Universiteit Utrecht

Modeling energy loss in a realistic geometry

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High p_T at LHC workshop Utrecht

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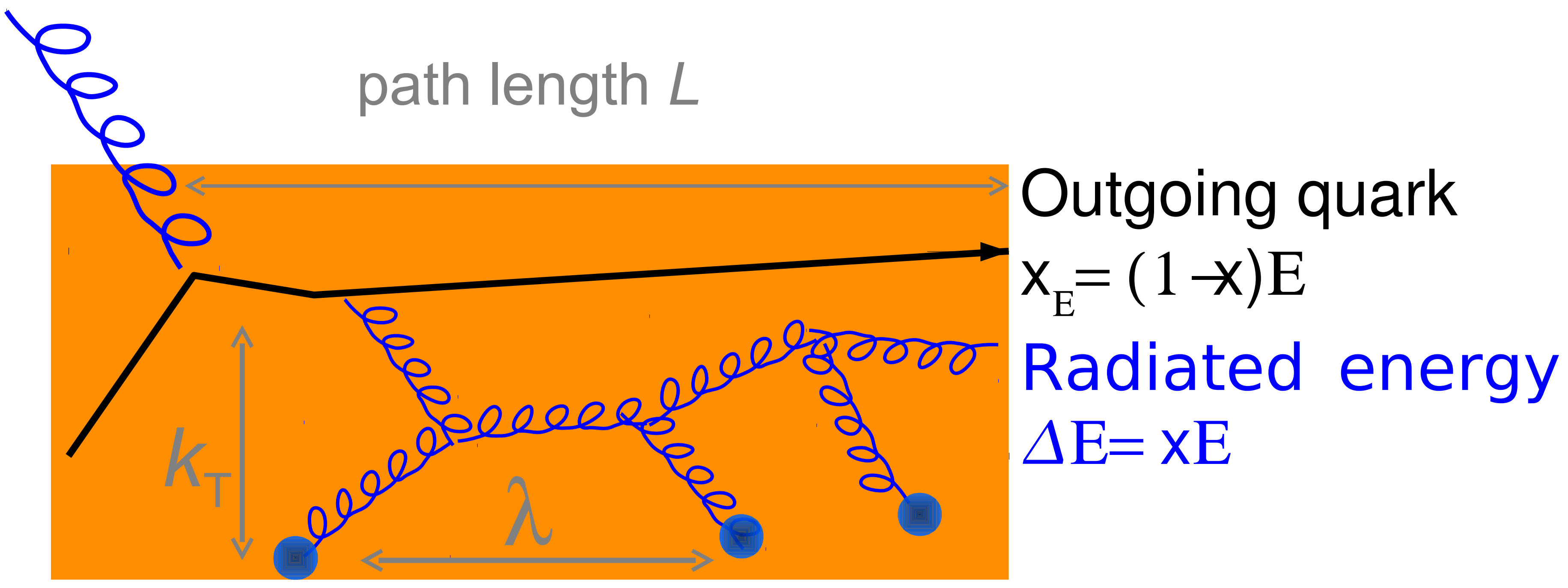
Schematic picture of energy loss mechanism

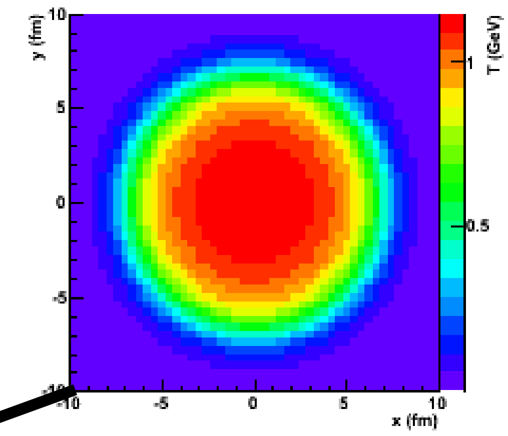
in hot dense matter



Geometry of HI collision

- Woods-Saxon profile
- Wounded Nucleon Scaling with optical Glauber
- Medium formation time: τ_0 = 0.6 fm
- Longitudinal Bjorken Expansion $1/\tau$
- Freeze out temperature: 150 MeV

Temperature profile of central collision

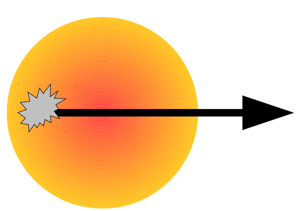


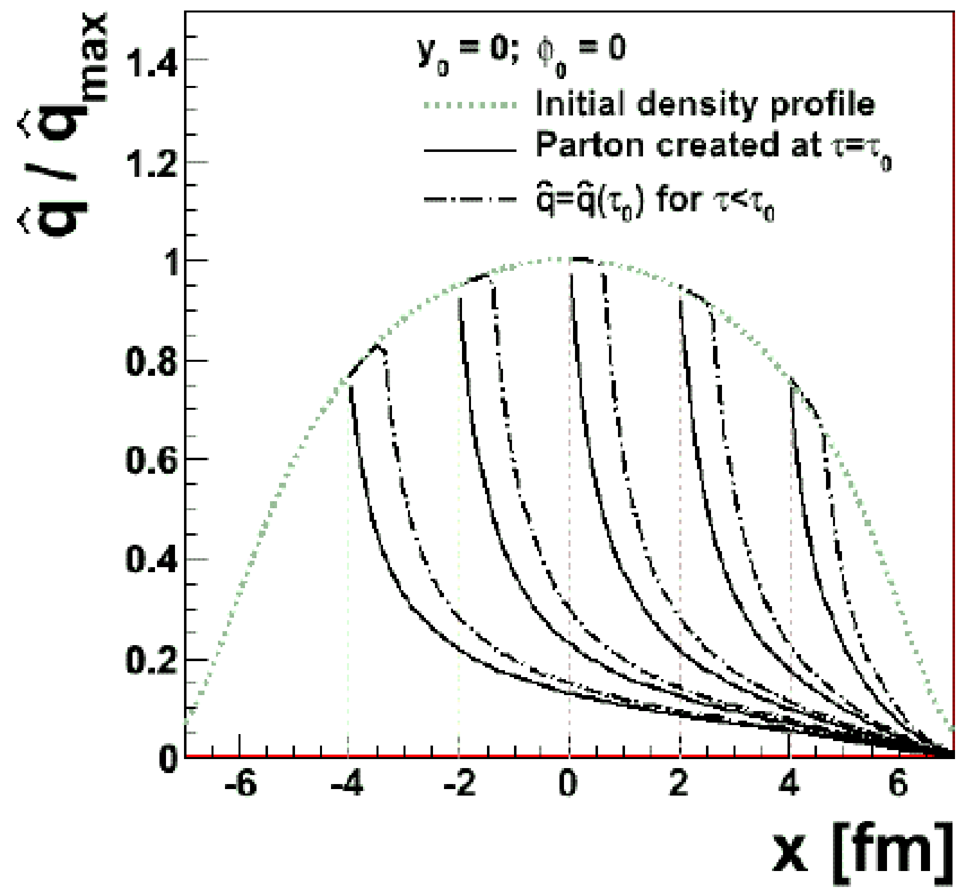
$$\frac{dN}{dp_{t,hadr}} = \frac{dN}{dp_{t,parton}} \circ P(\Delta E) \circ D(p_{t,hadr}/p_{t,parton})$$

Measurement	Input parton spectrum Known LO pQCD	**Energy loss** geometry medium	Fragmentation Function Known from e+e-

Medium density profile

- Parton travels through evolving medium
- Parton *sees* different medium at each step in space and time
- Density of medium decreases as function of space and time





Local qhat as function of space-time coordinate x for different starting points

Model input parameters

- Multiple soft scattering approximation (ASW-MS):

$$N_{gluon} = \int d\omega \frac{dI}{d\omega}(\omega_c, R) = \int d\omega \frac{dI}{d\omega}(\hat{q}, L)$$

"Medium density"

- Opacity expansion (GLV, etc.):

$$N_{gluon} = \frac{L}{\lambda} \int d\omega \frac{dI}{d\omega}(\mu, L)$$

#scattering centers Debye screening mass

- No qhat for opacity expansions.

$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda} \sim \frac{\mu^2}{\lambda}$$

- **How to determine input parameters in an evolving medium?**

Effective input variables

- Define integrals to average T, T^2, T^3 along parton path through the medium:

$$J_n^{(m)} = \int_0^\infty u^n T^m(u) du$$

- ASW-MS: qhat ~ T^3 → m=3

$$J_0^{(3)} \propto [L\hat{q}]_{eff} \text{ and } J_1^{(3)} \propto \omega_{c,eff}$$

$$\hat{q}_{eff} = \frac{2\omega_{c,eff}}{L_{eff}^2} \propto \frac{J_0^{(3)} \cdot J_0^{(3)}}{2J_1^{(3)}}$$

PQM

$$L_{eff} \propto \frac{2J_1^{(3)}}{J_0^{(3)}}$$

- OE's: $1/\lambda$ ~T → m=1
  μ^2 ~ T^2 → m=2

$$\bar{\omega_c} \propto T^2 L \propto J_0^{(2)}$$

$$\frac{L}{\lambda} \propto TL \propto J_0^{(1)},$$

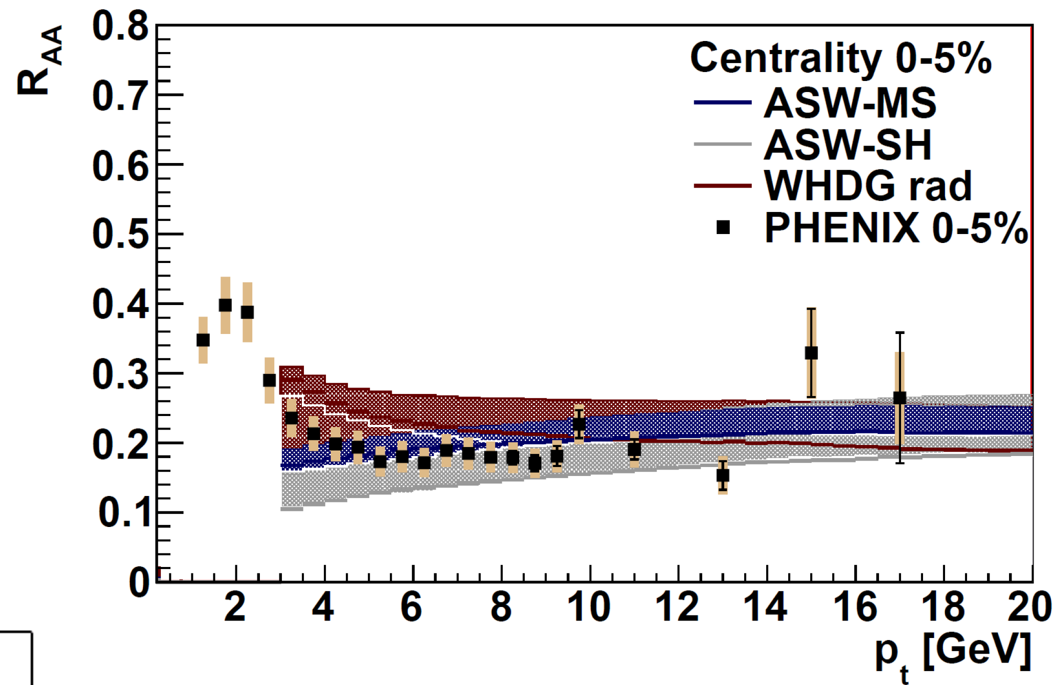
Assume for comparison with ASW-MS:

$$L_{eff}^{OE} = \frac{2J_1^{(2)}}{J_0^{(2)}}$$

$R_{A\,A}$ at RHIC

- Common input parameter for all models: Temperature
- **All models can be fitted to $R_{A\,A}$**
- Best fit is estimated by modified χ^2 analysis.
- Each best fit is has a 1σ uncertainty band (shaded area).

	If $\tau < \tau_0$ $\hat{q} = \hat{q}_0$	
	$\hat{q}_0$ (GeV/fm^2)	T_0 (MeV)
ASW-MS	$20.3^{+0.6}_{-5.1}$	973^{+6}_{-90}
WHDG rad	$5.7^{+0.3}_{-1.9}$	638^{+11}_{-81}
ASW-SH	$3.2^{+0.3}_{-0.3}$	524^{+17}_{-18}

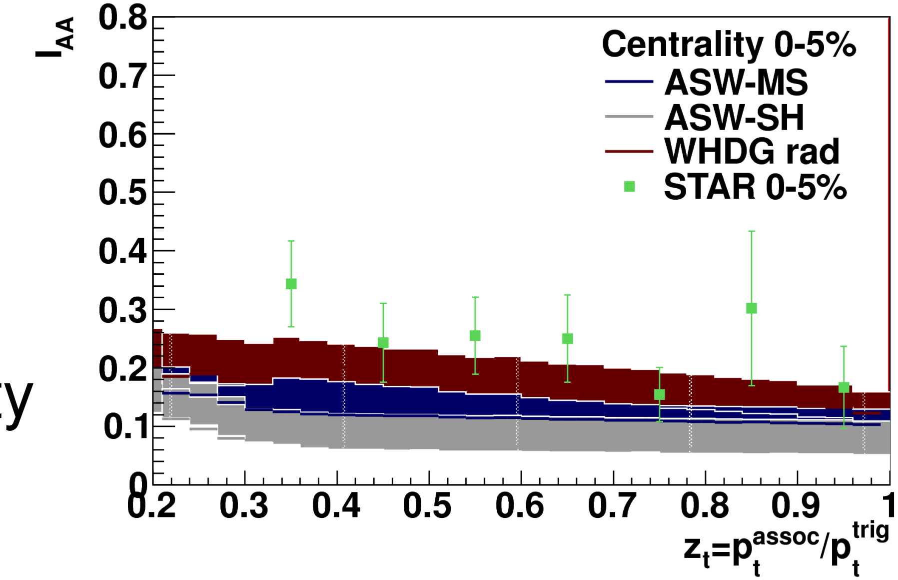


Factor 4-5 difference in density estimation between multiple soft scattering approximation and opacity expansions.

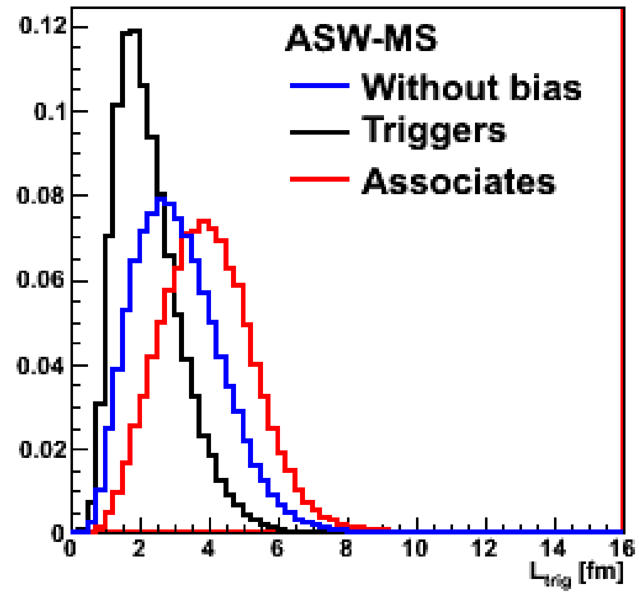
PHENIX data: Phys. Rev. ***C77****, 064907 (2008)*

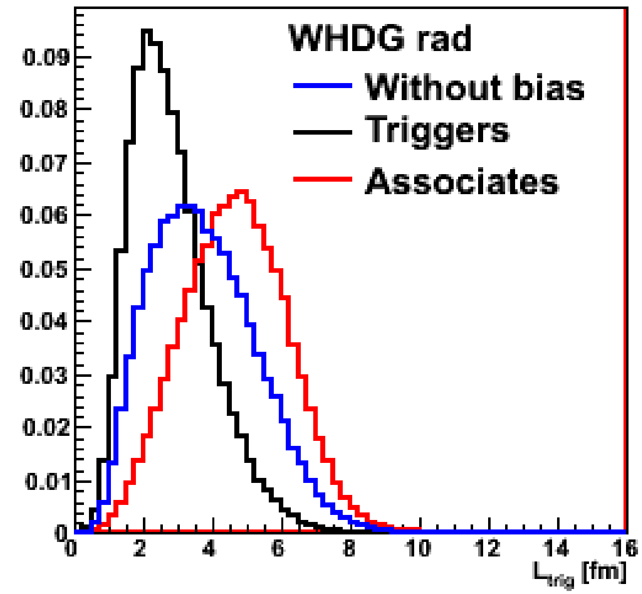
I_{AA} at RHIC

- Calibrate density using R_{AA}
- Most models underestimate I_{AA}
- Small difference in effective length definition for multiple soft and opacity expansion



- Next step: integrate realistic medium within GLV instead of calculating effective parameters





Opacity Expansion Single Gluon Spectrum

- General formula:

$$x\frac{dN_g}{dx} = \frac{C_R C_g g^2}{2\pi^3}\int \frac{d^2\mathbf{q}}{(2\pi)^2} d^2\mathbf{k}\; dz\; C(\mathbf{q}, z) \times \mathcal{K}(\mathbf{k}, \mathbf{q}, z)$$

in which:

$$\mathcal{K}(\mathbf{k}, \mathbf{q}, z) = \frac{\mathbf{k}\cdot\mathbf{q}(\mathbf{k}-\mathbf{q})^2 - \beta^2\mathbf{q}\cdot(\mathbf{k}-\mathbf{q})}{[(\mathbf{k}-\mathbf{q})^2+\beta^2]^2(\mathbf{k}^2+\beta^2)} \times \left[1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2+\beta^2}{2Ex}z\right)\right]$$

$$C(\mathbf{q}) = \frac{1}{C_s}(2\pi)^2\frac{d^2\Gamma_{\mathrm{el}}(\mathbf{q})}{d^2\mathbf{q}}$$

Reference: S. Caron-Huot & C. Gale, arXiv:1006.2379

- C(**q**) depends on medium properties.
- Explore effect of constant C(**q**) (uniform medium) vs position-dependent C(**q**) (non-uniform medium).

Scattering rate in (D)GLV

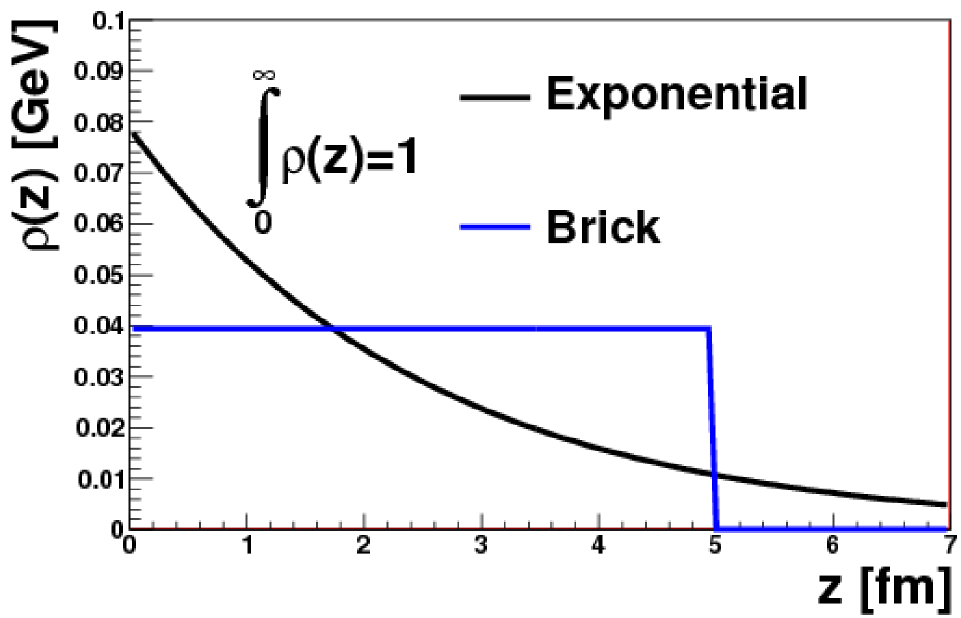
$$x\frac{dN_g}{dx} = \frac{C_R\alpha_s}{\pi}\frac{L}{\lambda}\int\frac{d^2\mathbf{q}}{\pi}\frac{2d^2\mathbf{k}}{\pi}\int dz\frac{\mu^2}{(\mathbf{q}^2+\mu^2)^2}\times\mathcal{K}(\mathbf{k},\mathbf{q},z)\times\rho(z)$$

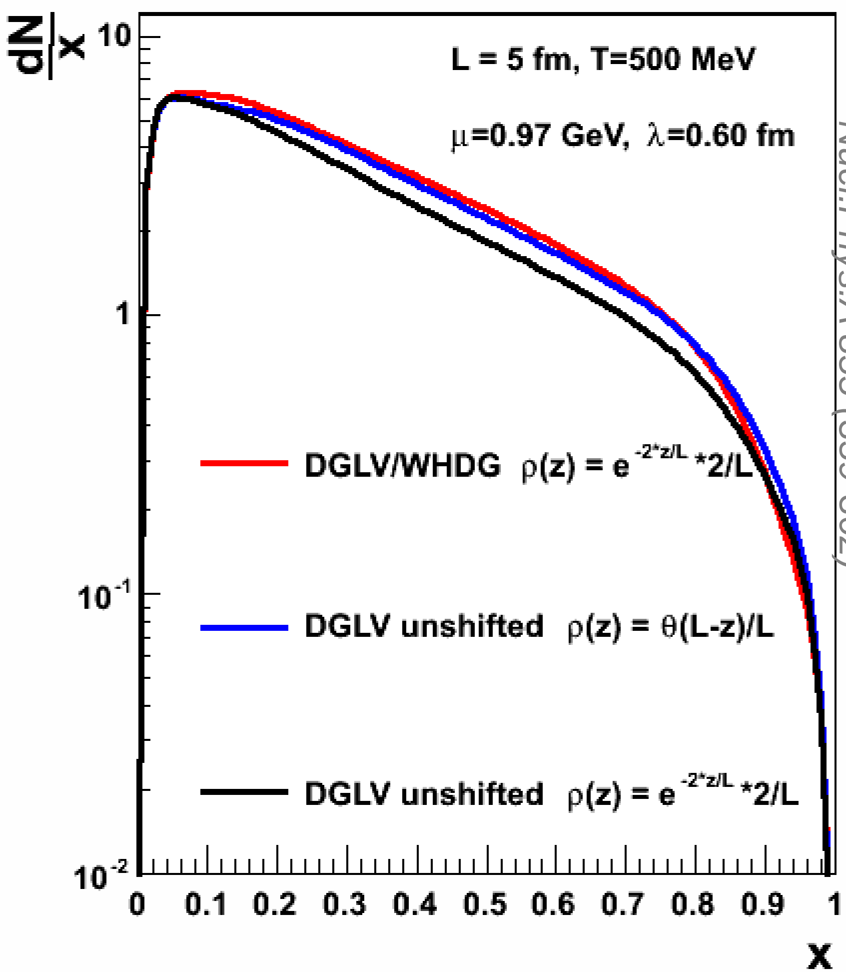
$$C(\mathbf{q},z)^{GLV} = \frac{(2\pi)^2}{\lambda C_R}\boxed{\frac{1}{\pi}\frac{\mu^2}{(q^2+\mu^2)^2}}\boxed{\rho(z)}$$

- Normalized Yukawa potential and ρ(z)
- ρ(z) is the probability to have a scattering at position z
  $\rightarrow \rho/\lambda$ = scattering rate per unit length
- Single gluon radiation spectrum is calculated for 1 scattering and then multiplied by the number of scatterings (=L/λ)

Single gluon spectrum (D)GLV

- Normalized $\rho(z)$ is varied and compared to the WHDG result
- In WHDG radiative change of variables **q** → **q+k** is applied
- **Similar spectrum in case of exponentially decaying and uniform (brick) distribution of scattering centers.**





Nucl.Phys.A 855 (359-362)

Local ρ and μ

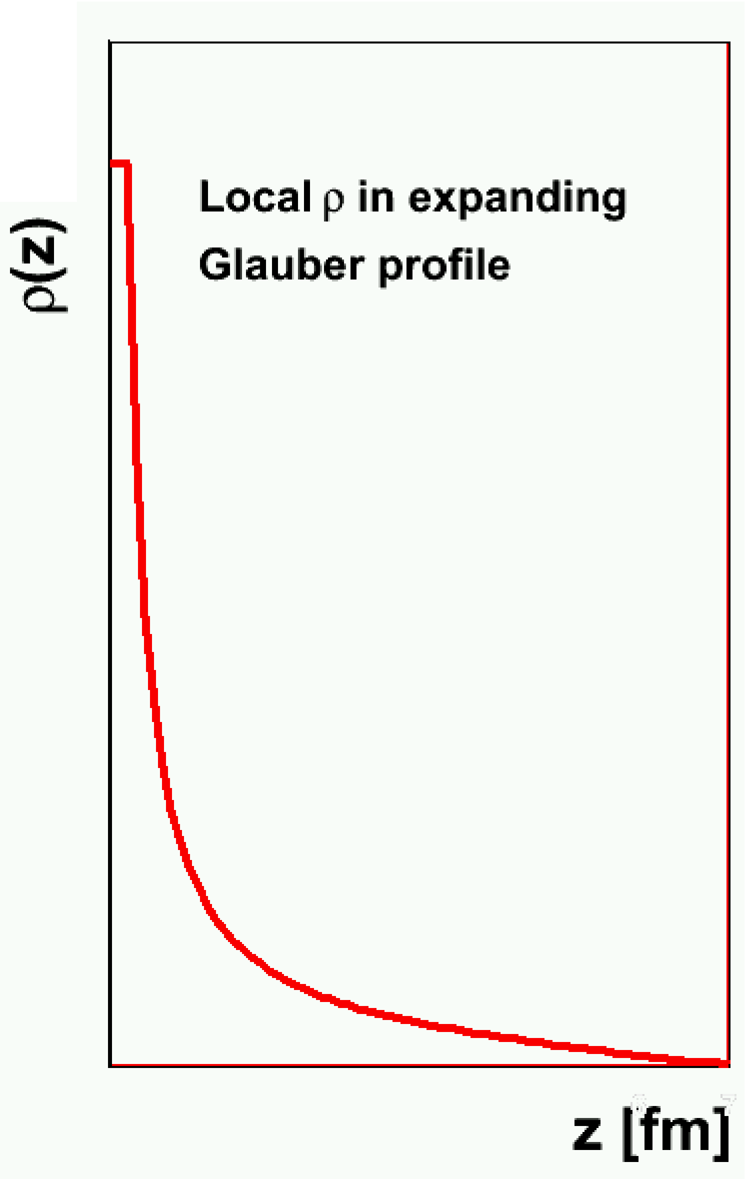
- ρ(z) = medium density = $\mathcal{N}$(z) ~ T^3
- Differential cross-section temperature dependent while the parton propagates through the medium.

$$C(\mathbf{q},\mathbf{z}) = \frac{g^4 \mathcal{N}(\mathbf{z})}{(\mathbf{q}^2+\mu(\mathbf{z})^2)^2}$$

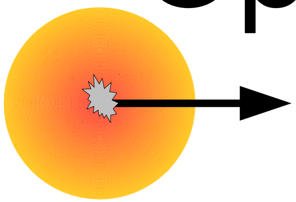
$$\mathcal{N}(\mathbf{z}) = \frac{\zeta(3)}{\zeta(2)}(1+\frac{1}{4}N_f)\mathbf{T}(\mathbf{z})^3$$

$$\mu(\mathbf{z})^2 = (1+\frac{1}{6}N_f)g^2\mathbf{T}(\mathbf{z})^2$$

- Medium: participant scaling + Bjorken expansion + constant medium density prior to formation time

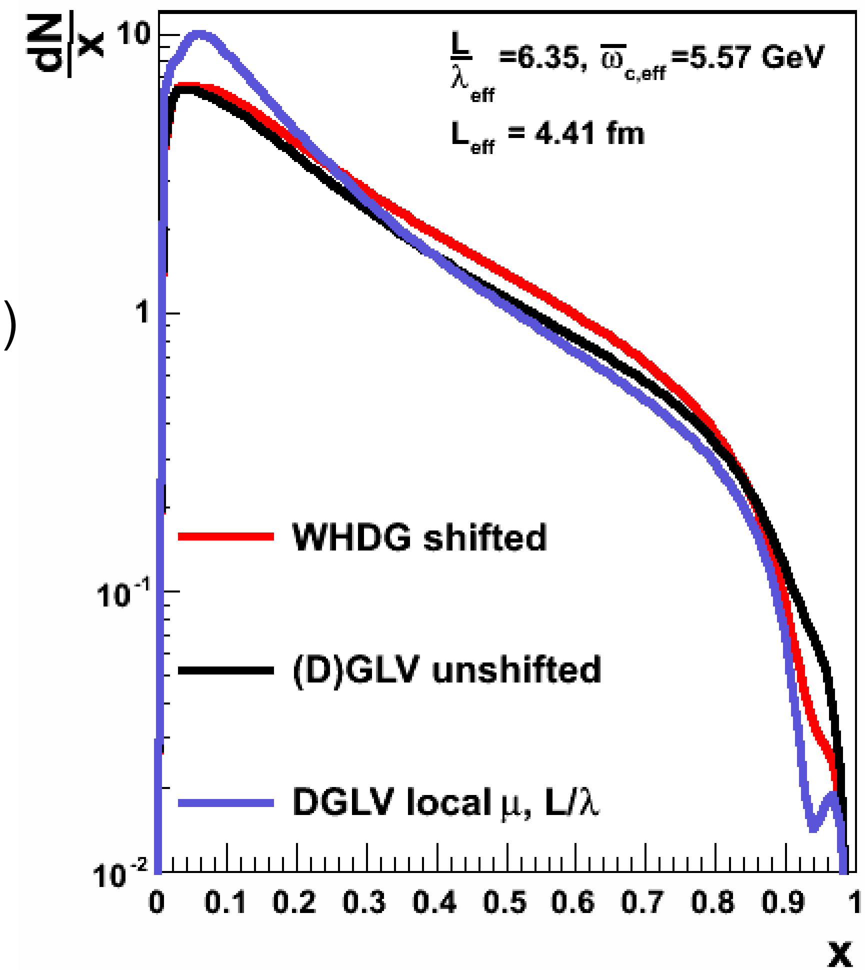


Opacity expansion + evolving participant scaling



- Parton starts at center of medium and moves radially outwards.
- Compare gluon spectrum for:
  - Average medium properties (WHDG shifted, DGLV unshifted)
  - Local parameters in evolving medium (DGLV local)

Single gluon spectrum



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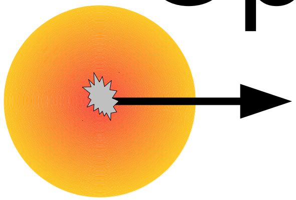
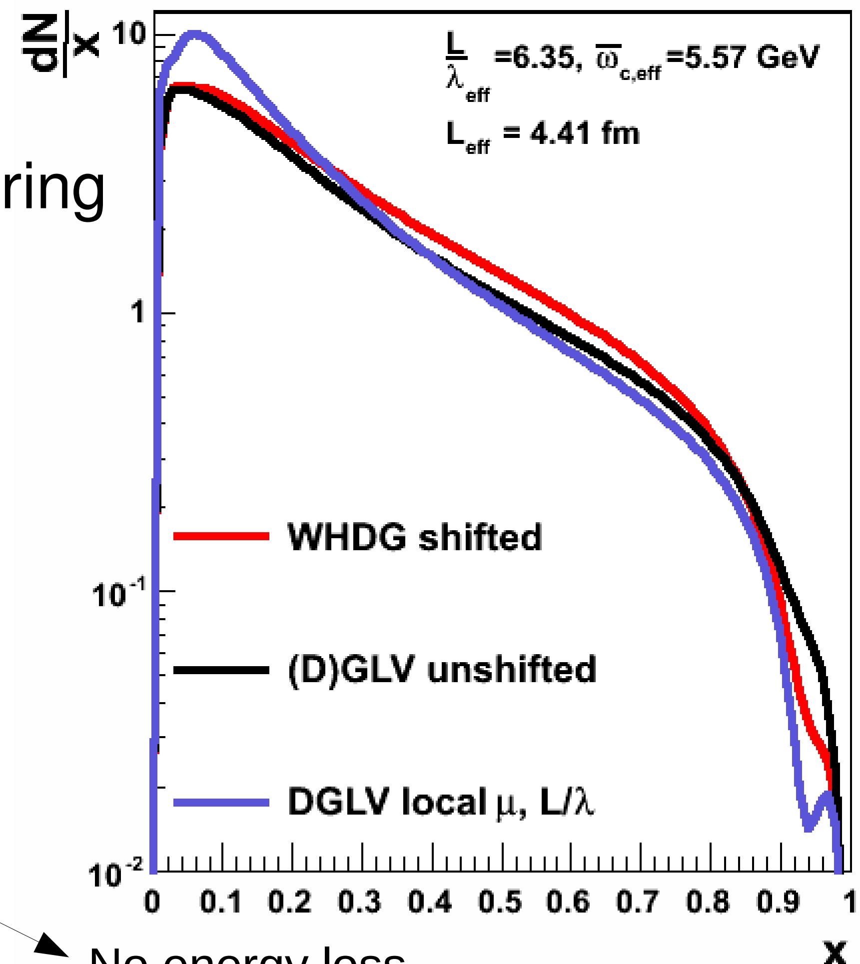
Opacity expansion + evolving participant scaling



- Parton starts at center of medium and moves radially outwards.
- More soft gluon radiation in case of inhomogeneous distribution of scattering centers

Single gluon spectrum



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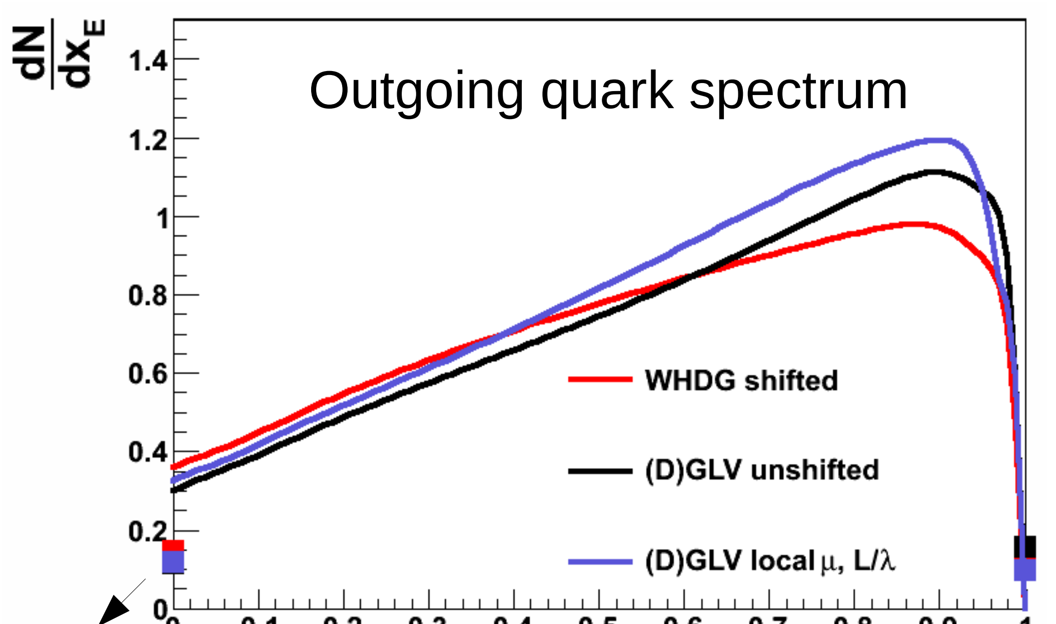


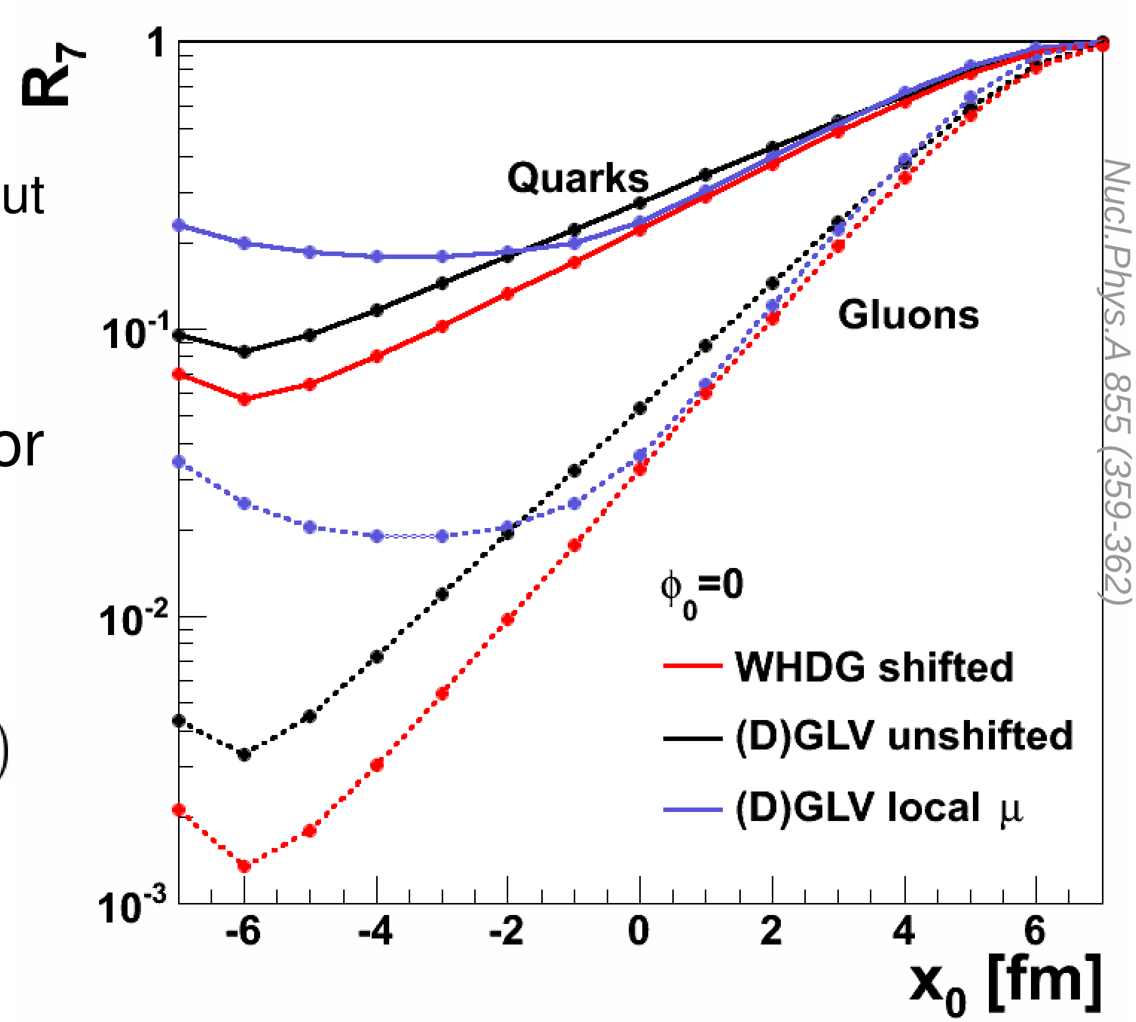
Parton is absorbed by the medium

No energy loss

Medium as seen by parton

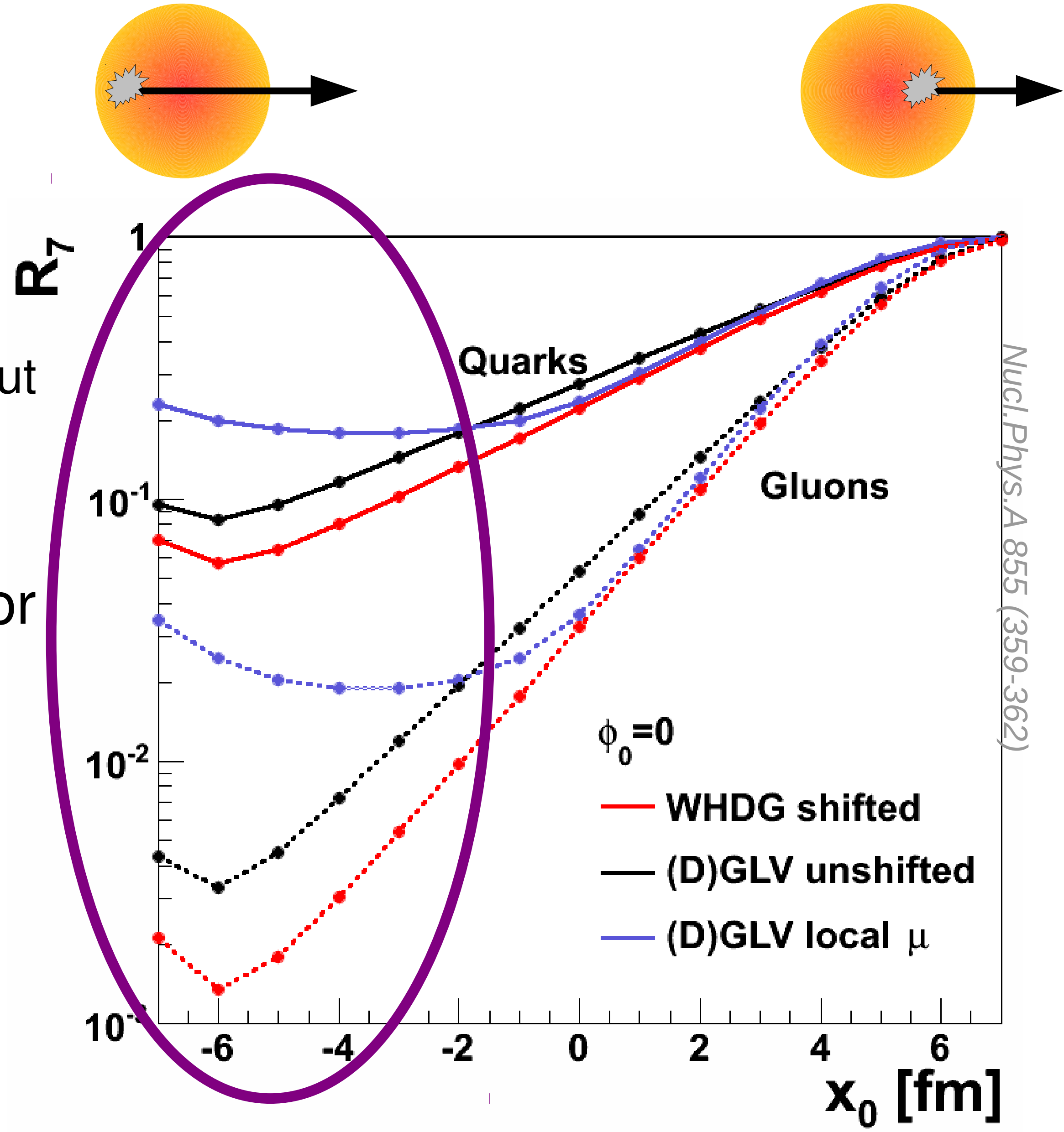
- Exercise:
  - Parton is created at x_0 and travels radially through the center of the medium until it leaves the medium or freeze out has taken place.
- Characterize energy loss of parton with suppression factor R_7

$$R_n = \int_0^1 d\epsilon (1-\epsilon)^{n-1} P(\epsilon)$$



Medium as seen by parton

- Exercise:
  - Parton is created at x_0 and travels radially through the center of the medium until it leaves the medium or freeze out has taken place.
- Characterize energy loss of parton with suppression factor R_7
- Large difference in energy loss for parton with long path lengths.



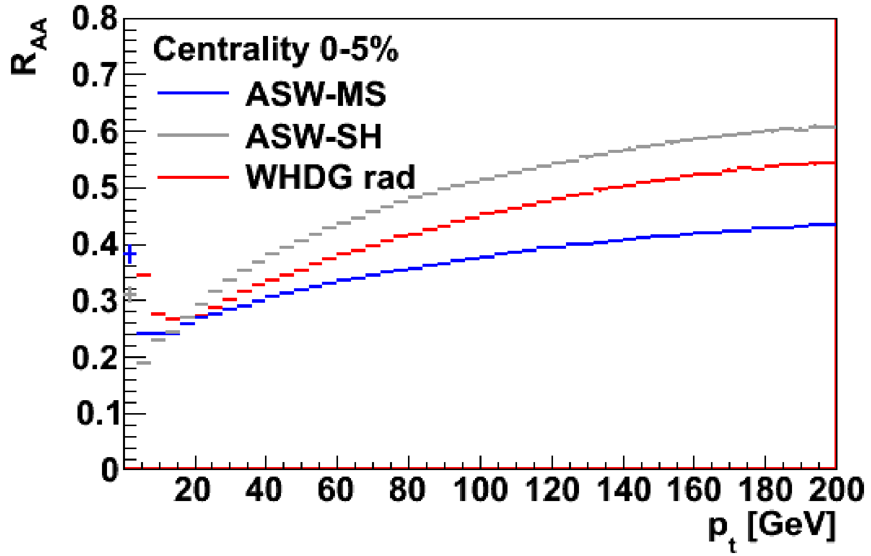
Summary

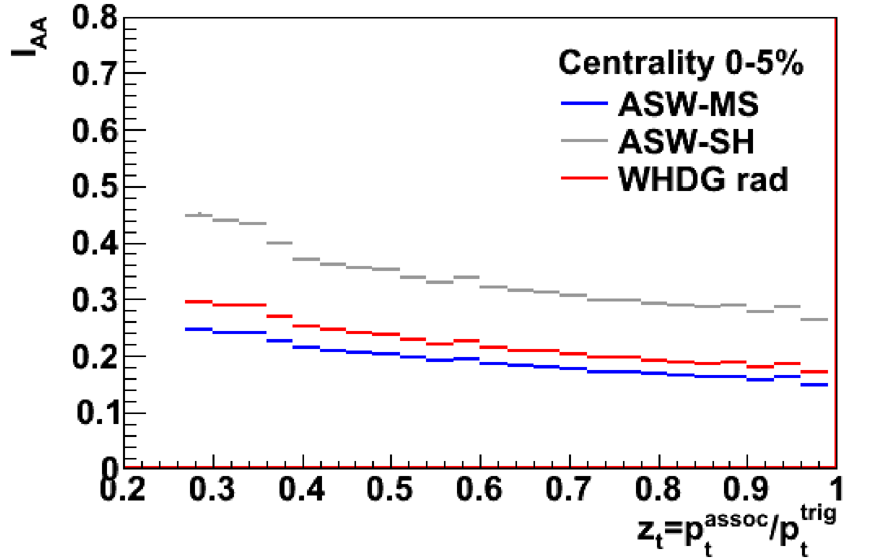
- Different energy loss models give different estimates for the medium density when fitting to RHIC data.
- Using effective values as input for the energy loss models overestimates the energy loss for partons with a long path length through the medium.

- **Long parton trajectory → NOT the same as equivalent brick** backup

R_{AA} and I_{AA} at LHC

- Assuming same medium density as at RHIC.
- Parton p_t spectrum for LHC flatter than at RHIC.
- Higher parton momenta than at RHIC.
- P_t dependence of R_{AA} *different for several models*
- For I_{AA}: $50 < p_{t,Trig} < 70$ GeV
  $p_{t,Assoc} > 20$ GeV





Suppression Factor

in a brick

- Hadron spectrum if each parton loses ϵ energy:

$$\frac{dN}{dp_t} = \frac{1}{[(1-\epsilon)p_t]^n}\frac{dp_t}{dp_t'} = \frac{1}{(1-\epsilon)^{n-1}p_t^n}$$

$p_t' = (1-\epsilon)\, p_t$

Weighted average energy loss:

$\epsilon = \Delta E/E$

$$R_n = \int_0^1 d\epsilon (1-\epsilon)^{n-1} P(\epsilon)$$

For RHIC: n=7

- R_7 approximation for R_{AA}.