Experimental flavour physics: an introduction- part 2

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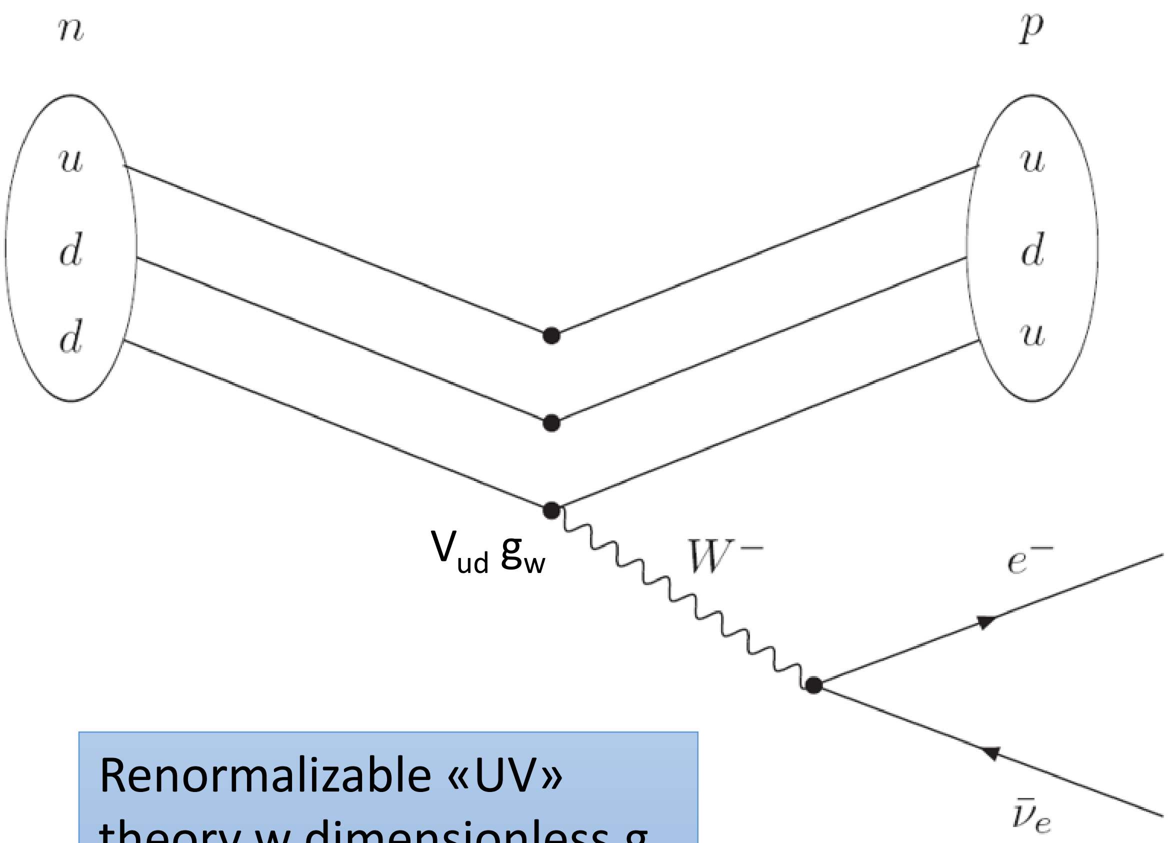
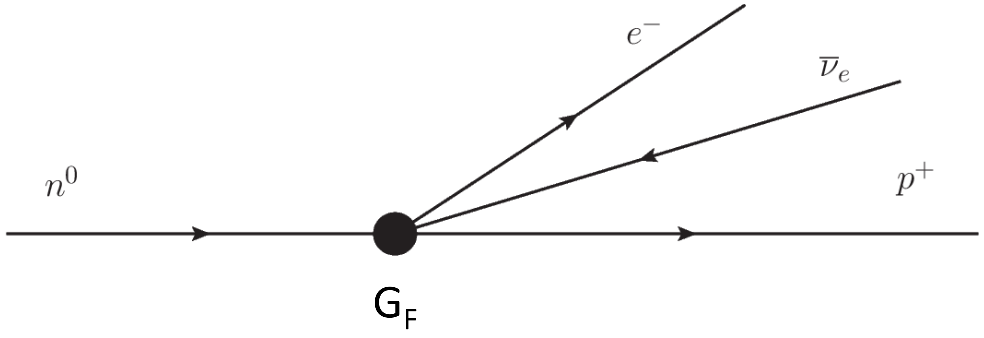
Outline

- NP and effective theories
- Flavour Changing Neutral Current processes
- Universality tests
- Charged lepton flavor/number violations

NP and effective theories (1)

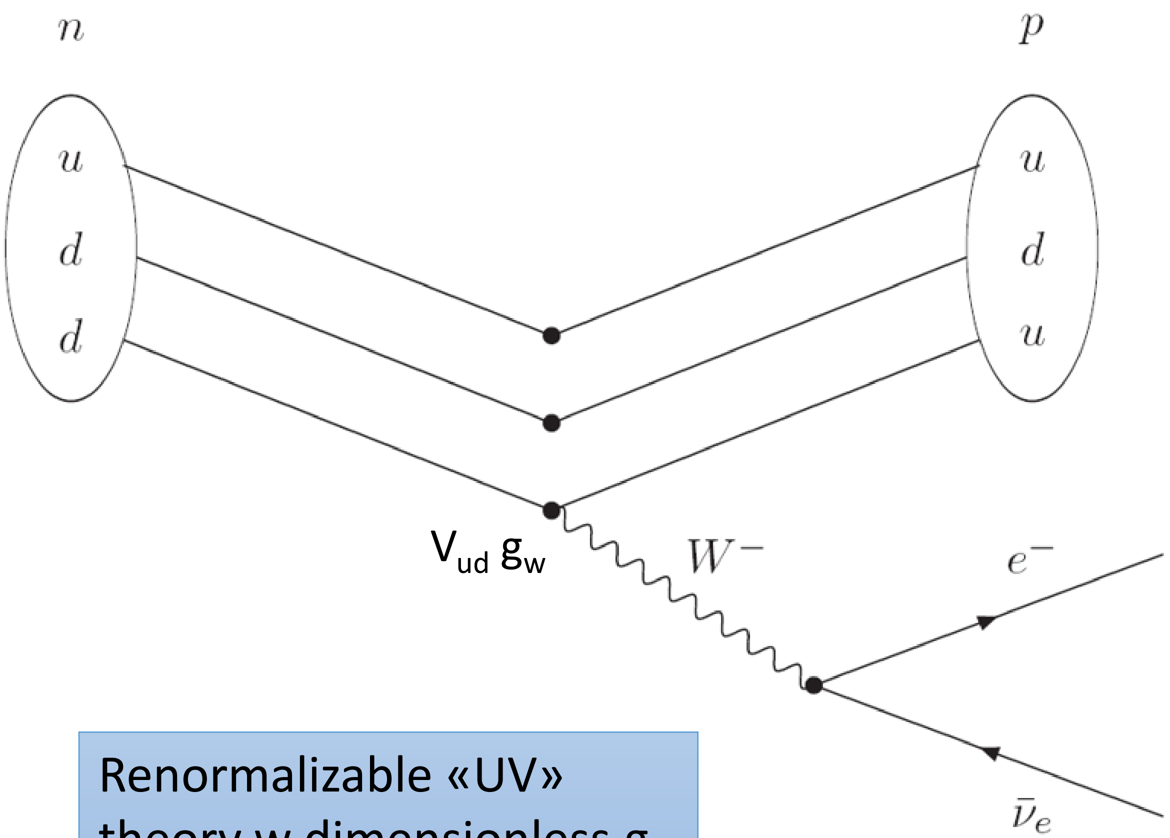


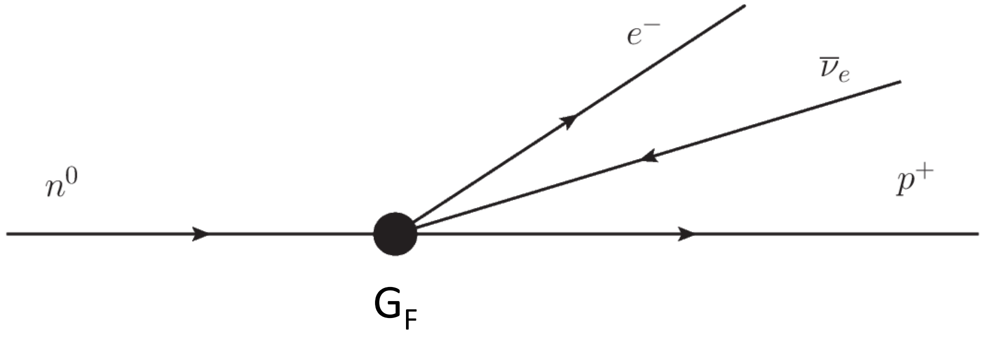
Renormalizable «UV» theory w dimensionless g_w coupling constant and propagator $1/M^2_W$



Non-renormalizable «effective» theory with $[E]^{-2}$ dimensional coupling constant G_F

NP and effective theories (1)





Renormalizable «UV» theory w dimensionless g_w coupling constant and propagator $1/M^2_W$

Non-renormalizable «effective» theory with dimension 6 operator and scale factor $1/\Lambda^2 \equiv 1/M_W^2$

NP and effective theories (2)

- A possibility to explore in a systematic way the effects of «UV completions» of the SM is to think that whatever they are, they should manifest at lower scale as effective theories (just like EW theory and 4 fermion Fermi interaction).

- Effective operators can be constructed combining SM fields and appropriate cutoff scale powers, and used to predict a phenomenology.

- In case no effect is seen in the experiment, set limits on $g_{NP}/\Lambda^{\mathrm{d}-4}$ with g_{NP} the dimensionless coupling constant of the UV New Physics and Λ a typical mass scale of the theory. (In absence of symmetries suppressing g_{NP} one can reasonably think of $g_{NP} \approx 1$)

Flavour physics is the true «energy frontier» ?

- From the European Particle Physics Strategy Briefbook (2019)

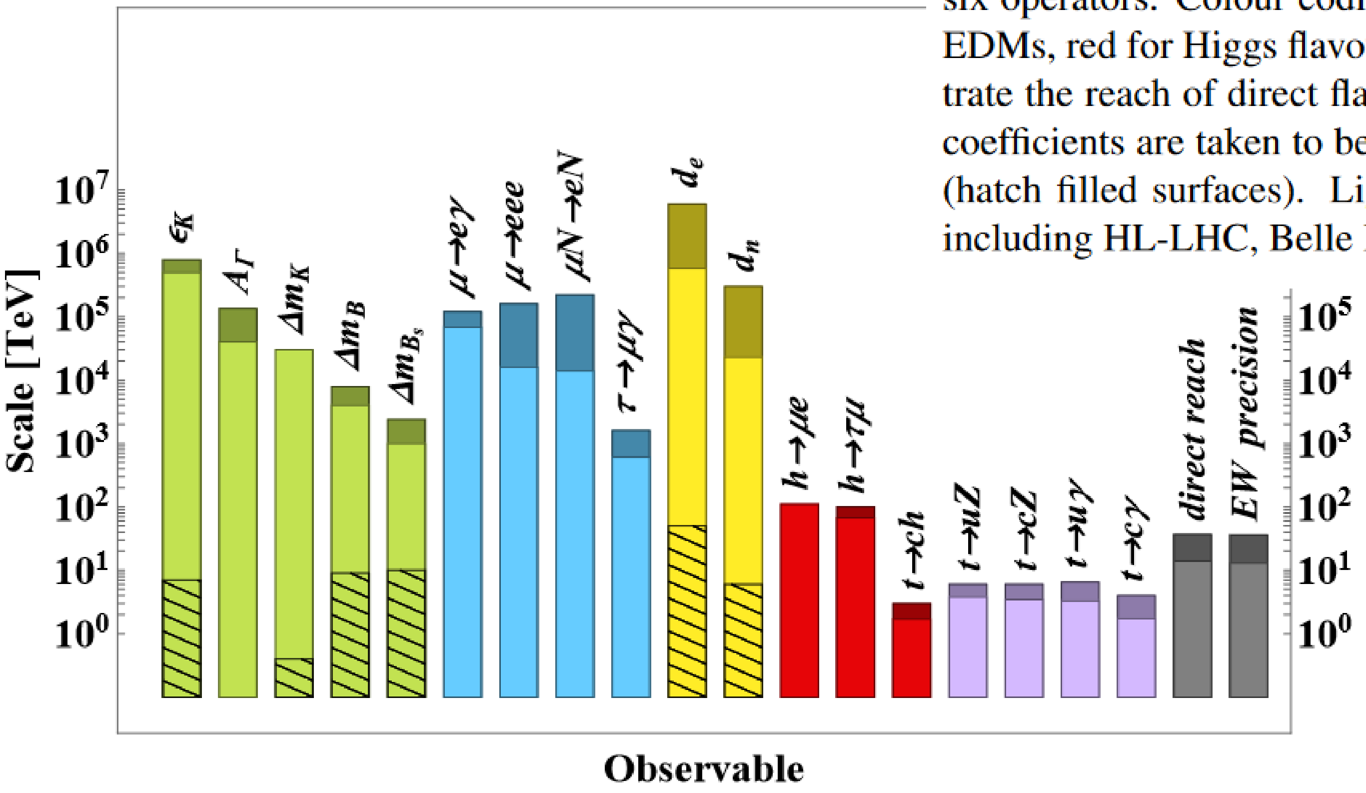
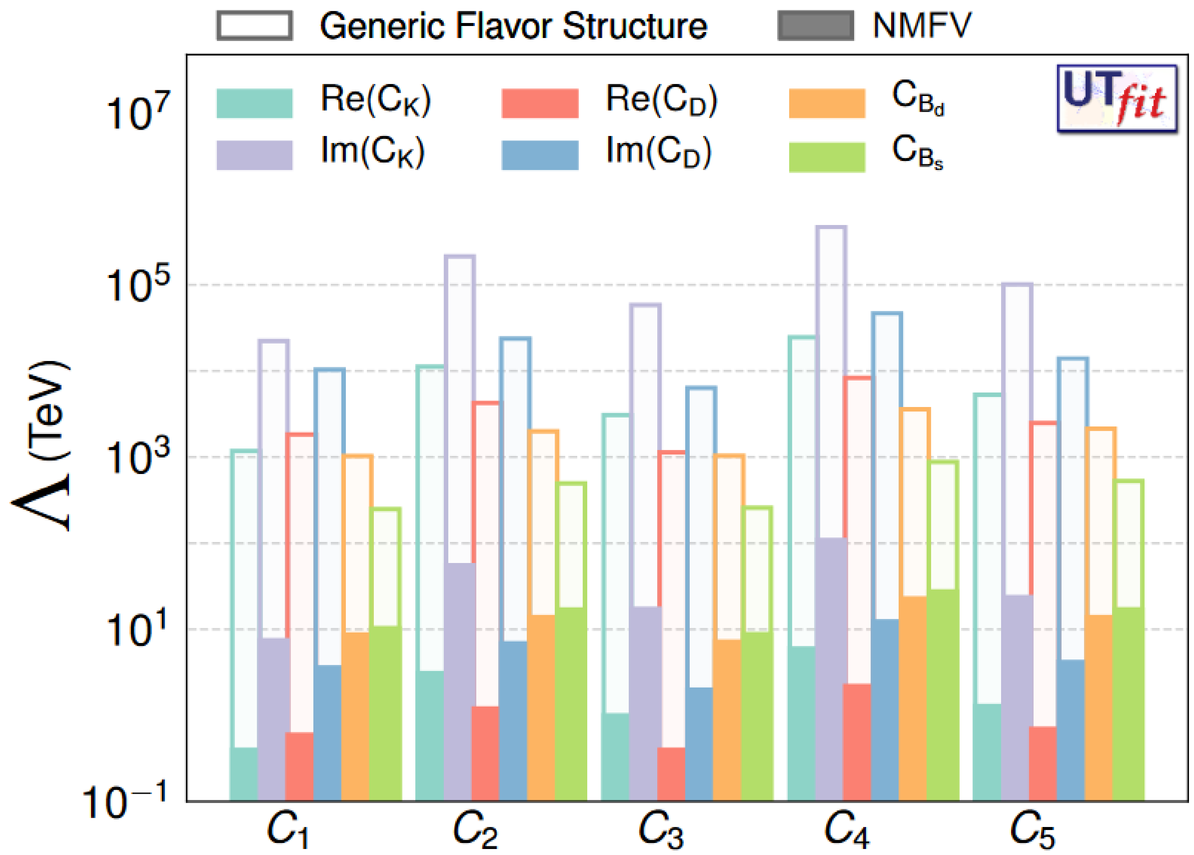


Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS).

UT fit: probing BSM scales



$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}$$

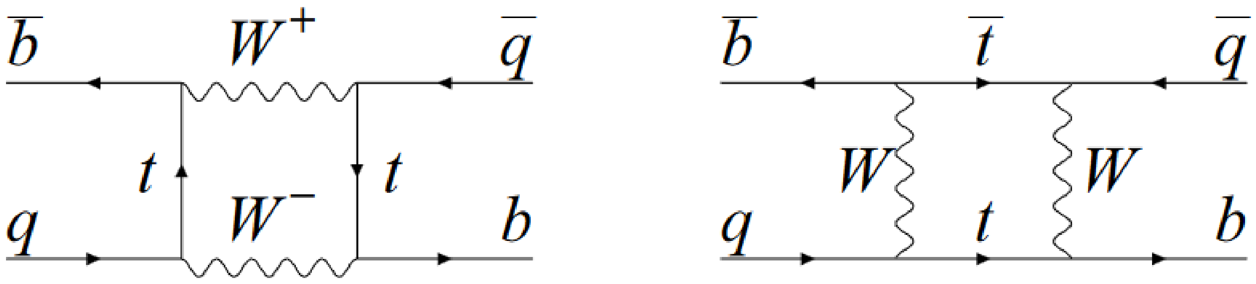
$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha}\gamma_\mu q_{iL}^{\alpha}\bar{q}_{jL}^{\beta}\gamma^\mu q_{iL}^{\beta} \,, \\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jR}^{\beta} q_{iL}^{\beta} \,, \\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jR}^{\beta} q_{iL}^{\alpha} \,, \\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jL}^{\beta} q_{iR}^{\beta} \,, \\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jL}^{\beta} q_{iR}^{\alpha} \,.
\end{aligned}$$

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

- Generic: $C(\Lambda) = \alpha/\Lambda^2$ — $F_i \sim 1$, arbitrary phase
- NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ — $F_i \sim |F_{SM}|$, arbitrary phase

Flavour Changing Neutral Currents

- The only flavour non-diagonal vertex in SM is *charged.* This means FCNC cannot occurr at tree level.
- However we have already seen some possible higher order diagrams for $\Delta F = 2\ ;\ \Delta Q = 0$ neutral meson oscillations: the «box» diagrams.
- Unitarity of CKM implies that in the limit of equal quark masses in the loop the box amplitude still vanishes ! (GIM mechanism). So virtual top quark exchange typically dominates the loop.



FCNC with $\Delta F = 1$

- While meson-antimeson oscillations have always $\Delta F = 2$ FCNC processes can happen also with $\Delta F = 1$
- Some of these happen to be strongly suppressed and/or very «clean» from the theoretical point of view in th SM, and as such well-suited for NP searches.

- $K^+ \to \pi^+ \nu\bar{\nu}$; $K_L \to \pi^0 \nu\bar{\nu}$
- $B_S(B_d) \to \mu^+\mu^-$; $b \to s\gamma$; $b \to sl\bar{l}$

$K^+ \to \pi^+ \nu\bar{\nu}$: needle in the haystack

- This is an extremely CKM suppressed FCNC where the amplitude is proportional to $|V_{ts}^* V_{td}| = \lambda^5$

SM branching ratios:
[arXiv:2109.11032]

$$K^+ \to \pi^+ \nu\nu(\gamma) = (8.62 \pm 0.42) \times 10^{-11}$$
$$K_L \to \pi^0 \nu\nu = (2.94 \pm 0.15) \times 10^{-11}$$

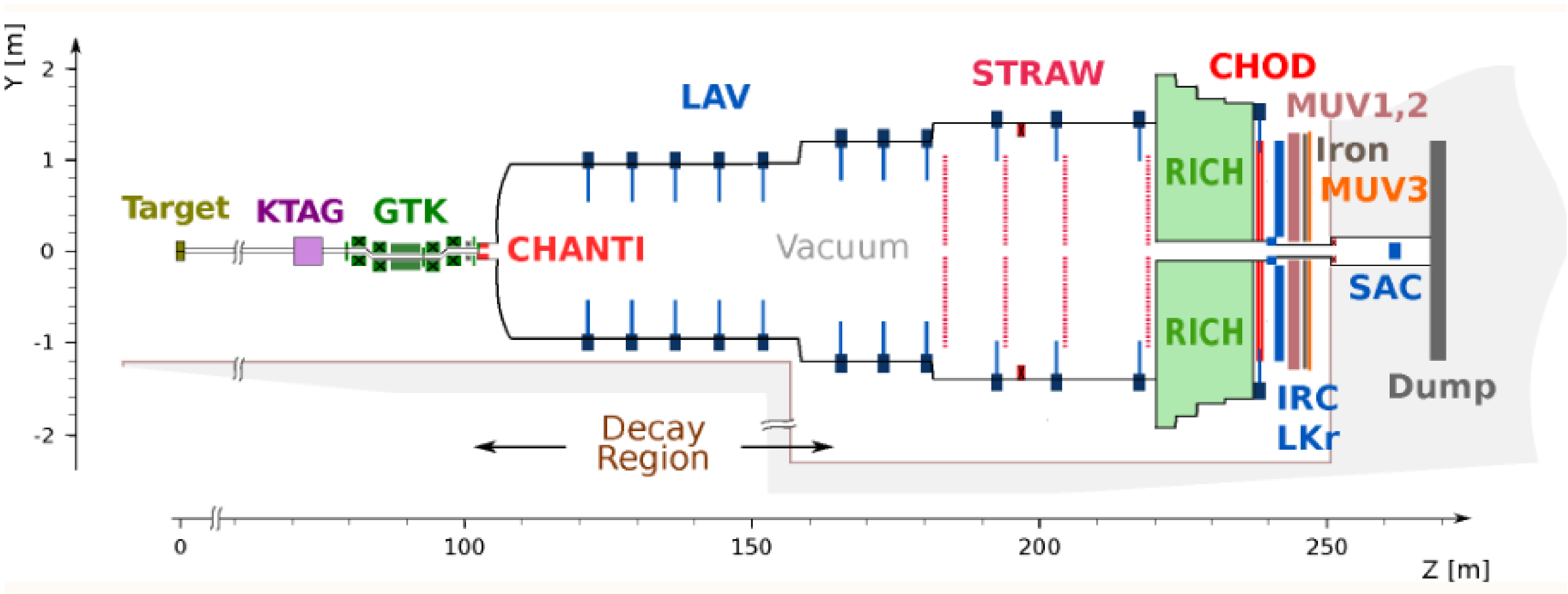
- SM prediction clean

- Sensitive to different NP scenarios.

- Cannot be measured in a «general purpose» setup, both for insufficent kaon flux and for lack of dedicated detection.

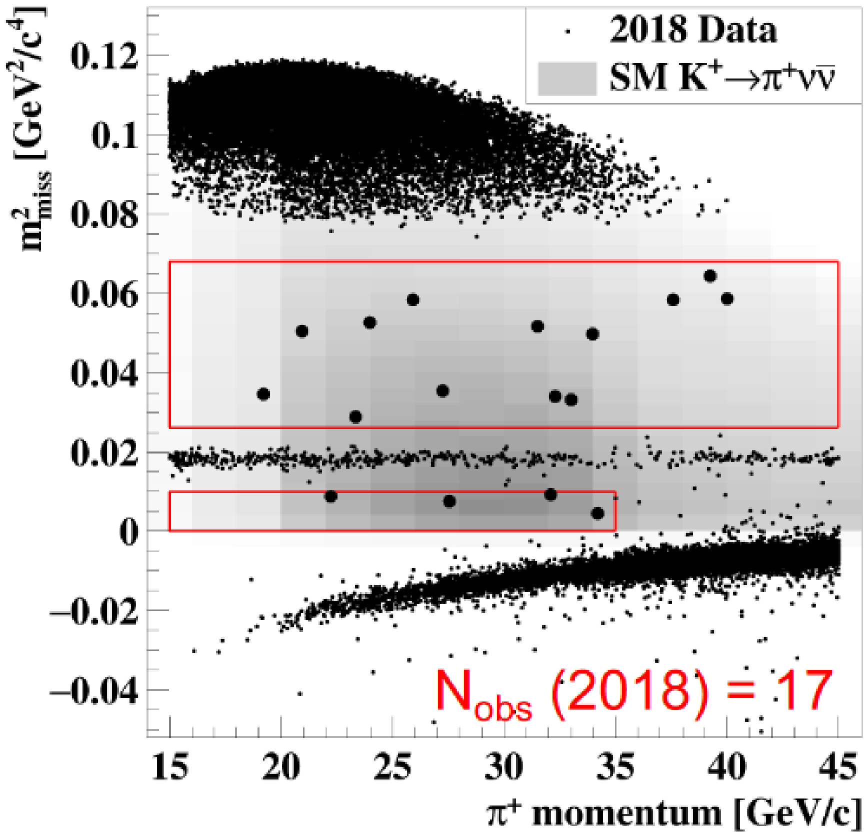
NA62 experiment at CERN

- A dedicated kaon factory with the main aim of measuring the BF of $K^+ \to \pi^+ \nu \bar{\nu}$.
- High intensity unseparated 75 GeV hadron beam
- Efficient detection/veto system

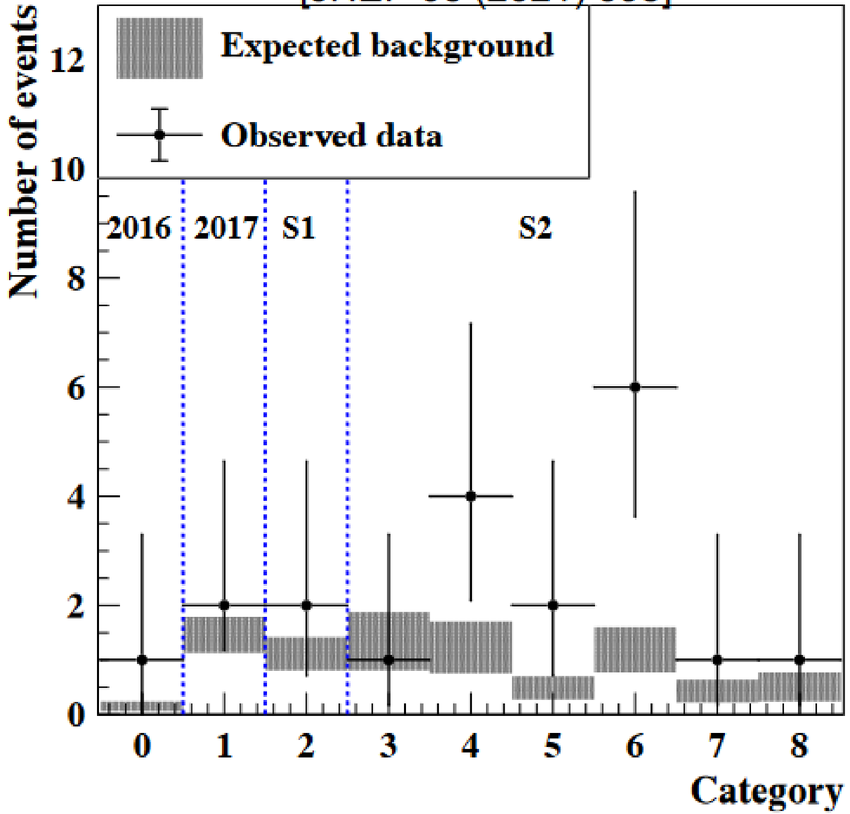


NA62: result

- Prospect: reach 15% accuracy with Run2 (currently ongoing until LHC LS3)



[JHEP 06 (2021) 093]



N_{obs} (Run1) = 20

$N^{exp}_{background} = 7.03^{+1.05}_{-0.82}$ $N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

$BR(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ at 68% CL

3.4σ significance

$K_L \rightarrow \pi^0 \nu\bar{\nu}$ the invisible needle…

- One of the best possible observables in Flavour physics, sometimes referred to as its «holy Grail».

- Pure CPV, measures directly the height of the UT.

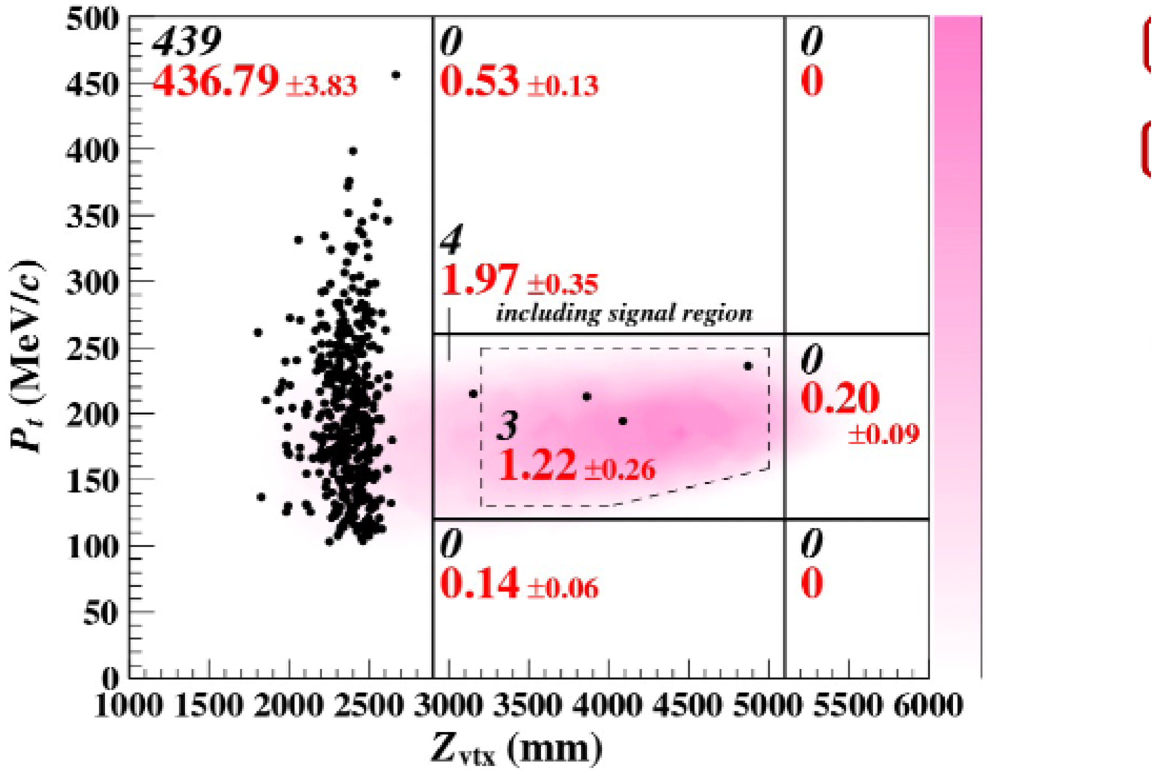
- Even more 3x more suppressed than the charged one.

- And definitely harder to measure…

KOTO at JPARC

- KOTO will collect 11 x more data
- Expect S.E.S. at level 10^{-11} by end 2026.
- Further upgrade…KOTO II

$BR(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ (90% CL)



Expected: 0.04 signal + 1.22 background events

Observed: 3 events in the signal box

PRL 126 (2021) 121801

Future Prospects (1)

HIKE: multi-purpose high-intensity kaon decay-in-flight experiments proposed at CERN SPS

High-intensity beams at CERN North Area after LS3 with x 4-6 current NA62 nominal
K^+ : 2.2 x 10^{13} decays per year K_L : 3.8 x 10^{13} decays per year

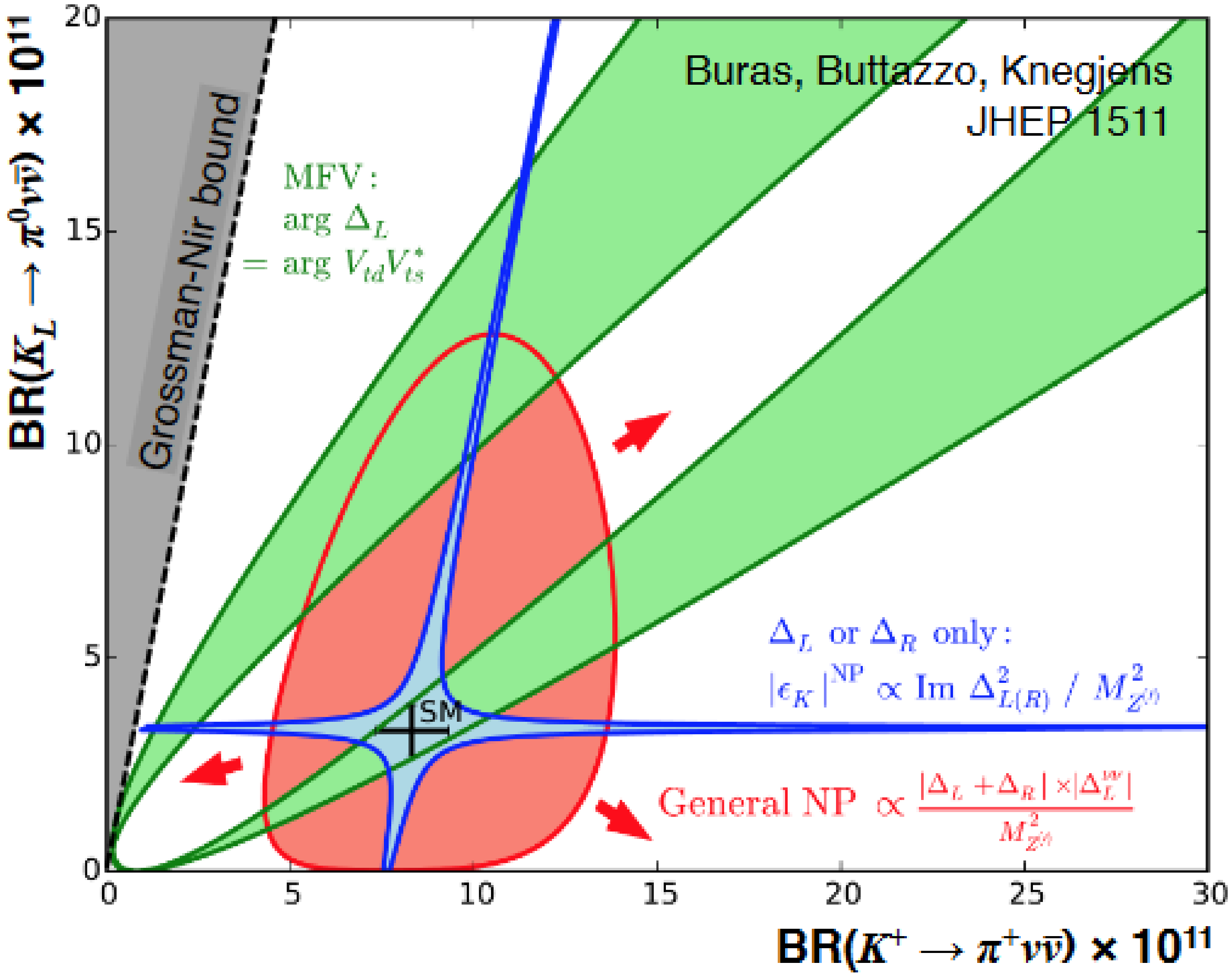
Phase 1 ($K^+ \to \pi^+ \nu\nu$ at ~5% precision), Phase 2 ($K_L \to \pi^0 l^+ l^-$ at ~20% precision)
Comprehensive program of rare kaon decays, precision measurements, searches

KOTO-II: high-beam-power experiment proposed at J-PARC Hadron Hall

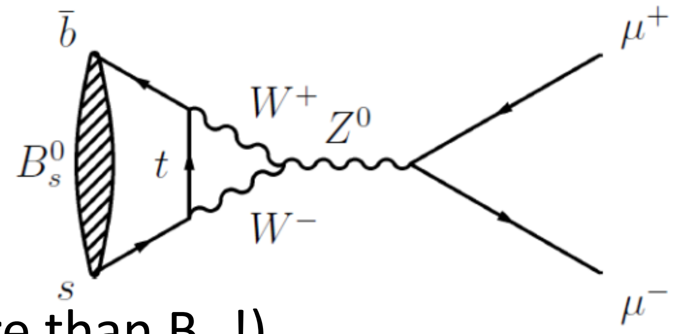
Increase proton beam power > 100 kW
New neutral beamline at 5 degrees: larger K_L yield, momentum = 5.2 GeV/c
Increase fiducial volume from 2x2m to 3x12m, new detectors

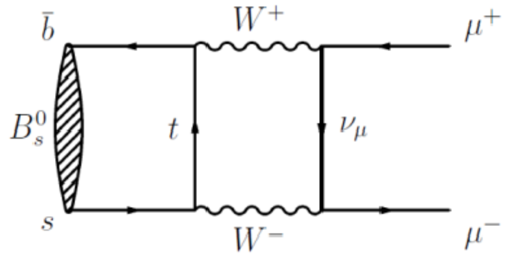
60 SM events of $K_L \to \pi^0 \nu\nu$ with S/B~1 in 3 years, ~20% precision
Search for exotic particles in $K_L \to \pi^0 X$

Future Prospects (2)

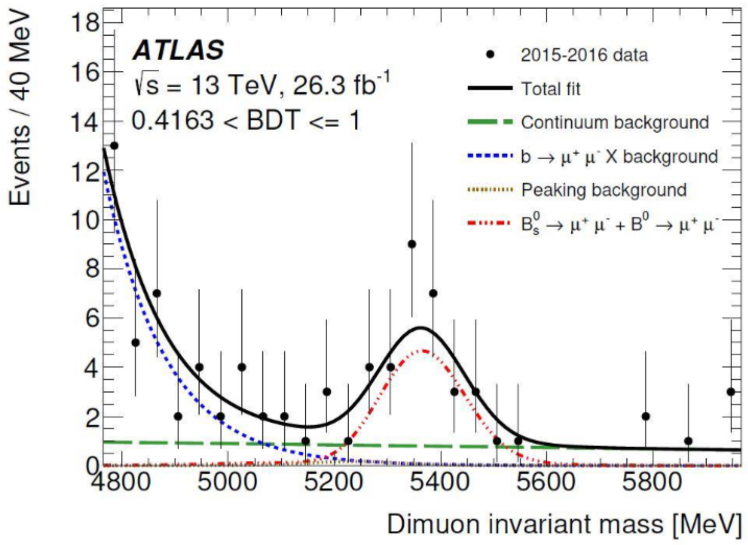


$B_s(B_d) \to \mu^+\mu^-$

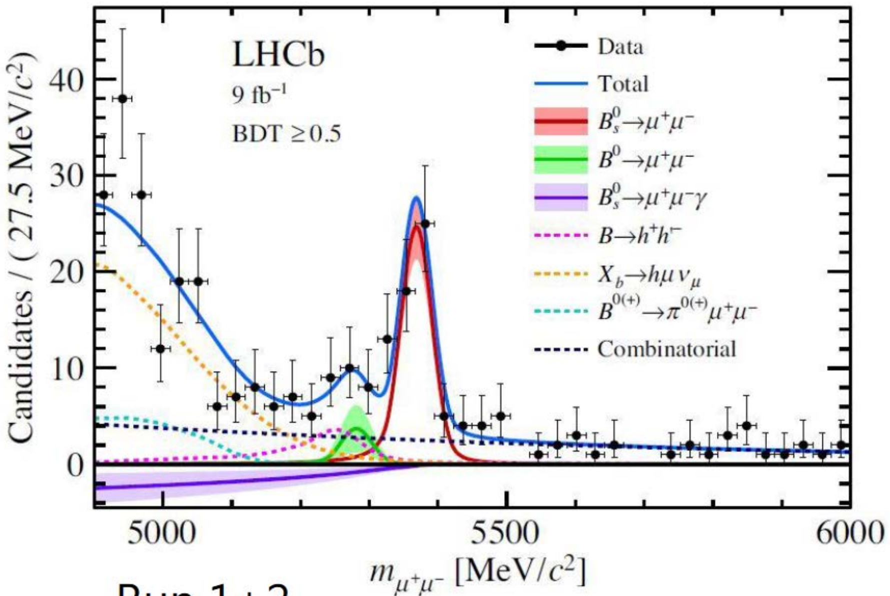




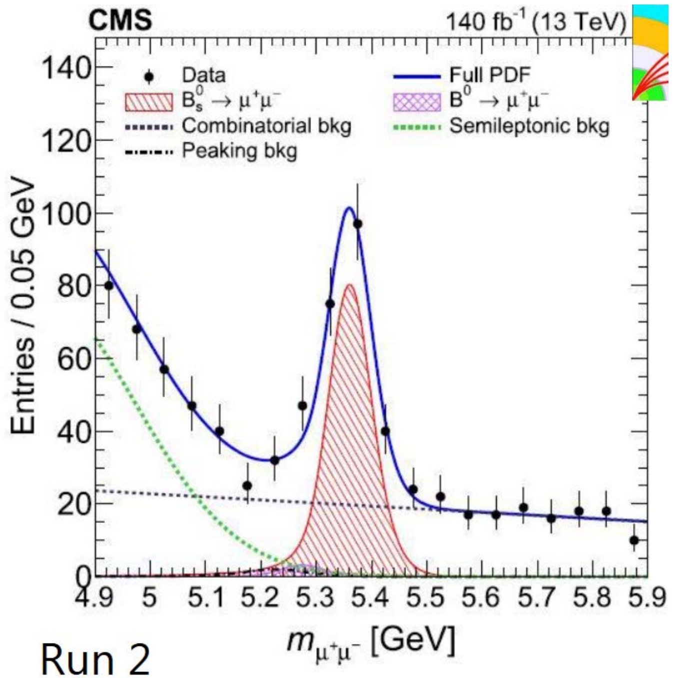
- FCNC, helicity and CKM suppressed (B_d more than B_s !)
- Thoretically clean (purely leptonic final state!); $O(10^{-9})$
- One of the golden channels to search for NP at LHCb…
- …turned out to be well measured by ATLAS and CMS too given the possibility to trigger on the muons in the final state !
- Still no sensitivity to B_d channel → $O(10^{-10})$



2015+16 data

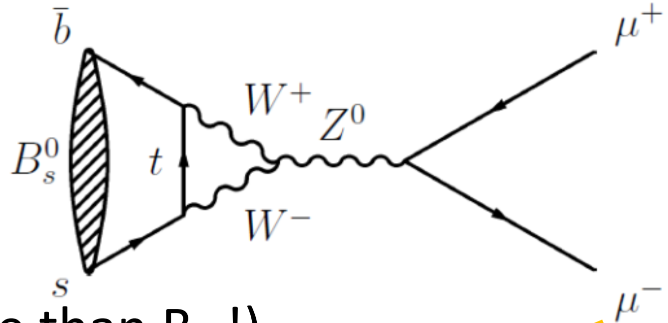


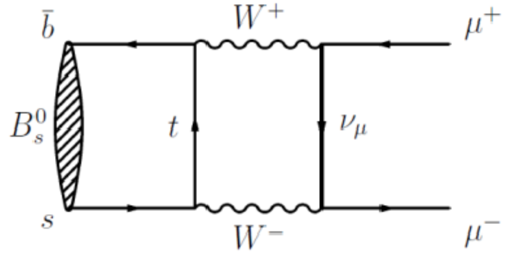
Run 1+2



Run 2

$B_s(B_d) \to \mu^+\mu^-$





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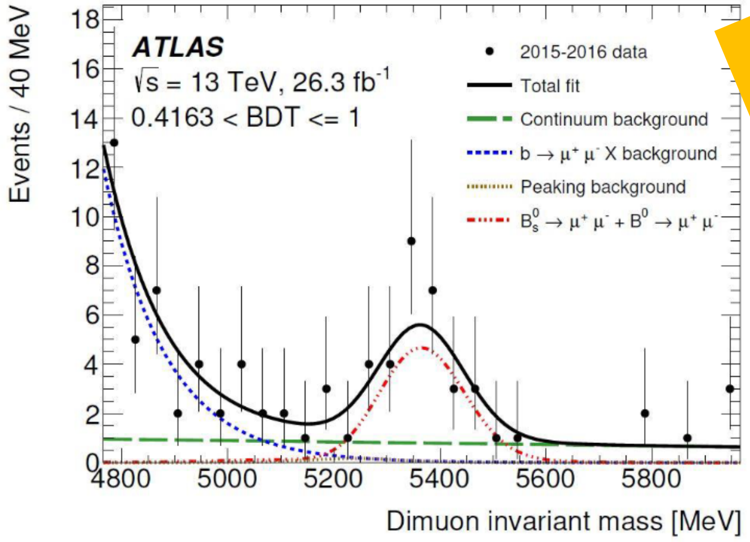
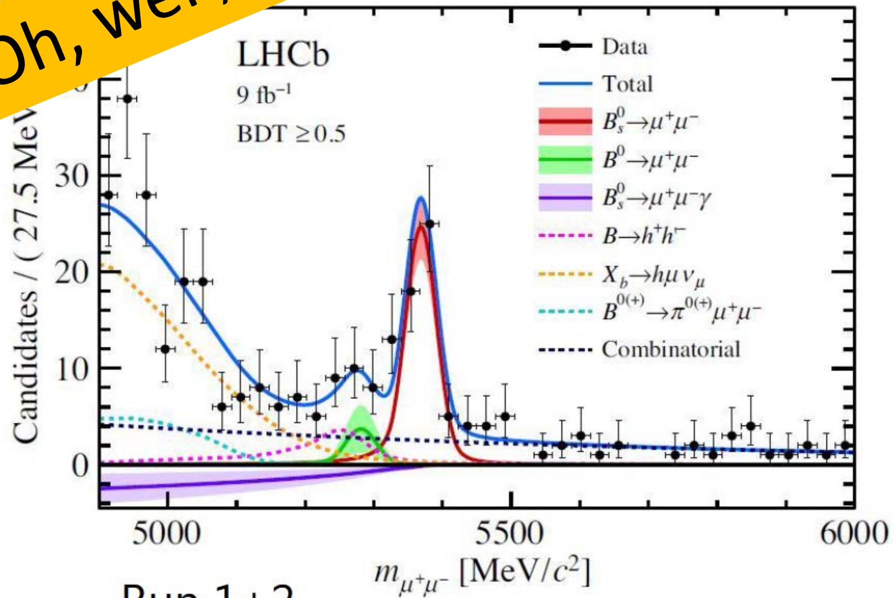
- Still no sensitivity to B_d channel → …

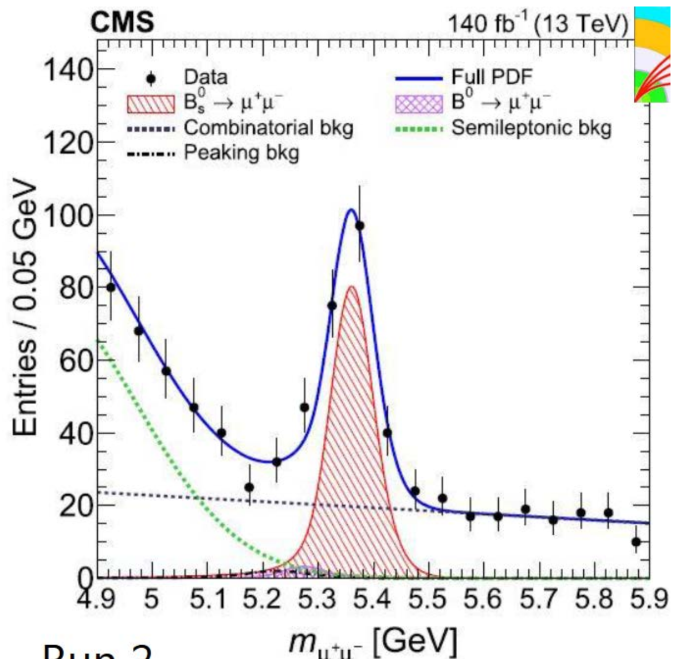
(Oh, well, finally, we see a bump !!)



2015+16 data

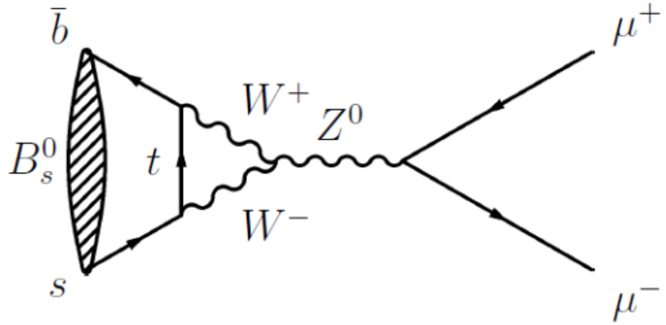


Run 1+2

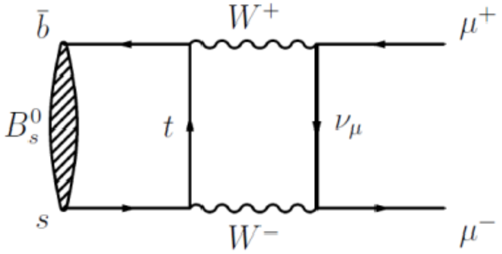


Run 2

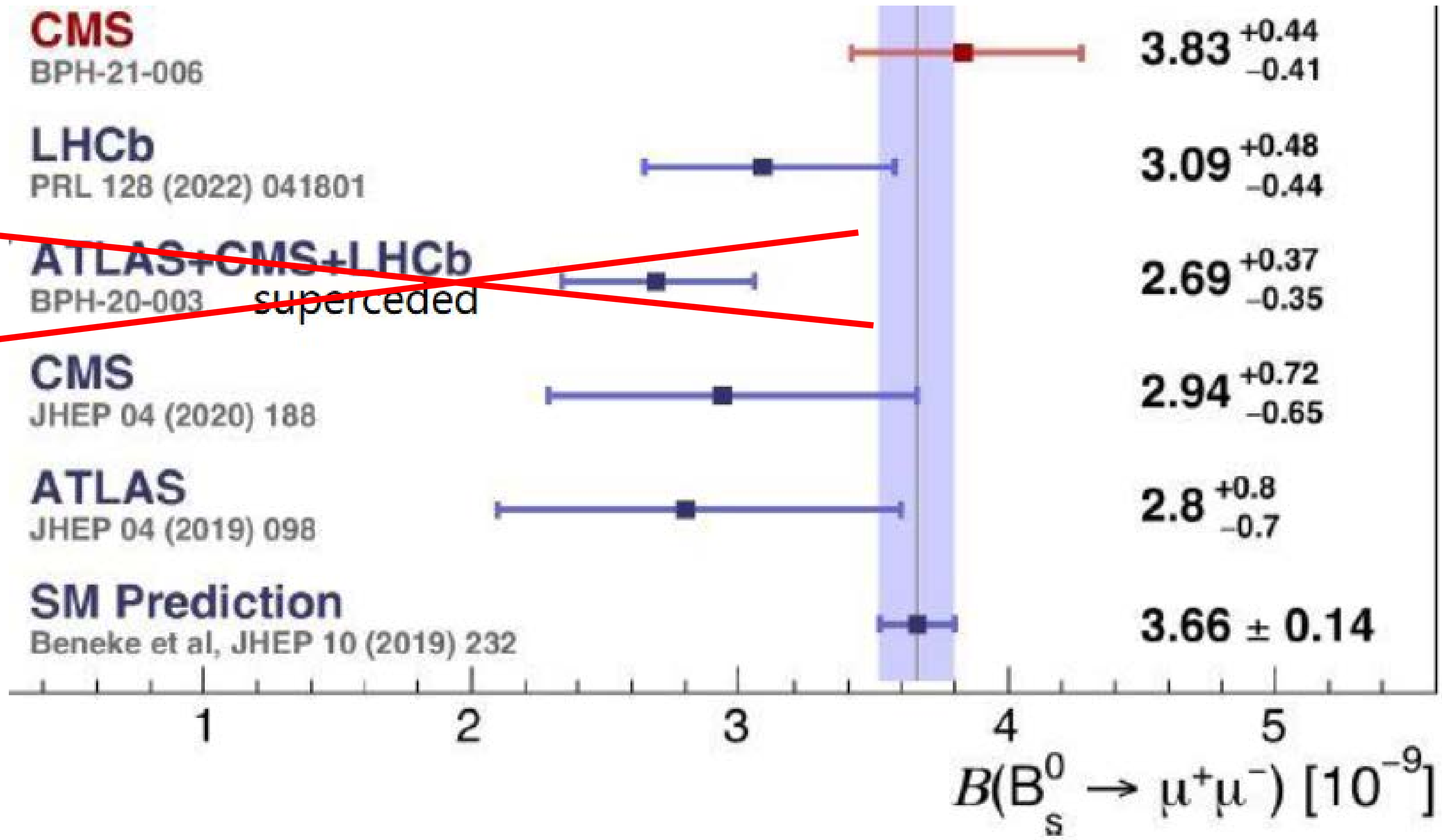
$$B_s(B_d) \to \mu^+\mu^-$$



$\bar{b}$
B_s^0
s
t
W^+
W^-
Z^0
μ^+
μ^-

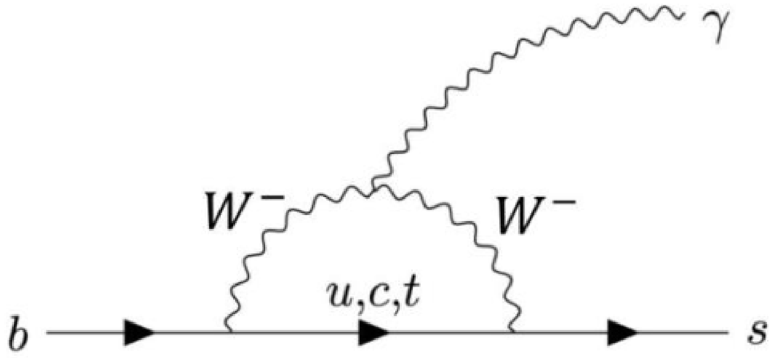


$\bar{b}$
B_s^0
s
t
W^+
W^-
ν_μ
μ^+
μ^-



CMS
BPH-21-006
3.83 +0.44 −0.41
LHCb
PRL 128 (2022) 041801
3.09 +0.48 −0.44
ATLAS+CMS+LHCb
BPH-20-003
superceded
2.69 +0.37 −0.35
CMS
JHEP 04 (2020) 188
2.94 +0.72 −0.65
ATLAS
JHEP 04 (2019) 098
2.8 +0.8 −0.7
SM Prediction
Beneke et al, JHEP 10 (2019) 232
3.66 ± 0.14
1
2
3
4
5
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ [10^{-9}]

$b \to s\gamma$

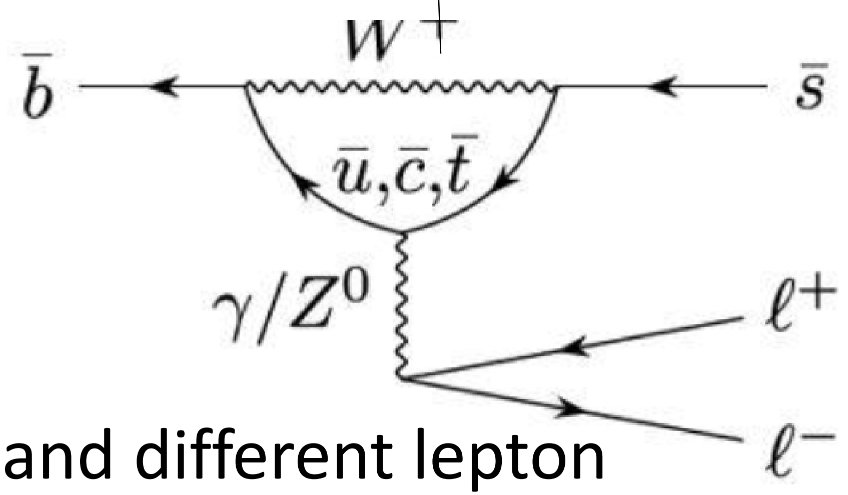


- Inclusive measurement, all final states with net strangeness.
- Clean SM prediction for BF = $(346 \pm 24) \times 10^{-6}$
- Several measurements performed by B factories up to about 10 years ago. Belle II is now re-entering the game (currently with limited statistics).

$\mathcal{B}(B \to X_s\gamma)$	Belle [550]	$347 \pm 15 \pm 40^{b}$	349 ± 19
	BABAR [1102]	$332 \pm 16 \pm 31^{b}$	
	Belle [1103]	$375 \pm 18 \pm 35^{b}$	
	BABAR [1104]	$352 \pm 20 \pm 51^{b}$	
	CLEO [551]	$329 \pm 44 \pm 29^{b}$	
	BABAR [1105]	$390 \pm 91 \pm 64^{b}$	

HFLAV fit: PHYS. REV. D 107, 052008 (2023)

$b \to s l \bar{l}$ and LFU (1)



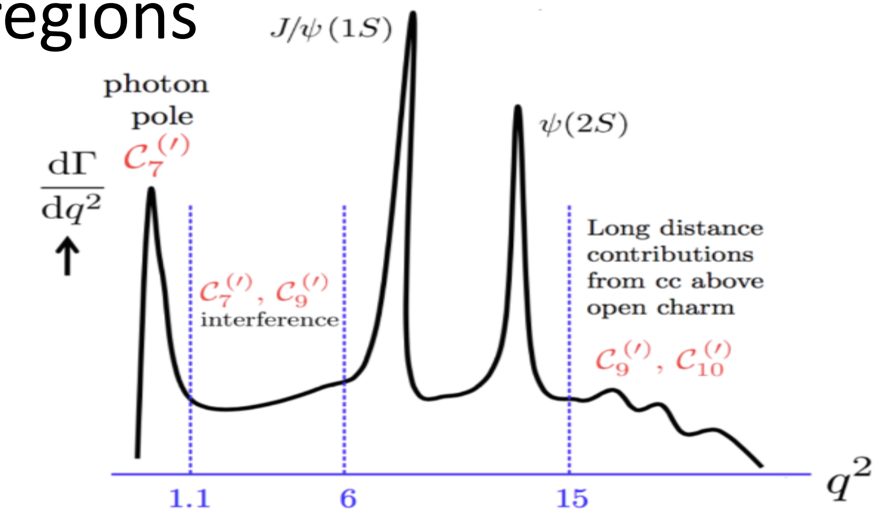
- Several final states with different strange mesons and different lepton pairs in the final state. Not all of them are «theoretically clean»

$$B \to K^{(*)}\mu^+\mu^-, B_s \to \phi\mu^+\mu^-, \Lambda_b \to \Lambda\mu^+\mu^-$$

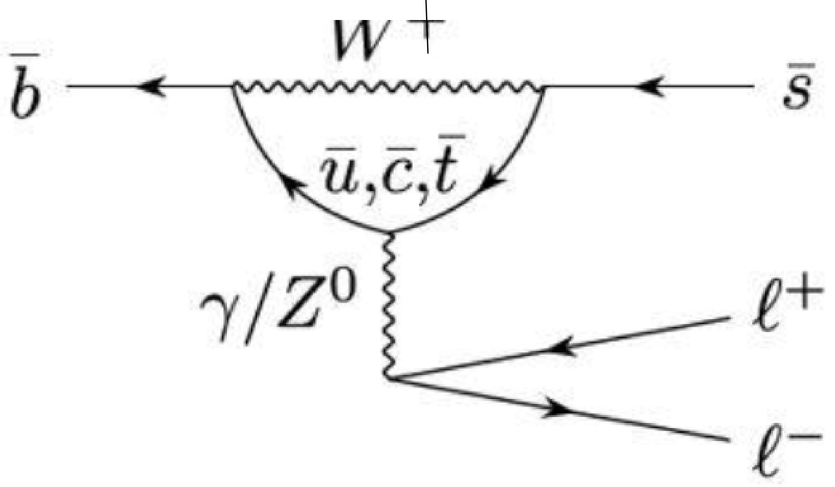
- Effective field theory provide model independent description, with different EFT operators dominant in different q^2 regions

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum C_i O_i$$

C_i - Wilson coefficients, O_i - operators



$b \to sl\bar{l}$ and LFU (2)

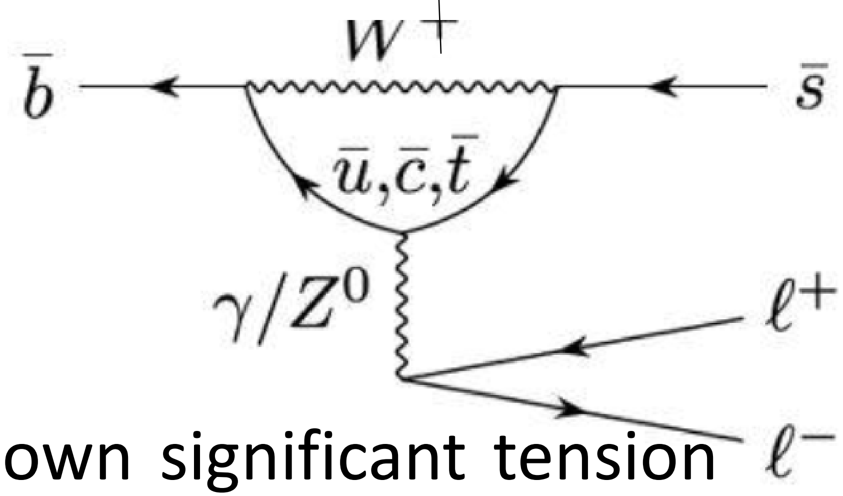


- A very clean observable, almost free of uncertainties coming from QCD effects is related to Lepton Flavor Universality:

$$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\cong} 1$$

SM predictions:
Bordone et al, EPJC76(2016)440
Isidori et al, JHEP12(2020)104
Isidori et al, JHEP10(2022)14

$b \to s l \bar{l}$ and LFU (2)



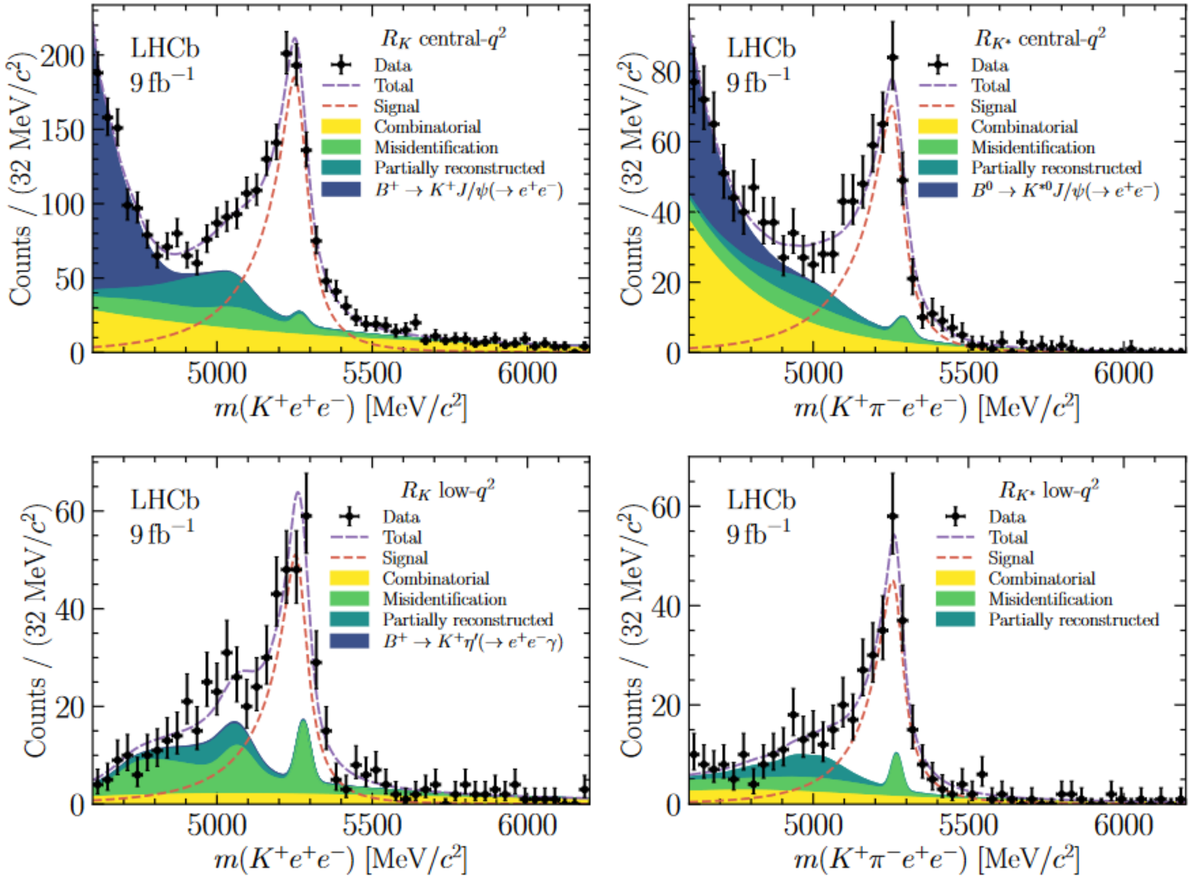
- Recent results on R_K and R_{K^*} from LHCb had shown significant tension (above 3 sigma) with the SM, and triggered a large interest on this process.
- However new measuremet presented this year, with a better control of **experimental systematic effects**, has reconciled the result with the SM.
- New, experimentally more solid observable: the «double ratio»:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+ \mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+ e^-))} = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\mathrm{rare}}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$

$b \to s l \bar{l}$ and LFU (3)

- Analysis done for both $B^+ \to K^+ l^+ l^-$ and $B^0 \to K^{*0} l^+ l^-$ and in separate q^2 regions of the dilepton.

- It supersedes the previous. Hints of NP are gone.



$$\text{low-}q^2 \begin{cases} R_K = 0.994\ ^{+0.090}_{-0.082}\ (\text{stat})\ ^{+0.029}_{-0.027}\ (\text{syst}), \\ R_{K^*} = 0.927\ ^{+0.093}_{-0.087}\ (\text{stat})\ ^{+0.036}_{-0.035}\ (\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949\ ^{+0.042}_{-0.041}\ (\text{stat})\ ^{+0.022}_{-0.022}\ (\text{syst}), \\ R_{K^*} = 1.027\ ^{+0.072}_{-0.068}\ (\text{stat})\ ^{+0.027}_{-0.026}\ (\text{syst}). \end{cases}$$

See: https://doi.org/10.1103/PhysRevLett.131.051803

LFU and NP

- LFU can be checked in tree level leptonic or semileptonic decays with a charged vertex.
- NP may manifest itself in precise measurements because of the different flavour structure and hence different coupling with one of the families (the third family is the usual suspect here…) wrt others.
- Ratios of BF help reducing both theoretical and systematic uncertainties.

LFU: Ke2/Kmu2 at NA62

- As an example take $R = \Gamma(K^+ \to e^+\nu_e)/\Gamma(K^+ \to \mu^+\nu_\mu)$, whose SM prediction is as accurate as 0.04% (!!!!!!!)

[M. Finkemeier, Phys. Lett. B 387 (1996)]

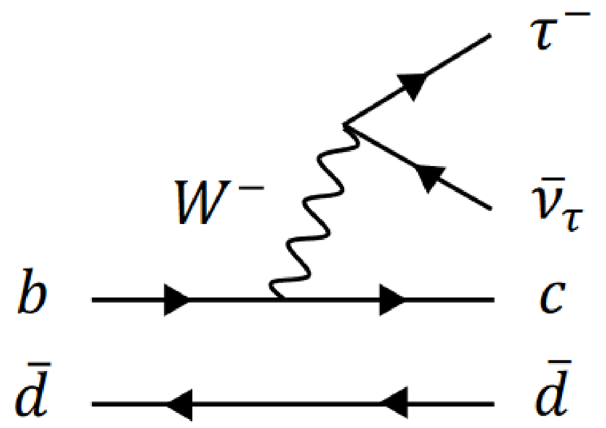
[V. Cirigliano and I Rosell, JHEP 0710:005 (2007)]

$$R = \frac{\Gamma(K^\pm \to e^\pm \nu_e)}{\Gamma(K^\pm \to \mu^\pm \nu_\mu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_{QED}) = (2.477 \pm 0.001) \cdot 10^{-5}$$

- NA62 collaboration did a dedicated run in 2007-2008 to measure this quantity. The final result $(2.488 \pm 0.010) \cdot 10^{-5}$, published in PLB 719 (2013) 326 was found to be fully compatible with the SM with a 0.4% accuracy.

- If the third generation is somewhat «special» tests involving heavier mesons which can decay in a τ lepton in the final state may be more sensitive to NP.

LFU: R(D) and R(D*)

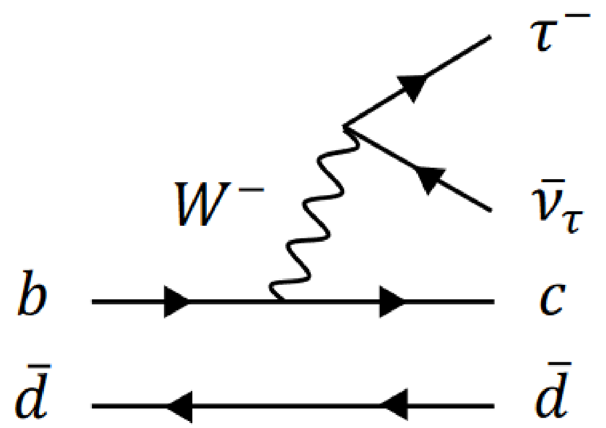


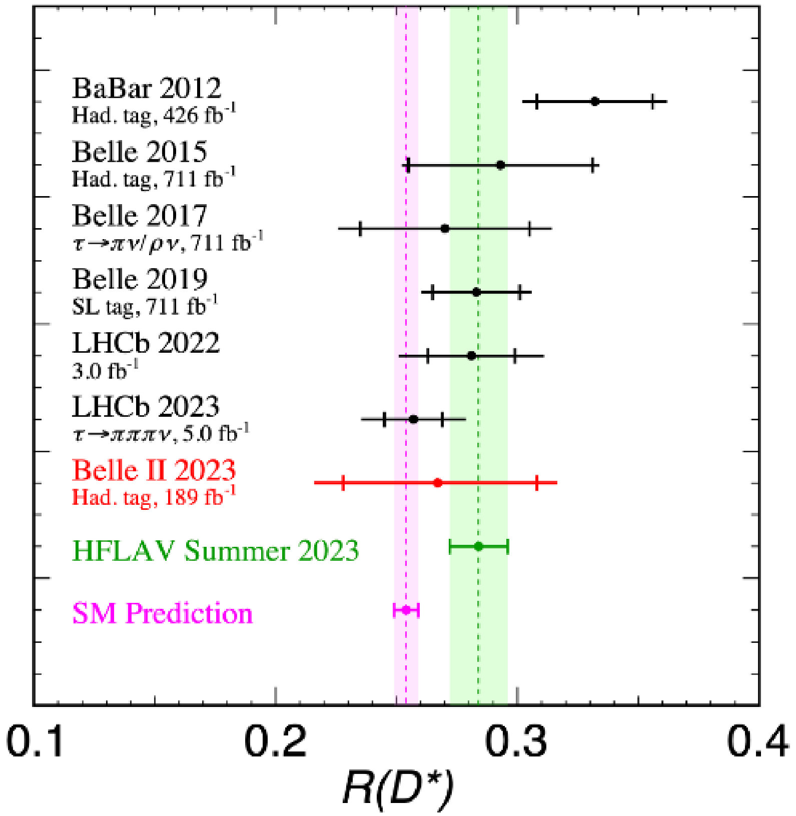
- Usual trick, define observables as ratios of BF:

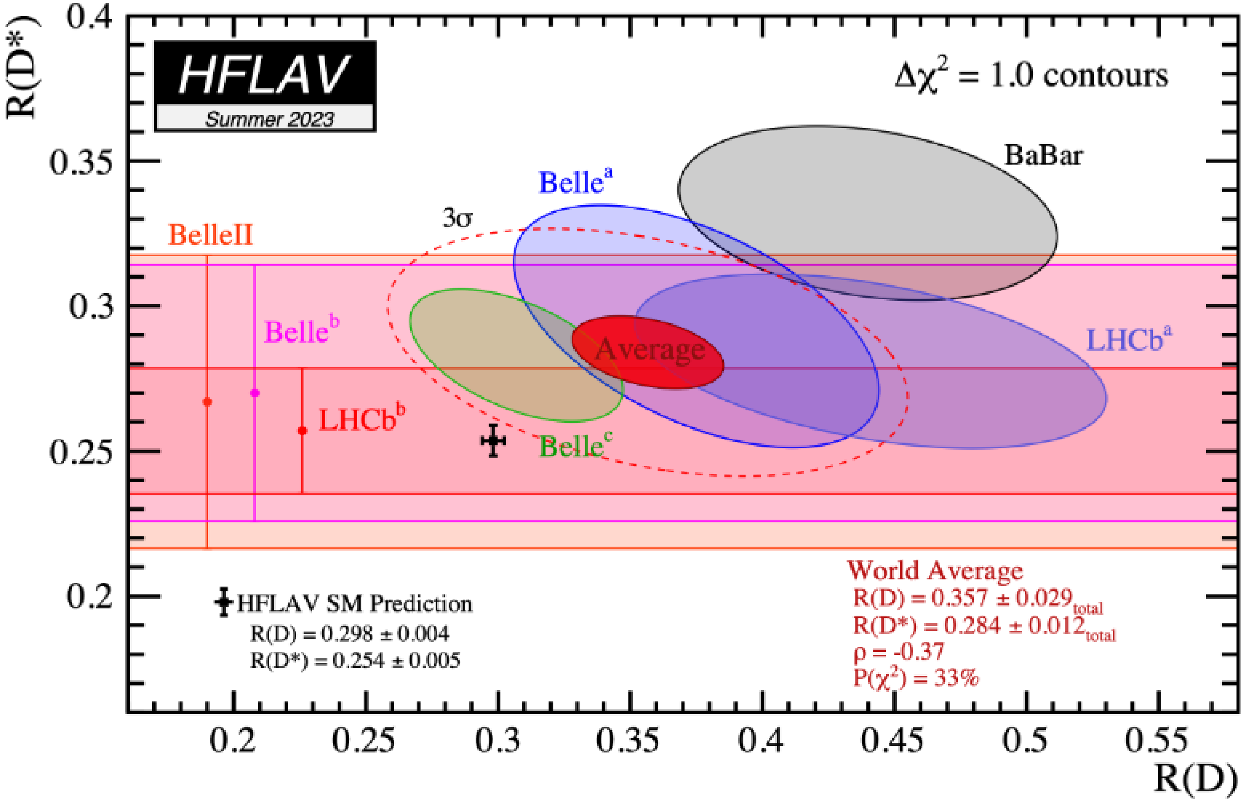
$$R_{D^*} = \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*l\nu)} \qquad R_D = \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to Dl\nu)}$$

- Several measurements from BaBar, Belle, Belle II, LHCb. HFLAG has updated their fit as of summer 2023, after new results on R(D*) presented at Lepton Photon 2023 in July.

LFU: R(D) and R(D*)





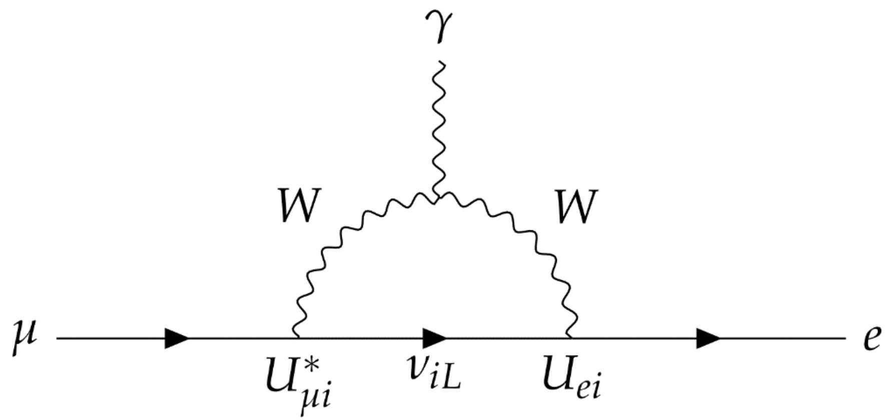


3.3 sigma tension if one combines the two obervables.

Lepton Flavour violation

- Lepton Flavour conservation, (and Lepton Universality) is strictly true for massless neutrinos.
- Neutrino oscillations obviously do not conserve lepton flavor, moreover their coupling are non universal (PMNS matrix).
- Charged Lepton Flavour Violation effects mediated by neutrino oscillations are however extremely small in the SM, so that any observation of this kind of process is unambiguous sign of NP.

CLFV: $\mu \to e\gamma$

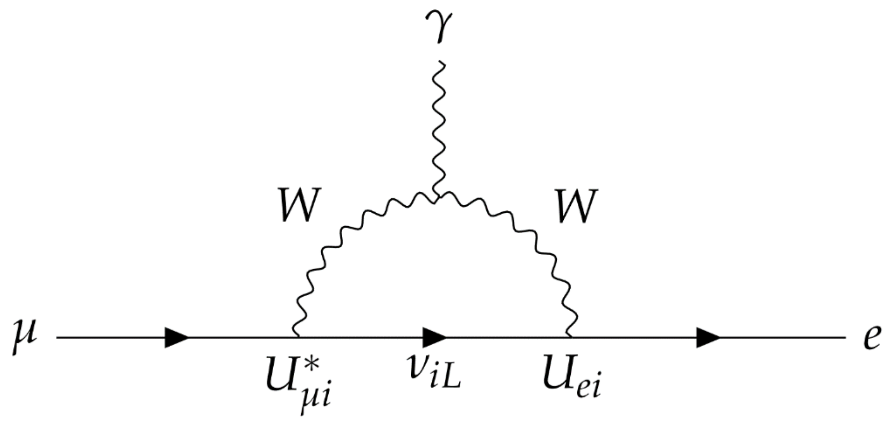


- BF: SM prediction $O(10^{-54})$

- Cannot be tested at «general purpose» facilities: need dedicated experiment to collect high statistics and to control background.

- MEG and MEG II experiments at PSI.

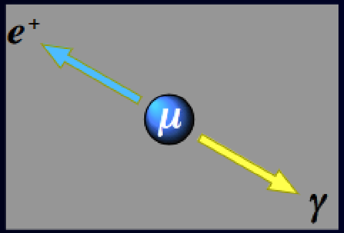
CLFV: $\mu \to e\gamma$



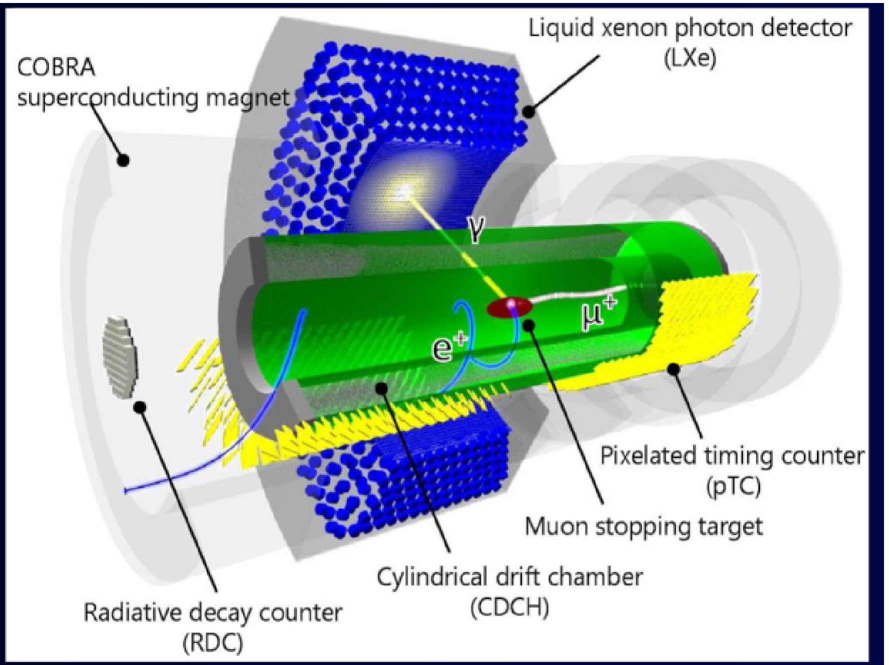
- Y. Kuno @ Lepton Photon 2023

MEG-II

- Event Signature (μ^+ decay at rest)
  - mono energetic, $m_e = m_\gamma = m_\mu/2$ (=52.8 MeV)
  - angle $\theta_{e\gamma}$=180 degrees
  - time coincidence $\Delta t_{e\gamma}$



- Backgrounds
  - physics background, $\mu^+ \to e^+\nu\bar{\nu}\gamma$
  - accidental background
    - e^+ in $\mu^+ \to e^+\nu\bar{\nu}$ and γ in $\mu^+ \to e^+\nu\bar{\nu}\gamma$
- MEG experiment at PSI
  - $B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13} \quad (90\,\%\,\mathrm{C.L.})$
- MEG II experiment at PSI
  - x10 times improvement



MEG II $:B(\mu^+ \to e^+\gamma) < 6 \times 10^{-14}$
- x2 muon beam intensity
- x2 all detector resolution
- x2 efficiency

CLFV: Mu3e, Mu2e, COMET

- Experiments in preparation at PSI (Mu3e) , FNAL (Mu2e), J-PARC (COMET). First results expected (not much) after 2025.

- Mu3e searches for $\mu^+ \rightarrow e^+e^+e^-$ decay with the aim of improving by more than 3 orders of magnitude the limit from SINDRUM experiment (BF < 10^{-12}).

- Mu2e and COMET search for a muon to electron conversion inside a muonic atom. $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$. Plan to reach sensitivities at level 10^{-16} on the conversion rate

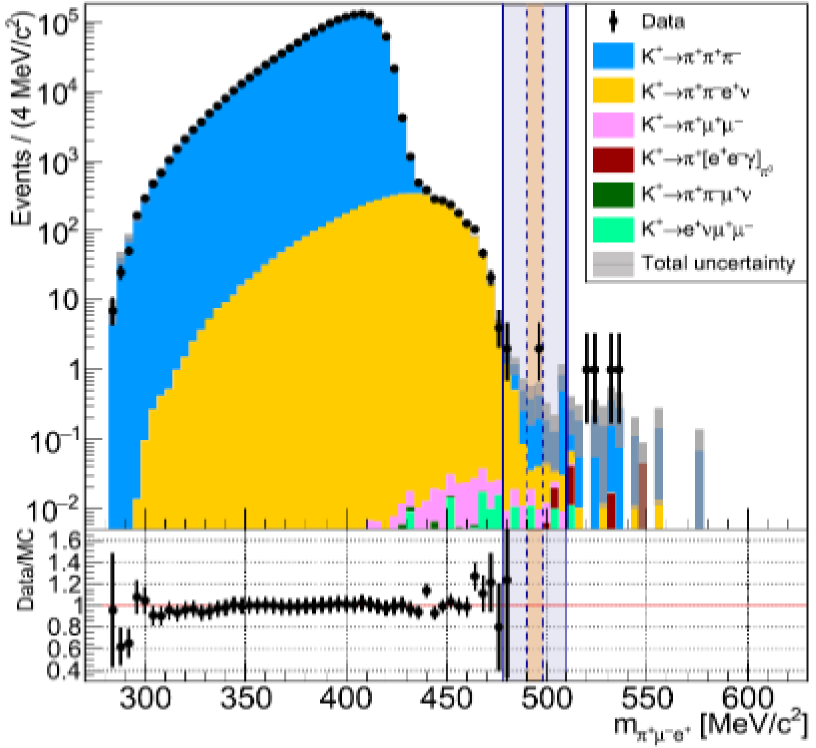
$$CR(\mu^-N \rightarrow e^-N) \equiv \Gamma(\mu^-N \rightarrow e^-N)/\Gamma(\mu^-N \rightarrow \text{all})$$

LFV in meson decays

- LFV can be searched also in meson decays.
- Two such processes are $K^+ \to \mu^+\pi^-e^+$ and $\pi^0 \to \mu^-e^+$
- These have been recently investigated at NA62 in PHYS. REV. LETT. 127,131802(2021)

- The same paper also searched for a Lepton Number Violating process, namely $K^+ \to \pi^-\mu^+e^+$ reaching comparable sensitivity.

LFV $K^+ \to \pi^+\mu^-e^+ (\pi^0 \to \mu^-e^+)$



Exp. bkg in SR: 0.92 ± 0.34(0.23 ± 0.15)
Observed events in SR: 2 (0)

$BR(K^+ \to \pi^+\mu^-e^+)$< 6.6 × 10^{-11} at 90%CL
$BR(\pi^0 \to \mu^-e^+)$< 3.2 × 10^{-10} at 90%CL

Conclusions

- A vast experimental program in Flavour Physics allows both to deetermine precisely some of the fundamental parameters of the SM and to test indirectly scales which are not directly acessible to current (and next gen…) accelerators.
- Interpretation of results needs careful and constant interplay with theory calculations, since often, especially in NP searches, what is looked for is a «small» correction to a «known» number. And «small» or «Nobel prize size» depends on the uncertainty you put on it…
- The program si fed by experimental inputs from large collider experiment, but profits also of smaller, specialized and dedicated experiments which allow to explore regions of parameters oterwis unaccesible.

Thank you