

Experimental particle. physics

esipap...

European School of Instrumentation
in Particle & Astroparticle Physics





Disclaimer : I now have
way longer hair, a pandemic
confinement side effect...

[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**
 - ✓ WI Experimental Particle Physics

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

The screenshot shows a GitHub repository page for 'marcodelmastro / ESIPAP-2021'. The repository has 1 branch and 0 tags. The 'Code' tab is selected, showing a list of files: 'Instructions', 'Tutorials', 'Dockerfile', and 'README.md'. The 'README.md' file is expanded, displaying the content 'ESIPAP 2021 - Experimental Particle Physics' and a 'Slides' section. The 'Slides' section contains the text: 'The slides of the lectures will appear in [this directory](#) as the course proceeds.' and 'Since this year the course will be held remotely because the pandemics, the PDF of the next lecture will be made available *before* the lecture itself to allow you to better follow.' The repository has 9 commits, 1 minute ago, and 5 pushes, 17 minutes ago. The 'About' section describes the repository as 'ESIPAP 2021 Experimental Particle Physics' and lists 'Readme', 'Releases' (no releases published), 'Packages' (no packages published), and 'Languages' (Jupyter Notebook 91.9%, Dockerfile 8.1%).

marcodelmastro / ESIPAP-2021

Code Issues Pull requests Actions Projects Wiki Security Insights Settings

main 1 branch 0 tags Go to file Add file Code

marcodelmastro Instructions addbf34 1 minute ago 9 commits

Tutorials Test setup 5 minutes ago

Dockerfile Testing Dockerfile 17 minutes ago

README.md Instructions 1 minute ago

README.md

ESIPAP 2021 - Experimental Particle Physics

Slides

The slides of the lectures will appear in [this directory](#) as the course proceeds.

Since this year the course will be held remotely because the pandemics, the PDF of the next lecture will be made available *before* the lecture itself to allow you to better follow.

About

ESIPAP 2021 Experimental Particle Physics

Readme

Releases

No releases published [Create a new release](#)

Packages

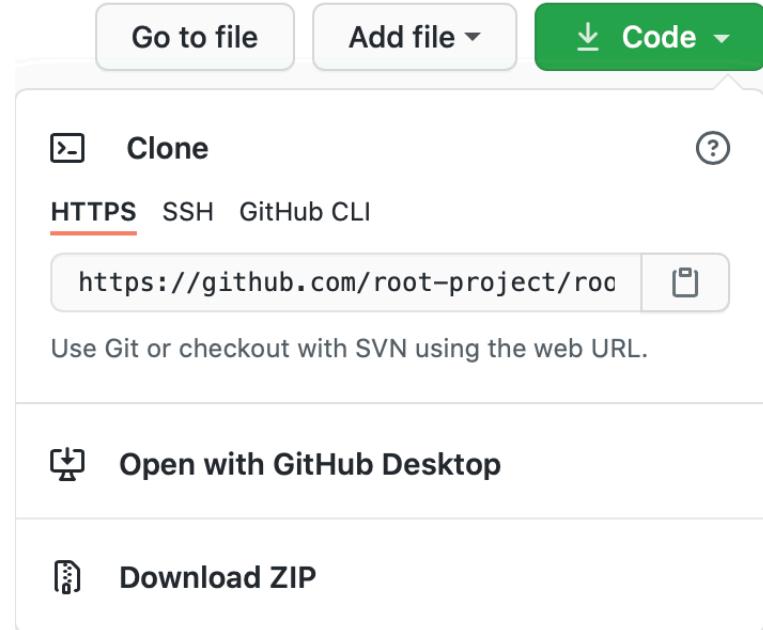
No packages published [Publish your first package](#)

Languages

Jupyter Notebook 91.9% Dockerfile 8.1%

<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!”

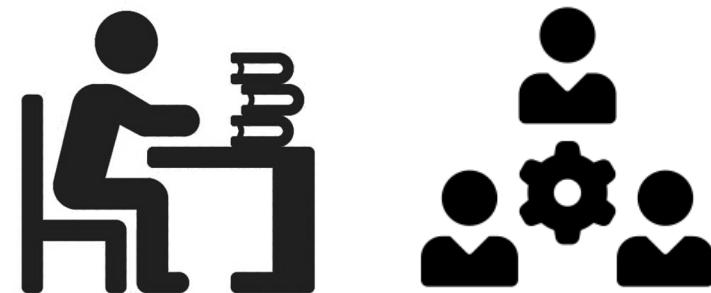


Enrico Fermi

<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

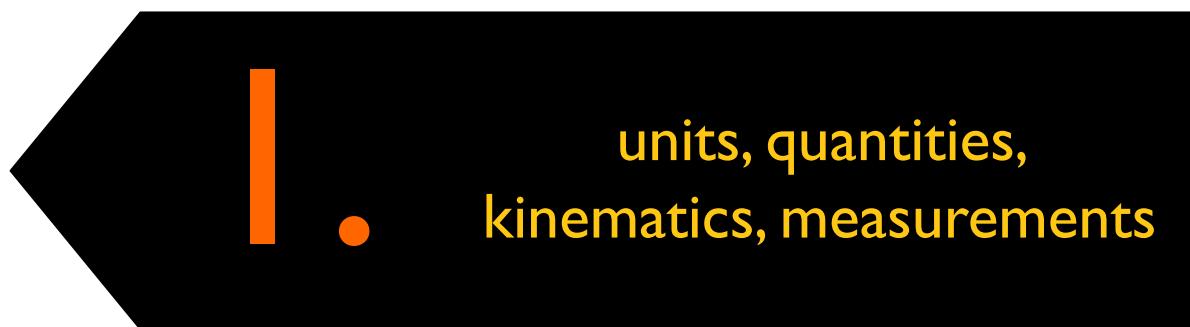
Program

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

Experimental particle. physics

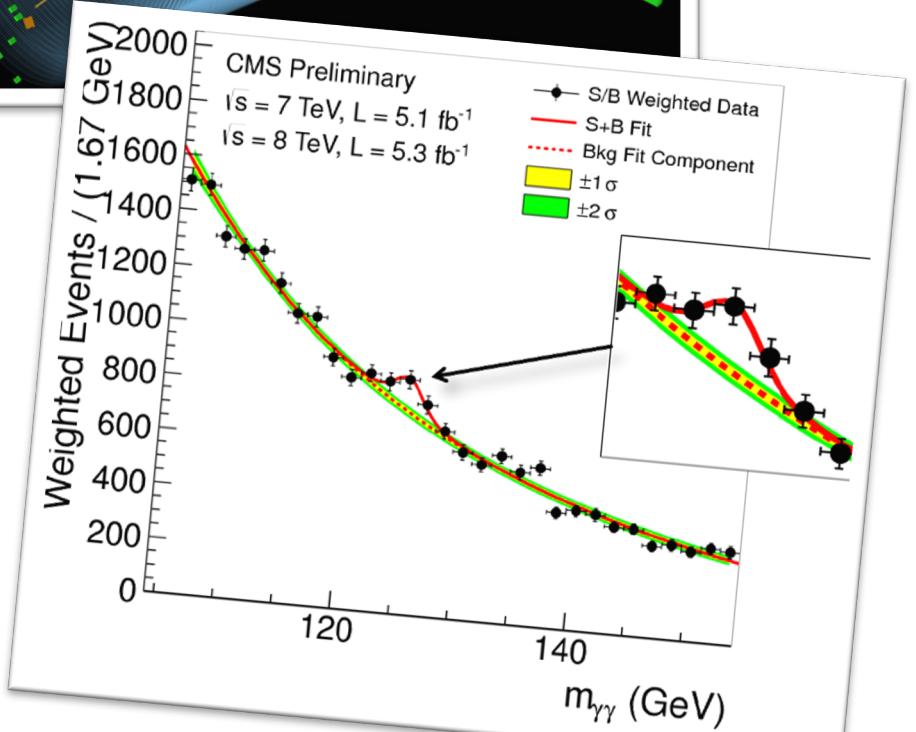
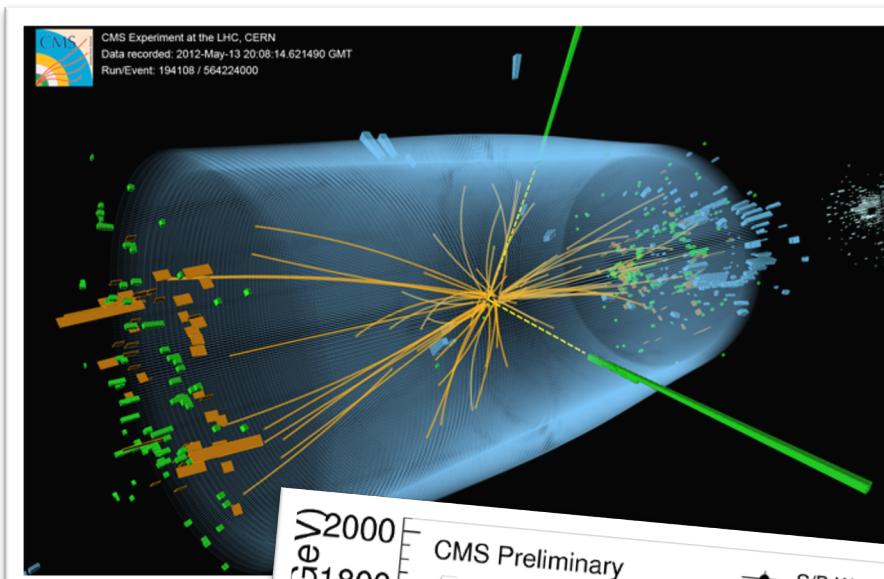
esipap...

European School of Instrumentation
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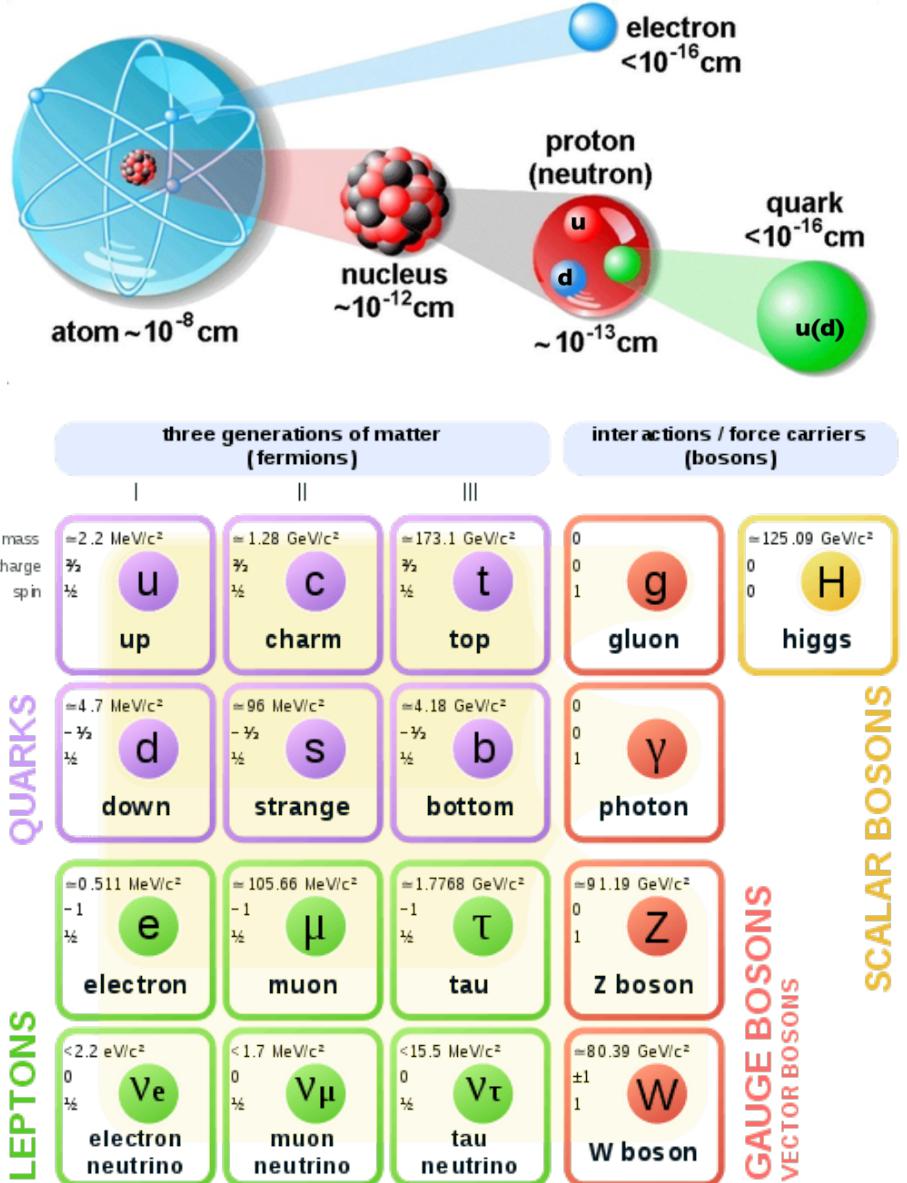


Experiment = probing/building theories with data!

$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s j^{a\mu} \partial_\mu g_\nu^a g_\mu^c - \frac{1}{4}g_s^2 j^{a\mu} j^{a\mu} g_\mu^a g_\mu^a + \\
& -\frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& \frac{1}{2}M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\mu 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_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\mu 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_\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 \left[\frac{2M^2}{g^2} + \right. \\
& \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^+) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
& W_\nu^+ \partial_\mu W_\mu^+) - A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^+) \right] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
& W_\mu^+ \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^+) + Z_\mu^0 (Z_\mu^0 W_\mu^+ W_\nu^- + \\
& \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\mu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + \\
& g^2 s_w (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^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
& gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 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^2} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
& ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w^2} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
& ig s_w 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^-] - \\
& ig s_w 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^-] - \\
& ig^2 \frac{1}{c_w^2} 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^2} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
& \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) - \frac{1}{2}g^2 \frac{s_w^2}{c_w^2} Z_\mu^0 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^- - \\
& W_\mu^+ \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \bar{e}^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \\
& W_\mu^+ \phi^+) - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \\
& g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda] + \\
& g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{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 s_w A_\mu [-(\bar{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)] + \\
& m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + ig c_w Z_\mu^0 [(\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
& \frac{ig}{4c_w} Z_\mu^0) [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
& \frac{ig}{4c_w} Z_\mu^0) [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 + \\
& 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\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) \nu^\lambda) - \\
& (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) u_j^\kappa)] + \frac{ig}{2\sqrt{2}} \frac{m_h^2}{M} [-(\bar{e}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
& \frac{ig}{2\sqrt{2}} \frac{m_h^2}{M} [-(\bar{e}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] + \\
& \frac{g}{2} \frac{m_h^2}{M} [H (\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma^\mu e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^e (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
& m_u^e (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^e (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^e (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
& \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_h^2}{M} H (\bar{d}_j^\lambda d_j^\kappa) + \frac{ig}{2} \frac{m_h^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \\
& \frac{ig}{2} \frac{m_h^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + X^+ (\partial^2 - M^2) X^+ + \bar{X}^-(\partial^2 - M^2) X^- + X^0 (\partial^2 - \\
& \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
& \partial_\mu \bar{X}^+ Y) + ig c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
& \partial_\mu \bar{Y} X^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^- X^+) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
& \frac{1-2c_w^2}{2c_w^2} ig M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w^2} ig M [\bar{X}^0 X^+ \phi^+ - \bar{X}^0 X^- \phi^-] + \\
& ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^- 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...



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)

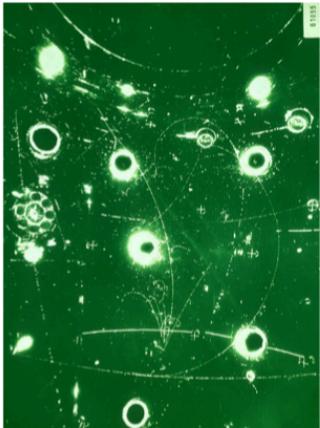
Higgs coupling to bosons (boson masses)

Higgs self-coupling (Higgs potential)

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

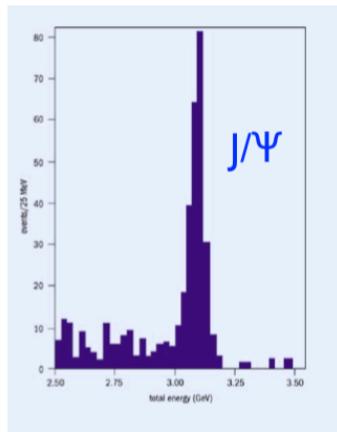
1972 – CERN

Neutral currents



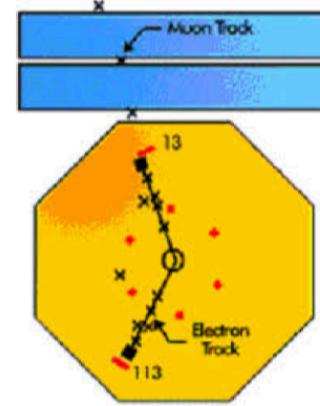
1974 – BNL, SLAC

Charm



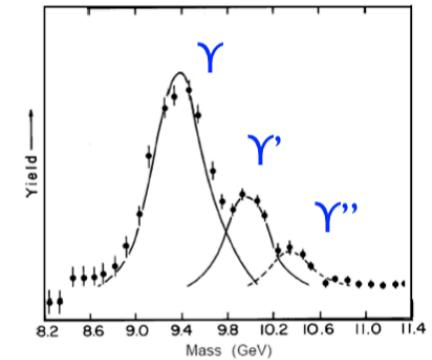
1976 – SLAC

Tau lepton



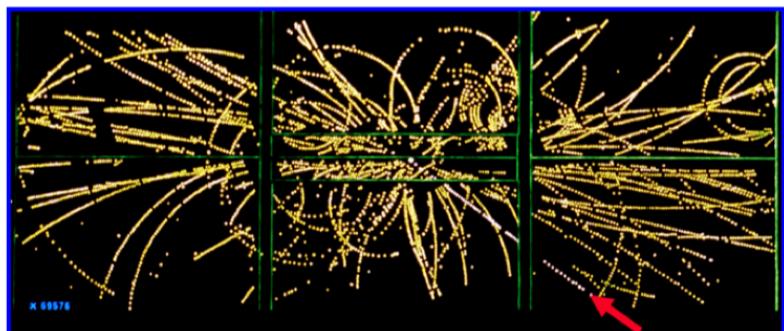
1979 – Fermilab

Beauty



1983 – CERN/SppS

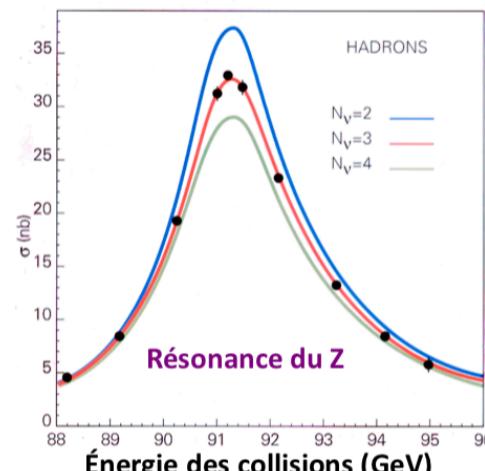
W and Z bosons



UA1, UA2

1990 – CERN/LEP

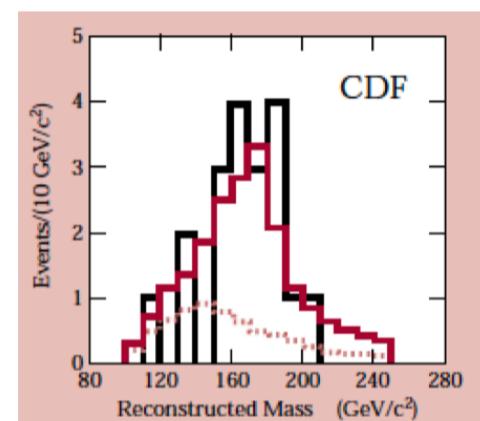
Three families of neutrinos



ALEPH, DELPHI, L3, OPAL
Experimental Particle Physics

1994 – Fermilab/TeVatron

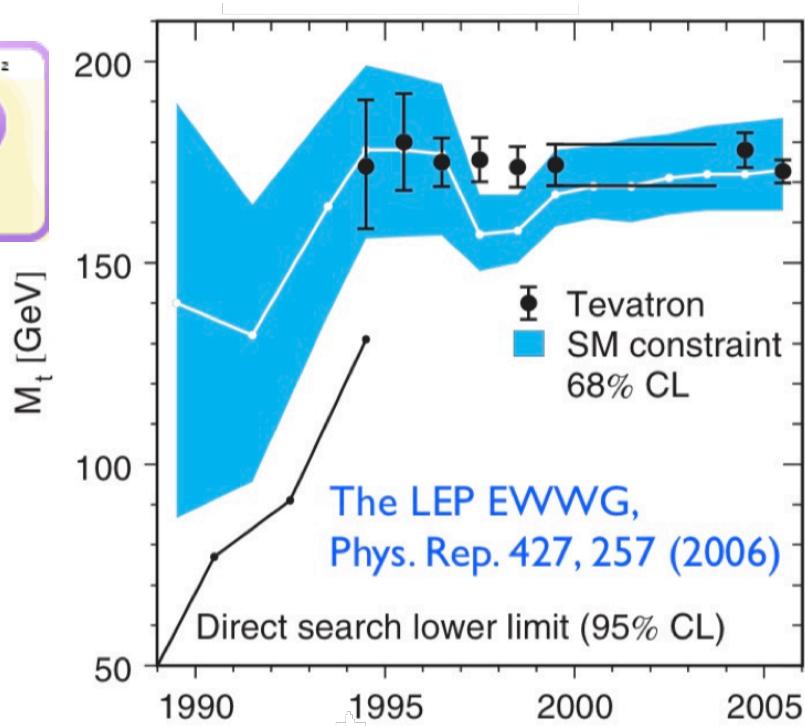
Top quark



CDF, D0

Before the LHC startup

$m_t = 173.1 \text{ GeV}/c^2$
 $\frac{1}{2}$
 $\frac{1}{2}$
t
top

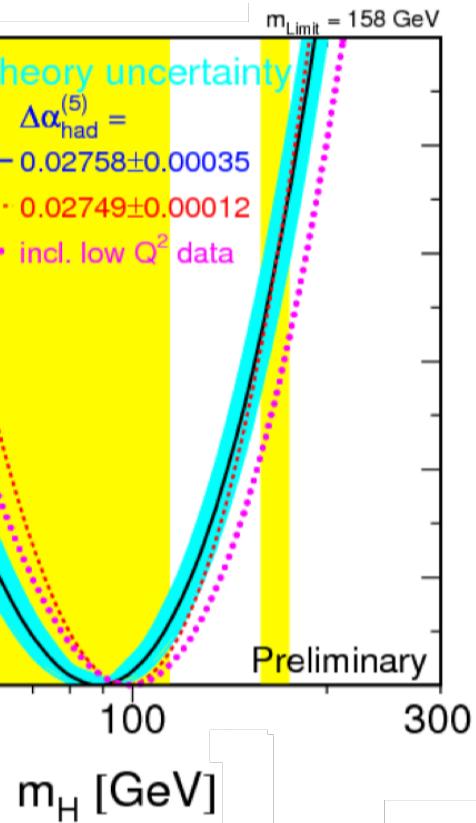


m_W measurement
at SppS and LEP-I
precision
measurements

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

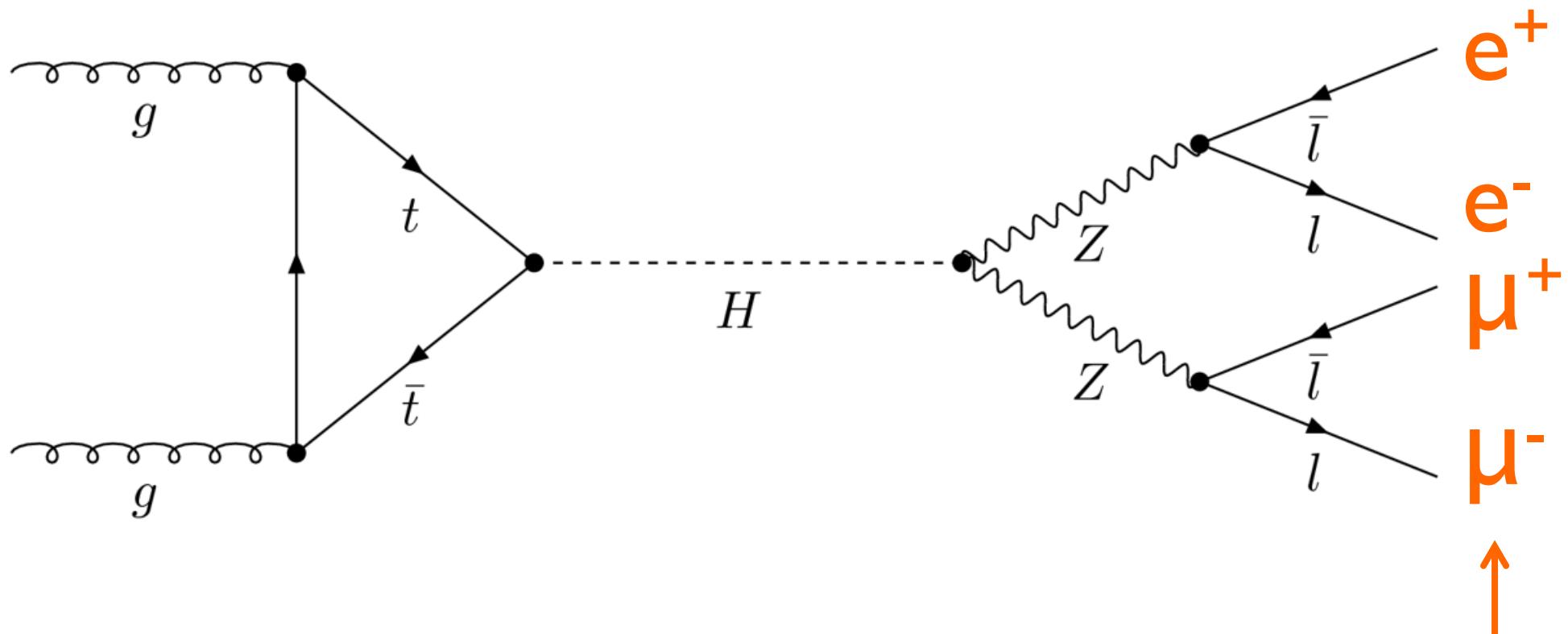
LHC “no loose theorem”

*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?

hadron
jets

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
1958: 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	1978: SLAC τ tau	1983: CERN Z Z boson
			2012: CERN H Higgs boson

decays?

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

interaction
modes?

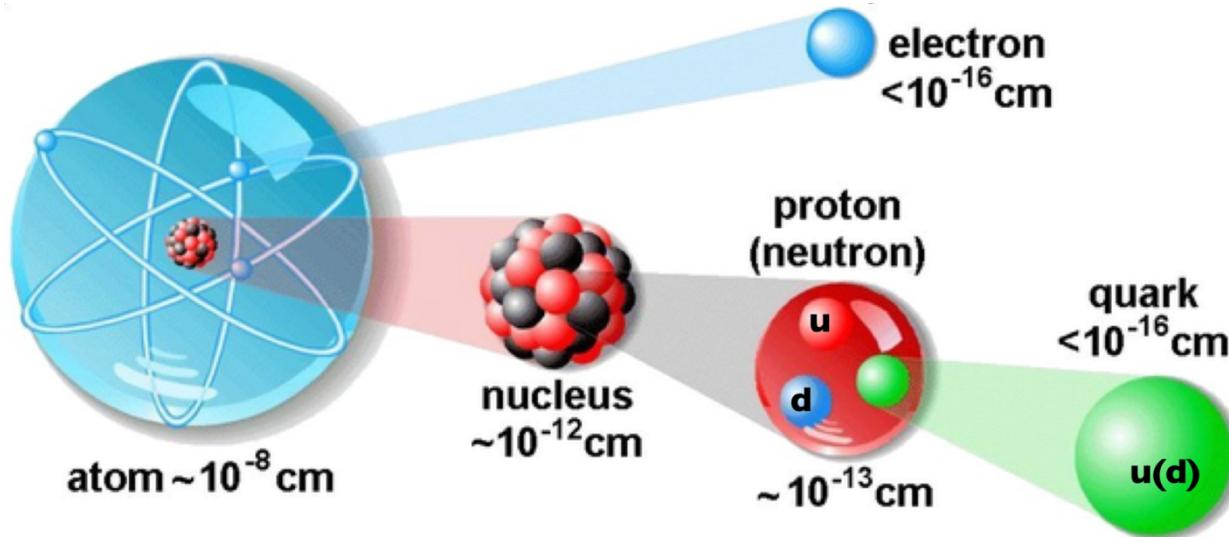
HEP, SI and “natural” units

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	$1 \text{ GeV}^{-1} = 0.1973$ fm
time	$1 \text{ GeV}^{-1} = 6.59 \times 10^{-25}$ s

Probing smaller and smaller scales...



Optical microscope resolution

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

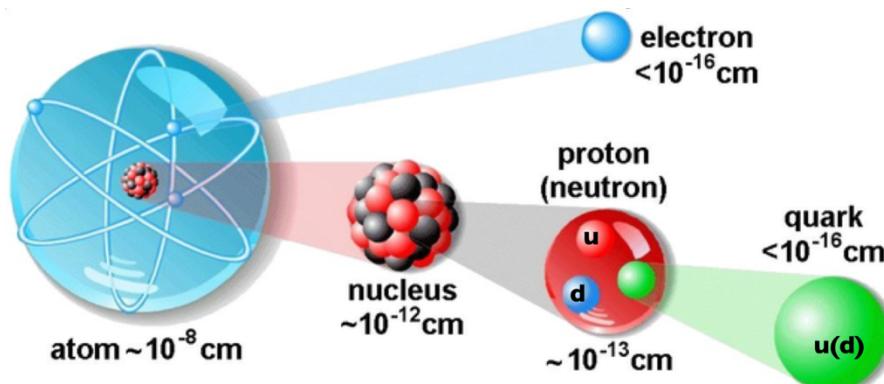
with θ = angular aperture of the light beam

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

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

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

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

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

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

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

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

$$E = m\gamma$$

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

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

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:

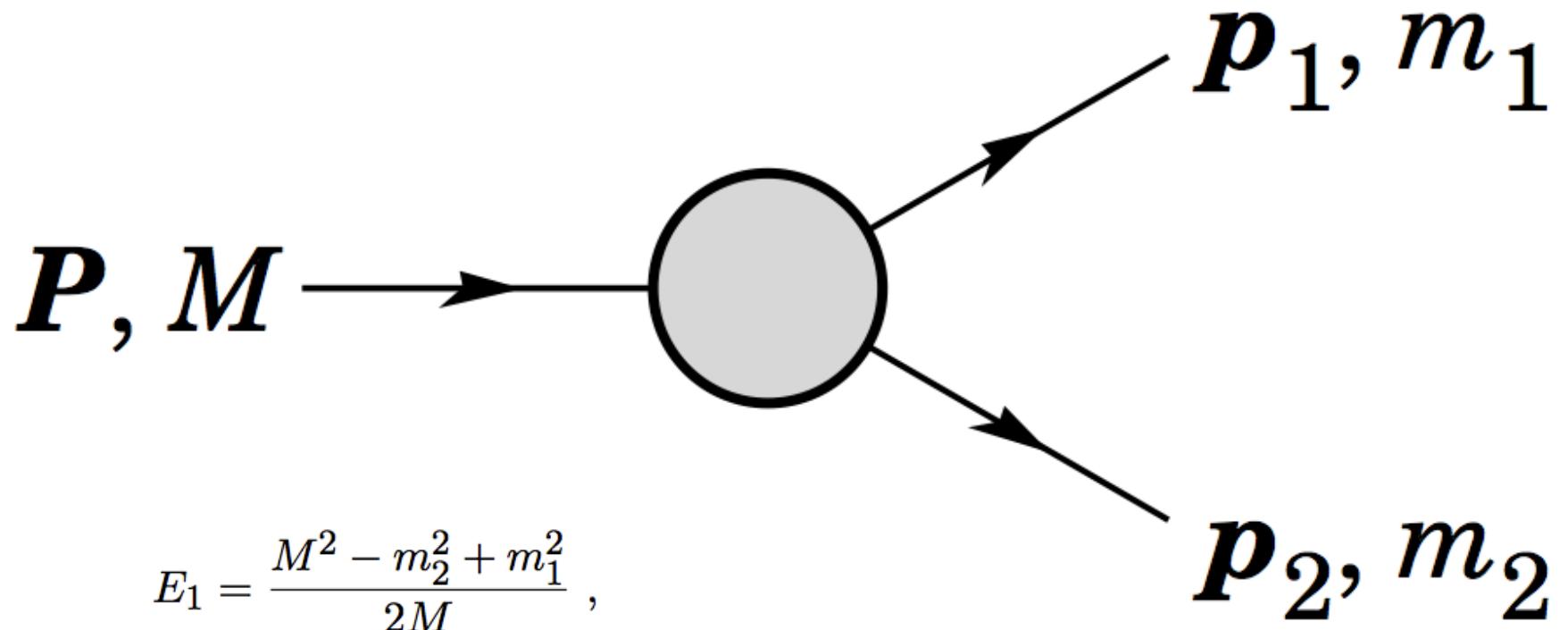
$$E_{\text{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

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



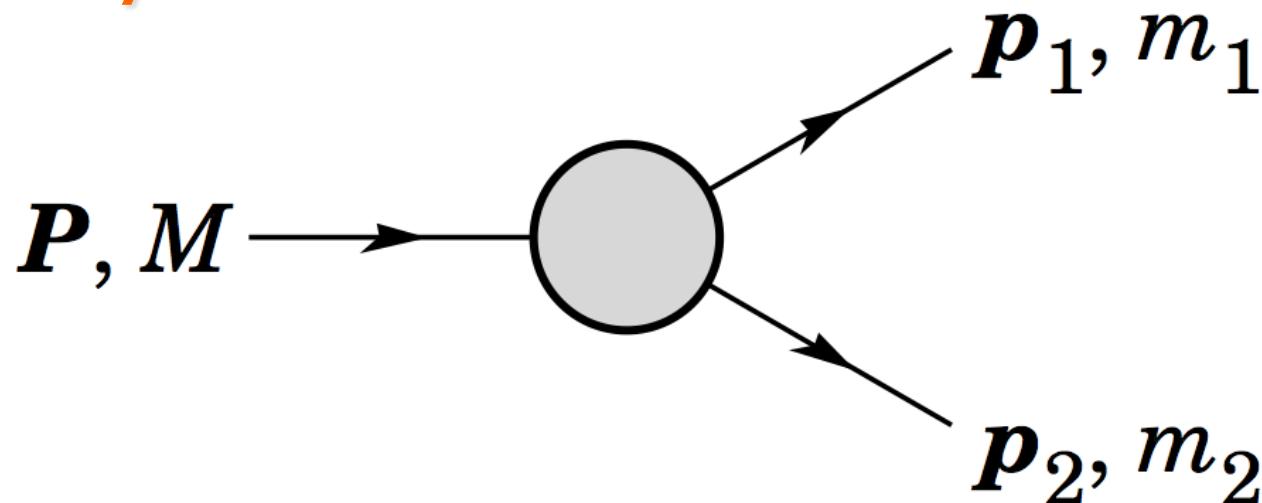
$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} ,$$

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

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



2-body decay

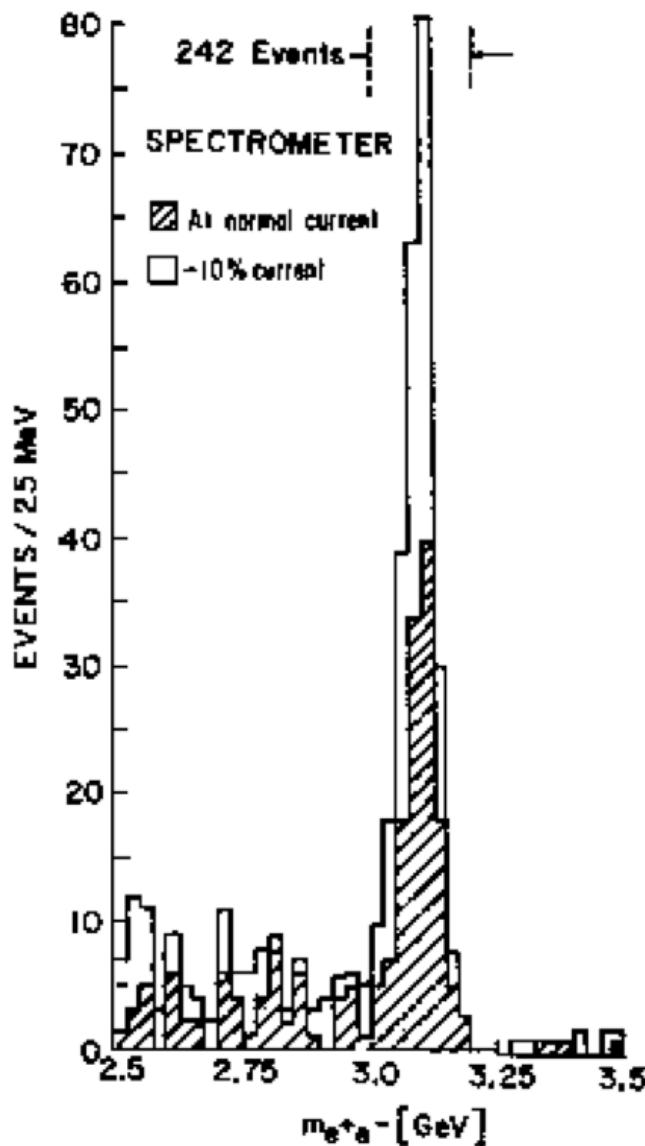


$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} ,$$

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

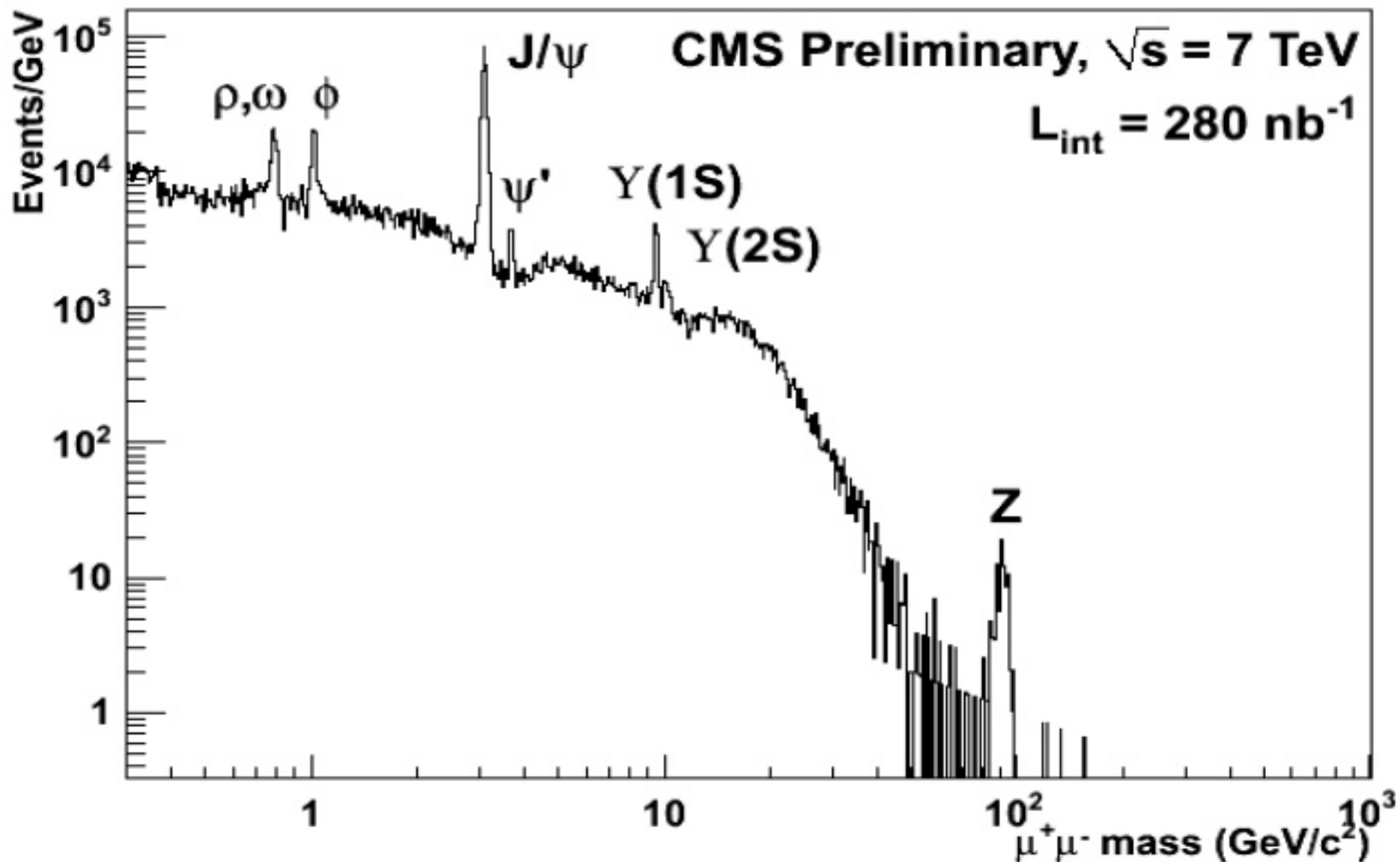
$$= \frac{[(M^2 - (m_1 + m_2)^2)(M^2 - (m_1 - m_2)^2)]^{1/2}}{2M}$$

Invariant mass

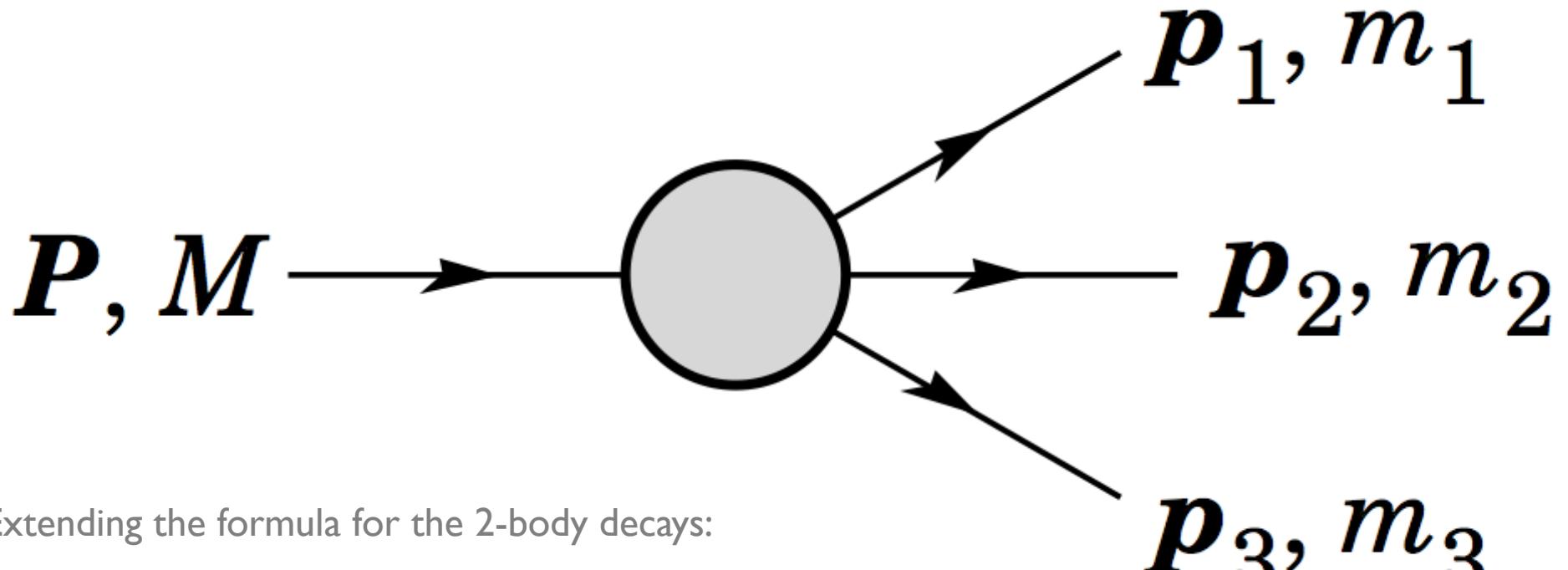


$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

Invariant mass



3-body decay



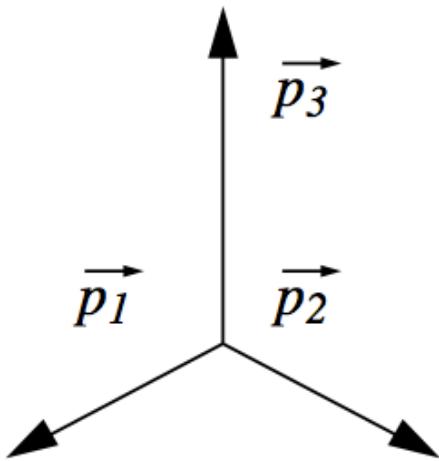
Extending the formula for the 2-body decays:

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

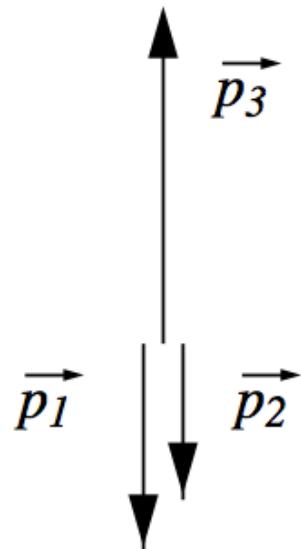
$$|\mathbf{p}_3| = \frac{[(M^2 - (m_{12} + m_3)^2)(M^2 - (m_{12} - m_3)^2)]^{1/2}}{2M}$$

3-bodies decay

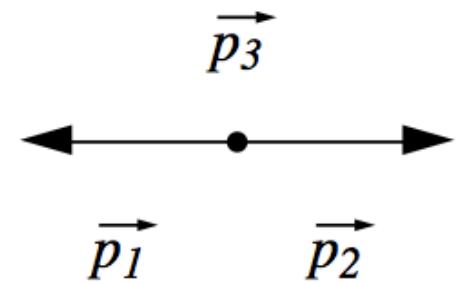
$$|\vec{p}_3| = \frac{[(M^2 - (m_{12} + m_3)^2) (M^2 - (m_{12} - m_3)^2)]^{1/2}}{2M}$$



(a)



(b)



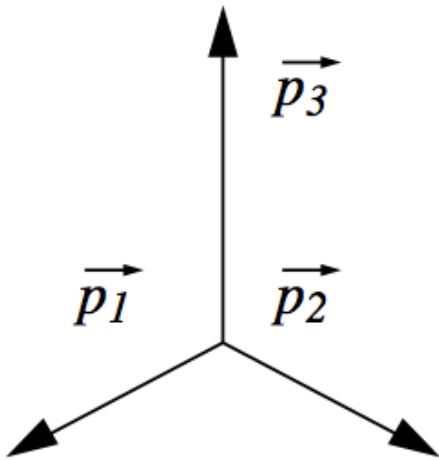
(c)

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

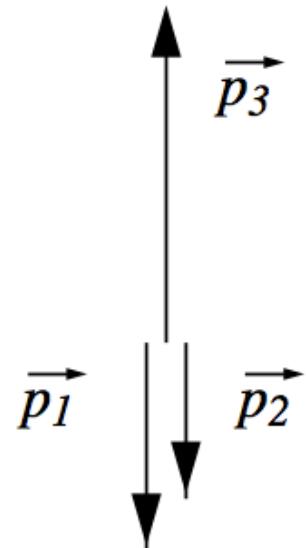


3-bodies decay

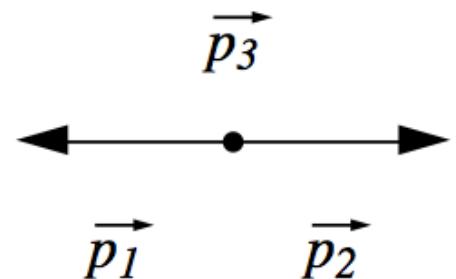
$$|\vec{p}_3| = \frac{[(M^2 - (m_{12} + m_3)^2) (M^2 - (m_{12} - m_3)^2)]^{1/2}}{2M}$$



(a)



(b)



(c)

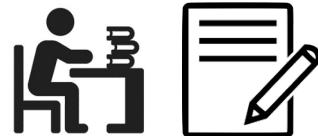
1) $\max(|\vec{p}_3|)$

$(m_{12})_{min} = m_1 + m_2 \rightarrow (b)$

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

$(m_{12})_{max} = M - m_3 \rightarrow (c)$

A real example: pion decay(s)



$$\begin{aligned}\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ &\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu\end{aligned}$$

2-body decay

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

3-body decay

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

pion decays at rest (2-body decay)

$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}c \simeq 30 \text{ MeV/c}$$
$$m_\nu = 0$$

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

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

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

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

A real example: pion decay(s)

pion decays at rest

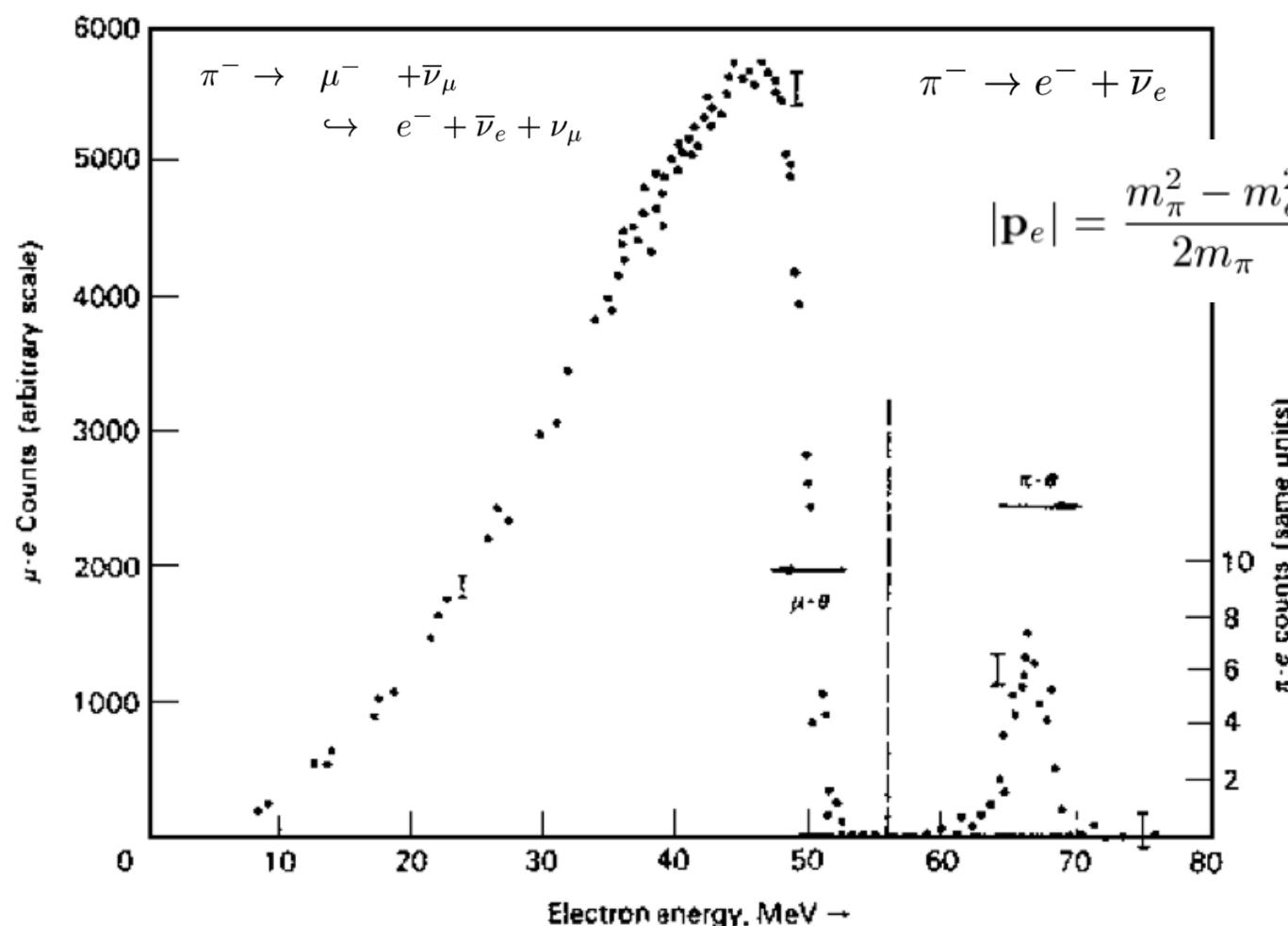
$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} c \simeq 30 \text{ MeV/c}$$

$$m_\nu = 0$$

in most cases
muon decays
at rest

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

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



3-bodies decay: Dalitz plot

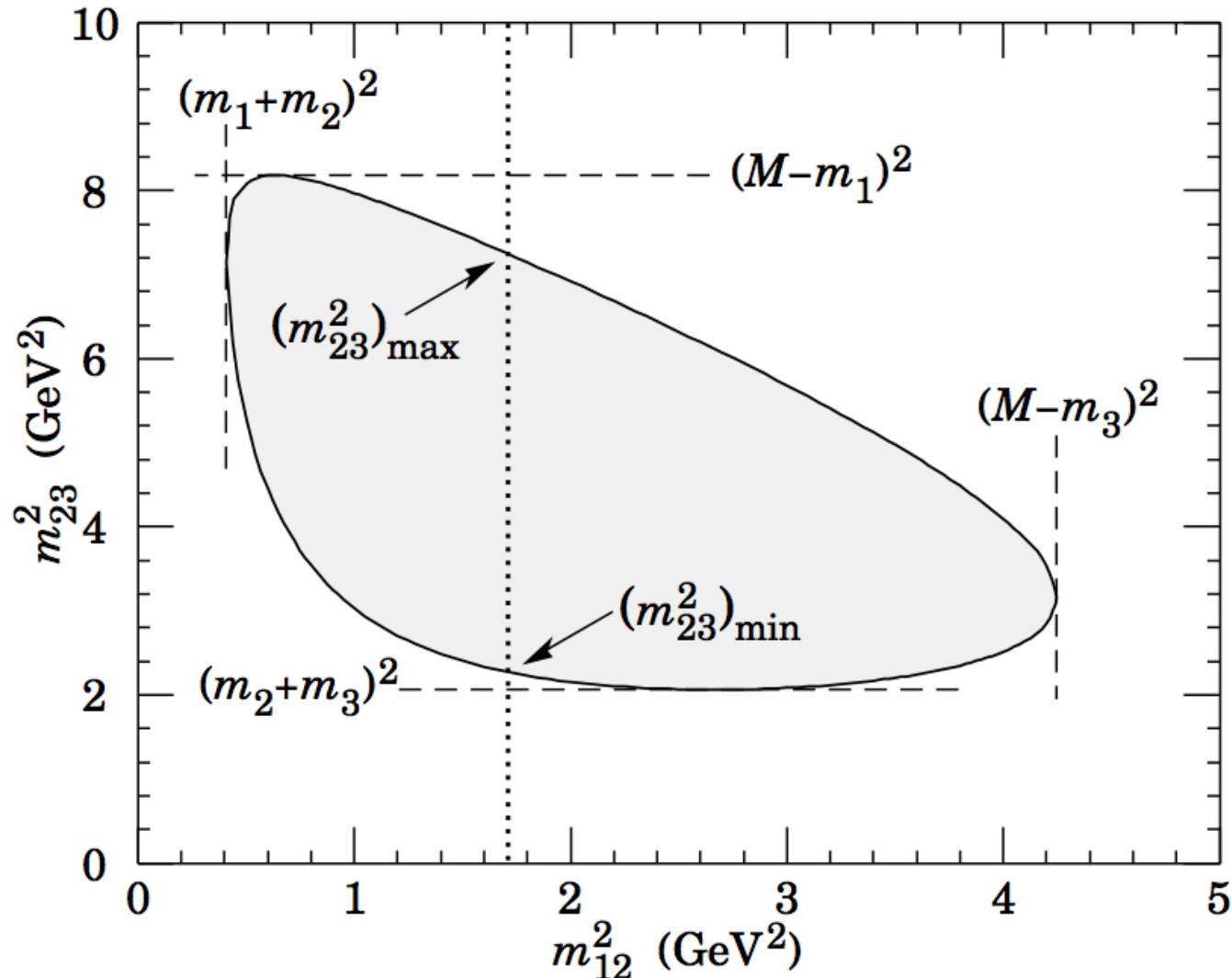
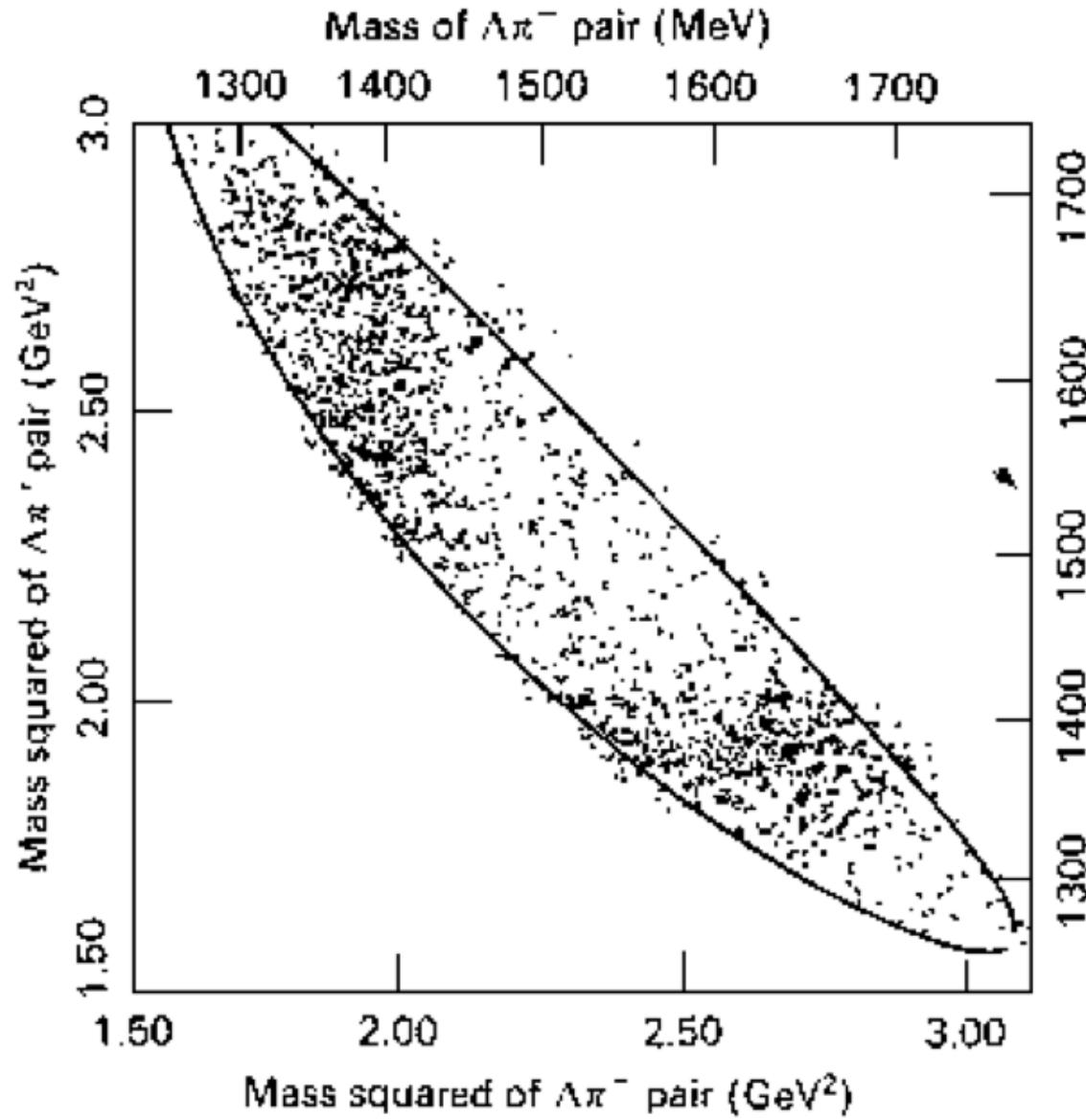
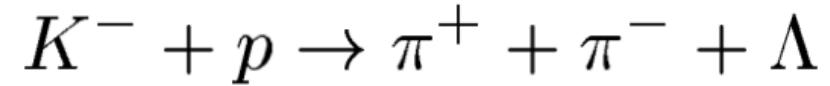
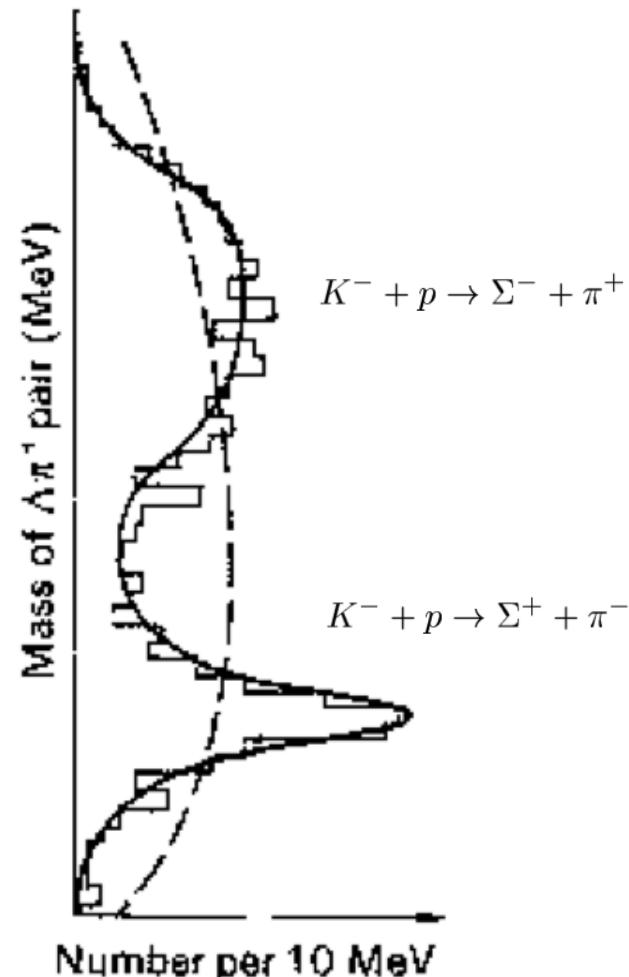
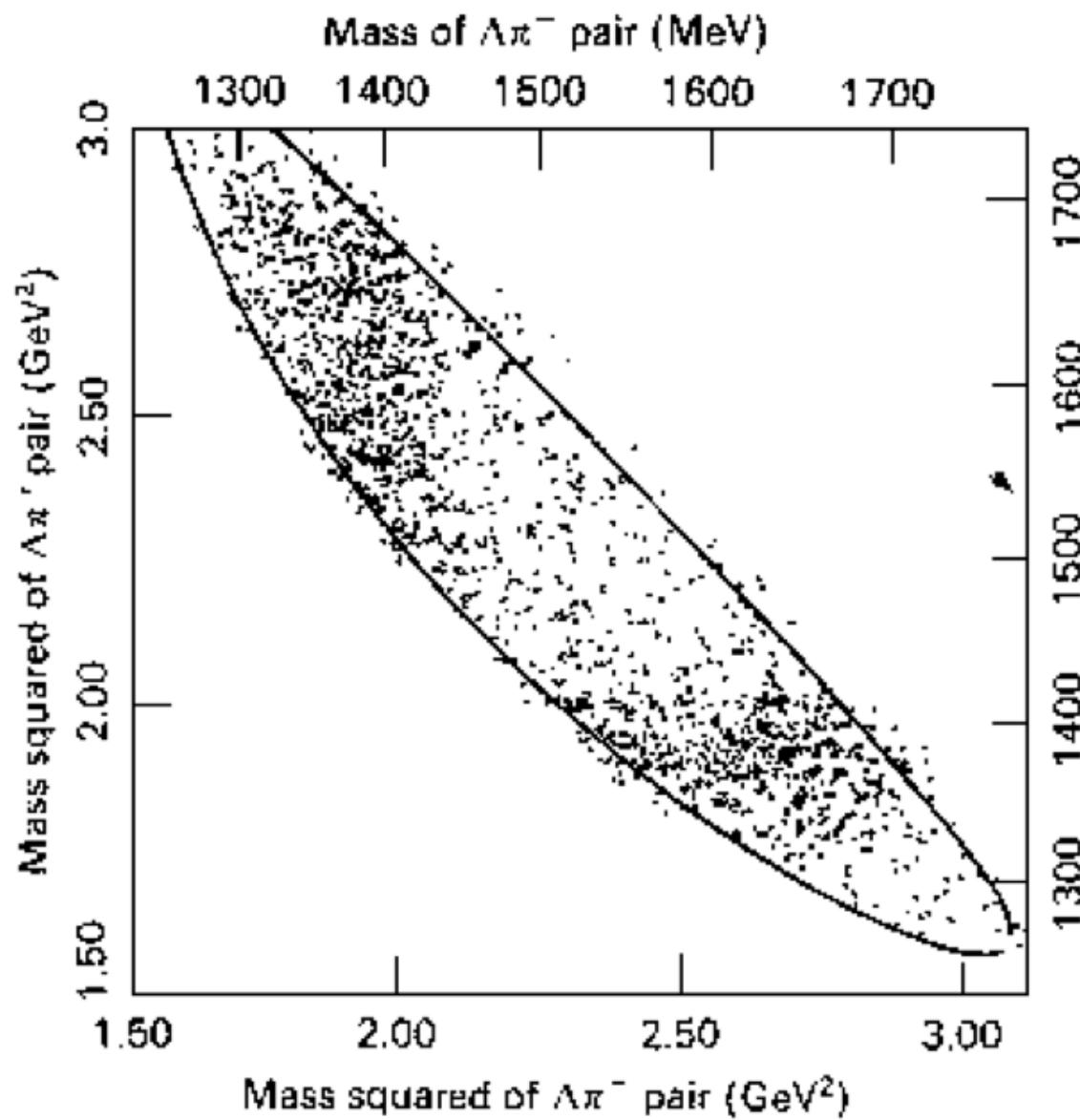
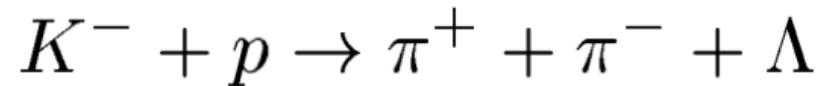


Figure 45.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+ \bar{K}^0 p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

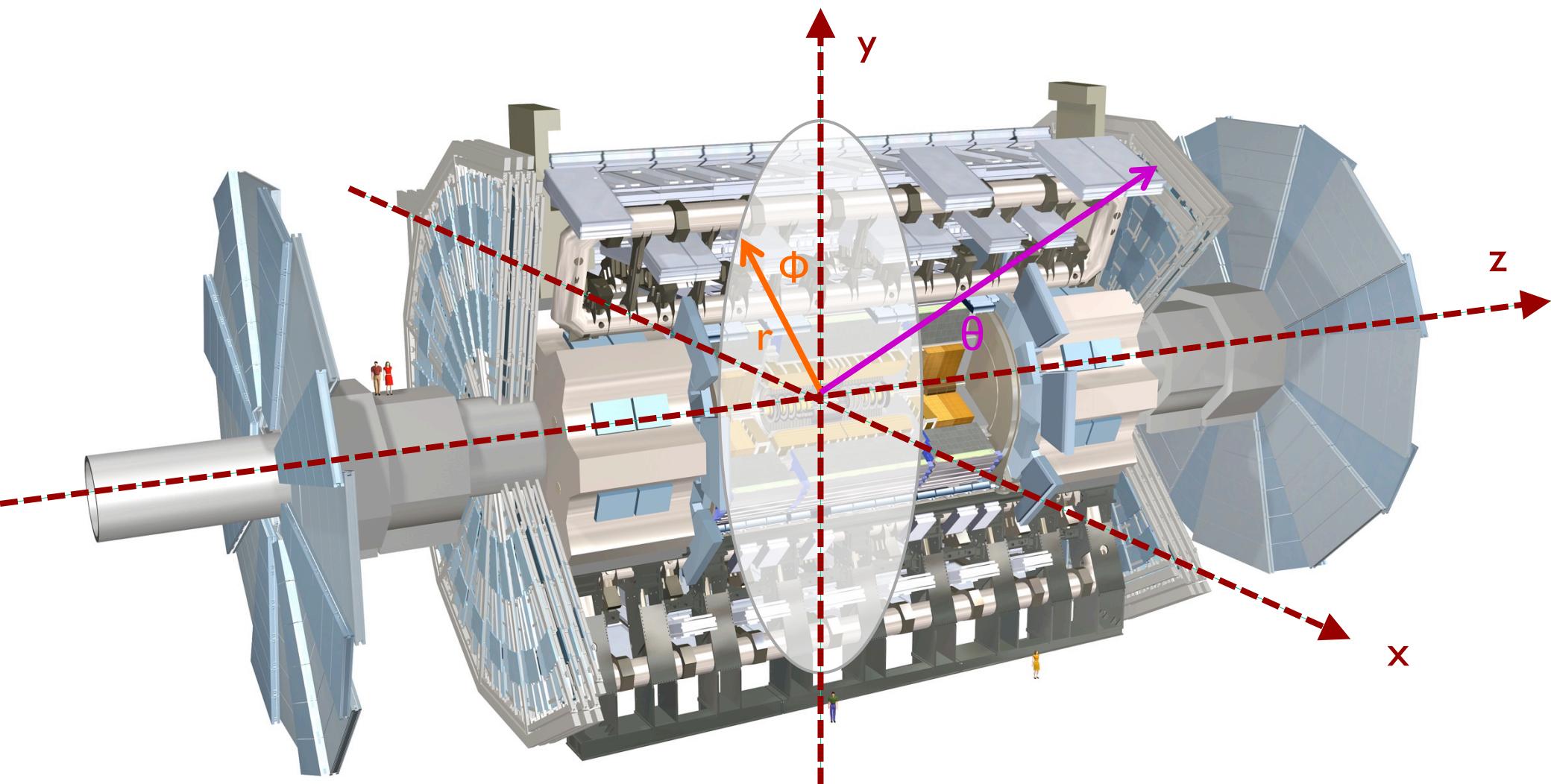
Multi-bodies decay



Multi-bodies decay



Collider experiment coordinates



Rapidity

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

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

- Particle physicists prefer to use modified rapidity along beam axis

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

Pseudorapidity

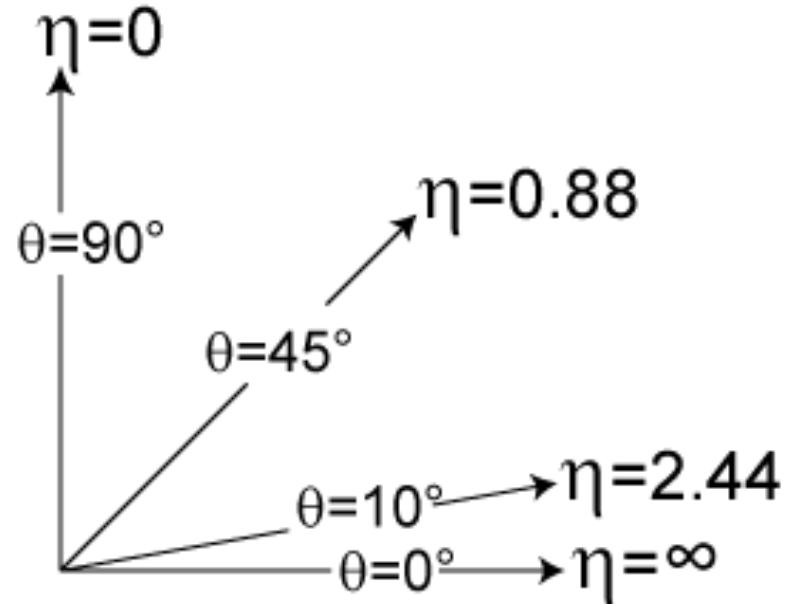
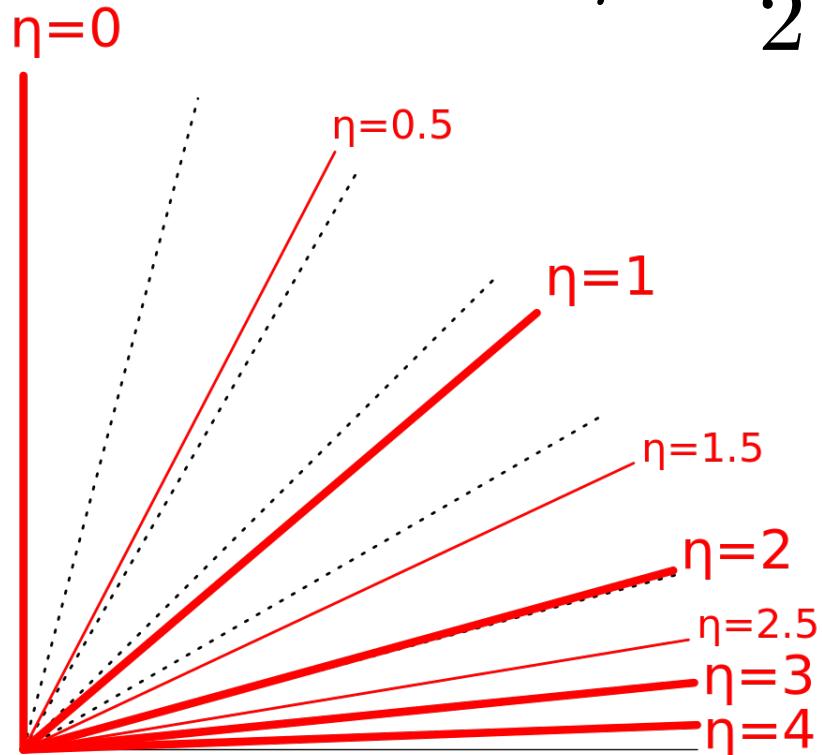
$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

$$\eta \simeq y$$

if $E \gg m$

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

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



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!

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

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

$$\begin{aligned} p_x &= p_T \cos \phi \\ p_y &= p_T \sin \phi \\ p_z &= p_T \sinh \eta \end{aligned}$$

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

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

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 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

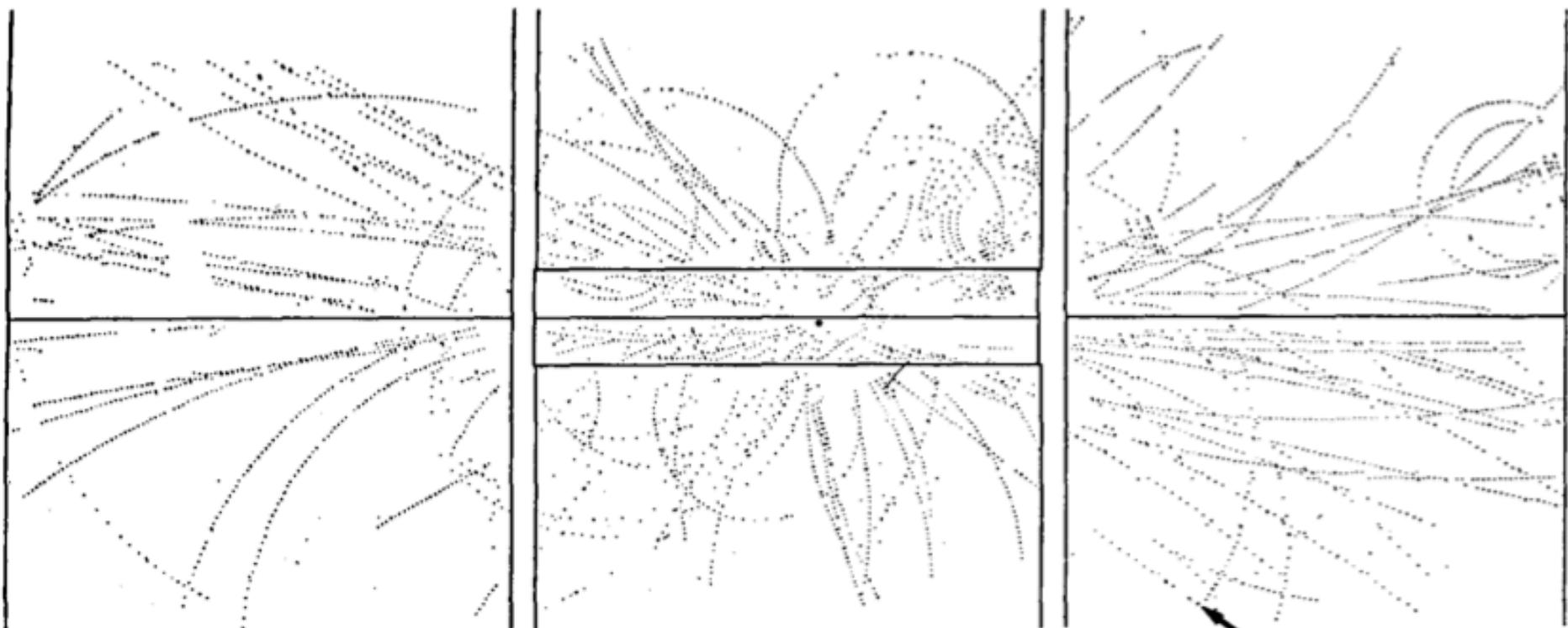
Volume 122B, number 1

PHYSICS LETTERS

24 February 1983

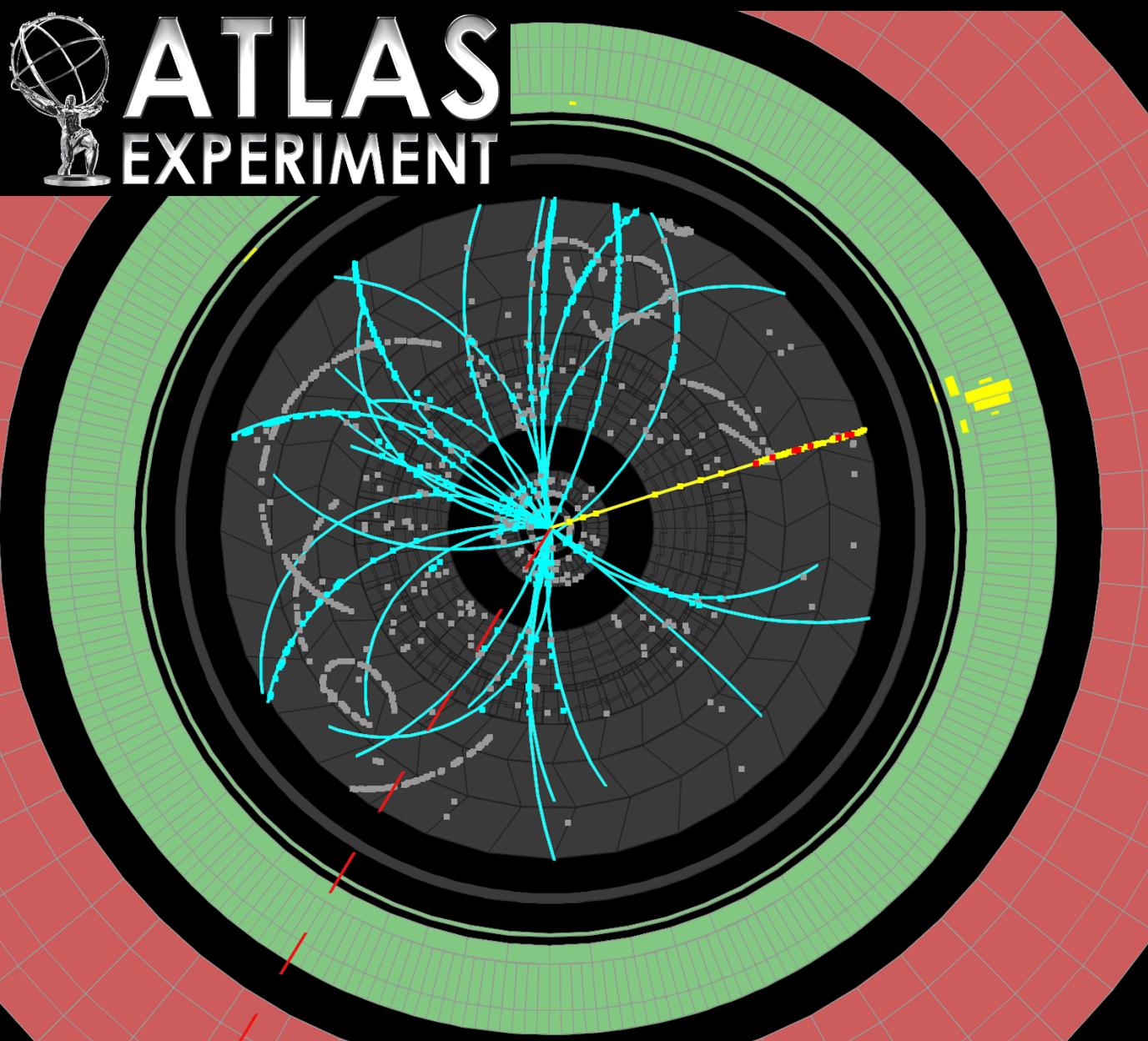
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EVENT 2958. 1279.



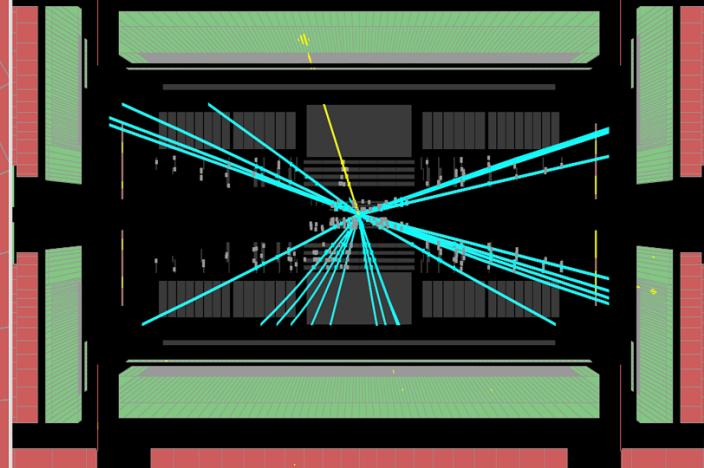


ATLAS EXPERIMENT



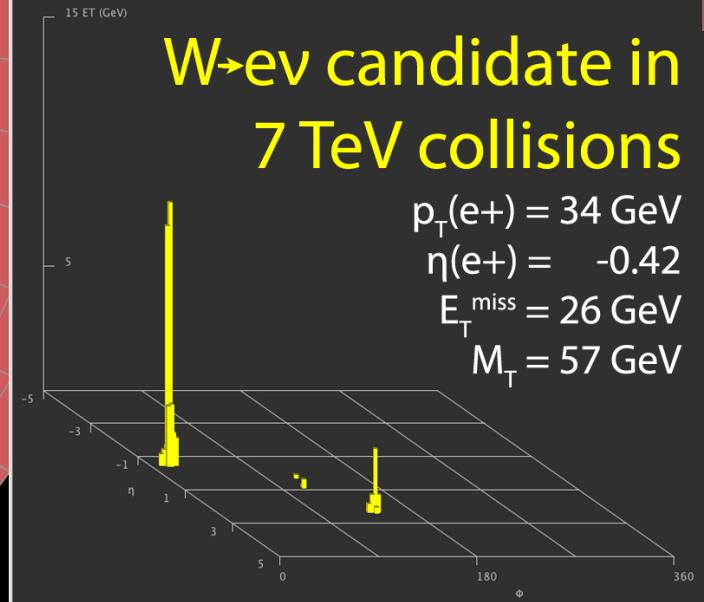
Run Number: 152409, Event Number: 5966801

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



**W \rightarrow ee candidate in
7 TeV collisions**

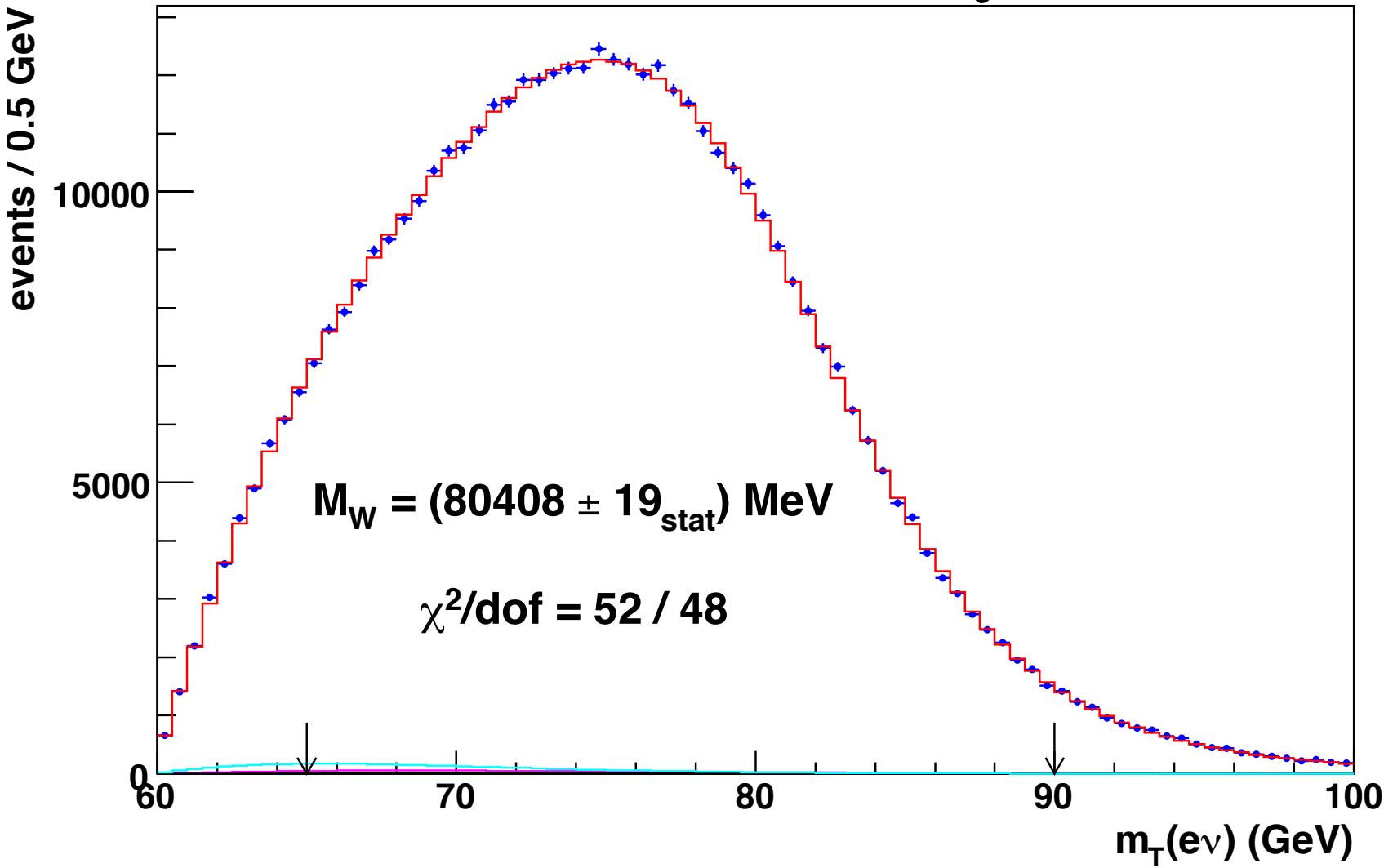
$p_T(e^+) = 34 \text{ GeV}$
 $\eta(e^+) = -0.42$
 $E_T^{\text{miss}} = 26 \text{ GeV}$
 $M_T = 57 \text{ GeV}$



$W \rightarrow e \nu$

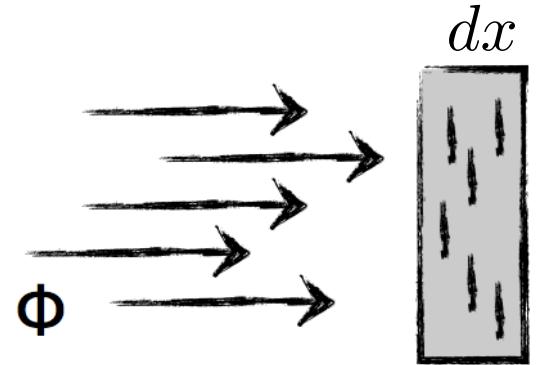
CDF II preliminary

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



Interaction cross section

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



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

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

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

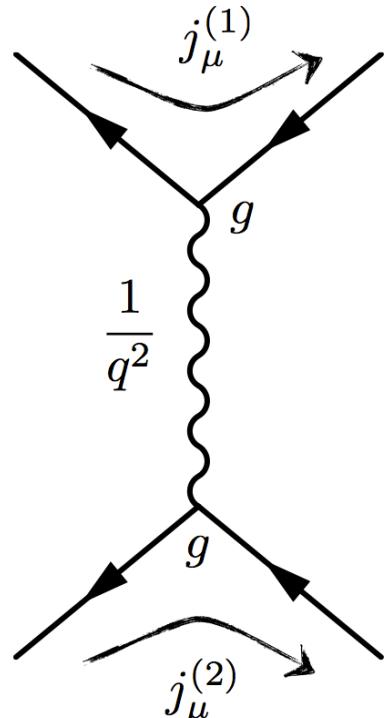
1b = 10⁻²⁸ m² (roughly the area of a nucleus with A = 100)



Antique Experimental Particle Physics

Fermi Golden Rule

From non-relativistic perturbation theory...

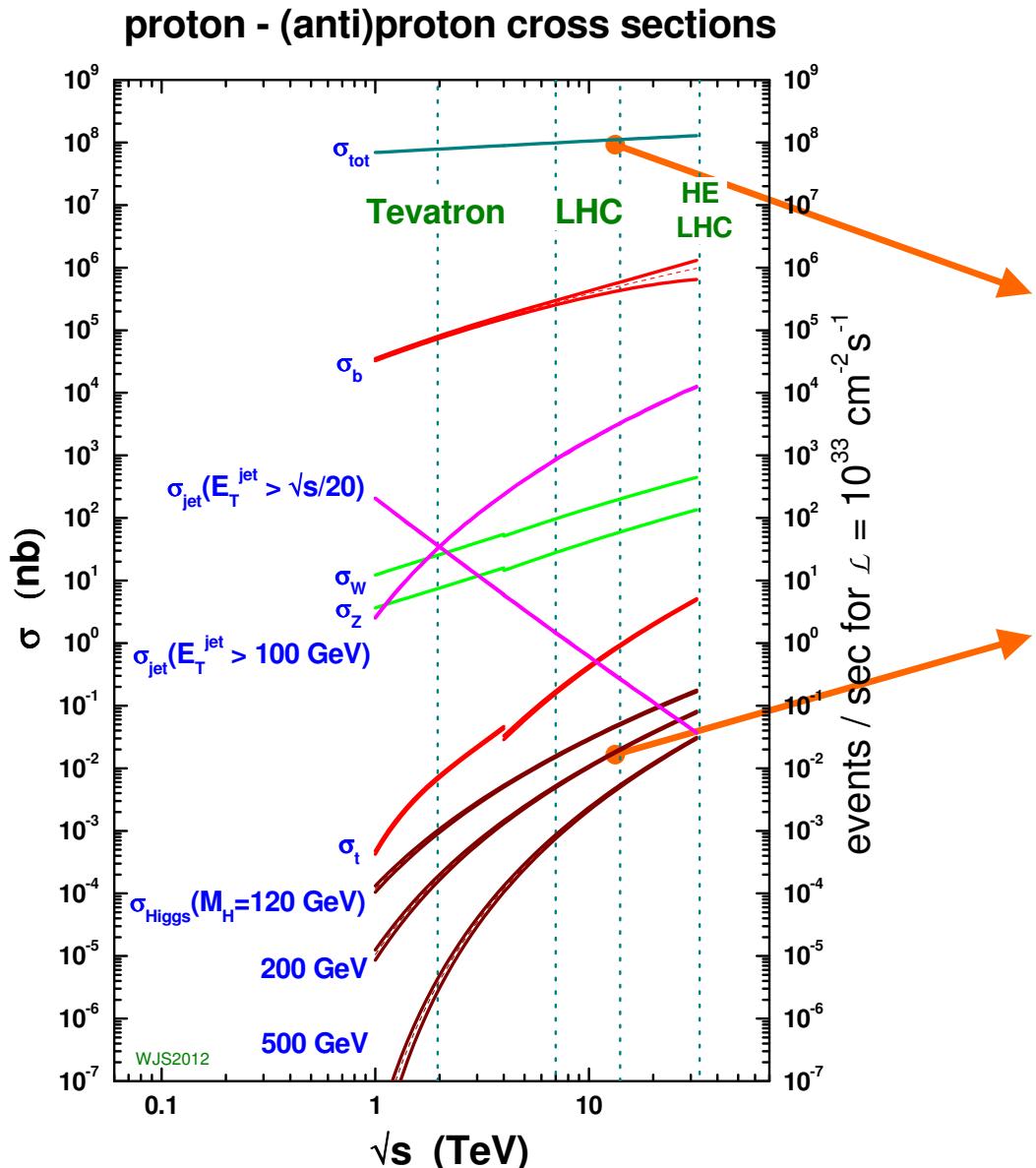


$$W_{if} = \frac{2\pi}{\hbar} \underbrace{|M_{if}|^2}_{[t^{-1}]} \underbrace{\frac{dN}{dE_f}}_{[E^{-1}]}$$

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

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

Cross-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% $H \rightarrow ZZ$

