Particle Physics and the Intensity Frontier

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Fermilab
Outline

• The Intensity Strategy
• Three Frontiers Scorecard
• Neutrinos
• Muons
• Kaons
History of Popular Graphics at the DOE

Then

Now
The Intensity Strategy

Question: Why haven’t we already observed all phenomena of relevance to fundamental physics?

1. The phenomena involve objects that are hard to make in the laboratory (e.g. black holes, heavy gluinos, ...)
2. The phenomena involve interactions that are fundamentally weak and thus rare
3. The phenomena involve interactions that are very short range and thus rare

In case #1, proceed to Energy or Cosmic Frontiers

In cases #2 and #3, we can use high intensities to observe rare phenomena
## Advancing the Frontiers: 1995 -2010

<table>
<thead>
<tr>
<th></th>
<th>Huge Surprising Discoveries</th>
<th>Evidence of New Fundamental Phenomena</th>
<th>First Observations or Strong Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity</strong></td>
<td>Neutrinos have mass!</td>
<td>g-2 anomaly (superpartners?)</td>
<td>Too numerous to enumerate here (hundreds)</td>
</tr>
<tr>
<td></td>
<td>Lepton flavor not conserved!</td>
<td>direct CP violation in kaons</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B -&gt; tau nu anomaly + other B puzzles</td>
<td></td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>Heavy top quark!</td>
<td>DZero muon asymmetry</td>
<td>Too numerous to enumerate here (hundreds)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(new CP violation and quark flavor violation?)</td>
<td></td>
</tr>
<tr>
<td><strong>Cosmic</strong></td>
<td>Dark matter is nonbaryonic and mostly cold!</td>
<td>Universe is flat (inflation?)</td>
<td>Too numerous to enumerate here (dozens)</td>
</tr>
<tr>
<td></td>
<td>Dark energy!?</td>
<td>Primordial density fluctuations (inflation?)</td>
<td></td>
</tr>
</tbody>
</table>
## Advancing the Frontiers: 2010 - 2025

<table>
<thead>
<tr>
<th></th>
<th>Huge Surprising Discoveries</th>
<th>Evidence of New Fundamental Phenomena</th>
<th>First Observations or Strong Limits</th>
</tr>
</thead>
</table>
| **Intensity** | Neutrinos violate CP!  
Charged leptons mix!  
Neutrinos see a new force!  
etc! | Leptogenesis!  
Grand Unification!  
The origin of matter! | Too numerous to enumerate here (hundreds) |
| **Energy**    | Nonstandard or No Higgs!  
Dark matter particles produced!  
New forces!  
New dimensions, etc! | Dark/hidden sectors!  
Grand Unification!  
The origin of matter! | Too numerous to enumerate here (hundreds) |
| **Cosmic**    | Dark matter particles observed!  
Dark energy is dynamical!  
Footprints of inflation!  
etc! | The origin of the universe!  
The fate of the universe! | Too numerous to enumerate here (hundreds) |
Origins

• The Origin of Mass:
  • How do massless chiral fermions become matter particles? (buzzword = “Higgs”)

• The Origin of Matter:
  • Why are there so many different kinds of matter particles with different properties? (buzzword = “Flavor”)

• The Origin of the Universe:
  • Where did matter come from in the first place, and why didn’t it all annihilate with antimatter? (buzzwords = “Leptogogenesis”, “Baryogenesis”)
1925:

Chemistry and spectroscopy + fundamentally new idea (quantum mechanics) = Theory of atomic structure

2025?

Neutrino, charged lepton, quark, (+?) properties + fundamentally new idea (????????) = Theory explaining both unity and origins of matter
1925:

Chemistry and spectroscopy + fundamentally new idea (quantum mechanics)

= Theory of atomic structure

makes scientists happy

2025?

Neutrino, charged lepton, quark, (+?) properties + fundamentally new idea (????????)

= Theory explaining both unity and origins of matter
1925:

Chemistry and spectroscopy + fundamentally new idea (quantum mechanics) = Theory of atomic structure

2025?

Neutrino, charged lepton, quark, (+?) properties + fundamentally new idea (????????) = Theory explaining both unity and origins of matter

$10 trillion game-changer!
Project X Intensity Frontier Physics Portfolio

• Neutrinos
  • Long baseline neutrino oscillations
  • Shorter (or no) baseline neutrino experiments

• Muons
  • Muon to electron conversion
  • anomalous g-2 of muon
  • Electric dipole moments

• Kaons
  • Rare charged kaon decays
  • Rare neutral kaon decays

• + more to come
Neutrinos are interesting

\[ \Delta m^2 \sim 2.4 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 \theta_{23} \sim 0.5 \]
\[ \sin^2 \theta_{13} < \text{few \%} \]
\[ \delta m^2 \sim 7.7 \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 \theta_{12} \sim 0.31 \]

Oscillation patterns; O(eV) cosmo limits

Red bars = neutrino papers by J.L. (times 250)

E. Lisi, talk at ICHEP 2010
Neutrinos are Messengers of New Physics

Neutrinos, unlike quarks:

• Have tiny masses
• May have “inverted” mass splittings
• Have large mixings
• Might be mixed with additional light fermions (“steriles”)
• Might be their own antiparticles (“Majorana”)
  • thus violating L and B - L
  • and having extra CP phases
  • and having superheavy partners

Furthermore:

• They oscillate flavors over macroscopic distances
• This oscillation phase is sensitive to the medium (matter effects)
• They are part of the dark matter and may be related to dark energy
• They may experience new interactions or exotic effects
How do neutrinos talk to the Higgs?

- Either neutrinos couple to the Higgs via superheavy partners, or via new TeV particles accessible at the LHC
- Need to nail down the neutrino masses, mixings, and possible CP phases
- Even more so if neutrinos have one or more sterile components

- Variants (inverse, +SUSY, +LR, +radiative, ...)

Type I, fermion singlet $N$, charge 0
Type II, scalar triplet $\Delta$, charge 0, 1, 2
Type III, fermion triplet $\Sigma$, charge 0, 1
Project X Long Baseline Neutrinos

\[ \sin^2(2\theta_{13}) \]

\[ \delta_{CP} \text{ coverage (\%)} \]

- Normal Hierarchy
- 5 yrs $\nu + 5$ yrs $\bar{\nu}$

- 2 MW
- 200 kt WC+
- 34 kt LAr
- 700 kW
- 100 kt WC+
- 17 kt LAr

$\theta_{13}$ (3$\sigma$)

MH (95\% CL)

CPV (3$\sigma$)

L. Whitehead

J. Lykken, “Particle Physics and the Intensity Frontier” 16 Project X Briefing, DOE, 17 Nov 2010
Intensity Frontier: Muons

- Muons
  - Muon to electron conversion
    - Not yet observed, requires new physics
  - Anomalous g-2 of muon
    - BNL experiment saw $>3$ sigma effect, requires new physics
  - Electric dipole moments of muon, electron, neutron, nuclei
    - Not yet observed, requires new physics

These could all come from the same new physics, involving both neutrinos new LHC-accessible particles
A scenario for new physics with muons

Some new heavy particles (e.g. sleptons and gauginos in supersymmetry) have quantum effects on leptons, e.g. the muon

- The lepton flavor conserving, CP conserving part of this contributes to muon g-2
- The lepton flavor conserving, CP violating part creates an EDM
- The lepton flavor violating part induces mu to e conversion. Note that a heavy Majorana neutrino sector will induce this automatically

A scenario for new physics with muons

In this picture a g-2 anomaly implies heavy lepton partners at the LHC, AND very likely signals for MEG and mu2e, AND possibly detectable EDMs

\[
\frac{a_\mu^{\text{MSSM}}}{1 \times 10^{-9}} \approx 1.5 \left( \frac{\tan \beta}{10} \right) \left( \frac{300 \text{ GeV}}{m_\ell} \right)^2 \text{sgn} \mu
\]

\[
\frac{d_e}{d_\mu} = \frac{\Sigma_{k=2,3} \text{Im}(\delta^{RR}_{e1k}(\delta^{LL}_\ell)_{k1})}{\text{Im}(\delta^{RR}_{e23}(\delta^{LL}_{\ell})_{32})}
\]

\[
\text{BR}(\mu \rightarrow e \gamma) \approx 2 \times 10^{-12} \left[ \frac{\Delta a_\mu^{\text{SUSY}}}{3 \times 10^{-9}} \right]^2 \left| \frac{(\delta^{LL}_{\ell})_{21}}{10^{-4}} \right|^2,
\]
Probing physics at 3,000 TeV?

A model-independent analysis of mu to e:

\[ \mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1) \Lambda^2} \bar{\mu}_R \sigma_{\mu \nu} e_L F^{\mu \nu} \]

\[ + \frac{\kappa}{(1 + \kappa) \Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{e} \gamma^\mu e). \]

Our previous scenario amounts to an interpretation of \( \Lambda \):

\[ \frac{1}{\Lambda^2} \sim \frac{g^2 e}{16\pi^2 M_{\text{SUSY}}^2} \theta_{e\mu}, \]

But \( \Lambda \) could directly correspond to a new 3,000 TeV energy scale, e.g. the scale of lepton compositeness

\[ B(\mu \rightarrow e \text{ conversion in } ^{48}\text{Ti}) > 10^{-18} \]

\[ B(\mu \rightarrow e \text{ conversion in } ^{48}\text{Ti}) > 10^{-16} \]

\[ B(\mu \rightarrow e\gamma) > 10^{-14} \]

\[ B(\mu \rightarrow e\gamma) > 10^{-13} \]
Intensity Frontier: Kaons

Leading Feynman diagrams relevant to $K \rightarrow \pi \nu \bar{\nu}$ decays

**Standard Model decay rates are small, easily affected by interference with new physics**

**Uncertainty in predictions is already small and will shrink more over time**

\[
B_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.51 \pm 0.72) \times 10^{-11}
\]

\[
B_{SM}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (2.54 \pm 0.48) \times 10^{-11},
\]
Effects of new physics, a conservative example: Minimal Flavor Violating Supersymmetry

Figure 1: Regions in the $m_t - m_{\tilde{\chi}}$ plane (lightest stop and chargino masses) allowing enhancements of $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ of more than 11% (yellow/light gray), 8.5% (red/medium gray) and 6% (blue/dark gray) in the MFV scenario, for $\tan \beta = 2$ and $M_{H^+} > 1$ TeV [the corresponding enhancements for $B(K_L \rightarrow \pi^0 \nu\bar{\nu})$ are 15%, 12.5% and 10%, respectively, see Eq. (21)].

G. Isidori et al, hep-ph/0604074
Effects of new physics, a conservative example: Minimal Flavor Violating Supersymmetry

Correlations provide a strong test of the hypothesis of Minimal Flavor Violation

C. Bobeth, M. Bona, A. Buras, T. Ewerth, M. Pierini, L. Silvestrini, A. Weiler hep-ph/0505110

its ment of ratios for extra dimensions, little-Higgs models, and so on. Note that although in some cases the branching "usual suspects," namely supersymmetric versions of the Standard Model, models with warped examples can be found in, for example, References 63, 68, and 69. These examples involve the space is peppered with predictions from different models for new physics. Several other concrete MFV. One can readily appreciate that the entire currently allowed region of the branching ratio can be affected much more than the other.

LHT, little-Higgs models with blue region (65). Abbreviations: CMFV, constrained minimal flavor violation; EFT, effective field theory; existence of a fourth generation. The Grossman-Nir bound refers to an isospin analysis that forbids the light brown dots depict allowed simultaneous values of the charged and neutral branching ratios in the from Reference 68, courtesy of Federico Mescia.

Predictions of different new physics models for the branching ratios for 

Figure 8


The Really Big Proton Gun

Project X uniquely enables a broad discovery program where many wonderful things may happen.

If history is any guide, this will include one or more big surprises.

Project X discoveries combined with advances from the Energy and Cosmic Frontiers will illuminate the unified origins of everything, and more.
Backup Slides
Thus suppose we can measure (with pretty good precision) the ratio

\[
\frac{BR(\mu \rightarrow e\gamma)}{R(\mu Ti \rightarrow e Ti)} \equiv C
\]
scan over mSUGRA models
note C is always between ~ 120 and 220
C. Yaguna, hep-ph/0502014

sensitivity to both $\tan \beta$ and the sign of $\mu$
E. Arganda, M-J Herrero, A. Teixeira, arXiv:0707.2955

-1.8, \delta_2 = 0
\frac{A_0}{m_N} (10^{10}, 10^{11}, 10^{14}) \text{ GeV}
\tan \beta = 50
\theta_{13} = 5^\circ, \theta_i = 0
\delta_1 = -1.8, \delta_2 = 0
\rho = 0

using other nuclei gives added handles
<table>
<thead>
<tr>
<th>Process</th>
<th>Present Bounds</th>
<th>Expected Future Bounds</th>
<th>Future Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(\mu \to e \gamma)$</td>
<td>$1.2 \times 10^{-11}$</td>
<td>$\mathcal{O}(10^{-13} - 10^{-14})$</td>
<td>MEG, PSI</td>
</tr>
<tr>
<td>$\text{BR}(\mu \to e e e)$</td>
<td>$1.1 \times 10^{-12}$</td>
<td>$\mathcal{O}(10^{-13} - 10^{-14})$</td>
<td>?</td>
</tr>
<tr>
<td>$\text{BR}(\mu \to e \text{ in Nuclei (Ti)})$</td>
<td>$1.1 \times 10^{-12}$</td>
<td>$\mathcal{O}(10^{-18})$</td>
<td>J-PARC</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to e \gamma)$</td>
<td>$1.1 \times 10^{-7}$</td>
<td>$\mathcal{O}(10^{-8})$</td>
<td>SuperB</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to e e e)$</td>
<td>$2.7 \times 10^{-7}$</td>
<td>$\mathcal{O}(10^{-8})$</td>
<td>SuperB</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to e \mu \mu)$</td>
<td>$2. \times 10^{-7}$</td>
<td>$\mathcal{O}(10^{-8})$</td>
<td>SuperB</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to \mu \gamma)$</td>
<td>$6.8 \times 10^{-8}$</td>
<td>$\mathcal{O}(10^{-8})$</td>
<td>SuperB</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to \mu \mu \mu)$</td>
<td>$2 \times 10^{-7}$</td>
<td>$\mathcal{O}(10^{-8})$</td>
<td>LHCb</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to \mu e e)$</td>
<td>$2.4 \times 10^{-7}$</td>
<td>$\mathcal{O}(10^{-8})$</td>
<td>SuperB</td>
</tr>
</tbody>
</table>

Table 5: Present [81] and upcoming experimental limits on various leptonic processes at 90% C.L.
<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>δLL</th>
<th>FBMSSM</th>
<th>LHT</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 - \bar{D}^0$</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>?</td>
</tr>
<tr>
<td>$\epsilon_K$</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
</tr>
<tr>
<td>$S_{\psi\phi}$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$S_{\phi K_S}$</td>
<td>★★★</td>
<td>★★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B \to X_s \gamma)$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$A_{7,8}(B \to K^* \mu^+ \mu^-)$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★★</td>
</tr>
<tr>
<td>$A_9(B \to K^* \mu^+ \mu^-)$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$B \to K^{(*)} \nu \bar{\nu}$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>$B_s \to \mu^+ \mu^-$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$K^+ \to \pi^+ \nu \bar{\nu}$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$K_L \to \pi^0 \nu \bar{\nu}$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$\mu \to e \gamma$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$\tau \to \mu \gamma$</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$\mu + N \to e + N$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$d_n$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$d_e$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$(g - 2)_\mu$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>?</td>
</tr>
</tbody>
</table>

Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★★ signals large effects, ★★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.
<table>
<thead>
<tr>
<th>observable</th>
<th>SM prediction</th>
<th>exp. current</th>
<th>exp. future</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\psi\phi}$</td>
<td>$\sim 0.036 \ [81]$</td>
<td>$0.81^{+0.12}_{-0.32} \ [1]$</td>
<td>$\sim 0.02 \ [193]$</td>
</tr>
<tr>
<td>$S_{\phi K_S}$</td>
<td>$\sin 2\beta + 0.02 \pm 0.01 \ [2]$</td>
<td>$0.44 \pm 0.17 \ [1]$</td>
<td>$(2 - 3)% \ [194]$</td>
</tr>
<tr>
<td>$S_{\eta' K_S}$</td>
<td>$\sin 2\beta + 0.01 \pm 0.01 \ [2]$</td>
<td>$0.59 \pm 0.07 \ [1]$</td>
<td>$(1 - 2)% \ [194]$</td>
</tr>
<tr>
<td>$A_{\text{CP}}(b \to s\gamma)$</td>
<td>$(-0.44^{+0.14}_{-0.24}) % \ [195]$</td>
<td>$(-0.4 \pm 3.6) % \ [1]$</td>
<td>$(0.4 - 0.5)% \ [194]$</td>
</tr>
<tr>
<td>$\langle A_7 \rangle$</td>
<td>$(3.4^{+0.4}_{-0.5})10^{-3} \ [140]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\langle A_8 \rangle$</td>
<td>$(-2.6^{+0.4}_{-0.3})10^{-3} \ [140]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\langle A_9 \rangle$</td>
<td>$(0.1^{+0.1}_{-0.0})10^{-3} \ [140]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>d_e</td>
<td>\ (e\ cm)$</td>
<td>$\sim 10^{-38} \ [196]$</td>
</tr>
<tr>
<td>$</td>
<td>d_n</td>
<td>\ (e\ cm)$</td>
<td>$\sim 10^{-32} \ [196]$</td>
</tr>
<tr>
<td>BR($B_s \to \mu^+\mu^-$)</td>
<td>$(3.60 \pm 0.37)10^{-9}$</td>
<td>$&lt; 5.8 \times 10^{-8} \ [146]$</td>
<td>$\sim 10^{-9} \ [199]$</td>
</tr>
<tr>
<td>BR($B_d \to \mu^+\mu^-$)</td>
<td>$(1.08 \pm 0.11)10^{-10}$</td>
<td>$&lt; 1.8 \times 10^{-8} \ [146]$</td>
<td></td>
</tr>
<tr>
<td>BR($B \to X_s\gamma$)</td>
<td>$(3.15 \pm 0.23)10^{-4} \ [200]$</td>
<td>$(3.52 \pm 0.25)10^{-4} \ [1]$</td>
<td></td>
</tr>
<tr>
<td>BR($B \to X_s\ell^+\ell^-$)</td>
<td>$(1.59 \pm 0.11)10^{-6} \ [201]$</td>
<td>$(1.59 \pm 0.49)10^{-6} \ [202, 203]$</td>
<td></td>
</tr>
<tr>
<td>BR($B \to \tau\nu$)</td>
<td>$(1.10 \pm 0.29)10^{-4}$</td>
<td>$(1.73 \pm 0.35)10^{-4} \ [112]$</td>
<td></td>
</tr>
</tbody>
</table>