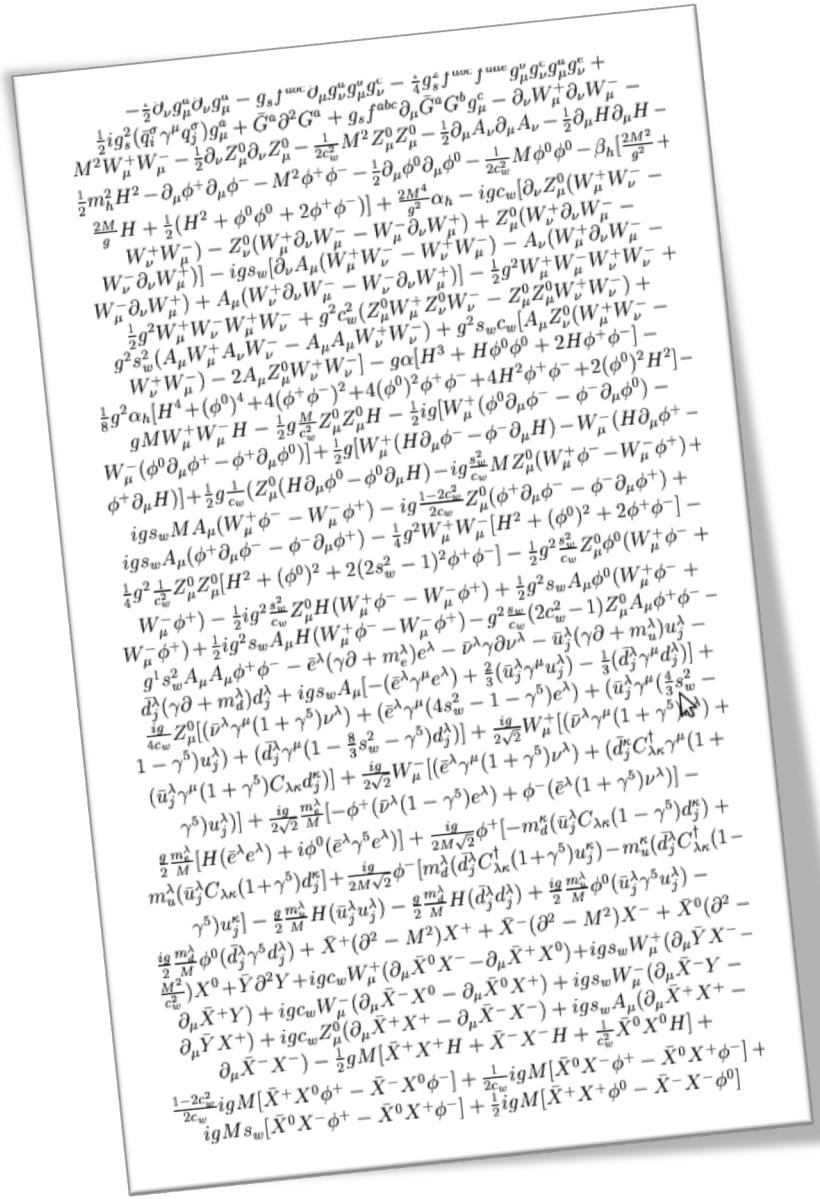
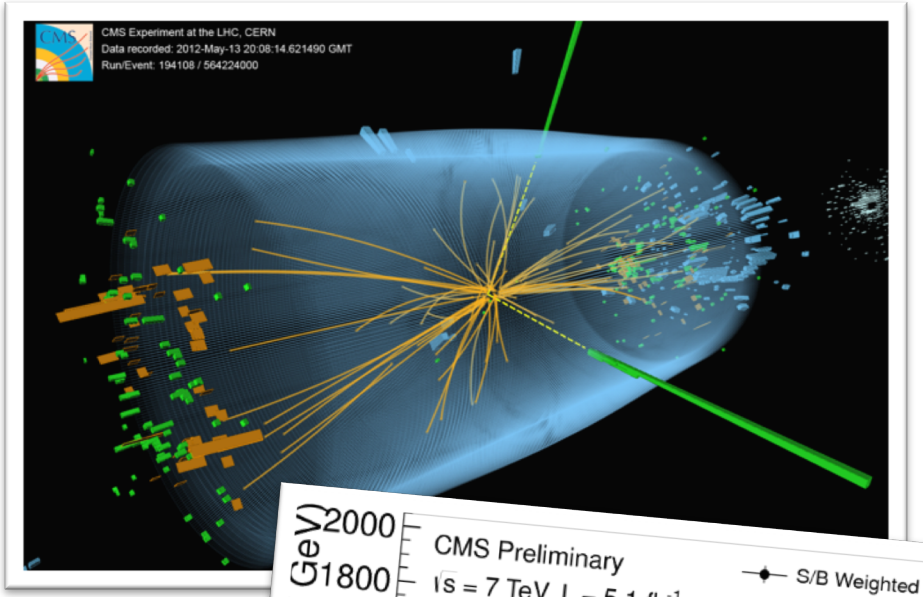
Experimental particle physics

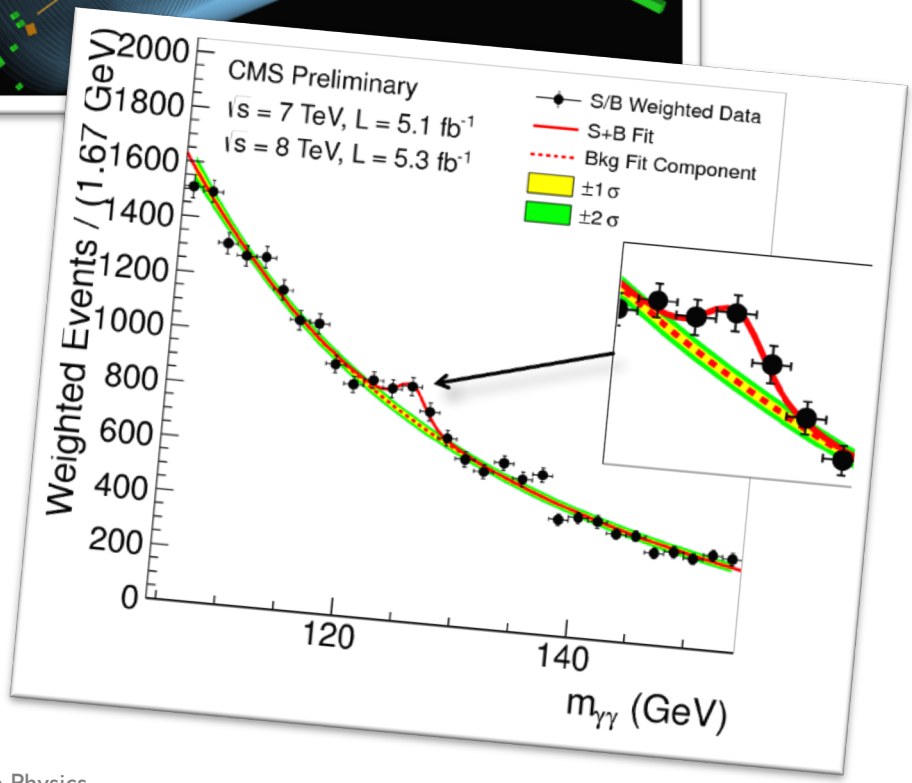
esipap
European School of Instrumentation in Particle & Astroparticle Physics

1. units, quantities, kinematics, measurements

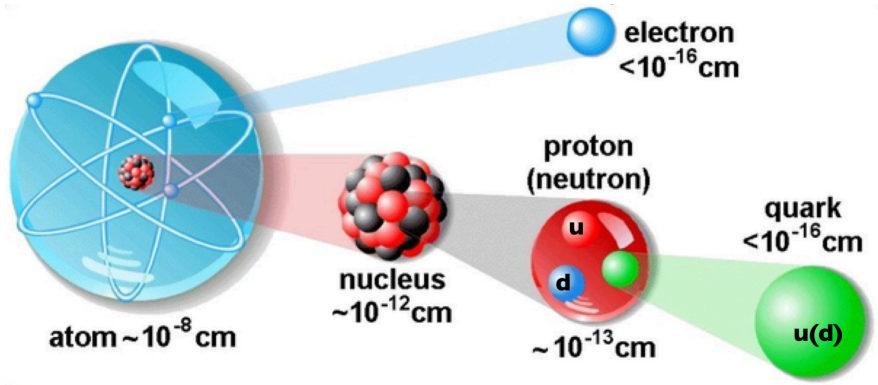
Experiment = probing/building theories with data!

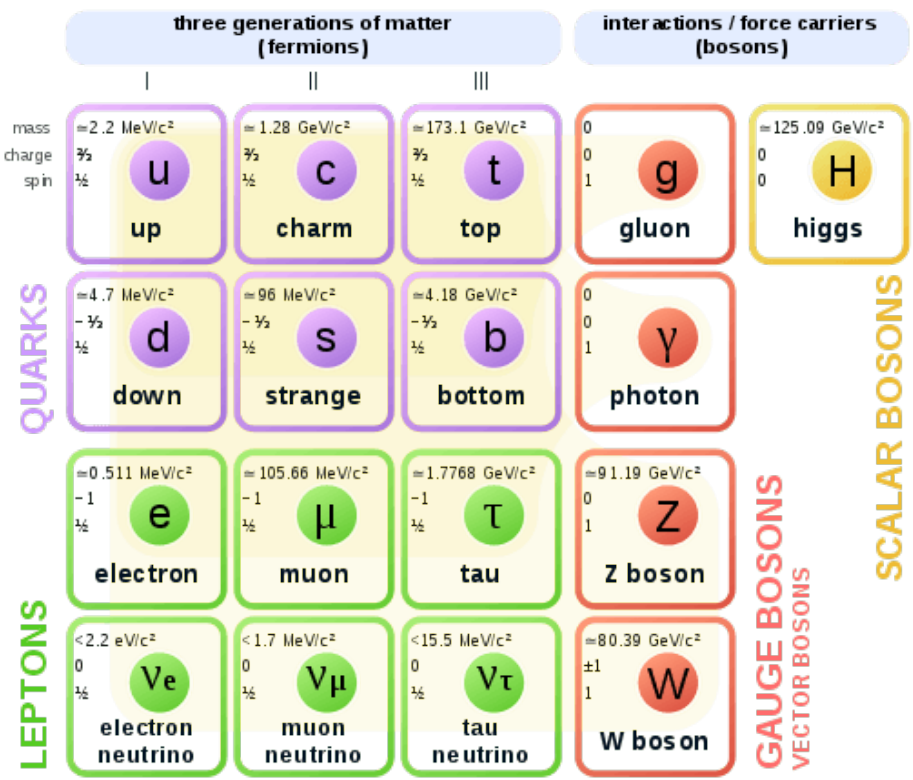






The Standard Model of particle physics…





Gauge bosons

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$+ i\bar{\Psi}\not{D}\psi$$

Gauge boson coupling to fermions (EW, QCD)

$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi)$$

$$+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

Higgs coupling to fermions (fermion masses)

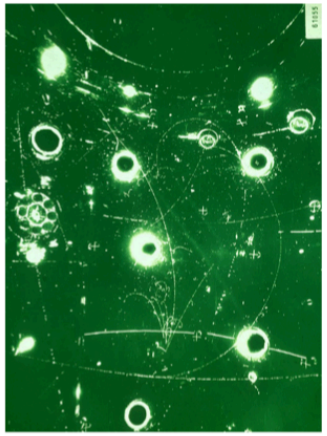
Higgs coupling to bosons (boson masses)

Higgs self-coupling (Higgs potential)

A theory built (and probed) over time…

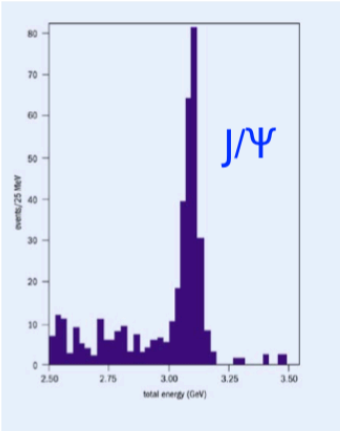
1972 — CERN

Neutral currents



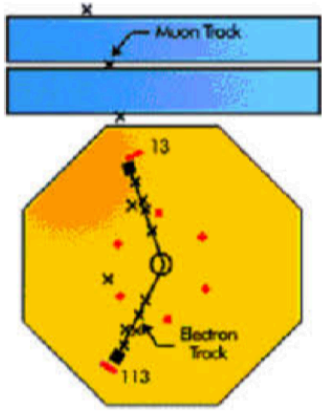
1974 — BNL, SLAC

Charm



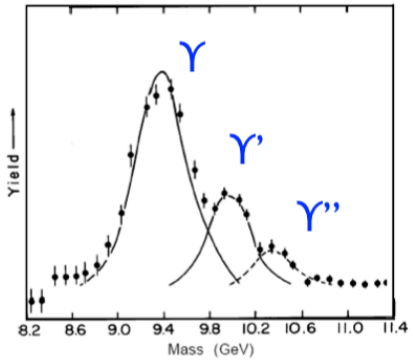
1976 — SLAC

Tau lepton



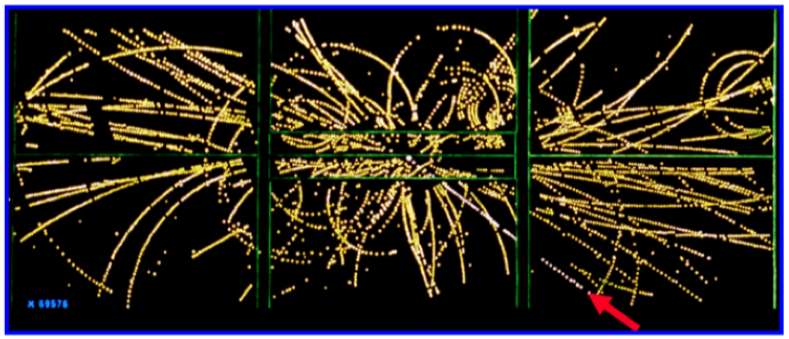
1979 — Fermilab

Beauty



1983 — CERN/SppS

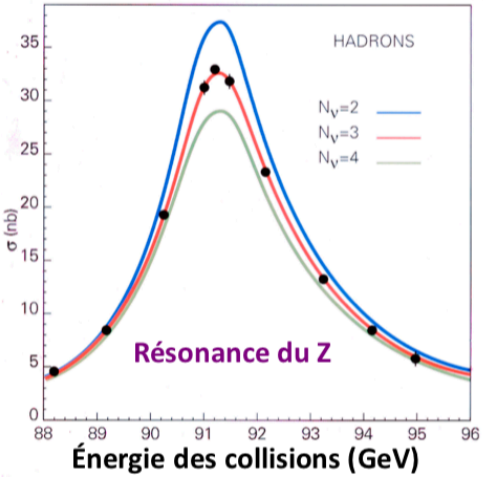
W and Z bosons



UA1, UA2

1990 — CERN/LEP

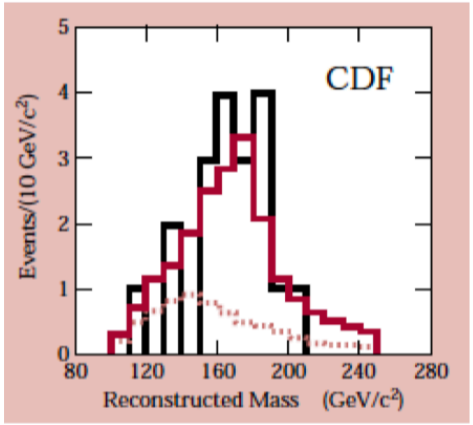
Three families of neutrinos



ALEPH, DEPHI, L3, OPAL

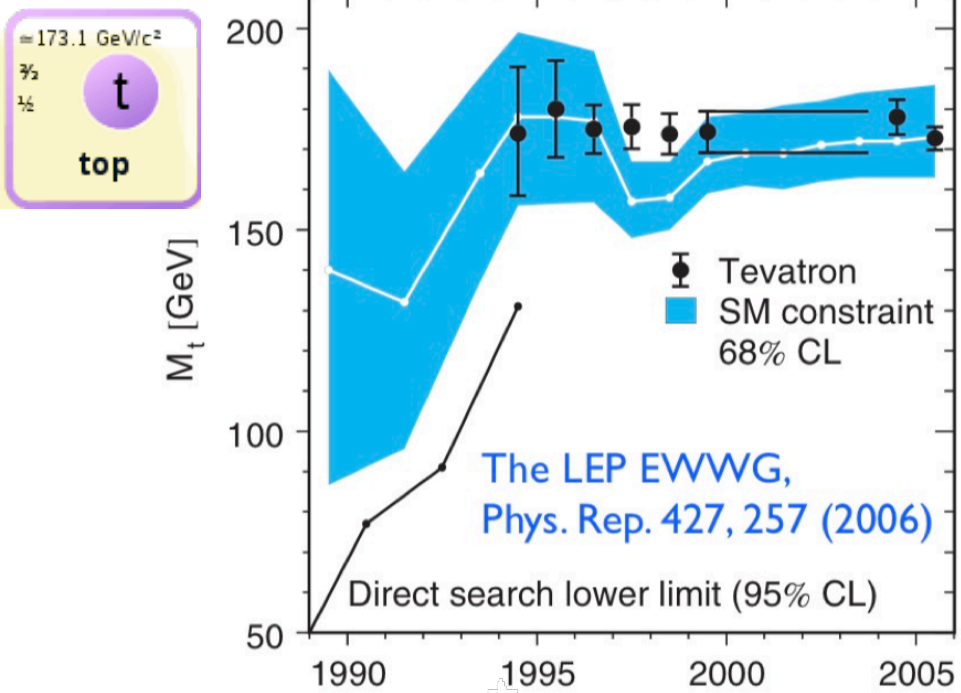
1994 — Fermilab/TeVatron

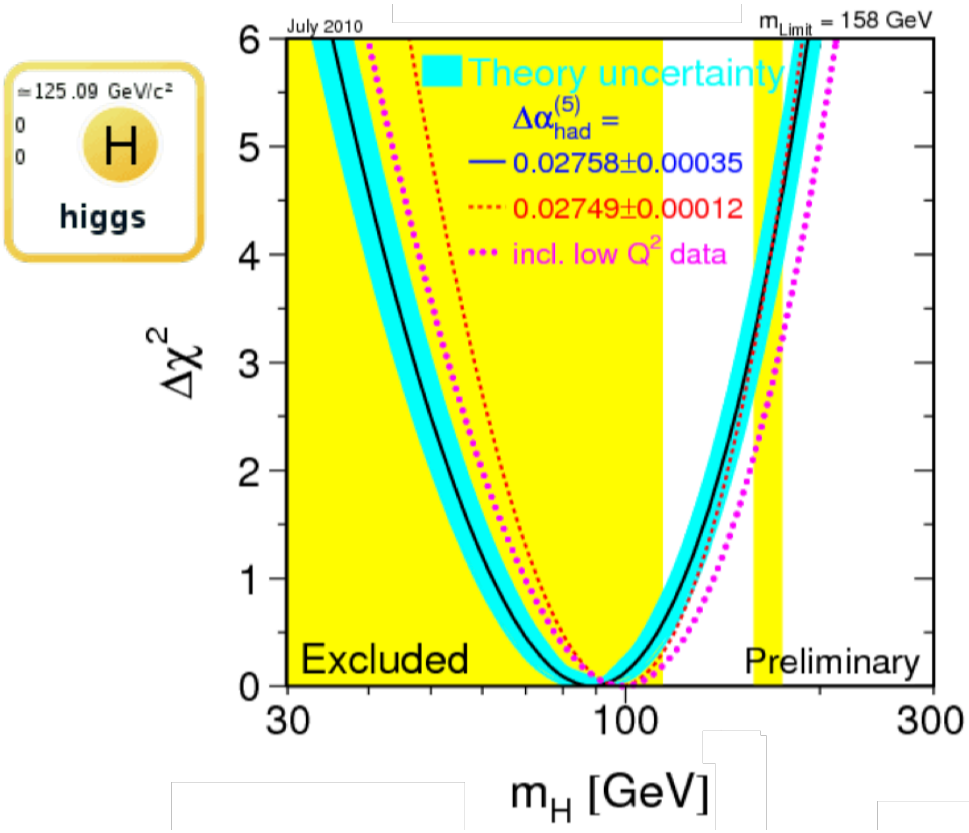
Top quark



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

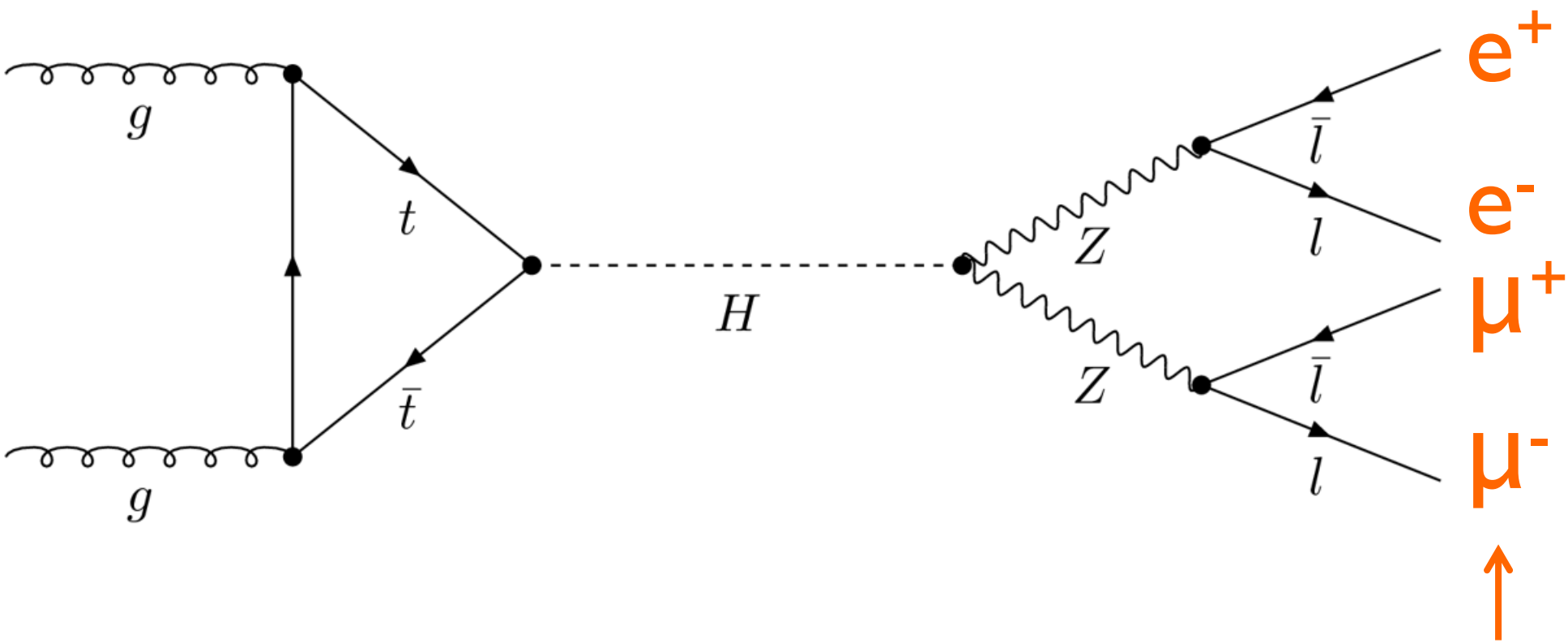
LHC "no loose theorem"

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



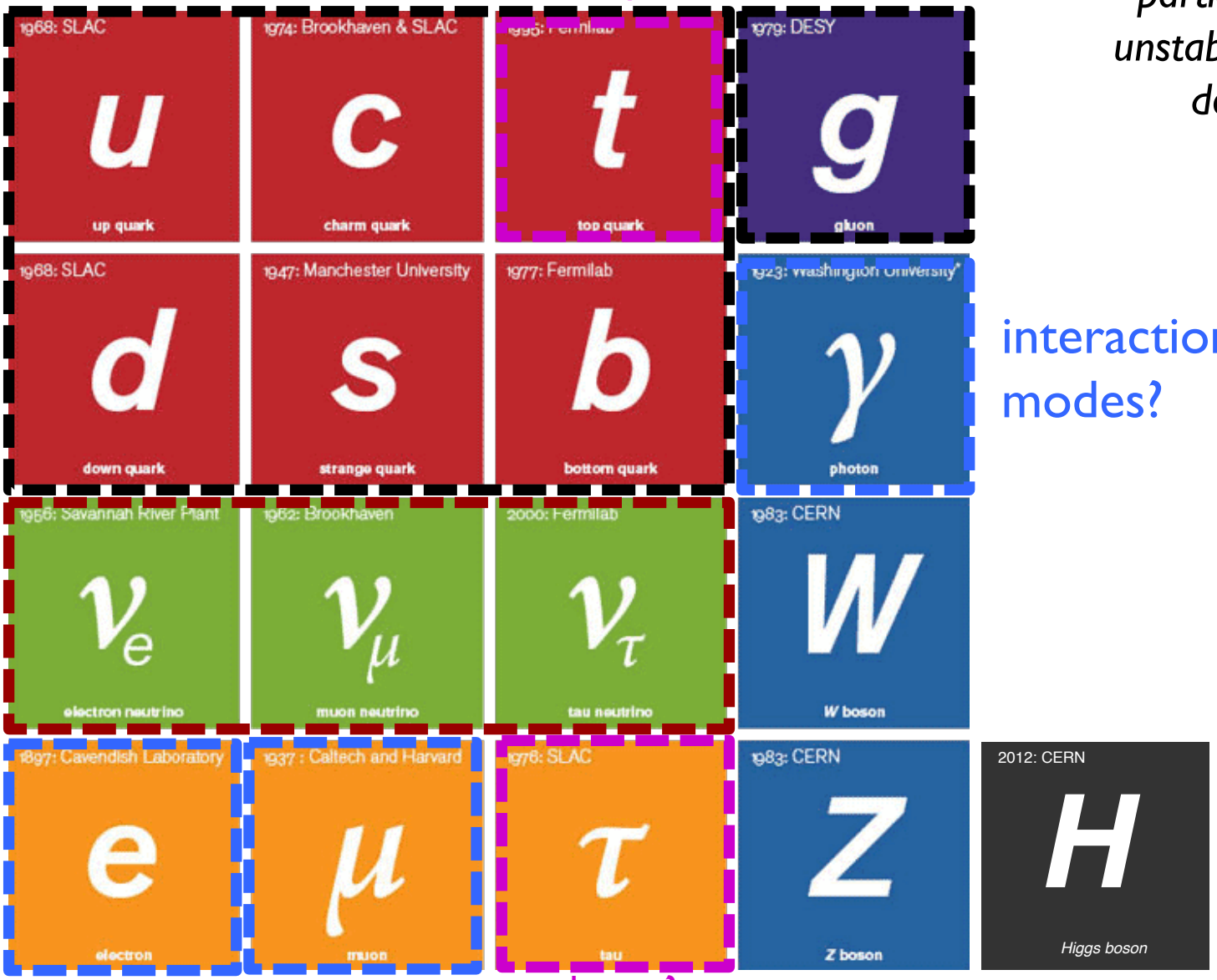
this is what we are looking for…

What do we want to measure?

… "stable" particles from unstable particle decays!

decays?

hadron jets



interaction modes?

invisible

in particle detectors at accelerators

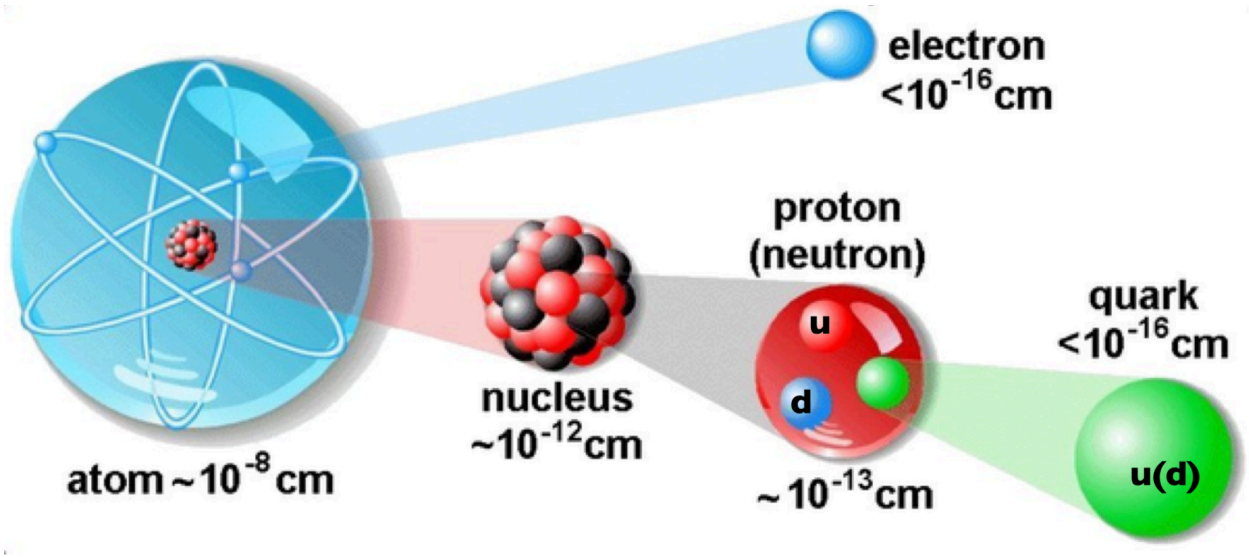
interaction modes?

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

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

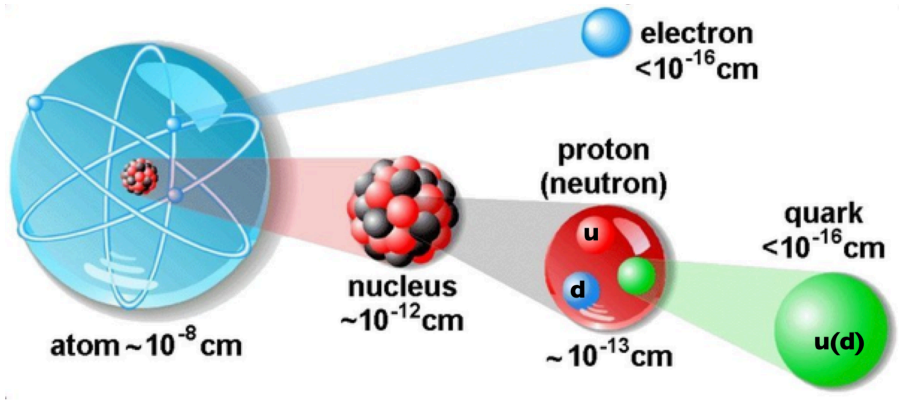
with θ = angular aperture of the light beam

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/c]*
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

- … and move at relativistic speed

Particle identification via measurement of several quantities…

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

Relativistic kinematics in a nutshell

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

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

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

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

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

$$E = m\gamma$$

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

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

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \frac{v}{c} \qquad t = t_0\gamma \qquad \ell = \frac{\ell_0}{\gamma}$$

time dilatation

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:

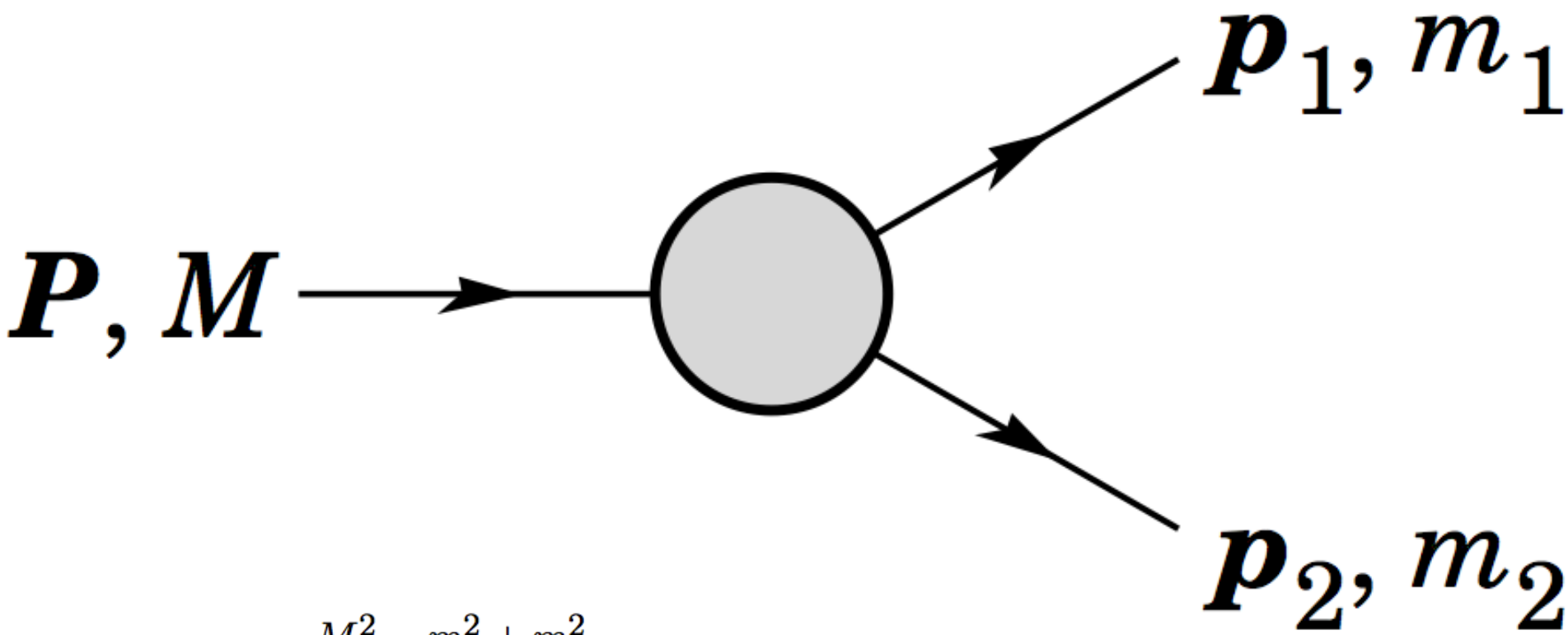
$$E_{\mathrm{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

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-bodies decay



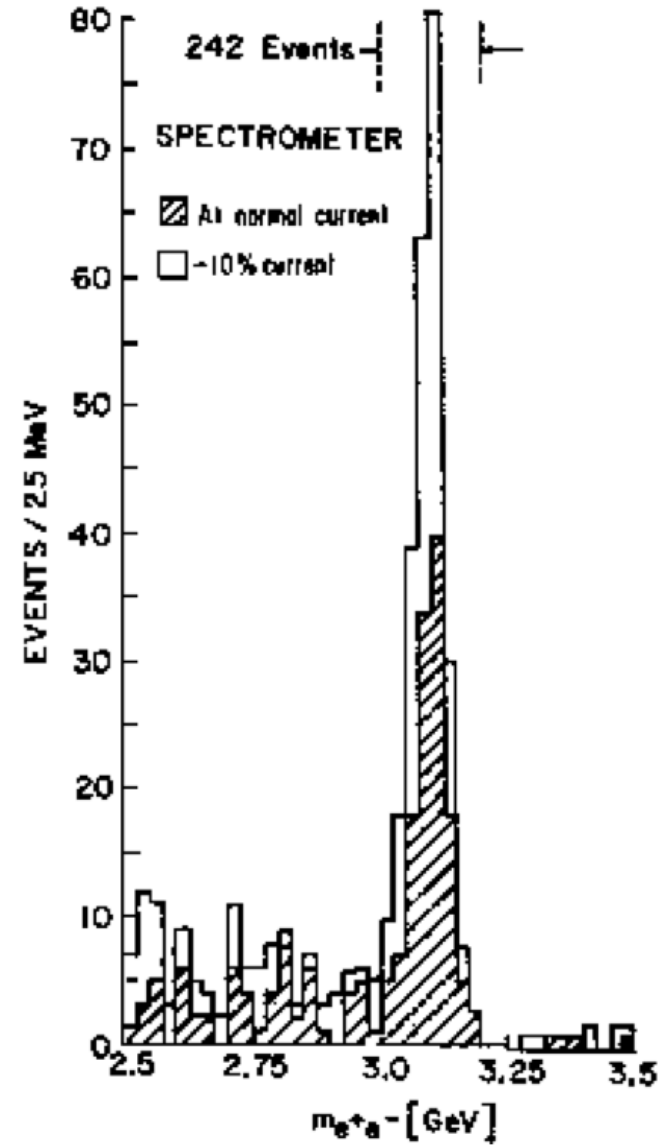
$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} \ ,$$

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

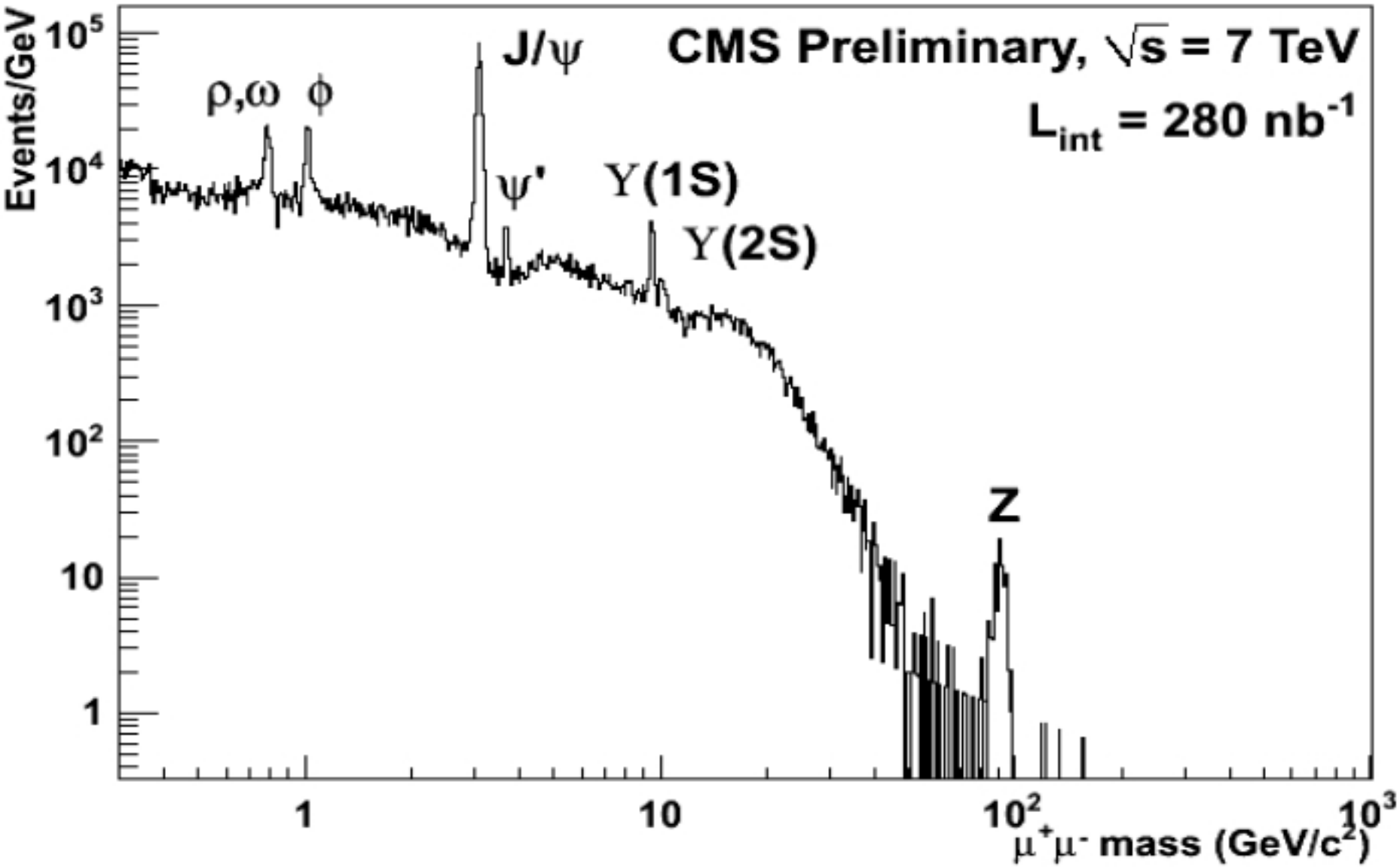
$$= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

Invariant mass

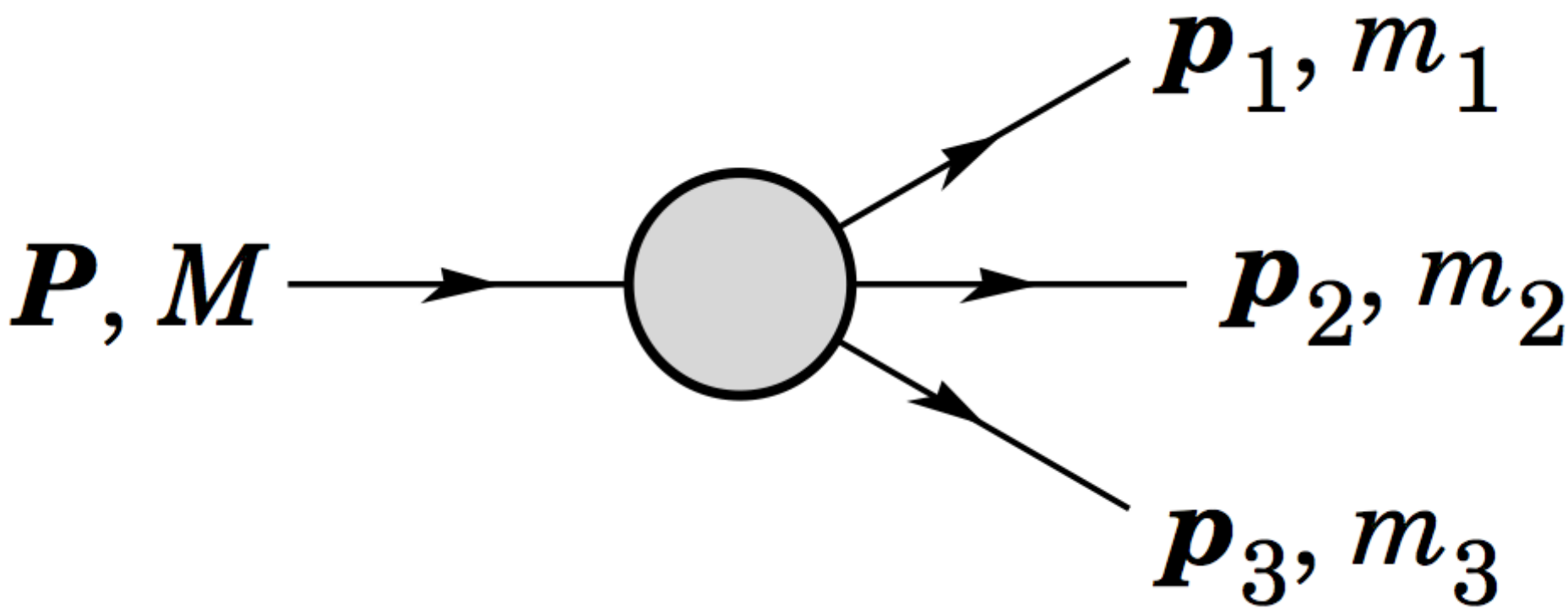
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



Invariant mass



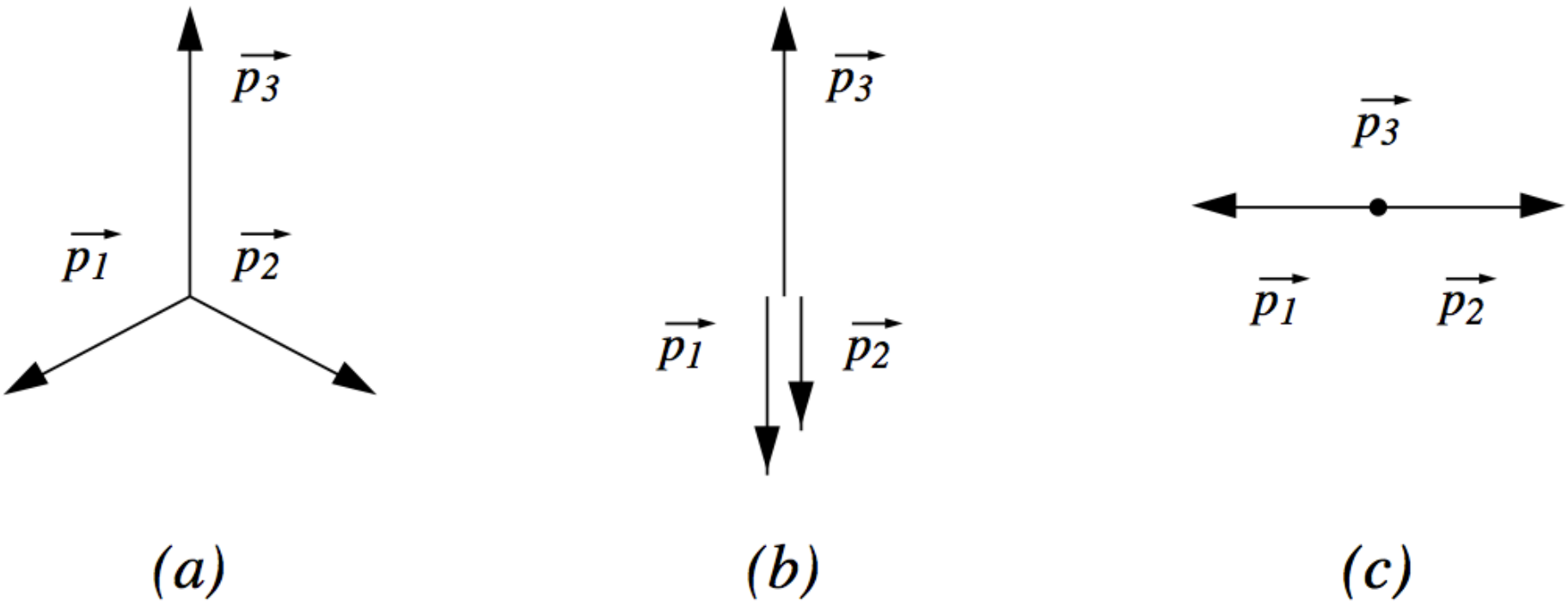
3-bodies decay



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

3-bodies decay

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



$$\max(|\vec{p}_3|) \qquad (m_{12})_{min} = m_1 + m_2$$

$$\min(|\vec{p}_3|) \qquad (m_{12})_{max} = M - m_3$$

A real example: pion decay(s)

pion decays at rest

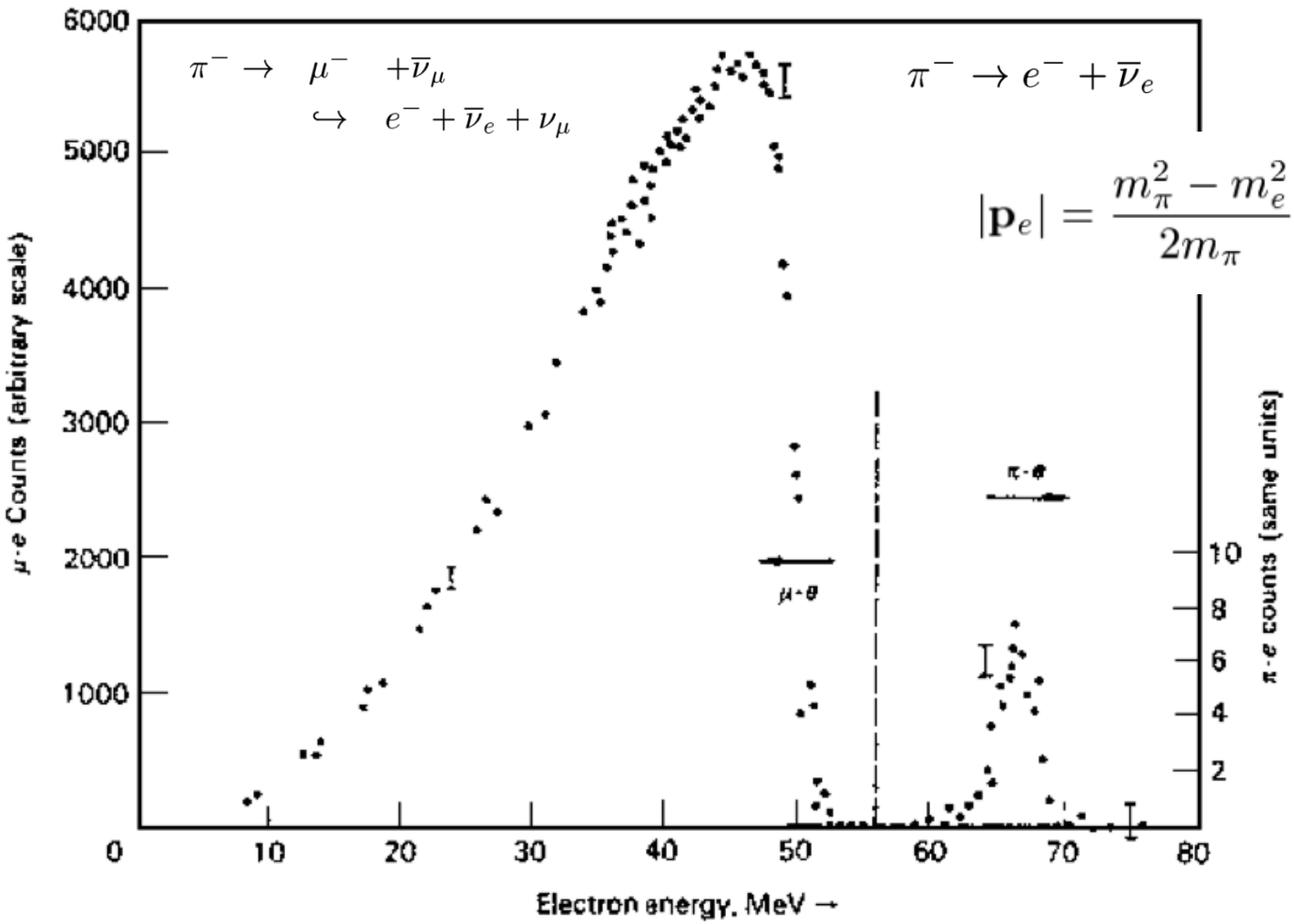
$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} c \simeq 30\,\mathrm{MeV/c}$$

$$m_\nu = 0$$

in most cases muon decays at rest

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

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



3-bodies decay: Dalitz plot

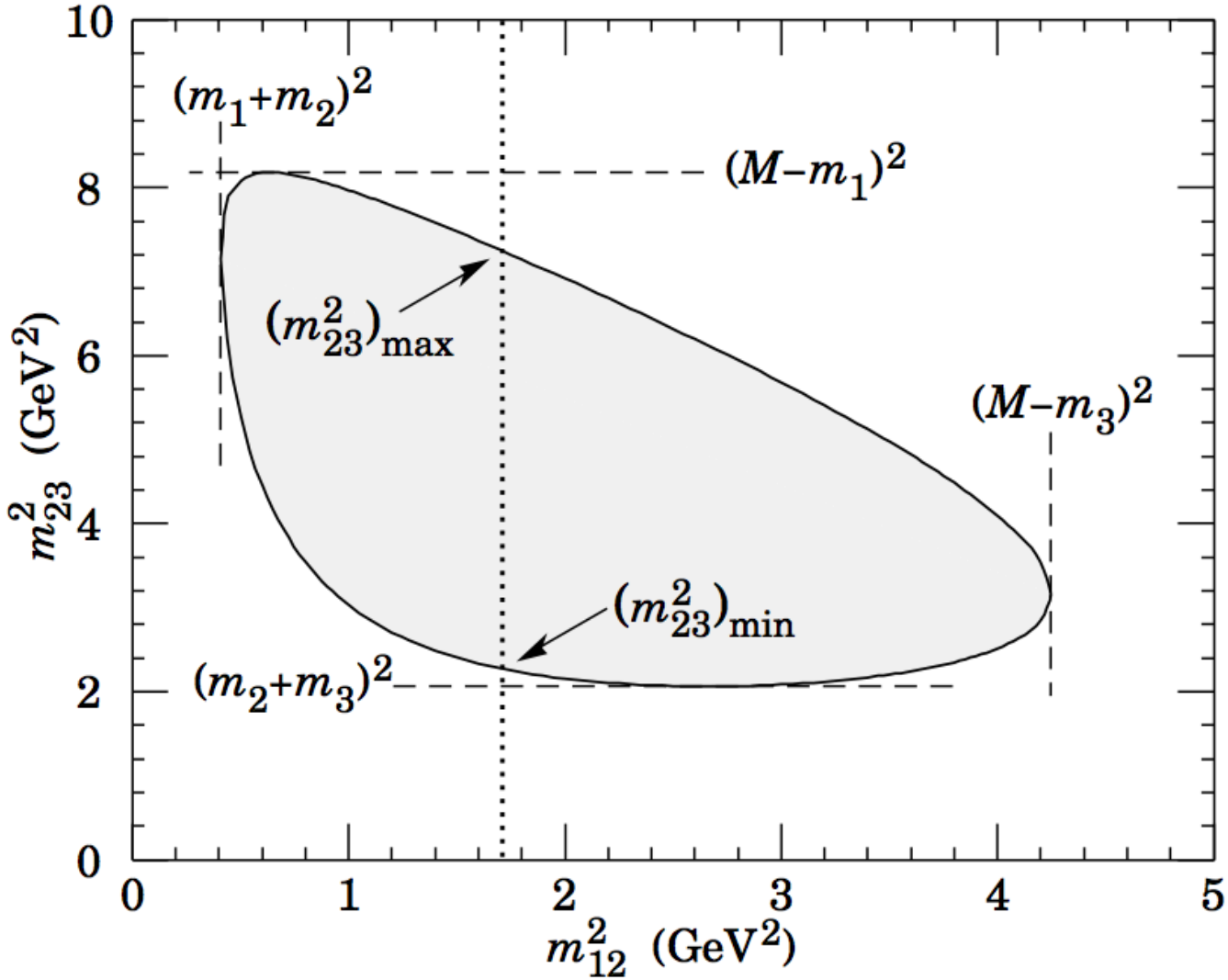
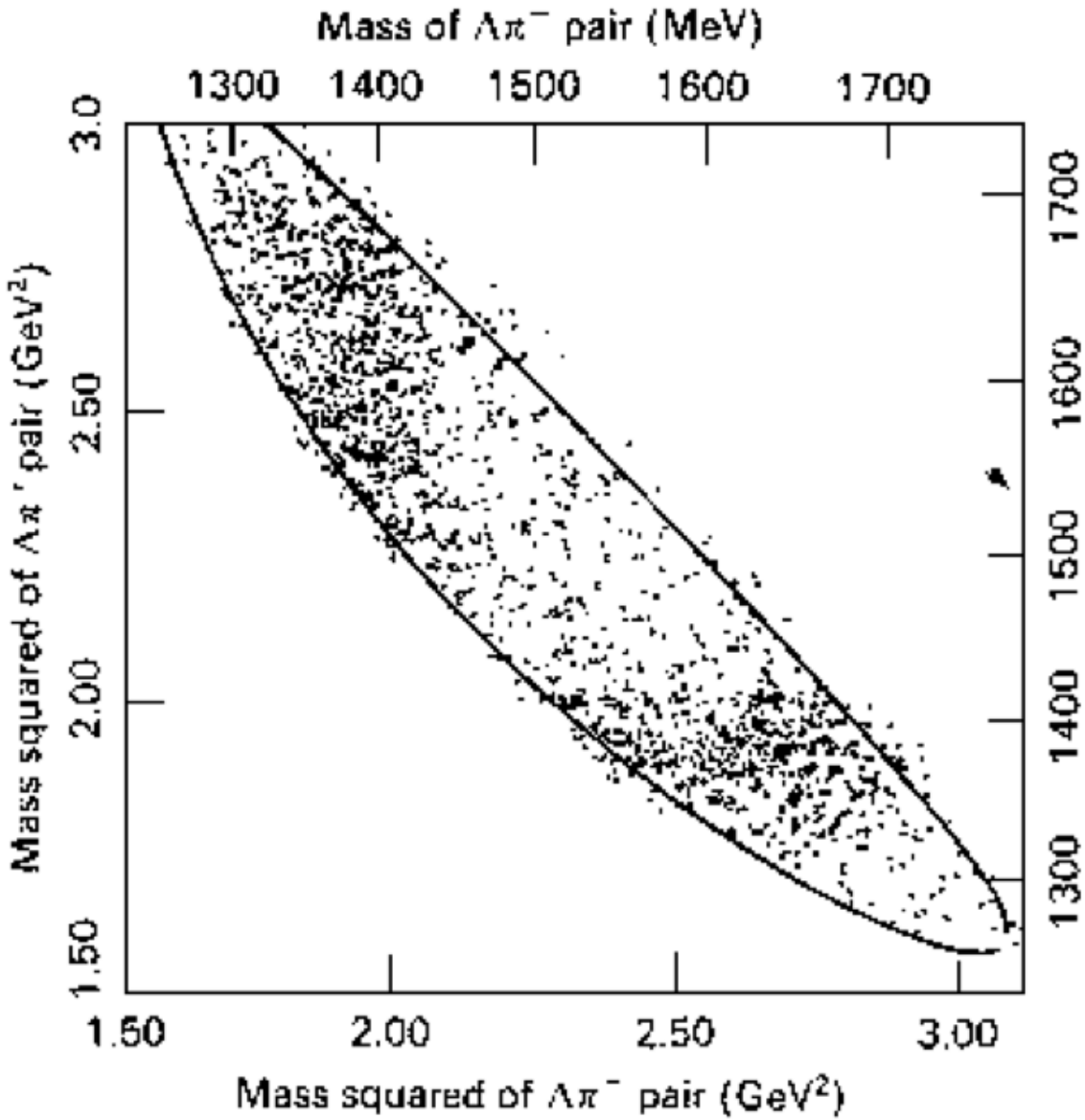


Figure 45.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+\overline{K}^0p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

Multi-bodies decay

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



Reaction threshold

$$\sqrt{s} \geq \sum_i m_i c^2$$

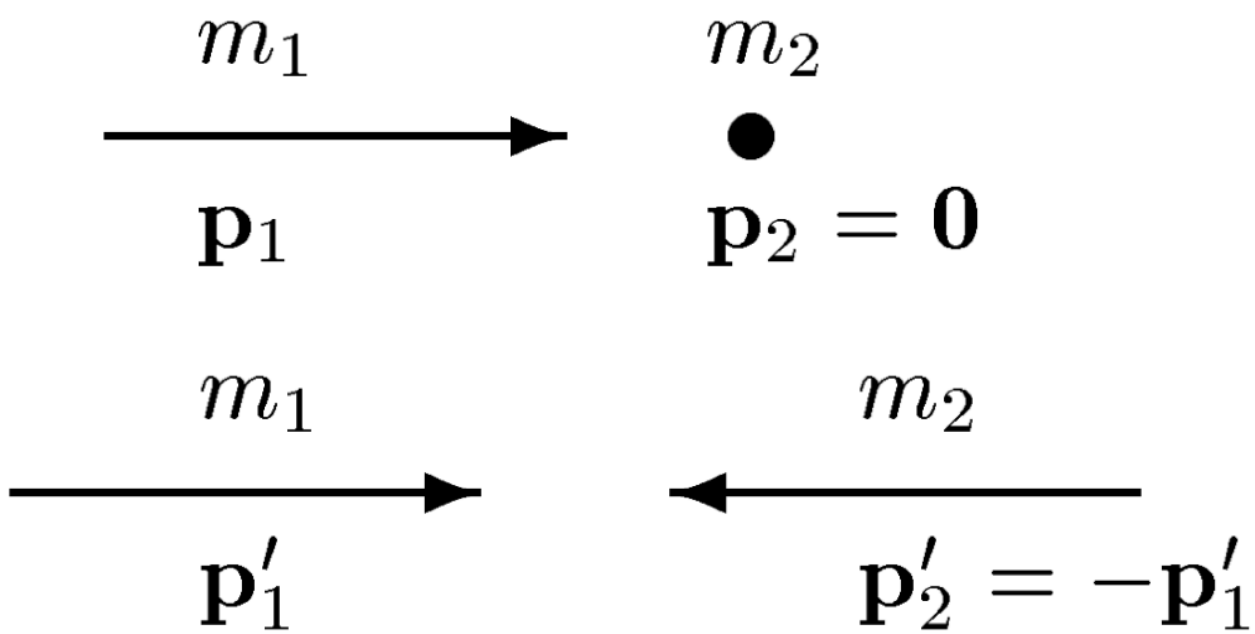
What energy should the pion have for this reaction to happen?

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

$$\begin{aligned} s &= (p_\pi + p_p)^2 c^2 = (E_\pi + m_p c^2)^2 - |\mathbf{p}_\pi|^2 \\ &= (m_\pi c^2)^2 + (m_p c^2)^2 + 2E_\pi (m_p c^2) \end{aligned}$$

$$E_\pi \geq \frac{(\sum_i m_i c^2)^2 - (m_\pi c^2)^2 - (m_p c^2)^2}{2 m_p c^2} \simeq 500\,\mathrm{MeV}$$

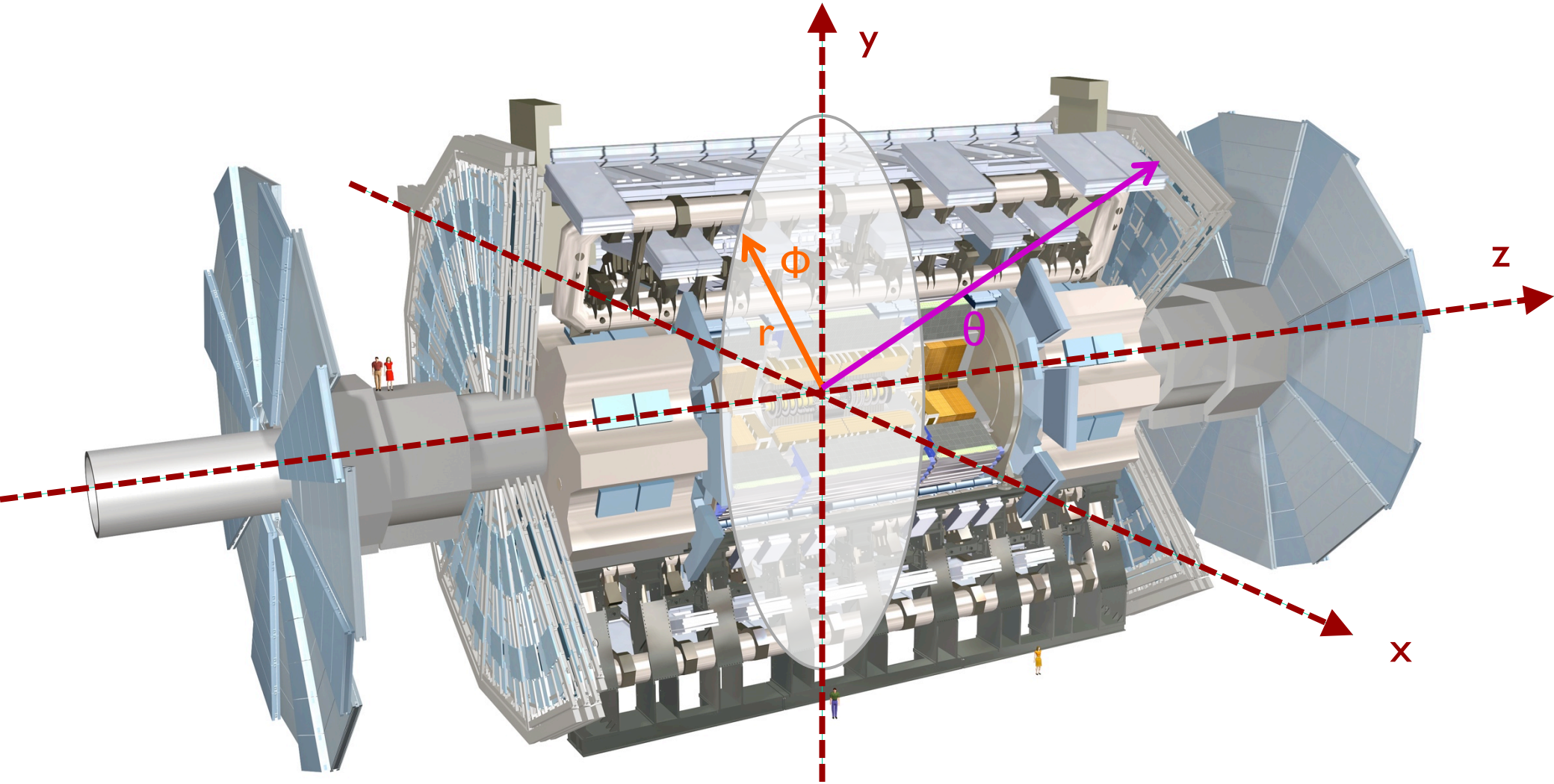
Fixed target vs. collider



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

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

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

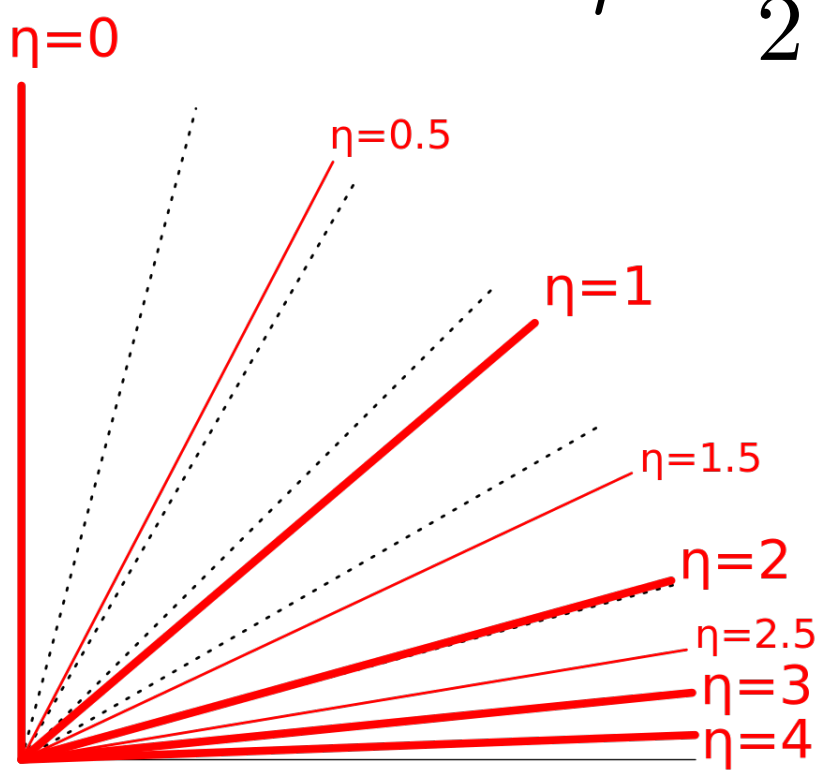
$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

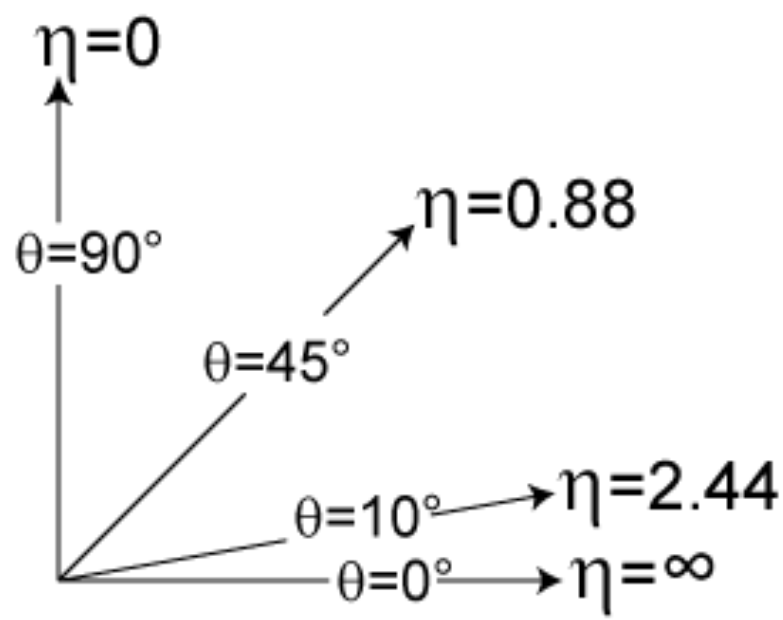
$$\eta \simeq y$$

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

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

- If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can 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 $m_1 = m_2 = 0$ $\quad M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos\phi_{12})$

W → e ν discovery

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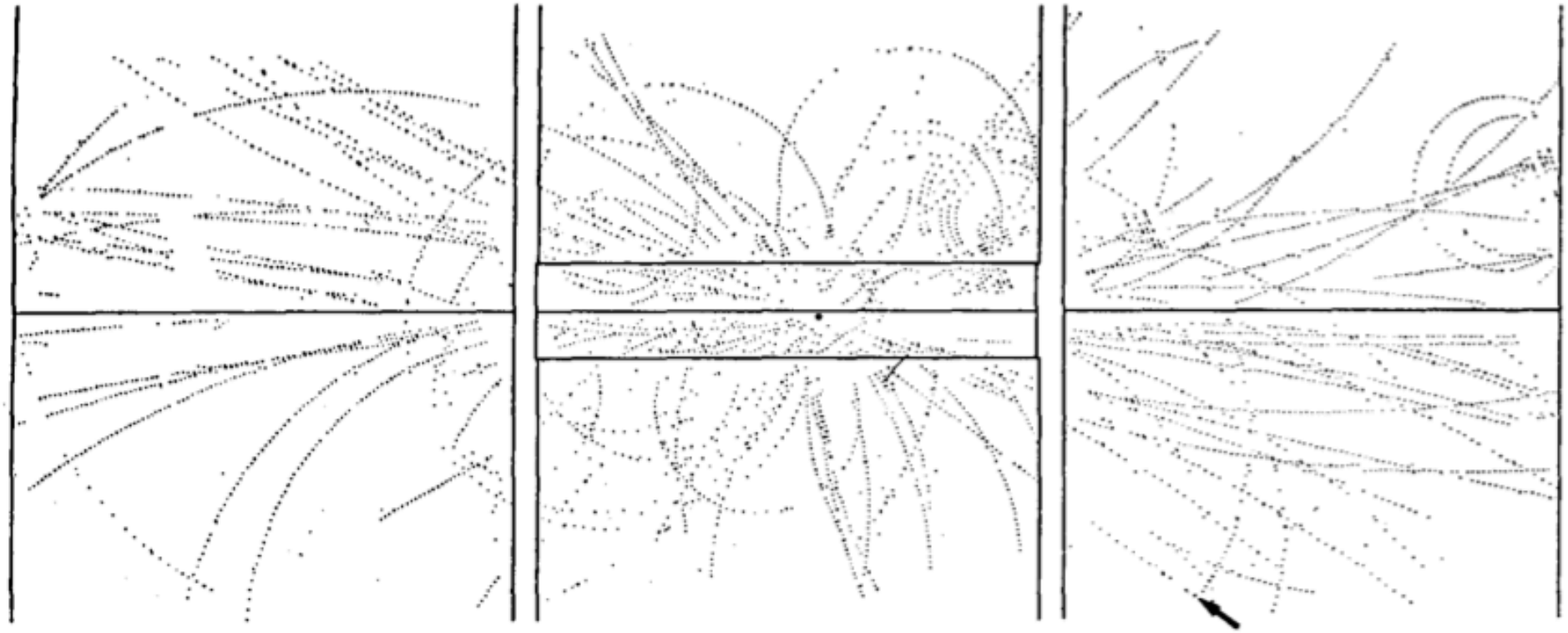
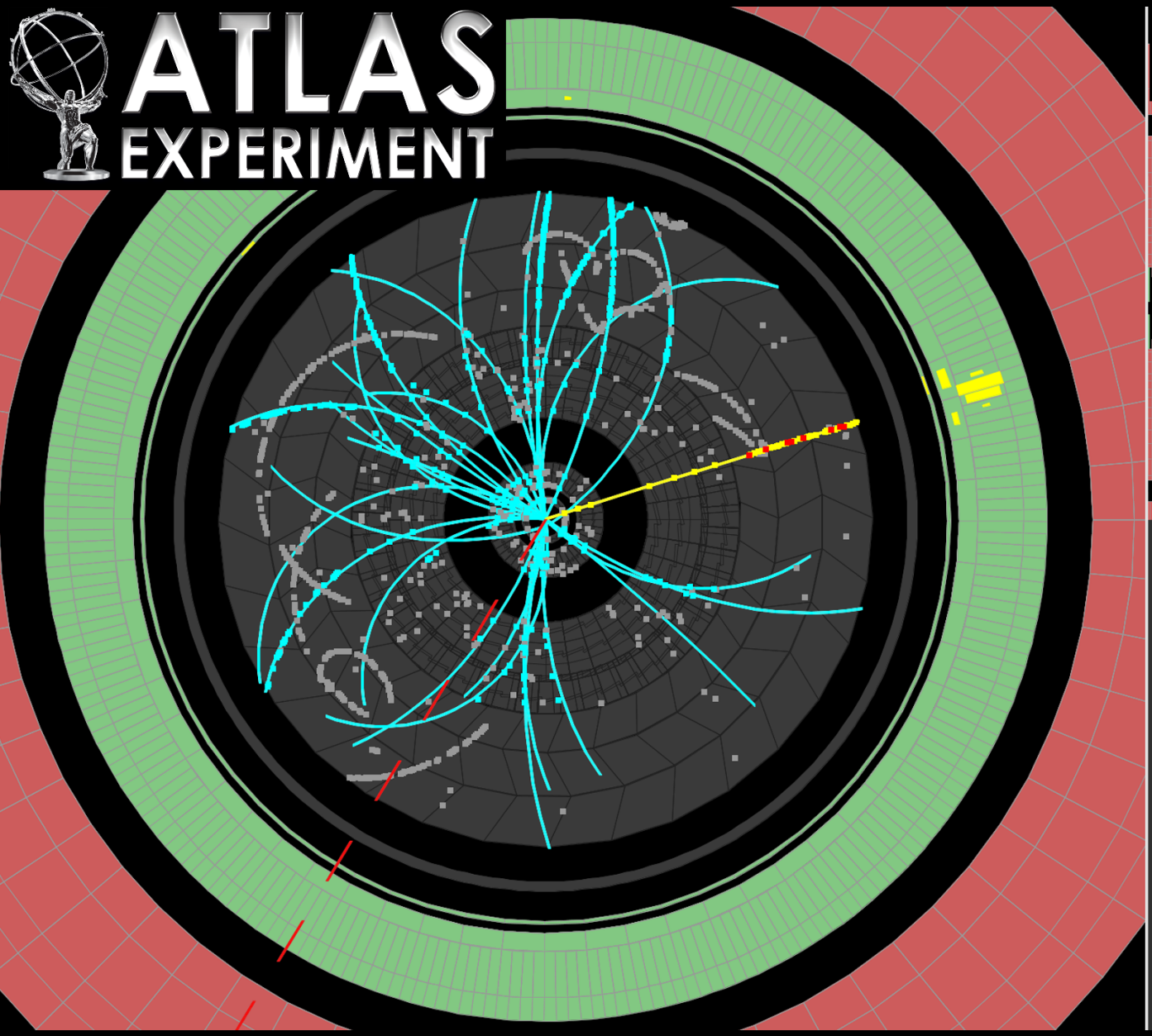
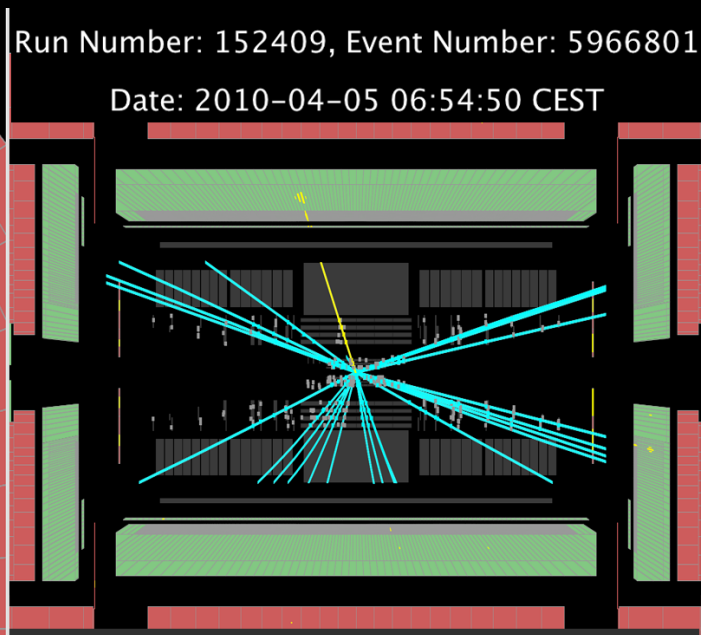
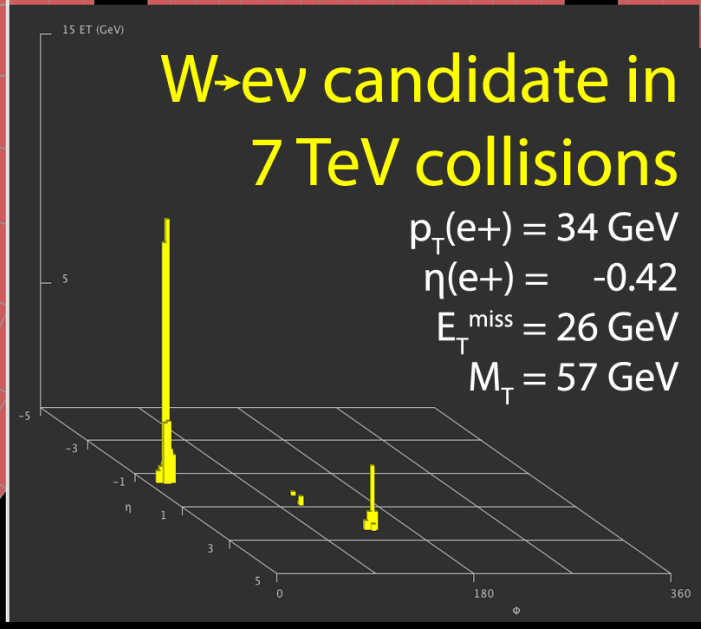




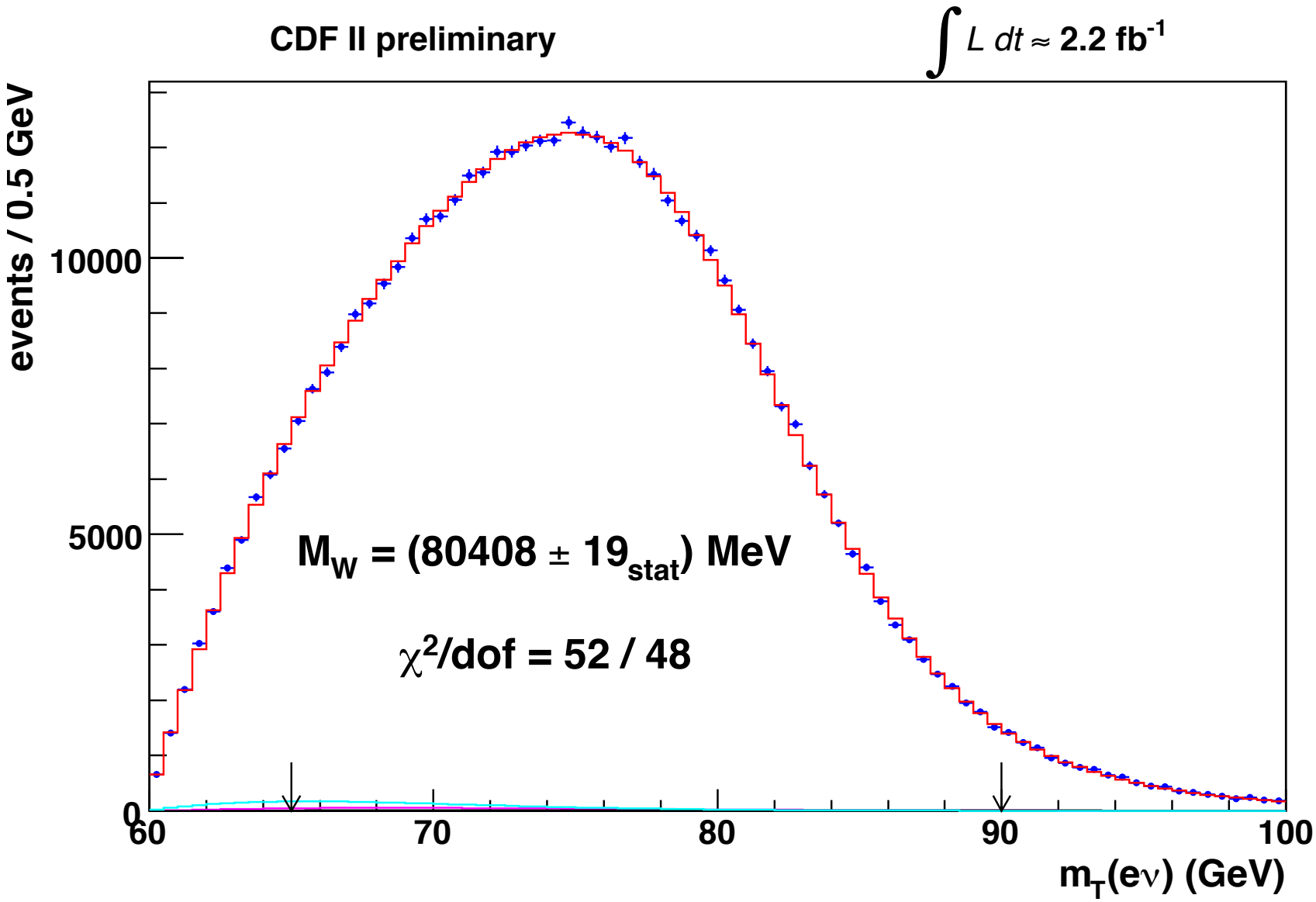




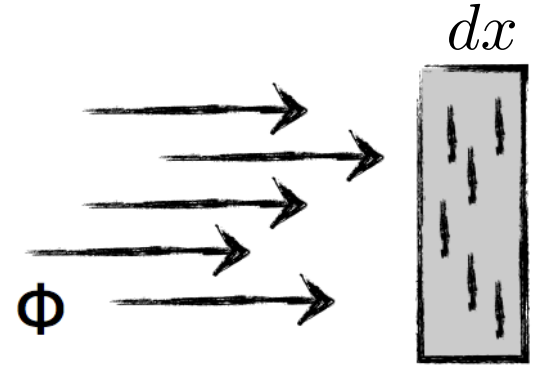
W→eν candidate in 7 TeV collisions

$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

W → e ν


CDF II preliminary
∫ L dt ≈ 2.2 fb-1
events / 0.5 GeV
10000
5000
0
60
70
80
90
100
mT(eν) (GeV)
MW = (80408 ± 19stat) MeV
χ2/dof = 52 / 48

Interaction cross section



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

Reactions per unit of time

$$\frac{dN_{\text{reac}}}{dt} = \Phi \overbrace{\sigma N_{\text{target}} dx}^{\text{area obscured by target particle}}$$

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

Reaction rate per target particle

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

Cross section per target particle

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

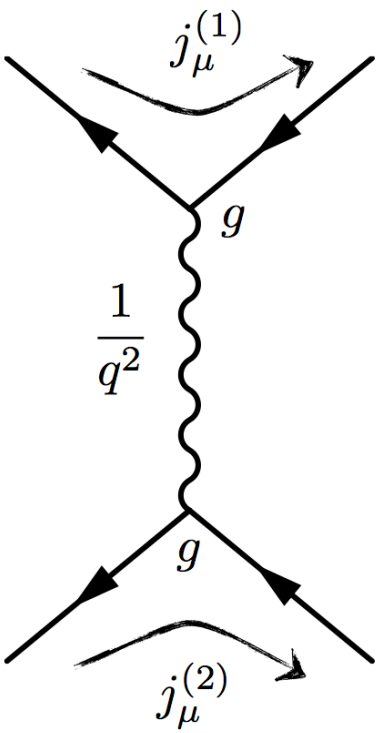
1b = 10^{-28} m^2 (roughly the area of a nucleus with A = 100)

Fermi Golden Rule

From non-relativistic perturbation theory…

transition probability *matrix element* *energy density of final states*

$$\overbrace{W_{if}}^{[t^{-1}]} = \frac{2\pi}{\hbar}\overbrace{|M_{if}|^2}^{[E]}\overbrace{\frac{dN}{dE_f}}^{[E^{-1}]}$$



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

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

Cross section: magnitude and units

Standard
cross section unit: $[\sigma] = \text{mb}$ with $1\ \text{mb} = 10^{-27}\ \text{cm}^2$

or in
natural units: $[\sigma] = \text{GeV}^{-2}$ with $1\ \text{GeV}^{-2} = 0.389\ \text{mb}$
$1\ \text{mb} = 2.57\ \text{GeV}^{-2}$

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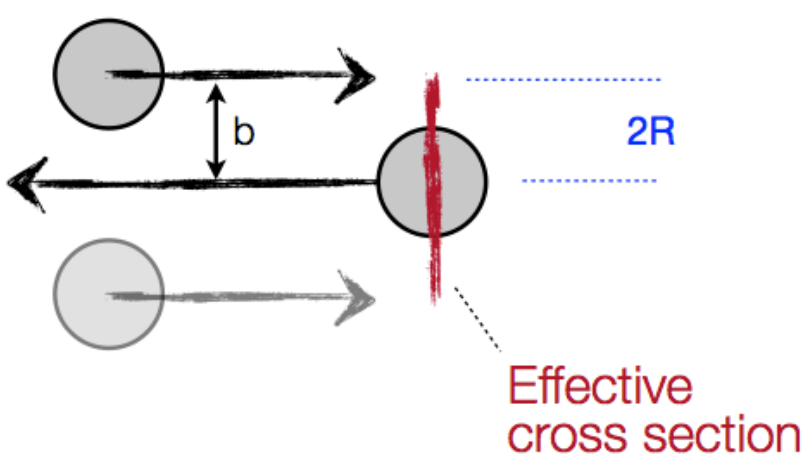
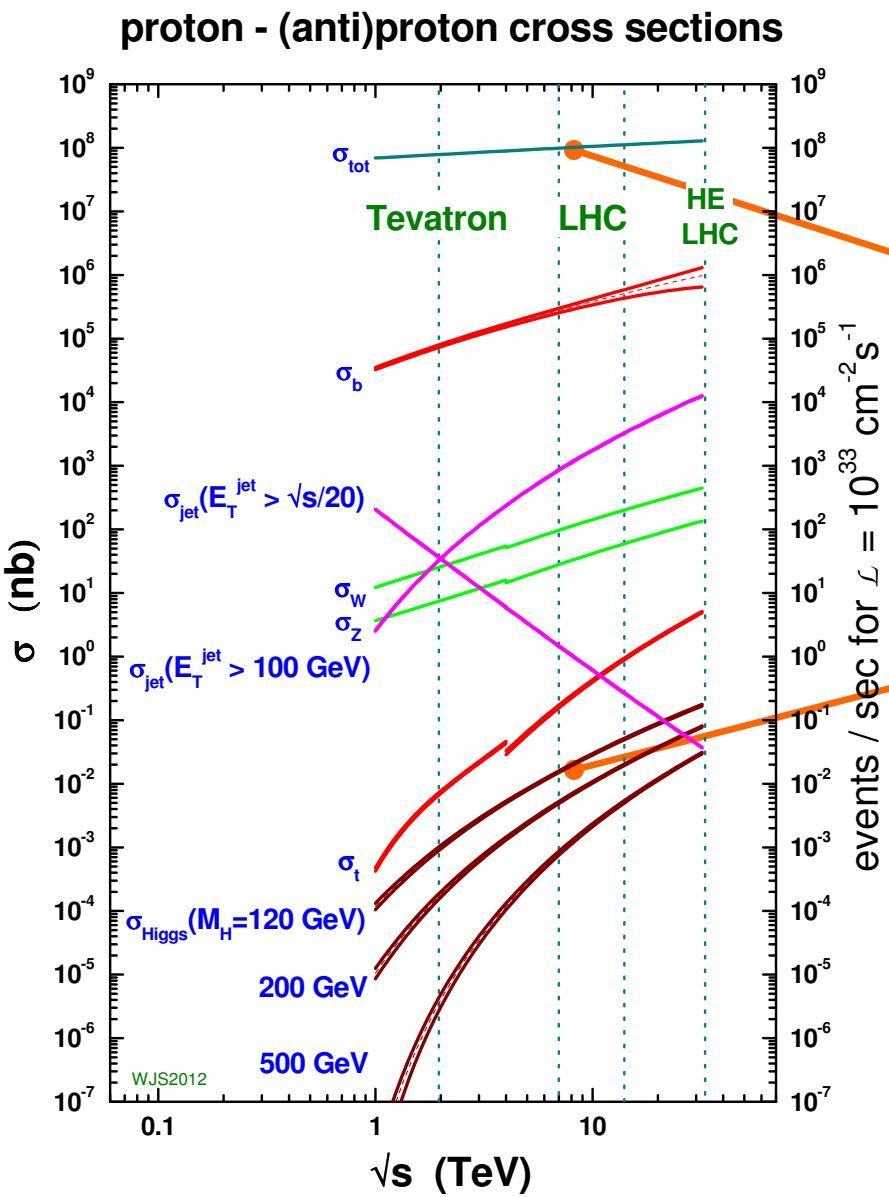
using: $\hbar c = 0.1973\ \text{GeV fm}$
$(\hbar c)^2 = 0.389\ \text{GeV}^2\ \text{mb}$

Estimating the
proton-proton cross section:



Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

Cross-sections at LHC



10^8 events/s

$\sim 10^{10}$

10^{-2} events/s ~ 10 events/min

[m_H ~ 125 GeV]

0.2% H → γγ
1.5% H → ZZ