Summary of Theory
Electroweak Interactions & Unified Theories

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Rencontres de Moriond 2014

Theory Summary Talk

Jean Iliopoulos

ENS PARIS

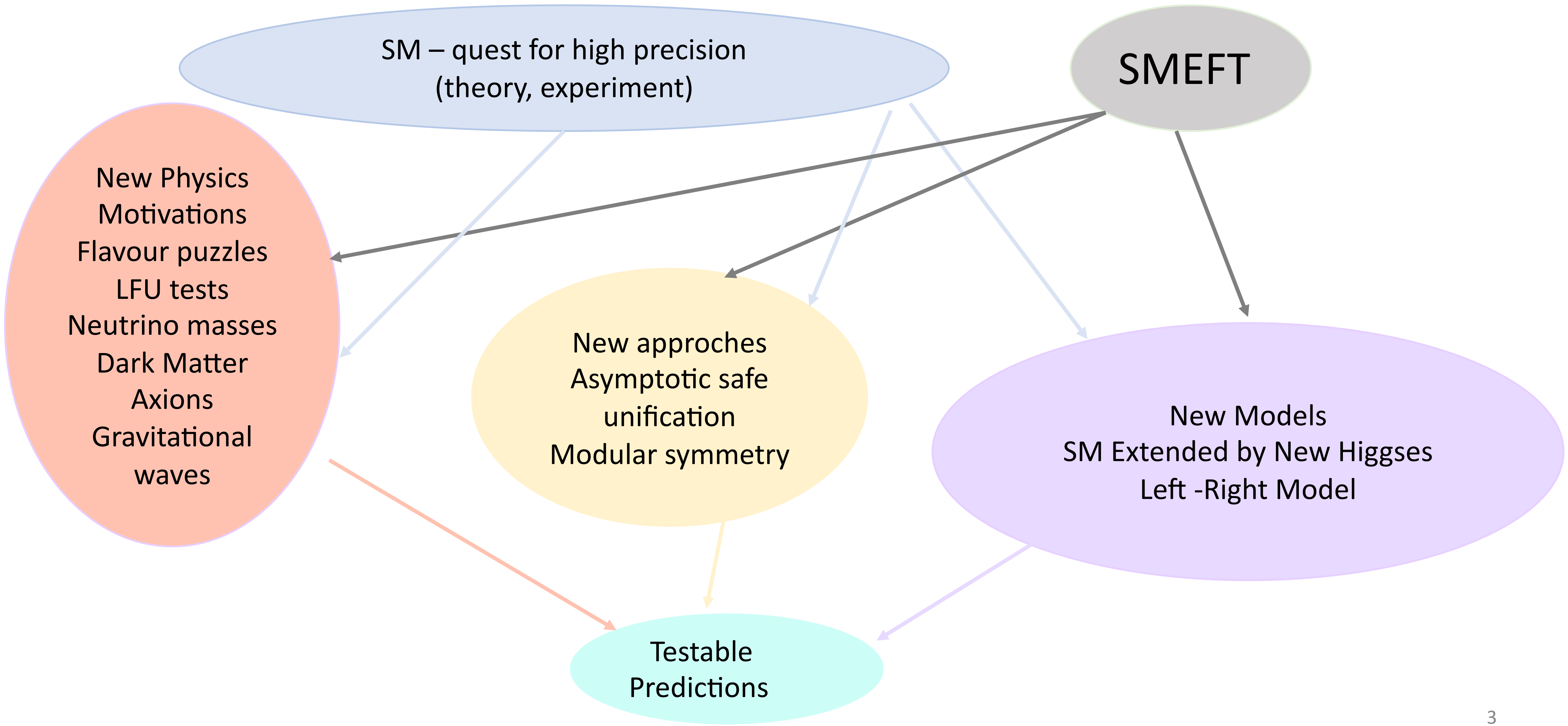
Contents:

10 years ago!

NEW PHYSICS must be around the corner…

- ….but we see no corner!

Outline


SM – quest for high precision
(theory, experiment)
SMEFT
New Physics
Motivations
Flavour puzzles
LFU tests
Neutrino masses
Dark Matter
Axions
Gravitational
waves
New approches
Asymptotic safe
unification
Modular symmetry
New Models
SM Extended by New Higgses
Left -Right Model
Testable
Predictions

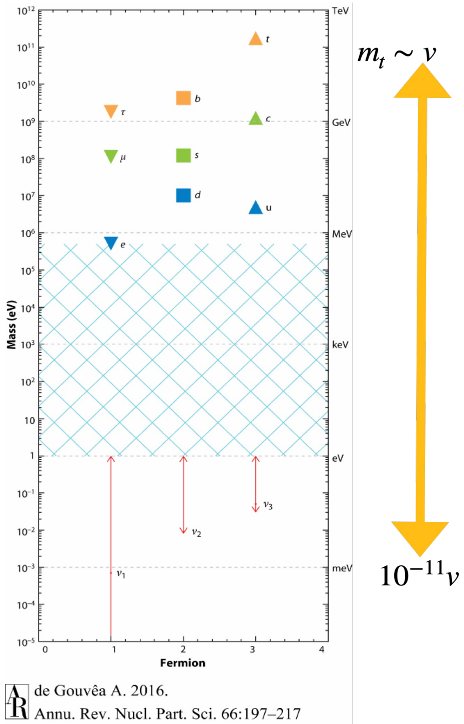
What SM cannot explain?

- Neutrino masses and mixings
- The presence of non-baryonic, cold dark matter
- Dark matter is neutral, colourless, non-baryonic, and massive. The only such particles in the SM are neutrinos, (these are too light, warm dark matter)
- The observed abundance of matter over anti-matter

> "I would rather have questions that can't be answered than answers that can't be questioned."
> — Richard Feynman

Unexplained features of the SM

- The inability to describe physics at Plankian scale
- The structure of fermion masses and mixing
- The smallness of measured electric dipole moments
- The comparable size of 3 gauge couplings
- The quantization of electric charge
- The number of fermion families



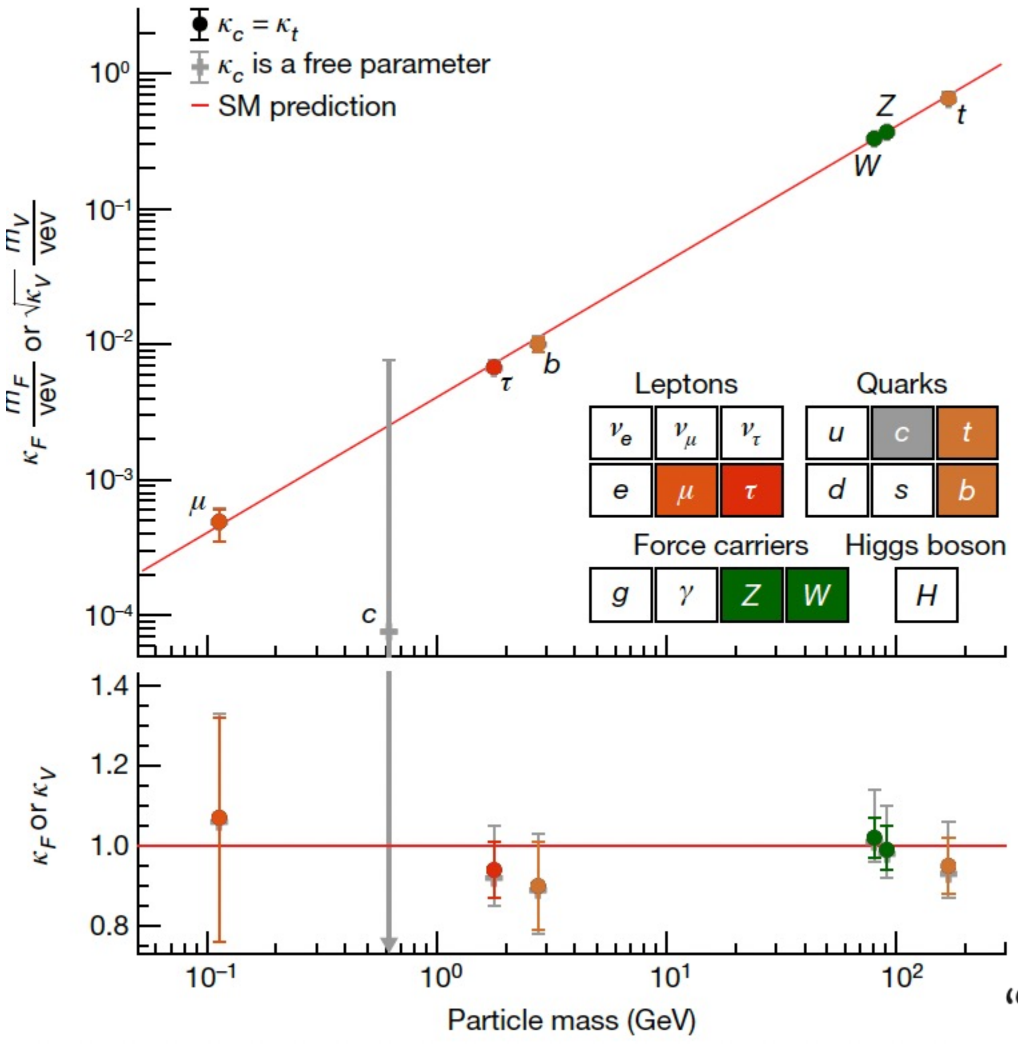
Do we understand this mass range?

Beyond Standard Model

We do not know what the rules of the game are; all we are allowed to do is to watch the playing. Of course, if we watch long enough, we may eventually catch on to a few of the rules. The rules of the game are what we mean by fundamental physics.

Richard Feynman

ATLAS, Nature, 607, 52–59 (2022)



A great test of the SM

This linear dependence tells us that masses of SM fermions (no neutrinos) originate from SM vev.

Evidence that the Higgs mechanism is responsible for the masses of weak bosons and the third generation of fermions!

“The progress of science has been largely a matter of discovering what questions should be asked.”

— **Steven Weinberg, To Explain the World: The Discovery of Modern Science**

Asymptotic UV safe unification of gauge and Yukawa couplings

Aldo Deandrea

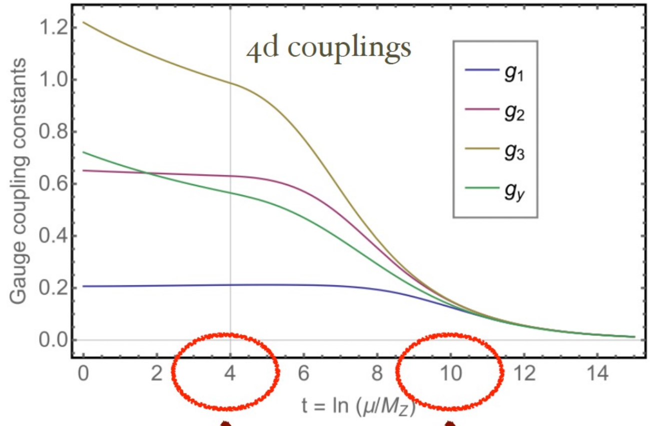
1. Asymptotically Safe (AS) theories with large N_f
2. AS via perturbative fixed points and Susy
3. AS via extra compact dimensions

Asymptotic unification is flow towards UV fixed point

Fixed point

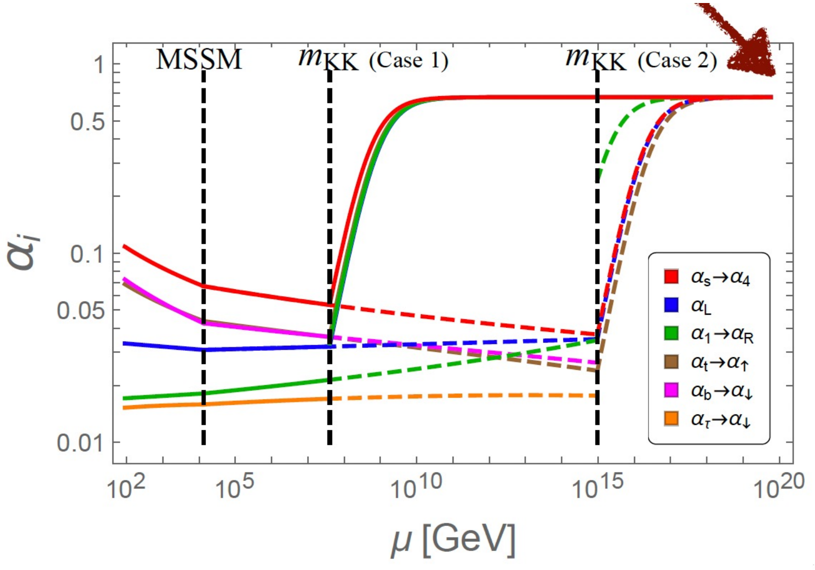
$\tilde{\alpha} = \mu R \alpha$ 5d 't Hooft coupling

$$2\pi \frac{d\tilde{\alpha}}{d\log\mu} = 2\pi\tilde{\alpha} + b_5\,\tilde{\alpha}^2 \quad \rightarrow \quad \tilde{\alpha}_{UV} = -\frac{2\pi}{b_5}$$



1st KK mode kicks in at t ~4

E_6: the UV fixed point $\tilde{\alpha}_{UV} = 2/3$



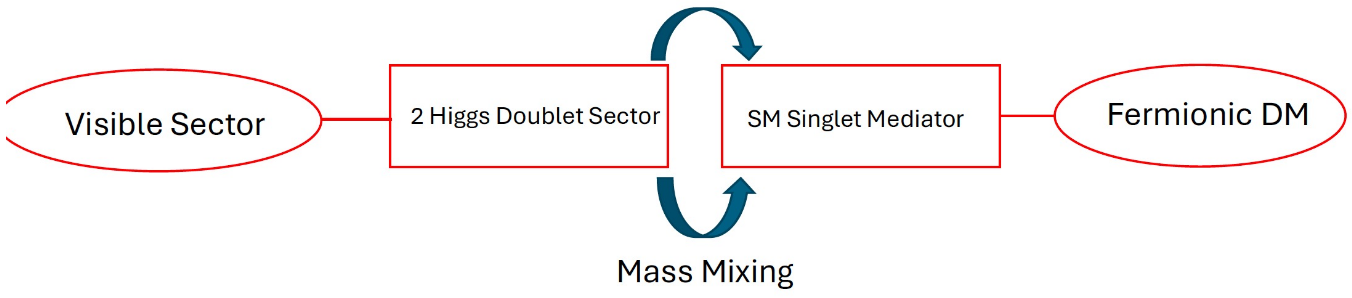
Only 1 generation allowed in the bulk

- New paradigm for (asymptotic) unification (aGUT)
- A dark Matter candidate (the lightest -field S)
- Baryogenesis can be reproduced (SU(5) model)
- E_6 model allows to unify gauge and Yukawa couplings (for one generation)
- Lower scale allowed (Model 1) from PS breaking (~10^3 TeV)
- Two light generation predicted by gauge anomalies on the SO(10) boundary (Model 2, high KK scale ~10^{16} GeV)

Status of Models with Extended Higgs Sectors

Giorgio Arcadi

General Setup



- Good compromise between theoretical consistency and predictivity (still limited number of free parameters);
- Benchmark for a large variety of collider studies;
- Interesting Dark Matter phenomenology.
- Possibility of triggering First Order Phase Transition (FOPT).

The 2HDM+s and 2HDM+a are very interesting BSM benchmarks which can be used to interpret very different experimental signals.
Arcadi & collaborators have considered the capability of such models of interpreting the 95 GeV excess at LHC.
In 2HDM+a , there is a possibility to reproduce g-2.

Direct bounds on Left-Right gauge boson masses

Luiz Vale Silva

$$LRM = \underbrace{SU(3)_C}_{g_s} \times \underbrace{SU(2)_L}_{g_L} \times \underbrace{SU(2)_R}_{g_R} \times \underbrace{U(1)_X}_{g_X}$$

$$\text{LR-SSB @ scale } \kappa_R, \gamma\text{: mixing } W_R^3 \text{ and } W_X$$

$$\downarrow$$

$$SM = SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\text{EW-SSB @ scale } \kappa_{EW}, \theta_W\text{: mixing } W_L^3 \text{ and } W_Y$$

$$\downarrow$$

$$SU(3)_C \times U(1)_{EM}$$

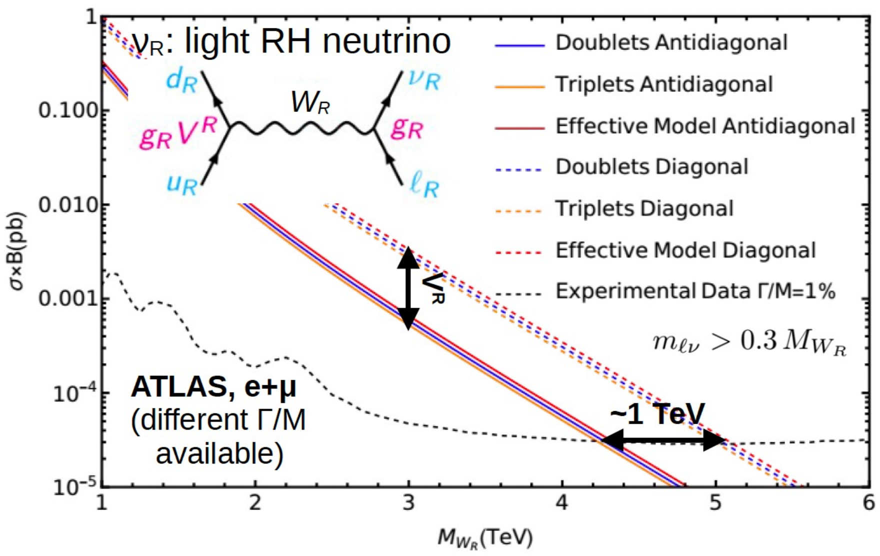
Scalar sector

$\Delta_R \sim (\mathbf{1},\mathbf{1},\mathbf{3})_1 , \ \Delta_L \sim (\mathbf{1},\mathbf{3},\mathbf{1})_1$ $\chi_R \sim (\mathbf{1},\mathbf{1},\mathbf{2})_{1/2} , \ \chi_L \sim (\mathbf{1},\mathbf{2},\mathbf{1})_{1/}$

triplet doublet

Fermionic sector

- Yukawa interactions: Dirac masses for (Q_L,Φ Q_R) and (L_L,Φ L_R)
-(Eff) Non-ren. dim.-5 interactions with SU(2)L and SU(2)R doublets.
- RH neutrinos are introduced (B-L is anomaly free);
- no additional fermion in the simplest version
- In (D), Dirac masses only; in (T), also Majorana masses, see-saw mechanism
- Extension of the PMNS matrix; R_H unitary counterpart $V_R$of the CKM-like matrix V_L in the quark sector
- P: V_R ~ V_L (manifest); C: V_R ~ V_L* (pseudo-manifest)



	Left	Right
$SU(2)_L$	2	1
$SU(2)_R$	1	2
quarks : $B = 1/3$	$\begin{pmatrix} U_L \\ D_L \end{pmatrix}$	$\begin{pmatrix} U_R \\ D_R \end{pmatrix}$
leptons : $L = -1$	$\begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ \ell_R \end{pmatrix}$

Channel		$\Phi + \chi_{L,R}$ (D)	$\Phi + \Delta_{L,R}$ (T)	$\chi_{L,R}$ (Eff)
$Z_R \to \ell_i \bar{\ell}_i$	M_{Z_R}	4.3	4.2	4.3
$W_R \to jj$, anti-diag.	M_{W_R}	2.1	2.0	2.1
$W_R \to \ell_i \bar{\nu}_R$, anti-diag.		4.3	4.2	4.3
$W_R \to jj$, diag.	M_{W_R}	2.9	2.7	3.0
$W_R \to \ell_i \bar{\nu}_R$, diag.		5.1	5.0	5.1

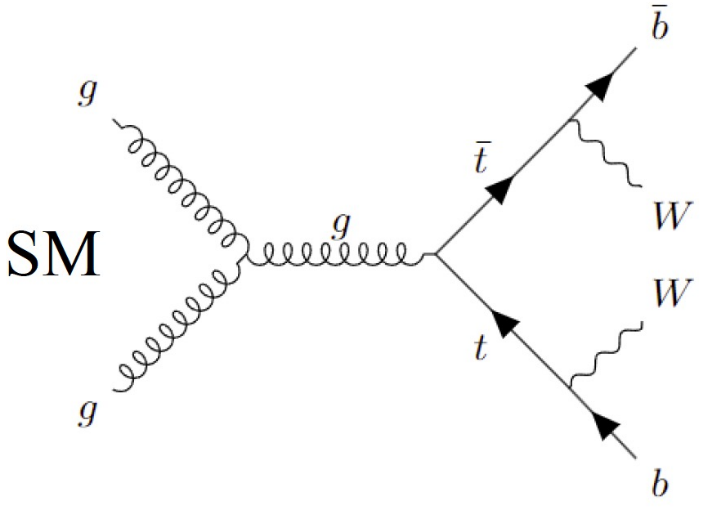
significant impact of the V^R texture, decay mode, and neutrino sector

masses in TeV, about 95%CL

νR: light RH neutrino

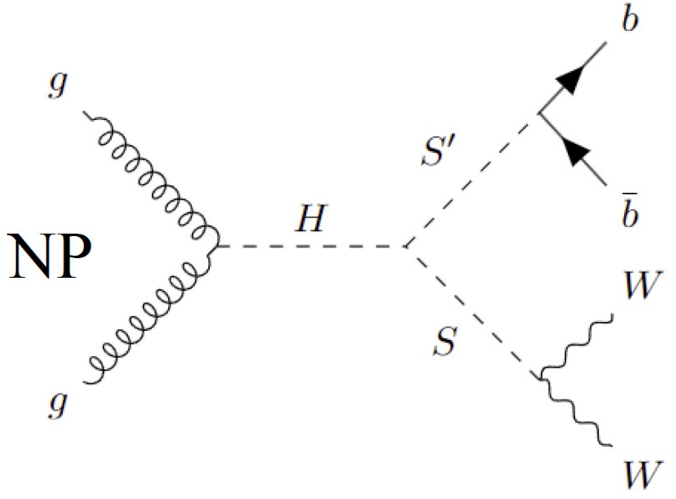
not significant impact of the scalar realization

New Higgses at the Electroweak Scale and Differential Top-Quark Distributions



Andreas Crivellin

ATLAS analysis normalized to the total cross section
- only sensitive to the shape of NP
- NP at small angels can explain deficit at large angles
- Associated production of new scalars decaying to WW and bb has a top-like signature



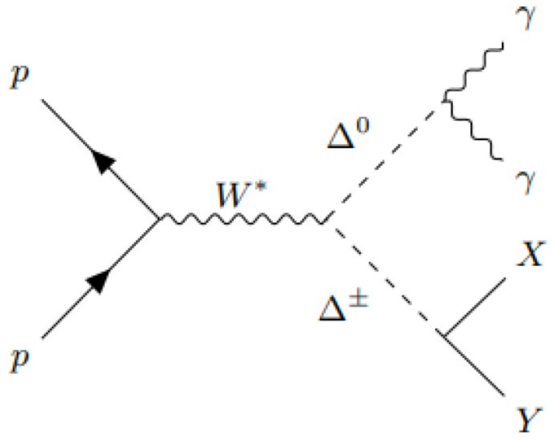
Related to the 95 GeV and 151.5 GeV hints?

- S'(95): Singlet decays dominantly to bb
- S(151.5): decays dominantly to WW

Is the 151.5 GeV Boson a Triplet?

Model
Δ2HDMS

Field	$SU(2)_L$	$U(1)_Y$
ϕ_s	2	0
ϕ_2	2	1/2
ϕ_1	2	1/2
Δ	3	0

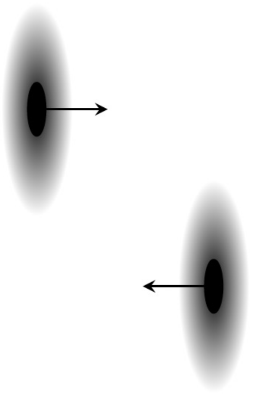


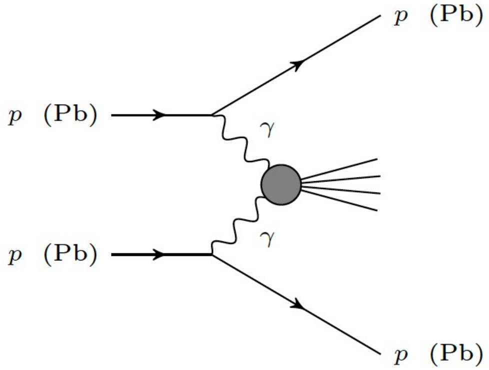
SM
SMEFT

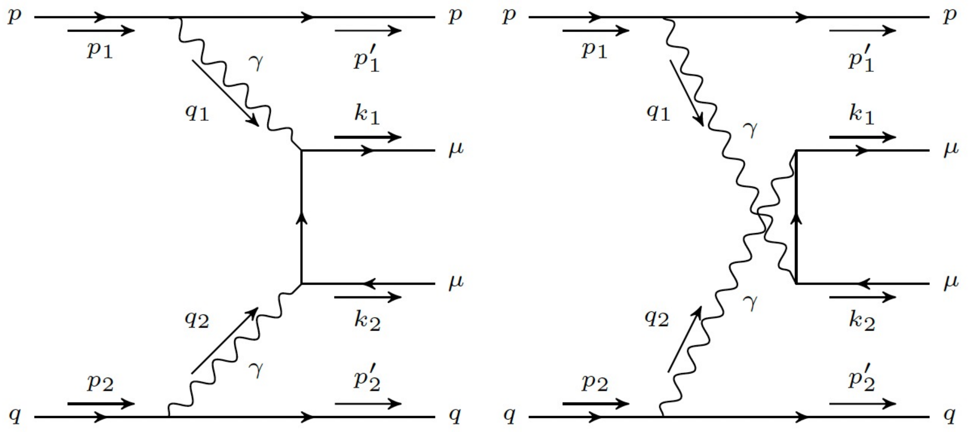
pp → ℓ⁺ℓ⁻X via γγ and γZ

S. I. Godunov

$$\sigma_{\text{inelastic}}(pp \to p\mu^+\mu^- X) = \sum_q \sigma(pq \to p\mu^+\mu^- q)$$







- It is possible to detect protons in forward detectors to reconstruct full kinematics.
- Accessible analytically with equivalent photons approximation (EPA).
- Formulae can be easily adopted for new particles (γ couples to electric charge).

$$Q^2 \lesssim (200\ \text{MeV})^2 \quad \Rightarrow \quad \frac{Q^2}{M_Z^2 + Q^2} \sim 10^{-5}$$

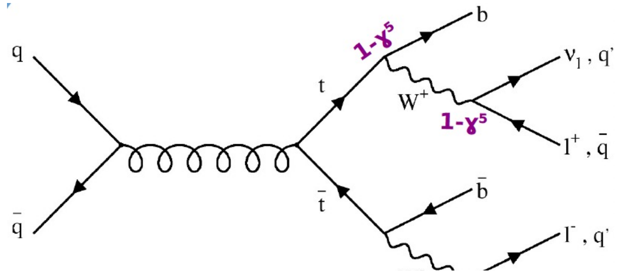
-For ultraperipheral collisions weak interaction correction is negligible.
-Weak interaction correction to the lepton pair production in semi-exclusive process gives few percent increase of the production cross section.
-When the lower limit on the net transverse momentum of the produced pair is set, the correction goes up and can reach 20 %.
-Numerical calculations were performed with the help of libepa (https://github.com/jini-zh/libepa) — a library for calculations of cross sections of ultraperipheral collisions (and beyond!) under the equivalent photonsapproximation.

Bell inequality with top quark pairs

Claudio Severi

Testing QM!

Top spin correlations
The weak decays t → Wb, W → ℓν
transfer the spin state to the decay products
Spin is an observable
Tops decay before hadronizing,
behaving like free, spinning particles



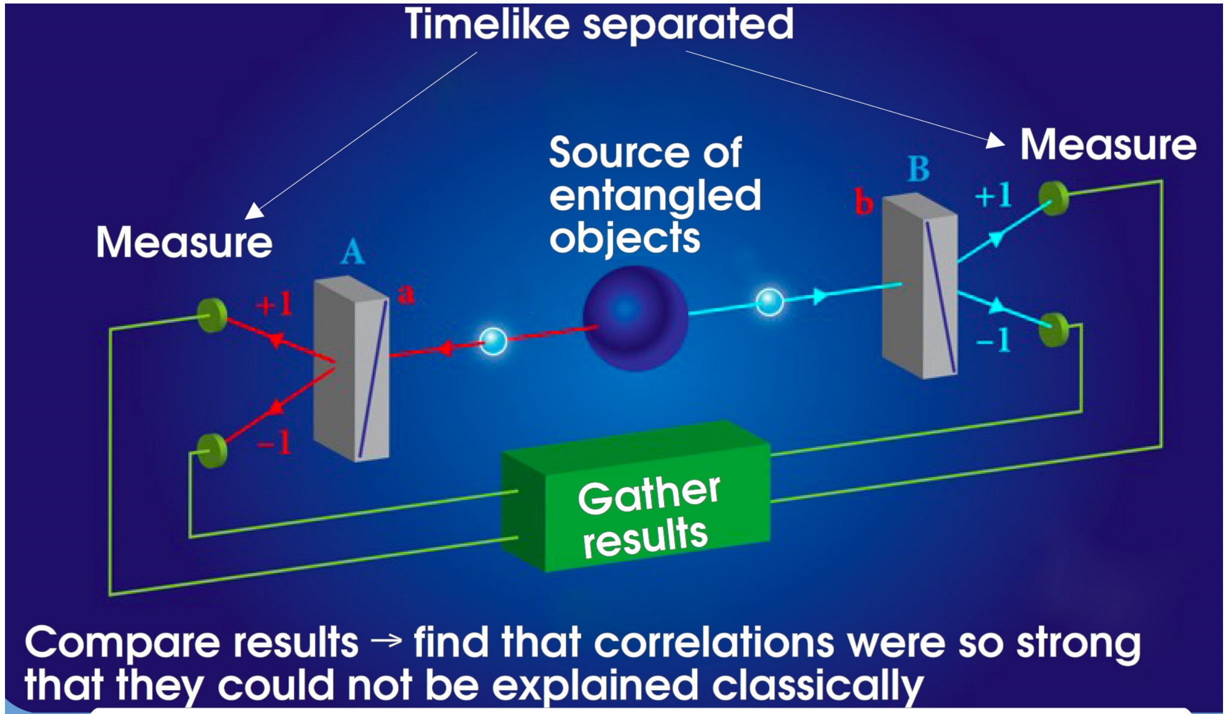
$$\rho = \frac{I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j}{4}$$

Entalgment

$$-C_{kk} - C_{rr} - C_{nn} > 1$$

Bell violation

$$\sqrt{2}\left| - C_{rr} + C_{nn}\right| \leq 2$$



$$|C(a_1, b_1) - C(a_1, b_2) + C(a_2, b_1) + C(a_2, b_2)| \leq 2$$

QM is exactly linear. Usually linear models are some "LO" approximation (eg. Maxwell eqns)

"Quantum" observables provide complementary information to classical ones

A series of studies have suggested a Bell beasurement is doable at the HL-L

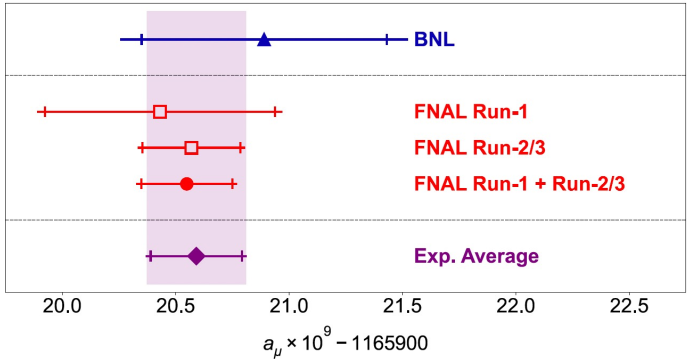
g-2

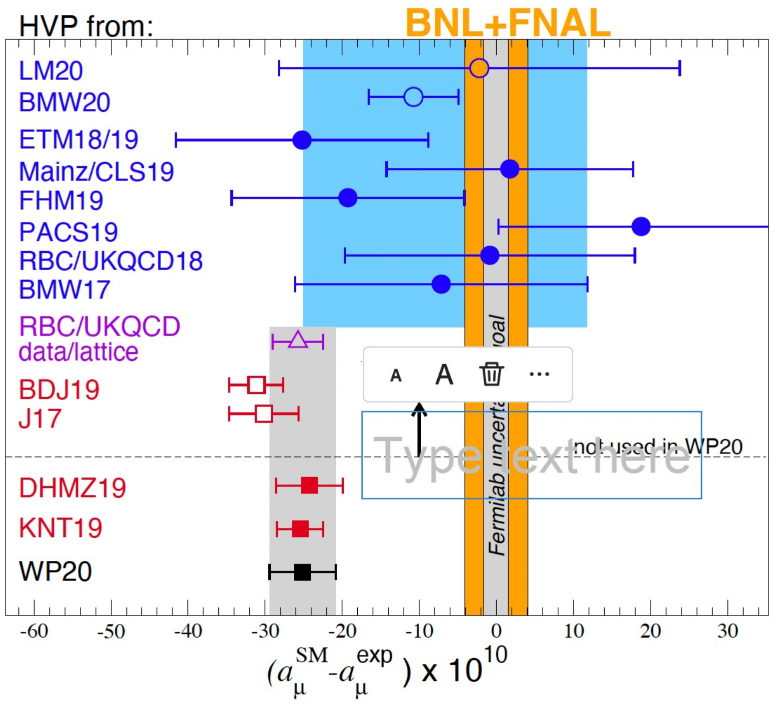
Despite officially retiring from Cornell in 1995, Kinoshita (born in Tokyo 1925) remained active in physics. In 2018, aged 93, he published a paper in *Physical Review D* (**97** 036001) refining his calculation of *g*-2 .His final paper – on the general theory of *g*-2 calculations to all orders – appeared the following year in *Atoms*

Status of muon g-2

Christoph Lehner

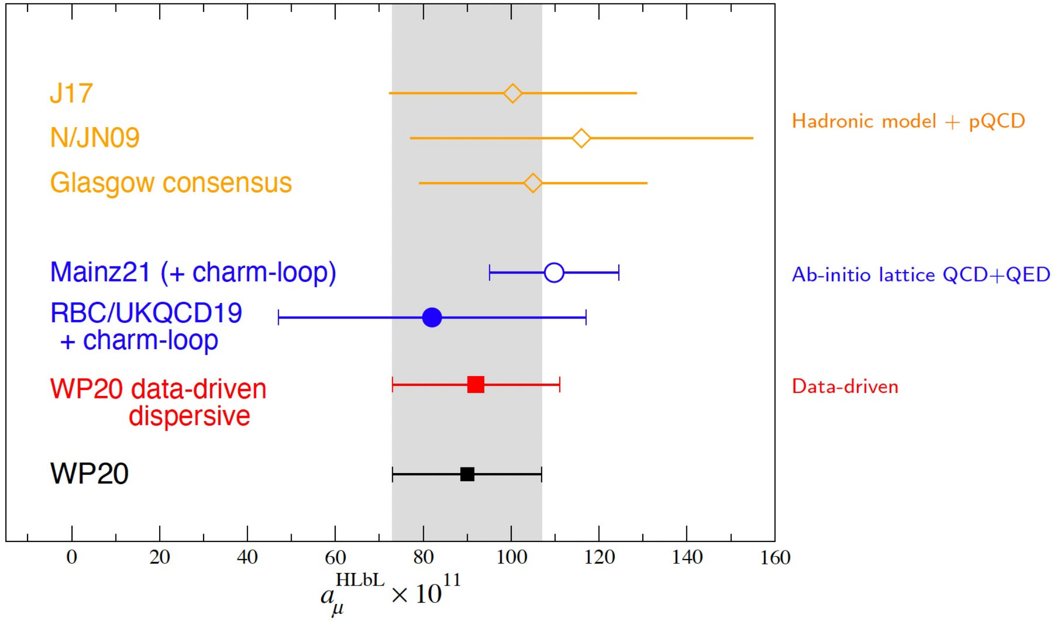
Experimental status (PRL 131 (2023) 16, 161802)





The **CMD-3, KLOE, BaBar** data in e+e- → ππ disagree among themsels

Status of hadronic light-by-light contribution



Systematically improvable methods are maturing; uncertainty to a_μ controlled at 0.15ppm; cross-checks detailed in Theory Initiative whitepape

-Short distance window (up to t_0 = 0.4 fm) dominated by pQCD; consistency between LQCD and LQCD/pQCD

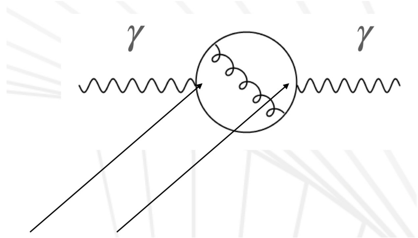
-Intermediate window (t_0 = 0.4 fm, t_1 = 1.0 fm);consistencybetween different LQCD results established

-The long-distance window is at this point not yet independently checked! Only BMW20 result at sub-percent precision. This is expected to change in 2024!

Electroweak precision physics (mixing angle using lattice input) at low energies, running of alpha

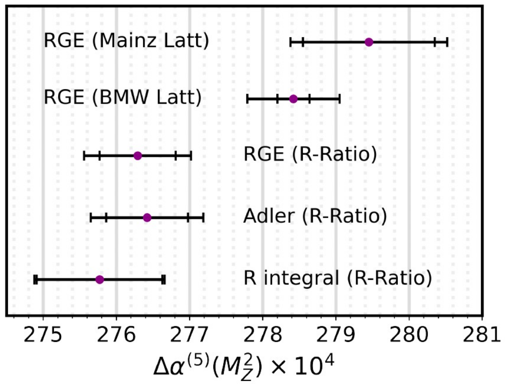
Rodolfo Ferro-Hernandez

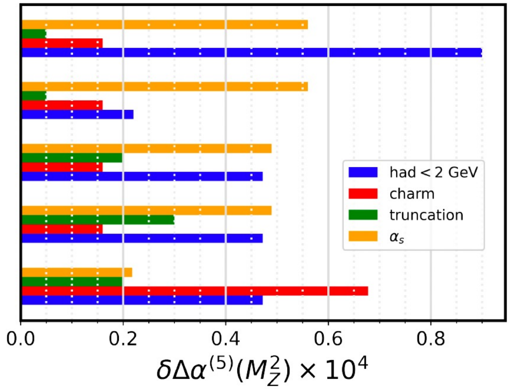
theoretically driven prediction for the hadronic contribution to the electromagnetic running coupling at the Z scale using lattice QCD and perturbative QCD



$\Delta\alpha^{(5)}(M_Z^2) = [279.5 \pm 0.9 \pm 0.59] \times 10^{-4}$ Mainz Collaboration

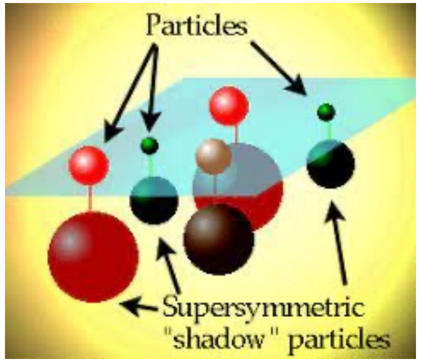
$\Delta\alpha^{(5)}(M_Z^2) = [278.42 \pm 0.22 \pm 0.59] \times 10^{-4}$ BMW Collaboration



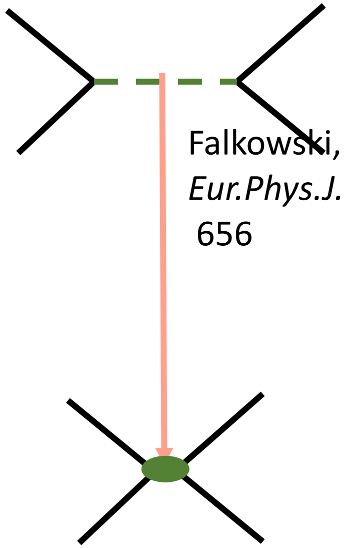


- Using lattice QCD as input $sin^2\hat{\theta}_W(0)$ is computed.
- They found a 3σ tension when compared to the result using cross section data from e^+e^-.
- As expected the tension is in the same direction as the tension in α.
- Tension smaller than the precision expected in future PV experiments.
- We computed the correlation of a_μ^{hpv} with both $sin^2\hat{\theta}_W(0)$ and $\hat{\alpha}$.
- There is consistency between the SM prediction and the experimental average of M_W^2

SMEFT role towards a theory of NP



new heavy particle



Falkowski, *Eur.Phys.J.C* 83 (2023) 7, 656

integrate out heavy field

There are many ways in which higher-dimensional operators can affect observables.

- **New vertices:** interaction vertices in the SMEFT Lagrangian that do not occur in the SM Lagrangian, due to symmetries or accidental reasons.
- **New Lorentz structures:** interaction vertices that do occur in the SM Lagrangian, but which appear in the SMEFT with a different number of derivatives, different contractions of Lorentz or spinor indices, etc.
- **Modified couplings:** corrections to the coupling strengths of the interaction terms present in the SM Lagrangian.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d\geq 5} \frac{C_k^{(d)}}{\Lambda^{d-4}} \mathcal{O}_k^{(d)}$$

$$\mathcal{L}_{D=6} = \mathcal{L}_{D=6}^{\text{bosonic}} + \mathcal{L}_{D=6}^{\text{Yukawa}} + \mathcal{L}_{D=6}^{\text{current}} + \mathcal{L}_{D=6}^{\text{dipole}} + \mathcal{L}_{D=6}^{\text{4-fermion}} .$$

Gauge fields, Higgs

Warsaw basis, Grzadkowski et al, 1008.4884

SMEFT papers: Manohar et al., 1308.2627, 1309.0819, 1310,4838, 1312.2014

N = 2499 dim-6 operators that conserve B and L — rich flavor structure!

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

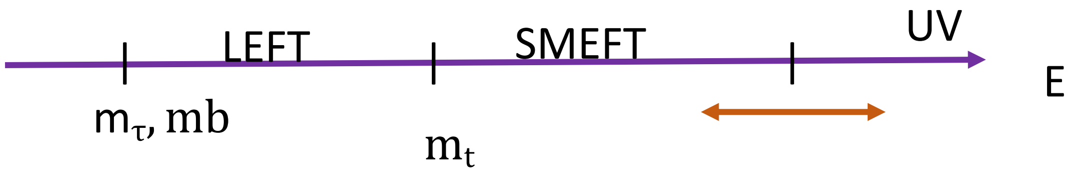
$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

From SMEFT to low energies (LEFT)

How to connect this set-up to low energy observables?



1. Renormalisation group evolution (RGE) running of Wilson coefficents from the matching scale down to electroweak scale;

2. Below the weak scale → EFT that is an $SU(3)_c \otimes U(1)_{em}$ gauge theory and contains the SM fermions, but not the top quark (H, W, Z, t are integrated out (1908.05295, Dekens&Stoffer)

3. The LEFT Lagrangian consists of QCD and QED and a tower of additional higher-dimension effective operators

4. The matching condition at the electroweak scale requires that the LEFT and SMEFT S-matrix elements for the light-particle processes agree:

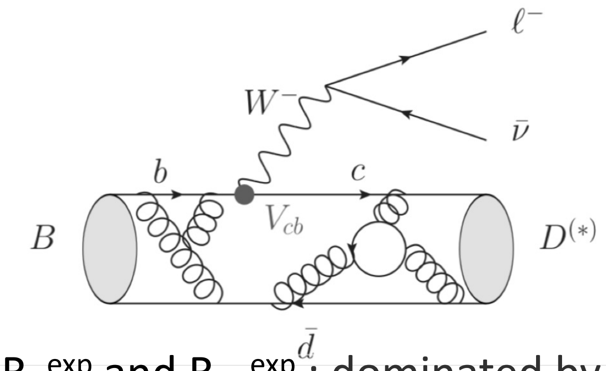
$$M_{LEFT} = M_{SMEFT}$$

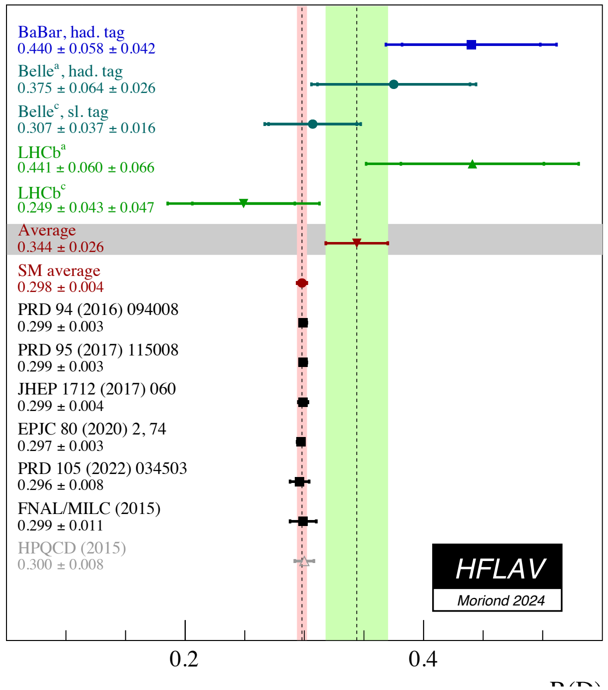
$$\mathcal{M}^{\mathrm{LEFT}}_{\mathrm{tree,\ ren.}} + \mathcal{M}^{\mathrm{LEFT}}_{\mathrm{ct}} + \mathcal{M}^{\mathrm{LEFT}}_{\mathrm{loop}} = \mathcal{M}^{\mathrm{SMEFT}}_{\mathrm{tree,\ ren.}} + \mathcal{M}^{\mathrm{SMEFT}}_{\mathrm{ct}} + \mathcal{M}^{\mathrm{SMEFT}}_{\mathrm{loop}} .$$

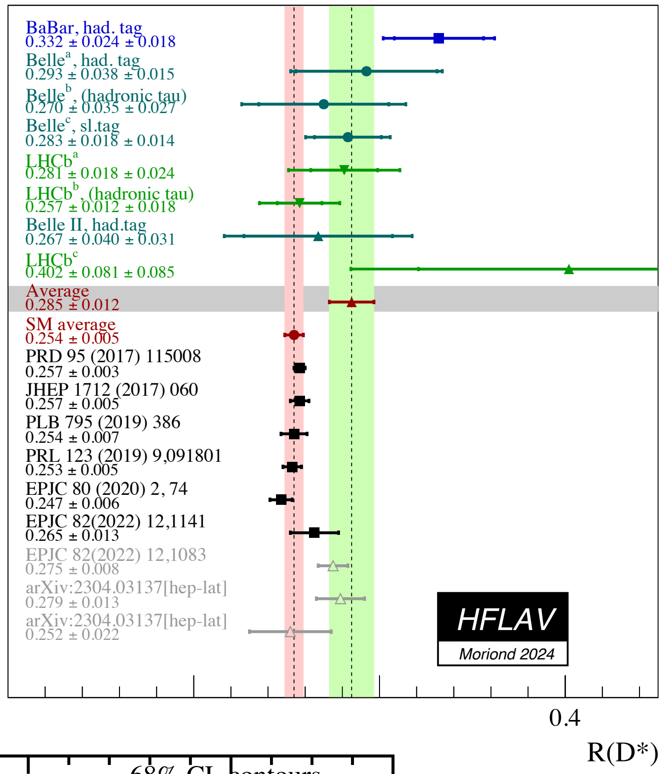
Flavour Physics
Beauty, Charm, CP violation

$R_{D^{(*)}}$ puzzle

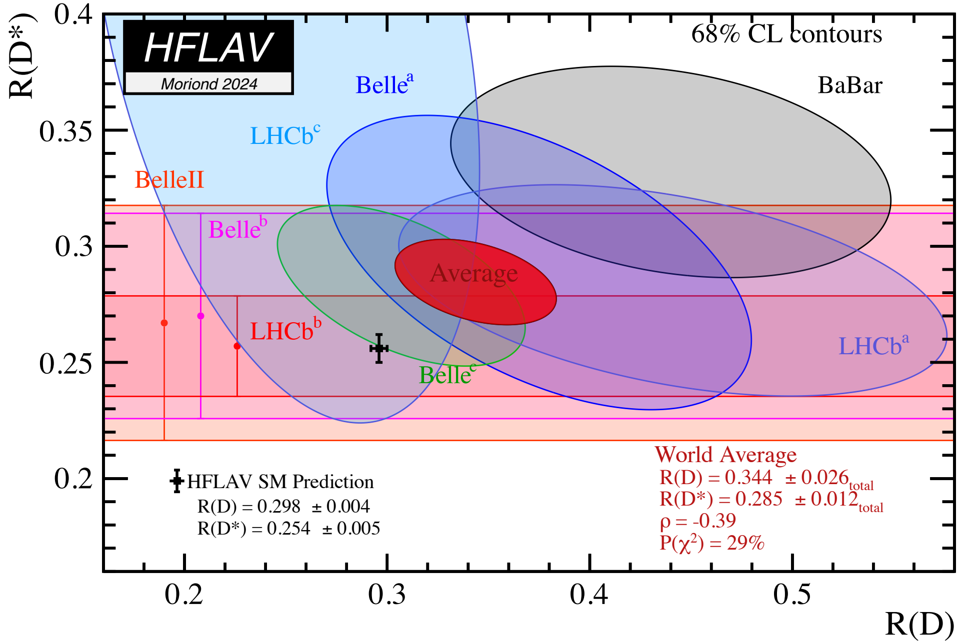
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}l\bar{\nu})}\Bigg|_{l\in\{e,\mu\}}$$







- R_D^{exp} and $R_{D^*}^{exp}$: dominated by BaBar!
- In $R_{J/\psi}^{exp}$ and $R_{\Lambda c}^{exp}$ limited precision.

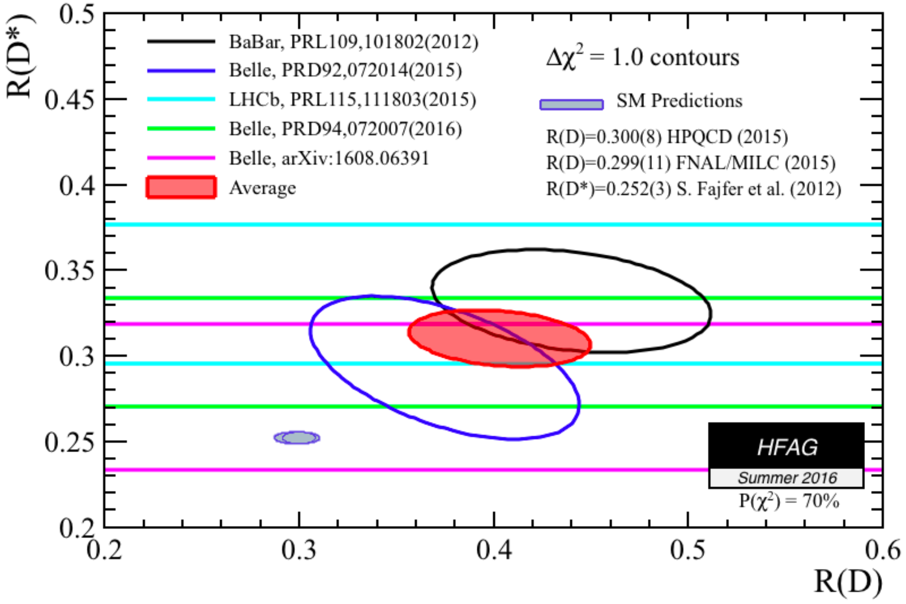


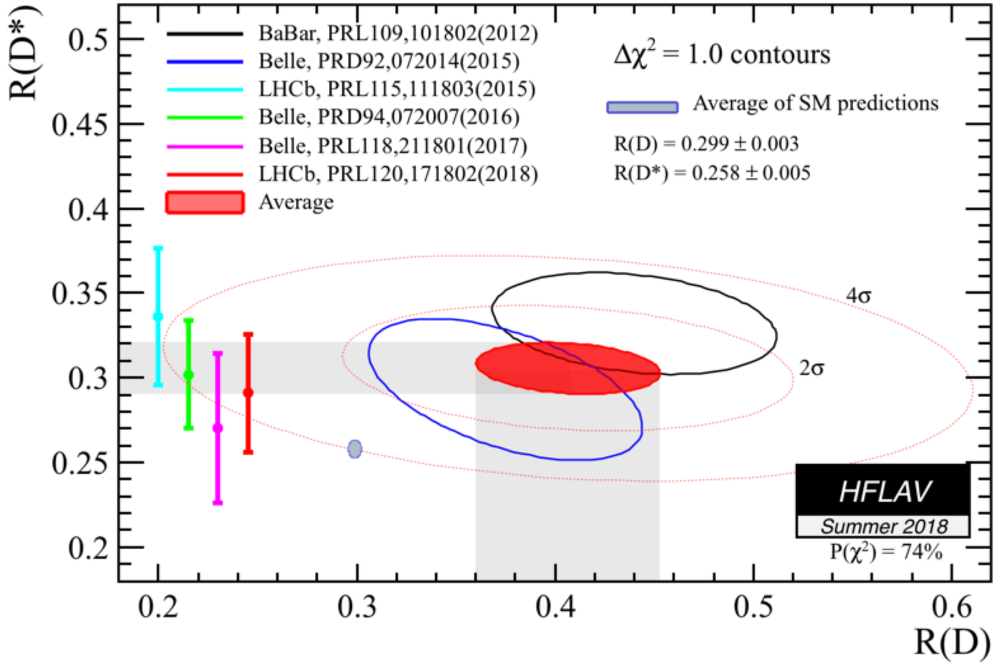
-Solution for the puzzle - New Physics (?!)

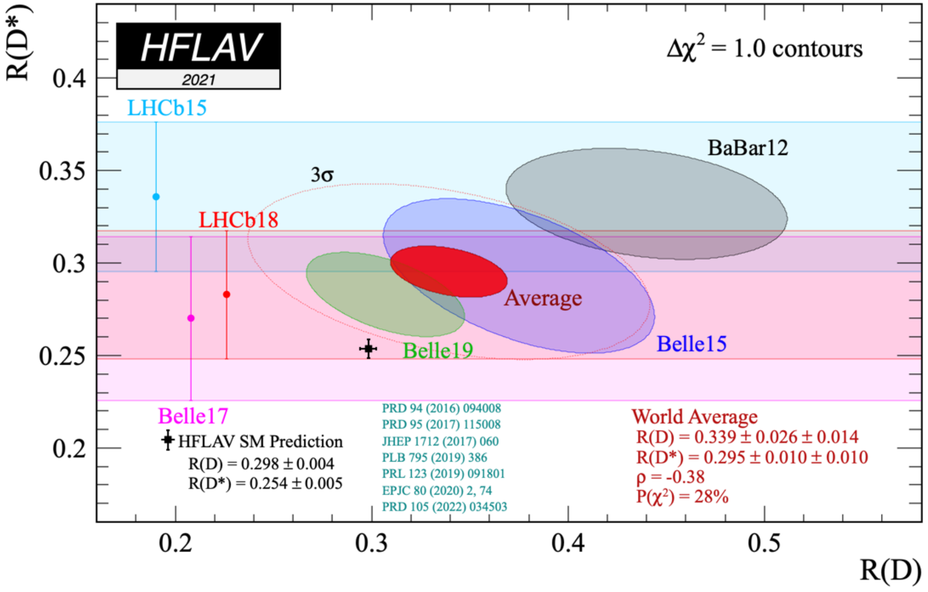
-Precise knowledge of form factors needed!

LHCb new results at Moriond 2024!

$R_{D(*)}$ over the years







There are still some issues!

$$< D^{(*)}(p',(\epsilon))|\bar{c}\,\Gamma^{\mu}\,b|B(p) >= \sum_j K_j^{\mu}\mathcal{F}_j(q^2)$$

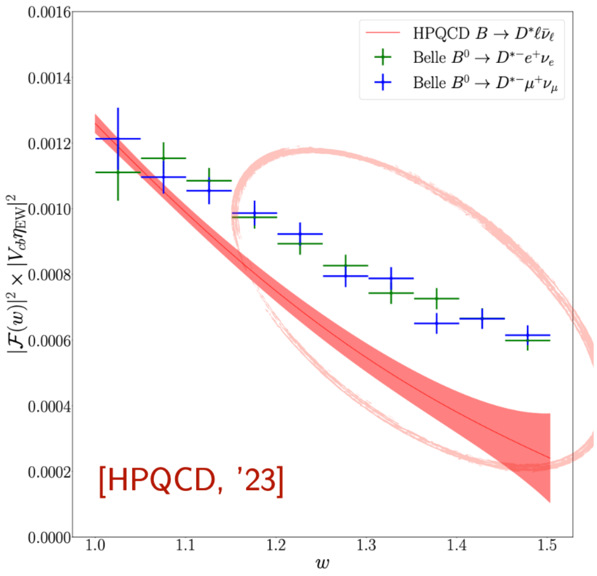
1) $B \to D$: one (two) form-factors with $f_0(0) = f_+(0)$ at $q^2 = 0$;
Lattice QCD at $q^2 \neq q^2_{max}$ for both form-factors.

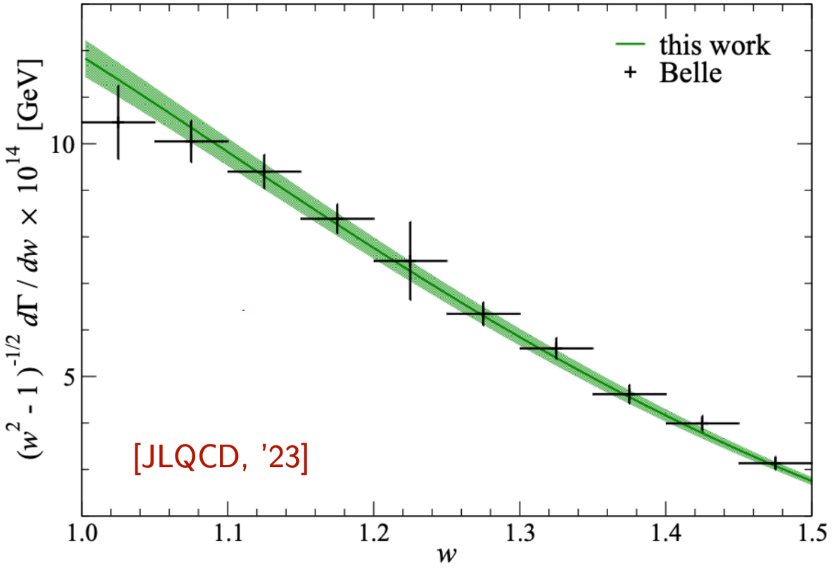
If q^2 spectrum for l= e,μ

$$R_D^{latt+exp} = 0.295(3)$$

$$R_D^{latt} = 0.293(5)$$

2) $B \to D^*$: three (four) form-factors;
First lattice results at $q^2 \neq q^2_{max}$! Tensions with $B \to D^* l\bar{\nu}$ exp. data





$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2\,m_B\,m_{D^*}}$$

JLQCD, R(D^*)=0.252 ± 0.022, Y.Aoki et al.2306.05657

independent LQCD results + Belle-II data needed!

$R_{D^{(*)}}$ explanation –scalar leptoquarks

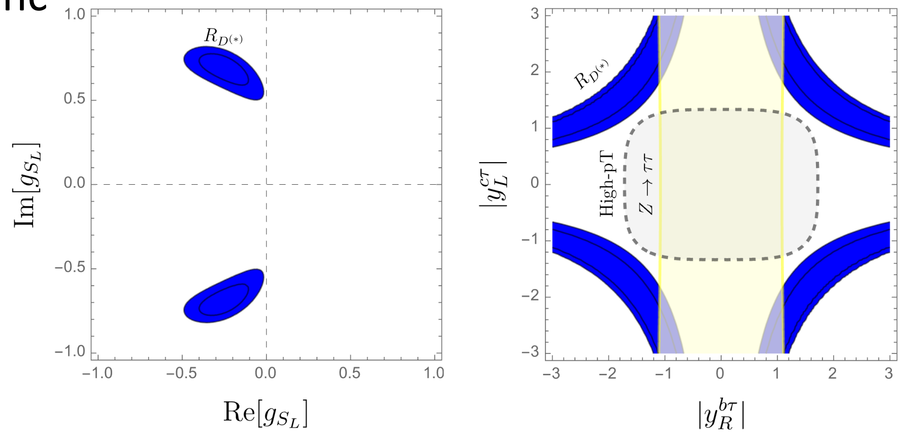
$$\mathcal{L}_{cc} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})\,(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\nu_L) + g_{V_R}\,(\bar{c}_R\gamma_\mu b_R)(\bar{\ell}_L\gamma^\mu\nu_L)$$
$$+\, g_{S_R}\,(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) + g_{S_L}\,(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T\,(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{ hc}$$

$$U_1 = (3, 12/3):\ g_{VL},\ g_{SR}$$
$$R_2 = (3, 2, 7/6):\ g_{SL} = 4g_T,$$
$$S_1 = (\bar{3}, 1, 1/3):\ g_{SL} = -4g_T,\ g_{VL}$$

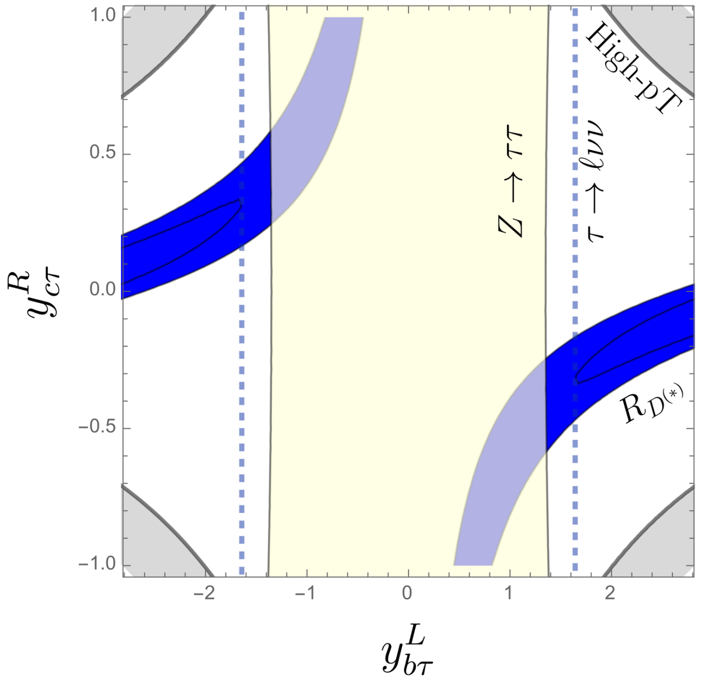
U_1 for the explanation needs both contribution!

minimal set of couplings

$m_{R_2} = 1.5$ TeV



$m_{S_1} = 1.5$ TeV



simple V-A picture is not working

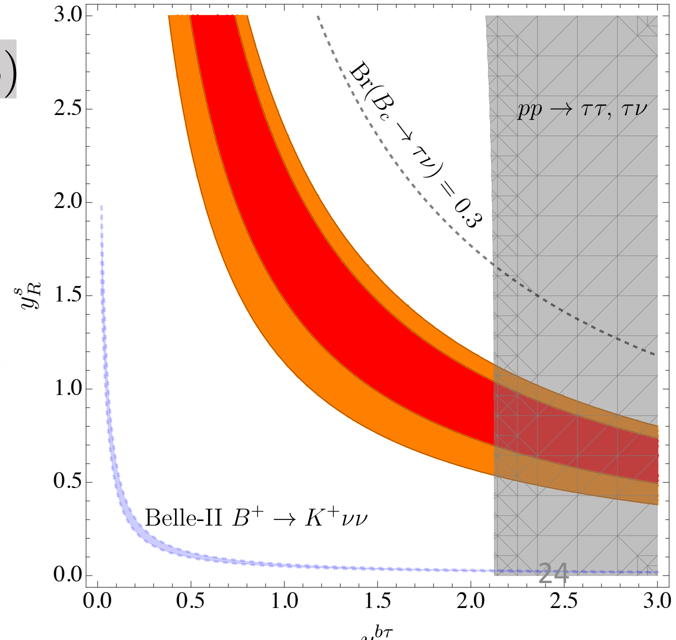
only S_1 explains $R_{D^{(*)}}$

$$\tilde{R}_2 = (3, 2, -1/6)$$

Right-handed neutrino

$$\mathrm{Br} \propto \left|\mathcal{A}_{\mathrm{SM}} + \mathcal{A}_{\mathrm{NP}}^{\nu_L}\right|^2 + \left|\mathcal{A}_{\mathrm{NP}}^{N_R}\right|^2 .$$

$m_{\tilde{R}_2} = 1.5$ TeV



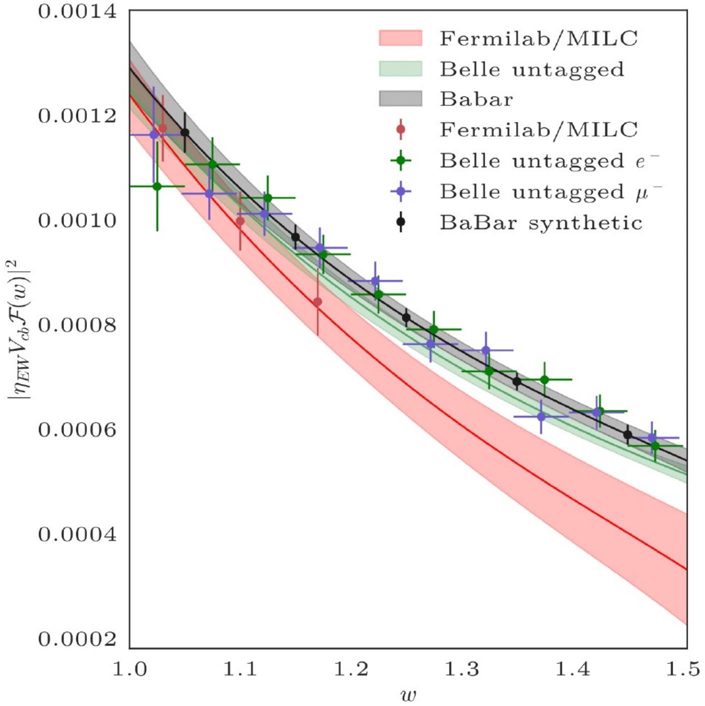
Bečirević, SF, Košnik, Pavičić, 2404.xxxxxx

A_{FB} and $F_L^{D^*}$ observables in $B \to D^* \, l \, \upsilon, l = e, \mu$

Marco Fedele

2305.15457, M. Blanke, A. Crivellin, S. Iguro, U. Nierste, S. Simula & L. Vittori

Form factors expansion FF $h_X(w) = \xi(w)\hat{h}_X(w)$
with the leading Isgur-Wise function $\xi(w)$
in α_s $1/m_{b,c}$
Iguro-Watanabe approach: expand each of the 10 I-W functs. as a power of, and fit to theory (LCSR and QCDSR) and experiment data up to a different order for each of the functions, selected by goodness-of-fi



$$
\begin{aligned}
F^e_{L,\,\text{Belle}} &= 0.485 \pm 0.017 \pm 0.005\,, \\
F^\mu_{L,\,\text{Belle}} &= 0.518 \pm 0.017 \pm 0.005\,, \\
F^e_{L,\,\text{Belle II}} &= 0.521 \pm 0.005 \pm 0.007\,, \\
F^\mu_{L,\,\text{Belle II}} &= 0.534 \pm 0.005 \pm 0.006\,.
\end{aligned}
$$

$$
\begin{aligned}
A^e_{\text{FB},\,\text{Belle}} &= 0.230 \pm 0.018 \pm 0.005\,, \\
A^\mu_{\text{FB},\,\text{Belle}} &= 0.252 \pm 0.019 \pm 0.005\,, \\
A^e_{\text{FB},\,\text{Belle II}} &= 0.219 \pm 0.011 \pm 0.020\,, \\
A^\mu_{\text{FB},\,\text{Belle II}} &= 0.215 \pm 0.011 \pm 0.022\,.
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{R}(D^*)_{\text{fit}} &= 0.265 \pm 0.005 \\
F^\ell_{L,\,\text{fit}} &= 0.515 \pm 0.005 \\
A^e_{\text{FB},\,\text{fit}} &= 0.227 \pm 0.007 \\
A^\mu_{\text{FB},\,\text{fit}} &= 0.222 \pm 0.007
\end{aligned}
$$

If the FF prediction for F_L^l and A_{FB}^l does not reproduce data, this cannot be fixed by introducing NP effects in light leptons as could be done for $R_{(D^*)}$

- Recent determination of A^l_{FB} and F^l_L from Belle and Belle II already have high precission
- Theory prediction A^l_{FB} and F^l_L are strongly correlated to RD(*), can be modified by new physics , the former are strongly NP insensitive.
- Theory determinations of FF should take in great attention their implications of the prediction A^l_{FB} and F^l_L , and consequent impact on extraction of V_{cb}^{exc}

b→ $s\ \mu\mu$ transition

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

It is important that LFU (e,μ) holds! – $RK_{(*)}$

$R^{\rm SM}_{K^{(*)}} = 1.00(1)$ Bordone et al., 1605.07633

$C_7^{SM} = 0.29;\ C_9^{SM} = 4.1;\ C_{10}^{SM} = -4.3;$

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}\sum_{q=s,d}\sum_{\ell=e,\mu}\sum_{i=9,10,S,P} V_{tb}V_{tq}^*(C_i^{bq\ell\ell}O_i^{bq\ell\ell} + C_i^{\prime bq\ell\ell}O_i^{\prime bq\ell\ell}) + \text{h.c.}\,.$$

Buras et al.,hep-ph/9311345;
Altmannshofer et al., 0811.1214;
Bobeth et al., hep-ph/9910220

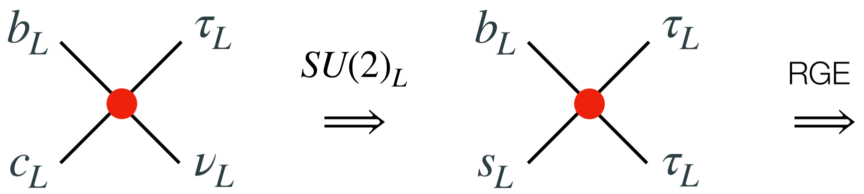
$$\begin{aligned}
O_9^{bq\ell\ell} &= (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, & O_9^{\prime bq\ell\ell} &= (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,\\
O_{10}^{bq\ell\ell} &= (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,, & O_{10}^{\prime bq\ell\ell} &= (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,,\\
O_S^{bq\ell\ell} &= m_b(\bar{q}P_R b)(\bar{\ell}\ell)\,, & O_S^{\prime bq\ell\ell} &= m_b(\bar{q}P_L b)(\bar{\ell}\ell)\,,\\
O_P^{bq\ell\ell} &= m_b(\bar{q}P_R b)(\bar{\ell}\gamma_5\ell)\,, & O_P^{\prime bq\ell\ell} &= m_b(\bar{q}P_L b)(\bar{\ell}\gamma_5\ell)\,.
\end{aligned}$$

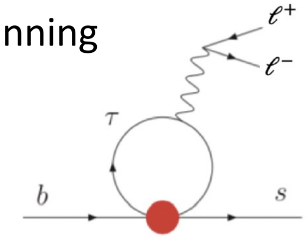
Angular observables, P_5' still remains (Descotes-Genon et al., 1207.2753, Matias et al., 1202.4266).

Universality in μ e is well established (at $\sim$ 5% level)

Universal contribution to C_9

Operators mix under running

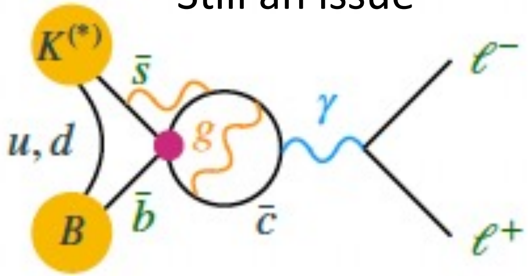




$C_9^{\rm univ.} = -0.64 \pm 0.22$

$\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} = -0.11 \pm 0.06$

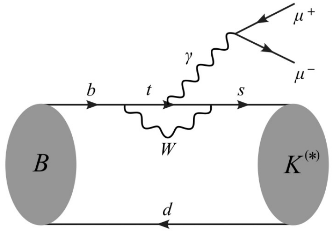
Still an issue



Bobeth, Haisch, arXiv:1109.1826; Crivellin et al., arXiv:1807.02068, Algueró et al., 1695189

Theoretical predictions for $b \to s\mu^+\mu^-$

Nico Gubernari

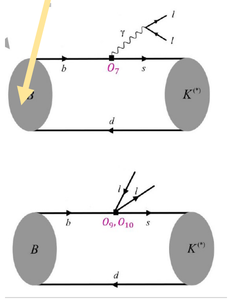


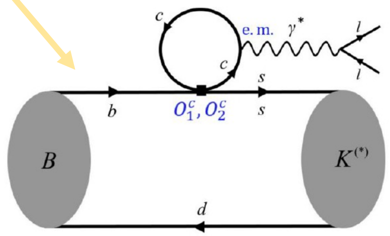
Tensions in $b \to s\mu^+\mu^-$

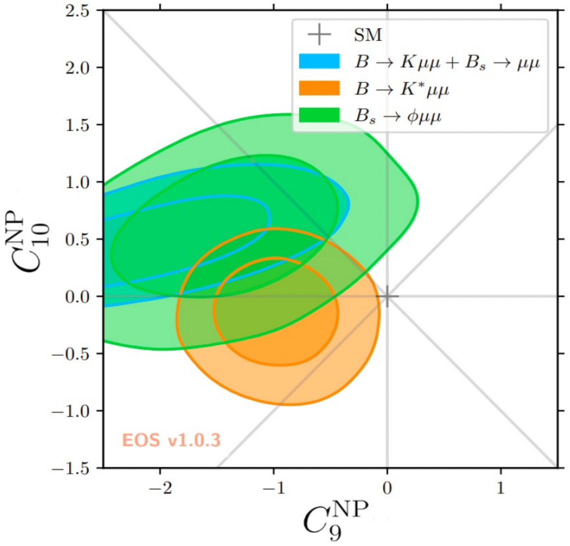
Hard and soft gluons are included in the calculation

Non-perturbative hadronic contributions

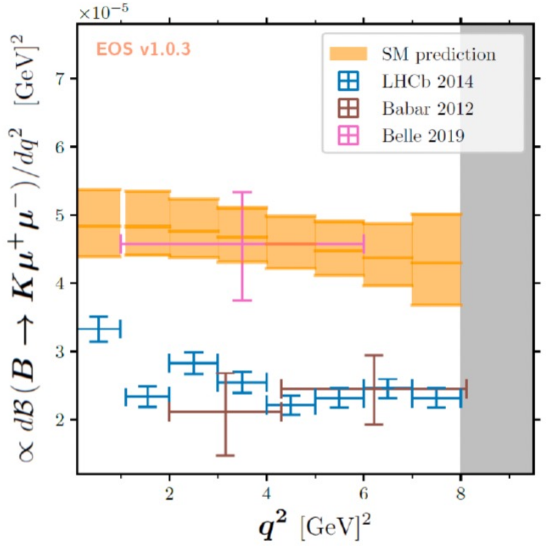
Local and non-local operators

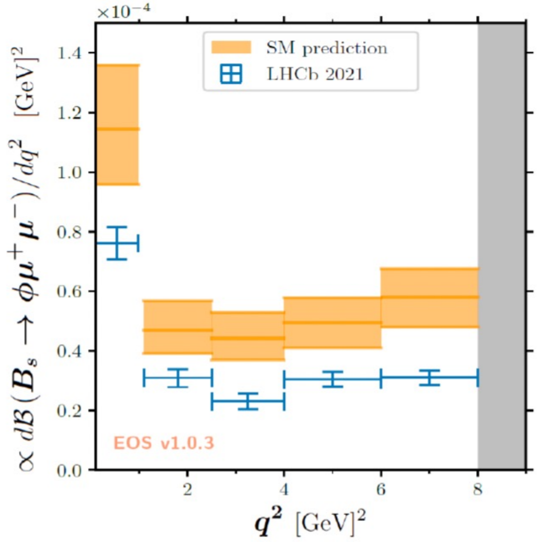






non-local effects cannot explain this tension





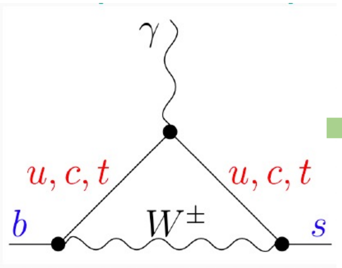
Independent on LFU in $R_{K(*)}$

- improved parametrization for local contribution $\mathcal{F}_\lambda$ with unitarity bounds combine LQCD (and LCSRs) in B → K (*)$\mu^+\mu^-$, Bs →ϕ $\mu^+\mu^-$
- new theoretical predictions for $\mathcal{H}_\lambda$ (besed on OPE and B → K (*) J/$\psi\mu^+\mu^-$
- new and precise SM predictions B → K (*)$\mu^+\mu^-$, Bs →ϕ $\mu^+\mu^-$

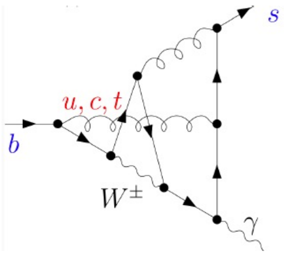
Precision b → sγ

Kay Schoenwald

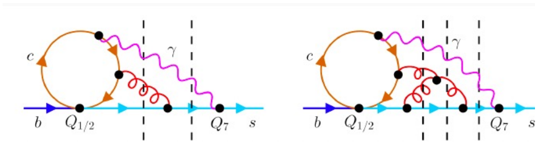
Wilson coefficent at hard scale $C_7(m_W)$



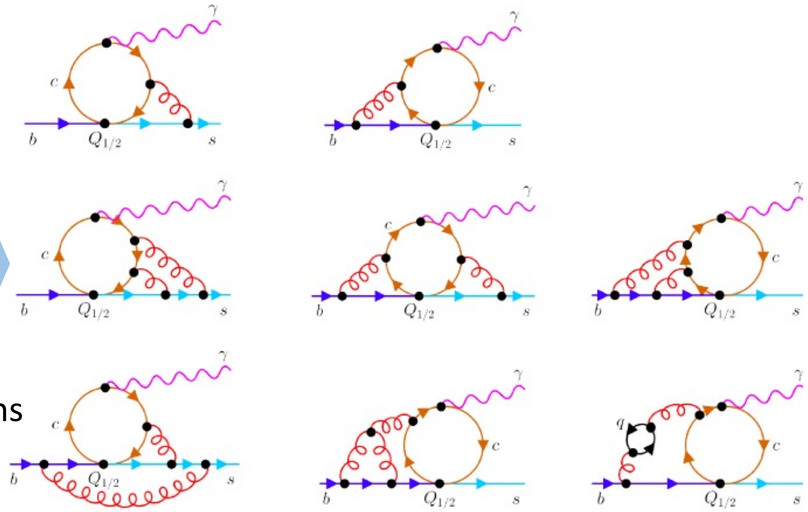
Inami, Lim



Misiak, Steinhauser



Interprate the cut diagram as vertex corrections



1. Generate all diagrams and express the amplitudes in terms of four-loop two-scale scalar integrals with unitarity cuts.
2. Reduce to master integrals with the help of Integration-By-Parts(IBP).
3. Using the IBP reduction we can find a system of differential equations

$$\frac{d}{dz} M_k(z = m_c^2/m_b^2, \epsilon) = R_{kl}(z, \epsilon) M_l(z, \epsilon)$$

4a. Solve the master integrals numerically with boundary values obtained for z → ∞.
4b. Calculate the master integrals numerically at the physical point with AMFlow

Experimental:

$$\mathcal{B}(\bar{B} \to X_s \gamma)^{\text{exp}}_{E_\gamma > 1.6\text{GeV}} = \underbrace{(3.49 \pm 0.19)}_{\pm 5.4\%} \times 10^{-4}$$

Theoretical (Misiak et al, 2020)

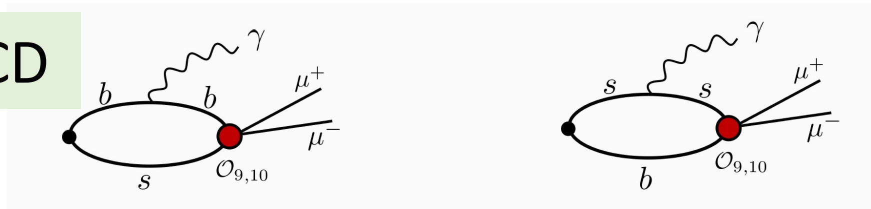
$$\mathcal{B}(\bar{B} \to X_s \gamma)^{\text{exp}}_{E_\gamma > 1.6\text{GeV}} = \underbrace{(3.40 \pm 0.17)}_{\pm 5.0\%} \times 10^{-4}$$

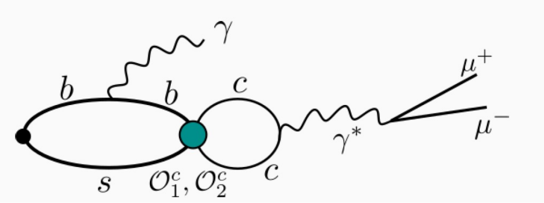
$$\pm 5\% = \sqrt{(\pm 3\%)^2 + (\pm 3\%)^2 + (\pm 2.5\%)^2}$$

Higher order parametric and non-perturbative

$B \to \mu^+ \mu^- \gamma$ at large q^2 from lattice QCD

Giuseppe Gagliardi



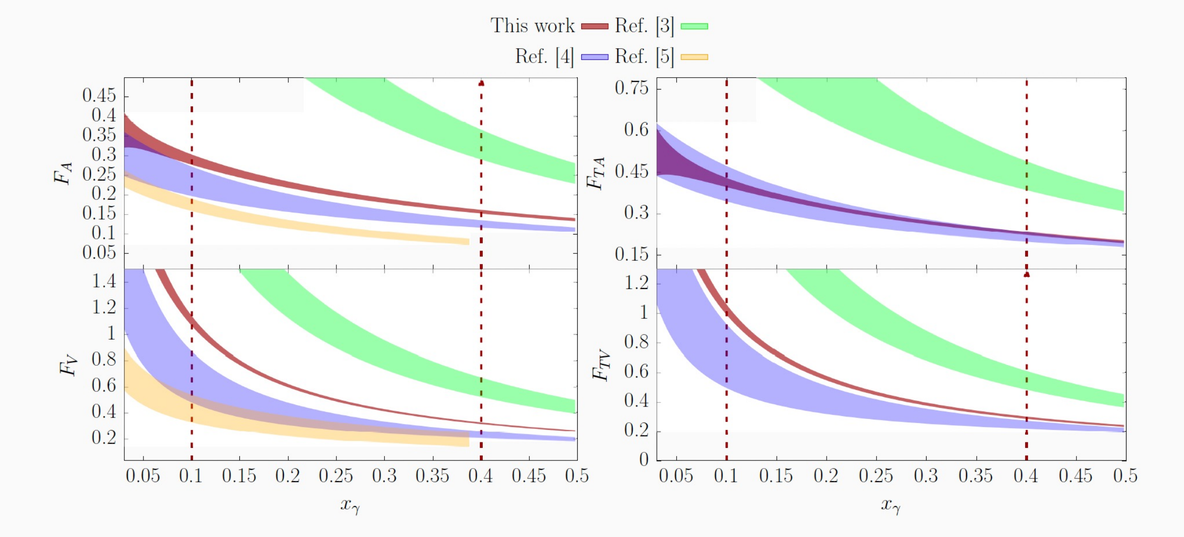


- The $B \to \mu^+ \mu^- \gamma$ allows for a new test of the SM prediction $b \to s$ FCNC transition
- Despite $O(\alpha_{em})$ suppression in comparison with $B \to \mu^+ \mu^-$ removal of helicity suppresion makes these rate comparable in magnitude
- At very high invariant mass of $\mu^+ \mu^-$, penguin operators appearing in WET , which are too difficult to compute on the lattice (but they are suppressed [Guadagnoli at al, 2017])

$$\mathcal{A}[\bar{B}_s \to \mu^+\mu^-\gamma] = -e\frac{\alpha_{\rm em}}{\sqrt{2}\pi} V_{tb}V_{ts}^*\varepsilon_\mu^* \left[\sum_{i=1}^{9} C_i \overbrace{H_i^{\mu\nu}}^{\rm NP-QCD} L_{V\nu} + C_{10}\left(\overbrace{H_{10}^{\mu\nu}}^{\rm NP-QCD} L_{A\nu} - \overbrace{\frac{i}{2} f_{B_s} L_A^{\mu\nu} p_\nu}^{\rm PT-contribution} \right) \right]$$

$$H_9^{\mu\nu}(p,k) = H_{10}^{\mu\nu}(p,k) = i \int d^4y\, e^{iky}\, \hat{\mathrm{T}} \langle 0 | [\bar{s}\gamma^\nu P_L b](0) J^\mu_{\rm em}(y) | \bar{B}_s(\boldsymbol{p}) \rangle$$

$$= -i\left[g^{\mu\nu}(k\cdot q) - q^\mu k^\nu\right] \frac{F_A}{2m_{B_s}} + \varepsilon^{\mu\nu\rho\sigma} k_\rho q_\sigma \frac{F_V}{2m_{B_s}}$$



- Ref. [3] = Janowski, Pullin , Zwicky , JHEP ’21 , light-cone sum rules.
- Ref. [4] = Kozachuk, Melikhov, Nikitin , PRD ’18 , relativistic dispersion relations.
- Ref. [5] = Guadagnoli, Normand, Simula, Vittorio, JHEP ’23, VMD/quark-model/lattice.

Looking for new physics through decays $b \to s\,\bar{\nu}\ \nu$

Olcyr Sumensari

SM

$$\mathcal{L}_{\rm eff}^{b\to s\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha_{\rm em}}{2\pi}\sum_i C_L^{\rm SM}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu\nu_{Li})$$

$\lambda_t = V_{tb}V_{ts}^*$

$$C_L^{\rm SM} = -X_t/\sin^2\theta_W = -6.32(7)$$

Buras et al.,1409.4557,
Altmannshofer et al., 0902.0160
Buras, 2209.03968

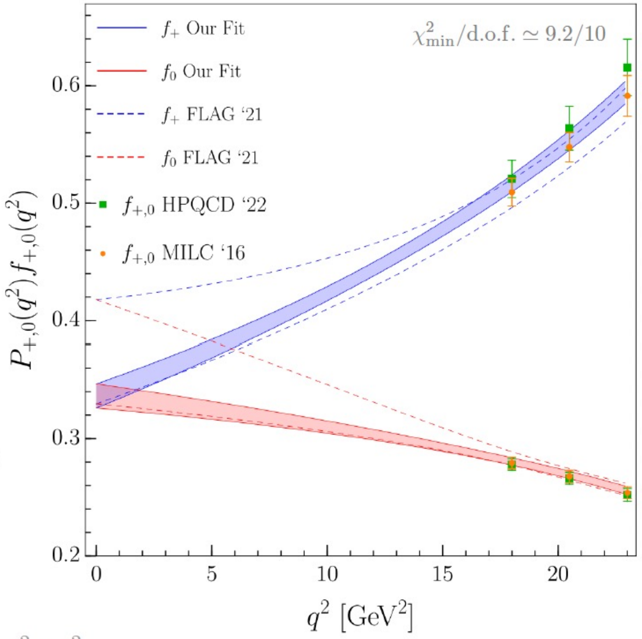
$$\mathcal{B}(B^\pm \to K^\pm\nu\nu) = (4.44 \pm 0.30)\times 10^{-6}\,,$$
$$\mathcal{B}(B^\pm \to K^{\pm *}\nu\nu) = (9.8 \pm 1.4)\times 10^{-6}\,,$$

$$R_{\nu\nu}^{K^{(*)}} = \mathcal{B}(B\to K^{(*)}\nu\bar{\nu})/\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})^{\rm SM}$$

$$R_{\nu\nu}^{K} = 5.4 \pm 1.5$$

Belle II 2023
2311.14647

Form factors – issue again!
CKM matrix element dependent



Pole factor:
$P_i(q^2) = 1 - q^2/M_i^2$

$$BR(B^+ \to K^+\nu\bar{\nu}) = (2.3 \pm 0.5^{+0.5}_{-0.4})$$

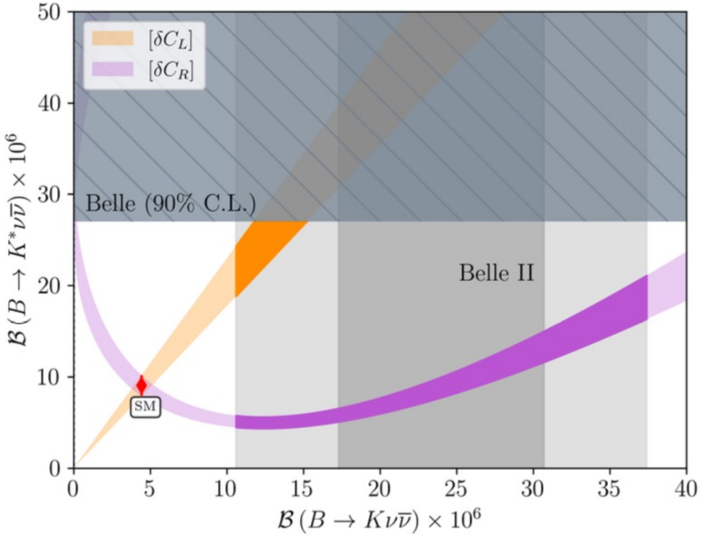
2.7 σ larger then SM prediction

A new anomaly?

Possibility for new physics through decays $b \to s\, \nu\, \bar{\nu}$

Assuming SM neutrinos a large contribution to the right-handed quark operator necessary!

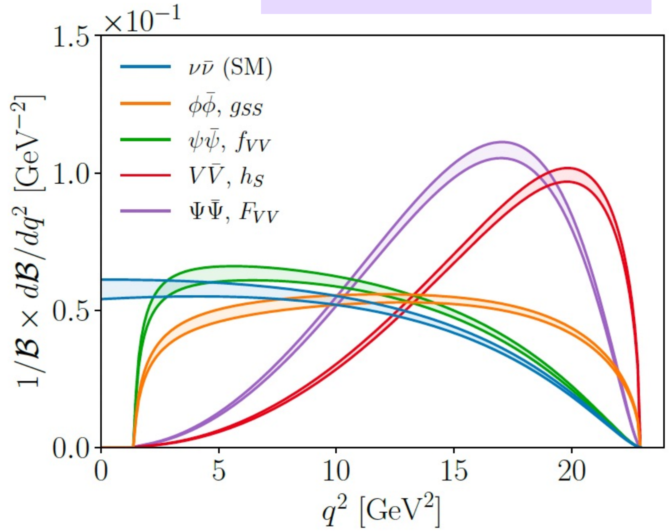
$$\mathcal{O}_R^{\nu_i \nu_j} = \frac{e^2}{(4\pi)^2} (\bar{s}_R \gamma_\mu b_R)(\bar{\nu}_i \gamma^\mu (1-\gamma_5)\nu_j)\,,$$

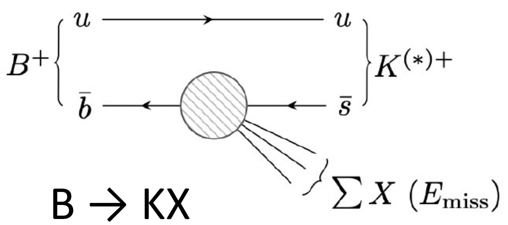


Allwicher et al, 2309.02246

$$\mathcal{B}(B \to K^{(*)}\nu\nu) = \mathcal{B}(B \to K^{(*)}\nu\nu)\Big|_{\rm SM} \left(1 + \delta\mathcal{B}^{\nu\nu}_{K^{(*)}}\right),$$

Invisible sector?





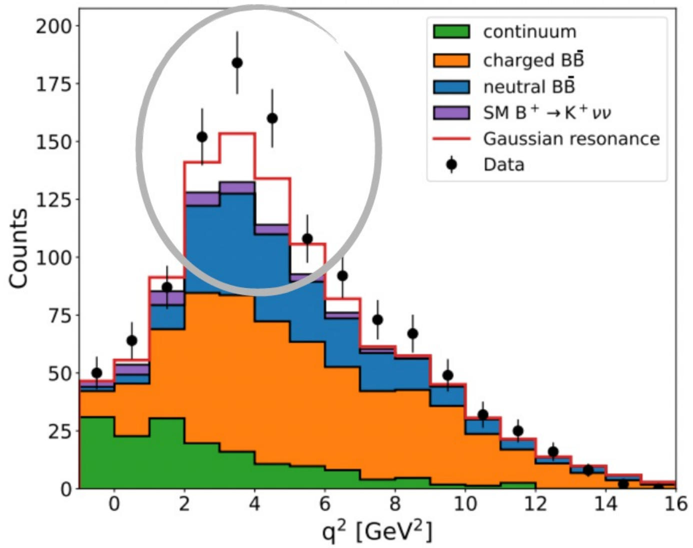
B → KX

B → K $\nu_L \nu_R$

B→K $\chi\chi$

B→K$\phi\phi$

Bolton, SF, Kamenik, Novoa-Brunet, 2403.13887



two-body decay, best

..t point (2.8 σ)

$m_X \sim 2$ GeV

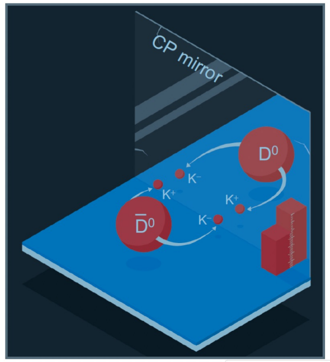
- for two inisible scalars or fermions mχ = 610 MeV

Bolton et al. '24

Searching for explanation in NP

Bause et al., 2309.00075, Allwicher et al, 2309.02246 Felkl et al., 2309.02940, He et al., 2309.12741, Altmannshofer et al. 2311.1469, Alonso-Alvarez et al. 2310.13043, Bolton, SF, Kamenik, Novoa-Brunet 2403.13887,…

Charm CP violation and searches



Stefan Schacht

Unique gate to flavour structure of up-type quarks

$$a_{CP}^{\rm dir}(D^0 \to K^+K^-) - a_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-) = (-0.161 \pm 0.028)\% \,.$$

The problem: Is it SM?

[LHCb 1903.08726, HFLAV 2021]

Direct CP Violation is an Interference Effect

$$a_{CP}^{\rm dir}(f) \equiv \frac{|\mathcal{A}(D^0 \to f)|^2 - |\mathcal{A}(\overline{D}^0 \to f)|^2}{|\mathcal{A}(D^0 \to f)|^2 + |\mathcal{A}(\overline{D}^0 \to f)|^2} \approx 2 r_{\rm CKM} r_{\rm QCD} \sin\varphi_{\rm CKM} \sin\delta_{\rm QCD}$$

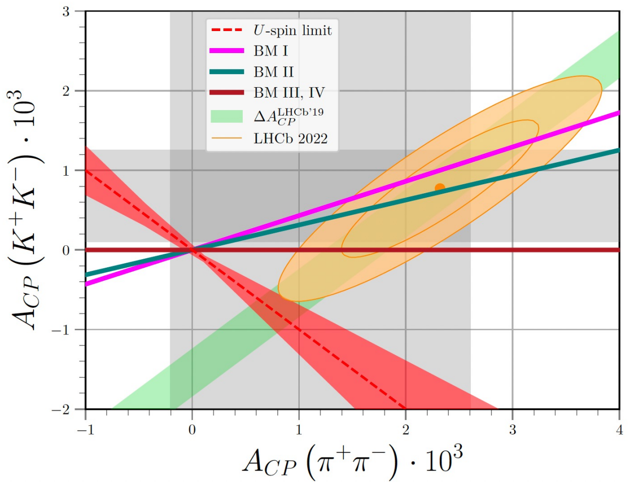
$$\mathcal{A} = 1 + r_{\rm CKM}\, r_{\rm QCD}\, e^{i(\varphi_{\rm CKM}+\delta_{\rm QCD})}$$

Prediction from SM CKM

$$\Delta a_{CP}^{dir} \sim 10^{-3} \times r_{\rm QCD}\,.$$

U-spin: $r_{\rm QCD} = \mathcal{A}^{\Delta U=0}/\mathcal{A}^{\Delta U=1}$

[Bause Gisbert Hiller Höhne Litim Steudtner 2210.16330]



Solving the Problem of Higher Order U-spin

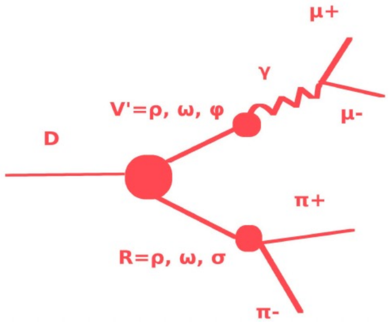
Theorems enabling calculations to arbitrary order.

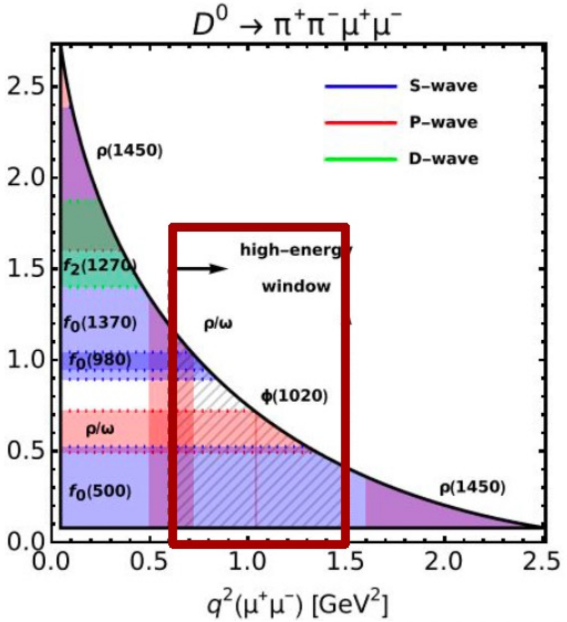
- We are able to determine a priori up to which order sum rules exist.
- We do not need explicit Clebsches. Big complexity reduction.
- Hope: Opens the door for precision in hadronic multi-body decays.

Gavrilova Grossman Schacht, 2205.12975

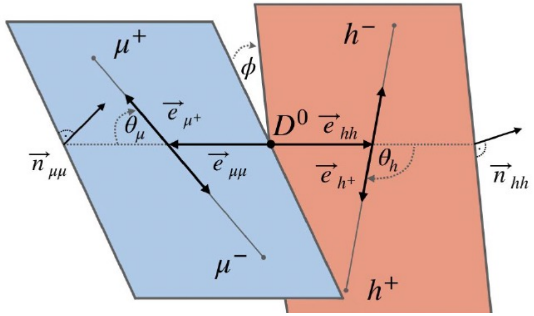
Resonances in $D^0 \to \pi^+\pi^-l^+l^-$ & sensitivity to New Physics

Eleftheria Solomonidi





$c \to u\, l^+l^-$ GIM and CKM suppression at work



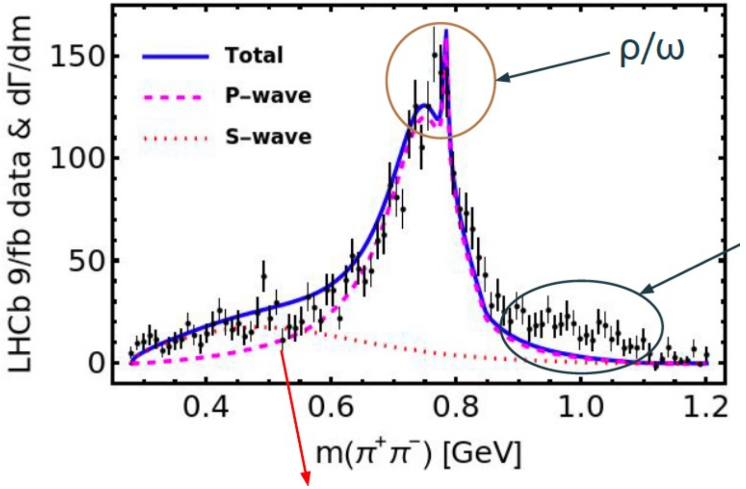
$D^0 \to \pi^+\pi^-l^+l^-$:
plenty of angular observables

$$\langle I_i\rangle_- \equiv \left[\int_0^{+1} d\cos\theta_\pi - \int_{-1}^{0} d\cos\theta_\pi\right] I_i\,, \quad \langle I_i\rangle_+ \equiv \int_{-1}^{+1} d\cos\theta_\pi I_i$$

$\langle I_i\rangle_+$			
i	S-wave	Null test	WCs
$1^\dagger$	○		$\lvert C_9^{\rm eff:S}\rvert^2,\ \lvert C_9^{\rm eff:P}\rvert^2$
$2^\dagger$	○		$\lvert C_9^{\rm eff:S}\rvert^2,\ \lvert C_9^{\rm eff:P}\rvert^2$
$3^\dagger$	×		$\lvert C_9^{\rm eff:P}\rvert^2$
4	✓		$C_9^{\rm eff:S}\,(C_9^{\rm eff:P})^*$
5	✓	yes	$C_9^{\rm eff:S}\,C_{10}^* + C_{10}\,(C_9^{\rm eff:P})^*$
$6^\dagger$	×	yes	Re $[C_9^{\rm eff:P}\,C_{10}^*]$
7	✓	yes	$C_9^{\rm eff:S}\,C_{10}^* + C_{10}\,(C_9^{\rm eff:P})^*$
8	✓		$C_9^{\rm eff:S}\,(C_9^{\rm eff:P})^*$
$9^\dagger$	×		$\lvert C_9^{\rm eff:P}\rvert^2$

$\langle I_i\rangle_-$			
i	S-wave	Null test	WCs
1	✓		$C_9^{\rm eff:S}\,(C_9^{\rm eff:P})^*$
2	✓		$C_9^{\rm eff:S}\,(C_9^{\rm eff:P})^*$
$4^\dagger$	×		$\lvert C_9^{\rm eff:P}\rvert^2$
$5^\dagger$	×	yes	Re $[C_9^{\rm eff:P}\,C_{10}^*]$
$7^\dagger$	×	yes	Re $[C_9^{\rm eff:P}\,C_{10}^*]$
$8^\dagger$	×		$\lvert C_9^{\rm eff:P}\rvert^2$

Significant improvement with
S-wave inclusion (~20% of total Br)



Inclusion of S-wave improves the SM-exp agreement & gives access to new observables that can help probe NP

Unitarity Triangles and CP violation

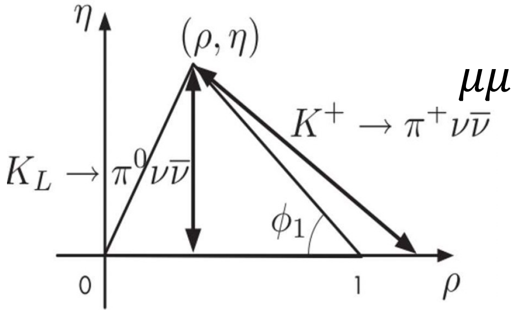
Amarjit Soni

- Motivation: It is exceedingly important to determine UTs as precisely as possible….
- Progress in lattice eps'….implications for both
- UTs though crucial for KUT
- K UT
- B UT: esp gamma

Quantity	This work	Experiment
$\mathrm{Re}(A_2)$	$1.74(15)(48) \times 10^{-8}$ GeV	$1.479(4) \times 10^{-8}$ GeV
$\mathrm{Im}(A_2)$	$-5.91(13)(1.75) \times 10^{-13}$ GeV	…
$\mathrm{Re}(A_0)$	$3.13(69)(95) \times 10^{-7}$ GeV	$3.3201(18) \times 10^{-7}$ GeV
$\mathrm{Im}(A_0)$	$-9.3(1.5)(2.8) \times 10^{-11}$ GeV	…
$\mathrm{Re}(A_0)/\mathrm{Re}(A_2)$	18.0(4.4)(7.4)	22.45(6)
$\omega = \mathrm{Re}(A_2)/\mathrm{Re}(A_0)$	0.056(14)(23)	0.04454(12)
$\mathrm{Re}(\varepsilon'/\varepsilon)$	$31.8(6.3)(11.8)(5.0) \times 10^{-4}$	$16.6(2.3) \times 10^{-4}$

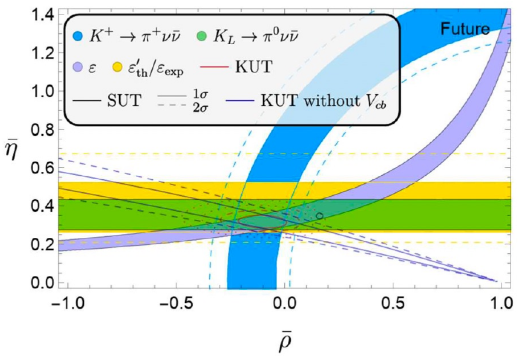
2306.06781

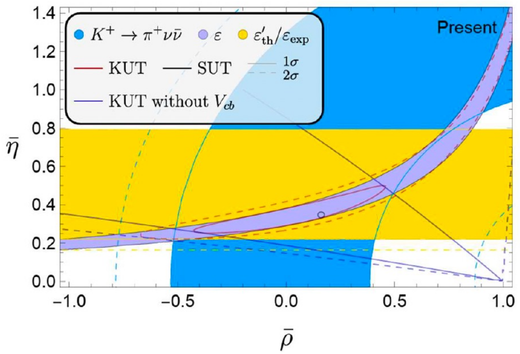
behind current RBC/UKQCD-PBC effort is Masaaki Tomii



- Naturalness assumed throughout:
- eps': Periodic Boundary Condition appear promising [with RBC-UKQCD]
- Improving LD contribution to $K^+ \to \pi^+ \ \nu\nu$ [with Enrico Lunghi]
- $K^0 \to \pi^0 \ \nu\nu$: should help significantly in constraining the extremely challenging gold plated mode: $K_L \to \pi^0 \ \nu\nu$. [with Stefan Schacht]

Reg gamma : [ADS revisit] path involving one π^0 stressed esp. promising for Belle-II.May be also for LHCb.





- Showed how using $\epsilon' + \epsilon$ + Br ($K^+ \to \pi^+ \ \nu\nu$) can construct the K-UT
- Also $K^0 \to \pi^0 \ \mu\mu$ input from LHCb, JPARC, pheno and lattice should provide
- important constraints for the gold plated $K_L \to \pi^0 \ \nu\nu$ mode being pursued by the KOTO expt @ JPARC
- UT gamma: D0 Dalitz decays with 1 pi0 in FS ….Belle-II, LHCb
- UT gamma: ADS PRD method should also be used => v likely get improve results

Neutrino masses and mixing angles

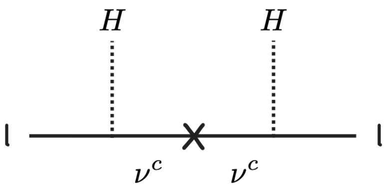
Neutrino masses

1. New chiral fermions include in the SM. Mass generated by Higgs Yukawa, after electroweak symmetry breakig
   Dirac mass.

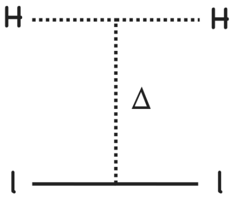
2. New Higgs boson (a new source of electroweak symmetry breaking) contributing only to neutrino masses.

3. New source of mass in the SM. In the SM all masses are pproportional to electroweak symmetry breaking.
In the limit v ⟶ 0 all SM particles are massless.

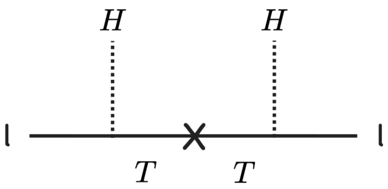
4. Neutrino masses signals a new mass scale. Neutrino masses are consequence of two symmetry-breaking scales .



type I



type II

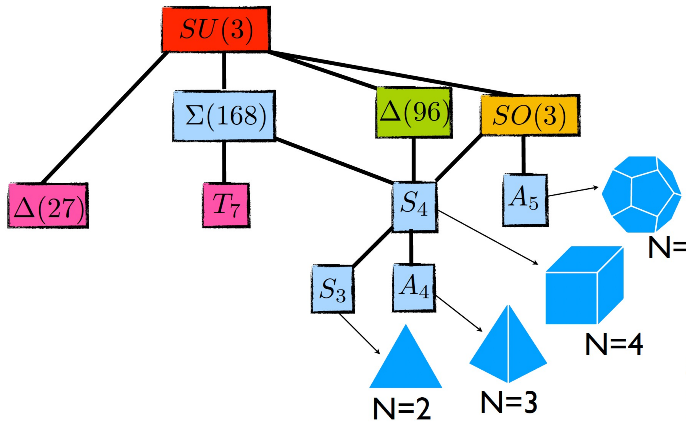


type III

Neutrino mixing sum rules

Stephen King

Non-Abelian family symmetry



Level N Modular Symmetry (Ratz talk)

PMNS matrix

$$U_{PMNS}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}1&0&0\\0&e^{i\frac{\alpha_{21}}{2}}&0\\0&0&e^{i\frac{\alpha_{31}}{2}}\end{pmatrix}$$

Atmospheric **Reactor** **Solar** **Majorana**

CP violating phase

$$=\begin{pmatrix}c_{12}c_{13}&s_{12}c_{13}&s_{13}e^{-i\delta}\\-s_{12}c_{23}-c_{12}s_{13}s_{23}e^{i\delta}&c_{12}c_{23}-s_{12}s_{13}s_{23}e^{i\delta}&c_{13}s_{23}\\s_{12}s_{23}-c_{12}s_{13}c_{23}e^{i\delta}&-c_{12}s_{23}-s_{12}s_{13}c_{23}e^{i\delta}&c_{13}c_{23}\end{pmatrix}$$

CP violating Majorana phases $\times\,\mathrm{diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$

Global fits
(Pre-Nove/T2K)
3σ ranges

$\theta_{23}=[39.6°, 51.9°]$ **Octant?**
$\sin^2\theta_{23}=\frac{1}{2}?\ 45°?$ **Max Mix?**

$\theta_{12}=[31.31°, 35.74°]$
$\sin^2\theta_{12}=\frac{1}{3}?\ 35.26°?$ **TBM?**

$\delta=[0°, 44°]\ \ \&\ \ [108°, 360°]$
$0°?\quad 180°?\quad 270°?$
CPC? **Max CPV?**

$\theta^e_{12}\neq 0$ **Assume**

Diagonal charged lepton, Klein neutrino symmetry $\theta^e_{23}\neq 0\quad \theta^e_{13}=0$

Solar sum rule

$$\cos\delta=\frac{\tan\theta_{23}\sin\theta_{12}^2+\sin\theta_{13}^2\cos\theta_{12}^2/\tan\theta_{23}-(\sin\theta^{\nu}_{12})^2\left(\tan\theta_{23}+\sin\theta_{13}^2/\tan\theta_{23}\right)}{\sin 2\theta_{12}\sin\theta_{13}}$$

First o second column of PMNS matrix preserved

Atmosferic sum rules

$$s^2_{12}=\frac{(1-3s^2_{13})}{3(1-s^2_{13})}\qquad \cos\delta=-\frac{\cot 2\theta_{23}(1-5s^2_{13})}{2\sqrt{2}s_{13}\sqrt{1-3s^2_{13}}}$$

$$s^2_{12}=\frac{1}{3(1-s^2_{13})}\qquad \cos\delta=\frac{2c_{13}\cot 2\theta_{23}\cot 2\theta_{13}}{\sqrt{2-3s^2_{13}}}$$

-Mixing sum rules are relics of simple PMNS matrices enforced by remnant symmetry which allows non-zero $\sin\theta_{13}$and predicts $\cos\delta$ (not δ)
-Solar sum rules from charged lepton corrections to simple PMNS matrices -Atmospheric sum rules from first/second column of simple PMNS matrix
-RG corrections can be small (NH) or large (2HDM, large)
-Future precision experiments will test sum rules and the symmetry approach

Modular Flavor Symmetries

Michael Ratz

The structure of fermion masses and mixing

Neutrino mass in traditional A_4 models

$$m_\nu = \frac{v_u^2}{\Lambda}\begin{pmatrix} 2a & -c & -b \\ -c & 2b & -a \\ -b & -a & 2c \end{pmatrix}$$

Neutrino mass in a ”modular” A_4 models

$$m_\nu = \frac{v_u^2}{\Lambda}\begin{pmatrix} 2Y_1(\tau) & -Y_3(\tau) & -Y_2(\tau) \\ -Y_3(\tau) & 2Y_2(\tau) & -Y_1(\tau) \\ -Y_2(\tau) & -Y_1(\tau) & 2Y_3(\tau) \end{pmatrix}$$

Highly predictive

$$\left.\begin{matrix} \Lambda \\ \operatorname{Re}\tau \\ \operatorname{Im}\tau \end{matrix}\right\} \xrightarrow{\text{predict}} \left\{\begin{array}{l} \text{3 mass eigenvalues } m_i \\ \text{3 mixing angles } \theta_{ij} \\ \text{3 phases (1 Dirac \& 2 Majorana)} \end{array}\right.$$

$\sin^2\theta_{12} = 0.295$

$\sin^2\theta_{23} = 0.651$

$\sin^2\theta_{13} = 0.0447$

$\delta_{\mathcal{CP}} = 279°$

$\frac{\Delta m^2_{\text{sol}}}{\Delta m^2_{\text{atm}}} = 0.0292$

Typical model

$$\mathscr{W}_{\text{lepton}} = Y_e^i\, L_i \cdot H_d\, E_i + \frac{1}{2}\kappa_{ij}(\tau)\, L_i \cdot H_u\, L_j \cdot H_u$$

Modular invariant holomorfic observables

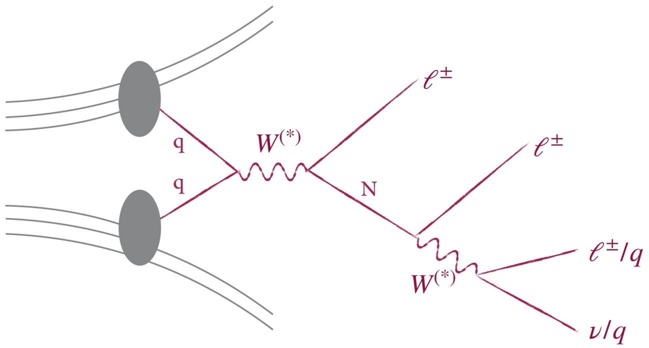
$$I_{ij}(\tau) := \frac{M_{ii}(\tau)\, M_{jj}(\tau)}{\left(M_{ij}(\tau)\right)^2} = \frac{\kappa_{ii}(\tau)\,\kappa_{jj}(\tau)}{\left(\kappa_{ij}(\tau)\right)^2} = \frac{m_{ii}(\tau,\overline{\tau})\, m_{jj}(\tau,\overline{\tau})}{\left(m_{ij}(\tau,\overline{\tau})\right)^2}$$

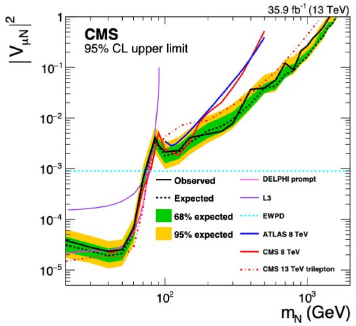
I_{ij} are fullt determined by masses and mixing angles and phases

-Bottom-up constructions may face problems in the UV
-Couplings are modular forms in a large class of string compactifications
-Eclectic flavor symmetries
-Modular flavor symmetries arise from magnetized tori
-Top-down mechanisms to stabilize τ are in qualitative agreement with τ values required by phenomenological fits

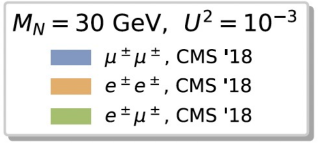
Probing the heavy neutrino hypothesis

Xabier Marcano

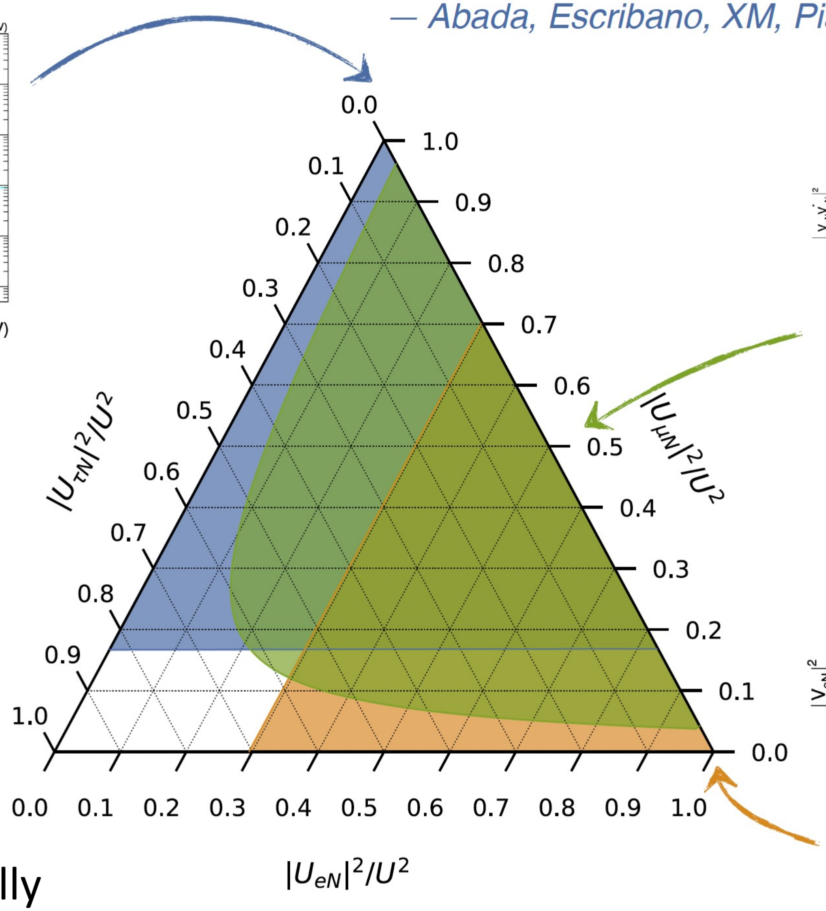


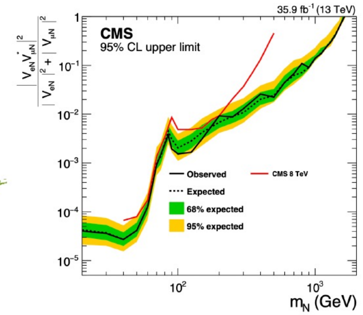


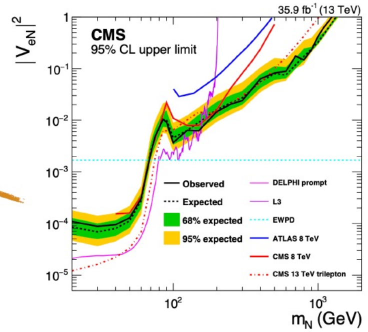
For a fixed mass and U²



— Abada, Escribano, XM, Piazza [2208.13882]—







Discriminate between neutrino mass models (low-scale seesaws)

Please provide sensitivities on (also) for each flavor channel individually $|U_{\alpha N}|^2\times$BR

E.g. in trilepton searches for :

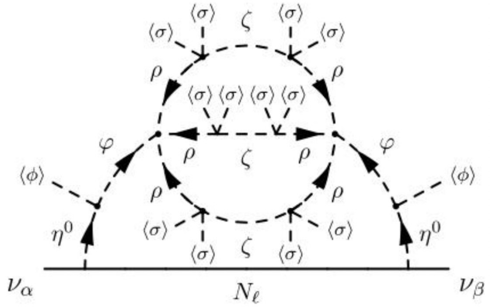
- $U_{\mu N}$ - Limits only from channel (to-do) μμμ
- Limits only from channel (to-do) eμμ
- Combined results (done)

Pheno & cosmo implications of scotogenic 3-loop neutrino mass models

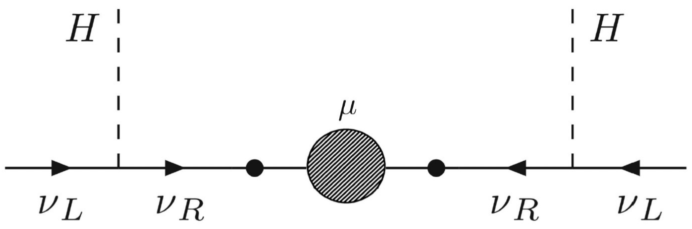
Tessio DE MELO

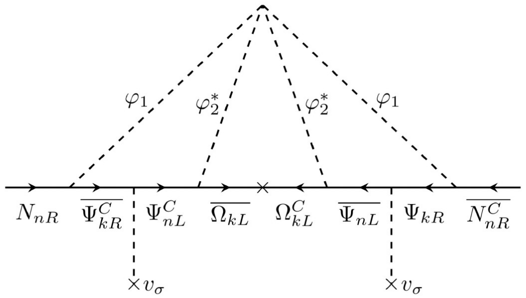
Z_2 symmetry forbids tree level Dirac mass term
U(1)’(global)symmetry forbids 1- and 2-loop mass terms

Field	N_{R_k}	η	φ	ρ	ζ	σ
$SU(2)_L$	**1**	**2**	**1**	**1**	**1**	**1**
$U(1)_Y$	0	$\frac{1}{2}$	0	0	0	0
$U(1)'$	0	3	3	-1	0	$\frac{1}{2}$
$\mathbb{Z}_2$	-1	-1	-1	-1	-1	1



3-loop Scotogenic ISS Model





- Right-handed neutrinos
- Extra neutral singlet fermions
- Vector-like fermion pair
- Singlet scalars

Field	ν_{kR}	N_{kR}	Ω_{kL}	Ψ_{kR}	Ψ_{kL}	φ_1	φ_2	σ
$SU(2)_L$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	0	0	0	0	0	0	0	0
$U(1)'$	-4	4	0	-5	-1	-1	-1	4
$\mathbb{Z}_2$	1	1	-1	-1	-1	-1	1	1

Radiative seesaw models are well motivated and testable extensions of the SM

❖ We discussed 2 examples of scotogenic models in which neutrinos masses are generated at the 3-loop level

❖ The 3-loop suppression allows the new particles to have masses in the TeV scale
without fine-tuning the model parameters

❖ Fermionic or scalar DM can easily be accommodated; stability is ensured by the same symmetries involved in the generation of neutrino masses

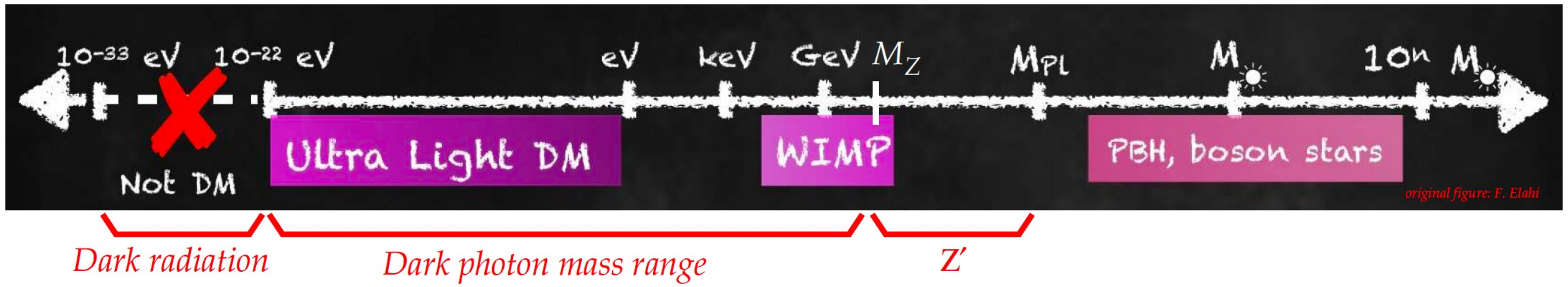
❖ Depending on the realization, the models are capable of accounting for specific problems; here we discussed the W mass anomaly and baryogenesis

❖ These models lead to sizable cLFV rates which are within the sensitivity of future facilities

Dark Matter, axions, gravitional waves

Status of Dark Photons

Jim Cline

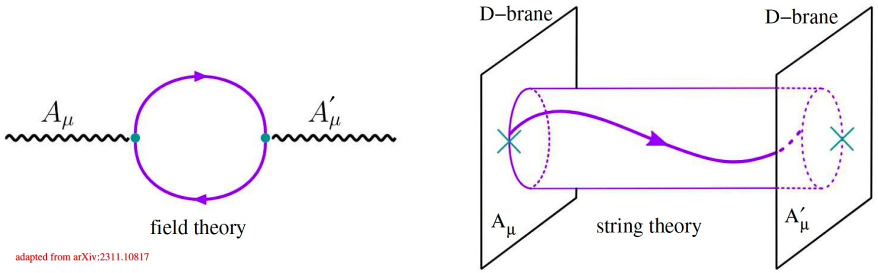


$$10^{-22}\,\mathrm{eV} < m_{A'} < m_Z;$$

Dark photon can function as:
- dark matter
- dark force mediator
- both!

Origin of m $_{A'}$: Higgs or Stueckelberg

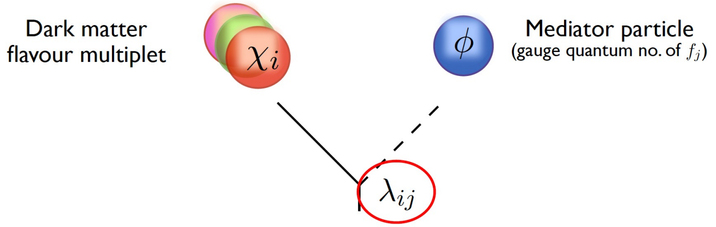
String theoretic origin of ϵ



-Dark photons: an extremely rich field, theoretically and experimentally
-Dark photons can be dark matter or enable DM
-They can explain anomalies: $(g-2)_\mu$, EDGES 21 cm dip, CDM small scale structure, SMBH mergers . . .
-Huge parameter space: consistency of UV completions with gravity can provide guidance
- E.g., Stueckelberg mass mechanism does imply new heavy physics at some scale, implies UV cutoff
-Higgs mass mechanism can lead to much stronger constraints

Flavoured Dark Matter and and LHC signatures

Jan Heisig



Dark Minimal Flavor Violation (DMFV):
[Agrawal, Blanke, Gemmler 1405.6709]
- Step beyond Minimal Flavor Violation (MFV)
- Dark flavor symmetry:
  $U(3)$ (Dirac), $O(3)$ (Majorana)

-simplified Dark Matter model in the Dark Minimal Flavour Violation framework.
-model complements the Standard Model with a flavoured
-Dark Matter Majorana triplet and a coloured scalar mediator

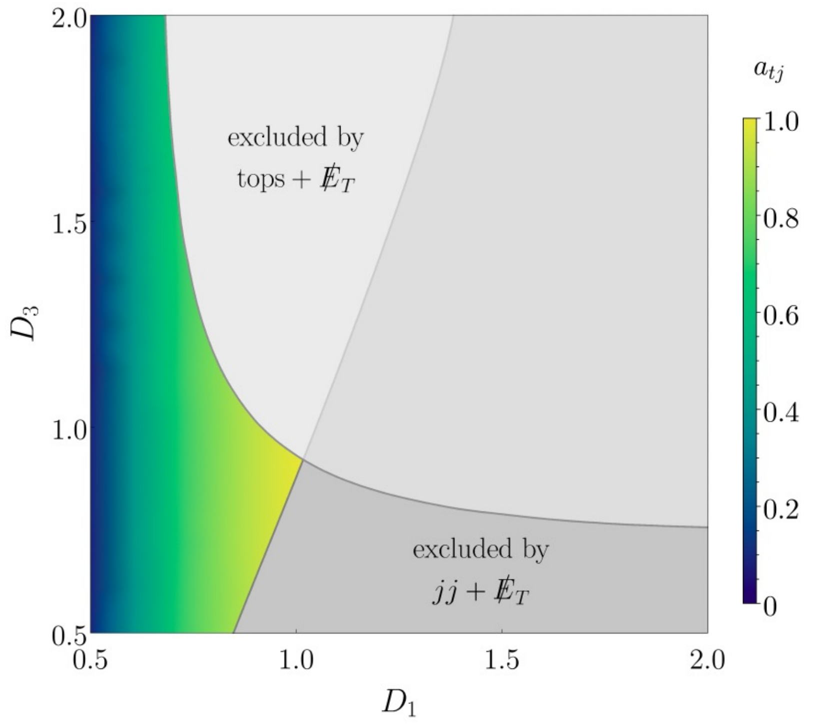
$$\phi = (3,1,2/3)$$

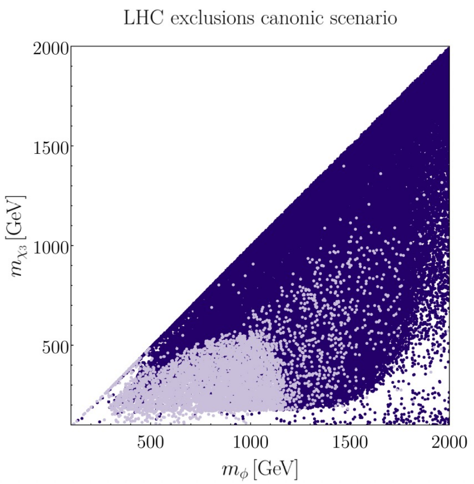
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\left(i\bar\chi\partial\!\!\!/\chi - M_\chi\bar\chi\chi\right) - \left(\lambda_{ij}\bar u_{Ri}\chi_j\phi + \text{h.c.}\right)$$
$$+(D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi + \lambda_{H\phi}\phi^\dagger\phi H^\dagger H + \lambda_{\phi\phi}\left(\phi^\dagger\phi\right.$$

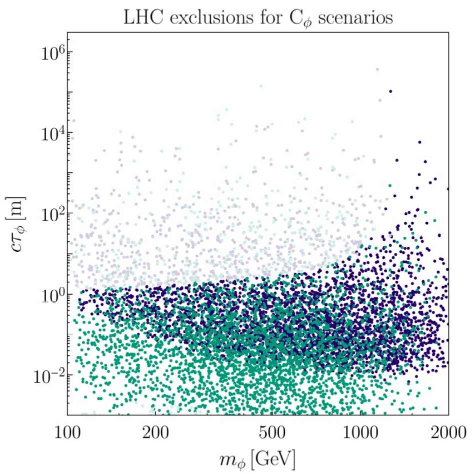
- Flavor constraints from D-meson mixing
- Direct detection constraints from LZ
- Indirect detection from AMS-02 cosmic-ray antiprotons
- Relic density $\Omega h^2 = 0.12$

$$a_{tj} = \frac{\sigma(tj + E\!\!\!/_T) - \sigma(\bar t j + E\!\!\!/_T)}{\sigma(tj + E\!\!\!/_T) + \sigma(\bar t j + E\!\!\!/_T)}$$

Dirac DM $\Rightarrow$ $a_{tj} \simeq$
Majorana DM $\Rightarrow$ $a_{tj} >$







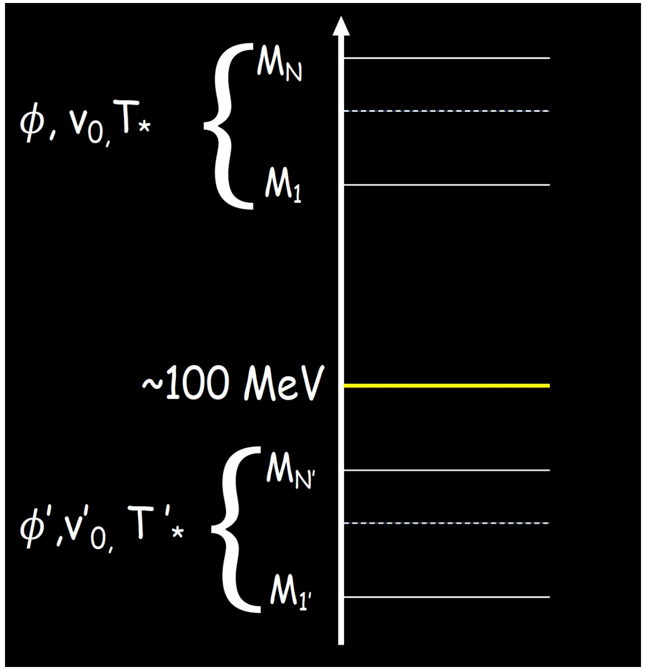
Flavored Majorana Dark Matter:
- Large regions of viable parameter space
- Canonical and conversion-driven freeze-out
- Current gaps in LHC searches:
- Complex decay chains
- Long-lived particles (intermediate lifetimes)
- Majorana-specific signatures
- Same-sign tops suffer from extra jets required
- Single-top charge asymmetry

Majorana mass generation, GWs and cosmological tensions

Pasquale Di Bari

Minimal model: one scalar, the GW signal turns out to be a few orders of magnitude below the experimental sensitivity of any experiment
The additional real scalar field $\boldsymbol{\eta}$ also undergoes a phase transition settling to its true vacuum prior to the φ phase transition

canonical seesaw scale



mini-seesaw scale or dark sector low scale

- The generation of Majorana mass might lead to the production of a stochastic GW cosmological background in the early universe at the seesaw scale or scales in the case of a multiple majoron model
- The split majoron model can motivate a modification of pre recombination era and be related to the generation of a light Majorana mass
- It can alleviate cosmological tensions and might solve a potential deuterium problem that might be regarded as a kind of signature of the model.
- At the phase transition GWs can be generated with a spectrum that can peak in the NANOGrav frequencies
- It cannot explain the whole signal, but it might contribute marginally in addition to SMBH binaries, and one can hope its contribution could be disentangled if SMBH binary spectrum will be better understood

Destabilizing Matter through a Long-Range Force

Hooman Davoudiasl

- Ultralight scalar φ
- Can be sourced by astronomical objects
- Long range force: local background effects
- Like an electric or gravitational field

$$O_7 = \frac{\phi\,(ud\,\ell)_R}{\Lambda^3}$$ dim-7

$$p \to \phi\, e^+$$

if $\langle\phi\rangle \neq 0$, dim-7 $\to$ dim-6: $\frac{\phi\,(uud\,\ell)_R}{\Lambda^3} \to \left(\frac{\langle\phi\rangle}{\Lambda}\right)\frac{(uud\,\ell)_R}{\Lambda^2}$

Neutron Star Heating via Nucleon Decay

New light physics can affect nucleon decay

- Alternative assumptions can make ϕ viable DM
- Example: allow for electron coupling $g_e\phi\,\bar{e}e$ with $g_e \sim 10^{-25}$
  - $g_e \lesssim 1.4\times10^{-25}$ at 2σ Microscope collaboration 2022; Fayet 2017
- $\phi \sim g_e n_e m_\phi^{-2}$ by "thermal misalignment" Batell, Ghalsasi, 2020
- ϕ starts oscillating once $H \sim m_\phi$ corresponding to $T \sim$ MeV, $n_e \sim T^3$
- For $m_\phi \sim 10^{-16}$ eV we find $\phi_i \sim 10^{25}$ eV
- Initial energy density $\rho_i \sim m_\phi^2\phi_i^2 \sim 10^{18}$ eV^4 redshifts like T^{-3}
- At $T \sim$ eV (matter-radiation equality): $\rho_i \to \mathcal{O}(\text{eV}^4) \Rightarrow \phi$ could be DM
- For $\rho_{\rm DM} \sim 0.3$ GeV cm^{-3} (Solar system): $\phi_{\rm DM} \sim 10^{13}$ eV, $\mathcal{O}(10)$ large thar
  - Would not lead to stronger constraint from nucleon decay data than from NS heating
  - Introduces time variation due to wavelike nature of ϕ DM
  - Further phenomenology beyond the scope of this talk

Gravitational Waves from Graviton Bremsstrahlung during Reheating

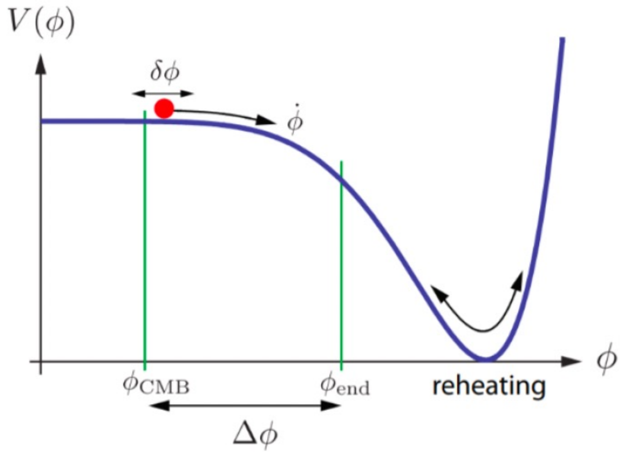
Nicolas Bernal

Gravitons → massless spin-2 particles

Perturbations of the metric $$g_{\mu\nu} \simeq \eta_{\mu\nu} + \frac{1}{M_P} h_{\mu\nu}$$

Graviton – matter interaction $$\sqrt{-g}\,\mathcal{L} \supset -\frac{1}{M_P} h_{\mu\nu} T^{\mu\nu}$$

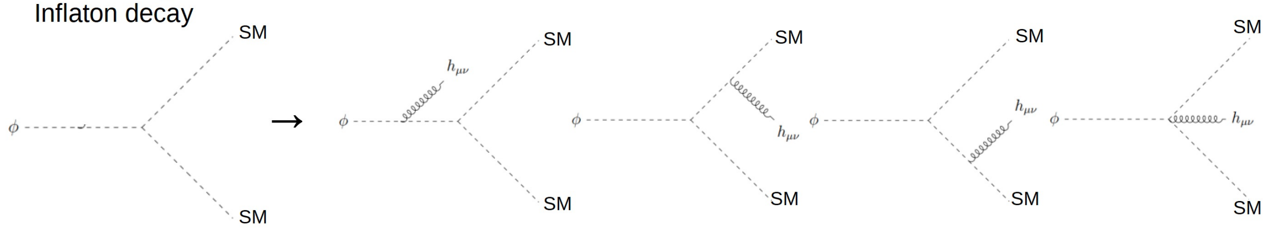
Graviton emission suppressed by $1/M_P^2$



* Inflaton decays or annihilation
* Inflaton potential during reheating
* Possible non-perturbative effects: Preheating
- fermions: Fermi blocking
- scalars: quartic couplings avoid tachyonic instabilities
- preheating not efficient in this setup

- Reheating happens after cosmic inflation
- Irreducible GW background produced during cosmic reheating
  * reheating dynamics (inflaton potential)
  * inflaton dynamics (decay or annihilation)
  * inflaton – matter coupling
- Quadratic potentials: Very large M and T_{rh}
- Steeper potential: significant boost for bosonic reheating
  * not that large M and T_{rh}
- Decay & annihilation: Possible boost of GW spectrum
- Reheating could be probed by graviton Bremsstrahlung

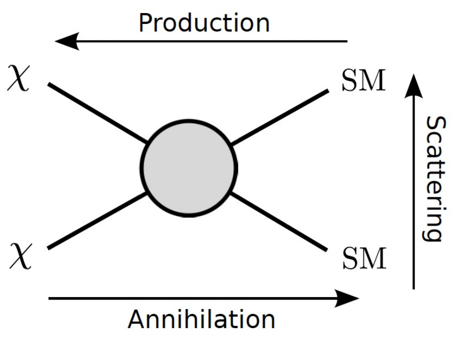
Reheating
Inflaton decay

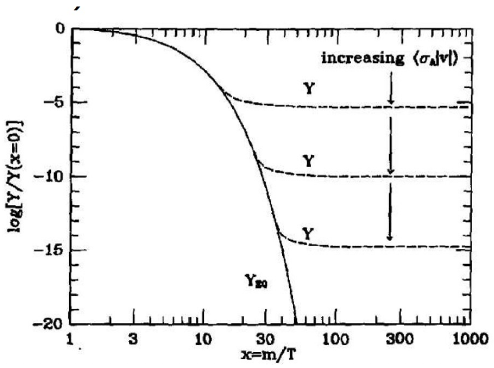


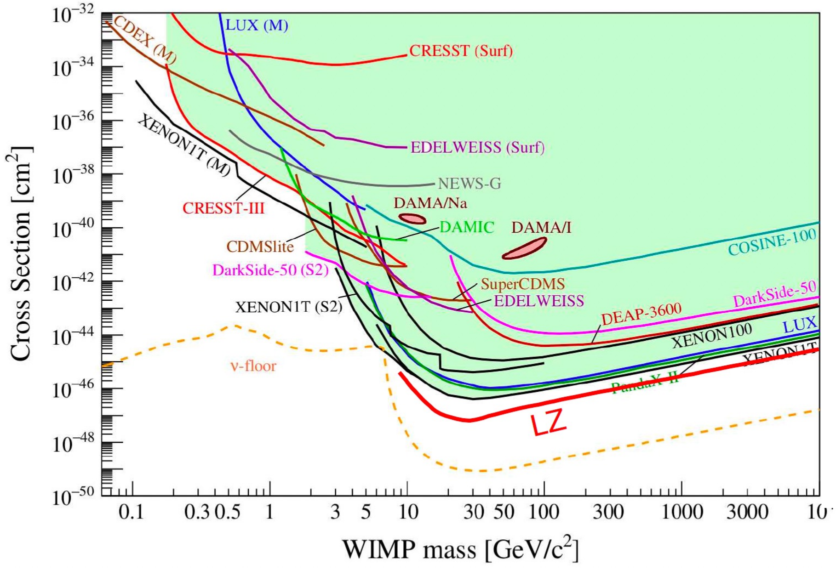
Signals of boosted dark matter and neutrinos

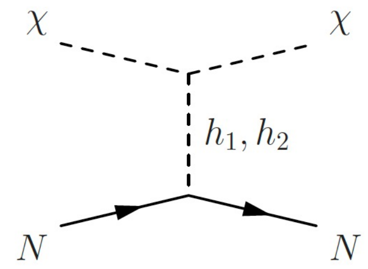
Takashi Toma

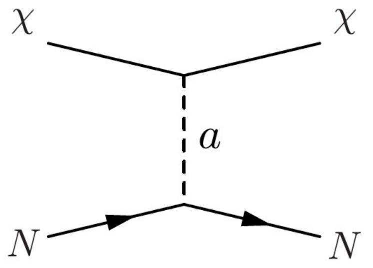
Thermal dark matter (WIMPs)











WIMP is thermalized with SM particles in early universe

$\Omega_\chi h^2 = 0.12$, roughly $\sigma \sim$ 1pb $\sim 10^{-26}$cm^3/s $\sim 10^{-36}$cm^2

Almost independent on DM mass
Mass range: 10 MeV – 100 TeV

1. Direct detection experiments impose the strong bound on (minimal) thermal DM models.
2. v suppressed cross section naturally evades the bound.
3. Such kind of DM can be searched if it is boosted somehow.
4. $\chi\chi \rightarrow \nu\bar{\chi}$ induces two distinctive gnals, which can be searched by DUNE, or combining DUNE and SK/HK/IceCube.

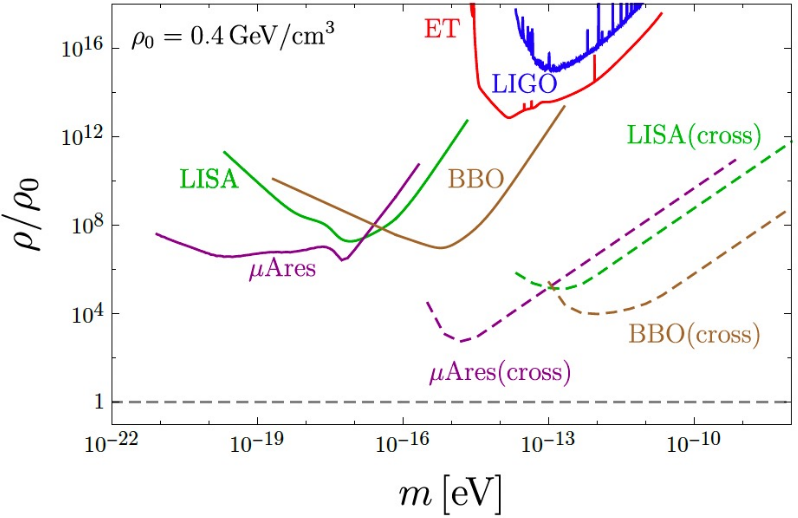
Probing ultralight Dark Matter in gravity wave detectors

Hyungin Kim

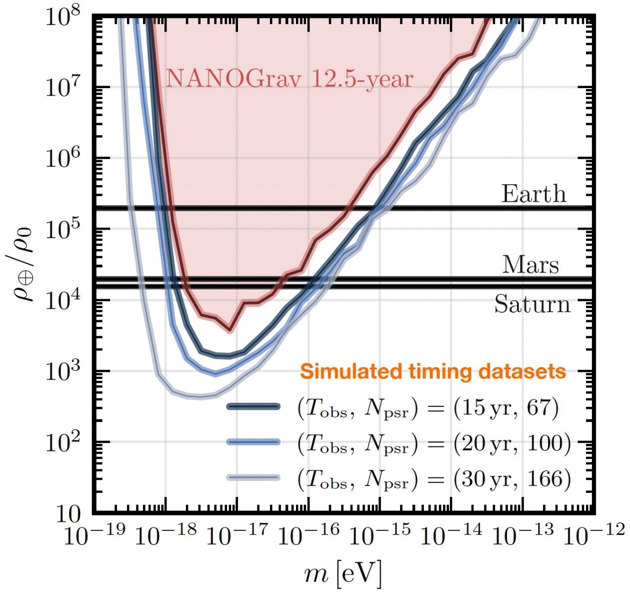
Recent numerical simulations of ultralight dark matter halo have observed an order one density fluctuation all over galaxies

Can we actually measure ULDM signals with GW interferometers?

all of the results shown here are sensitive to **ULDM density around/within the solar system**



The constraints and projections on dark matter density in the solar system. Here ρ_0 = 0.4 GeV/cm^3



The red line shows the 95% constraints on the dark matter density near the solar system derived by analyzing the NANOGrav 12.5-year data set.
All the constraints are normalized to ρ_0 = 0.4 GeV/cm^3

-the impacts of ULDM low- frequency stochastic fluctuations on pulsar timing observations and derived the overlap reduction function and the timing residual power spectrum induced by these fluctuations.
-these stochastic fluctuations allow us to probe ULDM in a mass range approximately six orders of magnitude higher than usual searches based on coherent ULDM oscillations

PTA might reach to a factor few times local DM density in next decades

Axions review

Pierre Sikivie

The Strong CP Problem

$$\mathcal{L}_{\rm QCD} = \ \dots \ + \ \bar{\theta}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta - \arg(m_u\, m_d\ \dots\ m_t)$$
$$= \theta - \arg\det(Y^u\, Y^d)$$

The absence of P and CP violation in the strong interactions requires

$\bar{\theta} \leq 10^{-10}$ from NEDM

$U_{PQ}(1)$, Peccei and Quin, 1977

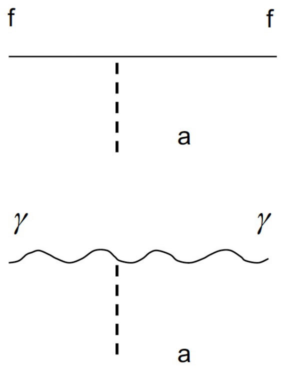
- is a symmetry of the classical action
- is spontaneously broken
- has a colour anomaly

$$\mathcal{L} = \ \dots \ + \ \frac{a}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \ + \ \frac{1}{2}\partial_\mu a\partial^\mu a$$

$$\bar{\theta} = \frac{a}{f_a}$$

and a light neutral pseudoscalar particle is predicted: the axion.

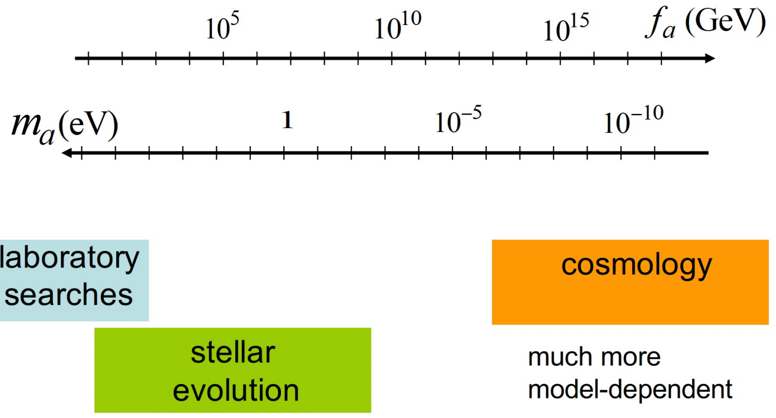
$$m_a \ \simeq \ 6\ \text{eV}\ \frac{10^6\ \text{GeV}}{f_a}$$



Axions are constrained

- beam dump experiments
- rare particle decays (K→ πa)
- radiative corrections $(g\text{-}2)_\mu$
- the evolution of stars

Axion constraints



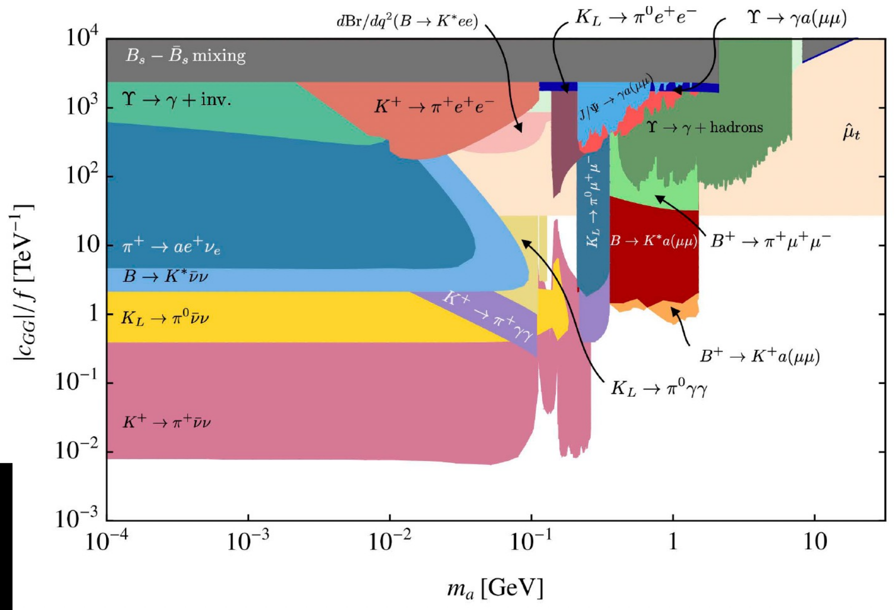
- Axions solve the strong CP problem
- A population of cold axions is naturally produced in the early universe which may be the dark matter today
- Axion dark matter is detectable
- Axion dark matter has distinctive properties in large scale structure formation

Axions and axion-like particles (ALPs)

Matthias Neubert

Peccei—Quinn solution to strong CP problem, 1977

- More generally, ALPs arise as pseudo Nambu—Golstone bosons of spontaneously broken global U(1) symmetry
- Axion mass and couplings to Standard Model are inversely proportional to
- For heavier ALPs, couplings to particles other than the photon can be probed in particle-physics experiments



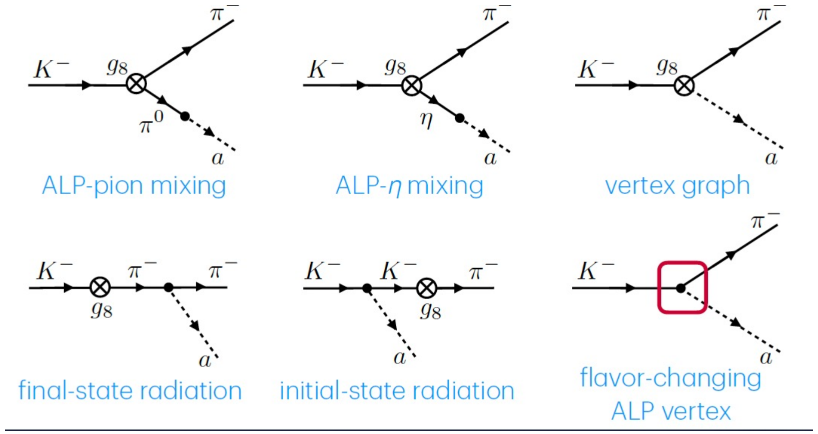
$$\mathcal{L}^{(p^2)}_{\rm QCD} = \frac{F^2}{8}\langle (D_\mu \Sigma)(D^\mu \Sigma^\dagger) + \chi \Sigma^\dagger + \Sigma \chi^\dagger \rangle + \frac{F^2}{8} H_0 \, (D_\mu \theta)(D^\mu \theta)$$

$$\mathcal{L}^{(p^2)}_{\rm weak} = \frac{F^4}{4}\left[G_8 \langle \lambda_6 L_\mu L^\mu \rangle + G_8^\theta \, (D_\mu \theta) \langle \lambda_6 L^\mu \rangle \right] + \text{h.c.}$$

$$L_\mu = \Sigma \, i \, (D_\mu \Sigma^\dagger)$$

$$D_\mu \theta = -2 \tilde{c}_{GG} (\partial_\mu a)/f$$

Cornella, Galda, MN, Wyler (2023)
Bauer, MN, Renner, Schnubel, Thamm (2021)



Axions and axion-like particles belong to a class of well-motivated light BSM particles with weak couplings to the Standard Model

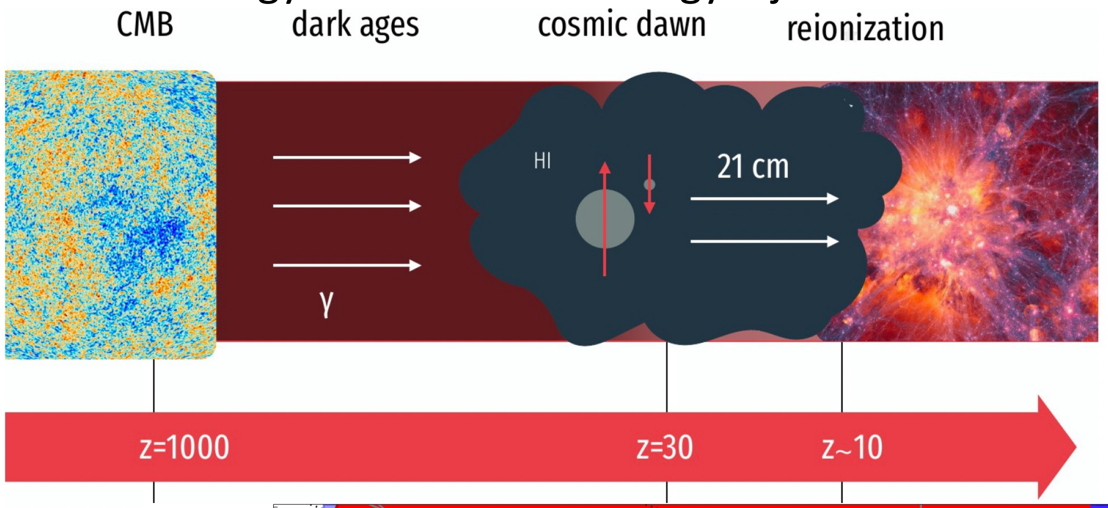
• They are interesting targets for searches in high-energy physics, using collider, flavour, and precision probes

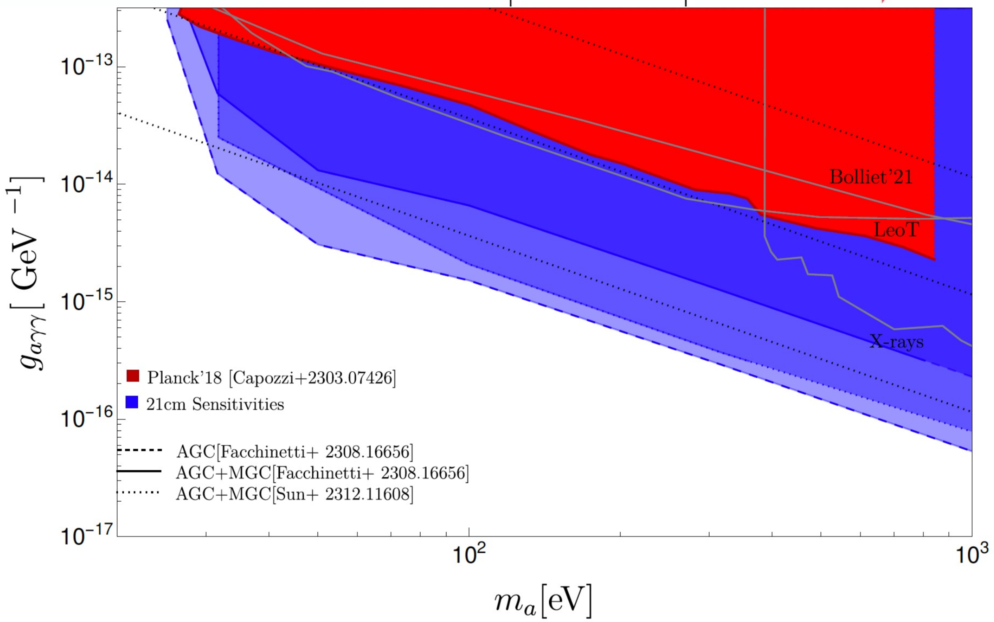
• Rare meson decays have been discussed in detail, with the process provides the strongest particle-physics bounds (for *ma* < 340 MeV) on almost all ALP couplings to the SM

Future 21cm Constraints on DM Energy Injection

Laura Lopez Honorez

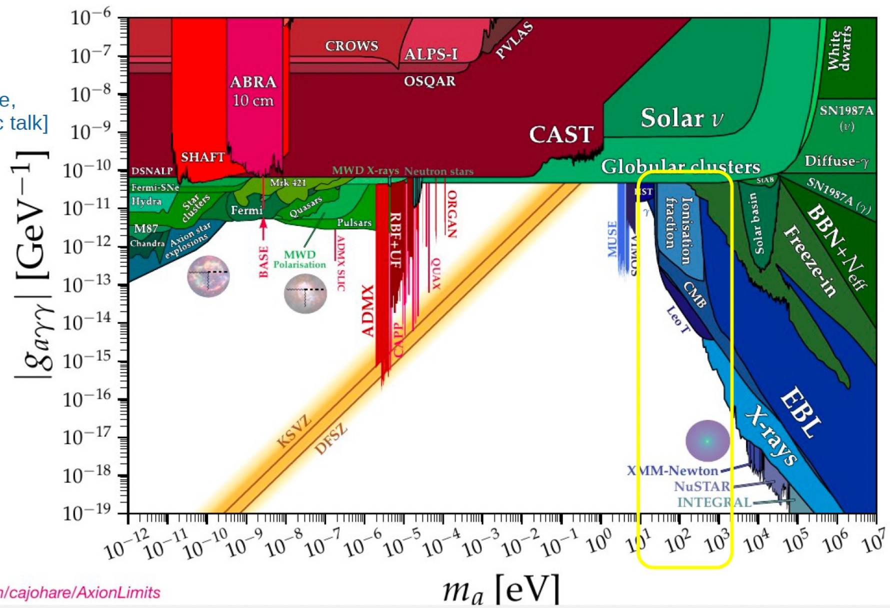
Cosmology Probes of DM energy injection





ALP decays into 2 photons

[see F. Calore, P. Sikivie, etc talk]



https://github.com/cajohare/AxionLimits

Dark matter energy injection through decays imply rather late time (later than WIMP) enhancement of ionization and IGM temperature.

Low z data such as 21cm power spectrum measurements might become a key probe for decaying DM

- We forecast HERA sensitivity with 331 antennas under deployment in South Africa and taking data.
- Expected to surpass CMB/ Lyman-α sensitivity and reach τDM > 1027−28 s.
- DM annihilation is the next step, checking the impact of the B(z).

Many thanks to presenters at Young Scientists Forum

Riccardo BARTOCCI: **Global analysis of the minimal MFV SMEFT**

Joshua LOCKYER: **Exploring near-conformal Hidden Valley theories**

David CABO: **Exploring t-Channel Models for Dark Matter**

Victor ENGUITA VILETA**: nEDM limits on ALP couplings to fermions**

Daniel NAREDO**:New global bounds on heavy neutrino mixing**

Outlook

Goals

Precision → Experiment, Lattice QCD, Higher orders corrections

Testing everything
LFU, BNV, …

Intermediate steps towards NP
SMEFT

Understanding Fermion mass spectrum

NP Models
NP Theories

Dark Matter, axions, GV - very active field with the bright future!

Thank you!

We absolutely must leave room for doubt or there is no progress and no learning. There is no learning without having to pose a question. And a question requires doubt. People search for certainty. But there is no certainty. **Richard P. Feynman**