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33rd Winter Workshop on
Nuclear Dynamics, Utah
January 2017

HIC for FAIR
Helmholtz International Center

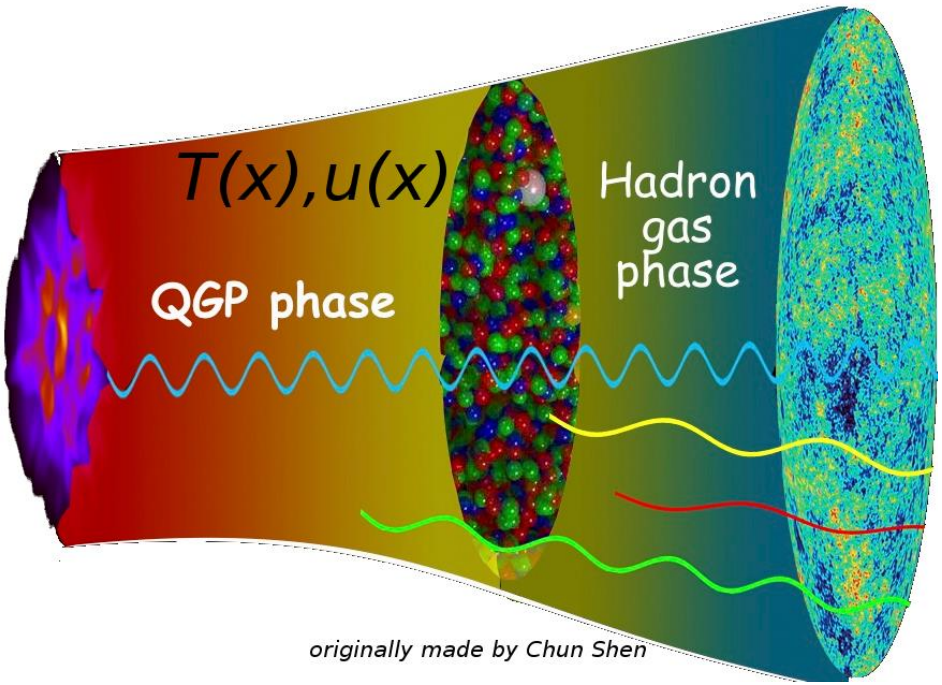
Photons
from the non-equilibrium QGP
and
how magnetic fields (might) change the picture

Carsten Greiner

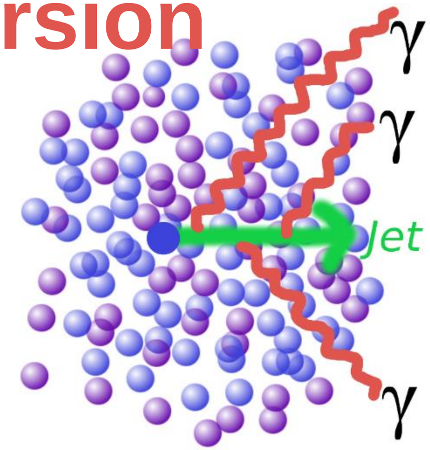
with **Moritz Greif** and Zhe Xu

Based on
arXiv:1612.05811
arXiv:1701.XXXXX

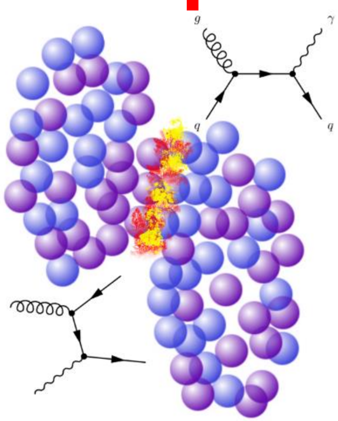
Photons in heavy-ion collisions



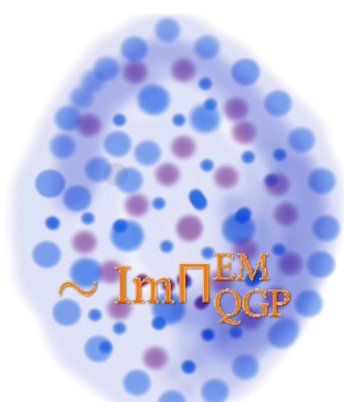
+ Jet-Photon conversion



Prompt



QGP



Hadron gas

Goals:

- **Understand production mechanisms**
- **Understand spectra & flow**

Microscopic transport model

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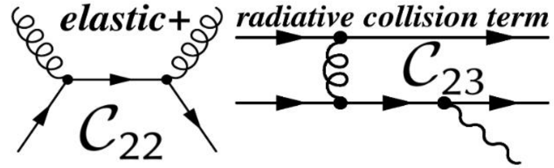
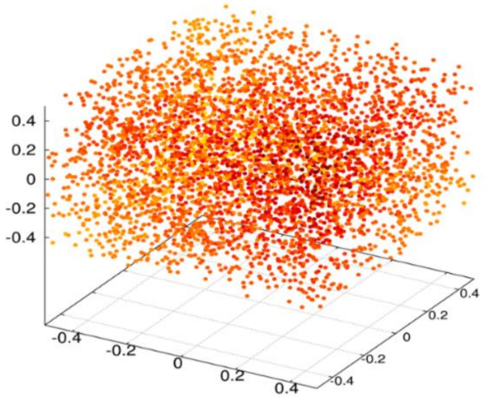
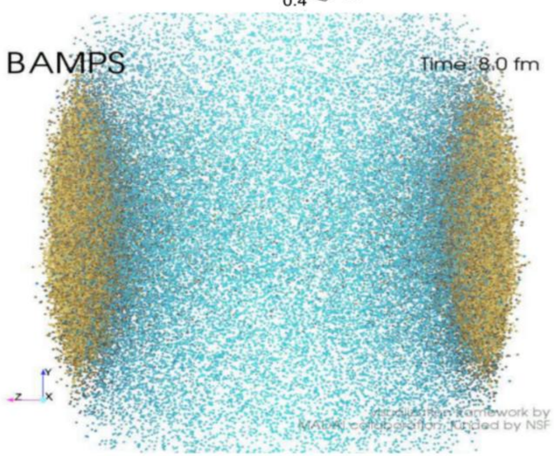
BAMPS: **B**oltzmann **A**pproach to **M**ulti-**P**arton **S**catterings

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







Box simulations & expanding QGP

Zhe Xu & Carsten Greiner, 2005

Phys. Rev. C 71, 064901

⋆ Spacetime-grid, stoch. collision probabs.

⋆ Tot. cross sections from **pQCD**: $\sigma_{22}(s)$, $\sigma_{23}(s)$

⋆ Fully Lorentz-invariant formulation

$$P_{22} = v_{rel} \frac{\sigma_{22}}{N_{test}} \frac{\Delta t}{\Delta^3 x}$$

$$P_{23} = v_{\mathrm{rel}} \frac{\sigma_{23}}{N_{test}} \frac{\Delta t}{\Delta^3 x}, \quad P_{32} = \dots$$

⋆ Massless onshell particles (ideal eos)

⋆ This talk: only classical statistics

⋆ See e.g.: PRD88,014018 / PRL102,202301 / PRL114,112301 / PRD90,094014 / PRL103,032301

BAMPS: 3+1d expanding heavy-ion collisions

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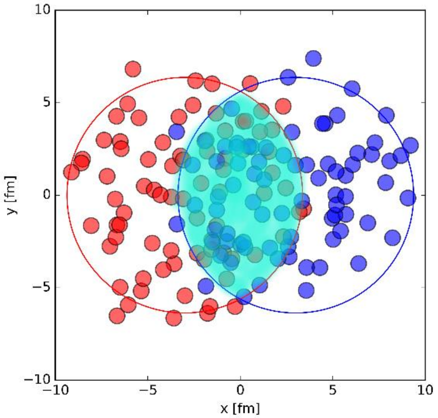
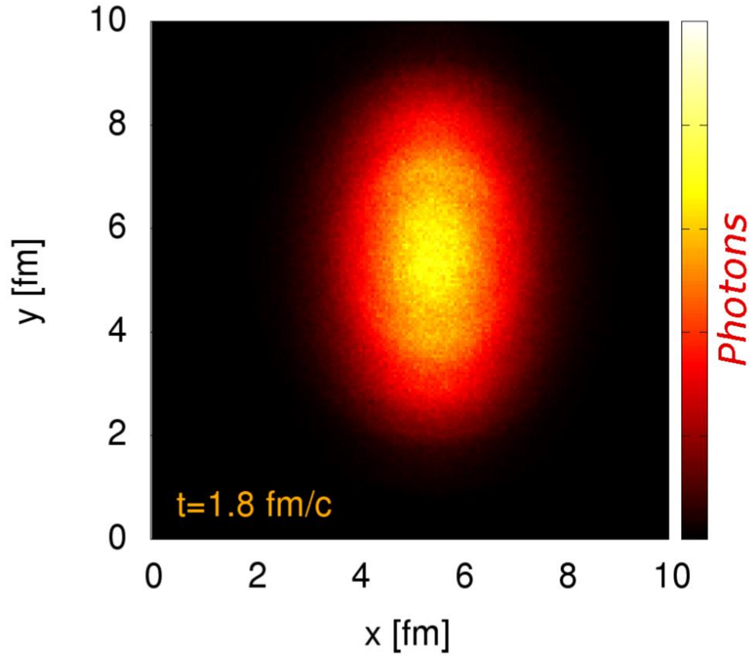


- Smooth Glauber initial **positions**
- Pythia 6 initial **momenta**: $pp \times N_{\text{binary}}$
- Reproduce $\mathrm{d}E_T/dy$ distribution for RHIC/LHC data
- v_2 & R_{AA} in common framework (PRL 114, 112301, 2015)

- Particle species: $q, \bar{q}, g, \gamma, e^+e^-$
- LO-γ-production, incl. bremsstrahlung $qq \longrightarrow qq\gamma$
- Born dilepton production
- Radiative gluons/photons: LPM-suppression modelled



Interactions in BAMPS

Light flavors + Gluons

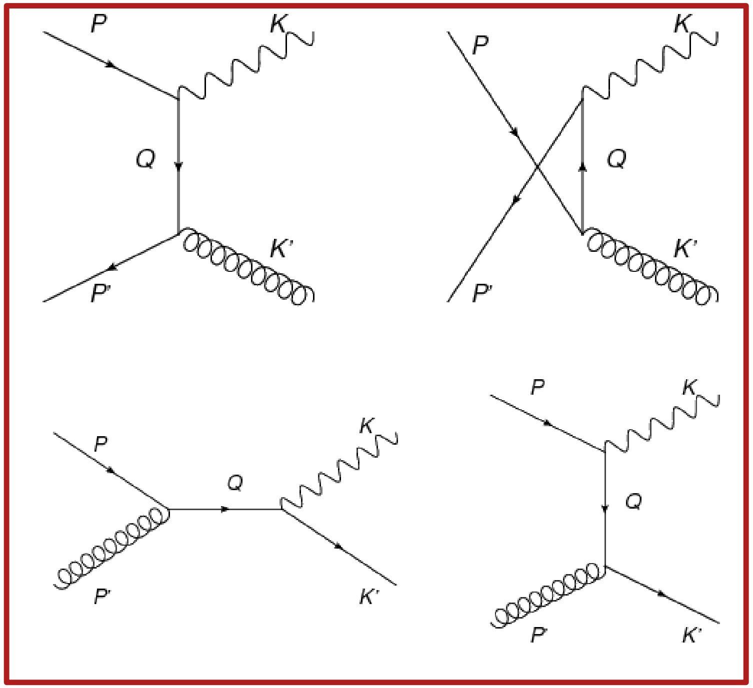
binary

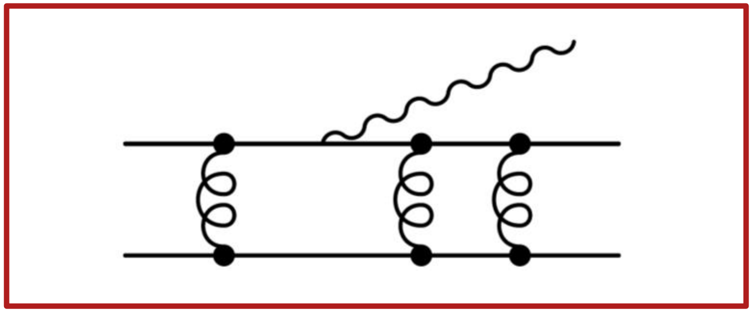
$$g\,g \rightarrow g\,g$$
$$g\,g \rightarrow q\,\bar{q}$$
$$q\,\bar{q} \rightarrow g\,g \quad \text{and} \quad q\,\bar{q} \rightarrow q'\,\bar{q}'$$
$$q\,g \rightarrow q\,g \quad \text{and} \quad \bar{q}\,g \rightarrow \bar{q}\,g$$
$$q\,\bar{q} \rightarrow q\,\bar{q}$$
$$q\,q \rightarrow q\,q \quad \text{and} \quad \bar{q}\,\bar{q} \rightarrow \bar{q}\,\bar{q}$$
$$q\,q' \rightarrow q\,q' \quad \text{and} \quad q\,\bar{q}' \rightarrow q\,\bar{q}'$$

inelastic

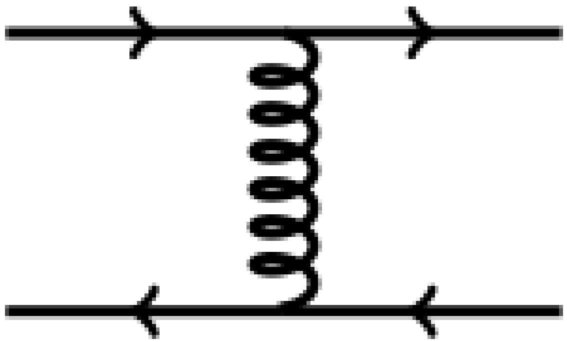
$$g\,g \leftrightarrow g\,g\,g$$
$$q\,g \leftrightarrow q\,g\,g \quad \text{and} \quad \bar{q}\,g \leftrightarrow \bar{q}\,g\,g$$
$$q\,\bar{q} \leftrightarrow q\,\bar{q}\,g$$
$$q\,q \leftrightarrow q\,q\,g \quad \text{and} \quad \bar{q}\,\bar{q} \leftrightarrow \bar{q}\,\bar{q}\,g$$
$$q\,q' \leftrightarrow q\,q'\,g \quad \text{and} \quad q\,\bar{q}' \leftrightarrow q\,\bar{q}'\,g$$

Photons





Elastic collisions



- **Leading-order pQCD cross sections**

$$\overline{|\mathcal{M}_{qq'\to qq'}|^2} = \frac{64\pi^2}{9}\alpha_s^2(t)\frac{u^2+s^2}{[t-m_D^2(\alpha_s(t))]^2}$$

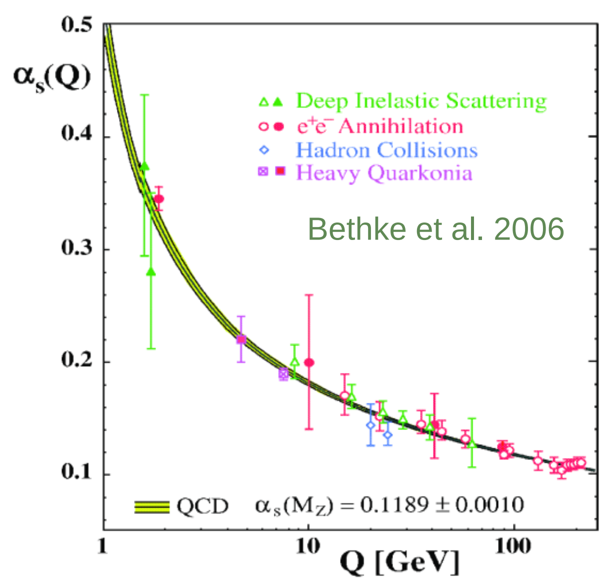
- **Divergences screened by (tuned) Debye mass**
- **Running coupling**

partons

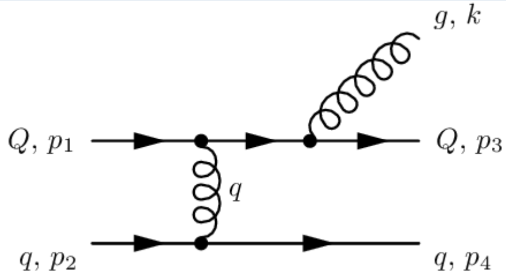
$g\,g \to g\,g$		
$g\,g \to q\,\bar{q}$		
$q\,\bar{q} \to g\,g$	and	$q\,\bar{q} \to q'\,\bar{q}'$
$q\,g \to q\,g$	and	$\bar{q}\,g \to \bar{q}\,g$
$q\,\bar{q} \to q\,\bar{q}$		
$q\,q \to q\,q$	and	$\bar{q}\,\bar{q} \to \bar{q}\,\bar{q}$
$q\,q' \to q\,q'$	and	$q\,\bar{q}' \to q\,\bar{q}'$

photons

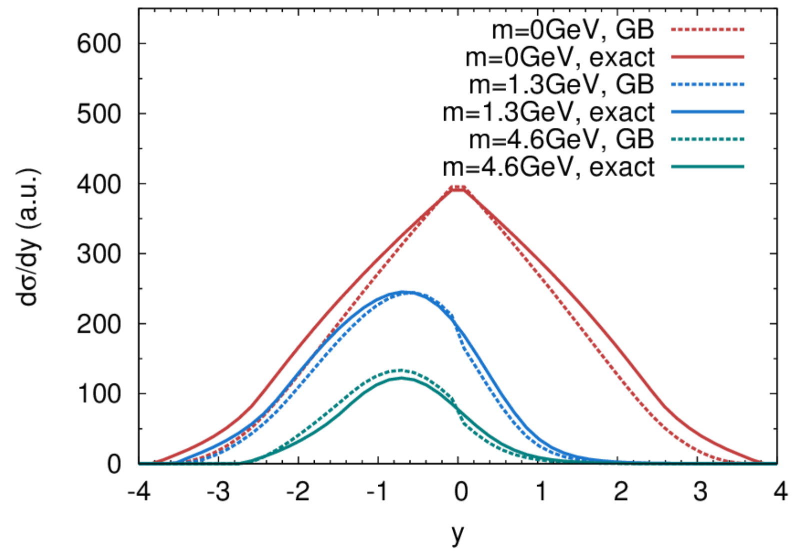
$gq \to q\gamma$ and $q\bar{q} \to g\gamma$



Gluons: Radiative collisions



$$
\begin{array}{lcl}
g\,g \leftrightarrow g\,g\,g & & \\
q\,g \leftrightarrow q\,g\,g & \text{and} & \bar{q}\,g \leftrightarrow \bar{q}\,g\,g \\
q\,\bar{q} \leftrightarrow q\,\bar{q}\,g & & \\
q\,q \leftrightarrow q\,q\,g & \text{and} & \bar{q}\,\bar{q} \leftrightarrow \bar{q}\,\bar{q}\,g \\
q\,q' \leftrightarrow q\,q'\,g & \text{and} & q\,\bar{q}' \leftrightarrow q\,\bar{q}'\,g
\end{array}
$$



Improved Gunion Bertsch (GB) approximation

$$
\left|\overline{\mathcal{M}}_{X\rightarrow Y+g}\right|^2 = \left|\overline{\mathcal{M}}_{X\rightarrow Y}\right|^2 \, P_g
$$

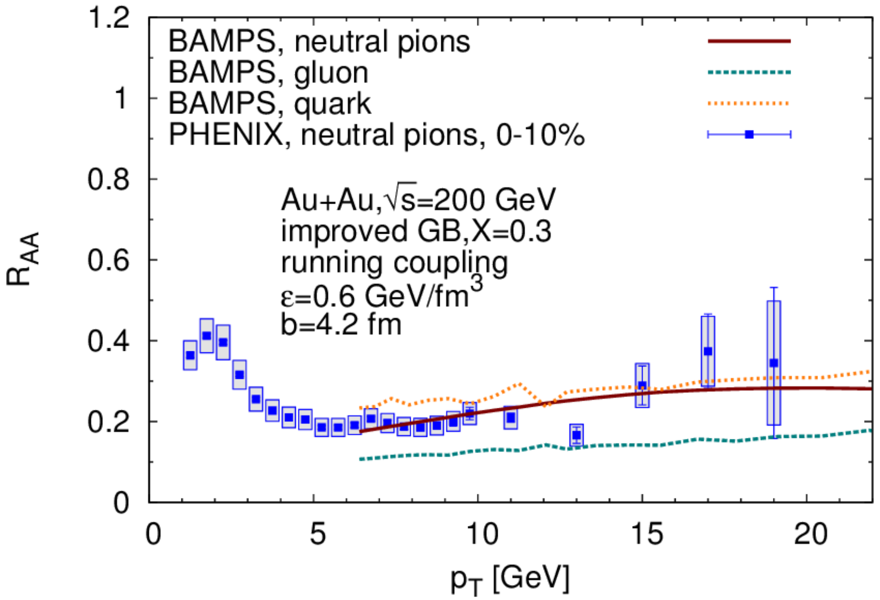
$$
P_g = 48\pi\alpha_s(k_\perp^2)\,(1-\bar{x})^2 \times \left[\frac{\mathbf{k}_\perp}{k_\perp^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + m_D^2\,(\alpha_s(k_\perp^2))}\right]^2
$$

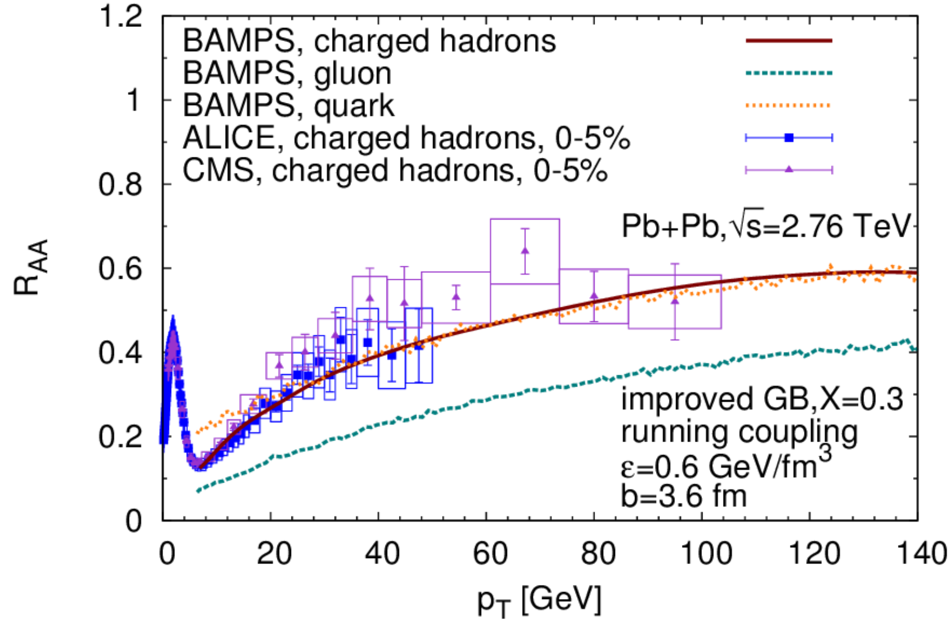
Effective QCD LPM effect:

Mean free path	$\lambda > X\,\tau$	Gluon formation time

Fochler, Uphoff, Xu, CG
Phys. Rev. D88 (2013)

Nuclear modification factor R_{AA}

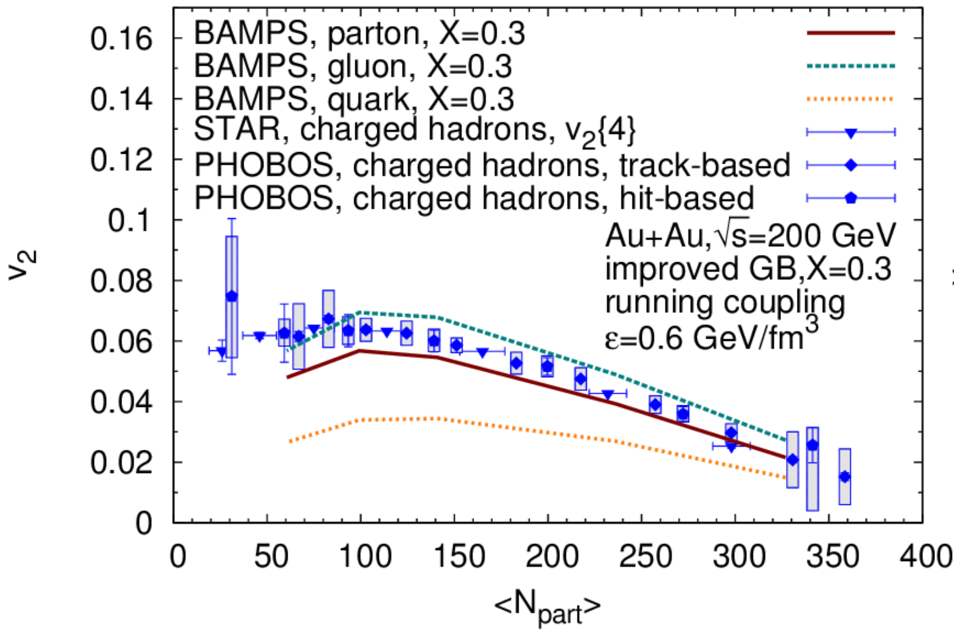


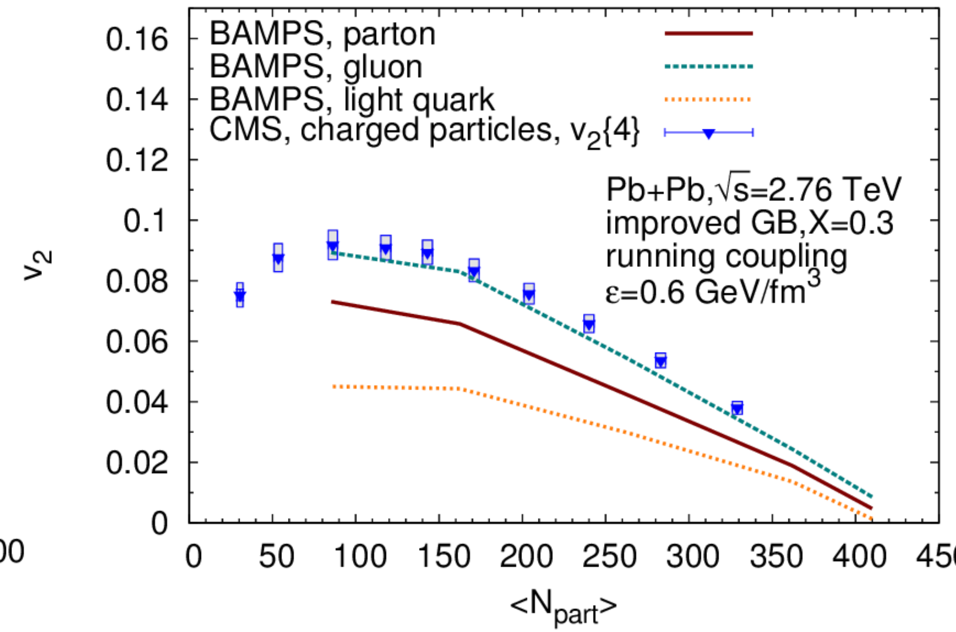


Phys. Rev. Lett. 114 (2015) 112301

- **Hadronization of high p_t partons with AKK fragmentation functions**
- **LPM parameter fixed by comparison to RHIC data**
- **Realistic suppression both for RHIC and LHC**

Elliptic flow v_2

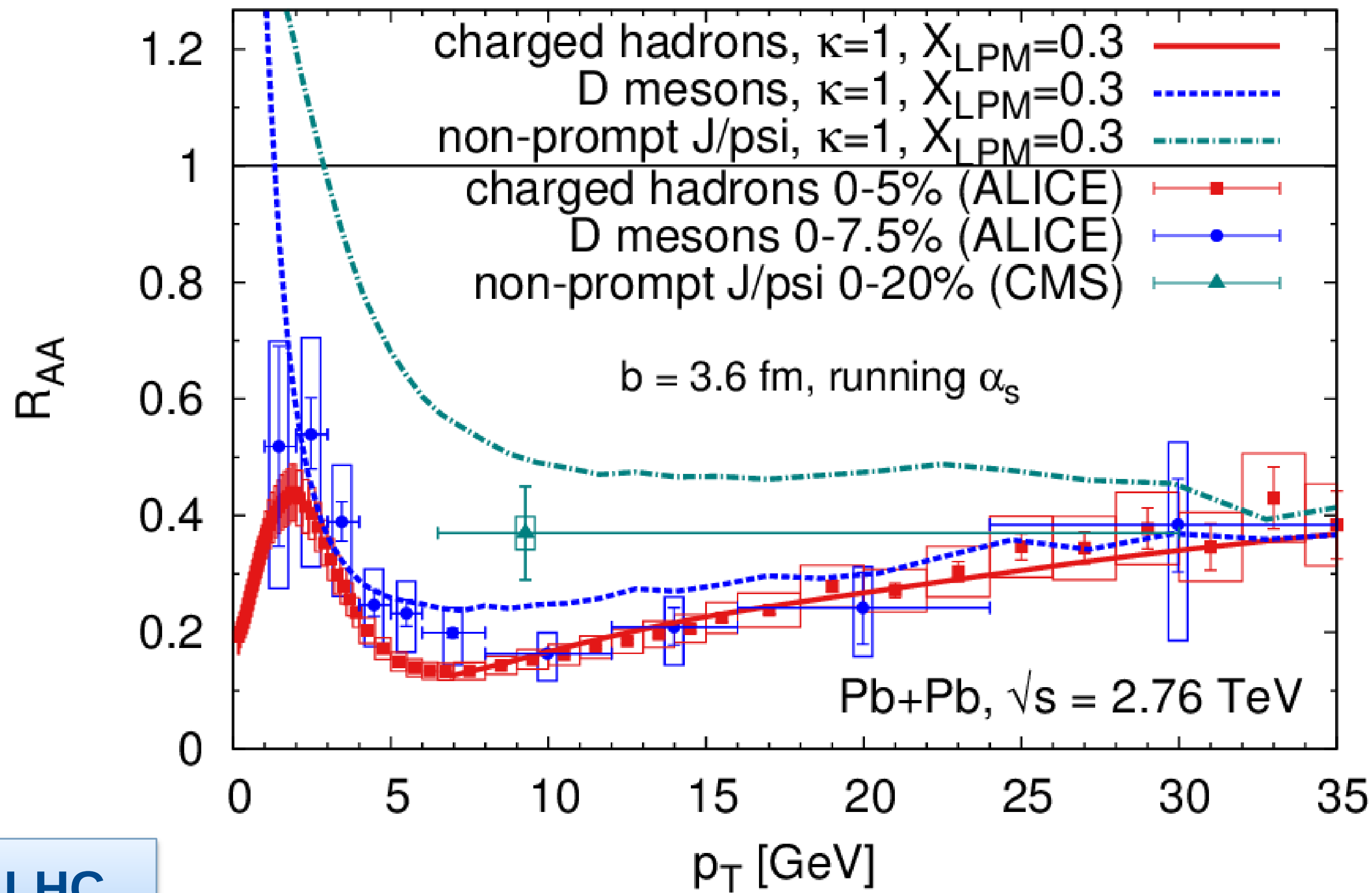




Phys. Rev. Lett. 114 (2015) 112301

- Same pQCD interactions lead to a sizeable elliptic flow for bulk medium
- No hadronization for bulk medium $\longrightarrow$ no hadronic after-burner

Heavy flavor and charged hadron R_{AA} at LHC



LHC

Transport coefficients

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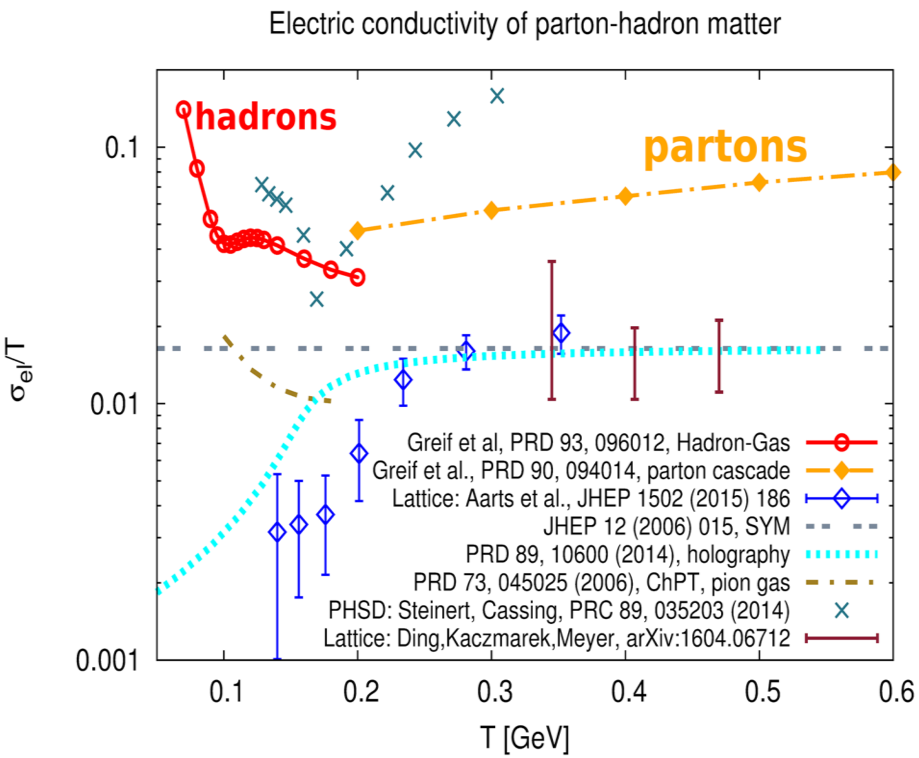
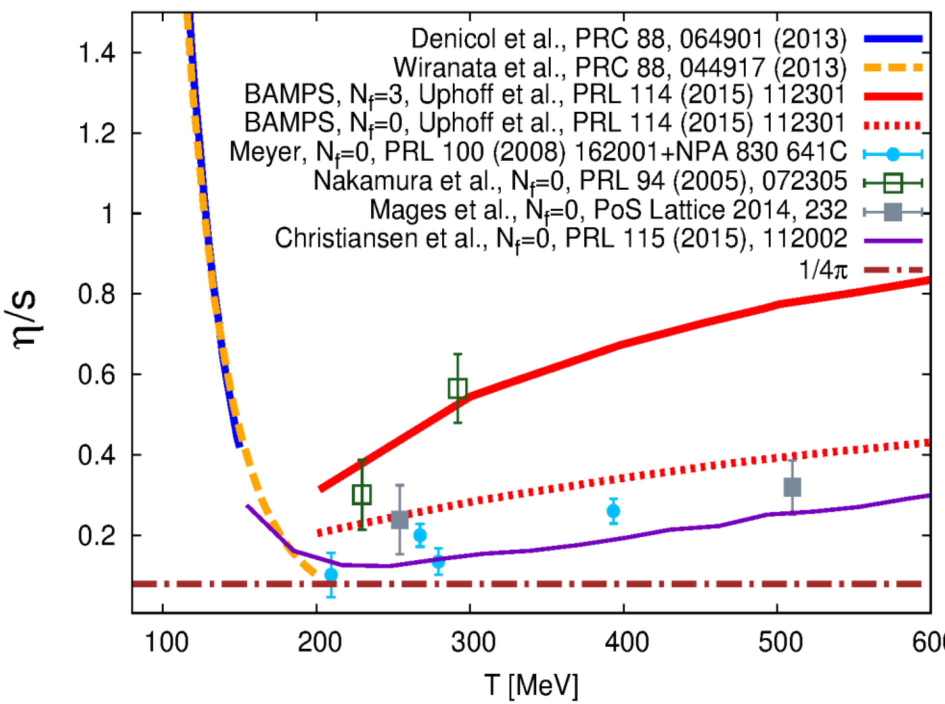


shear viscosity



<u>ongoing projects:</u>

→ baryon diffusion coefficient
→ charm diffusion coefficient
→ study effective couplings
→ momentum broadening: $\hat{q}$

<u>we have studied:</u>

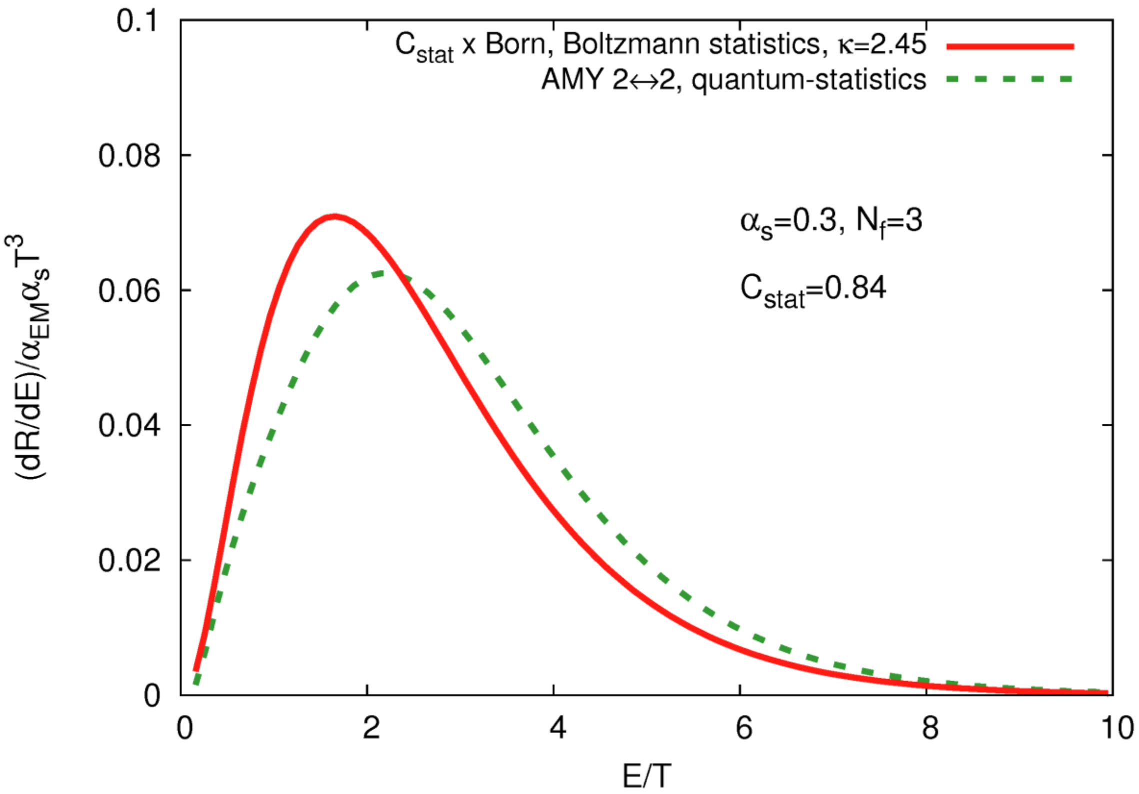
→ shear viscosity
→ heat conductivity
→ electric conductivity

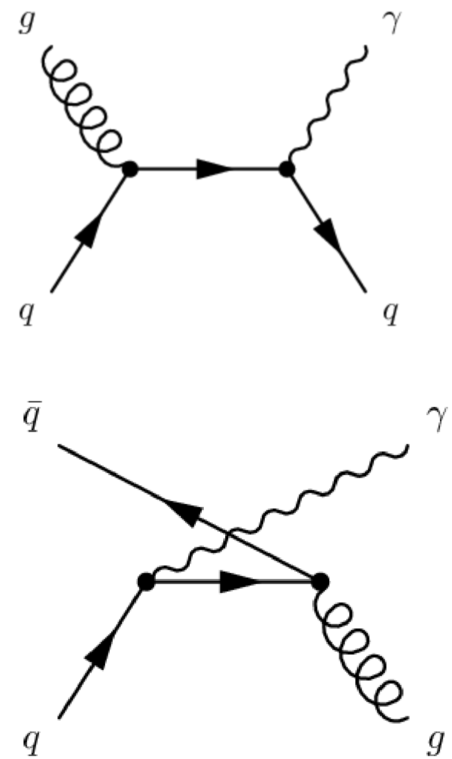
Binary photon production

$$|\mathcal{M}|^2_{\text{Compton}} = \frac{16}{3}\pi^2\alpha\alpha_s\left(\frac{s^2+st}{(s+m_{D,q}^2)^2}+\frac{s^2+st}{(u-m_{D,q}^2)^2}\right),\ |\mathcal{M}|^2_{\text{annihilation}} = \ldots$$

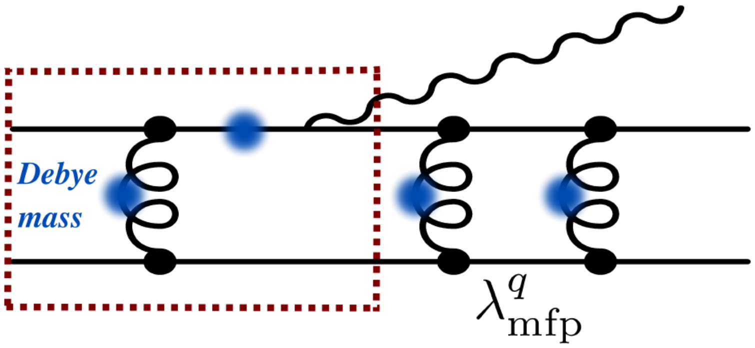
only naively screened propagators. **Correct** by $m_{D,q}^2 \longrightarrow \kappa m_{D,q}^2$.

Compare to analytic HTL result:





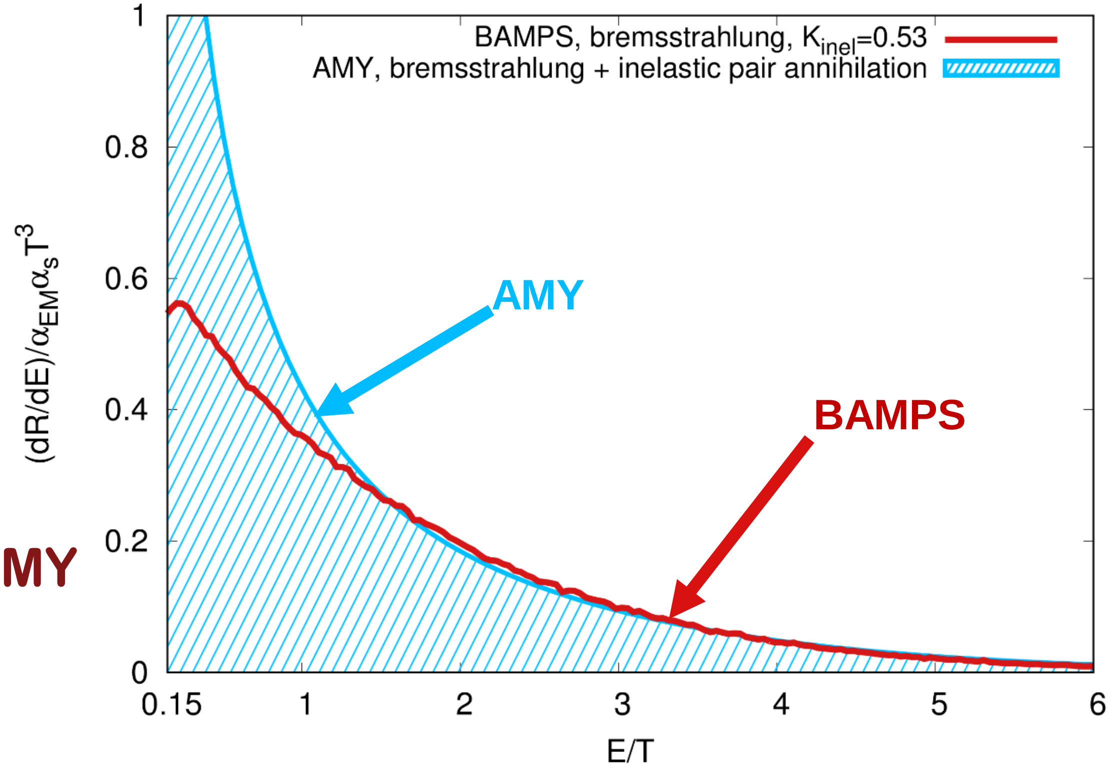
Exact photon bremsstrahlung in BAMPS



$$|\mathcal{M}_{2\to3}|^2 \to |\mathcal{M}_{2\to3}|^2\Theta(\lambda^q_{\mathrm{mfp,process}} - \tau_f^\gamma)$$

Compare to analytic AMY result:

- Exact matrix element
- Debye screening
- Specific mean free path
- K-factor 0.53 to match AMY



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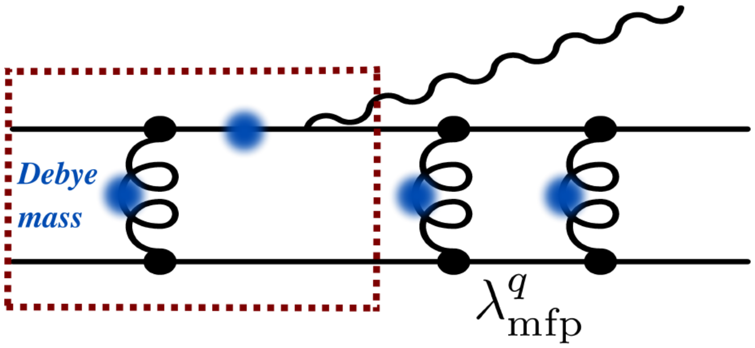

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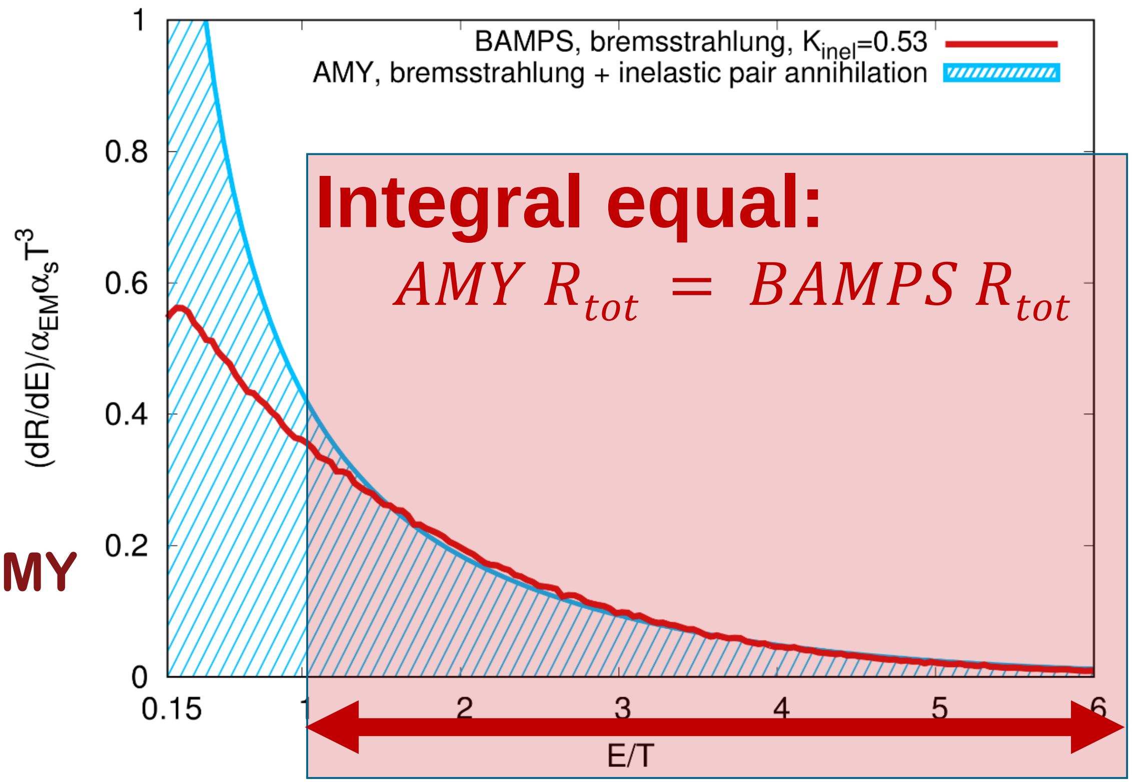
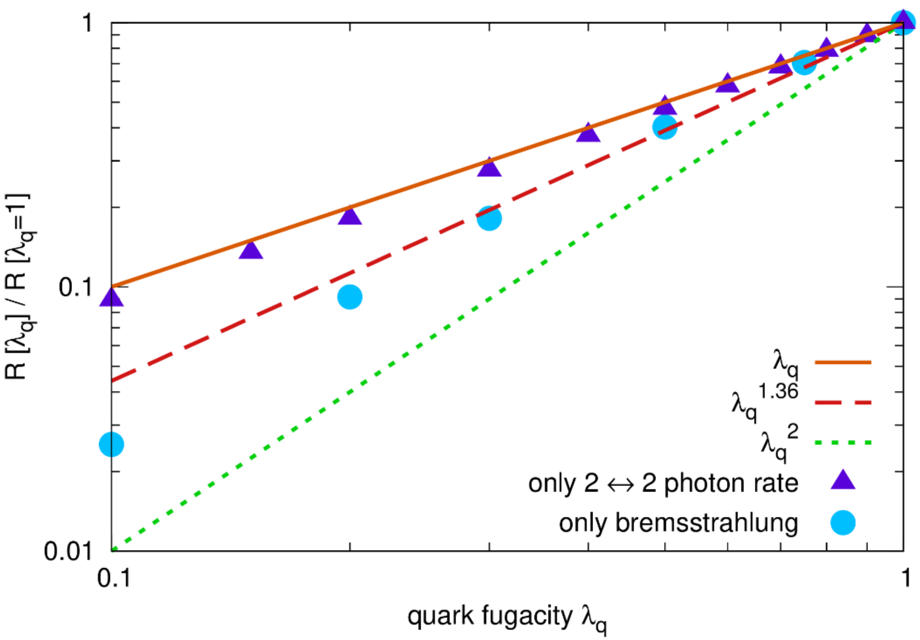


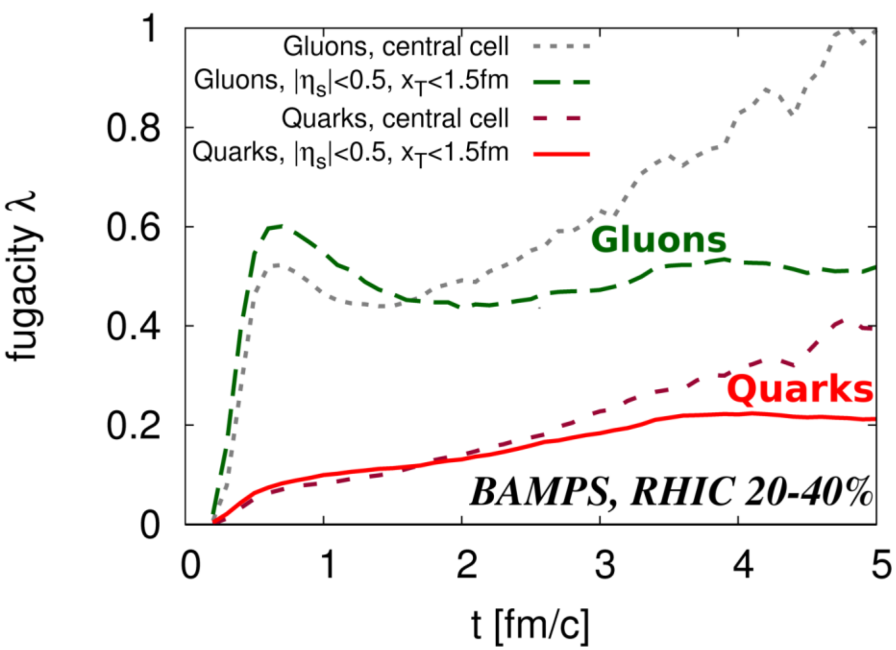
Fugacity dependence of rates

- **At RHIC: photon emission mainly before 3 fm/c**
- **Photon yield expected to be $10\% - 20\%$ of Hydro**

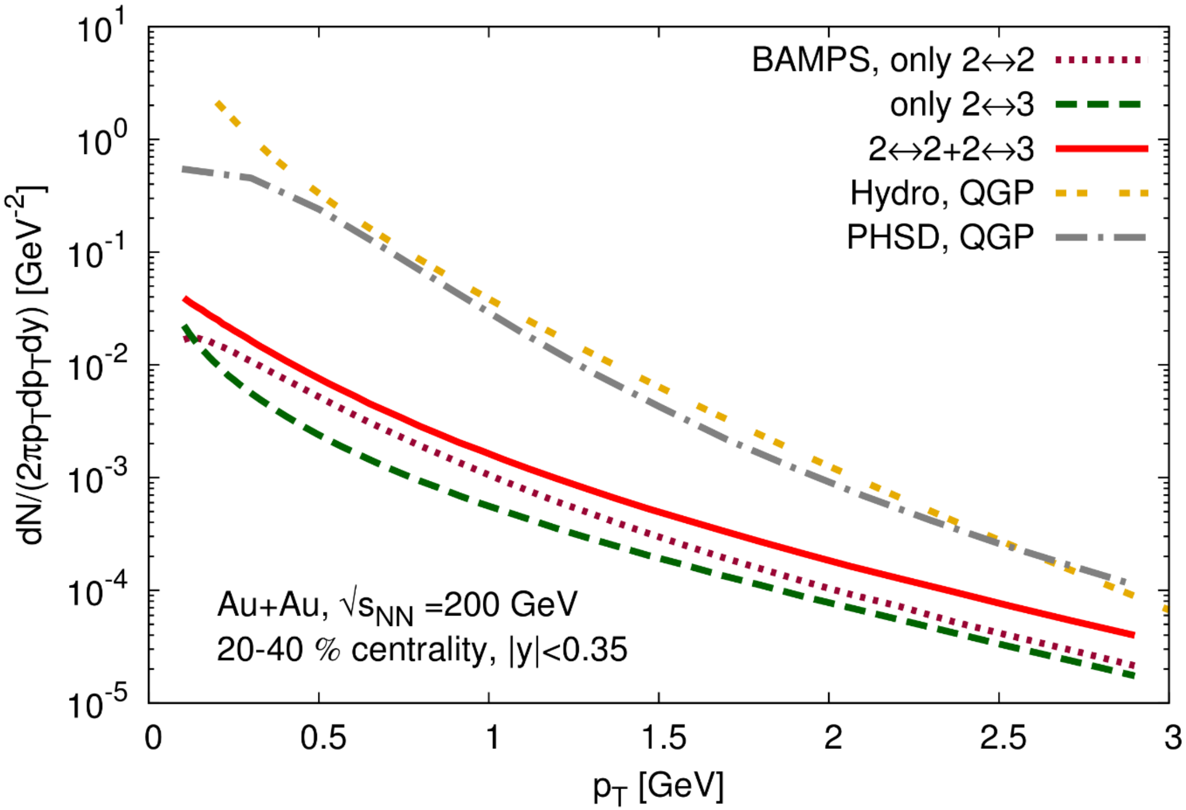
Elastic Rate: $R \sim \lambda_q \lambda_{\bar{q}/g} \cdot \ldots \cdot \frac{1}{(t - m_D(\lambda_q, \lambda_g))^2}$

Inelastic Rate: $R \sim \lambda_q^2 \cdot \ldots \cdot \frac{1}{(t - m_D(\lambda_q, \lambda_g))^2} \cdot \ldots \Theta\left(\lambda_{\mathrm{mfp}}(\lambda_{q/g}) - \tau_f\right)$





Photon spectra from BAMPS

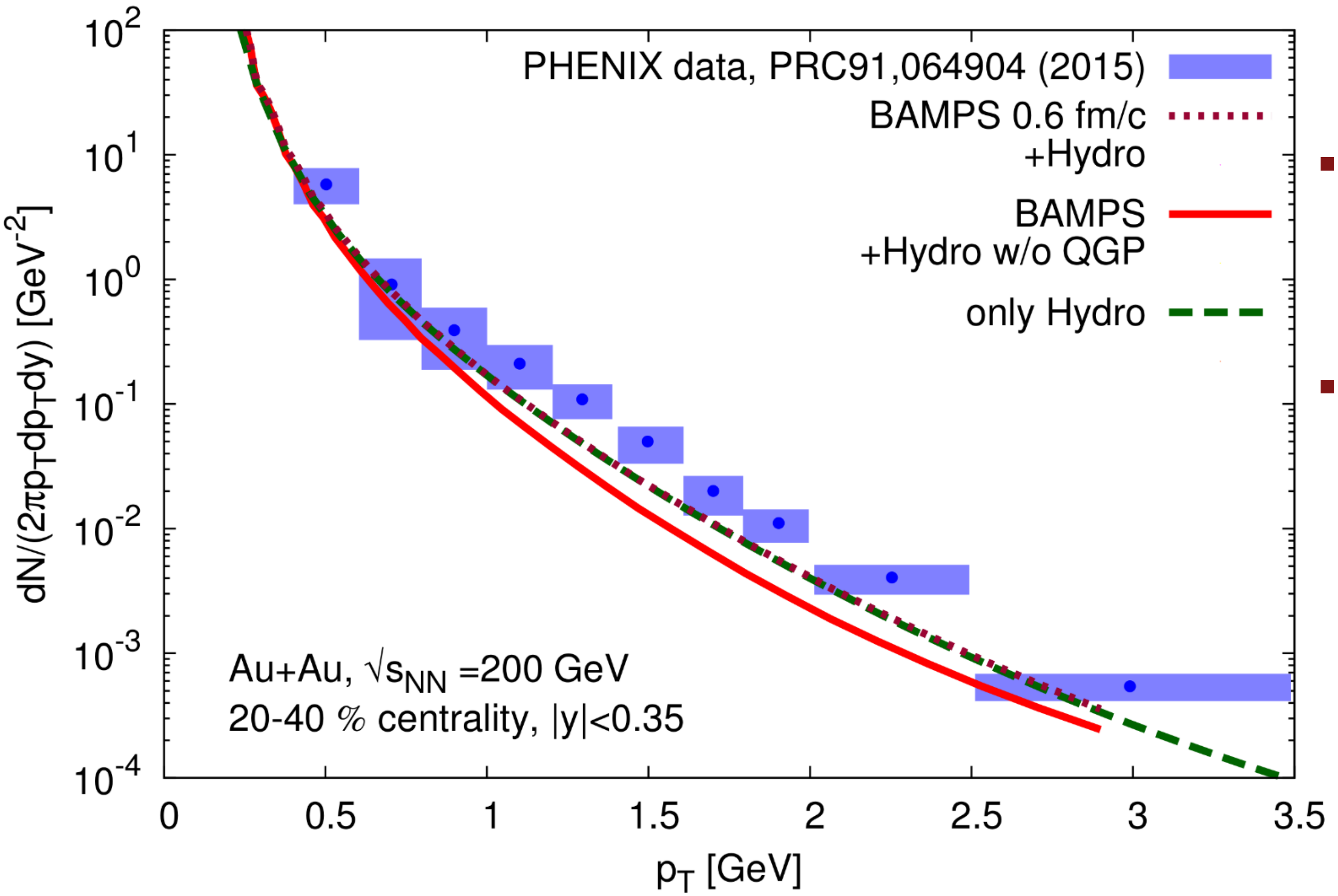


- **High effective temperature**
- **Lower yield due to fugacities**
- **Inelastic contribution important**
- **Initial state !?**

Hydro: Paquet et al, PRC 93 (2016), 044906
PHSD: Linnyk et al, PRC92 (2015), 054914

Photon spectra

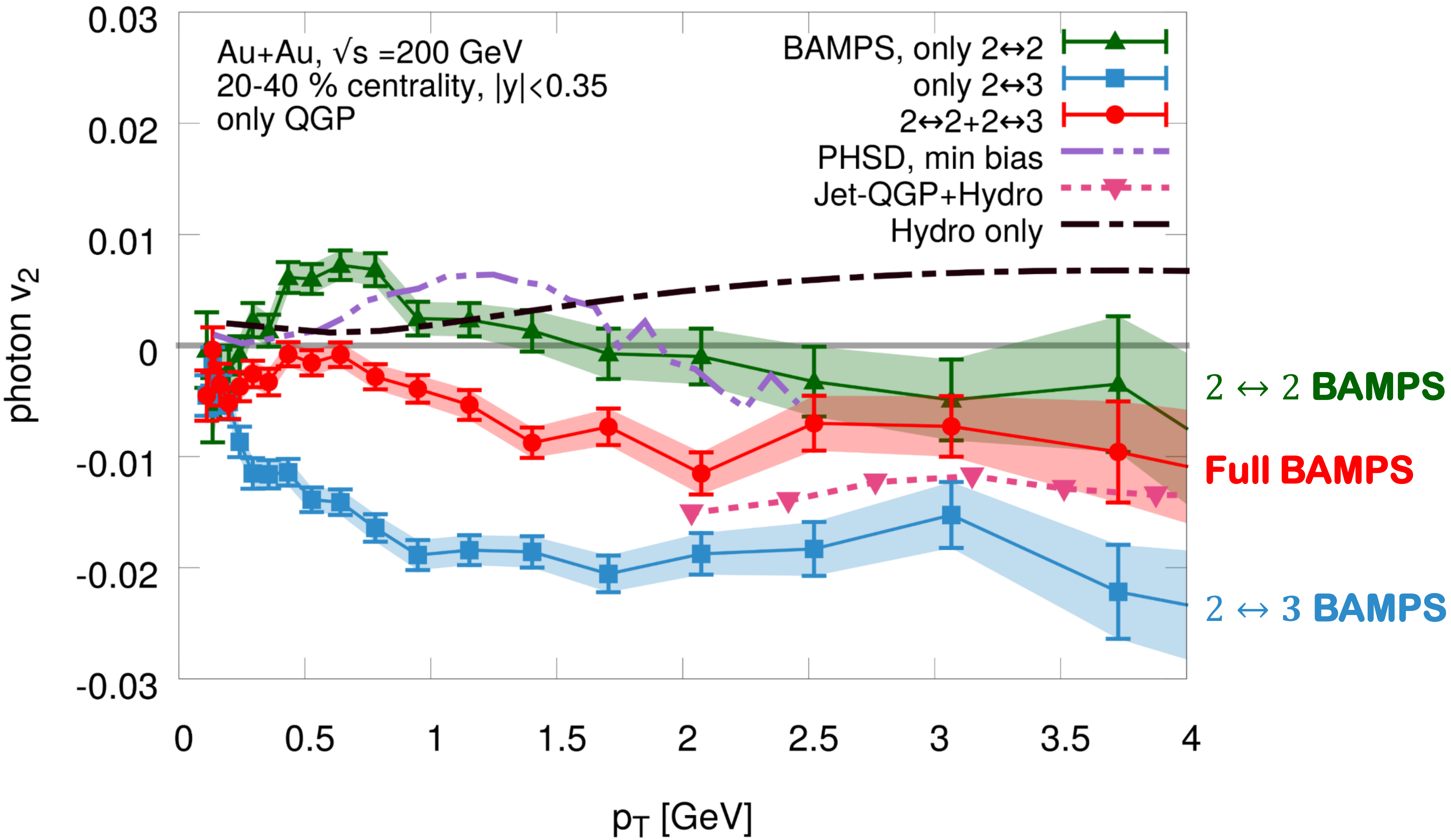
Toy plot: Naive “adding” of contributions (no „phase transition“)



- **Preequilibrium-phase only small difference**
- **Slight underestimation of data**

Hydro: Paquet et al, PRC 93 (2016), 044906

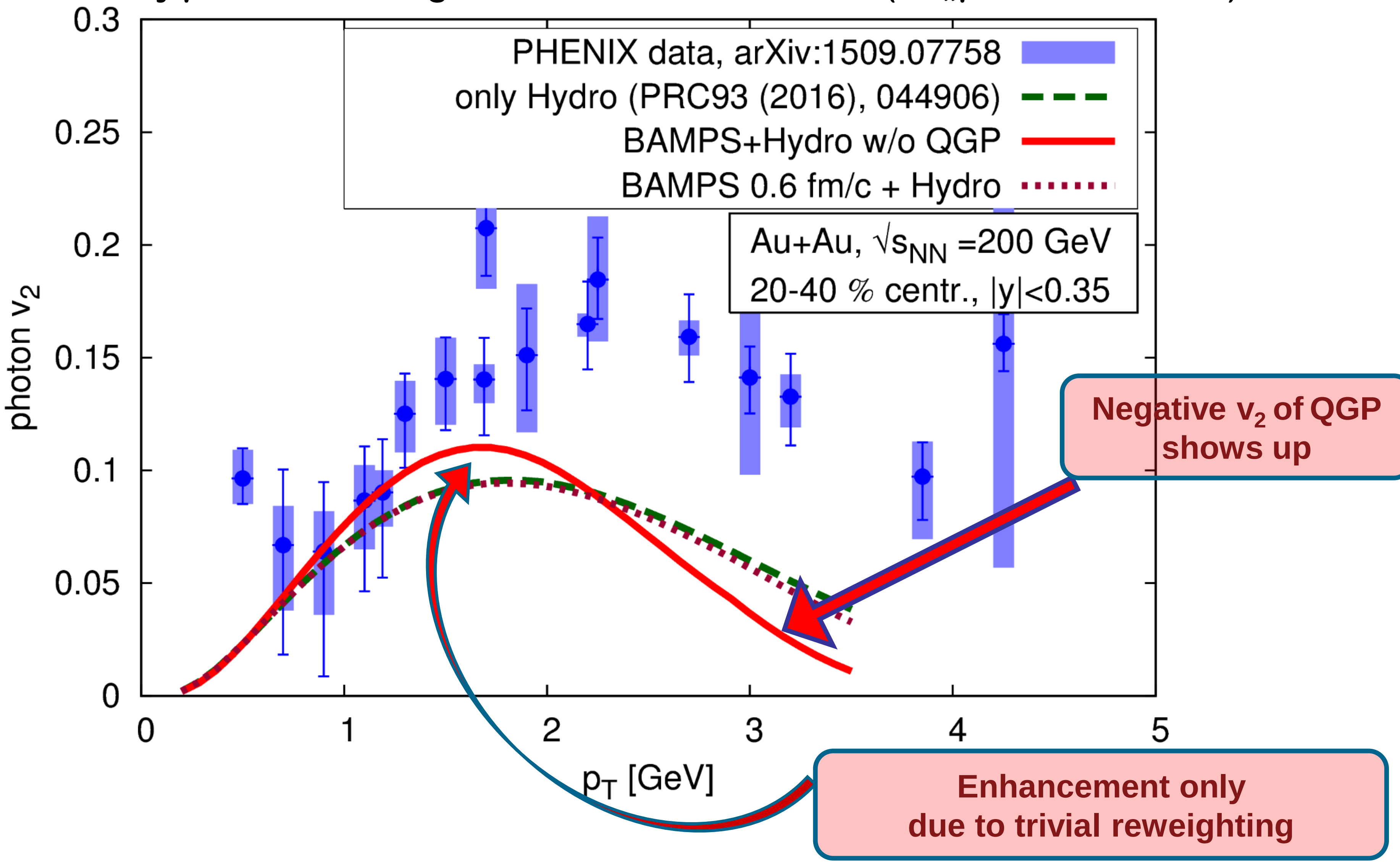
Photon v_2



Au+Au, √s =200 GeV
20-40 % centrality, |y|<0.35
only QGP
BAMPS, only 2↔2
only 2↔3
2↔2+2↔3
PHSD, min bias
Jet-QGP+Hydro
Hydro only
photon v2
pT [GeV]
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
0
0.5
1
1.5
2
2.5
3
3.5
4
2 ↔ 2 BAMPS
Full BAMPS
2 ↔ 3 BAMPS

Photon v_2

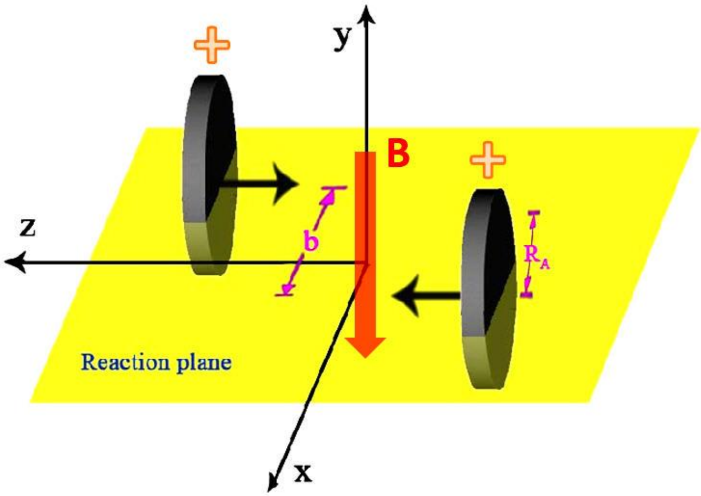
Toy plot: Naive "weighted sum" of contributions (no „phase transition")



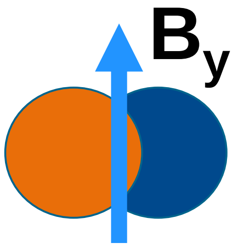
Magnetic fields can be strong!

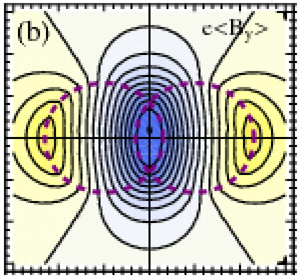
In heavy-ion collisions:

Strongest electromagnetic fields known in nature: 10^{19} Gauss



Magnetic field distribution:





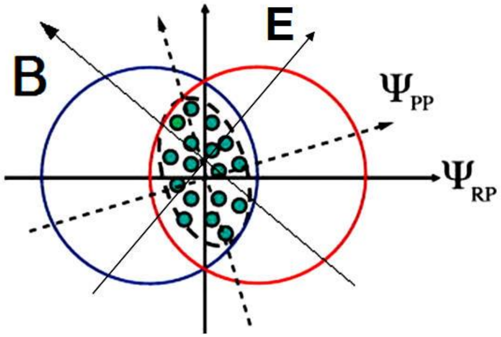
Occurence	Field strength [Gauss]
Lab: levitate a frog	10^5
Continuus field in lab	10^6
Neutron star/Magnetar	10^{10}
Heavy-ion collision	10^{19}

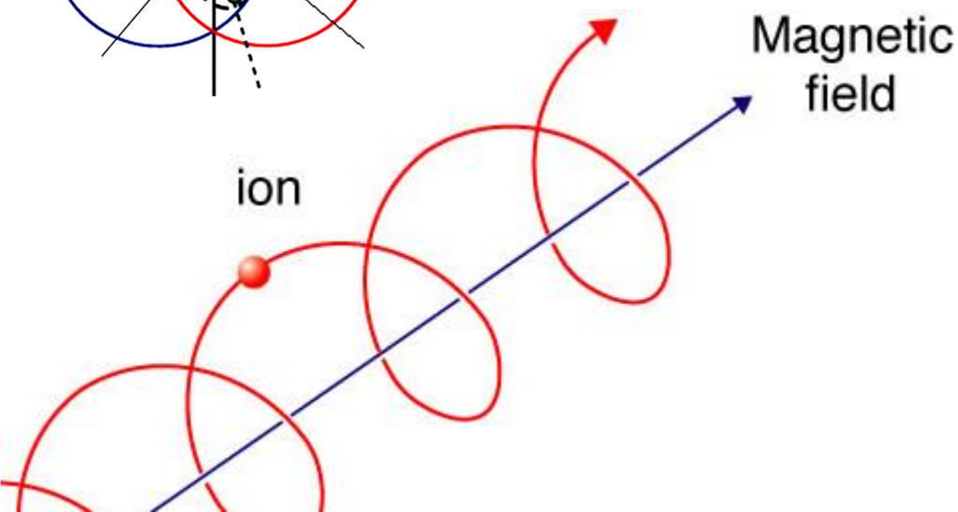
Lorentz force – mixer of the quark soup

Larmor radius:

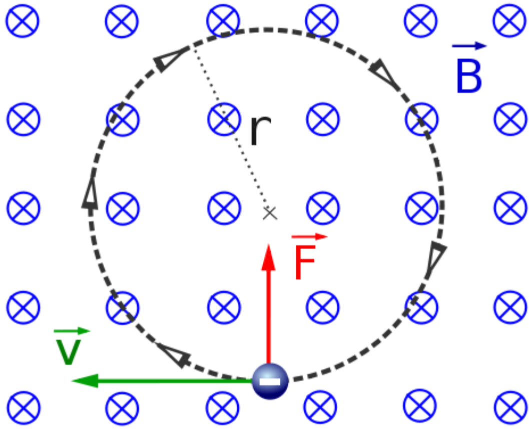
$$r_{Larmor} = \frac{p}{|q|B}$$

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

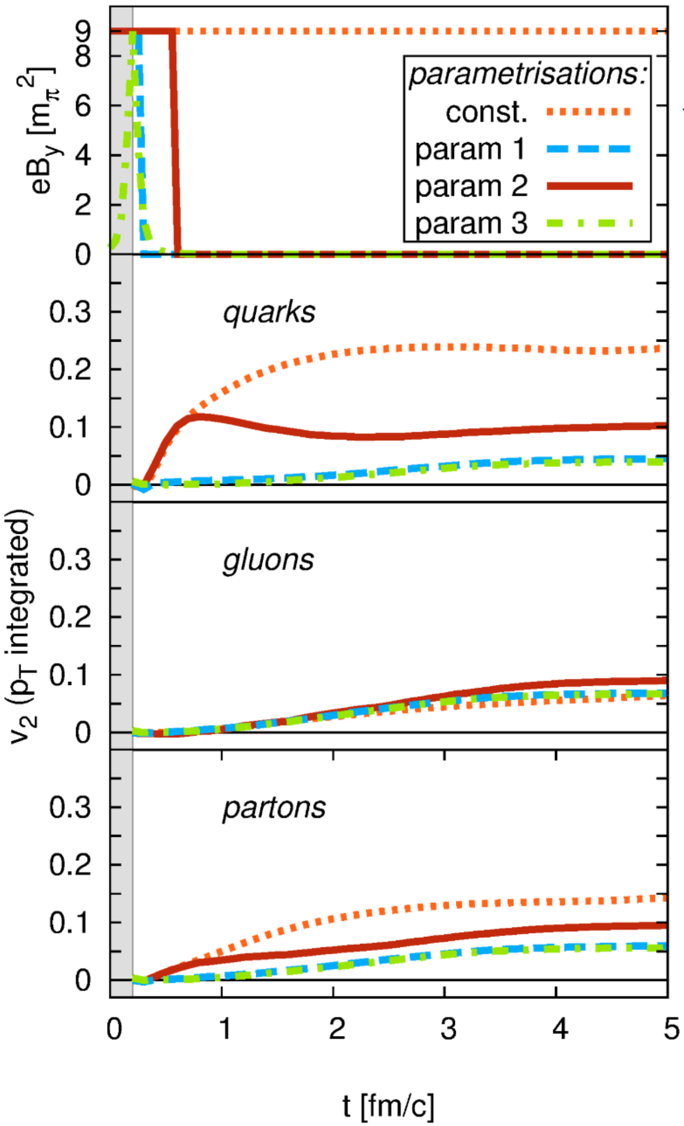




Larmor circular movement:



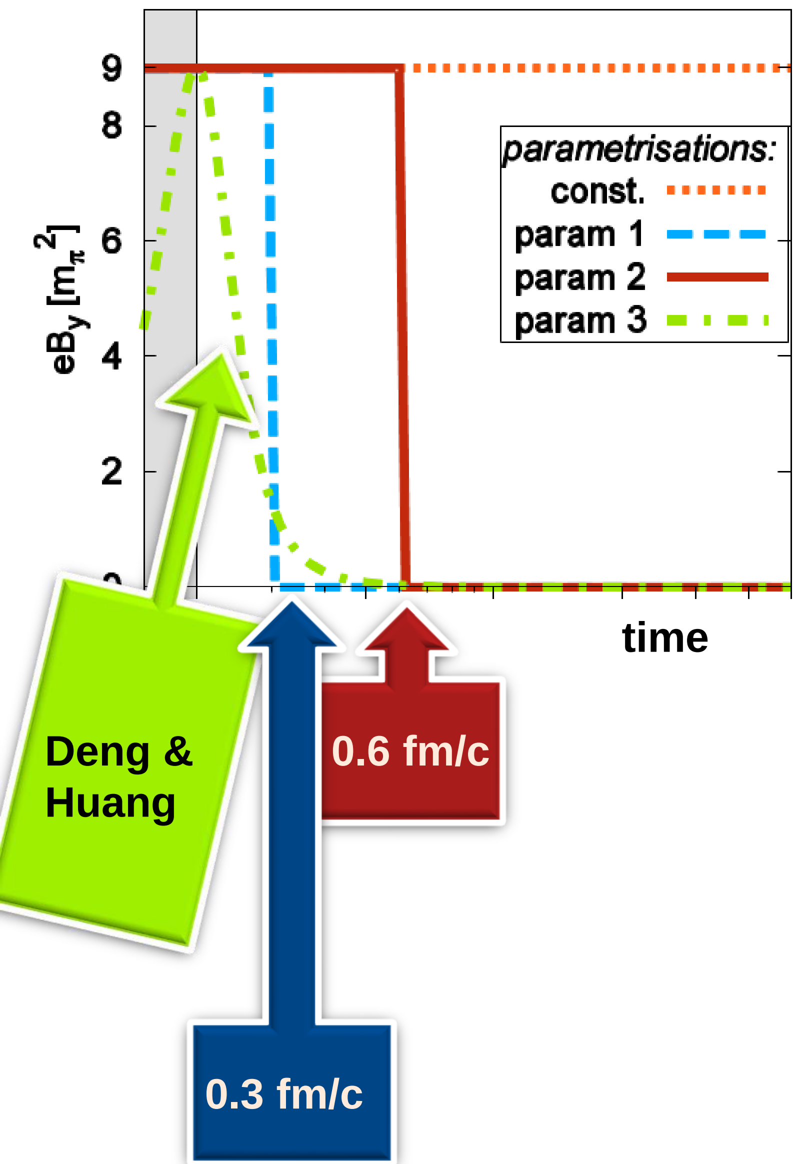
Parton v_2 with external magnetic fields



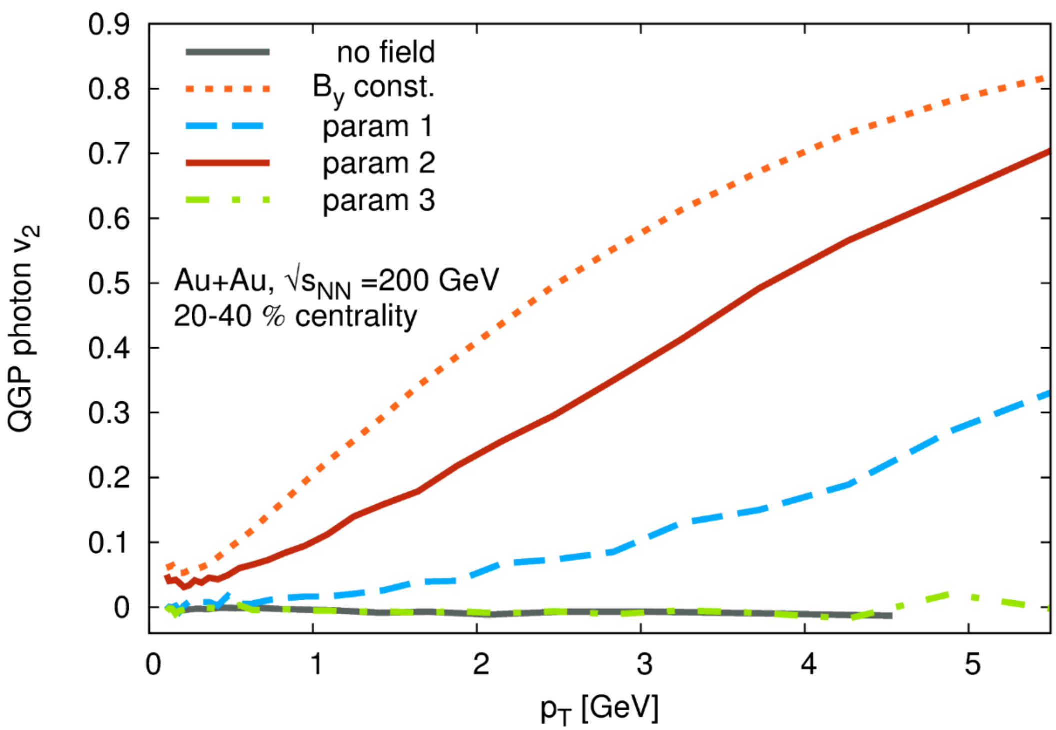
Still very rough parametrisations of the fields

- combined effect of initial field and later isotropisation
- quark v_2 increases early
- gluon v_2 nearly not affected
- parton v_2: average

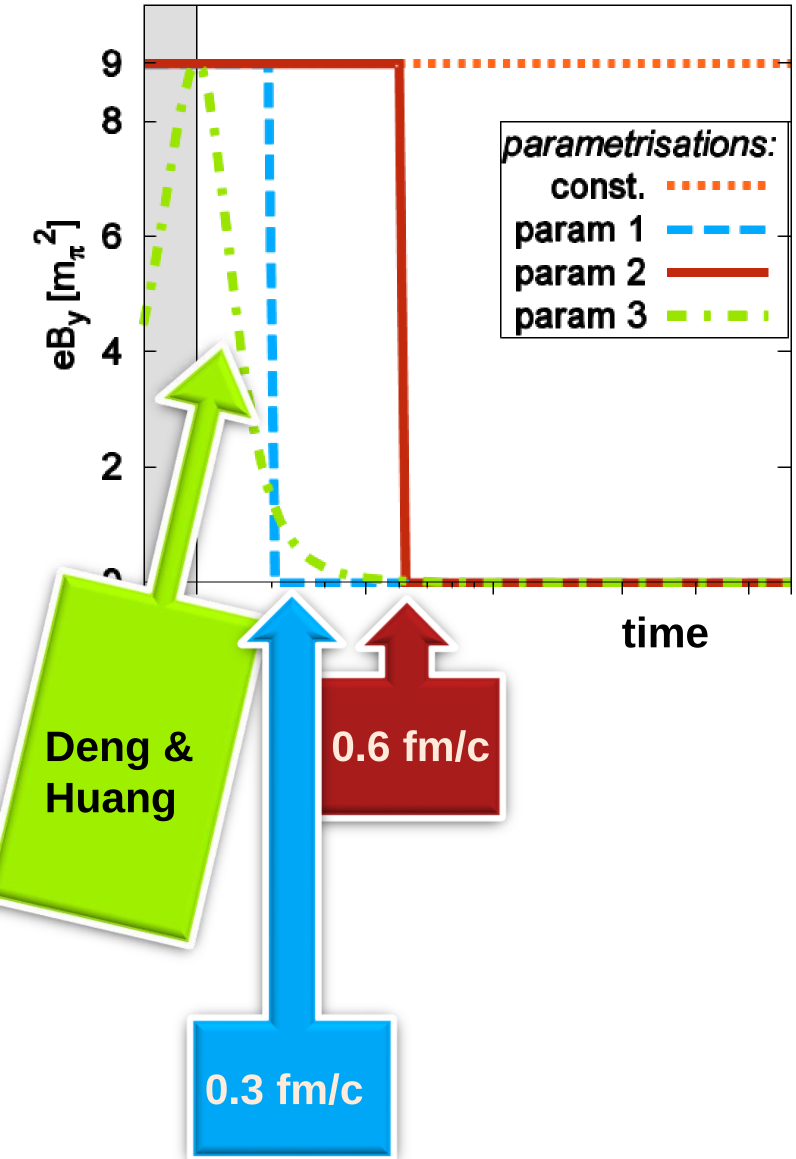
Rough parametrizations: strong effects



- Short initial magnetic fields: **strong** effect to momentum asymmetries
  - Explicit non-equilibrium effect
- Still little known about field strengths



p_T-dependent elliptic flow



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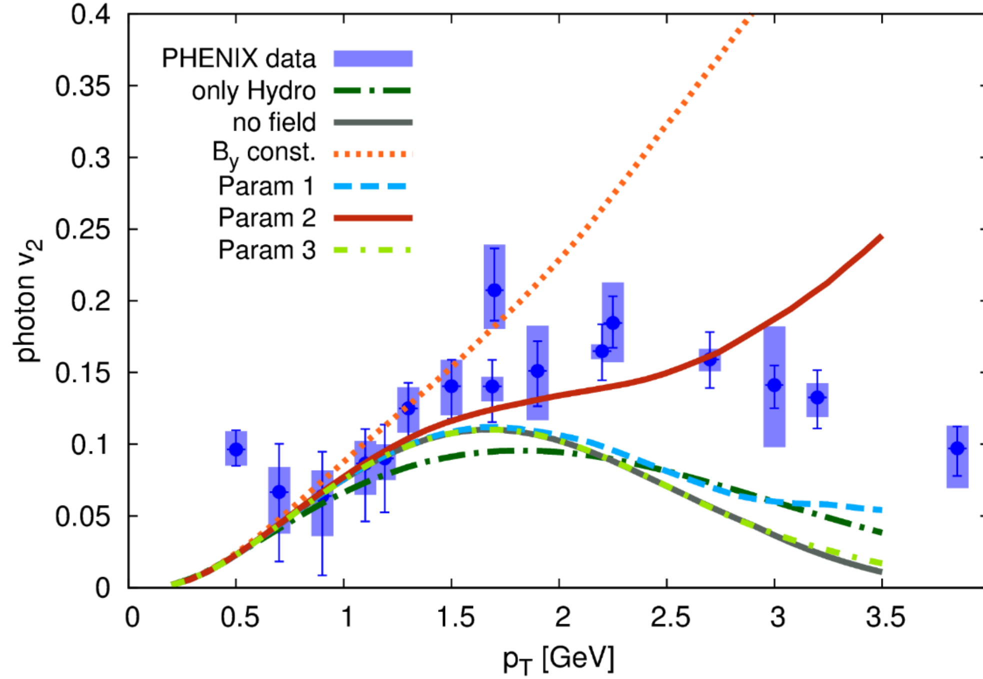
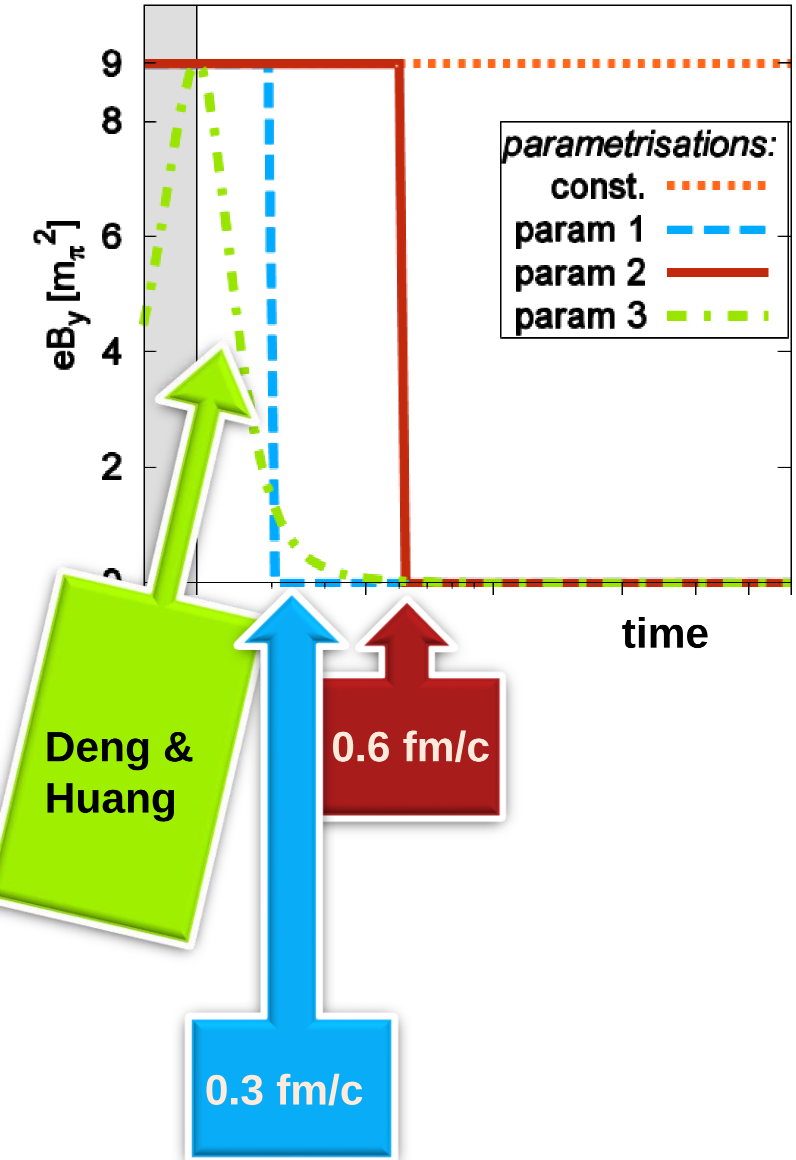
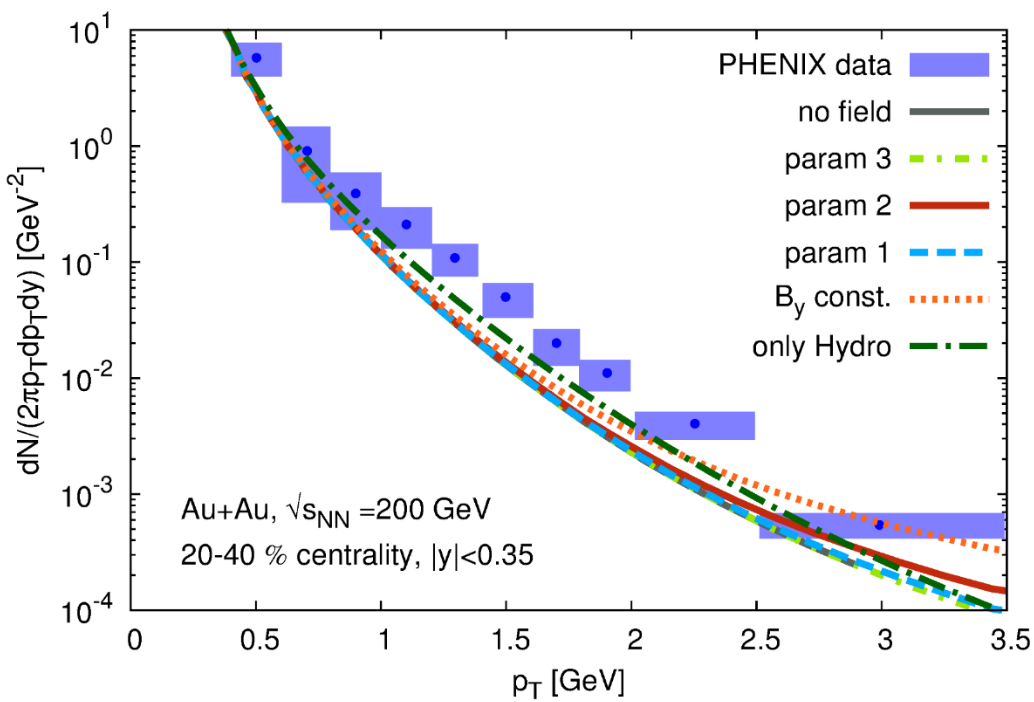


(Hydro contribution from: Paquet et al, PRC 93 (2016), 044906)

p_T-spectra

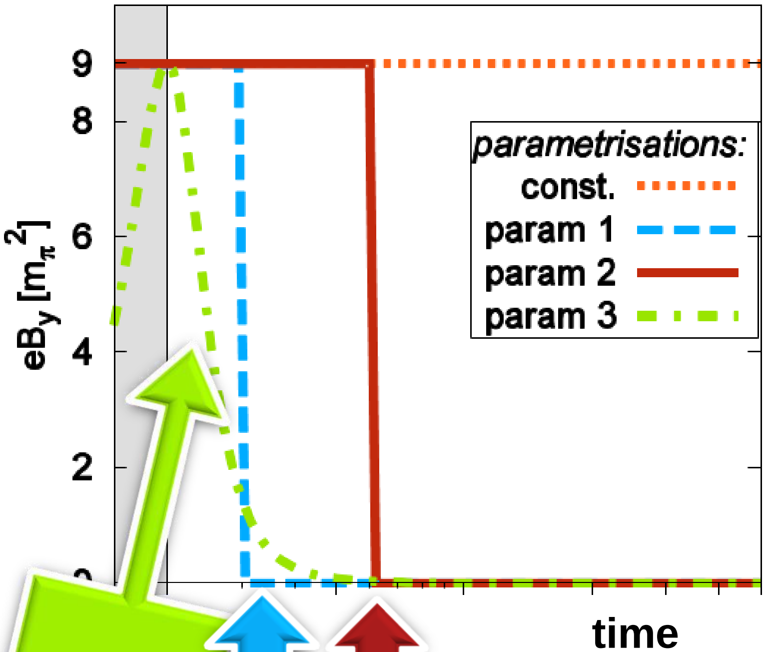


- Short initial magnetic fields: **small enhancement of the spectra**
- ***Exciting: enhancement of spectra AND flow***



(Hydro contribution from: Paquet et al, PRC 93 (2016), 044906)

p_T-spectra

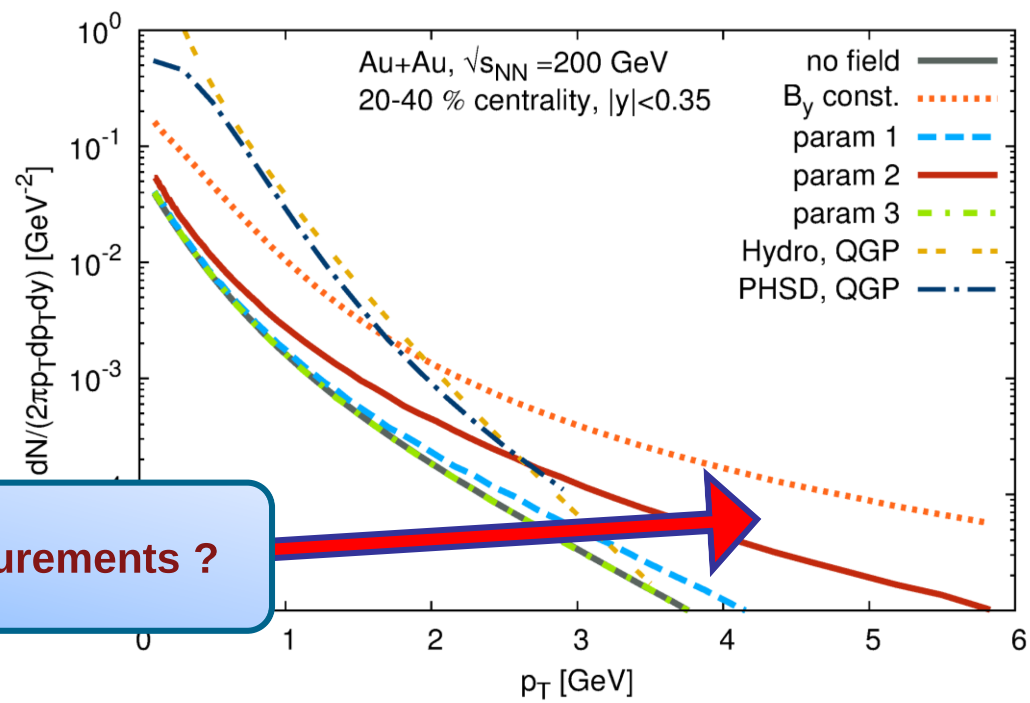


Deng & Huang

0.6 fm/c

0.3 fm/c

- **Short initial magnetic fields: small enhancement of the spectra**
- ***Exciting: enhancement of spectra AND flow***



High-p_T measurements ?

(Hydro contribution from: Paquet et al, PRC 93 (2016), 044906)

Conclusions & Outlook

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Non-equilibrium dynamics of heavy-ion collisions: BAMPS

- Full leading order photon production in transport approach
- Photon production in chemical & kinetic non-equilibrium
- Spectra and flow underestimate data

Based on arXiv:1612.05811

- Magnetic fields change the dynamics of the QGP
- Quarks and photons affected
- Magnetic fields show enhancement of flow and yield for photons

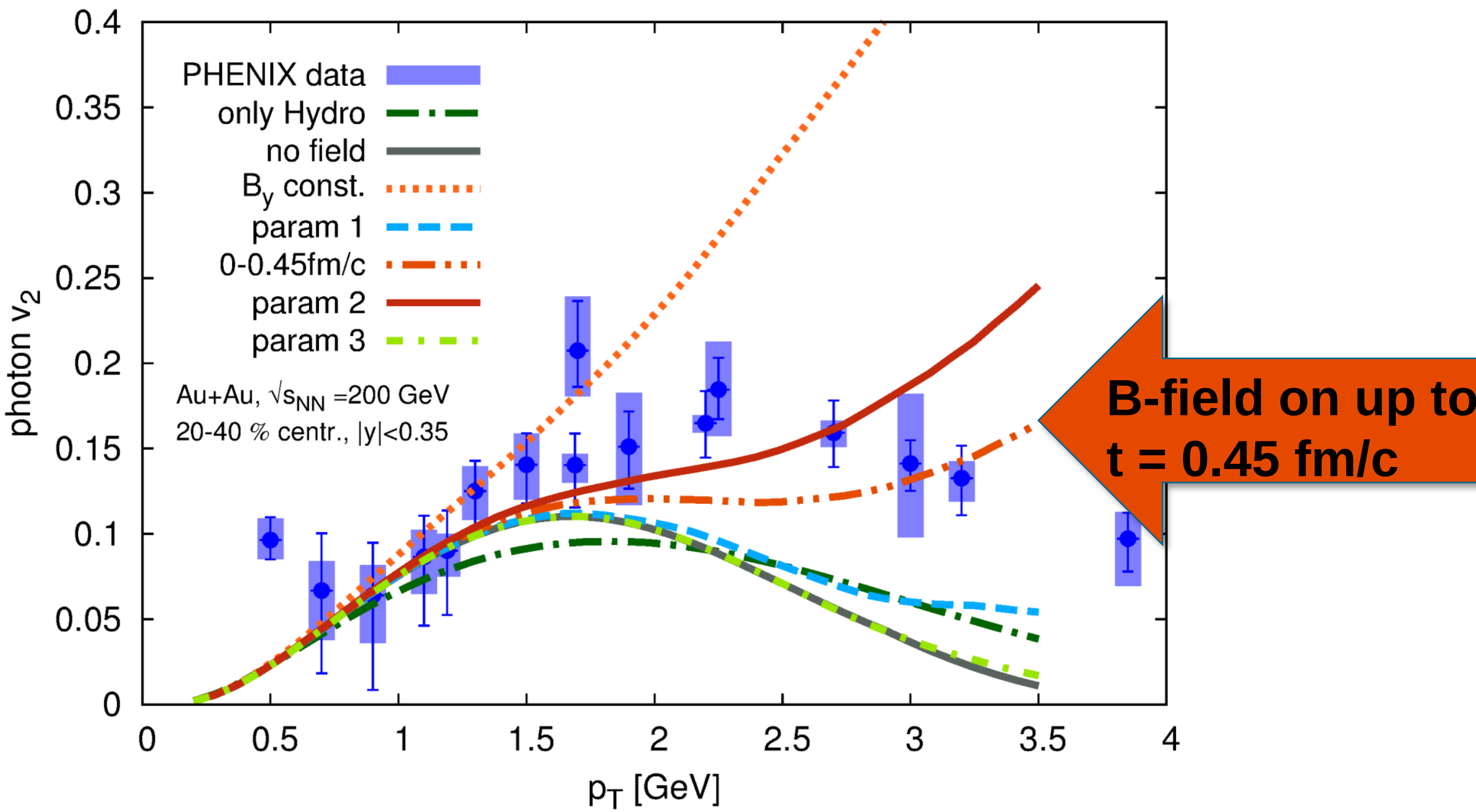
Preliminary! arxiv:1701:XXXX

Future tasks:

- Implement self-consistently Maxwell & Boltzmann equation in transport model (eg Hysterese)
- More quantitative calculations

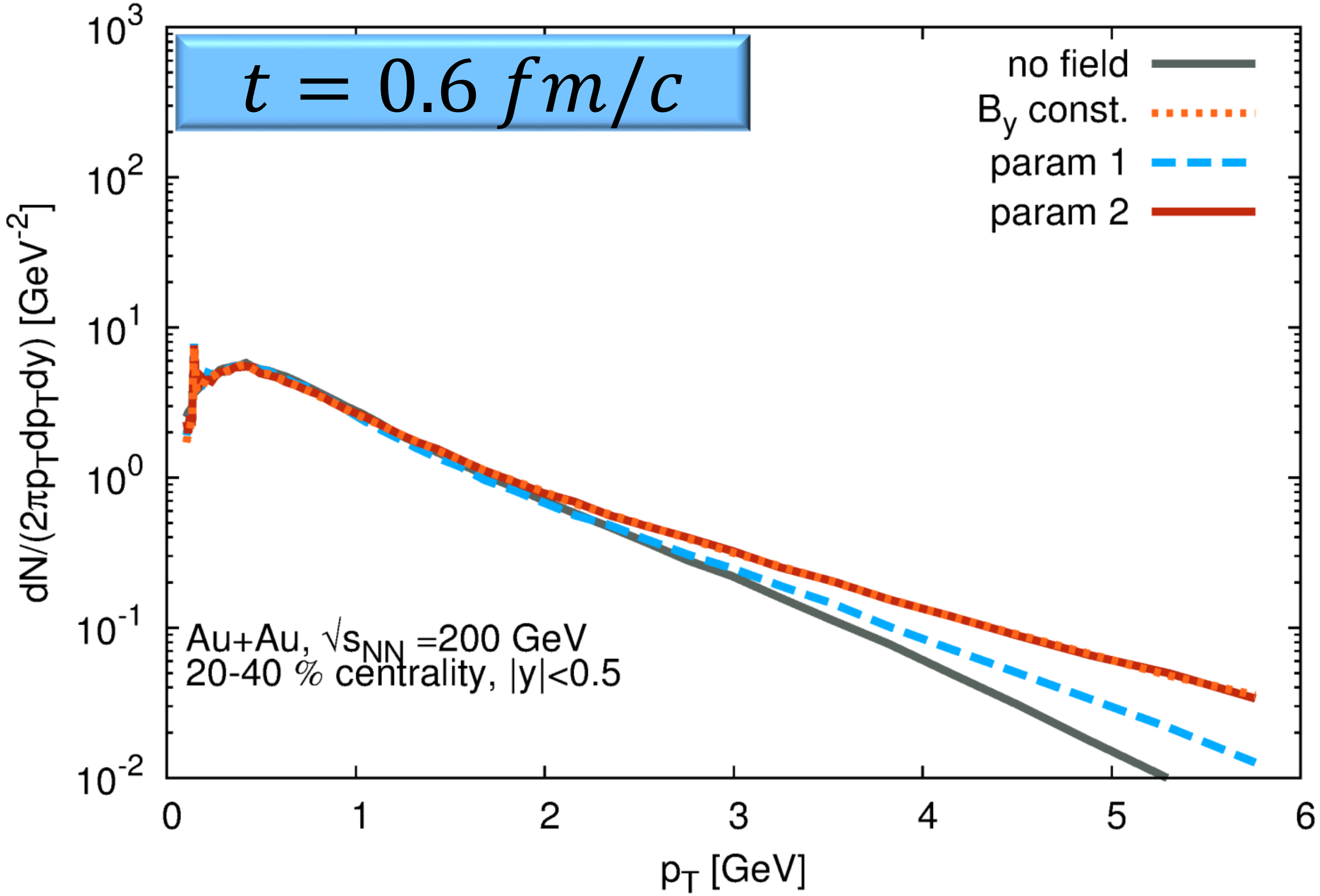
Backup slides

Photon v_2



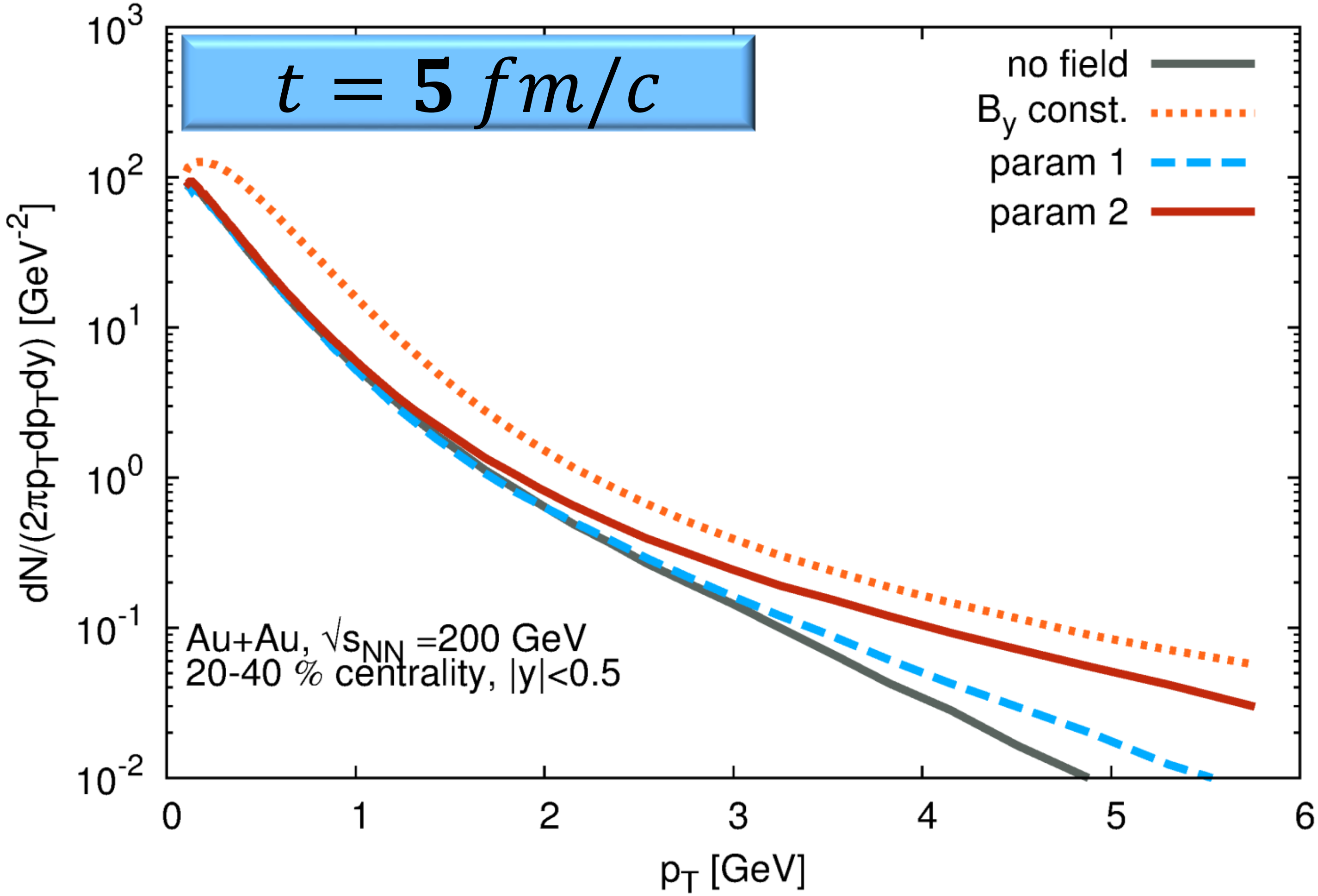
(Hydro contribution from: Paquet et al, PRC 93 (2016), 044906)

Quark spectrum

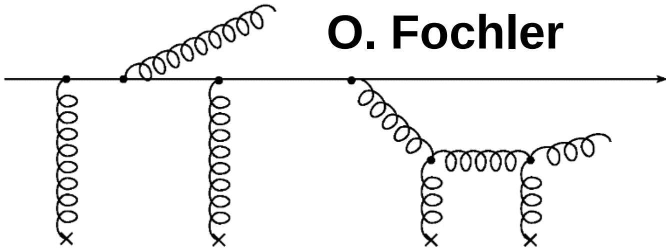


(Hydro contribution from: Paquet et al, PRC 93 (2016), 044906)

Quark spectrum



(Hydro contribution from: Paquet et al, PRC 93 (2016), 044906)



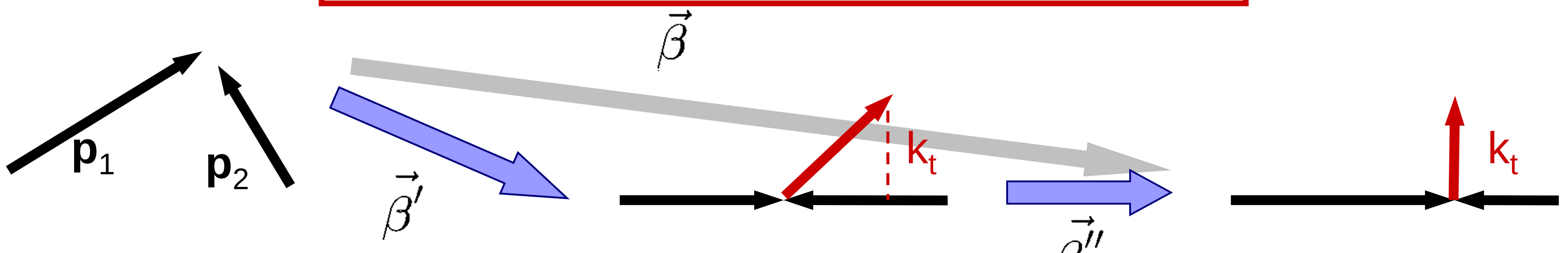
LPM - cutoff

- transport model: incoherent treatment of gg→ggg processes

➔ parent gluon must not scatter during formation time of emitted gluon

  - discard all possible interference effects (**Bethe-Heitler regime**)

$$|M_{gg\to ggg}|^2 \to |M_{gg\to ggg}|^2\,\Theta\left(\lambda-\tau\right)$$



lab frame
$\lambda = 1/ < n\sigma >$

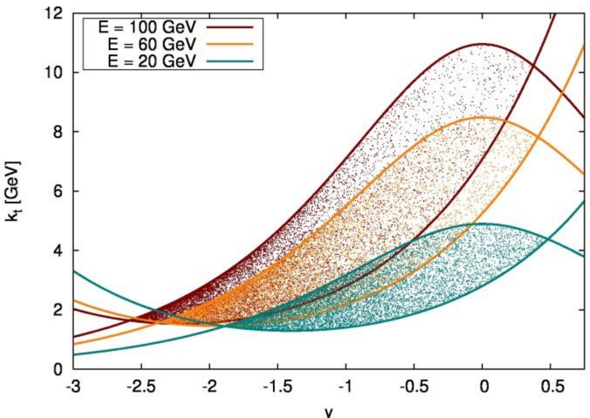
CM frame

$\beta'' = \tanh y$

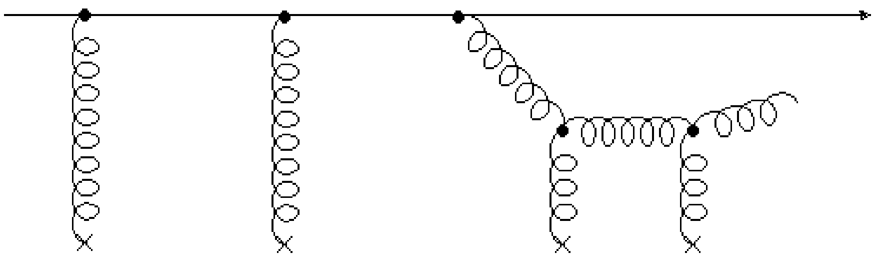
$\tau = 1/k_t$

total boost $\gamma = \gamma'\gamma''(1+\vec{\beta}'\vec{\beta}'') = \dfrac{\cosh y}{\sqrt{1-\beta'^2}}\left(1+\beta'\tanh y \cos\Theta\right)$

$$\Theta(\lambda-\tau) \to \Theta\left(k_\perp - \frac{\gamma}{\lambda}\right)$$

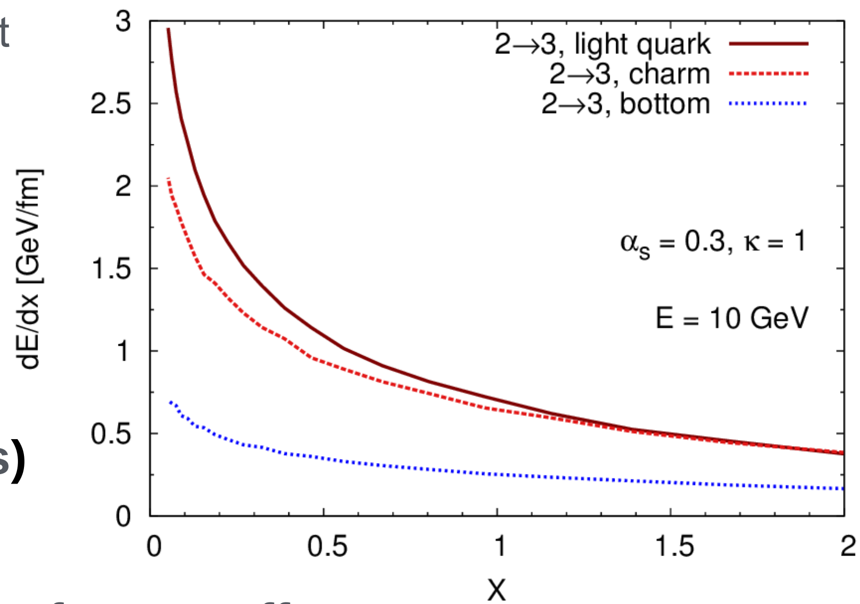


LPM cut-off



Mean free path $\lambda > X\,\tau$ **Formation time**

2 → 3 process only allowed if mean free path of jet larger than formation time of radiated gluon



$X = 0$ **No LPM effect**

$X = 1$ **Independent scatterings (forbids too many interactions)**

$0 < X < 1$ **Allows effectively some interference effects**

Radiative pQCD processes

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Exact matrix element

Kunszt, Pietarinen, Reya, Phys.Rev. D21 (1980)

$$\left|\overline{\mathcal{M}}\right|^2 = -16 \sum_{i,j=1}^{5} C_{ij} \frac{N_{ij}}{D_{ij}}$$

$$C = \frac{1}{3}\begin{pmatrix} 8 & 1 & 9 & -2 & -7 \\ & 8 & 9 & -7 & -2 \\ & & 18 & -9 & -9 \\ & & & 8 & 1 \\ & & & & 8 \end{pmatrix}$$

$$D = \begin{pmatrix} x_{31}^2 x_{54}^2, & 2x_{23}x_{31}x_{54}^2, & 4s_{12}x_{31}x_{54}^2, & 2s_{12}x_{31}x_{43}x_{54}, & 2s_{12}x_{31}x_{53}x_{54} \\ & x_{23}^2 x_{54}^2, & 4s_{12}x_{23}x_{54}^2, & 2s_{12}x_{23}x_{43}x_{54}, & 2s_{12}x_{23}x_{53}x_{54} \\ & & 4s_{12}^2 x_{54}^2, & 4s_{12}^2 x_{43}x_{54}, & 4s_{12}^2 x_{53}x_{54} \\ & & & s_{12}^2 x_{43}^2, & 2s_{12}^2 x_{43}x_{53} \\ & & & & s_{12}^2 x_{53}^2 \end{pmatrix}$$

$$N_{11} = x_{31}(-x_{42}x_{53} - x_{43}x_{52} + 2m_Q^2 x_{54}) + 2m_Q^2(x_{41}x_{52} + x_{42}x_{51} + x_{42}x_{53} + x_{43}x_{52} + 2m_Q^2 x_{54}),$$

$$N_{12} = x_{12}[x_{41}(2x_{52} + x_{53}) + x_{42}(2x_{51} + x_{53}) + x_{43}(x_{51} + x_{52}) + 4m_Q^2 x_{54}] + x_{23}[x_{41}(-2x_{51} + x_{52}) + x_{42}x_{51} + 2m_Q^2 x_{54}] + x_{31}[x_{41}x_{52} + x_{42}(x_{51} - 2x_{52}) + 2m_Q^2 x_{54}] - 4m_Q^2 x_{43}x_{53},$$

$$N_{13} = x_{12}[-2x_{31}x_{54} + x_{41}(4x_{52} + 3x_{53}) + x_{42}(4x_{51} + 3x_{53}) + x_{43}(3x_{51} + 3x_{52} + 2x_{53}) + 8m_Q^2 x_{54}] + x_{23}[x_{41}(-6x_{51} + x_{52} - x_{53}) + (x_{42} - x_{43})x_{51} + 4m_Q^2 x_{54}] + x_{31}[x_{41}x_{52} + x_{42}(x_{51} - 2x_{52} - 3x_{53}) - 3x_{43}x_{52}] + 2m_Q^2[x_{41}(2x_{51} + 4x_{52} + 3x_{53}) + x_{42}(4x_{51} - 2x_{52} + 5x_{53}) + x_{43}(3x_{51} + 5x_{52}) + 8m_Q^2 x_{54}],$$

$$N_{14} = x_{51}(-x_{12}x_{43} + x_{23}x_{41} + x_{42}x_{43}) + x_{31}[2x_{41}x_{52} + x_{42}(x_{51} - x_{54}) + 2x_{43}x_{52} + 2m_Q^2 x_{54}] + x_{41}[2(x_{41} + x_{43})x_{52} + x_{42}(2x_{51} + x_{53}) + 2m_Q^2(x_{53} + 2x_{54})] + 2m_Q^2 x_{43}(x_{53} + x_{54} - x_{51} - x_{52}),$$

$$N_{15} = N_{14}(4 \leftrightarrow 5), \quad N_{22} = N_{11}(1 \leftrightarrow 2), \quad N_{23} = N_{13}(1 \leftrightarrow 2), \quad N_{24} = N_{14}(1 \leftrightarrow 2), \quad N_{25} = N_{24}(4 \leftrightarrow 5),$$

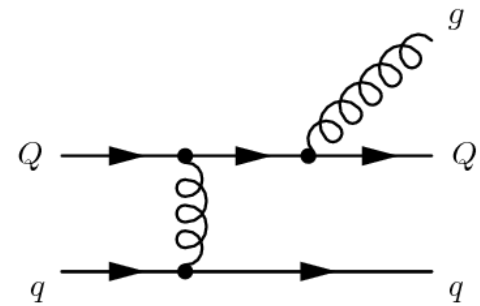
$$N_{33} = x_{12}[2x_{54}(x_{12} - x_{23} - x_{31}) + x_{41}(-2x_{51} + 6x_{52} + 5x_{53}) + x_{42}(-2x_{52} + 6x_{51} + 5x_{53}) + x_{43}(5x_{51} + 5x_{52} + 4x_{53}) + 28m_Q^2 x_{54}] + x_{23}[-2x_{31}x_{54} + x_{41}(-6x_{51} + x_{52} - 3x_{53}) + (x_{42} - 3x_{43})x_{51}] + x_{31}[x_{41}x_{52} + x_{42}(x_{51} - 6x_{52} - 3x_{53}) - 3x_{43}x_{52}] + 2m_Q^2[x_{41}(-4x_{51} + 4x_{52} + 7x_{53}) + x_{42}(4x_{51} - 4x_{52} + 7x_{53}) + x_{43}(7x_{51} + 7x_{52} + 2x_{53}) + 24m_Q^2 x_{54}],$$

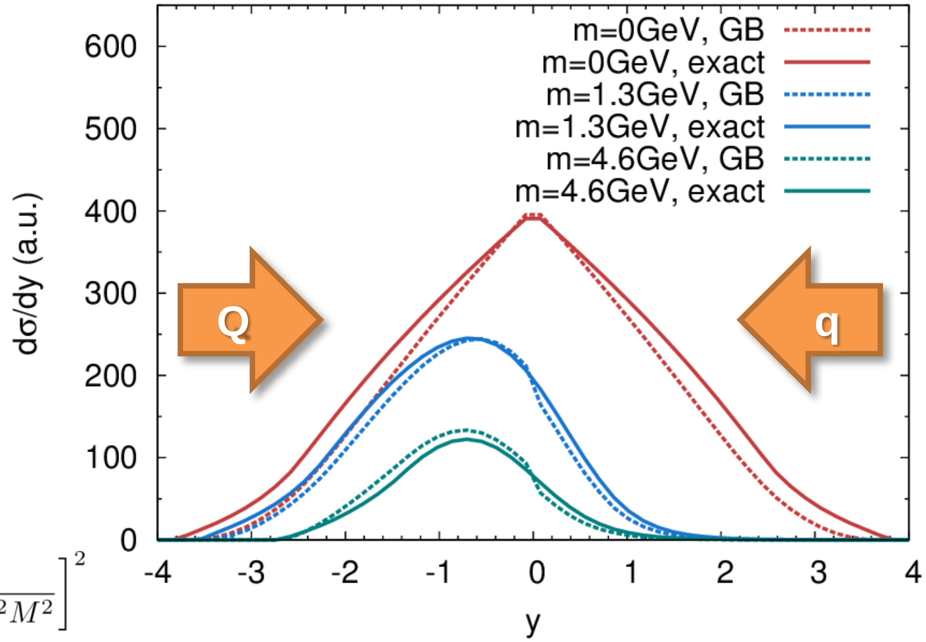
$$N_{34} = x_{12}[x_{54}(x_{23} + x_{31} + x_{42} + x_{41}) - 2x_{43}(x_{51} + x_{52})] + x_{23}[2x_{31}x_{54} + x_{41}(x_{52} - x_{53} - x_{54}) + 3x_{51}(x_{42} + x_{43}) + 8m_Q^2 x_{54}] + x_{31}[x_{42}(x_{51} - x_{53} - x_{54}) + 3x_{52}(x_{41} + x_{43}) + 8m_Q^2 x_{54}] + x_{41}[3(x_{41} + x_{43})x_{52} + x_{42}(x_{51} + x_{52} + 2x_{53}) + 2m_Q^2(x_{53} + 5x_{54})] + x_{42}[3(x_{42} + x_{43})x_{51} + 2m_Q^2(x_{53} + 5x_{54})] + 2m_Q^2 x_{43}(2x_{53} + 2x_{54} - 5x_{51} - 5x_{52}),$$

$$N_{44} = x_{43}(-x_{23}x_{51} - x_{31}x_{52} - 2m_Q^2 x_{53}),$$

$$N_{45} = x_{54}[x_{23}(x_{41} + x_{51}) + x_{31}(x_{42} + x_{52}) + 4m_Q^2(x_{53} + x_{54} + x_{43})] + x_{41}[x_{52}(x_{43} + 2x_{54}) + x_{53}(x_{52} - 2x_{42})] + x_{51}[-2x_{43}x_{52} + x_{42}(x_{53} + 2x_{54} + x_{43})],$$

$$N_{35} = N_{34}(4 \leftrightarrow 5), \quad N_{55} = N_{44}(4 \leftrightarrow 5).$$



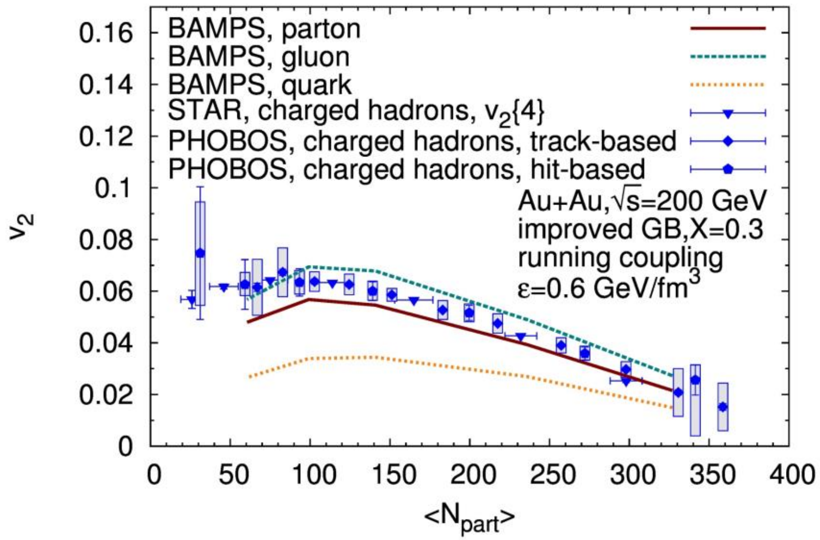


Gunion Bertsch (GB) approximation

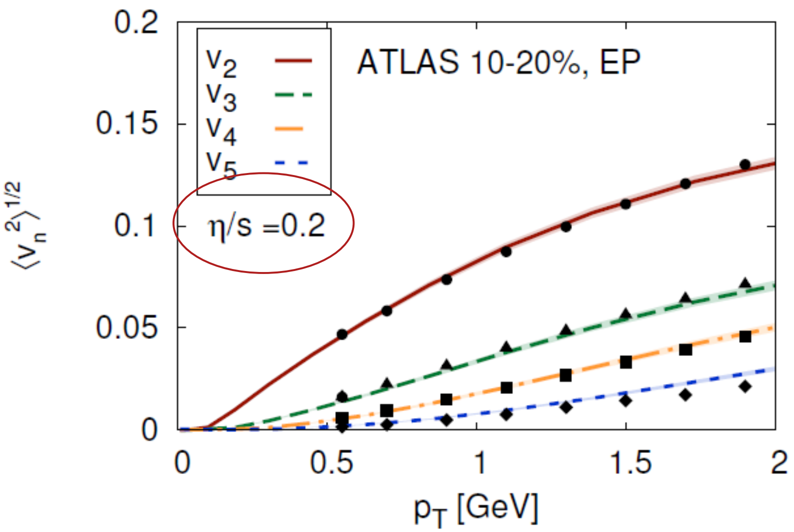
$$\left|\overline{\mathcal{M}}_{qQ\to qQg}\right|^2 = 12g^2(1-\bar{x})^2 \left|\overline{\mathcal{M}}_0^{qQ}\right|^2 \left[\frac{\mathbf{k}_\perp}{k_\perp^2 + x^2M^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + x^2M^2}\right]^2$$

Fochler, JU, Xu, Greiner, Phys. Rev. D88 (2013)

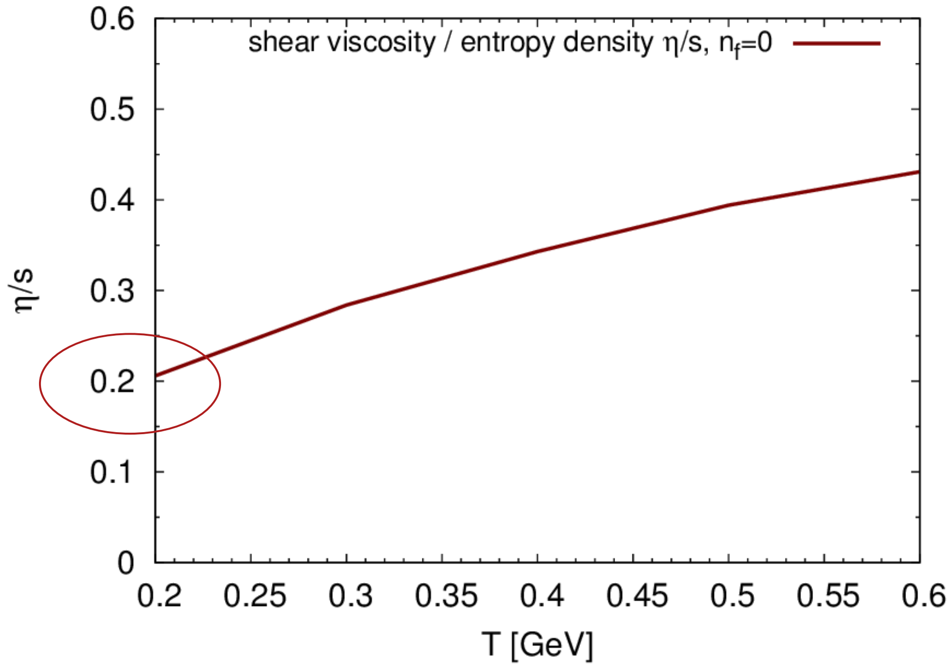
Shear viscosity as QGP transport parameter



Reason for large elliptic flow: Small shear viscosity to entropy density ratio



From parameters to calculations:



Phys. Rev. Lett. 114 (2015) 112301