FORESEE Presentation

Pizza Talk

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Pizza Seminar

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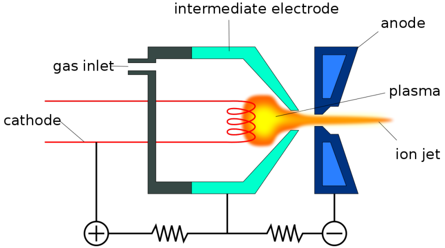
Presentation Overview

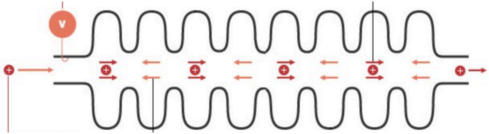
Path of a Proton at the LHC

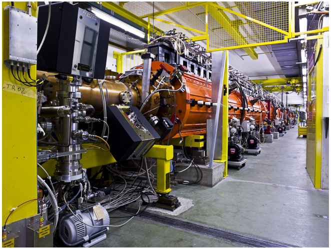
- H2 gas is injected into a device called a duoplasmatron
  - This device uses electric fields and free electrons to ionize H2 and the protons get guided by an electric field to the next stage
  - protons are produced through this process in bunches, consisting of about 1.15×10^{11} protons per bunch
- The particles are guided to LINAC2, a linear particle accelerator
  - protons are accelerated by radio frequency (RF) cavities, discussed on next slide



Path of a Proton at the LHC

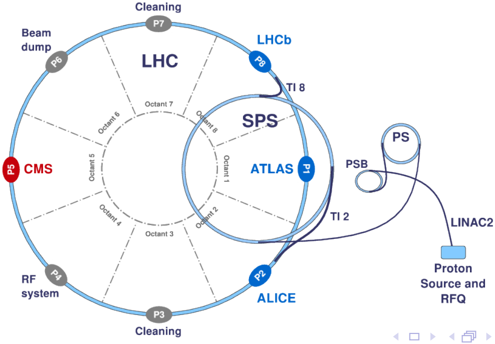
- protons enter linac2 and are accelerated by RF cavities
  - EM waves are generated using an antenna, the cavity is shaped in a way that allows the em waves to resonate
  - the waves oscillate in phase with the protons so that when it enters each cavity, the protons only feel a forward acceleration not a backward acceleration





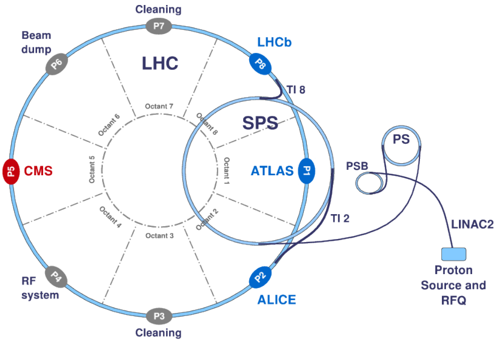
Path of a Proton at the LHC

- protons are accelerated into the Proton Synchrotron Booster
  - synchrotrons work very similarly to linear accelerators, they use RF cavities
  - the major difference is they periodically travel through strong magnetic fields, which keep the trajectory in a circle
- the protons undergo two more stages of synchrotrons
  - proton synchrotron
  - super proton synchrotron



Last Stage: LHC

- SPS splits the bunches into two beams that are directed into the LHC
- Like the synchrotron, LHC uses RF cavities and dipole magnets to accelerate and deflect proton beams

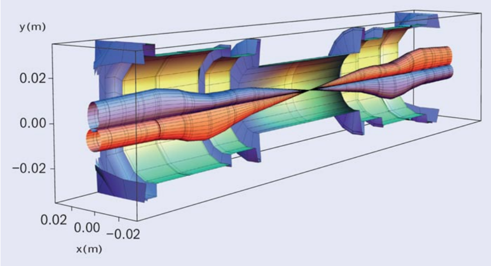


Interesting Facts

- full capacity is 2800 bunches, spaced roughly 7 m apart
- each bunch is about 30 cm in length
- initially the beam diameter is about a milimeter
- each proton is accelerated to an energy of 7 TeV
  - at this energy, the observed mass fo the proton is 7000 times heavier than it is at rest
- this is roughly the same as the kinetic energy of a flying mosquito
- if the mosquito had the same energy density of the proton...
  - the mosquito would contain the same amount of energy released in 1.7×10^{19} nuclear bombs
  - assuming a diameter and height of 2 m for each nuke, this is enough nukes to cover the entire earth... 400,000 times
  - this would reach a height of a low orbit satellite!

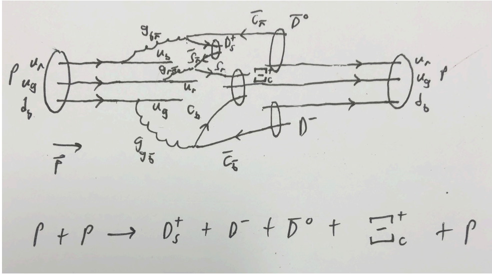
Intersecting the Beams

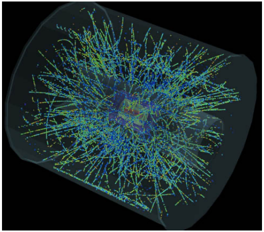
- beams are focused at one of the detectors and deflected so they intersect
  - beams are focused to 60 microns, or roughly the width of a human hair
  - even with 2800 bunches there are only 20 proton collisions per passing



Example of Colliding Protons

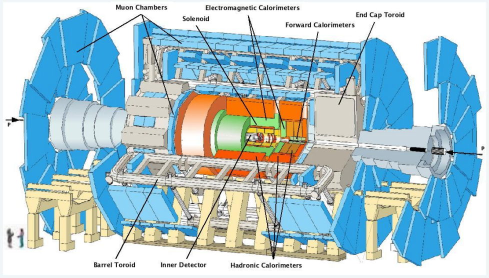
- an extremely simple example of how protons may collide inelastically
- examples are generally much more complicated and can produce hundreds of outgoing particles





Motivation for FASER

- as can be seen from the atlas detector a lot of effort is put into detecting particles in the transverse direction
- not a lot of effort is put into searching for particles in the tangential (forward) direction
- enter ForwArd Search ExpeRiment (FASER)



FASER

- FASER is located 480 m from the ATLAS detector in the forward direction
- it is designed to search for particles that are barely deflected after collisions
    - searches for particles such as dark photons, axion-like particles, sterile neutrinos, etc.
- it is an emulsion detector and measures energy of the particle
- we will focus on my research which involves a special type of sterile neutrino called heavy neutral leptons (HNL)
- to figure out if we have discovered a new particle we must compare with theory
- we must simulate this experiment... Enter FORward Experiment SEnsitivity Estimator (FORESEE)

FORESEE Motivation

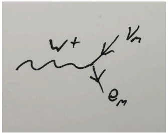
- FASER uses an emulsion detector, which detects the tracks of charged particles
  - this means HNL cannot be detected with these detectors
  - HNL's have a lifetime and can decay into standard model particles, and these can interact with the detector
- these detectors measure energy
- we can extract N(E) from experiment, the number of particles as a function of energy
  - this will give us the total number of particles as a function of energy, so to get the signal we are interested in we must subtract all known interactions to obtain the interesting portion
  - it is this distribution that we can compare with theory
- this analysis tells us we need FORESEE to produce $N_{HNL}(E)$ for HNL's
  - but first lets understand HNL's

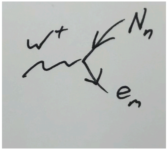
Heavy Neutral Leptons (HNLS)

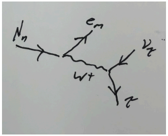
- the theory of HNL's is given by
  - $\mathcal{L}_{HNL} = \frac{1}{2}\bar{N}_m \partial\!\!\!/ N_m - \frac{1}{2}M_m\bar{N}_m N_m - \frac{1}{2}m_{ab}\bar{\nu}_a\nu_b - F_{am}\bar{L}_a N_m\tilde{\phi}$
  - where N is a $SU(3)\times SU(2)\times U(1)$ singlet
  - $\nu \sim$ standard model (SM) neutrinos $L = \begin{pmatrix}\nu \\ \ell\end{pmatrix}$, SM SU(2) doublet
    - ℓ SM lepton
  - ϕ Higgs SU(2) doublet
- can be rewritten as $\mathcal{L}_{HNL} = \frac{1}{2}\bar{N}_m \partial\!\!\!/ N_m - \frac{1}{2}\begin{pmatrix}\bar{\nu} & \bar{N}\end{pmatrix}\begin{pmatrix}m & \mu \\ \mu^T & M\end{pmatrix}\begin{pmatrix}\nu \\ N\end{pmatrix}$
  - we assume $M >> \mu >> m \approx 0$
- can be diagonalized (to get rid of cross terms)
  - $\mathcal{L}_{HNL} \supset -\frac{1}{2}\begin{pmatrix}\bar{\nu}' & \bar{N}'\end{pmatrix}\begin{pmatrix}-\mu^T M^{-1}\mu & 0 \\ 0 & M\end{pmatrix}\begin{pmatrix}\nu' \\ N'\end{pmatrix}$
  - this is the seesaw mechanism
  - $\nu' = \nu - UN$

Heavy Neutral Leptons (HNLS)

- $-\frac{1}{2}\bar{L}_m \not{D} L_m$ leads to terms like
  - $\frac{ig_2}{\sqrt{2}} W_\mu^+ (\bar{\nu}_m \gamma^\mu e_m) = \frac{ig_2}{\sqrt{2}} W_\mu^+ (\bar{\nu}'_m \gamma^\mu e_m) + \frac{ig_2}{\sqrt{2}} W_\mu^+ U_{mn} (\bar{N}_n \gamma^\mu e_m)$
  - these are Feynman diagram vertices, this allows N to interact with standard model particles
  - the reason for this amazing effect can be attributed to the Higgs term in the Lagrangian and this is what allows these particles to be detectable







All Together Now

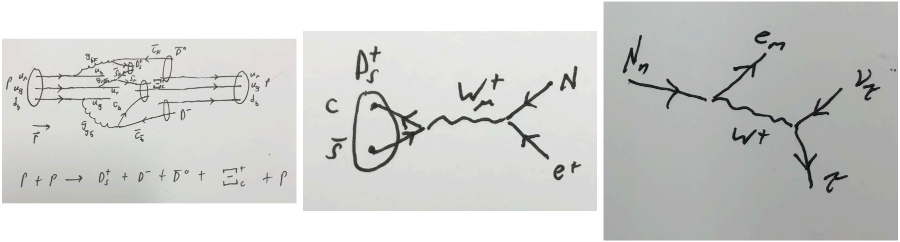


Figure: Left: proton collision; middle: meson decay; right: N decay

FORESEE

- protons collide and produce a bunch of particles, we care about particles that will produce HNL's
- main production comes from D_s mesons
- FORESEE utilizes Pythia and other generators to produce the spectra for such particles
  - the spectra is needed to keep track of the mesons deflection angle and it's momentum, so that we can find the energy and which mesons make it to the detector.

FORESEE Results; Example

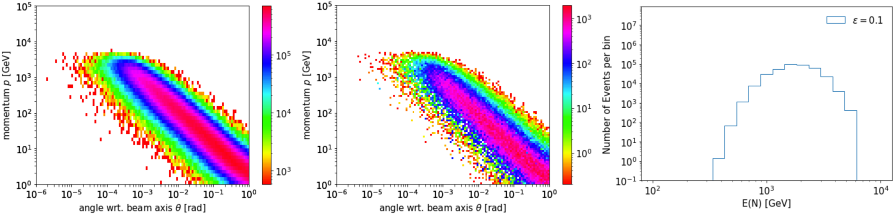
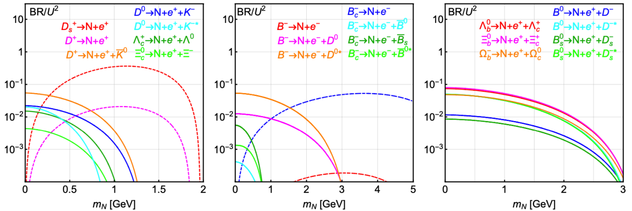


Figure: Left: D_s^+ spectra, Middle: HNL spectra, Right: E(N) distribution for HNL. U_e=.1, m_{HNL}=1 GeV; color bar is cross section

FORESEE Dominant HNL Productions

- to find the number of HNL hits into a certain decay channel we use the formula
  - $n_{sig} = \frac{\sigma_{mother}}{n} \frac{Br(H \to N+X)}{n} \mathcal{L} \cdot (\text{coupling correction}) \cdot prob_d ecay \cdot Br(N \to X)$



Pseudoscalar 2 body decay

- Pseudoscalars are mesons with total spin of 0 and odd parity

$$\frac{d\mathrm{Br}(\mathrm{H}^+ \to \mathrm{l}_\alpha^+ \mathrm{N})}{dE_N} = \tau_H \cdot \frac{G_F^2 f_H^2 M_H M_N^2}{8\pi} |V_H|^2 |U_\alpha|^2 \cdot \left(1 - \frac{M_N^2}{M_H^2} + 2\frac{M_l^2}{M_H^2} + \frac{M_l^2}{M_N^2}\left(1 - \frac{M_l^2}{M_H^2}\right)\right)$$
$$\times \sqrt{\left(1 + \frac{M_N^2}{M_H^2} - \frac{M_l^2}{M_H^2}\right)^2 - 4\frac{M_N^2}{M_H^2}} \cdot \delta\left(E_N - \frac{M_H^2 - M_l^2 + M_N^2}{2M_H}\right)$$

Pseudoscalar 3-body

- these are processes where we begin with a pseudoscalar and end with a pseudoscalar
- they are more difficult due to form factors and Dalitz plots for 3 body decays

$$\frac{d\mathrm{Br}(\mathrm{H} \to \mathrm{H}'\mathrm{l}_\alpha^+\mathrm{N})}{dE_N} = \tau_H \cdot |U_\alpha|^2 \cdot \frac{|V_{HH'}|^2 G_F^2}{64\pi^3 M_H^2} \times \int dq^2 \Bigg(f_-^2(q^2) \cdot \Big(q^2(M_N^2 + M_l^2) - (M_N^2 - M_l^2)$$

$$+ 2f_+(q^2)f_-(q^2)\left(M_N^2(2M_H^2 - 2M_{H'}^2 - 4E_N M_H - M_l^2 + M_N^2 + q^2) + M_l^2(4E_N M_H + M_l^2 -\right.$$

$$f_+^2(q^2)\Bigg((4E_N M_H + M_l^2 - M_N^2 - q^2)(2M_H^2 - 2M_{H'}^2 - 4E_N M_H - M_l^2 + M_N^2 + q^2)$$

$$- (2M_H^2 + 2M_{H'}^2 - q^2)(q^2 - M_N^2 - M_l^2)\Bigg)\Bigg)$$

Vector 3-body

- vector mesons have a total spin of 1 and an odd parity

$$\frac{d\mathrm{Br}(\mathrm{H}\to \mathrm{V}l_\alpha \mathrm{N}}{dE_N} = \tau_H \cdot |U_\alpha|^2 \cdot \frac{|V_{HV}|^2 G_F^2}{32\pi^3 M_H^2} \times \int dq^2 \Bigg(\frac{f_2^2}{2} \Bigg(q^2 - M_N^2 - M_l^2 -$$

$$+\frac{f_5^2}{2}\left(M_N^2+M_l^2\right)\left(q^2-M_N^2+M_l^2\right)\left(\frac{\Omega^4}{4M_V^2}-q^2\right)+2f_3^2 M_V^2\left(\frac{\Omega^4}{4M_V^2}-q^2\right)\Bigg(M_N^2+M_l^2-q^2 -$$

$$+2f_3 f_5\left(M_N^2\omega^2+\left(\Omega^2-\omega^2\right)M_l^2\right)\left(\frac{\Omega^4}{4M_V^2}-q^2\right)+2f_1 f_2\left(q^2\left(2\omega^2-\Omega^2\right)+\Omega^2\right.$$

$$+\frac{f_2 f_5}{2}\Bigg(\omega^2\frac{\Omega^2}{M_V^2}\left(M_N^2-M_l^2\right)+\frac{\Omega^4}{M_V^2}M_l^2+2\left(M_N^2-M_l^2\right)^2-2q^2$$

$$+f_2 f_3\Bigg(\Omega^2\omega^2\frac{\Omega^2-\omega^2}{M_V^2}+2\omega^2\left(M_l^2-M_N^2\right)+\Omega^2\left(M_N^2\right.$$

$$+f_1^2\Bigg(\Omega^4\left(q^2-M_N^2+M_l^2\right)-2M_V^2\left(q^4-\left(M_N^2-M_l^2\right)^2\right)+2\omega^2\Omega^2\left(M_N^2-q^2-M_l^2\right.$$

Figure:

Tau Particle Decays

$$\frac{d\mathrm{Br}\left(\tau \to \mathrm{HN}\right)}{dE_N} = \tau_\tau \cdot \frac{|U_\tau|^2}{16\pi} G_F^2 |V_H|^2 f_H^2 M_\tau^3 \cdot \left(\left(1 - \frac{M_N^2}{M_\tau^2}\right)^2 - \frac{M_H^2}{M_\tau^2}\left(1 + \frac{M_N^2}{M_\tau^2}\right)\right)$$

$$\times \sqrt{\left(1 - \frac{(M_H - M_N)^2}{M_\tau^2}\right)\left(1 - \frac{(M_H + M_N)^2}{M_\tau^2}\right)} \cdot \delta\left(E_N - \frac{M_\tau^2 - M_H^2 + M_N^2}{2M_\tau}\right) ,$$

$$\frac{d\mathrm{Br}\left(\tau \to \rho\mathrm{N}\right)}{dE_N} = \tau_\tau \cdot \frac{|U_\tau|^2}{8\pi} \frac{g_\rho^2}{M_\rho^2} G_F^2 |V_{ud}|^2 M_\tau^3 \cdot \left(\left(1 - \frac{M_N^2}{M_\tau^2}\right)^2 + \frac{M_\rho^2}{M_\tau^2}\left(1 + \frac{M_N^2 - 2M_\rho^2}{M_\tau^2}\right)\right)$$

$$\times \sqrt{\left(1 - \frac{(M_\rho - M_N)^2}{M_\tau^2}\right)\left(1 - \frac{(M_\rho + M_N)^2}{M_\tau^2}\right)} \cdot \delta\left(E_N - \frac{M_\tau^2 - M_\rho^2 + M_N^2}{2M_\tau}\right) ,$$

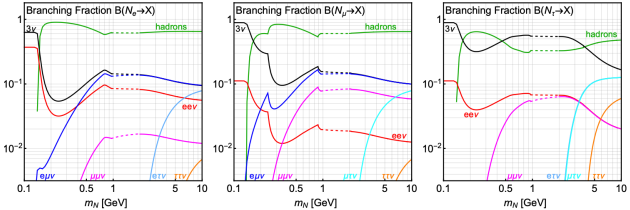
$$\frac{d\mathrm{Br}\left(\tau \to \nu_\tau \mathrm{l}_\alpha \mathrm{N}\right)}{dE_N} = \tau_\tau \cdot \frac{|U_\alpha|^2}{2\pi^3} G_F^2 M_\tau^2 \cdot E_N \left(1 + \frac{M_N^2 - M_l^2}{M_\tau^2} - 2\frac{E_N}{M_\tau}\right)\left(1 - \frac{M_l^2}{M_\tau^2 + M_N^2 - 2E_N M_\tau}\right)\sqrt{E_N^2 - M_N^2} ,$$

$$\frac{d\mathrm{Br}\left(\tau \to \bar{\nu}_\alpha \mathrm{l}_\alpha \mathrm{N}\right)}{dE_N} = \tau_\tau \cdot \frac{|U_\tau|^2}{4\pi^3} G_F^2 M_\tau^2 \left(1 - \frac{M_l^2}{M_\tau^2 + M_N^2 - 2E_N M_\tau}\right)^2 \sqrt{E_N^2 - M_N^2}$$

$$\times \left((M_\tau - E_N)\left(1 - \frac{M_N^2 + M_l^2}{M_\tau^2}\right) - \left(1 - \frac{M_l^2}{M_\tau^2 + M_N^2 - 2E_N M_\tau}\right)\left(\frac{(M_\tau - E_N)^2}{M_\tau} + \frac{E_N^2 - M_N^2}{3M_\tau}\right)\right)$$

Whats Next?

- next we will include decays into HNL coming from baryons
- next our focus will shift into the main decay channels for the HNL so we can determine signals for each of the decay channels



The End

Questions? Comments?