The 2016 Phenomenology Symposium will be held May 9-11, 2016 at the University of Pittsburgh. It will cover the latest topics in particle phenomenology and theory plus related issues in astrophysics and cosmology.

Early registration ended April 17, 2016. Registration closed May 1, 2016.

Talk submission ended April 24, 2016.

Conference banquet May 10, 2016.

Plenary program and full program are now available.

Tentative plenary topics and speakers:

- John Alison (Univ of Chicago): BSM searches at the LHC
- Barry Barish (Caltech): Observation of gravitational waves by LIGO
- Rachel Bean (Cornell Univ): Cosmology theory
- Nathaniel Craig (UC Santa Barbara): Naturalness of the electroweak scale
- Albert De Roeck (CERN / Univ of Antwerp / CMS): Standard Model physics at the LHC
- Pavel Fileviez Perez (Max Planck Institute, Heidelberg): Theories for baryon and lepton number violation
- Yuanning Gao (Tsinghua University): Physics from LHCb
- Francis Halzen (Univ of Wisconsin): Perspectives in astro-particle physics
- Mariangela Lisanti (Princeton): Dark matter theory and searches
- Hitoshi Murayama (IPMU / UC Berkeley): Particle physics future perspectives
- Ryan Patterson (Caltech): Perspectives on neutrino physics
- Maxim Perelstein (Cornell): Physics at the International Linear Collider
- Alex Pomarol (Barcelona): New dynamics in the EW sector
- Ira Rothstein (CMU): Particle physics perspectives on gravity
- Amarjit Soni (BNL): Flavor physics in the LHC era
- Matthew Szydagis (SUNY Albany): The Earthbound Quest for Galactic WIMP Recoils: LUX and Beyond
- Carlos Wagner (ANL / Univ of Chicago): Higgs physics: now and future
- Ciaran Williams (SUNY Buffalo): New developments in perturbative QCD

Parallel session mini-reviews:

- Nicolas Greiner (Univ of Zurich): NLO/MC tools
- Shufang Su (Univ of Arizona): Physics at future colliders
- Xerxes Tata (Univ of Hawaii): SUSY confronts the LHC

PITT PACC Travel Awards: With support from the NSF and DOE, there are a number of awards (up to $300 each) available to domestic graduate students for travel and accommodation to Pheno 16. A student applicant should send an updated CV and a statement of financial need, and arrange for a short recommendation letter sent from their thesis advisor, by email to pittpacc+award@pitt.edu. The decision will be based on the academic qualification, the talk submission to Pheno 16, and the financial need. The deadline for the application is April 10, and the winners will be notified by April 18. (Each research group may be limited to one awardee. Winners in the previous years may have lower priority for consideration. Winner institutes and names will be announced at the Symposium banquet.)

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Distance Visual Acuity Test (E Game)
(Read in good light at 10 feet.)

Line 1
20/200

Line 2
20/100

Line 3
20/40

Line 4
20/20

100 Millimeter Calibration Bar
(If not 100 mm, see text of visual acuity page.)
Distance Visual Acuity Test (E-Game)
(Read in good light at 10 feet.)
Disclaimer

• This type of talk can be dangerous
• Especially citing a paper but not its rival
• Solution:
  • no citations
  • except for mine

Agree
LHC score card

- origin of EWSB
  - Higgs discovery! But only a partial answer
- naturalness
  - None
- dark matter
  - None
- EW baryogenesis
  - No new CP violation
- unexpected
  - Perhaps??? 750 GeV diphoton???
July 4, 2012
discovery of Higgs boson

theory: 1964
design: 1984
construction: 1998
Scalar

- every elementary particles have spin
- electrons, photons, quarks, ....
- only Higgs boson doesn’t spin
- Faceless! A spooky particle
- I had proposed “Higgsless theories”
- *Is it the only one?*
- *does it have siblings? relatives?*
- Maybe it’s spinning in *extra dimensions?*
- maybe *composite?*
- *why did it freeze in?*
no sign of new physics that explains Higgs!
LHC score card

• origin of EWSB
  • Higgs discovery: not only a partial answer

• naturalness
  • None

• dark matter
  • None

• EW baryogenesis
  • No new CP violation

• unexpected
  • Perhaps?? 750 GeV diphoton???
IF SUPERSYMMETRY
DOESN’T PAN OUT,
IN
SCIENTISTS NEED A NEW WAY
PHYSICS
TO EXPLAIN THE UNIVERSE
?

AMERICAN

SCIENTIFIC

MACHINES THAT
CHANGE SHAPE

MEDICINE
AN OFF SWITCH
FOR CANCER

NEUROSCIENCE
HOW TO REACH
"VEGETATIVE"
PATIENTS

ScientificAmerican.com
315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE
Published: January 5, 1993

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful...
been there before

- CMB anisotropy
- universe younger than oldest stars?
- cosmologists got antsy
- it turned out a little “fine-tuned”
  - low quadrupole
  - dark energy

1% tuning
scalar top mass $\geq 10$ TeV preferred

Predicted range for the Higgs mass

Assumption: MSSM
Better Late Than Never

Even $m_{\text{SUSY}} \sim 10$ TeV ameliorates fine-tuning from $10^{-36}$ to $10^{-4}$
vector-like fermions? 100–1000 GeV

Nobody asked for it!
Matter particles

There must be three generations

Who ordered that??

I.I. Rabi

\[ \text{area} \propto \text{mass} \]
higher energies?

- Need to explore
- HL-LHC boosts reach
- We believe we should keep aiming at higher energies
- HE-LHC?
- 100 TeV pp would be great!
- Need to continue magnet R&D
- Possible first stage: FCCee upto 350 GeV
- CDR by 2018?
Another staged path

- guaranteed precision Higgs and top physics
- extendable 500 GeV to 1 TeV
- TDR exists
CLIC 3TeV
CDR exists TDR by 2018?
Plasma Wakefield

10 TeV

Delahaye et al, IPAC 2014
Rare effects from high energies

- Effects of high-energy physics mostly disappear by power suppression
  \[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots \]

- can be classified systematically

\[ \mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_{\nu\nu\nu} \]

\[ \mathcal{L}_6 = QQQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W^{a\mu}_\nu W^{b\nu}_\lambda W^{c\lambda}_\mu, \]

\[ (H^\dagger D^\mu H)(H^\dagger D_\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots \]
anarchy

Miriam-Webster: “A utopian society of individuals who enjoy complete freedom without government”

large mixing

neutrinos

symmetry

SU(3) Haar measure

KS probability = 44%
(de Gouvêa, HM)
max $\mathcal{CP}$ preferred
Power of Expedition

- Experimental reach [GeV] with significant simplifying assumptions
- EDM
- Dark matter
- LHC
- Quark flavor
- Lepton flavor
- Neutrino
- Proton decay

Unified Theories

courtesy: Zoltan Ligeti
Effective Operators

- Surprisingly difficult question
- In the case of the Standard Model
  - Weinberg (1980) on $D=6$ $\bar{B}$, $D=5$ $\bar{L}$
  - Buchmüller-Wyler (1986) on $D=6$ ops
  - 80 operators for $N_f=1$, $B$, $L$ conserving
  - Grzadkowski et al (2010) removed redundancies and discovered one missed
  - 59 operators for $N_f=1$, $B$, $L$ conserving
  - redundancies due to EOM, IBP
- Mahonar et al (2013) general $N_f$
- Lehman-Martin (2014,15) $D=7$ for general $N_f$, $D=8$ for $N_f=1$ (incorrect)
Repeating this at order $\epsilon^6$ we obtain the Hilbert series for dimension-six operators of the SM EFT:

$$\hat{H}_6 = H^3 H^\dagger H + 2Q^2 Q^\dagger + Q^\dagger L + Q^L + 2Q^\dagger LL + L^2 L^\dagger + uQH^2 H^\dagger + 2uu^\dagger QQ + uu^\dagger LL + u^2 u^\dagger + e^\dagger u^\dagger Q^2 + e^\dagger L^\dagger H^2 H + 2e^\dagger u^\dagger Q^\dagger L + eLHH + euQ^2 + 2euQL + ee^\dagger QQ + ee^\dagger LL + ee u u^\dagger + e^2 e^\dagger + d^\dagger Q^\dagger H^2 H + 2d^\dagger u^\dagger Q^\dagger + d^\dagger u^\dagger QL + d^\dagger e^\dagger Q^\dagger L + dQHH + 2duQ^2 + duQ^\dagger L + de^\dagger QL + de u^2 + 2dd^\dagger QQ + dd^\dagger LL + 2dd^\dagger uu^\dagger + dd^\dagger ee^\dagger + d^2 d^\dagger + u^\dagger Q^\dagger H^\dagger G_R + d^\dagger Q^\dagger HG_R + HH^\dagger G_R^2 + G_R^3 + uQHG_L + dQH^\dagger G_L + HH^\dagger G_L^2 + G_L^3 + u^\dagger Q^\dagger H^\dagger W_R + e^\dagger L^\dagger HW_R + d^\dagger Q^\dagger HW_R + HH^\dagger W^2_R + W^3_R + uQHW_L + eLH^\dagger W_L + dQH^\dagger W_L + HH^\dagger W^2_L + W^3_L + u^\dagger Q^\dagger H^\dagger B_R + e^\dagger L^\dagger HB_R + d^\dagger Q^\dagger HB_R + HH^\dagger B_RW_R + HH^\dagger B_R^2 + uQHB_L + eLH^\dagger B_L + dQH^\dagger B_L + HH^\dagger B_L W_L + HH^\dagger B_L^2 + 2QQ^\dagger HH^\dagger D + 2LL^\dagger HH^\dagger D + uu^\dagger HH^\dagger D + ee^\dagger HH^\dagger D + d^\dagger uH^2 D + du^\dagger H^2 D + dd^\dagger HH^\dagger D + 2H^2 H^\dagger D^2.$$ (3.16)

Setting all of the spurions equal to unity gives $\hat{H}_6 = 84$, the total number of independent local operators at dimension 6, but more information is contained in eq. (3.16). For instance, the counting can easily be further decomposed by baryon number violation, $76 + 8$. The perhaps more familiar ‘59 + 4’ counting is one in which hermitian conjugates of fermionic operators are not counted separately (such counting can of course also be obtained from eq. (3.16)).
Main idea

Brian Henning, Xiaochuan Lu, Tom Melia, HM

• Take kinetic terms as the zeroth order Lagrangian $(\partial \phi)^2$, $\bar{\psi}i\partial\psi$, $(F_{\mu\nu})^2$
• Classically, it is conformally invariant under $\text{SO}(4,2) \cong \text{SO}(6,\mathbb{C})$
• Operator-State correspondence in CFT tells us that operators fall into representations of the conformal group
• equation of motion: short multiplets
• remove total derivatives: primary states

$$H(\mathcal{D}, \phi_1, \cdots, \phi_n) = \int d\mu_{\text{conf}} d\mu_{\text{gauge}} \sum_k \mathcal{D}^k \chi_{\Delta_0+k,0}^* \text{PE} \left[ \frac{\phi_1}{\mathcal{D}^{d_1}} \chi_1 \right] \cdots \text{PE} \left[ \frac{\phi_n}{\mathcal{D}^{d_n}} \chi_n \right]$$
Hitoshi-no-MacBook-Pro.local 35: form hssm6.frm
No. of independent ops

\(N_f=1\)

\(N_f=3\)
$B_s$: Strangely Beautiful

- $\nu_\mu$ and $\nu_\tau$ mix a lot
- $(\nu_\mu, s_R)$, $(\nu_\tau, b_R)$ under GUT
- Perhaps big mixing between $s_R$ and $b_R$?
- I had predicted $O(1)$ effects of new physics on $B_s$

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ps}^{-1}$
Ceshire cat
Figure 5: Upper limits on the DM-nucleon cross section, at 90% CL, plotted against DM particle mass and compared with previously published results. Left: limits for the vector and scalar operators from the previous CMS analysis [10], together with results from the CoGeNT [60], SIMPLE [61], COUPP [62], CDMS [63, 64], SuperCDMS [65], XENON100 [66], and LUX [67] collaborations. The solid and hatched yellow contours show the 68% and 90% CL contours respectively for a possible signal from CDMS [68]. Right: limits for the axial-vector operator from the previous CMS analysis [10], together with results from the SIMPLE [61], COUPP [62], Super-K [69], and IceCube [70] collaborations.

Figure 6: Observed limits on the mediator mass divided by coupling, $M/p_g$, as a function of the mass of the mediator, $M$, assuming vector interactions and a dark matter mass of 50 GeV (blue, filled) and 500 GeV (red, hatched). The width, $G$, of the mediator is varied between $M/3$ and $M/8$. The dashed lines show contours of constant coupling $p_g$.

$K_{\text{LO}} = s_N / s_L$ of 1.4 for $d = \{2, 3\}$, 1.3 for $d = \{4, 5\}$, and 1.2 for $d = 6$ [71]. Figure 7 shows 95% CL limits at LO, compared to published results from ATLAS, LEP, and the Tevatron. Table 7 shows the expected and observed limits at LO and NLO for the ADD model.

Figure 8 shows the expected and observed 95% CL limits on the cross-sections for scalar un-
sociology

- in 1980s, dark matter was not as clear
- people tried to solve big problems in particle physics, i.e. naturalness, strong CP
- dark matter was optional, i.e. WIMP
- in 2010s, dark matter is a glaring problem
- but no sign of solution to naturalness
- perhaps naturalness is optional?
- rethinking: be more open-minded
Miracles

\[
\frac{n_{\text{DM}}}{s} = 4.4 \times 10^{-10} \text{ GeV}^{-1} \text{cm}^3 \text{s}^{-1}
\]

\[
\langle \sigma_{2 \to 2\nu} \rangle \approx \frac{\alpha^2}{m^2}
\]

\[
\alpha \approx 10^{-2}
\]

\[
m \approx 300 \text{ GeV}
\]

WIMP miracle\(^2\)

\[
\langle \sigma_{3 \to 2\nu^2} \rangle \approx \frac{\alpha^3}{m^5}
\]

\[
\alpha \approx 4\pi
\]

Hochberg, Kuflik, Volansky, Wacker

\[
m \approx 300 \text{ MeV}
\]

SIMP miracle\(^2\)

arXiv:1402.5143
SIMPlest Miracle

Yonit Hochberg, Eric Kuflik, HM, Tomer Volansky, Jay Wacker

- SU(2) gauge theory with four doublets
- SU(4)=SO(6) flavor symmetry
- $\langle q^i q^i \rangle \neq 0$ breaks it to Sp(2)=SO(5)
- coset space $SO(6)/SO(5)=S^5$
- 5 stable pions
- $\pi_5(S^5)=\mathbb{Z} \Rightarrow$ Wess-Zumino term

- $L_{WZ} = \epsilon_{abcde} \epsilon^{\mu \nu \rho \sigma} \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e$

SIMP miracle\(^3\)
also lack of cusps in dwarf galaxies
explore dark sector

dark QCD with SIMP

dark photon

Standard Model

$e^-$

$e^+$

$A'(\ast)$

$\gamma$

$\chi$

$\bar{\chi}$
$SU(2), N_f = 2$

$\alpha_D = 1/4\pi$

$m_\pi = 300$ MeV
SU(2), \(N_f = 2\)
\[\alpha_D = \frac{1}{4\pi}\]
\[m_\pi = 300 \text{ MeV}\]
Super KEK B & Belle II

50 ab⁻¹!

\[ E_{\gamma} = \frac{\sqrt{s}}{2} \left( 1 - \frac{M_{\text{inv}}^2}{s} \right) \]
The hidden sector may generally contain a multitude of states, including a hidden photon, and four parameters:

- the mediator mass
- the DM mass
- the coupling of the mediator to electrons
- the coupling of the mediator to the DM

The rest of the paper is organized as follows. In Sec. II we give a brief theoretical overview of LDM coupled through a light mediator. Sec. III contains a more detailed discussion of production rates, but will have a more significant effect on their predictions with respect to the mediator and is invisible in detectors; in particular, low-energy collisions, through an on- or off-shell mediator (such as light neutralino production through a Higgs boson, and consequently their couplings generically couple to SM fermions through mixing.

We will refer in the following to this restriction as the "perturbativity" constraint. We restrict which is necessary for the constraint is also equivalent to imposing in order to guarantee calculability of the model. Such a parameterization is the simplest example of such a setup is DM that does not necessarily indicate a abuse of notation, may refer to a generic (pseudo-)vector, or (pseudo-)scalar, and does not necessarily indicate a.

Starting in Sec. IV we derive constraints on the mediator mass using the collider such as Belle II. We conclude in Sec. VII. A short estimate the reach of a similar search in a future collider.

The hidden photon for some additional scenarios.

FIG. 1:

\[
e^+e^- \rightarrow \gamma + \text{hidden photon}\]

\[
E_\gamma = \frac{\sqrt{s}}{2} \left( 1 - \frac{M_{\text{inv}}^2}{s} \right)
\]

Yonit Hochberg, Eric Kuflik, HM
QCD axion
sterile neutrino
moduli w/ vector mediation
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

mass [GeV]

-10
-30
-20
-10
0
10
20
30
40
50

to fluffy

no good idea

mirolensing etc
PBH binary formed in early Universe

$\Omega_{\text{PBH}} / \Omega_{\text{DM}}$
Conclusions

• HEP: very exciting
• Higgs: need to understand it better
  • HL-LHC, ILC, FCCee
• naturalness: higher energies, precision
  • HE-LHC, FCCpp, CLIC, PWFA
• flavor physics, EDM, $0\nu\beta\beta$, p-decay
• baryogenesis:
  • $B$, $K$, LFV, neutrino oscillation
• dark matter: open mind, broad search
  • cosmology, direct, indirect, collider
theorist

experiments
healthy field!