Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Karlsruhe Institute of Technology

High Energy Cosmic Ray Interactions

(Lecture 1: Basics)

Ralph Engel

Karlsruhe Institute of Technology (KIT)

Outline

Lecture 1 – Basics, low-energy interactions

- Energies, projectile and target particles
- Cross sections
- Particle production threshold: resonances
- Hadronic interactions of gamma-rays

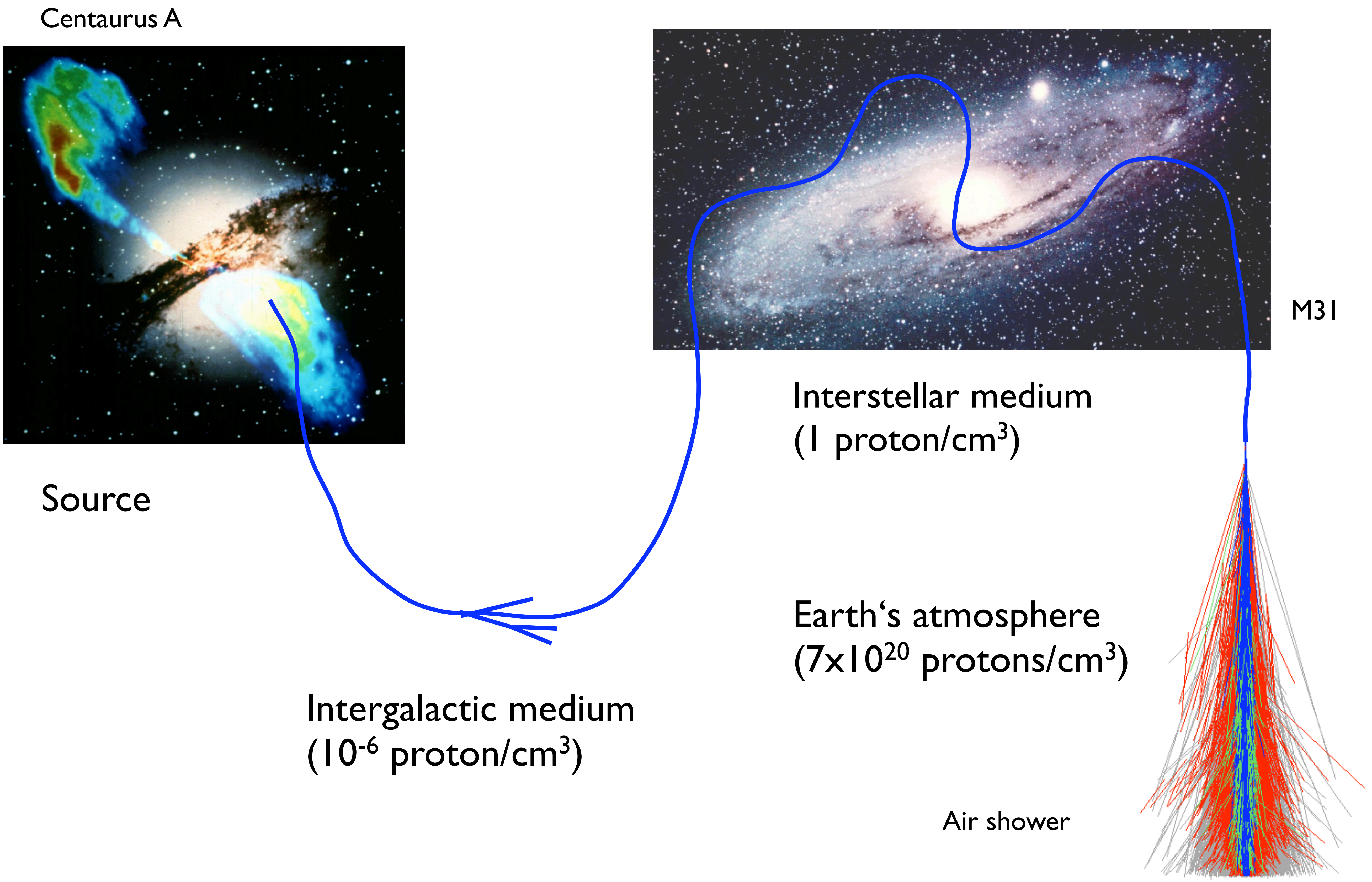
Lecture 2 – Intermediate energy physics

- Intermediate energy range: two-string models
- String fragmentation
- Rapidity, Feynman scaling
- Inclusive fluxes, spectrum weighted moments

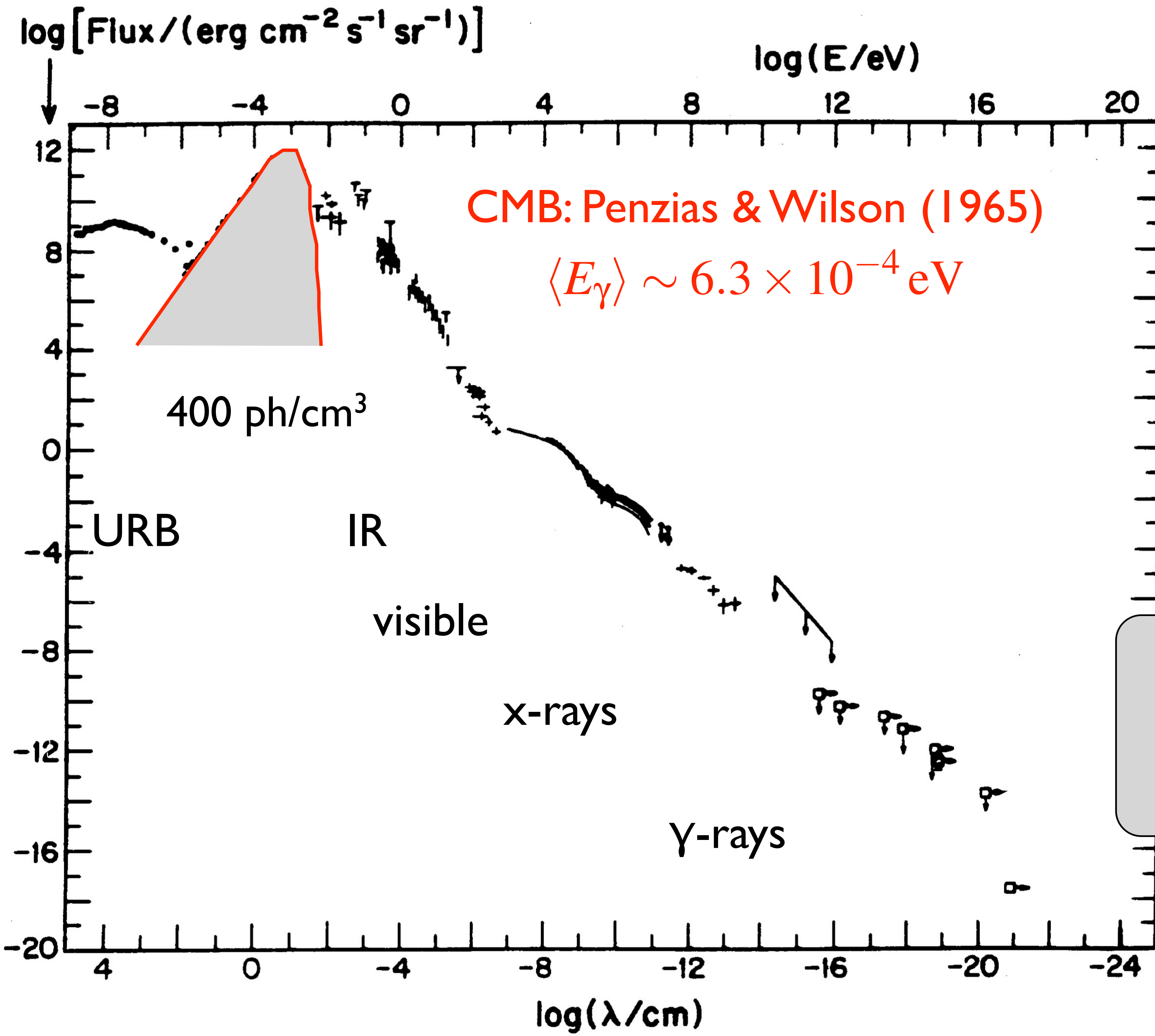
Lecture 3 – Highest energies, air shower phenomenology

- Minijets, multiple interactions, scaling violation
- Model predictions, uncertainties
- Elongation rate theorem
- Outlook: accelerator measurements

Examples of cosmic ray interactions



Radiation fields



Smaller interaction probability compensated by larger density

In source regions:
- much higher densities
- power-law spectra

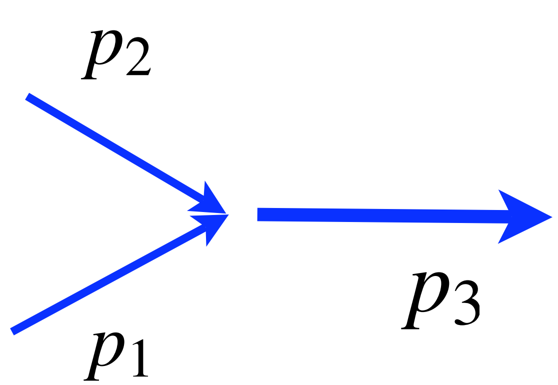
Four-momentum kinematics

Calculation with four-momenta (c=1) $\qquad p = (E, \vec{p})$

$$p_1 \cdot p_2 = E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2$$

$$p^2 = E^2 - \vec{p}^2 = m^2$$

Resonance production



Energy-momentum conservation

$$p_1 + p_2 = p_3$$

Mass of produced resonance

$$\begin{aligned} p_3^2 = m_3^2 = (p_1 + p_2)^2 &= (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 \\ &= p_1^2 + 2 p_1 \cdot p_2 + p_2^2 = m_1^2 + m_2^2 + 2E_1 E_2 - 2\vec{p}_1 \cdot \vec{p}_2 \end{aligned}$$

Laboratory and center-of-mass system

Mass of produced resonance

$$p_3^2 = m_3^2 = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$
$$= p_1^2 + 2p_1 \cdot p_2 + p_2^2 = m_1^2 + m_2^2 + 2E_1E_2 - 2\vec{p}_1 \cdot \vec{p}_2$$

Lab system: $p_1 = (E_1, \vec{p}_1)$ $p_2 = (m_2, \vec{0})$

$$\boxed{m_3^2 = 2m_2E_1 + m_1^2 + m_2^2}$$

Center-of-mass system (CMS, *): $\vec{p}_1^{\star} = -\vec{p}_2^{\star}$

$$\boxed{m_3^2 = (E_1^{\star} + E_2^{\star})^2}$$

CMS energy:

$$\boxed{E_{\rm cm} = \sqrt{s} = E_1^{\star} + E_2^{\star}}$$

Interaction of protons with photons of CMB

Energy threshold not sharp $E_{\gamma,\max} \approx 3 \times 10^{-3}\mathrm{eV}$

$$\boxed{E_{p,\min} = \frac{m_\Delta^2 - m_p^2}{E_{\gamma,\max}(1-\cos\theta)} \approx 5 \times 10^{19}\mathrm{eV}}$$

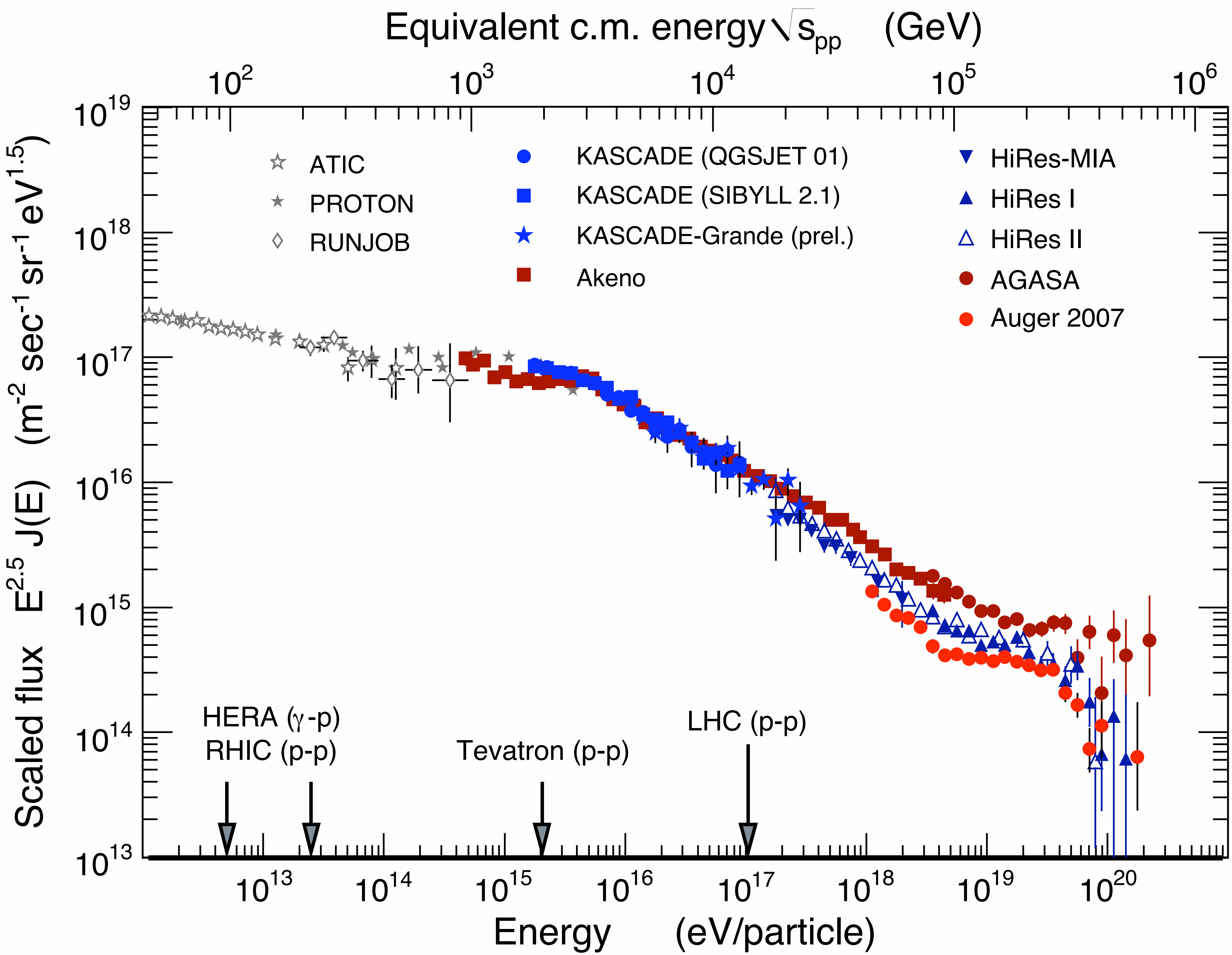
In proton rest frame:

$E_{\gamma,\mathrm{lab}} \approx 300\ \mathrm{MeV}$

Decay branching ratio proton:neutron = 2:1

Mean proton energy loss 20%

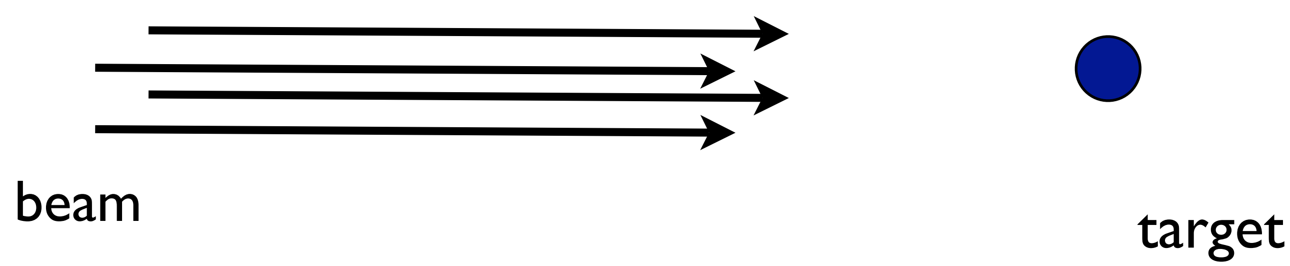
Decay isotropic up to spin effects



Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2 10^3 10^4 10^5 10^6
10^{19} 10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13}
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Auger 2007
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Energy (eV/particle)

Cross section

Defined as



$$\sigma = \frac{1}{\Phi}\frac{dN_{\mathrm{int}}}{dt}$$

(Units: 1 barn = 10^{-28} m^2
1 mb = 10^{-27} cm^2)

Flux of particles
on single target

$$\Phi = \frac{dN_{\mathrm{beam}}}{dA\,dt}$$

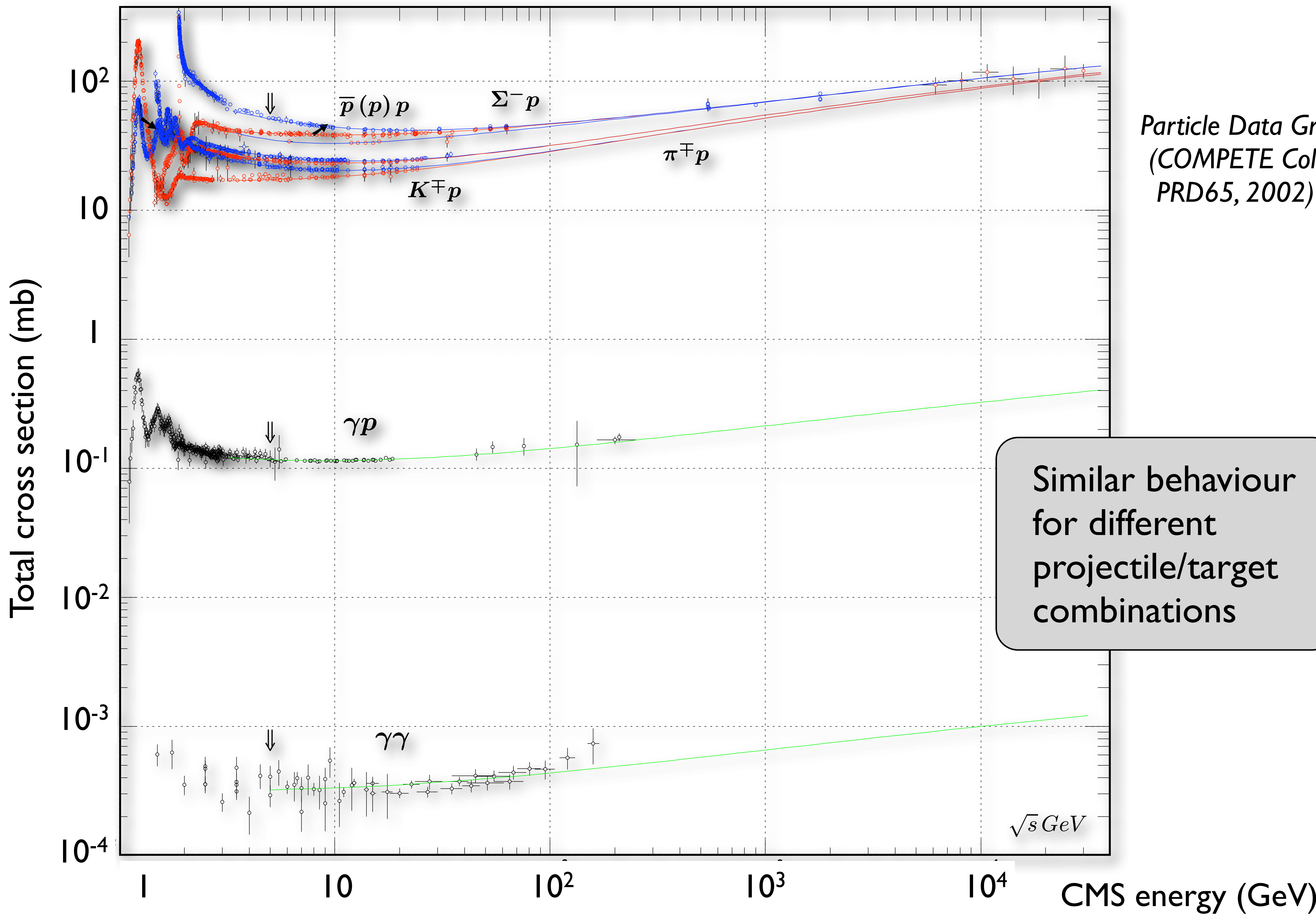
Interaction rate per unit time

Fundamental Lorentz-invariant quantity, can be measured at accelerators

``Master´´ equation for interaction rates

$$\frac{dN_{\mathrm{int}}}{dt\,dV} = \rho_{\mathrm{target}}\,\sigma\,\Phi$$

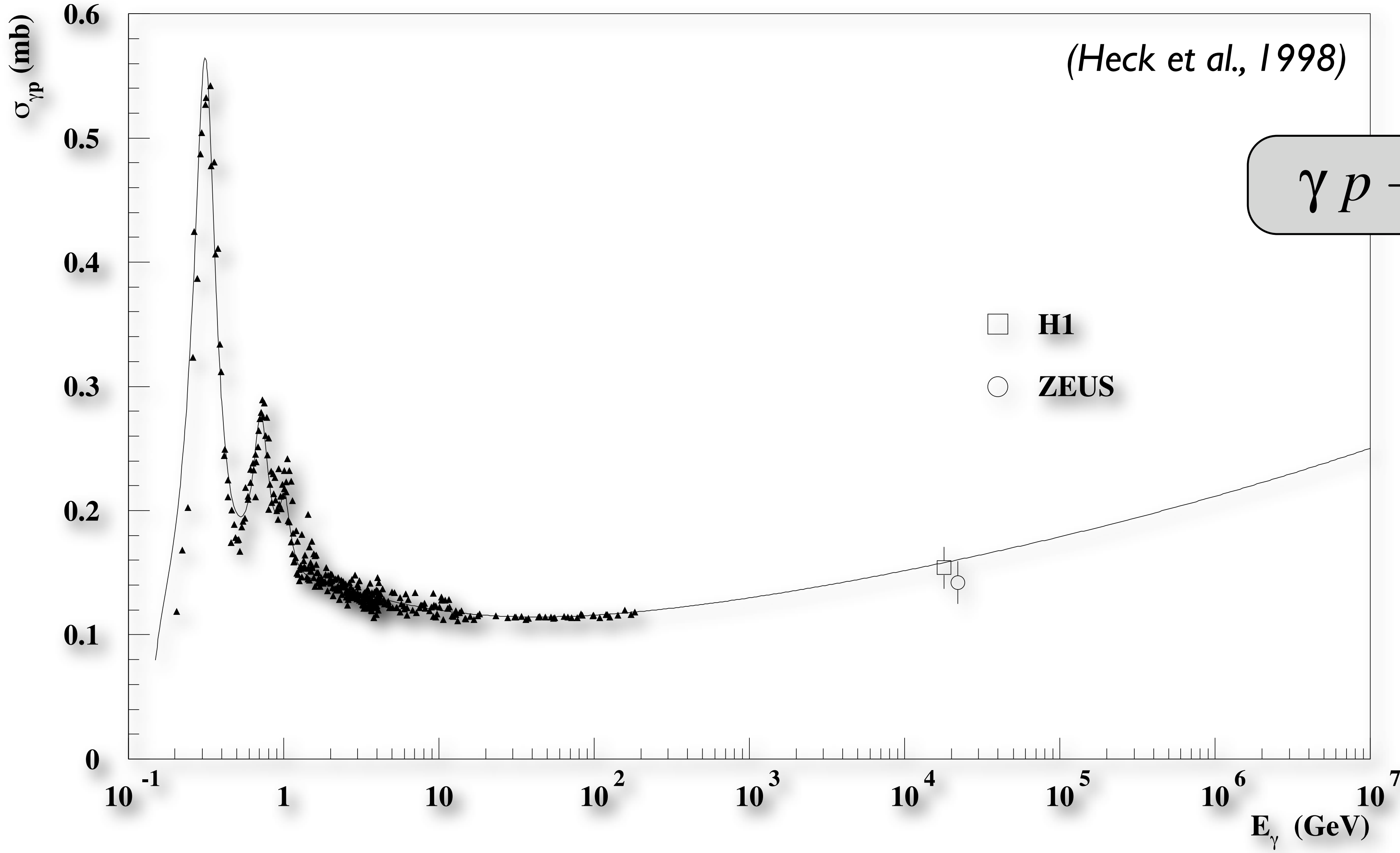
Compilation of total cross sections



Particle Data Group (COMPETE Collab. PRD65, 2002)

Similar behaviour for different projectile/target combinations

Simulation concepts: energy ranges



$$\gamma\, p \longrightarrow X$$

Resonances (fireball)

Scaling region (longitudinal phase space)

Minijet region (scaling violation)

???

Example:

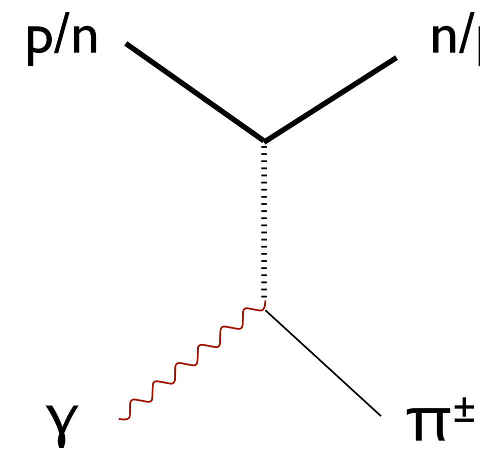
Low-energy interaction model SOPHIA

Description of proton/neutron interaction with background photons, Greisen-Zatsepin-Kuzmin effect

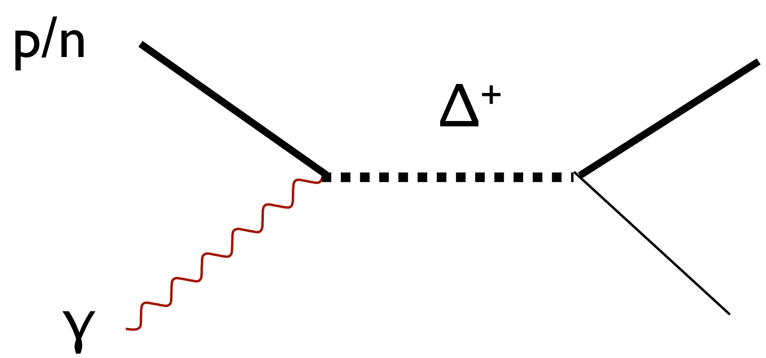
SOPHIA (Mücke et al. Comp. Phys. Commun. 124, 2000)

Diagrams implemented in SOPHIA

Direct pion production

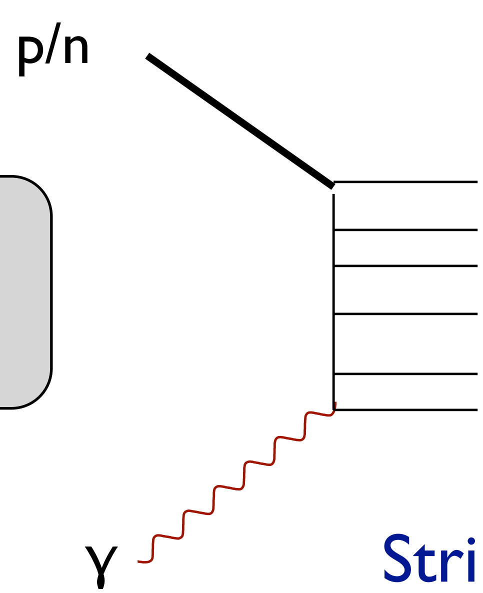


Resonance production (s channel)



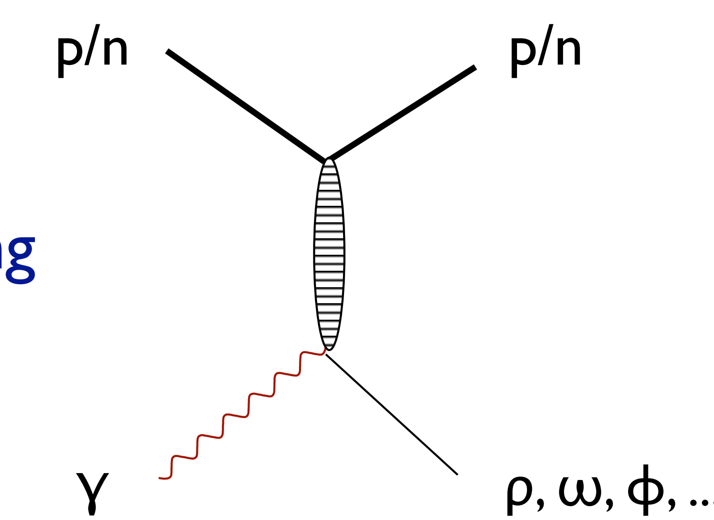
decay products (distribution depends only on spin etc. of resonance and that of products)

Multiparticle production



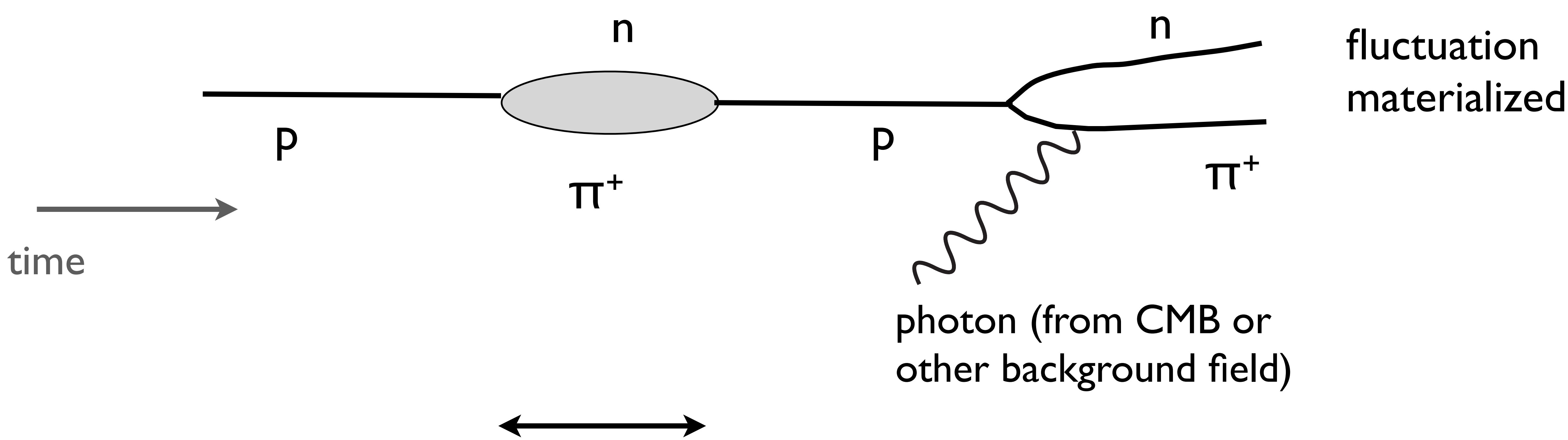
String model

Elastic scattering



Direct pion production

Possible interpretation: p fluctuates from time to time to n and π^+



Heisenberg uncertainty relation $\Delta E \Delta t \approx 1$

Energy threshold very low: $\boxed{E_{\mathrm{cm,min}} = m_\pi + m_p \approx 1.07\ \mathrm{GeV}}$

(Δ^+ resonance: 1.232 GeV)

Superposition of resonances

Baryon resonances and their physical parameters implemented in SOPHIA (see text). Superscripts $^+$ and ^{0} in the parameters refer to $p\gamma$ and $n\gamma$ excitations, respectively. The maximum cross section, $\sigma_{\max} = 4m_{\mathrm{N}}^2 M^2 \sigma_0/(M^2 - m_{\mathrm{N}}^2)^2$, is also given for reference

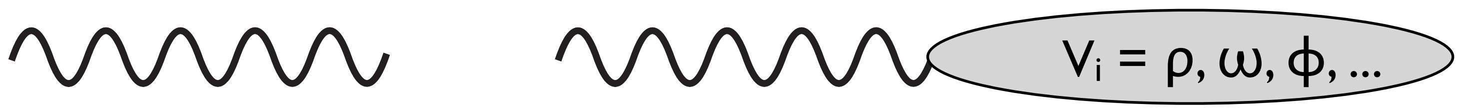
Resonance	M	Γ	$10^3 b_\gamma^+$	σ_0^+	$\sigma_{\max}^+$	$10^3 b_\gamma^0$	σ_0^0	$\sigma_{\max}^0$
$\Delta(1232)$	1.231	0.11	5.6	31.125	411.988	6.1	33.809	452.226
$N(1440)$	1.440	0.35	0.5	1.389	7.124	0.3	0.831	4.292
$N(1520)$	1.515	0.11	4.6	25.567	103.240	4.0	22.170	90.082
$N(1535)$	1.525	0.10	2.5	6.948	27.244	2.5	6.928	27.334
$N(1650)$	1.675	0.16	1.0	2.779	7.408	0.0	0.000	0.000
$N(1675)$	1.675	0.15	0.0	0.000	0.000	0.2	1.663	4.457
$N(1680)$	1.680	0.125	2.1	17.508	46.143	0.0	0.000	0.000
$\Delta(1700)$	1.690	0.29	2.0	11.116	28.644	2.0	11.085	28.714
$\Delta(1905)$	1.895	0.35	0.2	1.667	2.869	0.2	1.663	2.875
$\Delta(1950)$	1.950	0.30	1.0	11.116	17.433	1.0	11.085	17.462

Breit-Wigner resonance cross section

$$\sigma_{\mathrm{bw}}(s; M, \Gamma, J) = \frac{s}{(s - m_{\mathrm{N}}^2)^2} \frac{4\pi b_\gamma (2J+1) s \Gamma^2}{(s - M^2)^2 + s\Gamma^2}$$

Multiparticle production: vector meson dominance

Photon is considered as superposition of ``bare´´ photon and hadronic fluctuation

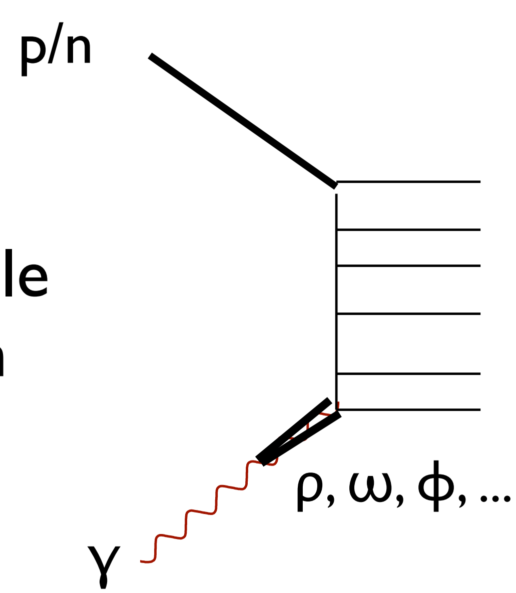


$$|\gamma\rangle = |\gamma_{\text{bare}}\rangle + P_{\text{had}} \sum_i |V_i\rangle$$

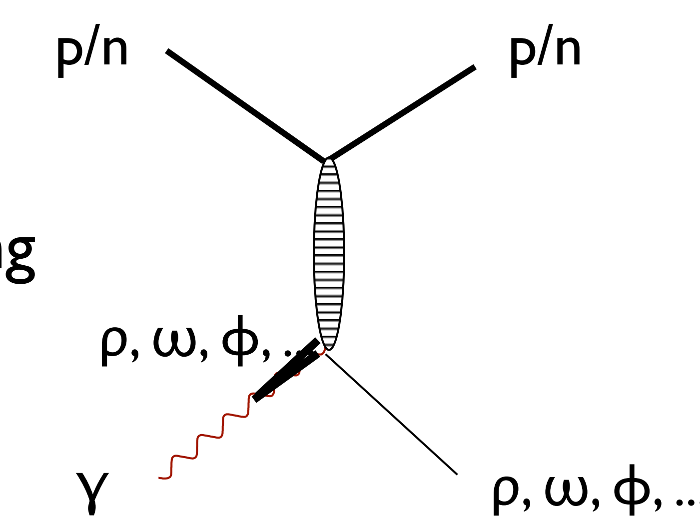
$$P_{\text{had}} \approx \frac{1}{300} \ \ldots \ \frac{1}{250}$$

Cross section for hadronic interaction ~1/300 smaller than for pi-p interactions

Multiparticle production

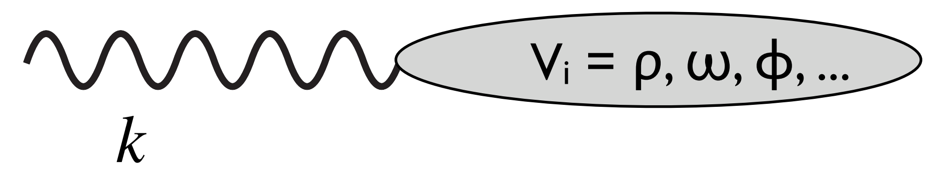


Elastic scattering



Lifetime of fluctuations

Consider photon with momentum k



Heisenberg uncertainty relation $\Delta E \, \Delta t \approx 1$

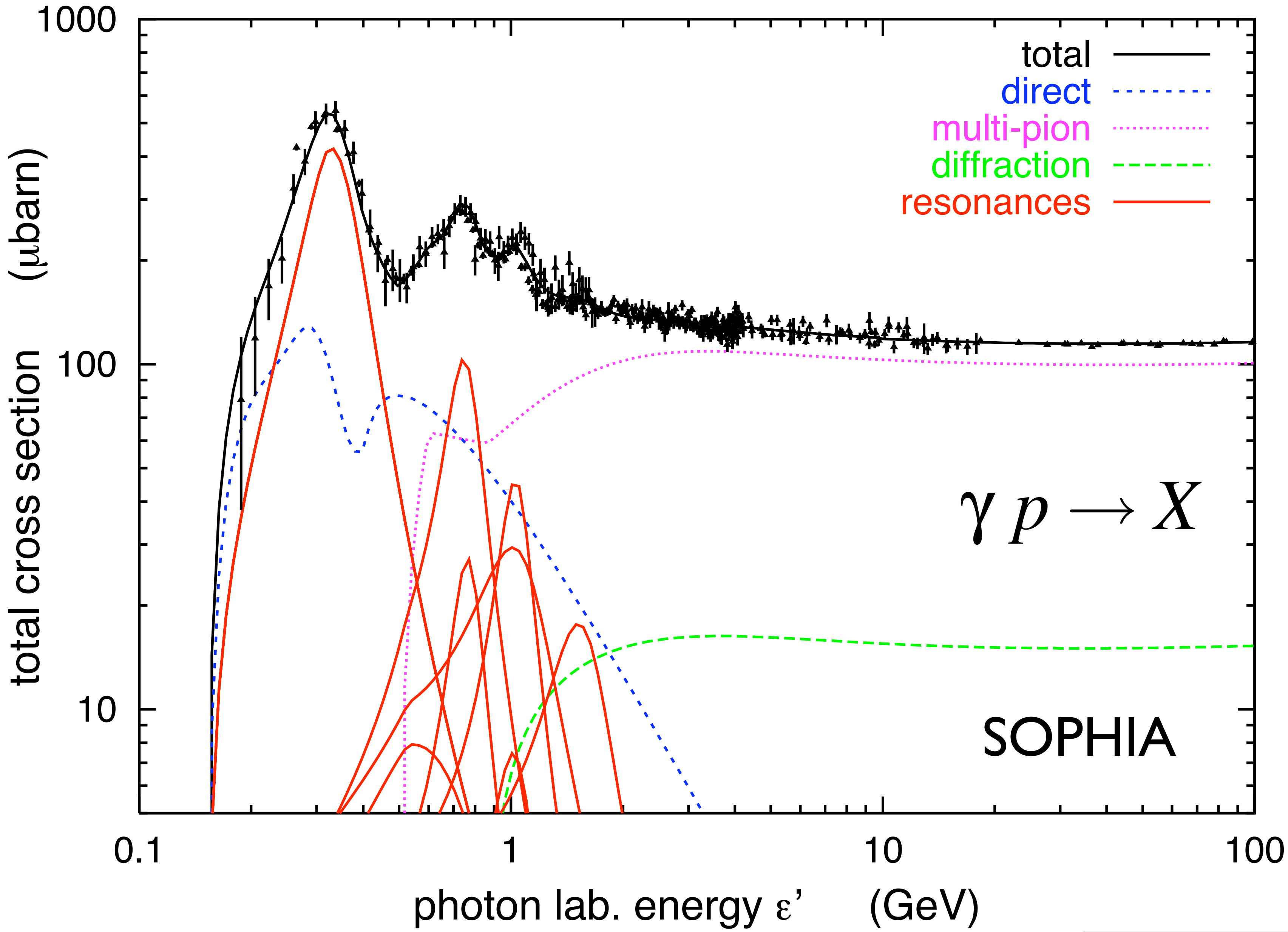
Length scale (duration) of hadronic interaction $\Delta t_{\text{int}} < 1\text{fm} \approx 5\text{GeV}^{-1}$

$$\Delta t \approx \frac{1}{\Delta E} = \frac{1}{\sqrt{k^2 + m_V^2} - k} = \frac{1}{k(\sqrt{1 + m_V^2/k^2} - 1)} \approx \frac{2k}{m_V^2}$$

Fluctuation long-lived for k > 3 GeV

$$\boxed{\Delta t \approx \frac{2k}{m_V^2} > \Delta t_{\text{int}}}$$

Putting all together: description of total cross section

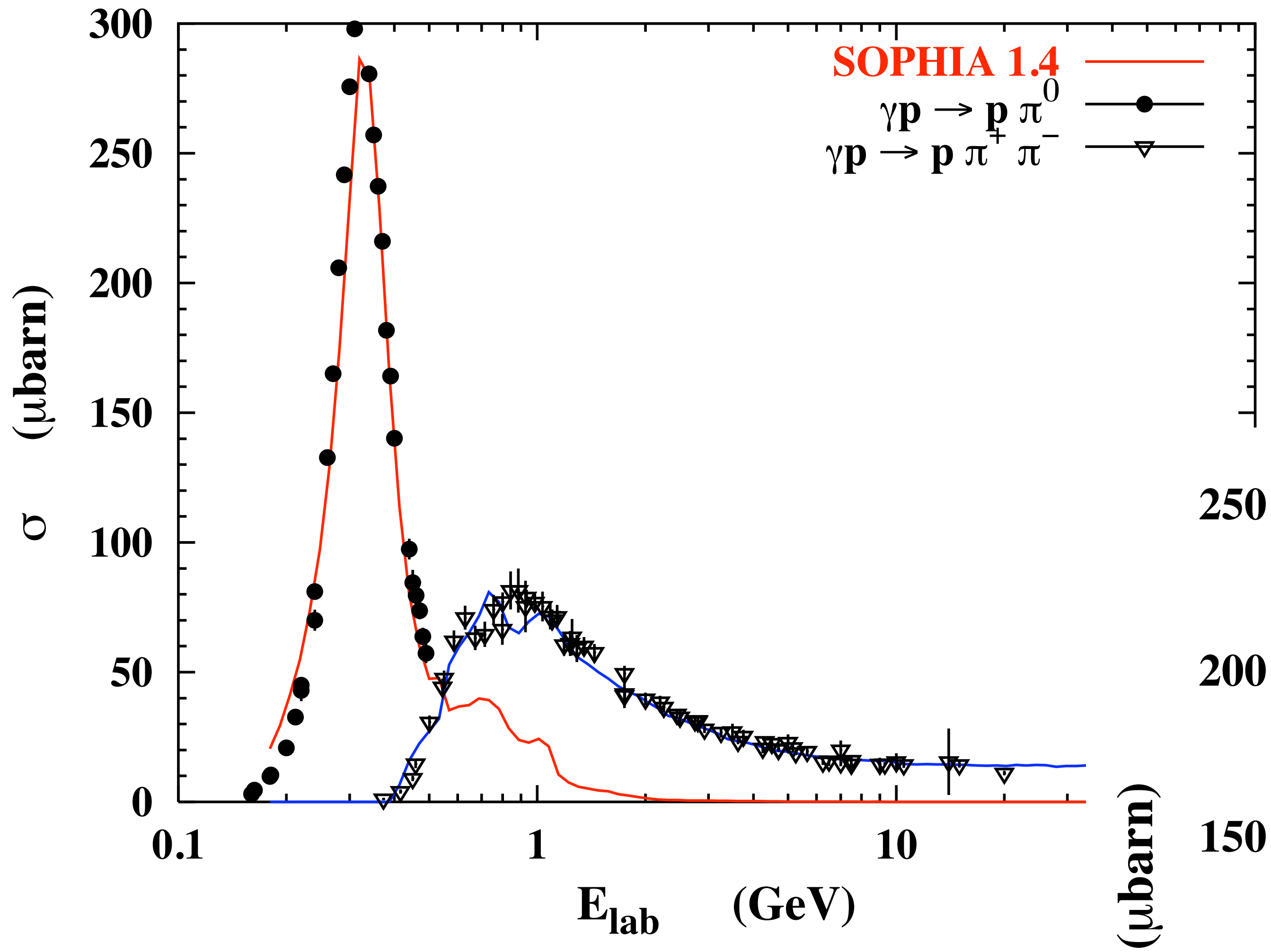


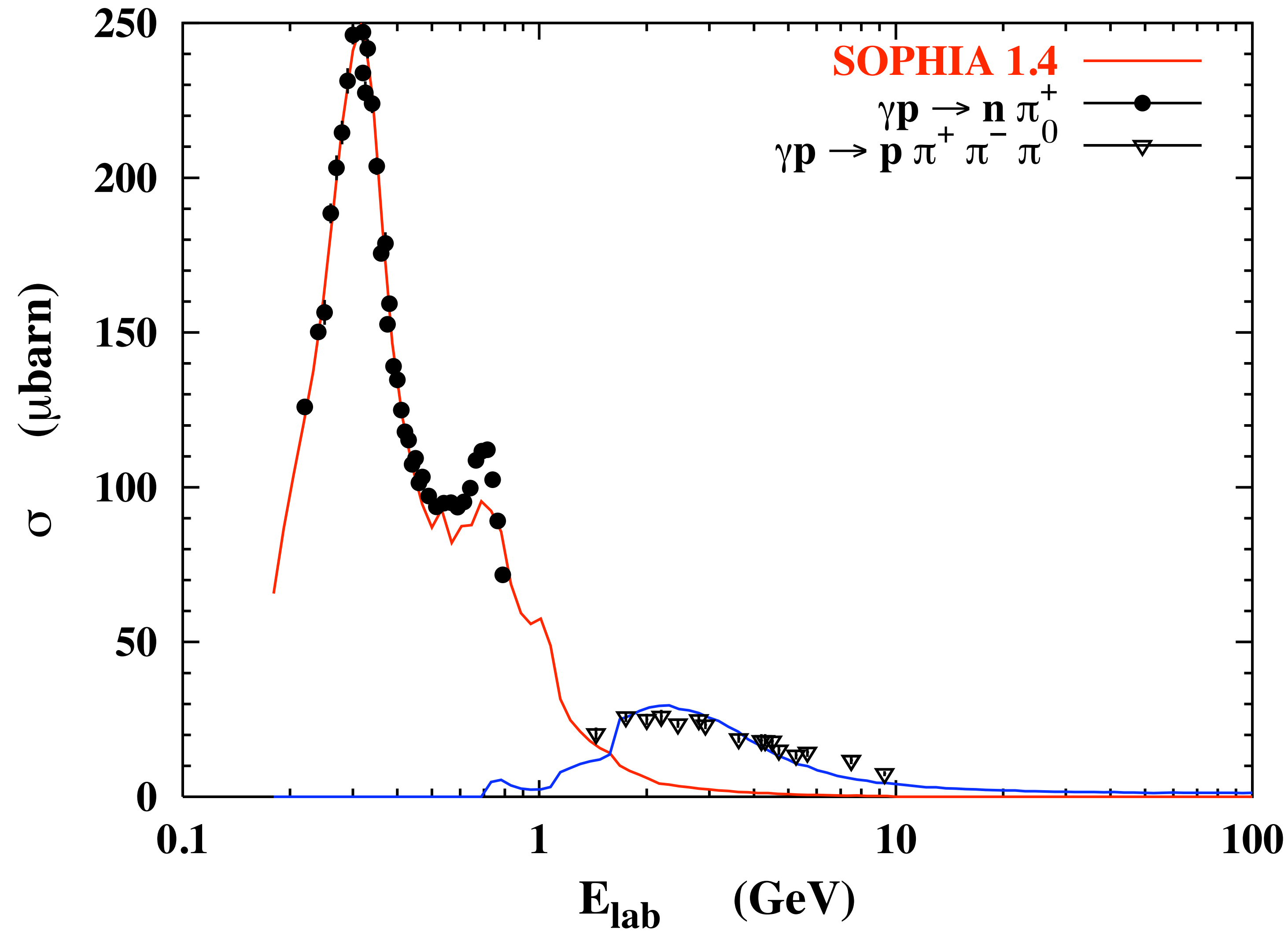
- PDG: 9 resonances, decay channels, angular distributions
- Regge parametrization at higher energy
- Direct contribution: fit to difference to data

Many measurements available, still approximations necessary

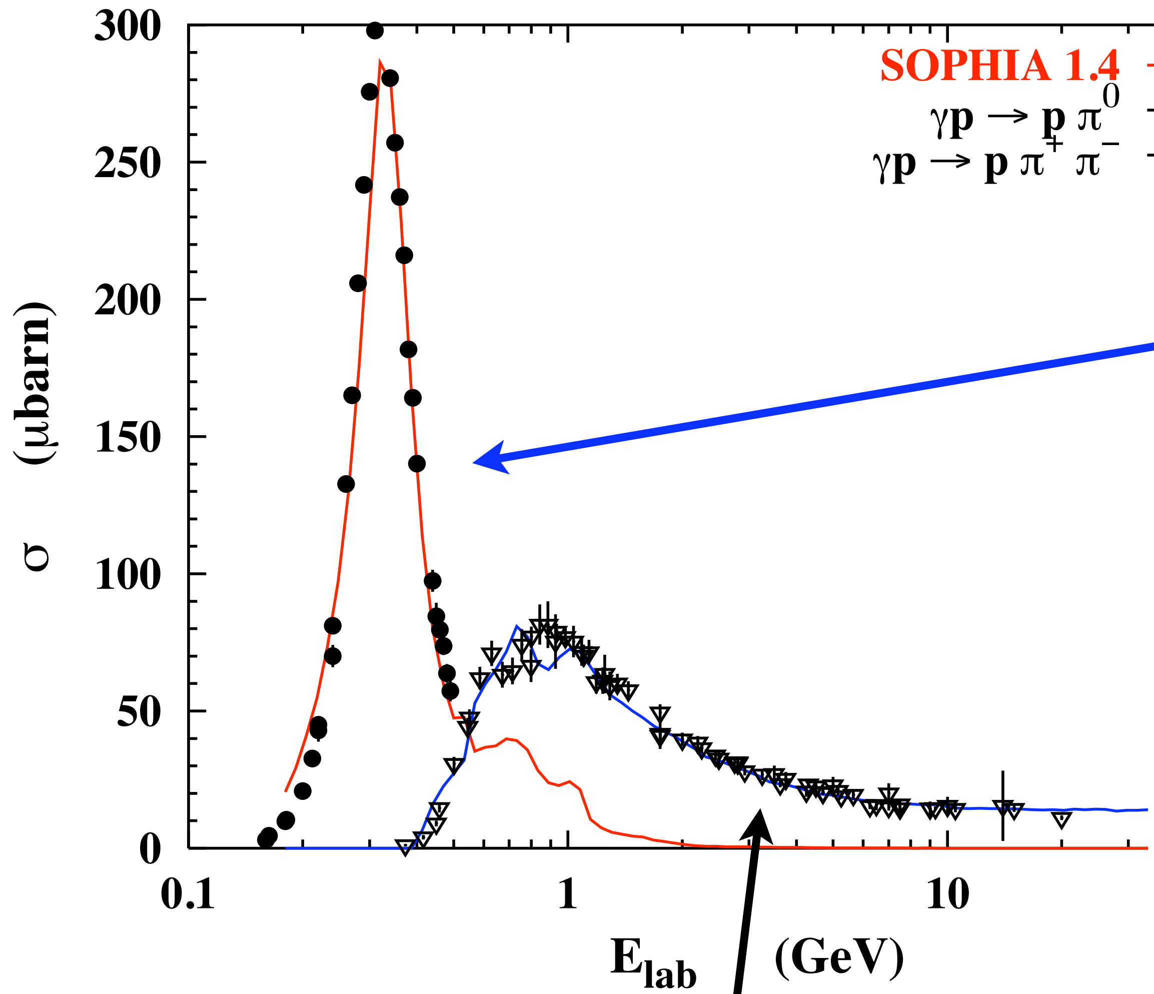
SOPHIA (Mücke et al. CPC124, 2000)

Comparison with measured partial cross sections

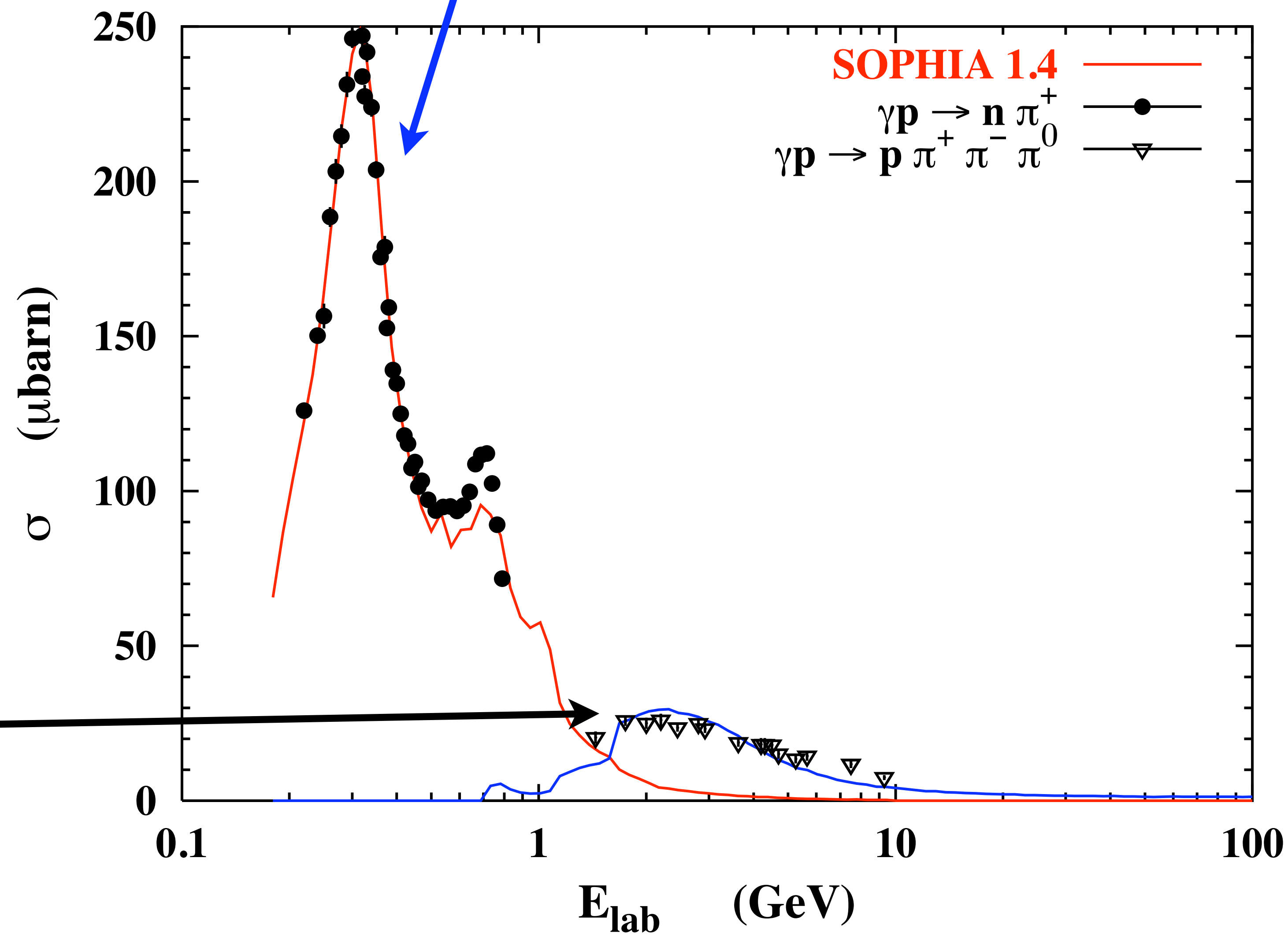




Comparison with measured partial cross sections



Resonance region



Continuum region
(multiparticle production)