Some fundamental questions

• What is the standard model of elementary particles and their interactions?
• What is the origin of mass and electroweak symmetry breaking?
• What is the role of anti-matter in Nature?
• What is dark matter?
• What are the masses of the neutrinos and how have they shaped the evolution of the universe?
• Are there additional spacetime dimensions?
• What is the nature of the dark energy?
• Are protons unstable?
• How did the universe begin?
• What was the role of gravity in the early universe?
• How do cosmic accelerators work, and what are they accelerating?
• Are there new states of matter at exceedingly high density and temperature?
• Is a new theory of matter and light needed at the highest energies?
## Quarks and Leptons

- Elem. Particles and High Energy Physics
- Fixed Targets and Colliding Beams
- The Standard Model
  - fundamental fermions, interactions, time scales
- Limitations of the Standard Model
- Fermions and Bosons
- Particles and Antiparticles
- Free Particles and their wave equations
- Helicity States
- Lepton Flavors
- Quark Flavors
Elementary particles and High Energy Physics

• In order to explore the substructure of matter we need to go to high energy
  - resolution is limited by deBroglie wavelength
  - \( \lambda = \frac{h}{p} \)

• Also, in order to produce new high mass particles we need higher energy
Fixed Target and Colliding Beam Accelerators

- Early experiments were done with a beam of particles and a fixed target
  - The energy in the center-of-mass is
    \[ s = E_{cm}^2 = (E_{beam} + m_{target})^2 - p_{beam}^2 \]
    \[ = 2 E_{beam} m_{target} + m_{target}^2 + m_{beam}^2 \]
  - \( E_{cm} \) only increases as the square root of \( E_{beam} \)
    (note \( \sqrt{s} = E_{cm} \))

- By colliding beams of particles, \( E_{cm} \) increases linearly with \( E_{beam} \)
  - \[ s = E_{cm}^2 = (E_{beam} + E_{beam})^2 - (p_{beam} - p_{beam})^2 \]
    \[ = 4 E_{beam}^2 \]
Colliding Beam Experiments

• Many experiments today are done with colliding beams
  - ATLAS & CMS
    at LHC (CERN)
    • $p\ p@\ 3.5\ \text{TeV/beam}$
    • World’s highest energy
    • Going to 7 TeV/beam
  - CDF & D0 (Fermilab)
    • $p\overline{p}@\ 1\ \text{TeV/beam}$
    • Was highest energy
  - KEKB (Japan)  $3.5\ \text{GeV}\ e^+\ \odot\ 8\ \text{GeV}\ e^-$
    • B Factory
A very successful model of elementary particles and their interactions (the Standard Model) has been developed (~1970s). It has stood up to all experimental tests, but we know it is incomplete

- The fundamental fermions
- The interactions
- The limitations
The Fundamental Fermions

- All matter is built from small number of fermions (spin 1/2) particles
- Leptons (integer charge) - six ‘flavors’
  - charged leptons (electron, muon, tau)
    - $\tau$ (muon) = 2.2 microsec  $\tau$ (tau) = 0.3 picosec.
  - neutral leptons (electron-neutrino, muon-neutrino, tau-neutrino)
- Quarks (fractional charge) - six ‘flavors’
  - up-type quarks (up, charm, top)
  - down-type (down, strange, bottom)
    - only up and down are stable
The Fundamental Fermions

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>&lt;1x10^-5</td>
<td>0</td>
</tr>
<tr>
<td>$\theta$</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>&lt;0.0002</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>&lt;0.02</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$</td>
<td>1.7771</td>
<td>-1</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx Mass GeV/c²</th>
<th>Electric Charge</th>
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</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ down</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$ charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$ top</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>
Fundamental Fermions in Nature

- Leptons exist as free particles
- Quarks have never been observed as free particles, only bound within composites, such as the proton (uud), the neutron (udd), the pion (u, anti-d), etc.
- This property of quarks is called ‘confinement’ and it is an important property of the strong interaction
- The stable particles are the lightest: the electron, u and d quarks, neutrinos.
The Interactions

- **Strong**
  - binds quarks, mediated by gluon (massless, spin 1)
- **Electromagnetic**
  - binds electrons in the atom (mediated by photon)
- **Weak**
  - responsible for $\beta$ decay; mediated by $W^\pm, Z^0$
    (massive, spin 1)
- **Gravity**
  - force between all matter, mediated by graviton
    (massless, spin 2)
The Electroweak Lagrangian

\[ \mathcal{L}_F = \sum_i \bar{\psi}_i \left( i \partial \varphi - m_i - \frac{g m_i H}{2 M_W} \right) \psi_i \]

\[ - \frac{g}{2 \sqrt{2}} \sum_i \bar{\Psi}_i \gamma^\mu (1 - \gamma^5) (T^+ W^\mu_\mu + T^- W^-_\mu) \Psi_i \]

\[ - e \sum_i q_i \bar{\Psi}_i \gamma^\mu \psi_i A^\mu \]

\[ - \frac{g}{2 \cos \theta_W} \sum_i \bar{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i Z^\mu . \]

\[ e = g \sin \theta_W \]

\[ \sin^2 \theta_W = 0.23 \]

Fermion Lagrangian

• KE and mass
• Charged weak
• Electromag.
• Neutral weak
The Interactions

Table 2.2, Perkins

<table>
<thead>
<tr>
<th></th>
<th>Gravity</th>
<th>Electromag.</th>
<th>Weak</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>field boson</td>
<td>graviton</td>
<td>photon</td>
<td>$W^\pm,Z$</td>
<td>gluon</td>
</tr>
<tr>
<td>spin-parity</td>
<td>$2^+$</td>
<td>$1^-$</td>
<td>$1^-, 1^+$</td>
<td>$1^-$</td>
</tr>
<tr>
<td>mass, GeV</td>
<td>0</td>
<td>0</td>
<td>$M_w=80.2$</td>
<td>0</td>
</tr>
<tr>
<td>range, m</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$10^{-18}$</td>
<td>$\leq 10^{-15}$</td>
</tr>
<tr>
<td>source</td>
<td>mass</td>
<td>electric charge</td>
<td>‘weak’</td>
<td>‘color’charge</td>
</tr>
<tr>
<td>coupling constant</td>
<td>$5 \times 10^{-40}$</td>
<td>$1/137$</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>typical cross-section, m$^2$</td>
<td>$10^{-33}$</td>
<td>$10^{-39}$</td>
<td>$10^{-30}$</td>
<td></td>
</tr>
<tr>
<td>lifetime, s</td>
<td>$10^{-20}$</td>
<td>$10^{-10}$</td>
<td>$10^{-23}$</td>
<td></td>
</tr>
</tbody>
</table>
Measuring the time scales

- Timescales of $10^{-10}$ seconds are straightforward, since particles typically travel at the speed of light, and distances of many mm are involved.
- Shorter times can be more difficult.
- Consider the time scale of the strong interaction: $10^{-23}$ sec.
  - For these particles, we must measure the ‘width’ $\Gamma = h/2\pi\tau$ (uncertainty principle).
Measuring the time scales

- If a particle travels millimeters, we can measure its trajectory with precision detectors (vertex detectors)
  
  \[ d = c \tau \]
  
  \[ = 3 \times 10^{10} \text{ cm/sec} \tau \]
  
  \[ = 3 \text{ mm} / 10^{-11} \text{ sec} \tau \]
  
  \[ = 3 \text{ mm} \tau / 10^{-11} \text{ sec} \]

(we can actually measure sub-millimeter flight distances)
Vertex Detector

Physics 661, Chapter 1
Measuring the time scales

- The uncertainty principle tells us that if we try to measure the mass of an unstable particle, there will be an uncertainty in that measurement
  - $\Delta E \Delta t > \frac{h}{4\pi}$
  - $\Gamma (\text{MeV}/c^2) = 7 \times 10^{-22}\text{sec} / \tau$

http://230nsc1.phy-astr.gsu.edu/hbase/quantum/parlif.html
The Limitations of the Standard Model

- Gravity is not explicitly included
- Neutrinos are assumed to be massless
- 17 arbitrary constants
  - masses (9) quarks and charged leptons
  - mixing angles (4) CKM matrix for the quarks
  - coupling constants (4) $G_F, \alpha, \alpha_s, \sin^2\theta_w$
- Six ‘copies’ of quarks and leptons assumed without understanding of reason for six
- Dark matter is not understood
Bosons and Fermions

- The fundamental particles are fermions (spin 1/2), but bosons can be constructed from even numbers of the fundamental fermions.
- For example, the pions are bosons and obey Bose-Einstein statistics.
- The application of Fermi-Dirac and Bose-Einstein statistics is important in the study of the fundamental particles, and we will make use of it:
  - An example is the understanding of the $\Delta^{++} = (\text{uuu})$ particle, which led to the realization of a new quantum number, color.
The particles and antiparticles

• Every particle has a corresponding antiparticle, with the same mass and lifetime, and opposite charge and magnetic moment.
• Dirac predicted this from fundamental considerations of relativity and quantum mechanics.
• The first antiparticle, the positron, was discovered in 1932 in a cloud chamber experiment with cosmic rays (Carl Anderson).
Particle and antiparticles

• Both bosons and fermions have antiparticles, however for fermions there is a conservation law: the difference in the number of fermions and antifermions is a constant.

• This law is the origin of the conservation of baryons number and lepton family number:
  - $n \rightarrow p e^- \overline{\nu}_e$
  - $\pi^- \rightarrow \mu^- \overline{\nu}_\mu$
  - $\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$
Particle and antiparticles

• This conservation law does not exist for bosons, so that the following reactions are all possible
  - $p \ p \rightarrow p \ p \ \pi$
  - $p \ p \rightarrow p \ p \ \pi \ \pi$
  - $p \ p \rightarrow p \ p \ \pi \ \pi \ \pi$

• A boson may be its own antiparticle
  - eq. $\pi^0$
Free particles and their wave equations

• Consider a relativistic version of the Schrodinger equation
  - \( E^2 = p^2 + m^2 \)
  - Substitute the operators,
    \( E = i\hbar \frac{\partial}{\partial t}, \quad p = -i\hbar \nabla \)
    and derive
  • Klein-Gordon equation
    \[ \frac{\partial^2 \psi}{\partial t^2} = (\nabla^2 - m^2) \psi \]
  • This equation was found to apply to bosons, not the electron (or fermions).
Free particles and their wave equations

- Fermions (Dirac equation)

\[ E\psi = (\alpha \cdot p + \beta m)\psi, \text{ where } E \& p \text{ are op.} \]

\[ \alpha_k = \begin{pmatrix} 0 & \sigma_k \\ \sigma_k & 0 \end{pmatrix} \quad \beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \]

\[ \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \]

notice this equation is linear in both space and time, unlike the Schrödinger equation
The Dirac equation can be re-expressed in covariant form:

\[
(i \gamma_\mu \frac{\partial}{\partial x_\mu} - m) \psi = 0
\]

\[
\gamma_k = \beta \alpha_k = \begin{bmatrix} 0 & \sigma_k \\ -\sigma_k & 0 \end{bmatrix}, \; k = 1,2,3
\]

\[
\gamma_4 = \beta
\]
• For a massless fermion of positive energy, the helicity is a good quantum number.

\[
\begin{align*}
\text{spin} & \quad \text{velocity} \\
\text{helicity} = +1 & \quad \text{RH} \\
\text{helicity} = -1 & \quad \text{LH}
\end{align*}
\]

• Massive particles are admixtures of LH and RH components:
  - at high energy, mass becomes less significant
  - neutrinos are nearly massless
Helicity States

• Interactions involving vector (eg. EM) or axial vector (1^+) conserve helicity in the relativistic limit

• Since Strong, EM, and Weak all involve vector or axial vector fields, helicity will be conserved in the high energy limit
# Leptons Flavors

<table>
<thead>
<tr>
<th></th>
<th>Strong</th>
<th>EM</th>
<th>Weak</th>
<th>Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\mu$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\tau$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Leptons Flavors

• The Standard Model includes massless neutrinos
  - left-handed neutrinos and RH antineutrinos
• Lepton flavors are conserved in interactions
  - $L_e, L_\mu, L_\tau$
  - $\text{mass}(\mu) = 106 \text{ MeV}/c^2$
  - $\text{mass}(e) = 0.5 \text{ MeV}/c^2$
  - However $\mu \rightarrow e \gamma$ is forbidden (exp: $\text{BR} < 1.2 \times 10^{-11}$)
• Neutrino oscillations are indications that the neutrinos have small masses and that flavor conservation will be violated at a small level
<table>
<thead>
<tr>
<th></th>
<th>Strong</th>
<th>EM</th>
<th>Weak</th>
<th>Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>d</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>c</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>s</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>t</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>b</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Quark Flavors

<table>
<thead>
<tr>
<th>Quantum Number</th>
<th>Rest Mass, GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>up I = 1/2</td>
<td>$m_u \approx m_d \approx 0.31$</td>
</tr>
<tr>
<td>strange S = -1</td>
<td>$m_s \approx 0.50$</td>
</tr>
<tr>
<td>charm C = +1</td>
<td>$m_c \approx 1.60$</td>
</tr>
<tr>
<td>bottom B = -1</td>
<td>$m_b \approx 4.6$</td>
</tr>
<tr>
<td>top T = +1</td>
<td>$m_t \approx 173$</td>
</tr>
</tbody>
</table>

Particles comprised of these quarks will have masses determined roughly by the rest masses of the quarks (internal interactions alter the mass some)
The strong interaction conserves each of the flavor quantum numbers
The related Figure 1.7 of Perkins does not make use of the neutrino mass limits derived from CMB:

\[ \Sigma m_\nu < 1 \text{ eV} \]
Quark Flavor Conservation

• Strange production and decay is a good example of how the quark flavor conservation law works

• Strange particles are always produced in pairs in strong interactions:
  \[ \pi^- \, p \rightarrow \Lambda \, K^0 \]
  • \( S(\Lambda) = -1 \), contains strange quark
  • \( S(K) = +1 \), contains antistrange quark
  • this is a strong interaction and therefore has a large cross section

• In the decays of strange particles, the strangeness may vanish:
  \[ \Lambda \rightarrow p \, \pi^- \quad (\{S = -1\} \rightarrow \{S = 0\}) \]
  • this process is not allowed by the strong interaction, therefore must involve the weak interaction, and is therefore slow.
Baryons and Mesons

- Quarks have never been observed in isolation in nature, only in bound states of three quarks or a quark and an antiquark
  - baryon = $QQQ$  \{three quark state\}
  - meson = $QQ$  \{quark antiquark pair\}

- Baryons and mesons are collectively referred to as hadrons and comprise all of the strongly interaction particles

- Baryons have half-integer spin (1/2, 3/2, 5/2, …) and mesons integer spin (0, 1, 2, …)
Baryons and antibaryons

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c$^2$</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>proton</td>
<td>uud</td>
<td>1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>anti-proton</td>
<td>$\bar{u}\bar{d}$</td>
<td>$-1$</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>udd</td>
<td>0</td>
<td>0.940</td>
<td>1/2</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>lambda</td>
<td>uds</td>
<td>0</td>
<td>1.116</td>
<td>1/2</td>
</tr>
<tr>
<td>$\Omega^-$</td>
<td>omega</td>
<td>sss</td>
<td>$-1$</td>
<td>1.672</td>
<td>3/2</td>
</tr>
</tbody>
</table>
Quark Mass

- There are two ways of describing the quark mass:
  - **constituent** quark mass (used in Perkins)
    - $m(u) \approx 0.31$ GeV $m(d) \approx 0.31$ GeV
  - **current** quark mass
    - $m(u) \approx 0.003$ GeV $m(d) \approx 0.006$ GeV

- Consider the mass of the two light mesons, the pion and the rho, both composed of $u\bar{d}$
  - $m(\pi) = 0.14$ GeV
  - $m(\rho) = 0.77$ GeV
  - constituent quark picture requires large spin-orbit interaction energy to explain difference
Cosmology

- Hot Big Bang Model relies on particle physics to attempt an explanation of the early universe
  - Temperature of early universe was very high
    - Connection to particle physics
  - Matter/anti-Matter Asymmetry
  - Inflation
    - Horizon problem, flatness problem
- Dark Matter
  - Galactic rotation curves, CMB
- Dark Energy
  - Distant supernovae, CMB
Antimatter limits

- Data indicates antimatter is rare in the present Universe
- 1998 AMS space shuttle data
- AMS on ISS launched May 16, 2011
We (and all of chemistry) are a small minority in the Universe.

Analysis of CMB yields measure of components of the universe.
What might we achieve in the next 20 years?

- Discover the Higgs
- Discover supersymmetry
- Solve the hierarchy problem
- Directly detect dark matter
- Understand dark-matter dynamics
- Discover axions
- Solve the cosmological constant problem
- Measure the equation of state of the dark energy
- Verify/disprove inflation
- Understand the origin of large-scale structure
- Understand the baryon asymmetry
- Understand neutrino masses and mixings
- Detect gravitational waves
- Understand gamma-ray bursts
- Discover extra spatial dimensions
- Quantize gravity
- Explain ultra-high-energy cosmic rays
- Understand CP violation (and P violation)
- Discover baryon-number violation
- Detect violations of Lorentz invariance, CPT, the Principle of Equivalence, Newton’s law of gravity
Standard Model Higgs

\[ W \xrightarrow{h} W + W \xrightarrow{h} W \]

\[ m_W \text{ [GeV]} \]

\[ m_H \text{ [GeV]} \]

August 2009

- LEP2 and Tevatron (prel.)
- LEP1 and SLD

68% CL

\[ m_t \text{ [GeV]} \]

Physics 661, Chapter 1
### Standard Model Higgs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(S)}(m_Z)$</td>
<td>$0.02758 \pm 0.00035$</td>
<td>$0.02758$</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$</td>
<td>$91.1874$</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
<td>$2.4959$</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
<td>$41.478$</td>
</tr>
<tr>
<td>$R_l$</td>
<td>$20.767 \pm 0.025$</td>
<td>$20.742$</td>
</tr>
<tr>
<td>$A_{0,l}$</td>
<td>$0.01714 \pm 0.00095$</td>
<td>$0.01645$</td>
</tr>
<tr>
<td>$A_l(P_o)$</td>
<td>$0.1465 \pm 0.0032$</td>
<td>$0.1481$</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$0.21629 \pm 0.00066$</td>
<td>$0.21579$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.1721 \pm 0.0030$</td>
<td>$0.1723$</td>
</tr>
<tr>
<td>$A_{0,b}$</td>
<td>$0.0992 \pm 0.0016$</td>
<td>$0.1038$</td>
</tr>
<tr>
<td>$A_{0,c}$</td>
<td>$0.0707 \pm 0.0035$</td>
<td>$0.0742$</td>
</tr>
<tr>
<td>$A_b$</td>
<td>$0.923 \pm 0.020$</td>
<td>$0.935$</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$0.670 \pm 0.027$</td>
<td>$0.668$</td>
</tr>
<tr>
<td>$A_l(SLD)$</td>
<td>$0.1513 \pm 0.0021$</td>
<td>$0.1481$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}(Q_{fb})$</td>
<td>$0.2324 \pm 0.0012$</td>
<td>$0.2314$</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>$80.399 \pm 0.023$</td>
<td>$80.379$</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.098 \pm 0.048$</td>
<td>$2.092$</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$173.1 \pm 1.3$</td>
<td>$173.2$</td>
</tr>
</tbody>
</table>

**Excluded**

**Preliminary**

$\Delta \alpha_{\text{had}}^{(S)} = 0.02758 \pm 0.00035$

$\Delta \alpha_{\text{had}}^{(S)} = 0.02749 \pm 0.00012$

inclus. low Q$^2$ data

$m_{\text{Limit}} = 157$ GeV
Higgs Boson Search at LHC

Monte Carlo Simulation of $pp \rightarrow \gamma \gamma X$

$\sigma_{TOT} \approx 100 \text{ mbarn}$

$\sigma_{HIGGS} \approx 10 \text{ pbarn}$

@ 7 TeV
5xH(120 GeV)

$\sqrt{s} = 7$ TeV, $\int L dt = 4.9$ fb$^{-1}$
$H \rightarrow ZZ \rightarrow 4l$

$H \rightarrow WW \rightarrow l\nu l\nu$

Physics 661, Chapter 1