

# A Non-Equilibrium Approach to Photon Emission from the Late Stages of Relativistic Heavy-Ion Collisions

Anna Schäfer

in collaboration with J. M. Torres-Rincon, C. Gale and H. Elfner

Based on: PRD 99 114021 (2019)



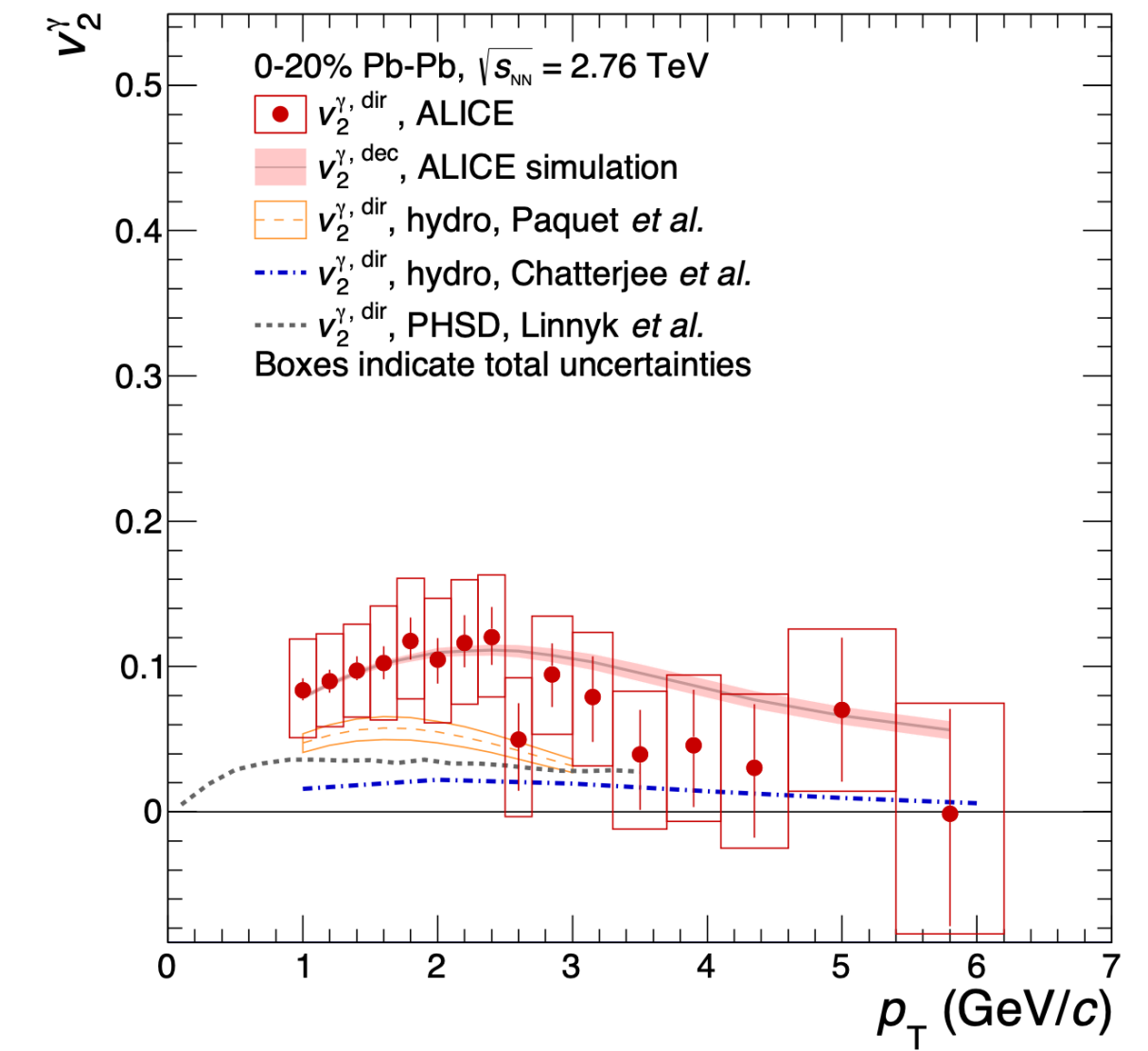
DAAD



# WHY PHOTONS FROM THE HADRON GAS?

Direct photon production in high-energy heavy-ion collisions not fully understood

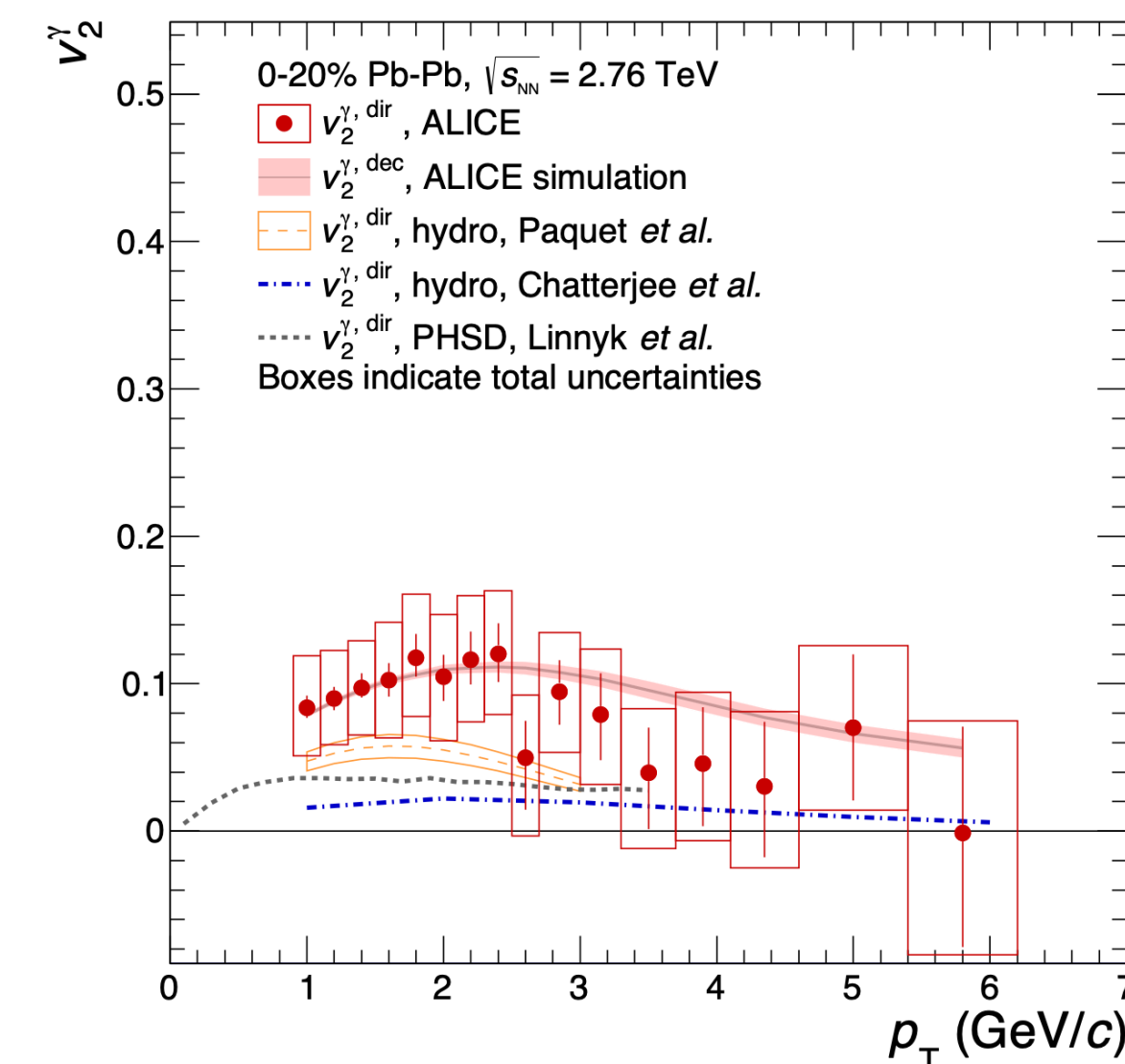
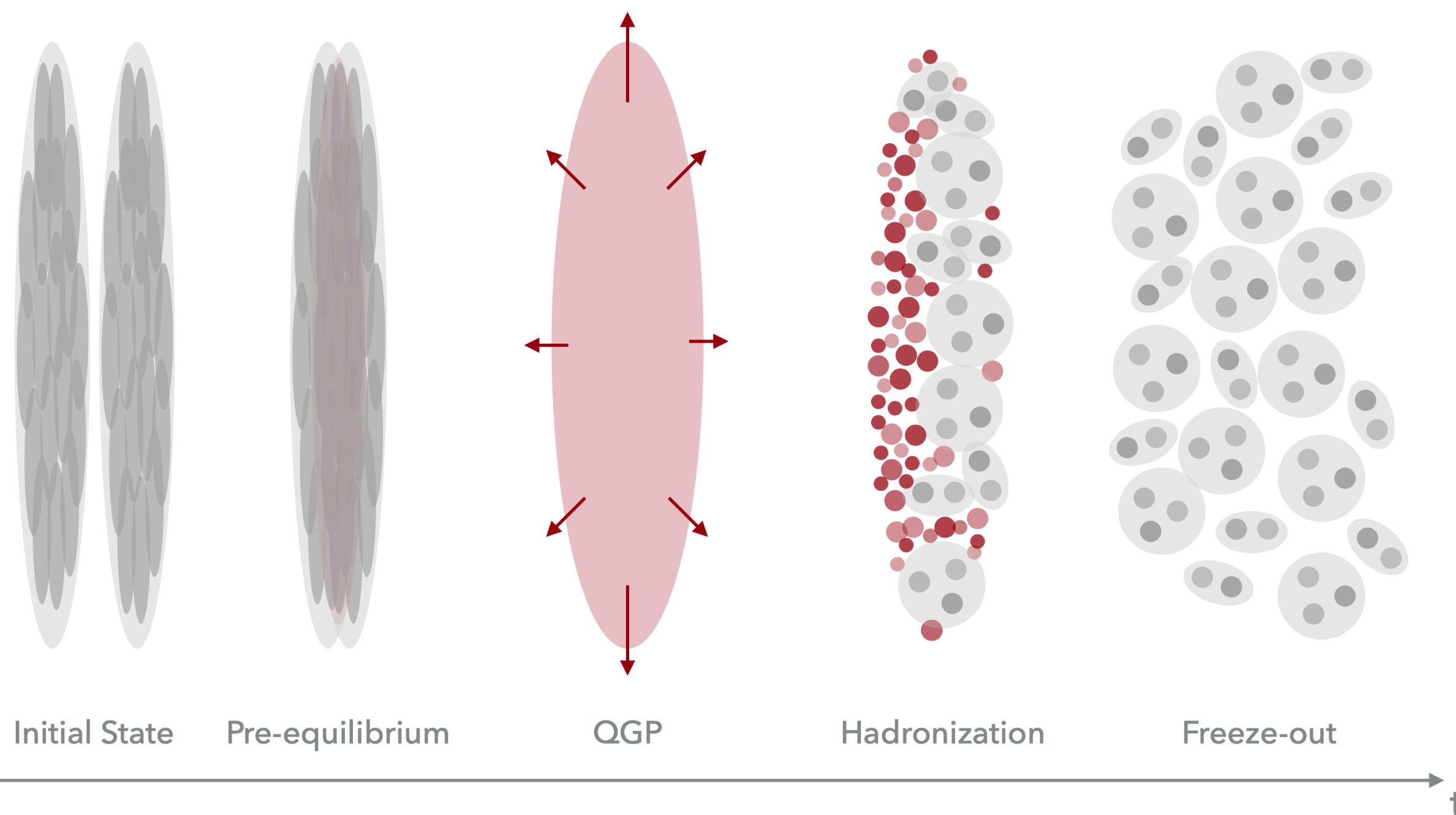
- ▶ Yield and flow cannot be described simultaneously within same model
- ▶ So far: hydrodynamic evolution with hadronic EoS for photon emission



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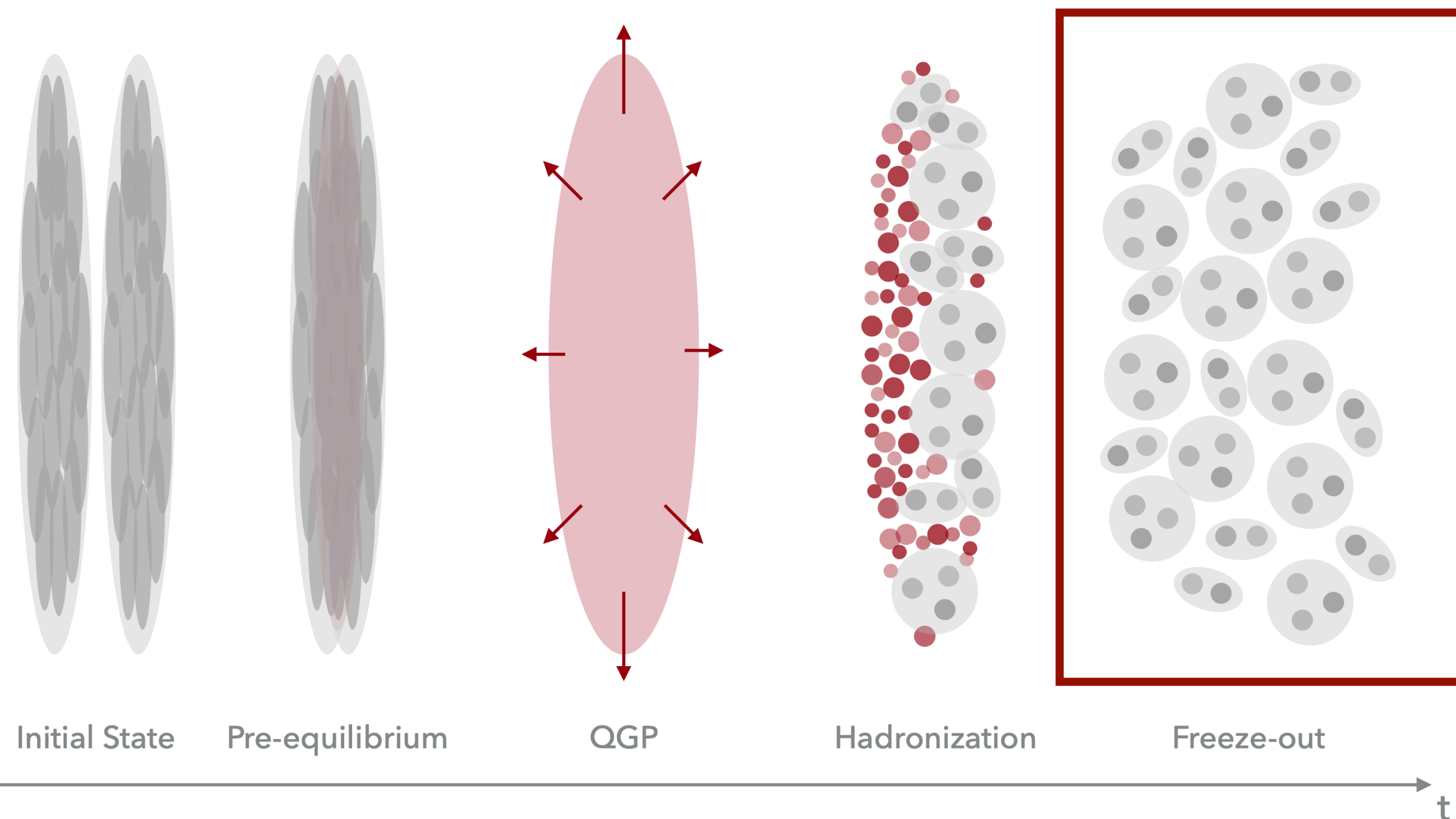
Importance of photons originating from late non-equilibrium hadronic phase?

- ▶ Study photon production by means of hybrid approaches, e.g. MUSIC + SMASH

# WHY PHOTONS FROM THE HADRON GAS?

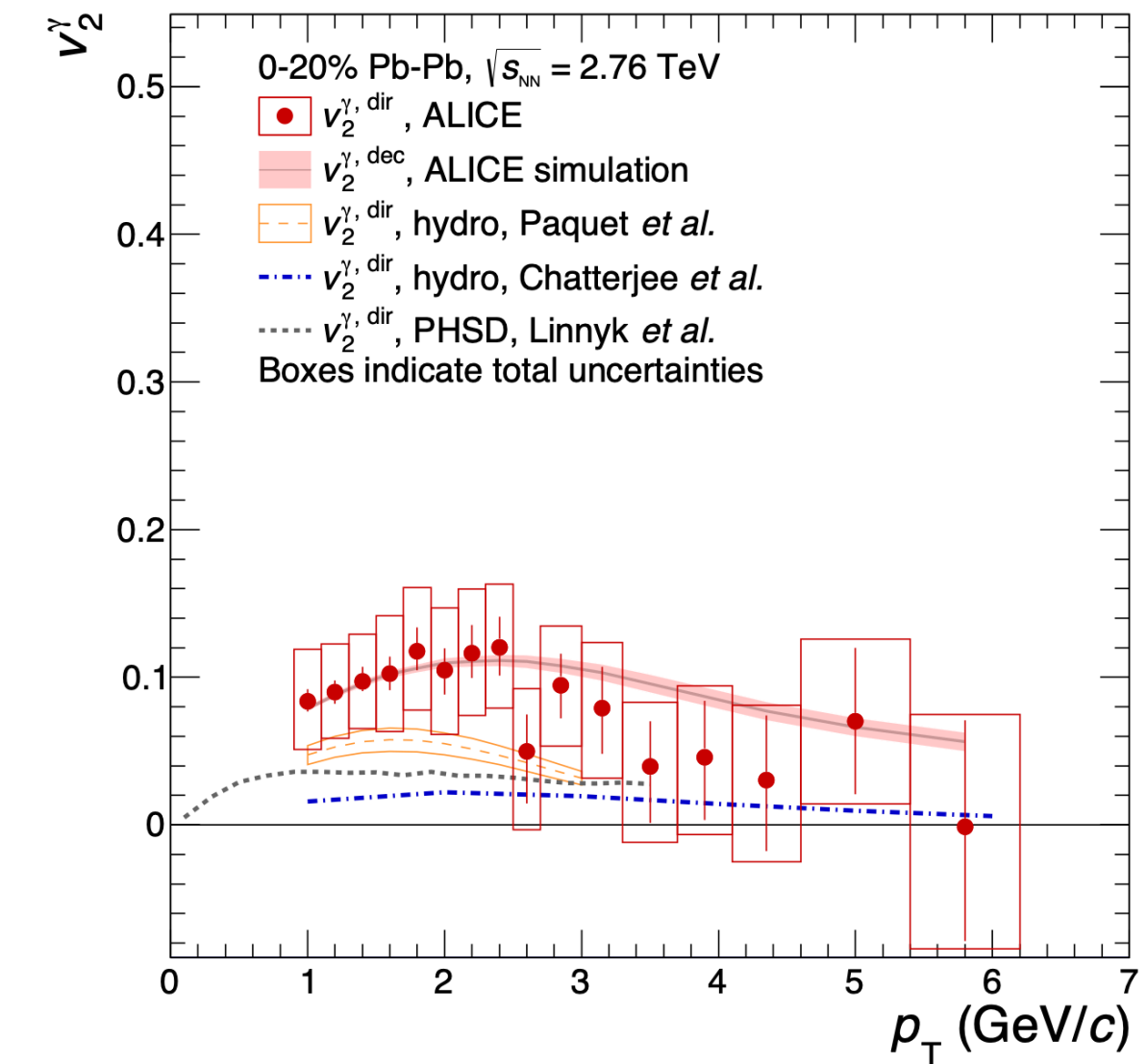
Direct photon production in high-energy heavy-ion collisions not fully understood

- ▶ Yield and flow cannot be described simultaneously within same model
- ▶ So far: hydrodynamic evolution with hadronic EoS for photon emission



**In this talk**

- ▶ Benchmark photon production in hadronic medium by means of hadronic transport approach (SMASH)



# MODEL DESCRIPTION

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- Simulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons
- Novel hadronic transport approach
- Effective solution of relativistic Boltzmann equation:

$$p_\mu \partial^\mu f + m \partial_{p_\mu} (F^\mu f) = C(f)$$

- Collision integral modeled through decays and formations of hadronic resonances
- Geometric collision criterion:  $d_{\text{coll}} < \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}$
- Strangeness production, dileptons, baryon stopping and bulk properties already studied successfully

<http://smash-transport.github.io>

Weil et al.: PRC 94 (2016)

Steinberg et al.: PRC 99 (2019)

DOI: 10.5281/zenodo.3484711

Tindall et al.: Phys. Lett. B770 (2017)

Rose et al.: PRC 97 (2018)

Mohs et al.: arXiv 1909.05586

Staudenmaier et al.: PRC 98 (2018)

Oliinychenko et al.: J. Phys. G 44 (2017)

# MODEL DESCRIPTION

See also talk  
by J.-B. Rose  
in EM I

See also  
poster by J.  
Hammelmann

See also  
poster by  
J. Mohs



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# SMASH DEGREES OF FREEDOM



N	$\Delta$	$\Lambda$	$\Sigma$	$\Xi$	$\Omega$	Unflavored			Strange	
N <sub>938</sub>	$\Delta_{1232}$	$\Lambda_{1116}$	$\Sigma_{1189}$	$\Xi_{1321}$	$\Omega^-_{1672}$	$\pi_{138}$	$f_0_{980}$	$f_2_{1275}$	$\pi_2_{1670}$	$K_{494}$
N <sub>1440</sub>	$\Delta_{1620}$	$\Lambda_{1405}$	$\Sigma_{1385}$	$\Xi_{1530}$	$\Omega^-_{2250}$	$\pi_{1300}$	$f_0_{1370}$	$f_2'_{1525}$		$K^*_{892}$
N <sub>1520</sub>	$\Delta_{1700}$	$\Lambda_{1520}$	$\Sigma_{1660}$	$\Xi_{1690}$		$\pi_{1800}$	$f_0_{1500}$	$f_2_{1950}$	$\rho_3_{1690}$	$K_1_{1270}$
N <sub>1535</sub>	$\Delta_{1900}$	$\Lambda_{1600}$	$\Sigma_{1670}$	$\Xi_{1820}$			$f_0_{1710}$	$f_2_{2010}$		$K_1_{1400}$
N <sub>1650</sub>	$\Delta_{1905}$	$\Lambda_{1670}$	$\Sigma_{1750}$	$\Xi_{1950}$		$\eta_{548}$		$f_2_{2300}$	$\phi_3_{1850}$	$K^*_{1410}$
N <sub>1675</sub>	$\Delta_{1910}$	$\Lambda_{1690}$	$\Sigma_{1775}$	$\Xi_{2030}$		$\eta'_{958}$	$a_0_{980}$	$f_2_{2340}$		$K_0^*_{1430}$
N <sub>1680</sub>	$\Delta_{1920}$	$\Lambda_{1800}$	$\Sigma_{1915}$			$\eta_{1295}$	$a_0_{1450}$		$a_4_{2040}$	$K_2^*_{1430}$
N <sub>1700</sub>	$\Delta_{1930}$	$\Lambda_{1810}$	$\Sigma_{1940}$			$\eta_{1405}$		$f_1_{1285}$		$K^*_{1680}$
N <sub>1710</sub>	$\Delta_{1950}$	$\Lambda_{1820}$	$\Sigma_{2030}$			$\eta_{1475}$	$\phi_{1019}$	$f_1_{1420}$	$f_4_{2050}$	$K_2_{1770}$
N <sub>1720</sub>		$\Lambda_{1830}$	$\Sigma_{2250}$				$\phi_{1680}$			$K_3^*_{1780}$
N <sub>1875</sub>		$\Lambda_{1890}$				$\sigma_{800}$		$a_2_{1320}$		$K_2_{1820}$
N <sub>1900</sub>		$\Lambda_{2100}$					$h_1_{1170}$			$K_4^*_{2045}$
N <sub>1990</sub>		$\Lambda_{2110}$				$\rho_{776}$		$\pi_1_{1400}$		
N <sub>2060</sub>		$\Lambda_{2350}$				$\rho_{1450}$	$b_1_{1235}$	$\pi_1_{1600}$		
N <sub>2080</sub>						$\rho_{1700}$				
N <sub>2100</sub>							$a_1_{1260}$	$\eta_2_{1645}$		
N <sub>2120</sub>										
N <sub>2190</sub>						$\omega_{783}$				
N <sub>2220</sub>						$\omega_{1420}$		$\omega_3_{1670}$		
N <sub>2250</sub>						$\omega_{1650}$				

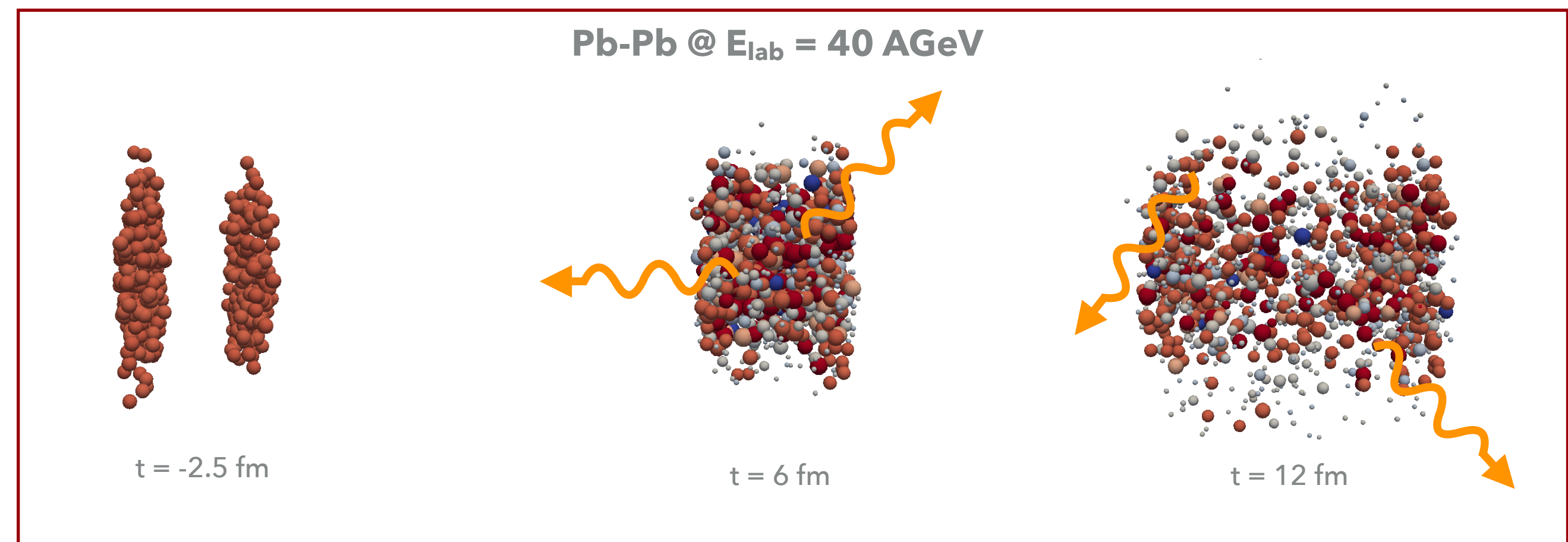
As of SMASH-1.7

- ▶ + corresponding antiparticles
- ▶ Perturbative treatment of photons and dileptons
- ▶ Isospin symmetry

## Perturbative Treatment

- ▶ EM coupling  $\ll$  strong coupling
- ▶ **Assumption:** Photons do not interact with medium after production
- ▶ Photons directly printed to a separate photon output
- ▶ Hadronic evolution proceeds as if no photon production had occurred

- Production in binary elastic and inelastic scattering processes
- Cross sections derived from chiral effective field theory based on [Turbide et al.: Int. J. Mod. Phys. A19 \(2004\)](#)



# THEORETICAL BACKGROUND

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- Chiral effective field theory with mesonic degrees of freedom
  - ▶ Pseudoscalar mesons
  - ▶ Vector mesons
  - ▶ Axial vector mesons
  - ▶ Photons
- Applied in 3+1D viscous hydrodynamics code (MUSIC)
  - ▶ Consistent hybrid model of MUSIC + SMASH to study photon production
  - ▶ Photon production in non-equilibrium vs. equilibrium expansion
- Further extensions possible, e.g.
  - ▶ Heffernan, Hohler, Rapp: Phys. Rev. C 91 (2015)
  - ▶ Holt, Hohler, Rapp: Nuc. Phys. A 945 (2016)

Turbide et al.: Int. J. Mod. Phys. A19 (2004)

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## Exchange via ( $\pi, \rho, a_1$ )

$$\pi^\pm + \rho^0 \rightarrow \pi^\pm + \gamma$$

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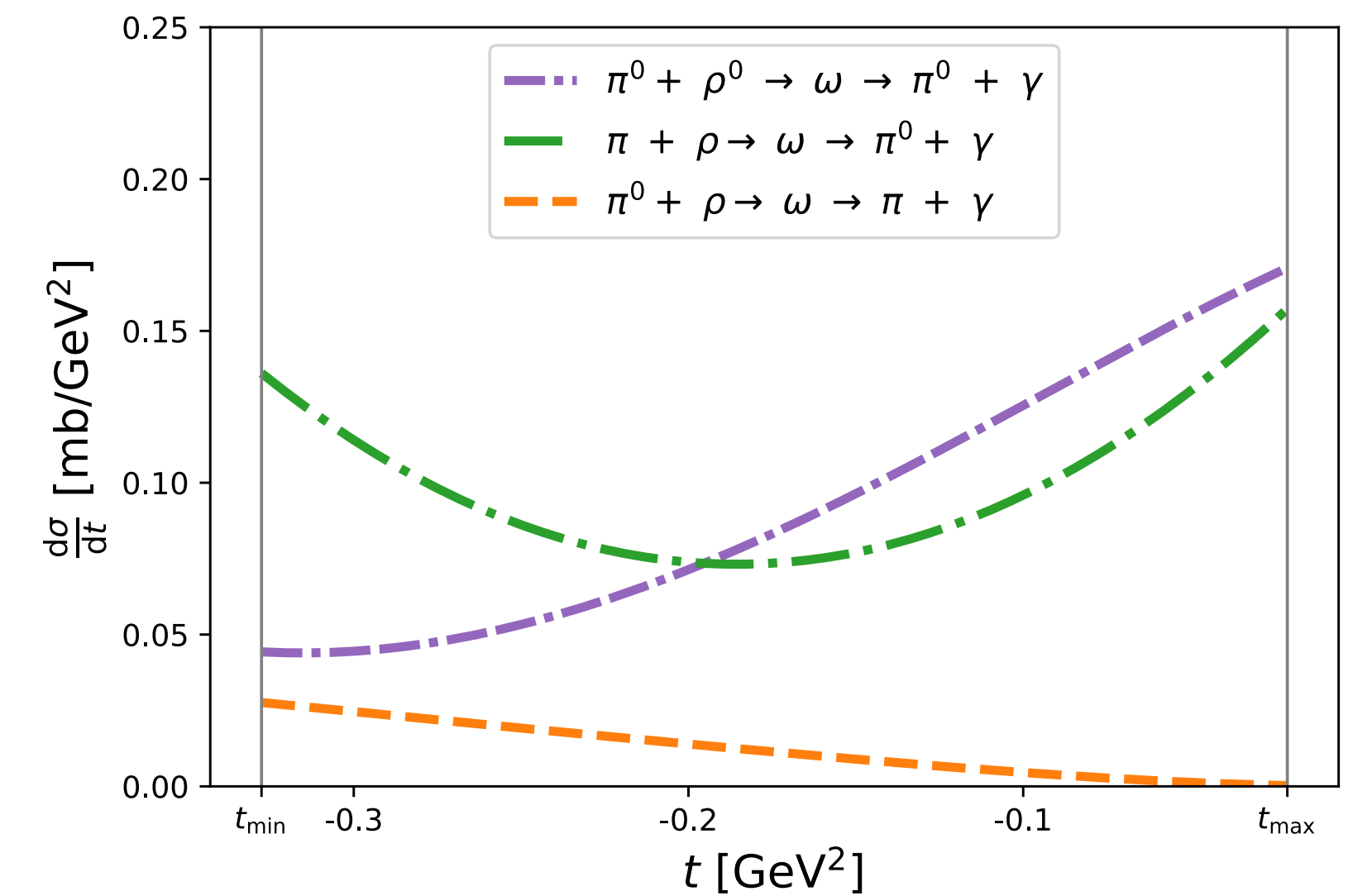
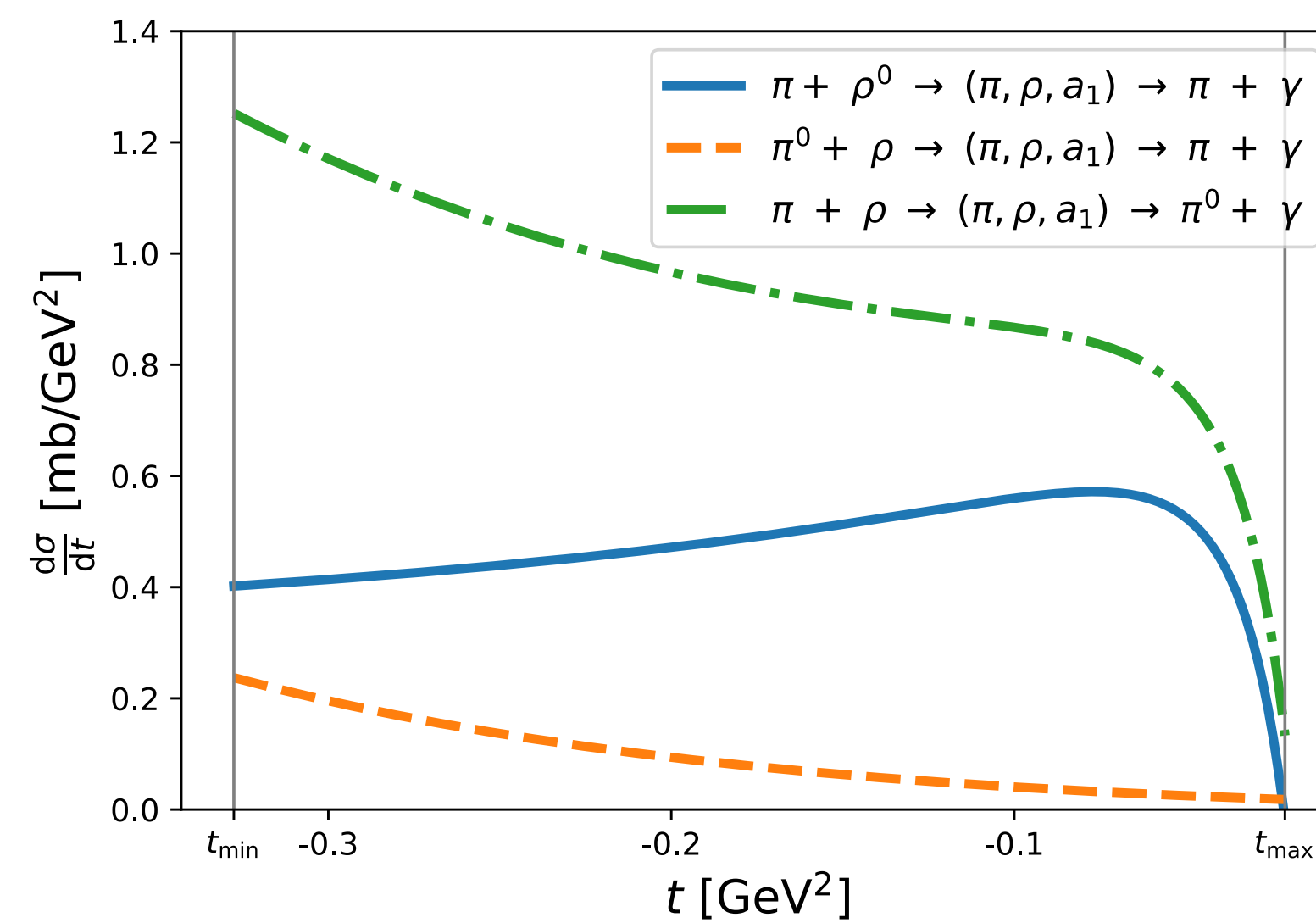
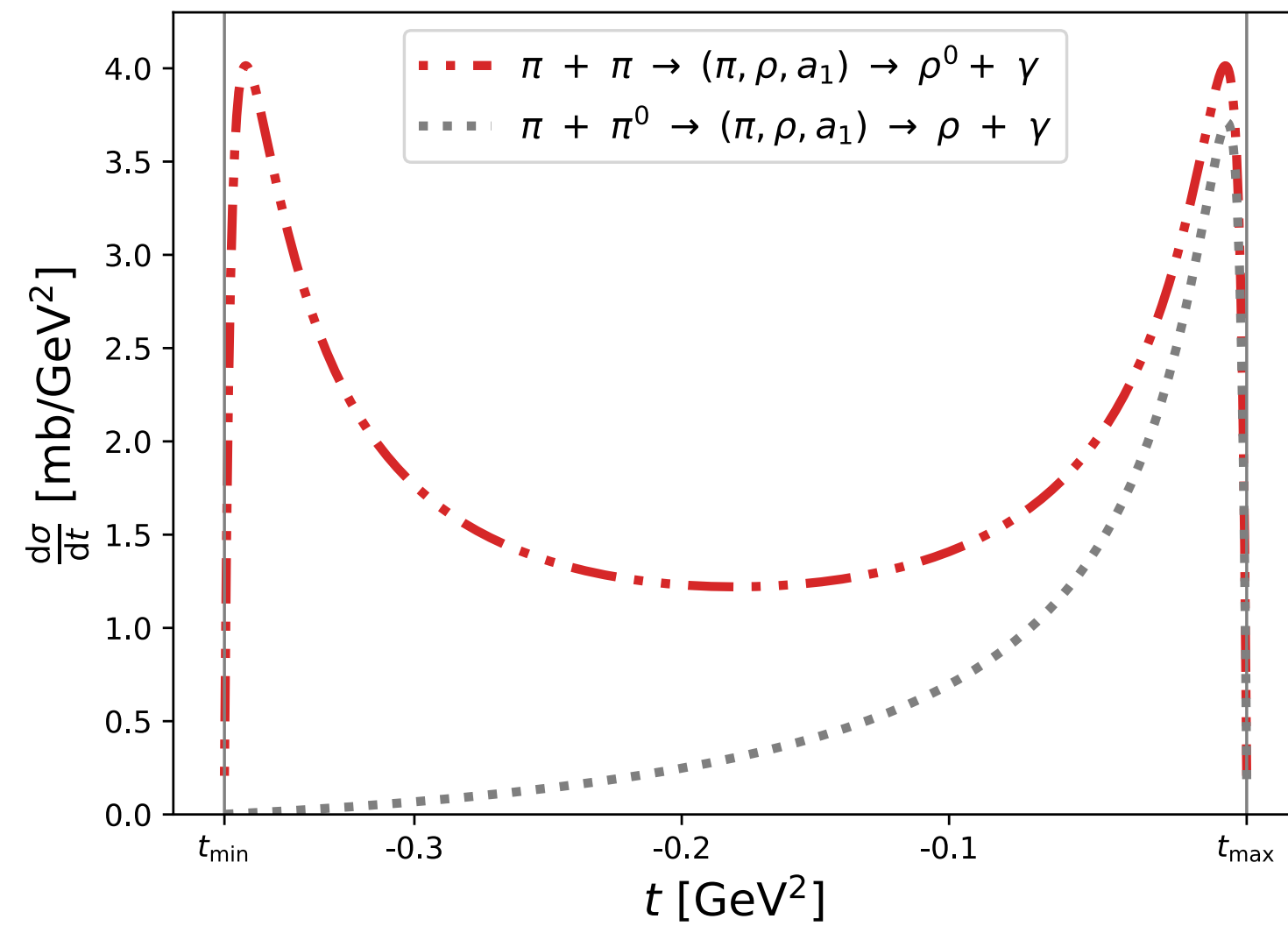
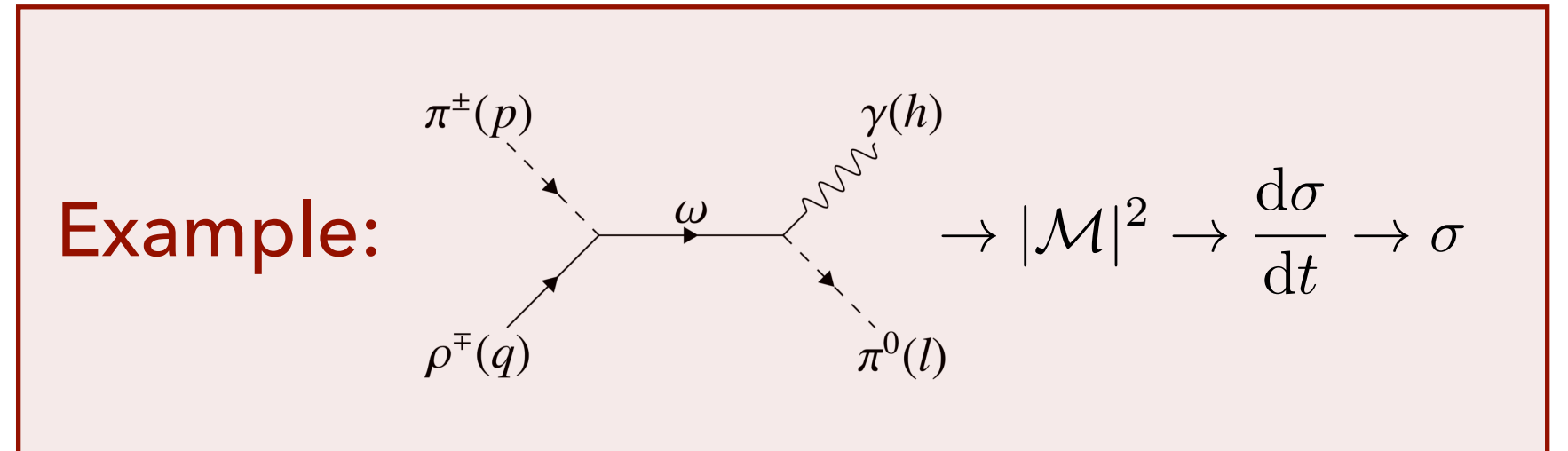
$$\pi^\pm + \rho^\mp \rightarrow \pi^0 + \gamma$$

Turbide et al.: Int. J. Mod. Phys. A19 (2004)

# PHOTON PRODUCTION CROSS SECTIONS

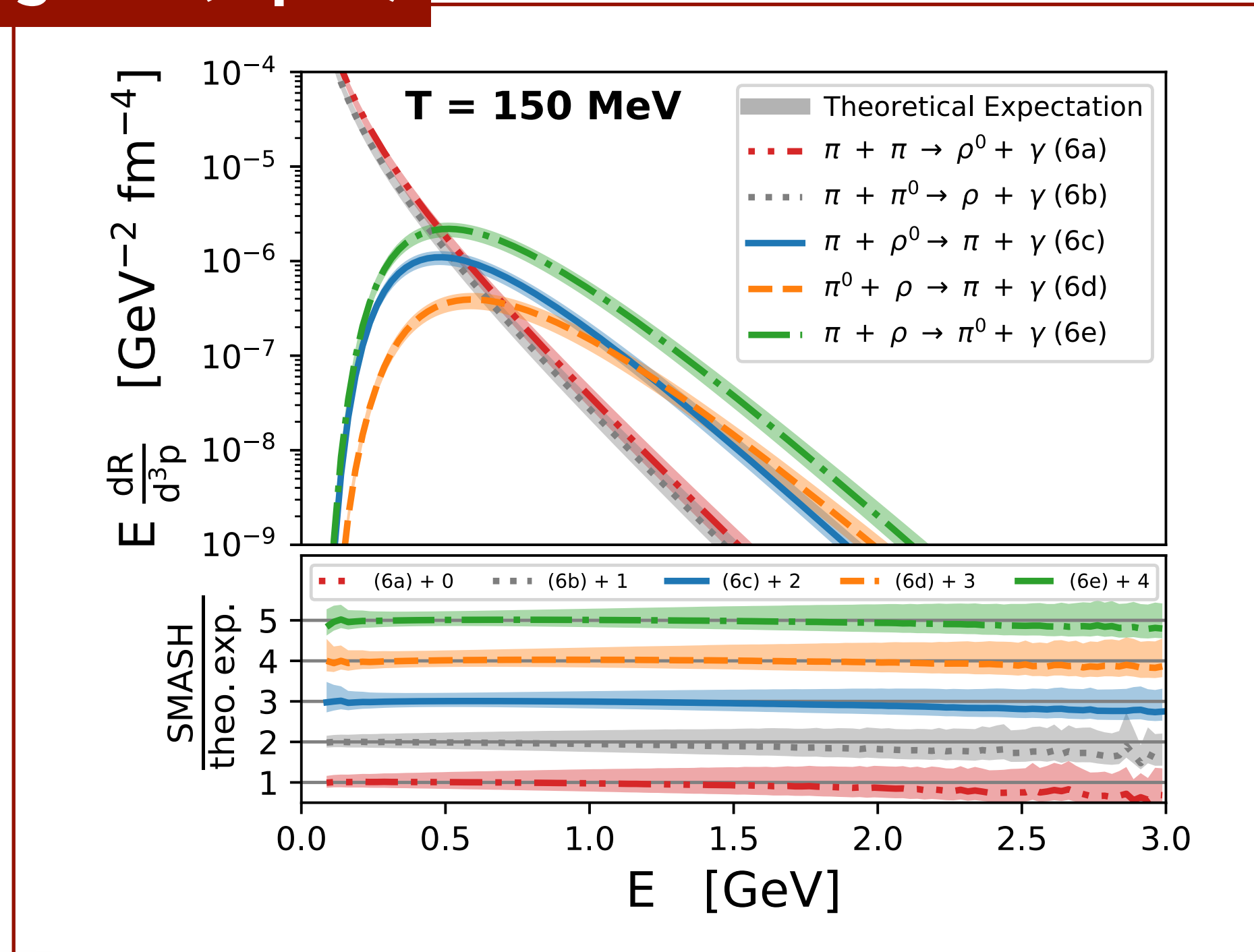
- Cross sections derived from scattering matrix elements
- Available and ready-to-use (C++):

<https://github.com/smash-transport/phoxtrot>

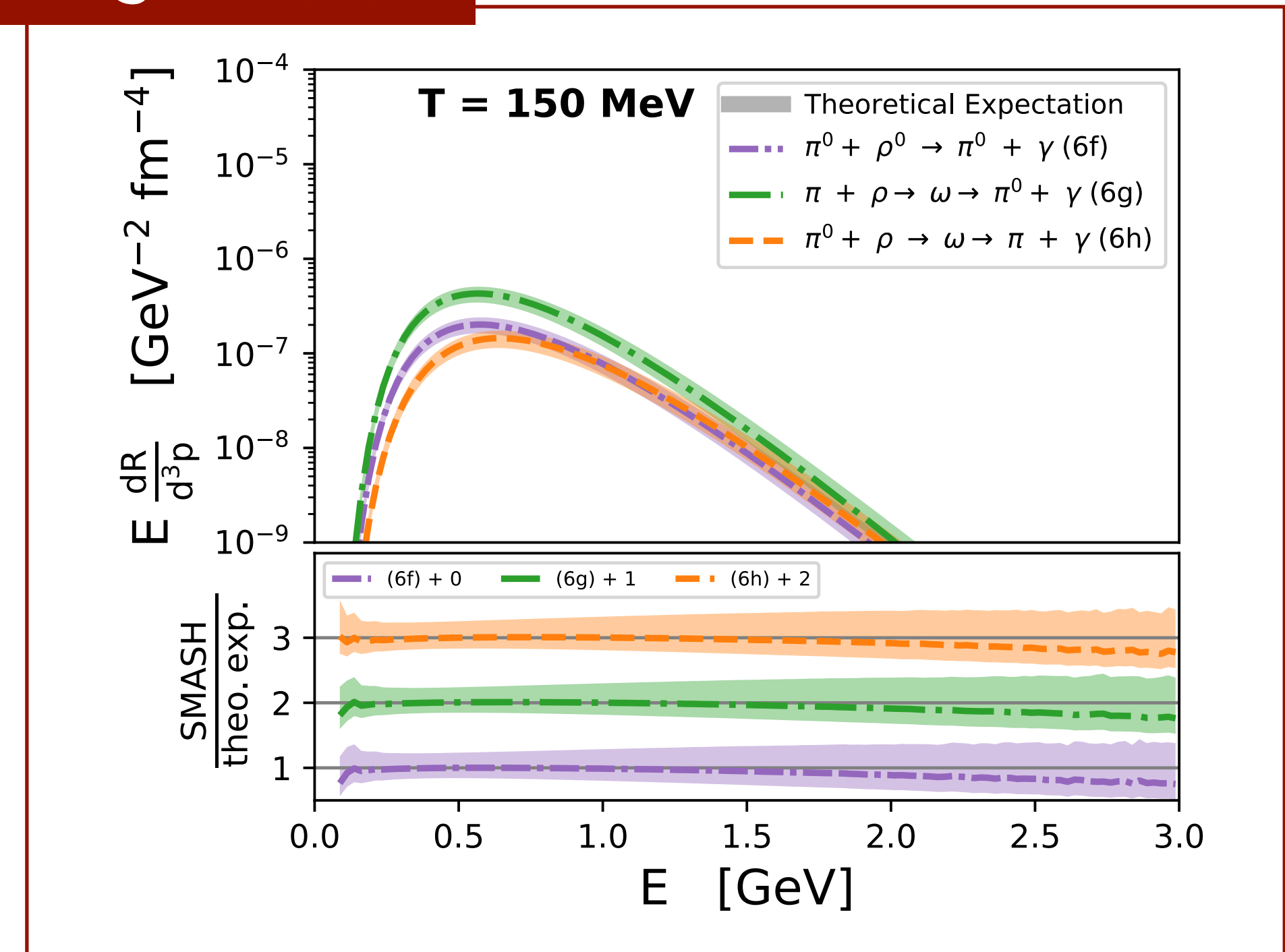


# PROOF OF CONCEPT I

## Exchange via ( $\pi, \rho, a_1$ )



## Exchange via ( $\omega$ )

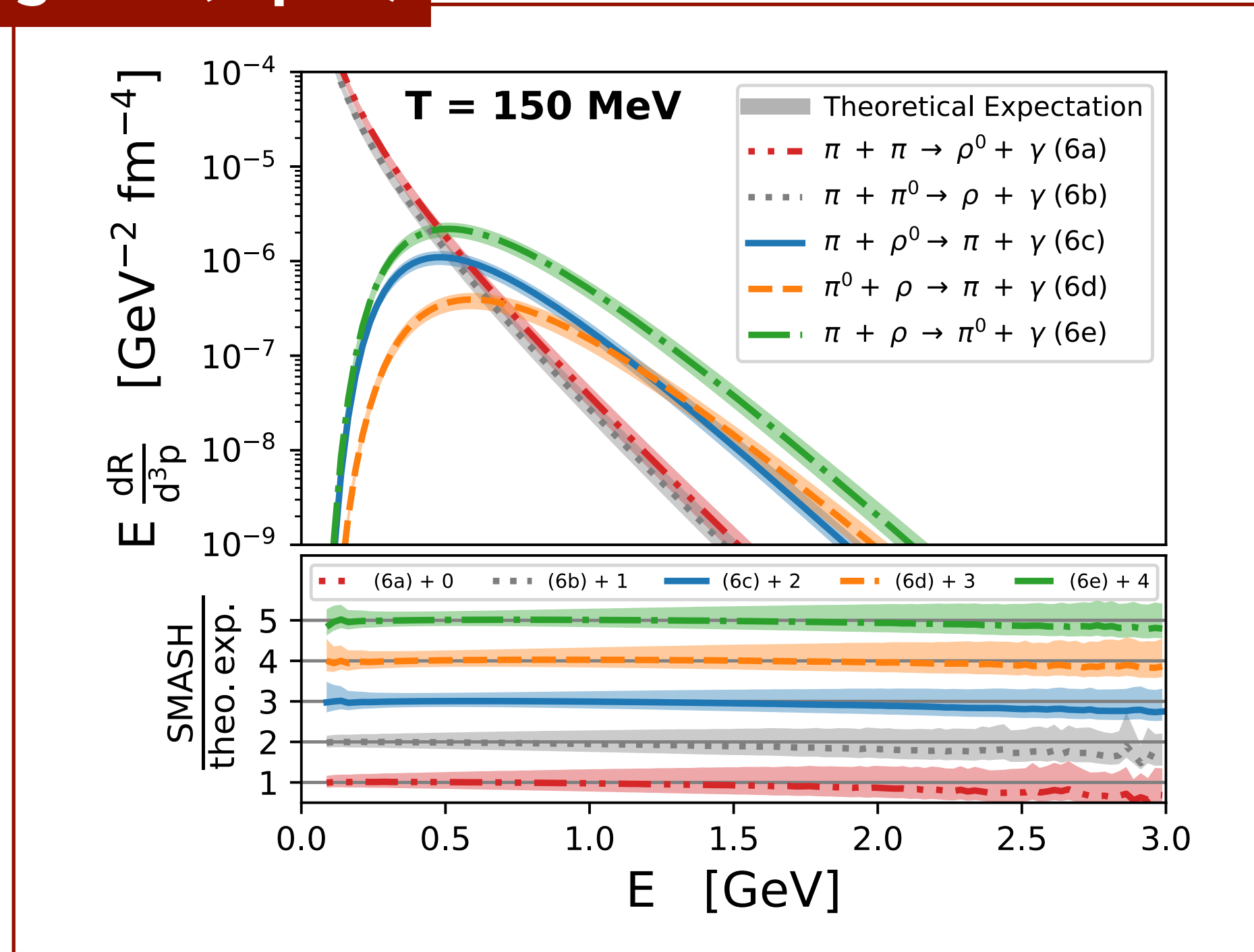


- **Thermal photon rate:** Number of photons produced per unit time and volume
- **SMASH setup:** Infinite matter simulation with  $\pi$  and  $\rho$  mesons in equilibrium
- Theoretical expectation nicely reproduced

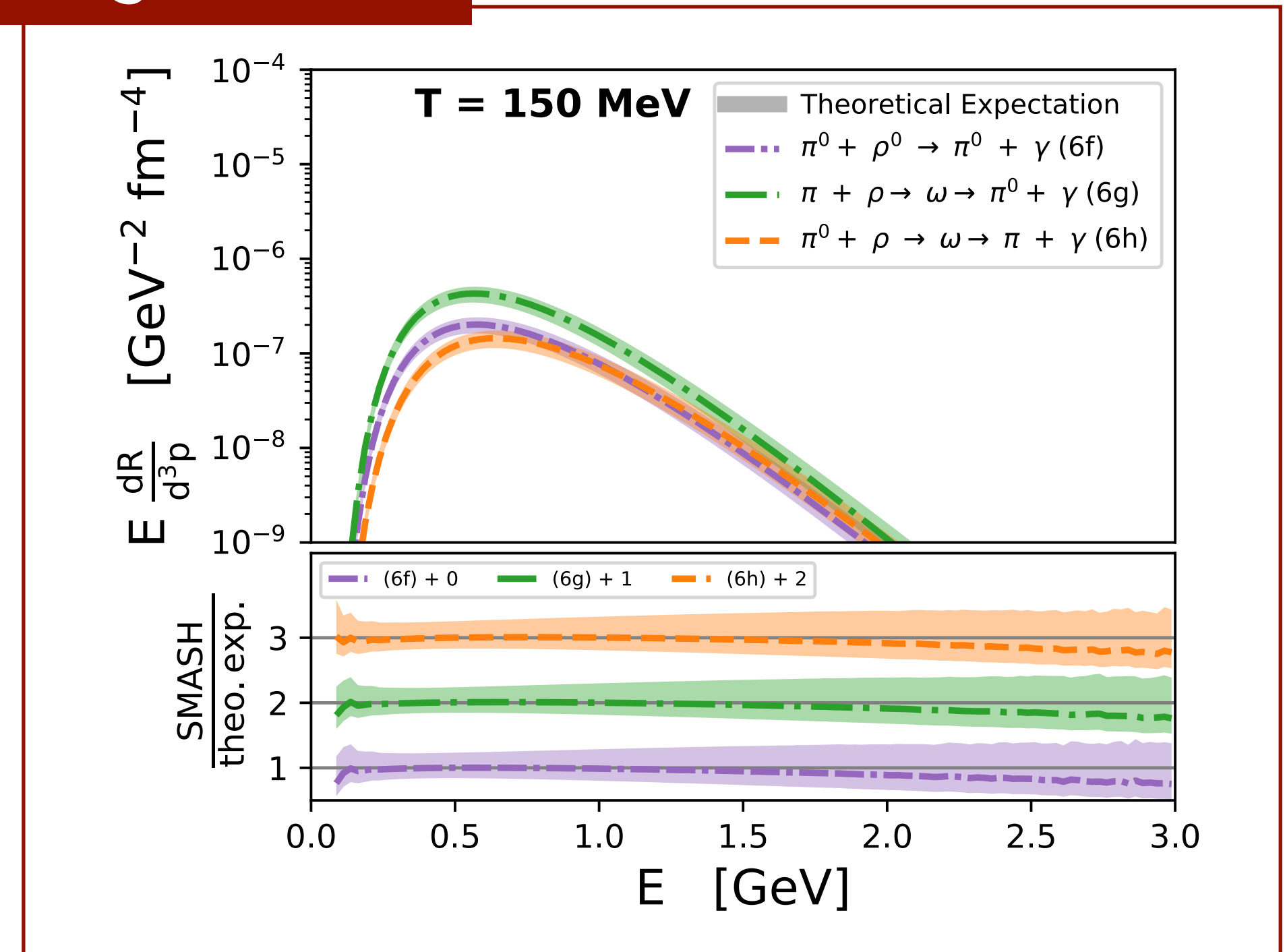
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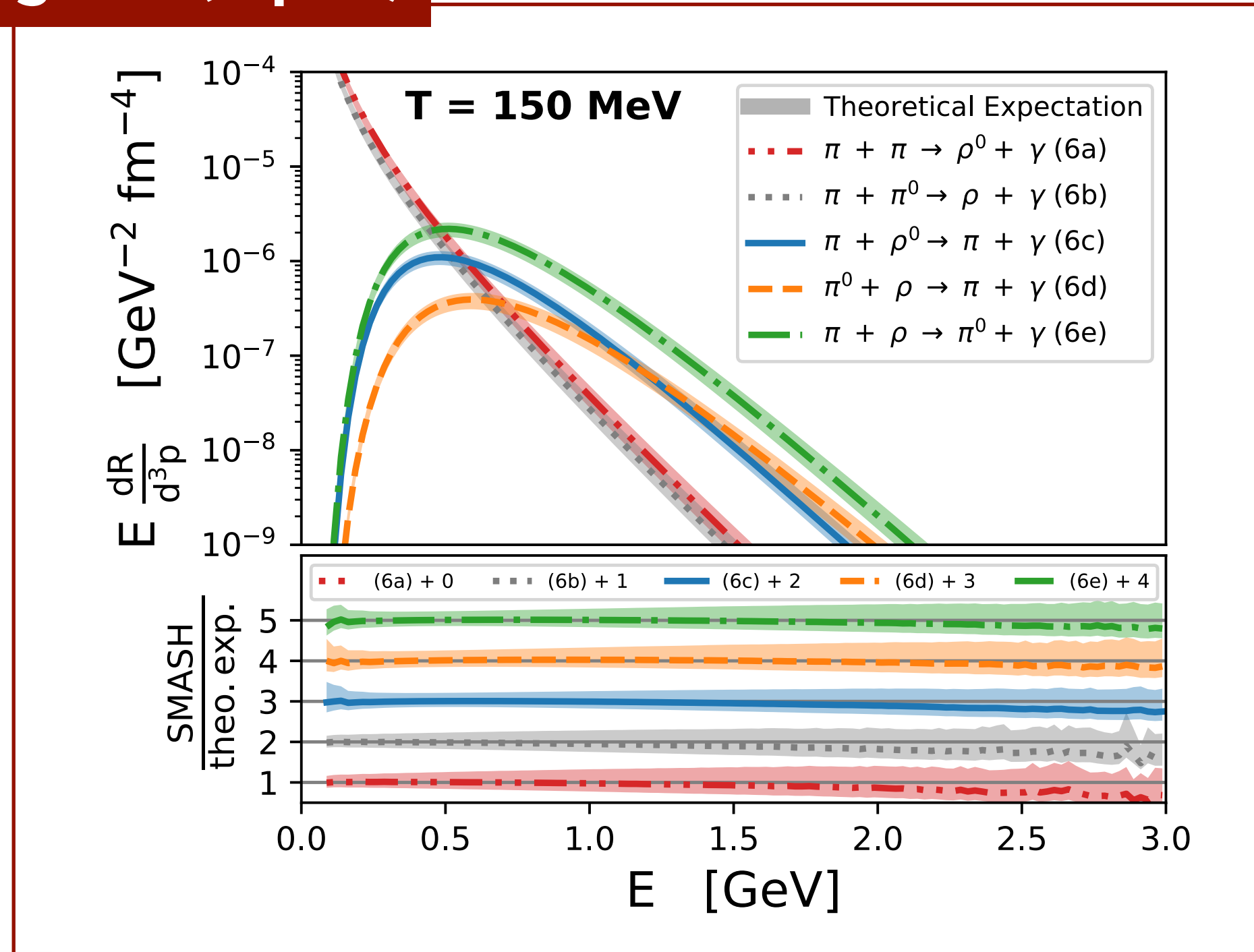


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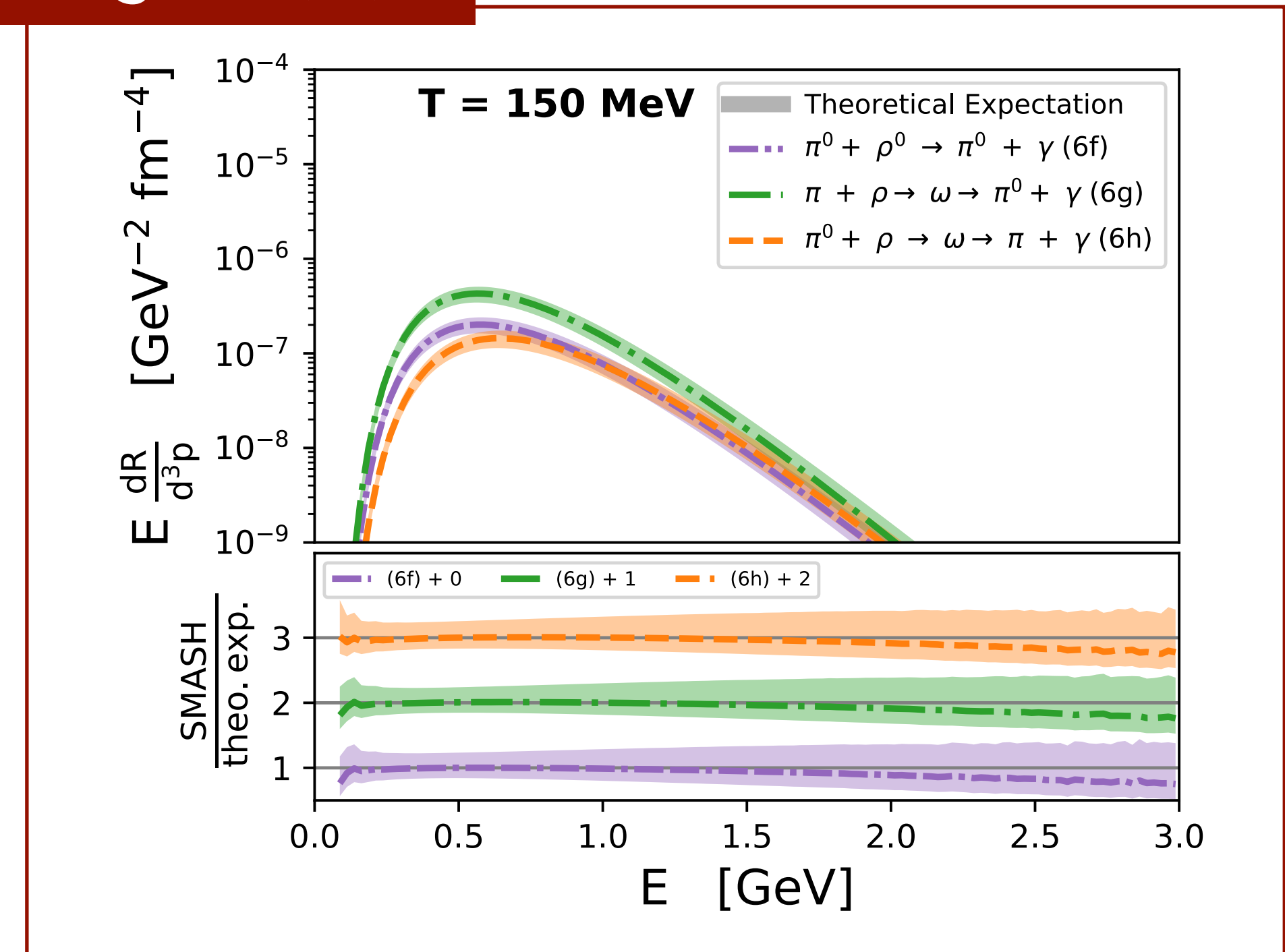
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► **From now on:** Combine channels with identical initial, final and mediating particles

# INTRODUCING FORM FACTORS

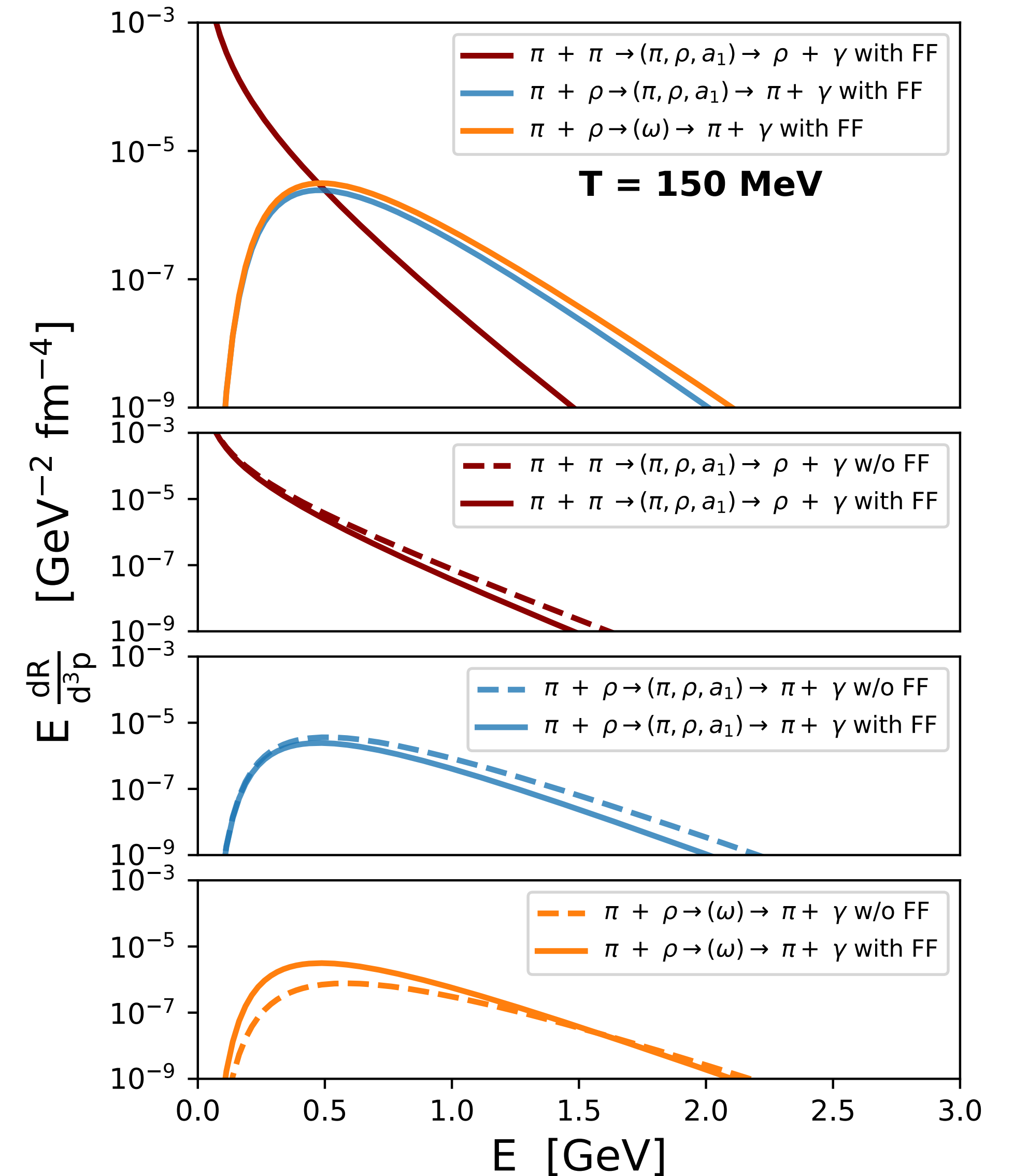
- Required to describe finite extend of fields at vertices
- Hadronic dipole form factor (FF)

## Exchange via $(\pi, \rho, a_1)$

- ▶ Reduction of photon production for low and high photon energies

## Exchange via $(\omega)$

- ▶ Increase for low high photon energies
- ▶ Reduction for high photon energies
- ▶ **Note:** Increased  $\pi$ - $\rho$ - $\omega$  coupling



Turbide et al.: Int. J. Mod. Phys. A19 (2004)

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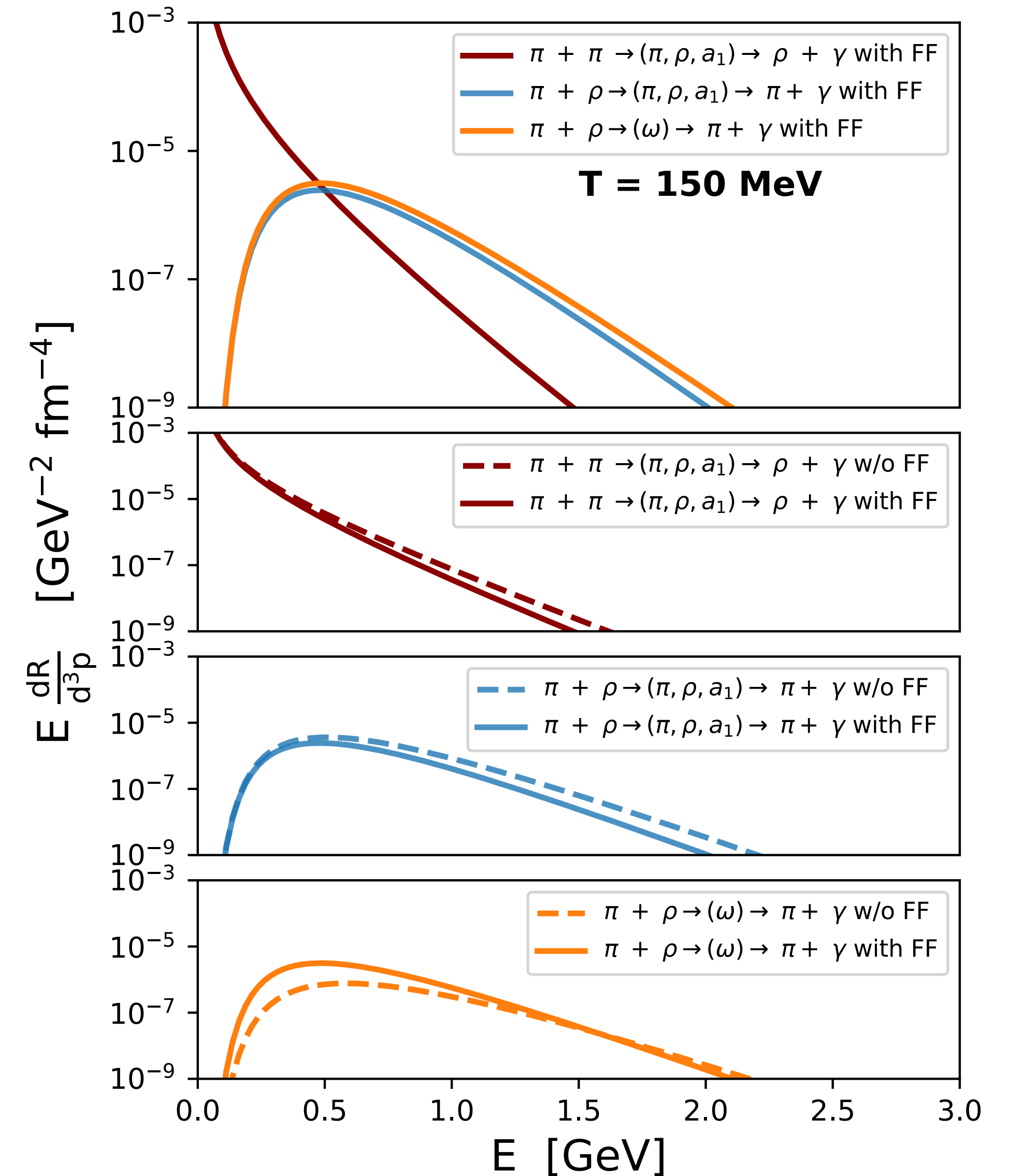
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## Exchange via ( $\omega$ )

- ▶ Increase for low high photon energies
- ▶ Reduction for high photon energies
- ▶ **Note:** Increased  $\pi$ - $\rho$ - $\omega$  coupling

➔ Form factors are important to describe photon production at intermediate energies

Turbide et al.: Int. J. Mod. Phys. A19 (2004)



# PROOF OF CONCEPT II

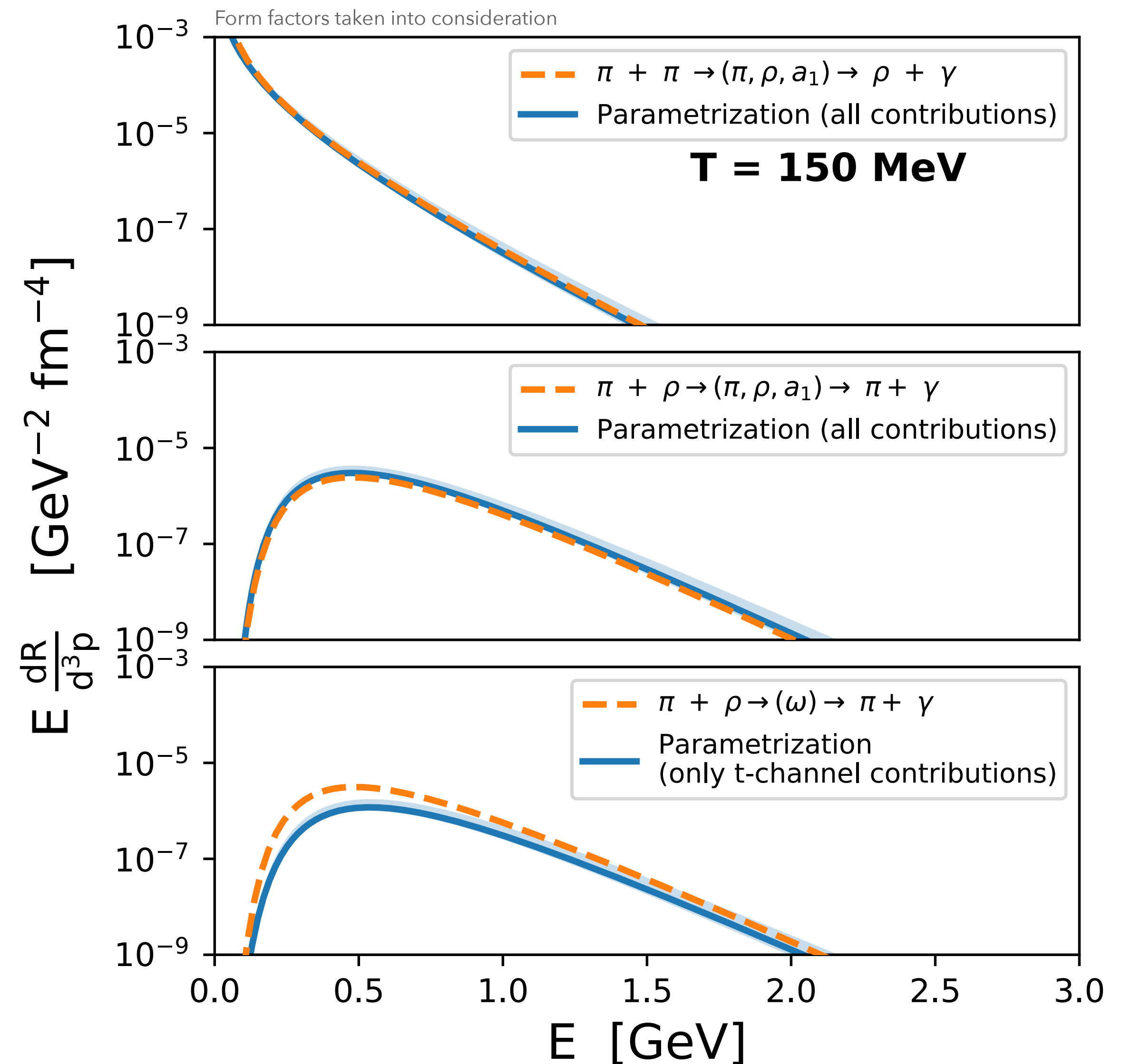
- Photon rate parametrization provided in [Turbide et al.: Int. J. Mod. Phys. A19 \(2004\)](#)
  - ▶ Applied in hydrodynamic simulations

## Exchange via ( $\pi, \rho, a_1$ )

- ▶ Excellent agreement at  $T = 150$  MeV within uncertainties

## Exchange via ( $\omega$ )

- ▶ SMASH provides significantly higher photon rates
- ▶ **Note:** Parametrization accounts for t-channel contributions only, SMASH contains t- and s-channel



# PROOF OF CONCEPT II



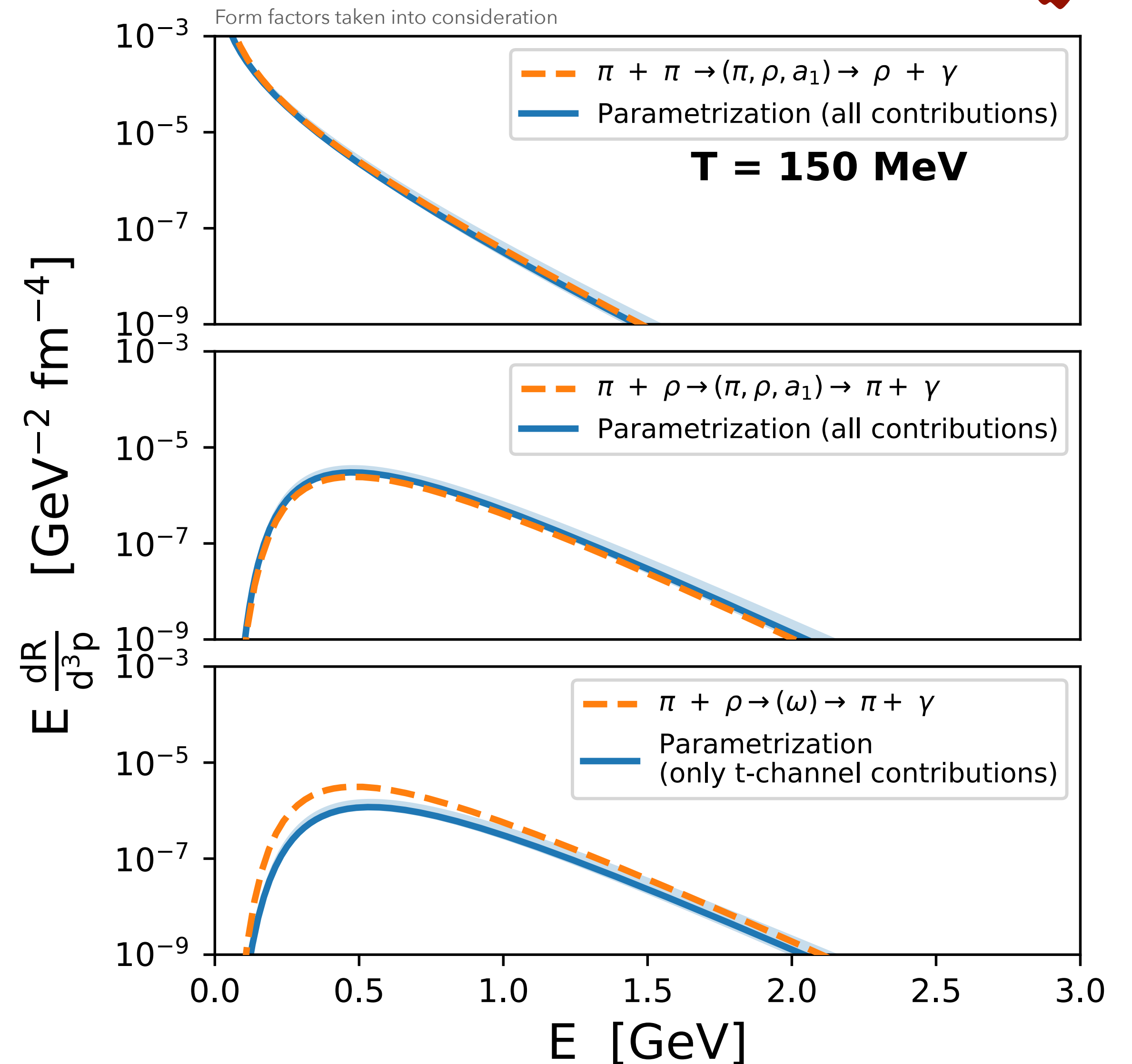
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# TEMPERATURE DEPENDENCE

- From now on:

Incoherently add ( $\pi, \rho, a_1$ )-mediated and ( $\omega$ )-mediated contributions for channels

$$\pi^0 + \rho^\pm \rightarrow \pi^\pm + \gamma \quad \text{and} \quad \pi^\pm + \rho^\mp \rightarrow \pi^0 + \gamma$$

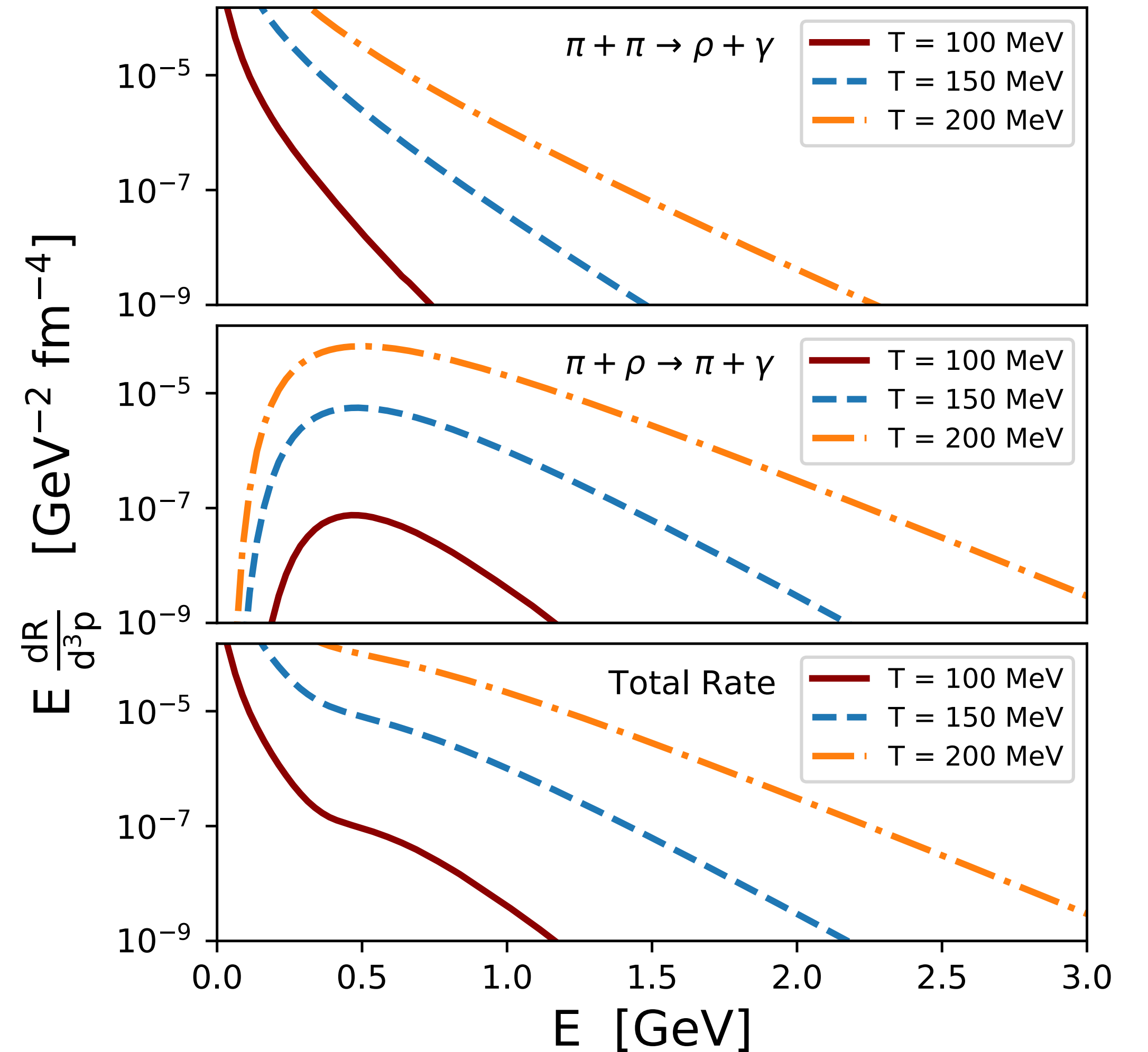
- Distinguish only between:

$$\pi + \pi \rightarrow \rho + \gamma \quad \text{and} \quad \pi + \rho \rightarrow \pi + \gamma,$$

independently of electric charge and mediator

## Observation

- Photon production clearly increases with rising temperatures
- $\approx 3$  orders of magnitude between  $T = 100$  MeV and  $T = 200$  MeV

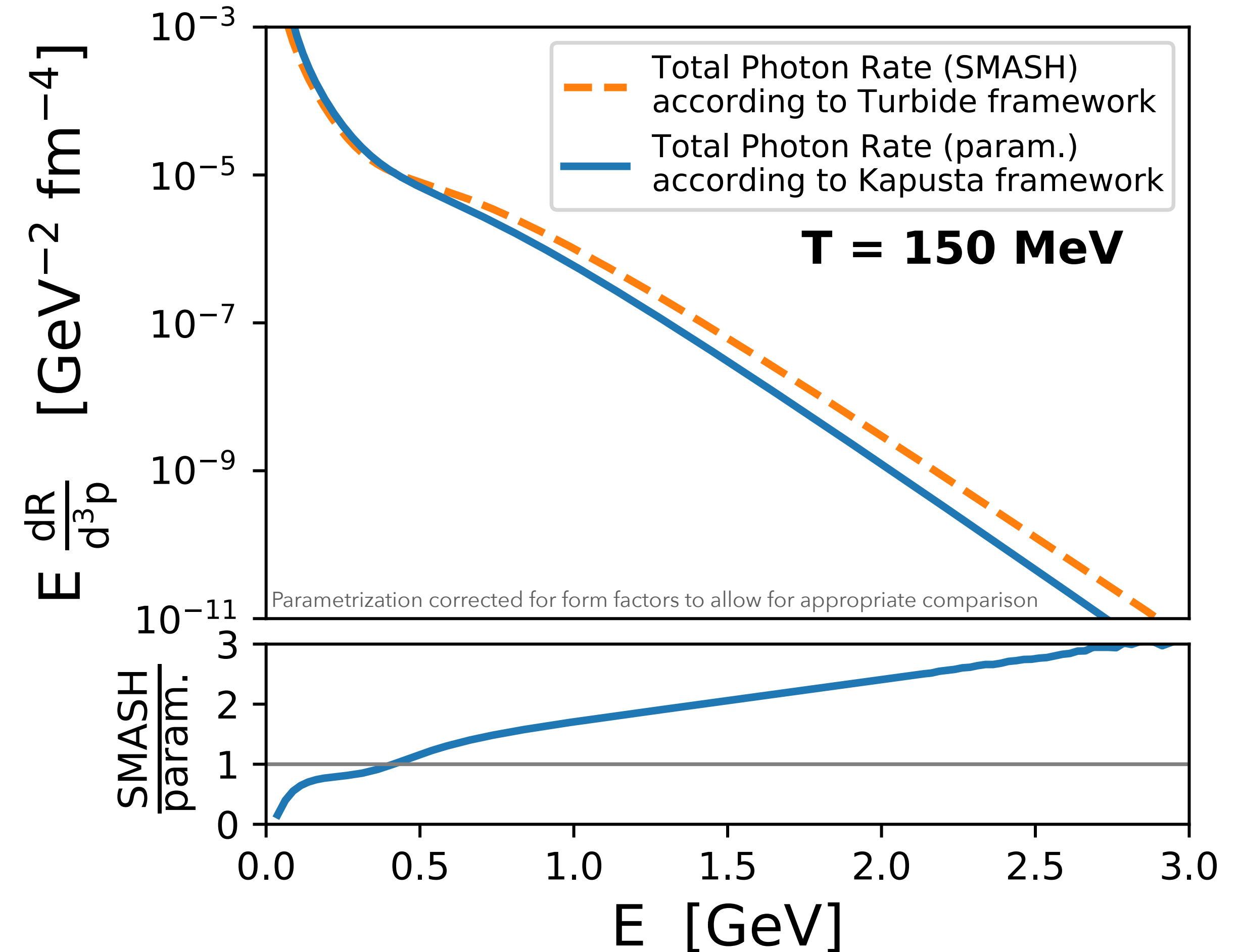


# QUANTIFYING THE DIFFERENCE TO PREVIOUS WORKS

- Photon production cross sections for  $\pi + \rho \rightarrow \pi + \gamma$  and  $\pi + \pi \rightarrow \rho + \gamma$  provided in [Kapusta et al.: Nucl.Phys. A544 \(1992\)](#)
  - ▶ **Major difference:** No  $\omega$  and  $a_1$  degree of freedom

## Observation

- ▶ SMASH < Kapusta for  $E_\gamma \lesssim 0.4$  GeV and vice versa
- ▶  $\omega$  and  $a_1$  processes contribute significantly  
Also identified by: [Holt et al.: Nuc. Phys. A 945 \(2016\)](#)
- ▶ Kapusta framework well applicable for photon production at low  $E_\gamma$
- ▶ More involved framework necessary for intermediate and high  $E_\gamma$



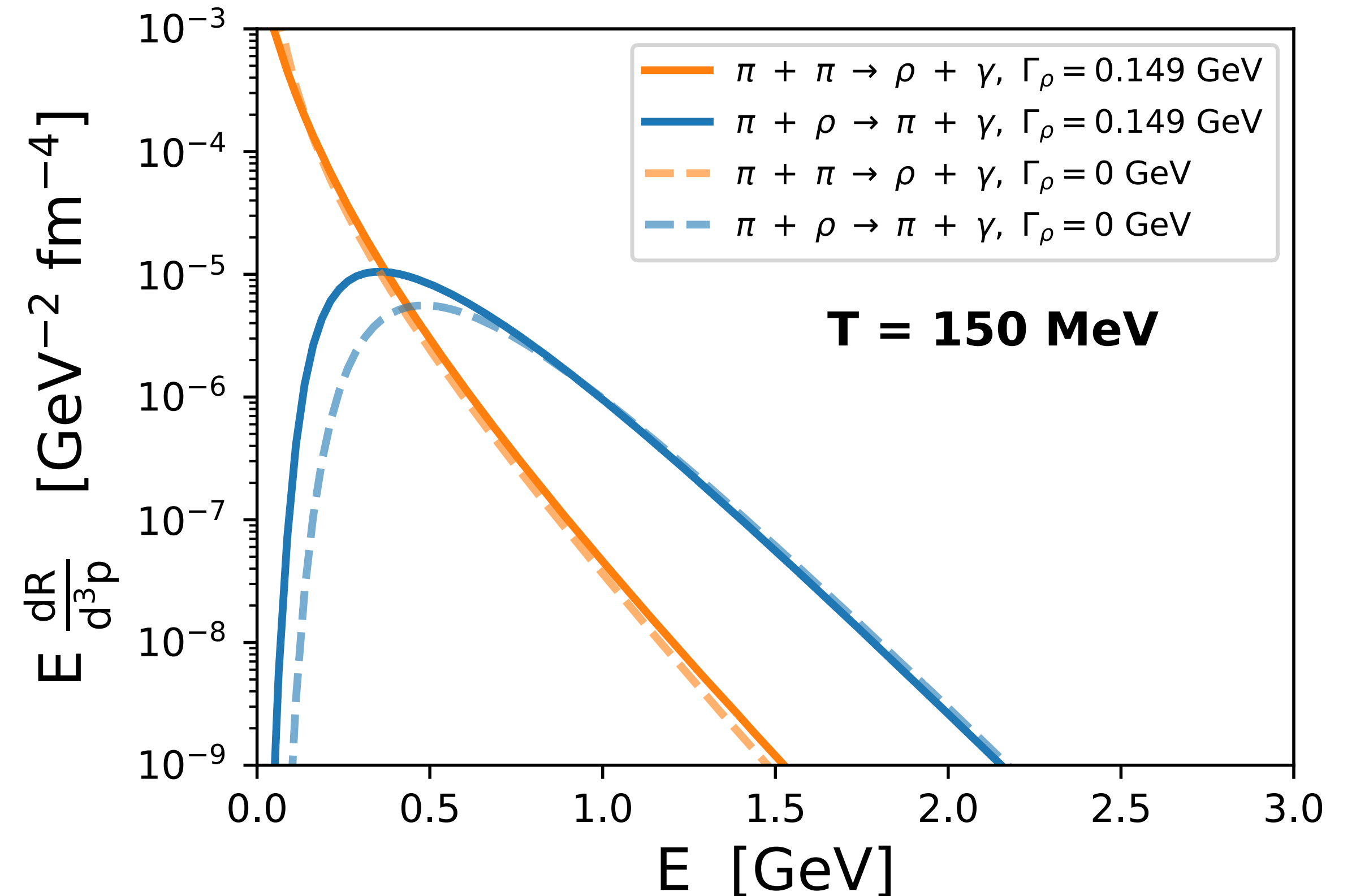
[H. Nadeau et al.: Phys. Rev. C45 \(1992\)](#)

# EXTENSION TO FINITE-WIDTH $\rho$ MESONS

- Up to now:  $\Gamma_\rho = 0$  GeV
- In reality:  $\Gamma_\rho = 0.149$  GeV
- Extend framework to account for finite width
  - ▶ Electromagnetic current not conserved anymore for processes mediated by  $\rho$  mesons
  - ▶ **Assumption:** In/outgoing and mediating  $\rho$  mesons have identical masses  
=> Current conservation is enforced

## Observation

- ▶ Significant enhancement of photon production for  $E_\gamma \leq 0.7$  GeV while  $\Gamma_\rho = 0.149$  GeV
- ▶ Finite  $\rho$  width should not be neglected



## Summary

- Cross sections for direct photon production in hadronic scatterings successfully derived
  - ▶ Available at <https://github.com/smash-transport/phoxtrot>
- Photon production implemented into hadronic transport approach (SMASH)
  - ▶ Good agreement with theoretical expectations and parametrization of thermal photon rate
- $\omega$  and  $a_1$  -mediated processes contribute significantly
- Clear enhancement of photon production, especially for low  $E_\gamma$ , once  $\Gamma_\rho = 0.149$  GeV

## Outlook

- Assess importance of non-equilibrium hadronic direct photon production by means of hybrid approach
  - ▶ MUSIC + SMASH with identical photon production framework

**BACKUP**

# EFFECTIVE LAGRANGIAN

$$\begin{aligned}
 \mathcal{L} = & \underbrace{\frac{1}{8} F_\pi^2 \text{Tr} (D_\mu U D^\mu U^\dagger)}_{\text{kinetic term \& interaction PS}} + \underbrace{\frac{1}{8} F_\pi^2 \text{Tr} (M (U + U^\dagger - 2))}_{\text{mass term PS}} - \underbrace{\frac{1}{2} \text{Tr} (F_{\mu\nu}^L F^{L\mu\nu} + F_{\mu\nu}^R F^{R\mu\nu})}_{\text{kinetic term \& interaction of V and AV}} \\
 & + \underbrace{m_0^2 \text{Tr} (A_\mu^L A^{L\mu} + A_\mu^R A^{R\mu})}_{\text{mass term V and AV}} + \underbrace{\gamma \text{Tr} (F_{\mu\nu}^L U F^{R\mu\nu} U^\dagger) - i\xi \text{Tr} (D_\mu U D_\nu U^\dagger F^{L\mu\nu} + D_\mu U^\dagger D_\nu U F^{R\mu\nu})}_{\text{higher order interaction of PS, V and AV}} \\
 & - \underbrace{\frac{2em_0^2}{g_0} B^\mu \text{Tr} (Q (A_\mu^L + A_\mu^R)) - \frac{1}{4} (\partial_\mu B^\nu - \partial_\nu B^\mu)^2 + \frac{2e^2 m_0^2}{g_0^2} B_\mu B^\mu \text{Tr} (Q^2)}_{\text{electromagnetic interaction of PS, V, AV and } \gamma} \\
 & + \underbrace{g_{VV\psi} \varepsilon_{\mu\nu\alpha\beta} \text{Tr} [\partial^\mu V^\nu \partial^\alpha V^\beta \psi]}_{\text{Wess-Zumino Term for V-V-PS-vertex}}
 \end{aligned}$$

PS = pseudoscalar mesons  
 V = vector mesons  
 AV = axial vector mesons

Turbide et al.: Int.J.Mod.Phys. A19 (2004)

# FINITE-WIDTH $\rho$ AND CONTACT TERM

- In case of finite-width  $\rho$ :

- EM current not conserved:

$$\partial_\mu J^\mu \neq 0$$

- $\Delta = \frac{m_\rho^2 - u}{M_\rho^2 - u} \neq 1$  while  $m_\rho \neq M_\rho$

- Treatment in SMASH:  $m_\rho = M_\rho$

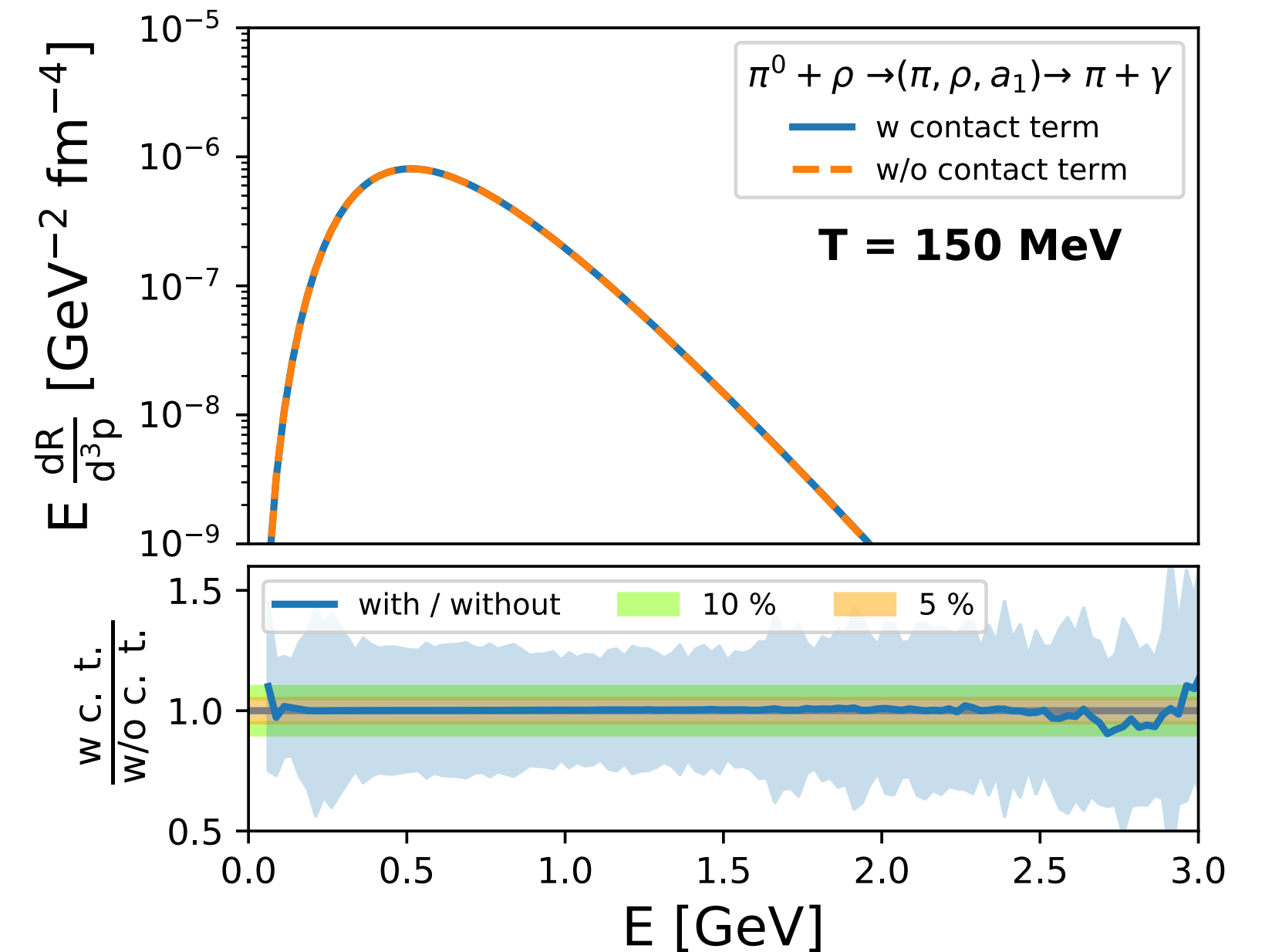
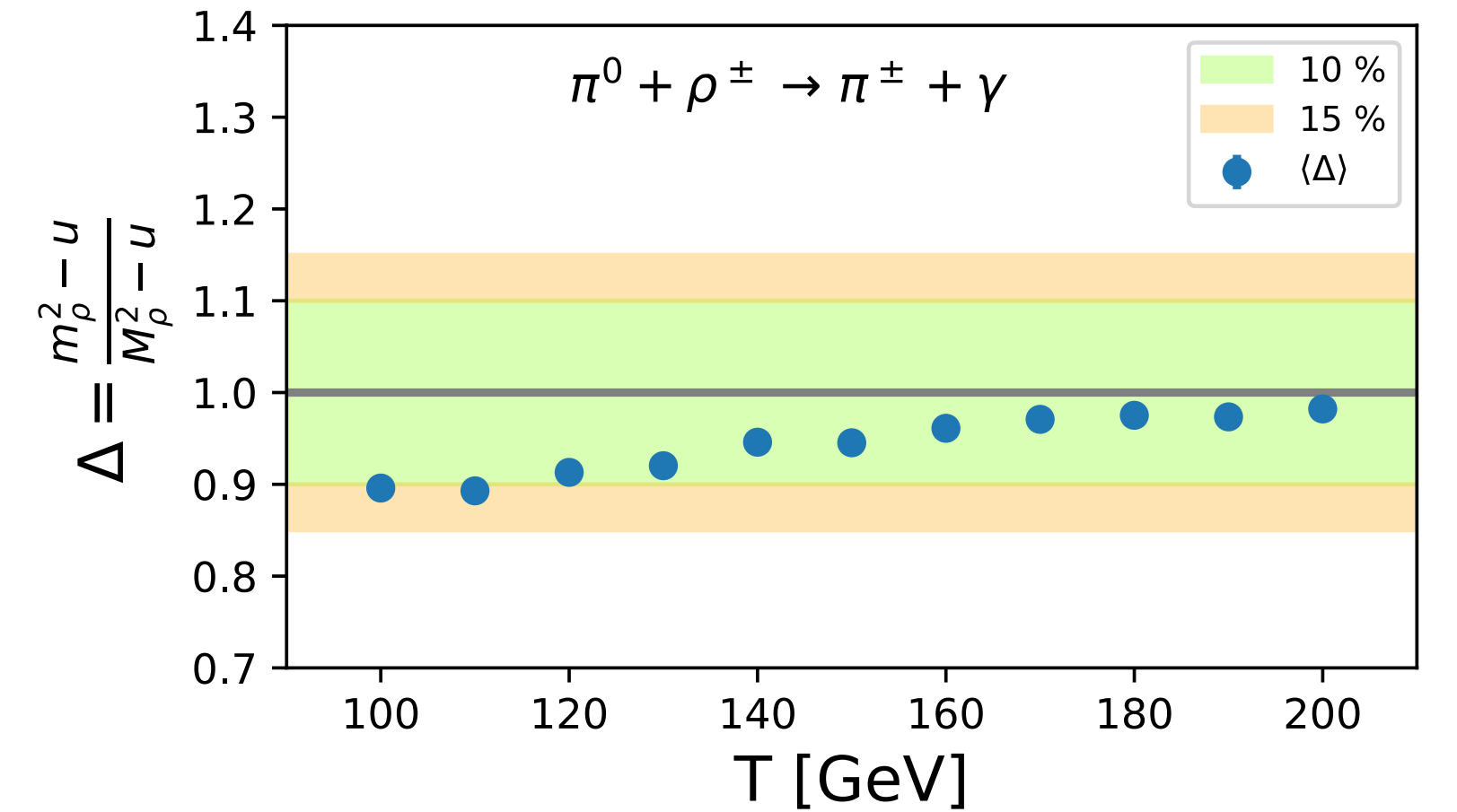
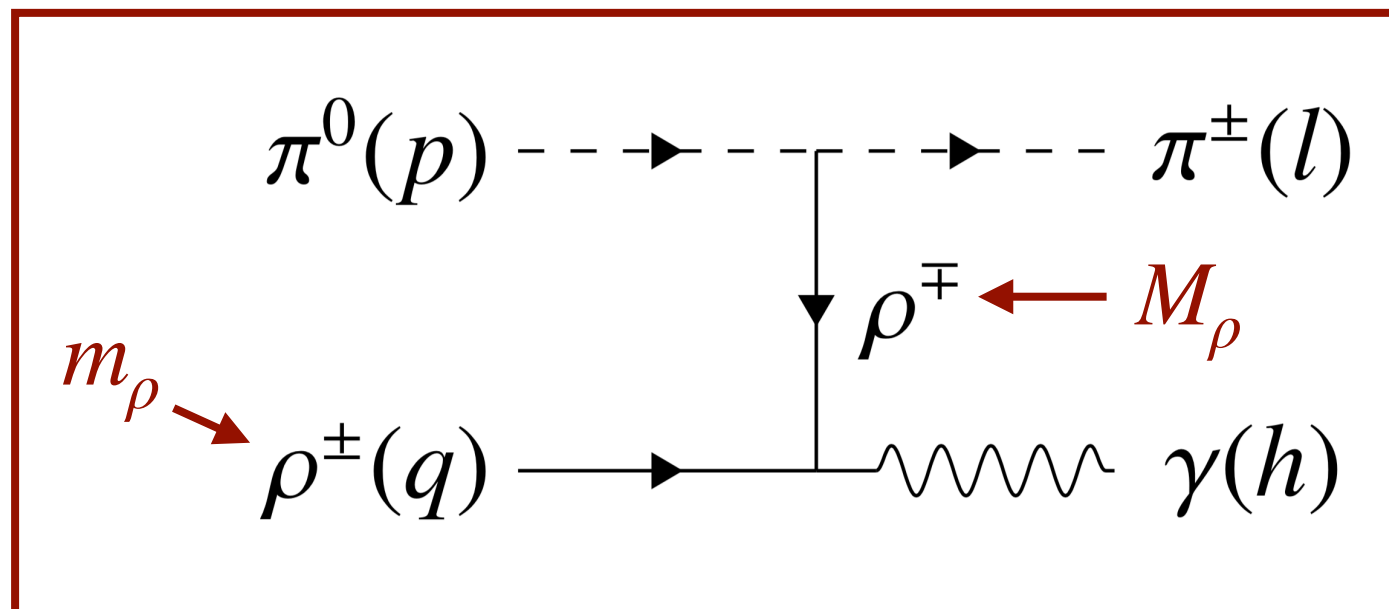
- Mass sampled from spectral function
- Systematic uncertainty of the model

## 2 Assessments

- Benchmark deviation of  $\Delta$  from 1 with
  - Assume  $M_\rho = 0.776$  GeV
- Construct contact term to restore current conservation
  - Enforce  $k_\mu (\mathcal{M}^\mu + \mathcal{M}_c^\mu) = 0$  while  $k_\mu \mathcal{M}^\mu \neq 0$

## Observation

- $\Delta$  differs at most 11% from unity
- Contact term has no effect on photon rate
- Assumption  $m_\rho = M_\rho$  is justified



# THERMAL PHOTON RATE

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Analytic formula:

$$E \frac{dR}{d^3p} = N \int (2\pi)^4 \delta^4(p_A + p_B - p_C - p) |\mathcal{M}|^2 f(E_A) f(E_B) (1 + \varepsilon f(E_C)) \\ \times \frac{1}{2(2\pi)^3} \frac{d^3p_A}{2E_A(2\pi)^3} \frac{d^3p_B}{2E_B(2\pi)^3} \frac{d^3p_C}{2E_C(2\pi)^3}$$

In the case of Boltzmann statistics:

$$E \frac{dR}{d^3p} = N \int \delta^4(p_A + p_B - p_C - p) |\mathcal{M}|^2 f(E_A) f(E_B) f(E_C) \frac{d^3p_A d^3p_B d^3p_C}{16(2\pi)^8}$$

Photon rate from SMASH:

$$E \frac{dR}{d^3p} = E \frac{dN}{4\pi p^2 dp \Delta t V} = \frac{1}{4\pi E \Delta t V} \frac{dN}{dE}$$

# FORM FACTOR

- Fourier Transform of charge distribution inside hadrons:

$$\hat{F}(q) = \int e^{-iqx} \rho(x) d^3x$$

- Parametrization as Hadronic Dipole Form Factor:

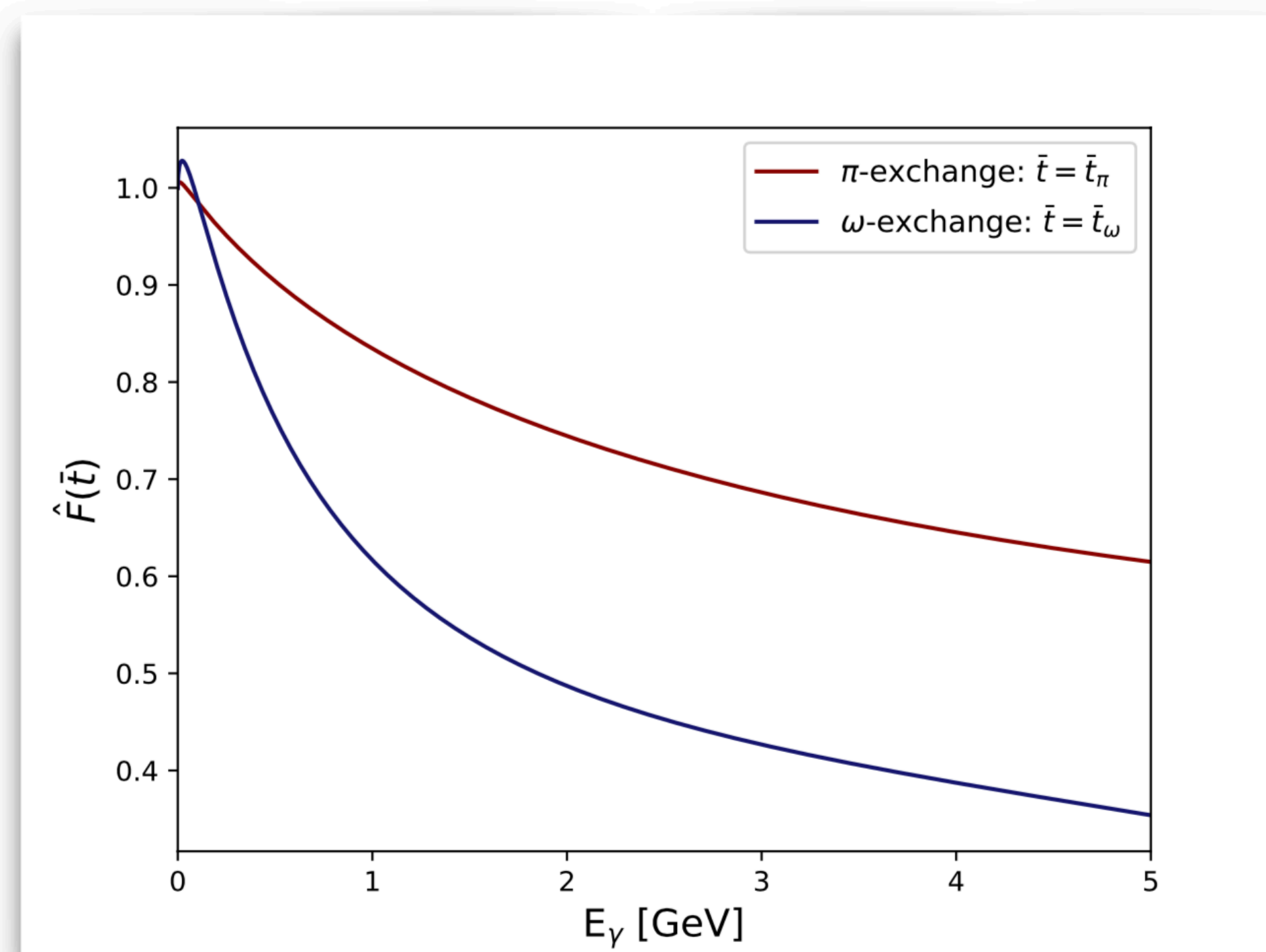
$$\hat{F}(E_\gamma) = \frac{2\Lambda^2}{2\Lambda^2 - \bar{t}(E_\gamma)}$$

- Application in SMASH:

$$\sigma_\gamma \rightarrow \hat{F}^4(E_\gamma) \cdot \sigma_\gamma$$

- Combination of channels:

$$\sigma_\gamma = \hat{F}_{(\pi\rho a_1)}^4 \sigma_{(\pi\rho a_1)} + \hat{F}_{(\omega)}^4 \sigma_{(\omega)}$$



$$\Gamma_{\omega \rightarrow \pi\gamma} \propto |\mathcal{M}|^2 \hat{F}^2$$

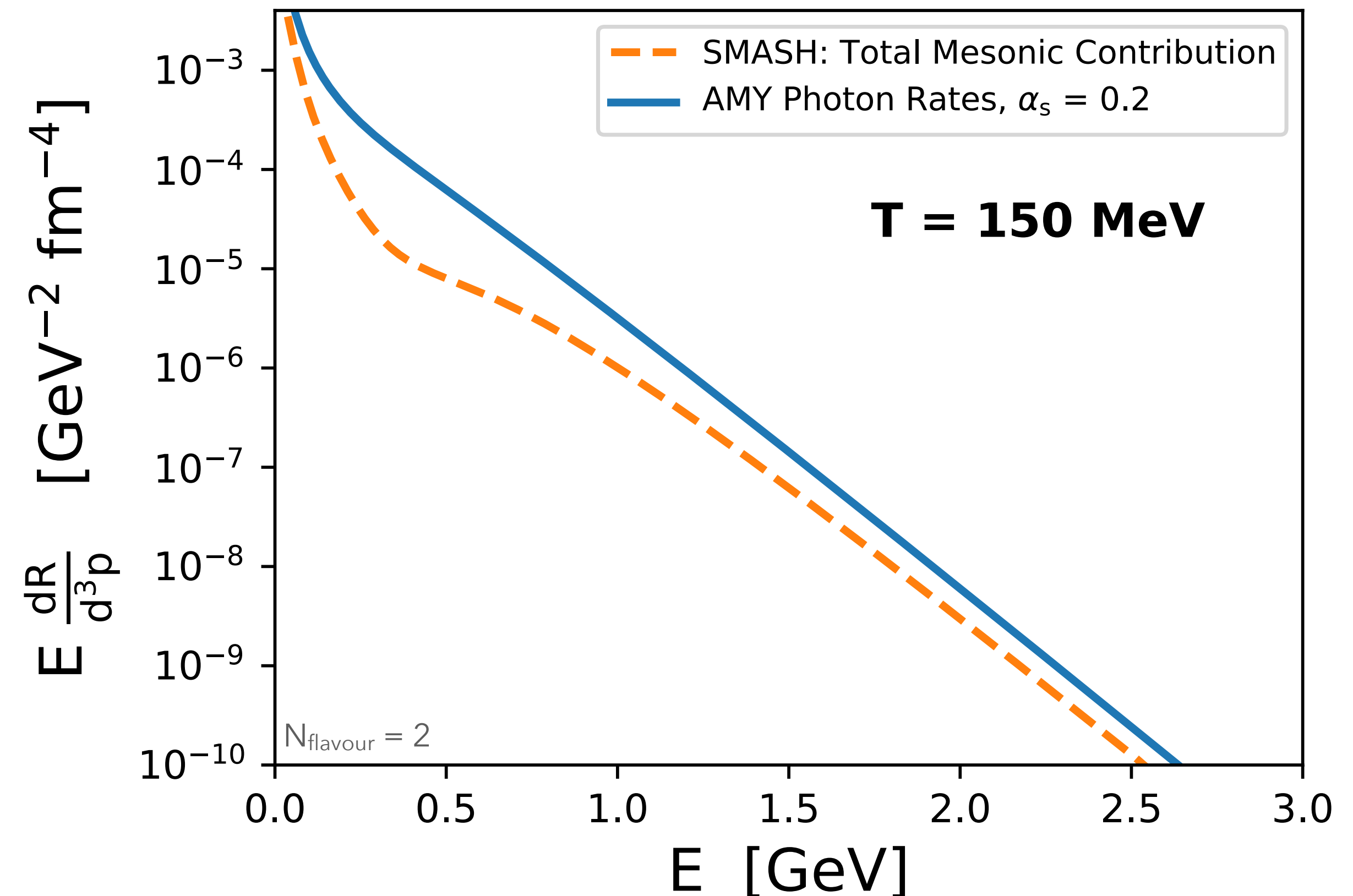
From experiment: 0.7174 MeV

# COMPARISON TO OTHER SOURCES OF DIRECT PHOTONS

- Qualitative comparison between **hadronic** SMASH photon rates and **partonic** AMY photon rates as in [Arnold et al.: JHEP12 \(2001\)](#)
  - ▶ Coincidence of hadronic and partonic rates observed in [Gale et al.: PRL114 \(2015\)](#)
  - ▶ A priori, neither framework expected to be viable close to  $T_c$

## Observation

- ▶ Both photon rates decrease with rising  $E_\gamma$
- ▶ AMY provides significantly higher rate, especially around  $E_\gamma \approx 0.5$  GeV
- ▶ **But:** SMASH lacks Bremsstrahlung, annihilation processes and LMP effect



[Arnold et al.: JHEP2001 \(2001\)](#)

# SIDENOTE: COMBINATION OF CHANNELS

## Exchange via $(\pi, \rho, a_1)$

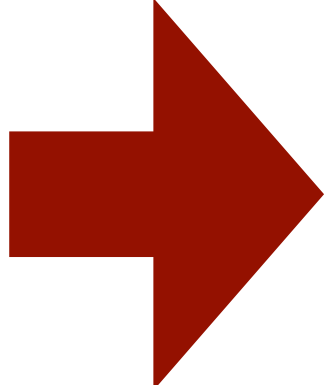
$$\pi^\pm + \rho^0 \rightarrow \pi^\pm + \gamma$$

$$\pi^0 + \rho^\pm \rightarrow \pi^\pm + \gamma$$

$$\pi^\pm + \rho^\mp \rightarrow \pi^0 + \gamma$$

$$\pi^\pm + \pi^\mp \rightarrow \rho^0 + \gamma$$

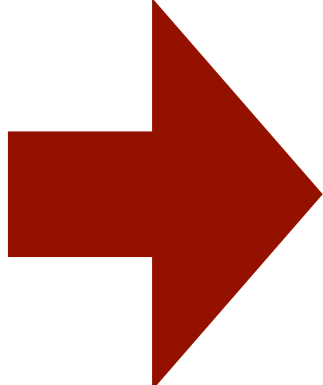
$$\pi^\pm + \pi^0 \rightarrow \rho^\pm + \gamma$$



## Exchange via $(\pi, \rho, a_1)$

$$\pi + \rho \rightarrow \pi + \gamma$$

$$\pi + \pi \rightarrow \rho + \gamma$$



## Exchange via $(\pi, \rho, a_1)$ and via $(\omega)$

$$\pi + \rho \rightarrow \pi + \gamma$$

$$\pi + \pi \rightarrow \rho + \gamma$$

## Exchange via $(\omega)$

$$\pi^0 + \rho^0 \rightarrow \pi^0 + \gamma$$

$$\pi^0 + \rho^\pm \rightarrow \pi^\pm + \gamma$$

$$\pi^\pm + \rho^\mp \rightarrow \pi^0 + \gamma$$

## Exchange via $(\omega)$

$$\pi + \rho \rightarrow \pi + \gamma$$