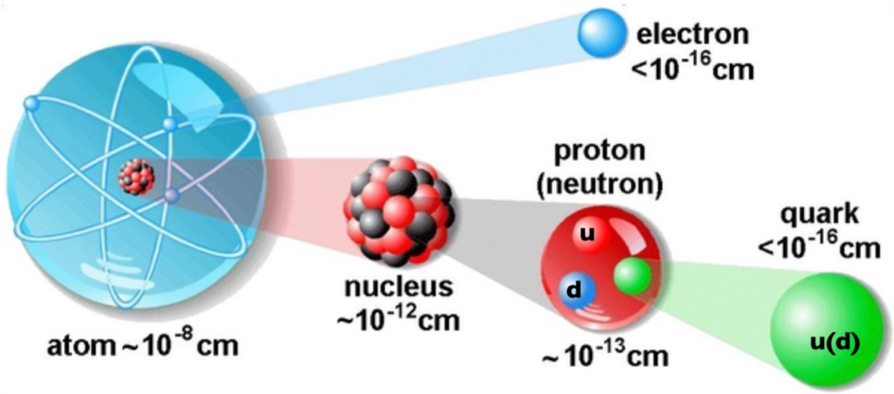
Experimental particle physics

European School of Instrumentation in Particle & Astroparticle Physics

A. kinematics & accelerators

Estimating order of magnitudes…



De Broglie wavelength

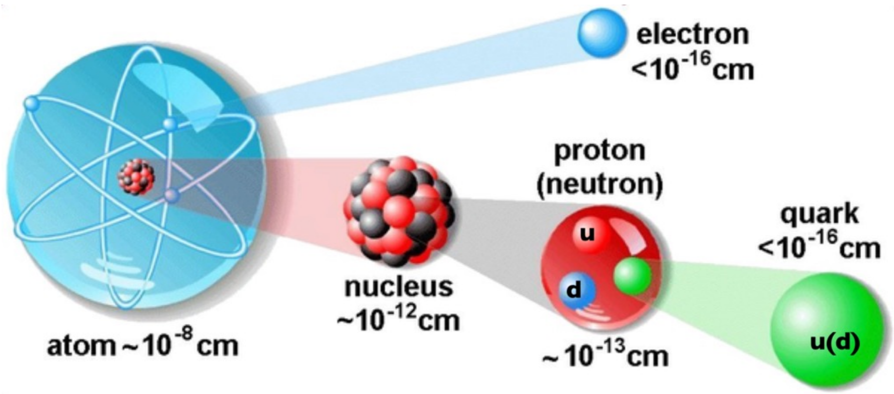
$$\lambda = \frac{h}{p} \qquad \Delta r \sim \frac{h}{p}$$

with p = transferred momentum

$$\lambda = \frac{h}{p} = \frac{2\pi\hbar c}{pc} = \frac{2\pi \times 197\,\mathrm{MeV\,fm}}{pc}$$

What?	*L [m]*	*p [GeV]*
Atom	10^{-10}	
Nucleus	10^{-14}	
Nucleon	10^{-15}	
Quark	10^{-18}	

Estimating order of magnitudes…



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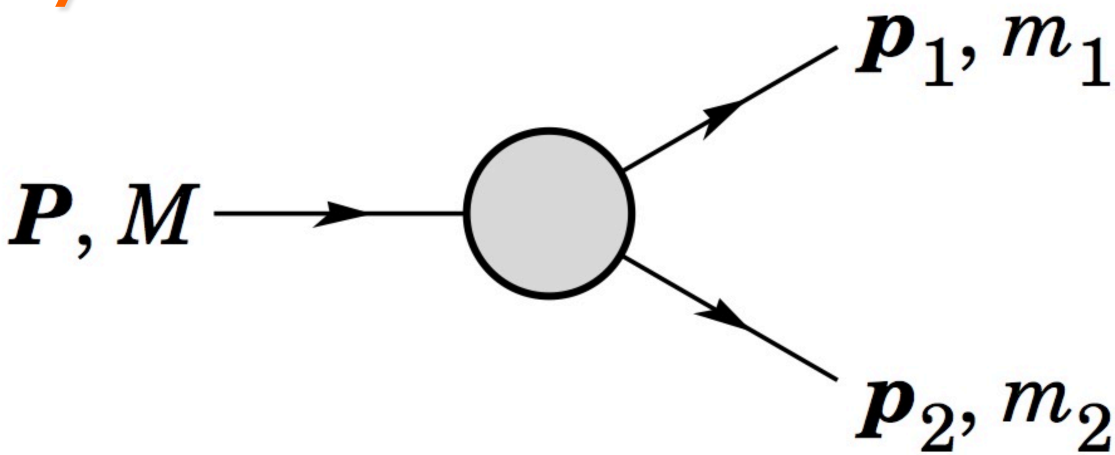
What?	*L [m]*	*p [GeV]*
Atom	10^{-10}	0.00001
Nucleus	10^{-14}	0.1
Nucleon	10^{-15}	1
Quark	10^{-18}	1000

2-body decay

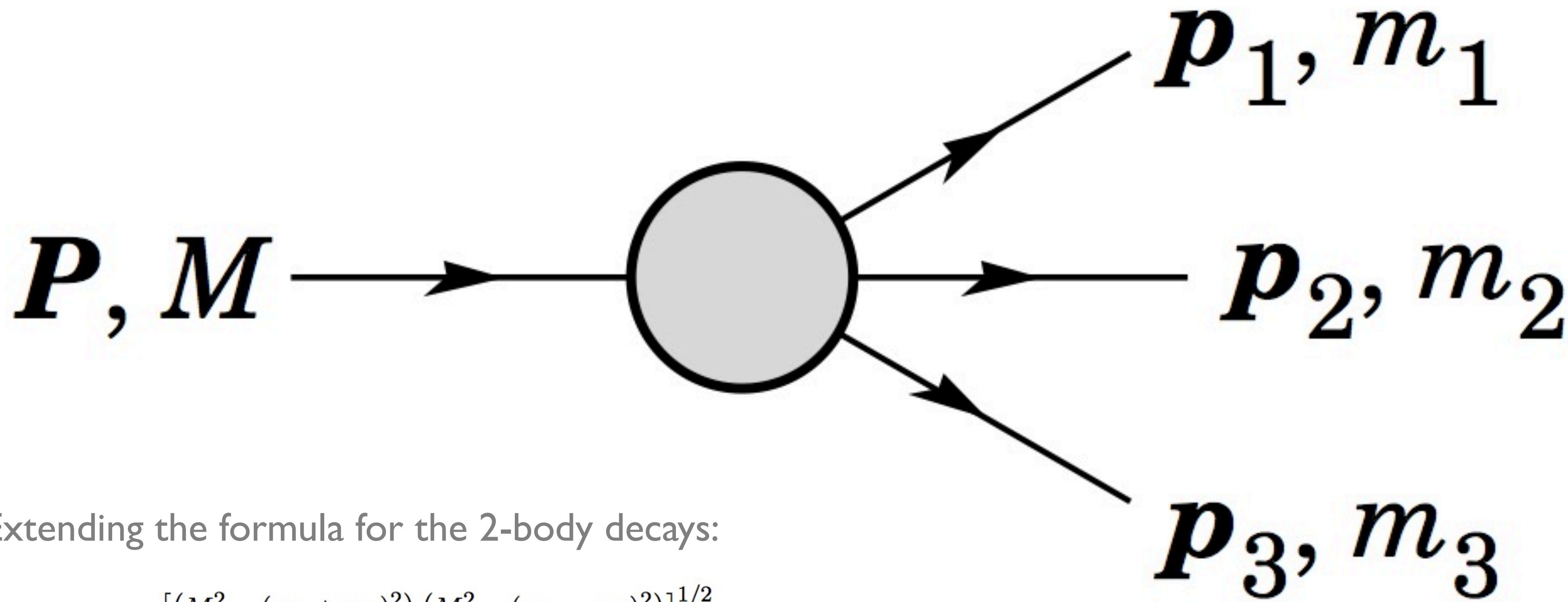


$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} ,$$

$$|\boldsymbol{p}_1| = |\boldsymbol{p}_2|$$

$$= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

3-body decay



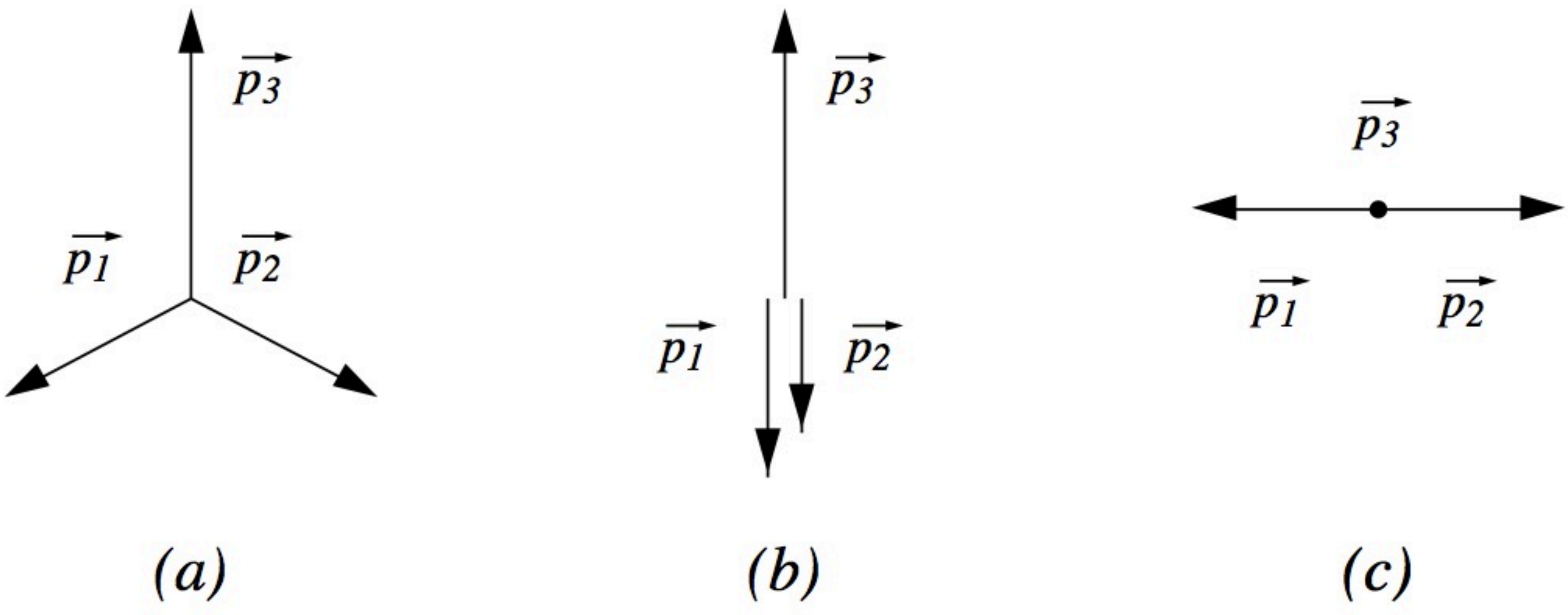
Extending the formula for the 2-body decays:

$$|\boldsymbol{p}_1| = |\boldsymbol{p}_2| = \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

$$|\boldsymbol{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2\right)\left(M^2 - (m_{12} - m_3)^2\right)\right]^{1/2}}{2M}$$

3-bodies decay

$$|\boldsymbol{p}_3| = \frac{\left[\left(M^2 - (m_{12}+m_3)^2\right)\left(M^2 - (m_{12}-m_3)^2\right)\right]^{1/2}}{2M}$$



1) $\max(|\vec{p}_3|)$ $\quad (m_{12})_{min} = m_1 + m_2$ → (b)

2) $\min(|\vec{p}_3|)$ $\quad (m_{12})_{max} = M - m_3$ → (c)

A real example: pion decay(s)

$$\pi^- \to \mu^- + \overline{\nu}_\mu$$
$$\hookrightarrow e^- + \overline{\nu}_e + \nu_\mu$$

pion decays at rest (2-body decay)

$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}c$$

$$m_\nu = 0$$

2-body decay

$$|\boldsymbol{p}_1| = |\boldsymbol{p}_2| = \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

3-body decay

$$|\boldsymbol{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2\right)\left(M^2 - (m_{12} - m_3)^2\right)\right]^{1/2}}{2M}$$

in most cases, muon decays at rest (3-body decays)

$$|\mathbf{p}_e|_{max} = \frac{m_\mu^2 - m_e^2}{2m_\mu}c$$

c

$$|\mathbf{p}_e|_{min} = 0$$

$$\pi^- \to e^- + \overline{\nu}_e$$

$$|\mathbf{p}_e| = \frac{m_\pi^2 - m_e^2}{2m_\pi}c$$

A real example: pion decay(s)

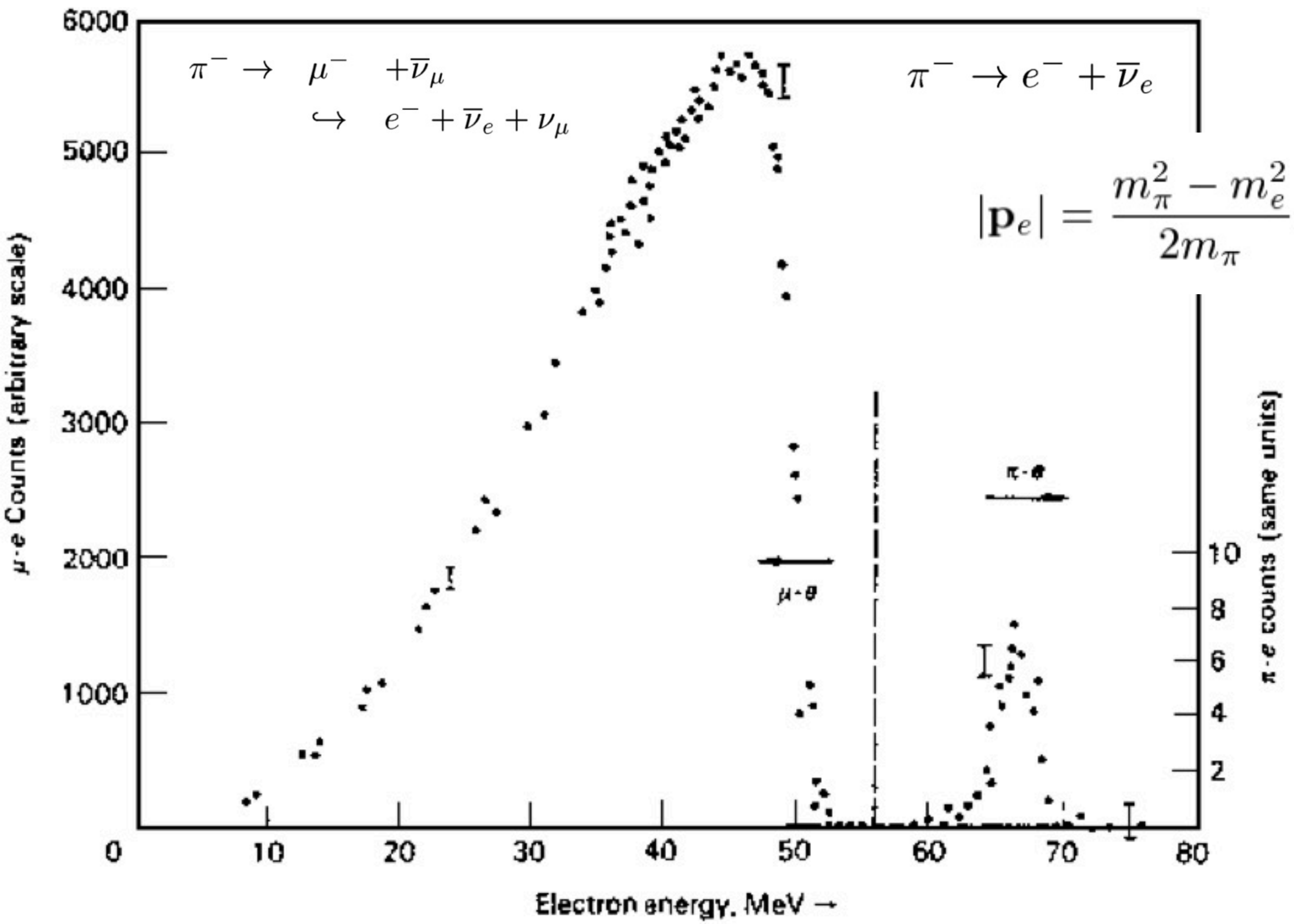
pion decays at rest

$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} c \simeq 30\,\mathrm{MeV/c}$$

in most cases muon decays at rest

$$\begin{aligned} |\mathbf{p}_e|_{max} &= \frac{m_\mu^2 - m_e^2}{2m_\mu} c \simeq 52\,\mathrm{MeV/c} \\ |\mathbf{p}_e|_{min} &= 0 \end{aligned}$$

$$m_\nu = 0$$



$$|\mathbf{p}_e| = \frac{m_\pi^2 - m_e^2}{2m_\pi} c \simeq 70\,\mathrm{MeV/c}$$

3-bodies decay: Dalitz plot

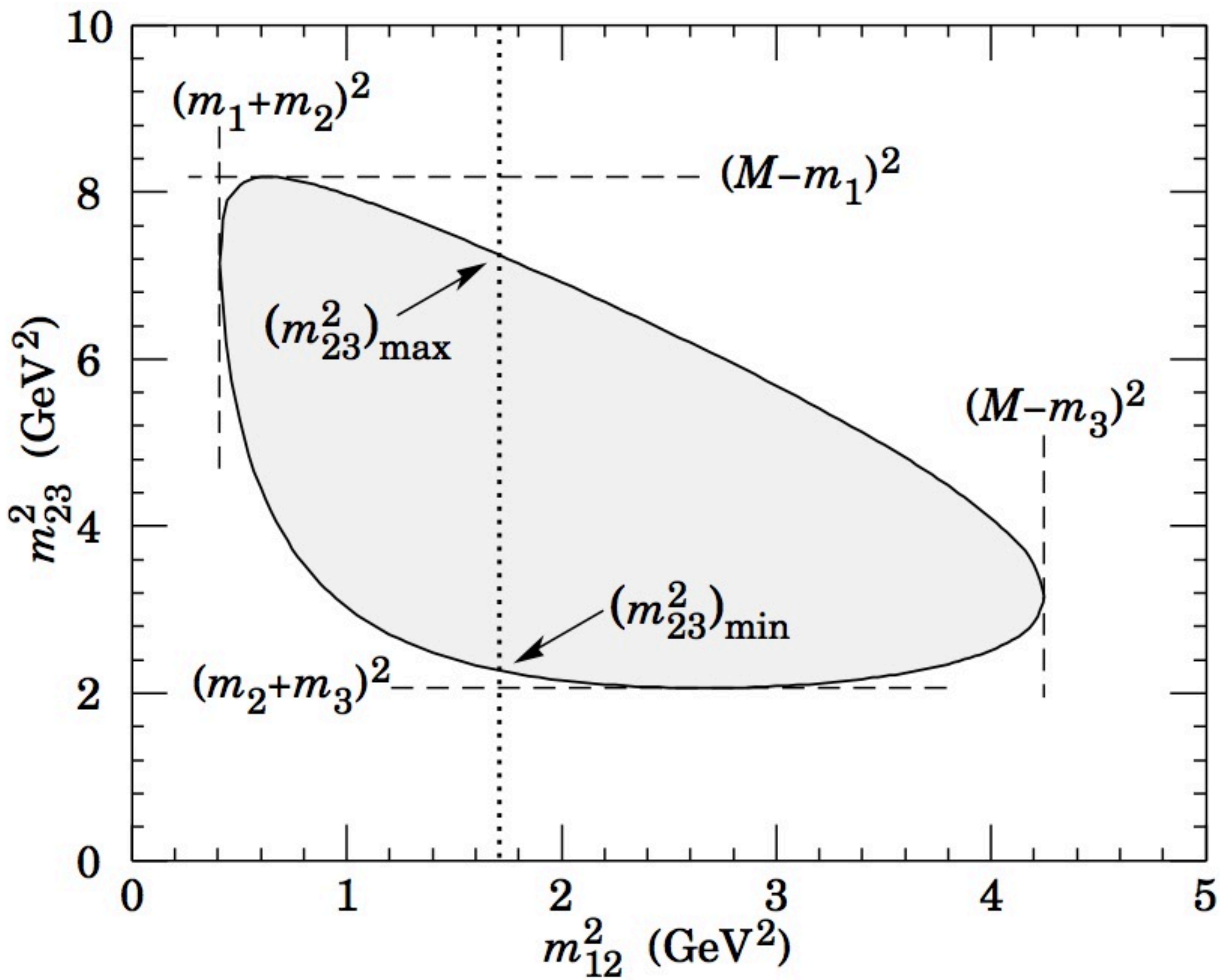
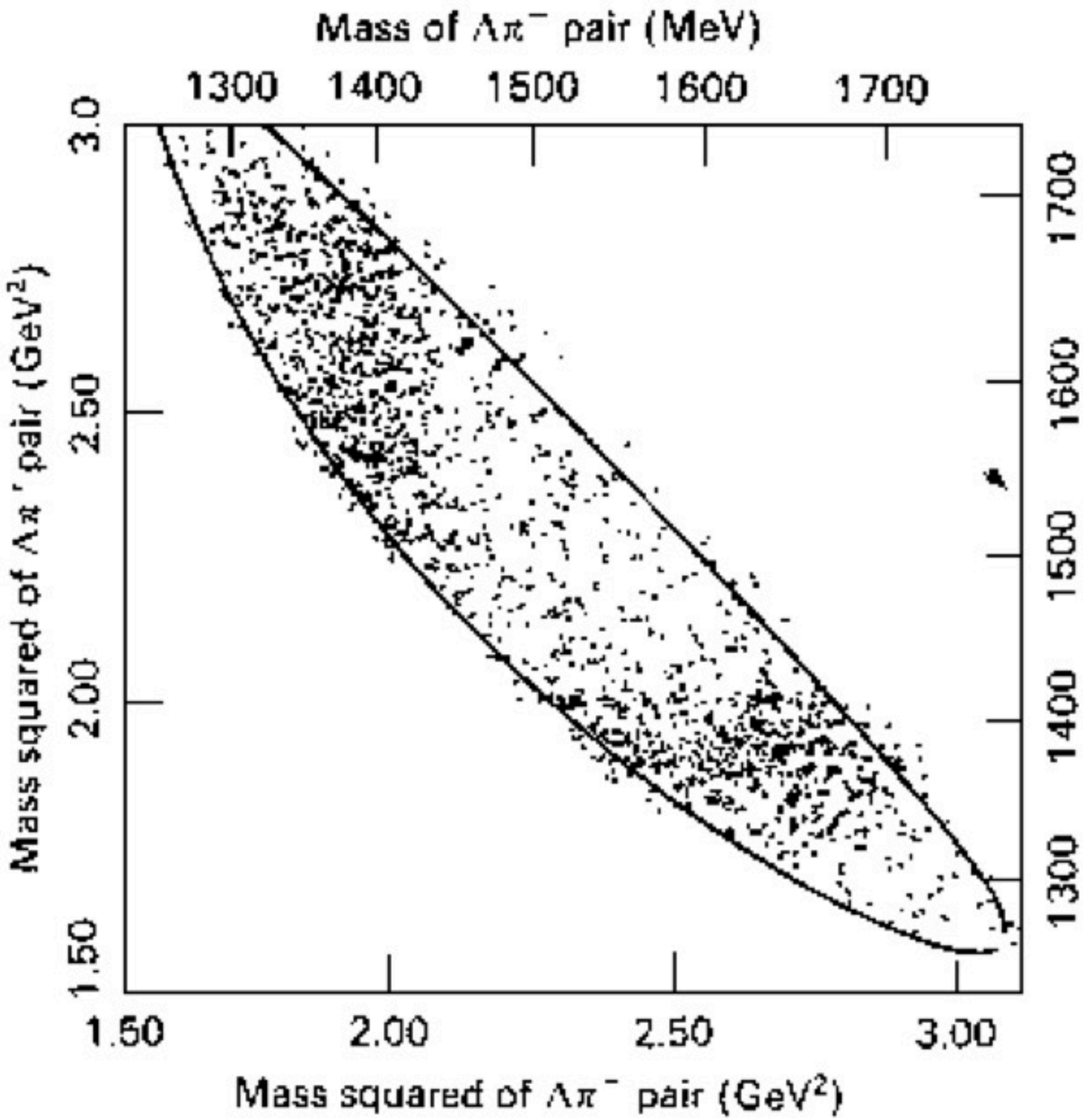


Figure 45.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+\overline{K}^0p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

Multi-bodies decay

$$K^- + p \to \pi^+ + \pi^- + \Lambda$$



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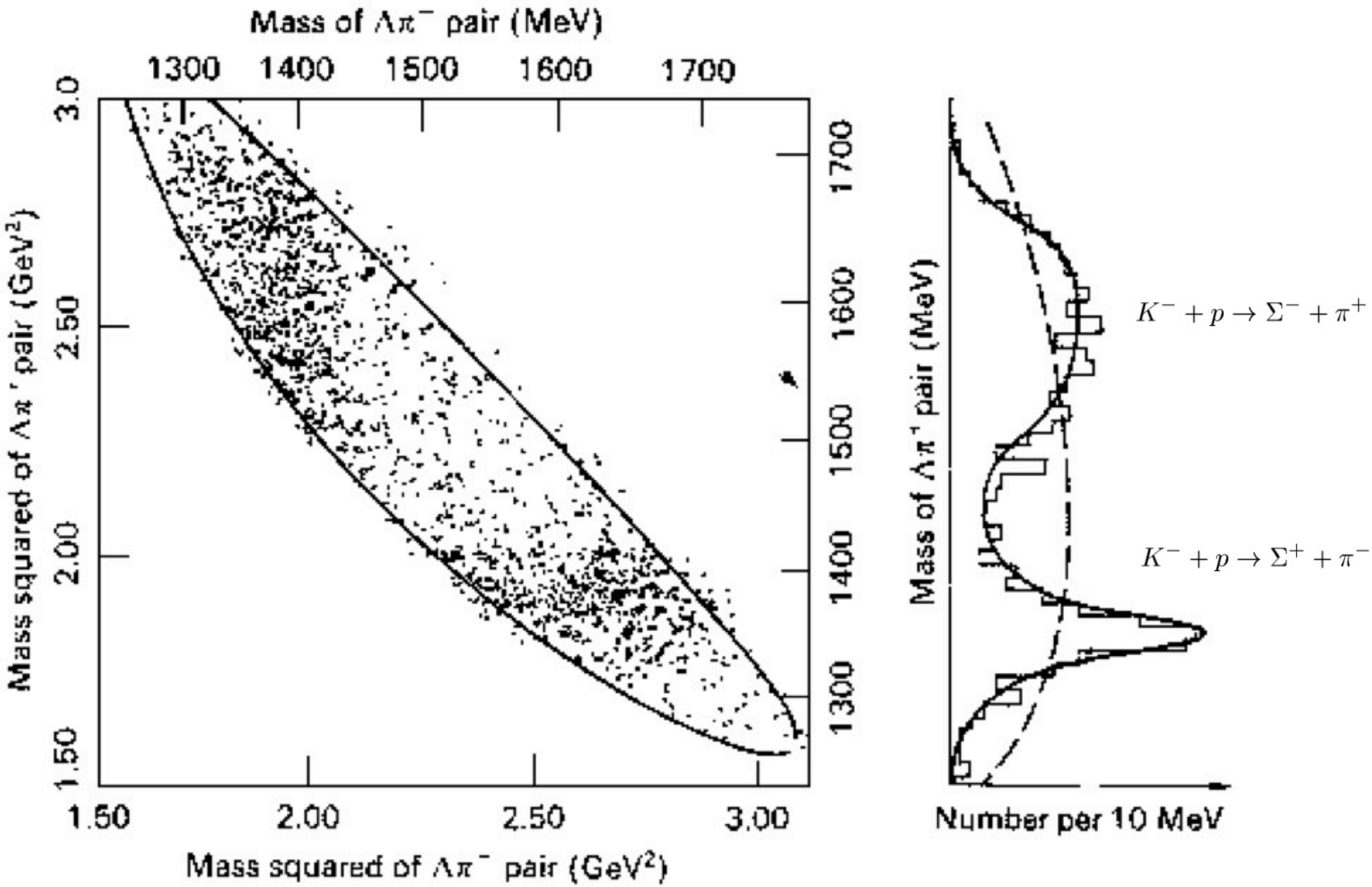


Center of mass energy

- In the center of mass frame the total momentum is 0
- In laboratory frame center of mass energy can be computed as:

$$E_{\mathrm{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

Hint: it can be computed as the "length" of the total four-momentum, that is invariant:

$$p = (E, \vec{p}) \qquad \sqrt{p \cdot p}$$

What is the "length" of a the four-momentum of a particle?

Reaction threshold

$$\sqrt{s} \geq \sum_i m_i$$

What energy should the pion have for this reaction to happen?

$$\pi + p \rightarrow \pi + \pi + \pi + p$$

Cosmic rays

- Protons with energy above the pion production threshold can produce them interacting with photons from relic cosmic radiation:
  - ✓ $E_\gamma \sim 10^{-3}$ eV

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

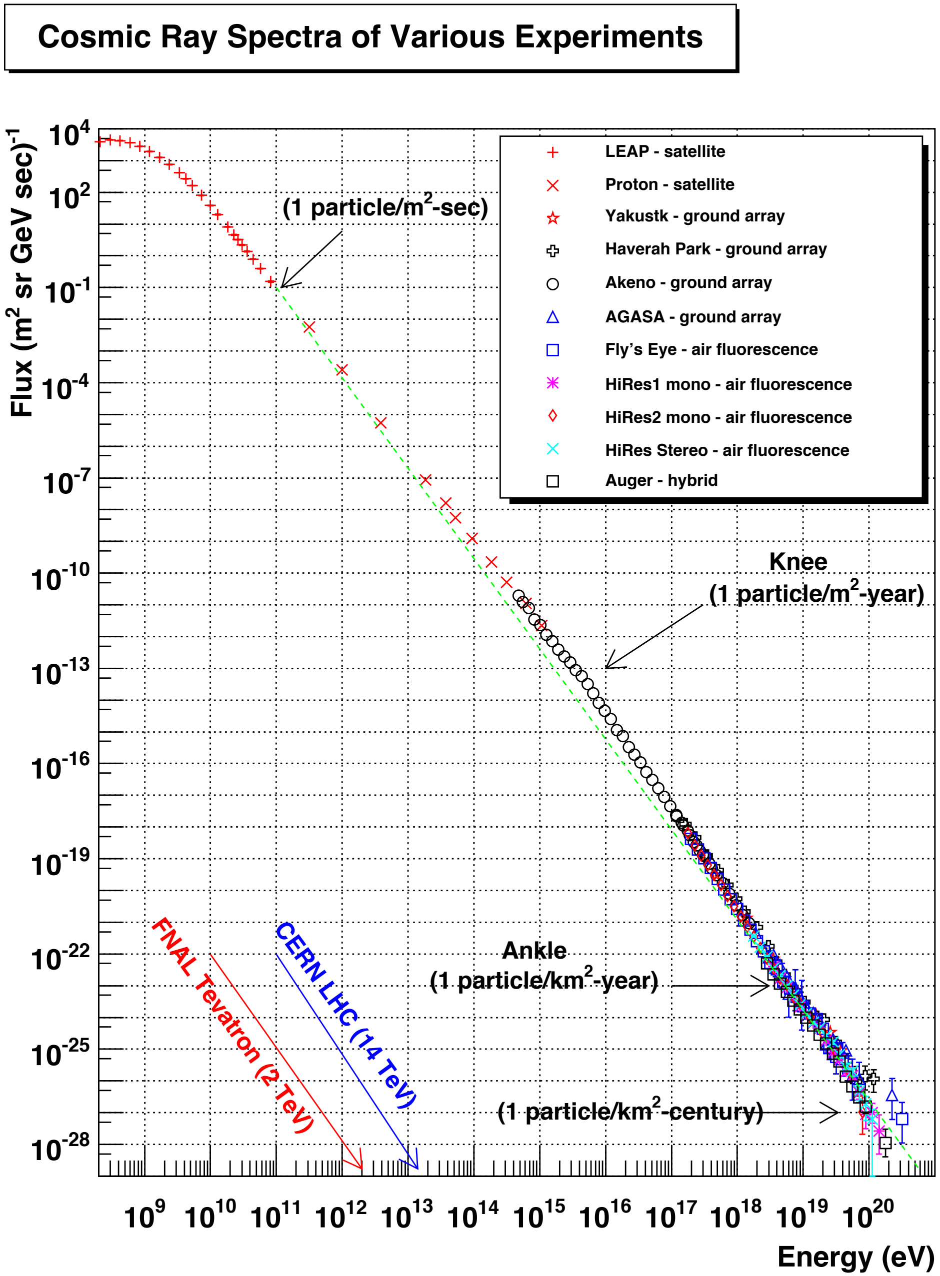
What is the maximum energy for a proton in the cosmic rays?

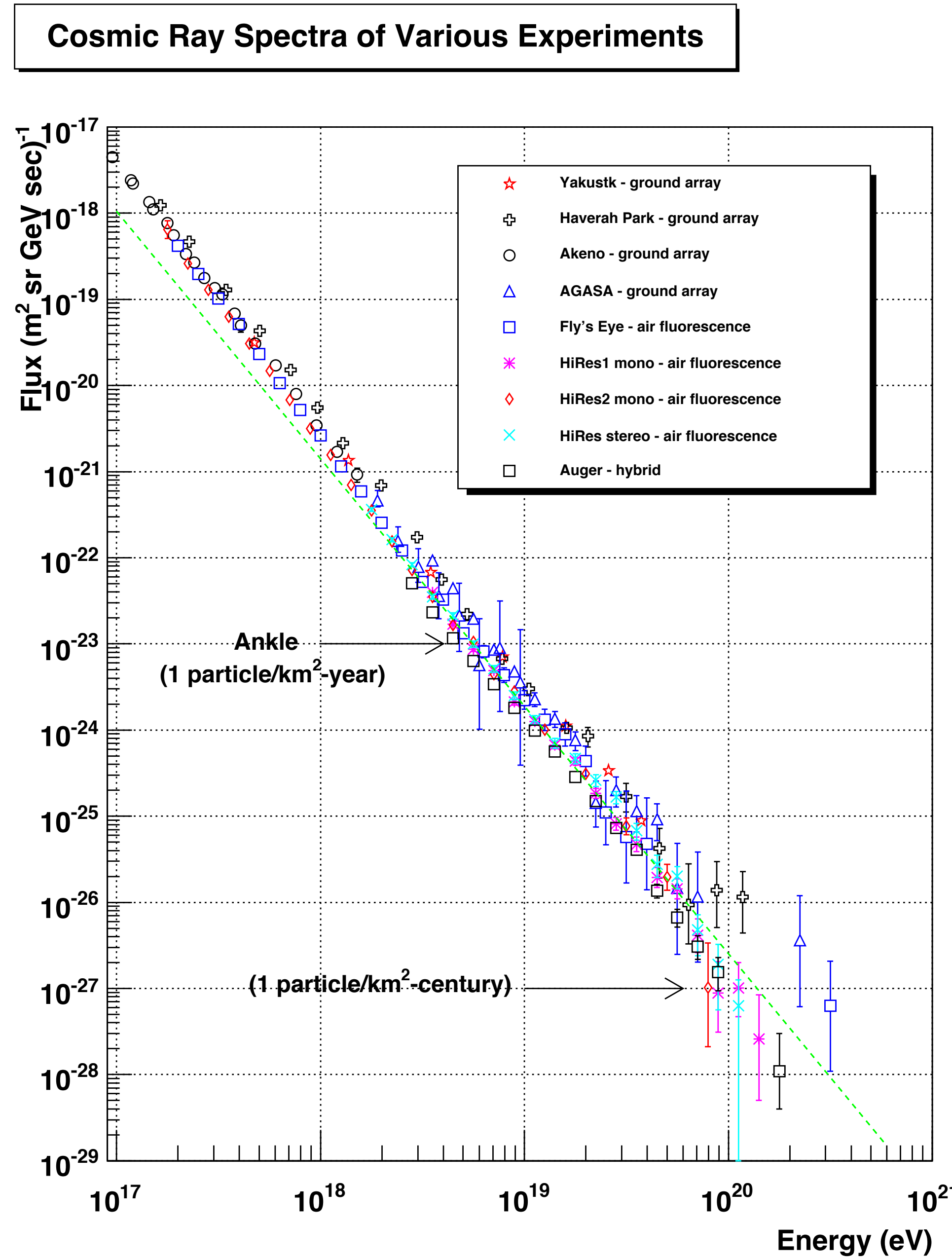
This energy is called the GKZ (Greisen–Zatsepin–Kuzmin) cut-off: protons above this energy see the space as a opaque medium, and decelerate…

- *Read this: [First Observation of the Greisen-Zatsepin-Kuzmin Suppression]*

Did we observe any extremely high-energetic cosmic rays above the GKZ cut-off?

- *Read this: [The Particle That Broke a Cosmic Speed Limit]*


Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)$^{-1}$
Energy (eV)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
(1 particle/m^2-sec)
Knee
(1 particle/m^2-year)
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)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HiRes2 mono - air fluorescence
HiRes stereo - air fluorescence
Auger - hybrid
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)

Luminosity and number of events

Number of events
in unit of time

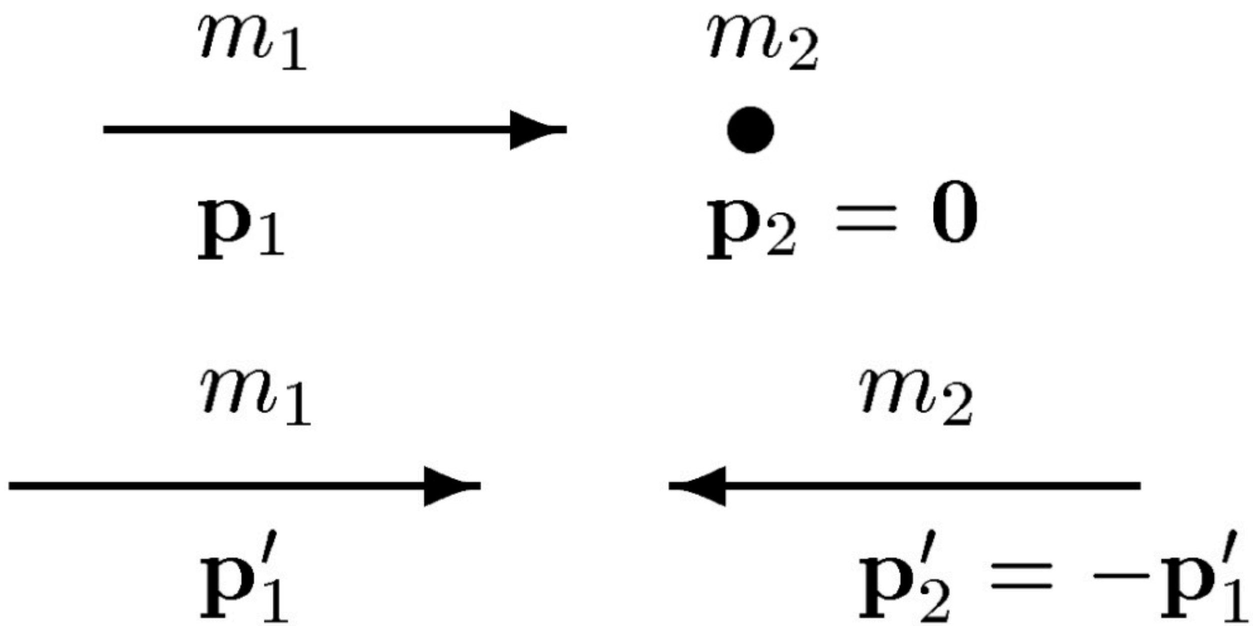
$$N = \mathcal{L} \cdot \sigma$$

$[t^{-1}]$ $[L^{-2}\,t^{-1}]$ $[L^{2}]$

$10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ $\sigma(pp \rightarrow tt) \sim 800\ \mathrm{pb}$

How many top quark pairs
produced in a year at LHC?

Fixed target vs. collider



How much energy should a fixed target experiment have to equal the center of mass energy of two colliding beam?

$$E_{\text{fix}} = 2\frac{E_{\text{col}}^2}{m} - m$$

LHC dipole magnetic field

Assuming a proton beam of momentum

p = 7 TeV

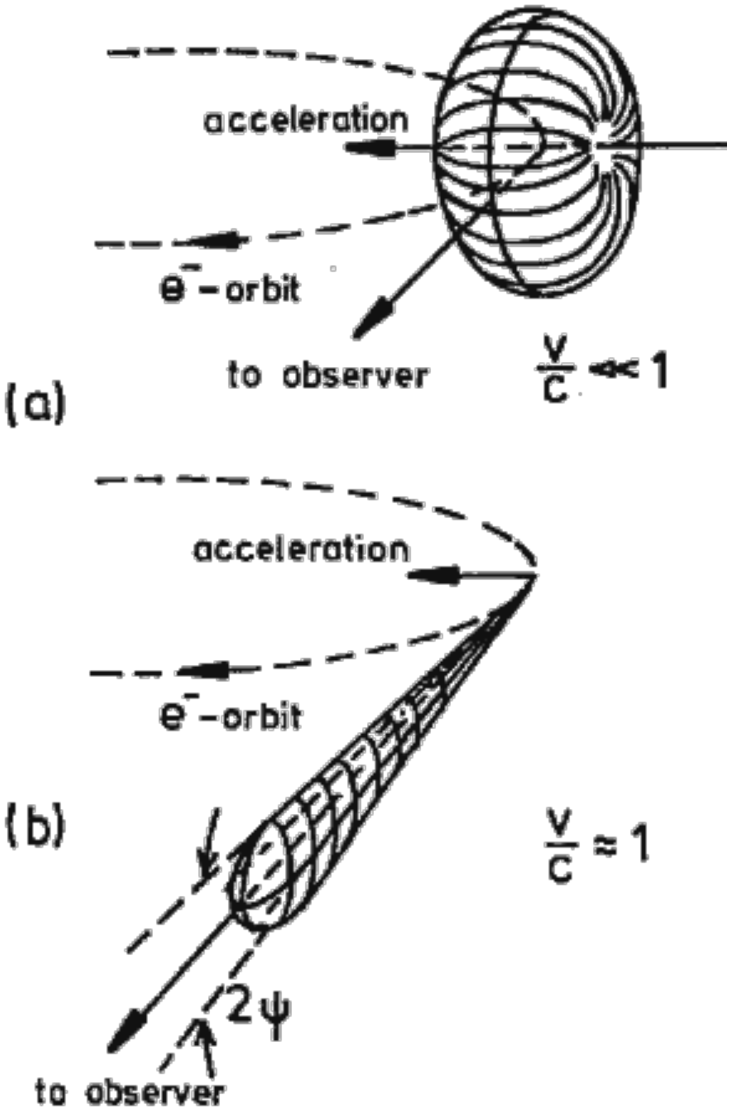
What is the magnetic field of the LHC dipoles?

Reminders:

- The LHC is 27 km long
- There are 1230 dipoles in LHC
- Each dipole is 14.4 m long

$$\frac{1}{R}[\mathrm{m}^{-1}] = 0.3\,\frac{B[\mathrm{T}]}{E[\mathrm{GeV}]}$$

Syncrotron radiation



energy lost per revolution

$$\Delta E = \frac{4\pi}{3}\frac{1}{4\pi\epsilon_0}\left(\frac{e^2\beta^3\gamma^4}{R}\right)$$

electrons vs. protons

$$\frac{\Delta E_e}{\Delta E_p} \simeq \left(\frac{m_p}{m_e}\right)^4$$

It's easier to accelerate protons to higher energies, but protons are fundamentals…

Accelerating electrons

- How much energy did electrons and positrons of E = 50 GeV loose in one round at LEP?
  - ✓ L = 27 km

$$\Delta E = \frac{4\pi}{3} \frac{1}{4\pi\epsilon_0} \left(\frac{e^2 \beta^3 \gamma^4}{R} \right)$$

hint…

$$\frac{e^2}{4\pi\varepsilon_0 \hbar c} = \alpha$$

Homework: a sampling calorimeter…

- The ATLAS electromagnetic calorimeter is made from roughly 2 mm thick layers of lead (Pb), interleaved by 2 mm wide gaps filled with liquid Argon (LAr).
  - ✓ Pb: Z = 82, A = 206,density =11.34 g/cm^3
  - ✓ LAr: Z = 18, A = 40 density = 1.4 g/cm3.
- At η = 0 the depth of the ATLAS electromagnetic calorimeter is ~22 X_0
- What is the calorimeter depth in cm?
  - ✓ Hint; compute X_0(Pb) and X_0(LAr)
- What would it be is if it was a homogeneous calorimeter (i.e. all made of LAr)?
- And if it was all made of Pb?