The rare processes and precision measurements frontier

Physics highlights, arXiV:2210.04765

Josh Barrow	MIT/Tel Aviv/Knoxville	Early Career
Jake Bennett	U. Mississippi	Early Career
Susan Gardner	U. Tennessee	Cosmic Frontier
Sophie Middleton	Caltech	Community Engagement Frontier
Eric Prebys	UC Davis	Accelerator Frontier
Manuel Franco Sevilla	U. Maryland	Energy Frontier

Marina Artuso
Syracuse U.

Alexey Petrov
Wayne State and U South Carolina

Bob Bernstein
Fermilab

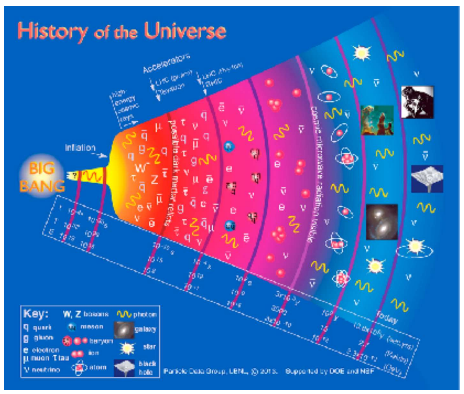
Topical Group	Co-Conveners	
Weak Decays of b and c	Angelo di Canto BNL	Stefan Meinel U Arizona
Strange and Light Quarks	Emilie Passemar Indiana U	Evgueni Goudovski Birmingham
Fundamental Physics and Small Experiments	Tom Blum UConn	Peter Winter ANL
Baryon and Lepton Number Violation	Pavel Fileviez Perez CWRU	Andrea Pocar Amherst
Charged Lepton Flavor Violation	Sacha Davidson IN2P3/CNRS France	Bertrand Echenard Caltech
Dark Sector at High Intensities	Stefania Gori UCSC	Mike Williams MIT
Hadron Spectroscopy	Rich Lebed Arizona State	Tomasz Skwarnicki Syracuse

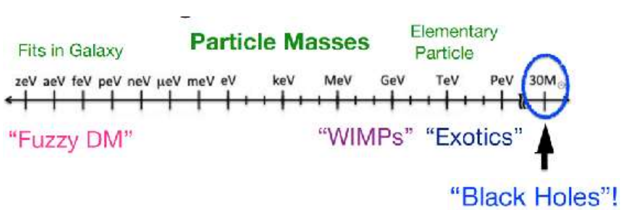
Marina Artuso, at NAS Committed on Elementary Particle Physics - Progress and Promise, Meeting # 6, April 3-4, 2023

Frontier themes well positioned in the realm of HEP community goal:

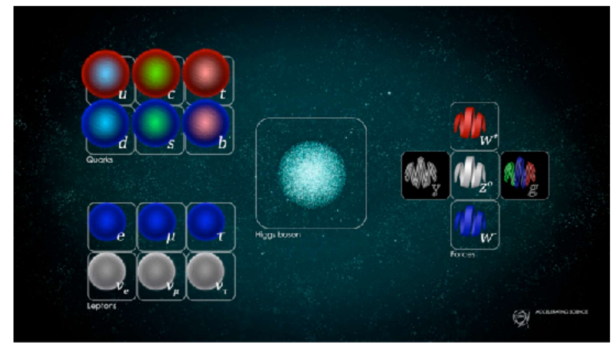
A search for deeper understanding with precision tools

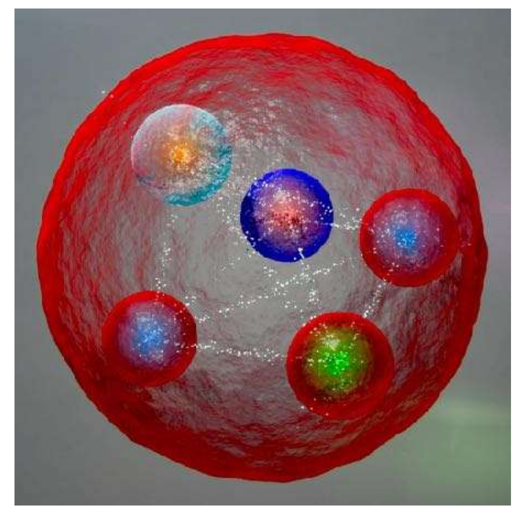
From matter-antimatter → Stable universe





- What we (particle physicists) would like:
  - An identification of the yet unknown constituents (dark matter and dark energy)
  - An understanding of the fundamental constituents of matter and their interactions
  - An understanding of the ways the fundamental constituents aggregate together

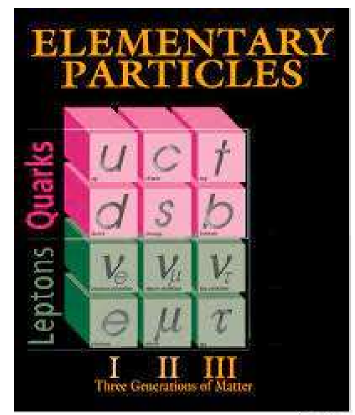




Flavor physics as a tool for discovery

- Flavor physics is defined as the physics that distinguishes the generations.
- We see three generations of quarks and leptons and ask:
  - What is the origin of this replication?
  - Is there any clue to a deeper understanding embedded in this rich pattern of mixing and decays?

Connections and differences between quarks and leptons offer rich phenomenology and many unexplored clues



A new P5 physics driver

Flavor physics as a tool of discovery

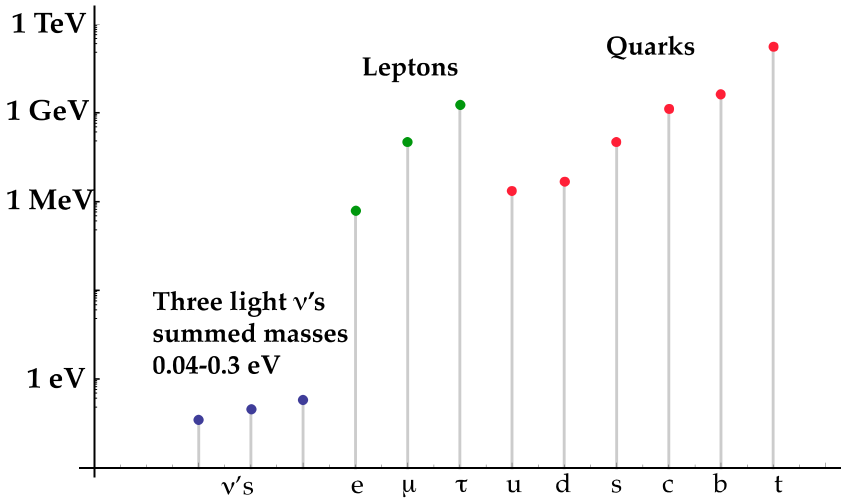
Beyond the minimum flavor violation paradigm in search for a deeper understanding of the microworld, this driver brings attention to the unique contributions of flavor physics to the “quest for the unknown” and has a solid track record for discovery

Absence of $K_L \to \mu\mu$	Charm quark (Glashow, Iliopoulos, Maiani, 1970
Δm_K :	$m_c \approx 1.5 GeV$ (Gaillard & Lee; Vainshtein& Khriplovich, 1974)
$B - \bar{B}$ mixing:	$m_t \geq 100 GeV$
$\mu \to e\gamma$ suppression:	2 neutrino flavors
....	....

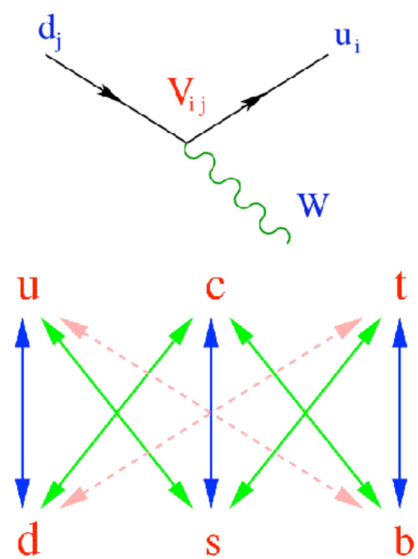
Fermions and their flavor

a rich and complex phenomenology

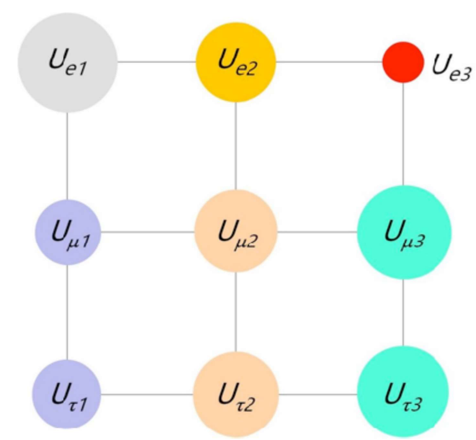
The masses



Quark mixing manifested in charged current interaction

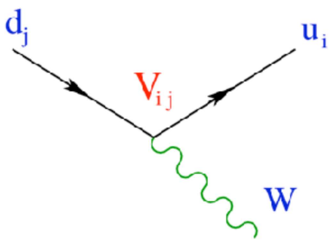


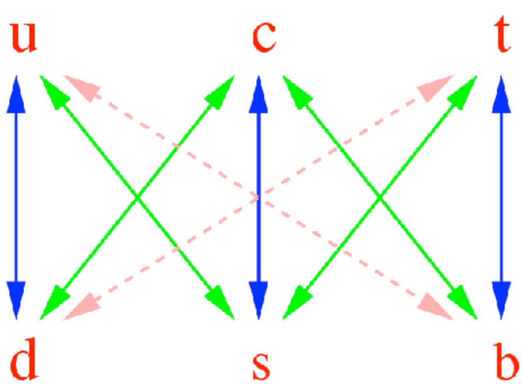
ν oscillations: evolution of initial neutrino state



The CKM matrix

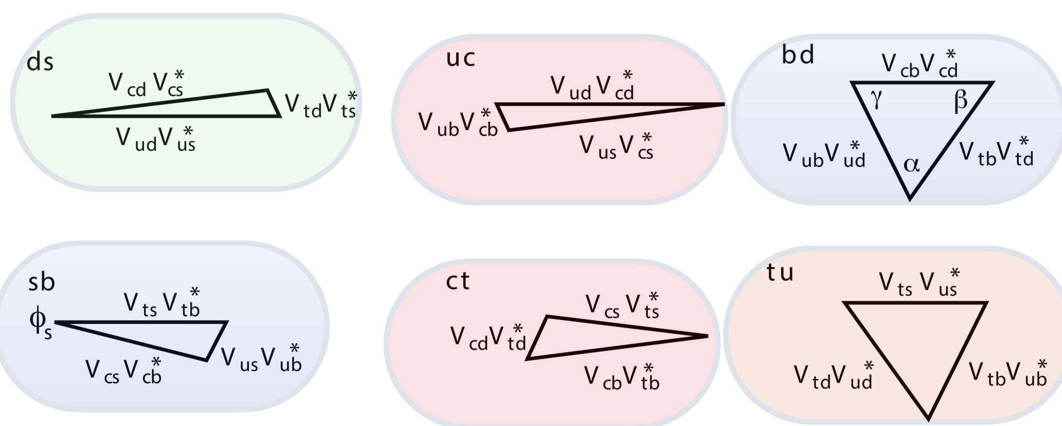
And its triangles





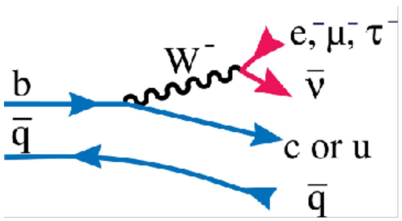
$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- Rich pattern of charge-changing weak transitions of quarks described by CKM matrix
- The CKM matrix is unitary ➡ 6 unitarity triangles
- Unitarity+ appropriate redefinition of quark phases. ➡ 4 independent parameters, η describing CP violation in the Standard Model



Search for new physics in b decays

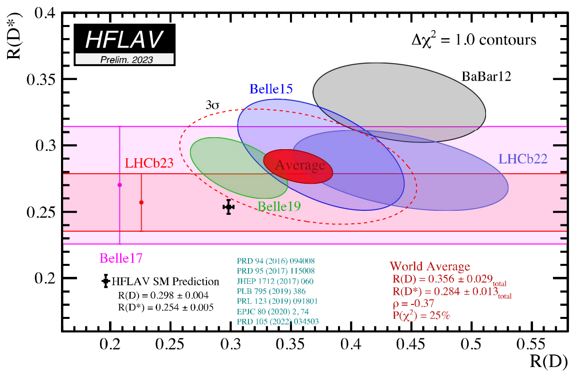
The general road map



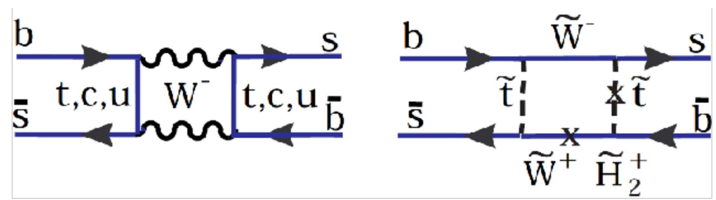
Tree diagrams: well-described by Standard Model, however:

Surprises may happen along the way

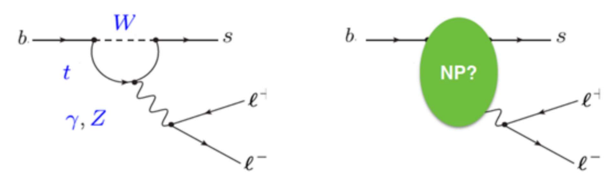
$$R(D^{(\star)}) \equiv \frac{\mathscr{B}(B \to D^{(\star)}\tau\nu)}{\mathscr{B}(B \to D^{(\star)}\mu\nu)}$$



Loop diagrams: sensitive to interference with new-physics particles: manifestations in rare decays and flavor oscillations



} Flavor oscillations



} Rare decays

Different rare decays more sensitive to specific Wilson coefficients

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$

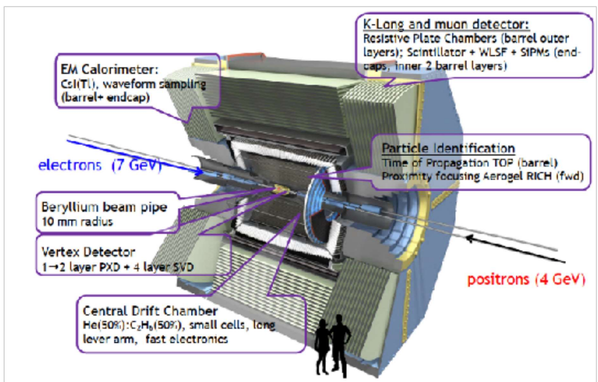
i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

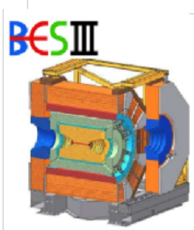
Experimental techniques

RPF Topical Group 1

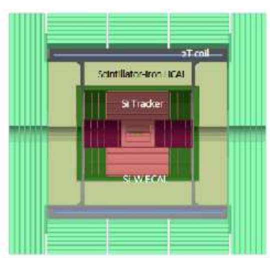
e^+e^- machines

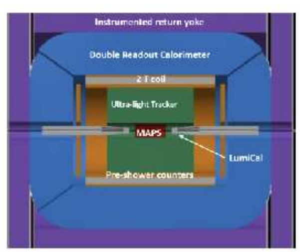
Belle, Belle II and possible upgrades





FCC-ee Z-factory



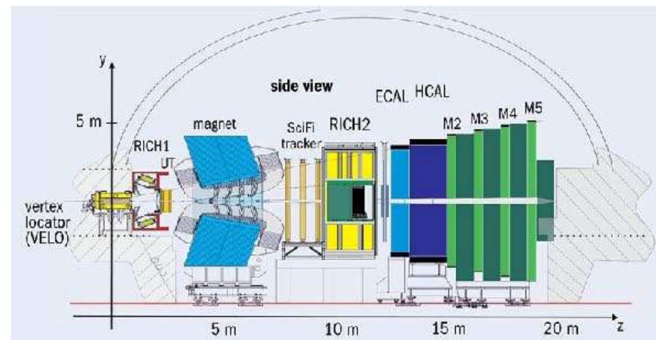


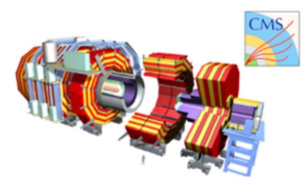
CLD

IDEA

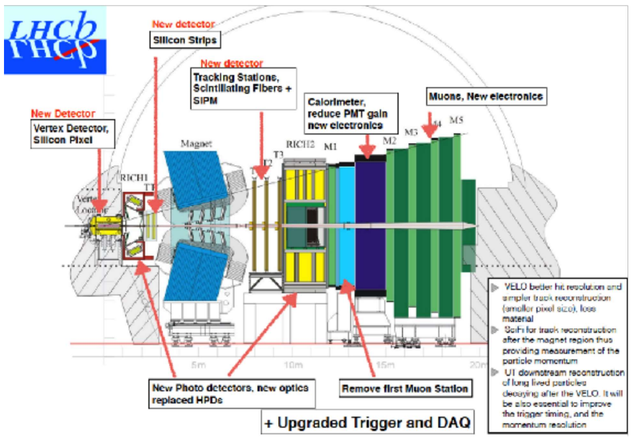
Hadron machines

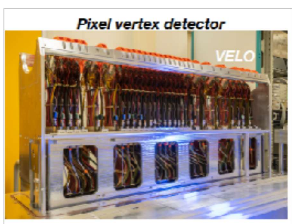
LHCb, currently LHCb Upgrade 1, Planned: LHCb Upgrade 2



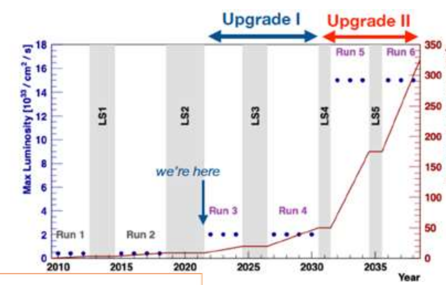


LHCb Upgrade Plans





Taking data now!



Upgrade I

- $L_{peak} = 2 \times 10^{33}\ cm^{-2} s^{-1}$
- $L_{int} = 50\ fb^{-1}$ during Run 3 + Run 4
- LHCb 50 fb^{-1}: healthy competition with Belle II at 50 ab^{-1}

Upgrade II

$\mathcal{L}_{peak} = 1.5\times10^{34} cm^{-2}s^{-1}$

$\mathcal{L}_{int} = 300 fb^{-1}$

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9,10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	49 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$, *etc.*)	6%	[29,30]	3%	—	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	17×10^{-5}	—	3.0×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	13×10^{-5}	[38]	4.3×10^{-5}	—	1.0×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	71%	[40,41]	34%	—	10%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}$($B_s^0 \to \phi\gamma$)	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}$($B_s^0 \to \phi\gamma$)	0.32	[51]	0.093	0.062	0.025
α_γ($\Lambda_b^0 \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.10	[61]	0.031	0.021	0.008
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62,64]	0.007	—	0.002

Belle II upgrade

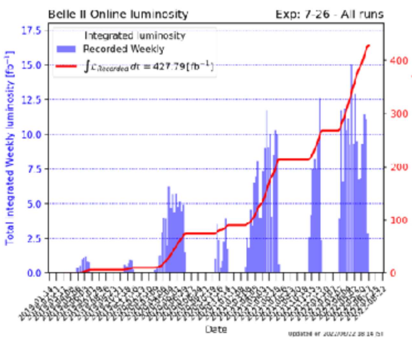
Projections and possible long term evolution

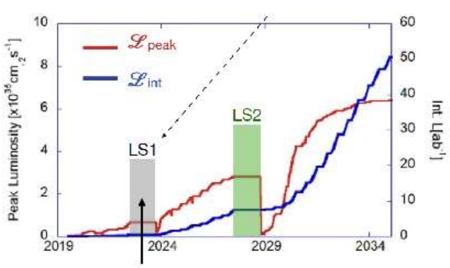
SuperKEKB:

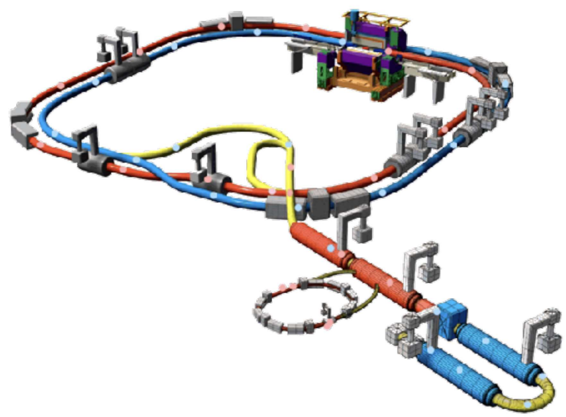
Asymmetric electron-positron collider at the $\Upsilon(4S)$

Target instantaneous luminosity: $\mathscr{L} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Max instantaneous luminosity: $\mathscr{L} = 4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$







- Nano-beam scheme
  - Increase beam current, squeeze beams at the IP, reduced beam energy asymmetry
  - Target beam height: 50 nm; current value: 300 nm

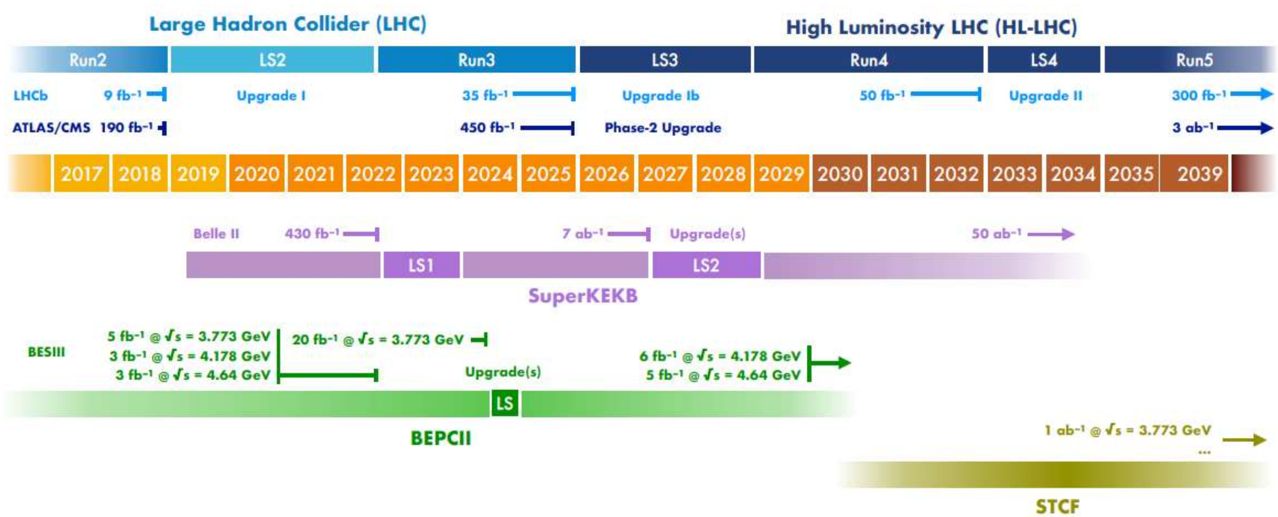
Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	Belle-II 250 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005	0.002
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°	0.8°
α/ϕ_2 (WA)	4°	2°	0.6°	0.3°
$\lvert V_{ub}\rvert$ (Exclusive)	4.5%	2%	1%	< 1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	0.03	0.015	0.007
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	0.07	0.025	0.018
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035	0.015
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.09	0.03	0.01
$R(B \to D^*\tau\nu)$	0.018	0.009	0.0045	<0.003
$R(B \to D\tau\nu)$	0.034	0.016	0.008	<0.003
$\mathcal{B}(B \to \tau\nu)$	24%	9%	4%	2%
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	–	25%	9%	4%
$\mathcal{B}(\tau \to \mu\gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}	3.1×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	0.073×10^{-9}

Table 2: Projected precision (total uncertainties, or 90% CL upper limits) of selected flavour physics measurements at Belle II.(The † symbol denotes the measurement in the momentum transfer squared bin $1 < q^2 < 6\ \mathrm{GeV}/c^2$.)

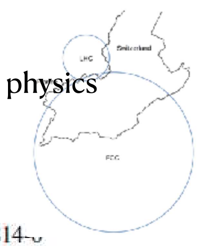
Further luminosity upgrades being studied

The overall blueprint

Heavy quarks and τ lepton



FCC-ee is considering a broad flavor physics program



Eur. Phys. J. Plus (2021) 136:837
https://doi.org/10.1140/epjp/s13360-021-01814-6

- High luminosity precision study of Z, W, H, and $t\bar{t}$

Table 1 Advantageous attributes for flavour physics studies at Belle II ($\Upsilon(4S)$), the LHC (pp) and FCC-ee (Z^0)

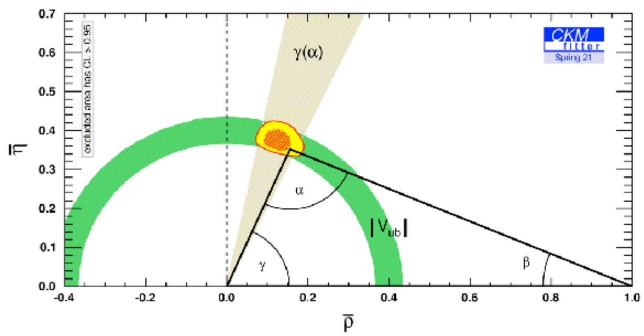
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

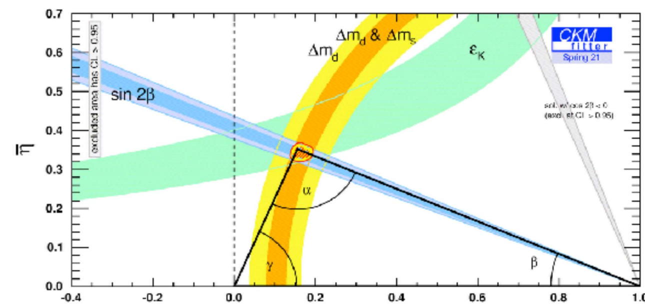
Table 2 Yields of heavy-flavoured particles produced at FCC-ee for 5×10^{12} Z^0 decays. The charge conjugate states have the same production yields. These yields are computed using the Z branching fractions and hadronisation rate reported in Refs. [4,5]. The B_c hadronisation fraction is assumed to be $f_{B_c} = 2 \times 10^{-3}$ [6]

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

CKM: the standard triangle, trees and loops

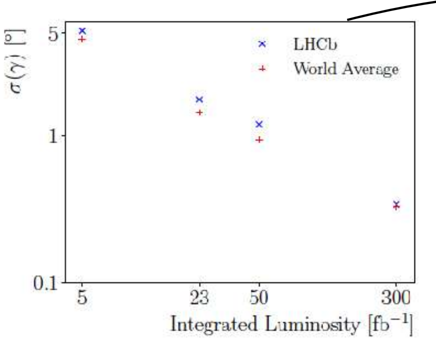
Where we are now

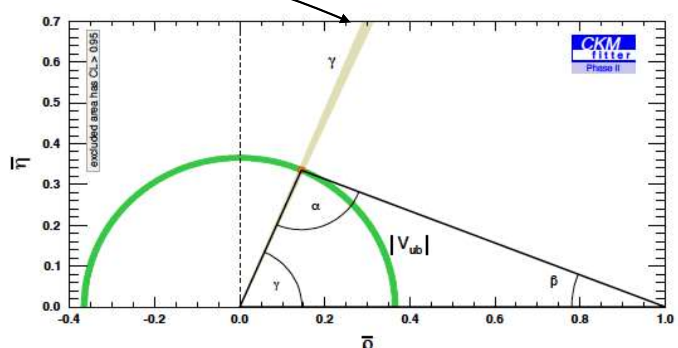


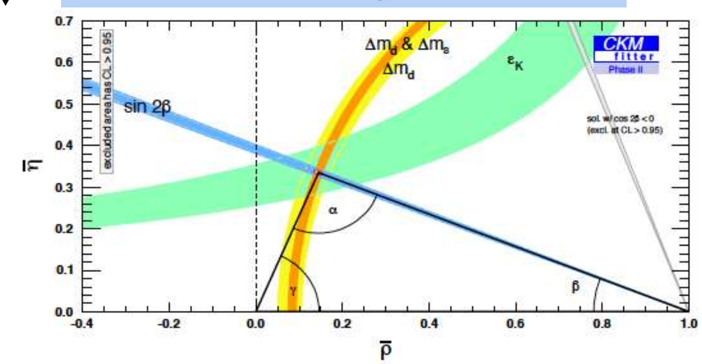


Phase II: end of HL-LHC

Bands shrink for higher statistics, more measurements and theoretical improvements (lattice QCD)



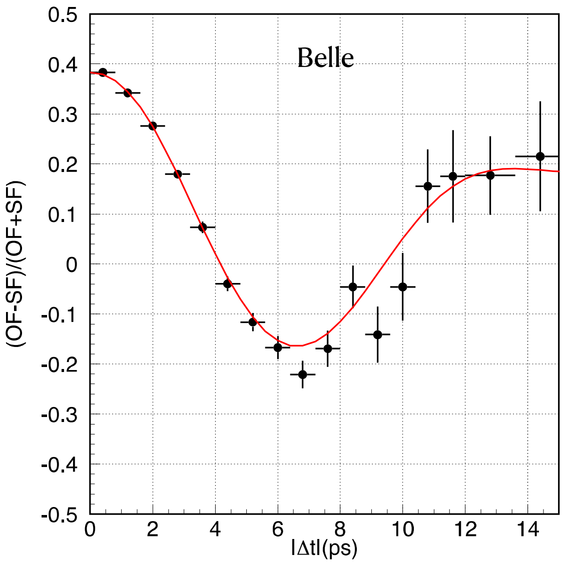




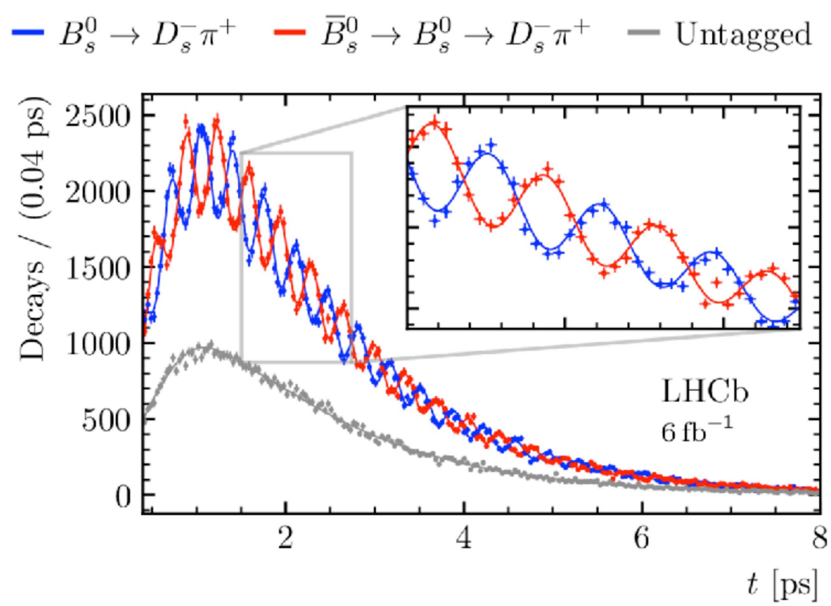
$B - \bar{B}$ mixing - the data

Particle Data Group collaboration, R. L. Workman et al., *Review of Particle Physics*, *PTEP* **2022** (2022) 083C01

$\Delta M_{\rm d} = 05065(19)\ {\rm ps}^{-1}$



$\Delta m_s = (17.7656 \pm 0.0057) ps^{-1}$

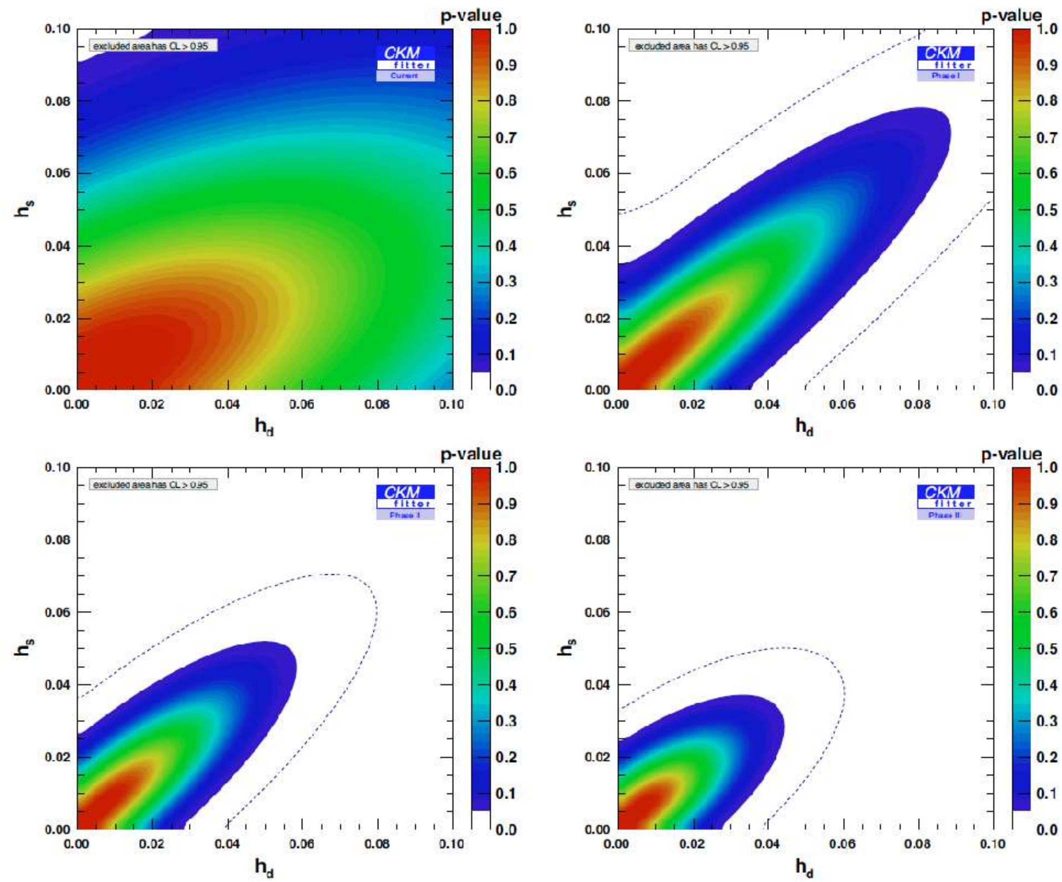


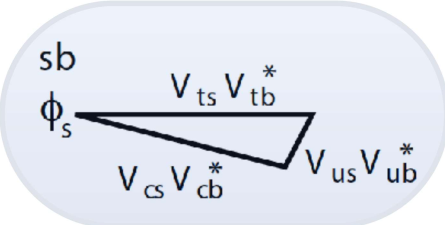
New physics in $B - \bar{B}$ mixing

Parameterization of new physics:

$$M_{12} = (M_{12})_{SM} \times (1 + he^{2i\sigma}),$$

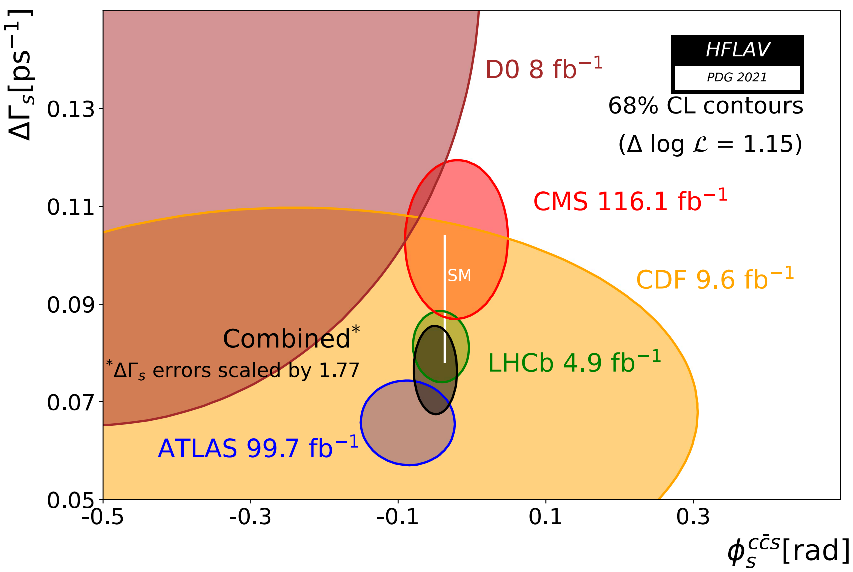
Phase I: LHCb 50/fb & Belle II 50/ab
Phase II: LHcb 300/fb and Belle 250/ab
Phase III: FCC-ee(new measurements): improvement related to assumed improvement in $|V_{cb}|$
Note: all these stages include theoretical improvements, in particular lattice QCD



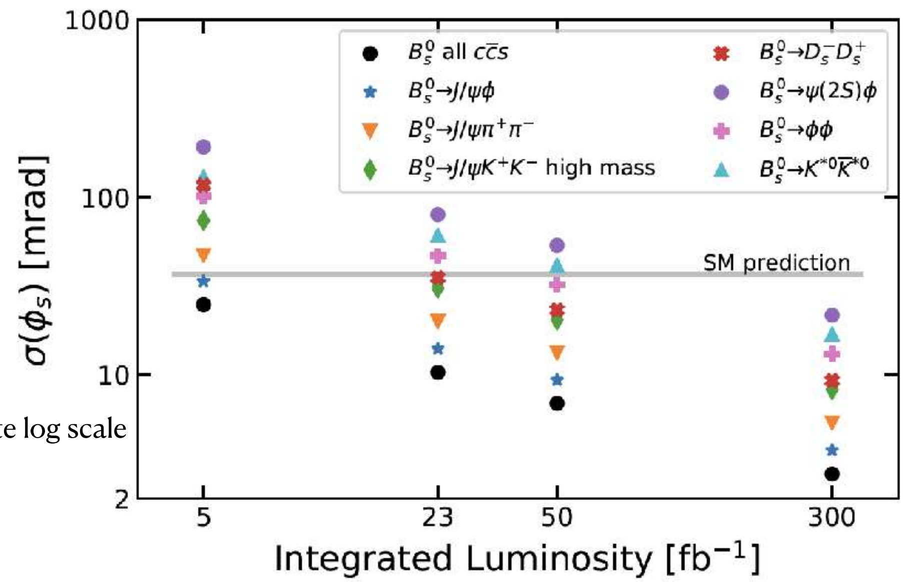


ϕ_s

Current status and future perspective



LHCb-TRD-023



Note log scale

The lesson from kaons

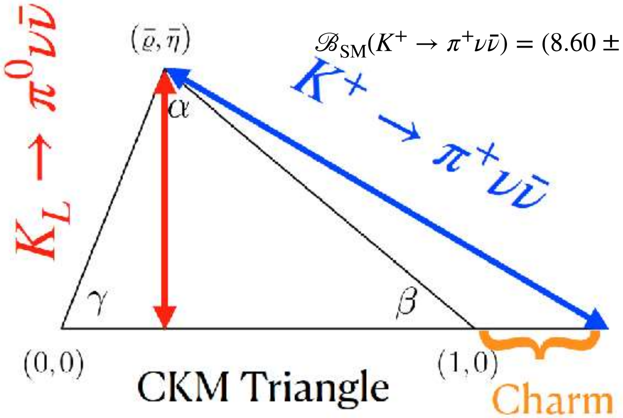
RPF Topical group 2

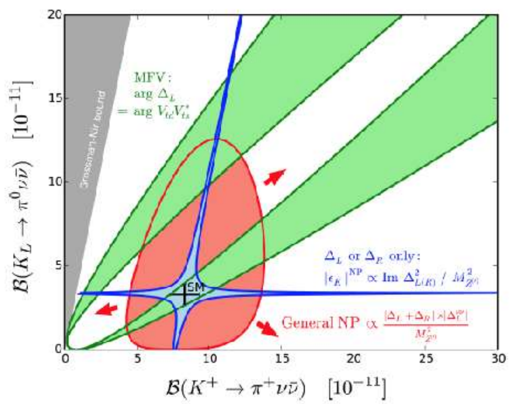
The K triangle

K, $\pi, \underbrace{\eta, \eta'}$
JEF at JLAB/REDTOP

$\mathcal{B}_{SM}(K_L \to \pi^0 \nu\bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}$

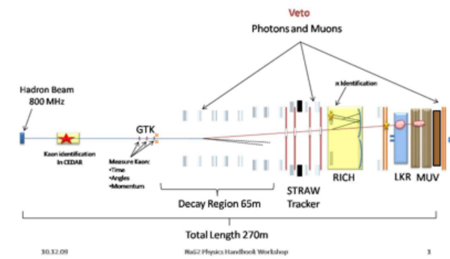
$\mathcal{B}_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$





NA62 @CERN
$K^+ \to \pi^+ \nu\bar{\nu}$

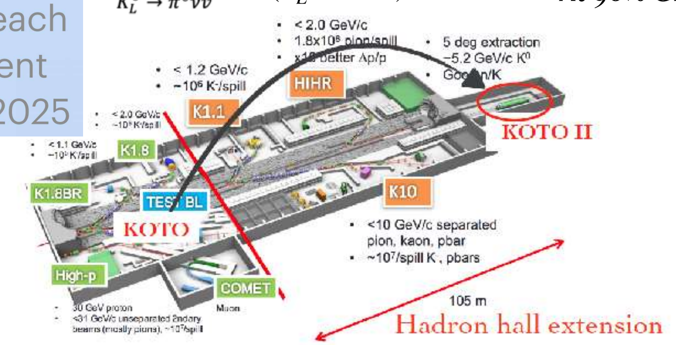
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$



HIKE:
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$
At 5% level
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$
At 20% level

Expected to reach SM single event sensitivity by 2025

$K_L^0 \to \pi^0 \nu\bar{\nu}$ $\quad \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9}$ At 90% CL



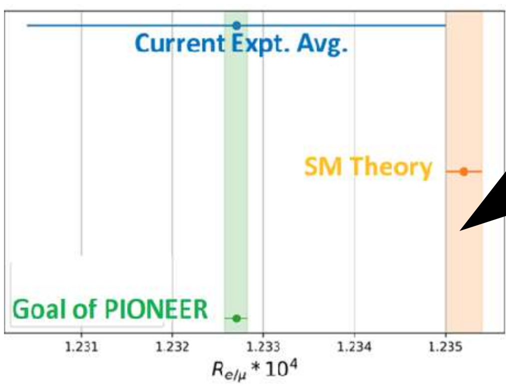
Fundamental physics from pion decays

- Standard Model theory:

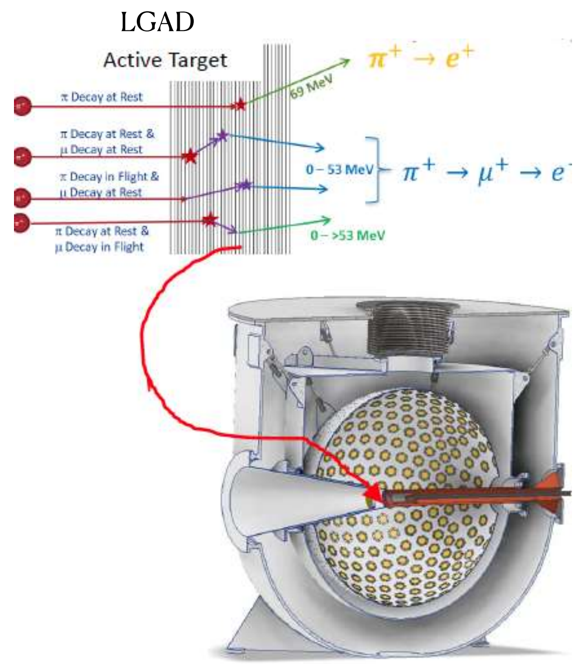
Theory: Marciano/Sirlin
→ Cirigliano/Rosell

$$R^{theory}_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = 1.23524(015) \times 10^{-4}$$

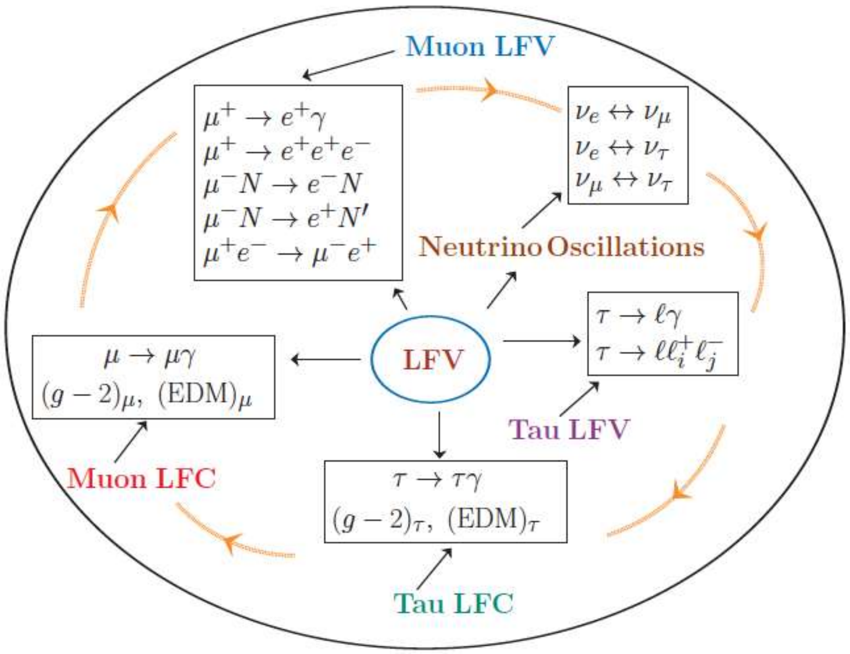
Current $\frac{g_e}{g_\mu} = 0.9990 \pm 0.0009 \quad (\pm 0.09\%)$ **Goal:** $\frac{g_e}{g_\mu} \sim \pm 0.005\%$



Pioneer Experiment at PSI

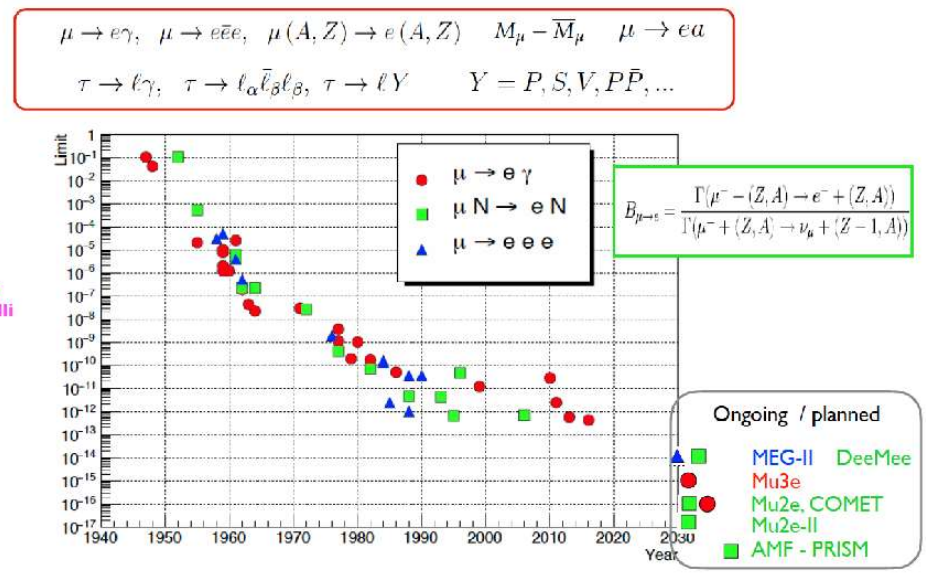


The clues unveiled by rare charged lepton decays

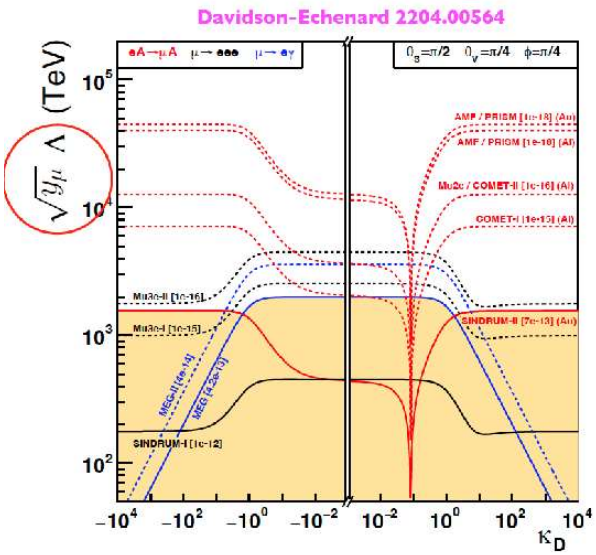


Modified from Calibbi-Signorelli 1709.00294

V. Cirigliano Snowmass CSS



The broad landscape of charged lepton flavor violation



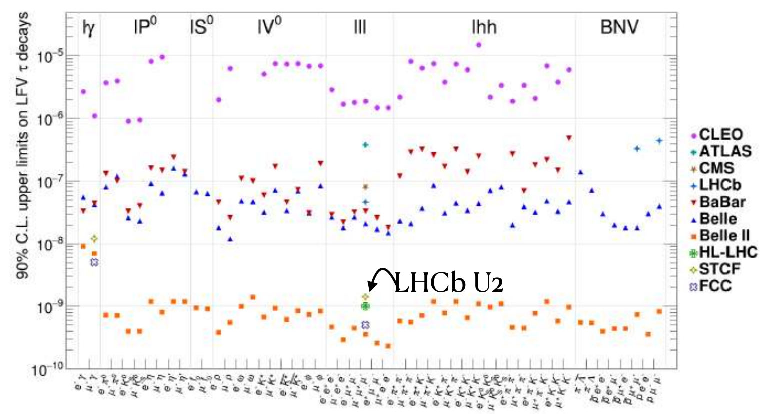
$\kappa_D = cotan(\theta_D - \pi/2)$

κ_D: relative strength of dipole vs four-fermion operators (inspired from the "κ parameterization" in 1303.0497)

$|\kappa_D| << 1$ dipole dominant
$|\kappa_D| >> 1$ four-fermion dominant

- Very high scale probed!
- Notion of 'best probe' is model-dependent
- Discovery opportunities in current and planned searches

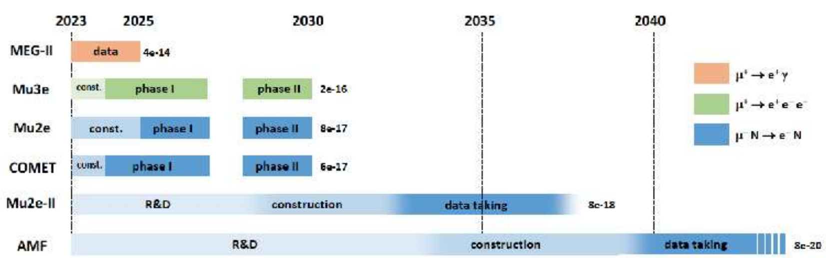
WP 2203.14919



$\mu \to e\gamma$

$\mu \to eee$

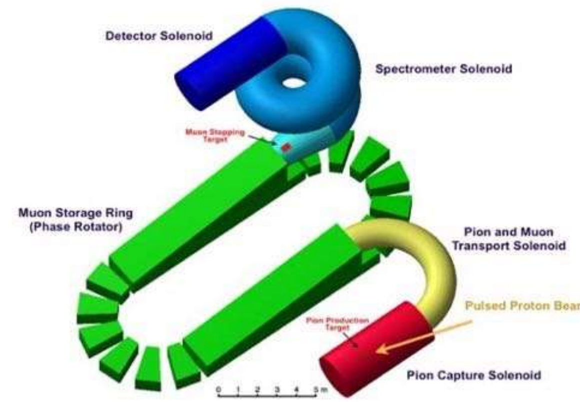
$\mu^- N \to e^- N$



A new idea developed in our studies

A μ campus at Fermilab

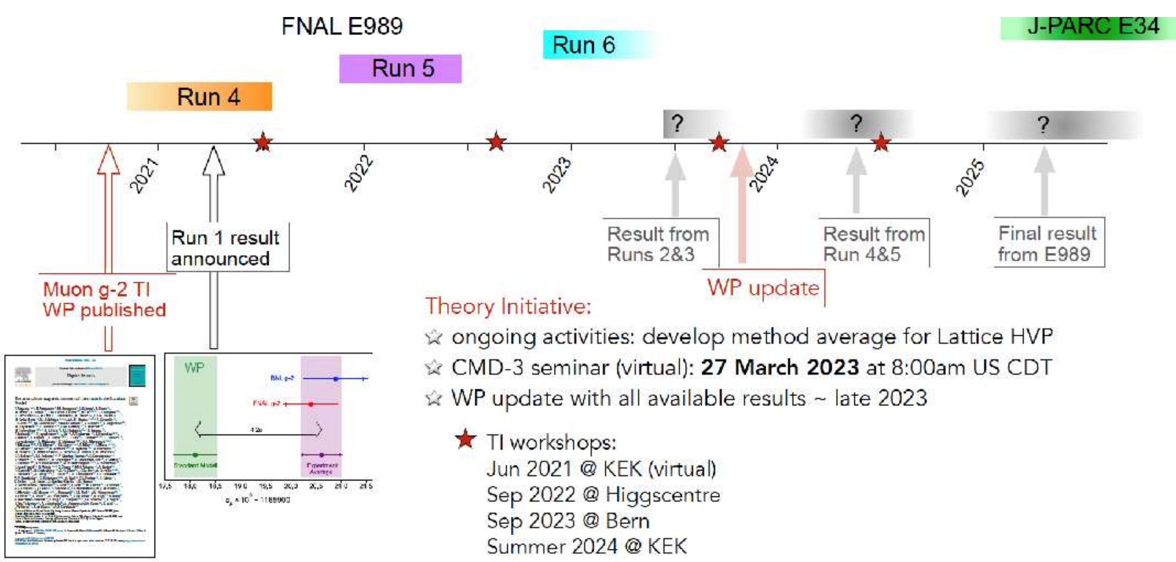
- Rationale for a new facility at Fermilab:
  - It provides order of magnitude increase in sensitivity for all the three muon channels: $\mu \to e\gamma, \mu \to 3e, \mu N \to eN$ and open new possibilities in $\mu N \to eN$ at high Z
  - Synergies with a dark matter program
  - It can host other μ experiments
  - Its technical challenges are synergistic with R&D towards a muon collider



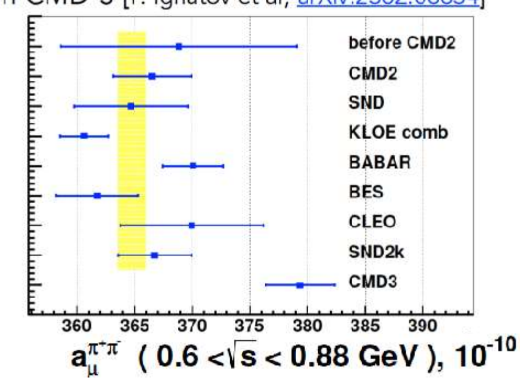
Muon g-2

A remarkable experimental achievement

Aida El-Khadra P5 townhall at FNAL



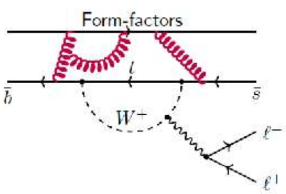
New: from CMD-3 [F. Ignatov et al, arXiv:2302.08834]

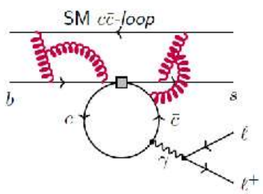


Interlude: the importance of QCD

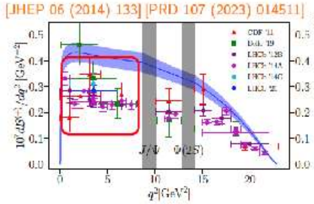
In obtaining an unambiguous interpretation of our new physics searches

- Two examples:
  - Search of new physics in $b \to s\ell\ell$



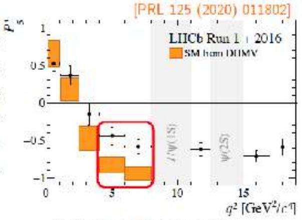


[JHEP 06 (2014) 133] [PRD 107 (2023) 014511]



Branching fractions affected by form-factors and $c\bar{c}$-loop

[PRL 125 (2020) 011802]



Angular observables affected by $c\bar{c}$-loop

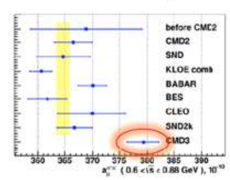
  - $g_\mu - 2$: we need to evaluate hadronic corrections:

[BMW coll. Nature 593 (2021) 7857]

$$a_\mu^{\rm HVP-LO} = 7075(55) \times 10^{-11}$$

Recent $e^+e^- \to \pi\pi$ **VEPP** data also [CMD-3 coll. hep-ex/2302.08834]

$$a_\mu^{\rm HVP-LO}[\pi\pi] = 3793(30) \times 10^{-11} \quad (0.6 < \sqrt{s} < 0.9\,{\rm GeV})$$



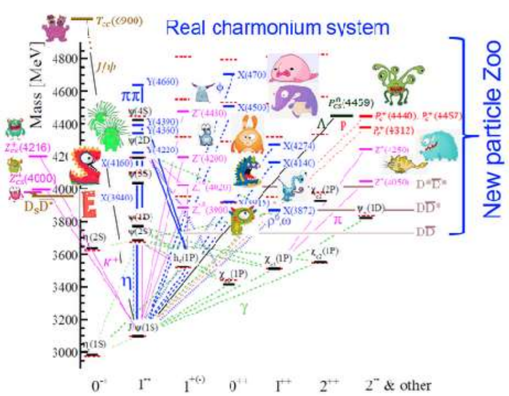
Interlude: the importance of QCD

In understanding the many pattern in which quarks assemble themselves

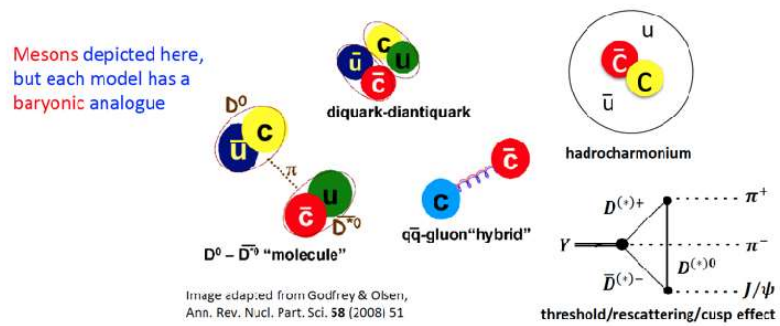
RPF Topical group 7

- Hadronic spectroscopy has given us a very broad landscape of states, both in the "conventional spectroscopy" and "exotic spectroscopy" categories.
- Do we understand all these states on the basis of bound aggregates of quarks and anti-quarks?

T. Skwarnicki @ CSS summer study



R. Lebed @ CSS summer study



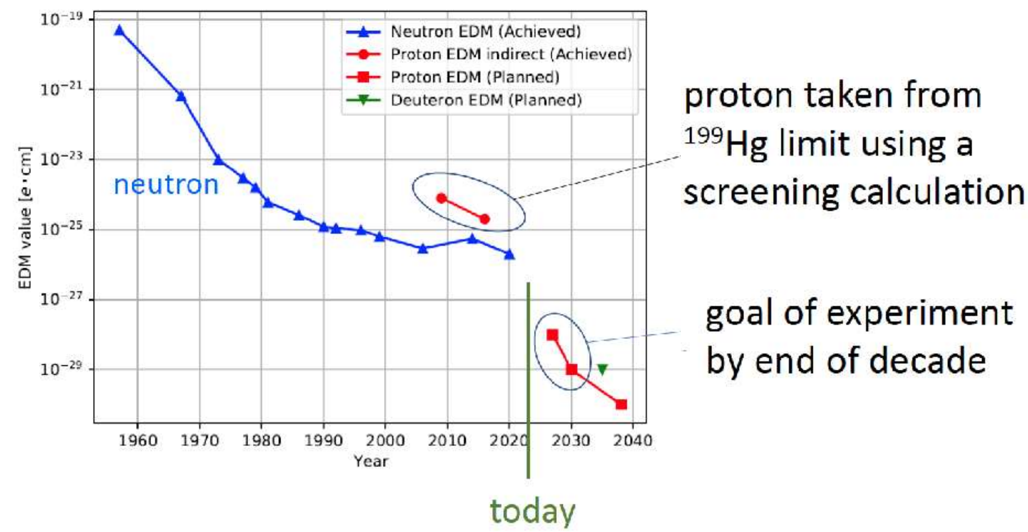
Electrical dipole moments

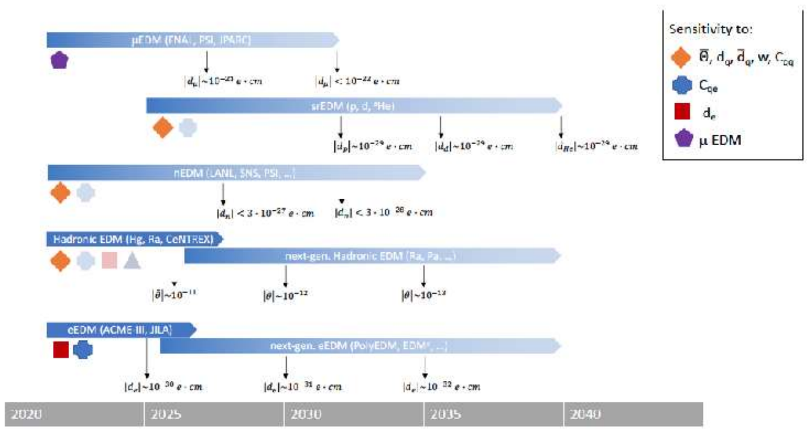
Search for new physics with precision measurements of fundamental quantities

- Priority on measuring electric dipole moment measurements at proton storage ring
- Goal: if seen at the planned level of sensitivity evidence for BSM physics, discriminate BSM theories, strong CP problem, discriminate between different baryogengesis scenarios…

RPF Topical Group 3

E. Stephenson @ FNAL P5 town-hall meeting

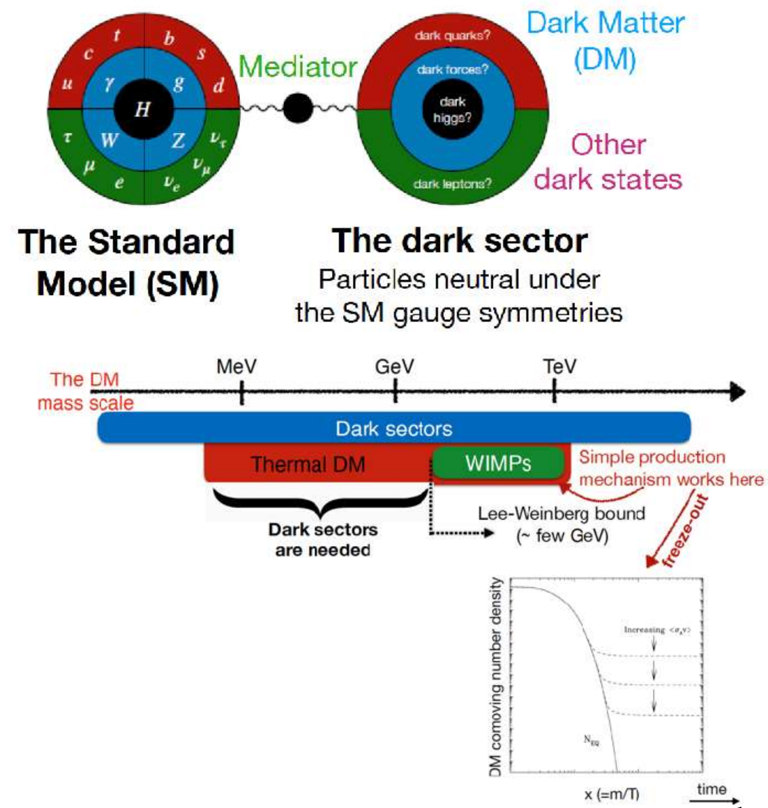




Dark sector

- The existence of dark matter motivates a dark sector neutral under SM forces
- Dark sectors are a compelling possibility for new physics, with potential of explaining the lightness of neutrinos, strong CP problem…
- Dark sectors are generally weakly coupled to SM matter (via portal interaction) and can have masses in the MeV to GeV range

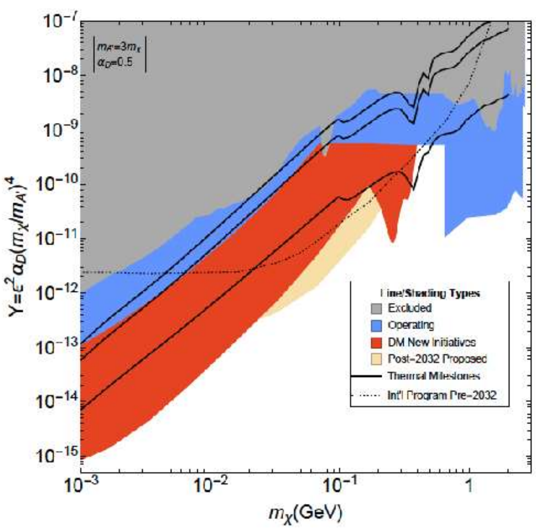
S. Gori at CSS Seattle



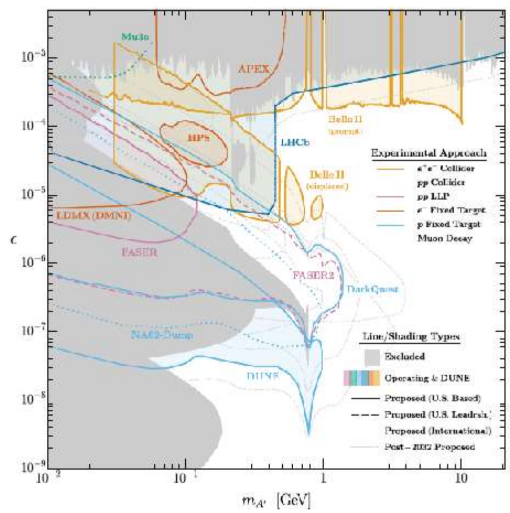
1

Three big ideas

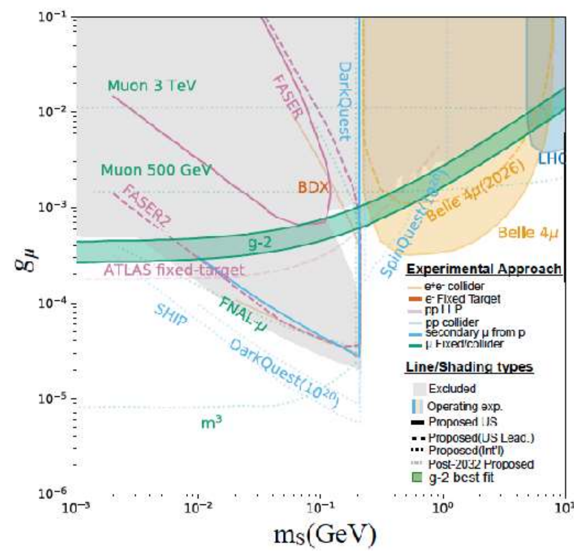
Production of dark matter particles



Exploring dark sector particles:
As an example dark photon parameter space



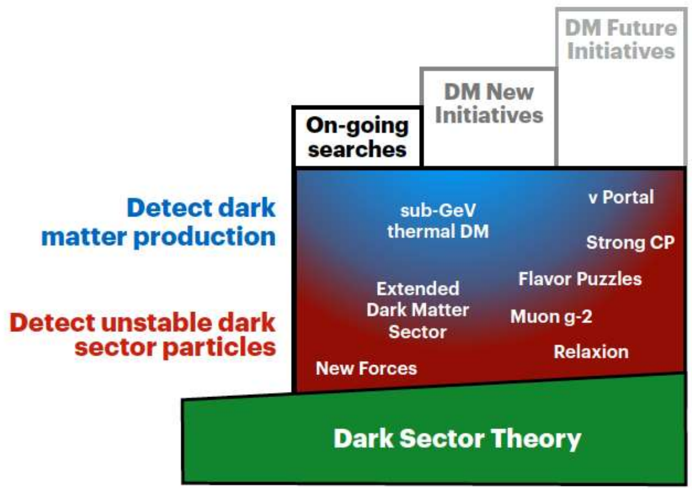
Dark sector might have complex flavor structure: as an example implications for g-2



A path to a vibrant discovery program

* Invest in fully funding projects supported by "DM New Initiative", LDMX and CCM

* Exploit the capabilities of existing multi-purpose detectors, especially Belle-II and LHCb.

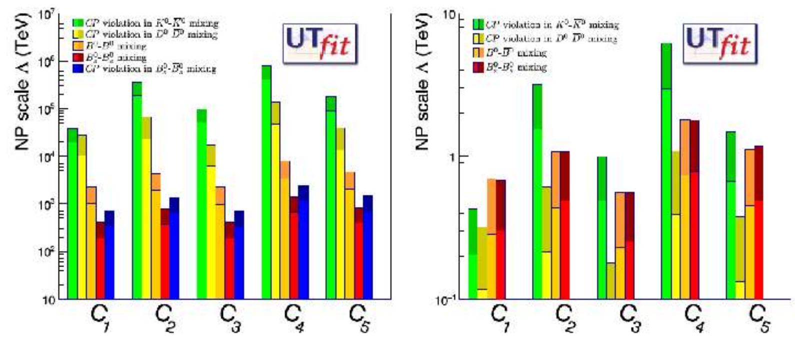


* Expand DMNI with focus on signals of visible decays of dark sector particles – proposals include proton and lepton beam-dump experiments, long-lived-particle detectors

* Support theory efforts to explore dark sector models and collaborate in dark-sector experiments – this has been at the foundation of essentially all ongoing and planned experimental activities in this growing field.

The role of the theory

- Effective field theory provides a framework to evaluate the physics implications of tensions with SM in experimental measurements, in particular, the energy scale at which the NP degrees of freedom can propagate on-shell.
- Phenomenological models of new physics explore the implications of heavy new physics for low/ medium energy phenomena
- Lattice QCD provides a computational approach to the hadronic matrix elements needed in extracting fundamental quantities from experimental data

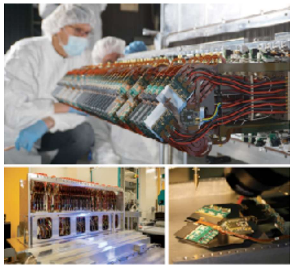


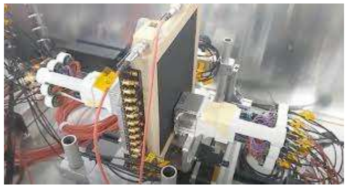
Developing the instruments of the future

While training a new generation of STEM scientists

Experimental approach	Technology	Property	Requirement
Quark flavor experiments	Solid State Tracking Detectors	Time stamp Radiation hardness	10–30ps/hit in the silicon pixel vertex detector fluences up to $5 \times 10^{16} n_{eq}/cm^2$
	Calorimetry	Time stamp resolution	10-30 ps/shower
	Trigger & DAQ	Real time processing Optical links	400-500 TB/sec Radiation-hard, fast, low-power and low-mass
LFV experiments (μ)	Staw Tube Tracker Calorimetry	timing Energy resolution timing	20 ps/track, low-mass, excellent momentum resolution $< 10\%/\sqrt{E}$, low cost Shower time stamp < 500 ps, dose > 900 KRad
EDMs	Controlled preparation of many coherent particles Laser locking, tuning and linewidth narrowing (many narrow-band lasers on target)	coherence times tunable narrow band	$\tau \geq 1s$ or $N >> 10^{12}$ < 1 MHz, $\lambda = 2002$ 400nm
Dark Sector (missing energy technique)	E&M calorimetry	Energy resolution	
Dark Sector (Beam Dump experiments)	photosensors	fast-timing photosensors	

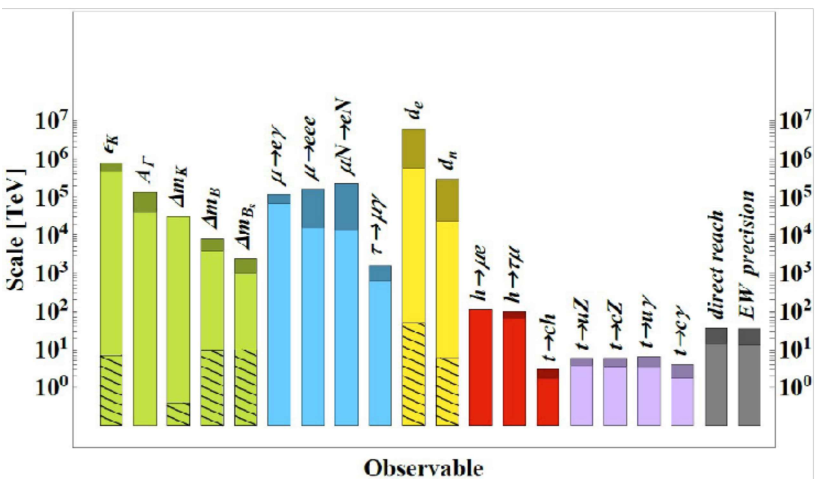
- Synergies in picosecond timing devices, novel ASIC technology, large data processing and innovative trigger algorithms, advances in calorimetry…





Conclusions

A rich physics program with abundant discovery potential



- We have laid out an ambitious program to probe the Standard Model with unprecedented precision and well-motivated paths toward new physics.
- Precision is the keyword for the next chapter of particle physics
- Any discovery will allow to refocus future priorities, both in experiments aiming at precision measurement and at HEP colliders
- Theory input, especially a broad program of hadronic matrix element calculations with lattice QCD, is necessary to succeed


Rare processes and precision measurements: a crossroad in our future journey
Accelerator frontier: new muon campus, polarized beams at KEK-b
Instrumentation frontier: ps timing, DAQ, software trigger, massless trackers
Computational frontier: Massive data storage/processing, real time triggers/ distributed intelligence, ML
Connections with other communities: nuclear physics [e.g neutrinoless ββ Decay, AMO (EDM, fundamental symmetries..)
Community engagement frontier: Leadership opportunities for young scientist, attention to training in an inclusive and nurturing environment, connections with industrial partners
Neutrino frontier: Leptogenesis/baryogenesis PMNS versus CKM Majorana or Dirac?
Theory frontier: interpretation and inspiration
Energy frontier: direct searches for new physics
Cosmic frontier: baryogenesis, the nature of dark matter

The end