What did we learn from the “QGP Brick” Problem?

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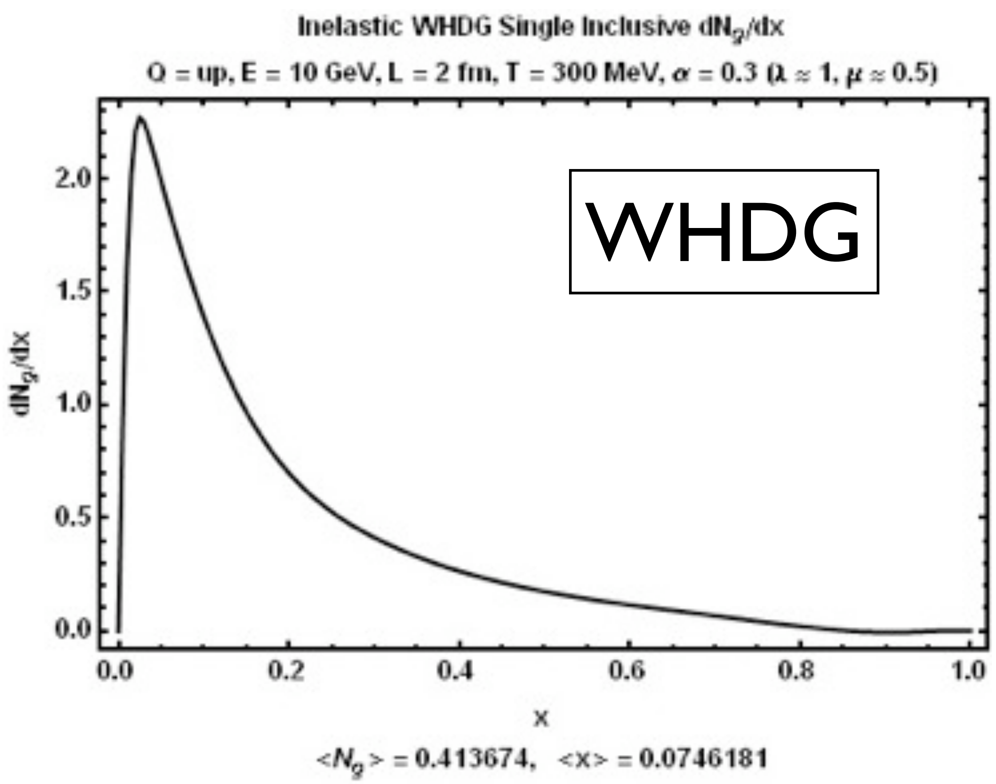
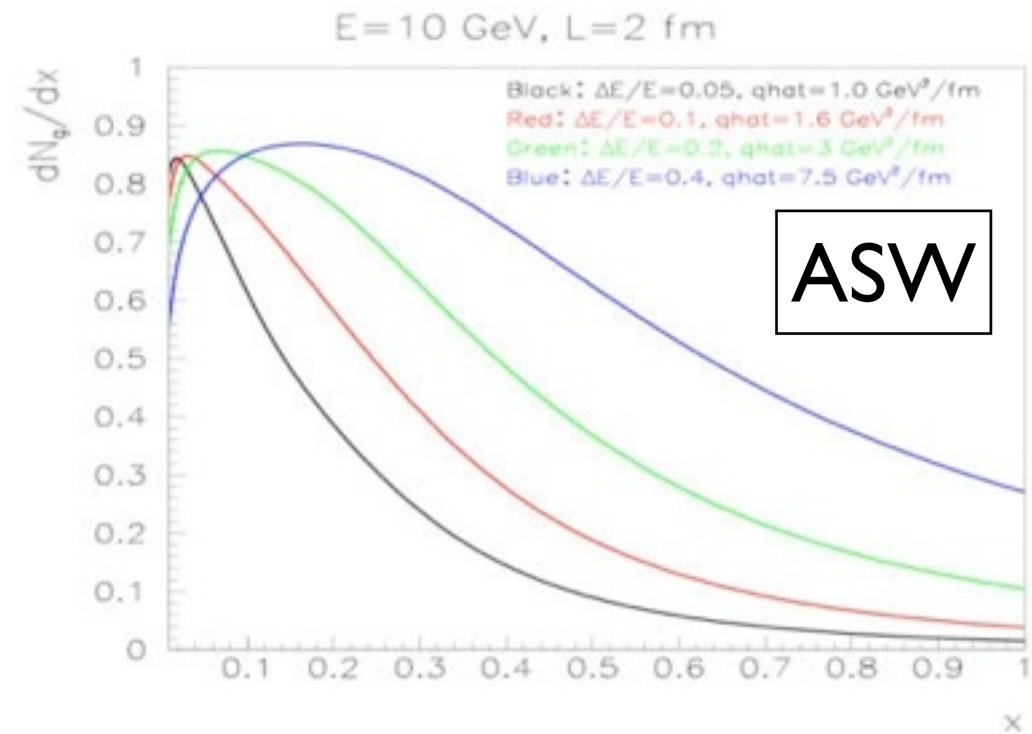
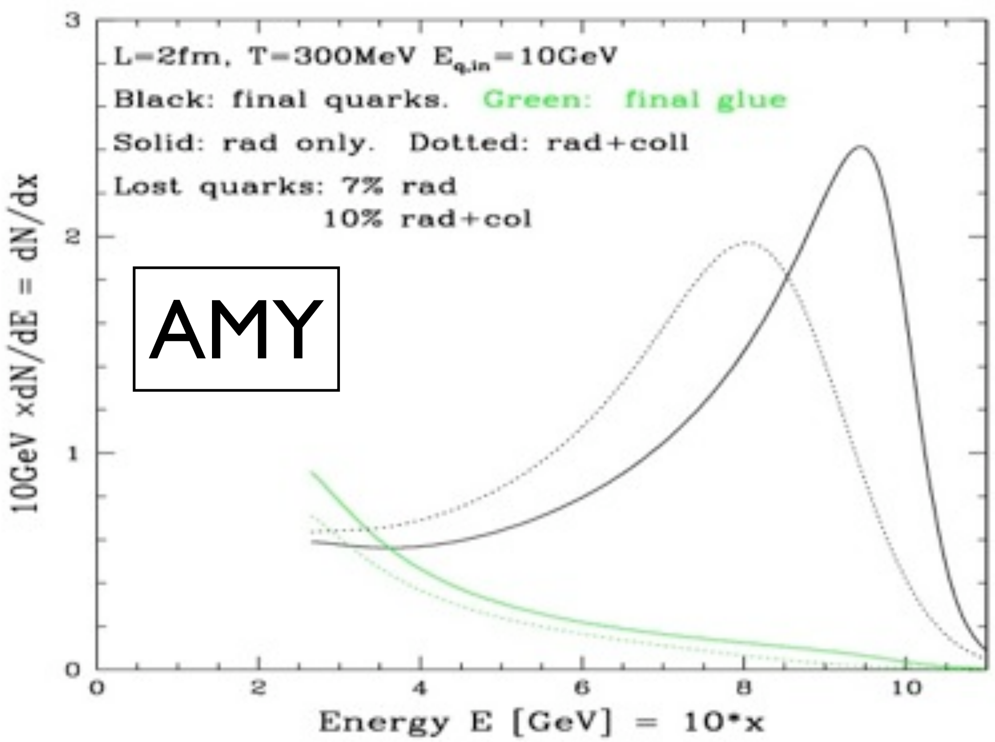
What did we learn from the “QGP Brick” Problem ?

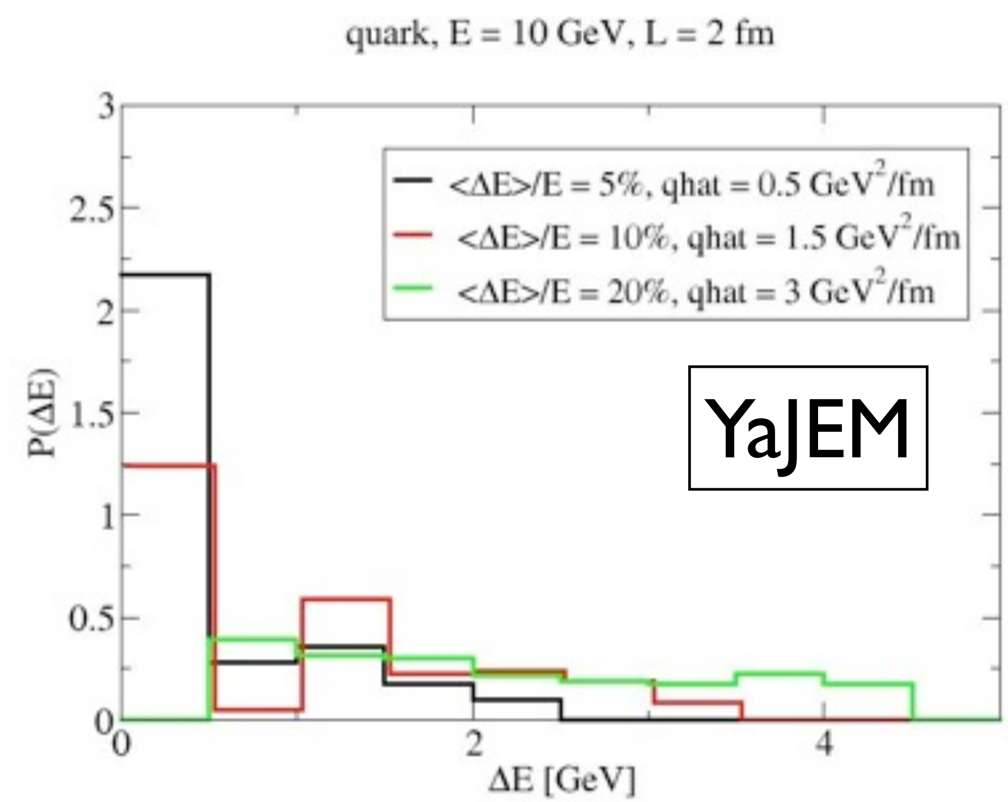
- The community can collaborate
- More popular than anticipated
- Specifying a problem completely is not easy
- The “QGP Brick” challenge was useful
- The “QGP Brick” will remain a benchmark

The Entrants - 1

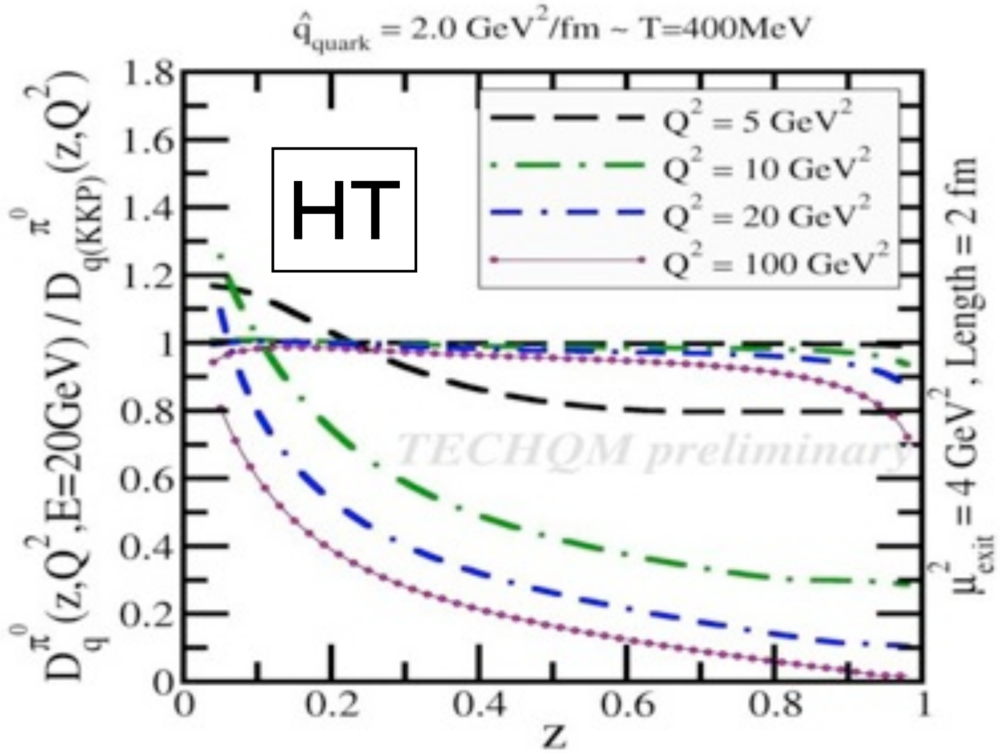


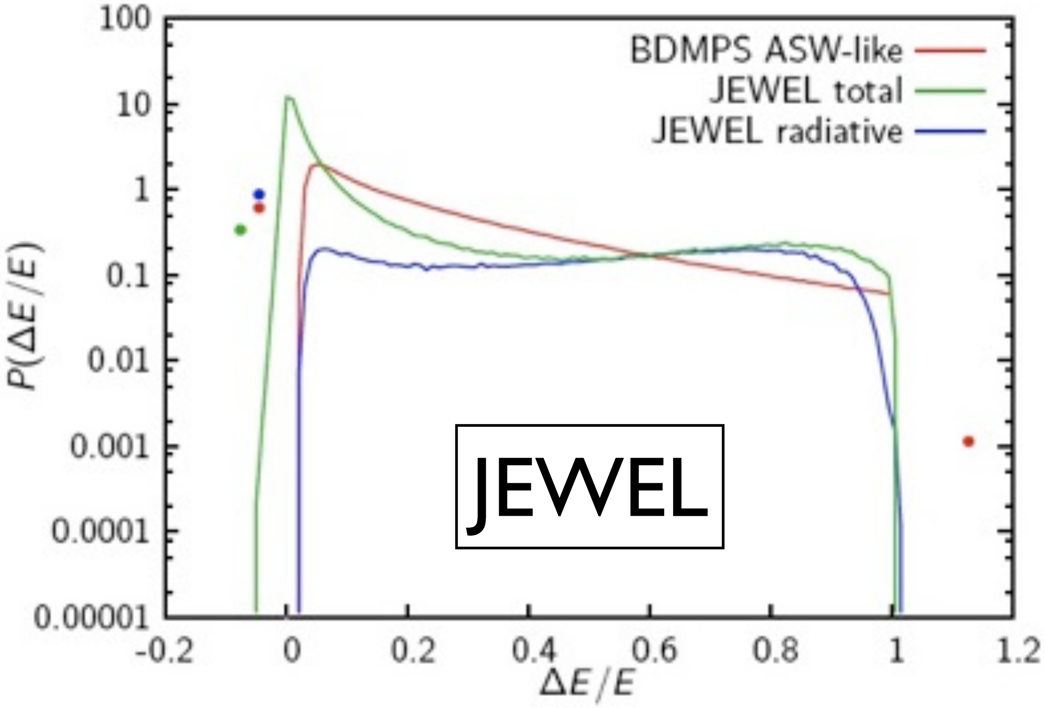


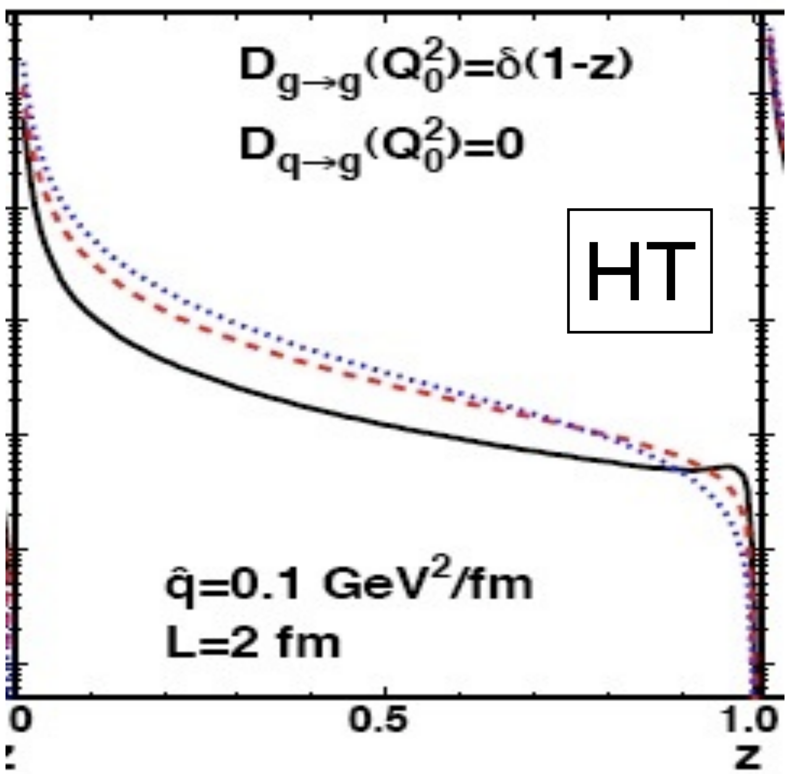


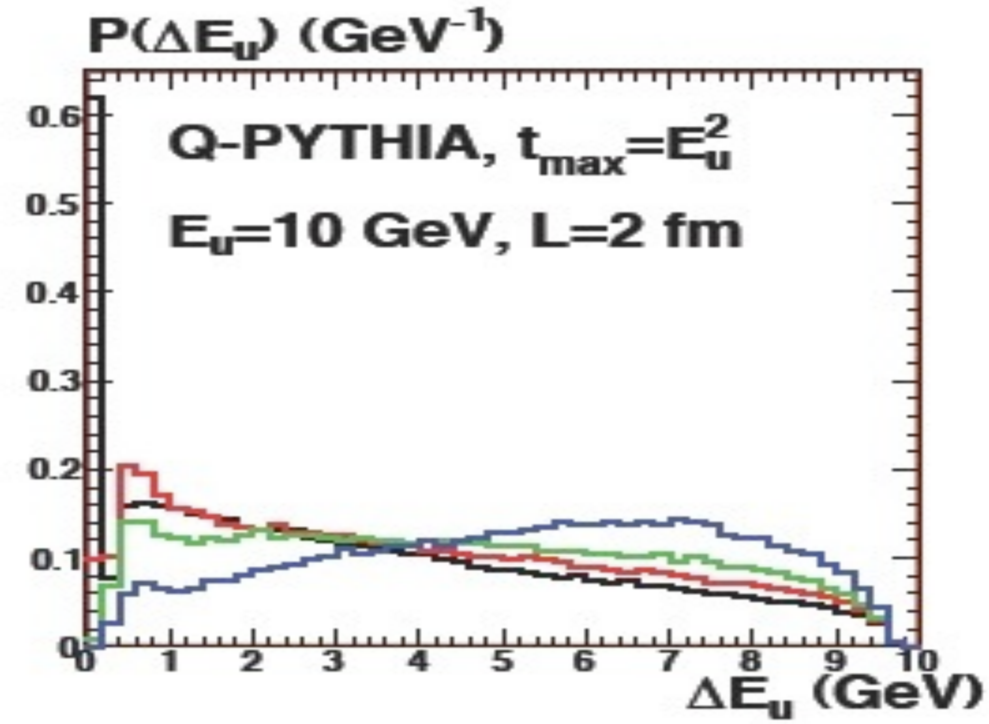


The Entrants - 2

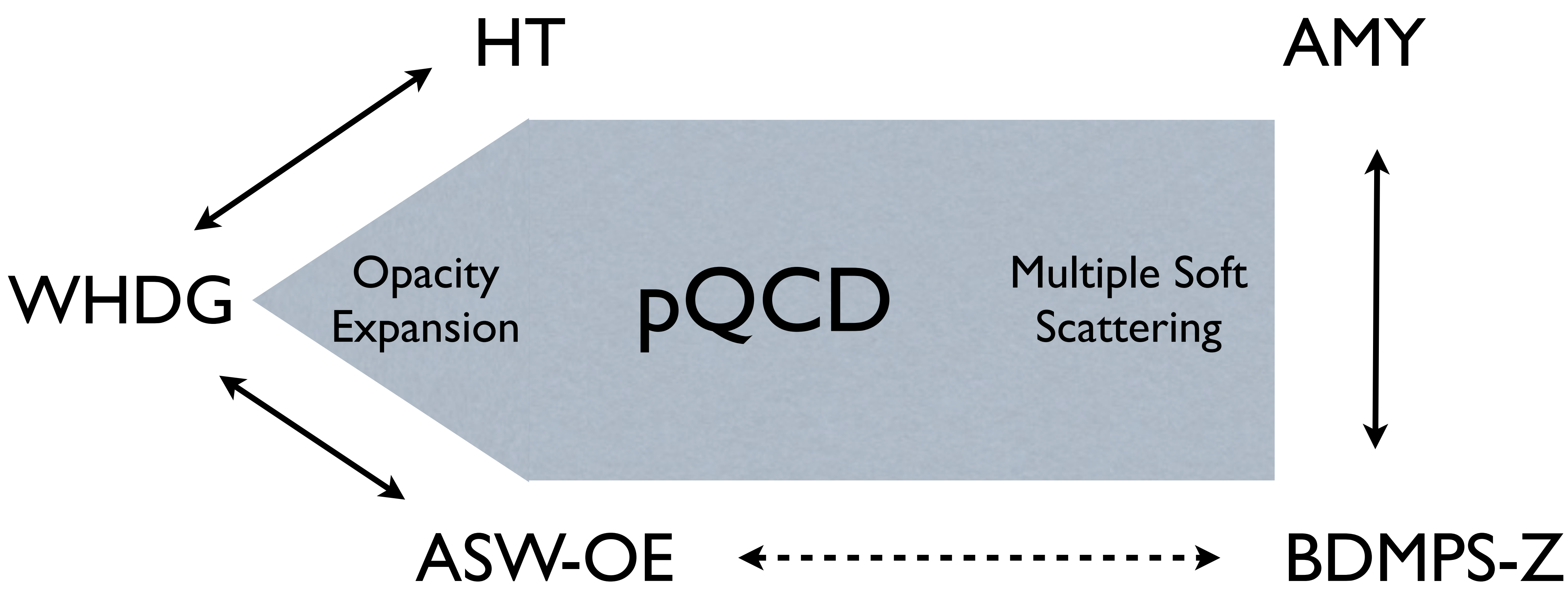








Making comparisons across the Jet Quenching Landscape



WHDG $\leftrightarrow$ ASW-LOE

$$x\frac{dN_g^{\mathrm{GLV}}}{dx} = \frac{C_R\alpha_s}{\pi}\frac{L}{\lambda}\int\frac{d^2\mathbf{q}}{\pi}\frac{\mu^2}{(\mathbf{q}^2+\mu^2)^2}\int\frac{2d^2\mathbf{k}}{\pi}\frac{\mathbf{k}\cdot\mathbf{q}(\mathbf{k}-\mathbf{q})^2}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^4}\int dz\left[1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2}{2Ex}z\right)\right]\rho(z)$$

$$\rho(z) = \begin{cases} \frac{1}{L}\theta(L-z) \\ \frac{2}{L}\exp(-2z/L) \end{cases}$$

$$\omega\frac{dI^{\mathrm{ASH-SH}}}{d\omega} = \frac{4\alpha_s C_R}{\pi}(n_0L)\gamma\int_0^\infty \tilde{q}d\tilde{q}\left[\frac{\tilde{q}^2-\sin\tilde{q}^2}{\tilde{q}^4}\right]\left(\frac{1}{\gamma+\tilde{q}^2}-\frac{1}{\sqrt{(\kappa^2+\tilde{q}^2+\gamma^2)^2-4\kappa^2\tilde{q}^2}}\right)$$

$\gamma = \tilde{\omega}_c/\omega$, $\tilde{\omega}_c = \frac{1}{2}\mu^2 L$, $\kappa = \sqrt{\omega L/2}$, and $n_0L = L/\lambda$

It all depends on what the meaning of "x" is....

$$x_+ = \frac{x_E}{2}\left(1+\sqrt{1-\left(\frac{k_\perp}{x_E E}\right)^2}\right)$$

WHDG

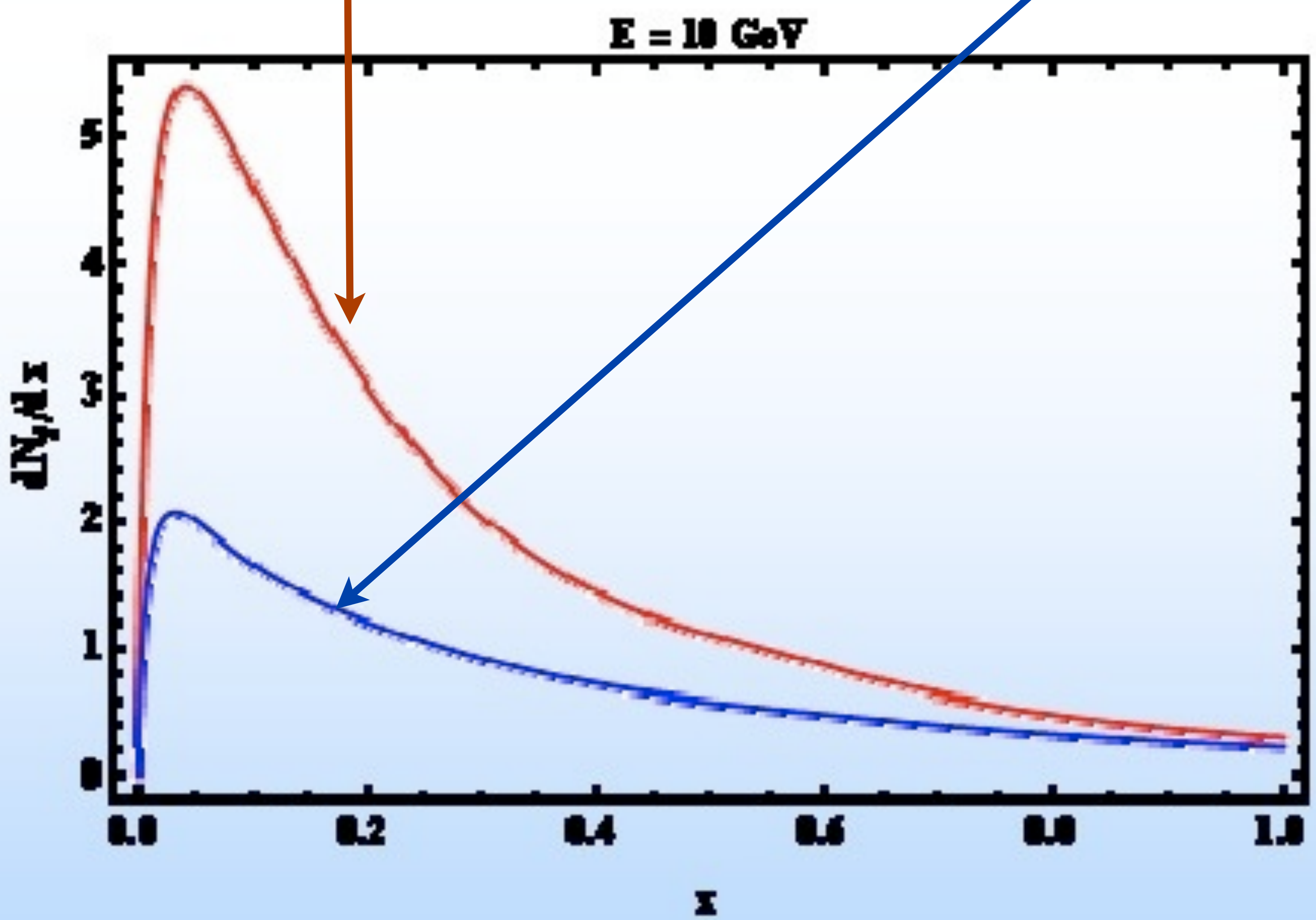
$$x_E = x_+\left(1+\left(\frac{k_\perp}{x_+E^+}\right)^2\right)$$

ASW

Identical in the $k_\perp/\omega$ limit, but ...

... but not when you consider the kinematic limit of $k_\perp$ for given ω.

WHDG	ASW
– $k_T < x_+ E^+ = 2\, x_+ E$	– $k_T < x_E\, E$
• $k_{max} = 2\, x\, (1\text{-}x)\, E$	• $k_{max} = x\, E$



Lesson:

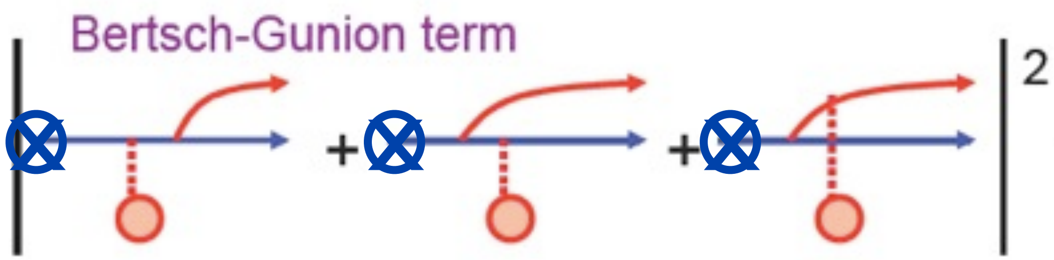
Kinematic assumptions beyond the strict validity of the eikonal/collinear approximation can have drastic consequences even at high energies, because radiation always tries to exhaust the available phase space.

Vac-med interference vs. LPM

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

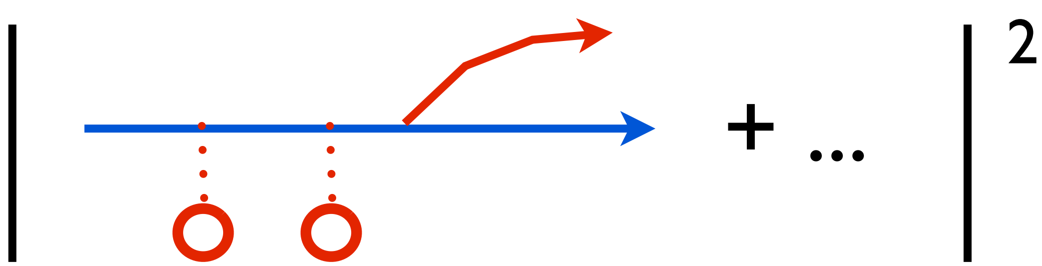
$$H(k_T) = \frac{1}{k_T^2}$$

Vacuum radiation



$$= |A(q_1)|^2 R(k;q_1) \equiv |A(q_1)|^2 \frac{q_1^2}{k^2 (k+q_1)^2}$$

WHDG
ASW-LOE
HT-LO



"True" LPM effect: Coherent action of multiple scatterings in the medium

BDMPS-Z AMY
GLV-HO ASW-HO

$$\omega \frac{dI^{(1)}}{d\omega\, dk_T dq_1\, dq_2} = \frac{\alpha_s C_R}{\pi^2} \left(|A(q_1)|^2 - V_{tot}\delta(q_1) \right) \left(|A(q_2)|^2 - V_{tot}\delta(q_2) \right)$$
$$\times \left[\frac{(n_0 L)^2}{2} R(k+q_1; q_2) - n_0^2 \frac{1-\cos LQ_1}{Q_1^2} R(k+q_1; q_2) + n_0^2 \frac{1-\cos LQ_1}{Q_1^2} R(k; q_1+q_2) \right]$$

Summary of insights: WHDG $\leftrightarrow$ ASW-LOE

- Different definitions of the variables x_+ and x_E;
- Importance of the kinematical region $k_\perp \sim \omega$, which violates the assumption of collinearity of the radiation process,
- Absence of exact energy and momentum conservation, both in the elementary process and in the convolution of successive radiation events (radiative cascade);
- Influence of different choices for the distribution of scattering centers (step function vs. exponential).
- Need for a consistent definition of q^ for quantitative comparison with other models.

$$\hat{q} = \rho \int d^2q_\perp \, q_\perp^2 \frac{d\sigma}{d^2q_\perp}$$

Summary of insights: WHDG $\leftrightarrow$ HT-LO

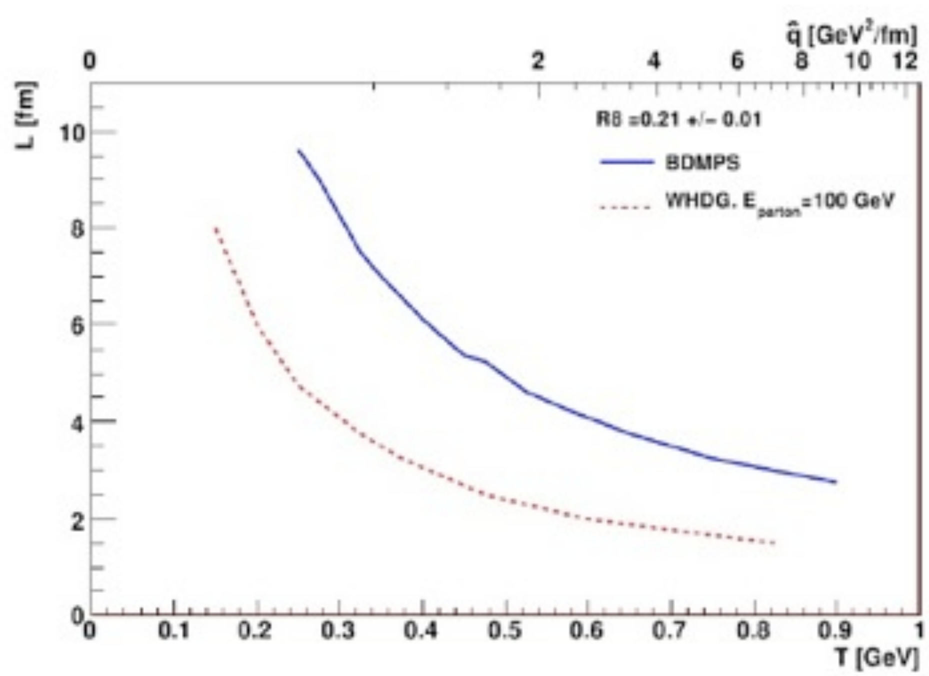
- HT implements energy-momentum conservation in the elementary process;
- HT assumes $k_{\perp} >> q_{\perp}$, i.e. virtuality is dominated by primary hard scattering;
- HT encodes the running of $\alpha_s(Q^2)$. For a first quantitative comparison with WHDG one should set α_s constant, and then explore the quantitative importance of the running of α_s;
- HT does not assume a specific model of the medium, but parametrizes the medium through a transport coefficient $\hat{q}$ (and $\hat{e}$ for elastic energy loss);
- HT exhibits sizable flavor change of leading parton.

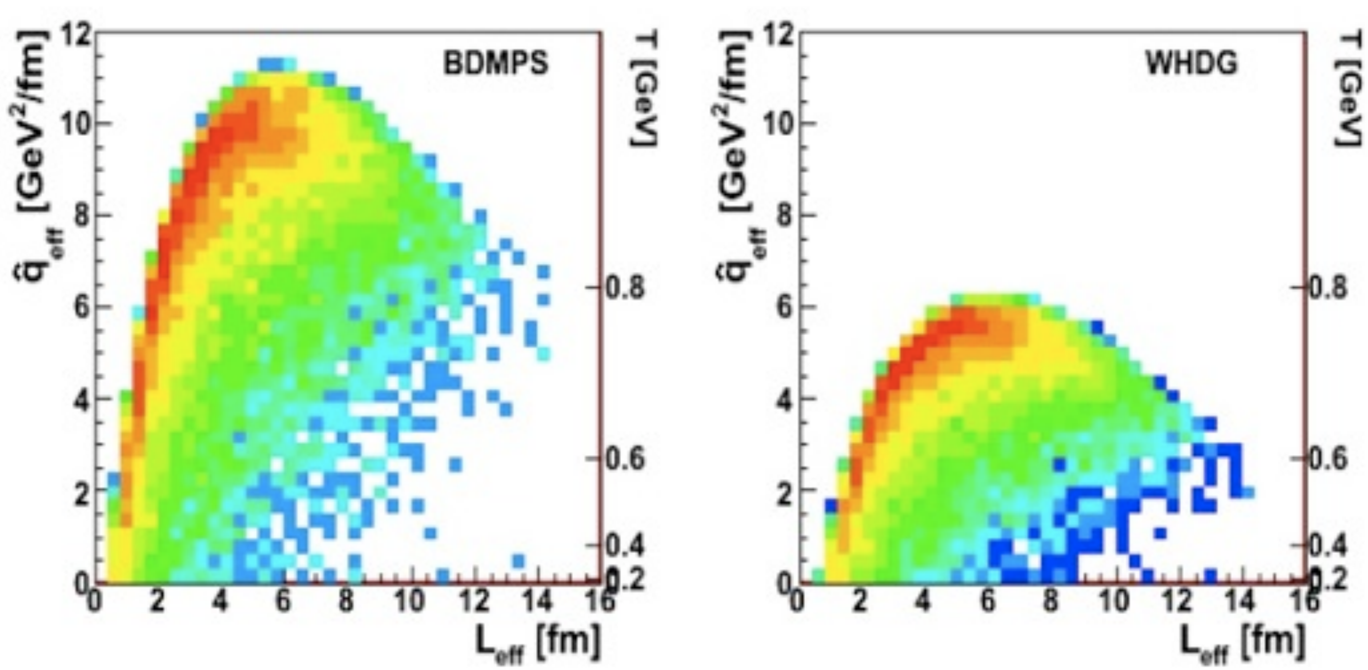
Summary of insights: BDMPS-Z $\leftrightarrow$ AMY

- AMY does not contain interference between vacuum and medium induced radiation;
- AMY implements exact energy and momentum conservation, both in the elementary process and in the radiative cascade;
- AMY treats the medium dynamically, not as collection of static scattering centers;
- Average energy loss is a bad approximation for true collisional energy loss;
- AMY and BDMPS both assume collinearity of the radiation; importance of large angle radiation needs to be studied;
- AMY exhibits sizable flavor change of leading parton.

Summary of insights: BDMPS-Z $\leftrightarrow$ WHDG

- Assignment of $\hat{q} = \mu^2/\lambda$ in WHDG seems to underestimate the true value of $\hat{q}$ by a factor 2-3;
- Correct definition: $\hat{q} = \langle k_\perp^2 \rangle / \lambda = \mu^2/\lambda_{tr}$.
- Results for WHDG and BDMPS-Z can be mapped into each other by a rescaling of T or L of the medium by factor ~2;
- Results of $\hat{q}$ fit for a dynamical medium differ by factor ~2.





Outlook (1)

- Origin of differences between 1st generation jet quenching formalisms is now well understood; they lie mostly outside the range of strict validity of the eikonal-collinear approximation.

- pQCD approach to jet quenching is alive and well.

- Reduction of uncertainty in q^ from R_{AA} to $\leq$ factor 2 seems possible with some effort.

- Most severe deficiencies are:
  - Energy-momentum conservation;
  - Vacuum radiation interference;
  - Consistent treatment of elastic & inelastic processes;
  - *Ad hoc* vacuum hadronization (?)

Outlook (2)

- A timely and comprehensive "TEC-HQM report" on the insights gained from the QGP Brick challenge would be a document of great value and with lasting impact.
  - "Timely" ≈ 3 months (?)
  - "Comprehensive" ⇔ circulated outline sketch (?)
- "1st generation" jet quenching formalisms will remain the basis for MC schemes and detailed modeling of jet evolution.
- 1st generation jet quenching codes will also provide test cases for more sophsticated schemes.

Outlook (3)

- Some other questions:
  - Can I_{AA} vs. R_{AA} be used to check consistency of q^ determination?
  - Can selection of jet virtuality ("jet mass") be used to discriminate between VMI and LPM ?
  - Can we probe the validity of vacuum hadronization assumption ? It must fail somewhere! (recombination? heavy quark hadrons?)
  - Can we rule out that QCD jets become nonperturbative once they "see" the QGP? Can we rule out that pQCD does <u>not</u> apply to jets in a QCD medium? What kind of fragmentation pattern would a thin [i.e. L << E/(dE/dx)] "AdS/CFT Brick" produce?