PSI Summer School

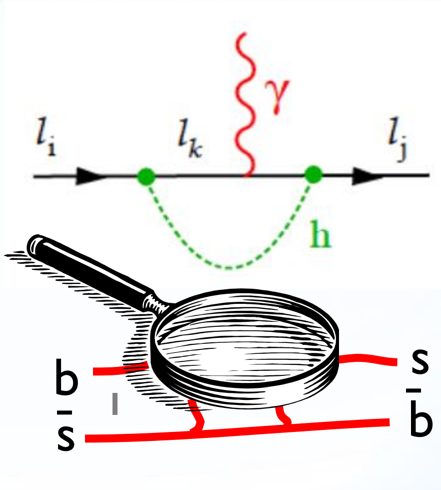
Particle Flavour Fever

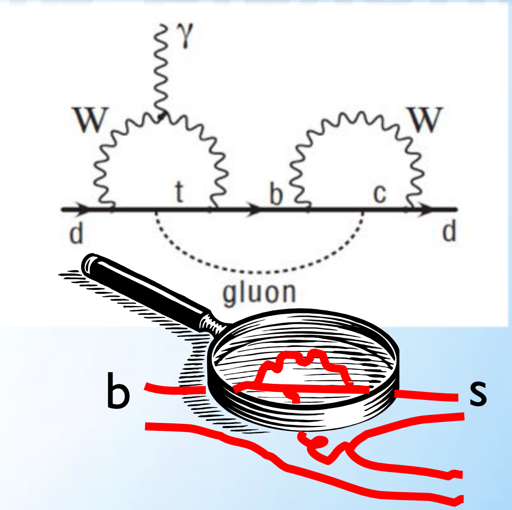
Lyceum Alpinum, Zuoz, August 12–18, 2018

* # Future Opportunities in Flavour Physics.

Frederic Teubert

CERN, EP Department





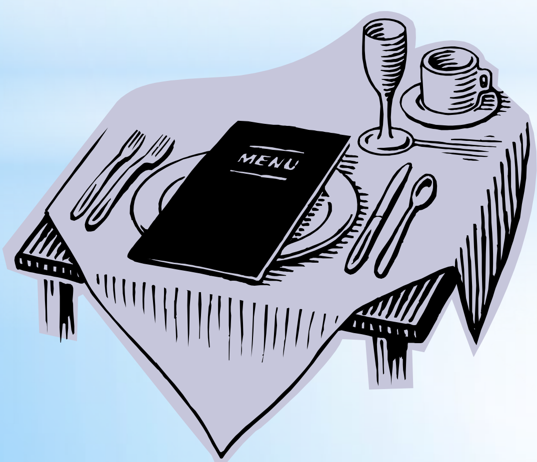
Plan of this lecture:

1. Introduction
2. History as a guide to the future
3. Flavour in the SM and beyond: what are the questions?
4. Future experimental facilities: opportunities and challenges:

   4.1 In the lepton sector

   4.2 In the quark sector

   4.3 Nucleon EDMs
5. Take home messages.



Lecturers

- Dmitry Budker (Mainz): Exotics searches in atoms and molecules
- Augusto Ceccucci (CERN): Exotics searches at low energy
- Sacha Davidson (Lyon): Exotics and flavour
- Tobias Golling (Geneva): Exotics searches in ATLAS and CMS
- Francis Halzen (Wisconsin): IceCube: Building a new window on the Universe from Antarctica
- Matthias Neubert (Mainz): Flavour physics in the Standard Model and beyond
- Patrick Owen (Zurich): Status of B anomalies
- David Straub (TU Munich): Interpreting B anomalies
- Frederic Teubert (CERN): Future opportunities in flavour physics

Loops approach

If the **precision** of the measurements is high enough, we can discover NP due to the effect of "virtual" new particles in loops.

But not all loops are equal… In **"non-broken" gauge theories** like QED or QCD the "decoupling theorem" (Phys. Rev. D11 (1975) 2856) makes sure that the contributions of **heavy ($M>q^2$) new particles are not relevant**. For instance, you don't need to know about the top quark or the Higgs mass to compute the value of $\alpha(M_Z^2)$.

However, in broken gauge theories, like in the SM weak interactions, radiative corrections are usually proportional to Δm^2, i.e. the size of the isospin symmetry breaking. Flavour in the SM is due to the Higgs Yukawa interactions which are not protected at all by any gauge symmetry!

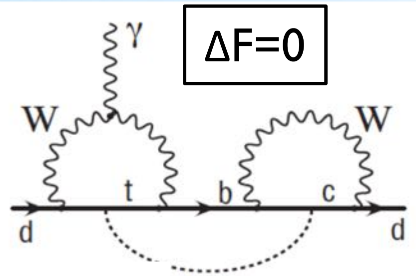
In general, larger effects of NP expected in loops where symmetry is more badly broken (3rd family in the SM) and/or in flavour physics where there is no symmetry at all.

Quantum interference: access to the couplings phase.

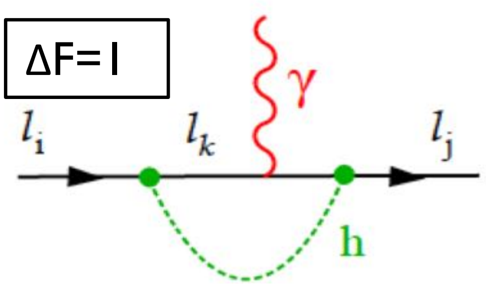
Moreover, through the study of **the interference of different quantum paths** one can access not only to the magnitude of the couplings of NP, but also to their phase (for instance, by measuring CP asymmetries). Within the SM, **only weak interactions through the Yukawa mechanism** can produce a non-zero CP asymmetry. It is indeed a big mystery why there is no CP violation observed in strong interactions (axions?)→ extra motivation for nucleon EDMs.

Therefore, precision measurements of FCNC can reveal NP that may be **well above the TeV scale**, or can provide key information on the **couplings and phases** of these new particles if they are visible at the TeV scale.

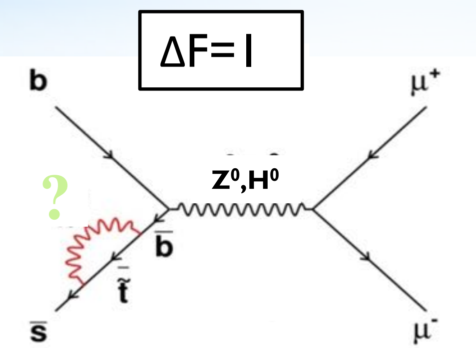
Direct and indirect searches *are both needed and equally important, complementing each other.*



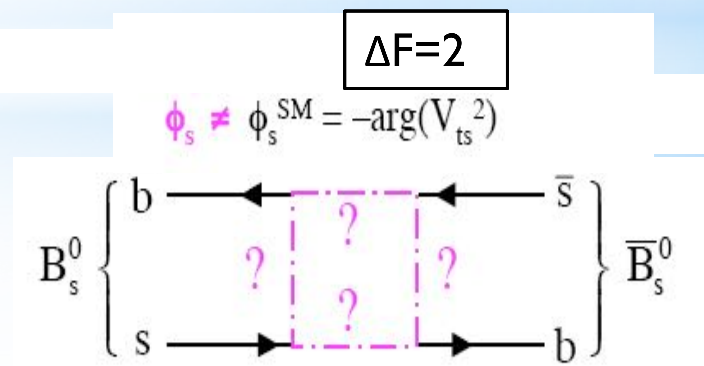
Nucleon EDMs



$l_i \to l_j \gamma$ LFV radiative decay



$B_s \to \mu^+\mu^-$ Higgs "Penguin"



B_s–$\bar{B}_s$ oscillations: "Box" diagram

Status of searches for NP

So far, no significant signs for NP from direct searches at the LHC while a (the SM?) Higgs boson has been found with a mass of ~125 GeV/c^2.

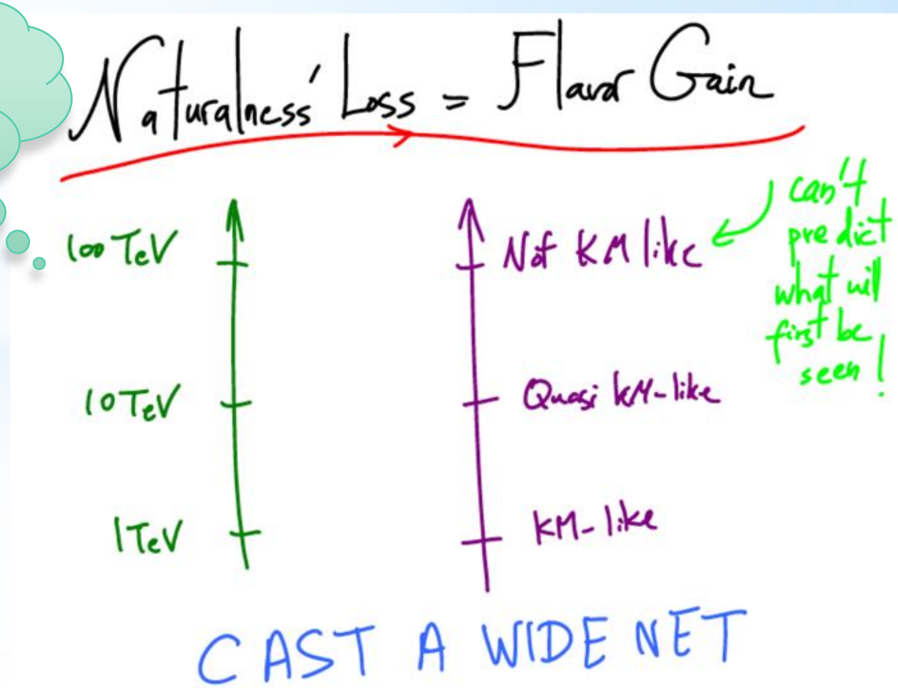
Before LHC/LEP, expectations were that *"naturally"* the masses of the new particles would have to be light in order to reduce the *"fine tuning"* of the radiative corrections to the Higgs mass. Theory departments were full of advocates of supersymmetric particles appearing at the TeV energy scale.

However, the absence of NP effects already observed in flavour physics implies some level of *"fine tuning"* in the flavour sector. Why, if there is NP at the TeV energy scale, it does not show up in precision measurements?

NP FLAVOUR PROBLEM → Minimal Flavour Violation (MFV).

N.Arkani-Hamed, Intensity Frontier Workshop (Nov 2011, Washington)

As we push the energy scale of NP higher, the NP FLAVOUR PROBLEM is reduced, hypothesis like MFV look less likely → **chances to see NP in flavour physics have increased** when Naturalness (in the Higgs sector) seems to be less plausible!



Brief historical interlude: examples of flavour physics experiments that defined the SM.

CP symmetry

K^0 can mix as strangeness is not conserved. In the language of the 60s:

$$K^0 \rightleftarrows \begin{matrix} \pi^0\pi^0 \\ \pi^+\pi^- \end{matrix} \rightleftarrows \bar{K}^0$$

If CP is conserved, then one can define two states $K_{1,2}$ that are eigenstates of both the weak interactions and the CP operator:

$$|K_1\rangle = \frac{1}{\sqrt{2}} \cdot \{ |K^0\rangle + |\bar{K}^0\rangle \} \quad \Rightarrow \quad CP\,|K_1\rangle = +\,|K_1\rangle$$

$$|K_2\rangle = \frac{1}{\sqrt{2}} \cdot \{ |K^0\rangle - |\bar{K}^0\rangle \} \quad \Rightarrow \quad CP\,|K_2\rangle = -\,|K_2\rangle$$

Gell-Mann, Pais *(PR 97 (1955) 1387))*

K_1 can decay into two pions while K_2 cannot if CP is conserved. All other possible decays channels for K_2 are suppressed by parity conservation (semi-leptonic) or by phase space. → **K_2 is expected to have a much longer lifetime than K_1 (x500).**

K mixing and CP violation

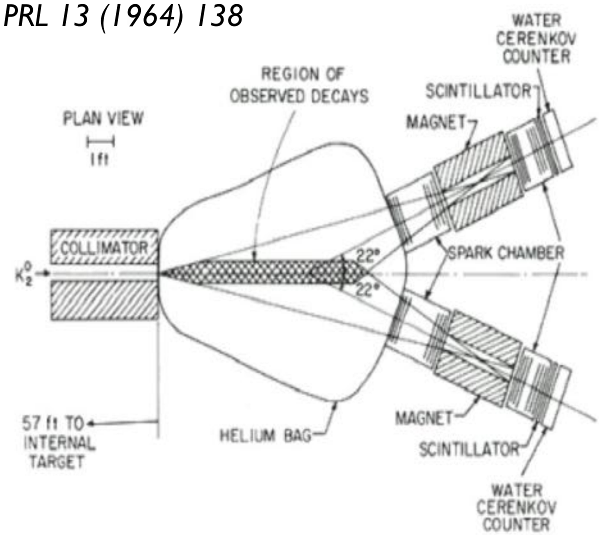
Christenson, Cronin, Fitch, Turlay (PRL, 13, 138, 1964): **Observation of $K_2 \rightarrow \pi^+\pi^-$.** The experiment shoot protons on a target to produce K^0, after a long enough trip in a vacuum pipe, they achieved a pure K_2 beam.

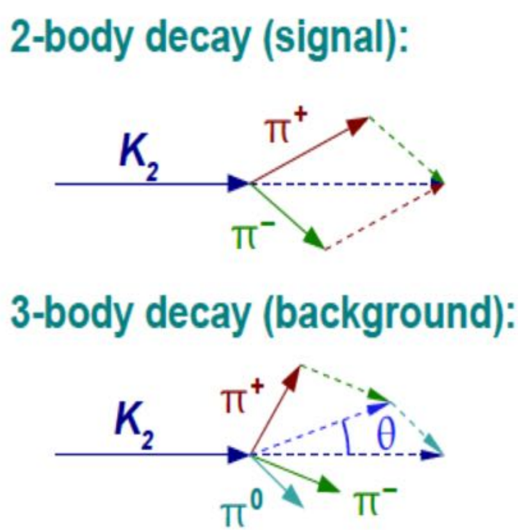
Experimentally use invariant mass (energy conservation) and angle between K_2 and $\pi^+\pi^-$ (momentum conservation). Find excess of ~56 events in the signal region: **$BF(K_2 \rightarrow \pi^+\pi^-) \sim 2\times10^{-3}$ → CP violation!**

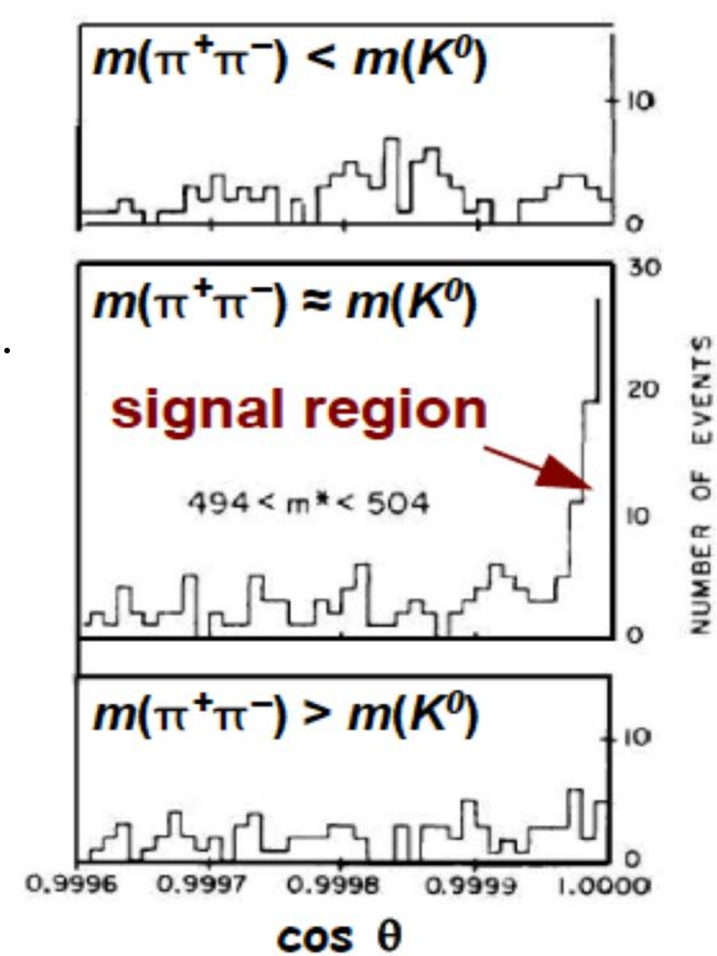
This was beyond what theory could explain then before the discovery of charm and beauty → Superweak models.

Absence of nEDM in the 50s excluded most of these models.

PRL 13 (1964) 138







Cabibbo and GIM mechanism

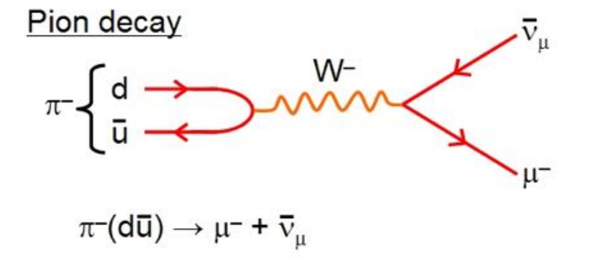
Moreover, the **weak coupling did not look to be universal**: why BR(K→μν) << BR(π→μν) after dealing with phase space?

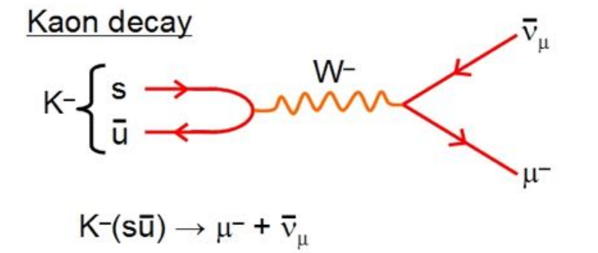
Cabibbo (1963): **weak interactions couples to a linear combination of the mass eigenstates,** using todays language:

$$d' = \cos\theta_c \cdot d + \sin\theta_c \cdot s$$

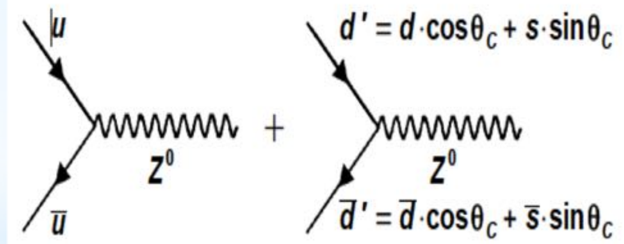
(PRL 10 (1963) 531)

$$\frac{s \to u\,W^-}{d \to u\,W^-} = \frac{\sin^2\theta_c}{\cos^2\theta_c} \approx \frac{1}{20}$$





But, if the neutral weak currents also couples to d' **expect large FCNC**. Experimentally, however, BR(K_2→μμ) ~7x10^{-9}.



Glashow, Ilioupoulos and Maiani (1970). *(PRD 2 (1970) 1285)*
Assume a **new (not yet observed quark)** in SU(2) quark doublets→ **FCNC cancel at tree level!**

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \text{ with } \begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \cdot \begin{pmatrix} d \\ s \end{pmatrix}$$

From the Δm_K measurements, $\mathbf{m_c}$ was predicted to be **~1.5 GeV!** Gaillard and Lee (1974)

(PRD 10 (1974) 894)

CKM mechanism

Kobayashi, Maskawa (1972): If we have 3 quark generations, CP violation is possible!

(FTP 49 (1973) 652)

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix} \quad \text{with} \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Even before finding charm (as needed for GIM to work), theorists were already requiring another quark family to be able to accommodate CP violation! Although this option was competing with Superweak models!

CKM mechanism (SM) was found by looking for:

1. **Rare processes protected by some symmetry of the current theory, but not necessarily conserved in the next version of the theory (e.g. CP).**
2. **Processes that should not be rare in the current theory, but that a new mechanism of the next version of the theory protects them (eg. FCNC).**

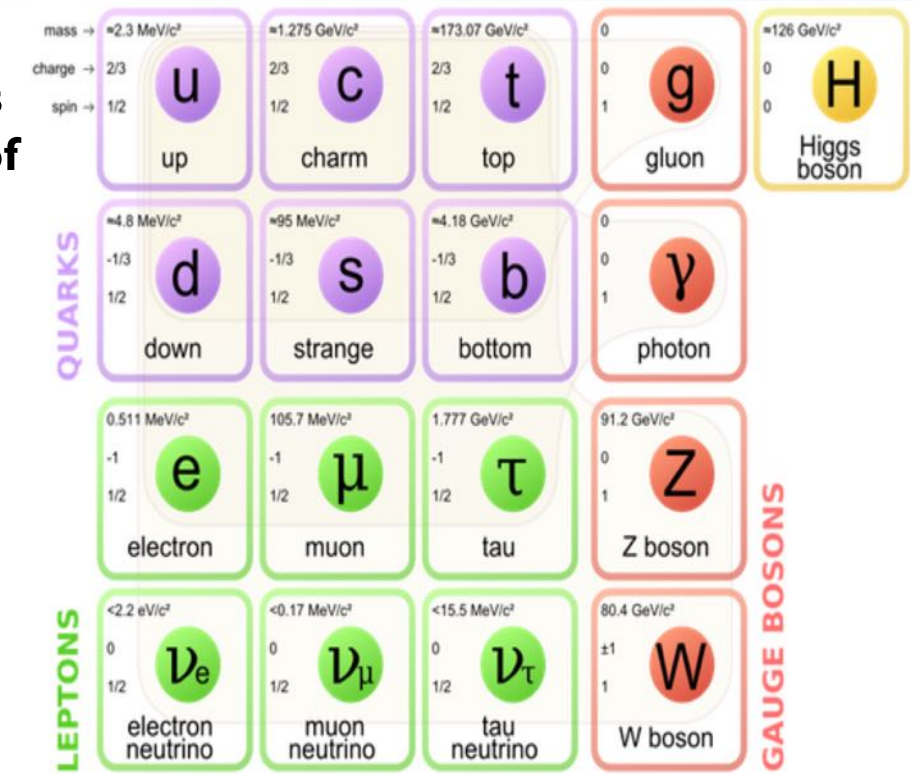
Flavour in the SM and beyond.

Flavour in the SM

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, A_a, \psi_i)$$

The **gauge component** is the **"elegant" part**. There is **no distinction between different generations** and has a **huge degree of symmetry.** We only need to know **α, θ_W, M_W** and **α_s** and everything is determined by the local gauge symmetry group: **$SU(3)_C \times SU(2)_L \times U(1)_Y$.**

The **Higgs component**, however, **breaks the flavour symmetry**. It is the **origin of the flavour structure** of the model. It is also the component that is **not stable to quantum corrections**. To describe this part we need a total of **14 parameters!**



The Standard Model of elementary particles

SM flavour problem

The origin of masses and mixings, together with the origin of family replications is probably the most pressing problem of the SM.

Flavour in the SM: Yukawa Mechanism in the quark sector.

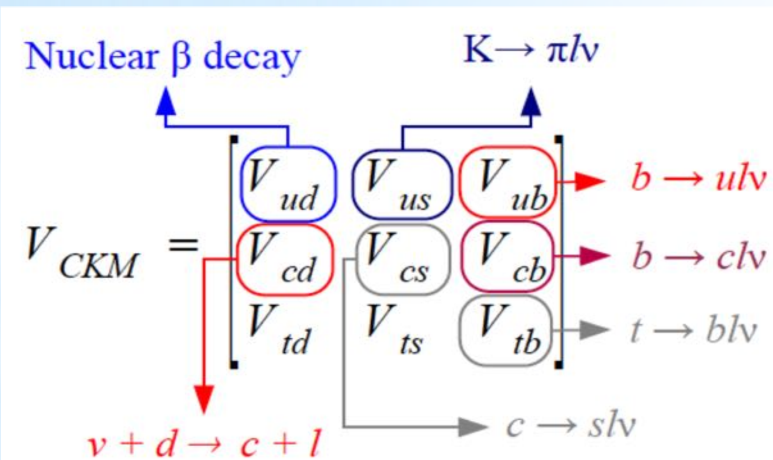
$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i\phi D_R^j + Y_u^{ij}\bar{Q}_L^i\tilde{\phi}U_R^j + Y_e^{ij}\bar{L}_L^i\phi E_R^j + \text{h.c.}$$

$$\lambda_d = \text{diag}(y_d, y_s, y_b)\ , \qquad \lambda_u = \text{diag}(y_u, y_c, y_t)\ , \qquad y_q = \frac{m_q}{v}\ .$$

$$Y_d = \lambda_d\ , \qquad Y_u = V^\dagger \lambda_u\ ,$$

The quark flavour structure within the SM is described by 6 couplings and 4 CKM parameters. In practice, it is convenient to move the CKM matrix from the Yukawa sector to the weak current sector. But don't be confused, in the SM quarks are allowed to change flavour as a consequence of the Higgs mechanism.

Using **Wolfenstein** parameterization (A, λ,ρ,η):



CKM

$$V = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2-\lambda^4/8(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2+A\lambda^4/2(1-2(\rho+i\eta)) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^5)$$

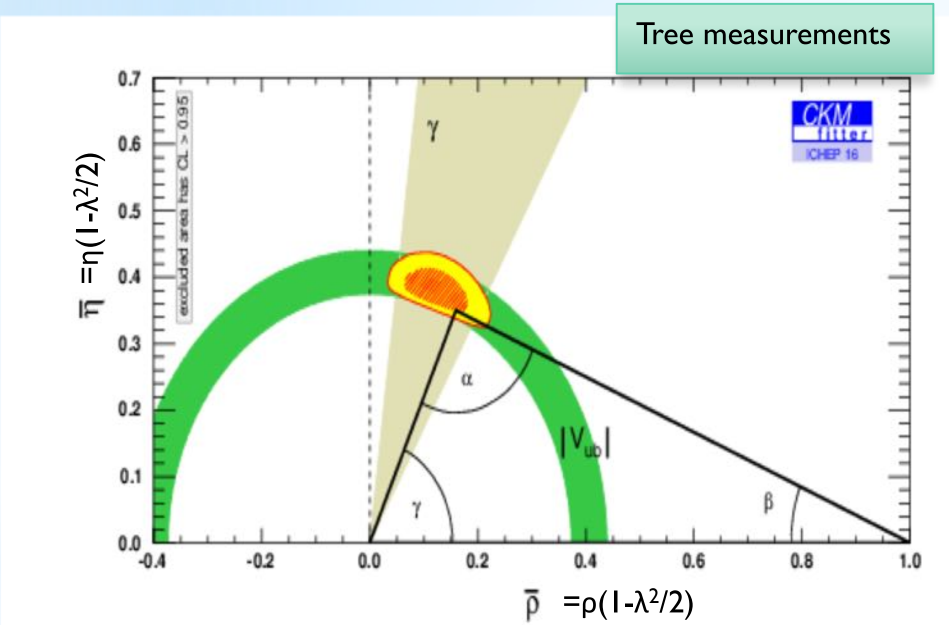
A = 0.80±0.02
λ= 0.225±0.001

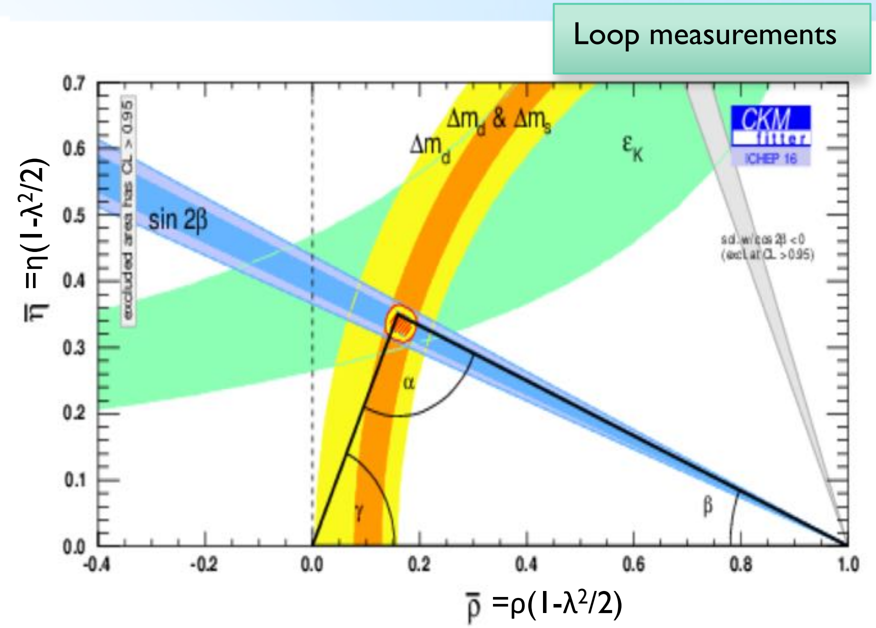
$\lambda = \sin\theta_c \approx V_{us}$ measured precisely in K semileptonic decays. Notice that all **V_{ij} couplings** can be accessed experimentally using **tree-level decays**, with the **exception of V_{td} and V_{ts} .**

Tree vs loop measurements

(A,λ,ρ,η) are not predicted by the SM. **They need to be measured!**

If we assume NP enters only (mainly) at loop level, it is interesting to compare the determination of the parameters (ρ,η) from processes dominated by tree diagrams **(V_{ub} ,V_{cb} , γ,…)** with the ones from loop diagrams **(ΔM_d&ΔM_s, β,ε_K , …)**.





Need to improve the future precision of the measurements at tree (loop) level in b→d(s) transitions to (dis-)prove the existence of NP contributions in loops relatively to tree processes.

Yukawa Mechanism in the lepton sector.

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i\phi D_R^j + Y_u^{ij}\bar{Q}_L^i\tilde{\phi}U_R^j + Y_e^{ij}\bar{L}_L^i\phi E_R^j + \text{h.c.}$$

In the SM the lepton Yukawa matrices can be diagonalized independently due to the global G_l symmetry of the Lagrangian, and therefore there are not FCNC.

$$\mathcal{G}_\ell = SU(3)_{L_L} \otimes SU(3)_{E_R}$$

However, the discovery that ν oscillate (and ν have mass) implies that Lepton Flavour is not conserved. The level of Charged Lepton Flavour Violation depends on the mechanism to generate neutrino masses (**Seesaw mechanism?**).

PMNS

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

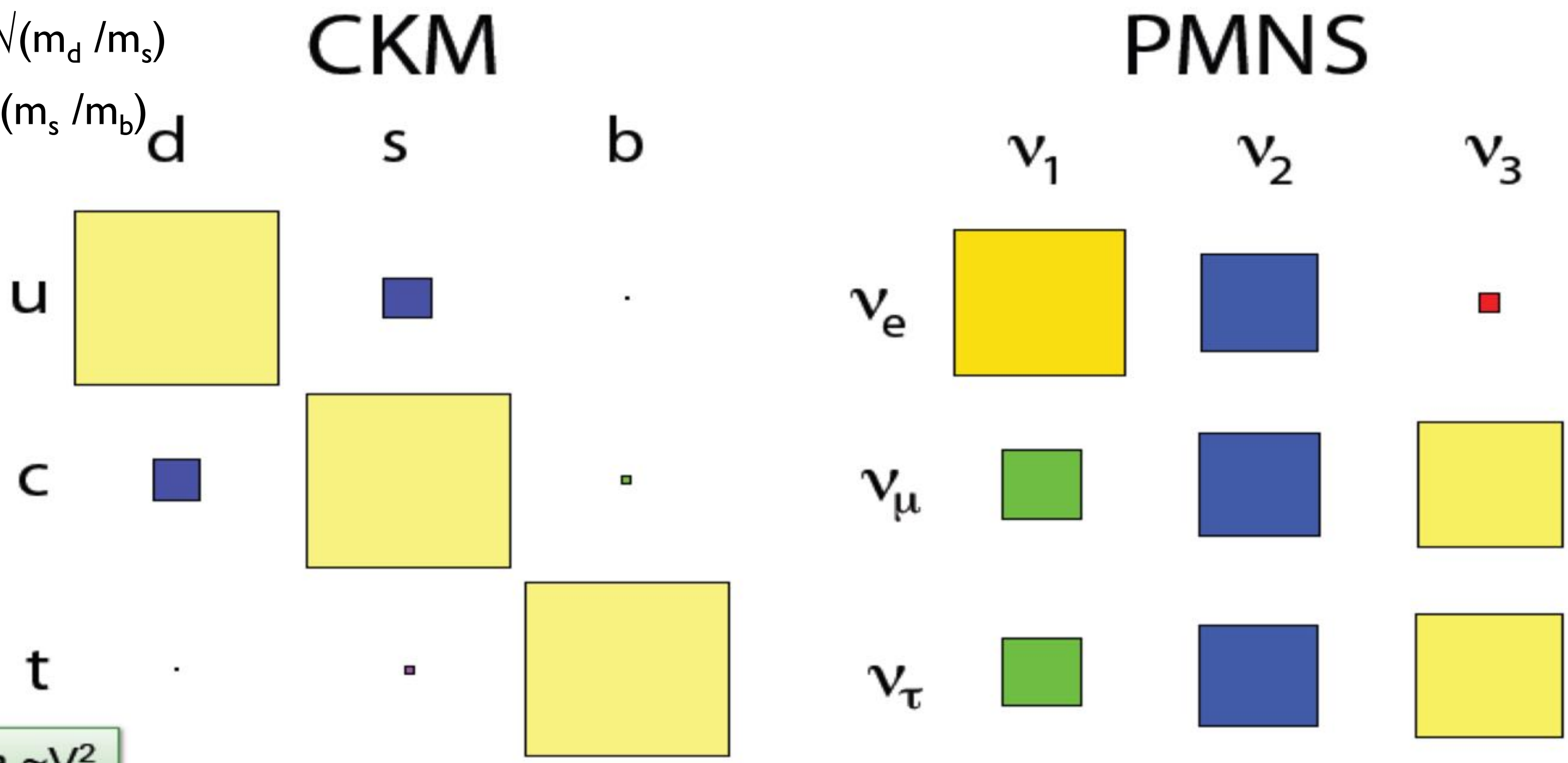
$$\theta_{12}[^\circ] = 33.36^{+0.81}_{-0.78}$$
$$\theta_{23}[^\circ] = 40.0^{+2.1}_{-1.5} \text{ or } 50.4^{+1.3}_{-1.3}$$
$$\theta_{13}[^\circ] = 8.66^{+0.44}_{-0.46}$$
$$\delta_{\rm CP}[^\circ] = 300^{+66}_{-138}$$

In general, while quark flavour changing Yukawa couplings to the Higgs are strongly suppressed by ΔF=2 indirect measurements, processes like H→τμ or H→τe are only loosely bounded (O(10%)).

Flavour structure is not simple!

$V_{us} \sim \sqrt{(m_d / m_s)}$

$V_{cb} \sim (m_s / m_b)$

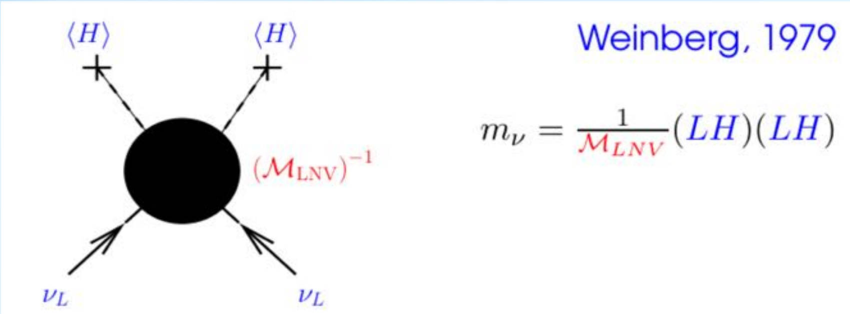


Area $\sim V^2$

Why these values? Are the two related? Are they related to masses?

Can the seesaw mechanism explain the very different structures between quarks and leptons?

Seesaw mechanism and LFV

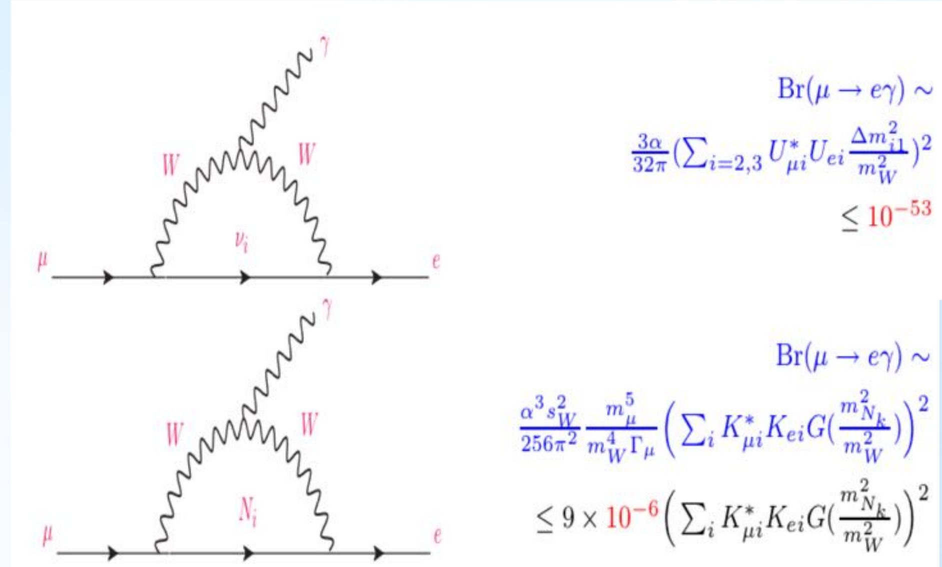


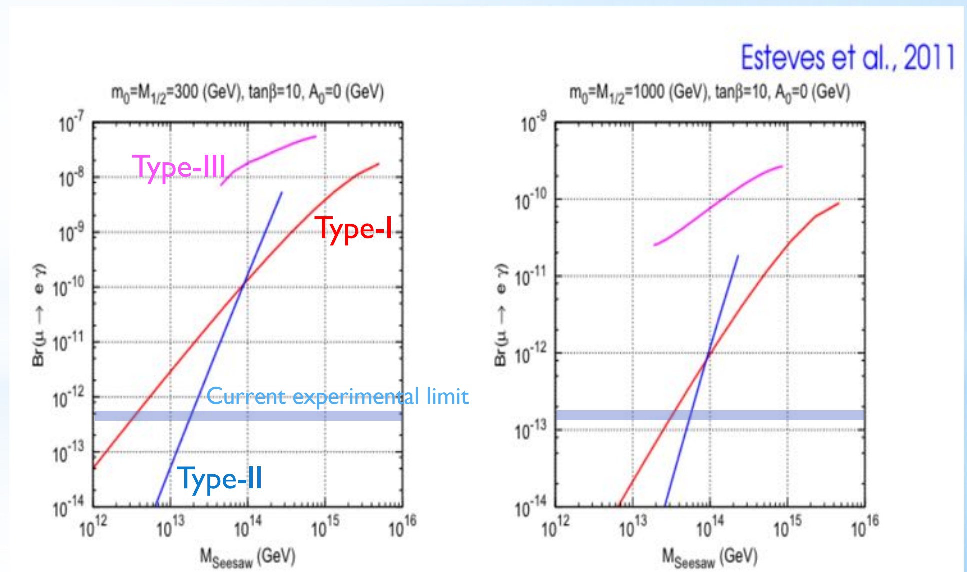
If neutrinos are **Dirac particles**, expect **very small** (far from experimental sens.) **LFV.**

However, if neutrinos are **Majorana particles** and something like the **Seesaw mechanism** is at work, **large values** (close to experimental sens.) are favoured.

In general, **many extensions of the SM with new states at the TeV scale generates large charged LFV.**

Future precision of LFV experiments should provide important information on the nature of the neutrino mass!





Flavour Beyond the SM

We know the **SM** does **not describe ν masses**, does not have **a good DM candidate** and **cannot explain the baryon asymmetry** in the Universe. Moreover, there is no explanation for the **flavour structure**, does **not include Gravity** and suffers from **fine-tuning issues in the Higgs sector.**

So, let's take the **SM as an approximation** to the true underlying theory:

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, A_a, \psi_i) + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

ν masses indicate already the existence of **d=5** operators in this expansion and of very **large values of Λ** (probably related to the breaking of Lepton Number). Precision FCNC measurements in the quark sector also indicate **large values of Λ.** On the other hand, the **d=2** operators in the **Higgs sector** require a **low value of Λ** to stabilize the Higgs mass term.

The search for the scale Λ at the High Energy Frontier is complemented by the sensitivity of (c_n/Λ^{d-4}) of experiments at the High Intensity Frontier.

Something in fashion: Lepton Non-Universality

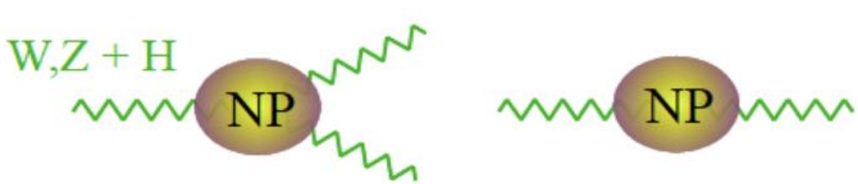
▶ <u>*Introduction*</u> [*a possible shift of parading in model-building*]

So far, the vast majority of BSM model-building attempts

- Concentrate only on the (SM gauge) hierarchy problem
- Postpone (ignore) the flavor problem, implicitly assuming the 3 families are "identical" copies (but for Yukawa-type interactions)

The recent flavor anomalies seem to suggest a <u>shift of paradigm</u>:

- <u>We should not ignore the flavor problem</u> [→ *new (non-Yukawa) interactions at the TeV scale distinguishing the different families*]
- A (very) different behavior of the 3 families (with special role for 3rd gen.) *may be the key to solve/understand also the gauge hierarchy problem*



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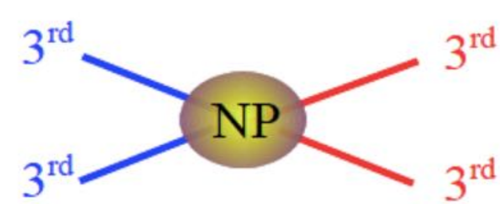


~~small (*less interesting...*)~~
large (*more interesting...*)

What about new sources of CP violation: EDMs

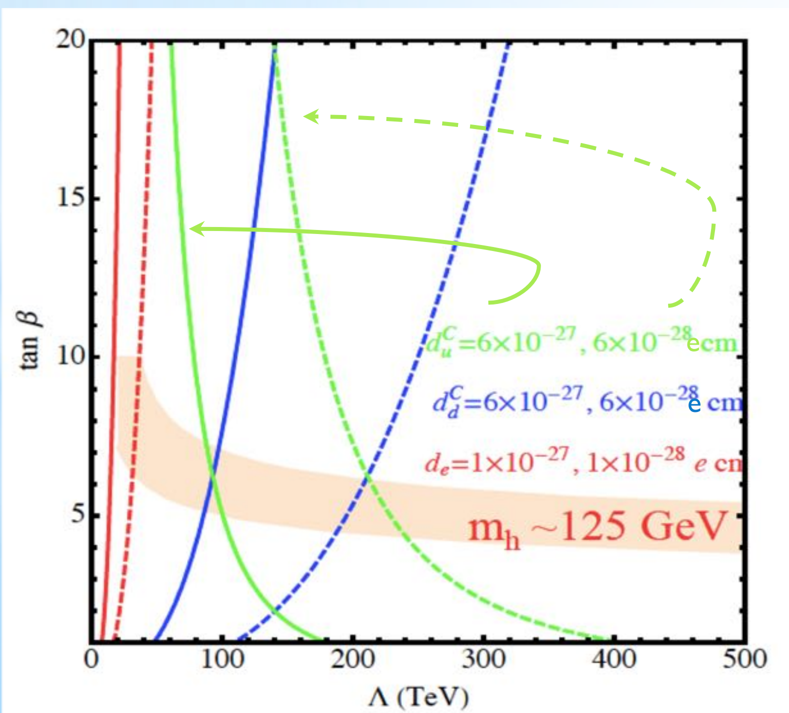
$d_n^{SM} \sim (10^{-16}$ e cm) x θ_{QCD} + (1-6) x 10^{-32} e cm.

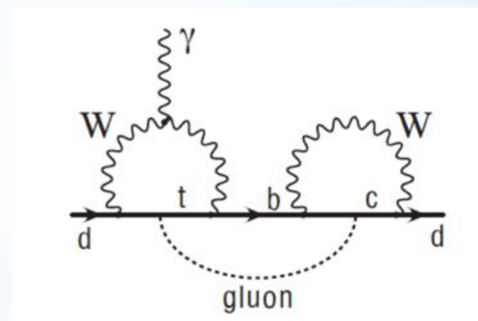
$d_n^{BSM} \sim (10^{-16}$ e cm) x $(v/\Lambda)^2$ x $\sin(\Phi)$ x $y_f F$

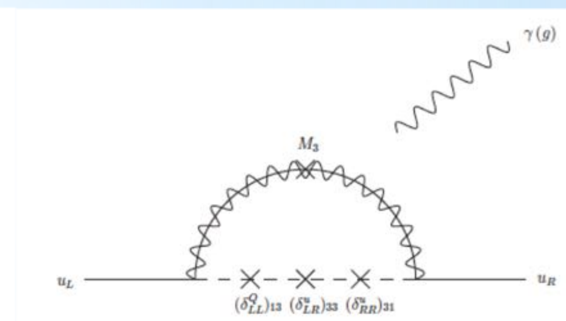
sin(Φ) → CPV phase must be large enough to explain baryogenesis.
$(v/\Lambda)^2$ → BSM mass scale?
y_fF → BSM dynamics: perturbative? strongly coupled? dependence on other parameters?

EDMs provide information on the three "frontiers": cosmic frontier (baryon asymmetry), high energy frontier (scale of BSM) and intensity frontier (couplings of BSM).

For example, take "minimally unnatural SUSY" → **probing scales as several 100 TeV!**







The search for nucleon/lepton EDMs is a very sensitive probe for new sources of CP violation at very large energy scales!

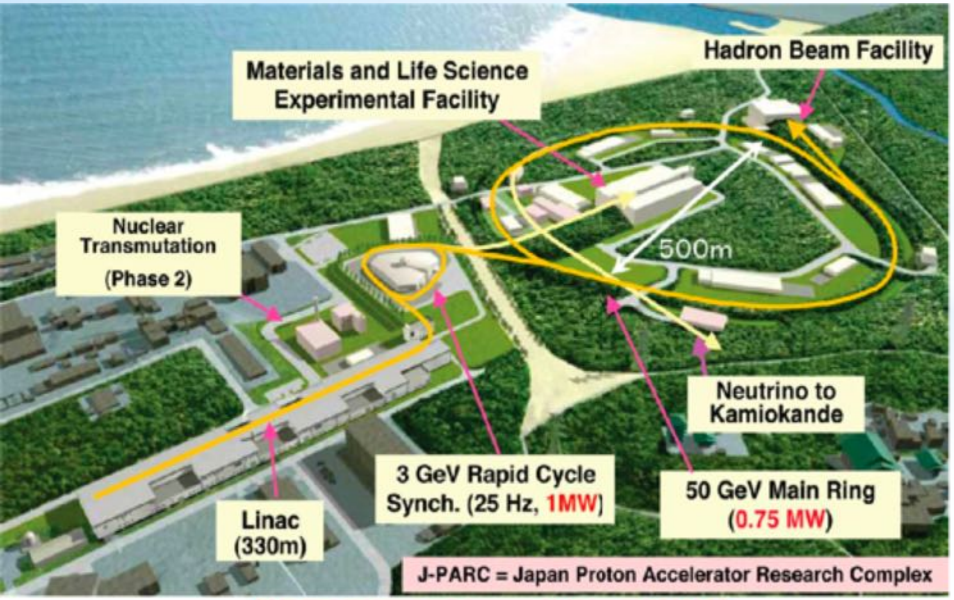
Future experimental facilities: opportunities and challenges.

μ/p-beams facilities

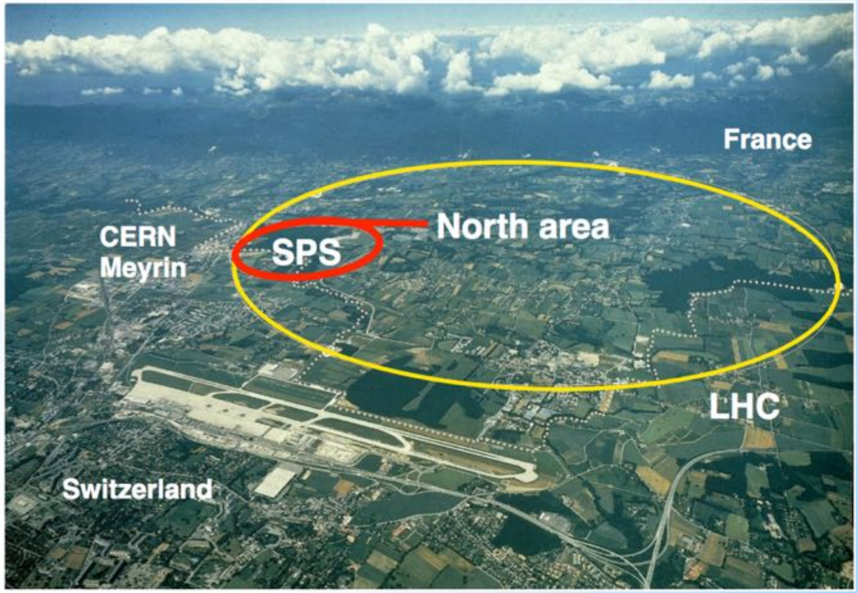
Laboratory / Beam Line	Energy / Power	Present Surface μ^+ rate (Hz)	Future estimated μ^+/μ^- rate (Hz)
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	"	$4 \cdot 10^8$	
πE5	"	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10}(\mu^+)$
J-PARC (JP)	(3 GeV, 1MW, Pulsed) currently 210 KW		
MUSE D-line	"	$3 \cdot 10^7$	
MUSE U-line	"		$2 \cdot 10^8(\mu^+)(2012)$
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11}(\mu^-)(2019/20)$
PRIME/PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12}(\mu^-)(> 2020)$
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10}(\mu^-)(2019/20)$
Project X Mu2e	(3 GeV, 750 kW, DC to pulsed)		$2 \cdot 10^{12}(\mu^-)(> 2022)$

Existing μ beams 10^8 Hz. Next 10 years experiments will be able to increase rate by at least x100.

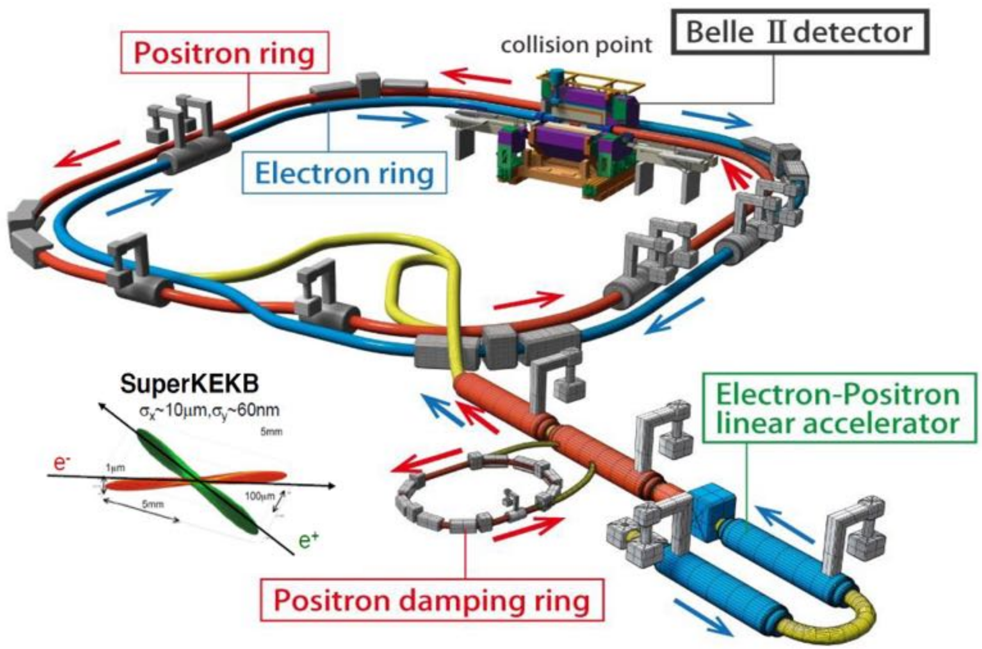
JPARC: $2\text{x}10^{14}$ 30 GeV PoT/3sec
SPS: 10^{12} 400 GeV PoT/sec

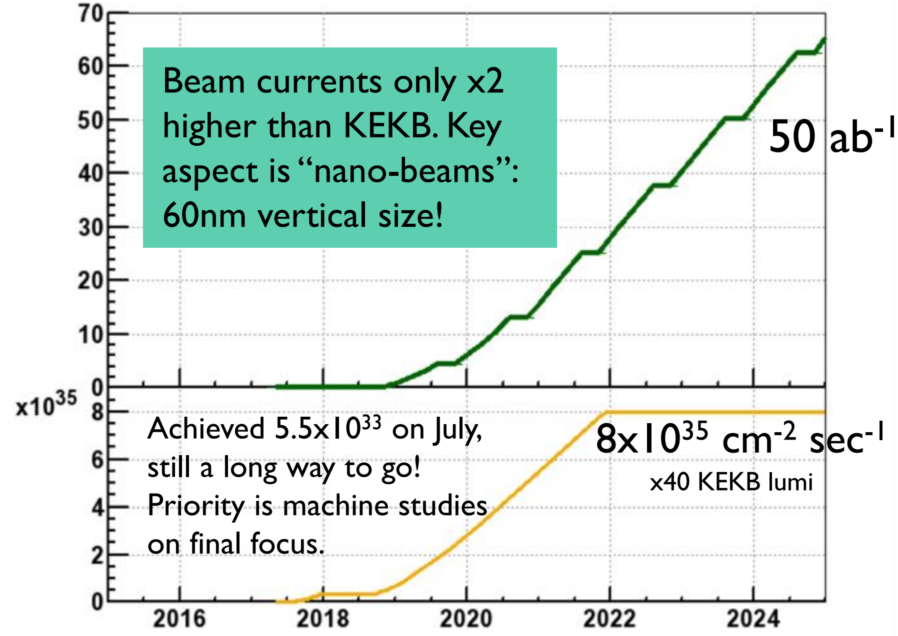


Joint Project between KEK and JAEA



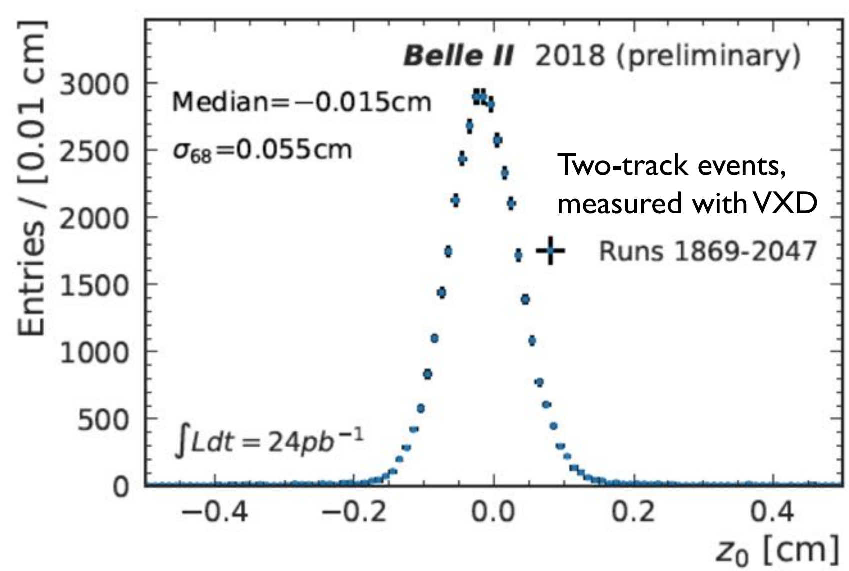
Colliders facilities: SuperKEKB

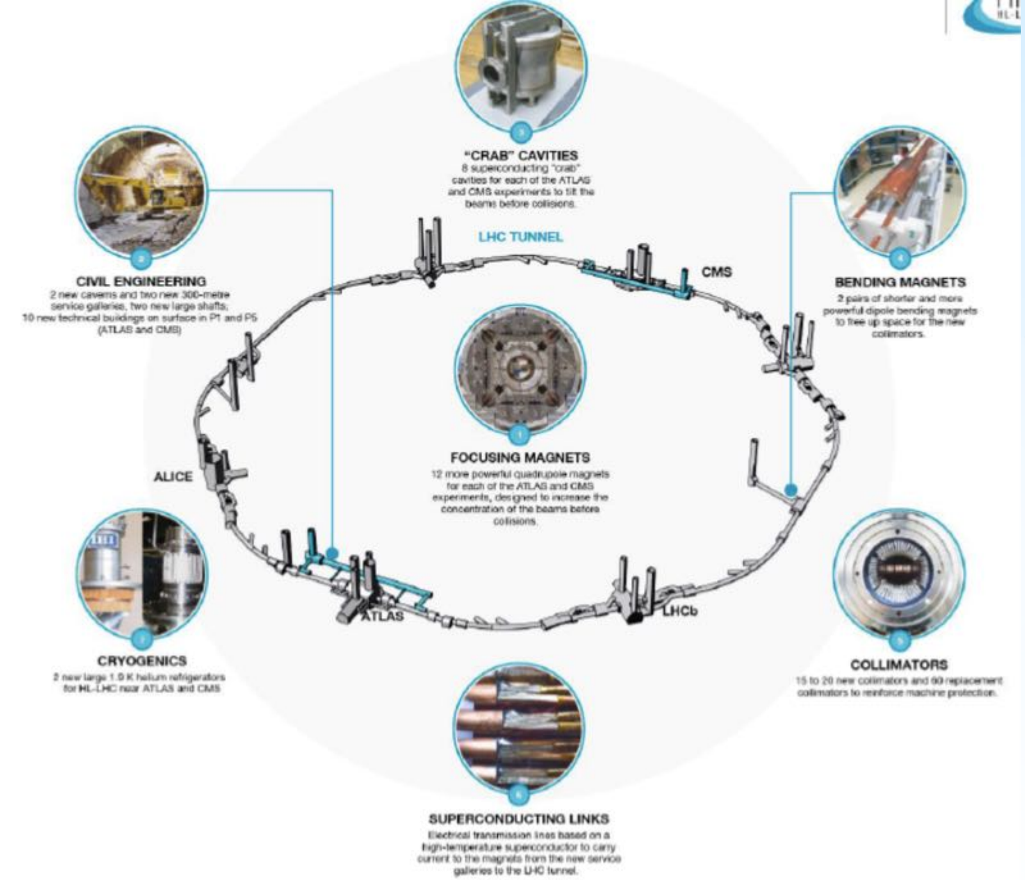




New positron damping ring and positron ring just commissioned (spring 2018). New **large crossing angle nano-beams** effectively reduce the bunch length from 10mm to 0.5mm!

Phase 2 completed. VXD will be installed later in 2018. **Full** detector Belle II **data taking (Phase 3) to start** in **Feb. 2019**.





Colliders facilities: HL-LHC

Replace **focusing magnets** with more **powerful** and **very large aperture** in ATLAS/CMS. Use **"CRAB"** cavities to increase overlap between beams.

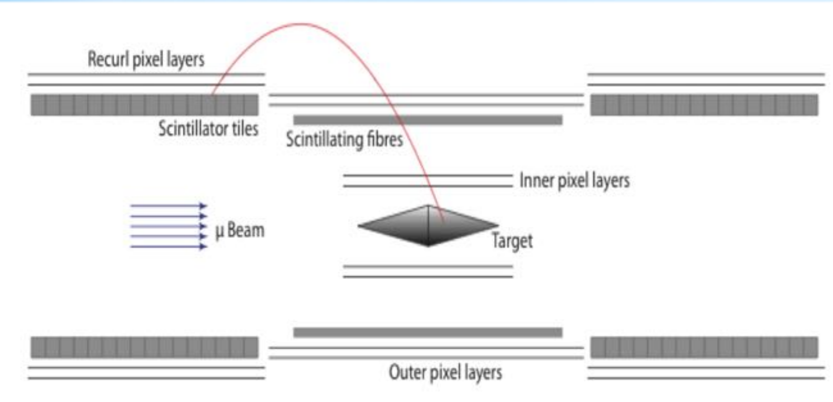
Peak luminosity **5×10^{34} cm^{-2} sec^{-1}** after leveling! Integrate **250 fb^{-1} per year**. Ultimate performance 7.5×10^{34} cm^{-2} sec^{-1}.

LHCb U2 integrated luminosity **limited** by **lifetime of focusing magnets** O(300 fb^{-1}). **Detector Pileup** in **ATLAS/CMS** up to **240**, in **LHCb U2** up to **50**.

2019 2020	2021 2022 2023	2024 2025 2026	2027 2028 2029	2030 2031	2032 203+
LS2	Run III	LS3	Run IV	LS4	Run V
LHCb 40 MHz UPGRADE I	$L = 2 \times 10^{33}$	LHCb Consolidate: Upgr Ib	$L = 2 \times 10^{33}$ 50 fb^{-1}	LHCb UPGRADE II	$L = 1\text{-}2 \times 10^{34}$ 300 fb^{-1}
ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	ATLAS Phase II UPGRADE	HL-LHC $L = 5 \times 10^{34}$	ATLAS	HL-LHC $L = 5 \times 10^{34}$
CMS Phase I Upgr	300 fb^{-1}	CMS Phase II UPGRADE		CMS	3000 fb^{-1}
Belle II 5 ab^{-1}	$L = 8 \times 10^{35}$	50 ab^{-1}			

Rule of thumb: 1ab^{-1} at Belle-II ~ 1fb^{-1} at LHCb

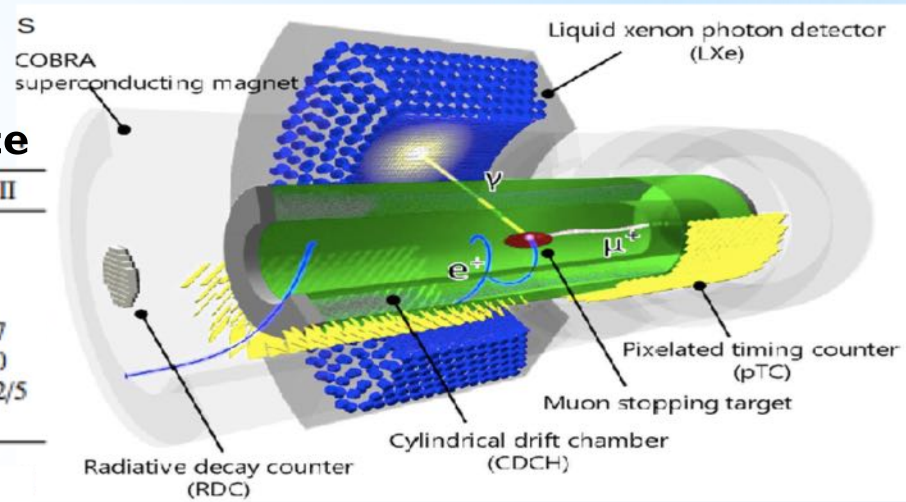
Detectors and technologies: Muon Experiments

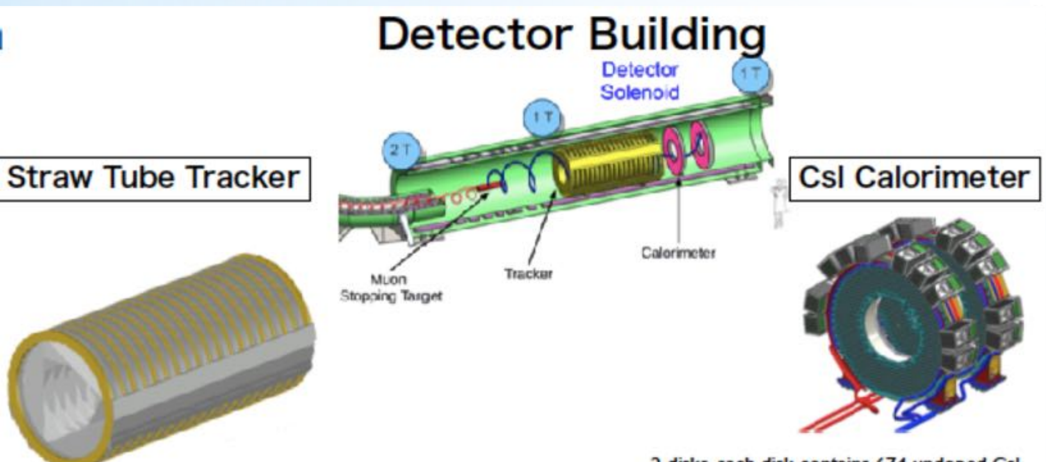


Mu3e detector needs to deal with **high rates** 0.1 MHz/mm^2 (NA62 Gigatracker 1.3 MHz/mm^2) with continuous reading, and minimal scattering → DMAPS (50 μm thick, less 1% radiation length, integrated sensor and readout).

Excellent e/γ resolution required for **MEG-II**, **twice better than MEG!**

PDF parameters	MEG	MEG II
E_{e^+} (keV)	380	130
θ_{e^+} (mrad)	9.4	5.3
ϕ_{e^+} (mrad)	8.7	3.7
z_{e^+}/y_{e^+} (mm) core	2.4/1.2	1.6/0.7
E_γ(%) (w>2 cm)/(w<2 cm)	2.4/1.7	1.1/1.0
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.6/2.2/5
$t_{e^+\gamma}$ (ps)	122	84





2 disks, each disk contains 674 undoped CsI crystals of 20x3.4x3.4cm^3

Mu2e detector is building a state of the art **CsI calorimeter**. Prototype shows performances as expected, for **100 MeV electrons** (**energy resolution ~7% and time resolution ~150ps**).

Detectors and technologies: Belle-II and LHCb UI

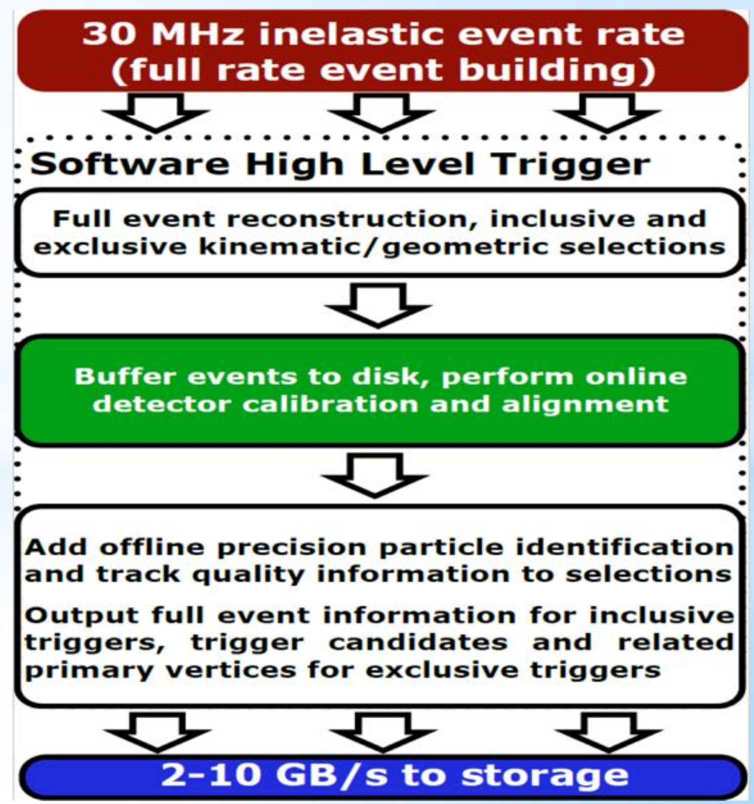
Innovative technologies used for **Belle-II→ pixel photon sensors** play central role (collaboration with industry)

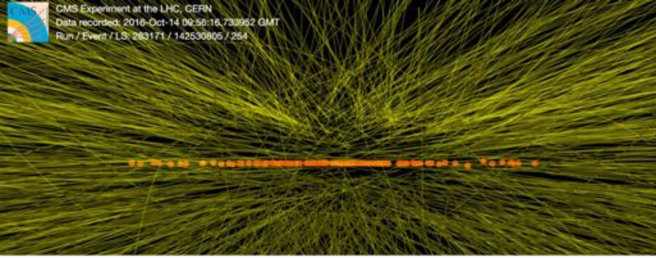
DEPFET pixel detector (**50 μm pixel** size, **75 μm thick**, air cooling). 2 layers at 14 and 22 mm radius (with 8 and 12 layers each).

LHCb upgrade 1 in 2019-20, is basically a front-end electronics upgrade to readout the full detector at 40 MHz → **Full software trigger.**

Target **luminosity x5** w.r.t. LHCb RUN1&2, and collect **50 fb^{-1}** during RUN3&4.

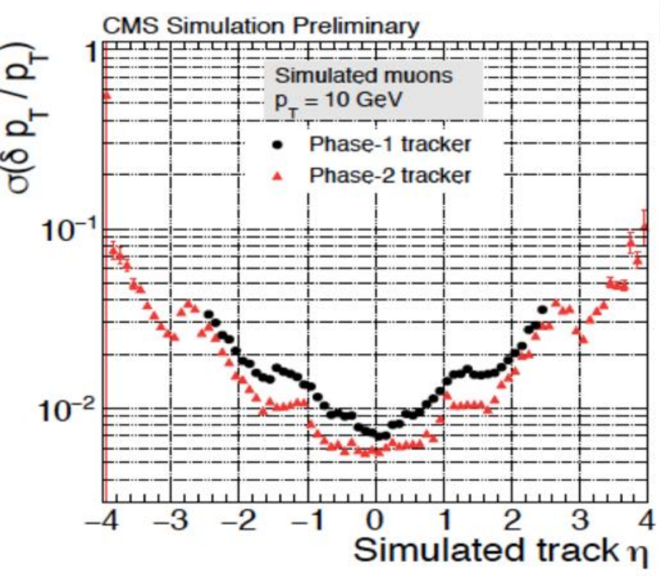
Some detectors are upgraded with **higher granularity and more radiation hardness** (like the vertex detector VELO).





Detectors and technologies: HL-LHC experiments

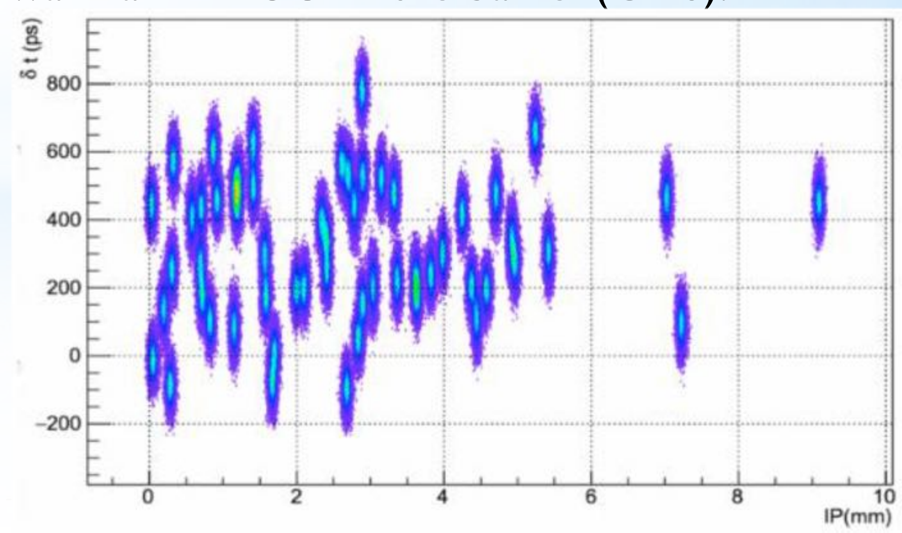
Detectors at **HL-LHC** need to mitigate the effect of **pileup O(200)**, and survive **2×10^{16} 1 MeV n_{eq}/cm^2.**



3D and **planar** sensors can reach the radiation requirements. Common effort (RD53) to develop chips with 65nm **CMOS technology**. **DMAPS** development important (profit from Belle-II experience). **CMS** phase 2 tracker is even **improving momentum resolution** w.r.t. phase 1. **L1 track trigger (CMS)** can improve also on low **Pt physics.**

In this environment, **timing** is absolutely needed to reduce pileup. **ATLAS/CMS** achieve **30ps/track** with thin layers of **LGAD** tiles forward and **LYSO** in the barrel (CMS).

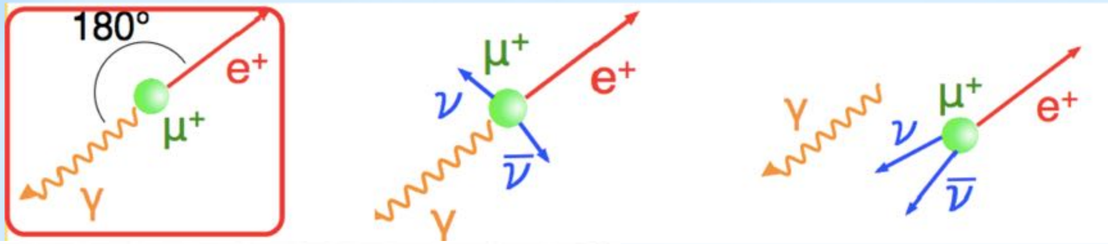
LHCb upgrade 2 in 2030, to use the full potential of HL-LHC, at **2×10^{34} cm^{-2} sec^{-1}**. Profit from generic detector **R&D for HL-LHC**, in particular timing layers and 4D tracking. New detector able to sustain radiation and occupancies.

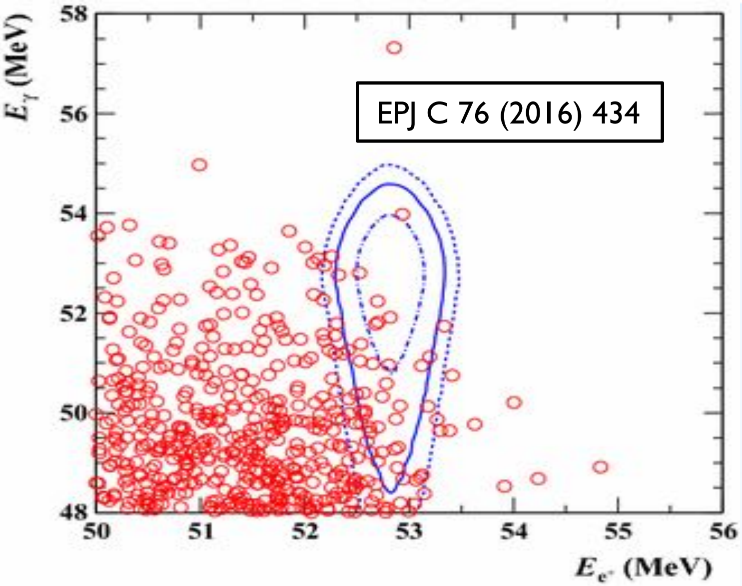


Opportunity, too, to **improve on ECAL performance**… may be critical to study e/μ universality.

Future measurements in the lepton sector.

CLFV: μ→eγ





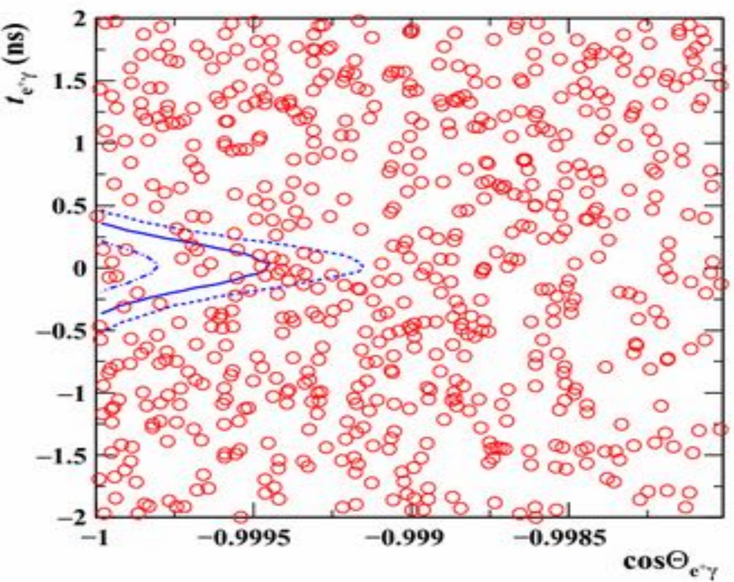
The **MEG collaboration** at PSI using 7.5x10^{14} stopped muons collected within 2009-13 have achieved a sensitivity of BR(μ→eγ)<4.2x10^{-13}@90%C.L.

Relevant variables $E_{\gamma,e}$ and the timing (e,γ) and $\cos\theta_{e\gamma}$

MEG upgrade (MEG-II) expects to increase x10 sensitivity with upgraded detector (2019-2021).

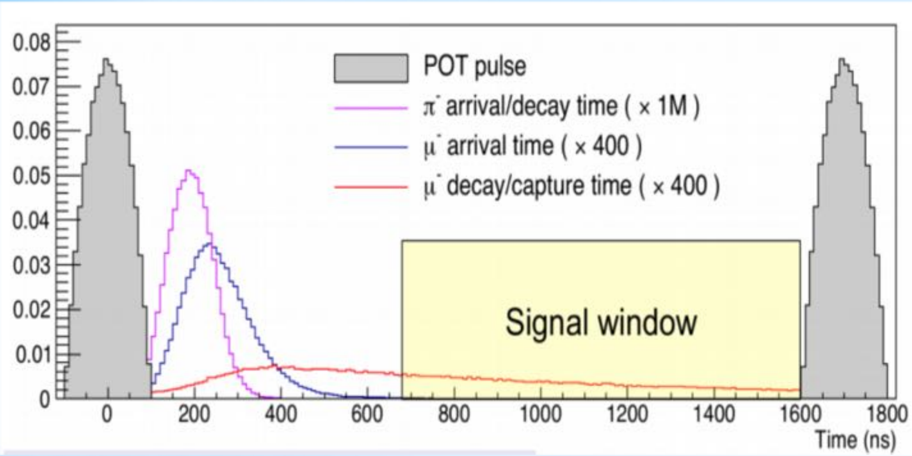
Difficult to further improve with this technique due to accidental backgrounds, which should increase with beam intensity.

$$N_{\rm acc} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta P_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T,$$



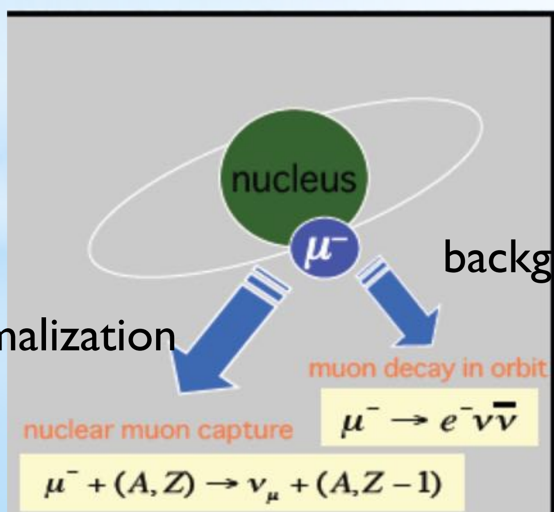
Maybe improving Δe_γ using converted photons, could overcome the lost in efficiency, in future proposals.

CLFV: μ→eN



More feasible is to improve on **μ→eN** conversions. Best existing limits from **SINDRUM-II at PSI**: R(μ→eAu) <7x10^{-13} @90% C.L. with O(10^{8}) μ^{-}/sec and time between pulses <20ns.

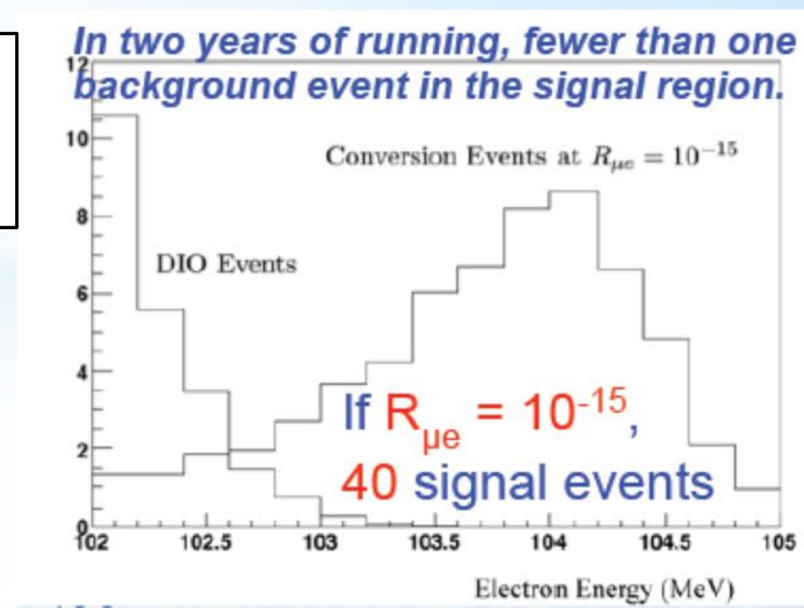
Mu2e at the **booster** will use O(10^{10}) μ^{-}/sec and time between pulses ~1700ns, to reach R(μ→eAl) <7x10^{-17} @90% C.L. In a similar time scale (>2020), and with similar beam parameters, **COMET-II** at **JPARC's main ring** will reach similar sensitivities. Preliminary studies show that an upgraded Mu2e and PRIME/PRISM (using Ti) at JPARC could increase x10 sensitivity of Mu2e.



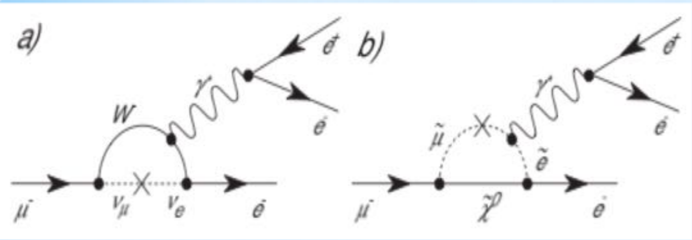
normalization

background

Single 105 MeV electron, beyond endpoint of DIO.

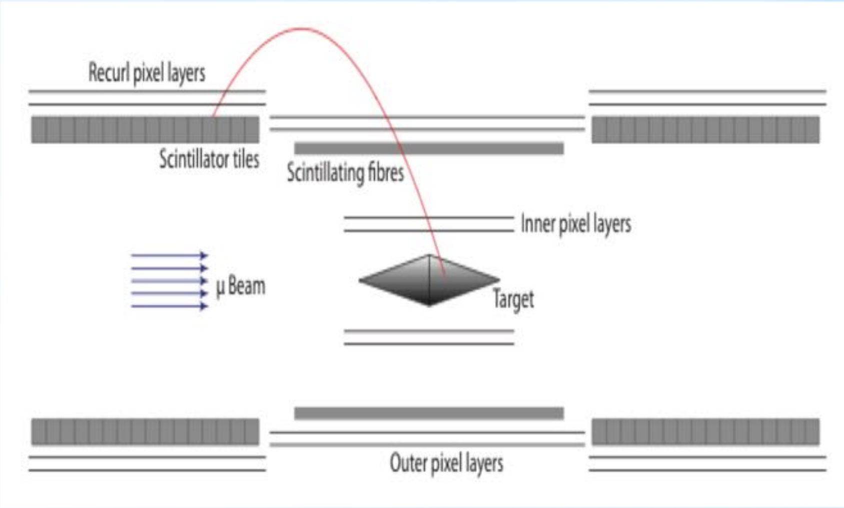


CLFV: $\mu \rightarrow eee$, $\tau \rightarrow \mu\mu\mu$



The best limit $BR(\mu \rightarrow eee) < 10^{-12}$ is from **SINDRUM**, with essentially zero bkg.

Mu3e proposal improves sensitivity to 10^{-16}, by using the proposed **HiMB line at PSI**, with rates of 2×10^9 μ/sec DC beams. Accidental bkg are under control with excellent detector resolution. Limitation may come from $\mu \rightarrow e\nu\nu\gamma(ee)$. Phase-1 (2019-21) aims for 10^{-15}.



In principle τ are more sensitive per event than μ since mass typically decreases GIM suppression, (>500), and allows for other contributions (e.g. Higgs contributions).

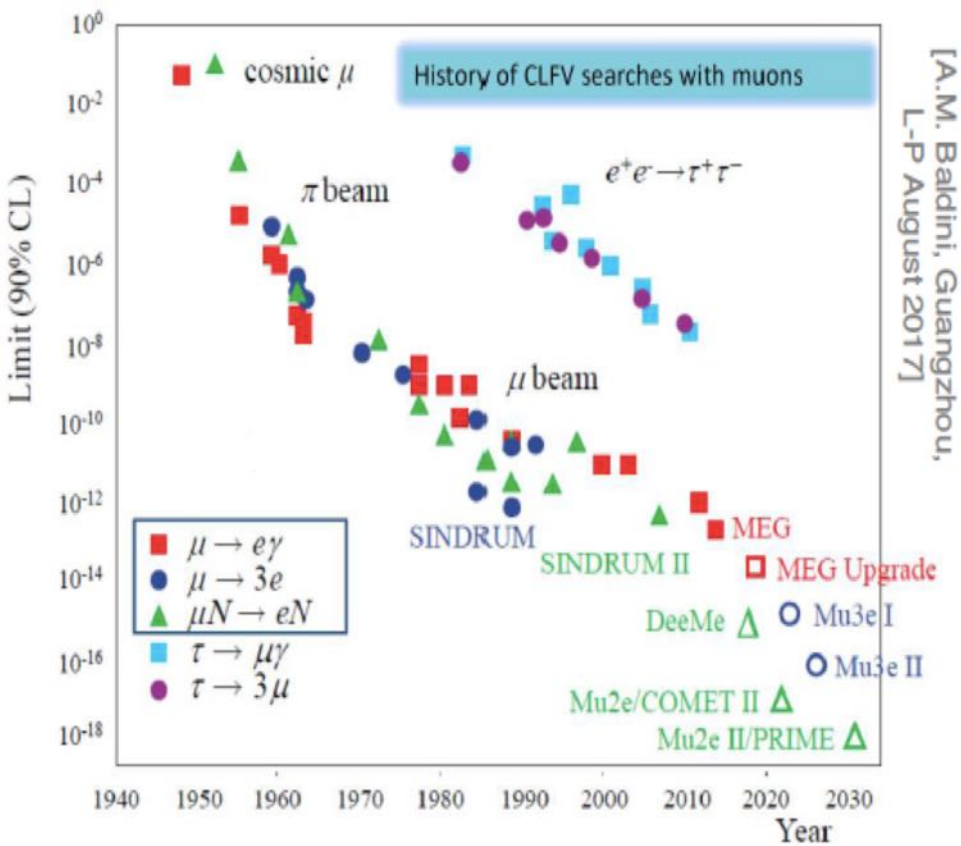
However, τ production rates at e^+e^- B-factories are not in the same league! With $\sim 1.4 \times 10^9$ τ events at the B-factories the best limits at 90% C.L. are:

	$BR(\tau \rightarrow \mu\gamma)$	$BR(\tau \rightarrow \mu\mu\mu)$
BELLE:	4.5×10^{-8}	2.1×10^{-8}
BABAR:	4.4×10^{-8}	3.3×10^{-8}

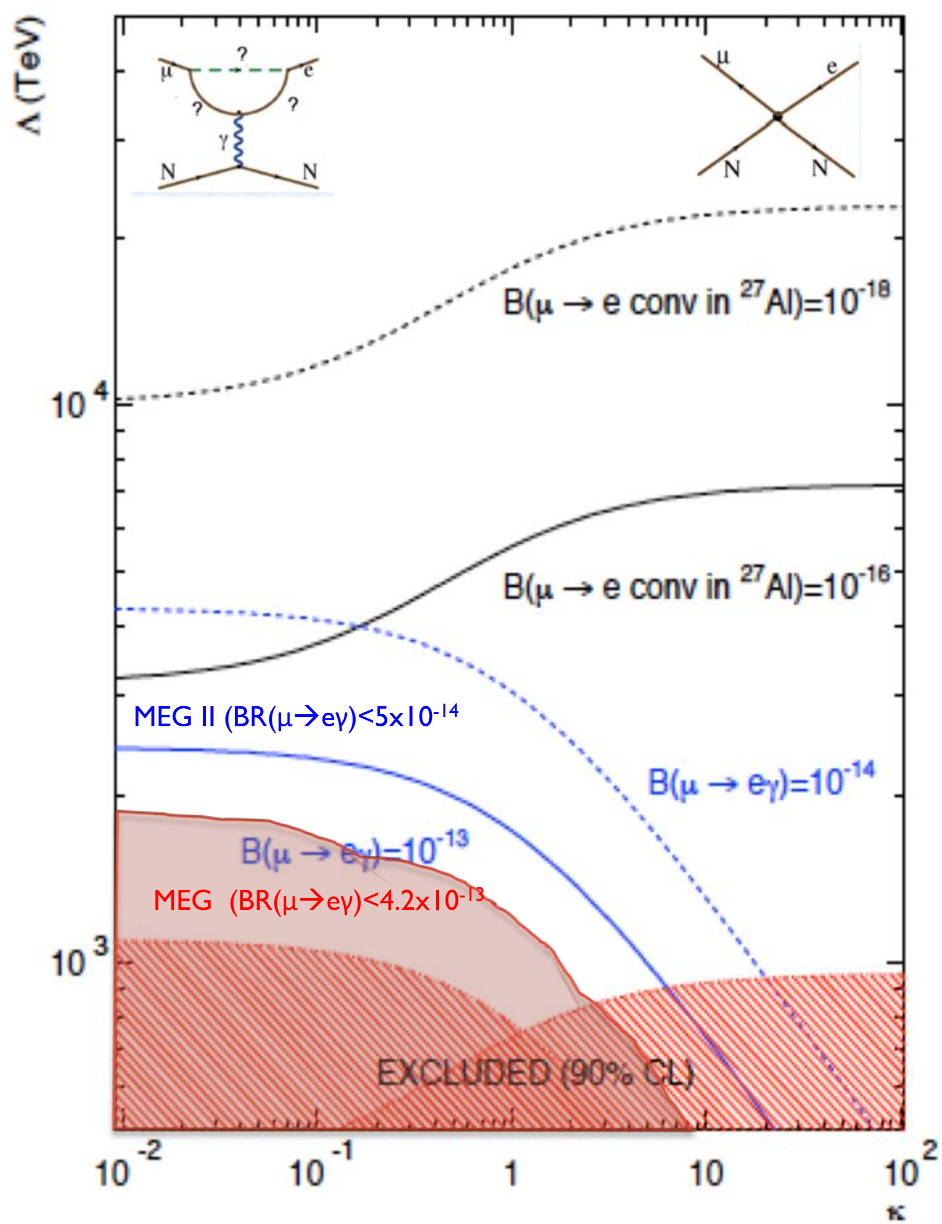
At the LHC τ are copiously produced $\sim 2 \times 10^{11}$ τ/fb^{-1} (mainly from charm decays, $\mathbf{D_s \rightarrow \tau\nu}$). **LHCb** has reached similar sensitivities for $BR(\tau \rightarrow \mu\mu\mu)$ than B-factories using only $3 fb^{-1}$, providing a world average limit on $BR(\tau \rightarrow \mu\mu\mu) < 1.2 \times 10^{-8}$ @90%CL.

Belle-II (2019-2025) aims to probe the region (10^{-9}-10^{-8}) with 50 ab^{-1}. LHCb Upgrade 2 proposal should reach similar sensitivities (203x). Some proposal to use charm production in fixed target beams.

CLFV overview



Modified from A.Gouvea and P.Vogel, arXiv:1303.4097



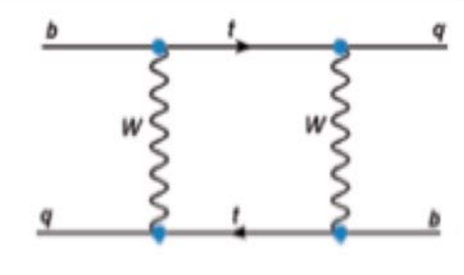
Typically two operators contribute as function of Λ:

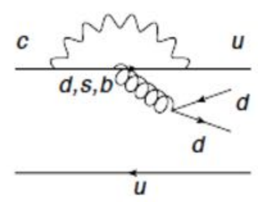
$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_R\gamma_\mu e_L \bar{f}\gamma^\mu f$$

And κ is the relative strength of their contribution.

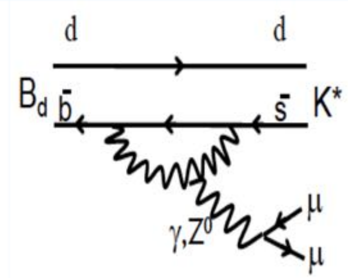
Future measurements in the quark sector.

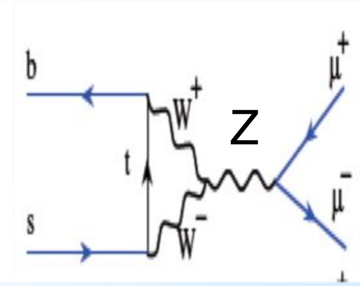
FCNC in quarks: loops categories



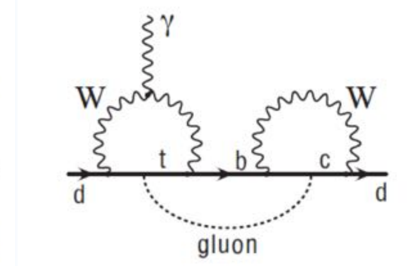


ΔF=2 box





ΔF=1 Penguins



ΔF=0 Penguins

Examples of quark Flavour transitions and type of loop processes:

	$b\to s$ ($\|V_{tb}V_{ts}\| \alpha \lambda^2$)	$b\to d$ ($\|V_{tb}V_{td}\| \alpha \lambda^3$)	$s\to d$ ($\|V_{ts}V_{td}\| \alpha \lambda^5$)	$c\to u$ ($\|V_{cb}V_{ub}\| \alpha \lambda^5$)
ΔF=2 box	$\Delta M_{Bs}, A_{CP}(B_s\to J/\Psi\Phi)$	$\Delta M_B, A_{CP}(B\to J/\Psi K)$	ΔM_K, ε_K	x,y, q/p,Φ
QCD Penguin	$A_{CP}(B\to hhh), B\to X_s\gamma$	$A_{CP}(B\to hhh), B\to X\gamma$	$K\to\pi^0 ll$, ε'/ε	$\Delta a_{CP}(D\to hh)$
EW Penguin	$B\to K^{(*)}ll$, $B\to X_s\gamma$	$B\to\pi ll$, $B\to X\gamma$	$K\to\pi^0 ll$, $K^\pm\to\pi^\pm\nu\nu$	$D\to X_u ll$
Higgs Penguin	$B_s\to\mu\mu$	$B\to\mu\mu$	$K\to\mu\mu$	$D\to\mu\mu$
ΔF=0 (EDMs)			n,p,d EDMs (d(u)→d(u))	

Tree Level Measurements: V_{ub},V_{cb},arg(V_{ub})

Current status of the CKM magnitudes

$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1 & \lambda & V_{ub} \\ -\lambda & 1 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The 2x2 matrix formed by **$|V_{ud}|$,$|V_{us}|$,$|V_{cd}|$ and $|V_{cs}|$** has been measured using nucleus, pion, kaon and charm decays to be "almost" unitary. It only depends on **λ= 0.2251±0.0003.**

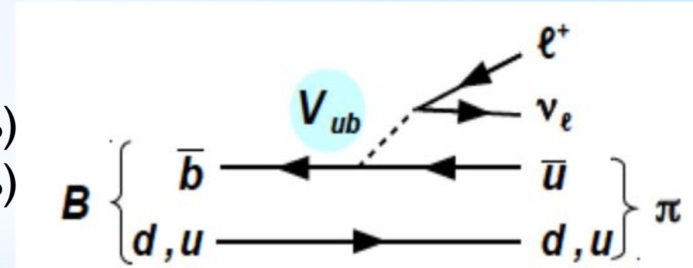
This sub-matrix is real up to $O(\lambda^5)$.

$|V_{ub}|$ and $|V_{cb}|$ are measured in semileptonic $B^{\pm}$ and B_d decays: inclusive and exclusive methods.

Exclusive measurements "easier" experimentally, but QCD form factors!

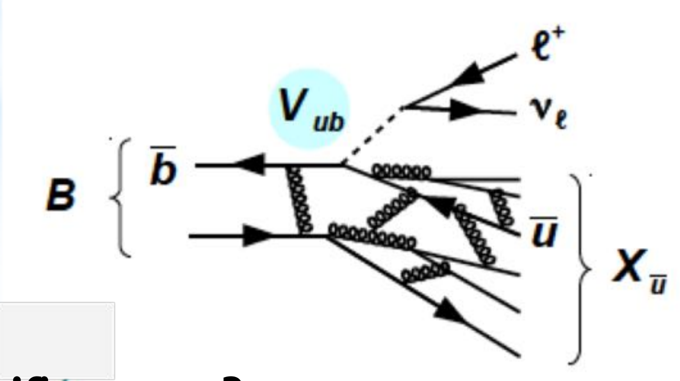
New Belle result using BGL z-expansion (using CLN model: $|V_{cb}|$ = (38.4±0.8)x10^{-3})

$|V_{ub}| = (3.65\pm0.27)\times10^{-3}$ (7%)
$|V_{cb}| = (42.5\pm1.0)\times10^{-3}$ (2%)



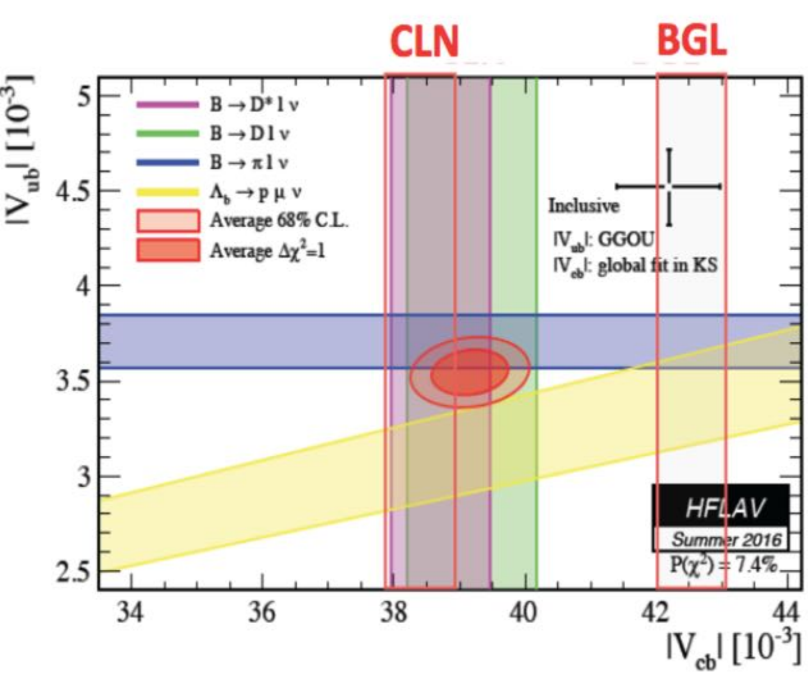
Inclusive measurements more robust theoretically, but need to control experimental backgrounds!

$|V_{ub}| = (4.52\pm0.14)\times10^{-3}$ (3%)
$|V_{cb}| = (42.2\pm0.8)\times10^{-3}$ (2%)



V_{ub} Inclusive measurement still ~20% higher, with significance ~3σ

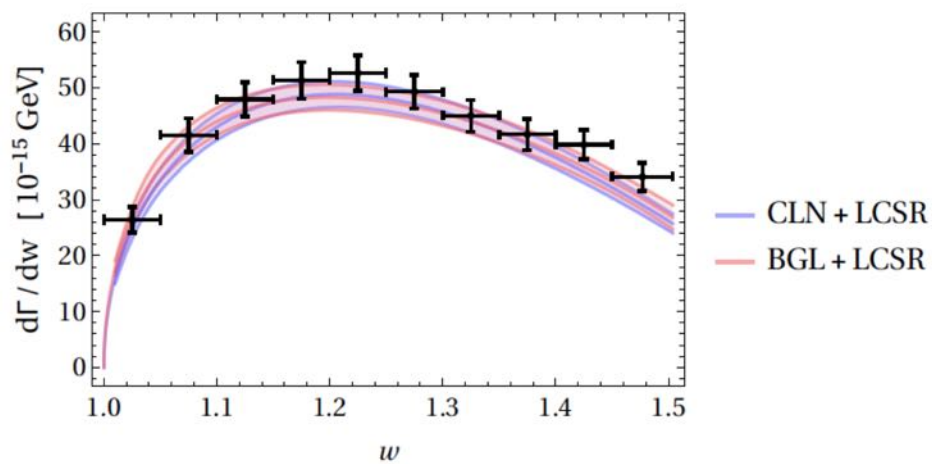
$|V_{ub}|$, $|V_{cb}|$ exclusive vs inclusive



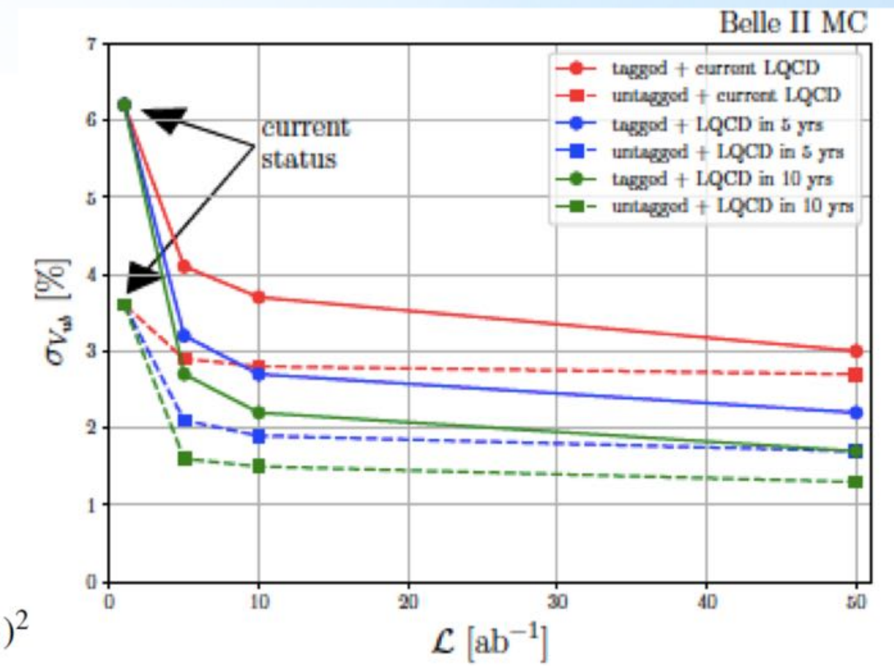
BGL fit of **B→D*lν** in good agreement with inclusive. But differences still persist in $|V_{ub}|$.

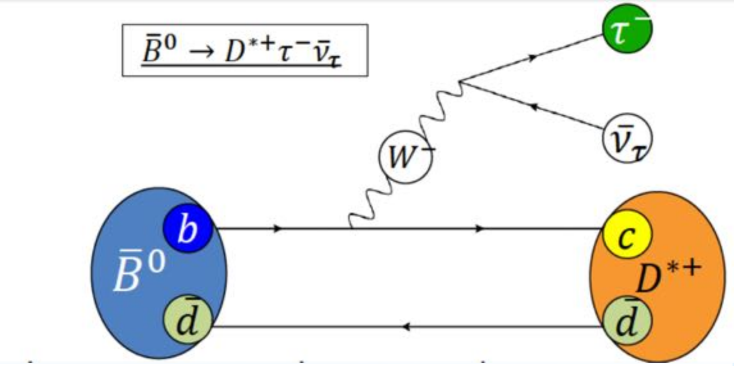
Belle-2 statistics should allow for a precise study of form factors, and open new clean decays like **σ(BR(B→μν))~7%. LHCb upgrades (1&2)** should help with the **exclusive** decays including **baryons.**

Expect to reach $\boldsymbol{\sigma(|V_{ub}|)_{incl.} \sim 3\%}$ and $\boldsymbol{\sigma(|V_{ub}|)_{exc.} \sim 2\%}$



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





Is LU violated in tree decays?

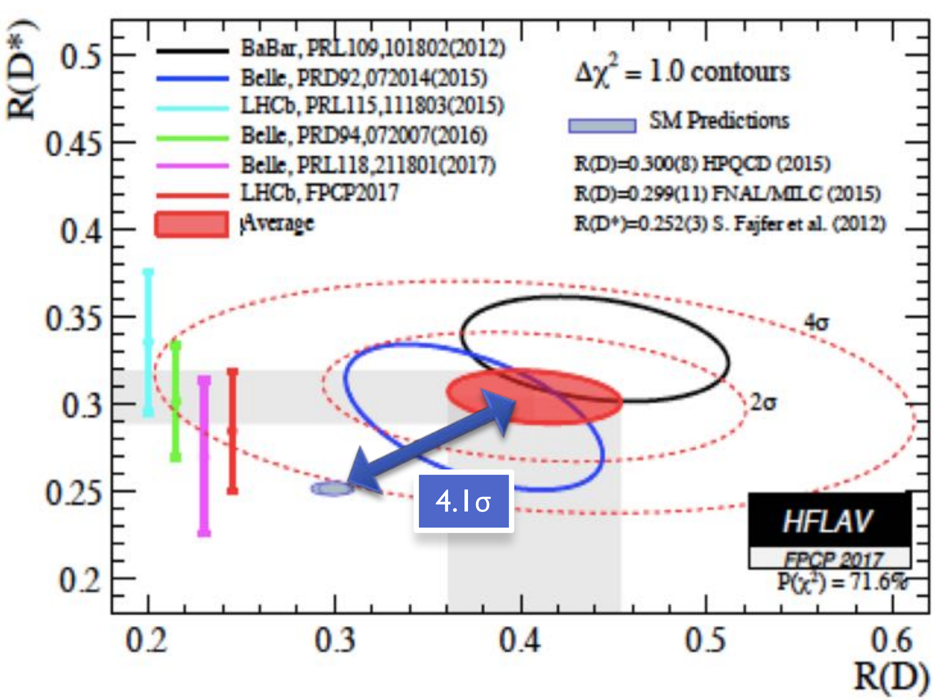
$$R(D) = \frac{\mathcal{B}(B \to D\tau^+\nu_\tau)}{\mathcal{B}(B \to D\ell^+\nu_\ell)}$$

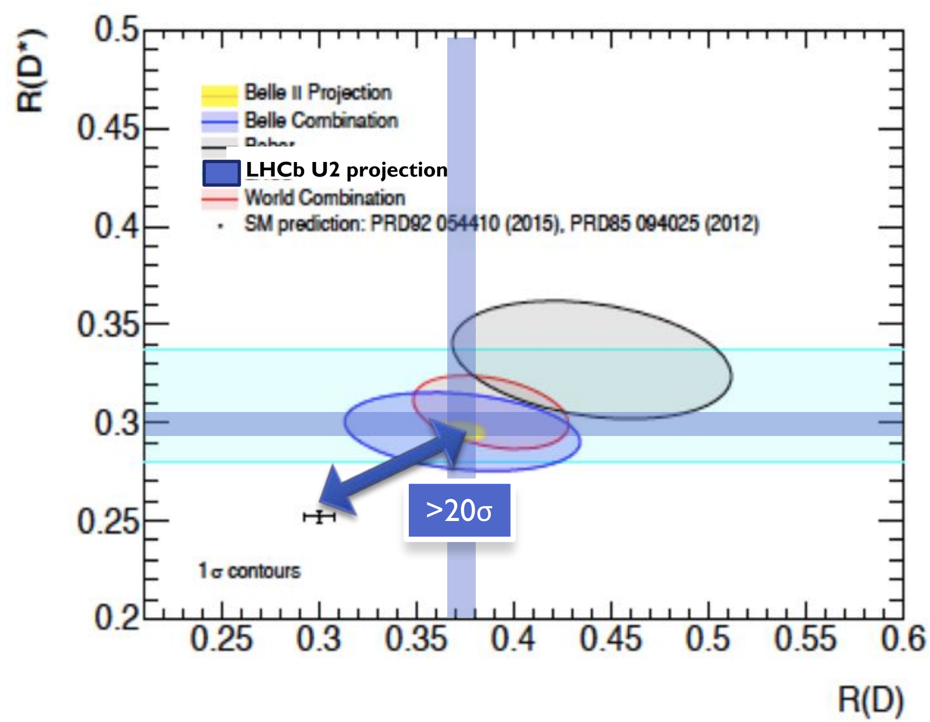
$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau^+\nu_\tau)}{\mathcal{B}(B \to D^*\ell^+\nu_\ell)}$$

Uncertainties on $|V_{cb}|$ drop out in ratio. Test of LU. Currently **σ(R(D*))~9%** and **σ(R(D))~12%.**

Both **Belle-2** and **LHCb U1** expect to reach a **~2% precision** on **R(D)** and **R(D*).** Moreover **LHCb U2** can also test LU in **B_c** and **Λ_c** decays with good precision, and **differential measurements!**

If current experimental central values stay, these future experiments should have a **clear NP observation**.





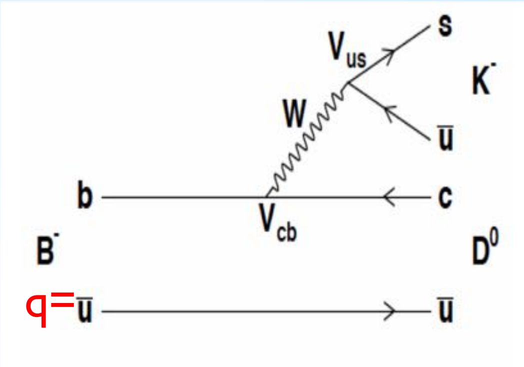
V_{ub} phase: Experimental Strategies

q=u: with D and anti-D in same final state

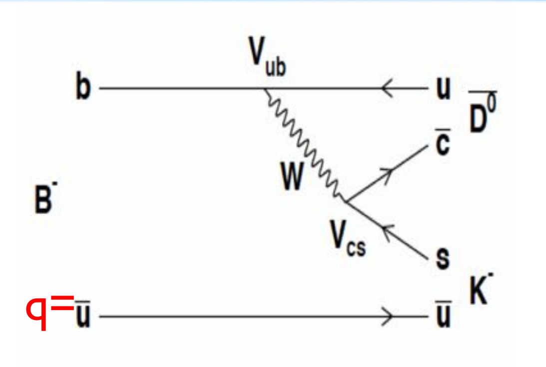
$B^{\pm} \rightarrow DX_s$ X_s={$K^{\pm}$, $K^{\pm}\pi\pi$, $K^{*\pm}$,…}

q=s: Time dependent CP analysis.
Inteference between B_s mixing and decay.

$B_s \rightarrow D^{\pm}_s K^{\mp}$



($|V_{cb}V_{us}|\alpha\lambda^3$)



($|V_{ub}V_{cs}|\alpha\lambda^3$)

In the case **q=u** the **experimental analysis is relatively simple**, selecting and counting events to measure the ratios between B and anti-B decays. NP contributions to D mixing are assumed to be negligible or taken from other measurements.

However the extraction of γ requires the knowledge of the ratio of amplitudes **($r_{B(D)}$)** and the difference between the strong and weak phase in B and D decays **($\delta_{B(D)}$)→charm factories input (CLEO/BESIII).**

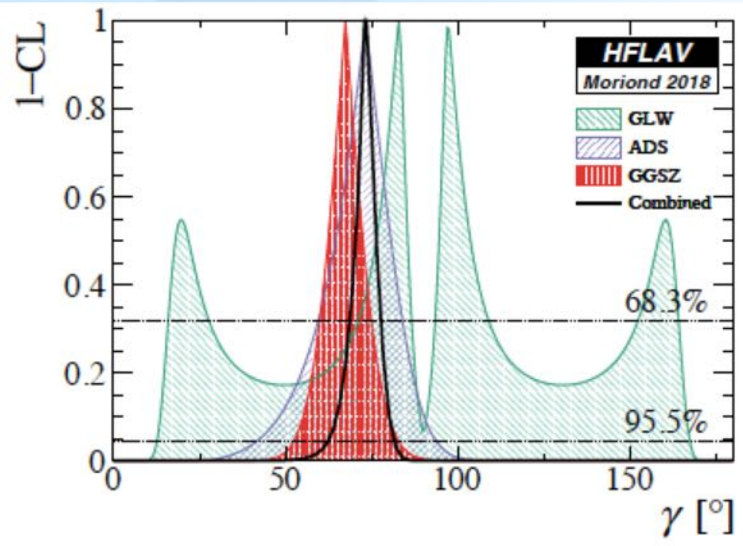
In the case **q=s**, a time dependent CP analysis is needed to exploit the interference between B_s mixing and decay. NP contributions to the mixing needs to be taken from other measurements ($B_s \rightarrow J/\Psi\varphi$).

V_{ub} phase: current status and future prospects

The most precise determination of γ from B-factories is from the Dalitz analysis (**GGSZ**) of the decays $B^{\pm} \to D(K_s\pi\pi) K^{\pm}$. Combining with the decays $B \to D_{CP}X_s$ (**GLW)** and the decays $B \to D(K^+\pi^-(\pi^0))X_s$ (**ADS**): BABAR: **$\gamma = 69\ ^{+17}_{-16}$°** ($r_B(DK)=0.092\pm0.013$)

Belle : **$\gamma = 68\ ^{+15}_{-14}$°** ($r_B(DK)=0.112\pm0.015$)

$$\tan\gamma \approx \frac{\eta}{\rho}$$

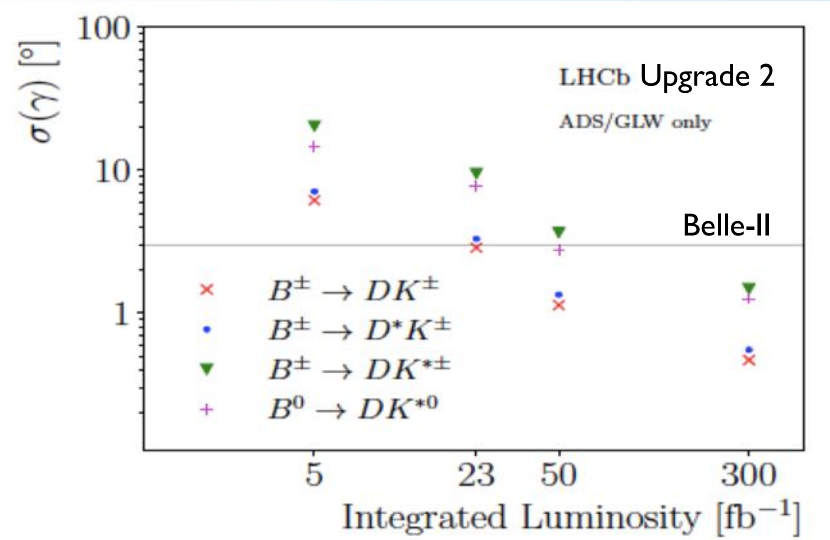


LHCb preliminary combination using mostly only RUN1 data dominates already now the world average:

$\gamma = 74.0^{+5.0}_{-5.8}$° ($r_B(DK)=0.099\pm0.005$) LHCb-CONF-2018-002

Excellent internal compatibility of GGSZ and GLW/ADS. Slight tension with still more precise loops determination:

$\gamma(\text{loops}) = 65.3^{+1.0}_{-2.5}$°



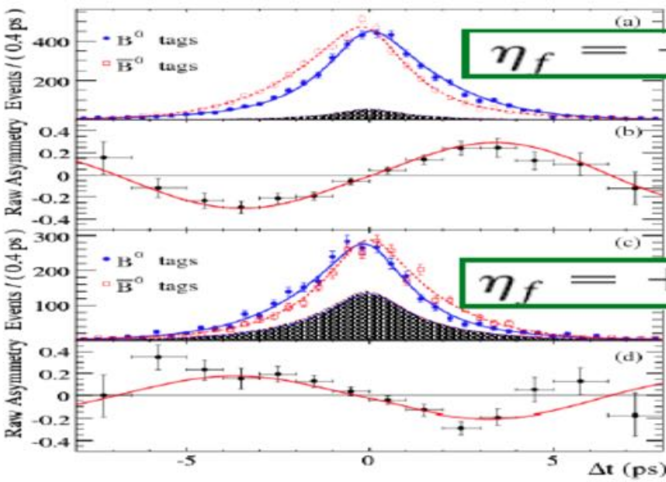
Belle-II projections reach **σ(γ)~3°** while **LHCb U1** should reach **σ(γ)~1°,** and **LHCb U2** should reach an **ultimate precision σ(γ)~0.35°,** which will allow for a comparison **of loops vs tree with similar precision.**

ΔF=2 Box Measurements

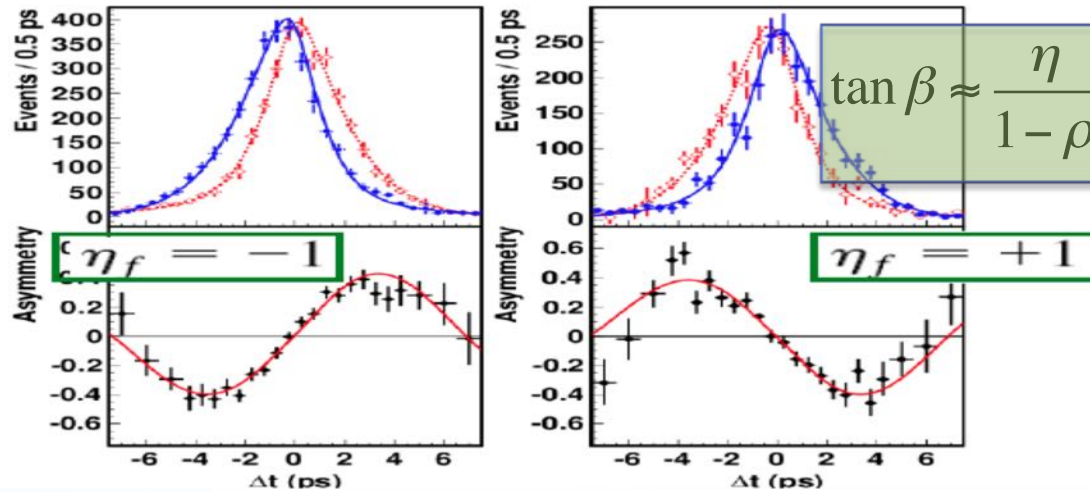
ΔF=2 box in b→d transitions: V_{td} phase

$B \to J/\psi K_s(K_L)$

BABAR PRD 79 (2009) 072009



BELLE PRL 108 (2012) 171802

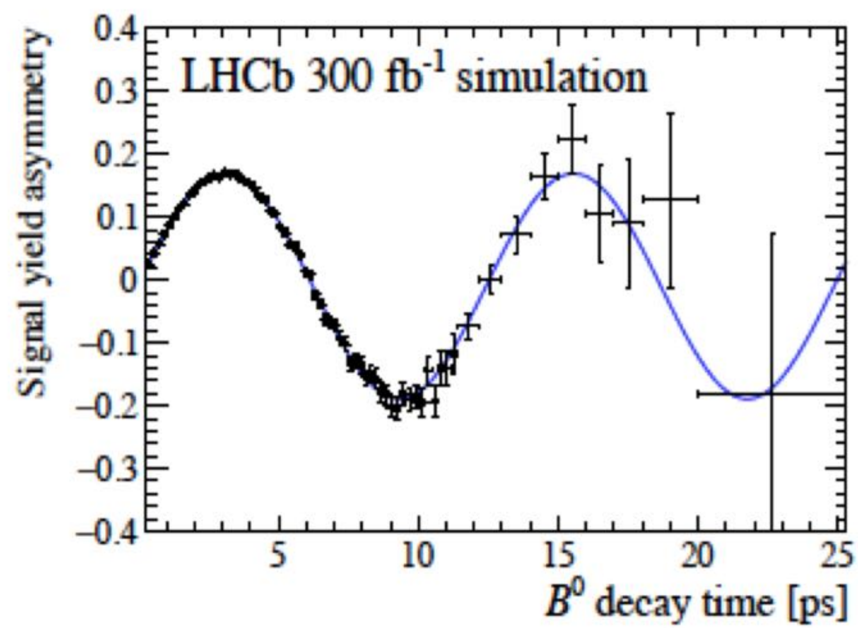


B-factories and LHCb (RUN-1) have measured **β** using J/ψK modes with similar precision :

sin(2β) = 0.690 ± 0.018 (2.6% precision)

However if there is NP affecting B_d mixing, the measurement is in reality **($\beta + \varphi_{bd}^{NP}$). Need to compare to tree level determination.**

LHCb U1 and **Belle-II** will each reach **~0.8%** while **LHCb U2** potential is **~0.4%!** . Statistics should allow to control penguin contributions.



ΔF=2 box in b→s transitions: V_{ts} phase

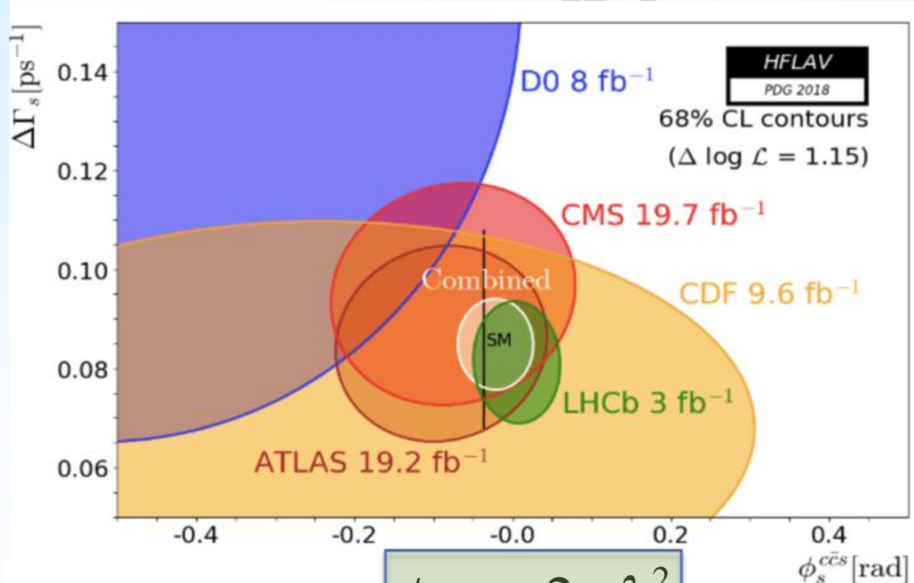
Angular analysis is needed in **B_s→J/ΨΦ** decays, to disentangle statistically the **CP-even and CP-odd** components.

LHCb results most precise, but also ATLAS/CMS contribute to the combination using **B_s→J/ΨKK:**

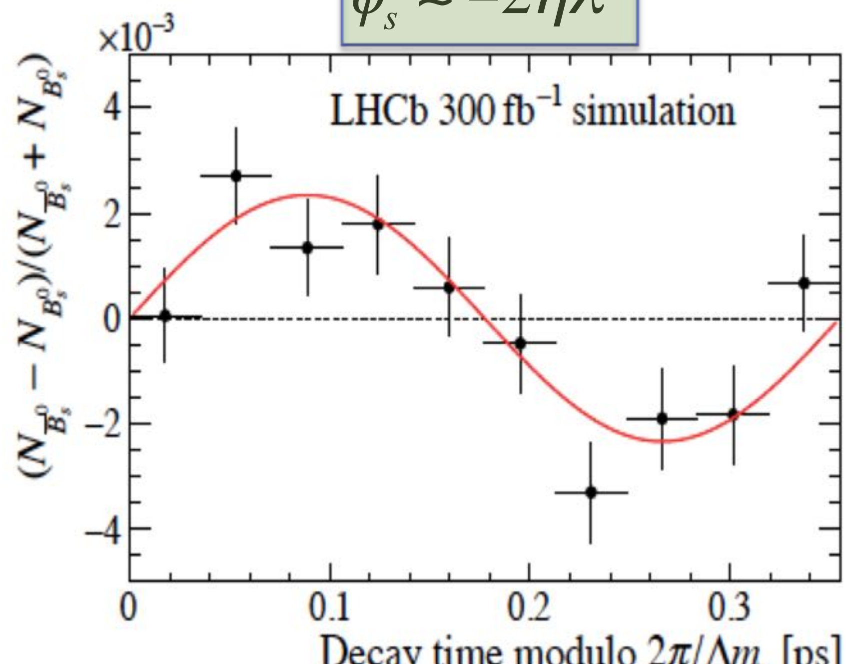
φ_s = (-21±31) mrad

to be compared with **φ_s = (-37±2)mrad** using *"tree level measurements"*.

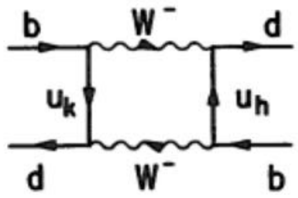
ATLAS/CMS may be able to reach a sensitivity better than **20 mrad with 3ab^{-1}**.
LHCb U2 sensitivity expected to be better than **3 mrad with 300 fb^{-1}** → Should allow for a **meaningful trees vs loop comparison** also for **b→s** transitions.



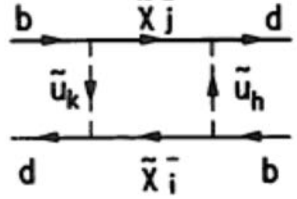
$$\phi_s \approx -2\eta\lambda^2$$



NP in ΔF=2 box status today



SM: $\frac{C_{SM}}{m_W^2}$



NP: $\frac{C_{NP}}{\Lambda^2}$

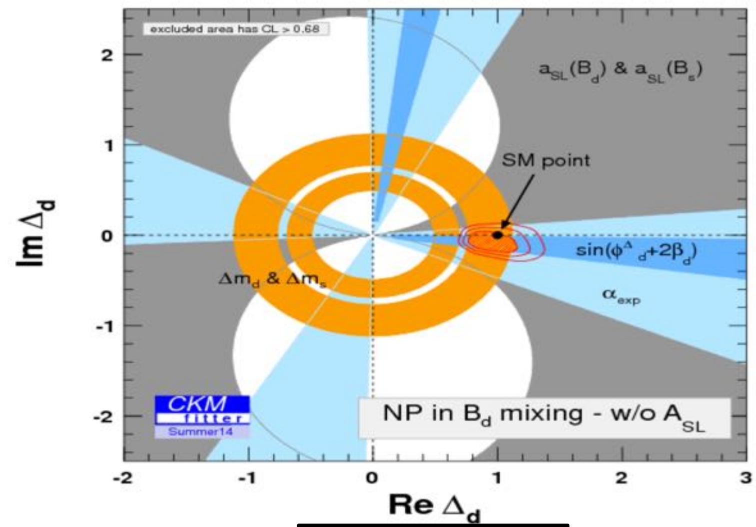
$$\langle B_q^0 | M_{12}^{SM+NP} | \overline{B}_q^0 \rangle \equiv \Delta_q^{NP} . \langle B_q^0 | M_{12}^{SM} | \overline{B}_q^0 \rangle$$

$$\Delta_q^{NP} = \mathrm{Re}(\Delta_q) + i \; Im(\Delta_q) = |\Delta_q| e^{i\phi_q^{\Delta}}$$

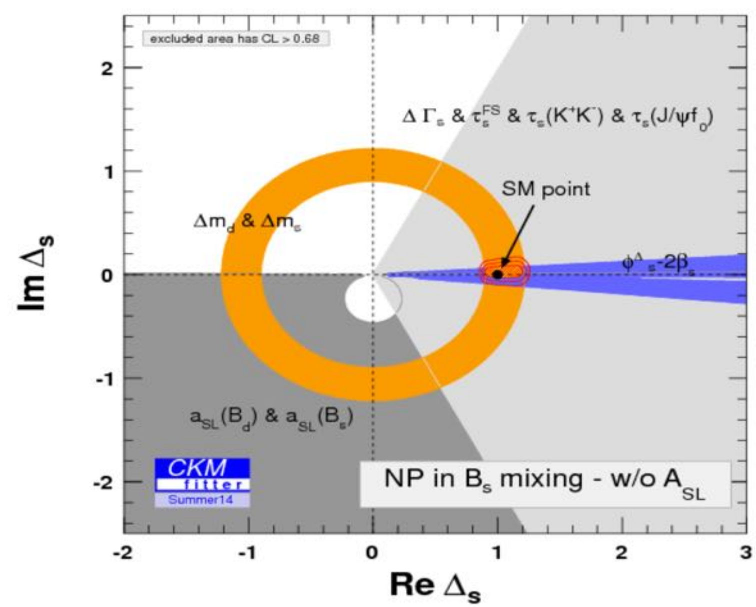
No significant evidence of NP in B_d or B_s mixing . Remember that what is named SM prediction in these plots, is in fact the determination from other measurements (tree level).

New φ^{Δ}_q in box diagrams constrained @95%CL to be <7° (<5°) for $B_d(B_s)$.

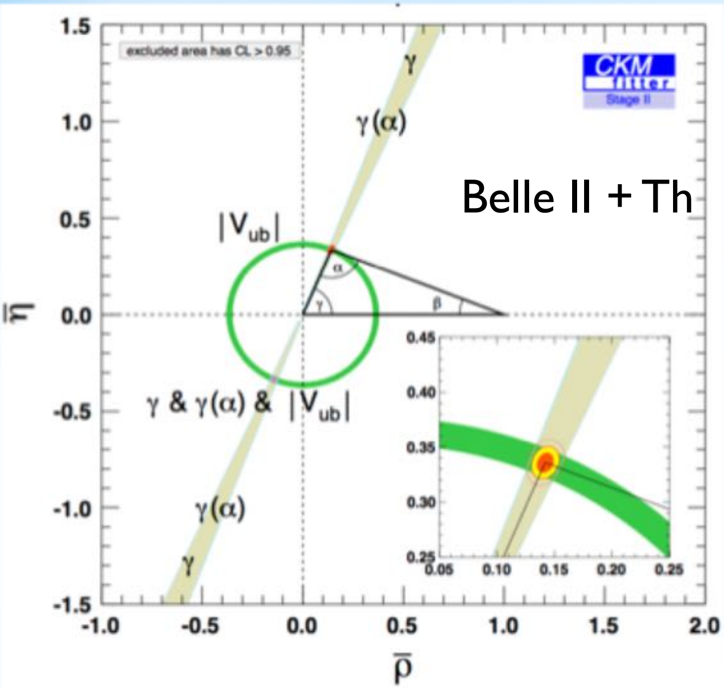
Need to increase precision to disentangle NP phases of few degrees in B_d and B_s mixing

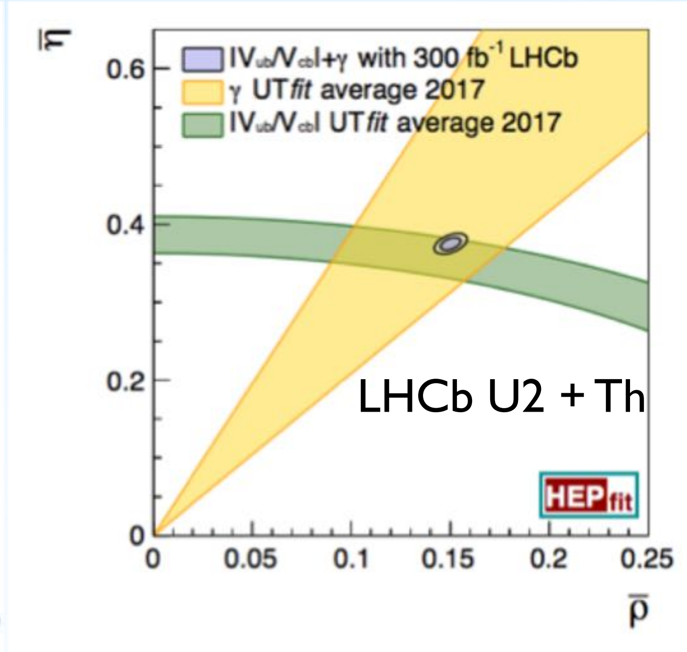


arXiv:1501.05013



NP in ΔF=2 box status ~2035

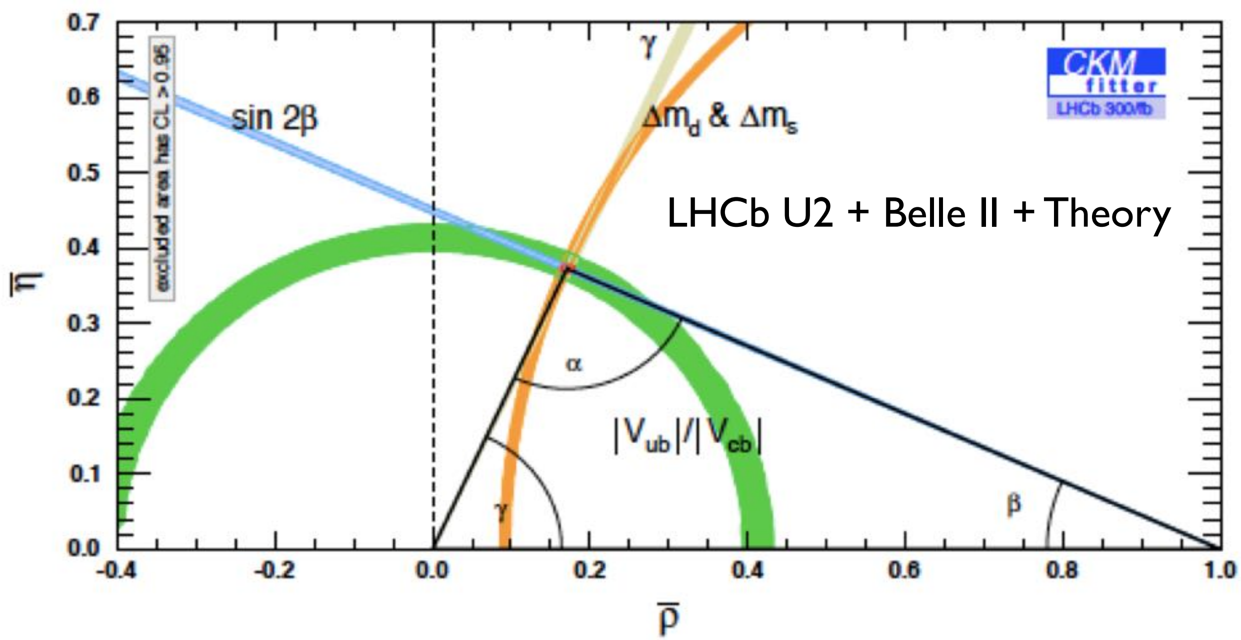




Circa 2035

<u>From tree processes:</u>
σ(ρ) ~ 2% , σ(η) ~ 1%

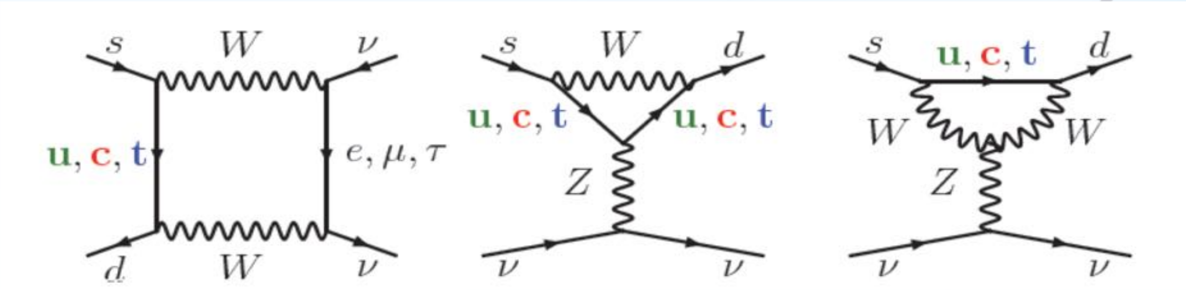
<u>From loop processes:</u>
σ(ρ) ~ 1% , σ(η) ~ 0.5%



$\Delta F=1$ EW Penguins and LNU in FCNC

$\Delta F=1$ EW penguins in s→d transitions: Kaon decays

s→d ($|V_{ts}V_{td}|\alpha\lambda^5$)



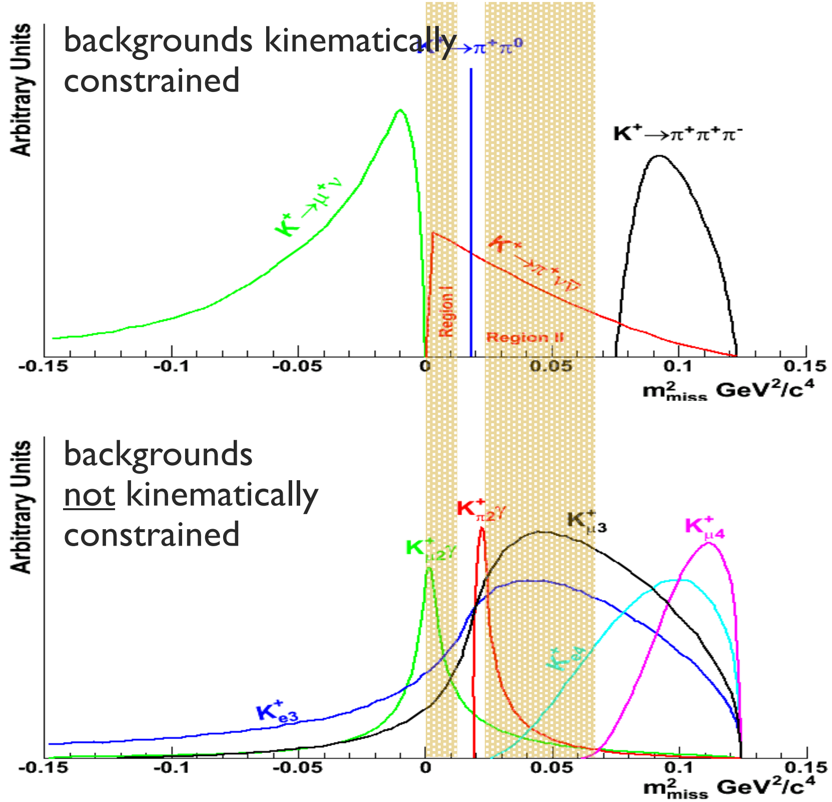
$K^+ \to \pi^+ \nu\nu$ and $K \to \pi^0 \nu\nu$ are certainly the "cleanest" Kaon decays (not long distance pollution affecting lepton modes, dominated by a single operator) and provide sensitivity to $|V_{td}|$.

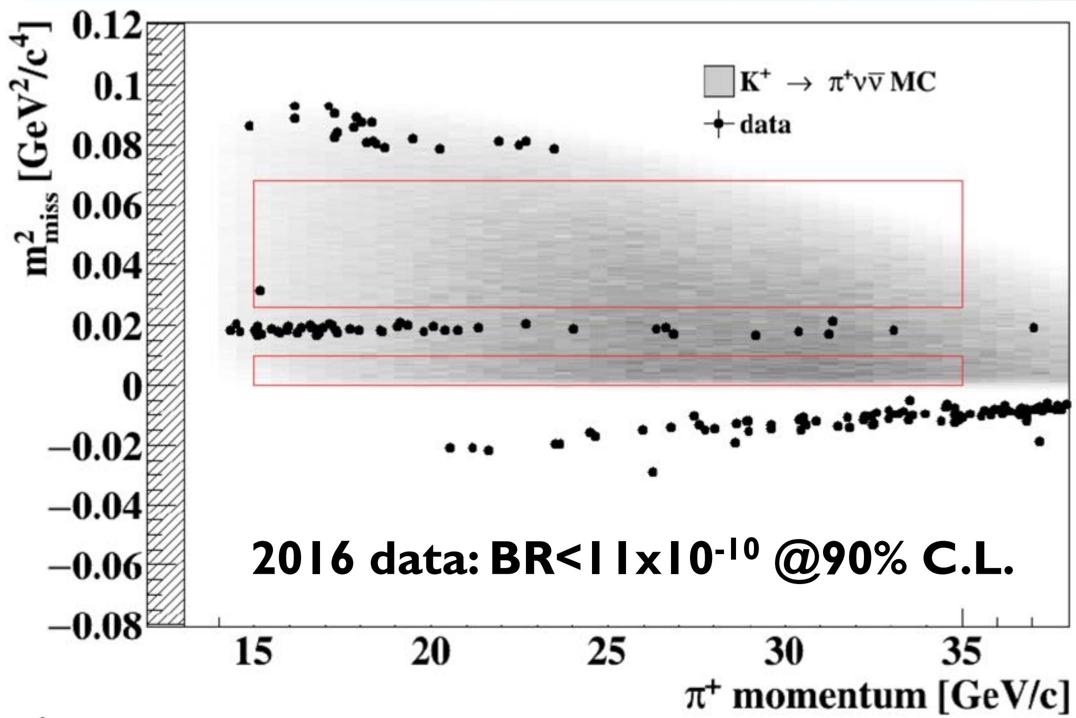
$BR_{TH}(K^+ \to \pi^+ \nu\nu) = (8.4 \pm 1.0) \times 10^{-11}$ and **$BR_{TH}(K^0 \to \pi^0 \nu\nu) = (3.4 \pm 0.6) \times 10^{-11}$** both uncertainties are expected to be below 10% ultimately. The charged(neutral) mode is sensitive to CP-conserving(violating) NP.

BNL E787/E949 observed 7 $K^+ \to \pi^+ \nu\nu$ candidates → **$BR=(17 \pm 11) \times 10^{-11}$**
KEK E391 had no $K^0 \to \pi^0 \nu\nu$ candidates → **$BR<2.6 \times 10^{-8}$ @90% C.L.**

NA62 data taking 2016-2018. Only 2016 (10^{11} K^+ decays) analyzed so far. Expect by the **end of 2018 ~x80 times more K^+** decays on tape.
KOTO data taking 2012, 2015-2018. Only 2015 (10^9 K^0 decays) analyzed so far. Already **>x2 times more K^0** decays on tape.

NA62 decay in flight technique

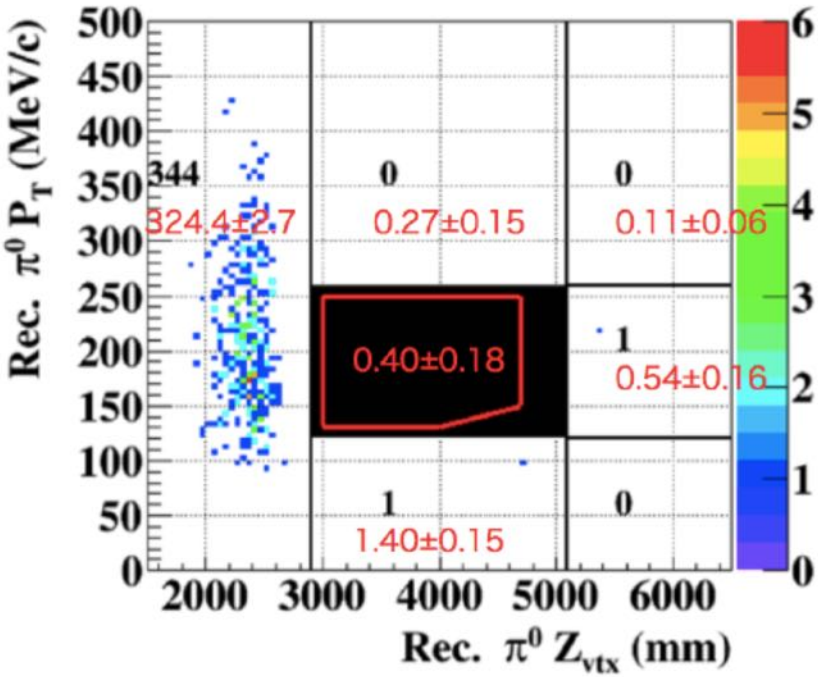




Process	Expected events in R1+R2
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{\mathbf{stat}} \pm 0.01_{\mathbf{syst}}$

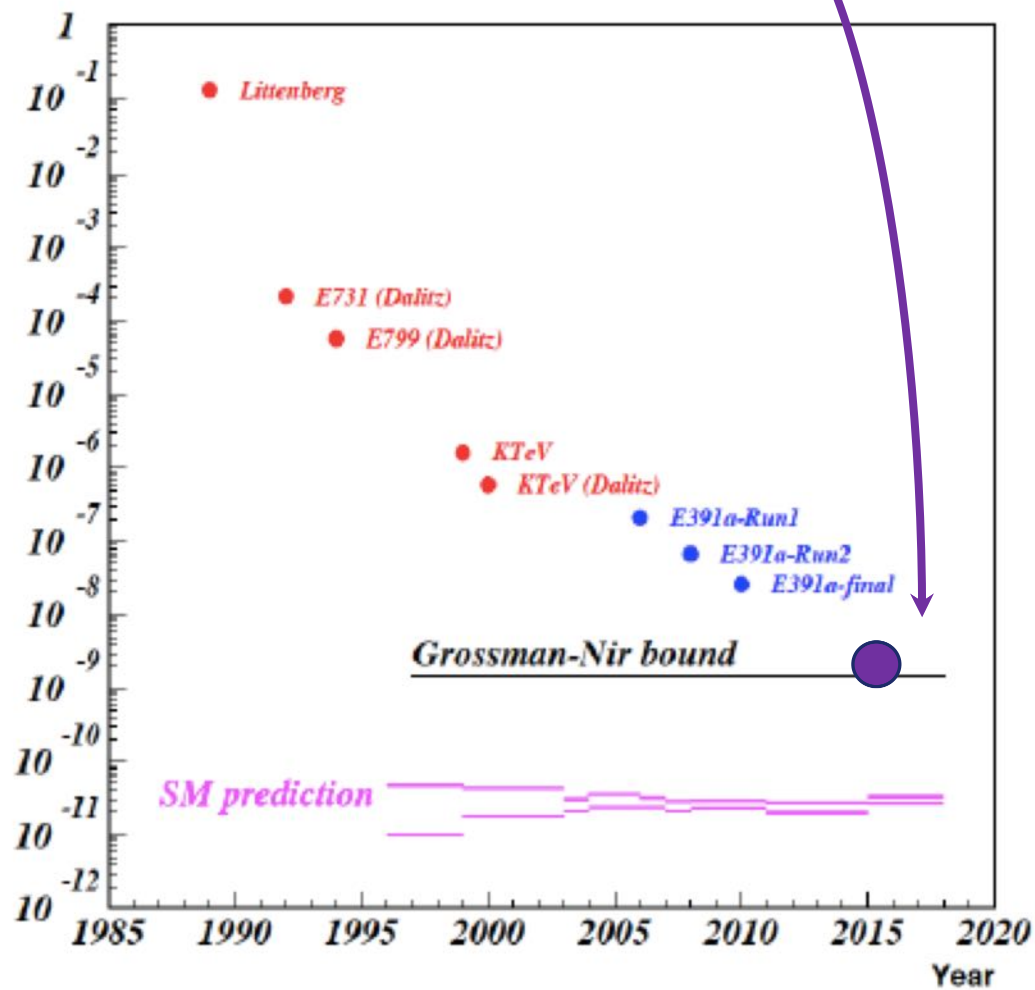
Expect to have **~20 SM** signal events, and **improve S/B** (in particular reducing upstream bkg). A measurement at the **10% level** of the branching ratio does not seem too way off.

KOTO: $K_L \rightarrow \pi^0 \nu\nu$



With **2015** data, **0 events** observed, 0.4 bkg expected, negligible SM signal:

BR<3.0×10^{-9} @90% C.L.

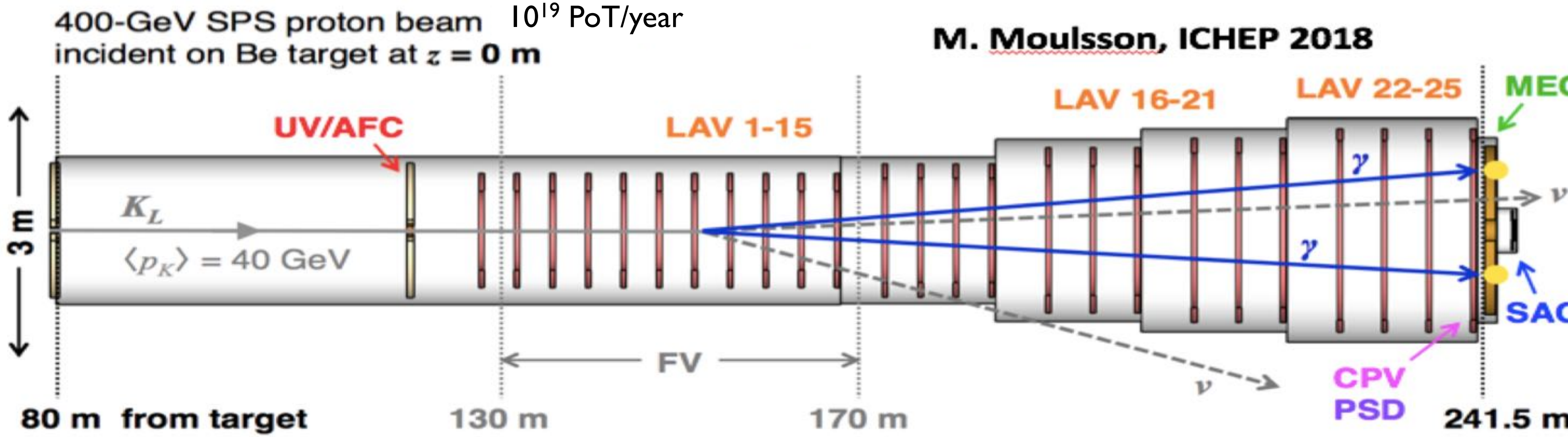


With **2015-2018** data already expect to improve **sensitivity by x2**, and reach the Grossman-Nir bound!

After 2018 summer, plans to **improve detector and increase power** from 50 kW to 90 kW. Reach **10^{-10} in a timely manner**.

KLEVER: future $K_L \to \pi^0 \nu\nu$

10^{19} PoT/year



KLEVER target sensitivity:
5 years starting Run 4

60 SM $K_L \to \pi^0 \nu\nu$
$S/B \sim 1$

δBR/BR($\pi^0 \nu\nu$) ~ 20%

Main detector/veto systems:

UV/AFC	Upstream veto/Active final collimator
LAV1-25	Large-angle vetoes (25 stations)
MEC	Main electromagnetic calorimeter
SAC	Small-angle vetoes
CPV	Charged particle veto
PSD	Pre-shower detector

Small-angle photon calorimeter system (SAC)

- Rejects high-energy γs from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

Beam comp.	Rate (MHz)	Req. $1-\varepsilon$
$\gamma, E > 5$ GeV	50	10^{-2}
$\gamma, E > 30$ GeV	2.5	10^{-4}
n	430	–

ΔF=1 Higgs penguins in b→d,s transitions

The pure leptonic decays of **K,D and B** mesons are an interesting case of EW penguin. The **helicity suppression** of the vector(-axial) terms, makes these decays particularly sensitive to **new (pseudo-)scalar** interactions →**Higgs penguins!**

These decays are well predicted theoretically, and experimentally are exceptionally clean. Within the SM,

$BR_{SM}(B_s \to \mu\mu) = (3.66 \pm 0.23) \times 10^{-9}$
$BR_{SM}(B_d \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$

PRL 112 (2014) 101801

The combined RUN-1 analyses from LHCb and CMS were published in Nature 522, 68 (2015), as the first **5σ** observation of the B_s decay, compatible with SM. ATLAS also produced compatible results with RUN-1 data although less precise.

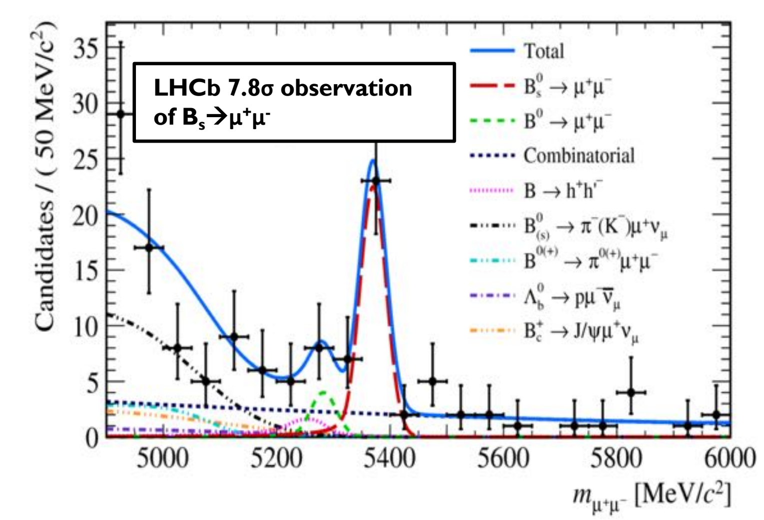
LHCb has updated the RUN-1 analysis **including 1.7 fb^{-1} RUN-2 data** and a first measurement of the effective $B_s \to \mu\mu$ lifetime, reaching a **~8σ** observation of the B_s mode by a single experiment:

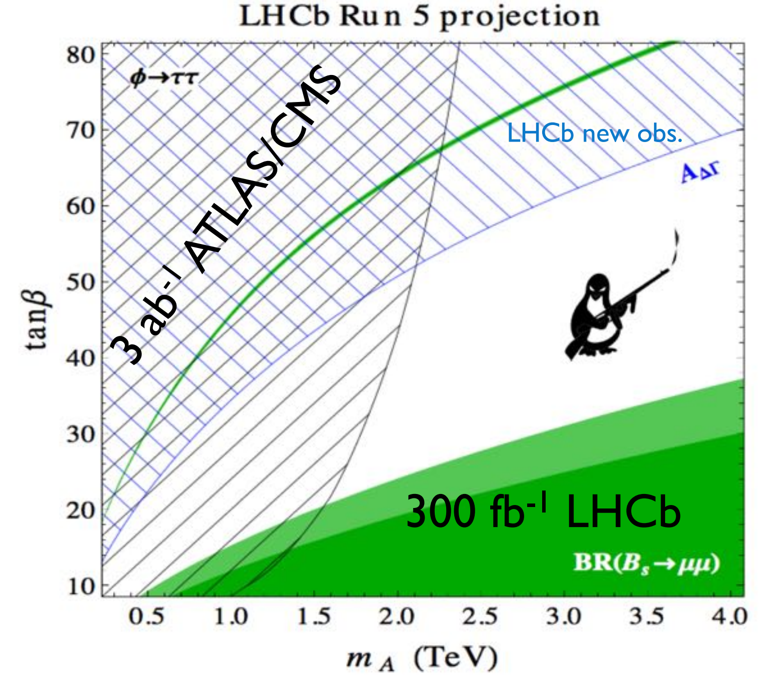
$BR(B_s \to \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$
$BR(B_d \to \mu\mu) < 3.4 \times 10^{-10}$ @95%C.L.

arXiv:1703.05747

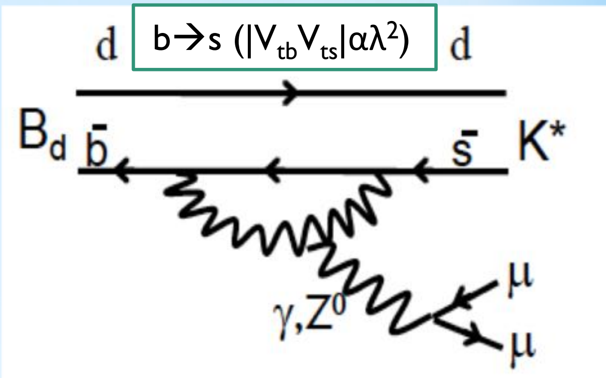
Next in the priority list is to observe the B_d mode, and measure **R= BR($B_d \to \mu\mu$) / BR($B_s \to \mu\mu$).** Needs **HL-LHC** to reach interesting precision: **CMS** can reach **20%** with 3ab^{-1}, and **LHCb U2** can reach **10%** with 300fb^{-1}. Any deviation from the SM prediction known within 1%, would imply **NP with non-MFV** structure.

Large statistics will allow to measure new observables: effective lifetime (~2%), CPV,…





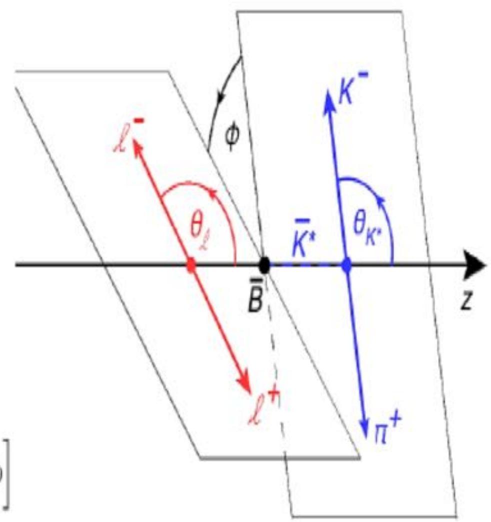
$B \to K^* \mu^+\mu^-$ is the golden mode to test new vector(-axial) couplings in b→s transitions.



K*→Kπ is self tagged (if your experiment has hadron ID), hence angular analysis ideal to test helicity structure.

Sensitivity to C_7, C_9 and C_{10} and their primed counterparts.

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^3(\Gamma+\bar{\Gamma})}{d\vec{\Omega}}\Big|_P = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_l - F_L\cos^2\theta_K\cos2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos2\phi + S_4\sin2\theta_K\sin2\theta_l\cos\phi + S_5\sin2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_l + S_7\sin2\theta_K\sin\theta_l\sin\phi + S_8\sin2\theta_K\sin2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin2\phi\Big]$$

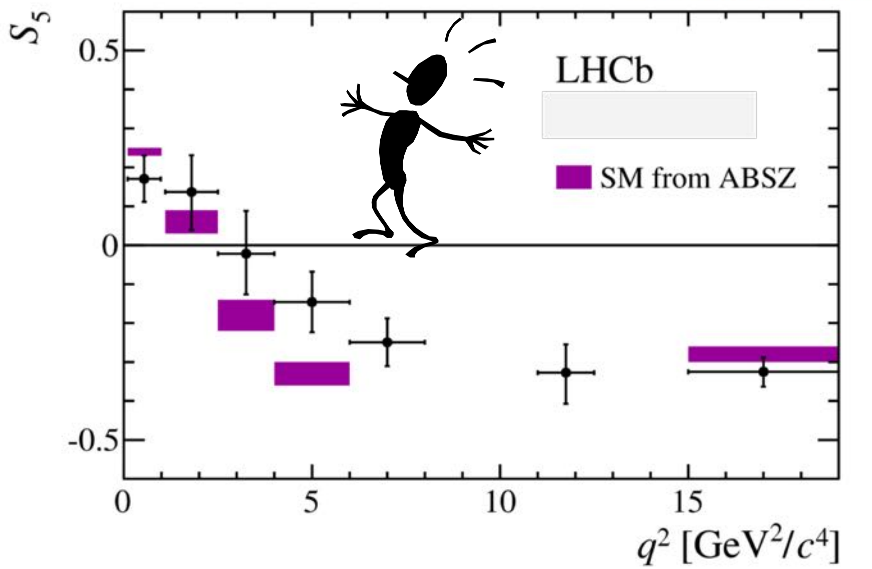


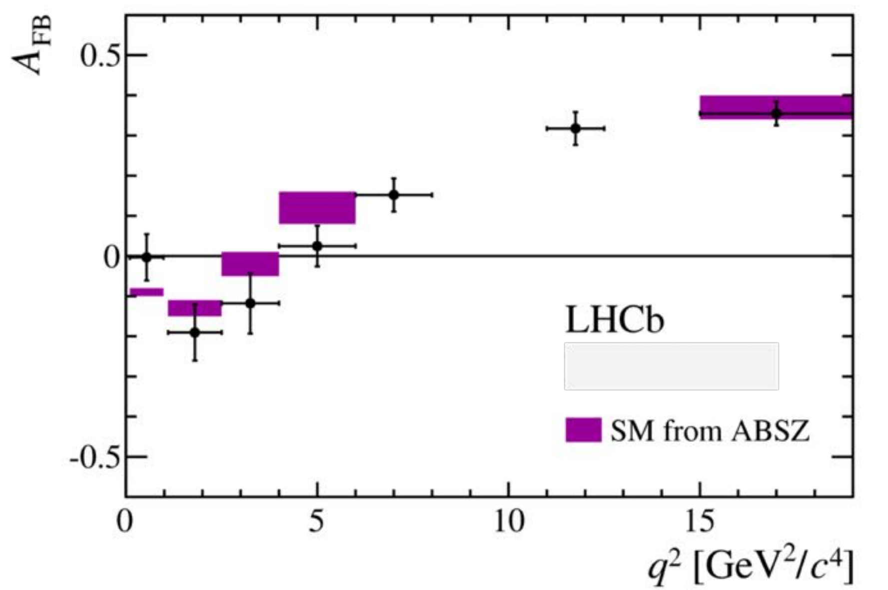
	sens. at low q^2	sens. at high q^2
F_L	$C_{7,9}, C'_{9,10}$	$C'_{9,10}$
A_{FB}	C_7, C_9	$C_{9,10}, C'_{9,10}$
S_3	$C'_{7,10}$	$C'_{9,10}$
S_4	$C_{7,10}, C'_{7,10}$	$C'_{9,10}$
S_5	$C_{7,9}, C'_{7,9,10}$	$C_9, C'_{9,10}$

Results from **B-factories and CDF** were very much limited by the statistical uncertainty. **LHCb, ATLAS and CMS** already had the largest sample after RUN-I.

JHEP 02 (2016) 104

SM: Aoife Bharucha, Straub, Zwicky, arXiv:1503.05534





LHCb « Tour de force » full angular analysis performed for the first time using RUN-I data.

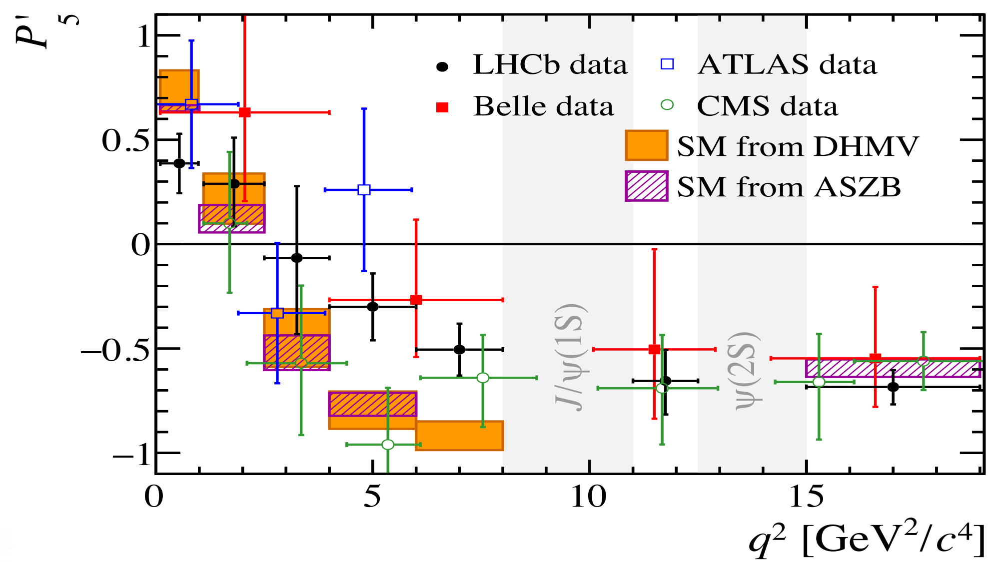
Most of the distributions are in good agreement with the expectations, with only some hints for deviations for the CP-averaged measurements of S_5 and A_{FB}.

$$S_5 \sin 2\theta_K \sin\theta_l \cos\phi$$

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

$$\tfrac{4}{3} A_{FB} \sin^2\theta_K \cos\theta_l$$

Belle P'_5 (1-D, electrons+muons) results in 2016 also seem to confirm LHCb results, albeit with large uncertainties.



ΔF=1 EW penguins in b→s transitions: Implications

The overall fit of b→sμμ measurements assuming the SM has a p-value of ~1%. Few measurements have a pull larger than 2σ

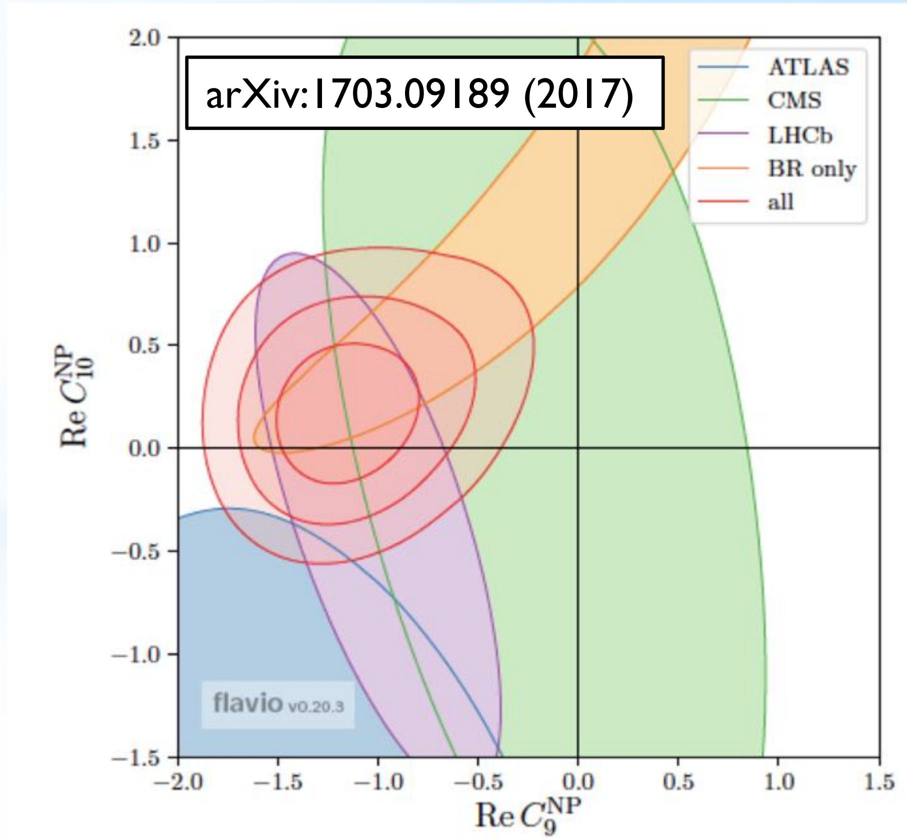
EPJ 75: 382 (2015)

Decay	Obs.	q^2 bin	SM pred.	Measurement		Pull
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	[1, 6]	0.48 ± 0.06	0.23 ± 0.05	LHCb	+3.1
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	[2, 4.3]	0.81 ± 0.02	0.26 ± 0.19	ATLAS	+2.9
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	[16, 23]	0.93 ± 0.12	0.37 ± 0.22	CDF	+2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	[4, 6]	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	−2.2
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	[4, 6]	0.54 ± 0.08	0.26 ± 0.10	LHCb	+2.1

While it could very well be that theoretical and/or experimental uncertainties are underestimated, it is also a fact that allowing for non-SM Wilson coefficients improves the p-value. For instance, reducing **C_9^{SM} by 25%** improves the quality of the fit to p~11%.

Coeff.	best fit	1σ	2σ	pull
C_9^{NP}	−1.21	[−1.41, −1.00]	[−1.61, −0.77]	5.2σ
C'_9	+0.19	[−0.01, +0.40]	[−0.22, +0.60]	0.9σ
C_{10}^{NP}	+0.79	[+0.55, +1.05]	[+0.32, +1.31]	3.4σ
C'_{10}	−0.10	[−0.26, +0.07]	[−0.42, +0.24]	0.6σ

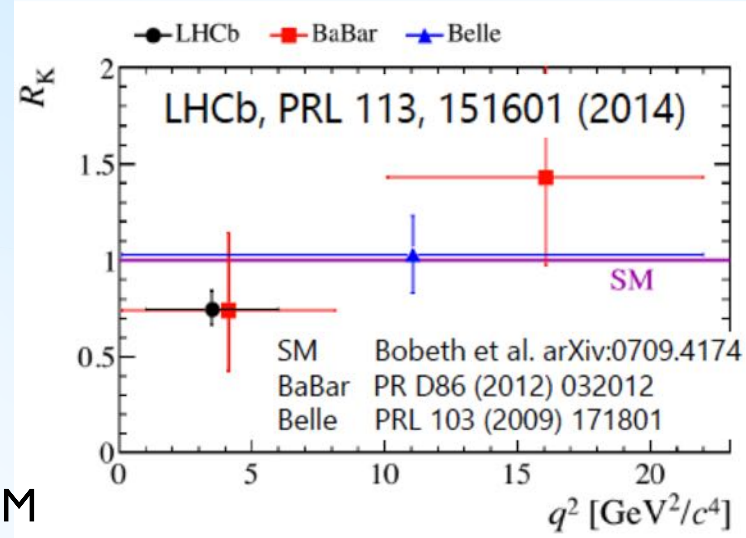
$$\text{pull} \equiv \sqrt{\chi^2_{\text{SM}} - \chi^2_{\text{best fit}}}$$



While NP could induce lepton non-universality in b→s ll transitions, hadronic uncertainties cannot do so. RUN-1 **LHCb** measurement of $\mathbf{R_K}$ **(low $\mathbf{q^2}$):**

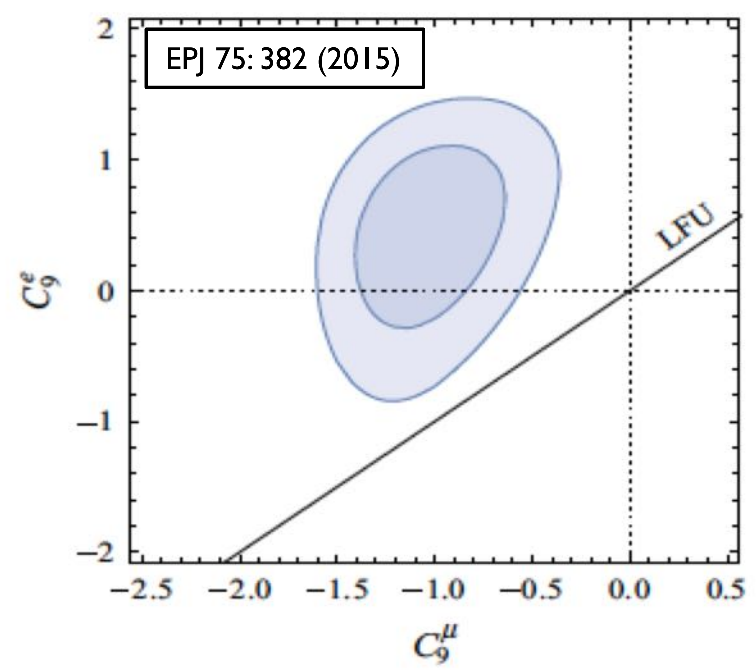
$$R_K = \frac{BR(B_u^+ \to K^+\mu^+\mu^-)}{BR(B_u^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.})$$

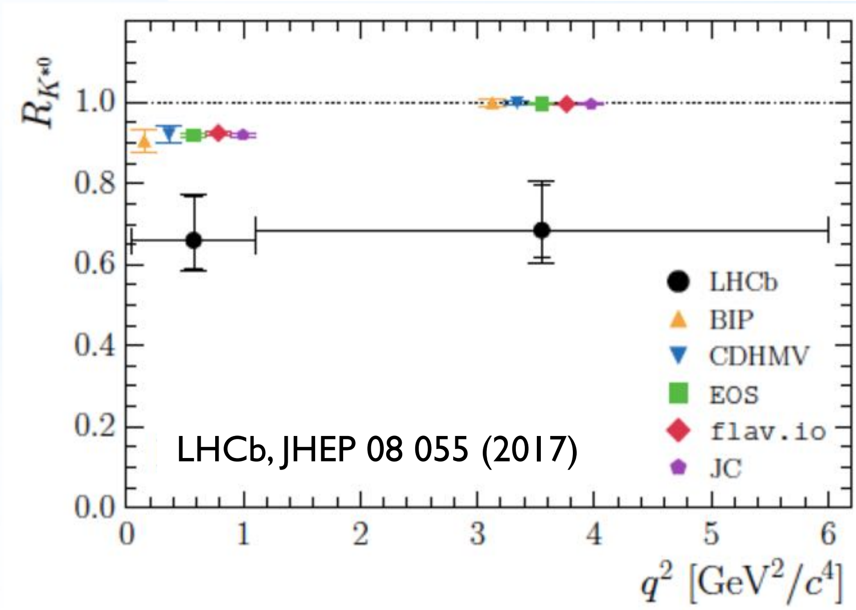
Shows a discrepancy (2.6σ) with the SM prediction.



B±→K±ee agrees with SM. A global fit, hence, shows C_9^e ~ SM while C_9^μ ~ non-SM. Using the fitted values for the Wilson coefficients, one can predict a similar ~(20-30)% reduction on:

$$R_K = \frac{Br(B \to K\mu^+\mu^-)}{Br(B \to Ke^+e^-)},\quad R_{K^*} = \frac{Br(B \to K^*\mu^+\mu^-)}{Br(B \to K^*e^+e^-)},\quad R_\phi = \frac{Br(B_s \to \phi\mu^+\mu^-)}{Br(B_s \to \phi e^+e^-)}$$

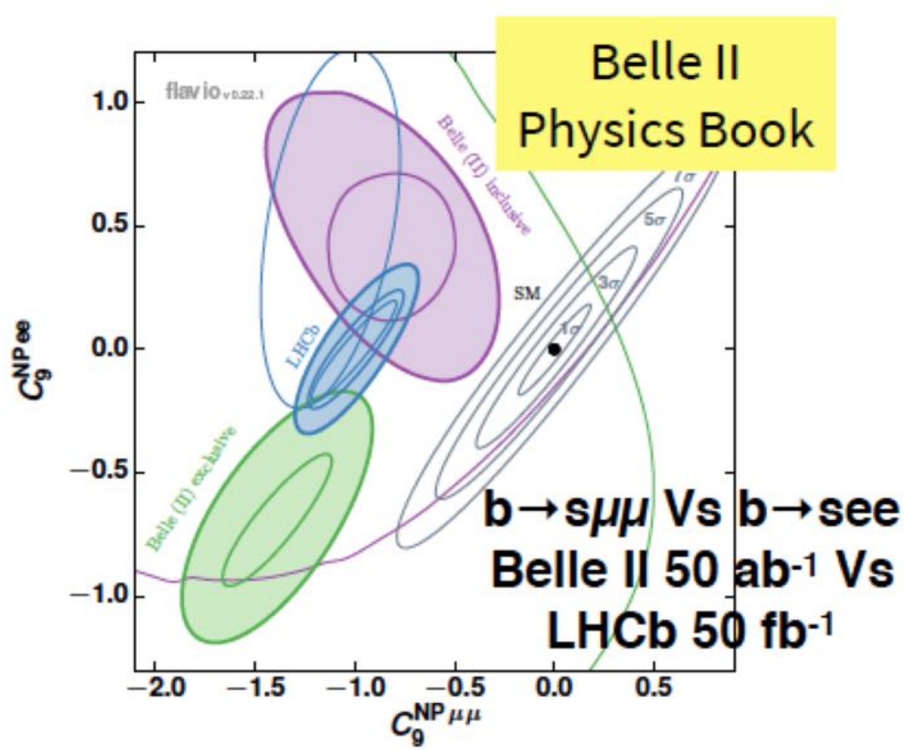


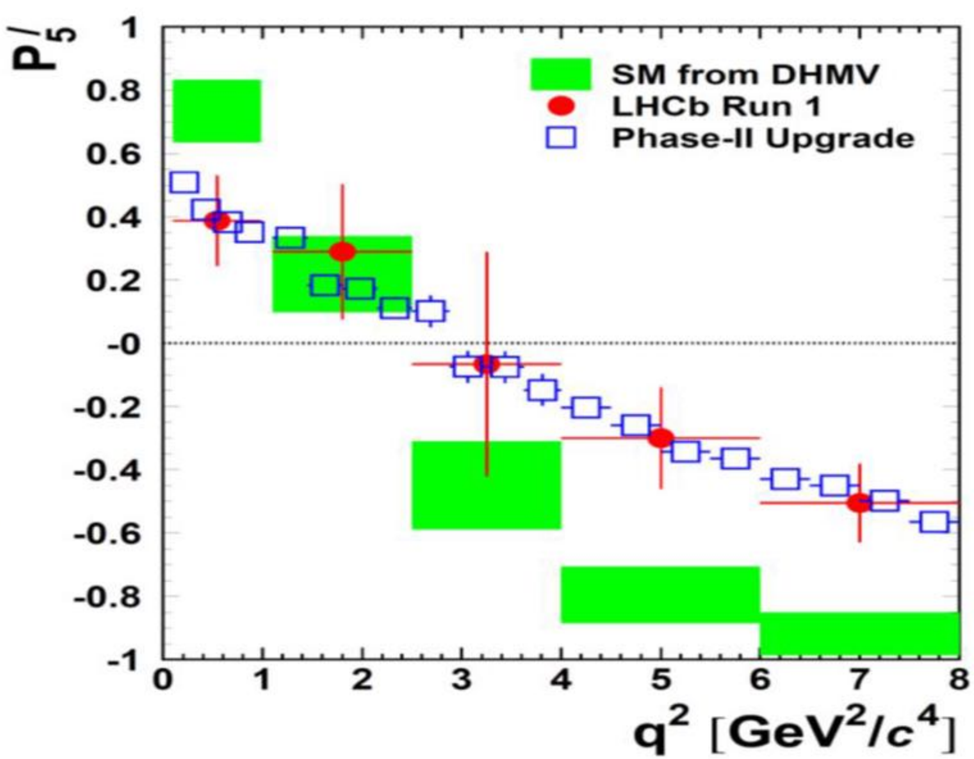


What can the future experiments do?

With the current size of LNU effects, **Belle-II** and **LHCb UI** should **clearly stablish NP**. However, for a **comprehensive study** including many **other b→sll transitions**, and for a clear observation of LNU effects in angular observables **(b→see)** the **LHCb U2 is necessary**.

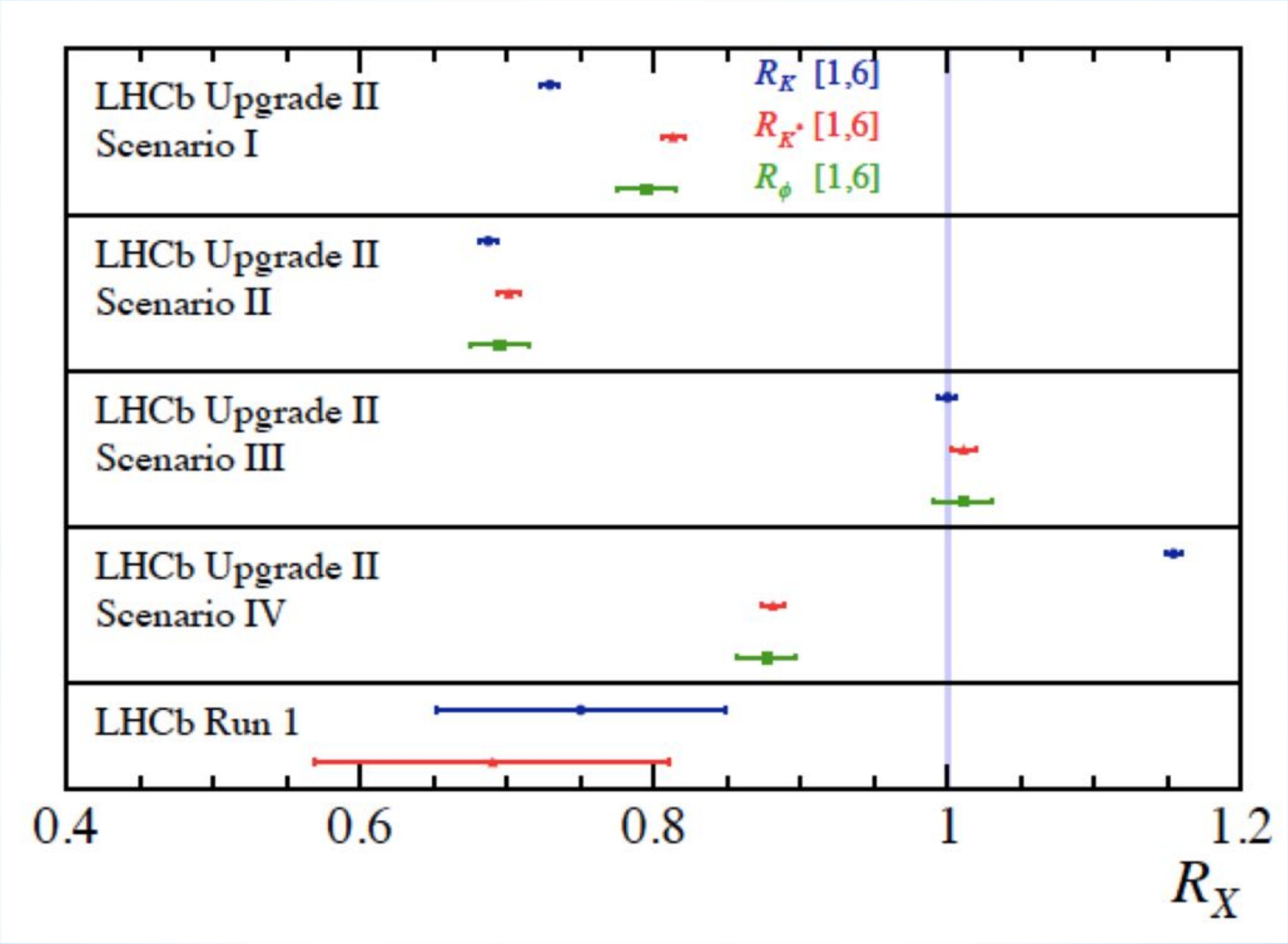
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–

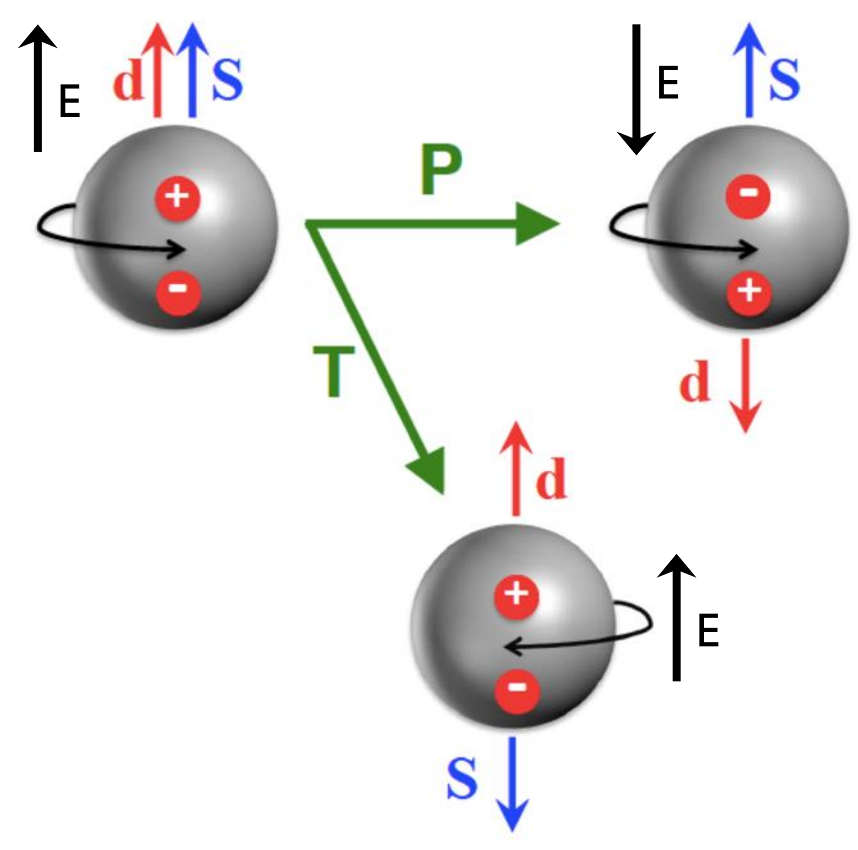




What can the future experiments do?

LHCb U2 statistics (and **improved calorimeter**) needed for a meaningful **angular analysis in b→see** transitions. Access to **several other LNU tests** with enough precision should allow to **discriminate NP scenarios**!





ΔF=0 EDM Measurements

Future Nucleon EDMs

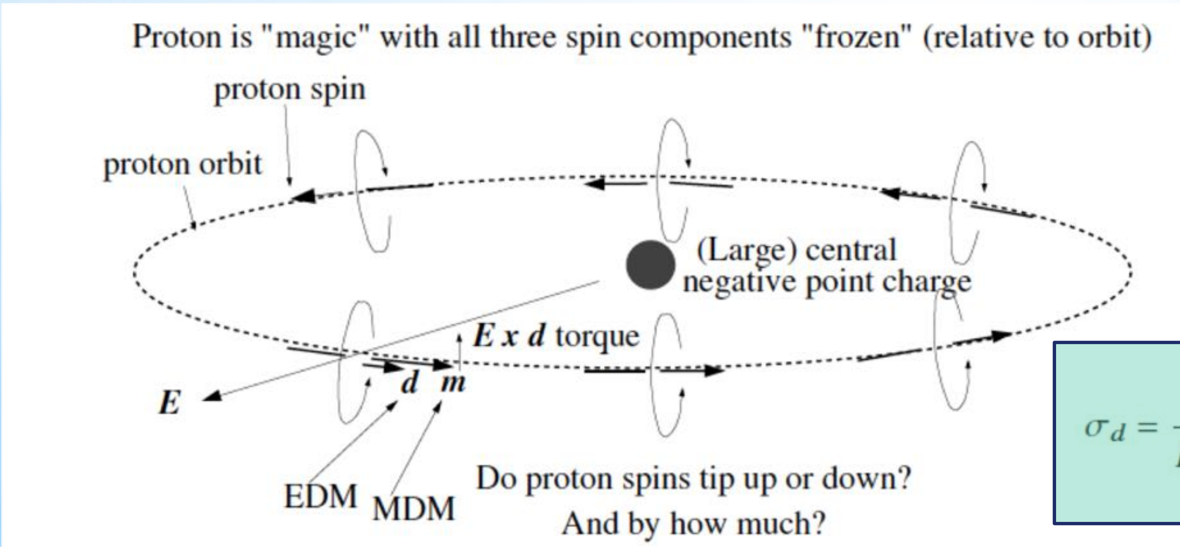
Best current sensitivity on neutron EDMs from ILL, with data collected (1998-2002):

$d_n < 3.6\times10^{-26}$ e cm @95% CL. PRD92 092003 (2015)

Current effort lead by PSI (**nEDM** Collaboration), expect sensitivity to **10^{-26} e cm** with data collected (2015-16). **FRM-II** reactor (Munich) could also reach similar sensitivities

Future efforts at PNPI-ILL, PSI and in particular at **SNS (Oak Ridge)** promises **$O(10^{-28})$.**

Proposal to use the **"frozen spin"** in all-electric storage ring (~500m circumference) with polarized **p at the "magic"** momentum **701 MeV**. Measure difference between **vertical polarization** at earlier and later times, extracting part of the beam in a polarimeter. Control systematics using CW and CCW beams (different effect of residual B field).

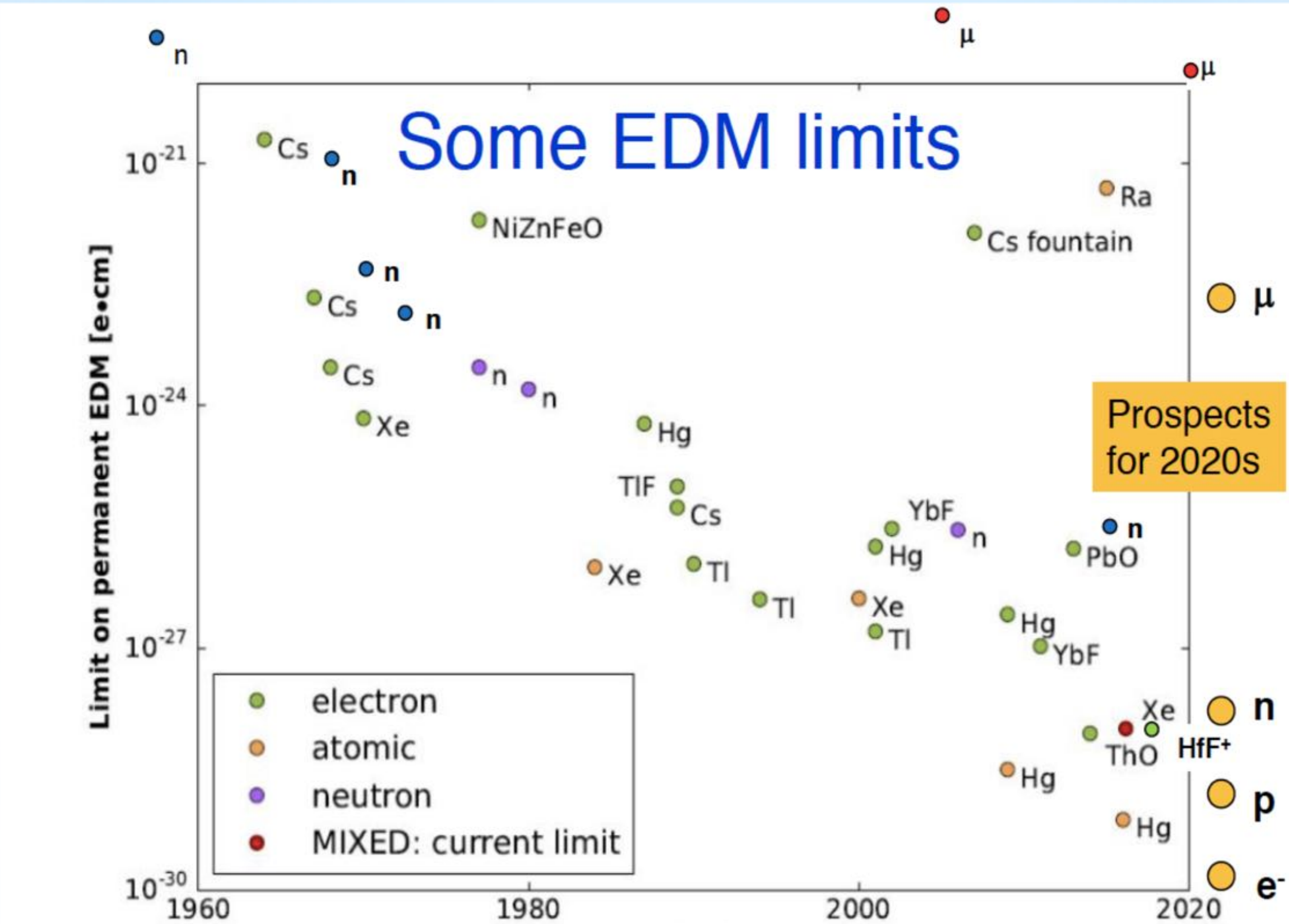


$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} + \left(-a_\mu + \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\frac{\vec{E}}{c}\right].$$

$$\vec{\omega}_{\mathrm{EDM}} = -\eta\frac{q}{2m}\left(\cancel{\vec{\beta}\times\vec{B}} + \frac{\vec{E}}{c}\right) = -\frac{\eta}{2mc}\vec{F},$$

$$\sigma_d = \frac{2\hbar}{PAE_0\sqrt{N_{\mathrm{tot,c}}T_{\mathrm{tot}}f\,\tau_{\mathrm{SCT}}}} \sim 2\times10^{-29} \text{ e cm (year)}$$

Future EDMs



Adapted from K. Jungmann et al., JPS Conf. Proc. 18(2017)011017

EDMs is the ultimate tool to seach for CP violation sources inclusively

Take Home Messages

The **SM** has **no explanation for flavour**. **FCNC** is one of the most powerful tools to get **indirect information about NP**, that ideally should provide an explanation for the quark and lepton masses and mixings parameters.

Experiments in the next **10 to 20 years** should improve by **several order of magnitude** what we know about **LFV** in **muon** and **tau** decays.

Should **improve by O(10)** the precision we have today on the **CKM parameters** in the **quark sector**, and provide **very powerful constrains in rare decays**.

New proposals to improve the precision on **nucleon EDMs** by **orders of magnitude,** may provide evidence for **new sources of CP violation**.

It could very well be that the so called **"B-anomalies"** are here to stay. We should find out soon with the LHC data and the startup of KEKB. If they are **confirmed, HL-LHC** and the **LHCb U2** are crucial to **discriminate between NP models.**

Don't give up yet!