RUB

SFB1491

Cosmic Interacting Matters
from source to signal

RAPP Center

HADRONIC INTERACTIONS IN CRPROPA

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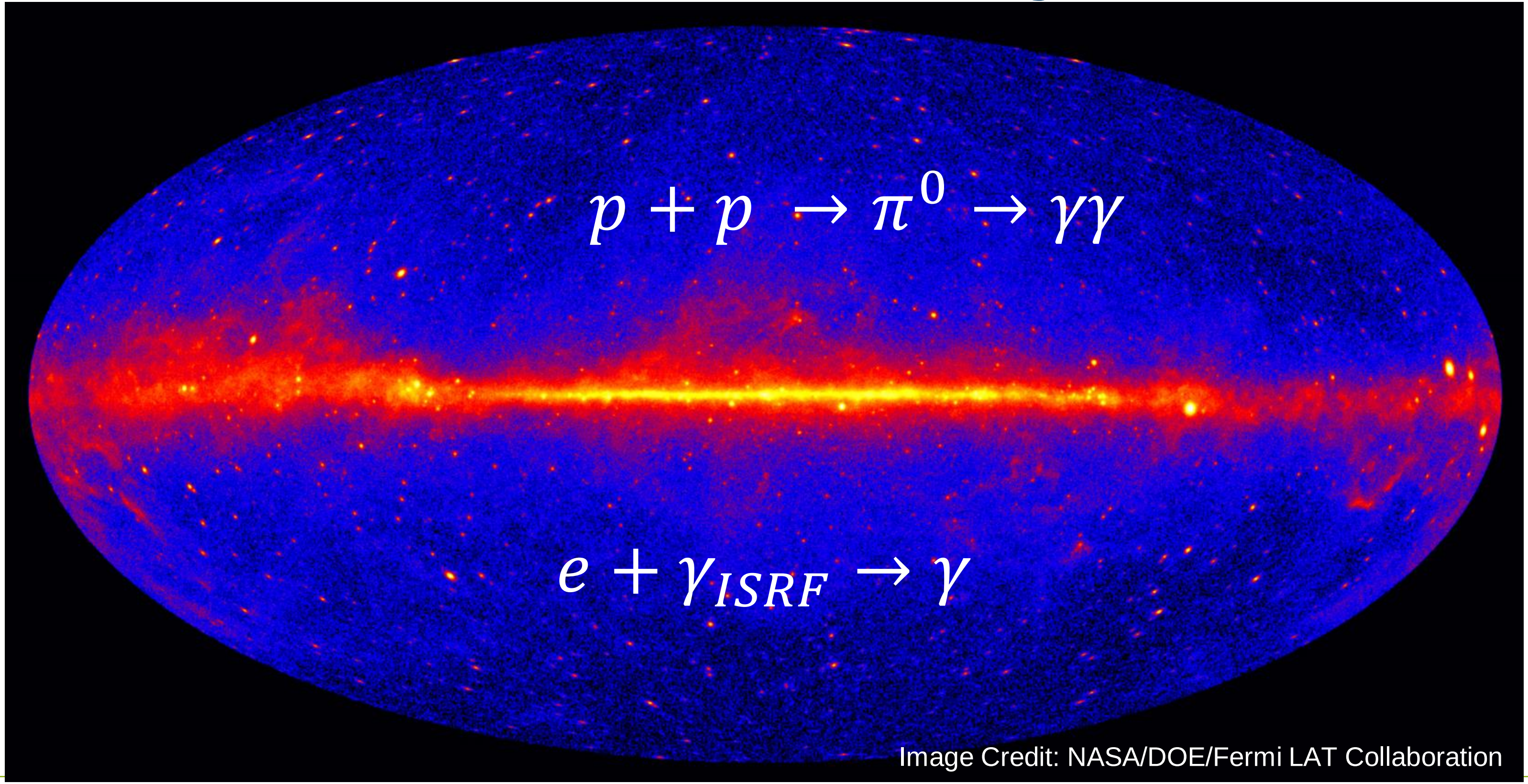
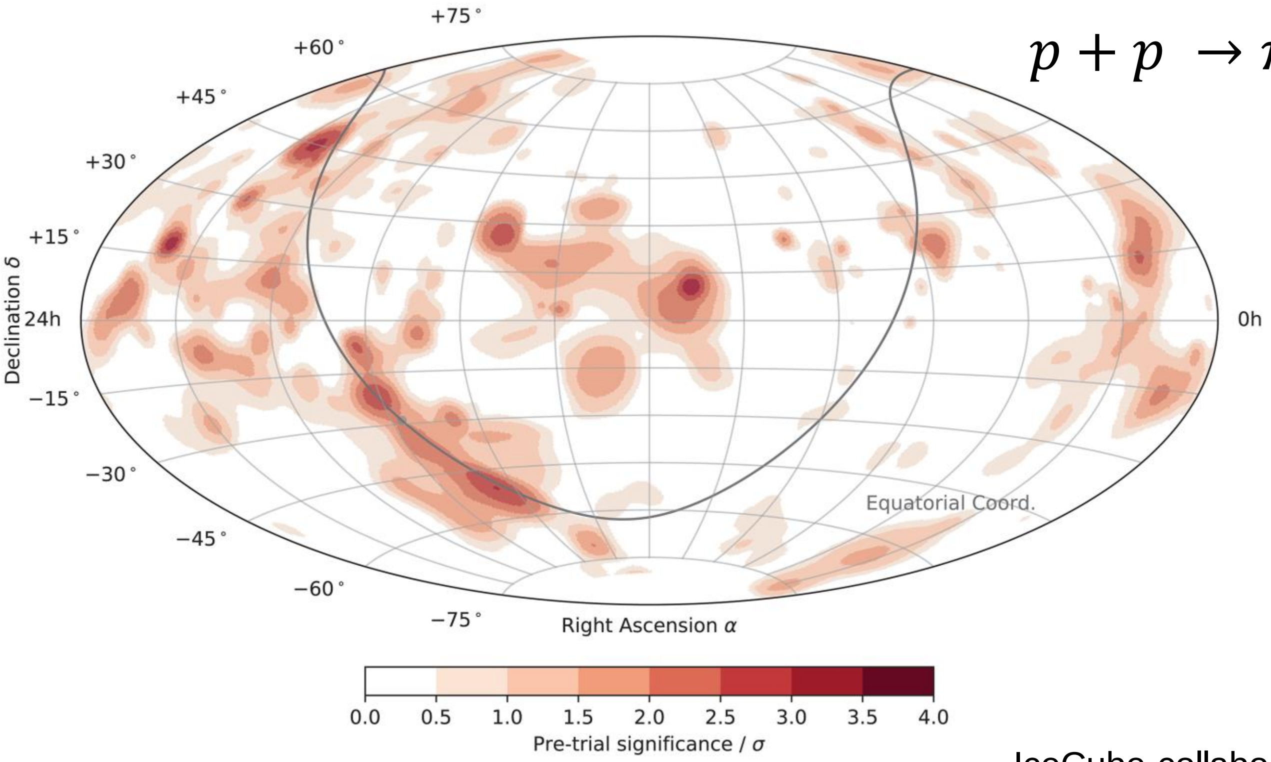
motivation

Impact of Galactic Cosmic Rays



Impact of Galactic Cosmic Rays

$$p + p \rightarrow \pi^{\pm} \rightarrow \nu_\mu \nu_e \nu_\mu \, e^{\pm}$$



IceCube collaboration, Science 380, 6652

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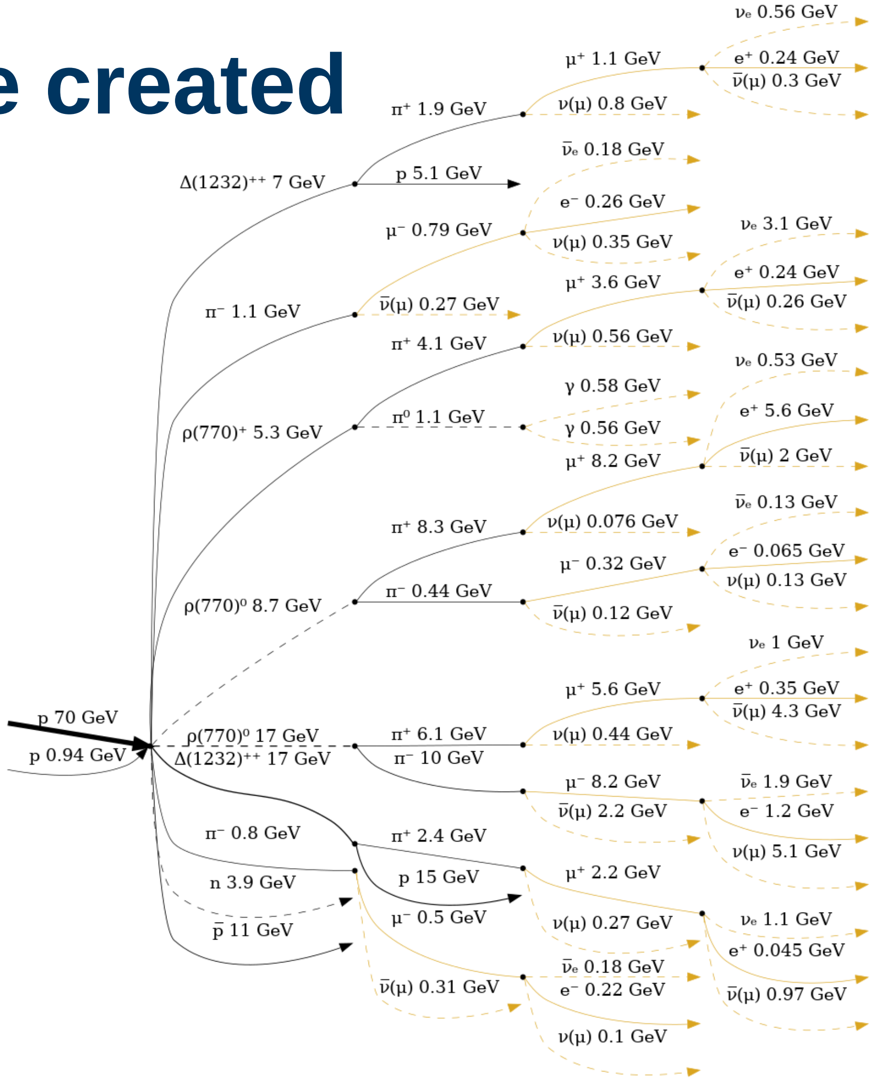
bunch of particles can be created

- $p + p \ \rightarrow \pi^0 \rightarrow \gamma\gamma$
  dominant process for diffuse galactic gamma-ray emission

- $p + p \ \rightarrow \pi^{\pm} \ \rightarrow e^{\pm}\, \nu_e\, \nu_\mu$
  production of (Galactic) neutrinos as seen in IceCube

- $p + p\ (A) \rightarrow \bar{p}, \bar{n}, \overline{He}$
  seen by AMS-02



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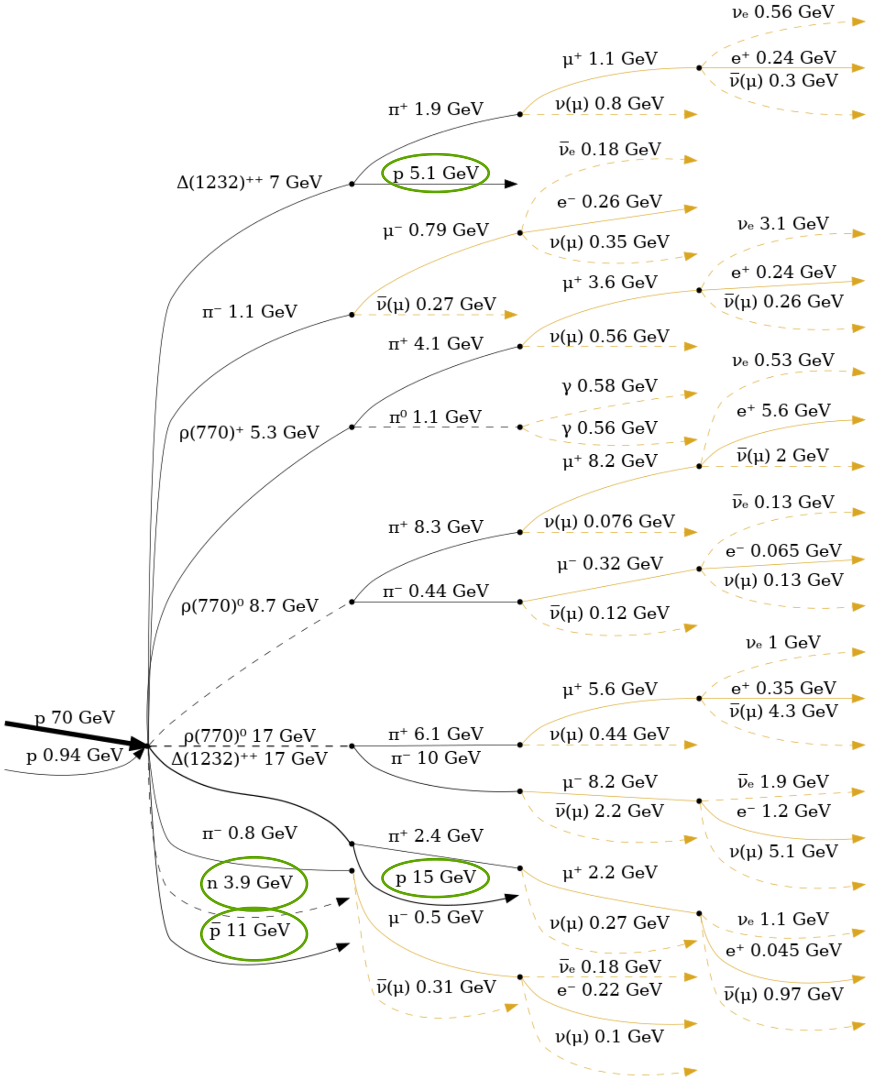
Final state of interaction

- e^{-}, e^{+}
- $\nu_e, \bar{\nu}_e$
- $\nu_\mu, \bar{\nu}_\mu$
- $p, \bar{p}, n, \bar{n}$

includes up scattered proton and primary after interaction



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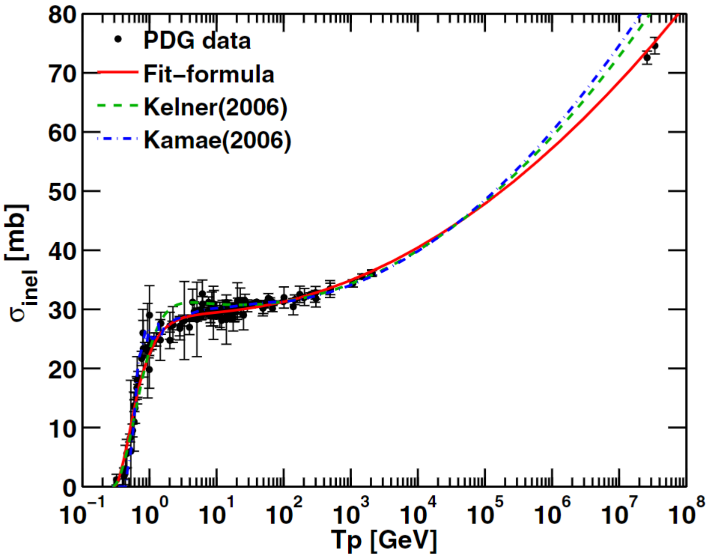
Crossection models

cross-section: inclusive and inelastic

Inelastic cross-section: Kafexhiu+ (2014)

$$\sigma_0(T_p) = [30.7 - 0.96\log(x) + 0.18\log^2(x)] \times [1 - x^{1.9}]^3 \text{ mb}$$

$$x = \frac{T_p}{T_p^{th}}\ ;\ T_p^{th} = 2m_\pi + \frac{m_\pi^2}{2\,m_p} \approx 0.2797\text{ GeV}$$



→ total interaction probability:

$$p = n_{gas} \cdot \sigma \cdot \Delta s$$

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cross-section: inclusive and inelastic

Differential inclusive cross-section:

For each secondary species s

$$\frac{d\sigma^{(s)}}{d\epsilon}(T_p, \epsilon) = \sigma_0(T_p) \cdot \frac{dN_s}{d\epsilon}$$

cross-section: inclusive models

Name	proj	targ.	Incl. secondaries	Primary energy	Secondary energy
Kelner+ (2006)	p	p	$\gamma, e, \nu_e, \nu_\mu$ or π	$0.1 - 10^5$ TeV	$10^{-3} \leq \frac{\epsilon}{T_p} \leq 1$
Kafexhiu+ (2014)	p	p	γ	$T_p < 512$ TeV	As primary
AAfrag Kachelrieß+ (2019)	p, He, C, Al, Fe, $\bar{p}$	p, He	$\gamma, e, \nu_e, \nu_\mu, p, n, \bar{d}, {}^3\overline{He}, {}^3\overline{\mathrm{H}}$	Proton: $5 - 10^{11}$ GeV	As primary
ODDK Orusa+ (2022, 2023)	$p, {}^2_1H, {}^3_2He, {}^4_2He, {}^{12}_6C, {}^{13}_6C, {}^{14}_7N, {}^{15}_7N, {}^{16}_8O$	p, He	$e^\pm, \gamma$	$e^\pm$: $10^{-4} - 10^3$ TeV γ: $10^{-4} - 10^4$ TeV	$10^{-5} - 10$ TeV $10^{-5} - 10^2$ TeV

CRPropa Plug-In

Precalculated data – for each secondary

- 2D – table with a CDF

$$\sigma_{\mathrm{CDF}}^{(s)}(T_p, \epsilon) = \int_{E_{th}}^{\epsilon} \mathrm{d}\epsilon' \, \frac{\mathrm{d}\sigma^{(s)}}{\mathrm{d}\epsilon'}$$

- Correction factor for missing energy loss $f_{loss}^{(s)}$

- Data are precalculated and collected with a config file
- Individual cross-section can be loaded and added to the module

workflow design

process - function

Decide on Interaction ?
- particle ID
- crosssection
- mass density

no →

Limit next step
$0.1\ \lambda_{\mathrm{MFP}}$

yes →

perform interaction

Number of secondaries per species

$$N^{(s)} = \frac{\sigma_{CDF}(T_p, T_p)}{\sigma_0(T_p)}$$

Sample secondary energy
- Random bin from CDF
- Random position in bin

Total energy loss

$$\sum_{s} \sum_{i=0}^{N^{(s)}} \epsilon_i \cdot f_{loss}^{(s)}$$

Add secondary if allowed

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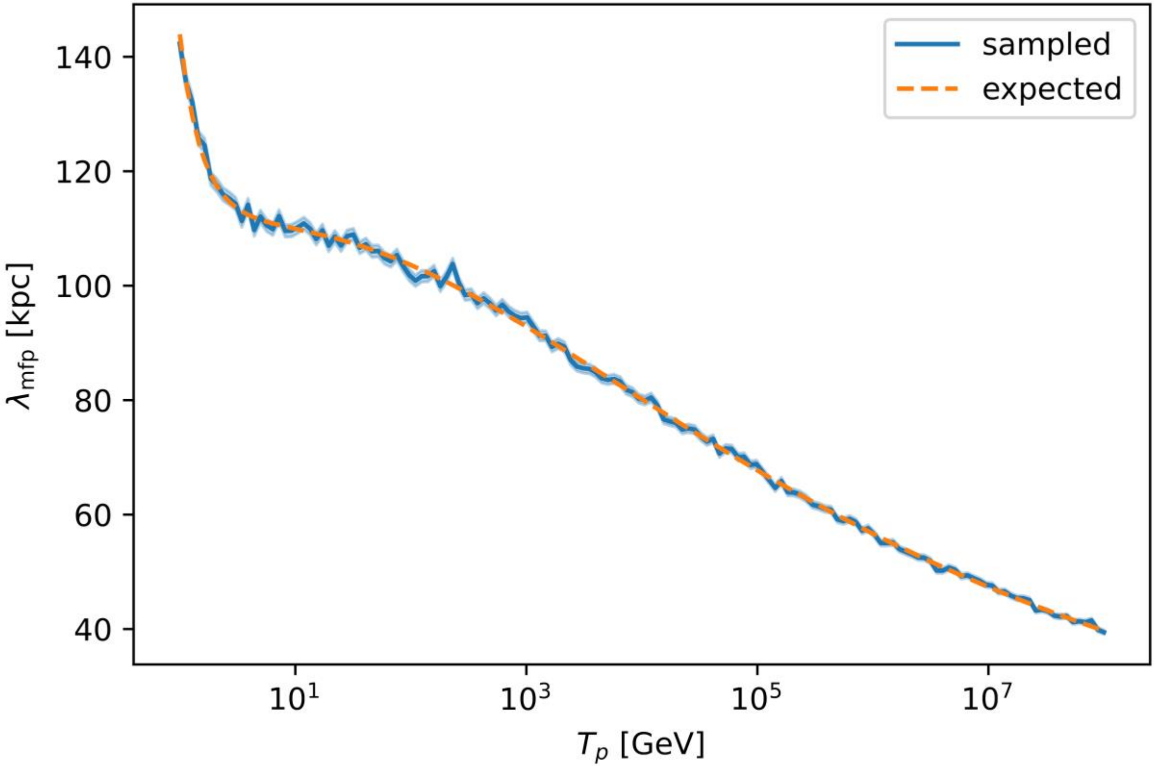
testing

mean free path

Mean free path

- 10^4 primary protons per energy
- Constant target density
  $n_H = 10^8 \text{ m}^{-3}$
- Fixed propagation step
  $\Delta s = 100$ pc
- Detect length for first interaction



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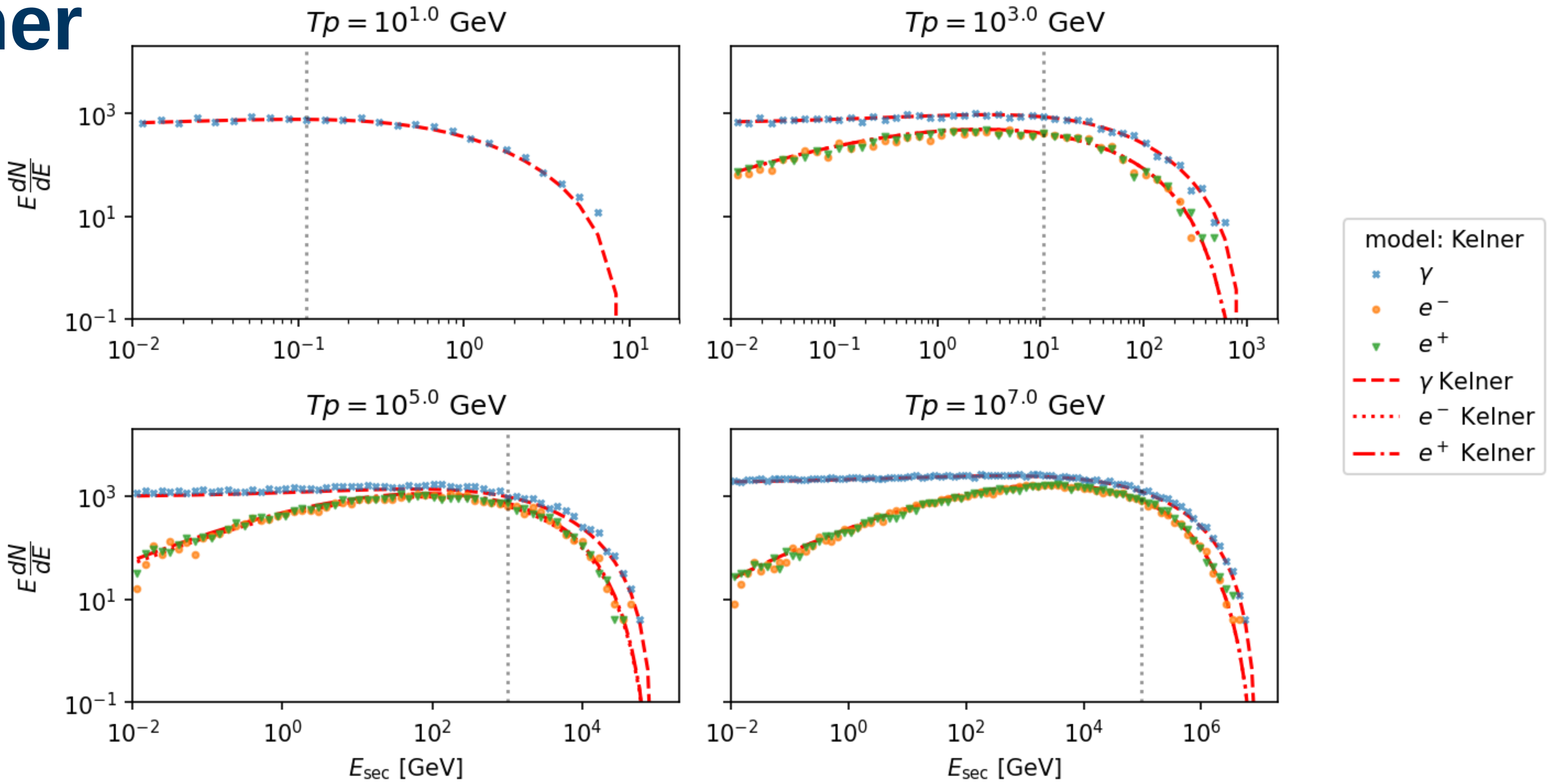
testing

yields

Simulation setup for testing yields

- Fixed primary energy T_p
- 10^5 calls of **`performInteraction`**
- Calculate spectra of secondary particles
- Compare to shape of differential cross section (normed at $10^{-2}\,T_p$)

Kelner



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testing

energy loss

Energy loss from crossection

Total energy loss per unit time:

$$-\frac{dE}{dt}(T_p) = \int_{E_{th}}^{T_p} d\epsilon \;\; v\, \epsilon\, n(\vec{r}) \sum_s \frac{d\sigma^{(s)}}{d\epsilon}(T_p, \epsilon)$$

Approximation by Krakau & Schlickeiser (2015)

$$\frac{dE}{dt}(T_p) \approx 3.85 \cdot 10^{-16} \cdot \left(\frac{n}{10^6\ \mathrm{m}^{-3}}\right) \cdot T_p^{1.28} \cdot \left(T_p + 200\ \mathrm{GeV}\right)^{-0.2}\ \mathrm{GeV/s}$$

Energy loss sampling

- 10^5 particles per primary energy
- Primary (kinetic energy) $1 \leq \frac{T_p}{\mathrm{GeV}} \leq 10^8$ with 70 points in logspace
- Density $n_H = 10^8\ \mathrm{m}^{-3}$
- Propagate only one step with $\Delta s = 0.01\,\lambda_{\mathrm{mfp}}$

$$\frac{dE}{dT} \approx \frac{\Delta E}{\Delta s/c}$$

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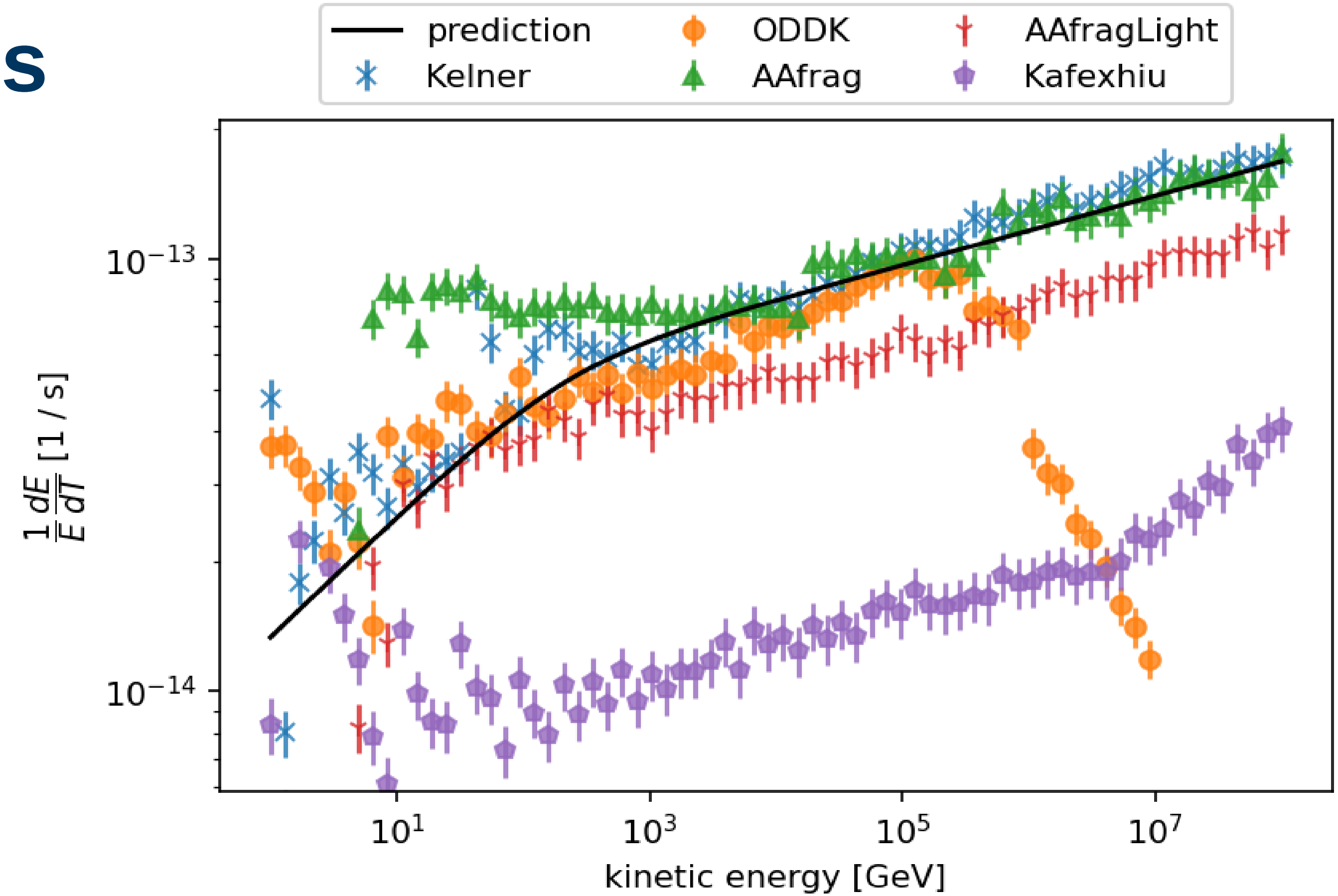
Energy loss



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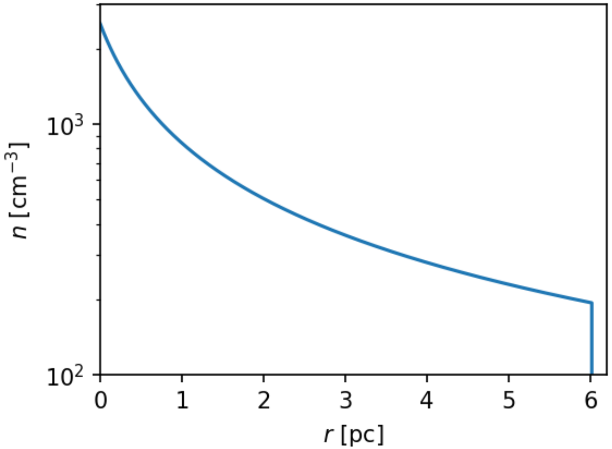
application

Giant Molecular Cloud

Giant Molecular Cloud – Rho Oph

- Spherical dens cloud $n(r) = \frac{n_0}{1+\frac{r}{R_0}}$
- Injection on a sphere around the cloud
- 10^8 particles with $1\,\mathrm{GeV} \leq T_p \leq 10^7\,\mathrm{GeV}$
- Direct detection of created γ-rays
- Injection spectrum reweighted to LIS

$$j_p(E) = 2.3\ E^{1.12}\ \beta^{-2} \left(\frac{E+0.67\ \mathrm{GeV}}{1.67\ \mathrm{GeV}}\right)^{-3.93} \ \frac{\mathrm{particle}}{\mathrm{GeV\ m^2\ s\ sr}}$$



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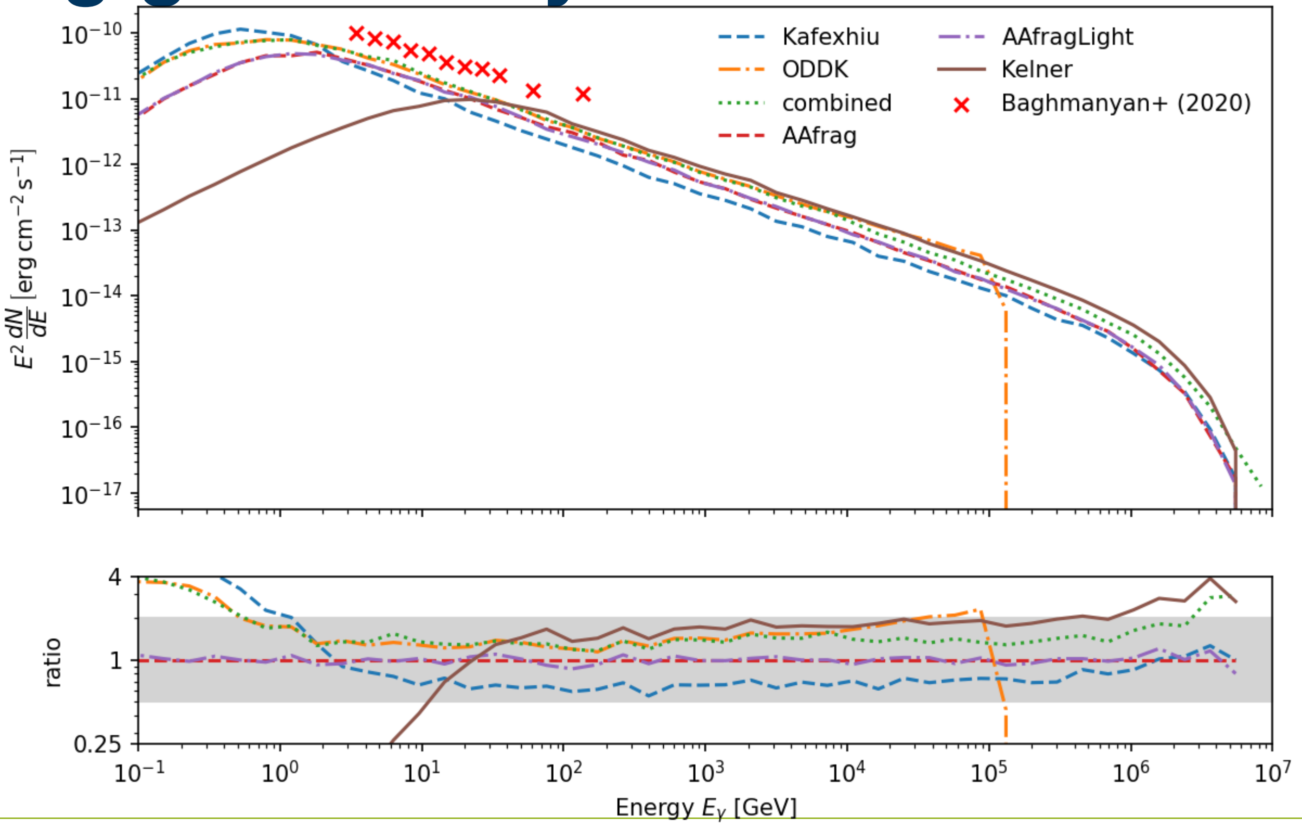
Resulting gamma-ray flux



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conclusion

Conclusion

- p-p interactions as a plug-in with custom secondaries
- Input: pre tabulated cross section for each secondary
- Tables available for: AAfrag, Kafexhiu, Kelner, ODDK
- Plug in tested for yields and energy loss
- results for different models with an uncertainty ~ 2 for astrophysical application

Backup slides

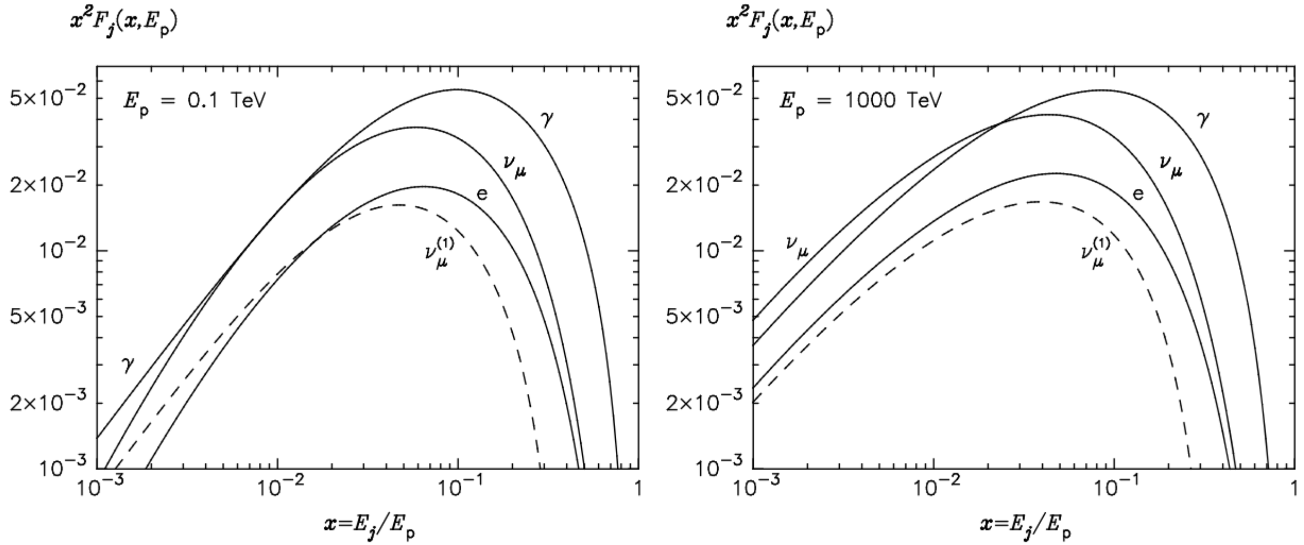
Differential cross-section models - Kelner

Paper: Kelner et al., PRD (2006) 034018, 74(3)

Energy range: $100\ \text{GeV} < T_p < 10^5\ \text{TeV}$ $\quad 10^{-3} \leq \frac{\epsilon}{T_p} \leq 1$

Included secondaries: $e^{\pm}$ (one species), ν_e, $\nu_\mu^{(1)}$, $\nu_\mu^{(2)}$ **or** $\pi^{\pm,0}$

interaction: p-p



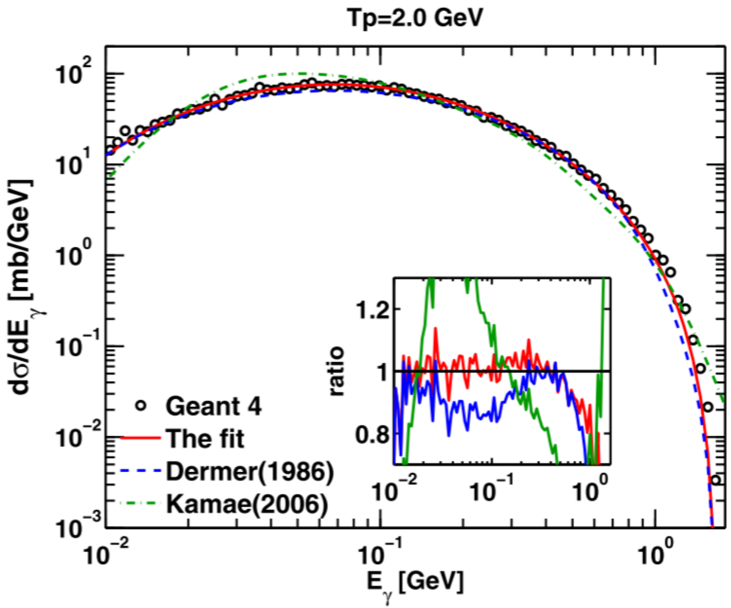
Differential cross-section models - Kafexhiu

Paper: Kafexhiu et al. PRD 90, 123014 (2014)

Included secondaries: γ

interaction: p-p

- Includes the $1\pi^0$ and $2\pi^0$ chanel
- Different parameters for different event generators



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Differential cross-section models - ODDK

Paper: Orusa et al. (2022, 2023)

Energy range:
$100 \text{ MeV} < T_p^{(e)} < 10^3 \text{ TeV}$
$10 \text{ MeV} < \epsilon_e \leq 10 \text{ TeV}$

$100 \text{ MeV} < T_p^{(\gamma)} < 10^4 \text{ TeV}$
$10 \text{ MeV} < \epsilon_\gamma \leq 100 \text{ TeV}$

Included secondaries: $e^\pm$ (separate), γ

interaction: projectile: ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O

target: p, He

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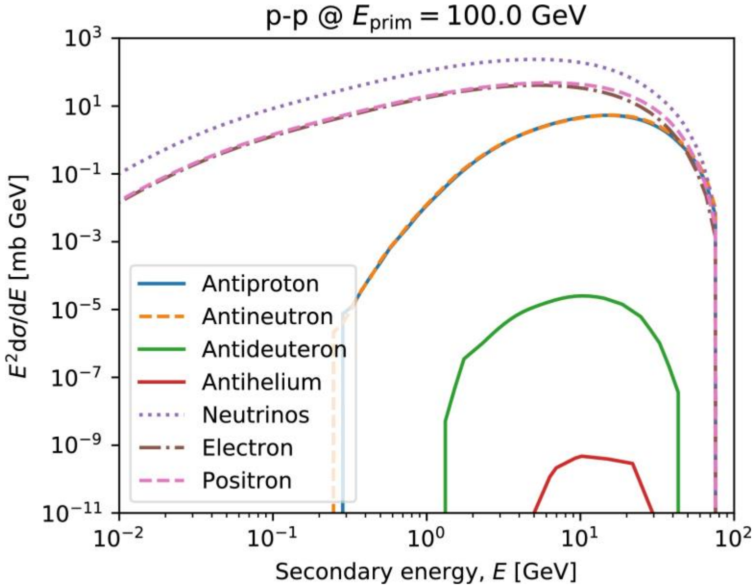
Differential cross-section models - AAfrag

Paper: Kachelrieß et al, (2019), Computer Physics Communications, 245, 106846

Included secondaries:

$e^-, \nu_e, \nu_\mu, \gamma, p, n, \bar{d},\ ^3\overline{He},\ ^3\overline{\mathrm{H}}$

interaction:
p-p, p-He, He-p, He-He, C-p, Al-p, Fe-p, $\bar{p}$-p, $\bar{p}$-p



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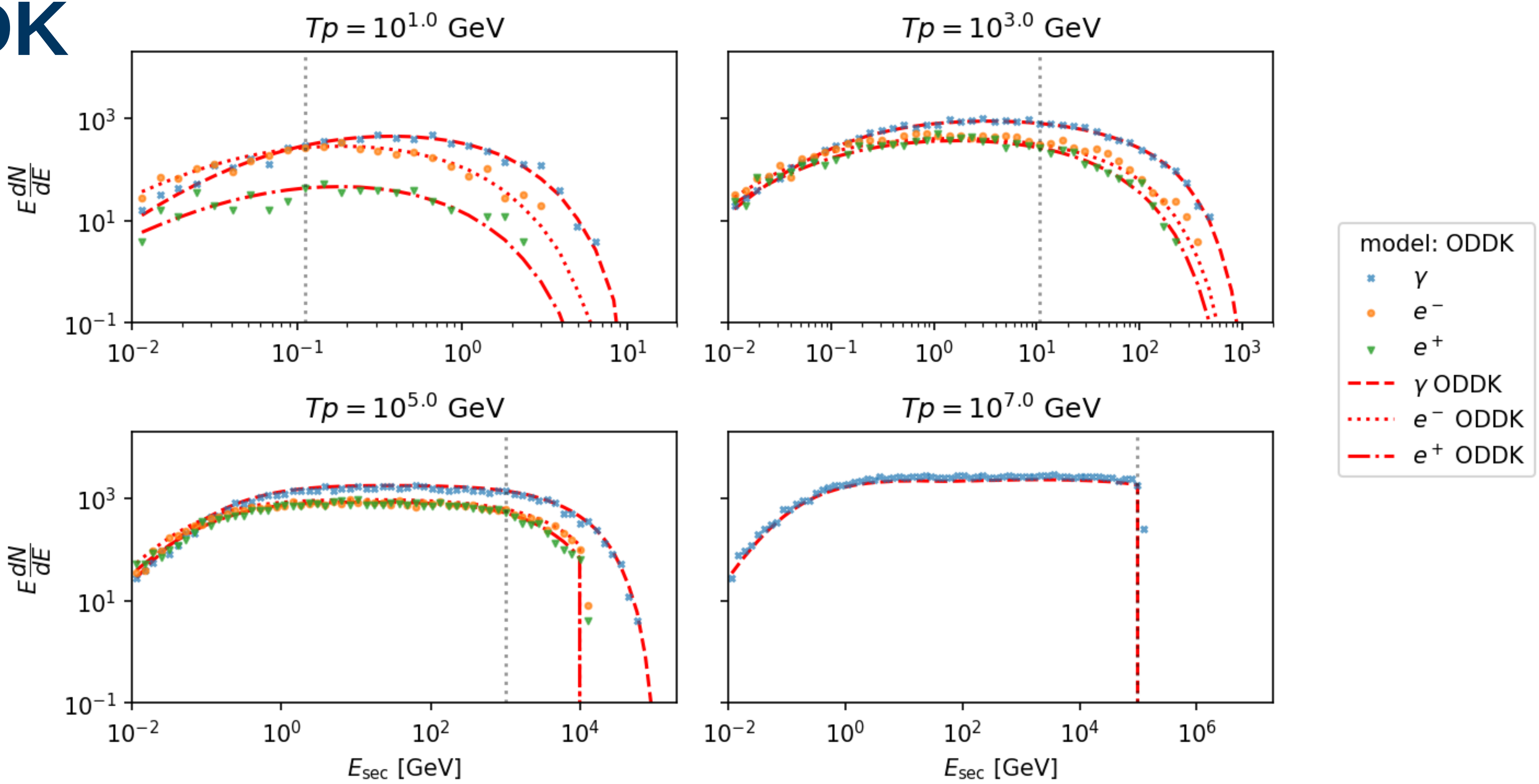
ODDK



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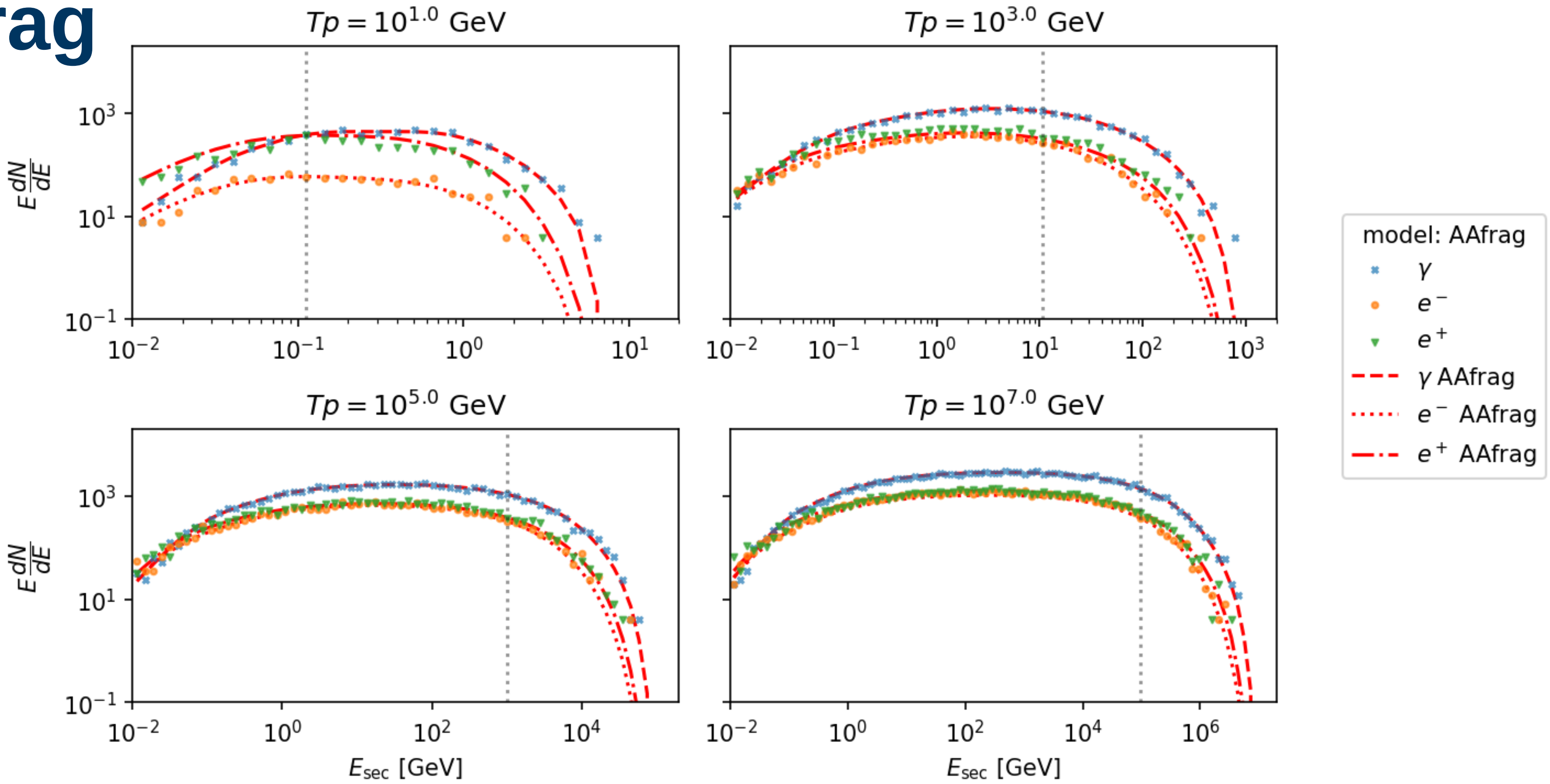
AAfrag



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