Intensity Frontier Overview

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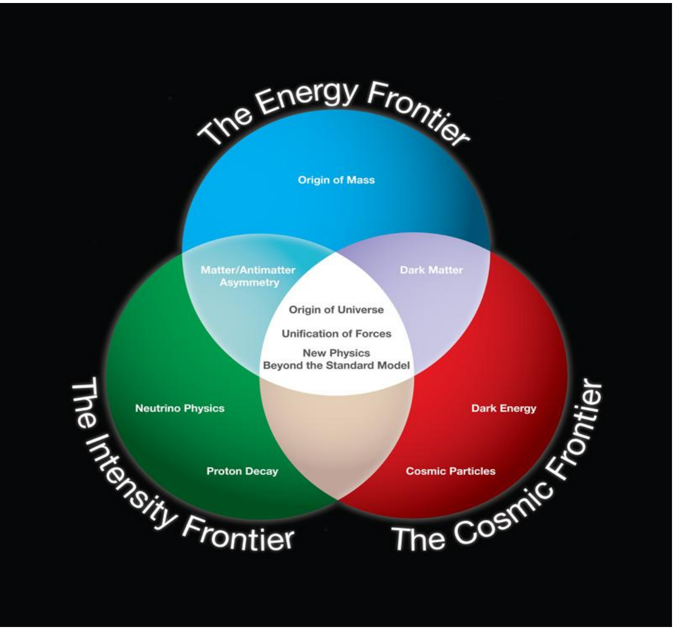
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

HEP and the Frontiers

Good representation of HEP



Shows multi-pronged approach to search for new physics

- **Direct Searches**
- **Precision Measurements**
- **Rare and Forbidden Processes**
- **Fundamental Properties of Particles and Interactions**
- **Cosmological observations**

Quote from Harry: "Respect for others and their work is the magic word we need for Snowmass"

The Intensity Frontier

Exploration of Fundamental Physics with

- intense sources
- ultra-sensitive, sometimes very massive, detectors

Intensity frontier science searches for

- Extremely rare processes
- Tiny deviations from Standard Model predictions

Precision measurements that indirectly probe quantum effects

Extends outside of HEP – Nuclear Physics sponsors some programs

Intensity Frontier Science

The Intensity Frontier addresses fundamental questions:

Are there new sources of CPV?

Is there CPV in the leptonic sector?

Are ν's Majorana or Dirac?

Do the forces unify?

Is there a weakly coupled Hidden Sector linked to Dark Matter?

Are apparent symmetries (B,L) violated at high scales?

What is the flavor sector of new physics?

Can we expand the new physics reach of the energy frontier?

The Intensity Frontier Manifesto

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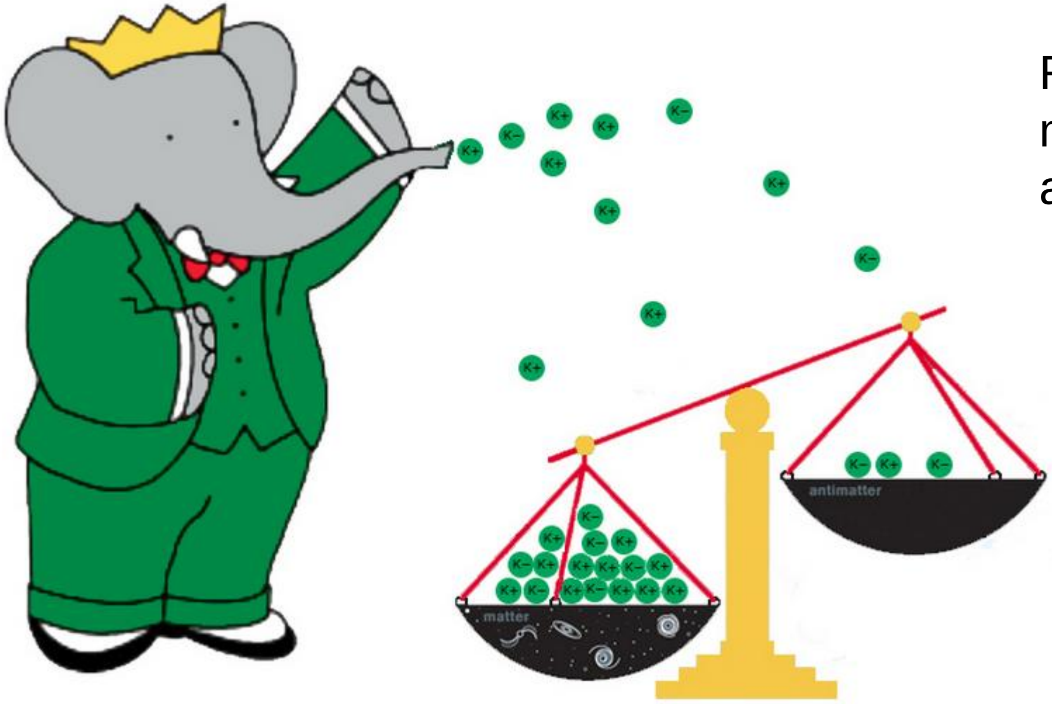
All frontiers of high energy physics aim to discover and understand the constituents of matter and their interactions at the highest energies, at the shortest distances, and at the earliest times in the Universe. The Standard Model fails to explain all observed phenomena: new interactions and yet unseen particles must exist. They may manifest themselves either directly, as new particles, or by causing Standard Model reactions to differ from often very precise predictions. The Intensity Frontier explores these fundamental questions by searching for new physics in processes extremely rare or those forbidden in the Standard Model. This requires the greatest possible beam intensities, as well as massive ultra-sensitive detectors. Many of these experiments are sensitive to new physics at higher mass scales, or weaker interaction strengths, than those directly accessible at the LHC or any foreseeable high-energy collider, thus providing opportunities for paradigm-changing new discoveries complementary to Energy and Cosmic Frontier experiments.

The range of experiments encompassing the Intensity Frontier is broad and diverse. Intense beams of neutrinos aimed over long distances at very large detectors will explore the neutrino mass hierarchy, search for CP violation and non-standard interactions, and increase sensitivity to proton decay. Multi-ton-scale detectors will determine whether neutrinos are their own antiparticles. Intense beams of electrons will enable searches for hidden-sector particles that may mediate dark matter interactions. Extremely rare muon and tau decay experiments will search for violation of charged lepton quantum numbers. Measurements of intrinsic lepton properties, such electric and magnetic dipole moments are another promising thrust. Rare and CP-violating decays of bottom, charm, and strange particles, measured with unprecedented precision, will be important to unravel the new physics underlying discoveries at the LHC. In any new physics scenario, Intensity Frontier experiments with sensitivities to very high mass scales will be a primary tool for exploration.

Maybe we need something more crisp…

Two main Themes:

1. Explore Symmetry Violation in Nature
   - CP, Baryon, Lepton Number Violation



Related to the matter anti-matter asymmetry

The IF Message

Two main Themes:

1. Explore Symmetry Violation in Nature
   - CP, Baryon, Lepton Number Violation
2. Explore High Energy Scales
   - IF explores very, very, very high energies!

Flavor Physics:

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

trivial kinematical factors

(adimensional) effective couplings

Neutrinos:

$$\frac{1}{\Lambda}(y_\nu L H)(y_\nu L H) + h.c. \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda}\, \overline{\nu_L}\, \nu_R^c.$$

New Physics Flavor Problem

New Physics is constrained by flavor physics observables. E.g. mixing and CP violation.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C_{\text{NP}}}{\Lambda^2} O_{ij}$$

$\Delta F = 2$ operator	Bounds on Λ [TeV] ($C = 1$)		Bounds on C ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	2.2×10^2	7.6×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	7.4×10^2	1.3×10^{-5}	3.0×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

From the Report of the Heavy Quarks working group, Fundamental Physics at the Intensity Frontier (2012), arXiv:1205.2671

If there is New Physics at the 1 TeV scale, its flavor structure is unnatural.

Flavor in the LHC Era

New Physics found at LHC
$\Rightarrow$ New particles with unknown flavor- and CP-violating couplings

New Physics NOT found at LHC

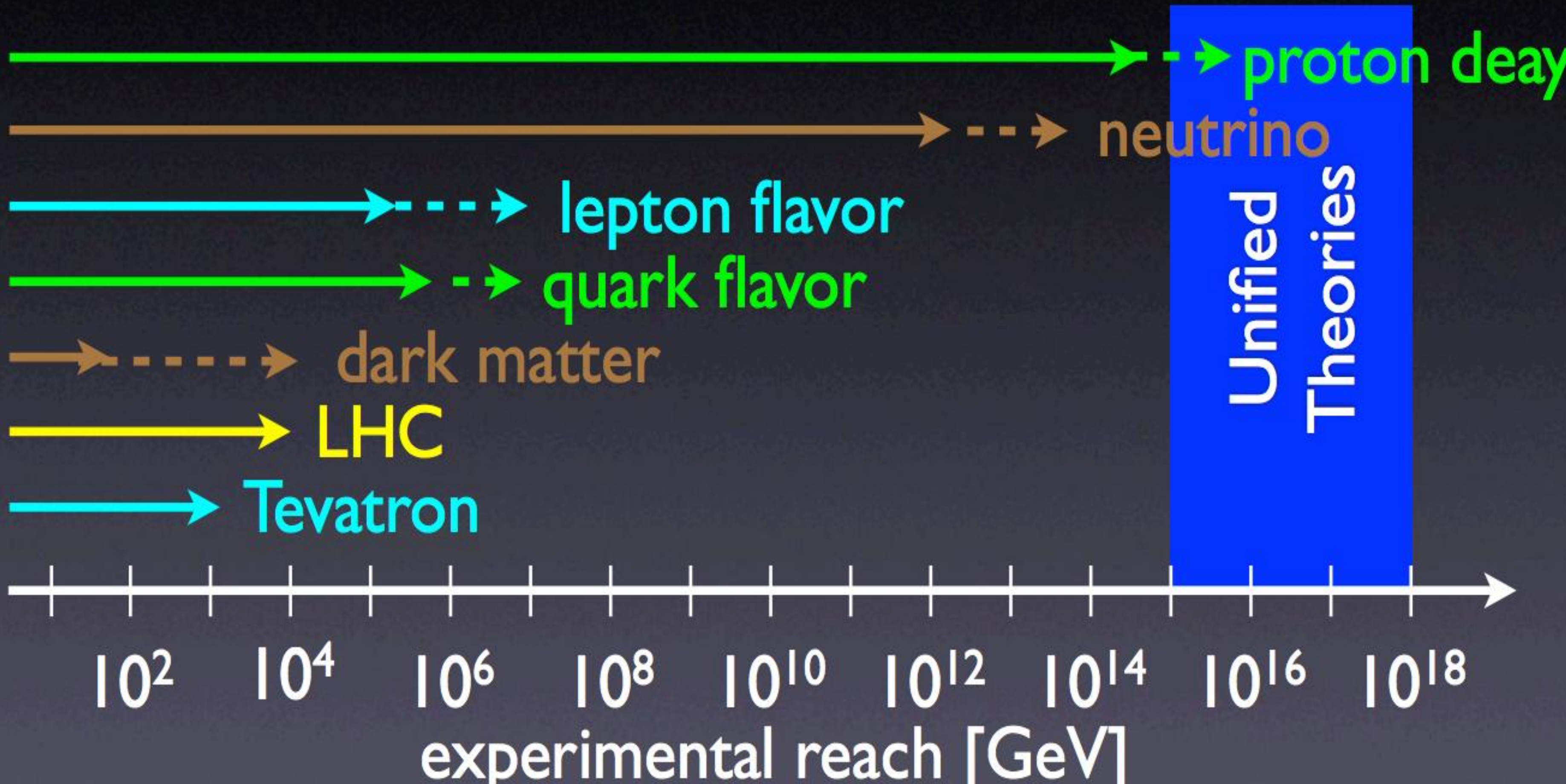
Precision flavor-physics expts will be needed sort out the flavor- and CP-violating couplings of the NP.

Precision flavor-physics expts will be needed since they are sensitive to NP at mass scales beyond the LHC.

Precision quark-flavor experiments (and lepton-flavor too) are essential.

A healthy U.S. HEP program will include a vigorous flavor-physics component (like Europe and Asia).

Power of Expedition



(with significant simplifying assumptions)

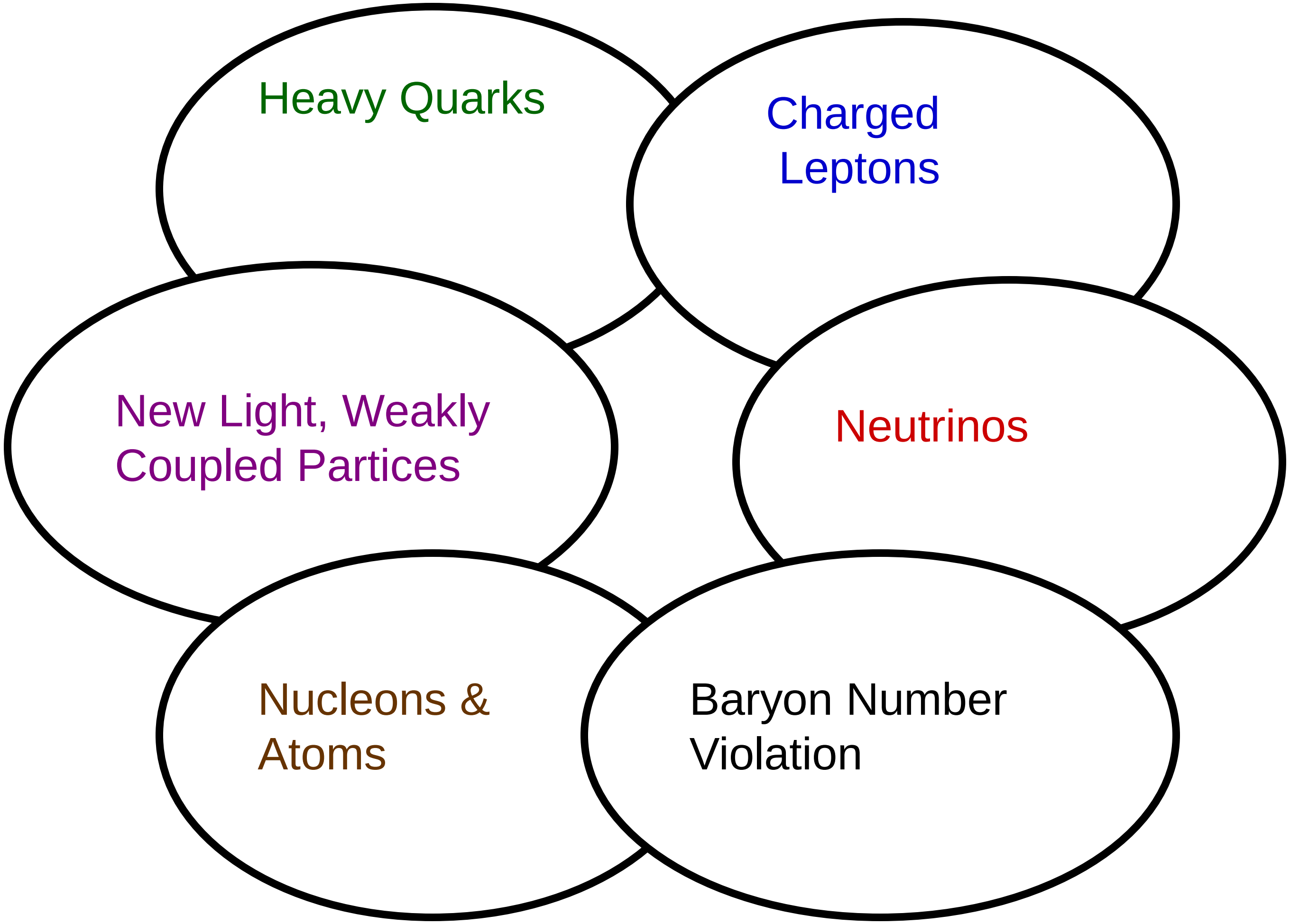
courtesy Zoltan Ligeti

The IF t-shirt

Thanks to
David Hitlin

The Intensity Frontier Program

The Intensity Frontier is a broad and diverse, yet connected, set of science opportunities



The Intensity Frontier Program

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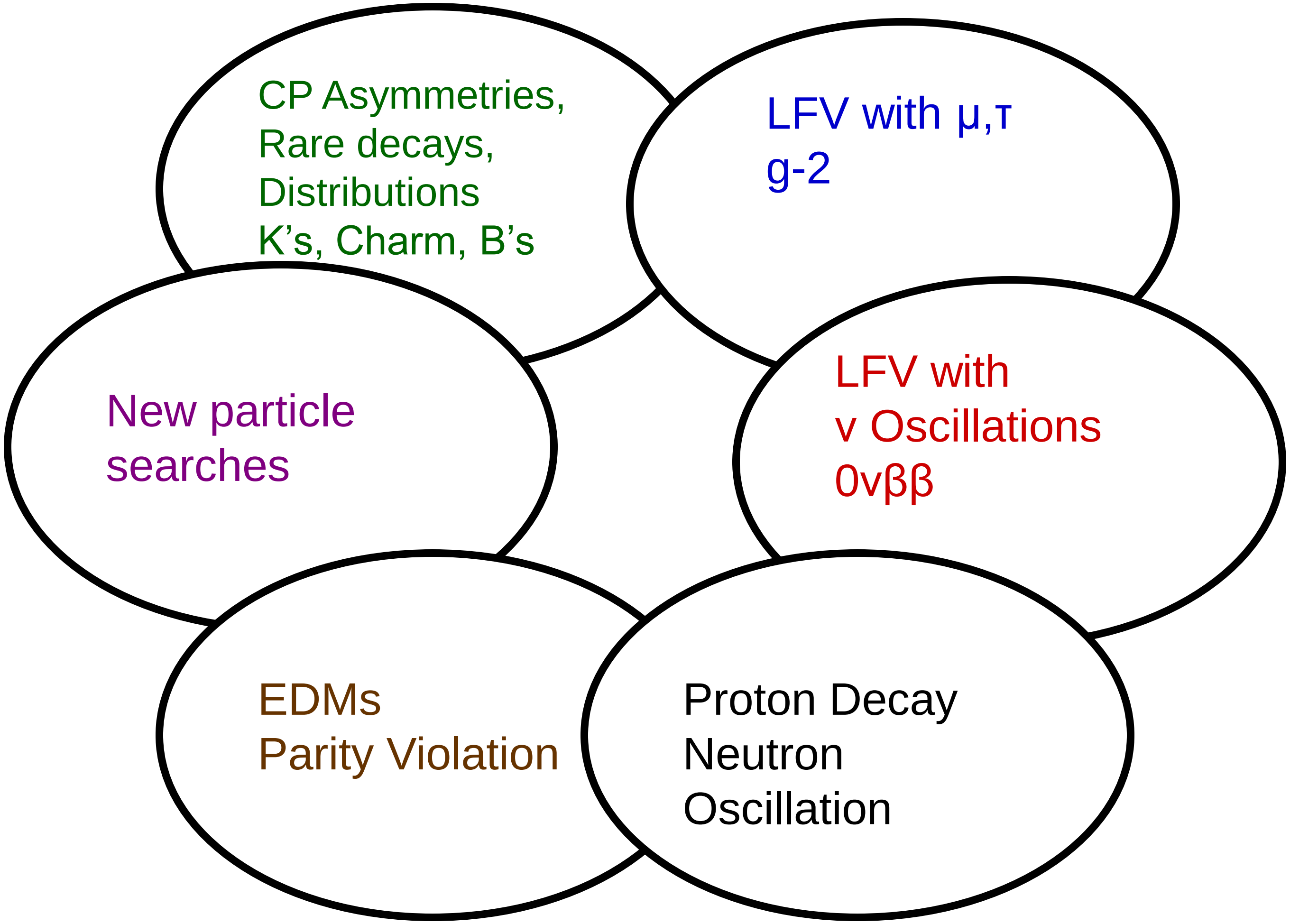


CSS13 Working Groups

Quark Flavor Physics:
Joel Butler, Zoltan Ligeti, Jack Ritchie

K, D & B Meson decays/properties

Charged Lepton Processes
Brendan Casey, Yuval Grossman, David Hitlin

Precision measurements with muons, taus

Neutrinos
Andre deGouvea, Kevin Pitts, Kate Scholberg, Sam Zeller

All experiments for properties of neutrinos. Accelerator & non-accel.

Baryon Number Violation
Kaladi Babu, Ed Kearns

Proton decay, Neutron Oscillation

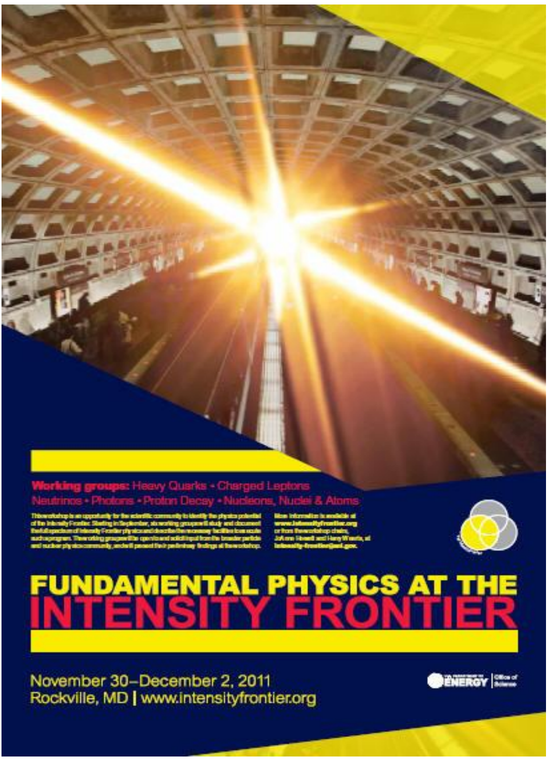
New Light, Weakly Coupled Particles
Rouven Essig, John Jaros, William Wester

“Dark” photons, paraphotons, axions, WISPs

Nucleons, Nuclei & Atoms
Krishna Kumar, Z.-T. Lu, Michael Ramsey-Musolf

Properties of nucleons, nuclei or atoms (EDM), as related to HEP

Intensity Frontier Workshop



Fundamental Physics at the Intensity Frontier **: Rockville, MD Nov 30-Dec 2, 2011**

Jointly Sponsored by DOE office of HEP and Nuclear Physics

~500 participants

3 days of vibrant talks and discussion

Charge:

Document the science opportunities at the Intensity Frontier

Identify experiments and facilities needed for components of program

Workshop Report

arXiv:1205.2671

Everyone who contributed is an author

- **~ 440 authors**
- **~ 220 pages**

Contents:

- **Exec Summary**
- **Chapter for each working group**
- **Technical Summary**

Intensity Frontier Plan for "Snowmass"

Develop strategy to be a global leader

- **Programs for this decade:**
  - Focus of Rockville workshop report
  - Well established with g-2, μ2e, Noua, LBNE, μBooNE, EXO/Cuore, HPS, Super-KEKB, LHCb
- **Programs for next decade**
  - Focus for "Snowmass" study
  - Fresh ideas encouraged! We need the very best ideas for new experiments
  - Want to develop world leading Intensity Frontier program
  - Demonstrate importance of Intensity Frontier science

Benchmark Models for the Intensity Frontier

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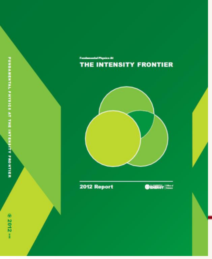
1. Supersymmetry: pMSSM flavor studies
2. Warped Extra Dimensions: Randall Sundrum flavor studies
3. Neutrino models that reach across the frontiers
4. Dark Photons and Axions

- Benchmarks provide a quantitative study of the capabilities of experiments
- Benchmarks provide the opportunity to demonstrate connections across the Intensity Frontier program
- Benchmarks provide the opportunity to demonstrate connections across the Frontiers

Conclusions

- The Intensity Frontier addresses important questions about Nature
- Main IF themes:
  - » Explore Symmetry Violation in Nature
  - » Explore Very High Energy Scales
- IF is an integral piece of a balanced program
- Join us at Snowmass!



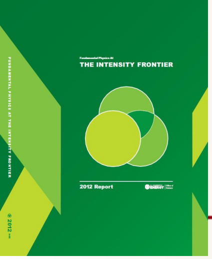
Physics #Intensity Frontier: Heavy Quarks

Heavy Quark Chapter Conclusions:

- **Essential component of world-wide balanced physics program**
- **Compelling physics case not predicated on theoretical progress**
- **Several exp'ts underway abroad – US should be involved**
- **US has opportunity to mount its own program in K Decays**

Observable	SM Theory	Current Expt.	Super Flavor Factories
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.03
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.02
γ from $B \to DK$		$\pm 11°$	$\pm 1.5°$
A_{SL}	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.03
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.15
$A_{\mathrm{CP}}(B \to X_{s+d}\gamma)$	< 0.005	0.06 ± 0.06	± 0.02
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 0.05 \times 10^{-4}$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\pm 0.2 \times 10^{-7}$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 0.13 \times 10^{-4}$
$\mathcal{B}(B \to X_s \ell^+\ell^-)$	1.6×10^{-6}	$(3.66 \pm 0.77) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$\mathcal{B}(B \to K\nu\overline{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 1 \times 10^{-6}$
$A_{\mathrm{FB}}(B \to K^*\ell^+\ell^-)_{q^2<4.3\,\mathrm{GeV}^2}$	-0.09	0.27 ± 0.14	± 0.04

Report shows future sensitivities for K Decays, as well as Charm & bottom processes at Super-Flavor Factories and upgraded LHCb



Physics #Intensity Frontier: Charged Leptons

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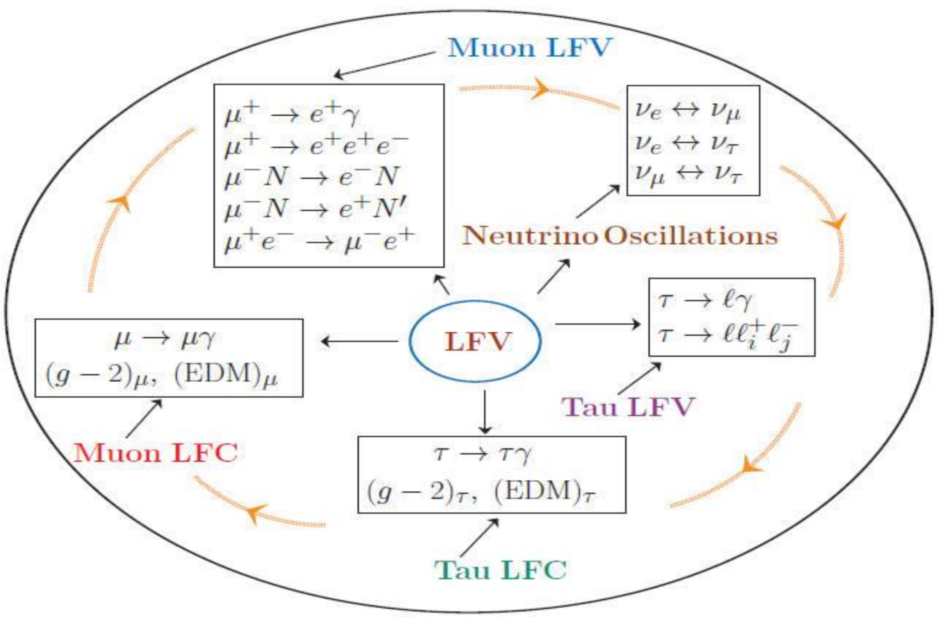
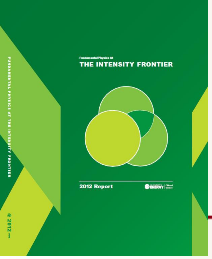
- **Charged Leptons easy to produce & detect**
  ⇒ precise measurements are possible
- **Hadronic uncertainties insignificant or controlled by data**
- **SM rates negligible in some cases so new physics stands out**
- **Directly probe couplings of new particles to leptons**
- **Diverse set of independent measurements**



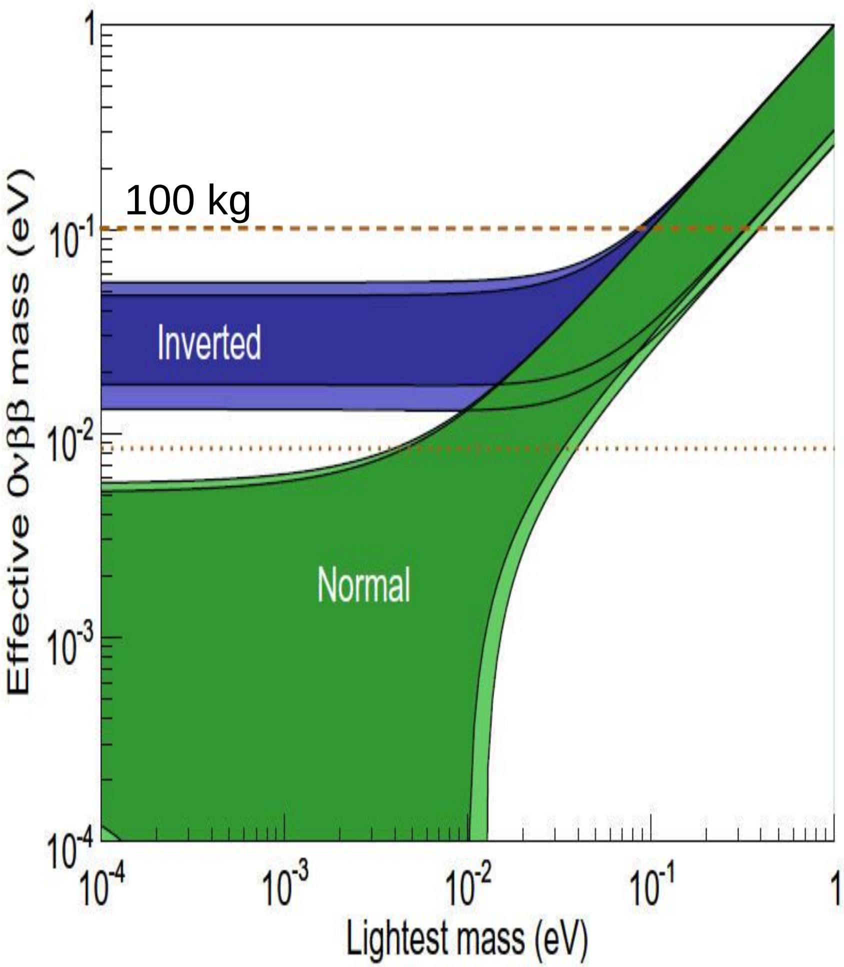
95% CL limits in CLFV with muons

Process	Current limit	Expected limit 5-10 years		Expected limit 10-20 years
$\mu^+ \to e^+\gamma$	2.4×10^{-12} PSI/MEG (2011)	1×10^{-13} PSI/MEG		1×10^{-14} PSI, Project X
$\mu^+ \to e^+e^-e^+$	1×10^{-12} PSI/SINDRUM-I (1988)	1×10^{-15} Osaka/MuSIC	1×10^{-16} PSI/$\mu 3e$	1×10^{-17} PSI, Project X
$\mu^- N \to e^- N$	7×10^{-13} PSI/SINDRUM-II (2006)	1×10^{-14} J-PARC/DeeMee	6×10^{-17} FNAL/Mu2e	1×10^{-18} J-PARC, Project X

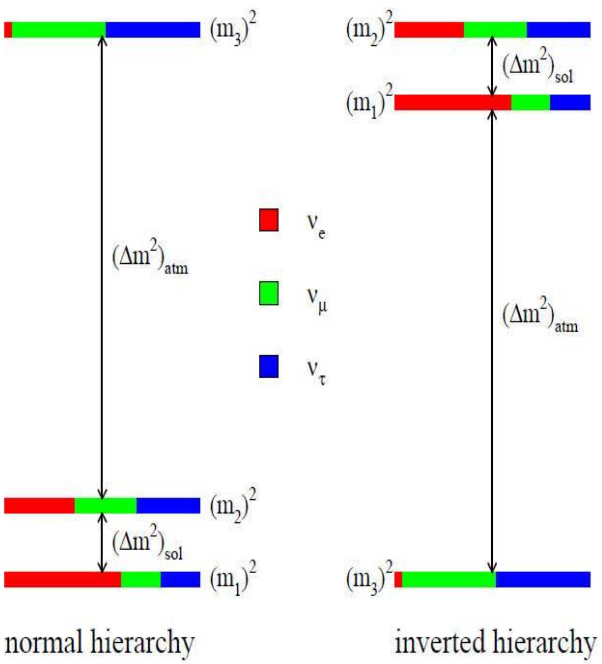


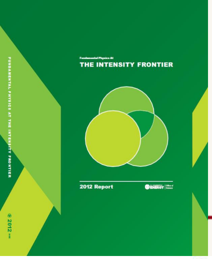
Physics #Intensity Frontier: Neutrinos

Neutrinoless Double Beta Decay

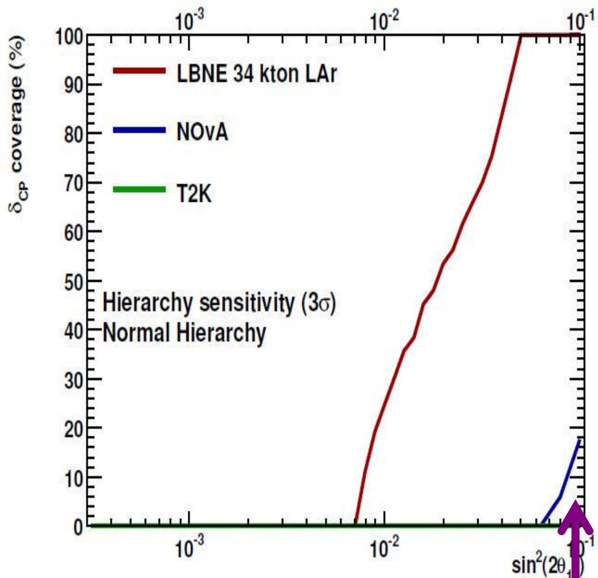


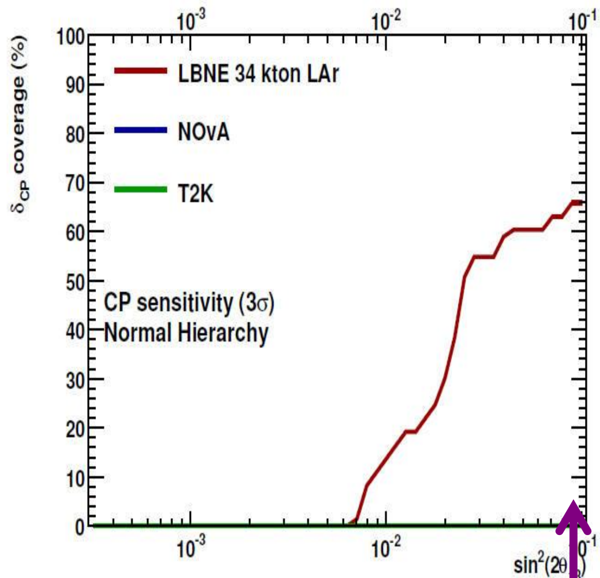
- Tests fundamental Nature of the neutrino
- Tests Lepton Number Violation





Physics #Intensity Frontier: Neutrinos

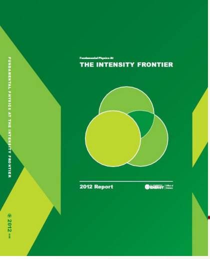




Projected sensitivities
LBNE: 5+5 yrs @ 700kW with 34 kt LAr
Nova: 3+3 yrs

Large θ_{13} allows for measurement of fundamental neutrino properties: CVP, Mass Hierarchy

Expt. Type	$\sin^2\theta_{13}$	$\text{sign}(\Delta m^2_{31})$	δ	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	Δm^2_{21}	NSI	ν_s
Reactor	⋆⋆⋆	⋆	–	–	⋆	⋆⋆	⋆⋆	–	⋆⋆
Solar	⋆	–	–	–	–	⋆⋆⋆	⋆	⋆⋆	⋆⋆
Supernova	⋆	⋆⋆⋆	–	–	–	⋆	⋆	⋆⋆	⋆⋆
Atmospheric	⋆⋆	⋆⋆	⋆⋆	⋆⋆	⋆⋆	–	–	⋆⋆⋆	⋆⋆
Pion DAR	⋆⋆⋆	–	⋆⋆⋆	⋆	⋆⋆	⋆	⋆	–	⋆⋆
Pion DIF	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆	⋆	⋆	⋆⋆	⋆⋆
Coherent ν–A	–	–	–	–	–	–	–	⋆⋆⋆	⋆⋆⋆
μ DIF	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆	⋆	⋆⋆	⋆⋆
β Beam	⋆⋆⋆	–	⋆⋆⋆	⋆⋆	⋆⋆	⋆	⋆	–	⋆⋆



Physics #Intensity Frontier: Neutrinos

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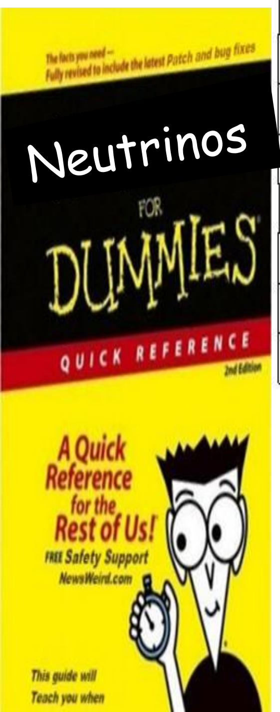
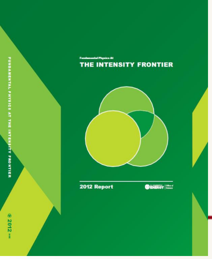
Guide to Neutrino Experiments for Dummies

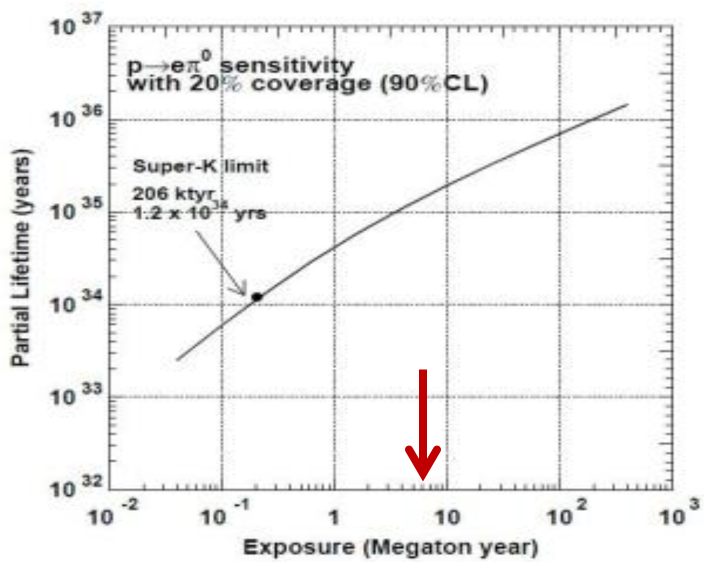
Expt. Type	ν_e disapp	ν_μ disapp	$\nu_\mu \leftrightarrow \nu_e$	ν_τ app[1]	Examples
Reactor	√√	–	–	–	KamLAND, Daya Bay, Double Chooz, RENO
Solar[2]	√√	–	√	–	Super-K, Borexino, SNO+, Hyper-K (prop)
Supernova[3]	√√	√	√√	–	Super-K, KamLAND, Borexino, IceCube, LBNE (prop), Hyper-K (prop)
Atmospheric	√	√√	√	√	Super-K, LBNE (prop), INO (prop), IceCube, Hyper-K (prop)
Pion DAR	√	–	√√	–	DAEδALUS
Pion DIF	–	√√	√√	√	MiniBooNE, MINERνA[4], MINOS(+, prop), T2K NOνA, MicroBooNE, LBNE (prop), Hyper-K (prop)
Coherent ν–A[5]	–	–	–	–	CLEAR (prop), Ricochet (prop)
μ DIF[6]	√	√√	√√	√	VLENF, NuFact
β Beam	√	–	√√	–	

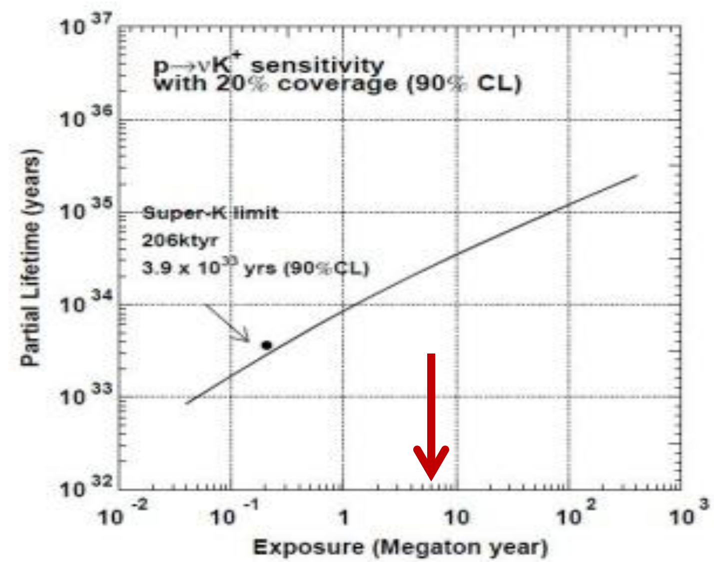




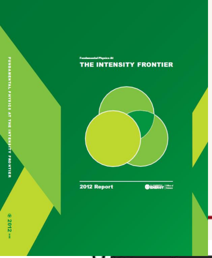
Physics #Intensity Frontier: Proton Decay

Proton decay experiments test theories of unification and baryon number violation

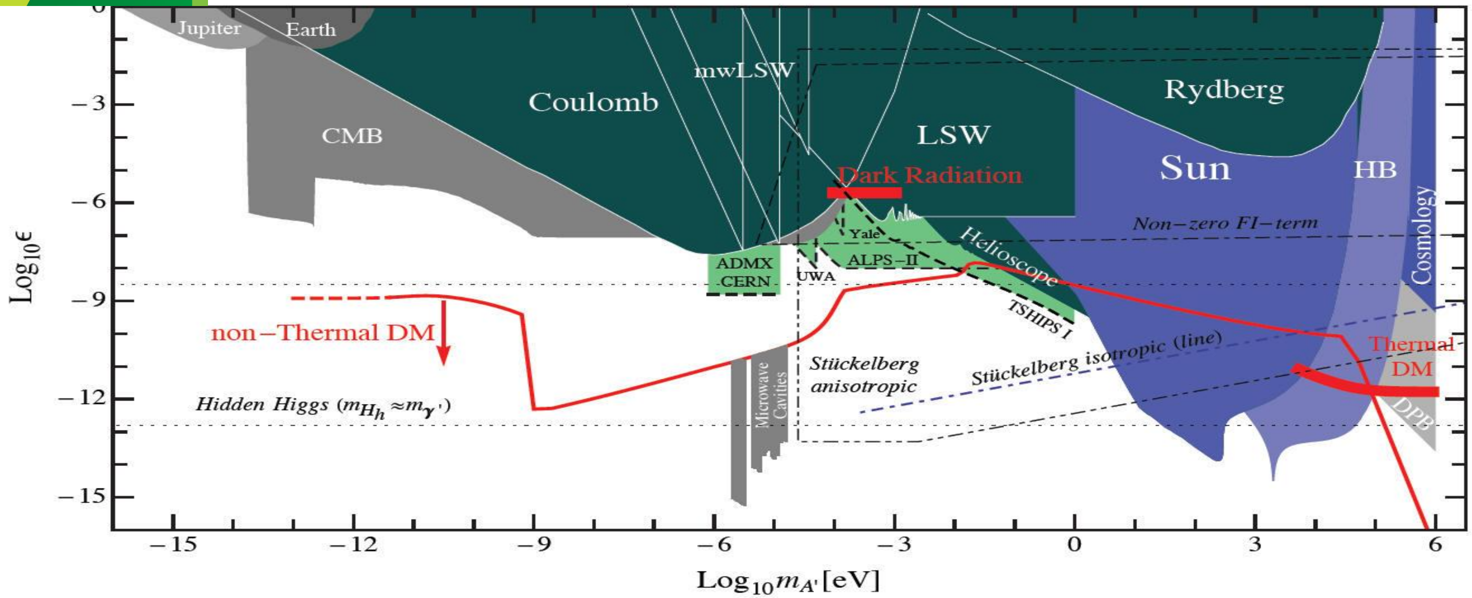




Future sensitivities at predicted levels for SUSY GUT models and related to LHC SUSY

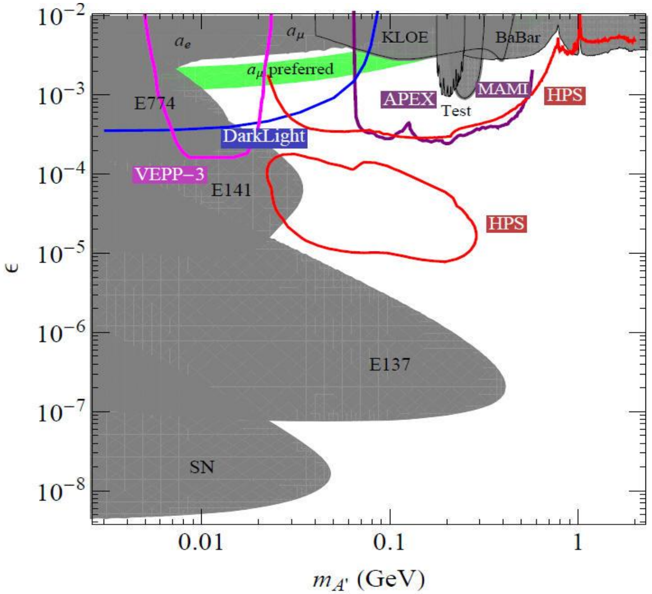


Physics #Intensity Frontier: Ultra-weak Hidden Sectors



Effective coupling to SM vs Mass plane

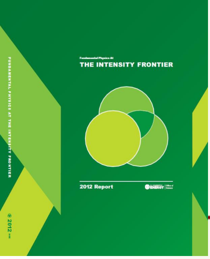
$m_{A'} < 1$ev



Hidden Sector Vector Portal/Heavy Dark Sector Photons:
Couplings to SM small enough to have missed so far, but big enough to find

Theories motivated by cosmic frontier
Signatures at Intensity and (Energy) frontiers

$m_{A'} > 1$ev



Physics #Intensity Frontier: Nucleons, Nuclei and Atoms

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Program in place to measure all

Electric dipole moments:

Excellent probes of new physics

Neutrons

SM-theory: 10^{-31} *e* cm   Exp: <2.9×10^{-26} *e* cm ➔ 5×10^{-28} *e* cm
2018 ➔ 10^{-28} *e* cm

Nucleus (Hg)

SM-theory: 10^{-33} *e* cm   Exp: <10^{-27} *e* cm ➔ 10^{-32} *e* cm

Electrons (cold molecules of YbF, ThO possible Fr)

SM-theory: 10^{-38} *e* cm   Exp: <1.05×10^{-27} *e* cm ➔ 3×10^{-31} *e* cm

Weak decays:

$$R^{\pi}_{e/\mu} \equiv \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$$

Th: 1.2351 (2) x 10^{-4}
Exp: 1.2300 (40) x 10^{-4} – 0.3% go to 0.05%

+ Kaons

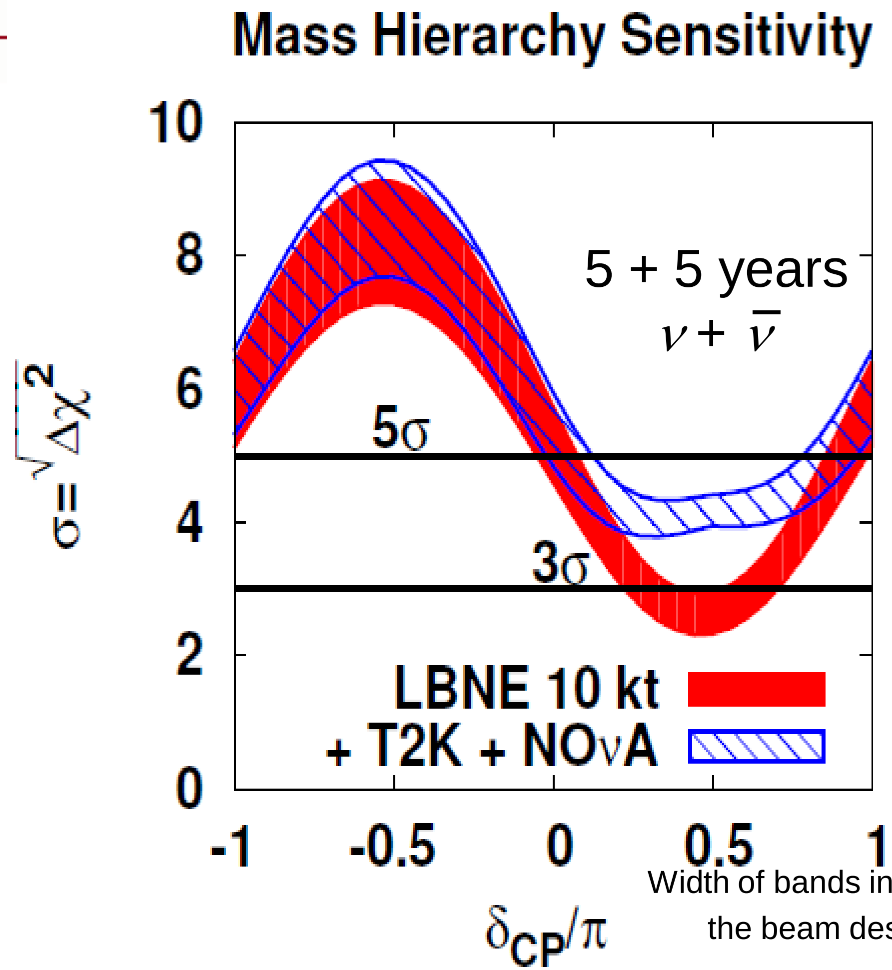
Nuclear β decay: precise measurement of V_{ud}, future measurement of *n* lifetime and decay correlations

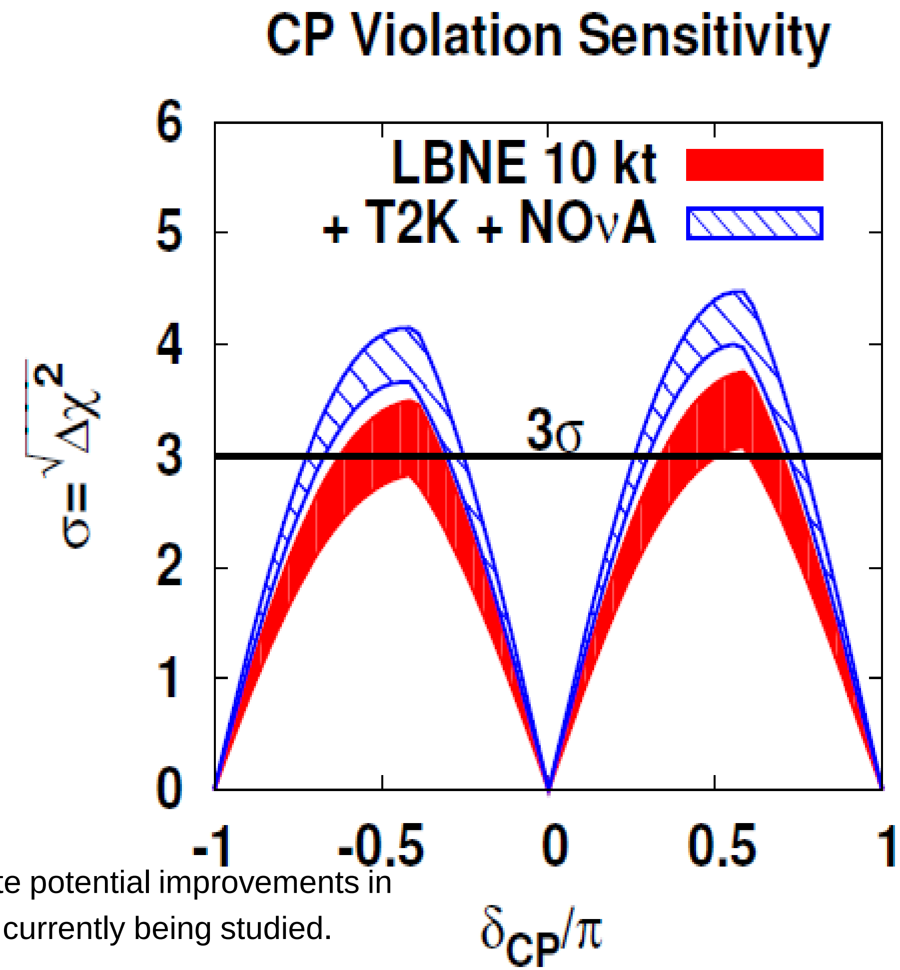
Neutral Currents:

Asymmetries

Polarized electron scattering from unpolarized targets & electrons (Moeller scatter)➔ precision measurements of weak mixing angle over large Q^2

LBNE Phase 1 Sensitivities

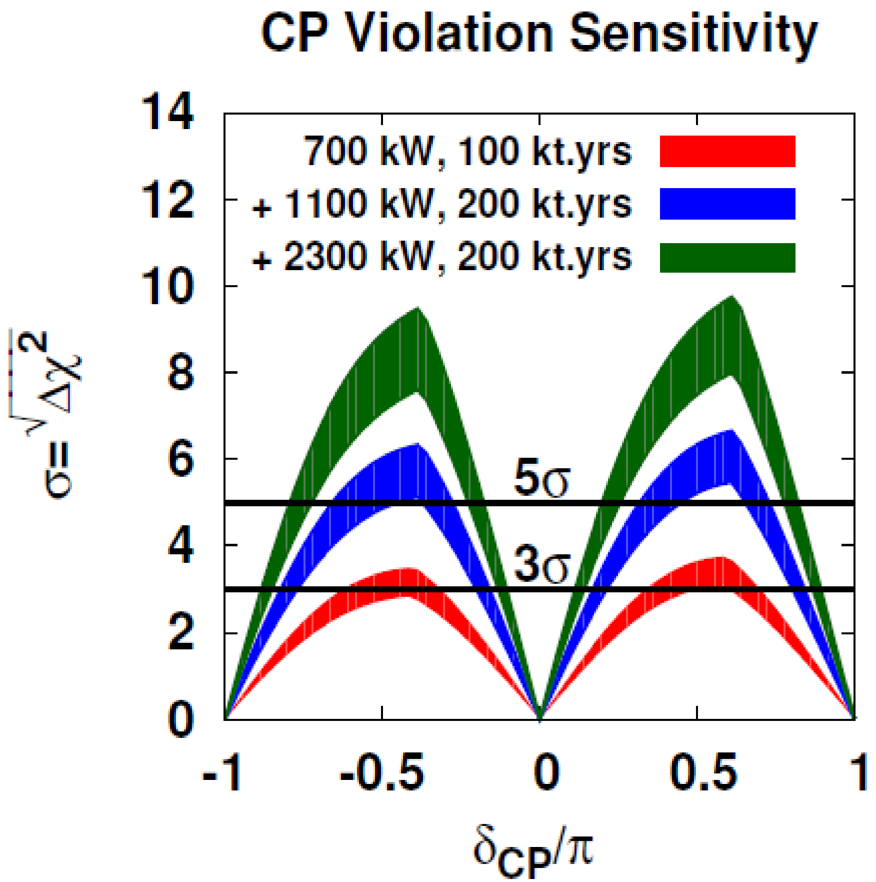


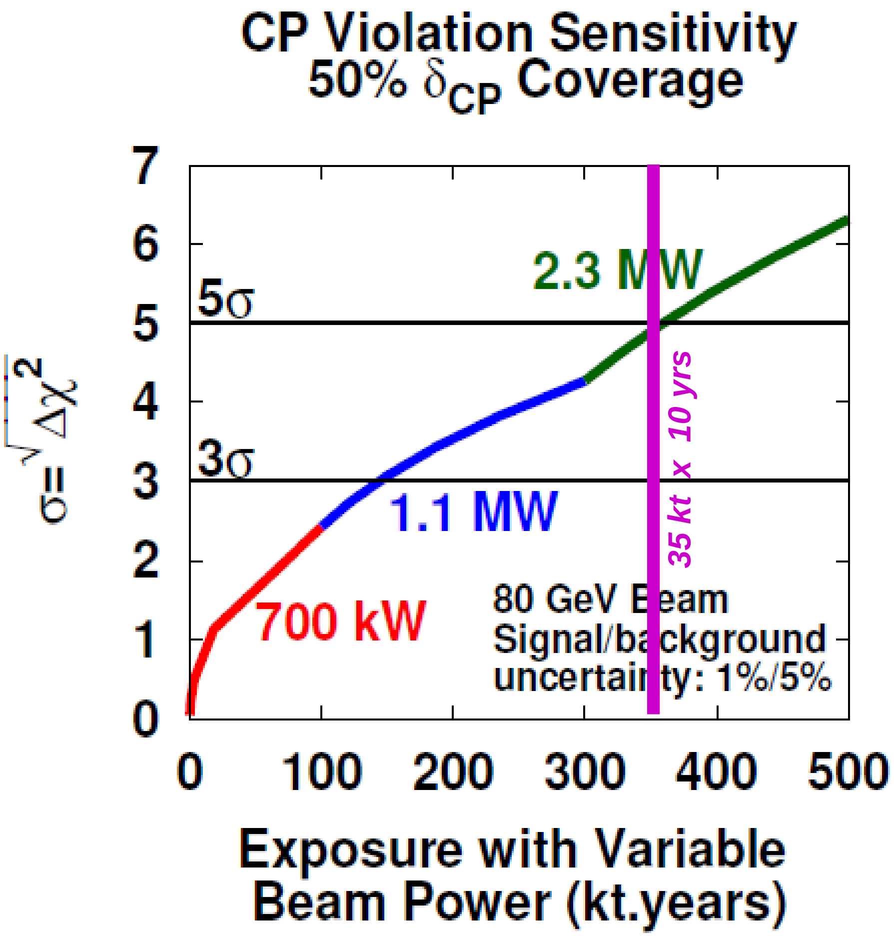


Width of bands indicate potential improvements in the beam design, currently being studied.

Combining atmospheric neutrino data (with an underground LBNE detector location) can further improve the mass hierarchy sensitivity.

LBNE Phased with Project X

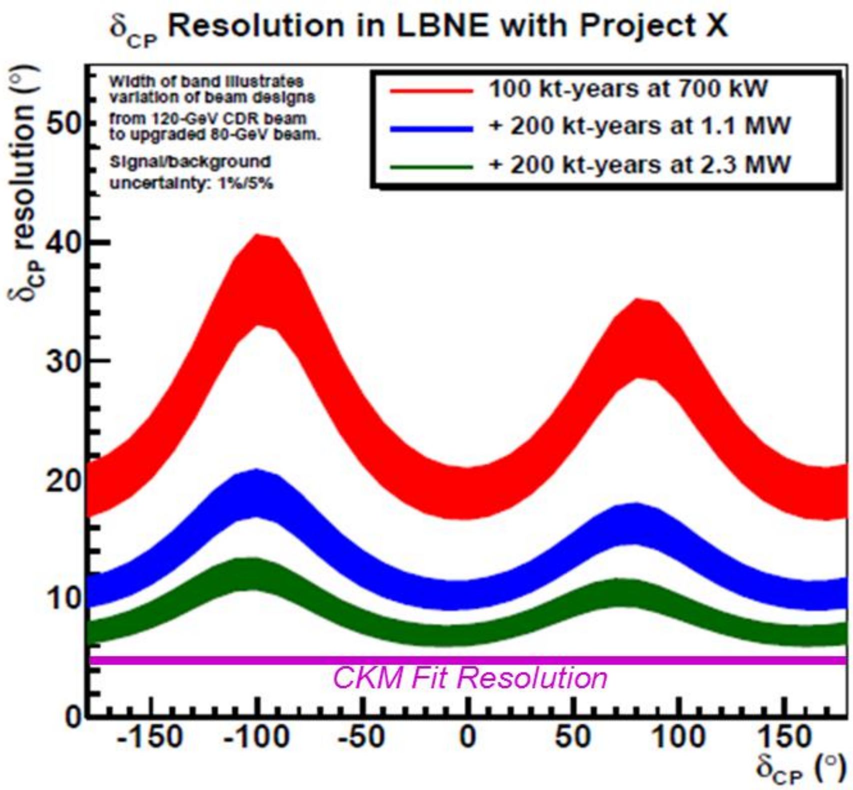




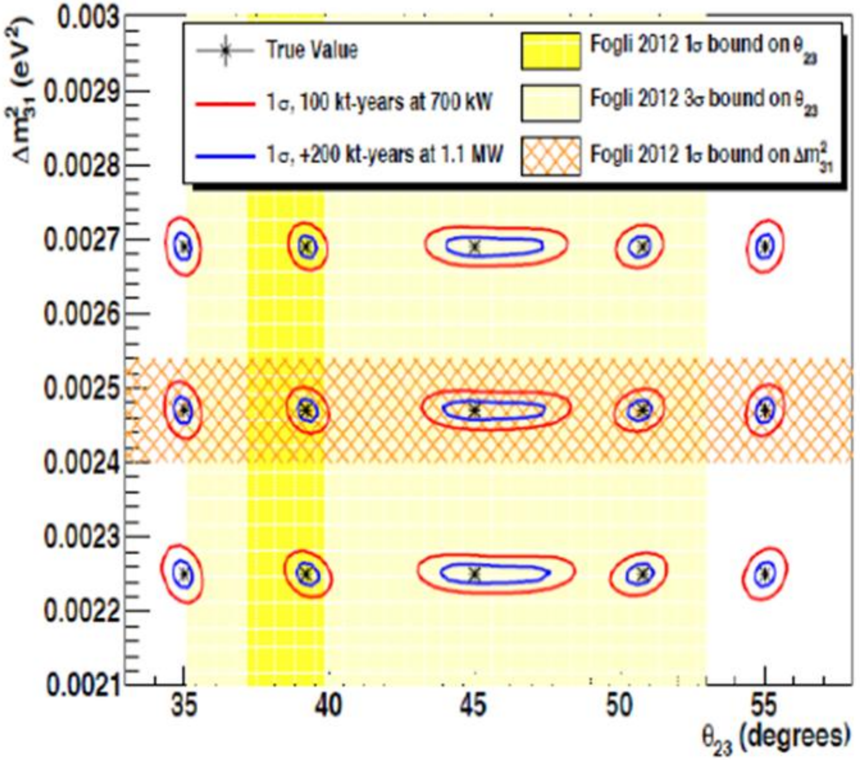
Phase 1 baseline and beam capabilities enable a program leading to > 5σ CP violation sensitivity.

LBNE Phased with Project X

δ_{cp} Resolution



θ_{23} vs Δm^2_{31}



LBNE + Project X enable an era high-precision neutrino oscillation measurements.

Kaon Projections

a few K observables

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu})$	7.8×10^{-11}	$1.73^{+1.15}_{-1.05} \times 10^{-10}$	$\sim$10% measurement from NA62 $\sim$5% measurement from ORKA $\sim$2% with Project X
$\mathcal{B}(K^0_L \to \pi^0 \nu\overline{\nu})$	2.43×10^{-11}	$< 2.6 \times 10^{-8}$	1st observation from KOTO $\sim$5% measurement with Project X
$\mathcal{B}(K^0_L \to \pi^0 e^+ e^-)_{SD}$	1.4×10^{-11}	$< 2.8 \times 10^{-10}$	$\sim$10% measurement with Project X
$\mathcal{B}(K^0_L \to \pi^0 \mu^+ \mu^-)_{SD}$	3.5×10^{-11}	$< 3.8 \times 10^{-10}$	$\sim$10% measurement with Project X
$\|P_T\|$ in $K^+ \to \pi^0 \mu^+ \nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 from TREK < 0.0001 with Project X
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$	2.477×10^{-5}	$(2.488 \pm 0.080) \times 10^{-5}$	$\pm 0.054 \times 10^{-5}$ from TREK $\pm 0.025 \times 10^{-5}$ with Project X
$\mathcal{B}(K^0_L \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ with Project X

From the Report of the Heavy Quarks working group, Fundamental Physics at the Intensity Frontier (2012), arXiv:1205.2671

LHCb Projections

Needs update

Observable	Precision as of 2011	LHCb ($5\ \mathrm{fb}^{-1}$)	Upgrade ($50\ \mathrm{fb}^{-1}$)
$\phi_s(B_s \to J/\psi\phi)$	0.16	0.019	0.006
$S(B_s \to \phi\phi)$	—	0.08	0.02
$S(B_s \to K^{*0}\bar{K}^{*0})$	—	0.07	0.02
$\beta(B^0 \to J/\psi K^0)$	1°	0.5°	0.2°
$S(B^0 \to \phi K^0_S)$	0.17	0.15	0.03
$\gamma(B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$	$\sim 4^\circ$	0.9°
$\gamma(B \to D_s K)$	—	$\sim 7^\circ$	1.5°
$B(B_s \to \mu^+\mu^-)$	—	30%	8%
$B(B^0 \to \mu^+\mu^-)/B(B_s \to \mu^+\mu^-)$	—	—	~35%
$S(B_s \to \phi\gamma)$	—	0.07	0.02
$A^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	—	0.14	0.03
$A_T^2(B^0 \to K^{*0}\mu^+\mu^-)$	—	0.14	0.04
$s_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	—	4%	1%

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Charm in B-physics Experiments

Charm production exceeds B production at LHC and in e^+e^- at the $\Upsilon(4S)$.
$\Rightarrow$ LHCb and Belle II will have unprecedented charm data samples.

- Rich program of charm studies "for free"
- Belle II and LHCb will make large improvements on mixing, CPV tests, rare decays, …

E.g., improvements in charm mixing measurements.

Observable	Current Expt.	LHCb ($5\ \mathrm{fb}^{-1}$)	Super Flavor Factories ($50\ \mathrm{ab}^{-1}$)	LHCb Upgrade ($50\ \mathrm{fb}^{-1}$)
x	$(0.63 \pm 0.20)\%$	$\pm 0.06\%$	$\pm 0.02\%$	$\pm 0.02\%$
y	$(0.75 \pm 0.12)\%$	$\pm 0.03\%$	$\pm 0.01\%$	$\pm 0.01\%$
y_{CP}	$(1.11 \pm 0.22)\%$	$\pm 0.02\%$	$\pm 0.03\%$	$\pm 0.01\%$
$\lvert q/p \rvert$	0.91 ± 0.17	± 0.085	± 0.03	± 0.03
$\arg(q/p)$	$(-10.2 \pm 9.2)^\circ$	$\pm 4.4^\circ$	$\pm 1.4^\circ$	$\pm 2.0^\circ$

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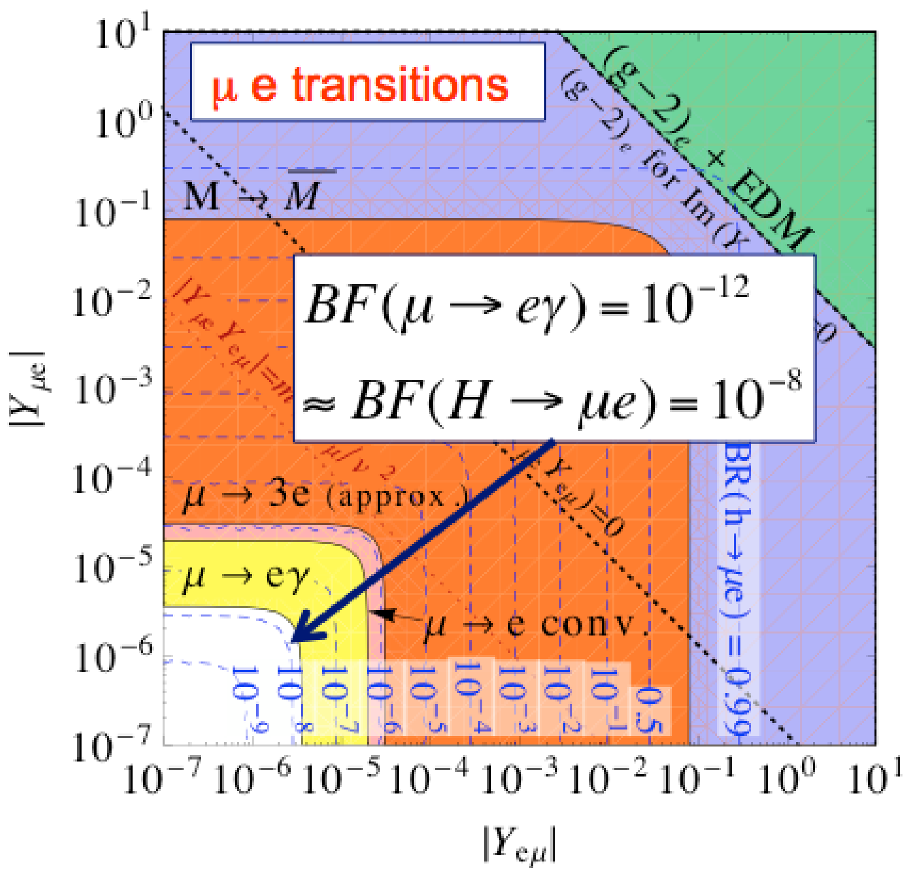
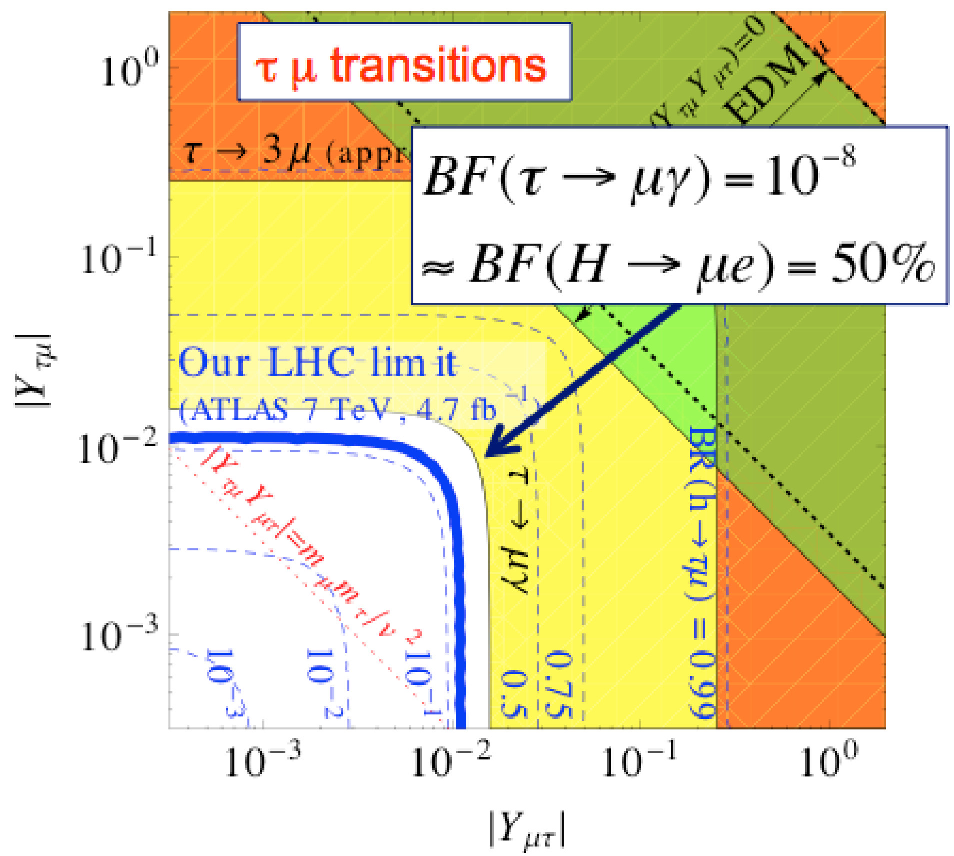
Integral part of a greater program

Roni Harnik: Synergies with the Higgs

- Use higgs to generate neutral currents





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