

Moriond 2026 (at 60). Theoretical Summary

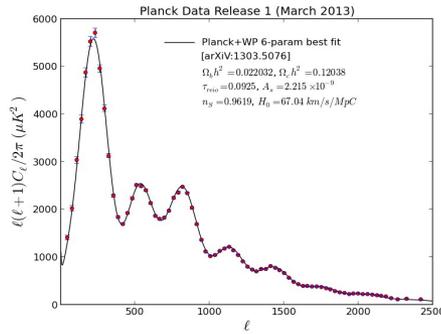
Maxim Pospelov
U of Minnesota

1. Opening Remarks. A bigger picture in a couple of slides.
2. SM is still going strong. Testing SM in different regimes. A few outstanding problems.
3. Revisiting flavor models, flavor violation and neutrino physics.
4. QCD in non-perturbative regime. Unfinished [and very hard] homework.
5. Dark matter, dark sectors, and all of that. Comments on Strong CP.
6. BSM searches discover new SM physics + Conclusions

1. Opening Remarks. A bigger picture in a couple of slides.
2. SM is still going strong. Testing SM in different regimes. A few outstanding problems. Tao Han, Andreas Crivellin, Stefan Dittmaier, Alberto Ramos, Moritz Bosse, Eleni Vryonidou.
3. Revisiting flavor models, flavor violation and neutrino physics. Dave Sutherland, Zoltan Ligeti, Alexandre Carvunis, Teppei Kitahara, Lukas Allwicher, Stephen King, Joachim Kopp, Martin González-Alonso, Ulrich Nierste, Claire Chevallier, Ryan Plestid, Yuichiro Nakai.
4. QCD in non-perturbative regime. Still unfinished [and very hard] homework. Alejandro Vaquero, Felix Erben, Laurent Lellouch
5. Dark matter, dark sectors, and all of that. Comments on Strong CP. Nicolas Grimbaum, Giorgio Arcadi, Despoina Dimakou, Ana Foguel, Pedro Schwaller, Yuichiro Nakai, Chandan Hati, Graham Kribs, Anson Hook, Raffaele D'Agnolo, Moritz Bosse, Mattia Di Mauro.
6. BSM searches discover new SM physics + Conclusions

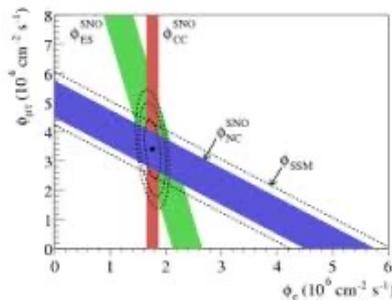
Clues for new beyond SM physics

1. *Precision cosmology*: 6 parameter model (Λ -CDM) correctly



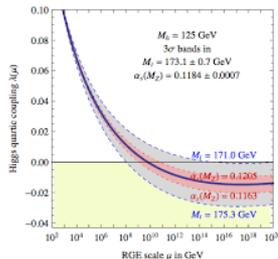
describes statistics of 10^6 CMB patches. Existence of dark matter and dark energy. Strong evidence for inflation.

2. *Neutrino masses and mixing*: Give us a clue [perhaps] that



there are new matter fields beyond SM. Some of them are not charged under SM.

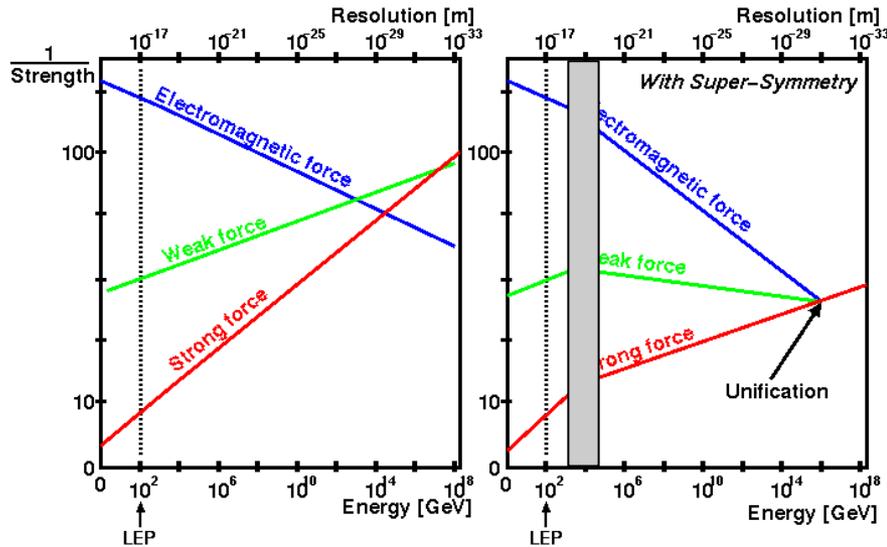
3. *Theoretical puzzles*: Strong CP problem, vacuum stability, hints



on unification, smallness of m_h relative to highest scales (GUT, M_{Planck})

4. *“Anomalous results”*: muon g-2, SBN neutrino anomalies, B-physics anomalies etc. ← A bit of a “revolving door”

SM in a bigger picture



- Gauge coupling unification (GUT) suggested by the structure of the SM representations unifies more “easily” with the help of SUSY particles.

- Pre-LHC expectations were pinned too much on the “naturalness of the weak scale” argument, postulating super-partners at a TeV.
- BEH scalar mass of 125 GeV is “somewhat uncomfortable” for SUSY theorists requiring, quite generically, heavier superpartners, to lift the Higgs mass so much above m_Z . Some fine tuning is re-introduced but 10-100 TeV SUSY is still an OK model
- We learned to take naturalness argument seriously but not literally...

SM as an Effective Field Theory ("bottom up" approach)

Less ambitious bottom-up BSM model-independent approach is to include all possible BSM operators + light(er) new states explicitly.

$\mathcal{L}_{2020s} = -m_H^2 (H_{SM}^+ H_{SM}) + \text{all dim 4 terms } (A_{SM}, \psi_{SM}, H_{SM}) +$
Neutrino mass operators (e.g. effective Dim=5)

+ (Wilson coeff. / Λ^2) \times Dim 6 etc $(A_{SM}, \psi_{SM}, H_{SM}) + \dots$

all lowest dimension portals $(A_{SM}, \psi_{SM}, H, A_{DS}, \psi_{DS}, H_{DS}) \times$
portal couplings

+ dark sector interactions $(A_{DS}, \psi_{DS}, H_{DS})$

SM -- Standard Model

DS – Dark Sector [possibly including dark matter states]

How to look for New Physics ?

1. High energy colliders.

$$\frac{1}{\Lambda^2}(\bar{e}e)(\bar{q}q) \rightarrow \sigma \propto \frac{E^2}{\Lambda^4} \rightarrow \Lambda > 10 \text{ TeV}$$

2. Precision measurements, especially when a symmetry is broken

$$\frac{1}{\Lambda_{\text{CP}}^2}(\bar{e}i\gamma_5 e)(\bar{q}q) \rightarrow \text{EDM}, \frac{1}{\Lambda_{\text{CP}}^2} < 10^{-10} G_F \rightarrow \Lambda_{\text{CP}} > 10^7 \text{ GeV}$$

3. Intensity frontier experiments where abnormal to SM appearance of FIPs (or sometimes disappearance, e.g. NA62, 64) can be searched.

$$pp \rightarrow \pi, K, B \rightarrow HNL + X \rightarrow HNL \text{ decay to SM}$$

4. DM searches: $\textit{Atom} + \textit{DM} \rightarrow \textit{visible energy}$

$$\textit{axion} + \textit{EM field} \rightarrow \textit{visible energy}$$

All these methods were actively discussed at our meeting.

SM, EW theory and BSM at the weak scale

R. Kogler: Current G-Fit results on precision EW determinations of the SM parameters. BSM fits in the kappa framework (new states are not introduced but HVV couplings are relaxed from their SM values)

S. Dittmaier: Results of NLO and NNLO calculations for the VBS, VV, VVV.

T. Han: Discussion of VBS, longitudinal W scattering processes, high-energy limits of the SM, and possible reach of future muon colliders.

A. Ramos: Sometimes complicated dynamics of the multi-Higgs models away from the perturbative regime can be studied on the lattice, and more rigorous inference about EW phase transitions can be made.

A. Crivellin: $\gamma\gamma$ excesses at 95 and 152 GeV might be actually real and originate from a triplet/singlet Higgs model. Motivates further exploration of these models in the $WWbb$ and $WW\gamma\gamma$ final states, preferably by the experimental collaborations themselves.

E. Vryonidou: seeks to quantify quantum entanglement of the heavy particle spin systems at colliders.

SM precision tests

R. Kogler

Top, Higgs etc appear at lower energies as virtual particles. EW precision observables can be used to determine masses. m_W in particular benefits

SM Fit Results

Recent updates

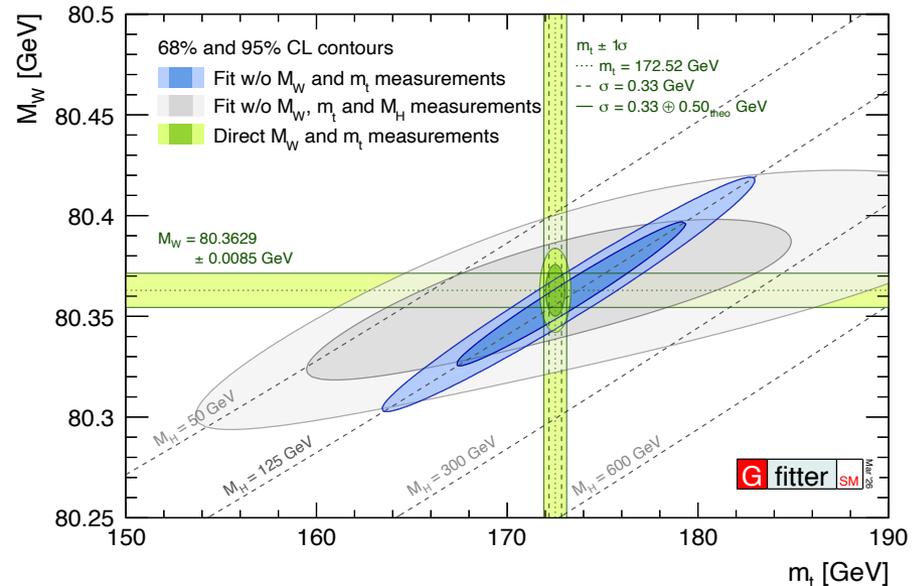
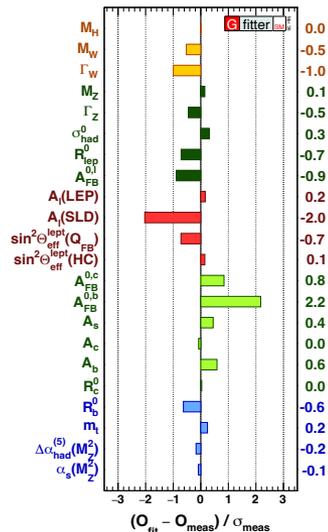
- Updated calculations of beam-beam effects on the LEP luminosity [Voutsinas et al, PLB 800, 135068 (2020)]
- Updated Bhabha cross section [Janot, Jadach, PLB 803, 135319 (2020)]

Good fit quality

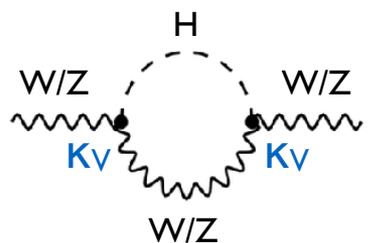
- $\chi^2 / \text{ndf} = 13.6 / 16$, p-value = 0.63
- χ^2 (2018) = 18.6
- χ^2 (2012) = 21.8

Indirect predictions:

- $m_H = 110^{+20}_{-17}$ GeV
- $m_W = 80.356 \pm 0.006$ GeV
- $m_t = 173.7 \pm 1.6$ GeV
- $\alpha_s(M_Z) = 0.1200 \pm 0.0028$



Departing from the SM within κ framework is difficult to define consistently at a loop level.



$$S = \frac{1}{12\pi} (1 - \kappa_V^2) \ln \left(\frac{\Lambda^2}{m_H^2} \right)$$

$$T = -\frac{3}{16\pi c_W^2} (1 - \kappa_V^2) \ln \left(\frac{\Lambda^2}{m_H^2} \right)$$

It might be that at two loops one would expect quadratic divergencies, and appearance of LEC like in ChPT

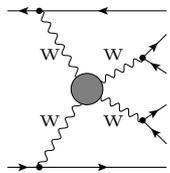
An observable $\propto (1 - \kappa_V^2) \times (1/(16\pi))^2 \times \frac{\Lambda^2}{v_{EW}^2}$

Vector Boson scattering and higher order effects

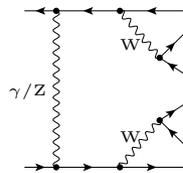
T. Han and **S. Dittmaier** gave interesting talks about the higher-order EW effects such as VV, VVV production and boson scattering (VBS).

Classification of LO diagrams for $pp \rightarrow VV' + 2\text{jets}$

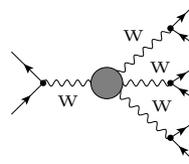
EW channels



VBS channels



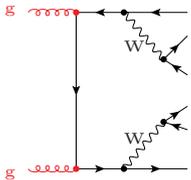
bkg diags



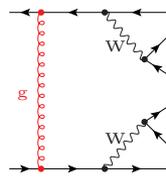
VVV channels

$$|\mathcal{M}_{EW}|^2 \propto \alpha^6$$

QCD channels



not for $W^\pm W^\pm$ production!



$$|\mathcal{M}_{QCD}|^2 \propto \alpha_s^2 \alpha^4$$

NLO corrections and scale uncertainty of integrated cross sections:

W^+W^+ scattering with ATLAS cuts:

S.D. et al. 2308.16716

	order	σ [fb]	δ [%]	Scale uncertainty
LO	$\mathcal{O}(\alpha^6 \alpha_s^0)$	1.24597(5)		-7.7% 9.9%
	$\mathcal{O}(\alpha^5 \alpha_s^1)$	0.051133(3)		-14.0% 17.7%
	$\mathcal{O}(\alpha^4 \alpha_s^2)$	0.18649(2)		-22.2% 31.6%
	sum	1.48359(5)		-9.8% 12.1%
NLO	$\mathcal{O}(\alpha^7 \alpha_s^0)$	-0.1747(5)	-11.8%	
	$\mathcal{O}(\alpha^6 \alpha_s^1)$	-0.0902(8)	-6.1%	
	$\mathcal{O}(\alpha^5 \alpha_s^2)$	-0.00017(19)	0.0%	
	$\mathcal{O}(\alpha^4 \alpha_s^3)$	-0.0033(7)	-0.2%	
	sum	-0.268(1)	-18.1%	
LO+NLO	sum	1.215(1)		-4.0% 1.5%

- W bosons are already “light” in the LHC context, as Sudakov corrections become important
- Achieved accuracy will allow the best quality interpretation of Run III and future HL LHC
- Experimental analysis requires consulting several theory sources (S. Dittmaier)

Vector boson physics and radiation zeros

T. Han: Further tests of vector boson scattering (VBS) are desirable. Only a handful number of examples where longitudinal W makes appearance, yet it is central to SM BEH mass mechanism.

Gauge / scalar separation: R. Capdevilla, TH, arXiv:2412.12336 (PRL)

$$\begin{aligned} f_1 \bar{f}_2 &\rightarrow W^\pm \gamma, \\ f_1 \bar{f}_2 &\rightarrow W^\pm Z, \\ f_1 \bar{f}_2 &\rightarrow W^\pm H. \end{aligned}$$

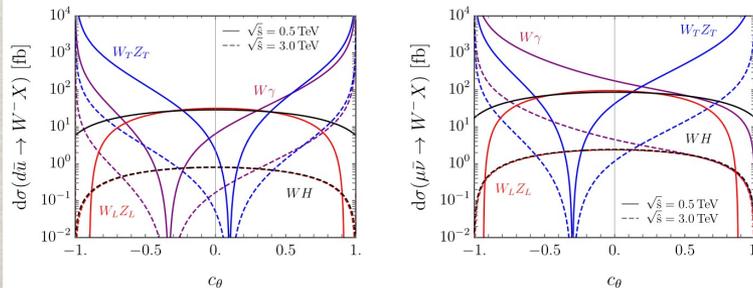
$$\begin{aligned} \mathcal{M}_{\pm\mp}^{W\gamma} &\approx -\frac{geV_{12}(\lambda_w - c_\theta)}{\sqrt{2}s_\theta} [Q_{(1-2)}c_\theta - Q_{(1+2)}], \\ \mathcal{M}_{\pm\mp}^{WZ} &\approx \frac{gg_z V_{12}(\lambda_w - c_\theta)}{\sqrt{2}s_\theta} [g_-^{(1-2)}c_\theta - g_-^{(1+2)}], \\ \mathcal{M}_{00}^{WZ} &\approx -\frac{g_z^2 V_{12}}{2\sqrt{2}} s_\theta g_-^{(1-2)} = \frac{g^2 V_{12}}{2\sqrt{2}} s_\theta, \\ \mathcal{M}_0^{WH} &\approx \frac{g^2 V_{12}}{2\sqrt{2}} s_\theta, \end{aligned}$$

- Gauge sector: Radiation Amplitude Zeros (RAZs)

$$\text{EM: } c_\theta^{W-\gamma} = \frac{Q_d + Q_u}{Q_d - Q_u}; \quad \text{EW (transverse): } c_\theta^{W^- Z_T} = \frac{g_-^d + g_-^u}{g_-^d - g_-^u}$$

Mikaelian, Samuel (1979) $c_{\theta_0} = \begin{cases} -1/3 (\approx 0.1) & \text{for } d\bar{u} \rightarrow W_T^- \gamma (W_T^- Z_T), \\ 1 (\approx -0.3) & \text{for } \ell^- \bar{\nu} \rightarrow W_T^- \gamma (W_T^- Z_T), \end{cases}$ U. Baur, TH, JO, (1994)

- Higgs scalar sector: $\mathcal{M}^{W_L Z_L}(\delta \ll 1) \approx \mathcal{M}^{W_L h}(\delta \ll 1)$



Radiation zeros were pointed out many years ago.

Natural consequence of many final states, WZ, Wγ.

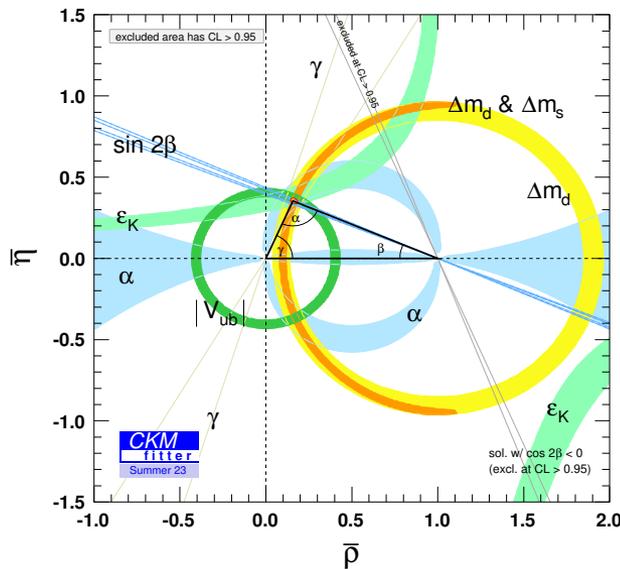
New observations of RAZ were just reported by ATLAS (**S Folgueras**) in the study of the Wγ final state

Take away messages I

1. SM is 1 year younger than the 1st Moriond meeting, and it is also going strong, thanks to the dedicated effort of multiple generations of physicists.
2. The electroweak fit to SM parameter continue to improve and deliver results where sometimes indirect determinations (m_W) surpass direct experimental accuracy.
3. On-going theoretical progress with small rare SM processes (VBS, VV, VVV etc) with O(fb) cross sections, allows for a more sophisticated use of already collected data at the LHC and the future anticipated stream of data.
4. While SMEFT framework is appropriate for many BSM searches, it may be “prematurely pessimistic” for some studies where actual new resonances are within LHC reach. Theorists should continue their work with some benchmark models that can be studied at the LHC.

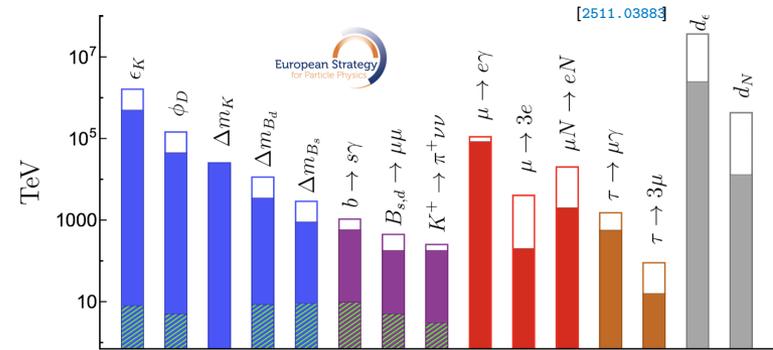
Importance of indirect probes. Flavor!

- Precision tests of CKM framework and lepton flavor conservation in the SM.
- Search of “hidden patterns” in masses/mixing of the quark and lepton sector of the SM.



Current Status

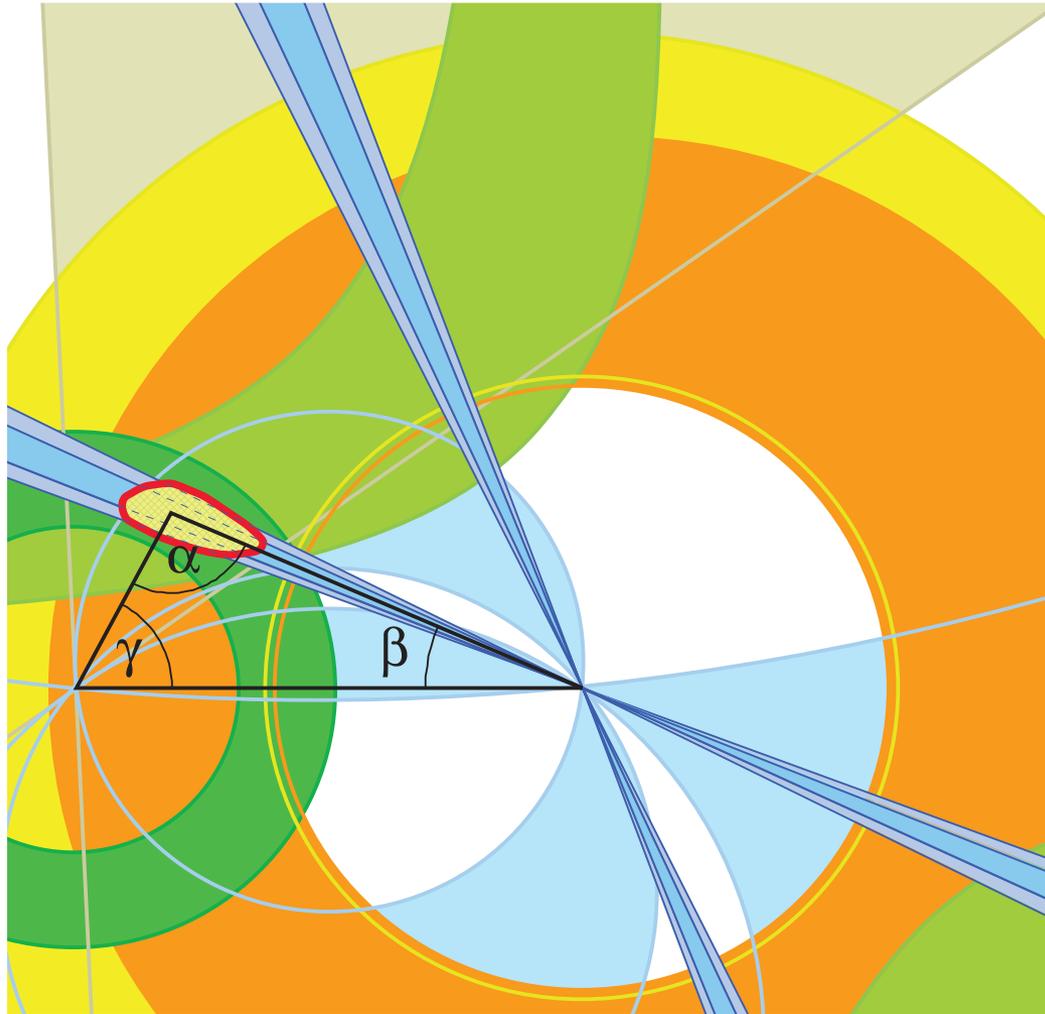
Indirect Searches



It is clear that “nearby” New Physics cannot have a generic flavour structure

- From **Z. Ligeti**, **L. Allwicher**’s talks
- Some unsolved [unlikely to be BSM] problems remain: *K*- π puzzle, slightly divergent inclusive/exclusive V_{cb} results etc.

Same figure, 2006



- Enormous experimental/ theoretical progress in the last 20 yrs !

EW penguins and more

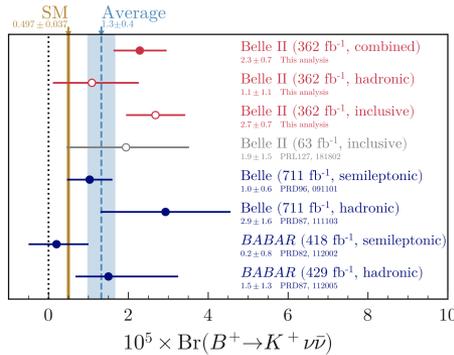
- EW penguins manifest themselves more and more!

Experimental Status

(see talk by Meihong Liu)

$$B \rightarrow K \nu \bar{\nu}$$

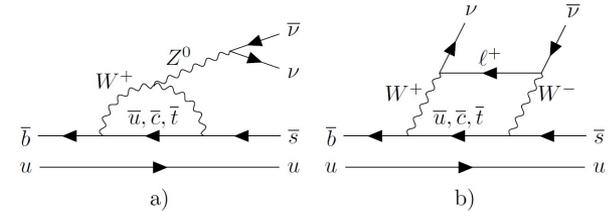
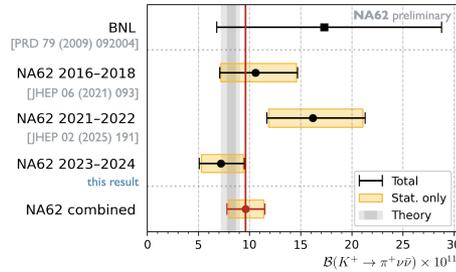
> Belle-II 2023



(see talk by Xiafei Chang)

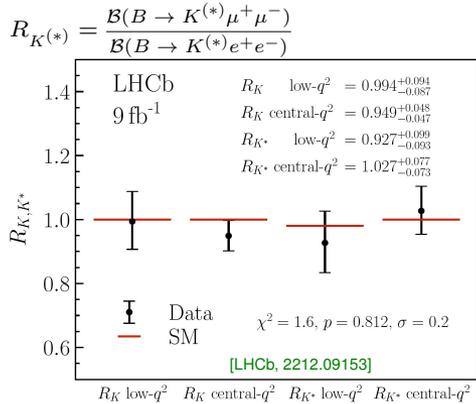
$$K \rightarrow \pi \nu \bar{\nu}$$

> NA62 2026 (La Thuile)

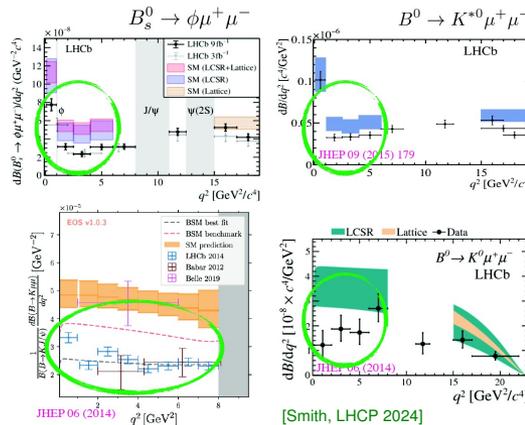


Slight excess in $B \rightarrow K \nu \bar{\nu}$ channel at Belle-II.

Needs a separation of NP from SM ← easy to say, hard to do...



$0.1 < q^2 < 1.1 \text{ GeV}^2$ (low- q^2), $1.1 < q^2 < 6.0 \text{ GeV}^2$ (central)

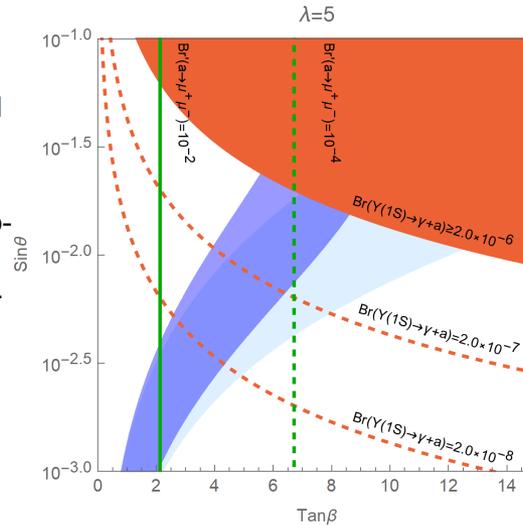


Flavor non-universality of the FCNC channel is gone. Other problems remain (P_5'). Note that strong/EM penguins are “invasive species”, not clean, and create “pollution”. Need non-perturbative treatment.

New physics re-interpretation:

Phenomenology of $B \rightarrow Ka$

- Since Belle II sees missing energy, a must dominantly decay to the Dark Sector, beyond the DFSZ model.
- Belle II data hint at $m_a \sim 2$ GeV.
- One-loop and two-loop contributions have opposite signs. Blue region explains Belle II data (dark blue: all, light blue: only one-loop).
- Look for displaced vertex decay $a \rightarrow \mu^+ \mu^-$. But branching fraction is unpredictable, since $B(a \rightarrow \text{dark sector})$ is free parameter.
- $Y(1S) \rightarrow \gamma a$ constrains the plot and could be “smoking gun” signal.



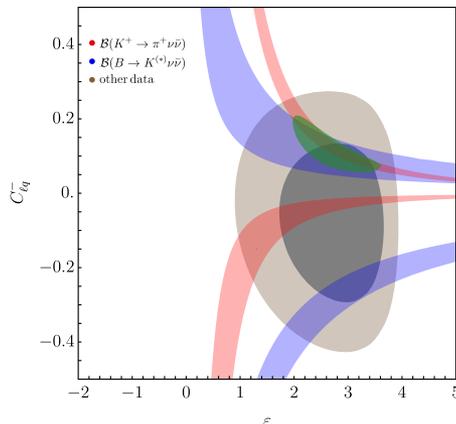
Excess could be interpreted as a new state emitted in the $B \rightarrow K$ transition (U Nierste),

14 Moriond 2026 electroweak B decays into light BSM particles Ulrich Nierste

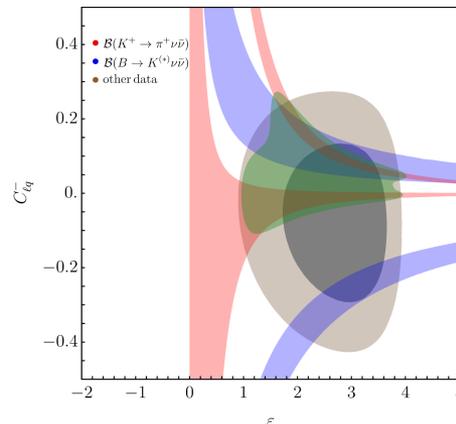
[Thanks to Marzia Bordone for updated plot]

Results: $C_{\ell q}^- - \varepsilon$

2024:



March 2026:



Or

Interpreted as a new SMEFT type operator that may be motivated by some flavor model (L. Allwicher)

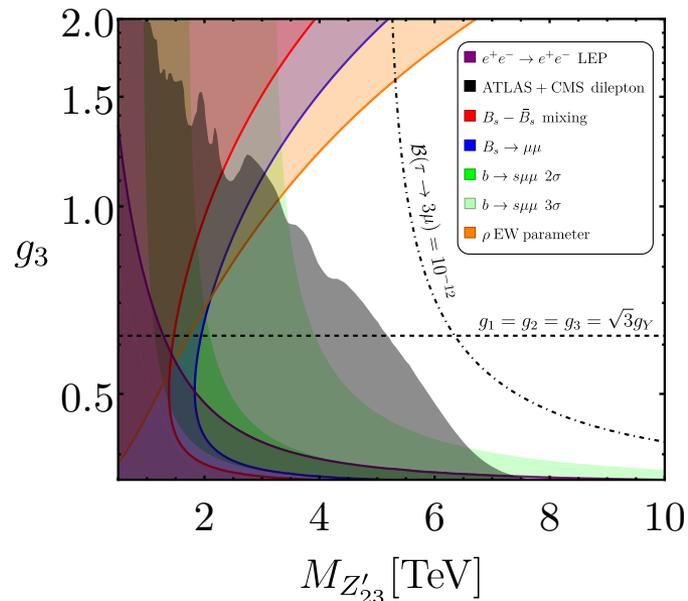
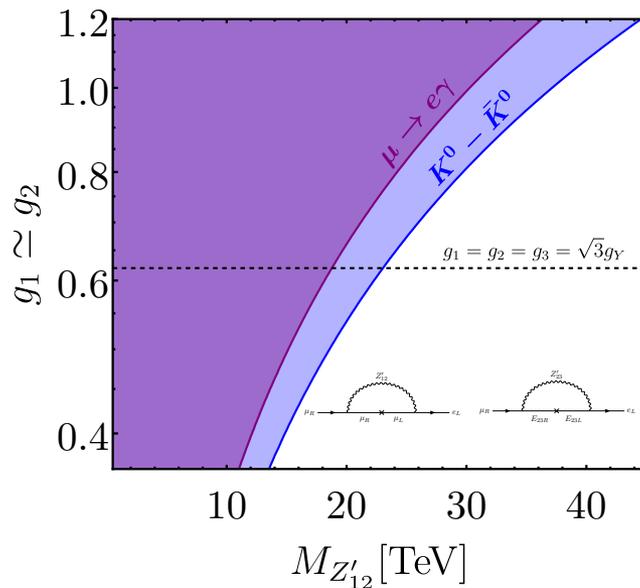
New twists to the flavor origin ideas

- Separate hypercharge group for each generation + sequential breaking (S. King)
- New composite nature of SM chiral fermions (R. Plestid)
- Higher representation of flavor spurions + approximate U(2) (D. Sutherland)
- Approximate U(2) at SMEFT level (L. Allwicher)

Expansion parameters $\epsilon_{ij}^{R,L} = \langle \phi_{ij}^{R,L} \rangle / \Lambda_{ij}$

M. Fernandez Navarro, S.F.K., A. Vicente 2506.21687

Observable consequences of Z'_{12} and Z'_{23}



Comments on flavor models

1. What is the predictive power of your flavor model ? For example,

$$Y_{d(u)} \sim \begin{pmatrix} \epsilon^3 & \epsilon^3 & \epsilon^4 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix}$$

Is it $Y_{d(u)} = c \times \begin{pmatrix} \epsilon^3 & \epsilon^3 & \epsilon^4 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix}$ or $Y_{d(u)} = \begin{pmatrix} c_{11}\epsilon^3 & c_{12}\epsilon^3 & c_{13}\epsilon^4 \\ c_{21}\epsilon^3 & c_{22}\epsilon^2 & c_{23}\epsilon^2 \\ c_{31}\epsilon^4 & c_{32}\epsilon^2 & c_{33} \end{pmatrix}$; $c_{ij} \sim O(1)$?

In one case you have 2 parameters/lots of predictivity in the second case you “explain” the hierarchy using small ϵ but not much predictivity with 10 parameters

2. Is the scale of a small mixing/mass parameter linked to weak scale or not?

$$\epsilon \simeq \frac{\langle \phi \rangle}{\Lambda} \quad \text{or} \quad \epsilon \simeq \frac{\langle H_{\text{SM}} \rangle}{\Lambda}$$

Second case is meaningfully probed by flavor and Higgs physics. Ex: $m_\mu \ll m_t$

Let me have $\mathcal{L} = \frac{H^\dagger H}{\Lambda^2} \bar{\mu}_R \mu_L H + h.c. \rightarrow m_\mu \bar{\mu} \mu + h_{125} \times \underline{3} \times \frac{m_\mu}{v_{\text{EW}}} \bar{\mu} \mu \quad \frac{\Gamma_{h \rightarrow \mu\mu}}{\Gamma_{h \rightarrow \mu\mu, \text{SM}}} = 9$ **18**

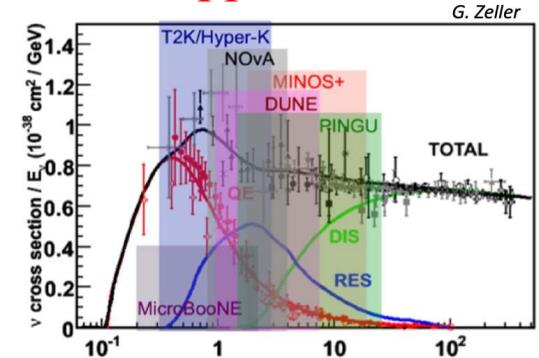
BSM searches with neutrino physics

New Interactions in Quasi-Elastic Scattering (< GeV)

- neutrino scatters on **nucleons**
- need to map **lepton-quark interactions** onto **lepton-nucleon interactions**

$$\frac{d\sigma_{\alpha\beta}}{dQ^2} = \underbrace{\frac{d\hat{\sigma}_{LL,\alpha}}{dQ^2}}_{\text{SM contribution}} \delta_{\alpha\beta} + \underbrace{\sum_X \left([\epsilon_X]_{\alpha\beta} \frac{d\hat{\sigma}_{LX,\alpha}}{dQ^2} \delta_{\alpha\beta} + h.c. \right)}_{\text{SM-BSM interference contributions}} + \underbrace{\sum_{X,Y,\beta} [\epsilon_X]_{\alpha\beta} [\epsilon_Y]_{\alpha\beta}^* \frac{d\hat{\sigma}_{XY,\alpha}}{dQ^2}}_{\text{pure BSM contributions}}$$

J. Kopp



M. Gonzalez-Alonso shows that new developments in CEvNS physics starts adding constraints on effective weak decay operators.

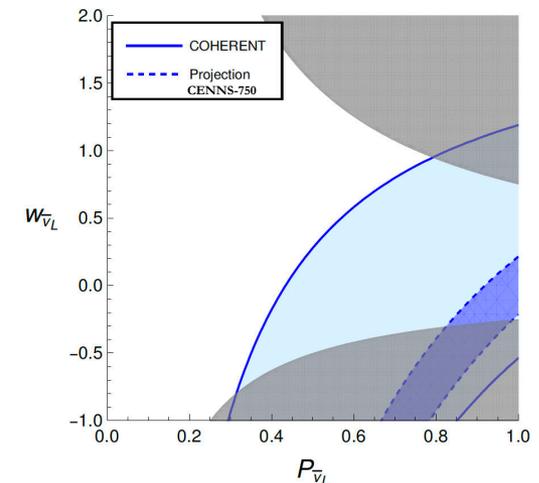
Muon decay parameters → COHERENT

COHERENT data
LAr + CsI
recoil & time distribution
(664 data)

COHERENT
SNS
Neutrino Science



$$0.54 P_{\nu_L} + 0.84 P_{\bar{\nu}_L} + 0.40 (P_{\nu_L} w_{\nu_L} - P_{\bar{\nu}_L} w_{\bar{\nu}_L}) = 1.25(21)$$



First extraction ever of these parameters!

For the first approach along these lines see **W. Pauli**, “The Violation of Reflection Symmetries in the Laws of Atomic Physics,” in *Niels Bohr and the Development of Physics*, ed. W. Pauli et al., Pergamon Press, London, ~1958 (festschrift for Niels Bohr’s 70th birthday).

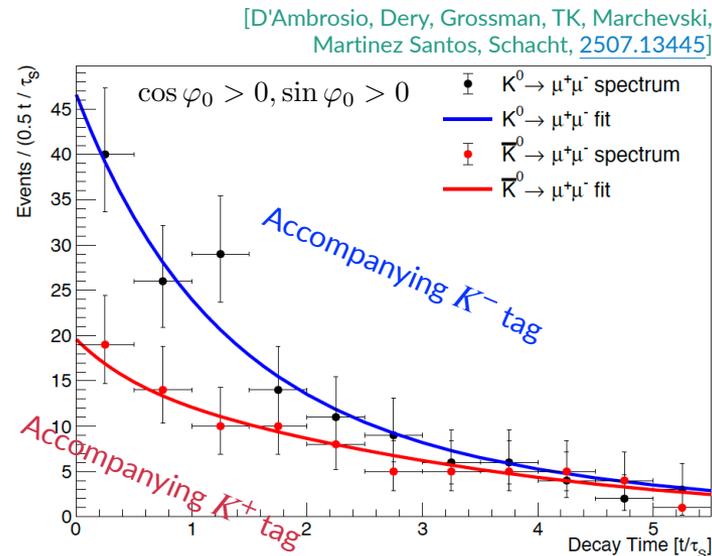
Di-muon decays of Kaons at the LHC

Currently, no $K^0 \rightarrow \mu\mu$ decays are observed by the LHCb. [K_L has a much larger branching but long lifetime.... LHCb improved limits on K_S , $\text{Br} < 2 \cdot 10^{-10}$]

T. Kitahara presented an idea of observing asymmetry of K^0 and \bar{K}^0 to muons at the LHCb.

Decay-time analysis

- We simulate the decay-time distribution for the **LHCb Upgrade II setup**
- It is clearly shown that the CP violation between $K^0 \rightarrow \mu^+\mu^-$ and $\bar{K}^0 \rightarrow \mu^+\mu^-$ can be measured for small decay time region



My understanding is that we are more than a factor of 20 away from seeing any $K \rightarrow \mu\mu$ decays, and perhaps a factor of \sim a few 100 before asymmetry can be probed

QCD in a non-perturbative regime

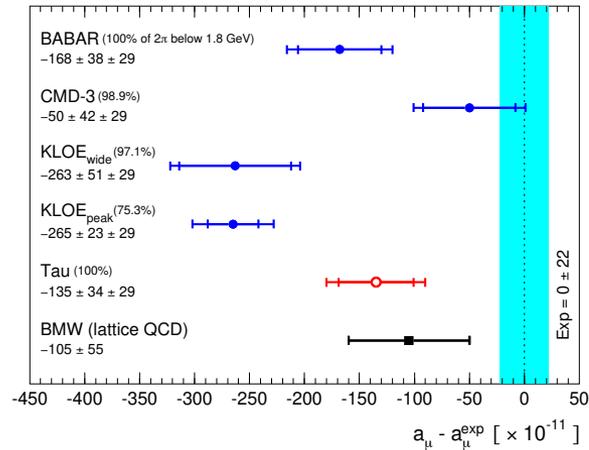
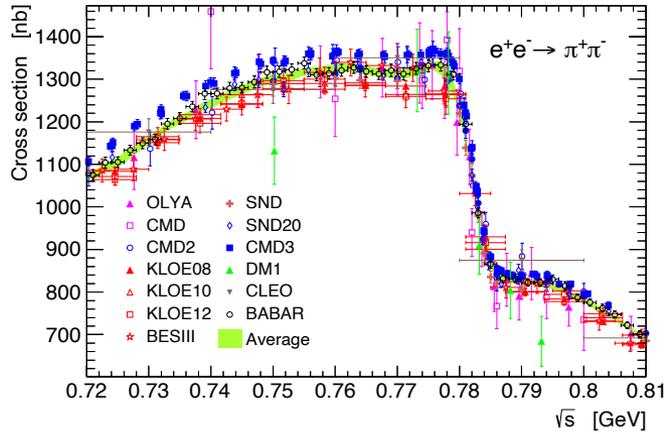
This year we had a number of lattice QCD talk, including more pedagogical, introducing the technique.

Alejandro Vaquero: discussion of on-going efforts to extract charged semileptonic form factors to improve, among other things, $|V_{cb}|$ extraction. An interesting observation that we should not *demand* uniformity of lattice results the same way we do not *force* different experiments to agree.

Felix Erben: Introduction to $B \rightarrow K^*$ form factor calculation. Unstable particle is treated via phase shifts a-la Luscher. Giant matrix diagonalizations to get to the right observables [aka distillation techniques]. Extension to low q^2 regime is challenging.

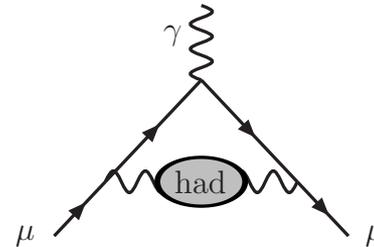
Laurent Lellouch: Introduction to lepton $g-2$ topic, followed by the review of the HVP results that drive theoretical uncertainties. Recent lattice QCD calculations [BMW] point to a much better agreement with the experimental result for the muon $g-2$ than previously believed.

Is there a muon g-2 problem?

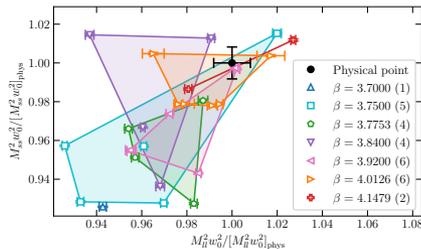


There is a significant scatter for the data-driven method and some recent results are very different (CMD3)

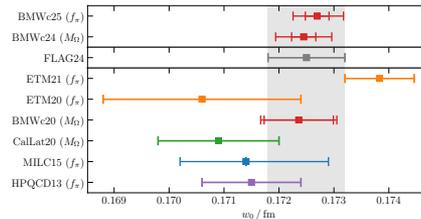
(From M. Davier et al, 2023)



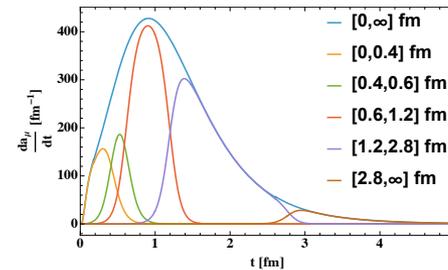
Strategy for improvement over BMW '20



New finer ("Monster") lattices:
 $a = 0.064 \text{ fm}$ [$96^3 \times 144$] \rightarrow
 $a = 0.048 \text{ fm}$ [$128^3 \times 192$]
 \rightarrow distance to continuum limit $\div 1.8$



Significantly improve tuning of QCD parameters
 \rightarrow (scale uncertainty) $^2 \div 2.1$



Break up calculation into set of 5 windows
 \rightarrow optimize calculation in small distance scale intervals

L. Lelouch

QCD in a non-perturbative regime

Newest results from BMW collaboration agree with experiment without any need for new physics, and almost match it in terms of error. Sub-% calculation of HVP (!)

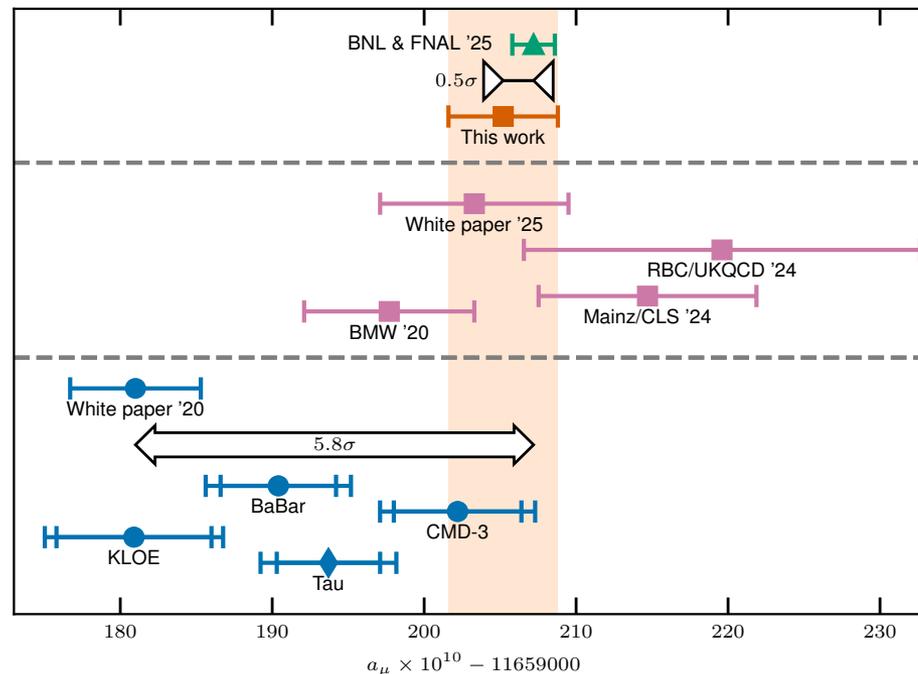
Experiment vs SM: March 2026

$$a_\mu|_{\text{expt}} = (11659207.15 \pm 1.45) \times 10^{-10}$$

$$a_\mu|_{\text{WP25}} = (11659203.3 \pm 6.2) \times 10^{-10}$$

$$a_\mu|_{\text{This work+WP25}} = (11659205.1 \pm 3.4) \times 10^{-10}$$

Spectacular results
presented by L. Lelouch



Take away messages II

1. Flavor physics continues to deliver nontrivial tests of the CKM paradigm, and there is still room for new physics (although current tensions are unlikely to originate from much beyond-TeV scale.)
2. SM mass/flavor sector is tied up to SM Higgs couplings. Continuing to test “Higgs linearity”, i.e. $g_{hff} \sim m_{hff}/v$ at the LHC is very important!
3. Further theoretical progress in quark flavor physics is likely to be related to the ability to treat QCD effects.
4. “Clean” channels still remain, especially in LFV and EDMs: $\mu \rightarrow e \gamma$, $\tau \rightarrow \mu \gamma$, electron, neutron and atomic EDMs etc. Huge progress in muon $g-2$ on the lattice, but a fairly confusing situation with data-driven analysis.
5. Coherent/regular ν scattering start delivering new sensitivity to modified by BSM interactions, complementing other channels. Theorists are here to help.

Dark sectors / dark matter / axions

- *Main difficulty in connecting dark matter to fundamental theories of particles and fields is in huge variety of reasonable options. WIMPs, asymmetric DM, secluded WIMPs, Freeze-in Dark matter, light bosonic dark matter including axions, ALPs, dark photons, extra light moduli Primordial Black holes etc.*

Lots of theoretical talks/ideas/suggestions at this meeting:

P. Schwaller: Confining dark sectors and dark pions (soft bombs?) at colliders

Y. Nakai: Providing explicit GMSB model with Nelson-Barr solution to strong CP.

C. Hati: Minimalistic asymmetric DM models

G. Kribs: Exploring phenomenology of dark baryon dark matter

A. Hook: Revisiting and relaxing limits on very light dark photon dark matter

R. D'Agnolo: Ode to axions + heterodyne detection idea

G. Arcadi: WIMPs benchmarks + modified early cosmology

M. Di Mauro: Secluded DM parameters tied to neutrino mass generation

M. Bosse, N. Grimbaum, D. Dimakou, A. Foguel

Strong CP problem and connection to $U(1)_A$

- QCD Lagrangian has a hidden parameter that is made physical by the nonperturbative lifting of the singlet pseudoscalar mass. [Yes, by instantons, but it is not even crucial.] Most crucially, $m_\eta^2 \rightarrow m_0^2$ at $m_q \rightarrow 0$, while pions become massless.

$$\mathcal{L}_{QCD} = -\frac{1}{4}(G_{\mu\nu}^a)^2 + \sum_{u,d} \bar{q}(iD_\mu\gamma_\mu - m_q)q + \frac{\theta g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a$$

$\theta m_q(qq) \quad \eta' \quad \theta m_q(qq)$


$$\rightarrow m_*(\bar{u}i\gamma_5 u + \bar{d}i\gamma_5 d)\theta + m_*(\bar{u}u + \bar{d}d)\theta^2/2 + \dots$$

m_* is the reduced quark mass, $m_u m_d / (m_u + m_d)$. The expectation value of the second term over the vacuum here is the vacuum energy dependence on the theta angle (and upon the rescaling the axion mass squared.) Would have been cancelled by Goldstone eta'

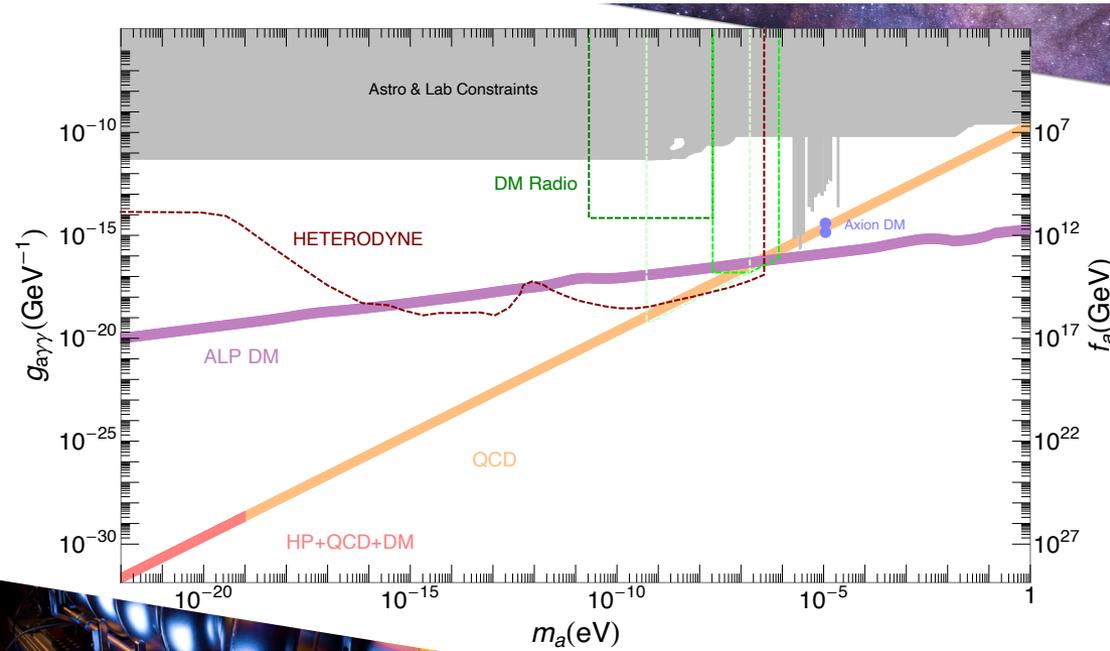
$$E_{\text{vac}}(\bar{\theta}) = \frac{1}{2}\bar{\theta}^2 m_* |\langle \bar{q}q \rangle| \times \left(1 - \frac{4m_* B}{m_0^2 + 4m_* B} \right) \quad B = F_\pi^{-2} |\langle \bar{q}q \rangle| = m_\pi^2 (m_u + m_d)^{-1}$$

Linear in theta correlators lead to CP-odd observables such as $\eta \rightarrow \pi\pi$, neutron EDM etc. Therefore, strong CP is real and can be resolved by dynamical relaxation (axion), by construction (e.g. discrete symmetries), or via a massless light quark (problematic) 26

Nothing new here, just the standard "party line".

Axions: theory, lab, astro...

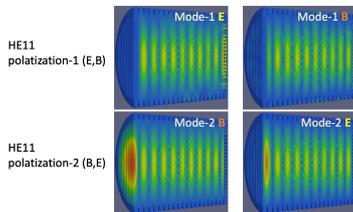
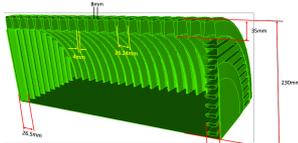
- Rafaele Tito d'Agnolo



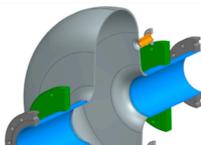
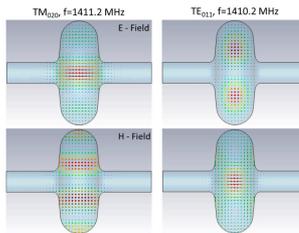
- DM Axion-assisted transfer of signal from one cavity to another, to access more expanded mass range.



2507.07173



arXiv:2207.11346



- First steps for this setup are made at SLAC and Fermilab.

SUSY theory a-la Nelson-Barr

- Y. Nakai

The physical strong CP phase : $\bar{\theta} \equiv \theta - \arg \det (M_u M_d)$

$$\mathcal{L} = \mu \underline{\bar{q}q} + a_{a\bar{f}} \underline{\eta_a} \bar{d}_{\bar{f}} q + y_{f\bar{f}} H Q_f \bar{d}_{\bar{f}} \quad \rightarrow \quad \mathcal{M} = \begin{pmatrix} \mu & a_{a\bar{f}} \eta_a \\ \boxed{0} & m_d \end{pmatrix}$$

Heavy quarks **CP breaking field**

- Rule of the game: start from $\theta = 0$, generate CP -violation spontaneously, makes sure that $\delta_{CKM} \sim O(1)$, while θ remain small. Generate BAU via AD. Non-decoupling of New Physics from EDM observables.

Fujikura, YN, Sato, Yamada (2022)

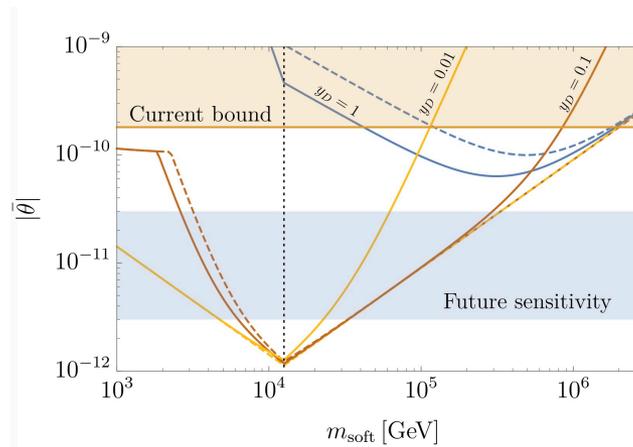
If **gravitino** gives DM ...

Lyman- α constraint $\rightarrow m_{3/2} \gtrsim 5.3 \text{ keV}$

Smallest value of $\bar{\theta}$

SCPV scale and reheating temperature are chosen to obtain the observed asymmetry and DM.

Consistency with SCPV via ~~SUSY~~ will be explored in a future study.



Future neutron EDM can probe this model with very large SUSY masses due “non-decoupling” effect of θ .

Confining Dark Sectors

- Confining sectors may provide natural/realistic DM candidates

PS, Stolarski, Weiler, 2015

P. Schwaller:

Dark flavour symmetries

Carmona, Elahi, Scherb, PS, 2411.15073

Dark QCD with n_f dark quarks Q_α

$$\mathcal{L}_D = -\frac{1}{4}(G_D^{\mu\nu,a})^2 + \bar{Q}_\alpha i \not{D} Q_\alpha - m_{Q,\alpha\beta} \bar{Q}_\alpha Q_\beta$$

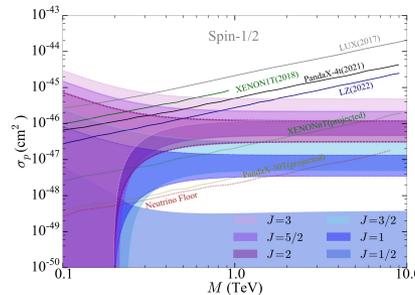
Global $SU(n_f) \times SU(n_f)$ symmetry in dark sector

Direct Detection through electroweak loops



EFT* with $M(\Sigma_0, \Lambda_0) \gg Mw$:

*(Majorana)



← 5-plet
← triplet

Chen, Ding, Hill [2309.02715]

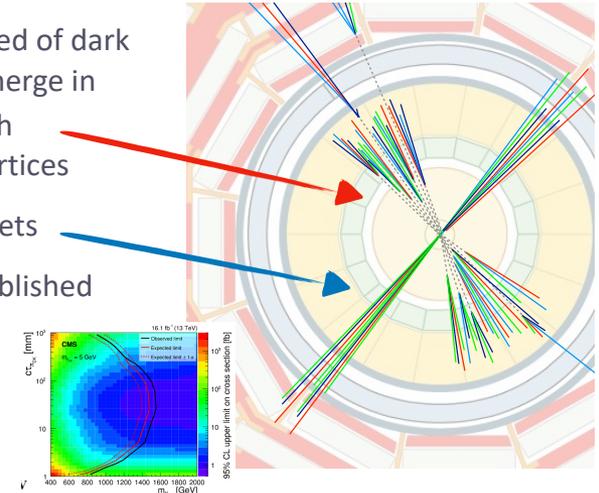
Smoking gun signature: emerging jets

Jets composed of dark pions π_D , emerge in detector with displaced vertices

Prompt SM jets

Now an established signature!

CMS-EXO-18-001
JHEP 02 (2019) 179
...



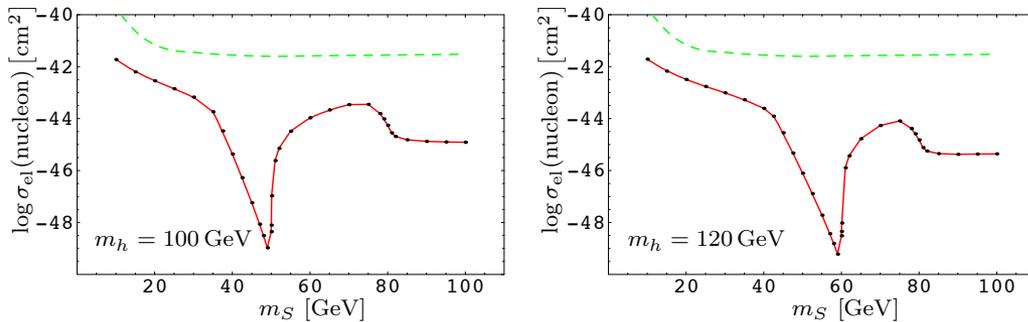
G. Kribs: Dark baryons with EW-charged constituents.

In both approaches there are interesting LHC consequences of "dark mesons" and reappearing jets. Nice overlap with experimental searches reported here!

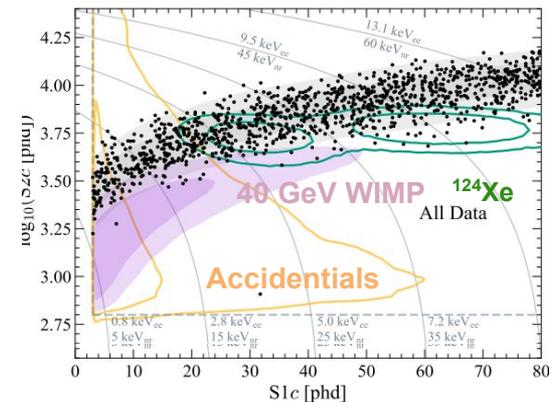
Take away messages III

1. Strong CP problem is real, and axions are most motivated explanation. Extremely hard to find, but we should keep trying.
2. We know how to build [very very many] dark matter models.
3. Experimental sensitivity of primarily Xe-dual-TPC suite of experiments caught up with many DM models, and mauled/killed them. You see the reflection of this in many of our talks.

My personal example: Higgs-portal DM, year 2000



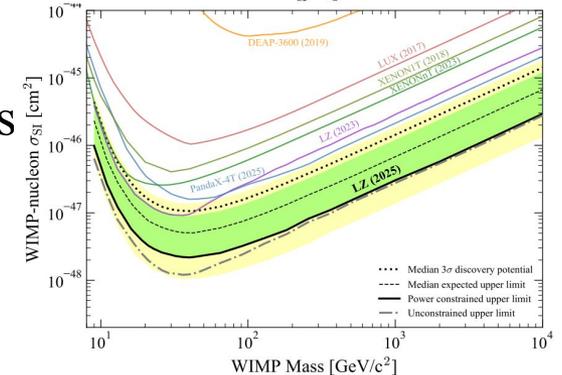
WIMP Results (WS2024) 



B. Penning for LZ ([almost] kills BEH-mediated WIMPs

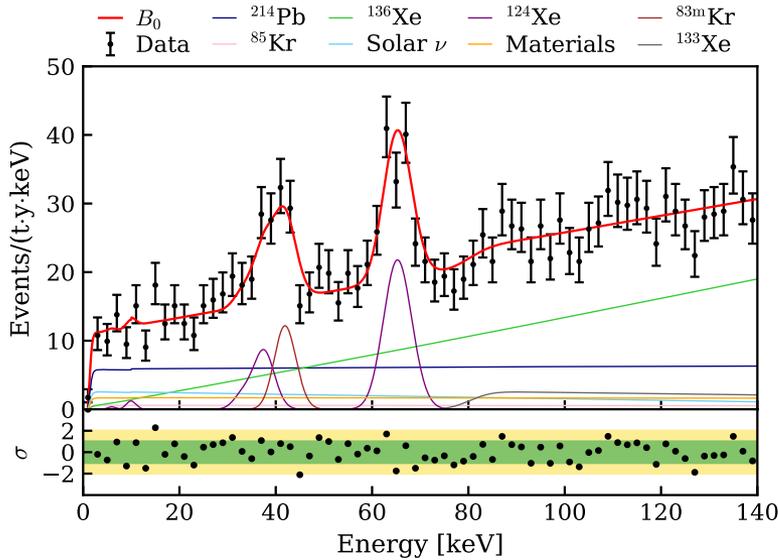
- World's best sensitivity for SI WIMP-type DM
- Observed SI exclusion:

$$\sigma_{\text{DM}}^{\text{SI}} = 2.2 \times 10^{-48} \text{ cm}^2 \text{ at } 40 \text{ GeV}/c^2$$

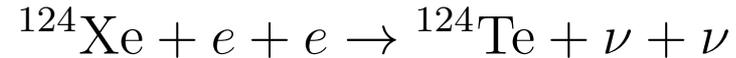


Important EW physics with BSM experiments

- Double EC capture in ^{124}Xe . **Xenon1T,nT, Panda-X** and **LZ**



51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
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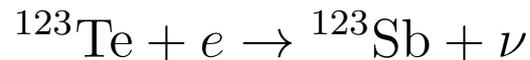


First direct observation of double electron capture $\tau = 1.8 \times 10^{22}$ yr

Neutrino-less channels will be interesting $^{124}\text{Xe} + e \rightarrow ^{124}\text{Te} + e^+$

G. Luchetti, additional slides

- EC in ^{123}Te . **CUORE** + preceding results by **Cuoricino** and **CUORE-0**

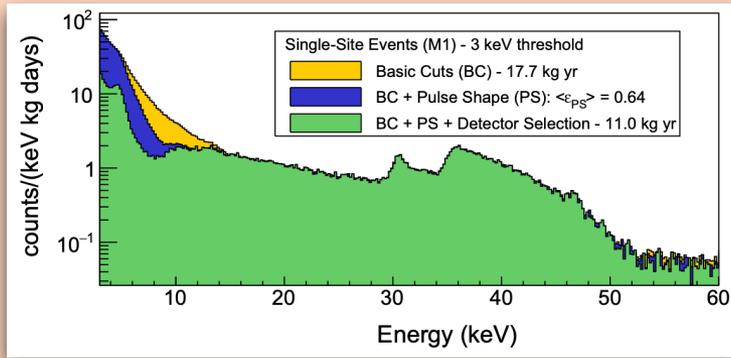


There is a significant anomaly built into the interpretation of CUORE results!

Important: CUORE currently does not claim the observation of EC in ^{123}Te .

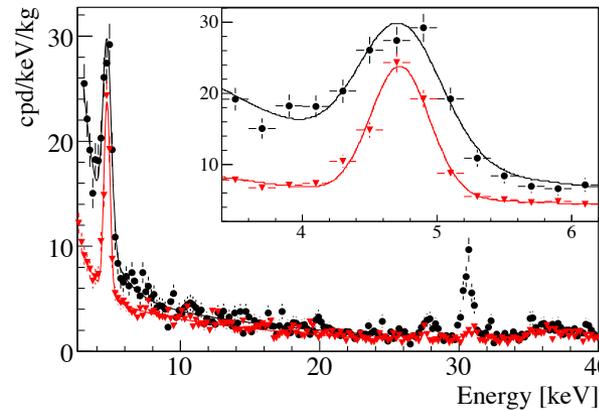
Exciting peaks ... at a wrong place

- **Low energy studies:** specific low-energy variables and event-level cuts to optimise sensitivity at keV-scale targeting  Phys. Rev. D 113, 012012 (2026)
- spectral studies potentially related to ^{121}Te , ^{123}Te , ^{125m}Te decays (not measured yet)



A. Campani, CUORE

Energy [keV]	Multiplicity	Rate [counts/(kg d)]
~ 4.7	M1	19.1 ± 1.0
~ 10	M1	0.66 ± 0.07
~ 13	M1	0.67 ± 0.07
~ 31	M1	1.35 ± 0.04
~ 36	M1	8.3 ± 0.3



CUORE-0 spectrum.
Peak at 4.7 keV

4.7 keV – EC from $2s_{1/2}$ state (L1)

30.5 keV – EC from $1s_{1/2}$ state (K)

$$\frac{\text{Rate(L1)}}{\text{Rate(K)}} \simeq \left(\frac{1}{8} + \text{small corr} \right) \times \left(\frac{E_\nu(\text{L1})}{E_\nu(\text{K})} \right)^6 \simeq 14.3$$

Experimental ratio $\sim 14.1 \pm 1.0$

Everything (energies and ratios of rates) is consistent with EC decay of ^{123}Te from L1 and K subshells. A big problem is that a 20 times (!) stronger line from L3 ($2p_{3/2}$) predicted by EC theory is missing!

EC theory of ^{123}Te decay in 1 slide

- This is so-called doubly forbidden unique transition with small Q value of 51.9 keV
- ^{123}Te ($I = 1/2$) \rightarrow ^{123}Sb ($I = 7/2$) requires large change in angular momentum and octupolar nuclear matrix element, call it T_{ijk} .
- It is the same nuclear matrix element for transitions from every electronic subshell Assumption of factorization that should work well due to a huge nuclear/electronic scale separation; Rate $\sim (T_{ijk})^2 \times |R(0)|^2$ or $(T_{ijk})^2 \times |R'(0)|^2$ for s and p waves etc.
- Captures from higher angular momentum electronic shell is favorable as the outgoing neutrino is allowed to be in a lower partial wave. $p_e(\text{orbit}) \gg E_\nu$
- Numerically, Rate(L3)/Rate(L1) ≈ 25 .
- L3 line at 4.1 keV is *missing*! Factorization must be broken (!!) This is not impossible but super-highly unusual. Some accidental cancellations for p3/2 wave electronic waves but not for s1/2.

Disclaimer: this is probably not a sign of new physics but a very unusual effect inside atomic physics. Deserves further studies with isotopically enriched ^{123}Te sample

M. Pospelov, 2013, unpublished, with some ideas how this could happen.

Conclusions

- *Moriond conference series remains a viable place for exchanging ideas and for experiment-theory interactions.*
- Theoretical thought, as reflected in excellent talks at this meeting, does not stay idle, and addresses SM and BSM physics at high-energy, in flavor, neutrino physics and rare observables. We make strong connection to cosmology via the dark matter, or more generically, dark sector studies.
- [For more detailed conclusions, see slides with “Take away messages”.]

From all the participants, huge thanks to the organizers for yet another superb Moriond meeting!!