Photon Production in a Hadronic Transport Approach

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In collaboration with Juan M. Torres-Rincon, Jonas Rothermel, Niklas Ehlert, Charles Gale and Hannah Petersen

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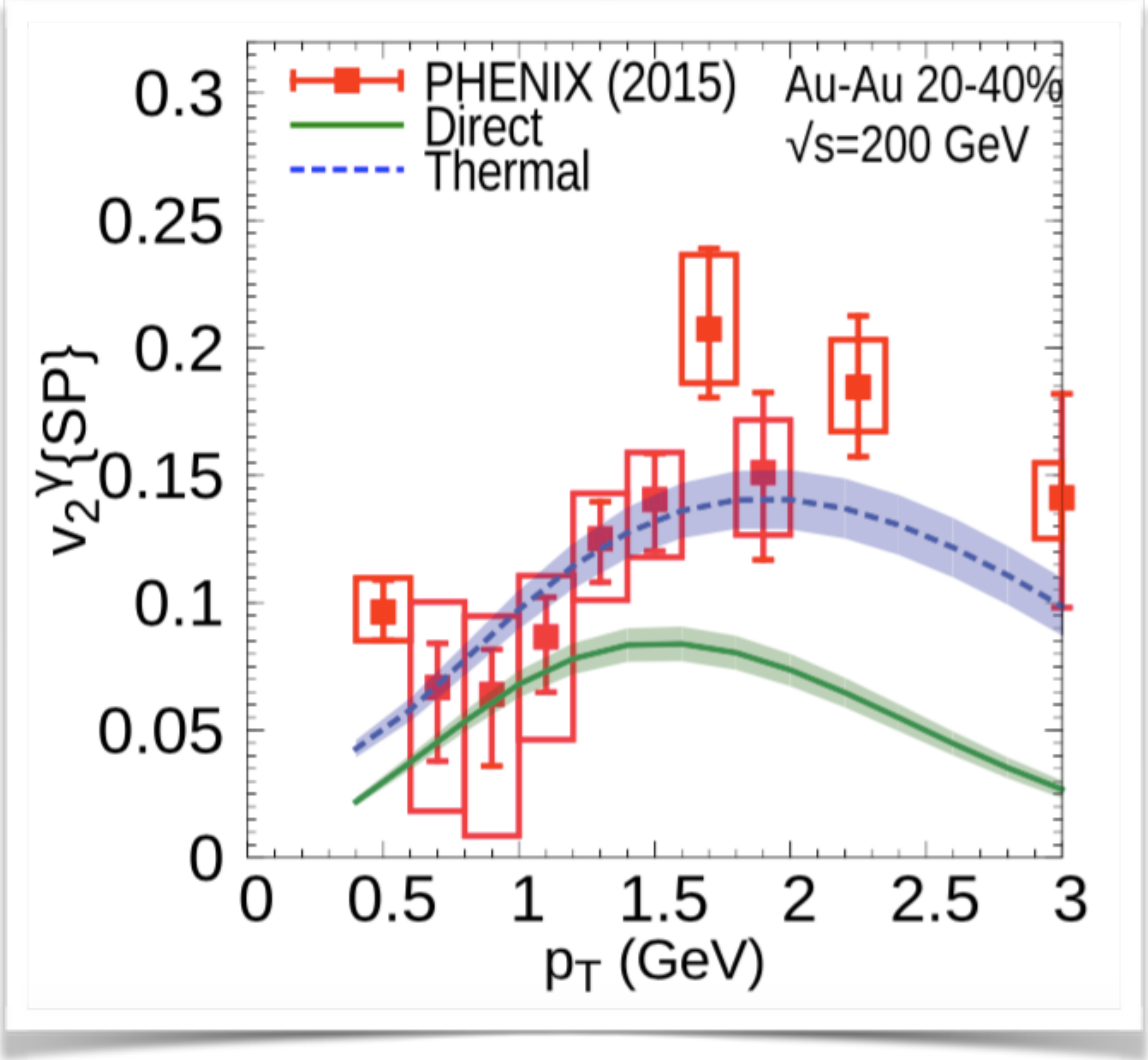
Why Photons?

- Direct Probes
  - -> Only Electromagnetic Interaction
  - -> Mean free path >> size of system
  - -> Emitted in all stages of HIC
    => Time-integrated picture

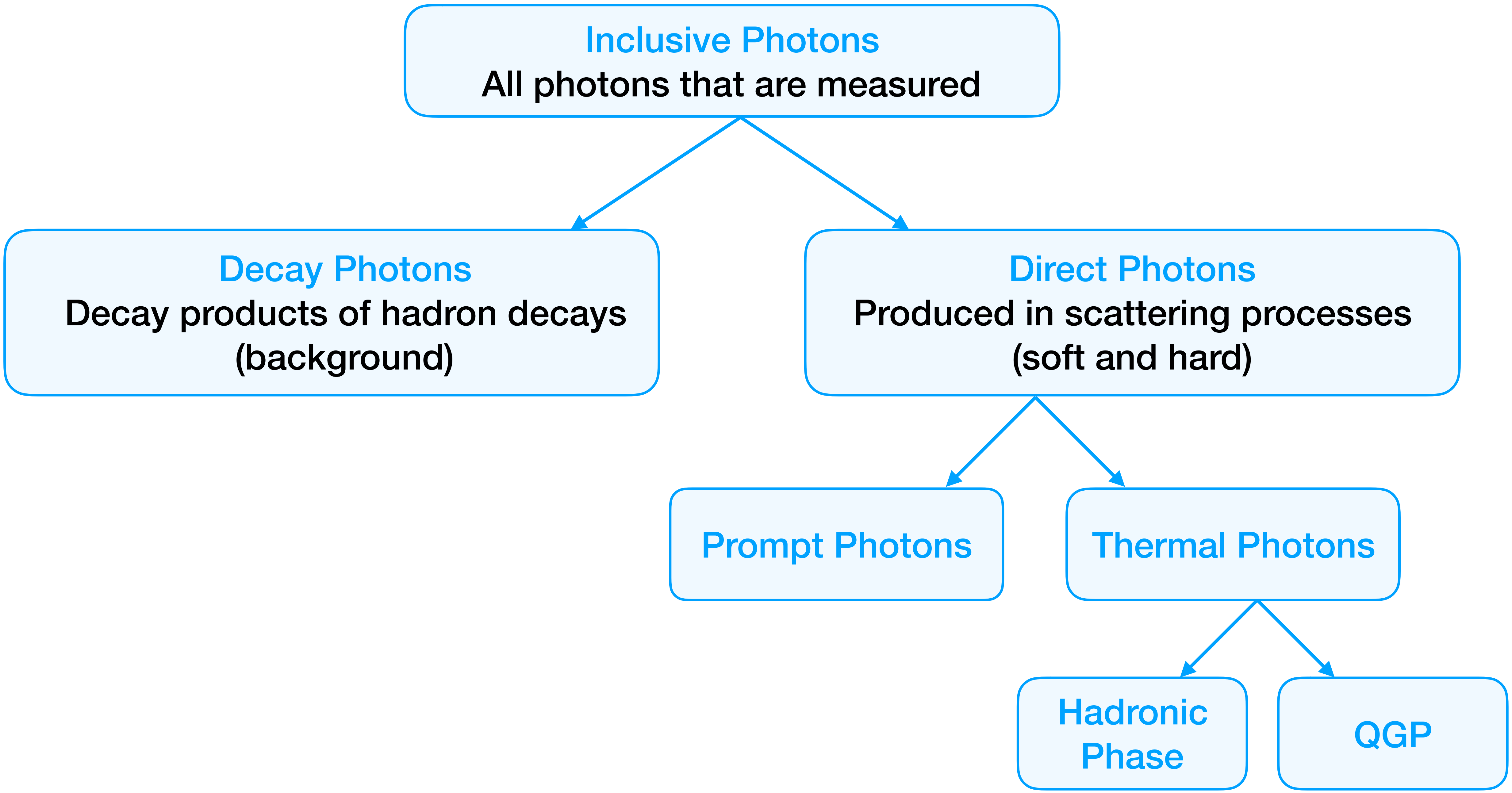
- Direct Photon Flow Puzzle
  - -> Observed at RHIC/LHC measurements
  - -> Unexpectedly large γ-momentum anisotropies

- Importance of photons from non-equilibrium hadronic phase?



Paquet et al. Phys. Rev. C 93, 044906

Direct Photons



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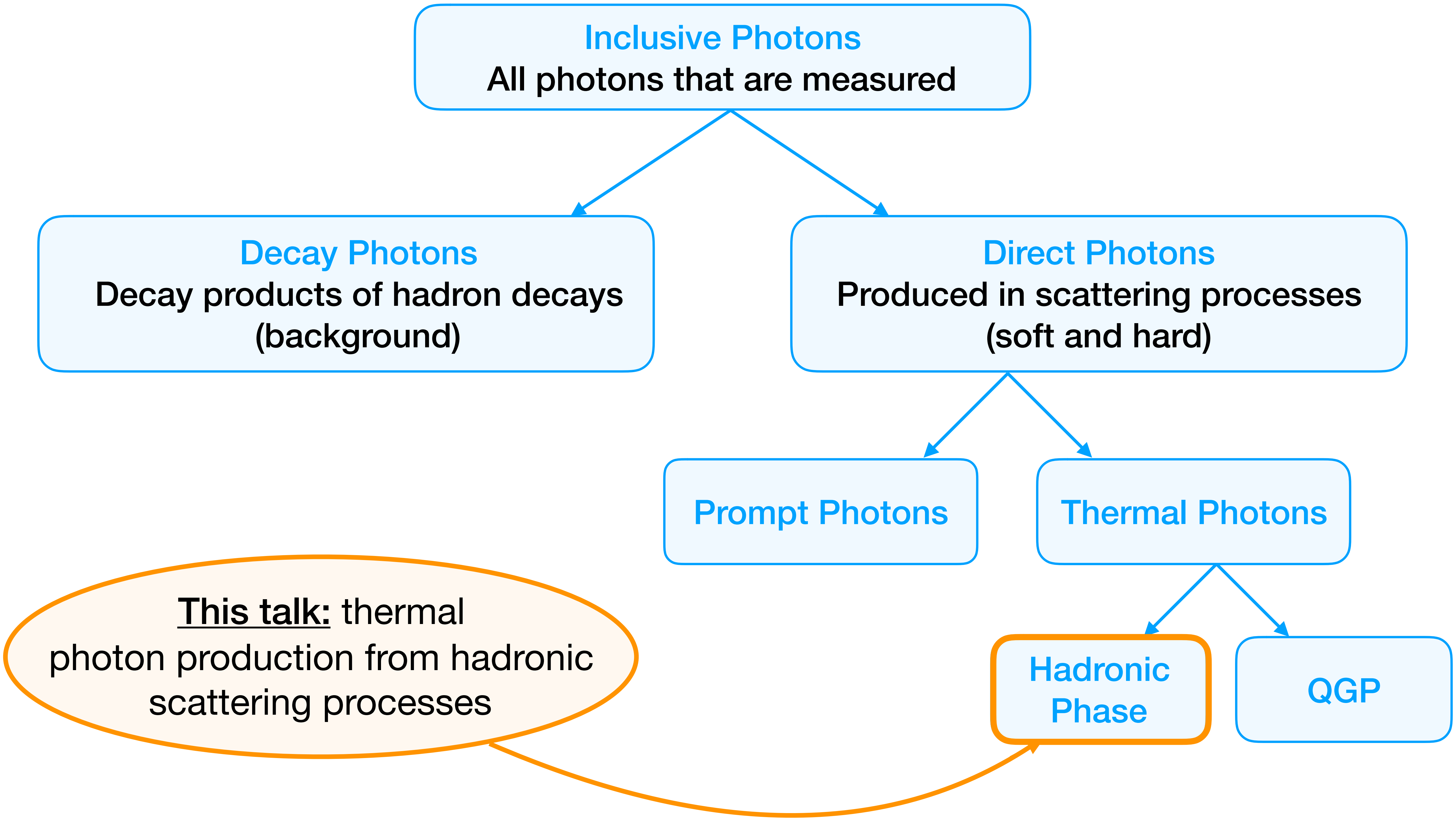

SMASH - A New Hadronic Transport Approach

What is SMASH?

SMASH =
Simulating Many Accelerated Strongly-Interacting Hadrons

C++ based hadronic transport model

Use of modern tools for development:
git, doxygen, redmine, …

Developed in the group of Hannah Petersen in Frankfurt

Features?

Effective solution of relativistic Boltzmann equation:

$$p^\mu \partial_\mu \, f + m \, \partial_{p_\mu} (F_\mu \, f) = C(f)$$

Geometric collision criterion:

$$d_{\text{coll}} < \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}$$

Description of low-energy HIC, hadron gases and late, dilute stages of HIC

Dileptons and bulk properties already studied successfully

Weil et al.: Phys. Rev. C 94 (2016), no.5
Staudenmaier et al.: arXiv 1711.10297 (2017)
Oliinychenko et al: J. Phys. G: 44 034001 (2017)

Rose et al.: arXiv 1709.03826 (2017)
Tindall et al.: Phys. Lett. B770 (2017)

Photons in SMASH

- Photon production in hadronic elastic and inelastic scattering processes

- Perturbative Treatment
  - EM-coupling is small compared to strong coupling
  - Assumption: photons do not interact with medium after production

  => Photons are not actually produced, they are directly printed to the output

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Set II

- Cross sections based on Turbide et al. framework
  Turbide et al.: Int.J.Mod.Phys. A19 (2004)
- More evolved effective field theory

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- More evolved effective field theory

<u>**From now on:**</u>
this framework

Turbide et al. Framework

- Chiral effective field theory with mesonic degrees of freedom:
  - Pseudoscalar mesons
  - Vector mesons
  - Axial vector mesons
  - Photon

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

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  => Proper calculation necessary

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- More realistic description than Kapusta et al. theory
- Used in state-of-the-art hydro code (MUSIC)
  => Hybrid model made up of SMASH and MUSIC?
- Further extensions possible, e.g.
  Heffernan, Hohler, Rapp: Phys. Rev. C 91 (2015)
  Holt, Hohler, Rapp: Nuc. Phys. A 945 (2016)

Photon Production Channels

Exchange via (π,ρ,a_1)

Exchange via (ω)

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

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

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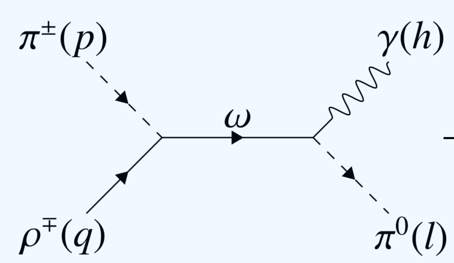
Example:



$$\rightarrow |\mathcal{M}|^2 \rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}t} \rightarrow \sigma$$

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Thermal Photon Rate

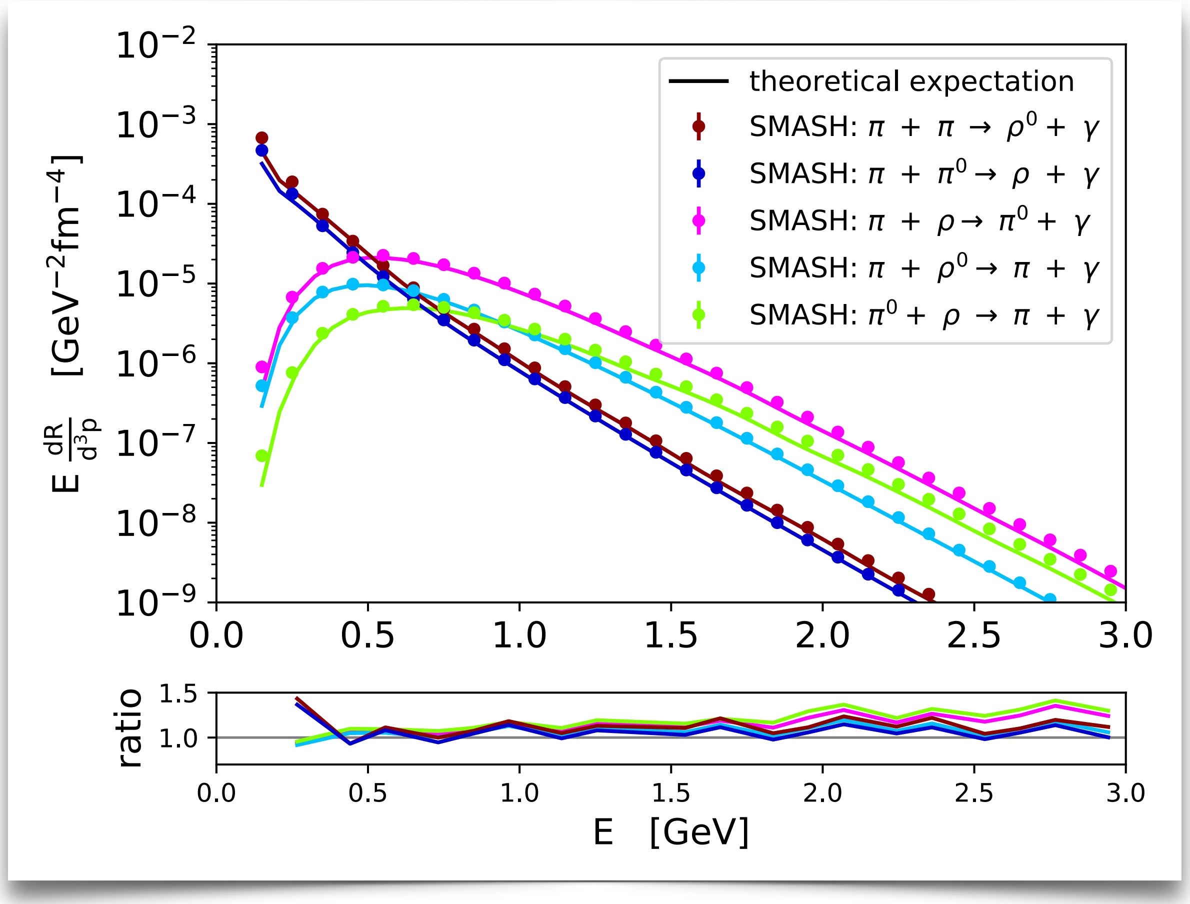
Thermal photon rate: number of photons produced per unit time and volume

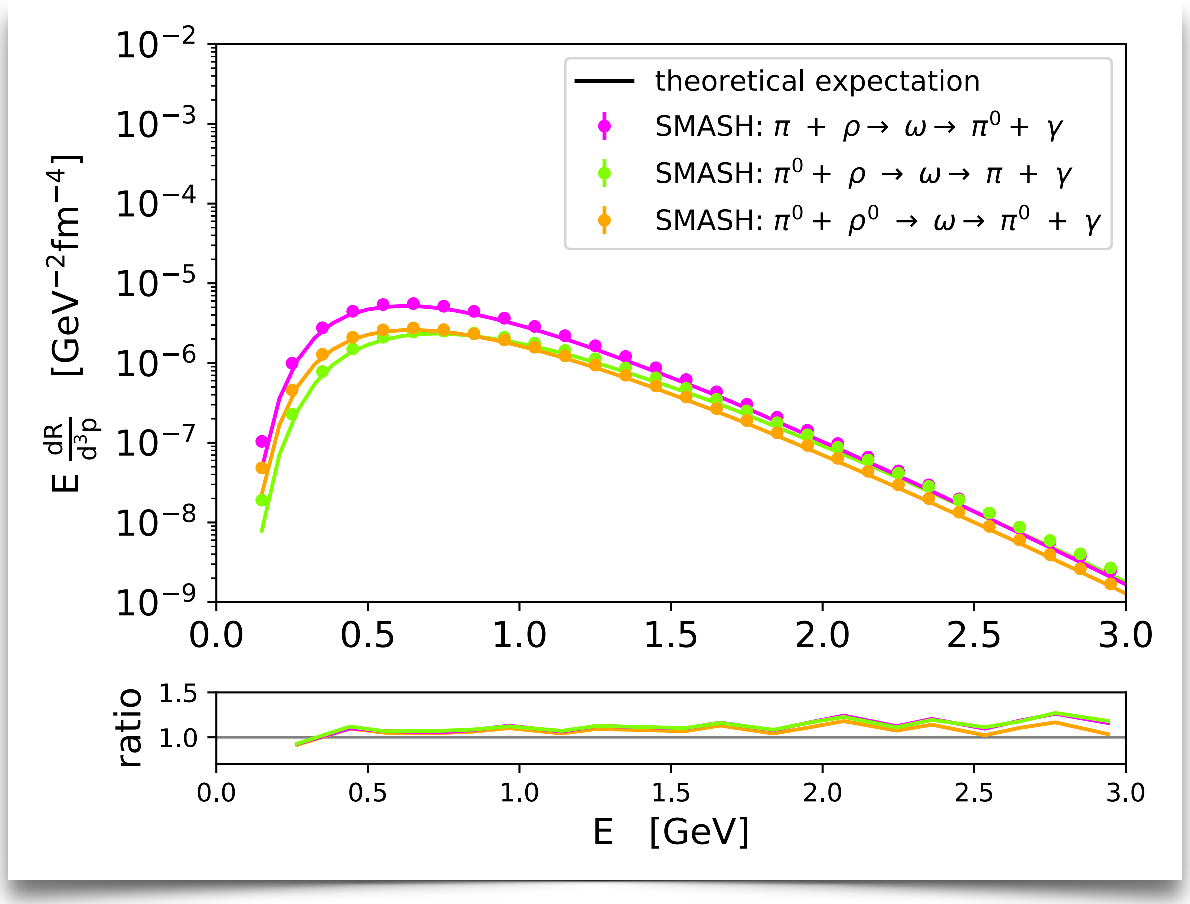
-> Allows for comparison to theoretical expectation

SMASH setup: Infinite matter simulation

-> Hadronic matter in thermal and chemical equilibrium at T = 200 MeV

Thermal Photon Rate





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SMASH setup: Infinite matter simulation

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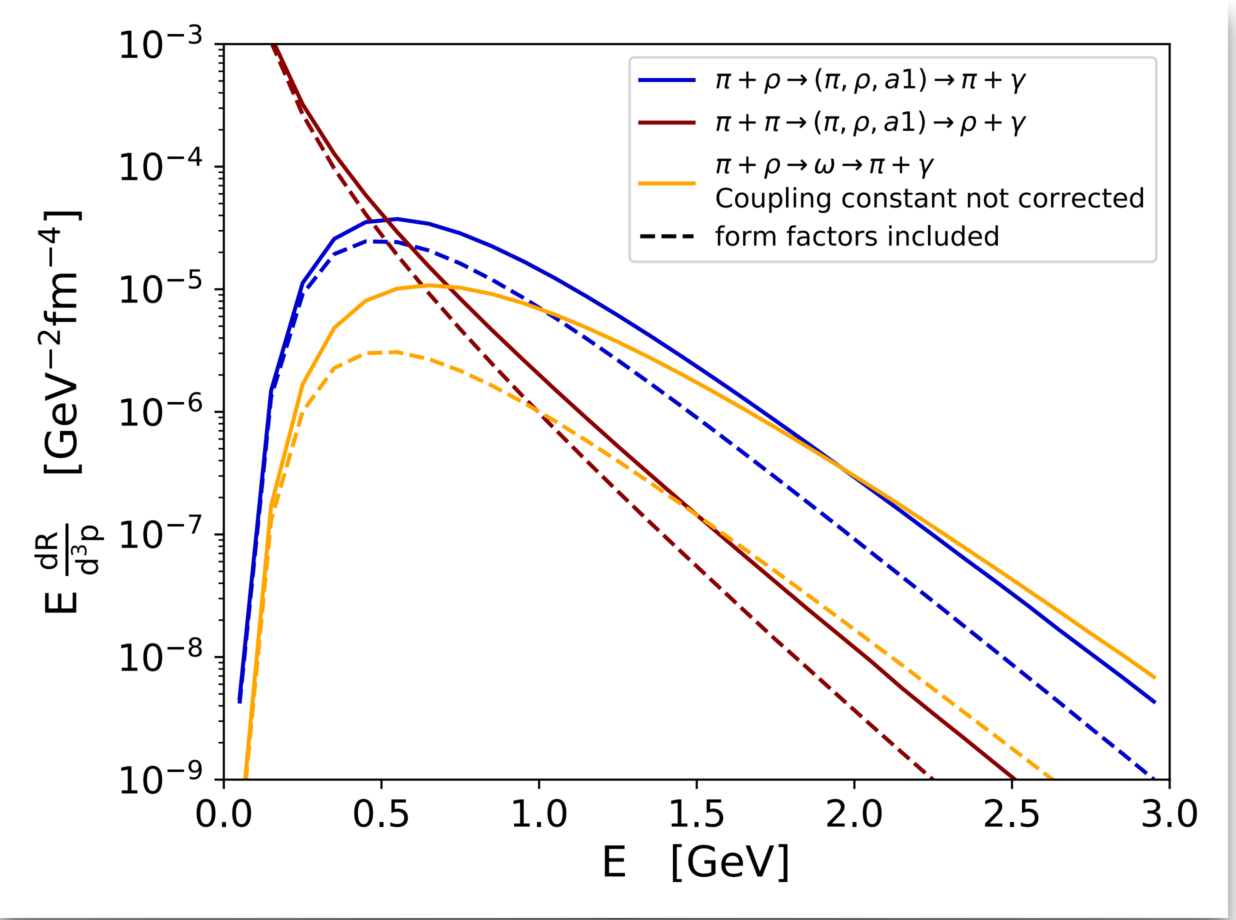
Form Factors

Form Factor:

- Necessary to account for finite extend of the fields at vertices
- Hadronic dipole form factor (global and energy-dependent)
- Different for (π,ρ,a_1) and (ω) mediated processes
- Reduction of photon rate (except for ω channels after correcting coupling constant)



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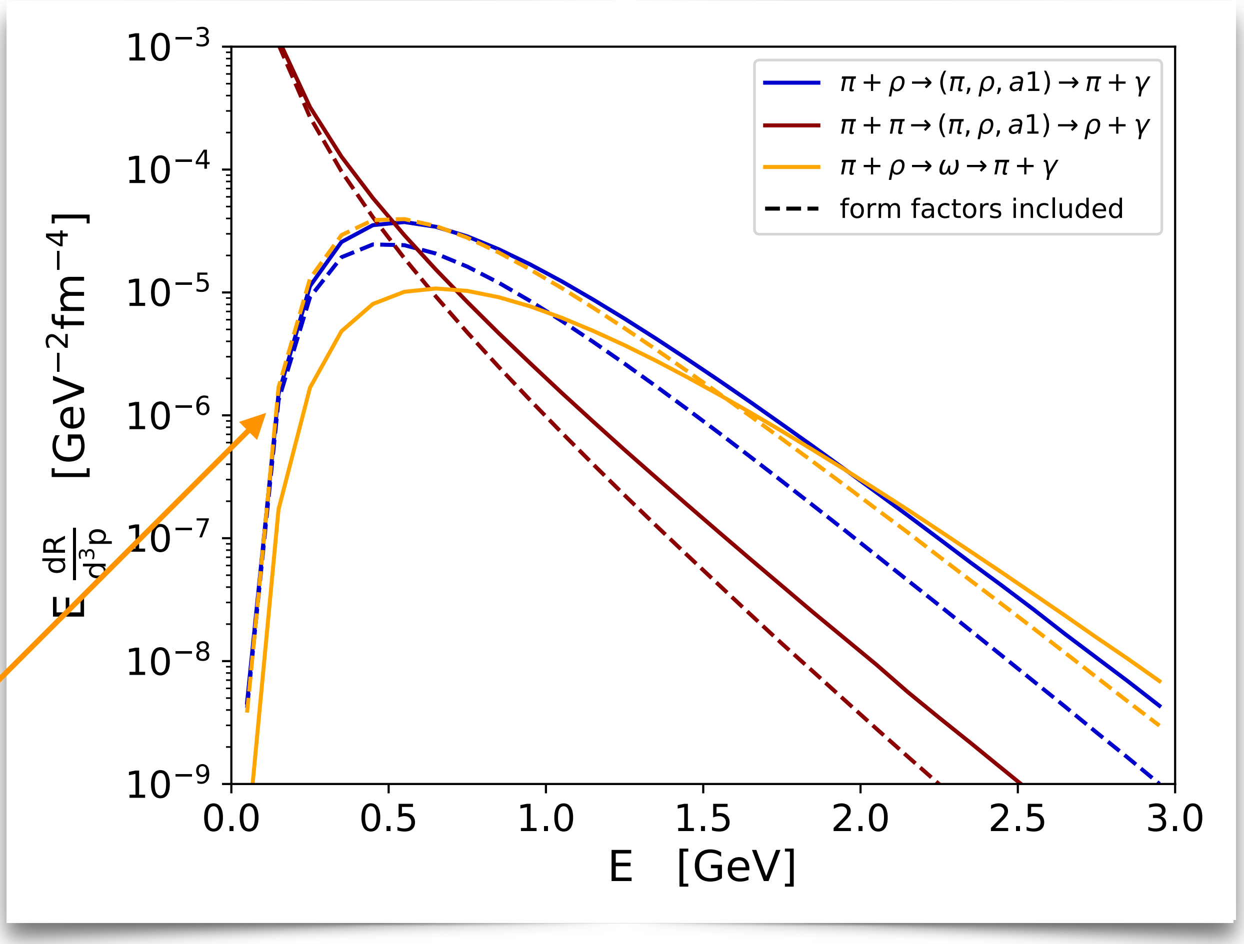
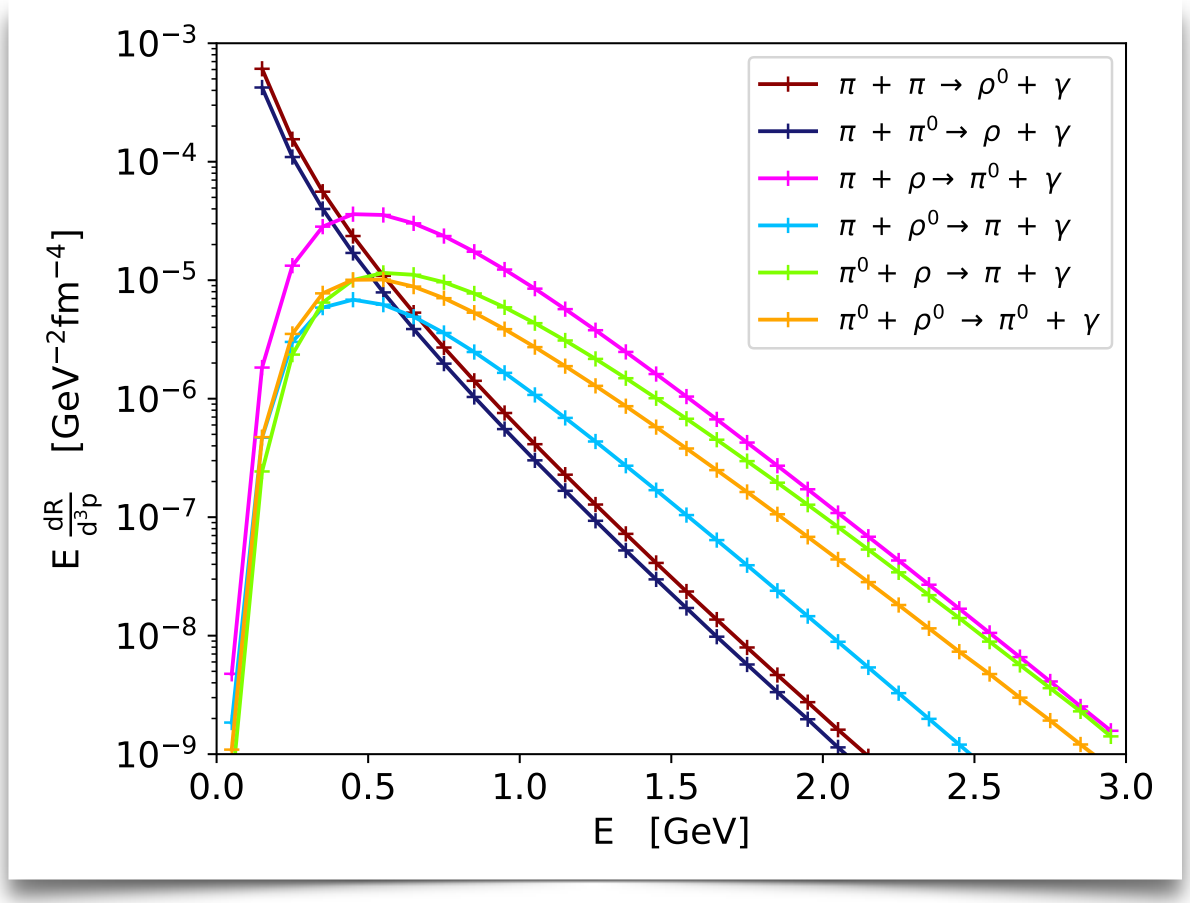


Note:
π-ρ-ω-coupling increases when applying form factors

Photon Rates from SMASH

Contribution of **individual**
π + π -> ρ + γ **and**
π + ρ -> π + γ **channels**



Form Factors included!

Photon Rates from SMASH

Contribution of **individual**
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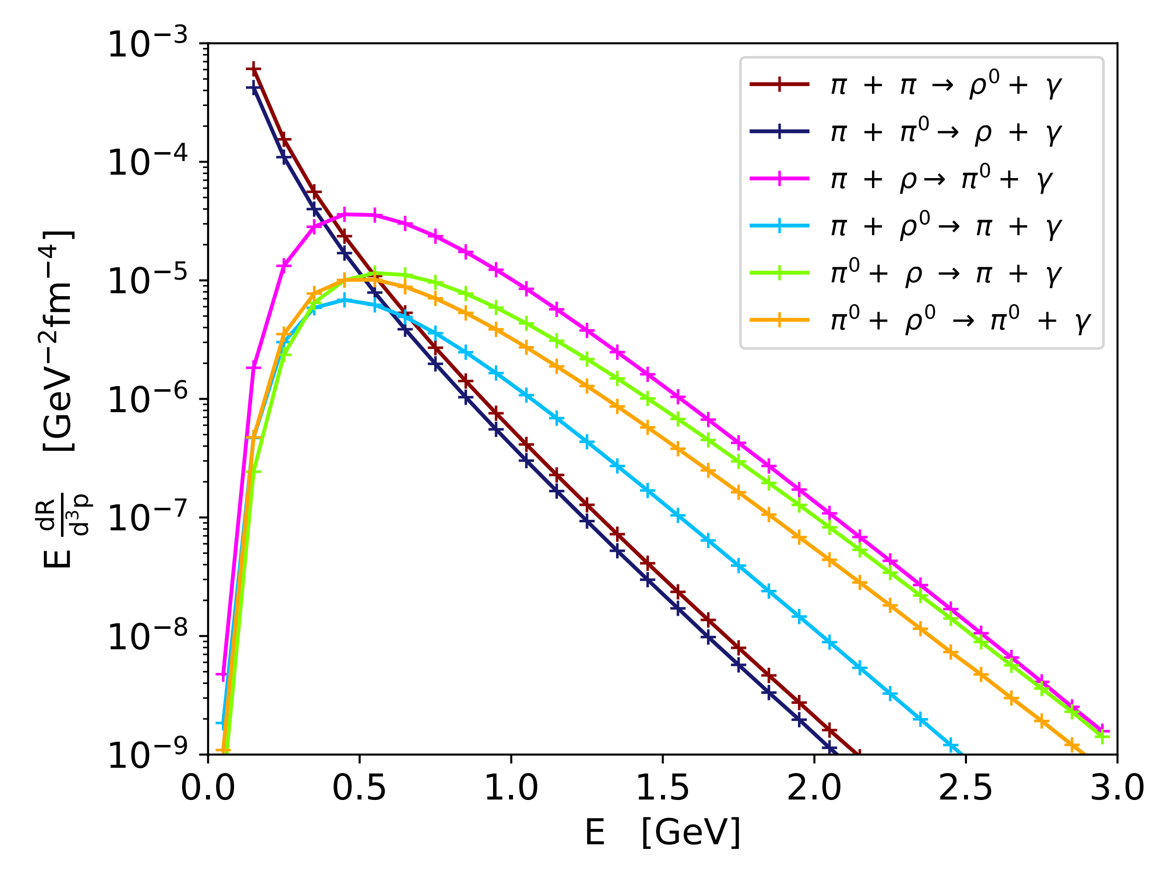
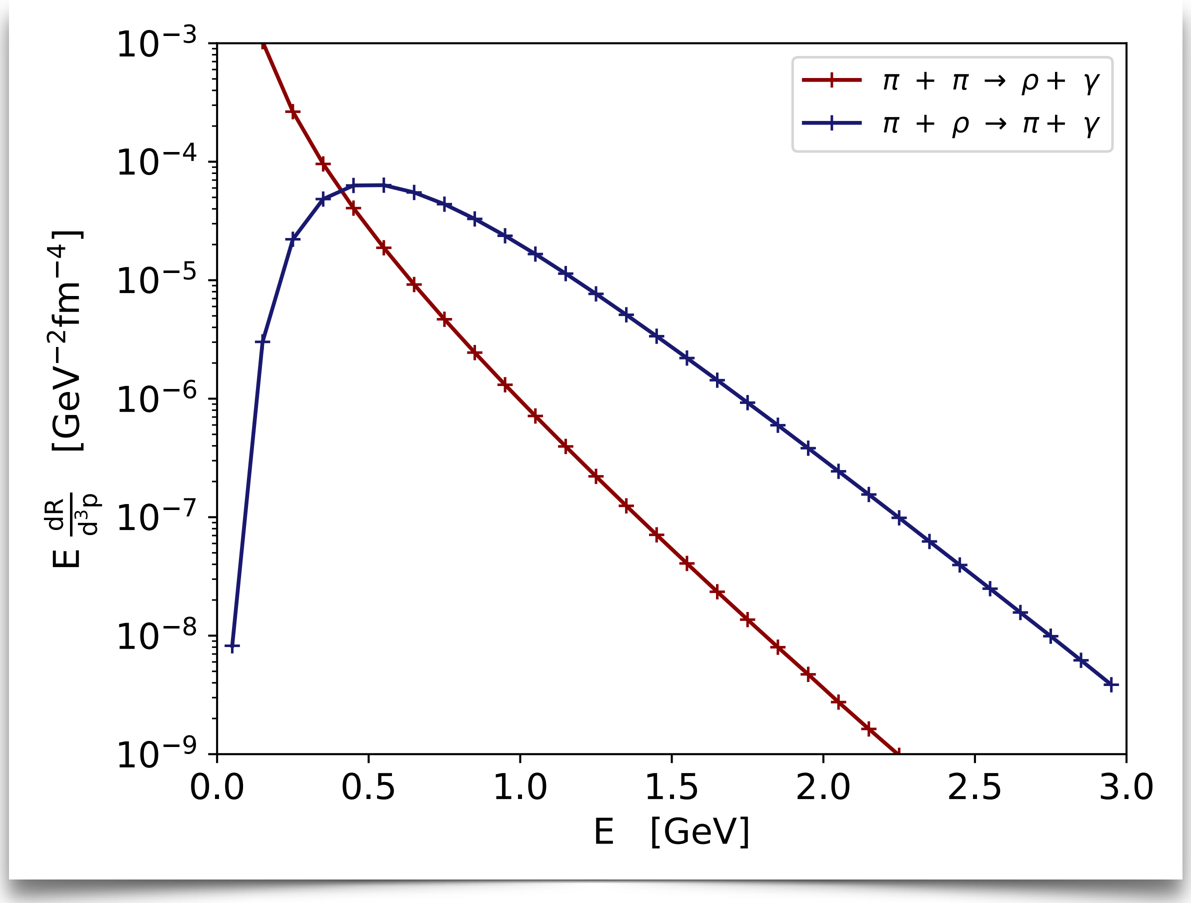
π + ρ -> π + γ channels

Contribution of **combined**
π + π -> ρ + γ and
π + ρ -> π + γ channels





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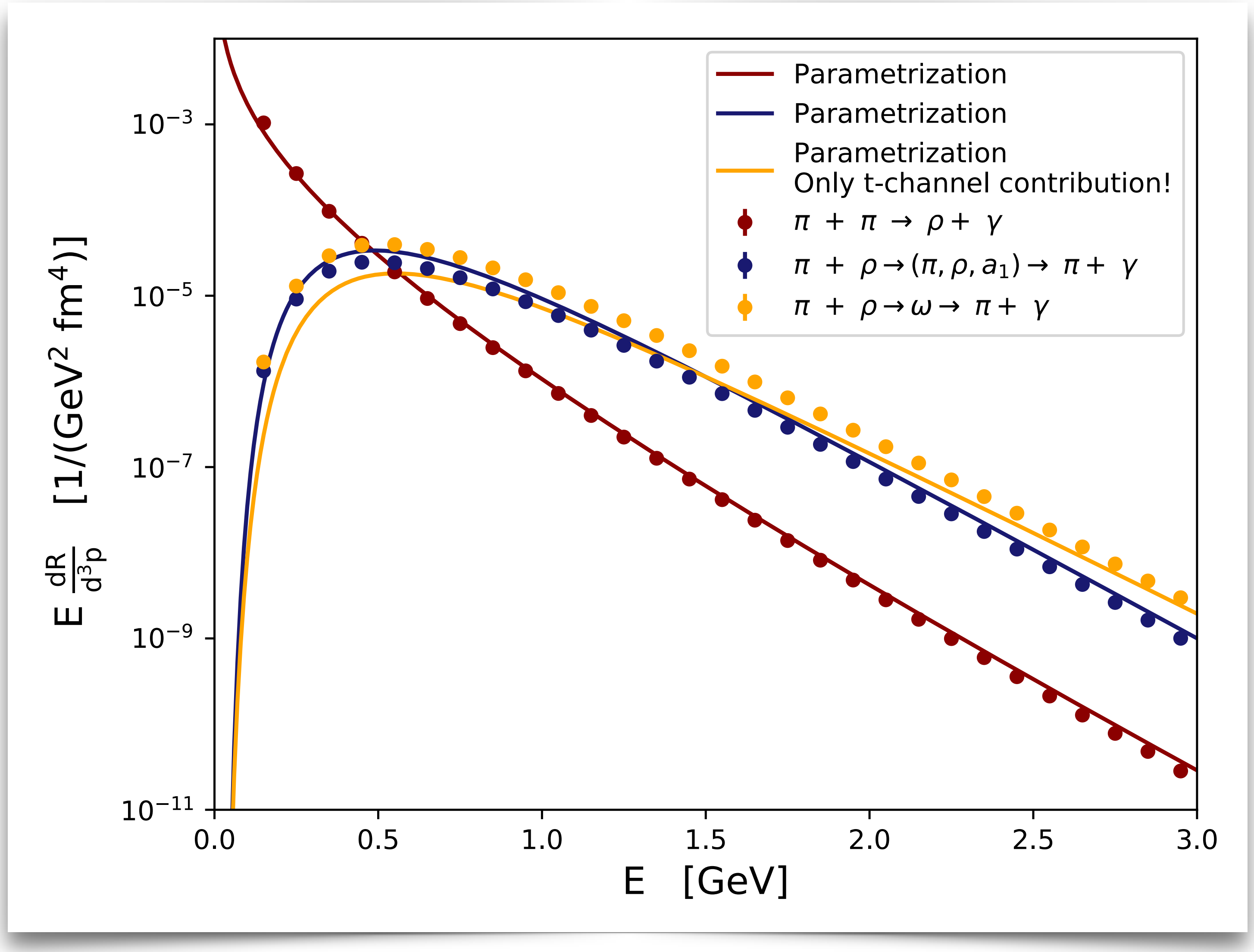
Comparison to Parametrized Rates



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Parametrizations used in Hydro Simulations (e.g. MUSIC)

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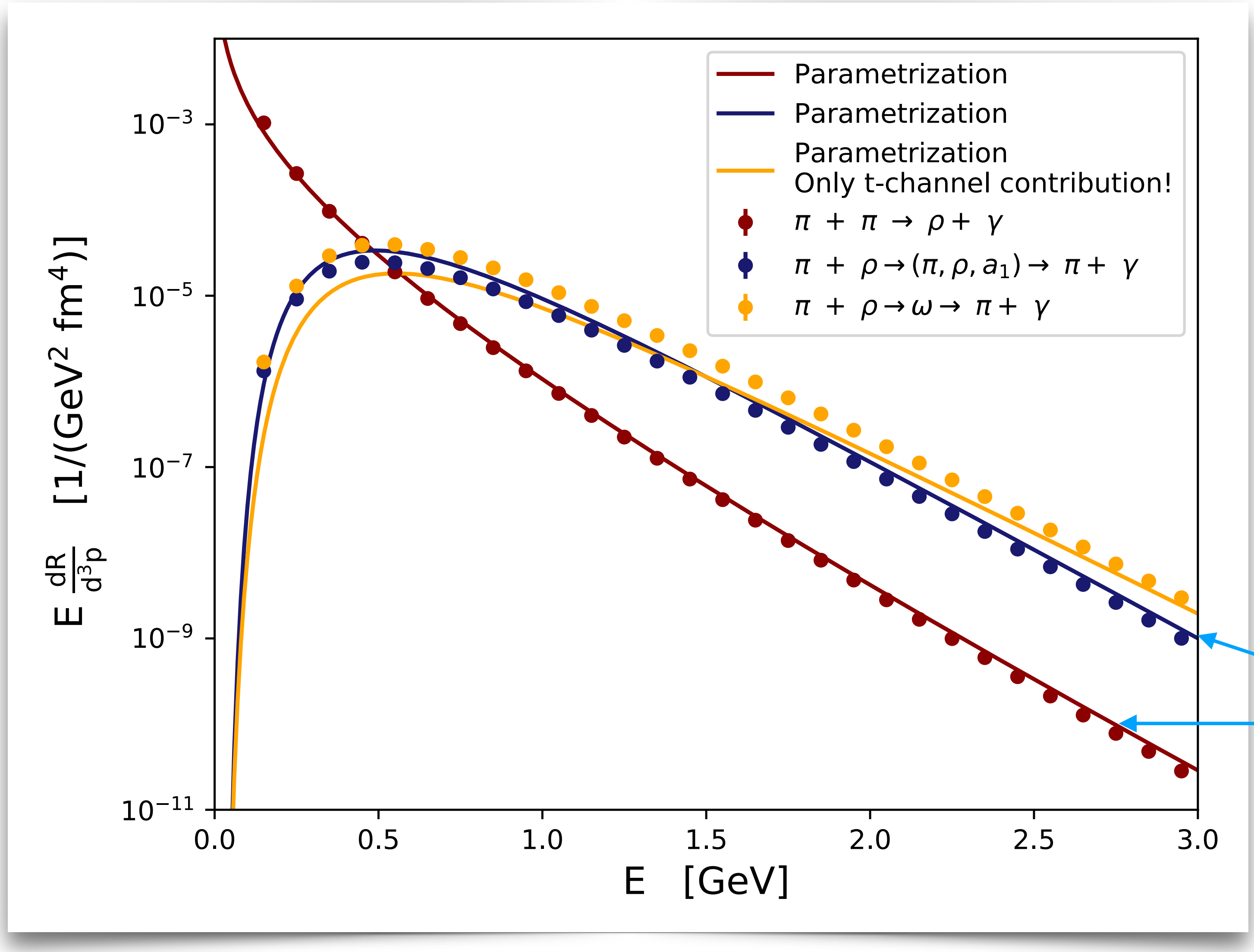

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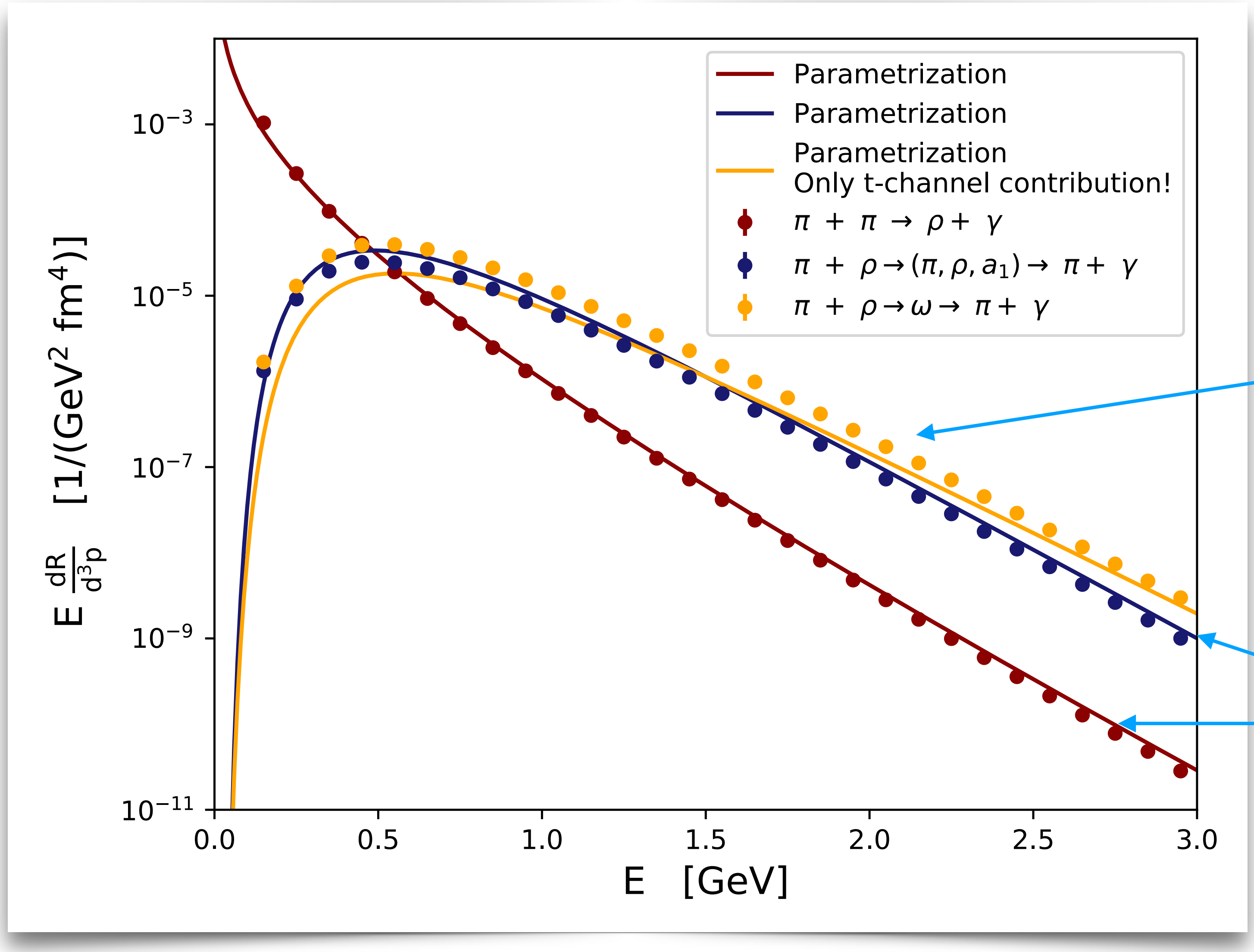

Systematic deviation

-> Parametrization only accounts for t-channel contributions

-> SMASH contains s- and t-channels

Parameterizations ok

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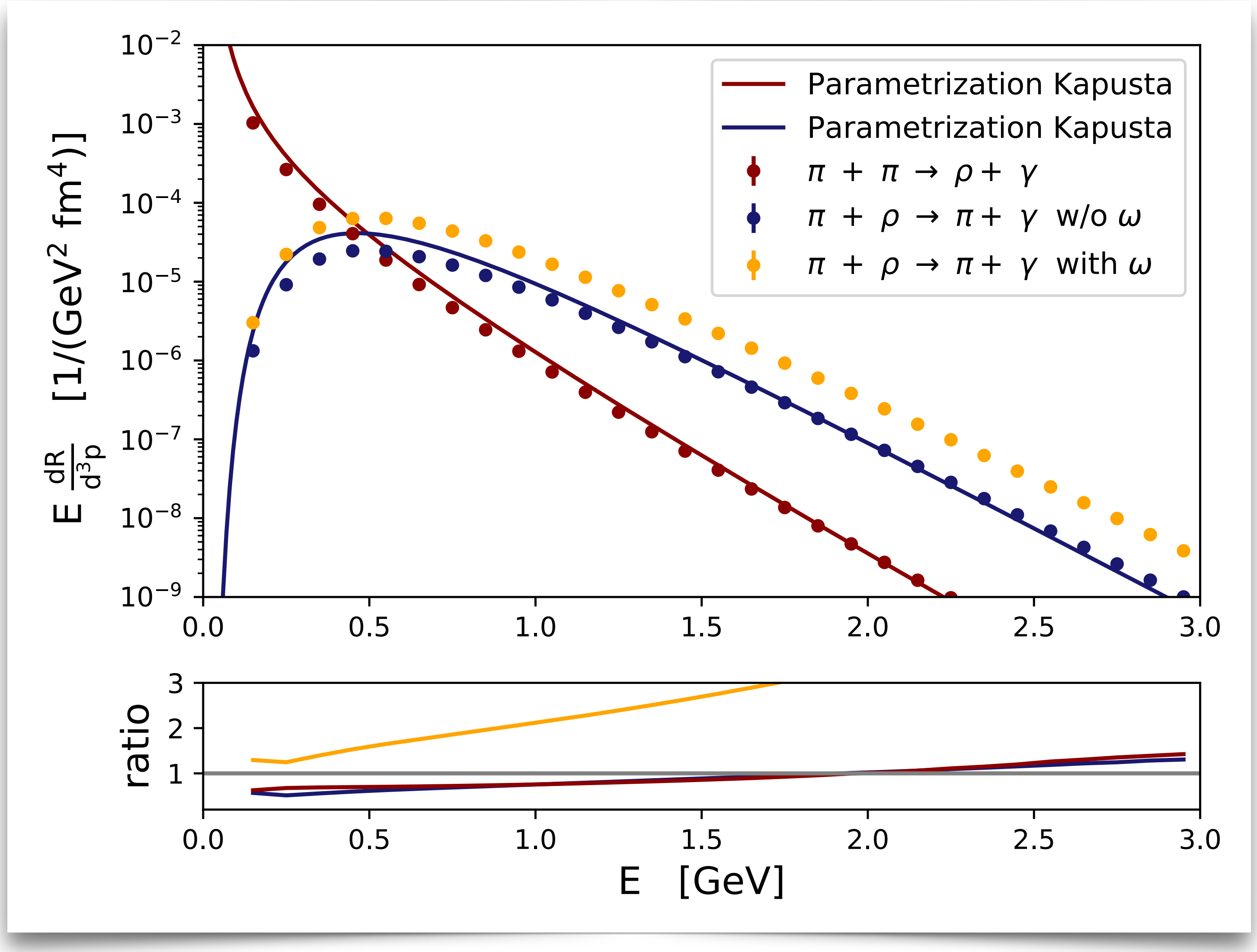
Quantifying the Difference to Kapusta et al. Framework



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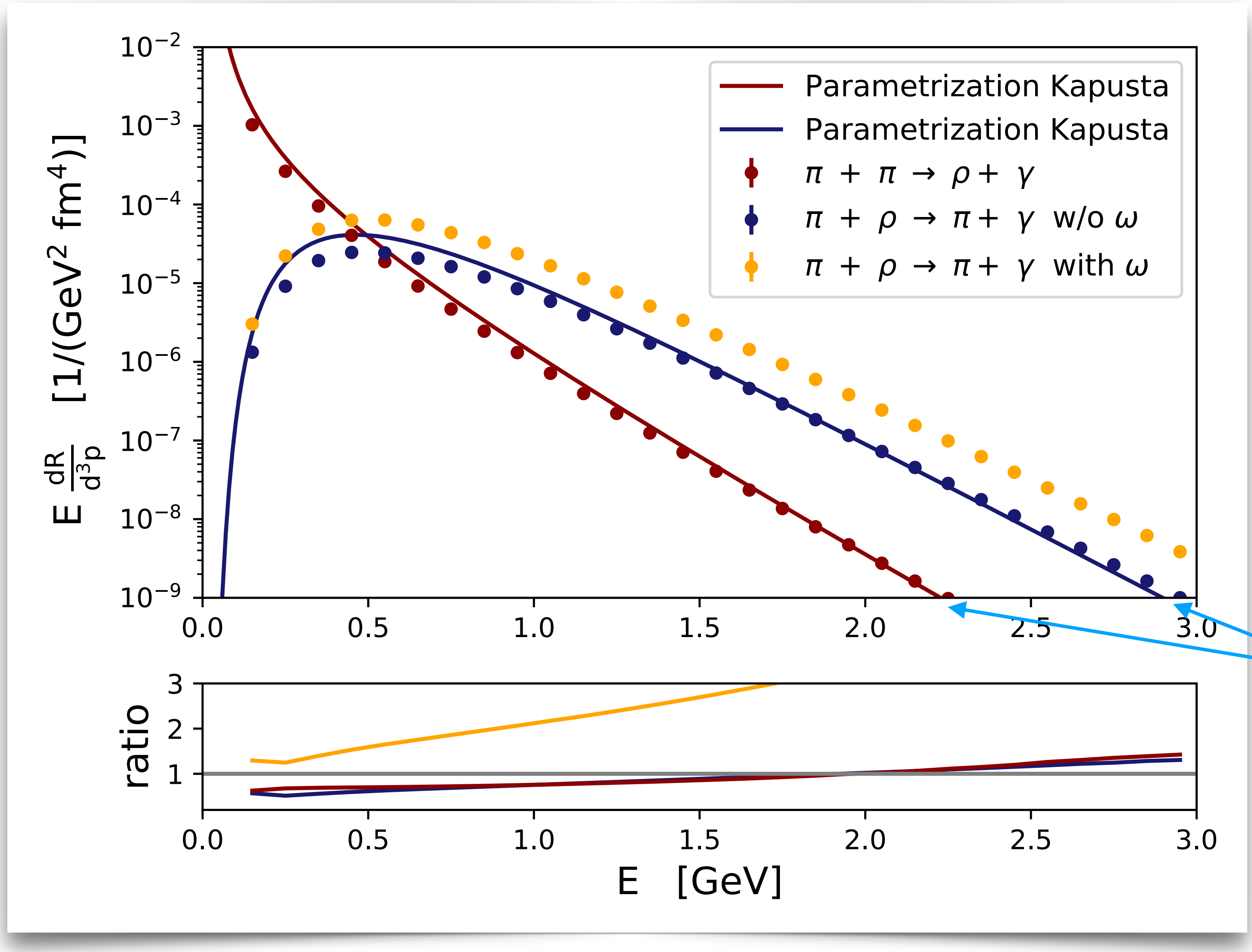

Kapusta > SMASH for small E
Kapusta < SMASH for large E

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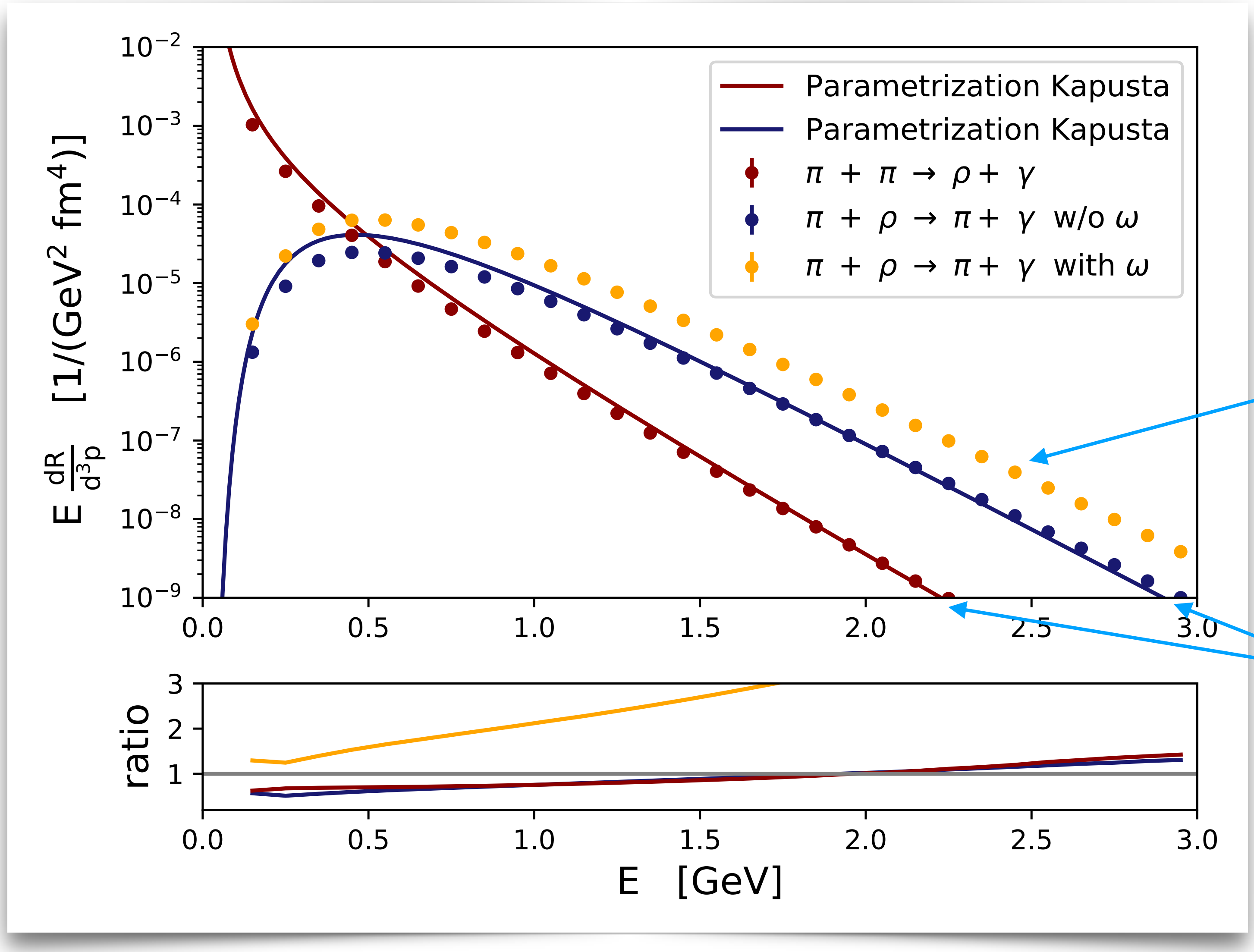

ω channels not included in Kapusta et al. framework:

-> Enhanced photon production in π + ρ -> π + γ channels within Turbide et al. framework

=> Enhanced photon production from hadronic rescattering phase in HICs

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Kapusta < SMASH for large E

Kapusta parametrizations taken from: H. Nadeau et al.: Phys. Rev. C45 (1992)
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Summary & Outlook

What has been done?

- Proper understanding of photon production in hadronic phase is important
- Hadronic photon production implemented and applied in SMASH
  - -> Results in good agreement with Turbide et al.
  - -> (ω) mediated processes contribute significantly
  - -> Justification for application of more complex effective field theory

Future Plans

- Extension by more production channels (e.g. involving strange mesons)
- Inclusion of 1 -> 3 production processes
- Apply SMASH within hybrid approach (MUSIC) based on the same underlying effective field theory

Backup

Turbide et al. Lagrangian

$$\mathcal{L} = \underbrace{\frac{1}{8} F_\pi^2 \, Tr\left(D_\mu U D^\mu U^\dagger\right)}_{\text{kinetic term \& interaction PS}} + \underbrace{\frac{1}{8} F_\pi^2 \, Tr\left(M\left(U + U^\dagger - 2\right)\right)}_{\text{mass term PS}} - \underbrace{\frac{1}{2} Tr\left(F_{\mu\nu}^L F^{L\mu\nu} + F_{\mu\nu}^R F^{R\mu\nu}\right)}_{\text{kinetic term \& interaction of V and AV}}$$

$$+ \underbrace{m_0^2 \, Tr\left(A_\mu^L A^{L\mu} + A_\mu^R A^{R\mu}\right)}_{\text{mass term V and AV}} + \underbrace{\gamma \; Tr\left(F_{\mu\nu}^L U F^{R\mu\nu} U^\dagger\right) - i\xi \, Tr\left(D_\mu U D_\nu U^\dagger F^{L\mu\nu} + D_\mu U^\dagger D_\nu U F^{R\mu\nu}\right)}_{\text{higher order interaction of PS, V and AV}}$$

$$\underbrace{- \frac{2em_0^2}{g_0} B^\mu \, Tr\Big(Q\left(A_\mu^L + A_\mu^R\right)\Big) - \frac{1}{4}\left(\partial_\mu B^\nu - \partial_\nu B^\mu\right)^2 + \frac{2e^2 m_0^2}{g_0^2} B_\mu B^\mu Tr\left(Q^2\right)}_{\text{electromagnetic interaction of PS, V, AV and } \gamma}$$

$$+ \underbrace{g_{VV\psi} \, \varepsilon_{\mu\nu\alpha\beta} \, Tr\left[\partial^\mu V^\nu \partial^\alpha V^\beta \psi\right]}_{\text{Wess-Zumino Term for V-V-PS-vertex}}$$

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

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

Thermal Photon Rate

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:

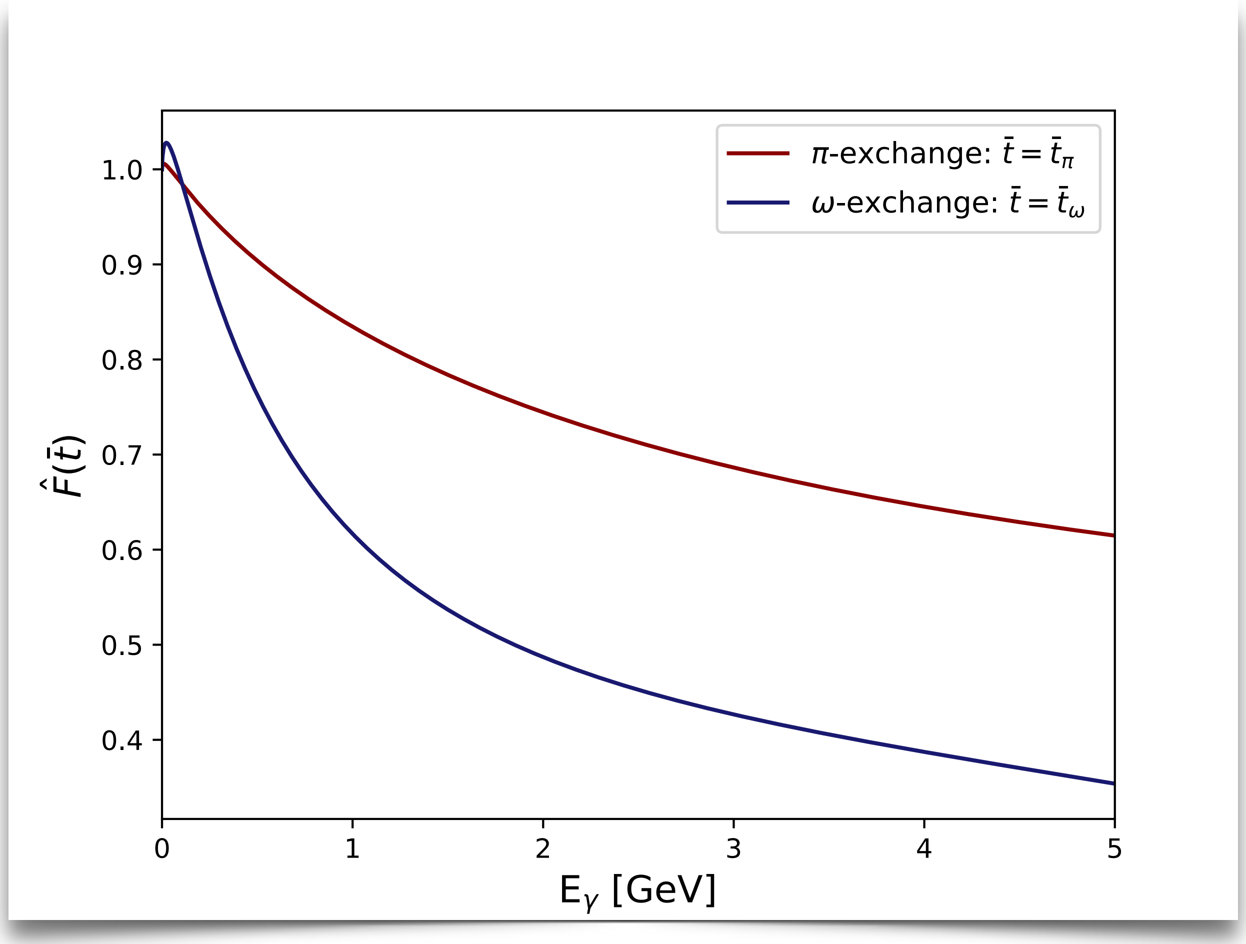
$$\hat{F}(E_\gamma) = \frac{2\Lambda^2}{2\Lambda^2 - \bar{t}(E_\gamma)}$$

- Application in SMASH:

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

- Combination of channels:

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



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

From experiment: 0.7174 MeV