Viscous corrections to photon emission in heavy-ion collisions

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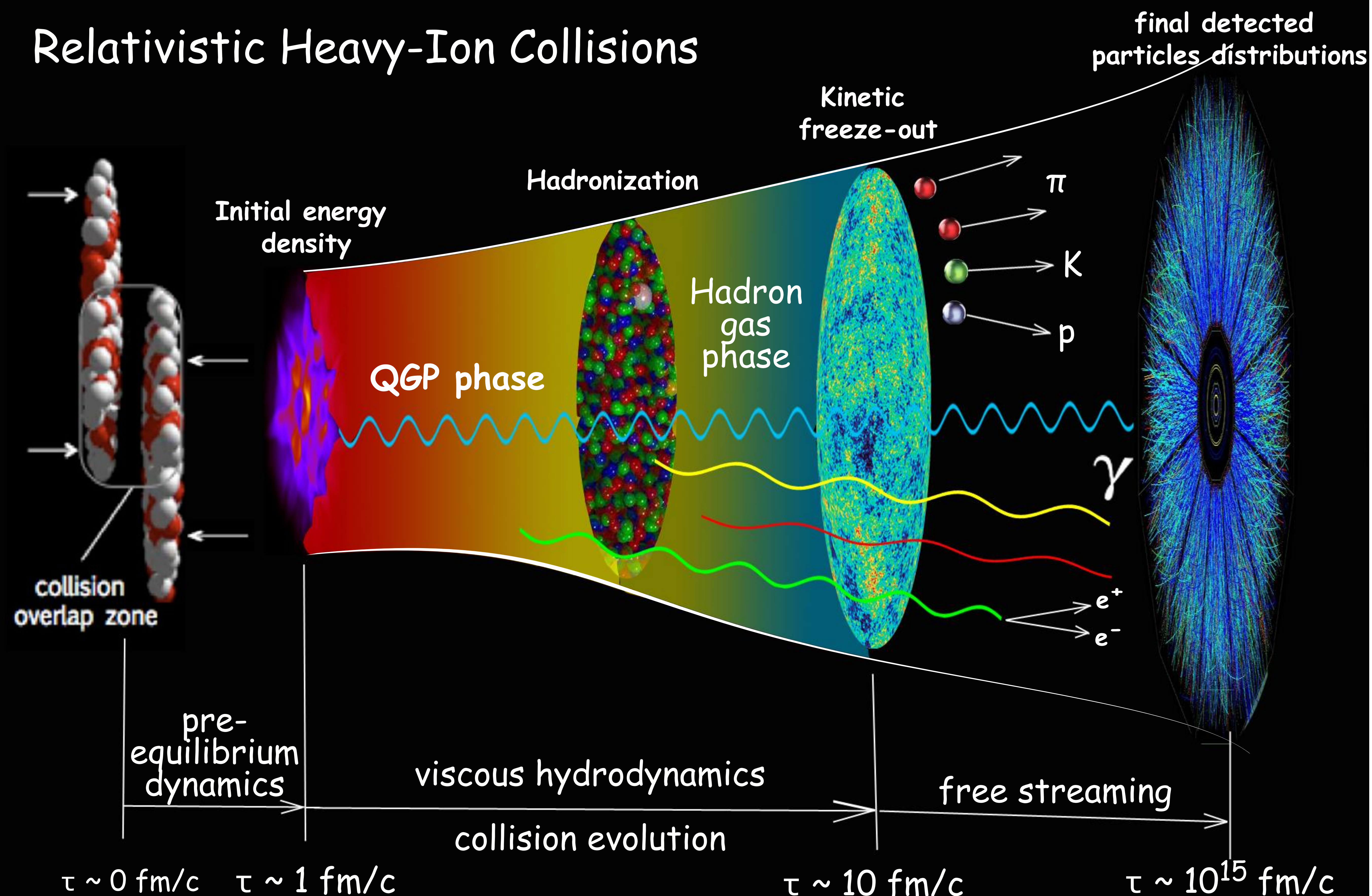
The Ohio State University

In collaboration with Ulrich Heinz, Charles Gale, Gabriel Denicol, Jia Liu, and Jean-Francois Paquet

May 19, 2014 Quark Matter Darmstadt

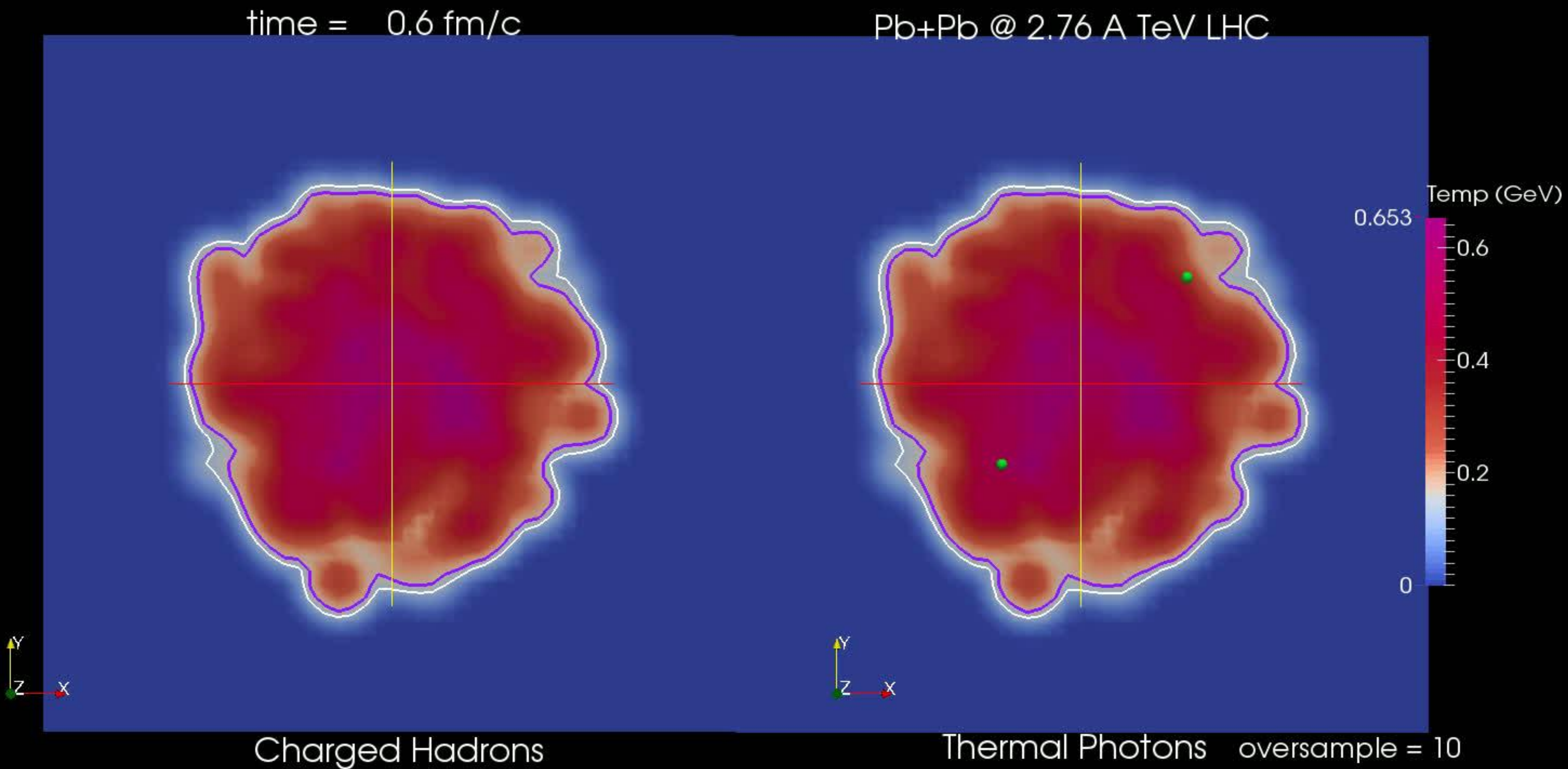
arXiv: 1308.2111, 1308.2440, 1403.7558

Little Bang



Relativistic Heavy-Ion Collisions
final detected particles distributions
Kinetic freeze-out
Hadronization
Initial energy density
π
K
p
Hadron gas phase
QGP phase
γ
collision overlap zone
e^+
e^-
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^{15} fm/c

Photons from Heavy-ion Collisions



State-of-the-art hydrodynamic modeling

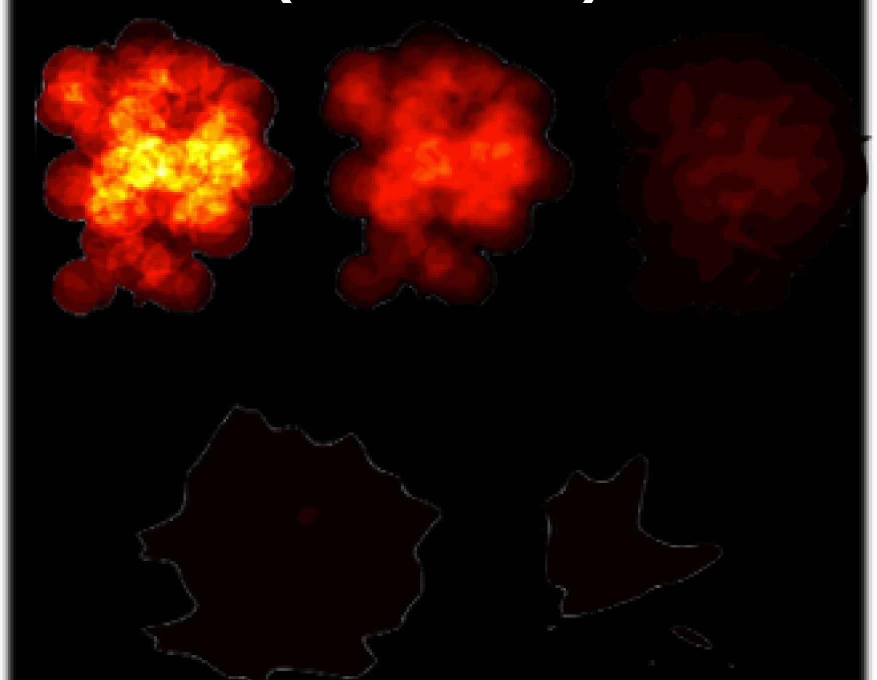
Initial Condition Generators (MC- KLN, MC- Glauber)

https://github.com/chunshen1987/iEBE.git

JET Collaboration

Thermal Photon Emission Rates

Hydrodynamic Simulations (VISH2+1)



HydroInfo Package

$e, s, p, T,$

$u^\mu, \pi^{\mu\nu}$

Thermal Photon Interface

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu} q_\mu q_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

$$E\frac{dN^\gamma}{d^3p} = \int d^4x\, q\frac{dR}{d^3q}$$

Hadrons spectra & v_n

Photon spectrum & v_n

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viscous corrections

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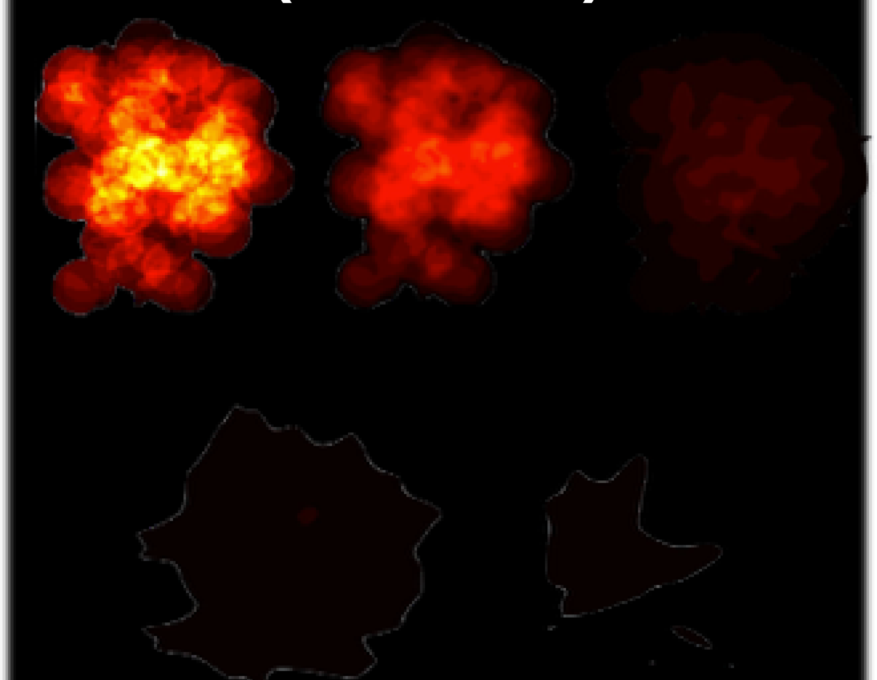

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viscous corrections

Hadrons spectra & v_n

Photon spectrum & v_n

Viscous Photon Emission Rates: General Formalism

Thermal photon emission rates can be calculated by

$$E_q \frac{dR}{d^3q} = \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} \frac{1}{2(2\pi)^3} |M|^2$$

$$\times f_1(p_1^\mu) f_2(p_2^\mu)(1 \pm f_3(p_3^\mu))(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - q)$$

With

$$f(p^\mu) = f_0(E) + f_0(E)(1 \pm f_0(E)) \frac{\pi^{\mu\nu} \hat{p}_\mu \hat{p}_\nu}{2(e+p)} \chi\left(\frac{p}{T}\right)$$

We can expand photon emission rates around the thermal equilibrium:

$$q \frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu} \hat{q}_\mu \hat{q}_\nu}{2(e+p)} a_{\alpha\beta} \Gamma^{\alpha\beta},$$

$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4} \hat{q}_\mu \hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2} u_\mu u_\nu + \frac{1}{2(u\cdot\hat{q})^2} g_{\mu\nu} - \frac{3}{2(u\cdot\hat{q})^3} (\hat{q}_\mu u_\nu + \hat{q}_\nu u_\mu).$$

Viscous Photon Emission Rates: General Formalism

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$$f(p^\mu) = f \quad \ldots \quad \frac{\pi^{\mu\nu}\hat{p}_\mu \hat{p}_\nu}{\ldots)} \chi \left(\frac{p}{T}\right)$$

We can expa... und the thermal equilibrium:

$\Gamma_0(q, T)$ $a_{\alpha\beta}\Gamma^{\alpha\beta}(q, T)$

calculated in fluid local rest frame

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta},$$

calculated in lab frame

$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4}\hat{q}_\mu\hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2}u_\mu u_\nu + \frac{\ldots}{2(u\cdot\hat{q})^2} \ldots \mu).$$

Viscous Photon Emission Rates: General Formalism

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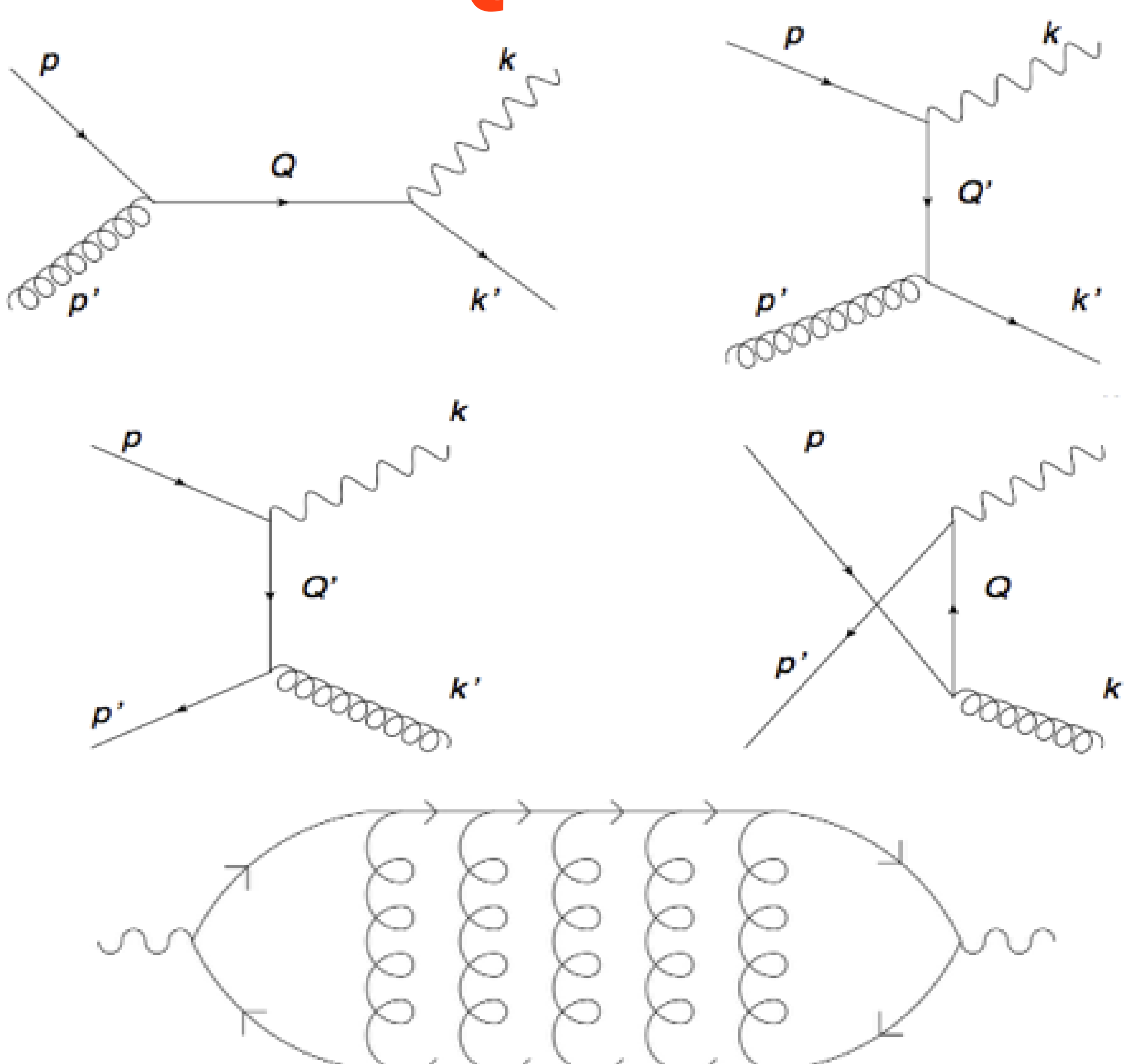
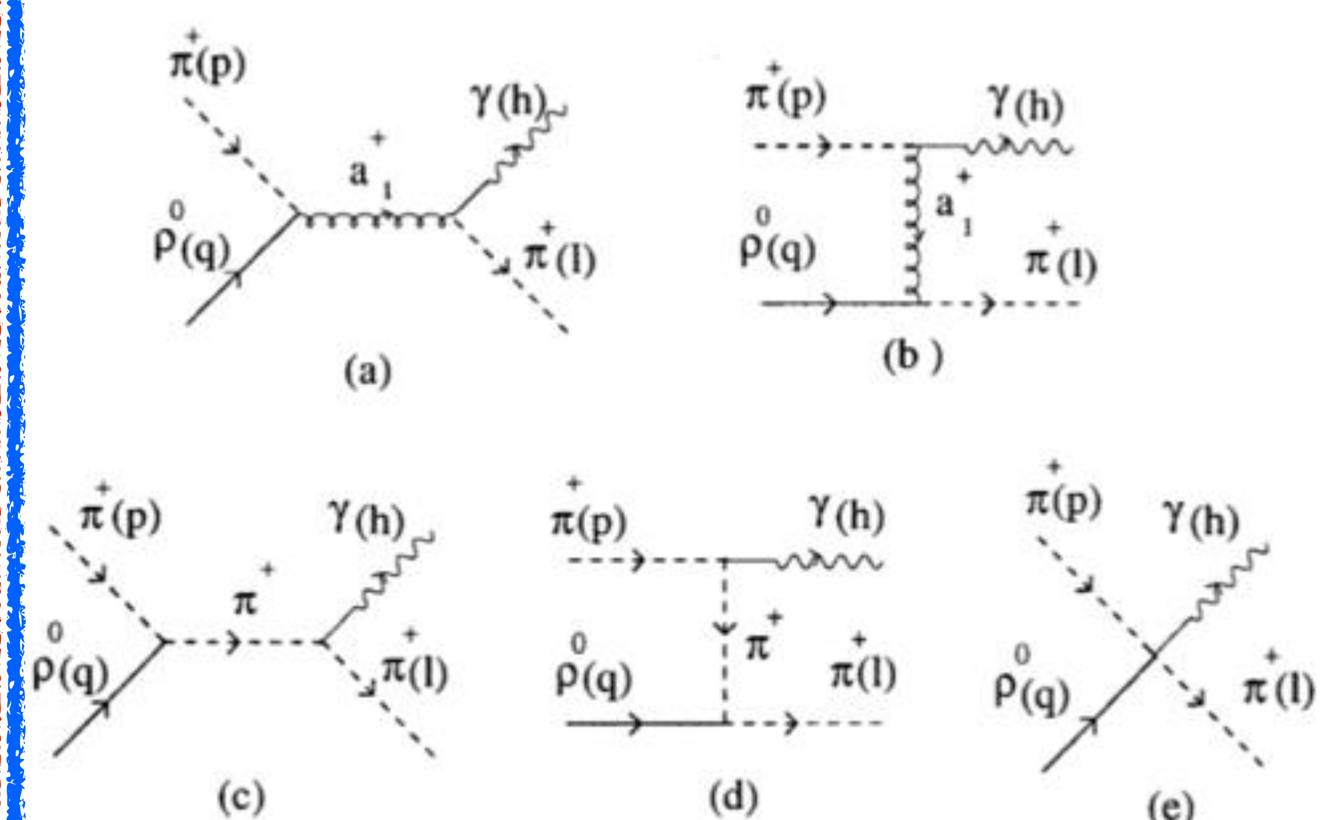
Equilibrium rates

QGP (AMY 2001)



Hadron Gas (TRG 2004)



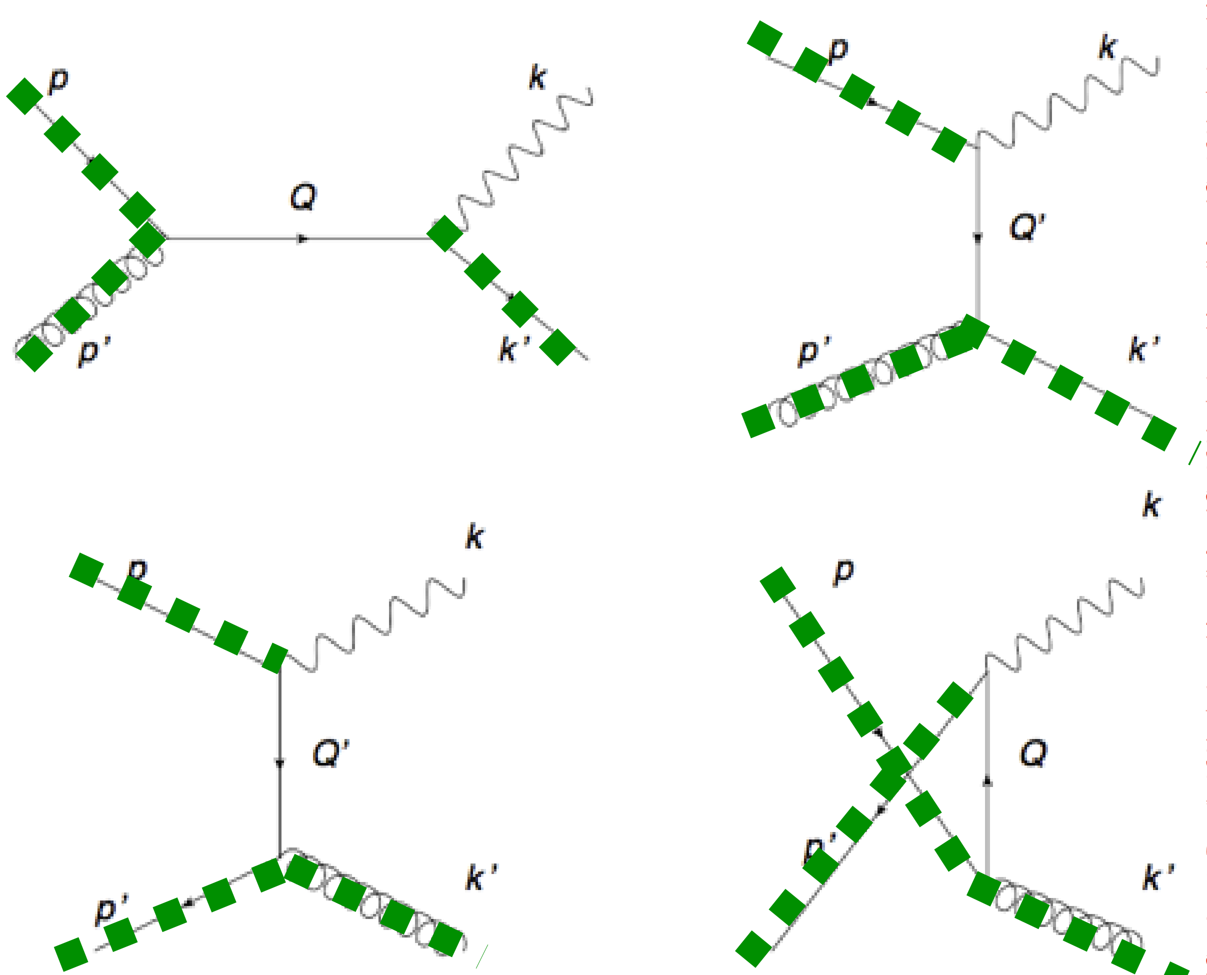
Viscous Photon Emission Rates: General Formalism

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu \hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

Equilibrium rates

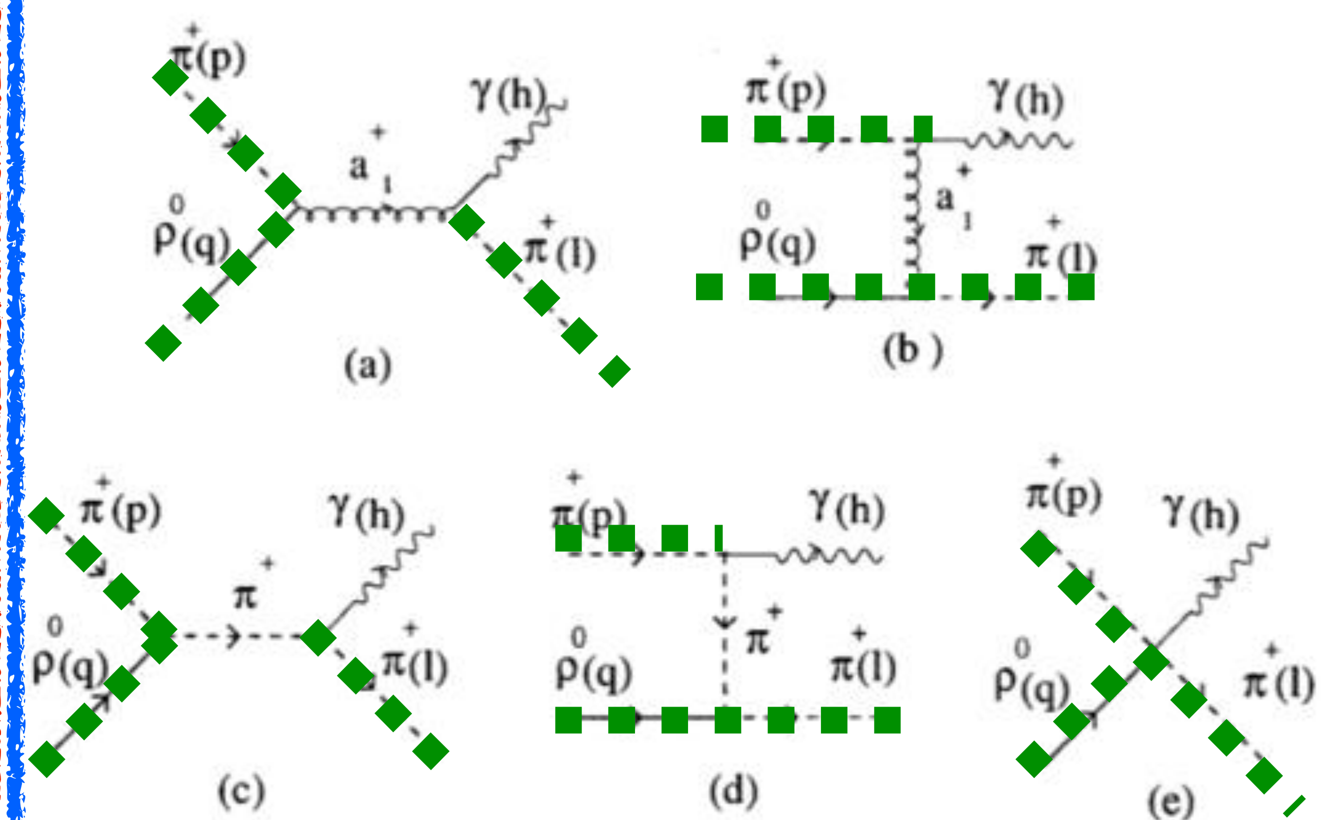
off-equilibrium δf corrections

QGP



Dusling NPA839 (2010) 70

Hadron Gas



Dion et al. PRC84 (2011) 064901

Viscous Photon Emission Rates: General Formalism

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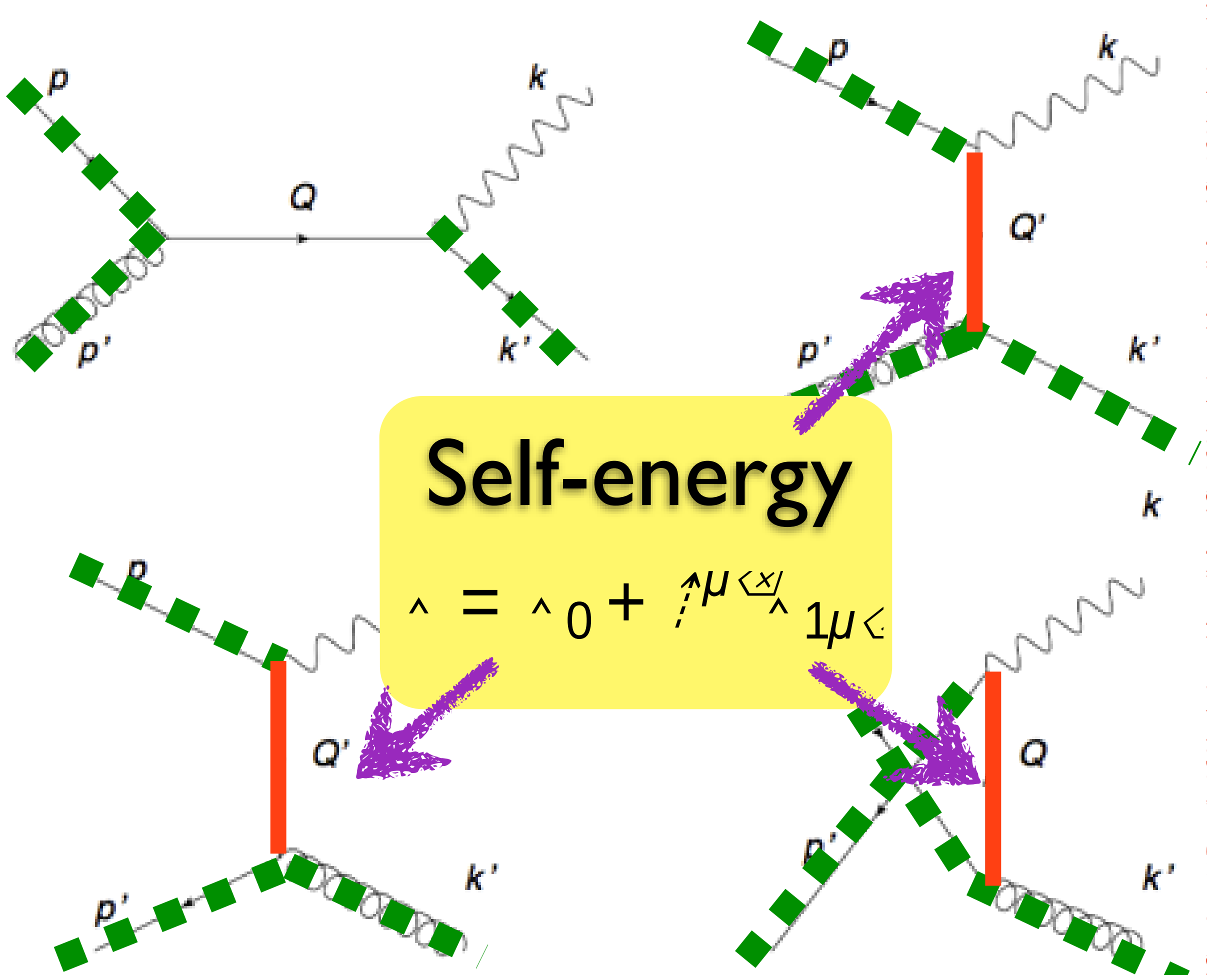
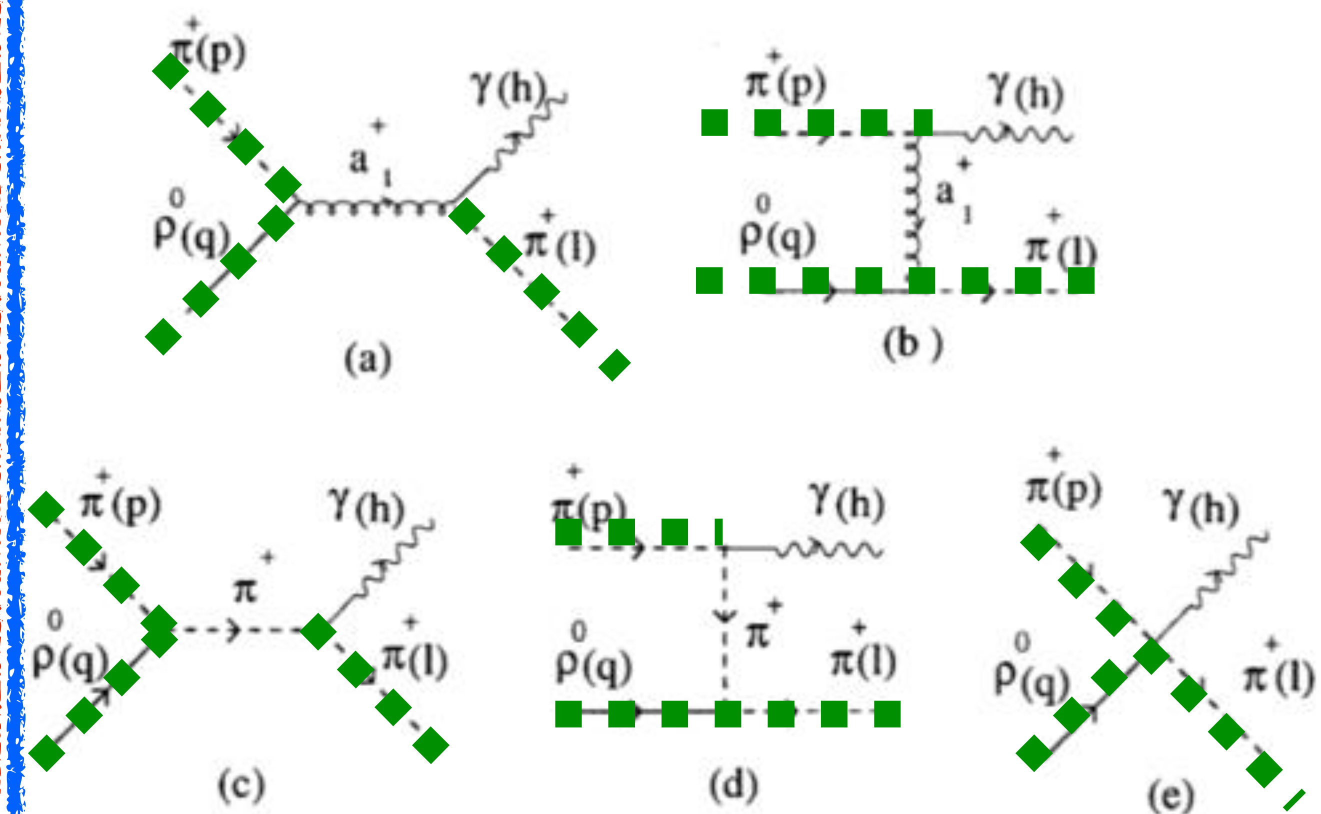
Equilibrium rates   off-equilibrium δf corrections

QGP

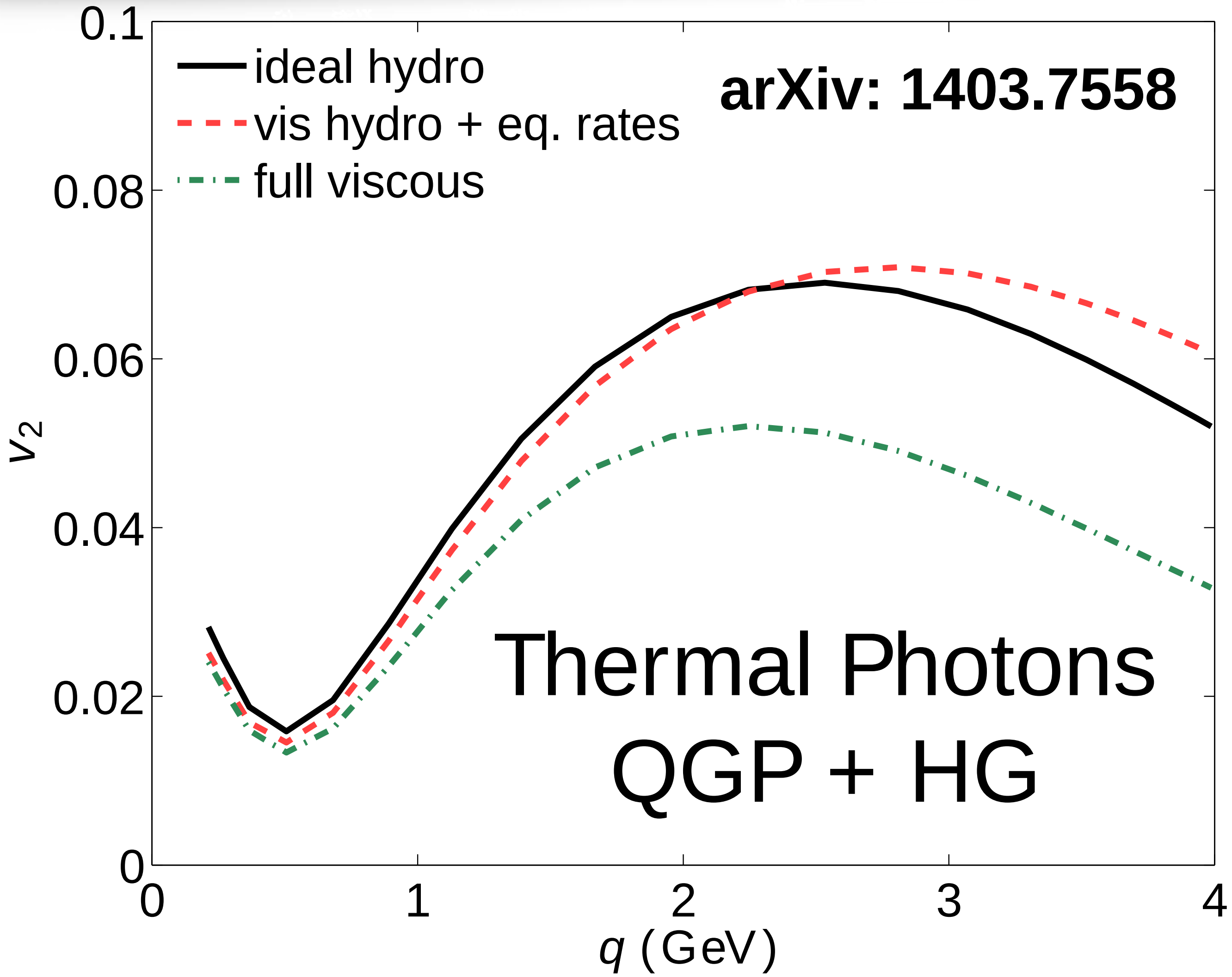


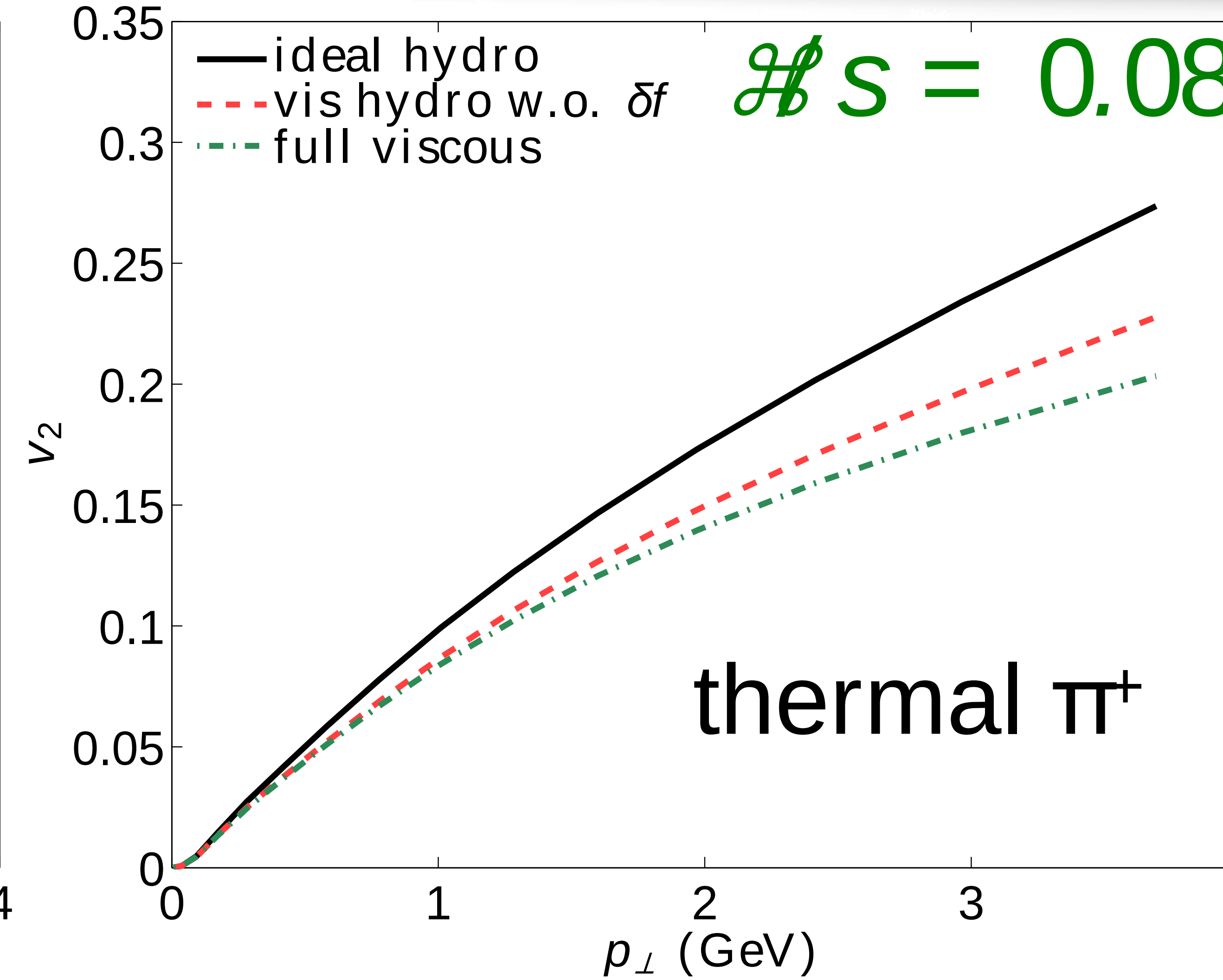
Shen, Paquet et al. (2014)

Hadron Gas



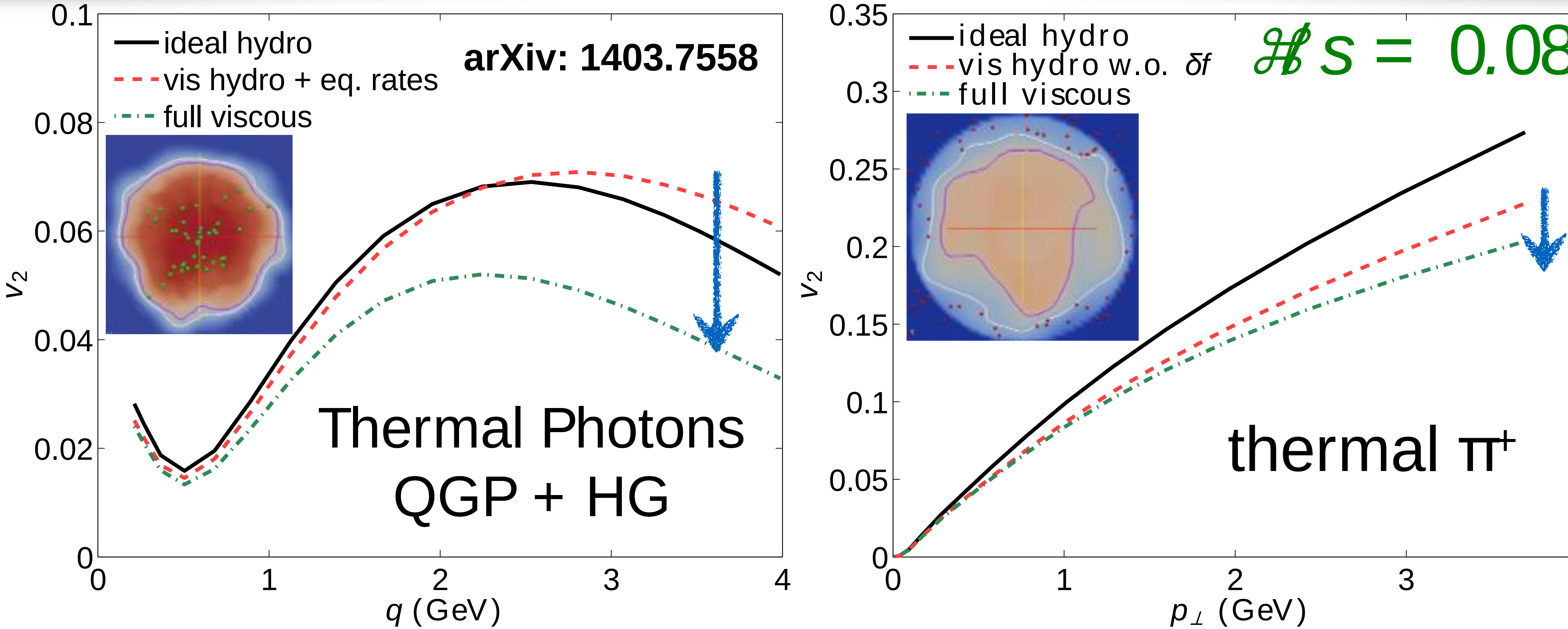
Viscous effects on photon elliptic flow





- Shear viscous suppression of photon v_2 is dominated by the viscous corrections to the photon emission rate
- Photon elliptic flow is sensitive to the larger shear stress tensor at early times

Viscous effects on photon elliptic flow



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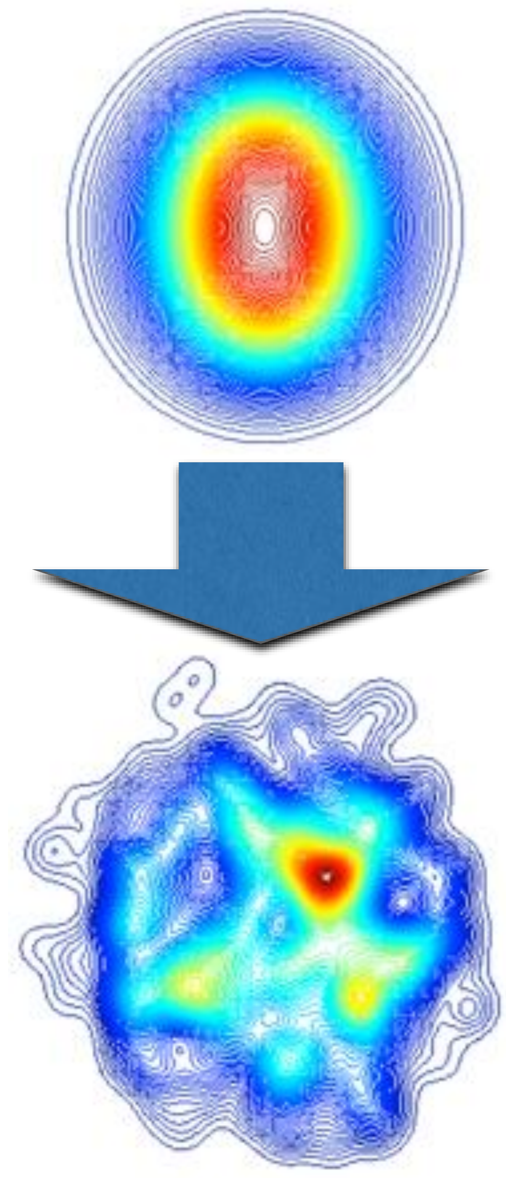
Definition of event-by-event $v_n^{\gamma,\mathrm{dir}}$

$$v_n^{\mathrm{dir}}(p_T) = \frac{R^{\gamma}(p_T)\, v_n^{\mathrm{incl}}(p_T) - v_n^{\mathrm{bg}}(p_T)}{R^{\gamma}(p_T) - 1}$$

$$R^{\gamma} = \frac{N^{\gamma\, incl}}{N^{\gamma\, bg}}$$

exact for a single event



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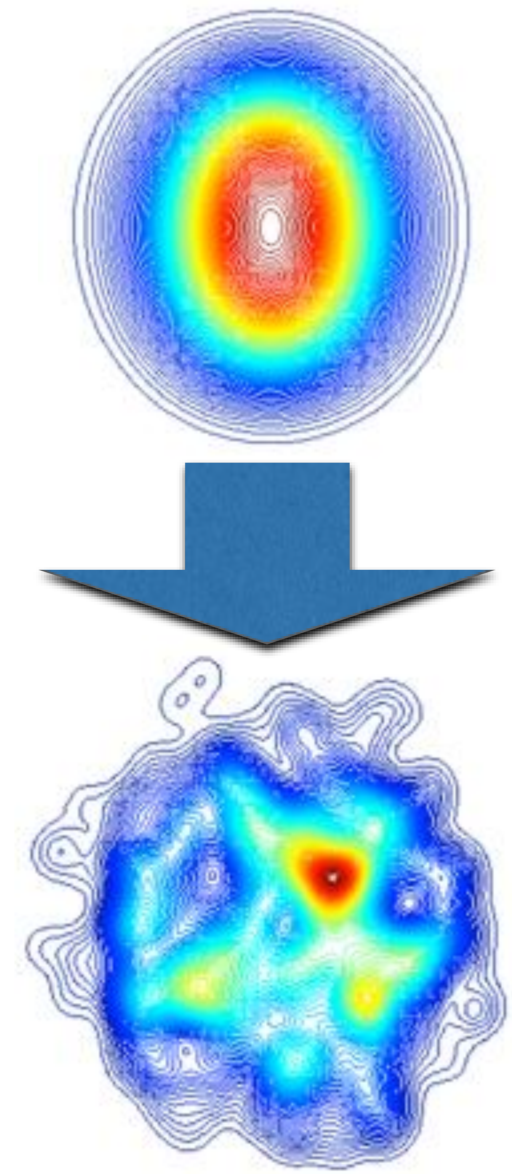
exact for a single event

But for **multiple** events,

Experiment: $$\frac{R^\gamma(p_T)\langle v_n^{\mathrm{incl}}(p_T)\rangle - \langle v_n^{\mathrm{bg}}(p_T)\rangle}{R^\gamma(p_T) - 1}$$

$$\bar{R}^\gamma(p_T) = \frac{\langle dN^{\gamma\,\mathrm{incl}}/dy\,p_T\,dp_T\rangle}{\langle dN^{\gamma\,\mathrm{bg}}/dy\,p_T\,dp_T\rangle}$$



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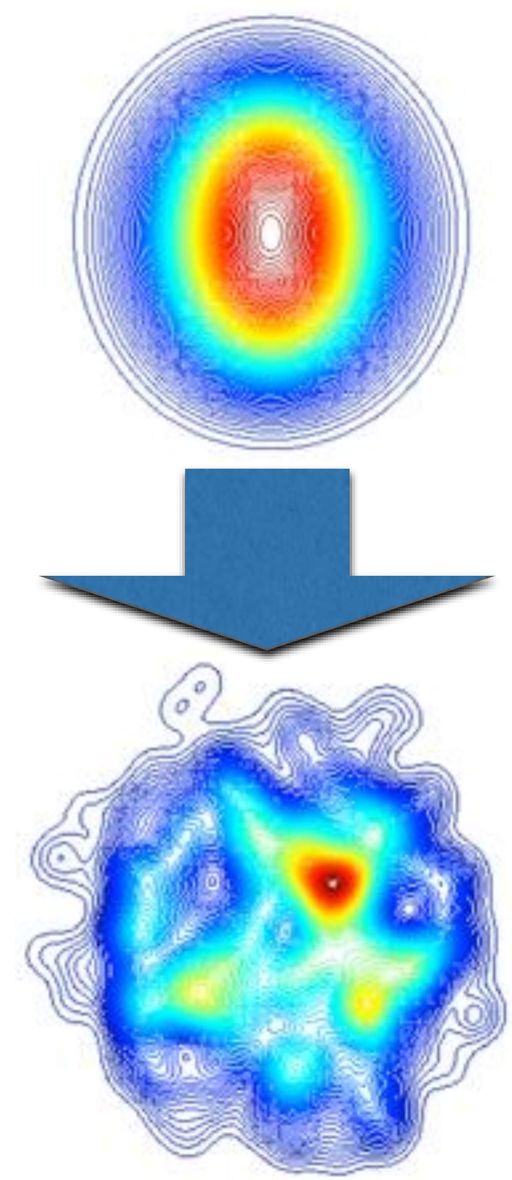

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Theory:
$$\langle v_n^{\mathrm{dir}}(p_T)\rangle = \left\langle \frac{R^\gamma(p_T)\, v_n^{\mathrm{incl}}(p_T) - v_n^{\mathrm{bg}}(p_T)}{R^\gamma(p_T) - 1} \right\rangle$$

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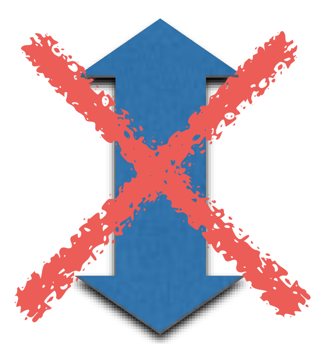

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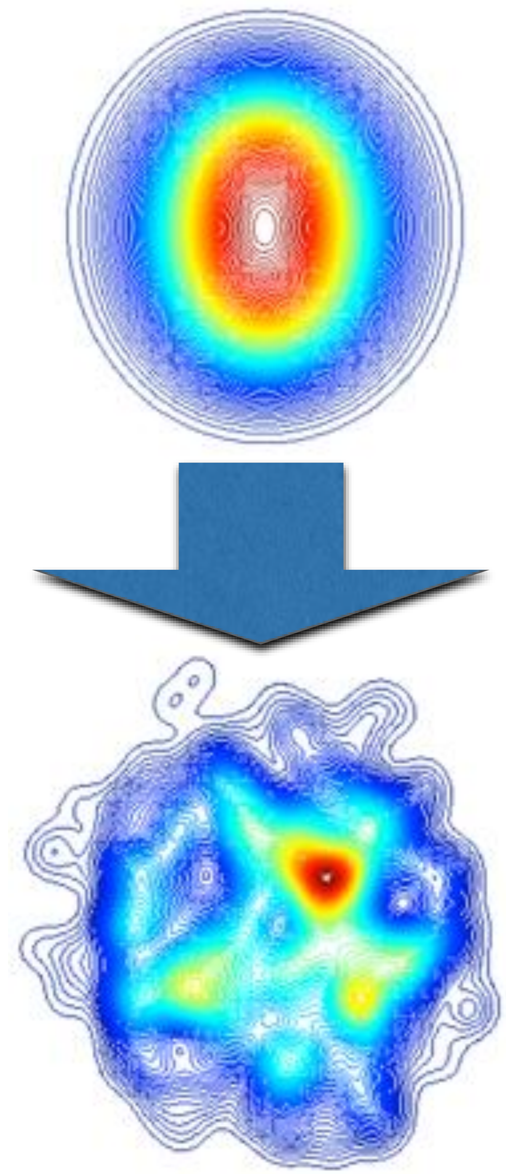
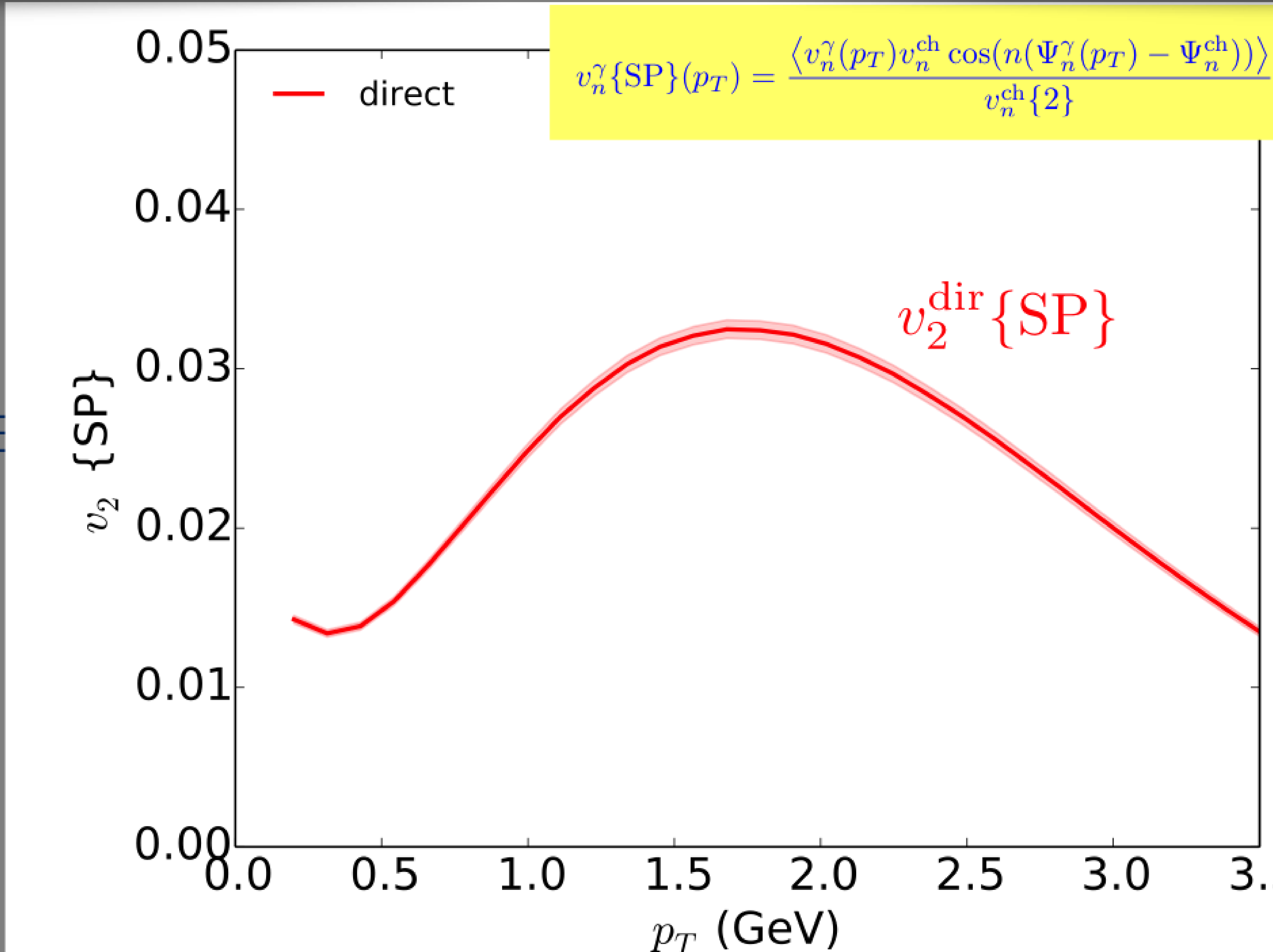


Definition of event-by-event $v_n^{\gamma,\mathrm{dir}}$

$$v_n^\gamma\{\mathrm{SP}\}(p_T) = \frac{\langle v_n^\gamma(p_T) v_n^{\mathrm{ch}} \cos(n(\Psi_n^\gamma(p_T) - \Psi_n^{\mathrm{ch}}))\rangle}{v_n^{\mathrm{ch}}\{2\}}$$

But

E



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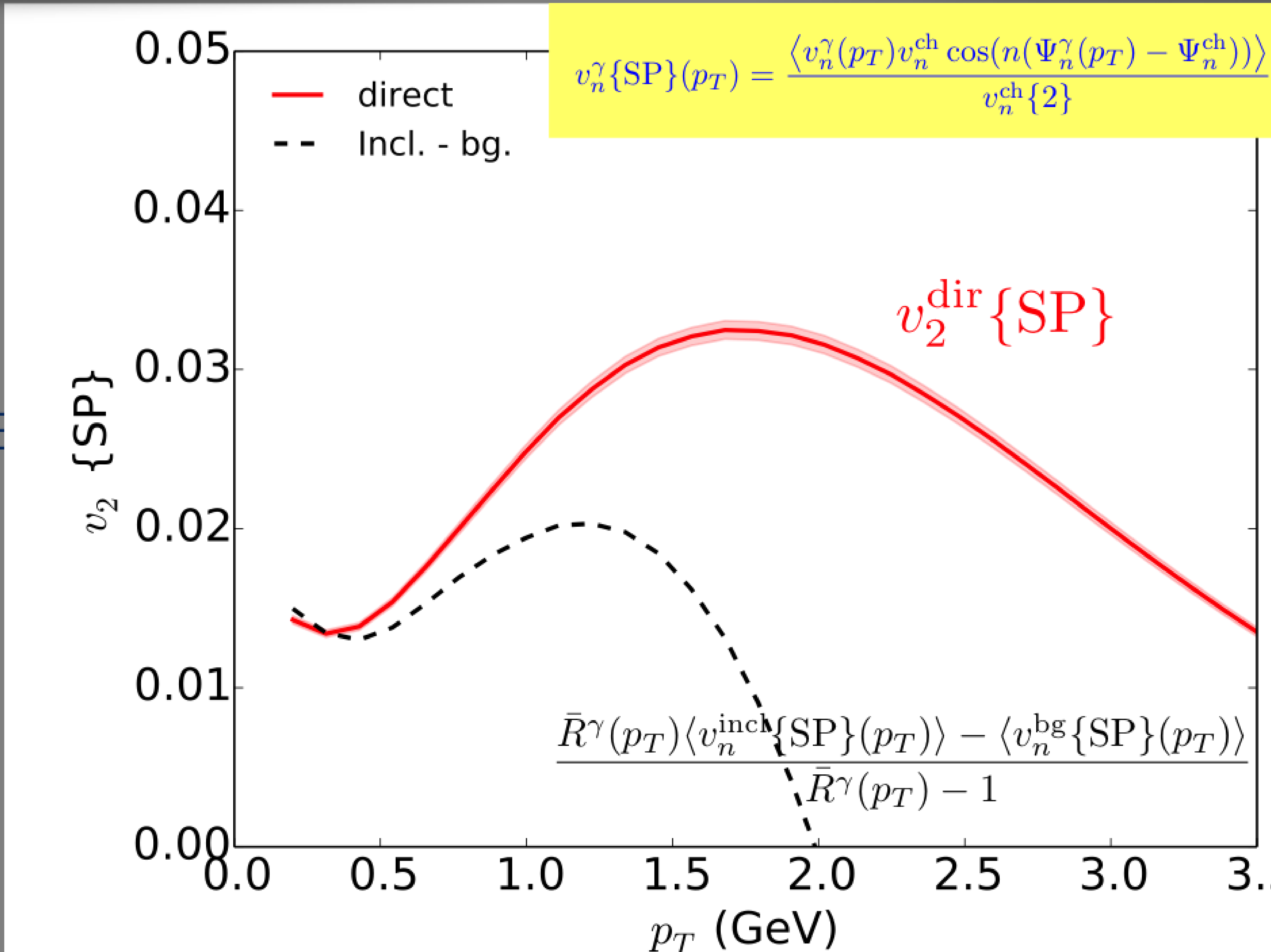

$$\frac{\bar{R}^{\gamma}(p_T)\langle v_n^{\mathrm{incl}}\{\mathrm{SP}\}(p_T)\rangle - \langle v_n^{\mathrm{bg}}\{\mathrm{SP}\}(p_T)\rangle}{\bar{R}^{\gamma}(p_T) - 1}$$

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exact for a single event

But for **multiple** events,

“extraction safe”

$$v_n^\gamma\{\mathrm{SP}\}(p_T) = \frac{\left\langle \frac{dN^\gamma}{dy\, p_T\, dp_T}(p_T)\, v_n^\gamma(p_T)\, v_n^{\mathrm{ch}} \cos(n(\Psi_n^\gamma(p_T) - \Psi_n^{\mathrm{ch}}))\right\rangle}{\left\langle \frac{dN^\gamma}{dy\, p_T\, dp_T}(p_T)\right\rangle v_n^{\mathrm{ch}}\{2\}}.$$

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theory ⟷ **experiment**

Poster:!
J-F. Paquet, **G21**

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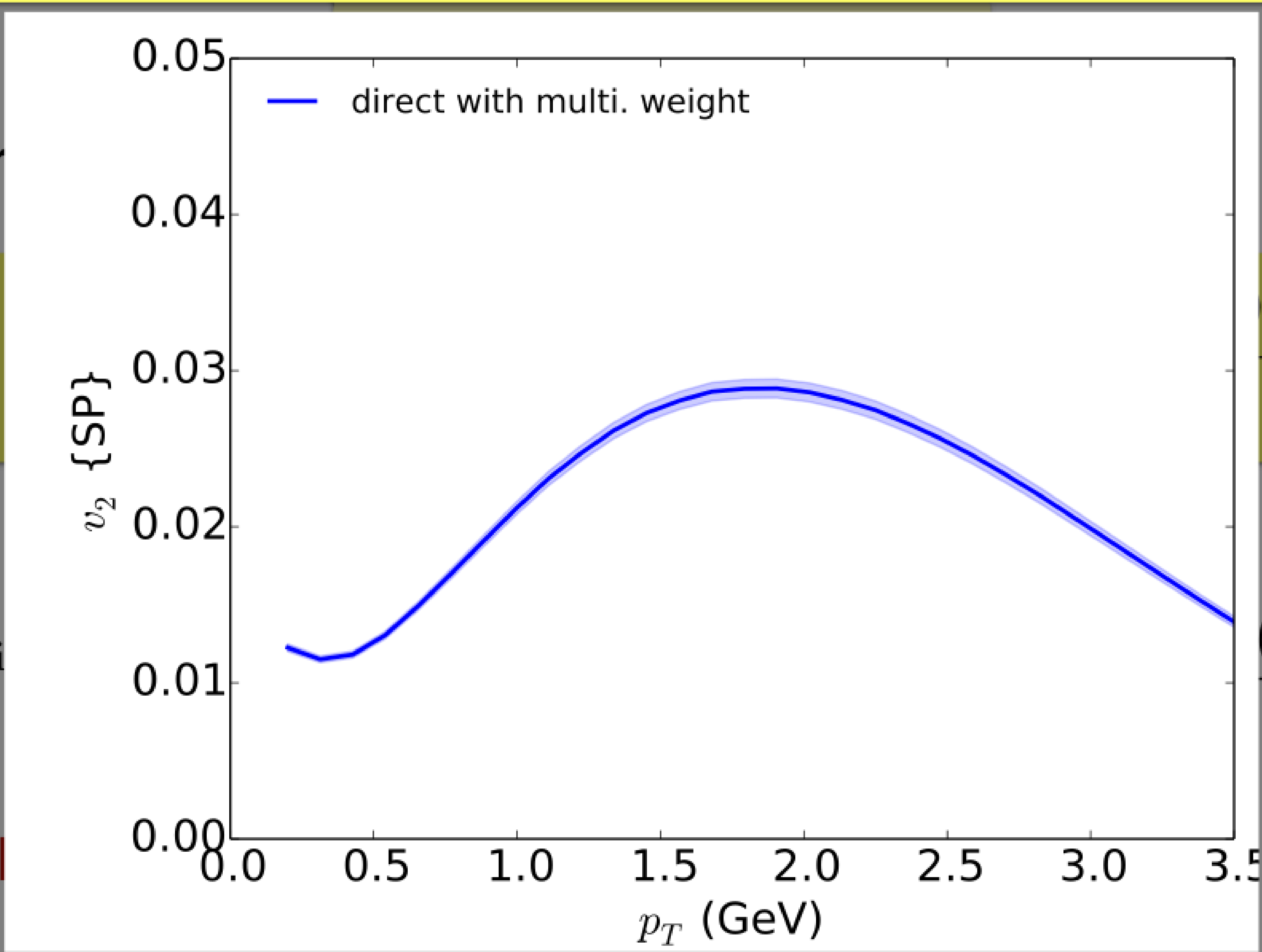
But for **r**



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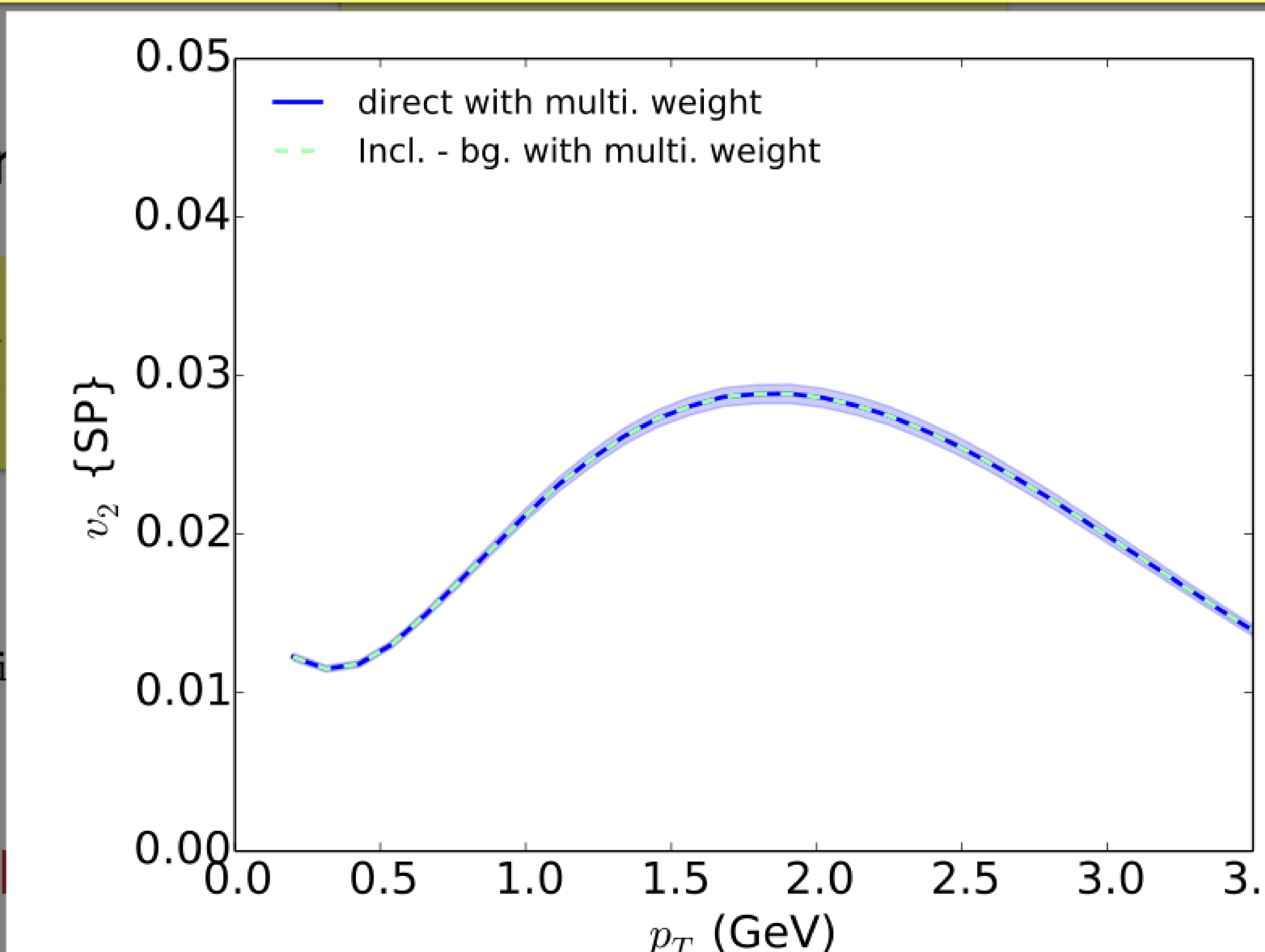

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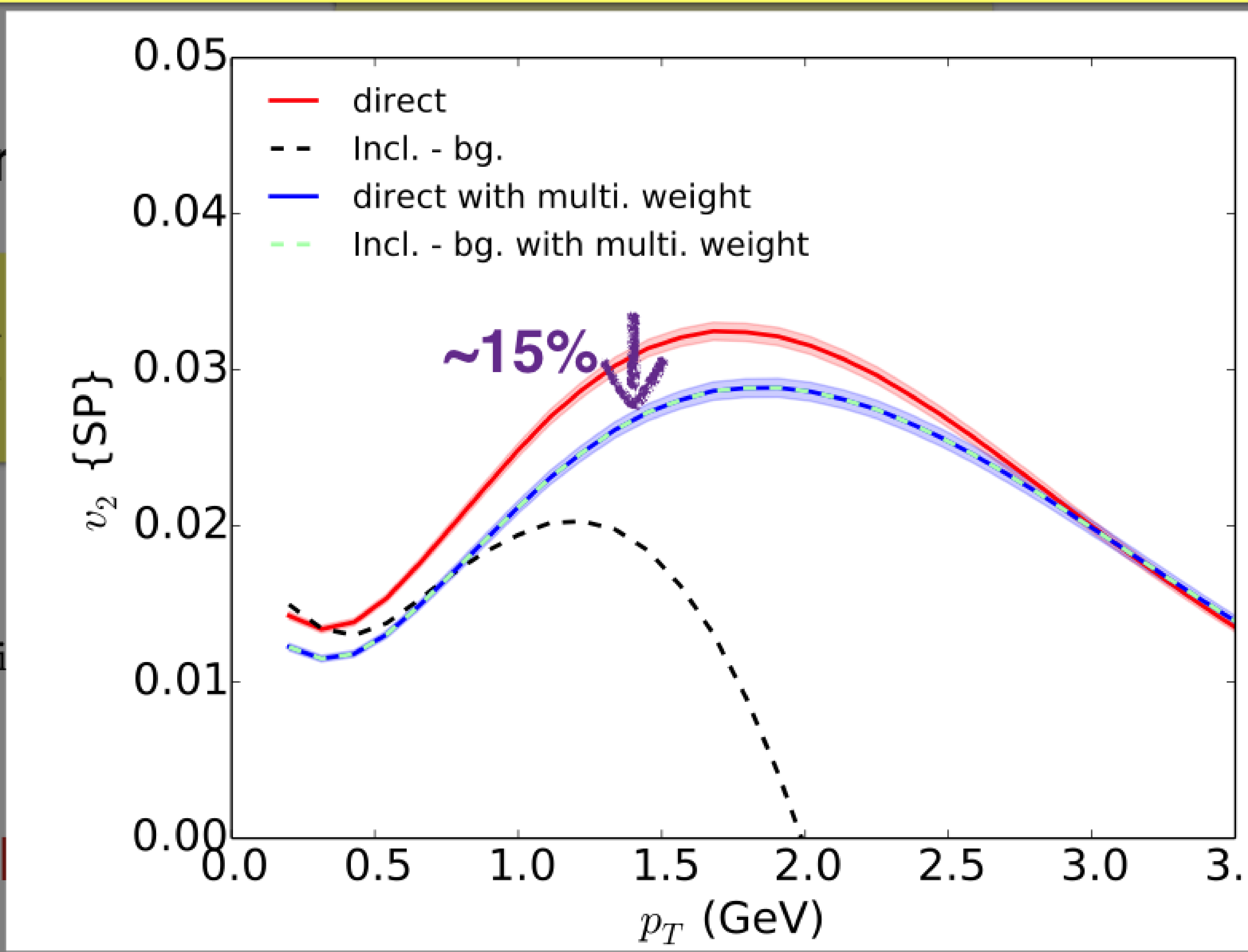
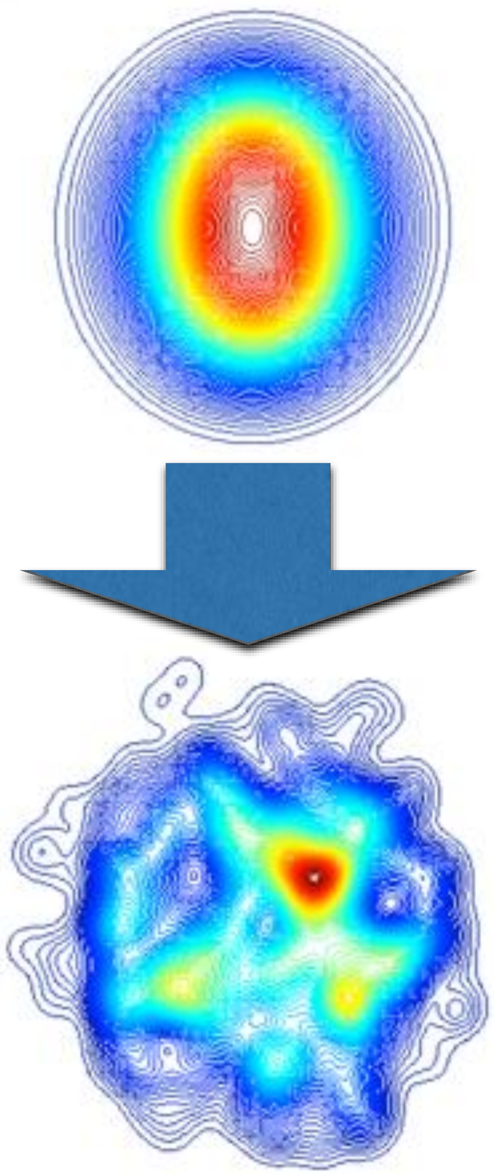
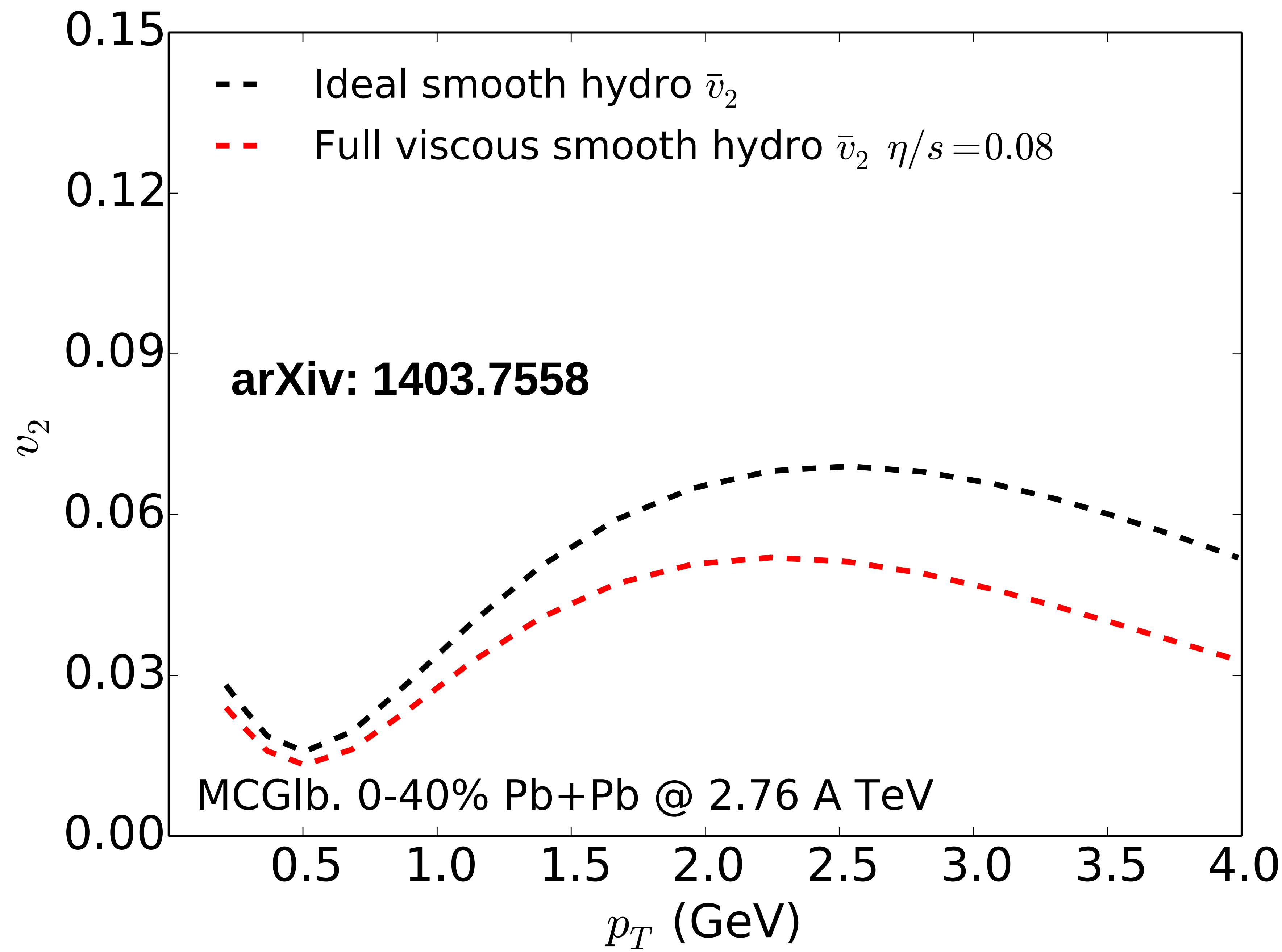


Fluctuation effects on photon elliptic flow





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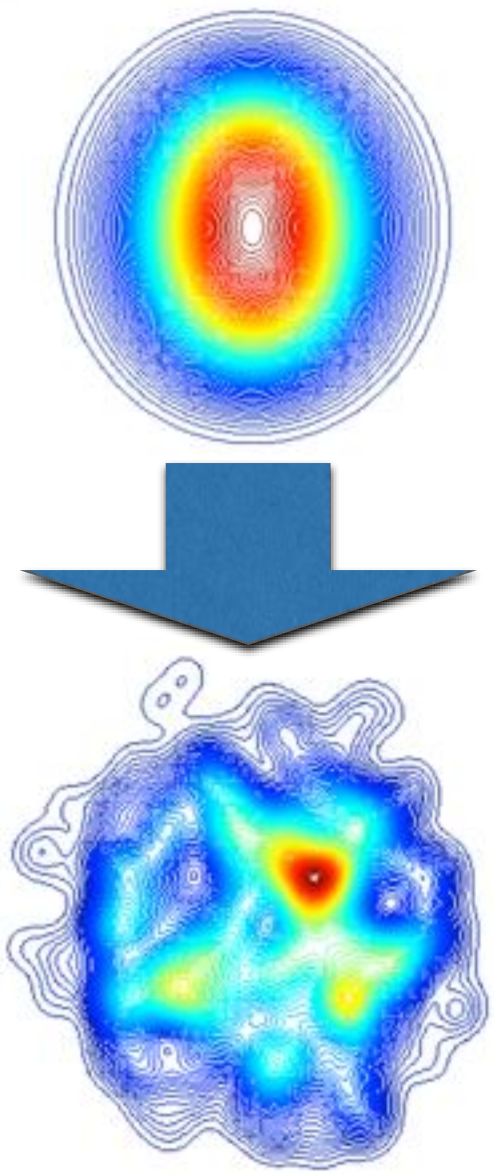
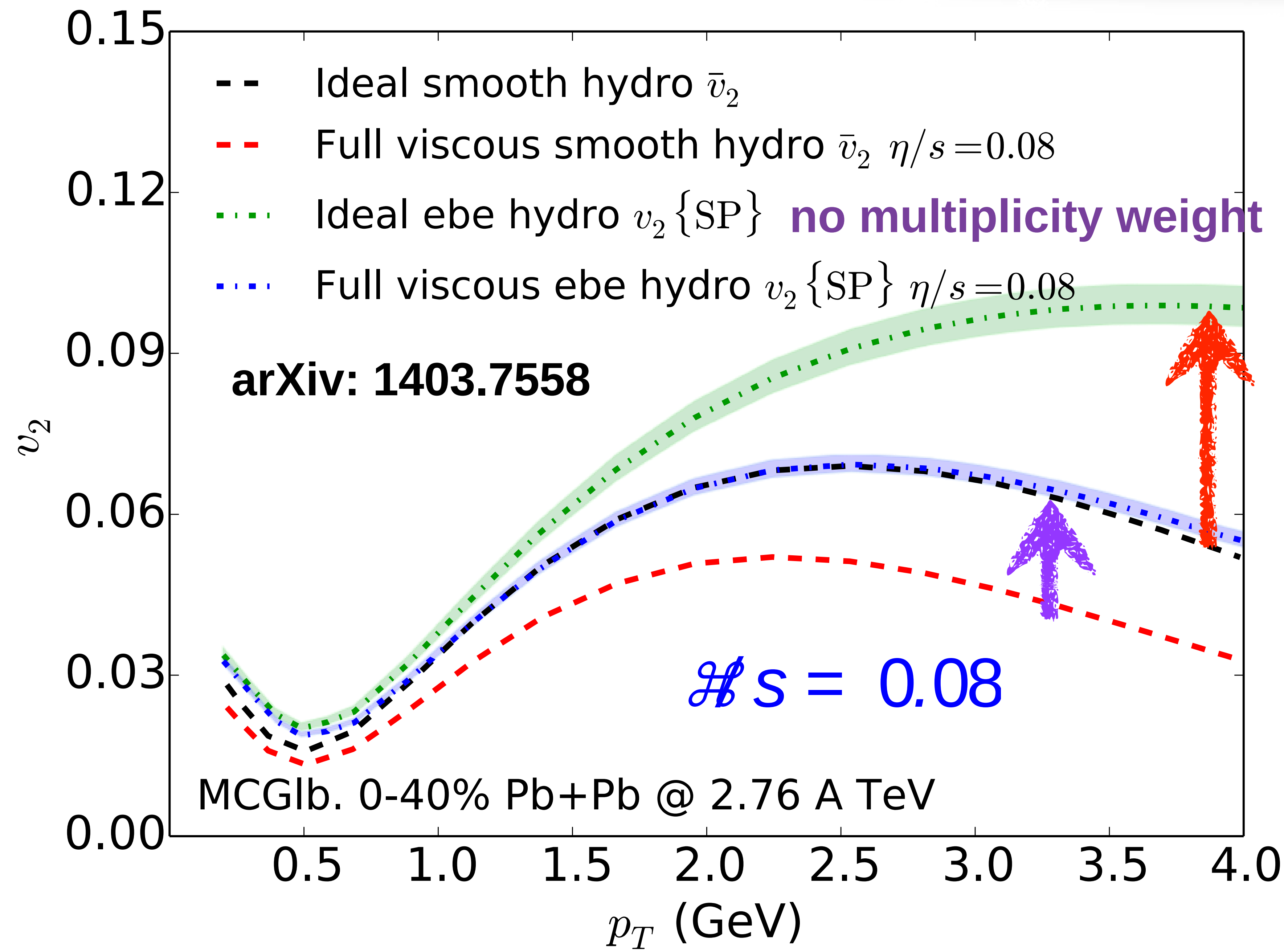
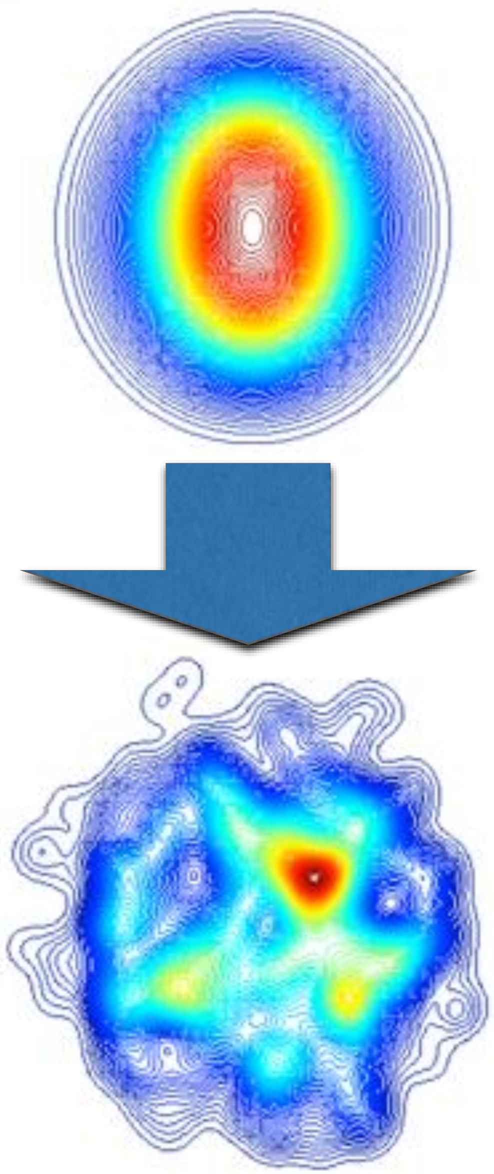
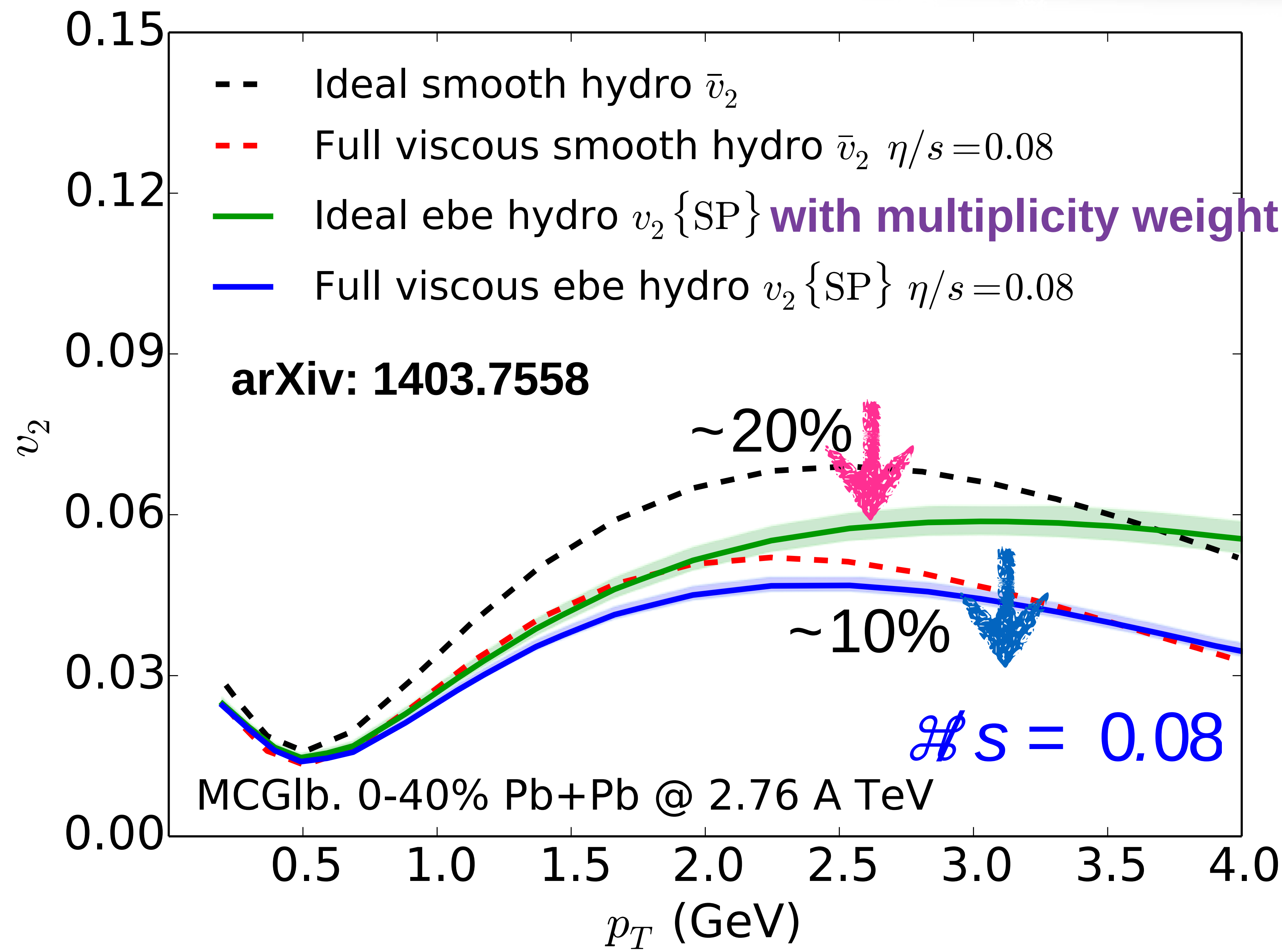




- Initial fluctuations increase photons' elliptic flow

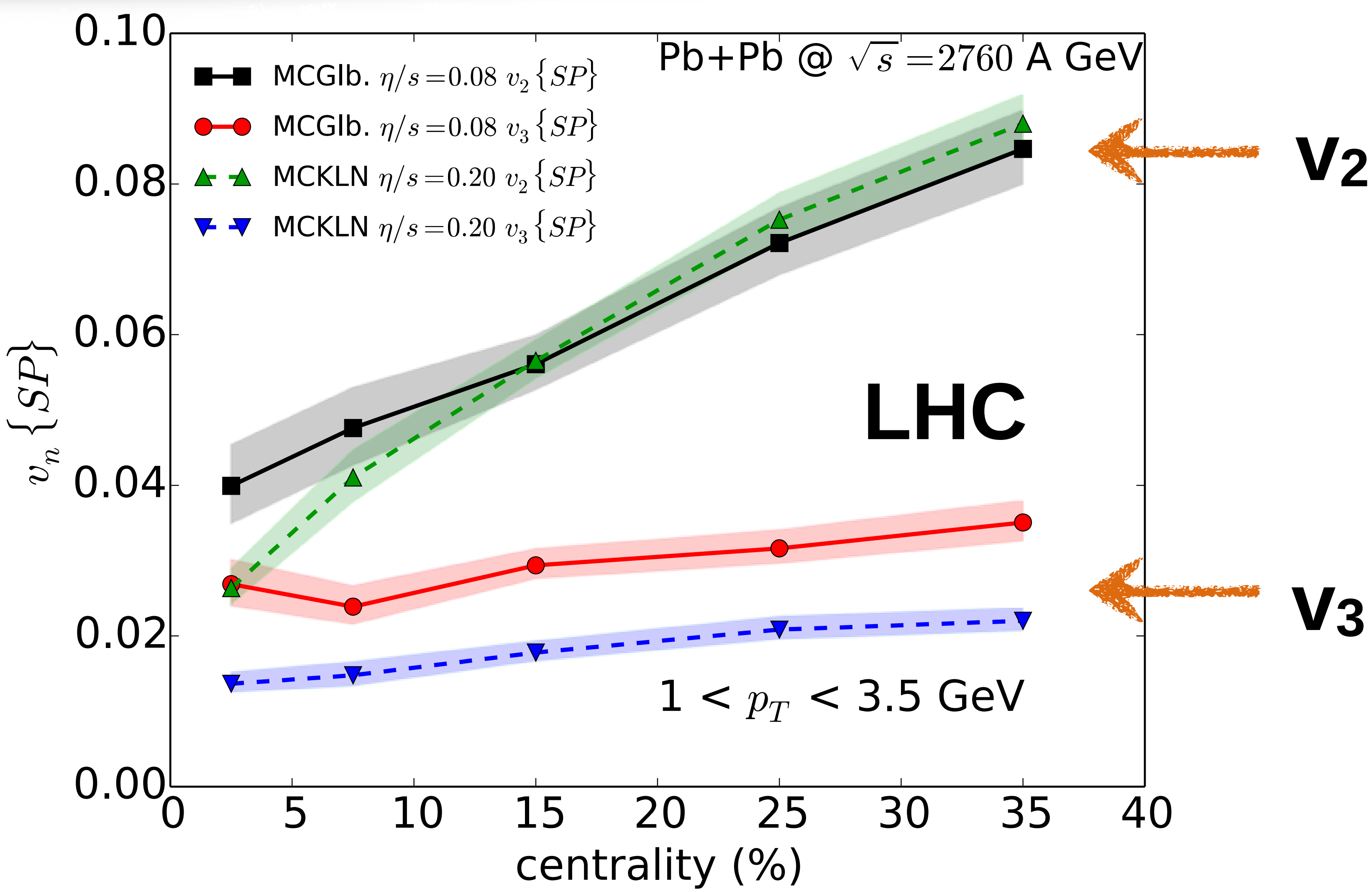
Fluctuation effects on photon elliptic flow





- Initial fluctuations increase photons' elliptic flow
- The additional photon multiplicity weighting biases e-b-e v_2 towards central collisions, resulting in ~10-20% smaller v_2 compared to smooth hydro

Event-by-Event Full Viscous Photon v_n

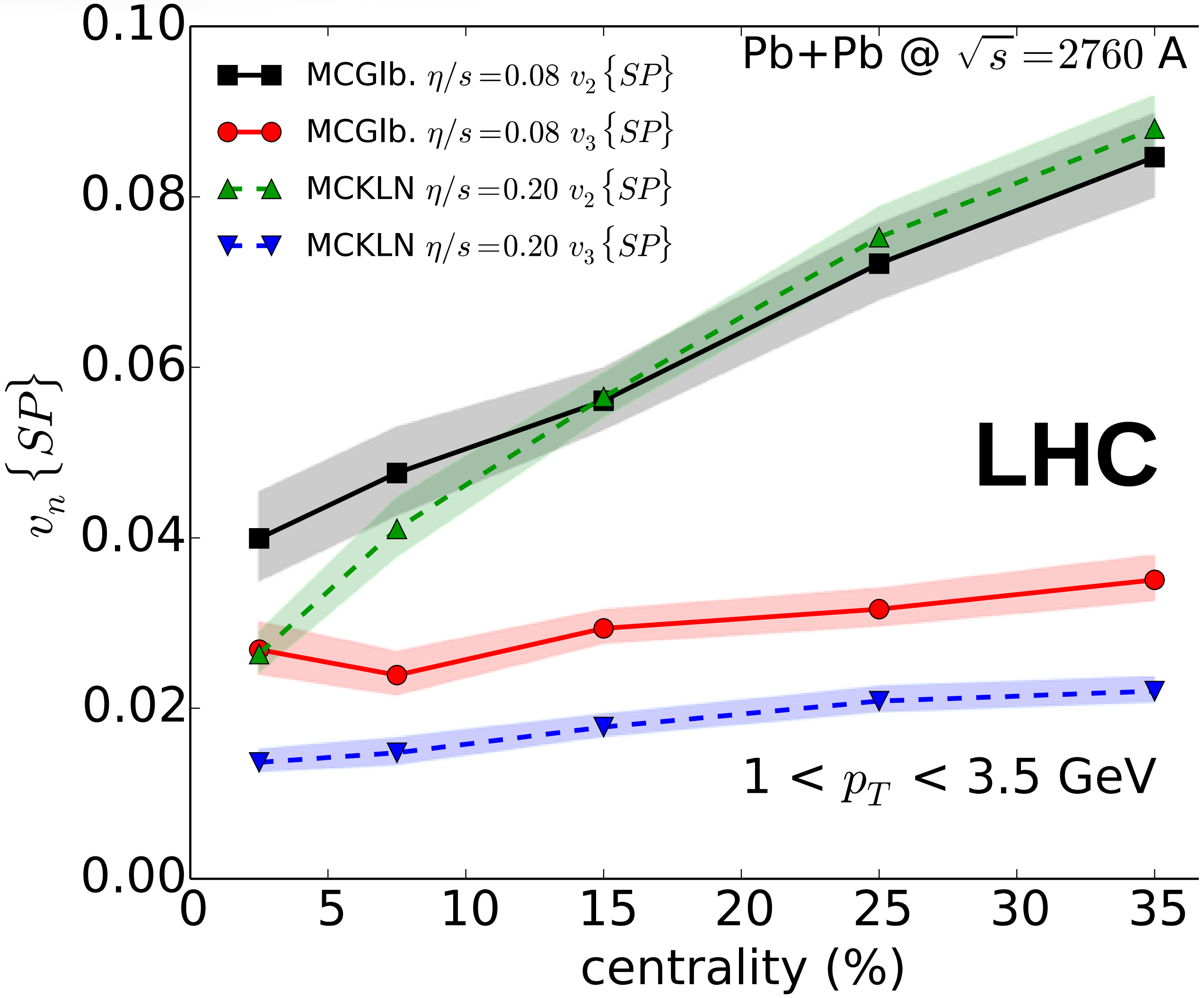


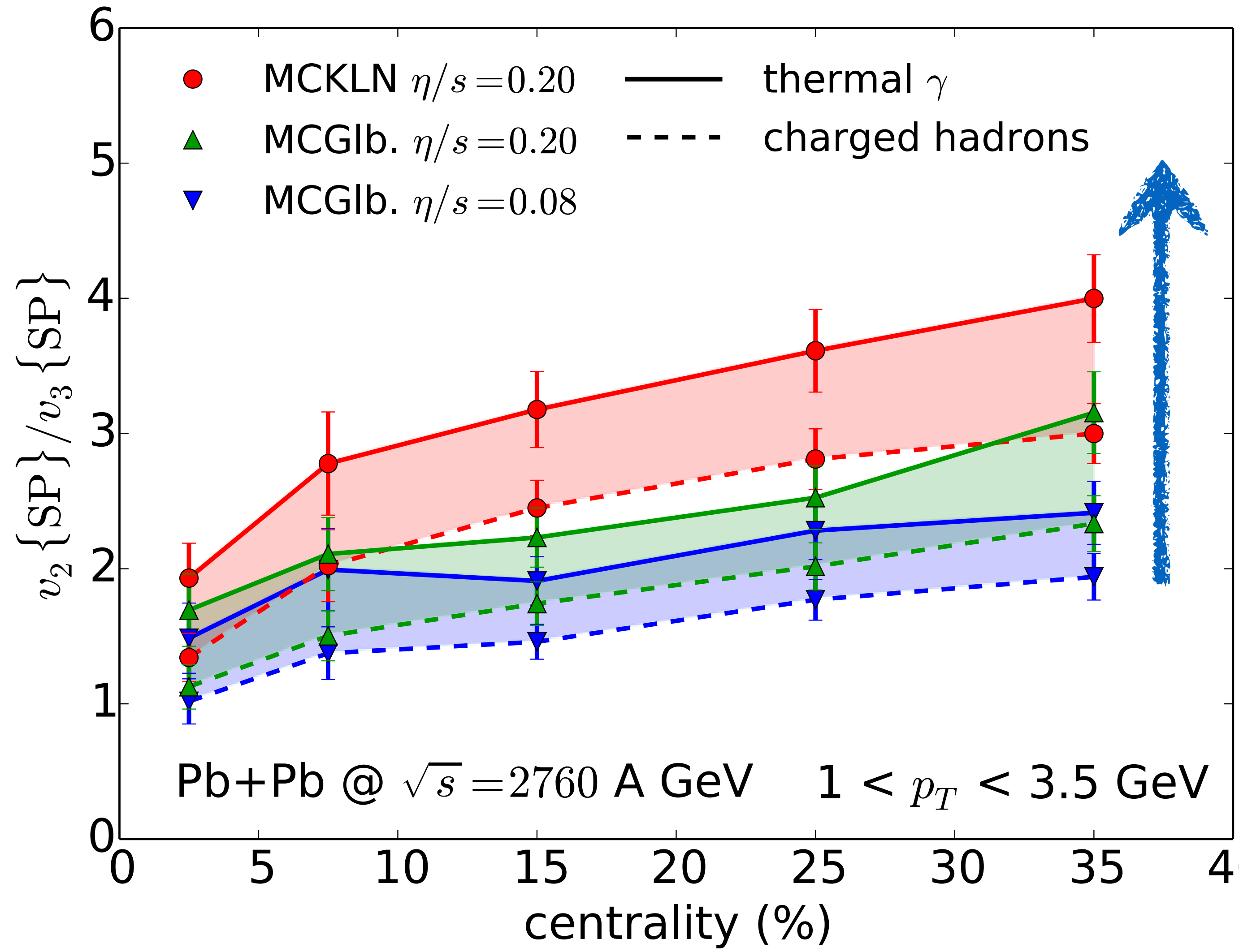
MCGlb. $\eta/s = 0.08$

MCKLN $\eta/s = 0.20$

- The anisotropic flows of photons show similar centrality dependence as hadron v_n

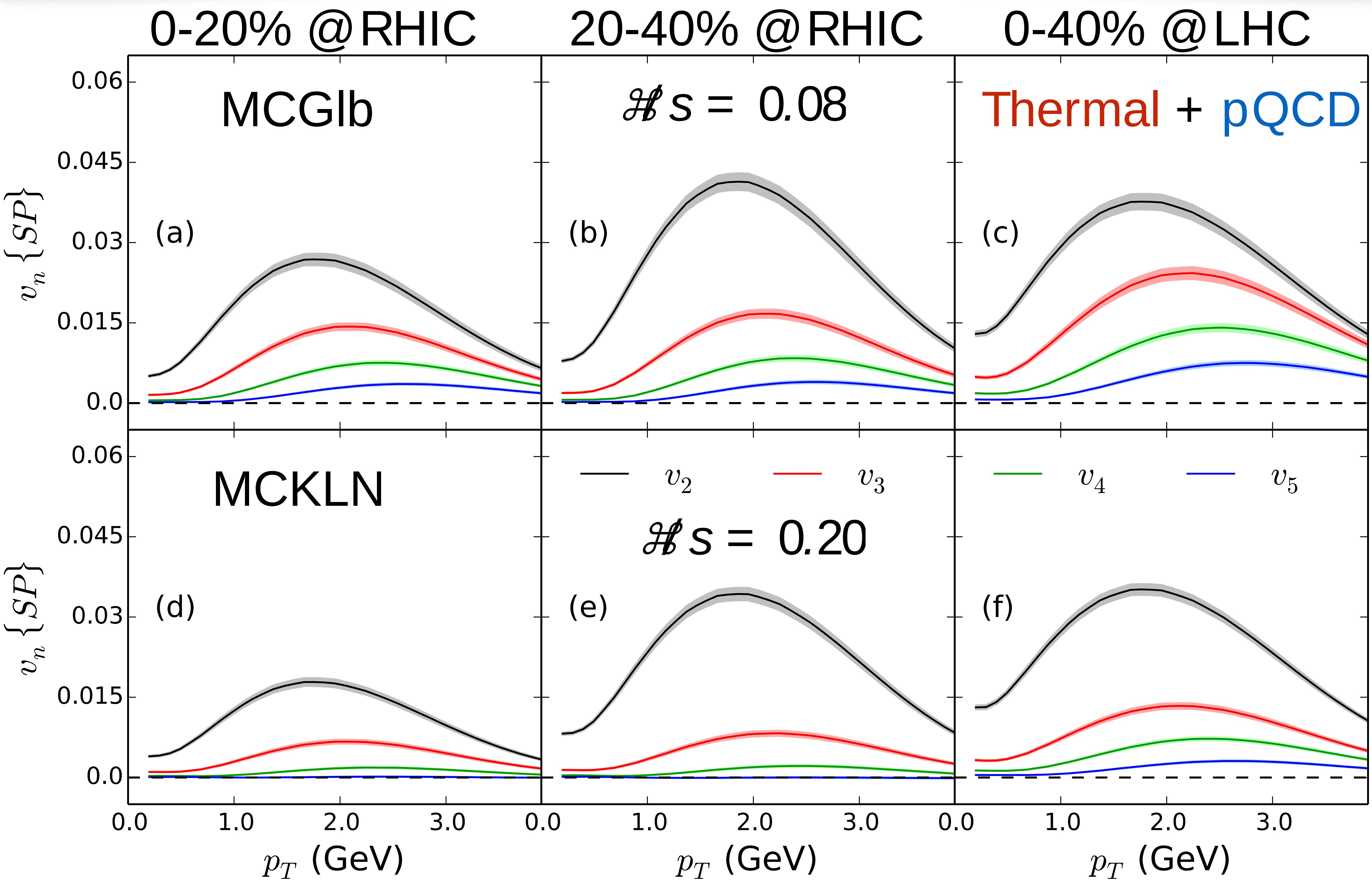
Event-by-Event Full Viscous Photon v_n





- The anisotropic flows of photons show similar centrality dependence as hadron v_n
- The ratio v_2/v_3 increases with the shear viscosity
- The centrality dependence of this ratio is stronger for the MCKLN model, driven by $_2$

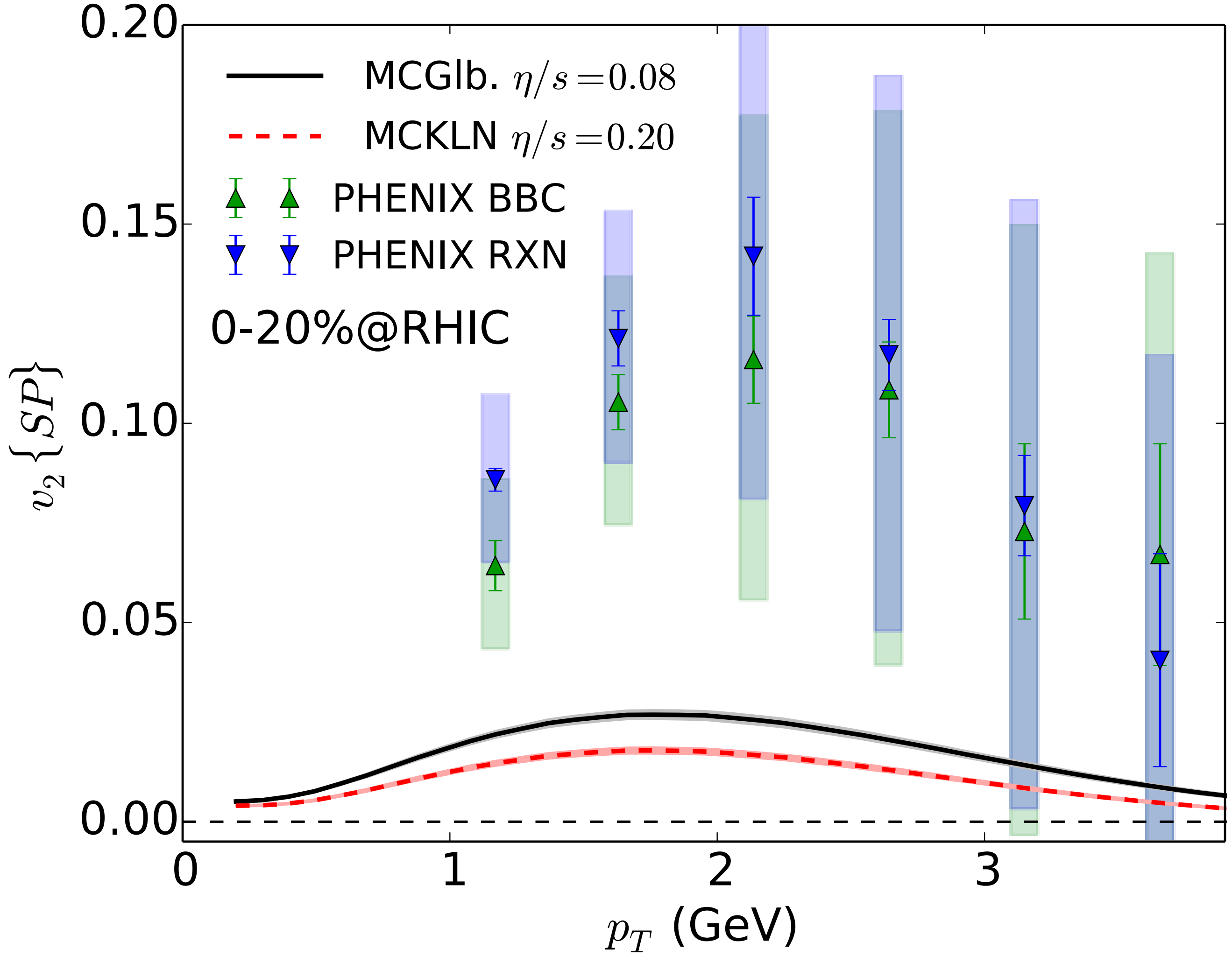
Event-by-Event Full Viscous Photon v_n



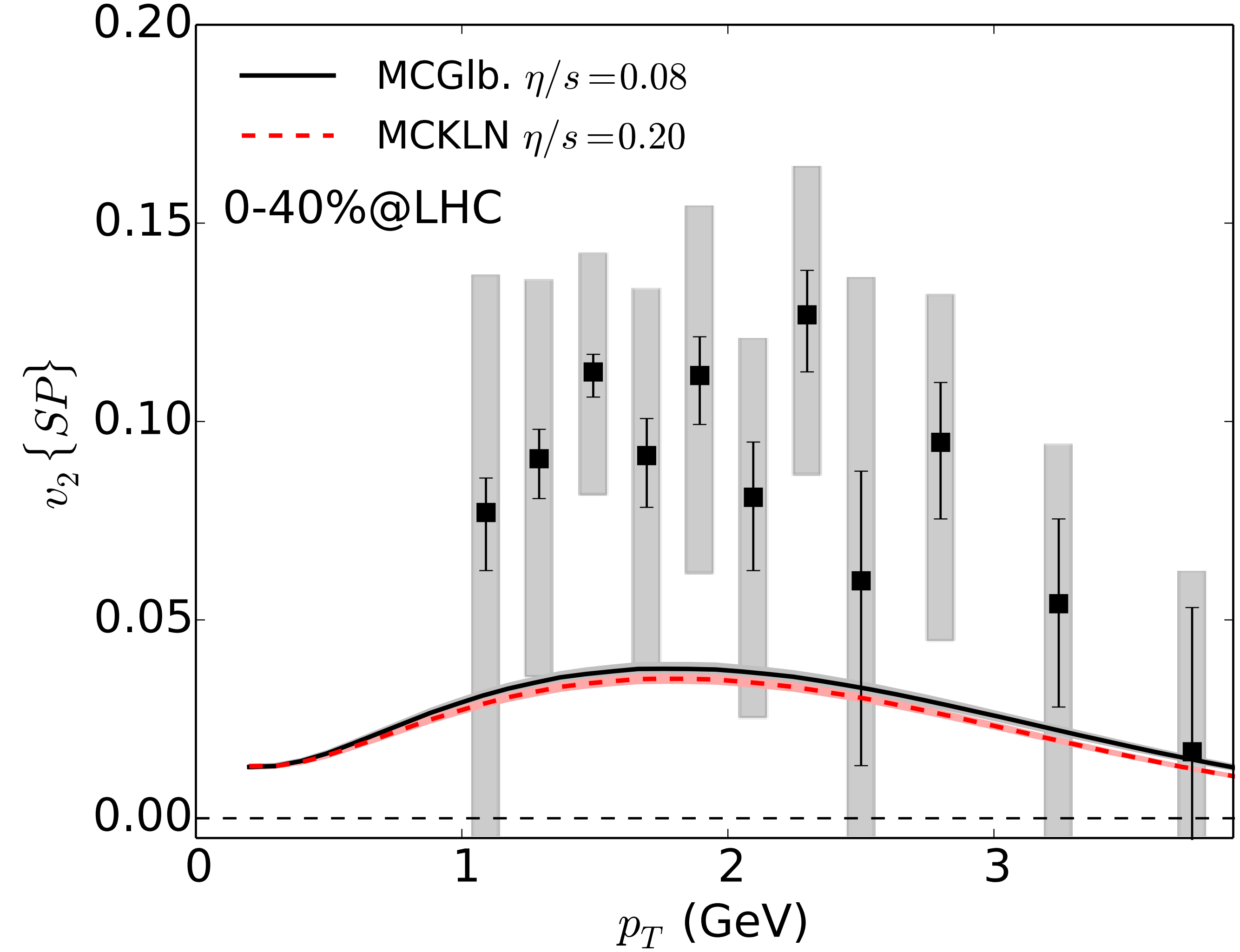
arXiv: 1308.2111

Comparisons with exp. data

RHIC 0-20%



LHC 0-40%

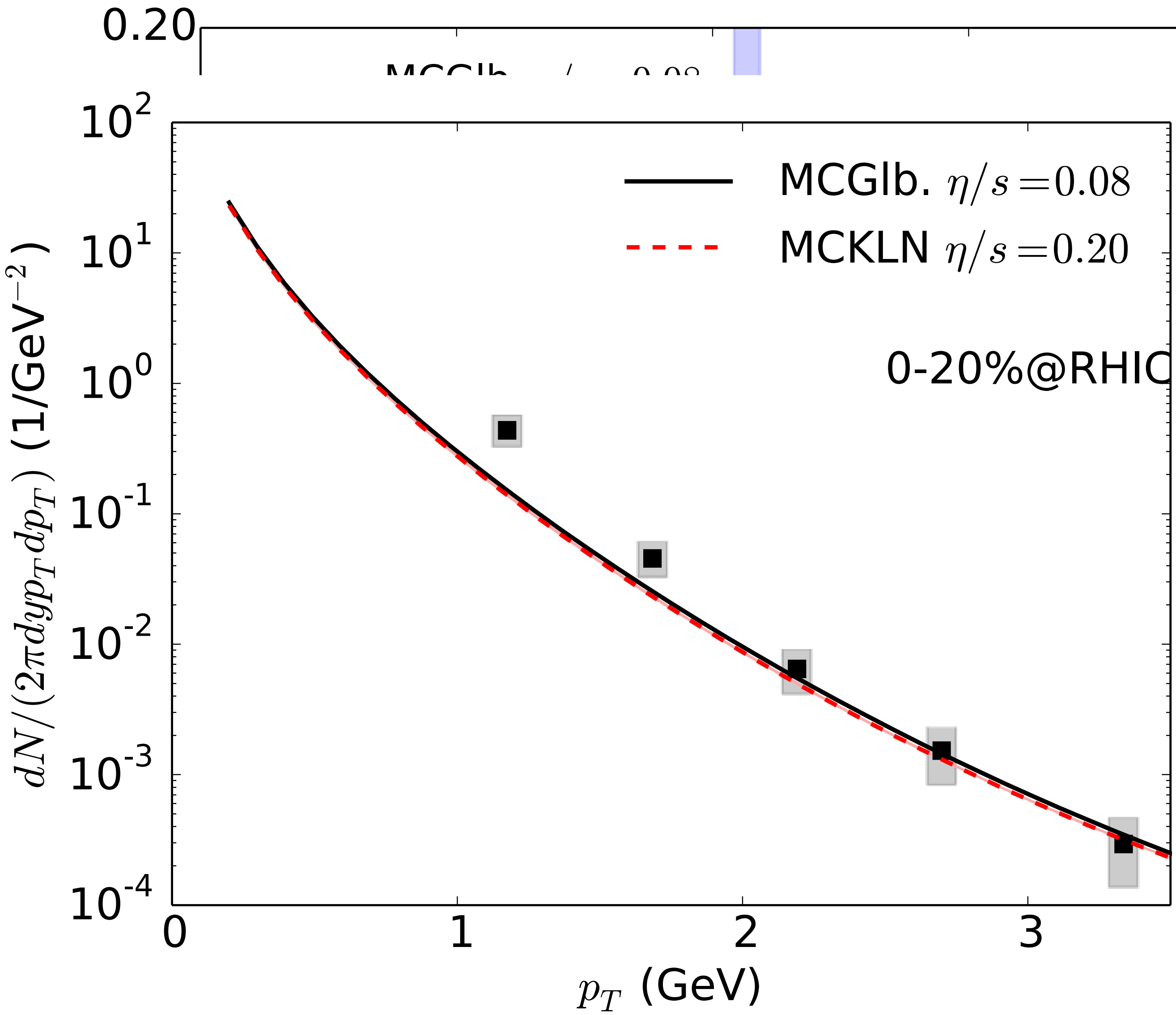


- Current calculations still underestimate the experimental data by a factor of 3

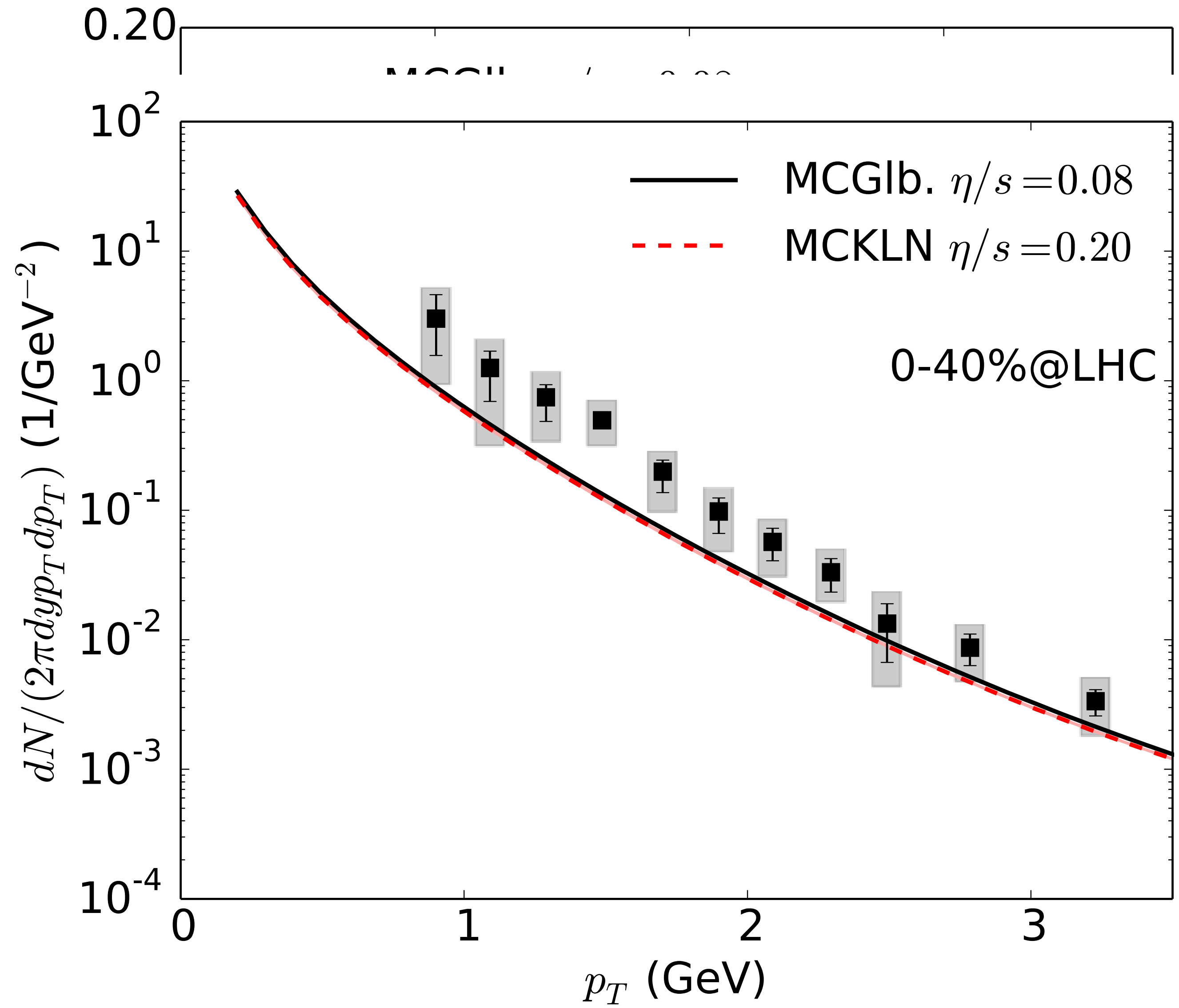
arXiv: 1308.2111

Comparisons with exp. data

RHIC 0-20%



LHC 0-40%



- Current calculations still underestimate the experimental data by a factor of 3
- Thermal yield is also missing in the azimuthally integrated photon spectra at low p_T

arXiv: 1308.2111

EM decays of short-lived resonances (I)

Thanks to Ralf Rapp and EMMI RRTF

Contributions from the short-lived resonances:

reaction	branching ratio
$\rho^0 \to \pi^+ + \pi^- + \gamma$	1%
$b_1(1235) \to \pi^\pm + \gamma$	$1.6 * 10^{-3}$
$h_1(1170) \to \pi^0 + \gamma$	$1.7 * 10^{-3}$
$a_1(1260) \to \pi^0 + \gamma$	$1.7 * 10^{-3}$
$f_1(1285) \to \rho_0 + \gamma$	5.5%
$a_2(1320) \to \pi^\pm + \gamma$	$2.68 * 10^{-3}$
$K^\star(892) \to K^0 + \gamma$	$2.4 * 10^{-3}$
$K^\star(892) \to K^\pm + \gamma$	$1 * 10^{-3}$
$K_1(1270) \to K^0 + \gamma$	$8.4 * 10^{-4}$
$K_1(1400) \to K^0 + \gamma$	$1.6 * 10^{-3}$
$K_2^\star(1430) \to K^+ + \gamma$	$2.4 * 10^{-3}$
$K_2^\star(1430) \to K^0 + \gamma$	$9 * 10^{-4}$

reaction	branching ratio
$N(1440) \to p + \gamma$	$4.15 * 10^{-4}$
$N(1440) \to n + \gamma$	$3 * 10^{-4}$
$N(1520) \to p + \gamma$	$4.15 * 10^{-3}$
$N(1520) \to n + \gamma$	$4.15 * 10^{-3}$
$N(1530) \to p + \gamma$	$2.25 * 10^{-3}$
$N(1530) \to n + \gamma$	$2.25 * 10^{-3}$
$N(1650) \to p + \gamma$	$1.2 * 10^{-3}$
$N(1650) \to n + \gamma$	$8.5 * 10^{-4}$
$N(1675) \to p + \gamma$	$1 * 10^{-4}$
$N(1675) \to n + \gamma$	$7.5 * 10^{-4}$
$N(1680) \to p + \gamma$	$2.65 * 10^{-3}$
$N(1680) \to n + \gamma$	$3.35 * 10^{-4}$
$N(1700) \to p + \gamma$	$3 * 10^{-4}$
$N(1700) \to n + \gamma$	$1.2 * 10^{-3}$
$N(1710) \to p + \gamma$	$4.1 * 10^{-4}$
$N(1710) \to n + \gamma$	$1 * 10^{-4}$
$N(1720) \to p + \gamma$	$1.5 * 10^{-3}$
$N(1720) \to n + \gamma$	$8 * 10^{-5}$

$\Delta(1232) \to N + \gamma$	0.6%
$\Delta(1600) \to N + \gamma$	$1.8 * 10^{-4}$
$\Delta(1620) \to N + \gamma$	$6.5 * 10^{-4}$
$\Delta(1700) \to N + \gamma$	$4.1 * 10^{-3}$
$\Delta(1905) \to N + \gamma$	$2.4 * 10^{-4}$
$\Delta(1910) \to N + \gamma$	$1 * 10^{-4}$
$\Delta(1920) \to N + \gamma$	$2 * 10^{-3}$
$\Delta(1950) \to N + \gamma$	$1.05 * 10^{-3}$

reaction	branching ratio
$\Lambda(1405) \to \Lambda + \gamma$	$5.4 * 10^{-4}$
$\Lambda(1405) \to \Sigma^0 + \gamma$	$2 * 10^{-4}$
$\Lambda(1520) \to \Lambda + \gamma$	$8.5 * 10^{-3}$
$\Lambda(1520) \to \Sigma^0 + \gamma$	2%
$\Sigma^0(1385) \to \Lambda + \gamma$	1.25%
$\Xi(1530) \to \Xi + \gamma$	4%

EM decays of short-lived resonances (II)

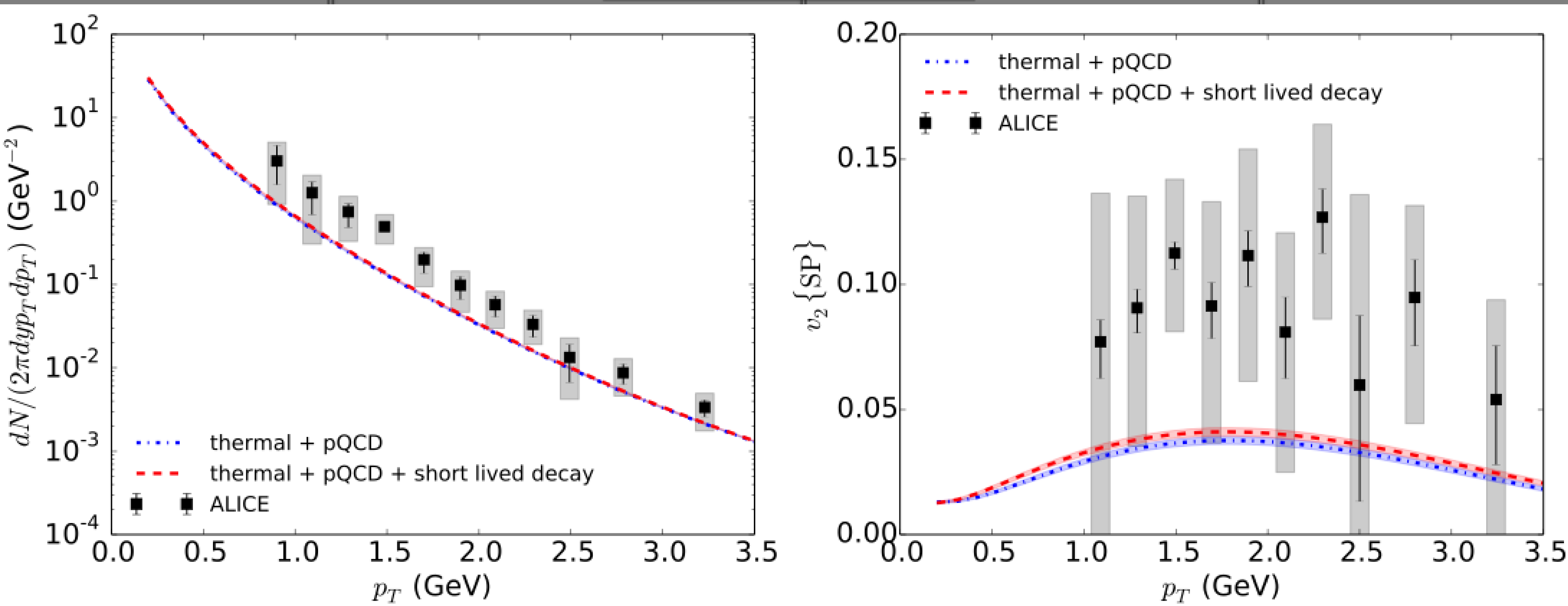
Thanks to Ralf Rapp and EMMI RRTF

Contributions from the short-lived resonances:

reaction	branching ratio

reaction	branching ratio
$N(1700) \to n + \gamma$	$1.2 * 10^{-3}$
$N(1710) \to n + \gamma$	$1 * 10^{-4}$
$N(1720) \to p + \gamma$	$1.5 * 10^{-3}$
$N(1720) \to n + \gamma$	$8 * 10^{-5}$

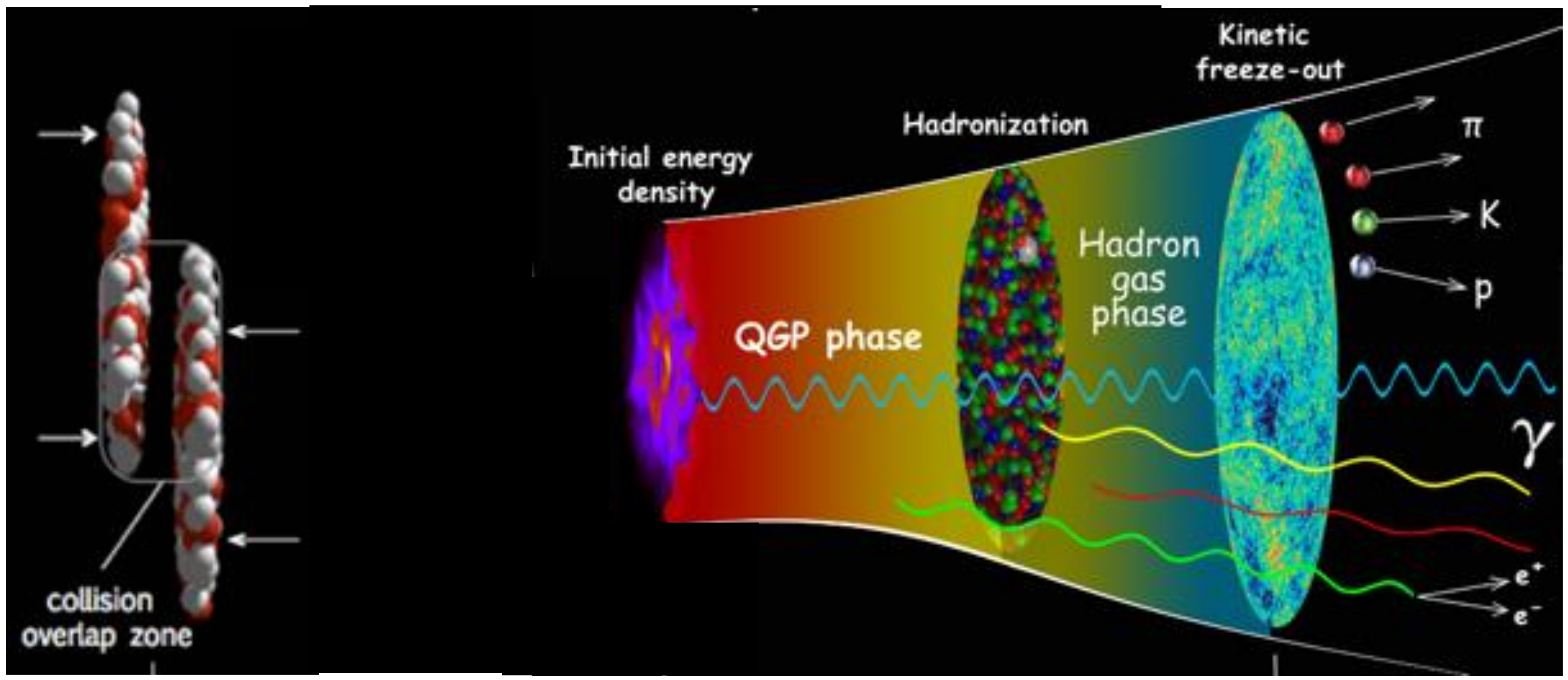
$\Delta(1232) \to N + \gamma$	0.6%
$\Lambda(1520) \to \Sigma^0 + \gamma$	2%
$\Xi(1530) \to \Xi + \gamma$	4%



Small but significant effects in the right direction

Pre-equilibrium flow (I)

Contributions from pre-equilibrium flow and $\pi^{\mu\nu}$:



Pre-equilibrium flow (II)

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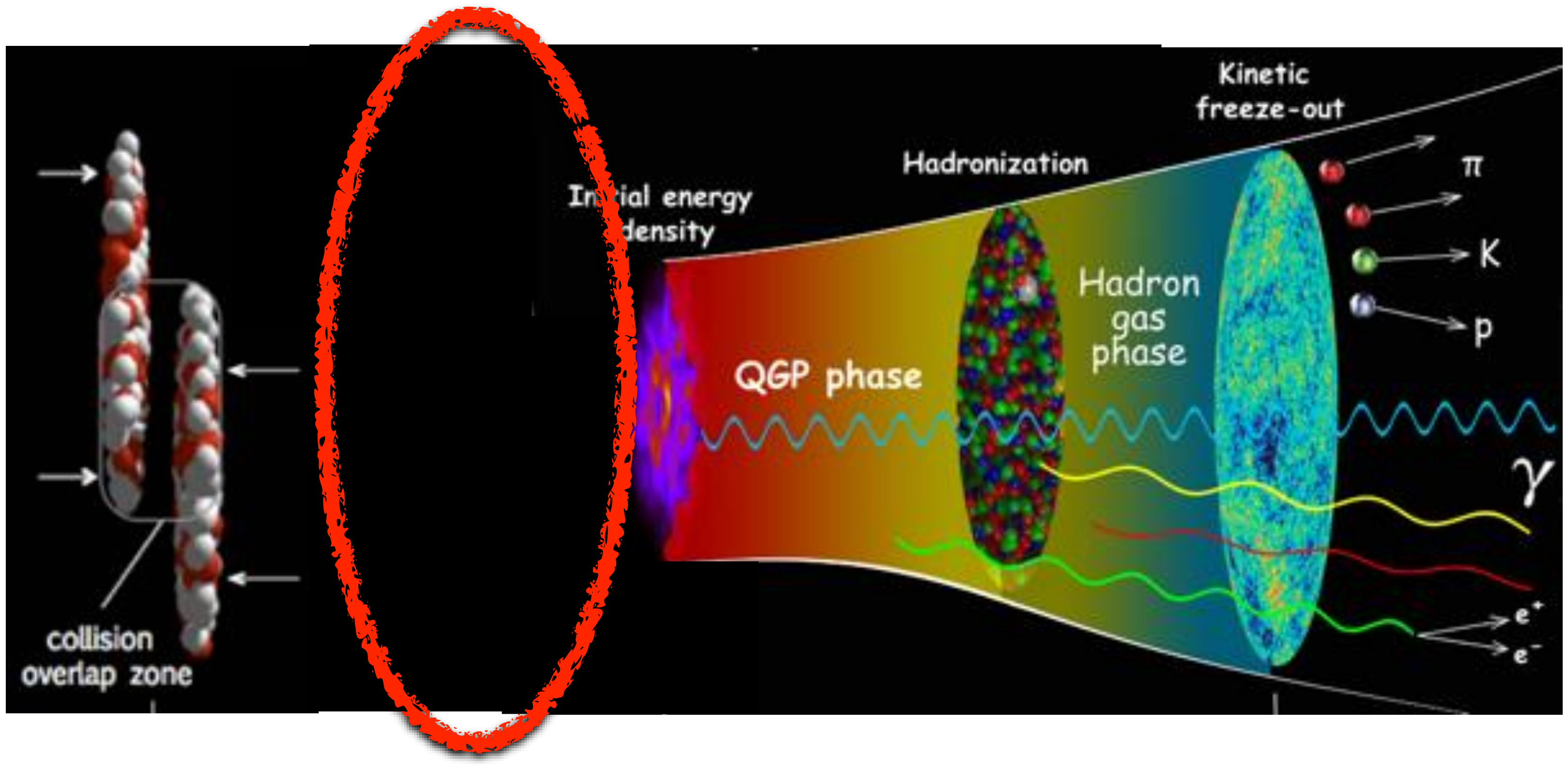


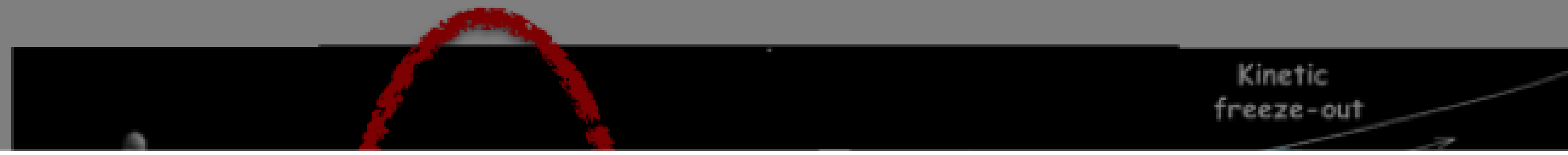
Free-streaming $f(\tau_s, \vec{x}, \vec{p}) = f(\tau_0, \vec{x} - \hat{p}(\tau_s - \tau_0), \vec{p})$

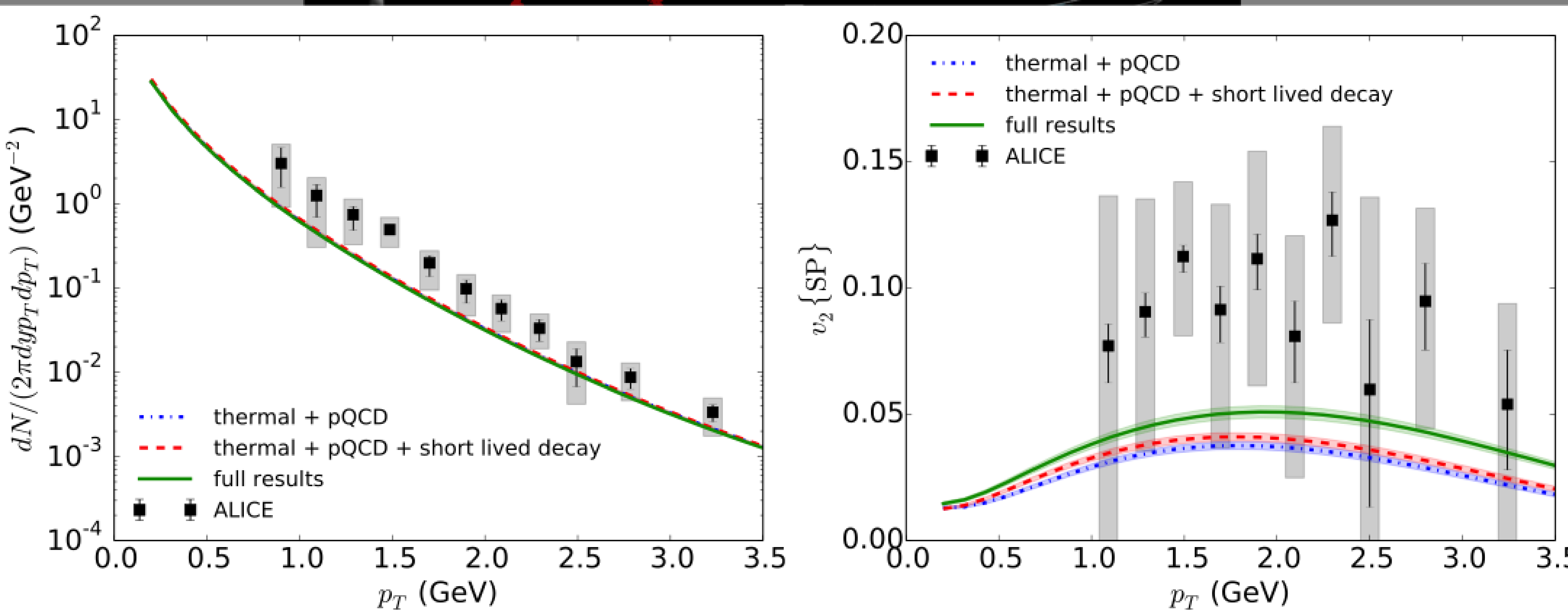
$$T^{\mu\nu}(\tau_s, \vec{x}) = \int \frac{d^3p}{E} p^\mu p^\nu f(\tau_s, \vec{x}, p)$$

$$T^{\mu\nu} u_\nu = e u^\mu \quad \Rightarrow \quad = e u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

Pre-equilibrium flow (III)

Contributions from pre-equilibrium flow and $\pi^{\mu\nu}$:





Small but significant effects in the right direction

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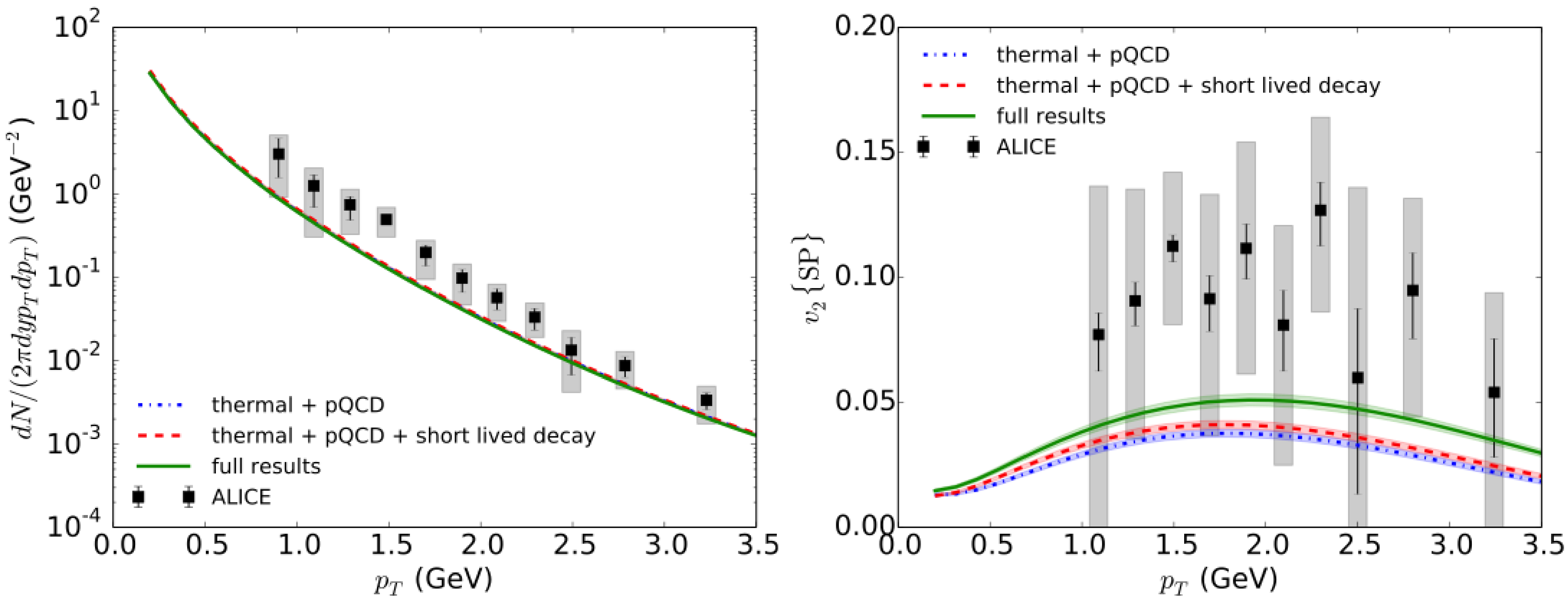

Small but significant effects in the right direction

Poster:
J-F. Paquet, **G21**

Conclusions

- We studied photon spectra and their anisotropic flows $\mathbf{v_n}$ from *event-by-event* viscous hydrodynamic medium

$$v_n^\gamma\{SP\}(p_T) = \frac{\left\langle \frac{dN^\gamma}{dy\, p_T\, dp_T}(p_T)\, v_n^\gamma(p_T)\, v_n^{ch} \cos\left(n\left(\Psi_n^\gamma(p_T) - \Psi_n^{ch}\right)\right)\right\rangle}{\left\langle \frac{dN^\gamma}{dy\, p_T\, dp_T}(p_T)\right\rangle v_n^{ch}\{2\}}.$$

- **Shear viscosity** suppresses photon v_n. Dominant suppression comes not from flow, but from the viscous correction to the production rates.

- **Elliptic** and **triangular** flow of photons are more sensitive than hadrons to shear stress at early times and to initial state fluctuations.

- **Short-lived resonance decays** and **pre-equilibrium flow** cause measurable increase of direct photon anisotropic flow.

- Still, experimental **data** appear to **require significantly more photon rate from the late evolution stage** than in implemented in the model

arXiv: 1308.2111, 1308.2440, 1403.7558 **https://github.com/chunshen1987/iEBE.git**

Conclusions

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R. Rapp
Mon. 15:20

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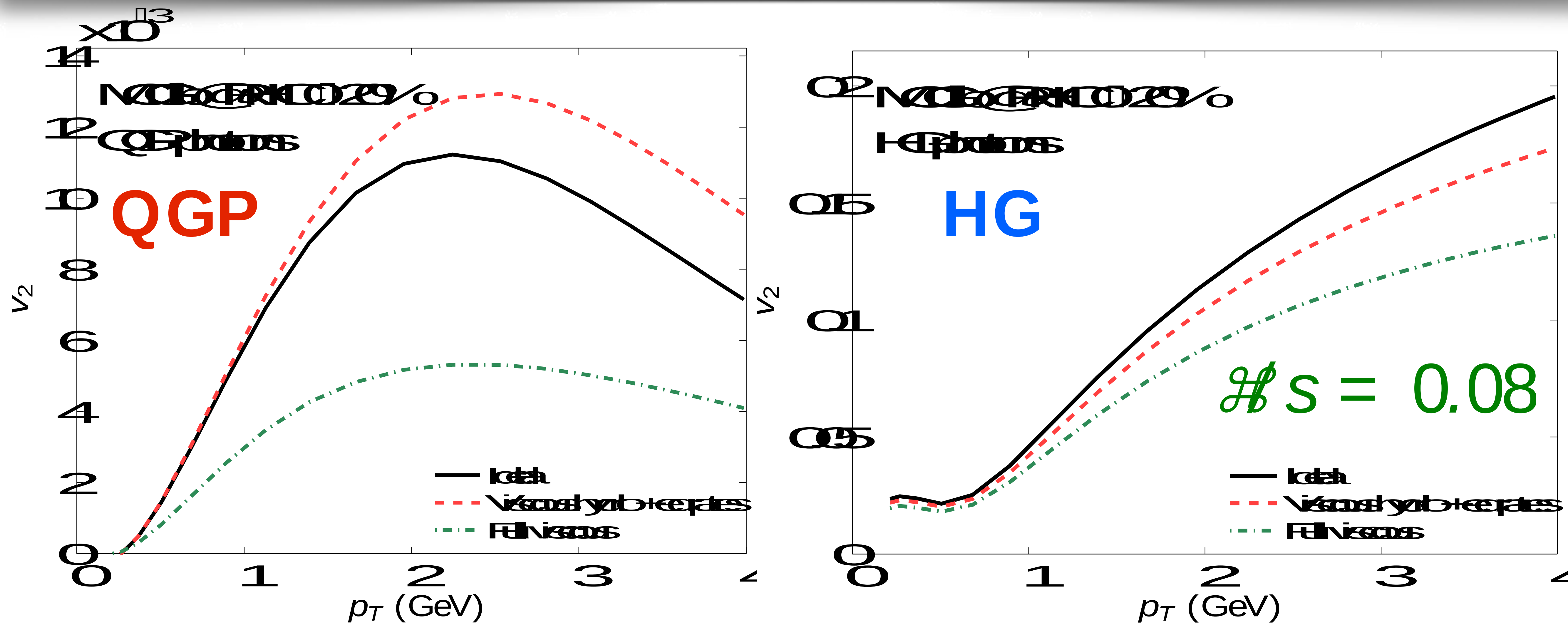
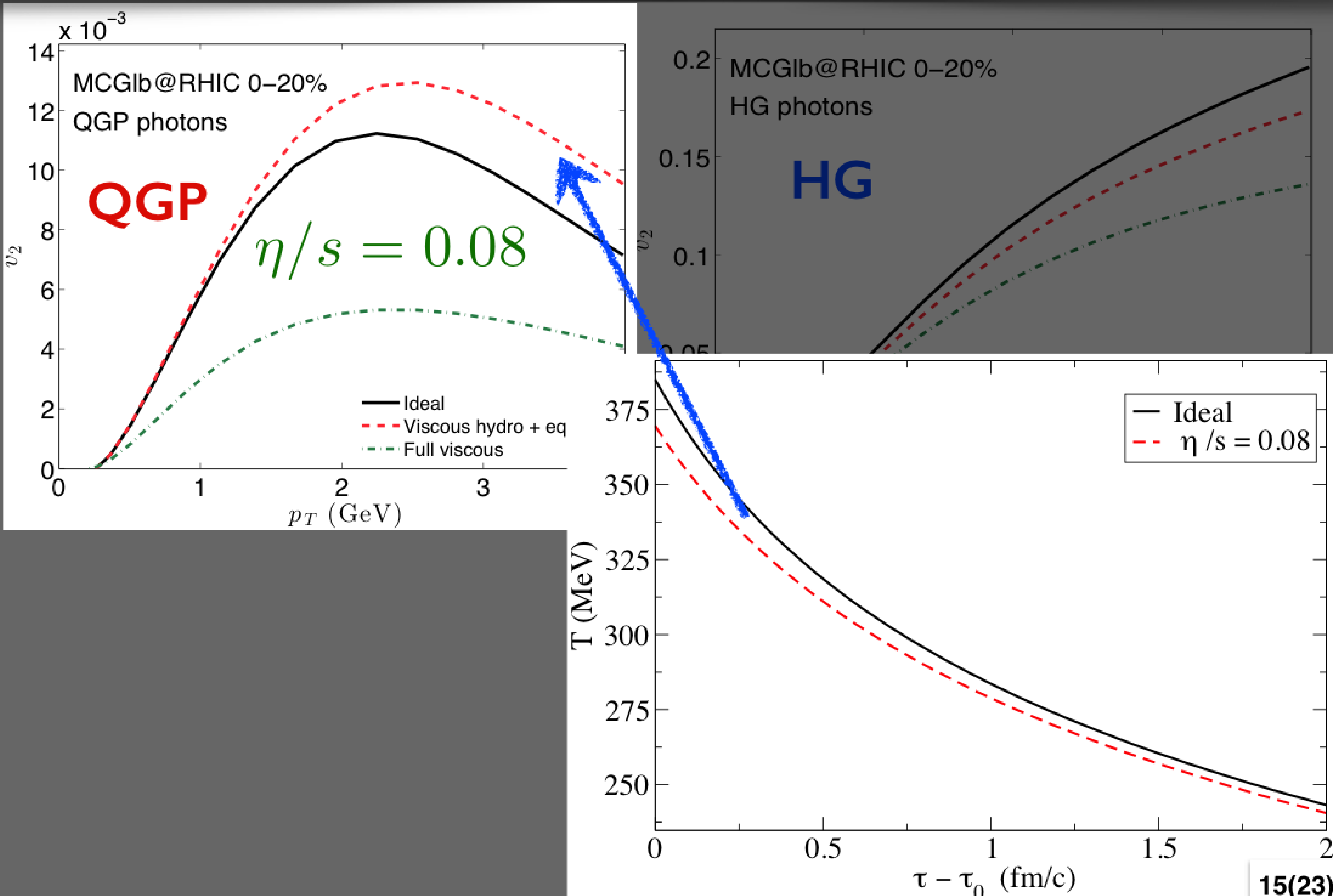
Back up

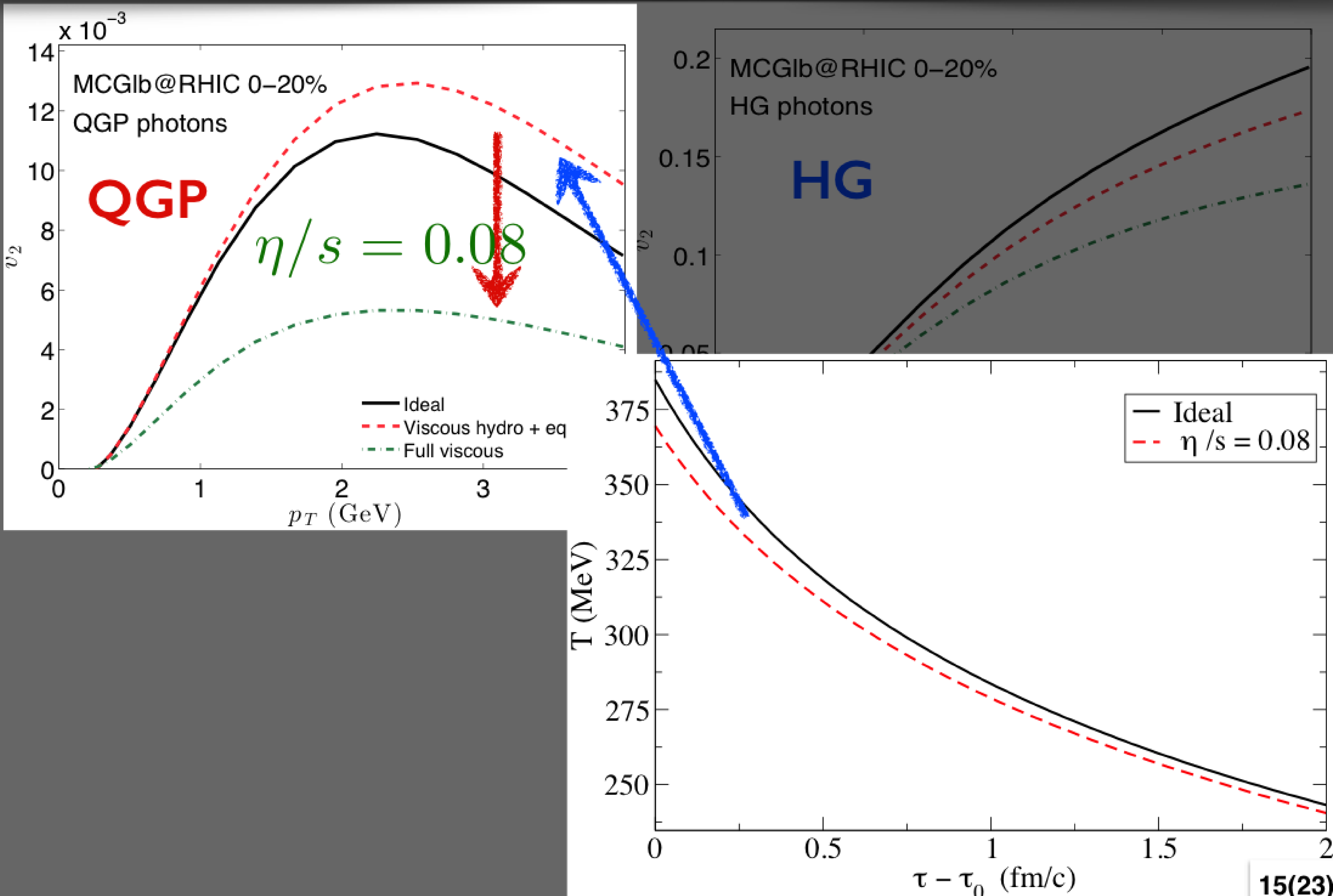
Viscous effects on photon elliptic flow



Viscous effects on photon elliptic flow



Viscous effects on photon elliptic flow



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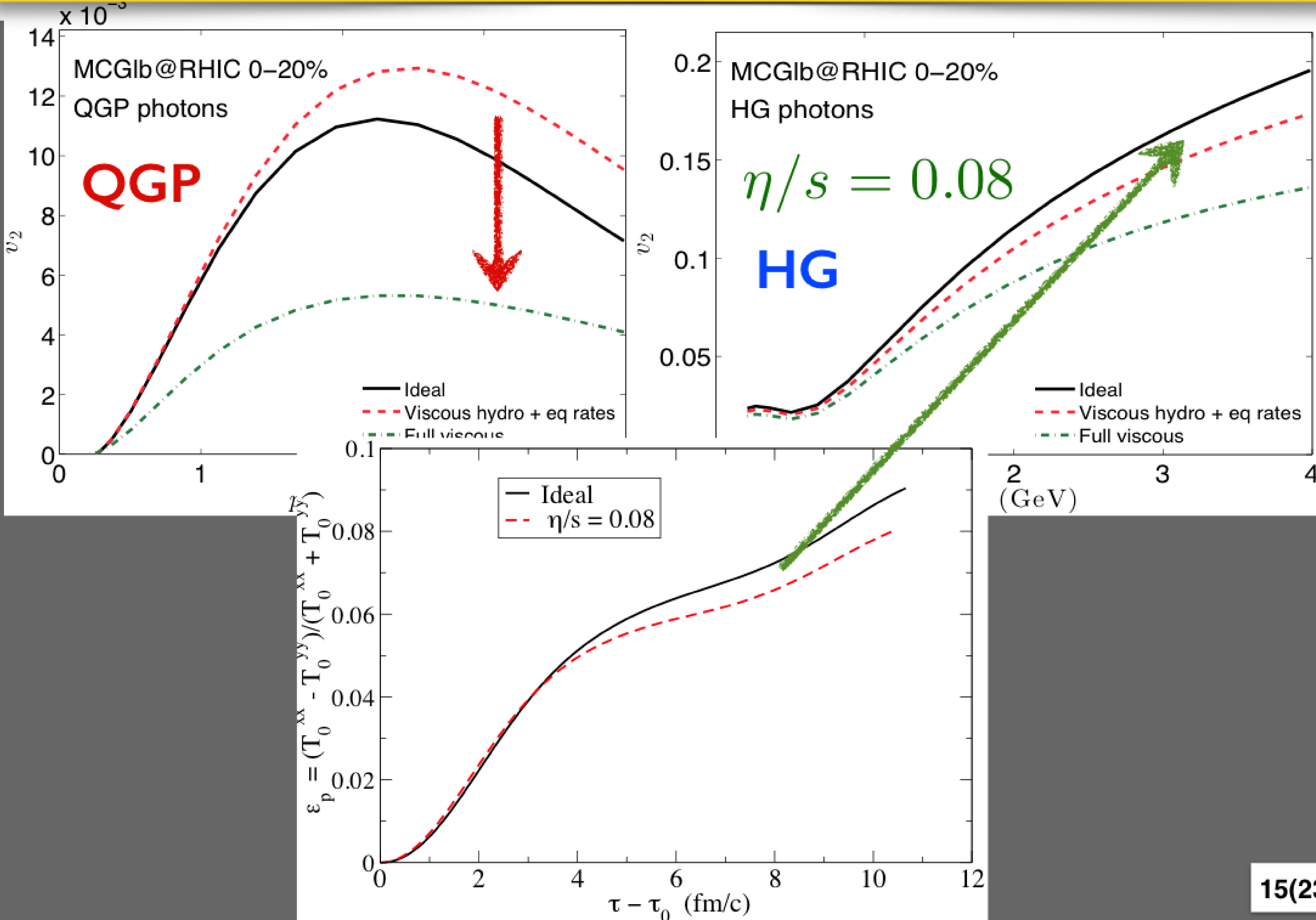
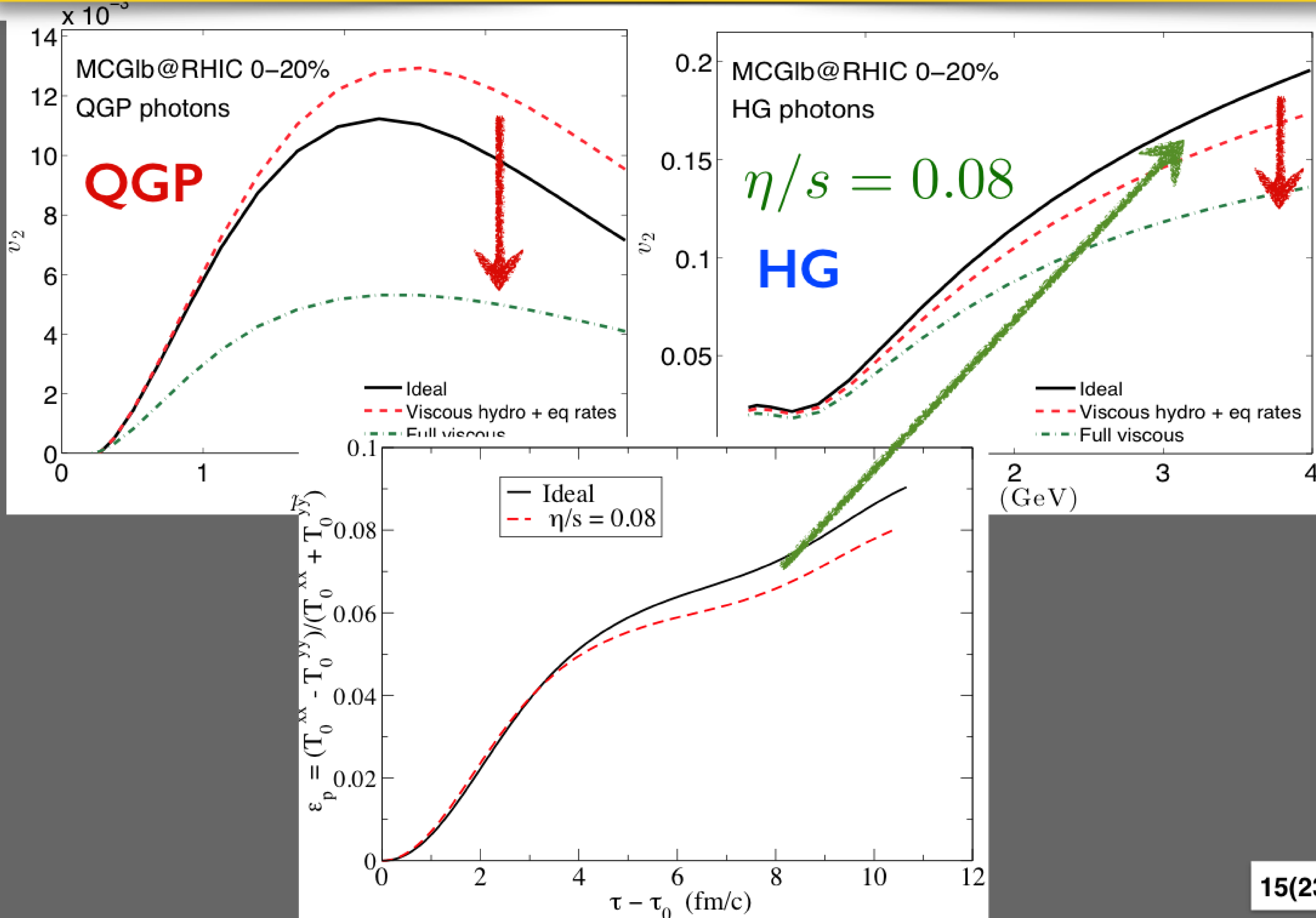
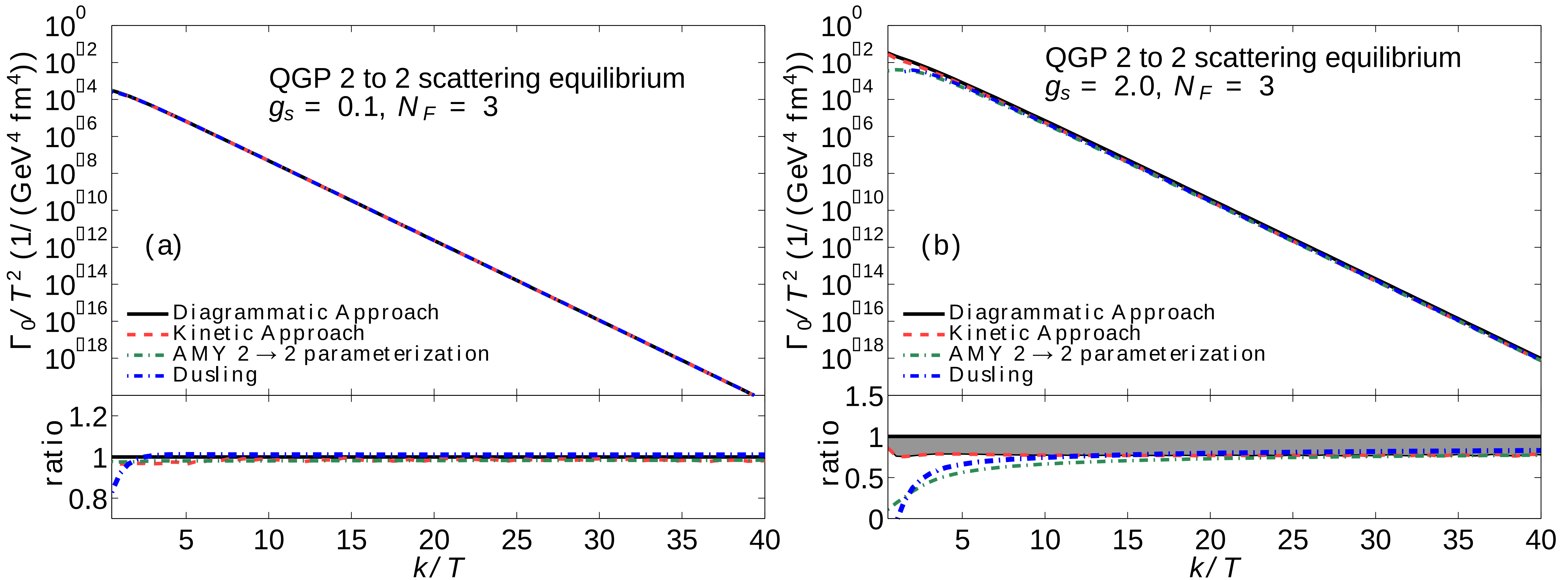


Viscous effects on photon elliptic flow



Photon Rates (QGP 2 to 2 processes only)

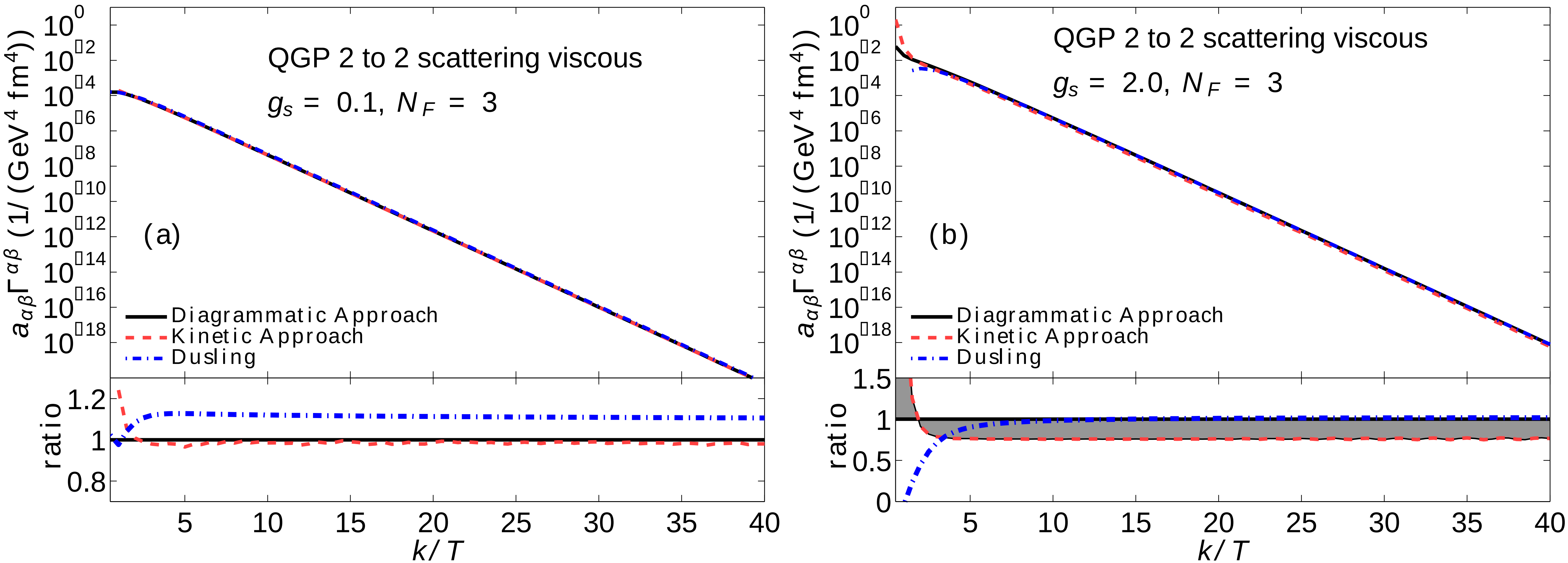
Equilibrium rates:



- For small g, results from diagrammatic approach agree well with kinetic approach and AMY
- For g = 2.0, diagrammatic approach gives 25% larger results compared to kinetic approach; difference are due to cut-off dependence.

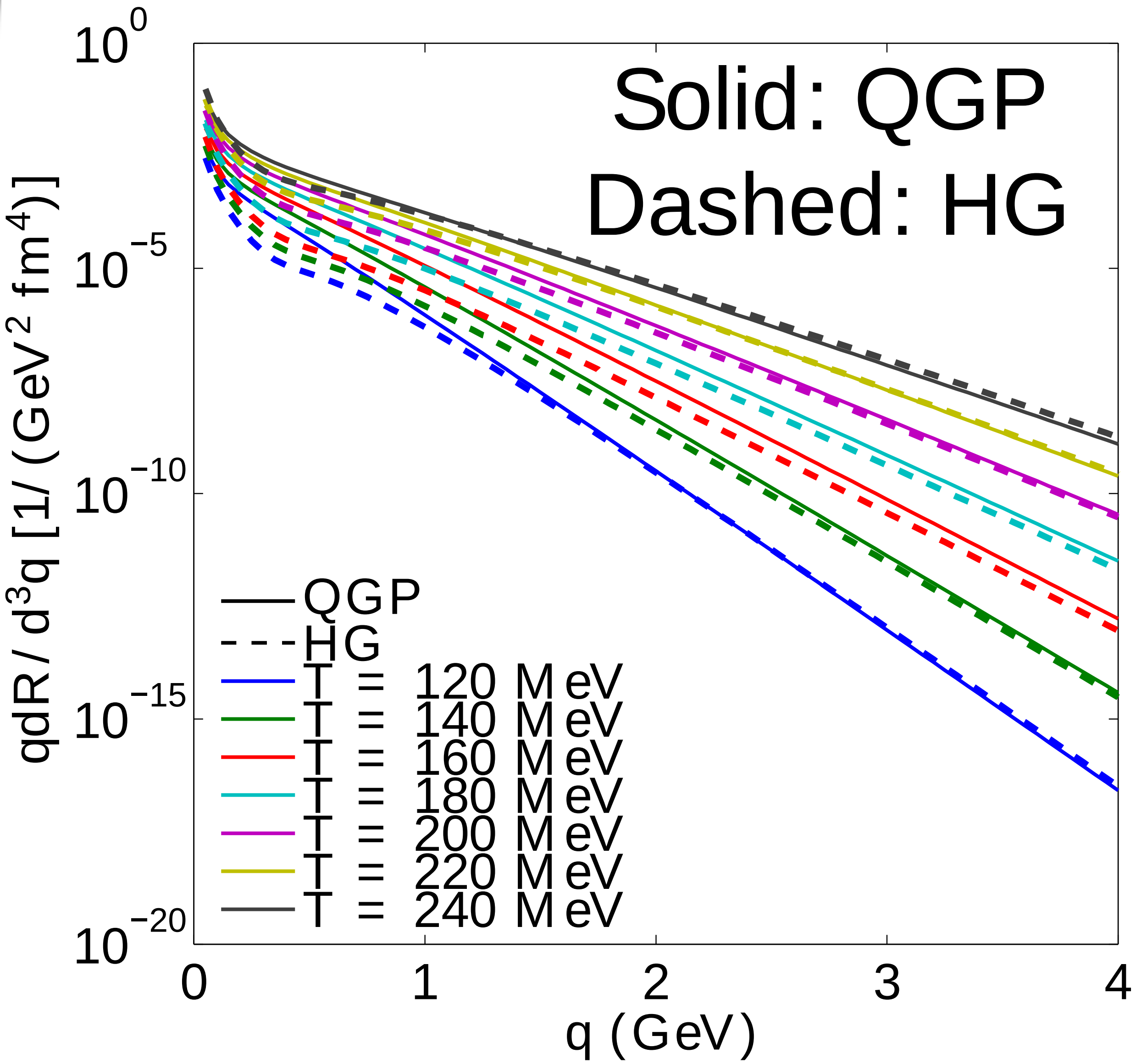
Photon Rates (QGP 2 to 2 processes only)

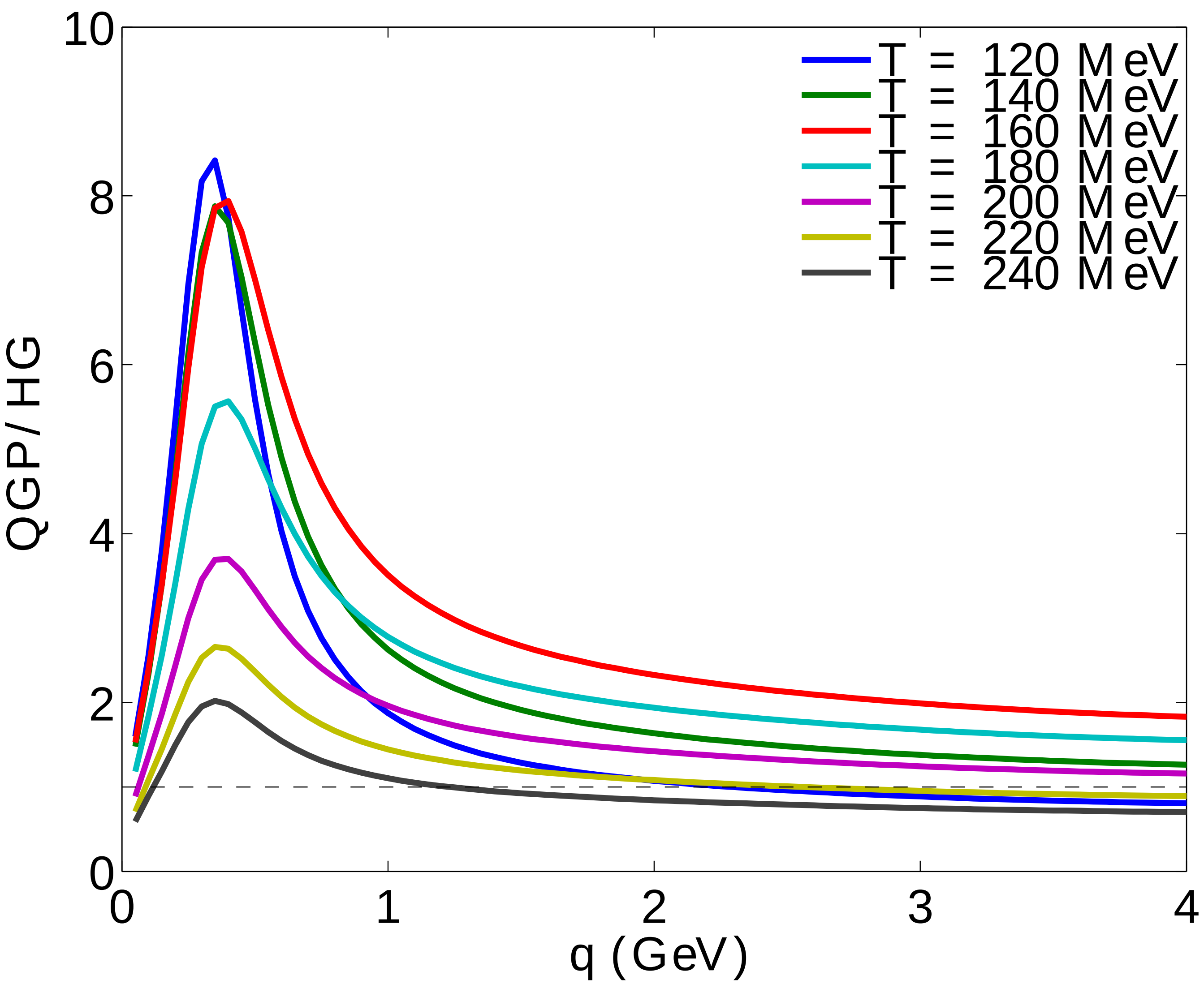
Viscous corrections:



- For small g, diagrammatic approach agrees with kinetic approach
- For g = 2, the deviations at small k/T may originate from different higher order $O(g^2 T)$ contributions

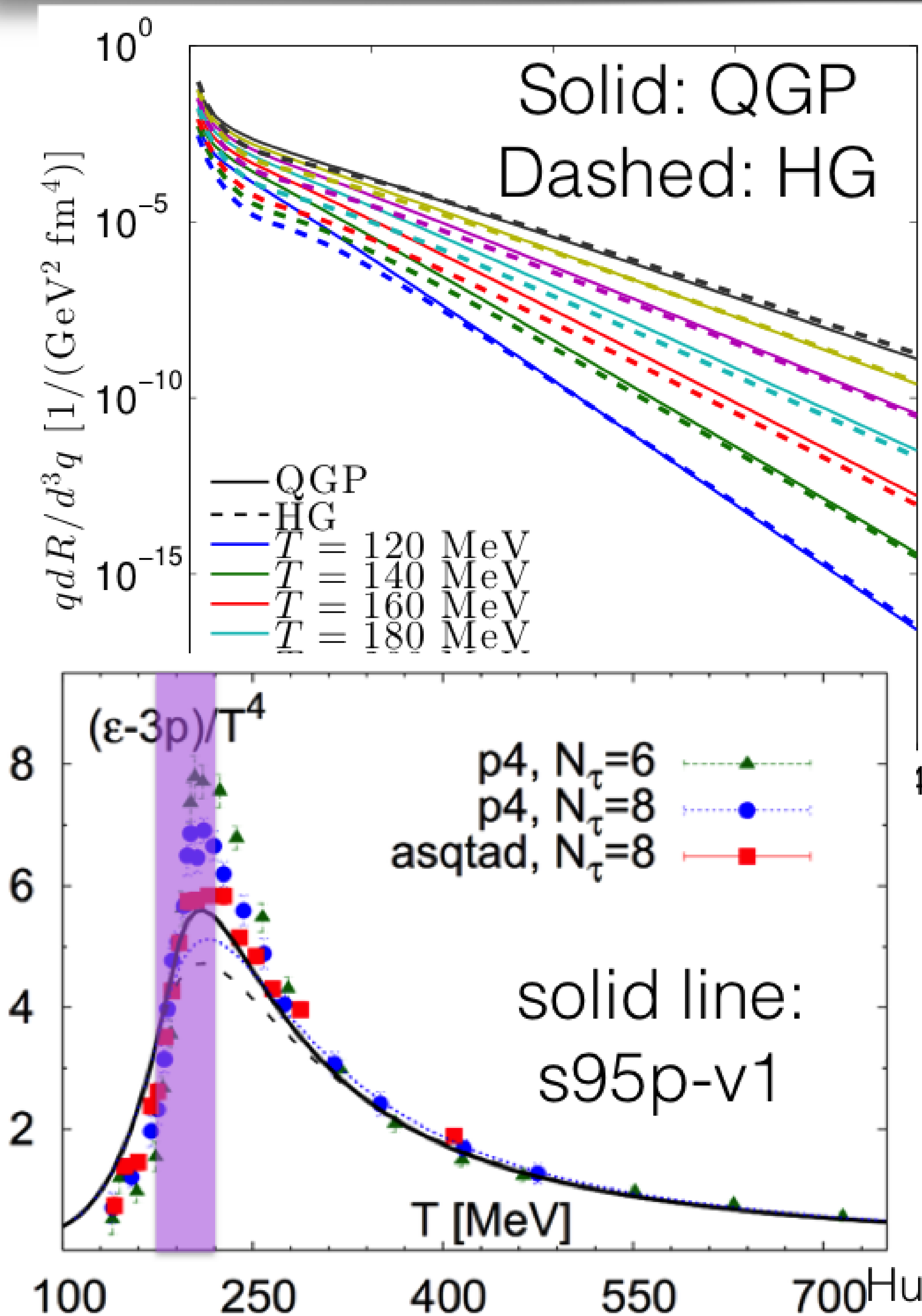
Photon Emission Rates QGP vs HG

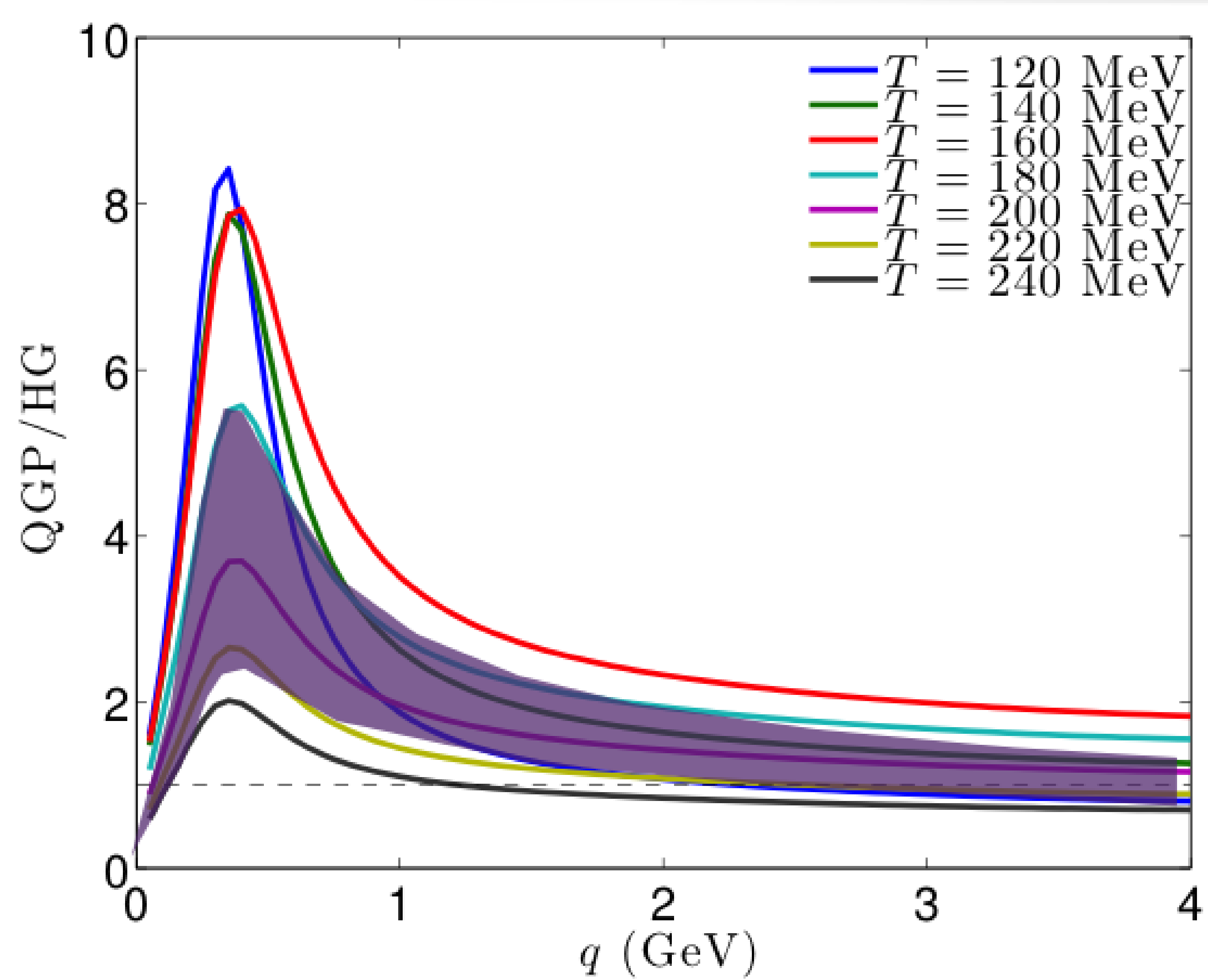




- QGP rates have very different p_T dependence compared to HG rates

Photon Emission Rates QGP vs HG

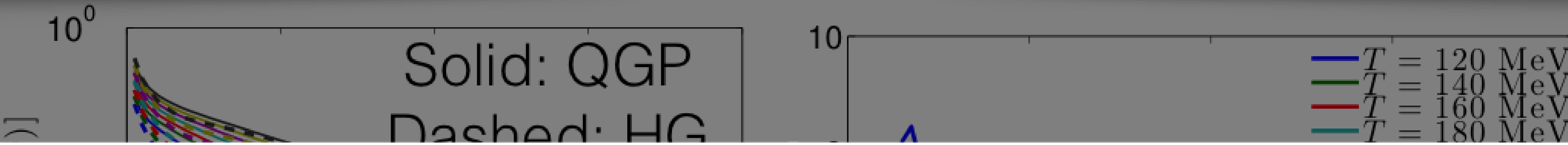


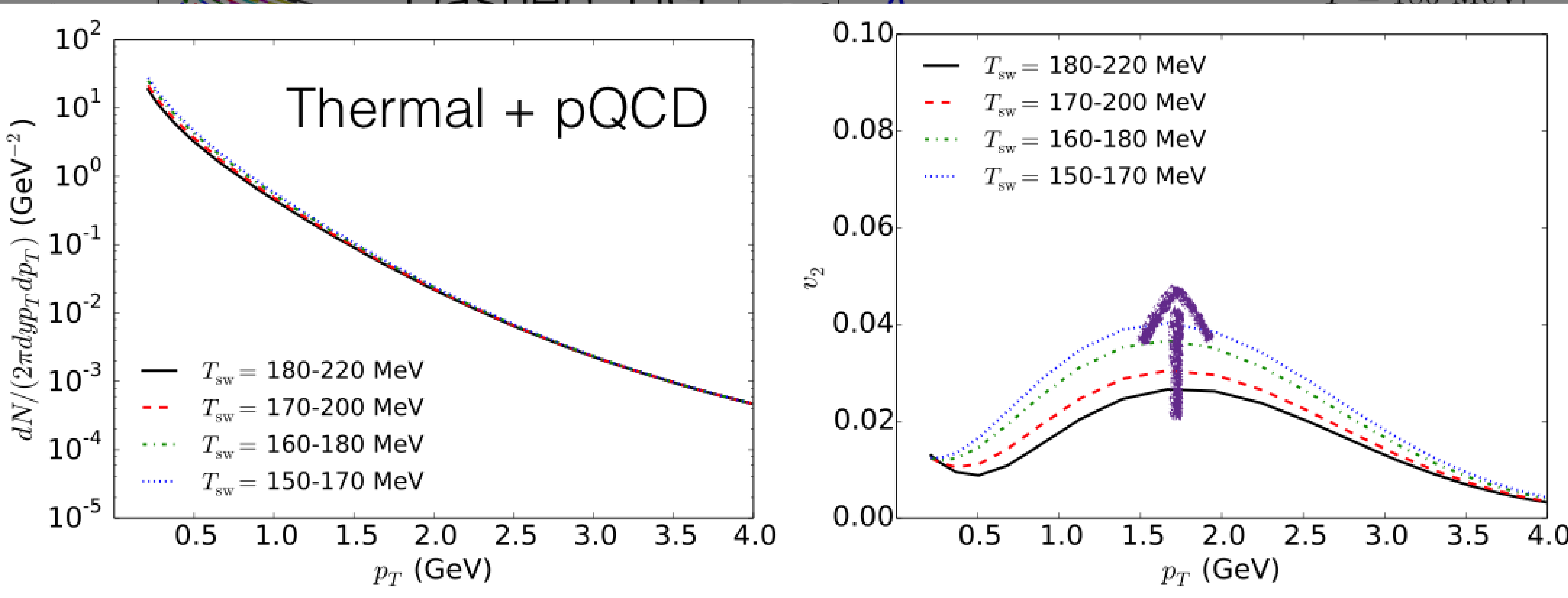


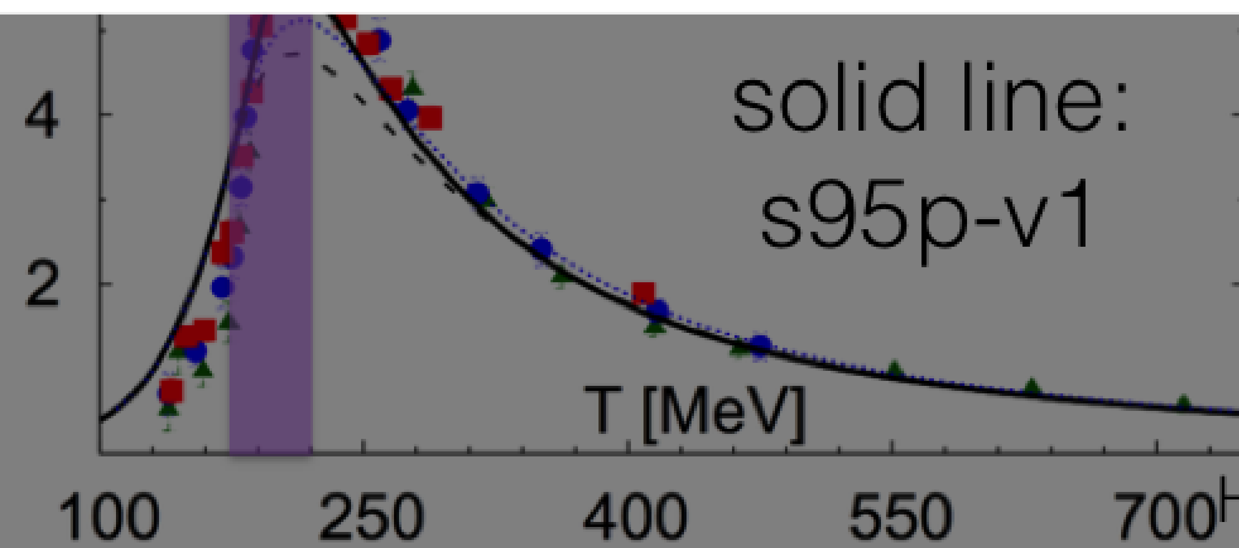
- QGP rates have very different p_T dependence compared to HG rates
- Estimated transition region for production rates, T ~ **184 - 220** MeV

Huovinen & Petreczky, Nucl.Phys. A837 (2010) 26-53

Photon Emission Rates QGP vs HG



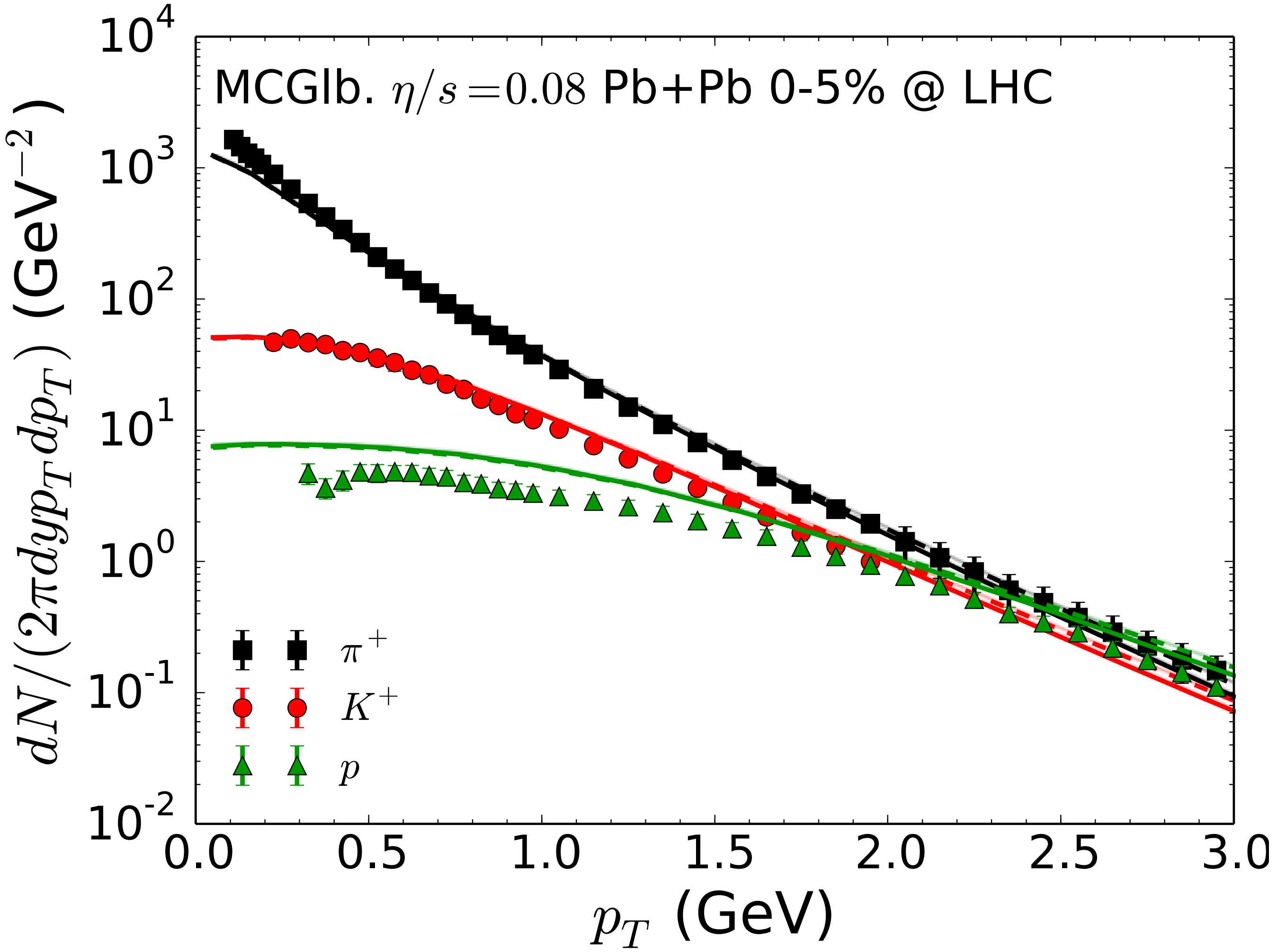


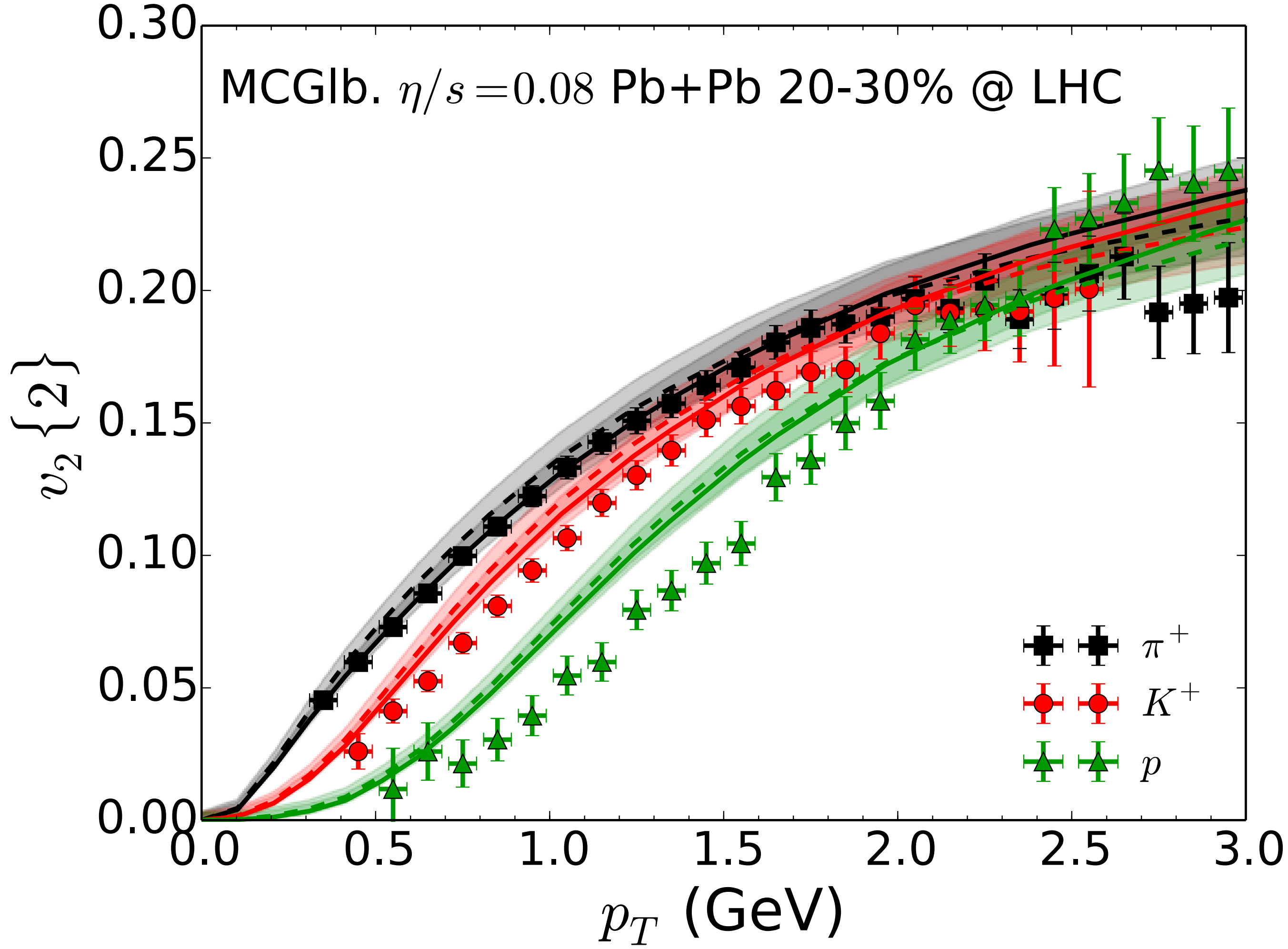


- p_T dependence compared to HG rates
- Estimated transition region for production rates, T ~ **184 - 220** MeV

Huovinen & Petreczky, Nucl.Phys. A837 (2010) 26-53

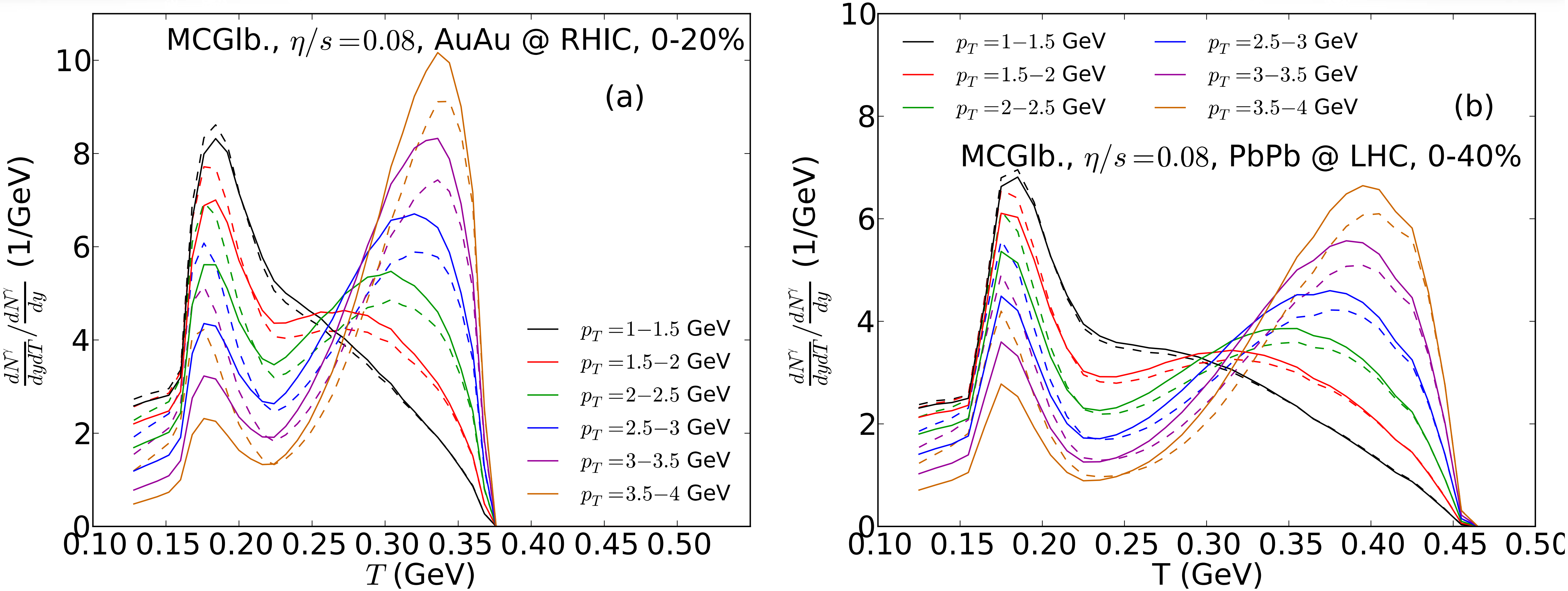
Pre-equilibrium flow effects on hadrons





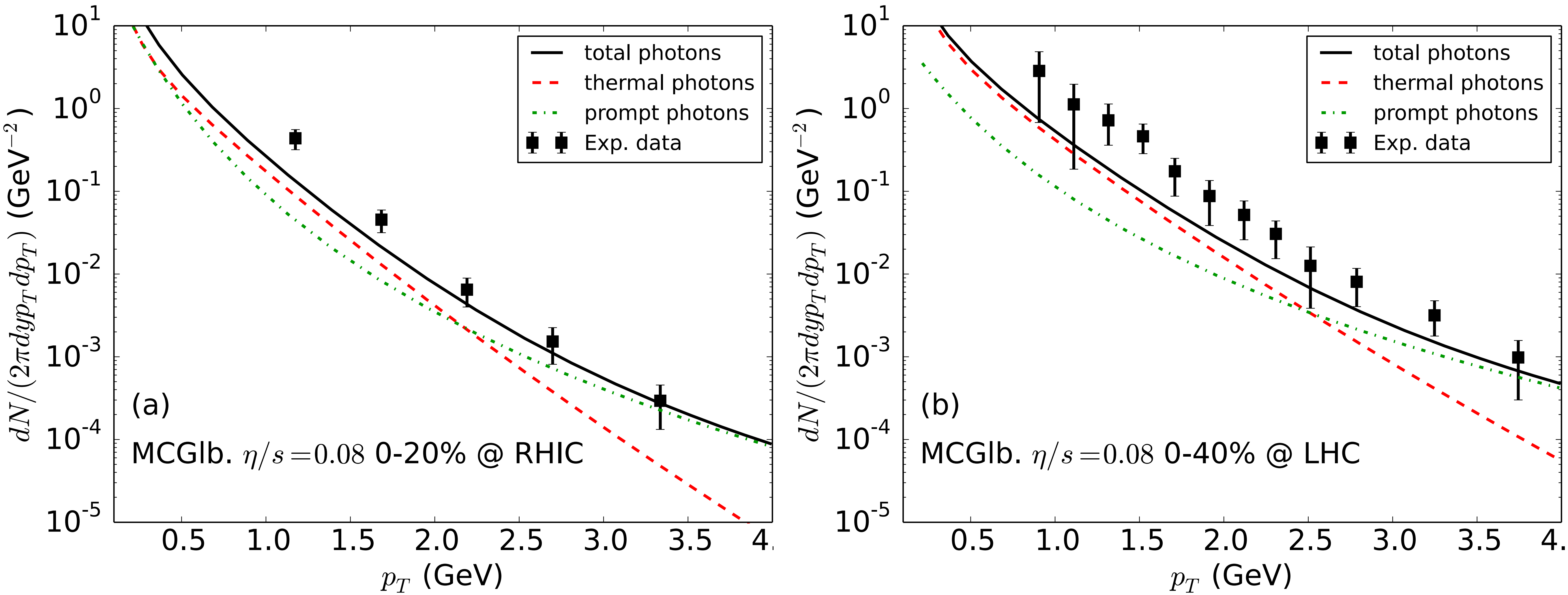
Dashed: with initial flow
Solid: without initial flow

Emission vs. Temperature



- High p_T photons are mostly emitted from high temperature region
- Peak photon production around T = 165-200 MeV due to large hydrodynamic space-time volume

Thermal Photon Spectra



- With all available thermal emission sources, our current calculations still underestimate measured direct photon spectra at low p_T at both RHIC and LHC energies
- Additional emission sources need to be included to improve the agreement between theory and data

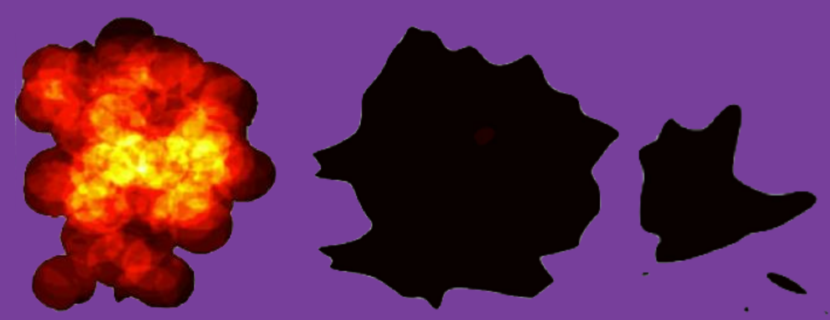
State-of-the-art hydrodynamic modeling

https://github.com/chunshen1987/iEBE.git

JET Collaboration

Initial Condition Generators (MC-KLN, MC-Glauber)

Hydrodynamic Simulations (VISH2+1)



UrQMD

Hadrons spectra & v_n

e-b-e VISHNU

HydroInfo Package

$u^{\mu}, \pi^{\mu\nu}$

Thermal Photon Emission Rates

Thermal Photon Interface

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu} q_\mu q_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

$$E\frac{dN^\gamma}{d^3p} = \int d^4x\, q\frac{dR}{d^3q}$$

Photon spectrum & v_n

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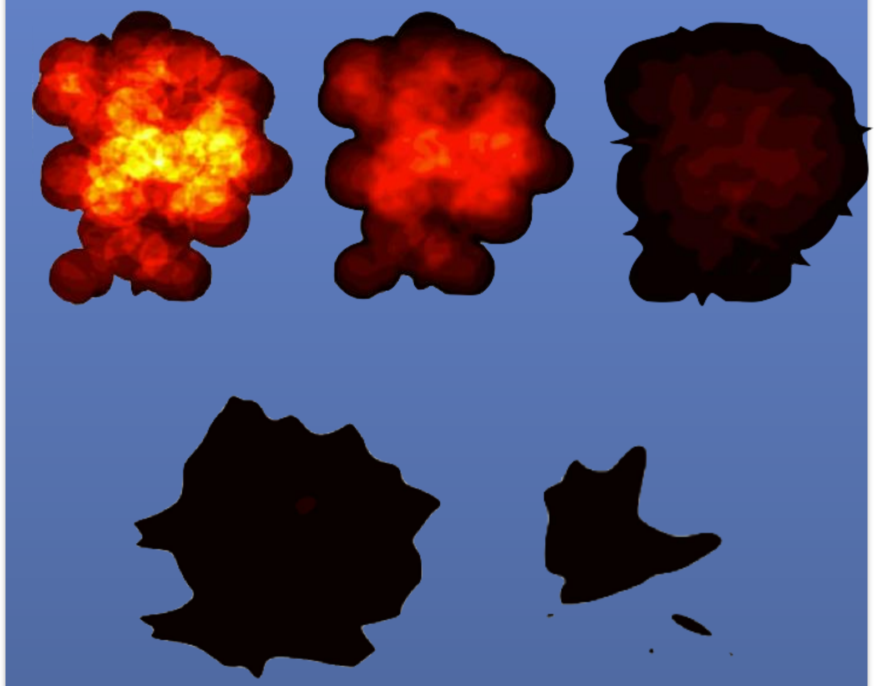

HydroInfo Package

$e, s, p, T,$

$u^{\mu}, \pi^{\mu\nu}$

Hadrons spectra & v_n

Your own Jet Quenching or Heavy Quark Package