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Brick problem:
comparing different formalisms

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Introduction / Outlook

- Parton energy loss in hot dense matter.
- Comparison of different models in realistic geometry.
- Brick problem.

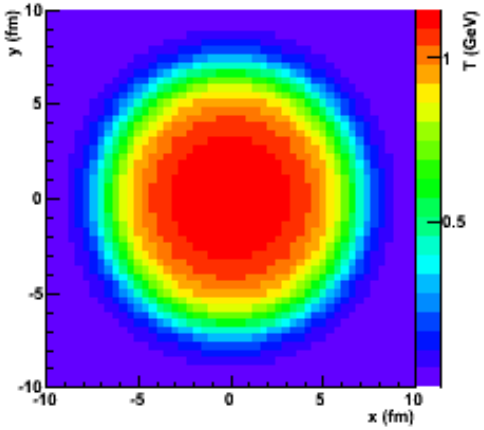
Energy loss models

- Apple-to-apple comparison of:
  - ASW-BDMPS
    *Phys.Rev.**D68** 014008*
  - Opacity expansion (OE):
    - ASW-SH: L/λ determined by T
      *Phys.Rev.**D68** 014008*
    - WHDG: Only radiative energy loss
      *Nucl.Phys.**A784** 426*
- Only radiative energy loss

Geometry of collision

- Woods-Saxon profile
- Optical Glauber
- Wounded Nucleon Scaling
- Bjorken Expansion, τ_0 = 0.2 fm

Temperature profile



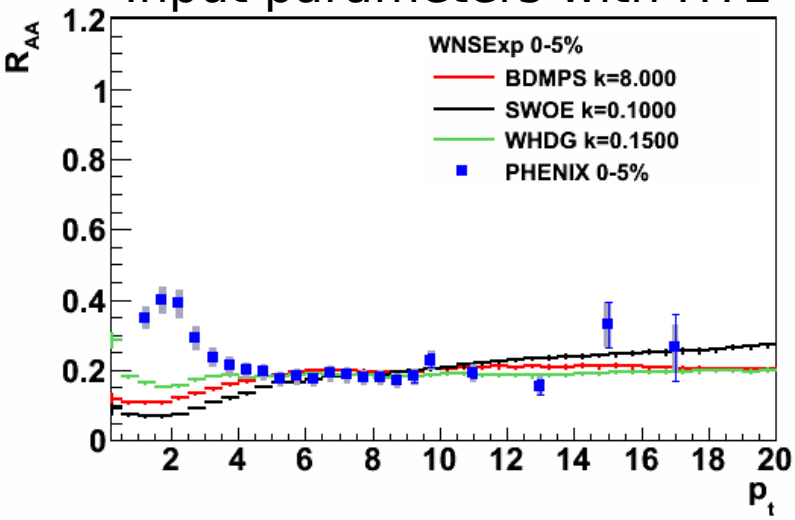
$$\frac{dN}{dp_{t,hadr}} = \frac{dN}{dp_{t,parton}} \circ P(\Delta E) \circ D(p_{t,hadr}/p_{t,parton})$$

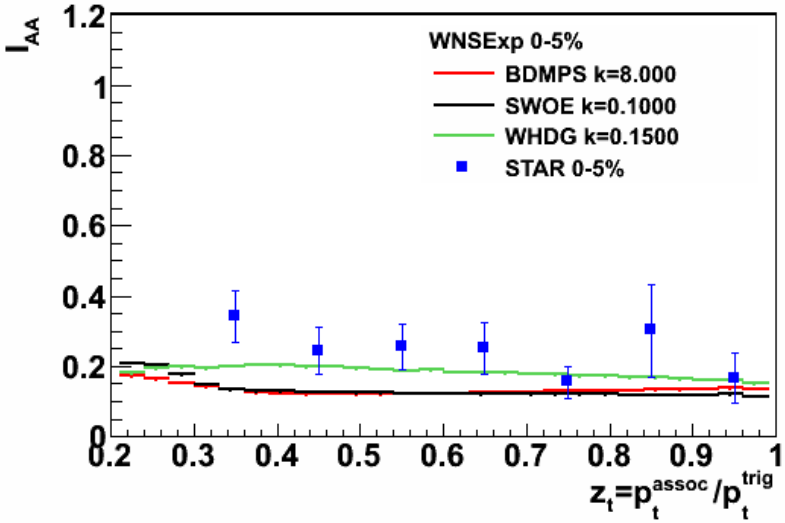
Measurement	Input parton spectrum Known LO pQCD	**Energy loss Has to be calculated**	Fragmentation Factor Known from e+e-

R_{AA} and I_{AA}

- All models can always be fitted to R_{AA}.
- Calibrate density using R_{AA} measurement, most models do not predict I_{AA}.

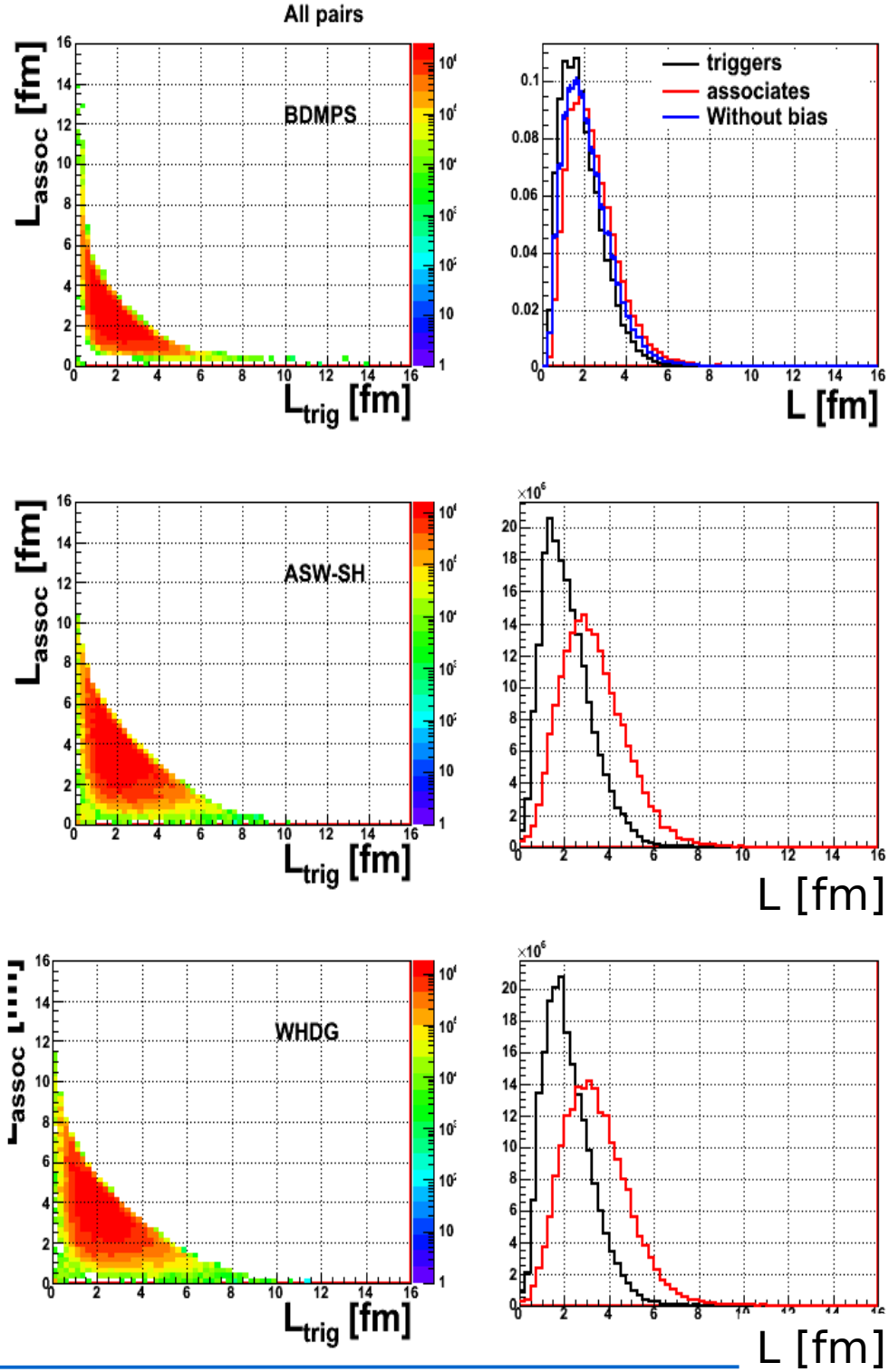
Quark-Gluon Gas: $N_f = 3$
FreezeOut at 150 MeV
Input parameters with HTL





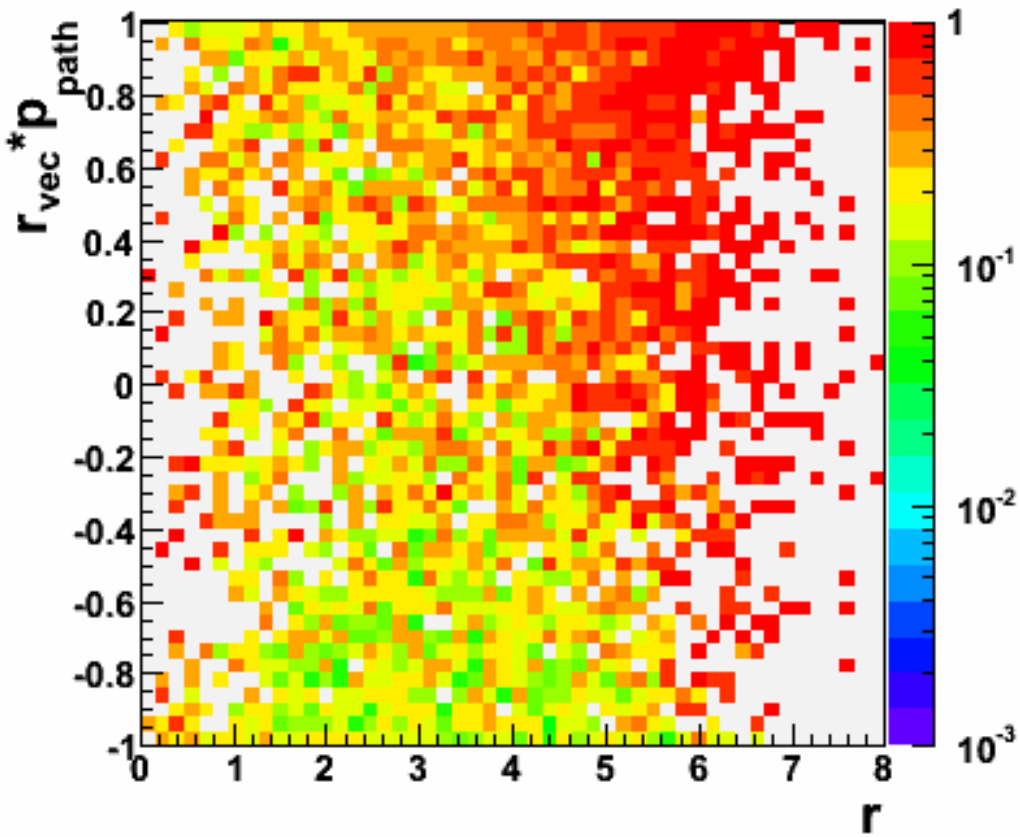
L_{trig} vs $L_{associate}$

- For RAA and IAA different mean path length.
- P_t Trigger > P_t Assoc
- Triggers bias towards smaller L



BDMPS

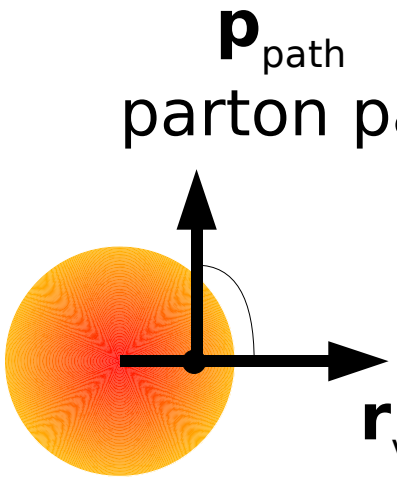
Survivors



Radial outward

Tangential

Radial inward

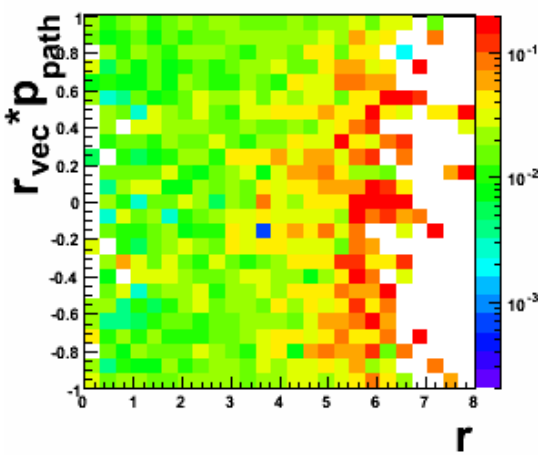


For all produced partons

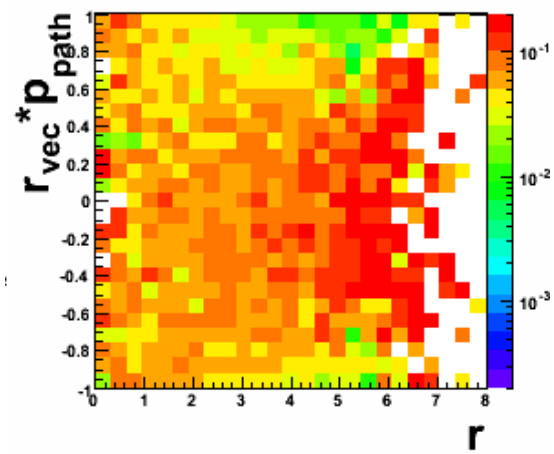
Back-to-back partons

- Surviving associate particles

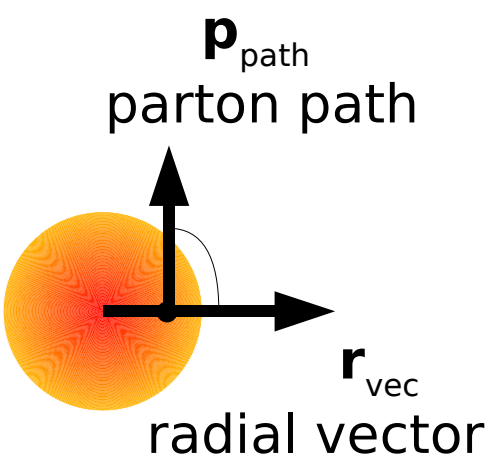
BDMPS



WHDG

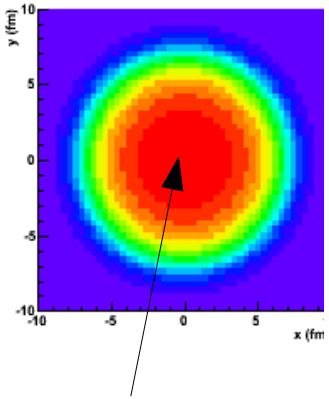


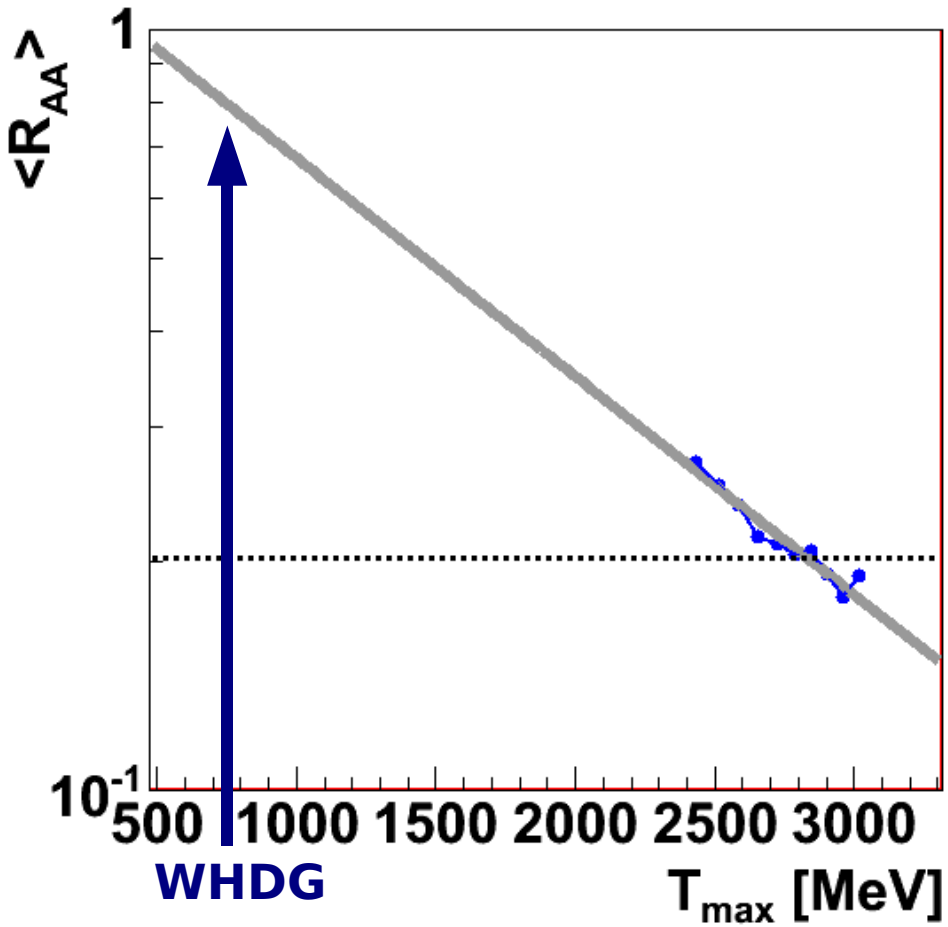
- Surviving partons in WHDG origin from deeper in the medium.
- By comparing different observables, more sensitive to differences between models.



Medium Properties

Initial Maximum Temperature





Bjorken expanding medium		Tmax (MeV)
BDMPS/ASW-MS	**HTL**	2586
ASW-SH	**HTL**	660
WHDG rad	**HTL**	756

- BDMPS needs denser medium to describe measurement.
- BDMPS R_{AA} with WHDG best fit 0.83

Calculations are for a quark-gluon gas with 3 active flavors.
Centrality 0-5 %. Best R_{AA} fits with freeze out at 150 MeV.
Model parameters calculated in HTL formalism.

TECHQM Brick Problem

Theory-Experiment Collaboration for Hot QCD Matter

- Brick: fixed length L and temperature T.
- Parton (quark) of energy E = 20 GeV.
- In brick parton loses energy due to gluon radiation.
- Apple-to-apple comparison of:
  - Multiple Soft Scattering (ASW/BDMPS) *Phys.Rev.**D68** 014008*
  - Opacity expansion (OE):
    - ASW-SH *Phys.Rev.**D68** 014008*
    - WHDG radiative *Nucl.Phys.**A784** 426*
  - AMY radiative *McGill - Private Communication Guanyou Qin and Bjoern Schenke*

Number of radiated gluons

- BDMPS:

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

- OE:

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

- No qhat for opacity expansions. $\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda} \sim \frac{\mu^2}{\lambda}$

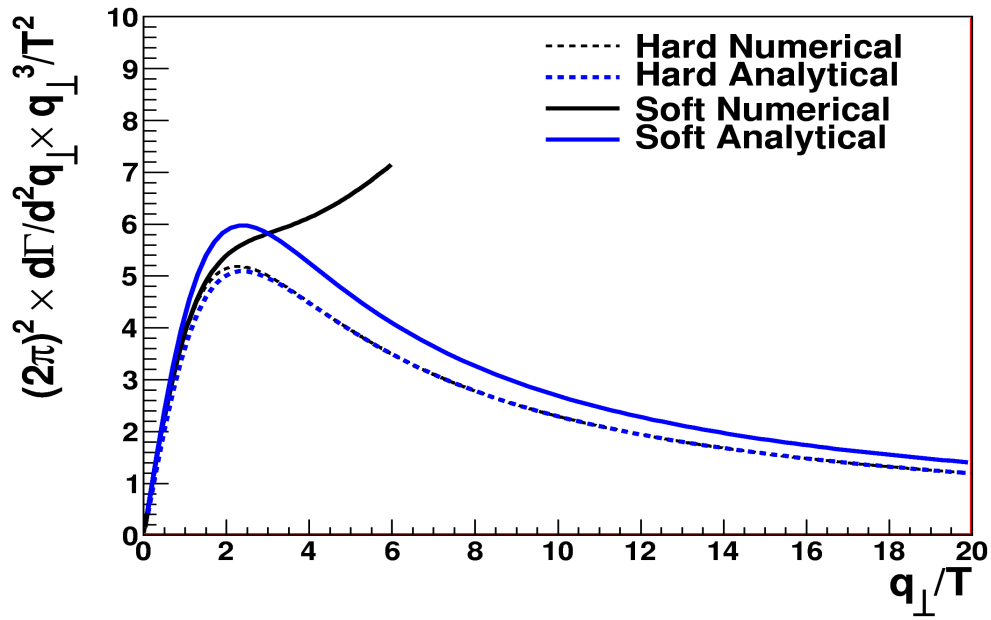
Relation between qhat and T

- LO HTL medium

$$\hat{q}(q_{max}) = \int_{q_\perp < q_{max}} d^2 q_\perp \frac{d\Gamma_{el}}{d^2 q_\perp} q_\perp^2$$

- High and low energy limit:

$$\frac{d\Gamma_{\rm el}}{d^2 q_\perp} \simeq \frac{C_R}{(2\pi)^2} \begin{cases} \frac{g^2 T m_{\rm D}^2}{q_\perp^2 (q_\perp^2 + m_{\rm D}^2)}, & q_\perp \ll T, \\ \frac{g^4 \mathcal{N}}{q_\perp^4}, & q_\perp \gg T, \end{cases}$$



- Combination:

$$\frac{d\Gamma_{\rm el}}{d^2 q_\perp} \simeq \frac{C_R}{(2\pi)^2} \times \frac{g^4 \mathcal{N}}{q_\perp^2 (q_\perp^2 + m_{\rm D}^2)}$$

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

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

Relation between qhat and T

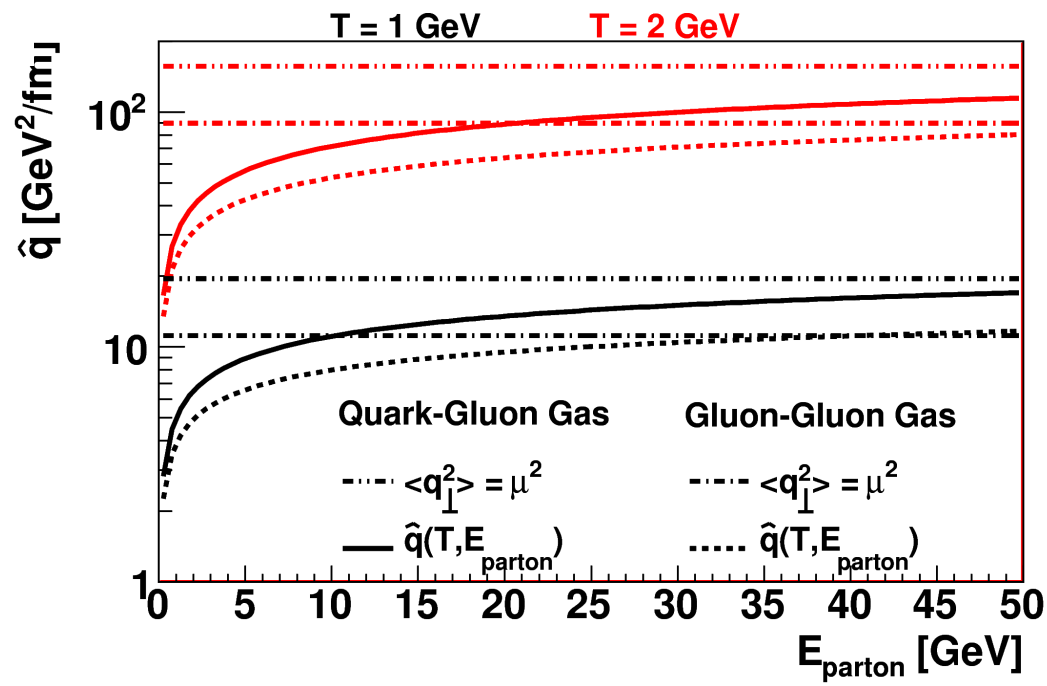
- LO HTL medium

$$\hat{q}(q_{max}) = \int_{q_\perp < q_{max}} d^2 q_\perp \frac{d\Gamma_{el}}{d^2 q_\perp} q_\perp^2$$

$$q_{\max} \sim g(ET^3)^{1/4}$$

- High and low energy limit:

$$\frac{d\Gamma_{\rm el}}{d^2 q_\perp} \simeq \frac{C_R}{(2\pi)^2} \begin{cases} \frac{g^2 T m_{\rm D}^2}{q_\perp^2 (q_\perp^2 + m_{\rm D}^2)}, & q_\perp \ll T, \\ \frac{g^4 \mathcal{N}}{q_\perp^4}, & q_\perp \gg T, \end{cases}$$



- Combination:

$$\frac{d\Gamma_{\rm el}}{d^2 q_\perp} \simeq \frac{C_R}{(2\pi)^2} \times \frac{g^4 \mathcal{N}}{q_\perp^2 (q_\perp^2 + m_{\rm D}^2)}$$

Relation between λ and T

- To overcome divergencies different cross section:

$$\frac{d\Gamma_{el}}{d^2 q_\perp} \simeq \frac{C_R}{(2\pi)^2} \times \frac{g^4 \mathcal{N}}{(q_\perp^2 + m_D^2)^2}$$

Results in:

$$\frac{L}{\lambda} = L \int d^2 q_\perp \frac{d\Gamma_{el}}{d^2 q_\perp} = 4\pi C_R \mathcal{N} \frac{\alpha_s^2}{m_D^2} L$$

$$\frac{1}{\lambda} = \rho_g \sigma_{gg} + \rho q \sigma_{qg} = \mathcal{N} \sigma$$

Suppression Factor

in a brick

- Hadron spectrum if each parton loses ϵ energy:

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

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

$\epsilon = \Delta E/E$

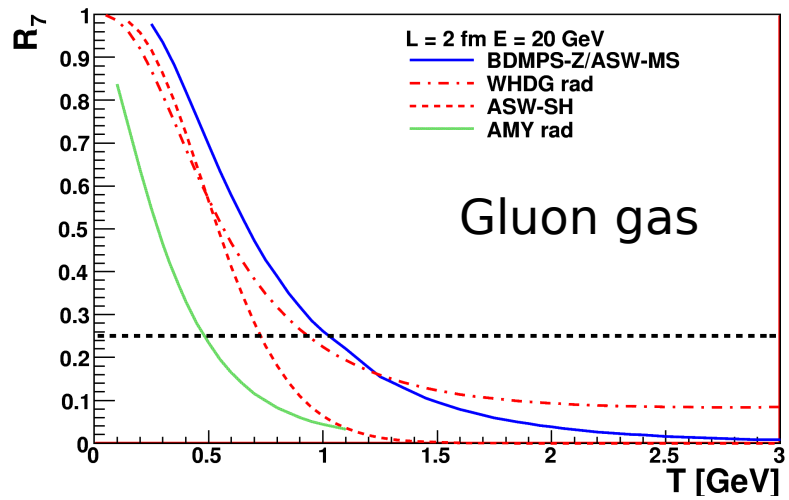
Weighted average energy loss:

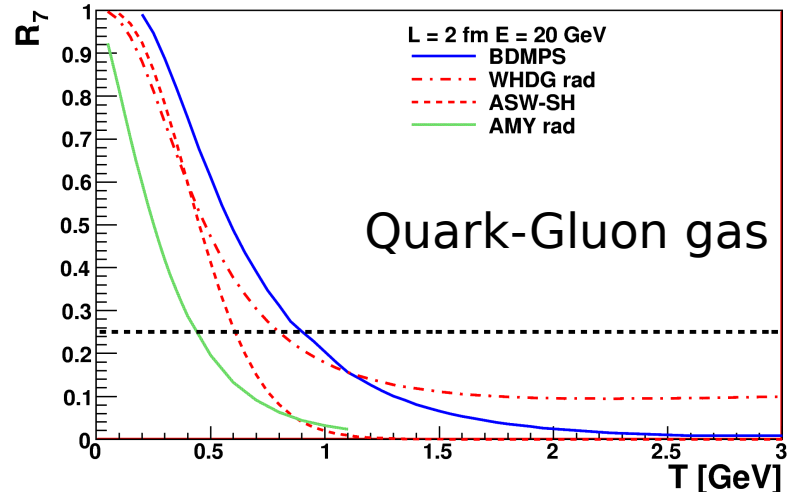
$$R_n = \int_0^1 d\epsilon (1-\epsilon)^{n-1} P(\epsilon)$$

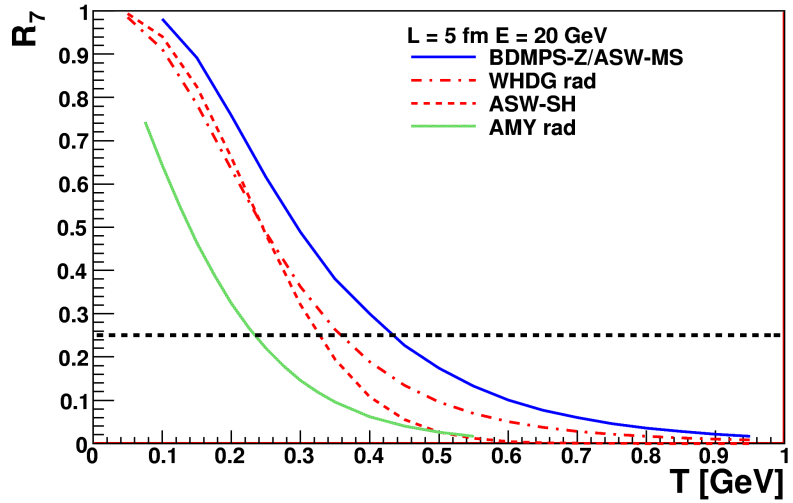
For RHIC n=7

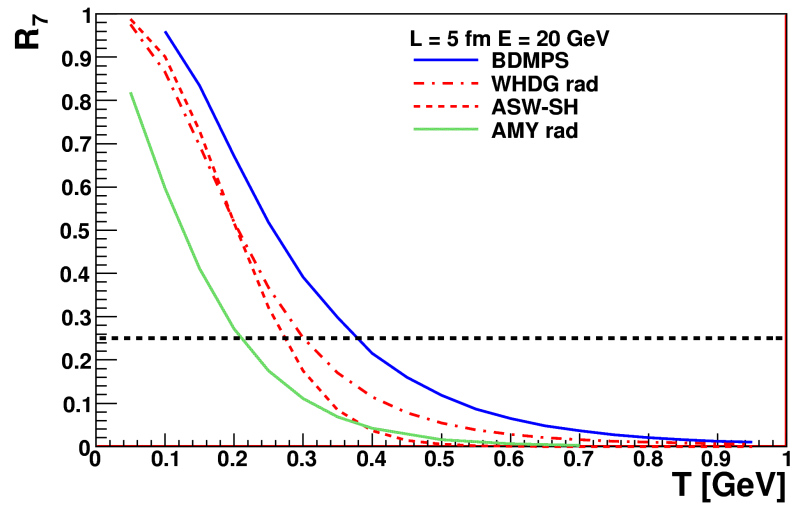
- R_7 approximation for R_{AA} in a brick.

Suppression in a brick vs T









R7=0.25	T (MeV)			
	BDMPS	WHDG rad	ASW-SH	AMY
L = 2 fm	1040	940	730	495
L = 5 fm	440	360	330	235

R7=0.25	T (MeV)			
	BDMPS	WHDG rad	ASW-SH	AMY
L = 2 fm	900	800	610	450
L = 5 fm	380	300	270	205

Suppression in a brick vs qhat

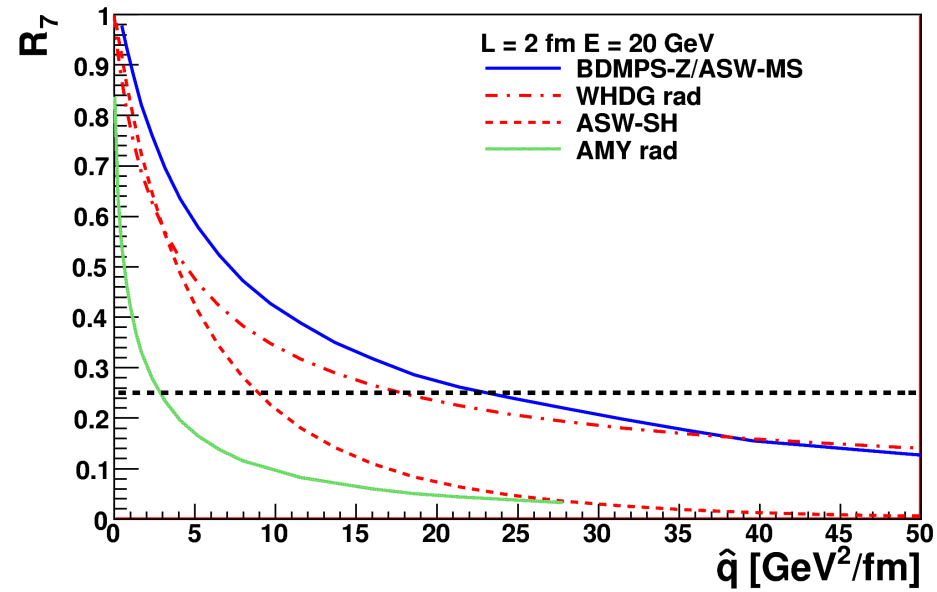
Gluon gas

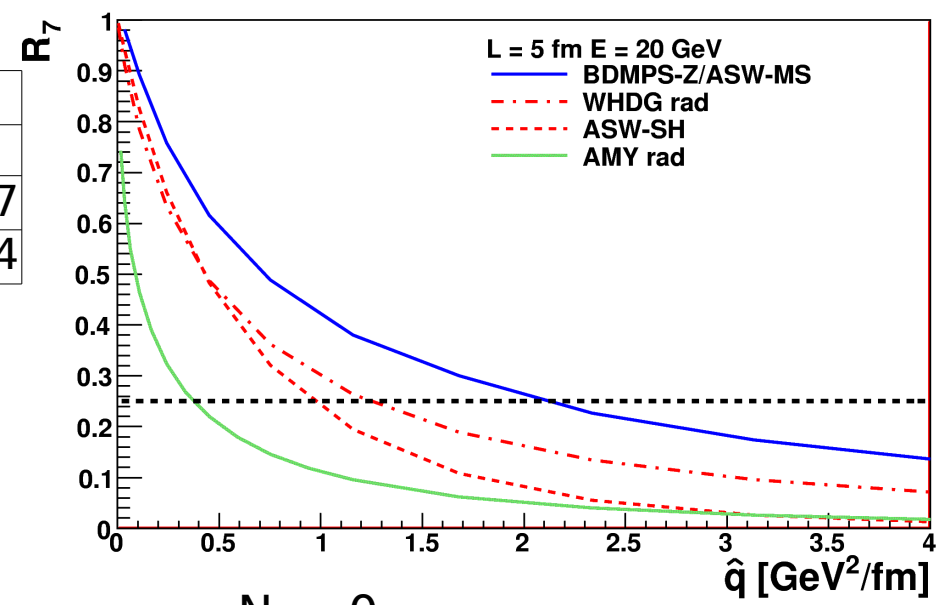
For all models:

$$\hat{q}(T) = \frac{C_R g^4 \mathcal{N}(T)}{4\pi} \ln\left(\frac{q^2_{max}(T)}{m^2_D(T)} + 1\right)$$

For which T is the common variable in all models.

R7=0.25	qhat (GeV^2/fm)			
	BDMPS	WHDG rad	ASW-SH	AMY
L = 2 fr	23.1	17.8	8.4	2.7
L = 5 fr	2.13	1.25	0.98	0.4





$N_f = 0$

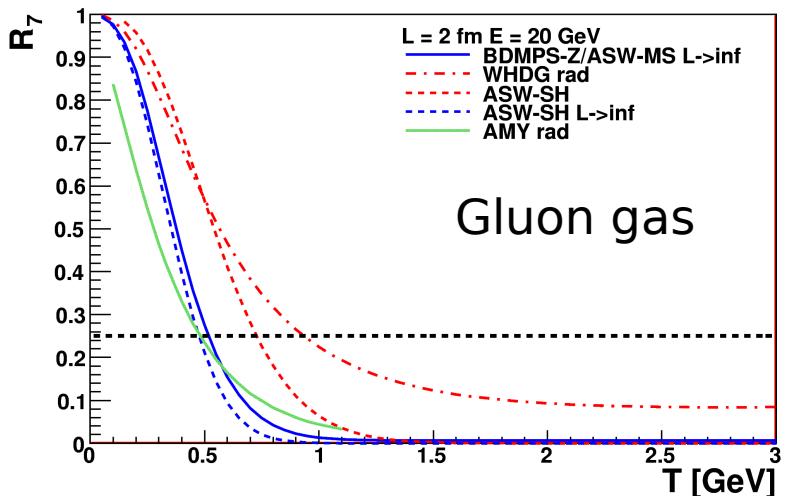
What do we learn from this?

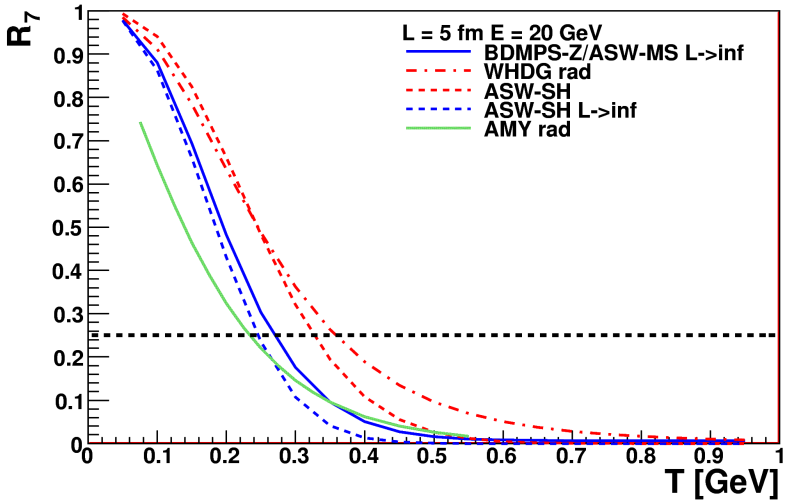
- BDMPS loses less energy than opacity expansions and AMY at same medium density.
- AMY requires 2.5 times (for L=2 fm) smaller temperature than BDMPS to reach same suppression.
- WHDG rad loses less energy than ASW-SH.

Gluon gas:

R7=0.25	T (MeV)			
	BDMPS	WHDG rad	ASW-SH	AMY
L = 2 fm	1040	940	730	480
L = 5 fm	440	360	330	235

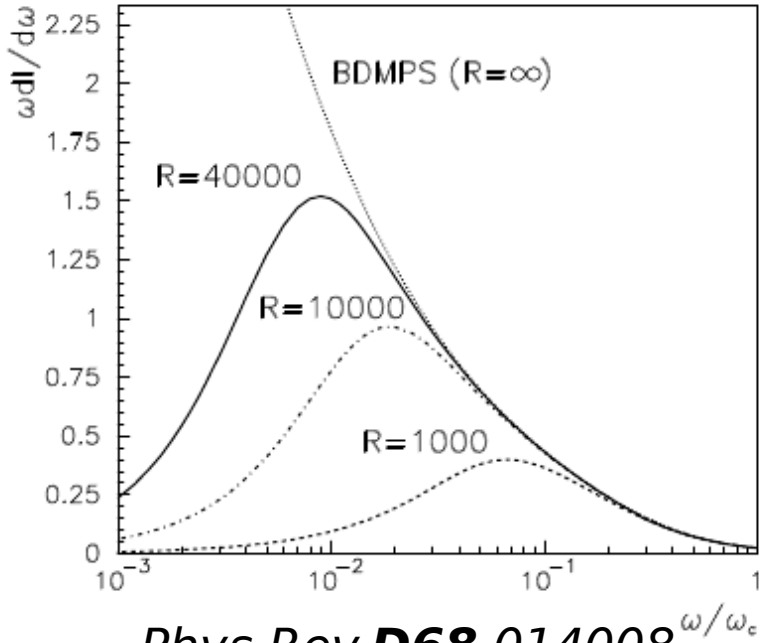
Suppression in a brick vs T





R7=0.25	T (MeV)			
	BDMPS	WHDG rad	ASW-SH	AMY
L = 2 fm	520	940	480	495
L = 5 fm	270	360	245	240

- BDMPS/ASW-MS and ASW-SH for limit L → ∞ (BDMPS limit)
- Vacuum interference vanishes in this limit.
- In collaboration with C. Salgado & N. Armesto & G. Qin



*Phys.Rev.**D68** 014008*

Suppression in a brick vs qhat

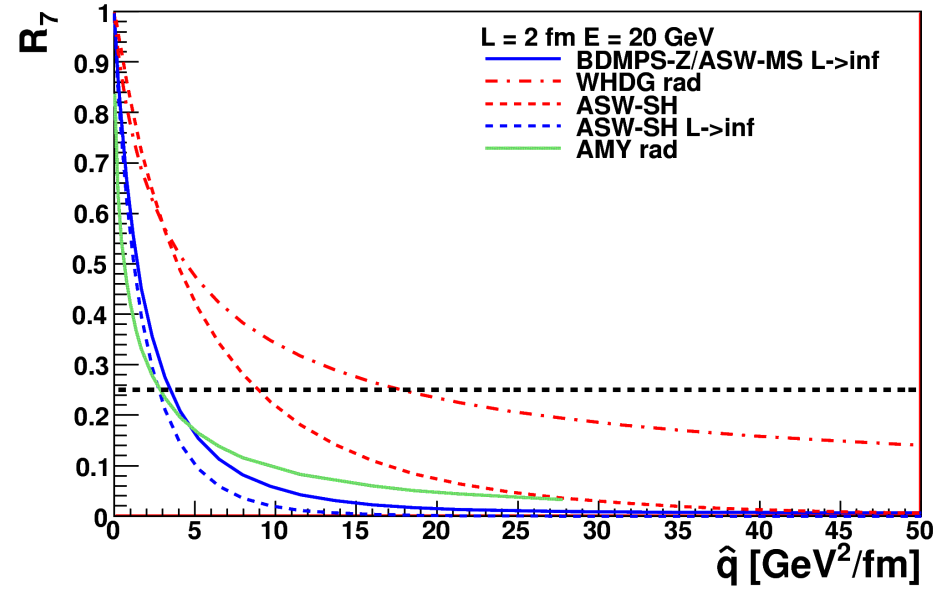
- BDMPS/ASW-MS and ASW-SH for limit L → ∞

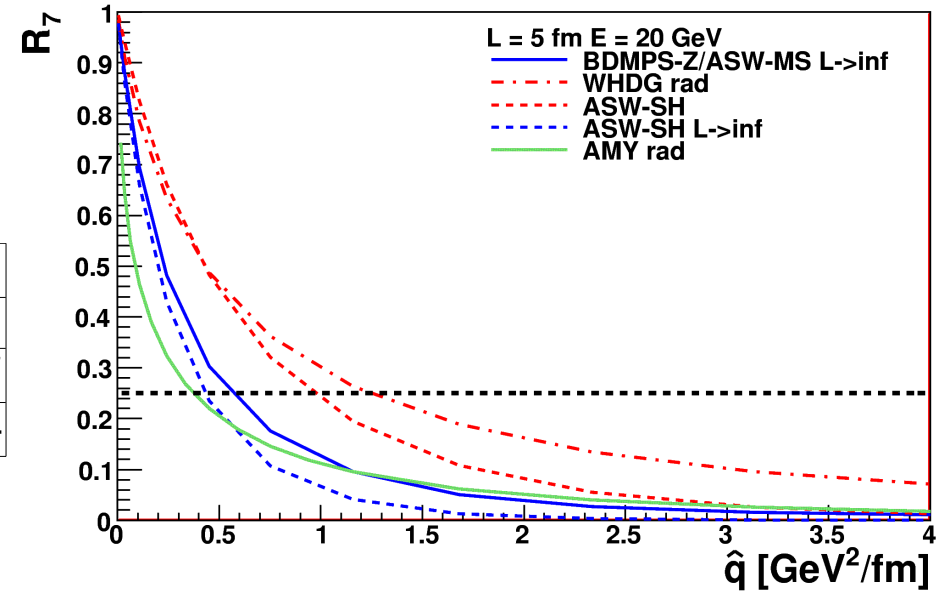
For all models:

$$\hat{q}(T) = \frac{C_R g^4 \mathcal{N}(T)}{4\pi} \ln\left(\frac{q^2_{max}(T)}{m^2_D(T)} + 1\right)$$

For which T is the common variable in all models.

R7=0.25	qhat (GeV^2/fm)			
	BDMPS	WHDG rad	ASW-SH	AMY
L = 2 fm	3.5	17.8	2.7	2.7
L = 5 fm	0.6	1.25	0.45	0.4

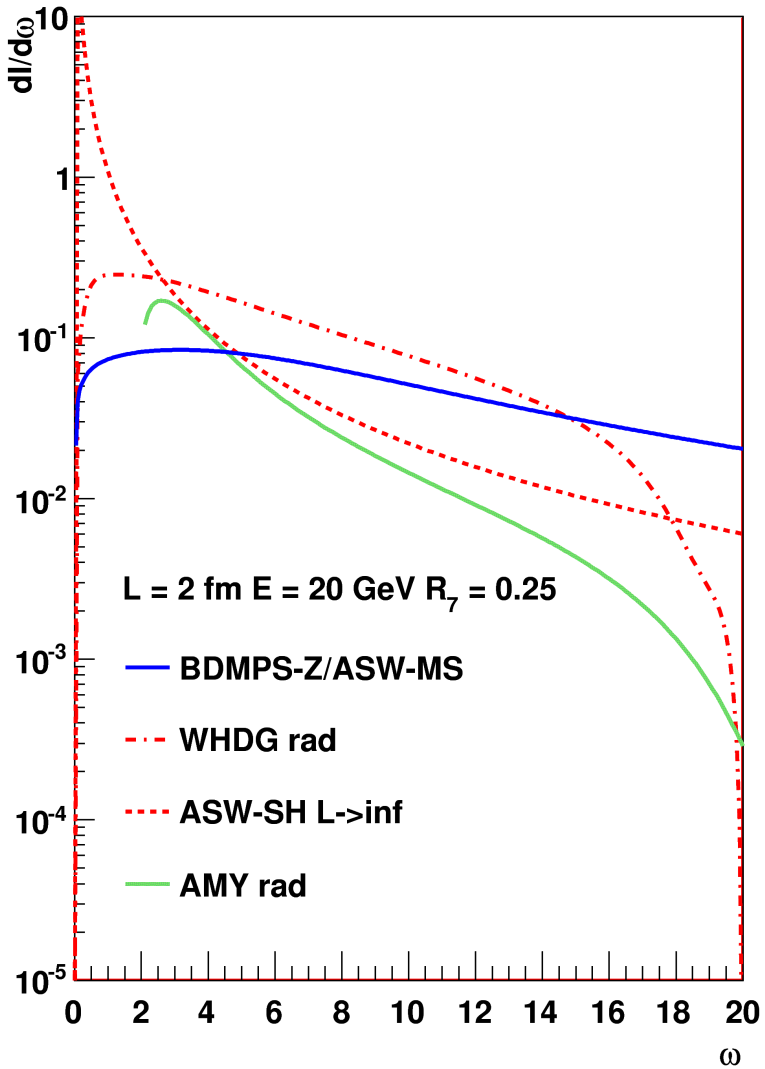


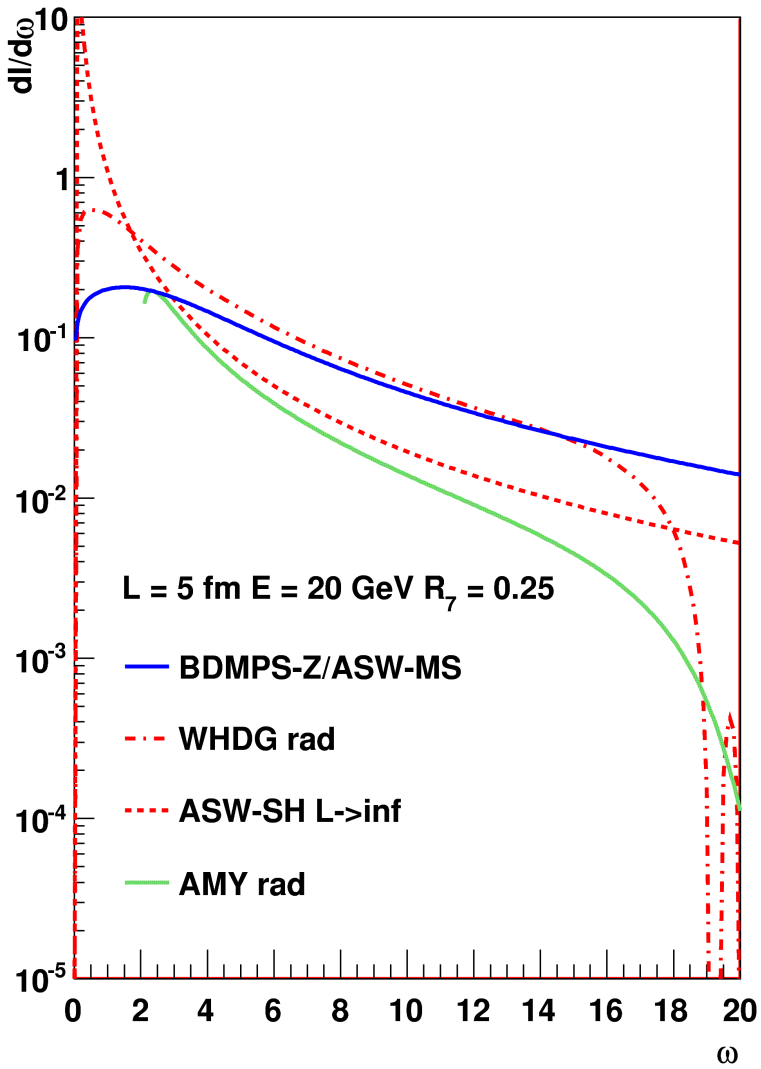


Gluon gas

$N_f = 0$

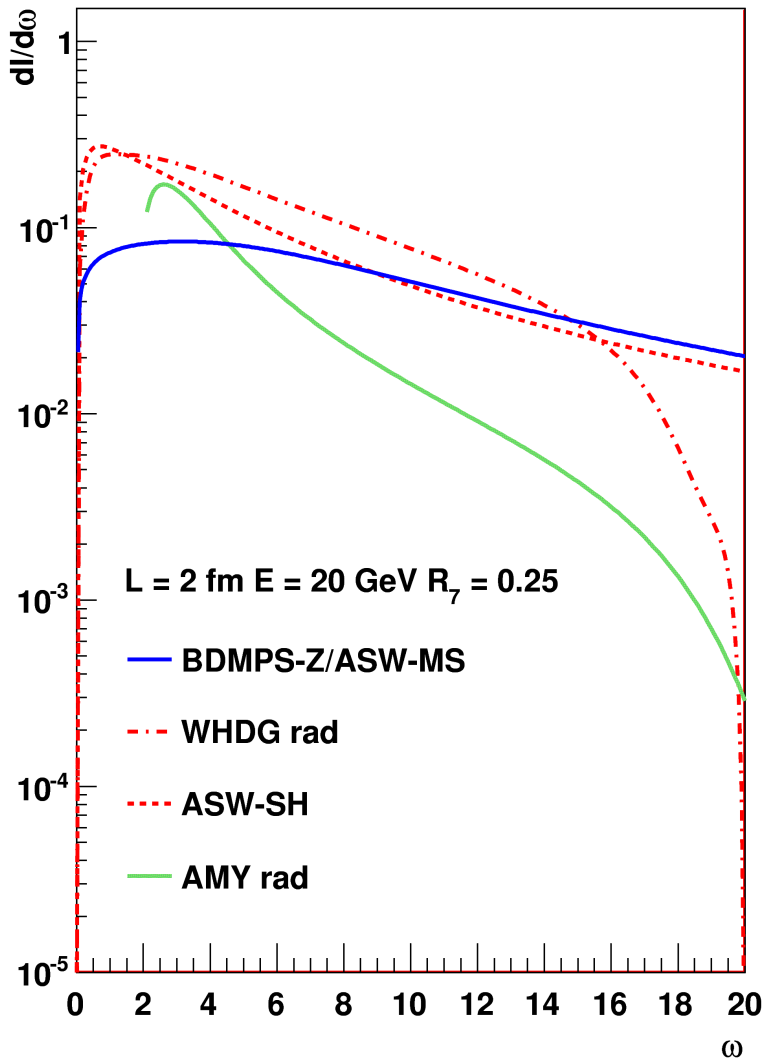
(Single) Gluon Spectra





Gluon spectrum BDMPS-Z/ASW-MS for small L limit.

(Single) Gluon Spectra

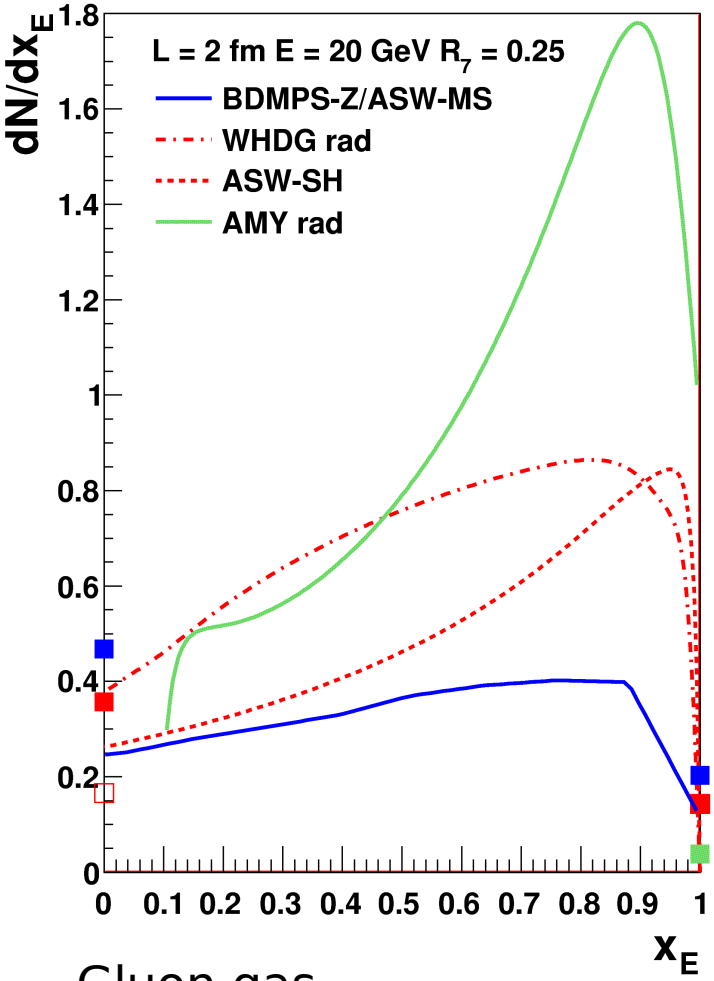


- ASW-MS and ASW-SH the same at large ω.
- WHDG smooth cutoff depending on E_{parton}.
- $N_{gluons,ASW\text{-}SH} \sim N_{gluons,WHDG}$
- $\langle\omega\rangle_{ASW\text{-}SH} > \langle\omega\rangle_{WHDG}$
- Opacity expansions more soft gluon radiation than BDMPS.
- $N_{gluons,BDMPS} < N_{gluons,OE}$
- For AMY spectrum soft gluons not shown.

Outgoing quark spectrum

$x_E = 1 - \Delta E/E$ $x_E = 0$: Absorbed quarks $x_E = 1$: No energy loss

- In Small L limit:
  2 times more partons without any energy loss for BDMPS compared to opacity expansions.
- Suppression factor R_7 dominated by:
  - BDMPS: partons without energy loss = discrete weight p_0
  - OE'S: p_0 and soft gluon radiation
  - AMY: soft gluon radiation



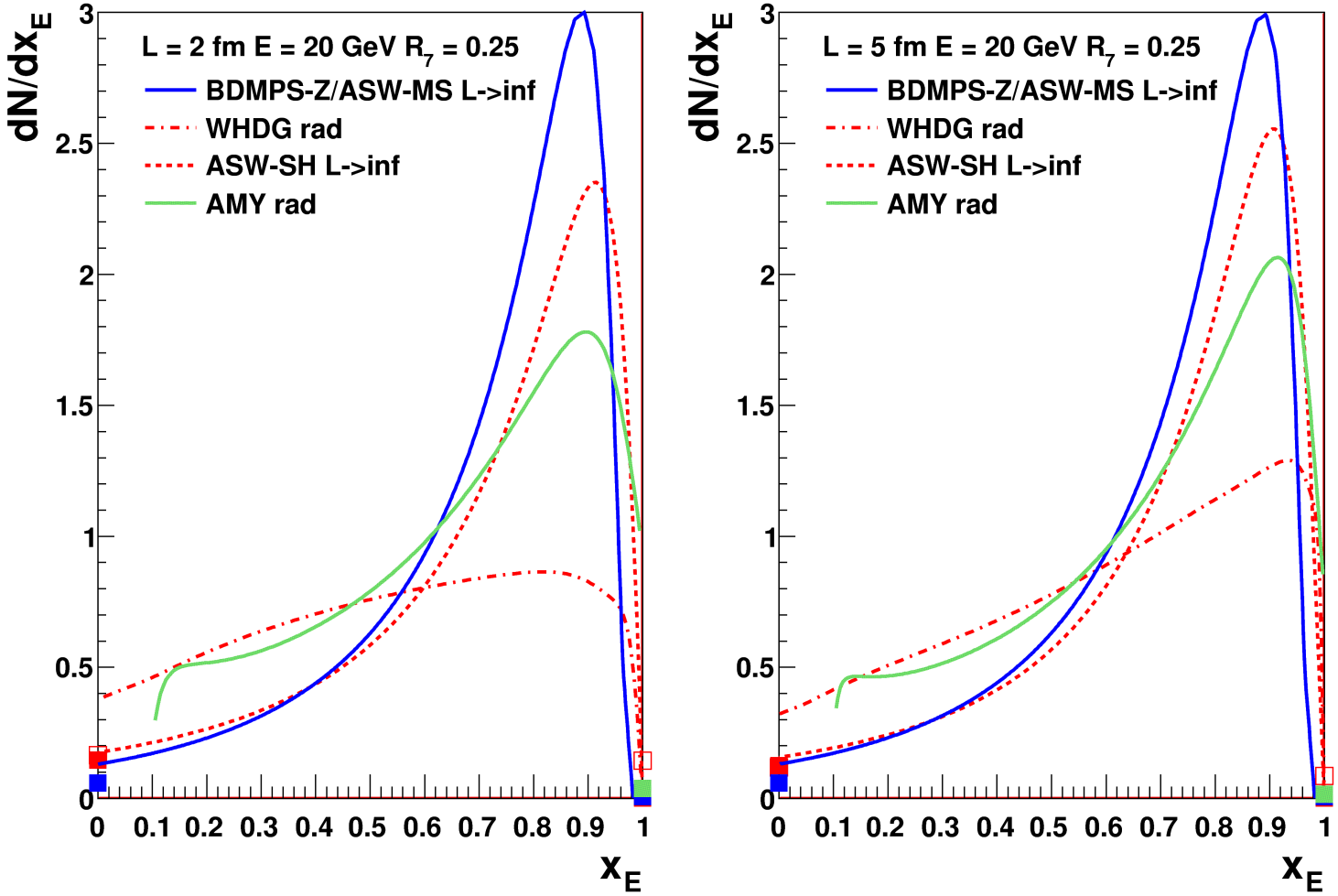
Gluon gas
Suppression:
$R_7 = 0.25$ for all models

Outgoing quark spectrum

$x_E = 1 - \Delta E/E$ $x_E = 0$: Absorbed quarks $x_E = 1$: No energy loss

Gluon gas

Suppression:
$R_7 = 0.25$
for all models

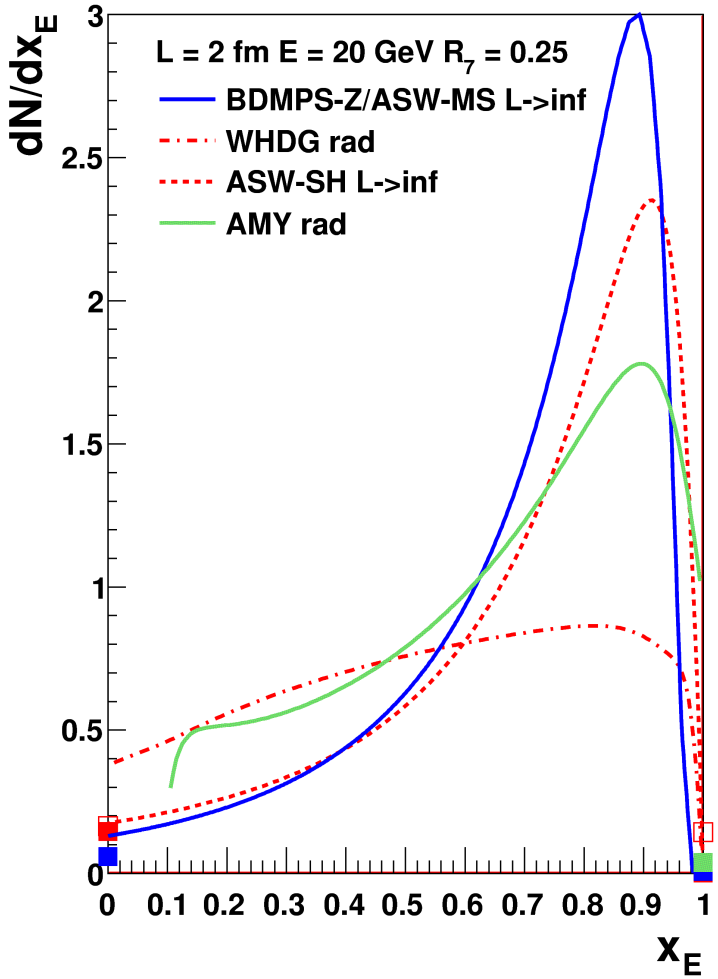


AMY: peak of leading parton at $x_E \sim 0.9$

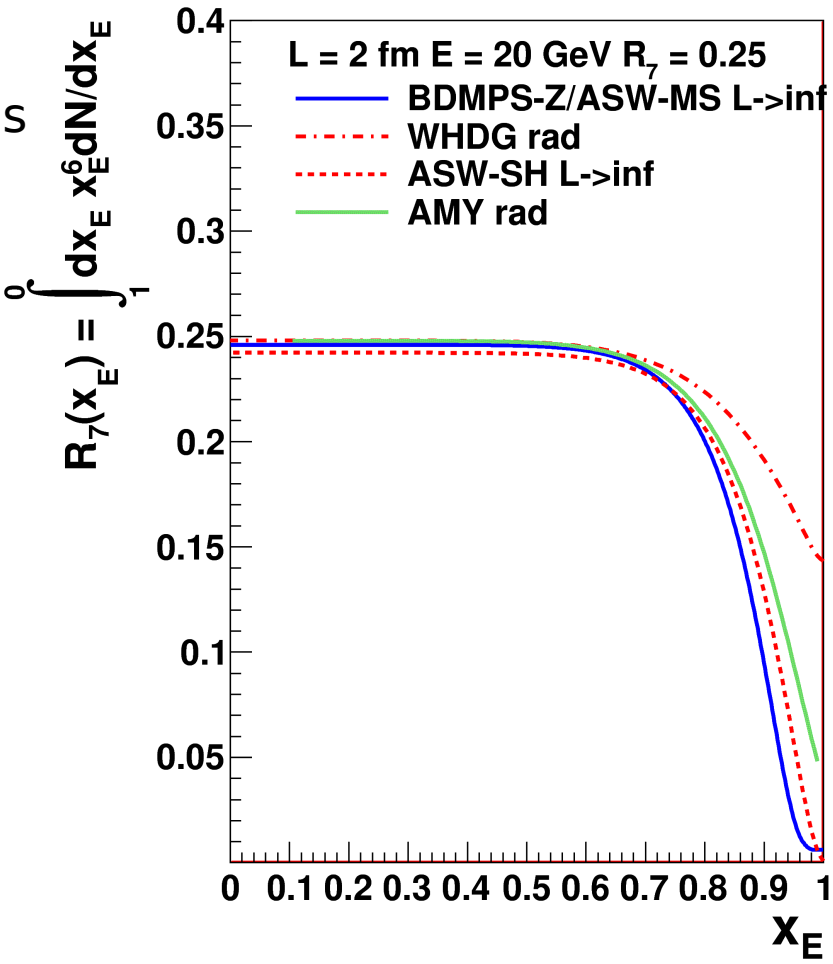
BDMPS: peak of leading parton at $x_E \sim 0.85$

R_7 vs x_E

R_7 as function of x_E
Integration from x_E=1 to x_E=0



Gluon gas



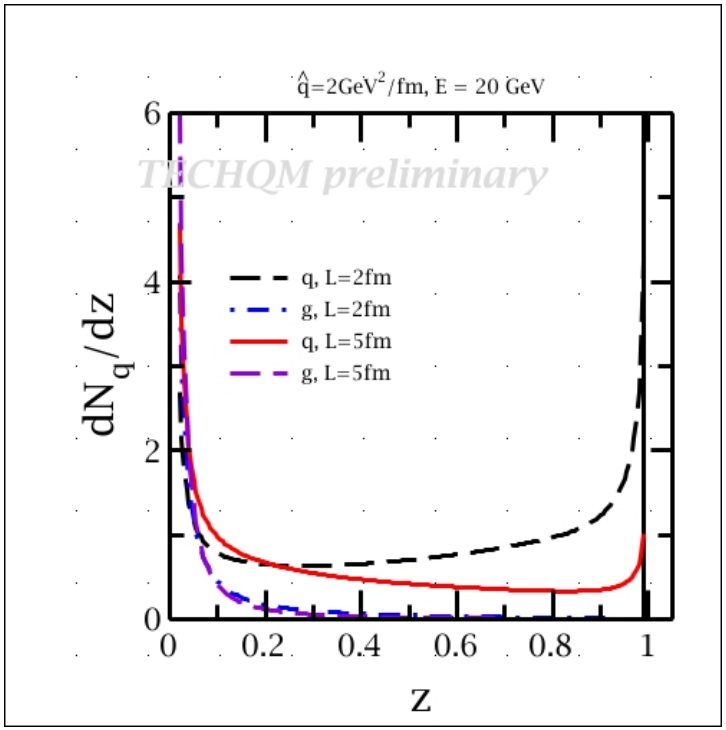
$R_{AA} \sim R_7$ only sensitive for $x_E < 0.7$

Summary

- A lot of progress in the brick problem.
- Direct comparison of
  - Multiple Soft Scattering Approximation
  - Opacity Expansions
  - AMY
- Fundamental difference between AMY and ASW-MS:
  Large L limit. Vacuum interference vanishes in this limit.
- With same suppression factor:
  Models show very different energy loss distributions due to:
  - Partons without any energy loss
  - Soft gluon radiation

Discussion

- What are the key differences between BDMPS and opacity expansion?
- What can we measure to distinguish different models?
- Higher Twist: coming up!



Backup

Medium Properties

Initial Maximum Temperature

- Unmodified medium qhat scales with density of medium:

$$\langle q_\perp^2 \rangle = \mu^2$$

- HTL

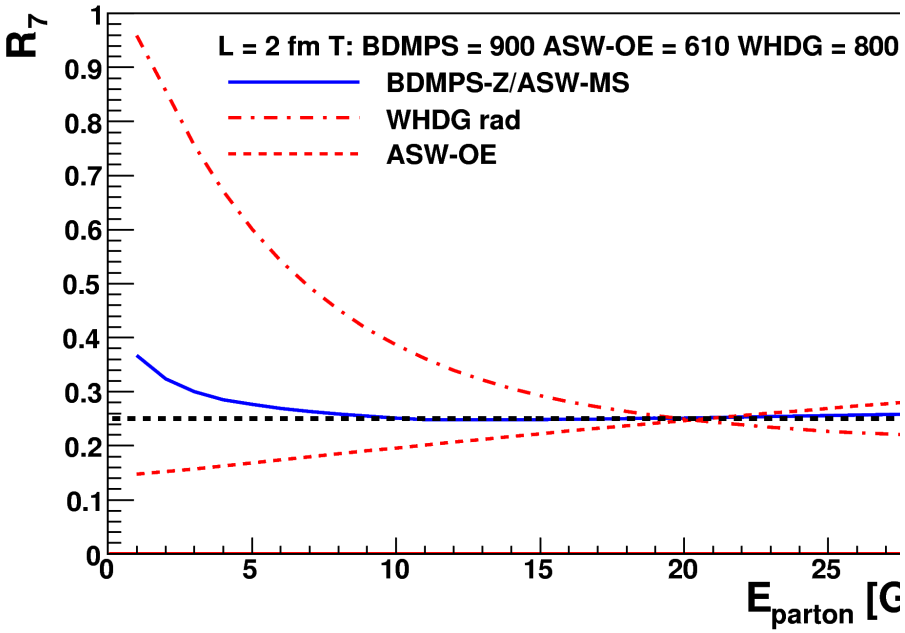
$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda}$$

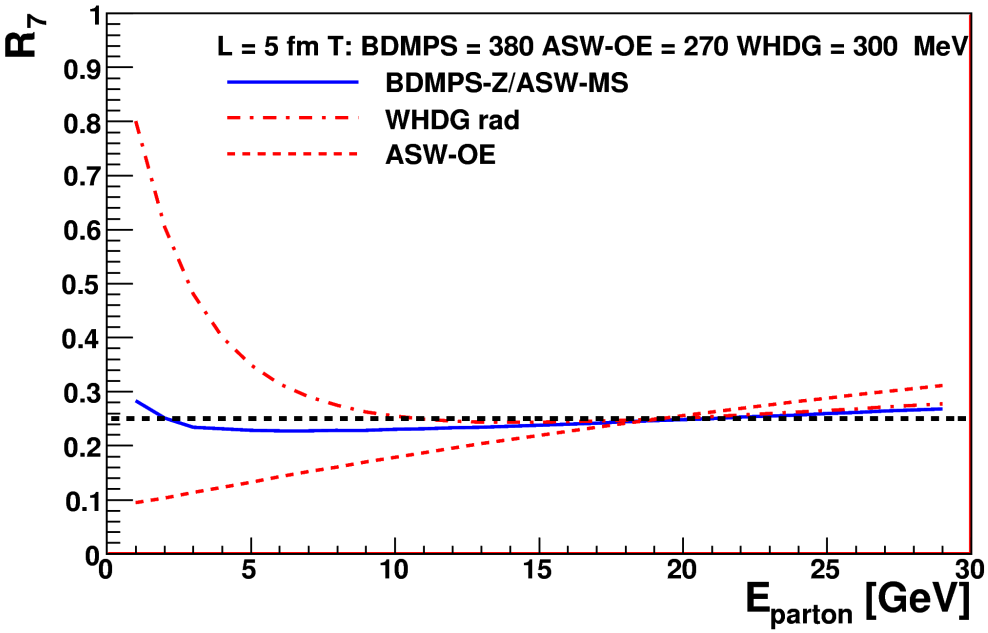
$$\hat{q} = \frac{\mu}{\lambda}$$

	Tmax (MeV)	WNSExp
BDMPS	**Unmodified**	4518
	HTL	2586
ASW-OE	**HTL**	660
WHDG	**HTL**	756

Calculations are for a quark-gluon gas with 3 active flavors.
Centrality 0-5 %. Best fits for HTL with freeze out at 150 MeV.

Suppression in a brick vs E_{parton}





- E_{parton} dependence of the models:
  - All models: Absorption if $\Delta E > E_{parton}$
  - BDMPS: Log of HTL qhat
  - WHDG: Single gluon cut off

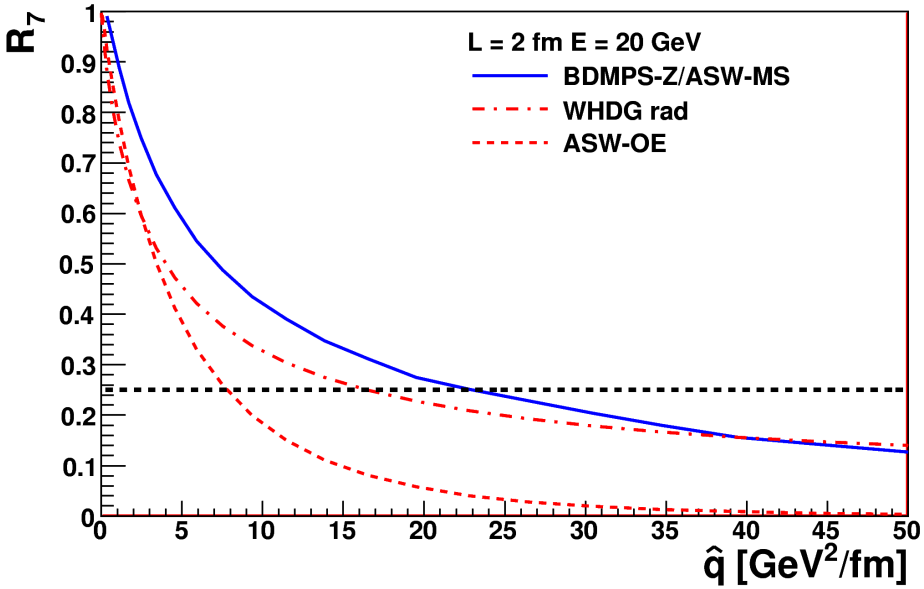
Suppression in a brick vs qhat

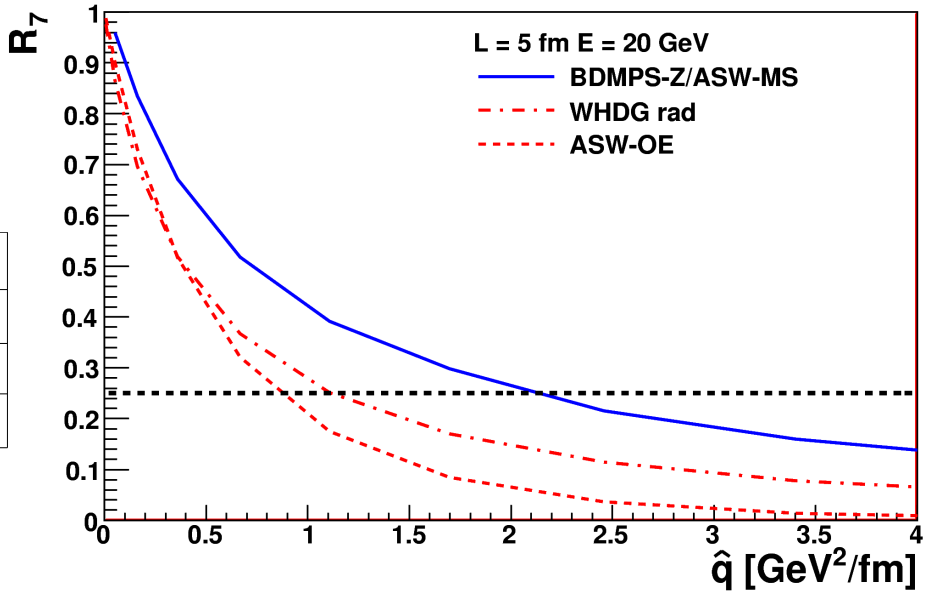
Quark-Gluon gas

For all models:

$$\hat{q}(T) = \frac{C_R g^4 \mathcal{N}(T)}{4\pi} \ln\left(\frac{q^2_{max}(T)}{m^2_D(T)} + 1\right)$$

For which T is the common variable in all models.





R7=0.25	qhat (GeV^2/fm)		
	BDMPS	WHDG rad	ASW-SH
L = 2 fm	23	17	8
L = 5 fm	2.2	1.1	0.9

Medium Properties

NGluons

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

$$\rho_g = \frac{1.202}{\pi^2} \times 16T^3$$

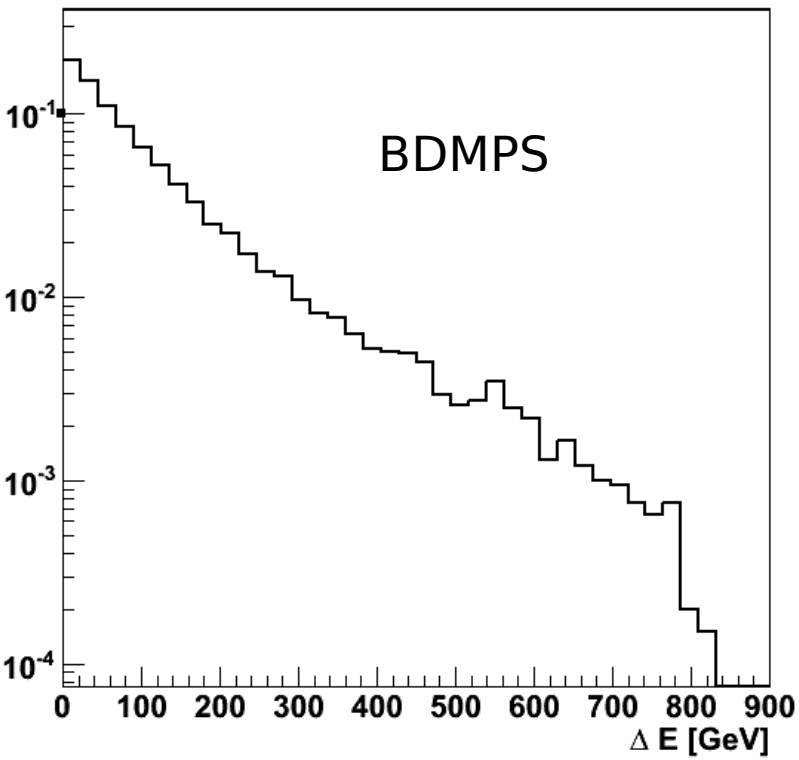
$$\mathcal{N} = \frac{\zeta(3)}{\zeta(2)}(1 + \frac{1}{4}N_f)T^3$$

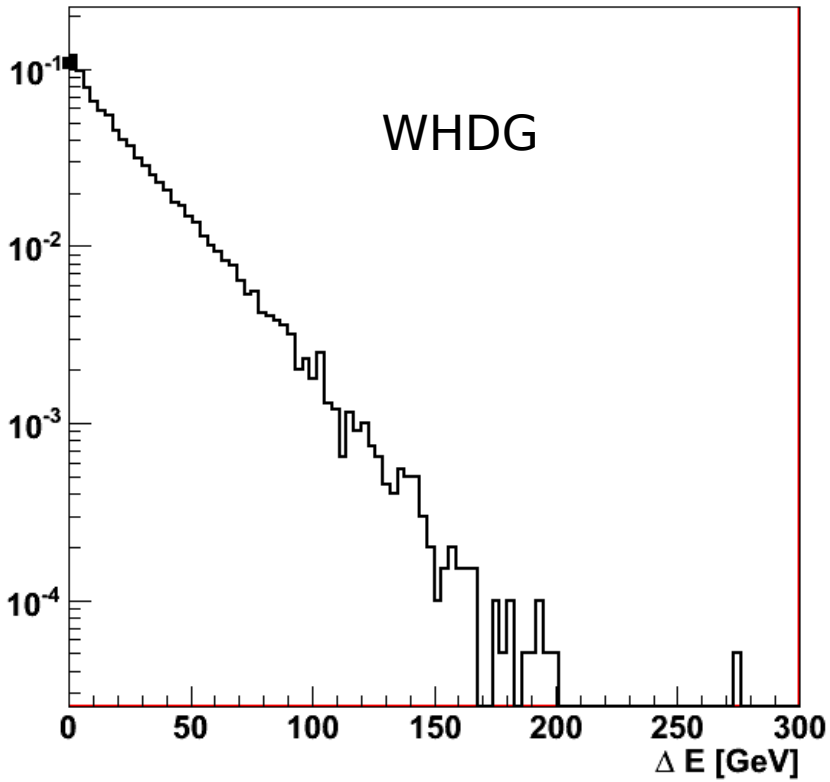
$$\frac{1}{\lambda} = \rho_g\sigma_{gg} + \rho q\sigma_{qg} = \mathcal{N}\sigma$$

	Ngluons	Coll	CollExp	WNS	WNSExp
BDMPS	K-Factor	3.20E+004	1.80E+006	1.90E+004	2.10E+006
	HTL	8050	4.90E+005	3220	3.90E+005
ASW-OE	HTL	920	9200	1030	6440
WHDG	HTL	1150	1.10E+004	773	9660

Calculations are for a quark-gluon gas with 3 active flavors.
Centrality 0-5 %. τ_0 = 0.2 fm

Energy loss distribution in full geometry

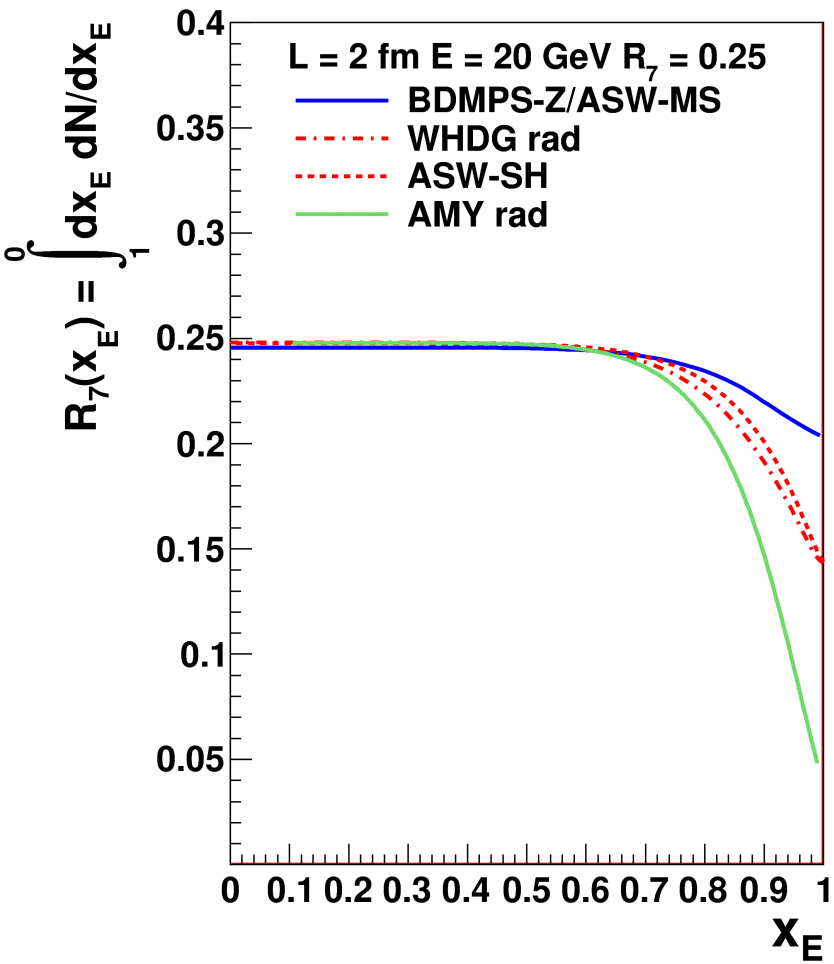


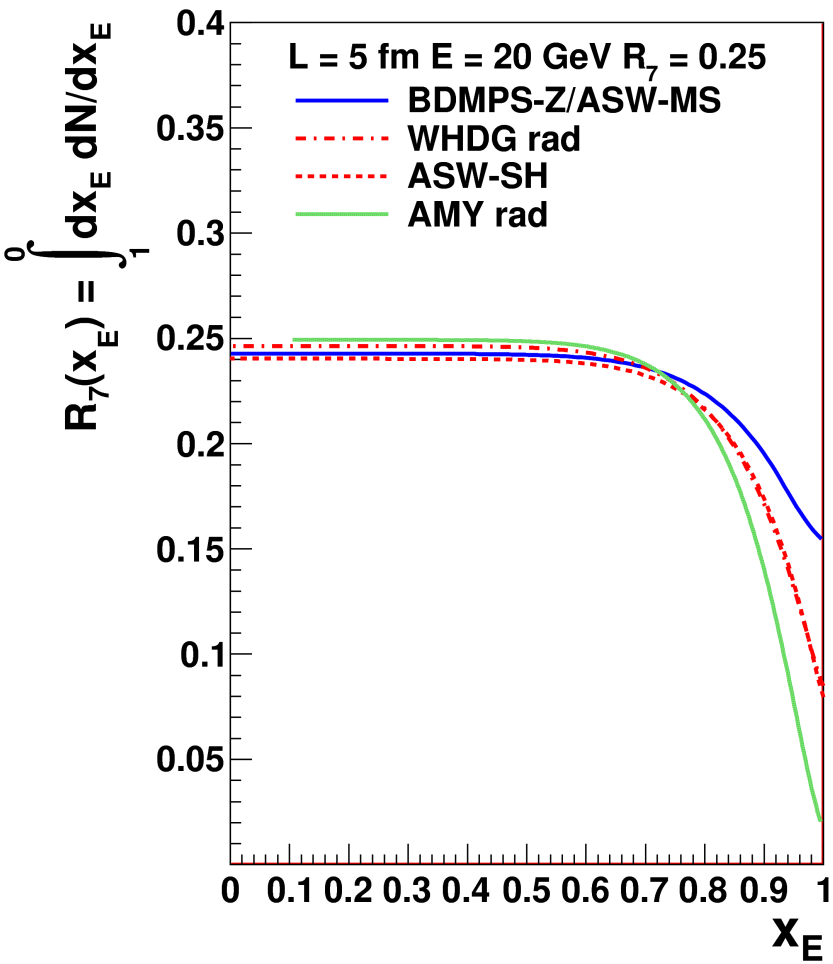


Longer tail in energy loss distribution for BDMPS.
Smooth cut off in single gluon radiation for WHDG.

R_7 vs x_E

Gluon gas

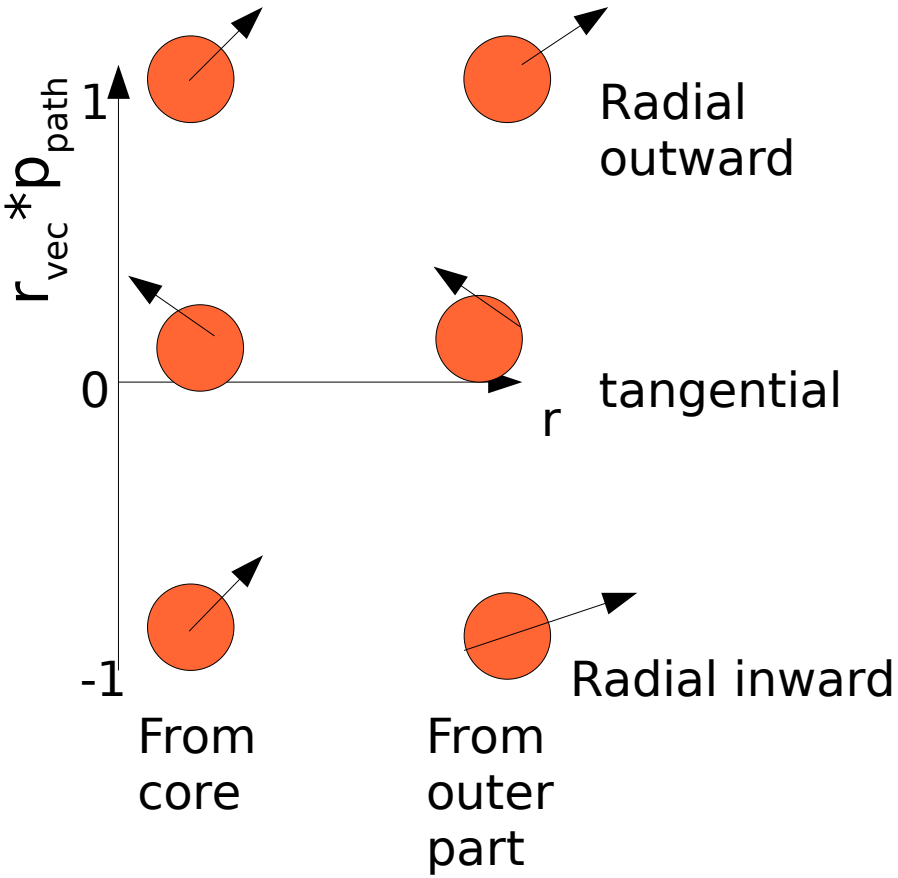




R_7 as function of x_E

BDMPS

Survivors



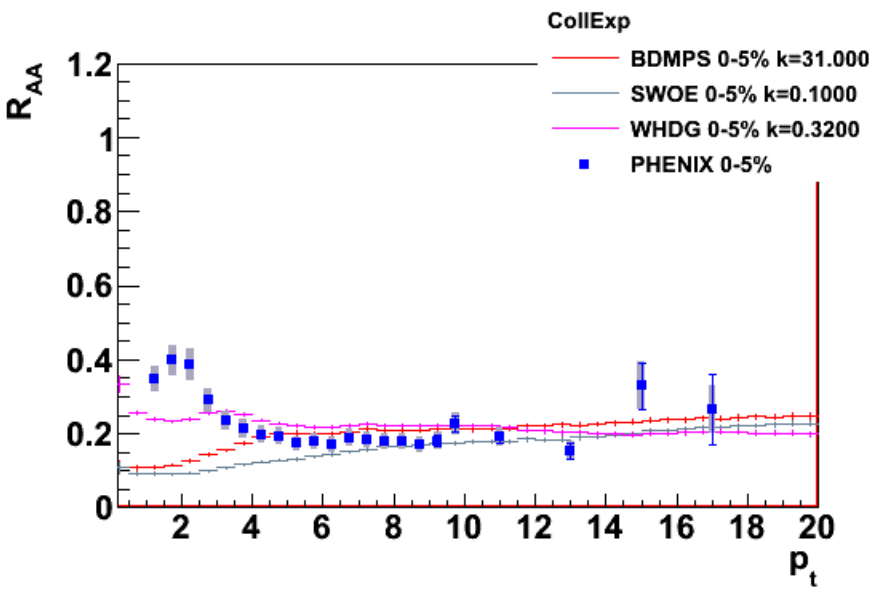
For all produced partons

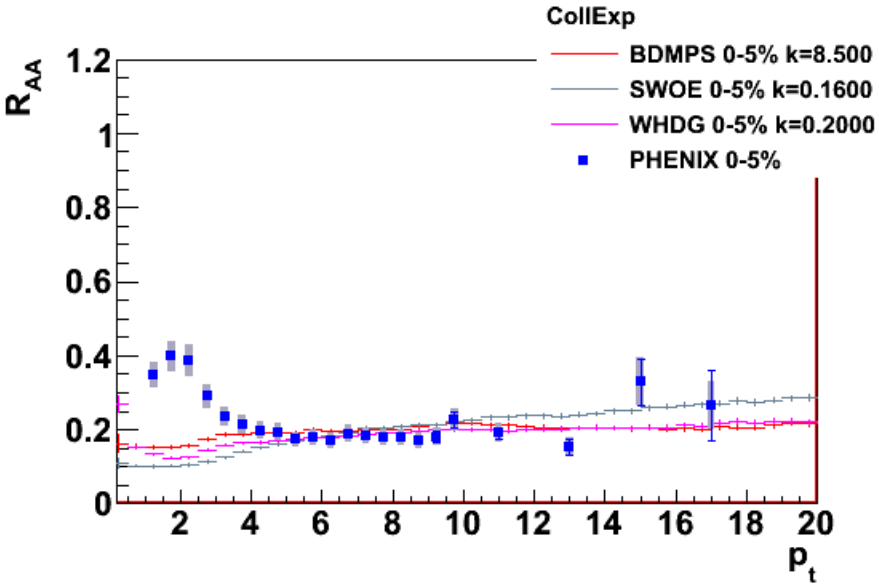
r = sqrt(x0^2+y0^2)

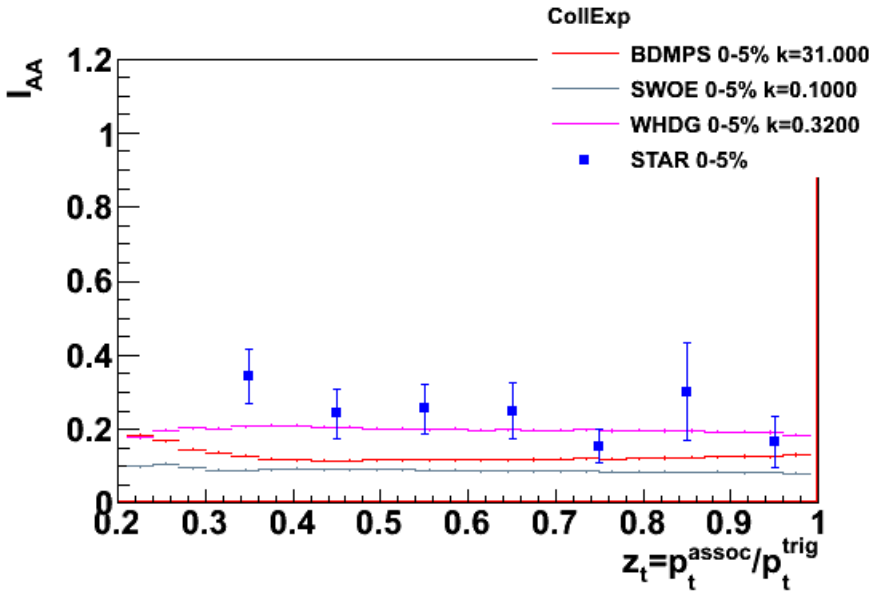
r_{vec}= (x0/r , y0/r)

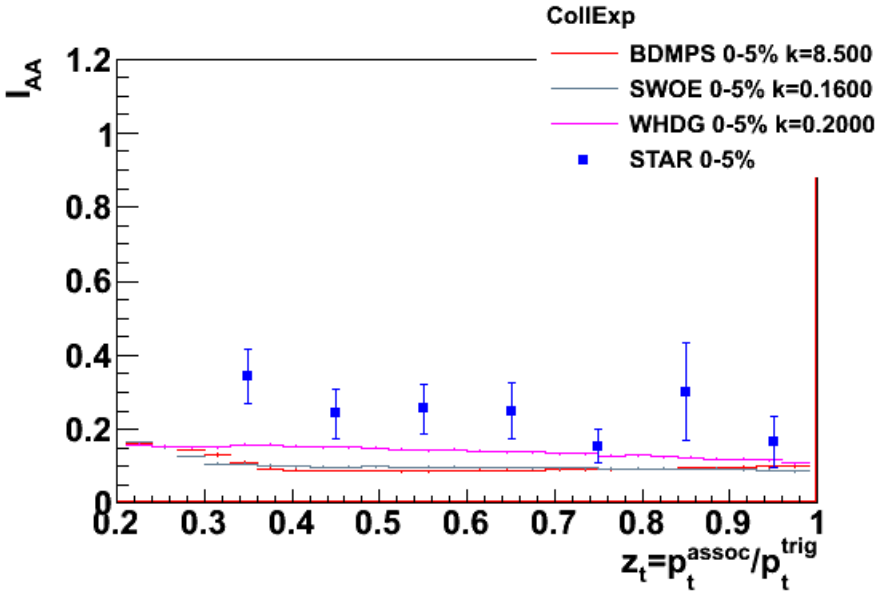
r_{path} = (cos(phi0) , sin(phi0))

Collisional scaling



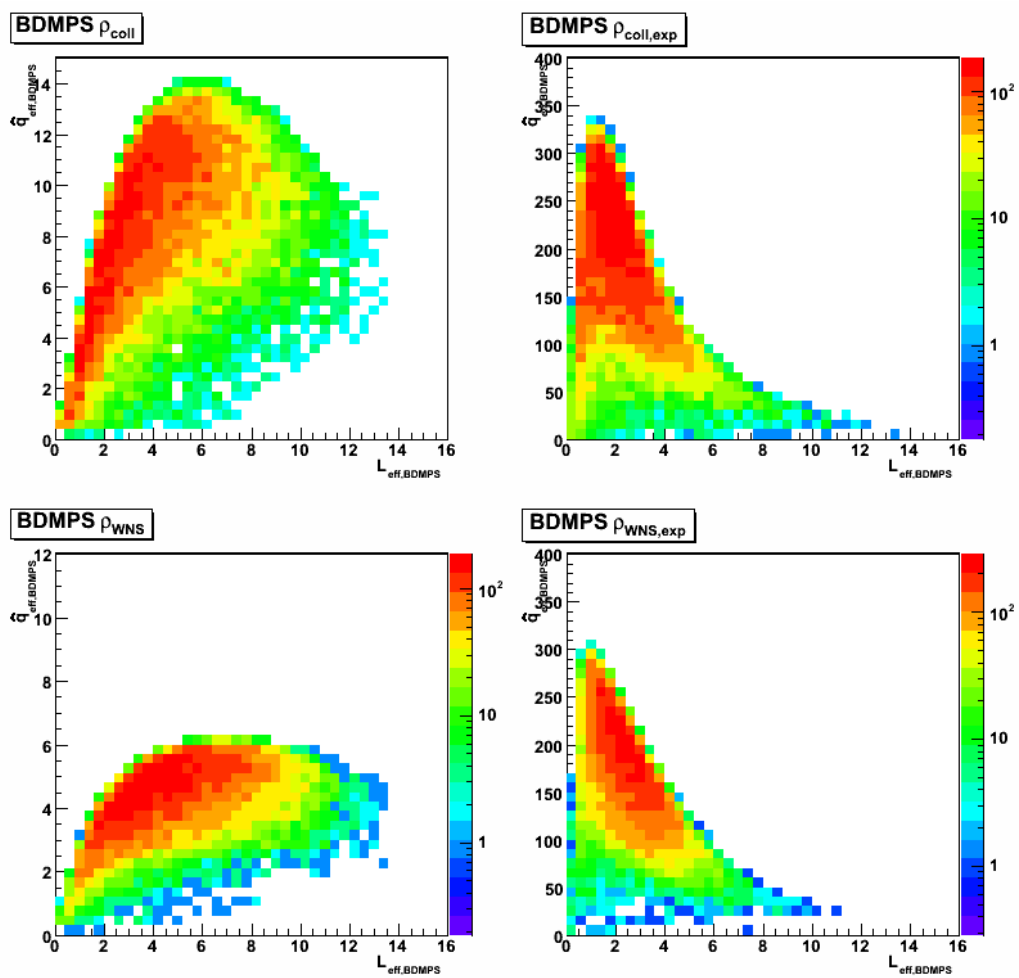




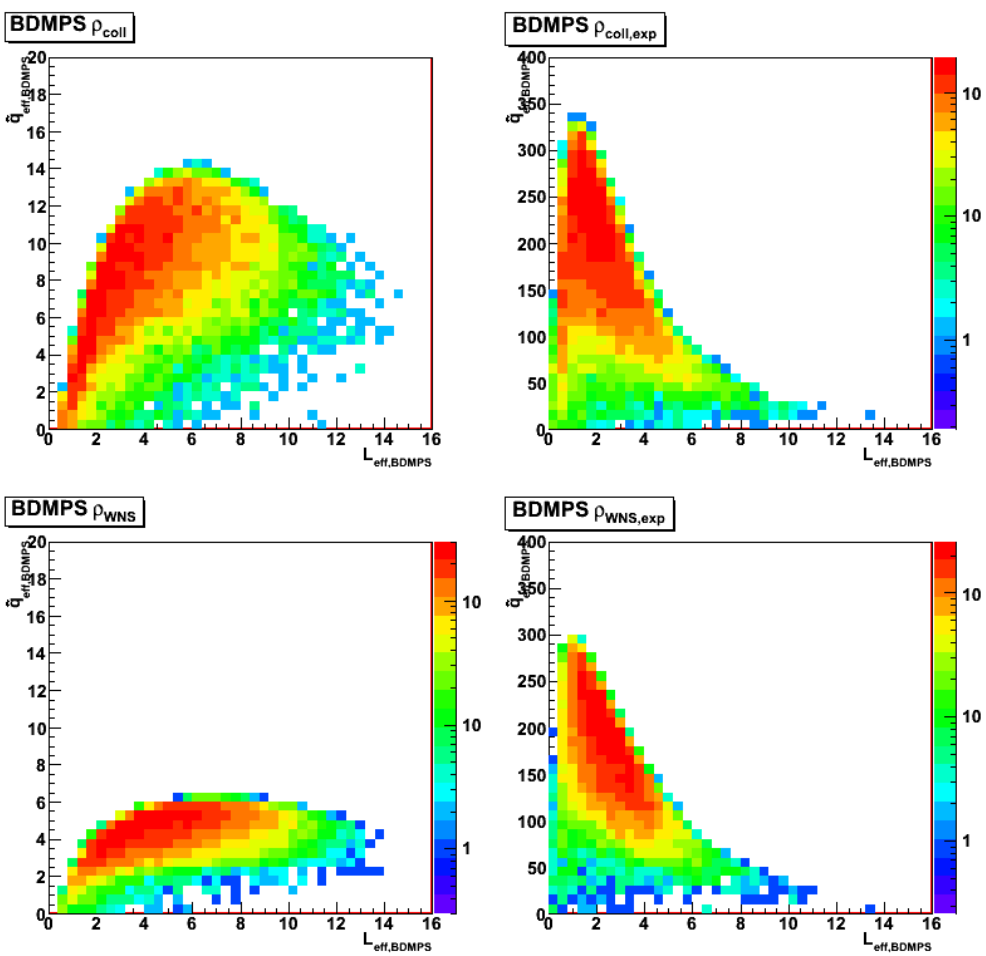


FreezeOut at 150 MeV

With FreezeOut



Without FreezeOut



Only effects static case