Experimental particle physics

European School of Instrumentation in Particle & Astroparticle Physics

0. presentation

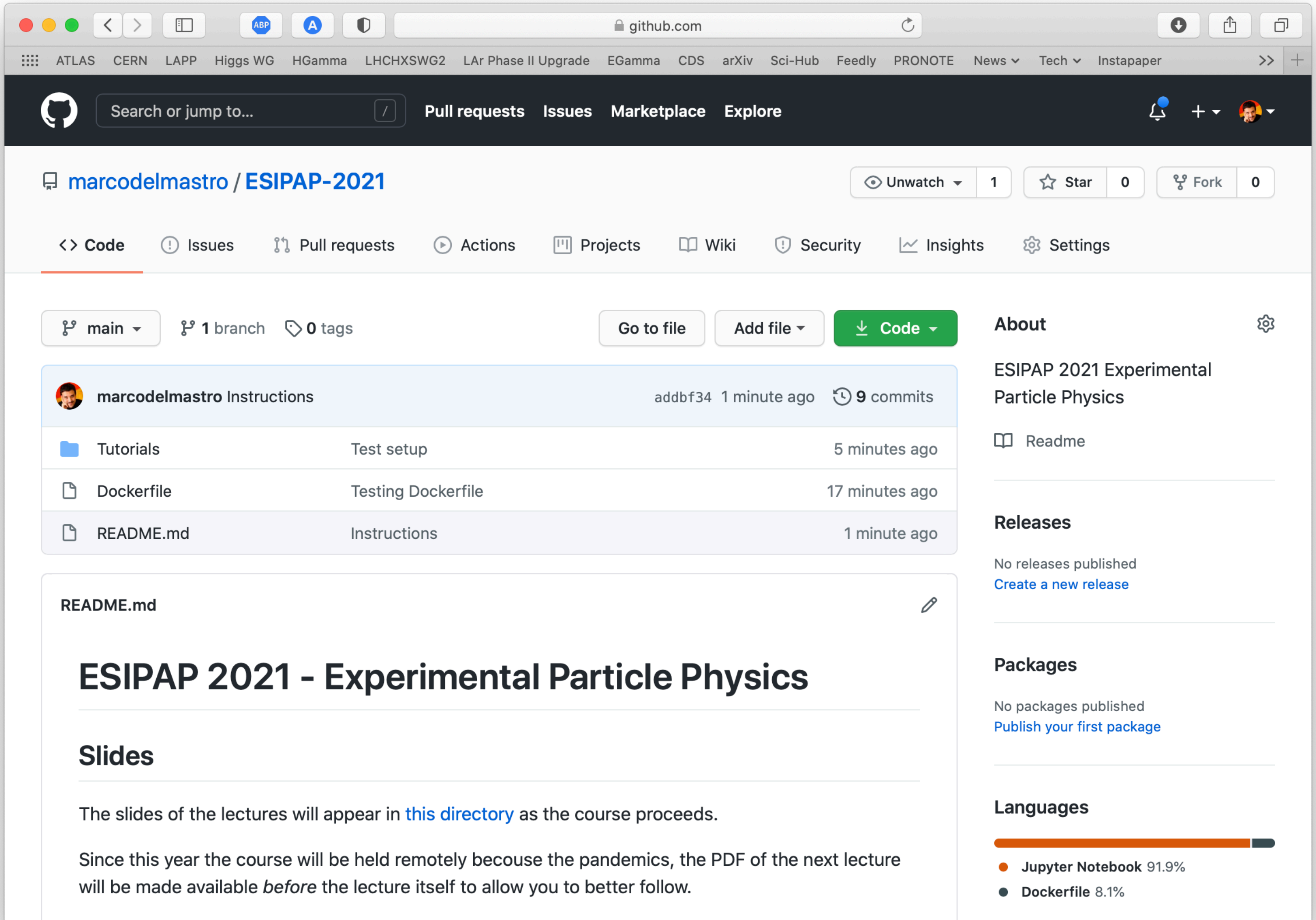
Marco Delmastro

esipap...
European School of Instrumentation in Particle & Astroparticle Physics

Full CV

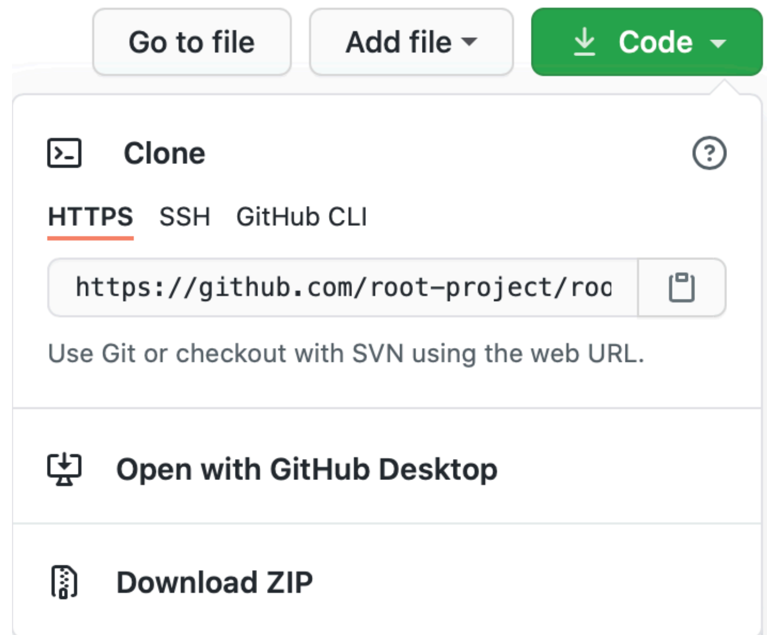
- Appointment and Affiliation
  - ✓ Research Director
  - ✓ CNRS/IN2P2 LAPP Annecy (France)
- Services to the profession
  - ✓ ATLAS Collaboration at CERN LHC
  - ✓ ATLAS Higgs Group Convener
- Expertise
  - ✓ Higgs Physics
  - ✓ QCD physics (photons + jets)
  - ✓ HEP Calorimetry
  - ✓ HEP Electronics and Signal Processing
  - ✓ Data Analysis and Statistics
- At ESIPAP
  - ✓ W1 Experimental Particle Physics

https://github.com/marcodelmastro/ESIPAP-2021



https://github.com/marcodelmastro/ESIPAP-2021

- Best option: clone repository…
  - ✓ `git clone https://github.com/marcodelmastro/ESIPAP-2021.git`
- … and update when needed
  - ✓ `cd ESIPAP-2021`
  - ✓ `git pull`



- Alternative option: download the repository as zip
  - ✓ But why? You'll need to re-download at each update. Take the opportunity to learn some basic git commands, you'll need them in the future…

how to derive the Bethe-Block formula

"*Culture isn't knowing ~~when Napoleon died~~. Culture means knowing how I can find out in two minutes.*"

Umberto Eco

http://www.spiegel.de/international/zeitgeist/spiegel-interview-with-umberto-eco-we-like-lists-because-we-don-t-want-to-die-a-659577-2.html

"If I could remember the names of all these particles, I'd be a botanist!"

Enrico Fermi

http://pdg.lbl.gov/

Calculations and groupwork

- *In normal times, I'd do some calculation on the whiteboard…*
  - ✓ In these special times, I'll attempt to do such calculations by **projecting my desk**
  - ✓ Please let me know if you can follow!

- *In normal times, I'd sometimes call you to do calculations on the whiteboard!*
  - ✓ In these special times, I'll ask you to do them by yourself either **alone** or in **small groups** using **breakout rooms**
  - ✓ We'll also use **breakout rooms** to do other groupwork

- *In normal times, I'd ask questions to you…*
  - ✓ I'll do it even in these special times!

"The only stupid questions are those that are not asked!

- During the lecture…
  - ✓ Raise your virtual hand in Zoom
  - ✓ Use the Zoom chat
  - ✓ Interrupt me!
- During the breaks…
- After the lecture…
  - ✓ Send me a DM in Slack
  - ✓ Post on the Slack channel
    - `#week-1-experimental-particle-physics`

Program

Tuesday	Wednesday	Thursday	Friday	Monday
Lecture 1 units, quantities, kinematics, measurements	Lecture 3 particle interactions in particle detectors	Lecture 4 systems used to identify and measure particle properties	Lecture 5 HEP data analysis basics and S/B optimization	*Tutorial D* *analysis of "classic" experiments (students' presentation)*
Lecture 2 a few things about particle accelerators	*Tutorial A* *particle kinematics* *particle interactions and detector response*	*Tutorial B* *event display challenge*	*Tutorial C* *data analysis exercise*	Lecture 6 detection of "invisible" particles

Experimental particle physics

1. units, quantities, kinematics, measurements

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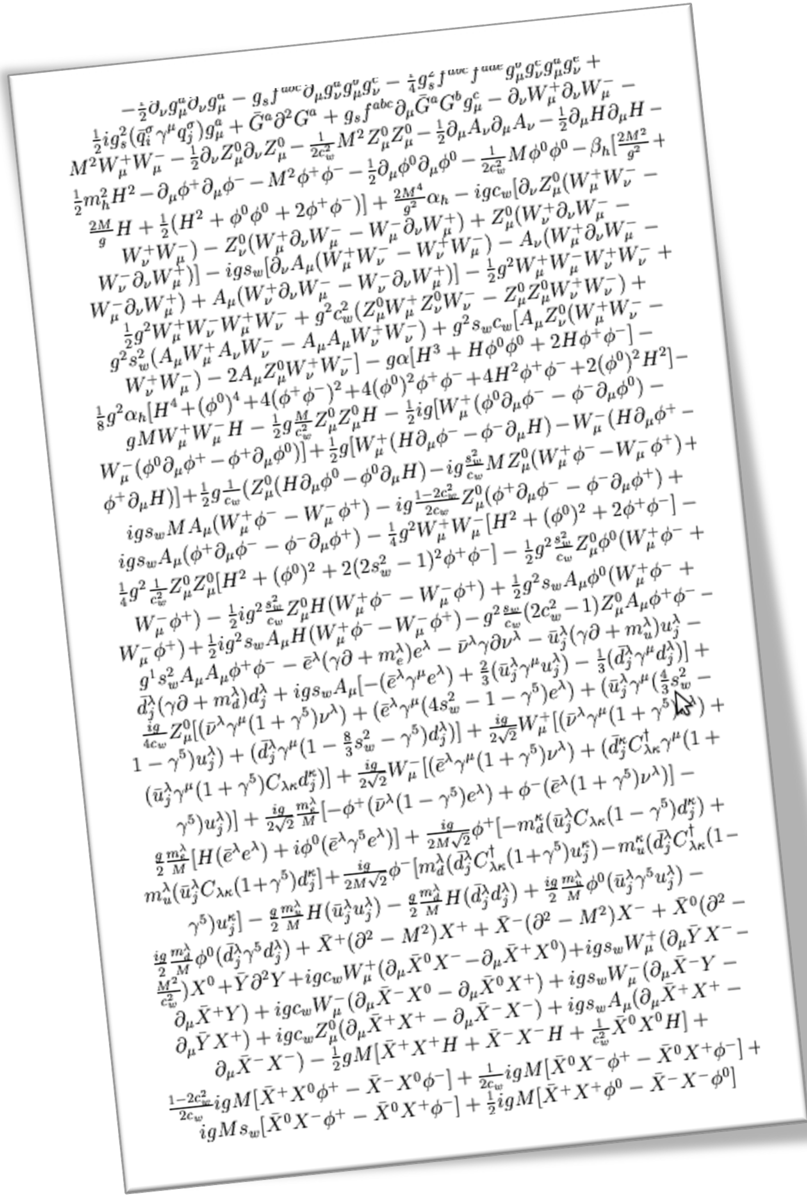
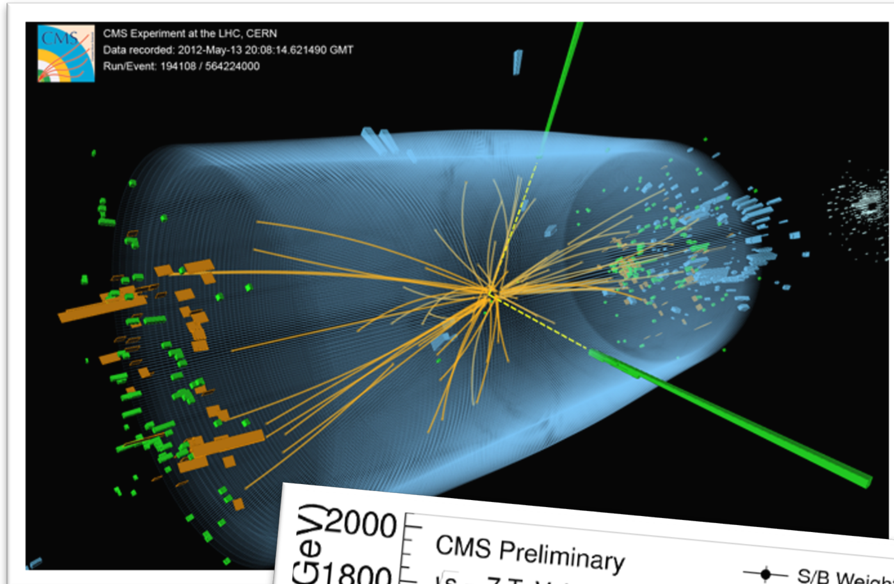
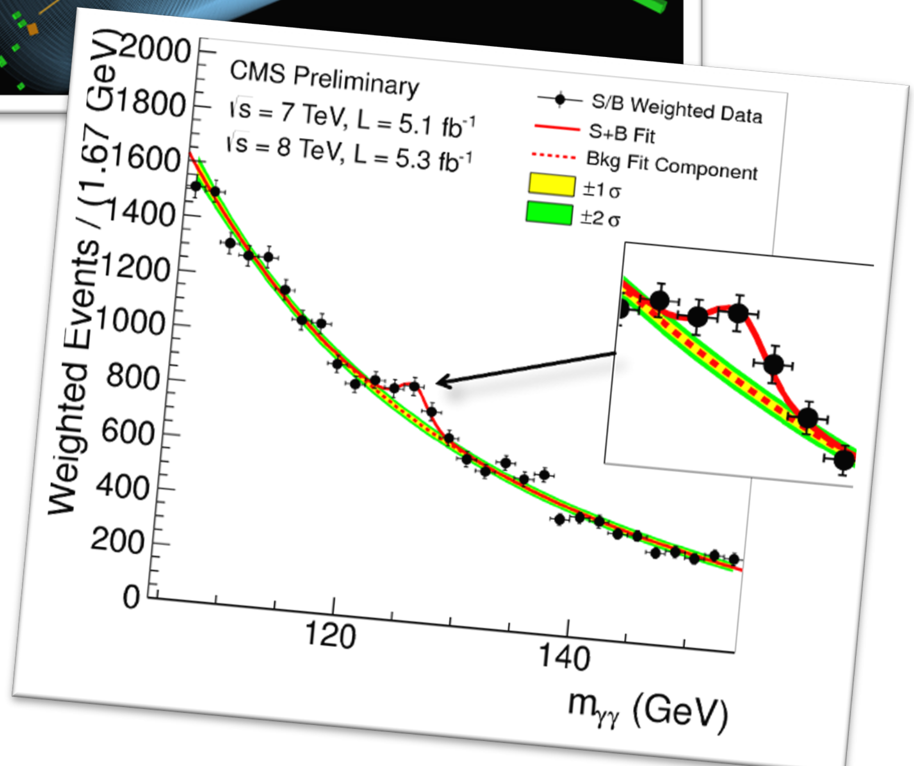
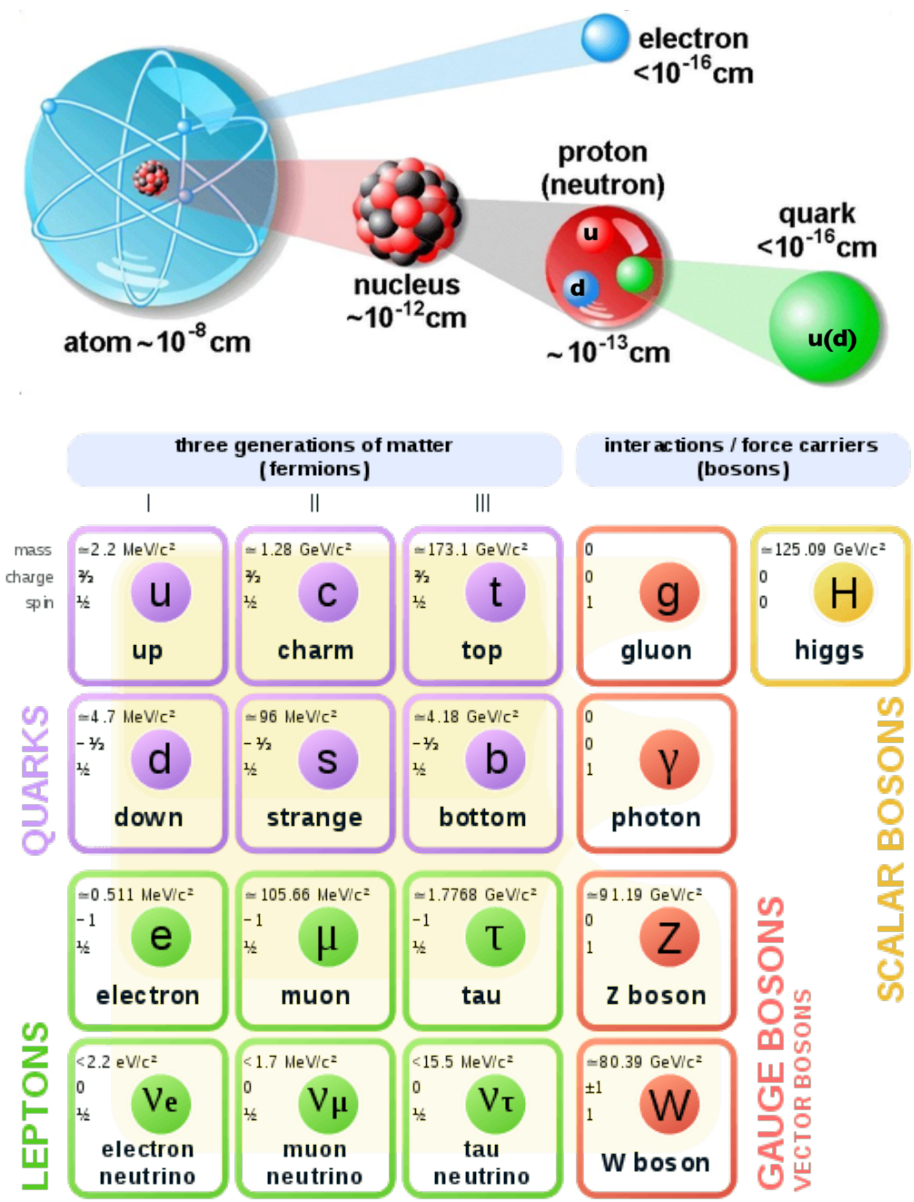
Experiment = probing/building theories with data!







The Standard Model of particle physics…



Gauge bosons

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

Gauge boson coupling to fermions (EW, QCD)

Higgs coupling to fermions (fermion masses)

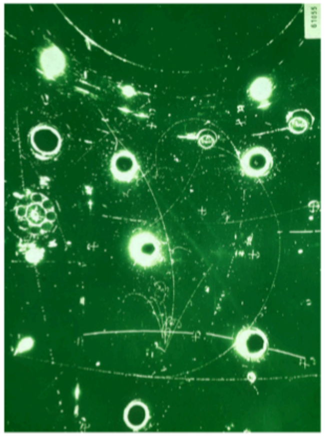
Higgs coupling to bosons (boson masses)

Higgs self-coupling (Higgs potential)

A theory built (and probed) over time…

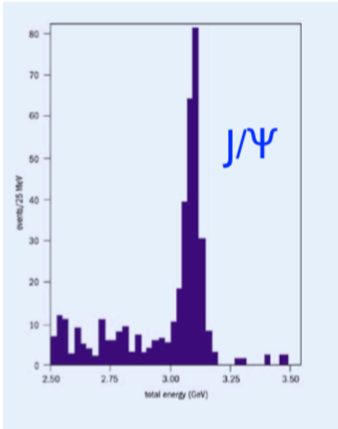
1972 – CERN

Neutral currents



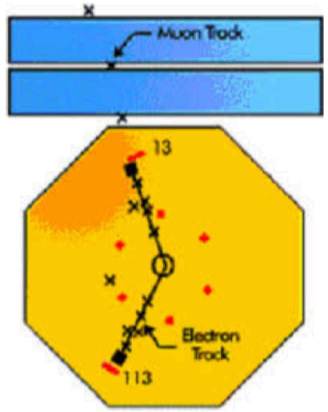
1974 – BNL, SLAC

Charm



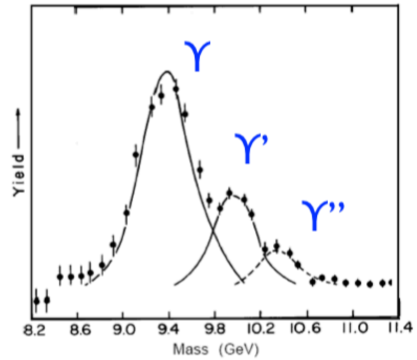
1976 – SLAC

Tau lepton



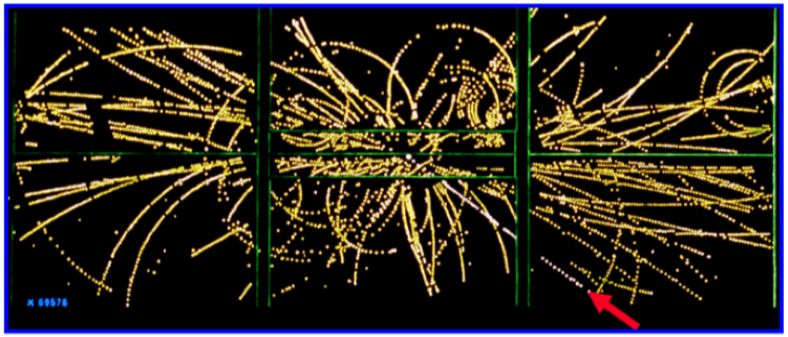
1979 – Fermilab

Beauty



1983 – CERN/SppS

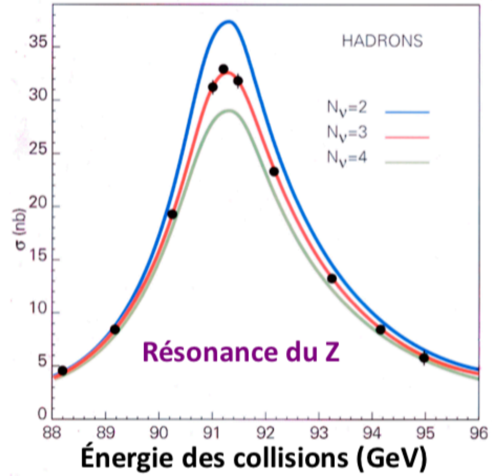
W and Z bosons



UA1, UA2

1990 – CERN/LEP

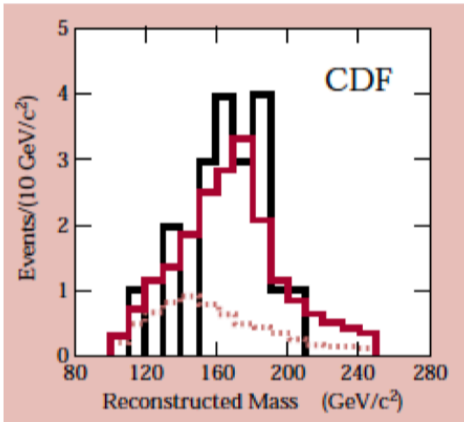
Three families of neutrinos



ALEPH, DEPHI, L3, OPAL

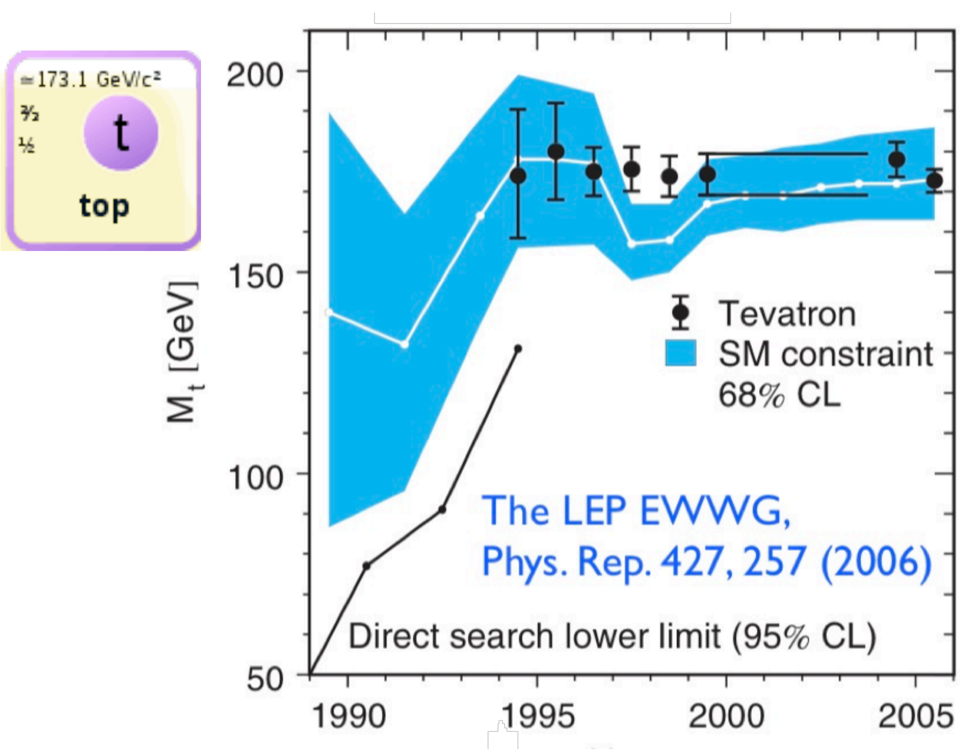
1994 – Fermilab/TeVatron

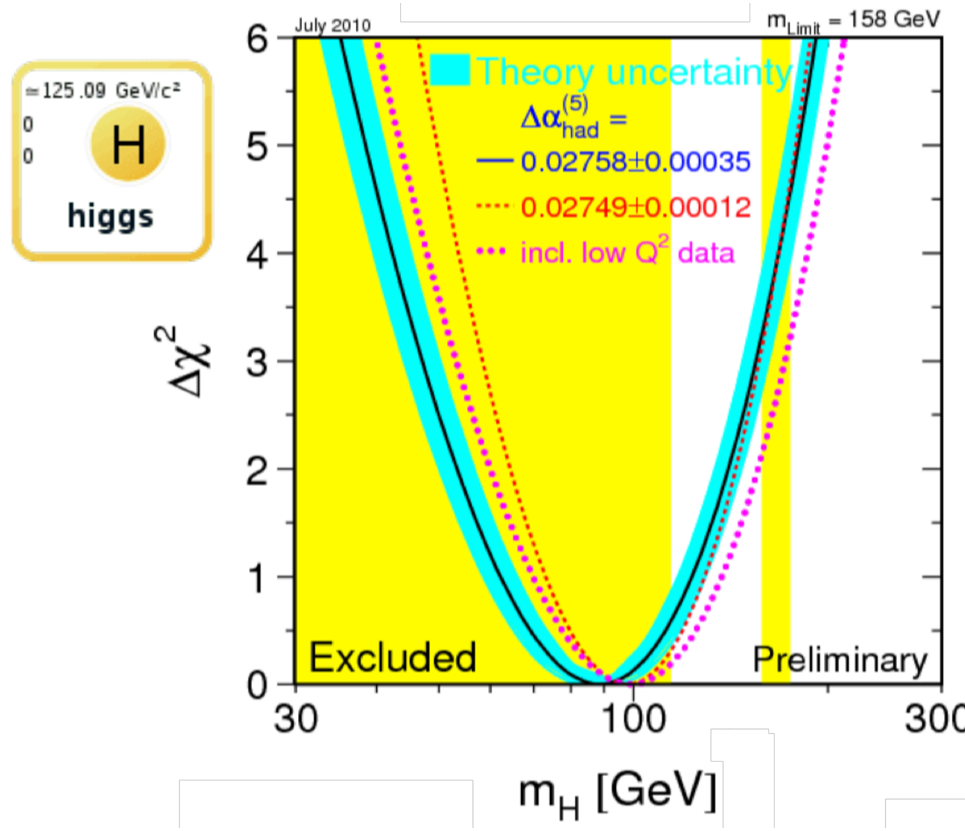
Top quark



CDF, D0

Before the LHC startup





m_W measurement at SppS and LEP-1 precision measurements

top quark discovery (1994)

m_W measurement at LEP-2

electroweak fit and indirect limit on m_H

Direct limits on Higgs production from LEP-2 and Tevatron

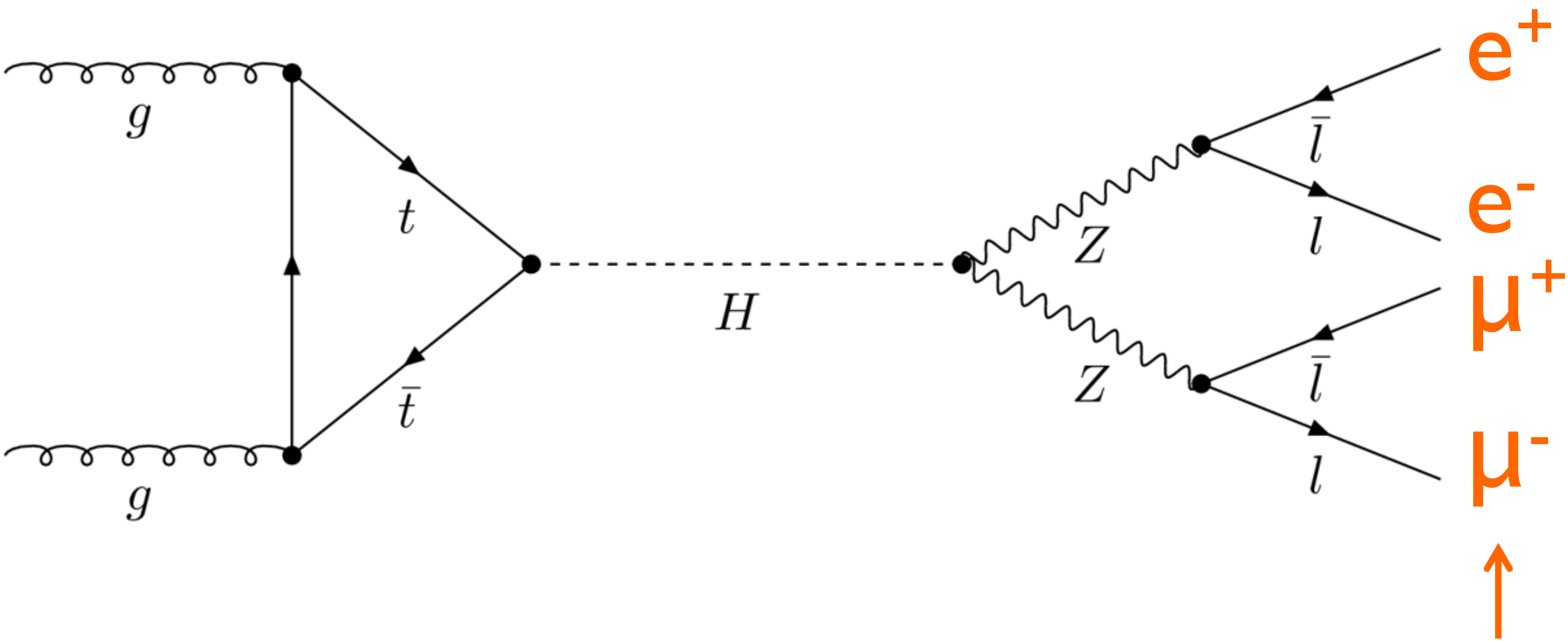
LHC "no loose theorem"

Either the Higgs boson is discovered,
or New Physics should manifest to avoid unitarity violation in WW scattering at TeV scale

What do we want to measure?

Example: let's assume a Higgs boson is produced at the LHC …
(how and how often we'll see later)

… we look for "stable" particles from an unstable particle decays



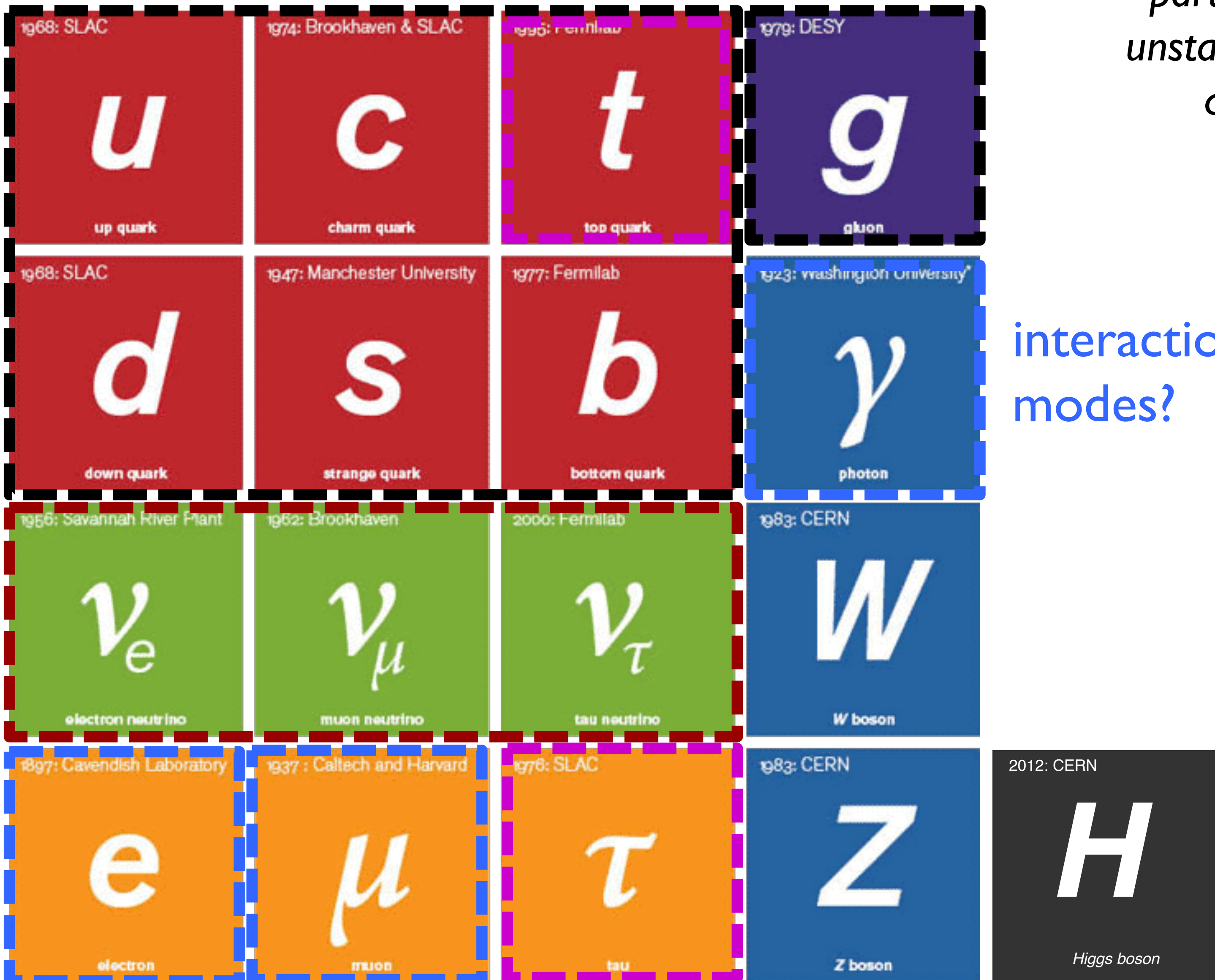
this is what we are looking for…

What do we want to measure?

… "stable" *particles from unstable particle decays!*

decays?

hadron jets



interaction modes?

invisible

in particle detectors at accelerators

interaction modes?

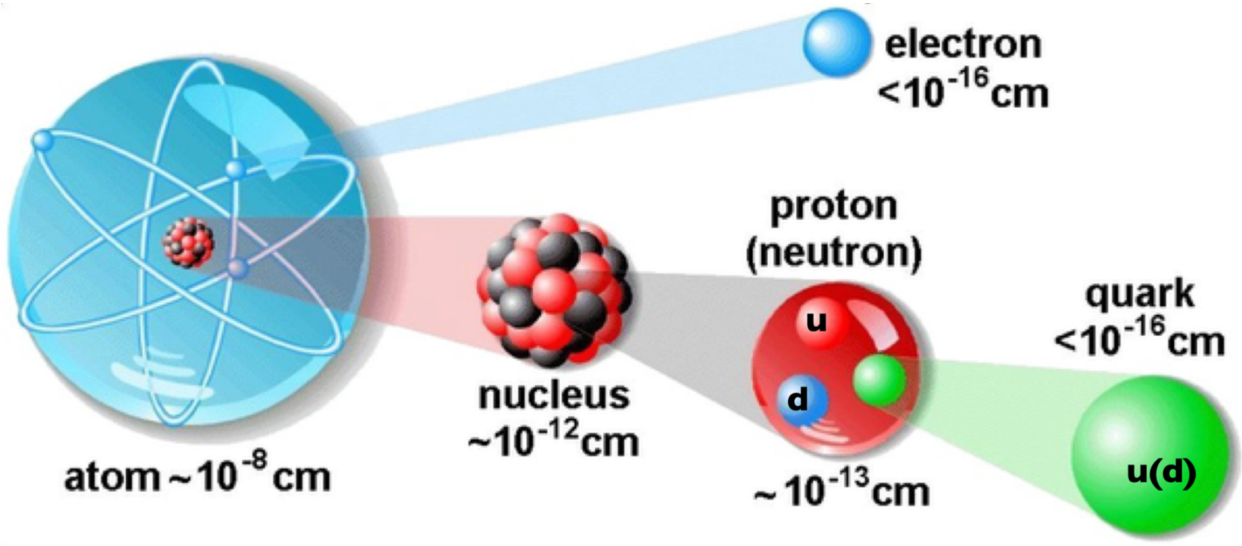
decays?

HEP, SI and "natural" units

Quantity	HEP units	SI units
length	1 fm	10^{-15} m
charge	e	$1.602 \cdot 10^{-19}$ C
energy	1 GeV	1.602×10^{-10} J
mass	1 GeV/c^2	1.78×10^{-27} kg
$\hbar = h/2\pi$	6.588×10^{-25} GeV s	1.055×10^{-34} Js
c	2.988×10^{23} fm/s	2.988×10^{8} m/s
$\hbar c$	197 MeV fm	…

	"natural" units ($\hbar = c = 1$)
mass	1 GeV
length	1 GeV^{-1} = 0.1973 fm
time	1 GeV^{-1} = 6.59×10^{-25} s

Probing smaller and smaller scales…



Optical microscope resolution

$$\Delta r \sim \frac{1}{\sin\theta}$$

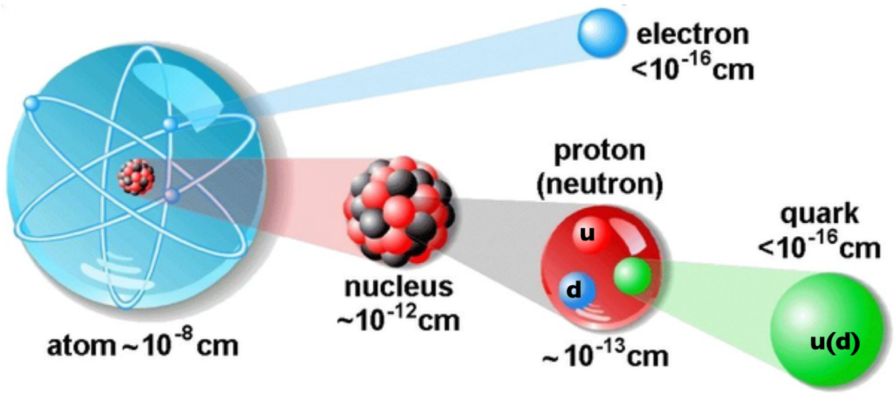
with θ = angular aperture of the light beam

De Broglie wavelength

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

with p = transferred momentum

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}	

Measuring particles

- Particles are characterized by
  - ✓ Mass [Unit: eV/c^2 or eV]
    - Composite? Fundamental?
  - ✓ Charge
    - What type (electric, weak, strong)?
    - Are there other charges? What is the origin of charge?
  - ✓ Energy [Unit: eV]
  - ✓ Momentum [Unit: eV/c or eV]

  - ✓ Interaction strength in each reaction
    - Reaction probabilities
  - ✓ Lifetime before their decay (or width)
  - ✓ Spin
    - Intrinsic angular momentum (boson: integer; fermions: semi-integer): origin?
    - Measured via angular distributions in scattering or decay processes

Particle identification via measurement of several quantities…

e.g. (E, p, Q) or (p, β, Q)
(p, m, Q) ...

- … and move at relativistic speed

Relativistic kinematics in a nutshell

$$E^2 = \vec{p}^2 c^2 + m^2 c^4 \qquad E^2 = \vec{p}^2 + m^2$$

$$E = m\gamma c^2 \qquad E = m\gamma$$

$$\vec{p} = m\gamma\vec{\beta}c \qquad \vec{p} = m\gamma\vec{\beta}$$

$$\vec{\beta} = \frac{\vec{p}c}{E} \qquad \vec{\beta} = \frac{\vec{p}}{E}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \frac{v}{c}$$

$$t = t_0\gamma$$

time dilatation

$$\ell = \frac{\ell_0}{\gamma}$$

length contraption

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:

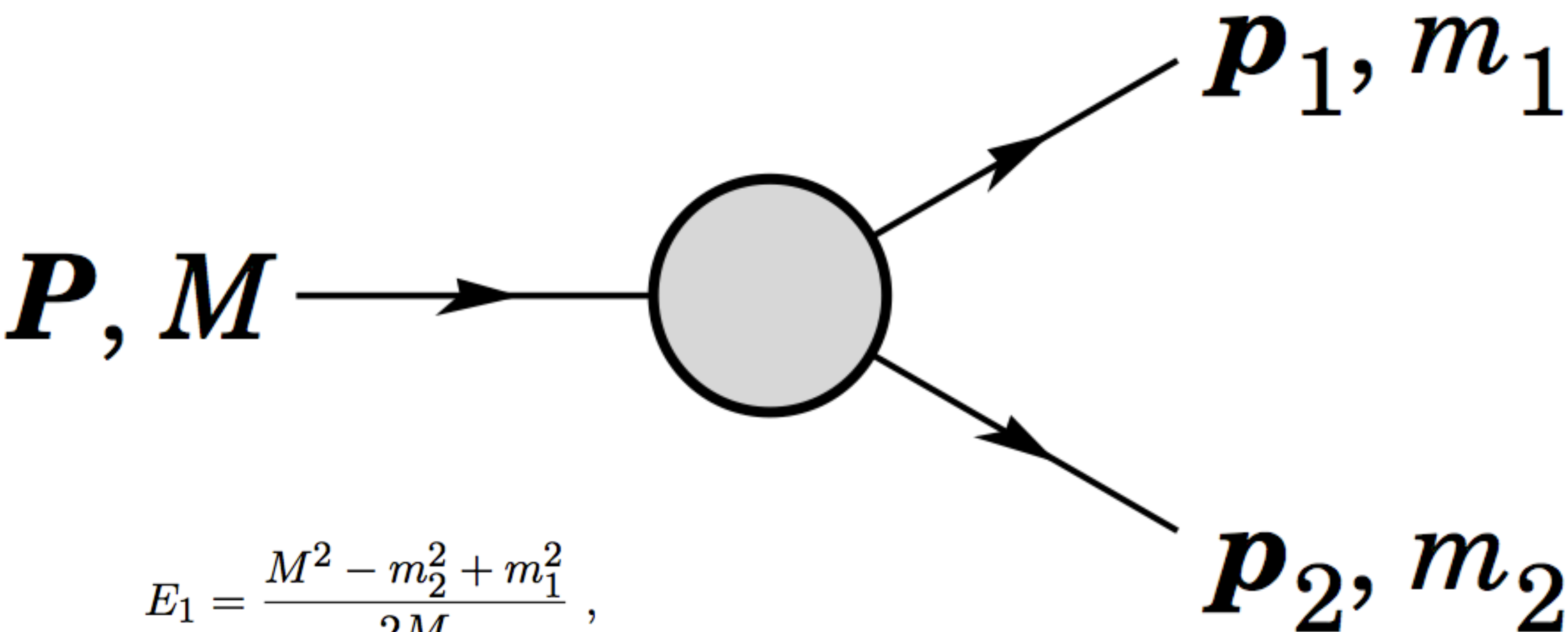
$$E_{\mathrm{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

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?

2-body decay

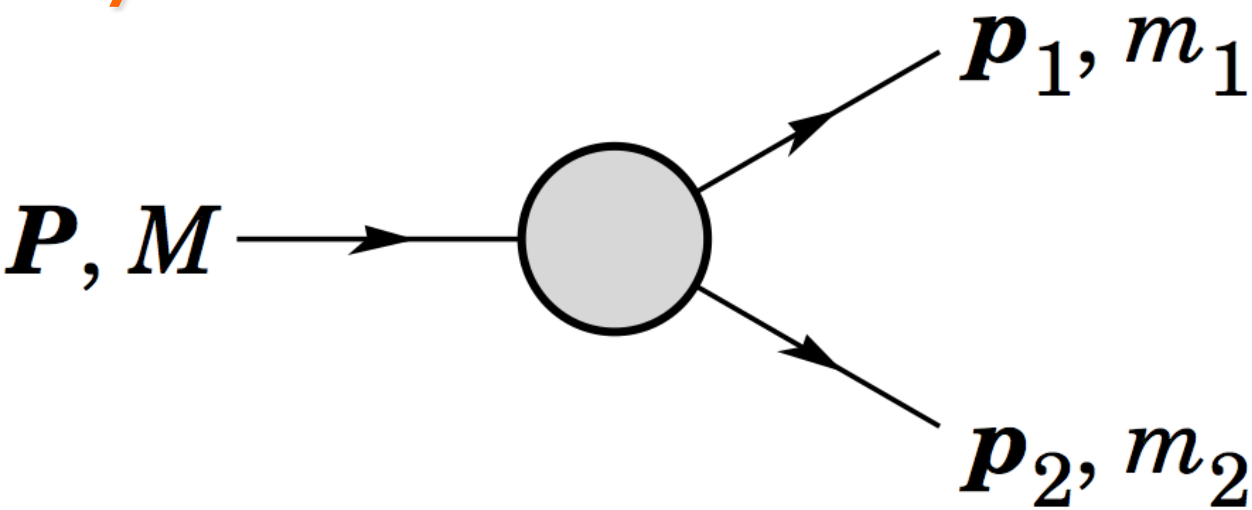


$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} \; ,$$

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

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

2-body decay

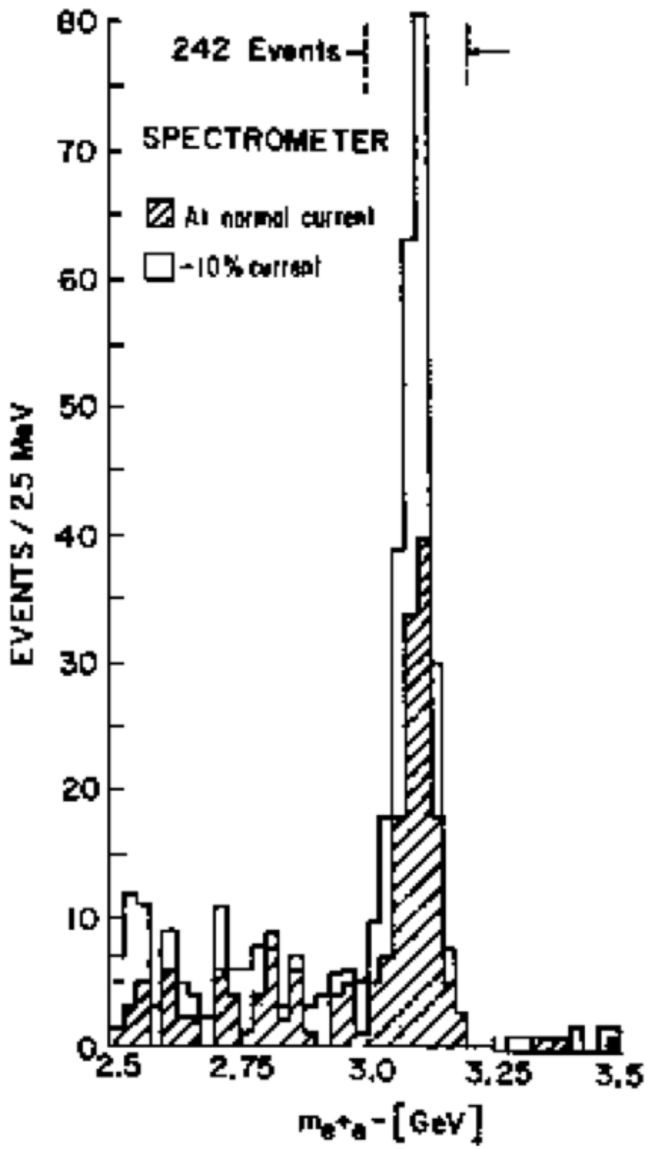


$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} \,,$$

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

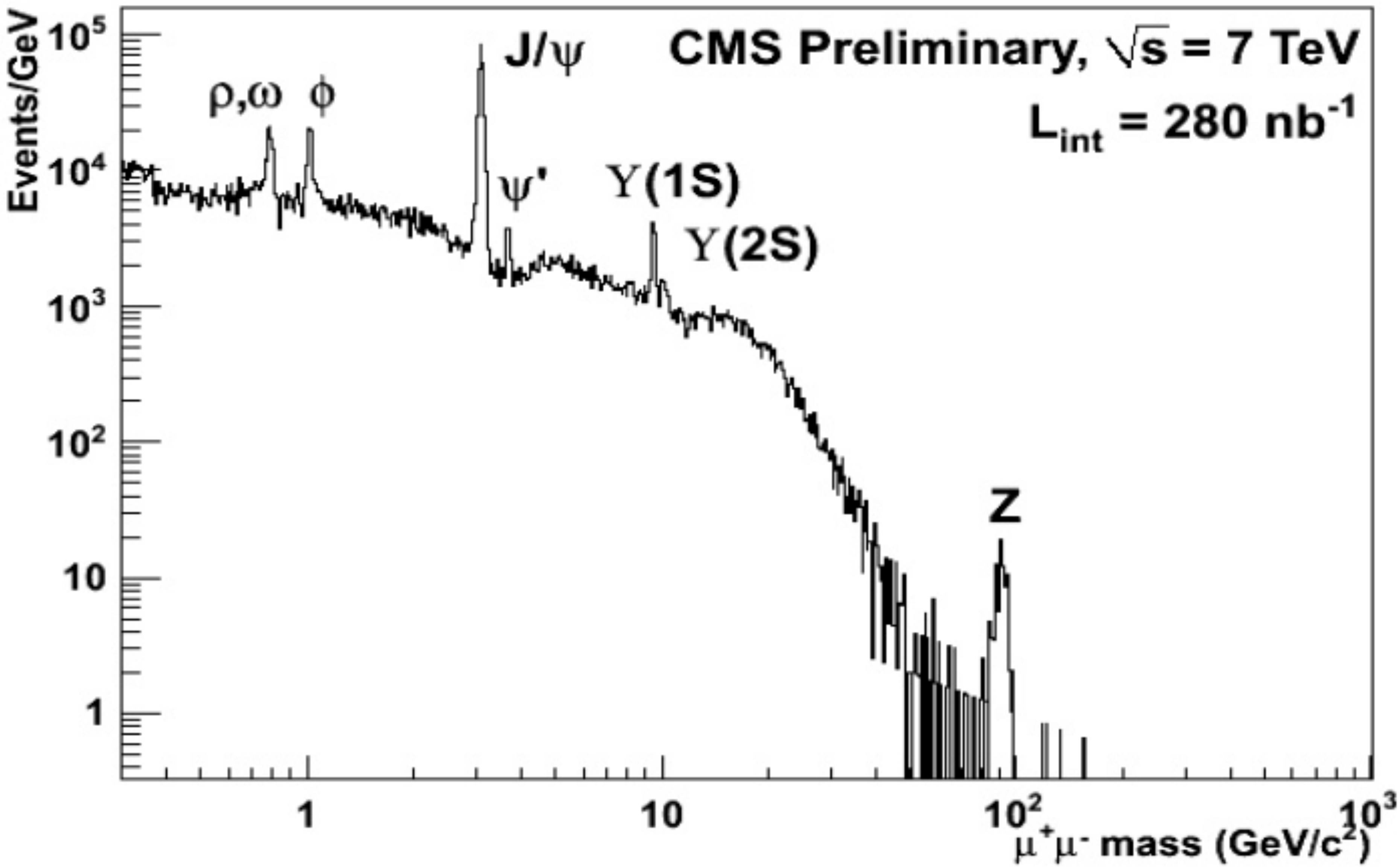
$$= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

Invariant mass

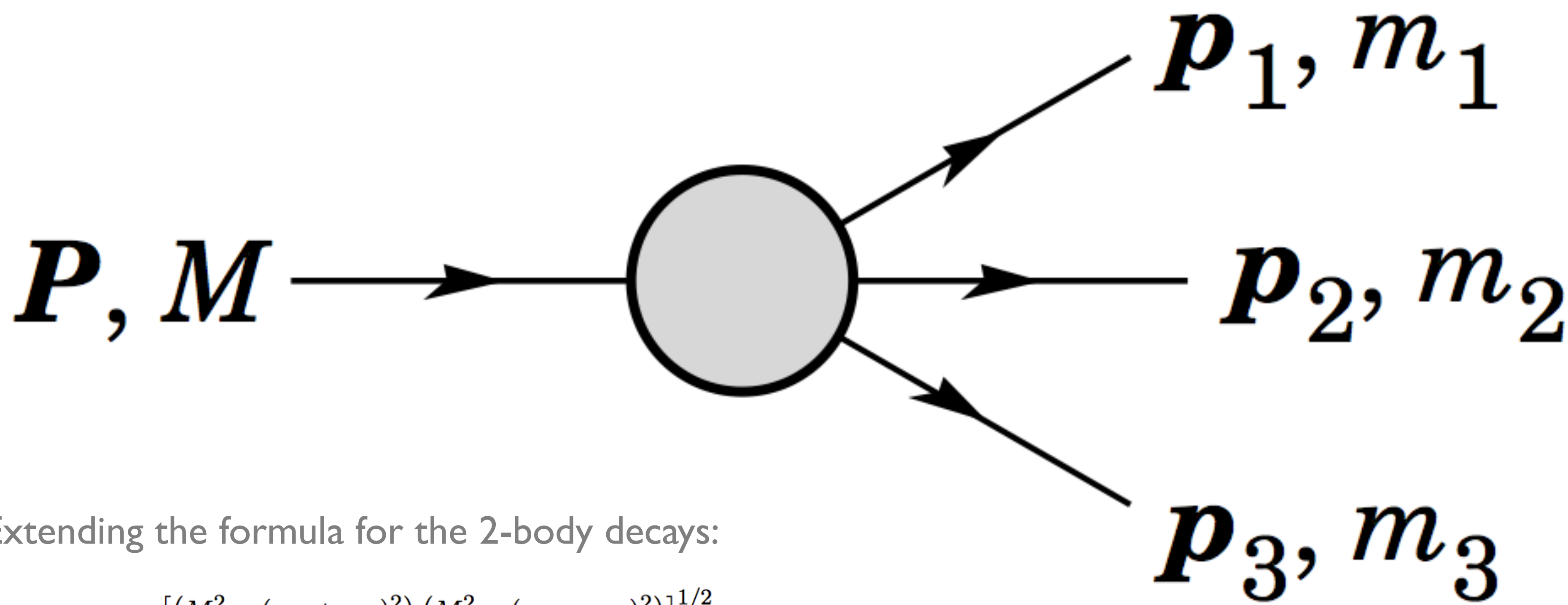


$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

Invariant mass



3-body decay



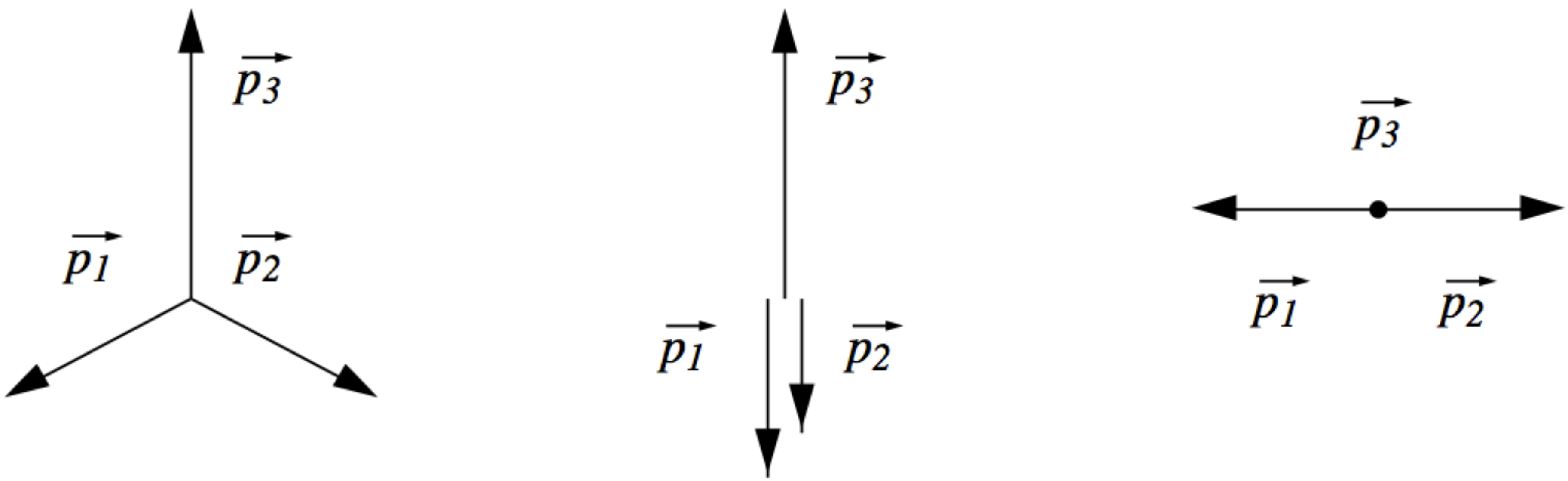
Extending the formula for the 2-body decays:

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

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

3-bodies decay

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



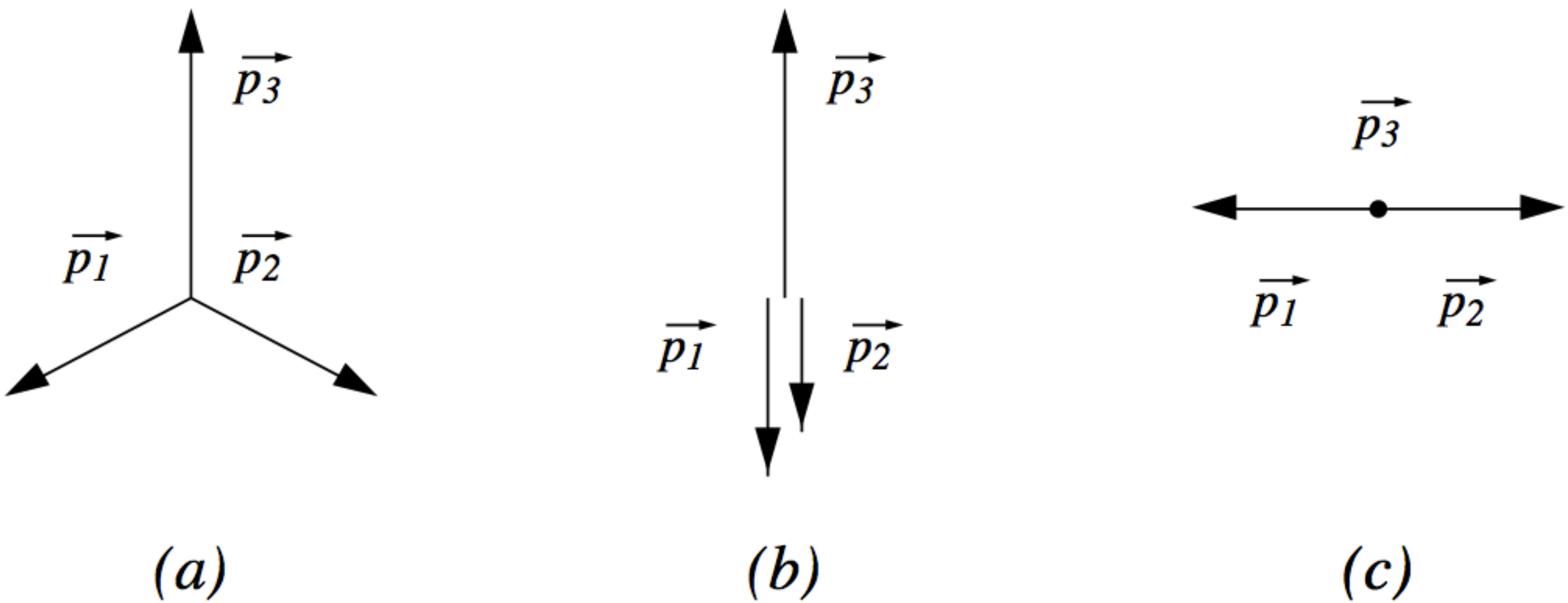
(a) *(b)* *(c)*

1) $\max(|\vec{p}_3|)$

2) $\min(|\vec{p}_3|)$

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)

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

pion decays at rest (2-body decay)

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

$$m_\nu = 0$$

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

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

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

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

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

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

A real example: pion decay(s)

pion decays at rest

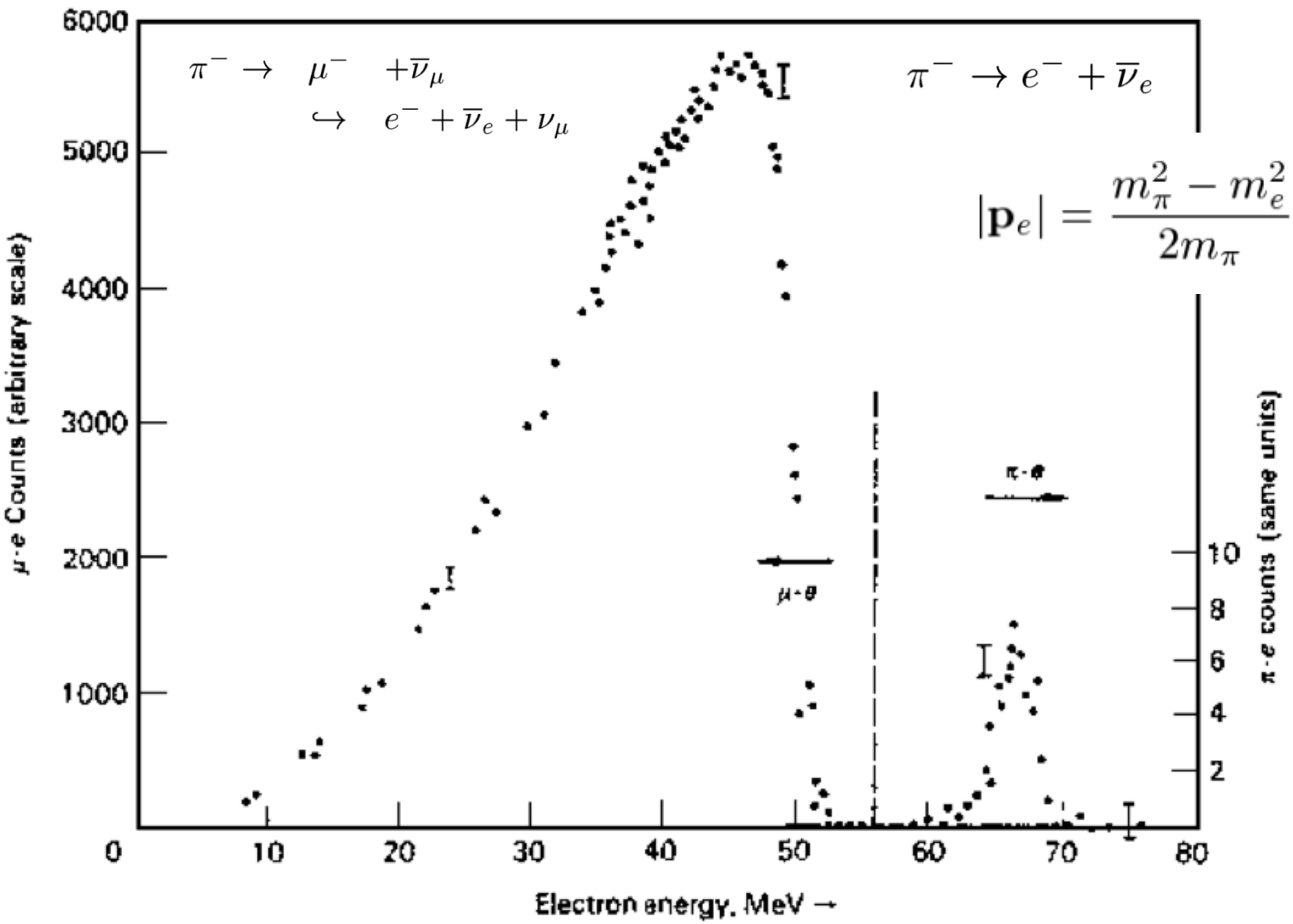
$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}c \simeq 30\,\mathrm{MeV/c}$$

$$m_\nu = 0$$

in most cases muon decays at rest

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

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



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

3-bodies decay: Dalitz plot

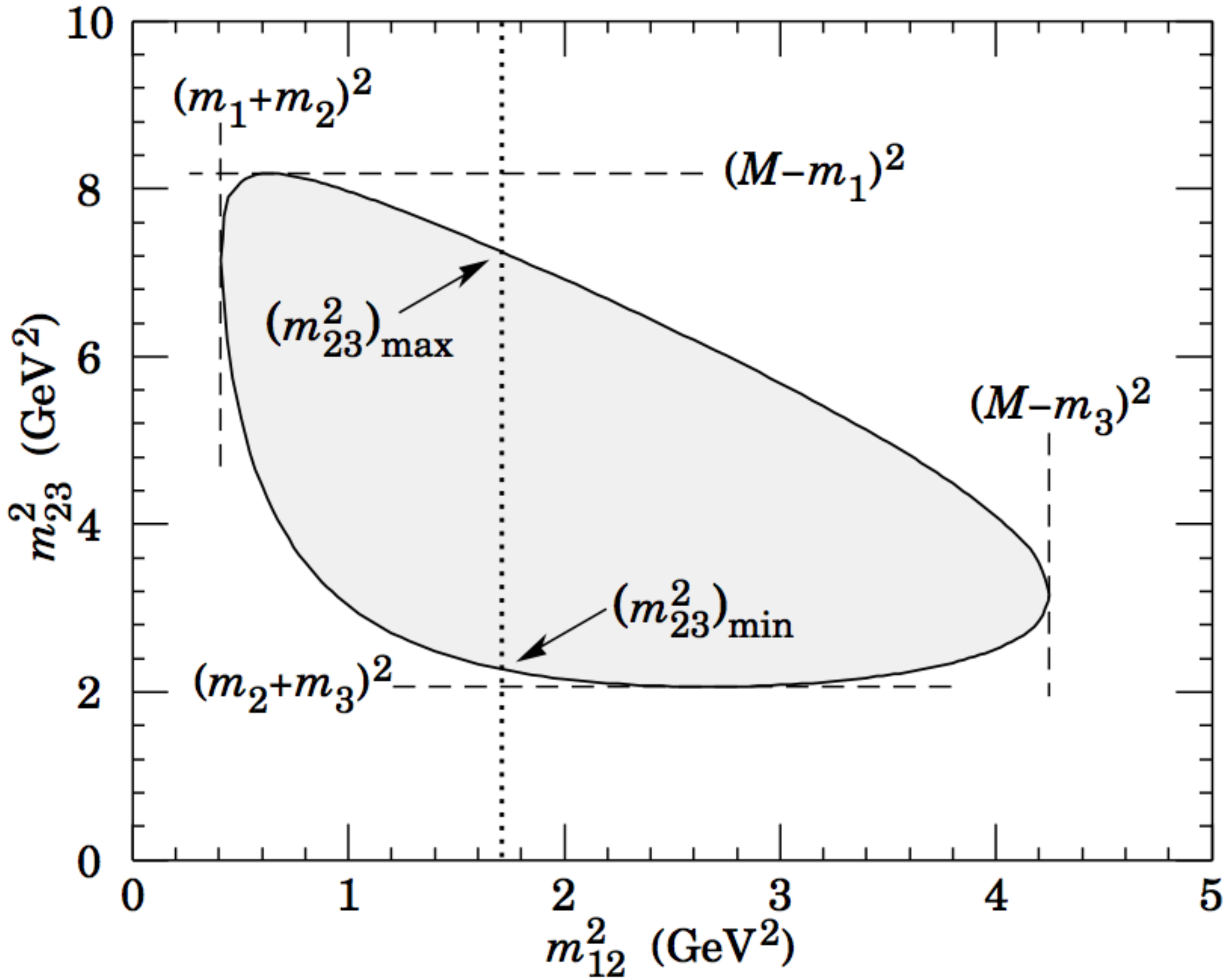
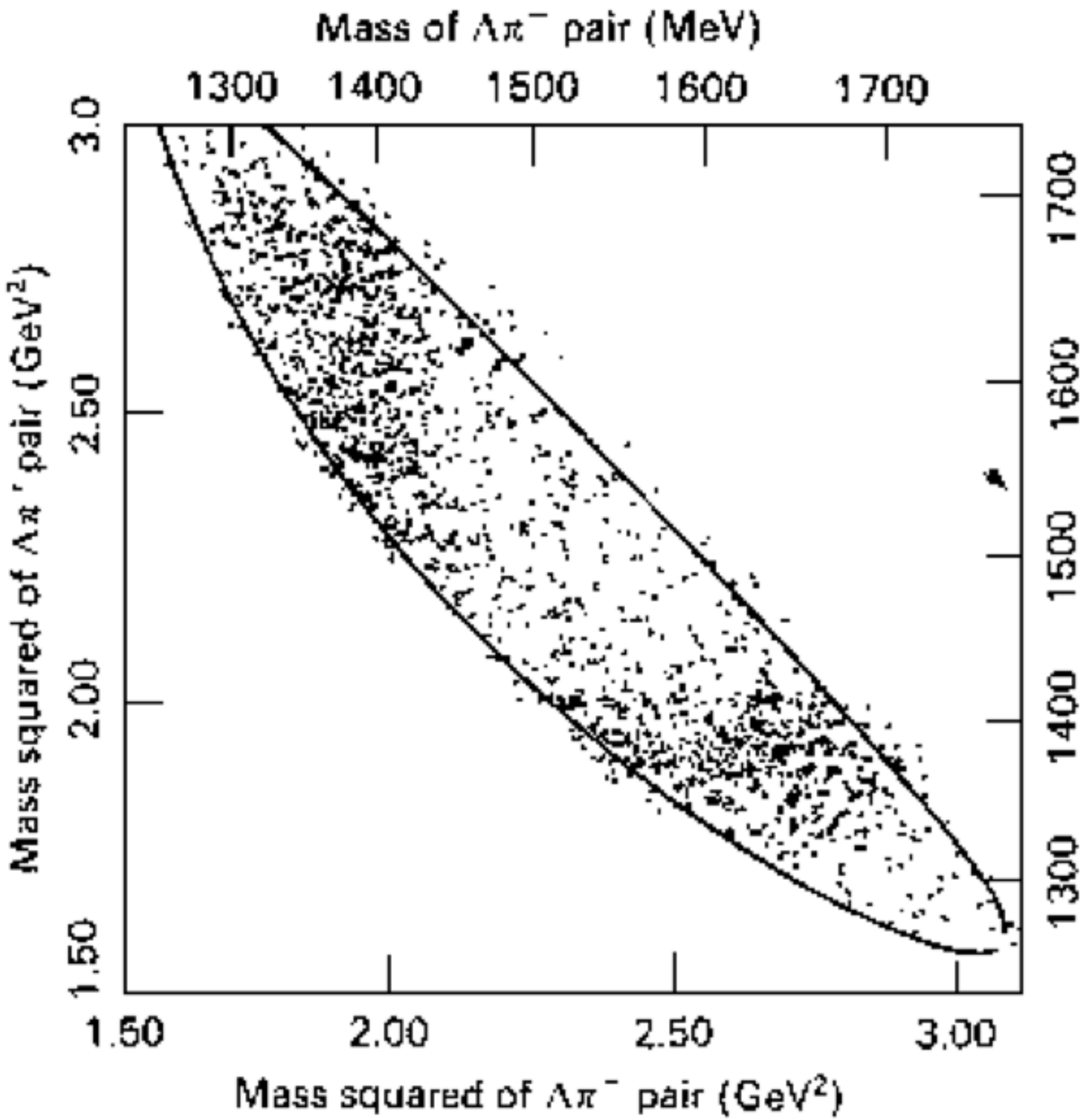


Figure 45.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+\overline{K}^0p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

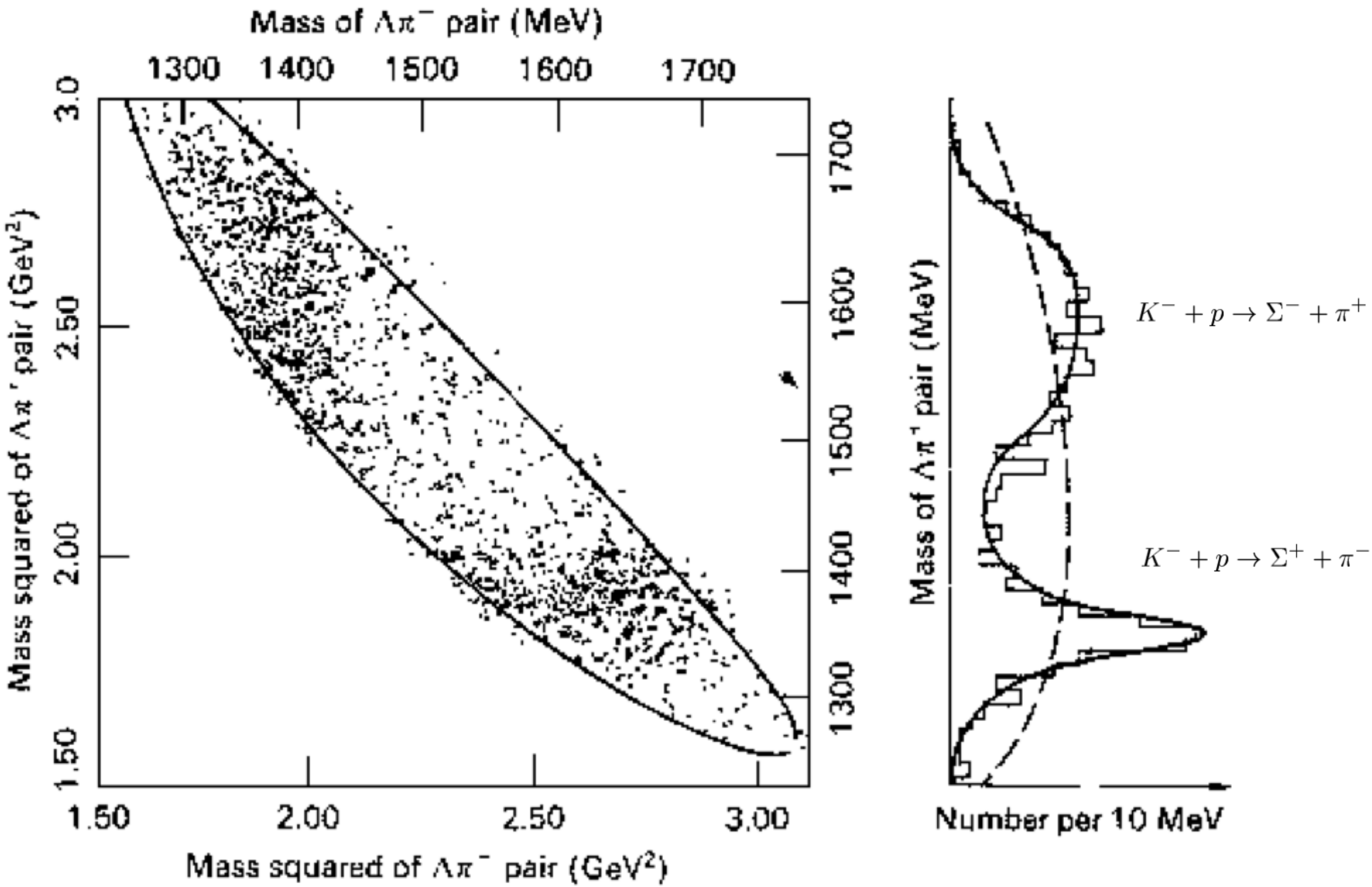
Multi-bodies decay

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

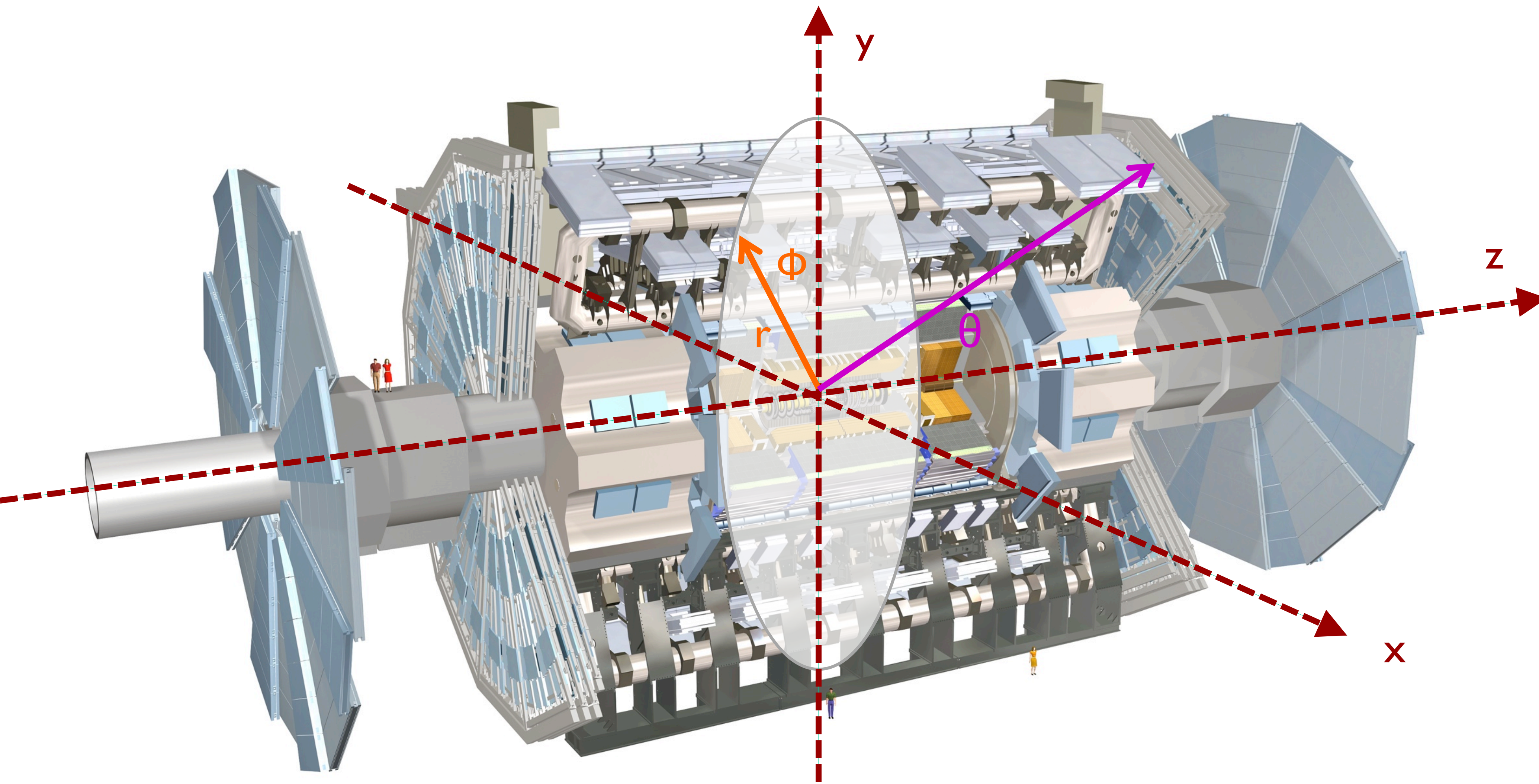


Multi-bodies decay

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



Collider experiment coordinates



Rapidity

Lorentz factor $\gamma = \frac{1}{\sqrt{1-\beta^2}} = \cosh\varphi$ Hyperbolic cosine of "rapidity"

$$E = m\cosh\varphi$$
$$|\vec{p}| = m\sinh\varphi$$

$$\varphi = \tanh^{-1}\frac{E}{|\vec{p}|} = \frac{1}{2}\ln\frac{E+|\vec{p}|}{E-|\vec{p}|}$$

- Particle physicists prefer to use modified rapidity along beam axis

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

Pseudorapidity

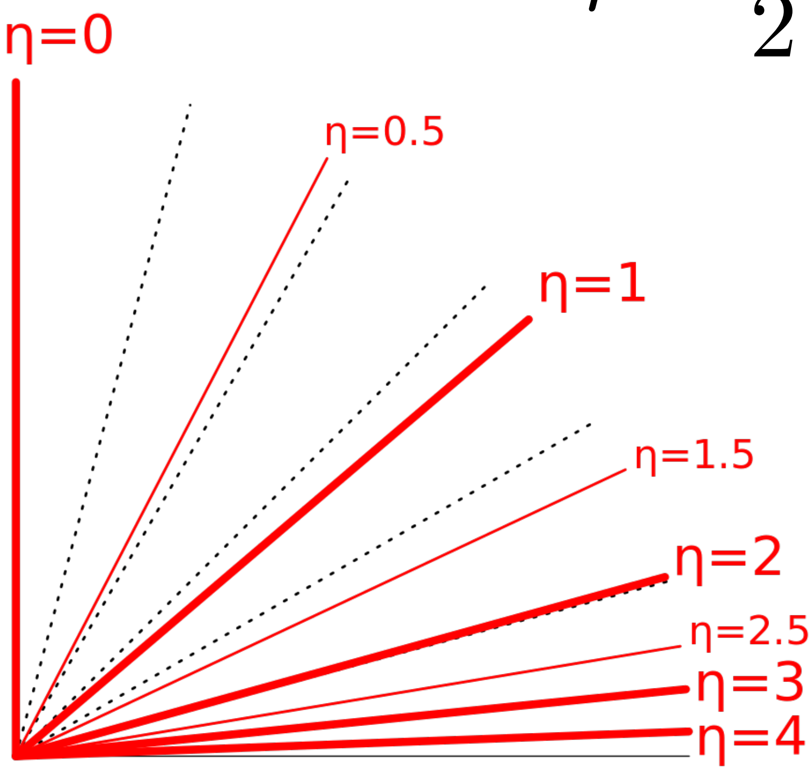
$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

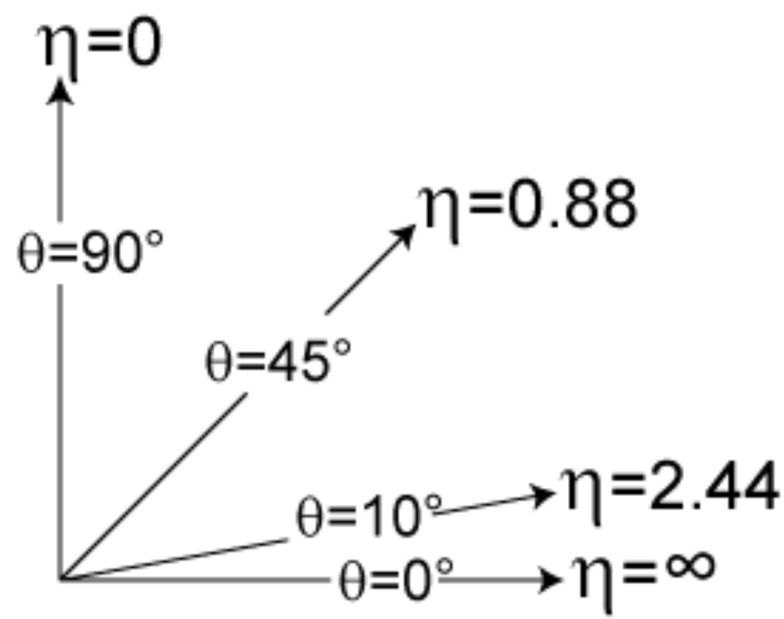
$$\eta = \frac{1}{2}\ln\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z}$$

$$\eta \simeq y$$

if E >> m

$$\eta = \frac{1}{2}\ln\left(\tan\frac{\theta}{2}\right)$$





Transverse variables

- At hadron colliders, a significant and unknown fraction of the beam energy in each event escapes down the beam pipe.
- Net momentum can only be constrained in the plane transverse to the beam z-axis!

$$\sum p_T(i) = 0$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$p_x = p_T \cos\phi$$

$$p_y = p_T \sin\phi$$

$$p_z = p_T \sinh\eta$$

$$|p| = p_T \cosh\eta$$

$$E_T = \frac{E}{\cosh\eta}$$

Missing transverse energy and transverse mass

- If invisible particle are created, only their transverse momentum can be constrained: missing transverse energy

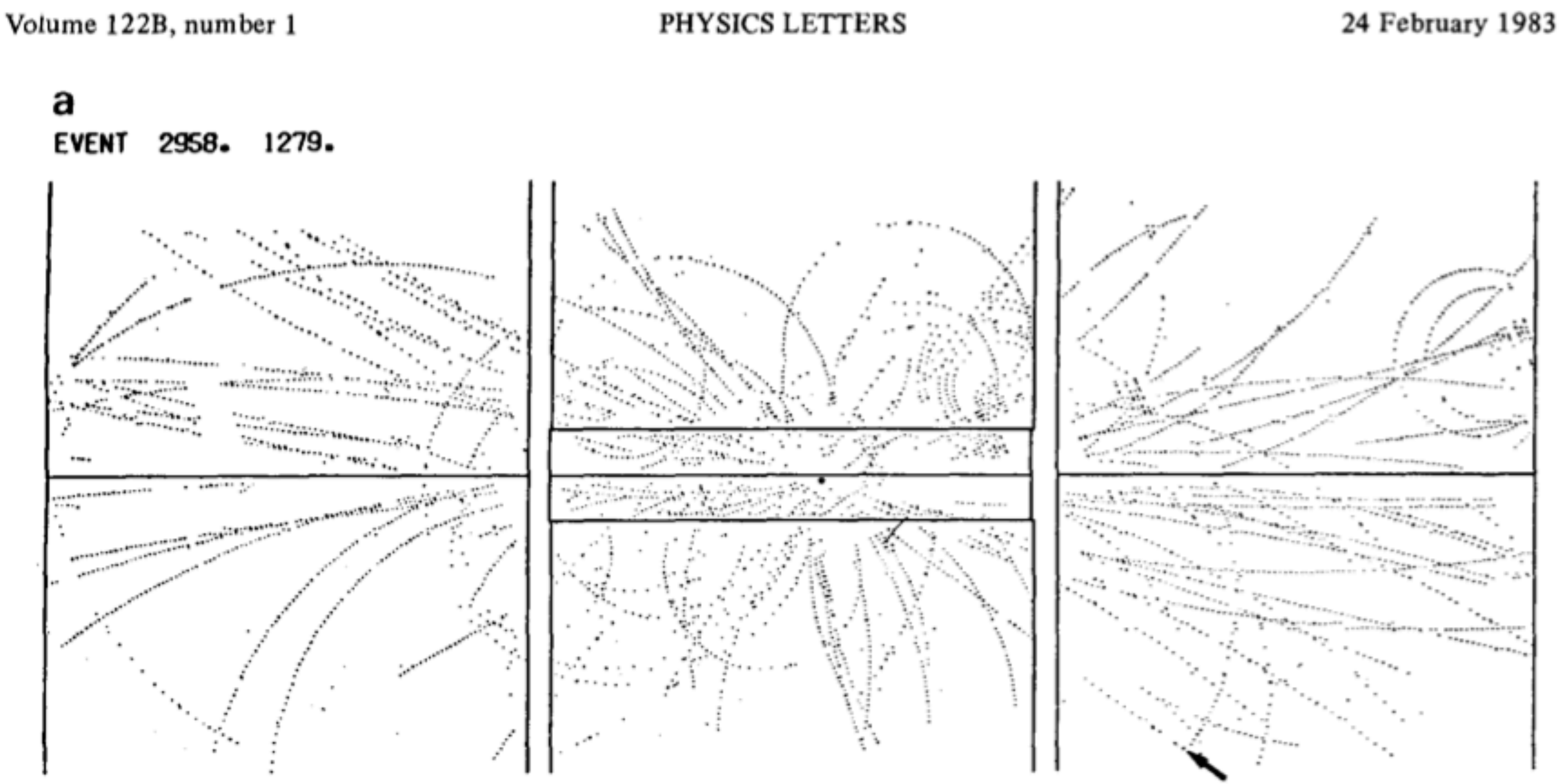
$$E_T^{\mathrm{miss}} = \sum p_T(i)$$

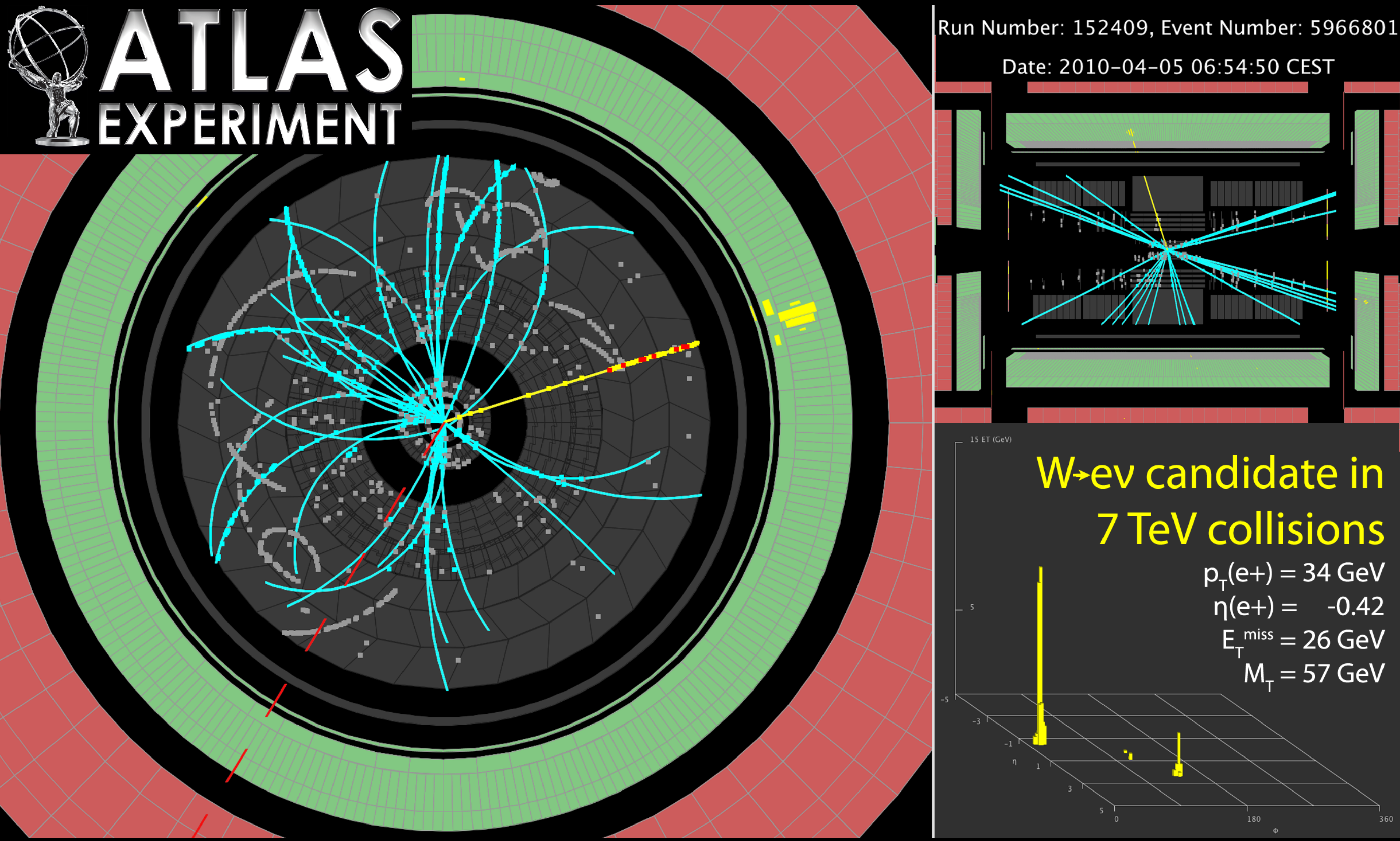
- If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can be constrained with the transverse mass quantity

$$\begin{aligned} M_T^2 &\equiv [E_T(1) + E_T(2)]^2 - [\boldsymbol{p}_T(1) + \boldsymbol{p}_T(2)]^2 \\ &= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \boldsymbol{p}_T(1) \cdot \boldsymbol{p}_T(2)] \end{aligned}$$

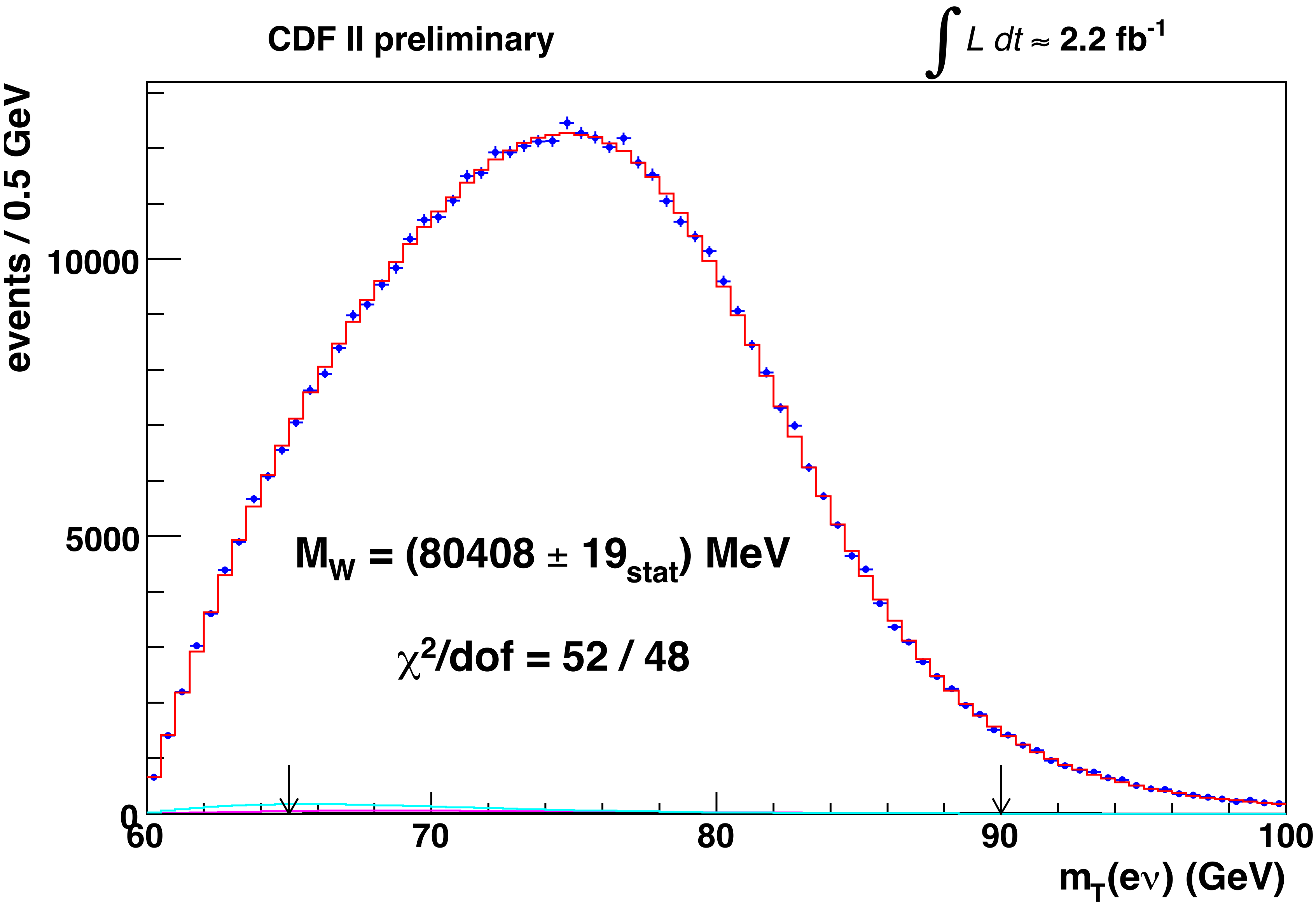
if $m_1 = m_2 = 0$ $\qquad M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos\phi_{12})$

W → e ν discovery



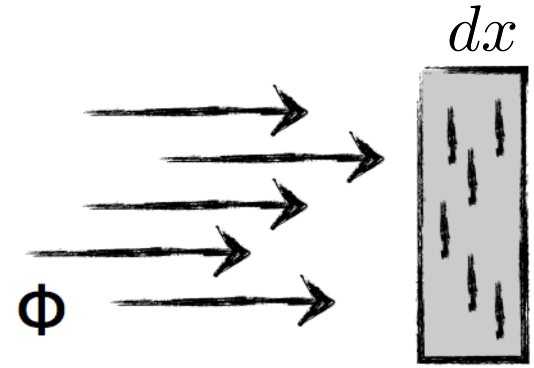

ATLAS EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
15 ET (GeV)
W→eν candidate in 7 TeV collisions
$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV
η
φ

W → e ν



CDF II preliminary
$\int L\, dt \approx$ 2.2 fb^{-1}
events / 0.5 GeV
10000
5000
0
60
70
80
90
100
$m_T(e\nu)$ (GeV)
$M_W = (80408 \pm 19_{stat})$ MeV
$\chi^2/dof = 52 / 48$

Interaction cross section



Flux $$\Phi = \frac{1}{S}\frac{dN_i}{dt}$$ $[L^{-2}\,t^{-1}]$

Reactions per unit of time $$\frac{dN_{\text{reac}}}{dt} = \Phi\overbrace{\sigma N_{\text{target}}\,dx}^{\textit{area obscured by target particle}}$$ $[t^{-1}]$

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

Reaction rate per target particle $$W_{if} = \Phi\sigma$$ $[t^{-1}]$

Cross section per target particle $$\sigma = \frac{W_{if}}{\Phi}$$ $[L^2]$ = reaction rate per unit of flux

1b = 10^{-28} m^2 (roughly the area of a nucleus with A = 100)

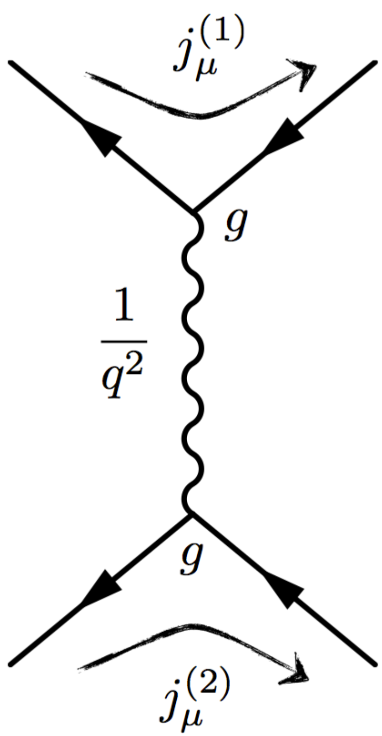

Fair
Antique

Fermi Golden Rule

From non-relativistic perturbation theory…

$$\underbrace{W_{if}}_{\text{transition probability}} = \frac{2\pi}{\hbar}\underbrace{|M_{if}|^2}_{\text{matrix element}}\underbrace{\frac{dN}{dE_f}}_{\text{energy density of final states}}$$

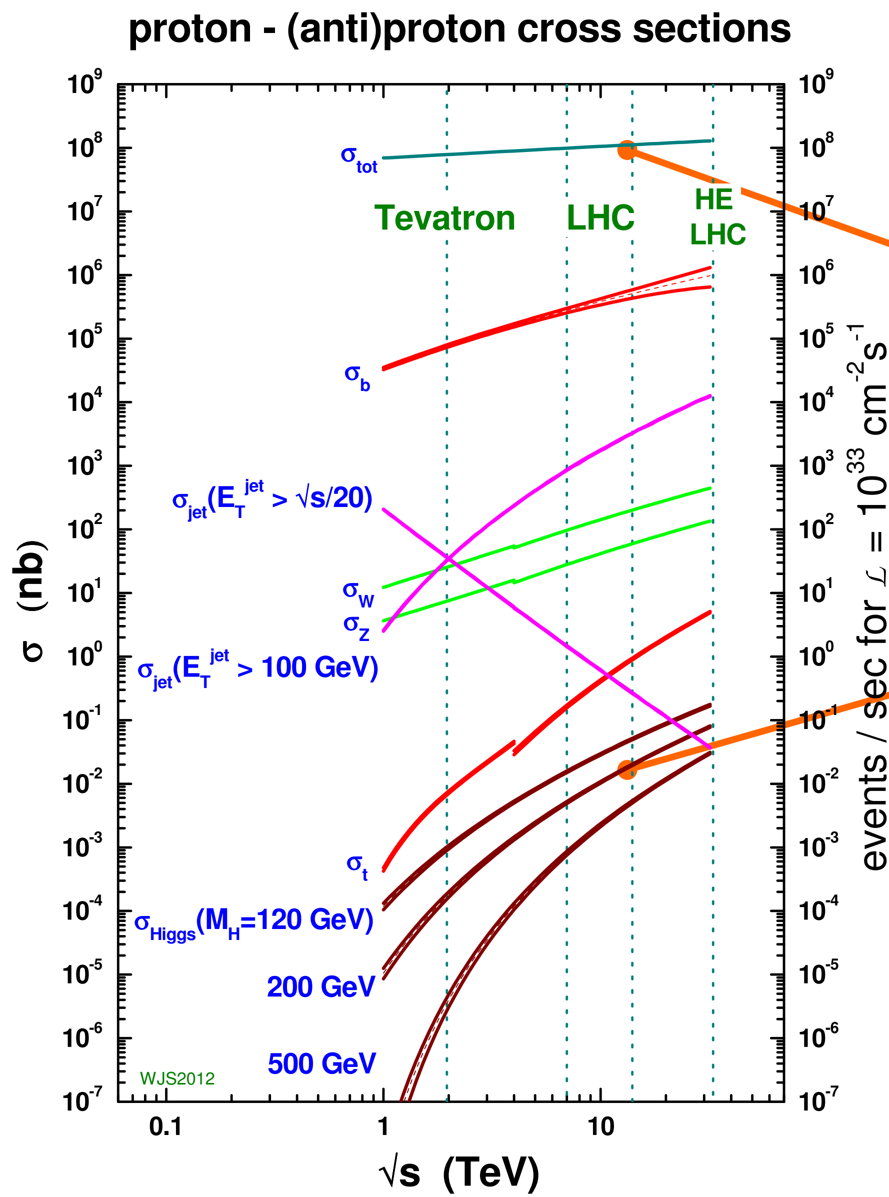
[t^{-1}] [E] [E^{-1}]



$$M_{if} = -i\int j_\mu^{(1)}\left(\frac{1}{q^2}\right)j_\mu^{(2)}d^4x$$

$$\sigma \sim |M_{if}|^2 \sim g^4\left(\frac{1}{q^4}\right)$$

Cross-sections at LHC



10^8 events/s

$\sim 10^9$

10^{-1} events/s ~ 10 events/min

[m_H ~ 125 GeV]

0.2% H → γγ

1.5% H → ZZ