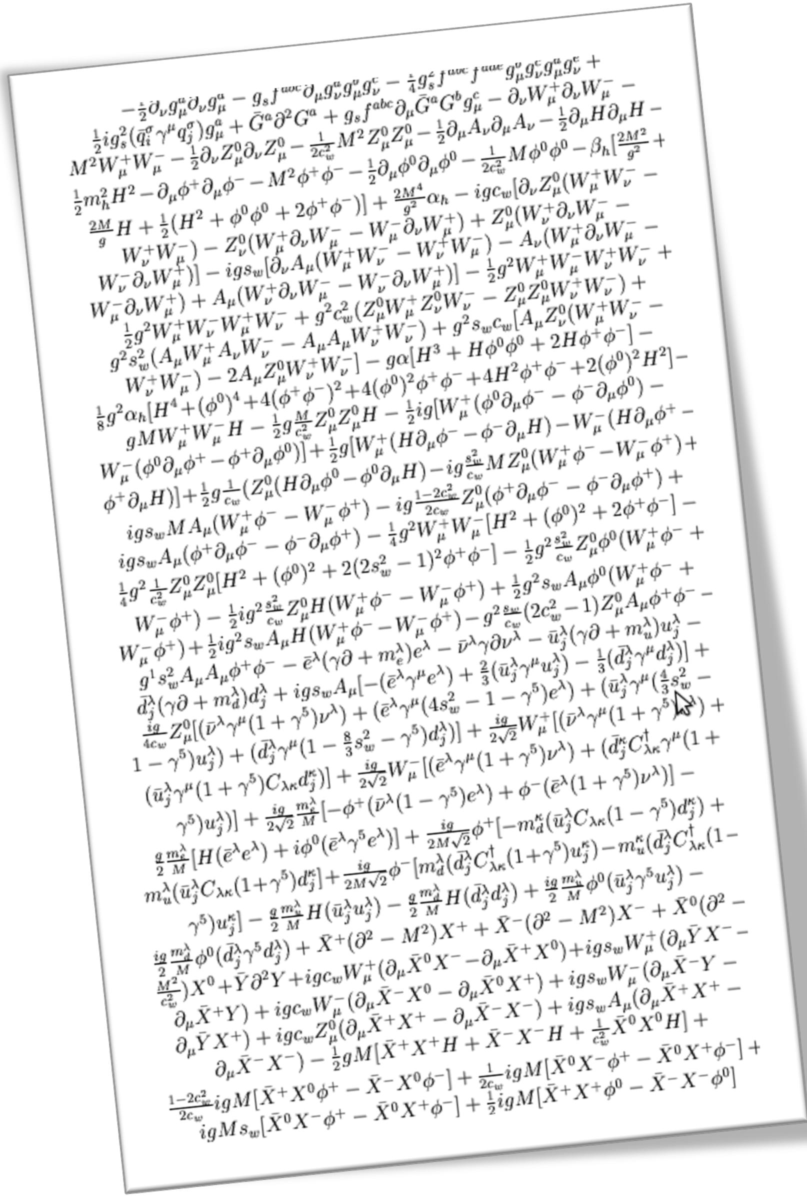
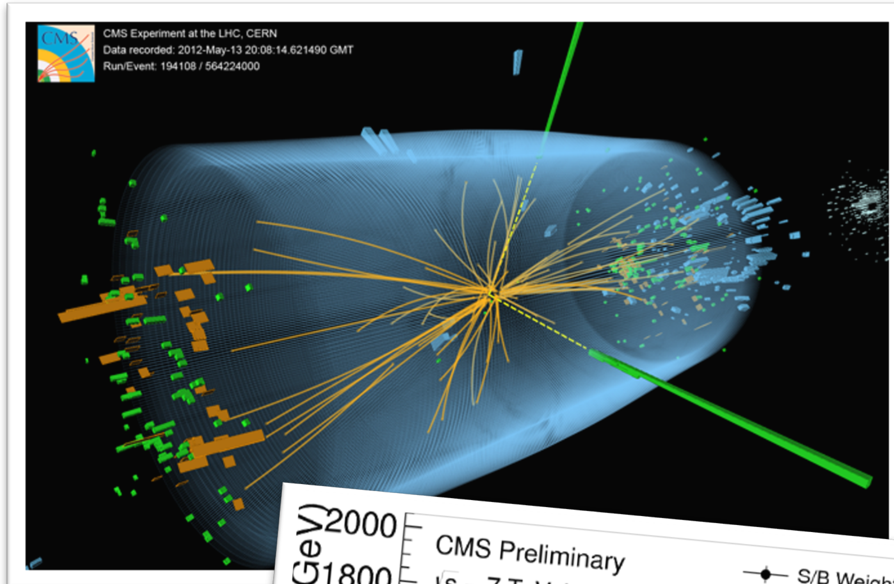
Experimental particle physics

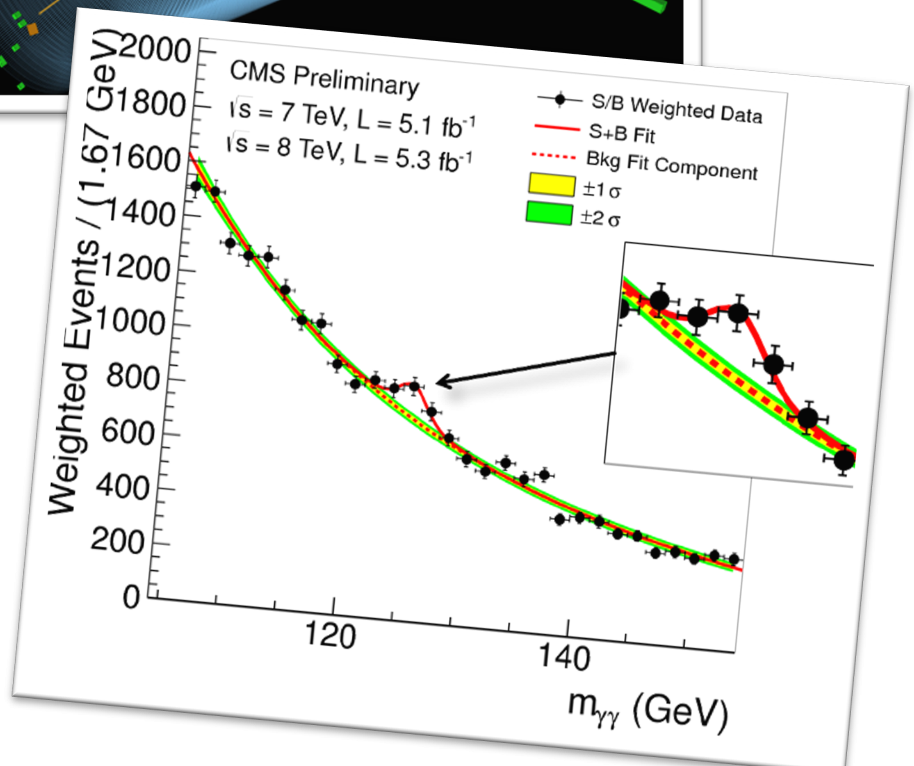
European School of Instrumentation in Particle & Astroparticle Physics

1. units, quantities, kinematics, measurements

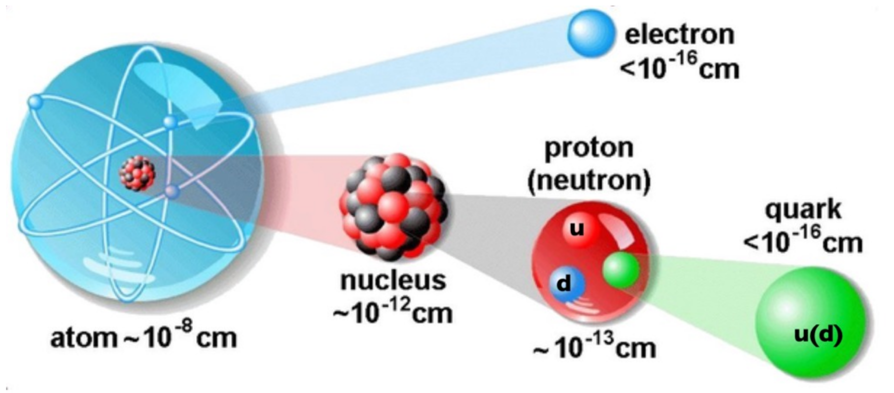
Experiment = probing/building theories with data!

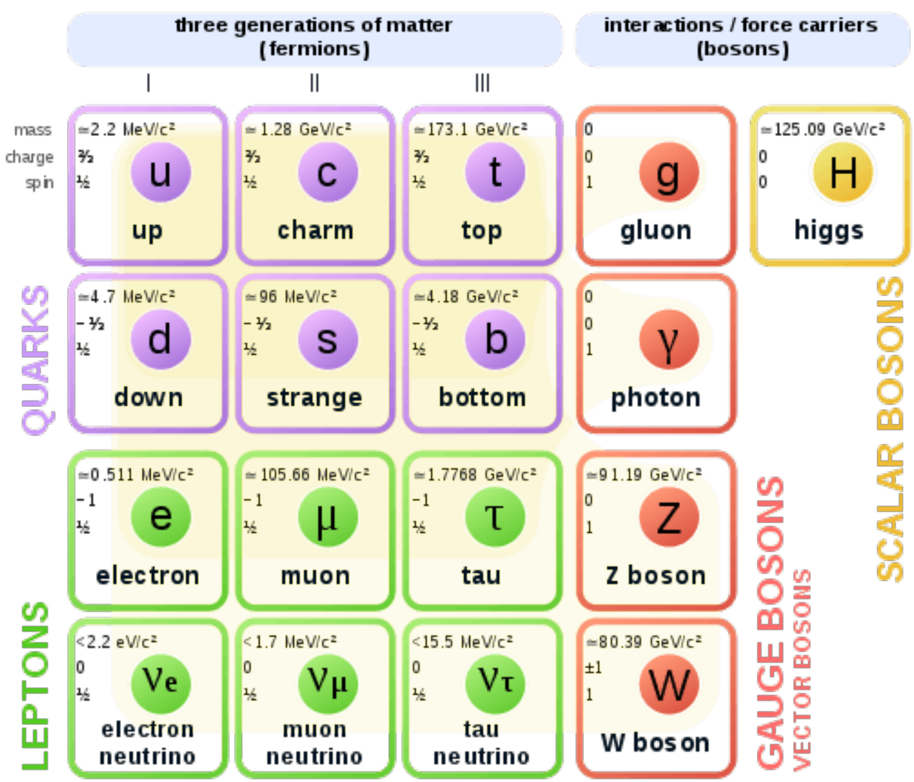






The Standard Model of particle physics…





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)

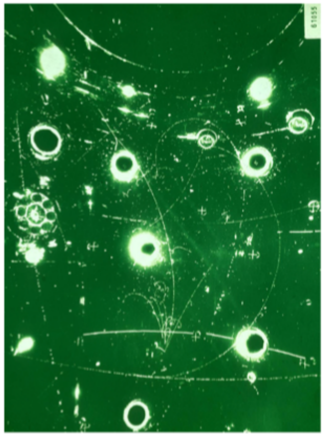
Higgs coupling to fermions (fermion masses)

Higgs coupling to bosons (boson masses)

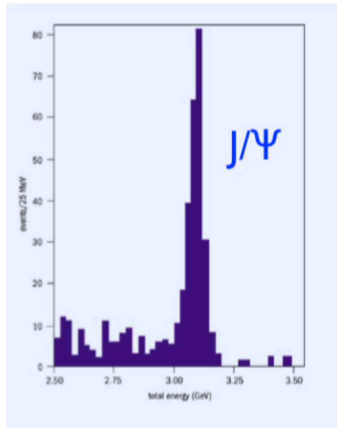
Higgs self-coupling (Higgs potential)

A theory built (and probed) over time…

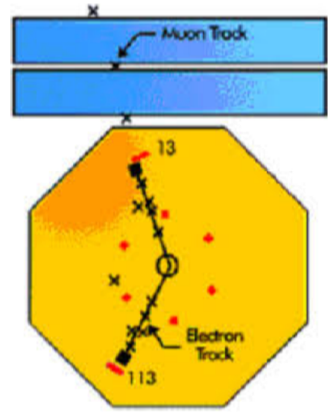
1972 – CERN
Neutral currents



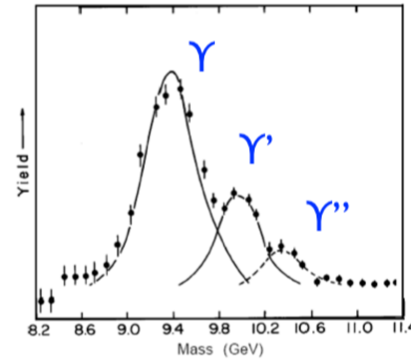
1974 – BNL, SLAC
Charm



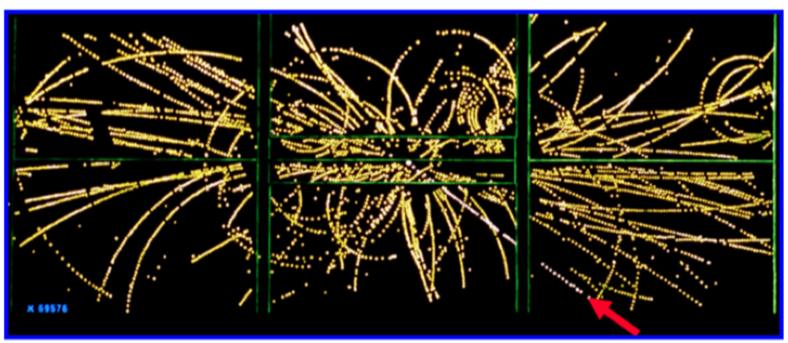
1976 – SLAC
Tau lepton



1979 – Fermilab
Beauty

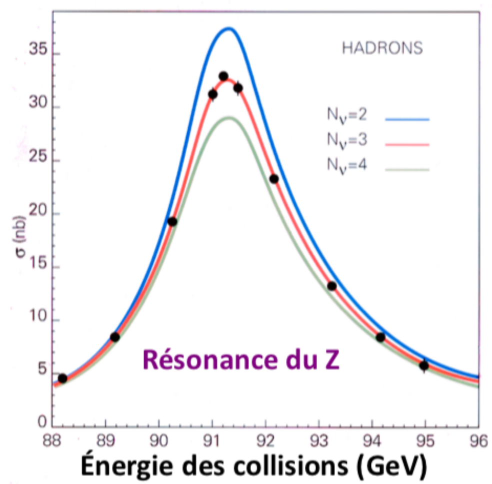


1983 – CERN/SppS
W and Z bosons



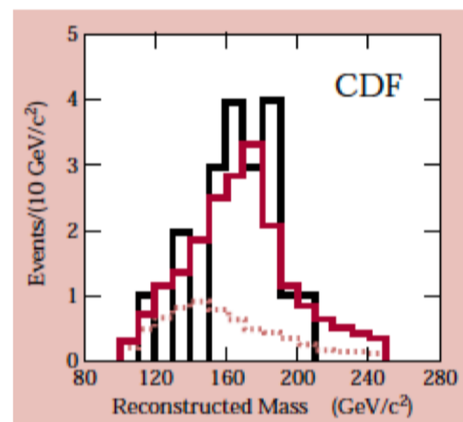
UA1, UA2

1990 – CERN/LEP
Three families of neutrinos



ALEPH, DEPHI, L3, OPAL

1994 – Fermilab/TeVatron
Top quark

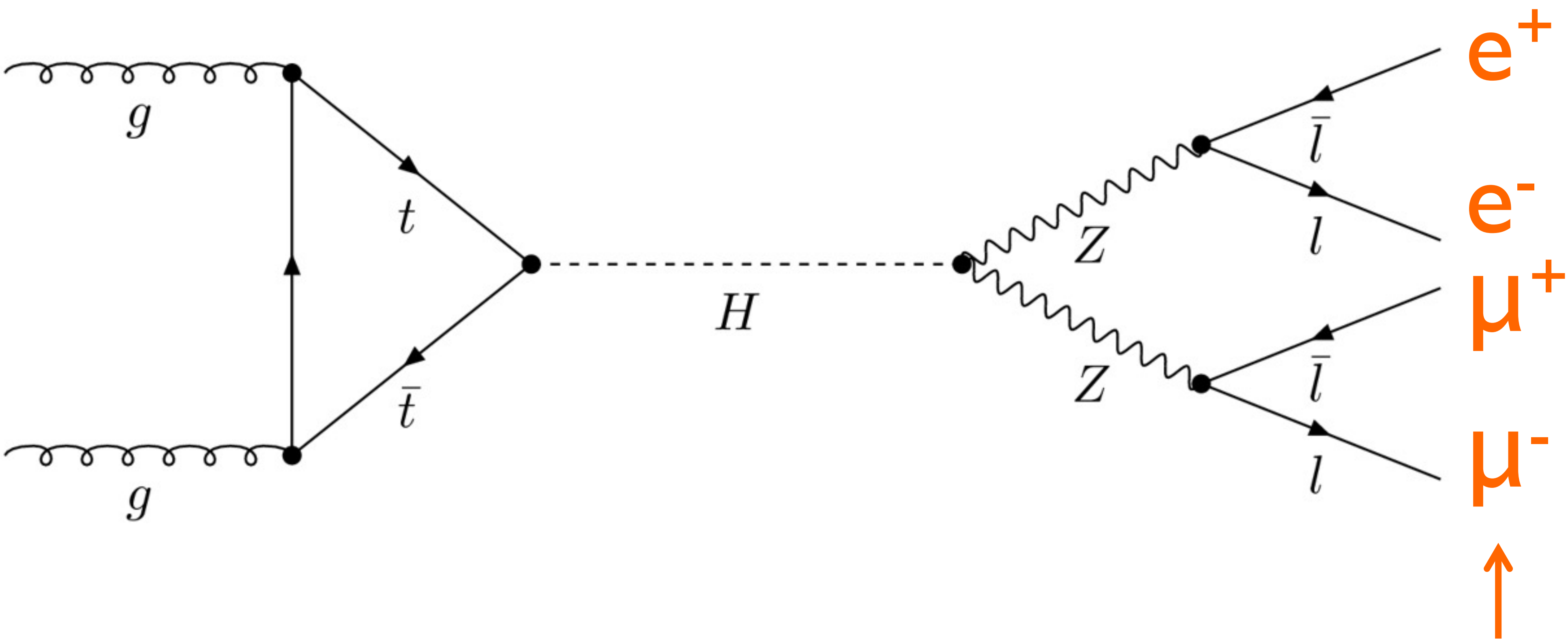


CDF, D0

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



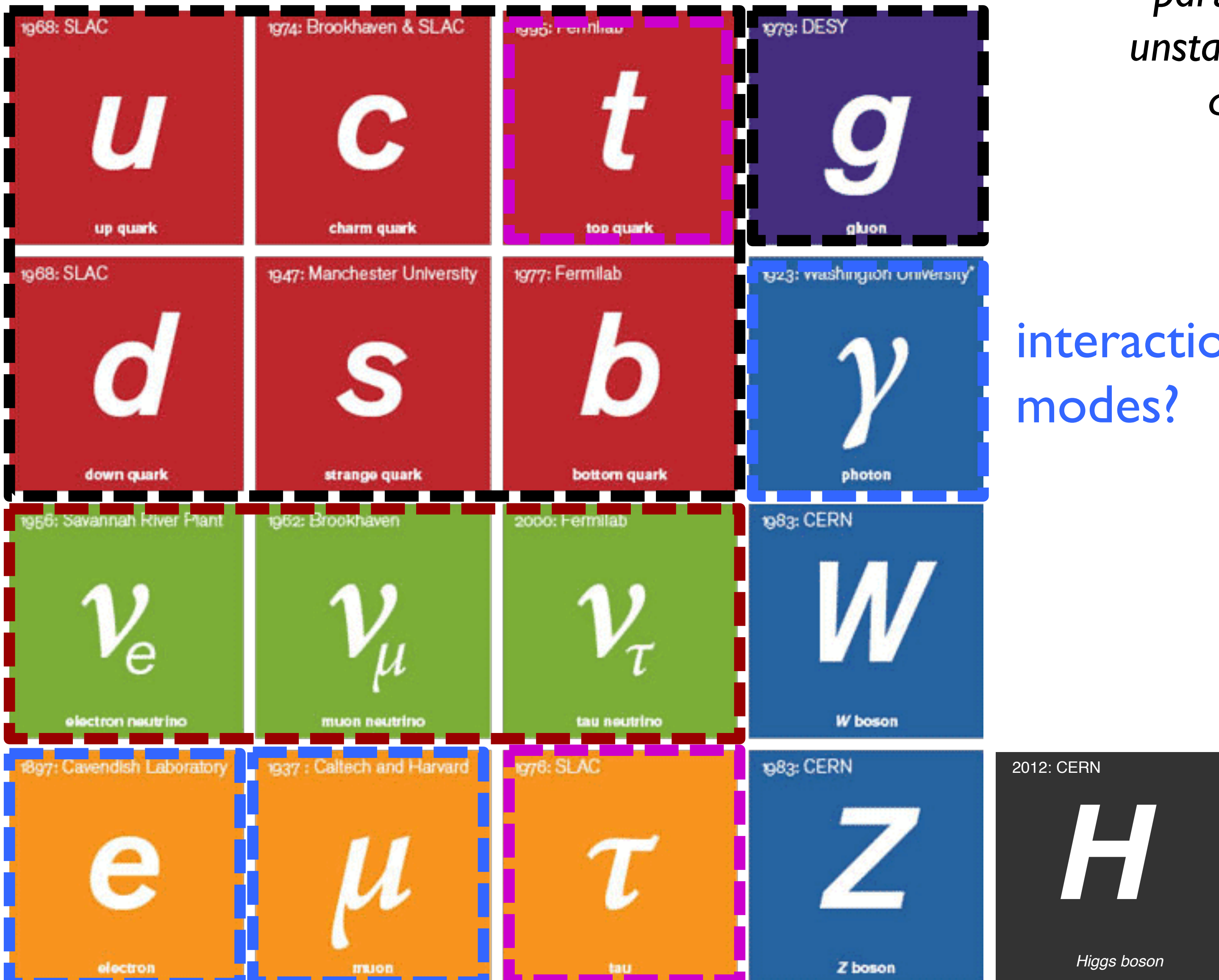
this is what we are looking for…

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?

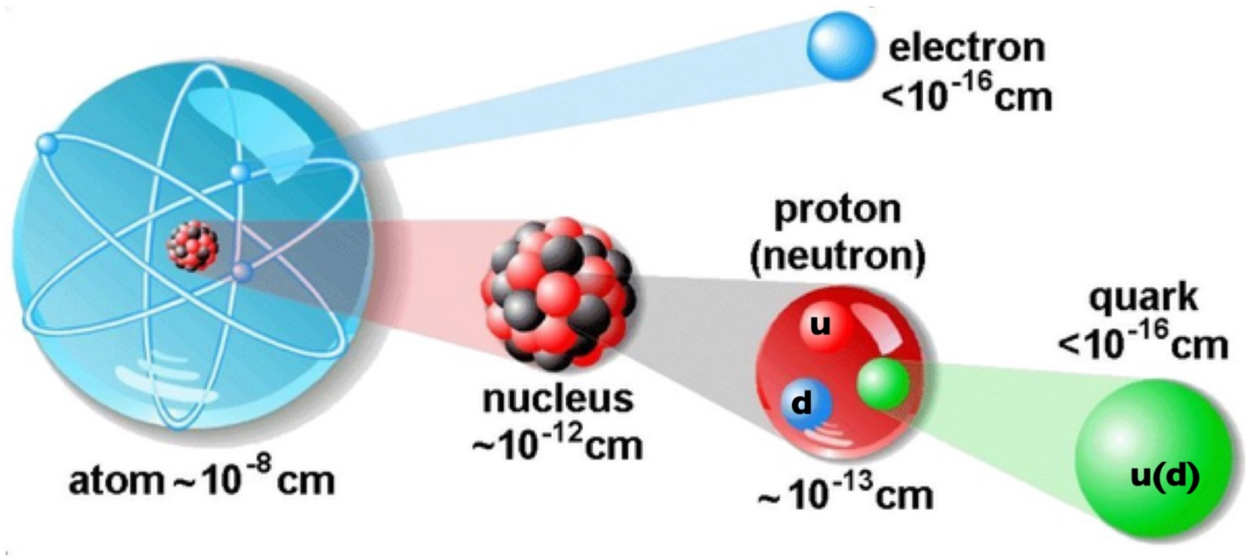
decays?

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

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

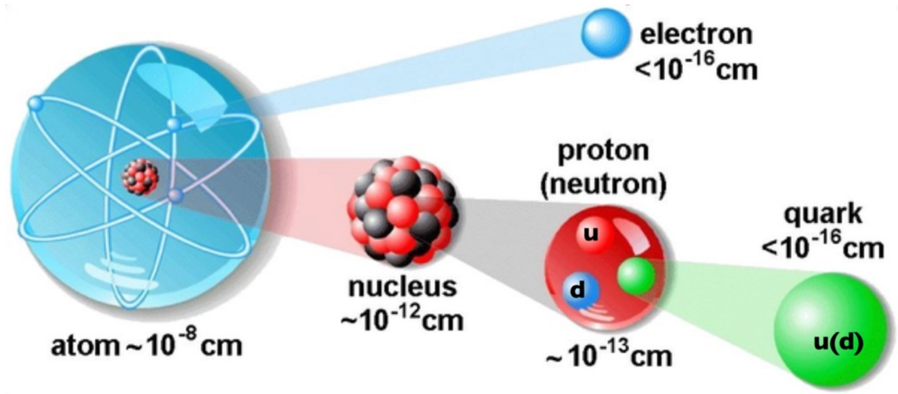
with θ = angular aperture of the light beam

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

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

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

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

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

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

$$t = t_0\gamma$$

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:

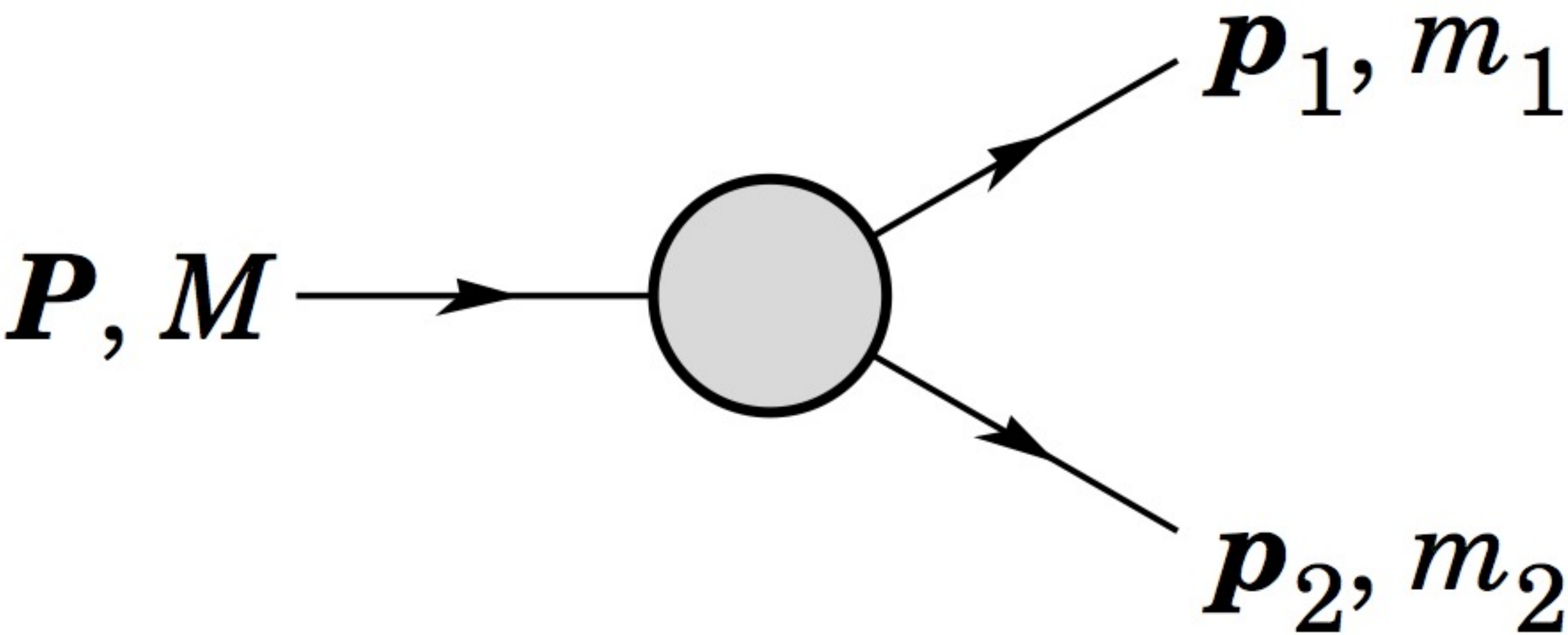
$$E_{\mathrm{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

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

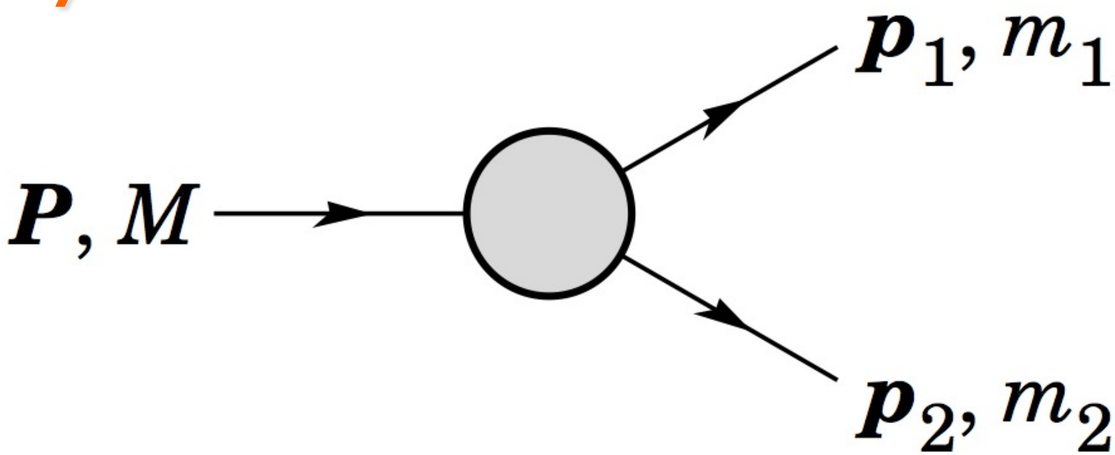
$$p = (E, \vec{p}) \qquad \sqrt{p \cdot p}$$

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

2-body decay



2-body decay

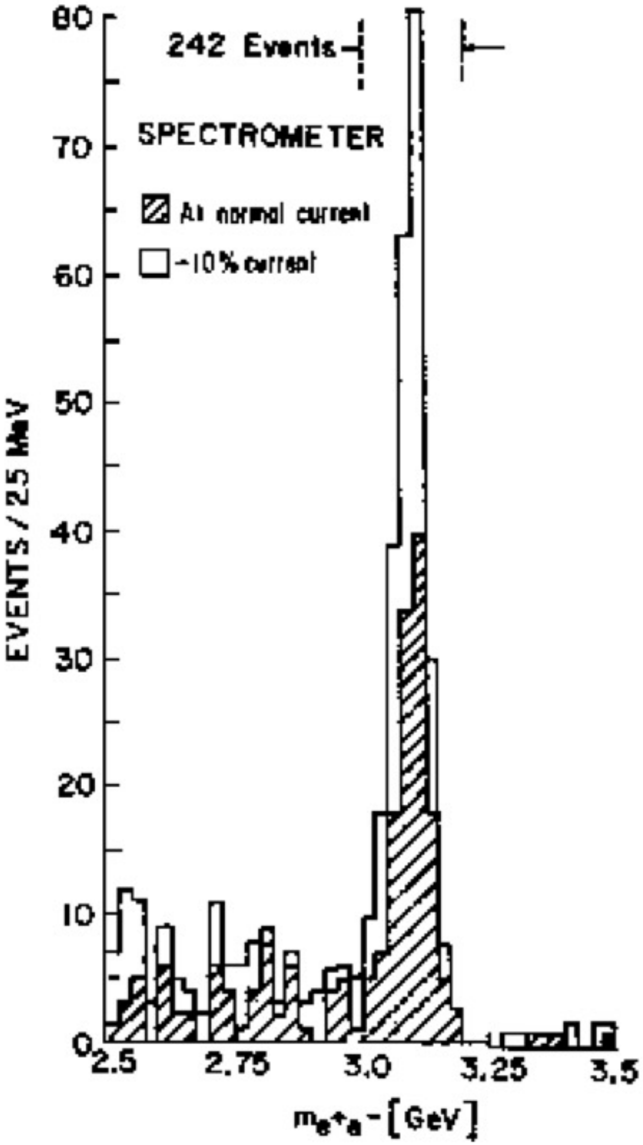


$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} ,$$

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

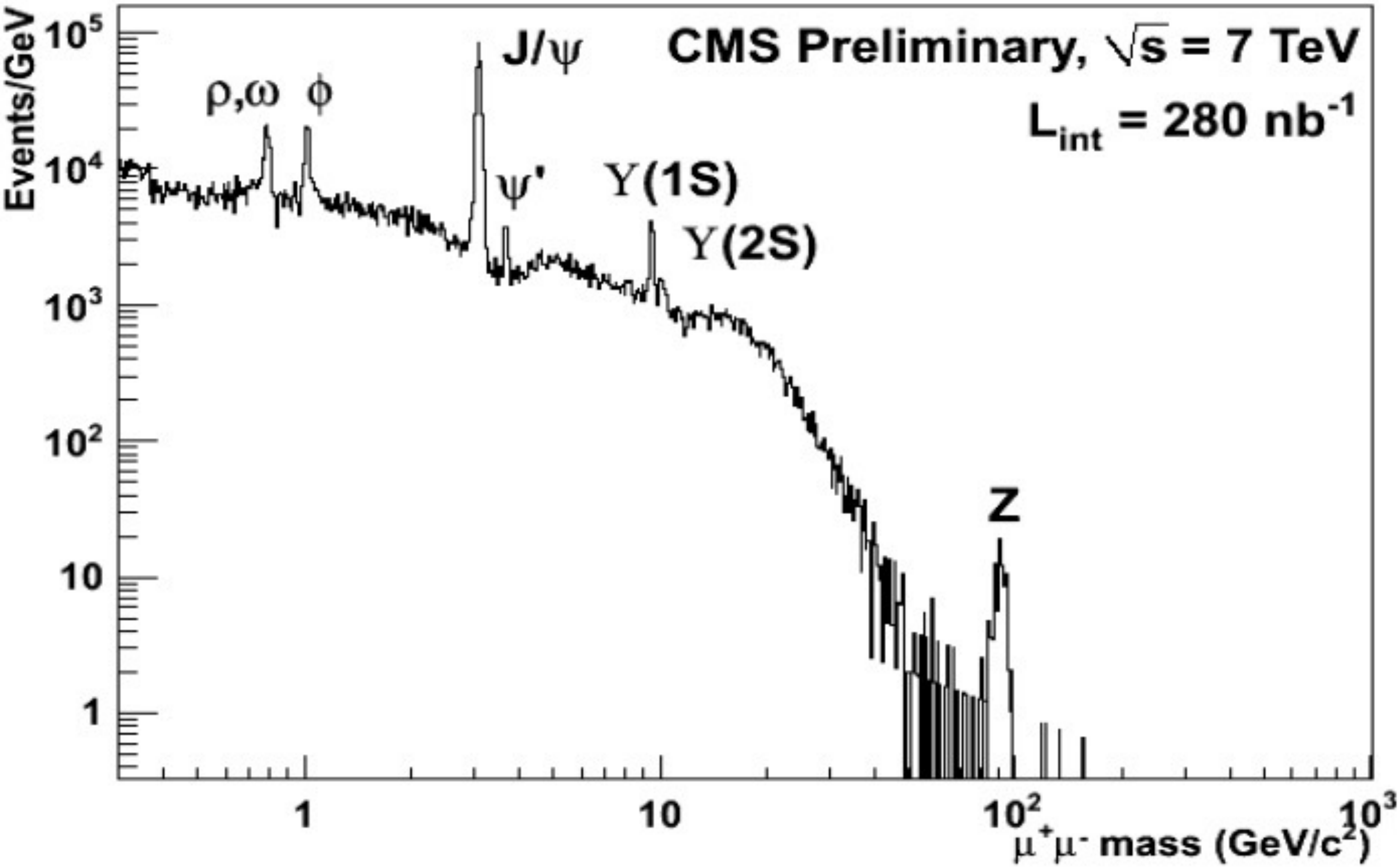
$$= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

Invariant mass

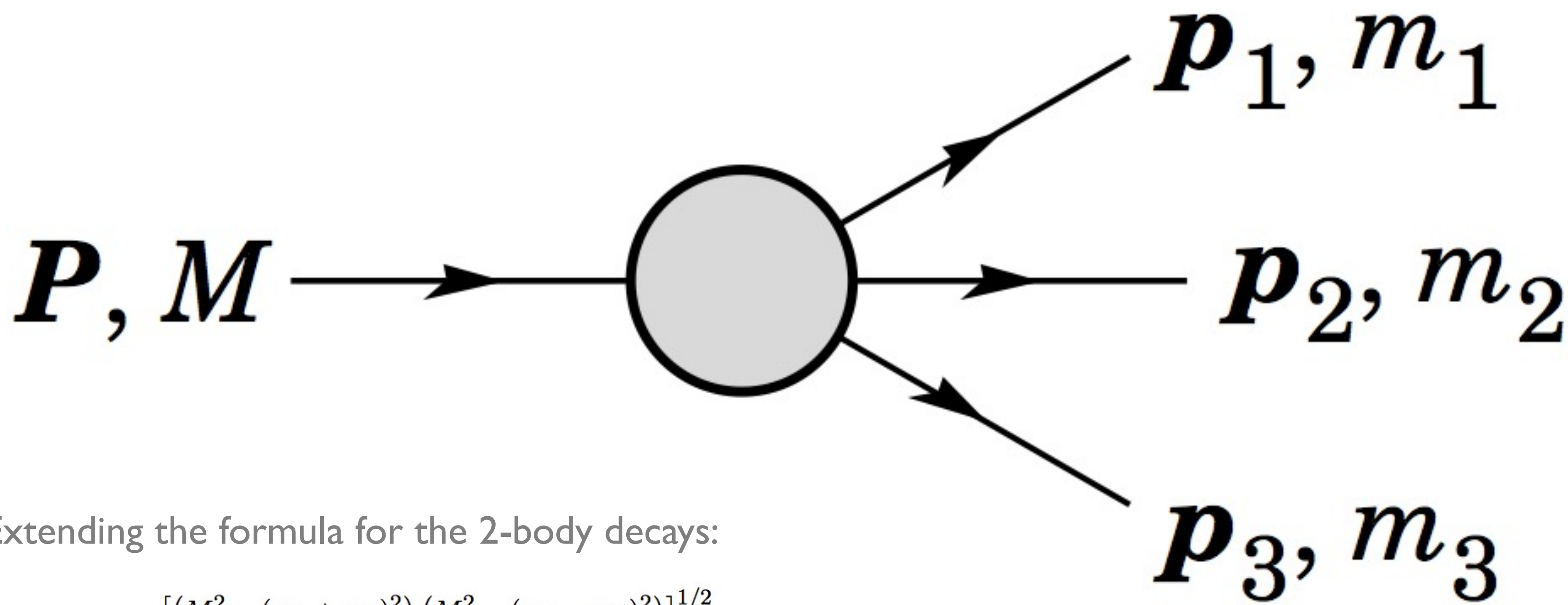


$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

Invariant mass



3-body decay



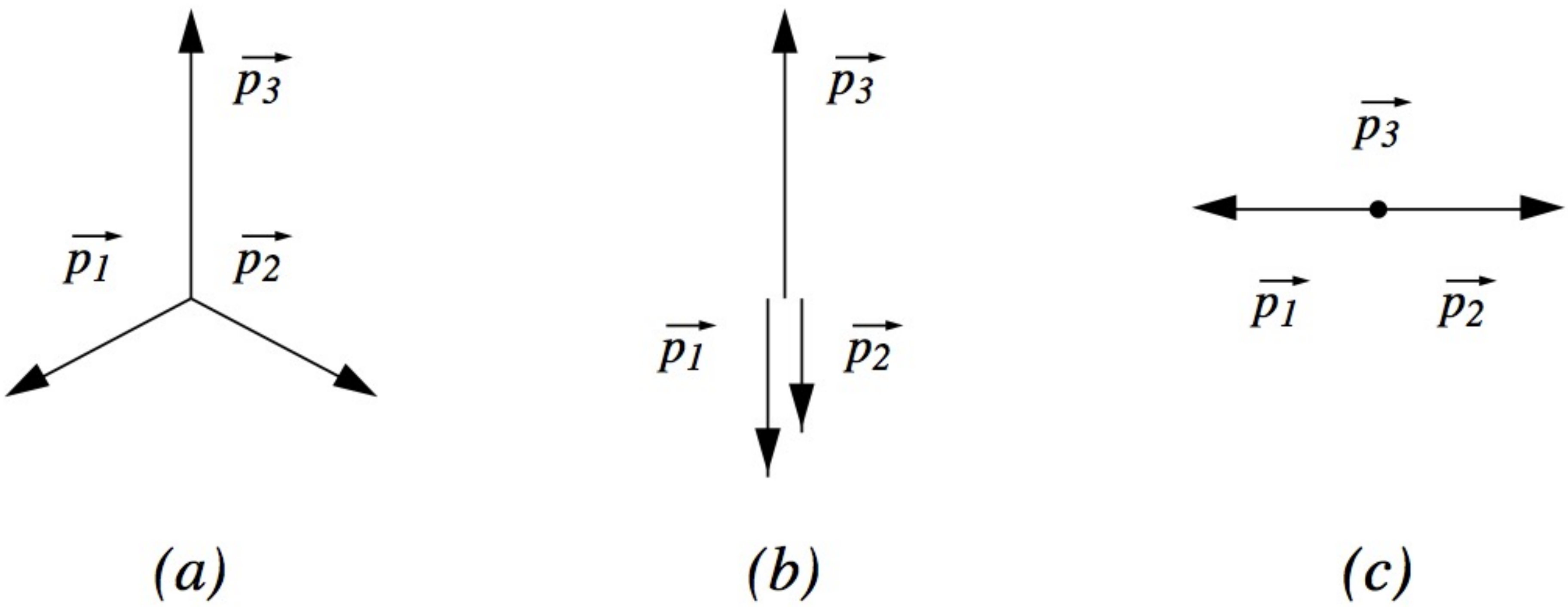
Extending the formula for the 2-body decays:

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

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

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

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

3-bodies decay: Dalitz plot

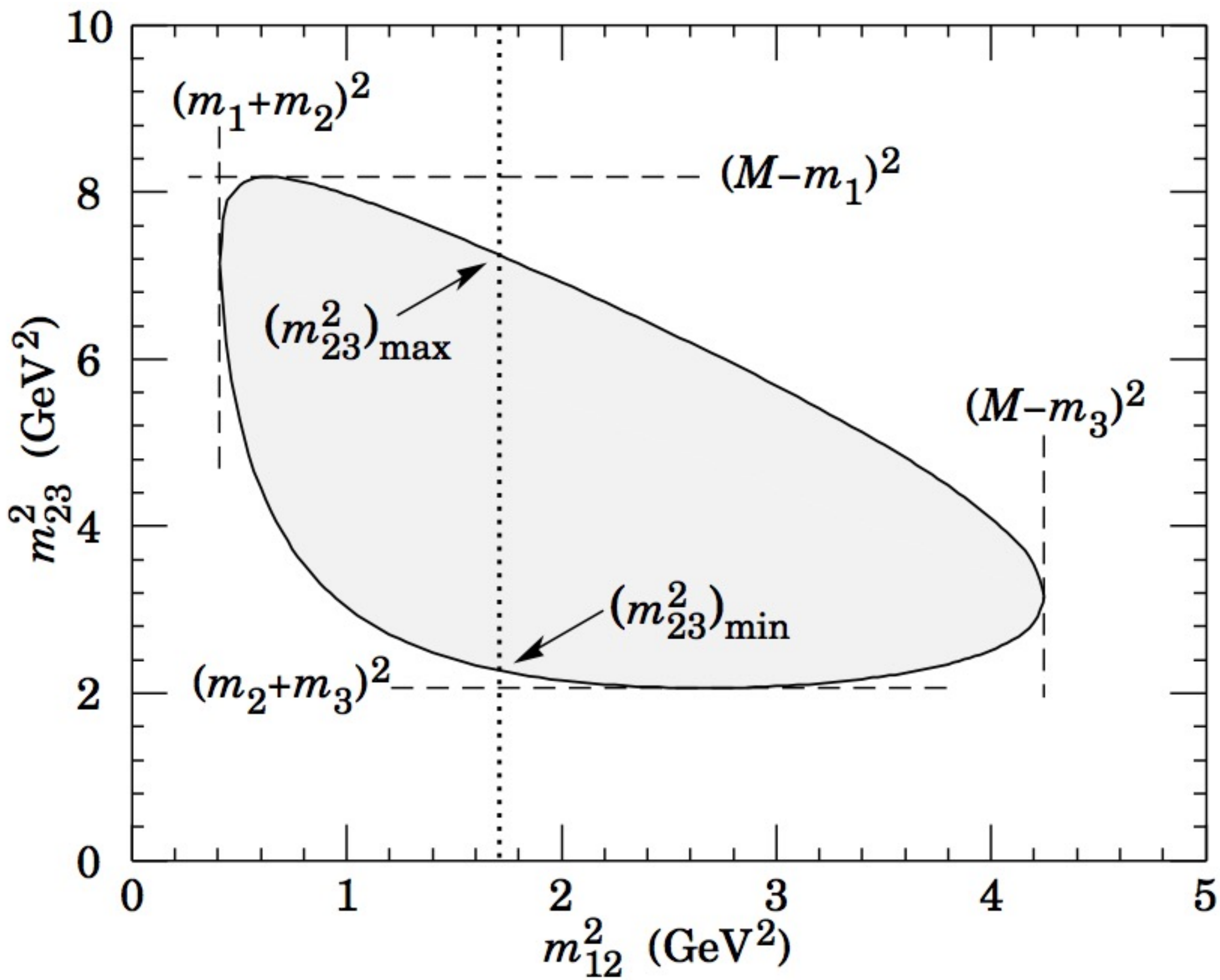
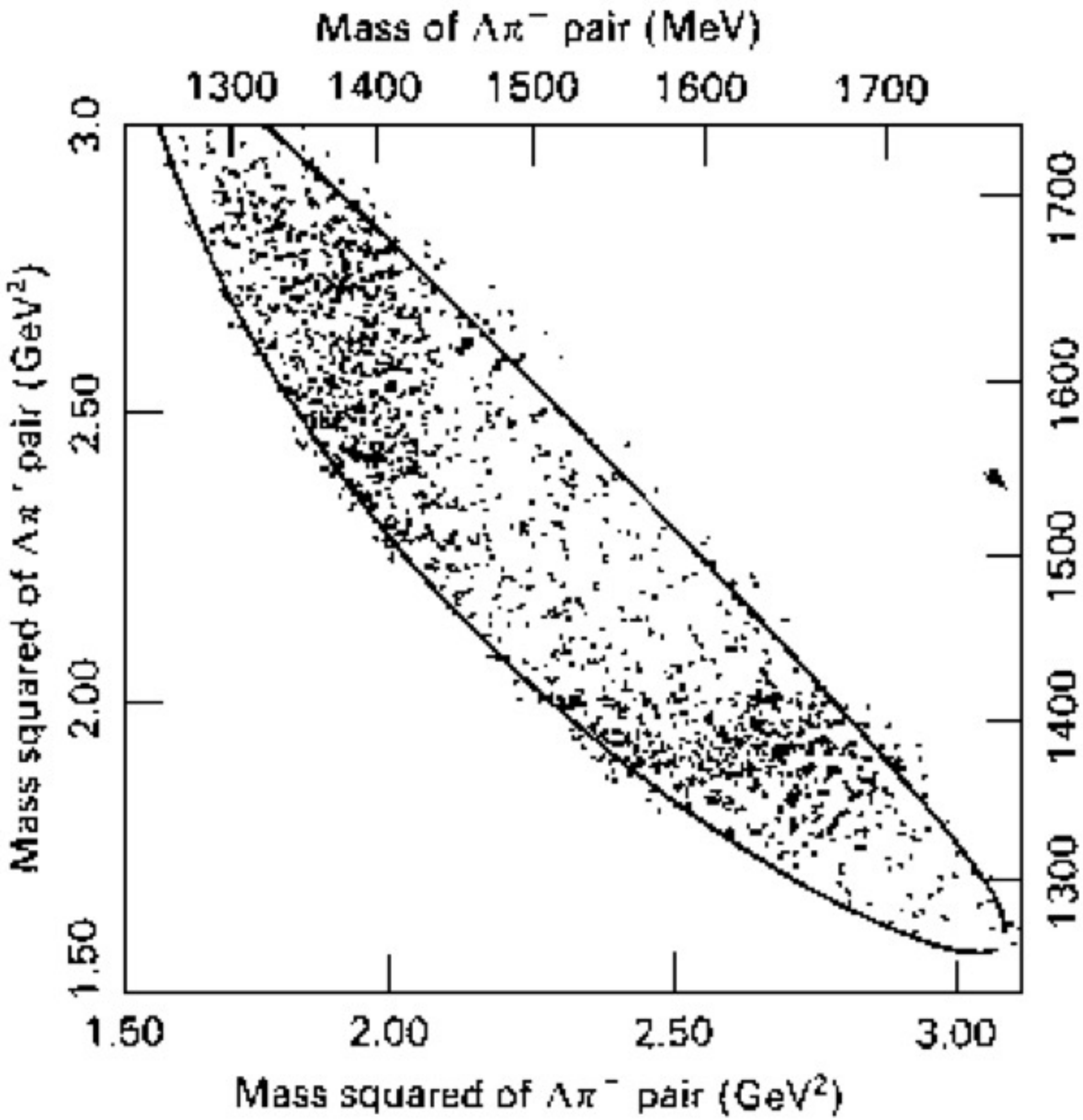


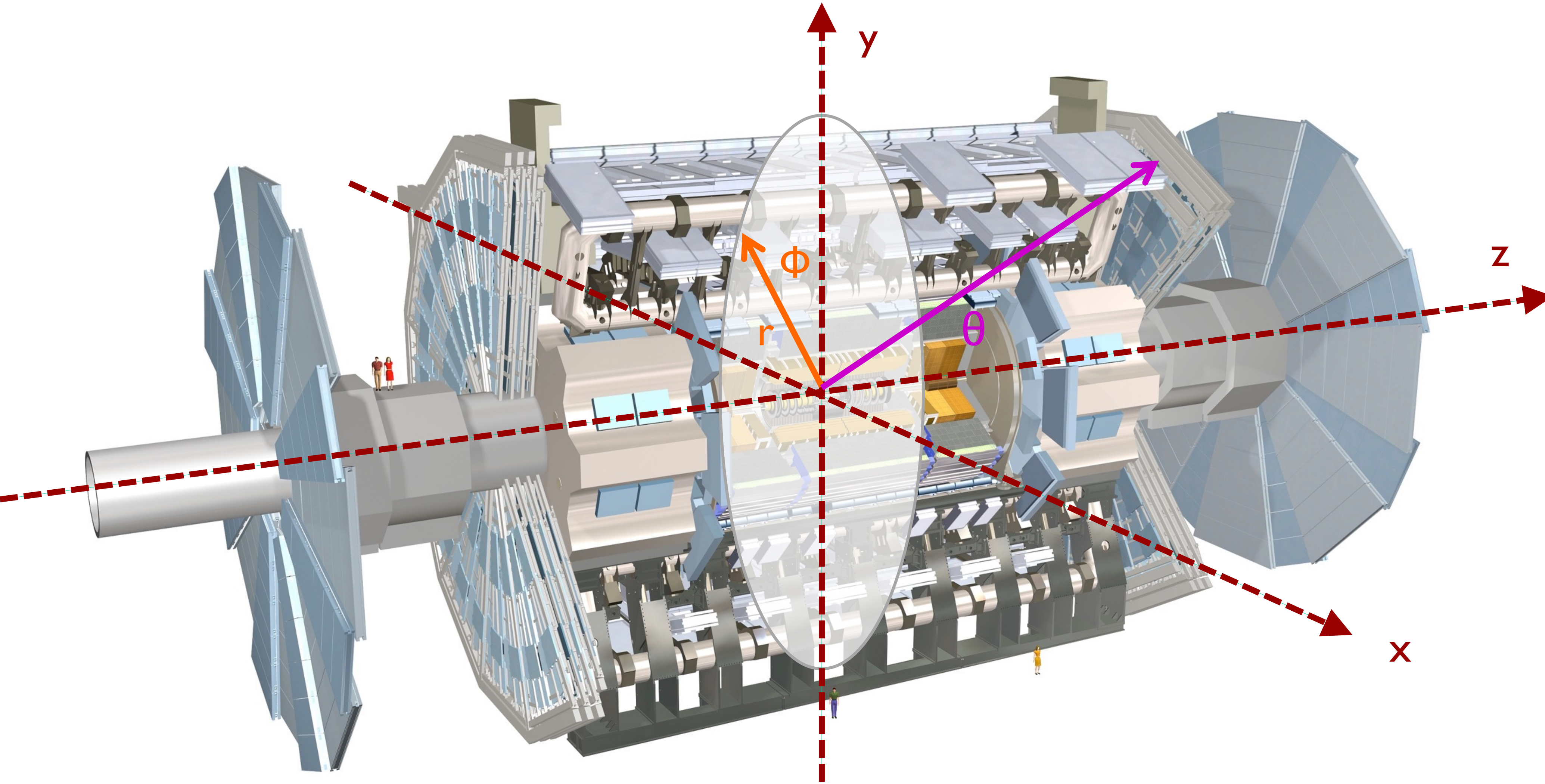
Figure 45.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+\overline{K}^0 p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

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

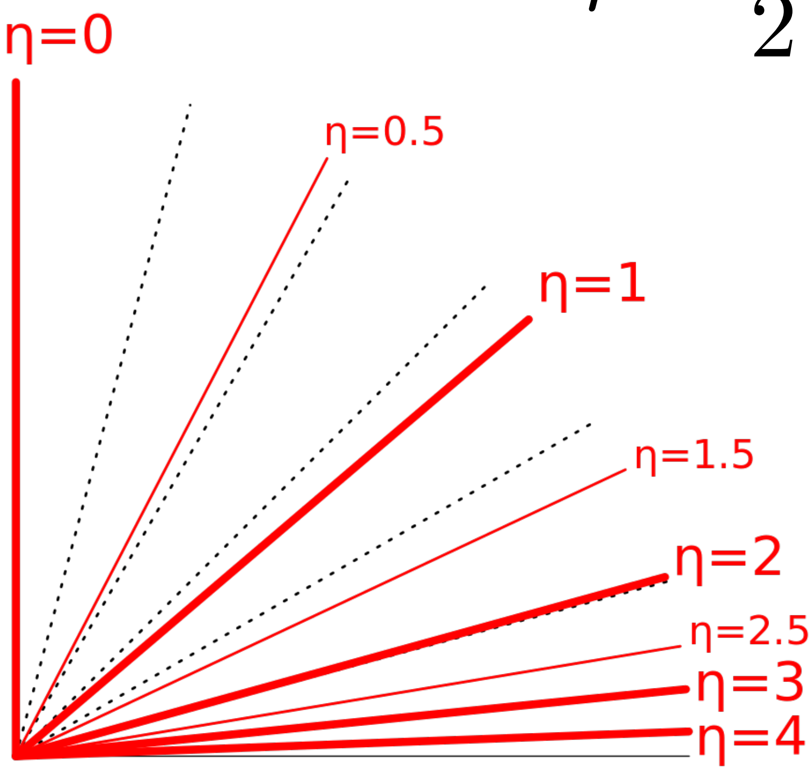
$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

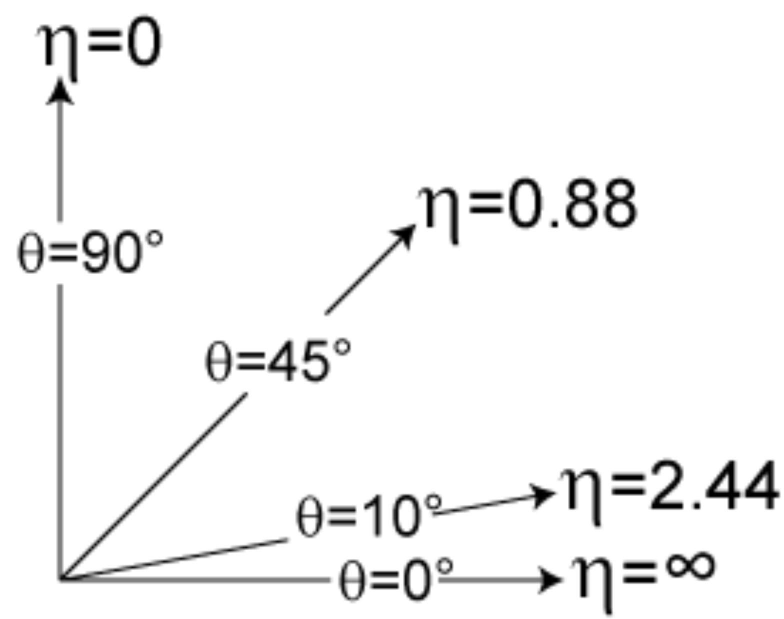
$$\eta \simeq y$$

if E >> m

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

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





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

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

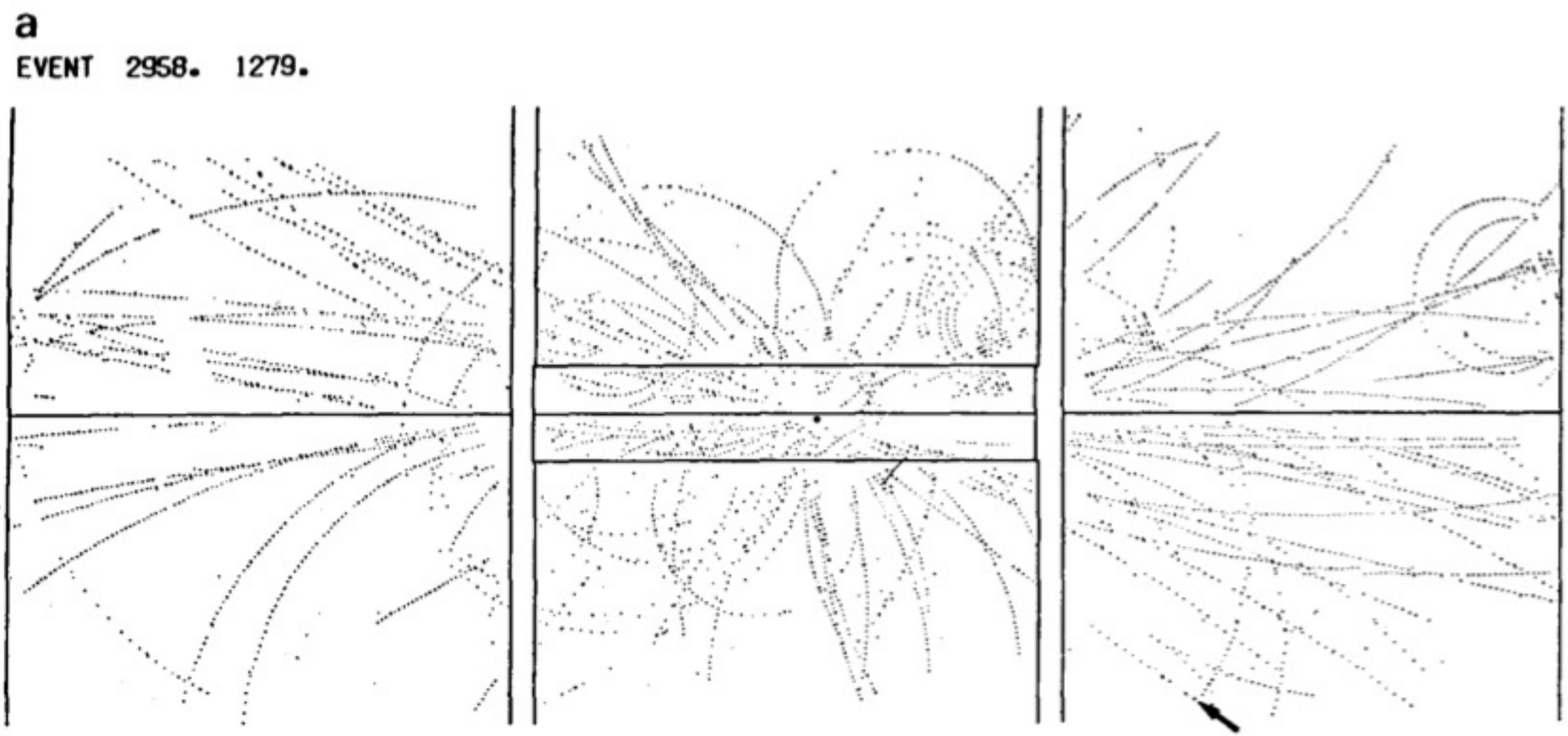
- If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can be constrained with the transverse mass quantity

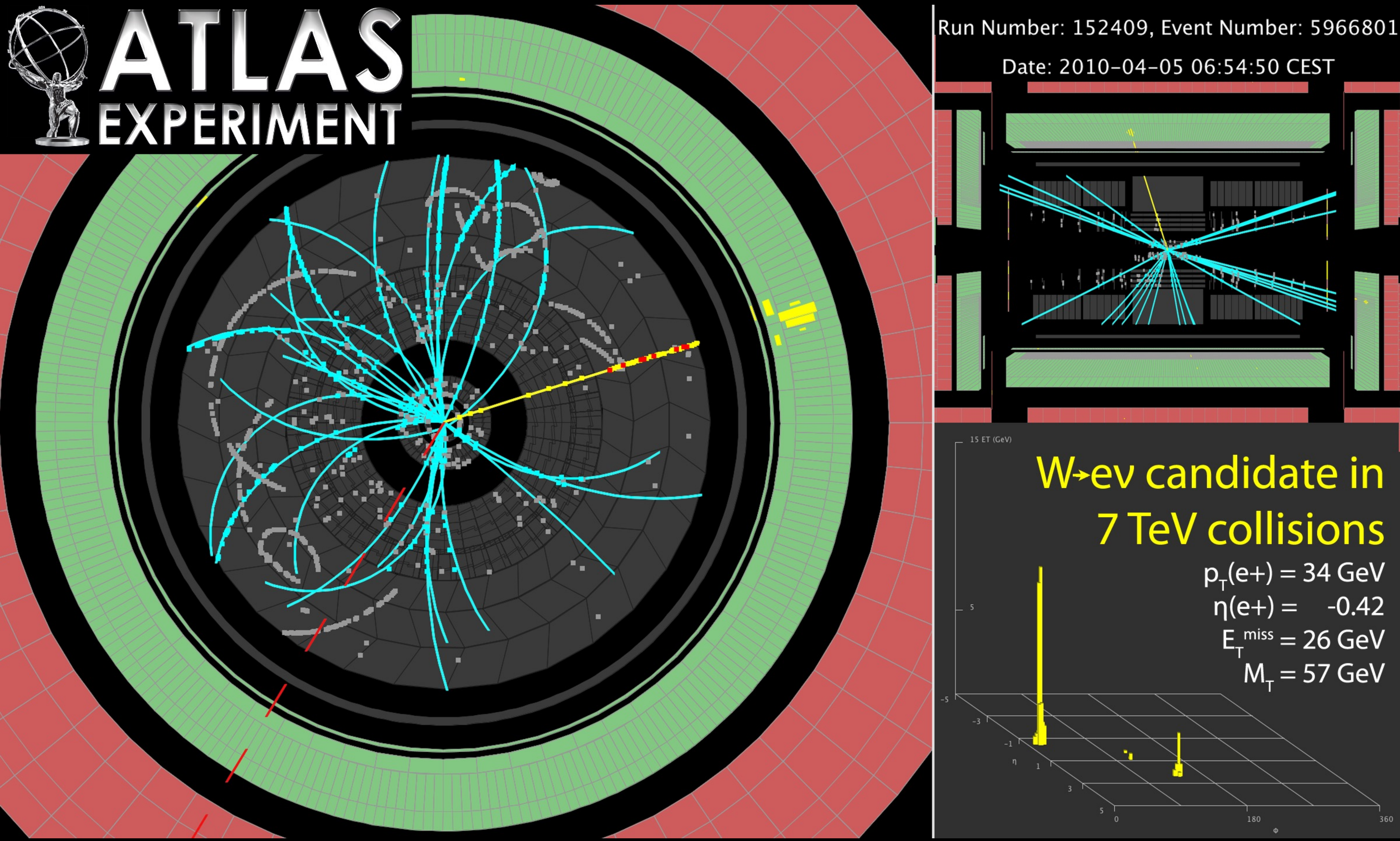
$$\begin{aligned} M_T^2 &\equiv [E_T(1) + E_T(2)]^2 - [\boldsymbol{p}_T(1) + \boldsymbol{p}_T(2)]^2 \\ &= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \boldsymbol{p}_T(1) \cdot \boldsymbol{p}_T(2)] \end{aligned}$$

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

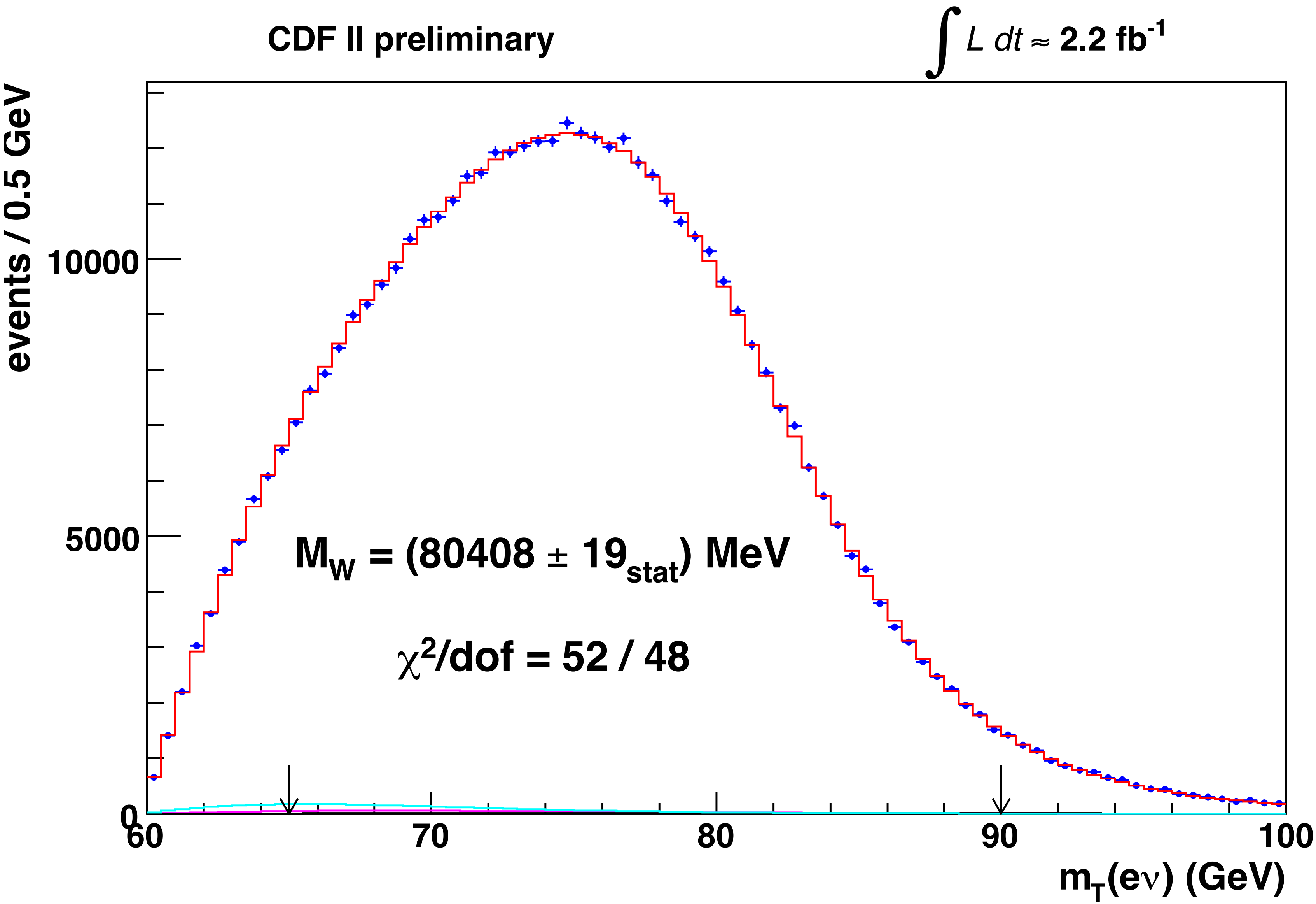
W → e ν discovery

Volume 122B, number 1 PHYSICS LETTERS 24 February 1983



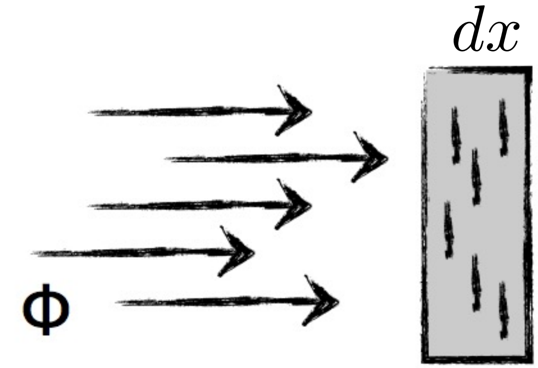

ATLAS EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in 7 TeV collisions
$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

$W \rightarrow e\,\nu$

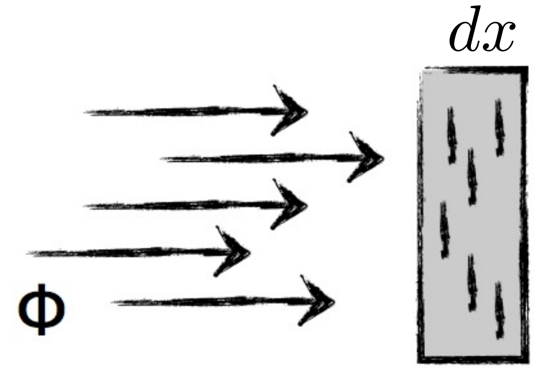


Interaction cross section

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



Interaction cross section



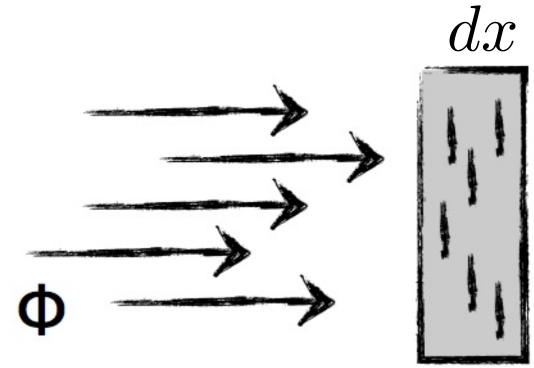
Flux $$\Phi = \frac{1}{S}\frac{dN_i}{dt}$$ [$L^{-2}\,t^{-1}$]

Reactions per unit of time

$$\frac{dN_{\mathrm{reac}}}{dt} = \Phi\overbrace{\sigma N_{\mathrm{target}}\,dx}^{\textit{area obscured by target particle}}$$ [t^{-1}]

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

Interaction cross section



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

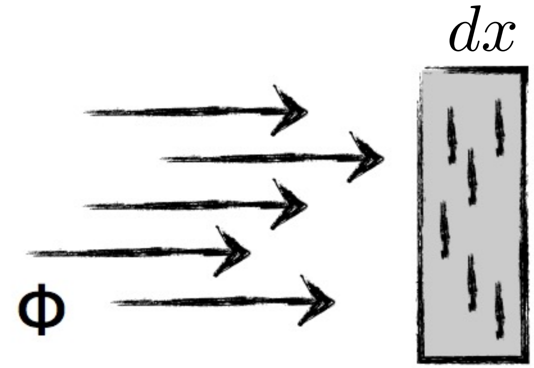
Reactions per unit of time

$$\frac{dN_{\mathrm{reac}}}{dt} = \Phi\overbrace{\sigma N_{\mathrm{target}}\,dx}^{\textit{area obscured by target particle}} \quad [t^{-1}]$$

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

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

Interaction cross section



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

Reactions per unit of time

$$\frac{dN_{\text{reac}}}{dt} = \Phi\,\overbrace{\sigma N_{\text{target}}\,dx}^{\text{area obscured by target particle}} \quad [t^{-1}]$$

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

Reaction rate per target particle

$$W_{if} = \Phi\sigma \quad [t^{-1}]$$

Cross section per target particle

$$\sigma = \frac{W_{if}}{\Phi} \quad [L^2]$$

= reaction rate per unit of flux

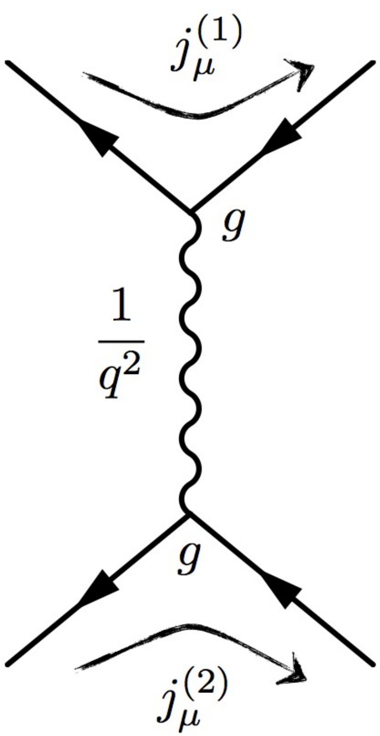
1 b = 10^{-28} m^2 (roughly the area of a nucleus with A = 100)

Fermi Golden Rule

From non-relativistic perturbation theory…

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

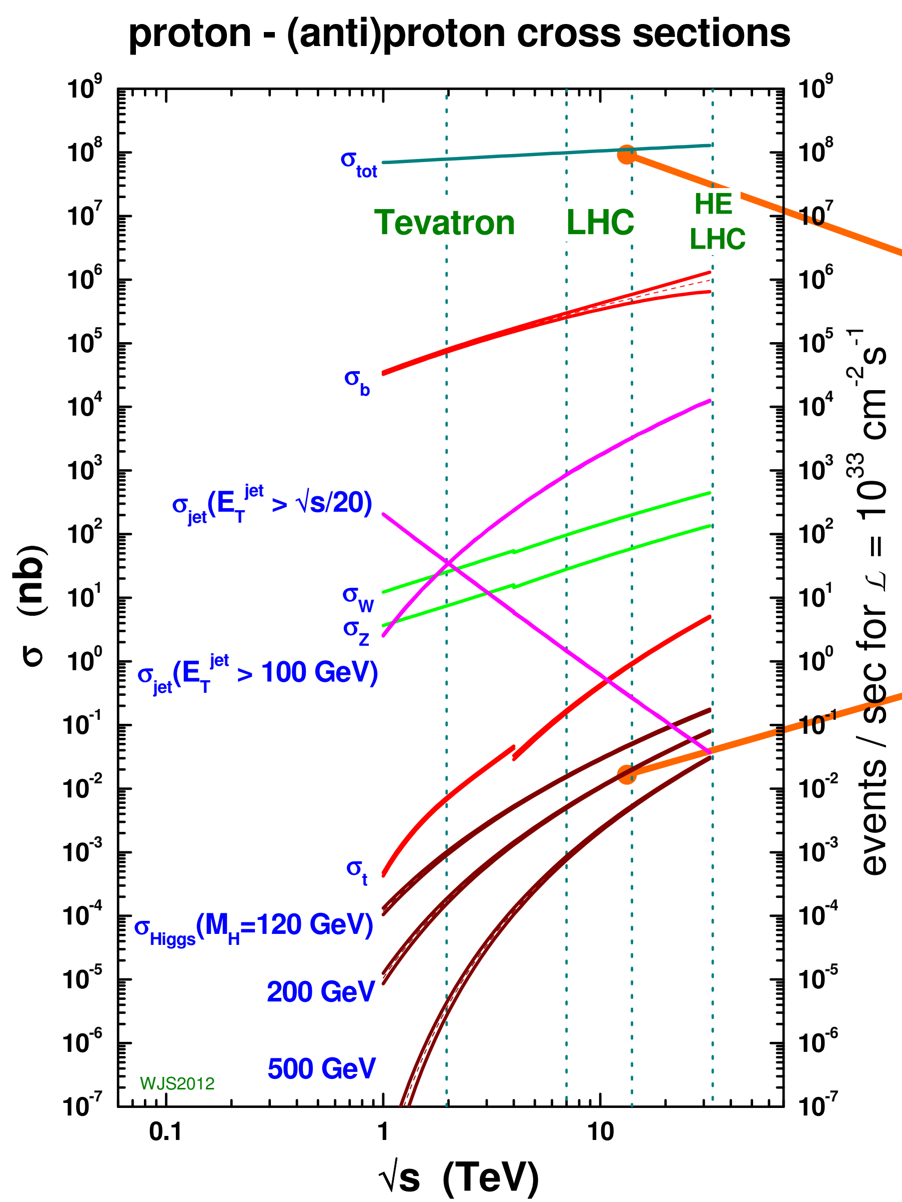
$[t^{-1}]$ $[E]$ $[E^{-1}]$



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

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

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