Flavour and Precision Physics

Hang Yin

Central China Normal University

Weak interaction and Neutrino Conference

Zhuhai, China

07/03/2023

Outlines

- Introduction
- Selected topics:
  - Anomalous
  - Precision
- Summary and prospects

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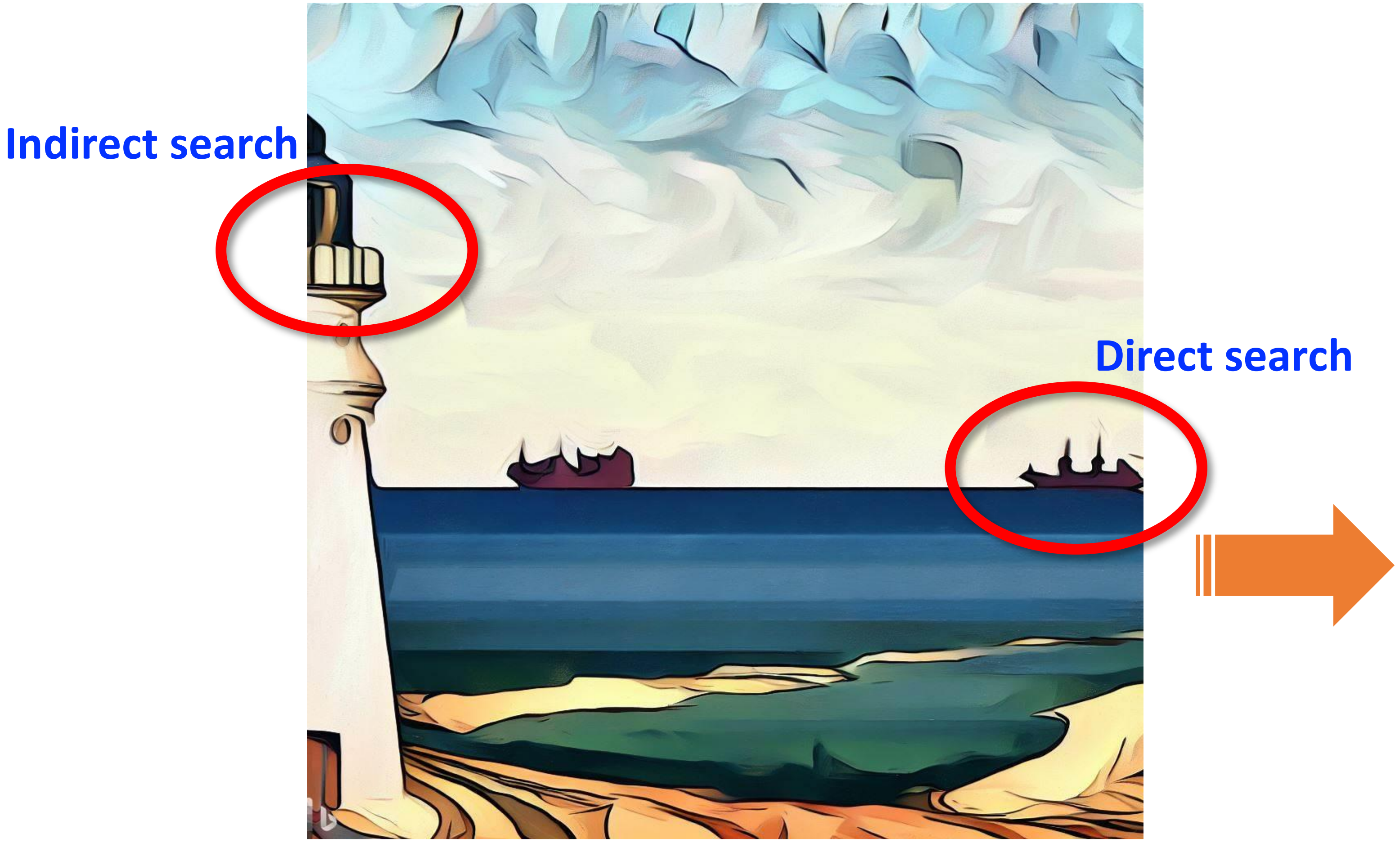
Selected topics (bias):

More talks in the Flavour and Precision physics sessions, also in two highlight talks

- **Recent measurements of CP violation** — **Yinghui Guan**
- **Lepton Favor Universality experimental highlights** — **Liang Sun**

More LHCb results are selected

Torwarding to the new physics



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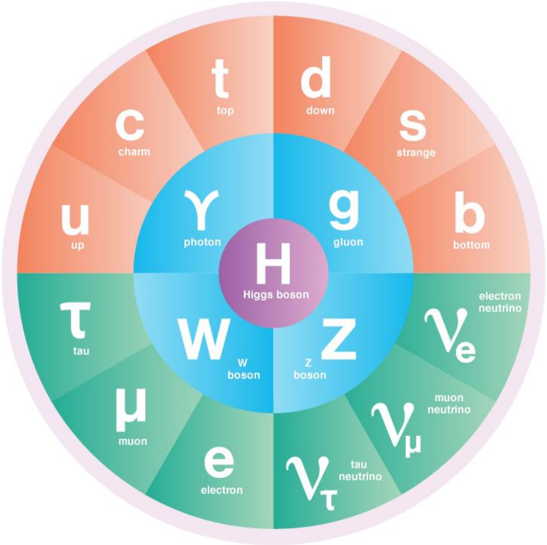
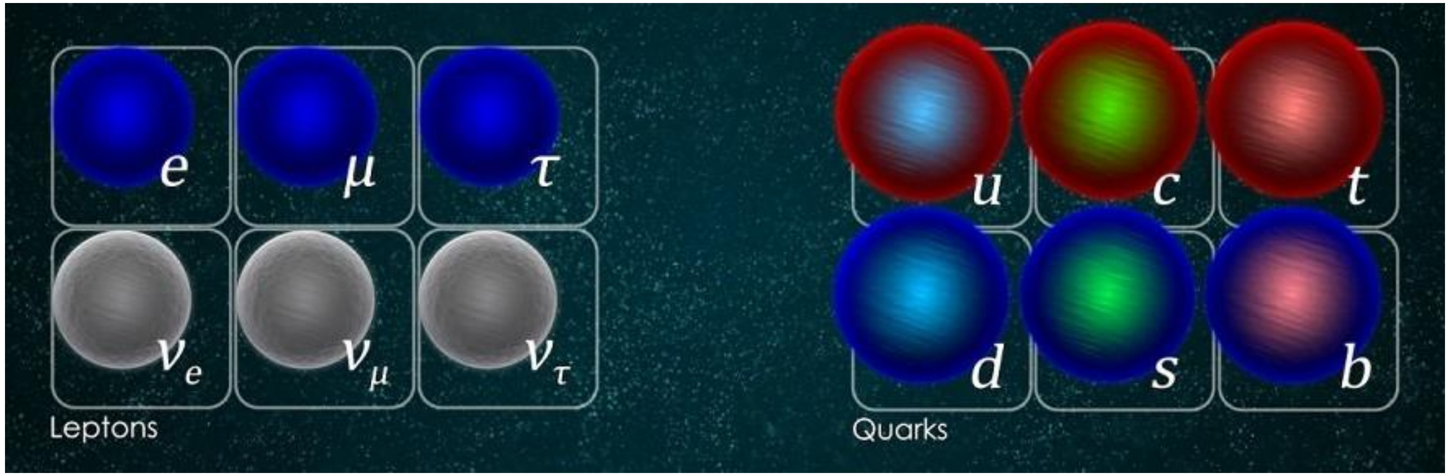
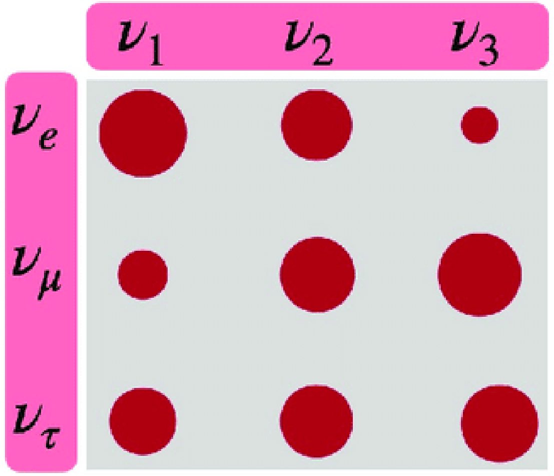
Flavor physics



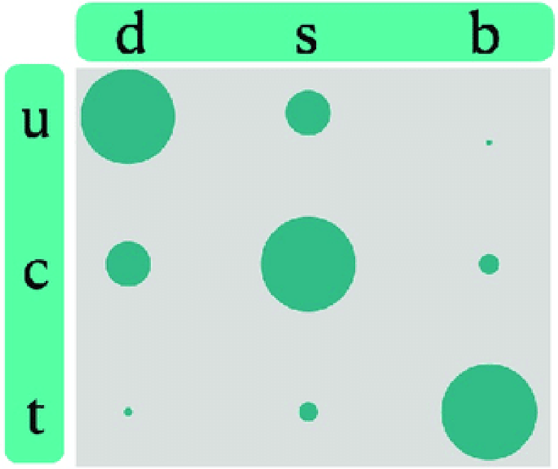
- **Fundamental questions :**
  - Matter-antiMatter asymmetry in the Universe
  - Any physics beyond the Standard model (BSM)
- **Precision study of flavour and CP symmetry breaking can probe BSM physics at energy scale inaccessible directly at colliders**
  - Looking for new sources of CP violation
  - Precision flavour measurements to test the Standard Model(SM)
  - Looking for new phenomena in rare or forbidden decays
    - Flavour changing neutral current
    - Lepton flavour universality violation
    - Lepton flavour number violation

Flavour: lepton and quark





Leptonic PMNS mixing matrix

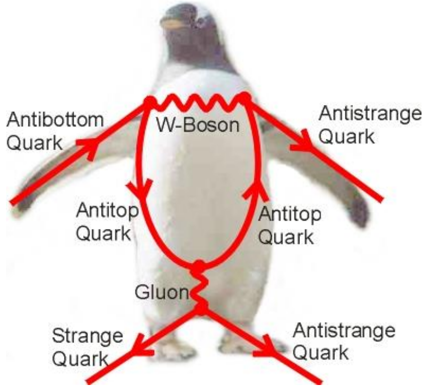


Quark CKM mixing matrix

Flavour changings are see in both **lepton** and **quark** sectors

However,

- In tree level, neutral lepton only
- In quark sector, two transitions
  - Charge Current:
    - $b \to c l^- \nu$, tree level
  - Neutral current (FCNC):
    - $b \to s$, loop level



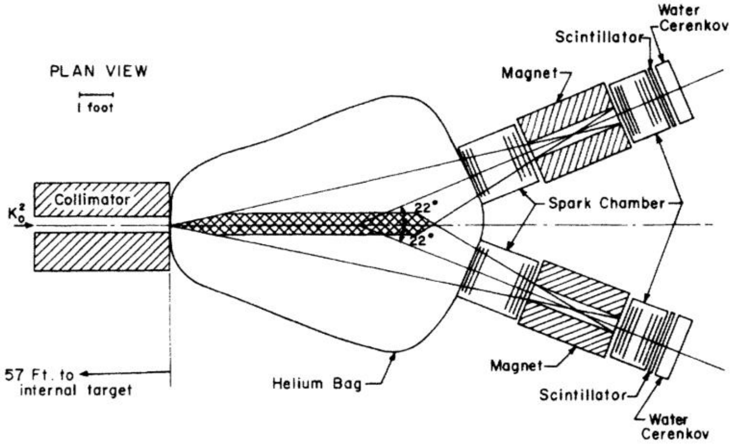
Flavour physics is a key-tool

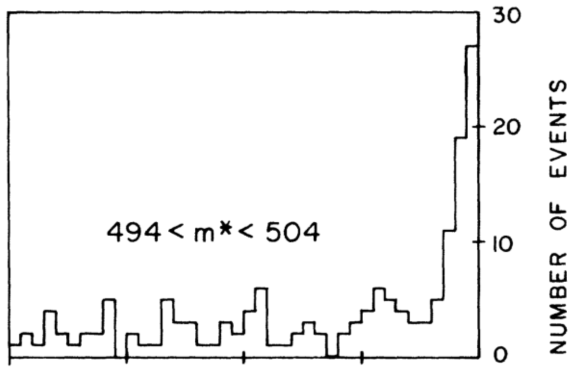
- **CP violation and FCNC: sensitive probes of short distance physics**
  - Probed scales: $\gg 1\ \mathrm{TeV}$, depending on C_{NP}
  - Many tests limited by statistics not by systematics nor theory

$A(\psi_i \to \psi_j + X) = A_0 \left(\frac{C_{SM}}{v^2} + \frac{C_{NP}}{\Lambda_{NP}^2}\right)$, where Λ_{NP}^2 (C_{NP}) is NP scale (coupling)

- **1964: CP violation in the decay of Kaon meson**
  - Observation of $K_L \to \pi\pi$

$\Longrightarrow$ **Three generations**

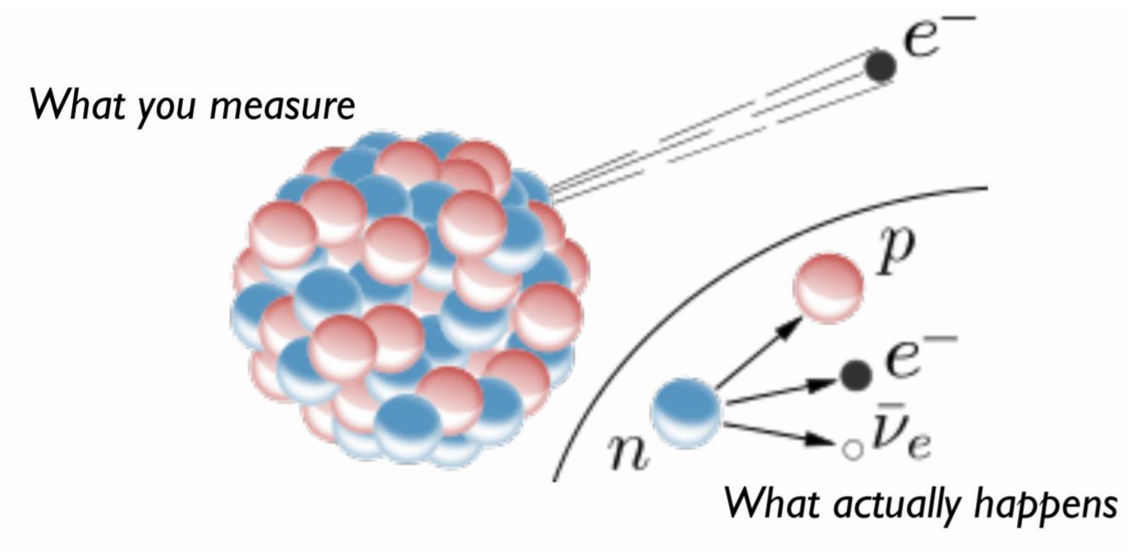


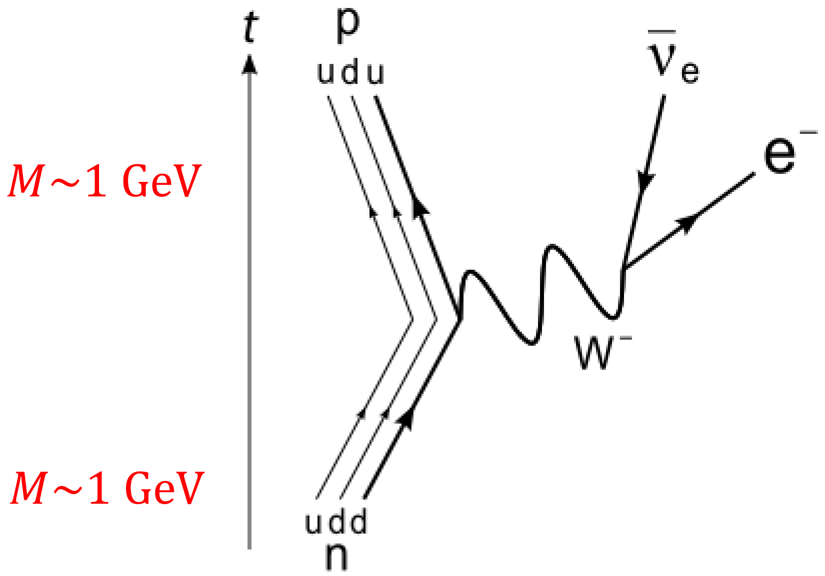


Phys. Rev. Lett. 13 (1964) 138

Indirect search

- ***β* decay** **of the neutron:**
  Phenomena taking place at ~ 1 GeV reveals physics at the 100 GeV scale

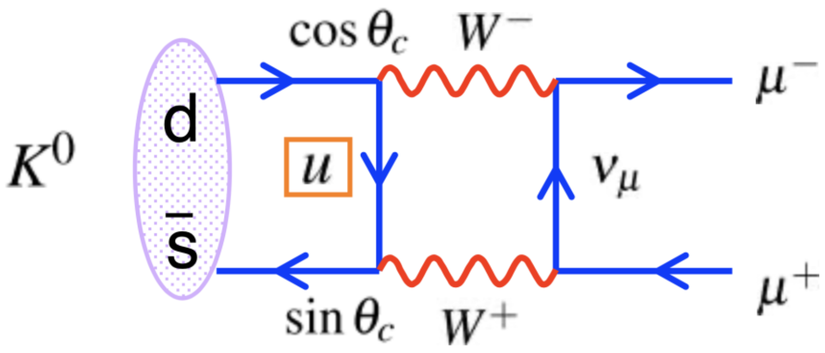




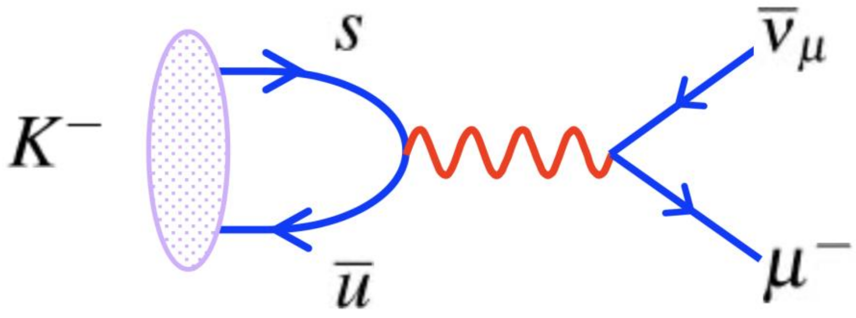
GIM mechanism and charm quark

- Cabibbo angle theory explained the hadronic decay of kaon, and many other experimental results at that time
- However, for the K^0 decays:
  - $\mathcal{B}(K^+ \to \mu^+ \nu_\mu) = (63.56 \pm 0.11)\%$
  - Not observed yet, at that time
    - $\mathcal{B}(K_L^0 \to \mu^+ \mu^-) = (6.84 \pm 0.11) \times 10^{-9}$

Observed at 1973, [Phys. Rev. Lett. 30 (1973) 1336]



$M_1 \propto g_W^4 cos\theta_c sin\theta_c$

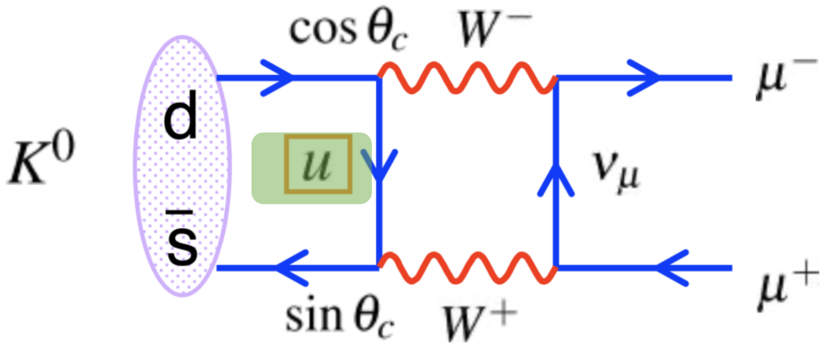


$M_1 \propto g_W^2 sin\theta_c$

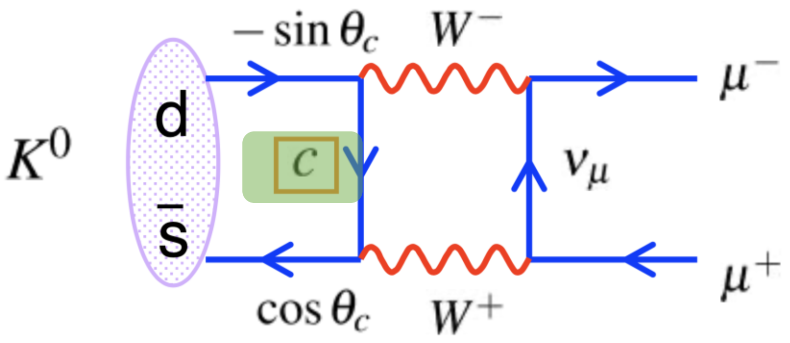
GIM mechanism and charm quark

- **1970: Led Glashow, Illiopoulos and Maiani to postulate existence of an extra quark (4th quark, charm quark)**
  - Before discovery of charm quark in 1974

PRD 2 (1970) 1285-1292



$M_1 \propto g_W^4 cos\theta_c sin\theta_c$



$M_2 \propto -g_W^4 cos\theta_c sin\theta_c$

Same final state to sum ampliutdes

$$|M|^2 = |M_1 + M_2|^2 \approx 0$$

Cancellation not exact because $m_u \neq m_c$

CKM matrix

- **Extend ideas to three quark flavours: Cabibbo, Kobayashi, Maskawa**

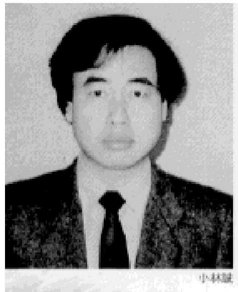
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak eigenstates   Mass eigenstates

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Timeline:
Sep. 1972: predict 3 generations
Nov. 1974: discovery of J/Ψ (c quark)
July. 1977: discovery of Υ (b quark)
Fed. 1995: discovery of top quark

Prog. of Theor. Phys., 49 (1973) 652-657



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

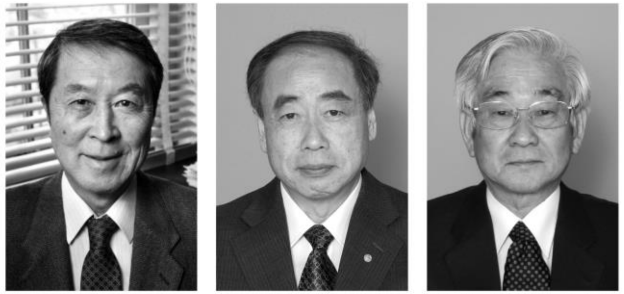
CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

The Nobel Prize in Physics 2008



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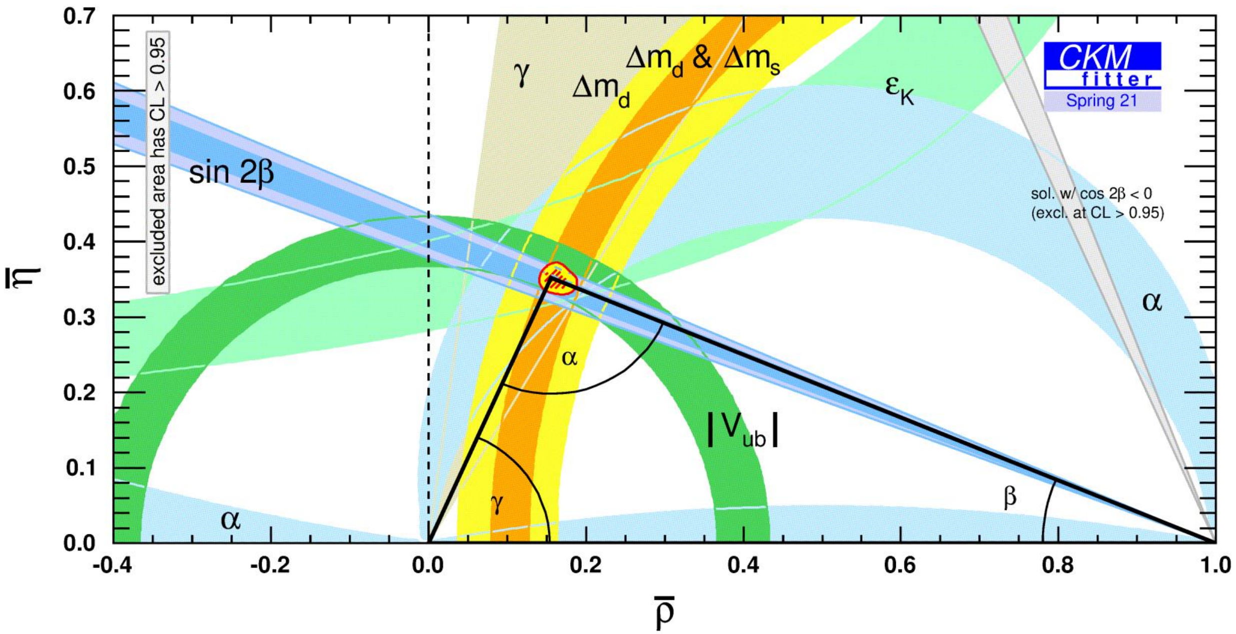
Prize share: 1/2

© The Nobel Foundation Photo: U. Montan
Makoto Kobayashi
Prize share: 1/4

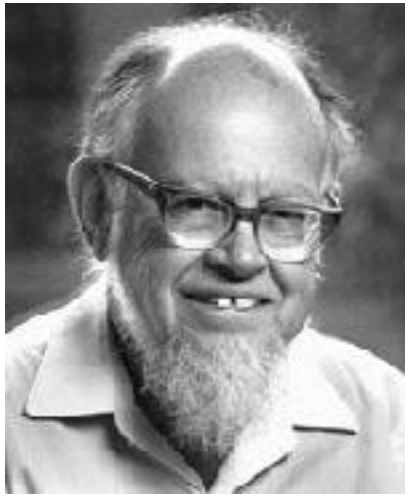
© The Nobel Foundation Photo: U. Montan
Toshihide Maskawa
Prize share: 1/4

CKM: wolfgenstein parameterization

$$V_{CKM}=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}=\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}+O(\lambda^4)$$



CP violation: if and only if $\eta \neq 0$



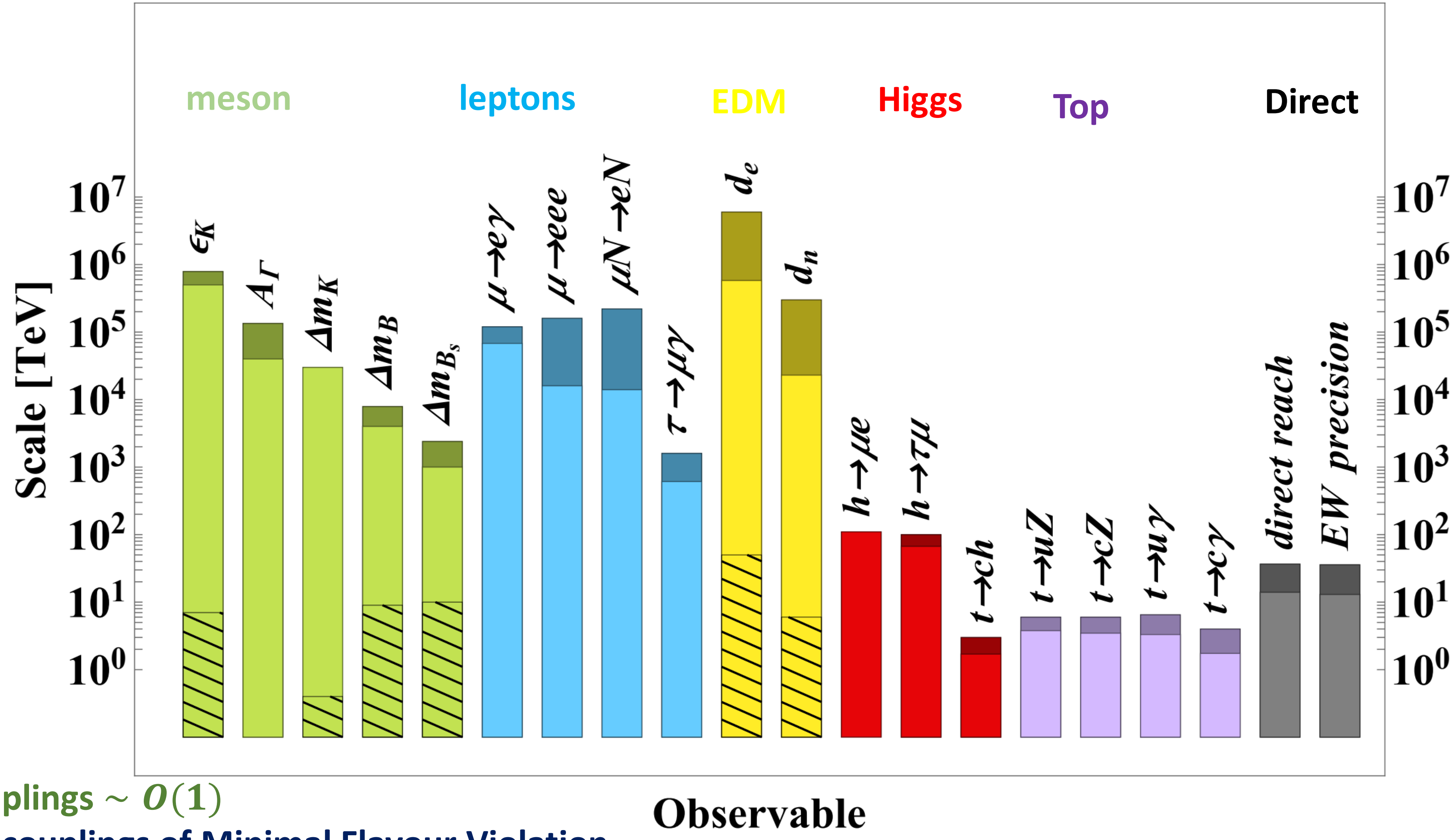
Sensitivity

arXiv: 1910.11775

CERN-ESU-004
10 January 2020

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

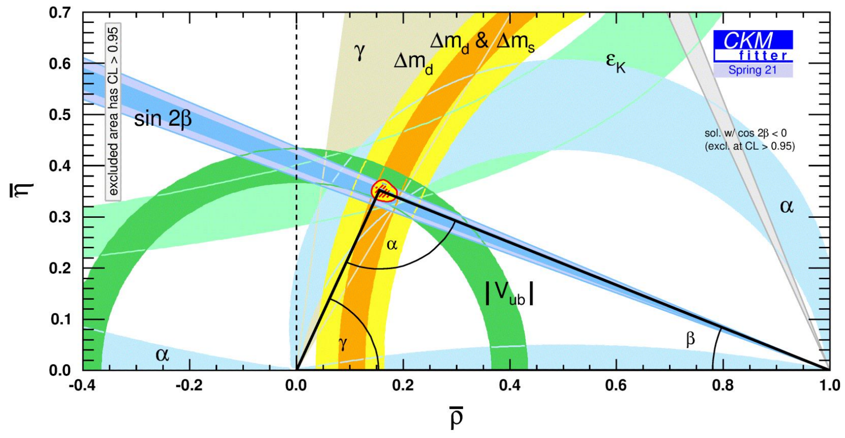


Light region: couplings $\sim \mathcal{O}(1)$

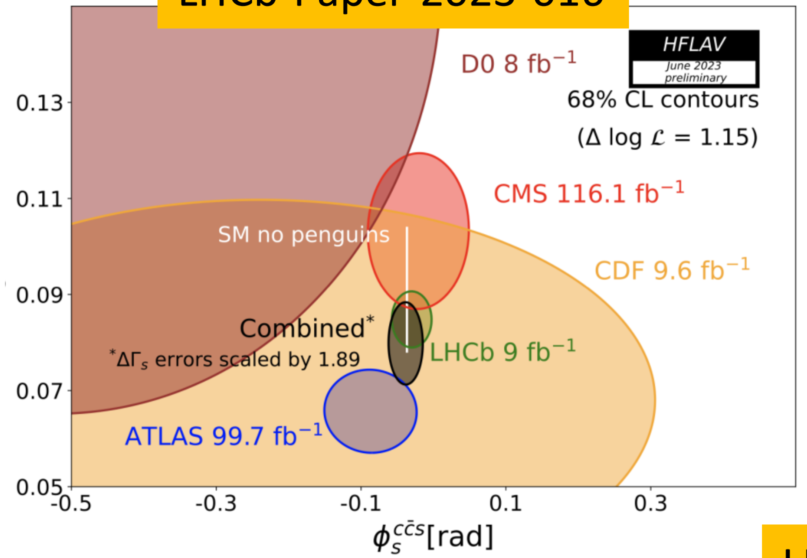
Shadow regions: couplings of Minimal Flavour Violation

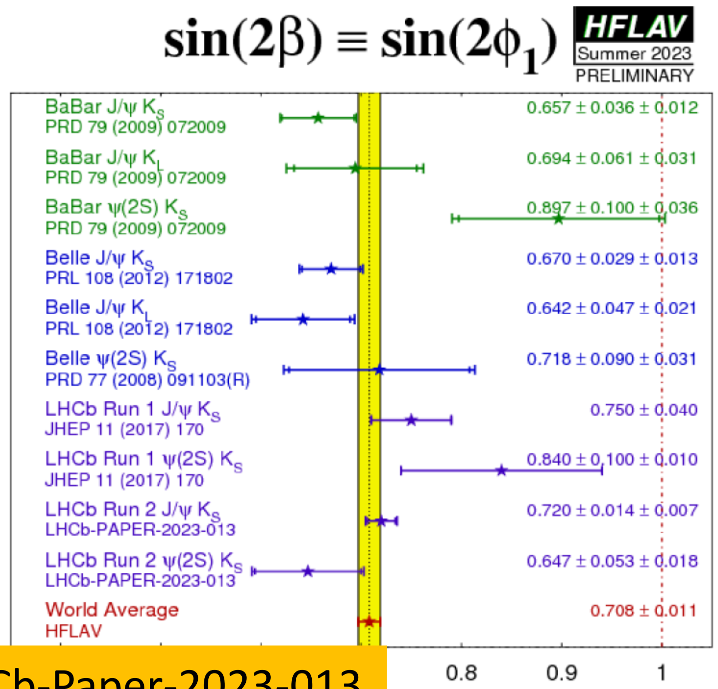
What do we have?

More heavy flavour results from LHCb can be found in Kechen Li's parallel talk

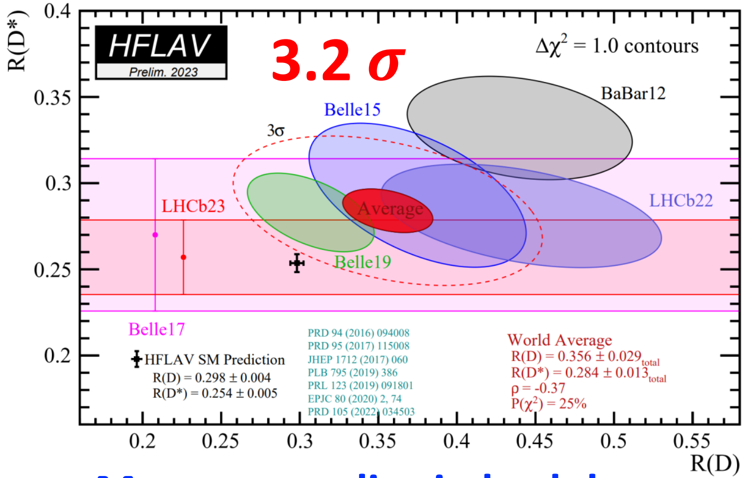


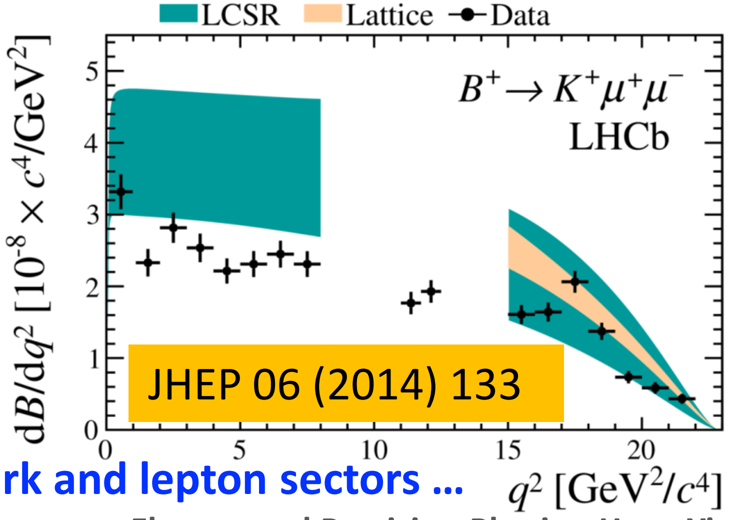
LHCb-Paper-2023-016



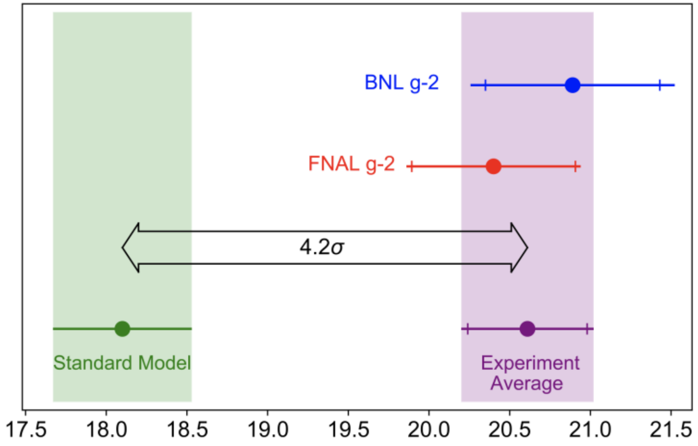


LHCb-Paper-2023-013





JHEP 06 (2014) 133

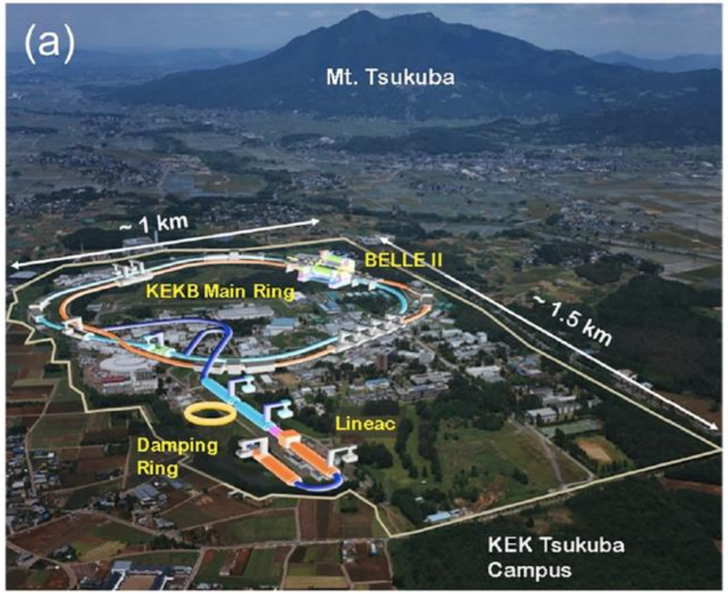


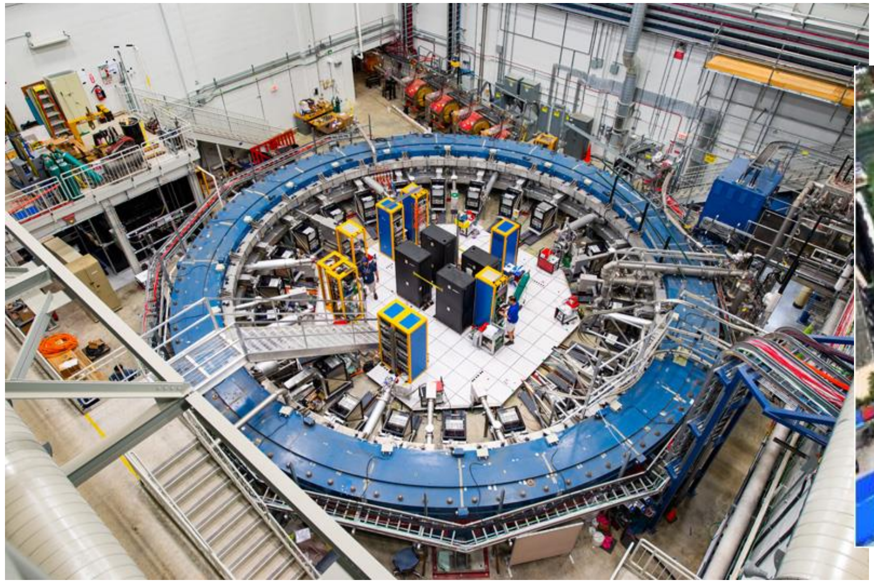
PRL 126 (2021) 141801

Many anomalies in both heavy quark and lepton sectors …

Facilities

- LHC
  - LHCb
  - ATLAS/CMS
- Belle-II
- BES-III
- g-2, COMET, mu2e

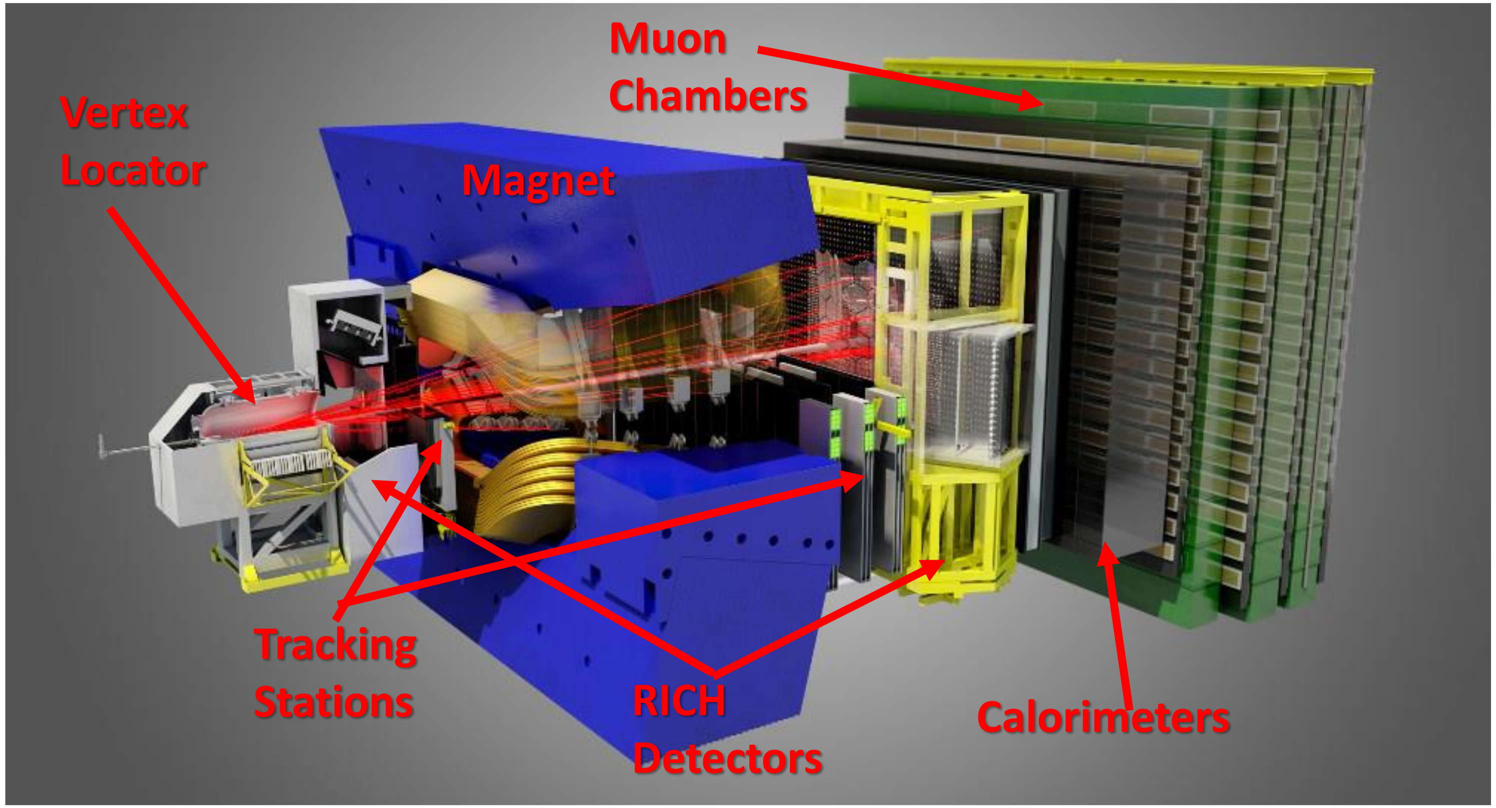


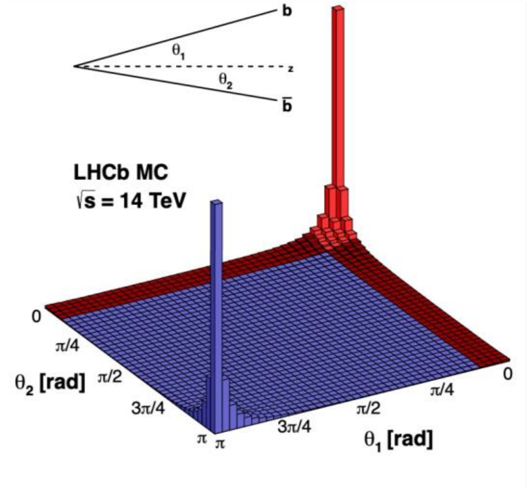


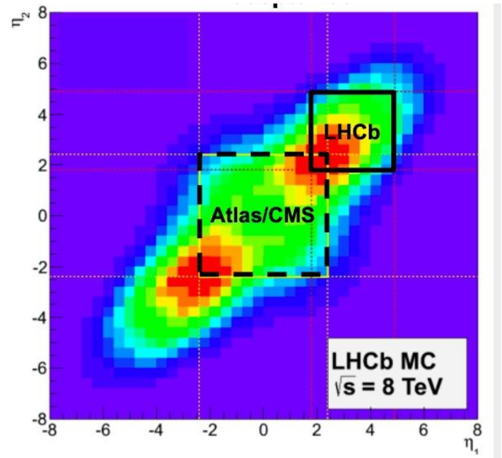
The LHCb experiment

JINST 3 (2008) S08005
Int. J. Mode. Phys. A30 (2015) 1530022

- **The LHCb detector is single-arm forward spectrometer**
  - Designed for the heavy flavour physics, with $2 < \eta < 5$



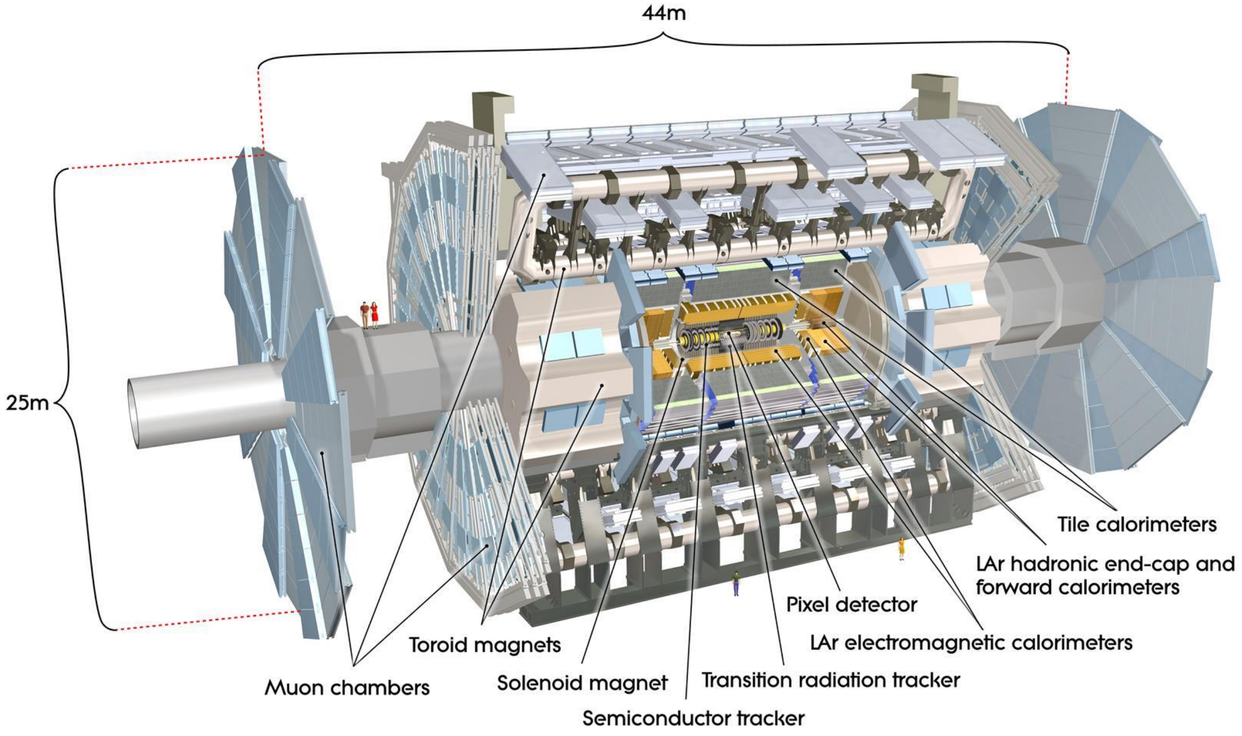


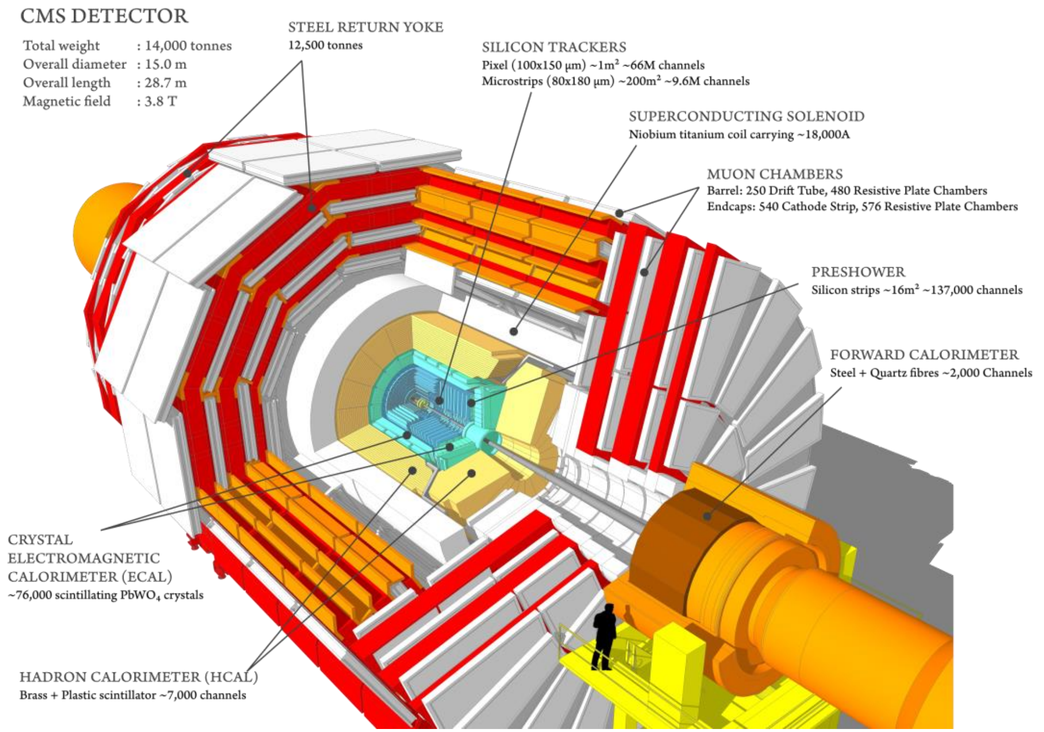


The ATLAS and CMS experiments

JINST 3 (2008) S08003
JINST 3 (2008) S08004

Covering **~4π** solid angle
No hadron identification

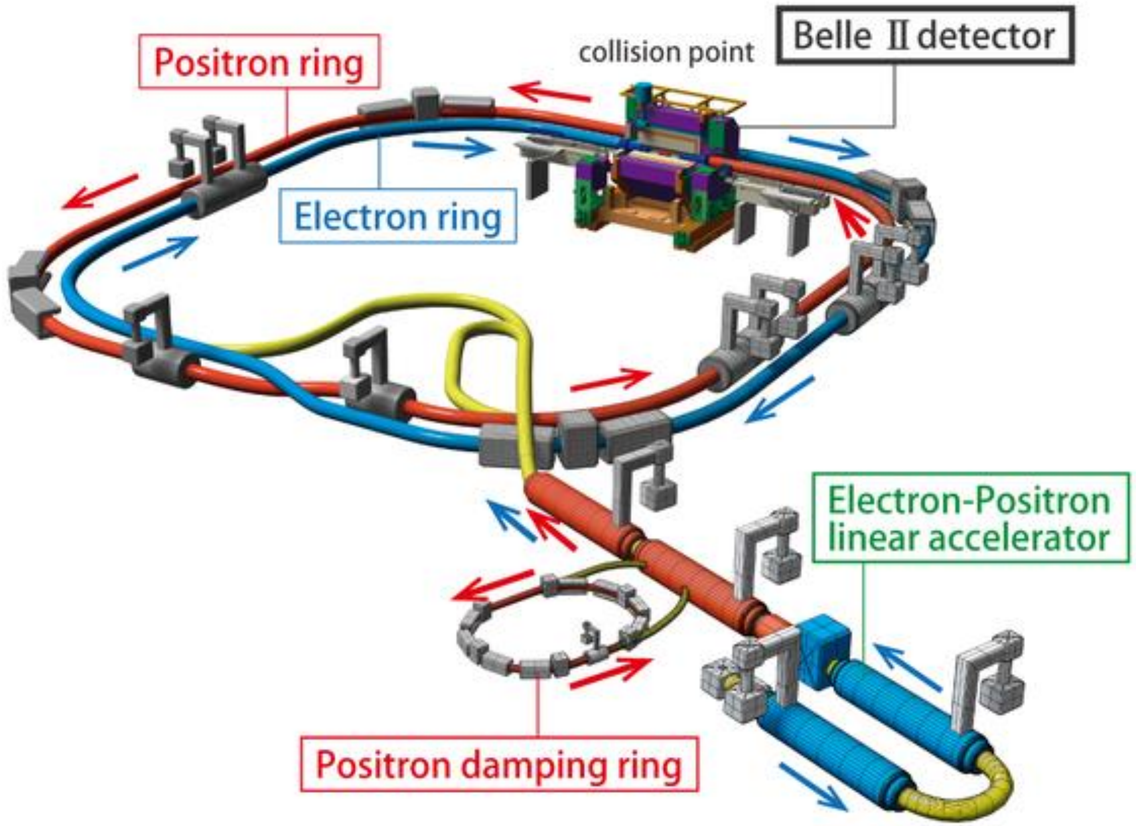


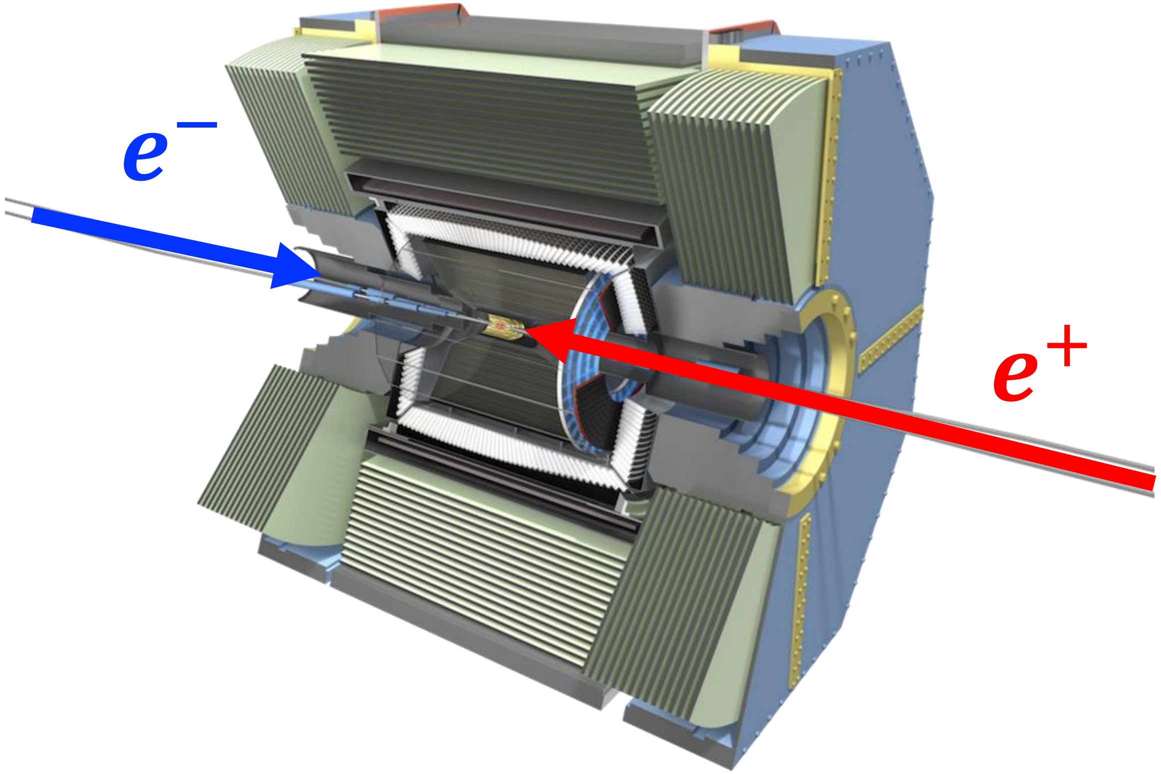


General purpose detector, B phyiscs focusing on $\mu^+\mu^-X$ final state

Belle-II experiment

- SuperKEKB accelerator: 7 GeV e^- + 4 GeV e^+

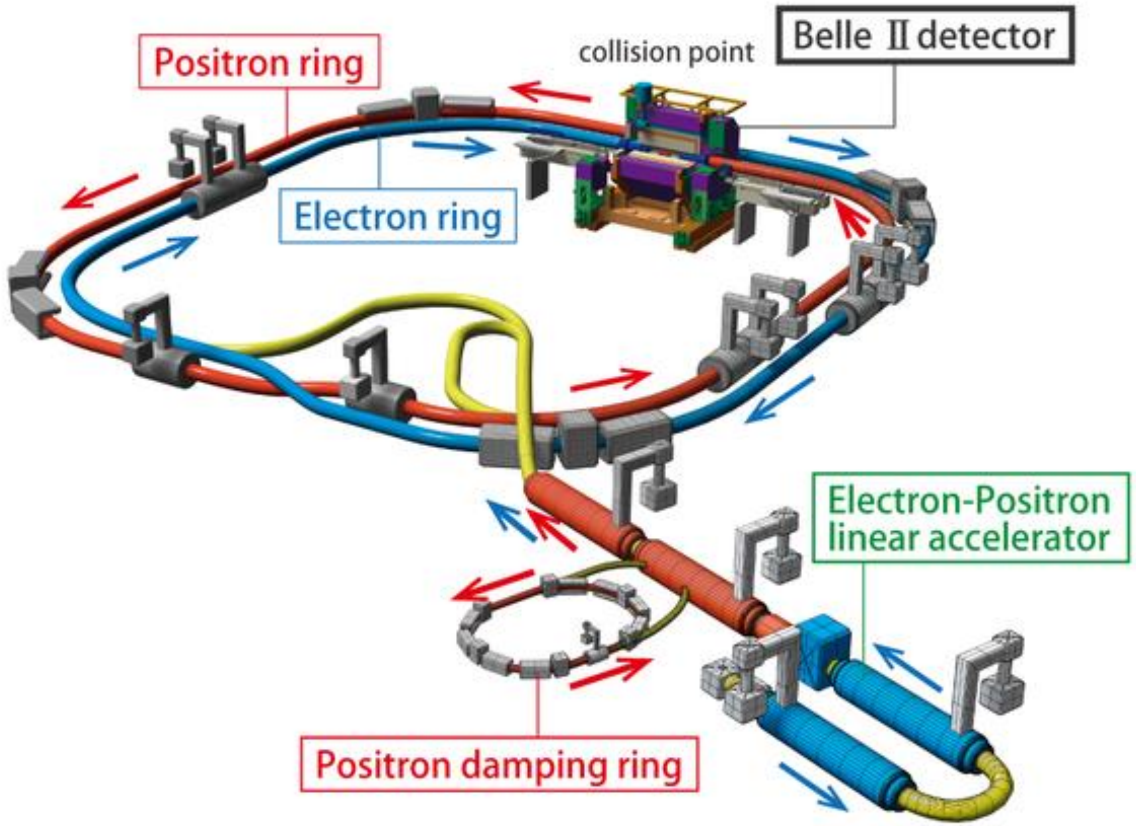


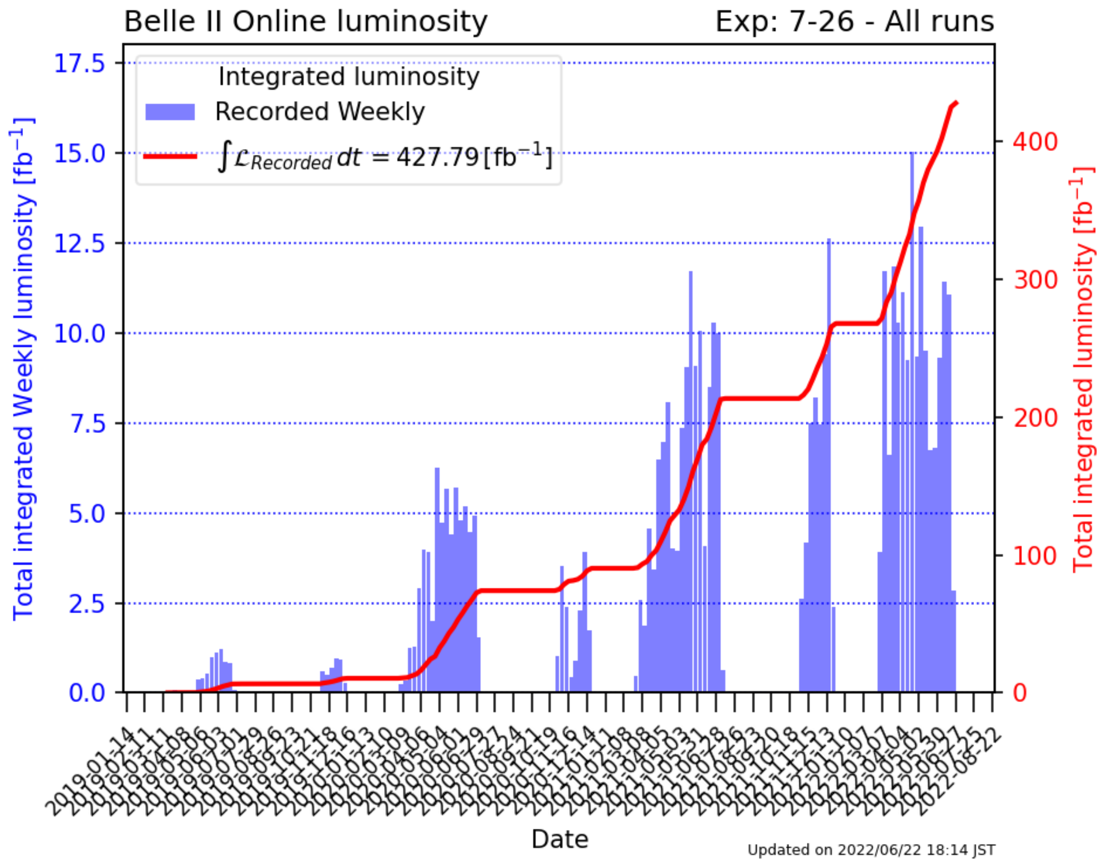


arXiv:1011.0352
NIM Phs. Res. A 907, 188 (2018)

Belle-II experiment

- **SuperKEKB accelerator: 7 GeV e^- + 4 GeV e^+**

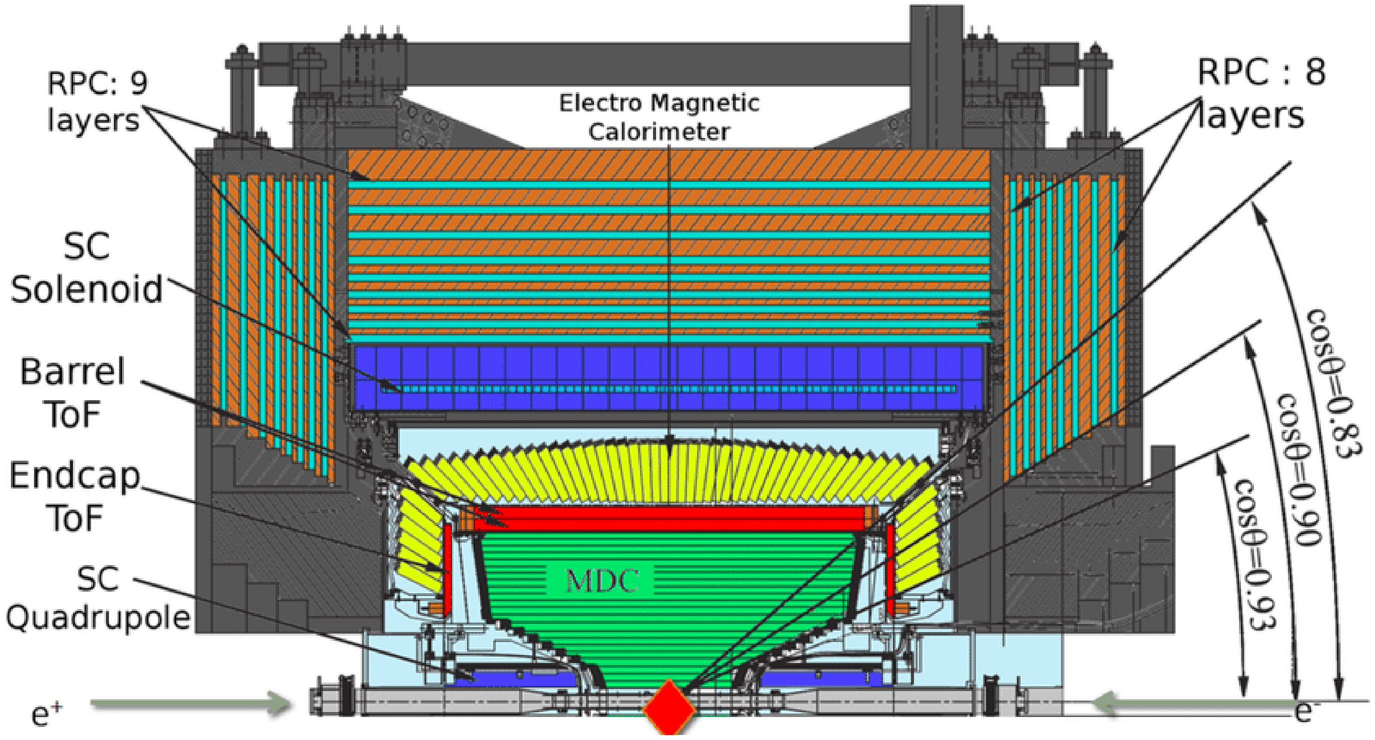




New luminosity world record: $4.7 \times 10^{34}\ cm^{-2}\ s^{-1}$

BES-III experiment

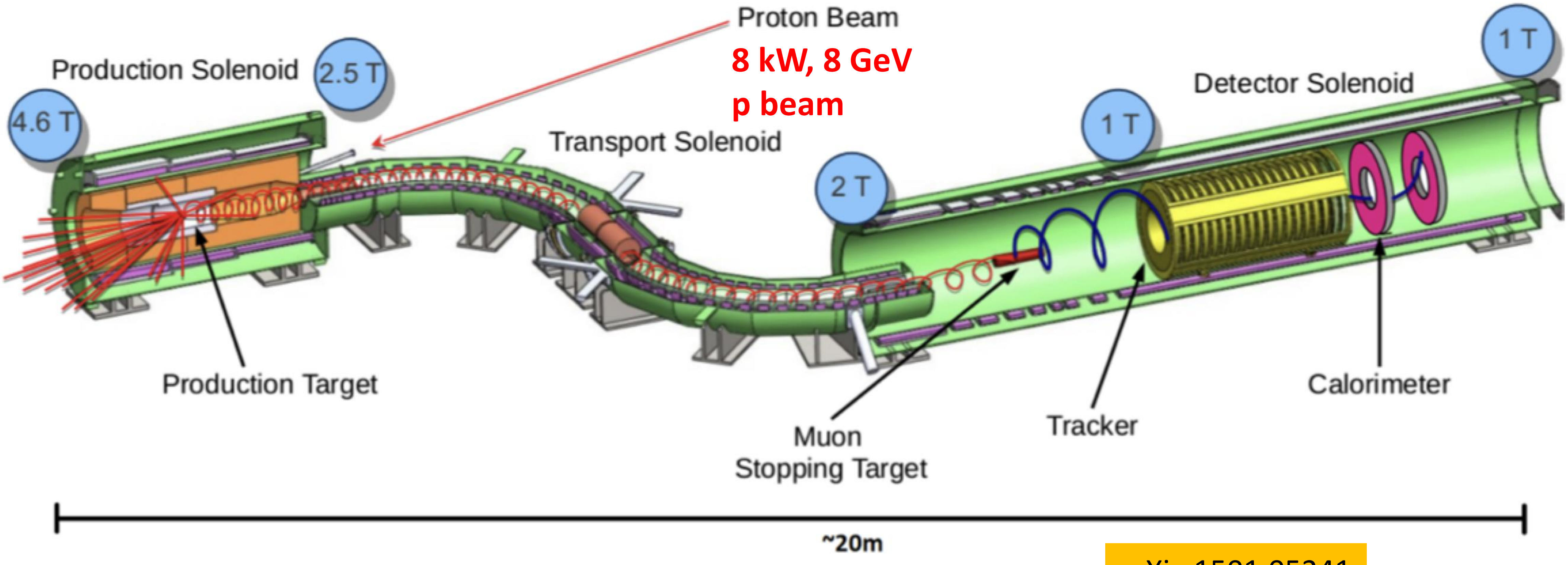
- **Electron-positron collider: center-of-mass energy of ranging between 2 to 5 GeV**
  - Charm, charmonium, light hadron, τ lepton, QCD …



NIM A 614, 345 (2010)

The mu2e experiment

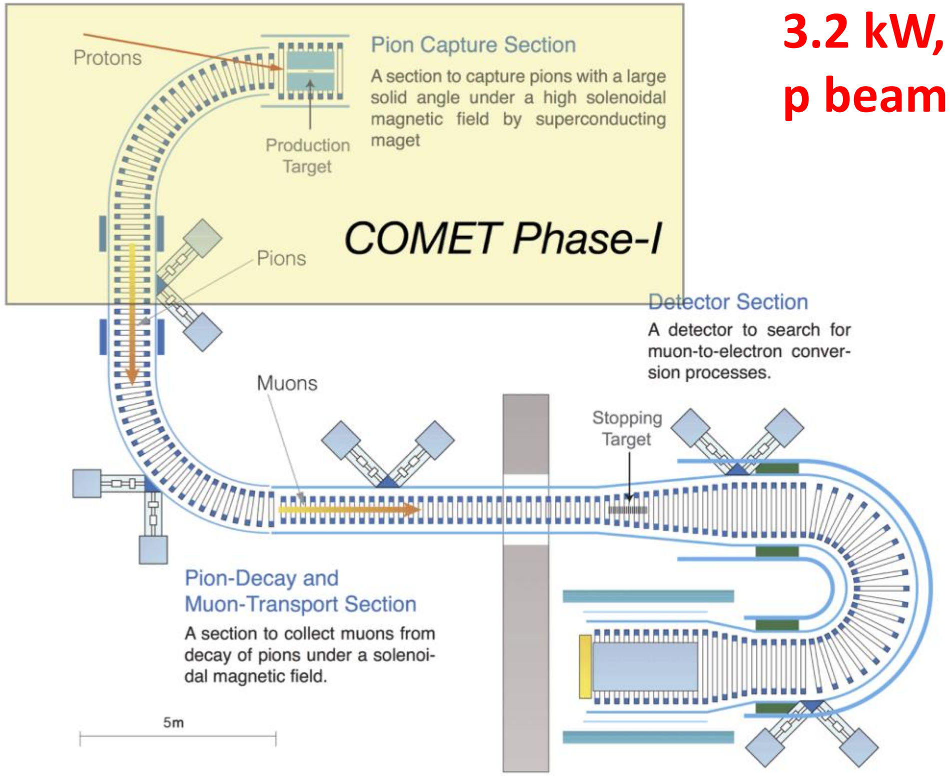
- Search for coherent, neutrinoless conversion of muon into electron in a muonic atom (Fermilab)



arXiv:1501.05241

The COMET experiment

- **COherent Muon to Electron Transition**
- **Search for $\mu^- + N \rightarrow e^- + N$ (J-PARC)**



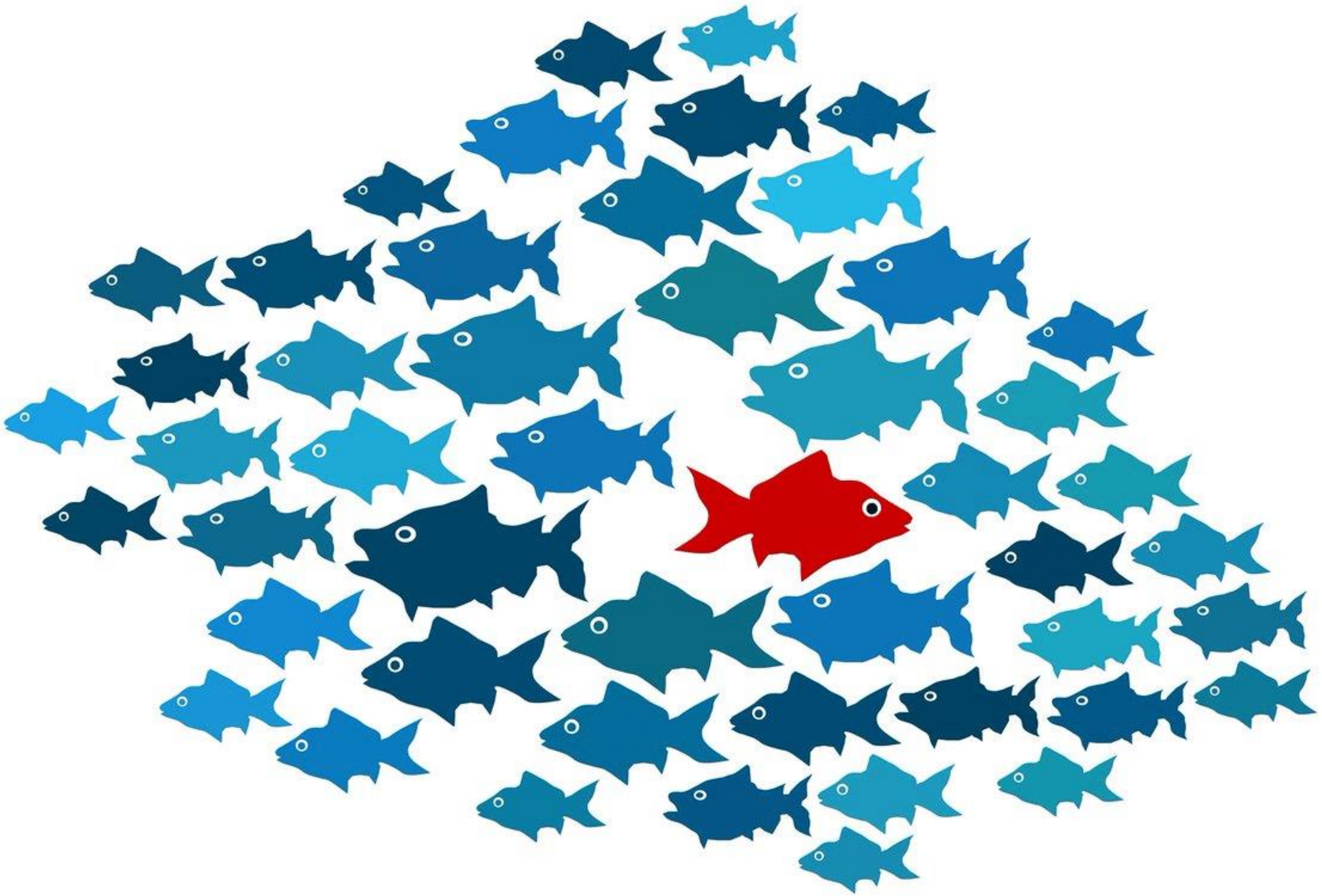
3.2 kW, 8 GeV p beam

Phase I

Beam power	3.2 kW
Energy	8 GeV
Average current	0.4 μA
Beam emittance	10 πmm · mrad
Proton per bunch	$< 10^{10}$
Extinction	10^{-9}
Bunch spacing	1.17 μsec
Bunch length	100 ns

PTEP 2020 (2020) 3, 033C01

Selected topics: anomalies

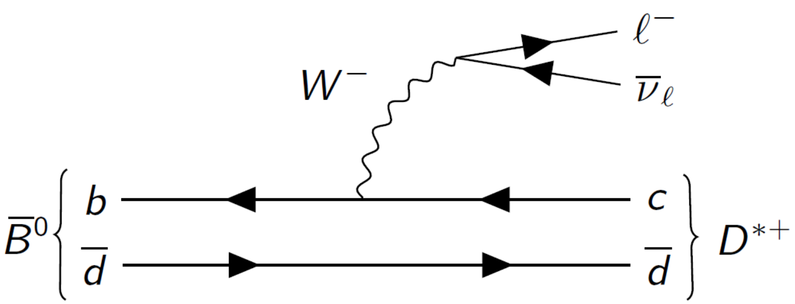


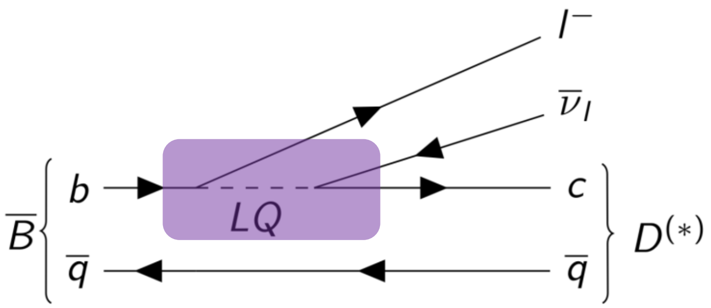
Lepton Flavour Universality (LFU)

- In SM, EW couplings to each lepton generation are identical (except Yukawa)
- However, New Physics (NP) could contribute to these couplings (particularly 3rd generation of leptons)
- Ratio of branching fraction of different lepton species ideal for this LFU test

$$R(H_c) = \frac{BF(H_b \to H_c l\nu)}{BF(H_b \to H_c l'\nu)}, \text{ where } l, l' = e, \mu, \tau$$

H_c could be $D^{*+}, D^0, D^+, D_s^+, \Lambda_c^+, \cdots$

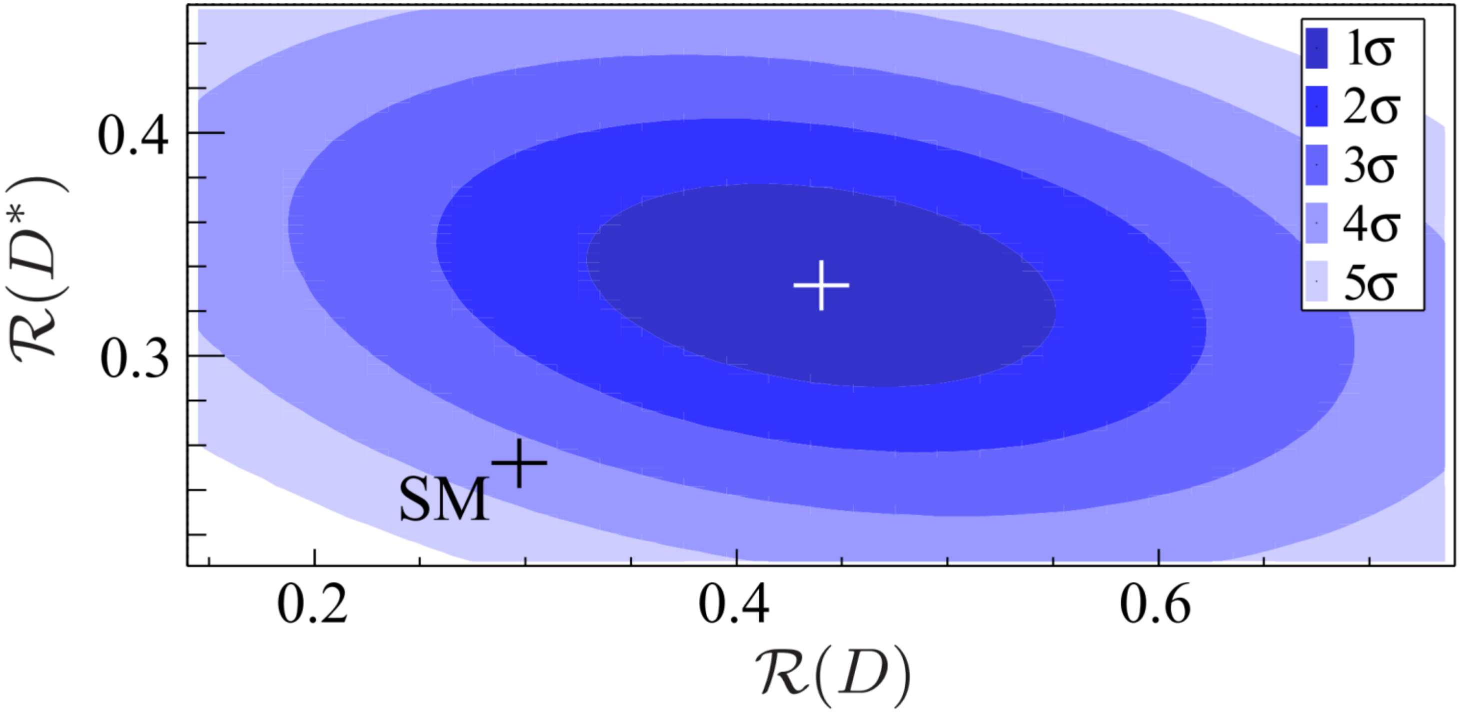


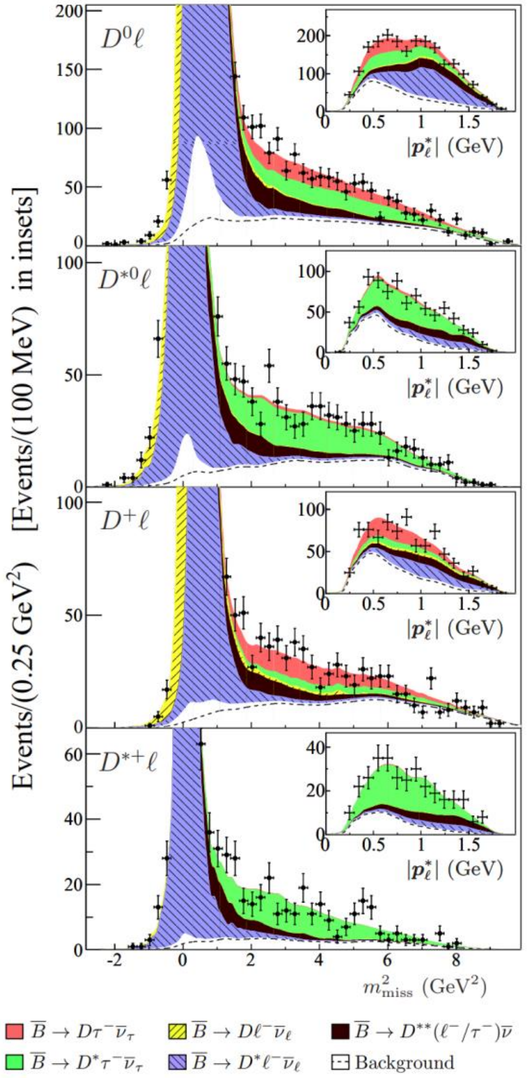


Hints of NP since 2012

- Babar Collaboration

PRL 109, (2012) 101802
PRD 88, (2013) 072012

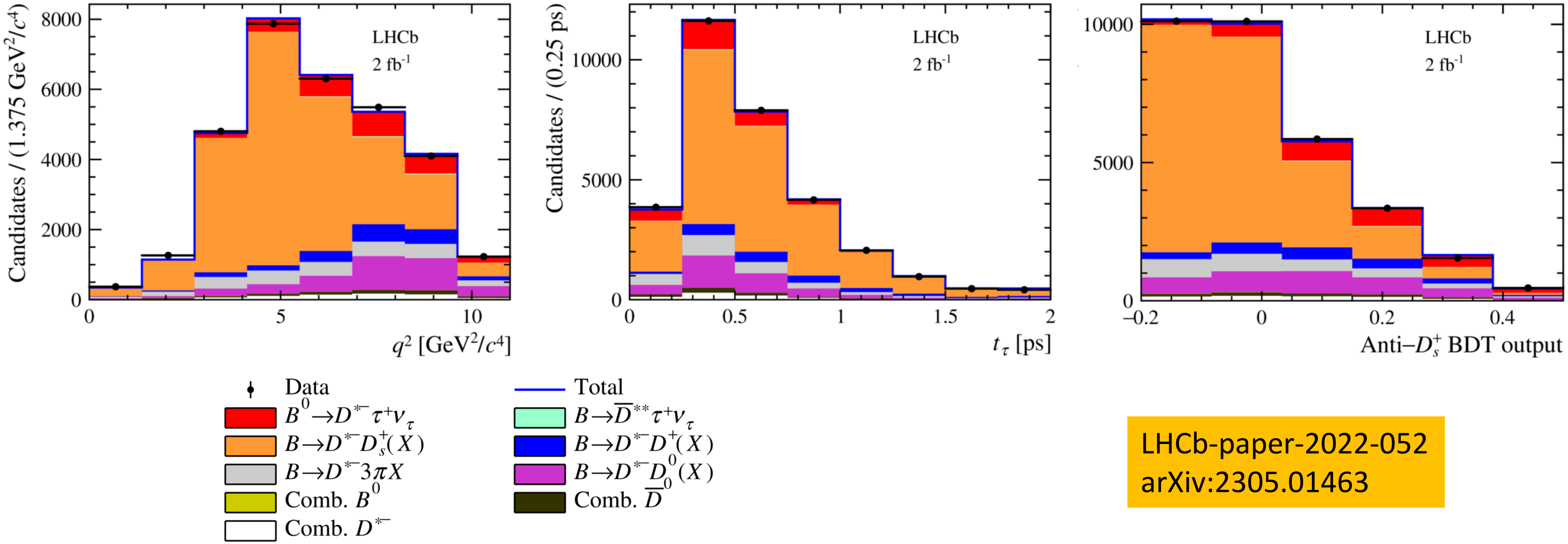




New result from the LHCb

- LHCb experiment update $R(D^{*-})$ measurement recently (13 TeV)
  - τ and μ channel

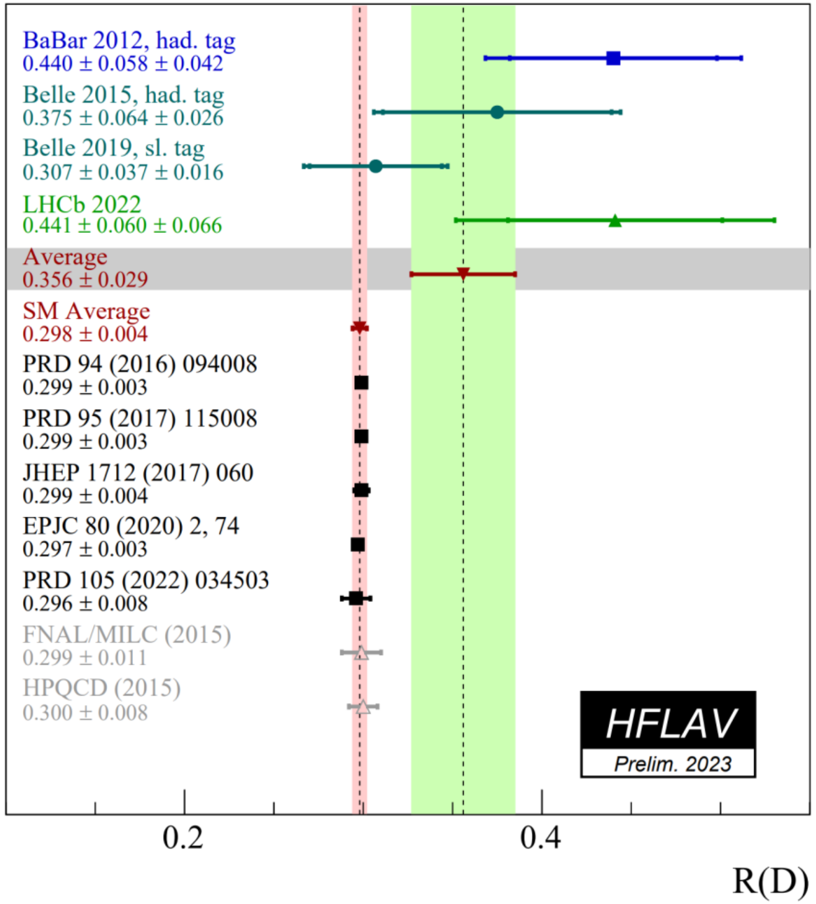
$R(D^{*-}) = 0.247 \pm 0.015(stat.) \pm 0.015(syst.) \pm 0.012(ext)$

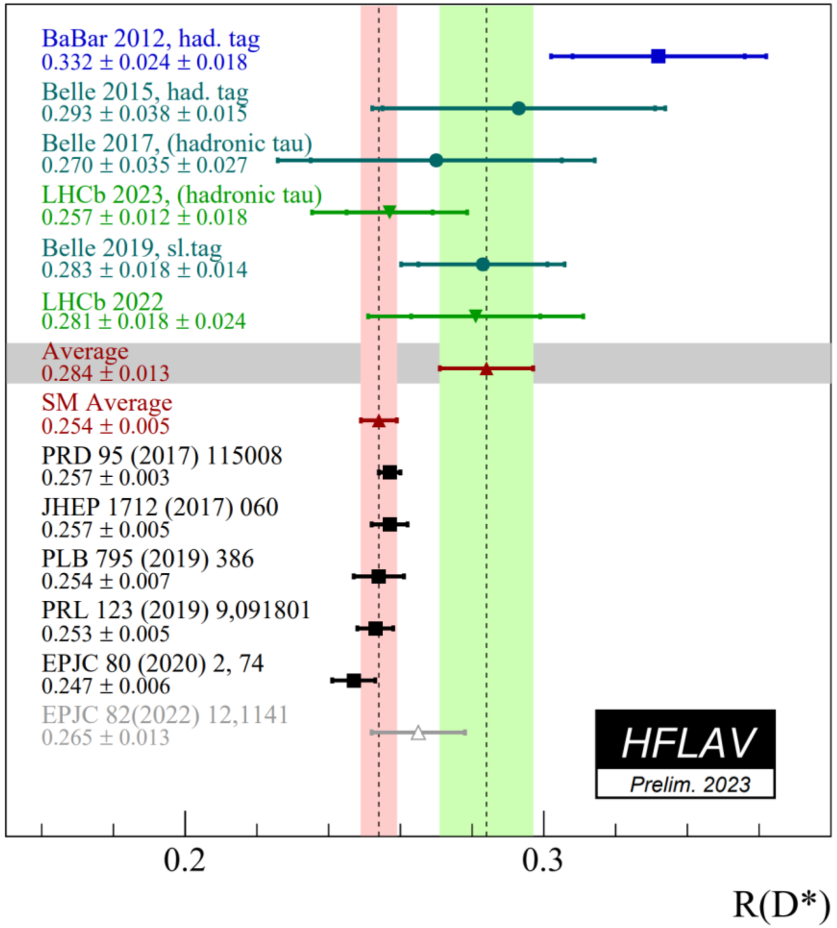


LHCb-paper-2022-052
arXiv:2305.01463

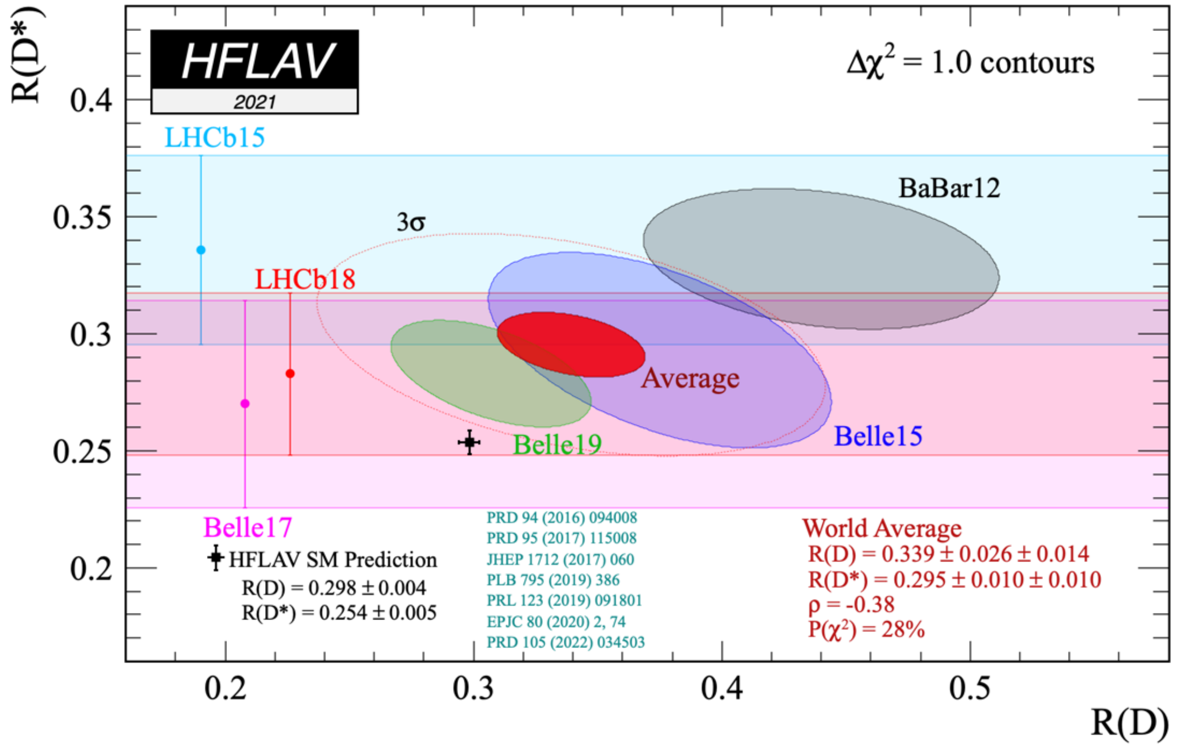
Combination

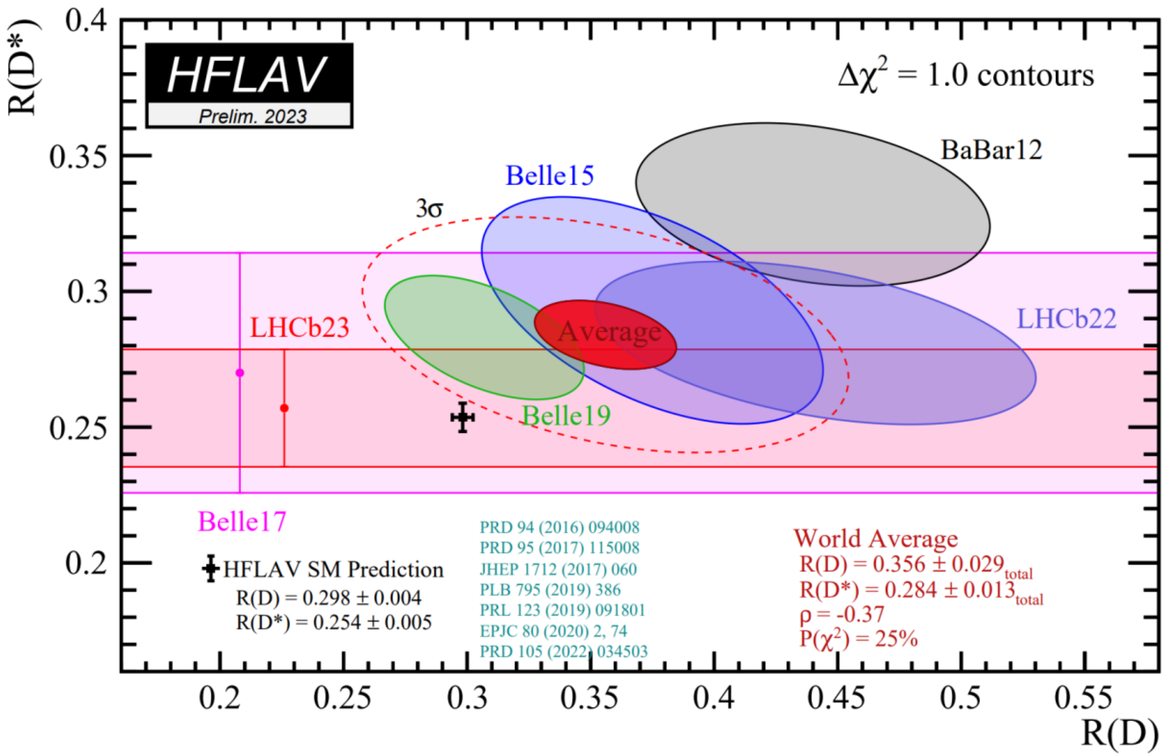
- With new results from the LHCb, world average becomes:





World average



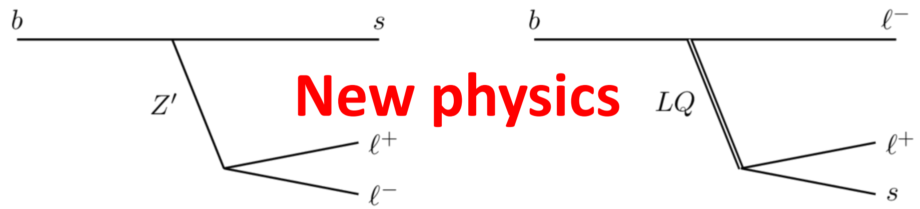


3.2 σ

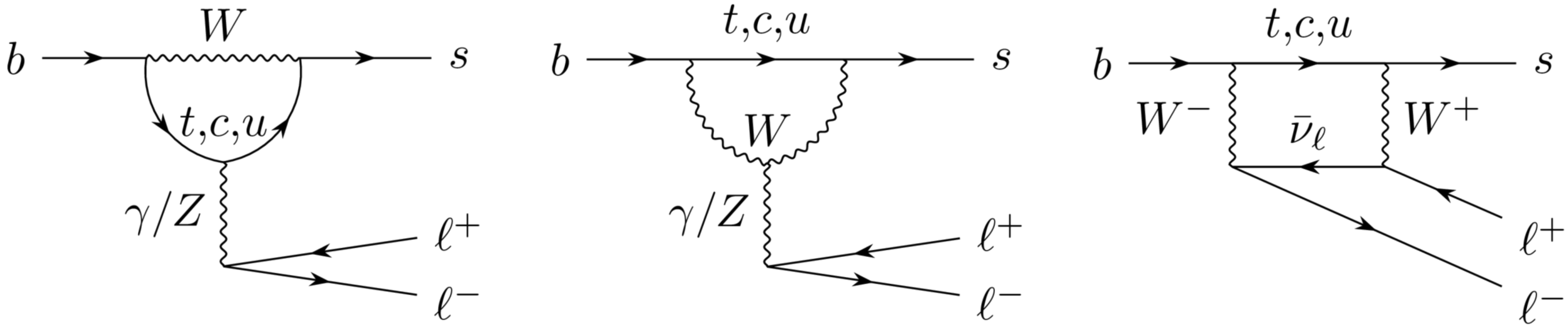
Long standing 3 σ deviation in the heavy flavour physics!

Lepton Favour universality

- Flavour changing neutral current: FCNC
  - $b \to s$ transition
  - Rare penguin decays, suppressed in the SM
  - $< \ 10^{-6}$, mediated via loops



New physics



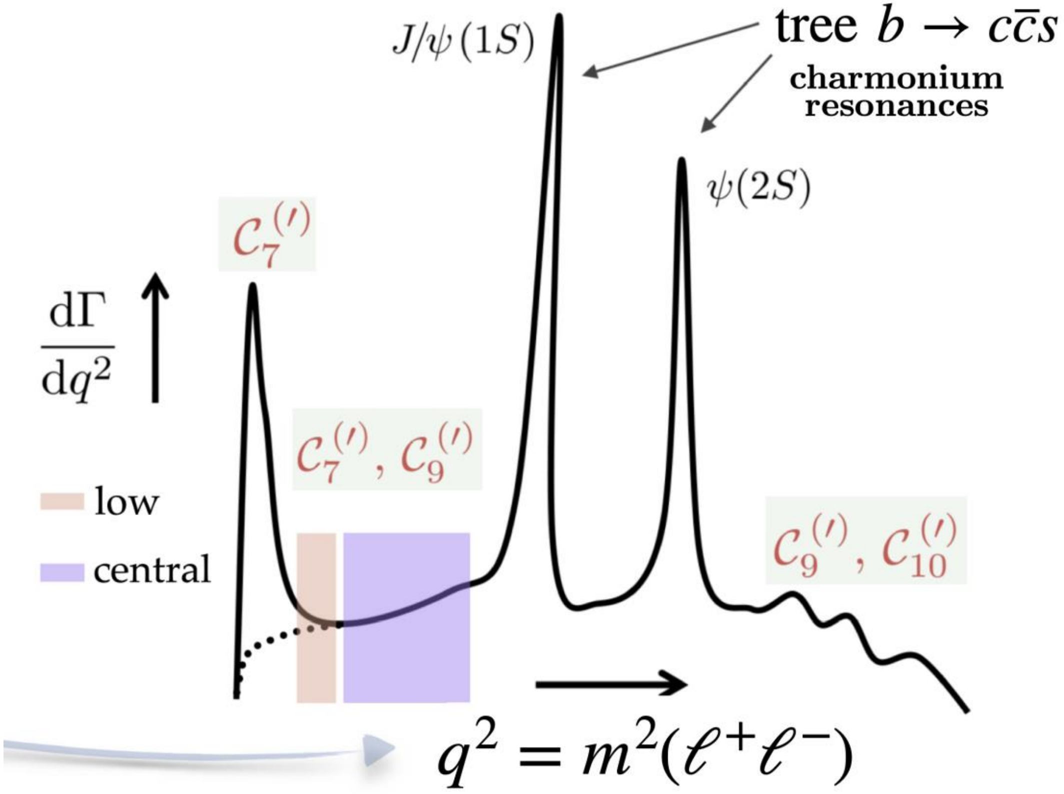
SM

What we can measure?

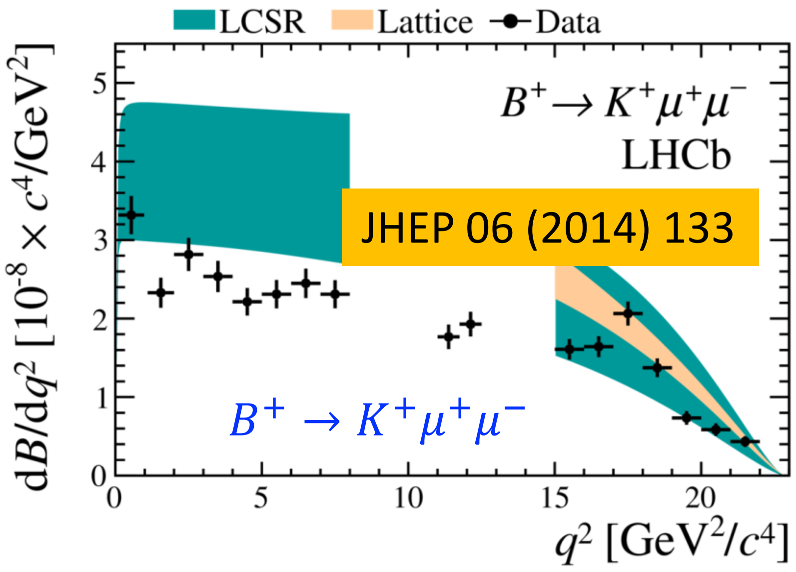
- **Differential branching fraction**: $(dB(B \to H(s)\mu^+\mu^-)/dq^2)$
  - large theory uncertainties: hadronic form factor

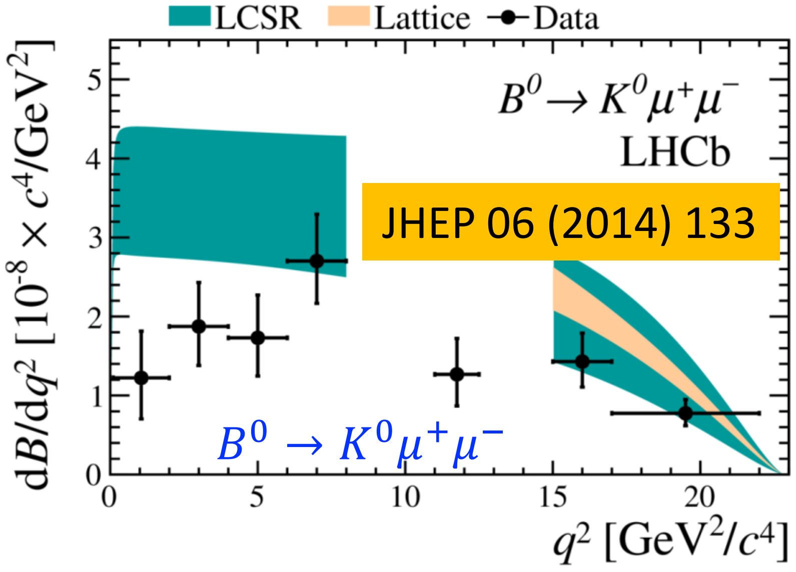
- **Angular measurment** (P_5')
  - Effective Hamiltonian:
    - $H_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i^{SM} + \Delta_i^{NP}) O_i$
    - Wilson coefficients: C_i

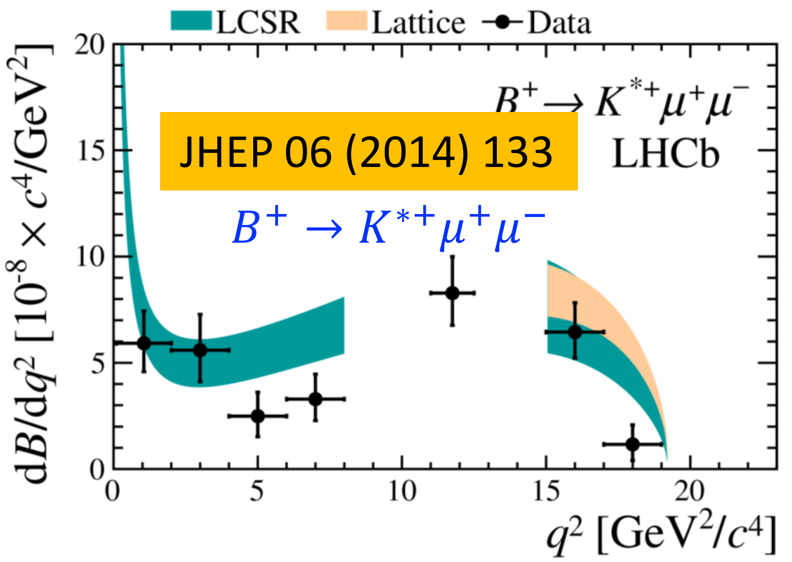
- **Lepton universality ratio**
  - R_K, R_{K^*} …
  - Theoretically robust

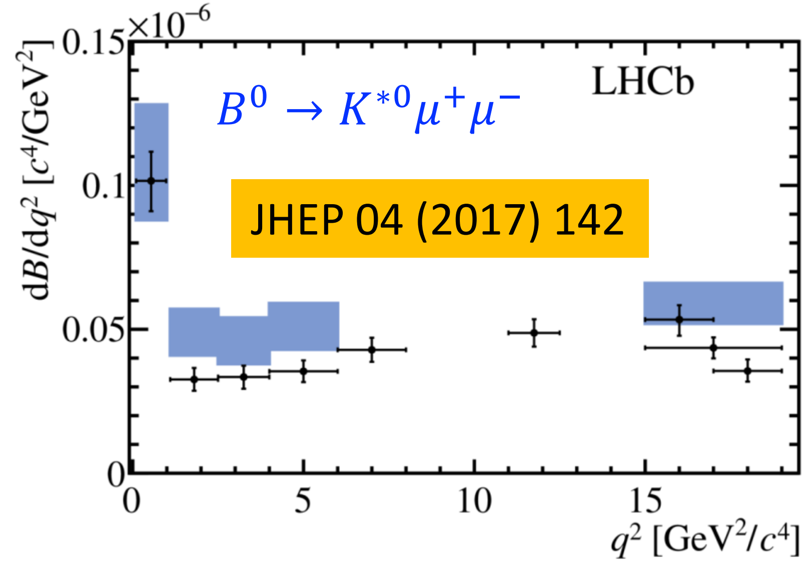


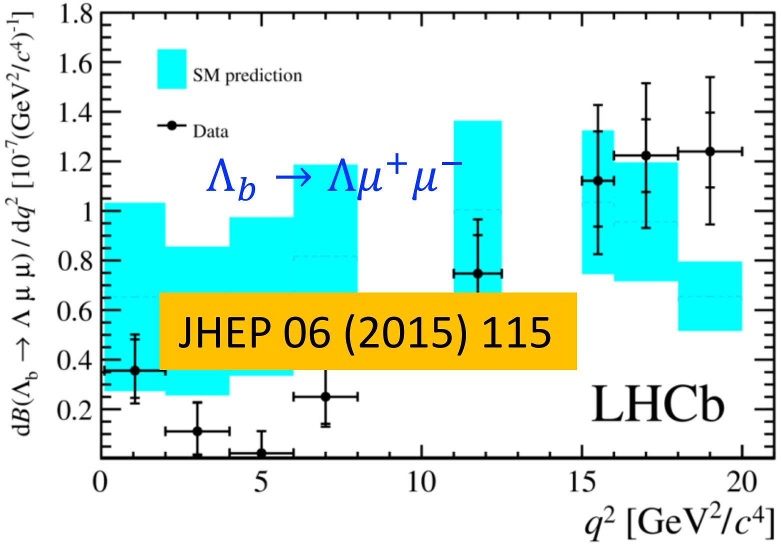
Differential BR

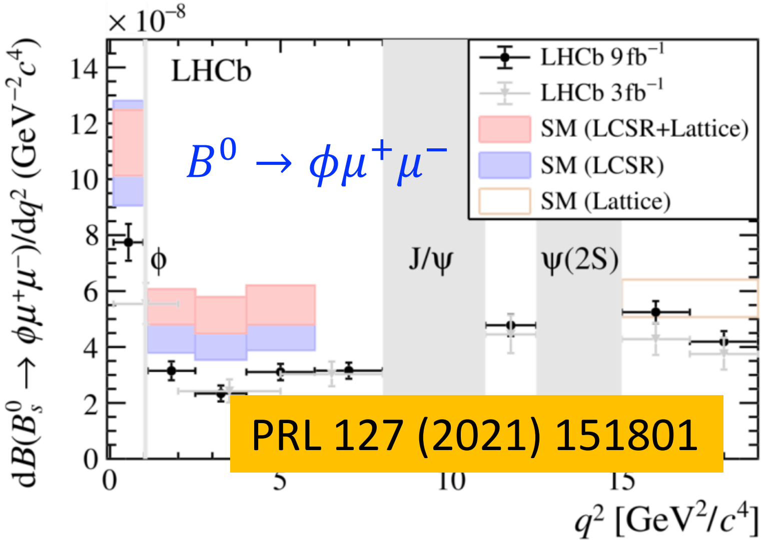




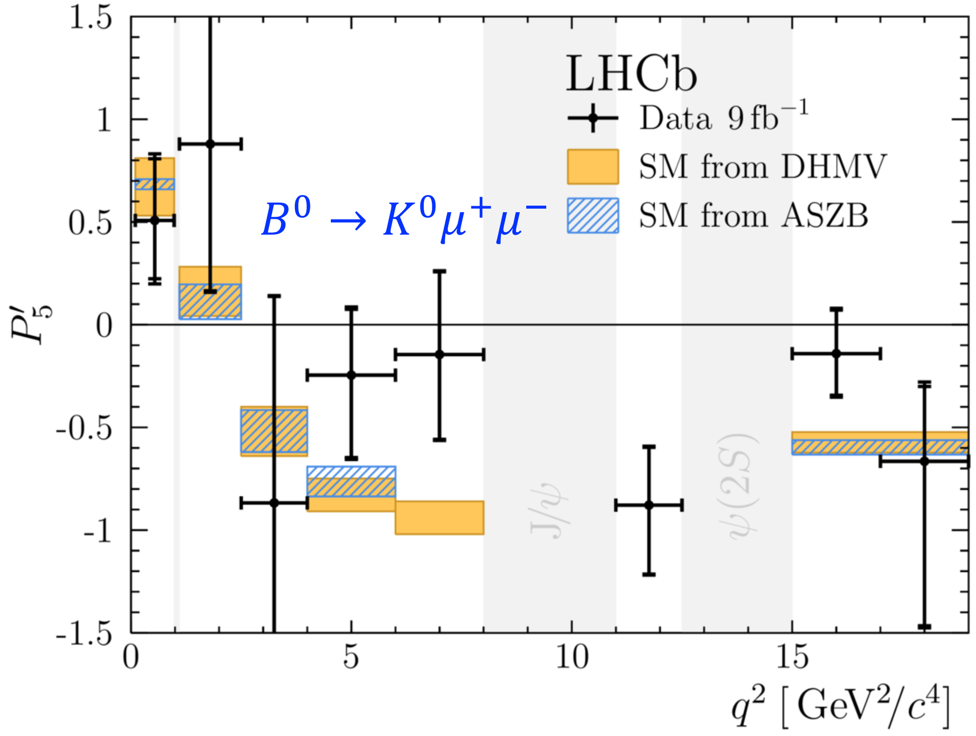




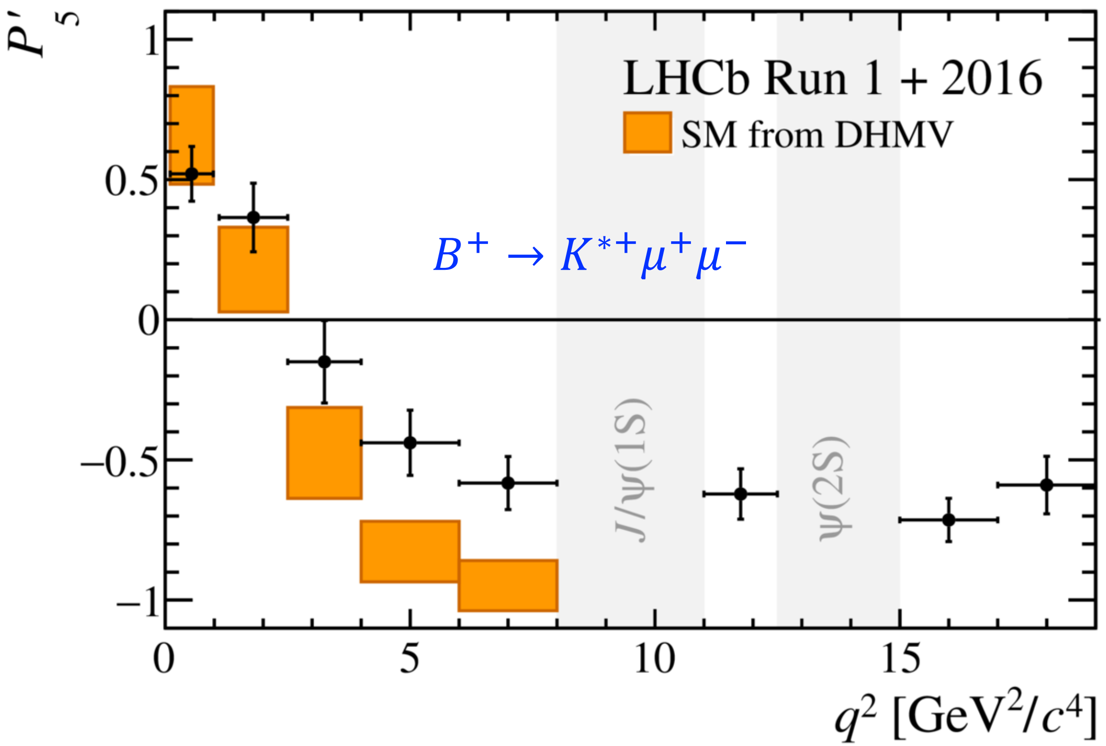




Angular measurements



PRL 125 (2020) 011802



PRL 126 (2021) 161802

Improved LU measurement from LHCb

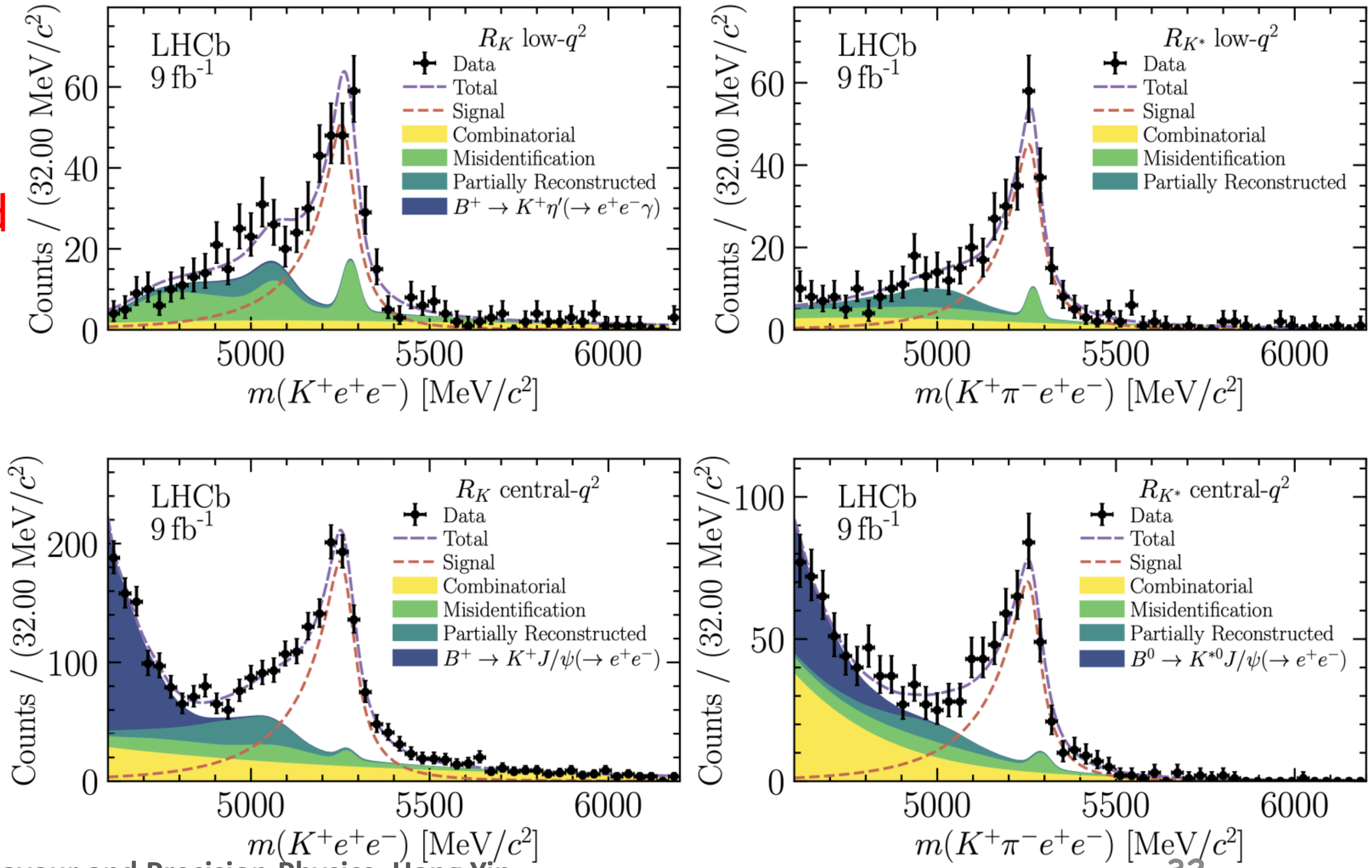
LHCb-Paper-2022-045, arXiv:2212.09153
LHCb-Paper-2022-046, arXiv:2212.09152

- Simultaneous analysis of R_K and R_{K^*}

- Electron mode:
  - mis-ID background found

- Muon mode:
  - consistent with before

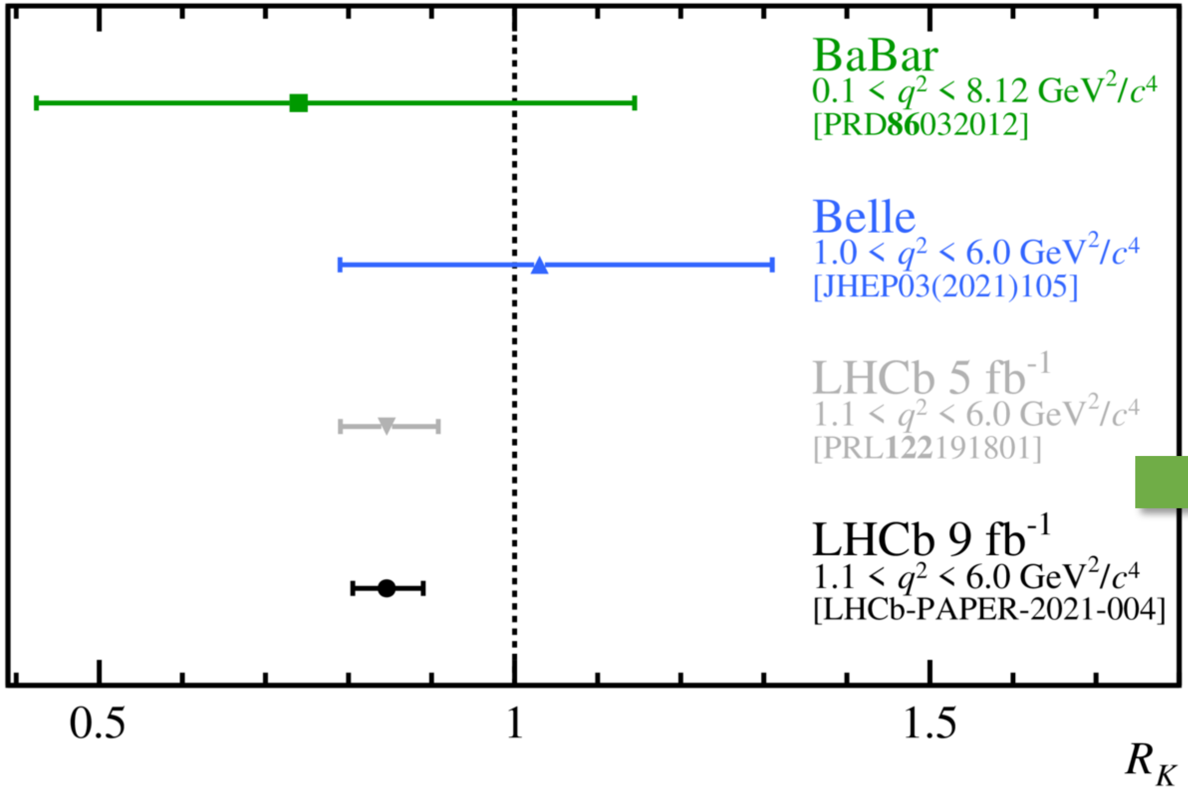
- Still statistically dominated

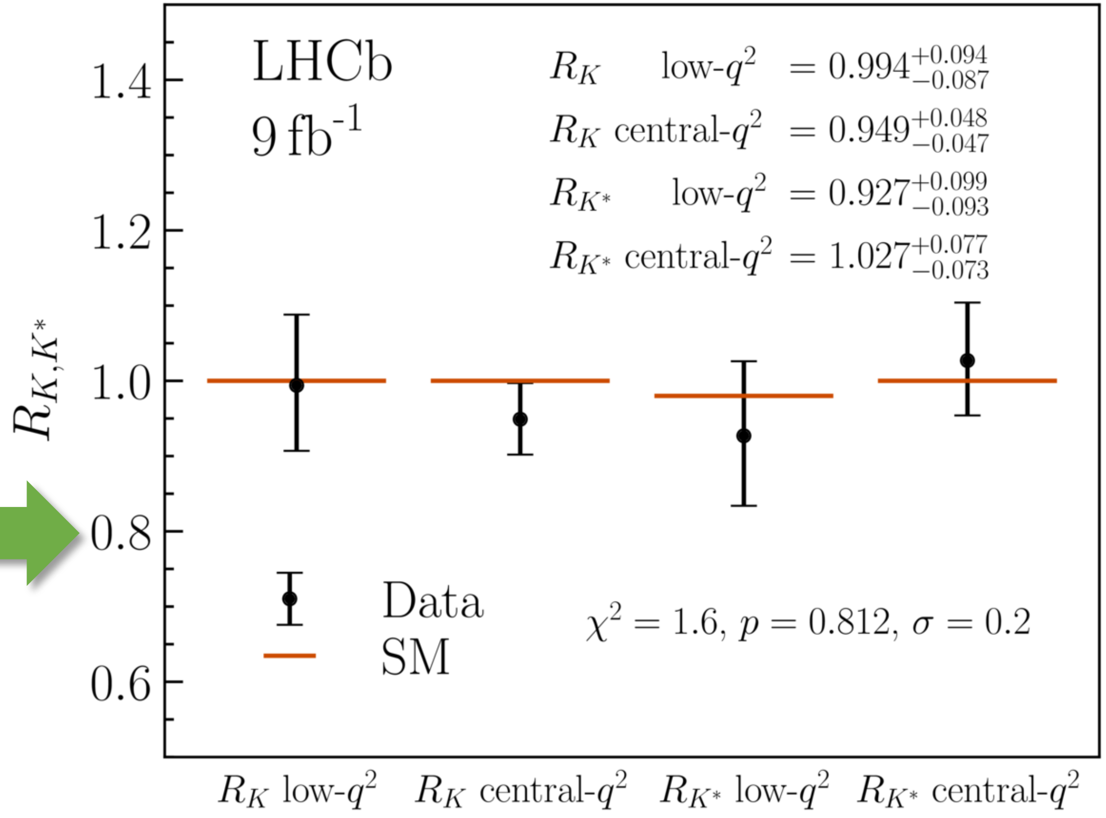


In agreement with SM

- R_K and R_{K^*} consistent with 1

LHCb-Paper-2022-045, arXiv:2212.09153
LHCb-Paper-2022-046, arXiv:2212.09152





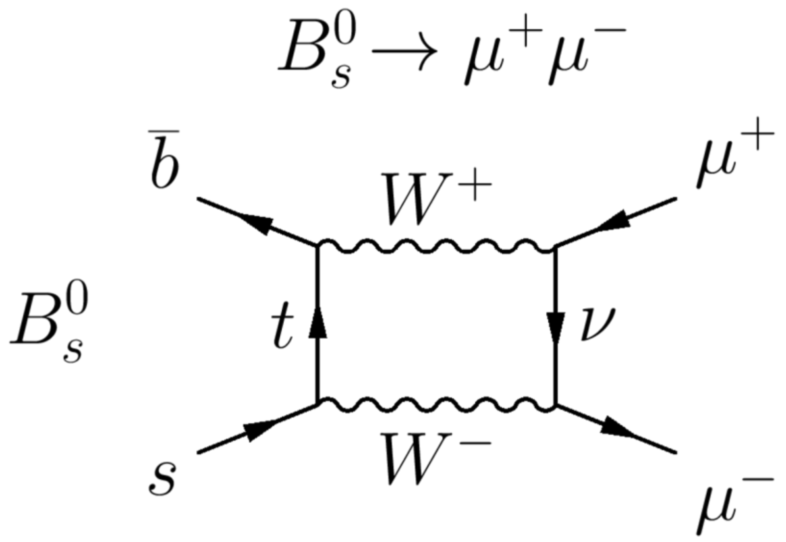
Selected topics: precision

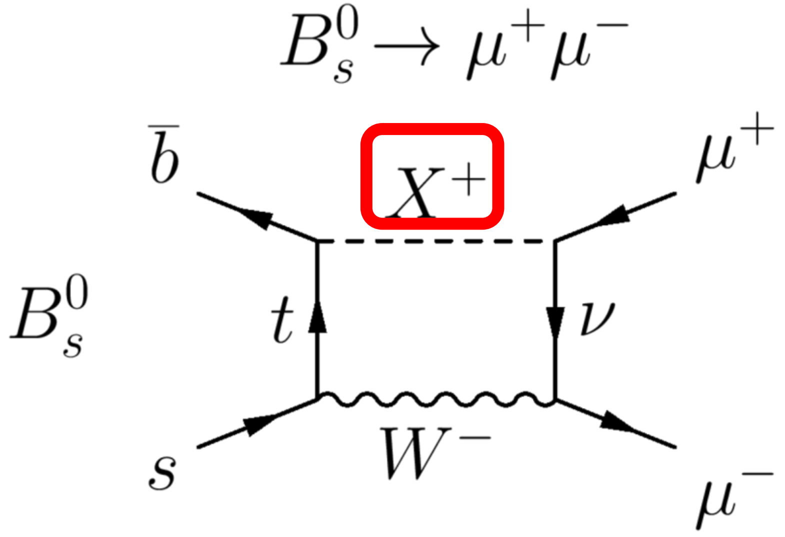
$B^0_{d,s} \to \mu^+\mu^-$ search

- **Golden modes in NP searches:**
  - Flavour Changing Neutral current
  - No tree diagram, only higher orders
  - Helicity suppressed
  - Possible new physics in the loops

- **Precise SM prediction:**
  - $B(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
  - $B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$

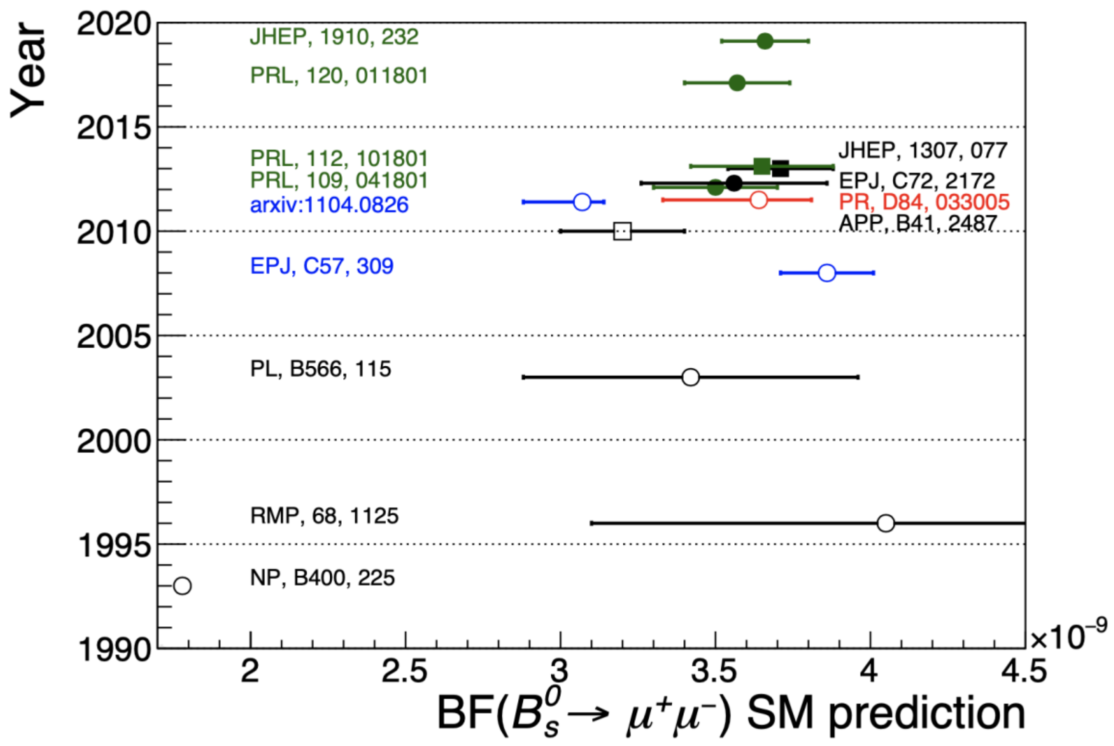
PRL 112 (2014) 101801
JHEP 10 (2019) 232

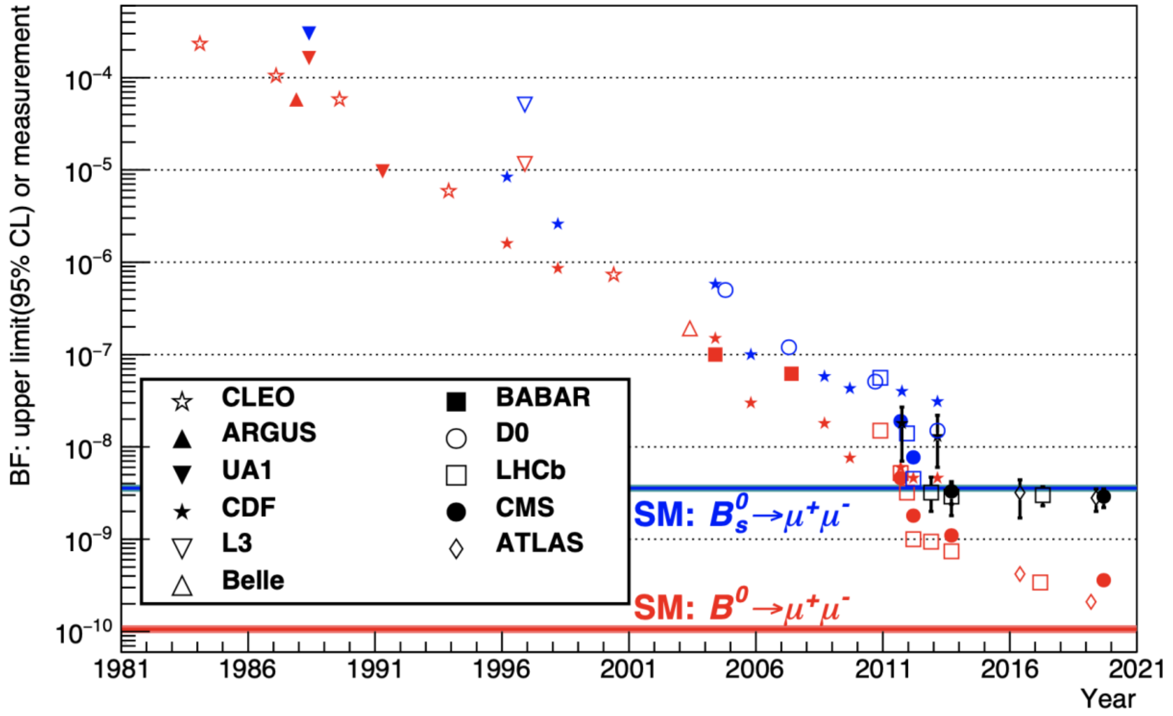




$B^0_{d,s} \to \mu^+\mu^-$ search

- Golden modes in NP searches

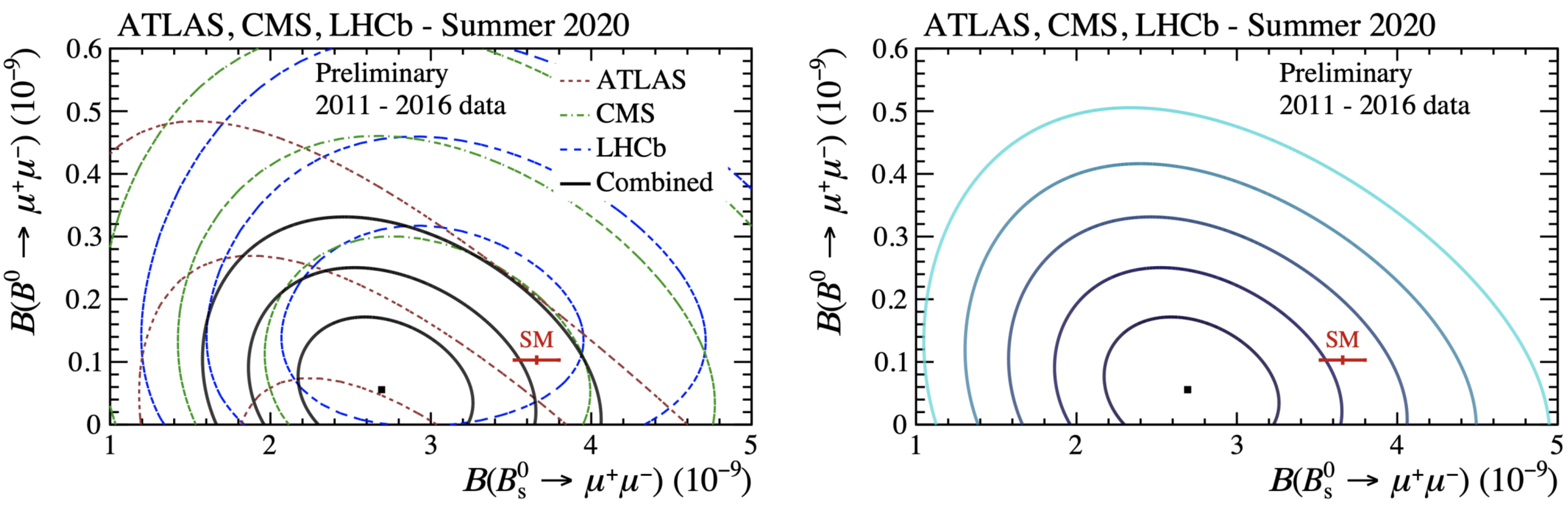




Mod. Phs. Lett. A 35 (2020) 2030017

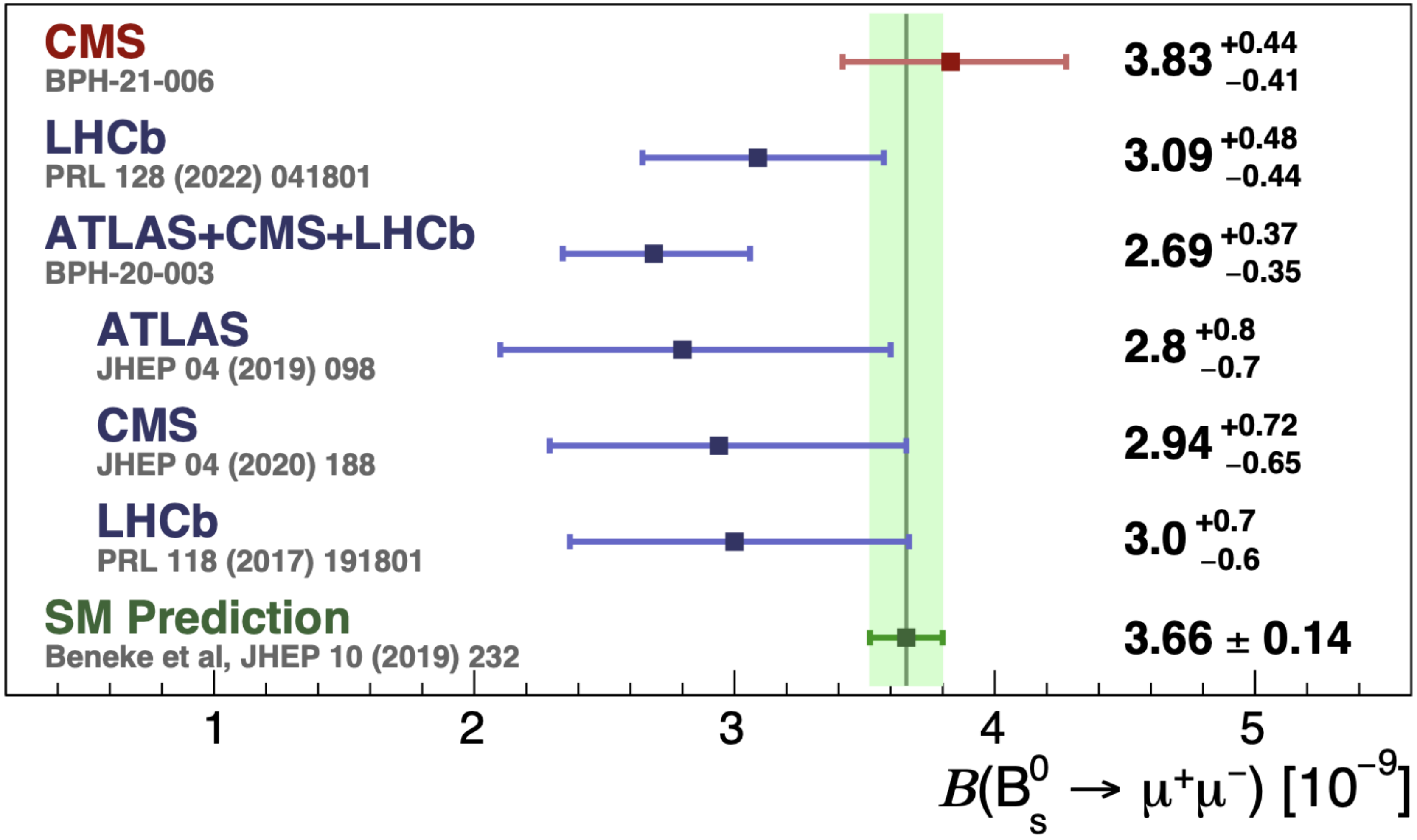
$B^0_{d,s} \to \mu^+\mu^-$ search

- Golden modes in NP searches: precisely predicted in the SM



LHCb-CONF-2020-002

$B_{d,s}^0 \to \mu^+\mu^-$ status



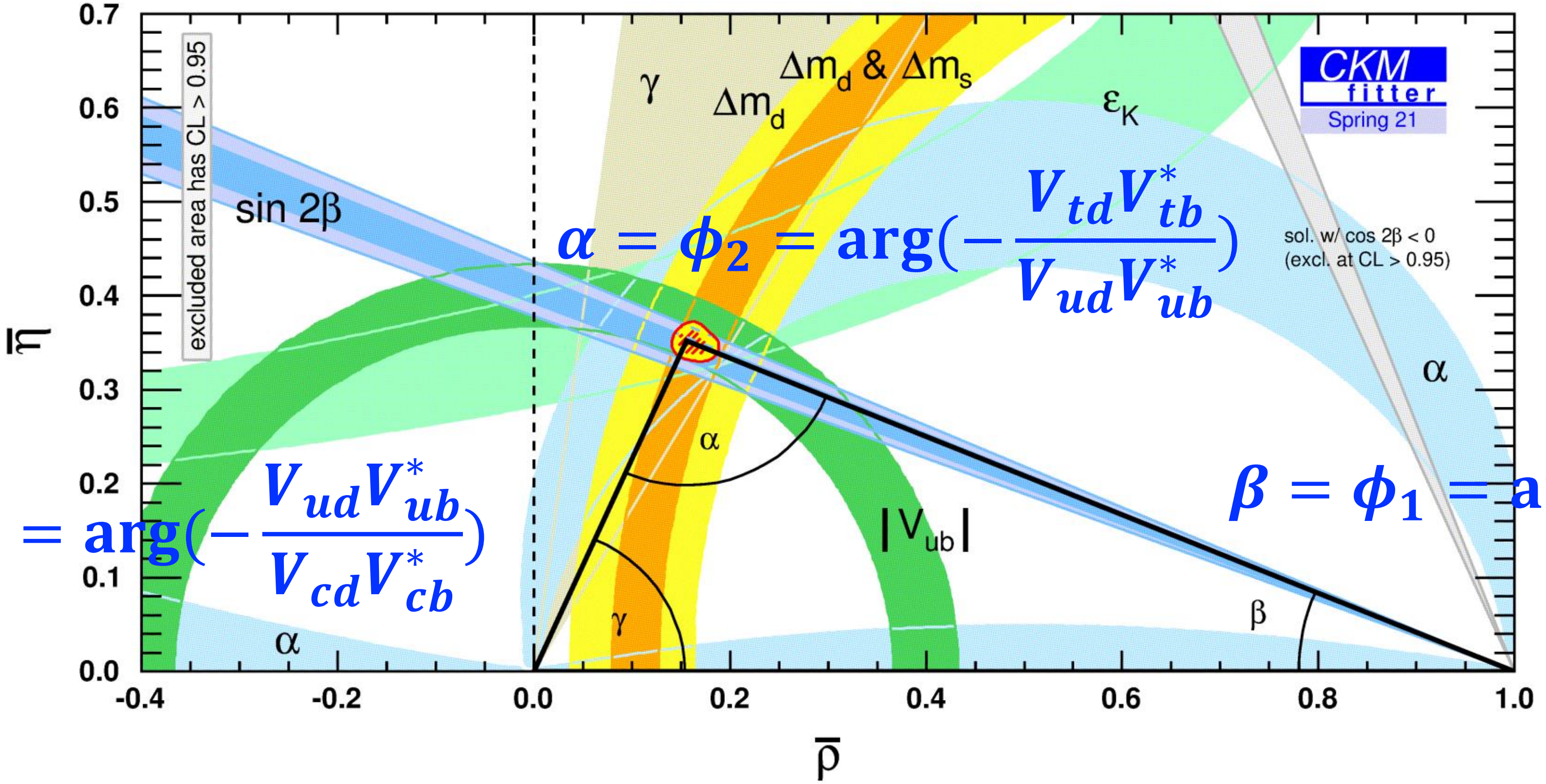
New CMS value in line with the SM

More data are needed to improve precision

arXiv: 2211.13030

Unitarity triangle

- The unitarity triangle exploits the relation:
  - $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$

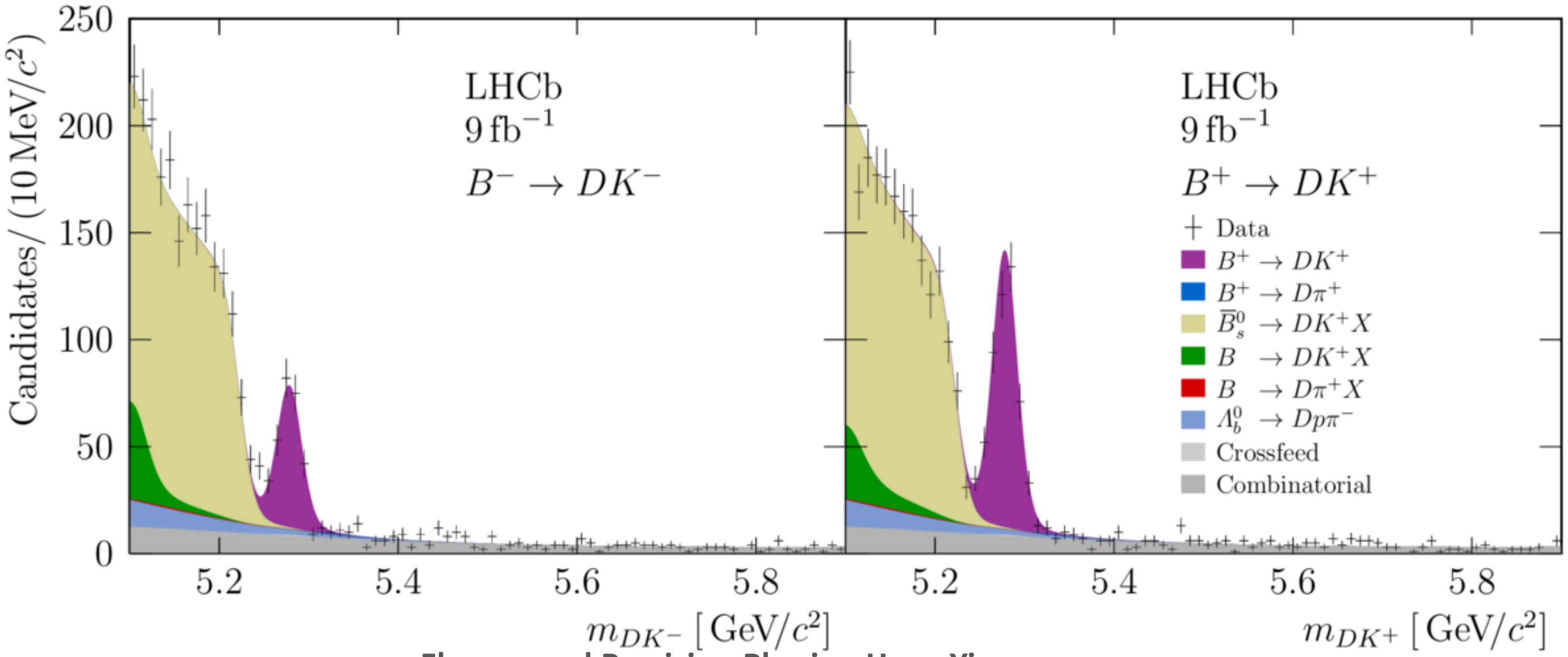
$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$

$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$

γ direct measurement

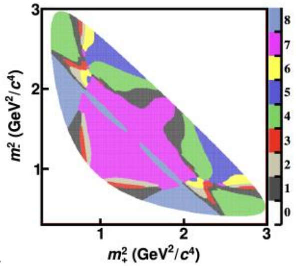
LHCb-PAPER-2022-017, arXiv:2209.03692

- $B^{\pm} \to DK^{\pm}/\pi^{\pm}$ in binned $D^0 \to K\pi\pi\pi$ phase space
- Phase space regions with difference in sensitivity due to different strong phase
- One of the most precise single direct measurement of γ



γ combination

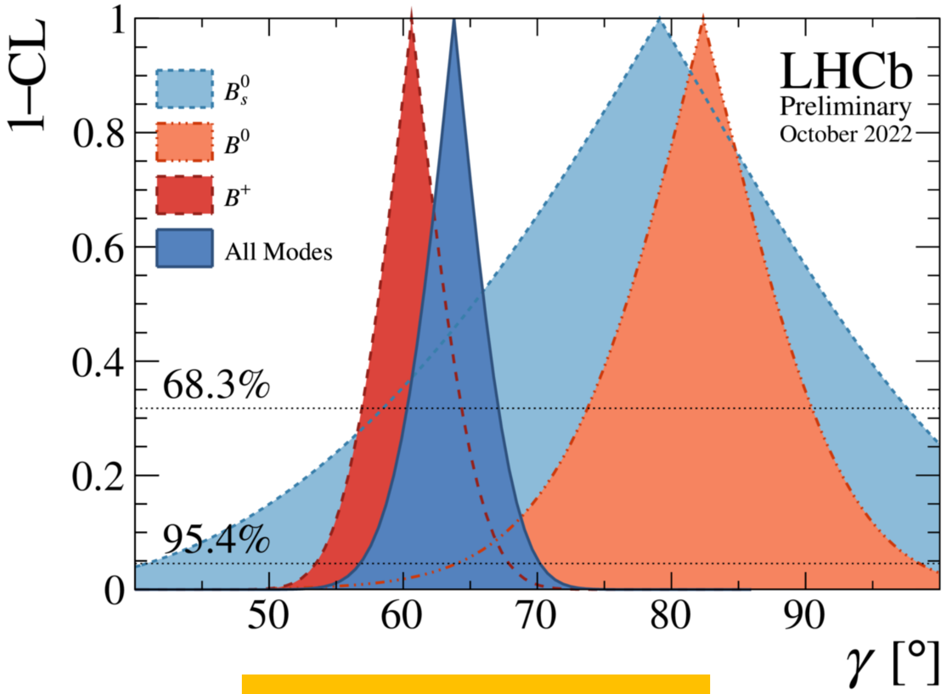
For the strong phase of D meson, we need input from BESIII
For example: $\psi(3770) \to D\bar{D}$ [PRD 101 (2020) 112002]



- Combining all LHCb results for γ

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]	Run 1&2	As before

Good agreement with CKM fitter
Limited by statistics

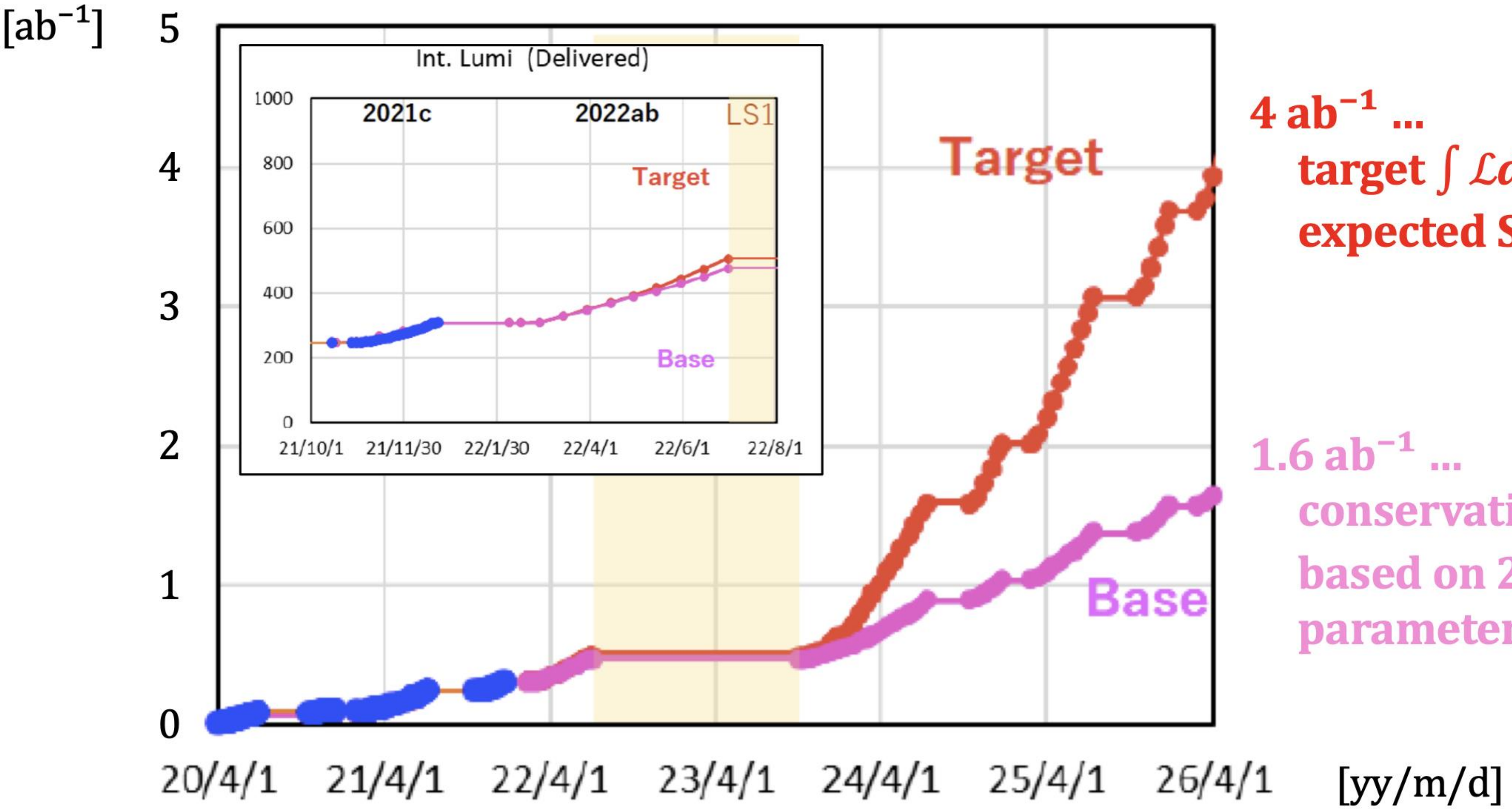


LHCb-CONF-2022-003

$(63.8^{+3.5}_{-3.7})$

The future

Belle-II



4 ab^{-1} ...
target $\int \mathcal{L}dt$ including expected SuperKEKB improvement

1.6 ab^{-1} ...
conservative $\int \mathcal{L}dt$ estimate based on 2021 SuperKEKB parameters

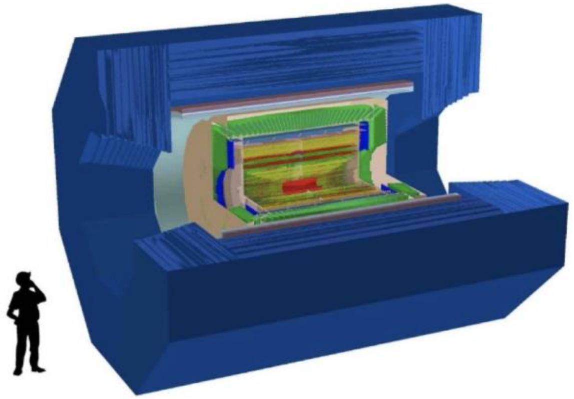
STFC (Super tau-charm factory)

- **CME : 2-7 GeV**
- **Peaking $\mathcal{L}$: >5×10^{34} cm^{-2} s^{-1}**
- **Potential to further improve the lumi and realize polarized beam**
- **Double storage ring : ~800 m , injection : ~ 300m**
- **BESIII-Like detector**
- **Cost 4.5B RMB**

arXiv:2303.15790

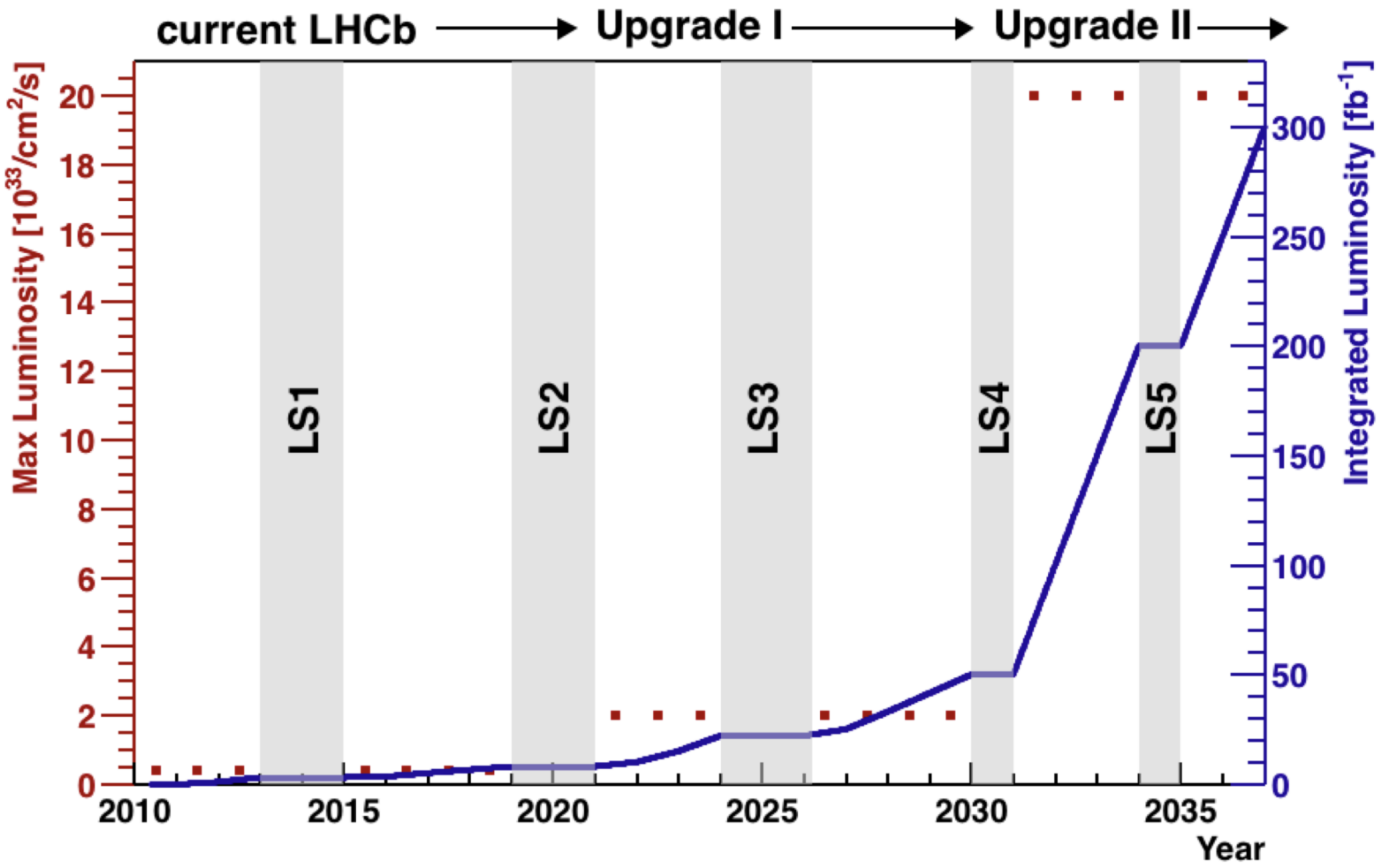
From Gang Li's talk at Aug. 2022

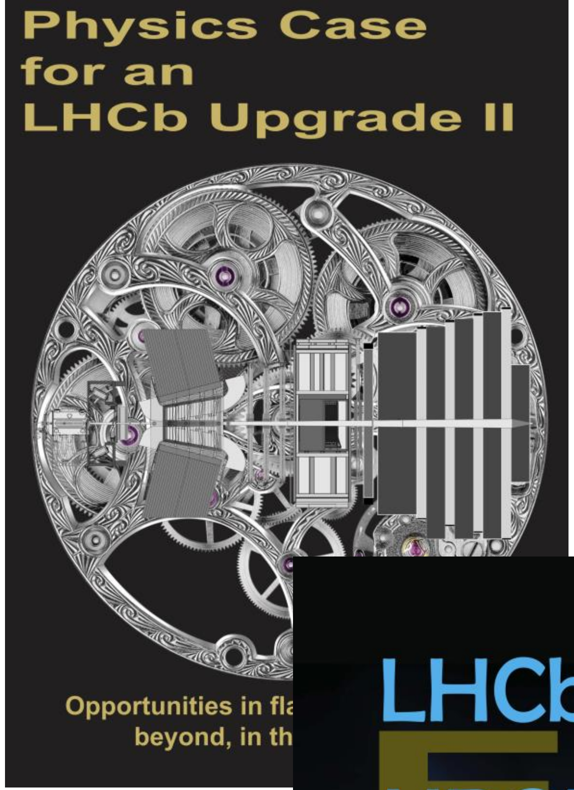
Rich of Physics: unique for physics with c and τ lepton

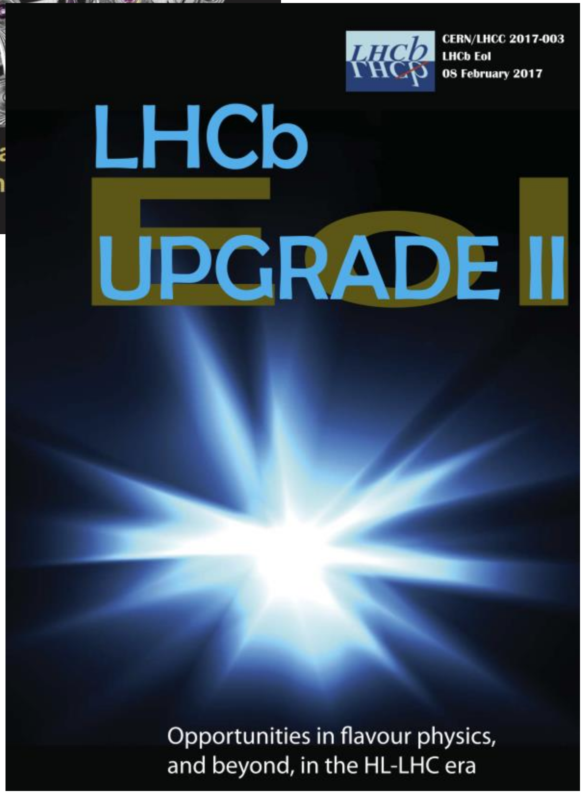


LHCb upgrade

CERN-LHCC-2017-003
CERN-LHCC-2018-027



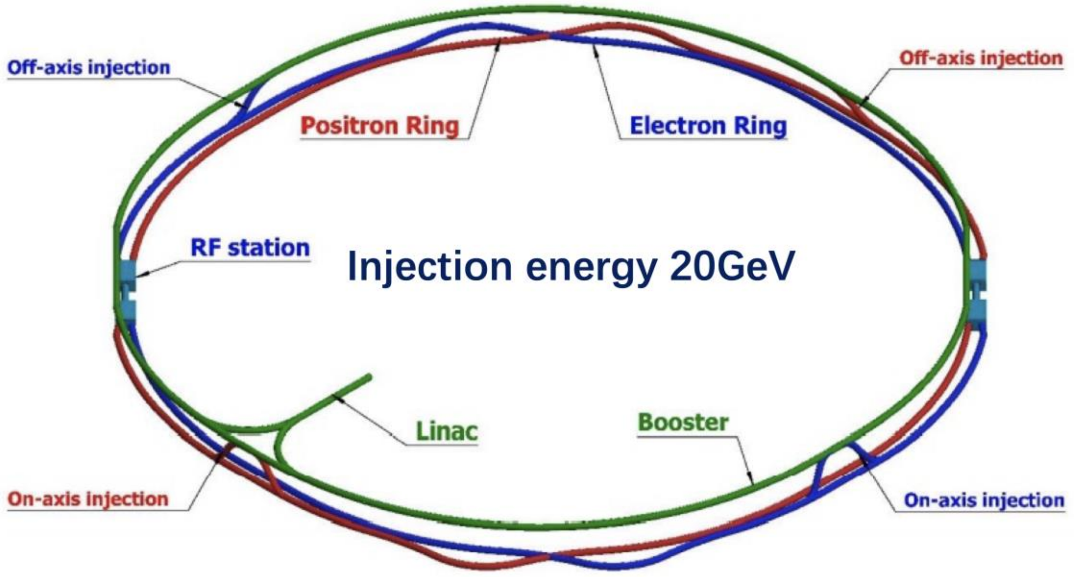


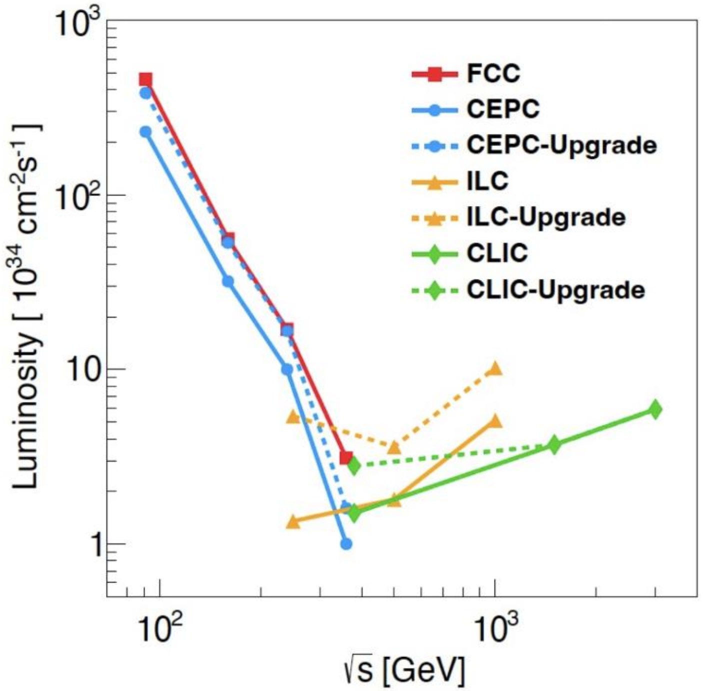


Opearte at up to $1.5 \times 10^{34} cm^{-2} s^{-1}$ and collect 300 fb^{-1}+

CEPC

- 100 km double ring design (30 MW SR power, upgradeable to 50 MW)
- Switchable between Higgs/Z/W modes without hardware change
- New baseline for Linac (C-band, 2 GeV)

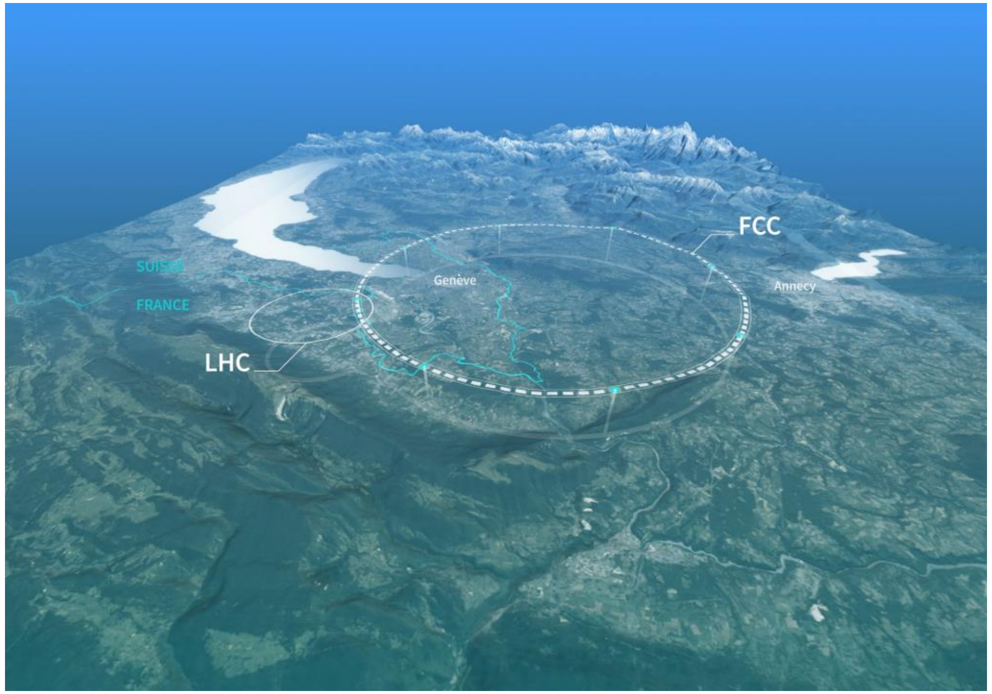




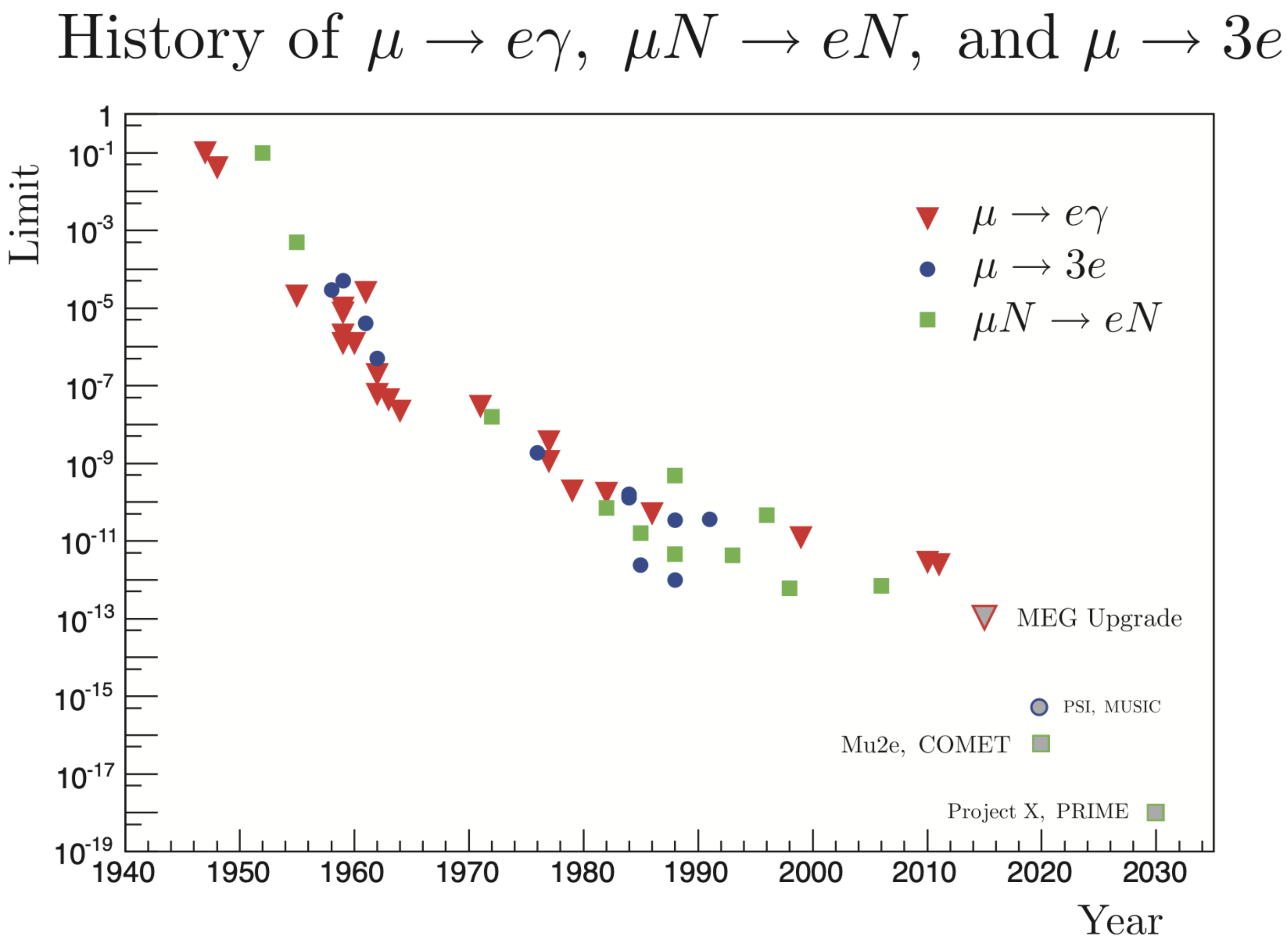
FCC-ee

- Similar design: longer timescale, higher design luminosity
- First e^+e^- collisions in the middle of 2040s
- Extremely interesting for EW physics, also b and τ physics

c.m. energy [GeV]	lum./ IP [10^{34} cm^{-2}s^{-1}]	int. lum./year (2 IPs) [ab^{-1}/yr]	run time [yr]	power [MW]
91	200	48	4	259
160	20	6	1–2	277
240	7.5	1.7	3	282
365	1.3	0.34	5	354



The journey of CLFV search …



Mu2e and COMET aim to imporve by a factor 10^4

Phys. Report 532 (2013) 27

Summary

- Flavour physics plays key roles in the particle physics
- Still many anamolies in the flavour physics
  - $b \to sll$ differential BR and angular measurements
  - LFU
  - g-2
  - …
- A precision flavour physics era ahead of us
  - Belle II and LHCb upgrades will bring preciesion that not been achieved before
  - New colliders/facilities are coming: STCF, Fcc-ee
  - Lepton flavour experiments: g-2, COMET, mu2e

The Golden Age by Pietro da Cortona

Backup

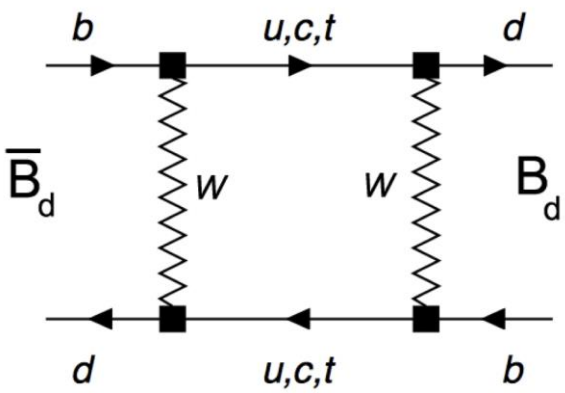
B^0 mixing to probe top mass

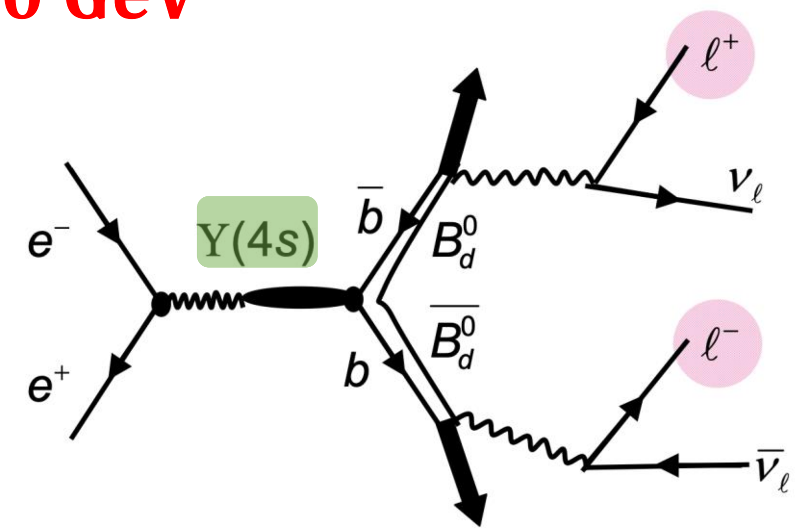
- **1987**: B_d mixing from **ARGUS** ($\sqrt{s} = 10.58$ GeV)

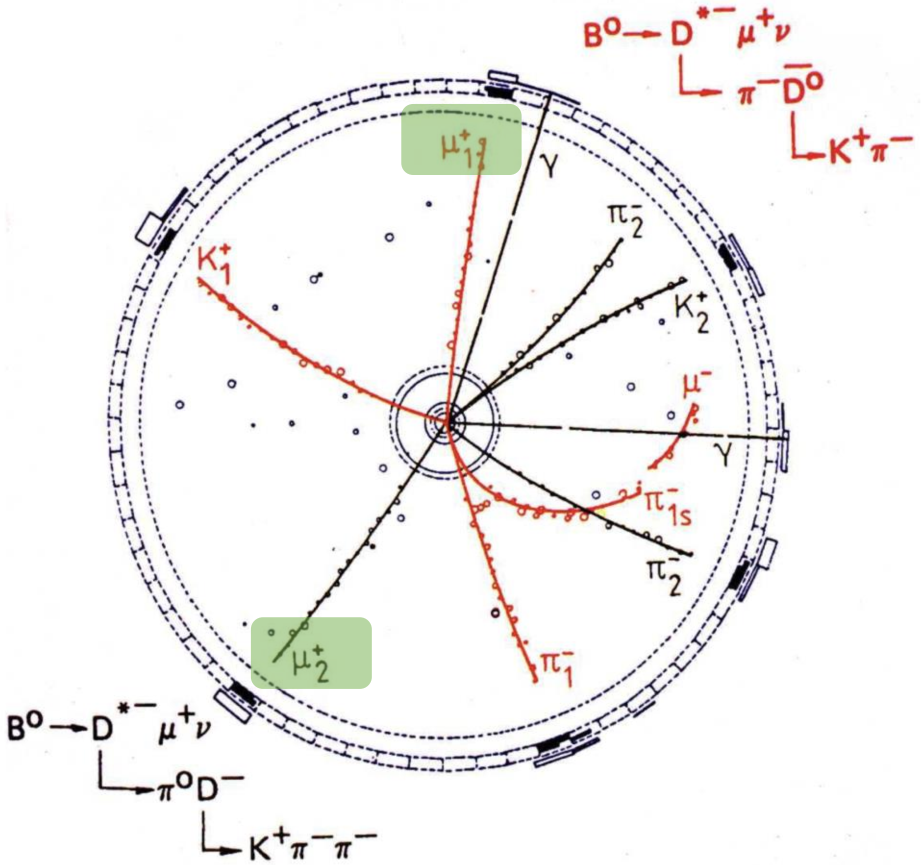
PLB 192 (1987) 245

  - $\Delta m_d \sim 0.00002 \times \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \; ps^{-1} \sim 0.5\, ps^{-1}$

$\Rightarrow m_t > 50$ GeV

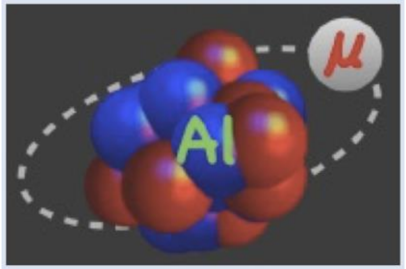






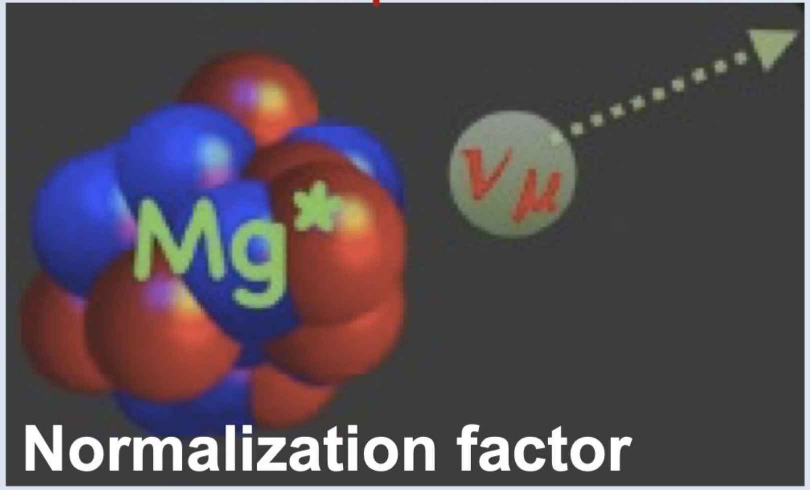
$\mu + N \rightarrow e + N$: experimental technique

- Beam of low momentum muons
- Muons stopped in Al target
- Muons trapped in orbit around the nucleus
- Look for $\mu^- N(A,Z) \rightarrow e^- N(A,Z)$ events: mono-energetic e^- with $E \sim M_\mu$ produced
- Normalize to muon captures counting emitted muonic X-rays

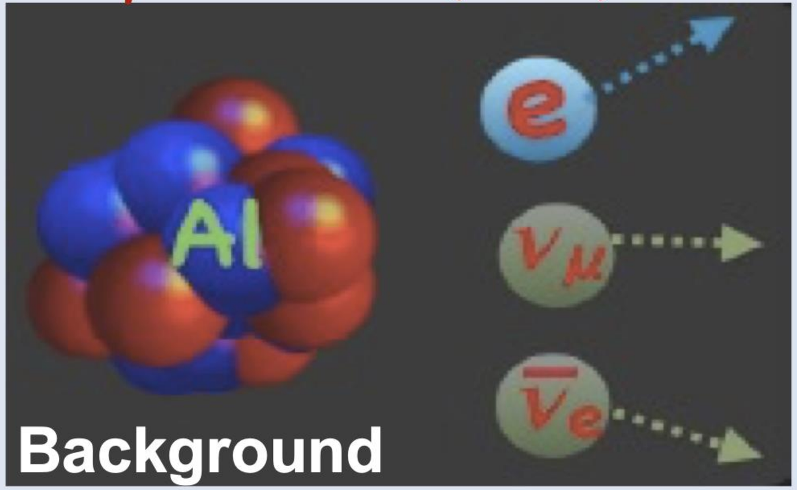


$\tau_\mu^{Al} = 864$ ns

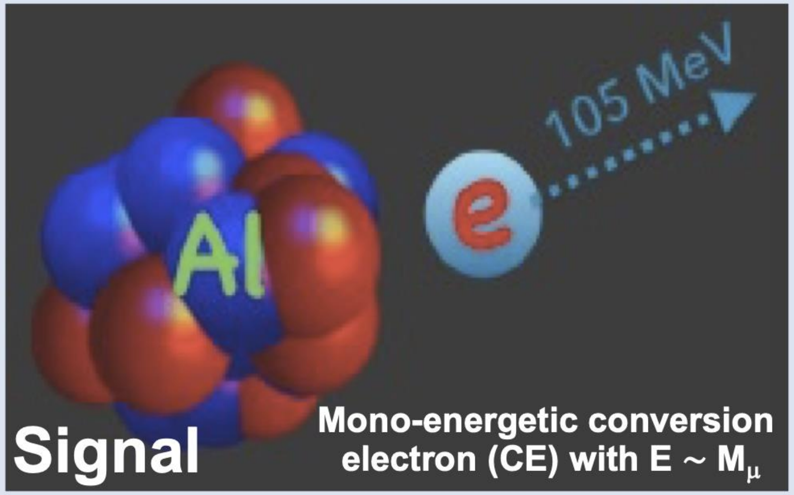
Nuclear capture ~ 61%



Decay In Orbit (DIO) ~ 39%

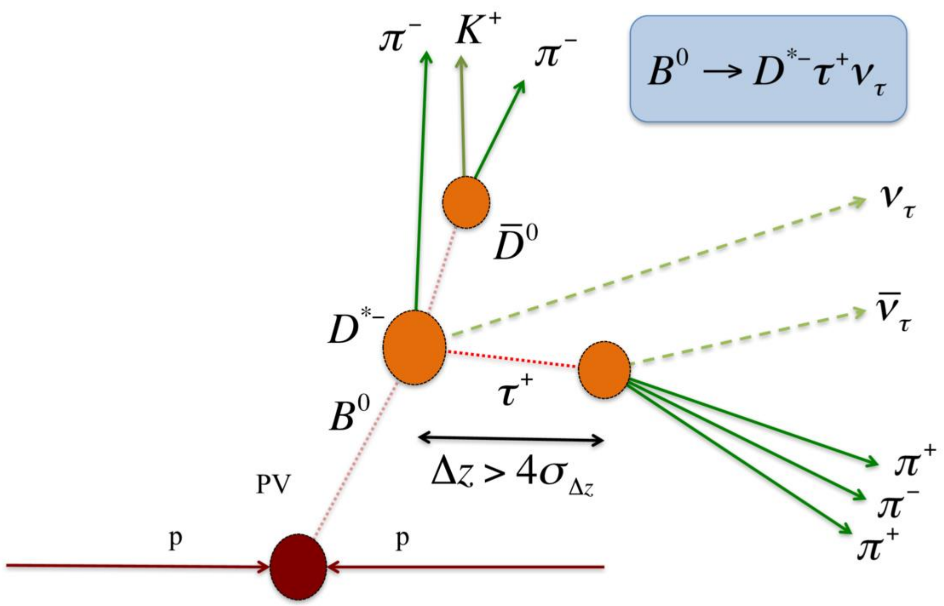


Conversion < 10^{-12}



A ratio measurement

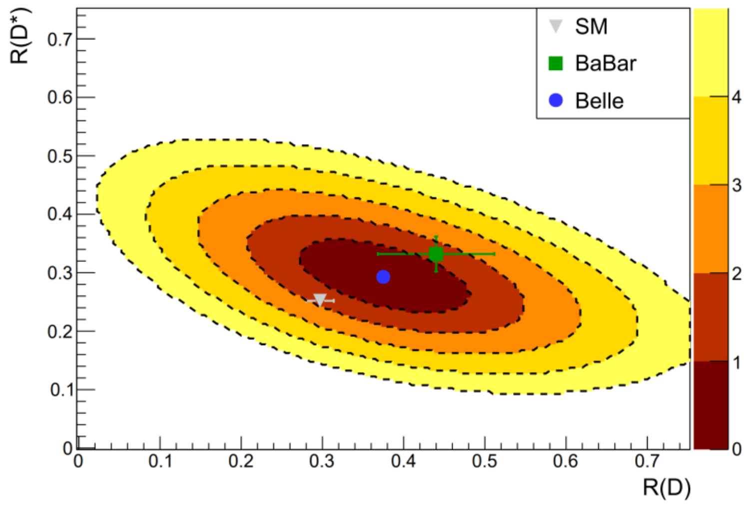
- Advantages:
  - Precision: large b-hardon production and lar
    - $b \to cl\nu$ transitions: charge current, tree level, a f
  - Uncertainties: hadronic form factor uncertai uncertainties are cancelled
    - SM prediction: 0.300 ± 0.008, from Lattice calcul Phys.Rev.D 92, 054410 (2015)]
    - 0.254 ± 0.005



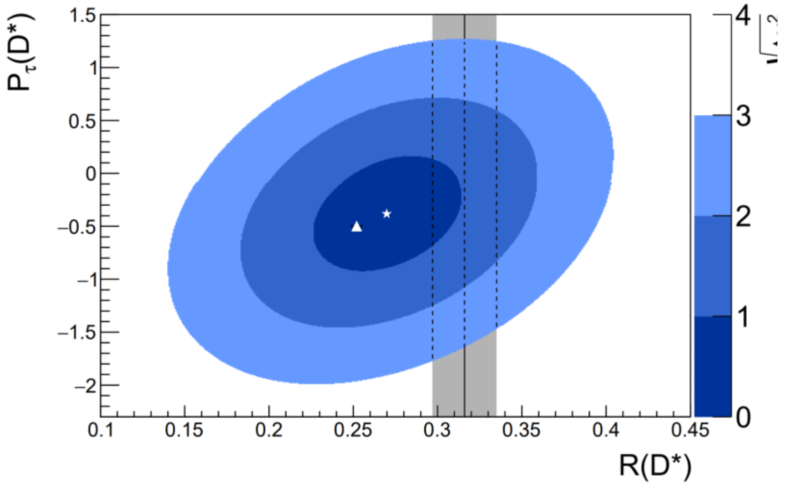
- Challenges:
  - Neutrinos: missing neutrinos in the final state, affects the resolution of observables @LHCb
  - Large background: partially reconstructed background contamination
  - Size of Simulation: large simulation samples needed for modelling signal and bkg

Hints of NP since 2012

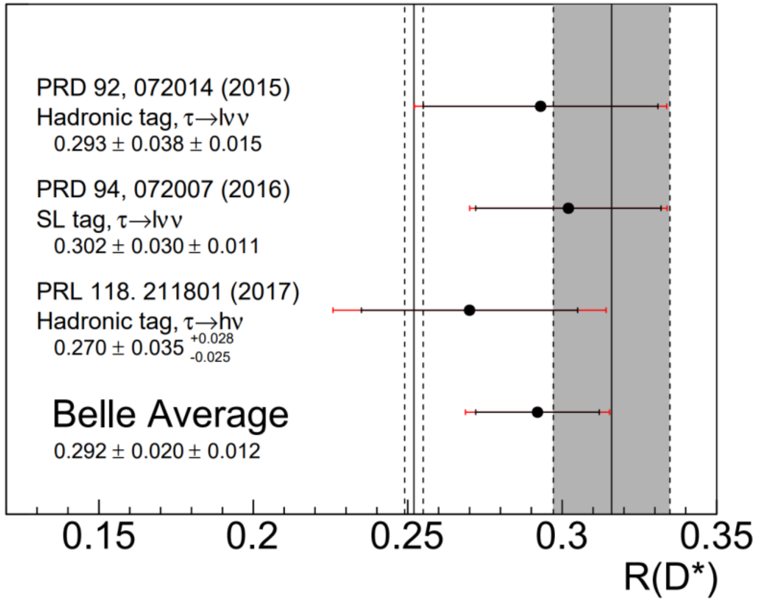
- Belle Collaboration



PRD 92, (2015) 072014



PRL 118, (2017) 211801

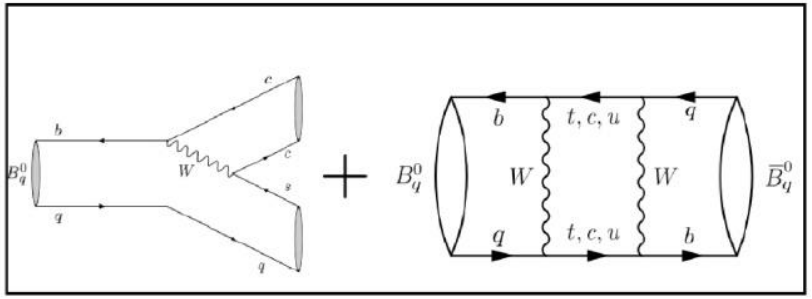


PRD 97, (2018) 012004

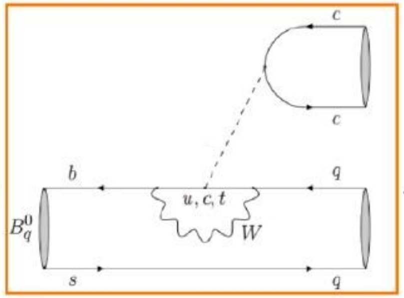
Phys.Rev.Lett. 124 (2020) 16, 161803

ϕ_s measurements

- CP violation phase arising from interference between mixing and decay, precisely predicted
- Golden channel exploited by LHCb, ATLAS, CMS: $B_s^0 \to J/\psi\,\phi$
  - Statistically limited
  - HFLAV combination: $\phi_s = -0.041 \pm 0.025\,rad$

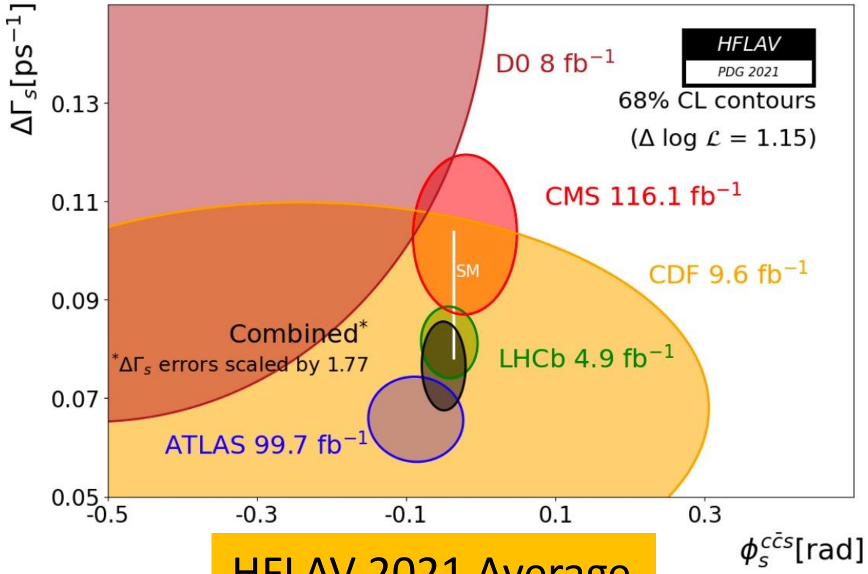


Dominant SM "tree" contribution



Higher order "penguin" contributions from non-perturbative hadronic effects

NP could be difficult t distinguish from penguins...



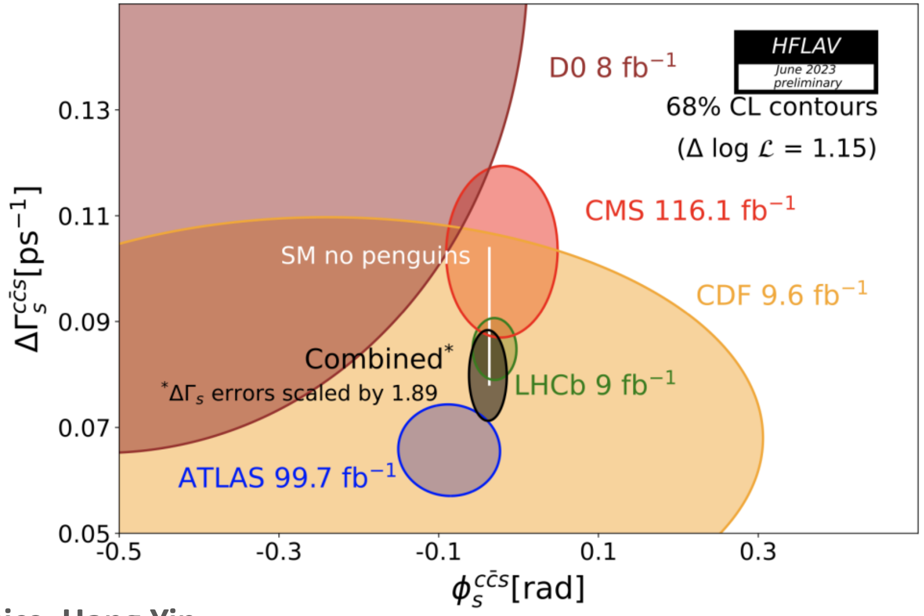
HFLAV 2021 Average

ϕ_s measurements

More details can be found in Peilian and Vukan's CERN seminar talk

LHCb-paper-2023-016, in preparation

- The most precise measurement to date
  - $\phi_s = -0.039 \pm 0.022 \pm 0.006$ rad
- Updated with full data-set (combined all results)
  - $\phi_s = -0.050 \pm 0.017$ rad (23% improvement)
  - $\phi_s^{c\bar{c}s} = -0.039 \pm 0.016$ rad (15% improvement)
- Consistent with the prediction of global fits assuming SM
  - No evidence of CP violation



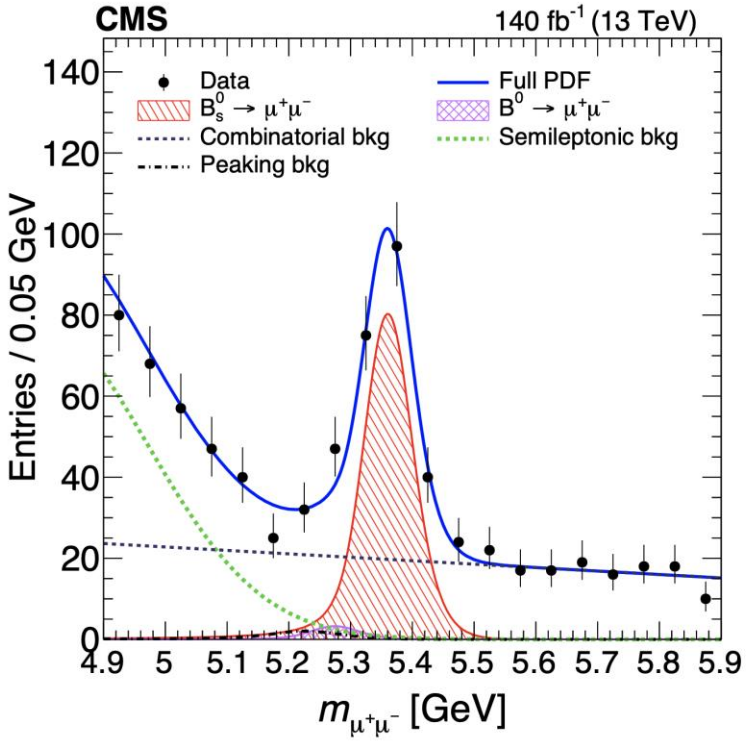
γ angle measurement

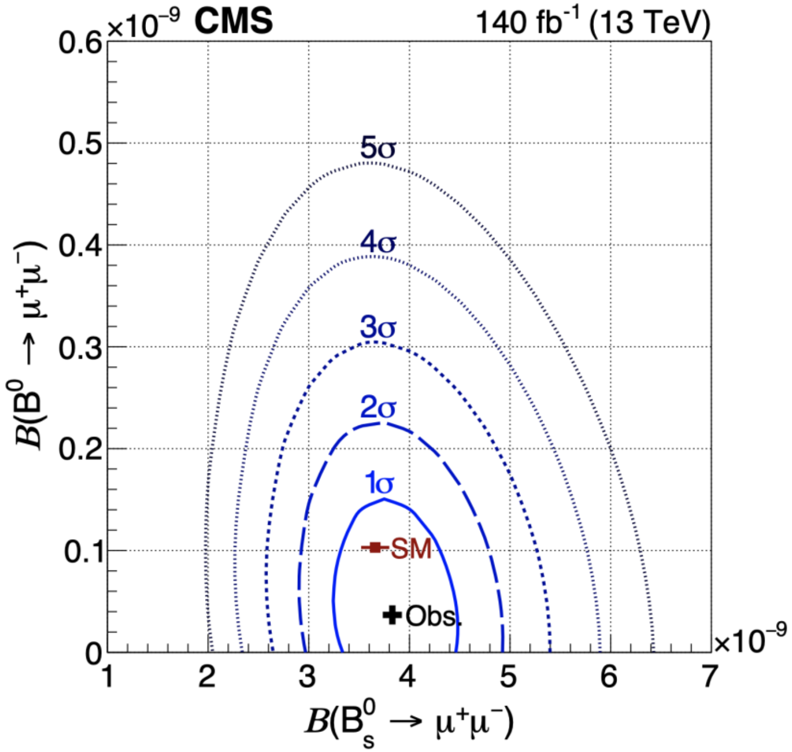
$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

1. GLW (Gronau-London-Wyler) method:
$D^{(*)}$ decay into CP eigenstates, eliminating further hadronic uncertainties from the $D^{(*)}$ decays
2. ADS (Atwood-Dunietz-Soni) method:
$D^{(*)}$ decay with a pattern of Cabibbo dominance/suppression that counteracts the colour suppression/dominance of the B decay
3. GGSZ (Giri-Grossman-Soffer-Zupan) method:
Dalitz analysis of three body $D^{(*)}$ decays, including a dependence on the amplitude mode for $D^{(*)}$ decays

	Process	Constraint	Process	Constraint
			$B \to D^{(*)}\ell\nu$	$\|V_{cb}\|$ versus form factor $F^{B\to D^{(*)}}$
			$B \to X_c\ell\nu$	$\|V_{cb}\|$ versus OPE
			$B \to \pi\ell\nu$	$\|V_{ub}\|$ versus form factor $F^{B\to\pi}$
Tree	$B \to D^{(*)}K^{(*)}$	γ	$B \to X_u\ell\nu$	$\|V_{ub}\|$ versus OPE
			$M \to \ell\nu$	$\|V_{UD}\|$ versus decay constant f_M
			$M \to N\ell\nu$	$\|V_{UD}\|$ versus form factor $F^{M\to N}$
				or $M \to N$ amplitude
	$B \to (c\bar{c})K^{(*)}$	β	ϵ_K ($K\overline{K}$ mix)	$V_{ts}V_{td}^*$ and $V_{cs}V_{cd}^*$
				versus bag parameter B_K
Loop	$B \to \pi\pi, \rho\pi, \rho\rho$	α	Δm_d ($B^0\overline{B}^0$ mix)	$\|V_{tb}V_{td}^*\|$ versus bag parameter B_{B^0}
	$B_s^0 \to J/\psi\phi$	β_s	Δm_s ($B_s^0\overline{B}_s^0$ mix)	$\|V_{tb}V_{ts}^*\|$ versus bag parameter $B_{B_s^0}$

$B^0_{d,s} \to \mu^+\mu^-$ status





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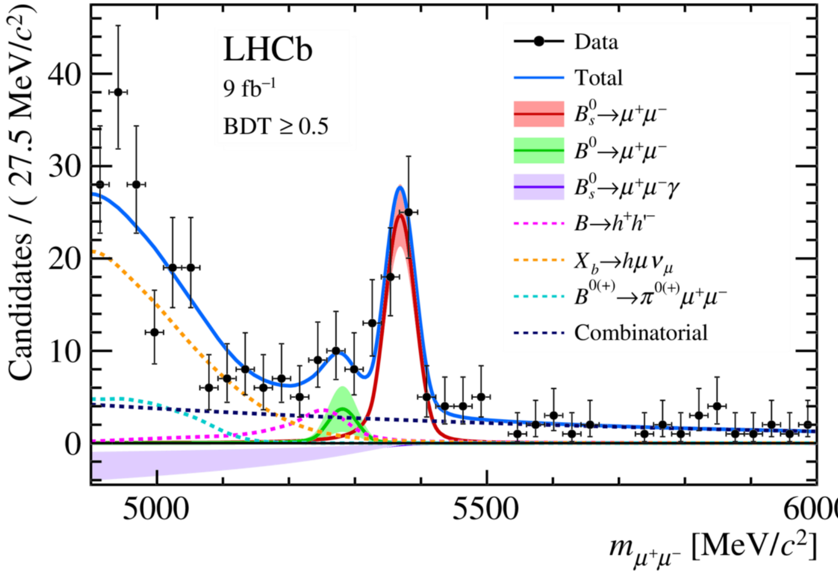

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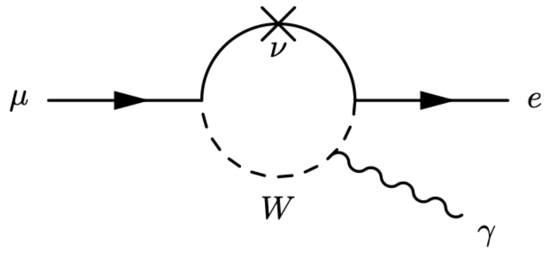
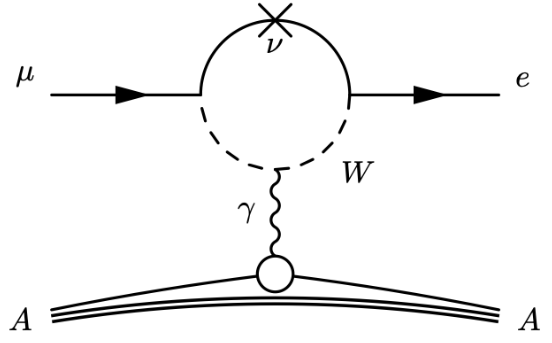
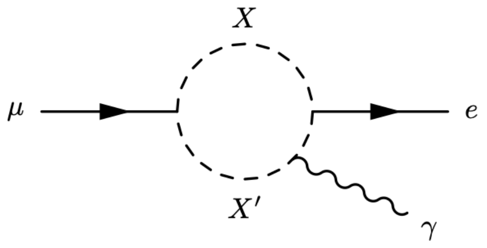
Charged lepton falvour violation (CLFV)

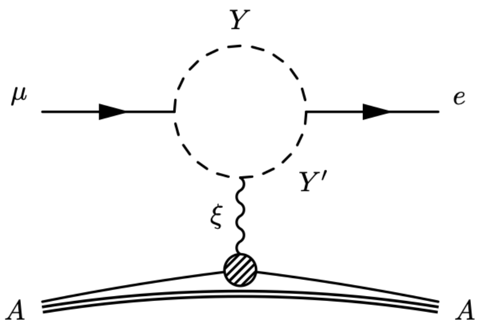
- CLFV processes strongly suppressed in SM
  - Not forbidden due to neutrino oscillation
  - rates $\propto \frac{m_\nu^4}{m_W^4} < 10^{-50}$
  - enhanced in the new physics



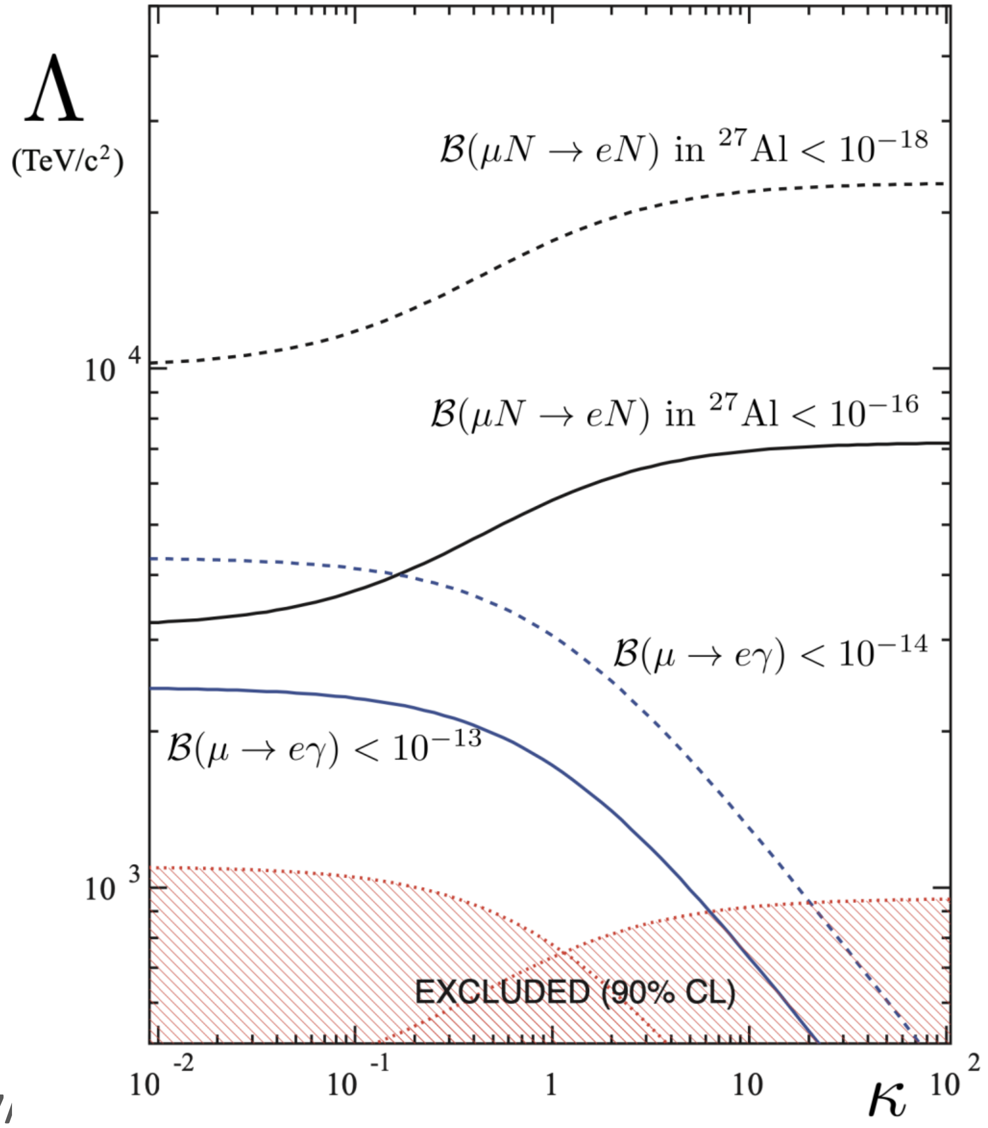


- μ decays
  - $\mu \to e\gamma, \mu \to eee, \mu + N \to e + N^{(\prime)}, \mu^- pp \to e^+ nn$
- τ decays
  - $\tau \to e\gamma, \tau \to eee$
  - $\tau \to \mu\gamma$ can be highly enhanced in the NP model





Effective mass scale



- Upper to 10^4 TeV

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \text{ h.c.}$$
$$+\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + \text{ h.c.}\,.$$