Precision Science Working Group

All-Scientists Retreat

4 May 2017

D. Glenzinski, B. Kiburg, J. Whitmore on behalf of the PSWG

Introduction: Precision Science

- Precision science refers to experiments that attempt to **break the established laws of physics** by testing predictions to the **highest accuracy** and searching for phenomena that are either **extremely rare or forbidden**. Deviations from expectations are an indication of new particles and new interactions.

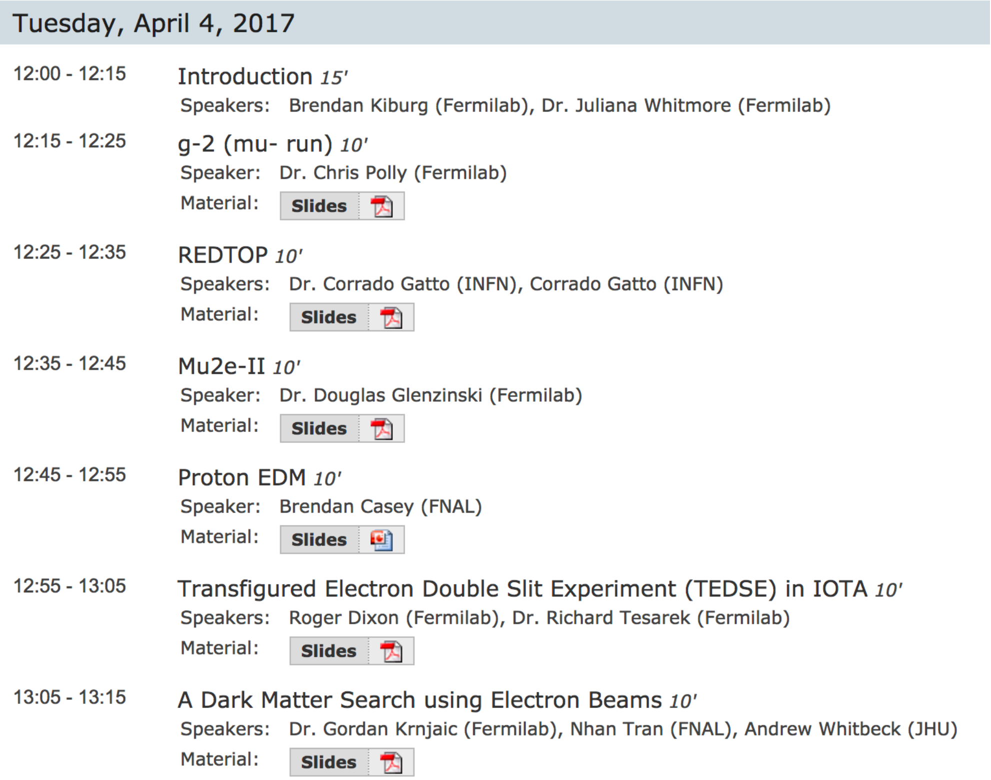
- P5 Science Driver -- Explore the Unknown: new particles, interactions and physical principles

Agenda

Precision Science Working Group met twice

April 4th and 20th

Agenda: https://indico.fnal.gov/categoryDisplay.py?categId=664



Tuesday, April 4, 2017

12:00 - 12:15 Introduction *15'*
Speakers: Brendan Kiburg (Fermilab), Dr. Juliana Whitmore (Fermilab)

12:15 - 12:25 g-2 (mu- run) *10'*
Speaker: Dr. Chris Polly (Fermilab)
Material: **Slides**

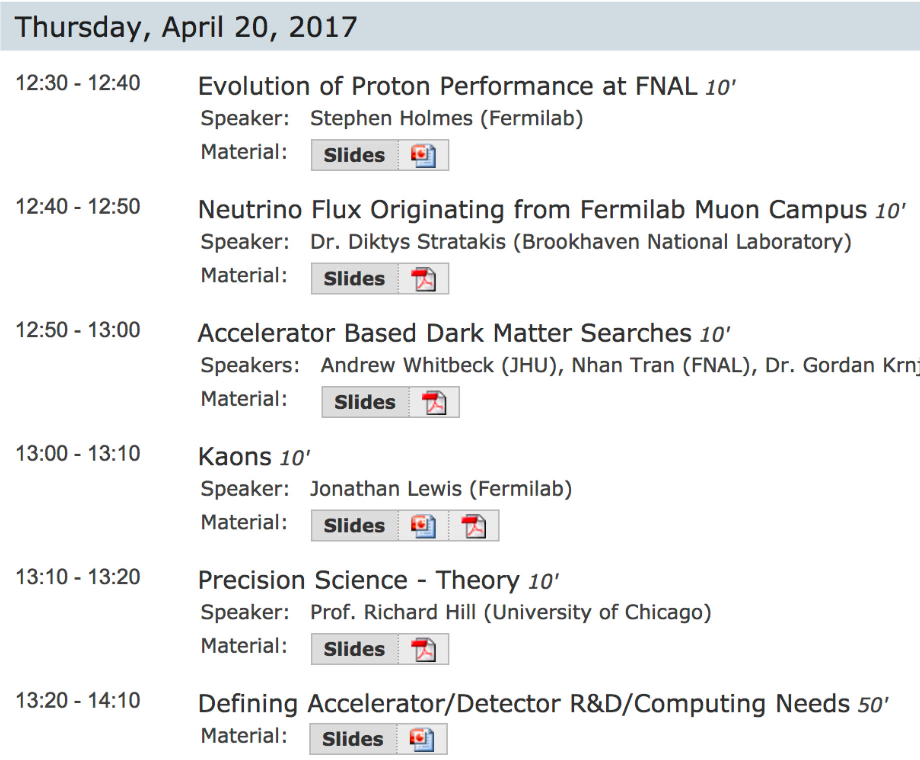
12:25 - 12:35 REDTOP *10'*
Speakers: Dr. Corrado Gatto (INFN), Corrado Gatto (INFN)
Material: **Slides**

12:35 - 12:45 Mu2e-II *10'*
Speaker: Dr. Douglas Glenzinski (Fermilab)
Material: **Slides**

12:45 - 12:55 Proton EDM *10'*
Speaker: Brendan Casey (FNAL)
Material: **Slides**

12:55 - 13:05 Transfigured Electron Double Slit Experiment (TEDSE) in IOTA *10'*
Speakers: Roger Dixon (Fermilab), Dr. Richard Tesarek (Fermilab)
Material: **Slides**

13:05 - 13:15 A Dark Matter Search using Electron Beams *10'*
Speakers: Dr. Gordan Krnjaic (Fermilab), Nhan Tran (FNAL), Andrew Whitbeck (JHU)
Material: **Slides**



Thursday, April 20, 2017

12:30 - 12:40 Evolution of Proton Performance at FNAL *10'*
Speaker: Stephen Holmes (Fermilab)
Material: **Slides**

12:40 - 12:50 Neutrino Flux Originating from Fermilab Muon Campus *10'*
Speaker: Dr. Diktys Stratakis (Brookhaven National Laboratory)
Material: **Slides**

12:50 - 13:00 Accelerator Based Dark Matter Searches *10'*
Speakers: Andrew Whitbeck (JHU), Nhan Tran (FNAL), Dr. Gordan Krn
Material: **Slides**

13:00 - 13:10 Kaons *10'*
Speaker: Jonathan Lewis (Fermilab)
Material: **Slides**

13:10 - 13:20 Precision Science - Theory *10'*
Speaker: Prof. Richard Hill (University of Chicago)
Material: **Slides**

13:20 - 14:10 Defining Accelerator/Detector R&D/Computing Needs *50'*
Material: **Slides**

Our Interpretation

- No attempt at prioritization
  - Multi-parameter optimization requiring input from all stakeholders
  - Laboratory, Agencies, Community

- We defined the charge
  - Relative to what we know now and experiments that are already planned, identify possibilities about efforts that advance searches for the unknown

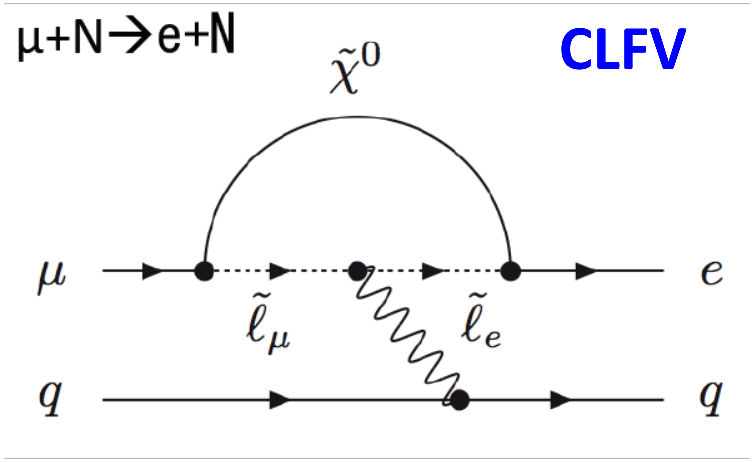
- Map out what needs to be studied to inform the next stage of the planning process

- Physics → Possibilities → Needs

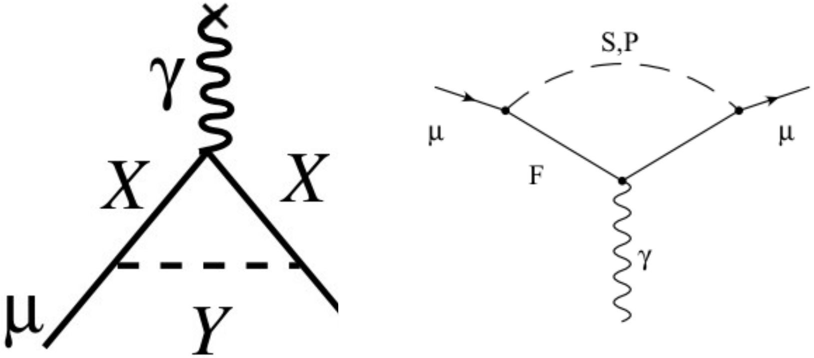
From the Unknown to New Physics

CLFV

$\mu + N \rightarrow e + N$



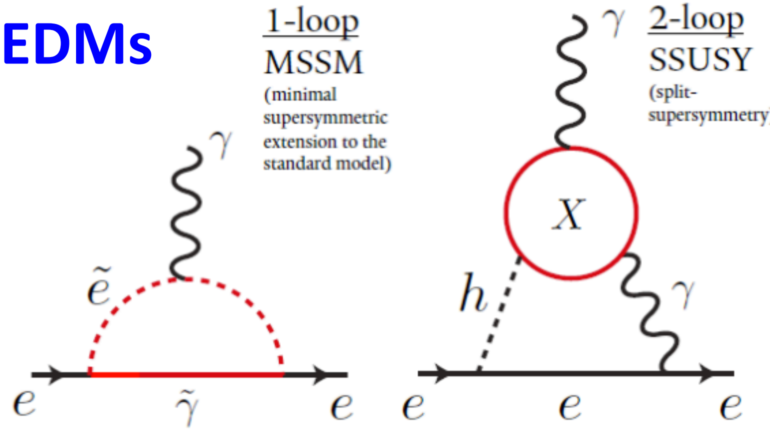
Muon g-2



EDMs

1-loop
MSSM
(minimal supersymmetric extension to the standard model)

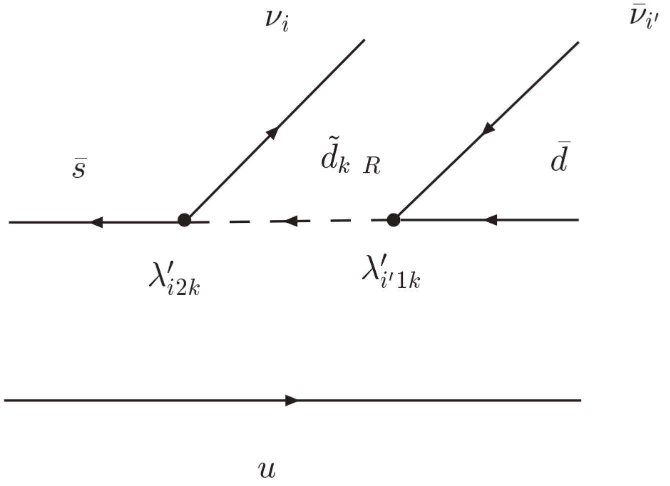
2-loop
SSUSY
(split-supersymmetry)



10^{-25}-10^{-27} e cm

10^{-27}-10^{-29} e cm

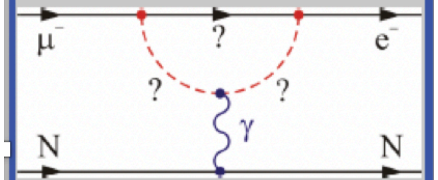
Rare Decays



Discovery of New Processes

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

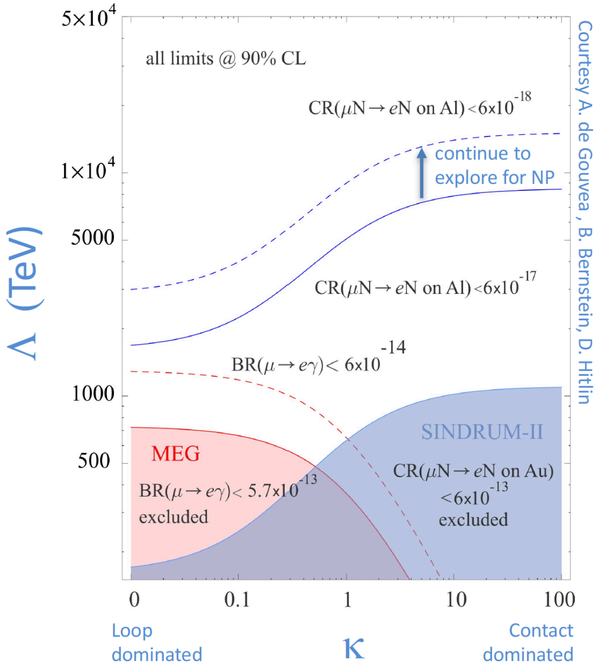
Loops



κ<< 1

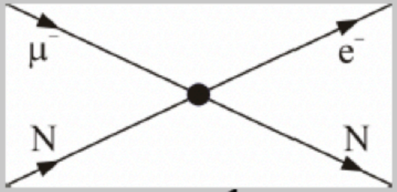
magnetic moment type operator

μ→ eγ rate ~300X μN → eN rate



Courtesy A. de Gouvea , B. Bernstein, D. Hitlin

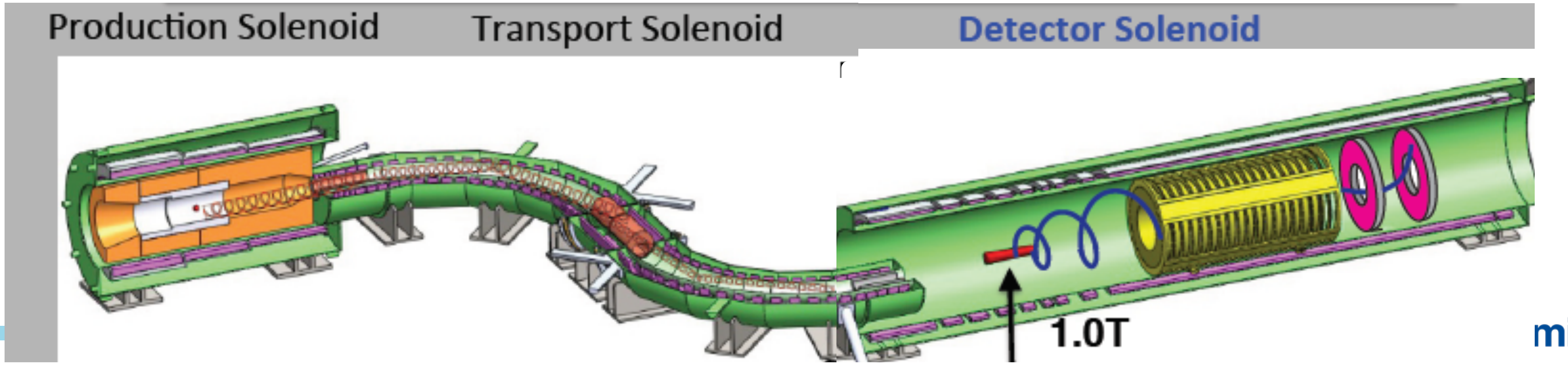
Contact Interactions



κ>> 1

four-fermion interaction

μN→ eN rate >> μ→ eγ rate

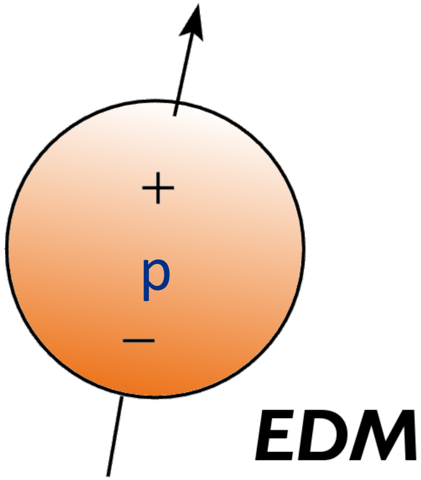


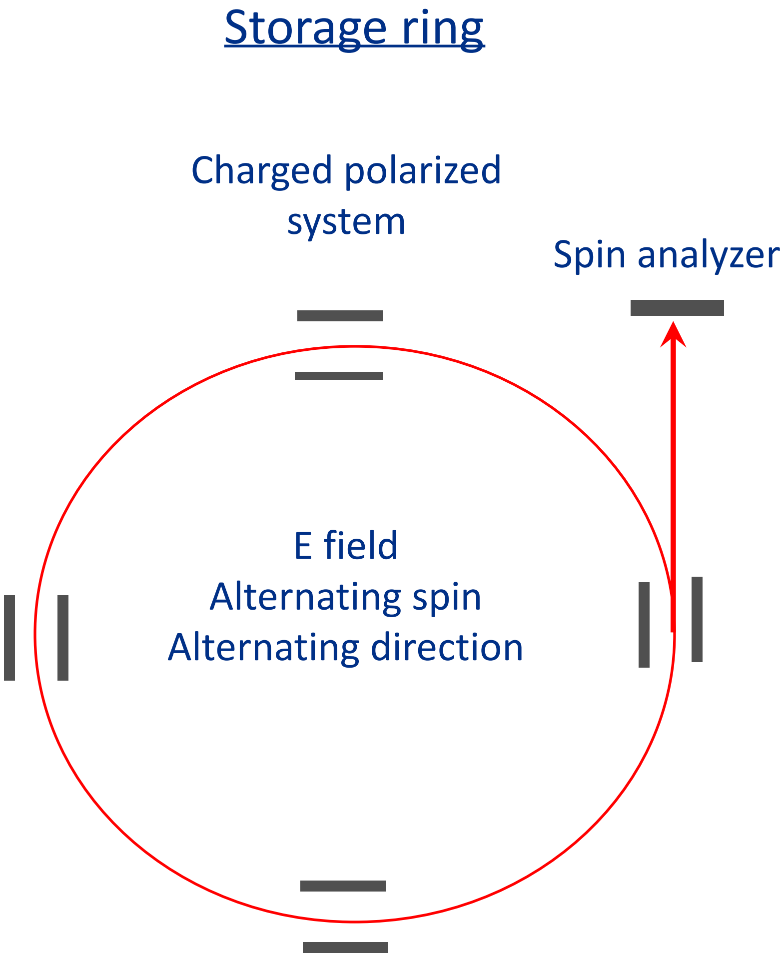
Discovery of New Particle Properties

Near-future detection of a permanent, non-zero EDM indicates a New Physics source of CP violation

Atomic, Molecular EDMs have interpretation complications

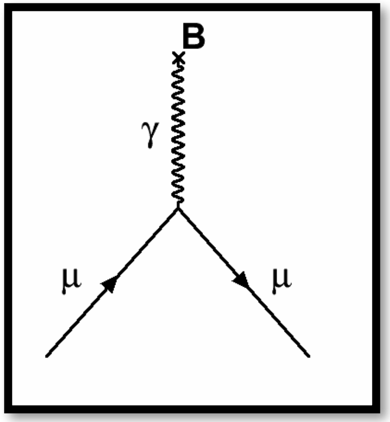
Bare particle EDM

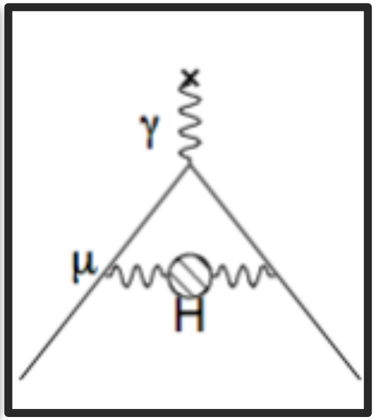


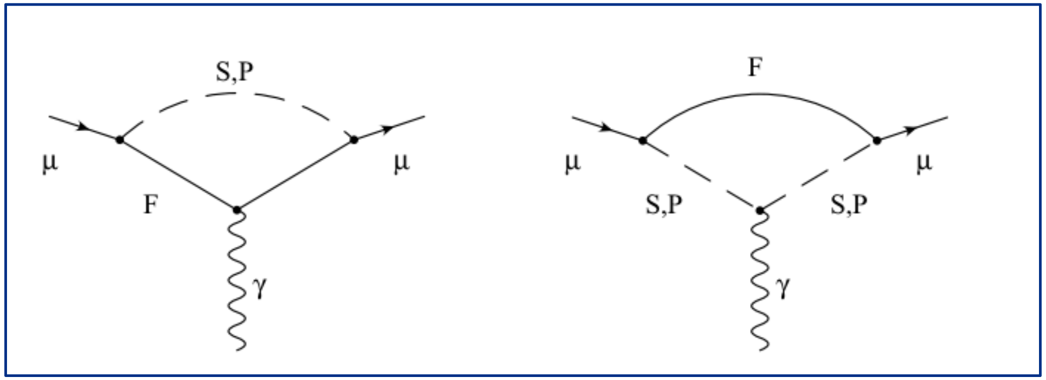


Precision Measurements of Particle Properties

Tease out small contributions from new interactions/particles



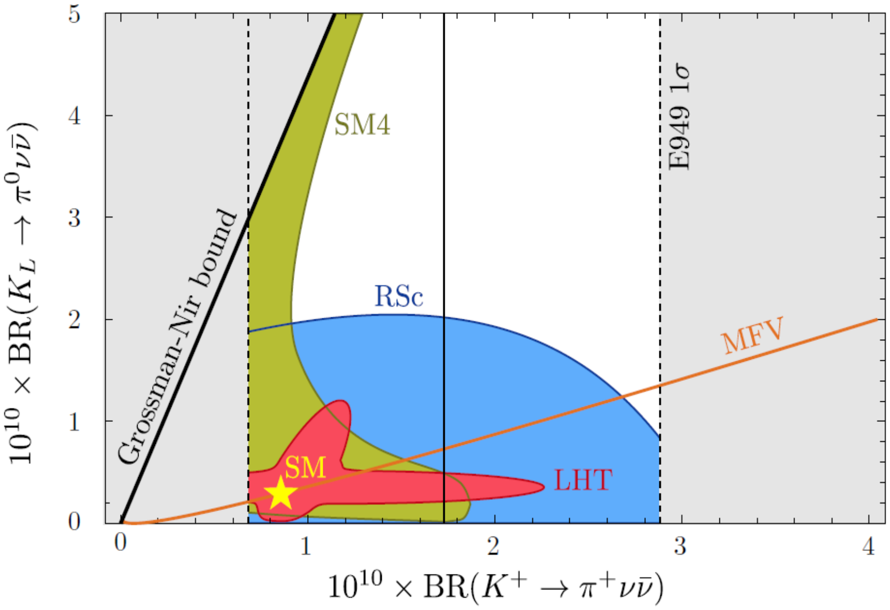




Maximize physics from this investment

Precision Measurements of Rare Decays

NP contributions to kaon decay



SM rate calcs: ~5% precision

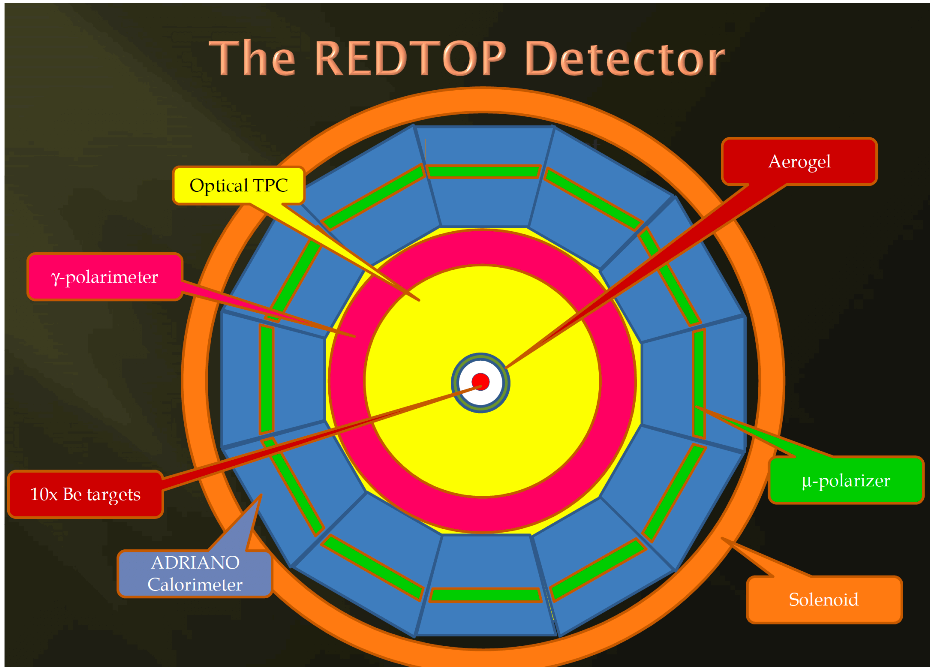
CERN NA-62 ($K^+ \rightarrow \pi^+ \nu\nu$)

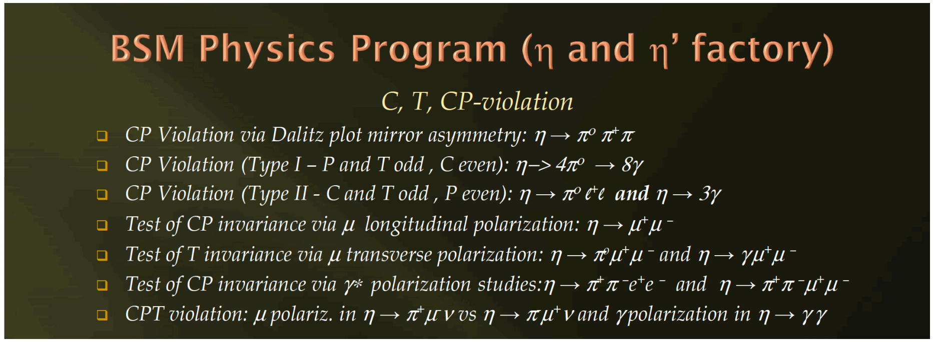
~100 SM events

J-PARC E14 "KOTO" ($K^0 \rightarrow \pi^0 \nu\nu$)

~3 SM events

Disallowed Decay Modes





BSM Physics Program (η and η' factory)

C, T, CP-violation

- ❑ *CP Violation via Dalitz plot mirror asymmetry:* $\eta \rightarrow \pi^o \pi^+ \pi$
- ❑ *CP Violation (Type I – P and T odd , C even):* $\eta \text{->} 4\pi^o \rightarrow 8\gamma$
- ❑ *CP Violation (Type II - C and T odd , P even):* $\eta \rightarrow \pi^o \ell^+ \ell$ **and** $\eta \rightarrow 3\gamma$
- ❑ *Test of CP invariance via* μ *longitudinal polarization:* $\eta \rightarrow \mu^+ \mu^-$
- ❑ *Test of T invariance via* μ *transverse polarization:* $\eta \rightarrow \pi^o \mu^+ \mu^-$ *and* $\eta \rightarrow \gamma \mu^+ \mu^-$
- ❑ *Test of CP invariance via* $\gamma*$ *polarization studies:*$\eta \rightarrow \pi^+ \pi^- e^+ e^-$ *and* $\eta \rightarrow \pi^+ \pi^- \mu^+ \mu^-$
- ❑ *CPT violation:* μ *polariz. in* $\eta \rightarrow \pi^+ \mu^- \nu$ *vs* $\eta \rightarrow \pi^- \mu^+ \nu$ *and* γ *polarization in* $\eta \rightarrow \gamma\gamma$

Muon Beam Experiments

Experiment	Accelerator Needs	Detector R&D	Comments
g-2 using μ^-	Use existing g-2 beamline. Need to switch polarity of several elements	New inflector would increase μ storage efficiency by 50%	CPT test μ^+/μ^- yield ~ 2.5/1 Program planning.
Mu2e-II ($\mu^- N \rightarrow e^- N$)	PIP-II Protons (0.8-3 GeV) ~100kW pulsed	v.Low mass tracker Production Target APD/SiPM for BaF2 calorimeter	x10 improvement Mu2e & COMET: $R_{\mu e} < 7 \times 10^{-17}$ by ~2026 Reuse as much Mu2e as possible
$\mu^+ \rightarrow$ eee or $\mu^+ \rightarrow e+\gamma$	Use PIP-II to deliver low momentum μ^+ beam (~20 MeV/c) $10^9 – 10^{10}$ μ/s DC beam	v.Low mass tracker with good vertexing	x10-100 improvement MEG: $BF_{e\gamma} < 4 \times 10^{-14}$ by ~2021 Mu3e: $BF_{eee} < 10^{-14}$ by ~2022 Reuse some of Mu2e?

Muon Beam Experiments

Experiment	Accelerator Needs	Detector R&D	Comments
Light DM Exp (LDMX)	~3 GeV Muons Need ~5 x 10^{14} total DC beam preferred, but pulsed can be used		Especially motivated if g-2 anomaly persists Reuse most of LDMX(e)?
Muon Capture on hydrogen / deuterium	Low energy muon beam, high extinction	Improved TPC reconstruction	Connections to nucleon axial radius → important for DUNE

Other Programs

Experiment	Accelerator Needs	Detector R&D	Comments
REDTOP η Factory at AP50 (in Delivery Ring)	CW Protons: Single 8 GeV proton pulse to DR. Decelerate to 1.8-4.5 GeV. Slow extract over ~40 sec	Optical TPC Multi-readout calorimeter, Active muon polarimeter	Broad program of rare decays, CP, QCD. Connections to proton radius puzzle
Proton EDM	Polarized proton beam. All E Storage Ring.		Phased approach 10^{-19} e-cm in ~5y 10^{-29} e-cm in ~10y Leverages g-2 expertise
1000 event level $K^0 \rightarrow \pi^0 \nu\nu$ $K^+ \rightarrow \pi^+ \nu\nu$	High purity beam		KOTO: BF_0 to 50% by 2020 NA62: BF_+ to 10% by 2020

Electron Beam Experiments

Experiment	Accelerator Needs	Detector R&D	Comments
Transfigured Electron Double Slit Experiment (TEDSE)	10-50 MeV electrons Utilize IOTA or FAST . Electri/magnetic deflector septa	None	Resolve long standing quantum mechanics puzzles (electron wavefunction)

Further down the road

- Q from Accelerator WG: What R&D should they be working on a decade from now to enable the Next-to-Next-Experiment? Beyond PIP-III

- Muons
  - Very high intensities (high beam powers/target handling)
  - Monoenergetic sources of stopped muons (Muon Cooling)
  - Excellent extinction
  - Pure beam
- Kaons
  - Monoenergetic
  - High Beam Purity (SRF separators)
- Etas / Other Rare Meson Decays
  - High Intensities
- Proton
  - Polarized source

Summary

- Suite of ideas for the future of Precision Science
  - Natural Extensions
  - New Programs
  - Creative Experiments

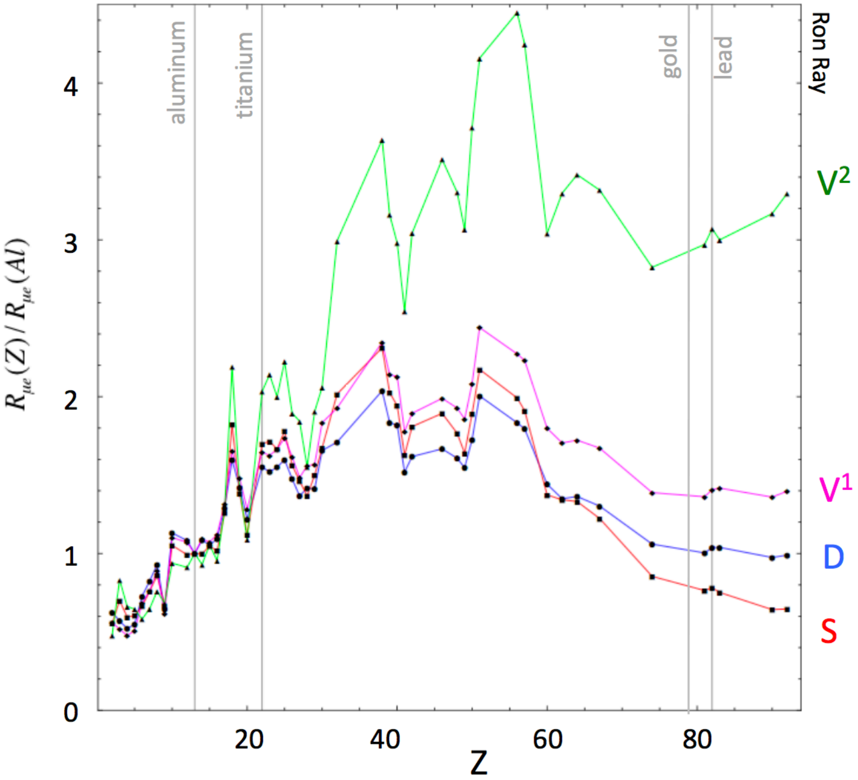
- Variety of challenges
  - Accelerator
  - Detector
  - Computing
  - Remaining Nimble and adapting to community developments

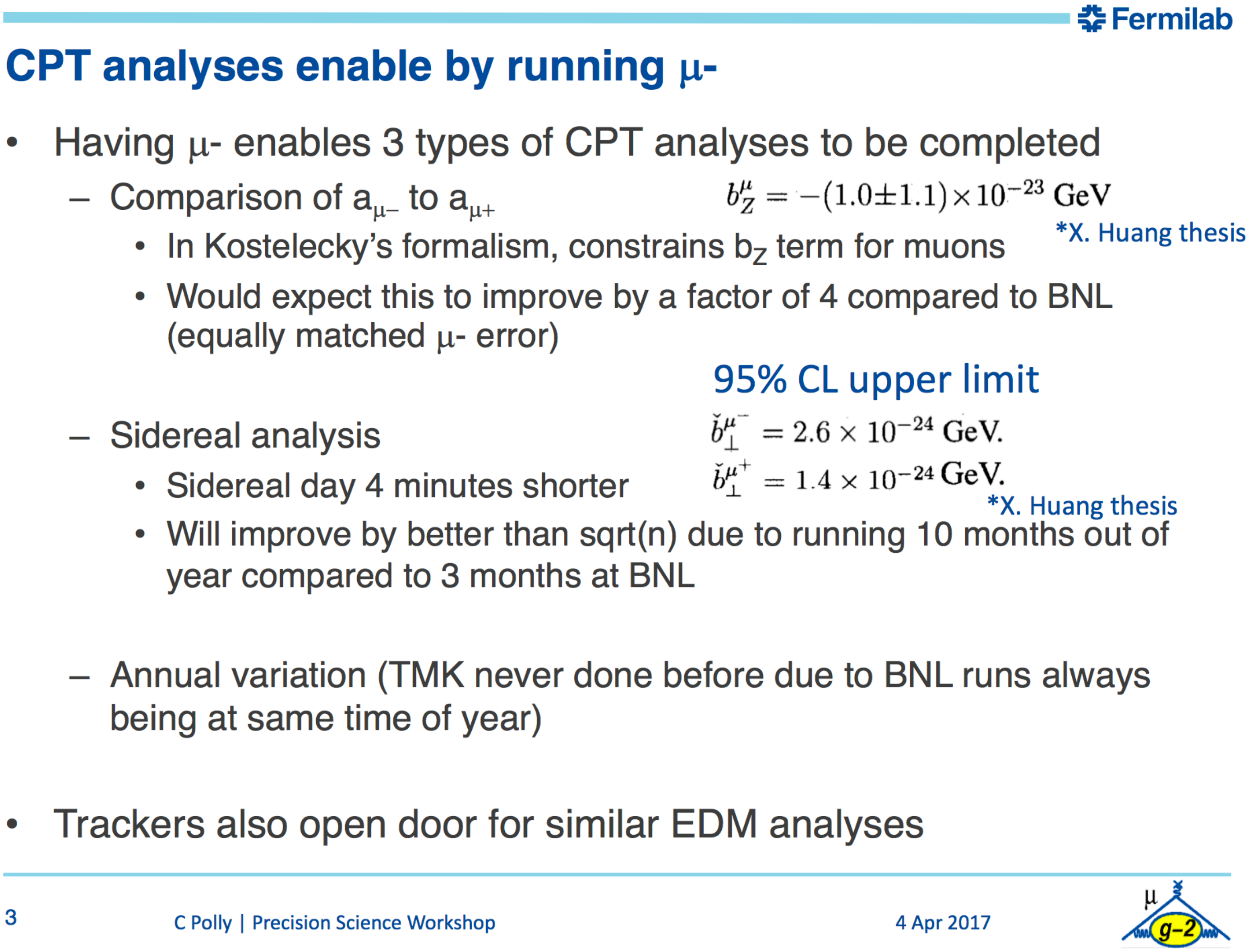
- BACKUPS

Upgrade Motivation with Mu2e signal

- A x10 improvement in sensitivity allows measuring $R_{\mu e}$ to ~10%
  - will probe underlying New Physics operators

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)





CPT analyses enable by running μ-

- Having μ- enables 3 types of CPT analyses to be completed
  - Comparison of $a_{\mu-}$ to $a_{\mu+}$
    - In Kostelecky's formalism, constrains b_Z term for muons
    - Would expect this to improve by a factor of 4 compared to BNL (equally matched μ- error)
  - Sidereal analysis
    - Sidereal day 4 minutes shorter
    - Will improve by better than sqrt(n) due to running 10 months out of year compared to 3 months at BNL
  - Annual variation (TMK never done before due to BNL runs always being at same time of year)
- Trackers also open door for similar EDM analyses

$$\check{b}_Z^{\mu} = -(1.0 \pm 1.1) \times 10^{-23}\ \mathrm{GeV}$$

*X. Huang thesis

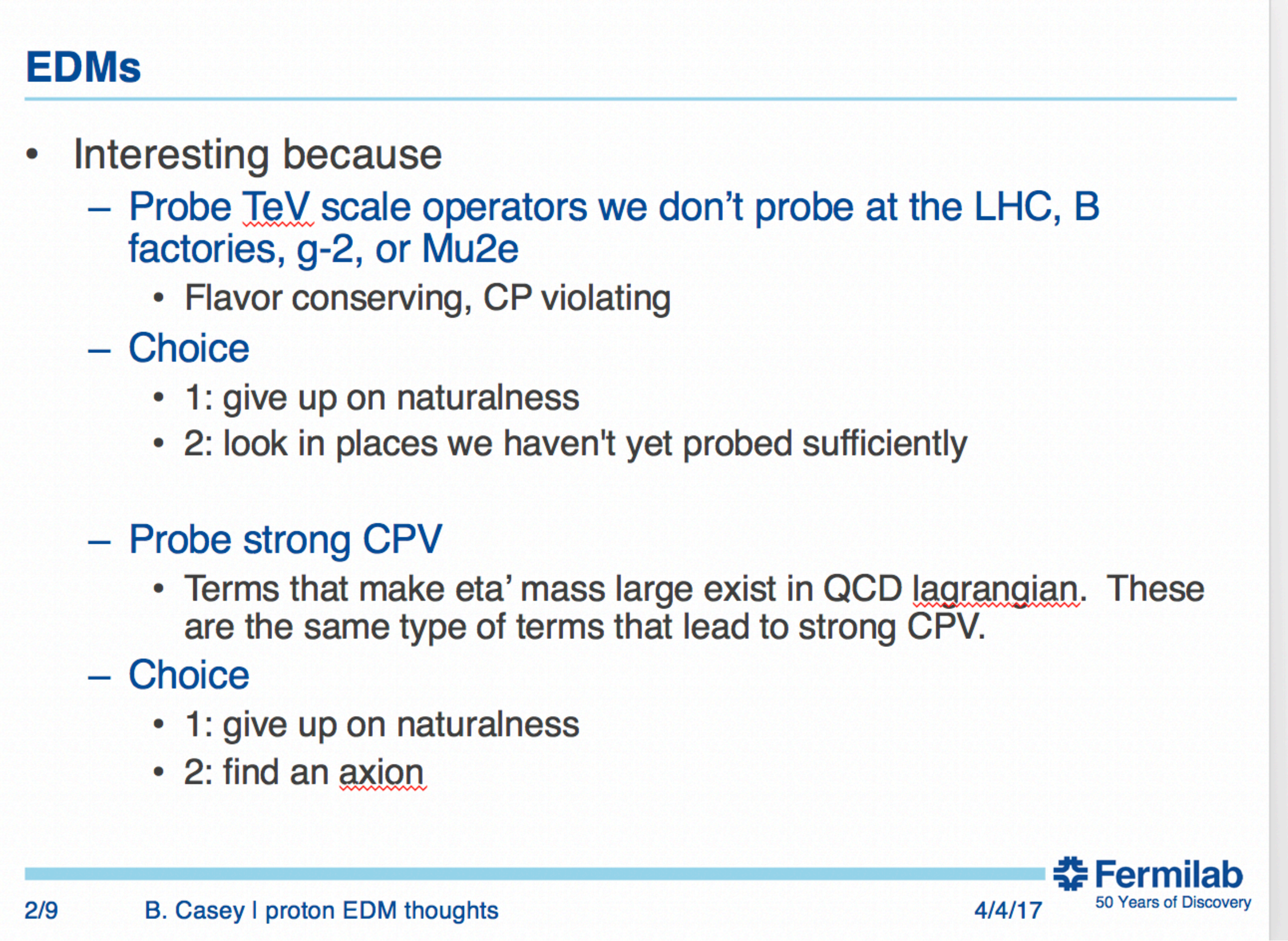
95% CL upper limit

$$\check{b}_{\perp}^{\mu^-} = 2.6 \times 10^{-24}\ \mathrm{GeV}.$$

$$\check{b}_{\perp}^{\mu^+} = 1.4 \times 10^{-24}\ \mathrm{GeV}.$$

*X. Huang thesis

3 C Polly | Precision Science Workshop 4 Apr 2017



EDMs

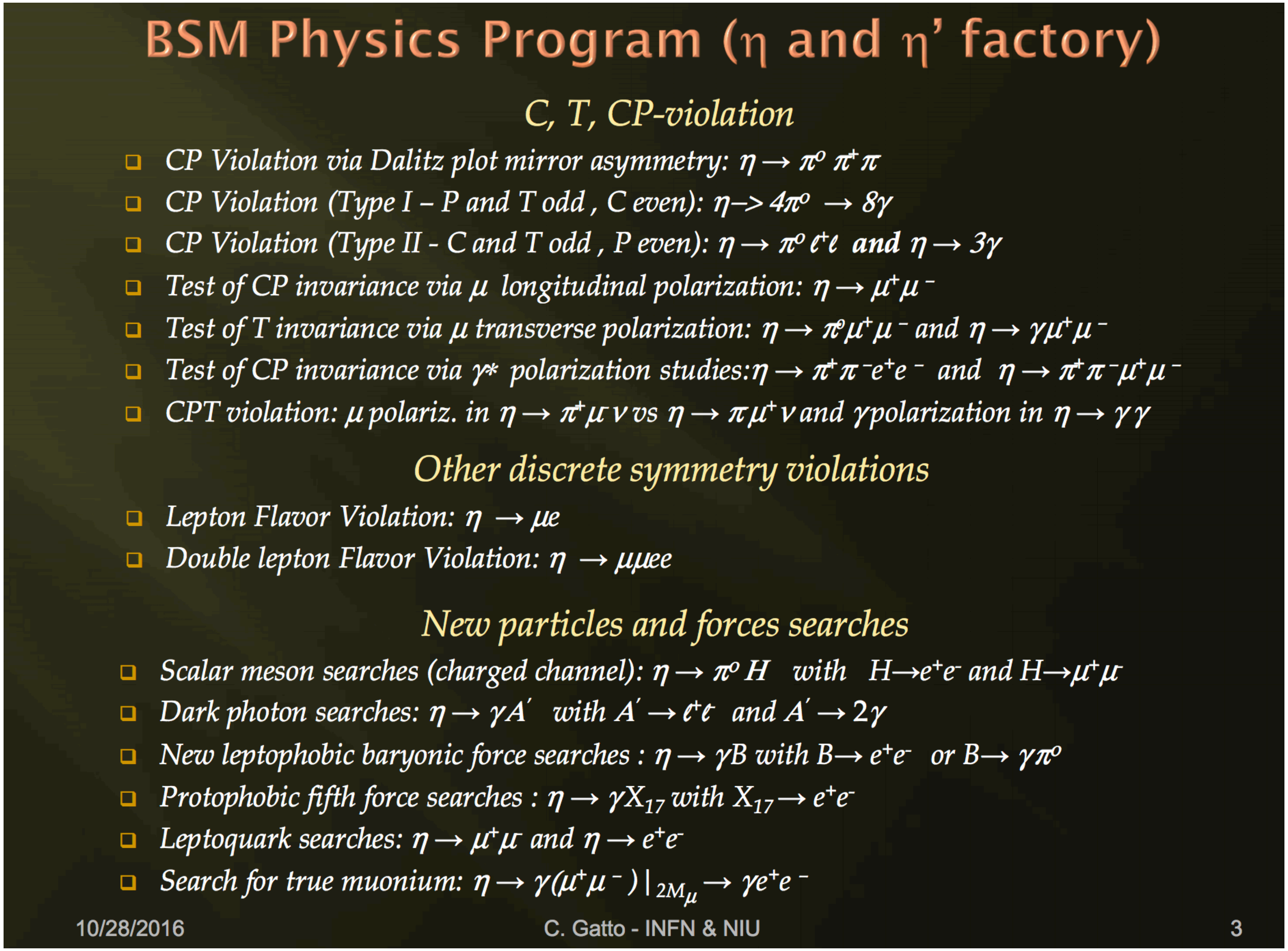
- Interesting because
  - Probe TeV scale operators we don’t probe at the LHC, B factories, g-2, or Mu2e
    - Flavor conserving, CP violating
  - Choice
    - 1: give up on naturalness
    - 2: look in places we haven't yet probed sufficiently

  - Probe strong CPV
    - Terms that make eta’ mass large exist in QCD lagrangian. These are the same type of terms that lead to strong CPV.
  - Choice
    - 1: give up on naturalness
    - 2: find an axion

2/9 B. Casey I proton EDM thoughts 4/4/17

Fermilab
50 Years of Discovery

REDTOP PHYSICS 1/2



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- CP Violation (Type II - C and T odd , P even): $\eta \rightarrow \pi^o \ell^+ \ell$ **and** $\eta \rightarrow 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \rightarrow \mu^+ \mu^-$
- Test of T invariance via μ transverse polarization: $\eta \rightarrow \pi^o \mu^+ \mu^-$ and $\eta \rightarrow \gamma \mu^+ \mu^-$
- Test of CP invariance via γ* polarization studies:$\eta \rightarrow \pi^+ \pi^- e^+ e^-$ and $\eta \rightarrow \pi^+ \pi^- \mu^+ \mu^-$
- CPT violation: μ polariz. in $\eta \rightarrow \pi^+ \mu^- \nu$ vs $\eta \rightarrow \pi \mu^+ \nu$ and γ polarization in $\eta \rightarrow \gamma \gamma$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \rightarrow \mu e$
- Double lepton Flavor Violation: $\eta \rightarrow \mu \mu e e$

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \rightarrow \pi^o H$ with $H \rightarrow e^+ e^-$ and $H \rightarrow \mu^+ \mu^-$
- Dark photon searches: $\eta \rightarrow \gamma A'$ with $A' \rightarrow \ell^+ \ell^-$ and $A' \rightarrow 2\gamma$
- New leptophobic baryonic force searches : $\eta \rightarrow \gamma B$ with $B \rightarrow e^+ e^-$ or $B \rightarrow \gamma \pi^o$
- Protophobic fifth force searches : $\eta \rightarrow \gamma X_{17}$ with $X_{17} \rightarrow e^+ e^-$
- Leptoquark searches: $\eta \rightarrow \mu^+ \mu^-$ and $\eta \rightarrow e^+ e^-$
- Search for true muonium: $\eta \rightarrow \gamma (\mu^+ \mu^-) |_{2M_\mu} \rightarrow \gamma e^+ e^-$

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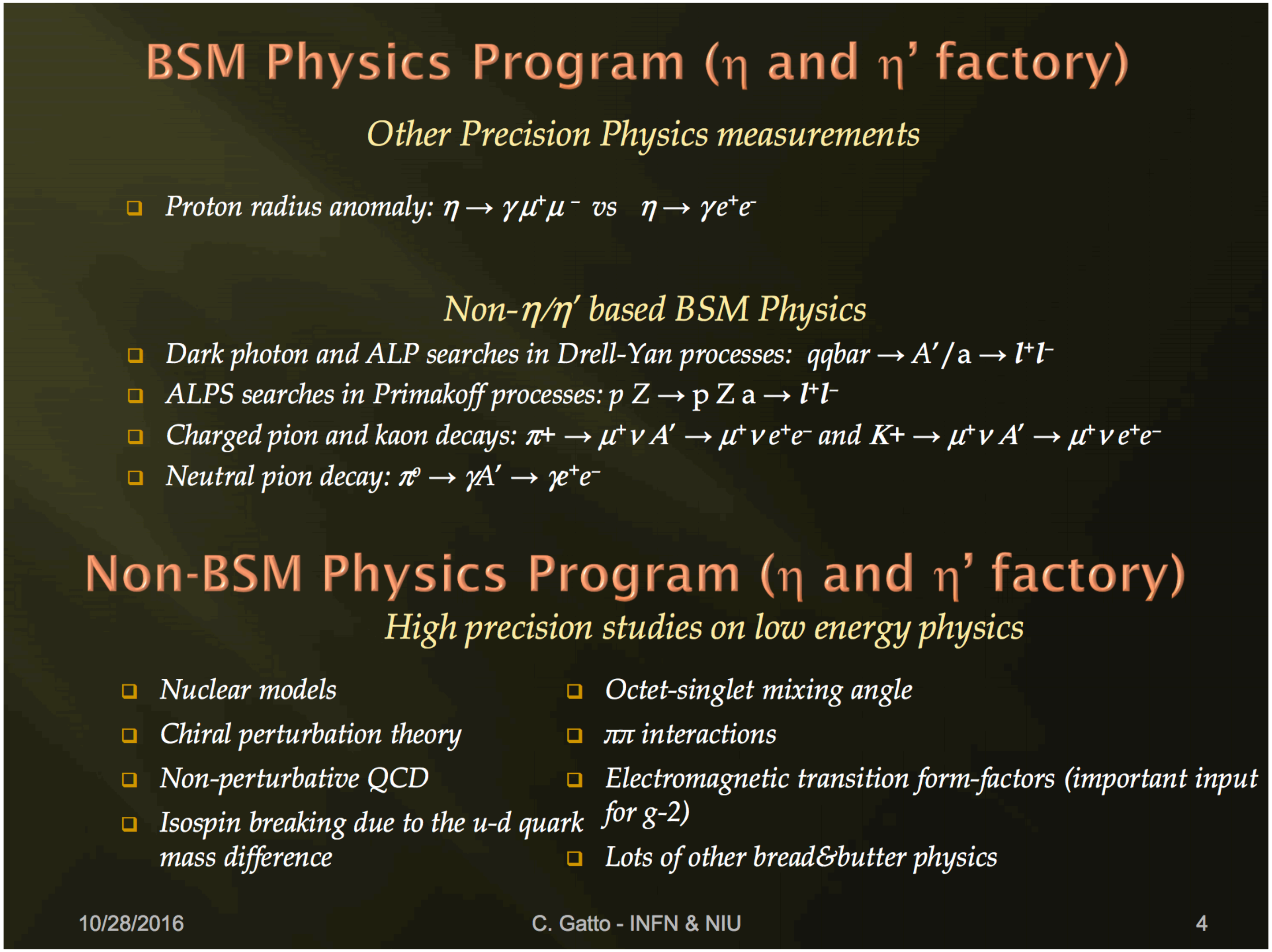
REDTOP PHYSICS 2/2



BSM Physics Program (η and η' factory)

Other Precision Physics measurements

- *Proton radius anomaly:* $\eta \rightarrow \gamma \mu^+ \mu^-$ *vs* $\eta \rightarrow \gamma e^+ e^-$

Non-η/η' based BSM Physics

- *Dark photon and ALP searches in Drell-Yan processes:* *qqbar* $\rightarrow A' / a \rightarrow l^+ l^-$
- *ALPS searches in Primakoff processes:* $p\,Z \rightarrow p\,Z\,a \rightarrow l^+ l^-$
- *Charged pion and kaon decays:* $\pi+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+ e^-$ *and* $K+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+ e^-$
- *Neutral pion decay:* $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$

Non-BSM Physics Program (η and η' factory)

High precision studies on low energy physics

- *Nuclear models*
- *Chiral perturbation theory*
- *Non-perturbative QCD*
- *Isospin breaking due to the u-d quark mass difference*
- *Octet-singlet mixing angle*
- *ππ interactions*
- *Electromagnetic transition form-factors (important input for g-2)*
- *Lots of other bread&butter physics*

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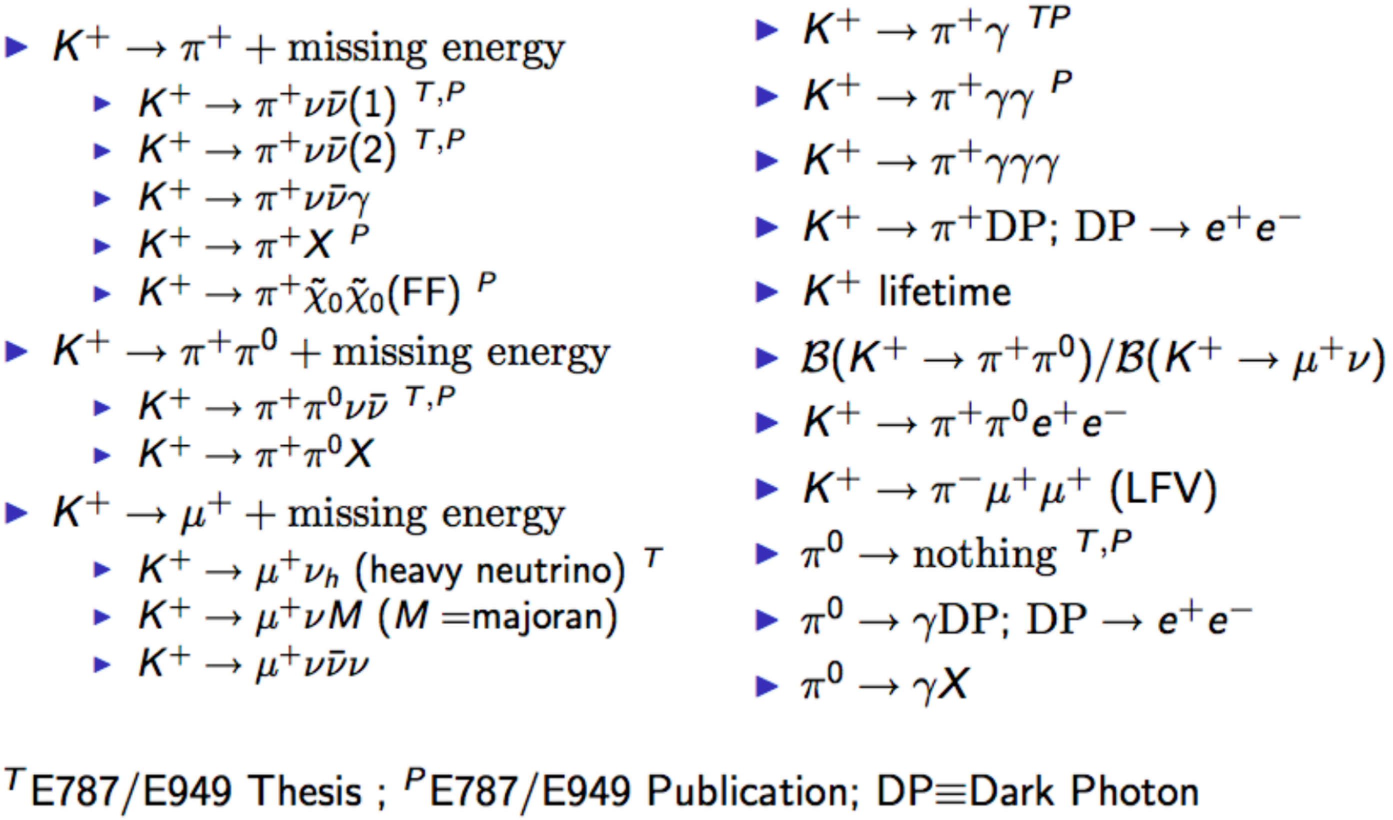
Kaon physics

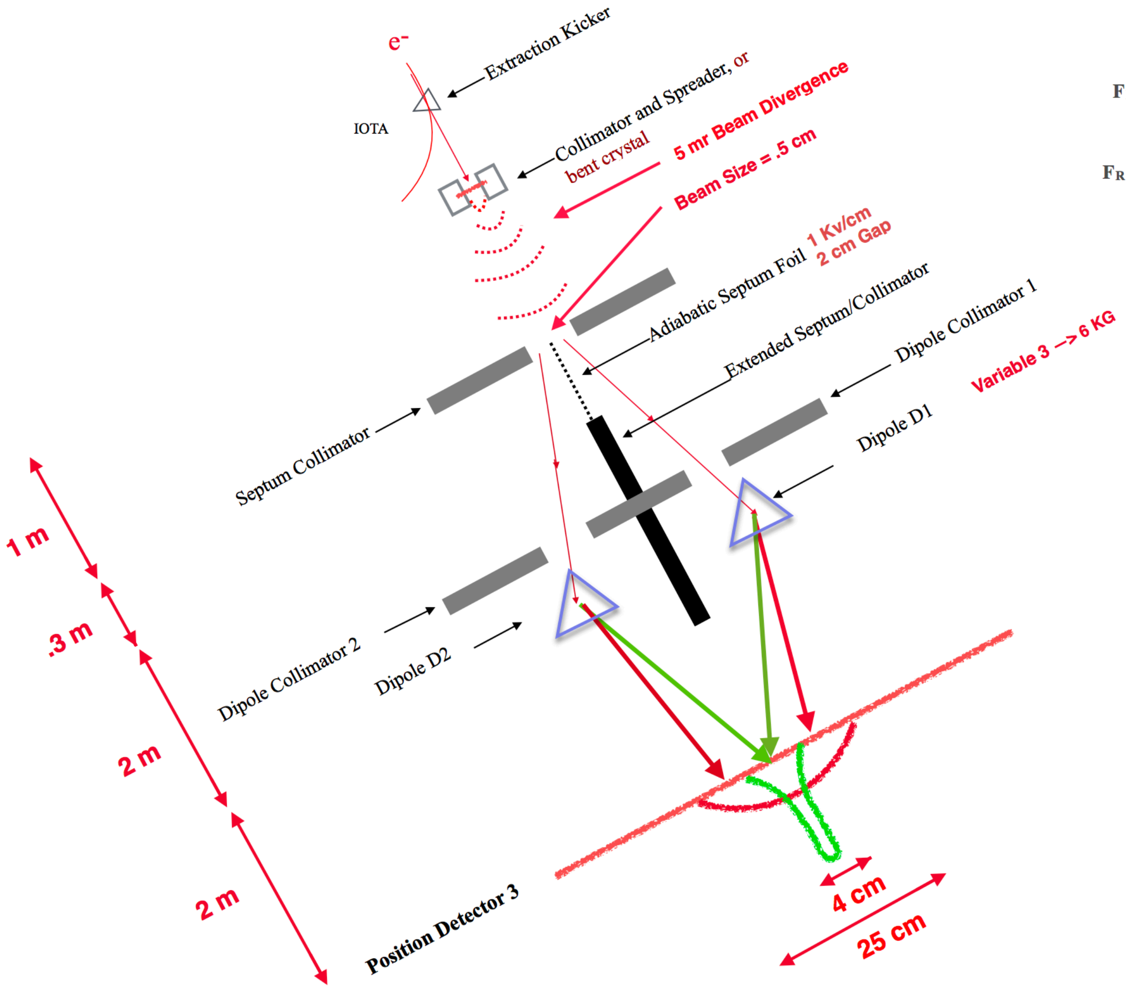
Other topics

- Many other channels to be explored:



- $K^+ \to \pi^+ +$ missing energy
    - $K^+ \to \pi^+ \nu\bar{\nu}(1)$ ^{T,P}
    - $K^+ \to \pi^+ \nu\bar{\nu}(2)$ ^{T,P}
    - $K^+ \to \pi^+ \nu\bar{\nu}\gamma$
    - $K^+ \to \pi^+ X$ ^{P}
    - $K^+ \to \pi^+ \tilde{\chi}_0 \tilde{\chi}_0(\mathrm{FF})$ ^{P}
- $K^+ \to \pi^+\pi^0 +$ missing energy
    - $K^+ \to \pi^+\pi^0 \nu\bar{\nu}$ ^{T,P}
    - $K^+ \to \pi^+\pi^0 X$
- $K^+ \to \mu^+ +$ missing energy
    - $K^+ \to \mu^+ \nu_h$ (heavy neutrino) ^{T}
    - $K^+ \to \mu^+ \nu M$ ($M =$majoran)
    - $K^+ \to \mu^+ \nu\bar{\nu}\nu$
- $K^+ \to \pi^+ \gamma$ ^{TP}
- $K^+ \to \pi^+ \gamma\gamma$ ^{P}
- $K^+ \to \pi^+ \gamma\gamma\gamma$
- $K^+ \to \pi^+ \mathrm{DP}$; $\mathrm{DP} \to e^+e^-$
- K^+ lifetime
- $\mathcal{B}(K^+ \to \pi^+\pi^0)/\mathcal{B}(K^+ \to \mu^+\nu)$
- $K^+ \to \pi^+\pi^0 e^+e^-$
- $K^+ \to \pi^-\mu^+\mu^+$ (LFV)
- $\pi^0 \to$ nothing ^{T,P}
- $\pi^0 \to \gamma\mathrm{DP}$; $\mathrm{DP} \to e^+e^-$
- $\pi^0 \to \gamma X$

^{T}E787/E949 Thesis ; ^{P}E787/E949 Publication; DP≡Dark Photon



$$F_L = q[vxB+E] \int dx\, \Psi^2{}_L(x)$$

$$F_R = q[vx(-B)-E] \int dx\, \Psi^2{}_R(x)$$

R. Dixon 4-4-17