lecture 6. hadronic processes

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Advanced Astroparticle Physics

NPAC M2

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in today's class...

- **relativistic kinematics**
  - review of relativistic kinematics
- **cross sections**
- **particle interactions**
  - general formulation
  - mean free paths
- **propagation of cosmic particles**
  - electrons
  - photons
  - nuclei
  - neutrinos

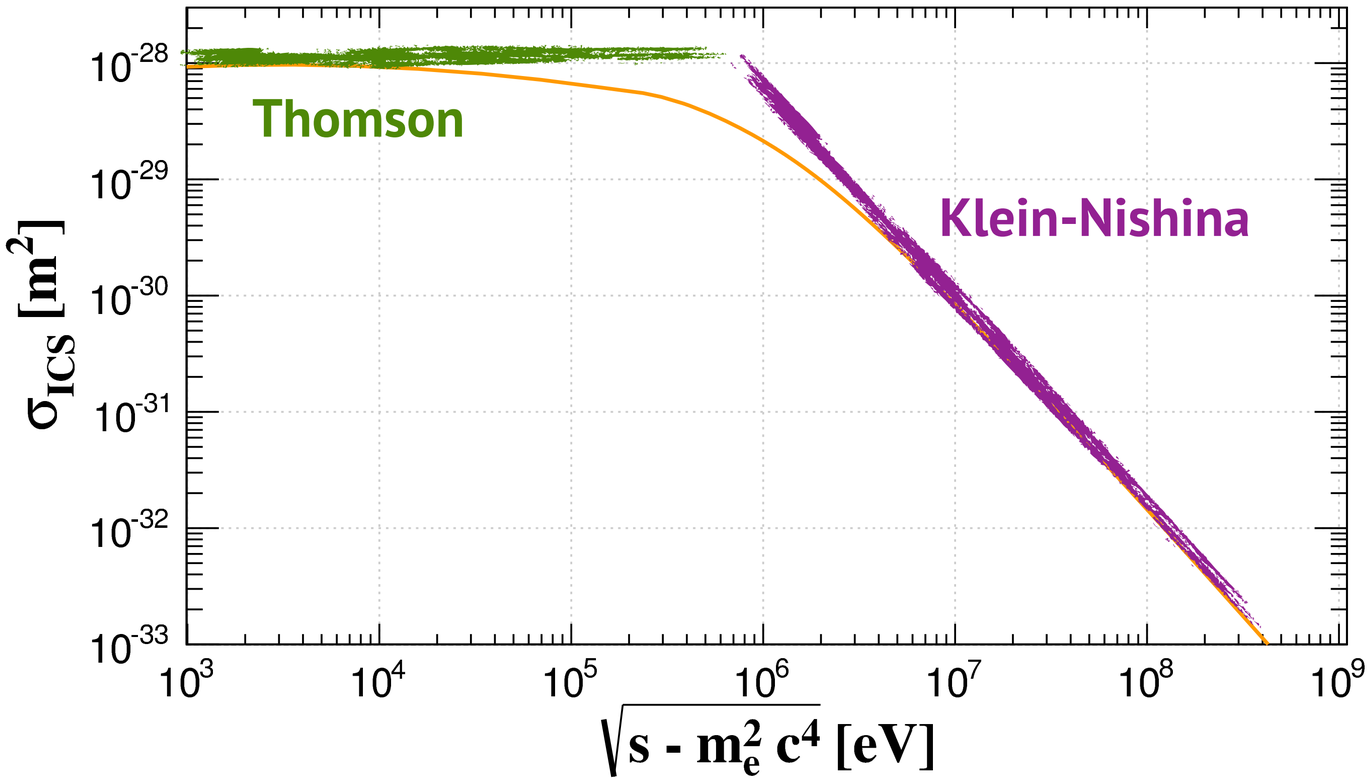
electromagnetic processes

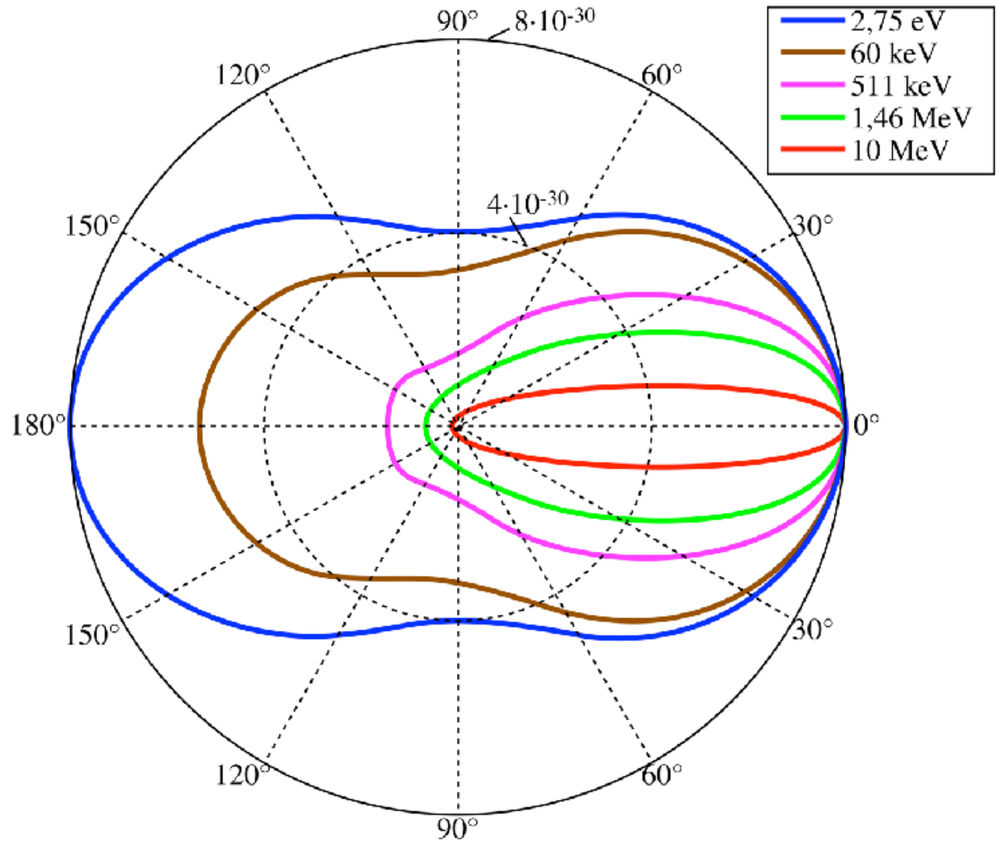
inverse Compton scattering

$$e^{\pm} + \gamma_{\mathrm{bg}} \rightarrow e^{\pm} + \gamma$$

cross section

$$\sigma(s) = \frac{3\sigma_T}{8\beta}\frac{m_e^2 c^4}{s}\left[\frac{2}{\beta(1+\beta)}(2+2\beta-\beta^2-2\beta^3) - \frac{1}{\beta^2}(2-3\beta^2-\beta^3)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$





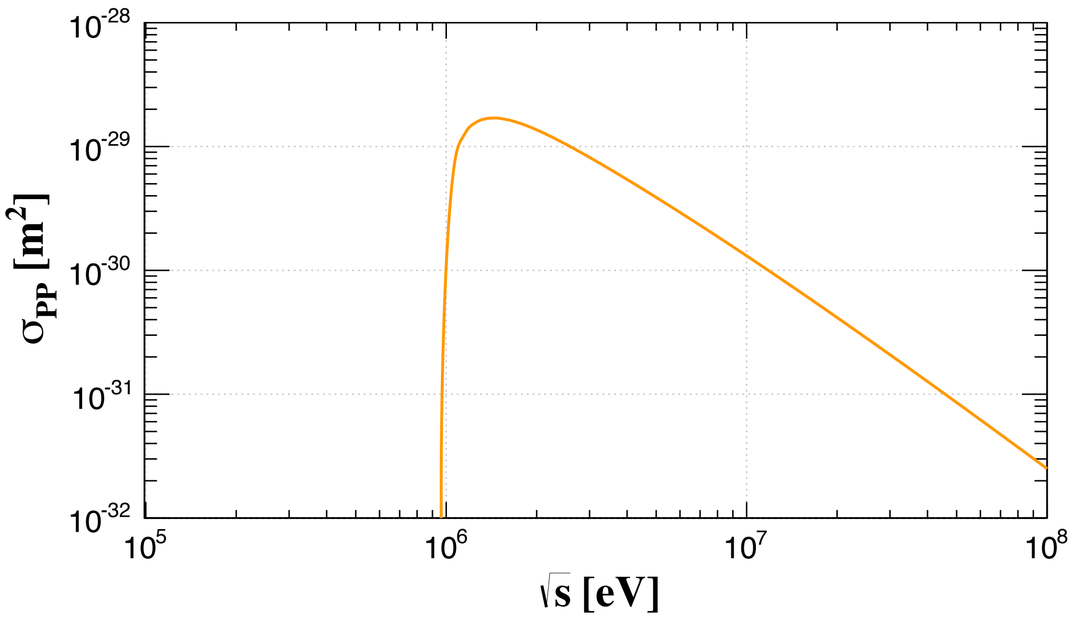
https://en.wikipedia.org/wiki/Klein%E2%80%93Nishina_formula#/media/File:Klein-Nishina_distribution-en.svg

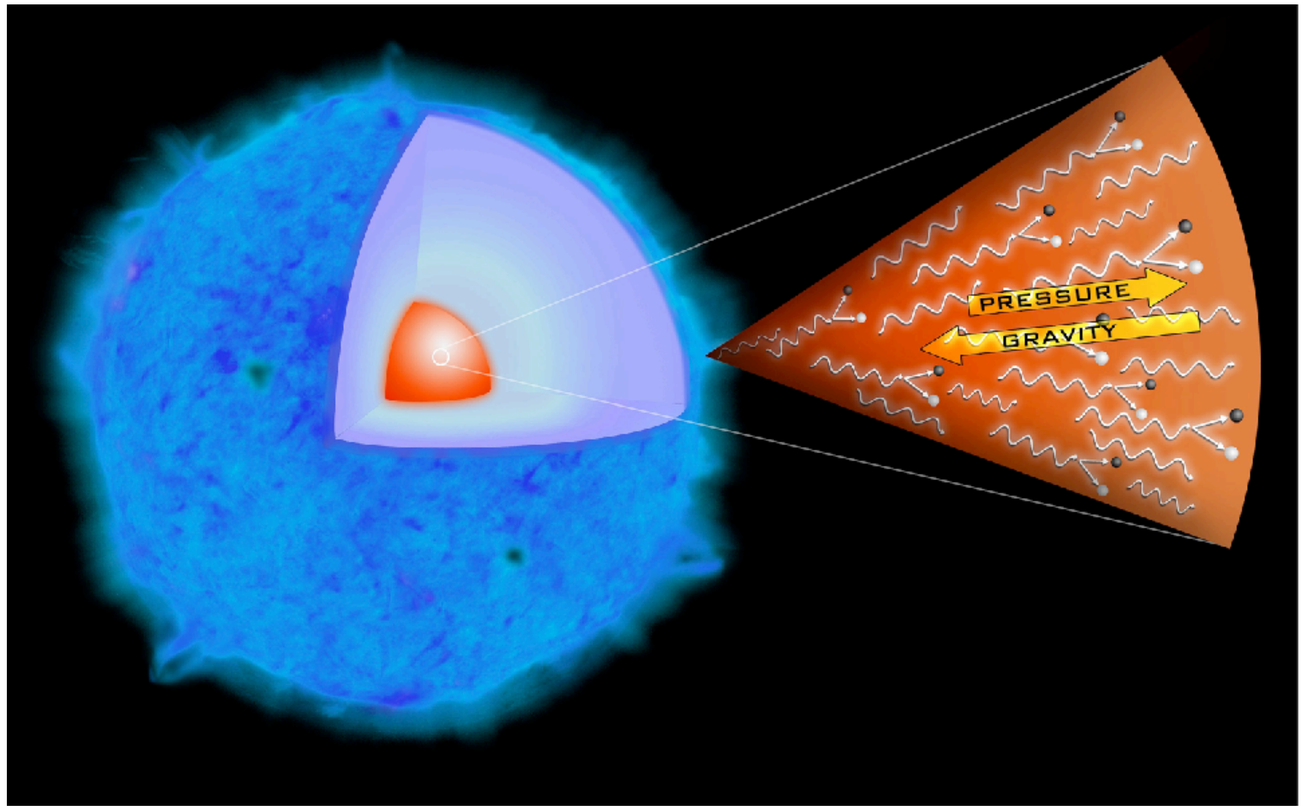
Breit Wheeler pair production

$$\gamma + \gamma_{\mathrm{bg}} \rightarrow e^{+} + e^{-}$$

cross section

$$\sigma(\beta) = \frac{3\sigma_{\mathrm{T}}}{16}\left(1-\beta^{2}\right)\left[\left(3-\beta^{4}\right)\ln\left(\frac{1+\beta}{1-\beta}\right) - 2\beta\left(2-\beta^{2}\right)\right]$$

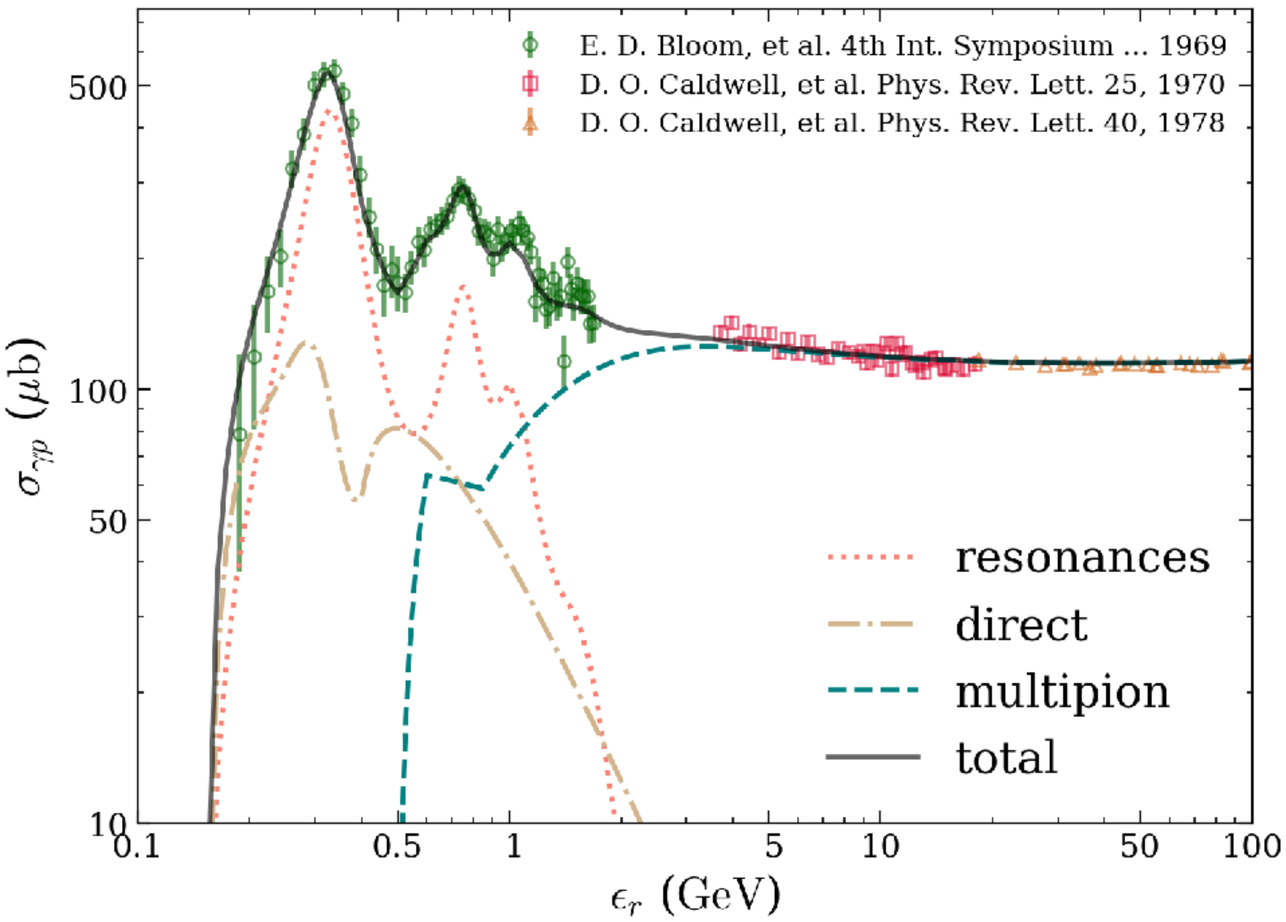




hadronic processes

$$p + \gamma_{\rm bg} \rightarrow \cdots$$

Morejon et al. JCAP 11 (2019) 007. arXiv:1904.07999

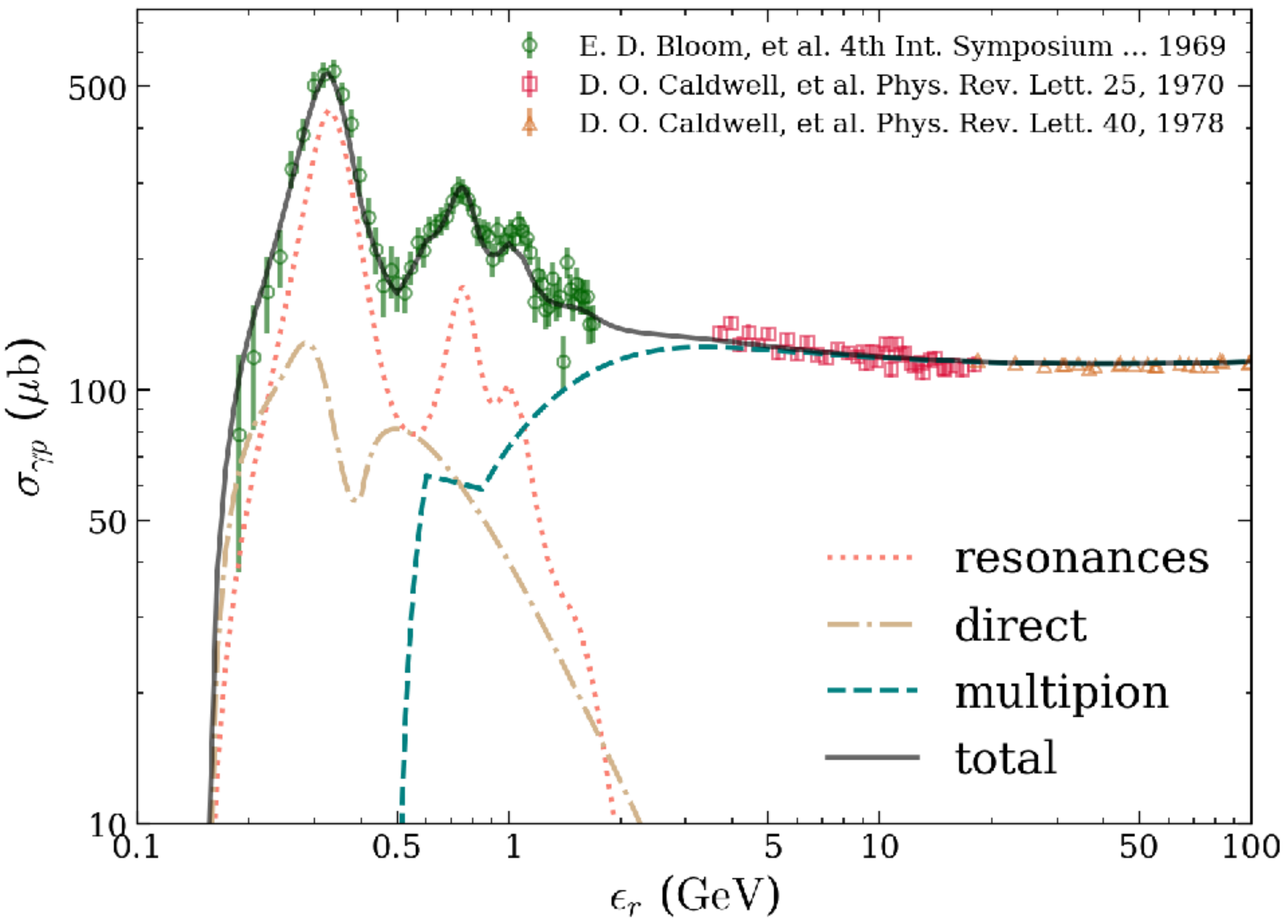


Exercise. In the figure ε_r refers to the photon energy in the proton res frame. Knowing that, what should the value of ε_r be for a proton of 10^{20} eV interacting with the CMB (ε ~0.6 meV in the lab frame)?

hadronic processes. proton-photon interactions: Bethe-Heitler pair production

$$ {}^{A}_{Z}X + \gamma_{\mathrm{bg}} \rightarrow {}^{A}_{Z}X + e^{+} + e^{-} $$

Morejon et al. JCAP 11 (2019) 007. arXiv:1904.07999



$$p + \gamma_{\rm bg} \rightarrow \Delta^+$$
$$n + \gamma_{\rm bg} \rightarrow \Delta^0$$

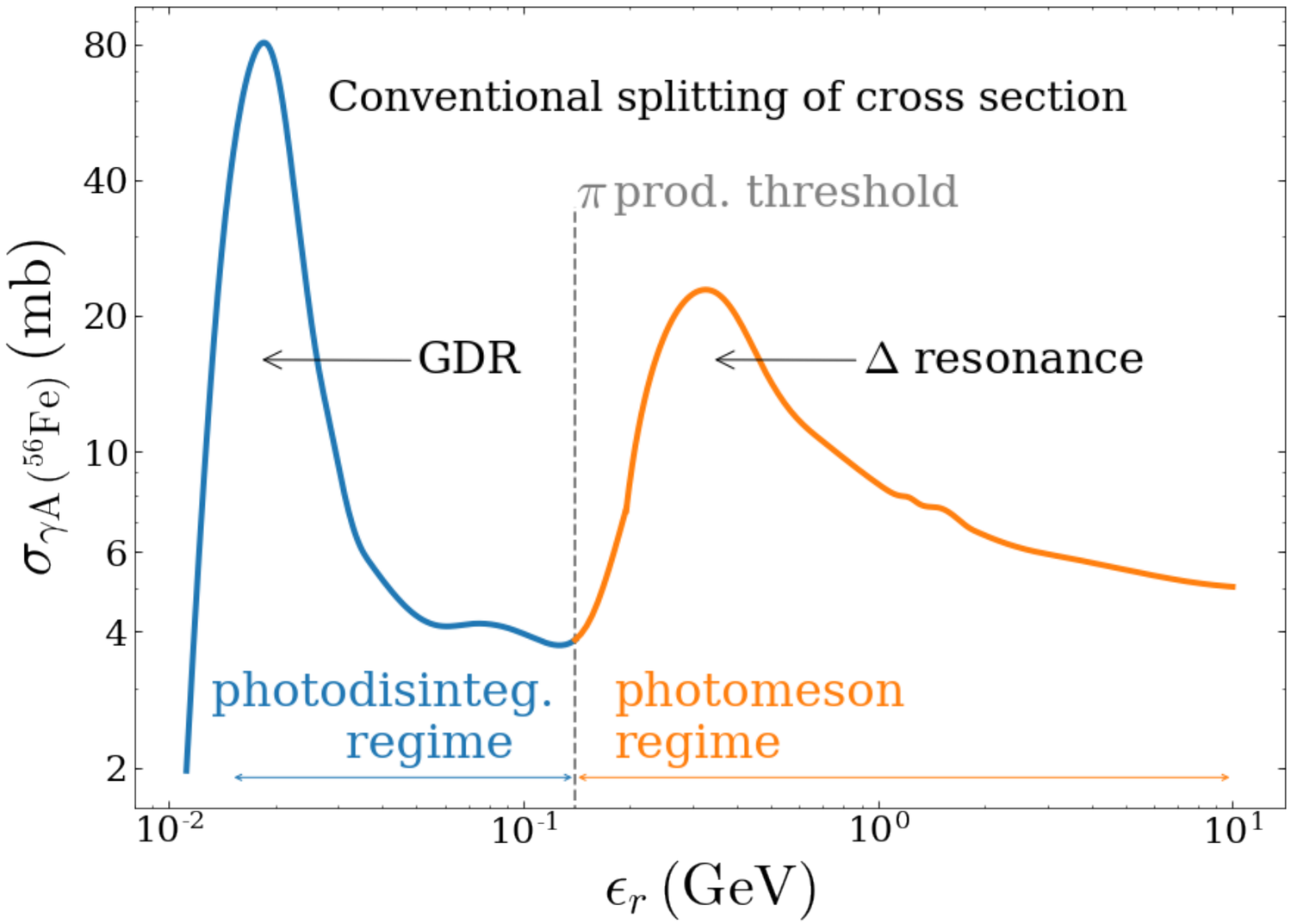
$$\Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \qquad \Delta^0 \rightarrow \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$$

$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\pi^- \rightarrow \bar{\nu}_\mu + \mu^-$$

$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$
$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$$

** main channels only*

$$
\begin{aligned}
{}^{A}_{Z}X + \gamma_{\mathrm{bg}} &\rightarrow {}^{A-1}_{Z-1}X + p \\
{}^{A}_{Z}X + \gamma_{\mathrm{bg}} &\rightarrow {}^{A-1}_{Z}X + n \\
{}^{A}_{Z}X + \gamma_{\mathrm{bg}} &\rightarrow {}^{A-4}_{Z-2}X + \alpha \\
{}^{A}_{Z}X + \gamma_{\mathrm{bg}} &\rightarrow \dots
\end{aligned}
$$

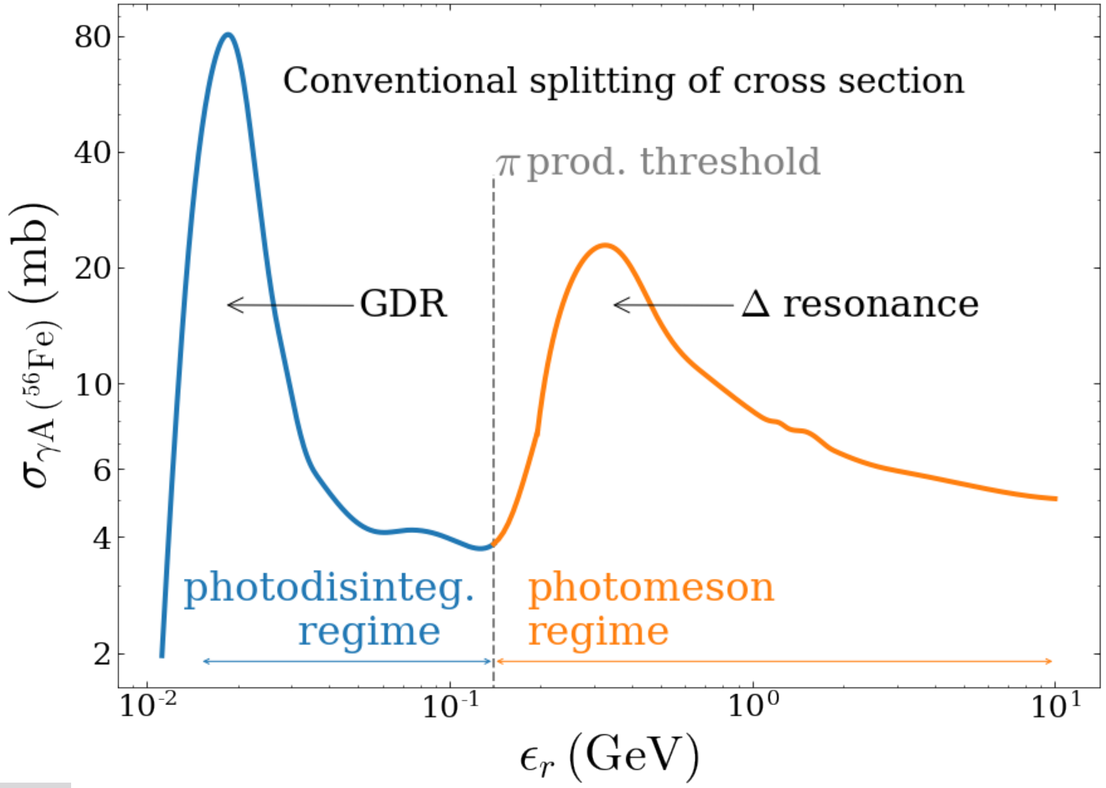


Morejon et al. JCAP 11 (2019) 007. arXiv:1904.07999

hadronic processes. **nucleus-photon interactions**

$$
\begin{aligned}
{}^{A}_{Z}X + \gamma_{\rm bg} &\rightarrow {}^{A-1}_{Z-1}X + p \\
{}^{A}_{Z}X + \gamma_{\rm bg} &\rightarrow {}^{A-1}_{Z}X + n \\
{}^{A}_{Z}X + \gamma_{\rm bg} &\rightarrow {}^{A-4}_{Z-2}X + \alpha \\
{}^{A}_{Z}X + \gamma_{\rm bg} &\rightarrow \dots
\end{aligned}
$$

Morejon et al. JCAP 11 (2019) 007. arXiv:1904.07999



- photodisintegration
- heavier nuclei do not disintegrate as slowly as lighter ones

$$s = (P_\gamma + P_A)^2 = (P'_\gamma + P'_A)^2$$

$$[Zm_p + (A-Z)m_n]^2c^4 + 2\,[Zm_p + (A-Z)m_n]c^2\,\varepsilon'$$

$$[Zm_p + (A-Z)m_n]^2c^4 + 2E\varepsilon(1-\beta\cos\theta)$$

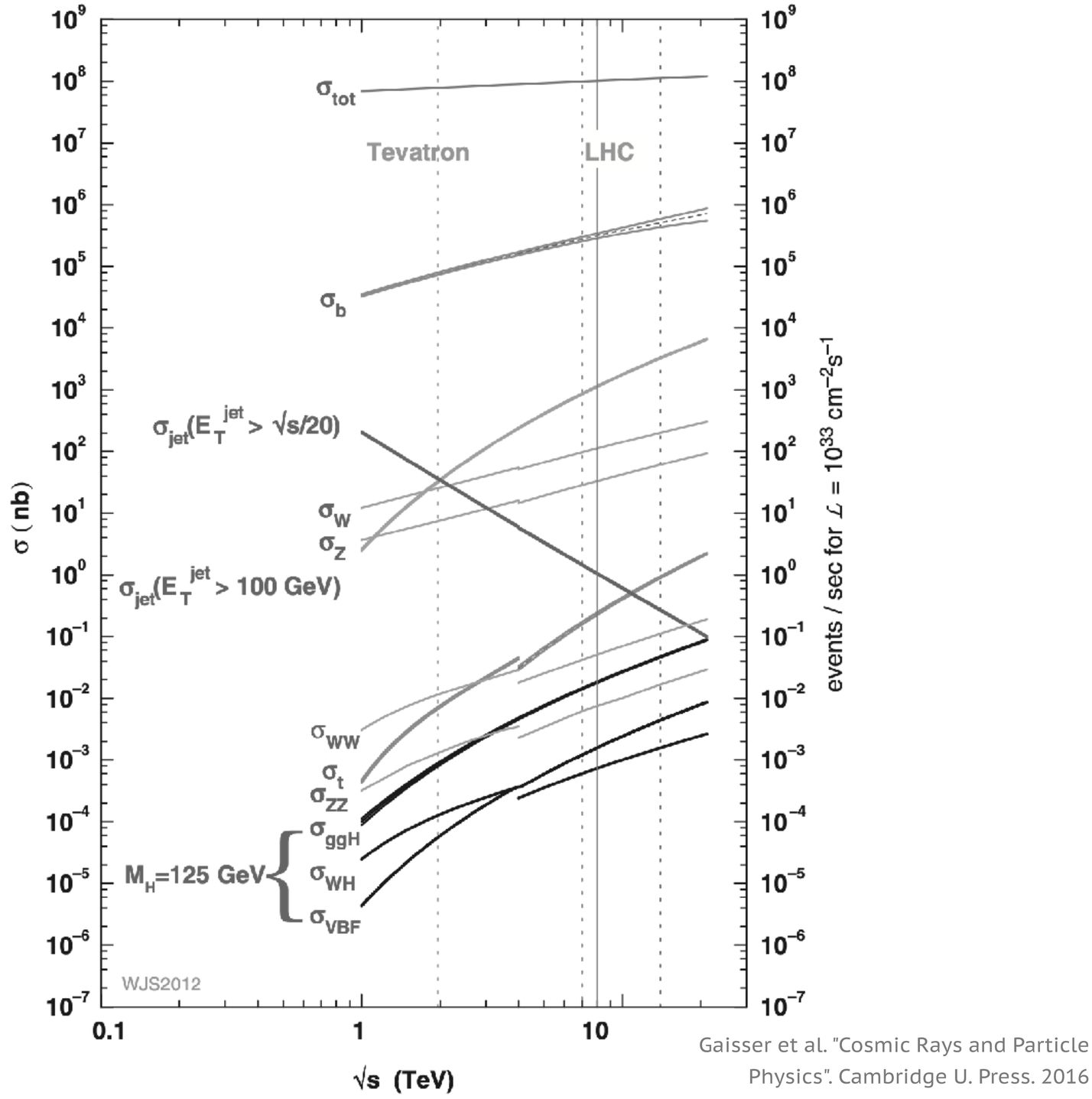
$Zm_p + (A-Z)m_n \approx Am_p$

$$A^2m_p^2c^4 + 2Am_pc^2\varepsilon'$$

$$A^2m_p^2c^4 + 2E\varepsilon(1-\beta\cos\theta)$$

$$E_A \gtrsim \frac{Am_pc^2}{1-\beta\cos\theta}\frac{\varepsilon'}{\varepsilon}$$

$$p + p \rightarrow \begin{cases} p + p + \pi^0 \\ p + p + \pi^0 + \pi^0 \\ p + n + \pi^+ + \pi^0 \\ p + n + \pi^+ + \pi^- + \pi^0 \end{cases}$$

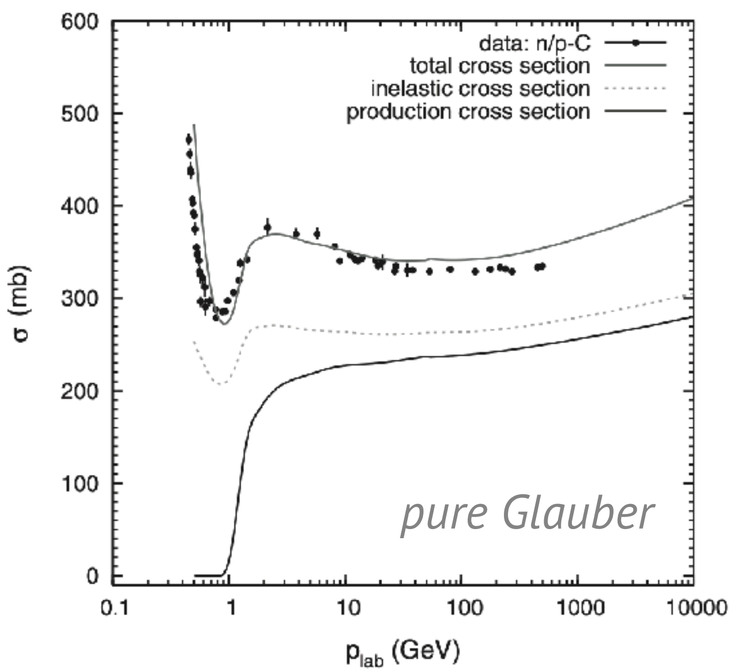


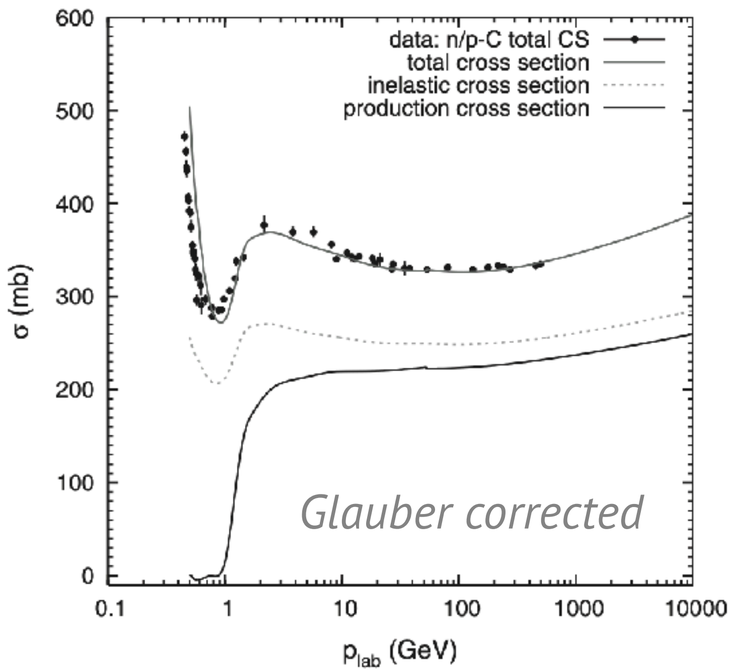
Gaisser et al. "Cosmic Rays and Particle Physics". Cambridge U. Press. 2016

$$ {}^{A}_{Z}X + {}^{A_{\mathrm{bg}}}_{Z_{\mathrm{bg}}}X_{\mathrm{bg}} \rightarrow \dots $$

- use proton-proton cross sections as templates
- **Glauber model** for cross sections
- coherent **superposition** of nucleon-nucleon interactions

$$ \sigma_{\mathrm{inel}} \approx \int d^2b \left[1 - \exp\left(-\sigma_{\mathrm{tot}}^{\mathrm{nn}} \right) T_{\mathrm{bg}}(\vec{b}) \right] $$





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