Parametrization of γ-ray production cross-sections for pp interactions in a broad proton energy range from the kinematic threshold to PeV energies

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Outline

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2. Present Parametrizations v.s. Experimental Data
3. Parametrization $pp \rightarrow \pi^0$ cross section
4. Parametrization of $pp \rightarrow \gamma$ differential cross section
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Why a new parametrization?

We need an accurate parametrization that:

1. Can fit all available Experimental Data (especially at low energies)
2. Is able to fit the High Energy Hadronic models results (MC codes)
3. Connects smoothly High and Low energy regions

Motivation

- Space-based γ-ray instruments probe with high accuracy $E_\gamma \sim 100$MeV (e.g. Fermi-LAT)
- Very hot astrophysical plasma applications (BH accretion disk)
- Astrophysical sources have wide range of proton energy and none of the current parametrizations can cover this energy interval accurately

Widely used $pp \to \gamma$ models/parametrisation

- Isobar + scaling model Dermer (1986)
  (connects $\Delta(1232)$ *Isobar + scaling model* calculations)

- Parametrization from Kamae et.al. (2006), $488\mathrm{MeV} < T_p < 512$ TeV
  (Uses $\Delta(1232)$ *and res(1600) group of resonances + Blattnig et.al. (2000) parametrizations + PYTHIA 6*)

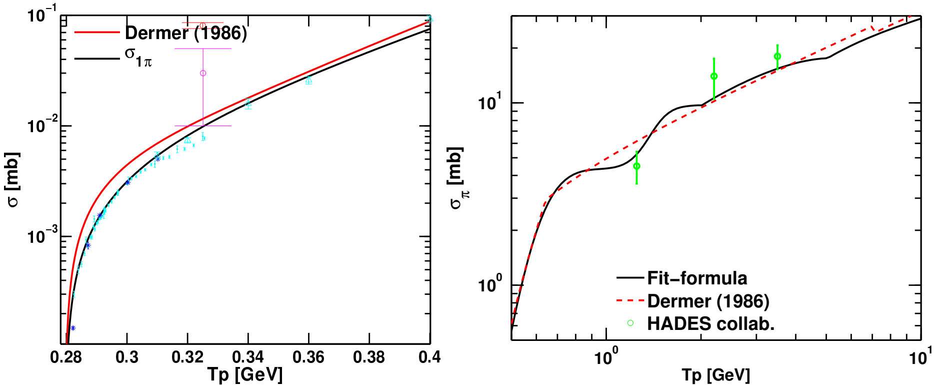
- Parametrization from Kelner et.al. (2006), $0.1 \leq T_p \leq 10^5$ TeV
  (Parametrization of *QGSJET and SIBYLL* results)

Exp. DATA

v.s.

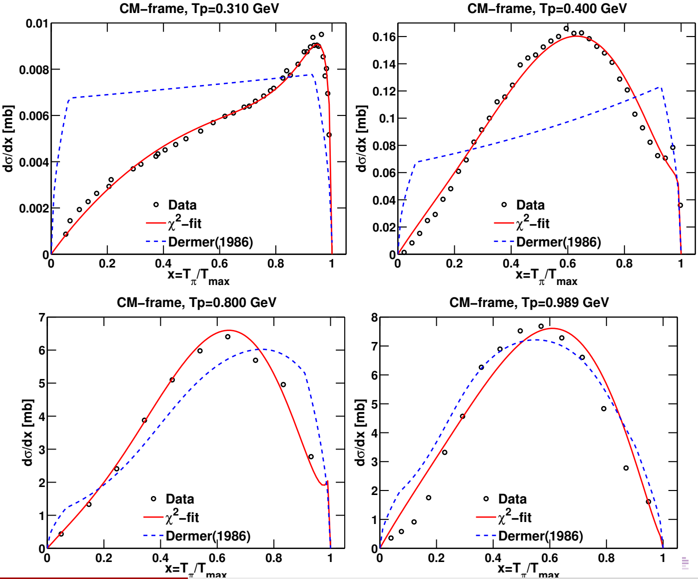
Present Parametrizations

Inclusive σ_π, Dermer(1986) v.s. Exp. Data

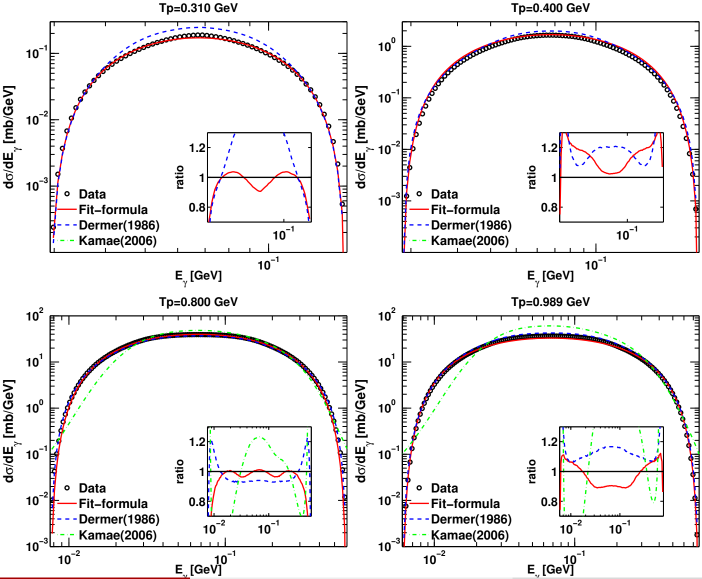


1) $T_p \sim 0.3$ GeV, is 70-80 % higher (important for very hot plasma)
2) $1 < T_p < 2$ GeV, is at least 20 % different and doesn't mimic data

C.M. frame π^0 spectra, Dermer(1986) v.s. Exp. Data



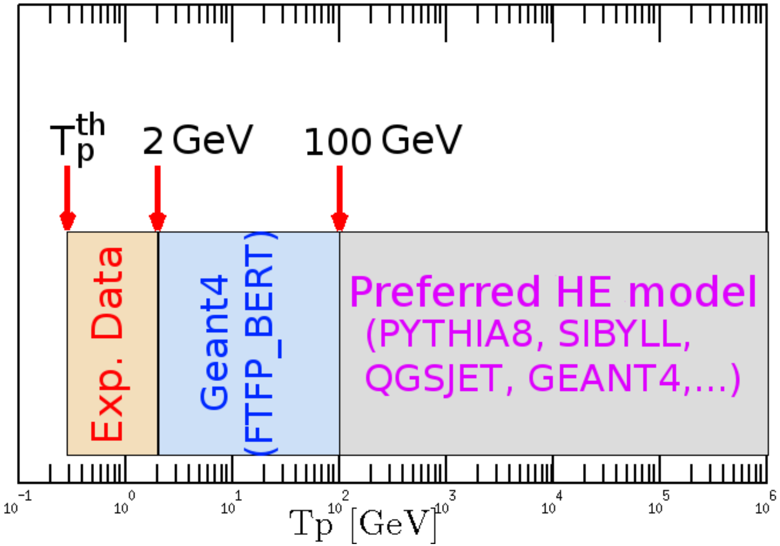
γ-ray spectra, Exp.Data, Dermer(1986), Kamae(2006)



Thus, a parametrization is needed that:

- Revise the low energy $\sigma(pp \rightarrow \gamma)$
- Expands to very high energies

Models considered for the parametrization



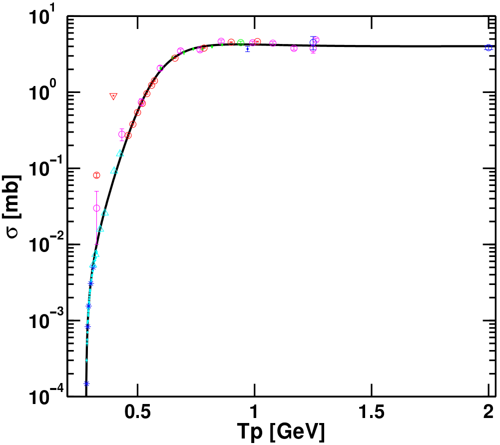
Pion production Cross-Section σ_π

- For $T_p \leq 2$ GeV; Dominate 1 & 2π production channels
  - $pp \to pp\pi^0$
  - $pp \to pp2\pi^0$
  - $pp \to \{pn/D\}\pi^+\pi^0$
- For $T_p > 2$ GeV; Multi pion production (multiplicity from MC codes)

Cross section

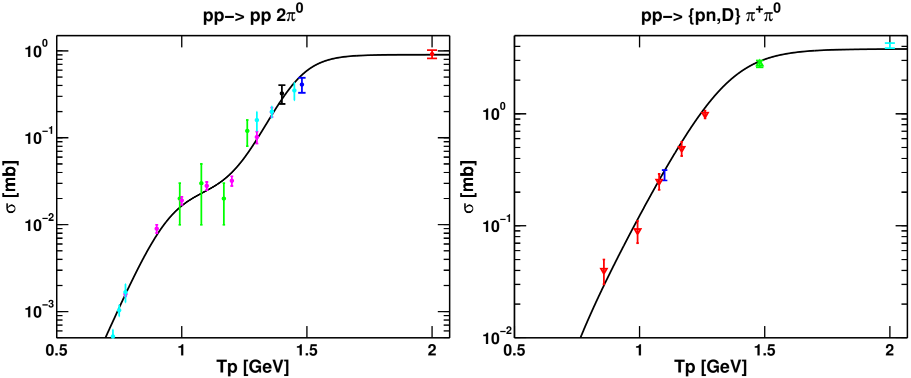
$$\sigma_\pi = \begin{cases} \sigma_{1\pi} + \sigma_{2\pi} & : (T_p^{\mathrm{th}} < T_p \leq 2 \ \mathrm{GeV}) \\ \sigma_{\mathrm{inel}} \times \langle n_{\pi^0} \rangle & : (T_p > 2 \ \mathrm{GeV}) \end{cases} \quad (1)$$

Single pion production channel



$$\sigma_{1\pi} = \sigma_0 \times \eta^{1.95}(1 + \eta + \eta^5) \times \left[f_{BW}(\sqrt{s})\right]^{1.86} \quad (2)$$

Two pion production channels



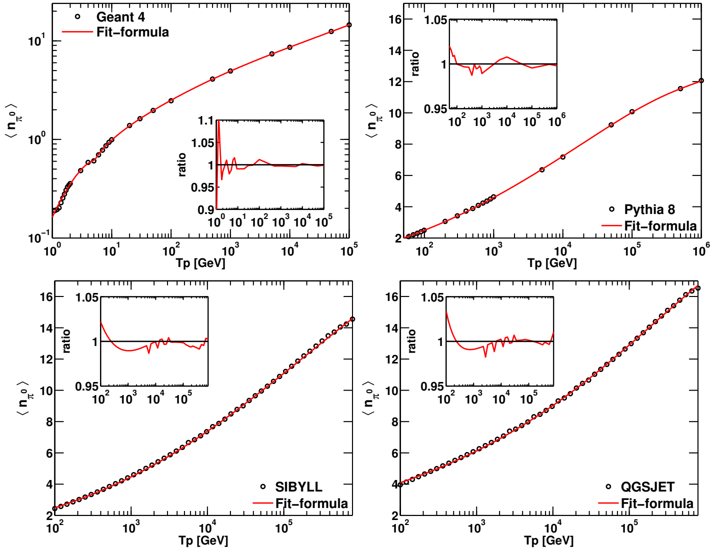
$$\sigma_{2\pi} = \frac{5.7\ \mathrm{mb}}{1 + \exp\left(-9.3(T_p - 1.4)\right)} \tag{3}$$

Parametrization of $\langle n_{\pi^0} \rangle$ for Geant4, Pythia8, SIBYLL and QGSJET

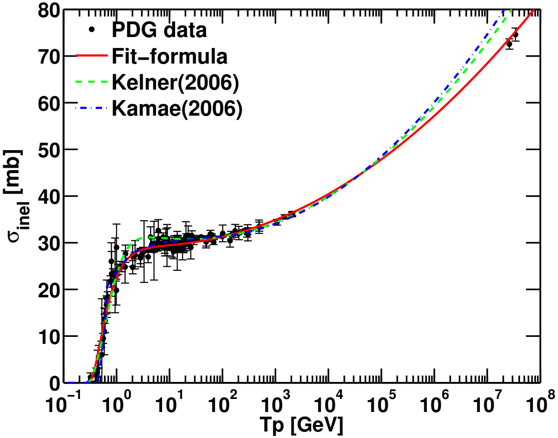
If $Q_p = (T_p - T_p^{\mathrm{th}})/m_p$ and $\xi_p = (T_p - 3\ \mathrm{GeV})/m_p$

$$\langle n_{\pi^0} \rangle = \begin{cases} a_1 + a_2\, Q_p + a_3\, Q_p^2 & : 2 < T_p < 5\ \mathrm{GeV} \\ b_1 \xi_p^{b_4} \left[1 + \exp\left(-b_2 \xi_p^{b_5}\right)\right] \left[1 - \exp\left(-b_3 \xi_p^{1/4}\right)\right] & : T_p \geq 5\ \mathrm{GeV} \end{cases} \tag{4}$$

$\langle n_{\pi^0} \rangle$ for Geant4, Pythia8, SIBYLL and QGSJET



p–p inelastic cross section



$$\sigma_{\rm inel} = \left(30.7 - 0.96\,\log\left(\frac{T_p}{T_p^{\rm th}}\right) + 0.18\,\log^2\left(\frac{T_p}{T_p^{\rm th}}\right)\right) \times \left[1 - \left(\frac{T_p^{\rm th}}{T_p}\right)^{1.9}\right]^3 \quad (5)$$

Parametrization of the γ-ray spectrum

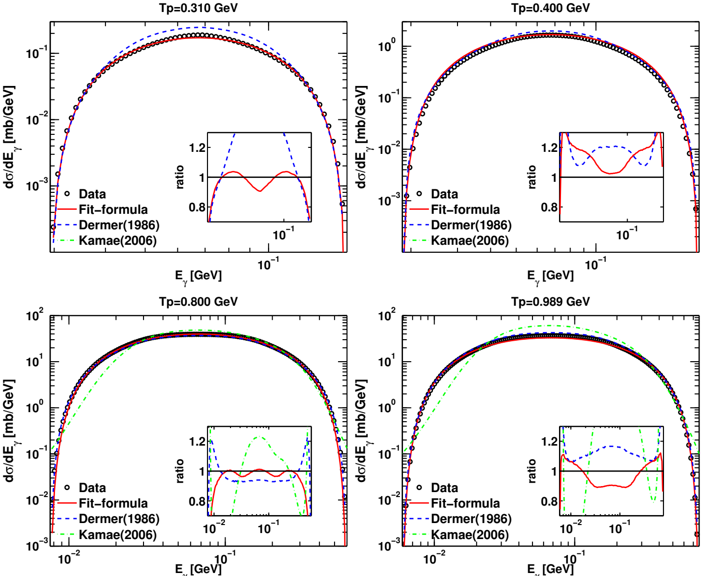
$$\boxed{\frac{d\sigma}{dE_\gamma}(T_p, E_\gamma) = A_{\max}(T_p) \times F(T_p, E_\gamma)} \tag{6}$$

$$\boxed{A_{\max}(T_p) = b_1 \times \theta_p^{-b_2} \times \exp\left(-b_3{}^2 \times \log^2(\theta_p)\right) \times \frac{\sigma_\pi(T_p)}{m_p}} \tag{7}$$

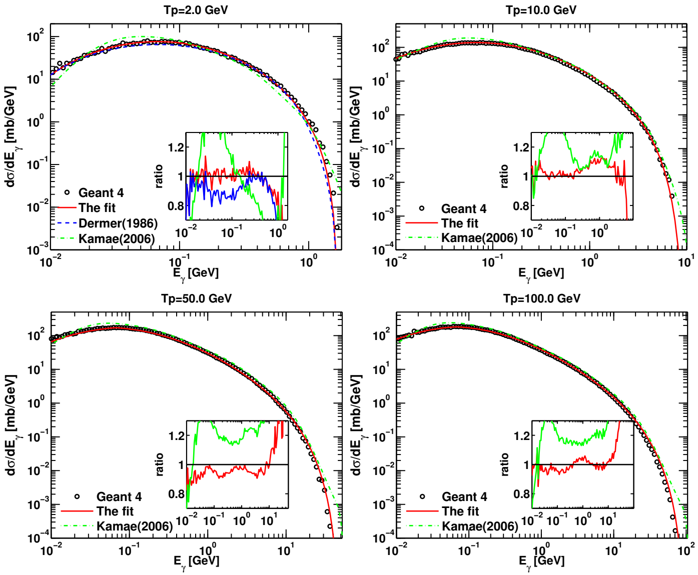
$$Y_\gamma = E_\gamma + \frac{m_\pi^2}{4\,E_\gamma}, \quad X_\gamma = \frac{Y_\gamma - m_\pi}{Y_\gamma^{\max} - m_\pi}$$

$$\begin{aligned} F(T_p, E_\gamma) &= (1 - X_\gamma)^{\kappa(T_p)}, \quad \text{for} \quad \mathrm{T_p^{th}} \leq \mathrm{T_p} < 1\ \mathrm{GeV}, \\ F(T_p, E_\gamma) &= \frac{(1 - X_\gamma)^{\beta(T_p)}}{\left(1 + \frac{X_\gamma}{C}\right)^{\alpha(T_p)}}, \quad \text{for} \quad 1 \leq \mathrm{T_p} < 20\ \mathrm{GeV}, \\ F(T_p, E_\gamma) &= \frac{\left(1 - \sqrt{X_\gamma}\right)^{\delta}}{\left(1 + \frac{X_\gamma}{C}\right)}, \quad \text{for} \quad \mathrm{T_p} \geq 20\ \mathrm{GeV} \end{aligned} \tag{8}$$

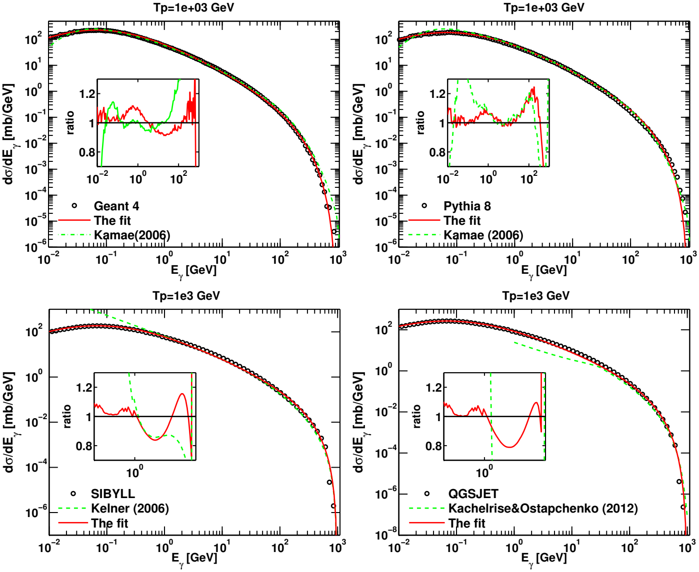
Gamma-ray spectra for $T_p < 1$ GeV



Geant4 γ-ray spectra for $1 \leq T_p \leq 100$ GeV



Gamma-ray spectra fits at $T_p = 1$ TeV



Summary

We have a new parametrization for $pp \to \gamma$ production cross section

- It covers the energy $T_p^{\mathrm{th}} \leq T_p \leq 1$ PeV
- Simple & Accurate formulas (< 20 %)
- Flexible to switch between different Hadronic models

For more details ⇒ arXiv:1406.7369 [astro-ph].