Beyond the Standard Model: Where do we go from here?

Flavour Overview
or
The (Excessive) Success of the Standard Model

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John Hopkins Workshop – GGI, Florence – October 2018

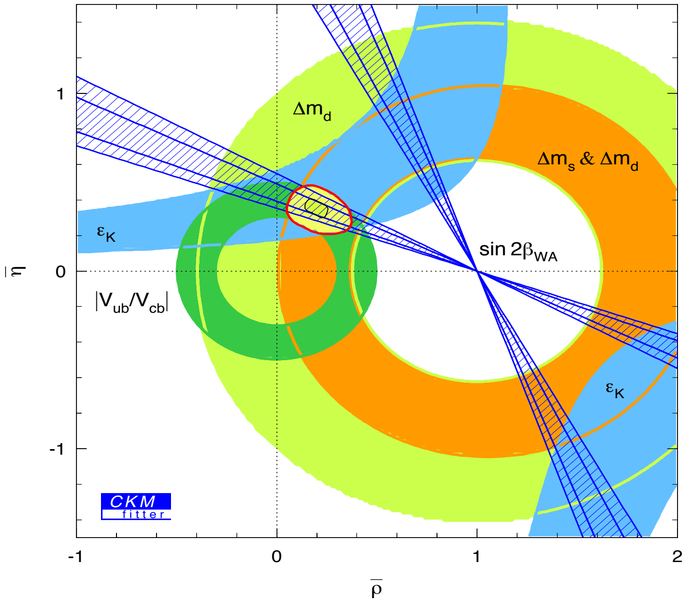
The Common Lore

The SM is considered the low-energy effective theory of a more complete theory which holds at a higher scale. New particles are expected to show up at the EW scale to solve the hierarchy problem and have sizeable couplings to SM particles, so they can be detected either via direct detection or via their indirect effects in loops.

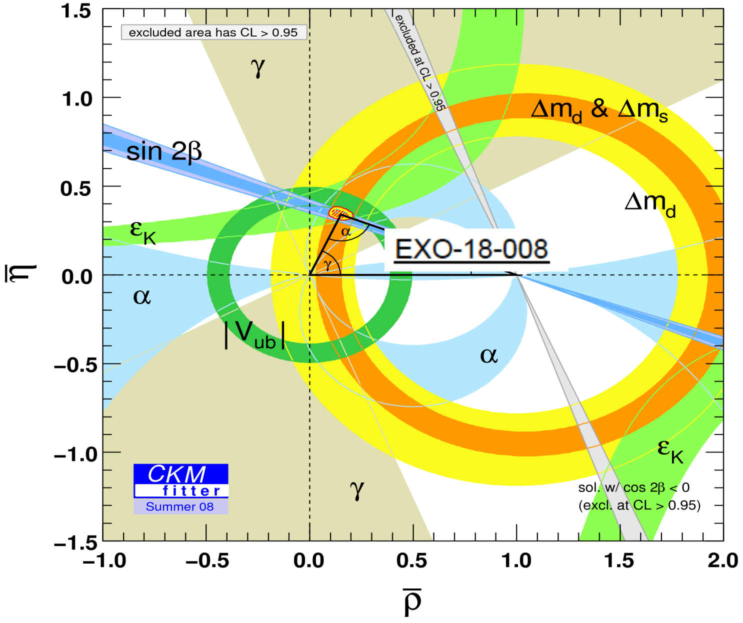
Flavor physics = test of the CKM paradigm

The impressive (excessive) success of the SM

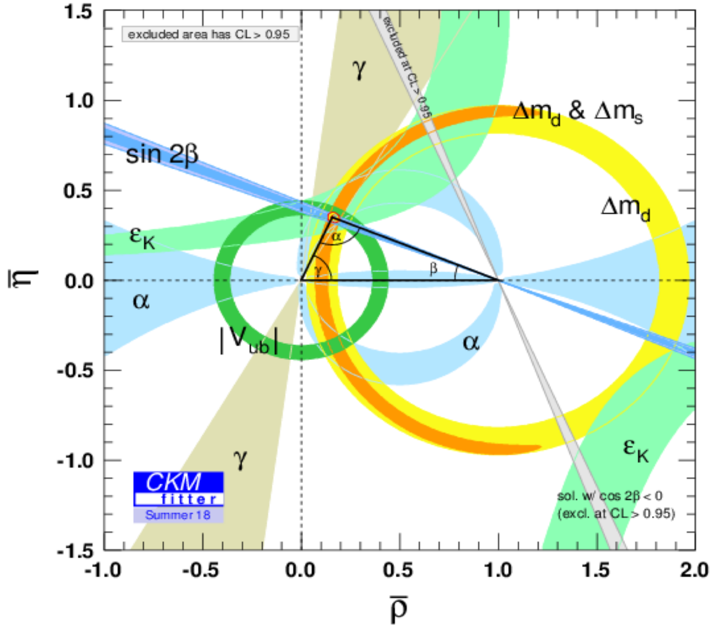
EPS 2001 → ICHEP 2008 → ICHEP 2018



~ Pre B factories



Pre-LHC



LHC and B factories 2018

Dramatic progress in the last ~20 years.

Flavor data sets

Experiment	$\int L dt$	$\sigma(bb)$	$\sigma(cc)$	$\sigma(ss)$	operation
BaBar	530 fb^{-1}	1.1 nb	1.6 nb	0.4 nb	1999-2008
Belle	1040 fb^{-1}	1.1 nb	1.6 nb	0.4 nb	1999-2010
BESIII	16 fb^{-1}	-	6 nb (3770 MeV)	-	2008 -
KLOE2	5.5 fb^{-1}	-		$\sim 3\,\mu$b (1020 MeV)	2014-2018
ATLAS	$> 100\,fb^{-1}$	250-500 μb	-	-	2009 -
CMS	$> 100\,fb^{-1}$	250-500 μb	-	-	2009 -
LHCb	$1 + 2 + > 5$ fb^{-1}	250 - 500 μb	1200 - 2400 μb	$\sim 10^{13} K_S/\text{fb}^{-1}$	2009 -
NA62	-	-	-	$> 5 \cdot 10^{12} K^+$ decays in FV	2016 -
Belle-II	> 0.5 fb^{-1} (50 ab^{-1})	1.1 nb	1.6 nb	0.4 nb	2018 -

A wealth of experimental results in the last decade is constraining the CKM matrix with unprecedented level of precision.

The CKM Matrix

$$V_{\mathrm{CKM}} \propto \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\, e^{-i\gamma} \\ -\,|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\, e^{-i\beta} & -\,|V_{ts}|\, e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$

The SM describes the mixing of quarks of different generations through the weak force.
3 Generations, 1 Phase: single source of CPV in the SM.

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$B \to \pi\pi,\ \rho\rho$	α / Φ_2	$B \to D^* l\nu / b \to c l \nu$	$\|V_{cb}\|$ via Form factor / OPE
$B \to D^{(*)} K^{(*)}$	γ / Φ_3	$B \to \pi l \nu / b \to u l \nu$	$\|V_{ub}\|$ via Form factor / OPE
$B \to J/\psi K_s$	β / Φ_1	$M \to l \nu (\gamma)$	$\|V_{UD}\|$ via Decay constant f_M
$B_s \to J/\psi \Phi$	β_s	ε_K	(ρ, η) via B_K
$K \to \pi \nu$ anti-ν	ρ, η	$\Delta m_d, \Delta m_s$	$\|V_{tb} V_{t\{d,s\}}\|$ via Bag factor B_B
		$B_{(s)} \to \mu+ \mu-$	$\|V_{t\{d,s\}}\|$ via Decay constant f_B

The CKM Matrix: the angle γ

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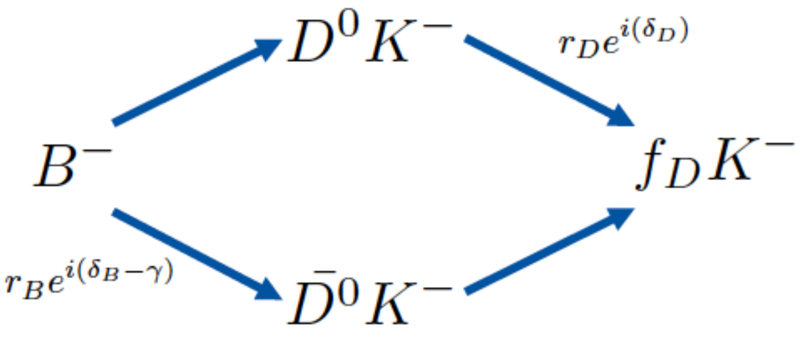
$K \to \pi\, \nu$ anti-ν	ρ, η

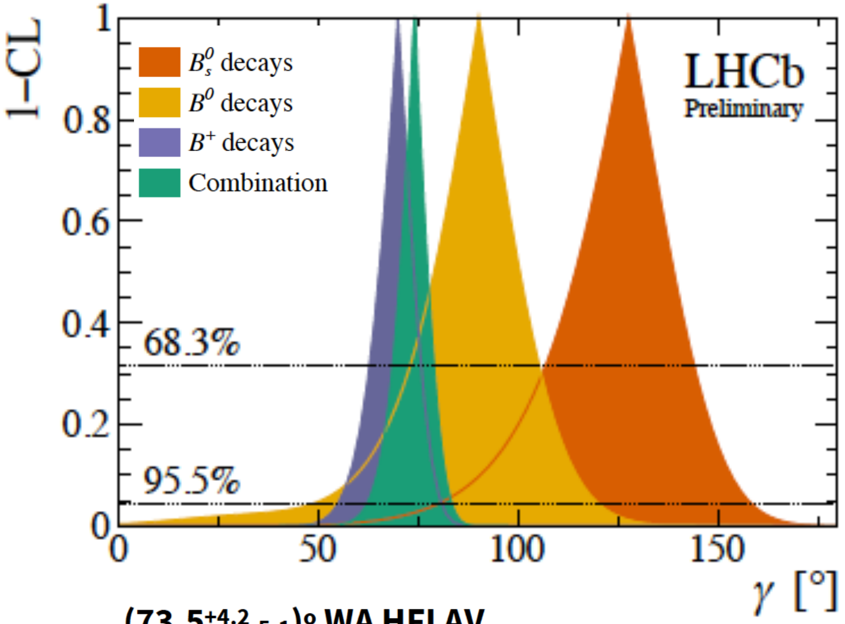


Sensitivity from interference of $b \to c$ and $b \to u$ amplitudes

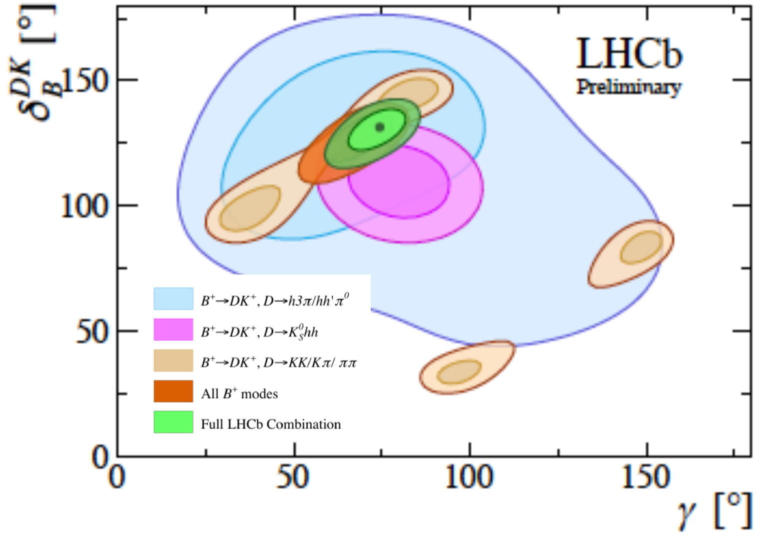
The angle γ

LHCb arXiv:1806.01202
LHCb JHEP 1803 (2018) 059
LHCb PLB777 (2018) 16-30
LHCb JHEP 1806 (2018) 084

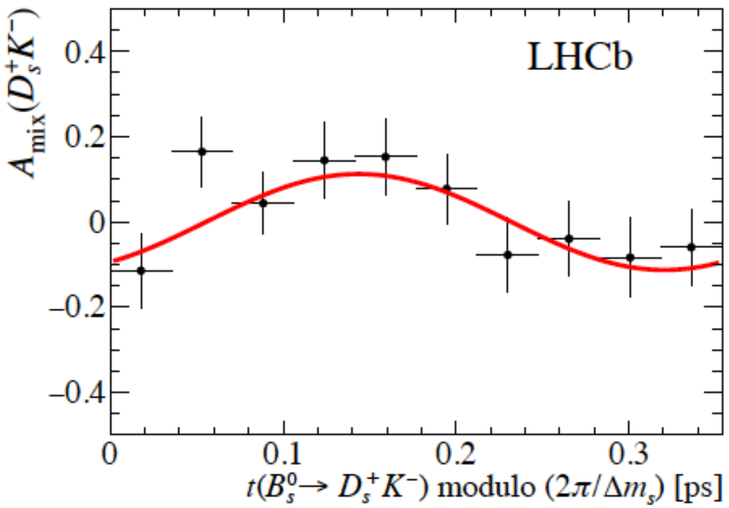
Can be measured from tree-level processes only, standard candle in the SM.
Theory is "pristine" in this approach, theory uncertainty o(10^{-7}).
Triumph of LHCb with B^0, B^{+-}, B_s combination with D phase input from Cleo-c (BESIII data coming)
Now reaching an accuracy comparable to α.



$(73.5^{+4.2}_{-5.1})°$ **WA HFLAV**
$(73.5^{+5.1}_{-5.7})°$ **LHCb**
$(65.3^{+1.0}_{-2.5})°$ **Indirect CKMFitter**



Measurement of the CKM angle γ using $B^\pm \to DK^\pm$ with $D \to K^0_S\pi^+\pi^-, K^0_S K^+K^-$ decays



New time-dependent measurements in $B \to D\pi$ $(2\Phi_1 + \Phi_3)$ and $B_s \to D_sK$ $(\Phi_s - \Phi_3)$

The CKM Matrix: the angle β

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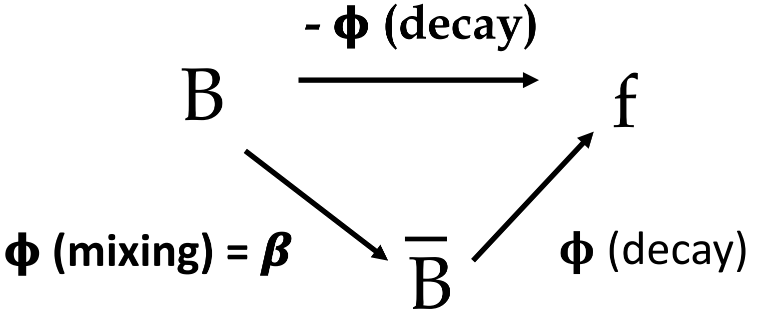
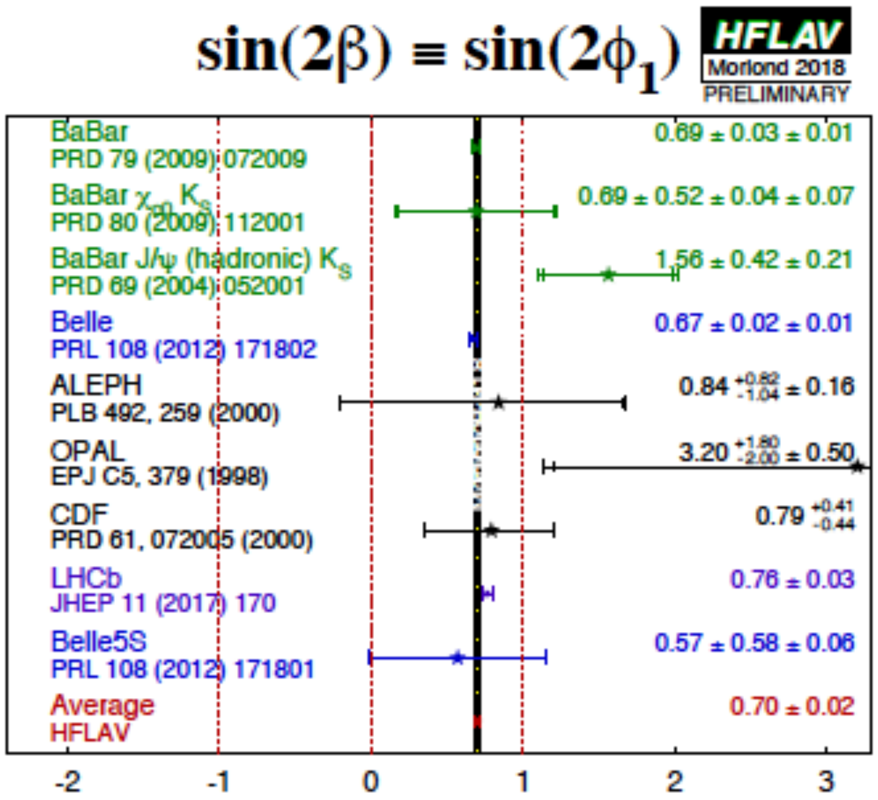
$K \to \pi\, \nu\, anti\text{-}\nu$	ρ, η



Sensitivity from interference between decay with and without mixing

The angle β

Belle+Babar arXiv: 1804.06153
Belle+Babar arXiv: 1804.06152
LHCb JHEP 1711 (2017) 170
LHCb PRD95 5, 052005 (2017)



0.70±0.02 WA HFLAV

$0.740^{+0.020}_{-0.025}$ Indirect CKMFitter

Ambiguity in the sign of $\cos(2\beta)$ solved by BaBar+Belle:

$\cos(2\beta) > 0$ at 7σ

Penguin pollution constrained by the measurement of the $B^+ \longrightarrow J/\psi K^+$ asymmetry well below the current experimental uncertainty on $\sin(2\beta)$:

$$\phi^{\rm eff}\,(\text{obs}) = \phi\,(\text{tree}) + \Delta\phi\,(\text{penguin}) + \phi\,(\text{NP})$$

$$\Delta\phi\,(\text{penguin}) = (-1.10^{+0.70}_{-0.85})^\circ$$

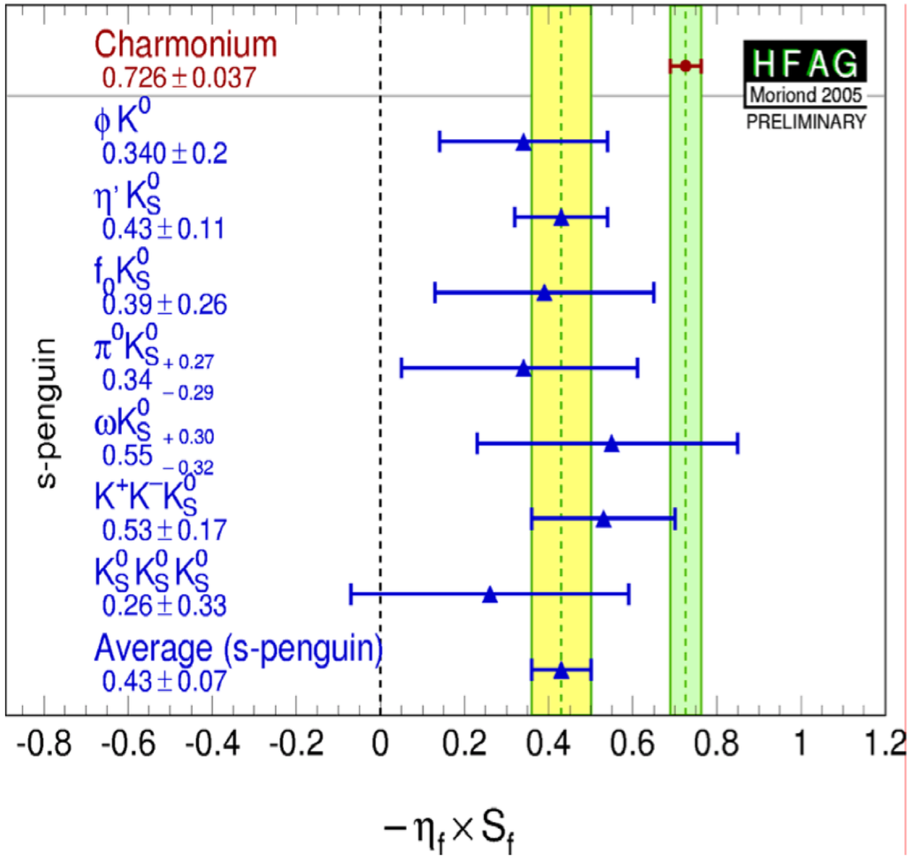
$$\Delta\phi\,(\text{obs}) = 1.6^\circ$$

Accuracy from LHCb rapidly approaching that of B-factories. Very good agreement with indirect $\sin(2\beta)$ determination, no hints of NP.

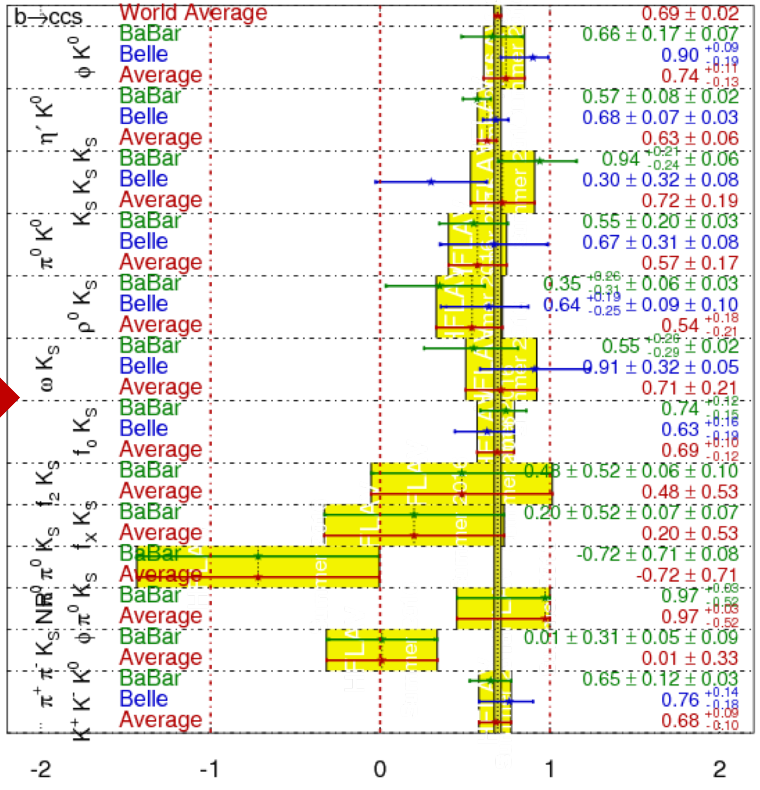
…. and this has not always been the case:

CKM2005 – **3.7σ** between $b \to c\bar{c}s$ and *s*-penguins

sin(2*β*^eff) in 2005



sin(2β^eff) ≡ sin(2φ1^eff) HFLAV Summer 2016



…. Anomalies come and go …

The CKM Matrix: the angle βs

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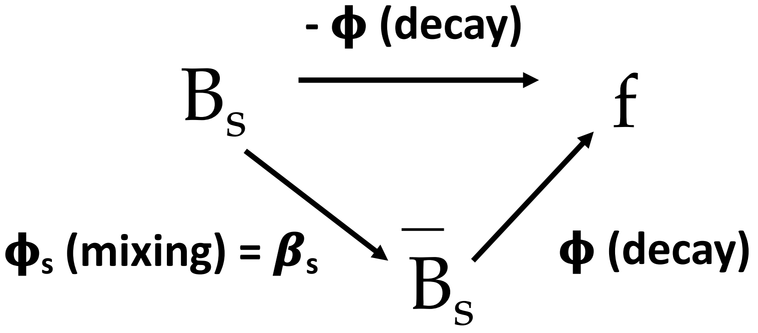
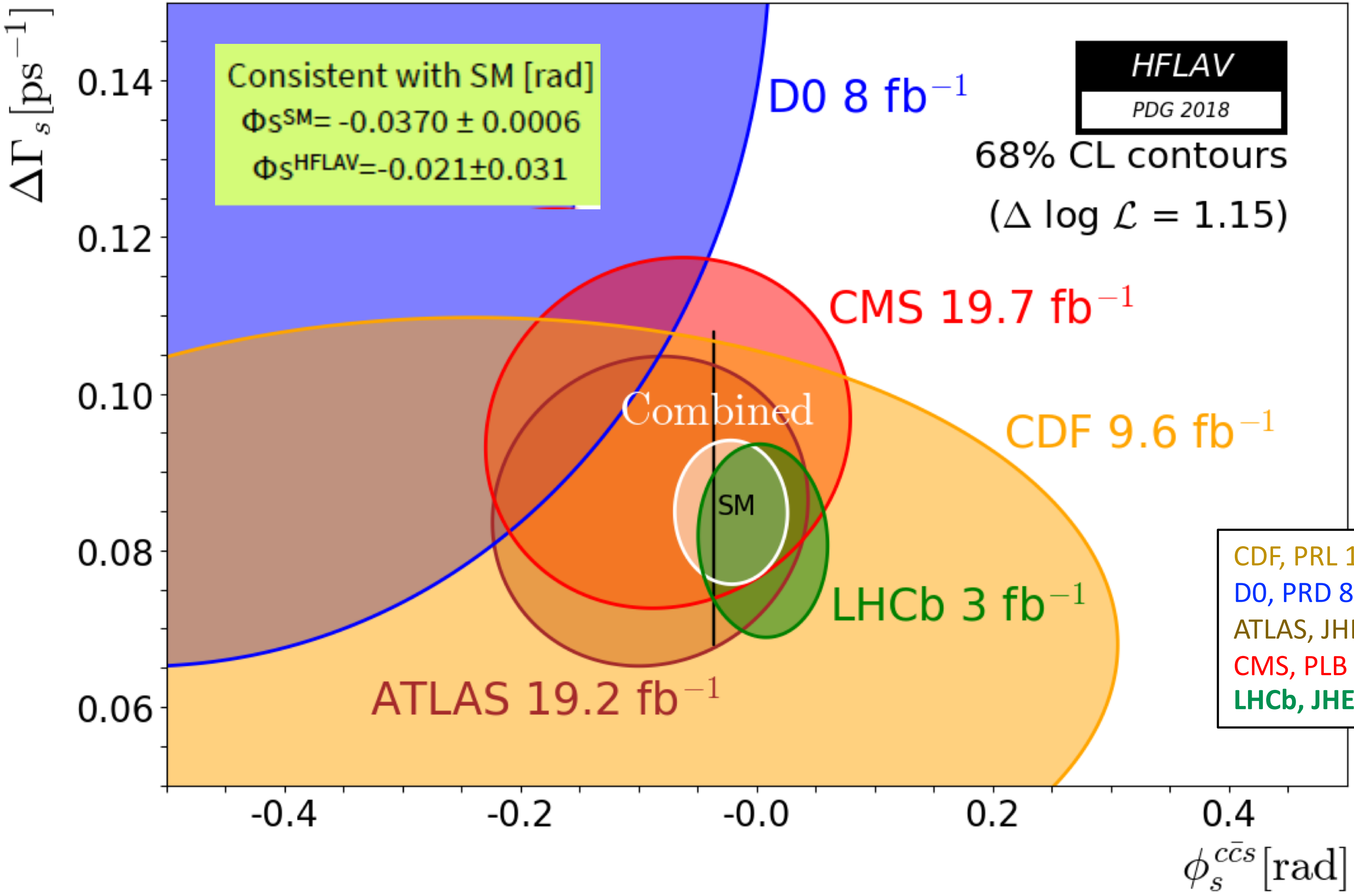
$K \to \pi \nu$ anti-ν	ρ, η



Sensitivity from interference between decay with and without mixing

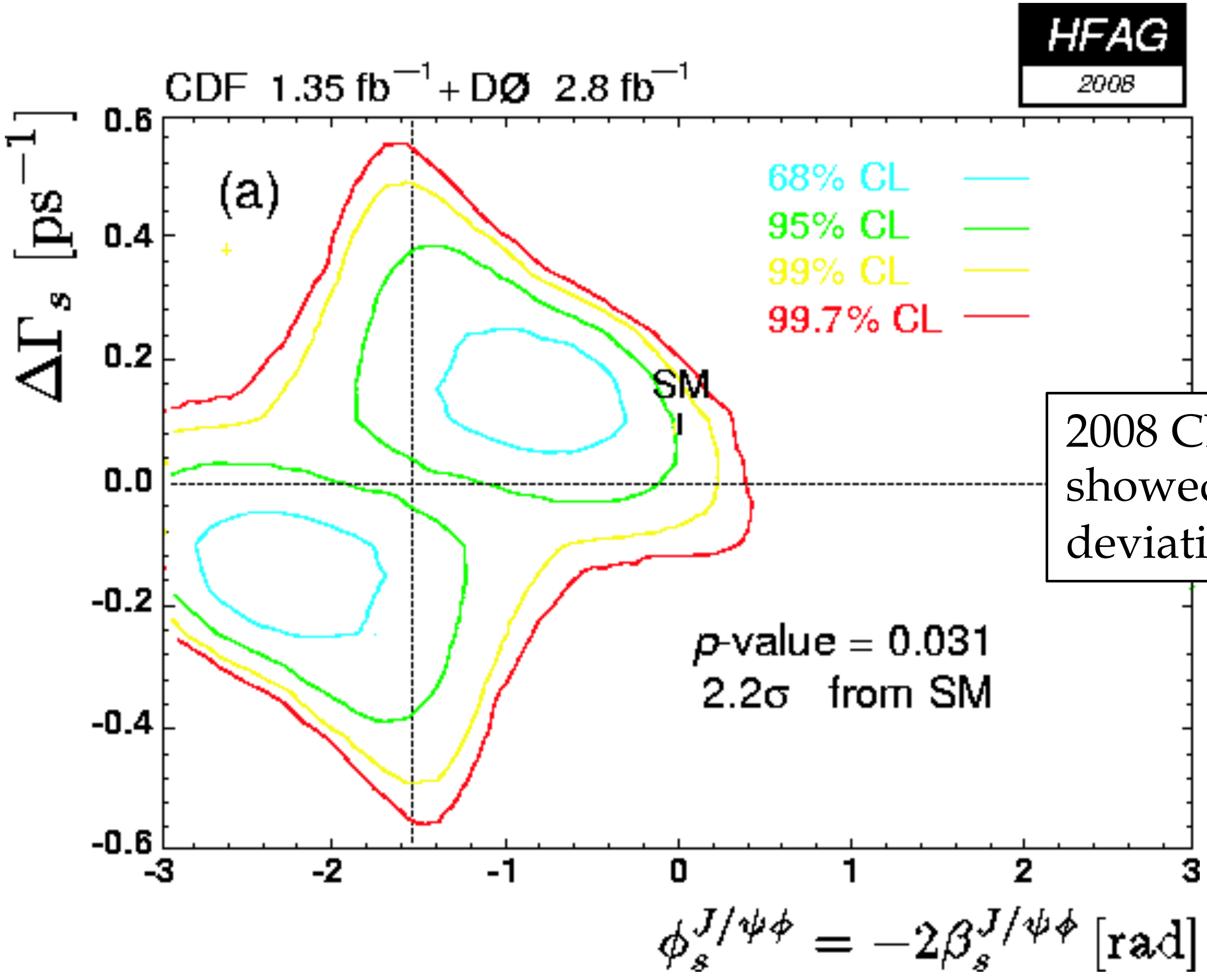
The angle ϕ_s = -2βs



CDF, PRL 109 (2012), 171802
D0, PRD 85 (2012) 032006
ATLAS, JHEP 08 (2016) 147
CMS, PLB 757 (2016) 97
LHCb, JHEP 08 (2017) 037

Remarkable agreement between measurements and SM predictions

…. and also in this case this was not always the case:



2008 CDF and D0 measurements showed an intriguing 2.2 σ deviation from SM predictions

…. Anomalies come and go …..

Scale of New Physics from the analysis of FCNC ΔF=2 transitions

The SM is considered the low-energy effective theory of more complete theory which holds at a higher scale. New particles are expected to show up at the EW scale to solve the hierarchy problem and they are expected to have sizeable couplings to SM particles, hence they can be detected either via direct detection or via indirect effects in loops.

$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\rm eff}^{\rm full} | \overline{B}_q \rangle}{\langle B_q | H_{\rm eff}^{\rm SM} | \overline{B}_q \rangle} = \frac{F_i L_i}{\Lambda^2} = \frac{C_i^{NP}}{\Lambda^2} e^{i\phi_{NP}}$$

Similar for K and D

F_i is a function of the (complex) NP flavor coupling,
L_i is a loop factor that is present in models with no tree-level FCNC
Λ is the scale of NP, typical mass of new particles mediating $\Delta F = 2$ transitions

Scale of New Physics

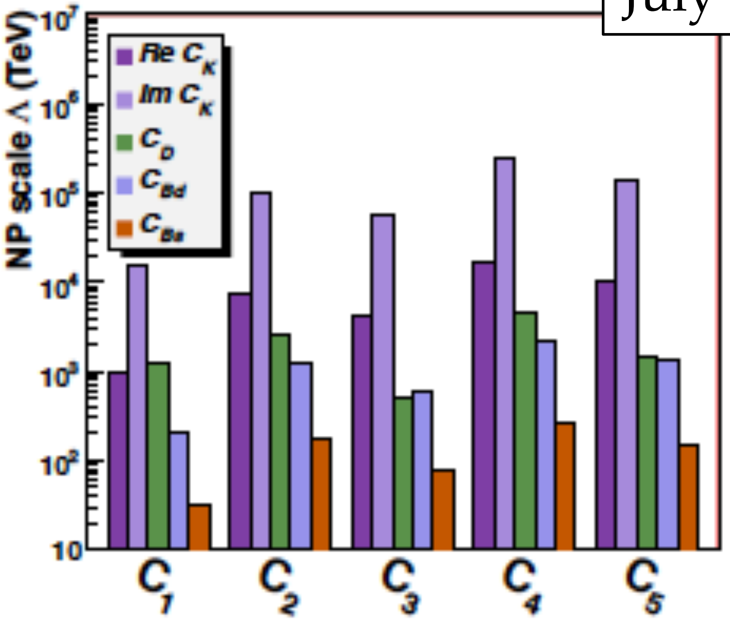
$$C_i^{NP} = 1,\ \phi_i^{NP} = \text{any value (generic flavour)},$$
$$C_i^{NP} = \text{CKM},\ \phi_i^{\rm NP} = \text{any value (NMFV)},$$
$$C_i^{NP} = \text{CKM},\ \phi_i^{NP} = \text{SM (MFV)}$$

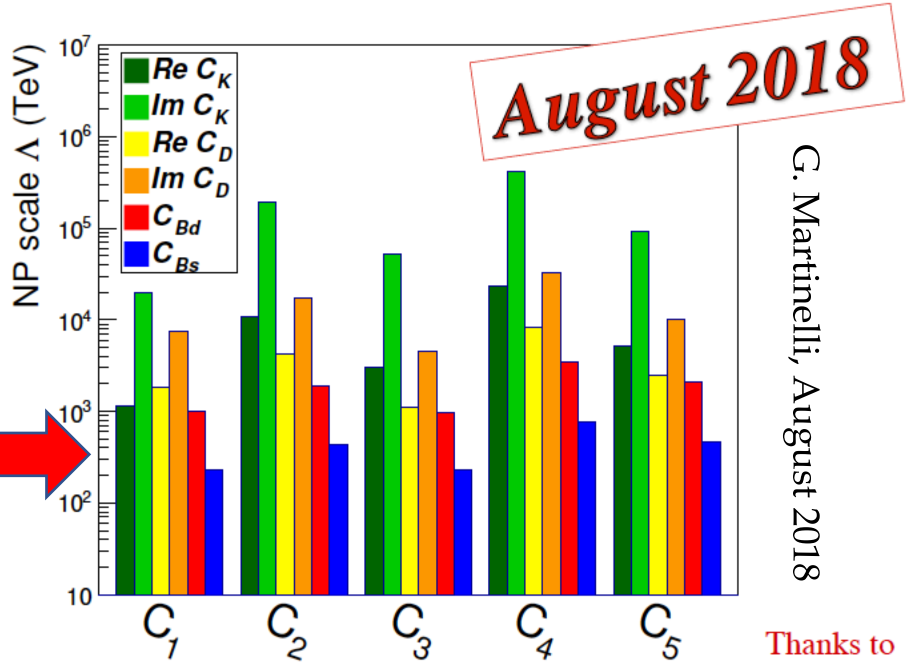
Limits on the Λ scale for strong coupling, C_i (NP) ~ 1, any phase

Dramatic increase of the Λ scale from low-energy measurements in the last ten years
Constraints from Kaon physics still dominate ($\Lambda \sim 10^5$), followed by charm ($\Lambda \sim 10^4$), beauty ($\Lambda \sim 10^3$)

UTFit, 0707.0636

July 2007





G. Martinelli, August 2018

Thanks to
L. Silvestrini

ε_K	$\Lambda = 5\ 10^5$ TeV
D	$\Lambda = 5\ 10^4$ TeV
B_d	$\Lambda = 5\ 10^3$ TeV
B_s	$\Lambda = 10^3$ TeV

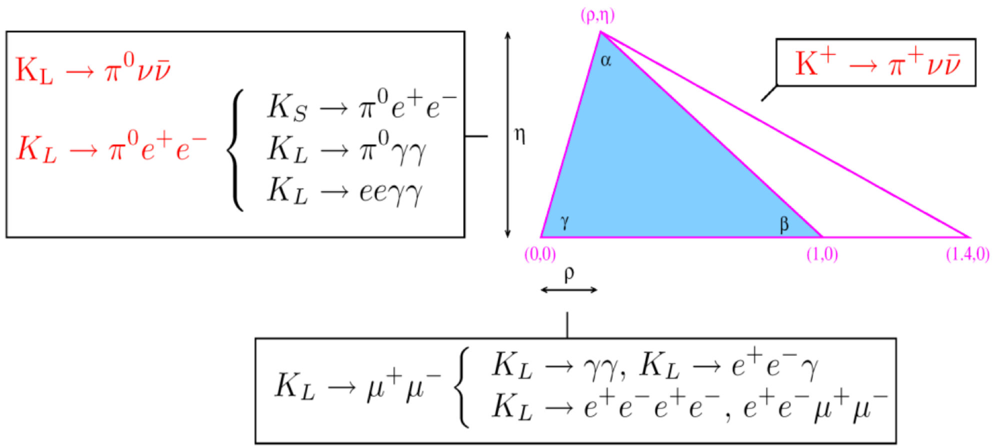
Possible NP operators:

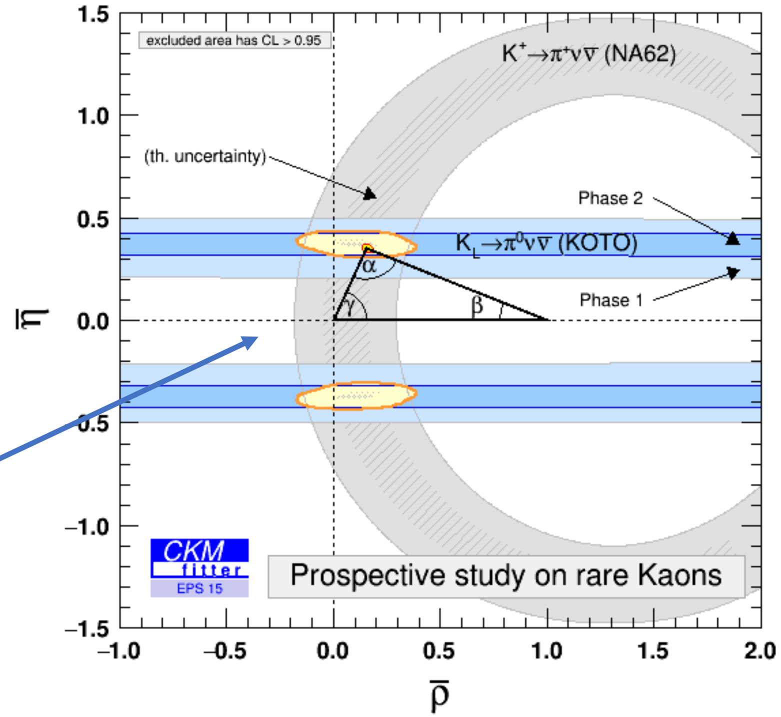
$$Q_1^{q_iq_j} = \bar{q}^\alpha_{jL}\gamma_\mu q^\alpha_{iL}\bar{q}^\beta_{jL}\gamma^\mu q^\beta_{iL}\,,$$
$$Q_2^{q_iq_j} = \bar{q}^\alpha_{jR} q^\alpha_{iL}\bar{q}^\beta_{jR} q^\beta_{iL}\,,$$
$$Q_3^{q_iq_j} = \bar{q}^\alpha_{jR} q^\beta_{iL}\bar{q}^\beta_{jR} q^\alpha_{iL}\,,$$
$$Q_4^{q_iq_j} = \bar{q}^\alpha_{jR} q^\alpha_{iL}\bar{q}^\beta_{jL} q^\beta_{iR}\,,$$
$$Q_5^{q_iq_j} = \bar{q}^\alpha_{jR} q^\beta_{iL}\bar{q}^\beta_{jL} q^\alpha_{iR}\,.$$

New Physics either is very heavy or it mimics the SM in its flavor-breaking pattern…

A completely independent way of constraining CKM: rare kaon decays

K physics alone can fully constrain the CKM unitarity triangle.
Comparison with B physics can provide description of NP flavour dynamics





Theory predictions

$$BR(K^o \to \pi^o \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

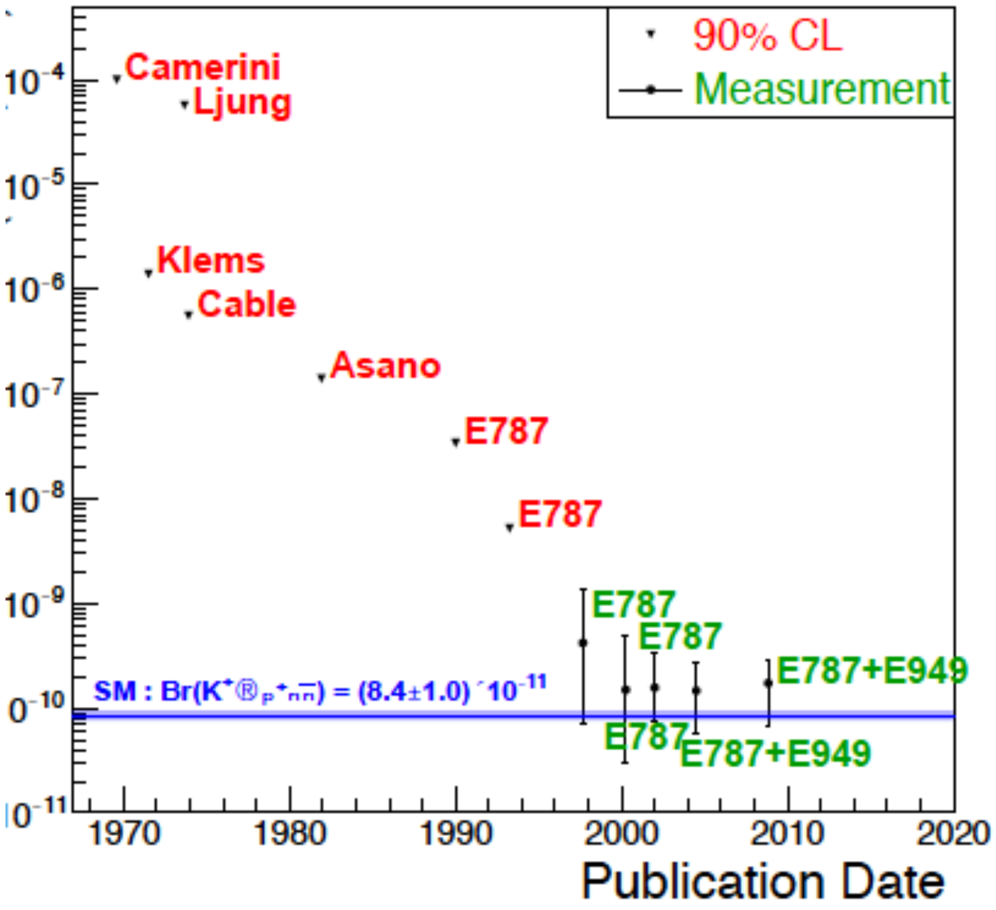
[Buras et al. JHEP 1511 (2015) 33]

Constraints in the ($\bar{\rho}$, $\bar{\eta}$) plane, using a prospective scenario for the NA62 and KOTO experiments.

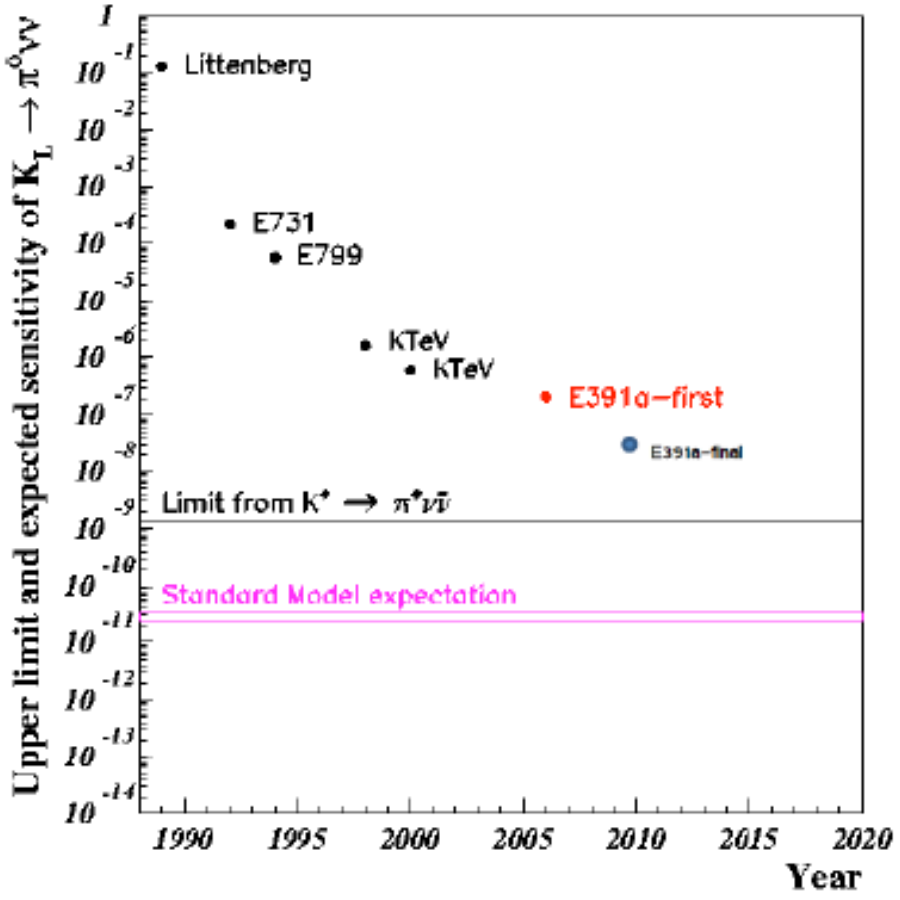
- For NA62, a measurement of BR($K^+ \to \pi^+ \nu\nu$) with a 10% accuracy is assumed;
- For KOTO, a two-step prospective scenario is assumed : first, a 3σ evidence for the $K_L \to \pi^0 \nu\nu$ decay (Phase 1, lighter blue), followed by a later measurement of BR($K_L \to \pi^0 \nu\nu$) with 10% accuracy (Phase 2, darker blue).

K ⟶ π ν νbar: experimental status - the past

$K^+ \longrightarrow \pi^+ \nu$ νbar



$K_L \longrightarrow \pi^0 \nu$ νbar

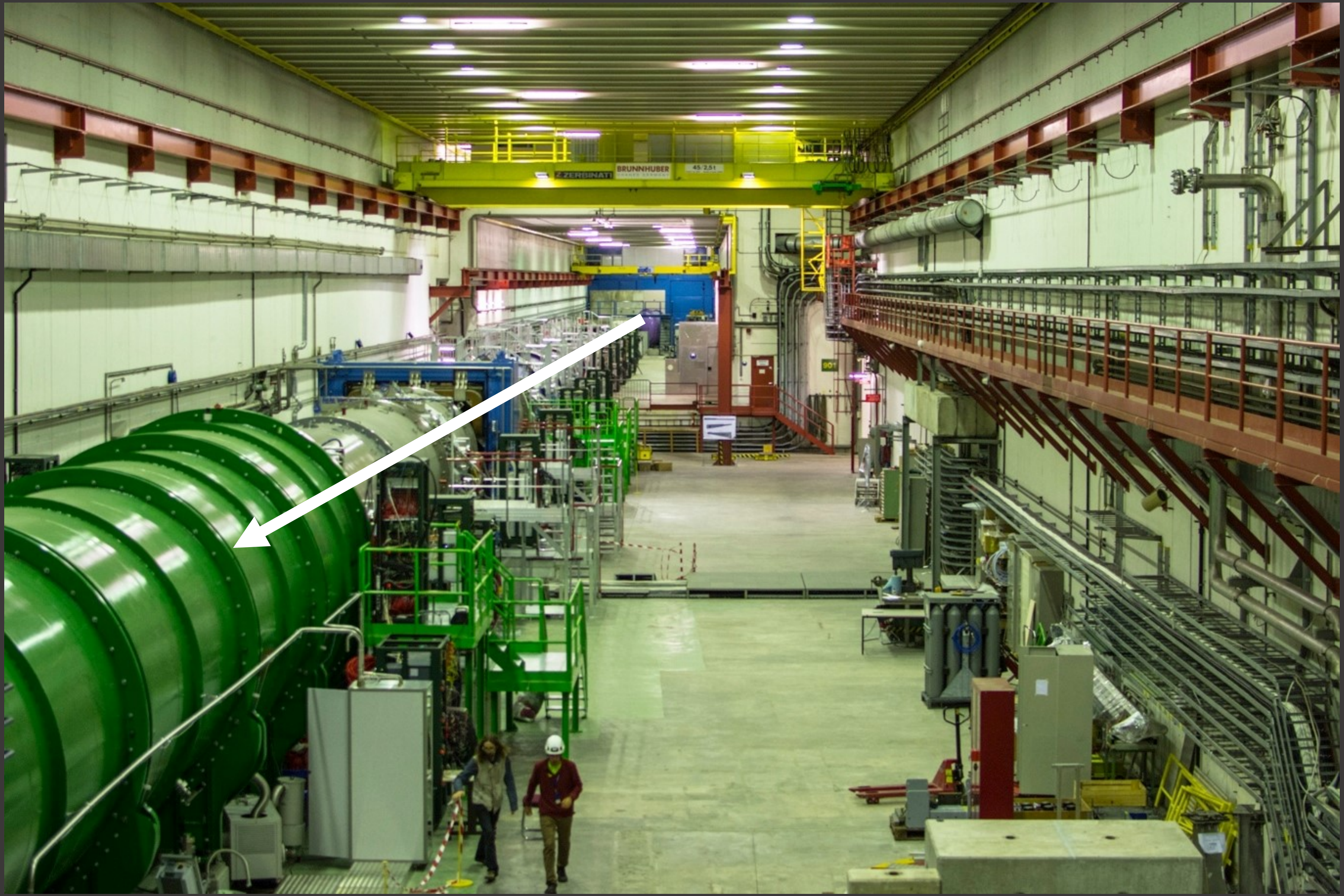


$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)

$BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L.) Phys. Rev. D 81, 072004 (2010)

The NA62 experiment @ K12 in EHN3

https://na62.web.cern.ch/



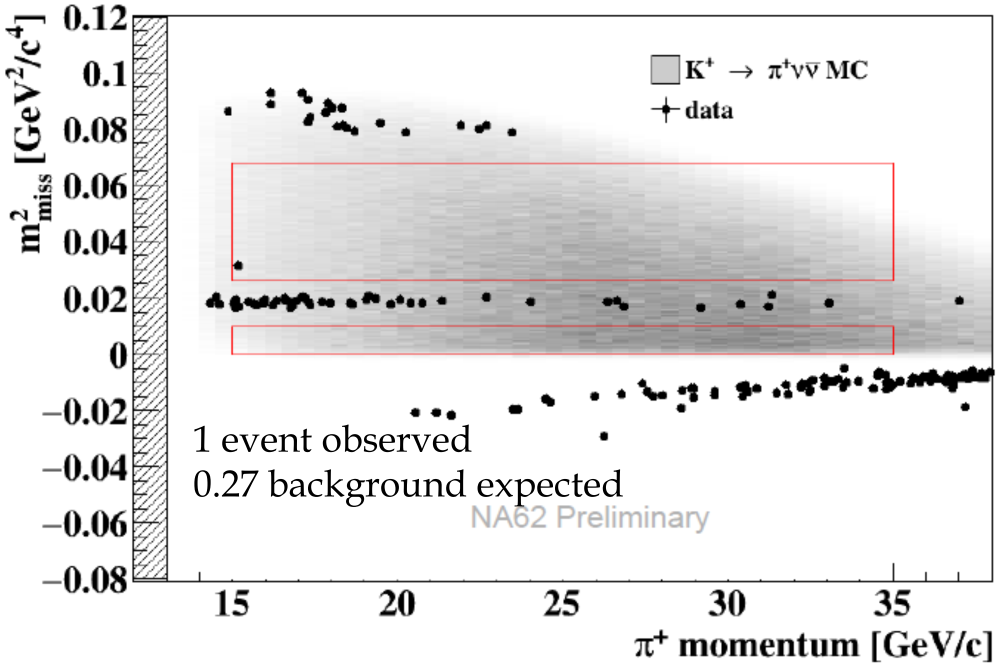
NA62 is taking data with the aim of measuring BR($K^+ \longrightarrow \pi + \nu\ \nu$bar) with 10% accuracy

K⟶π ν ν experimental status: the present/future

- **NA62 is taking data with the aim at measuring BR($K^+ \longrightarrow \pi^+\nu\nu$ bar) with 10% accuracy**:
  - Current limit based of 2016 data (10^{11} K decays, ~1% of the total data sample)

$$\boxed{BR_{2016}(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10} \text{ @ } 95\%\ CL}$$

  - 20 SM events expected with the 2017-2018 dataset.
  - data taking after 2018 to be approved:
    - expected ultimate sensitivity under evaluation.



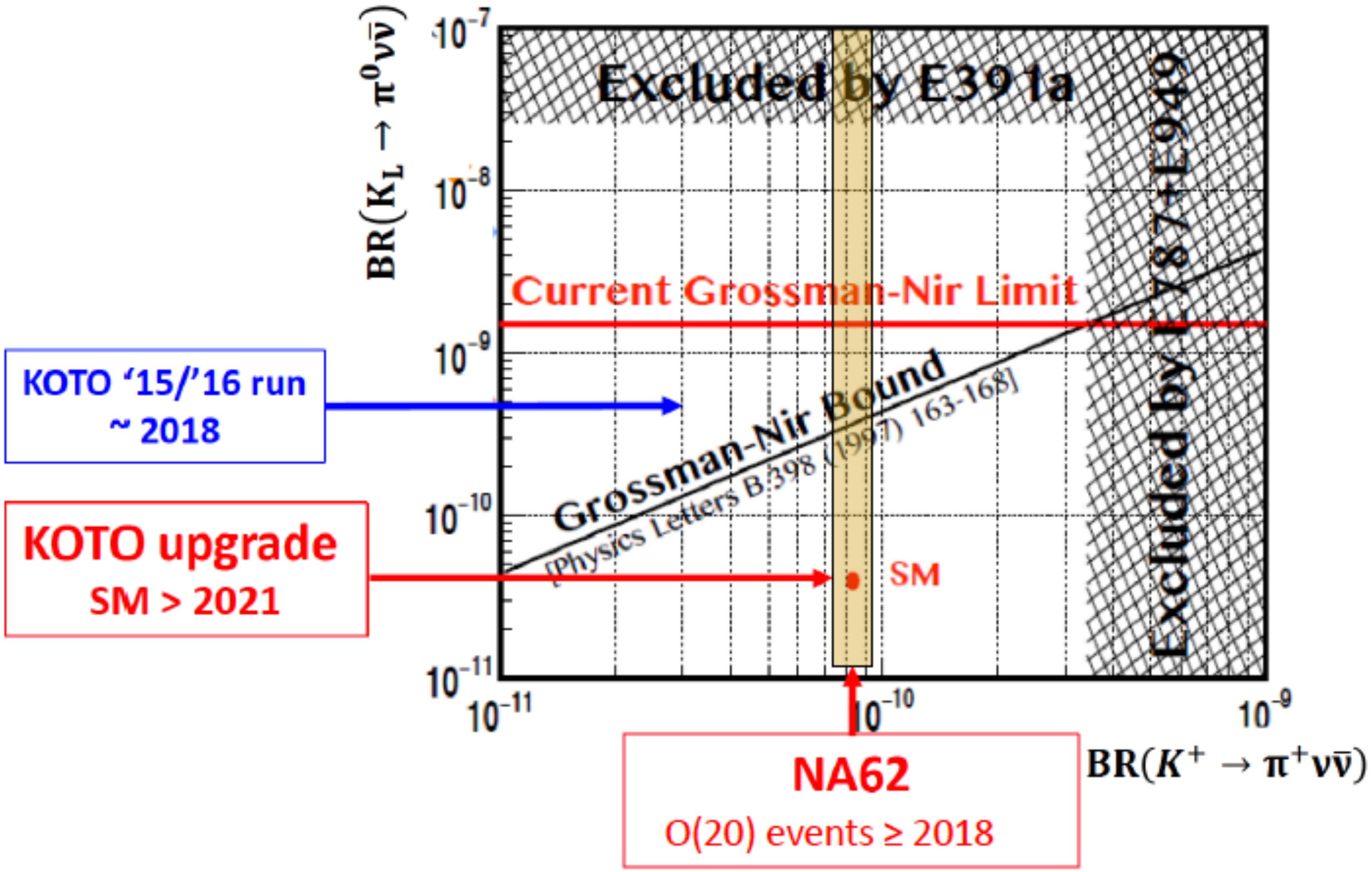
- **KOTO has presented at ICHEP 2018 a limit based on the 2015 dataset:**

$$\boxed{\text{BR } (K_L \longrightarrow \pi^0\nu\nu) < 3.0 \times 10^{-9} \text{ @ } 90\%\ \text{CL}}$$

  and aims to reach the SM sensitivity after 2021.

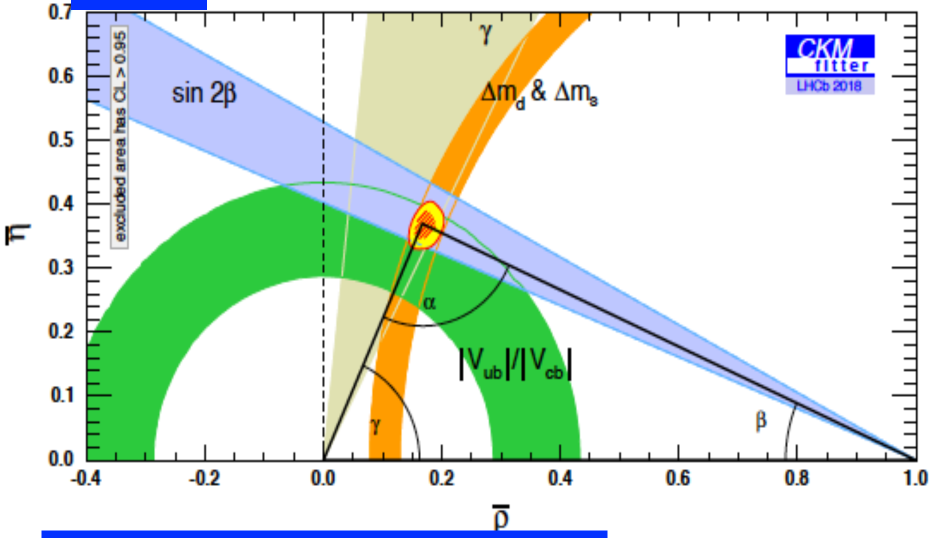
- **KLEVER proposal at CERN**
  aims to measure the BR($K_L \longrightarrow \pi^0$ v vbar) with 20% accuracy by 2030++

K⟶ π ν νbar: near prospects

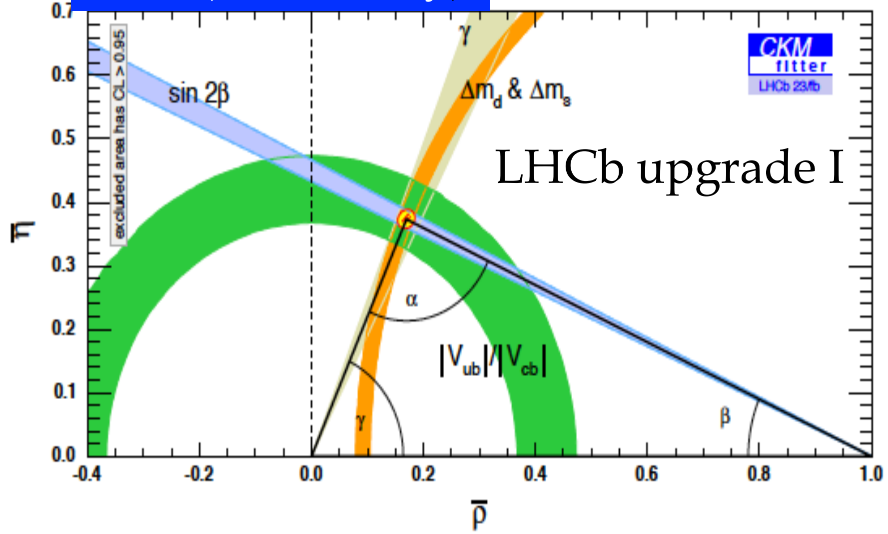


Progress on the CKM knowledge expected in the next ~10-20 years

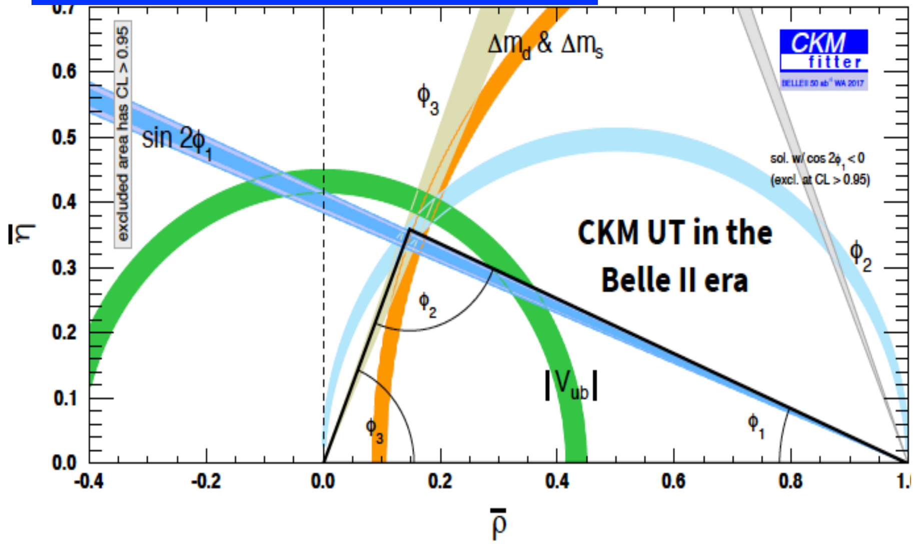
2018



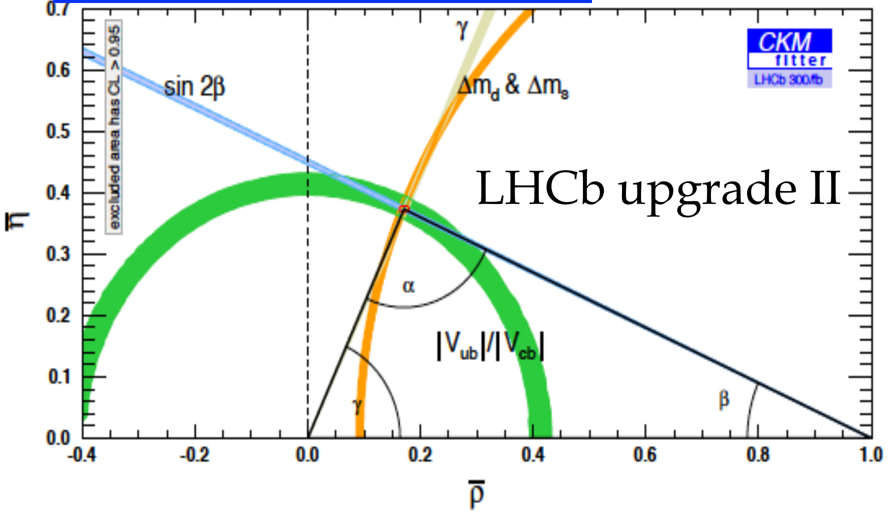
2025 (LHCb only)



2025 (LHCb and Belle II)



2035: LHCb Upgrade II



Rare B decays
(or: the famous B anomalies)

Lepton Flavor Universality

Lepton Flavor Universality (LFU) is a basic property of the SM: universal coupling with the three lepton generations.

$$\mathcal{L}_f = \bar{f} i D_\mu \gamma^\mu f \quad f = l_L^i,\ q_L^i,\ i = 1,2,3$$

for each of three generations in weak interactions

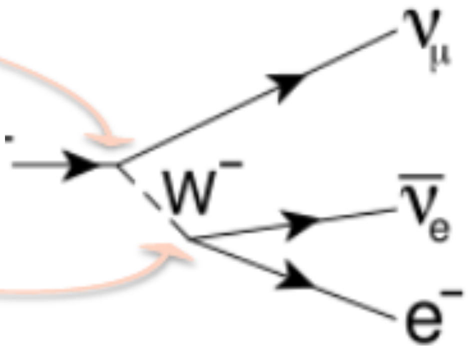
$$D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau}\cdot\vec{W}_\mu + ig'\frac{1}{2}Y_W B_\mu$$

the same for all SM fermions

$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

$$\frac{g^2}{8m_W^2} = \frac{G_F}{\sqrt{2}}$$

the same coupling of lepton
and its neutrino with
W for all three lepton generations!



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$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

$$\frac{g^2}{8m_W^2} = \frac{G_F}{\sqrt{2}}$$

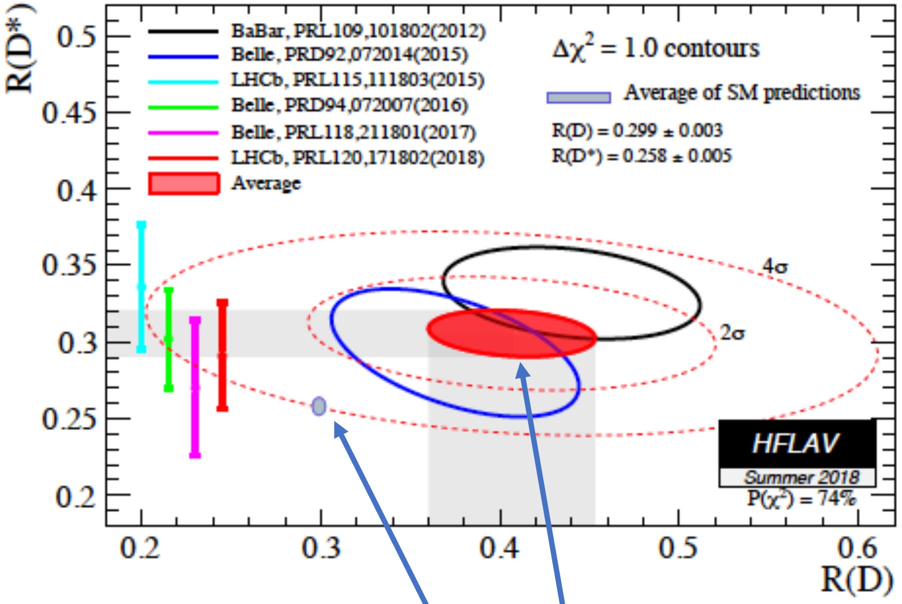
However LFU is not a fundamental symmetry of the SM:

it is accidental in the gauge sector, where the gauge bosons equally couple to the different lepton flavors.
LFU is broken by the Higgs couplings to masses, which are flavor-specific,
but they have a negligible effect on the partial widths of the decays.

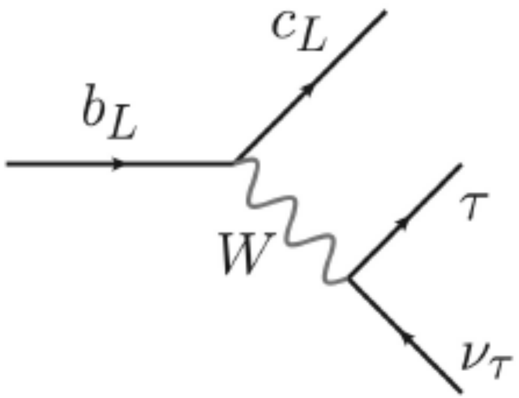
LFU tested up to percent precision in Z⟶ l+ l- and J/ψ ⟶ l+ l- decays (PRD 98 (2018) 030001)

The first B-anomaly: b ⟶ charm charged currents, tree level

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$



World average near 3.9 σ away from SM predictions



HFLAV averages:

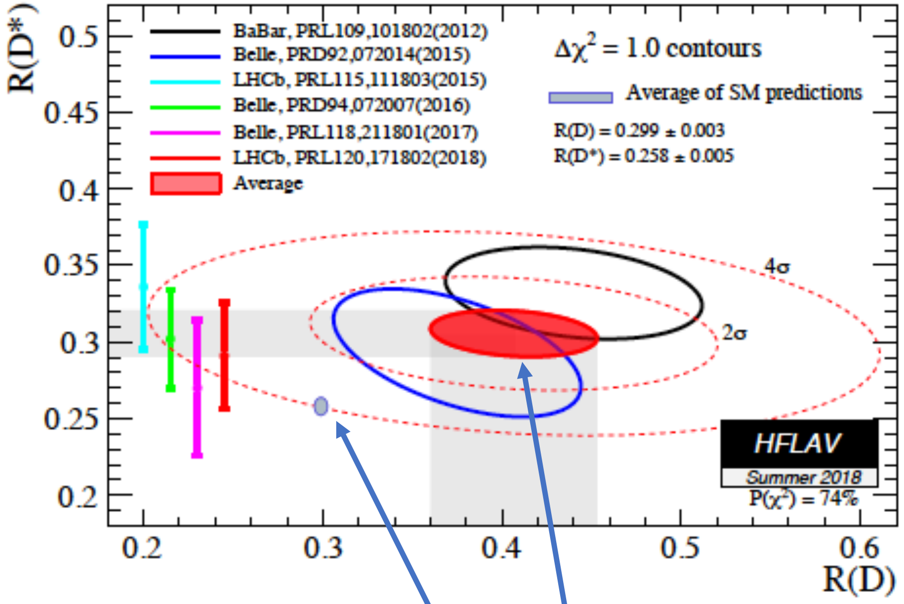
$$\begin{aligned} R(D^*) &= 0.304 \pm 0.013 \pm 0.007 \quad (3.4\,\sigma) \\ R(D) &= 0.407 \pm 0.039 \pm 0.024 \quad (2.3\,\sigma) \end{aligned}$$

Theory predictions:

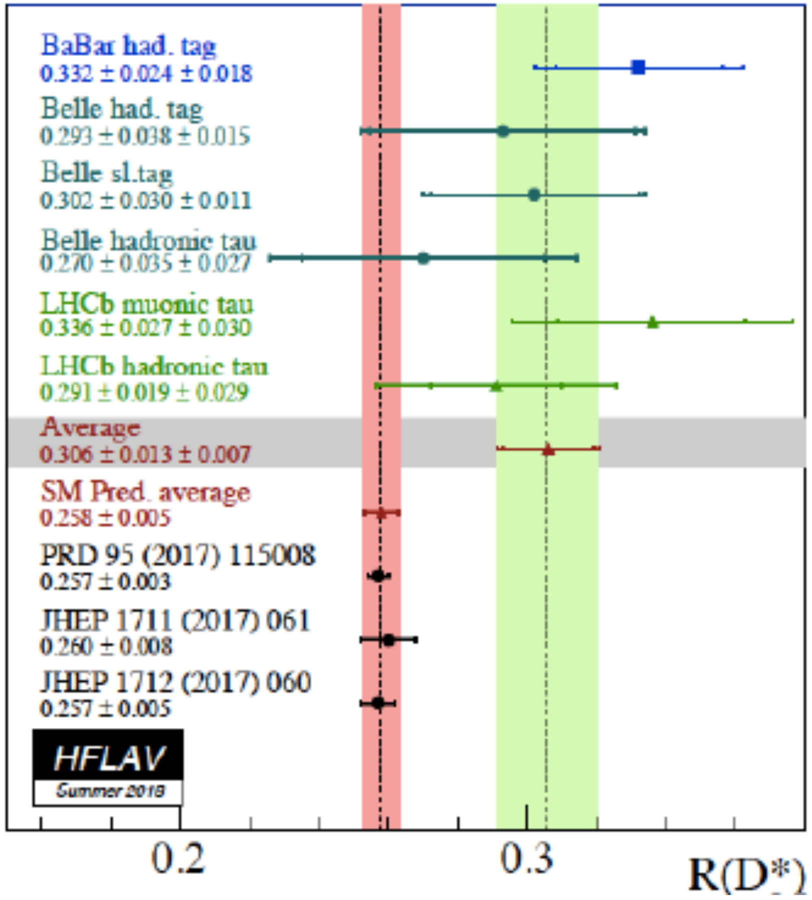
$$\begin{aligned} R(D^*) &= 0.252 \pm 0.003 \quad \text{Fajfer, 2012} \\ R(D) &= 0.300 \pm 0.008 \quad \text{HFLAV average} \end{aligned}$$

The first B-anomaly: b ⟶ charm charged currents, tree level

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$



World average near 3.8 σ away from SM predictions



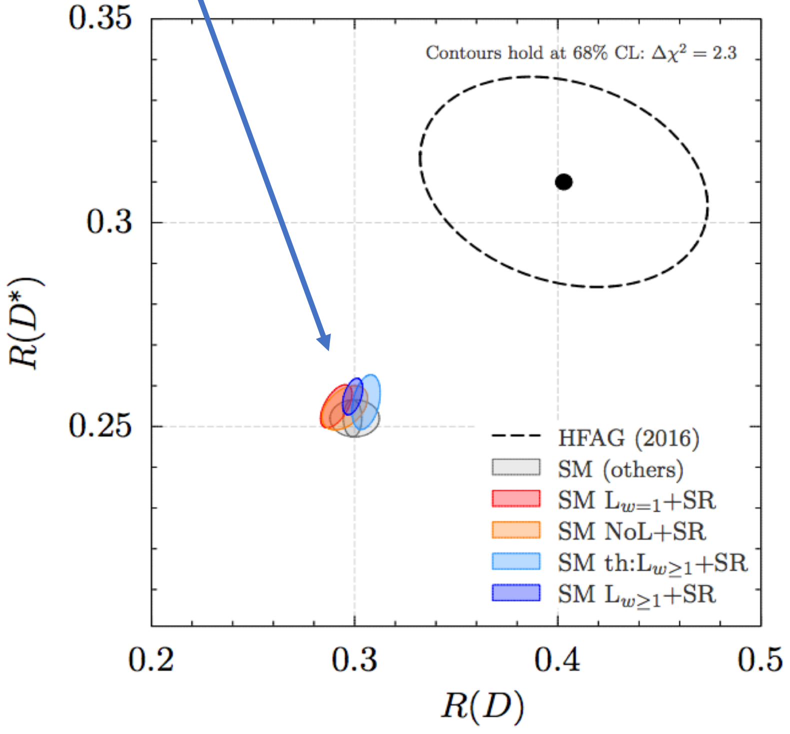
However:

- R(D*) with hadronic modes are 1 σ consistent with SM
- Belle R(D*) combination < 2 σ from SM

The first B-anomaly: b ⟶ charm charged currents, tree level

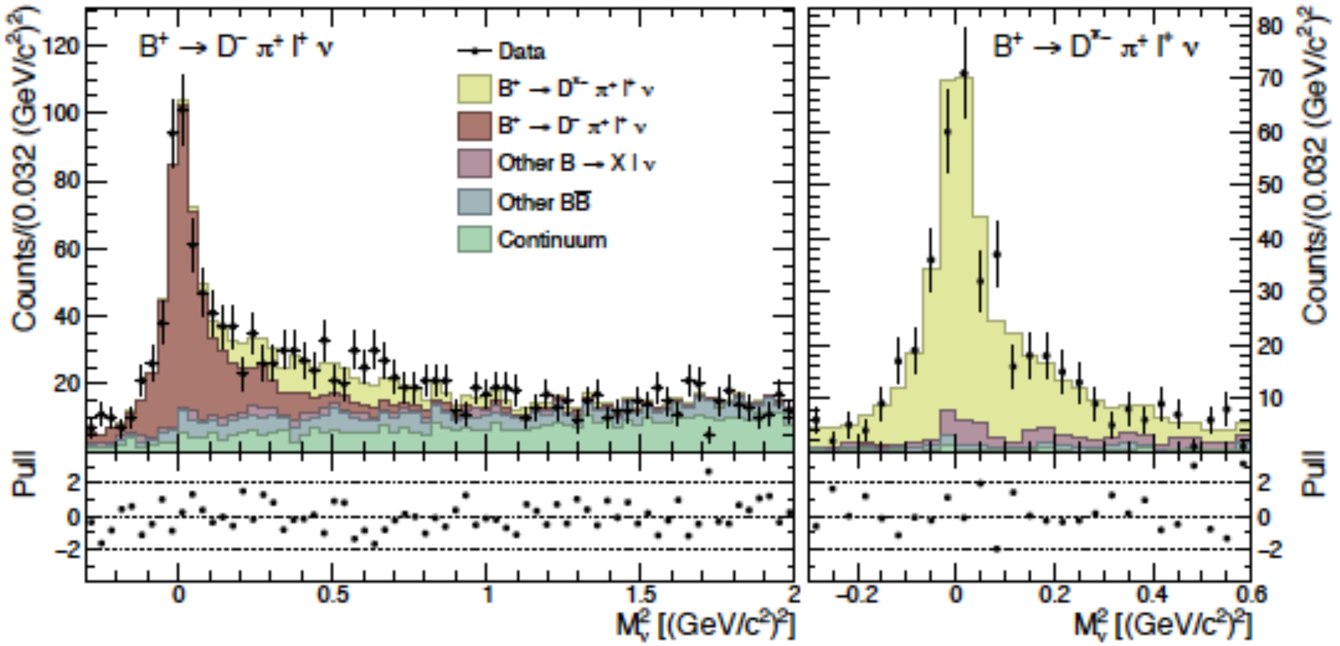
Theory well under control:

Bernlochner et al, 1703.05330



Theory predictions:
Fajfer, Kamenik, Nisandzic, 1203.2654
Bailey et al, 1206.4992
Beciveric et al., 1206.4977
Bernlochner, Ligeti, Papucci, Robinson, 1703.05330
Bigi, Gambino, Schacht, 1707.09509

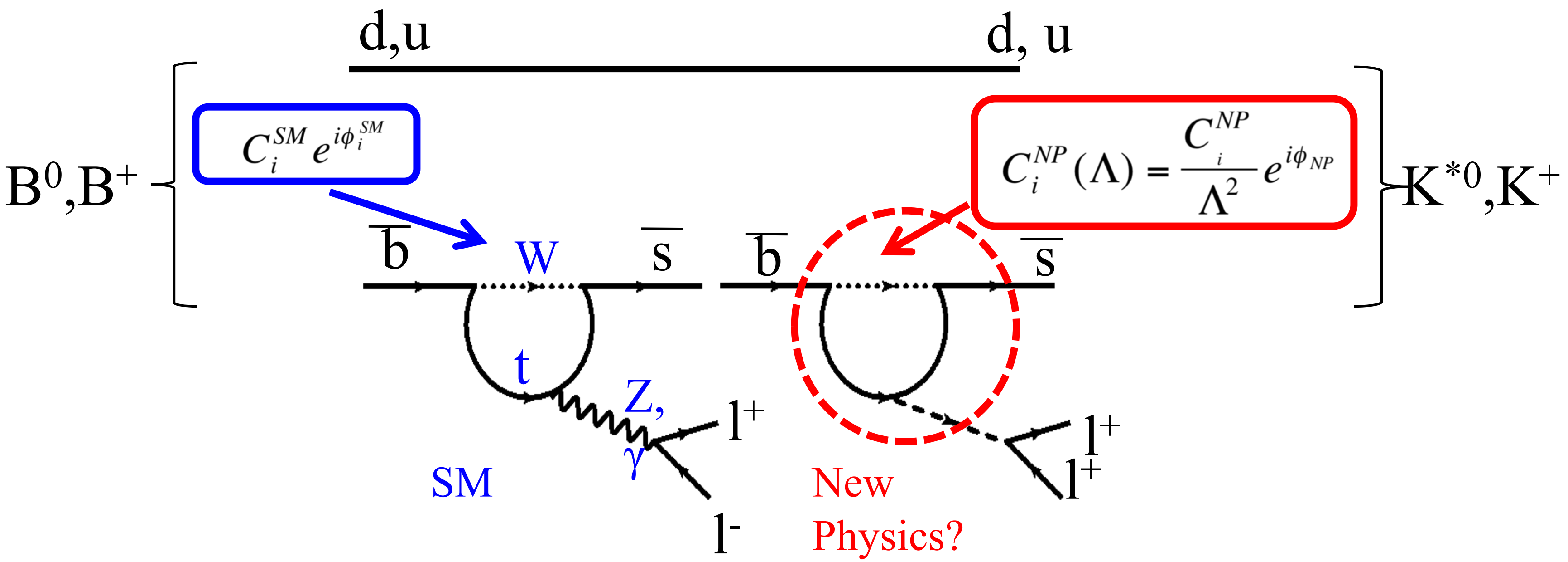
Experimental caveat:
τ are mimicked by background (enhancement).
more studies of B⟶ D**(⟶D n π) l ν necessary



Measurement of the branching fraction of B→D$^{(*)}\pi\ell\nu$ at Belle using hadronic tagging in fully reconstructed events

P. Urquijo, ICHEP 2018
Belle, PRD 98 (2018) 012005, arXiv 1803.06444

The second set of b-anomalies: FCNC semi-leptonic transitions b ⟶ s l+ l-



$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \frac{e^2}{16\pi^2} \sum_i (C_i Q_i + C_i' Q_i') + h.c.$$

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

Scale of New Physics

$C_i^{NP} = 1,\ \phi_i^{NP} =$ any value (generic flavour),

$C_i^{NP} =$ CKM, $\phi_i^{NP} =$ any value (NMFV),

$C_i^{NP} =$ CKM, $\phi_i^{NP} =$ SM (MFV)

FCNC semileptonic $b \longrightarrow s\, l^+ l^-$ decays : Decay Rates

The experimental measurements of the BR tend to lie below the SM expectations across the full q^2 range.
The discrepancy is largest for the $B_s \longrightarrow \phi\, \mu\, \mu$ decay in the large recoil region ($1 < q^2 < 6$ GeV^2/c^4), 3σ discrepancy.

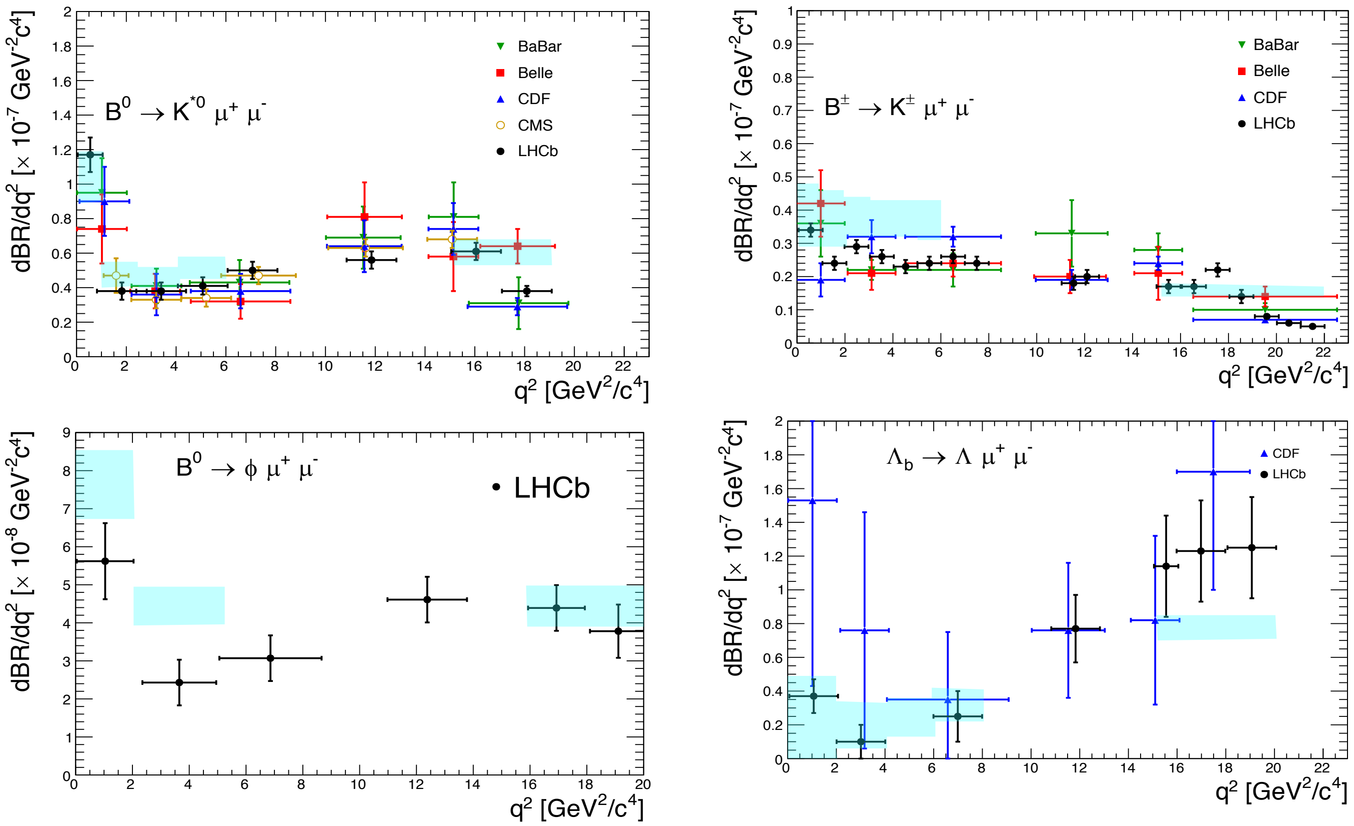
Theory predictions:

LCSR (low q^2):

Ball et al., PRD 71 (2005) 014015
Bharucha, JHEP 05 (2012) 092
Sentitemsu et al., JHEP 02 (2015) 126
Straub et al, JHEP 08 (2016) 098

Lattice QCD (high q^2)

Ball, Zwicky PRD 71 (2005) 014029
Bailey et al PRD 93 (2016) 025026
Horgan et al. PRD 89 (2014) 094501



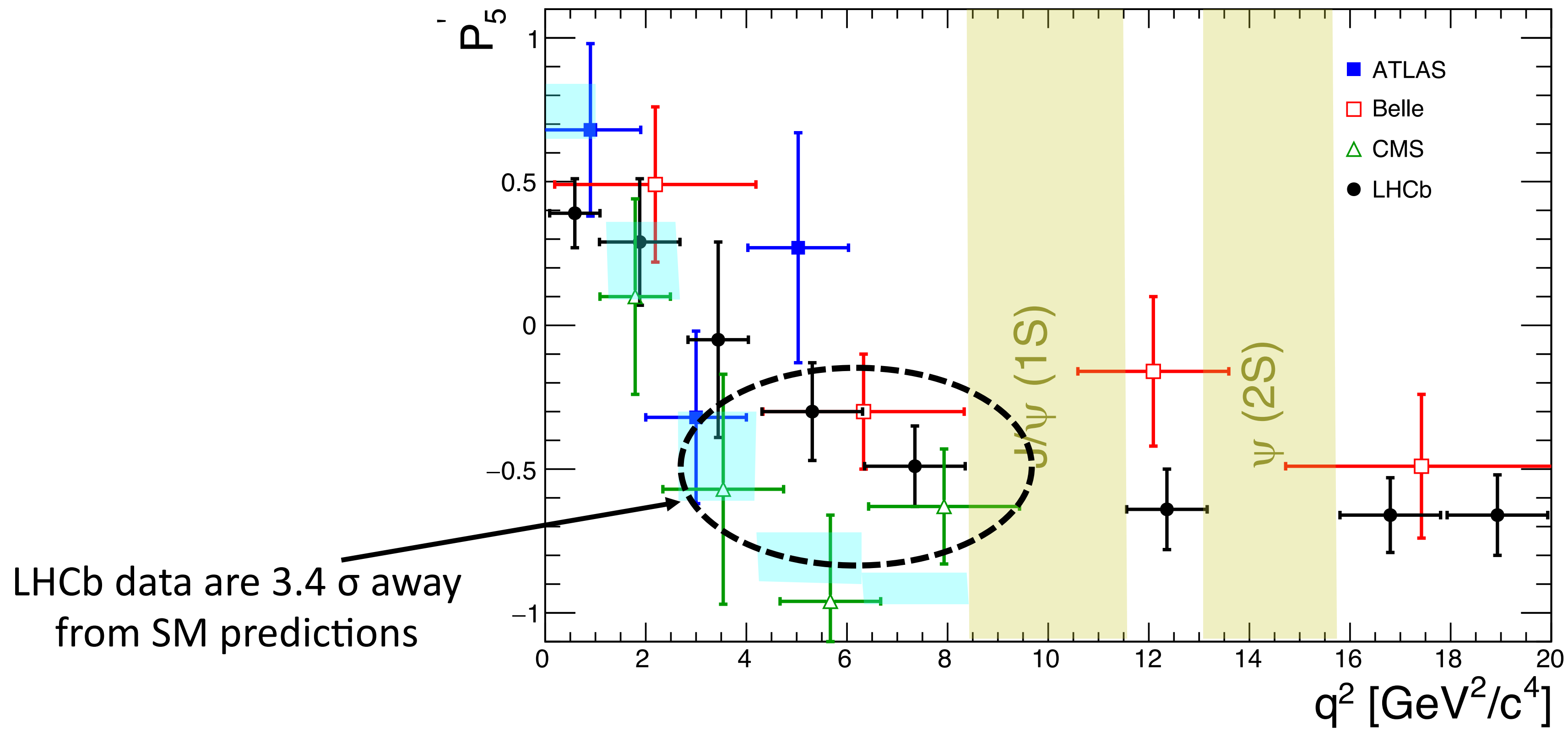
Experimental results:

BaBar, PRD 86, 032012 (2012)
Belle, PRL 103, 171801 (2009)
CDF, PRL 107, 201802 (2011)
CMS, PLB 753, 424 (2016)
LHCb, JHEP 06, 133 (2014)
LHCb, JHEP 11, 047 (2016)
LHCb, JHEP 09, 179 (2015)
LHCb, JHEP 06, 115 (2015)

Theory caveat: exclusive decays $B \longrightarrow M\, l^+ l^-$ to a meson M require the knowledge of the $B \longrightarrow M$ form factors in the full kinematic range $4m^2 < q^2 < (m_B - m_M)^2$. Data today are more precise than theory.

FCNC semileptonic $b \longrightarrow s\, l^+ l^-$ decays : Angular Distributions

ATLAS, CMS, LHCb and Belle have performed a full angular analysis of the $B_d \longrightarrow K^* \mu\mu$- channel.
While the large majority of the angular observables is consistent with SM expectations, the LHCb measurement of the P'_5 variable shows hints of deviations from SM predictions in the region $4 < q^2 < 8$ GeV^2



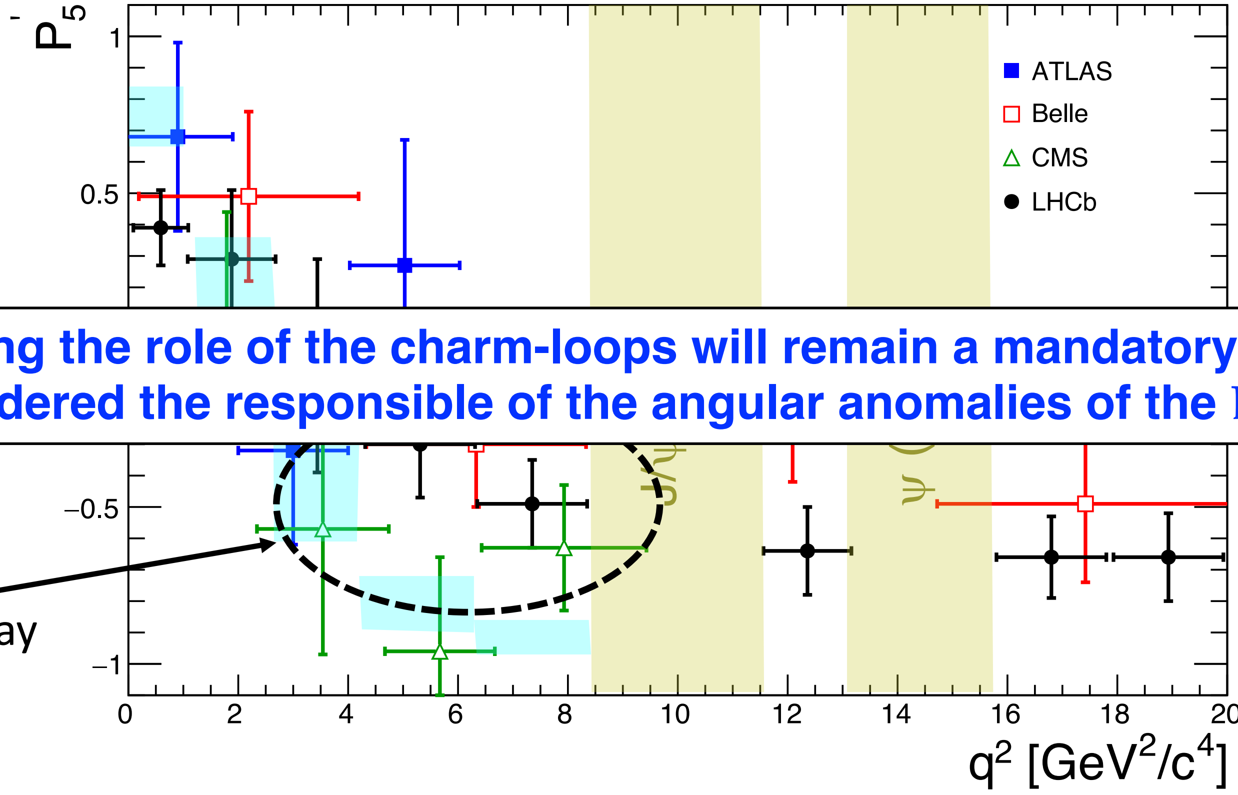
Theory predictions:
Descotes-Genon et al. JHEP 12, 125 (2014).

Data:
LHCb, JHEP 02 104 (2016)
Belle, PRL 118, 11801 (2017)
ATLAS-CONF-2017-023
CMS, PLB 81, 517 (2018)

The main challenge on the theory side is represented by soft gluon corrections to the charm loop, that have been estimated in LCSR but remain the largest source of uncertainty

FCNC semileptonic $b \rightarrow s\, l^+ l^-$ decays : Angular Distributions

ATLAS, CMS, LHCb and Belle have performed a full angular analysis of the Bd $\rightarrow$ K* μμ- channel. While the large majority of the angular observables is consistent with SM expectations, the LHCb measurement of the P'_5 variable shows hints of deviations from SM predictions in the region $4 < q^2 < 8$ GeV^2



LHCb data are 3.4 σ away from SM predictions

Theory predictions:
Descotes-Genon et al. JHEP 12, 125 (2014).

Data:
LHCb, JHEP 02 104 (2016)

Clarifying the role of the charm-loops will remain a mandatory task before NP can be considered the responsible of the angular anomalies of the $B_d \rightarrow K^*\, \mu\mu$ mode

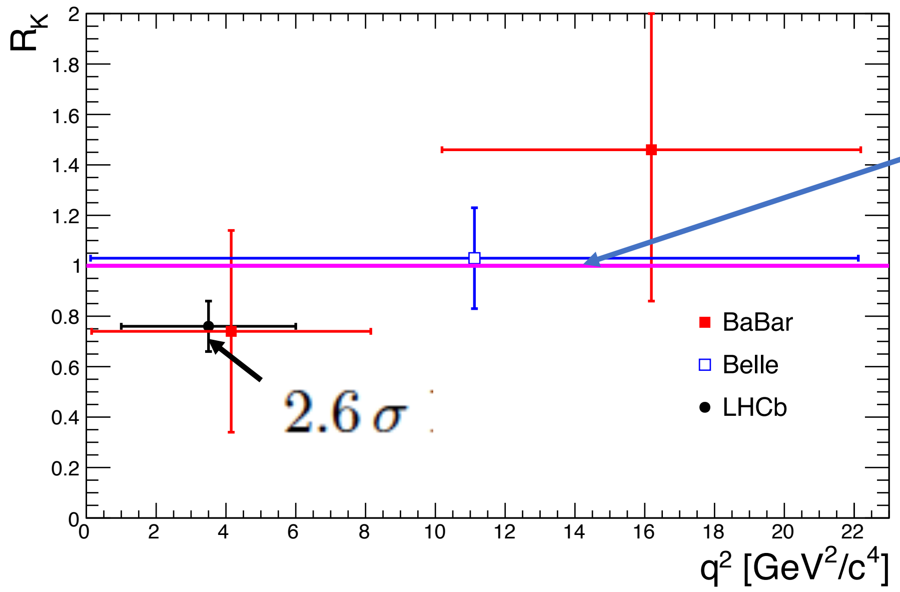
The main challenge on the theory side is represented by soft gluon corrections to the charm loop, that have been estimated in LCSR but remain the largest source of uncertainty

Lepton Flavor Universality in FCNC

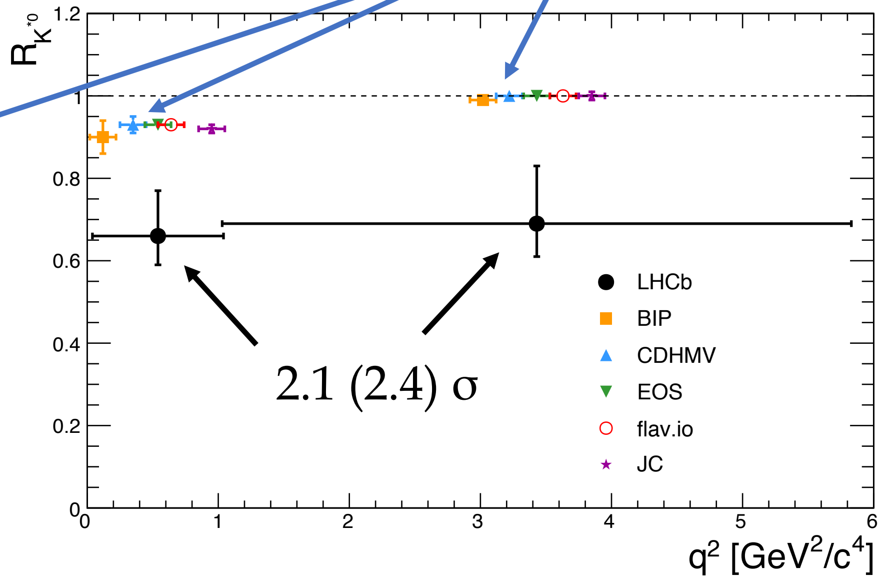
LFU violation in neutral currents has been measured in b ⟶ sl+ l- (with l = e, μ) transitions involving ratios of branching fractions:

$$R_{K^{(*)}} = \left.\frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}\right|_{q^2 \in [q^2_{min}, q^2_{max}]}$$

SM values known at o(1%) level
See Bordone, Isidori et al., EPJC 76 (2016) 440
and References defined in arXiv:1705..05802



LHCb, PRL 113 (2014) 151601
BaBar, PRD 86, (2012) 032012
Belle, PRL 103 (2009) 171801

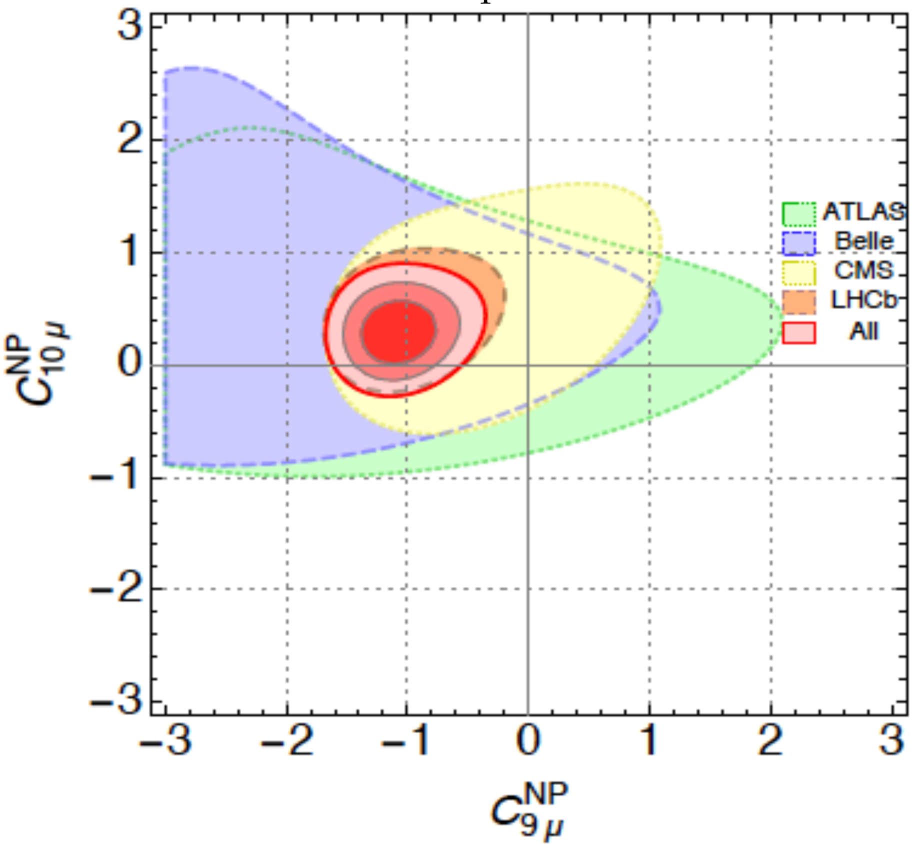


LHCb, JHEP 08 (2017) 055

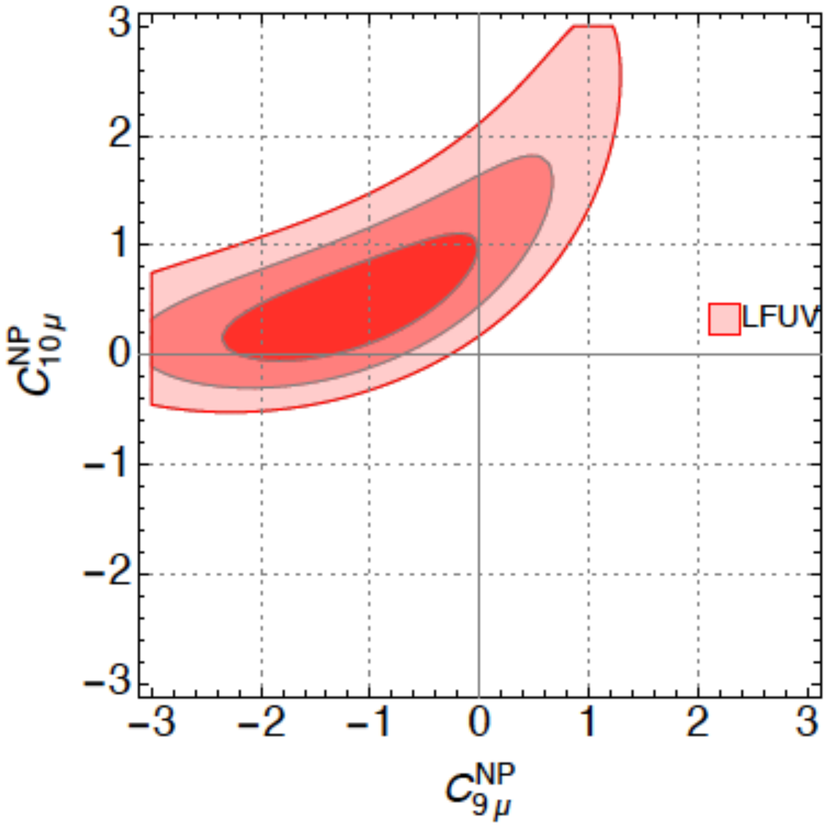
Model independent fits

C_9(NP) deviates from 0 by >4σ
Independent fits by many groups favour: C_9 (NP) ~ -1 or C_9 (NP) = -C_{10} (NP)

Capdevila, Crivellin, Descotes-Genon, Matias 1704.05340



All b ⟶ s l+ l- observables
(decay rates, angular observables, R_K, R_{K^*})



Only R_K, R_{K^*} from LHCb

More updated fit results in David Straub's talk

NP explaining both $R_{D(*)}$ and $R_{K(*)}$ anomalies

S Fajfer, ICHEP 2018

$$\boxed{R^{exp}_{D^{(*)}} > R^{SM}_{D^{(*)}}}$$

$$\mathcal{L}_{NP} = \frac{1}{(\Lambda^D)^2} 2\,\bar{c}_L \gamma_\mu b_L \bar{\tau}\gamma^\mu \nu_L$$

$$\boxed{\Lambda^D \simeq 3\,\mathrm{TeV}}$$

$$\Lambda^D = \Lambda$$

NP in FCNC $B \to K^{(*)}\mu^+\mu^-$
has to be suppressed

$$\boxed{R^{exp}_{K^{(*)}} < R^{SM}_{K^{(*)}}}$$

$$\mathcal{L}_{NP} = \frac{1}{(\Lambda^K)^2} \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L$$

$$\boxed{\Lambda^K \simeq 30\,\mathrm{TeV}}$$

If the scale is the same $\Lambda^D \sim \Lambda^K$

$$\boxed{\frac{1}{(\Lambda^K)^2} = \frac{C_K}{\Lambda^2} \qquad C_K \simeq 0.01}$$

suppression factor

Models at the TeV scale explaining both $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies

Scalar LQ as pseudo-Nambu-Goldstone boson

Gripaios et al, 1010.3962,
Gripaios et al., 1412.1791,
Marzocca 1803.10972...

Models with scalar LQs

Hiller & Schmaltz, 1408.1627,
Becirevic et al. 1608.08501, SF and Kosnik, 1511.06024, Becirevic et al., 1503.09024,
Dorsner et al, 1706.07779,
Cox et al., 1612.03923,
Crivellin et al.,1703.09226...

W', Z' in warped space

Megias et al.,1707.08014

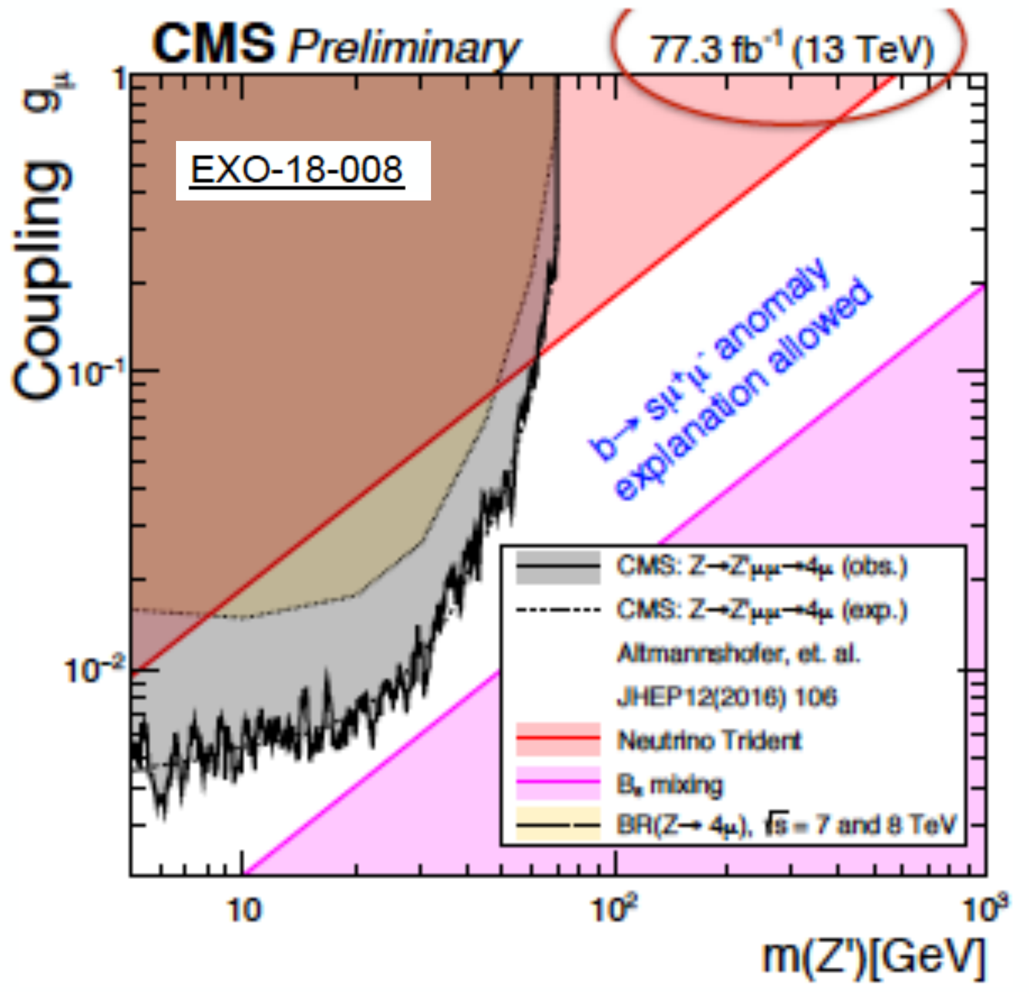
Vector resonances (from techni-fermions)

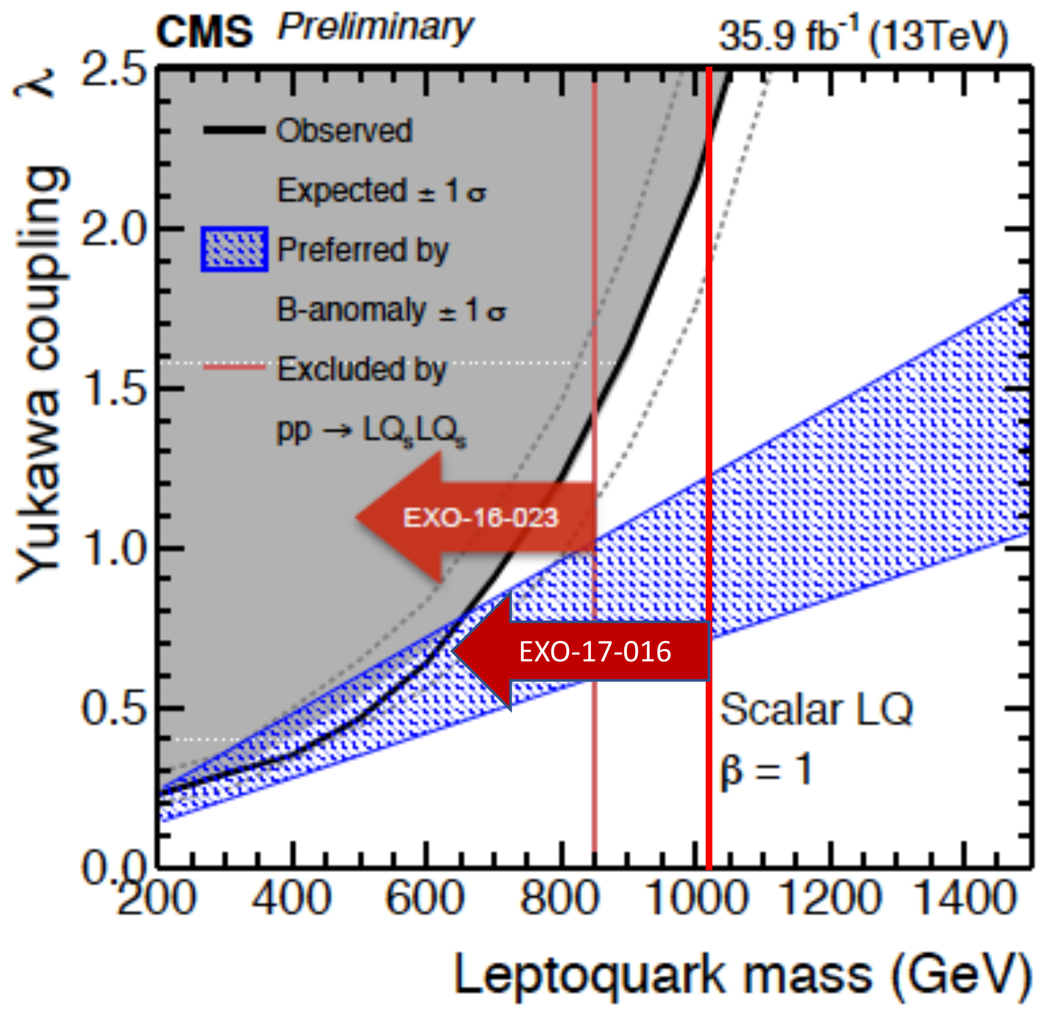
Barbieri et al.,1506.09201, Buttazzo et al. 1604.03940,
Barbieri et al., 1611.04930
Blanke & Crivellin, 1801.07256,...

Gauge bosons

Greljo et al., 1804.04642
Cline, Camalich, 1706.08510
Calibbi et al.,1709.00692
Assad et al., 1708.06350
Di Luzio et al.,1708.08450
Bordone et al.,1712.01368, 1805.09328...

Direct searches for Z′ and scalar Lepto-Quarks

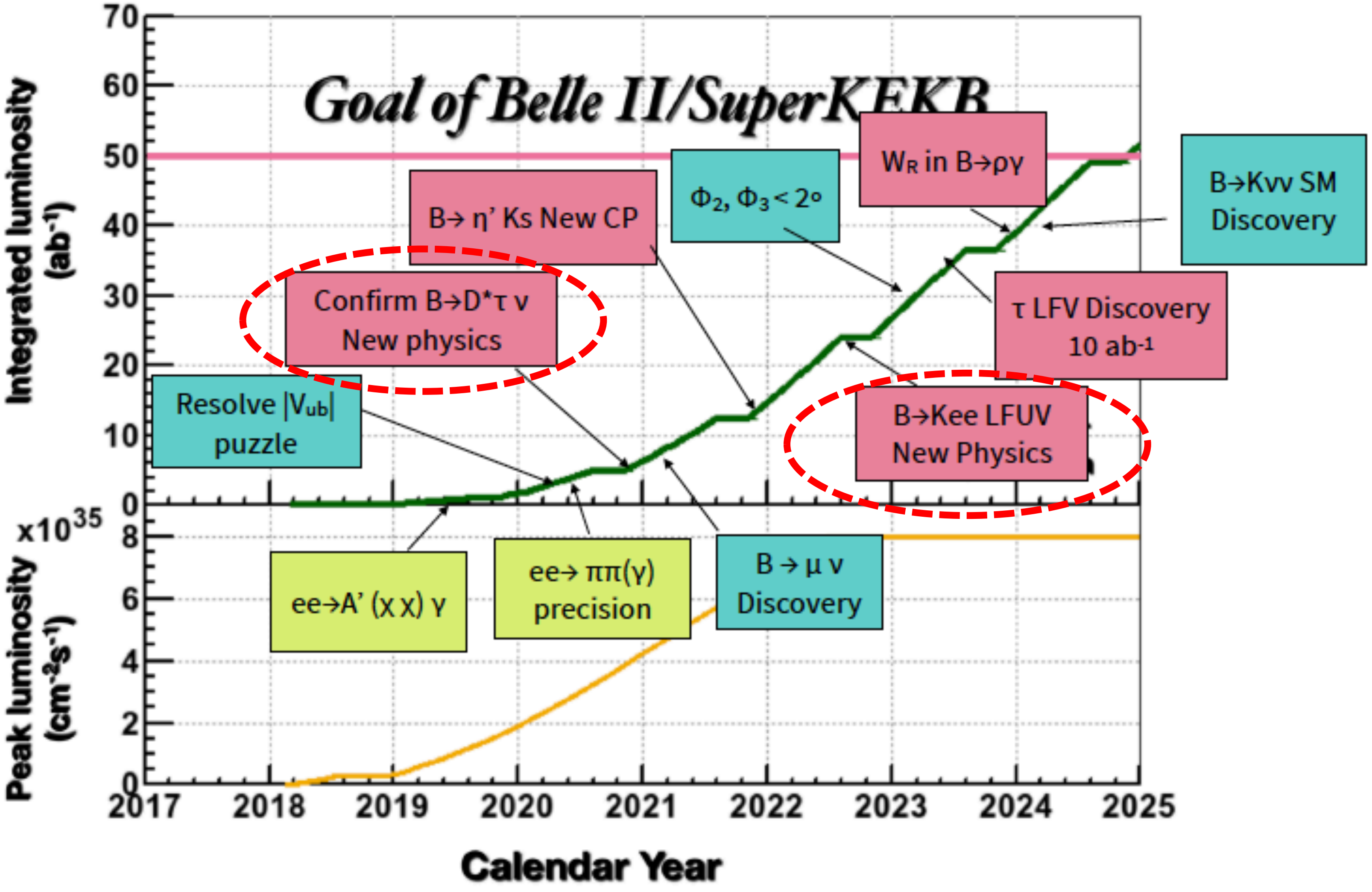




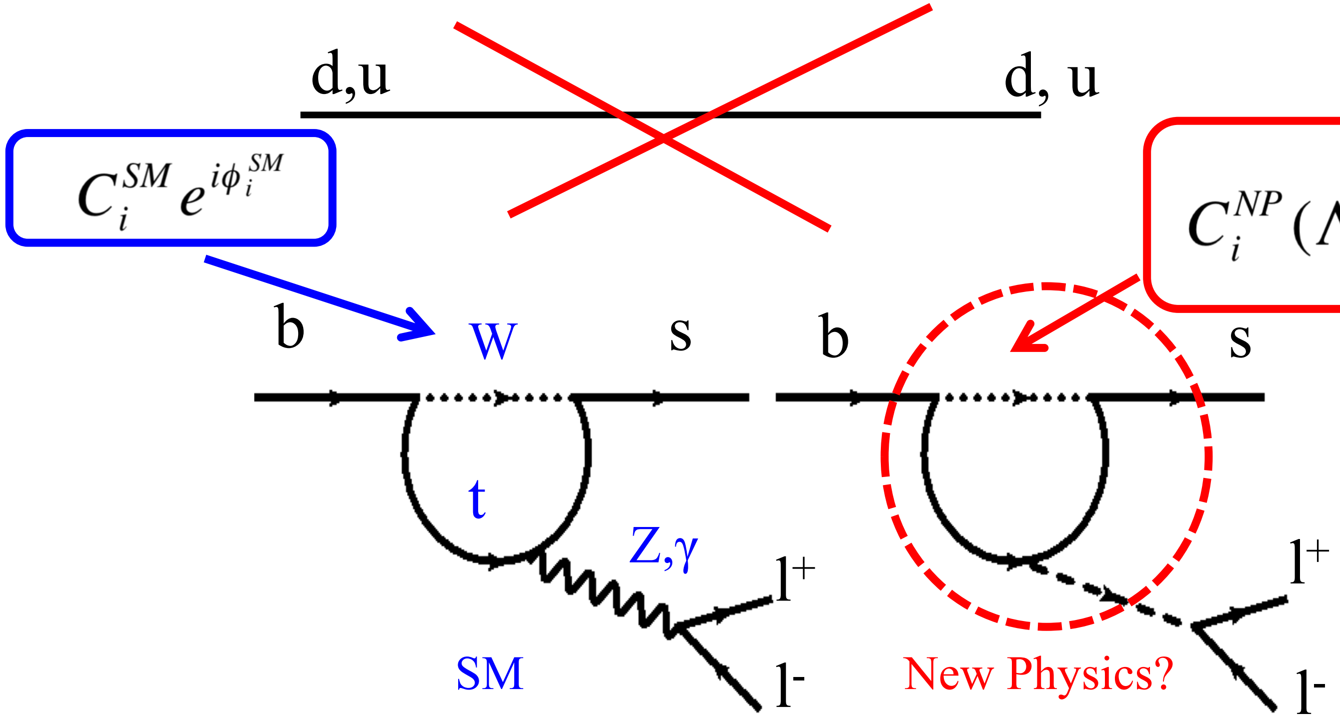
ATLAS and CMS are exploring the region favoured by the LHCb anomalies
(sensitivity so far driven by CMS results)

…and Belle-II in a few years will help to clarify these patterns:

P. Urquijo, ICHEP 2018



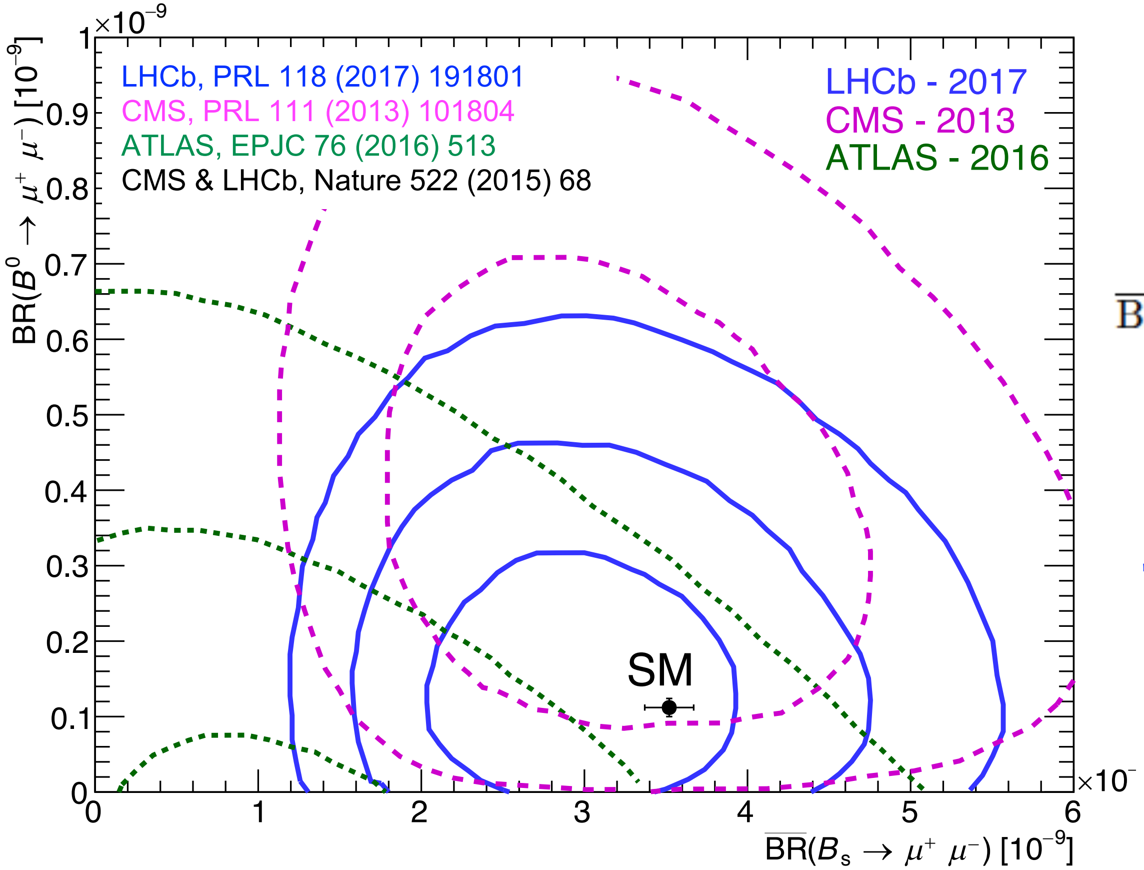
Back to the main diagram:



Sensitive to the scalar & pseudo-scalar penguins

You can recognize here the main diagram that drives the $B^0_{(s)} \to \mu^+\mu^-$ decays…

The BR($B_s \to \mu^+\mu^-$) and BR ($B^0 \to \mu^+\mu^-$)



Experimental Values:

$$\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-)_{\mathrm{CMS}} = (3.0^{+1.0}_{-0.9}) \times 10^{-9},$$

$$\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-)_{\mathrm{LHCb\ 2017}} = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9},$$

$$\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-)_{\mathrm{ATLAS}} = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$

BR($B^0 \to \mu^+\mu^-$) < 3.4×10^{-10} @ 95% CL (LHCb)

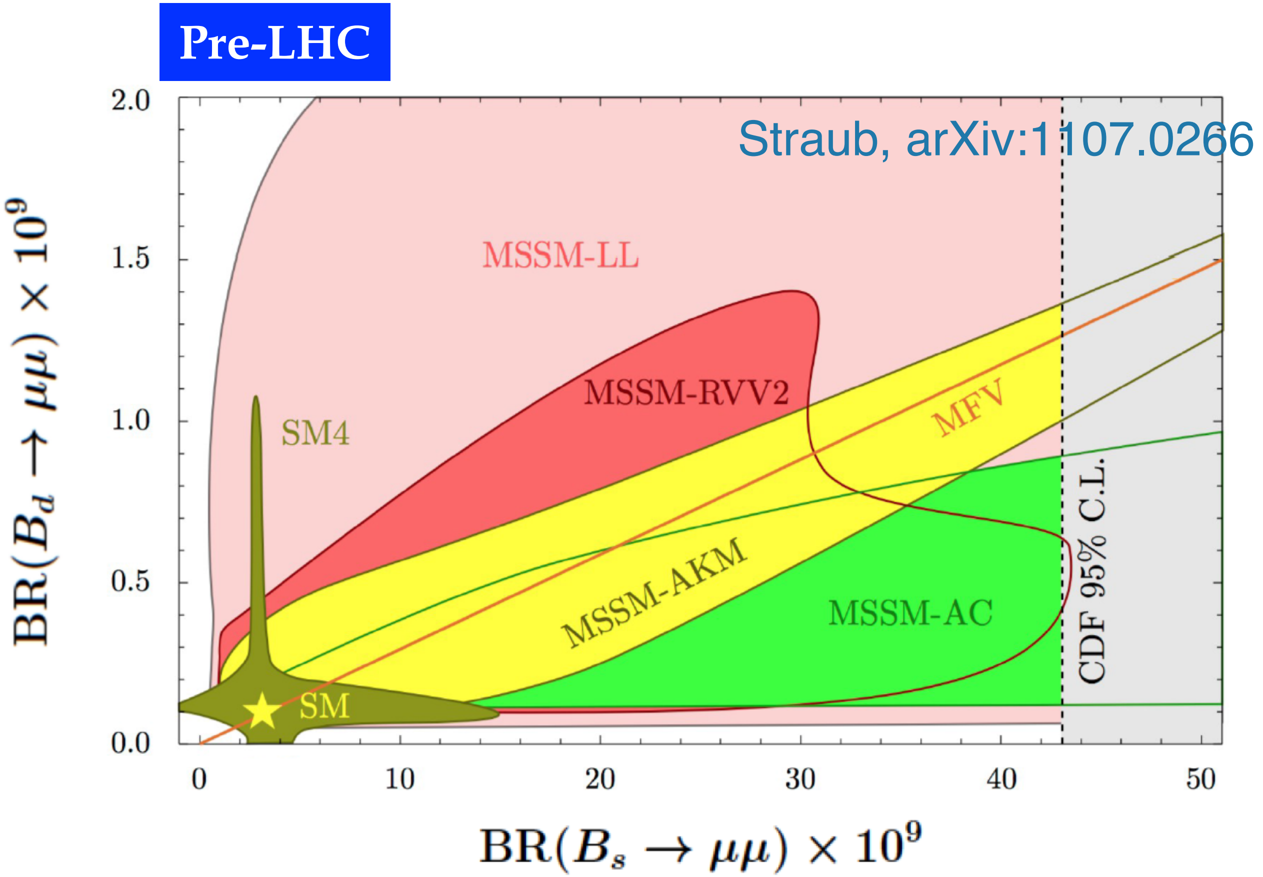
Theory predictions:

BR($B_s^0 \to \mu^+\mu^-$) = (3.66 ± 0.23) x 10^{-9}

BR($B^0 \to \mu^+\mu^-$) = (1.06 ± 0.09) x 10^{-10}

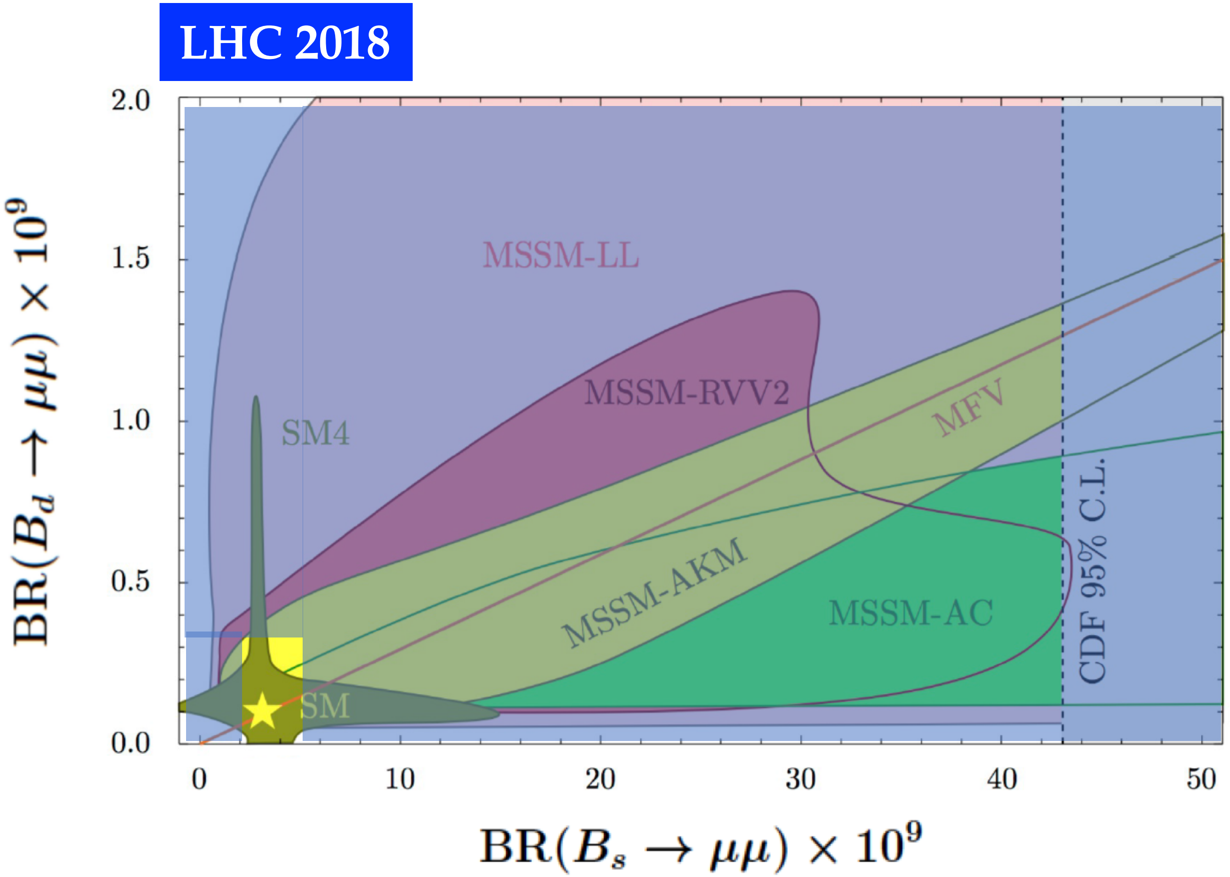
Excellent agreement between measurements and SM predictions

The BR($B_s \to \mu^+\mu^-$) and BR ($B^0 \to \mu^+\mu^-$) and New Physics



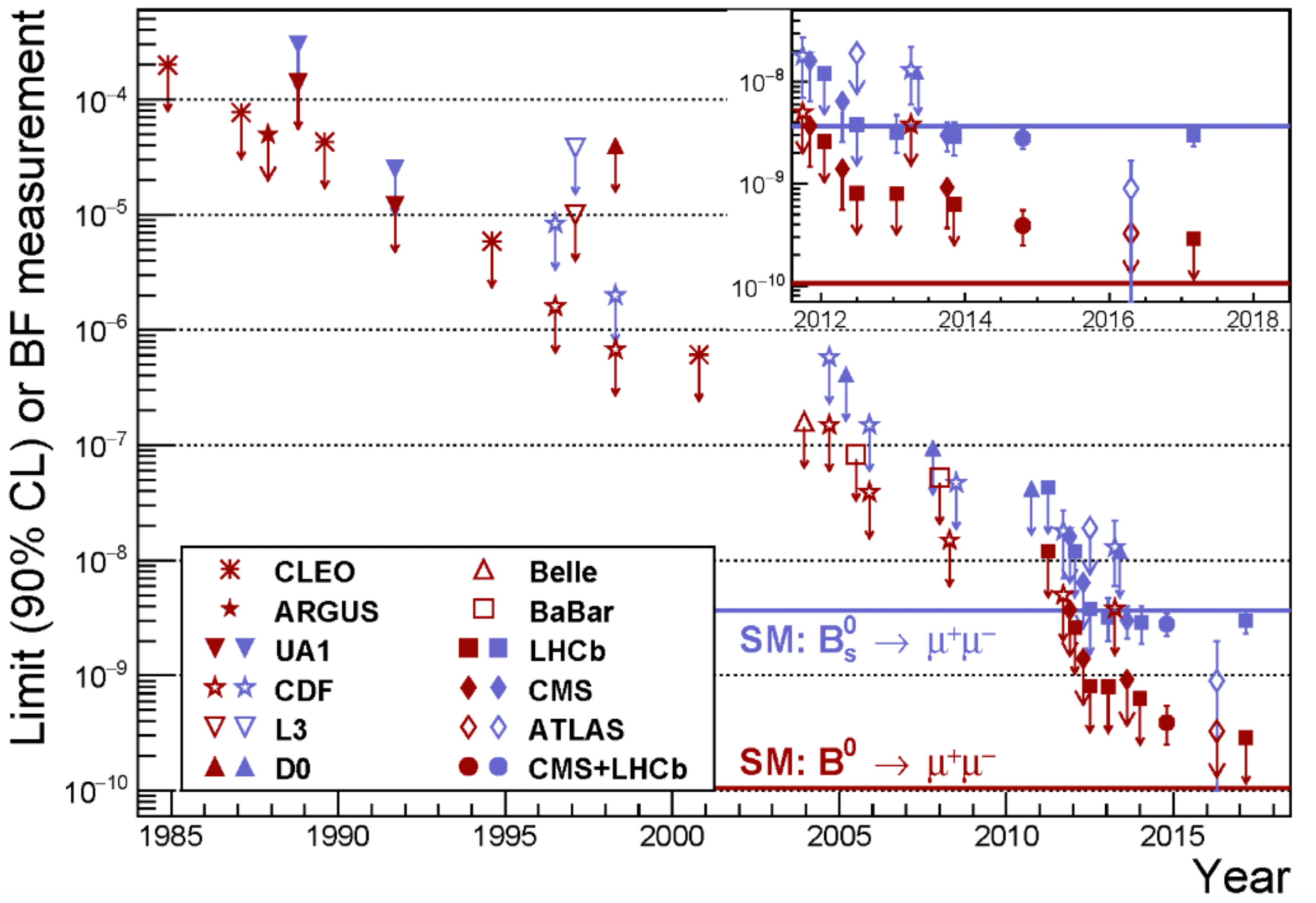
NP contributions arising from scalar or pseudo-scalar operators could lift the helicity suppression possibly enhancing the value of the branching fractions. These modes are particularly sensitive to models with an extended Higgs sector, as in MSSM with two Higgs doublets or in supersymmetric models with non-universal Higgs masses, etc (infinite literature on this topic).

The BR($B_s \longrightarrow \mu^+\mu^-$) and BR ($B^0 \longrightarrow \mu^+\mu^-$) and New Physics



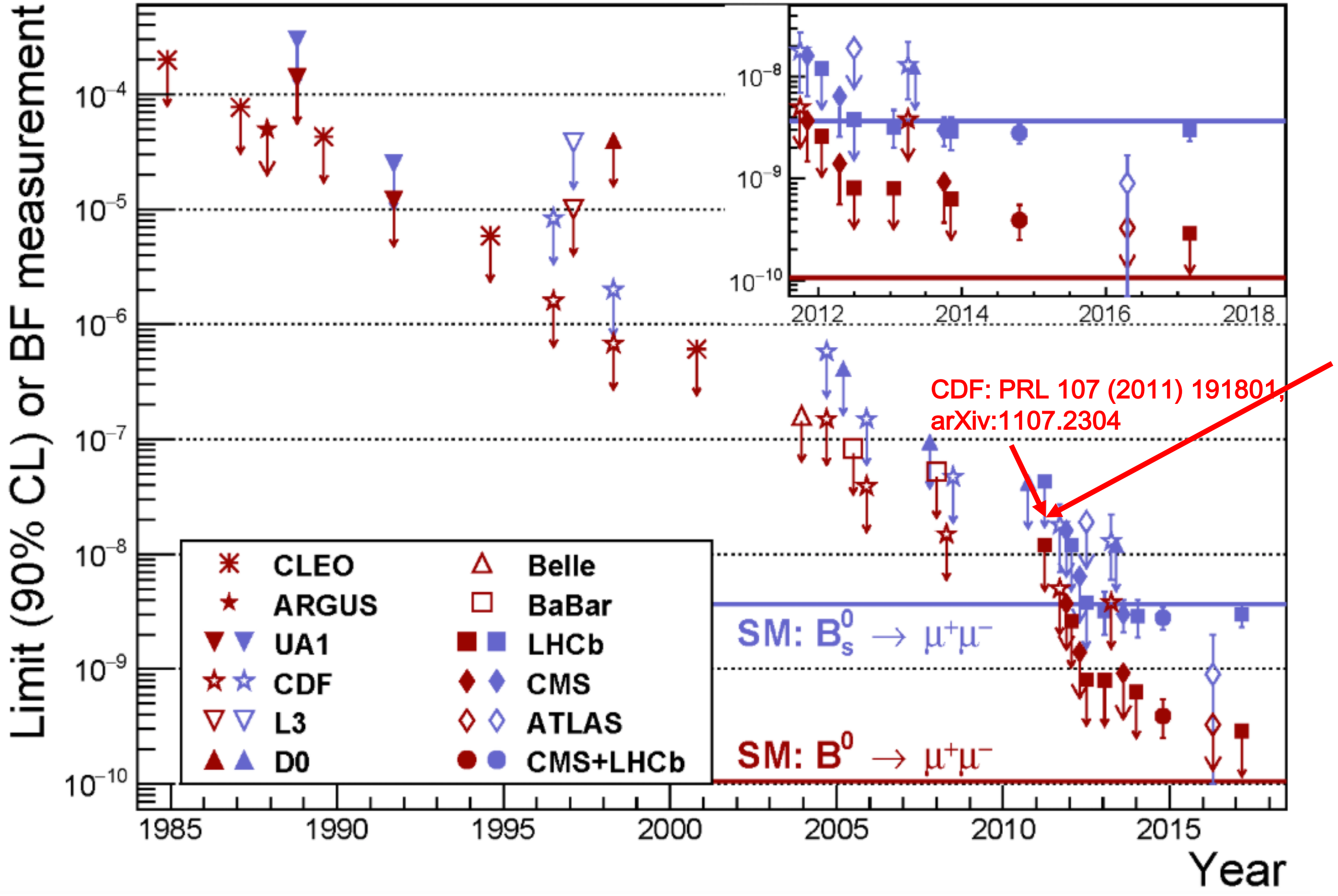
A killer for BSM theories with extended Higgs sector.

The BR($B_s \longrightarrow \mu^+\mu^-$) and BR ($B^0 \longrightarrow \mu^+\mu^-$): a story 30 years long



.. but was not always plain sailing…

The BR($B_s \longrightarrow \mu^+\mu^-$) and BR ($B^0 \longrightarrow \mu^+\mu^-$): a story 30 years long

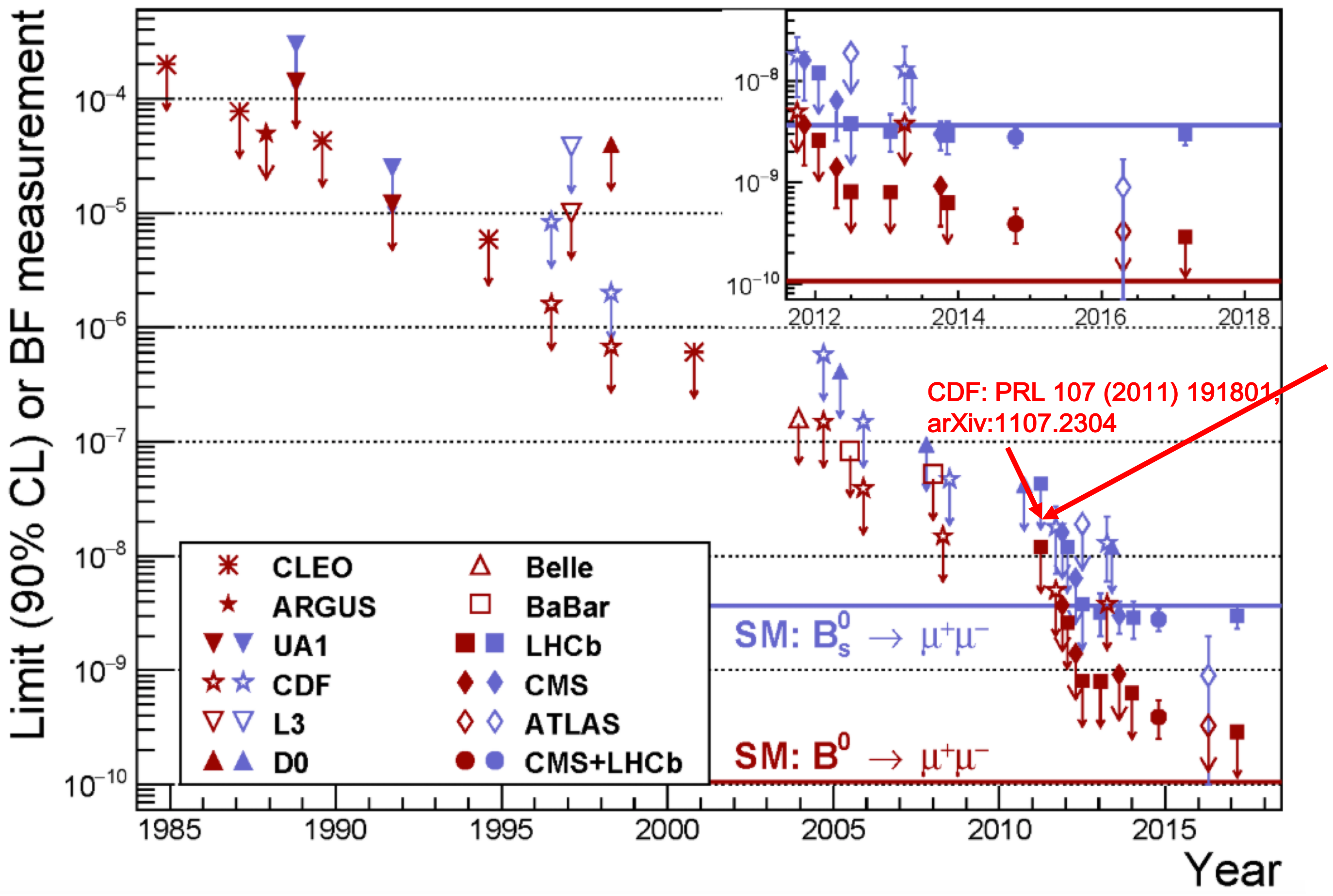


July 2011:

CDF publishes the 3 σ evidence for:

BR($B_s \longrightarrow \mu^+\mu^-$) = $(1.8^{+1.1}_{-0.9})10^{-8}$ **~5 BR(SM)**

The BR($B_s \to \mu^+\mu^-$) and BR ($B^0 \to \mu^+\mu^-$): a story 30 years long



July 2011:
CDF publishes the 3 σ evidence for:
BR($B_s \to \mu^+\mu^-$) = $(1.8^{+1.1}_{-0.9})10^{-8}$ **~5 BR(SM)**

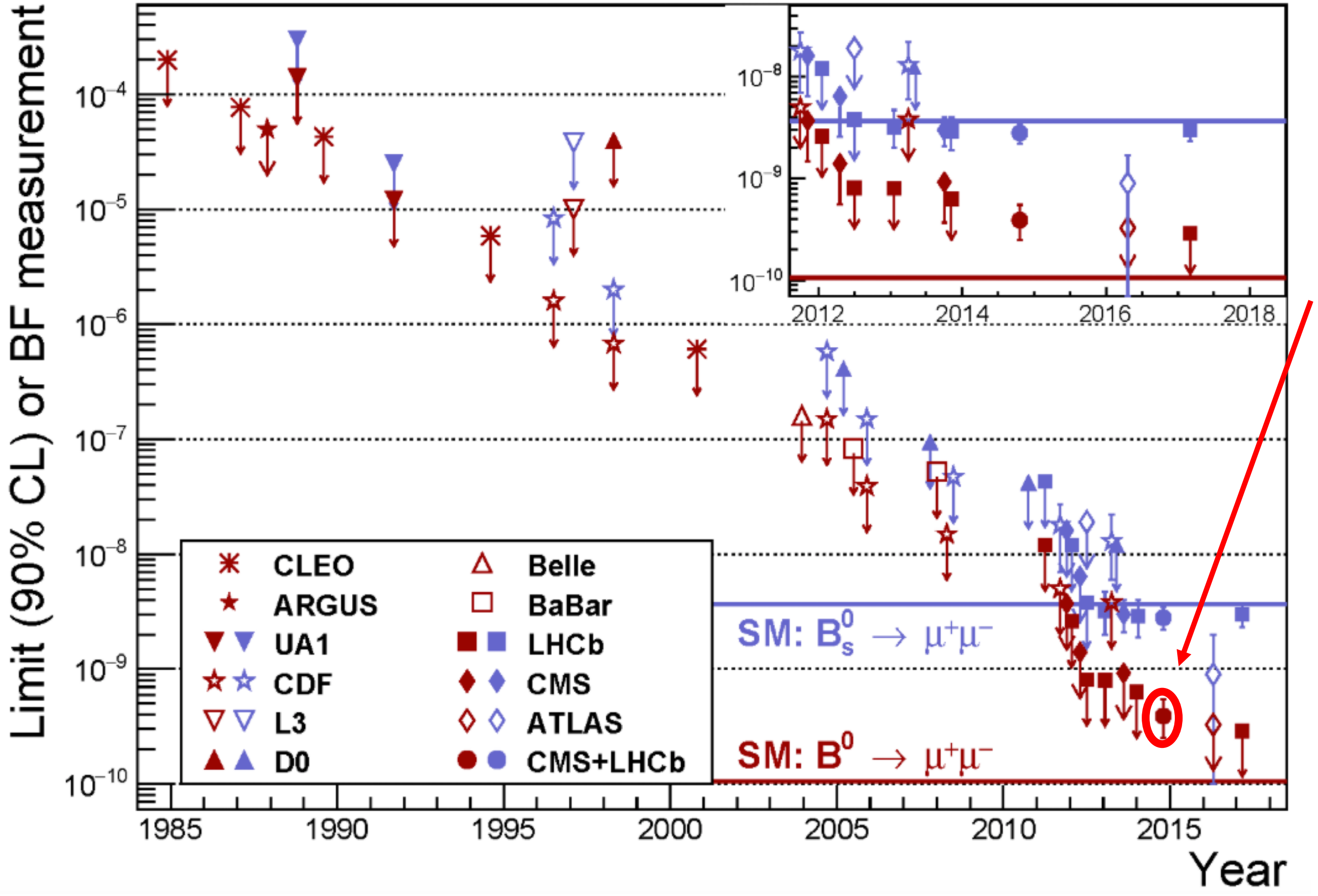
EPS 2011 (few weeks later):
Guy Wilkinson presents at EPS (Grenoble) the first LHCb + CMS combination:

BR($B_s \to \mu^+\mu^-$) < 1.1 10^{-8} @ 95% CL
and excludes the CDF central value at 99.7% CL

....Anomalies come and go....

(or about the importance of having independent measurements from independent experiments)

The BR($B_s \to \mu^+\mu^-$) and BR ($B^0 \to \mu^+\mu^-$): a story 30 years long



2015:

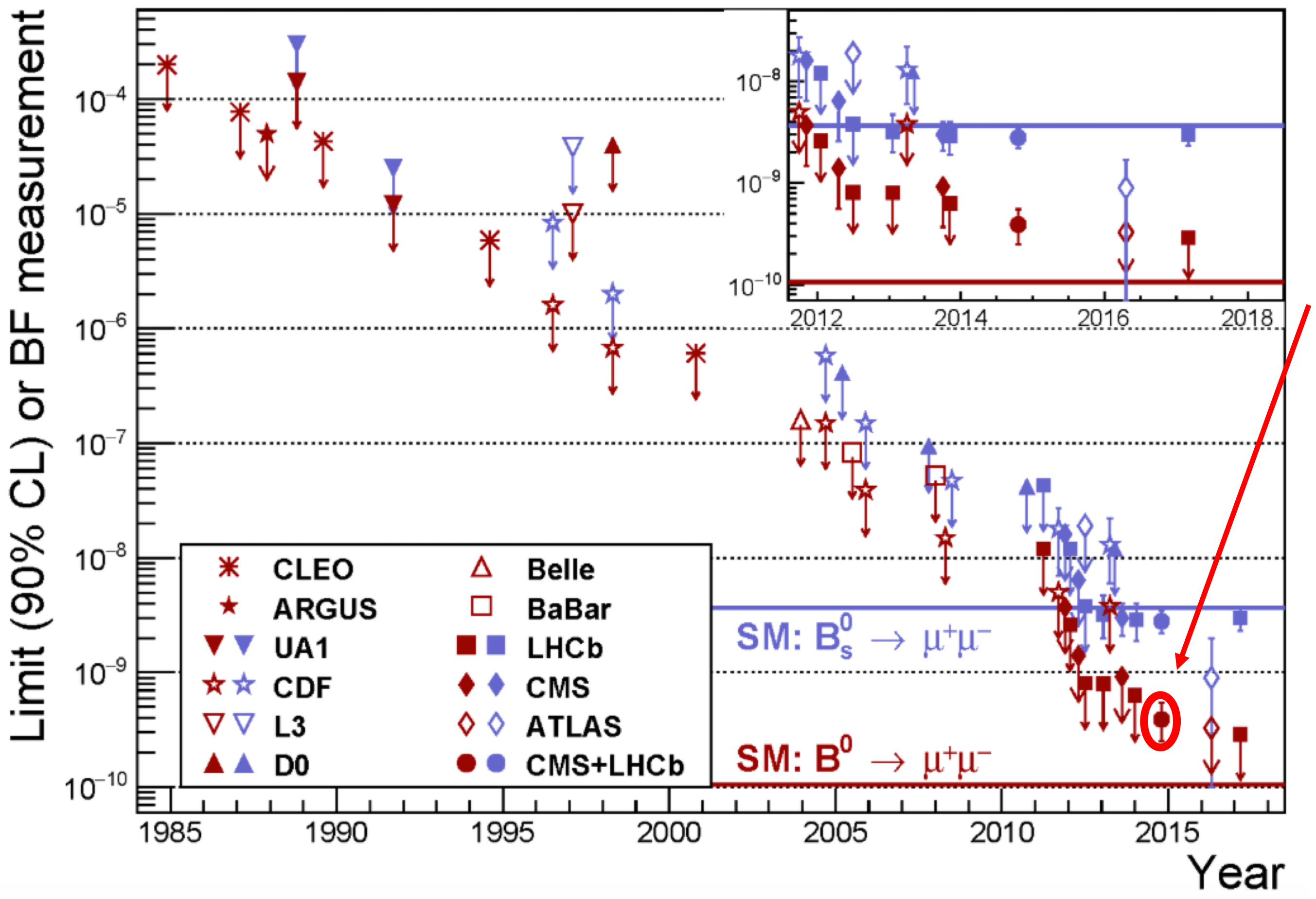
LHCb and CMS see 2σ excess each in the decay $B^0 \to \mu^+\mu^-$.

LHCb+CMS combination, Nature 522 (2015) 68:

$B^0 \to \mu^+\mu^-$ observed at 3σ

BR($B^0 \to \mu^+\mu^-$) = $(3.9^{+1.6}_{-1.4}) \times 10^{-10}$ ~ **4 BR(SM)**

The BR($B_s \to \mu^+\mu^-$) and BR ($B^0 \to \mu^+\mu^-$): a story 30 years long



2015:
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LHCb+CMS combination, Nature 522 (2015) 68:

$B^0 \to \mu^+\mu^-$ observed at 3σ
$BR(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \sim 4\ BR(SM)$

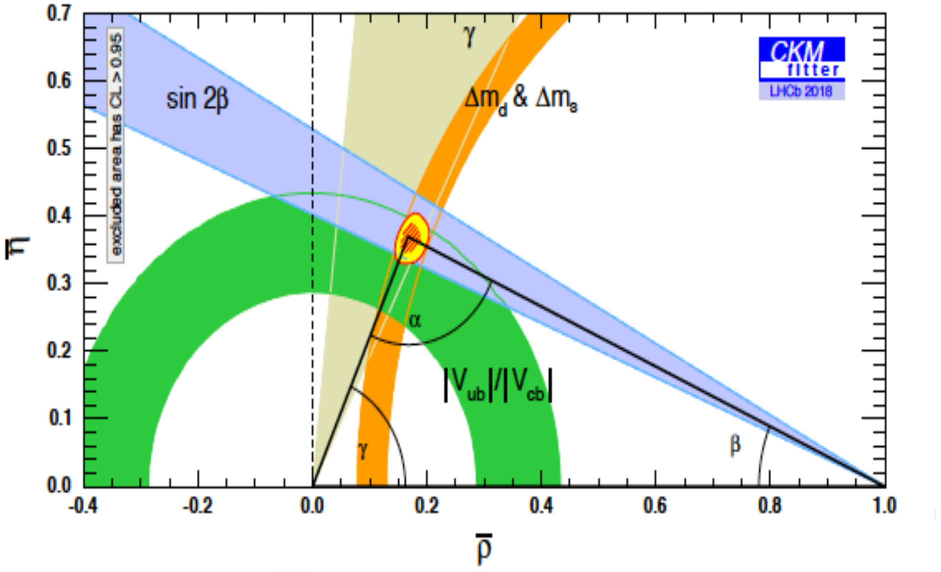
2017:
LHCb excludes this value at > 95% CL:
PRL 118 (2017) 191801

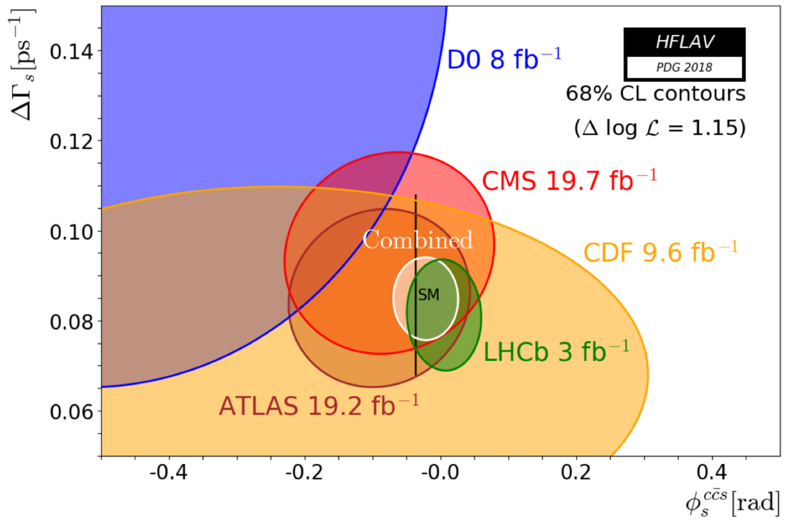
$BR(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 95% CL

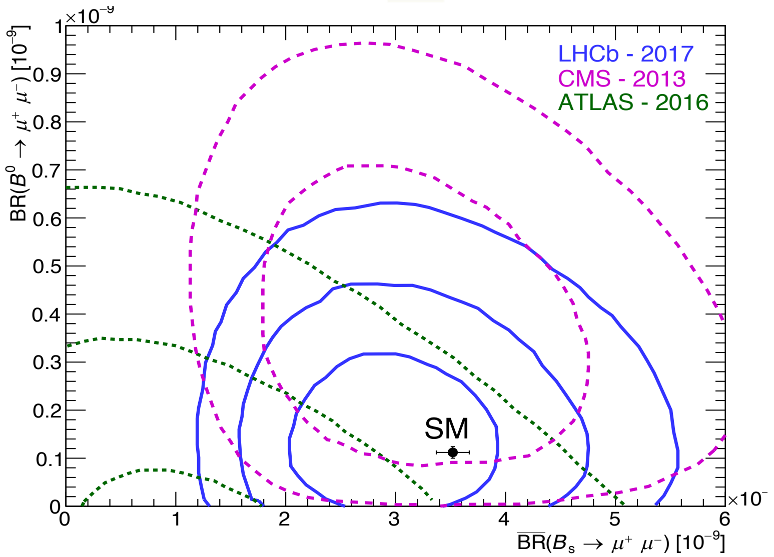
….Anomalies come and go ….

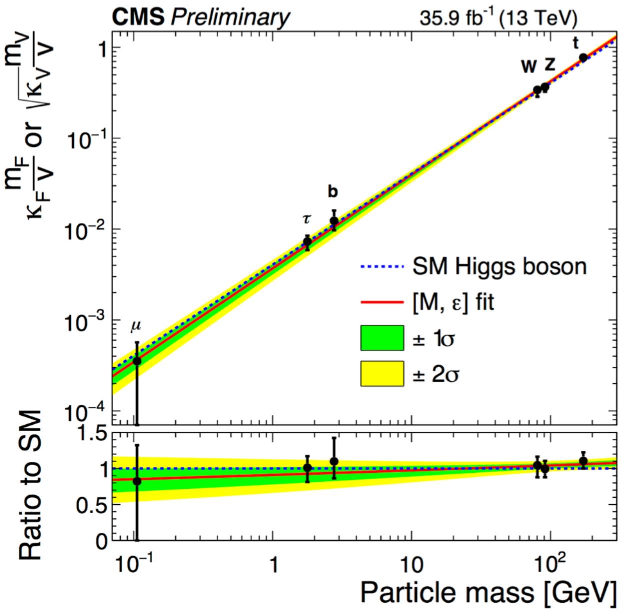
(or about how the combination of 2 σ effects can produce a (fake) hint of New Physics….)

The (excessive) Success of the Standard Model







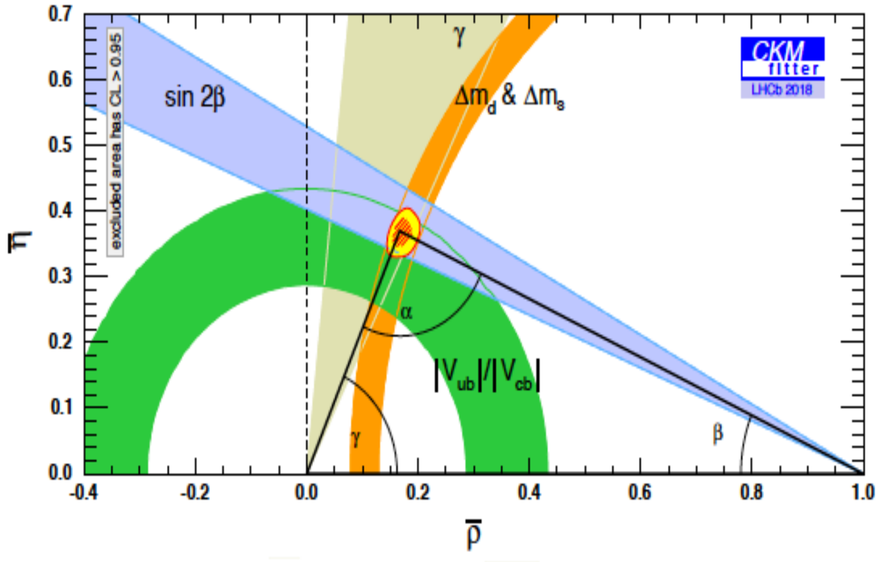


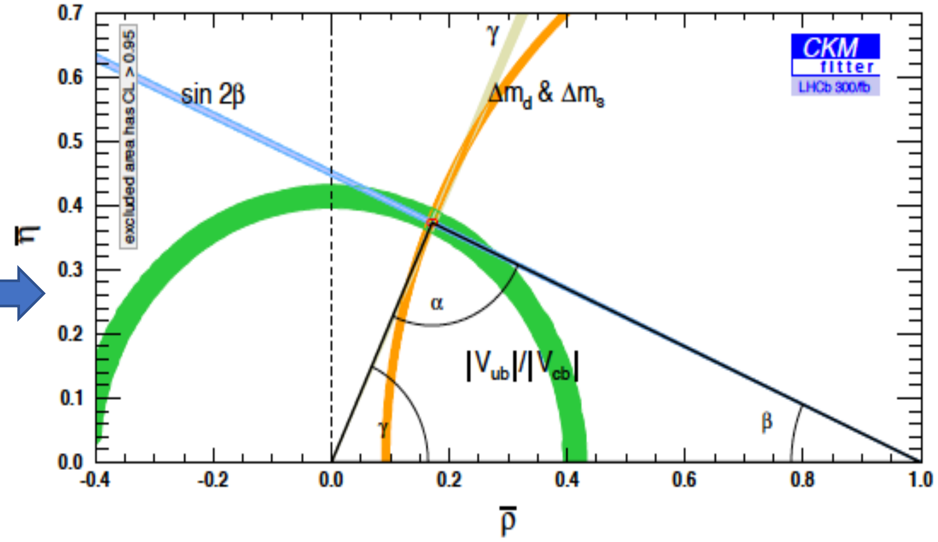
Where do we go from here ?

"While the absence of NP appears as a paradox to us, still the picture repeatedly suggested by the data in the last 20 years is simple and clear: ***the SM, extended to include some form of Dark Matter and Majorana's neutrinos****, which can explain the active neutrino masses and oscillations via the see-saw mechanism and the baryogenesis through leptogenesis,* ***can be valid up to some very high energy, possibly up to the Planck scale****."*

Guido Altarelli,
Proceedings of Vulcano Workshop 2014
Frontier Objects in Astrophysics and Particle Physics

Where do we go from here ?





A viable possibility… but is it the only one?

Where do we go from here ?

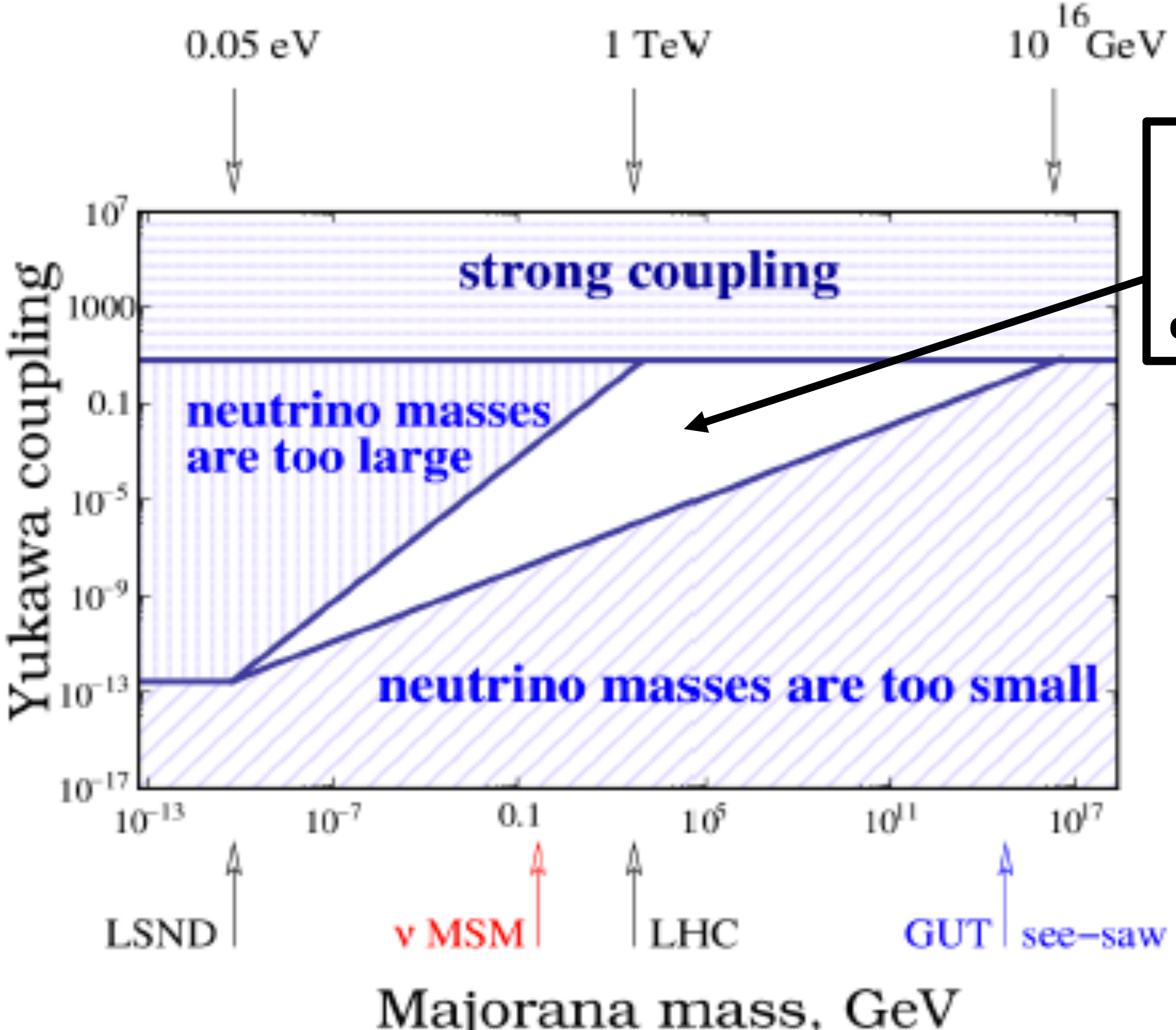
- So far the experimental efforts in the accelerators' domain have been concentrated on the discovery of NP with masses at the TeV scale (or above) and sizeable couplings to SM particles.

- We did not observe so far unambiguous deviations from SM predictions, hence:
  → either NP is very heavy and/or it mimics the SM in its flavor-breaking pattern
  → **or it is below the Fermi scale and couples very feebly (hence they are very long-lived) to SM particles and so far escaped detection.**

An attractive possibility and a change of paradigm in the accelerators' domain.

Heavy neutrinos as explanation of the neutrino masses and oscillations

See-saw mechanism with RH neutrinos with Yukawa couplings to the Higgs and SM leptons. RH neutrinos can have masses from 10^{-9} to 10^{15} GeV.



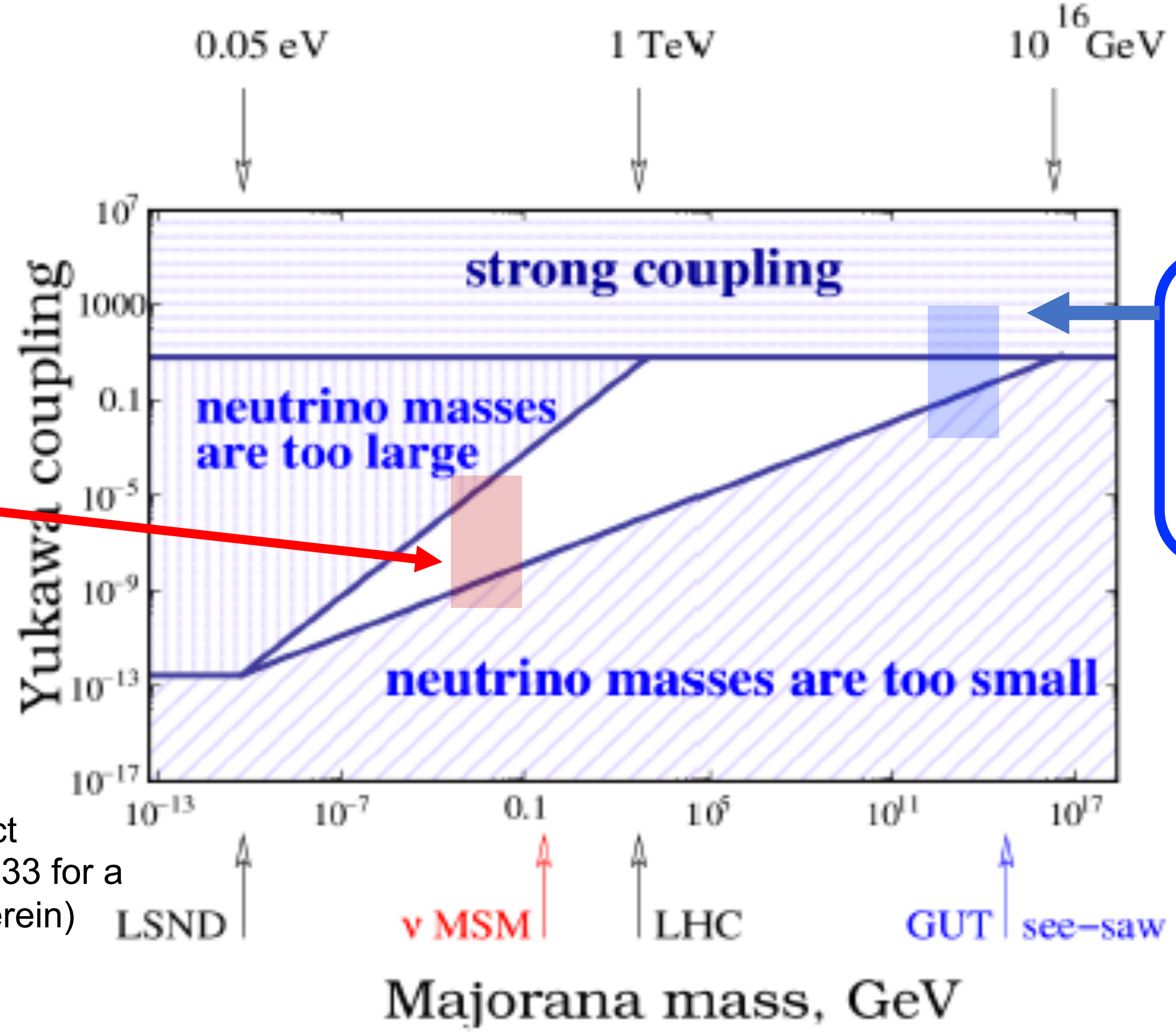
Any number in the white area works to be consistent with the observed pattern of neutrino masses and oscillations

Heavy neutrinos as explanation of the neutrino masses and oscillations

See-saw mechanism with RH neutrinos with Yukawa couplings to the Higgs and SM leptons. RH neutrinos can have masses from 10^{-9} to 10^{15} GeV.

Alternative choice: EW see-saw (νMSM)

It is "natural" to assume that the masses of the RH neutrinos are at EW scale



Popular choice: GUT see-saw

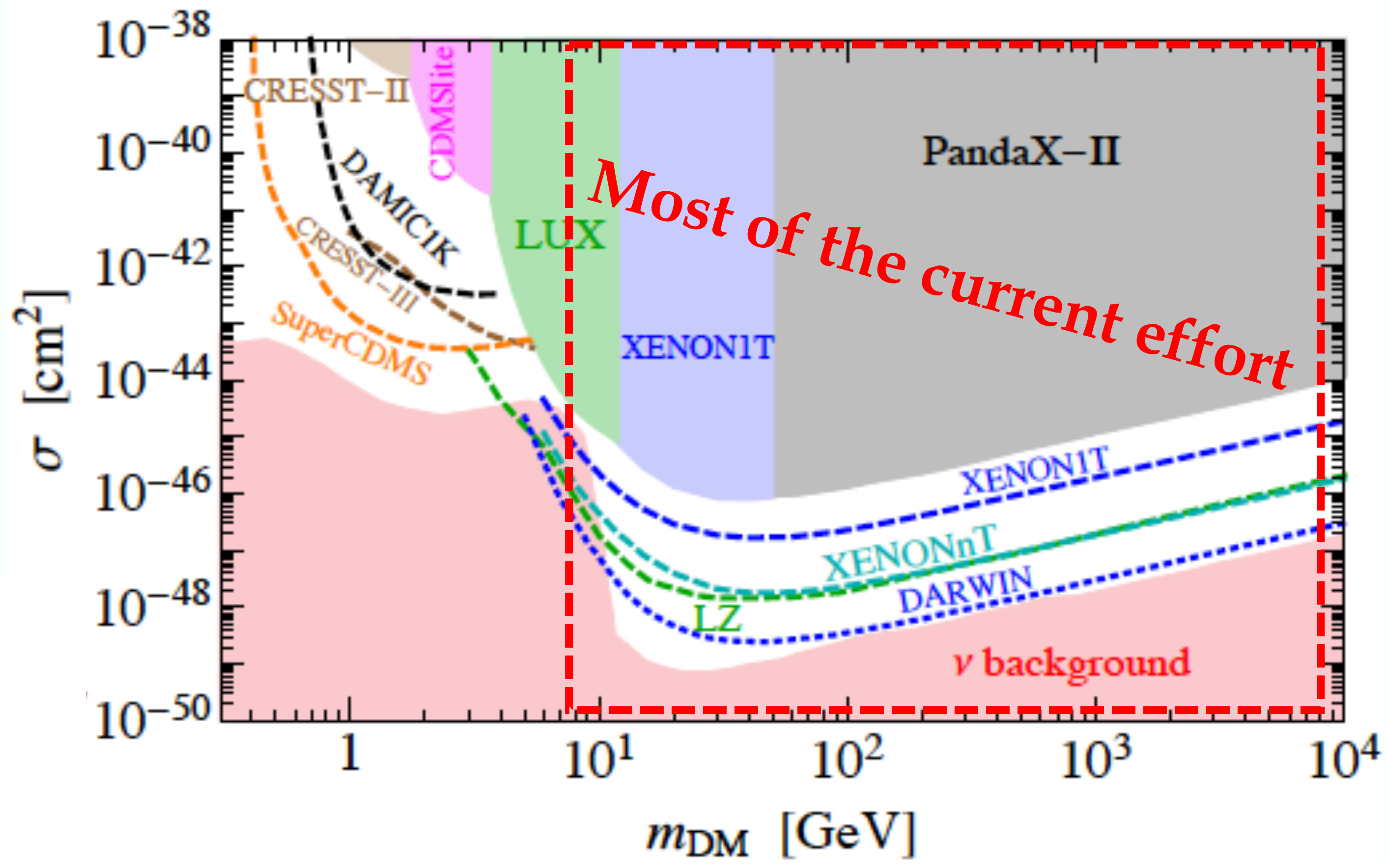
It "natural" to assume that Yukawa couplings of the RH neutrinos are similar to SM Yukawa.

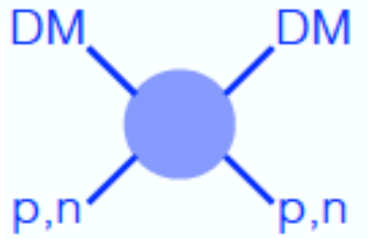
Heavy neutrinos below the Fermi scale

Infinite literature on the subject (see Shaposhnikov et al.,1808.10833 for a recent study and references therein)

Search for Dark Matter with thermal origin

DM candidates with thermal origin can have mass between 10 keV and 100 TeV.





< 10 keV
DM too hot, spoils structure formation

~ m_e — **1 MeV**

~ m_p, m_n — **1 GeV**

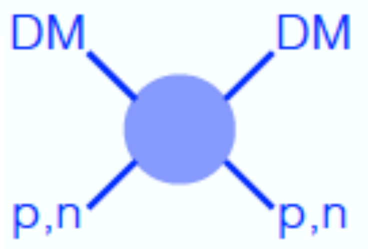
WIMPs paradigm — **M_Z**

10 TeV

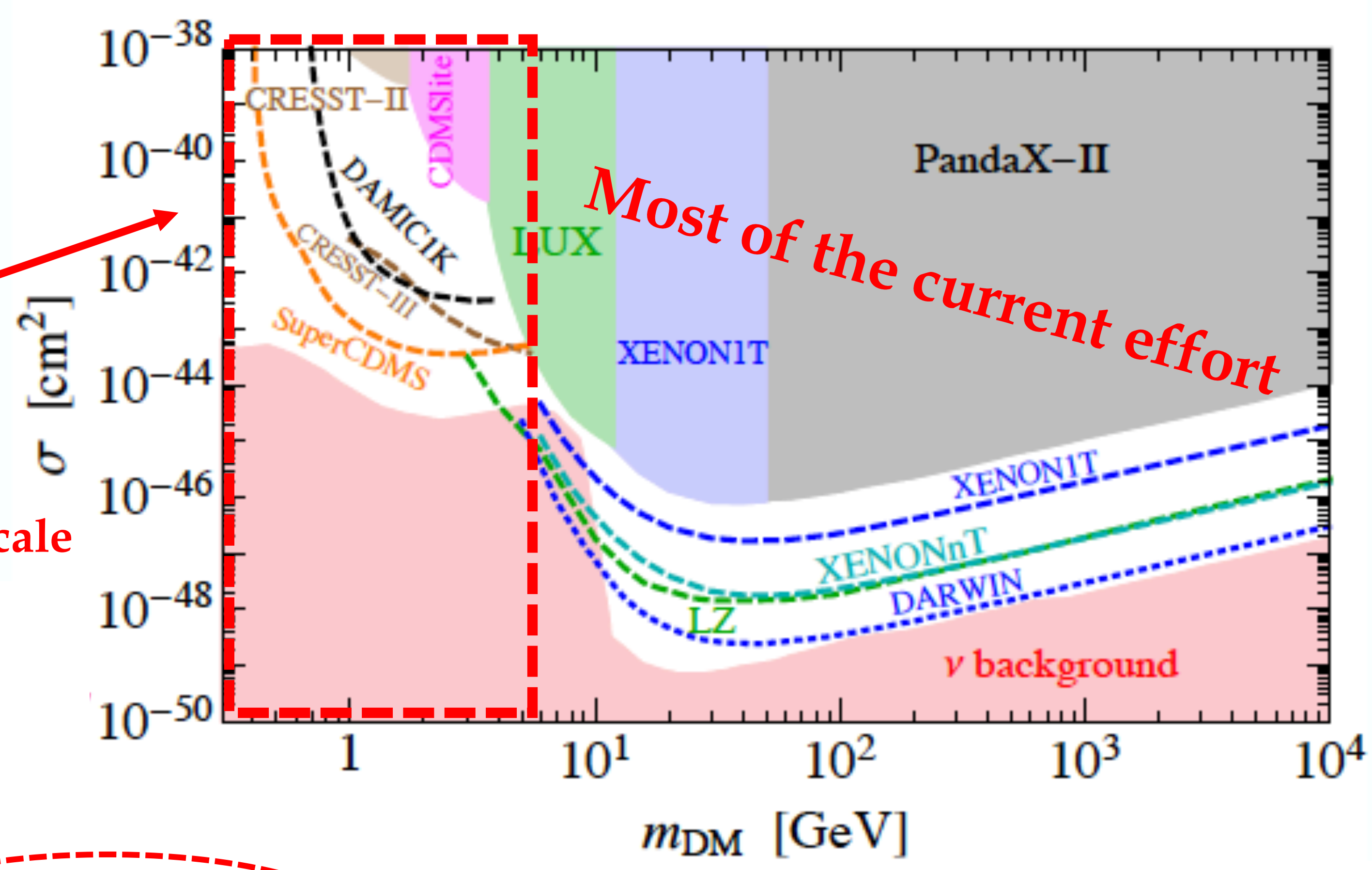
> 100 TeV
DM overproduced

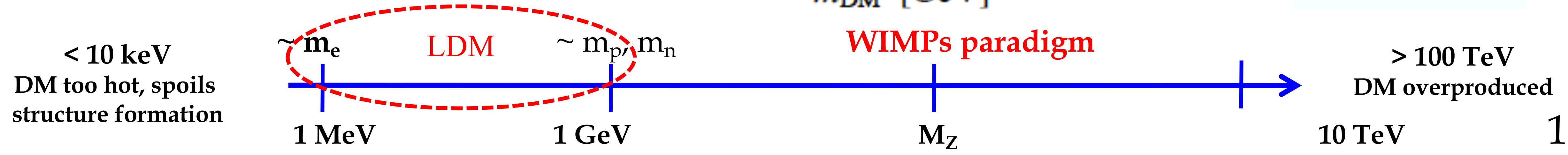
Search for Dark Matter with thermal origin

DM candidates with thermal origin can have mass between 10 keV and 100 TeV.



Light Dark Matter and corresponding light mediators below the Fermi scale





Using existing/future (flavor) facilities to study the Dark Sector

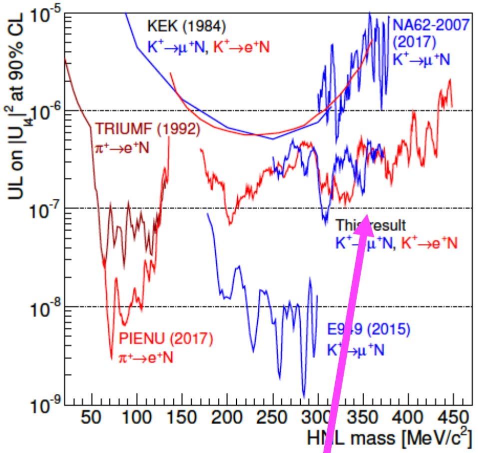
Kaon, D, B physics

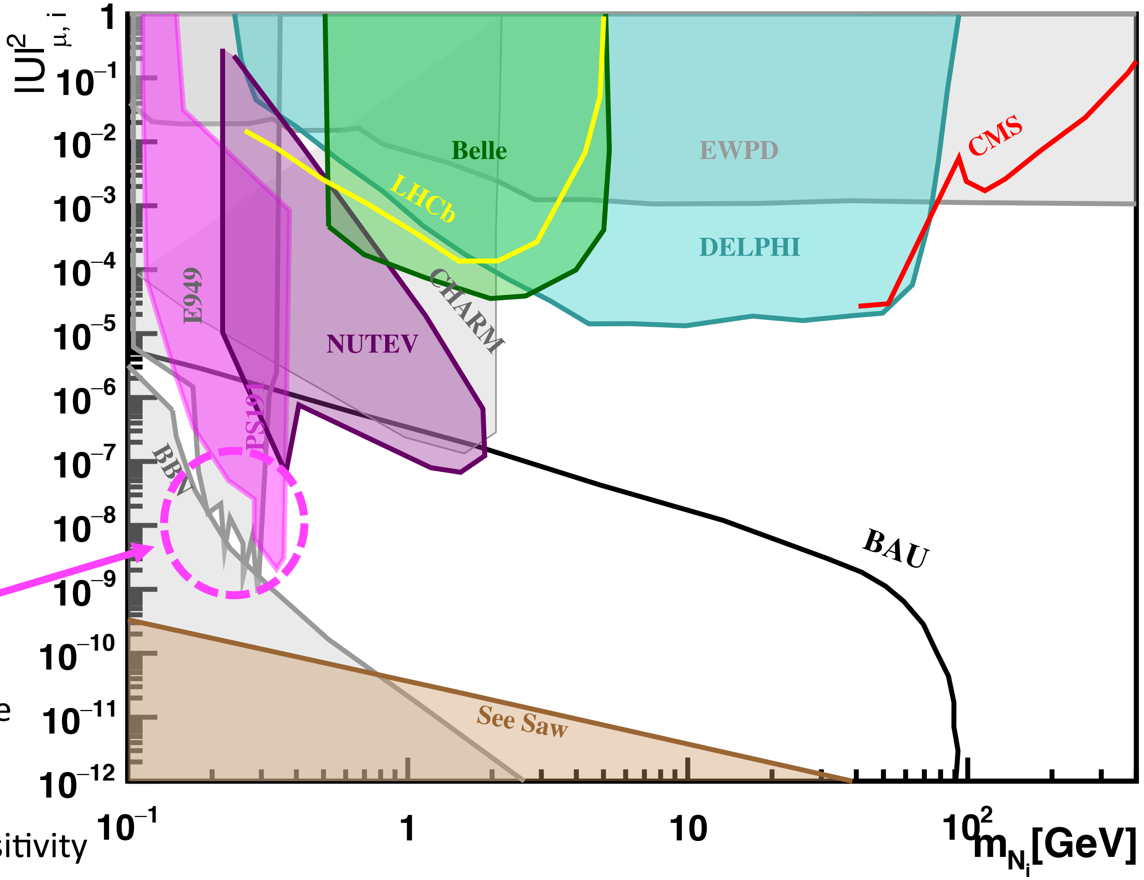
Hidden Sector physics

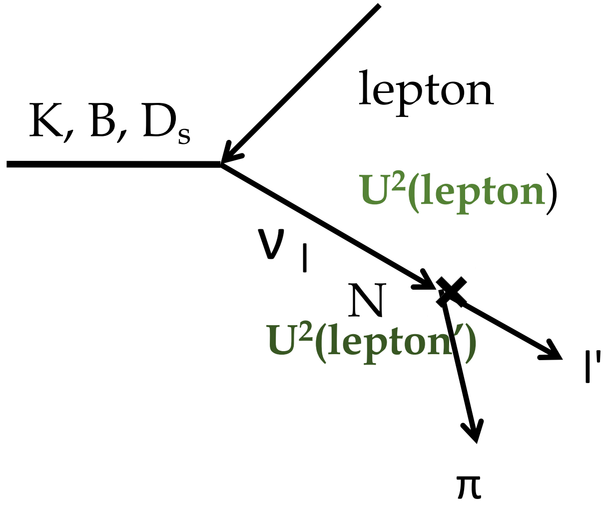
Using existing/future (flavor) facilities to study the Dark Sector

Heavy neutrinos below the EW scale

NA62, PLB778 (2018) 137







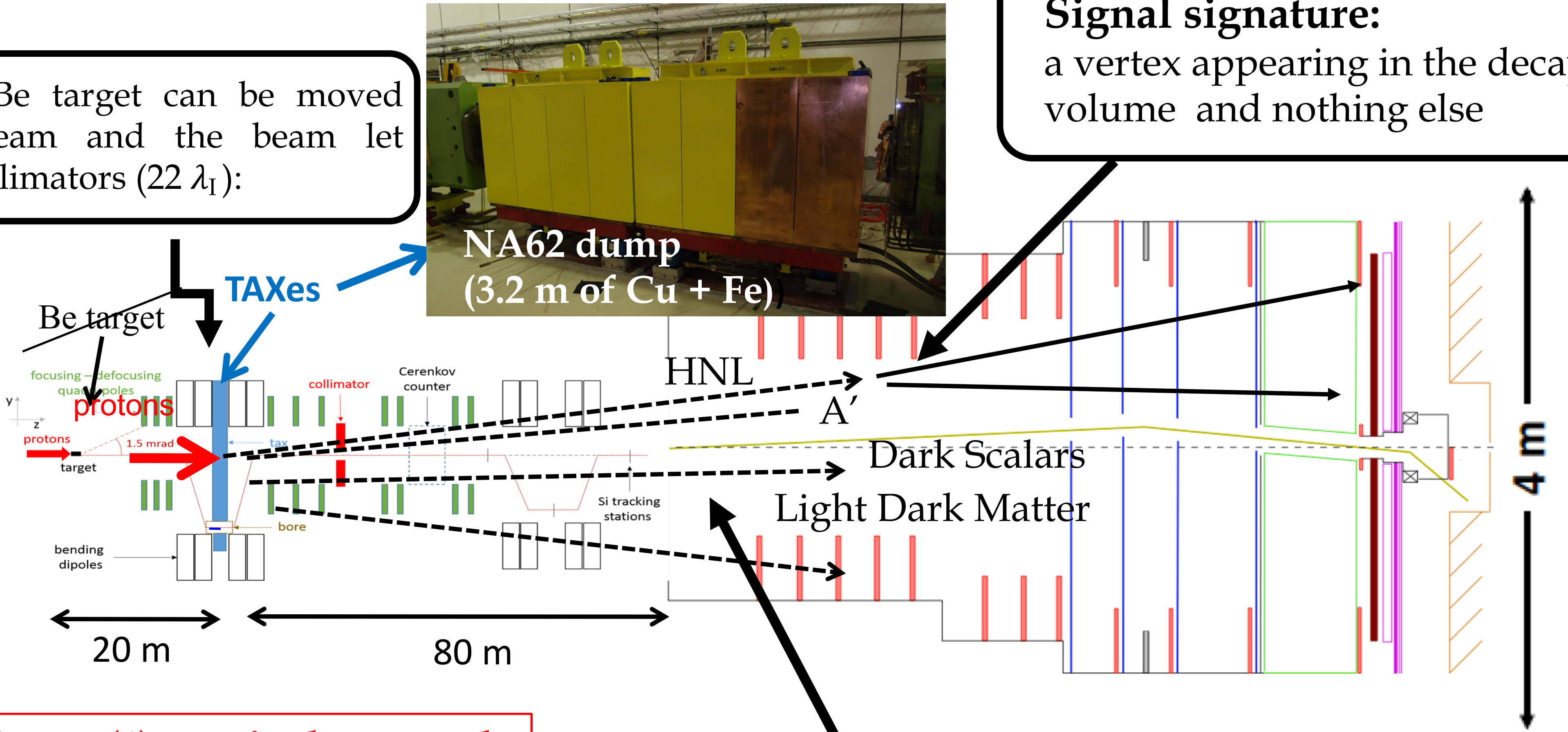
NA62 in kaon mode:
K+ ⟶ μ+ N, N ⟶ anything
(same missing mass technique used for the K+ ⟶ π+ ν νbar golden mode).
expect to reach the E949 sensitivity with 2016-2018 dataset.

CMS, PRL 120 (2018) 221801
Belle, PRD87 (2013) 071102
LHCb, PRD 85 (2012) 112004
Delphi, Zphys C 74 (1997) 57
CHARM Phys. Lett. 166B (1986) 473
NuTeV, PRL 83 (1999), 4943
E949: PRD 91 (2015) 052001
PS191: PLB 2013 (1988) 332

NA62 in "dump" operation mode

Dump mode: the Be target can be moved away from the beam and the beam let impinging on the collimators (22 λ_I):

Signal signature:
a vertex appearing in the decay volume and nothing else

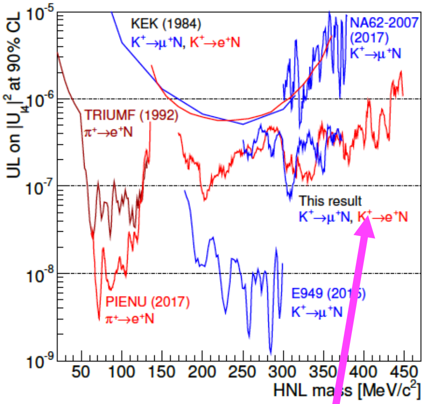


Proposal to dedicate o(1) year in dump mode at the end of the kaon mode period (2023^{++}).

Heavy Neutral Leptons, Dark Photons, Dark scalars, and ALPS can be originated by charm, beauty and photons produced in the interaction of protons with the dump.

Using existing/future (flavor) facilities to study the Dark Sector

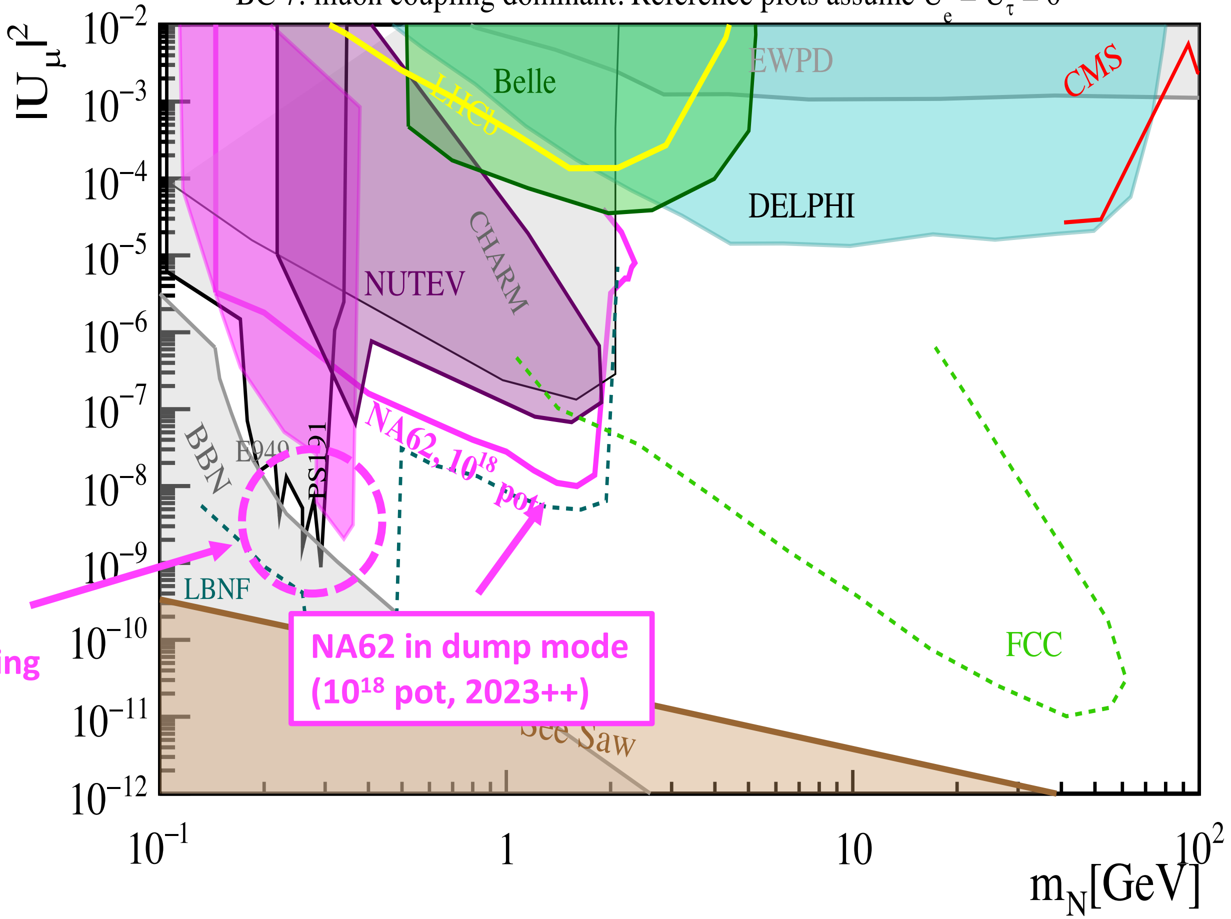
NA62, PLB778 (2018) 137



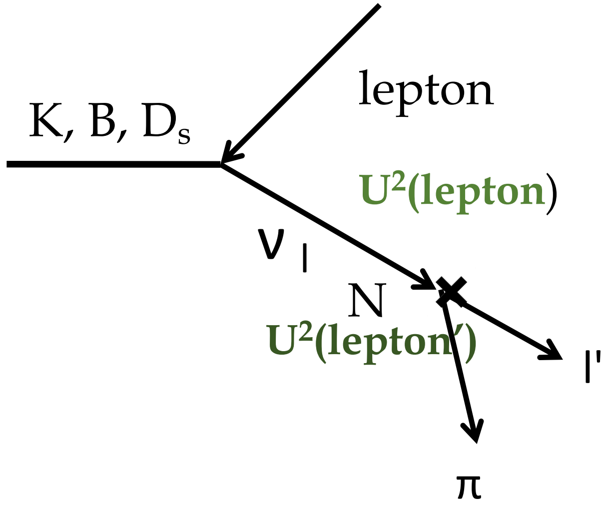
NA62 in kaon mode:

$K+ \longrightarrow \mu+ N$, $N \longrightarrow$ anything

Heavy neutrinos below the EW scale



NA62 in dump mode (10^{18} pot, 2023++)



CMS, PRL 120 (2018) 221801
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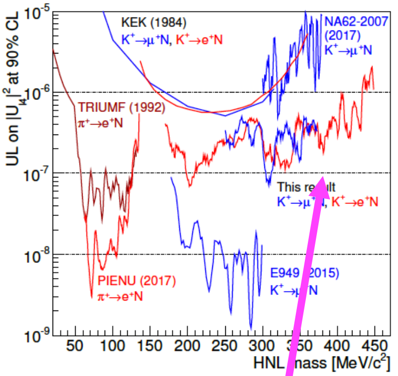
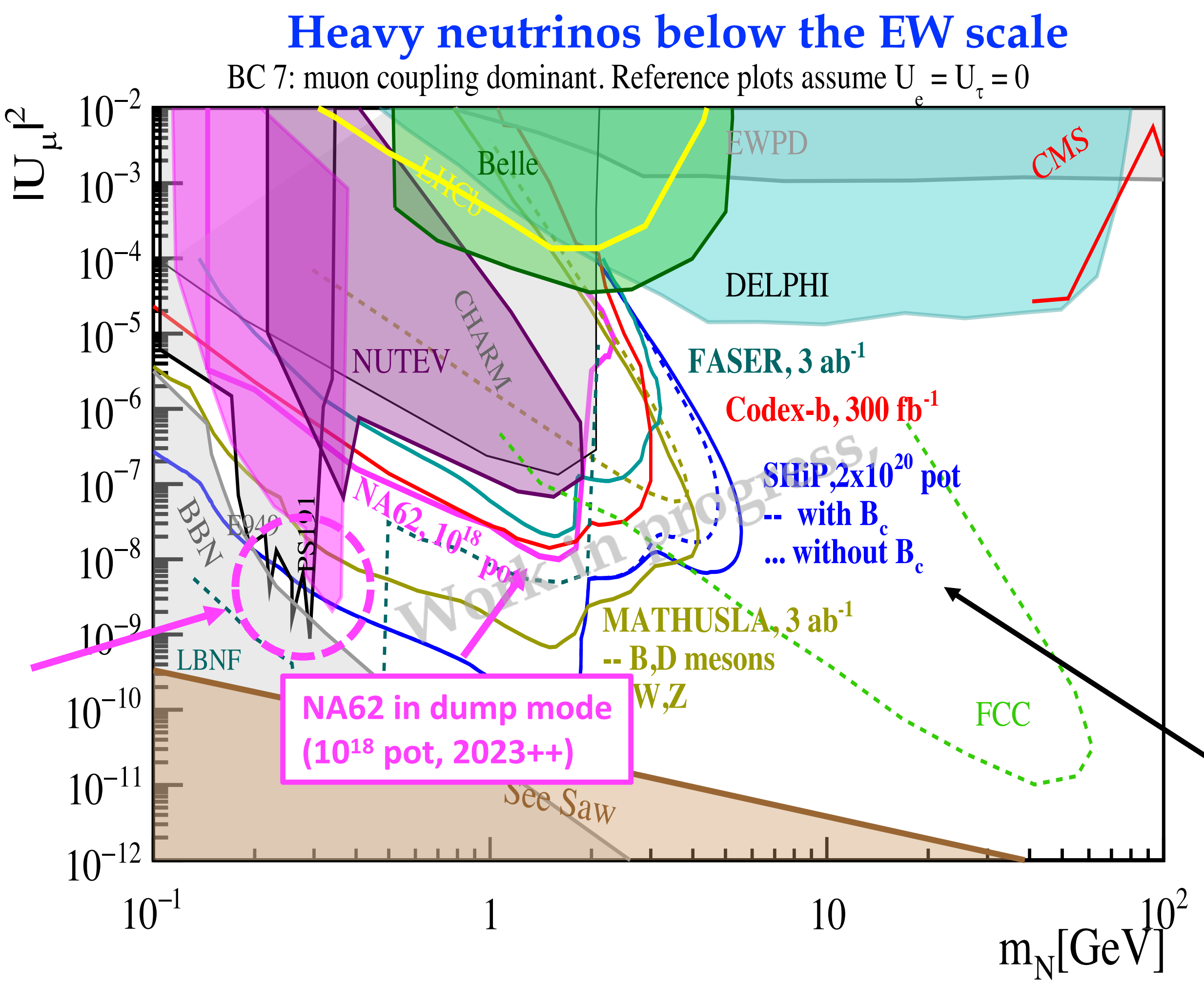
Using existing/future (flavor) facilities to study the Dark Sector

NA62, PLB778 (2018) 137

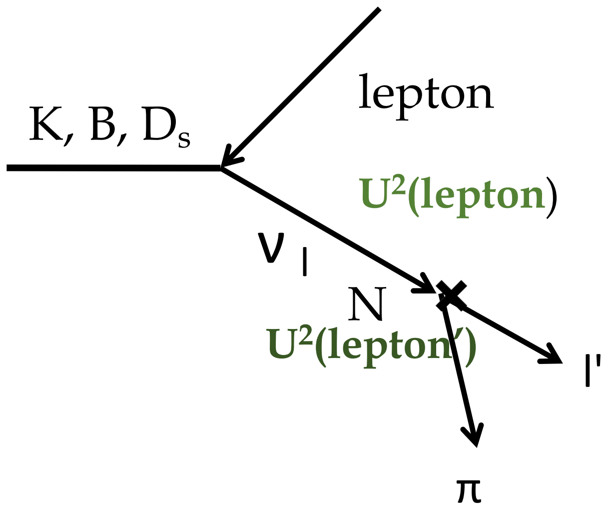


NA62 in kaon mode

$K+ \longrightarrow \mu+$ N, N $\longrightarrow$ anyt



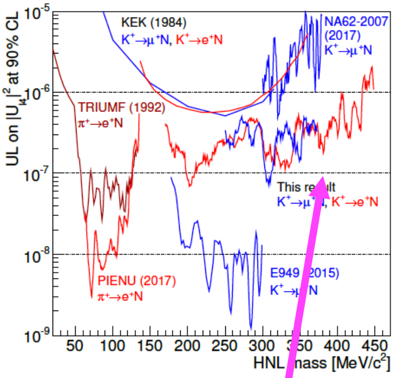
NA62 in dump mode
(10^{18} pot, 2023++)



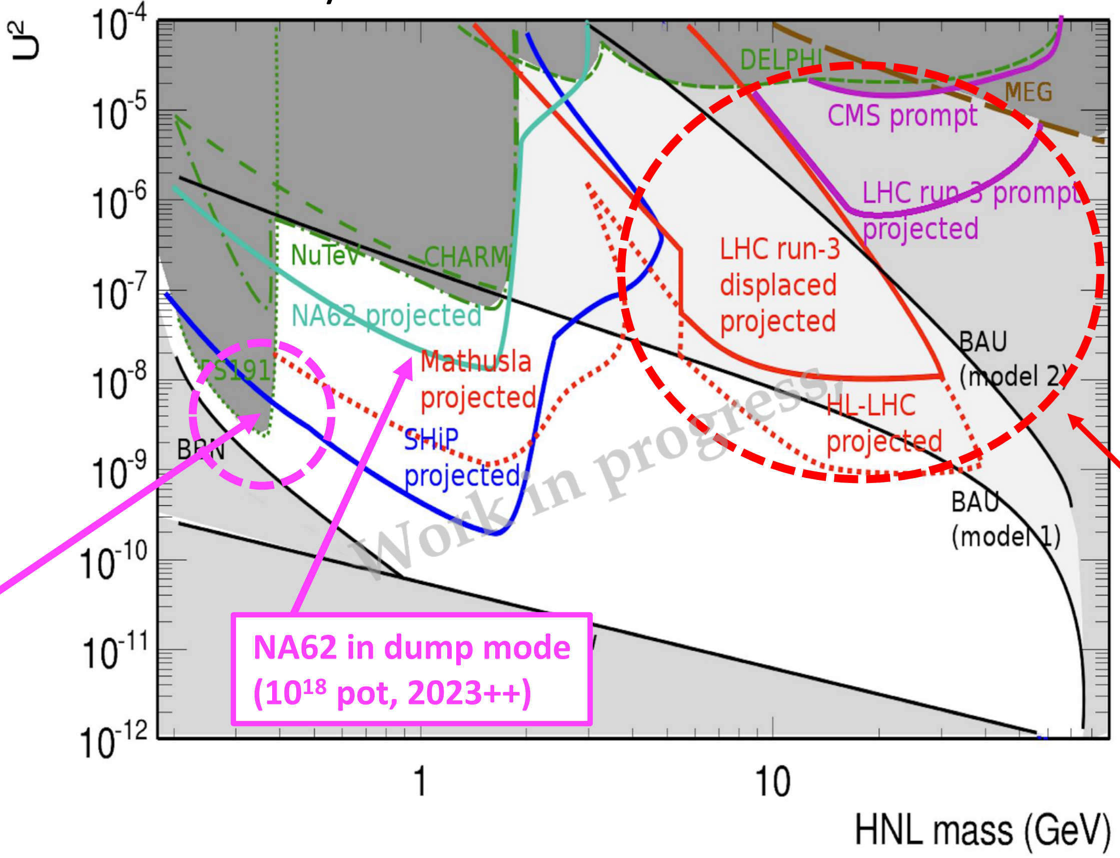
Projects presented in the Physics Beyond Colliders Study group (documents in preparation for ESPP)
See J. Jaeckell talk tomorrow

Using existing/future (flavor) facilities to study the Dark Sector

NA62, PLB778 (2018) 137



Courtesy of A. De Roeck.



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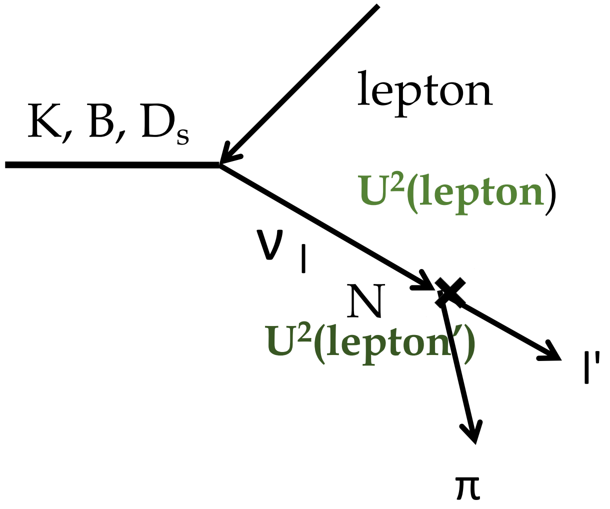
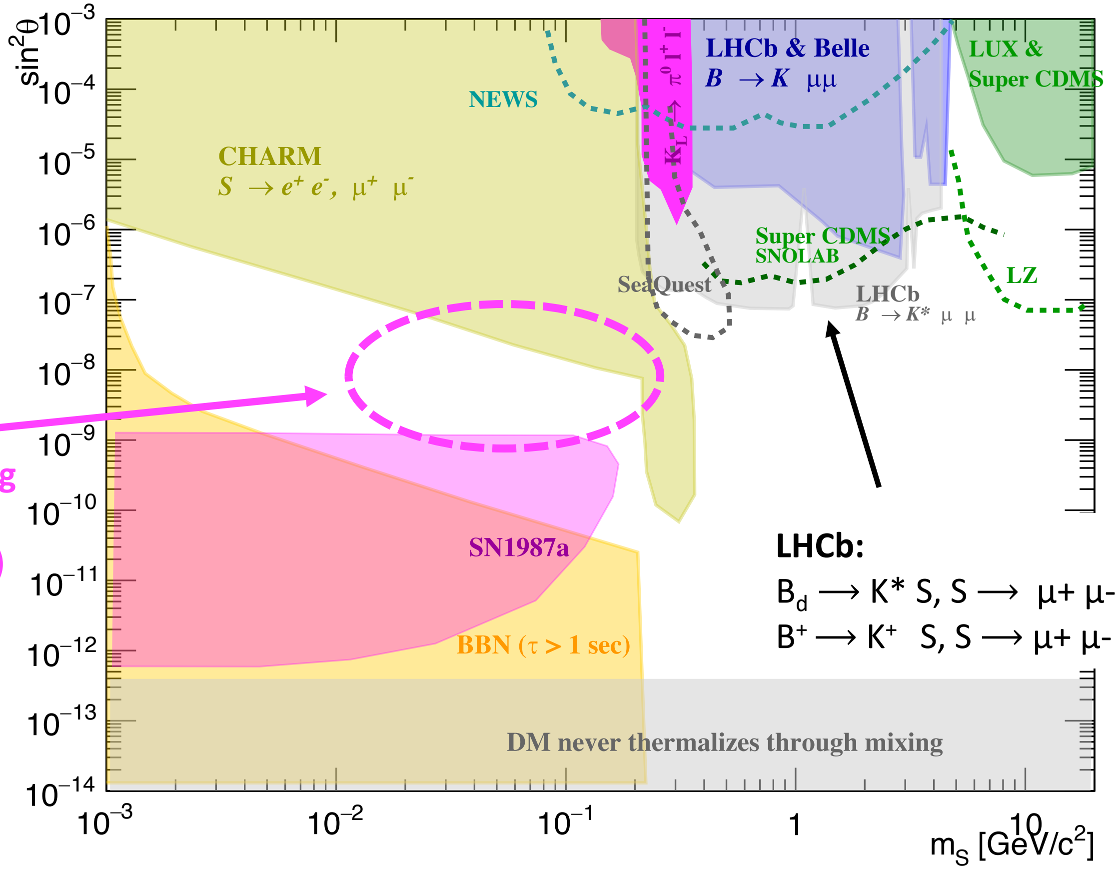


Sensitivity to HNL from LHC, HL-LHC: plot being prepared for the LLP white paper (P. Mermod)

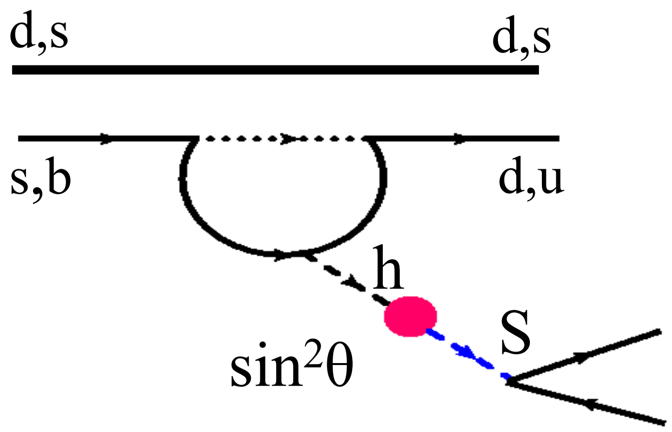
Using existing/future (flavor) facilities to study the Dark Sector

Light Dark Matter and corresponding light mediators: the Dark Scalar case

NA62:
$K+ \longrightarrow \pi+$ S, S $\longrightarrow$ anything
(by product of the main
$K+ \longrightarrow \pi+$ ν vbar analysis)



LHCb:
$B_d \longrightarrow K^*$ S, S $\longrightarrow$ μ+ μ- ,PRL 15 (2015), 161802
$B^+ \longrightarrow K^+$ S, S $\longrightarrow$ μ+ μ- ,PRD 95 (2017) 071101

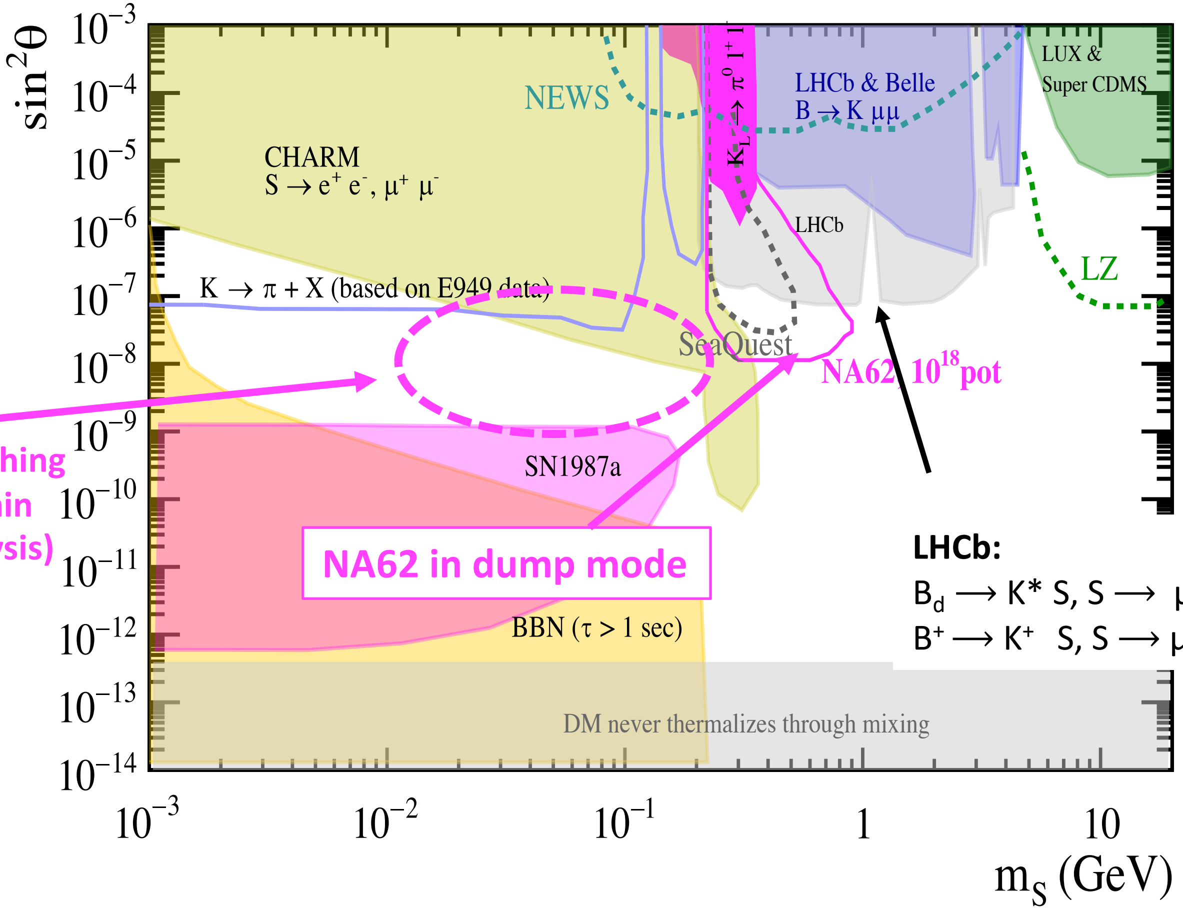


μ+μ-, e+ e-, ν vbar

See for example, Rept.Prog.Phys. 79 (2016) no.12, 124201 and references therein
and G.Perez et al, JHEP 1706 (2017) 050

Using existing/future (flavor) facilities to study the Dark Sector

Light Dark Matter and corresponding light mediators: the Dark Scalar case



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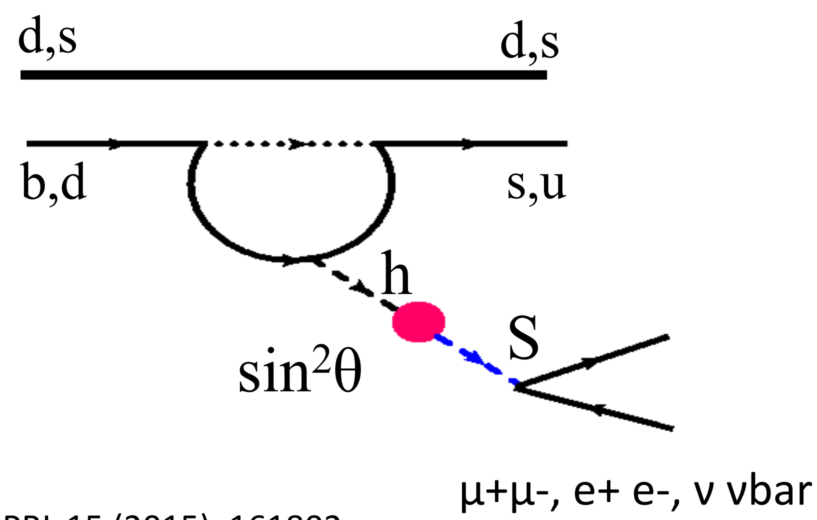

Using existing/future (flavor) facilities to study the Dark Sector

Light Dark Matter and corresponding light mediators: the Dark Scalar case

NA62:
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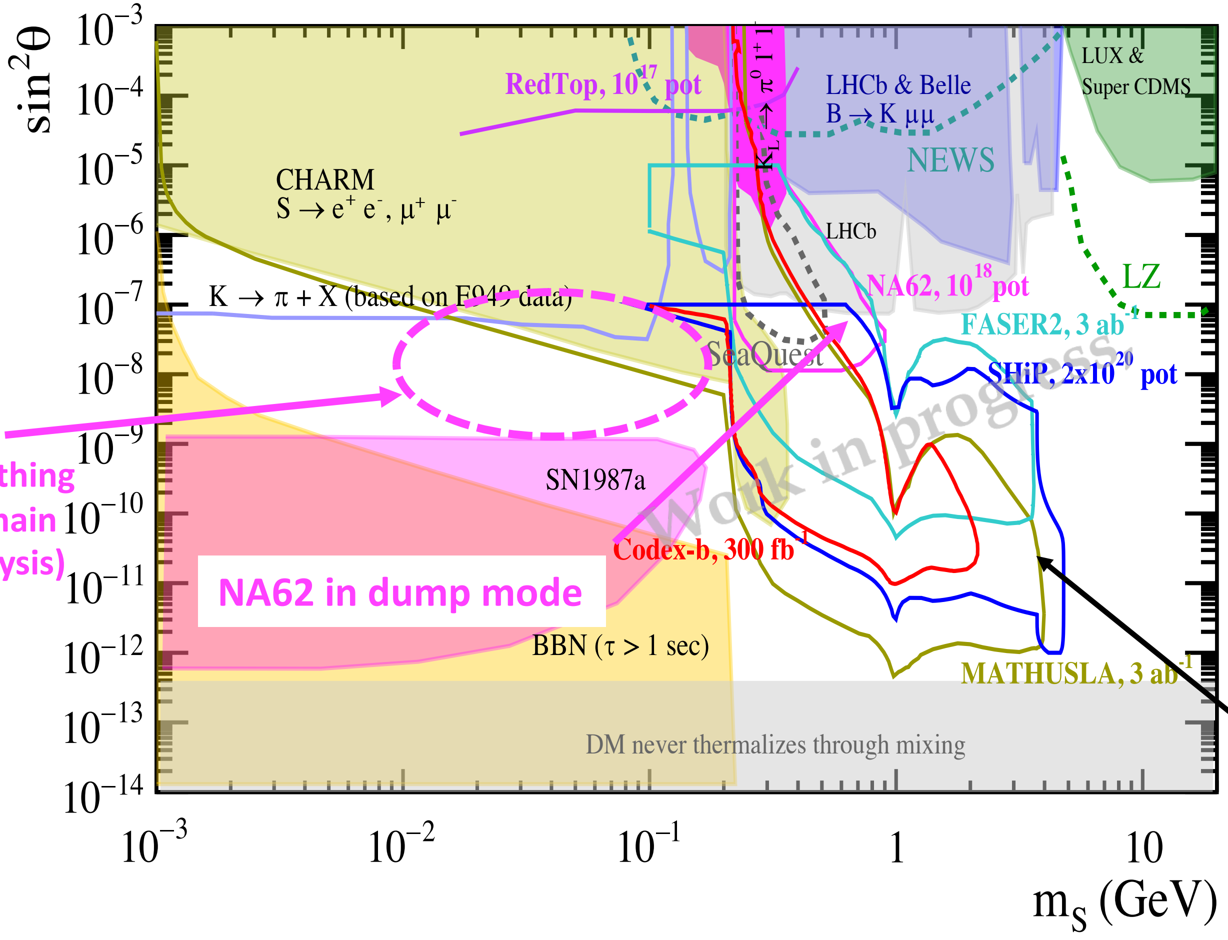
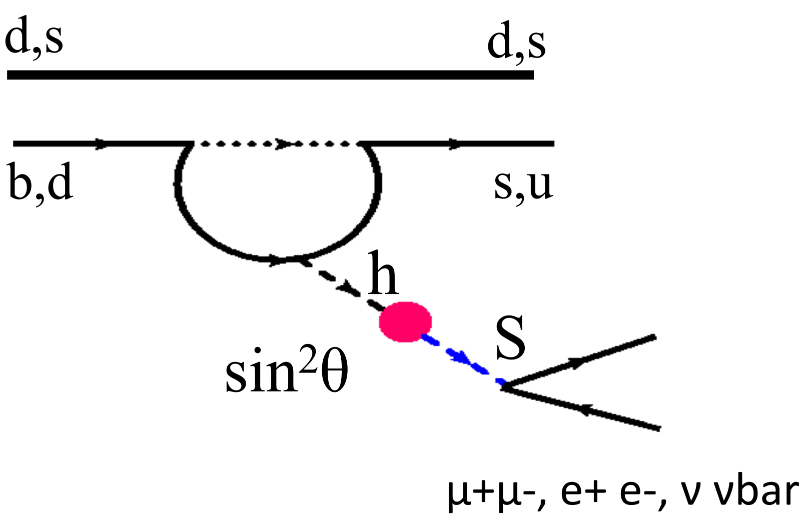
(by product of the main
$K^+ \longrightarrow \pi^+ \nu$ vbar analysis)





Projects presented in the
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Conclusions

Conclusions

- A wealth of experimental results in the last few years are constraining NP contributions in the CKM paradigm, in particular in $b \to s\, l^+ l^-$ transitions, with unprecedented level of precision.

- We did not observe so far unambiguous deviations from SM predictions, hence:

  - either NP is very heavy and/or mimic the SM in its flavor-breaking pattern:
    $\longrightarrow$ LHCb upgrade(s), Belle-II, NA62, ATLAS/CMS, etc. will keep testing this paradigm during the HL-LHC era;

  - or it is below the Fermi scale and couples very feebly to SM particles and so far escaped detection:
    $\longrightarrow$ new proposals at existing and/or future (flavor) facilities (but not only) will possibly test this new paradigm in the next 5-15 years.

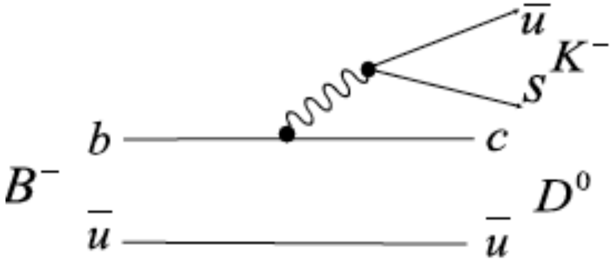
………Where do we go from here?

SPARES

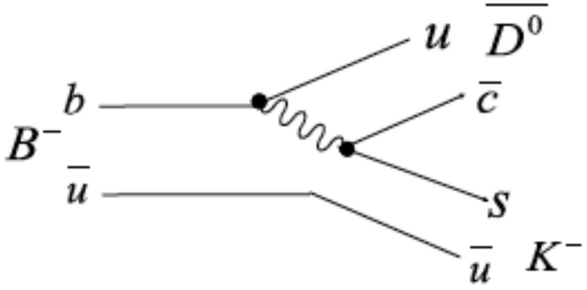
P. Urquijo, ICHEP 2018

Φ_3/γ (phase of V_{ub}) Determination

- Theory is "pristine" in these approaches, << 1% on Φ_3



Favoured



Suppressed

$$r_B = \frac{|A_{\text{suppressed}}|}{|A_{\text{favoured}}|} \approx \frac{V_{ub}V^*_{cs}}{V_{cb}V^*_{us}} \times [\text{colour supp.}] = 0.1 - 0.2$$

Relative weak phase is Φ_3, Relative strong phase is δ_R

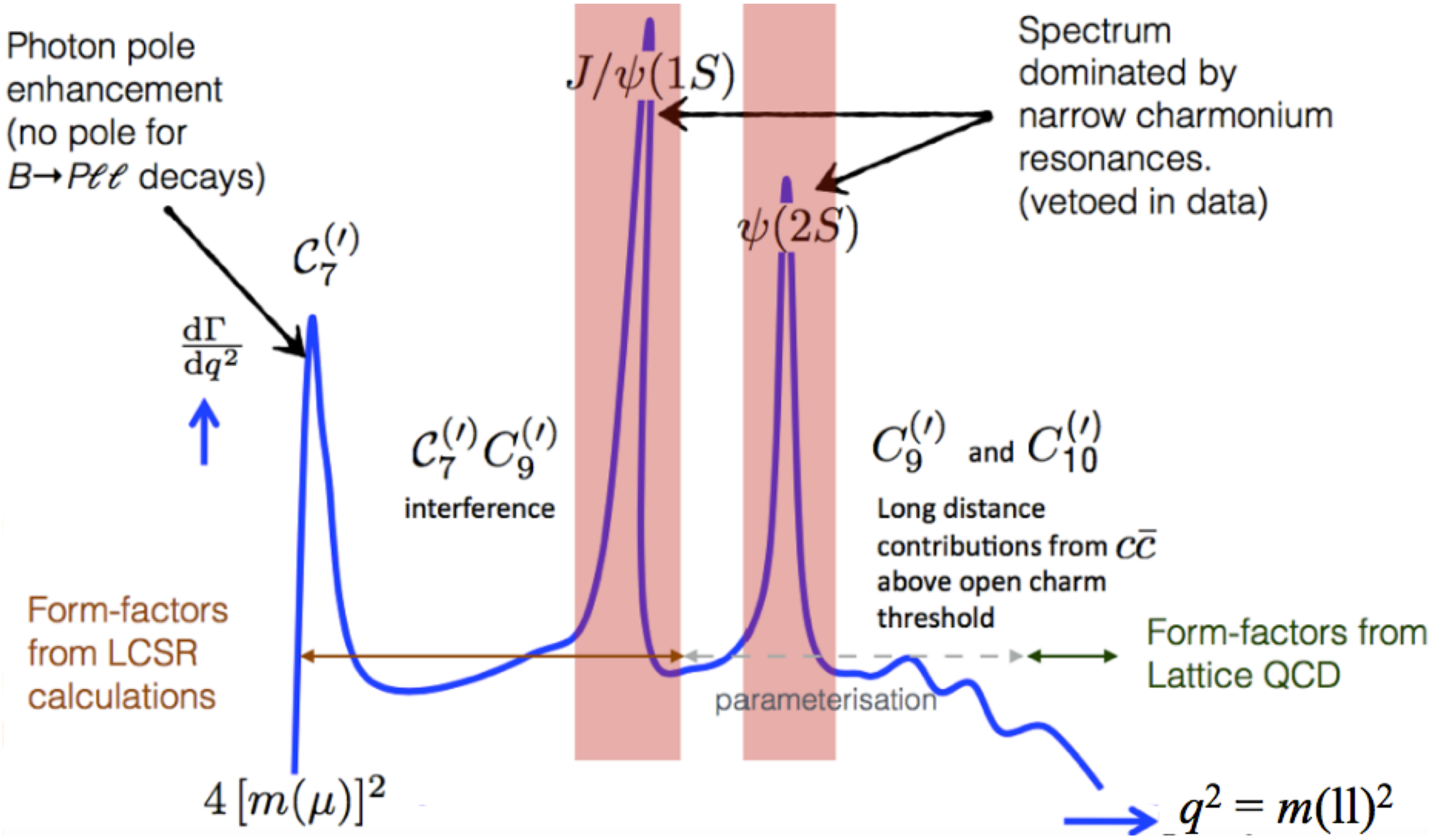
A dream of Belle & Babar: difficult due to V_{ub} and colour suppression. Many Direct CPV techniques developed at the B-factories.

3 D^0 mode categories:

- D_{CP}, CP eigenstates [GLW]
- D_{sup}, Doubly cabibbo suppressed [ADS]
- 3-Body [GGSZ]

- LHCb Φ_3 from 98 observables

B decay	D decay	Method
$B^+ \to DK^+$	$D \to h^+h^-$	GLW
$B^+ \to DK^+$	$D \to h^+h^-$	ADS
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K^0_s h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K^0_s h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K^0_s K^+\pi^-$	GLS
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalit:
$B^0 \to DK^{*0}$	$D \to K^0_s\pi^+\pi^-$	GGSZ
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD



Photon pole enhancement (no pole for $B \to P\ell\ell$ decays)
$\mathcal{C}_7^{(\prime)}$
$\frac{d\Gamma}{dq^2}$
$\mathcal{C}_7^{(\prime)} \mathcal{C}_9^{(\prime)}$
interference
$J/\psi(1S)$
$\psi(2S)$
Spectrum dominated by narrow charmonium resonances. (vetoed in data)
$\mathcal{C}_9^{(\prime)}$ and $\mathcal{C}_{10}^{(\prime)}$
Long distance contributions from $c\bar{c}$ above open charm threshold
Form-factors from LCSR calculations
parameterisation
Form-factors from Lattice QCD
$4\,[m(\mu)]^2$
$q^2 = m(ll)^2$

PBC-BSM: physics targets

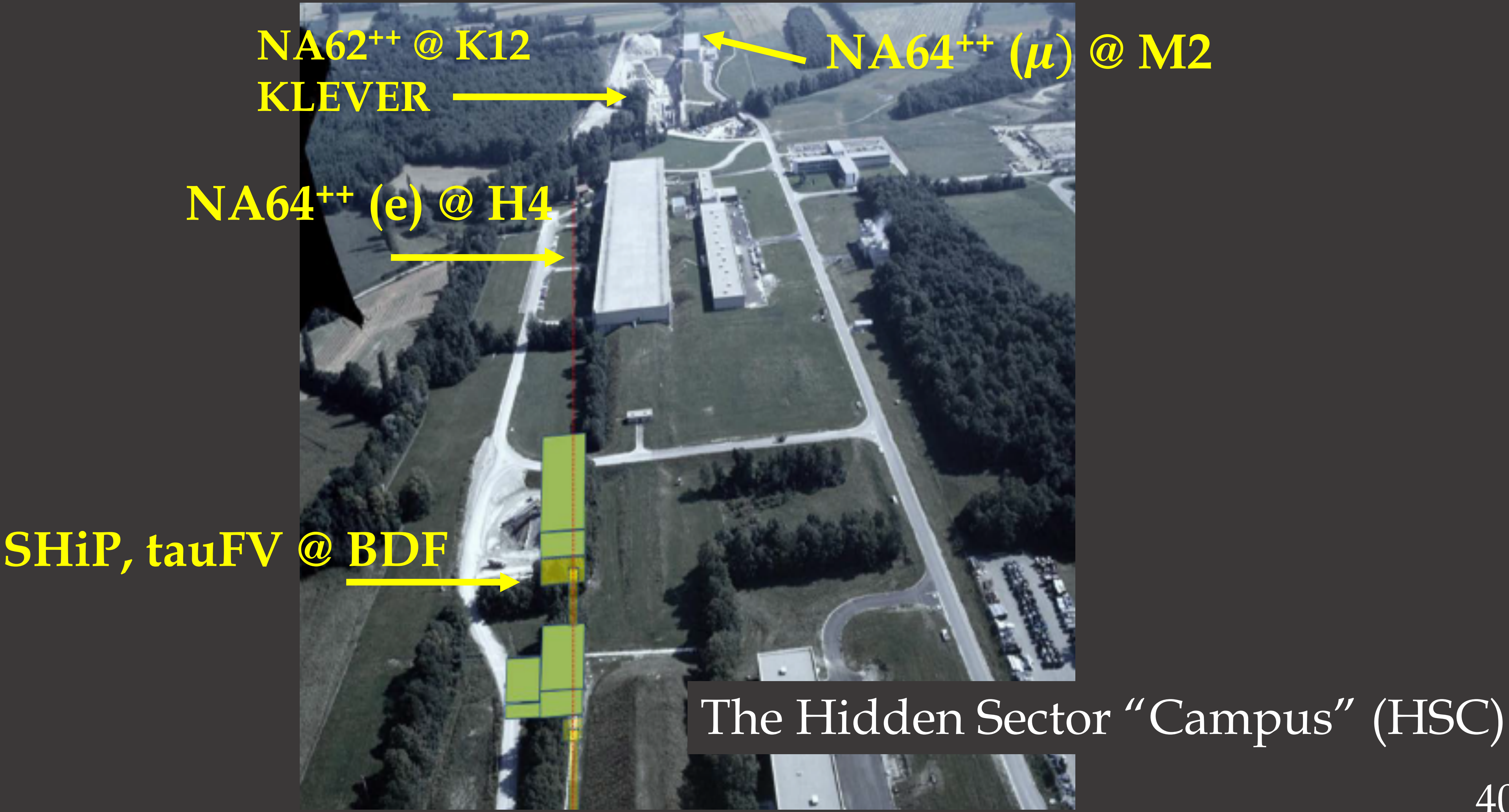
Light thermal DM and corresponding light mediators, RH neutrinos at the GeV scale,
Axions and axion-like particles, EDM in proton/deuteron and in long-lived charmed hadrons;
Ultra-TeV New Physics in extremely rare processes.

Light mediators must be SM singlets, hence options limited by SM gauge invariance:

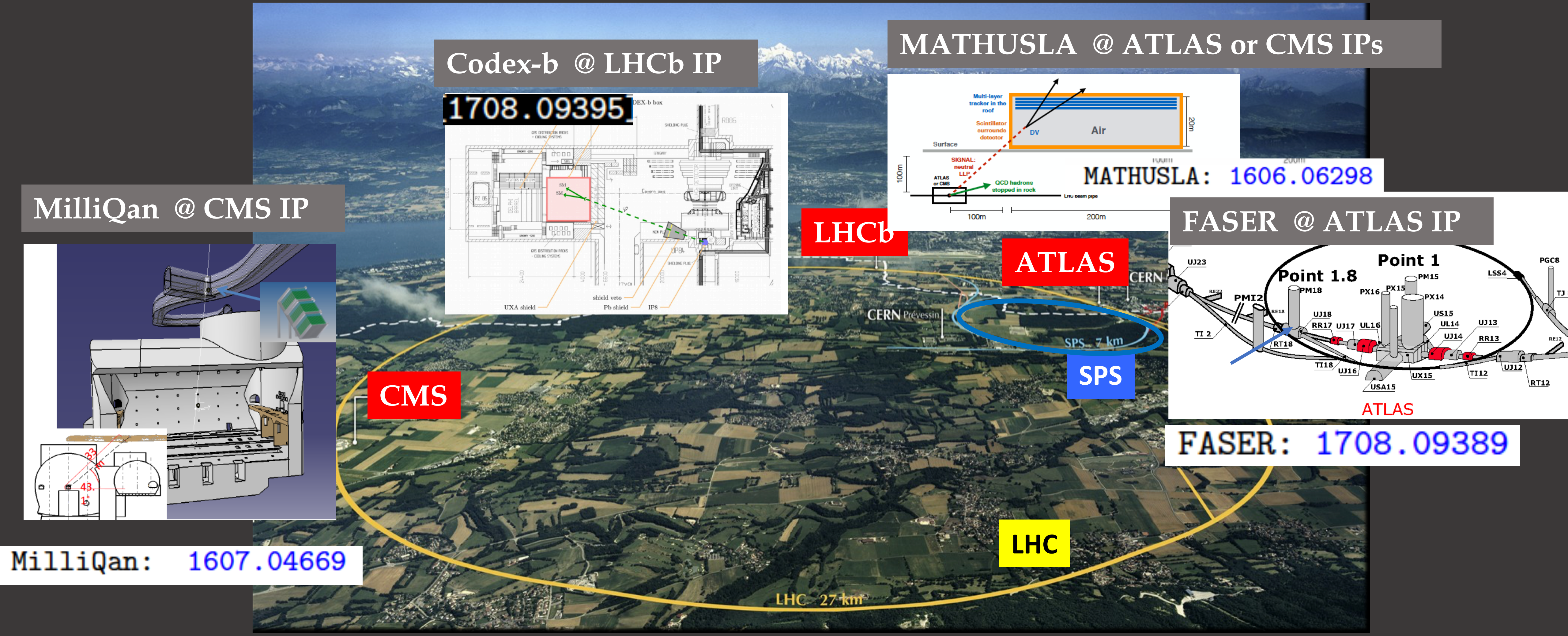
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

This is the set of the simplest fields and renormalizable interactions that can be added to the SM to answer the three fundamental questions.

Aerial picture of the North Area



MilliQan, MATHUSLA, FASER, Codex-b @ the LHC IPs



+ an extremely active LLP community inside ATLAS, CMS and LHCb collaborations