I have so much to cover in this talk I don't have time for the standard apology about not covering everything properly so please read this and accept my apology

Flavor Physics at Snowmass

R. Bernstein, FNAL

DPF 2013

see Hewett et al., 1205.2671 and
Report of Heavy Quarks Working Group
http://www.ph.utexas.edu/~heavyquark/

Snowmass Flavor Reports in Preparation

Snowmass Talks: https://indico.fnal.gov/conferenceTimeTable.py?confId=6890#all.detailed

Snowmass Conveners

- Intensity Frontier: JoAnne Hewett and Harry Weerts
  - Quark Flavor Physics:
    - Joel Butler, Zoltan Ligeti, Jack Ritchie
      - *K*, *D*, & *B* Meson decays and properties
  - Charged Lepton Processes
    - Brendan Casey, Yuval Grossman, David Hitlin
      - precision measurements with muons and taus
      - searches for rare decays

Future Flavor Physics Program

- B Physics
  - BELLE-II
  - LHCb
  - ATLAS/ CMS
- Charm
  - BELLE-II
  - LHCb
  - ATLAS/ CMS
  - BES-III
  - Panda
  - τ-charm
- on-shore Kaons
  - KLOE-2
  - NA62
  - TREK
  - KOTO
  - ORKA
  - PX: Kaons
- Muons
  - g-2
  - MEG Upgrades
  - Mu3e
  - Mu2e
  - PX: Muons
  - COMET

Project X
projectx.fnal.gov
physics: 1306.5009

what are all these people doing?

Role of Flavor Physics

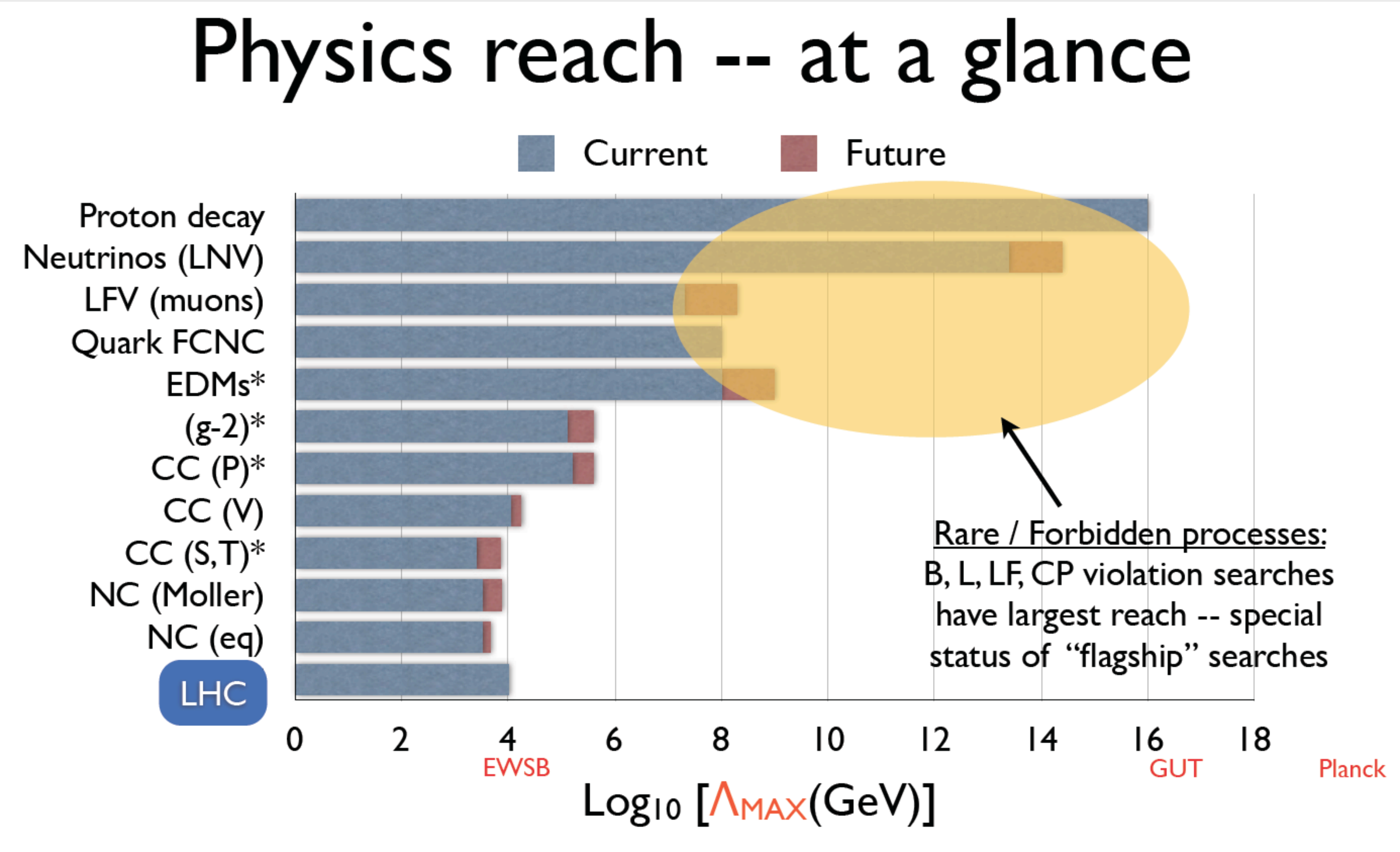
- Main Goal over coming decades is to find BSM physics
- Wide consensus that we need to look in many places: colliders, neutrinos, and flavor physics
- Flavor Physics is
  - interconnected: measurements in one sector imply results in other sectors
  - complementary: ***constructive interference*** among measurements in searching for and understanding new physics

Not a Bad Track Record...

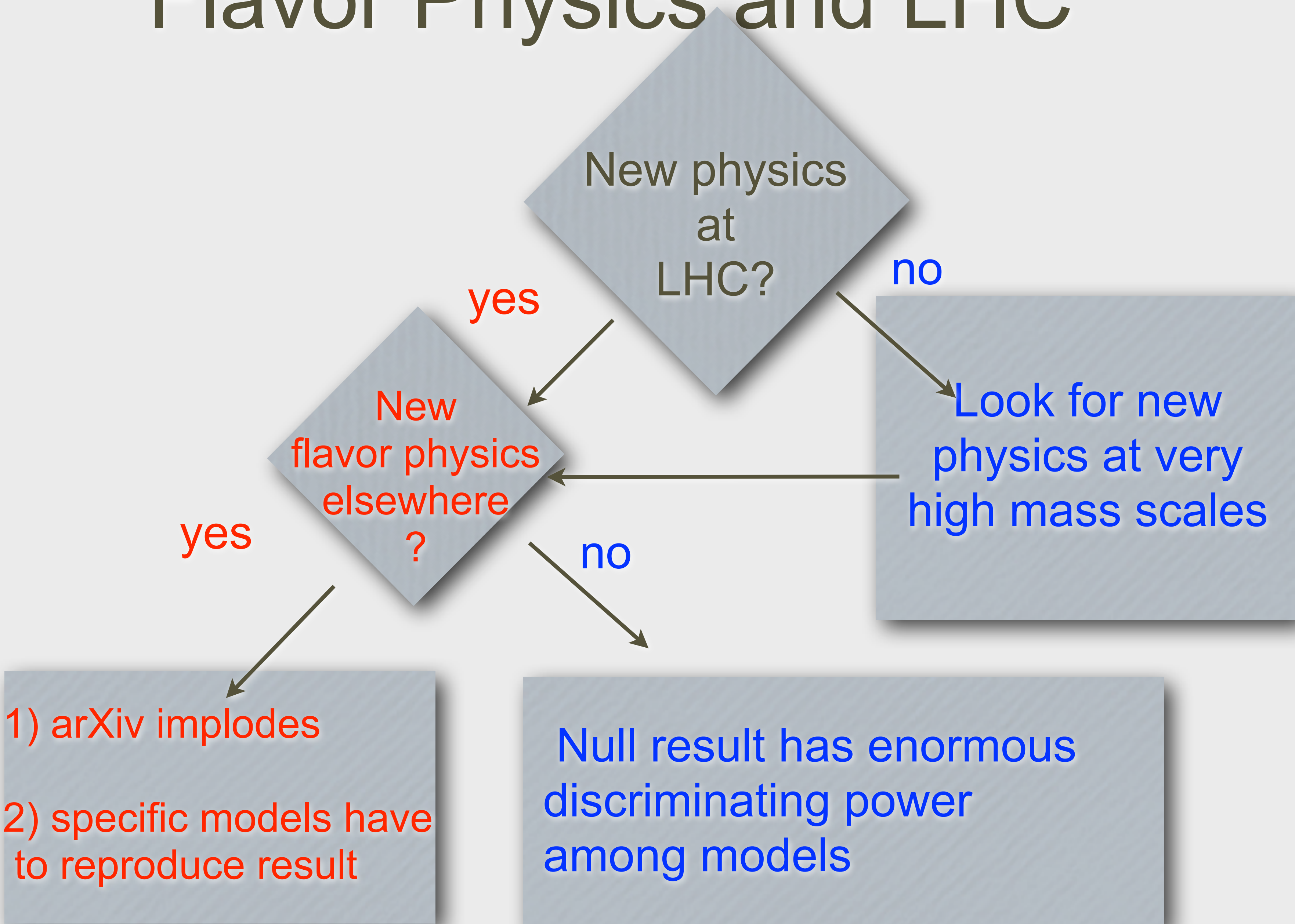
- Much of the SM structure came from flavor physics!
  - β decay predicted the neutrino
  - Absence of FCNC in $K_L \to \mu^+\mu^-$ required charm and GIM mechanism
  - Direct CP-violation and CKM matrix of 3 generations
- And now, constraints on new physics to $>10^3$ TeV/c^2

Flavor Physics: Rare Processes and Precision Measurements

adapted from V. Cirigliano and M.J. Ramsey-Musolf, 1304.0017

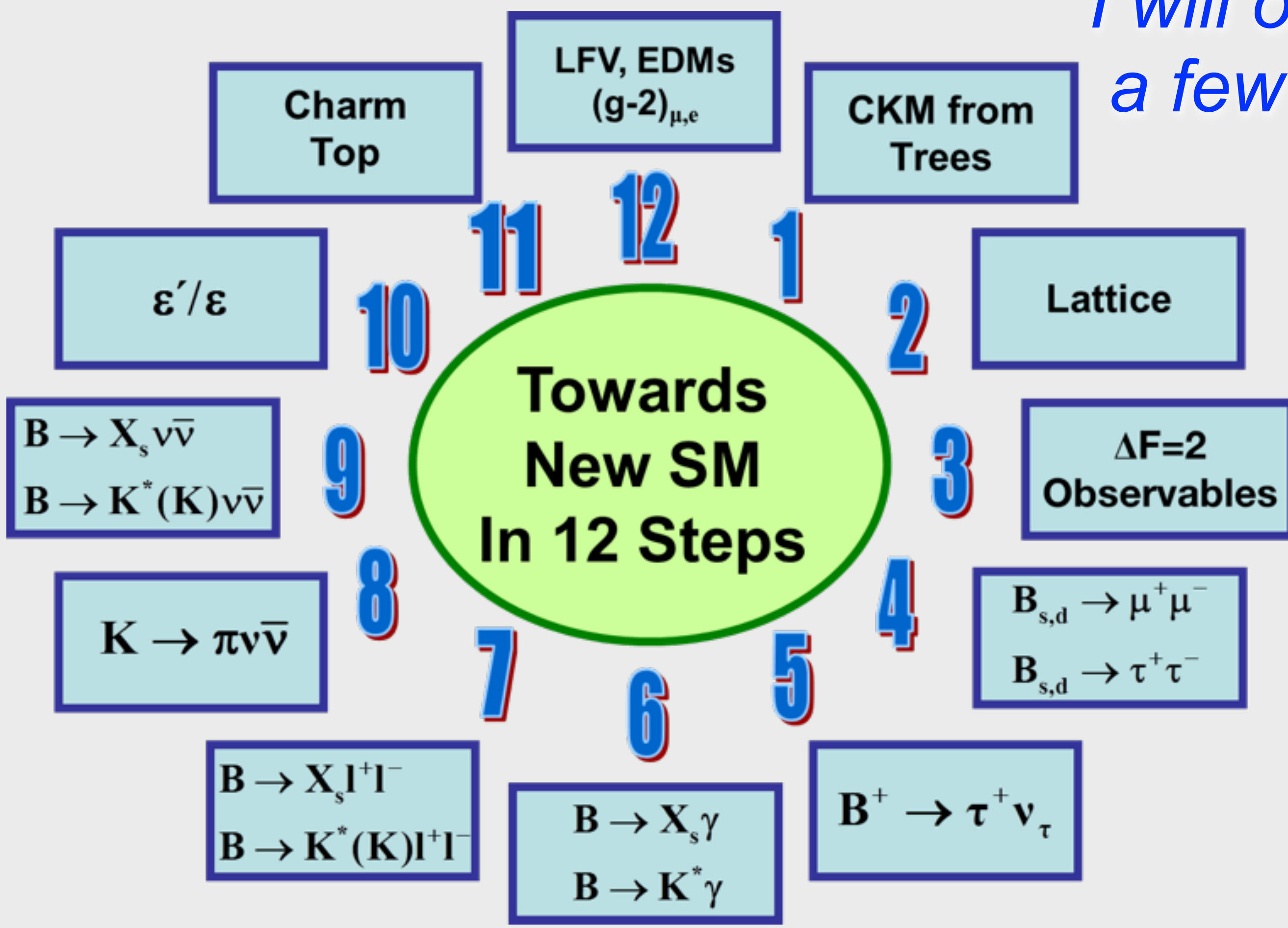


Flavor Physics and LHC



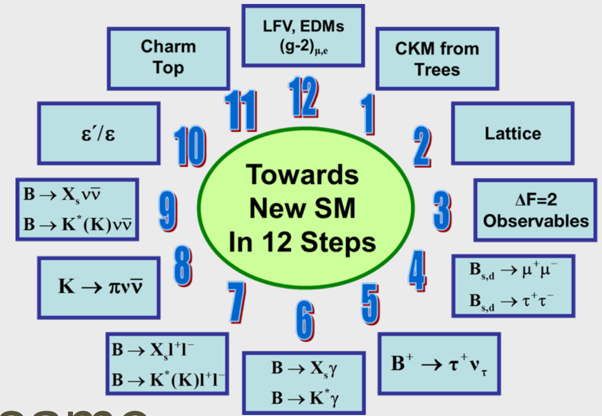
Where Do We Look?: 12-step program

I will only cover a few of these



A. Buras & J. Girrbach, 1306.3775

Discovery and Discrimination



- These measurements do not give the same information
- They check and reinforce each other in a web of measurements
- Complementarity and interconnectedness are a strength of a diverse program
- Taken together, provide great model discrimination and discovery potential

Flavor Physics is Fundamental:

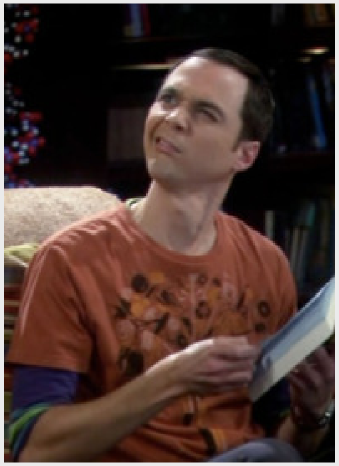
- Because it speaks to the generation puzzle:
  - why is there more than one generation of quarks and leptons?
- Because knowing a mass scale is not enough:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{\text{flavor structure and coupling strength}}{\Lambda^2}$$

dim-6 example

  - the Lagrangian has a numerator and a denominator (we tend to focus on the denominator)
- Because flavor physics provides discovery and discrimination

Flavor Physics and Mass Scales:



- There's already a problem:
  - the hierarchy problem: $\Lambda \sim \quad 1\ \text{TeV}/c^2$
  - flavor bounds: $\Lambda > 10\text{-}10^5\ \text{TeV}/c^2$

depends on numerator!

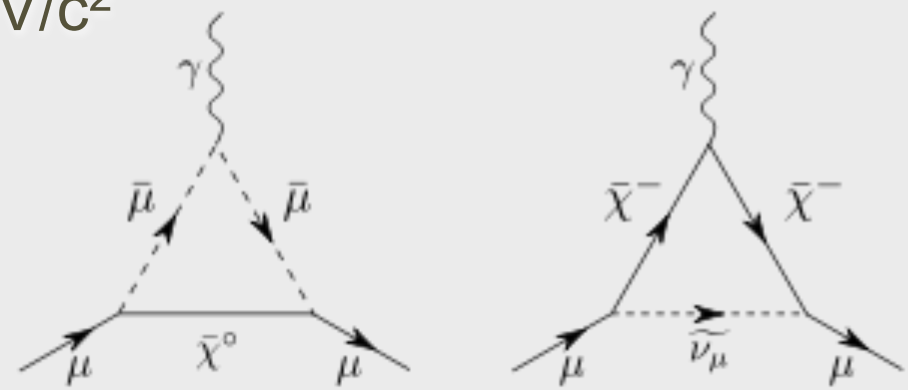
- BSM ideas *must* explain the flavor problem:
  - "Natural" to have seen flavor effects already
  - Back to the numerator: Minimal Flavor Violation, for example, is an assumption
  - Flavor is an *input*, not a *output*

Part I: High Mass Scales

- Heavy particles can be indirectly accessed through low energy processes
  - for example, beta decay
  - if $g \approx e$, $M_W \approx 100$ GeV/c^2

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

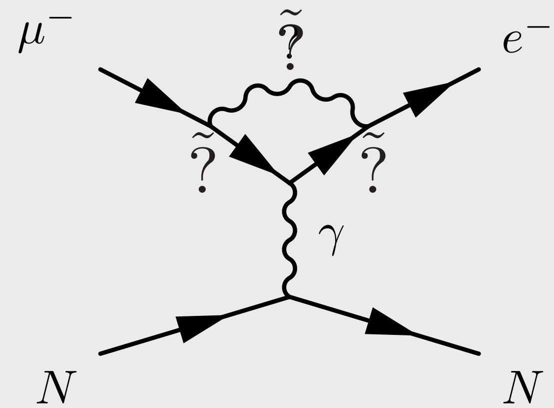
- And through loops
  - g-2 of the muon



A. Czarnecki and W.J. Marciano, Phys. Rev. D64 013014 (2001) in MSSM

$$\Delta a_\mu \approx 130 \times 10^{-11} \tan\beta \, \mathrm{sgn}\, \mu \, \left(\frac{100 \text{ GeV}}{M_{\text{SUSY}}}\right)^2$$

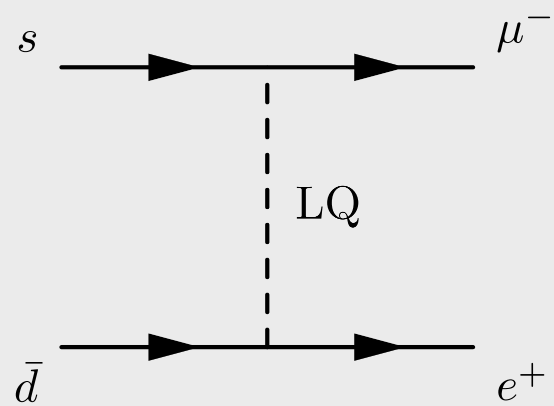
Part I: High Mass Scales



- And through rare decays
  - in muons:

$$\mu \to e\gamma \text{ or } \mu N \to eN$$

$$\mathcal{BR}(10^{-16}) \Rightarrow M_{\mathrm{NP}}(1000\ \mathrm{TeV/c^2})$$



  - in kaons

$$K_L \to \mu e \text{ via leptoquark}$$

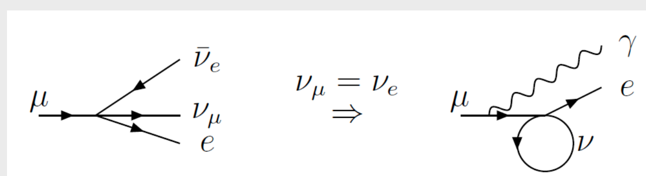
$$M_{\mathrm{NP}} \approx 200\ \mathrm{TeV/c^2} \left(\frac{10^{-12}}{\mathcal{BR}}\right)^{0.25}$$

Part II, The Generation Puzzle: “Who ordered that?”

– I.I. Rabi

After the μ was discovered, it was logical to think the muon is just an excited electron:

- expect BR($\mu \to e\gamma$) ≈ 10^{-4}
- Unless another ν, in Intermediate Vector Boson loop, cancels (footnote in Feinberg, 1958)



[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \to e + \nu + \bar{\nu}$.

10.1103/
PhysRev.
110.1482

Modern Phrasing

- New physics flavor problem:
  - no new physics at the TeV scale that would mediate charged lepton flavor violation (CLFV)
  - there must be a very high mass scale or a very great suppression in the couplings
  - so you have to look for extremely rare decays or make precise measurements

Charged Lepton Flavor Experiments

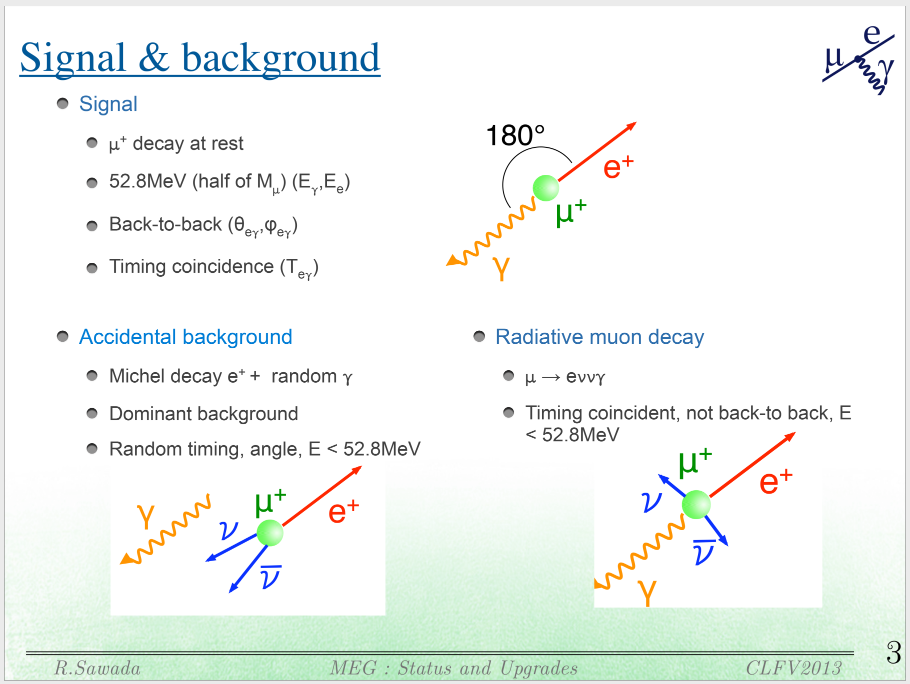
clfv2013.le.infn.it

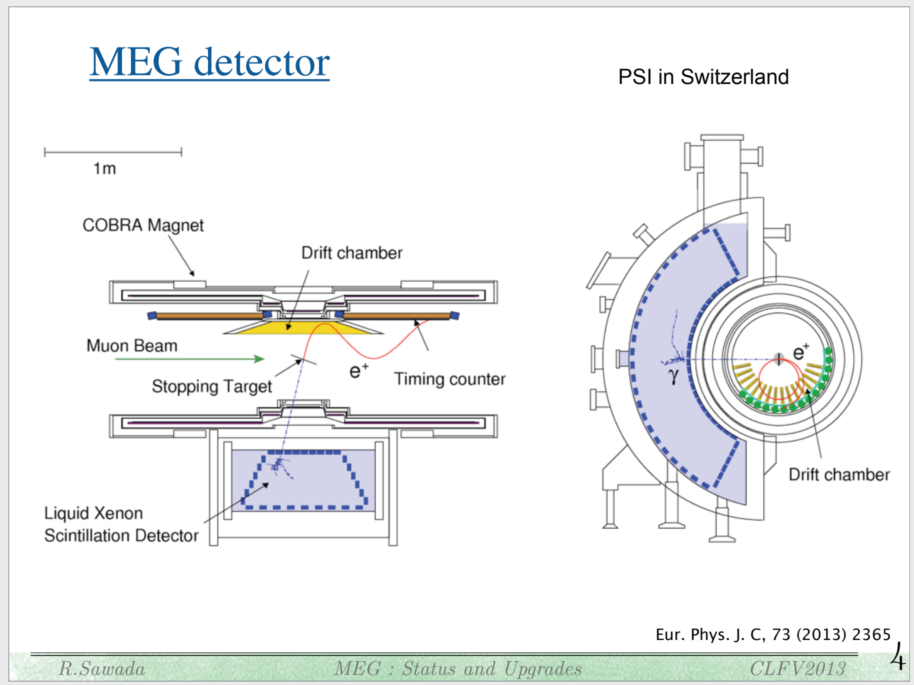
RHB and P.S. Cooper: 1307.5787v2

- So there's been lots of study since 1940 or so:
  - muons: $\mu \to e\gamma$, $\mu \to 3e$, $\mu N \to eN$
    - PSI, and now FNAL, J-PARC, Project X
  - taus: $\tau \to e\gamma$, $\tau \to 3l$
    - BELLE, BaBar, moving to BELLE-II, LHC
  - kaons: $K_L \to \mu e, \pi^o \mu e, \ldots$ $K^+ \to \pi^o \mu e$, $\pi^- l^+ l^+, \pi^+ l^+ (l')^-$
    - BNL, now CERN NA62 and FNAL/ORKA and PX

MEG: $\mu \to e\gamma$

- Measurement: < 5.7 x 10^{-13} @ 90%CL
  - stopped muons at PSI





J. Adam et al., 1303.0754

MEG: Status and Upgrades

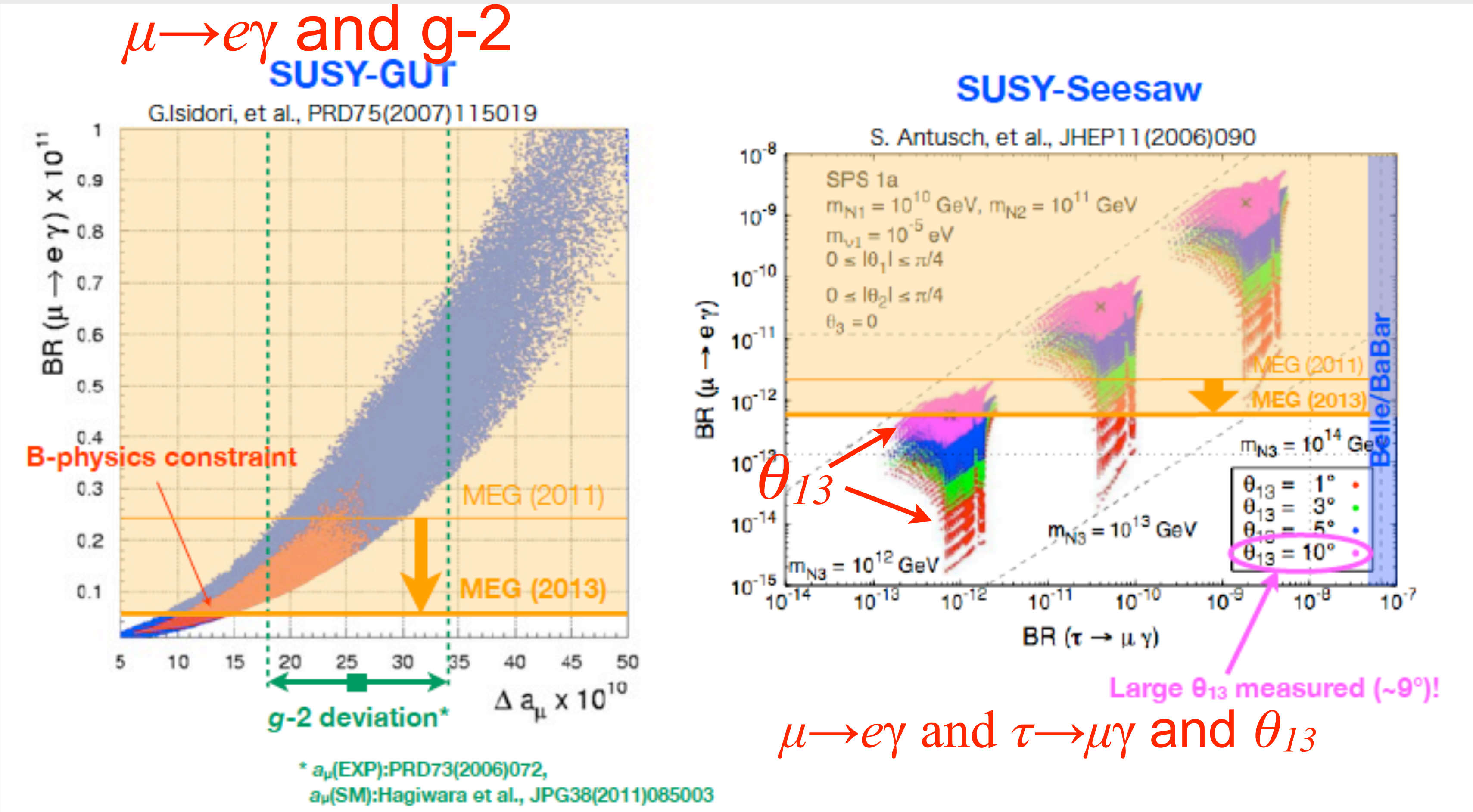
- Background increases with rate, resolution:

$$\mathcal{B}(\text{one event background}) \propto (\frac{R_\mu}{D})(\Delta t_{e\gamma})\frac{\Delta E_e}{m_\mu/2}\left(\frac{\Delta E_\gamma}{15 m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

- Want as low rate as feasible, constant, and as good energy and angular resolution as possible: two quadratic terms, one in energy, one in angle.
    - so, is $m_\mu = E_e + E\gamma$ and are they back-to-back?
        - innovative new tracker and upgrade LXe calorimeter
- MEG will improve photon energy and angular resolution for upgrade

Why Upgrade?

- Models are highly constrained, especially in combination with other CLFV measurements
  - for example, SUSY-GUT or SUSY-Seesaw



Muon-to-Electron Conversion

muon converts to electron in the field of a nucleus

$$\mu^- N \rightarrow e^- N$$

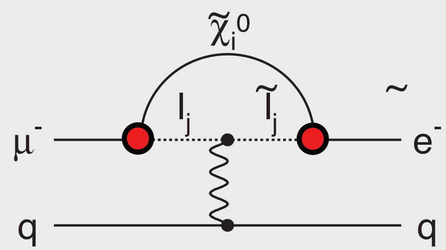
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

- Charged Lepton Flavor Violation (CLFV)
  - manifest beyond Standard Model physics
  - SES of 2.5×10^{-17}, 0.4 evt bkg; 5σ discovery at $\sim 10^{-16}$
  - Standard Model Background of 10^{-54}

Contributions to $\mu \rightarrow e$ Conversion

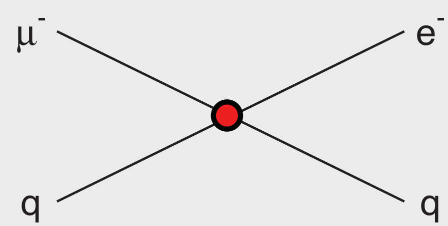
Supersymmetry

rate ~ 10^{-15}



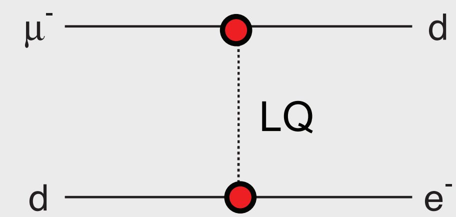
Compositeness

Λ_c ~ 3000 TeV



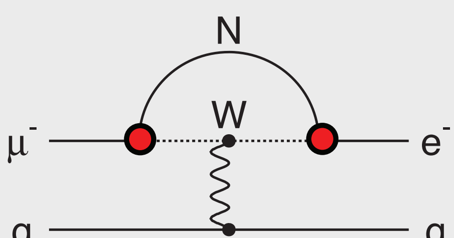
Leptoquark

M_{LQ} =
3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



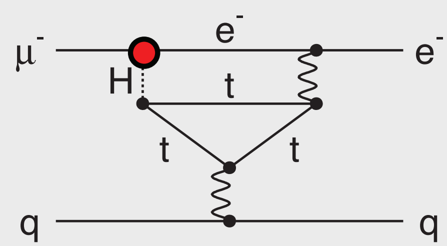
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



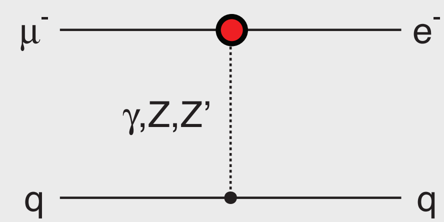
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4} g(H_{\mu\mu})$



Heavy Z'
Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c^2

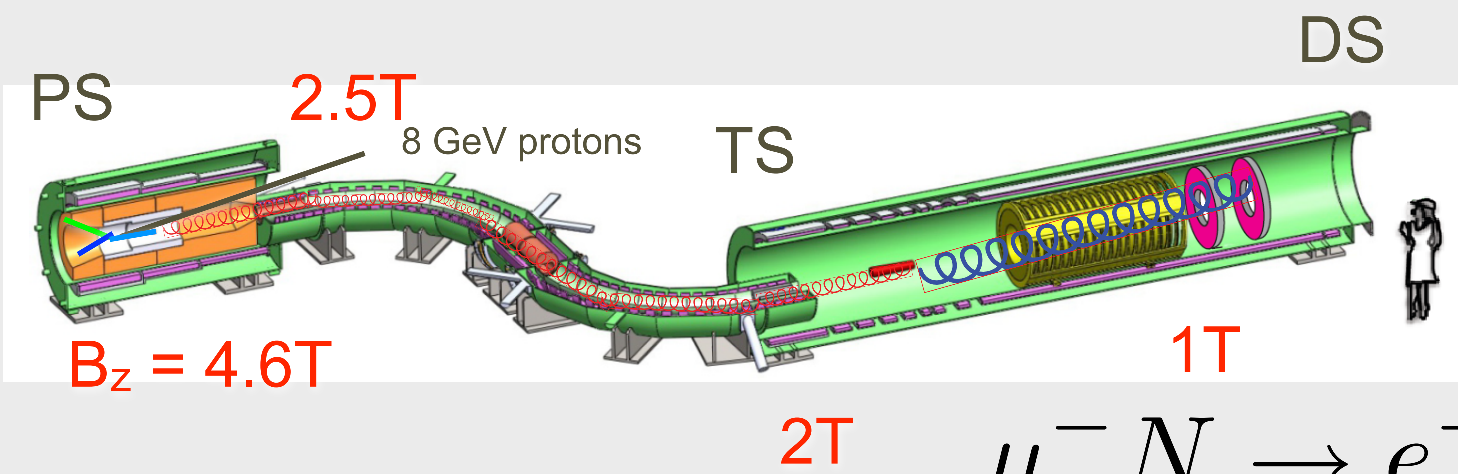


also see Flavour physics of leptons and dipole moments, 0801.1826 ;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126 ;
de Gouvea and Vogel, 1303.4097

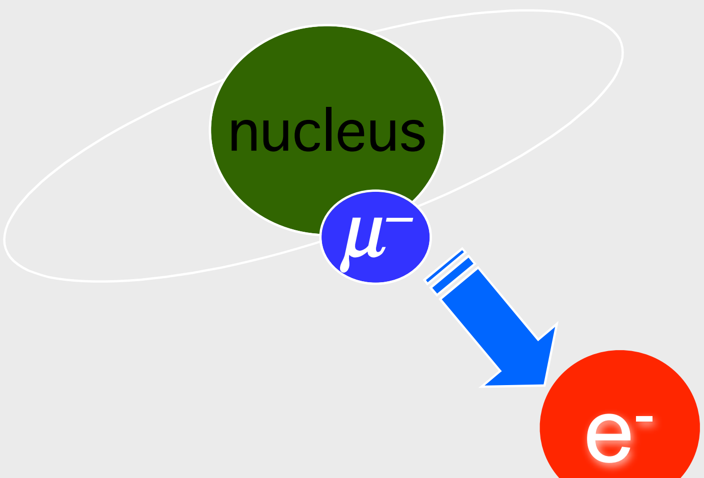
Mu2e

first data early 2020

4.6T ⟶ B-field gradient ⟶ 1T



$$\mu^- N \rightarrow e^- N$$



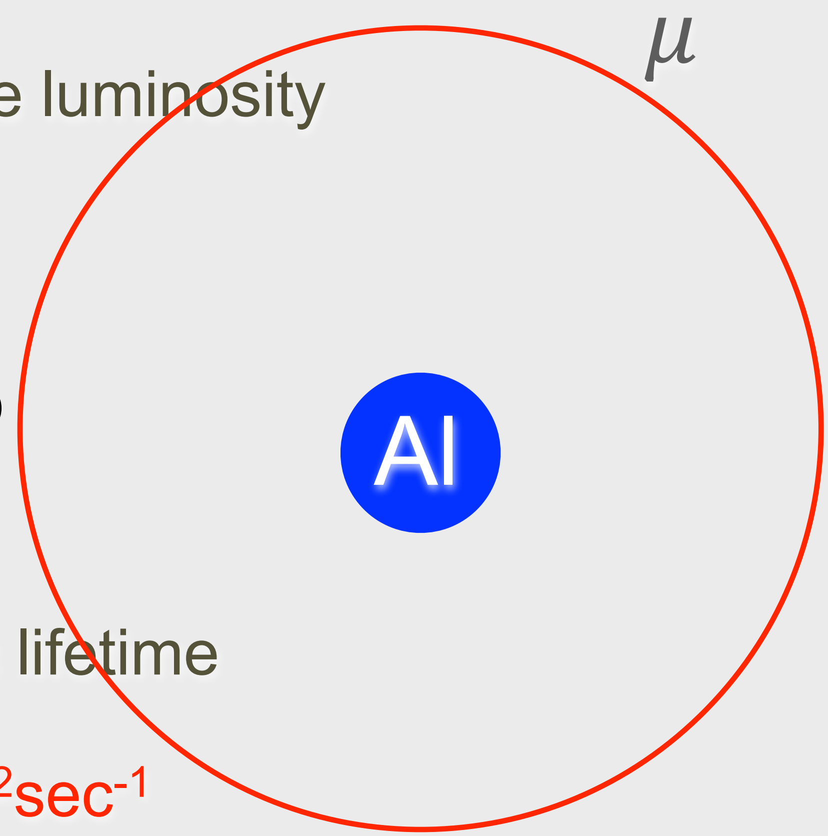
- A single mono-energetic electron, clean signal
- If N = Al, E_e = 105. MeV
- electron energy depends on Z: explore new physics after discovery

Kutschke, Chen, Group, A. Mukherjee, this conf.

Measuring 10^{-17} in Collider Units

- The captured muon is in a 1s state and the wave function overlaps the nucleus (picture ~ to scale)
- We can turn this into an effective luminosity
- Luminosity = density x velocity

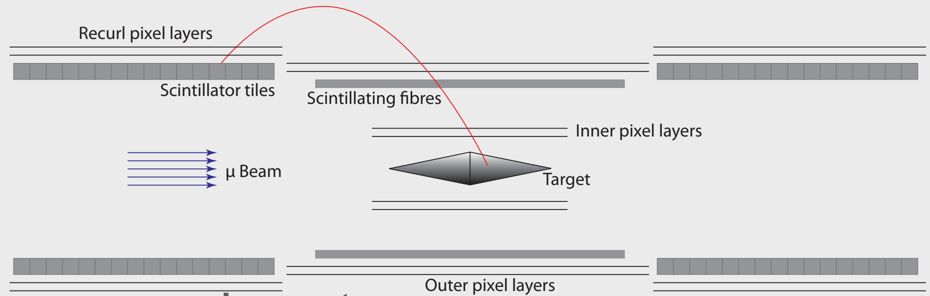
$$|\psi(0)|^2 \times \alpha Z = \frac{m_\mu^3 Z^4 \alpha^4}{\pi} = 8 \times 10^{43}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1})$$



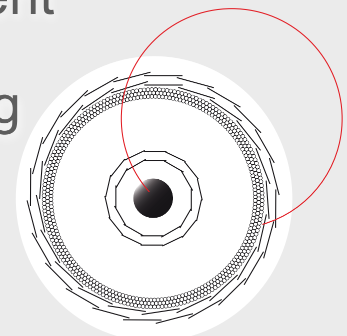
- Times 10^{10} muons/sec X 2 μsec lifetime
- Effective Luminosity of 10^{48} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

A. Czarnecki, clfv.le.infn.it

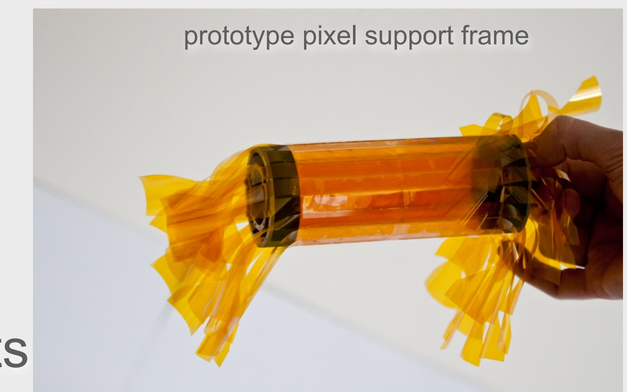
Muon to Three Electrons



- Approved at PSI: 10^4 beyond previous experiment
  - Stopped μ^+ beam with Pixels and Scintillating Fibers



- $\mu^+ \to 3e$ shares much with $\mu^+ \to e\,\gamma$:
  - Accidentals and Resolution
  - Physics: SM radiative $\mu^+ \to e^+ e^- e^+ \nu\nu$: $\sim 10^{-16}$
  - Need high resolution tracker
  - Methods and knowledge of muon experiments well developed at PSI and MEG



prototype pixel support frame

http://www.psi.ch/mu3e/DocumentsEN/LOI_Mu3e_PSI.pdf

Next Generation Muon CLFV

- Extensive discussions of $\mu N \rightarrow eN$ upgrades at Project X
- New experimental designs for $\mu \rightarrow 3e$, $\mu \rightarrow e\gamma$
- Beyond planned upgrades: Hitlin, Knoepfel et al., 1307.1168
  - focus on converting the photon and trading rate (loss to conversion) for resolution (magnetic *p* better than calorimeter *E*)

$$\mathcal{B}(\text{one event background}) \propto (\frac{R_\mu}{D})(\Delta t_{e\gamma})\frac{\Delta E_e}{m_\mu/2}\left(\frac{\Delta E_\gamma}{15 m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

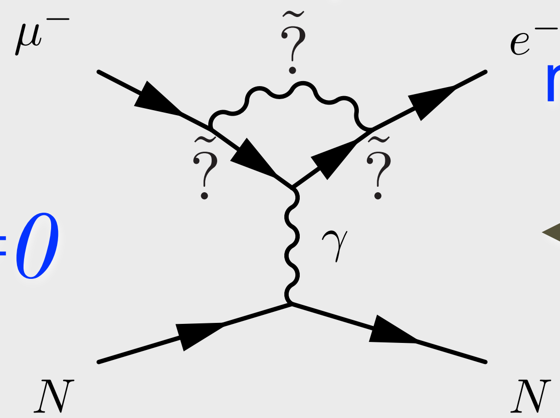
  - plus pointing to vertex for a pair of tracks
- Use flux to recover rate and time structure at Project X to have multiple experiments in one site

Common Framework for All Three Experiments

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

"Loops"

$\kappa = 0$



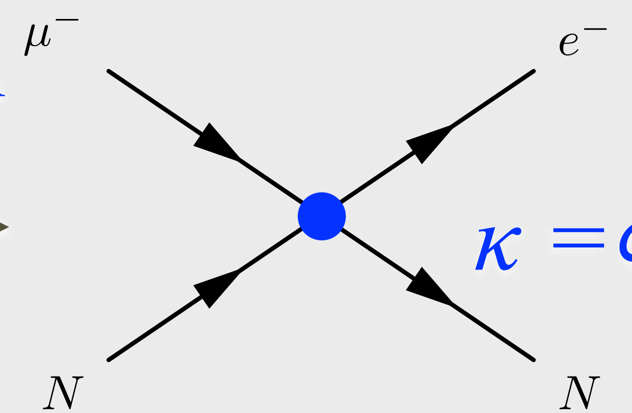
Supersymmetry and heavy neutrinos

mass scale Λ

κ

$\longleftrightarrow$

"Contact Terms"



$\kappa = \infty$

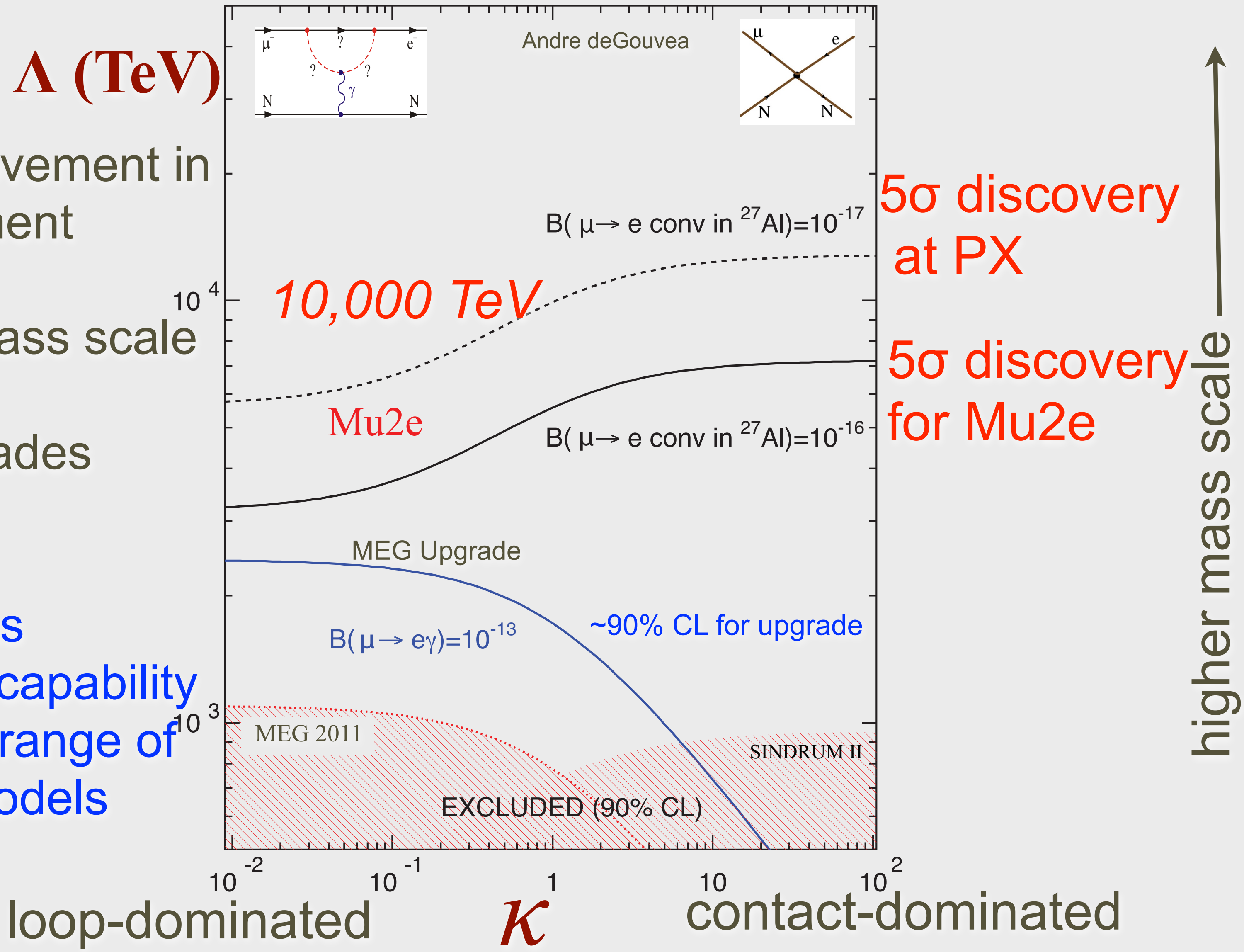
New particles at high mass scale (leptoquarks, heavy Z,...)

Contributes to $\mu \rightarrow e\gamma$
(just imagine the photon is real)

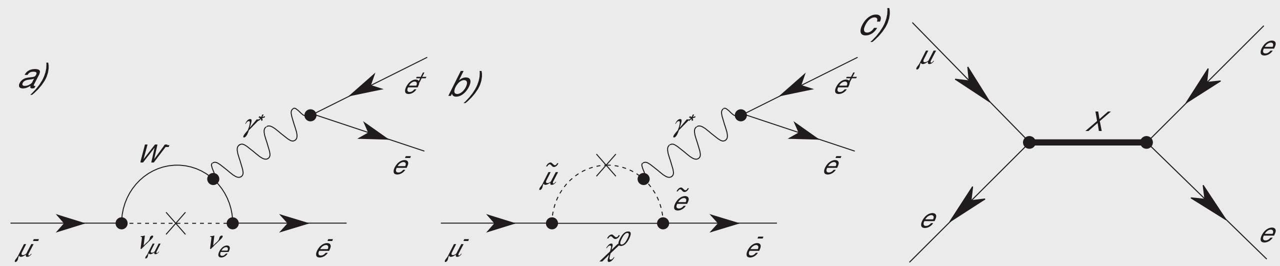
Does not produce $\mu \rightarrow e\gamma$

$\mu \to e$ Conversion and $\mu \to e\gamma$

- Mu2e:
  - 10^4 improvement in measurement
  - x10 in mass scale
  - PX upgrades shown
  - Mu2e has discovery capability over wide range of physics models

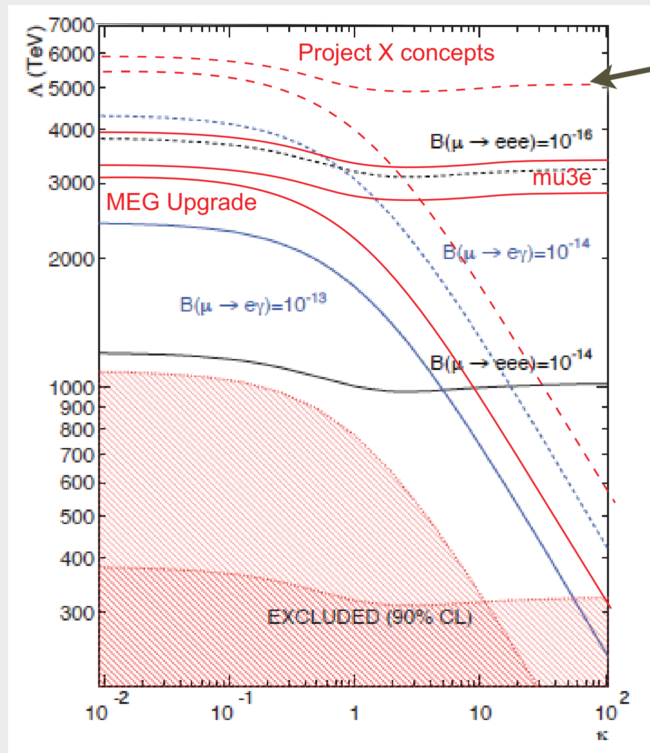


$\mu\rightarrow 3e$, $\mu\rightarrow e\gamma$, and $\mu N\rightarrow eN$



Hisano

- “Sister” process to $\tau\rightarrow 3l$
- The meaning of κ is not the same as previous page since the underlying diagrams are different, but still indicative
- PSI proposal to 10^{-16}
- PX concept another x10
- Competitive with other channels



Project X concept: Echenard at Snowmass

PSI proposal and its upgrade

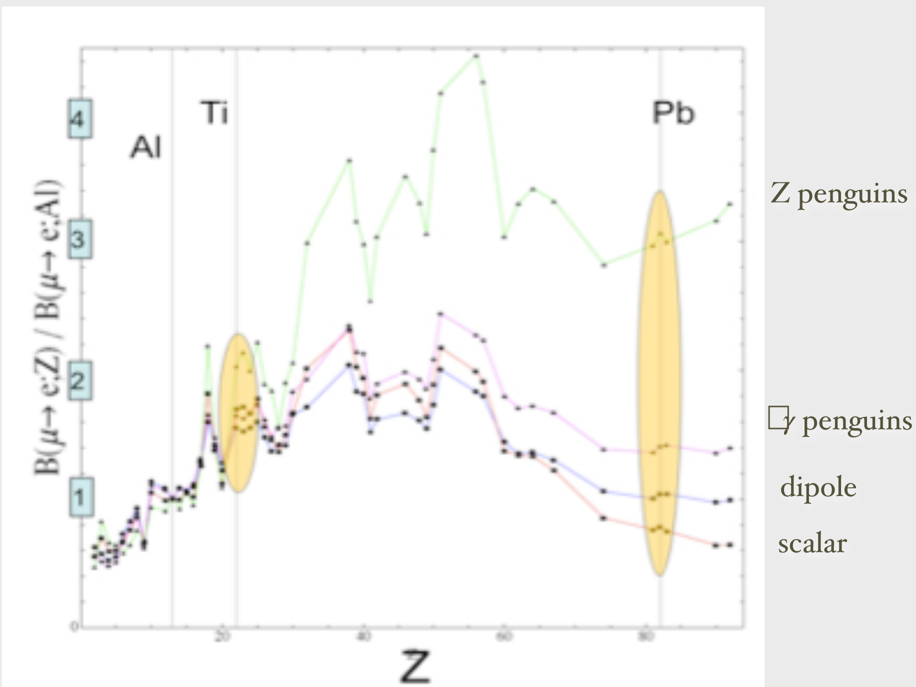
adapted by Hitlin from de Gouvea and Vogel 1303.4097v2

Evolution of Mu2e

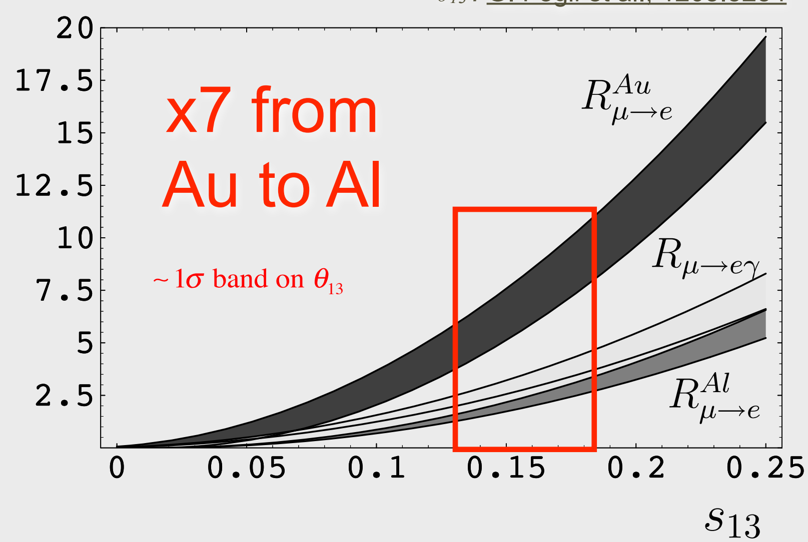
Knoepfel et al., 1307.1168

- If a discovery, then a different nucleus is the next step; Mu2e upgrades to improve the limit, and studying higher Z appears promising

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon, 0904.0957, Phys.Rev. D80 (2009) 013002



θ_{13} : G. Fogli et al., 1205.5254



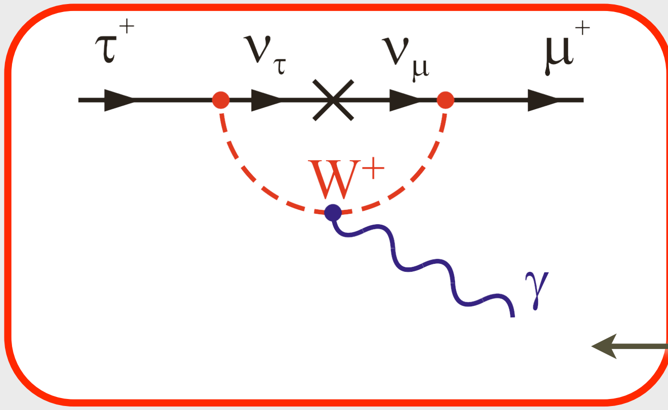
V. Cirigliano, B. Grinstein, G. Isidori, M. Wise, hep-ph /0608123 Nucl.Phys.B728:121-134,2005

5% measurement on Al/Ti needed to see split

CLFV and Tau Decays

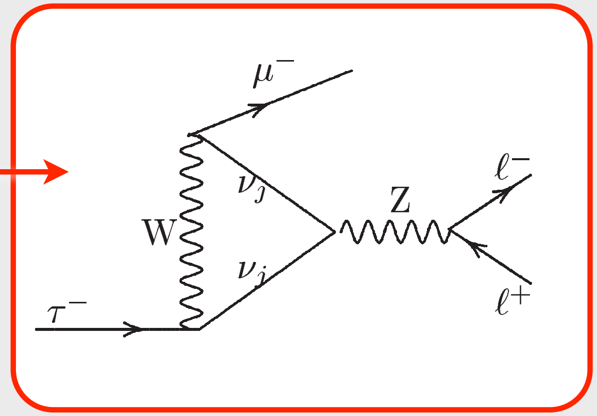
τ processes also suppressed in Standard Model but less:

Lee, Shrock
Phys.Rev.D16:1444,1977



$\ln\left(\frac{m_3^2}{M_W^2}\right)^2$

$\left(\frac{\Delta m_{23}^2}{M_W^2}\right)^2$



Pham, hep-ph/9810484

SM ~ 10^{-49}

SM ~ 10^{-14} ?

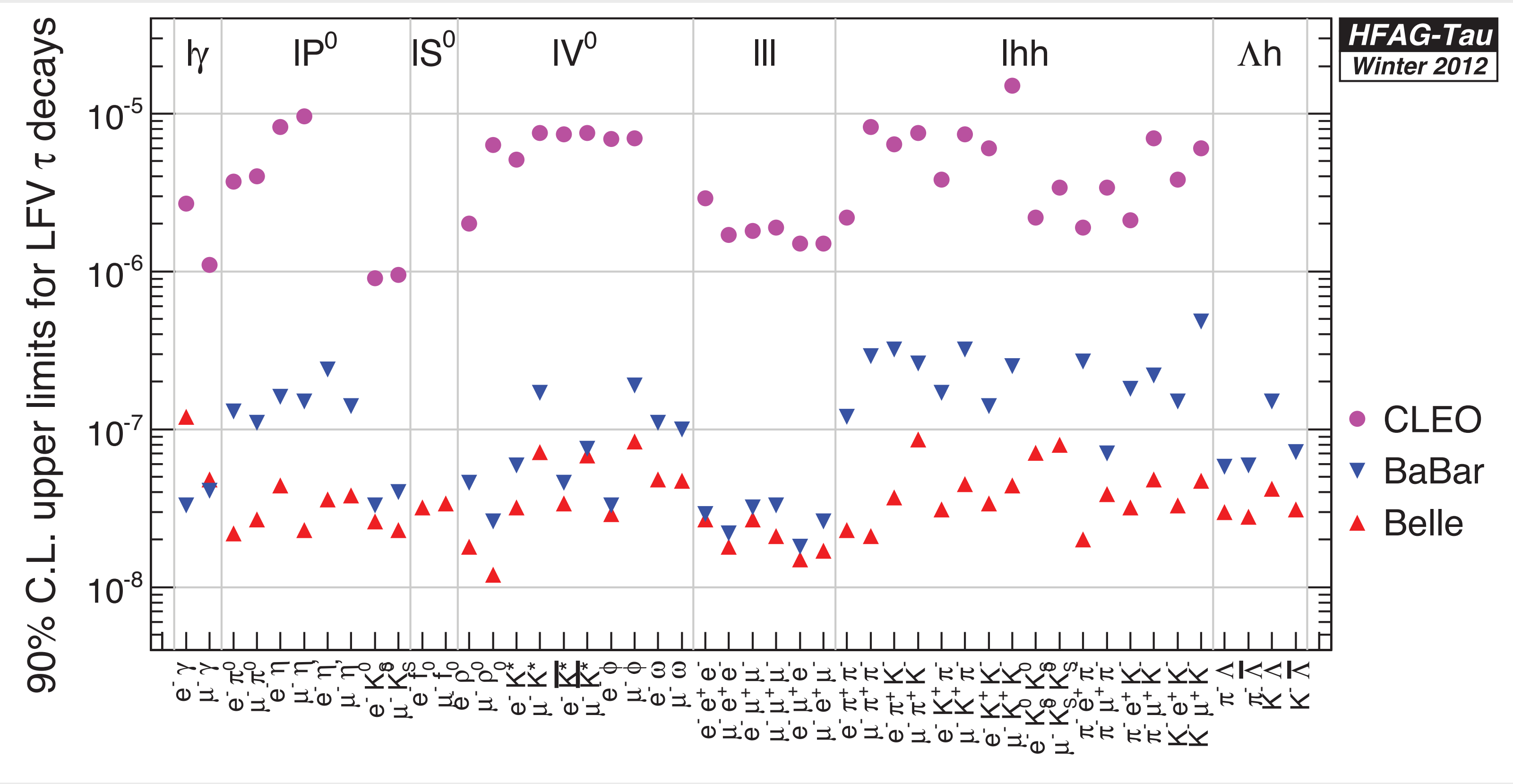
Good News:
Beyond SM rates can be orders of magnitude larger than in associated muon decays

Bad News:
τ's hard to produce: ~10^{10} τ/*yr* vs ~10^{11} μ/*sec* in upcoming muon experiments

τ's help pin down models and sometimes biggest BR

Extensive Program at e^+e^-

- 48 τ modes, typically at few x 10^{-8}
- Expect x10 – x100 in many modes at BELLE-II



LHCb and CLFV

B. Khanji, clfv2013.le.infn.it,

also see dx.doi.org/10.1016/j.physletb.2013.05.063, dx.doi.org/10.1016/j.physletb.2013.06.010, 1307.4889

- τ, *B*, and *D* Modes
  - already published:

90% CL	LHCb	Comment
$\tau \to 3\mu$	8.3 x 10^{-8}	Belle is x4 better
$\tau \to \underline{p}\mu^{+}\mu^{-}$	4.6 x 10^{-7}	first ever!
$\tau \to \bar{p}\mu^{+}\mu^{-}$	5.4 x 10^{-7}	first ever!

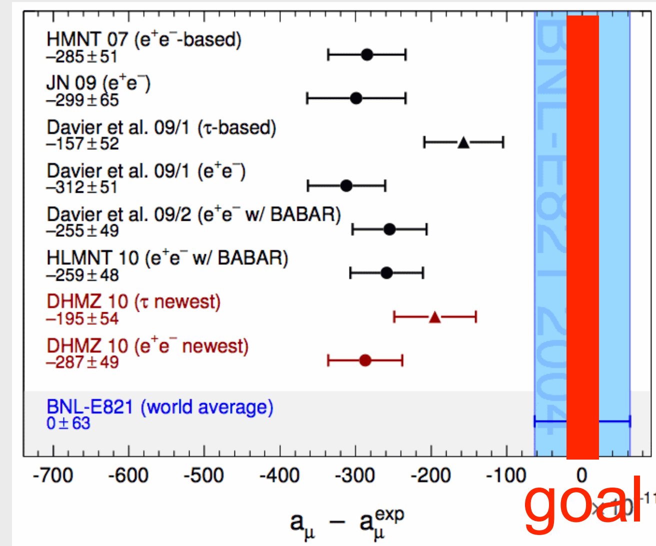
  - Looking forward to improvements
  - competition between statistics of LHCb, neutral modes at BELLE-II. Also CMS/ATLAS! Stay tuned.

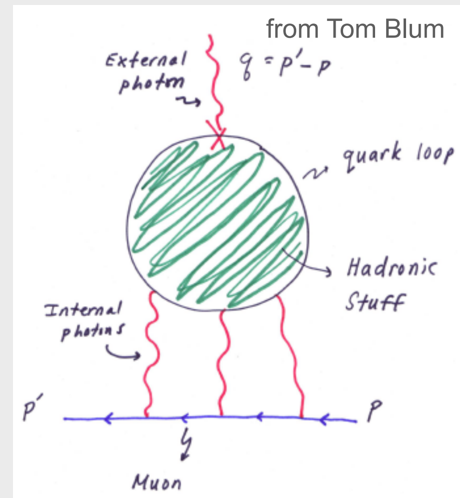
g-2

Run at FNAL in 2016; if central value stays constant, will be ~5σ instead of ~3.5σ

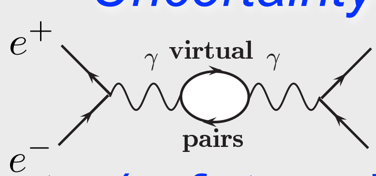
- Theoretical Uncertainties:
  - Current HLBL would need to be off by ~11σ to explain central value
    - target lattice error of 15% keeps pace with next measurement
    - Smaller uncertainty on HVP
  - *Future Theory Uncertainty can drop to keep pace with new g-2 Experimental Uncertainty yielding 8σ*

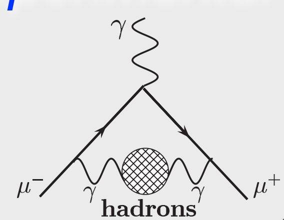
new g-2 proposal





HLBL: need lattice





new data (+ future lattice) → HVP

Van De Water, Snowmass

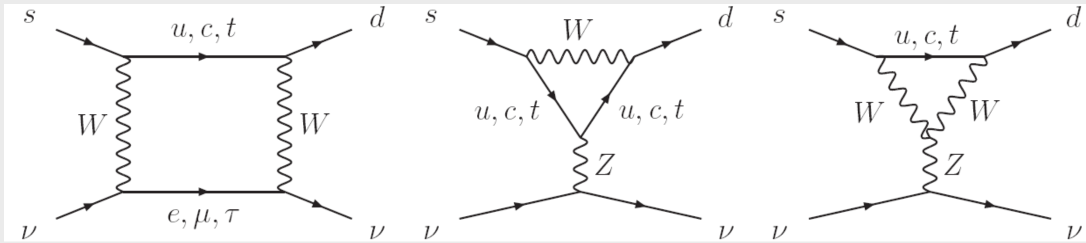
Ring at FNAL!

cue "Close Encounters" music...

Rare Kaon Decays

focus on $K \to \pi\nu\bar{\nu}$

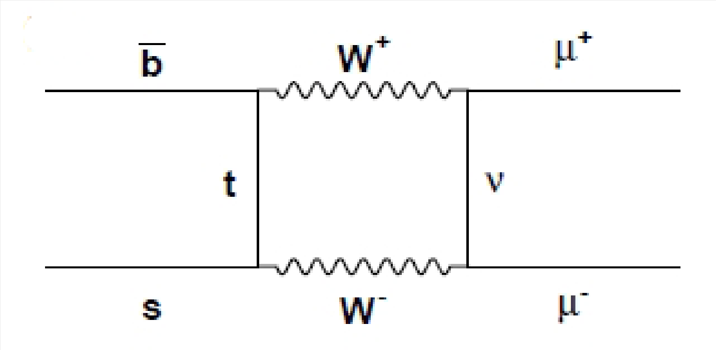
Kronfeld et al.,1306.5009



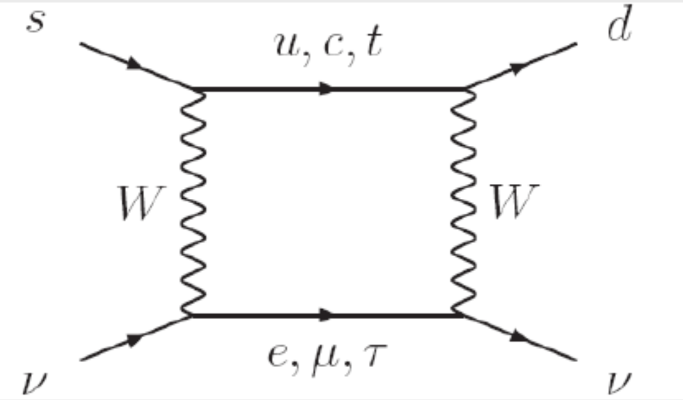
- Flavor Changing Neutral Current Process
- Precise Theoretical Predictions Possible:
  - Short-distance can be calculated precisely
  - Semileptonic K_L decays provide matrix elements
  - Quadratic GIM suppresses long-distance
- So exquisitely sensitive to BSM physics

Interconnections

- So now we've seen $B_s \to \mu\mu$ at >3.5, 4.3σ at LHCb and CMS (consistent with SM ~3 x 10^{-9} with ~30% errors)
- The $K \to \pi\nu\nu$ processes are related: basically same diagrams
- Can probe new physics very precisely in kaon system; many, many papers on exploiting these relationships



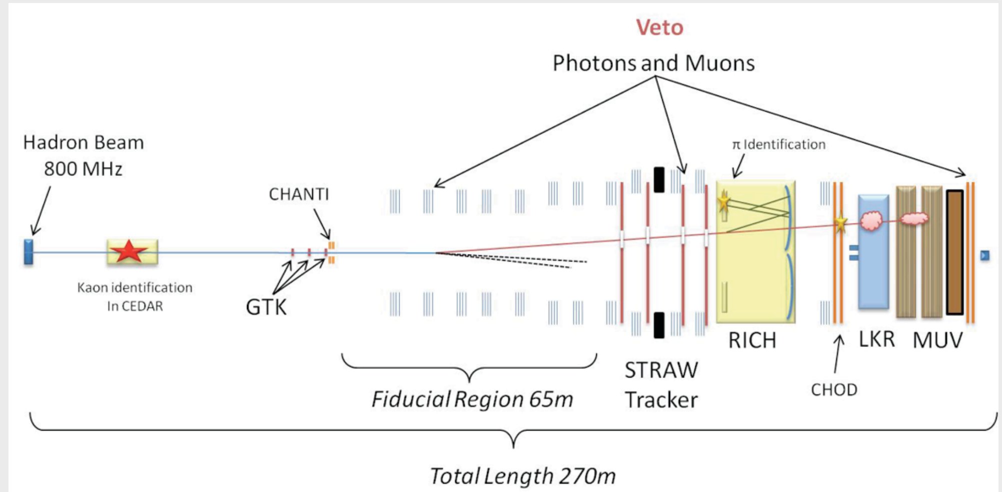
these are probing the same physics



LHCb,1211.2674 and CMS, 1307.5025

annihilation diagrams too

Worldwide Effort: CERN NA-62

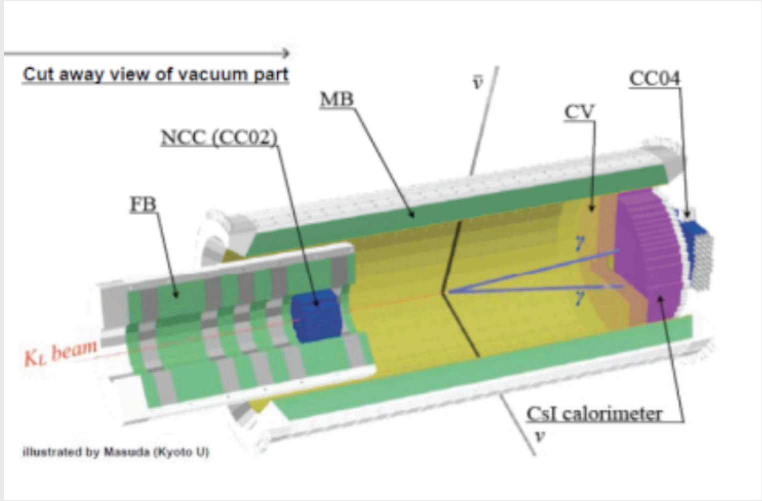


- Decay-in-flight
- Builds on NA-31/NA-48
- Expect ~55 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events/yr with ~7 bkg events for ~100 total events, or 10% measurement of branching fraction
- Complementary technique to stopped K^+ at ORKA

E. Worcester, Kaon 2013

Worldwide Effort: J-PARC KOTO

- Pencil beam decay experiment
- Improved J-PARC beam line
- 2nd generation detector building on E391 at KEK
- Re-using KTeV CsI crystals for better resolution and veto power
- Expect ~ 3 $K_L \rightarrow \pi^o \nu\bar{\nu}$ (SM)



J. Xu, this conf.

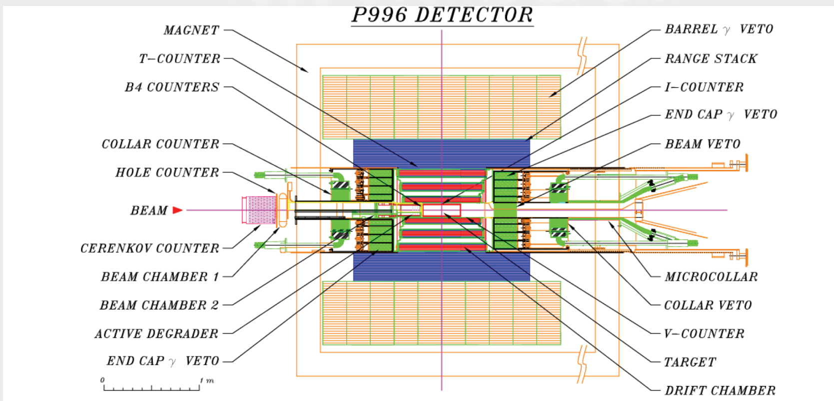
E. Worcester, Kaon 2013

Improved $K^+\to\pi^+\nu\bar{\nu}$, $K_L\to\pi^o\nu\bar{\nu}$

ORKA:

a 4th generation detector

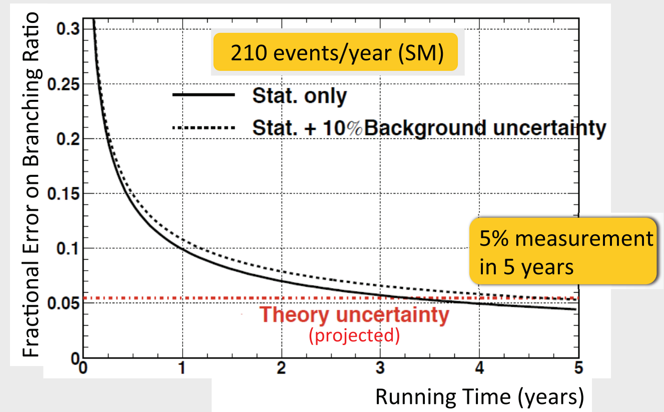
~ 1000 events at SM



Expect ×100 sensitivity relative to BNL experiment: ×10 from beam and ×10 from detector

A. Mazzacane, this conf.

ORKA $K^+\to\pi^+\nu\bar{\nu}$ Sensitivity

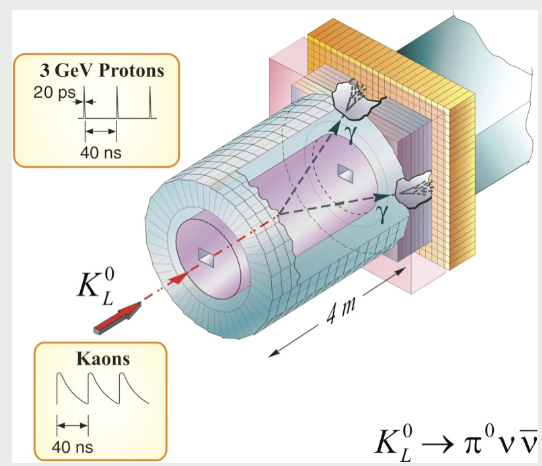


http://www.fnal.gov/directorate/program_planning/Dec2011PACPublic/ORKA_Proposal.pdf

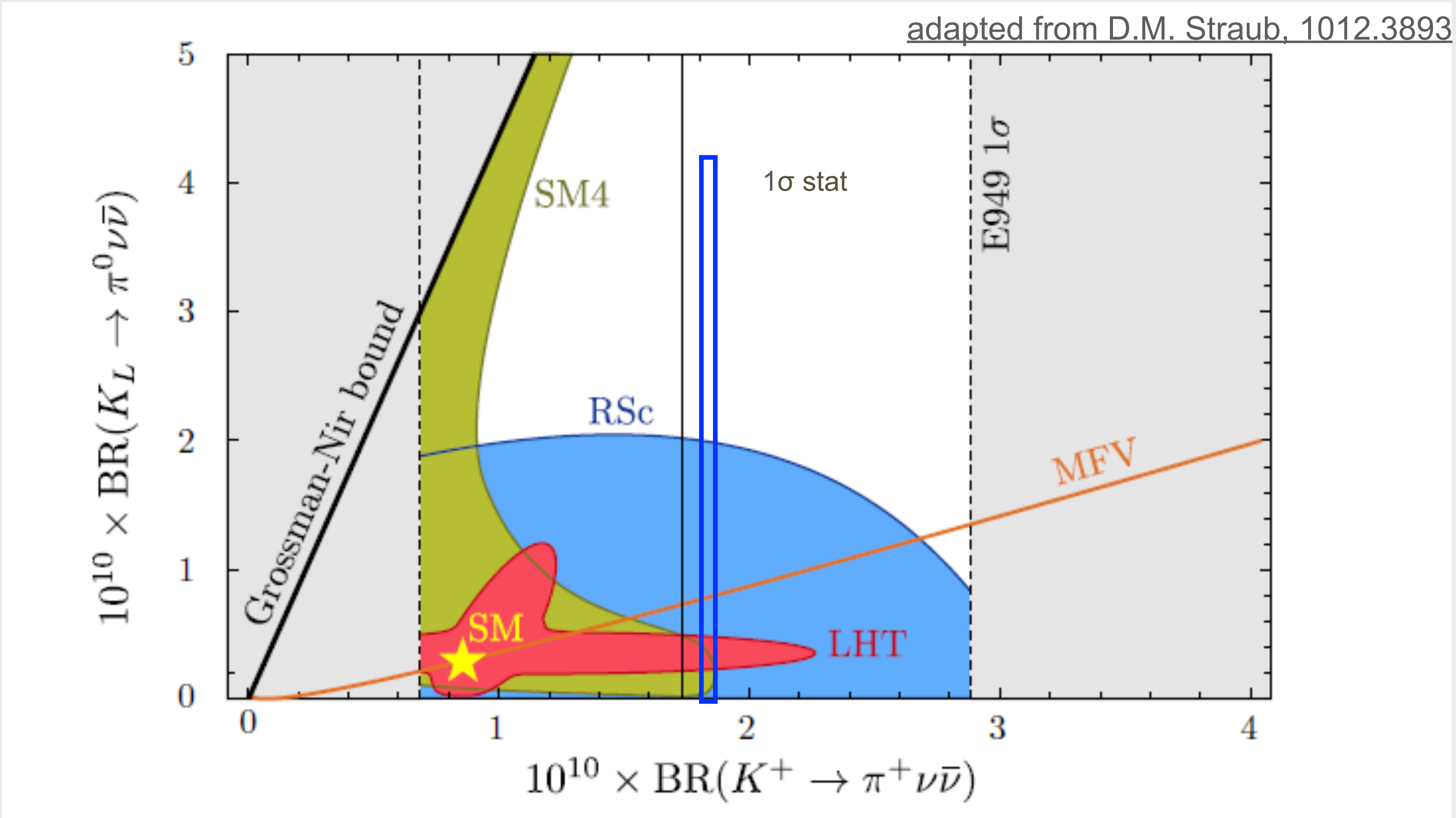
E. Worcester, Kaon 2013

- ORKA: $K^+\to\pi^+\nu\bar{\nu}$ has Stage 1 Approval, based on understood, incremental upgrades to BNL949

- $K_L\to\pi^o\nu\bar{\nu}$ at Project X: use time structure for TOF constraint



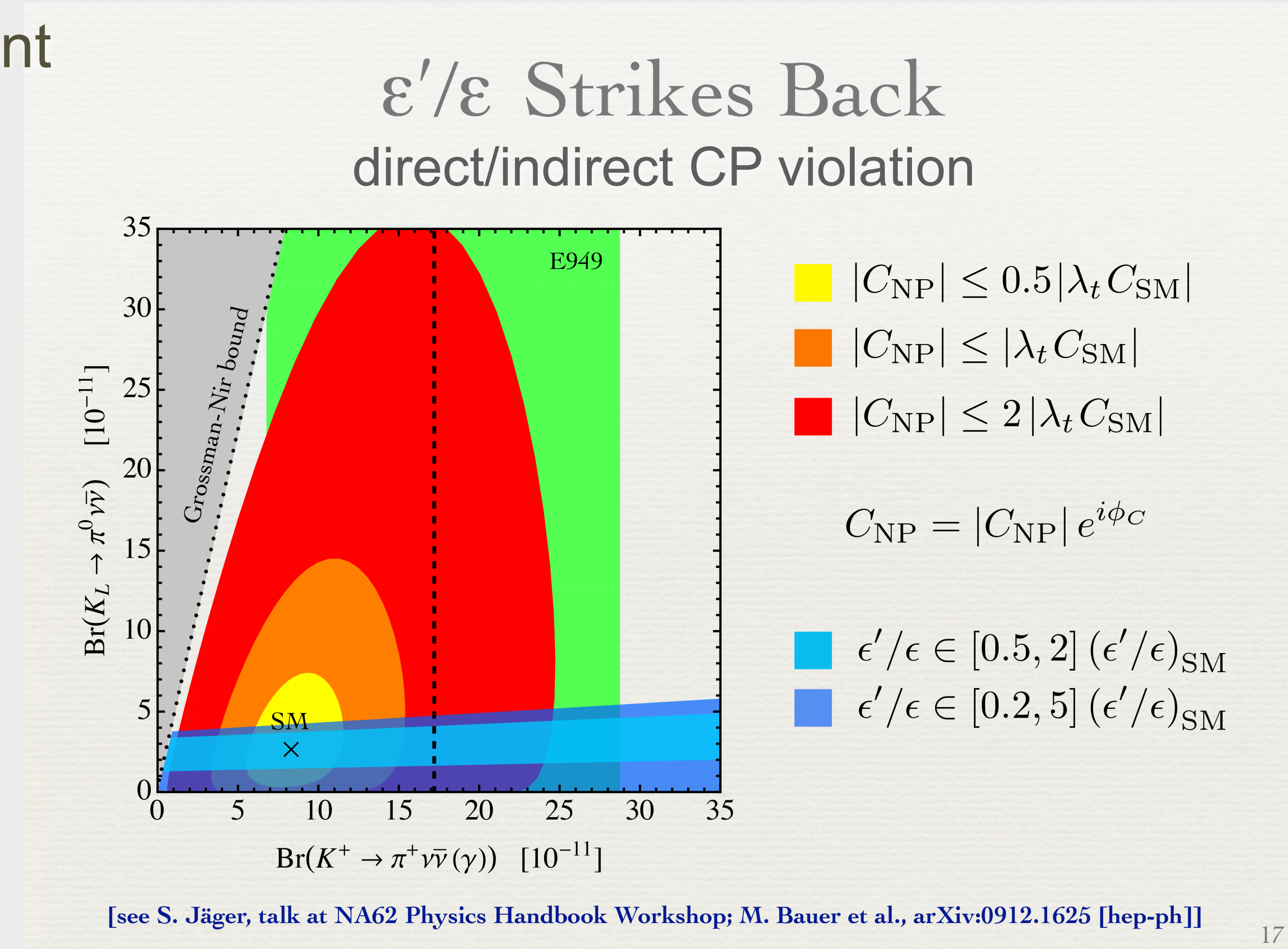
Some Examples



- ORKA: ~5% ΔB/B on branching ratios roughly shown

Overconstrain System

- Strong constraint for Z-Penguins
- Stringent correlation present in MSSM, RS, compositeness
- Measurements of CP in *B* system, *B*→*μμ*, *K**l^+l^- in good agreement: rare kaon decays offer "smoking-gun" opportunities



U. Haisch, PXPS2012,https://indico.fnal.gov/conferenceDisplay.py?ovw=True&confId=5276

More Interconnections

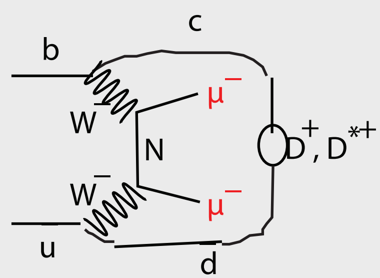
- Rare *B, D, K* decays and Neutrinoless Double Beta Decay:
  - are neutrinos Majorana?
    - leptogenesis from Majorana phases:
      - linked to baryogenesis and Sakharov conditions, requiring C or CP violation
    - neutrino mass from CKM phases

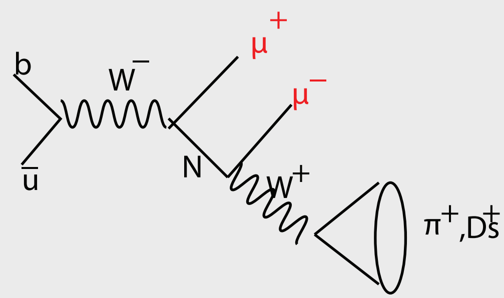
very complicated and no direct connection to low-energy observables; see Mu-Chun Chen at Snowmass

  - what is the source of neutrino mass?
    - Higgs or something else or both?

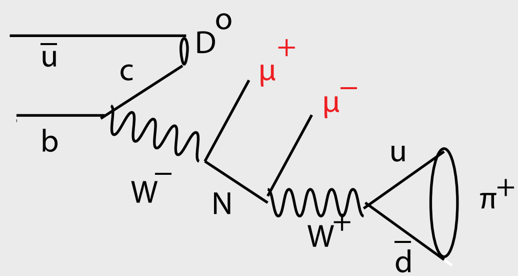
W. Buchmüller,R.D. Peccei, and T. Yanagida,10.1146/annurev.nucl.55.090704.151558

B mesons, Kaons, $0\nu2\beta$: Frontier Invariant



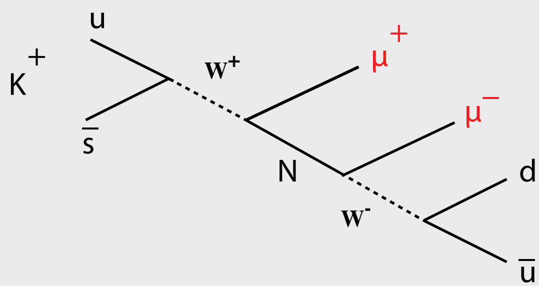


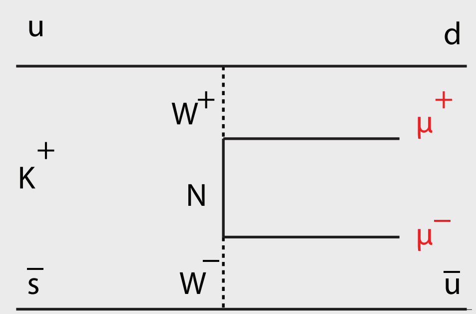
B mesons



N: particle to antiparticle

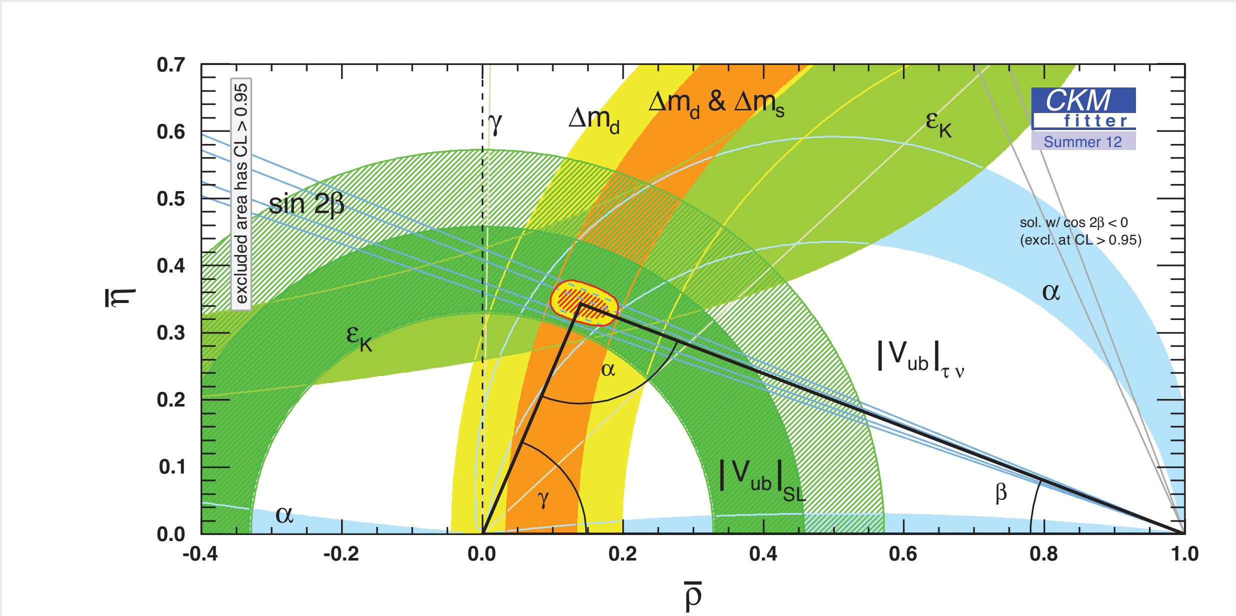
heavy neutrinos: Majorana or Dirac?





Kaons

Structure of CKM Matrix



combination of many experiments over years!

- *K*, *B* and *D* decays:
  - Four CKM parameters plus *W*, *Z* and quark masses
  - plus ~100 other flavor changing operators

see Zoltan Ligeti, Snowmass

  - ~20% corrections from new physics in loops still allowed

Incomplete List of Important Topics I Won't Cover

many talks at this conf.

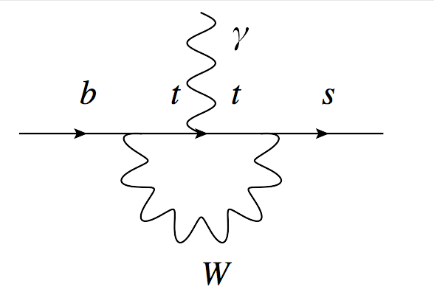
- CPV in $\tau \to K\pi\nu$ (2.8σ)
- V_{ub}, V_{cb} inclusive/exclusive tension
- D^o -$\bar{D}^o$ mixing
- $B \to D^*\tau\nu$ tension persists, $B \to \tau\nu$ tension gone
- α, β, γ determinations
- CP Asymmetries in

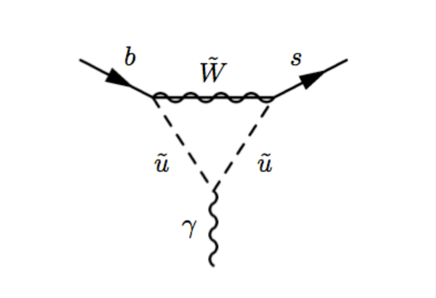
$$S_{J/\psi K_S} - S_{\phi K_S},\ S_{\psi K_S} - S_{\eta' K_S},\ S_{J/\psi\phi} - S_{\phi\phi}\ldots$$

Where to Look?

- 2nd-3rd generation fermions (escape bounds from kaon physics)
    - e.g. in SUSY GUTs the near-maximal θ_{23} may imply large mixing between s_R and b_R and $\tilde{s}_R$ and $\tilde{b}_R$
- $B \to X_s\gamma$ especially interesting (3% at SuperKEKB)
    - SUSY in loops, ~ analogous to $\mu \to e\gamma$ or $\mu N \to eN$ diagrams

finding deviations from SM
$B \to X_s\gamma$
is complementary to
$\mu \to e\gamma$ discovery





Role of Lattice

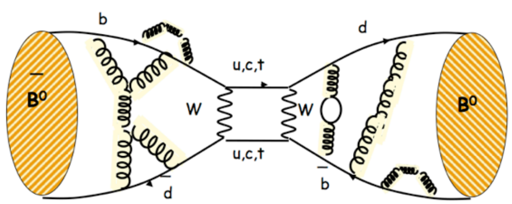
- Experimental improvements demand better lattice calculations: e.g. g-2 or f_B or ε_K
    - how can lattice methods be useful for interpreting data?
- Lattice has matured and we need to renormalize our attitude

Laiho at Snowmass   Van de Water Colloquium at Snowmass

Laiho, Lunghi & Van de Water, Phys.Rev.D81:034503,2010

example:

$B-\overline{B}$ mixing

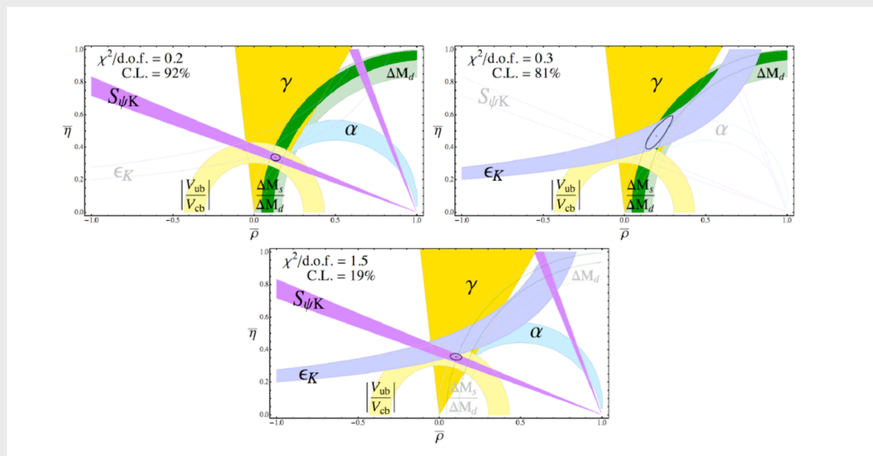


$$\Delta M_d = (\text{known}) \times |V_{td}^* V_{tb}|^2 \times \langle \overline{B^0}|\mathcal{O}_{\Delta B=2}|B^0\rangle$$

$$\sim f_{B_d}^2 B_{B_d}$$

f_B

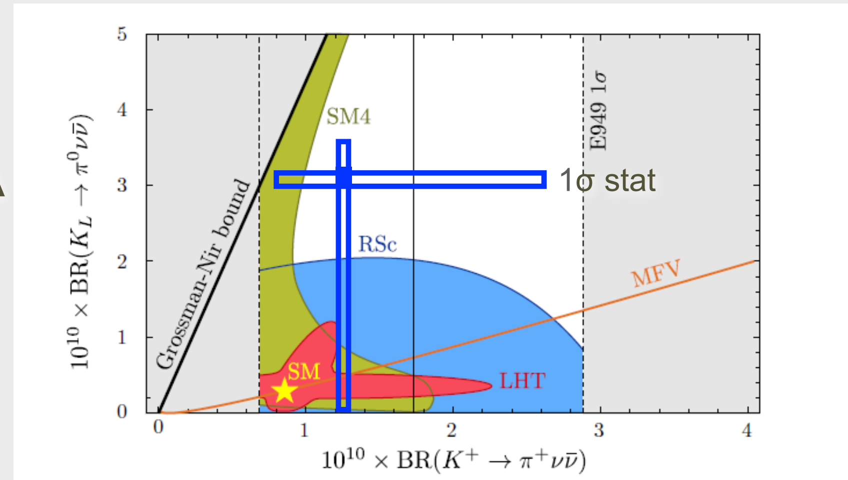
El-Khadra, FPCP 2012

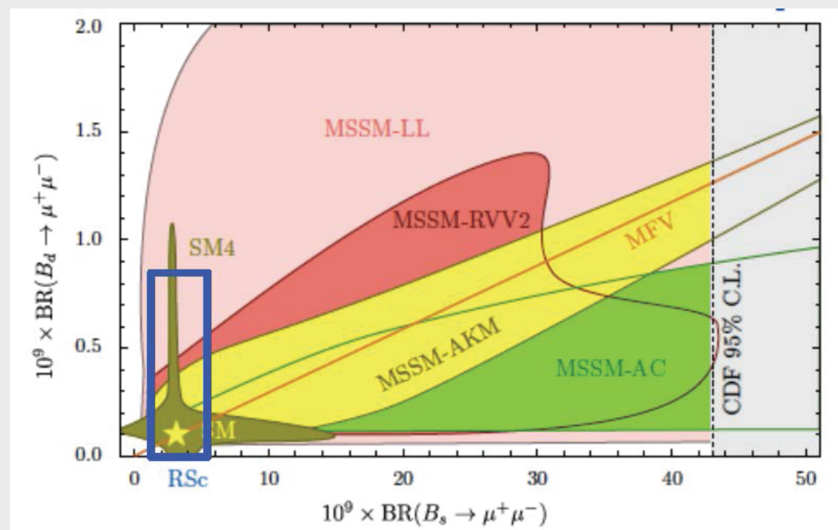


Lattice, CKM, *B* and *K* modes

- ~30% on *B* modes: how much better?
- 5% measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ at ORKA
  SM BR ~ 7.8 x 10^{-11}
- ~1000 SM $K_L \to \pi^o \nu\bar{\nu}$ events at Project X
  SM BR ~ 2.4 x 10^{-11}
- Point about lattice and CKM:
  - *B* meson statistical error will get smaller but we need a better f_B determination from the lattice to get below ~8%
  - K^+ errors need better CKM determinations (another interconnection)

adapted from D. M. Straub, arXiv:1012.3893



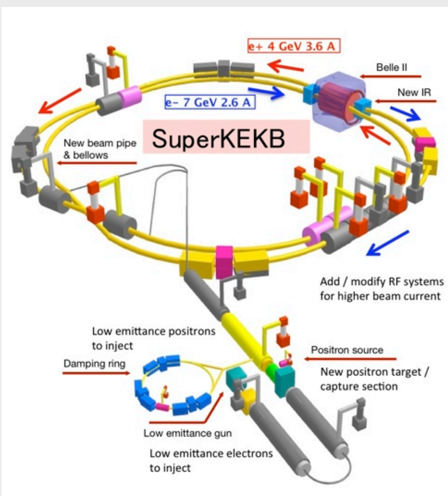


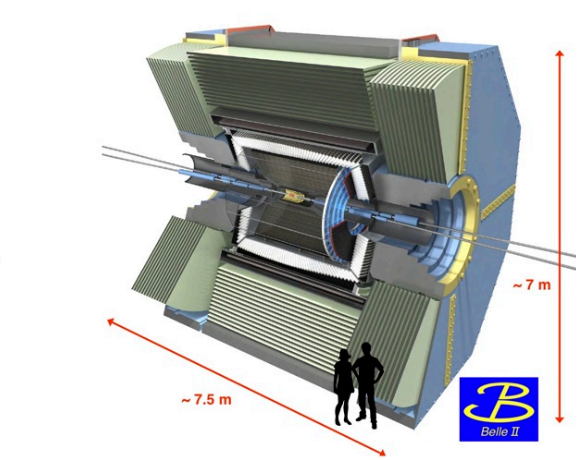
adapted from D. M. Straub, 1205.6094

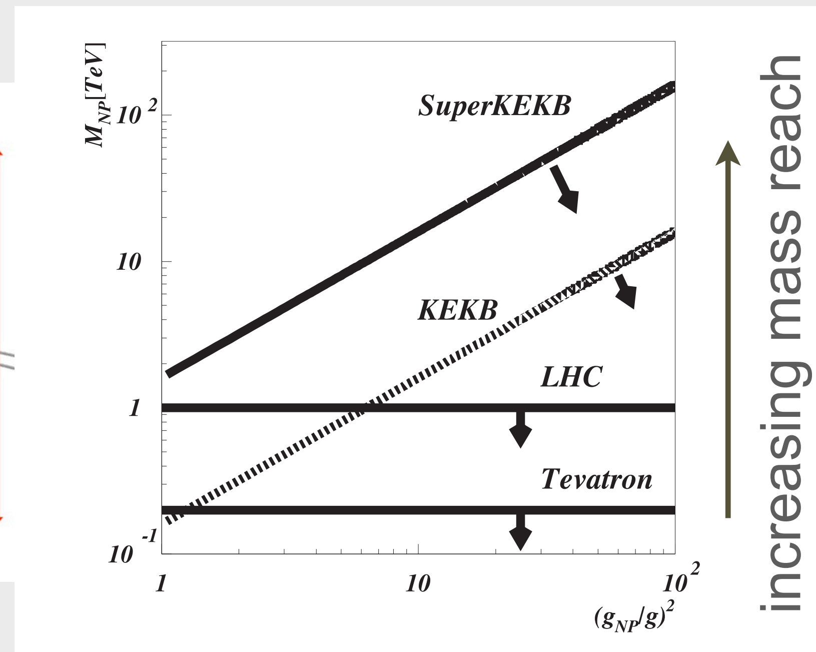
B Physics: Future Facilities

- SuperKEKB and BELLE-II: **50 x 10^9** $B\overline{B}$ pairs
  - Peak L ~ 8 x 10^{35} cm^{-2} s^{-1}, x 40 KEKB, 50 ab^{-1} by 2023

S. Vahsen, this conf.







MFV, Mass vs Coupling

Akeroyd et al. hep-ex/0406071

B Physics at LHC

many talks at this conf.

- LHCb
  - 3 fb^{-1} at 7-8 TeV, 5-7 3 fb^{-1} at 13 TeV by 2018
  - 50 fb^{-1} long-term requires upgrade (2018)
    - replacement or upgrade of most detector systems
    - trigger changes to readout at 40 MHz, software filter
- 8% measurement of $B_s \to \mu\mu$ (x3 better than current, but need better lattice measurement to improve past that)
- With ATLAS and CMS, a deep and important program

Role of Charm Physics

Feldmann et al. 1202.3795v1; Van Tilburg, 1303.2614; Aaij et al., 1111.5000

- SM very successful in over-constraints of CKM and not done yet

  (sadly leaving out top flavor physics)

- But rare decays and CP are a path we should take
  - and the bramble of long-distance might be cleared up with advances on the lattice
- Can look at physics of up-quarks in FCNC:
  - D^o-$\overline{D}^o$ mixing, direct and mixing induced CP, rare decays.
- *One* example (should be < 0.1%)

$$\Delta A_{CP} = A_{CP}(D^o \to K^- K^+) - A_{CP}(D^o \to \pi^- \pi^+) = (-0.645 \pm 0.180)\%$$

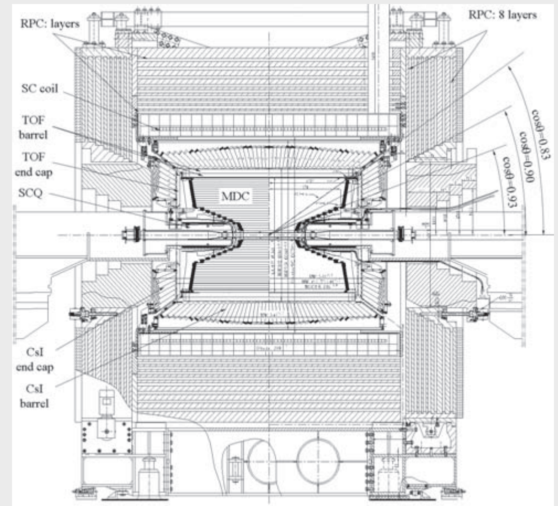
$$\Delta A_{CP} = \ 0.49 \pm 0.30 \pm 0.14(\pi \text{ tagged}), -0.34 \pm 0.15 \pm 0.14(\mu \text{ tagged})$$

Charm Facilities

- More Charm Produced at LHC than *B*'s Produced at LHC and in e^+e^- at Υ(4s)

- Tau-Charm Factories

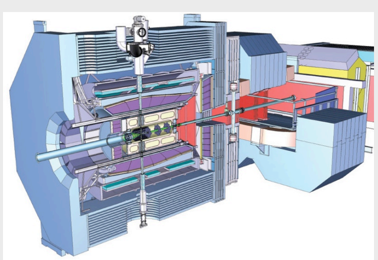
BESIII, 0911.4960v1



  - BES-III underway at BEPCII (Beijing), 10^{33} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, x10 CLEO-c

  - BINP Super c/τ and Italy post-SuperB and Turkey

  - plus $p\bar{p} \rightarrow c\bar{c}$ in Panda at FAIR (GSI, Darmstadt)



Electric Dipole Moments

- **CP Violation and the Matter/Antimatter Asymmetry in the Universe**
    - Sakharov Criteria
        - Baryon Number Violation
        - CP & C violation
        - Departure from Thermal Equilibrium

- Standard Model CP violation is insufficient
    - Must search for new sources of CP
        - *B* factories, LHC, Neutrinos, EDMs
- Electroweak Baryogenesis still viable

M. Carena et al., hep-ph/9202409,
Nucl. Phys. B 503, 387 (1997)
Li, Profumo, Ramsey-Musolf : 0811.1987
Cirigliano, Li, Profumo, Ramsey-Musolf: JHEP 1001:002,2010

K.S. Babu et al.,Phys. Rev. D 64 (2001) 053009
J. Feng et al. ,hep-ph/0107182v1

$$H = -\vec{\mu} \bullet \vec{B} - \vec{d} \bullet \vec{E}$$

EDMs

	E	B	$\vec{\mu}, \vec{d}$
P	-	+	+
C	-	-	-
T	+	-	-

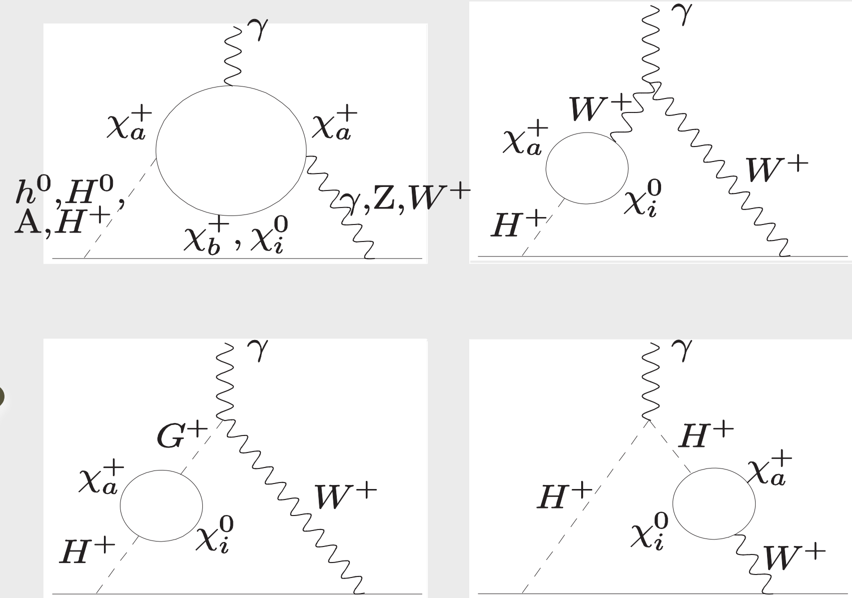
$\vec{d}, \vec{S}$

parallel for intrinsic EDM of a point particle

- EDMs are a unique and powerful probe into non-CKM sources of CP violation (strong CP problem)
- Muon EDM in the SM < 10^{-36}: a discovery is NP
  - Most models predict linear scaling, so electron EDM provides a strong constraint: $d_e < 1.6\text{x } 10^{-27}$ e-cm
  - But some predict quadratic or cubic scaling

EDMs and SUSY

$H \rightarrow \gamma\gamma$



- SUSY Contribution
  - electroweak baryogenesis?

Y.Li, S. Profumo, M. Ramsey-Musolf,
PRD 78, 075009, 2008;
PLB 673, 95, 2009.

Table 1: Summary of how the CP-violating sources in MSSM generate various CP-odd operators at one-loop and two-loop level.

CP-violating phases	one-loop contribution	two-loop contribution
$\phi_{e,u,d}$	$d_{u,d,e}^{1-loop}, \tilde{d}_{u,d}^{1-loop}, C_{ff'}$	no
$\phi_{\mu,c,s}$	no	no
$\phi_{\tau,t,b}$	no	$d_{u,d,e}^{2-loop}(\tilde{t},\tilde{b},\tilde{\tau}),\ \tilde{d}_{u,d}^{2-loop}(\tilde{t},\tilde{b},\tilde{\tau}),\ d^{3G}$
$\phi_{1,2}$	$d_{u,d,e}^{1-loop}, \tilde{d}_{u,d}^{1-loop}, C_{ff'}$	$d_{u,d,e}^{2-loop}(\chi^{\pm,0})$
ϕ_3	$d_{u,d}^{1-loop}, \tilde{d}_{u,d}^{1-loop}, C_{ff'}$	d^{3G}

Li, Profumo, Ramsey-Musolf 1006.1440

EDMs In Storage Rings

$$\vec{\omega} = -\frac{Qe}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{Qe}{2m}\left[\eta\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

$$\vec{d} = \eta\left(\frac{Qe}{2mc}\right)\vec{s}$$

Bargmann-Michel-Telegdi Eqn. (1959)

watch for precession; these two terms in different planes

- First line is about g-2; second line is about EDMs
  - x100 muon improvement in EDM comes along with FNAL g-2
- Longer Term Prospects:
  - Can choose E(r) to cancel first line in OR
  - All-Electric variant proposed for *proton* EDM

http://www.bnl.gov/edm/

Rare Isotope Storage Ring EDMs

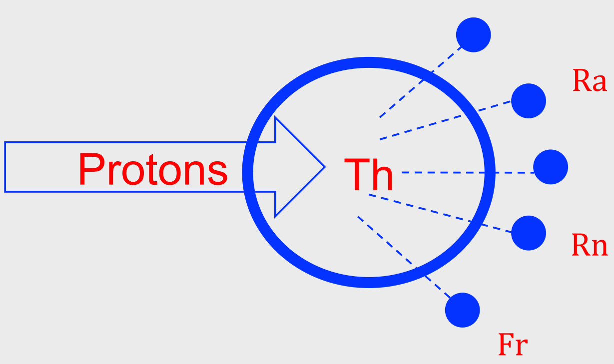
Kronfeld et al. PX Physics, 1306.5009

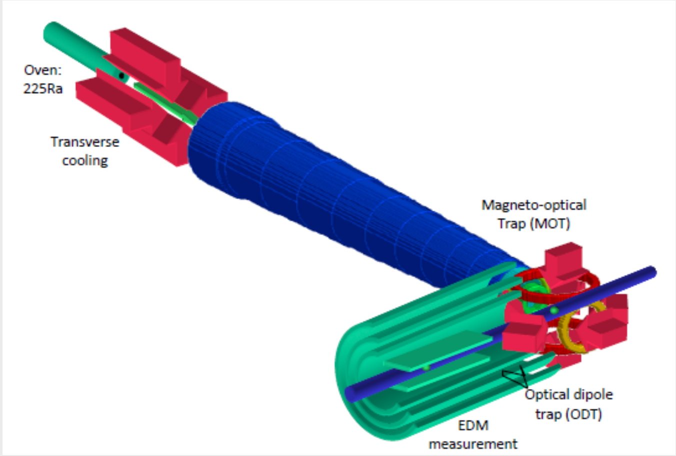
- new possibility with Project X; heavy isotopes open new windows into EDMs with cross-checks of signals and unique possibilities

J. Engel, Michael J. Ramsey-Musolf, U. Van Kolck, 1303.2371

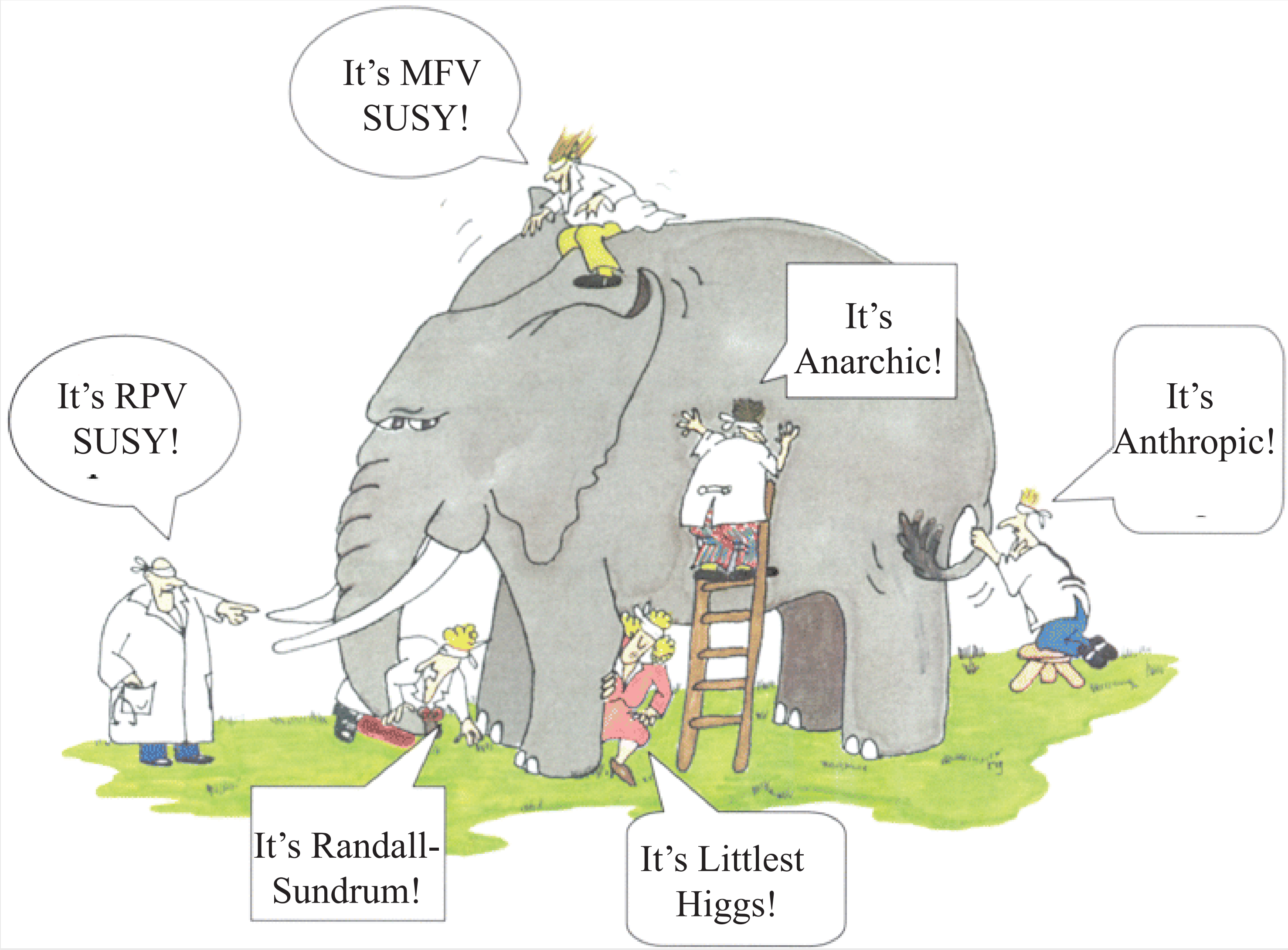
Table 1: Projected sensitivities for $^{221/223}$Ra and the corresponding sensitivities in ^{199}Hg at TRIUMF, FRIB, and Project X.

Facility	TRIUMF-ISAC	FRIB (^{223}Th source)	Project X
Rate	2.5×10^{7} s^{-1}	1×10^{9} s^{-1}	3×10^{10} s^{-1}
# atoms	3.5×10^{10}	1.4×10^{12}	4.2×10^{13}
EDM Sensitivity	1.3×10^{-27} e·cm	2×10^{-28} e·cm	5×10^{-29} e·cm
^{199}Hg equivalent	1.3×10^{-29} e·cm	2×10^{-30} e·cm	5×10^{-31} e·cm



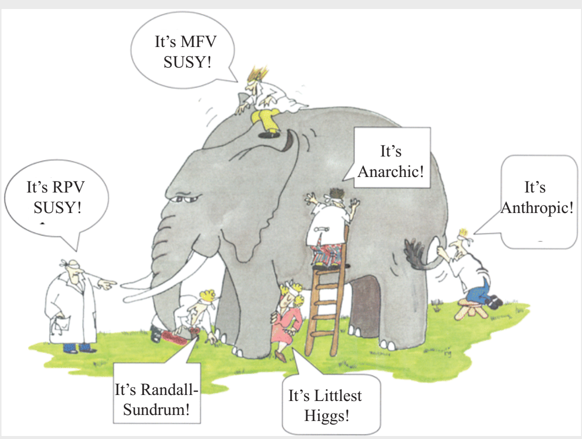


How It Seems With Single Measurements



Theme: Complementarity

- People tend to think about the rows: "experiment *X* is best"



	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

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.

W. Altmanshofer et al. 0909.1333v2

Theme: Complementarity

- Think about the columns: a combination of experiments is required

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}\,(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

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.

my take: brave experimenter cutting down models; model-builders might differ

Flavor Physics Conclusions

- Flavor physics is an essential element in the international particle physics program
  - central component in discovering new physics
  - access to mass scales up to 10^4 TeV/c^2 or beyond
  - huge power to distinguish among models with multiple, reinforcing measurements

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{\text{flavor structure and coupling strength}}{\Lambda^2}$$

Snowmass Conclusions

- US poised to become world leader in flavor physics
  - charged lepton flavor violation (Mu2e) and muon g-2
  - rare kaon decay program: ORKA
  - EDMs: muon, proton, isotopes
  - highly suppressed decays of strange, charm, and bottom quarks
  - measurements of CKM parameters, both in new physics and necessary inputs for other measurements
  - progress in the lattice is sharpening theory predictions
- US is part of this program through ATLAS, CMS, LHCb, BELLE-II, ...
- And can build on this physics with world-leading facility at Project X

Summary

- Rabi, the son of poor immigrants, reported that his mother made him a scientist. Every day when he returned home from school, rather than ask (as most mothers did), “What did you learn today?” Rabi’s mother asked, “Izzy, did you ask any good questions?”
- Flavor Physics is about *great* questions

Additional Material

Not to Forget CLFV in Kaons

Moulson, KAON 2013,1306.3361v2

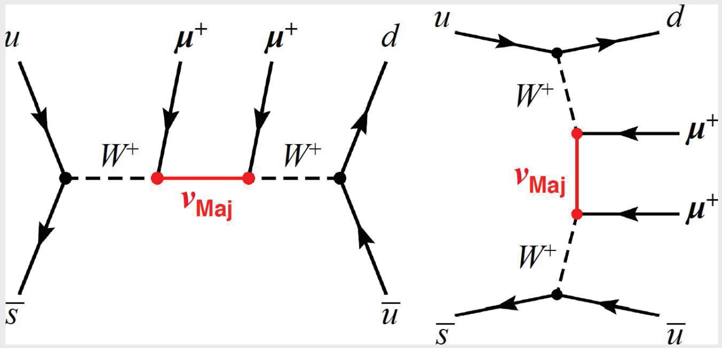


Figure 1: Lowest-order diagrams contributing to $K^+ \to \pi^- \mu^+ \mu^+$. The decay can proceed if the neutrino exchanged can annihilate itself, i.e., if it is its own antiparticle.

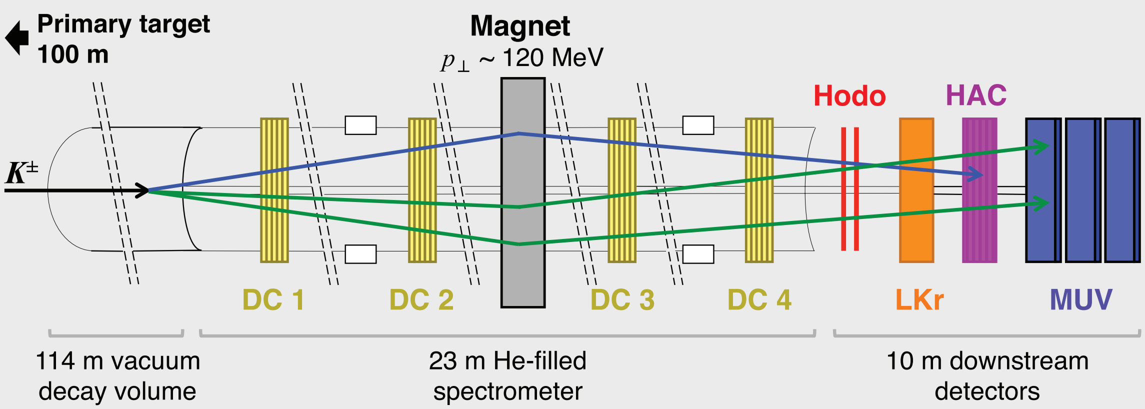
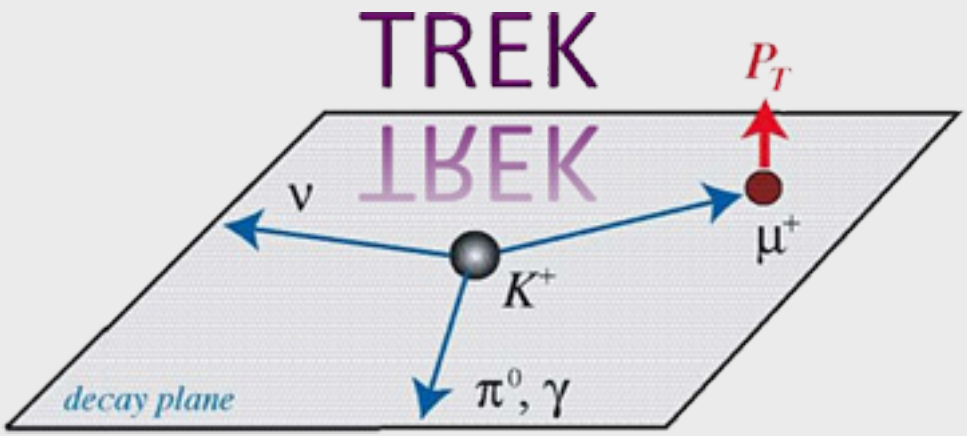


Figure 2: Schematic diagram of the NA48/2 experiment, showing drift chambers (DC1–4), trigger hodoscope (Hodo), NA48 liquid-krypton electromagnetic calorimeter (LKr), hadronic calorimeter (HAC), and muon vetoes (MUV).

TREK: CP Beyond SM

at J-PARC

- T-Violation in Charged K decays through polarization asymmetry in $K^+ \rightarrow \pi^o \mu \nu$
  - needs >100 kW
- Lepton Flavor Universality through $\frac{\Gamma(K \rightarrow e\nu)}{\Gamma(K \rightarrow \mu\nu)}$



The "Magic Momentum"

- We have to focus the muons and use electric quadrupoles; this shifts $\vec{\omega}_a$

$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]$$

plus an EDM term for later

no focusing

with focusing

- Choose the "magic momentum" 3.094 GeV/c and $\gamma = 29.3$

$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \underbrace{\cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1} \right)}}_{0} \frac{\vec{\beta} \times \vec{E}}{c} \right]$$

Cold g-2

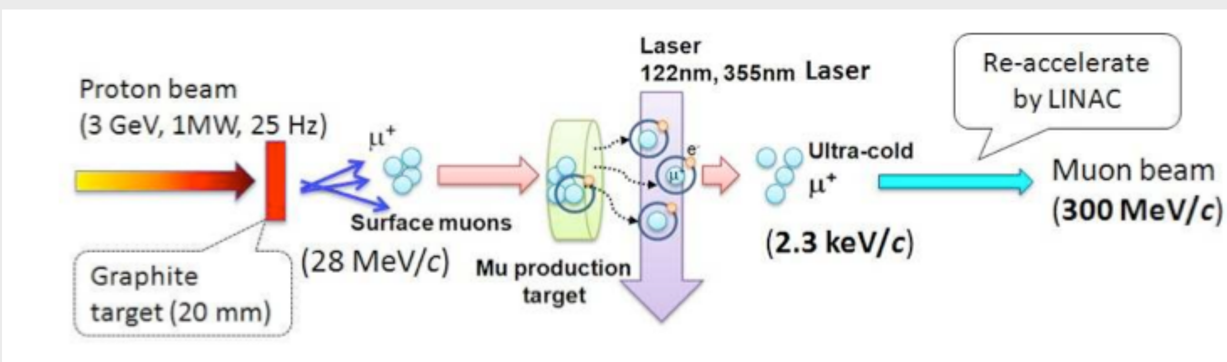
- If cold, don't need E: no "magic momentum" required

$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$

$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B}\right]$$

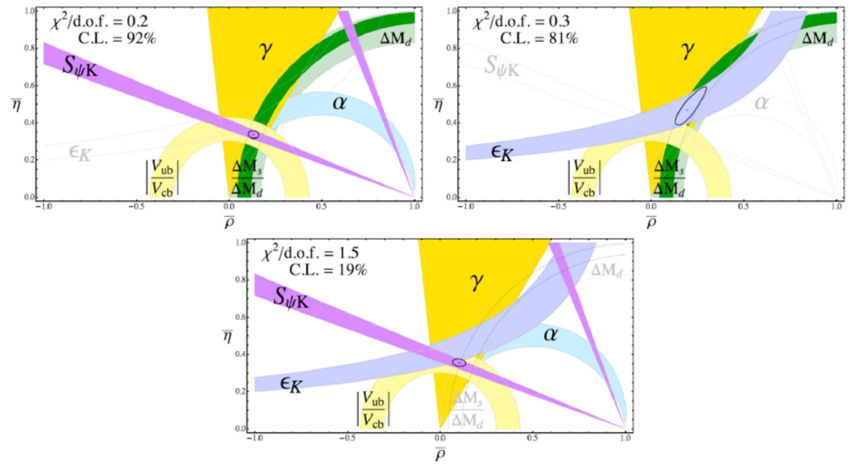
- And measure EDM $\quad \frac{Qe}{2m}\left[\eta\left(\vec{\beta}\times\vec{B}\right)\right]$

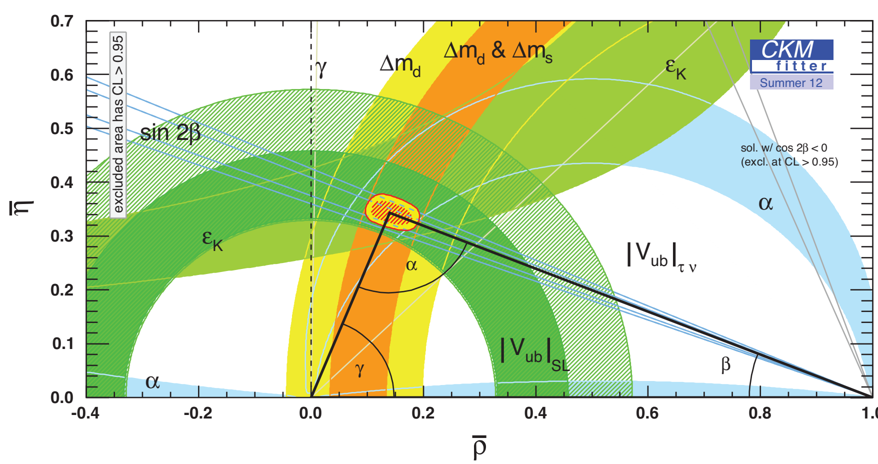
- But muonium rate too low for now



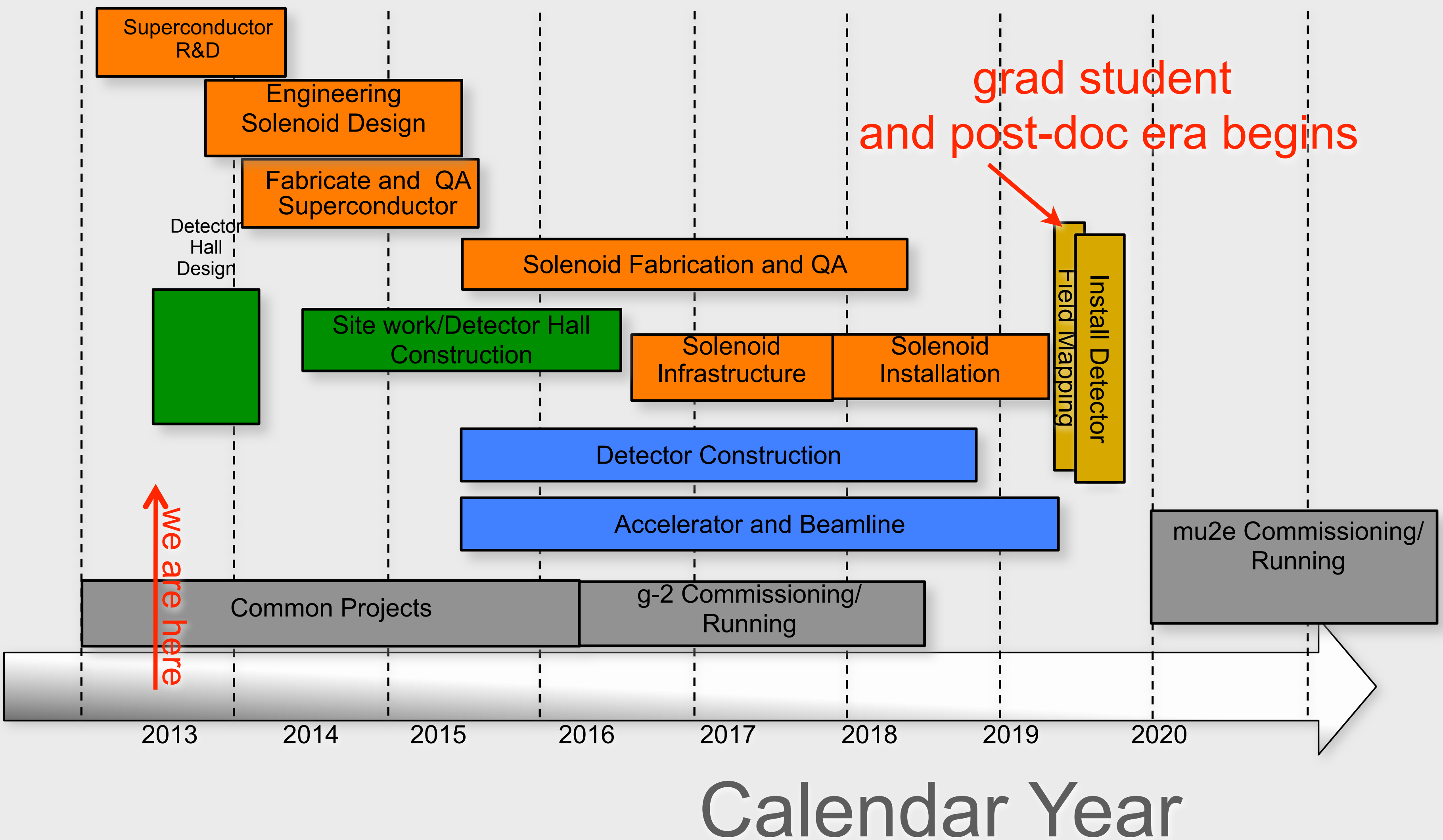
CKM Fitter and UTfit

- Why are these so different?
- Frequentist v. Bayesian
- CKMFitter uses Rfit for theory errors, which typically leads to less stringent constraints
- Use different estimates for hadronic matrix elements from lattice QCD
- Hopefully will start using identical inputs from FLAG



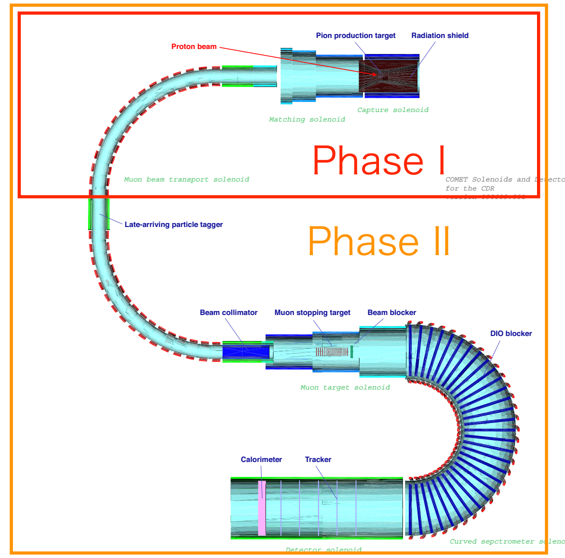


Mu2e Schedule

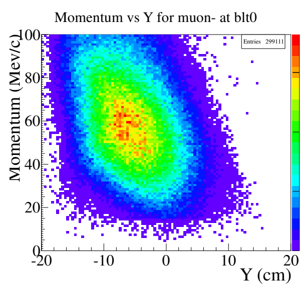


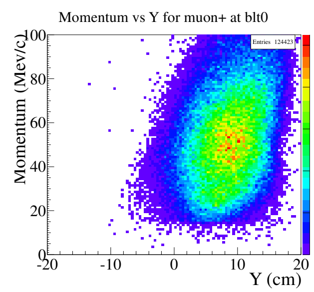
COMET Phase I & II

- Phase I
  - Beam background study and achieving an intermediate sensitivity of <10^{-14}
    - 8GeV, ~3.2kW, ~3 weeks of DAQ
- Phase II
  - 8GeV, ~56 kW, 1 year DAQ to achieve the COMET final goal of < 10^{-16} sensitivity

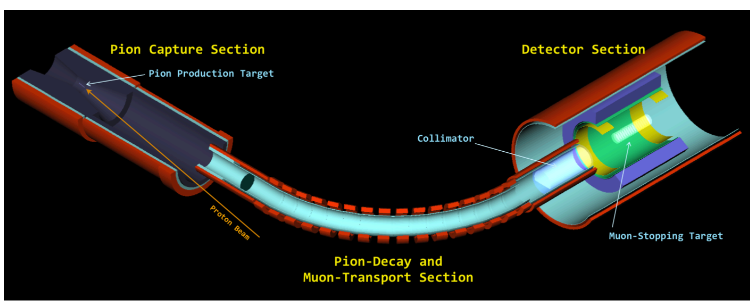


μ^-



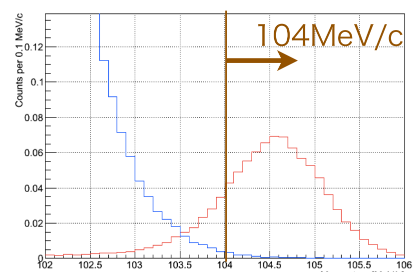


μ^+



Phase I

0.03 BG expected in 1.5×10^6 sec running time



Phase I
2013-2015
Facility construction
2013-2016
Magnet construction & installation
2016
Eng. run & Physics run
Phase II
Eng. run in 2020(?)

ORKA Status

- ORKA Approval Status:
  - Stage-1 (scientific) approval from Fermilab, CD-0 materials submitted to DOE-OHEP, in discussion with DOE on CD-0 schedule, active discussion with foreign partners.
- ORKA Support from US agencies:
  - Fermilab: Beamline design and CDF detector infrastructure preparation/ preservation ongoing now in advance of IARC operations in the CDF assembly hall commencing in FY15-Q1.
  - Explicit DOE-OHEP: Intensity Frontier (KA22) R&D proposal approved, administered through BNL. Steve Kettell is the R&D project manager.
  - Other US agencies: In active discussion with collaborators supported by the NSF.
- ORKA cost & schedule:
  - Recently completed a comprehensive cost review. Current estimate is $50M (FY13) for the detector Project, three associated AIPs for the beamline, target, and dump work. 3-year construction period, goal of commencing operations at the end of the decade.

Project X Evolution

Program:	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR
MI neutrinos	515-1200 kW**	1200 kW	2450 kW
8 GeV Neutrinos	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*
8 GeV Muon program e.g, (g-2), Mu2e-1	0-20 kW*	0-20 kW*	0-172 kW*
1-3 GeV Muon program, e.g. Mu2e-2	80 kW	1000 kW	1000 kW
Kaon Program	0-75 kW** (<45% df from MI)	1100 kW	1870 kW
Nuclear edm ISOL program	0-900 kW	0-900 kW	0-1000 kW
Ultra-cold neutron program	0-900 kW	0-900 kW	0-1000 kW
Nuclear technology applications	0-900 kW	0-900 kW	0-1000 kW

projectx.fnal.gov