Quark and lepton flavor at Snowmass

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with contributions from A. Di Canto, S. Davidson, E. Goudzovski, S. Meinel, and E. Passemar

PBC Annual Workshop
March 2021

Snowmass process

Snowmass provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners.

The Snowmass study is organized into 10 frontiers: energy, neutrino physics, rare processes and precision measurements, cosmic, theory, accelerator, instrumentation, computational, underground facilities and community engagement.

All information available at: https://snowmass21.org

Due to the pandemic, high level activities will be on hold until the end of June, 2021. Topical group and cross-frontier activities are either paused or reduced to a significantly lower level.

Timeline:

- August 31, 2020: Letter of Interest (LOI) submission
- March 15, 2022: White Paper submission to arXiv
- June 30, 2022 : Preliminary reports by the Frontiers
- July, 2022 : Snowmass Community Summer Study (CSS) at UW-Seattle
- September 30, 2022: All final reports by TGs and Frontiers

White paper submission are encouraged from anybody!
Feel free to reach frontier or topical group conveners for further information.

Rare processes and precision measurements frontier is divided into 7 working groups

RF1: Weak decays of b and c quarks

RF2: Weak decays of strange and light quarks

RF3: Fundamental Physics in Small Experiments

RF4: Baryon and Lepton Number Violating Processes

RF5: Charged Lepton Flavor Violation (electrons, muons and taus)

RF6: Dark Sector Studies at High Intensities

RF7: Hadron Spectroscopy

Practicalities

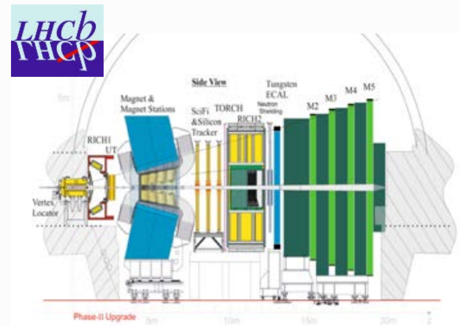
Frontier website: https://snowmass21.org/rare/start
Kick-off Workshop (https://indico.fnal.gov/event/44121)
Town hall meeting (https://indico.fnal.gov/event/45713)

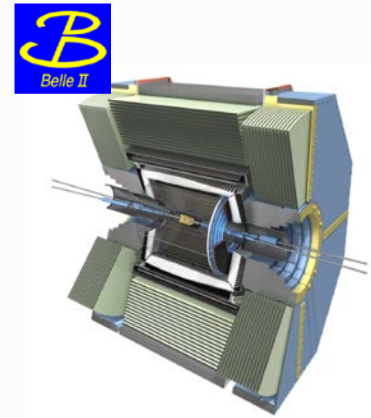
A selection of quark / lepton flavor activities over the past few months @ Snowmass
(my apology if your favorite topic isn't covered)

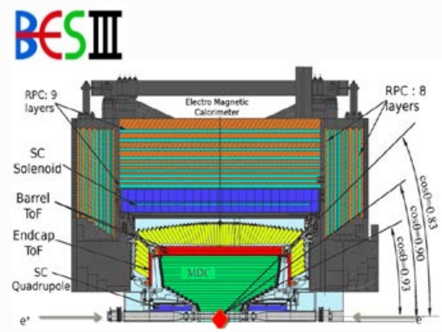
Heavy quark decays (RF1)

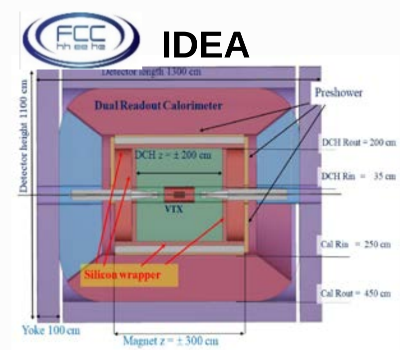
Summary of topics discussed in LOIs

- High precision in CKM unitarity tests
- B and B_s mixing and CPV
- Rare decays
- CPV in baryons
- Charm mixing and CPV
- Lepton flavor / universality violation









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LHCb / Belle II will investigate b decays with unprecedented precision over a wide range of final states during the next decade

Physics prospects

Observables	Expected exp. uncertainty	Facility (2025)
UT angles & sides		
ϕ_1 [°]	0.4	Belle II
ϕ_2 [°]	1.0	Belle II
ϕ_3 [°]	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	1%	Belle II
$\|V_{cb}\|$ excl.	1.5%	Belle II
$\|V_{ub}\|$ incl.	3%	Belle II
$\|V_{ub}\|$ excl.	2%	Belle II/LHCb
CPV		
$S(B \to \phi K^0)$	0.02	Belle II
$S(B \to \eta' K^0)$	0.01	Belle II
• $\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	4	Belle II
• $\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	0.20	LHCb/Belle II
(Semi-)leptonic		
• $\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	7%	Belle II
$R(B \to D\tau\nu)$	3%	Belle II
$R(B \to D^*\tau\nu)$	2%	Belle II/LHCb
Radiative & EW Penguins		
• $\mathcal{B}(B \to X_s\gamma)$	4%	Belle II
• $A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	0.03	Belle II
$S(B \to \rho\gamma)$	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	0.3	Belle II
• $\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	15%	Belle II
• $\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	20%	Belle II
$R(B \to K^*\ell\ell)$	0.03	Belle II/LHCb

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Observable	LHCb 2018	LHCb 2025	Belle II 2030	End of HL-LHC (2039) LHCb	End of HL-LHC (2039) ATLAS/CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+K^-$	$(^{+17}_{-22})°$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})°$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\|V_{ub}\|/\|V_{cb}\|$	6% [201]	3%	1%	1%	–
B_s^0, $B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

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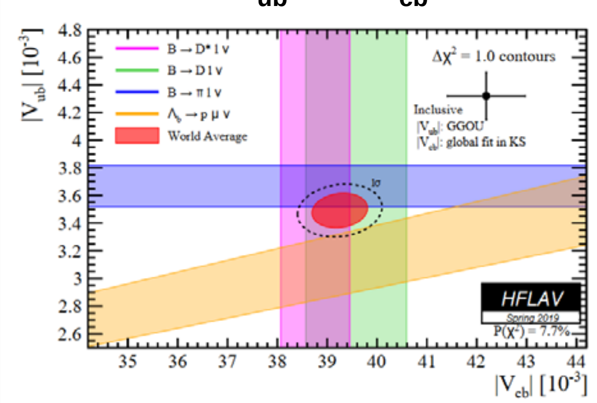
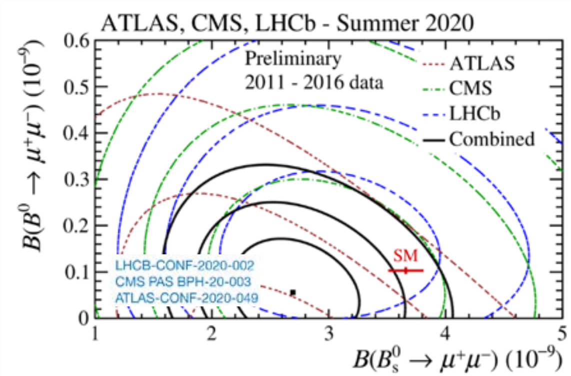
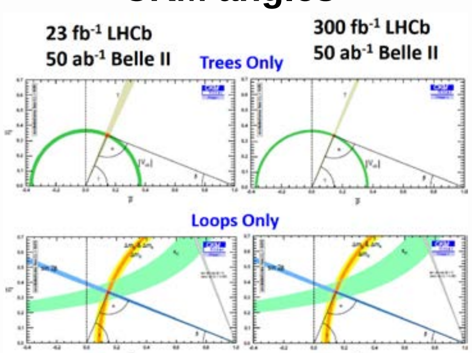
V_{ub} and V_{cb}



Rare B_s decays

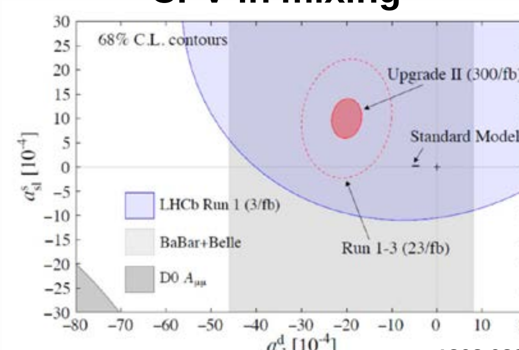


CKM angles



arXiv:1812.076382

CPV in mixing



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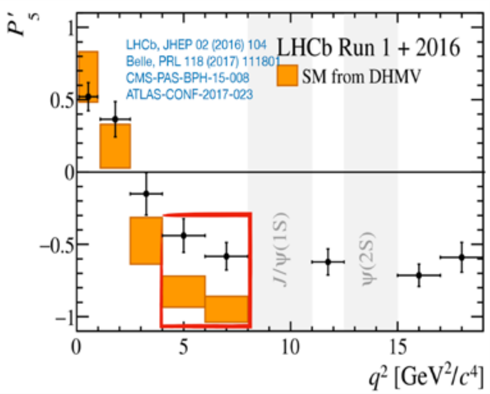
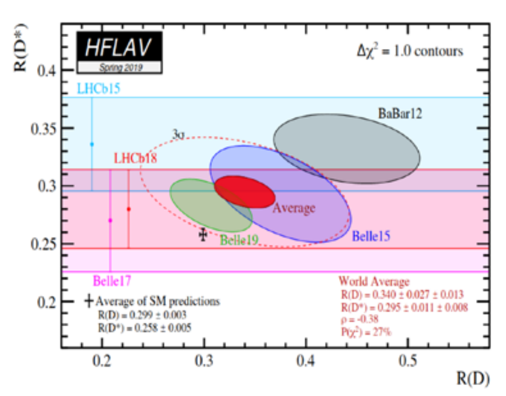
RF/SNOWMASS21-RF1_RF0_Bennett-021.pdf
RF/SNOWMASS21-RF1_RF0_Lenz_Siegen-054.pdf

RF/SNOWMASS21-RF1_RF0-022.pdf
RF/SNOWMASS21-RF6_RF1_Alakabha_Datta-018.pdf
TF/SNOWMASS21-TF6_TF0-RF1_RF0_Wolfgang_Altmannshofer-074.pdf

A series of "anomalies" has been (recently) observed B decays

- P'_5 anomaly ($B \to K^* \mu\mu$ angular dist.)
- small $B \to H_s \mu\mu$ rates ($H_s = K, K^*, \phi$)
- LFU violation in $B \to K^{(*)} ll$ ($l = e, \mu$)
- small $B_s \to \mu\mu$ rate
- large R(D) and R(D*) ratios
- ……





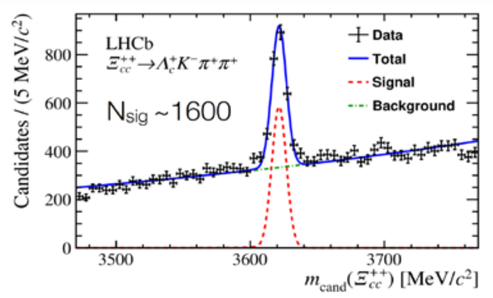
New physics? Uncertainties in theoretical predictions? Experimental issues?

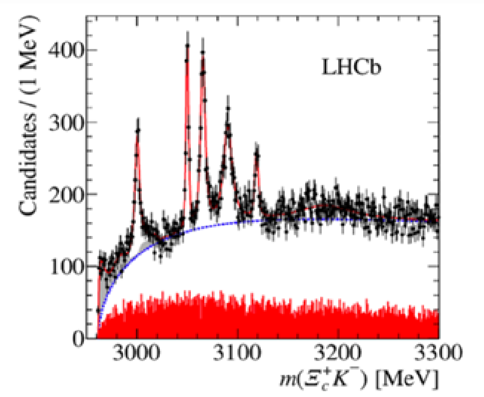
- Improve precision of experimental measurements and investigate more channels
- Improve theoretical calculations → importance of lattice QCD effort
- Theoretical analyses of "anomalies" in model independent EFT fits to investigate properties of new physics

Dedicated activities to explore these anomalies in the near future

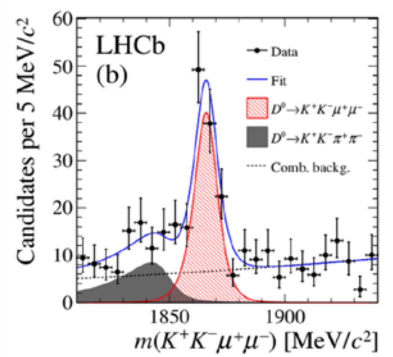
RF/SNOWMASS21-RF1_RF0_Dominik_Mitzel-021.pdf
RF/SNOWMASS21-RF1_RF4_BelleII-030.pdf
RF/SNOWMASS21-RF1_RF7_BINP-019.pdf

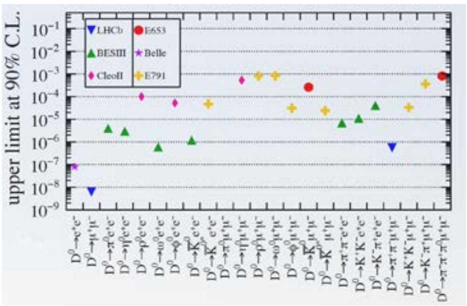
Spectroscopy



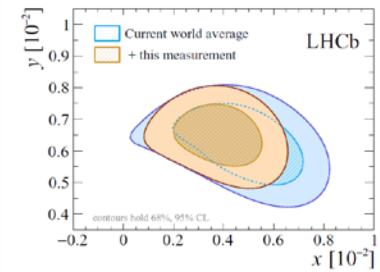


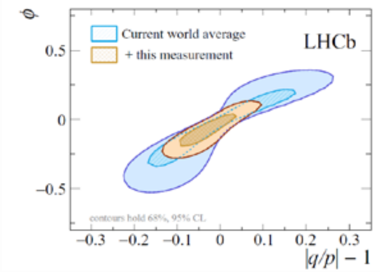
Rare decays

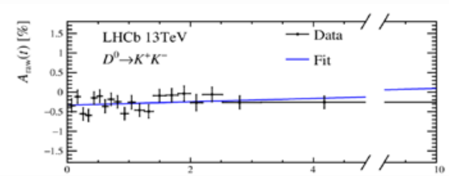




Mixing and CP violation



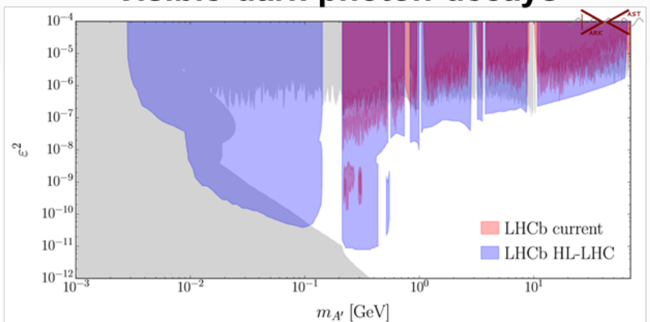




Future activities at LHCb, Belle II & proposed STCF + theoretical developments

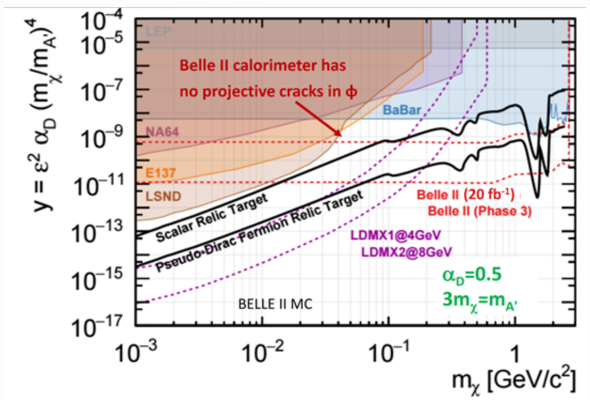
Sample of FIP searches at heavy flavor experiments

Visible dark photon decays

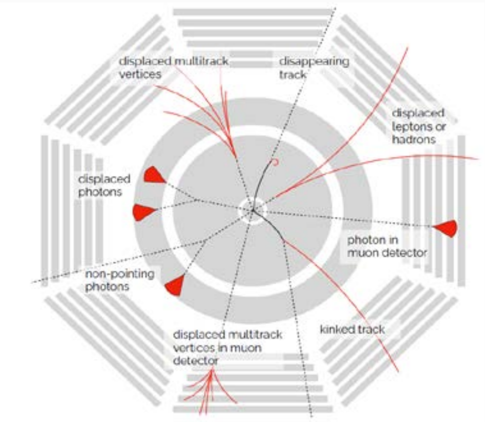


+Belle II (and many other experiments)

Invisible dark photon decays

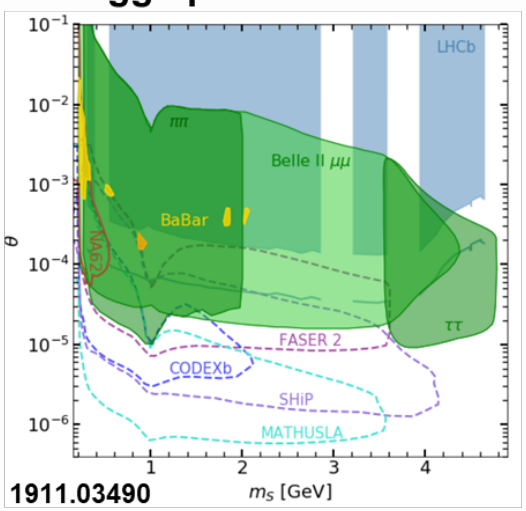


LLP searches @ Belle II



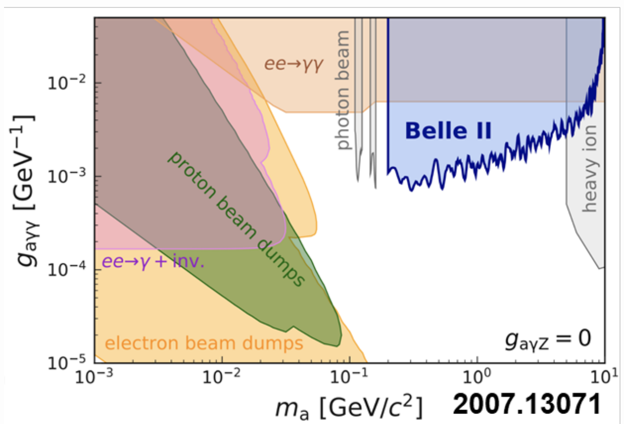
+ Gazelle @ Belle II
(New LLP detector)

Higgs-portal dark scalar



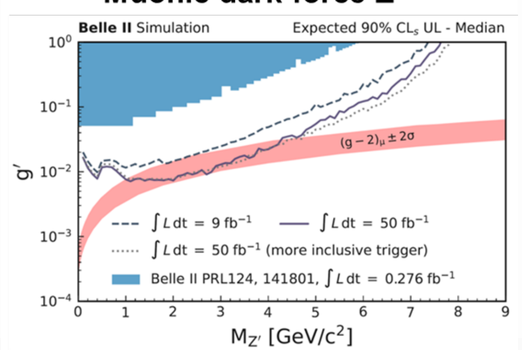
1911.03490

ALP a→γγ decays @ Belle II



2007.13071

Muonic dark force Z'



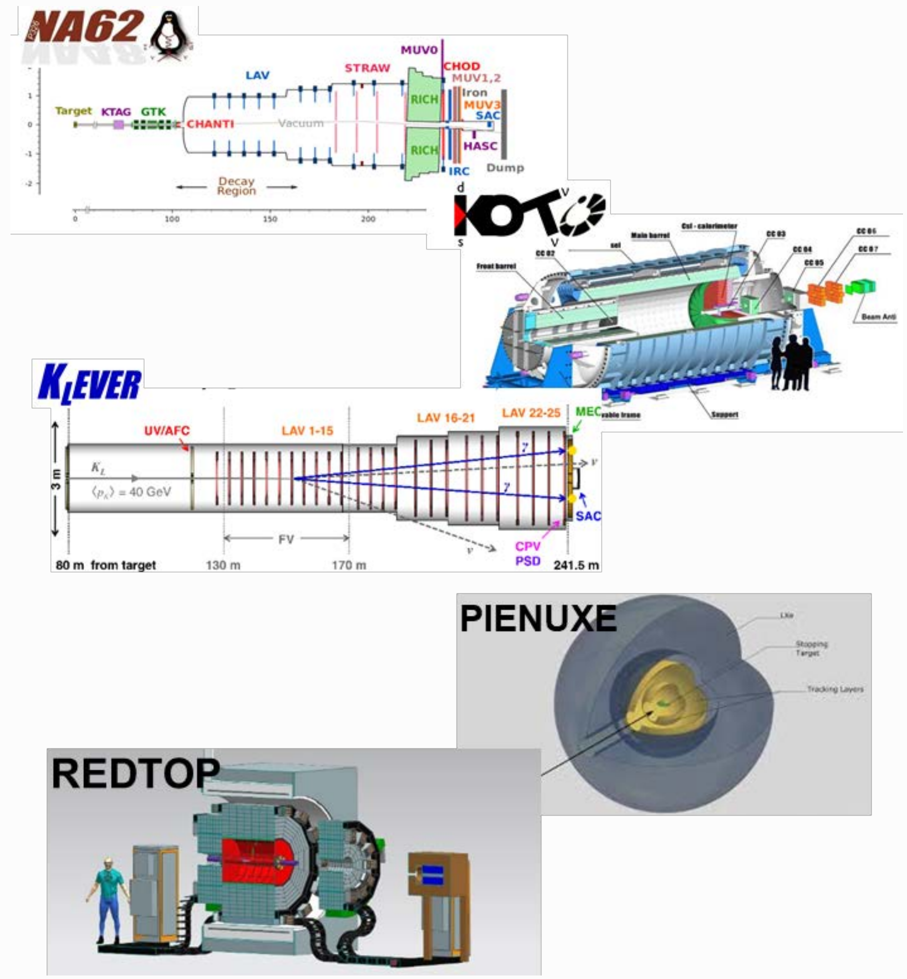
E. Graziani – ICHEP 2020

See FIP 2020 workshop report (2102.12143) for more!

Light quark decays (RF2)

Summary of topics discussed in LOIs

- Rare kaon decays
- η/η' factory
- Hyperon decays and J/ψ factory
- Charged pion decays and V_{ud}
- First row CKM unitary (V_{ud}, lattice, radiative corrections,…)



$K_L \to \pi^0 \nu\nu$ - KOTO @ JPARC

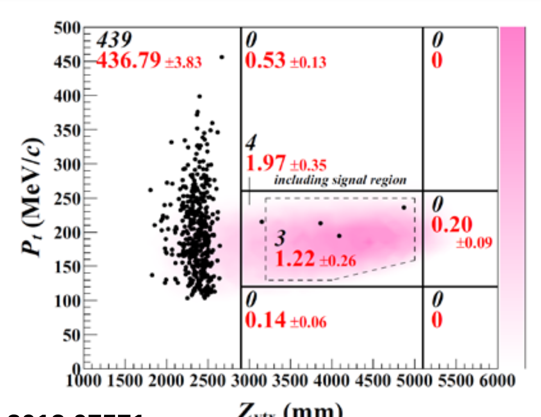
Current results (2015 data):

- BF < 3.0 x10^{-9} @ 90% CL ***PRL 122 (2019) 021802***
- Theory $(3.4 \pm 0.6) \times 10^{-11}$ ***JHEP 11 033 (2015)***

Latest analysis of 2016-18 data (2012.07571)

- Observe 3 events in the signal region for a total estimated background of 1.22 ± 0.26
- Build additional detector to reject $K^\pm$ bkg

KOTO Phase 1 expect to reach SM sensitivity by 2025



2012.07571

$K^\pm \to \pi^\pm \nu\nu$ - NA62 @ CERN

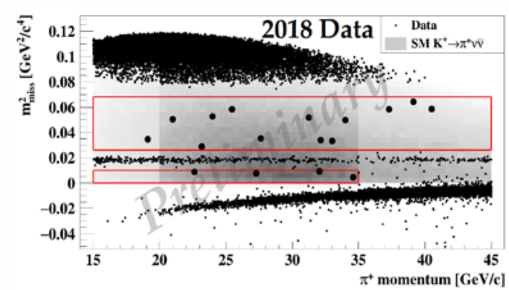
Current results (2016-18 data):

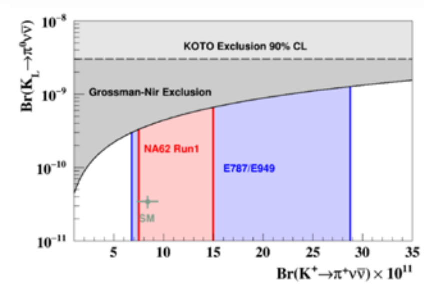
- Measured $(11.0^{+4.0}_{-3.5} \pm 0.3) \times 10^{-11}$ ***ICHEP 2020***
- Expected signal / bkg: 10 / 7 events
- Total observed: 20 events, 3.5σ significance
- Theory $(8.4 \pm 1.0) \times 10^{-11}$ ***JHEP 11 033 (2015)***

Plans for Run 2 (from LS2 to LS3)

- Data taking resume in July 2021 with key modifications to reduce background and higher beam intensity

Expect to measure BR($K^\pm \to \pi^\pm \nu\nu$) with uncertainty ~10%





https://indico.cern.ch/event/965896

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RF/SNOWMASS21-RF2_RF0-..._Norman_Christ-066.pdf
RF/SNOWMASS21-RF2_RF0-..._Antonin_Portelli-055.pdf

Sample of FIP scenarios that can be explored with kaon decays

Charged kaon

- Dark scalar or ALP in $K^+ \to \pi^+ X$, $\pi^+\pi^0 X$ and $K_L \to \pi^0 X$, $\pi^0 \pi^0 X$ decays
- Dark scalar or vector in $K^+ \to \mu^+ \nu X$ decay
- Long-lived heavy neutral leptons in $K^+ \to (\pi^0)\, e^+ N$ or $K^+ \to \mu^+ N$ decays
- Short-lived HNL in $K^+ \to l^+_\alpha N$, $N \to l^+_\beta l^-_\beta \nu$ decay
- Invisible dark photon (A’) in $K^+ \to \pi^+\pi^0$ A’ decays

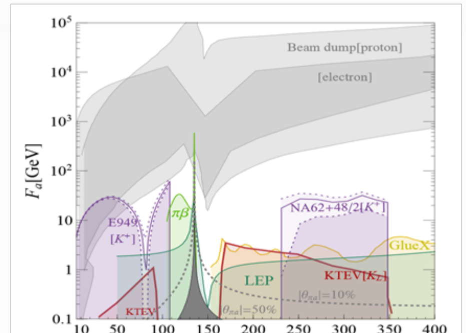
Neutral kaons

- Massless dark photon (γ’) in $K_L \to \gamma\gamma$’ or $K_L \to \pi^0\gamma\gamma$’

…and more in the FIP 2020 report

ALP

$K^+ \to \pi^+ + a(\to \gamma\gamma)$, $K^0 \to \pi^0 + a(\to \gamma\gamma)$

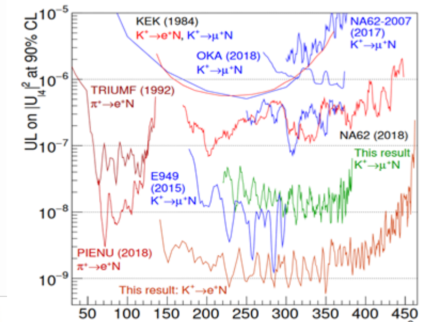


2005.05170

Heavy neutral lepton

$K \to eN$ / $K \to \mu N$

$\Gamma(K^\pm \to l^\pm N) = \Gamma(K^\pm \to l^\pm \nu_l)\rho(m_N)\,|U_{l4}|^2$



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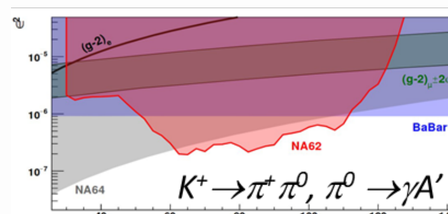
Dark photon



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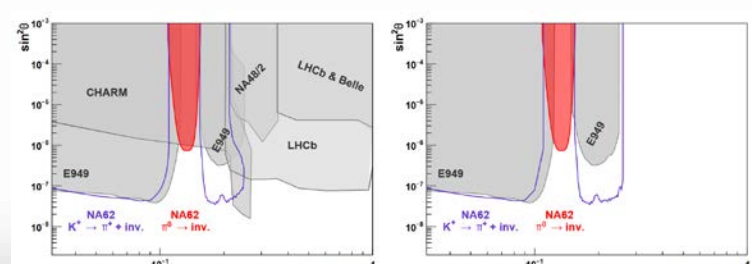
Dark scalar



2011.11329

RF/SNOWMASS21-RF6_RF0-034.pdf

Kaon physics – future proposals

A next generation of experiment would be required to make a precision measurement of $K^\pm \to \pi^\pm \nu\nu$ and a significant observation of $K_L \to \pi^0 \nu\nu$

High intensity K^+ and K_L beams at SPS, CERN

4 phases with same primary beamline and interchangeable detectors:

- "NA62x4": $K^\pm \to \pi^\pm \nu\nu$
- NA62 in beam dump mode (improved sensitivity to FIP)
- KLEVER: $K_L \to \pi^0 \nu\nu$
- Intermediate stage: K_L beam + charged-particle tracking/PID: $K_L \to \pi^0 l^+l^-$; LFV and radiative K_L decays

KOTO Step-2

- Construction around 2025 and ~100 events at SM level with S/N~1 (3y data)
- Two major upgrades to increase kaon flux and detector acceptance

Message from US Kaon LOI: "Both out of intellectual interest and a desire to maintain breadth in the US physics program, the US kaon physics community would like to explore possibilities for expanded US participation in the current and next-generation rare kaon decay experiments at JPARC and CERN. We would also like to hold open the possibility for more major contributions to these experiments or for a complementary US-based experiment if the science points in that direction **(RF/SNOWMASS21-RF2_RF0_Worcester-092.pdf)"**

RF/SNOWMASS21-RF2_RF0-010.pdf
RF/SNOWMASS21-RF2_RF1-058.pdf
RF/SNOWMASS21-RF2_RF0_Y.W.Wah-065.pdf
RF/SNOWMASS21-RF2_RF0_Worcester-092.pdf

Very rich physics program, including searches for new particles and forces

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^0\pi^+\pi^-$
- CP Violation (Type I - P and T odd , C even): $\eta \to 4\pi^0 \to 8\gamma$
- CP Violation (Type II - C and T odd , P even): $\eta \to 4\pi^0 l^+l^-$ and $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$
- Test of CP invariance via γ^* polarization studies: $\eta \to \pi^+\pi^-e^+e^-$ and $\eta \to \pi^+\pi^-\mu^+\mu^-$
- Test of CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-e^+e^-$
- Test of T invariance via μ transverse polarization: $\eta \to \pi^0\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ polarization in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ and γ polarization in $\eta \to \gamma\gamma$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+e^- + c.c.$
- Double lepton Flavor Violation: $\eta \to \mu^+\mu^+e^-e^- + c.c.$

Non-η/η' based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: $q\bar{q} \to A'/a \to l^+l^-$
- $p + D \to {}^3\mathrm{He}^+ + X_{17}$ with $X_{17} \to e^+e^-$
- ALP's searches in Primakoff processes: $pZ \to pZa \to l^+l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K^+ \to \mu^+\nu A' \to \mu^+\nu\, e^+e^-$
- Neutral pion decay: $\pi^0 \to \gamma A' \to \gamma\, e^+e^-$

Other Precision Physics measurements

- Proton radius anomaly: $\eta \to \gamma\,\mu^+\mu^-$ vs $\eta \to \gamma\, e^+e^-$
- All unseen leptonic decay mode of η/η' (SM predicts $10^{-6} \div 10^{-9}$)

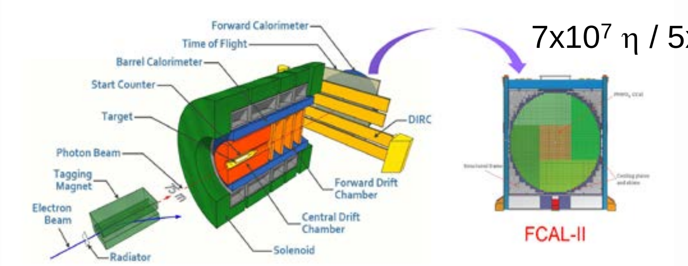
High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

New particles and forces searches

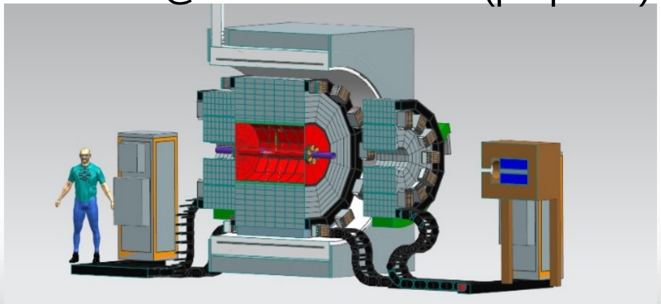
- Scalar meson searches (charged channel): $\eta \to \pi^0 H$ with $H \to e^+e^-$ and $H \to \mu^+\mu^-$
- Dark photon searches: $\eta \to \gamma A'$ with $A' \to l^+l^-$
- Protophobic fifth force searches: $\eta \to \gamma X_{17}$ with $X_{17} \to e^+e^-$
- New leptophobic baryonic force searches: $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^0$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
- Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma\, e^+e^-$

Jefferson Eta Factory (JEF) @ JLab (approved)



$7\mathrm{x}10^7\ \eta$ / $5\mathrm{x}10^7\ \eta'$ per 100 days

REDTOP @ FNAL or CERN (proposal)



10^{12} - 10^{13} η /year
10^{10} - 10^{11} η'/ year

Very rich physics program, including searches for new particles and forces

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^0\pi^+\pi^-$
- CP Violation (Type I - P and T odd , C even): $\eta \to 4\pi^0 \to 8\gamma$
- CP Violation (Type II - C and T odd , P even): $\eta \to 4\pi^0 l^+l^-$ and $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$
- Test of CP invariance via γ^* polarization studies: $\eta \to \pi^+\pi^-e^+e^-$ and $\eta \to \pi^+\pi^-\mu^+\mu^-$
- Test of CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-e^+e^-$
- Test of T invariance via μ transverse polarization: $\eta \to \pi^0\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ polarization in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ and γ polarization in $\eta \to \gamma\gamma$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+e^- + c.c.$
- Double lepton Flavor Violation: $\eta \to \mu^+\mu^+e^-e^- + c.c.$

Non-η/η' based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: $q\bar{q} \to A'/a \to l^+l^-$
- $p + D \to {}^3He^+ + X_{17}$ with $X_{17} \to e^+e^-$
- ALP's searches in Primakoff processes: $pZ \to pZa \to l^+l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K^+ \to \mu^+\nu A' \to \mu^+\nu\, e^+e^-$
- Neutral pion decay: $\pi^0 \to \gamma A' \to \gamma\, e^+e^-$

Other Precision Physics measurements

- Proton radius anomaly: $\eta \to \gamma\,\mu^+\mu^-$ vs $\eta \to \gamma\, e^+e^-$
- All unseen leptonic decay mode of η/η'(SM predicts $10^{-6} \div 10^{-9}$)

High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \to \pi^0 H$ with $H \to e^+e^-$ and $H \to \mu^+\mu^-$
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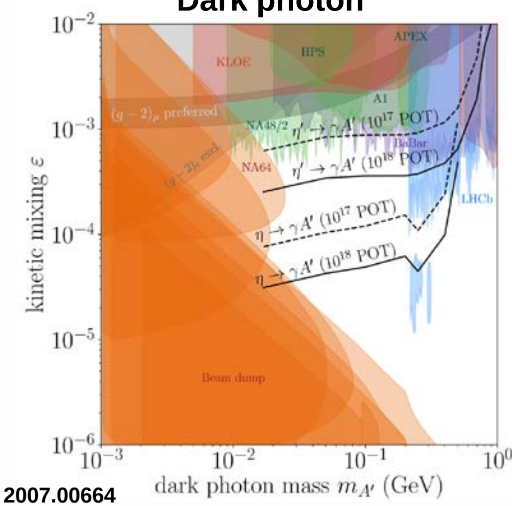
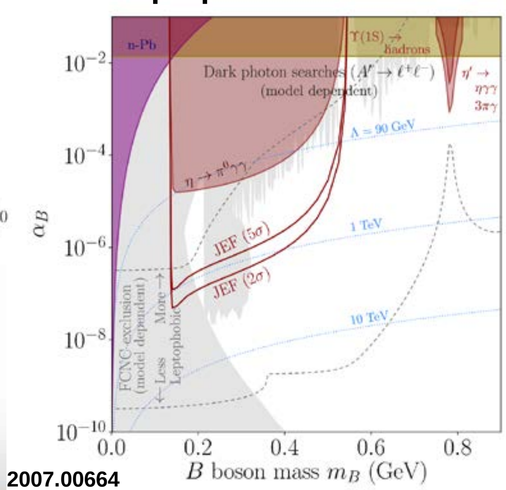
Dark photon



2007.00664

Leptophobic dark force



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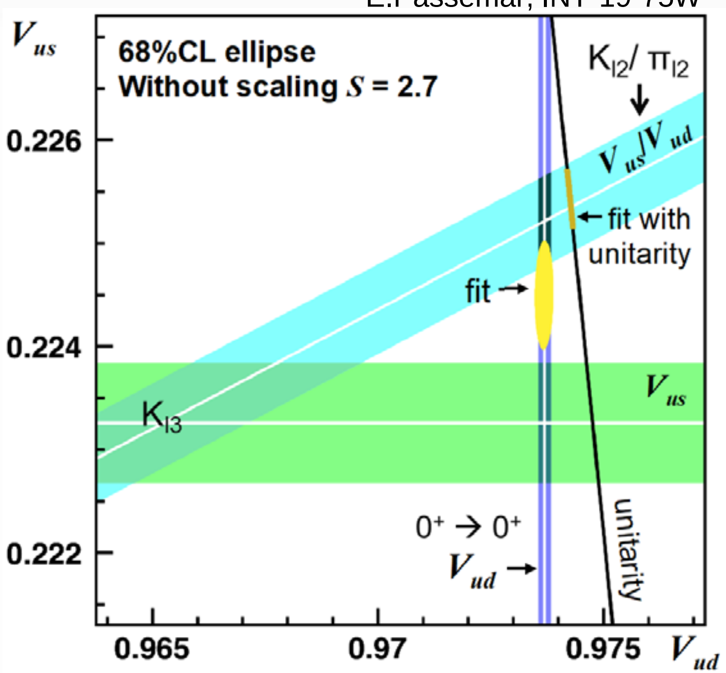
Tension between V_{us} and V_{ud} extracted from fit and CKM unitarity

E.Passemar, INT-19-75W



$$\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$$

Fit results, no constraint

V_{ud} = **0.97368(14)**

V_{us} = **0.22450(35)**

χ^2/ndf = 7.2/1 (0.7%)

Δ_{CKM} = **−0.00154(32)**

-4.8σ

Inputs

$|V_{ud}|$ = **0.97370(14)**

$|V_{us}|$ = **0.2233(6)**

$|V_{us}|/|V_{ud}|$ = **0.2313(5)**

BSM physics? Unidentified systematic errors?

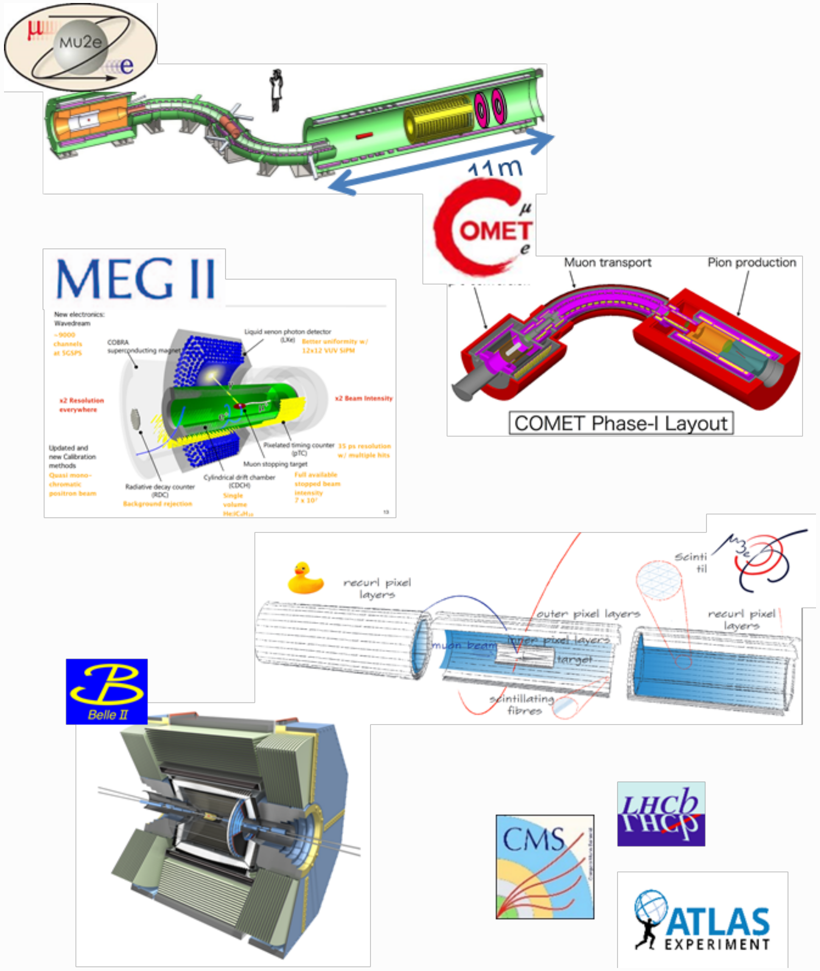
On-going work and new proposals

- Systematic improvement of lattice QCD calculations
- Improve V_{ud} measurement from neutron decays (UCN) and pion beta decays (PIENUXE)

Charged lepton flavor violation (RF5)

Summary of topics discussed in LOIs

- Muon decays and transitions
- Muonium-antimuonium
- Tau decays and transitions
- CLFV in heavy state decays
- CLFV in meson/baryon decays
- New facilities and new experiments



Muon decays and transitions

μ-e conversion

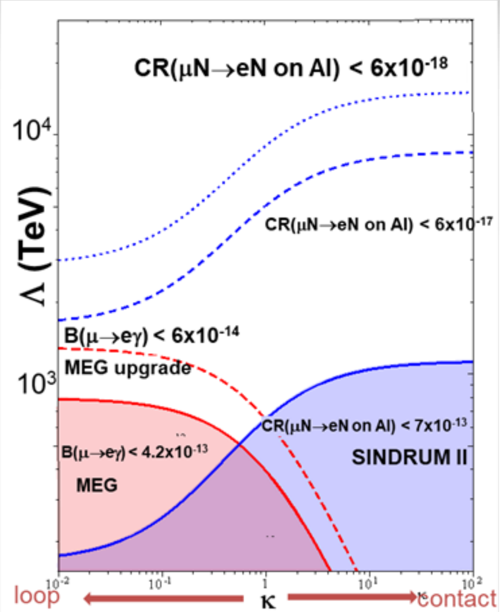
DeeMee at J-PARC → $R_{\mu e} \sim 10^{-14}$
COMET at J-PARC → $R_{\mu e} \sim 10^{-17}$
Mu2e at FNAL → $R_{\mu e} \sim 10^{-17}$

μ→eγ decays

MEG II → BF ~ 6×10^{-14}

μ→eee decays

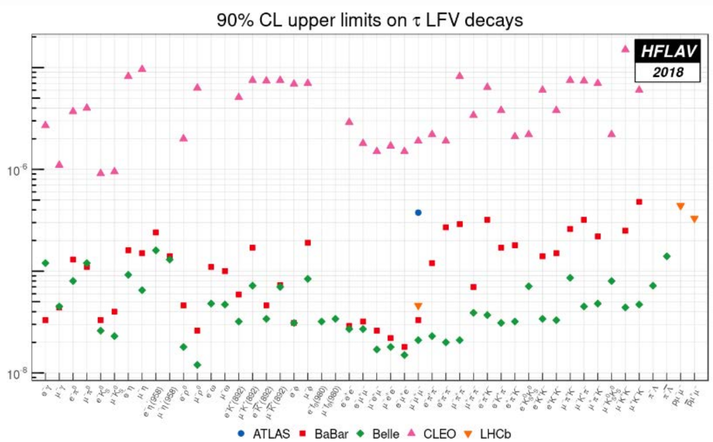
Mu3e → BF ~ 10^{-15} - 10^{-16}



de Gouvêa, & Vogel,1303.4097

Tau decays

LHCb, Belle II, Atlas, CMS,… → BF ~ 10^{-9} - 10^{-}



Higgs decays

Atlas, CMS → $|Y_{\alpha\beta}| \sim 10^{-3}$ - 10^{-4}

…..

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RF/SNOWMASS21-RF5_RF0-100.pdf
RF/SNOWMASS21-RF6_RF4-EF3_EF4_Mogens_Dam-119.pdf
RF/SNOWMASS21-RF7_RF1_STCF-013.pdf
RF/SNOWMASS21-RF5_RF0_MEGII-062.pdf
RF/SNOWMASS21-RF0_RF0-EF4_EF0-AF5_AF0_Banerjee_Roney-046.pdf

Muon decays and transitions

μ-e conversion

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μ→eγ decays

MEG II → BF ~ 6×10^{-14}

μ→eee decays

Mu3e → BF ~ 10^{-15} - 10^{-16}

Tau decays

LHCb, Belle II, Atlas, CMS → BF ~ 10^{-9} - 10^{-10}

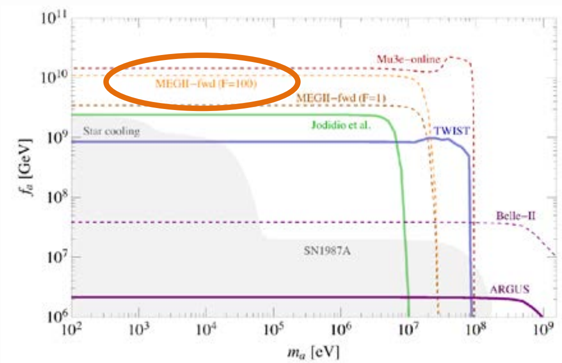
Higgs decays

Atlas, CMS → $|Y_{\alpha\beta}| \sim 10^{-3}$ - 10^{-4}

.....

MEGII-fwd

Add forward detector to MEGII to search for LFV axions



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Systematic search for light NP

signature	$\mu \to e X_{NP}$	$\mu \to e\gamma X_{NP}$	$\mu \to e\nu X_{NP}$	$\mu \to e\nu\bar{\nu} X_{NP}$
$\mu \to e + \text{inv}$	$a\|_{\text{inv}}, \gamma_d\|_{\text{inv}}$	–	$N\|_{\text{inv}}$	$a\|_{\text{inv}}, \gamma_d\|_{\text{inv}}$
$\mu \to 3e$	$a, \gamma_d \to e^+e^-$	–	–	–
$\mu \to e2\gamma$	$a \to \gamma\gamma$	–	–	–
$\mu \to e\gamma + \text{inv}$	$a, \gamma_d \to \gamma + \text{inv}$	$a\|_{\text{inv}}, \gamma_d\|_{\text{inv}}$	$N \to \gamma + \text{inv}$	$a, \gamma_d \to \gamma + \text{inv}$
$\mu \to 3e\gamma$	$a \to e^+e^-\gamma$	$a, \gamma_d \to e^+e^-$	–	–
$\mu \to e + 3\gamma$	$\gamma_d \to 3\gamma$	$a \to \gamma\gamma$	–	–
$\mu \to e2\gamma + \text{inv}$	$a, \gamma_d \to \gamma\gamma + \text{inv}$	$N \to \gamma + \text{inv}$	–	$a \to 2\gamma$
$\mu \to 3e + \text{inv}$	$a, \gamma_d \to e^+e^- + \text{inv}$	–	$N \to e^+e^-\nu$	$a, \gamma_d \to e^+e^-$

Table 1. Common signatures expected in the $\mu \to X_{NP} X_{SM}$ decays, where X_{NP} is for illustration taken to be either a (pseudo)scalar a, a dark vector, γ_d, or a heavy neutral lepton N.

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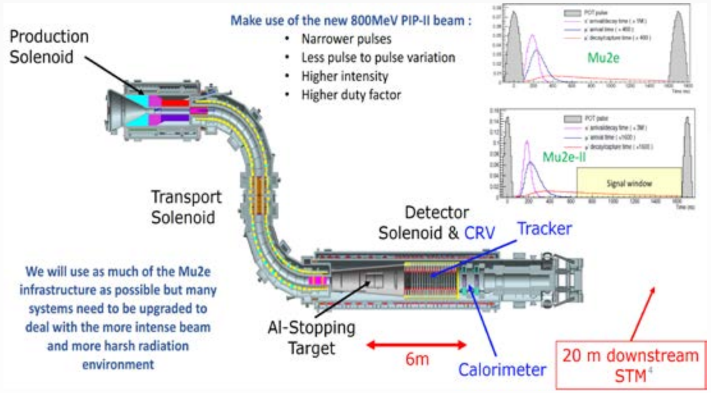
RF/SNOWMASS21-RF5_RF0-100.pdf
RF/SNOWMASS21-RF6_RF4-EF3_EF4_Mogens_Dam-119.pdf
RF/SNOWMASS21-RF7_RF1_STCF-013.pdf
RF/SNOWMASS21-RF5_RF0_MEGII-062.pdf
RF/SNOWMASS21-RF0_RF0-EF4_EF0-AF5_AF0_Banerjee_Roney-046.pdf

Mu2e II ($\mu \to e$ conversion)



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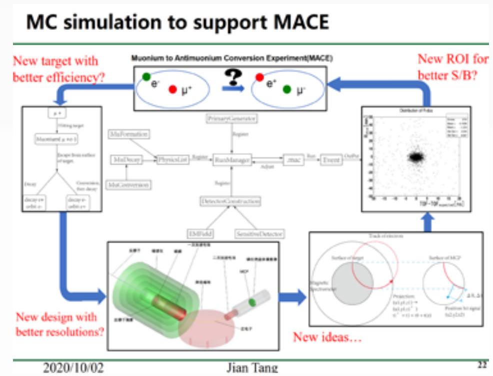
MACE (Mu-Mubar conversion)



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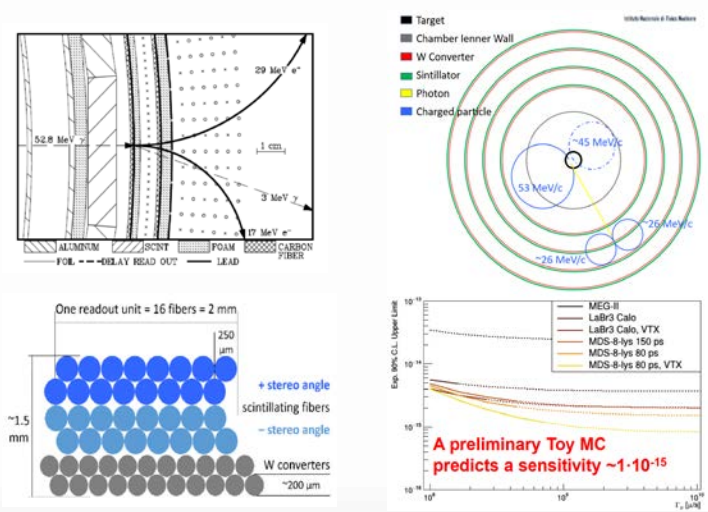
Courtesy: Jiang-Yu Tang

New concept for $\mu \to e\gamma$



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Several new concepts and proposals to improve sensitivity on

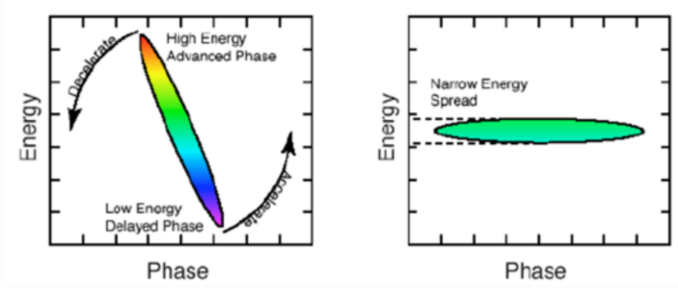
- **$\mu \to$ e gamma**
- **μ -e conversion**
- **mu-mubar conversion**

by one or many orders of magnitude !

ENIGMA: a new facility for a next generation of muon experiment with high intensity muon beams using PIP II at FNAL

Muon beam for μN - eN conversion with the possibility to use high Z target

- Based on PRISM concept
- Compressor ring + Fixed Field Alternating gradient (FFA) ring to phase rotate the muons
- Monochromatic muon beam with extremely low pion contamination
- Could reach **SES of the order of 10^{-19}**



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RF/SNOWMASS21-RF5_RF0-AF5_AF0_J_Pasternak-096.pdf

Surface muon beam for $\mu \rightarrow e\gamma$ $\mu \rightarrow eee$ decays

- Fully exploit PIP II capabilities to produce extremely large flux of surface muons
- Could potentially improve upon MEG II by **factor 100 and explore O(10^4) TeV SUSY-like models**

Approximate stopped muon rates

Facility	Stopped Muon Rate/
Current PSI	2×10^8
HiMB at PSI	10^{10}
Mu2e Design (+ mode)	10^{11}
PIP-II	$>10^{12}$

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Many synergies with muon collider and neutrino factories – just started to explore

Potentially transformative

Proposal for an upgraded low energy muon facility for

- Muon Spin Resonance (μSR with μ^+) for materials science, chemistry, & biology
- Muon catalyzed fusion with low energy μ^-

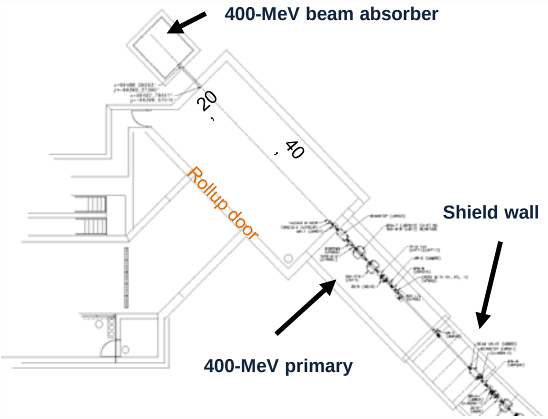
Possibilities at FNAL

- Upgrade MuCool Test Area (MTA) or new facility for PIP II
- Explore heavy targets to boost π^+ and π^- production
- Estimated Muon Production @MTA with a segmented Tantalum target:

  >1000 μ^+ or μ^-/s (average), ~200,000 μ^-/s (peak)
  cm^2 spot size
  4–100 MeV

- On-going work to define physics objectives, design beamline and plan associated experiments

400-MeV MTA Facility



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Low energy muon facility at Fermilab offers immediate and long-term science opportunities and capabilities not achievable at other facilities !

Quark and lepton flavors are both a cornerstone of the SM and very sensitive probes of New Physics.

They are an essential component of current and future particle physics programs. A vigorous experimental program is underway, and new ideas have been proposed to further push the boundaries.

Complementarity is key! Flavor is an important piece of the puzzle, but we need a combination of low-energy and high-energy measurements to pinpoint the nature of New Physics.

Important role of theory in this physics program, in particular lattice QCD.

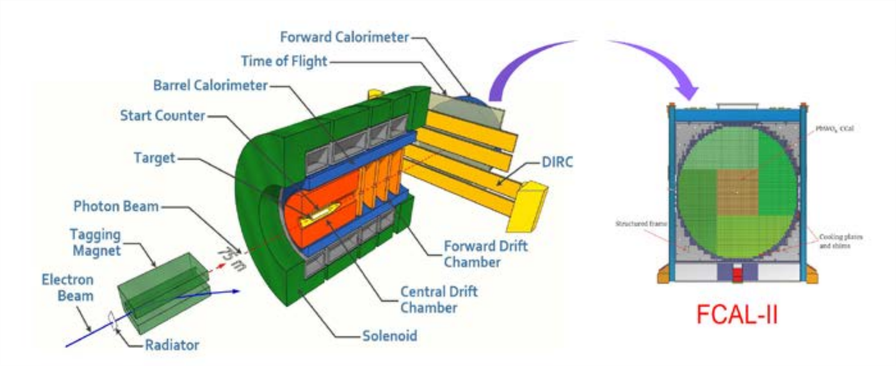
So join us to define a strong and exciting vision for the future of quark and lepton flavors

Extra material

RF/SNOWMASS21-RF2_RF0_Liping_Gan-017.pdf
RF/SNOWMASS21-RF2_RF6-IF6_IF3_REDTOP_Collaboration_-_new-083.pdf
RF/SNOWMASS21-RF2_RF0_Sergi-085.pdf
RF/SNOWMASS21-RF6_RF2_Sean_Tulin-117.pdf

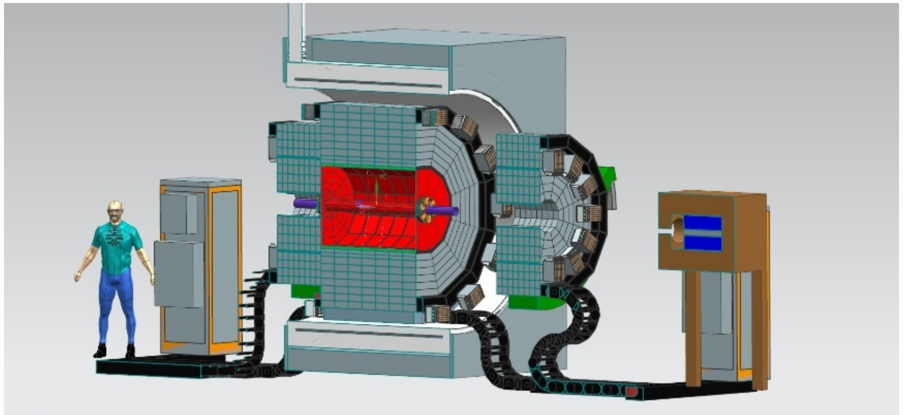
Jefferson Eta Factory (JEF) @ JLab (approved)

- GlueX + upgraded forward calorimeter at Jefferson Lab
- 8.4-11.7 GeV tagged photon beam on LH2 target
  $\rightarrow$ 7x10^7 η / 5x10^7 η' per 100 days



REDTOP @ FNAL or CERN (proposal)

- Compact detector, optical TPC with dual readout calorimeter
- Aim to collect 10^{12} - 10^{13} η /year and 10^{10} - 10^{11} η'/ year



+ activities at A2, Belle-II, BESIII, KLOE-II, GlueX, WASA-at-COSY,…

LHCb expanding its physics reach towards strange physics complementary to the core program

- Encouraging Run 1-2 results on $K_s \rightarrow \mu^+\mu^-$ and $\Sigma^+ \rightarrow p\mu^+\mu^-$
- Upgraded trigger will provide unprecedented sensitivity to many channels
- Complementary to K_L and K^+ dedicated experiments

LHCb major player for K_S and hyperons rare decays

Sensitivity Studies (1808.03477)

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K^0_S \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K^0_S \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K^0_S \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K^0_S \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K^0_L \to \mu^+\mu^-$	~ 1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~ 3.0	~ 7.0
$K^+ \to \pi^+\pi^+\pi^-$	~ 2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~ 1.0	~ 4.0
$K^+ \to \pi^+\mu^+\mu^-$	~ 2	6.3 (2.3) $\times 10^{-3}$	0.030 (0.014)	~ 1.5	~ 4.5
$\Sigma^+ \to p\mu^+\mu^-$	~ 0.13	0.28 (0.28)	0.64 (0.64)	~ 1.0	~ 3.0
$\Lambda \to p\pi^-$	~ 0.45	0.41 (0.075)	1.3 (0.39)	~ 1.5	~ 5.0
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~ 0.45	0.32 (0.31)	0.88 (0.86)	–	–
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~ 0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	–	–
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~ 0.03	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	–	–
$\Xi^- \to p\pi^-\pi^-$	~ 0.03	0.41(0.05)	0.94 (0.20)	~ 3.0	~ 9.0
$\Xi^0 \to p\pi^-$	~ 0.03	1.0 (0.48)	2.0 (1.3)	~ 5.0	~ 10
$\Omega^- \to \Lambda\pi^-$	~ 0.001	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~ 7.0	~ 20

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \pi^+\pi^-e^+e^-$	1	1.0 (0.18)	2.83 (1.1)	~ 2.0	~ 10
$K^0_S \to \mu^+\mu^-e^+e^-$	1	1.18 (0.48)	2.93 (1.4)	~ 2.0	~ 11
$K^+ \to \pi^+e^-e^+$	~ 2	0.04 (0.01)	0.17 (0.06)	~ 3.0	~ 13
$\Sigma^+ \to pe^+e^-$	~ 0.13	1.76 (0.56)	3.2 (1.3)	~ 3.5	~ 11
$\Lambda \to p\pi^-e^+e^-$	~ 0.45	$< 2.2 \times 10^{-4}$	~ 17 (< 2.2) $\times 10^{-4}$	–	–

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \mu^+e^-$	1	1.0 (0.84)	1.5 (1.3)	~ 3.0	~ 8.0
$K^0_L \to \mu^+e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	~ 3.0	~ 7.0
$K^+ \to \pi^+\mu^+e^-$	~ 2	3.1 (1.1) $\times 10^{-3}$	16 (8.5)$\times 10^{-3}$	~ 2.0	~ 8.0

R=ratio of production, ε=ratio of efficiencies

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