Rare Processes and Precision Measurements Frontier

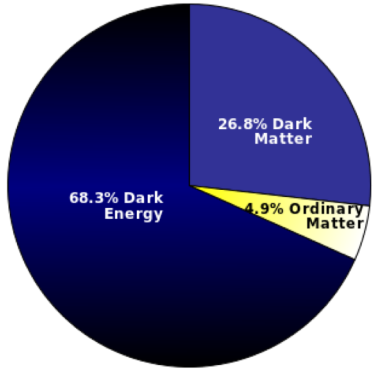
Conveners: Marina Artuso, Syracuse University
Robert Bernstein, FNAL & Alexey Petrov, WSU

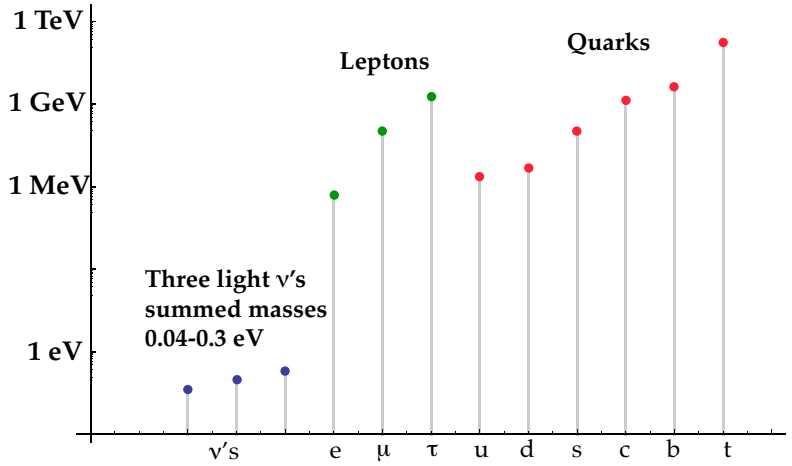
Disclaimer: summary is illustrative and not comprehensive – apologies for the many interesting topics omitted

For more information

https://snowmass21.org/rare/start ← Including calendar of events

The big ideas



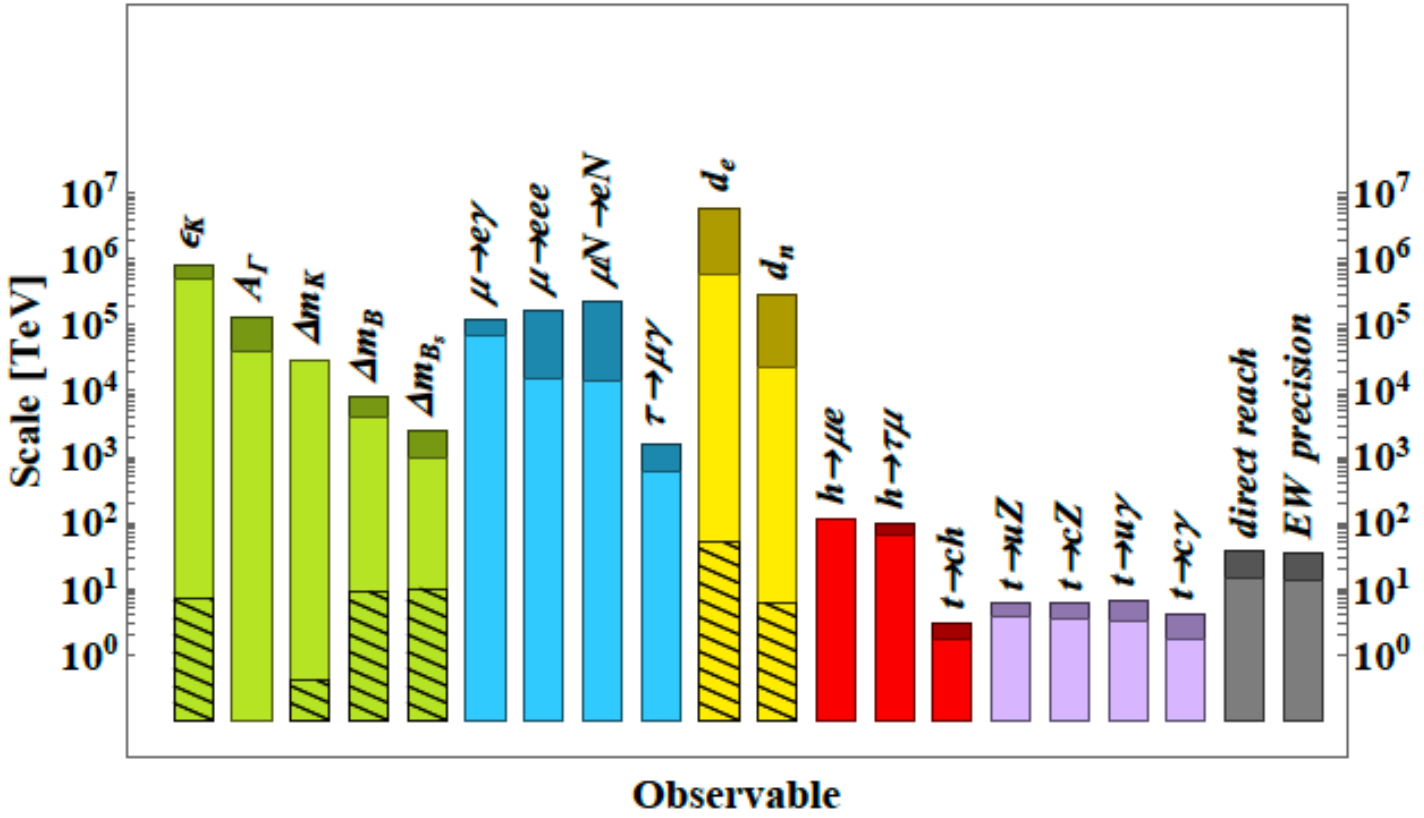


The Standard Model of Particle Physics is very successful, but we still have some important questions:

- What is the nature of what makes up most of the universe? [what are dark matter/dark energy made of?]
- Hierarchy problem I: why is the Higgs mass stable at 125 GeV and $m_{Plank} \sim 10^{19}$ GeV
- Many mass hierarchies [from m_e to m_t]
- Stability of the universe [baryon asymmetry]
- Mass scale of the new physics [what is the mass gap between EW scale and the new physics scale]. (how much bigger than ~1 TeV?]

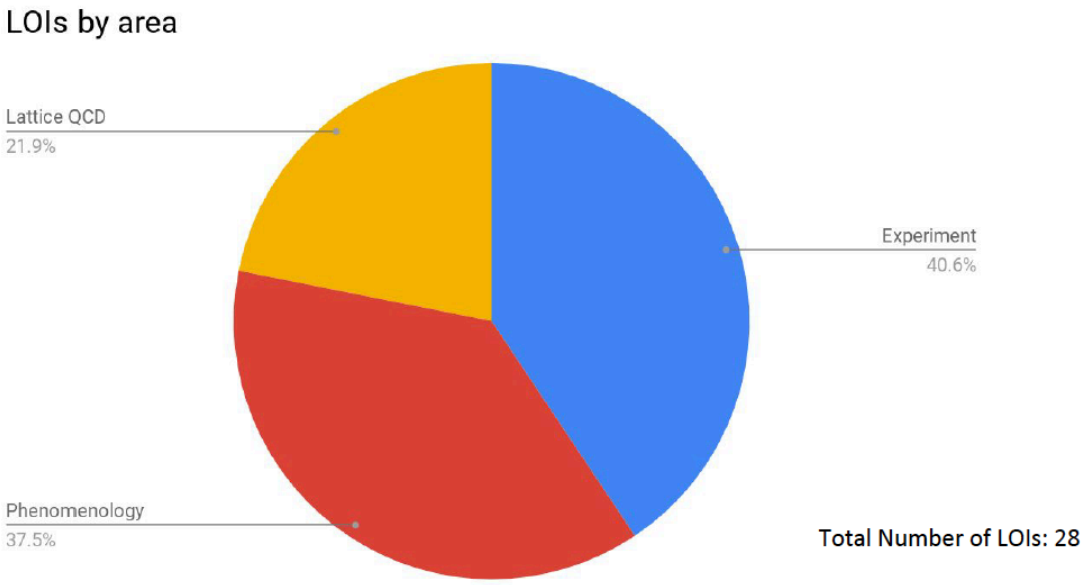
The approach

- Use indirect evidence for new physics manifesting itself in suppressed decays, probe high mass scale not reachable with direct production at colliders.



TG-1 Weak decays of heavy quarks

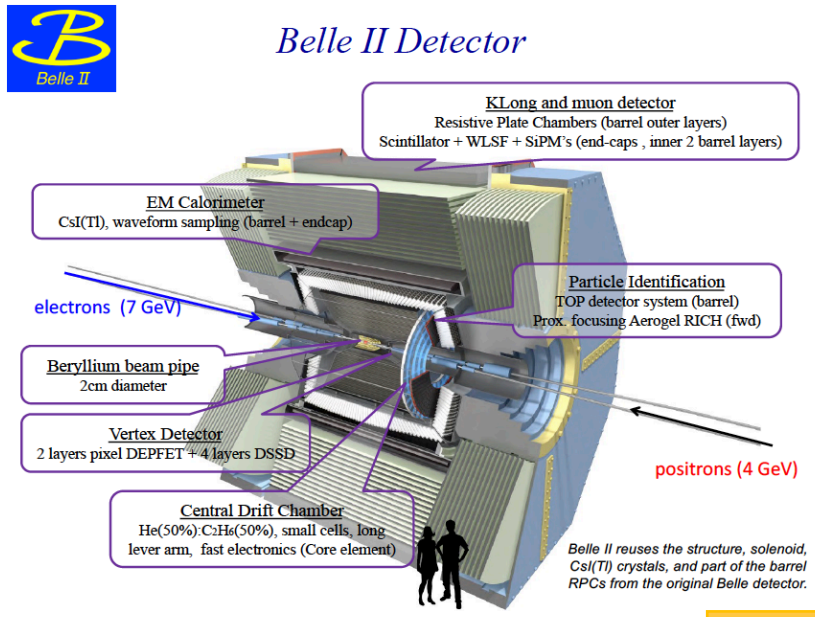
- Conveners A. di Canto and S. Meinel
- More information at https://snowmass21.org/rare/weakbc

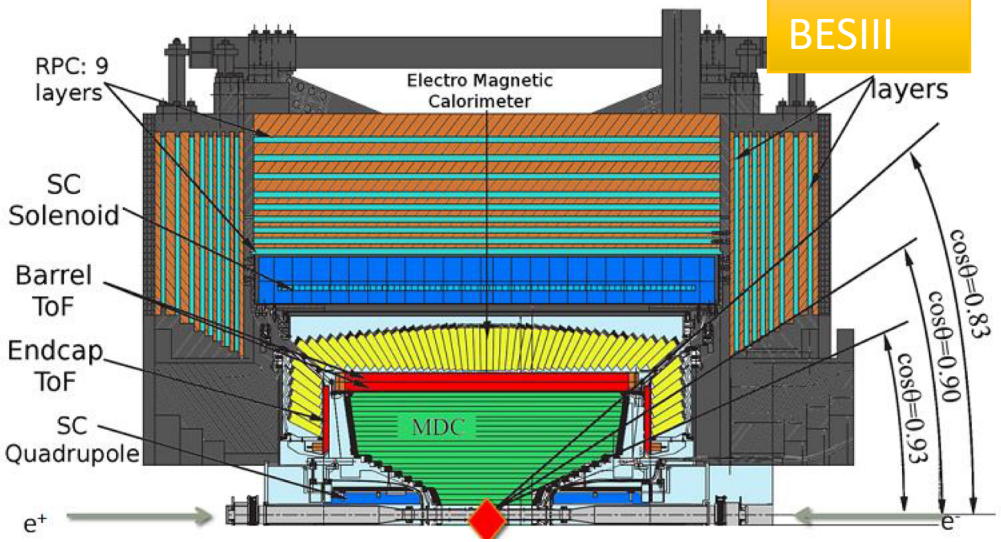


Important themes:

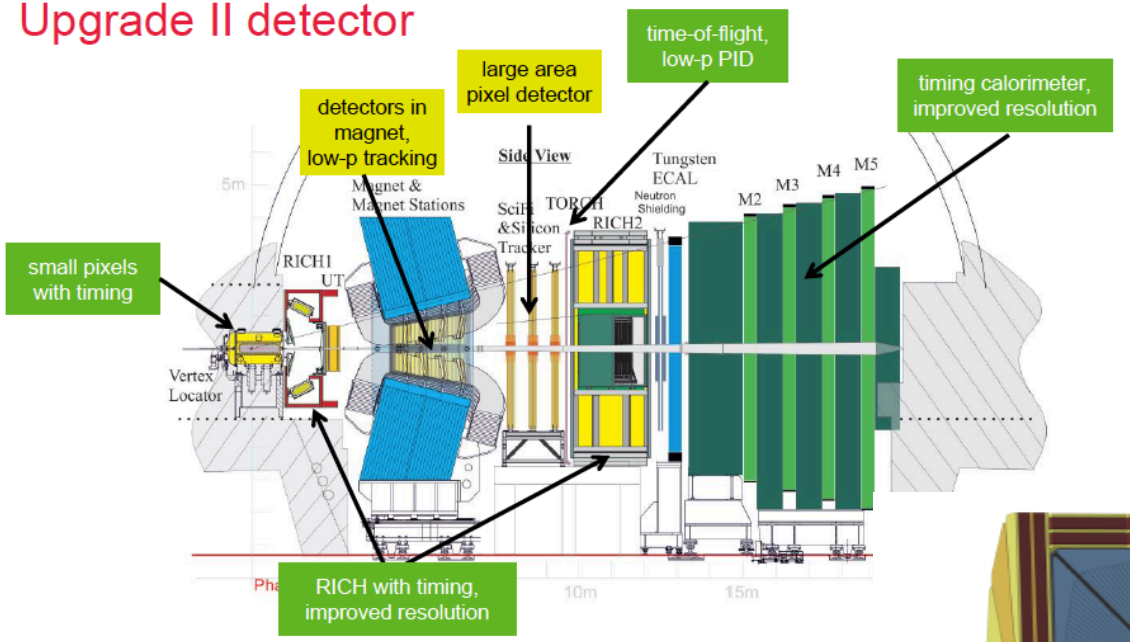
- Research in heavy flavor physics is an essential component of particle physics
- Anomalies, semileptonic b decays and charm physics among the most discussed topics
- Lattice LOIs: importance of precise form factors for semileptonic decays, new methods for inclusive decays on the lattice

Experiments for heavy-quark studies



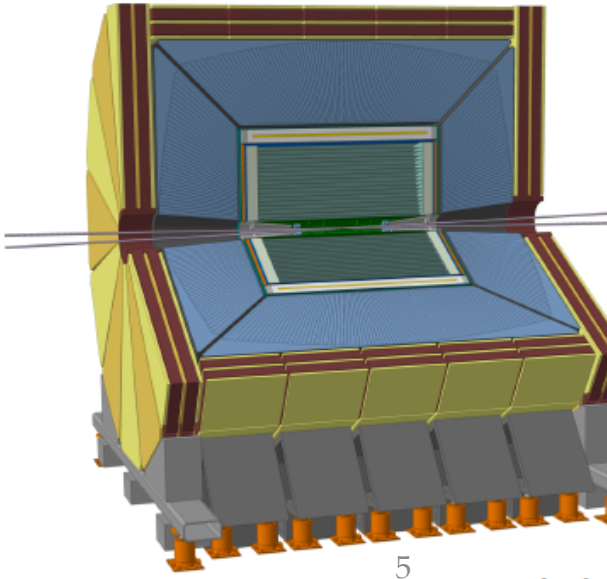


LHCb NOW ⇒
Upgrade II detector



Also ATLAS/CMS NOW ⇒HL-LHC

FCC-EE

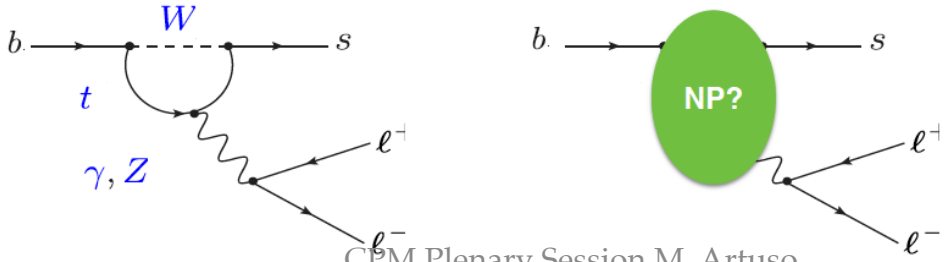


Two phenomenological approaches:

- Cabibbo-Kobayashi-Maskawa matrix contains many (complex) couplings **not predicted by SM**, several constraints relate them⇒many precision measurements allow multifaceted challenge to the SM

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

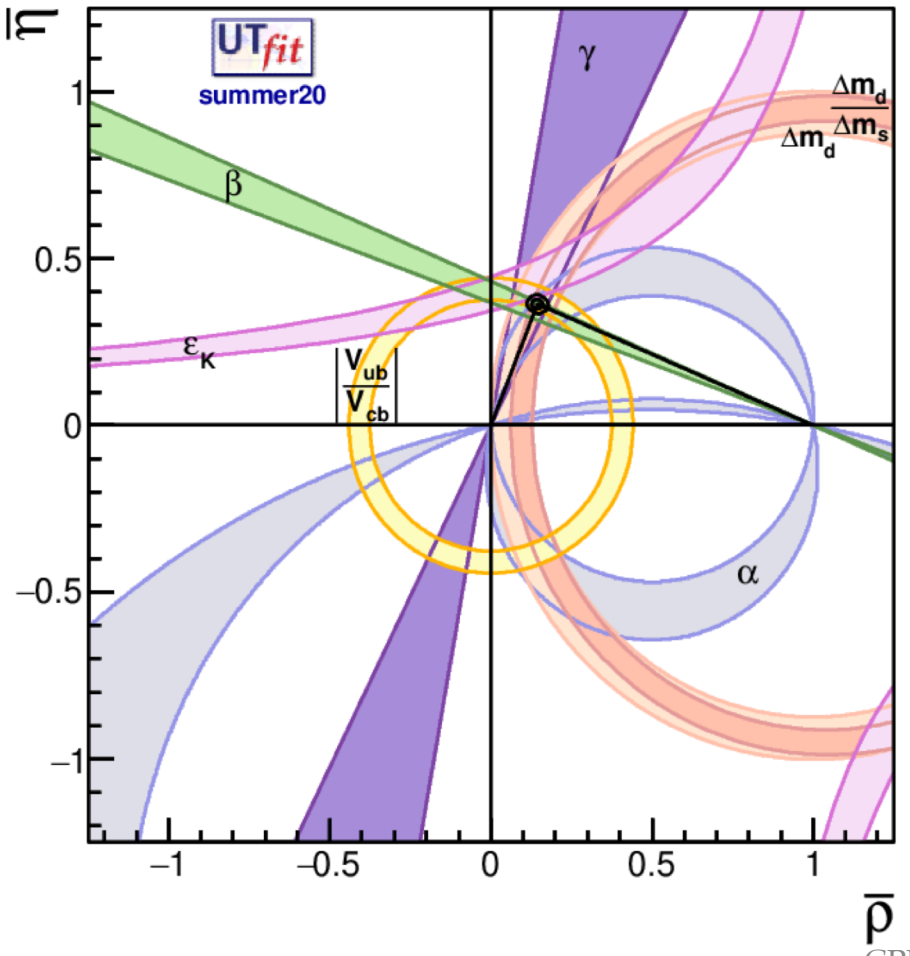
- Anomalies in suppressed decays as indirect probe for new physics

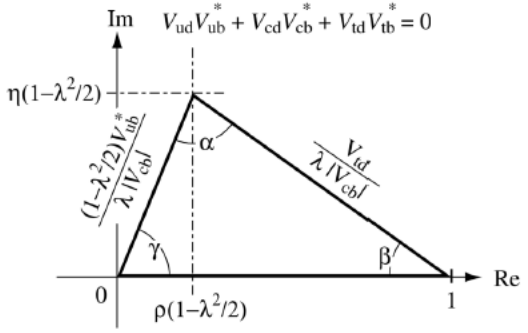


CKM triangles

currently:

γ best measurement by LHCb





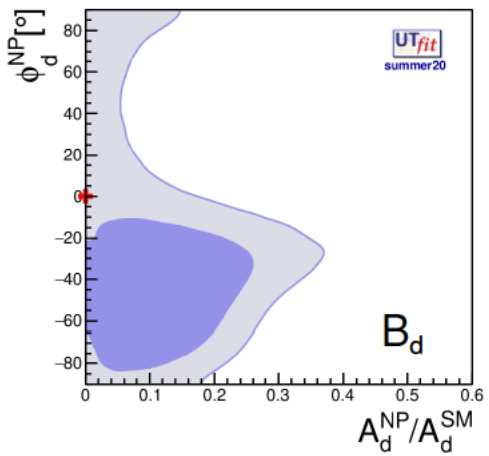
Example: New physics in mixing, evolution of constraints:

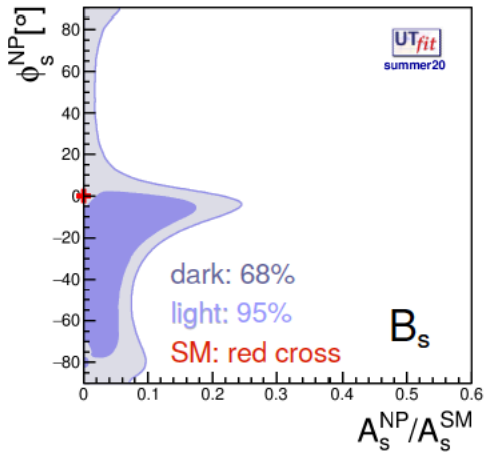
Marcella Bona, ICHEP2020

UTfit update

NP parameter results

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$





The ratio of NP/SM amplitudes is:

< 26% @68% prob. (37% @95%) in B_d mixing

< 18% @68% prob. (25% @95%) in B_s mixing

The role of the lattice

V_{cb} and V_{ub}

from FLAG

$|V_{cb}|$ *(excl)* = (39.44 ± 0.59) 10^{-3}

$|V_{cb}|$ *(incl)* = (42.19 ± 0.78) 10^{-3}

~2.8σ discrepancy

from HFLAV

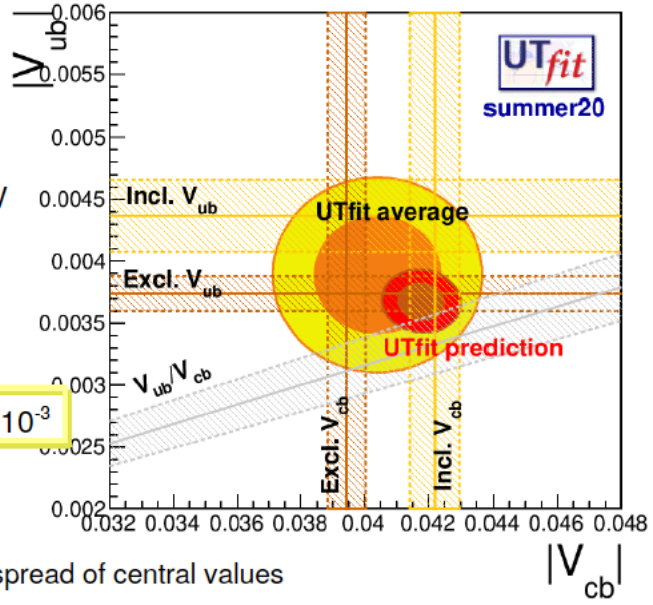
from FLAG

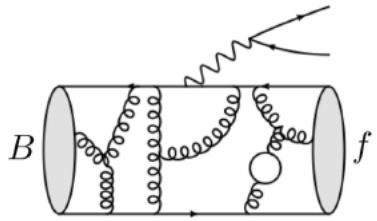
$|V_{ub}|$ *(excl)* = (3.74 ± 0.14) 10^{-3}

$|V_{ub}|$ *(incl)* = (4.37 ± 0.25 ± 0.26 *[flat]*) 10^{-3}

~1.9σ discrepancy

from HFLAV adding a flat uncertainty covering the spread of central values



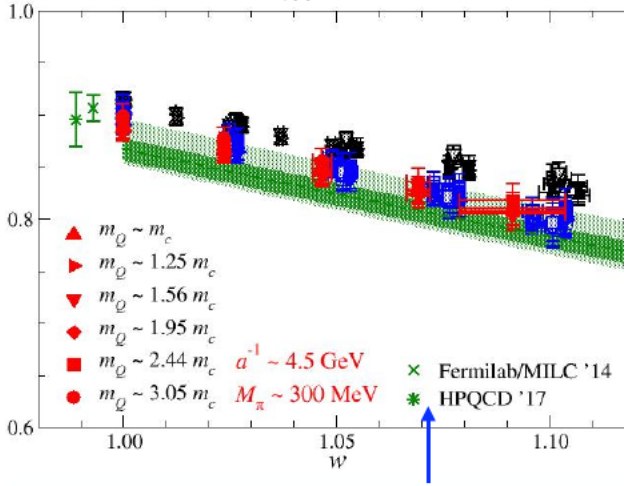


→ Non-perturbative QCD, i.e. difficult to compute

(Lattice QCD, QCD factorisation, Light-cone sum rules...)

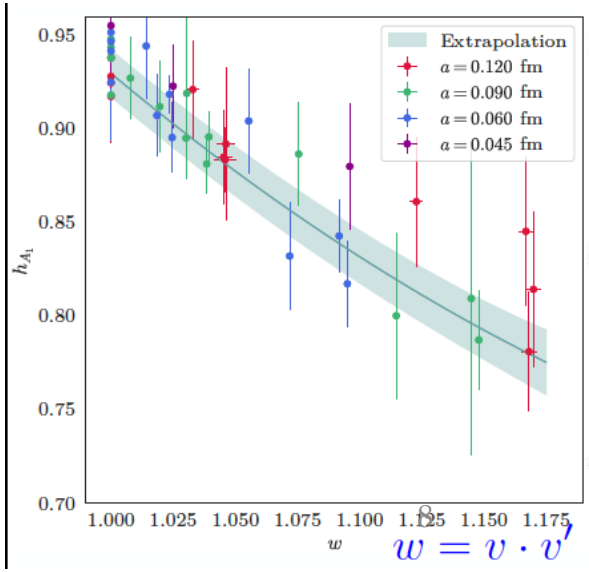
See JLQCD 1912.11770 + Taneko (APLAT20)

h_{A1} vs w



est. errors : 1-2% stat, 1-3% syst.

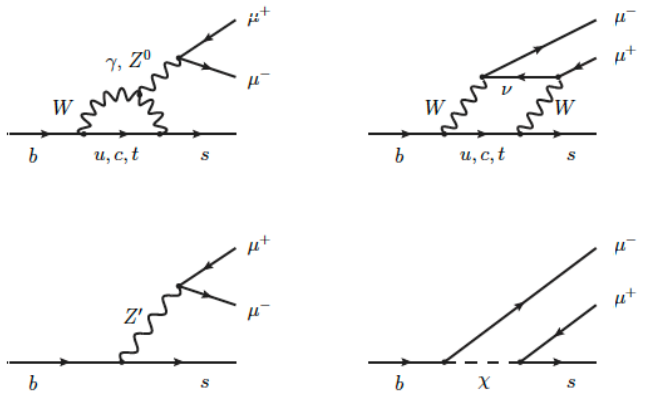
See FNAL/MILC 1912.05886



$w = v \cdot v'$

Indirect evidence for new physics in $b \to s\ell^+\ell^-$

$C_i(\mu)$ different from SM & structure of new physics

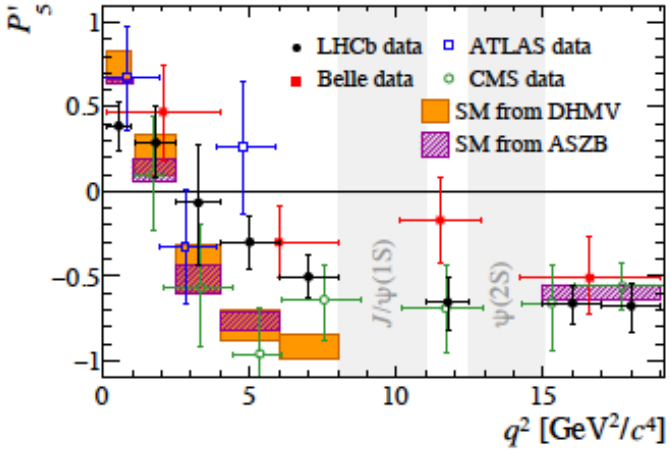


$$\mathcal{H}_{\text{eff}} \sim \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

$C_i(\mu)$ → Wilson coefficients (perturbative, short-distance physics, sensitive to E > μ)

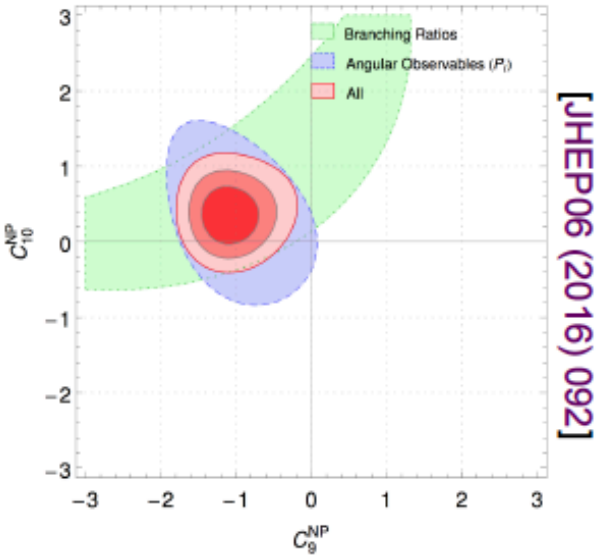
O_i → Local operators (non-perturbative, long-distance physics, sensitive to E < μ)

Differential distributions



[PLB 781 (2018) 517]
[JHEP 10 (2018) 047]
[PRL 118 (2017) 111801]
[JHEP 02 (2016) 104]

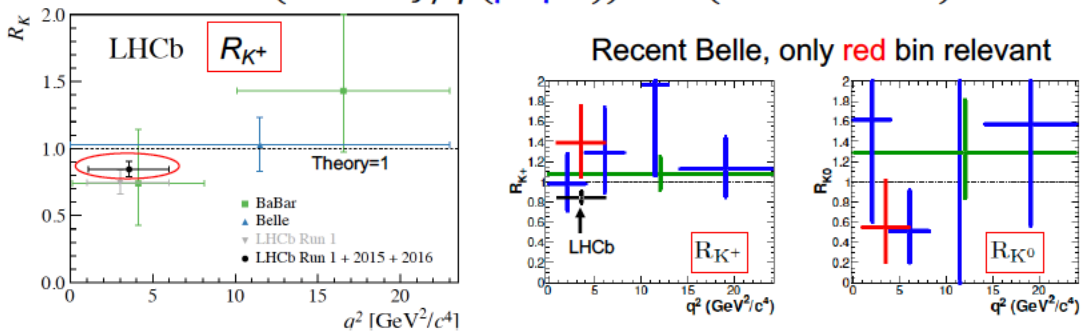
EFT analysis



[JHEP06 (2016) 092]

LVU violation and BSM interpretation

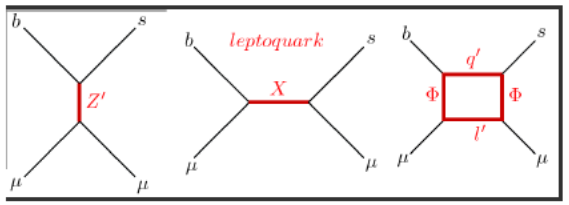
$$R_{K(*)} = \frac{B(B\to K^{(*)}\mu^+\mu^-)}{B(B\to K^{(*)}J/\psi(\mu^+\mu^-))} \frac{B(B\to K^{(*)}J/\psi(e^+e^-))}{B(B\to K^{(*)}e^+e^-)}$$



Recent Belle, only red bin relevant

- LHCb: $R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$ 2.5σ
- Not confirmed by Belle but large errors

Example of BSM interpretation



Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

Lot of those models predict also LFV b→seμ, b→seτ,...

G.Isidori, FPCP 2020: correlations among b→s(d)ll' within the U(2)-based EFT

	μμ (ee)	ττ	νν	τμ	μe
b → s	R_K, R_{K^*} O(20%)	$B \to K^{(*)}\tau\tau$ → 100×SM	$B \to K^{(*)}\nu\nu$ O(1)	$B \to K\tau\mu$ → 10^{-6}	$B \to K\mu e$???
b → d	$B_d \to \mu\mu$, $B \to \pi\mu\mu$, $B_s \to K^{(*)}\mu\mu$ O(20%) [R_K=R_π]	$B \to \pi\tau\tau$ → 100×SM	$B \to \pi\nu\nu$ O(1)	$B \to \pi\tau\mu$ → 10^{-7}	$B \to \pi\mu e$???

Validation: new predictions confirmed by observation

TG2:

- TG conveners E. Passemar and E.
- More information at:
  - https://snowmass21.org/rare/weaksud

This topical group will address the following topics:
1. Rare kaon decays: $K^+ \to \pi^+ \upsilon\upsilon$, $K_L \to \pi^0 \upsilon\upsilon$, $K_L \to \pi^0 l^+ l^-$.
2. CP-violation in kaon sector (ε'/ε, etc.)
3. Lepton universality in kaon and pion decays
4. Rare η and η' decays
5. First-row CKM unitarity tests
6. Related theory, including lattice QCD

24 LOIs covering all the topics of interes

The message from rare K decays

Example of top down BSM approach

NP in Z'

Buras/Buttazzo/Knegjens: 1507.08672

From Jason Aebischer

$K^+ \to \pi^+ \bar{\nu}\nu$ and $K_L \to \pi^0 \bar{\nu}\nu$: correlation

Grossman-Nir Bound Grossman/Nir: hep-ph/9701313

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \leq 4.3\, \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$

New KOTO measurement

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\text{KOTO}} = 2.1^{+2.0(+4.1)}_{-1.1(-1.7)} \times 10^{-9}$ Shinohara: KAON2019

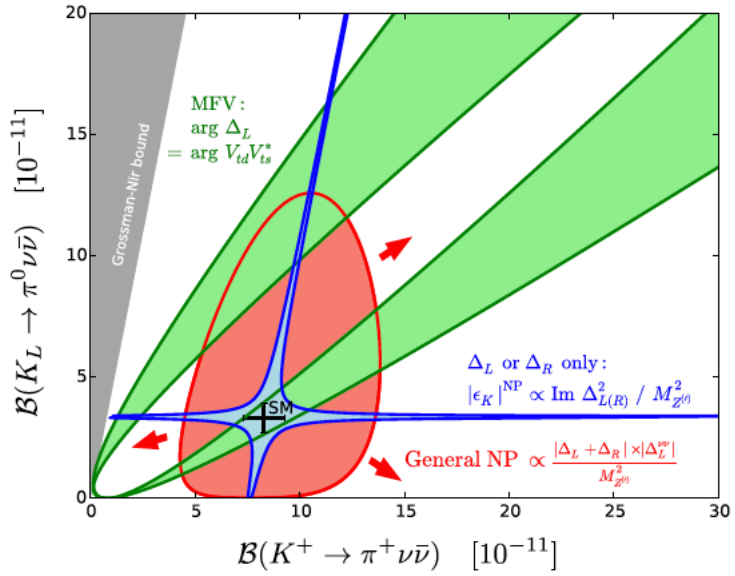
↪violation of GN bound

Explanations

Heavy/light NP Kitahara/Okui/Perez/Soreq/Tobioka:1909.11111

$\Delta I = 3/2$ He/Ma/Tandean/Valencia:2002.05467,2005.02942

Z' and $L_\mu - L_\tau$ Fuyuto/Hou/Kohda:1412.4397

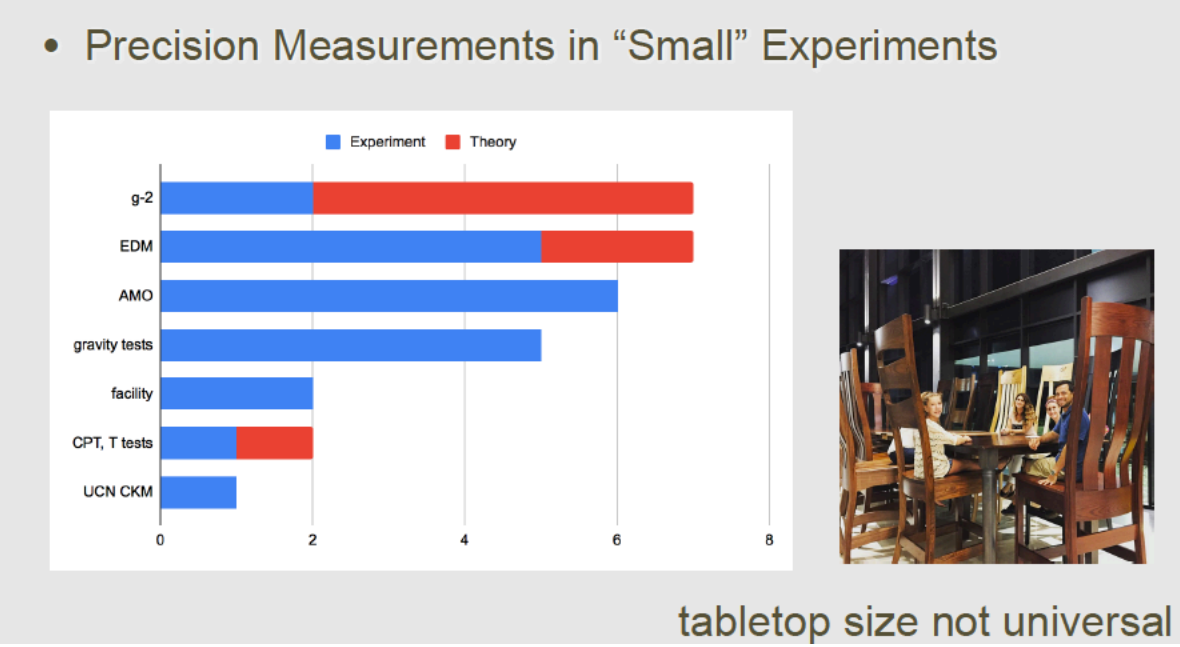


Also possible backgrounds- charged K being evaluated

Koji Shiomi @beauty2020

TG3: Precision measurements in "small" experiments

- Conveners: T. Blum and P. Winter
- more information at
  - https://snowmass21.org/rare/fund



g-2
Muon (low-energy/ storage rings)
EDM
CPT tests
Connection with Atomic Molecular and Optical (AMO) physics

Example: multiple approaches to electric dipole moments

More details at https://indico.fnal.gov/event/44782/

- Multiple facilities, methods, and even sub-fields!

Great Future Expectations

- $d_n \rightarrow 10^{-27}$-10^{-28} e-cm Neutron Spallation/Reactor Sources
- $d_e \rightarrow 10^{-30}$ e-cm or better! (Molecules) ACME
- d_p & $d_D \rightarrow 10^{-29}$e-cm Storage Ring Proposal (BNL/COSY)

Pave the way for a new generation of storage ring experiments d_e, d_p, d_D, d(^{3}He), d(radioactive nuclei), d_μ

Several orders of magnitude improvement expected

All Very Well Motivated – Must Do Exps.

13

Marciano MDM/EDM Workshop

TG4- Baryon number and lepton number violating processes

Conveners: P. Fileviez Perez, A.Pocar
More information at: https://snowmass21.org/rare/blv

❑Topics addressed

- Theories for baryon and lepton number violation: P. Fileviez Perez (CWRU), M.B. Wise (Caltech)
- Neutrinoless double beta decays: V. Cirigliano (LANL), A. Pocar (UMass)
- Baryon and Lepton number violation at colliders: R. Ruiz (Lovain Univ.), E. Thomson (UPenn)
- Proton decay: E. Kearns (Boston Univ.), S. Raby (Ohio State Univ.)
- n-nbar oscillations: K. Babu (OSU), L. Broussard (ORNL)
- More exotic L and B violating processes: S. Gardner(Univ. of Kentucky), J. Heeck (UC-Irvine)
- Connections to Cosmology: A. Long (Rice Univ.), C. Wagner (Univ. of Chicago/ANL)

Lepton number violation – Synergy with NF

Lepton Number Violation: Neutrinoless double beta decay experiment

- An experimental program for tonne-scale on DBD experiments is under way, with with half-life sensitivity ~10^28 years, under the stewardship of DoE-NP in the US
- Extending the experimental reach of OnDBD is well motivated by theory and has strong complementarity with the HEP program at accelerators searching for LNV processes
- Experimental avenues to go 'beyond the tonne scale' are emerging from the community, with 6 LOI' received on On DBD experimental topics (1 on bolometers, 5 with ideas for Xe-136). Many more On DBD LOI's received by NF05. RF04 and NF05 are jointly moving ahead with a shared approach for On DBD. Joint workshops for 'beyond the tonne scale On DBD' planned in Dec. + Spring and white papers expected for:
  - CUPID-1T: distributed array of detectors, with synergies with low-mass DM, and quantum sensor development.
  - Several ambitious Xe-based detectors, which include R&D on HPGXe TPCs, the implementation o Ba daughter tagging (by NEXT and nEXO collaborators), and very large experiments (50 t with DarkNoon and ~1kton with GXe ar LXe TPCs with procurement of isotope, development of low-ra and fast electronics / scintillation detectors as key activities for the next decade)
- Snowmass can: identify the community for the future, synergies with neutrino, dark matter, QIS programs (including underground facilities), and

Andrea Pocar (UMass Amherst) and Pavel Filieviez Perez (CWRU)

Baryon number violation

Baryon Number violation: proton decay and n-nbar oscillations

- Proton decay is currently heavily constrained by SuperK, but its search is well motivated
- The search of proton decay mostly benefits from increased detector size. HyperK will naturally take over from SuperK
- Two LOI's received, from SuperK and HyperK: both experiments have a rich neutrino program (solar, accelerator, supernova). DUNE and JUNO presented at the BLV workshop in July, but did not submit proton-decay LOI's.

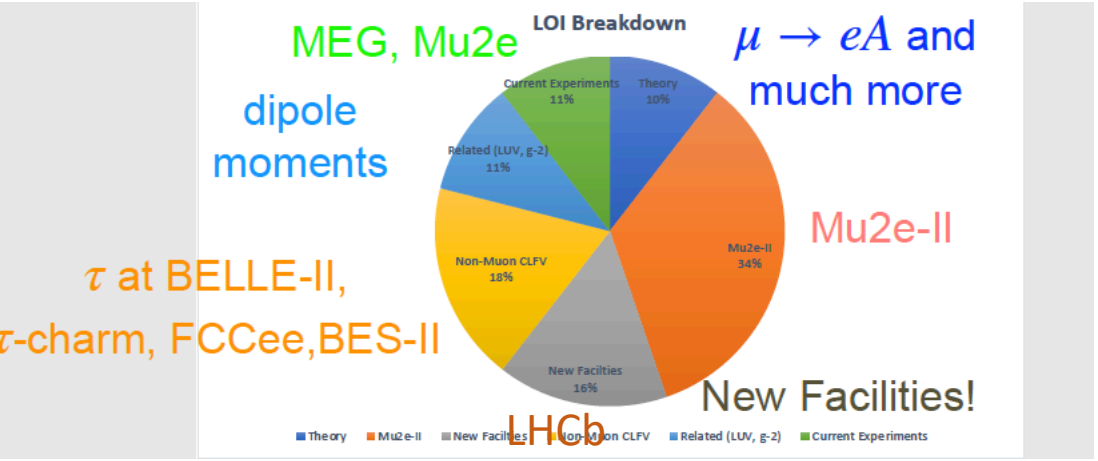
- DeltaB = 2 searches are well motivated, and experimentally searched in n—nbar oscillations
- Four LOIs received (three invited, one very technically specific), all stemming from a topical workshop in the Summer and thus well-coordinated.
- The long-term program looks at the European Spallation source with HIBEAM/NNBAR sequence, with important development work at ORNL.
- On the shorter time scale, DUNE can reach interesting sensitivity.
- Contributed papers are expected for all phases of the program, as outlined in the LOIs

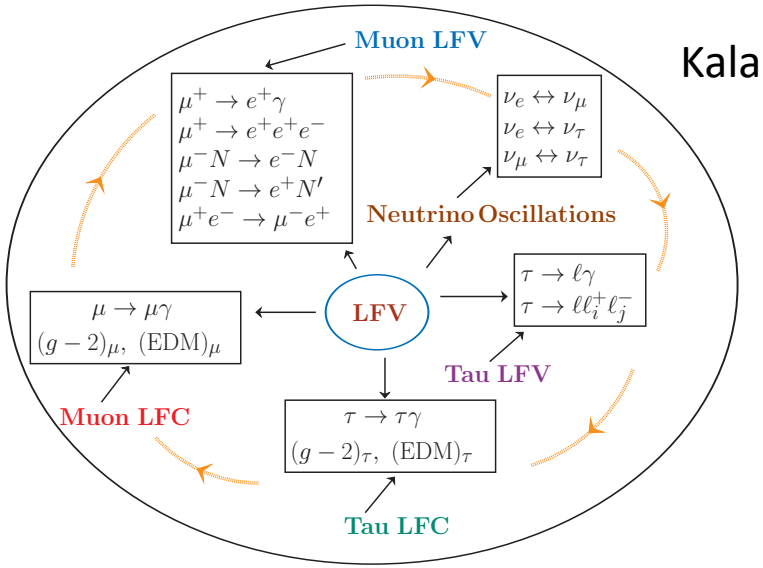
Baryon number violating processes in heavy baryons being explored by LHCb

TG5- Charged lepton flavor violation

Topical conveners: B. Echenard & S. Davidson

More information at
https://snowmass21.org/rare/clfv





Kaladi Babu

1.Muon and tau LFV reactions (mu→e gamma, mu→3e, mu-e conversion, tau decays)
2.Muonium-antimuonium oscillations and LFV leptonium decays
3.Meson and baryon LFV decays (K→ pi e mu, B → K tau ell, …)
4.Decays of heavy states (h,t,Z,Z'…) and other LFV processes at colliders
5.Light to heavy lepton LFV transitions (EIC, muon beam,…)

Flavor violation in μ decays

90 operators!

Davidson arxiv:2010.00317

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{\zeta}\sum_{Lor} \frac{C^{\zeta}_{Lor}}{v^2}\mathcal{O}^{\zeta}_{Lor} + h.c.$$

EFT analysis of LFV $\mu \to e$ Processes

2 lepton

$$\mathcal{O}_{D,L} = m_\mu \overline{e_R}\sigma^{\alpha\beta}\mu_L F_{\alpha\beta} \qquad m_\mu \overline{e_L}\sigma^{\alpha\beta}\mu_R F_{\alpha\beta}$$

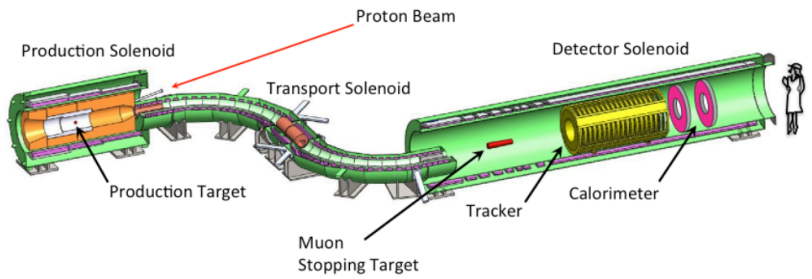
$$\mathcal{O}_{GG,Y} = \tfrac{1}{v}(\bar{e}P_Y\mu)G_{\alpha\beta}G^{\alpha\beta} \quad , \quad \mathcal{O}_{G\tilde{G},Y} = \frac{1}{v}(\bar{e}P_Y\mu)G_{\alpha\beta}\widetilde{G}^{\alpha\beta}$$

$$\mathcal{O}_{GGV,Y} = \tfrac{1}{v^2}(\bar{e}\gamma^\sigma P_Y\mu)G_{\alpha\beta}\partial_\beta G^{\alpha\sigma}, \quad \mathcal{O}_{G\tilde{G}V,Y} = \frac{1}{v^2}(\bar{e}\gamma^\sigma P_Y\mu)G_{\alpha\beta}\partial_\beta \widetilde{G}^{\alpha\sigma}$$

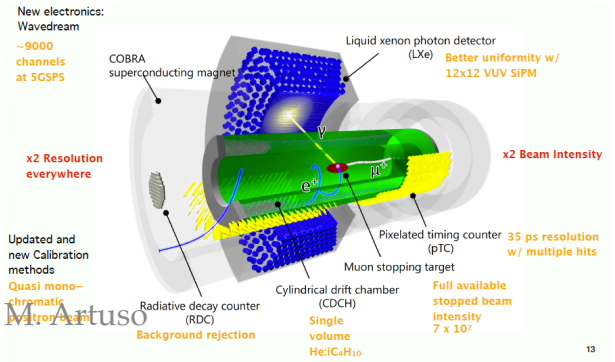
$$\mathcal{O}_{FF,Y} = \tfrac{1}{v}(\bar{e}P_Y\mu)F_{\alpha\beta}F^{\alpha\beta} \quad , \quad \mathcal{O}_{F\tilde{F},Y} = \frac{1}{v}(\bar{e}P_Y\mu)F_{\alpha\beta}\widetilde{F}^{\alpha\beta}$$

$$\mathcal{O}_{FFV,Y} = \tfrac{1}{v}(\bar{e}\gamma^\sigma P_Y\mu)F^{\alpha\beta}\partial_\beta F_{\alpha\sigma}, \quad \mathcal{O}_{F\tilde{F}V,Y} = \frac{1}{v}(\bar{e}\gamma^\sigma P_Y\mu)F^{\alpha\beta}\partial_\beta \widetilde{F}_{\alpha\sigma}$$

Mu2e/mu2eII, Bernstein



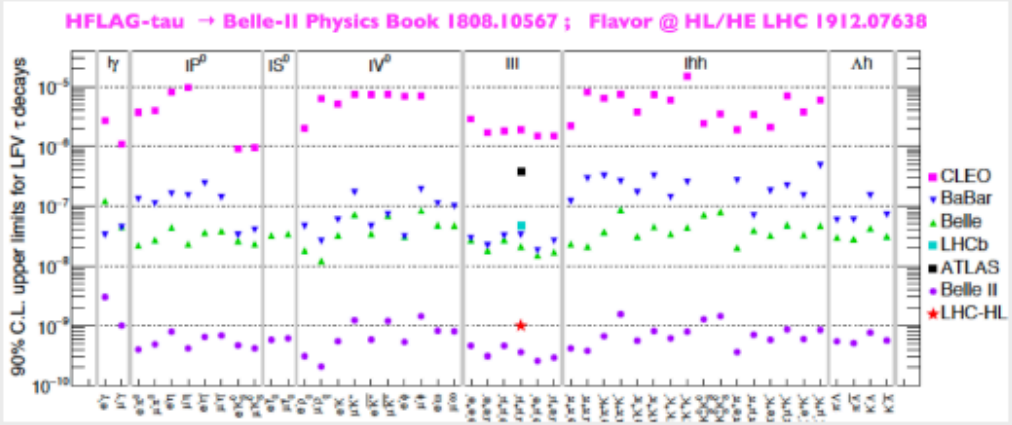
MegII- A. Baldini et al. arXiv:1301.7225v2



CLFV in τ decays

- Very broad portfolio, 1-2 order of magnitudes expected
- τ effects can be quite large and these are compelling measurements

x100



	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$	•••
$O^{4\ell}_{S,V}$	✓	–	–	–	–	–	
O_D	✓	✓	✓	✓	–	–	
O^q_V	–	–	✓	✓	–	–	
O^q_S	–	–	✓	✓	–	–	
O_{GG}	–	–	✓	✓	–	–	
O^q_A	–	–	–	–	✓	✓	
O^q_P	–	–	–	–	✓	✓	
$O_{G\tilde{G}}$	–	–	–	–	–	✓	
•••							

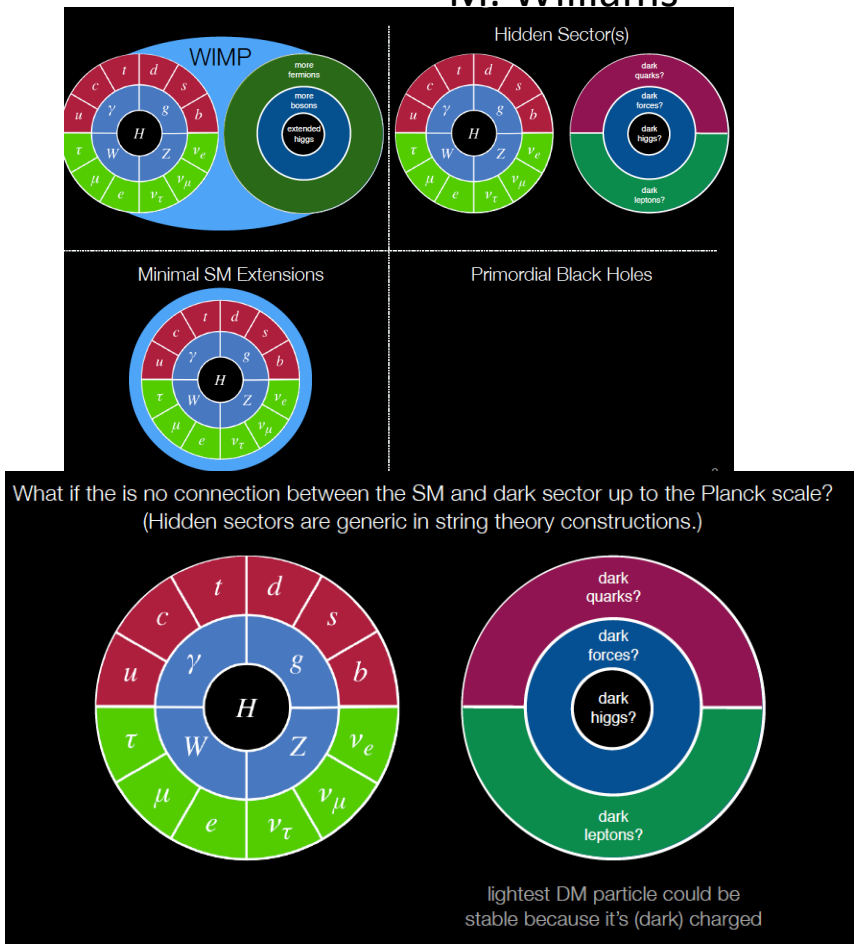
Tree-level contributions to τ→μ processes from low-scale operators Celis-VC-Passemar 1403.5781

probing many effective operators

Cirigliano

TG6- Dark Sector Studies at High Intensities

M. Williams



TG Conveners: S. Gori and M. Williams
More information: https://snowmass21.org/rare/dark

Main topics and highlights (1)

Dark sectors at high and middle energy colliders (3 talks):
Dark sectors at LHCb.
(Long lived & prompt) dark sectors at Belle II.

Dark sectors at kaon factories (3 talks):
NA62 (both Kaon decays and beam-dump mode), KOTO, and KLEVER (future exp.).
Theory effort in interpreting results in terms of several benchmark models.

Dark sectors at eta factories (1 talk)
Jefferson Eta Factory & REDTOP (future exp.).
Collaboration of theorists (model landscape and predictions) and experimentalists.

Dark sectors at MEGII (1 talk)
Searches for lepton flavor violating dark sectors @ the proposed upgrade MEGII-fwd

Dark sectors at Neutron Facilities (1 talk)
Search for neutron transformations into sterile neutrons @
Oak Ridge National Laboratory + European Spallation Source

LOI submitted

54 LOIs received in total.
23 LOIs with RF6 as primary topical group. 19 talks at the RF town-hall
The other 31 LOIs are cross group with: 3-AF, 2-CF, 12-EF, 12-NF, 2-other RF

Our working group contains 7 main topics (and corresponding sub-conveners):

1. Theory (B. Batell (U. of Pittsburgh, P. Schuster (SLAC))
2. e^+e^- experiments (C. Hearty (UBC))
3. Fixed-target experiments (G. Krnjaic (Fermilab), P. Harris (MIT), N. Toro (SLAC))
4. Kaon factories (B. Dobrich (CERN), J. Zupan (U. of Cincinnati))
5. Low masses @ EF facilities (P. Ilten (U. of Cincinnati))
6. Neutrino experiments (P. Coloma (IFT))
7. Other opportunities

Several LOIs submitted for each topics.

TG7- Hadron spectroscopy

Conventional and exotic spectroscopy both light and heavy hadrons

Conveners: R. Lebed and T. Skwarnicki
More information at https://snowmass21.org/rare/hadron_spectroscopy

- 5 LoIs from ongoing experimental programs (LHCb, BelleII, CMS, BESIII, GlueX): seeking support for continued participation from U.S. and upgrade programs
- 6 LoIs related to future new facilities:
  - Three future e^+e^- tau-charm factory proposals (USTC, Novosibirsk, repurposing of BEPC as dedicated J/ψ factory?): seeking American participation [combined whitepaper]
  - Potential of Z-pole e^+e^- machines: capability studies (nothing yet on hadron spectroscopy)
  - EIC: seeking support for EIC and collaborators for development of hadron spectroscopy program
  - Dedicated charm-photoproduction facility: EIC is not optimal, JLab upgrade?
- 5 theory related LoIs:
  - JPAC: theorists & experimentalists collaborating on amplitude analysis tools: need support
  - Lattice QCD (2 LoIs): support for simulations of more complicated hadrons
  - Development of phenomenological models of diquark-based and hadronic molecules (2 LoIs): support for theorists, seeking more interactions with experimentalists

Connections with other frontiers

- Intersections identified at CPM:
  - Some of these physics studies (anomalies in heavy quark decays, hadron spectroscopy, CLFV violation are synergistic with EF)
  - Some our building blocks (nature of the neutrino, dark matter, dark sector) are intersectional with many frontiers (EF, CF, NF)
- Importance to maintain connections with Theory frontier:
  - Interpretation of data
  - Lattice QCD important for relevant matrix elements
  - Develop more realistic simulations
- Importance of developing a robust instrumentation program that allows next detectors to achieve maximum sensitivity
- Importance of developing efficient computing algorithm that allow efficient processing of large data volumes with high selectivity and flexibility to optimize selection criteria for physics of interest (New Physics Evolving Strategy)
- Initial discussion with Accelerator frontier on new accelerator concepts for high-intensity μ beams

Our plans

- We need to transition from LOIs to contributed papers:
  - several LOIs synergistic and benefit from consolidation
- Further exploration of the themes in our frontier and distillation of key physics drivers
  - Material organization and planning for write-up
  - Further exploration of connections with other frontiers developed during these parallel session
- Methodology: ad hoc meetings when needed, big workshop planned before July meeting (probably early June, hopefully at least hybrid)

Conclusions

"there is a crack in everything [even SM]
That's how the light gets in"

[Leonard Cohen]

Our openings:

- ❑ The crack through precision tests of the SM
- ❑ The crack through rare processes

An exciting path is ahead of us in the period encompassed in the Snowmass study

We are working enthusiastically with our early career partners (Sophie Middleton, Josh Barrow and Jake Bennett) and we hope to strengthen our collaboration with the community engagement frontier to be better advocates of our science, strengthen the diversity of our work force, and work with industry to develop the instruments of the future.

The end