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}}$$

CMS, Phys.Rev. C84 (2011) 024906





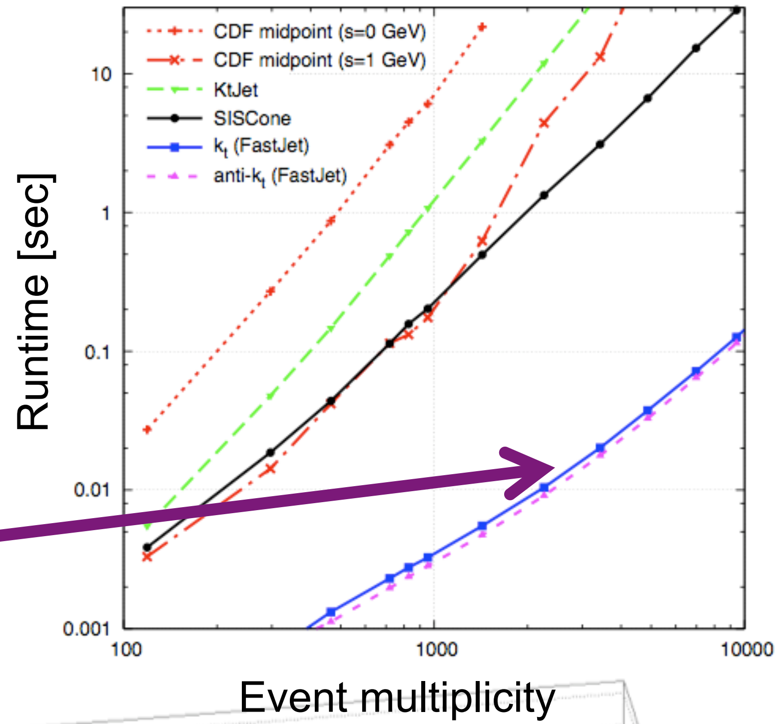
Strongly enhanced dijet asymmetry

IV.18. Jet Finding at high event multiplicity (TH)

- Tremendous recent progress on jet finding algorithms

  - novel class of IR and collinear safe algorithms satisfying SNOWMASS accords
    kt(FastJet)
    anti-kt(FastJet)
    SISCone

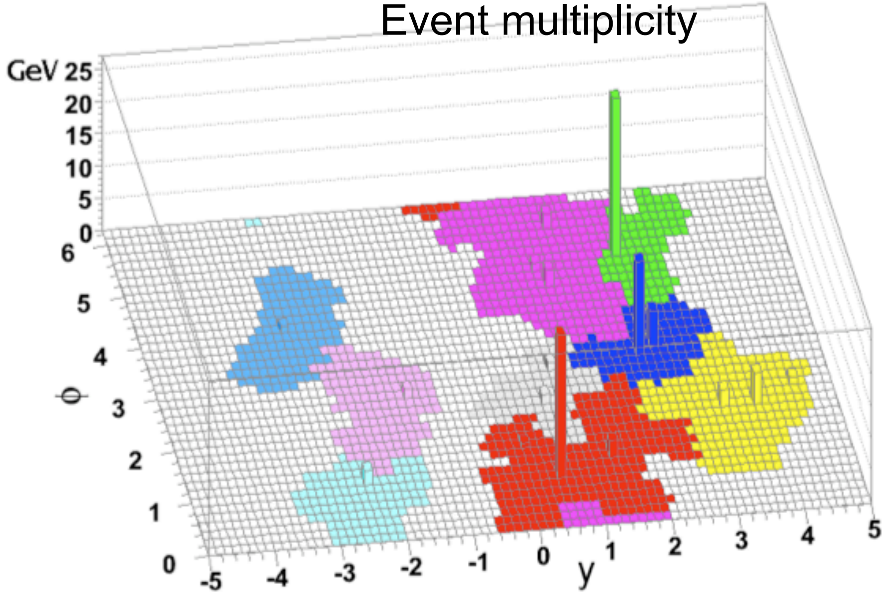
    M. Cacciari, G. Salam, G. Soyez, JHEP 0804:005,2008
  - new standard for p+p@LHC
  - fast algorithms, suitable for heavy ions!



- Catchment area of a jet

  - novel tools for separating soft fluctuations from jet remnants

  - interplay with MCs of jet quenching needed



IV.19. Jet Finding at high event multiplicity (exp)

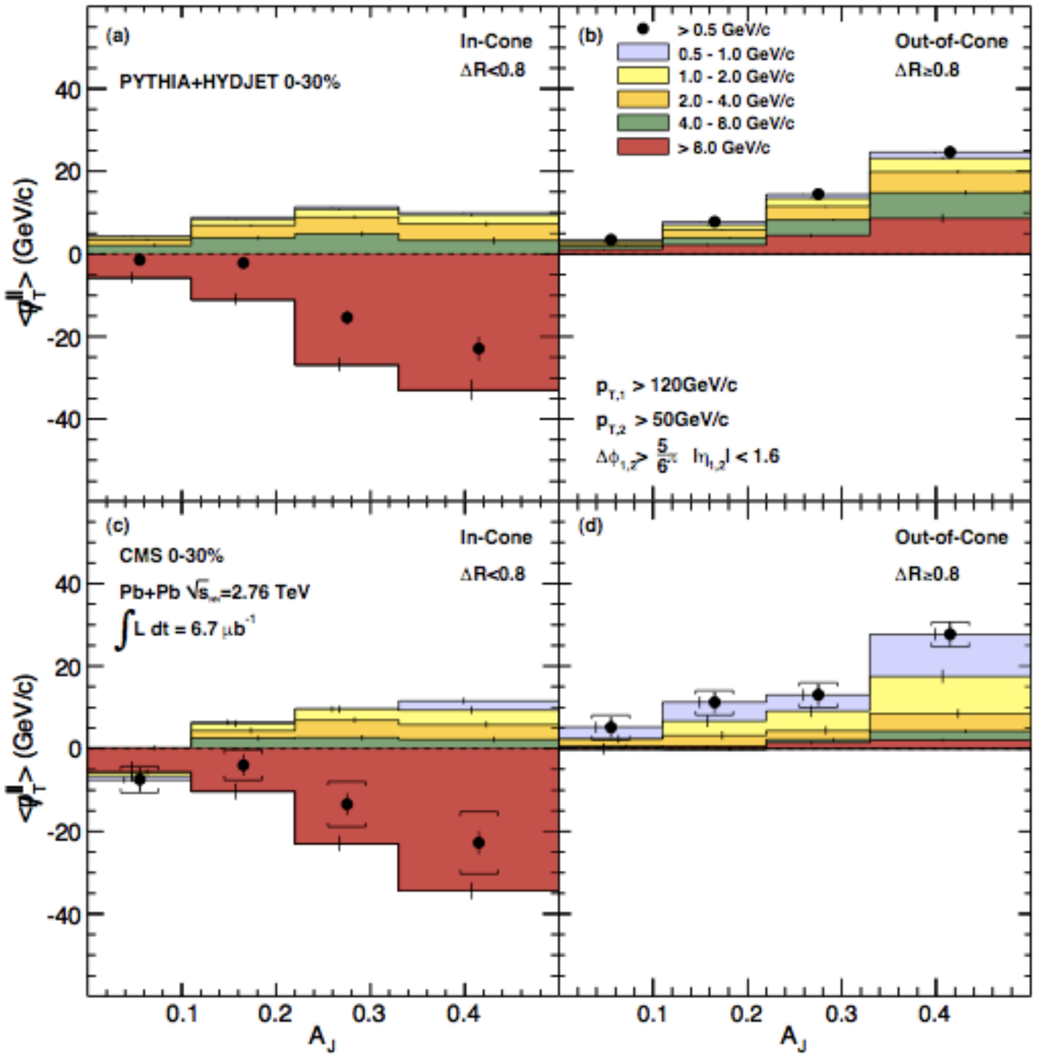
CMS, Phys.Rev. C84 (2011) 024906

- Impressive experimental checks

  energy 'lost' from jet cone

  - found completely out-of-cone

  - found in soft components at very large angles

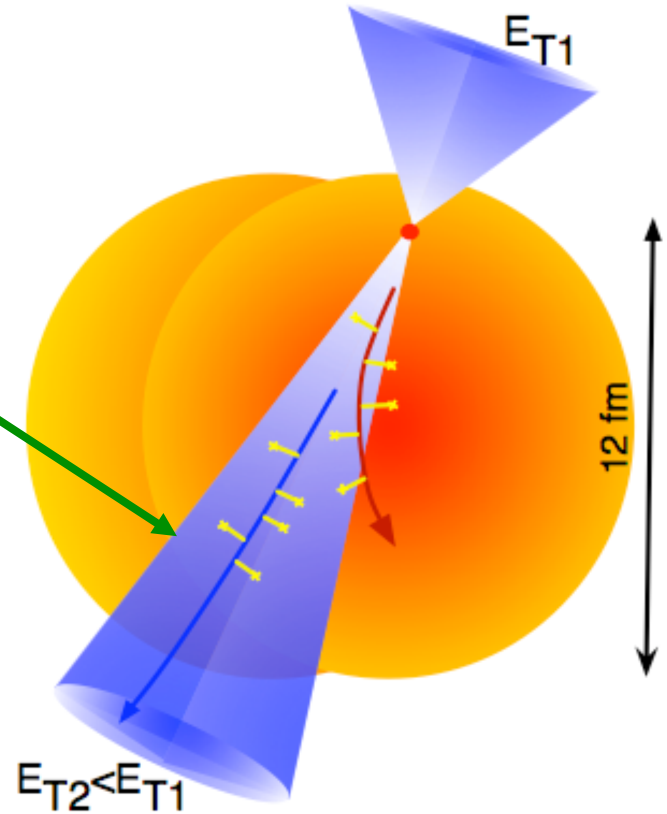


- Angular distribution of dijets almost unchanged

Some Qualitative Considerations

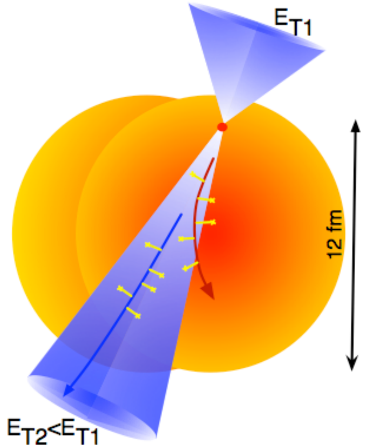
Problem 1: How can the suppression of R_{AA}
and the quenching of reconstructed jets
be understood in the same dynamical picture?

Problem 2: How can this jet broaden
(as suggested by A_j-dependence)
while $\Delta\Phi$ - dependence
is almost unaffected?



IV.20. Jet quenching via jet collimation?

J. Casalderrey-Solana, G. Milhano, U.A. Wiedemann, arXiv:1012.0745

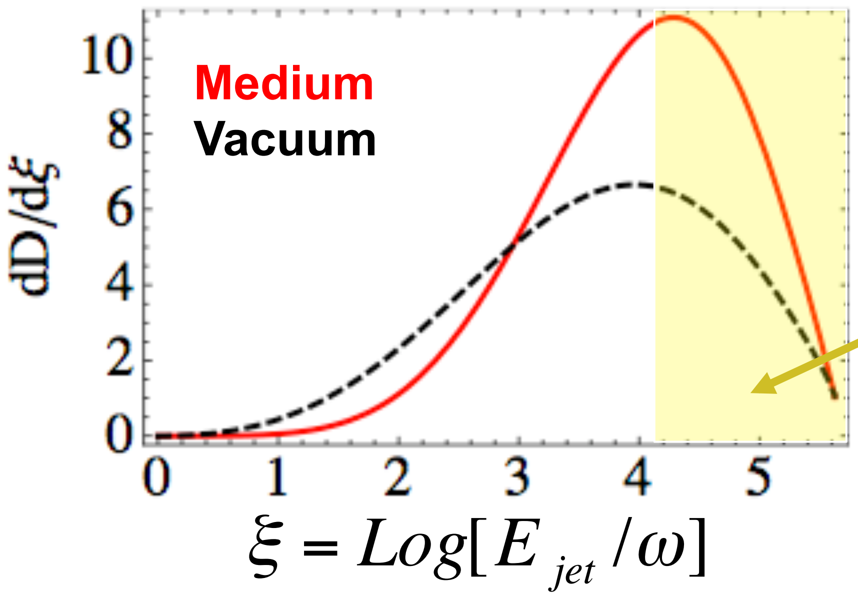


In medium, formation times of soft partons are shorter

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}, \qquad \tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

So **soft gluons** are there early in the shower and they are radiated at larger angle

$$\langle \theta^2 \rangle = \frac{\langle k_T^2 \rangle}{\omega^2} = \frac{\hat{q} L}{\omega^2}$$



A significant fraction of the total jet energy is soft modes

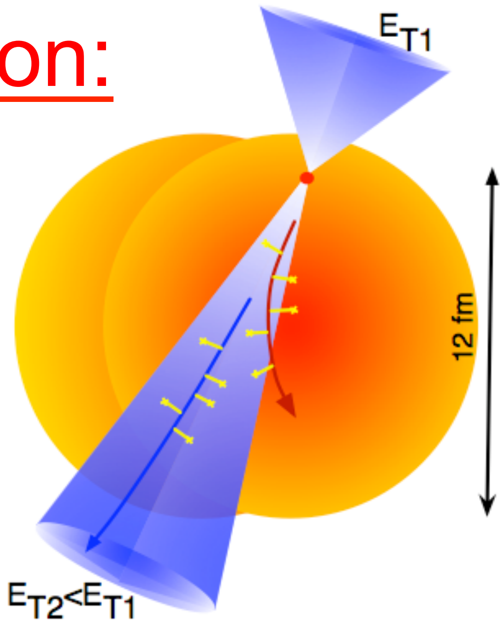
$$\omega \leq \sqrt{\hat{q} L}$$

And can be radiated at angles

$$\langle \theta \rangle \geq 1$$

Complete decorrelation from jet axis!

IV. 21. Jet quenching via jet collimation:



Facts from first data on dijet asymmetry:

- in Pb-Pb, on average, > 10 GeV more radiated outside cone of recoil jet

- Aj-distribution is broad: some event fraction radiates >20 GeV more energy outside cone of recoil jet

- If 20 GeV were radiated in single component, this would induce significant $\Delta\Phi$-broadening, which is not observed

=> medium-induced radiation must be in **multiple soft components**

Medium = frequency collimator which trims away

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

of the jet by moving them to angles $\langle \theta \rangle \geq 1$

J. Casalderrey-Solana, G. Milhano, U.A. Wiedemann arXiv:1012.0745

Estimate: $30 \leq \hat{q} L \leq 90\, GeV^2$ gets $O(10\, GeV)$ out of jet cone.

IV. 22. Towards a MC of jet quenching

Qualitatively:

Radiative parton energy loss naturally contains key elements for understanding quenching of reconstructed jets:

- medium-induced gluon formation time shows inverted dependence on gluon energy
- size of dijet asymmetry (~ 10 GeV outside wide cone) can be accomodated naturally

How to get **from qualitative considerations to quantitative analysis?**
Strategy pursued here:

- start from analytically known baseline (BDMPS)
- find exact MC implementation of this baseline
- extend MC algorithm to go beyond eikonal limit
- do physics …

Recall IV.9. Example: N=2 opacity

(4.15)

$$\frac{dI(N=2)}{d\ln\omega\, dk_T} = \frac{\alpha_s C_R}{\pi^2} \int dq_1 \left(|A(q_1)|^2 - \sigma_{el}\delta(q_1) \right) \int dq_2 \left(|A(q_2)|^2 - \sigma_{el}\delta(q_2) \right)$$

$$\times \left[\frac{(nL)^2}{2} \underbrace{R(k+q_1;q_2)}_{\text{Incoherent}} - n^2 \frac{1-\cos LQ_1}{Q_1^2} \left\{ \underbrace{R(k+q_1;q_2)}_{\text{Incoherent}} - \underbrace{R(k;q_1+q_2)}_{\text{Coherent}} \right\} \right]$$

Formation times

(4.16)

$$\tau_{f,n} = \frac{1}{Q_n} = \frac{2\omega}{\left(k_T + \sum_{i=1}^{n} q_i\right)^2}$$

define interpolation scale between totally coherent and incoherent limit

(4.17)

$$n^2 \frac{1-\cos LQ_1}{Q_1^2} \longrightarrow \begin{cases} 0 & , L > \tau_{f1} \\ n^2 L^2/2 & , L < \tau_{f1} \end{cases}$$

Formally, determine totally coherent and incoherent limiting cases by taking $L \to 0$ or $L \to \infty$ for $nL = fix$

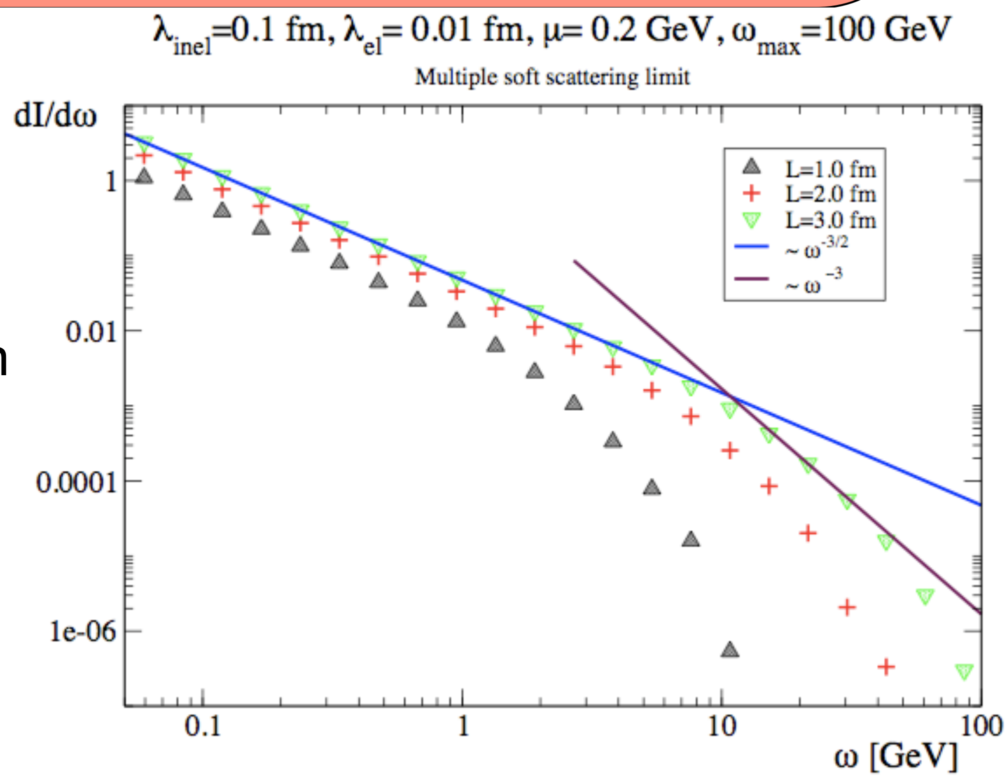
Basic idea of jet quenching Monte Carlo:

Zapp, Stachel, Wiedemann, Phys. Rev. Lett. 103: 152302, 2009
JHEP 1107:118, 2011

Gluon fragmentation in vacuum shows interference pattern:
Implemented probabilistically e.g. via angular ordering constraint

Gluon fragmentation in medium shows interference pattern:
Implemented probabilistically via formation time constraint

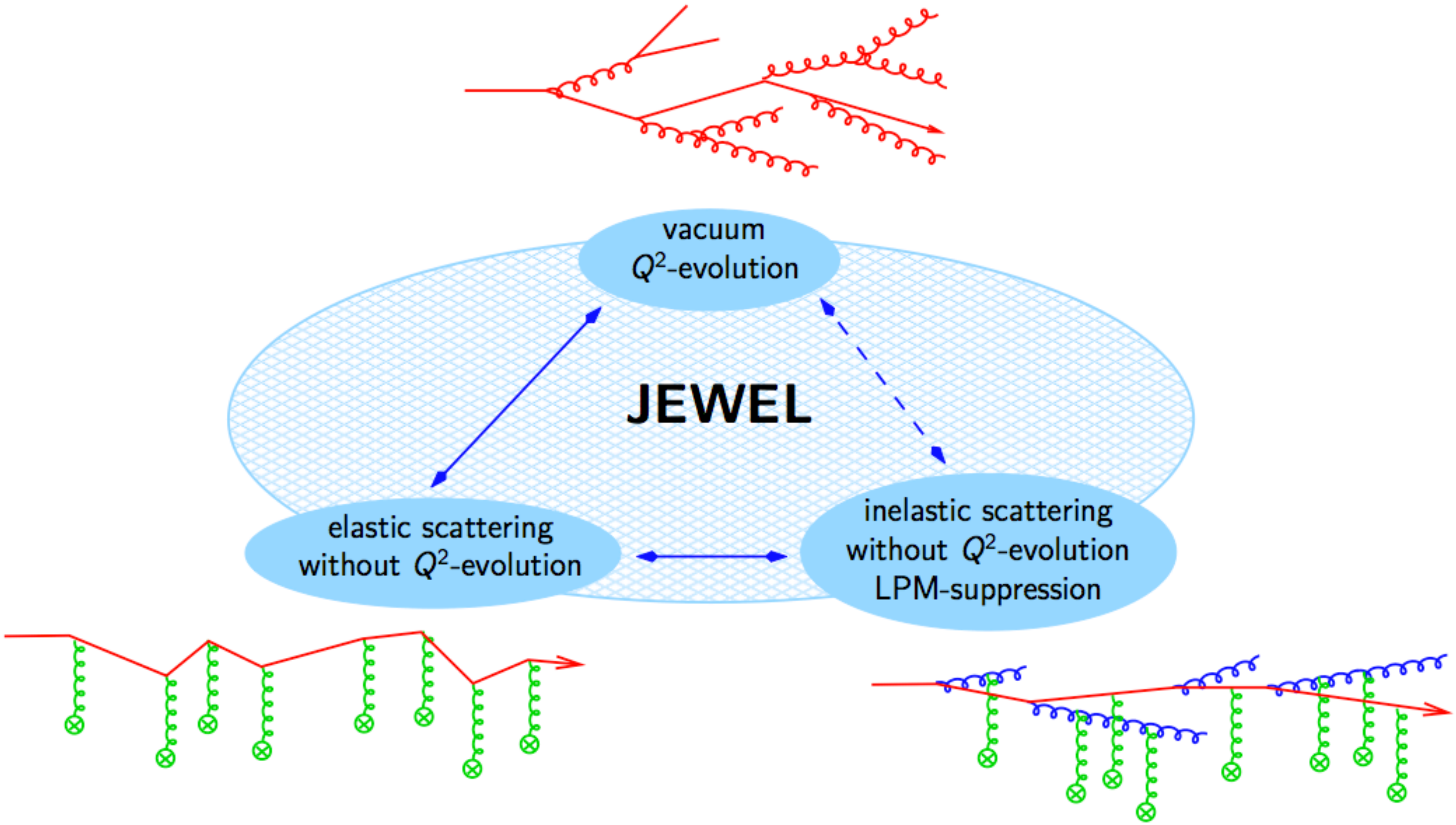
The resulting local and probabilistic Monte Carlo algorithm provides a **quantitatively exact** implementation of all features of the BDMPS-Z formalism.



IV.23. JEWEL: jet evolution with energy loss

K. Zapp, et al., **Eur.Phys.J.C60:617-632,2009, and work on progress**

Anchor modeling on theoretically well-controlled limits:



Note: there are many complementary works to implement jet quenching in MC event generators

IV.24. LHC: high-pt opportunities in coming years

The probes:

- Jets
- identified hadron specta
- D-,B-mesons
- Quarkonia
- Photons
- Z-boson tags

The range:

Q^2 ,x, A, luminosity

Abundant yield

of hard probes

+ robust signal

(medium sensitivity

>> uncertainties)

= detailed understanding

of dense QCD matter