Status of the TECHQM 'brick problem'

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NWO

TECHQM

https://wiki.bnl.gov/TECHQM/index.php/Main_Page

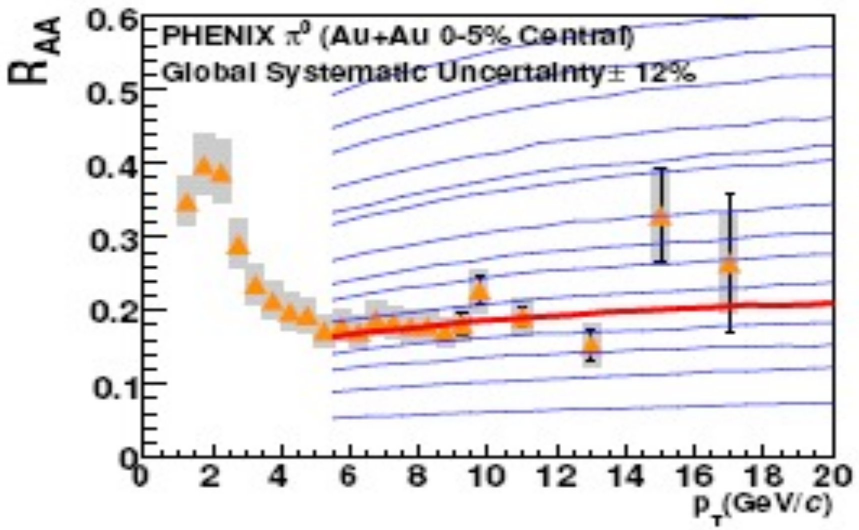
Theory-Experiment Collaboration on Hot Quark Matter

- Forum to discuss comparison between theory and experiment in areas where there is a potential significant quantitative understanding
- Two subgroups:
  - Parton energy loss
  - Elliptic flow/Hydro
- Workshops/meetings:
  - BNL May 2008
  - LBL Dec 2008
  - CERN July 2009
  - BNL (with CATHIE) Dec 2009

This talk is about Parton Energy loss

Energy loss formalisms I

PHENIX, arXiv:0801.1665,
J. Nagle WWND08



PQM $\langle\hat{q}\rangle = 13.2^{+2.1}_{-3.2}$ GeV^2/fm

WHDG $dN_g/dy = 1400^{+200}_{-375}$

ZOWW $\varepsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm

AMY $\alpha_s = 0.280^{+0.016}_{-0.012}$

Large difference in medium density:

GLV, AMY: T = 300-400 MeV BDMPS: T ~ 1000 MeV

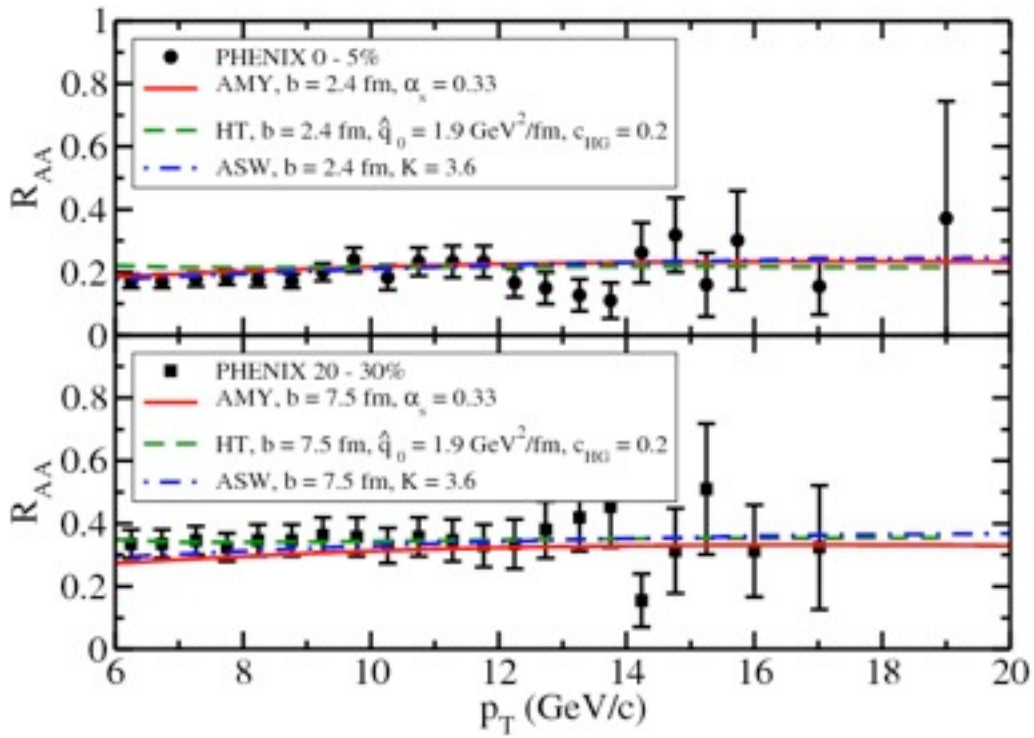
Different calculations use different geometries – not clear what dominates

Energy loss formalisms II

Compare 3 formalisms with
`same' Hydro geometry:

ASW: $\hat{q} = 10 - 20\ \mathrm{GeV}^2/\mathrm{fm}$
HT: $\hat{q} = 2.3 - 4.5\ \mathrm{GeV}^2/\mathrm{fm}$
AMY: $\hat{q} \approx 4\ \mathrm{GeV}^2/\mathrm{fm}$

AMY: T ~ 400 MeV

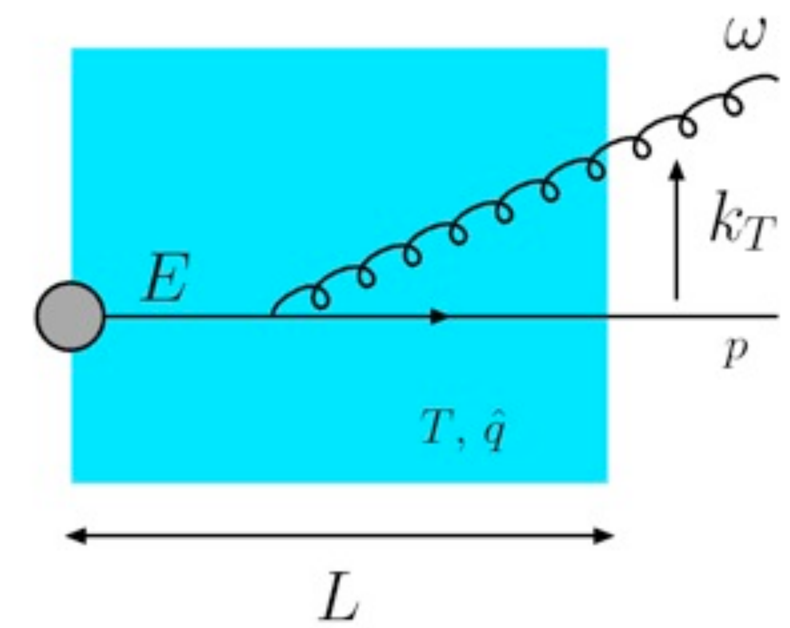


Bass et al, PRC79, 024901

Different formalisms give different energy loss at given density, path length

Why:
Different physics implemented? Or `technical' differences?
What are the main uncertainties?

The Brick Problem



Gluon(s)

Compare energy-loss in a well-defined model system:
Fixed-length *L* (2, 5 fm)
Density *T, q*
Quark, *E* = 10, 20 GeV

Plot: outgoing gluon, quark distributions

Two types of comparison:
- Same density
- Same suppression

Four formalisms

Multiple gluon emission

- **Hard Thermal Loops (AMY)**
  - Dynamical (HTL) medium
  - Single gluon spectrum: BDMPS-Z like path integral
  - No vacuum radiation

Fokker-Planck rate equations

- **Multiple soft scattering (BDMPS-Z, ASW)**
  - Static scattering centers
  - Gaussian approximation for momentum kicks
  - Full LPM interference and vacuum radiation

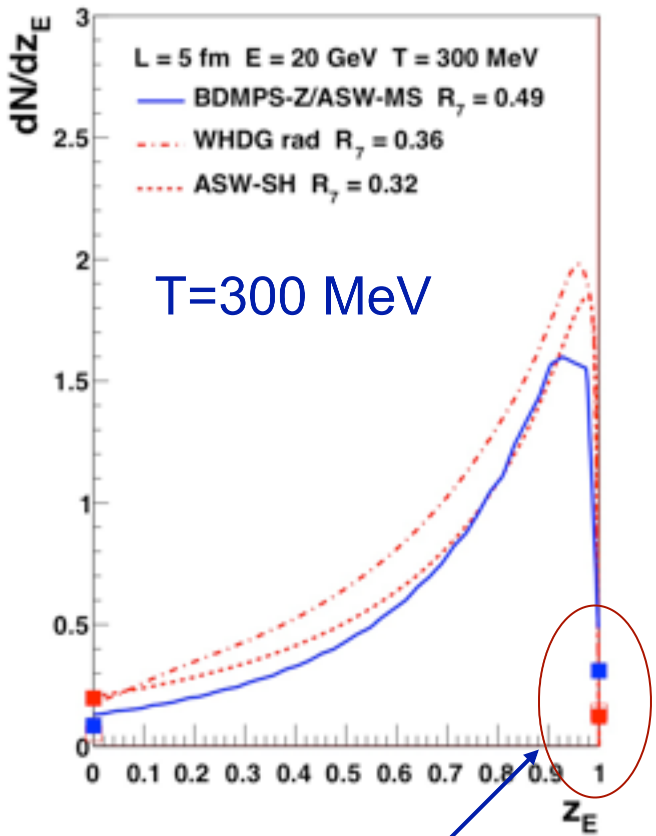
Poisson ansatz (independent emission)

- **Opacity expansion ((D)GLV, ASW-OE)**
  - Static scattering centers, Yukawa potential
  - Expansion in opacity L/λ (N=1, interference between two centers default)
  - Interference with vacuum radiation
- **Higher Twist (Guo, Wang, Majumder)**
  - Medium characterised by higher twist matrix elements
  - Radiation kernel similar to GLV
  - Vacuum radiation in DGLAP evolution

DGLAP evolution

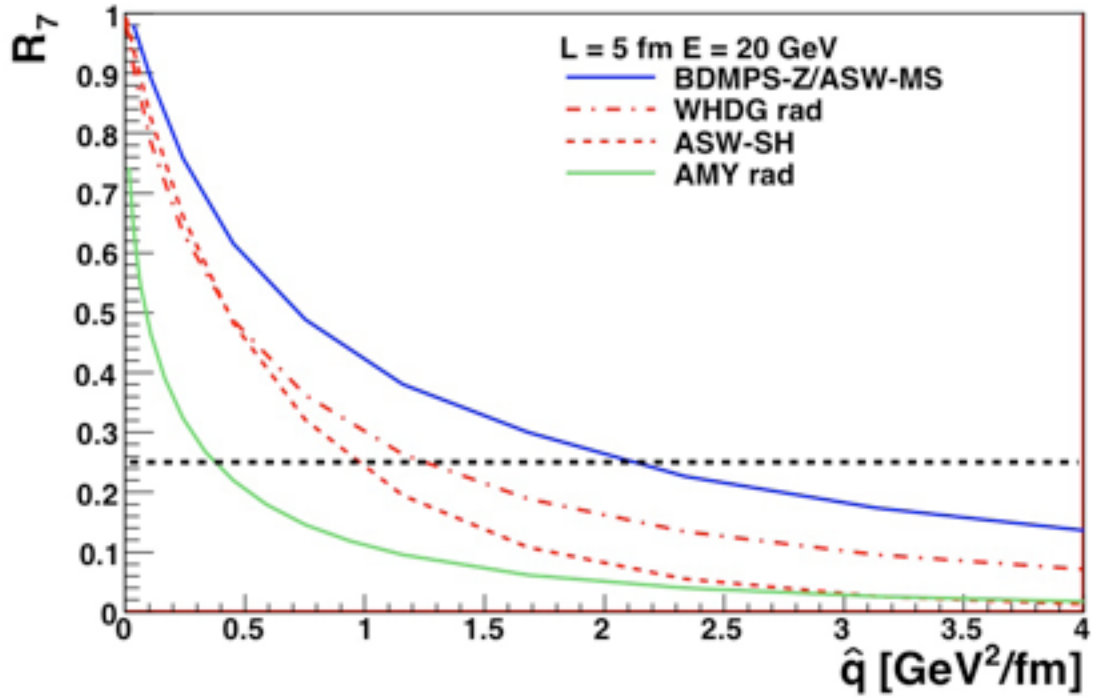
Some brick results

Outgoing quark spectrum



$R_{AA} > P_0$

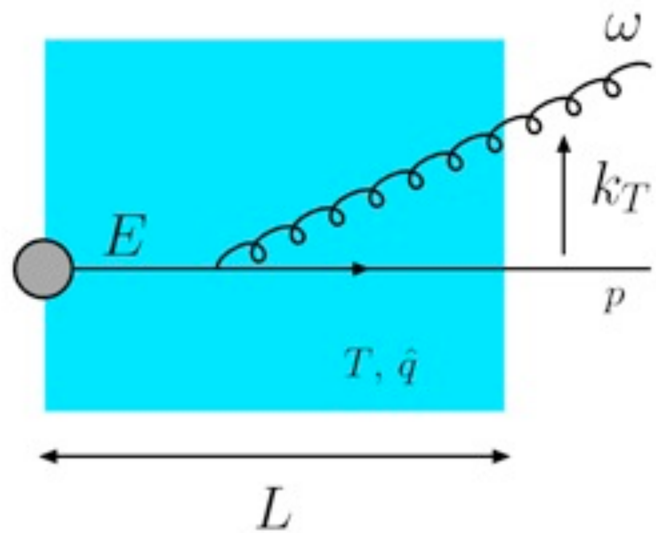
$$R_n = \int_0^1 d\varepsilon\, (1-\varepsilon)^{n-1}\, P(\varepsilon) \quad R_n \approx R_{AA} \text{ for } \frac{1}{p_T^n} \text{ spectrum}$$



Large differences in medium density for $R_7 = 0.25$

→ Difference between formalisms sizable even in simple geometry

Limitations of soft collinear approach



Calculations are done in soft collinear approximation:

Soft: $\omega << E$ Collinear: $k_T << \omega$

Need to extend results to full phase space to calculate observables (especially at RHIC)

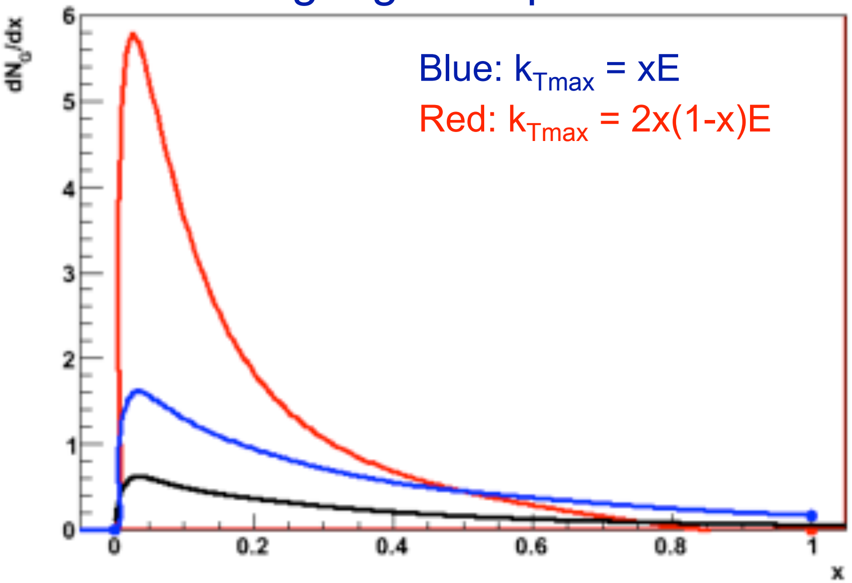
Soft approximation not problematic:
For large E, most radiation is soft
Also: $\omega > E \Rightarrow$ full absorption

Cannot enforce collinear limit:
Small ω, $\omega \rightarrow k_T$ always a part of phase space with large angles

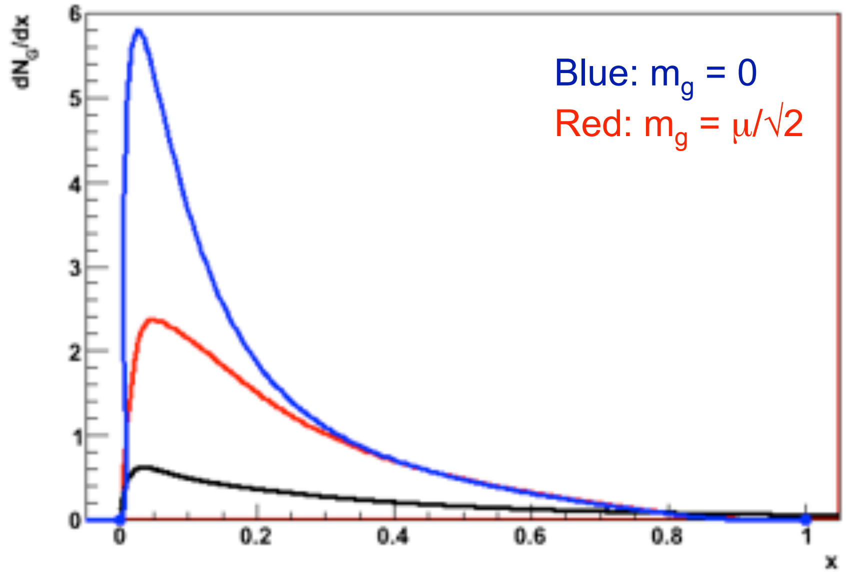
Opacity expansions

GLV and ASW-SH

Single-gluon spectrum



Single-gluon spectrum



Horowitz and Cole, PRC81, 024909

Different definitions of *x*:

ASW: $x_E = \frac{\omega}{E}$ GLV: $x_+ = \frac{\omega_+}{E_+}$

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

$x_+ \sim x_E$ in soft collinear limit, but not at large angles

Different large angle cut-offs:

$k_T < \omega = x_E E$

$k_T < \omega = 2x_+ E$

Factor ~2 uncertainty from large-angle cut-off

Opacity expansion vs multiple soft

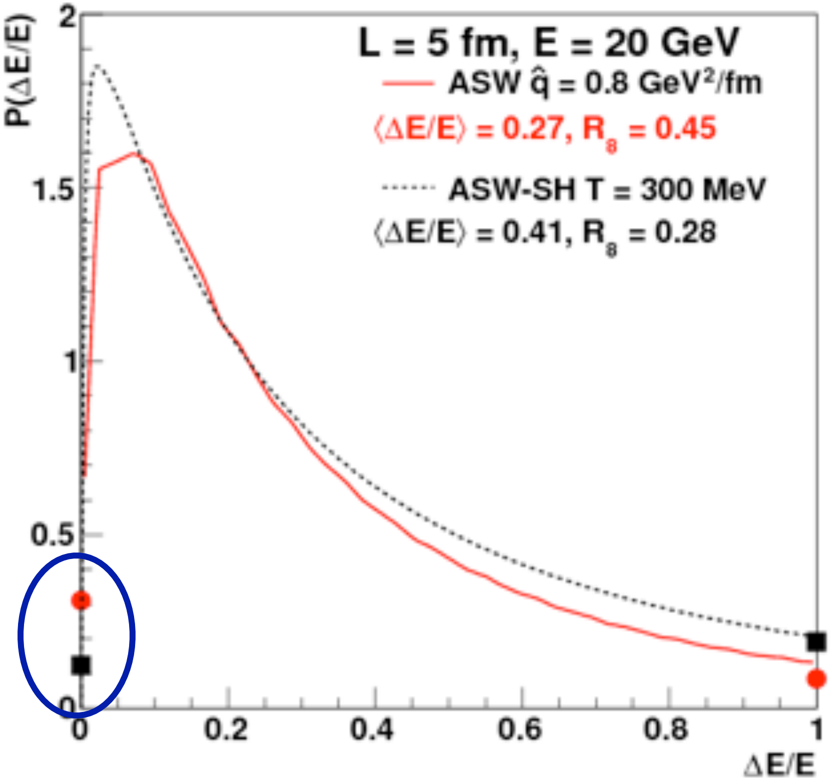
OE and MS related via path integral formalism

Salgado, Wiedemann, PRD68, 014008

Different limits:

SH (N=1 OE): interference between neighboring scattering centers

MS: 'all orders in opacity', gaussian scattering approximation



So far, not clear which difference dominates.
Would like: OE with gaussian and/or all orders (Wicks)

Quantitative differences sizable

AMY and BDMPS

Single-gluon kernel from AMY based on scattering rate:

$$\frac{d\Gamma_{el}}{d^2q_\perp} = \frac{1}{(2\pi)^2} \frac{g^2 T m_D^2}{q_\perp^2 (q_\perp^2 + m_D^2)}$$

BMPS-Z use harmonic oscillator:

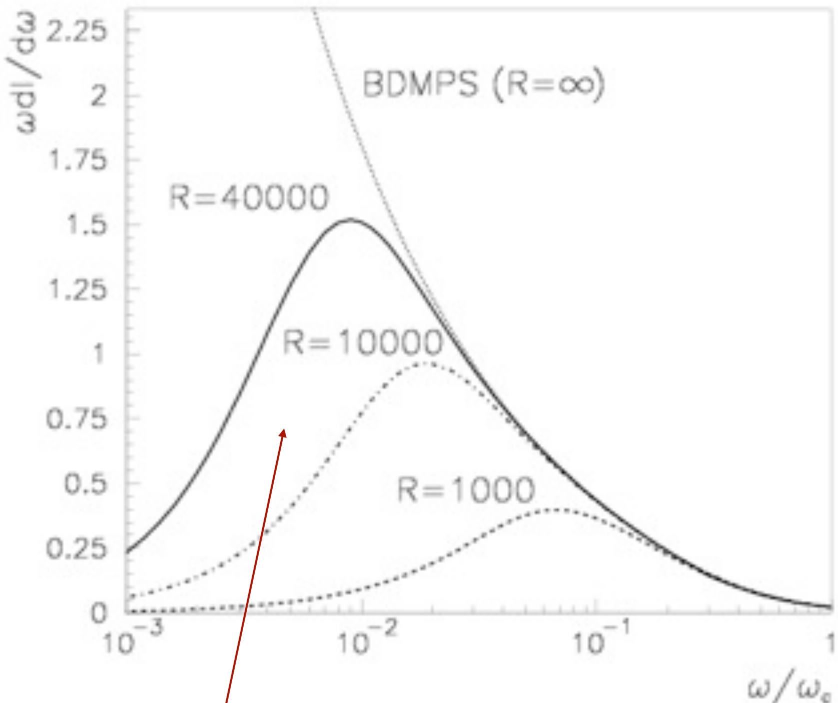
$$\Gamma_2(\mathbf{b}, t) = \int d^2q_\perp \frac{d\Gamma_{el}}{d^2q_\perp} \left(1 - e^{i\mathbf{b}\cdot\mathbf{q}_\perp}\right)$$

$$\bar{\Gamma}_2(\mathbf{b}, t) = \frac{1}{4}\hat{\bar{q}} b^2$$

BDMPS-Z:

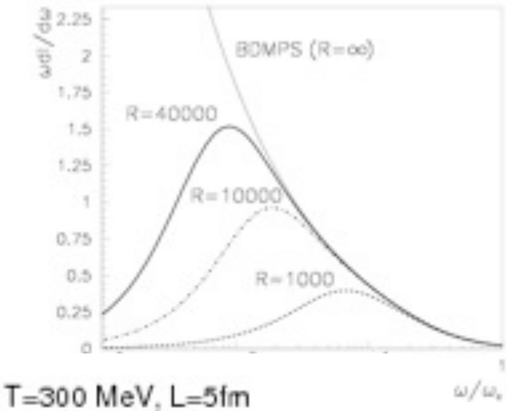
$$k\frac{dI}{dk} = \frac{\alpha x P_{s\to g}(x)}{\pi} \ln|\cos(\omega_0 L)|$$

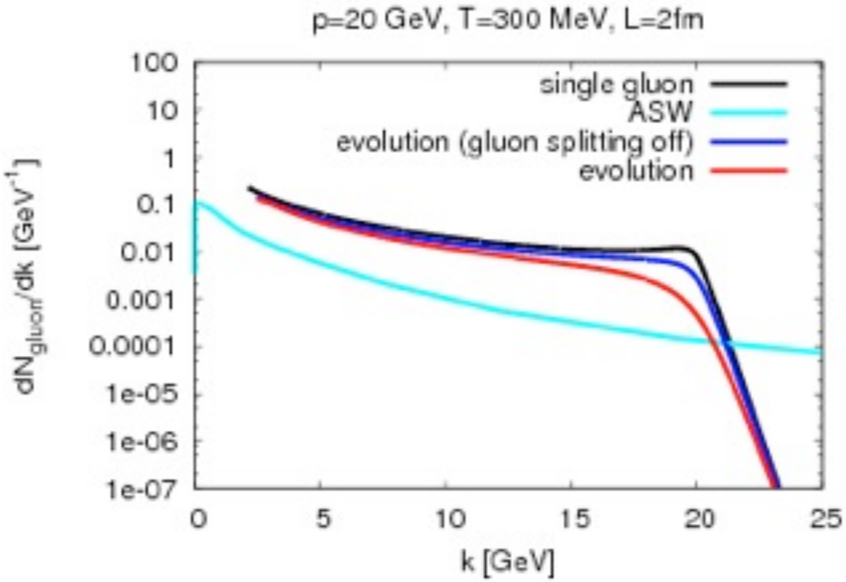
Salgado, Wiedemann, PRD68, 014008

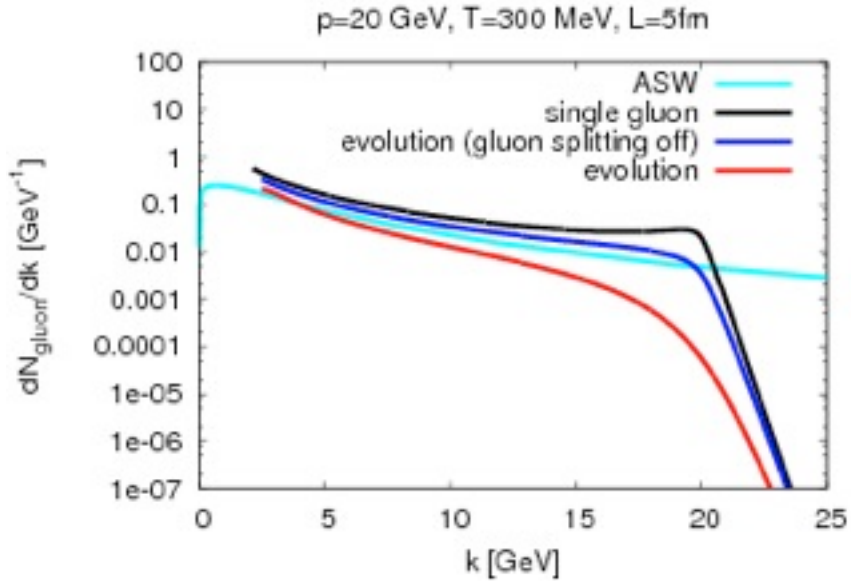


Finite-L effects:
Vacuum-medium interference
+ large-angle cut-off

AMY and BDMPS







Large difference between AMY and ASW at L=2 fm?

HT and GLV

Single-gluon kernel GLV and HT 'similar'

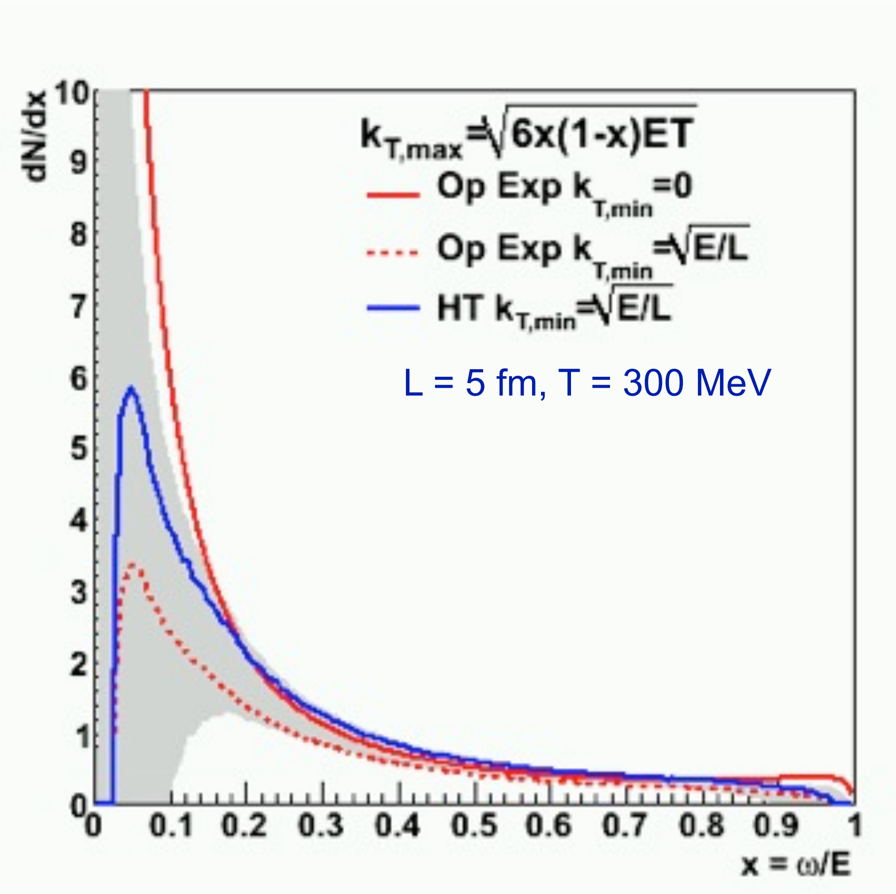
HT: $$\frac{dN}{dx\,dk_T^2} = \frac{\alpha_s C_F}{\pi} P_{qg}(x) F_{gg} \frac{1}{k_T^4} \Omega$$

OE: $$\frac{dN}{dx\,dk_T^2} \approx \frac{\alpha_s C_F}{\pi} P_{qg}(x) \frac{1}{\lambda} \frac{\mu^2}{\left(k_T^2 + \mu^2\right)^2} \Omega$$

$$\Omega = \int_0^L d\xi \left[1 - \cos\left(\frac{k_T^2 \xi}{2\,p\,z\,(1-z)}\right)\right]$$

HT: $\tau < L \Rightarrow k_T > \sqrt{(E/L)}$

kernel diverges for $k_T \to 0$



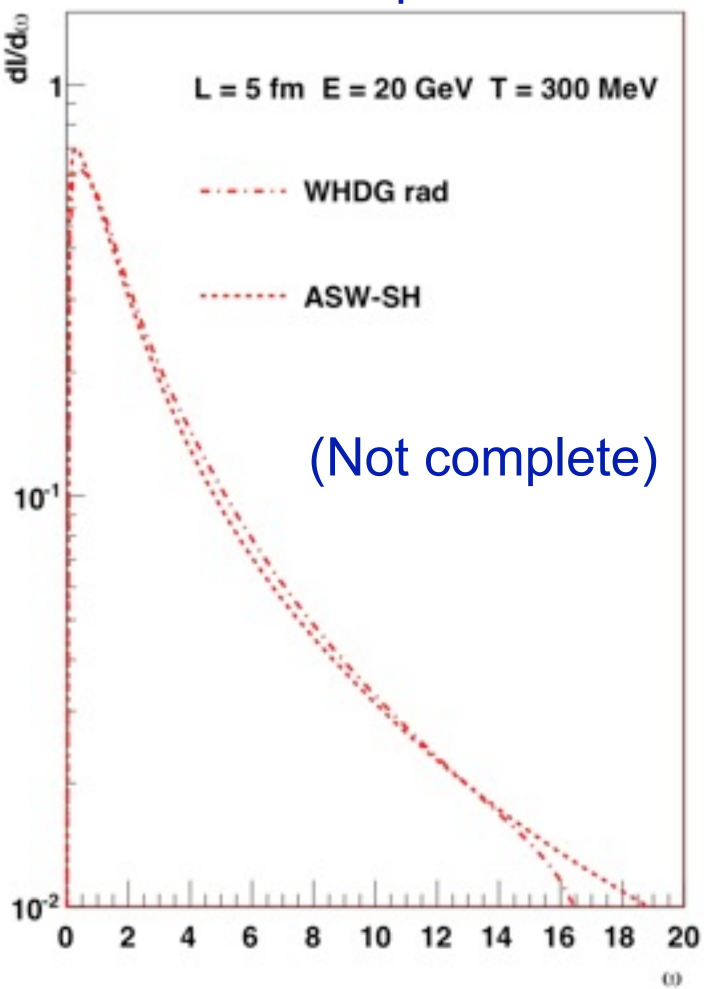
Large uncertainty from k_{Tmax}

HT: $$k_{T,\max} = \sqrt{2\,x\,(1-x)\,E\,3\,T}$$

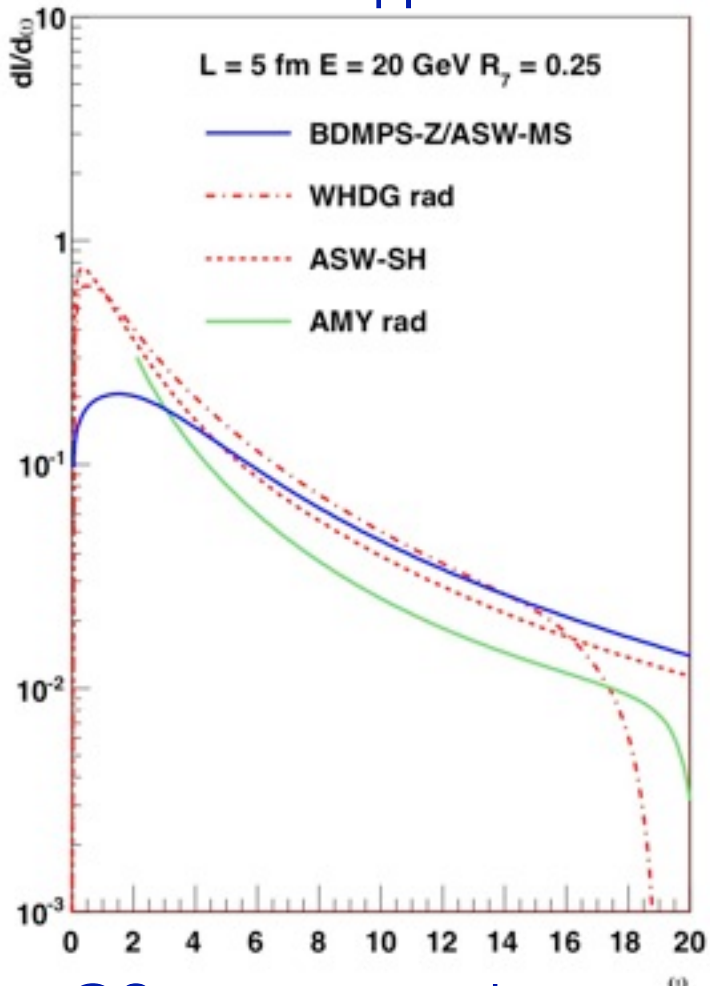
GLV: $$k_{T,\max} = \sqrt{2\,x\,(1-x)\,E} \qquad q_{T,\max} = \sqrt{3\,E\,T}$$

Single gluon spectra

Same temperature



Same suppression

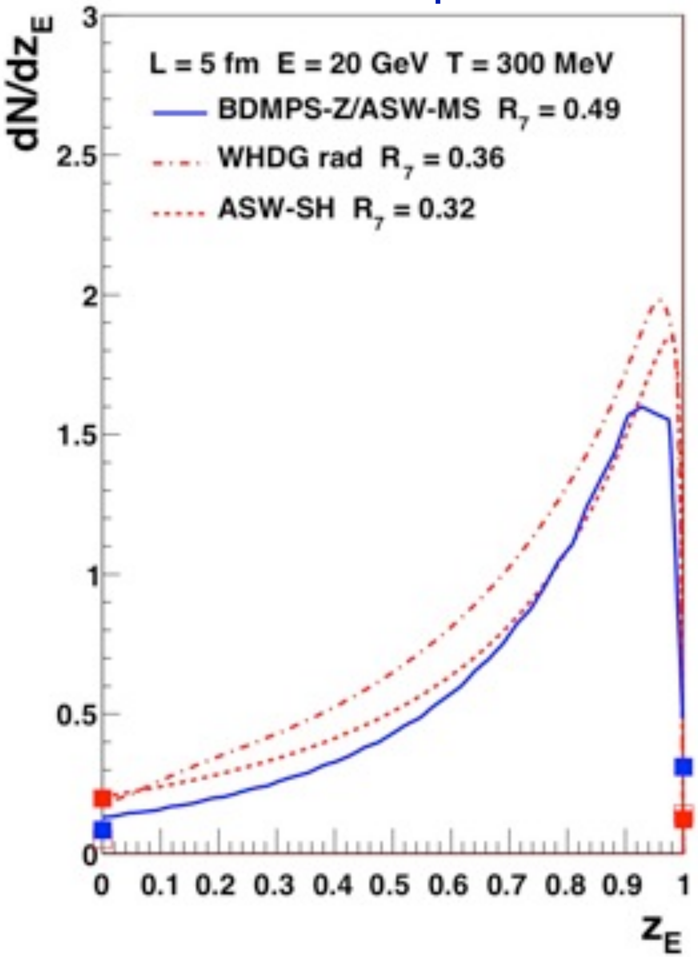


@Same temperature:
AMY > OE > ASW-MS

@Same suppression:
OE (AMY?) peaked at low ω
ASW-MS not so much

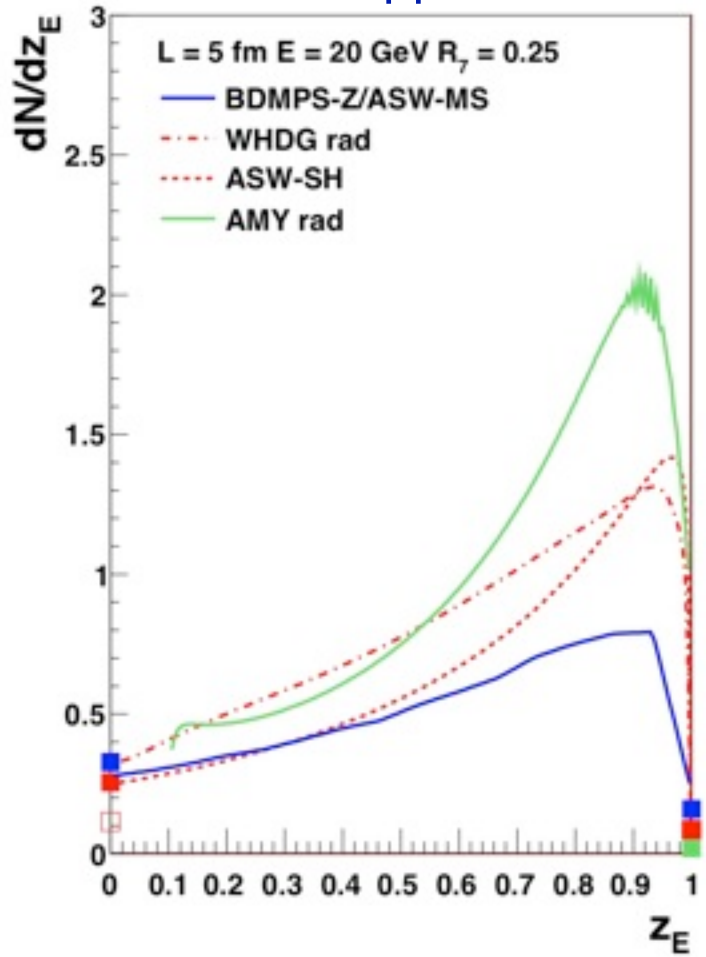
Outgoing quark spectra

Same temperature



ASW-MS less suppression than OE at T=300 MeV

Same suppression

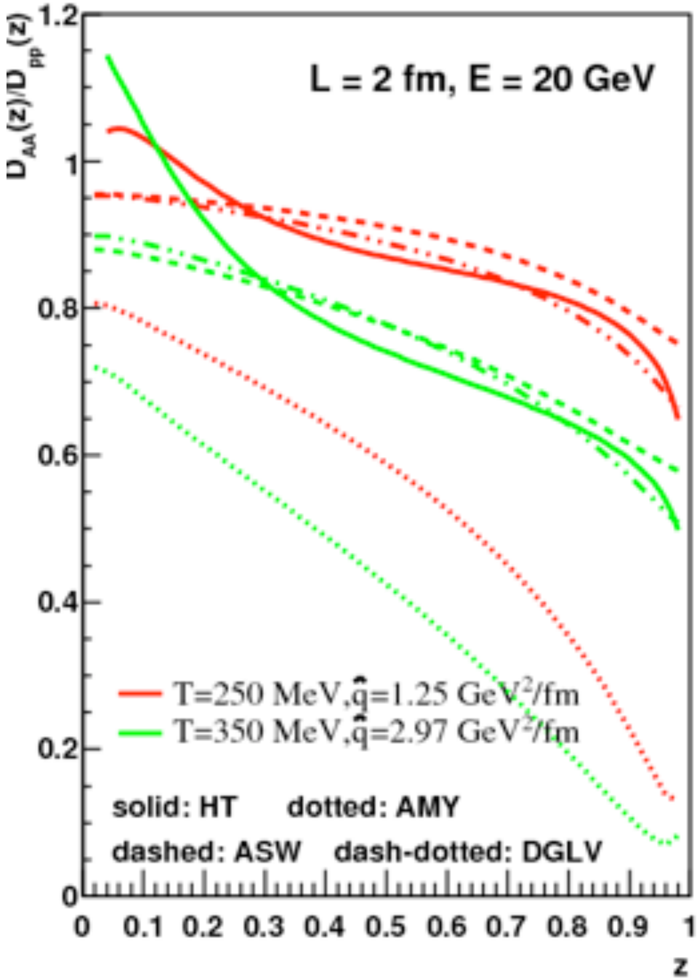


At $R_7 = 0.25$

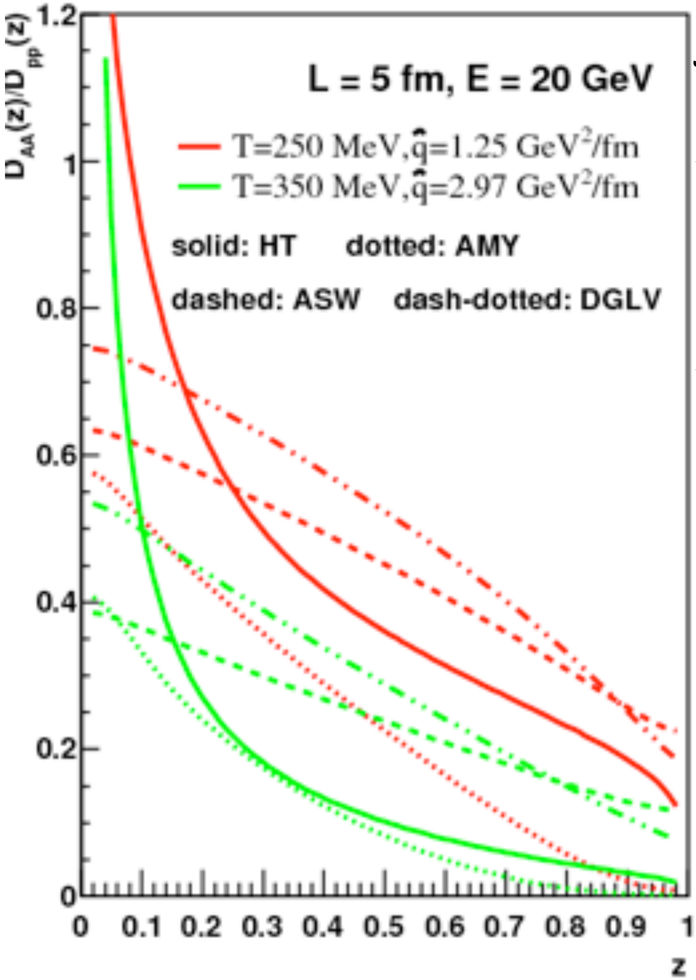
P_0 small for ASW-MS

$P_0 = 0$ for AMY by definition

Fragmentation function



L=2 fm, T=250, 350 MeV
GLV, HT, ASW-MS similar
AMY: large suppression

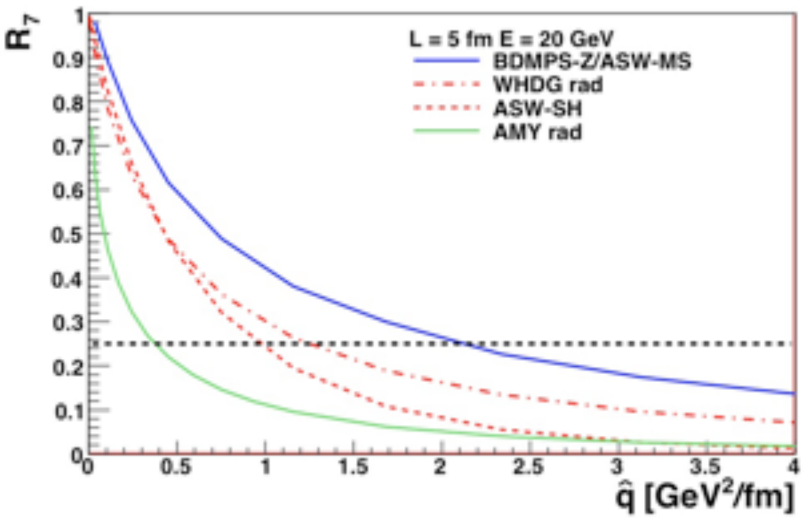


Majumder, van Leeuwen, arXIv:1002.2206

L=2 fm, T=250, 350 MeV
AMY, HT larger suppression
than OE, MS

Conclusion

- Tentative summary:
  - AMY shows strongest suppression
    Lack of vacuum radiation?
  - ASW-MS: smallest suppression
    Soft scattering or interference or both?
  - OE, HT similar, between MS and AMY



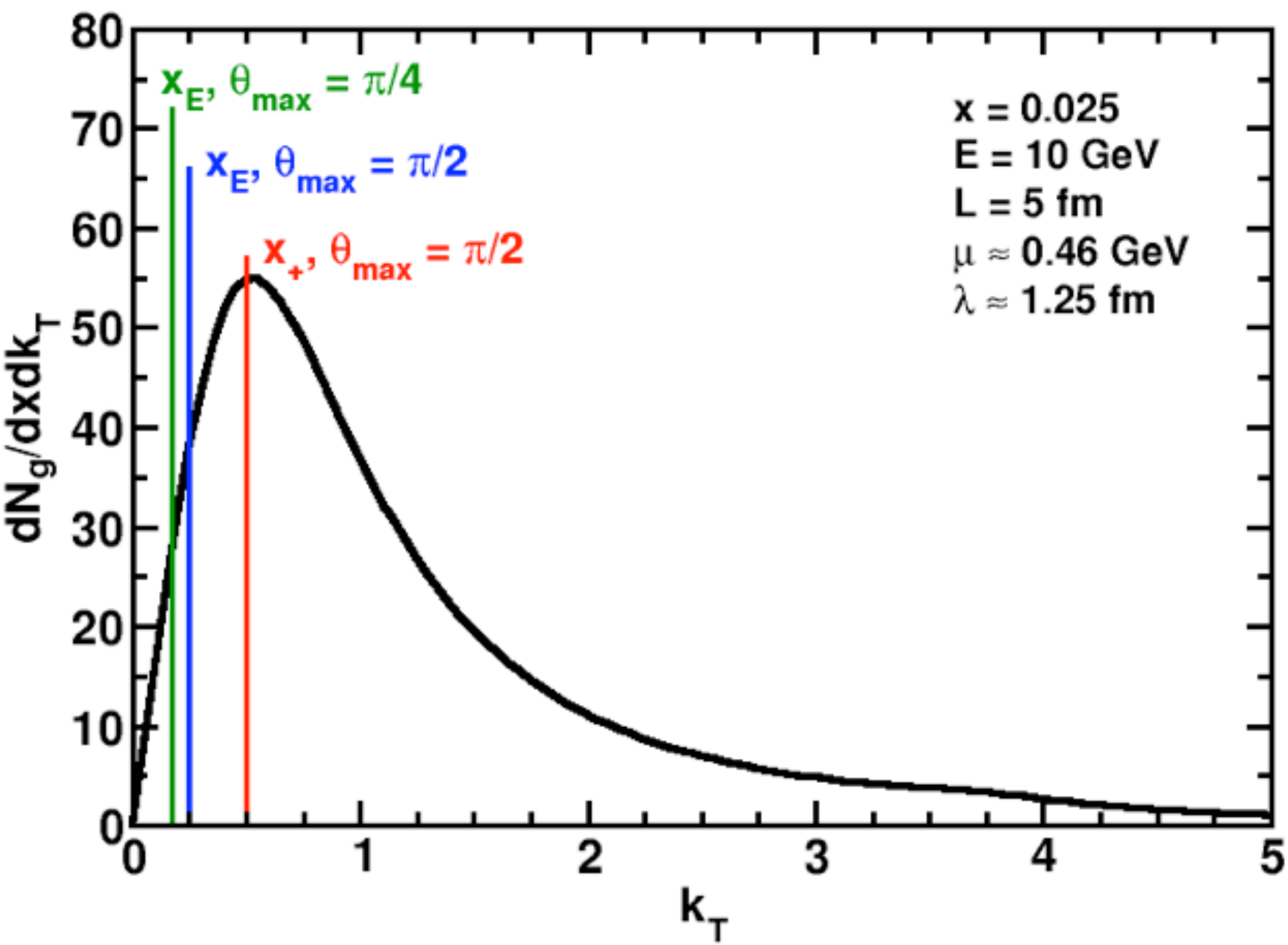
- Large uncertainties associated with large angle radiation in all formalisms
- Differences between formalisms large at single-gluon level
  R_{AA} probably not sensitive to details of multi-gluon treatment

In preparation: TECHQM publication with more detailed report

Thanks to all in TECHQM who contributed !

Extra slides

X+ vs xE



x_E, $\theta_{max} = \pi/4$
x_E, $\theta_{max} = \pi/2$
x_+, $\theta_{max} = \pi/2$
x = 0.025
E = 10 GeV
L = 5 fm
$\mu \approx$ 0.46 GeV
$\lambda \approx$ 1.25 fm
$dN_g/dxdk_T$
k_T
0
10
20
30
40
50
60
70
80
1
2
3
4
5