Experimental High Energy Physics at Rutgers

Amitabh Lath
Graduate Student Open House
March 15, 2023
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Before we get started:
We support ALL our Graduate Students!
Including Summer Support!
A Myth about Particle Physics

Experiments are HUGE!

Industrial scale physics...

No individual creativity...
A Myth about Particle Physics

Experiments are HUGE! Industrial scale physics...

WRONG
Particle Physics

Small groups, really interesting physics.

Lots of room for individual creativity
Neutrinos

Is there a sterile neutrino?
What is going on with all these anomalies in the neutrino sector?
Andrew T. Mastbaum
Email: mastbaum@physics.rutgers.edu
Sterile neutrinos and (other) BSM in a high intensity $\nu$ beam
Oscillation analysis, dark sector searches, hardware & DAQ
MicroBooNE, 10/2021

Events Observed / Predicted (no eLEE)

- MicroBooNE Observed
- Predicted, no eLEE \((x = 0.0)\)
- Predicted, w/ eLEE \((x = 1.0)\)

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Observed</th>
<th>Predicted, no eLEE</th>
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<tbody>
<tr>
<td>lep CCQE</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>leNp0π</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>le0p0π</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>leX</td>
<td>1.0</td>
<td>1.0</td>
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No evidence for "simplest" explanations of short-baseline neutrino anomalies

arxiv:2110.14054 (submitted to PRL)

MicroBooNE's 12m-long detector is contained inside a large cryogenic tank, filled with 150 tonnes of liquid argon at \(-185^\circ C\).
Neutrinos at Rutgers
Short-Baseline Neutrino Program

Rutgers Physics at SBN

Neutrino-nucleus interactions

PRL 123, 131801 (2019)

-1.00 ≤ \( \cos(\theta^{\text{reco}}_\mu) \) < -0.50

MicroBooNE 1.6 \( \times \) 10^{20} POT

\[
\frac{d\sigma}{dp_{\mu}^\text{reco}} \left( \frac{\text{cm}^2}{\text{GeV}} \right) = \begin{cases} 
0 & \text{if } \cos(\theta^{\text{reco}}_\mu) \leq -1.00 \\
0.01 & \text{if } -1.00 < \cos(\theta^{\text{reco}}_\mu) < -0.50 \\
0.1 & \text{if } -0.50 \leq \cos(\theta^{\text{reco}}_\mu) < 0.00 \\
0.4 & \text{if } 0.00 \leq \cos(\theta^{\text{reco}}_\mu) \leq 0.50 \\
0.86 & \text{if } 0.50 \leq \cos(\theta^{\text{reco}}_\mu) \leq 1.00 
\end{cases}
\]

\( d\sigma/\text{d}p_{\mu}^\text{reco} \) for MicroBooNE 1.6 \( \times \) 10^{20} POT

Genie v2.12.2 + Emp. MEC

Genie v3.0.6 G1810a0211a

GiBUU 2019

NuWro 19.02.1

Data (Stat. & Syst. Unc.)

\( \mu^- \rightarrow \pi^- + 2\text{e}^- + \text{3}\nu_\mu \)

\( \alpha \)

7.7 MeV

\( \sim 10,000 \text{ e} \)

\( \sim 150,000 \text{ y} \)

\( T_{1/2} = 164 \text{ ms} \)

\( \beta \)

3.3 MeV

\( \sim 100,000 \text{ e} \)

\( \sim 30,000 \text{ y} \)

New LArTPC analysis techniques

Heavy QCD axions

Millicharged particles

ICARUS-T600

MicroBooNE

SBND
Neutrinos at Rutgers

Neutrino CP violation, mass ordering, BSM, and more
LAr Near Detector analysis and instrumentation R&D
Figure 9. Gallery of four representative cosmic ray induced events collected with Module-0. In all cases, the central plane in grey denotes the cathode, and the color scale denotes the collected charge in units of thousands of electrons. (b) denotes an electromagnetic (EM) shower. (d) is "neutrino-like" in that the vertex of this interaction appears to be inside the active volume.

Near Detector Readout R&D @ Rutgers

Prototype @ Uni. Bern, 4/2021

(a) Stopping Muon + Michel $e^-$

(b) EM Shower

(c) Multi-Prong Shower

(d) "Neutrino-like"
Particle Physics at the Energy Frontier
The Rutgers Faculty on CMS

- Six professors, six postdocs, several graduate students and undergrads
  - [http://www.physics.rutgers.edu/hex/](http://www.physics.rutgers.edu/hex/)
- Scott Thomas and his group also signs CMS papers
- Sevil Salur (nex) works on p-Pb/Pb-Pb collisions at CMS

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So where is the new physics?

Am I going to be in the hunt for it?
New Physics is more difficult than it used to be...

Mass of W/Z predicted from beta decay, muon decay.

Fermi constant $G_F$ proportional to $1/M^2_W$
New Physics is more difficult than it used to be...

Mass of top quark predicted from precision electroweak measurements.

Weak asymmetries rule!

Also, triangle anomaly. Neutral pion decay goes awry without top quark!
New Physics is more difficult than it used to be…

Prediction of Higgs mass circa 2009. This was a cottage industry. Throw everything you know (W/Z mass, top, EW asymmetries) into a minimizer et viola.
New Physics is more difficult than it used to be...

Prediction of Higgs mass circa 2009. This was a cottage industry. Throw everything you know (W/Z mass, top, EW asymmetries) into a minimizer et viola.

Observed 2012. Mass (as of 2023) 125.35 GeV.
Ok, go ahead and brag about the Higgs boson...
Higg Boson Discovery 2012
Di-photon mode

\[ \frac{S}{(S+B)} \text{ Weighted Events} / 1.5 \text{ GeV} \]

CMS \[ \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \quad \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \]

Unweighted

Data
S+B Fit
B Fit Component

\begin{align*}
\pm 1 \sigma & \\
\pm 2 \sigma & 
\end{align*}

2/28/19
New Physics is more difficult than it used to be...

Problem: Higgs is too light. Hierarchy problem.

Solution: ???

Is it SUPERSYMMETRY? the ultimate Supergroup!

Is the Higgs some sort of composite? Technicolor? Other models?

Something else that nobody has thought of yet?
New Physics is more difficult than it used to be...

Problem: Higgs is too light. Hierarchy problem.

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The guidance from theory is not as precise as it used to be.
Example of RU HEX group
Creativity
Very large background from gluon scattering

- jets are everywhere
- jets fluctuate A LOT
- there is always a "cloud" of soft particles from multiple interactions and proton remnants

Jets can mimic all possible rare particles – electrons, muons, photons

- photons are especially tricky
“Doing Physics with proton-proton collisions is like trying to reconstruct the workings of a fine Swiss watch embedded in colliding bags of garbage ...”
Dalitz Plots: A blast from the 1950’s
Dalitz Plots: A blast from the 1950’s
Top Quark!

Hmmmmm!
Hmmmmm!
750 GeV diphoton excess

From Wikipedia, the free encyclopedia

The 750 GeV diphoton excess in particle physics was an anomaly in data collected at the Large Hadron Collider (LHC) in 2015, which could have been an indication of a new particle or resonance,\(^8\)[9]. The anomaly was absent in data collected in 2016, suggesting that the diphoton excess was a statistical fluctuation.\(^1\)[2] In the interval between the December 2015 and August 2016 results, the anomaly generated considerable interest in the scientific community, including about 500 theoretical studies.\(^10\)[11][12][13] The hypothetical particle was denoted by the Greek letter \( \Phi \) (pronounced digamma) in the scientific literature, owing to the decay channel in which the anomaly occurred.\(^3\) The data, however, were always less than five standard deviations (sigma) different from that expected if there was no new particle, and, as such, the anomaly never reached the accepted level of statistical significance required to announce a discovery in particle physics.\(^14\)

After the August 2016 results, interest in the anomaly sank as it was considered a statistical fluctuation.\(^15\) Indeed, a Bayesian analysis of the anomaly found that whilst data collected in 2015 constituted "substantial" evidence for the digamma on the Jeffreys scale, data collected in 2016 combined with that collected in 2015 was evidence against the digamma.\(^16\)

750 GeV?
New Techniques: Machine Learning (AI)
ML: Gaussian Process Regression

Model selection and signal extraction using Gaussian Process regression

Abhijith Gandrakota,\textsuperscript{a} Amit Lath,\textsuperscript{b} Alexandre V. Morozov\textsuperscript{b} and Sindhu Murthy\textsuperscript{c}

\textsuperscript{a}Fermi National Accelerator Laboratory, Batavia, IL, U.S.A.
\textsuperscript{b}Department of Physics & Astronomy, Rutgers, The State University of New Jersey, Piscataway, NJ, U.S.A.
\textsuperscript{c}Department of Physics, Carnegie Mellon University, Pittsburgh, PA, U.S.A.

\textit{E-mail:} abhijith@fnal.gov, lath@physics.rutgers.edu, morozov@physics.rutgers.edu, sindhum@andrew.cmu.edu
Gaussian Process Regression

Signal extraction.

More robust than fitting arbitrary functions

More scalable to high statistics

First publication. Useful in all fields...
New Techniques: Scouting

40 MHz Scouting for Phase 2?

Maurizio Pierini

40 MHz Scouting for Phase 2?
RU contribution to Higgs discovery
Higgs $\rightarrow \gamma \gamma$

Di-Photon Resolution

Squeeze Resonance

$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{1}{2} \sqrt{\frac{\sigma_{E_{\gamma_1}}^2}{E_{\gamma_1}^2} + \frac{\sigma_{E_{\gamma_2}}^2}{E_{\gamma_2}^2} + \sigma_{\phi}^2}$

Local Corrections:

Semi-Local Corrections:
Higgs $\to \gamma\gamma$

Di-Photon Resolution

Squeeze Resonance

Local Corrections:

\[ \frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{1}{2} \sqrt{\frac{\sigma_{E_{\gamma_1}}^2}{E_{\gamma_1}^2} + \frac{\sigma_{E_{\gamma_2}}^2}{E_{\gamma_2}^2} + \sigma_{\varphi}^2} \]
Higgs $\rightarrow \gamma\gamma$

Di-Photon Resolution

Squeeze Resonance

Pointing Resolution:

$$\sigma_{m_{\gamma\gamma}} = \frac{1}{2} \sqrt{\frac{\sigma_{E_{\gamma_1}}^2}{E_{\gamma_1}^2} + \frac{\sigma_{E_{\gamma_2}}^2}{E_{\gamma_2}^2} + \sigma_{\varphi}^2}$$

$$\sigma_\varphi^2 = f(\eta_{\gamma_1}, \phi_{\gamma_1}, r_{\gamma_1}, \rho_0) \frac{\sigma_z^2}{\rho_0^2}$$

Primary Vertex Algorithm

Converted

Unconverted

13 Vertices
Higgs $\rightarrow \gamma\gamma$

Di-Photon Resolution

Squeeze Resonance

Pointing Resolution:

$\sigma_{m_{\gamma\gamma}} = \frac{1}{2} \sqrt{\frac{\sigma_{E_{\gamma_1}}^2}{E_{\gamma_1}^2} + \frac{\sigma_{E_{\gamma_2}}^2}{E_{\gamma_2}^2} + \sigma_{\varphi}^2}$

$\sigma_{\varphi}^2 = f(\eta_{\gamma_i}, \phi_{\gamma_i}, r_{\gamma_i}; \rho_0) \frac{\sigma_z^2}{\rho_0^2}$

$f(\eta_{\gamma_i}, \phi_{\gamma_i}, r_{\gamma_i}; \rho_0) = \left[ \frac{\text{sech} \eta_{\gamma_1} \frac{\text{sech} \eta_{\gamma_1} \tanh \eta_{\gamma_2} - \tanh \eta_{\gamma_1} \text{sech} \eta_{\gamma_2} \cos(\phi_{\gamma_1} - \phi_{\gamma_2})}{1 - \tanh \eta_{\gamma_1} \tanh \eta_{\gamma_2} - \text{sech} \eta_{\gamma_1} \text{sech} \eta_{\gamma_2} \cos(\phi_{\gamma_1} - \phi_{\gamma_2})}}{r_{\gamma_1}} \rho_0 \right] + \left[ \frac{\text{sech} \eta_{\gamma_2} \frac{\text{sech} \eta_{\gamma_2} \tanh \eta_{\gamma_1} - \tanh \eta_{\gamma_2} \text{sech} \eta_{\gamma_1} \cos(\phi_{\gamma_1} - \phi_{\gamma_2})}{1 - \tanh \eta_{\gamma_2} \tanh \eta_{\gamma_1} - \text{sech} \eta_{\gamma_2} \text{sech} \eta_{\gamma_1} \cos(\phi_{\gamma_1} - \phi_{\gamma_2})}}{r_{\gamma_2}} \rho_0 \right]^2$

Largely Ameliorates CMS lack of Photon Pointing Ability
Higgs $\rightarrow \gamma\gamma$

Di-Photon Energy Resolution
Machine Learning Algorithms
+ Mass Factorized Di-Photon
Kinematics Machine Learning
Algorithm

$S/(S+B)$ Contrast Reweighting

1. First Indication for Higgs
Boson in CMS

2. Definitive Evidence for
Discovery Level Signal of
the Higgs Boson in CMS
Higgs \rightarrow \gamma \gamma
We have interesting hints from Run2 data of where new physics could be.

Come see me after this!
We have interesting hints from Run2 data of where new physics could be.

Come see me after this!

Did I mention that we support ALL our Graduate Students!

Including Summer Support, travel to conferences help finding postdocs and jobs in industry...
WHO IS YOUR UNION? (the AAUP-AFT)

The American Association of University Professors (AAUP) (founded 1970). One of the first faculty unions in the US.

TA's and GA's joined AAUP in 1972. You are in the same union as the faculty here!

Post-docs joined in 2009 as a bargaining unit of AAUP-AFT

WHY WE ARE FIGHTING FOR A BETTER CONTRACT

- Your contract expired half a year ago!
- Grad TAs make minimum wage: $11,000 below the Middlesex, NJ cost of living.
- We are asking for an immediate 23.2% raise, from $30,162 to $37,150.
- Dozens of successful graduate and faculty strikes across the US over the last year. Major opportunity for change, but we need to work together.
What can you do right now?

1: Join the Union. 2: Sign the Strike Pledge

TIMELINE OF NEXT STEPS:

Feb 13 - Feb 28: Strike Pledge (saying you will vote to strike, this is not a strike vote. This is extremely important, and all of us should sign it!)

Feb 28: Board of Governors Rally @ Newark
(actions on other campuses)

February 28- March 10: Strike Authorization Vote (before Spring Break)

After March 22: Strike Announcement Action

March 27 - April 17: STRIKE WINDOW