

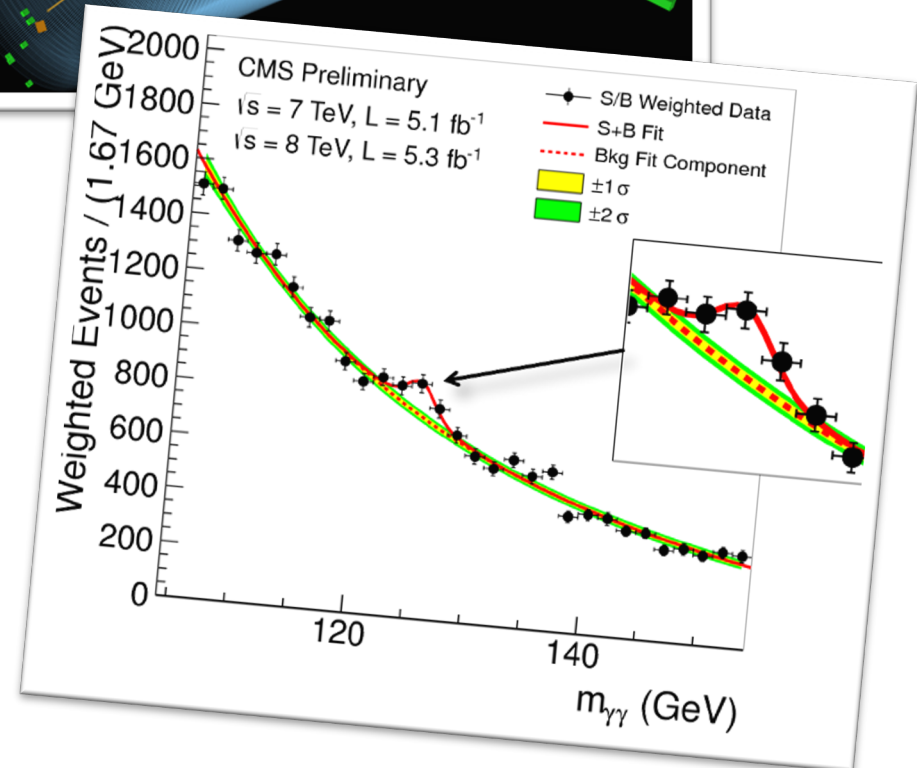
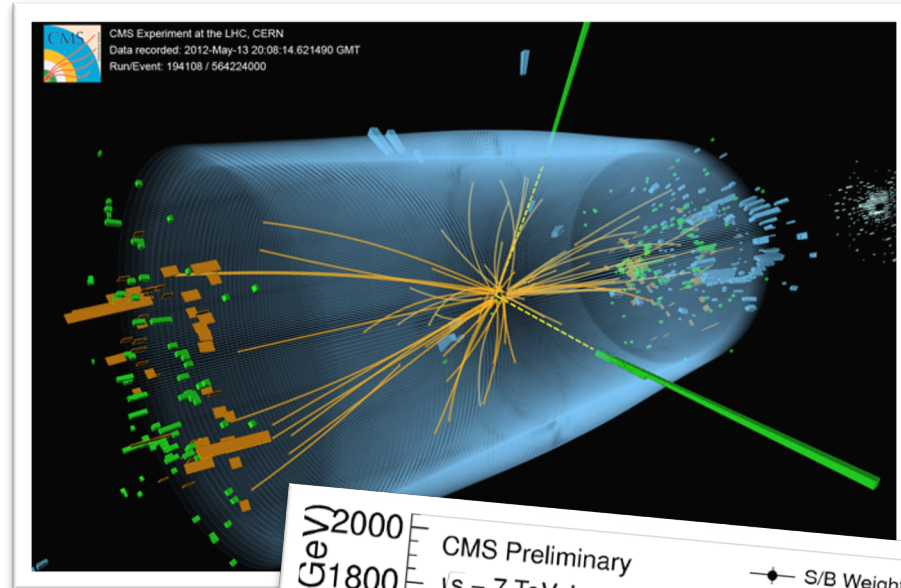
Experimental particle. physics



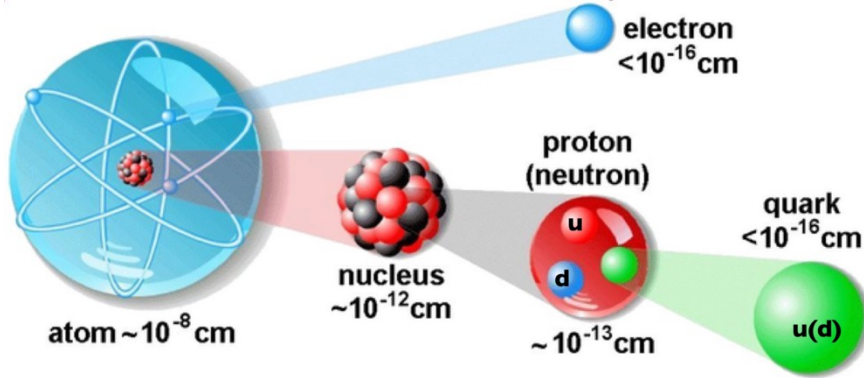
units, quantities,
kinematics, measurements

Experiment = probing/building theories with data!

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\mu^a g_\mu^b g_\mu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^a g_\mu^b g_\mu^c g_\mu^d g_\mu^e + \\
 & \frac{1}{2}i g_s^2 (\bar{q}_i^a \gamma^\mu q_j^a) g_\mu^a + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a G^b G^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \frac{(2M^2)}{g^2} + \\
 & \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) + \frac{2M^4}{g^2} \alpha_h - ig_{cw} [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^-) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\mu^+) - ig_{sw} [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\mu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
 & \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig_{cw} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig_{sw} M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig_{sw} A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - e^\lambda (\gamma \partial + m_e^\lambda) e^\lambda + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \\
 & \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig_{sw} A_\mu [-(e^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
 & \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{1}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa) + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
 & \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} M [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_h^2}{M} [H (e^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_e^\lambda (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_h^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_h^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_h^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \frac{ig}{2} \frac{m_h^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig_{sw} W_\mu^+ (\partial_\mu \bar{X}^- X^+ - \\
 & \partial_\mu \bar{X}^+ X^-) + ig_{cw} W_\mu^- (\partial_\mu \bar{X}^- X^+ - \partial_\mu \bar{X}^+ X^-) + ig_{sw} W_\mu^- (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \frac{1}{c_w} \bar{X}^0 X^0 H + \\
 & \partial_\mu \bar{X}^- X^+ - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^+ X^0 \phi^- - \bar{X}^- X^0 \phi^+] + \\
 & ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$



The Standard Model of particle physics...



three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u up	mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c charm	mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t top	0 0 1 g gluon	mass $\approx 125.09 \text{ GeV}/c^2$ 0 0 0 H higgs
QUARKS mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ d down	mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b bottom	0 0 1 γ photon	SCALAR BOSONS
mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ e electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ μ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ τ tau	0 0 1 Z Z boson	
LEPTONS mass $< 2.2 \text{ eV}/c^2$ 0 spin $\frac{1}{2}$ ν_e electron neutrino	mass $< 1.7 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_μ muon neutrino	mass $< 15.5 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_τ tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ ±1 spin 1 W W boson	
			GAUGE BOSONS VECTOR BOSONS	

Gauge bosons

$\mathcal{L} =$

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

Gauge boson coupling to fermions (EW, QCD)

Higgs coupling to fermions (fermion masses)

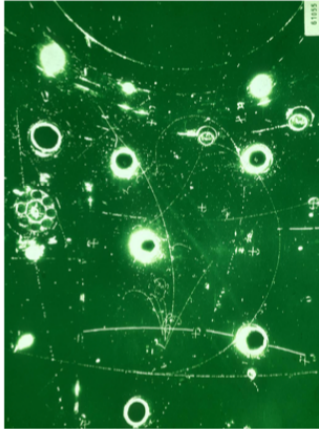
Higgs coupling to bosons (boson masses)

Higgs self-coupling (Higgs potential)

A theory built (and probed) over time...

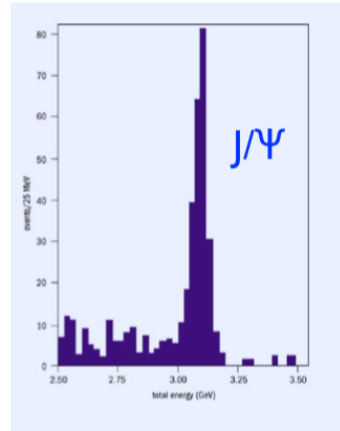
1972 — CERN

Neutral currents



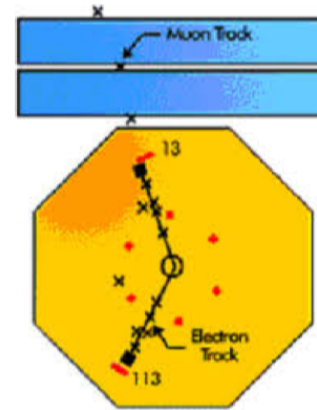
1974 — BNL, SLAC

Charm



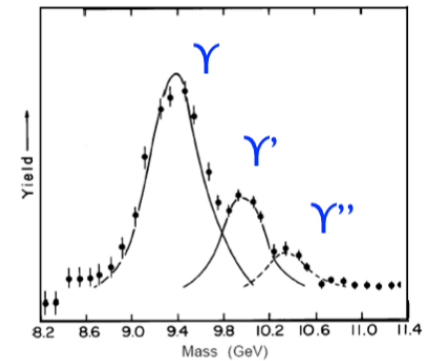
1976 — SLAC

Tau lepton



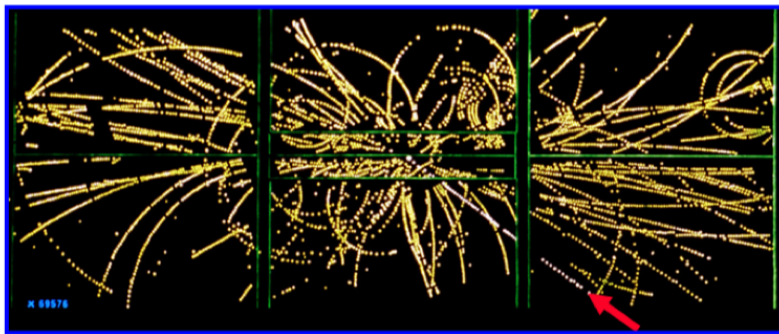
1979 — Fermilab

Beauty



1983 — CERN/SppS

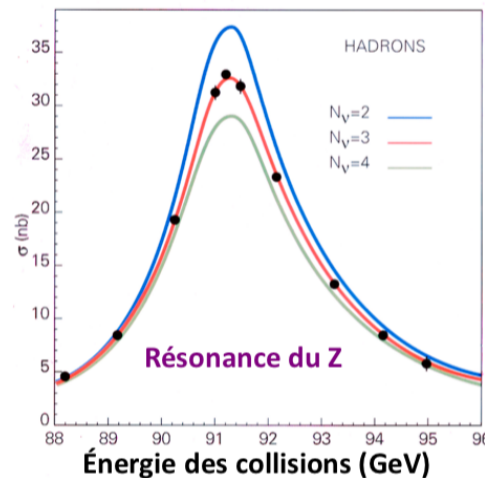
W and Z bosons



UA1, UA2

1990 — CERN/LEP

Three families of neutrinos

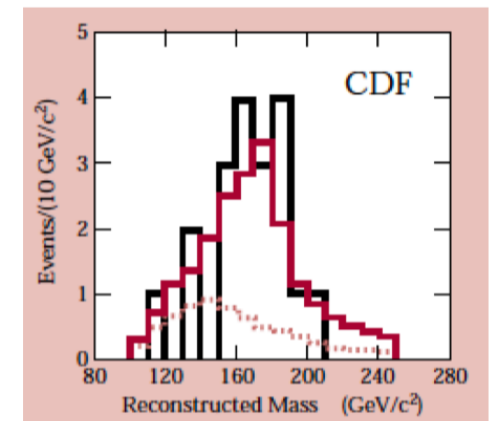


ALEPH, DEPHI, L3, OPAL

Experimental Particle Physics

1994 — Fermilab/TeVatron

Top quark

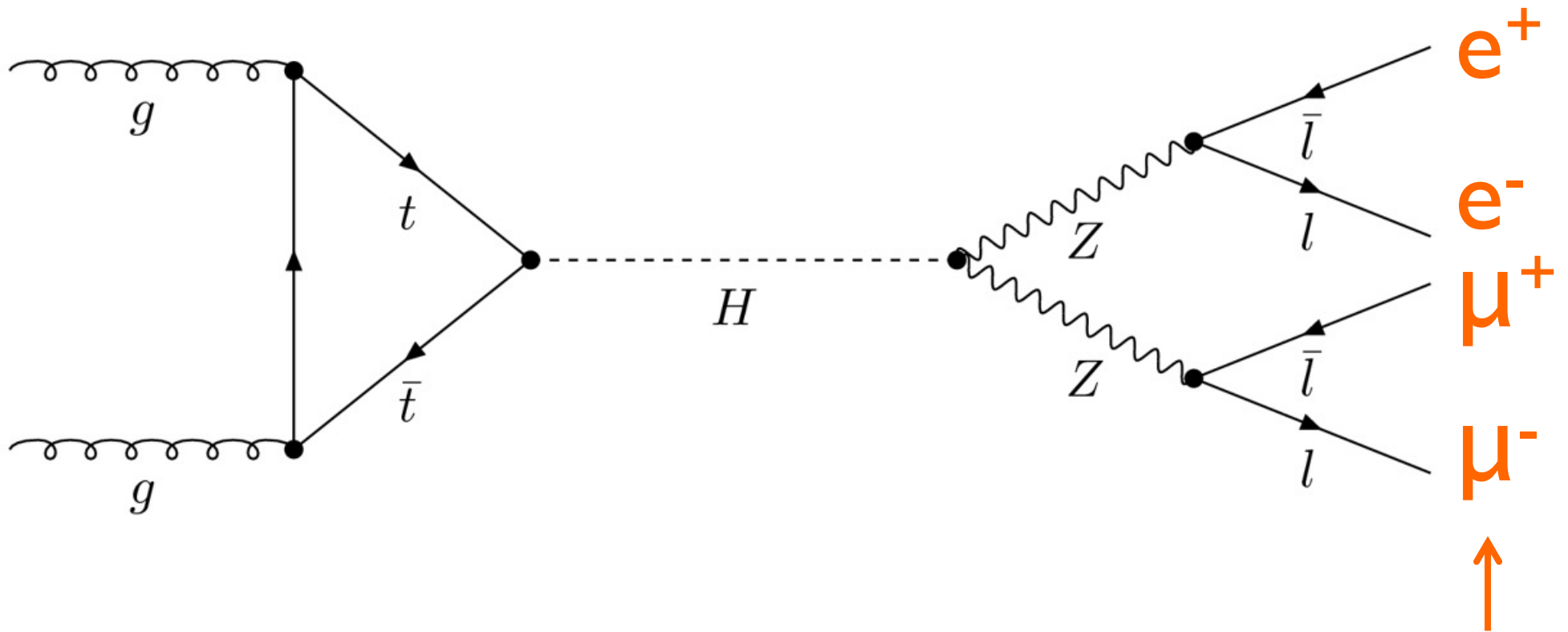


CDF, D0

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?

decays?

... “stable”
particles from
unstable particle
decays!

hadron
jets

interaction
modes?

invisible
*in particle
detectors at
accelerators*

interaction
modes?

1968: SLAC u up quark	1974: Brookhaven & SLAC c charm quark	1995: Fermilab t top quark	1979: DESY g gluon
1968: SLAC d down quark	1947: Manchester University s strange quark	1977: Fermilab b bottom quark	1923: Washington University γ photon
1956: Savannah River Plant ν_e electron neutrino	1962: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN W W boson
1897: Cavendish Laboratory e electron	1937: Caltech and Harvard μ muon	1976: SLAC τ tau	1983: CERN Z Z boson
			2012: CERN H Higgs boson

decays?

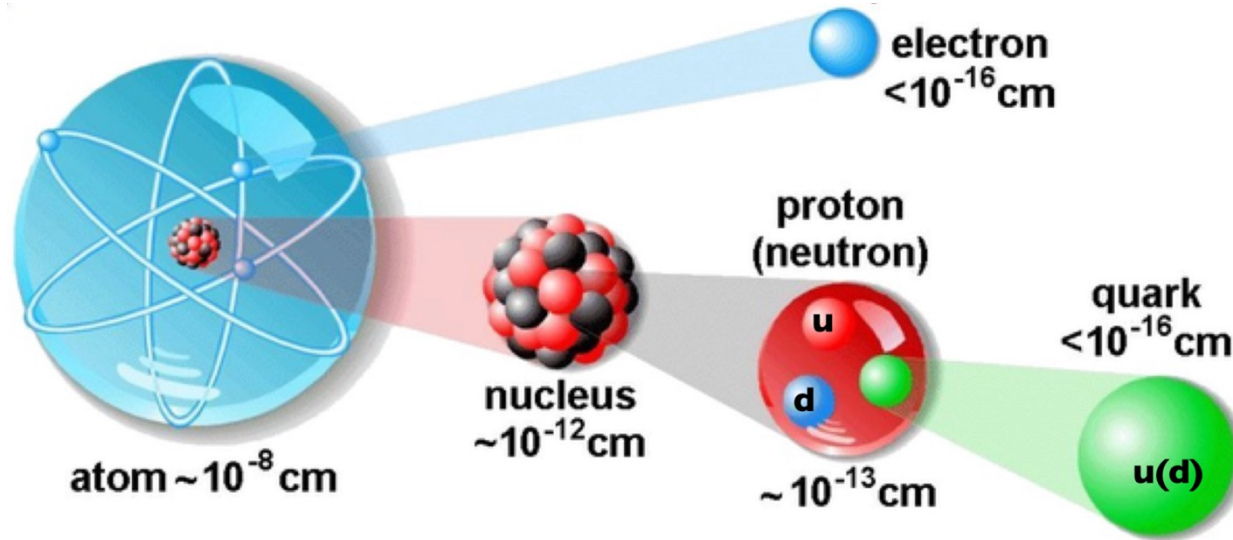
HEP, SI and “natural” units

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

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

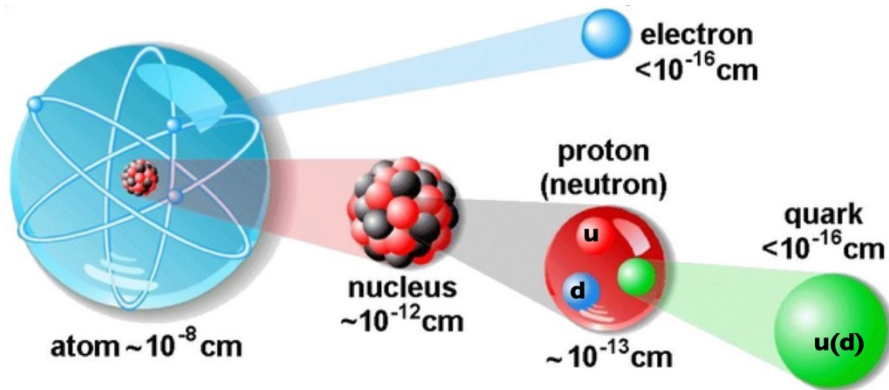
with θ = angular aperture of the light beam

De Broglie wavelength

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

with p = transferred momentum

Estimating order of magnitudes...



De Broglie wavelength

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

with p = transferred momentum

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

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
- ... 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

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

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

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

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

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

$$E = m\gamma$$

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

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

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

$$\beta = \frac{v}{c}$$

$$t = t_0 \gamma$$

time dilatation

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

length contraction

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:

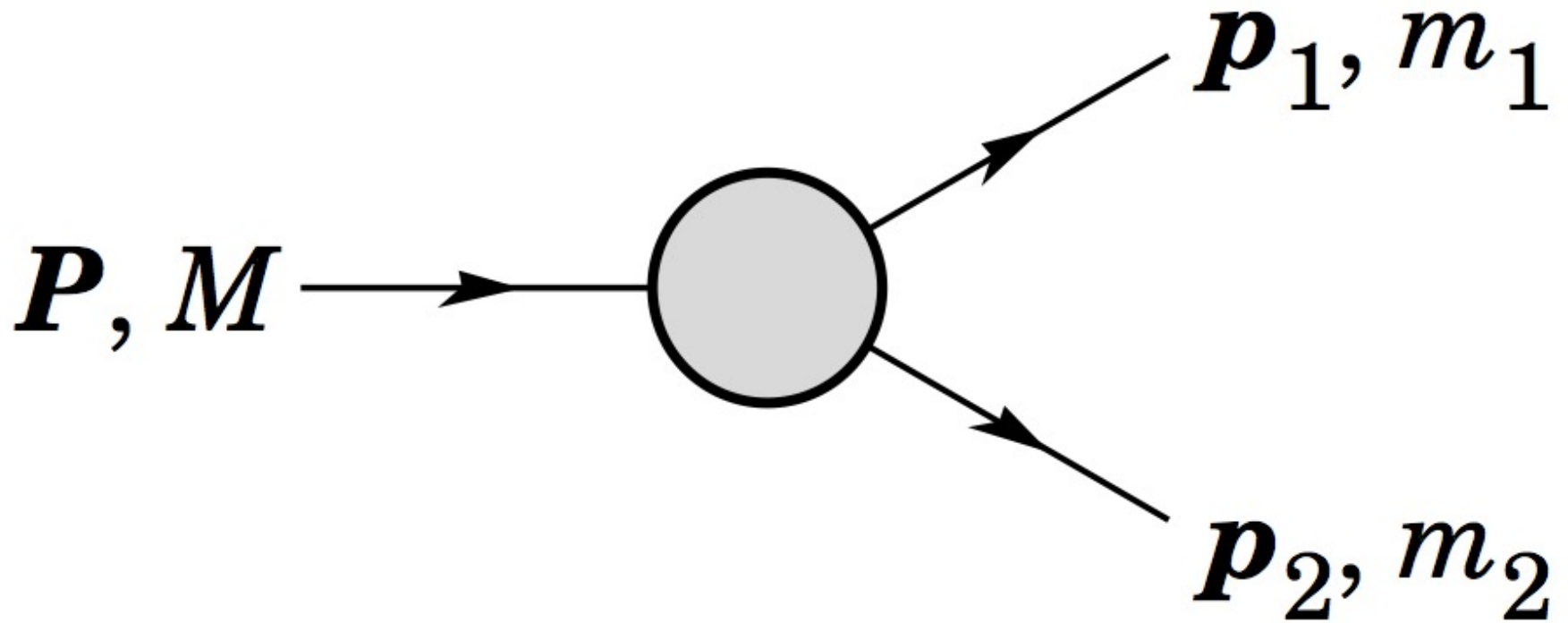
$$E_{\text{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

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

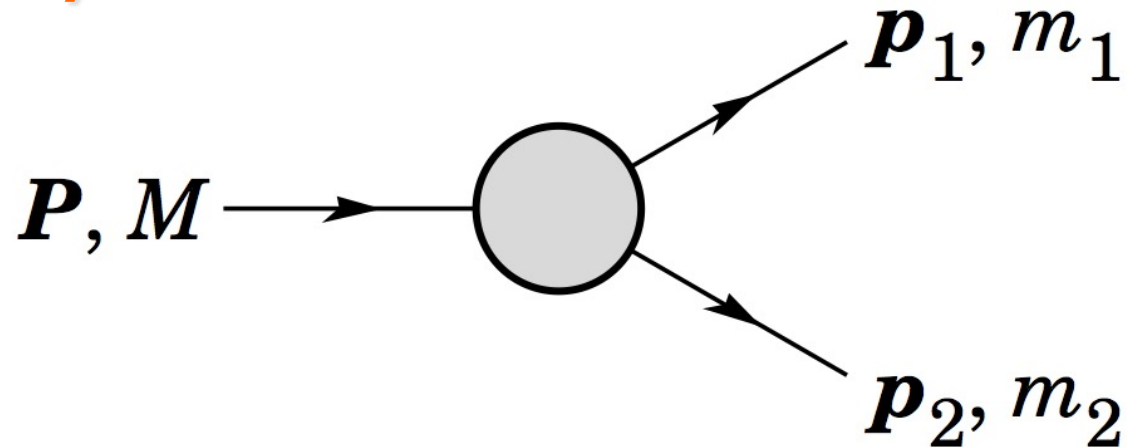
$$p = (E, \vec{p}) \quad \sqrt{p \cdot p}$$

What is the “length” of a the four-momentum of a particle?

2-body decay



2-body decay

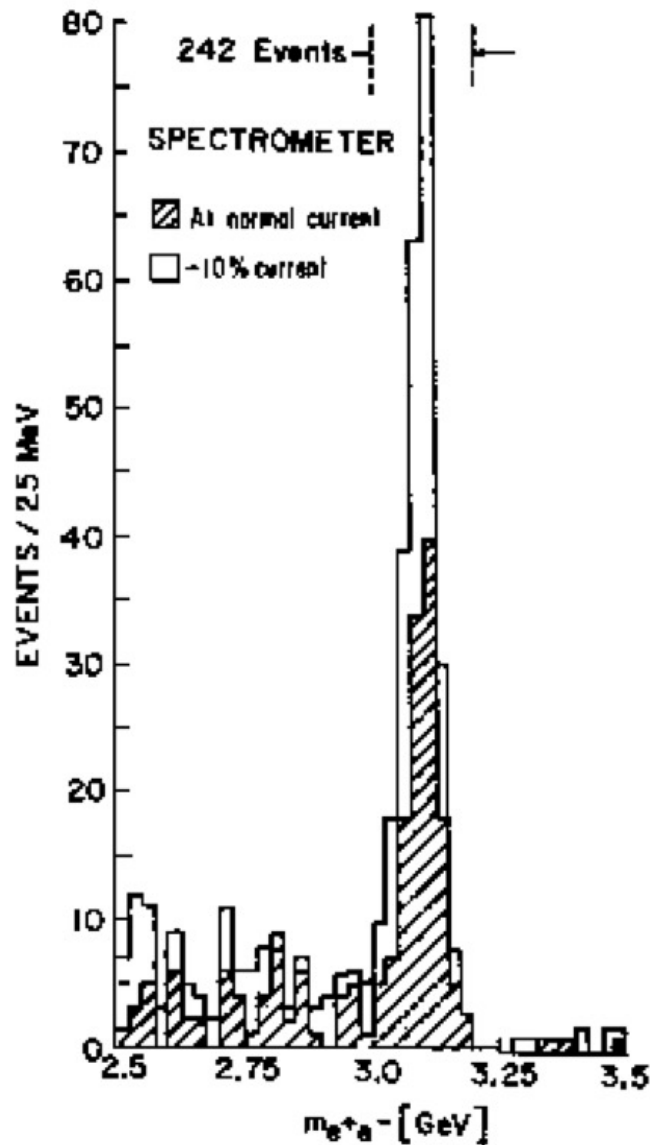


$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} ,$$

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

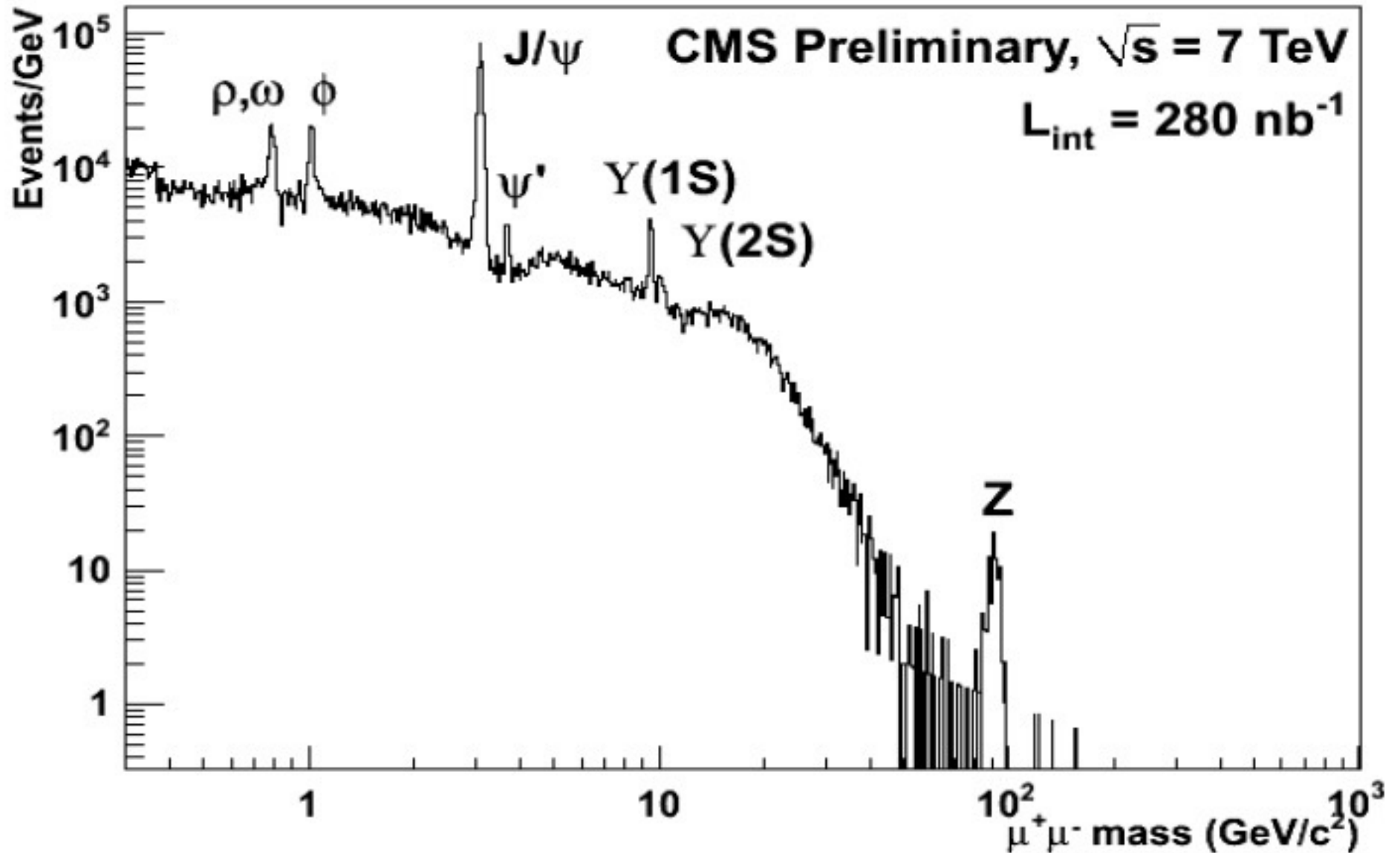
$$= \frac{[(M^2 - (m_1 + m_2)^2) (M^2 - (m_1 - m_2)^2)]^{1/2}}{2M}$$

Invariant mass

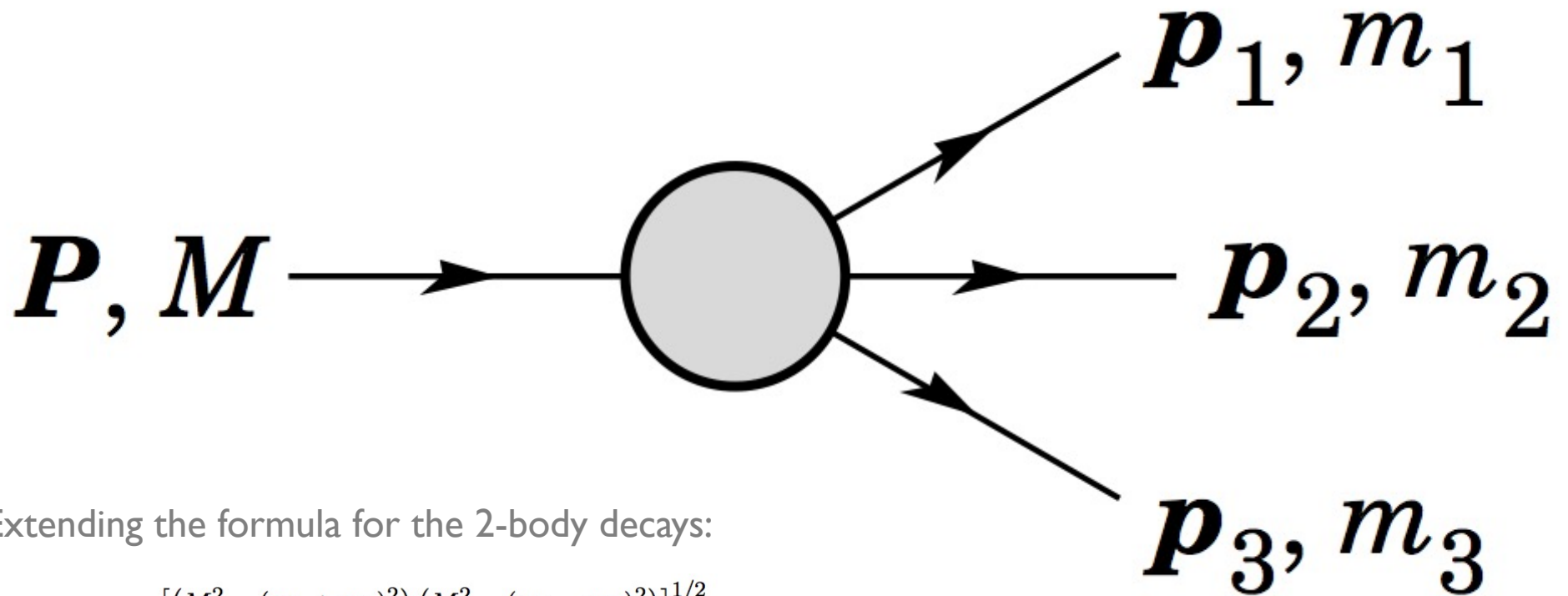


$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

Invariant mass



3-body decay



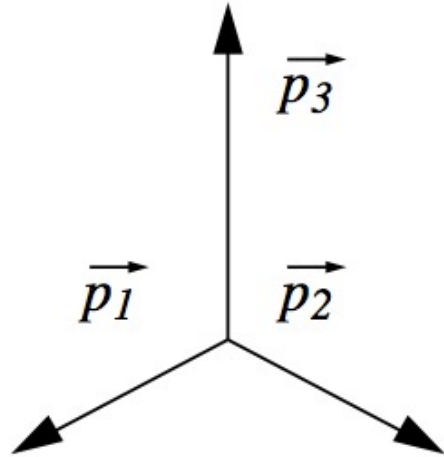
Extending the formula for the 2-body decays:

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

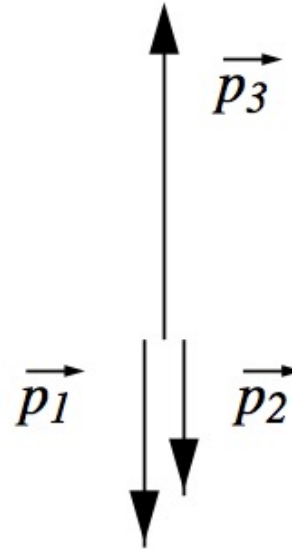
$$|\mathbf{p}_3| = \frac{[(M^2 - (m_{12} + m_3)^2)(M^2 - (m_{12} - m_3)^2)]^{1/2}}{2M}$$

3-bodies decay

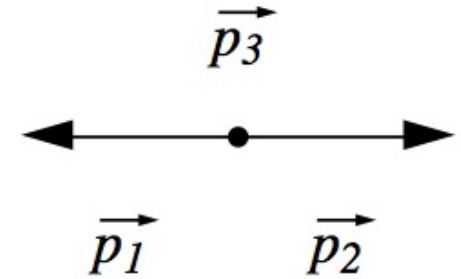
$$|\vec{p}_3| = \frac{[(M^2 - (m_{12} + m_3)^2)(M^2 - (m_{12} - m_3)^2)]^{1/2}}{2M}$$



(a)



(b)



(c)

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

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



3-bodies decay: Dalitz plot

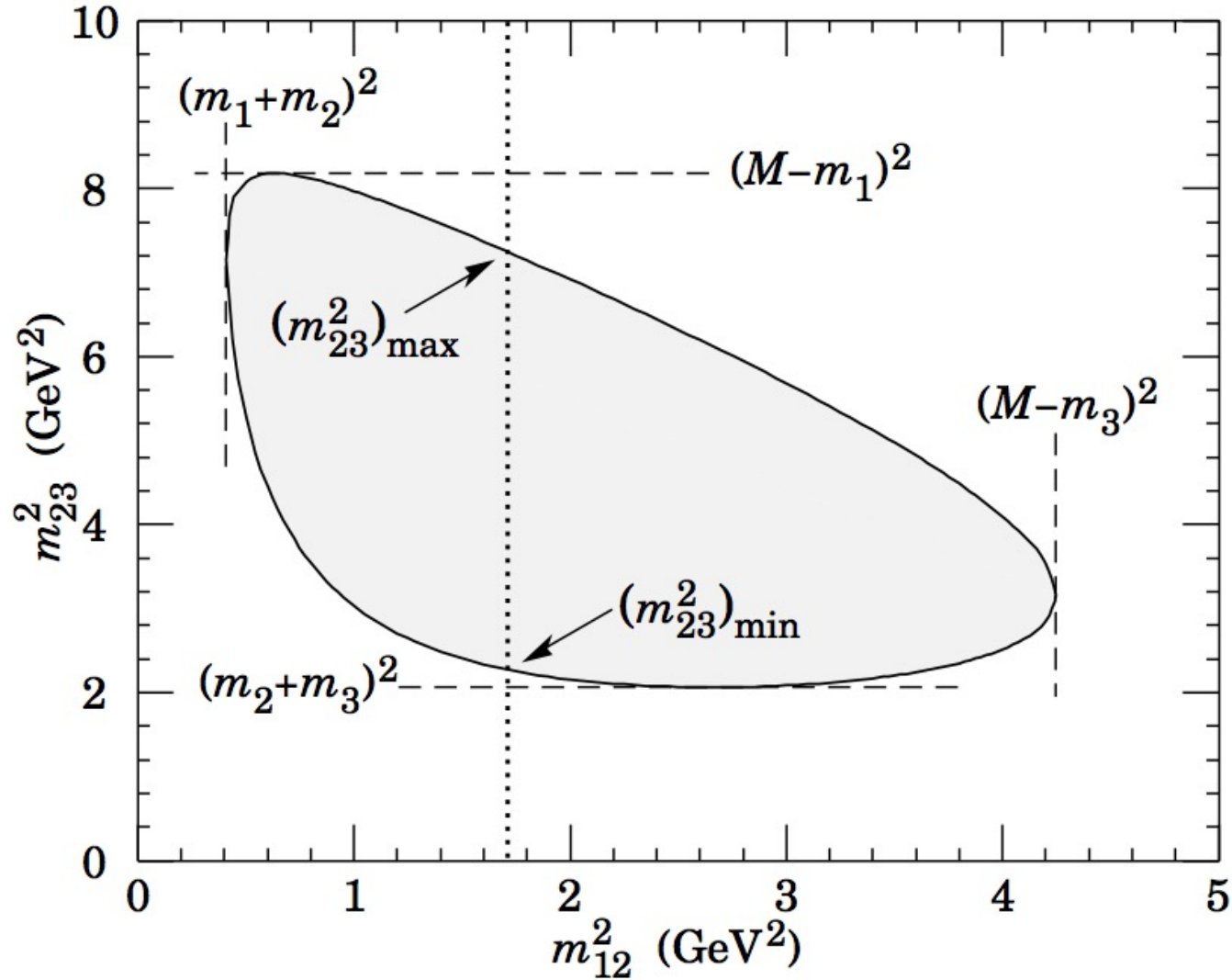
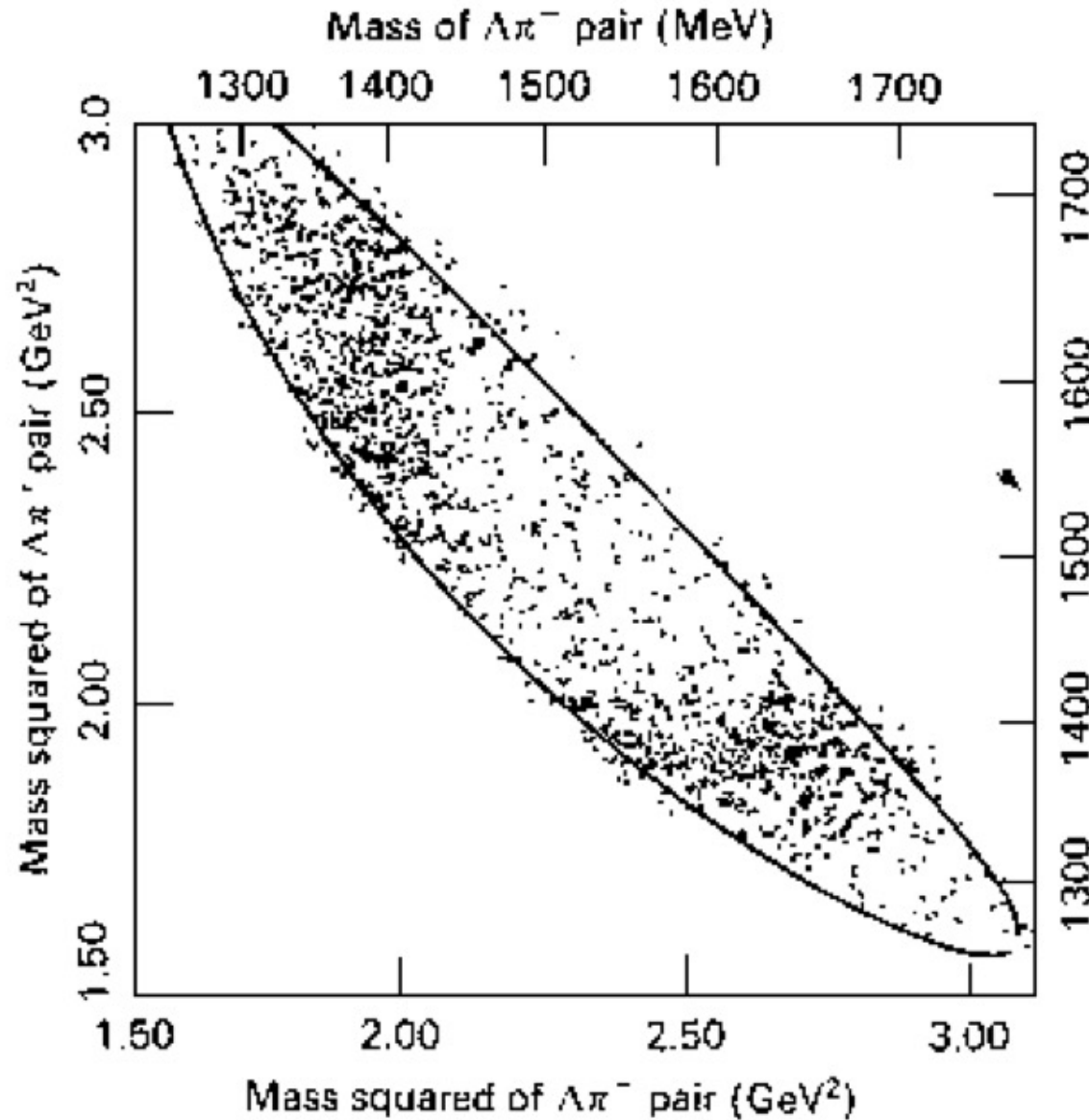


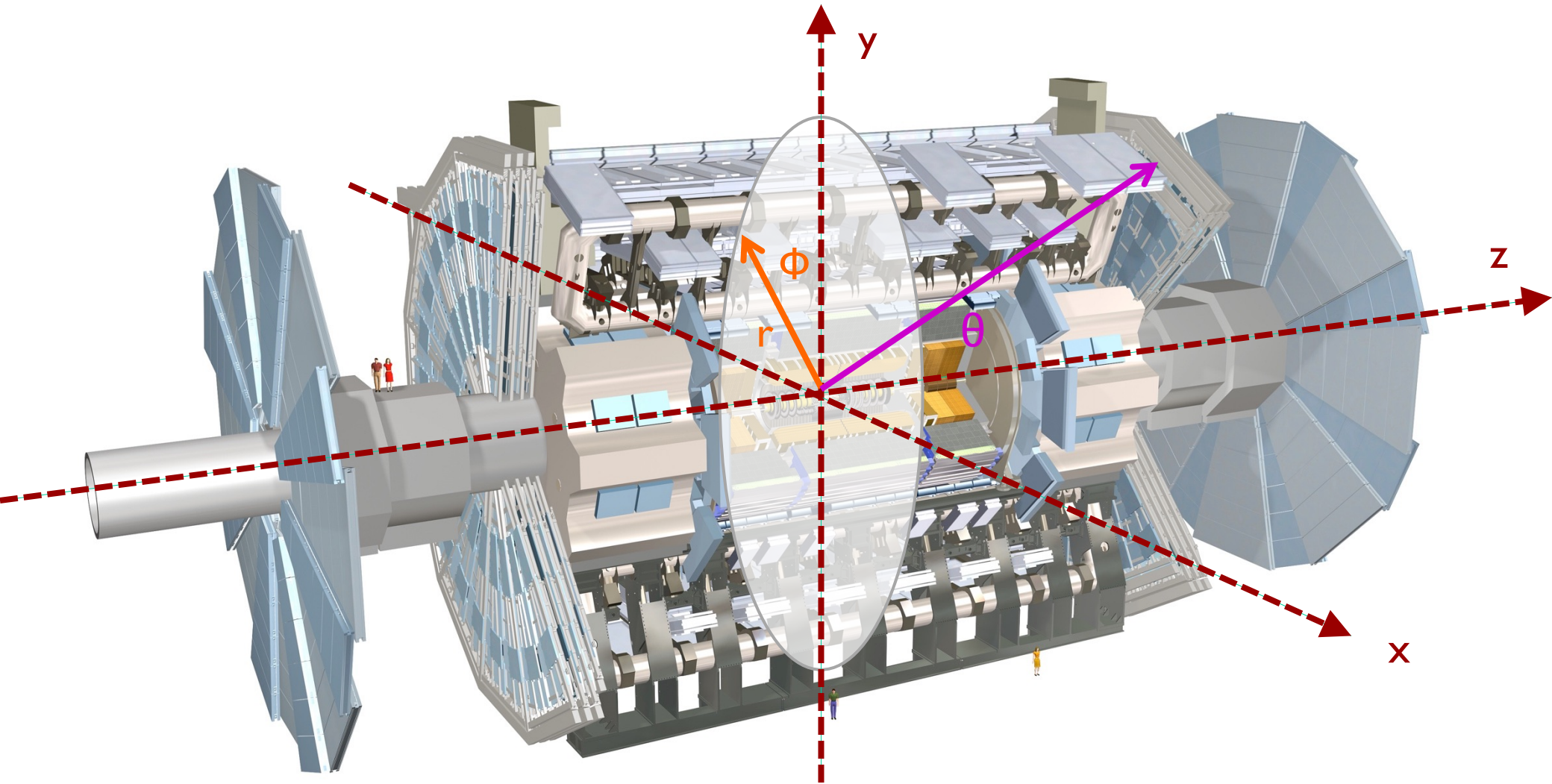
Figure 45.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+\bar{K}^0 p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

Multi-bodies decay

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



Collider experiment coordinates



Rapidity

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

$$\begin{aligned} E &= m \cosh \varphi \\ |\vec{p}| &= m \sinh \varphi \end{aligned} \quad \varphi = \tanh^{-1} \frac{E}{|\vec{p}|} = \frac{1}{2} \ln \frac{E + |\vec{p}|}{E - |\vec{p}|}$$

- Particle physicists prefer to use modified rapidity along beam axis

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

Pseudorapidity

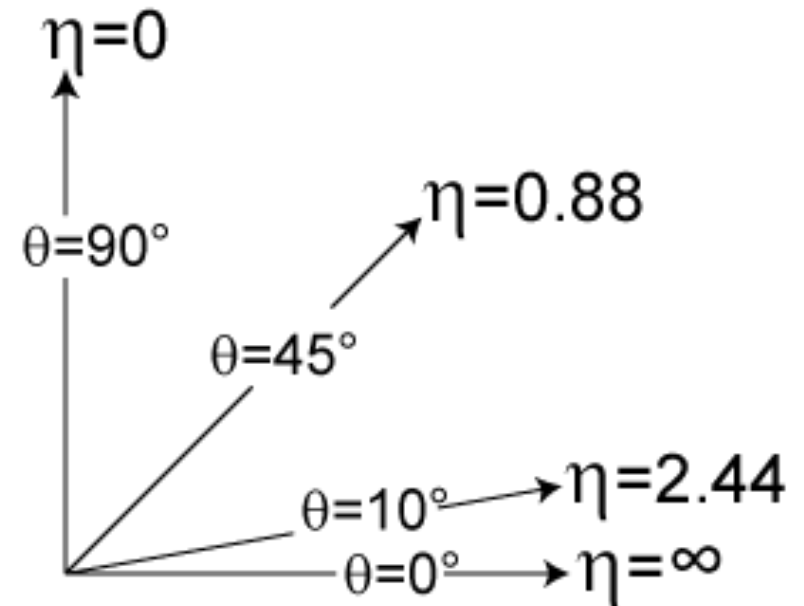
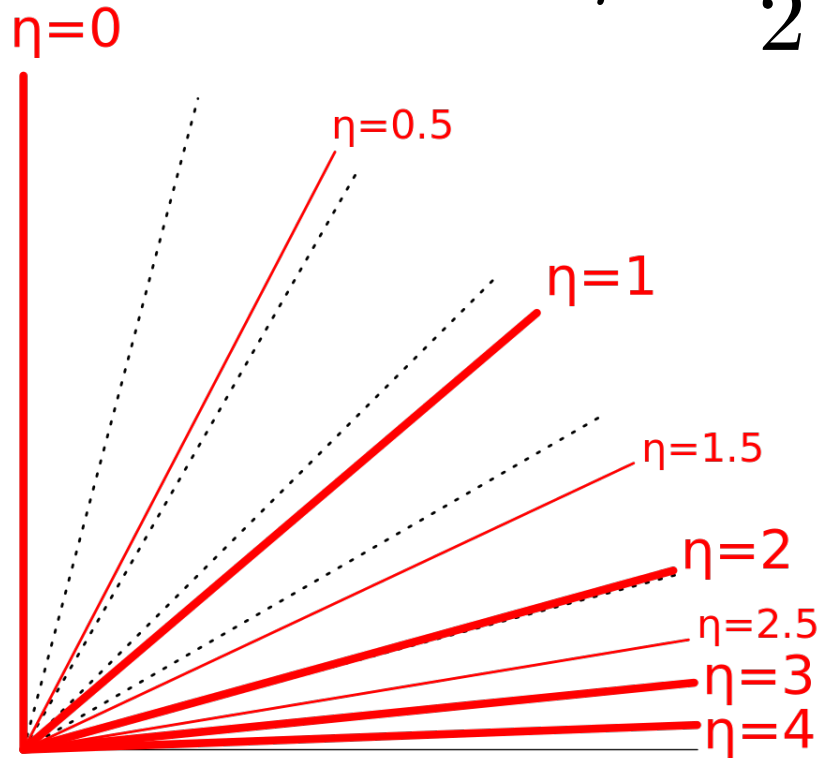
$$\eta = \frac{1}{2} \ln \frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}$$

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

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

$$\eta \simeq y$$

if $E \gg m$



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 particles 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 into two particles one of which is invisible, the mass of the parent particle can be constrained with the **transverse mass quantity**

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

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

$W \rightarrow e \nu$ discovery

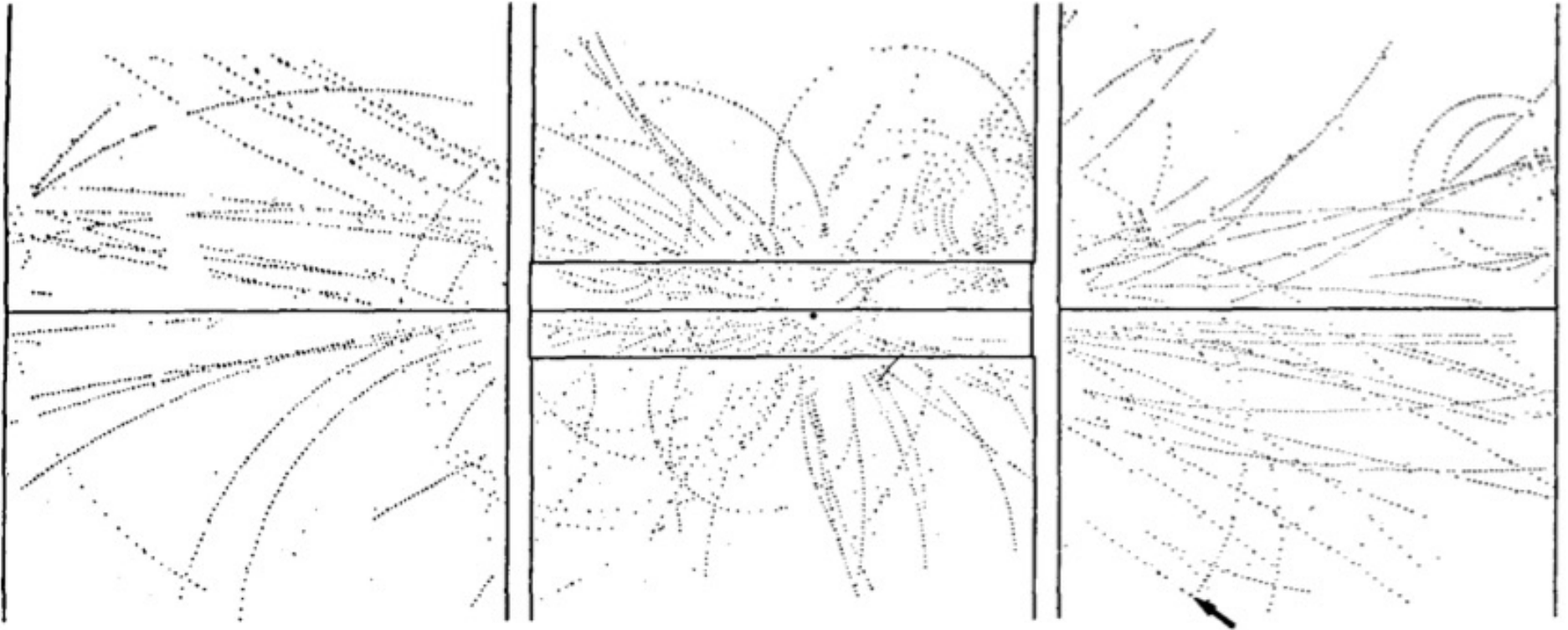
Volume 122B, number 1

PHYSICS LETTERS

24 February 1983

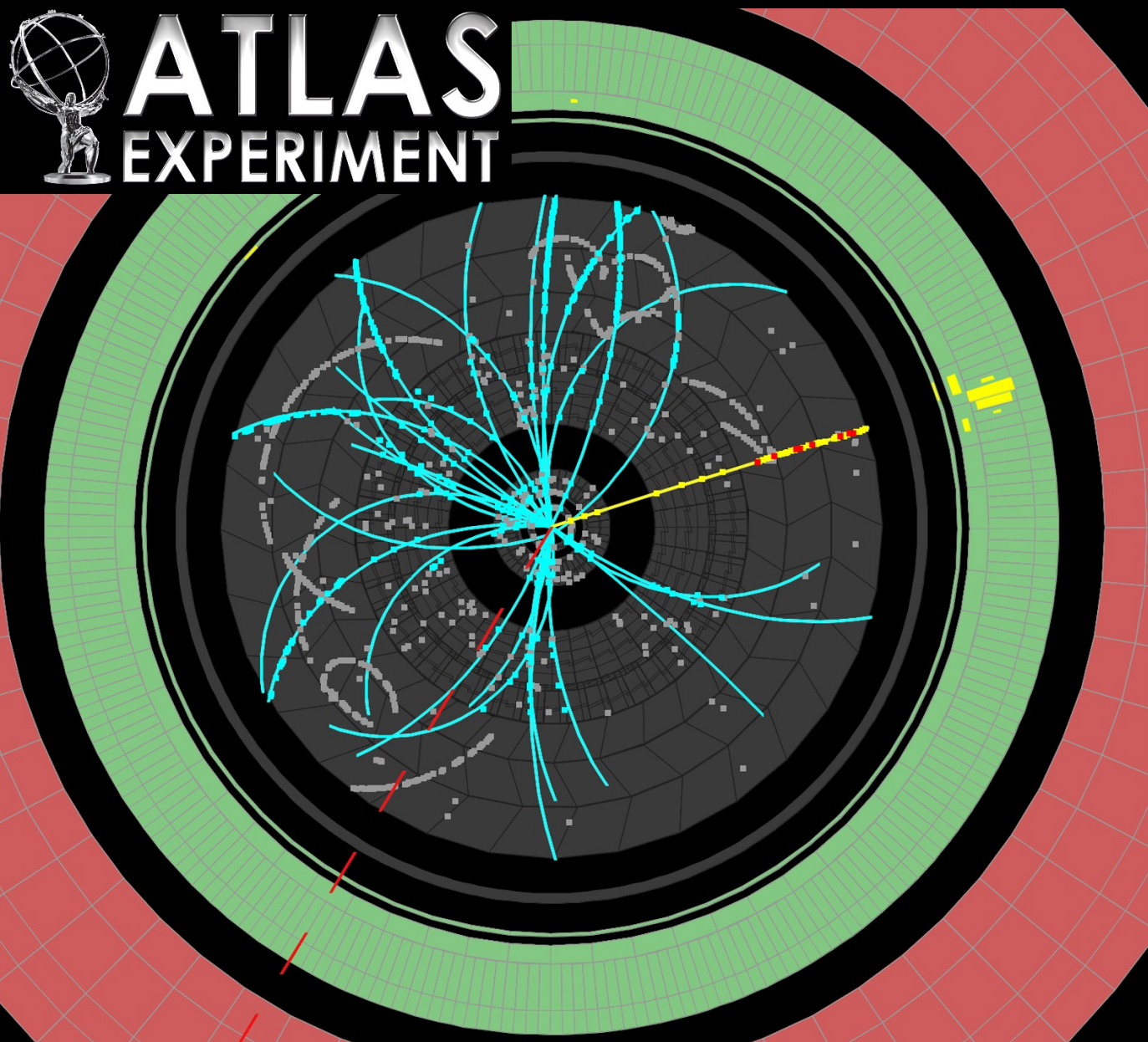
a

EVENT 2958. 1279.



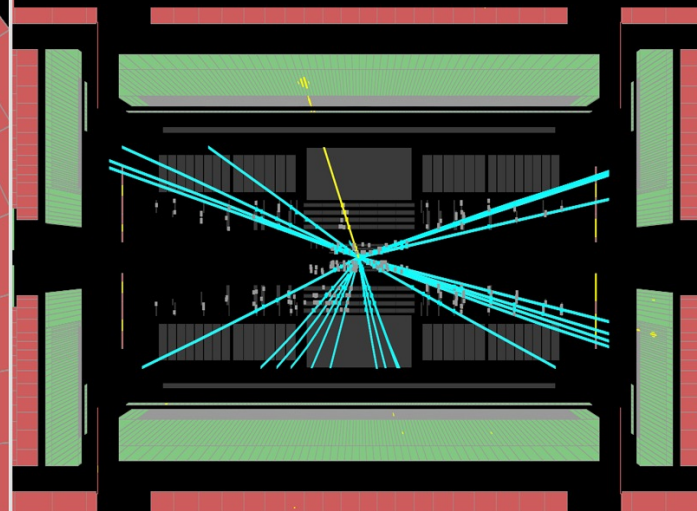


ATLAS EXPERIMENT



Run Number: 152409, Event Number: 5966801

Date: 2010-04-05 06:54:50 CEST



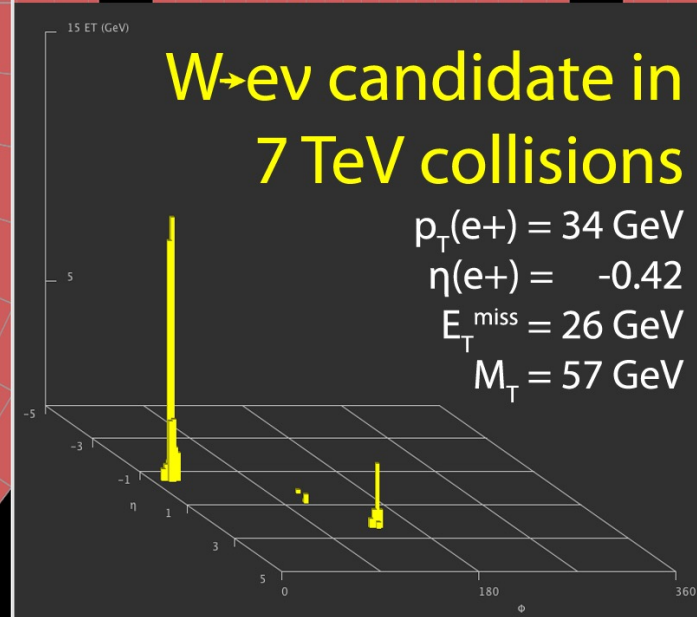
W→ev candidate in 7 TeV collisions

$p_T(e^+) = 34 \text{ GeV}$

$\eta(e^+) = -0.42$

$E_T^{\text{miss}} = 26 \text{ GeV}$

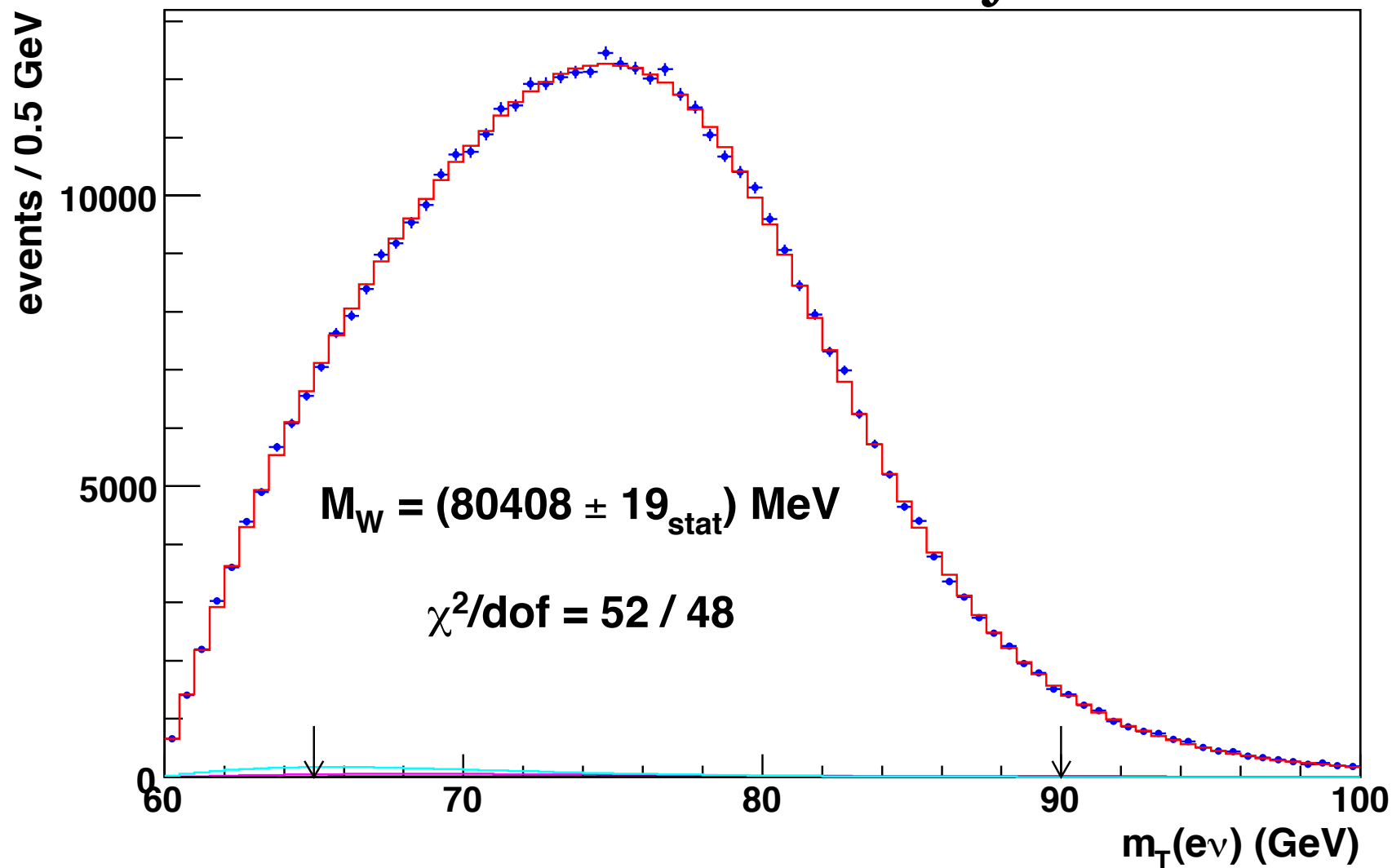
$M_T = 57 \text{ GeV}$



$W \rightarrow e \nu$

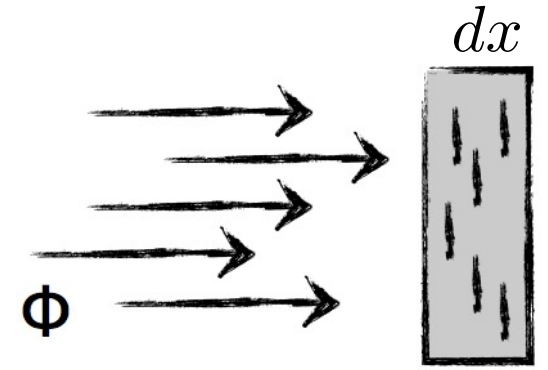
CDF II preliminary

$$\int L dt \approx 2.2 \text{ fb}^{-1}$$



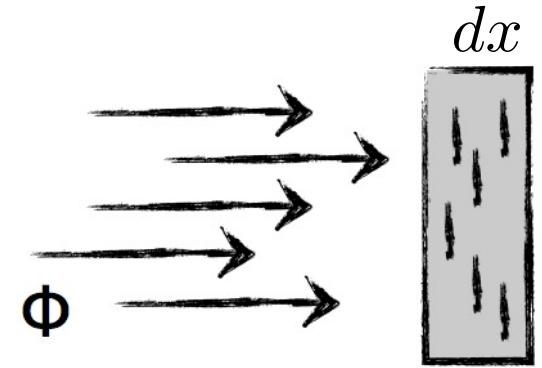
Interaction cross section

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



Interaction cross section

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



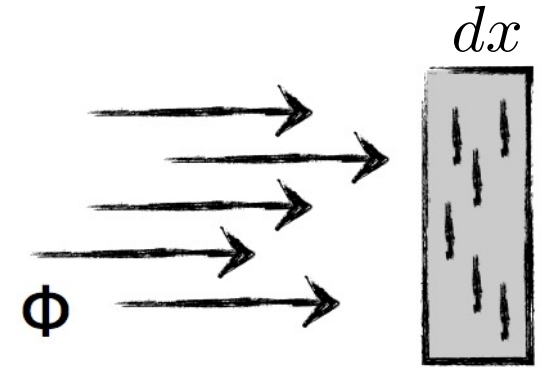
Reactions per unit of time

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

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

Interaction cross section

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



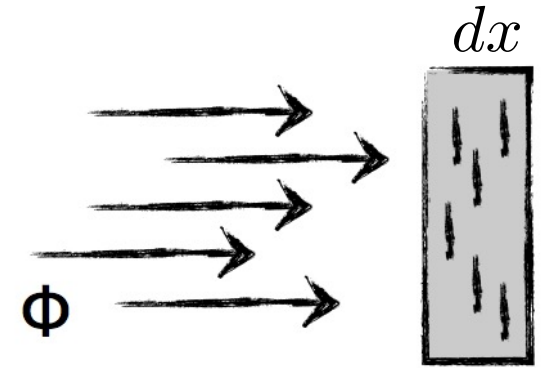
Reactions per unit of time $\frac{dN_{\text{reac}}}{dt} = \Phi \overbrace{\sigma N_{\text{target}} dx}^{\text{area obscured by target particle}}$ $[t^{-1}]$

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

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

Interaction cross section

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



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

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

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

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

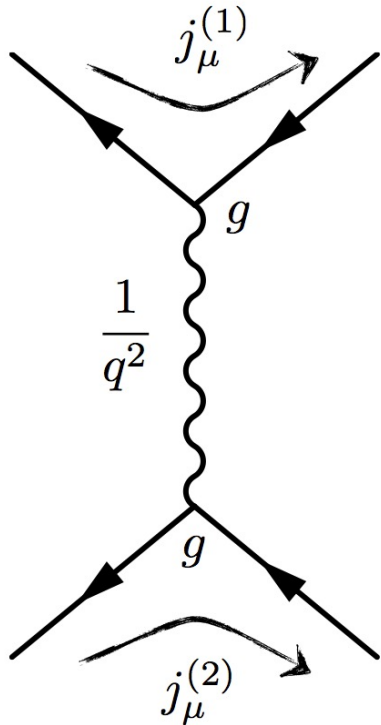
Fermi Golden Rule

From non-relativistic perturbation theory...

transition probability matrix element energy density of final states

$$W_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 \frac{dN}{dE_f}$$

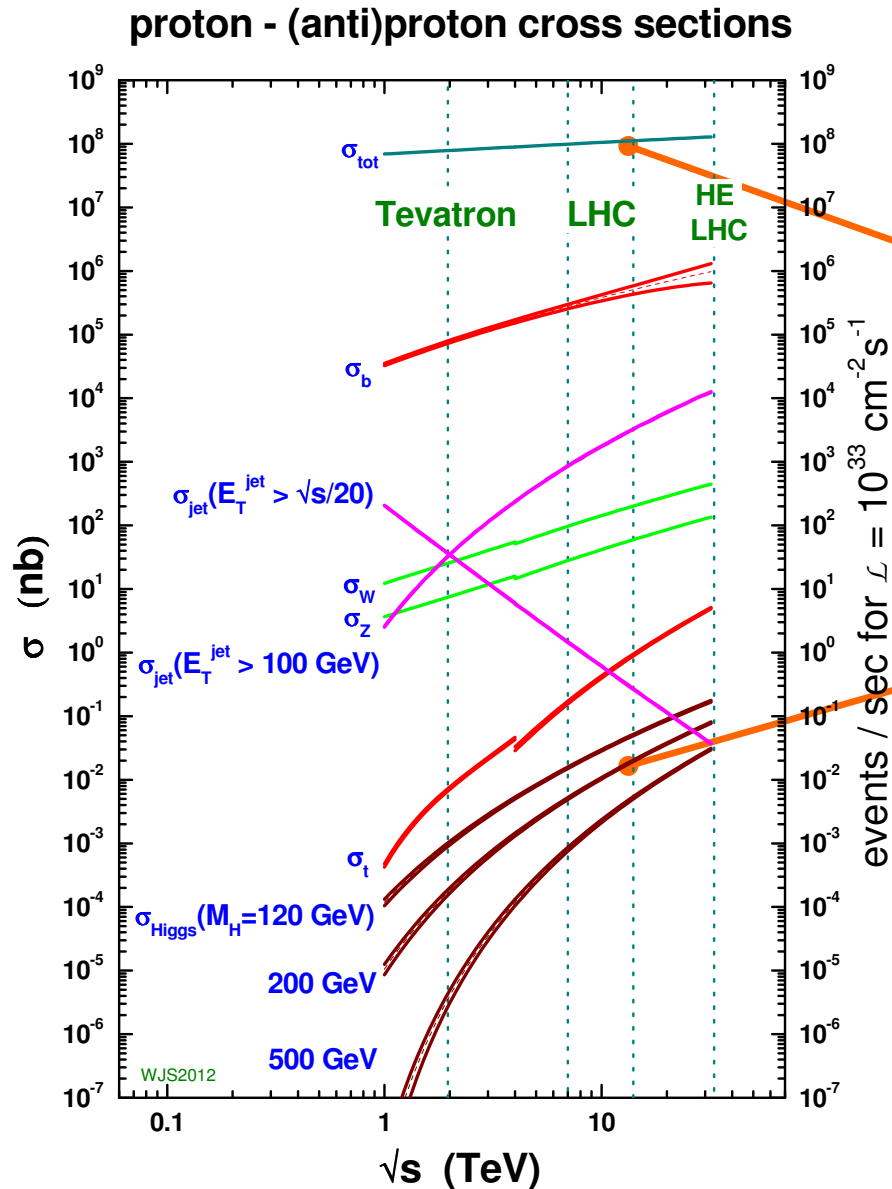
$[\tau^{-1}]$
 $[E]$
 $[E^{-1}]$



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

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

Cross-sections at LHC



10^8 events/s

$\sim 10^9$

10^{-1} events/s \sim
10 events/min

$[m_H \sim 125 \text{ GeV}]$

0.2% $H \rightarrow \gamma\gamma$

1.5% $H \rightarrow ZZ$