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H-QM Helmholtz Research School Quark Matter Studies

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Electromagnetic probes from a parton cascade

Moritz Greif

in collaboration with
Carsten Greiner, Sören Schlichting,
Florian Senzel, Zhe Xu

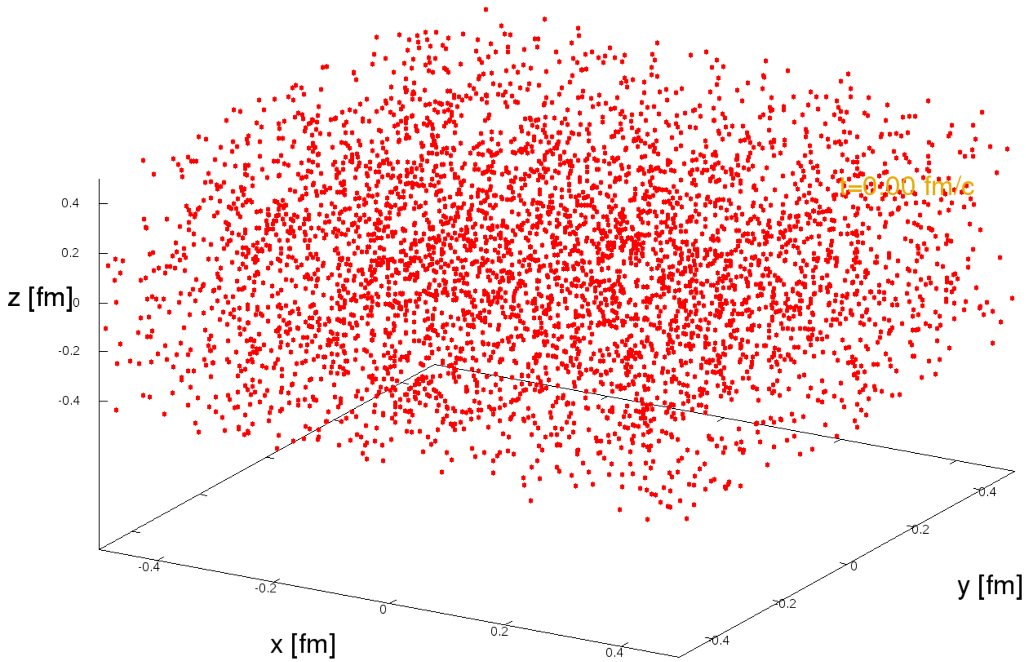
Phys.Rev. C95, 054903, 2017

Phys.Rev. C96, 014903, 2017

CRC-TR 211 Strong-interaction matter under extreme conditions

ECT*, Trento, 26.11.2018

Parton cascade „BAMPS“



Solves the Boltzmann equation
(numerically exact, Monte Carlo)

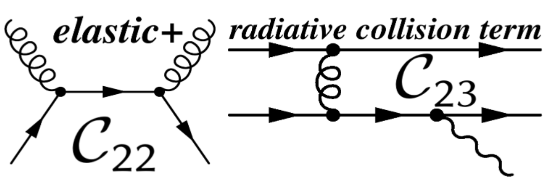
"$f(x,p)$" ← **Single particle distribution function**

- Quarks + Gluons
- pQCD cross sections
- Elastic + radiative scattering
- Ideal equation of state

Used as model for heavy-ion collision:
Expanding 3+1d geometry,
Different initial states

BAMPS: Boltzmann Approach to Multi-Parton Scatterings

$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{22}[f] + \mathcal{C}_{23}[f]$$



Xu & Greiner, PRC 71 (2005) 064901

Initial state in „BAMPS“

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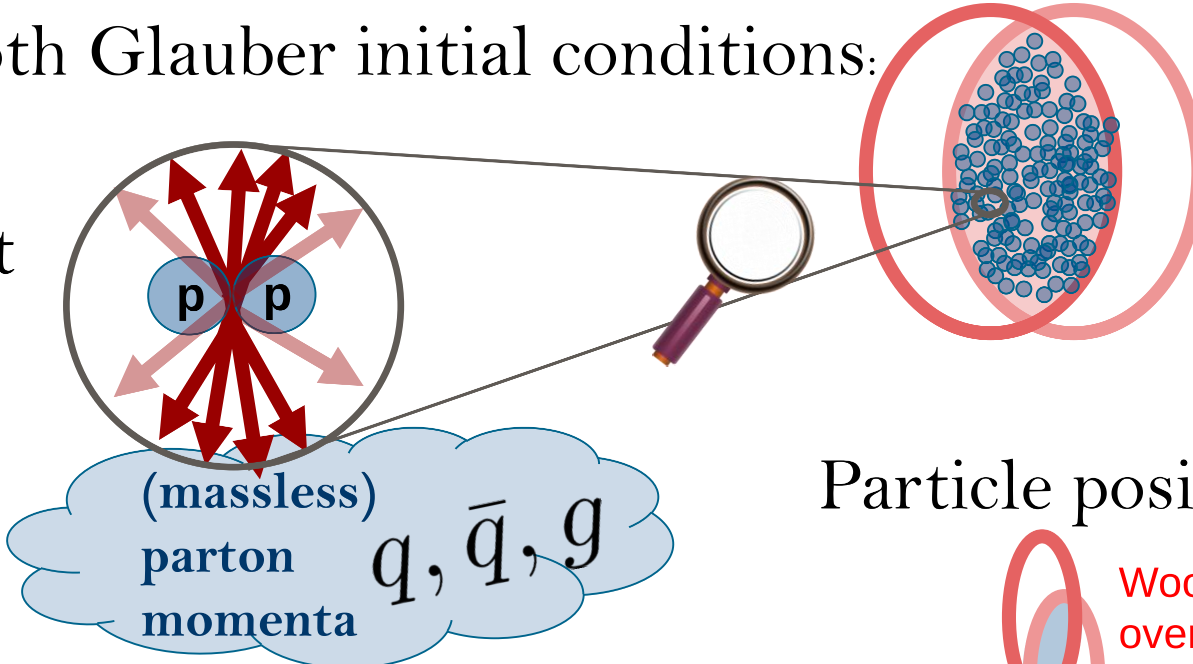
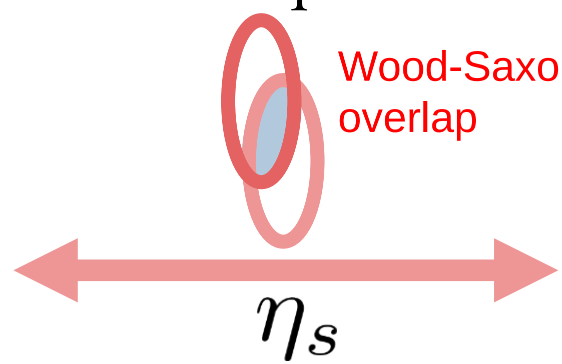
Smooth Glauber initial conditions:

Pythia event generator:



Particle positions:



Hard partons scale with N_{binary}

Soft partons scale with $\sim 0.1\, N_{binary}$

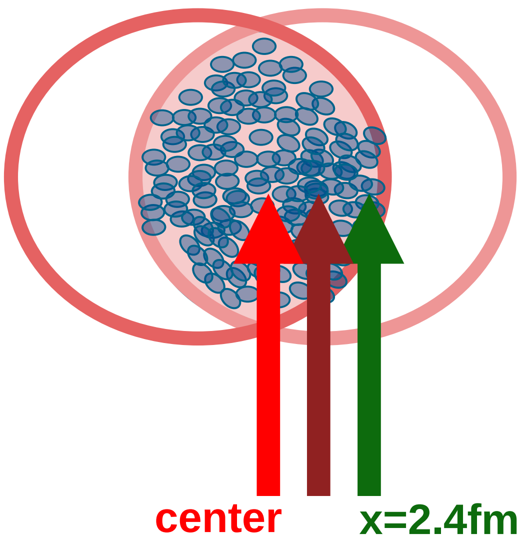
Formation time: $t_{\text{form}} = \frac{1}{p_T} \cosh y$

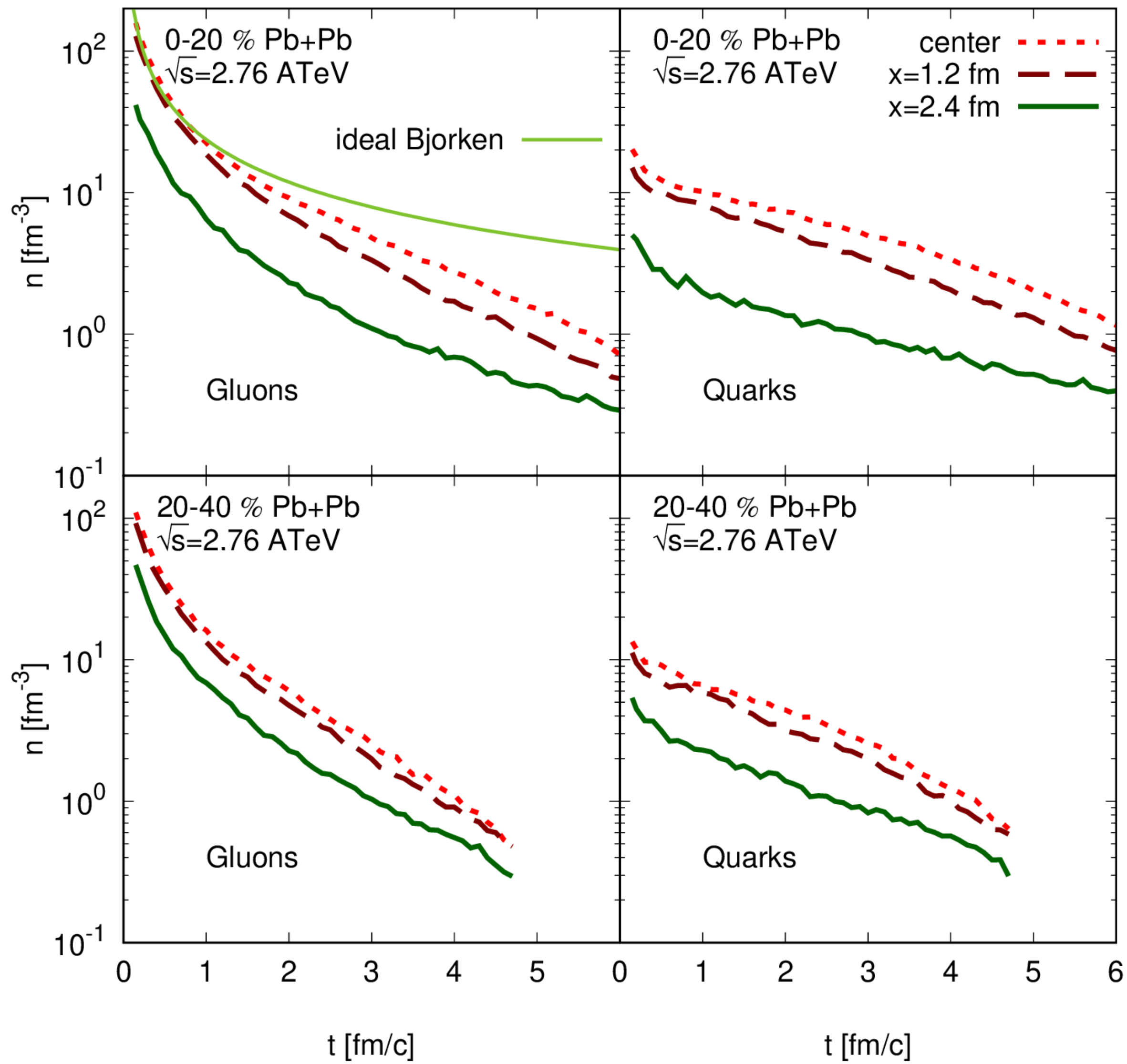
(only if $t > t_{\text{form}}$ interactions allowed)

Xu & Greiner, PRC 71 (2005) 064901

Thermodynamic Evolution

Particle density n at midrapidity





Thermodynamic Evolution

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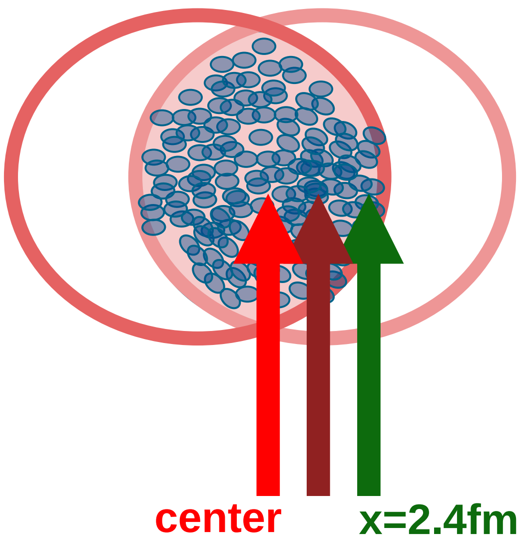
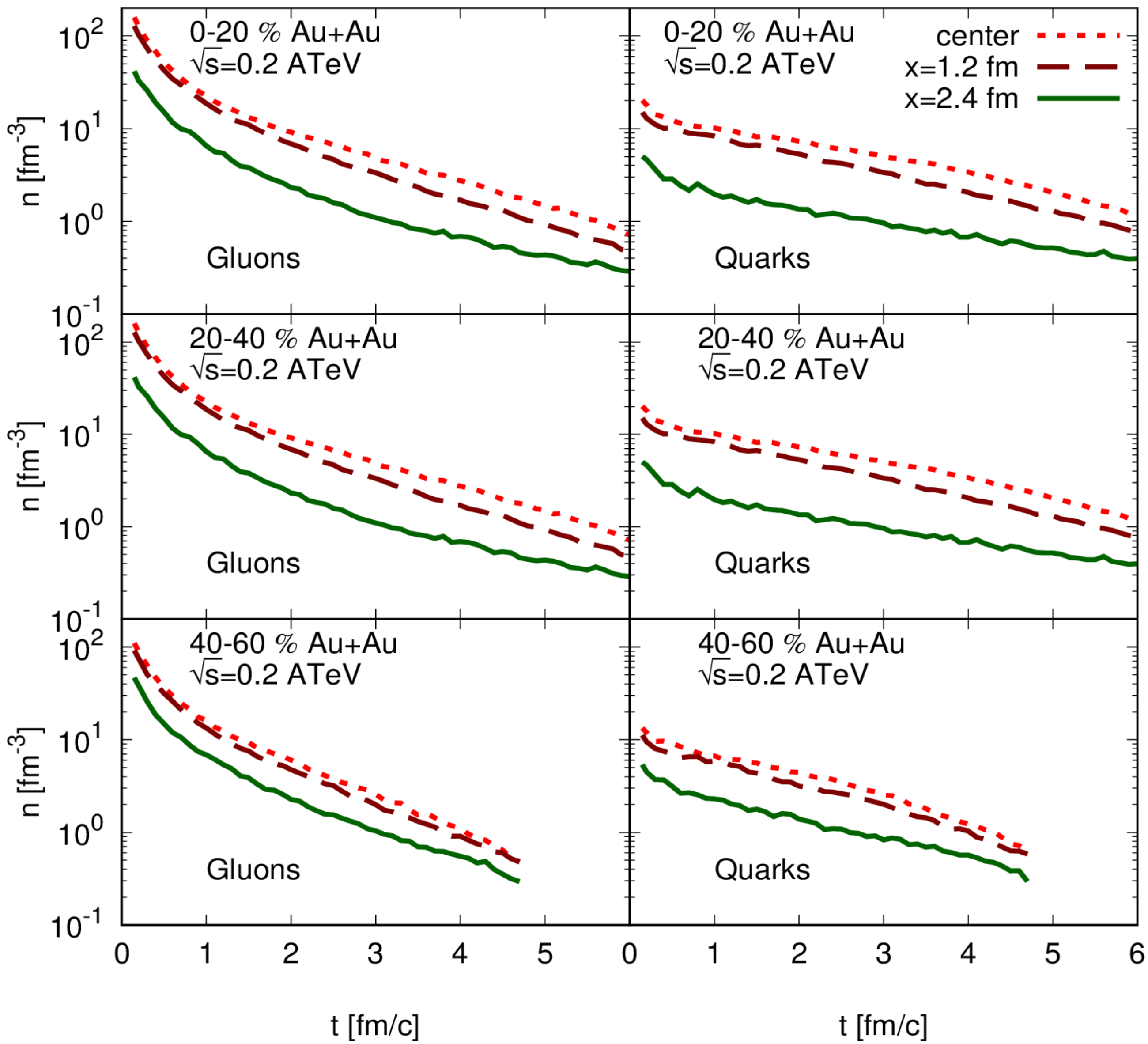
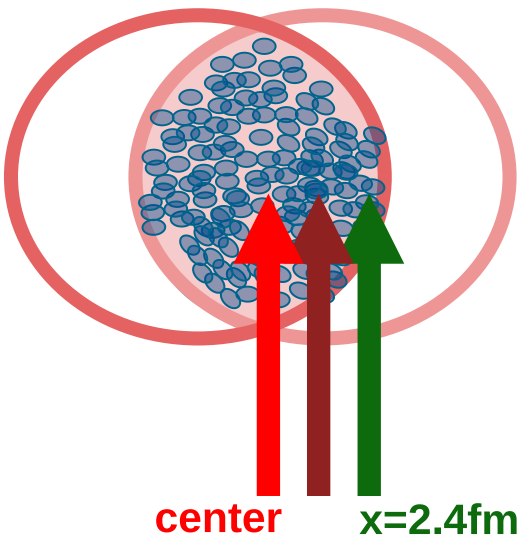
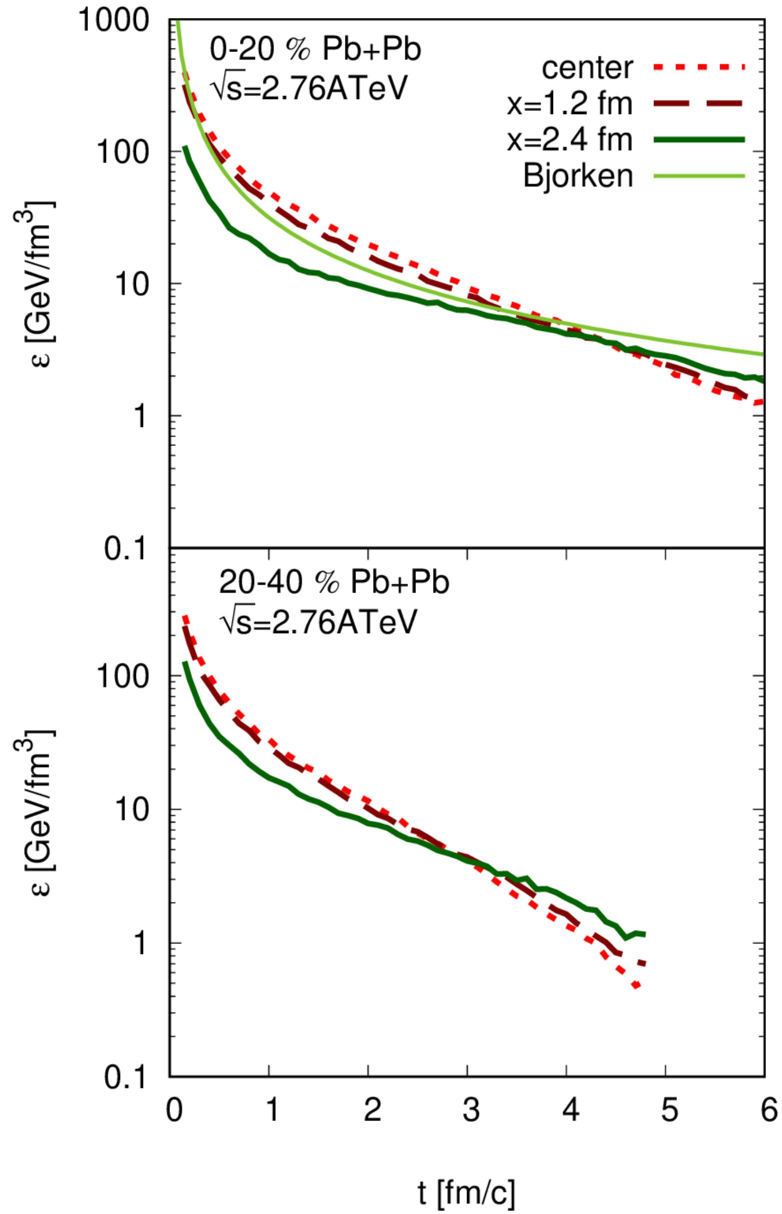




Thermodynamic Evolution

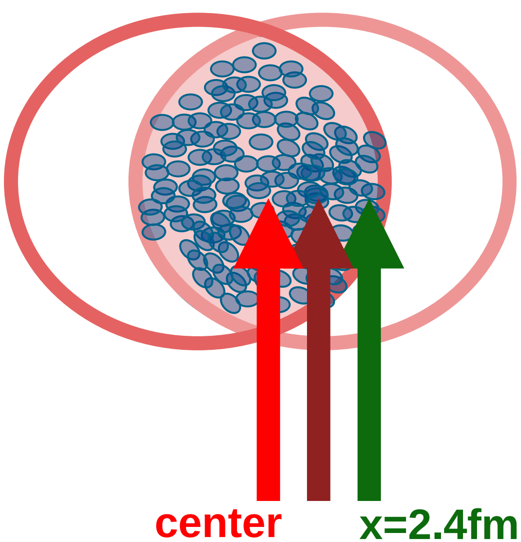
energy density at midrapidity

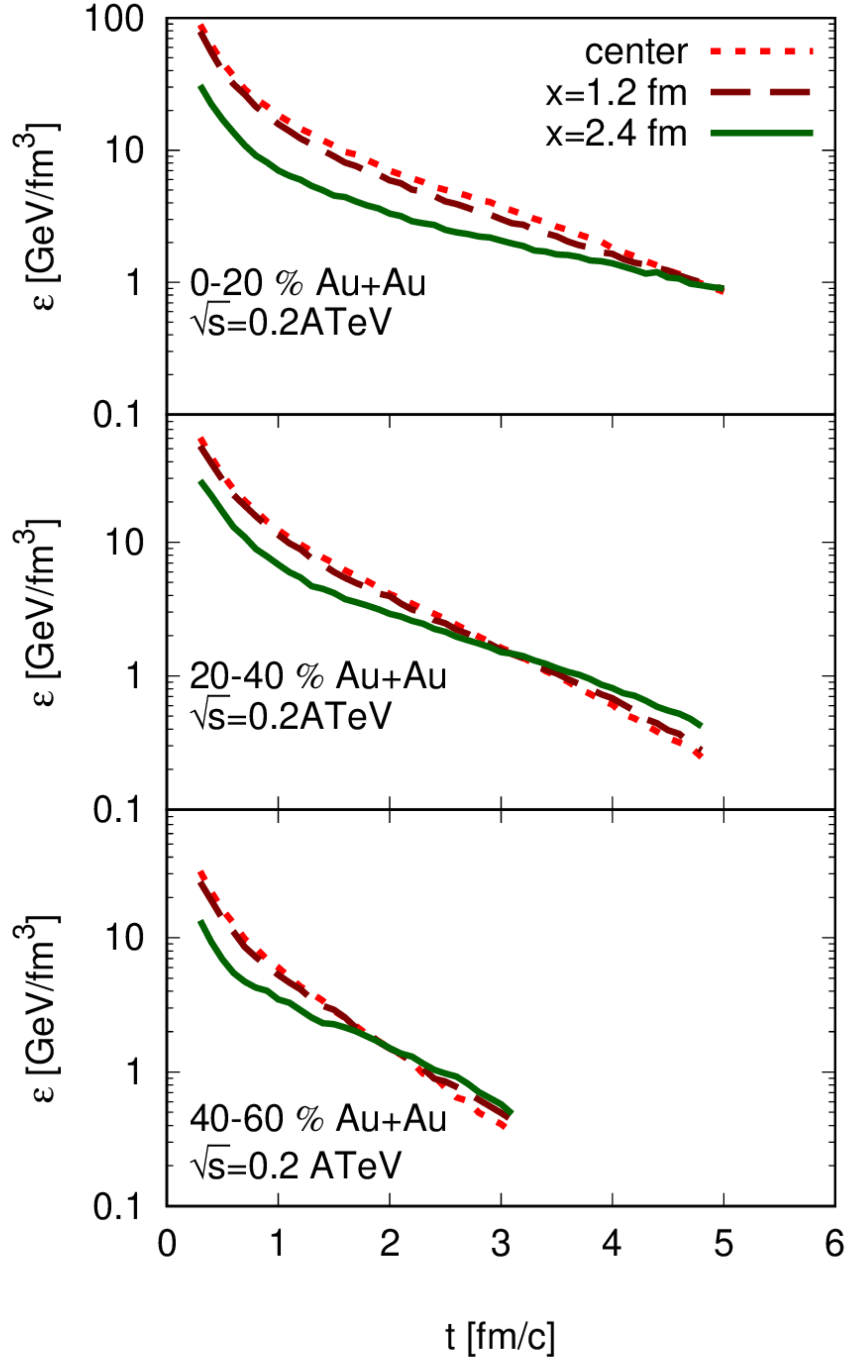




Thermodynamic Evolution

energy density at midrapidity





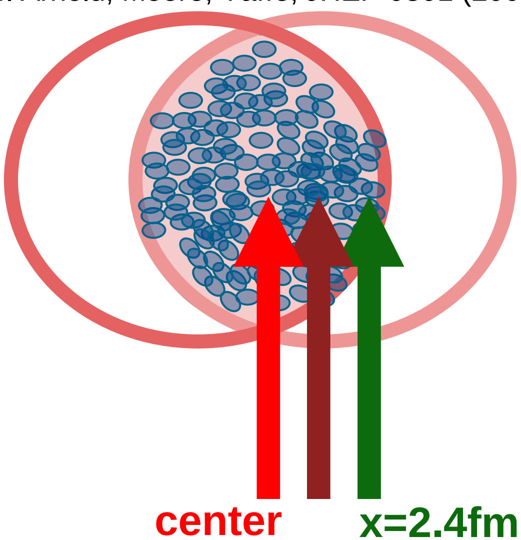
Thermodynamic Evolution

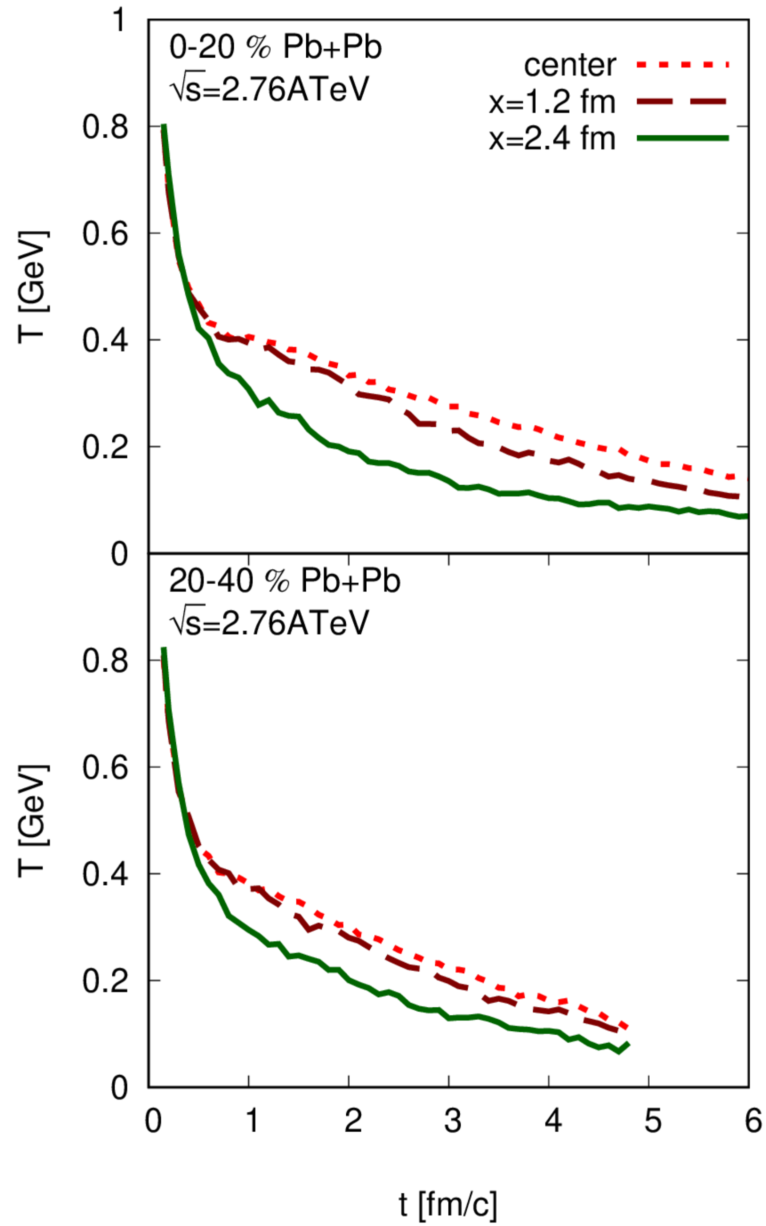
Temperature
at midrapidity

$$\mathcal{I} = \frac{1}{2}\int \frac{d^3\vec{p}}{(2\pi)^3 E_p} E_p f \qquad \mathcal{J} = \int \frac{d^3\vec{p}}{(2\pi)^3 E_p} f$$

$$T_\star^{1\text{st}} = \sum_{\text{species i}} \nu_i \frac{g^2 C_i}{d_A}\mathcal{I}_i \Big/ \sum_{\text{species i}} \nu_i \frac{g^2 C_i}{d_A}\mathcal{J}_i$$

(cf. Arnold, Moore, Yaffe, JHEP 0301 (2003) 030)





Thermodynamic Evolution

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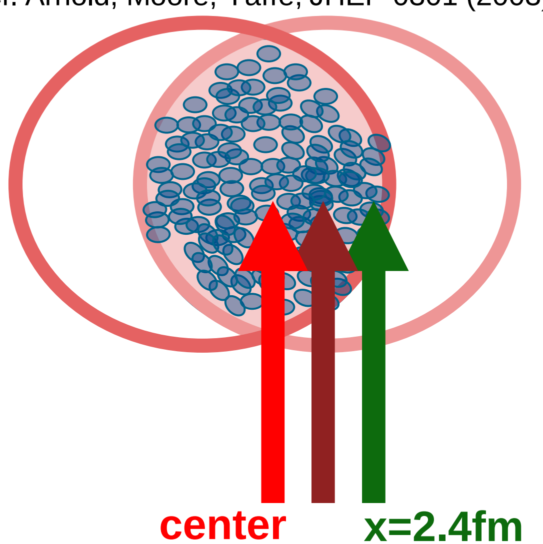
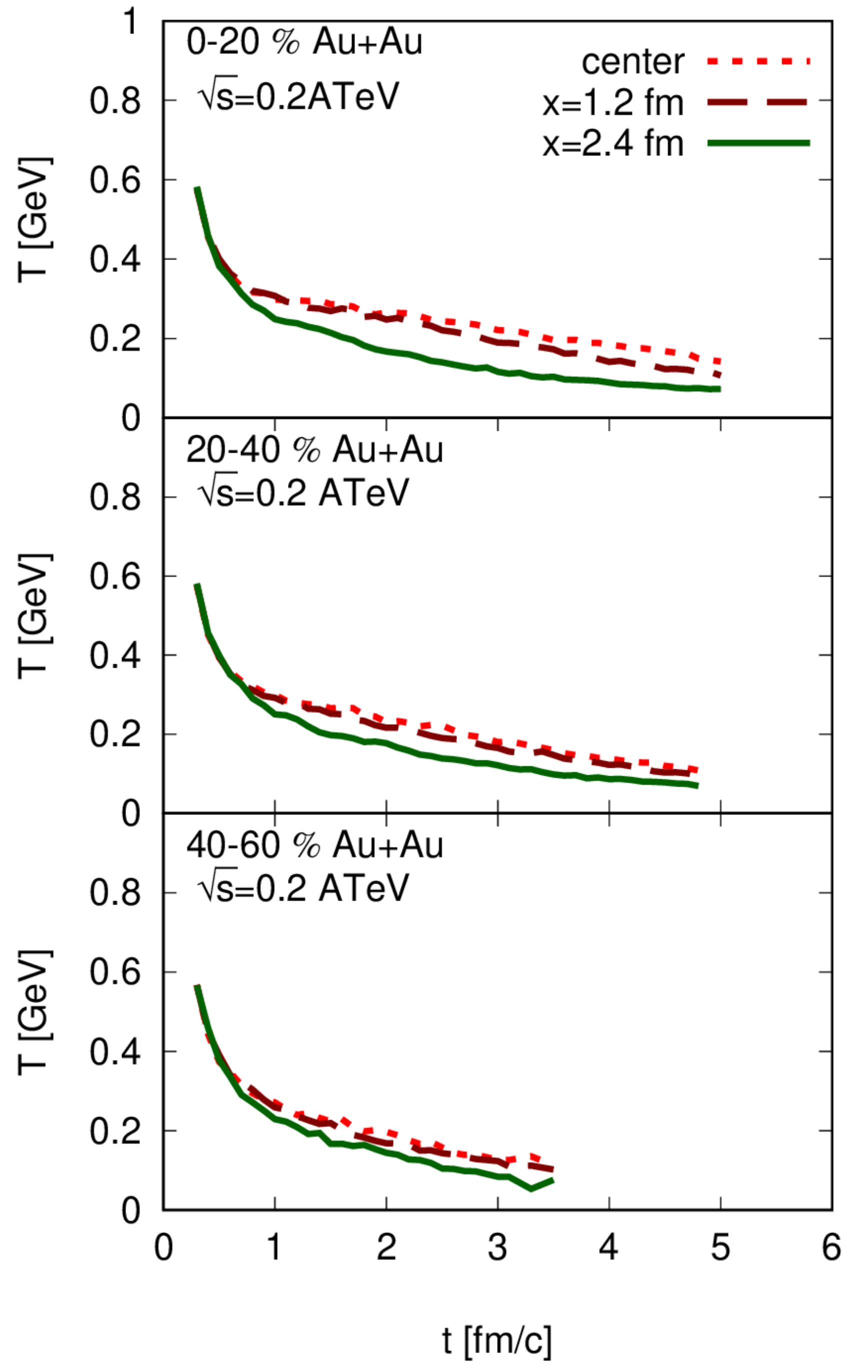
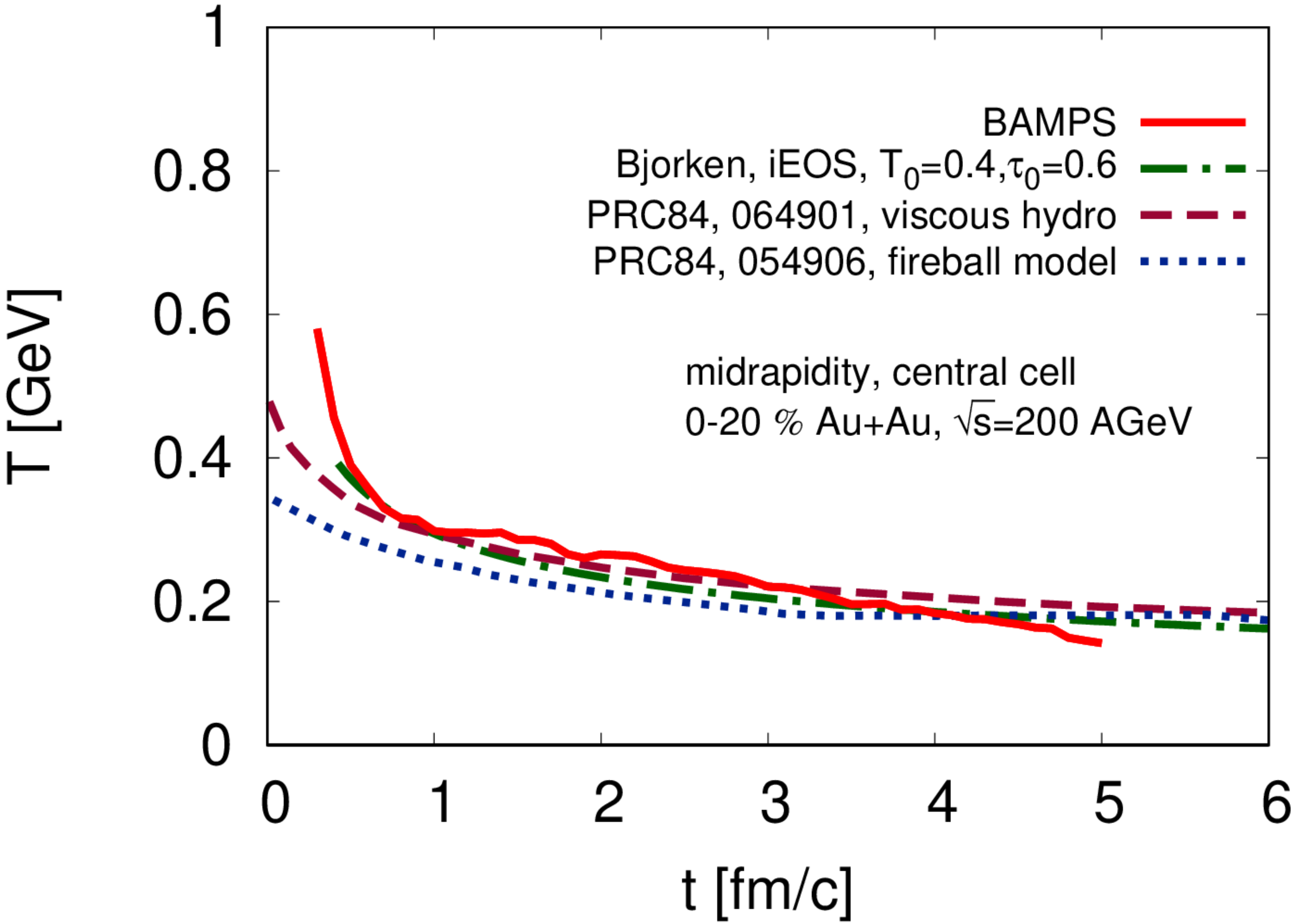


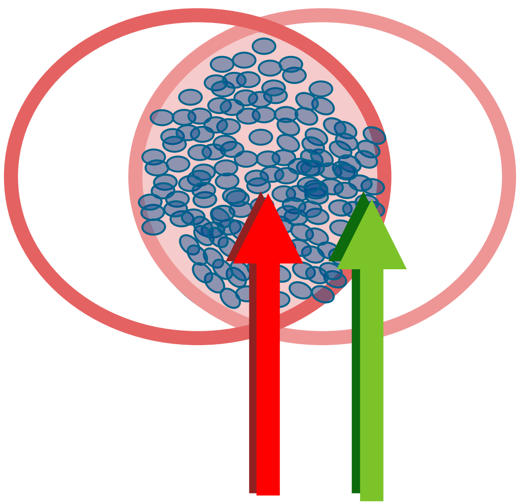


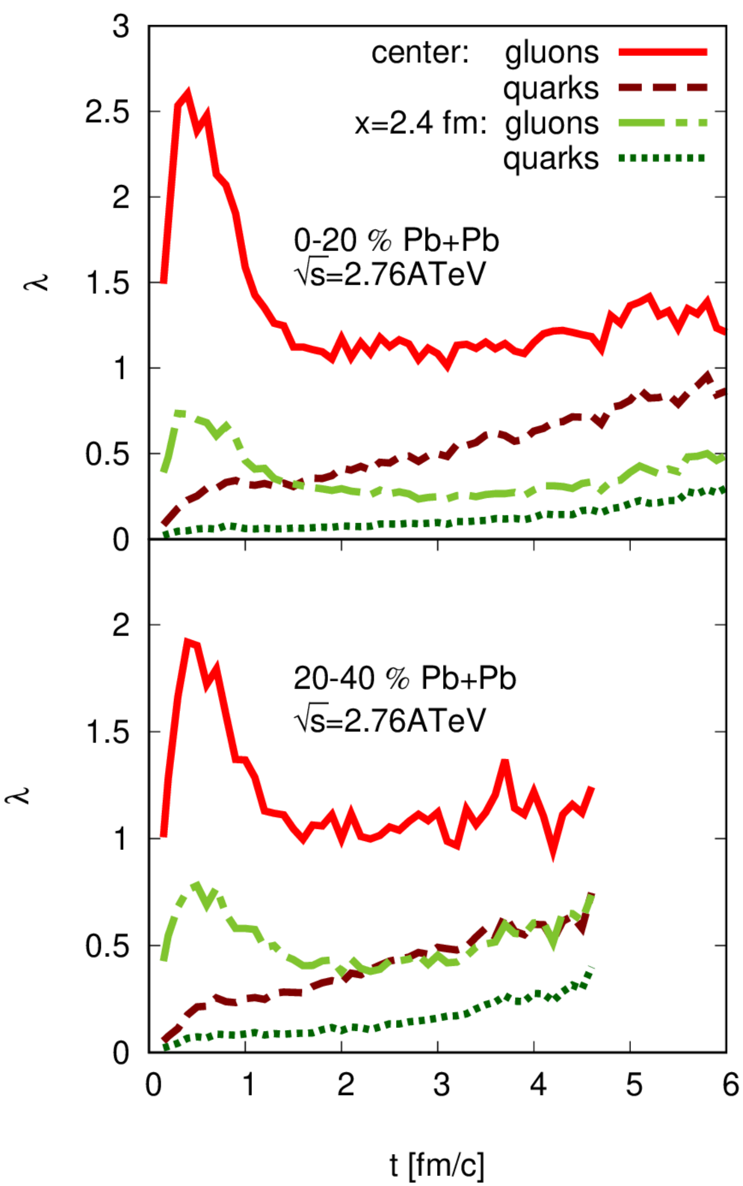
Thermodynamic Evolution



Chemical Evolution

Fugacity $\lambda = n/n_{\mathrm{eq.}}$
at midrapidity





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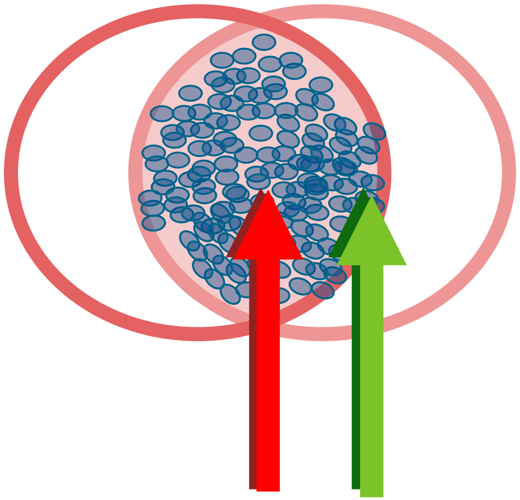
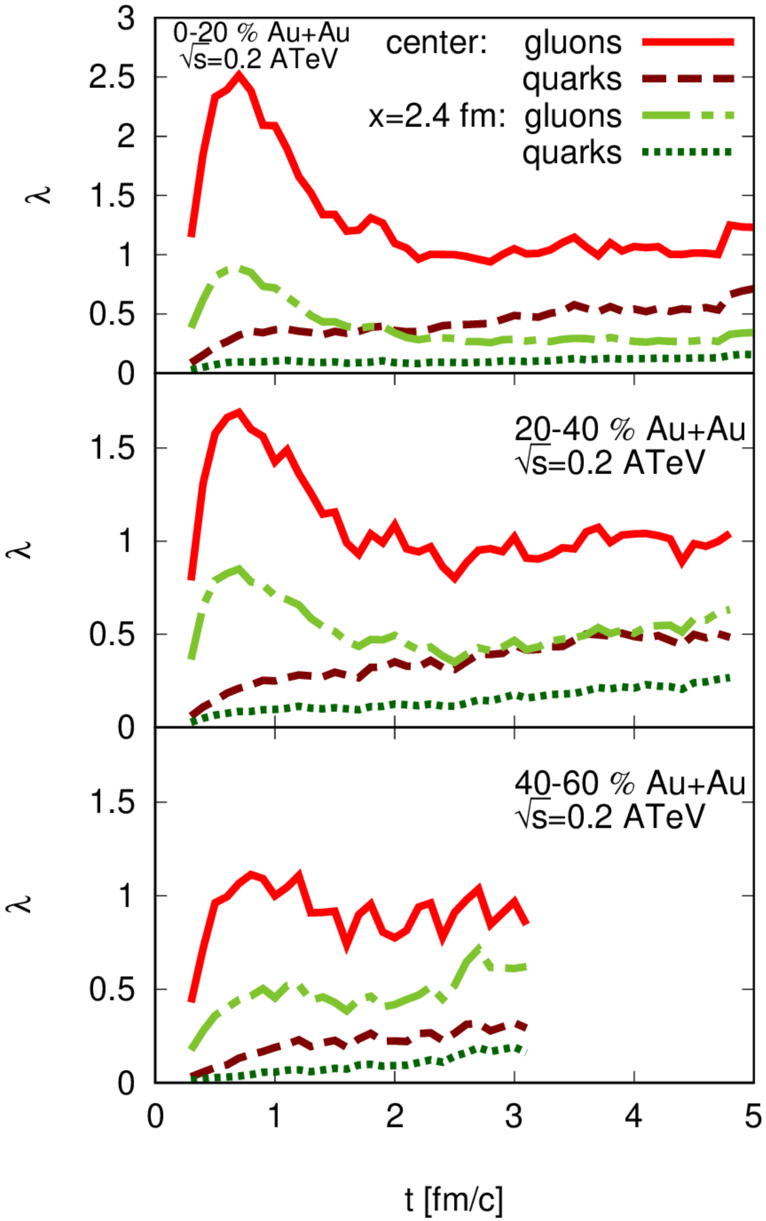
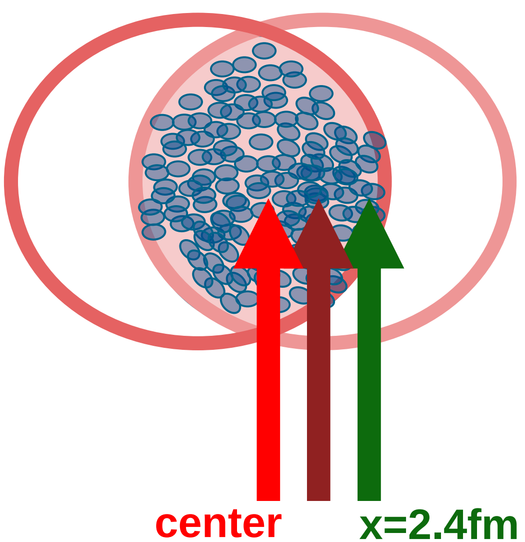
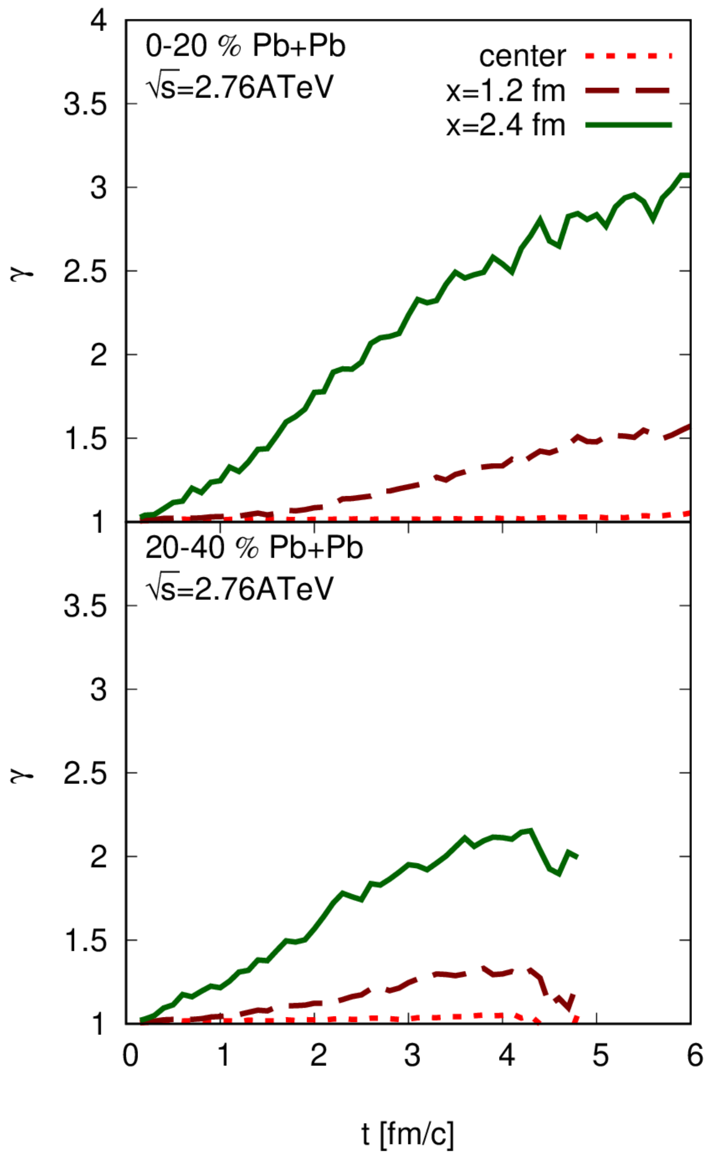




Dynamic Evolution

Velocity (Boost) at midrapidity





Dynamic Evolution

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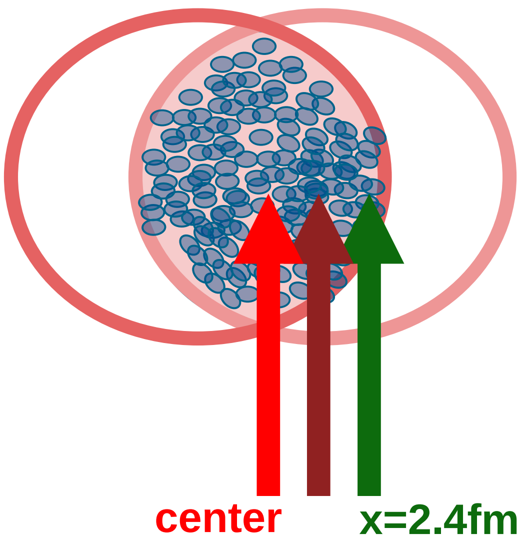
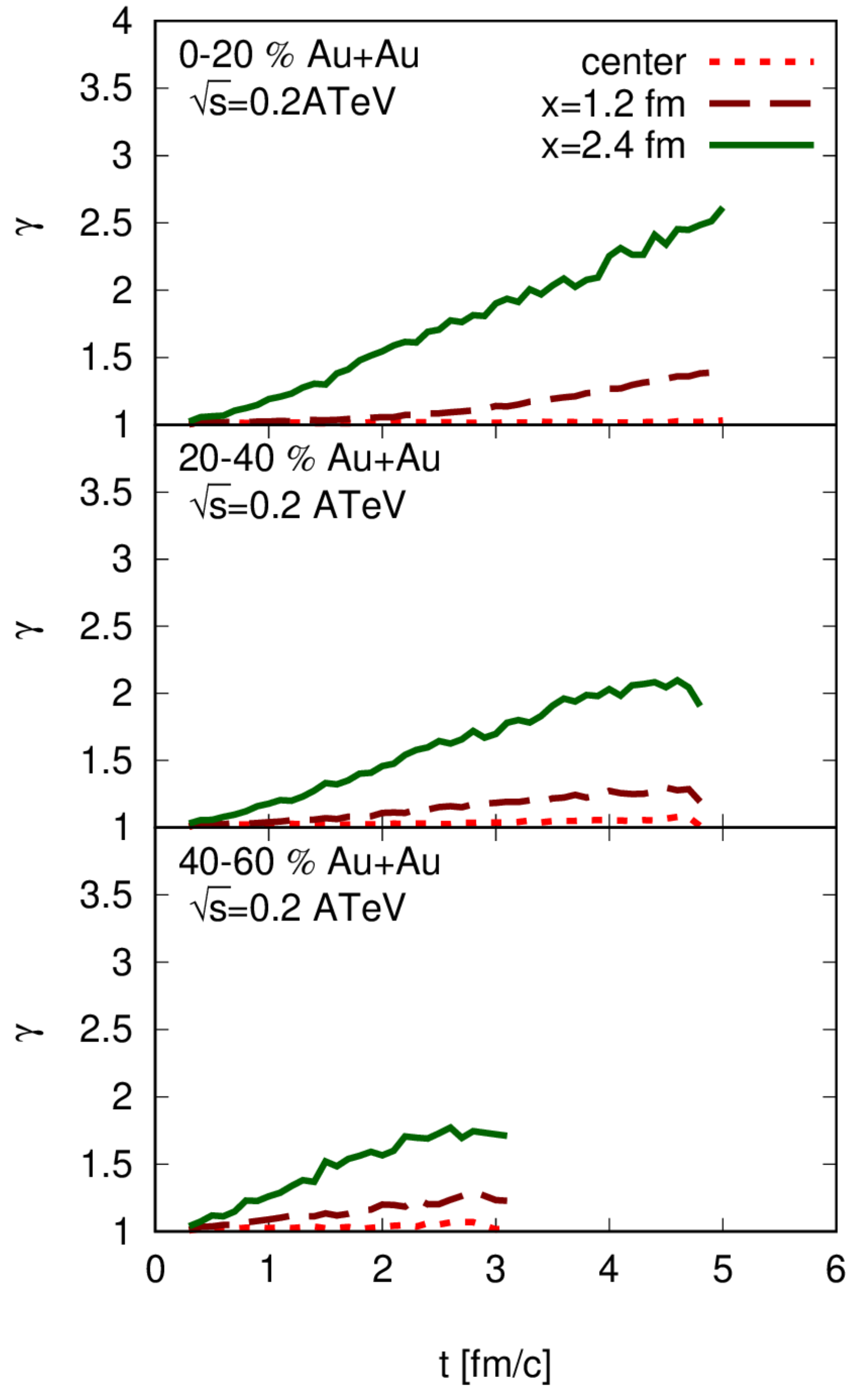
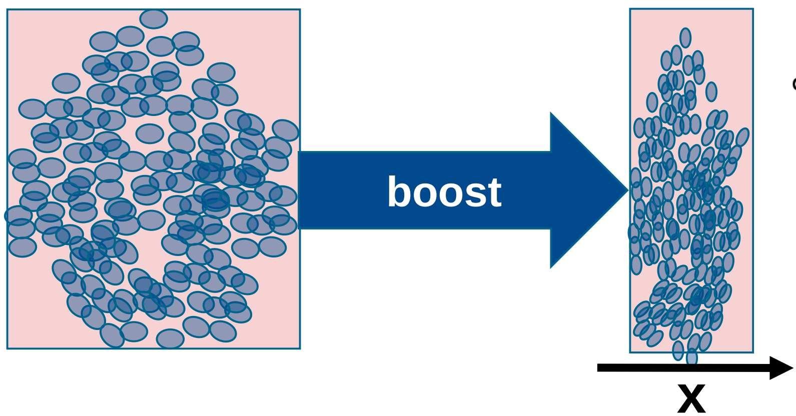


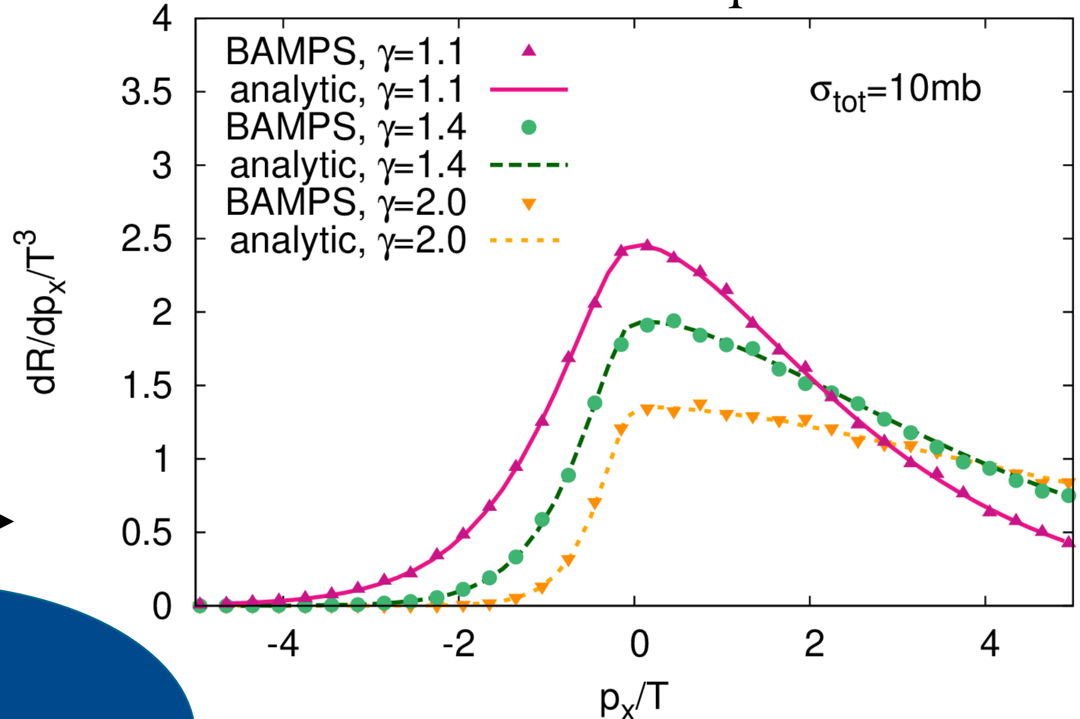


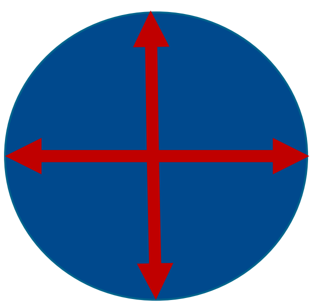
Velocity – Elliptic flow relation

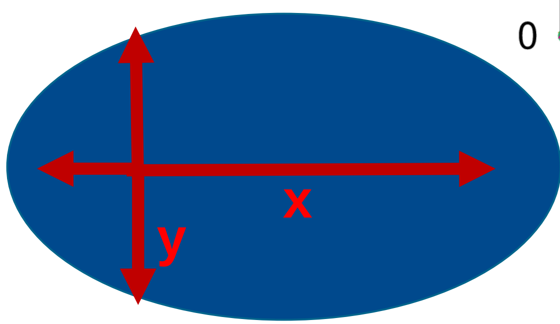
$$v_2 = (p_x^2 - p_y^2)/(p_x^2 + p_y^2)$$



Production rate of particles







momentum distribution isotropic

momentum distribution deformed

$$\gamma = 2 \rightarrow v_2 \sim 0.5$$

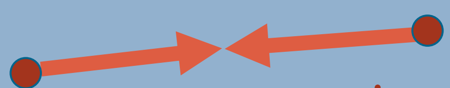
$$\gamma = 1.1 \rightarrow v_2 \sim 0.1$$

(R=Production rate dN/dV/dt [GeV^4])

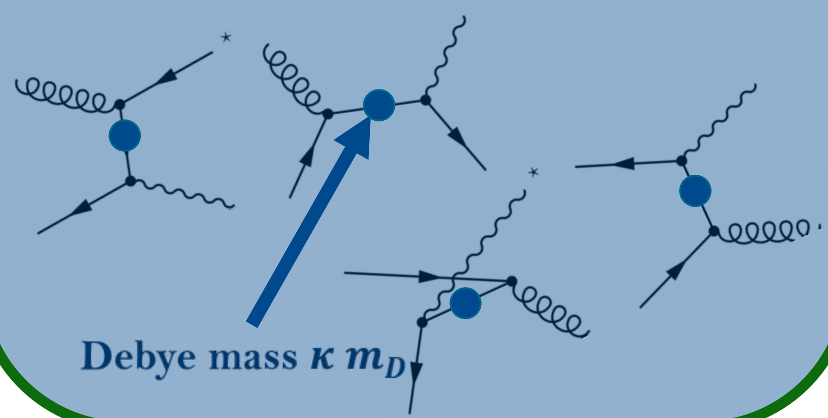
Photon production in BAMPS

2←→2 scattering

Diagrams, microscopic collisions



2-2 cross sections, tuned to HTL rate (via Debye mass)

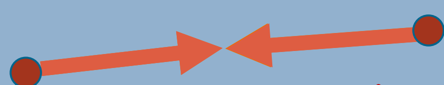


MG. et al., Phys.Rev. C95, 054903, 2017

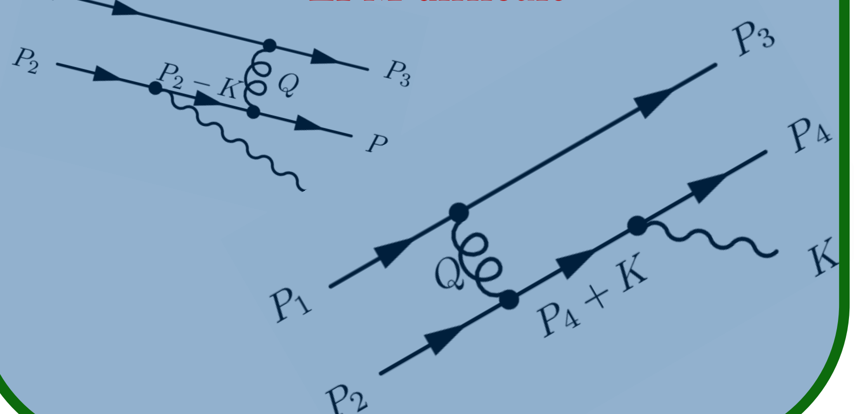
Photon production in BAMPS

2→3 scattering: two independent methods

Diagrams, microscopic collsisions



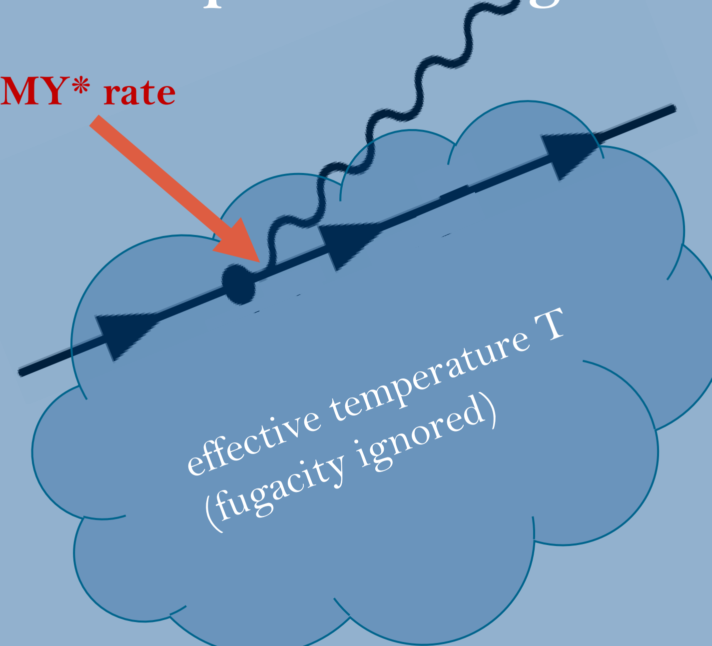
2-3 cross sections,
tuned to AMY,
LPM difficult



MG. et al., Phys.Rev. C95, 054903, 2017

Rate approach „microscopic“ coarse graining

AMY* rate



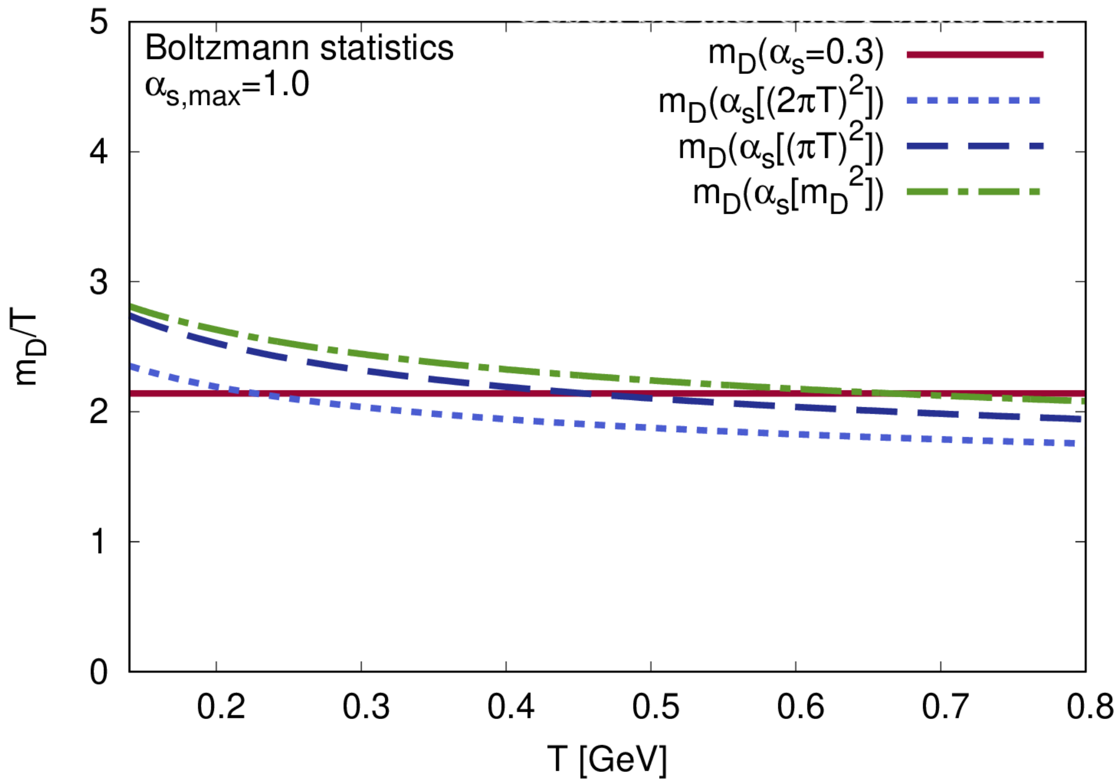
*** Arnold, Moore, Yaffe, JHEP 0112 (2001) 009**

22 photoproduction under control

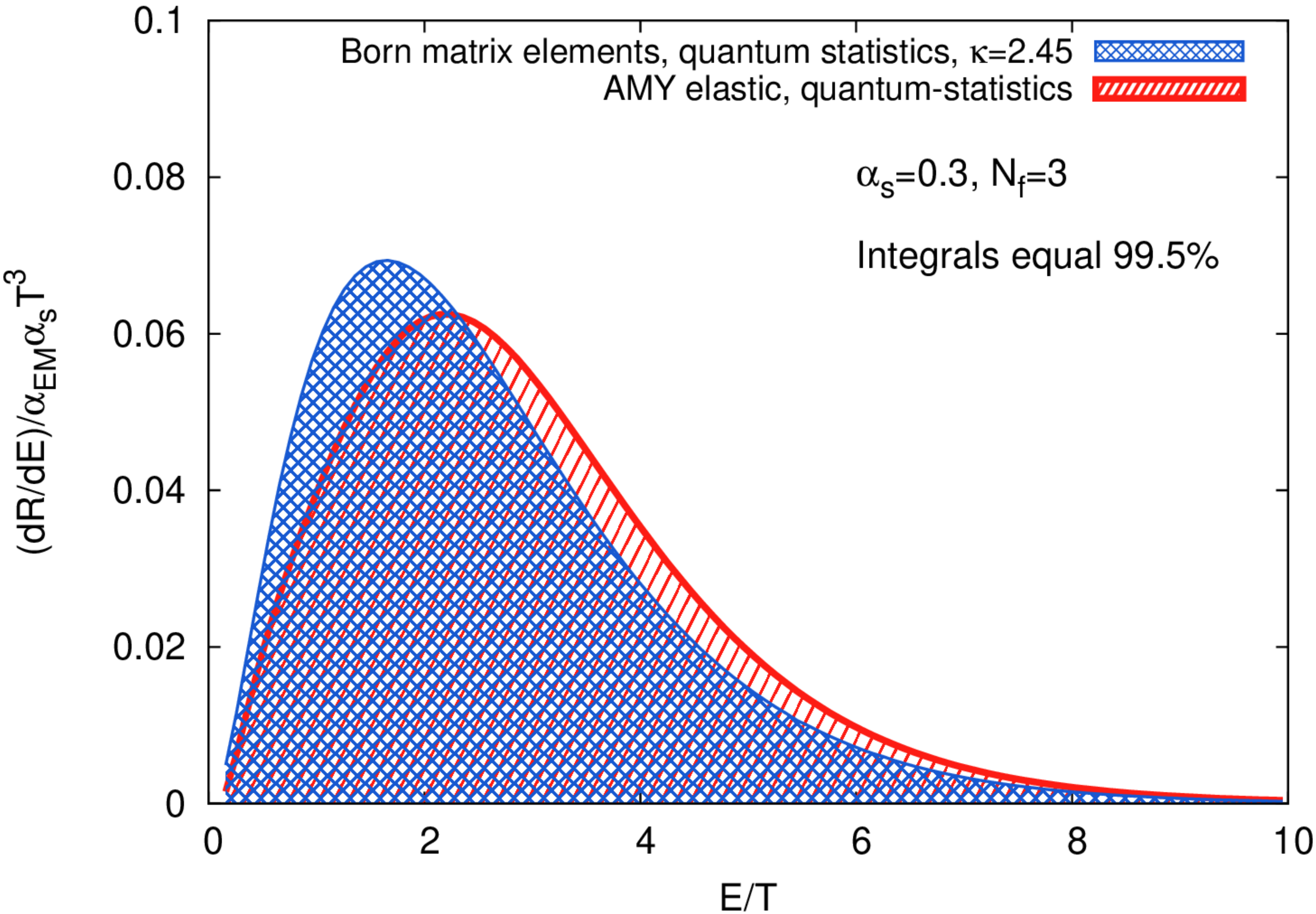
1.) Naive screening with Debye mass: $\frac{1}{t^2} \rightarrow \frac{1}{(t-m_D^2)^2}$

2.) tune Debye mass: $m_D^2 \rightarrow \kappa m_D^2$

3.) tune overall ME
(missing quantum statistics): $|\mathcal{M}|^2 \rightarrow C_{\text{stat}}|\mathcal{M}|^2$



22 photoproduction under control



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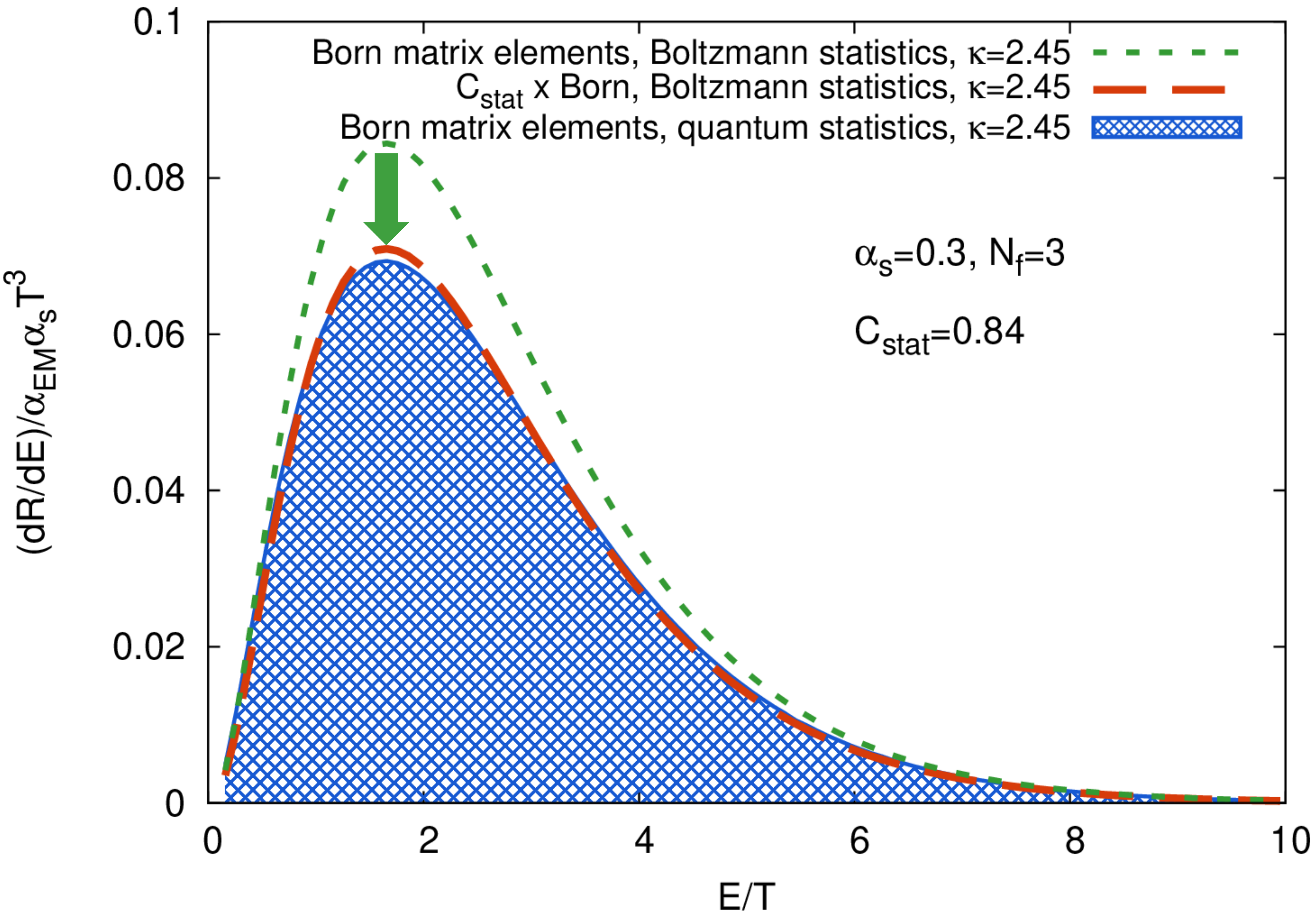

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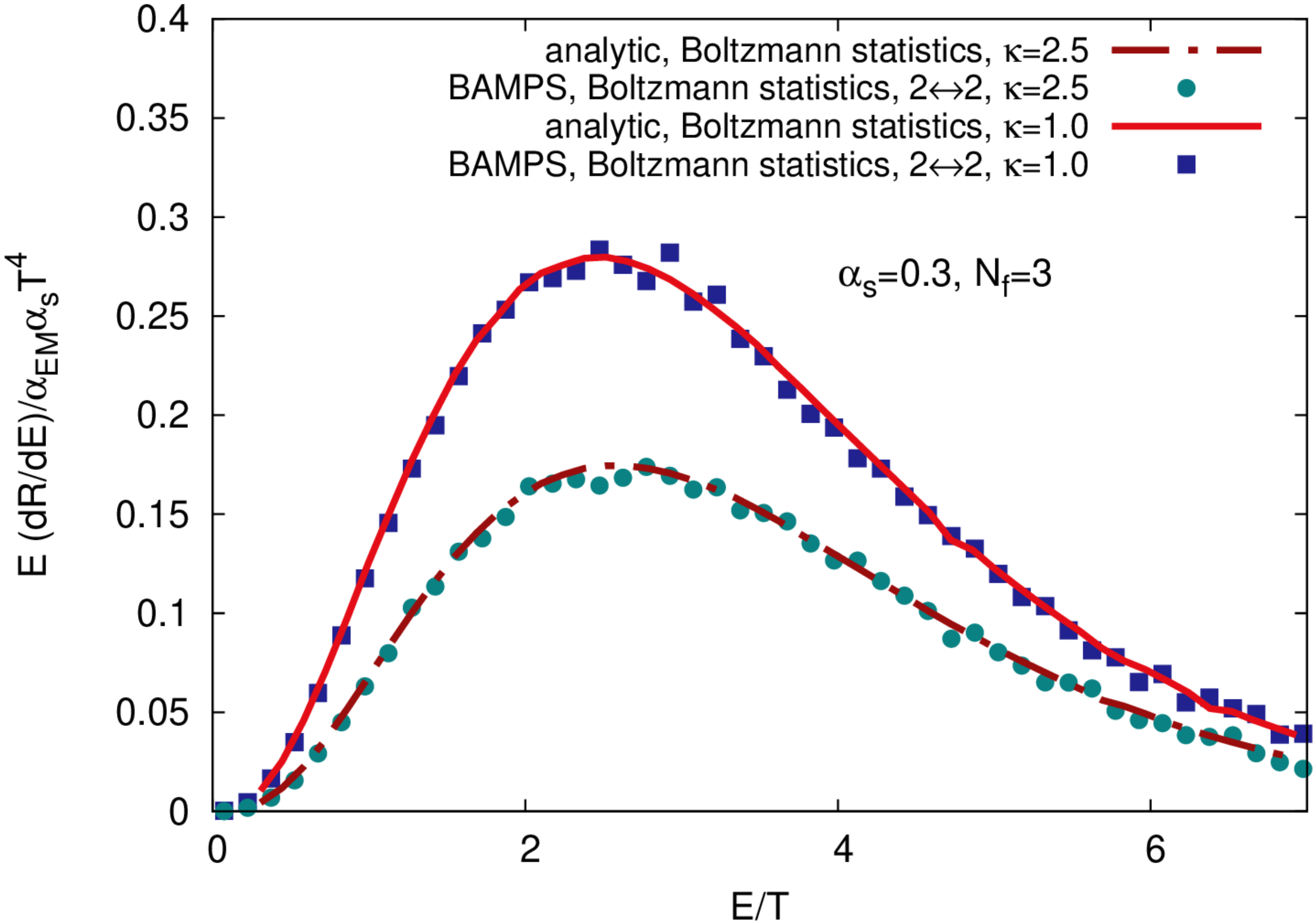

Photon production in BAMPS

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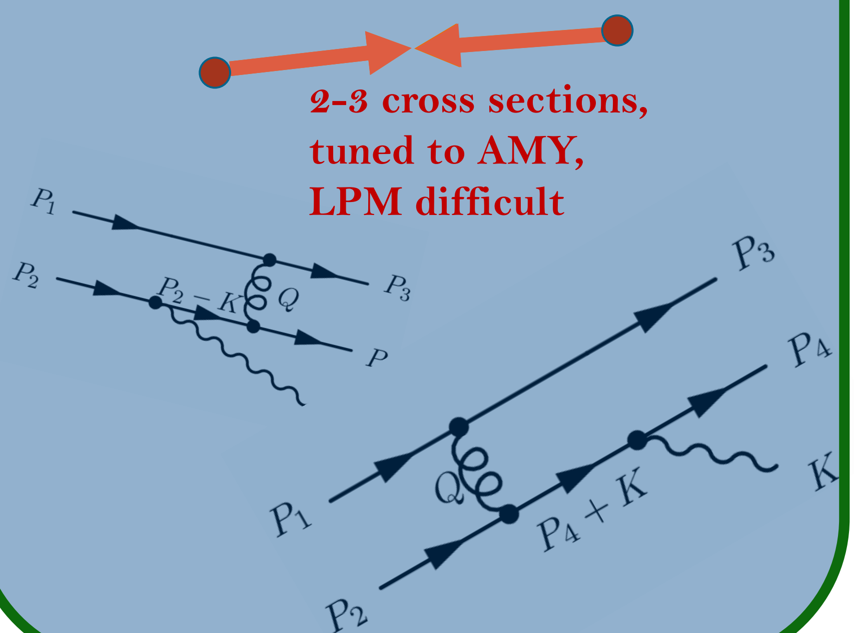
2→3 scattering: two independent methods

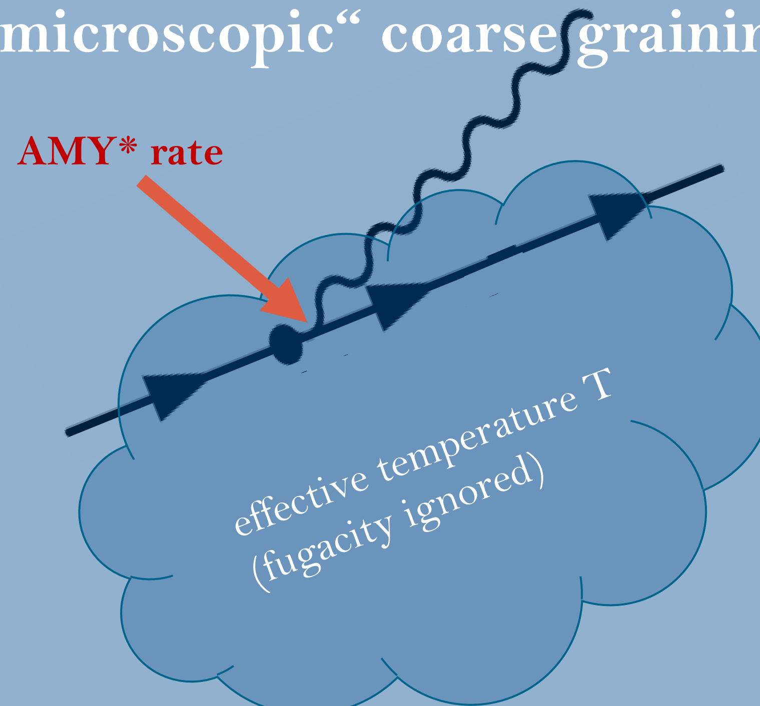
Method 1

Diagrams, microscopic collsisions

2-3 cross sections, tuned to AMY, LPM difficult



Rate approach „microscopic“ coarse graining



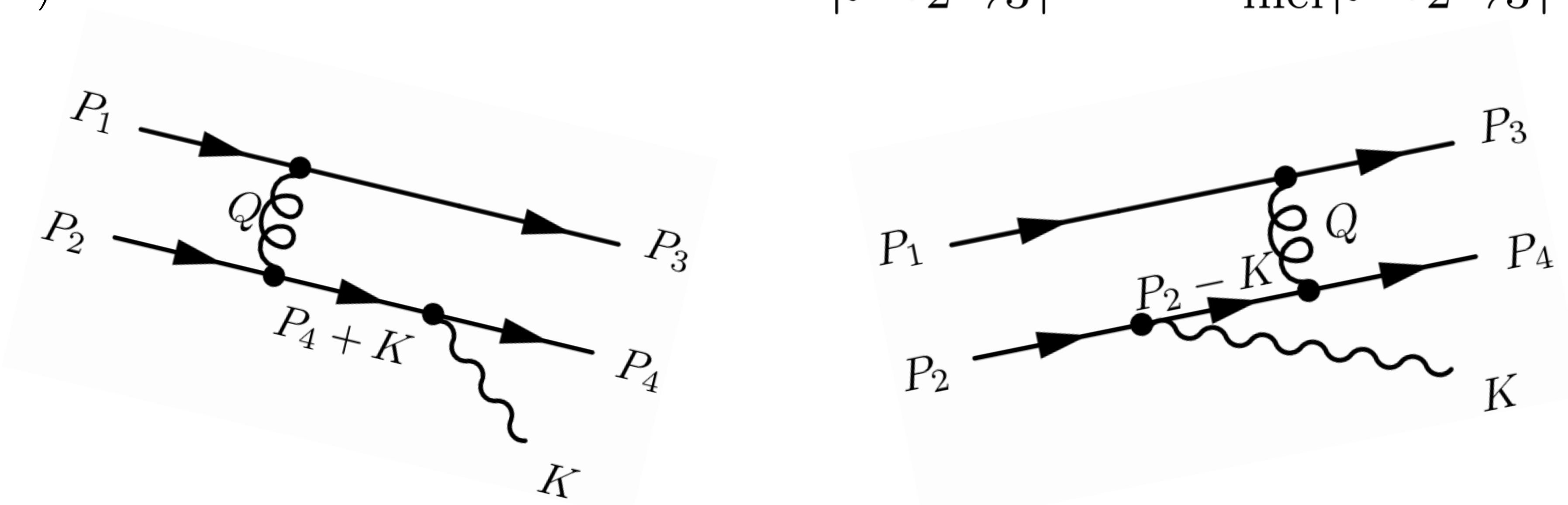
* Arnold, Moore, Yaffe, JHEP 0112 (2001) 009

2->3 photoproduction under control

1.) Naive screening with Debye mass: $\frac{1}{t^2} \rightarrow \frac{1}{(t-m_D^2)^2}$

2.) simple LPM model: $|\mathcal{M}_{2\rightarrow 3}|^2 \rightarrow \Theta(\lambda - \tau_{\text{form}})|\mathcal{M}_{2\rightarrow 3}|^2$

3.) tune overall Matrix element: $|\mathcal{M}_{2\rightarrow 3}|^2 \rightarrow K_{\text{inel}}|\mathcal{M}_{2\rightarrow 3}|^2$

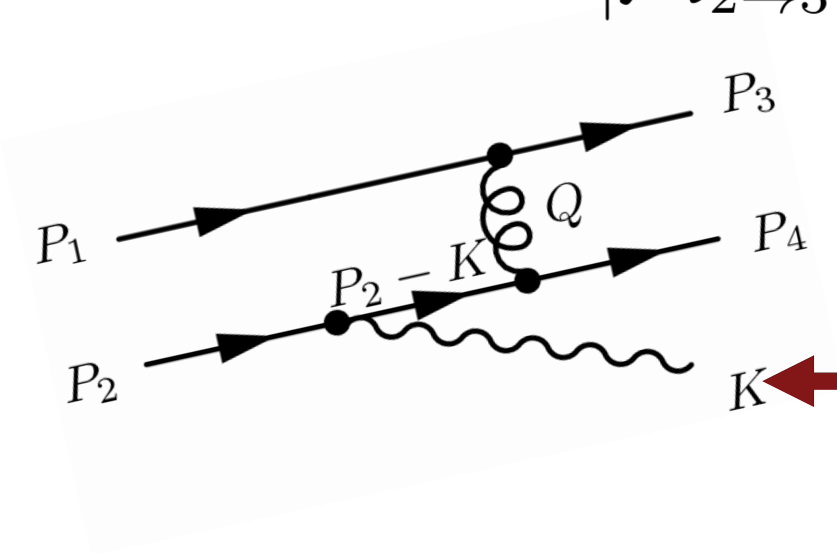


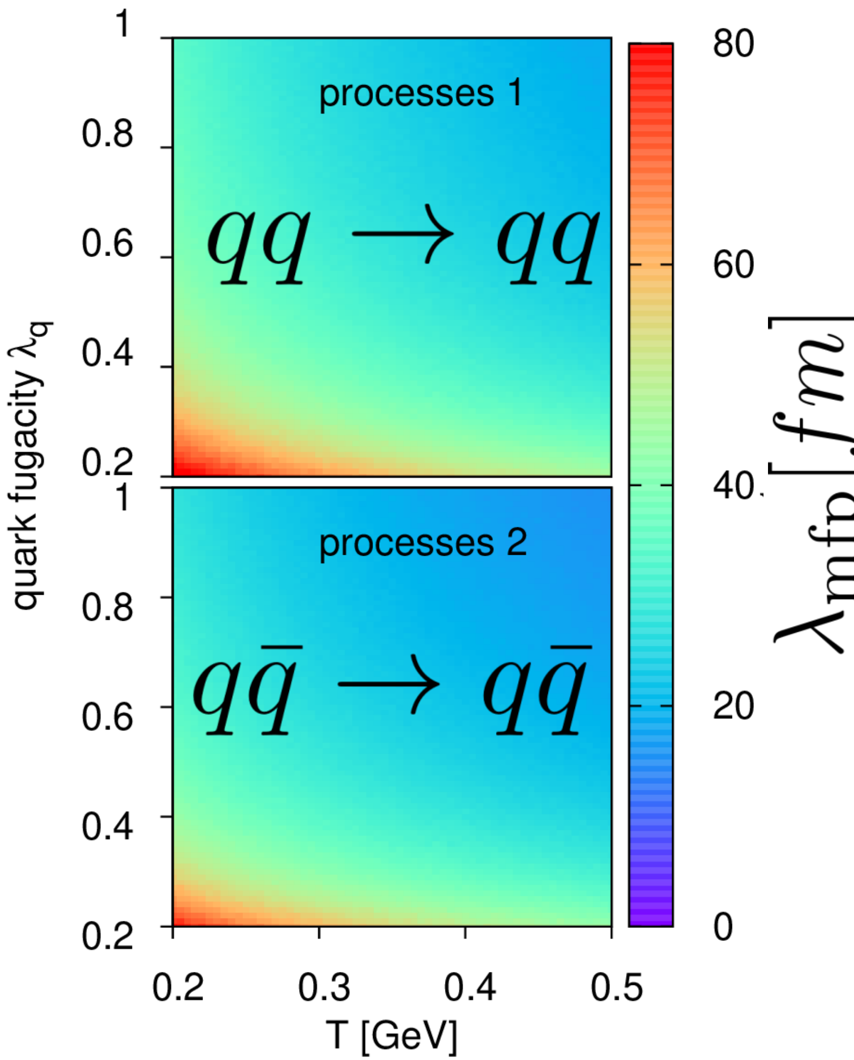
- Numeric integration for total cross section
- Multi-dimensional Metropolis sampling for differential cross section

MG. et al., Phys.Rev. C95, 054903, 2017

2->3 photoproduction under control

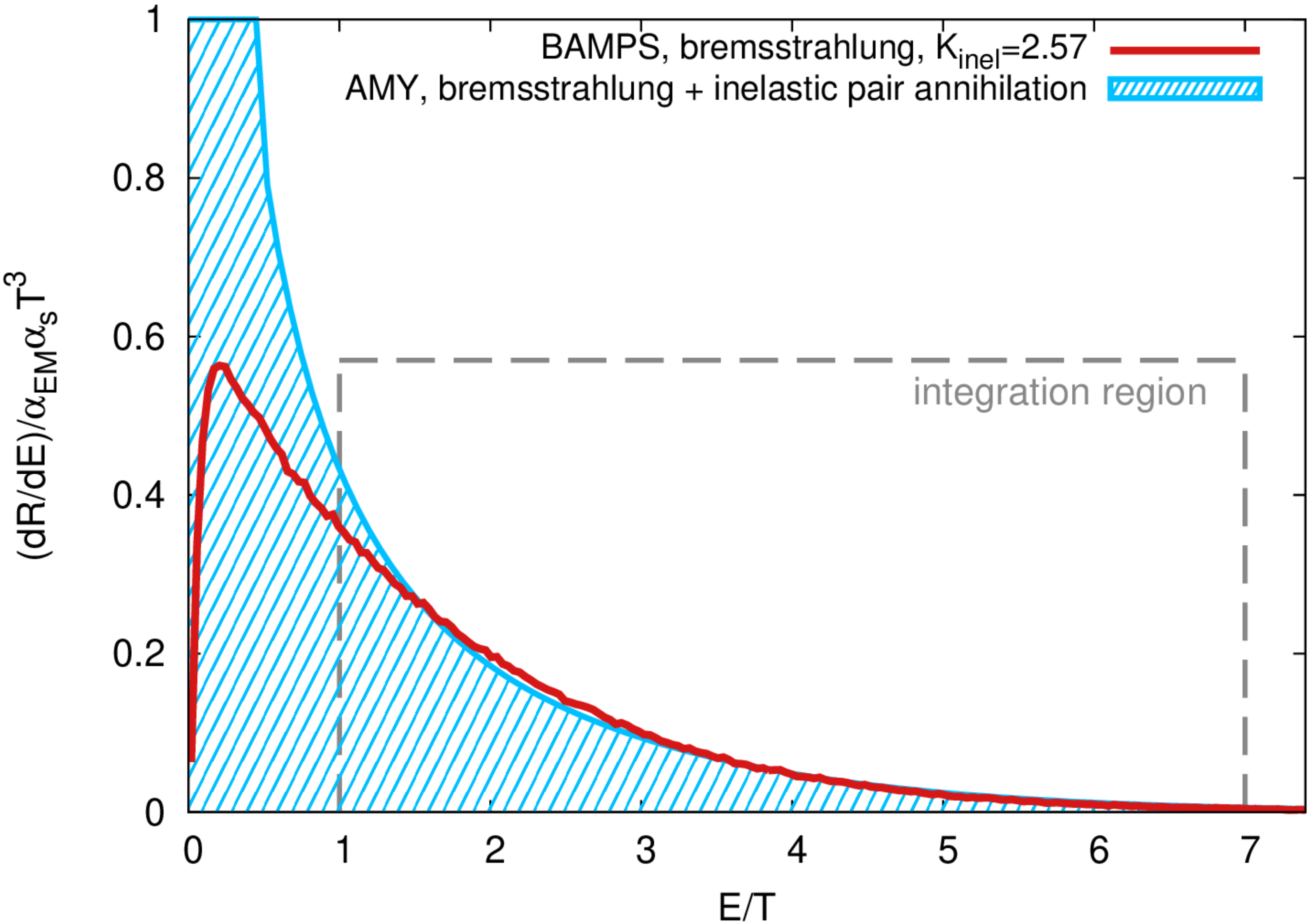
simple LPM model: $|\mathcal{M}_{2\to3}|^2 \to \Theta(\lambda_{\mathrm{mfp}} - \tau_{\mathrm{form}})|\mathcal{M}_{2\to3}|^2$





- Formation time of photon $\tau = k_T^{-1}$
- Mean-free path of corresponding processes, T and fugacity dependent

2->3 photoproduction under control



2->3 photoproduction under control

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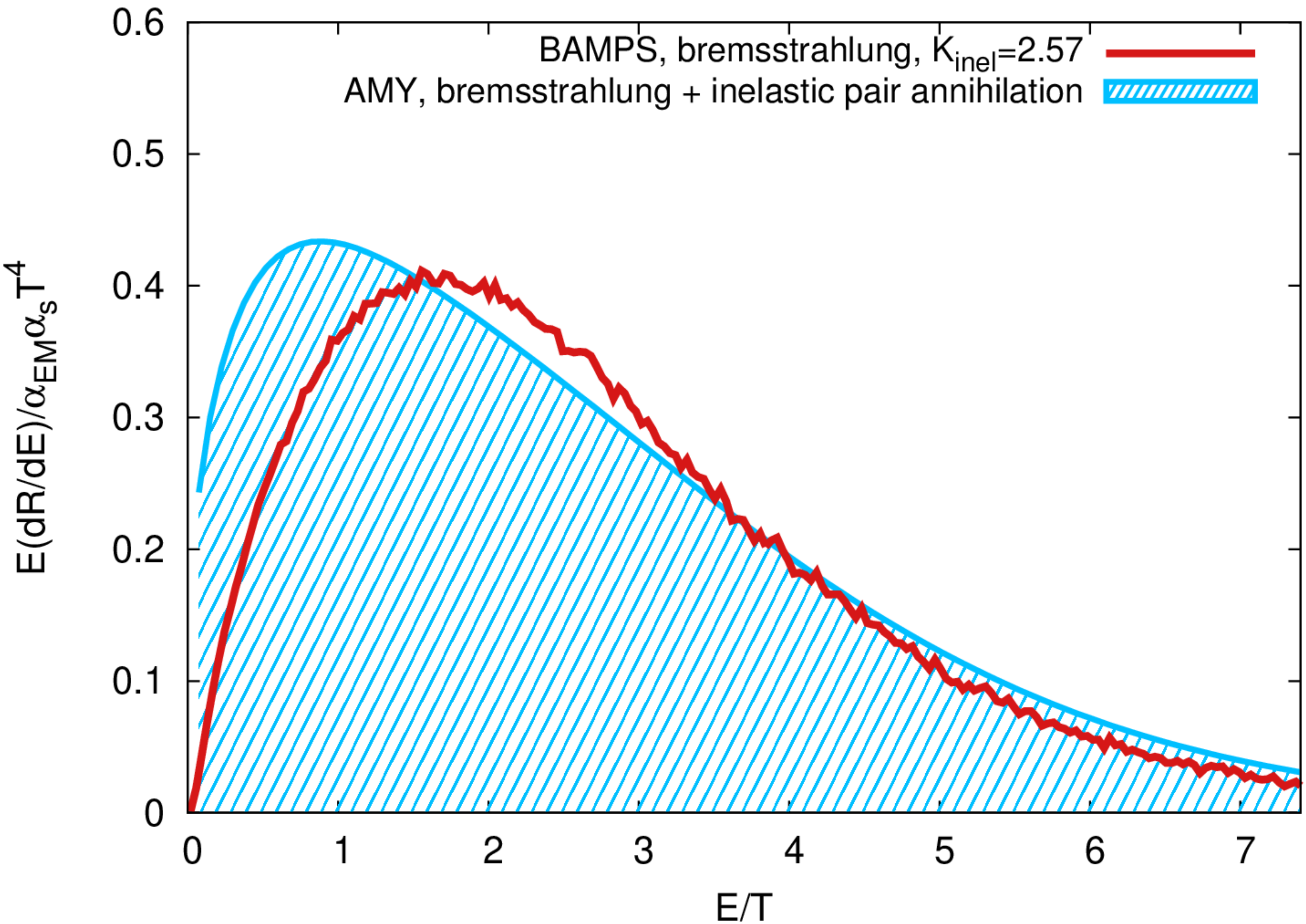

Photon production in BAMPS

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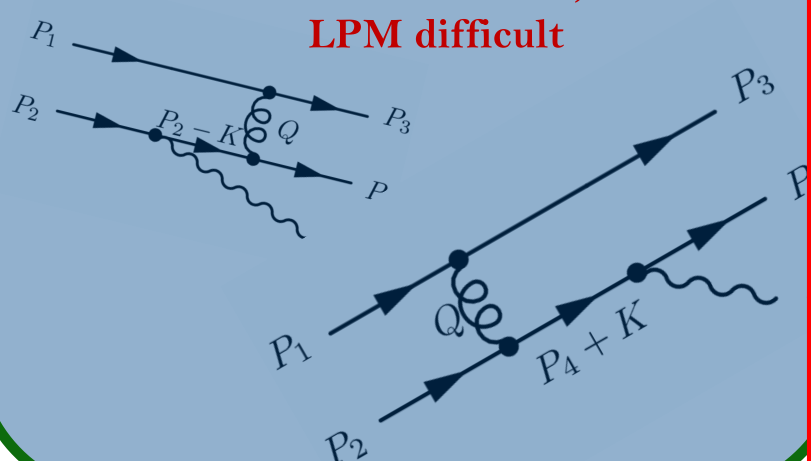
2→3 scattering: two independent methods

Method 2

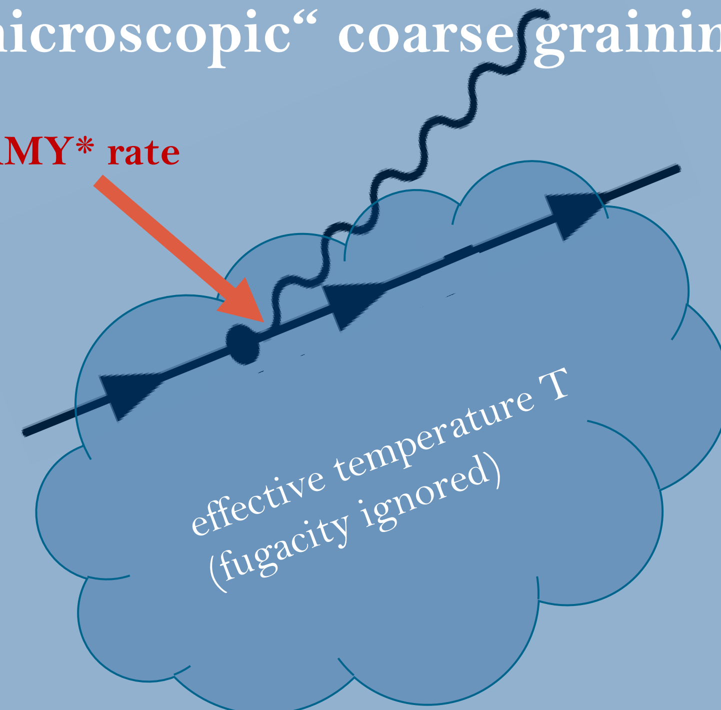
Diagrams, microscopic collsisions

2-3 cross sections, tuned to AMY, LPM difficult



Rate approach „microscopic“ coarse graining

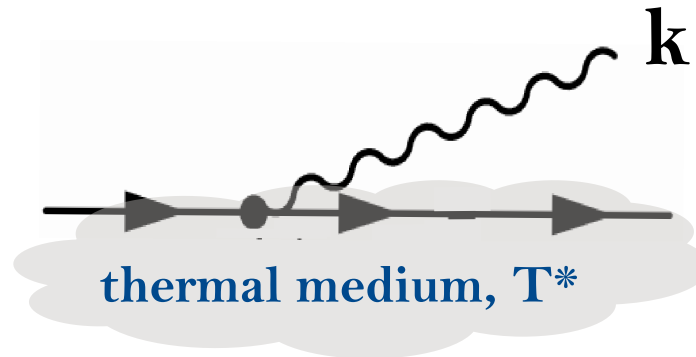
AMY* rate



* Arnold, Moore, Yaffe, JHEP 0112 (2001) 009

AMY rate for photon emission of quark

massless quark, momentum P



Rate dN/dtdk for emission, at temperature T:

$$\frac{\mathrm{d}\Gamma_f^{\gamma}(p,k,T)}{\mathrm{d}k} = \frac{q_f^2}{e^2}\frac{\alpha_{EM}k^4}{4p^7}\left[1-f_F(p-k)\right]\frac{1+(1-x)^2}{x^3(1-x)^2}\int\frac{\mathrm{d}^2\vec{p}_\perp}{(2\pi)^2}2\vec{p}_\perp\cdot \mathrm{Re}\vec{f}(\vec{p}_\perp,p,k)$$

AMY Kernel

Arnold, Moore, Yaffe, JHEP 0206 (2002) 030

Solved via Differential Equation, cf. e.g. Aurenche, Gelis, Moore, Zaraket, JHEP 0212 (2002) 006
Courtesy to J.F. Paquet for help.

AMY rate for photon emission off a quark

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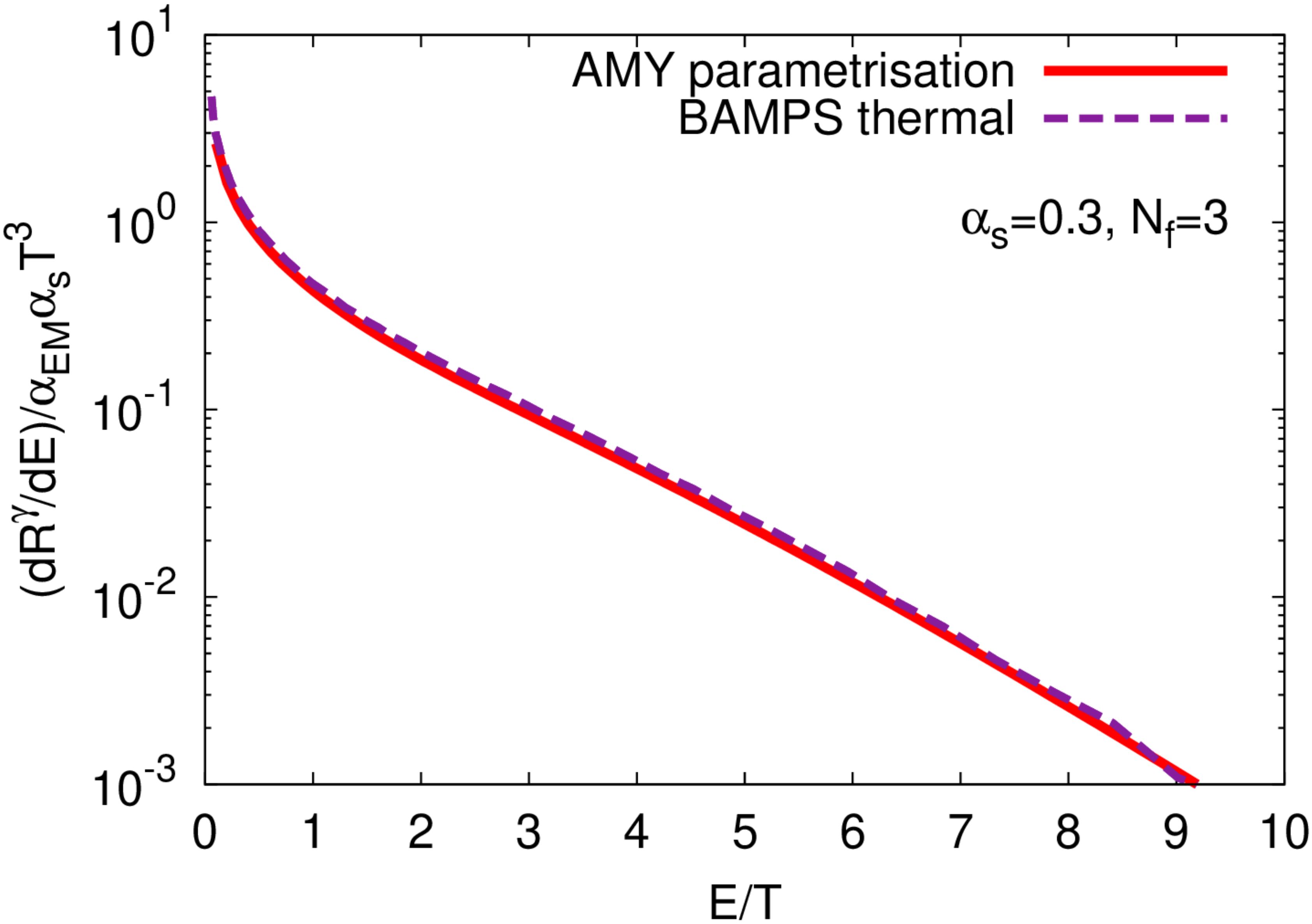

AMY rate for photon emission off a quark

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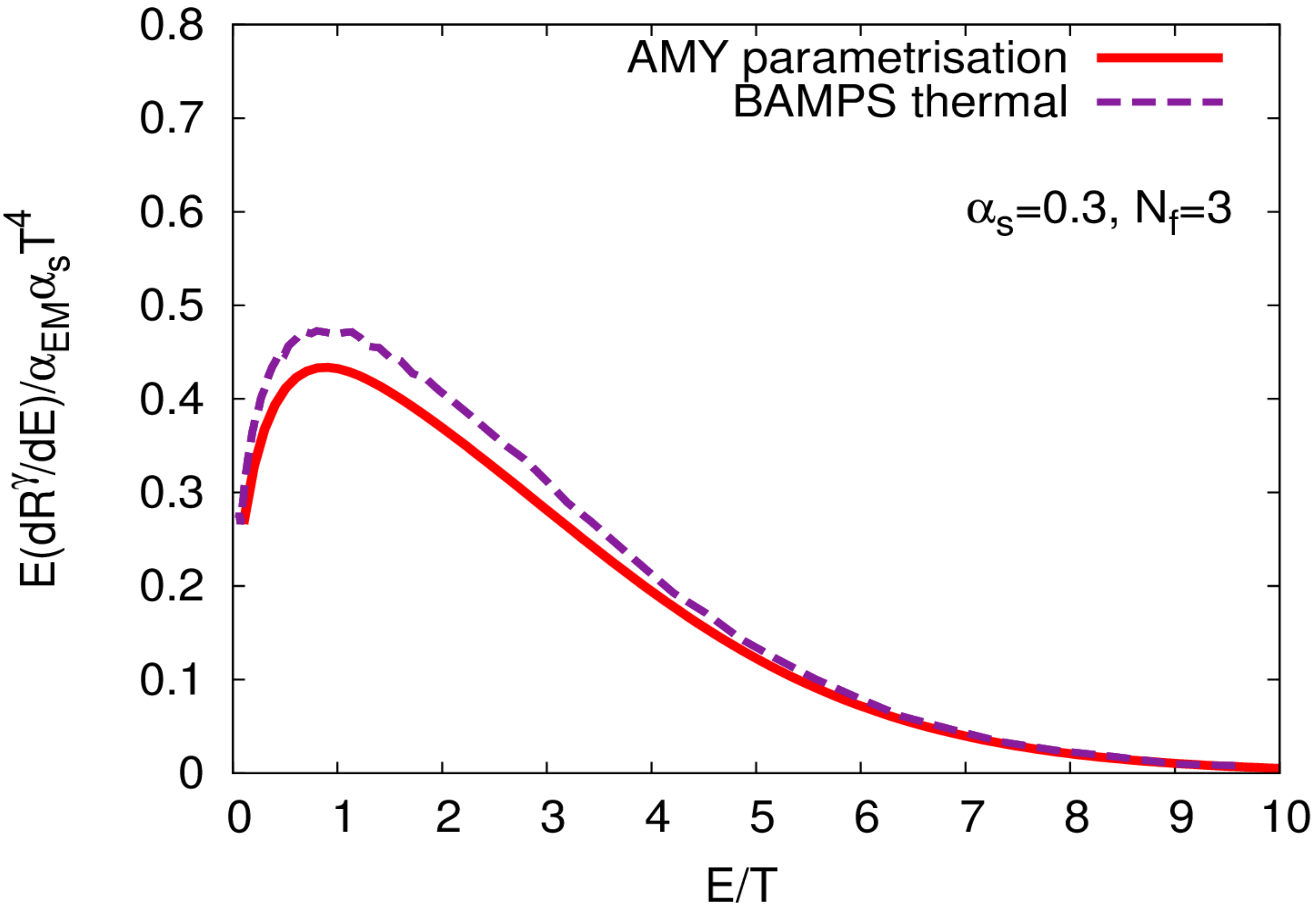


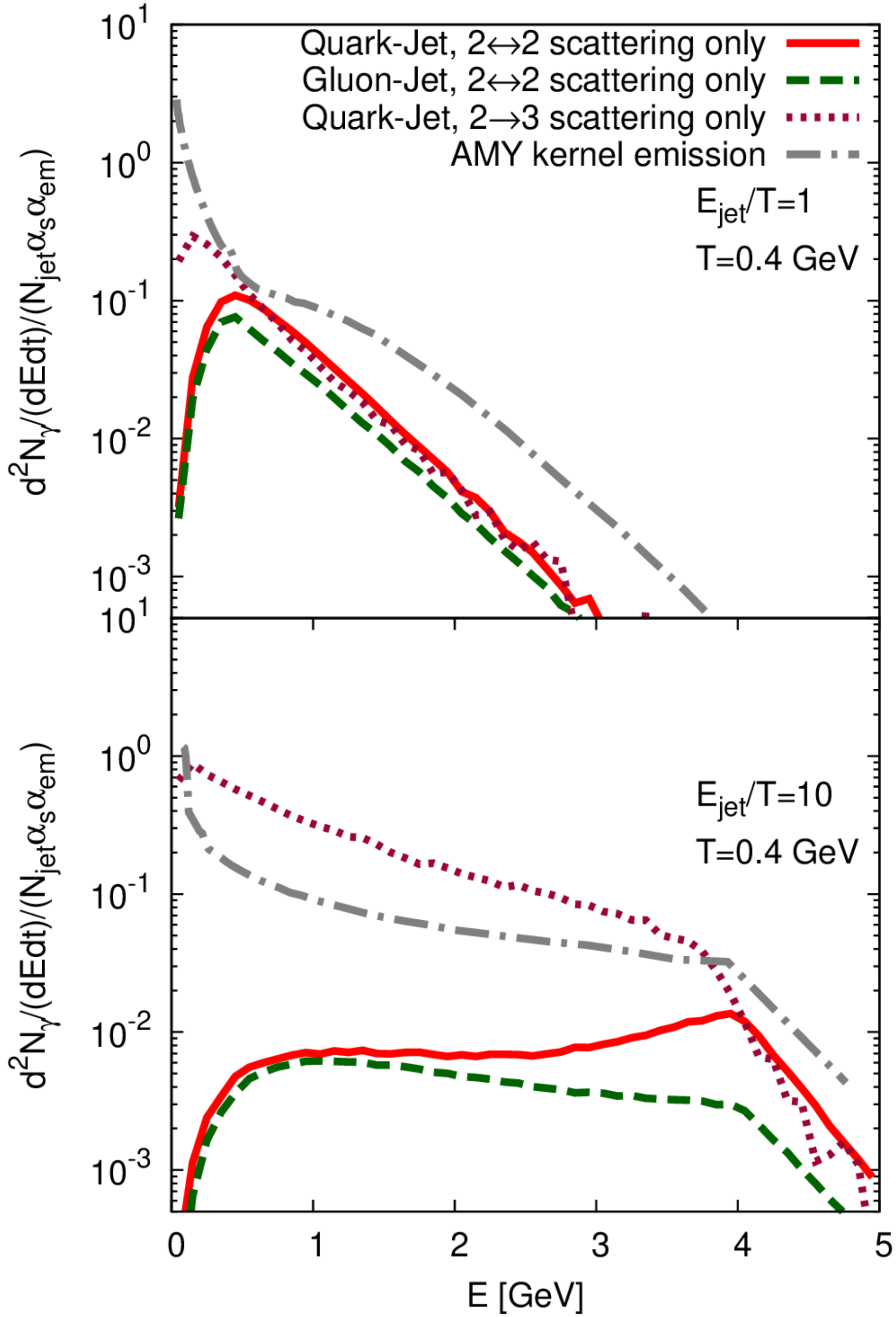
Differential kinematics

„Jet" = single particle responsible for emission

Quark-"jet"

vs.

Gluon-"jet"



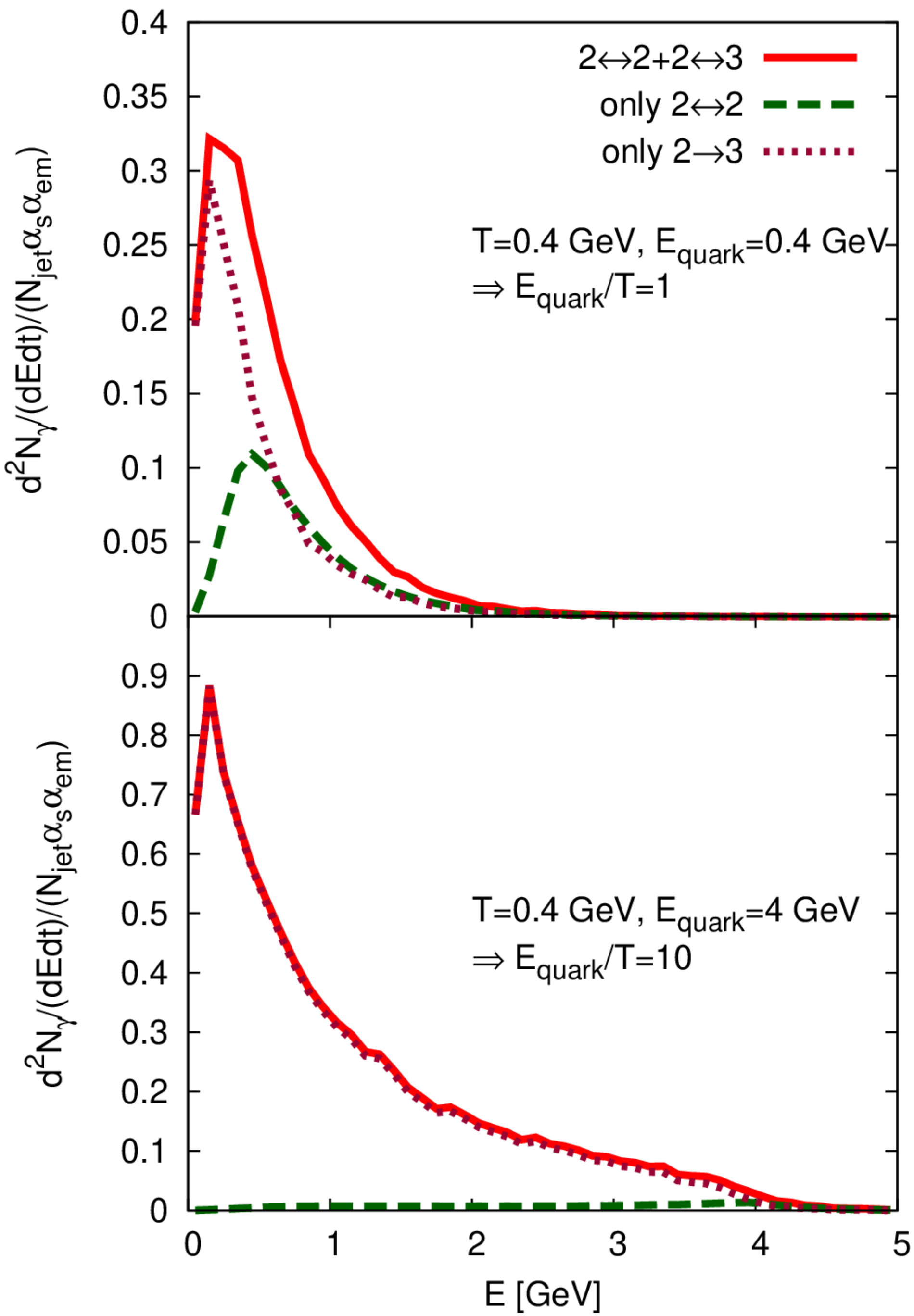
Differential kinematics

„Jet“ = single particle responsible for emission

2 → 3

vs.

2 → 2

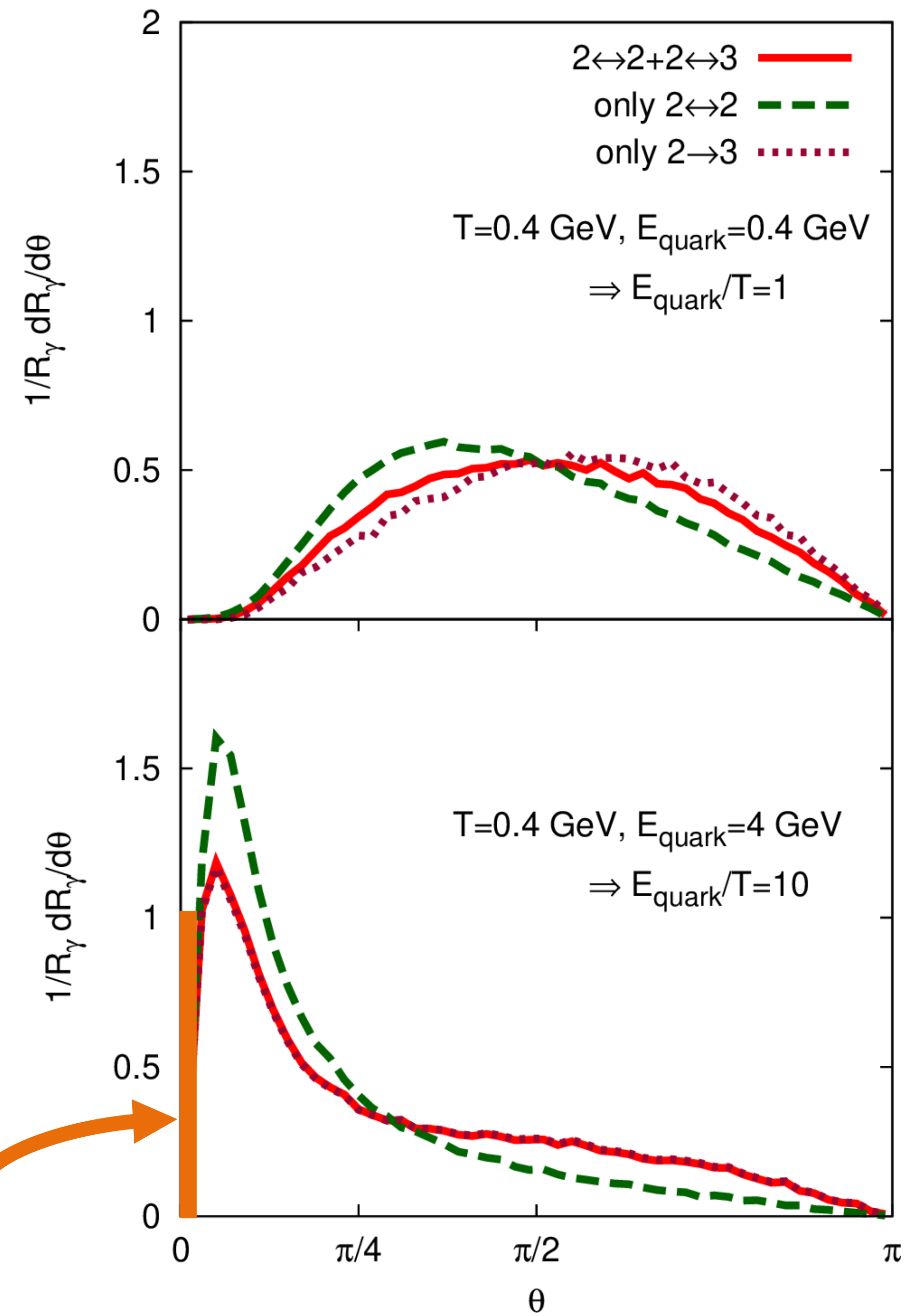


Differential kinematics

Emission angle $2 \rightarrow 3$

vs.

$2 \rightarrow 2$



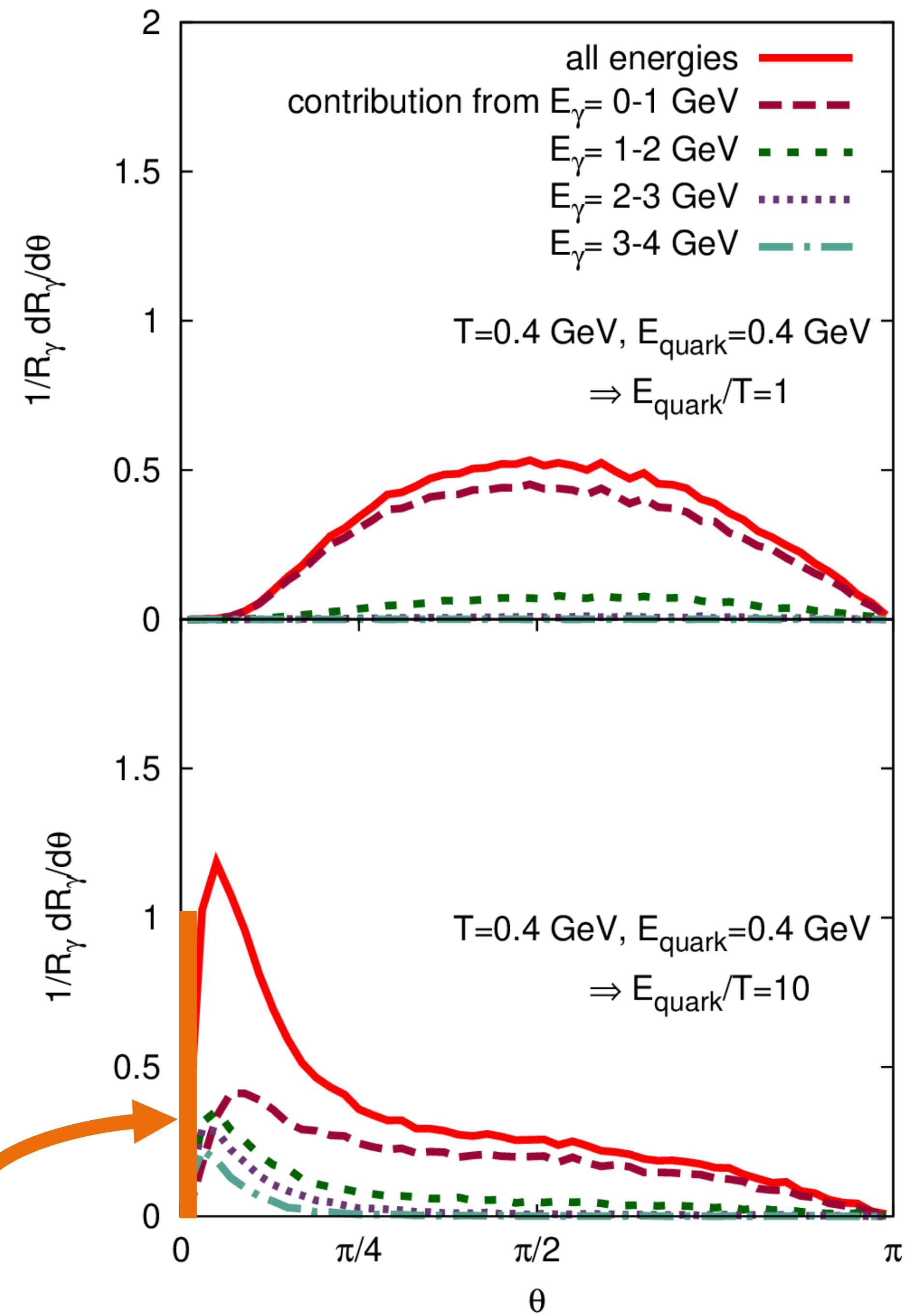
AMY exactly collinear

Differential kinematics

Emission angle @ different Photon energies

→ Higher photon energy – more collinear

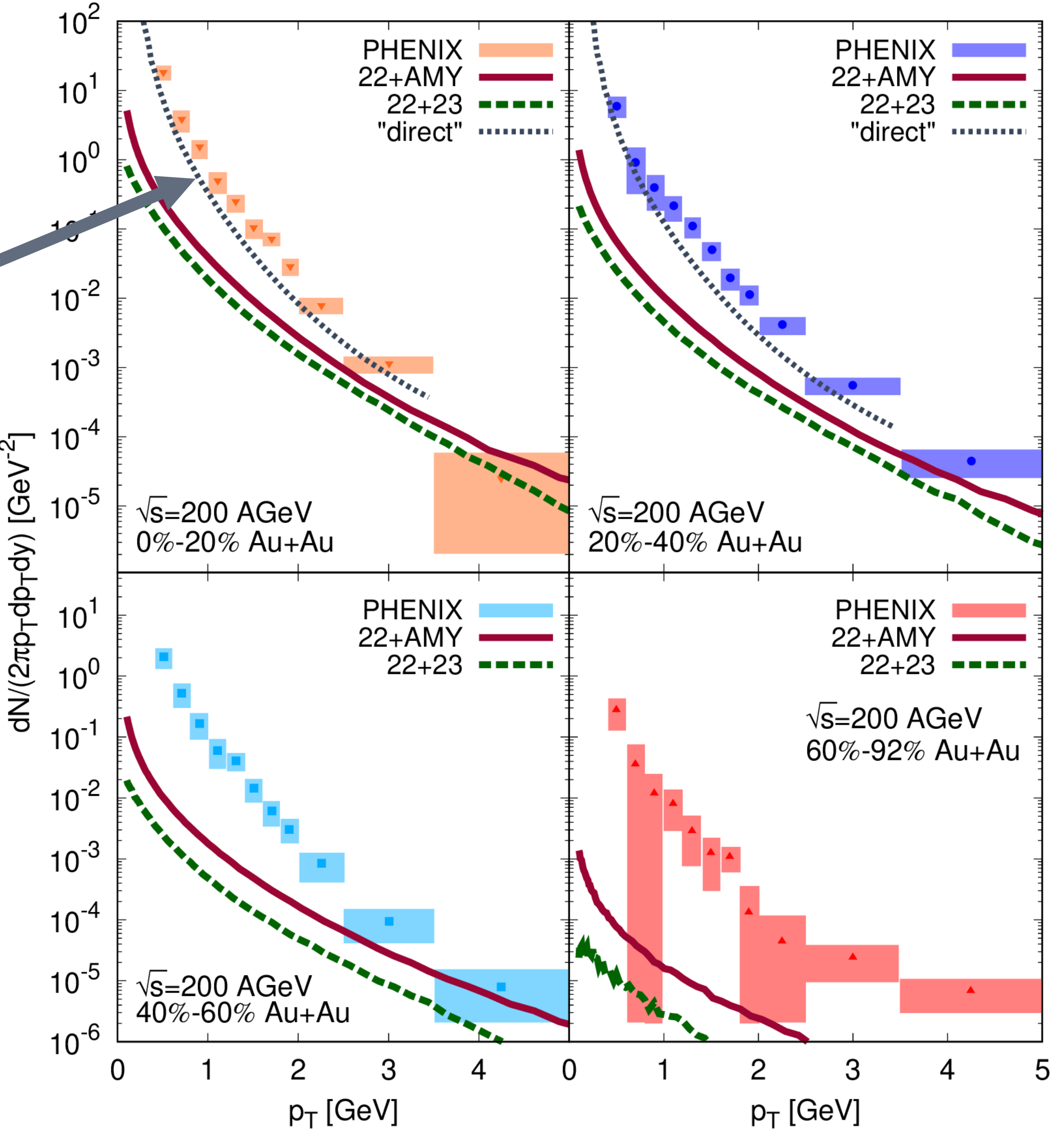
AMY exactly collinear



RHIC

„direct" = prompt + BAMPS AMY (QGP) + MUSIC (Hadron gas)

(MUSIC results from Paquet et al., Phys.Rev. C93, 044906 (2016))

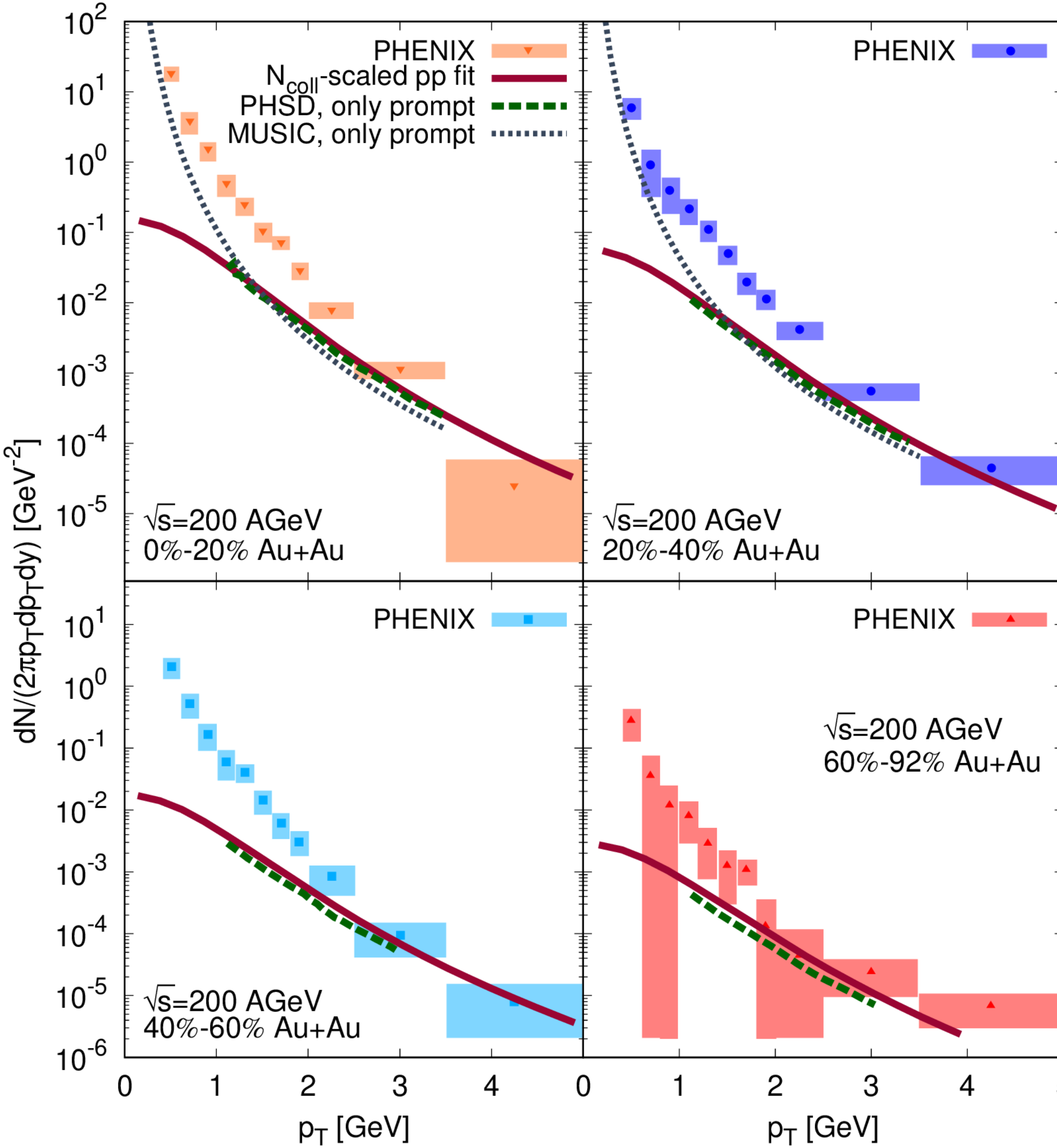


Heavy-ion collision

RHIC

Prompt contribution from literature

Paquet et al., Phys.Rev. C 93, 044906 (2016)
Linnyk et al., Phys.Rev. C 92, 054914 (2015)
PHENIX, Phys.Rev. C 91, 064904 (2015)



Heavy-ion collision

RHIC

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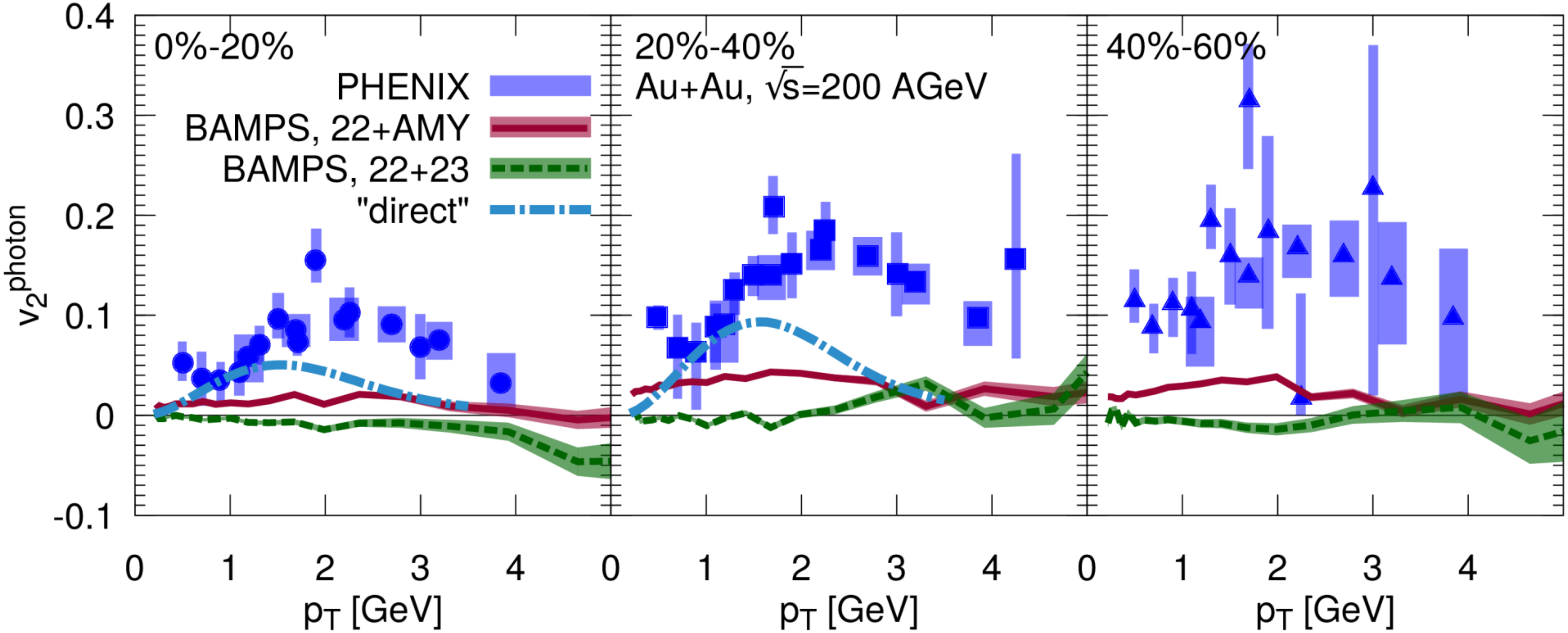
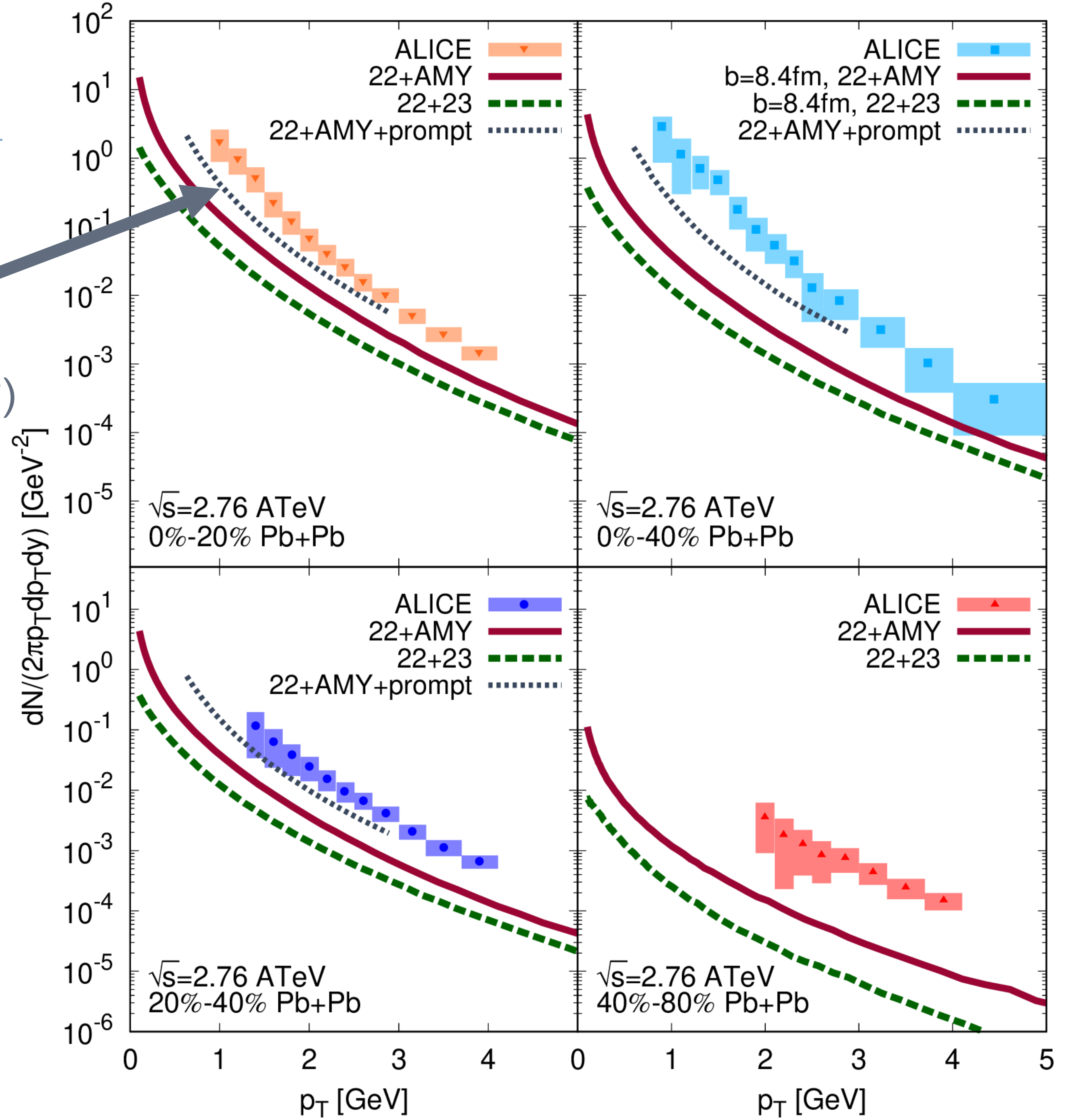


„direct“ = prompt + BAMPS AMY (QGP) + MUSIC (Hadron gas)

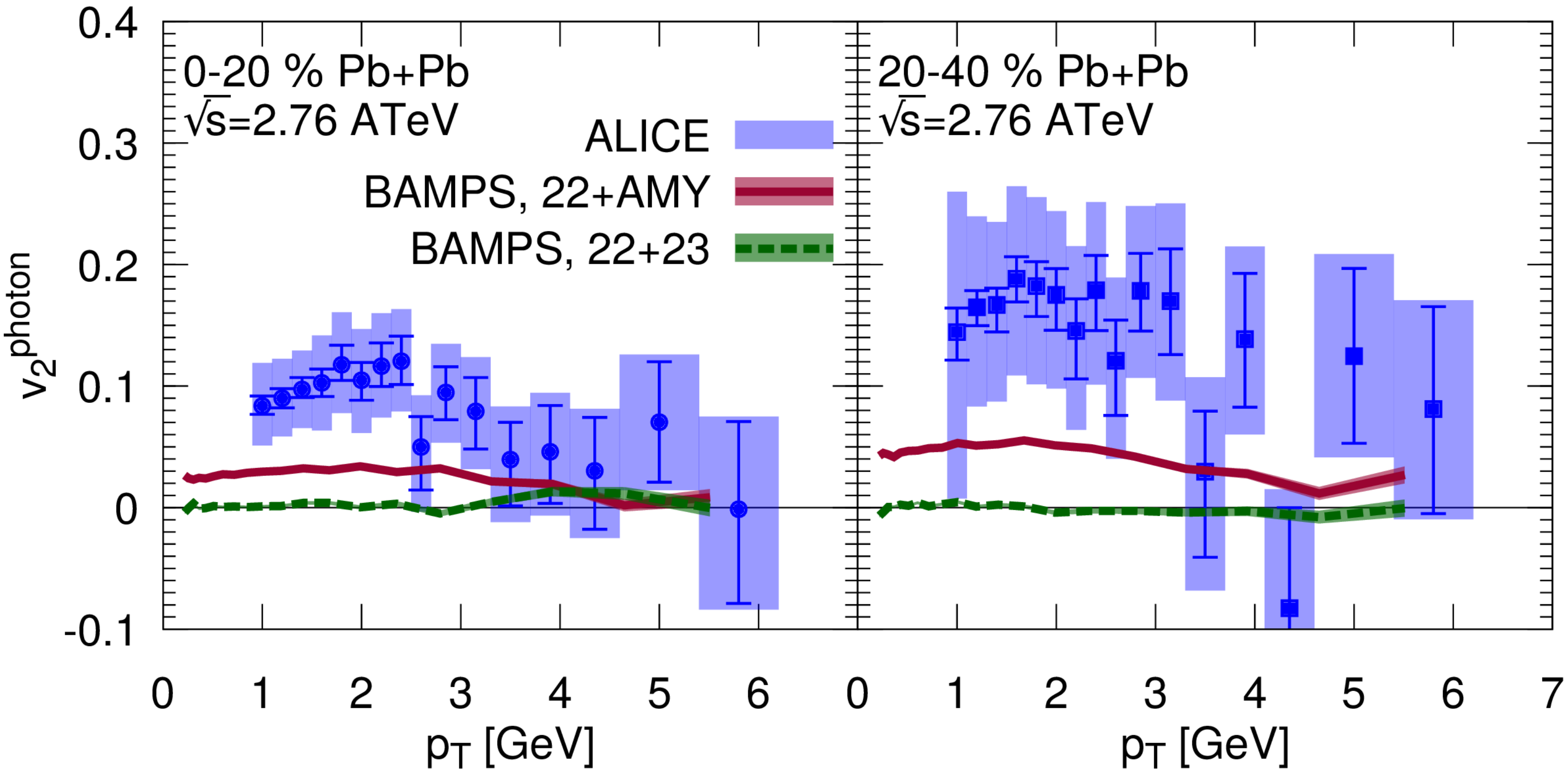
PHENIX, Phys.Rev. C94 (2016) no.6, 064901

LHC

prompt + BAMPS (QGP)
HG missing



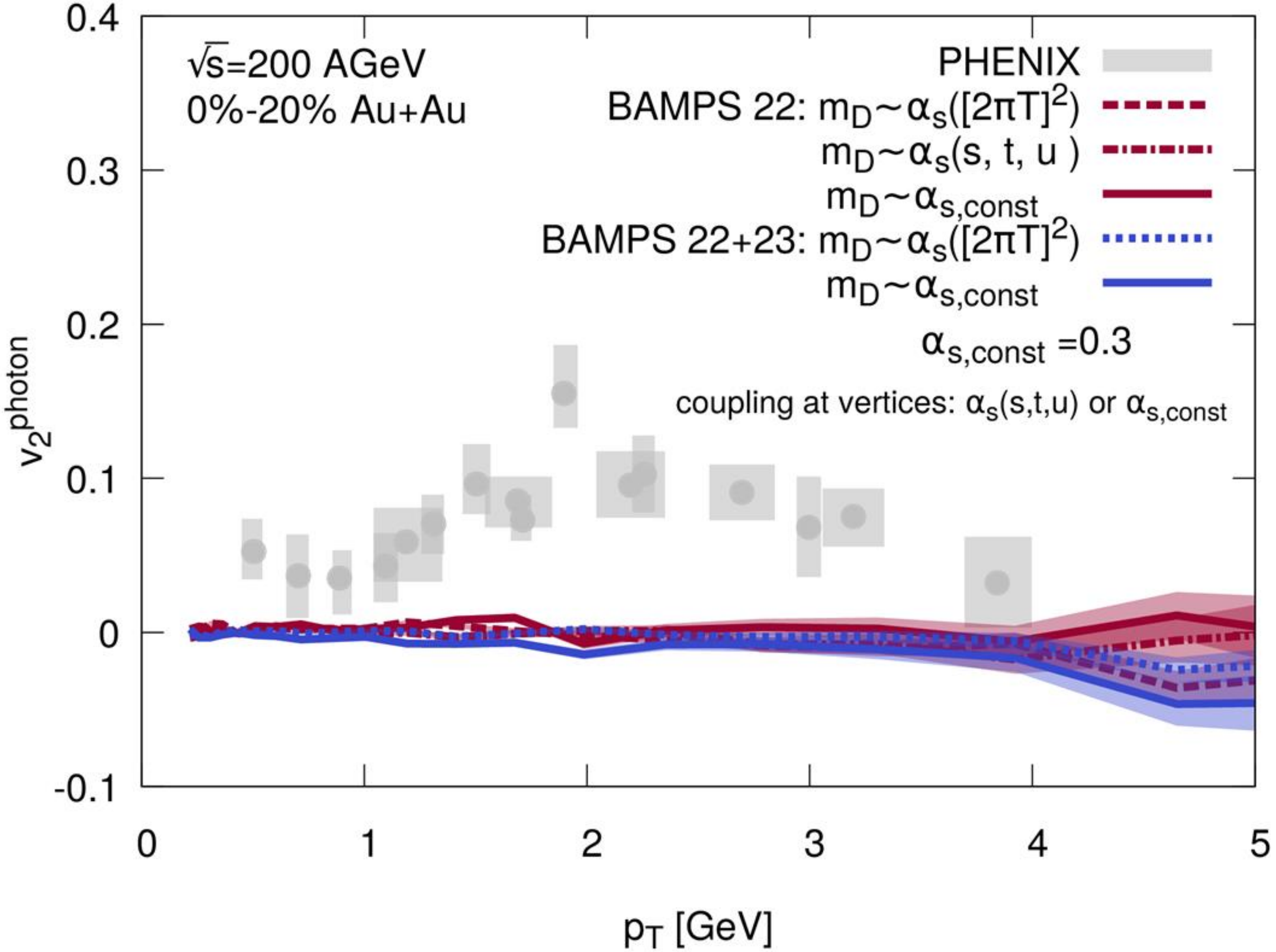
ALICE, Phys.Lett. B754 (2016) 235-248



Only BAMPS (QGP)

Mike Sas for ALICE, arXiv:1810.03861

Effect of running coupling



Only BAMPS (QGP)

Artificially fast chem. equilibration

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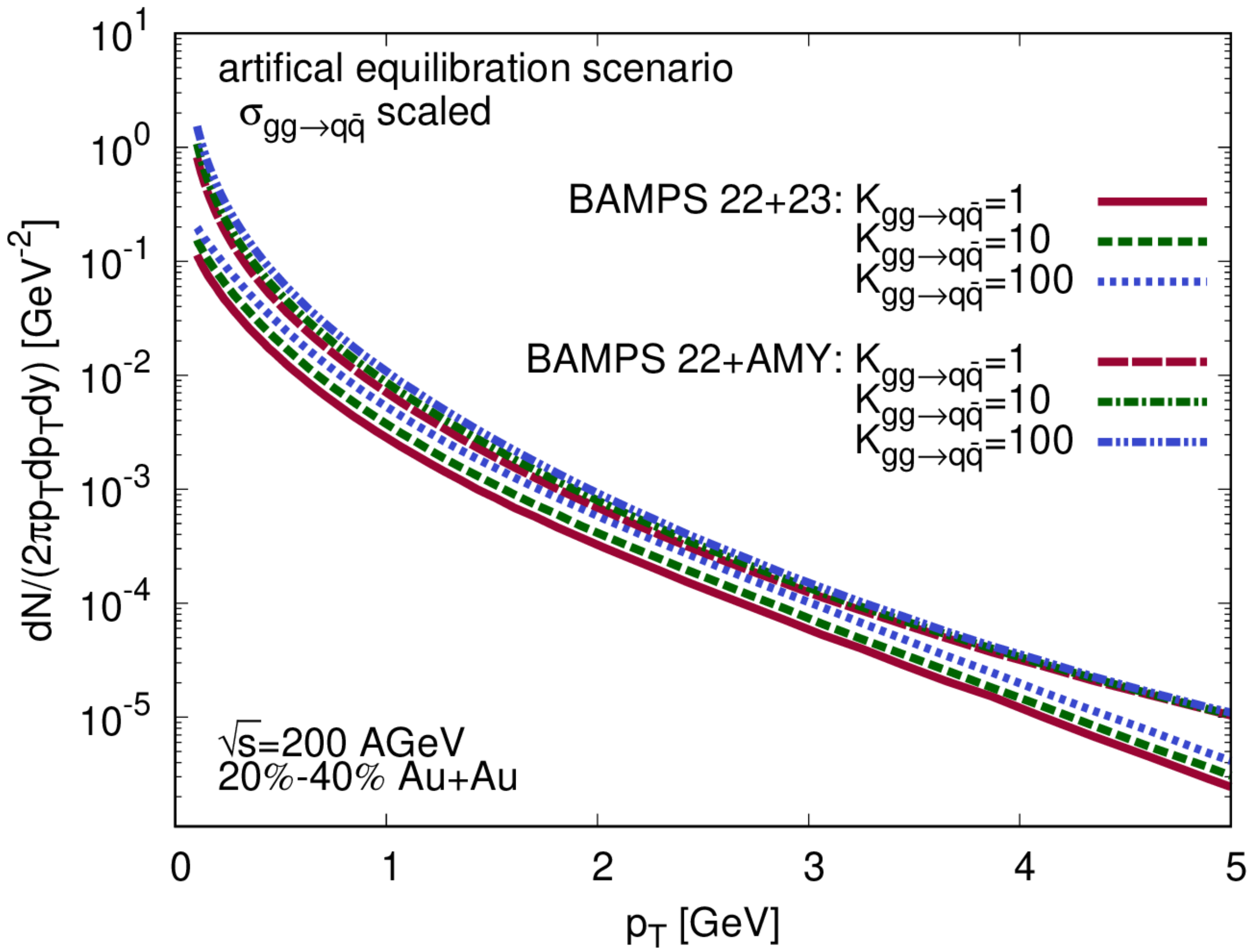

Only BAMPS (QGP)

Outlook: Hadronization

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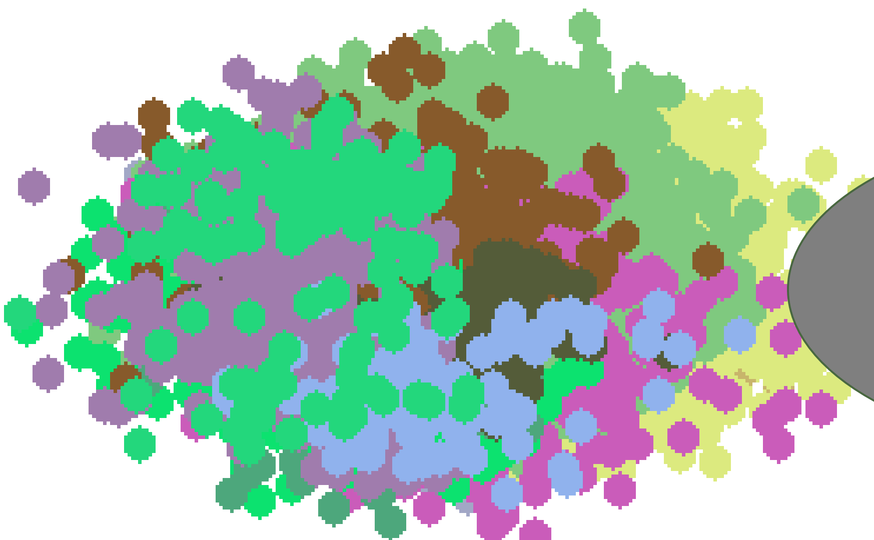
Local freeze-out criterion (energydensity)

Connect partons via colors

Hadron observ ables

Initial state → BAMPS → Cluster-Algorithm → HERWIG →

- Cluster independence
- Color connections
- Freeze-out criterion dependence



Distance-of-Closest Approach (last possible interaction)

See e.g., Bahr et al., HERWIG++, Eur.Phys.J. C58 (2008) 639-707
Courtesy to Simon Plätzer from HERWIG

Flow effect from Hadronization?

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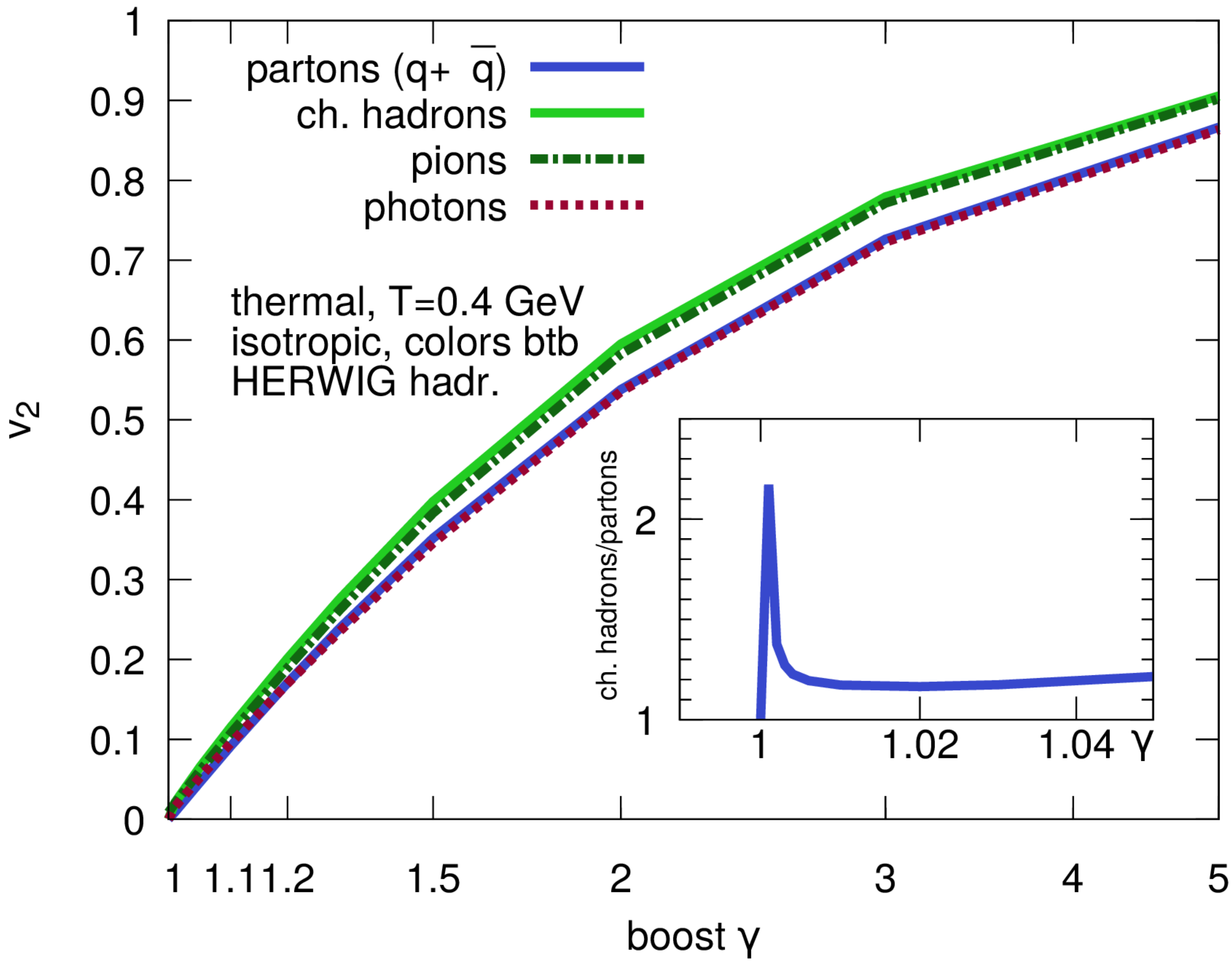
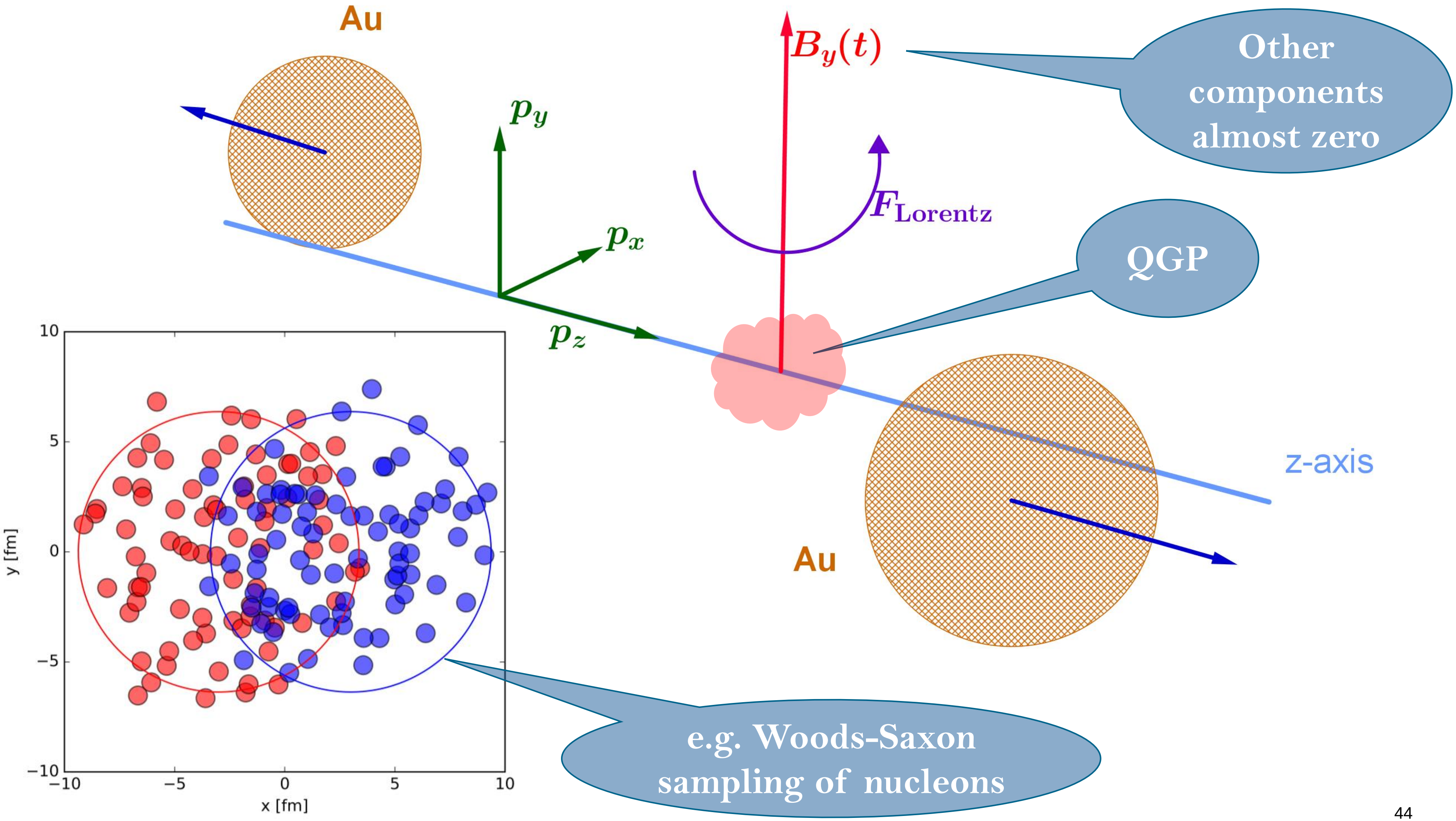


Initial magnetic fields?

Magnetic field influence on the early time dynamics of heavy-ion collisions

MG, Carsten Greiner, Zhe Xu, Phys.Rev. C96 (2017) no.1, 014903



Initial magnetic fields-strong but short

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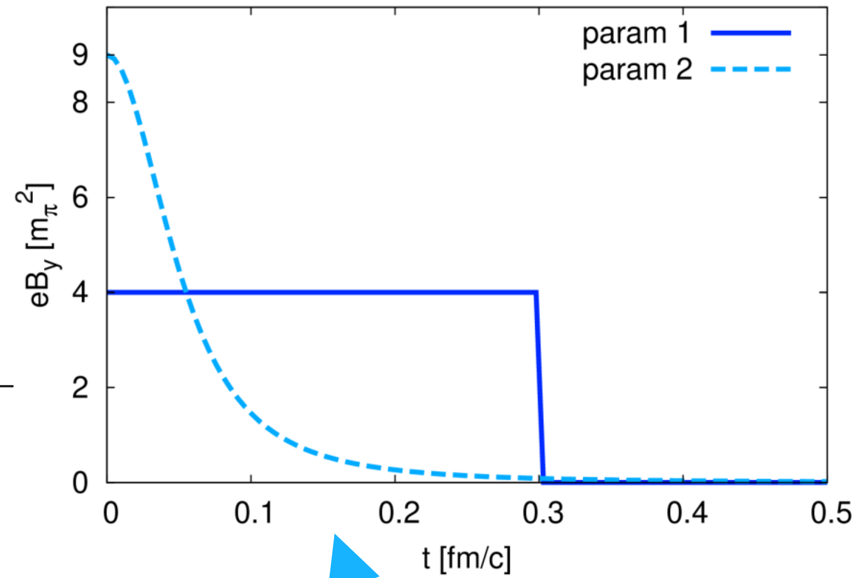
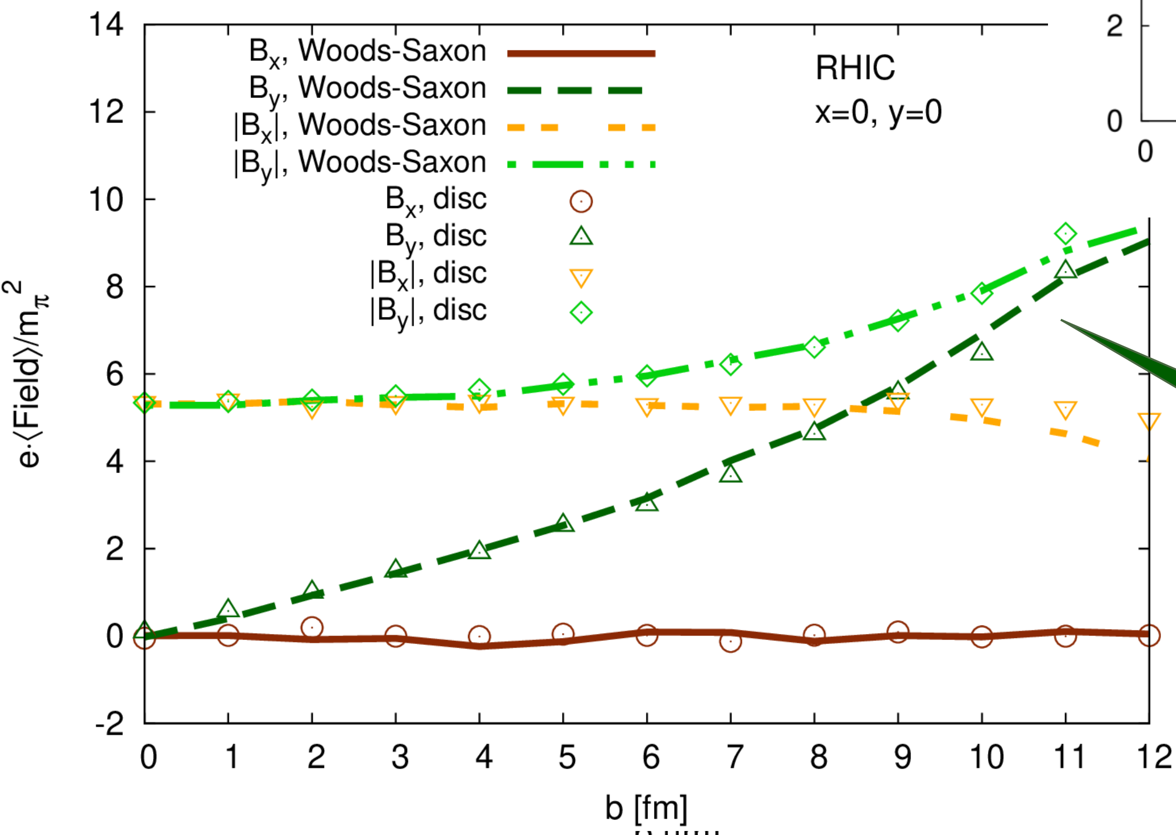
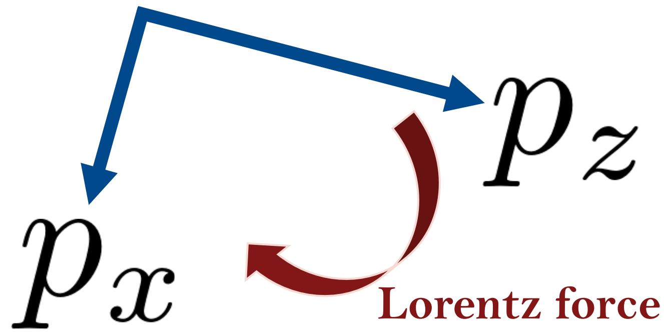
- Simple parameterization
- „induction effect“ ignored
- Initial parton state: simple power law (exponent n), Boost invariant





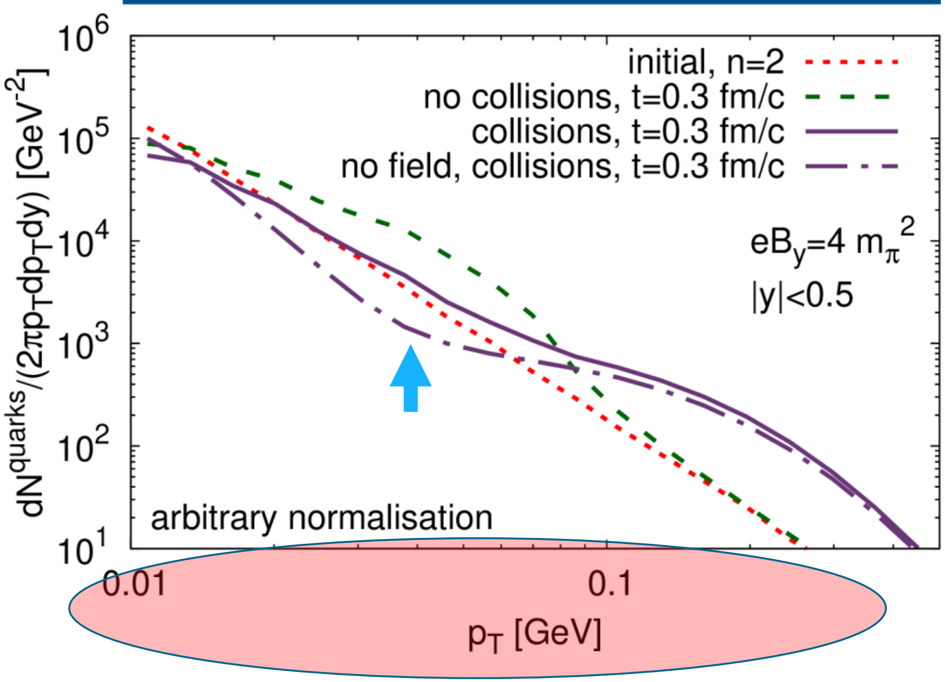
Large field, but relaxes fast to zero

Effect on quark spectra and flow?

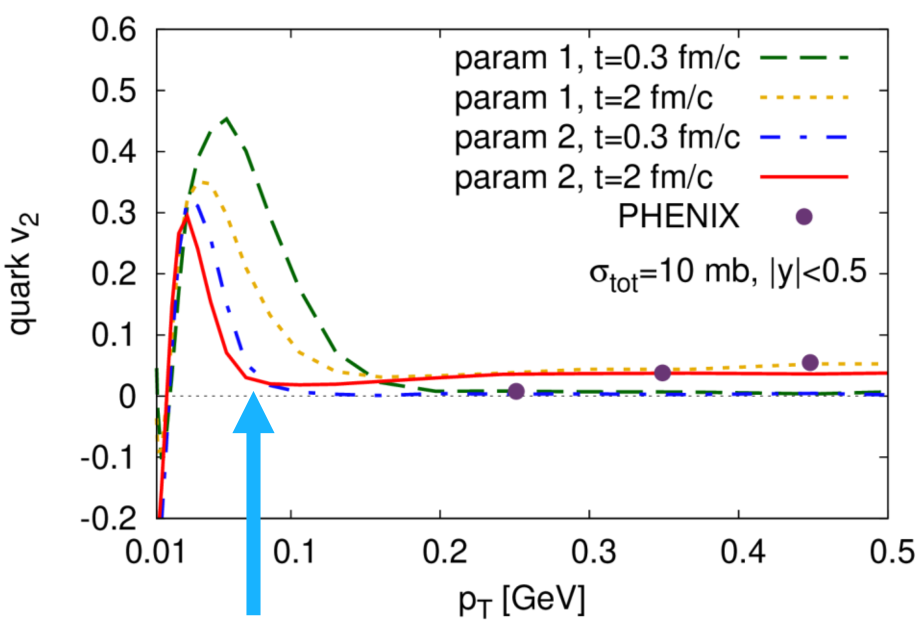


$$v_2 = \frac{p_x^2 - p_y^2}{p_T^2}$$

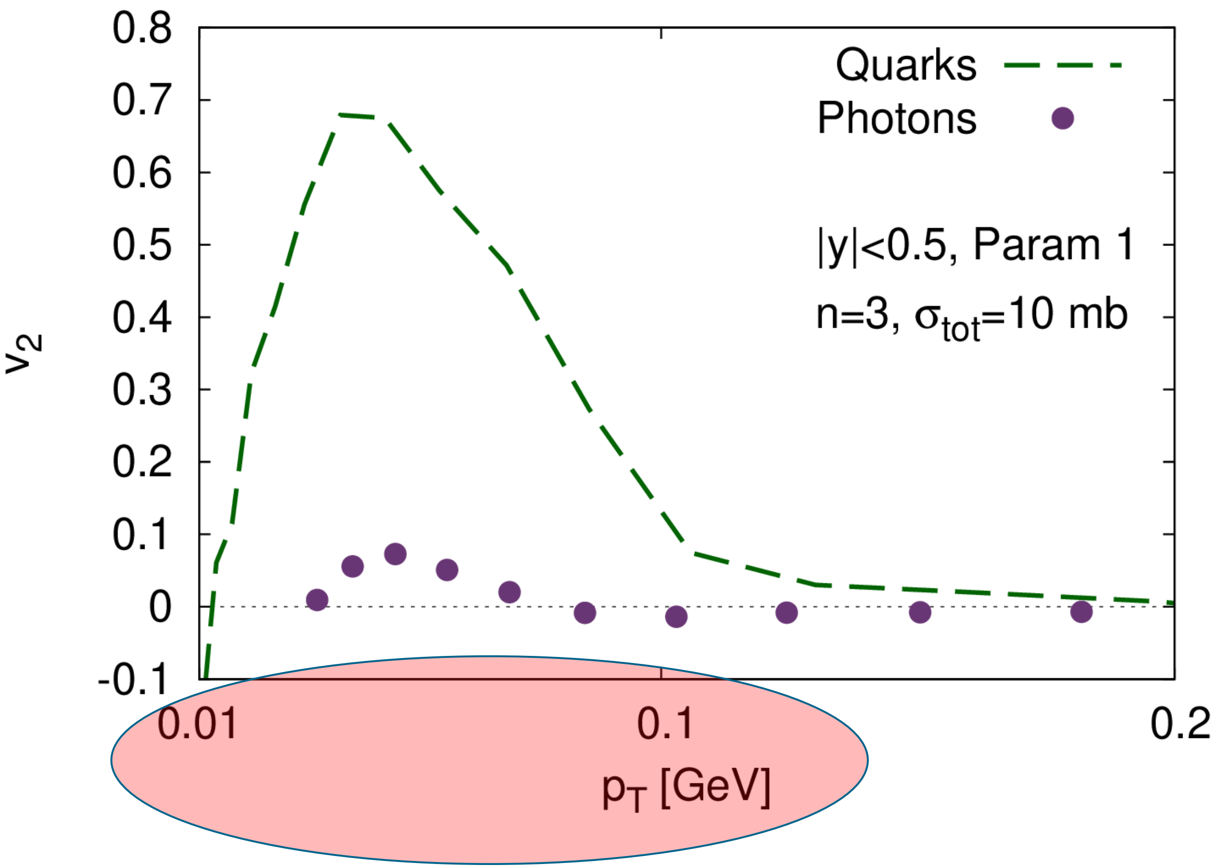
Quark spectrum, w and w/o collisions:



Elliptic flow only at very low p_T



Effect on photons?



- Small effect even with **<u>optimistic</u>** assumptions:
  - Initial quarks (not pure glue, CGC)
  - Magnetic field persistent for some time (parameterization 1)
  - No formation times (quarks immediately affected by field)
- My personal take home message: no effect

Photons from partonic transport

What ?

- Microscopic leading order photon production in partonic transport
- Radiative photons using two different methods
- Matrix elements provide angular-differential kinematics

Results:

- Chemical quark undersaturation → little photon yield
- Strict collinearity of AMY changes flow → still too little
- Running coupling can help
- Magnetic field effect maybe irrelevant

Future possibilities:

- Prompt photons constraints?
- Chemical composition of initial state?
- Hadronization of parton cascade opens new doors