RECENT ADVANCES IN NON-EQUILIBRIUM PHYSICS OF THE HADRONIC STAGE

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Based on

OGM, J. Staudenmeier, A. Schäfer, J. Torres-Rincon, and H. Elfner. arXiv: 2107.08812

A. Schäfer, OGM, J.F. Paquet, H. Elfner and C. Gale. *In preparation*

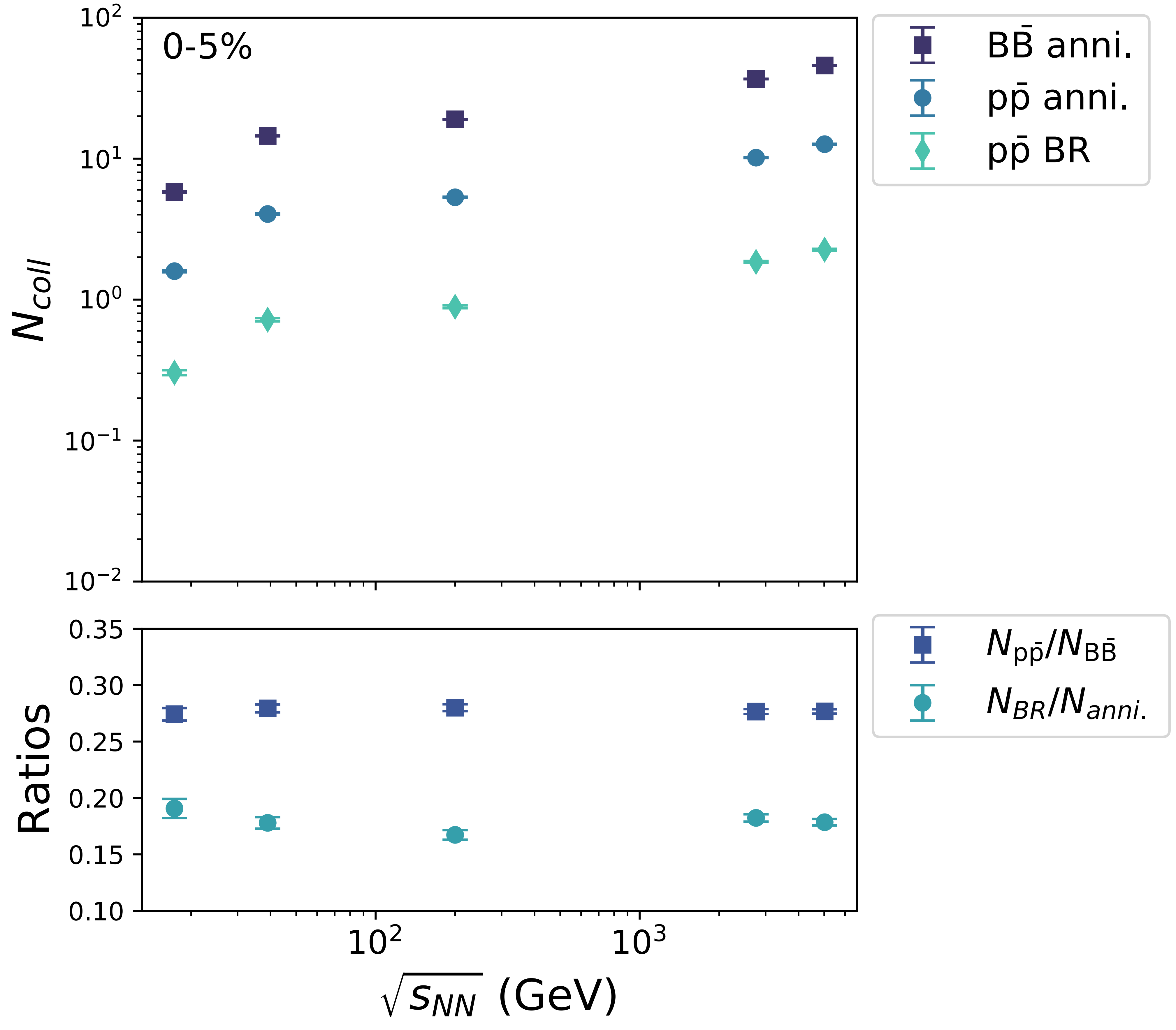
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

CRC-TR 211 Strong-interaction matter under extreme conditions

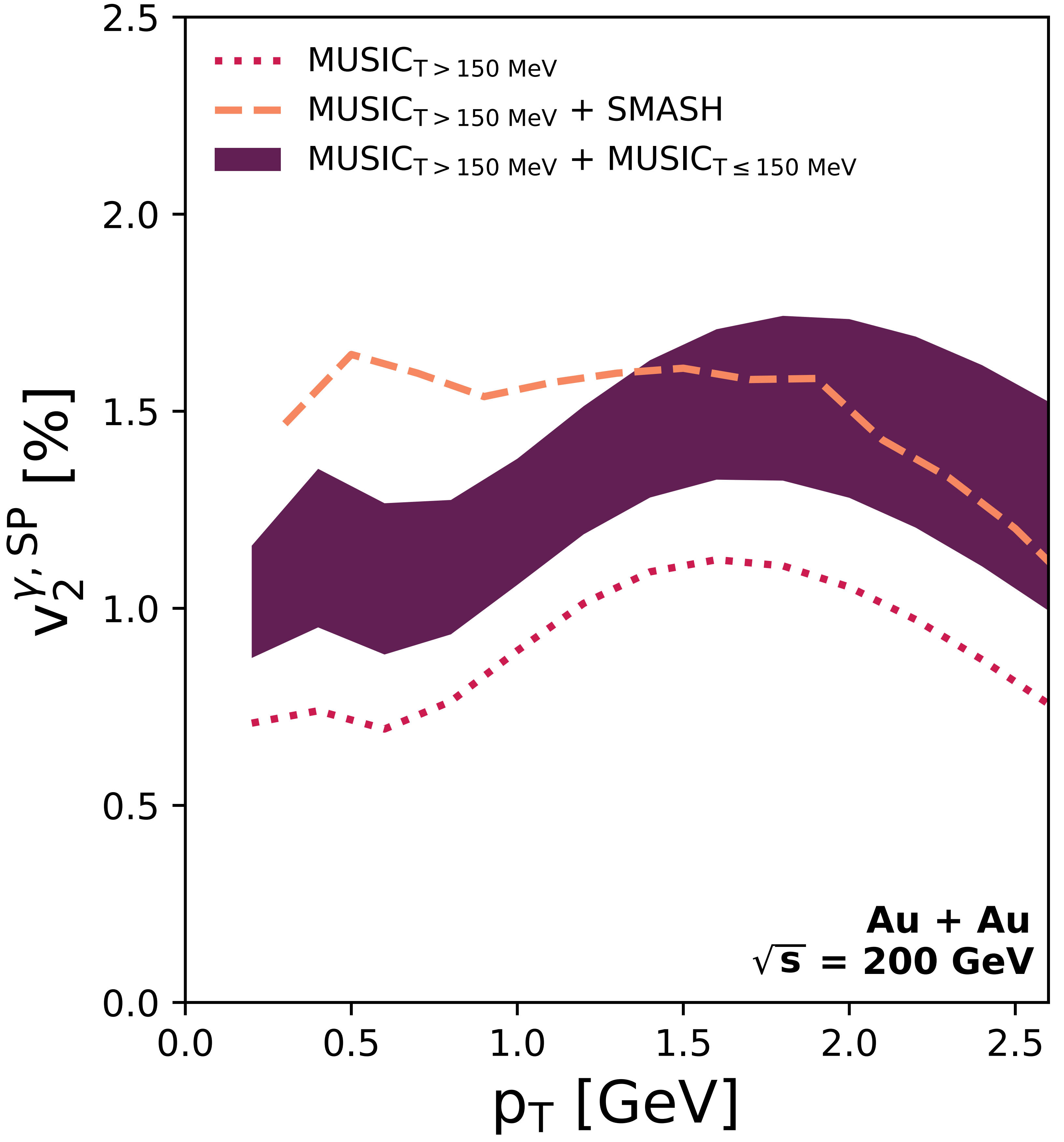
MOTIVATION.
THE ROLE OF NON-EQ DYNAMICS

TODAY'S TALK

$P\bar{P}$ REGENERATION IS NON-NEGLIGIBLE



NON-EQ EFFECTS ENHANCE PHOTON FLOW



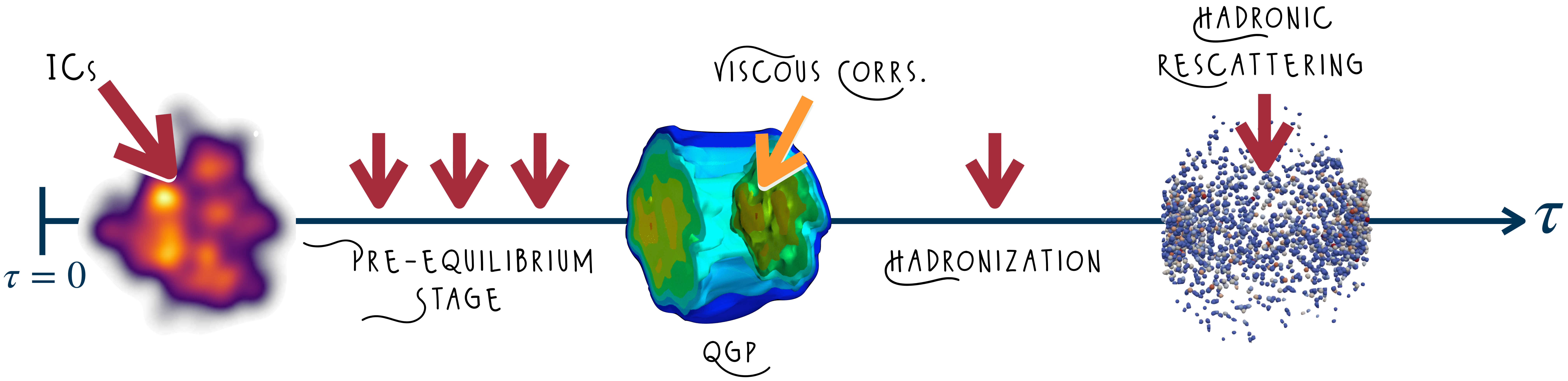
MOTIVATION

- Heavy-Ion Collisions create an Isolated Quantum System

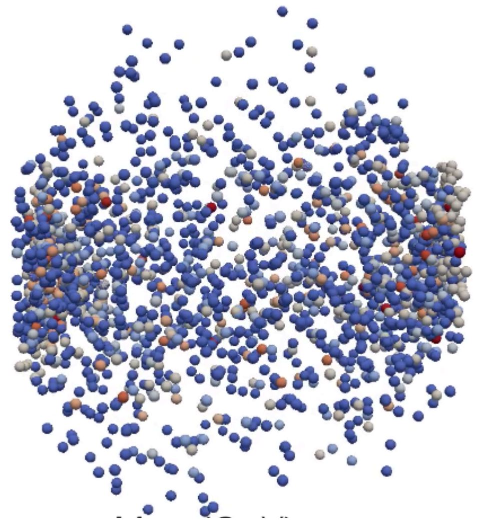
  which is
  - Initially far away from any equilibrium
  - Self-interacting
  - Expanding against the vacuum

- A system battling to thermalize against all odds.

How does non-eq. dynamics affect

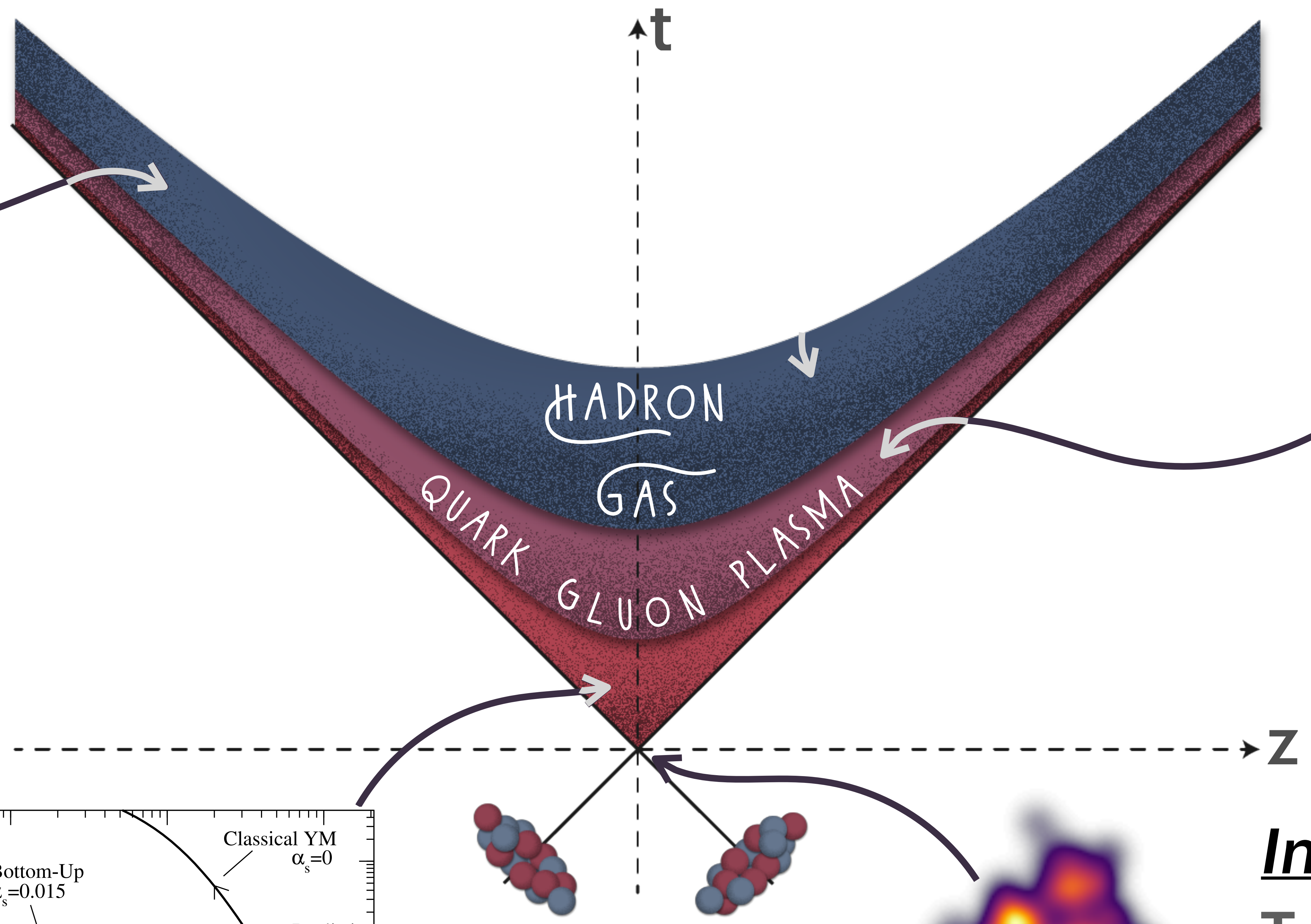


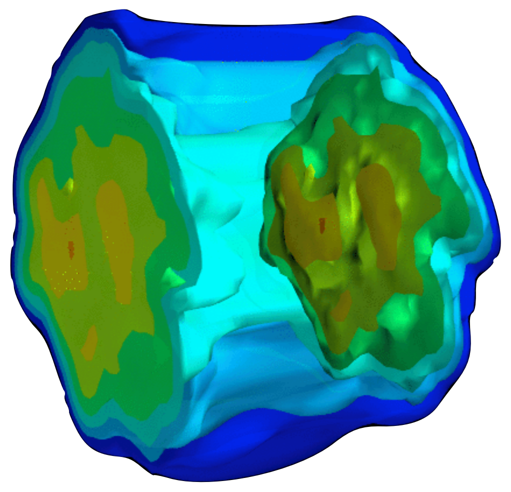
The Standard Model of Heavy Ion Collisions: A hybrid model



Afterburner

SMASH
UrQMD



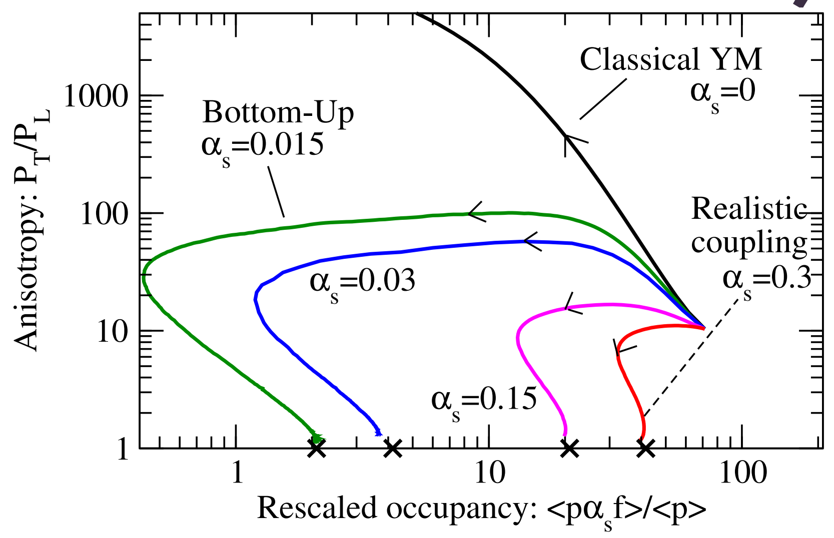


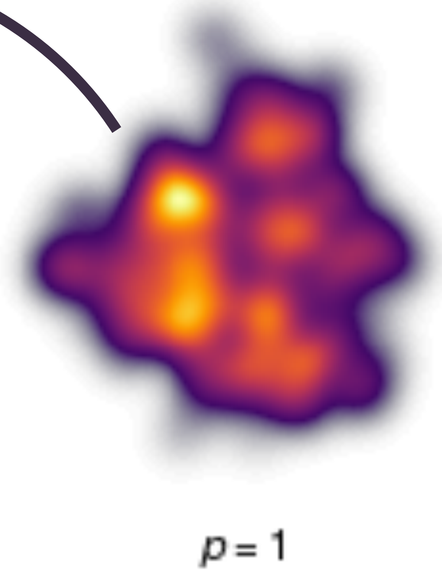
Hydro

VISH
MUSIC
vHLLE

Pre-equilibrium

AMY EKT
KøMPøST



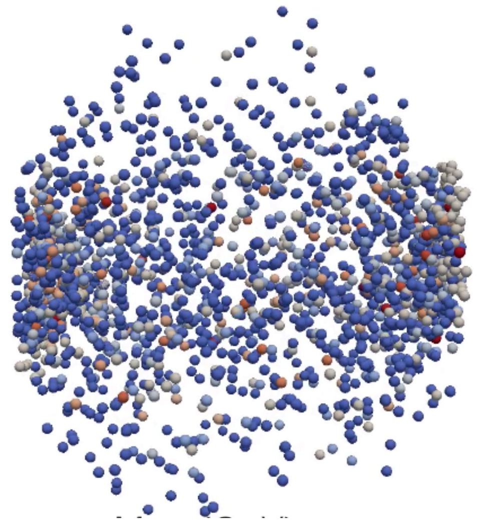


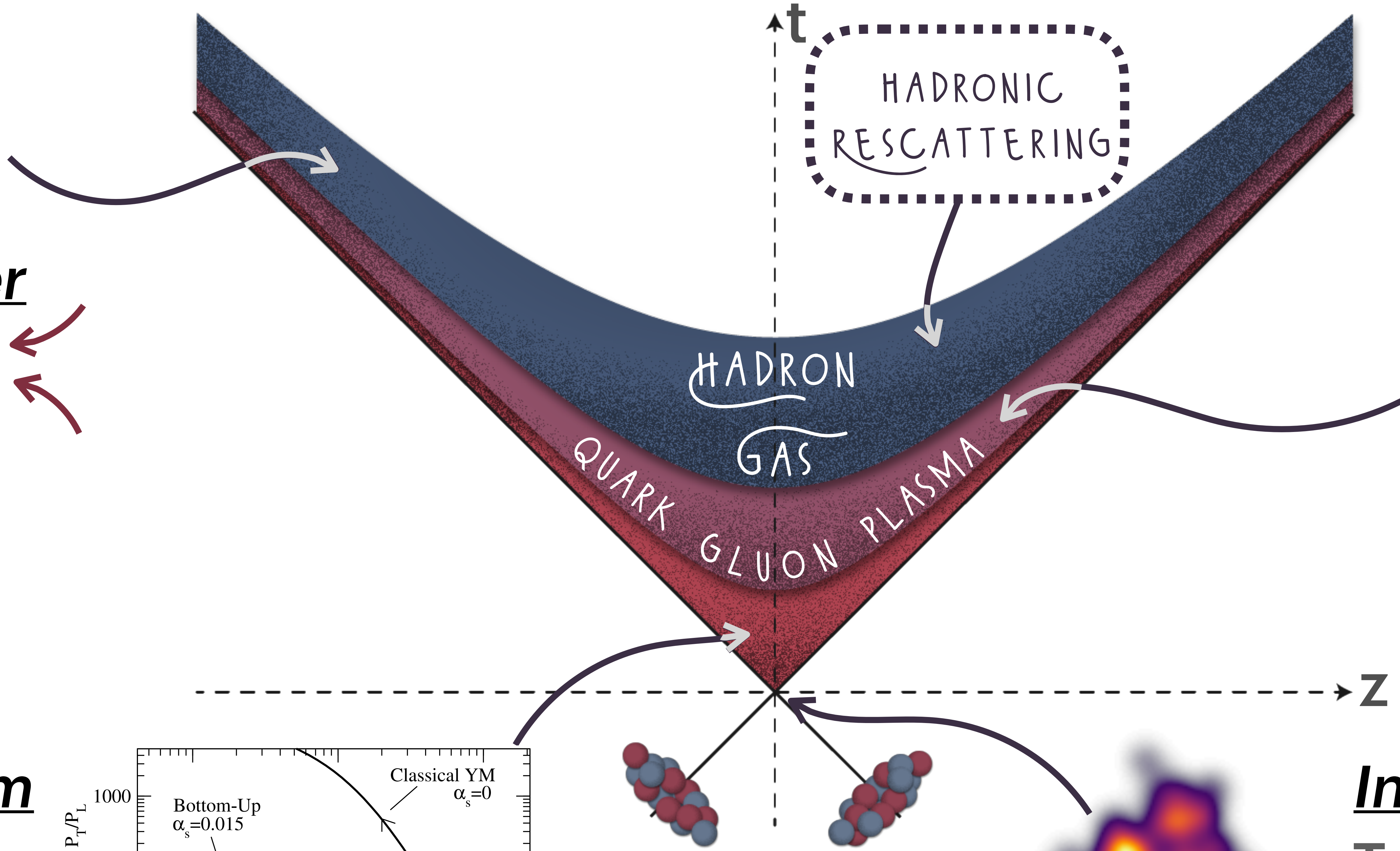
Initial Conditions

TRENTO
IP-Glasma
MAGMA

[1] From Kurkela and Zhu Phys.Rev.Lett. 115 (2015) no.18, 182301

The Standard Model of Heavy Ion Collisions: A hybrid model



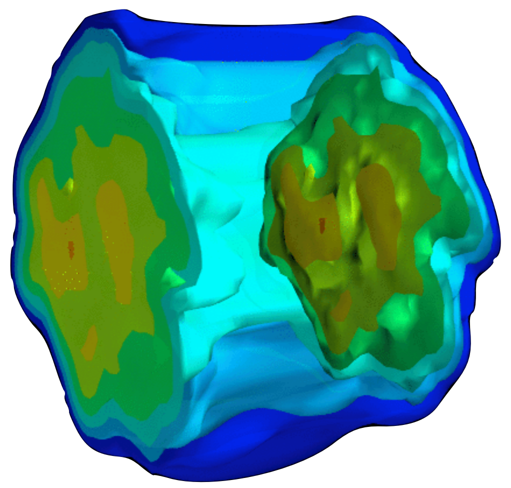


Afterburner

SMASH

UrQMD

Hydro



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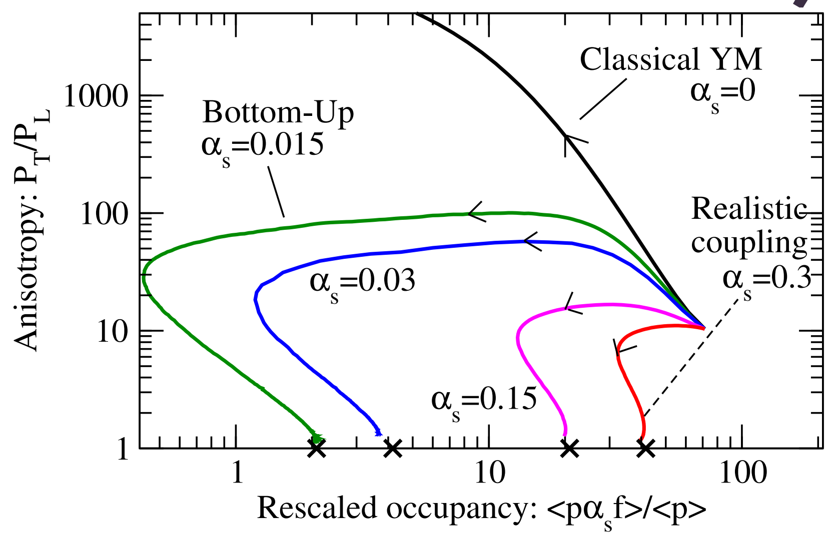

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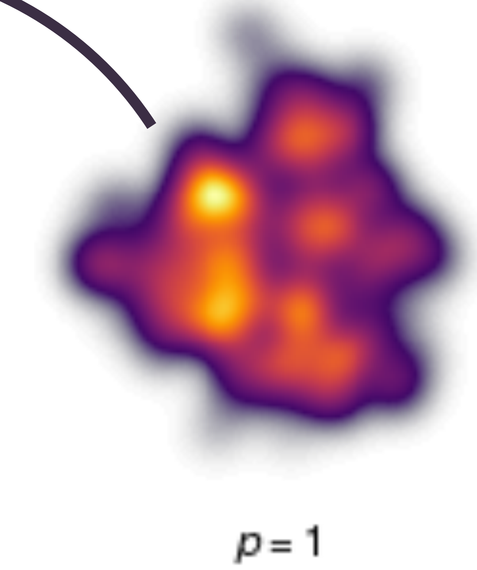


TRENTO

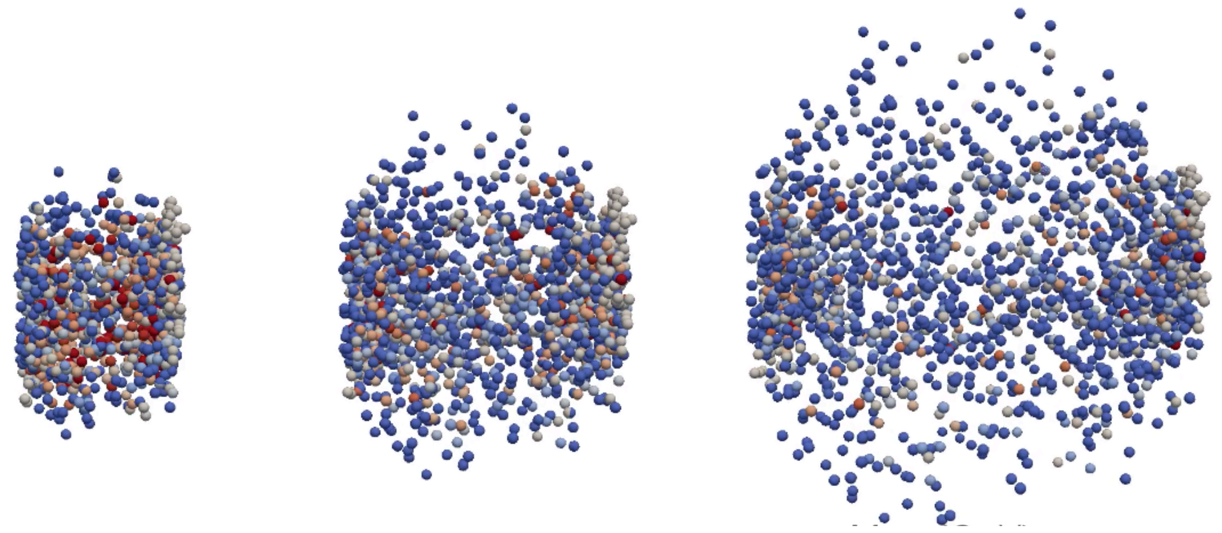
IP-Glasma

MAGMA

[1] From Kurkela and Zhu Phys.Rev.Lett. 115 (2015) no.18, 182301

SMASH*

- ***S**imulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons*



- Hadronic transport approach
- Includes hadrons with masses up to ~ 2 GeV
- Particles propagate and collide on the basis of physical cross sections
- Effective solution to Boltzmann equation: $p_\mu \partial^\mu f + m\, \partial_{p_\mu} (F^\mu f)^\mu = C[f]$
- Successfully studied bulk properties, as well as dilepton and strangeness production

SMASH 1.8
https://smash-transport.github.io
https://doi.org/10.5281/zenodo.3484711

Weil *et al*, *Phys.Rev.C* 94 (2016) 5, 054905
Steinberg *et al*, *Phys.Rev.C* 99 (2019) 6, 064908
Mohs *et al*,*J.Phys.G* 47 (2020) 6, 065101
Rose *et al*, *J.Phys.G* 48 (2021) 015005
Steinberg *et al*, arXiv: 1912.09895
Staudenmeier *et al*, *Phys.Rev.C* 98 (2018) 5, 054908

DEGREES OF FREEDOM

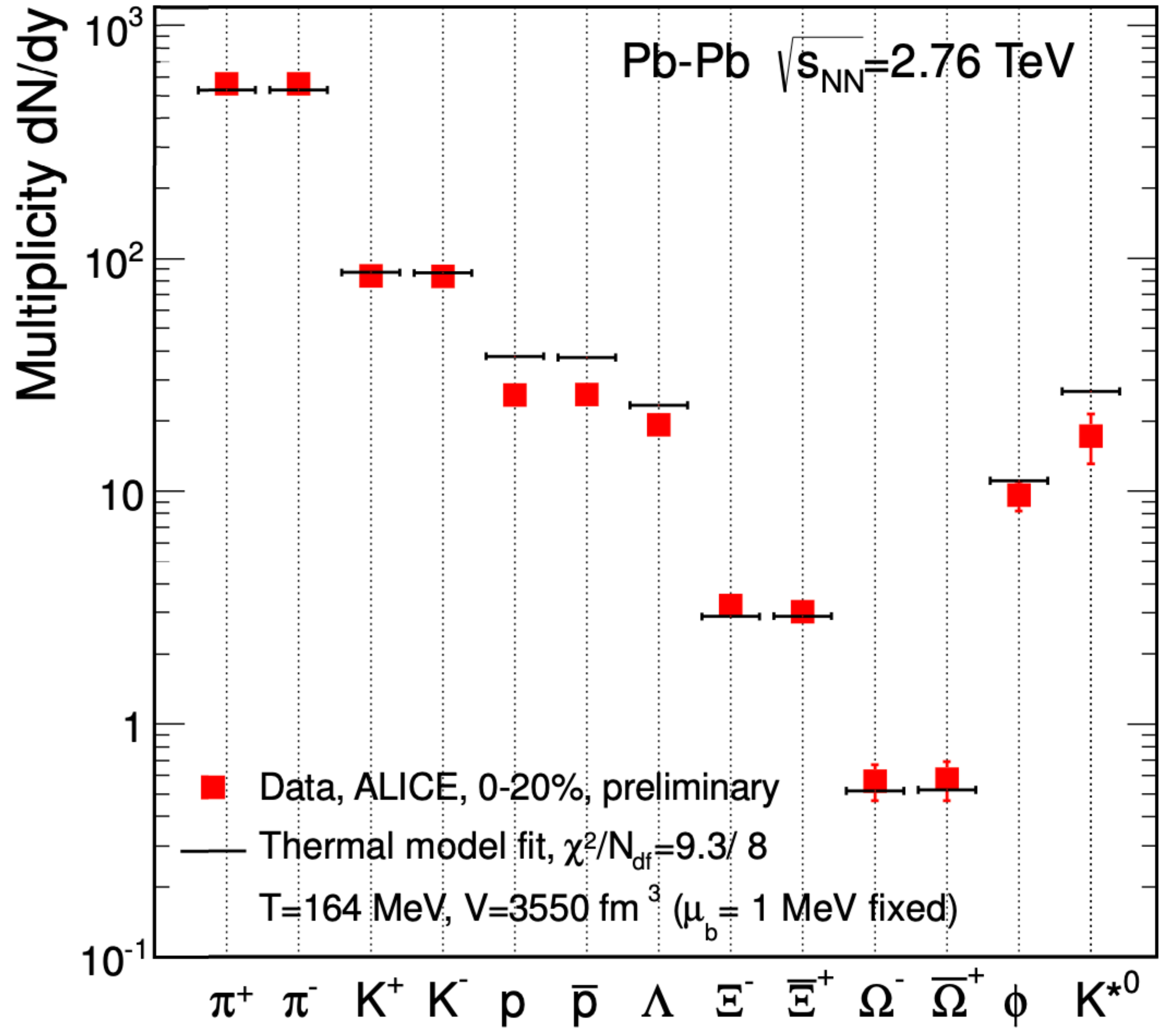
N	Δ	Λ	Σ	Ξ	Ω	Unflavored				Strange
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω_{1672}	π_{138}	$f_{0\ 980}$	$f_{2\ 1275}$	$\pi_{2\ 1670}$	K_{494}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω_{2250}	π_{1300}	$f_{0\ 1370}$	$f_{2\ 1525}$	$\rho_{3\ 1690}$	K^*_{892}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}		π_{1800}	$f_{0\ 1500}$	$f_{2\ 1950}$	$\phi_{3\ 1850}$	$K_{1\ 1270}$
N_{1535}	Δ_{1900}	Λ_{1600}	Σ_{1670}	Ξ_{1820}		η_{548}	$f_{0\ 1710}$	$f_{2\ 2010}$	$a_{4\ 2040}$	$K_{1\ 1400}$
N_{1650}	Δ_{1905}	Λ_{1670}	Σ_{1750}	Ξ_{1950}		η_{958}	$a_{0\ 980}$	$f_{2\ 2300}$	$f_{4\ 2050}$	K^*_{1410}
N_{1675}	Δ_{1910}	Λ_{1690}	Σ_{1775}	Ξ_{2030}		η_{1295}	$a_{0\ 1450}$	$f_{2\ 2340}$		$K^*_{0\ 1430}$
N_{1680}	Δ_{1920}	Λ_{1800}	Σ_{1915}			η_{1405}	ϕ_{1019}	$f_{1\ 1285}$		$K^*_{2\ 1430}$
N_{1700}	Δ_{1930}	Λ_{1810}	Σ_{1940}			η_{1475}	ϕ_{1680}	$f_{1\ 1420}$		K^*_{1680}
N_{1710}	Δ_{1950}	Λ_{1820}	Σ_{2030}			σ_{800}	$h_{1\ 1170}$	$a_{2\ 1320}$		$K_{2\ 1770}$
N_{1720}		Λ_{1830}	Σ_{2250}			ρ_{776}	$b_{1\ 1235}$	$\pi_{1\ 1400}$		$K^*_{3\ 1780}$
N_{1875}		Λ_{1890}				ρ_{1450}	$a_{1\ 1260}$	$\pi_{1\ 1600}$		$K_{2\ 1820}$
N_{1900}		Λ_{2100}				ρ_{1700}		$\eta_{2\ 1642}$		$K^*_{4\ 2045}$
N_{1990}		Λ_{2110}				ω_{776}		$\omega_{3\ 1670}$		
N_{2060}		Λ_{2350}				ω_{1420}				
N_{2080}						ω_{1650}				
N_{2100}										
N_{2120}										
N_{2190}										
N_{2220}										
N_{2250}										

[AS OF SMASH 1.8]

$p\bar{p}$ REGENERATION IN THE HADRONIC STAGE

$p\bar{p}$ DYNAMICS

- Mismatch of the predicted (anti-)proton yields in thermal models
- Annihilation alleviated the problem
- Dynamical regeneration was estimated to be relevant (Pan and Pratt)



HOWEVER…

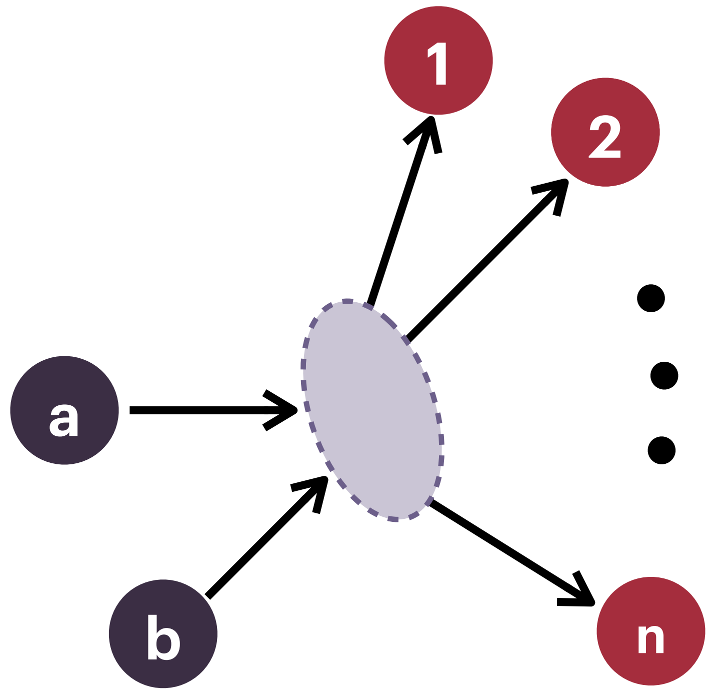
- Annihilation happens through many channels

$$p\bar{p} \leftrightarrow l\pi \quad l = 1,2,\ldots$$

- No transport code has implemented the back-reaction

Andronic *et al*, *Nucl.Phys.A* 904-905 (2013) 535c-538c
Y. Pan and S. Pratt, (2014), arXiv:1210.1577

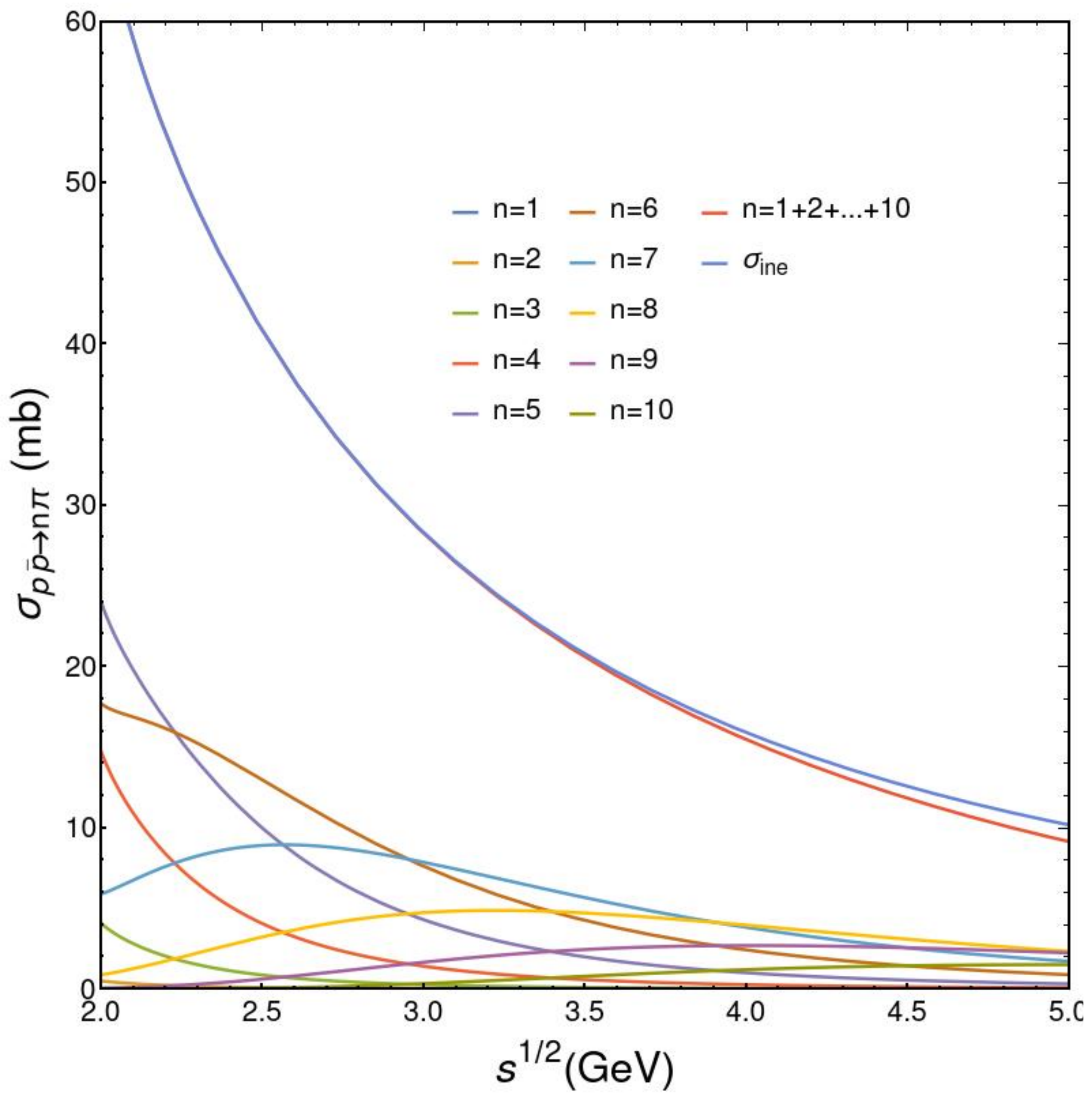
$P\bar{P}$ ANNIHILATION

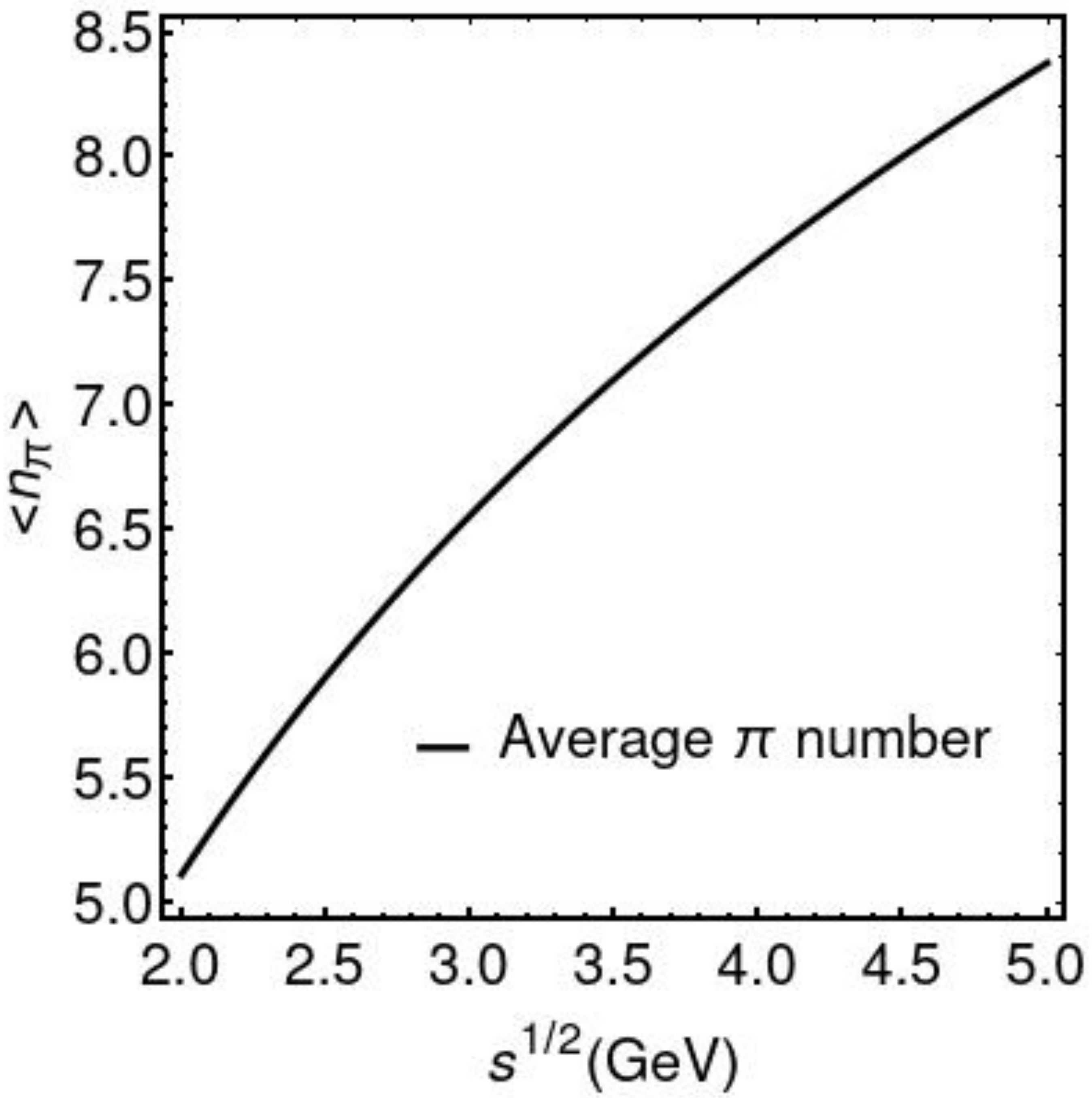


- Annihilation happens through many channels $p\bar{p} \leftrightarrow l\pi \quad l = 1,2,\ldots$
- Channels with high number of final state particles as expensive

$$P_{n\to m} = \frac{1}{\mathcal{S}'!}\frac{\Delta t}{(\Delta^3 x)^{n-1}}\frac{1}{\prod_{j=1}^{n} 2E_j}\int d\Phi_m \, \overline{|T_{n\to m}|^2} \ ,$$

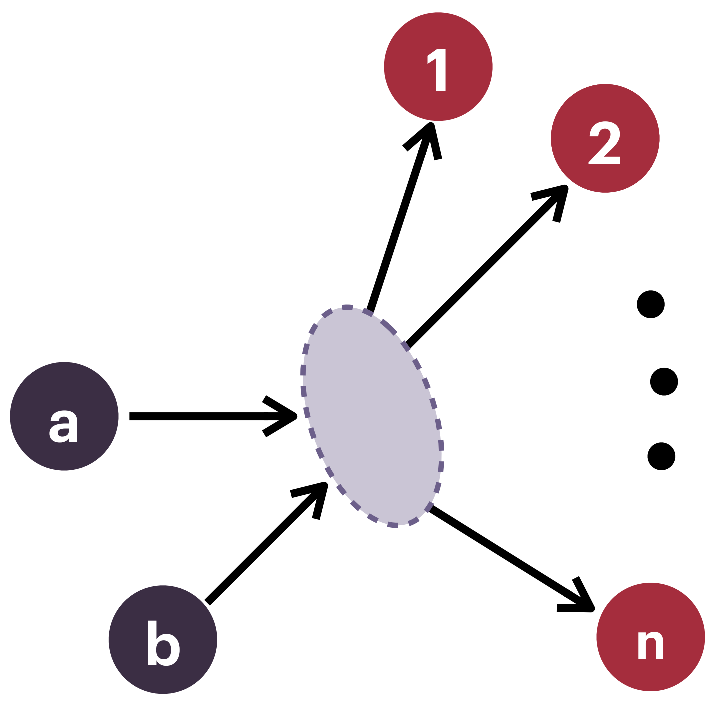
- **Expensive part is the back-reaction!**





Dover *et al*, Prog. Part. Nucl. Phys. 29, 87 (1992)

$P\bar{P}$ ANNIHILATION



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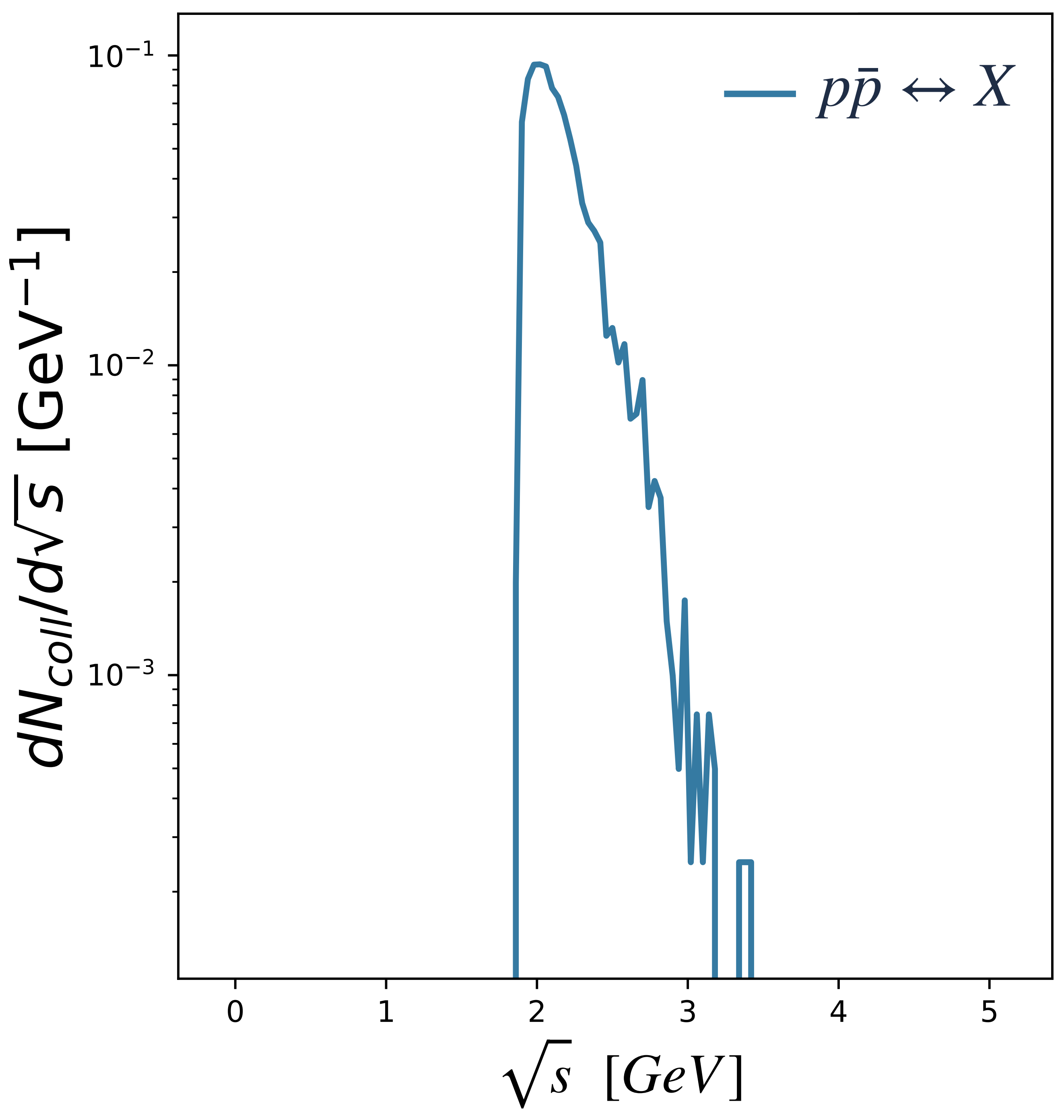

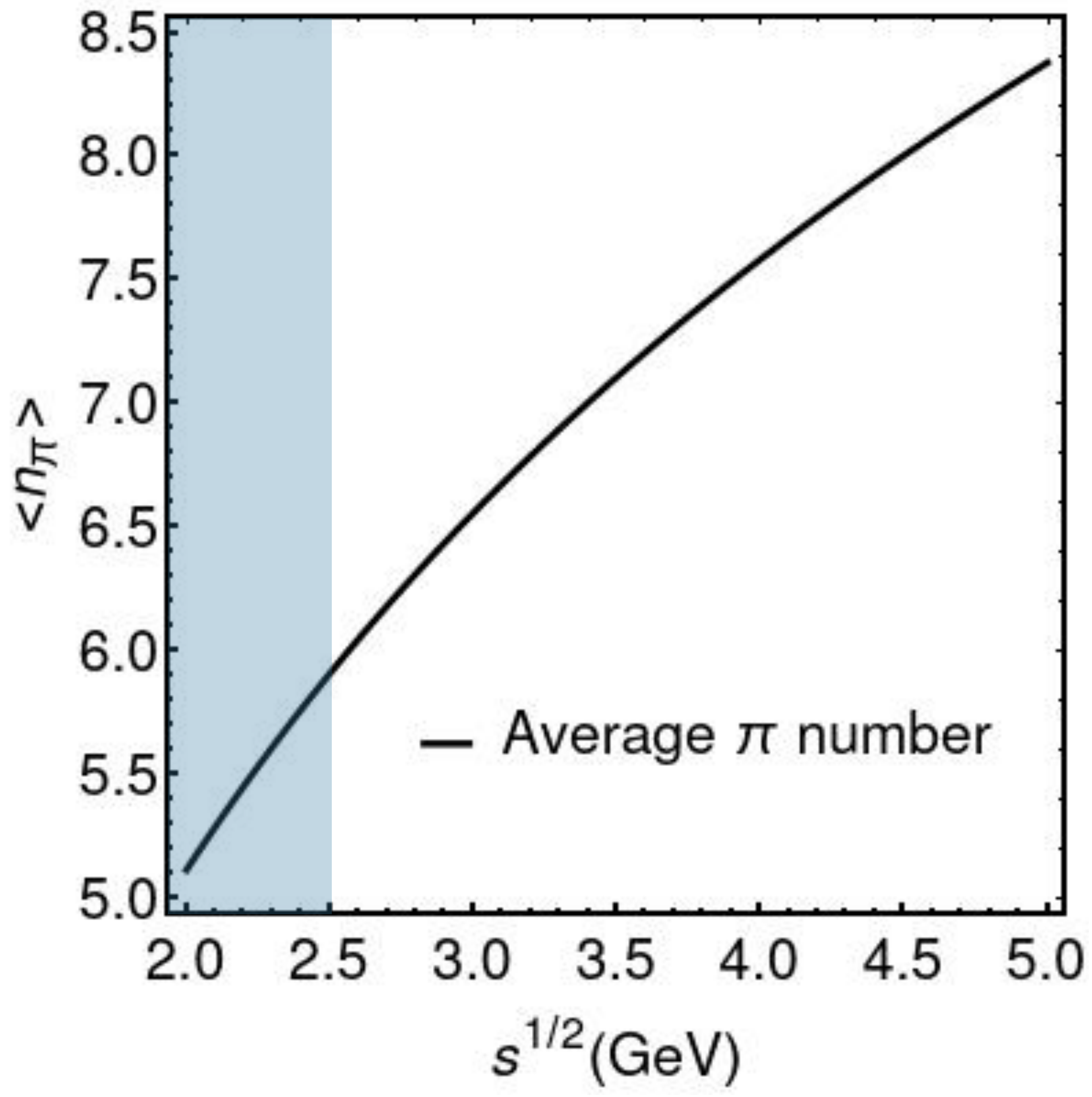

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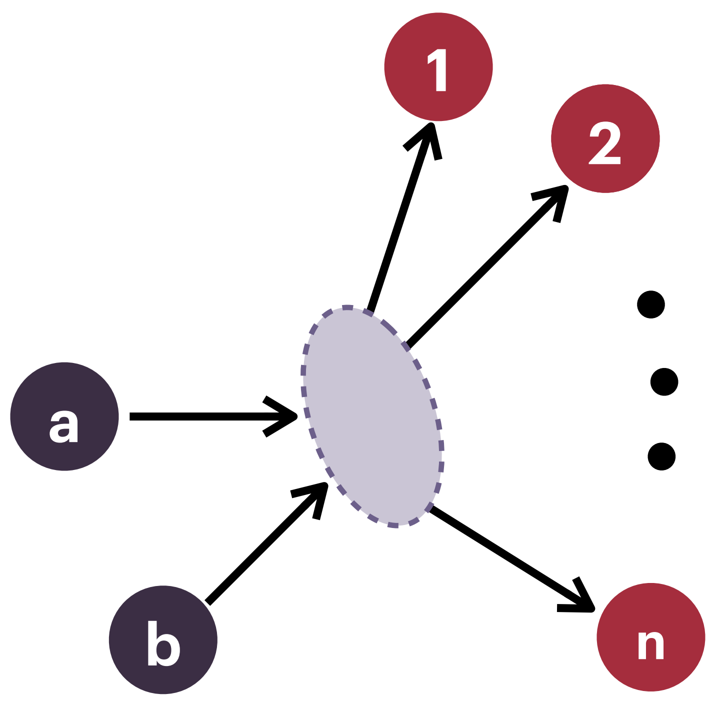

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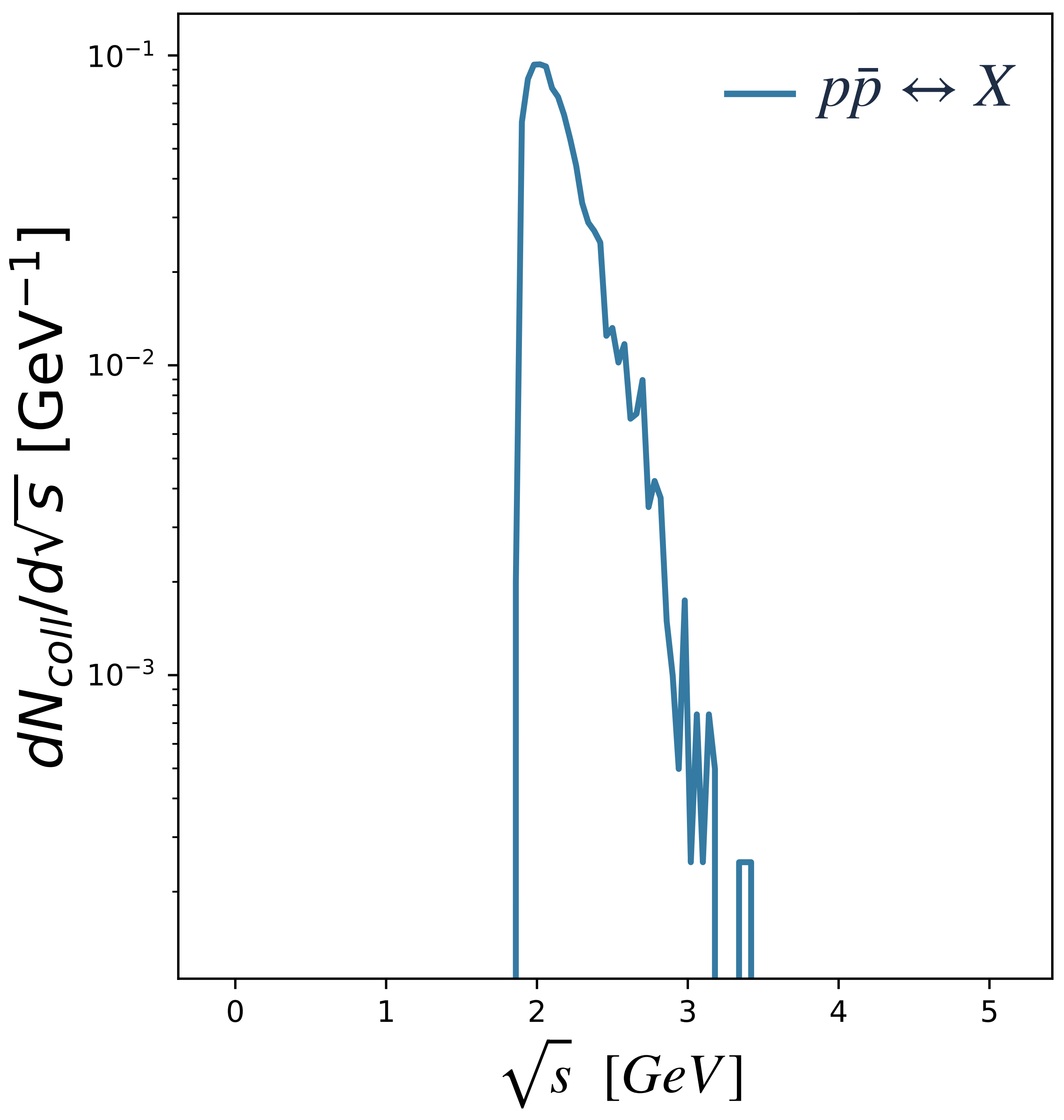
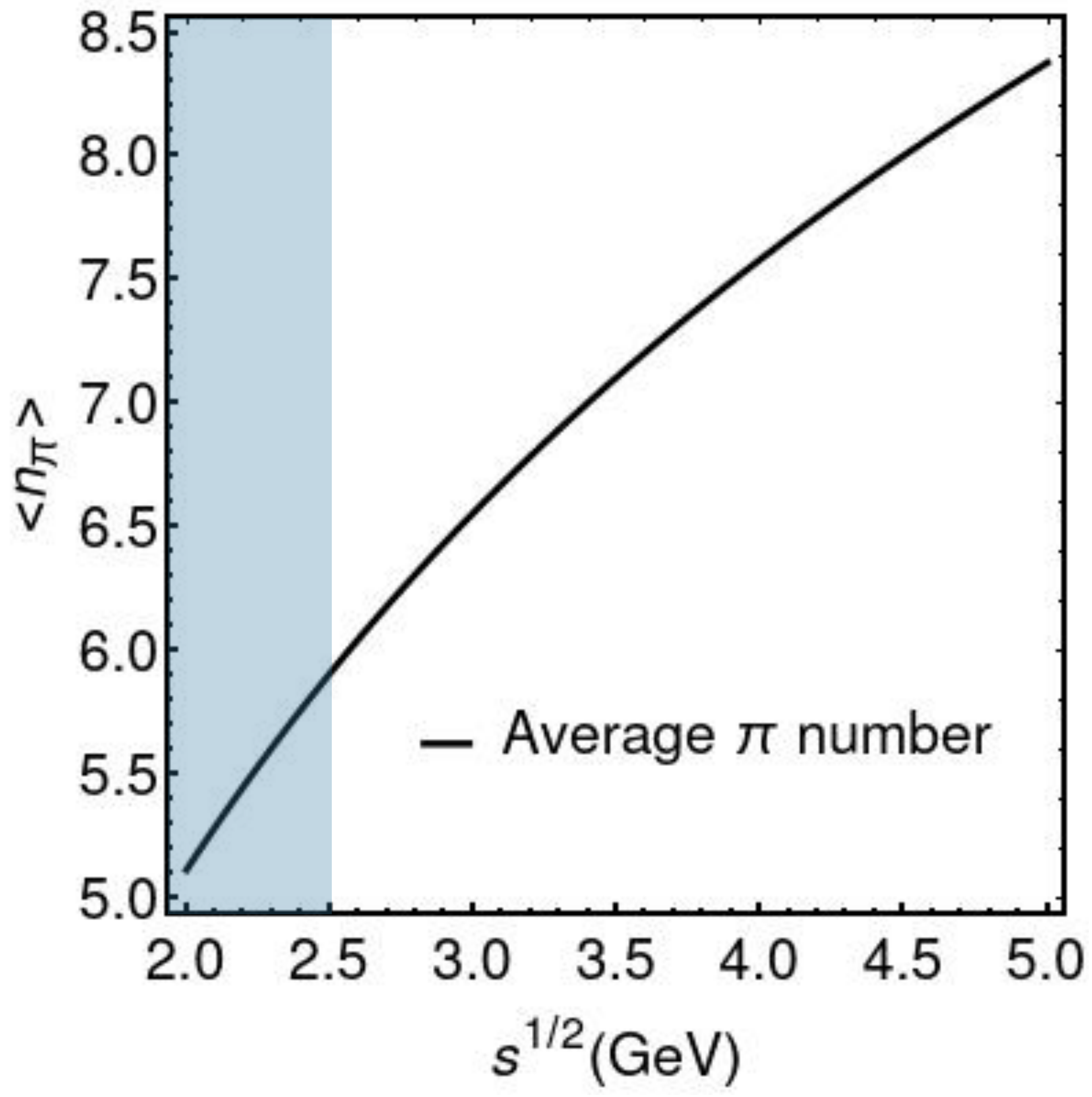
- **Expensive part is the back-reaction!**

We choose to implement $l = 5$ as an effective approach





STOCHASTIC TREATMENT

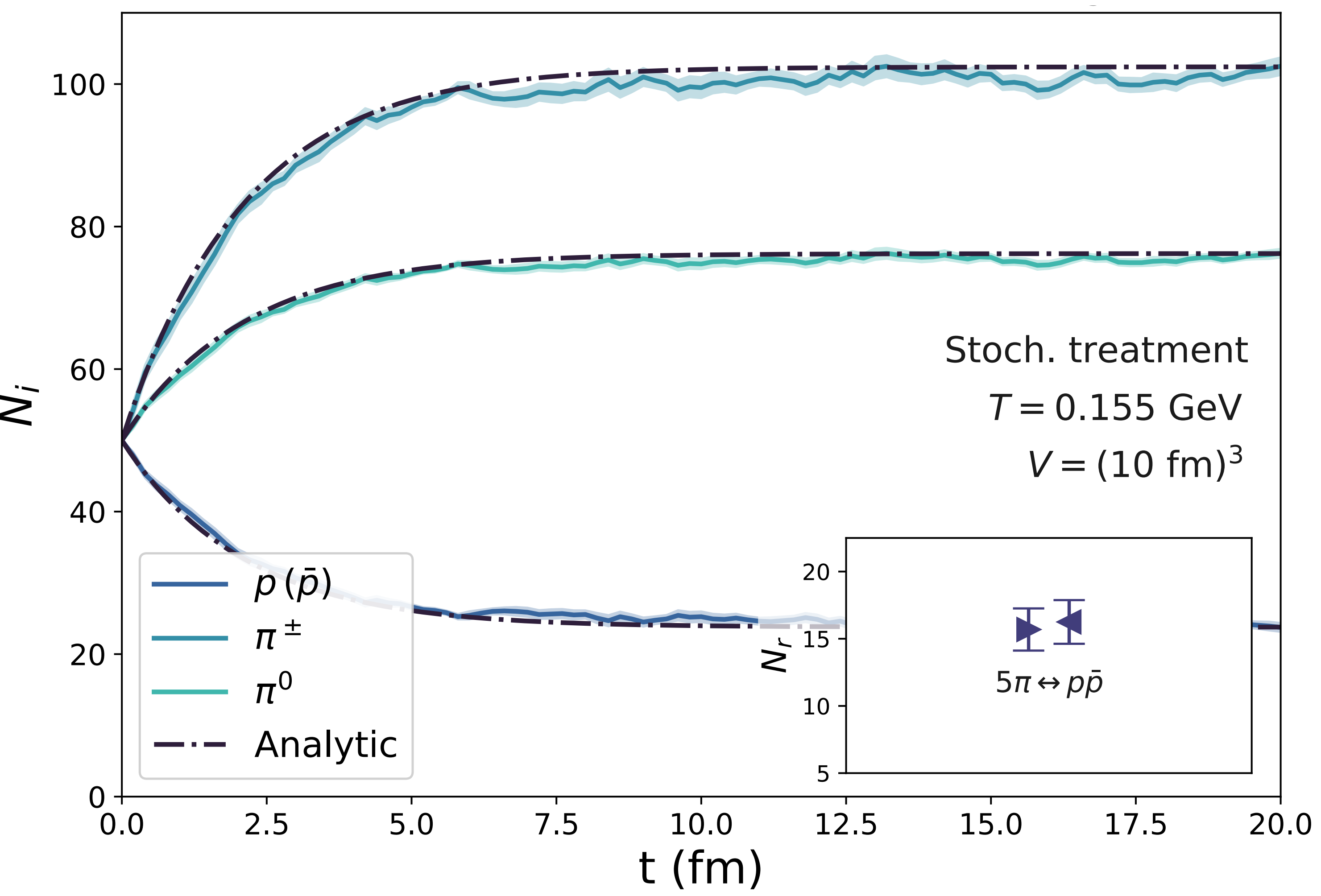
- Probability given by

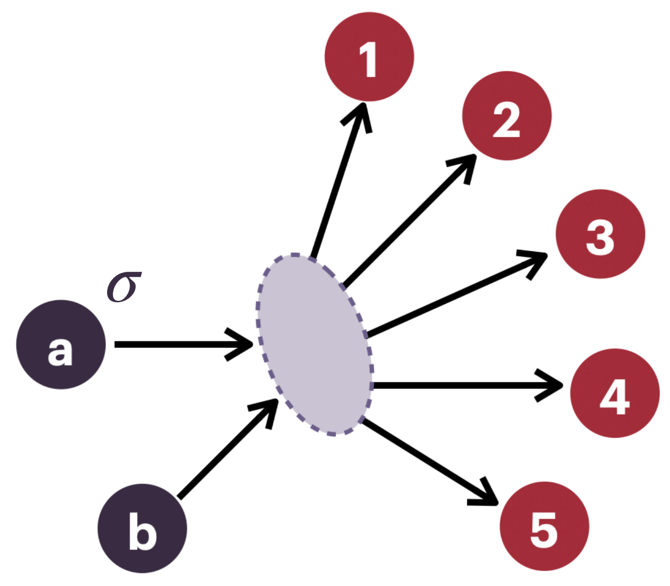
$$P_{5\to 2} = g_1' g_2' \left[\prod_{f=1}^{5} \frac{1}{g_f 2E_f}\right] \frac{S_5}{S_2'} \frac{\Delta t}{(\Delta^3 x)^4} \frac{\lambda(s, m_1'^2, m_2'^2)}{\Phi_5} \frac{\sigma_{2\to 5}}{4\pi s}$$

- Computationally more expensive

- Faster equilibration

Infinite hadronic matter





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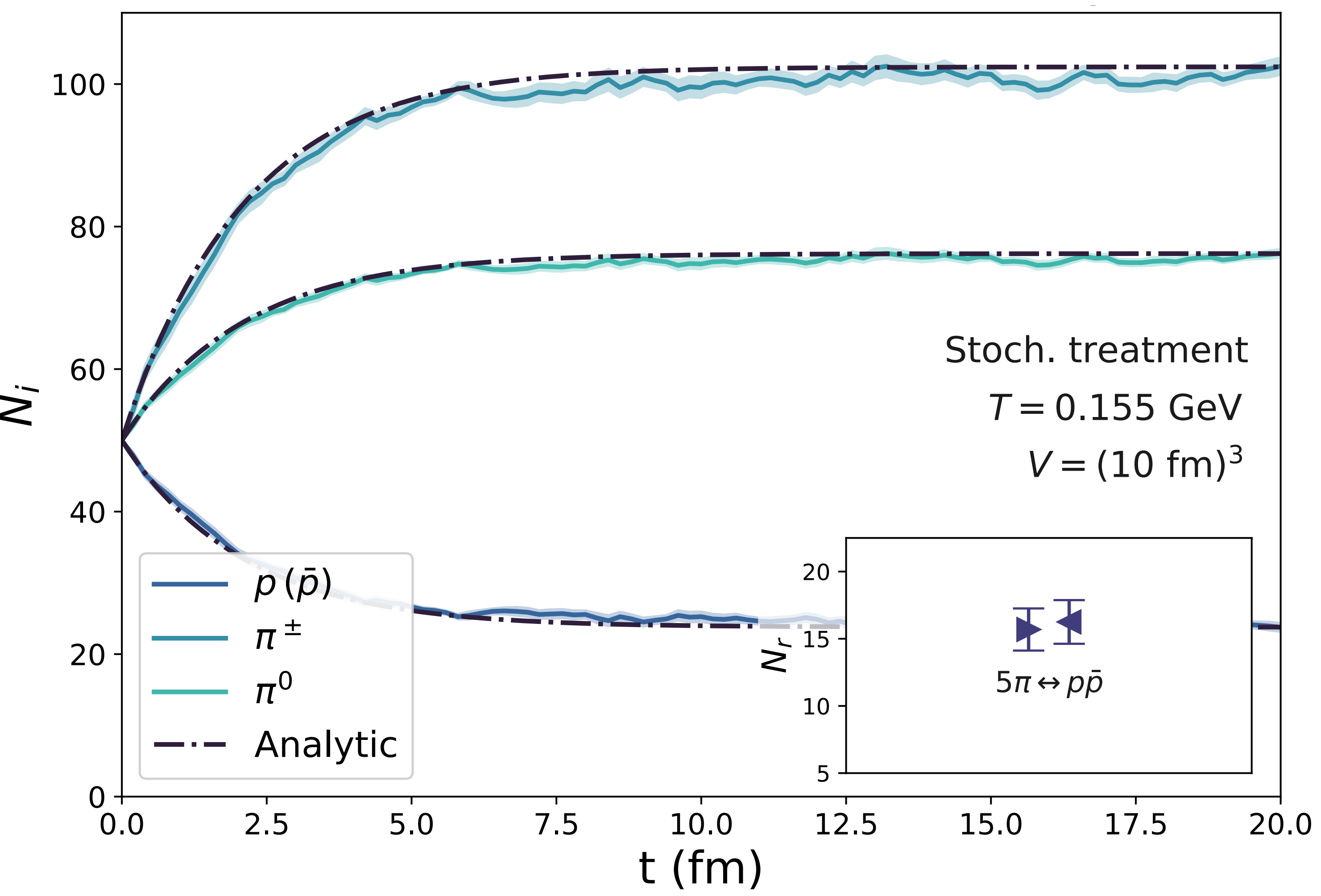
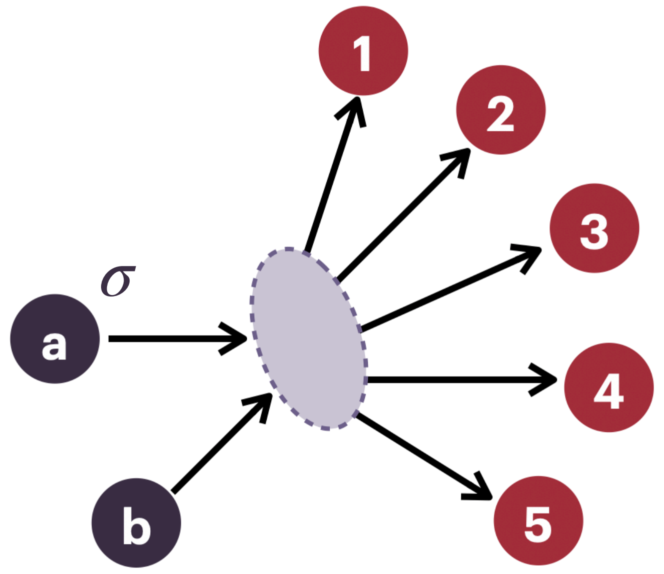


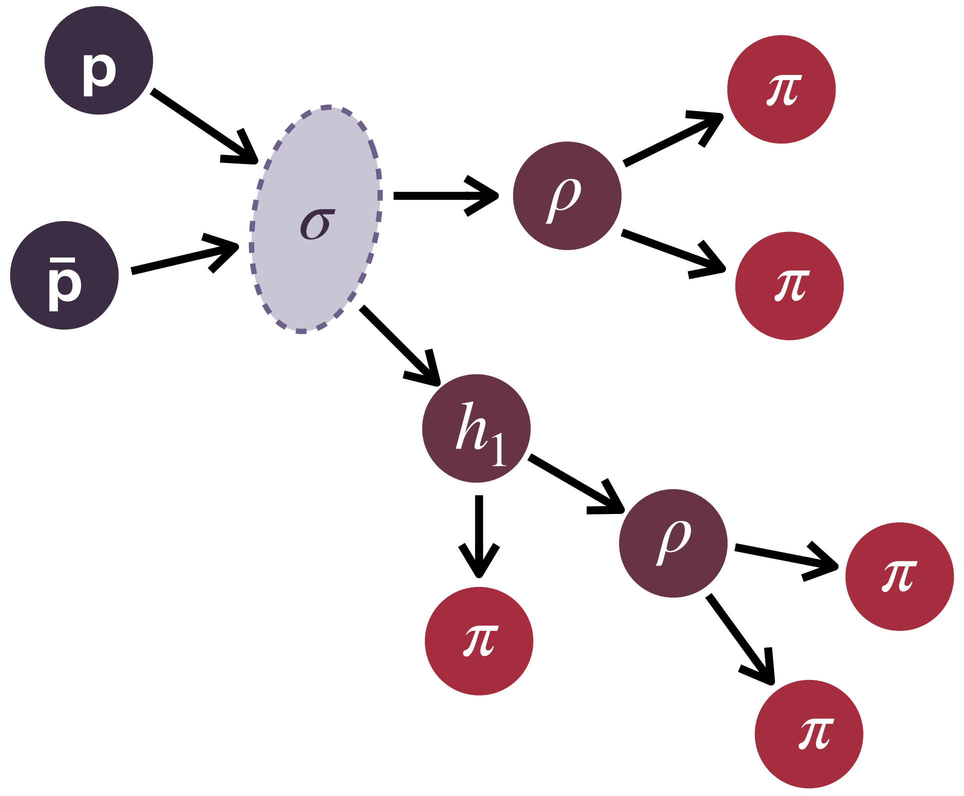


RESONANCE TREATMENT

- Indirect, via resonances

$$p\bar{p} \leftrightarrow h_1 \rho \qquad h_1 \leftrightarrow \rho\,\pi \qquad \rho \leftrightarrow \pi\,\pi$$

- Can be stochastic or geometric
- Slower equilibration



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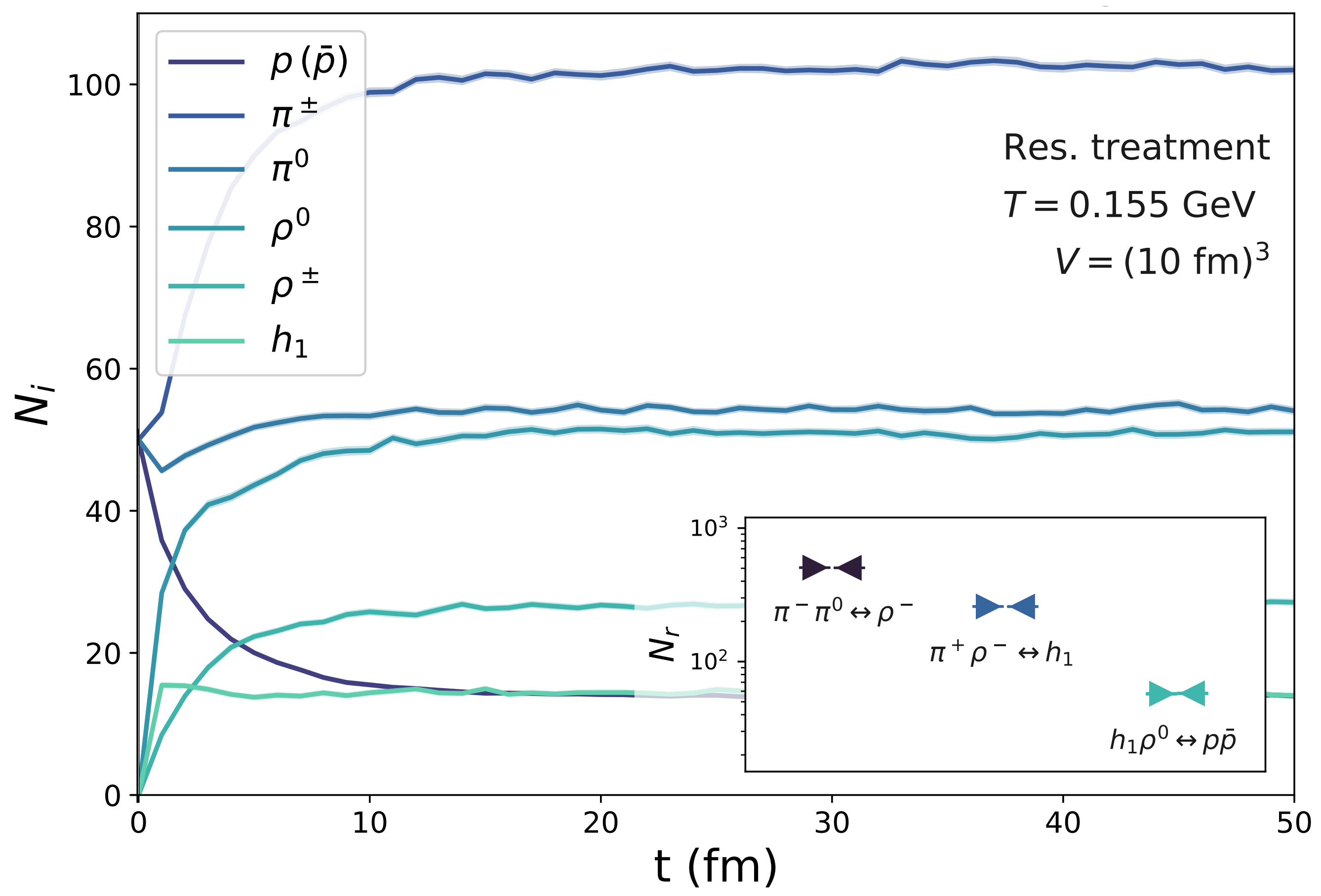


N. Demir, Ph.D. thesis, Duke University (2010).
Rose, *et al*, Phys. Rev. C 97, 055204 (2018)

SO, SUMMARIZING

Backreaction for pp annihilation was implemented ✓

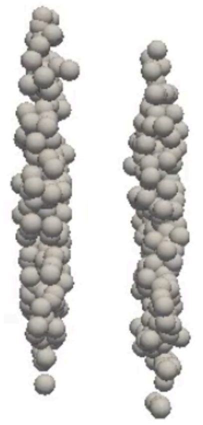
Many channels, choose n=5 as an effective approach ✓

Two different ways to perform it ✓

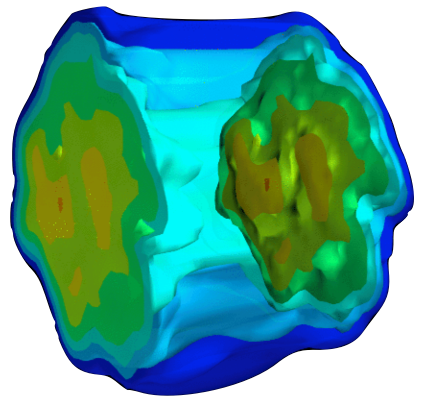
Now we have to run it in collisions

THE SMASH-VHLLE HYBRID

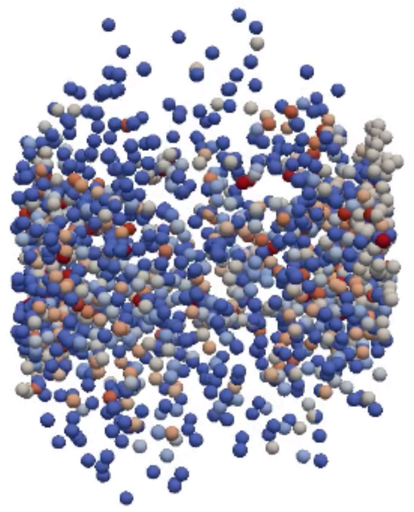
INITIAL CONDITIONS | ***SMASH AS INITIAL CONDITIONS***

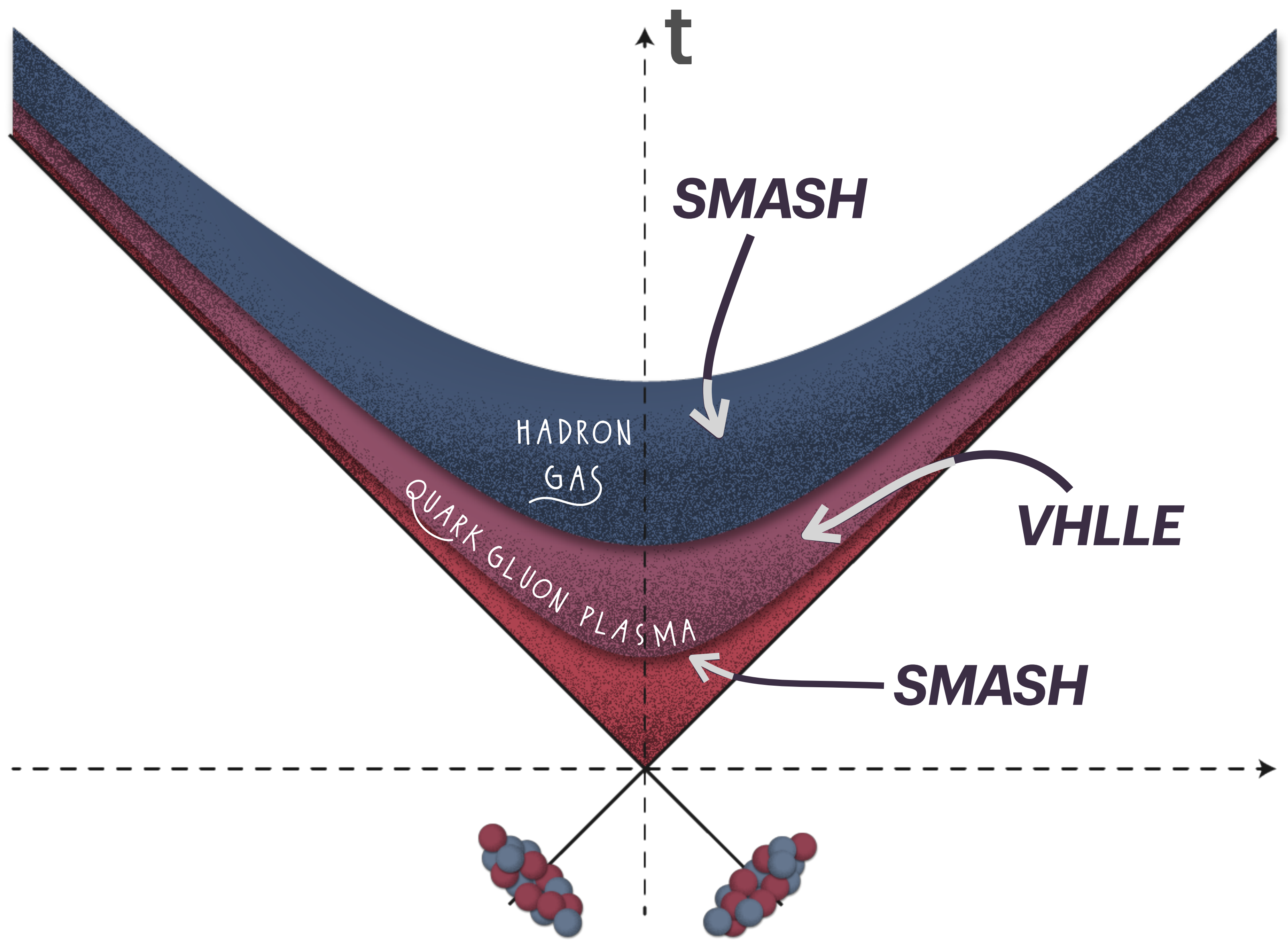


QGP STAGE | ***VHLLE (3+1) VISCOUS HYDRO***



HADRON STAGE | ***SMASH AS AN AFTERBURNER***



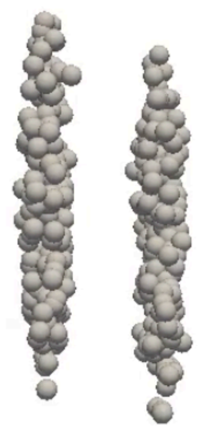


Moreland *et al. Phys.Rev.C* 92 (2015) 1, 011901
Schenke *et al Phys.Rev.C* 82 (2010) 014903
Weil *et al Phys.Rev.C* 94 (2016) 5, 054905

Hydro and transport illustrations by B.Schenke and J.Mohs

THE SMASH-VHLLE HYBRID

INITIAL CONDITIONS | *SMASH AS INITIAL CONDITIONS*



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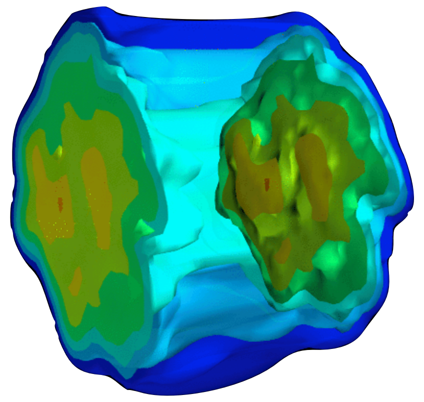
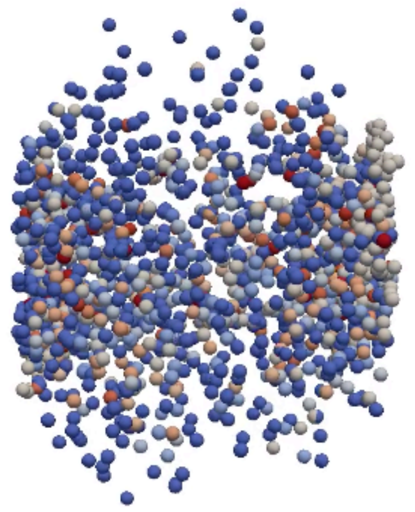


HADRON STAGE | *SMASH AS AN AFTERBURNER*



SOME TECHNICAL DETAILS

Averaged initial conditions for 0-5%, 20-30% and 40-50%

Systems: Au-Au at 39, 200 GeV
Pb-Pb at 17.3 GeV
and 2.76, 5.02 TeV

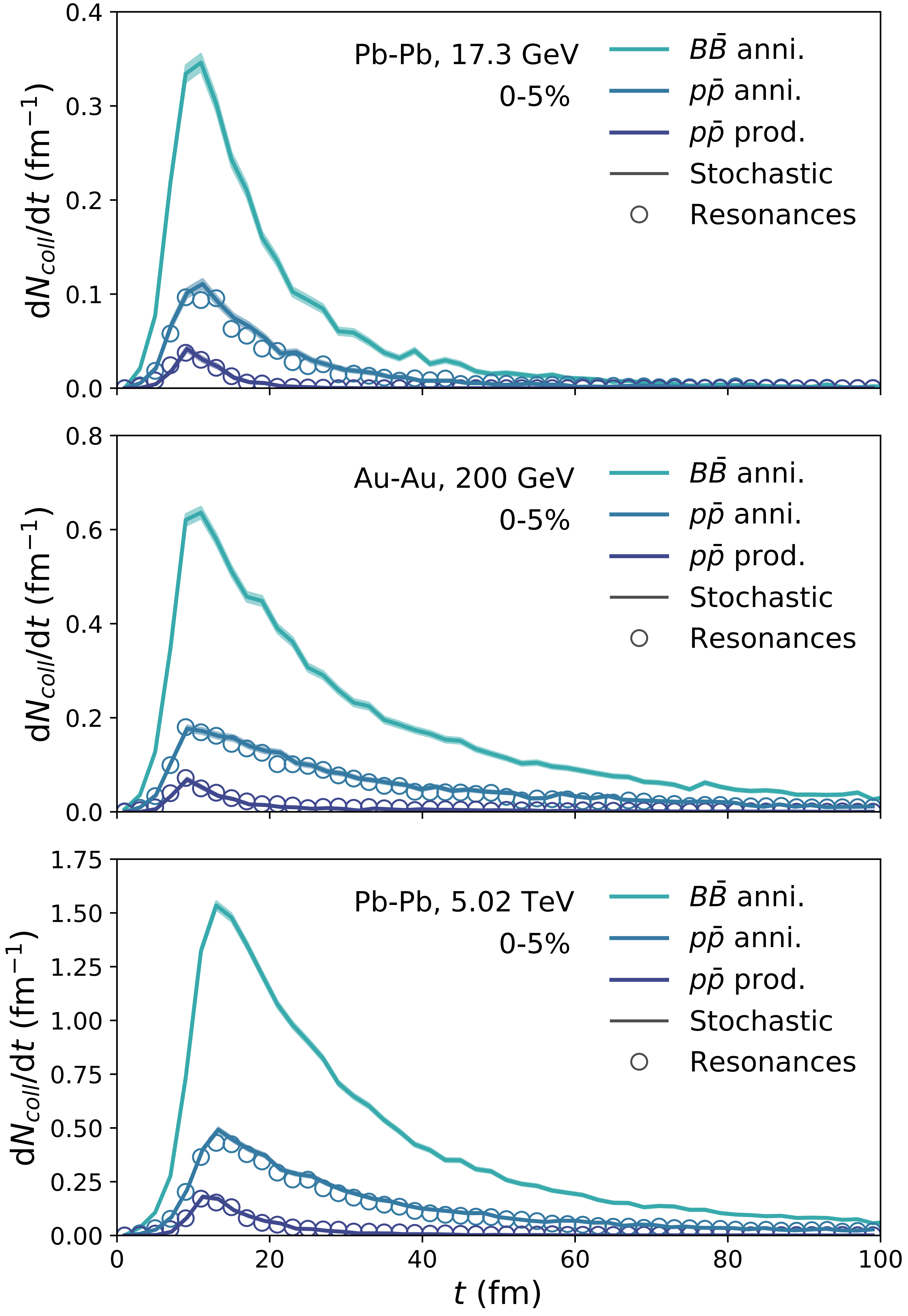
Viscous Hydro

$\eta/s = 0.1$ and $\zeta/s = 0.05$

Transition Temperature T=150 MeV

EoS: HoTQCD+SMASH HRG

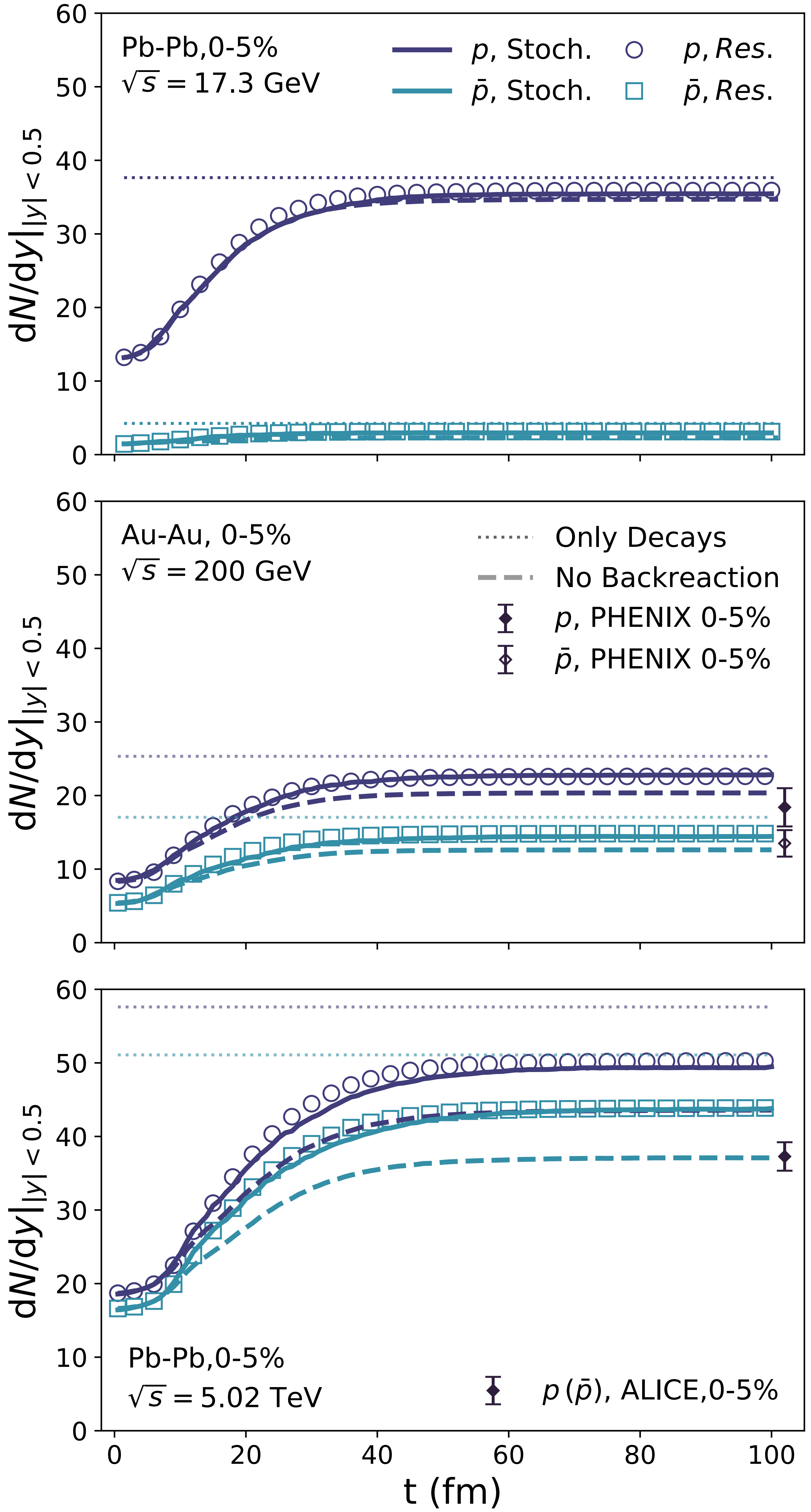
Hydro and transport illustrations by B.Schenke and J.Mohs



COMPARISON

- Stochastic and resonance treatments present excellent agreement

- Agreement holds through the centrality and energy ranges



COMPARISON

- Stochastic and resonance treatments present excellent agreement

- Agreement holds through the centrality and energy ranges

YIELDS

-Three scenarios

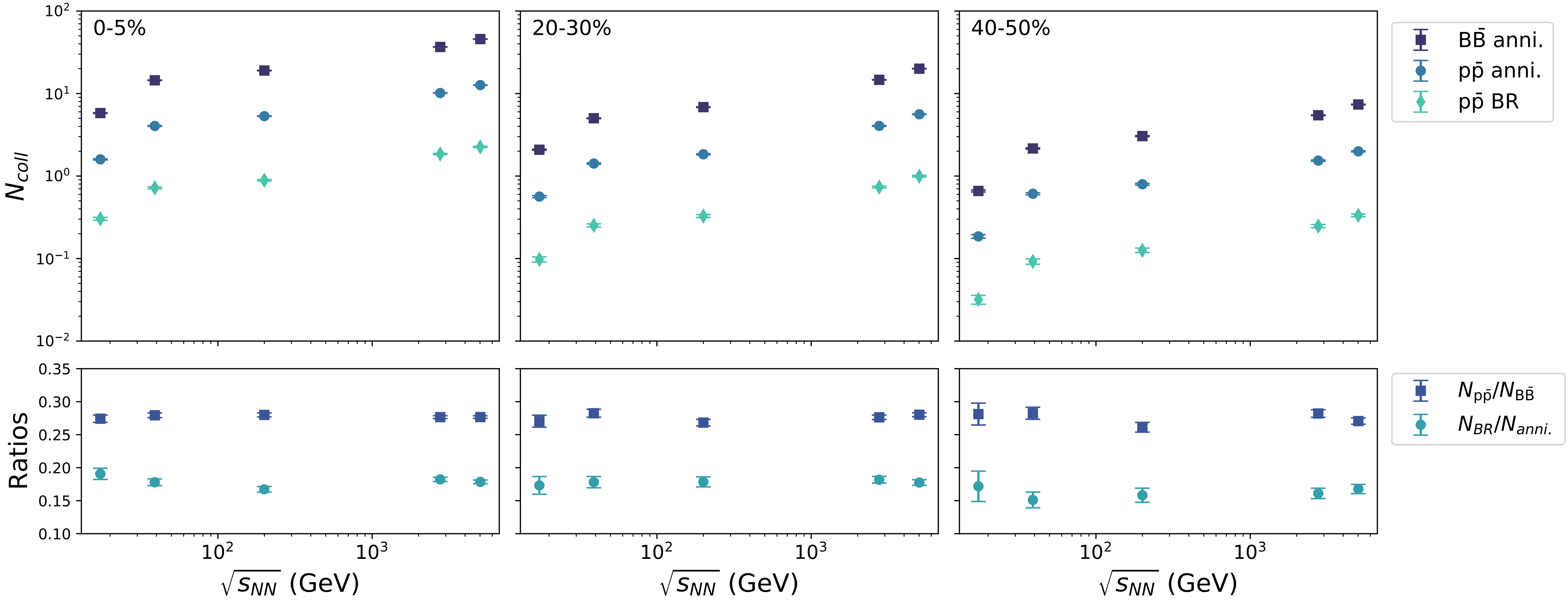
With regeneration
No regeneration
Decay after particlization

-Regeneration is non-negligible and becomes more prominent for increasing collision energy.

-Net decrease of the (anti-)proton yield is observed.

$P\bar{P}$ AS A PROXY

- The ratio of backward/forward reactions is 15-20%, stable in all systems.
- $p\bar{p}$ annihilations to the number of (non-nucleon) baryon annihilations, stable in all systems
- Use pp as a proxy to understand $B\bar{B}$



CONCLUSIONS

- First afterburner calculation employing detailed balance for proton-antiproton annihilation
- We have shown the agreement between stochastic and resonance approaches
- We have found the backward/forward reaction ratio to be of 15-20%, stable throughout a large collision energies and centralities
- Dynamical interplay of annihilation and regeneration does play a non-negligible role for the proton yield, and has to be accounted for when modeling the system
- Approach could be further improved by new channels

LATE-TIME NON-EQUILIBRIUM PHOTONS

DIRECT PHOTONS

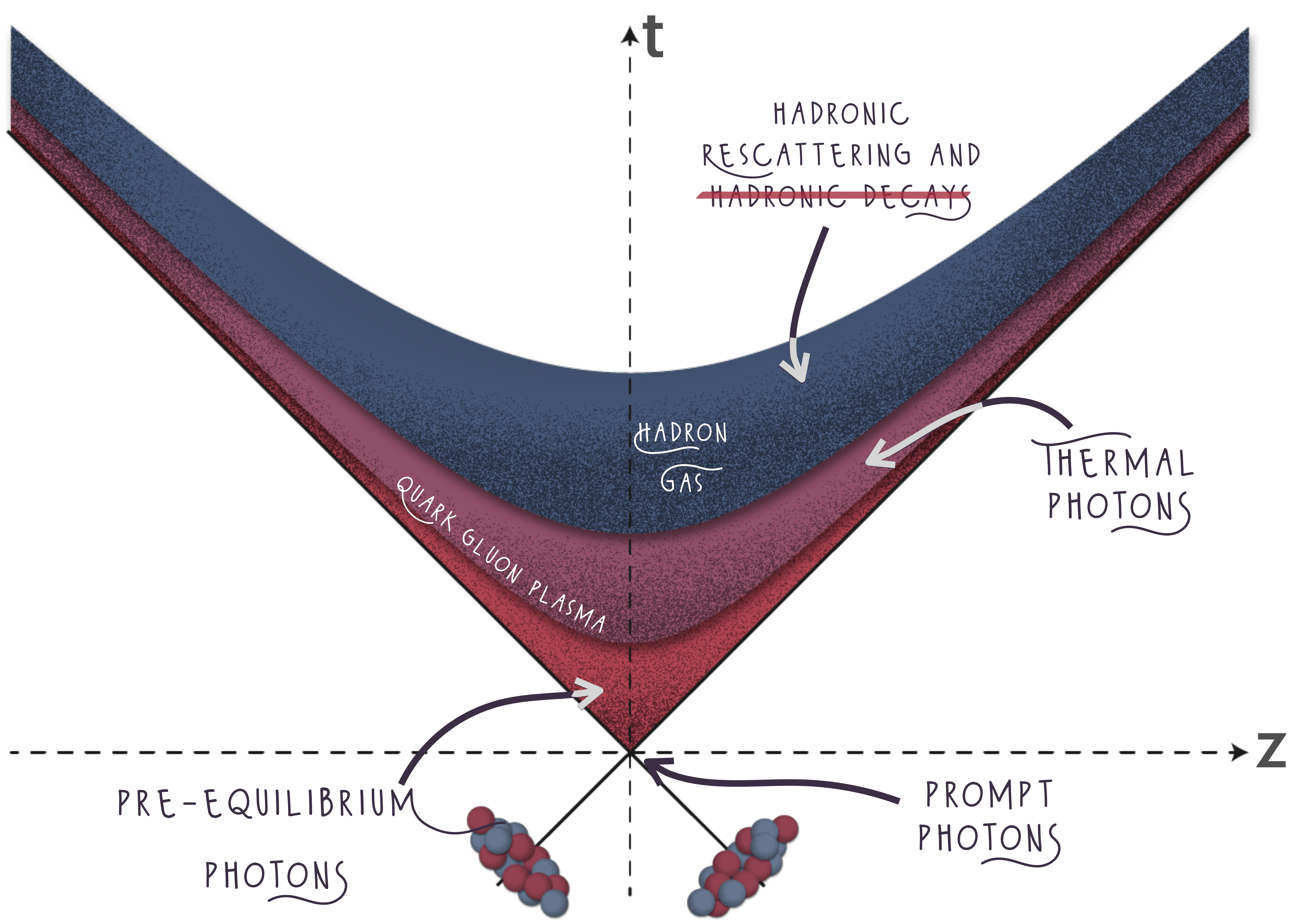
- Photons not produced in decays
- No strong interactions
- Mean free path in medium > medium size

  Photons escape, virtually unscathed

AS A CONSEQUENCE...

- Different sources through the evolution
- Photons are particularly sensitive to the evolution of the system

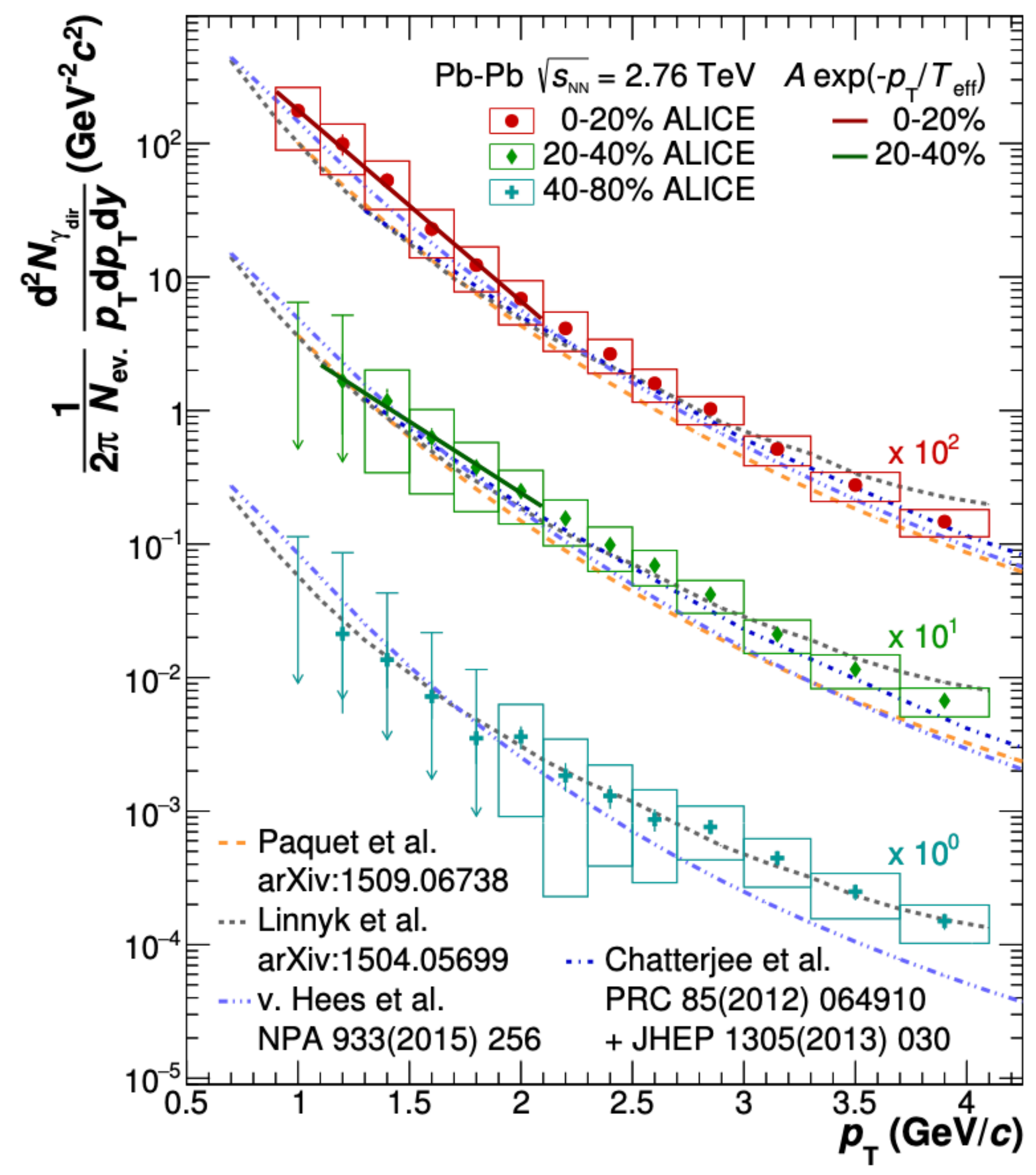
The Standard Model of Heavy Ion Collisions



HOWEVER.

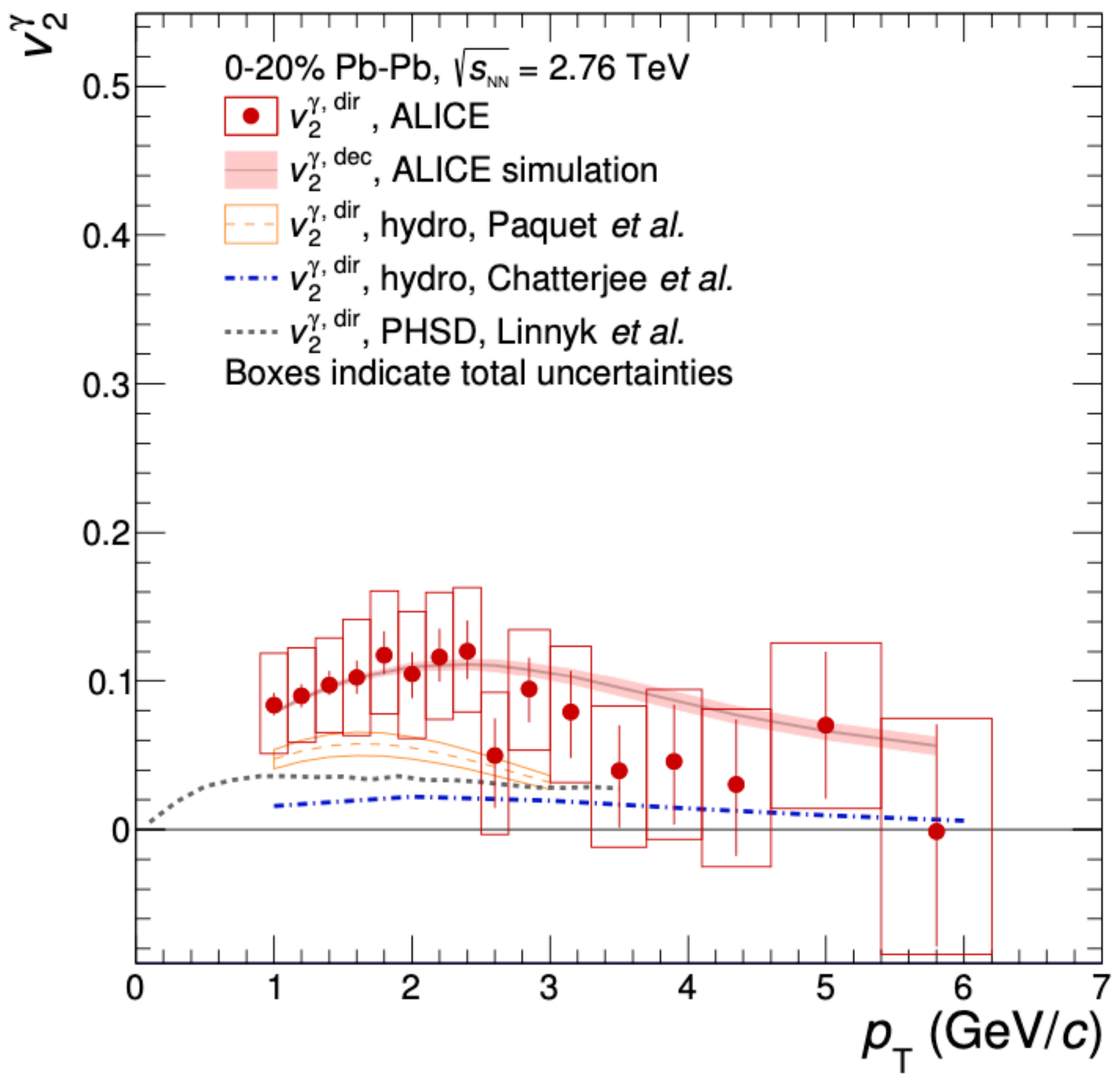
DIRECT PHOTONS

HOWEVER, direct photons are not well understood.



DIRECT PHOTON PUZZLE

"THE INABILITY TO SIMULTANEOUSLY DESCRIBE BOTH OF THE PHOTON YIELD AND ANISOTROPY."

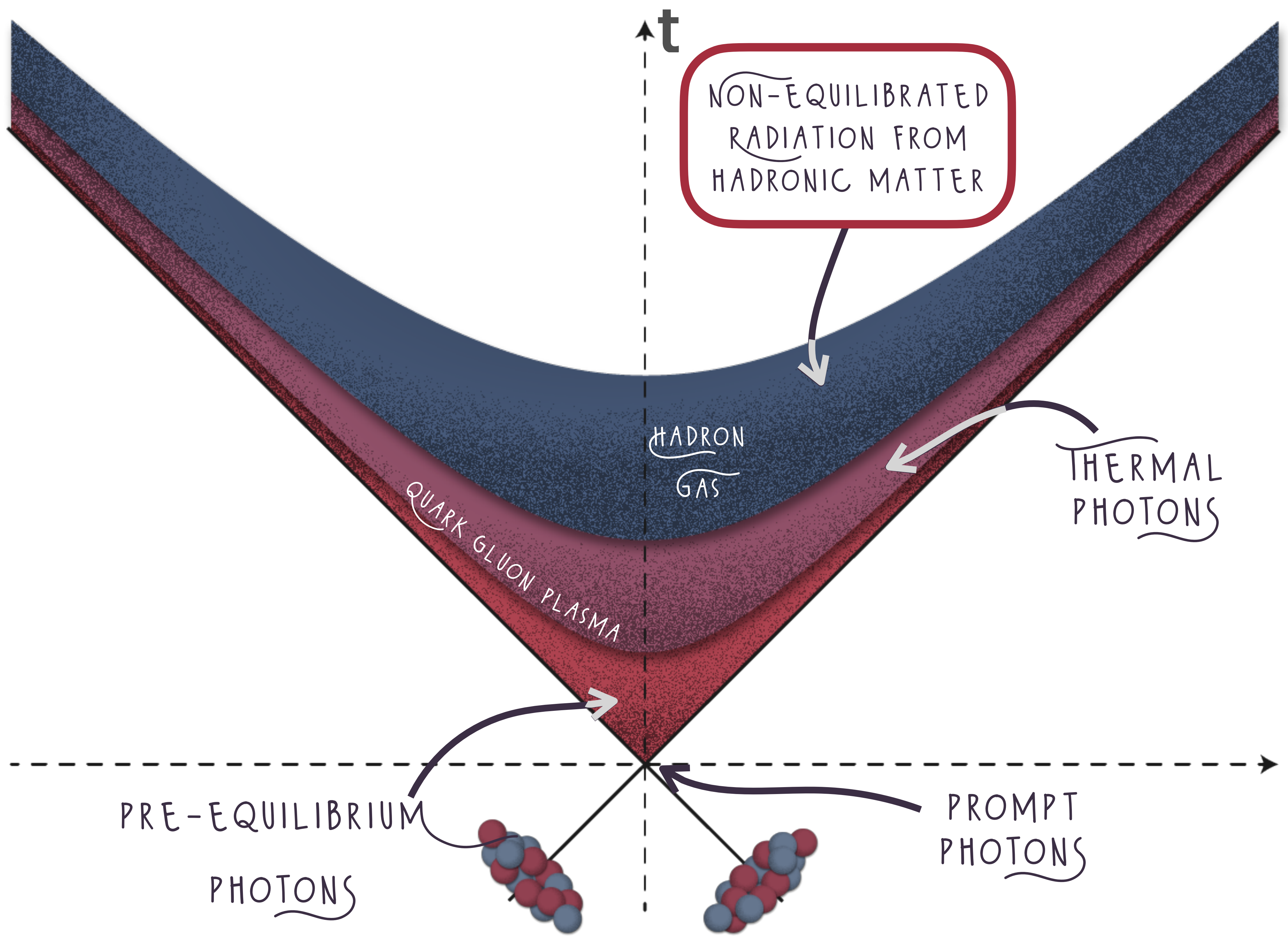


Acharya et al. (ALICE), Phys.Lett.B 789 (2019)
Adam et al. (ALICE), Phys. Lett. B754 (2016)

HYDRO IS NOT ENOUGH

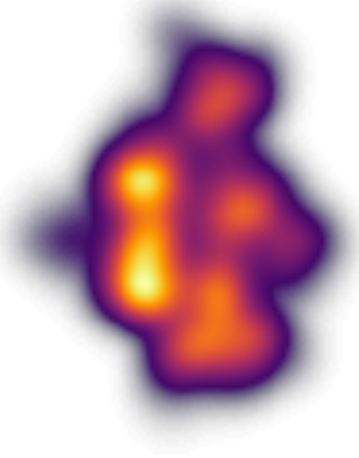
- Photons created from thermal sources consistently fail to reproduce the data
- Non-equilibrium effects seem to play an important role in the production of direct photons
- In this talk: focus on photons from hadronic transport.
    - Hadrons fall out of equilibrium, produce photons out-of-equilibrium
    - Late-time production carries potentially higher anisotropies

The Standard Model of Heavy Ion Collisions

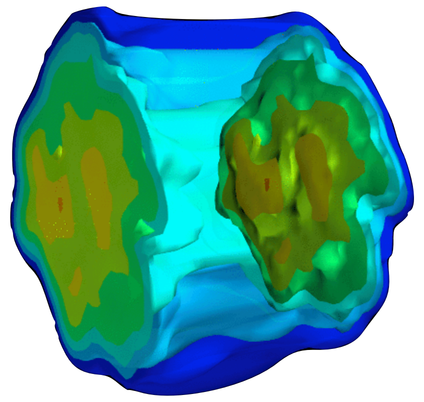


THIS HYBRID APPROACH

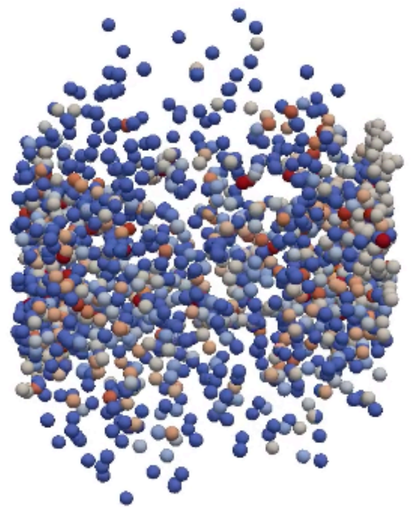
INITIAL CONDITIONS | *T_RENTO*

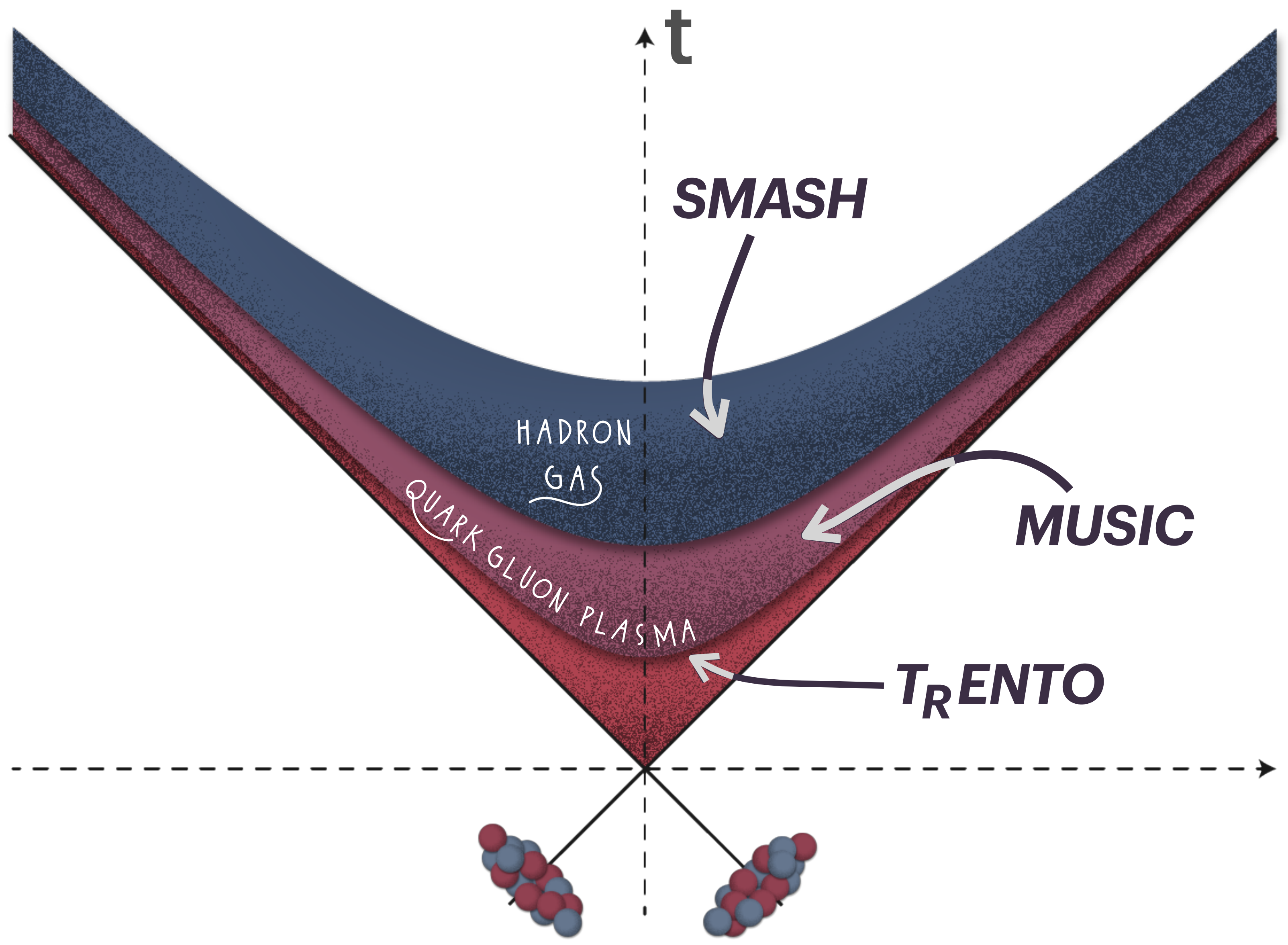


QGP STAGE | *MUSIC (3+1) IDEAL HYDRO*



HADRON STAGE | *SMASH AS AN AFTERBURNER*



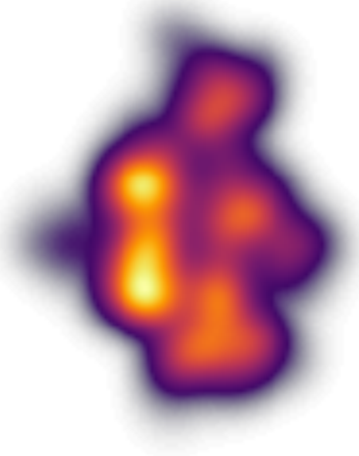


Moreland *et al. Phys.Rev.C* 92 (2015) 1, 011901
Schenke *et al Phys.Rev.C* 82 (2010) 014903
Weil *et al Phys.Rev.C* 94 (2016) 5, 054905

Hydro and transport illustrations by B.Schenke and J.Mohs

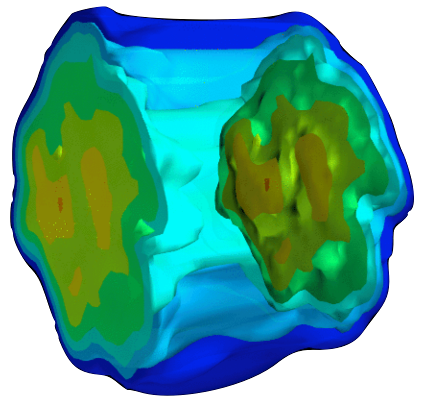
THIS HYBRID APPROACH

INITIAL CONDITIONS | ***T_RENTO***

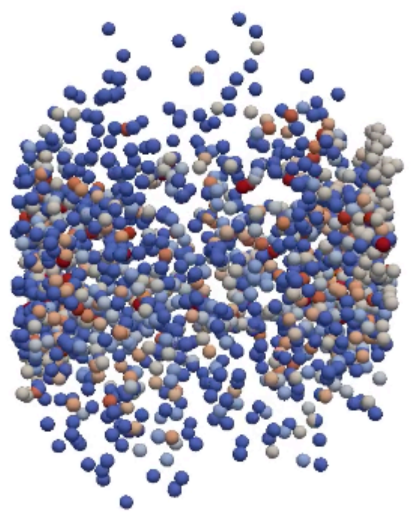


$p = 0$

QGP STAGE | ***MUSIC (3+1) IDEAL HYDRO***



HADRON STAGE | ***SMASH AS AN AFTERBURNER***



PHOTON SOURCES

Hydrodynamical - Thermal Rates

QGP: AMY, JHEP 0112 (2001) 009

HRG: Turbide *et al*, Phys. Rev. C69, 014903 (2004)

Transport - SMASH photons

Meson scattering

Schäfer *et al*, *Phys.Rev.D* 99 (2019) 11, 114021

SOME TECHNICAL DETAILS

Average (smooth) initial conditions for b = 5 fm

Ideal Hydro

Transition Temperature T=150 MeV

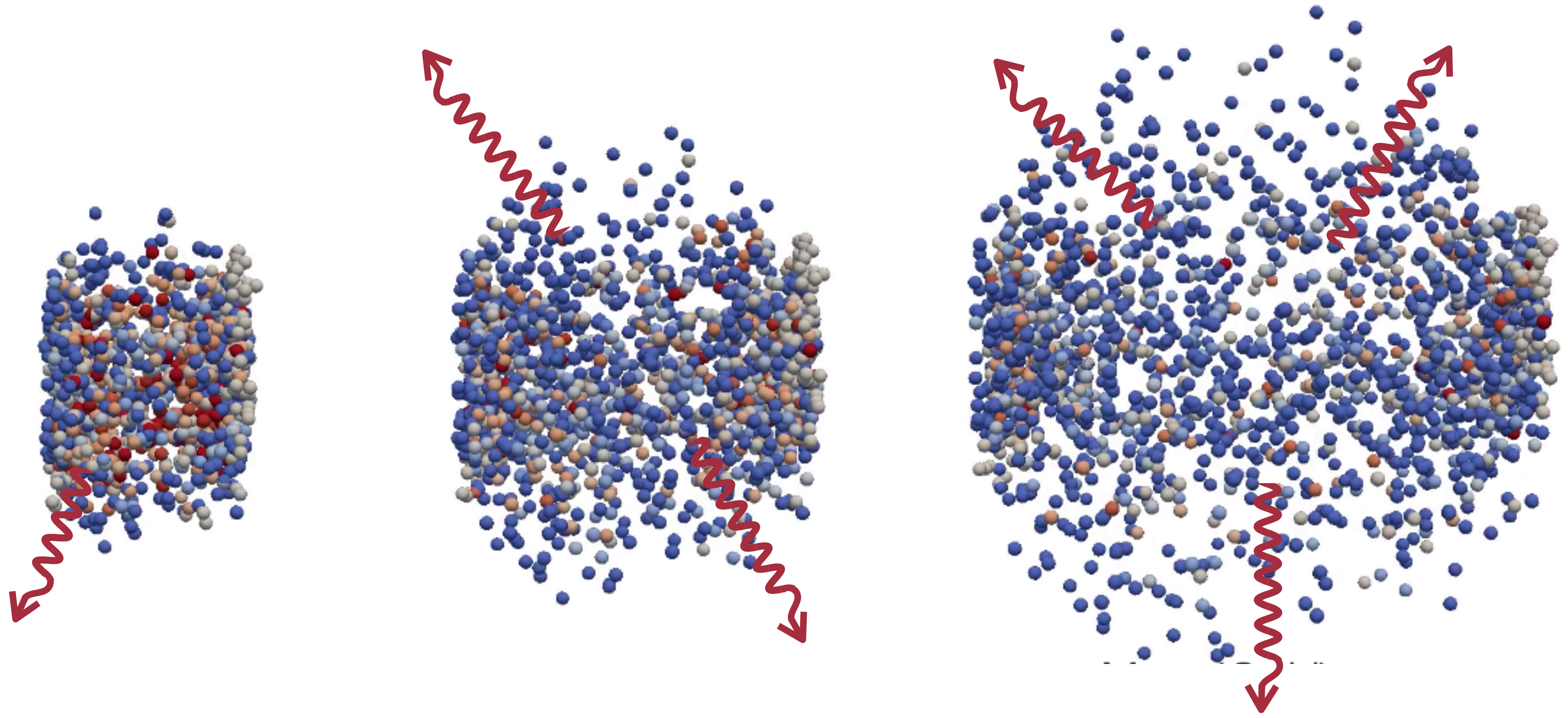
EoS: HoTQCD+SMASH HRG

PHOTONS FROM HADRONIC TRANSPORT

- Non-equilibrium production of photons in hadronic matter
- Perturbative production - no backreaction
- U(1) symmetric Chiral Effective Lagrangian for →
  [Ogawa *et al*,Prog. Theor. Phys. Suppl, 1967.]

- Pseudoscalar mesons	- Axial vector mesons
- Vector mesons	- Tensor resonances

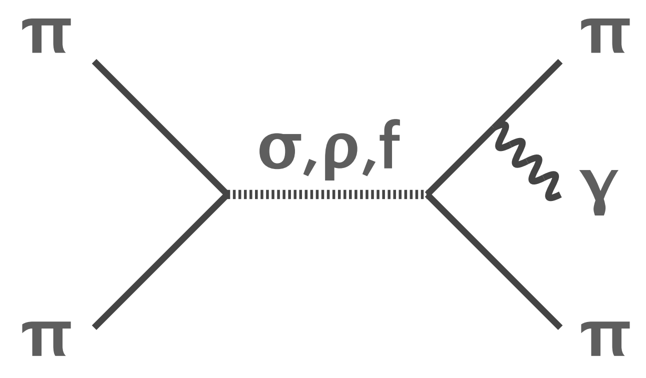
- Photons are sampled when underlying meson scattering happens
- Photon kinematic properties are sampled from differential cross-section
- Main contributions: meson-bremsstrahlung and 2-to-2 scattering processes



PHOTONS FROM HADRONIC TRANSPORT

MESON BREMSSTRAHLUNG

Photon production from pion 2-to-3 process. Mediated by σ,ρ and f resonances



Get differential and total cross section from the Chiral Lagrangian

We use $\frac{d\sigma}{dk d\theta}$ to sample the direction and momentum of photons

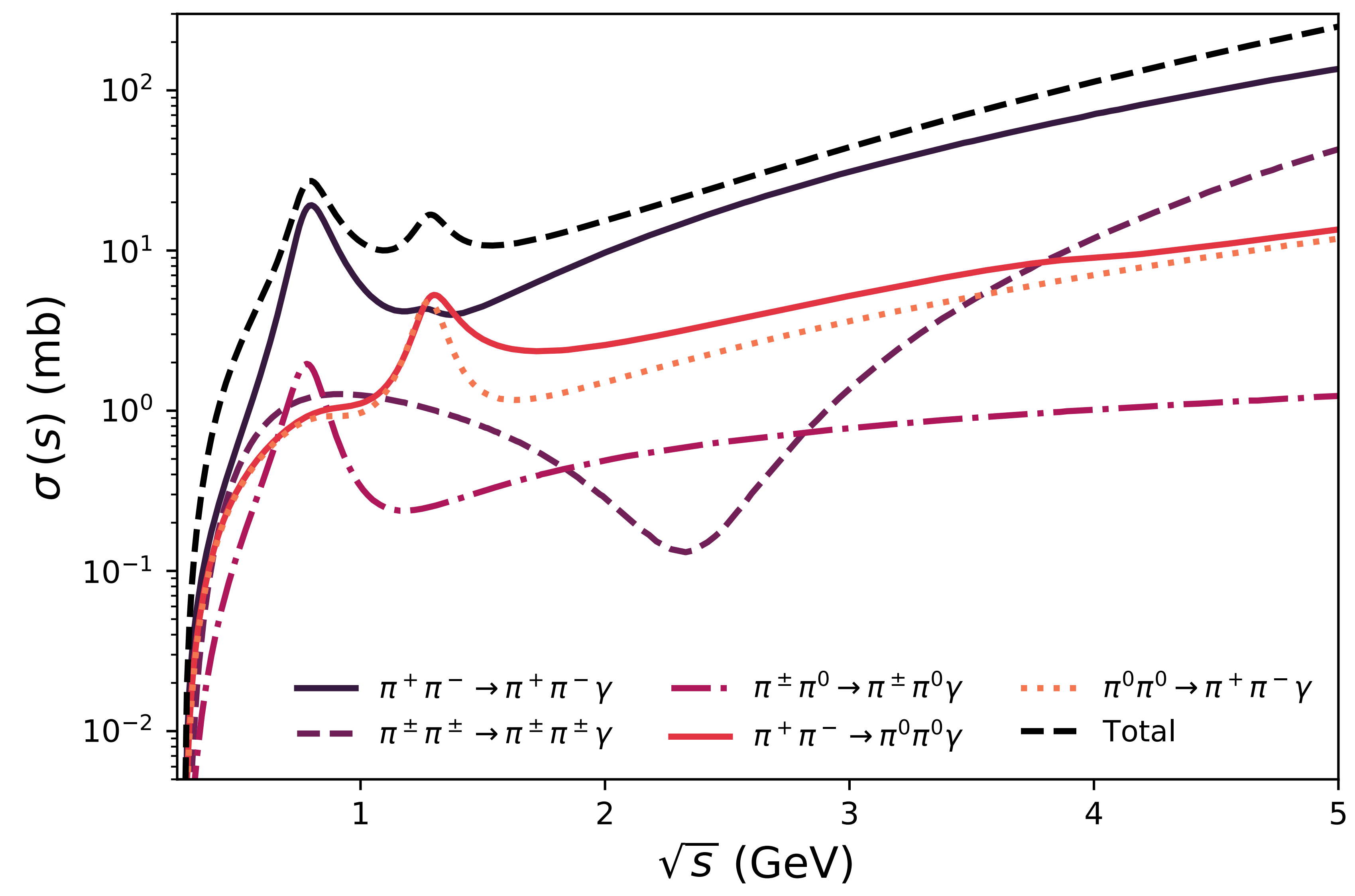
COMPARISON TO THERMAL RATES

SMASH setup: thermal matter with periodic box

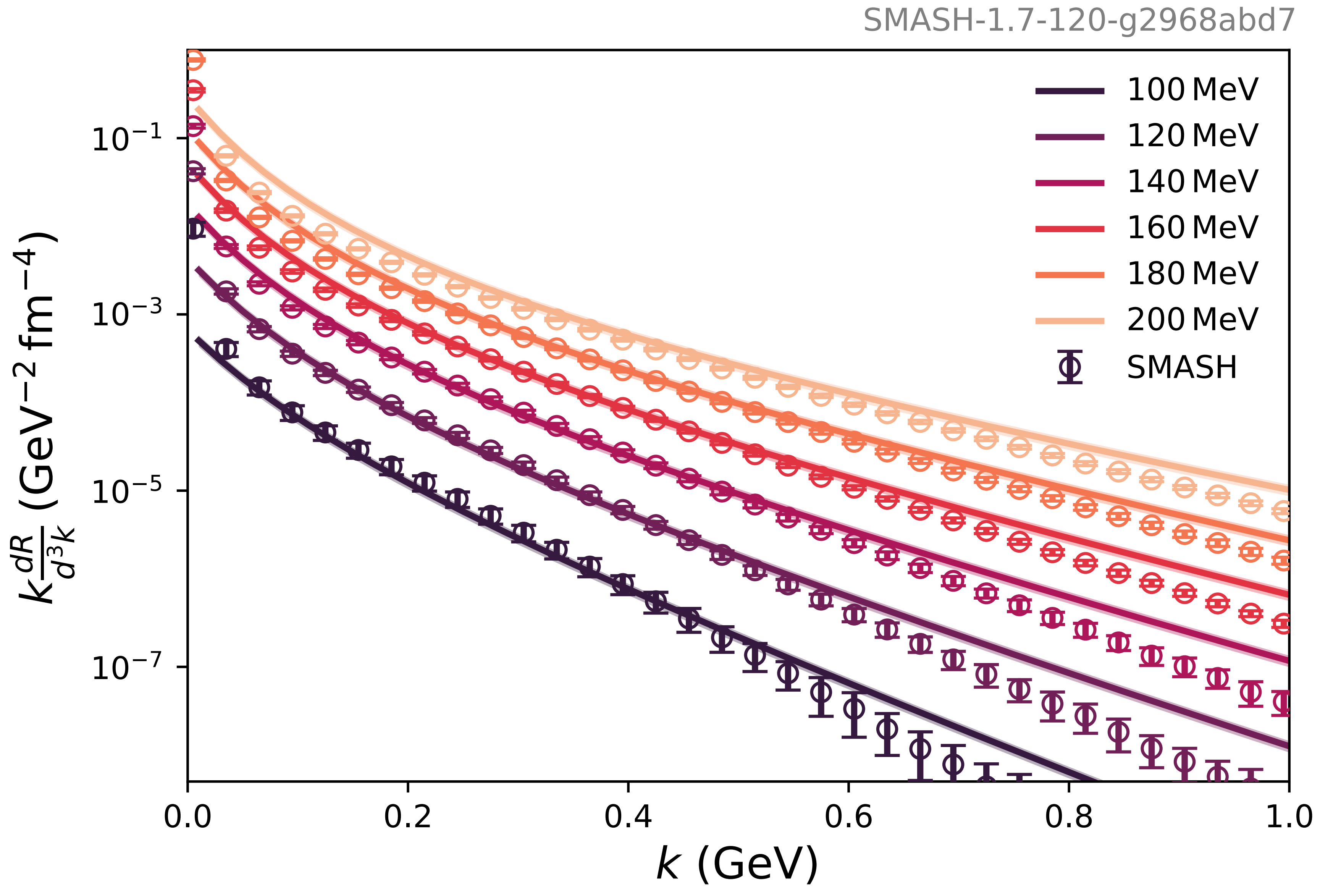
Compute Thermal photon rates: 4-volume density of photons

Fair agreement to known parametrizations

Total cross-section



Comparison to thermal rate

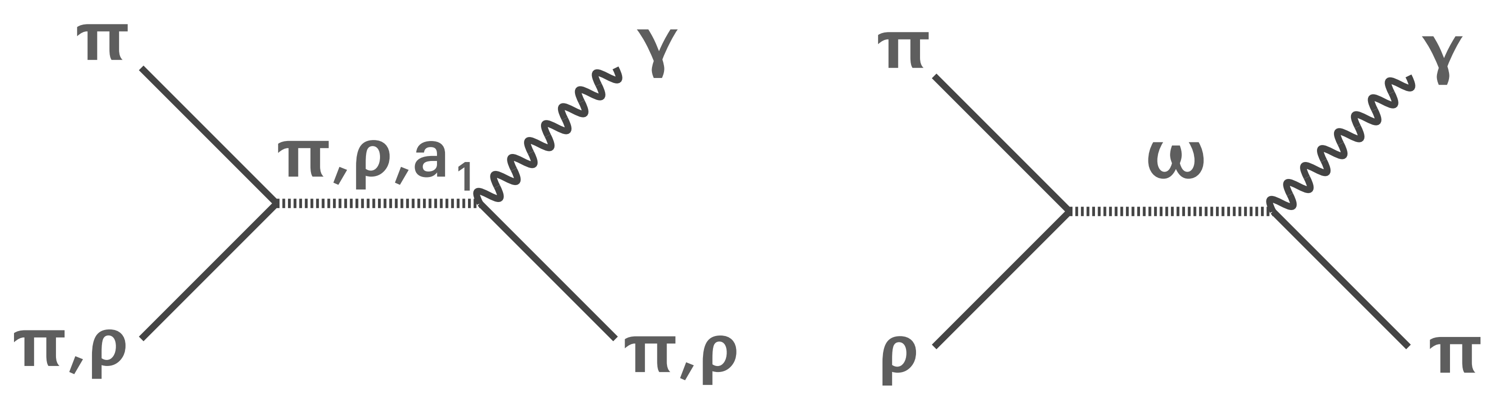


Eggers *et al*, *Phys. Rev.*, D (1996)
Liu and Rapp. *Nucl. Phys.*, A (2007).
Linnyk *et al*. Phys.Rev. C (2015)

PHOTONS FROM HADRONIC TRANSPORT

2-TO-2 SCATTERINGS

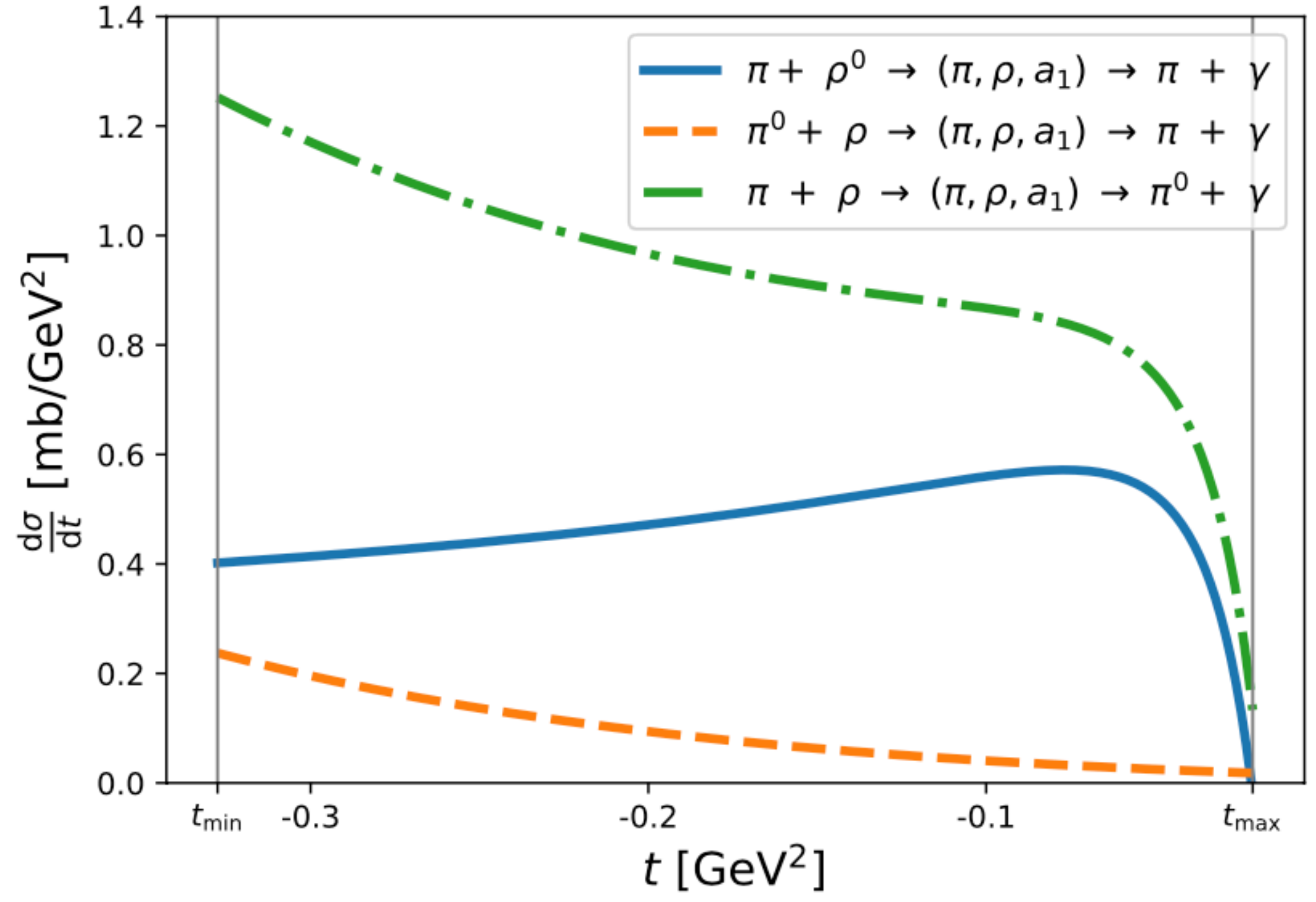
Photon production from pion 2-to-2 process.



Get differential and total cross section from the Chiral Lagrangian

We use $\frac{d\sigma}{dt}$ to sample the direction and momentum of photons

Total cross-section (some channels)



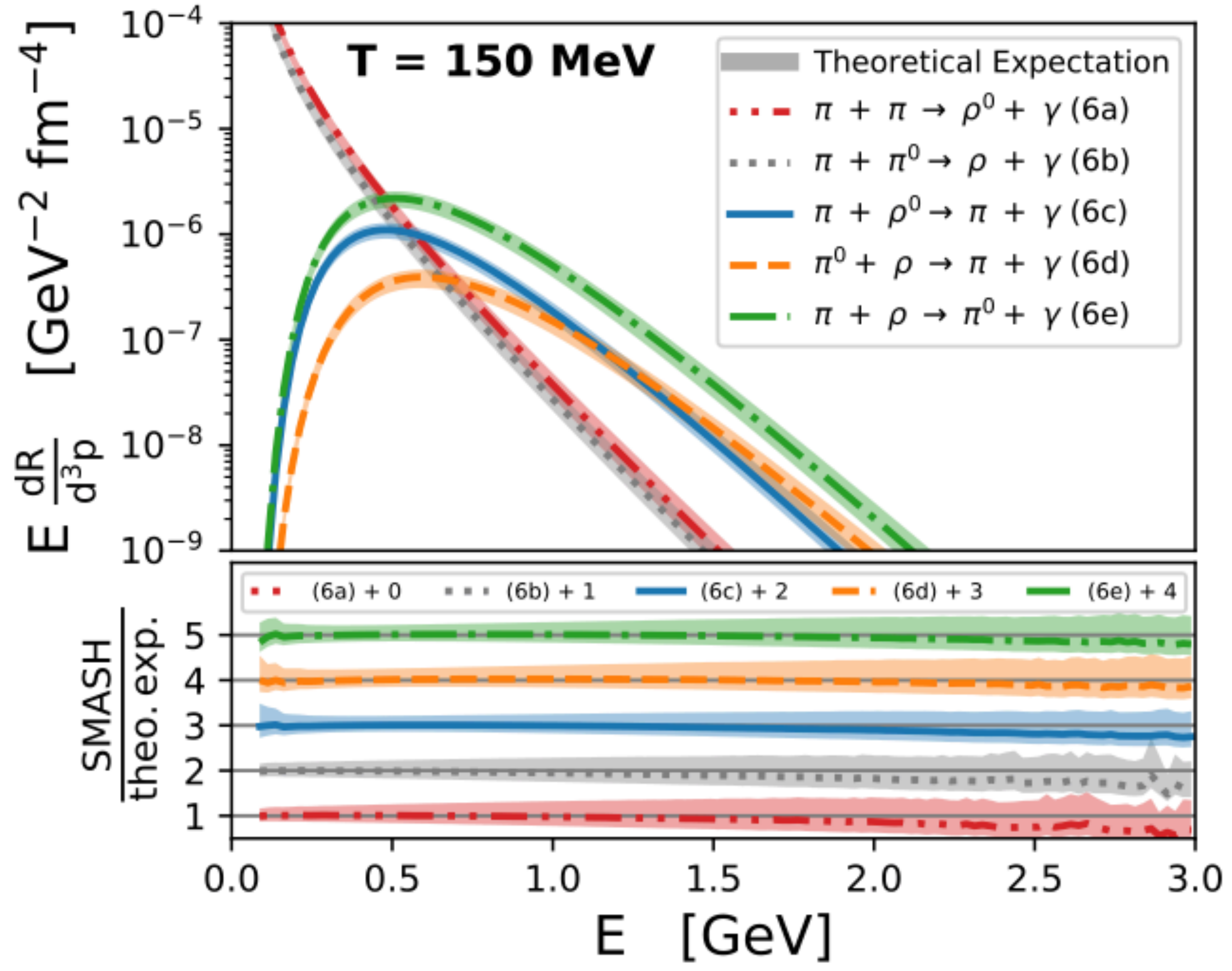
COMPARISON TO THERMAL RATES

SMASH setup: π-ρ thermal matter with periodic box.

Compute Thermal photon rates: 4-volume density of photons

Very good agreement to known parametrization

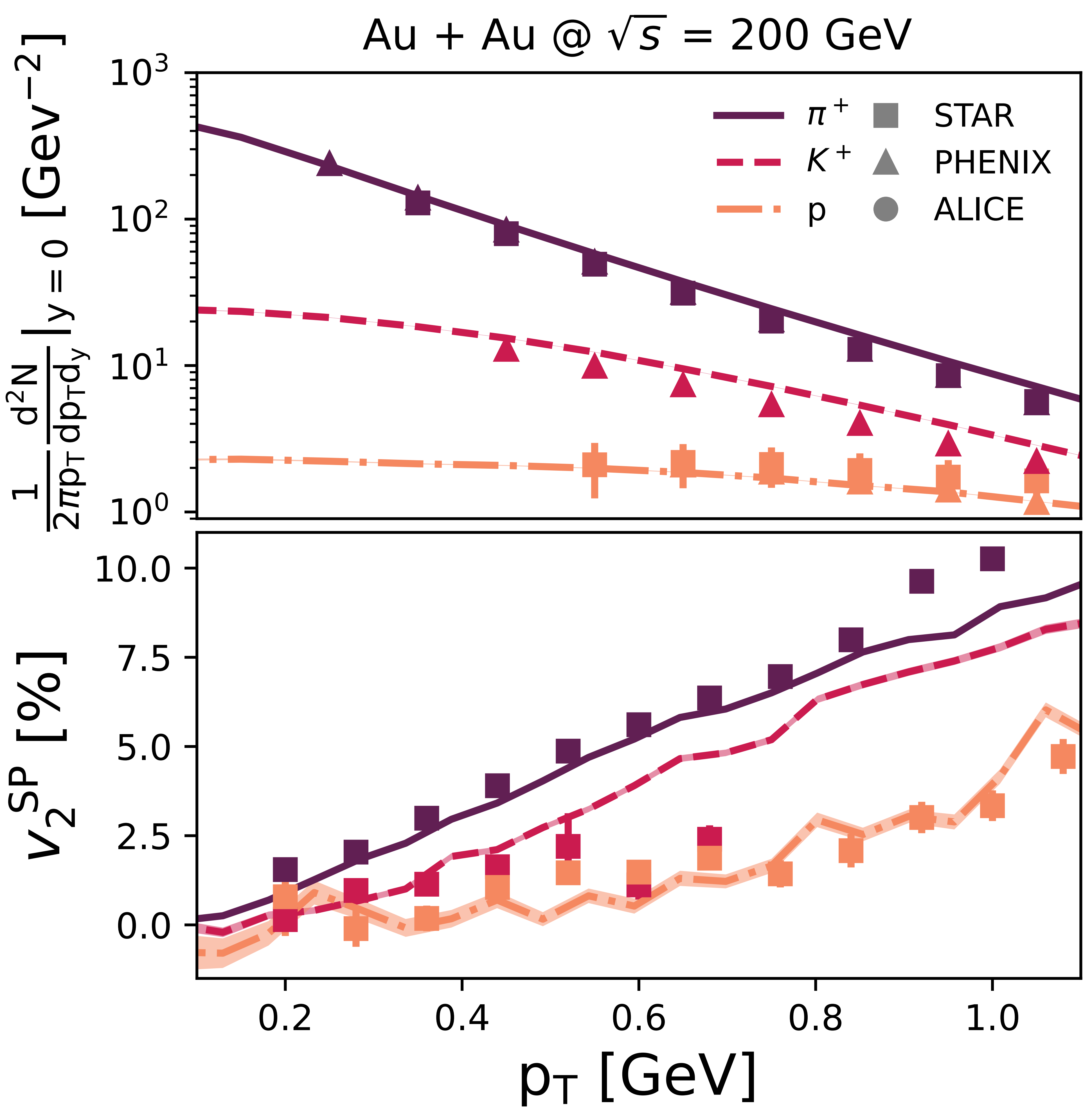
Comparison to thermal rate (some channels)



[Schäfer *et al*, *Phys.Rev.D* 99 (2019) 11, 114021]

LATE-TIME NON-EQUILIBRIUM PHOTONS

- This study:
  - Au-Au 200 GeV y=0
  - b=5 fm → ~ 10-20%
  - Particlization at T=150 MeV
- Check hadronic observables



HADRONS

LATE-TIME NON-EQUILIBRIUM PHOTONS

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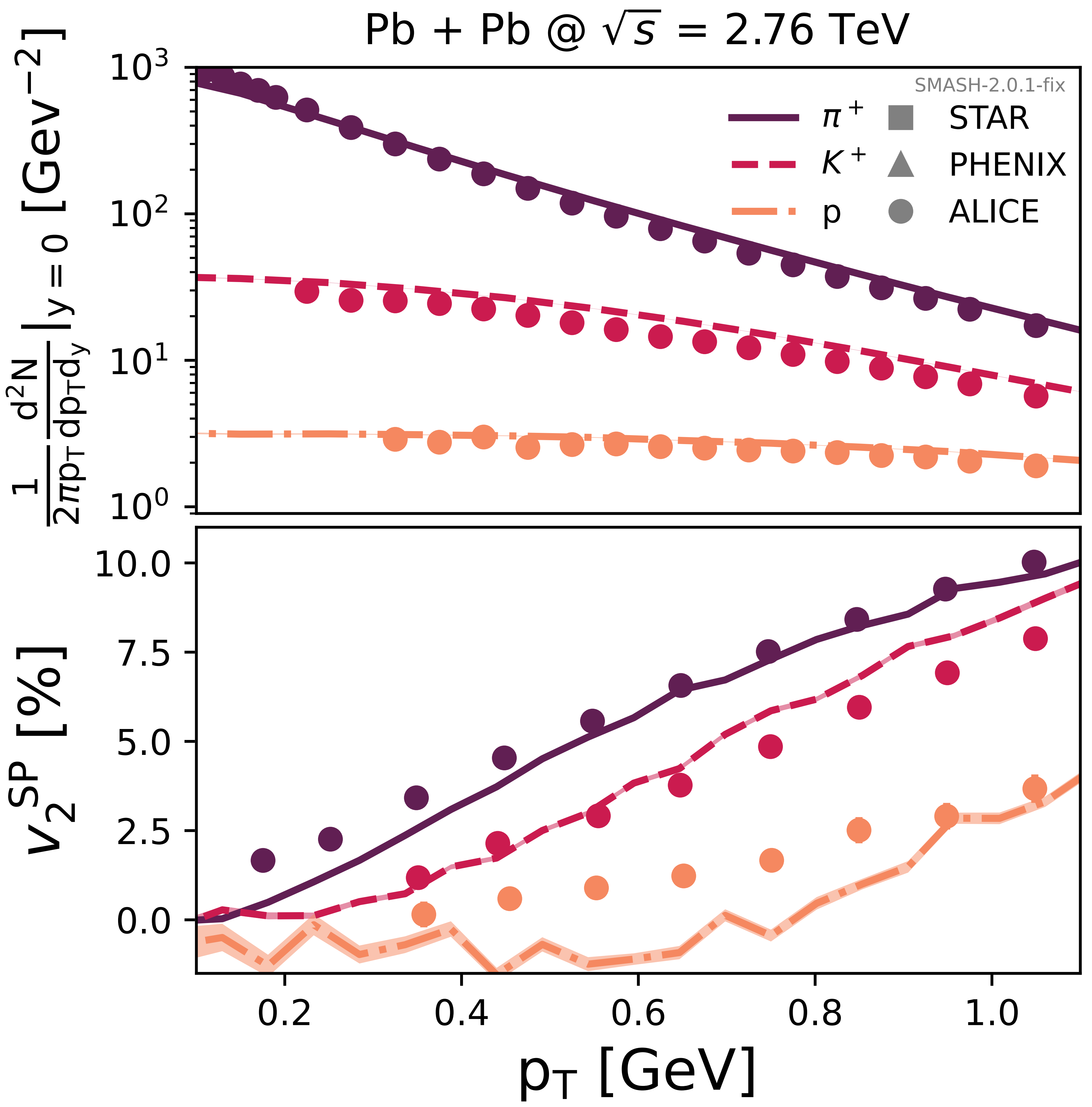


LATE-TIME NON-EQUILIBRIUM PHOTONS

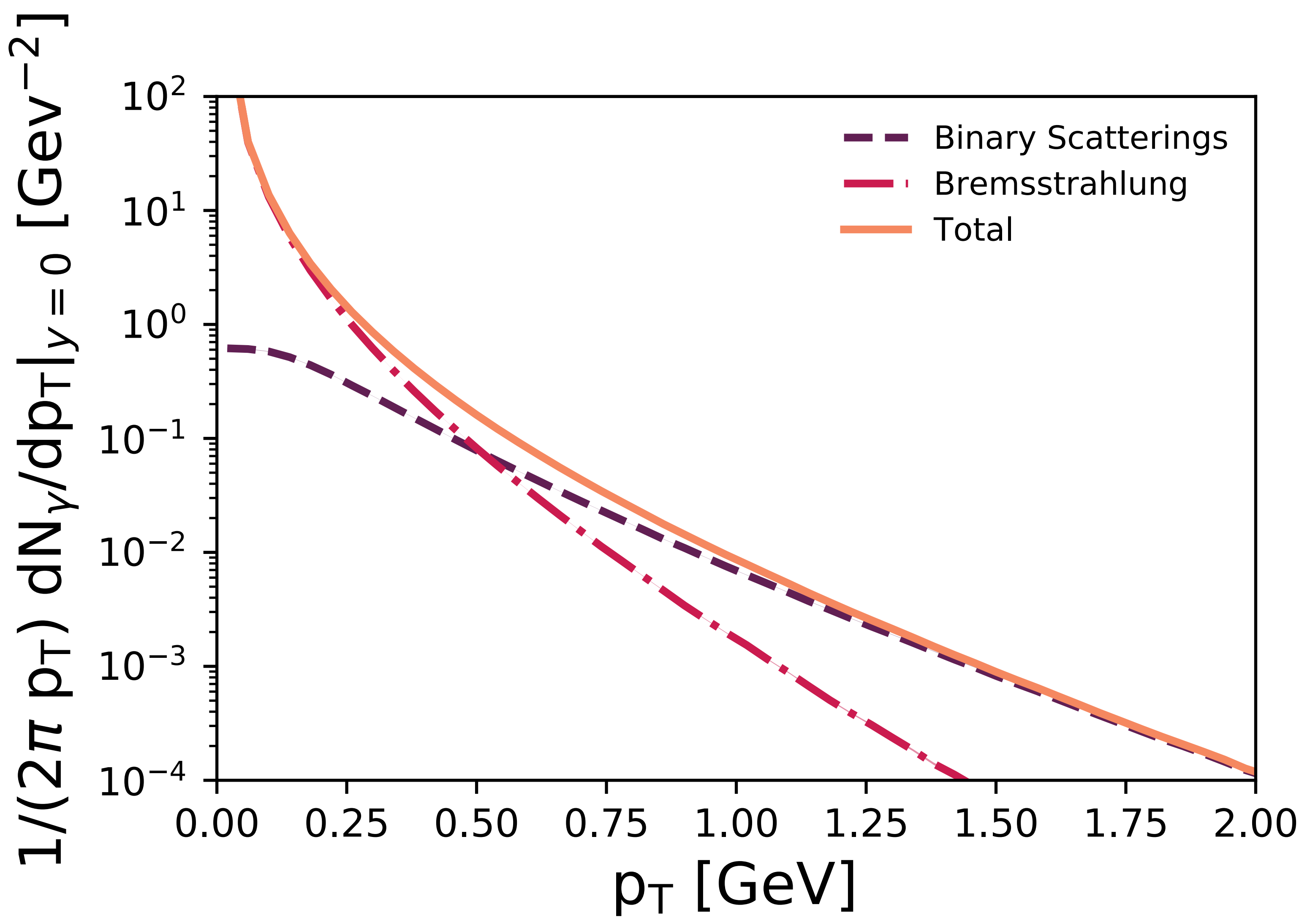
- This study:
  - Au-Au 200 GeV, Pb-Pb 2.76 TeV
  - b=5 fm → ~ 10-20%
  - Particlization at T=150 MeV

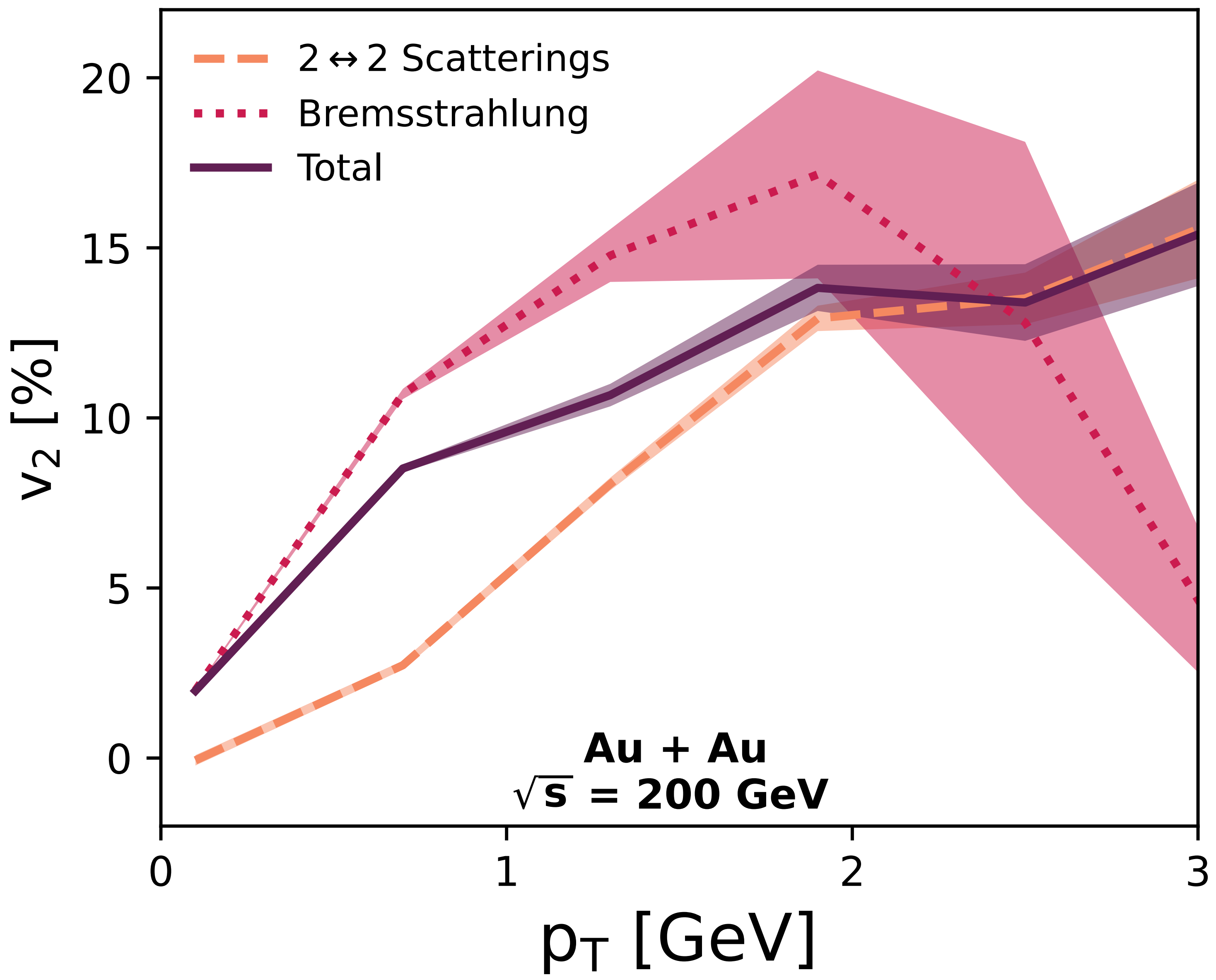
- Check hadronic observables ✓

- Computed yield and anisotropy of photons. For v_2 we used

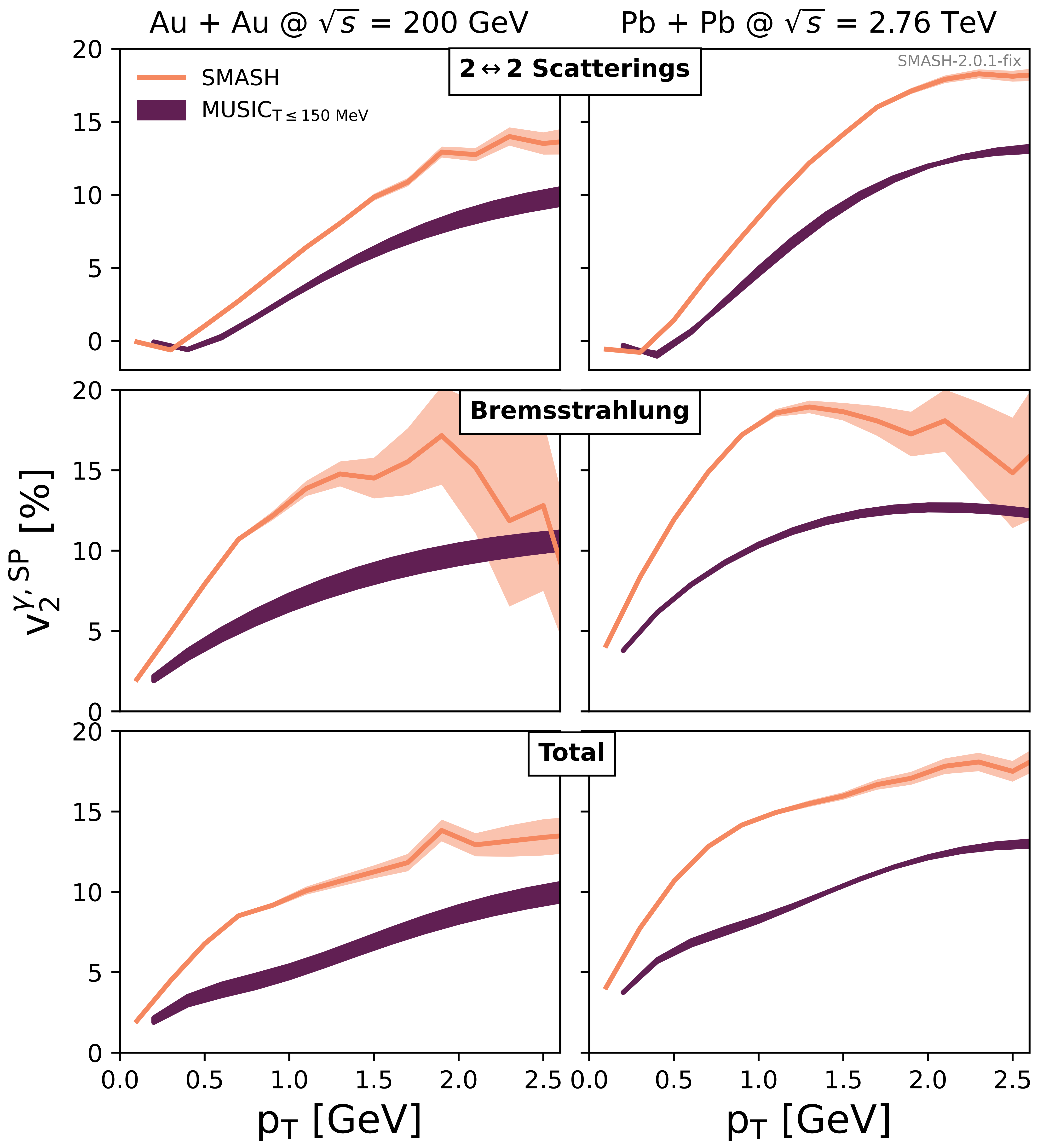
$$v_2(p_\perp) = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_\perp^2 \rangle}$$

- Photon anisotropies are measured relative to the hadronic event plane





PHOTONS



HYDRO VS. TRANSPORT

Comparison

Photons from SMASH (transport)
vs. MUSIC (Hydro, Hadronic)

Hydro Photons produced using thermal rates:

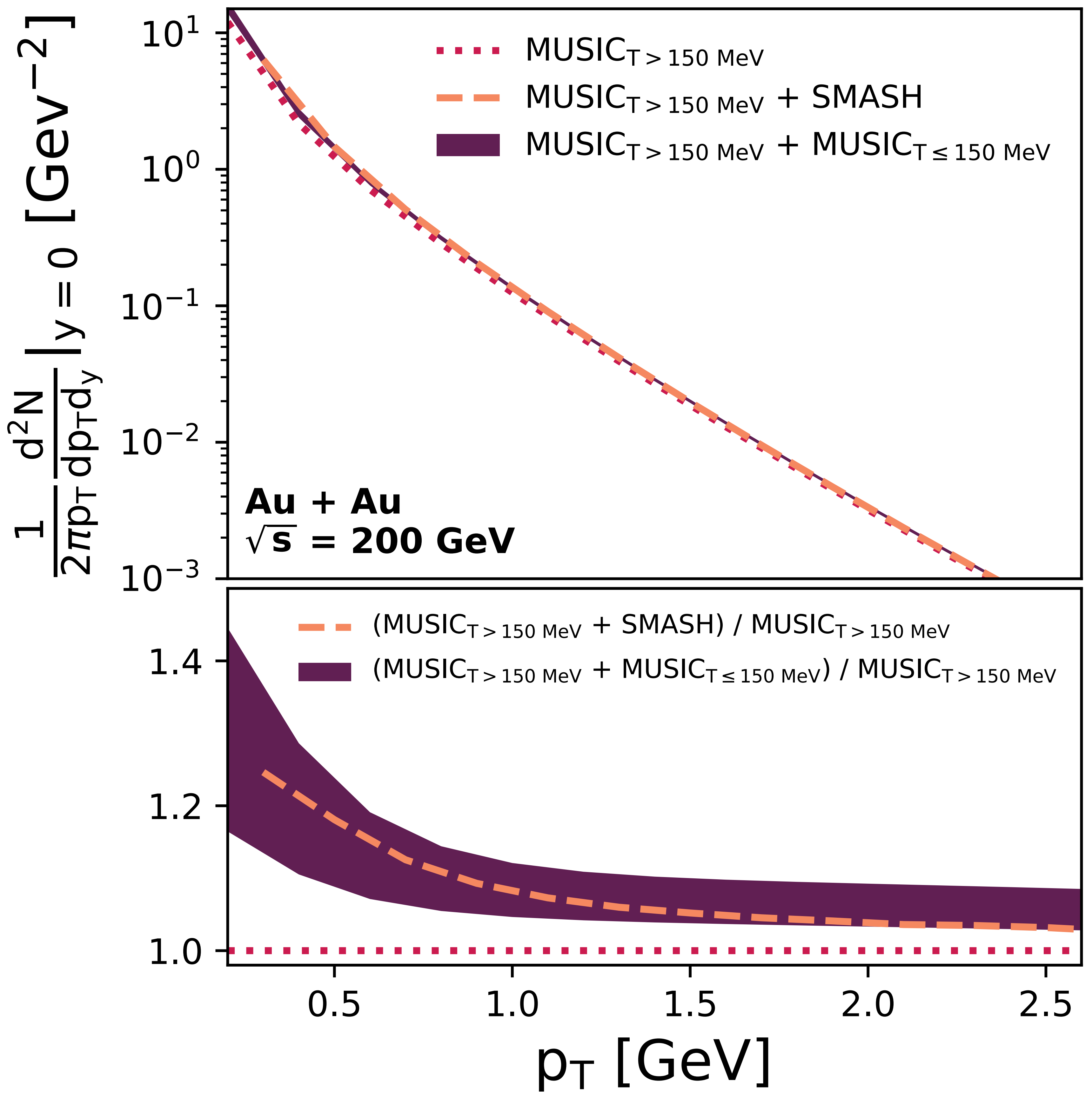
Eq. vs Non-Eq. Effects

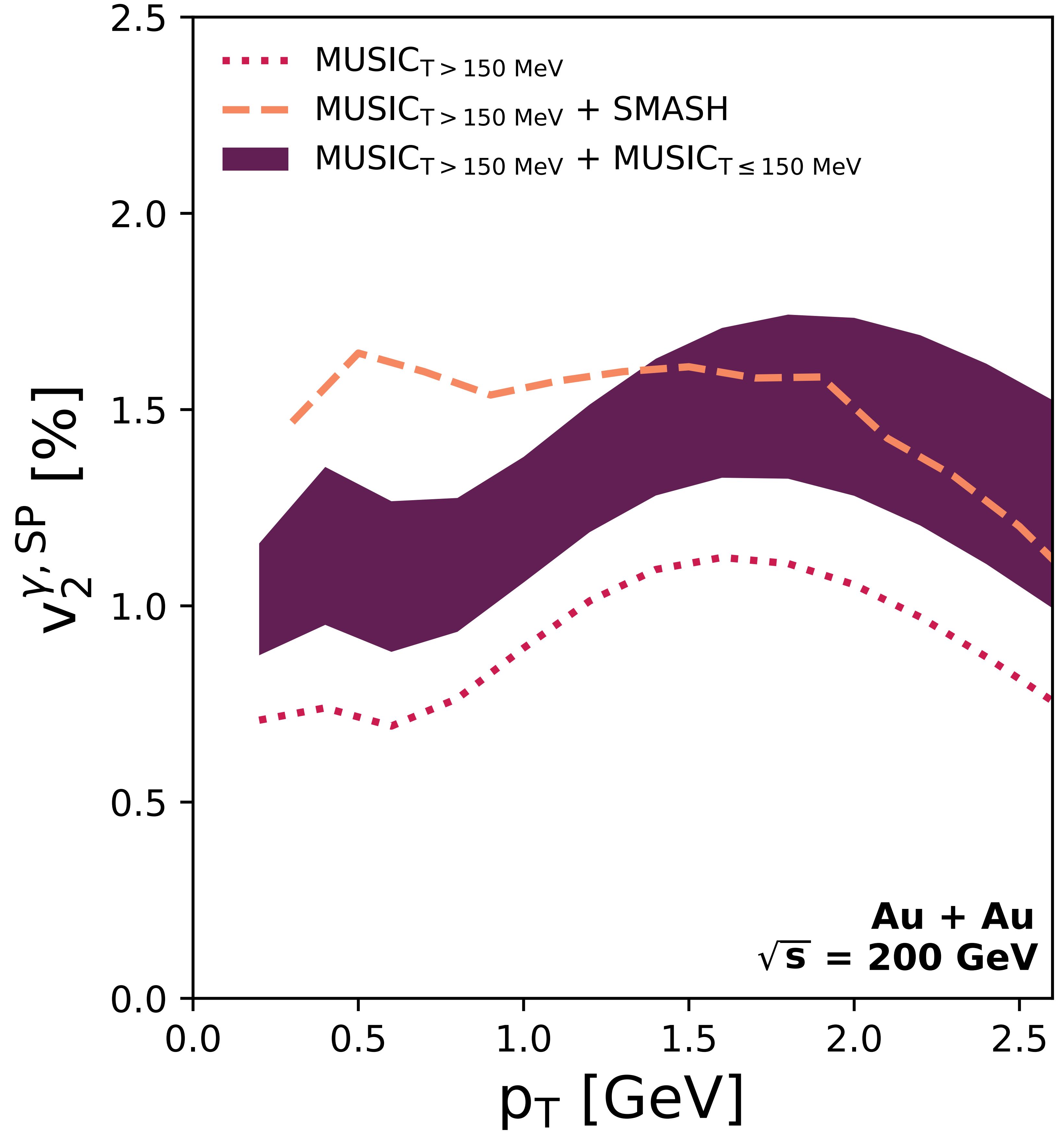
Note: Total is a weighted average!

NON-EQUILIBRIUM EFFECTS ENHANCE PHOTON ANISOTROPIES

QGP VS. HADRONIC MATTER

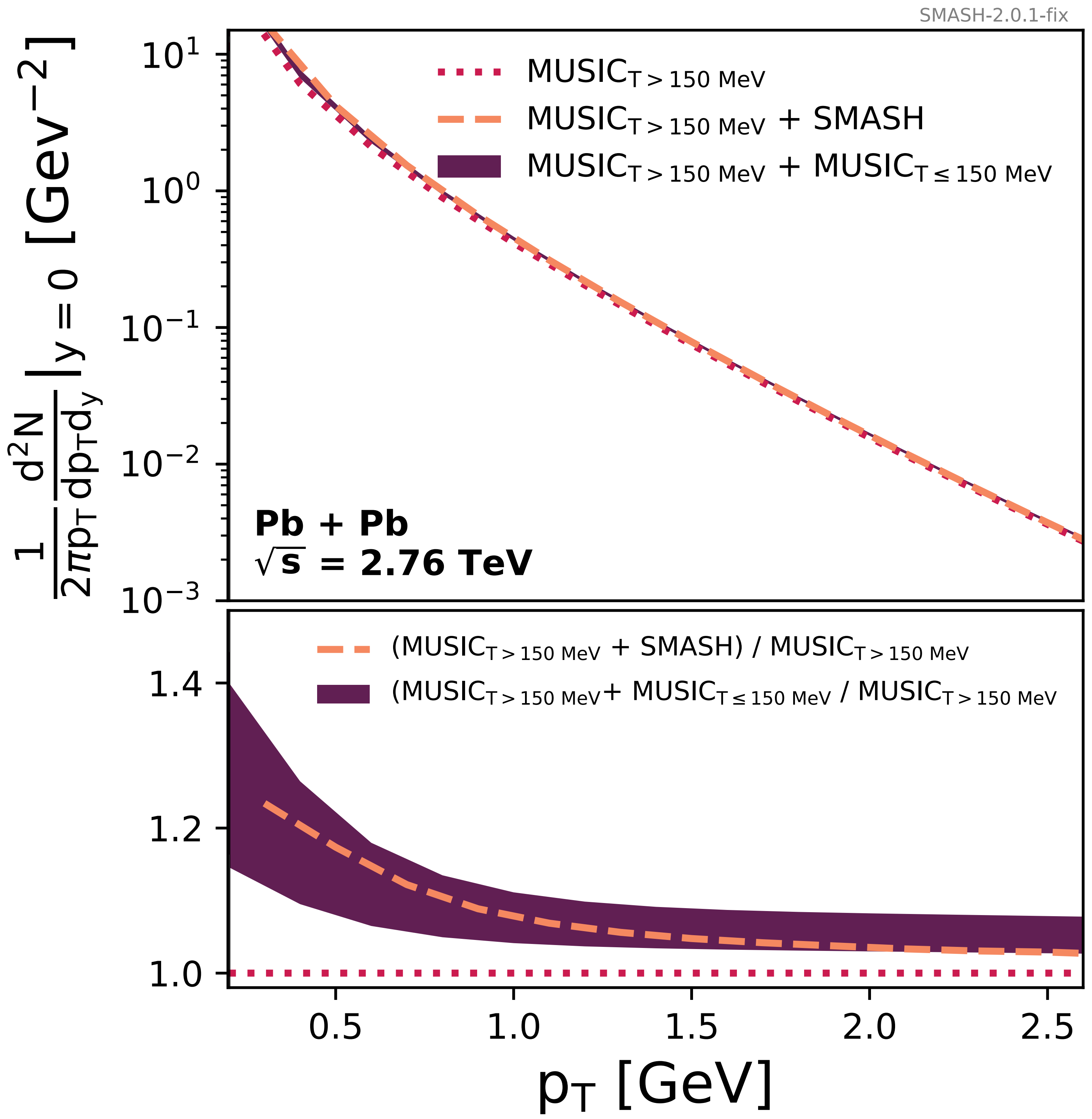
[RHIC]

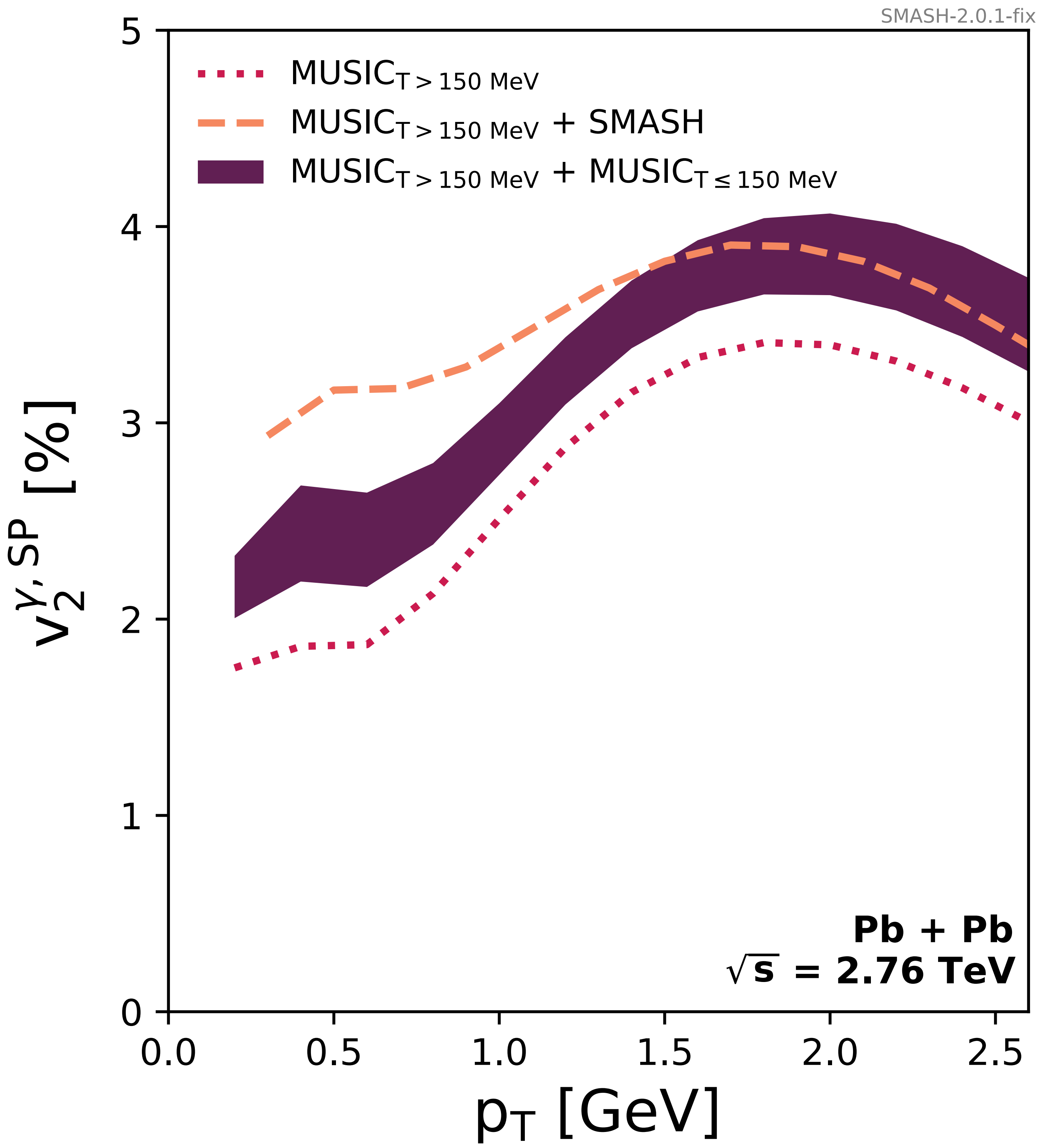




QGP VS. HADRONIC MATTER

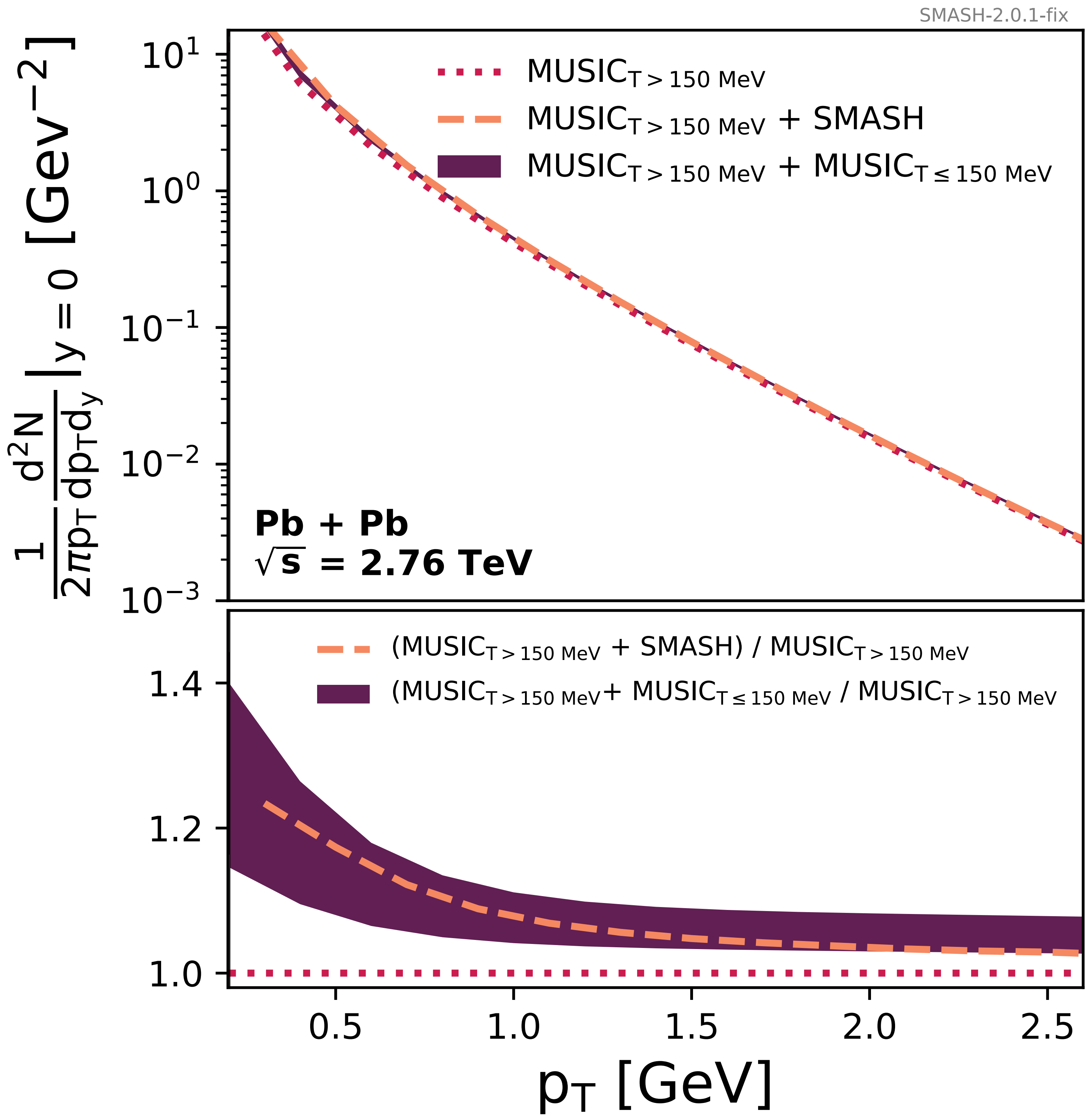
[LHC]

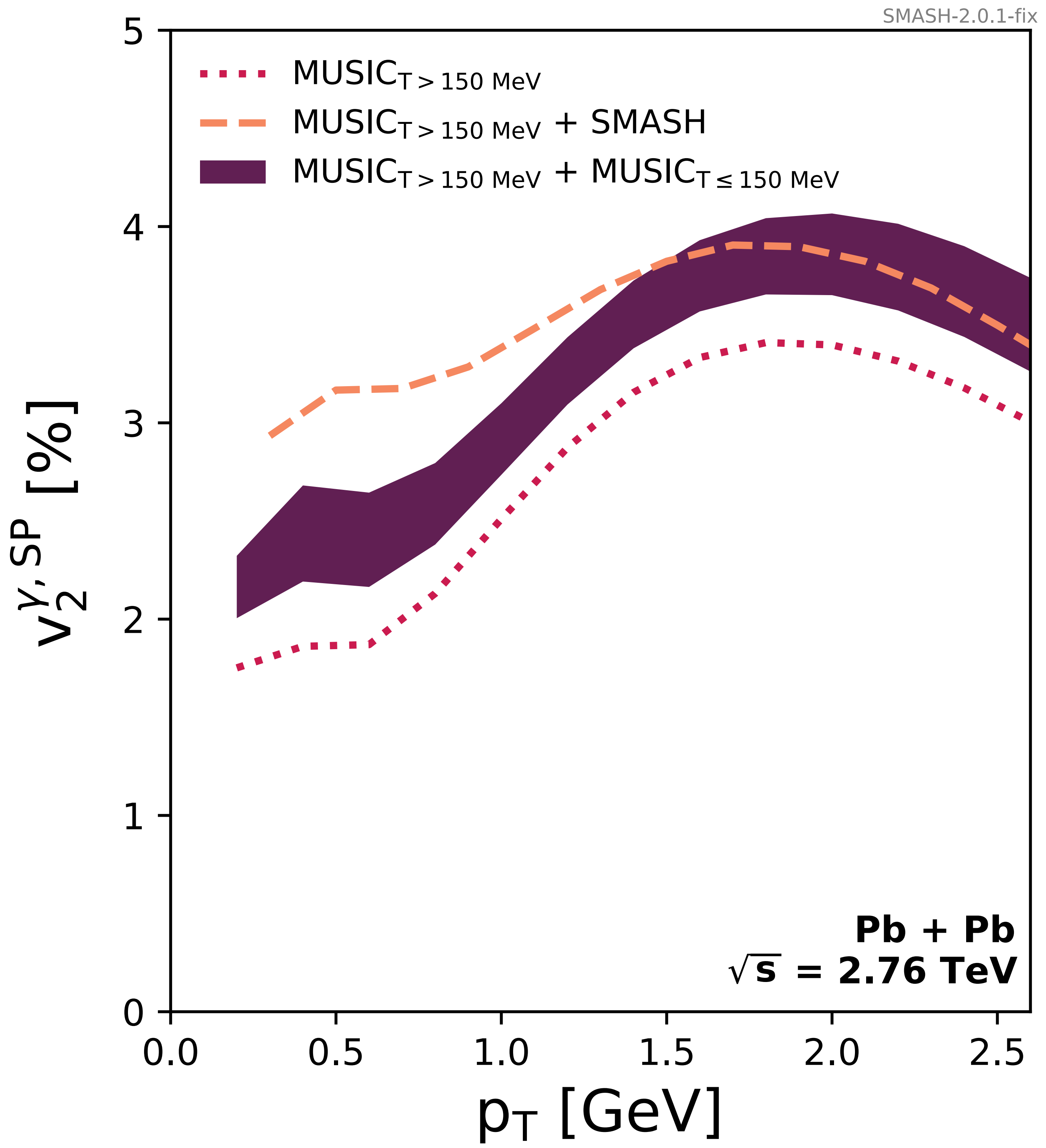




QGP VS. HADRONIC MATTER

[LHC]





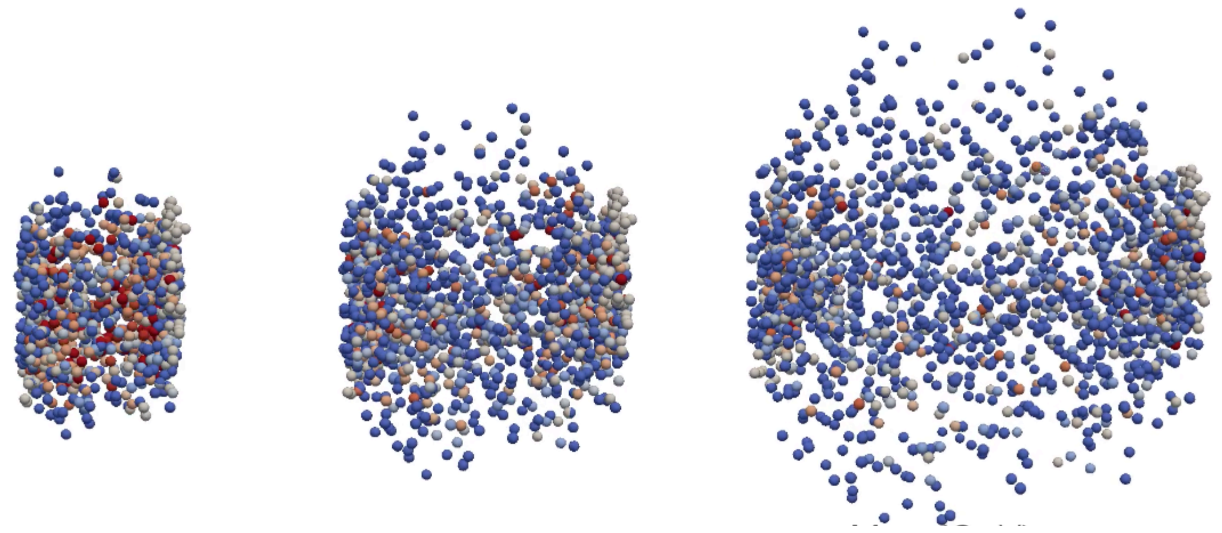
HADRONIC STAGE IS RELEVANT! NON-EQ. EFFECTS SHOULD BE ACCOUNTED FOR.

CONCLUSIONS

- First full hybrid calculation for photon production at high beam energies
- Late time non-equilibrium effects are significant for anisotropy generation
- Non-trivial to resolve the discrepancies in the photon observables
- Run realistic event-by-event case to compare to data
- Approach could be further improved by new channels (Kaon, Baryonic...)

BACKUP SLIDE

SMASH*



- ***SMASH*** can perform interactions based on two collision criteria

- Geometric criterion
  - Decision of whether collisions happens is based on the geometric interpretation of the cross section
  - Criterion is only available for 2-to-2 collisions

$$d_\perp < d_{\text{int}} = \sqrt{\frac{\sigma}{\pi}}$$

- Stochastic criterion
  - Defines a probability for a reaction of a given particle set
  - Criterion available for all *n*,*m*.
  - 1-to-3, 2-to-3 and 2-to-5 reactions already implemented

$$P_{n\to m} = \frac{1}{\mathcal{S}'!}\frac{\Delta t}{(\Delta^3 x)^{n-1}}\frac{1}{\prod_{j=1}^{n} 2E_j}\int d\Phi_m \overline{|T_{n\to m}|^2}\,,$$

Weil *et al*, *Phys.Rev.C* 94 (2016) 5, 054905
Steinberg *et al*, *Phys.Rev.C* 99 (2019) 6, 064908
Mohs *et al*,*J.Phys.G* 47 (2020) 6, 065101
Rose *et al*, *J.Phys.G* 48 (2021) 015005
Steinberg *et al*, arXiv: 1912.09895
Staudenmeier *et al*, *Phys.Rev.C* 98 (2018) 5, 054908