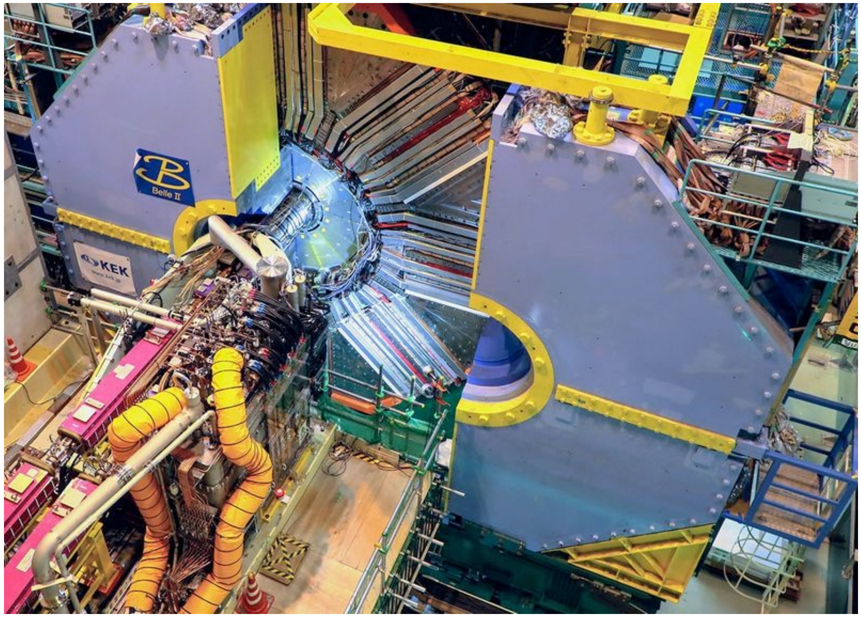
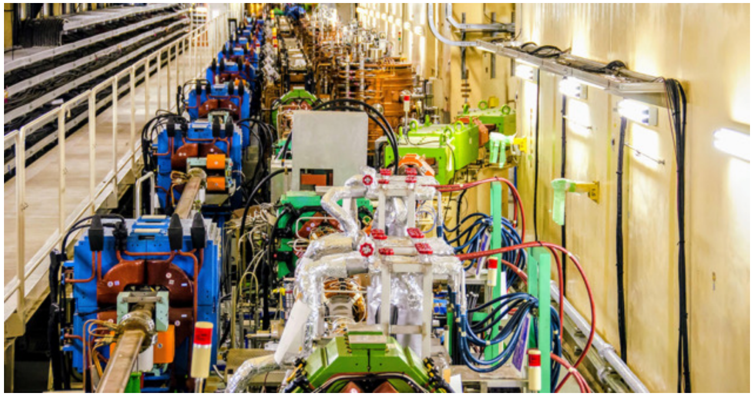
Belle II: Opportunities for NP Discoveries in B physics

Tom Browder, University of Hawai'i at Manoa



The complex superconducting final focus is partially visible here (before closing the endcap).



Inside the SuperKEKB tunnel

Apres Snowmass and the last Belle II Physics Run (Leo's talk) (L_{peak}=4.7 x 10^{34}/cm^2/sec, Int(L dt) > 2.5 fb^{-1} /day, which are new world records. A BaBar-sized data sample is now "on tape".)

A few early Physics Results from Belle II: B Physics

Opportunities for *new physics discoveries* and the road ahead (the Belle II Physics Book, Snowmass Belle II Physics Whitepaper (WP) and other WPs)

Belle II/SuperKEKB Snowmass WPs:
https://confluence.desy.de/display/BI/Snowmass+2021

Snowmass 2022 (*International* Physics Rodeo)

Scenes from the actual Snowmass Rodeo in Colorado

N.B. Snowmass was *just held* in Seattle, Washington in summer of 2022. The last one was held in Minneapolis, Minnesota in 2013. It is unlikely that there will ever be another month-long planning meeting in Snowmass, CO.

Historical note: Young(ish) Scientist Pier Oddone (originally from Peru/Italy) introduced the concept and first proposal for an asymmetric energy B-factory to the broad HEP community at a Snowmass in 1988.

Revisionist History and Paradigm Shift

The B factory experiments, Belle and BaBar, discovered large CP violation in the B system in 2001, compatible with the SM and provided a large range of CKM measurements. These provided the experimental foundation for the 2008 Nobel Prize to Kobayashi and Maskawa.

In the meantime, the LHC was constructed in 2008, ATLAS and CMS completely changed the nature of high energy physics. Of particular importance was the landmark discovery in 2012 of the Higgs boson.

This discovery was recognized by the 2013 Physics Nobel Prize to Englert and Higgs.

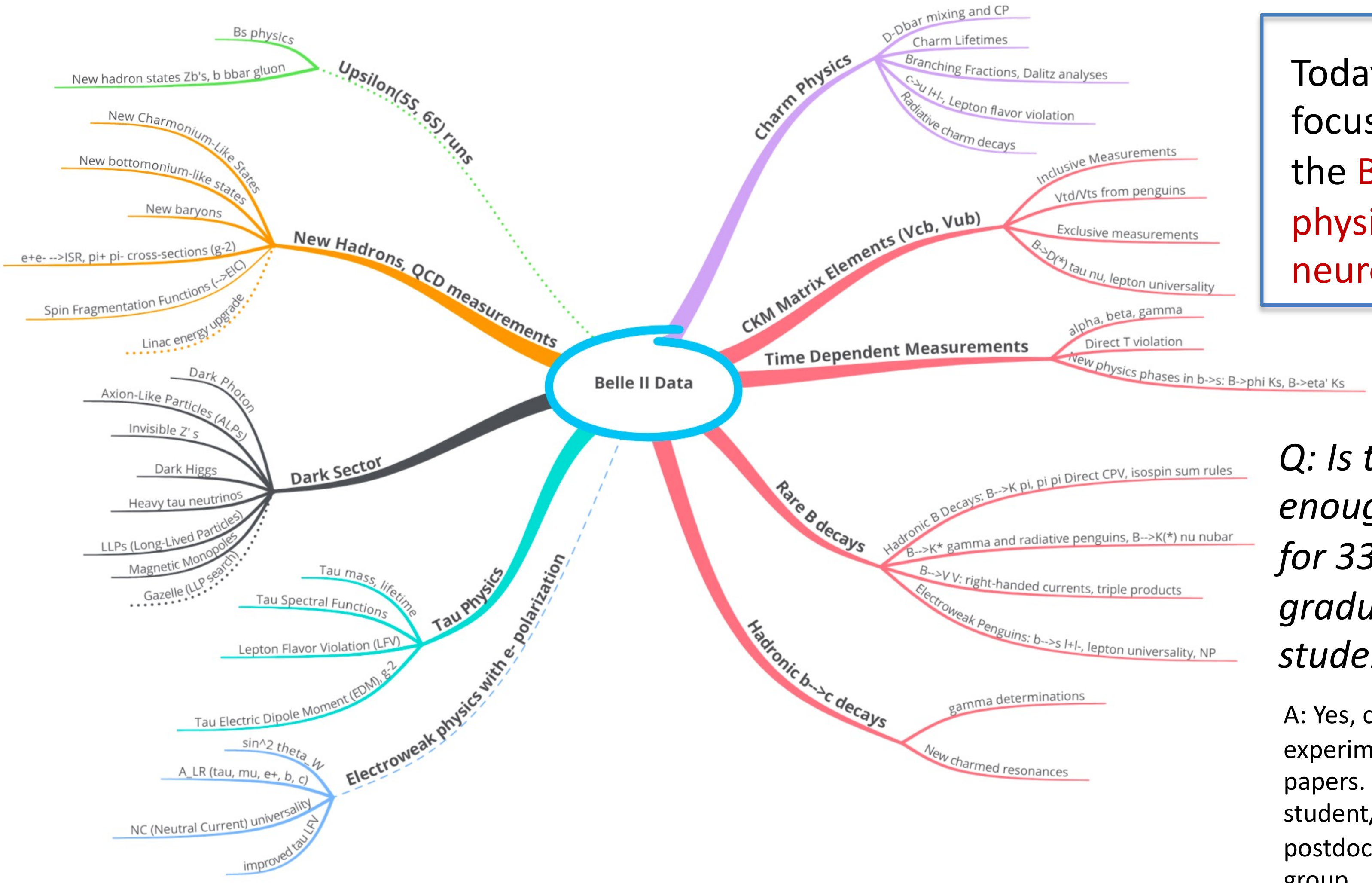
In addition, the high pT experiments, established tight constraints on direct production of high mass particles (e.g. M(Z'), M(W')>3 TeV, vector-like fermions > 800 GeV) and limits on SUSY. This *noble search* continues with the high luminosity LHC.

Paradigm shift: inspired by intriguing results from B factories, LHCb and the potential of Belle II, the possibility of finding new physics in flavor has emerged as a *complementary* route to the LHC.

Younger theorists: Dark Sector may be another path.

Belle II Physics “Mind Map” for Snowmass 2022

Wealth of new physics possibilities in different domains of HEP (weak, strong, electroweak interactions). Many opportunities for *initiatives* by young scientists.



- Belle II Data
  - Upsilon(5S, 6S) runs
    - Bs physics
    - New hadron states Zb's, b bbar gluon
  - New Hadrons, QCD measurements
    - New Charmonium-Like States
    - New bottomonium-like states
    - New baryons
    - e+e- -->ISR, pi+ pi- cross-sections (g-2)
    - Spin Fragmentation Functions (-->EIC)
    - Linac energy upgrade
  - Dark Sector
    - Dark Photon
    - Axion-Like Particles (ALPs)
    - Invisible Z' s
    - Dark Higgs
    - Heavy tau neutrinos
    - LLPs (Long-Lived Particles)
    - Magnetic Monopoles
    - Gazelle (LLP search)
  - Tau Physics
    - Tau mass, lifetime
    - Tau Spectral Functions
    - Lepton Flavor Violation (LFV)
    - Tau Electric Dipole Moment (EDM), g-2
  - Electroweak physics with e- polarization
    - sin^2 theta_W
    - A_LR (tau, mu, e+, b, c)
    - NC (Neutral Current) universality
    - improved tau LFV
  - Charm Physics
    - D-Dbar mixing and CP
    - Charm Lifetimes
    - Branching Fractions, Dalitz analyses
    - c->u l+l-, Lepton flavor violation
    - Radiative charm decays
  - CKM Matrix Elements (Vcb, Vub)
    - Inclusive Measurements
    - Vtd/Vts from penguins
    - Exclusive measurements
    - B->D(*) tau nu, lepton universality
  - Time Dependent Measurements
    - alpha, beta, gamma
    - Direct T violation
    - New physics phases in b->s: B->phi Ks, B->eta' Ks
  - Rare B decays
    - Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
    - B-->K* gamma and radiative penguins, B-->K(*) nu nubar
    - B-->V V: right-handed currents, triple products
    - Electroweak Penguins: b-->s l+l-, lepton universality, NP
  - Hadronic b-->c decays
    - gamma determinations
    - New charmed resonances

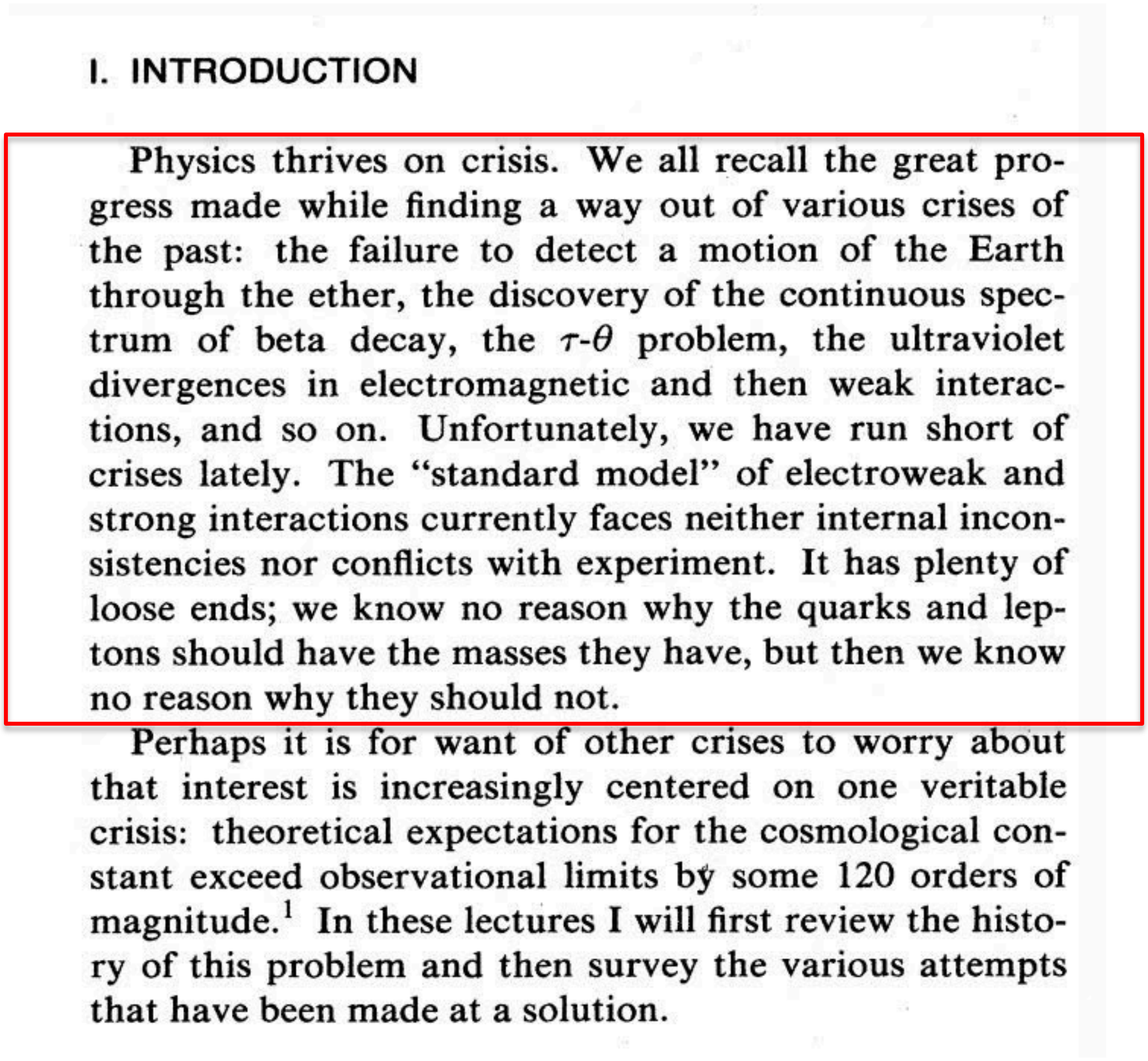
Today, we focus on the B physics neurons.

Q: Is there really enough physics for 330 graduate students ?

A: Yes, c.f. B factory experiments, >500 papers. Most by Phd student/advisor, postdoc or small group.

Dashed lines indicate extensions to SuperKEKB/Belle II that can enhance the physics reach of the facility. WP’s https://confluence.desy.de/display/BI/Snowmass+2021

Steve Weinberg on crises in physics.



I. INTRODUCTION

Physics thrives on crisis. We all recall the great progress made while finding a way out of various crises of the past: the failure to detect a motion of the Earth through the ether, the discovery of the continuous spectrum of beta decay, the τ-θ problem, the ultraviolet divergences in electromagnetic and then weak interactions, and so on. Unfortunately, we have run short of crises lately. The "standard model" of electroweak and strong interactions currently faces neither internal inconsistencies nor conflicts with experiment. It has plenty of loose ends; we know no reason why the quarks and leptons should have the masses they have, but then we know no reason why they should not.

Perhaps it is for want of other crises to worry about that interest is increasingly centered on one veritable crisis: theoretical expectations for the cosmological constant exceed observational limits by some 120 orders of magnitude.[1] In these lectures I will first review the history of this problem and then survey the various attempts that have been made at a solution.

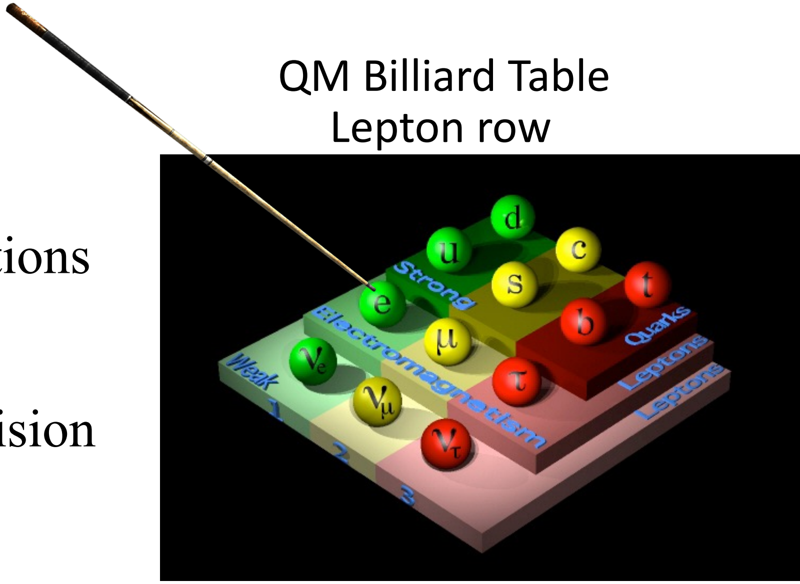
BTW can you identify the three Nobel Prize Winners ?

Do you know all the crises that Weinberg is referring to ?

BTW: now cosmology is stuck in its version of the Standard Model.

FAQ: What is meant by "lepton universality" ?

QM Billiard Table
Lepton row



This refers to the weak interaction

The weak couplings of leptons of different generations are the *same in the Standard Model.*

Lepton universality has been tested to O(1%) precision for lepton decays, pion and kaon decays….e.g.

$$g_\mu / g_\tau = 1.001 \pm 0.003$$

However in the *b →c charged current* weak interaction and *b →s neutral current* weak interaction, there are experimental hints of its breakdown (~3σ level) at the 10-15% level.

For example,

$$R_D = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)}$$

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

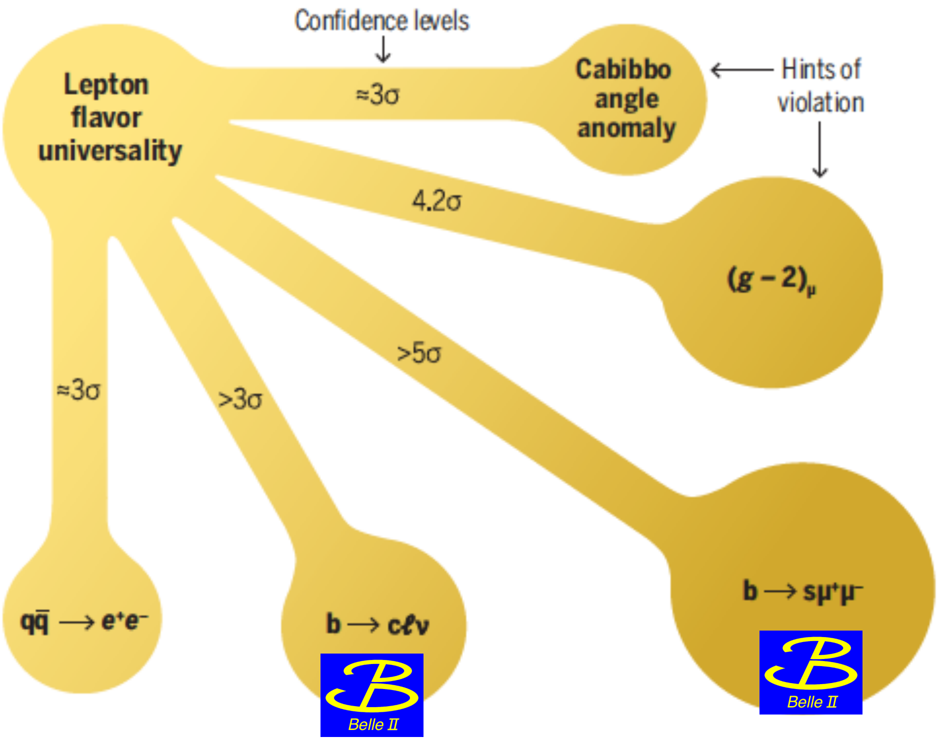
$$l = e^-, \mu^-$$

Deviate from their SM expectations

An *emerging* crisis in High Energy Physics.

Possible violations of lepton flavor universality are getting harder to ignore

Shown are five hints for the violation of lepton flavor universality from existing experimental data, with the size of each circle and length of each arm reflecting the level of confidence for the experimental data to break away from standard model predictions.



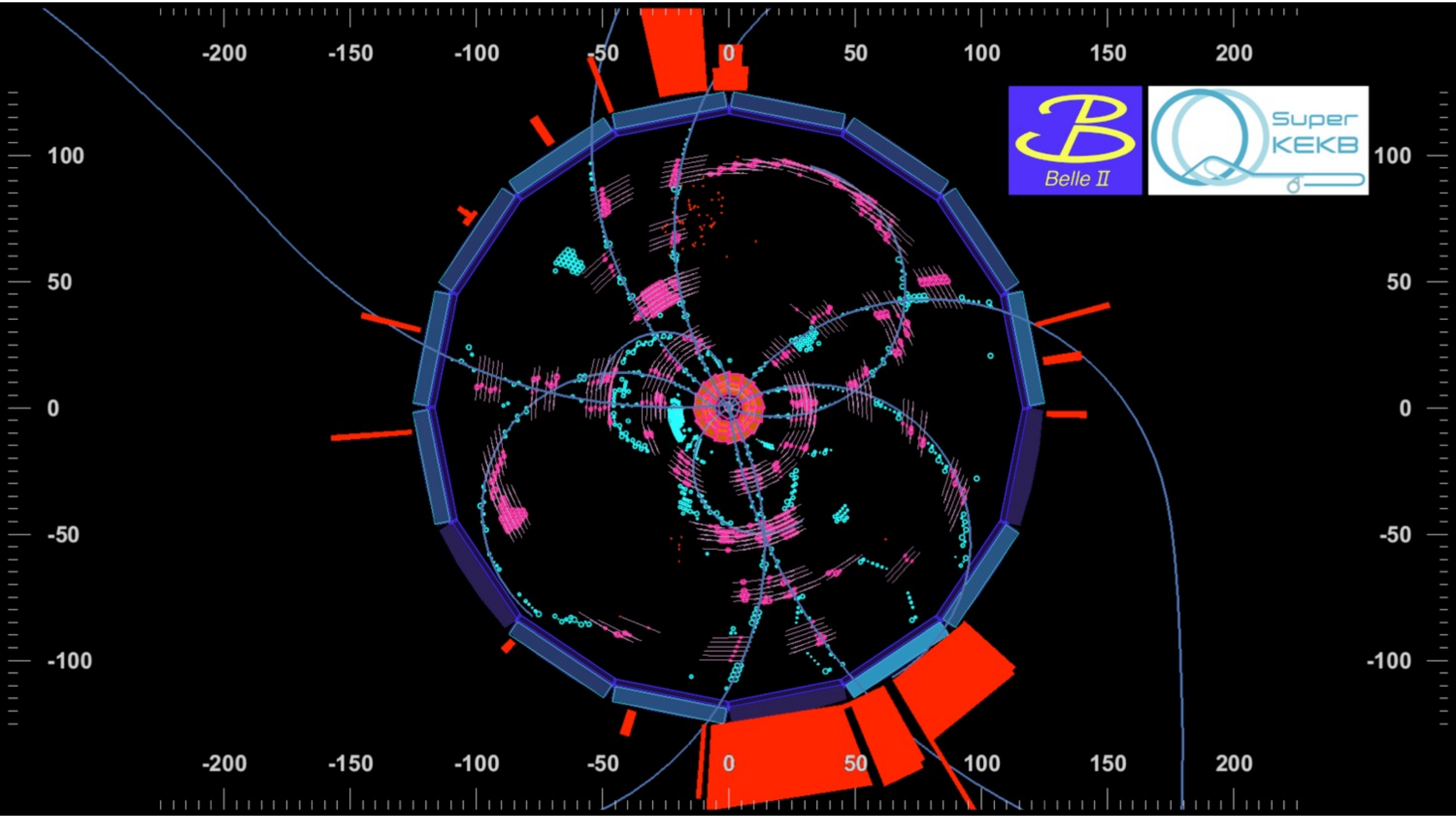
From December 2021 SCIENCE magazine article by A. Crivellin and M. Hoferichter.

What are we doing to address this in Belle II ?

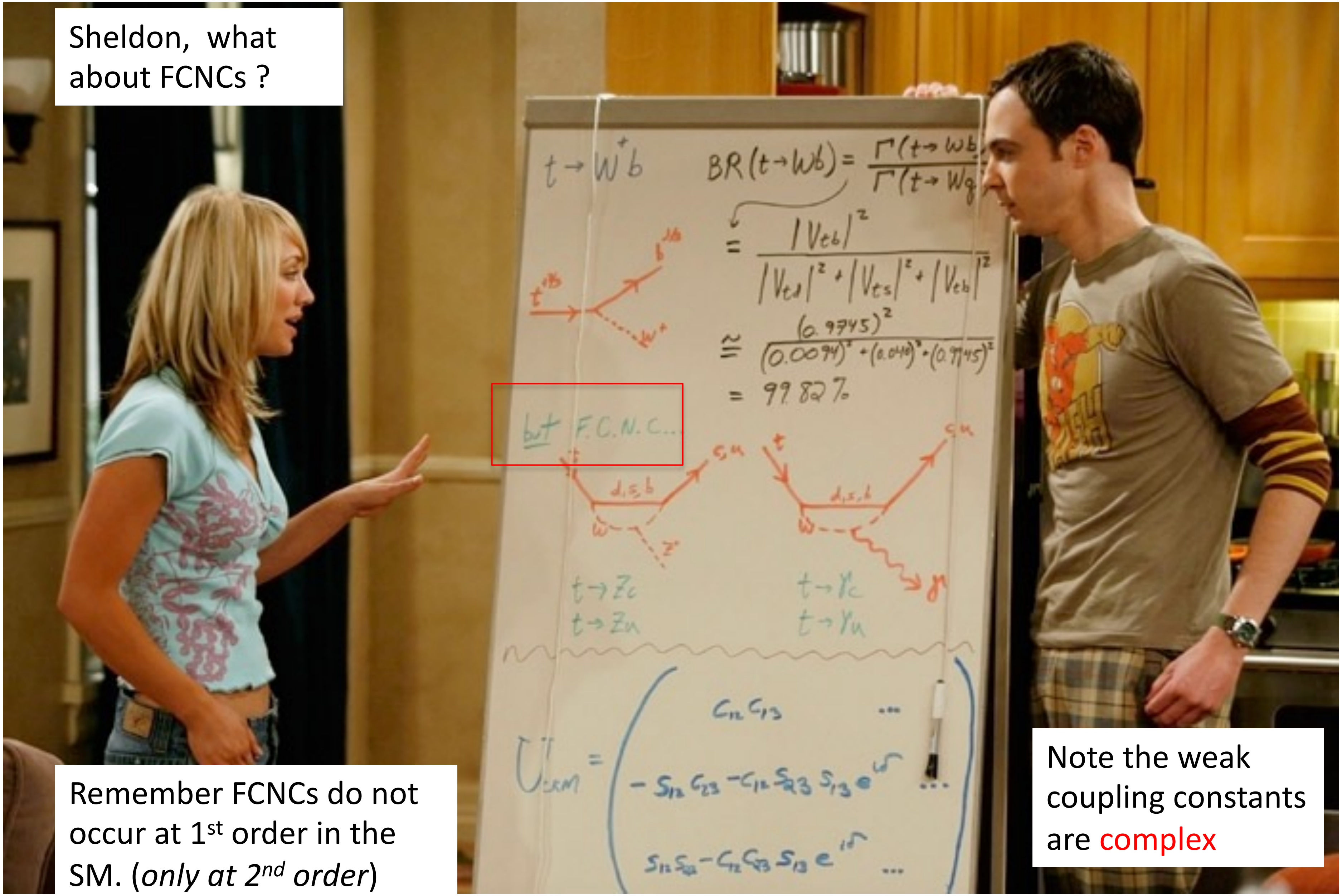
Is it real ?

Let's carry out a program of measurements at Belle II to find out.

How Early B Physics Results from the Physics Run ("Phase 3") are connected to this high energy physics crisis ?



Big Bang Theory (Flavor Changing Neutral Currents)



Sheldon, what about FCNCs ?

Remember FCNCs do not occur at 1st order in the SM. (*only at 2nd order*)

Note the weak coupling constants are complex

Belle II's CsI(Tl) calorimeter (~Belle with improved waveform sampling and timing). 8736 crystals covering 90% of the solid angle.

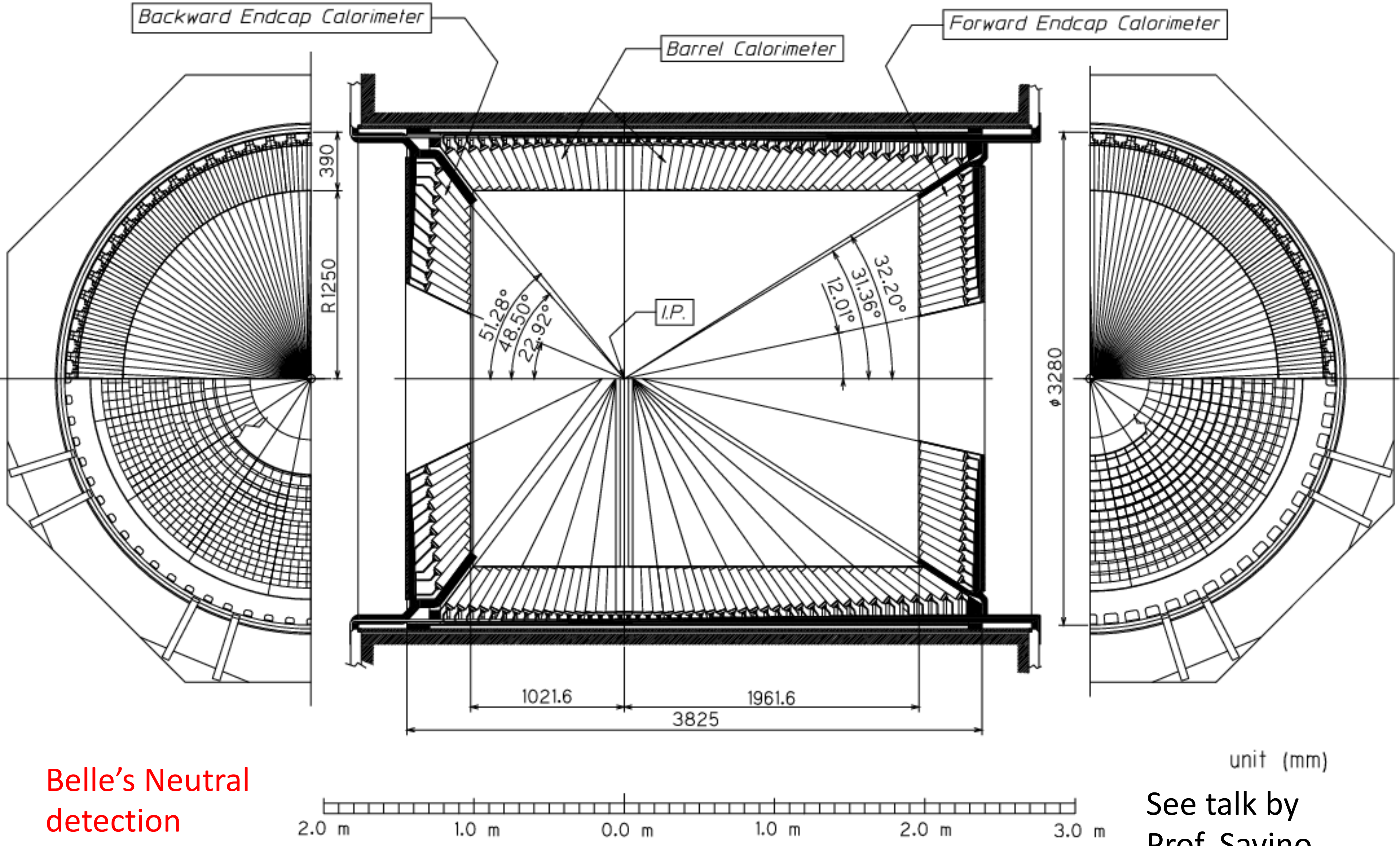


Fig. 69. Overall configuration of ECL.

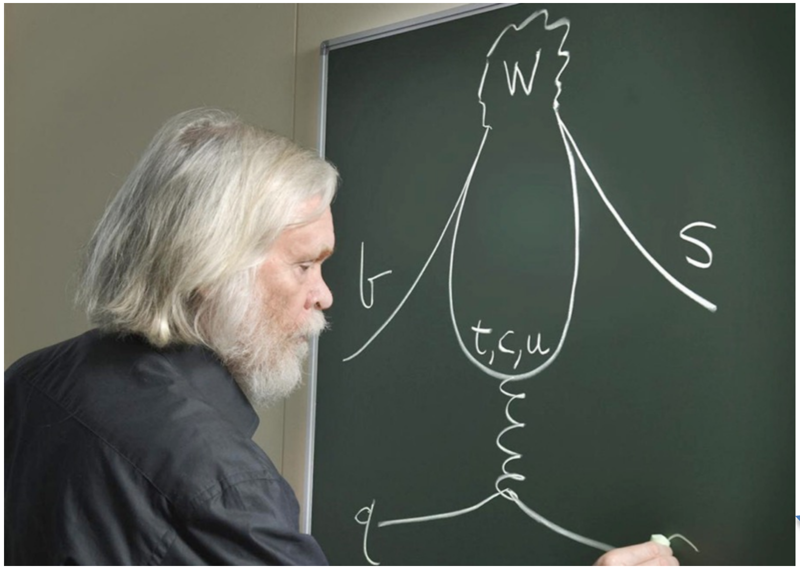
Belle's Neutral detection superpower

See talk by Prof. Savino Longo.

2019

Re-discovery of Radiative Penguins at Belle II

1975: Vainshtein, Zakharov and Shifman



Examine the following b→s γ decay modes in the Belle II Phase 3 dataset.

$$B^0 \to K^{*0}\gamma \to K^+\pi^-\gamma$$

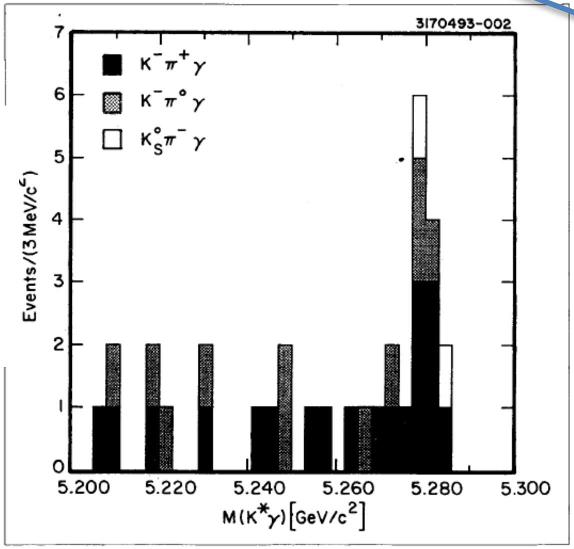
$$B^+ \to K^{*+}\gamma \to K^+\pi^0\gamma$$

$$B^+ \to K^{*+}\gamma \to K_S^0\pi^+\gamma$$

1993 CERN Courier:

CORNELL
CLEO discovers
B meson penguins

N.B. Using 1.5 x 10^6 B meson pairs



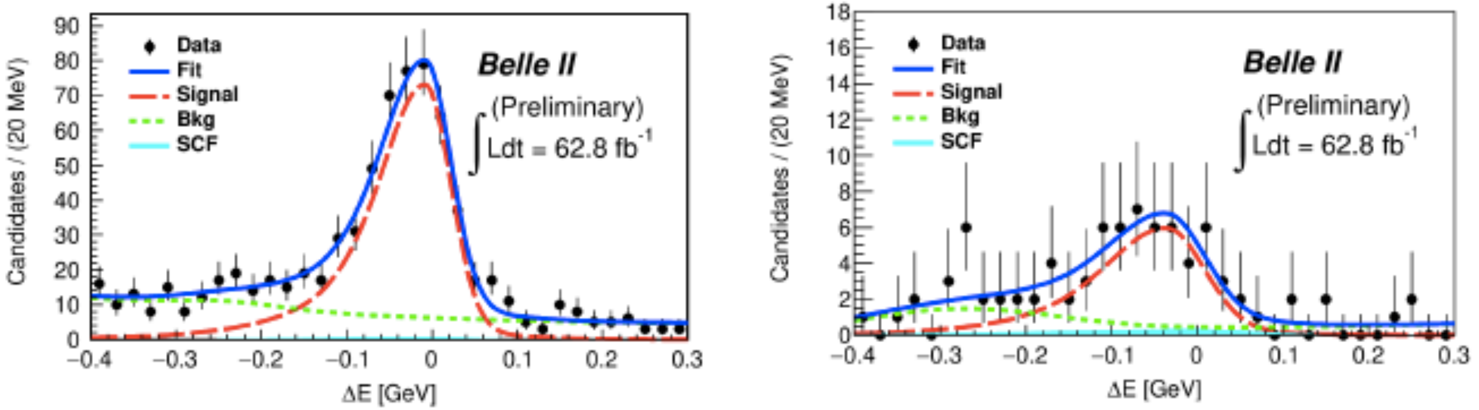
John Ellis, the CERN theorist who coined the name "Penguin".

Ed Thorndike,
Rochester,
CLEO

Belle II, 2021

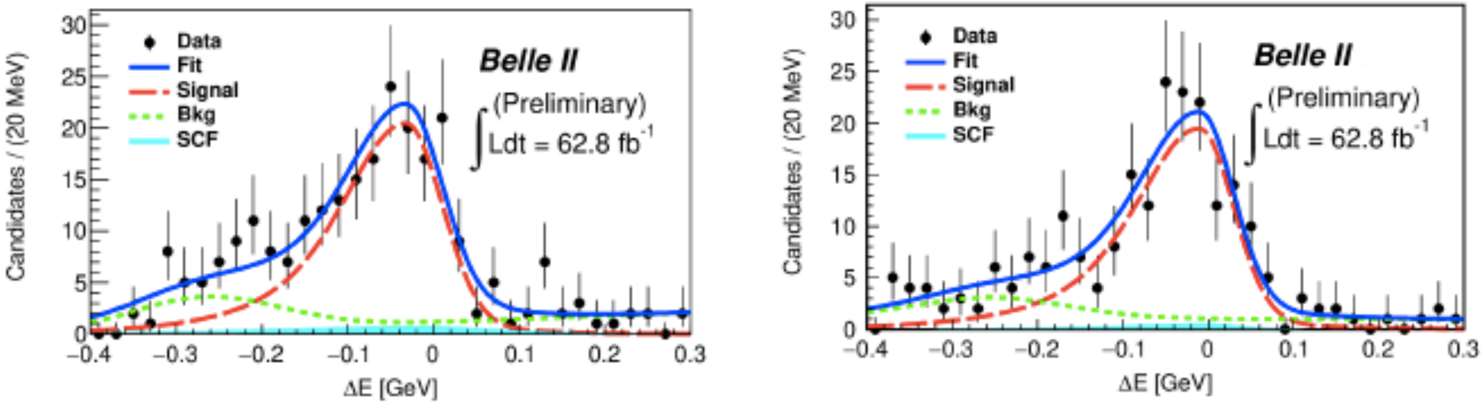
$$\Delta E = E_{recon} - E_{beam}$$

BELLE2-CONF-2021-028, Radiative Penguin Status



(a) $B^0 \to K^{*0}[K^+\pi^-]\gamma$

(b) $B^0 \to K^{*0}[K^0_S\pi^0]\gamma$



(c) $B^+ \to K^{*+}[K^+\pi^0]\gamma$

(d) $B^+ \to K^{*+}[K^0_S\pi^+]\gamma$

Figure 2. ΔE distributions for each $B \to K^*\gamma$ mode with the fit result superimposed. The black dots with error bars denote the data, the blue curve denotes the total fit, the dashed red curve is the signal component, the dotted green curve is the background component, and the filled cyan region is the misreconstructed signal component.

Belle II, 2021

BELLE2-CONF-2021-028

Skip if time is short

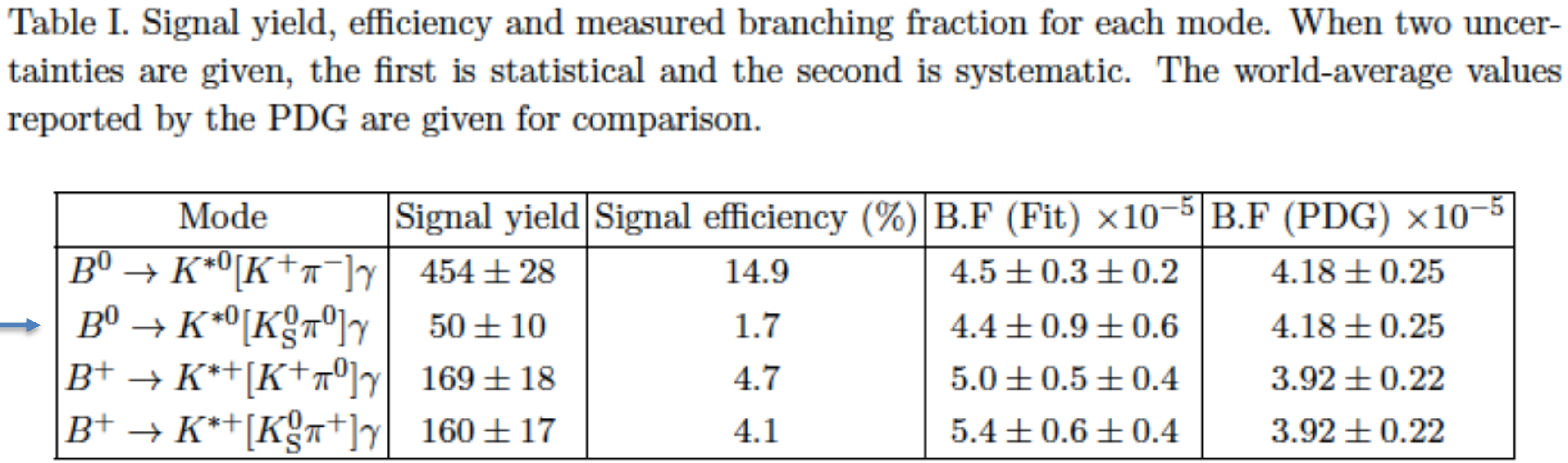


Table I. Signal yield, efficiency and measured branching fraction for each mode. When two uncertainties are given, the first is statistical and the second is systematic. The world-average values reported by the PDG are given for comparison.

Mode	Signal yield	Signal efficiency (%)	B.F (Fit) $\times 10^{-5}$	B.F (PDG) $\times 10^{-5}$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	454 ± 28	14.9	$4.5 \pm 0.3 \pm 0.2$	4.18 ± 0.25
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	50 ± 10	1.7	$4.4 \pm 0.9 \pm 0.6$	4.18 ± 0.25
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	169 ± 18	4.7	$5.0 \pm 0.5 \pm 0.4$	3.92 ± 0.22
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	160 ± 17	4.1	$5.4 \pm 0.6 \pm 0.4$	3.92 ± 0.22

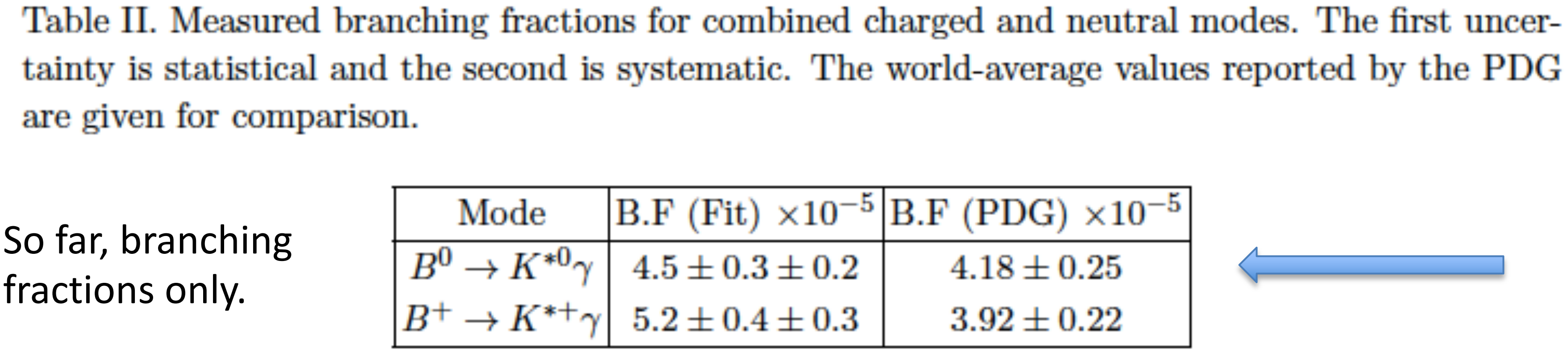


Table II. Measured branching fractions for combined charged and neutral modes. The first uncertainty is statistical and the second is systematic. The world-average values reported by the PDG are given for comparison.

Mode	B.F (Fit) $\times 10^{-5}$	B.F (PDG) $\times 10^{-5}$
$B^0 \to K^{*0}\gamma$	$4.5 \pm 0.3 \pm 0.2$	4.18 ± 0.25
$B^+ \to K^{*+}\gamma$	$5.2 \pm 0.4 \pm 0.3$	3.92 ± 0.22

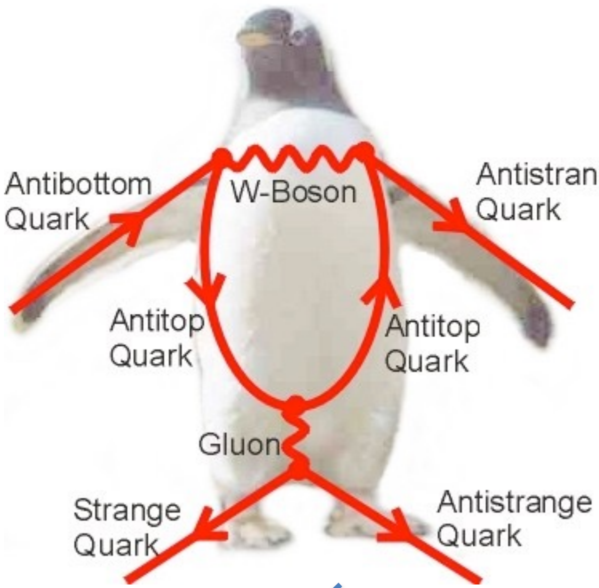
So far, branching fractions only.

Move on to gluonic penguins:

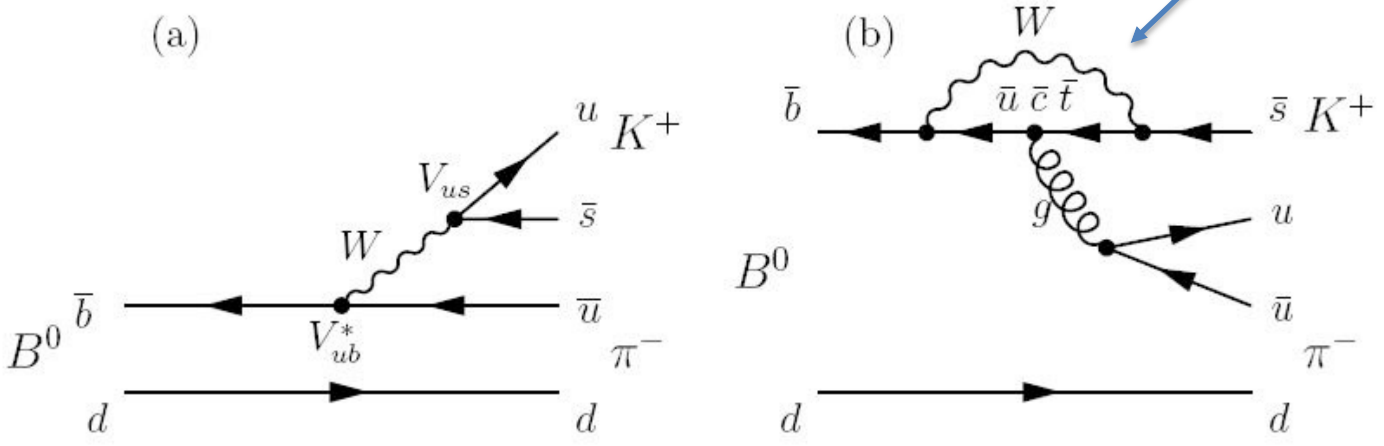
Rare Decay Mascot/Feynman Diagram

Let's consider

$$B^0 \to \pi^- K^+$$



Feynman diagrams for this process



Feynman tree (a) and penguin (b) diagrams for the $B_d^0 \to K^+\pi^-$ decay

N.B. Both amplitudes contribute, but the (b→s) Penguin is larger and has a different weak phase (V_{ts} vs V_{ub}).

nature Vol 452|20 March 2008|doi:10.1038/nature06827

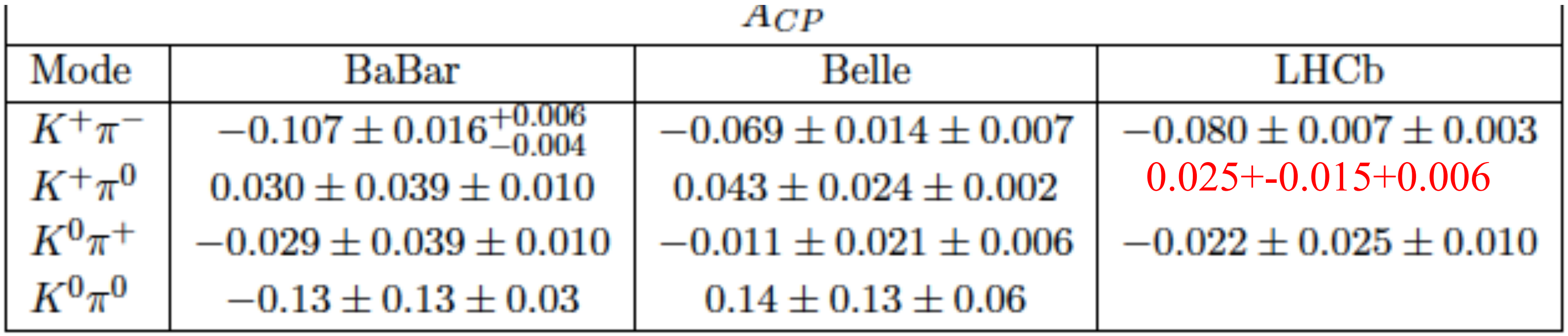
LETTERS

In 2008, “the K pi puzzle” appeared in Nature. Charged and neutral A(CP’s) for B→Kπ penguins differ. Is this a sign of new physics ?

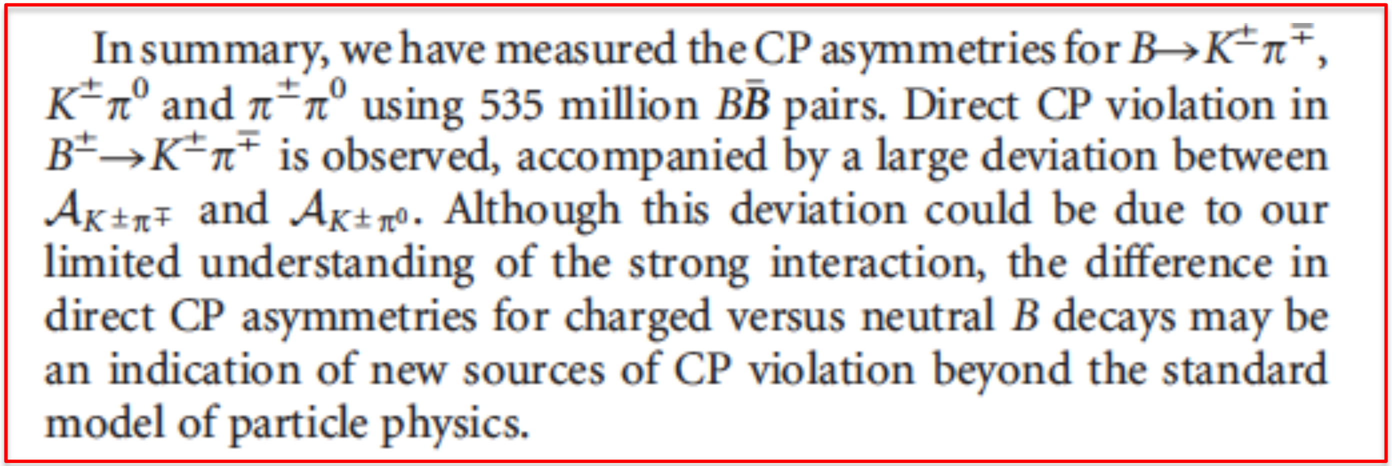
Difference in direct charge-parity violation between charged and neutral *B* meson decays

The Belle Collaboration*

Also confirmed by BaBar



	$\mathcal{A}_{CP}$		
Mode	BaBar	Belle	LHCb
$K^+\pi^-$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	$-0.069 \pm 0.014 \pm 0.007$	$-0.080 \pm 0.007 \pm 0.003$
$K^+\pi^0$	$0.030 \pm 0.039 \pm 0.010$	$0.043 \pm 0.024 \pm 0.002$	0.025+-0.015+0.006
$K^0\pi^+$	$-0.029 \pm 0.039 \pm 0.010$	$-0.011 \pm 0.021 \pm 0.006$	$-0.022 \pm 0.025 \pm 0.010$
$K^0\pi^0$	$-0.13 \pm 0.13 \pm 0.03$	$0.14 \pm 0.13 \pm 0.06$	



In summary, we have measured the CP asymmetries for $B \to K^{\pm}\pi^{\mp}$, $K^{\pm}\pi^0$ and $\pi^{\pm}\pi^0$ using 535 million $B\bar{B}$ pairs. Direct CP violation in $B^{\pm} \to K^{\pm}\pi^{\mp}$ is observed, accompanied by a large deviation between $\mathcal{A}_{K^{\pm}\pi^{\mp}}$ and $\mathcal{A}_{K^{\pm}\pi^0}$. Although this deviation could be due to our limited understanding of the strong interaction, the difference in direct CP asymmetries for charged versus neutral *B* decays may be an indication of new sources of CP violation beyond the standard model of particle physics.

“Trapping” the Electroweak Penguin in B→K π

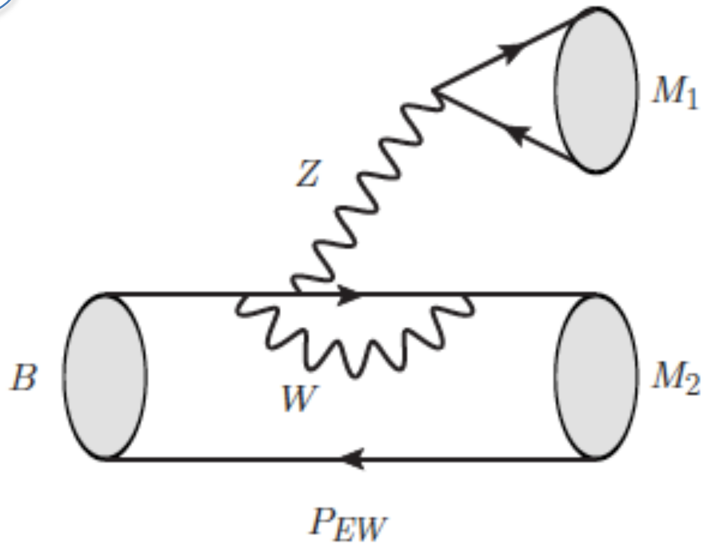
https://arxiv.org/abs/hep-ph/0508047

The isospin sum rule

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

(You may need to review isospin symmetry for the strong interaction)

NP can enter through this type of diagram, which would violate the sum rule



Michael Gronau

Have now observed the four B→K π modes, needed for the *isospin sum rule test* of NP. This includes the difficult mode B→K_S π^0. Now have A_{CP} for all 4 modes and sensitivity estimates for the future.

Examples of hadronic penguins (b→s gluon) at Belle II.

$B \rightarrow K^- \pi^+$ and c.c.

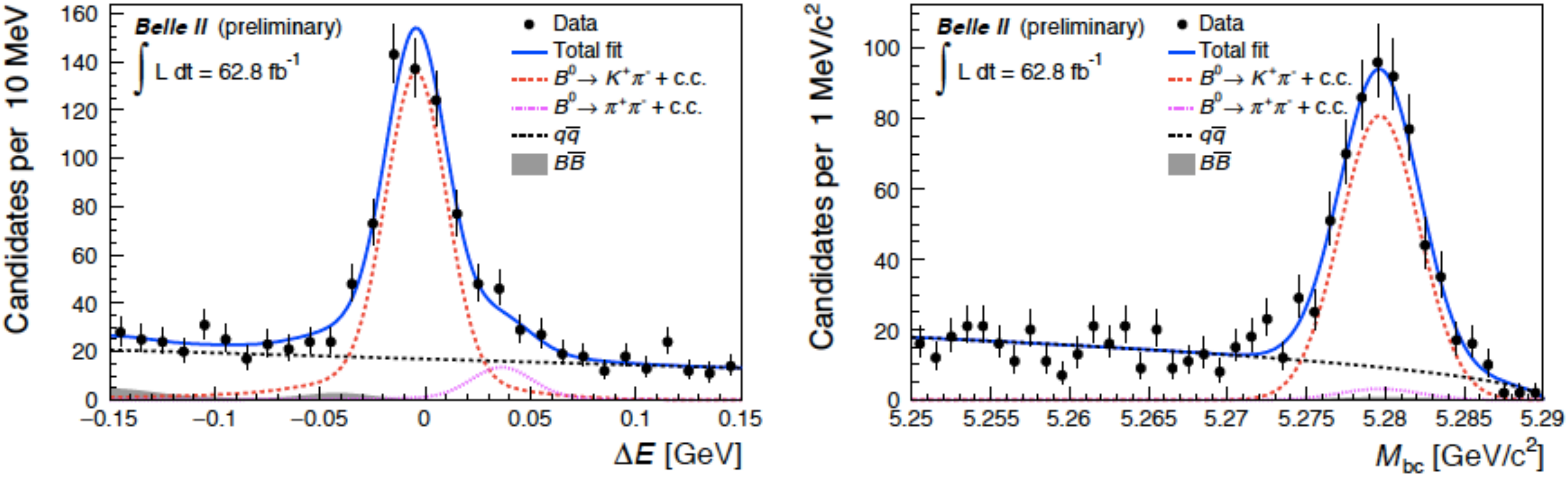
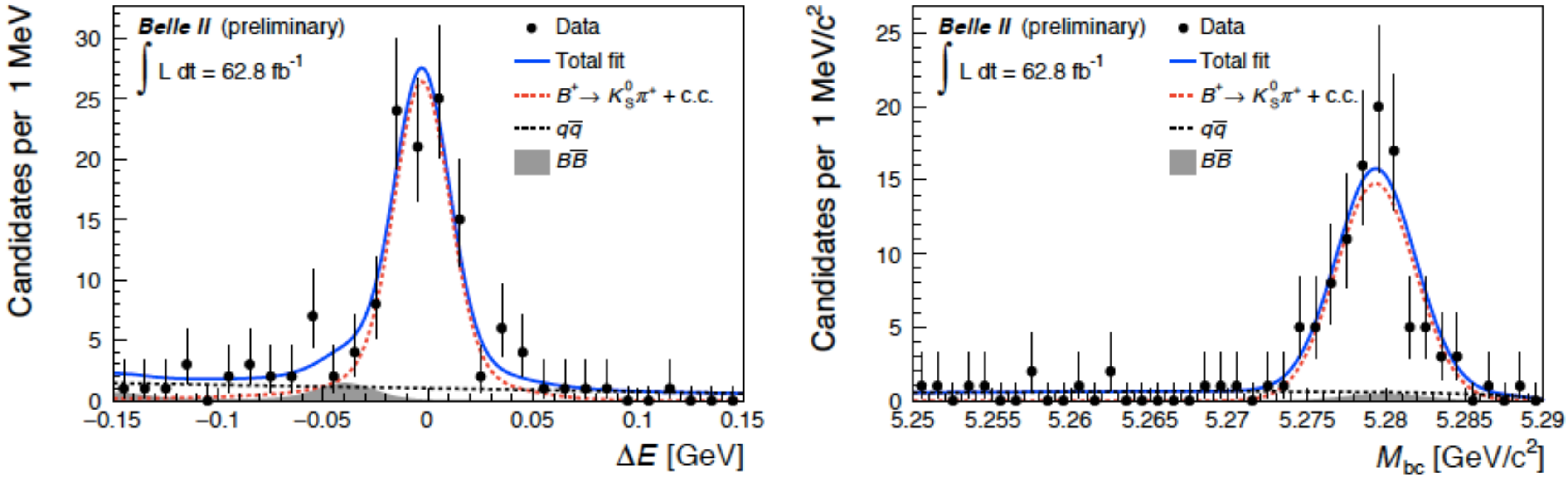


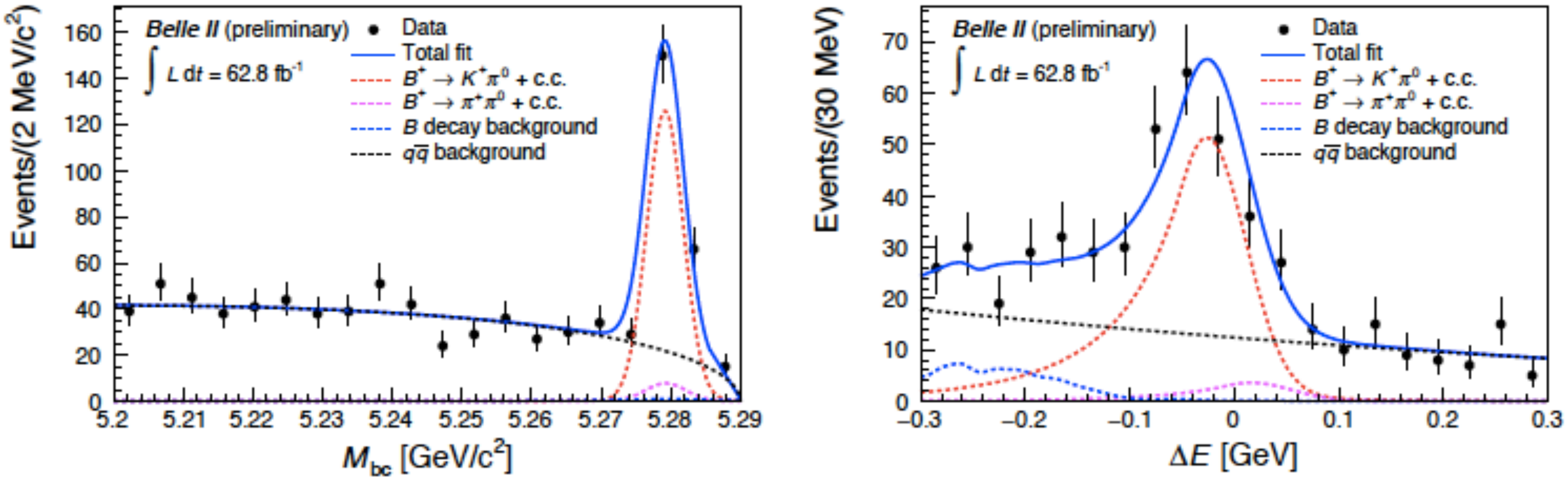
FIG. 2. Distributions of ΔE (left) and M_{bc} (right) for $B^0 \to K^+\pi^-$ candidates reconstructed in 2019–2020 Belle II data, selected with an optimized continuum-suppression and kaon-enriching selection. The distributions are shown in signal-enriched regions of $5.273 < M_{\mathrm{bc}} < 5.286\ \mathrm{GeV}/c^2$ and $-0.04 < \Delta E < 0.03$ GeV, respectively. Fit projections are overlaid.

Details in https://arxiv.org/abs/2106.03766

These modes uses Belle II's other superpowers: tracking (Soeren Prell) and Particle ID (Alan Schwartz).

More examples of hadronic penguins ($b \to s$ gluon) at Belle II (modes with one Ks or one pi-zero)





Details in https://arxiv.org/abs/2106.03766 ; https://arxiv.org/abs/2105.04111

Belle II's first result on $A_{CP}(B^0 \rightarrow K^0 \pi^0)$

Update with x3 data at Moriond 2022

About 50 events with 62 fb^{-1}

Difficult: Not self-tagging.

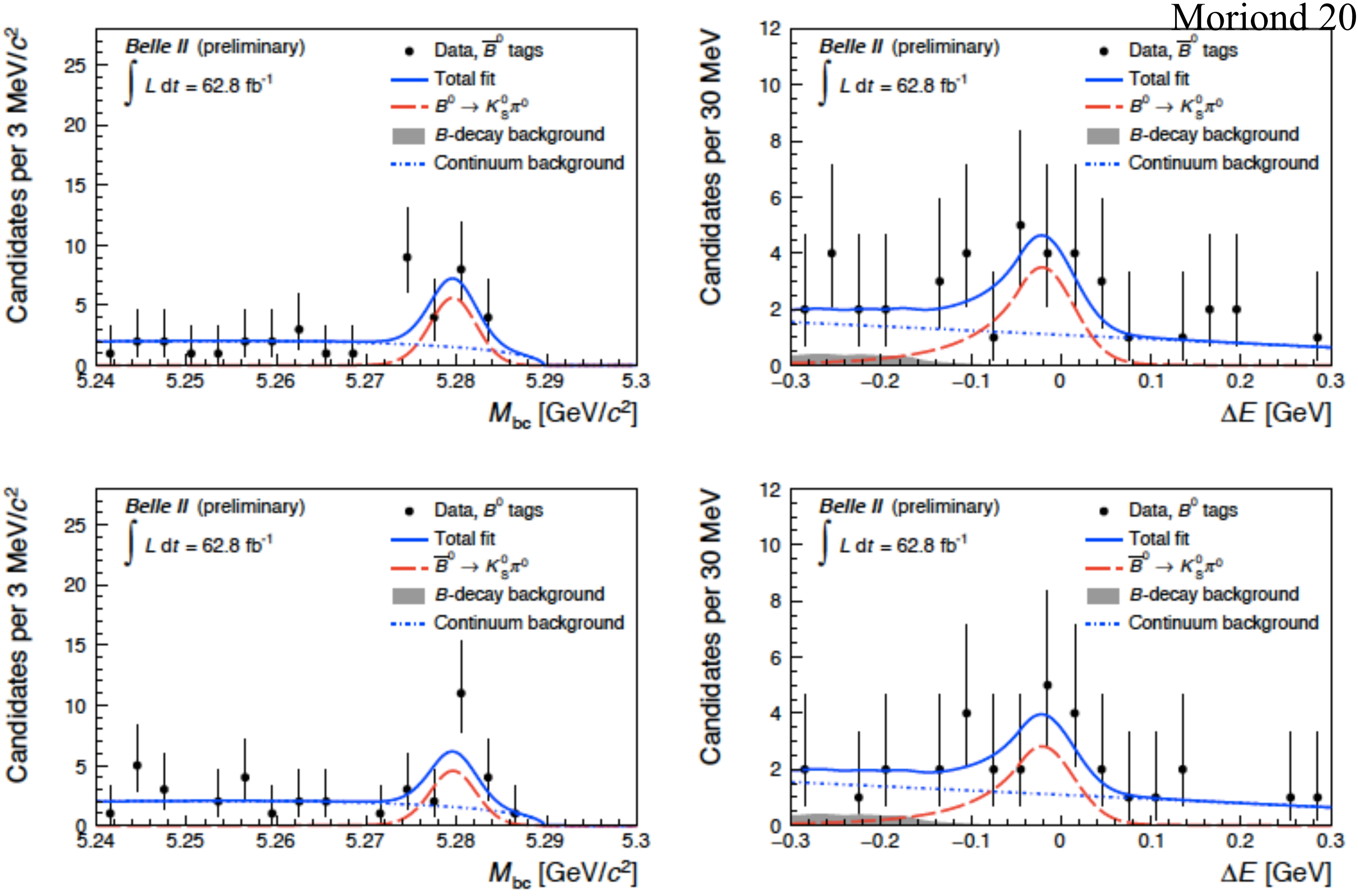
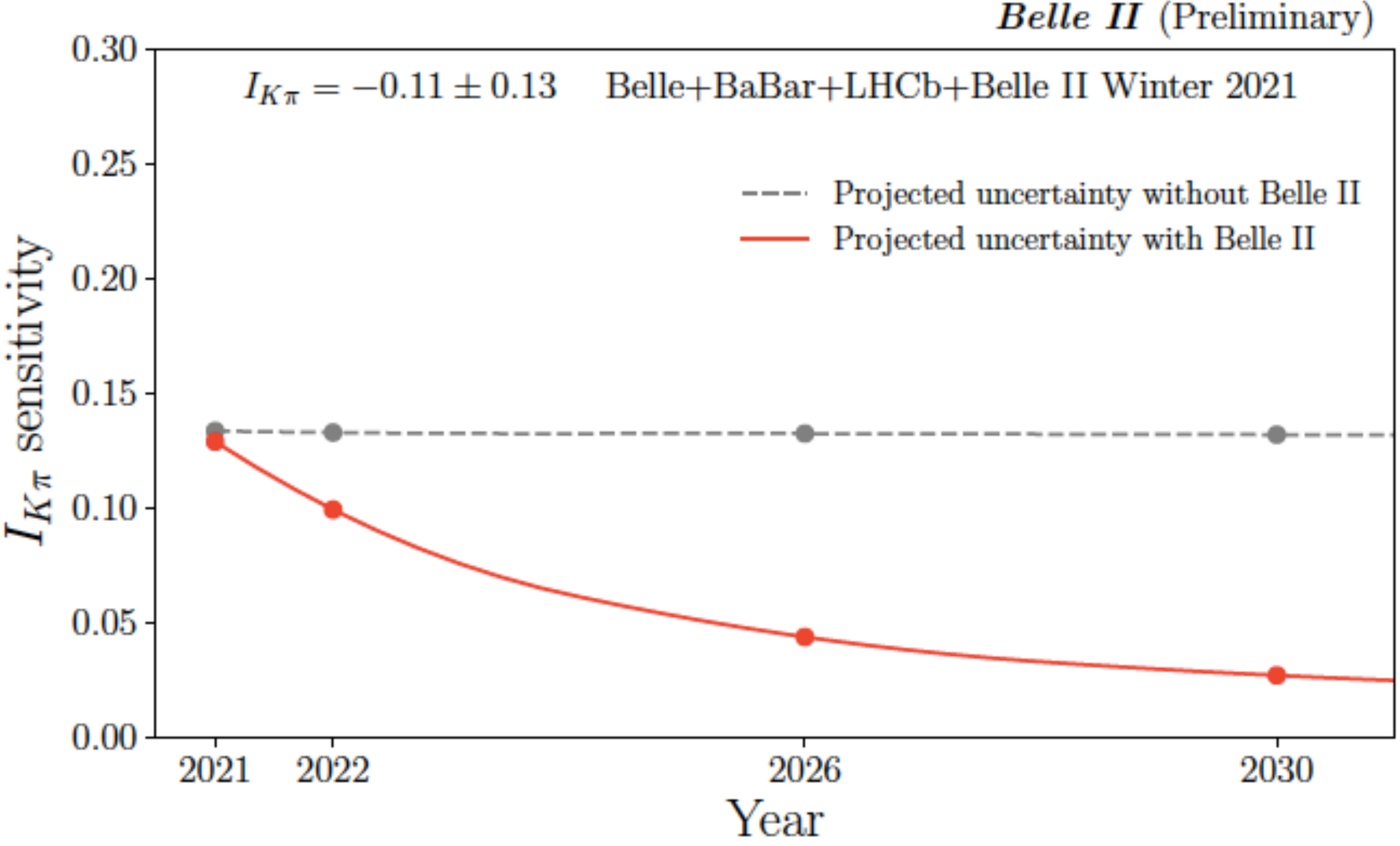


FIG. 3. Flavor-specific (M_{bc}, ΔE) projections on 2019-2020 Belle II data. The top panel shows candidates where B_{tag} is tagged as a $\bar{B}^0$ (signal-side: B^0) and the bottom panel for candidates where B_{tag} is tagged as a B^0 (signal-side: $\overline{B}^0$). The distribution and fit are integrated over r-bin in the good tag region $0.25 \leq r \leq 1$ and in the signal region (left panel: $-0.16 < \Delta E < 0.08$ GeV, right panel: $M_{\text{bc}} > 5.27\,\text{GeV}/c^2$).

Details in https://arxiv.org/abs/2104.14871

https://arxiv.org/abs/2104.14871



Without Belle II measurements of $A_{CP}(B^0 \rightarrow K^0 \pi^0)$, we are stuck.

Need Belle II's neutral superpowers

FIG. 4. The projected uncertainty on $I_{K\pi}$ with and without Belle II inputs. The inputs for $I_{K\pi}$ are averages of the estimated updates from ongoing LHCb and Belle II experiments with current world averages [10]. The red curve shows a projection when updates on the complete set of $K\pi$ measurements are considered, and the grey curve is the case if only $A_{K^+\pi^-}, A_{K^+\pi^0}, A_{K^0\pi^+}$ are updated by LHCb. The projection corresponds to the luminosity plans from LHCb and Belle II.

A unique contribution of Belle II to testing the K π isospin sum rule

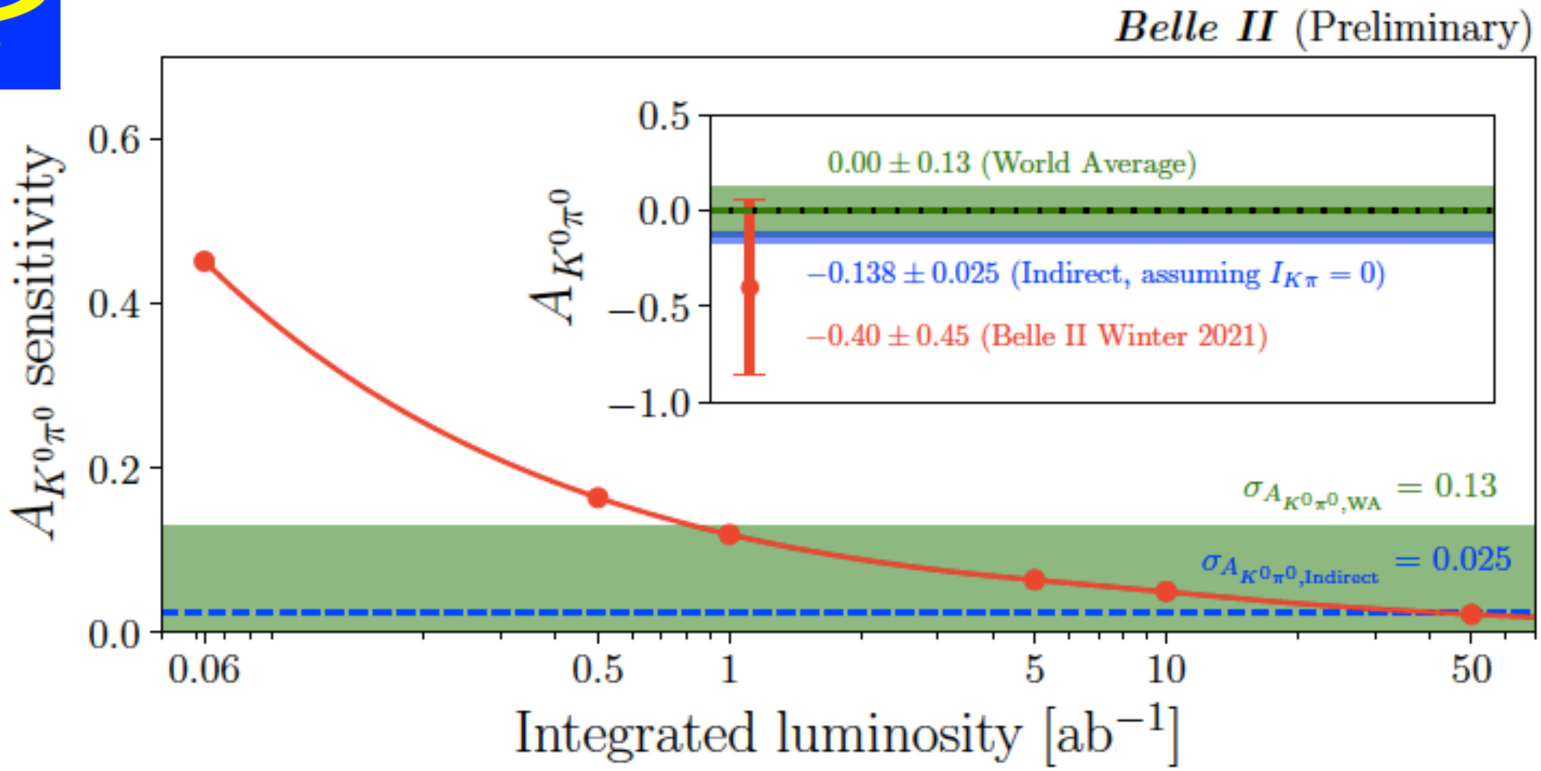
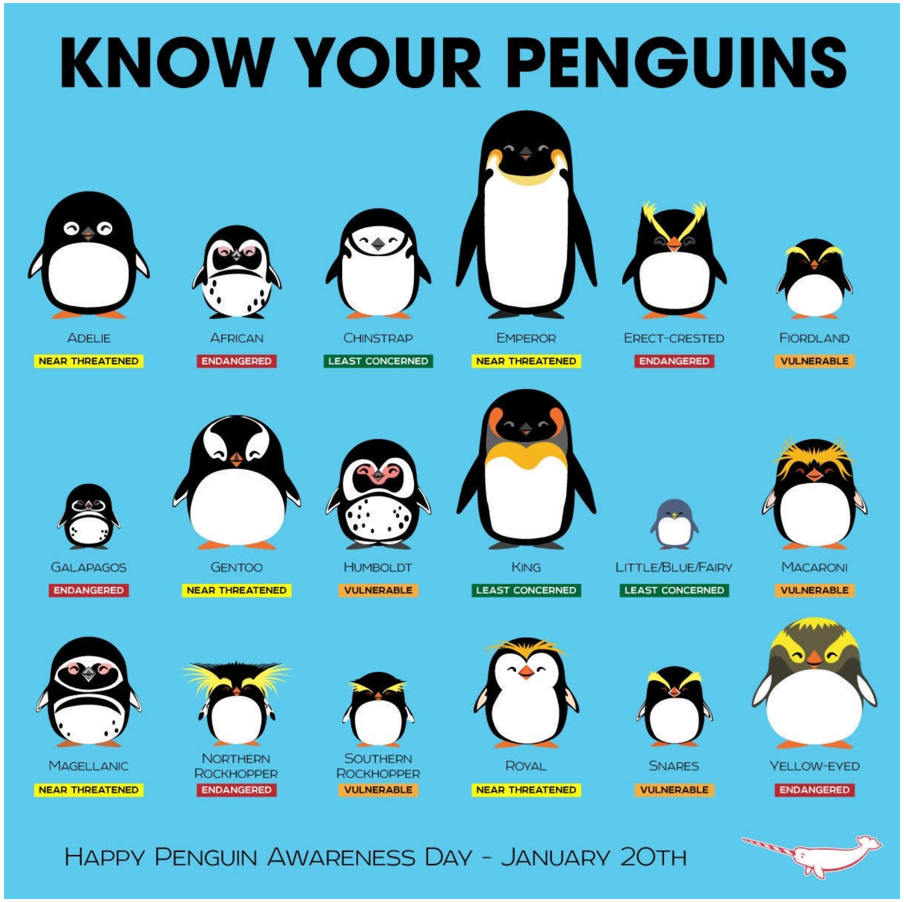


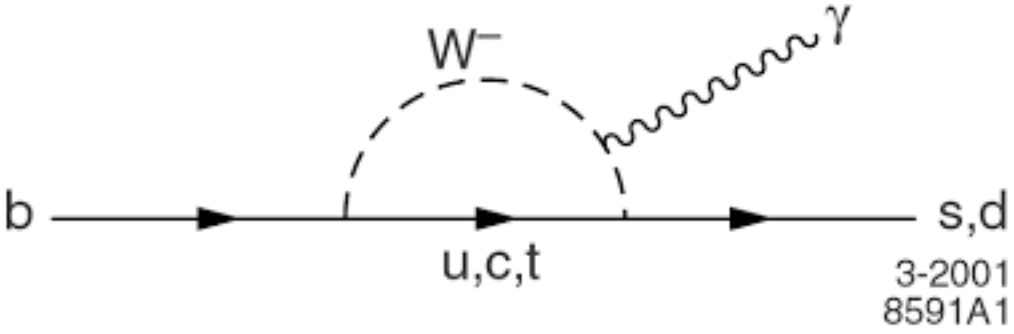
FIG. 5. The projected uncertainty on $\mathcal{A}_{K^0\pi^0}$ measurement. The inset panel shows the comparison of (red marker) the measurement reported here with (green band) the world average value, and (blue band) the indirect determination from Eq. 1 assuming $I_{K\pi} = 0$ and world average values for the other inputs. The red curve in the main panel is Belle II's expected uncertainty on the $\mathcal{A}_{K^0\pi^0}$ measurement as a function of the integrated luminosity, while the green and blue dashed lines are the uncertainties of the world average value and of the indirect determination, respectively.

Details in https://arxiv.org/abs/2104.14871

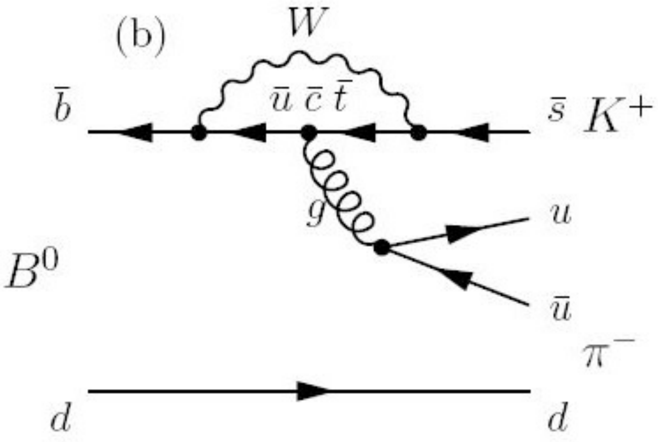
Recap:



"Radiative Penguin"



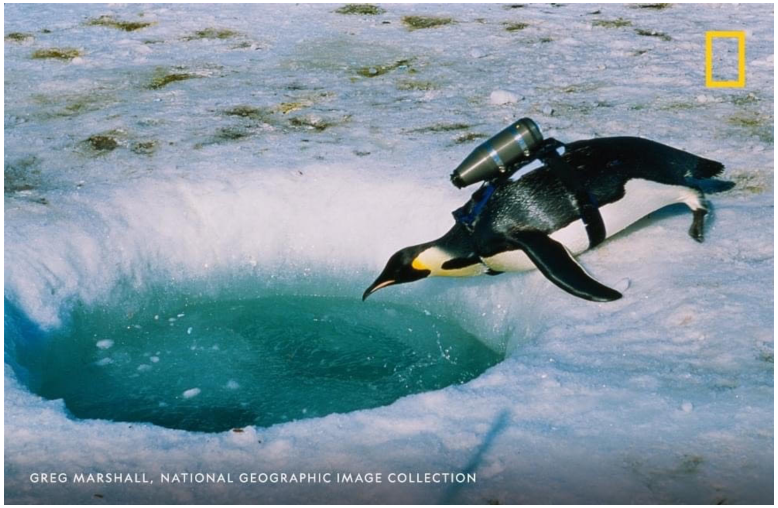
"Gluonic Penguin"



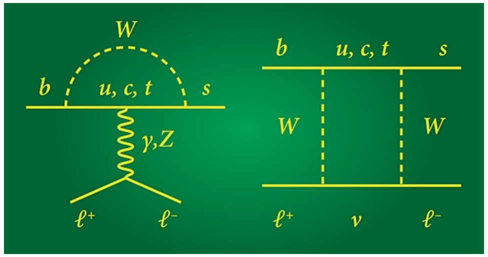
Now will describe some speculations about how Belle II might discover new physics Beyond the SM (BSM)

Research penguin

Photo Credit: National Geographic

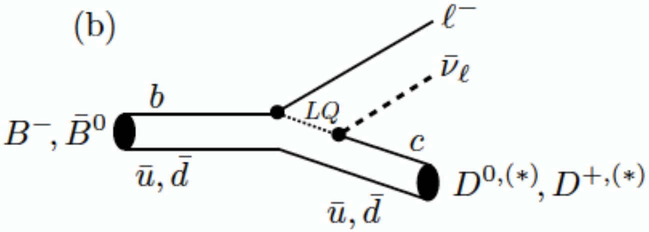

GREG MARSHALL, NATIONAL GEOGRAPHIC IMAGE COLLECTION

Exploring the unknown with b→s “electroweak penguins”:
(weak neutral current)



Sequoia National Forest

Discovering NP with b→c l ν “trees”:
(weak charged current)



A Snowmass Highlight (shown at Cincinnati and Seattle)

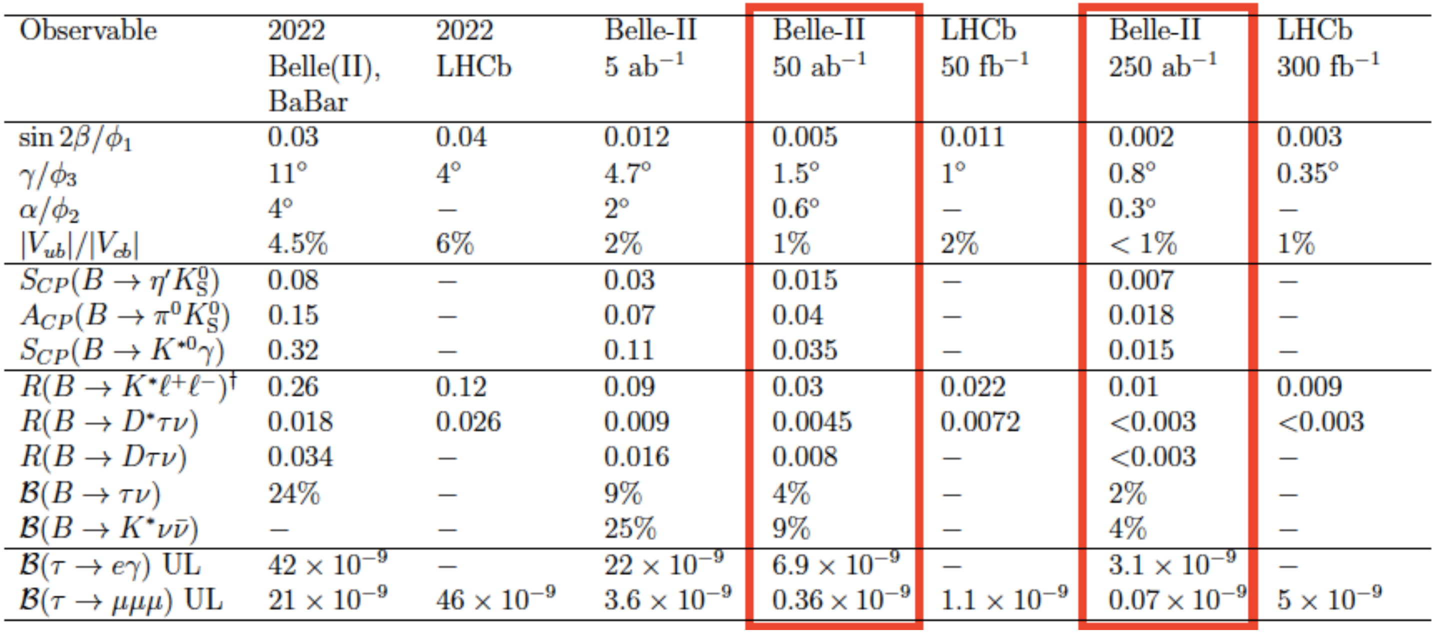
What happens at 1, 5, 50 ab^{-1}
(or even 250 ab^{-1} in the 2030's)?

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. $B \to K\nu\nu$, $\mu\nu$), inclusive decays, time dependent CPV in B_d, τ physics.

LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

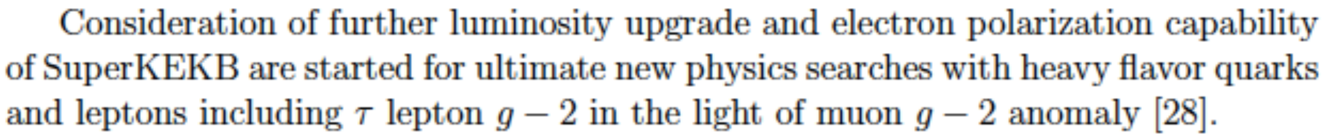
Upgrades
Most key channels will be stats. limited (not theory or syst.).



Observable	2022 Belle(II), BaBar	2022 LHCb	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	LHCb 50 fb^{-1}	Belle-II 250 ab^{-1}	LHCb 300 fb^{-1}
$\sin 2\beta/\phi_1$	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/ϕ_3	11°	4°	4.7°	1.5°	1°	0.8°	0.35°
α/ϕ_2	4°	–	2°	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	4.5%	6%	2%	1%	2%	< 1%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	–	0.03	0.015	–	0.007	–
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	–	0.07	0.04	–	0.018	–
$S_{CP}(B \to K^{*0}\gamma)$	0.32	–	0.11	0.035	–	0.015	–
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.12	0.09	0.03	0.022	0.01	0.009
$R(B \to D^*\tau\nu)$	0.018	0.026	0.009	0.0045	0.0072	<0.003	<0.003
$R(B \to D\tau\nu)$	0.034	–	0.016	0.008	–	<0.003	–
$\mathcal{B}(B \to \tau\nu)$	24%	–	9%	4%	–	2%	–
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	–	–	25%	9%	–	4%	–
$\mathcal{B}(\tau \to e\gamma)$ UL	42×10^{-9}	–	22×10^{-9}	6.9×10^{-9}	–	3.1×10^{-9}	–
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	46×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	1.1×10^{-9}	0.07×10^{-9}	5×10^{-9}

The dagger refers to a measurement in the range $1 < q^2 < 6$ GeV^2/c^2

JAHEP report to Snowmass: Arxiv 2203:13979



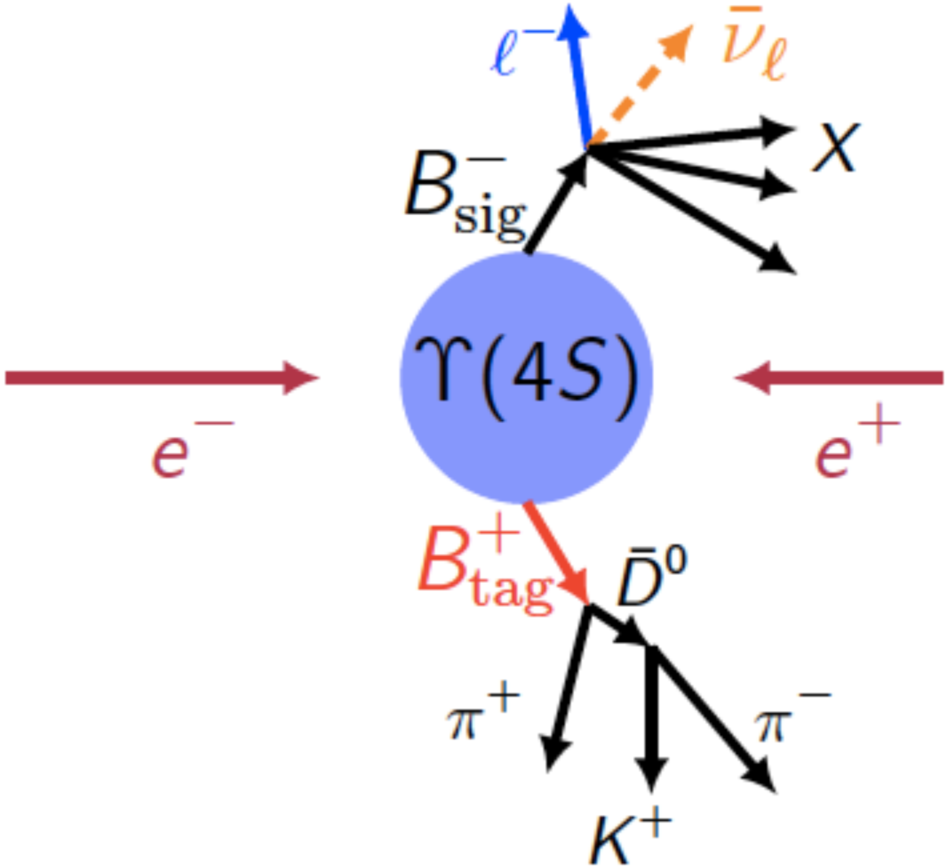
Consideration of further luminosity upgrade and electron polarization capability of SuperKEKB are started for ultimate new physics searches with heavy flavor quarks and leptons including τ lepton $g-2$ in the light of muon $g-2$ anomaly [28].

Some critical Belle II capabilities for flavor (B) physics

Full and equally strong capabilities for electrons and muons

Photons, K_S's with excellent resolution and efficiency

Neutrinos via "missing energy" and missing momentum. Hermeticity.



https://arxiv.org/abs/2008.06096

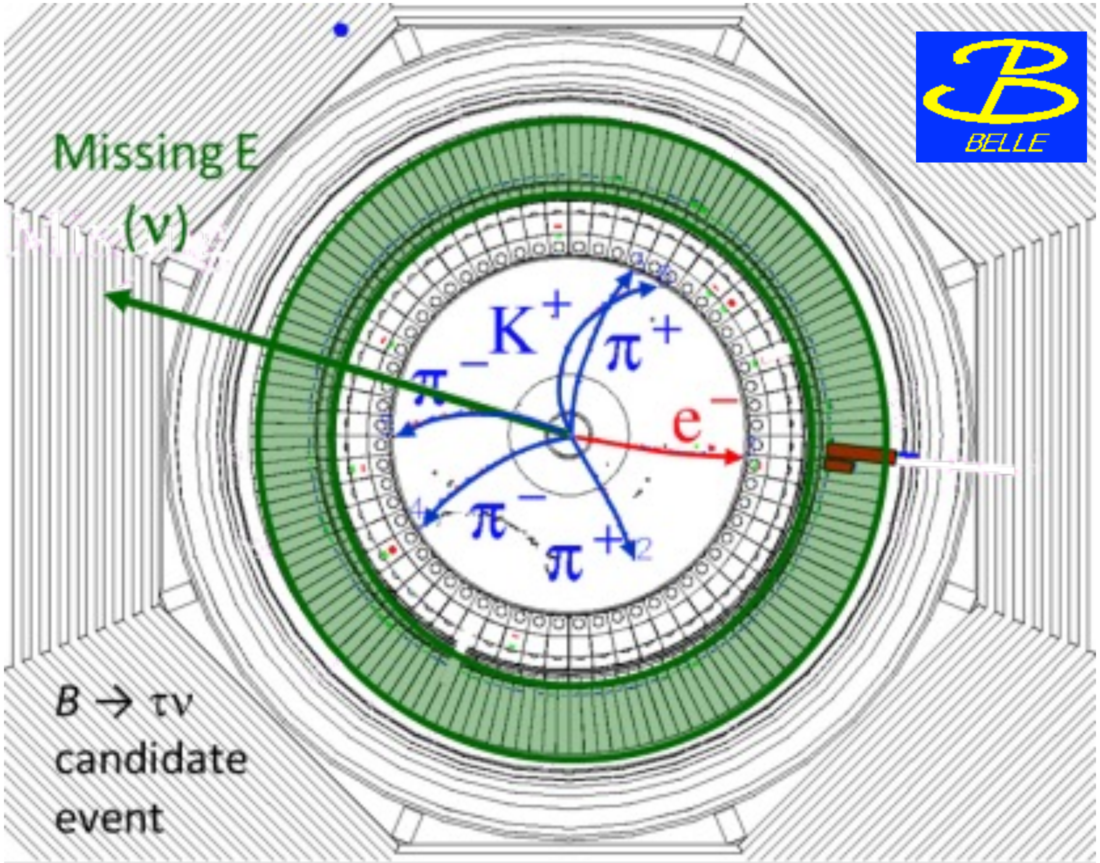
This is now called FEI "Full Event Interpretation" and uses large numbers of tag modes via a BDT (Boosted Decision Tree).

$Clean\ but\ efficiency\ \varepsilon{\sim}0.5\%$

T. Keck et al., Comput. Softw. Big Sci. 3, 6 (2019), arXiv:1807.08680 [hep-ex].

Example of a Missing Energy Decay (B→τν) *in old Belle Data* (recorded before 2010)

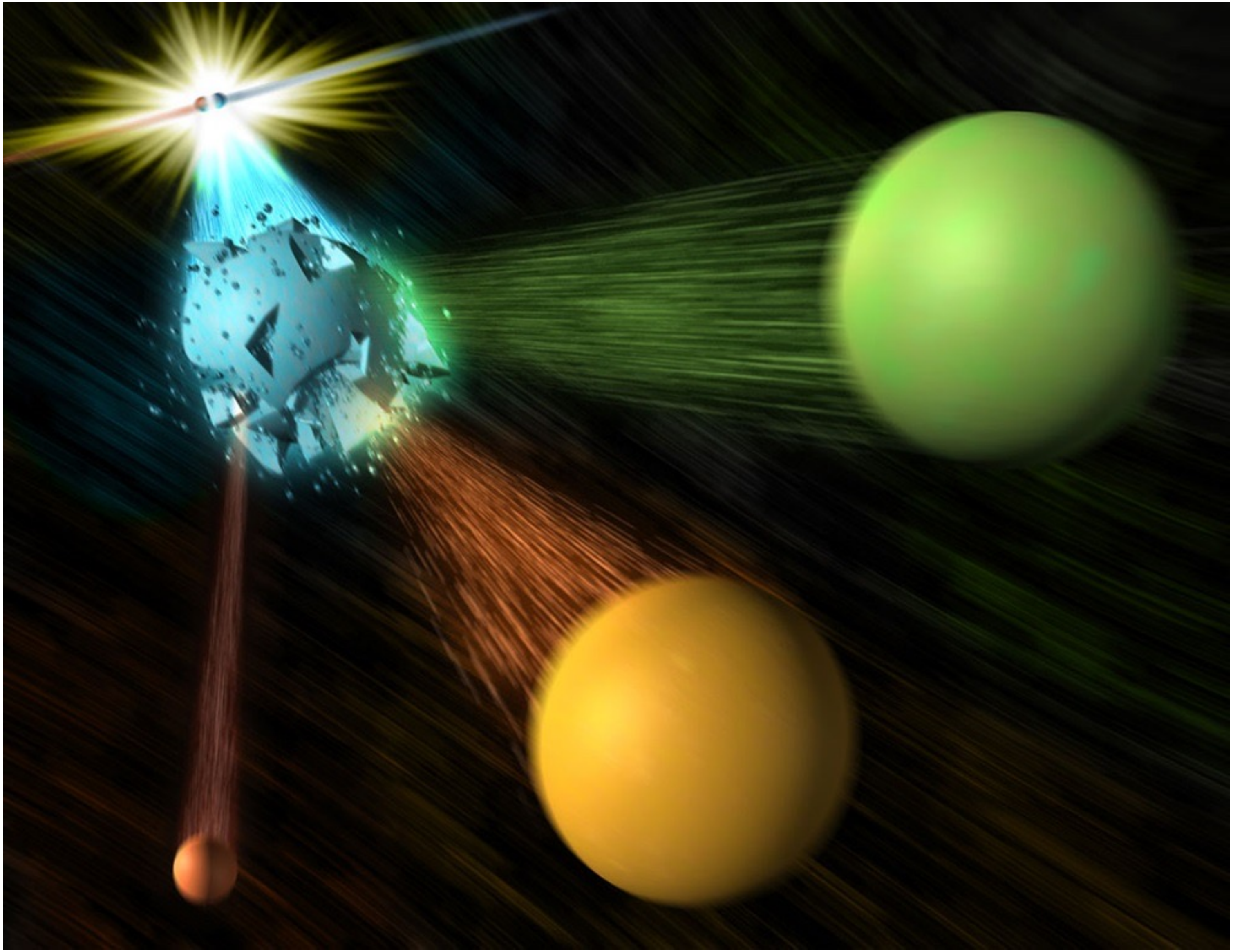
$$B^+ \rightarrow D^0\pi^+$$
$$(\rightarrow K\pi^-\pi^+\pi^-)$$
$$B^- \rightarrow \tau(\rightarrow e\nu\bar{\nu})\nu$$



The clean e+e- environment (and the CsI(Tl) crystal calorimeter) makes this possible.

SLAC
Outreach

Possible breakdown of lepton universality in $B \rightarrow D^{(*)} \tau \upsilon$

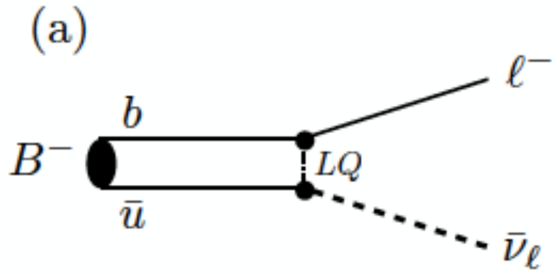


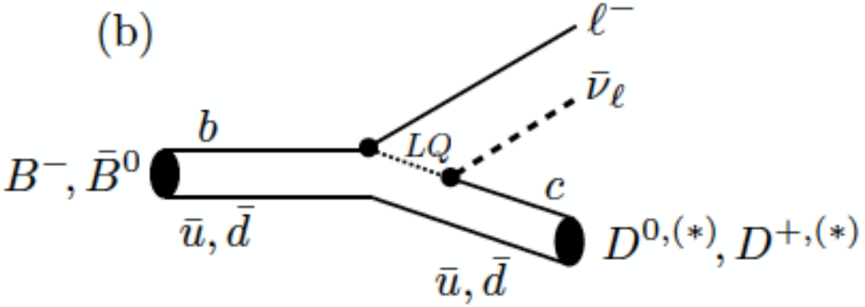
Let’s try to understand this picture of the production process (EM) and a weak decay

$B \rightarrow D^{(*)}\,\tau\,\upsilon$, possible breakdown of lepton universality

$$R_D^{(*)} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu_\ell)}$$

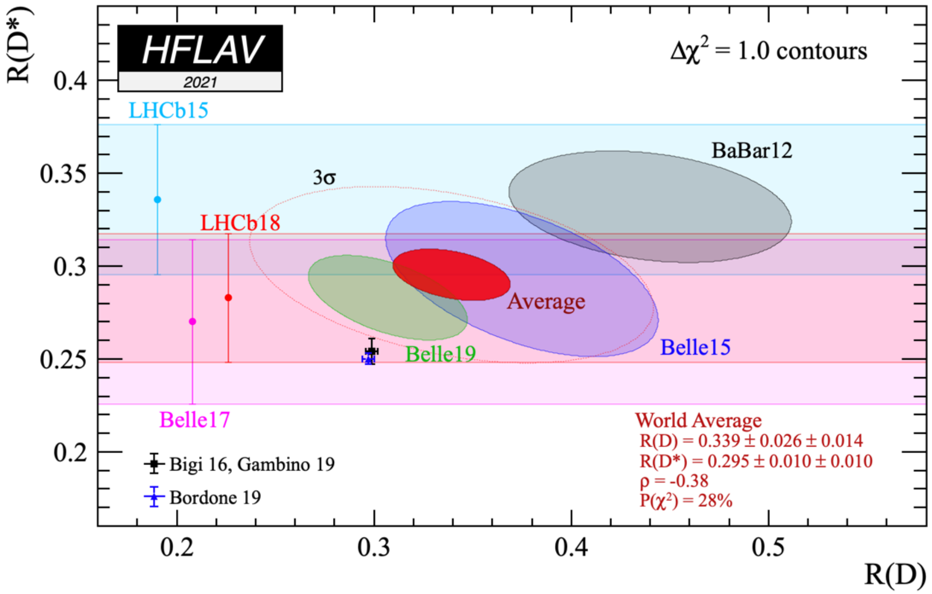
Some new physics possibilities (leptoquarks (LQ), charged Higgs type 3 etc..):





	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

This is NP in the weak b→c charged current

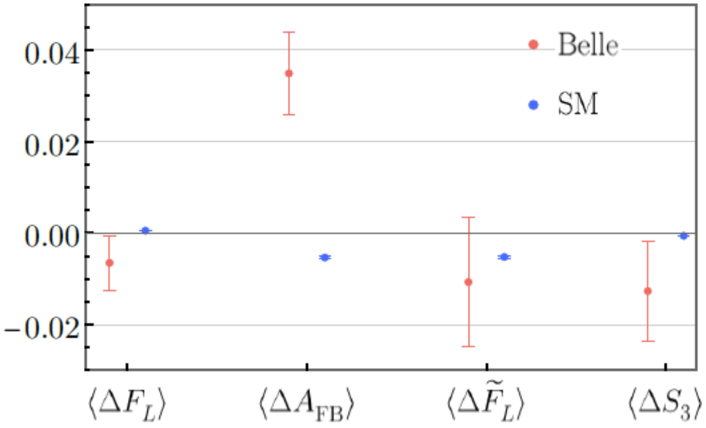


With current data from Belle, LHCb and BaBar:

Evidence of lepton universality breakdown in semileptonic B decays with τ leptons. Last Belle measurement (2019) with semileptonic tags brings down the WA discrepancy from 4→3.4σ

Hot and fairly New: ΔA_{FB} in b→c l ν (LFU violation)

$$\Delta A_{FB}(B \to D^{*+}\ell\nu) = A_{FB}(B \to D^{*+}\mu^-\bar{\nu}) - A_{FB}(B \to D^{*+}e^-\bar{\nu})$$



~4σ deviation in Eur. Phys. J.C. 81 (2021). Theoretical meta-analysis of 0.71 ab^{-1} of Belle data from Arxiv 1809.03290 (E. Waheed et al (Belle)).

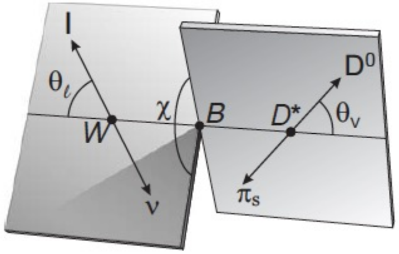
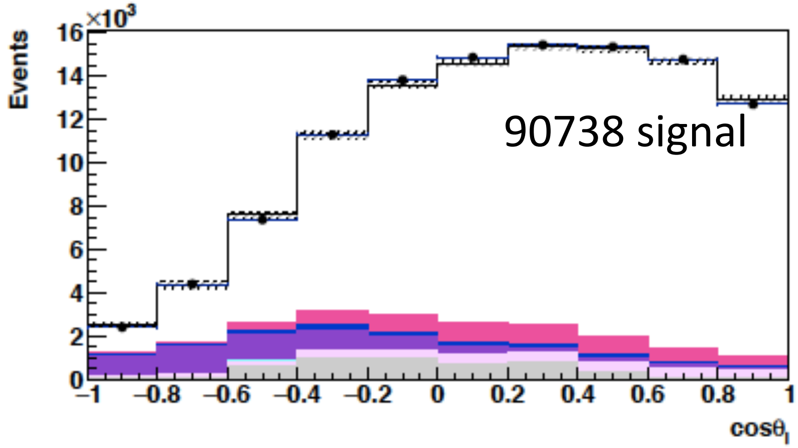
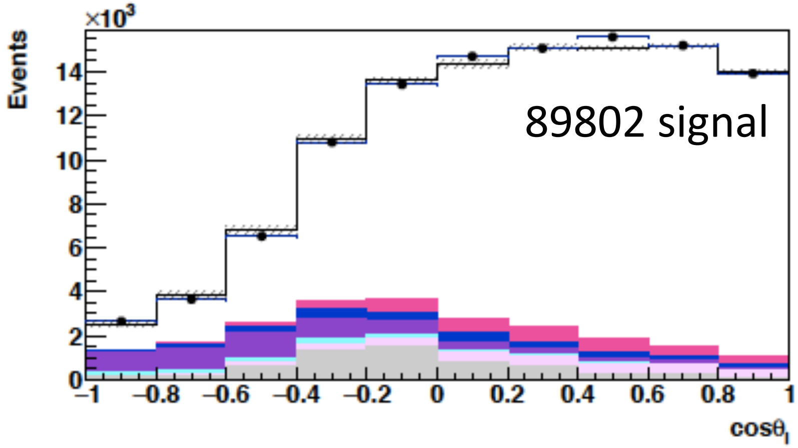


FIG. 3. Definition of the angles θ_ℓ, θ_V and χ for the decay

“untagged”, no FEI used.



90738 signal

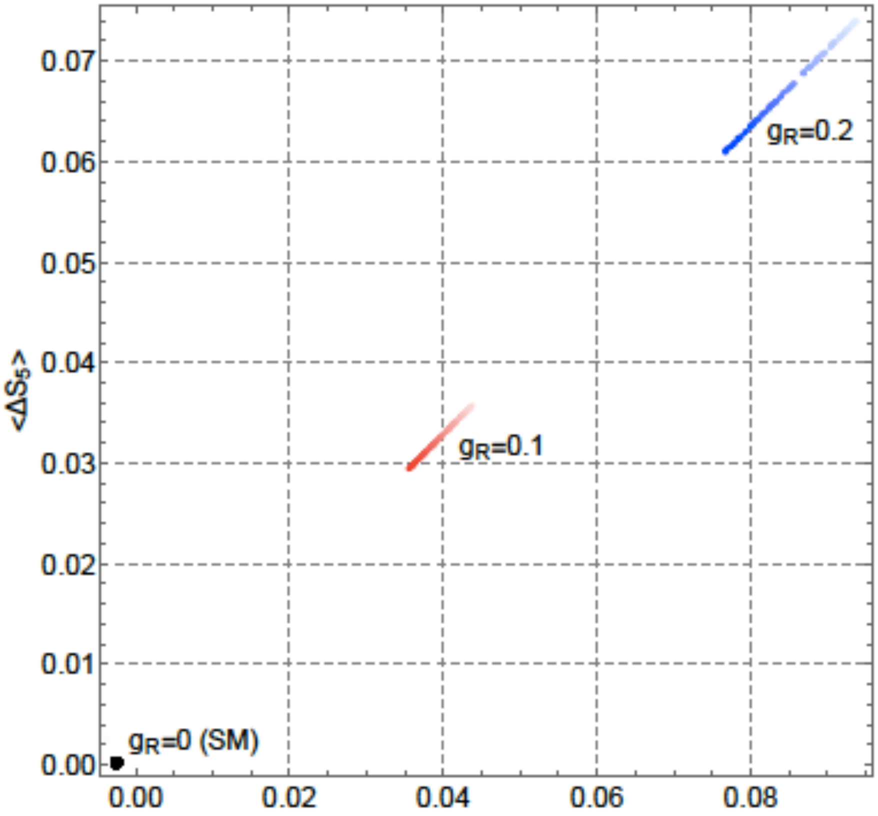


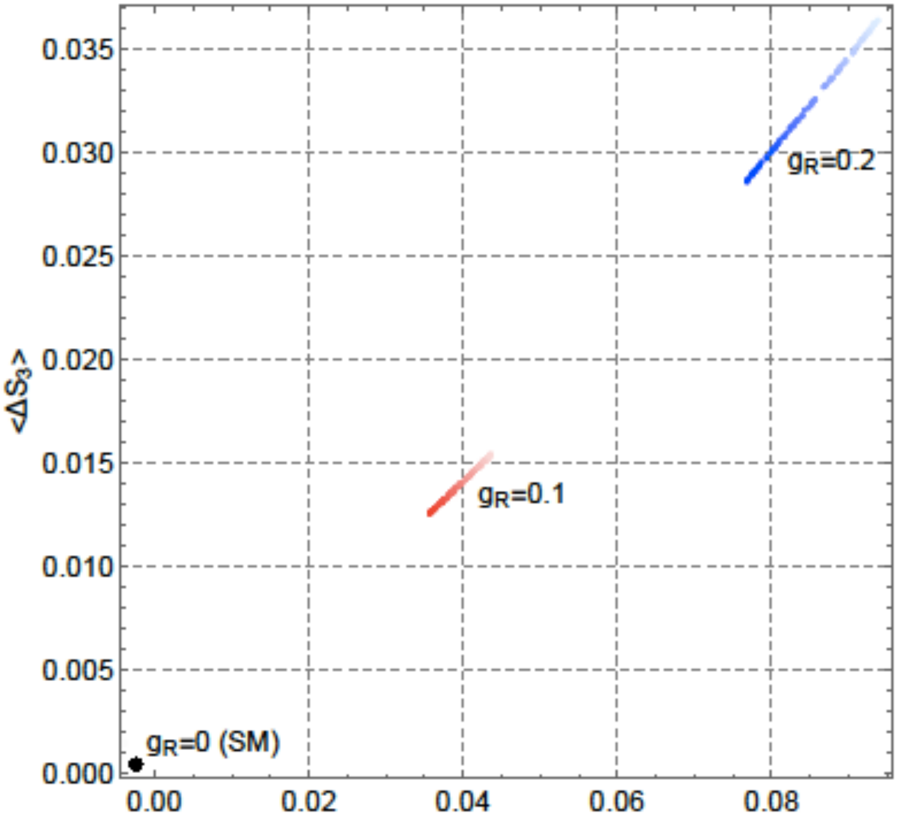
89802 signal

Evidence for NP couplings in b→cμν ?

$$\Delta A_{FB}(B \to D^{*+}\ell\nu) = A_{FB}(B \to D^{*+}\mu^-\nu) - A_{FB}(B \to D^{*+}e^-\nu)$$

NP implies correlated angular asymmetries (ΔA_{FB} vs ΔS_5 or ΔS_3).





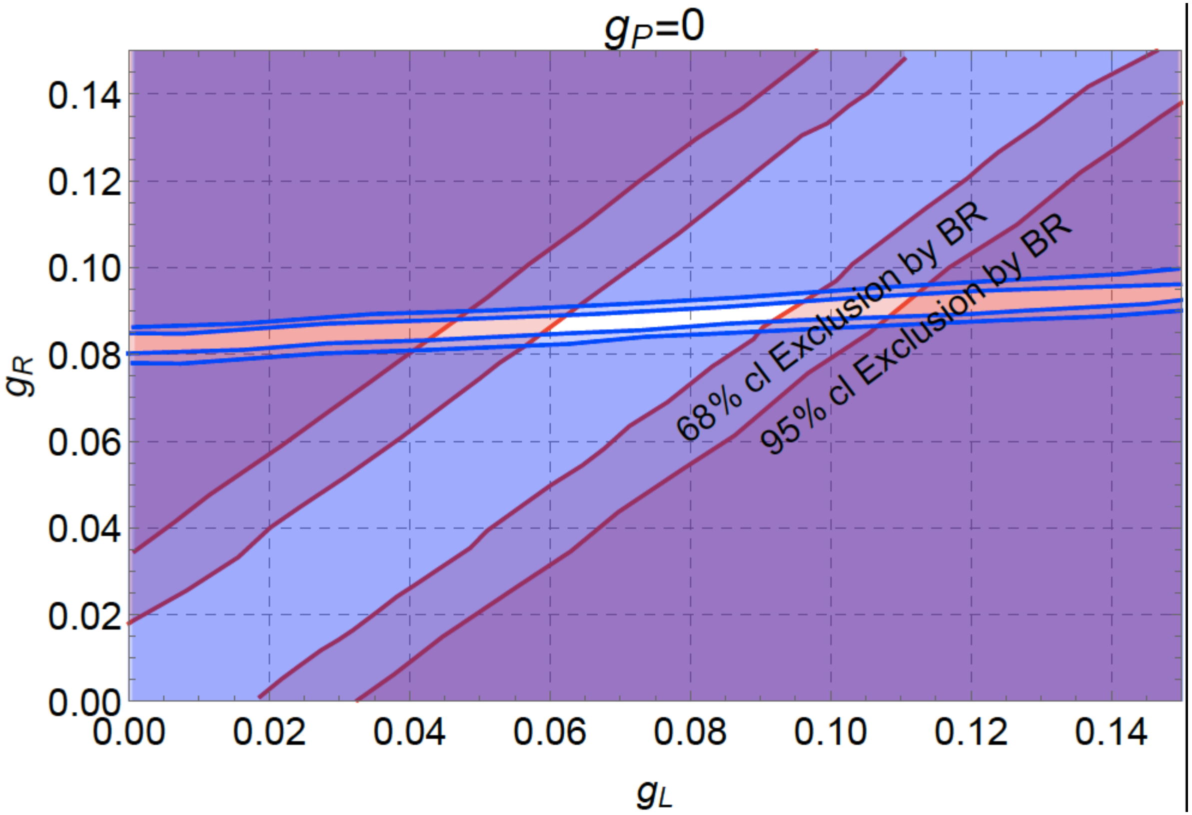
https://arxiv.org/abs/2203.07189	Snowmass WP
https://arxiv.org/abs/2206.11283	PRD version

Snowmass Highlight:

$$\Delta A_{FB}(B \to D^{*+}\ell\nu) = A_{FB}(B \to D^{*+}\mu^{-}\nu) - A_{FB}(B \to D^{*+}e^{-}\nu)$$

+ constraints on NP coupling parameters@250 ab^{-1}

N.B. Form Factor uncertainties cancel out in Δ variables



Angular asymmetries provide a tighter constraint on NP LFUV couplings (right-handed V+A, extra left-handed V-A and pseudo-scalar couplings).

https://arxiv.org/abs/2203.07189

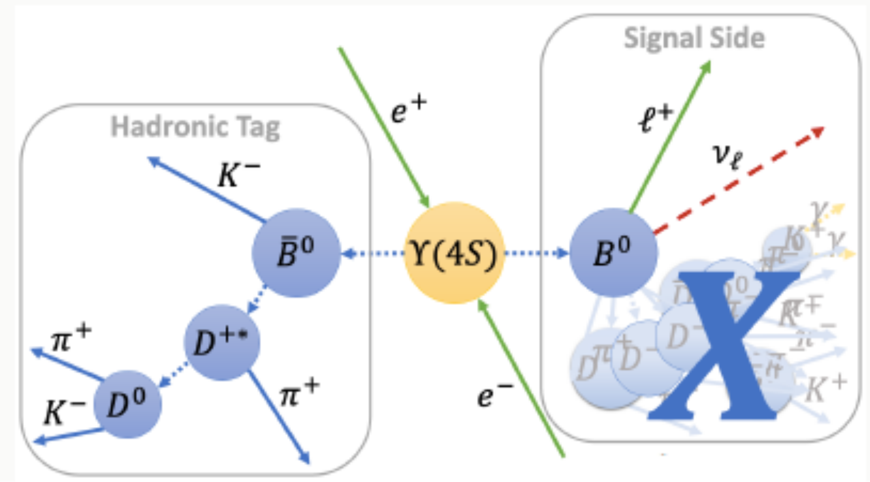
Plots: Quinn Campagna (Ole Miss)

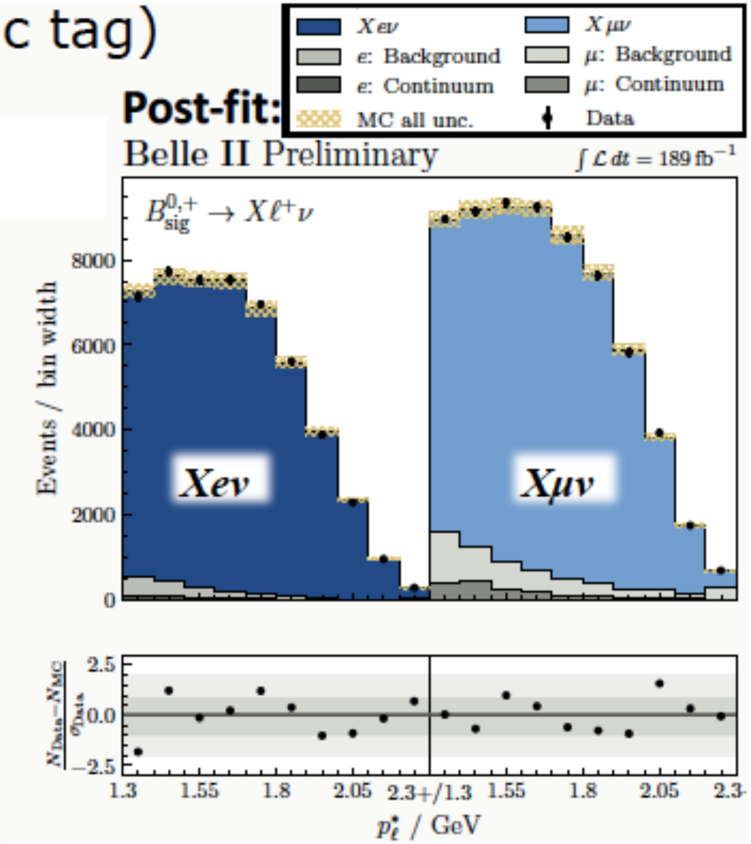
https://arxiv.org/abs/2206.11283

Test of e/μ universality (Belle II)

- Inclusive b→cl⁻ν analysis (hadronic tag)

$$R(X_{e/\mu}) = \frac{\mathscr{B}\,(B\to Xe\nu)}{\mathscr{B}\,(B\to X\mu\nu)}$$



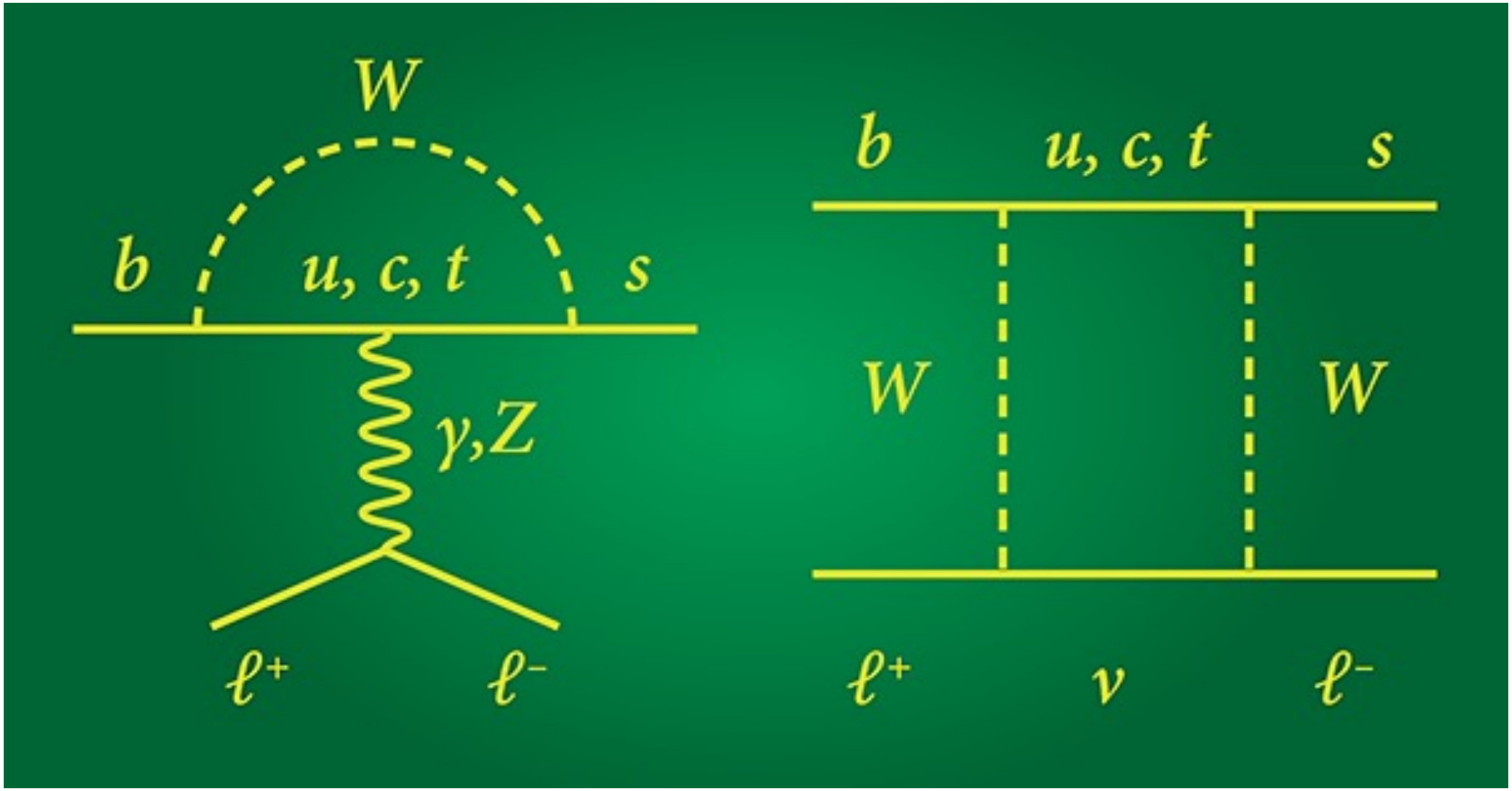


$$R(X_{e/\mu})^{p^*_\ell>1.3\mathrm{GeV}} = 1.033 \pm 0.010^{\mathrm{stat}} \pm 0.020^{\mathrm{syst}}$$

➢ Most precise LFU test in b→cl⁻ν to date

  ➢ precursor to an inclusive *B→Xτν* / *B→Xlν* measurement

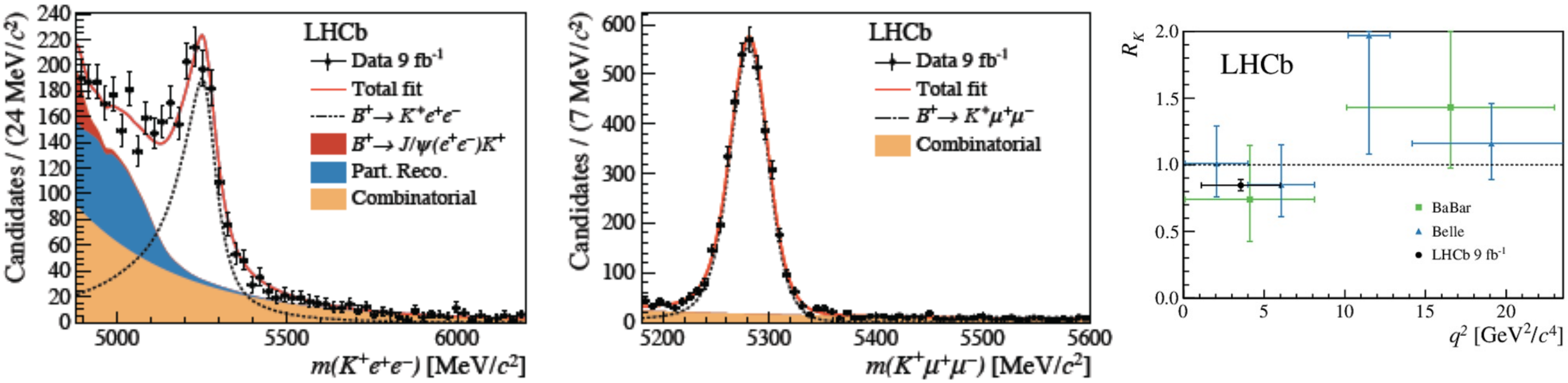
Lepton Universality Tests in b→s l+ l- transitions



"Electroweak Penguin" "Box"

Possible breakdown of Lepton Universality in b→s l+ l- transitions by the LHCb experiment at CERN, reported in 2021.

https://arxiv.org/abs/2103.11769, published in Nature



$$R_K = \frac{BF(B^+ \to K^+\mu^+\mu^-)}{BF(B^+ \to J/\psi(\to \mu^+\mu^-)K^+} \Big/ \frac{BF(B^+ \to K^+e^+e^-)}{BF(B^+ \to J/\psi(\to e^+e^-)K^+}$$

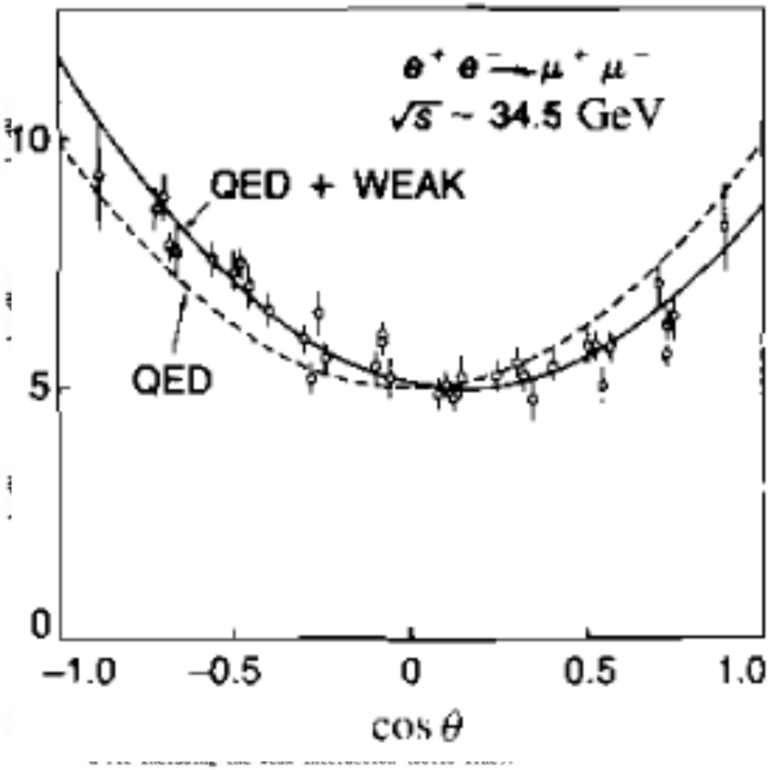
$$R_K(1.1 < q^2 < 6.0\ \mathrm{GeV}^2/\mathrm{c}^4) = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

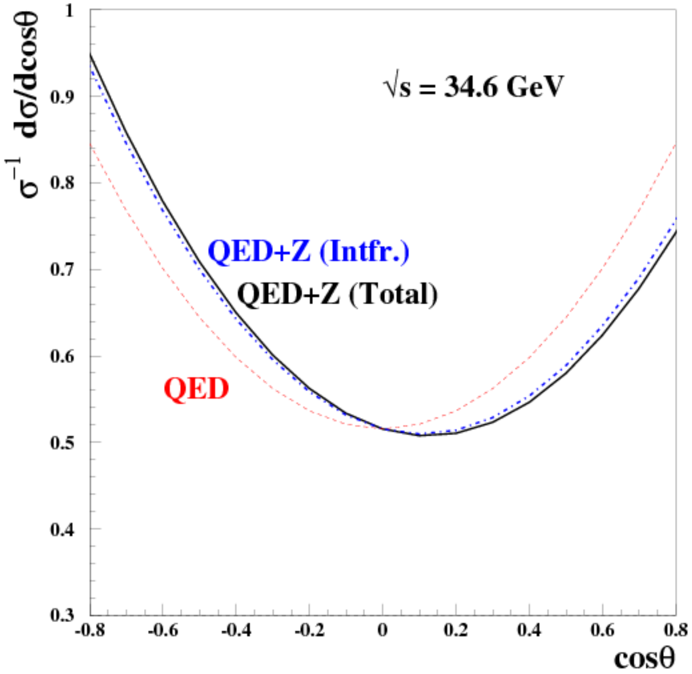
<1 (lepton universality prediction)

And thus this *might indicate* the breakdown of the Standard Model of Particle Physics (3.1 σ)

Note: $q^2 = M^2(l^+\ l^-)$

High Energy Physics History: finding NP in A_{FB} (using interference)

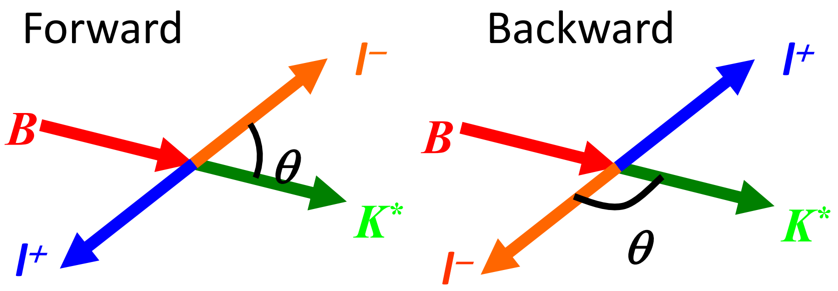


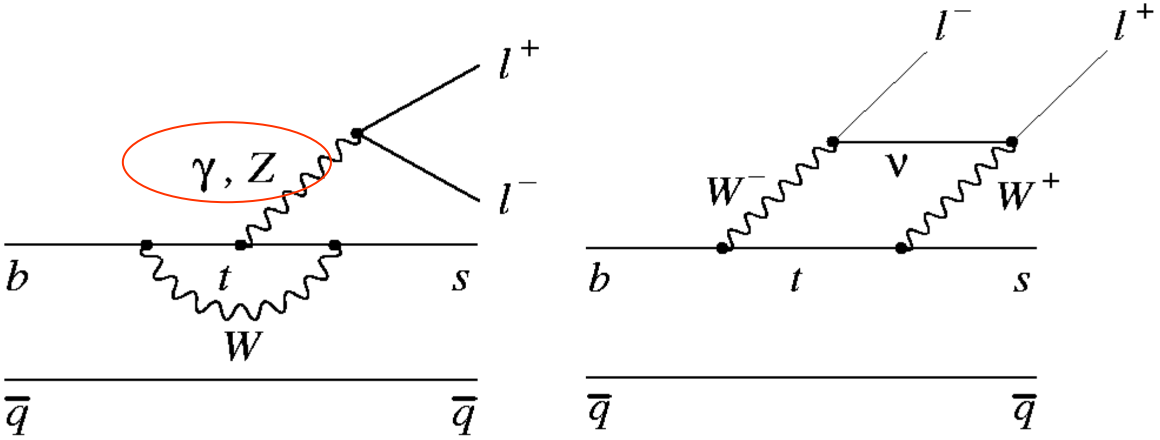


Conclusion: There is a Z boson at higher energy even though colliders of the time did not have enough $\sqrt{s}$ to produce it

$A_{FB}(B \rightarrow K^{*} l^{+} l^{-})(q^{2})$

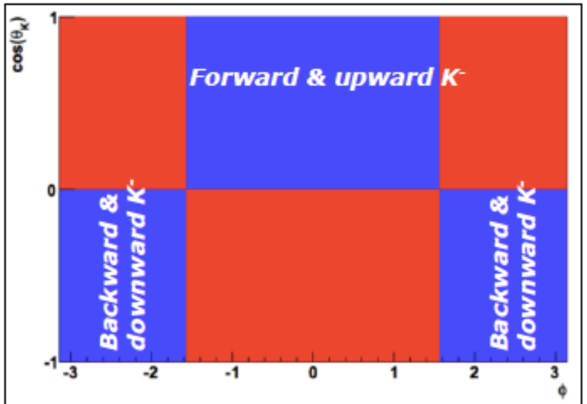
The SM forward-backward asymmetry in b →s l^+ l^- can arise from the ***interference*** *between γ and Z^0 contributions.*



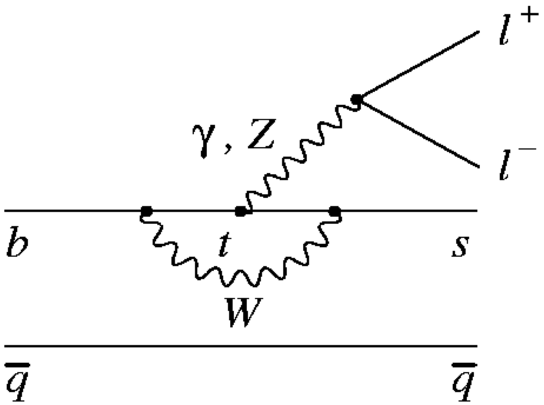


Note that all the heavy particles of the SM (W, Z, top) enter in this decay.

More on $A_{FB}(B \rightarrow K^* l^+ l^-)(q^2)$ and $S_5(q^2)$



Counting S_5: blue minus red



Can in effect vary √s for NP

A_{FB} depends on $q^2 = M^2(l^+l^-)$

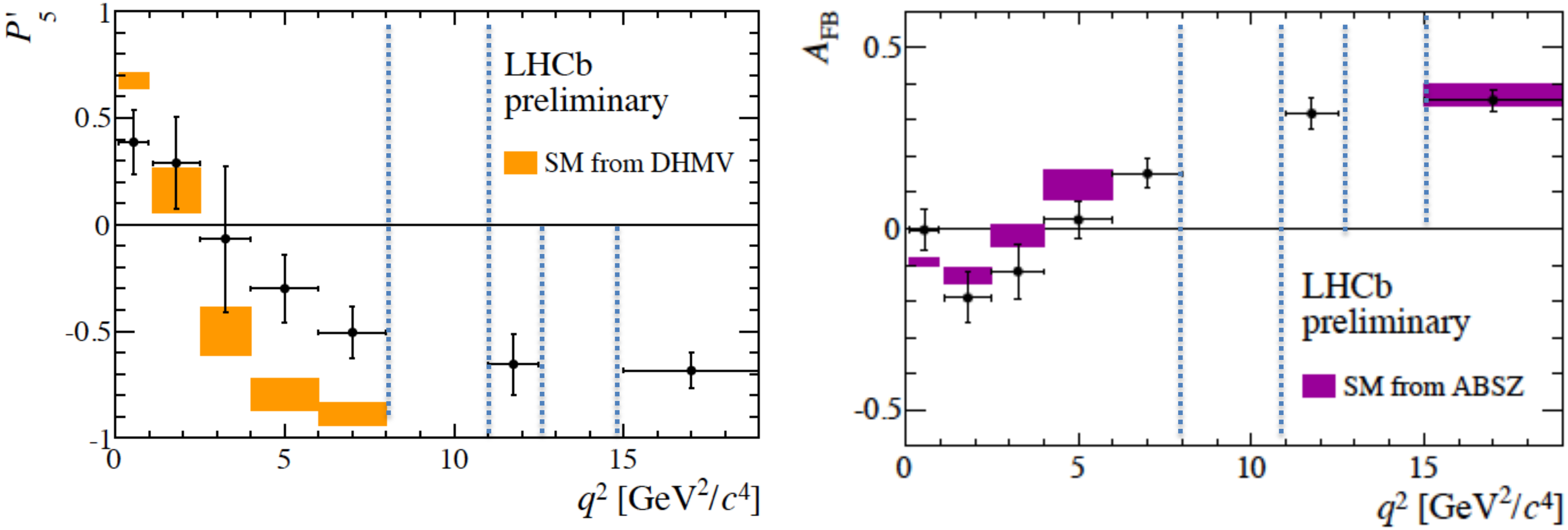
$$A_{FB}(B \rightarrow K^* \ell^+ \ell^-) = -C_{10}\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7F_2\right]$$

G. Burdman, Phys.Rev. D57 (1998) 4254

The “zero-crossing” of A_{FB} depends only on a ratio of form factors and is a relatively *clean* observable.

LHCb 3fb^{-1} results on B →K* $\mu^+\mu^-$ (q^2)

A different angular asymmetry, involving χ



"The P_5' measurements are only compatible with the SM prediction at a level of 3.7σ…..A mild tension can also be seen in the A_{FB} distribution, where the measurements are systematically <=1σ below the SM prediction in the region $1.1<q^2< 6.0$ GeV^2"

These angular asymmetries persist in 2022

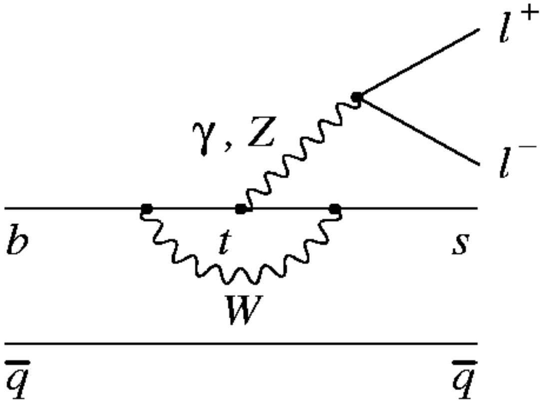
Theory from http://arxiv.org/abs/1407.8526

Experiment from LHCb-CONF-2015-002

Comment on $B \to K^* \mu^+\mu^- (q^2)$ $(b \to s\, l^+ l^-)$

Is HEP History repeating itself ? [*but make sure this is not a SM resonance/ non–factorizable/long distance effect.*]

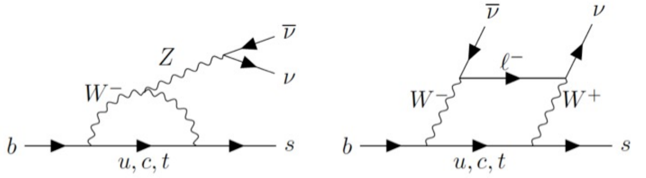
Why would NP appear first in this mode (and not others) ?



Possible answer: All the heavy particles of the SM (t, W, Z) and maybe NP (except the Higgs) appear here. Sensitive to NP via QM interference (linear effects). ++*Lepton Flavor Universality Violation*

Feynman Diagrams
and Model Building

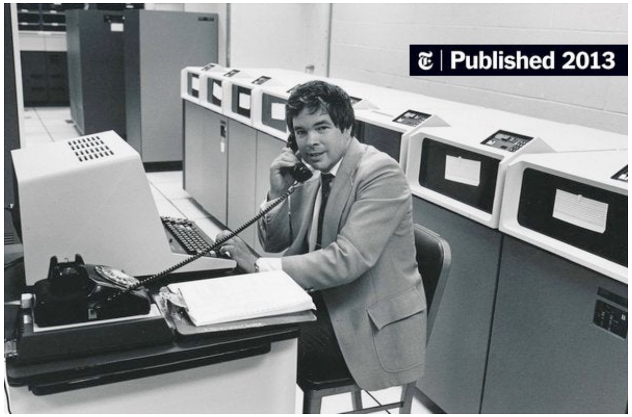
Feynman family and diagrams



(a) Penguin diagram (b) Box diagram

Paradigm shift

Effective Field Theory
→Wilson Coefficients



Ken Wilson (”Wilson coefficients”)

C_7, C_9, C_{10}

New Physics Couplings in b→s

The effective Hamiltonian for $b \to s$ transitions can be written as

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

and we consider NP effects in the following set of dimension-6 operators,

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,.$$

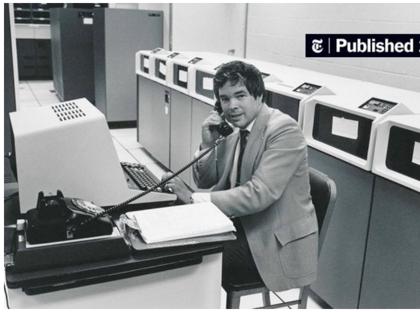
The primes are NP right-handed couplings.

New Physics Couplings in b→s

Feynman
family and
diagrams

The effective Hamiltonian for $b \to s$ transitions can be written as

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$



Ken Wilson

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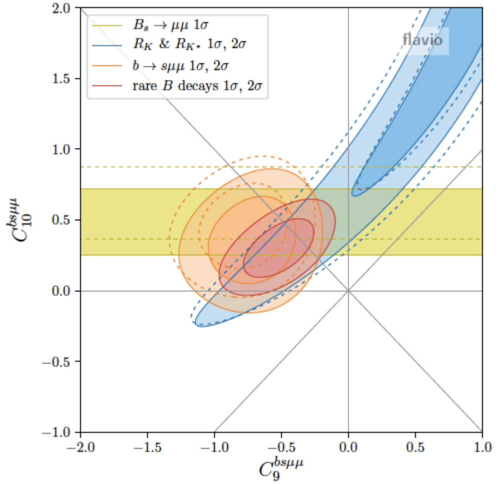
$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,.$$

The primes are right-handed couplings.

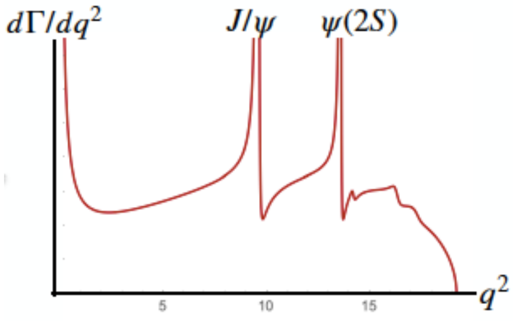


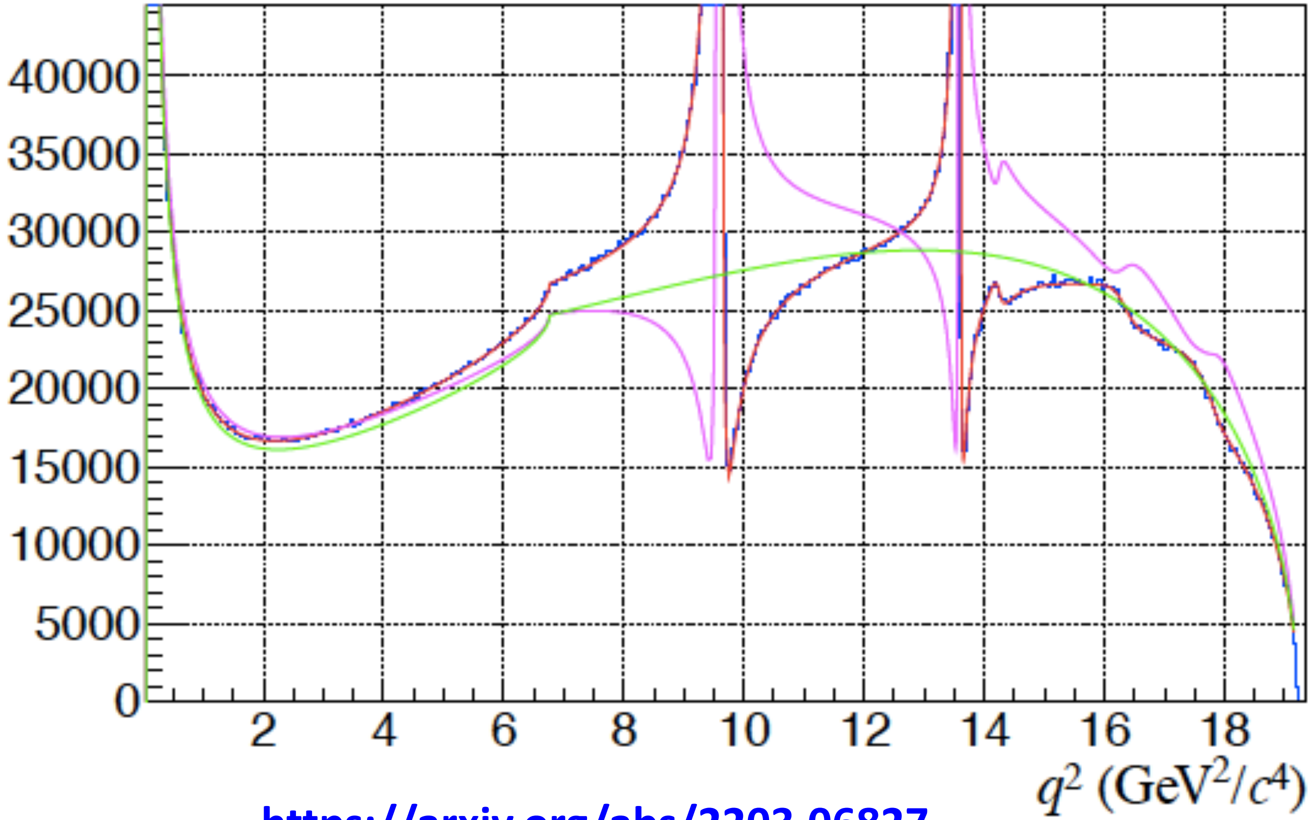
Altmanshofer, Stangel fit to all data (mostly LHCb)
https://arxiv.org/pdf/2103.13370.pdf

		$b \to s\mu\mu$		LFU, $B_s \to \mu\mu$		all rare B decays	
	Wilson coefficient	best fit	pull	best fit	pull	best fit	pull
NP errors	$C_9^{bs\mu\mu}$	$-0.75^{+0.22}_{-0.23}$	3.4σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.73^{+0.15}_{-0.15}$	5.2σ
	$C_{10}^{bs\mu\mu}$	$+0.42^{+0.23}_{-0.24}$	1.7σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.54^{+0.12}_{-0.12}$	4.7σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.53^{+0.13}_{-0.13}$	3.7σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.39^{+0.07}_{-0.07}$	5.6σ
SM errors	$C_9^{bs\mu\mu}$	$-0.88^{+0.22}_{-0.21}$	3.7σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.78^{+0.15}_{-0.15}$	5.3σ
	$C_{10}^{bs\mu\mu}$	$+0.44^{+0.21}_{-0.21}$	2.1σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.54^{+0.12}_{-0.12}$	4.8σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.58^{+0.17}_{-0.18}$	3.6σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.39^{+0.07}_{-0.07}$	5.5σ

C_9 : >5σ from the SM

Be very careful about 5σ New Physics (NP) claims, leftmost column assumes minimal *QCD, resonance effects in angular asymmetries and* q^2 *distribution.*





The green curve is the short-distance b→s l^+l^- contribution. The non-factorizable phase is an uncertainty.

https://arxiv.org/abs/2203.06827

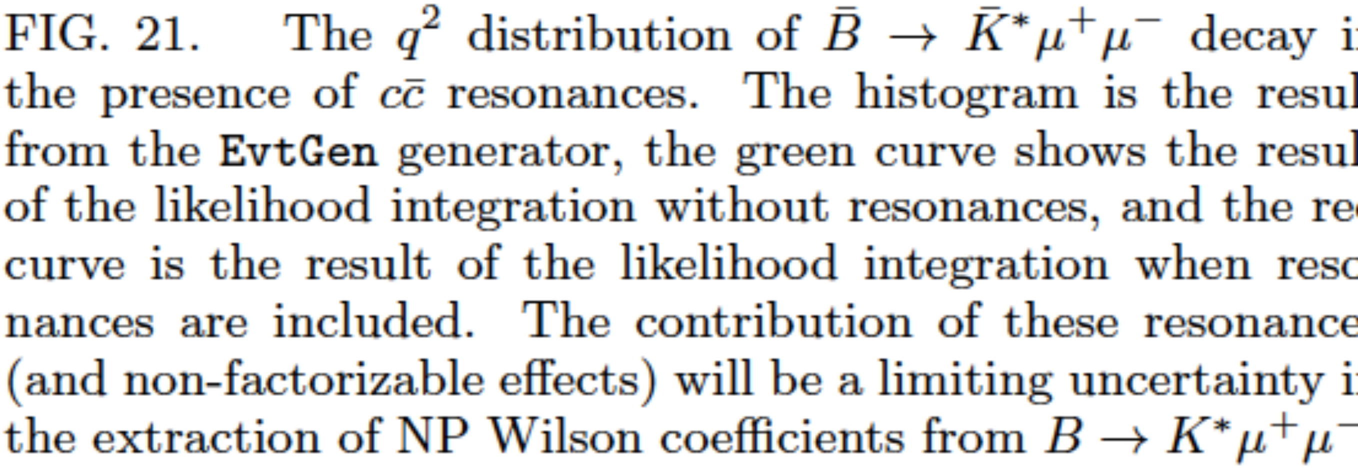


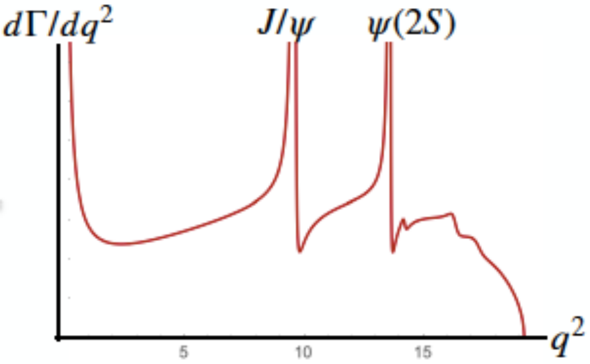
FIG. 21. The q^2 distribution of $\bar{B} \to \bar{K}^*\mu^+\mu^-$ decay i
the presence of $c\bar{c}$ resonances. The histogram is the resul
from the `EvtGen` generator, the green curve shows the resul
of the likelihood integration without resonances, and the re
curve is the result of the likelihood integration when reso
nances are included. The contribution of these resonance
(and non-factorizable effects) will be a limiting uncertainty i
the extraction of NP Wilson coefficients from $B \to K^*\mu^+\mu^-$

There are also uncertainties in B→K* form factors.

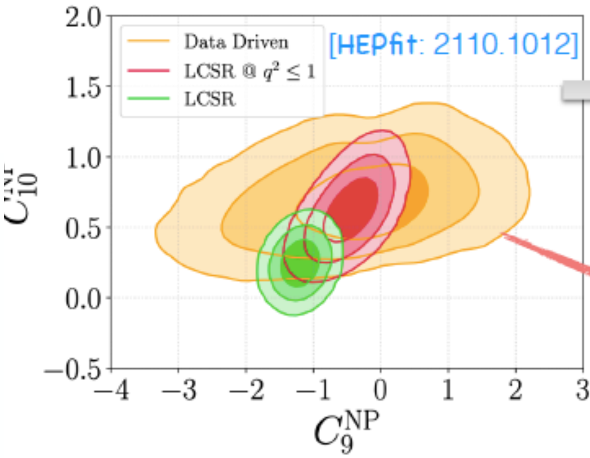

Alexei Sibidanov

A Cincinnati Snowmass Highlight:

Angular analysis



Resonant b→c cbar s contributions



Global fits to current $b \to s\ell\ell$ data with three different treatments to parametrize charm-loop effects

Hadronic uncertainties due to long distance physics can overshadow new physics

Further cancellation required for angular observables

☑ use different lepton flavors: $\frac{S_i^{b\to s\mu\mu}(q^2)}{\Gamma_f^{b\to s\mu\mu}(q^2)} - \frac{S_i^{b\to see}(q^2)}{\Gamma_f^{b\to see}(q^2)}$

Q-observables
[Capdevila *et. al*, '16]
[Belle: '16]

☑ Directly extract $\boxed{\Delta C_9 = \delta C_9^{b\to s\mu\mu} - \delta C_9^{b\to see}}$

The solution to the problem is the Delta (Δ) Observables.

https://arxiv.org/abs/2203.06827

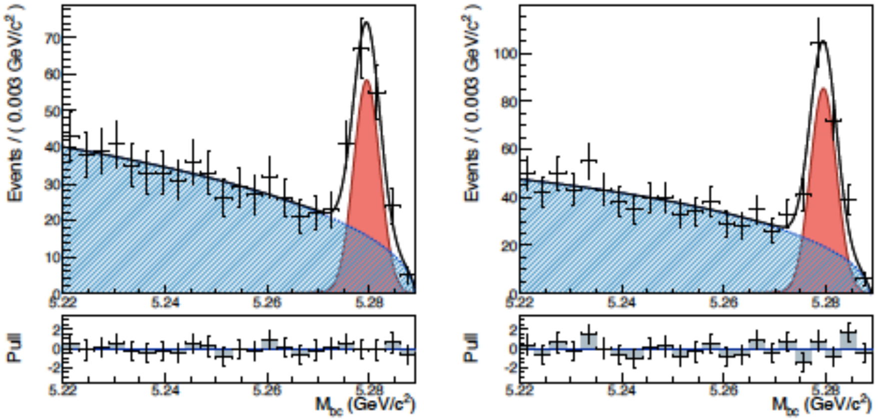


FIG. 1. Distribution of the beam-energy constrained mass for selected $B \to K^* e^+ e^-$ (left) and $B \to K^* \mu^+ \mu^-$ (right). Combinatorial background (shaded blue), signal (red filled) and total (solid) fit functions are superimposed on the data points

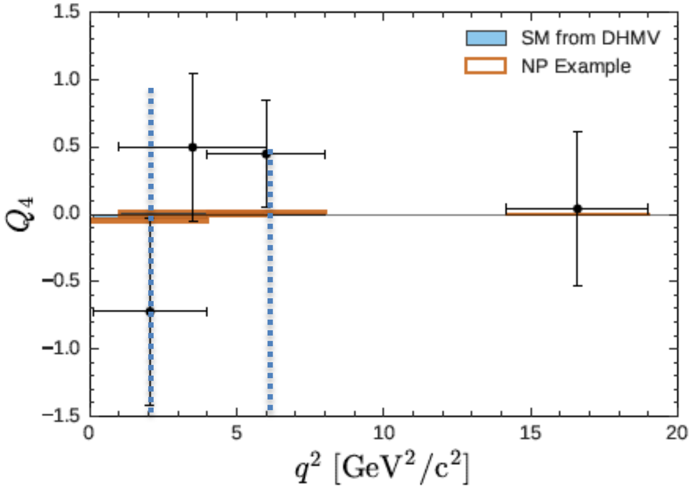
$$\Delta P_4' = P_4'(B \to K^* \mu^+ \mu^-) - P_4'(B \to K^* e^+ e^-)$$

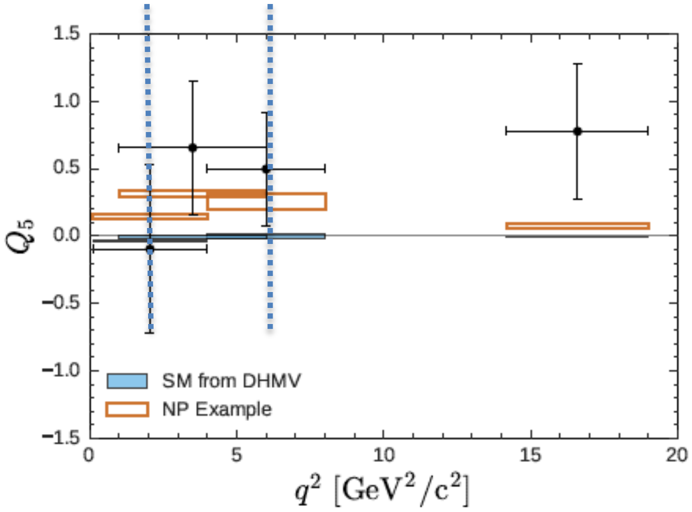
a.k.a. Q_4

$$\Delta P_5' = P_5'(B \to K^* \mu^+ \mu^-) - P_5'(B \to K^* e^+ e^-)$$

a.k.a. Q_5

Belle has tried out some of the Δ Observables with 0.7 ab^{-1}

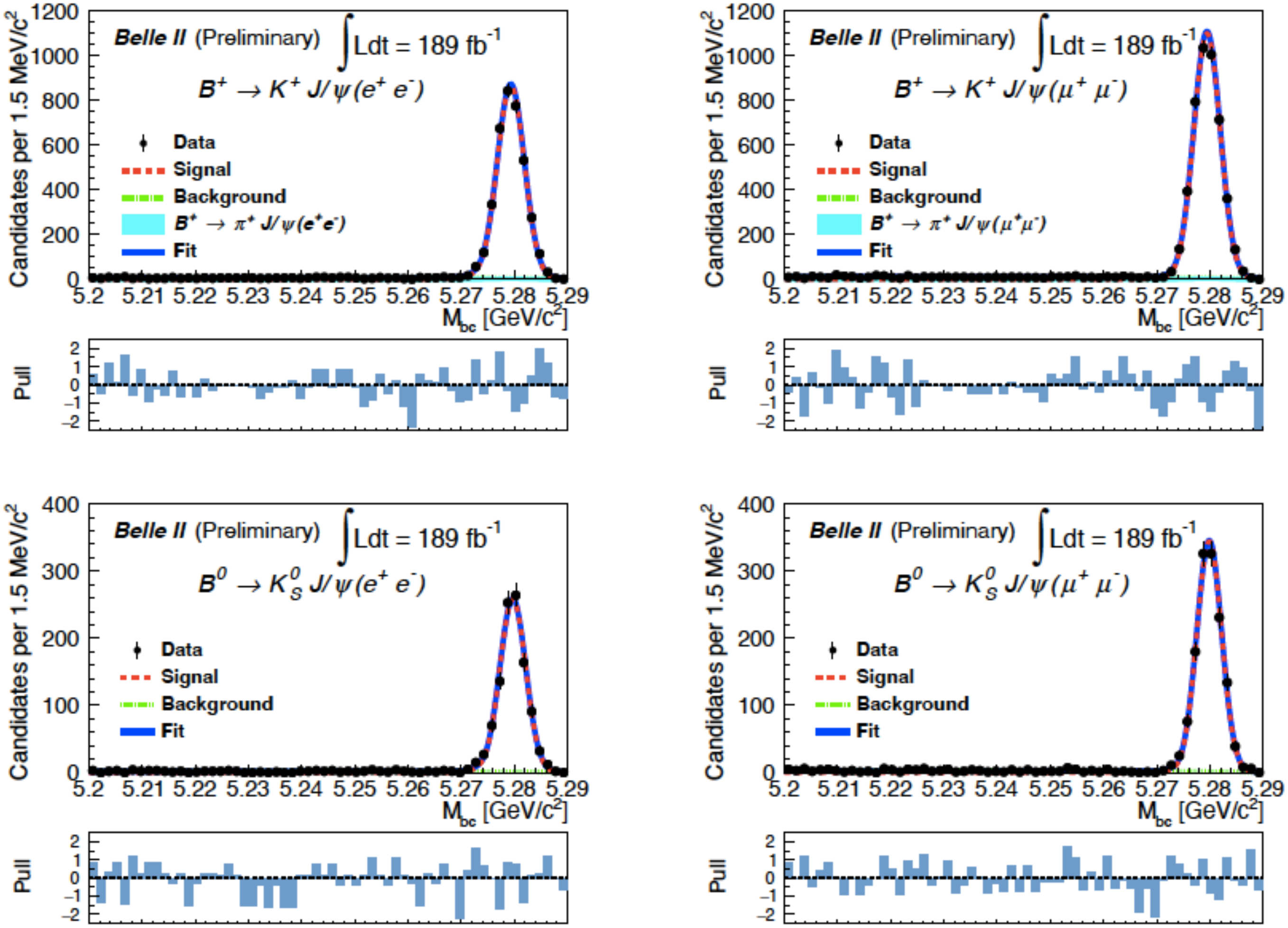




S. Wehle, C. Niebuhr, S. Yashchenko, et al.
(Belle Collaboration), PRL118, 111801 (2017)

Belle II is gearing up for e vs μ lepton universality tests (e.g. $B \rightarrow K\, J/\psi$, $\psi \longrightarrow l^+ l^-$ from recent data, 190 fb^{-1})

Includes brems recovery for electrons



https://arxiv.org/abs/2207.11275

$$R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$$

$$R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$$

Reminder and Motivation:

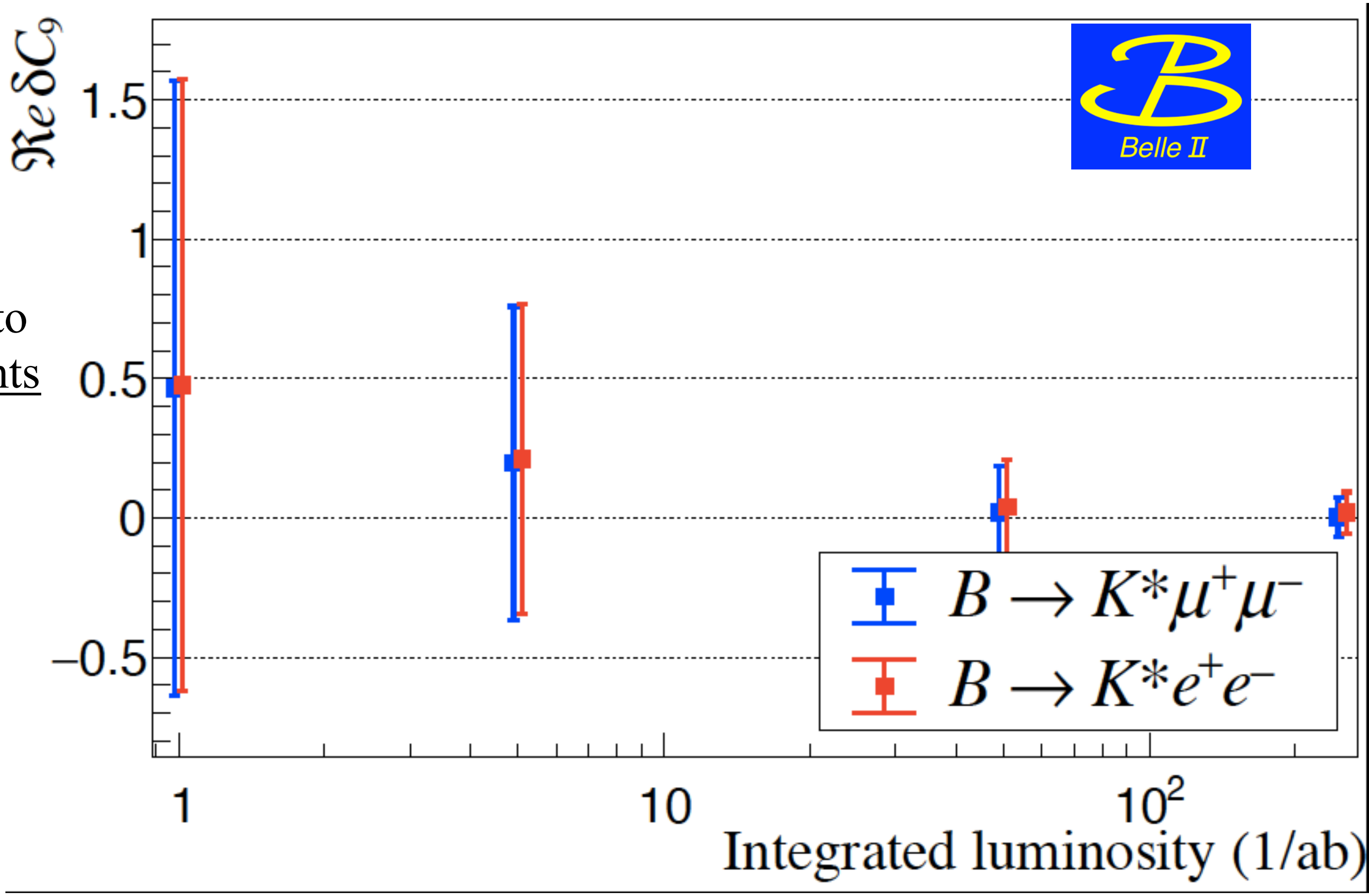
C_9 : Global fit to world b→s data gives a $>5\sigma$ deviation from the SM

What about the future ?

Estimates use pseudo-experiments with 4-D unbinned maximum likelihood fits to 4 variables in $B \to K^* l^+ l^-$ to extract Wilson coefficients C_i directly from data.

Use $q^2 > 1$ GeV^2 and $|q^2 - M^2| < 0.25$ GeV^2 and assume 25% Belle efficiency

A. Sibidanov et al.



https://arxiv.org/abs/2203.07189

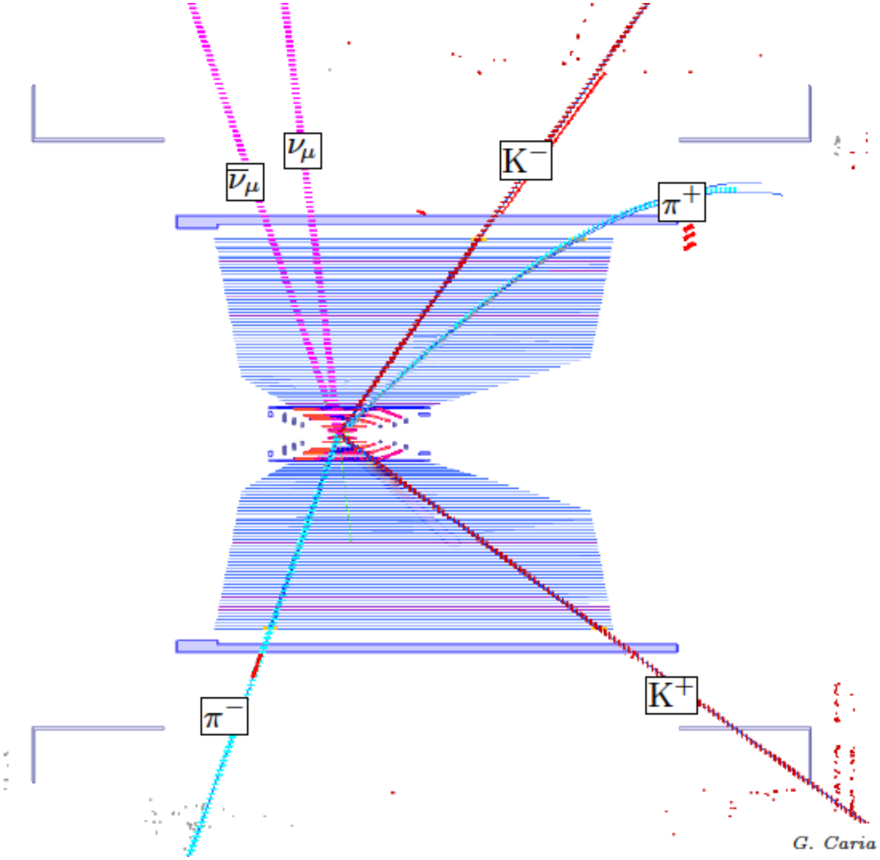
What’s Ahead for Belle II ?

“Missing Energy Decay” in a Belle II GEANT4 MC simulation

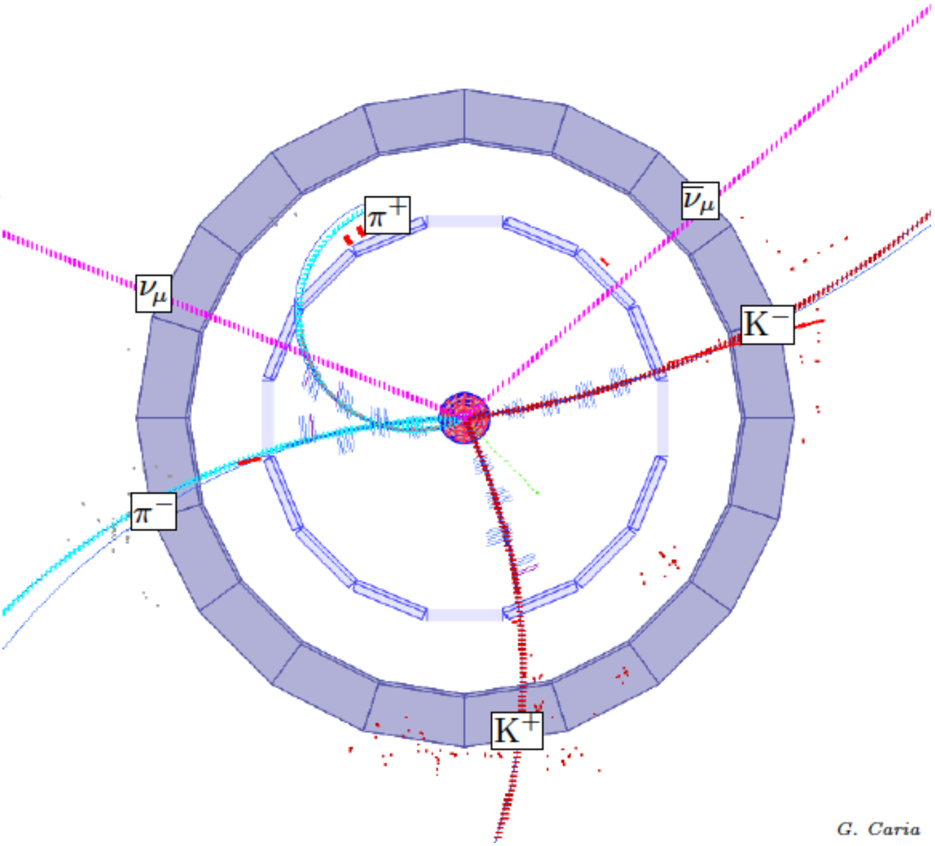
Signal: B→K ν ν

tag mode: B→Dπ; D→Kπ

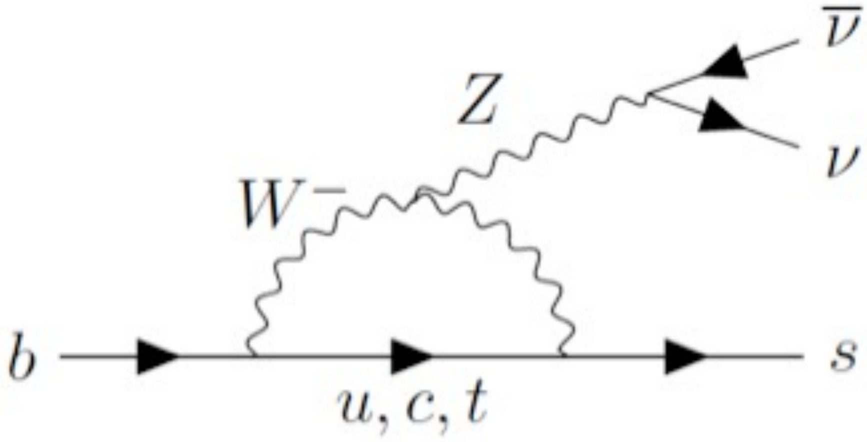
View in r-z



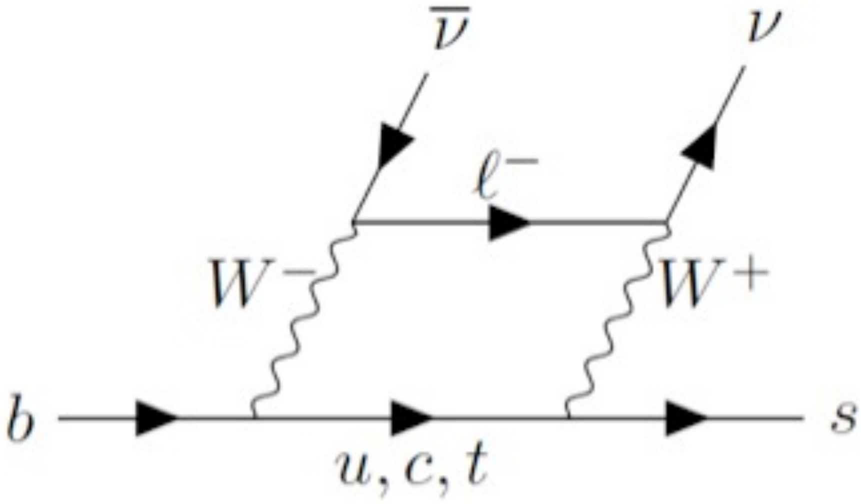
Zoomed view of the vertex region in r--phi



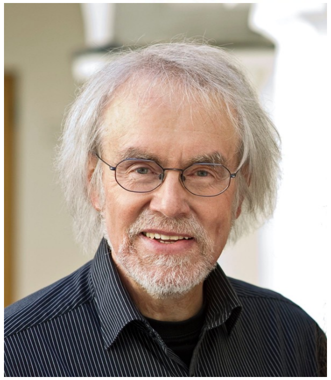
$B \to K\nu\bar{\nu}$: NP without hadronic uncertainties



(a) Penguin diagram



(b) Box diagram



Andrezj
Buras

Note that in contrast to $B \rightarrow K^{(*)} l^+ l^-$ angular asymmetries, there are NO long distance (charm annihilation) contributions from $B \rightarrow J/\psi\ K^{(*)}$ and $B \rightarrow \psi(2S)\ K^{(*)}$

For example, https://arxiv.org/abs/1409.4557

The $B \rightarrow K^{(*)}$ nu nubar modes are accessible to Belle II (and Belle), but might be hard at a hadron experiment.

Calibration Mode for B→K nu nubar

$$B^+ \to J/\psi K^+, J/\psi \to \mu^+\mu^-$$

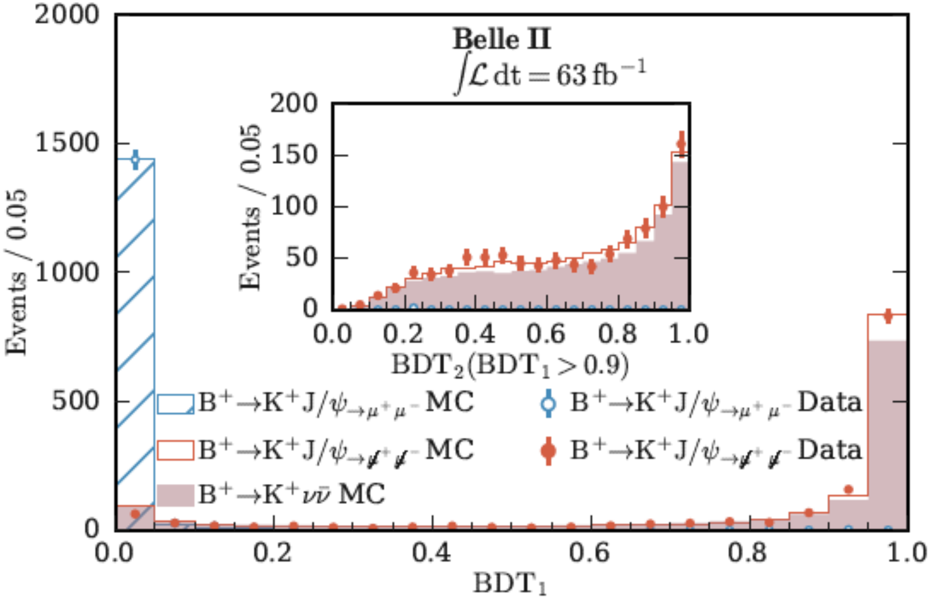


FIG. 2: Distribution of the classifier output BDT$_1$ (main figure) and BDT$_2$ for BDT$_1 > 0.9$ (inset). The distributions are shown before ($J/\psi_{\to\mu^+\mu^-}$) and after ($J/\psi_{\to\not\mu^+\not\mu^-}$) the muon removal and update of the kaon-candidate momentum of selected $B^+ \to K^+ J/\psi$ events in simulation and data. As a reference, the classifier outputs directly obtained from simulated $B^+ \to K^+\nu\bar\nu$ signal events are overlaid. The simulation histograms are scaled to the total number of $B^+ \to K^+ J/\psi$ events selected in data.

$$B \to K\nu\bar\nu$$

Hadronic FEI or semileptonic FEI, require full reconstruction of individual decay modes, effective efficiency is 1% at best.

New Idea (Sasha Glazov et al): *Try inclusive ROE (Rest Of the Event)* tagging and improve efficiency by a factor of 5-10. Backgrounds are higher but manageable by fitting.

Use two BDTs: BDT1 for continuum bkg suppression and then BDT2 to distinguish B Bbar bkg from signal.

B→K nu nubar candidates: p_T(K) distribution in BDT2 bins

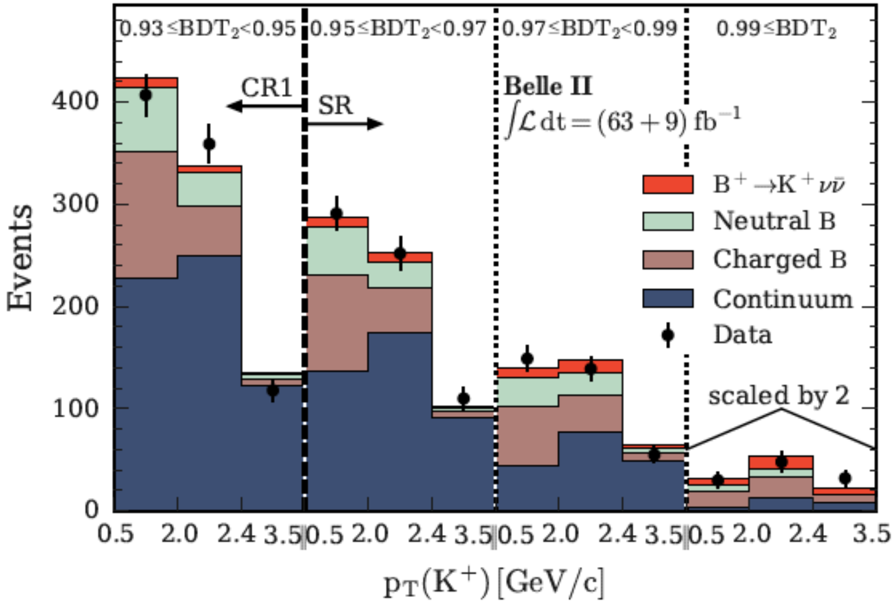


FIG. 3: Yields in on-resonance data and as predicted by the simultaneous fit to the on- and off-resonance data, corresponding to an integrated luminosity of 63 fb^{-1} and 9 fb^{-1}, respectively. The predicted yields are shown individually for charged and neutral B-meson decays and the sum of the five continuum contributions. The leftmost three bins belong to CR1 with BDT$_2$ $\in$ [0.93, 0.95] and the other nine bins correspond to the SR, three for each range of BDT$_2$ $\in$ [0.95, 0.97, 0.99, 1.0]. Each set of three bins is defined by $p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c. All yields in the rightmost three bins are scaled by a factor of two.

inclusive ROE (Rest Of the Event) tagging

$$B \to K\nu\bar{\nu}$$

There is an excess from a 2D histogram fit, which corresponds to

$$\mu = [4.2^{+2.9+1.8}_{-2.8-1.6}] \times SM$$

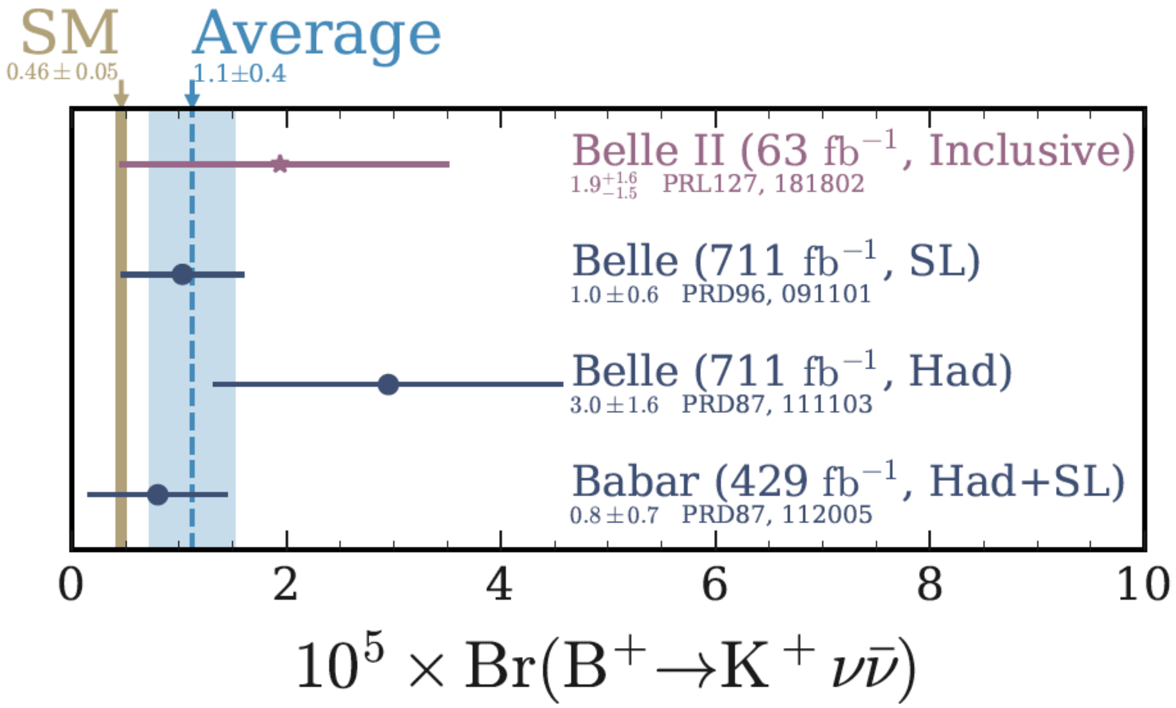
B→K ν νbar: NP without hadronic uncertainties

An emerging anomaly ???

$B \to K\nu\bar{\nu}$

New Technique from Belle II with inclusive ROE (Rest of the Event) tagging.

Phys. Rev. Lett. 127, 181802, (20



Now apply to old Belle and new Belle II data. Stay tuned.

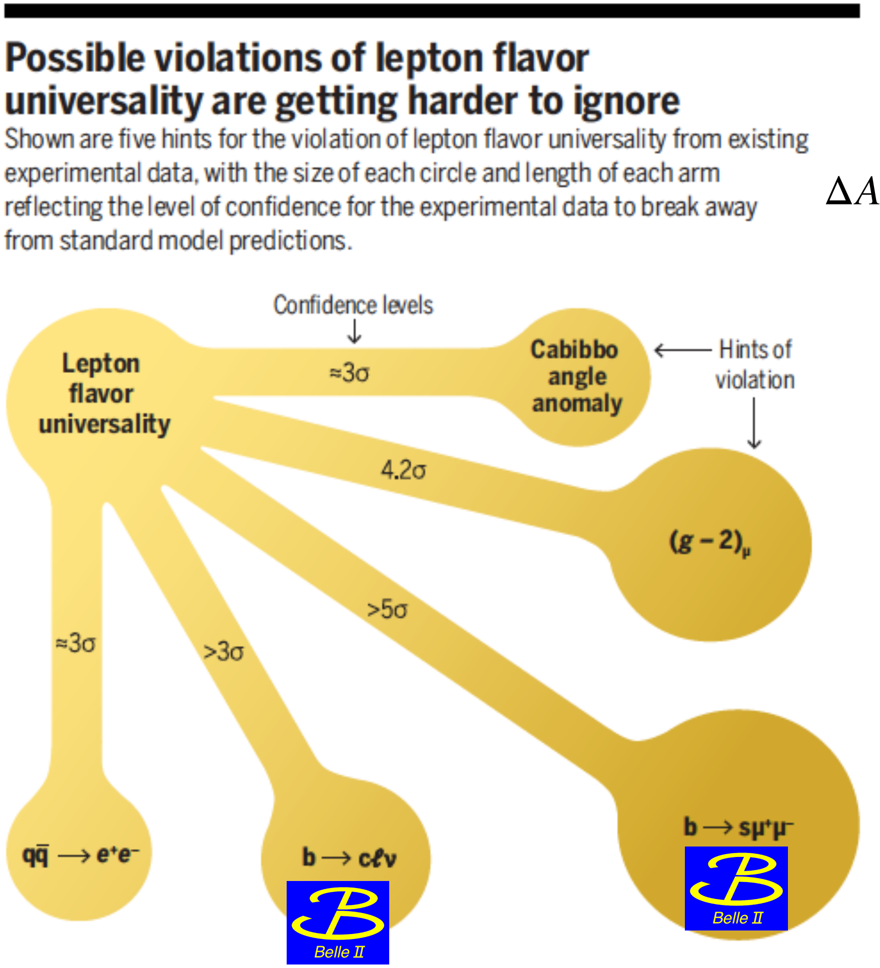
But it is also possible that NP shows up in b→s l+ l- but not in b→s nu nubar or vice-versa

Dark matter could also play a major role.

>>>This is one way that Belle II could discover New Physics soon <<<

More details in this theory preprint (TEB, N. Deshpande, R. Mandal, R. Sinha): https://arxiv.org/abs/2107.01080, published as Phys. Rev. D. 104, 053007 (2021)

Conclusion: Here are some more examples of how Belle II might find New Physics in the coming years.



Possible violations of lepton flavor universality are getting harder to ignore

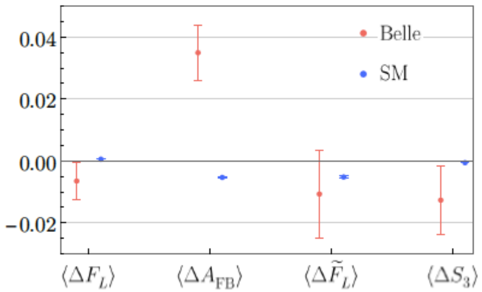
Shown are five hints for the violation of lepton flavor universality from existing experimental data, with the size of each circle and length of each arm reflecting the level of confidence for the experimental data to break away from standard model predictions.

From December 2021 SCIENCE magazine article by A. Crivellin and M. Hoferichter.

Belle II's Strong and Unique Capabilities for New Physics and resolution of HEP Anomalies:

$$\Delta A_{FB}(B \to D^{*+}\ell\nu) = A_{FB}(B \to D^{*+}\mu^-\nu) - A_{FB}(B \to D^{*+}e^-\nu)$$

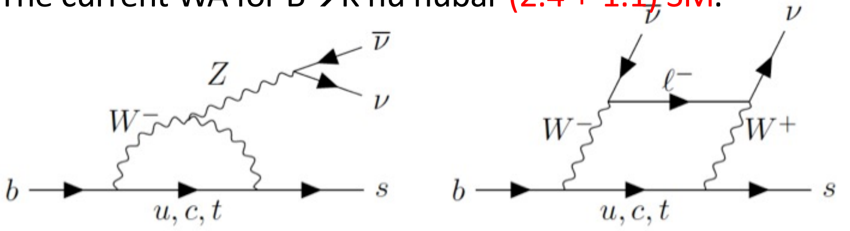
ΔA_{FB} A 4\sigma deviation from the SM is found in Belle data (0.71 ab^{-1})



Eur. Phys. J.C. 81 (2021).

https://arxiv.org/abs/2104.02094

Belle II's unique inclusive and missing energy capabilities.
The current WA for B→K nu nubar (2.4 +-1.1) SM.



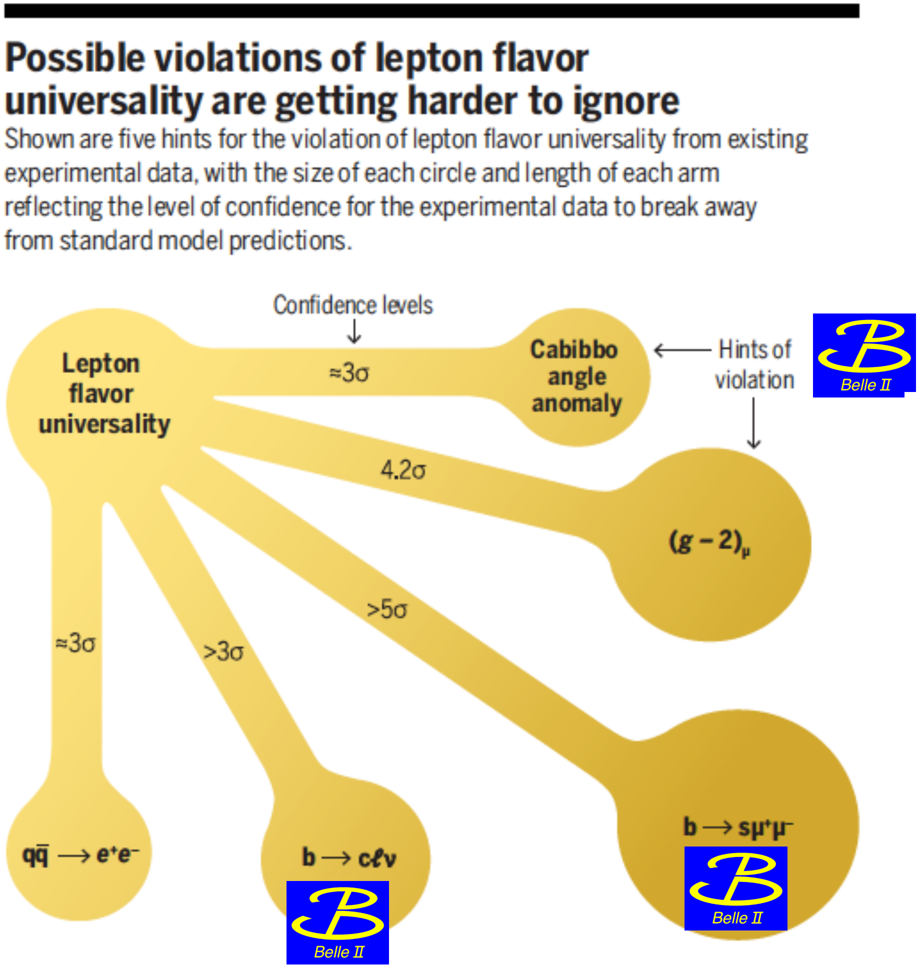
(a) Penguin diagram

(b) Box diagram

Belle II; Phys. Rev. Lett. 127, 181802 (2021)

But these modes require lots of data….”There is no royal road to new physics” (to paraphrase Euclid).

But wait there's more…..



Possible violations of lepton flavor universality are getting harder to ignore

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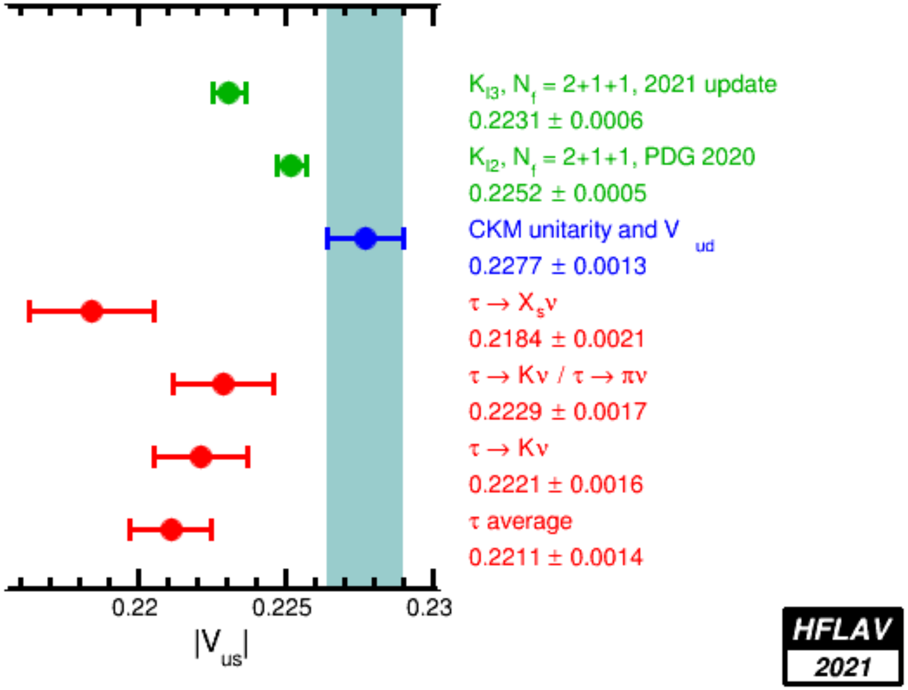
From December 2021 SCIENCE magazine article by A. Crivellin and M. Hoferichter.

A major supporting role of Belle II in the resolution of two more of the other HEP anomalies.

Belle II can contribute to the resolution of the Cabibbo Angle Anomaly (CAA)

There is a ~3σ discrepancy between $|V_{us}|$ measured from tau and kaon semileptonic decays.

Belle II will measure $|V_{us}|$ in inclusive tau decays to high precision



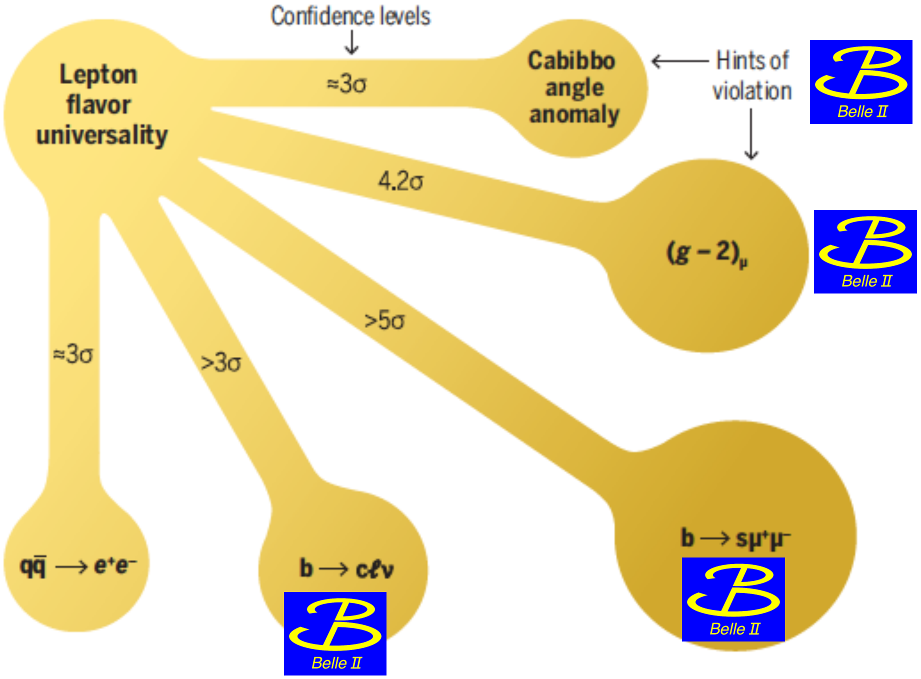
The CAA could be another hint of lepton flavor universality violation

+But wait there's more…..

Belle II can contribute to g-2

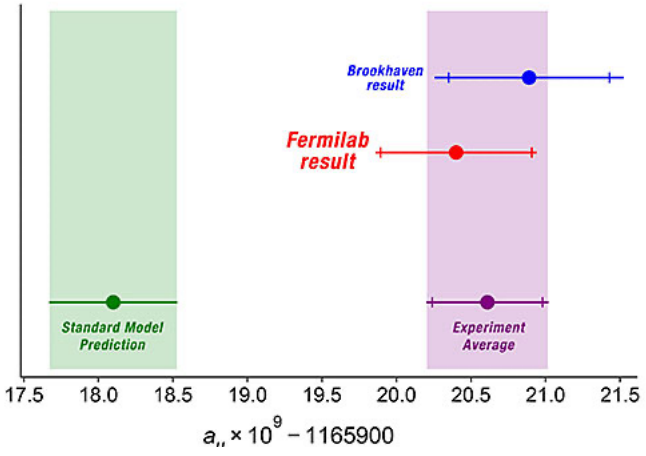
Possible violations of lepton flavor universality are getting harder to ignore

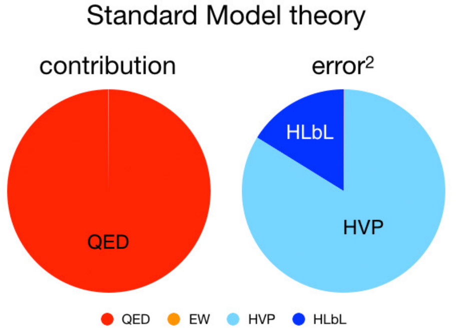
Shown are five hints for the violation of lepton flavor universality from existing experimental data, with the size of each circle and length of each arm reflecting the level of confidence for the experimental data to break away from standard model predictions.



From December 2021 SCIENCE magazine article by A. Crivellin and M. Hoferichter.

A major supporting role of Belle II in the resolution of two more of the other major HEP anomalies





KLOE and BaBar data disagree

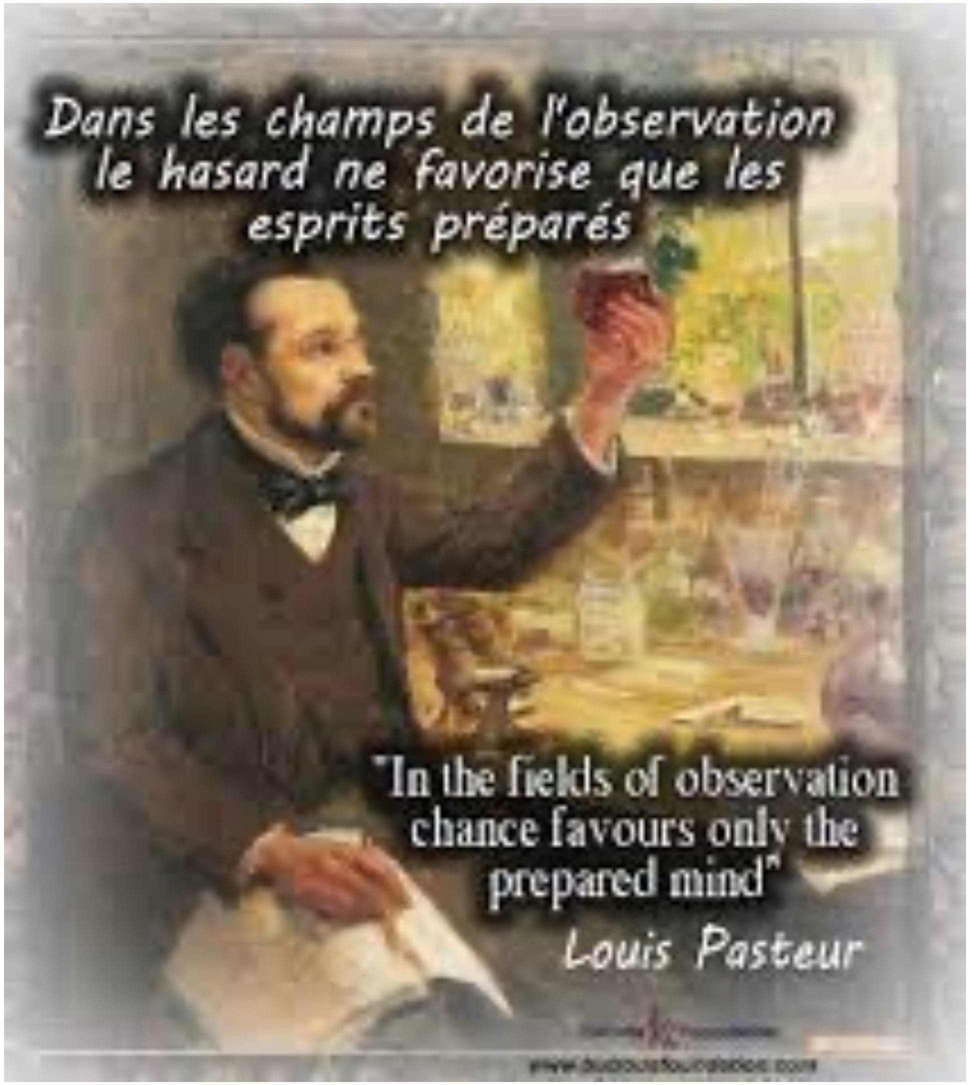
Belle II can measure the cross-section for $e^+e^- \to \pi\pi$ vs sqrt(s) and reduce the hadronic vacuum polarization error in g-2 (dominant theory uncertainty). This could help to determine whether there is really New Physics in g-2 (muon).

New Physics Opportunities

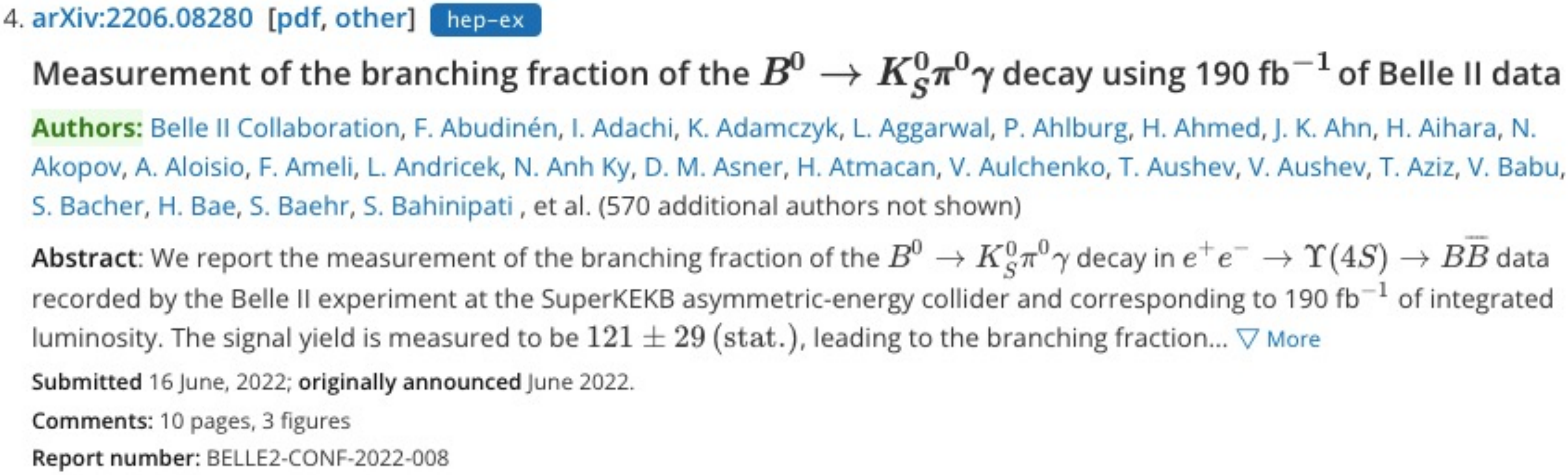
Belle II Executive Summary for Snowmass
https://arxiv.org/abs/2203.10203

- Apologies for only covering a small range of possibilities.
- Leverage Belle II's unique photon, electron, π^0, missing energy capabilities for rare B decays. From Snowmass: *Use Δ Observables to find LFU violation in angular asymmetries (ideally suited for Belle II at high luminosity).*
- A number of b→s and b→c processes have hints of NP. (New: pay attention to B→K ν vbar as new data comes in, Belle II has demonstrated improved sensitivity). Along with B→$D^{(*)} \tau \nu$ and $D^{(*)} l \nu$ (b→c), the *anomalies* will be studied in detail at Belle II in the near future.
- *A lot to learn at this workshop to allow you to make the next round of discoveries. Belle II has strong and unique capabilities for New Physics discoveries and resolution of the major high energy physics anomalies (and not just B physics).*

Backup slides



More Belle II Superpowers



4. arXiv:2206.08280 [pdf, other] hep-ex

Measurement of the branching fraction of the $B^0 \to K^0_S\pi^0\gamma$ decay using 190 fb^{-1} of Belle II data

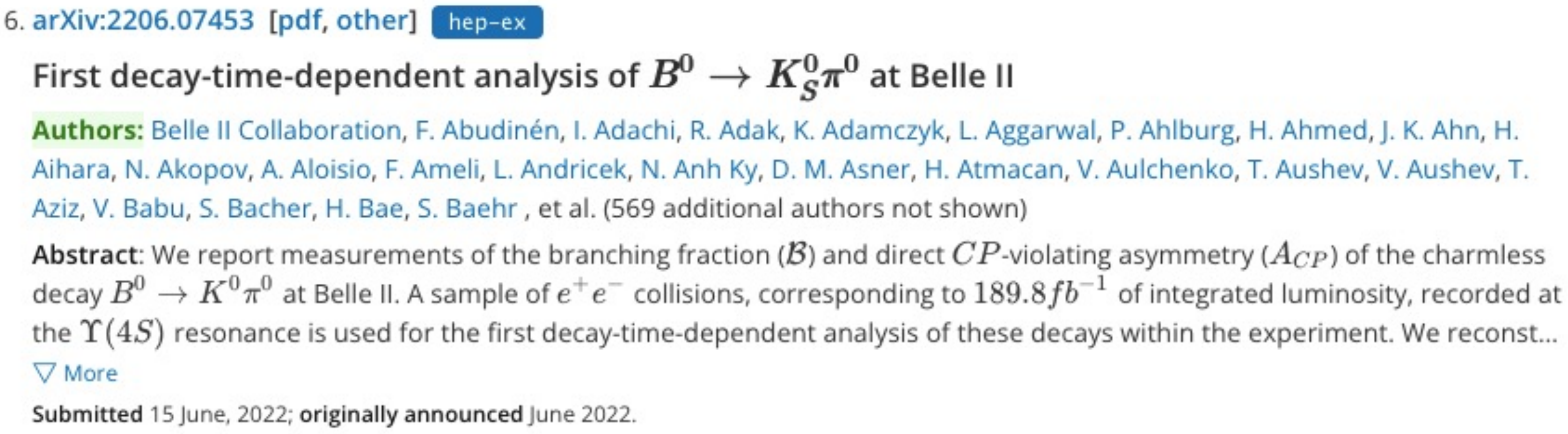
Authors: Belle II Collaboration, F. Abudinén, I. Adachi, K. Adamczyk, L. Aggarwal, P. Ahlburg, H. Ahmed, J. K. Ahn, H. Aihara, N. Akopov, A. Aloisio, F. Ameli, L. Andricek, N. Anh Ky, D. M. Asner, H. Atmacan, V. Aulchenko, T. Aushev, V. Aushev, T. Aziz, V. Babu, S. Bacher, H. Bae, S. Baehr, S. Bahinipati , et al. (570 additional authors not shown)

Abstract: We report the measurement of the branching fraction of the $B^0 \to K^0_S\pi^0\gamma$ decay in $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ data recorded by the Belle II experiment at the SuperKEKB asymmetric-energy collider and corresponding to 190 fb^{-1} of integrated luminosity. The signal yield is measured to be $121 \pm 29\,(\mathrm{stat.})$, leading to the branching fraction... ▽ More

Submitted 16 June, 2022; **originally announced** June 2022.

Comments: 10 pages, 3 figures

Report number: BELLE2-CONF-2022-008



6. arXiv:2206.07453 [pdf, other] hep-ex

First decay-time-dependent analysis of $B^0 \to K^0_S\pi^0$ at Belle II

Authors: Belle II Collaboration, F. Abudinén, I. Adachi, R. Adak, K. Adamczyk, L. Aggarwal, P. Ahlburg, H. Ahmed, J. K. Ahn, H. Aihara, N. Akopov, A. Aloisio, F. Ameli, L. Andricek, N. Anh Ky, D. M. Asner, H. Atmacan, V. Aulchenko, T. Aushev, V. Aushev, T. Aziz, V. Babu, S. Bacher, H. Bae, S. Baehr , et al. (569 additional authors not shown)

Abstract: We report measurements of the branching fraction ($\mathcal{B}$) and direct CP-violating asymmetry (A_{CP}) of the charmless decay $B^0 \to K^0\pi^0$ at Belle II. A sample of e^+e^- collisions, corresponding to $189.8 fb^{-1}$ of integrated luminosity, recorded at the $\Upsilon(4S)$ resonance is used for the first decay-time-dependent analysis of these decays within the experiment. We reconst... ▽ More

Submitted 15 June, 2022; **originally announced** June 2022.

B→K ν vbar: NP *without* hadronic uncertainties !

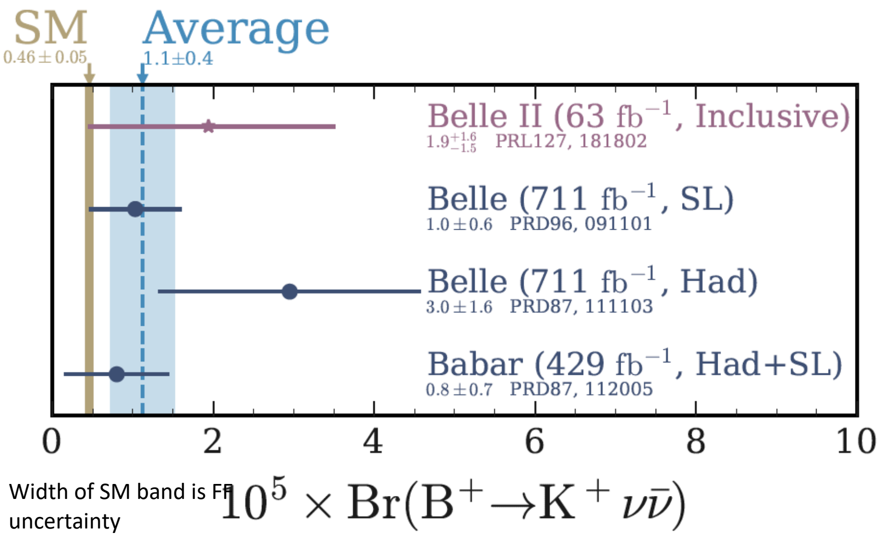
4% experimental error on B→K^* ν *vbar with Belle II@250 ab*$^{-1}$

$$B \to K\nu\bar{\nu}$$

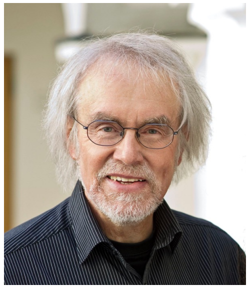
New Technique from Belle II with inclusive ROE (Rest of the Event) tagging improves sensitivity.

Phys. Rev. Lett. 127, 181802, (2021

An emerging anomaly ???



Width of SM band is FF uncertainty



Andrezj
Buras

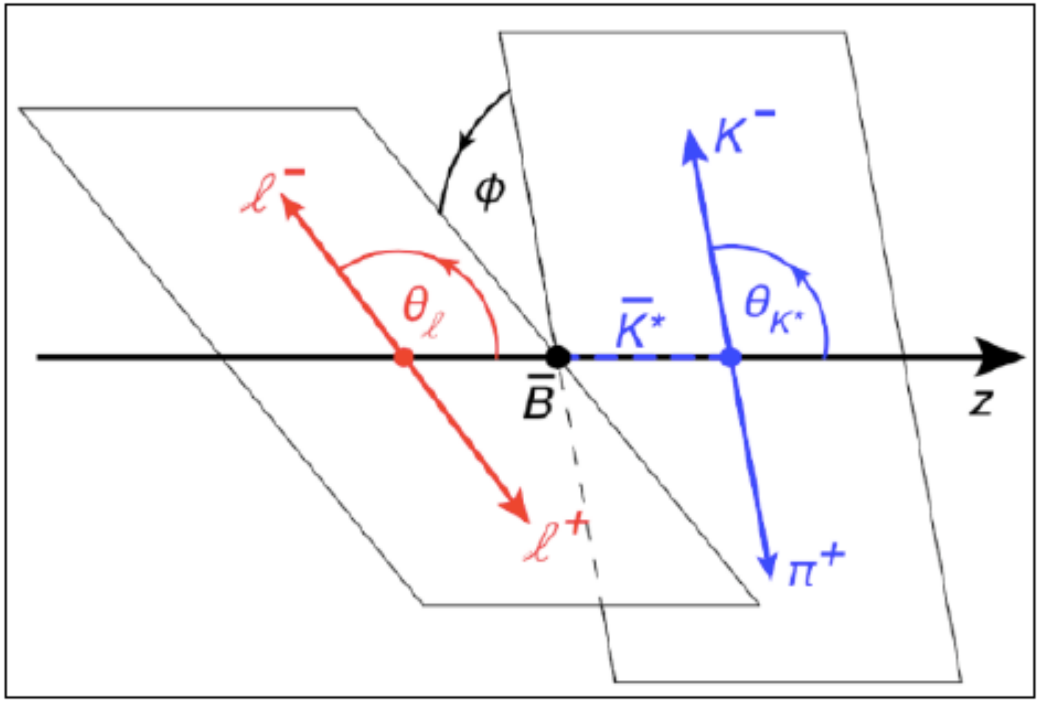
“Note there are
no charm loops here”-
Wolfgang A.

But it is also possible that NP shows up only in b→s l+ l- but not in b→s nu nubar or vice-versa. The two classes of EWPs are related but distinct.

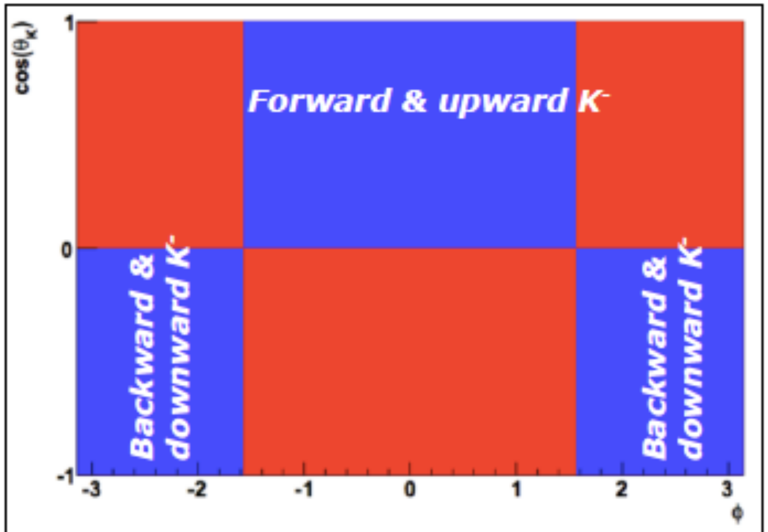
This is one way that Belle II could discover New Physics soon. For example: https://arxiv.org/abs/2107.01080, Phys. Rev. D. 104, 053007 (2021)

Dark matter could also play a major role.

Angular asymmetries



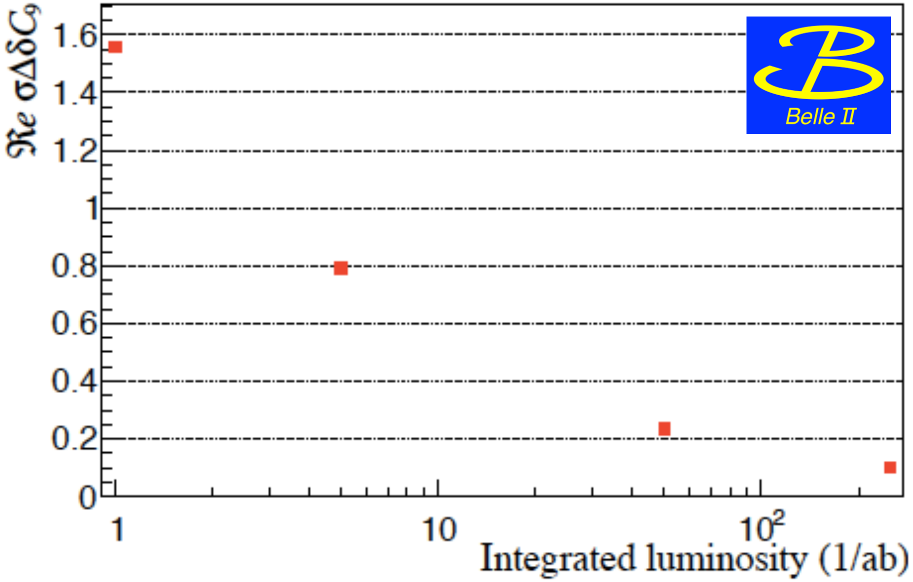
P_5':

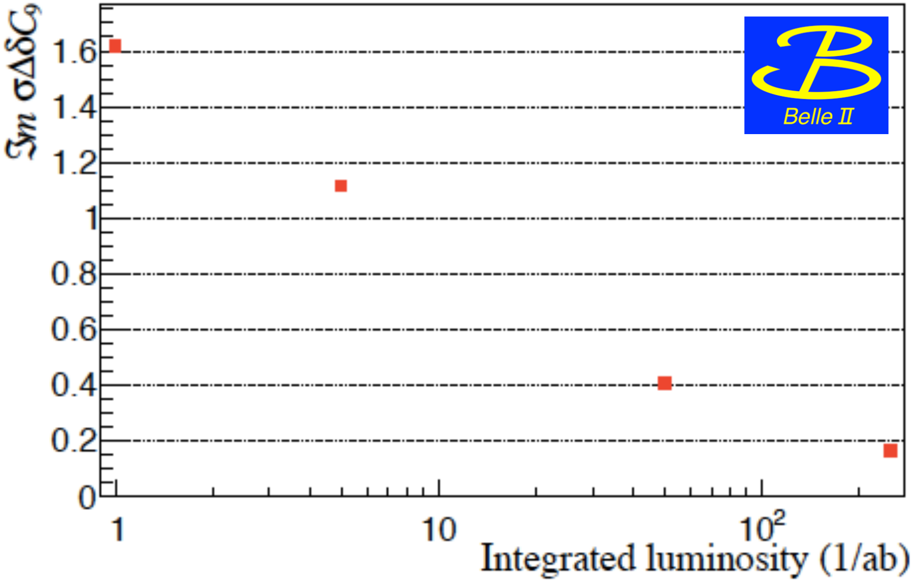


Counting S_5: blue minus red

Snowmass Bullet Point:

Use the Δ Observables in $B\to K^*\ l^+\ l^-$ to discover New Physics at Belle II without QCD and hadronic uncertainties.

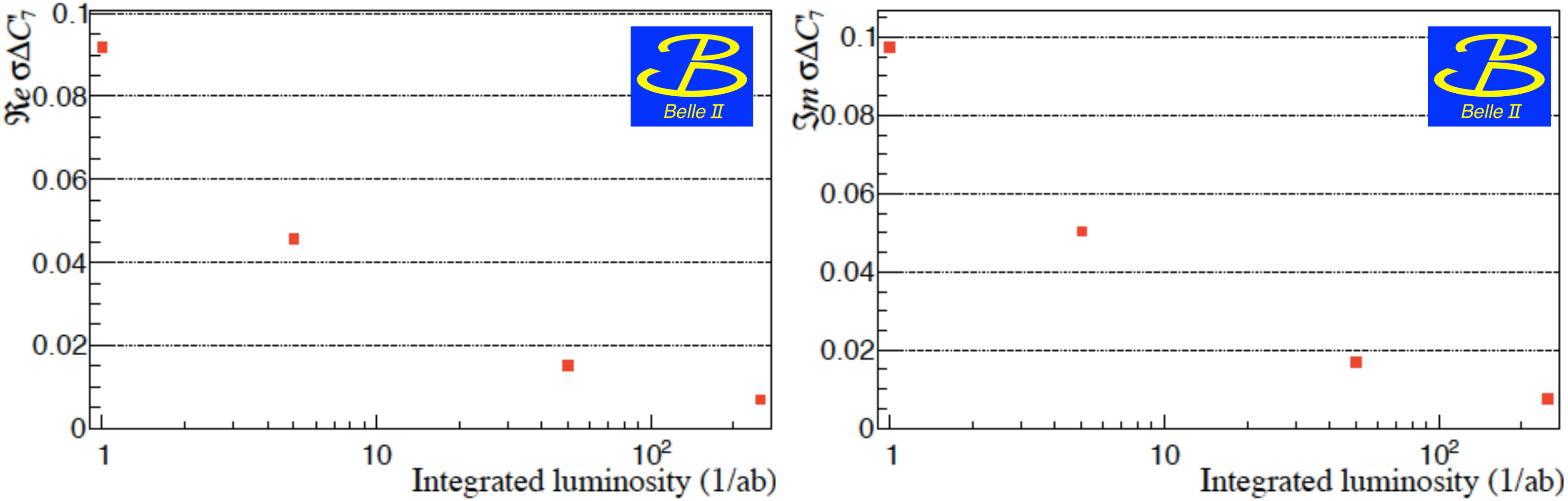




A. Sibidanov et al., https://arxiv.org/abs/2203.07189

Belle II Sensitivity to NP Right-Handed Currents, (C_7')

A. Sibidanov et al., https://arxiv.org/abs/2203.07189



Snowmass Bullet Point:

Use the Δ Observables in $B \rightarrow K^* \, l^+ l^-$ to discover New Physics at Belle II without QCD and hadronic uncertainties.

FAQ: How do Belle II at KEK and LHCb at CERN capabilities compare ?

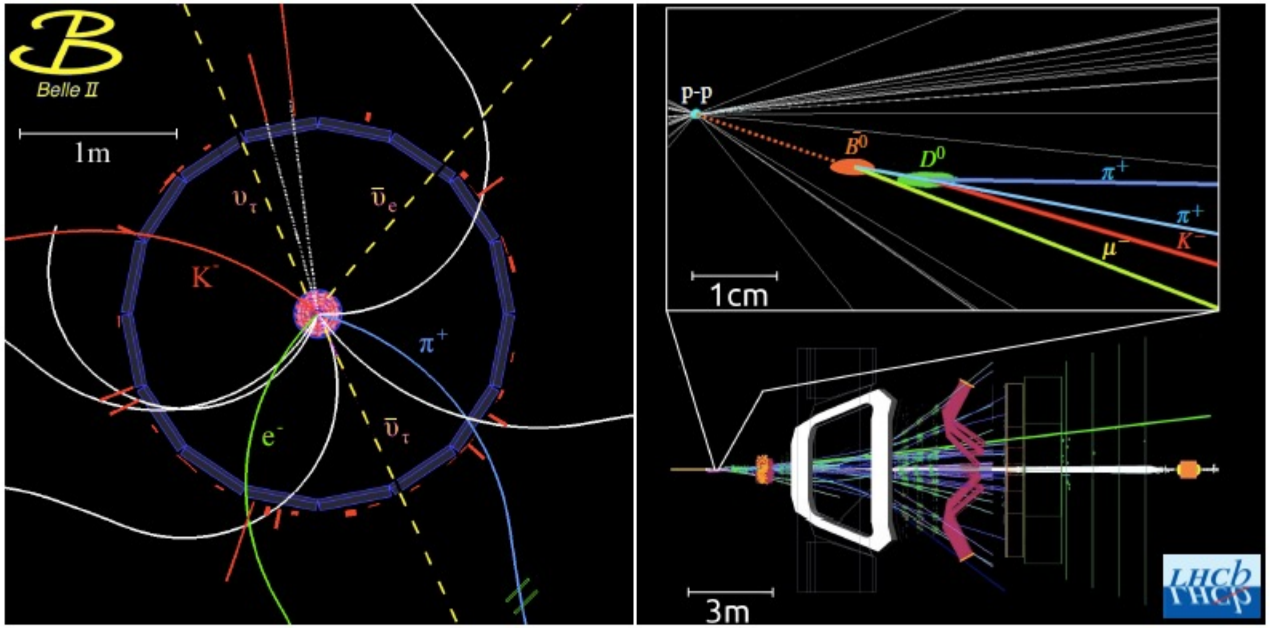


Figure credit:
G. Ciezarak et al,
Nature
546, 227 (2017)

++Belle II can do the dark sector

1. LHCB has a large b bbar cross-section (hundreds of microbarns versus nanobarns) and good sensitivity, signal to background, for modes with dimuons, and all charged final states using vertexing. Triggering and flavor tagging effs. are much lower than in e+e-.

2. Belle II has a simple and clean event environment with B^0 -anti B^0 pairs produced in *a coherent QM state with no additional particles*.

3. Belle II can measure inclusive processes

4. Belle II can measure electrons just as well as muons. (important for lepton universality checks).

5. Belle II can measure final states with γ's, Kshorts and missing neutrinos *well.*

Rule of thumb for statistics in this case:
1 fb^{-1} at LHCb is 1 ab^{-1} at Belle II.
(➔Need good SuperKEKB performance and long runs in the coming years)

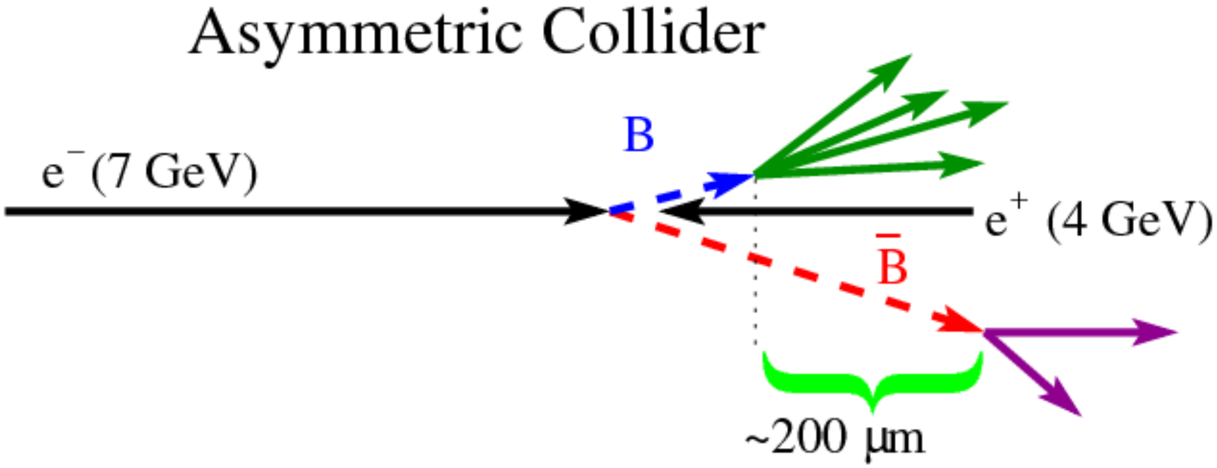
The B^0-anti B^0 meson pairs at the Upsilon(4S) are produced in a coherent, *entangled* **quantum mechanical state**.

(Exercise: why is there a minus sign ?)

$$|\Psi>=|B^0(t_1,f_1)\overline{B^0}(t_2,f_2)>-|B^0(t_2,f_2)\overline{B^0}(t_1,f_1)>$$

Need to measure decay times to observe CP violation (particle-antiparticle asymmetry).

One B decays →collapses the flavor wavefunction of the other anti-B. (N.B. One B must decay before the other can mix) [*exercise: explain*]

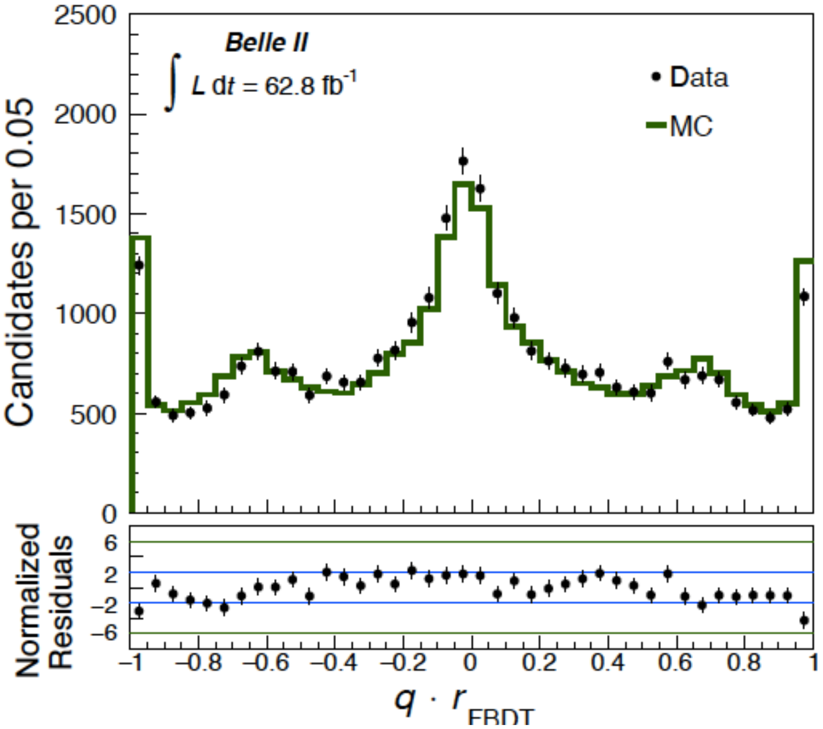


Not to scale

The beam energies are asymmetric (7 on 4 GeV)

The decay distance is increased by around a factor ~7

2021 update: Flavor Tagging (b quark or anti-b quark ?)



Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	l^-
Intermediate Kinetic Lepton	l^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum P*	l^-, π^-
Fast-Slow-Correlated (FSC)	l^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

$\overline{B}^0 \to D^{*+}\,\overline{\nu}_\ell\,\ell^-$
$\hookrightarrow D^0\,\pi^+$
$\hookrightarrow X\,K^-$

$\overline{B}^0 \to D^+\,\pi^-\,(K^-)$
$\hookrightarrow K^0\,\nu_\ell\,\ell^+$

$\overline{B}^0 \to \Lambda_c^+\,X^-$
$\hookrightarrow \Lambda\,\pi^+$
$\hookrightarrow p\,\pi^-$

Time-independent method with 62.8 fb^{-1}

	$\varepsilon_{\mathrm{eff},i} \pm \delta\varepsilon_{\mathrm{eff},i}$		
r- Interval	FBDT	DNN	Belle
0.000 – 0.100	0.1 ± 0.1	0.0 ± 0.1	0.0
0.100 – 0.250	0.5 ± 0.2	0.3 ± 0.1	0.4 ± 0.1
0.250 – 0.500	3.3 ± 0.5	2.3 ± 0.4	2.3 ± 0.1
0.500 – 0.625	3.3 ± 0.5	4.2 ± 0.5	3.5 ± 0.1
0.625 – 0.750	6.1 ± 0.6	3.8 ± 0.5	4.6 ± 0.2
0.750 – 0.875	5.4 ± 0.5	5.9 ± 0.6	5.5 ± 0.1
0.875 – 1.000	11.3 ± 0.6	12.3 ± 0.7	13.8 ± 0.3
Total	30.0 ± 1.3	28.8 ± 1.3	30.1 ± 0.4

So far, the fast BDT does better than deep learning neural net.

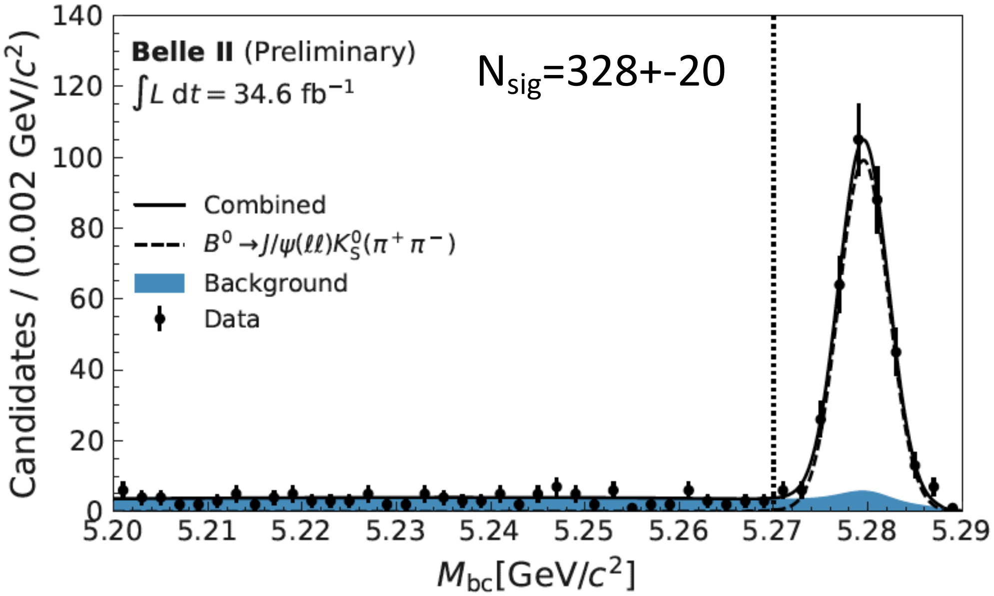
We obtain epsilon_eff = epsilon(1-2 w)^2 = 30.0+-1.2+-0.4 %, which is similar to the Belle result of 30.1+-0.4%

https://arxiv.org/abs/2008.02707, submitted to EPJC

Observation of B→J/ψ K_S and the road to CPV

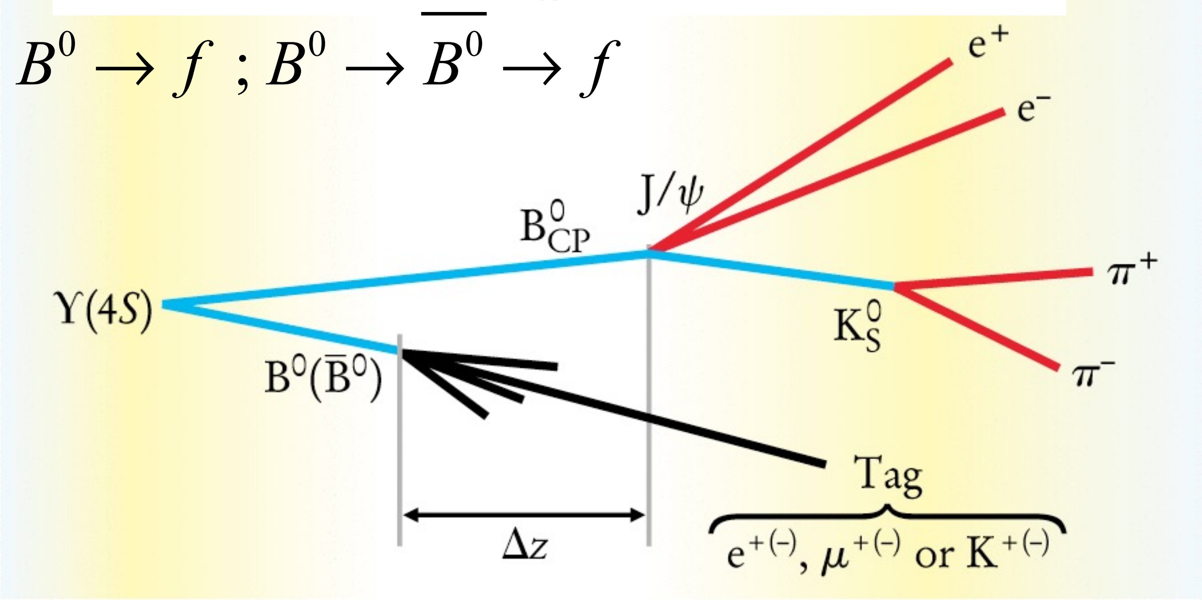
A “Golden” CP Eigenstate

Test with 17% of the Phase 3 data sample.



Now apply a *simplified analysis:*

1) Only one CP eigenstate
2) No beam spot constraint
3) Flavor tagging does not separate r-bins



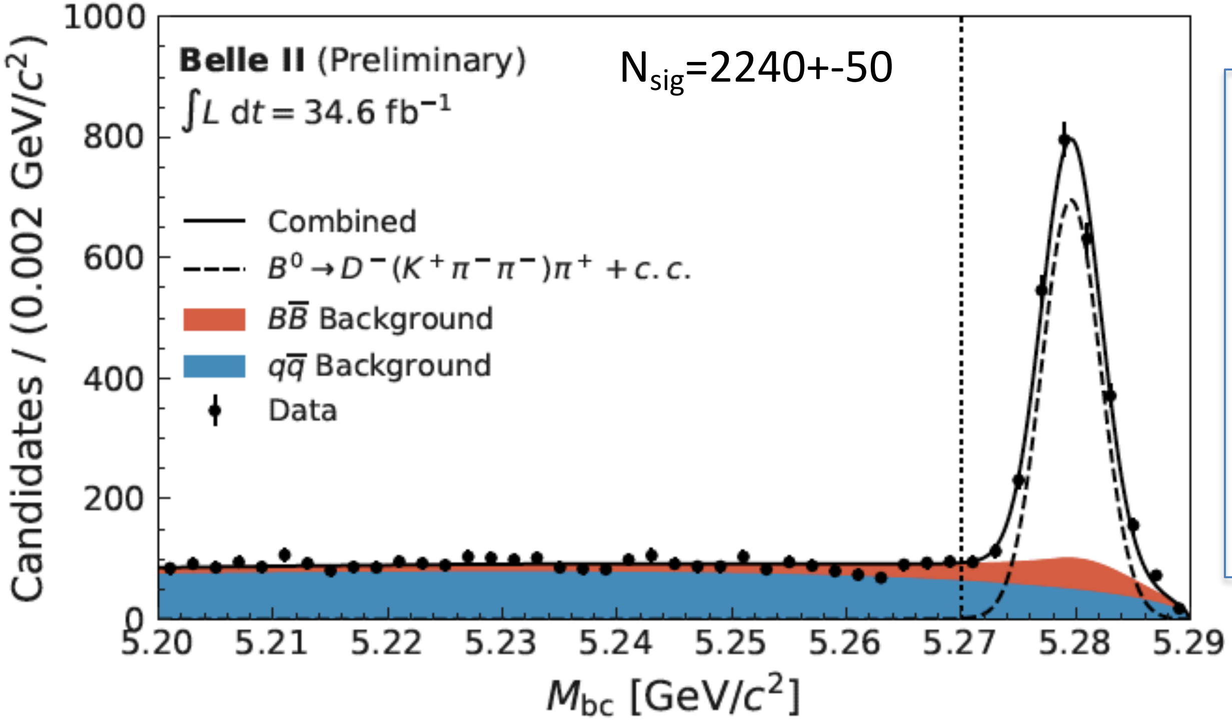
$$B^0 \to f\ ;\ B^0 \to \overline{B^0} \to f$$

$$\Delta t \approx \frac{\Delta z}{\beta\gamma}$$

Figure credit: Physics Today

This is a flavor-specific B decay mode with a charged track topology similar to the B→J/ψ K_S signal.

B^0→$D^- \pi^+$ is not self-conjugate and is not a CP eigenstate (but can be used to check time-dependence of B-Bbar mixing).

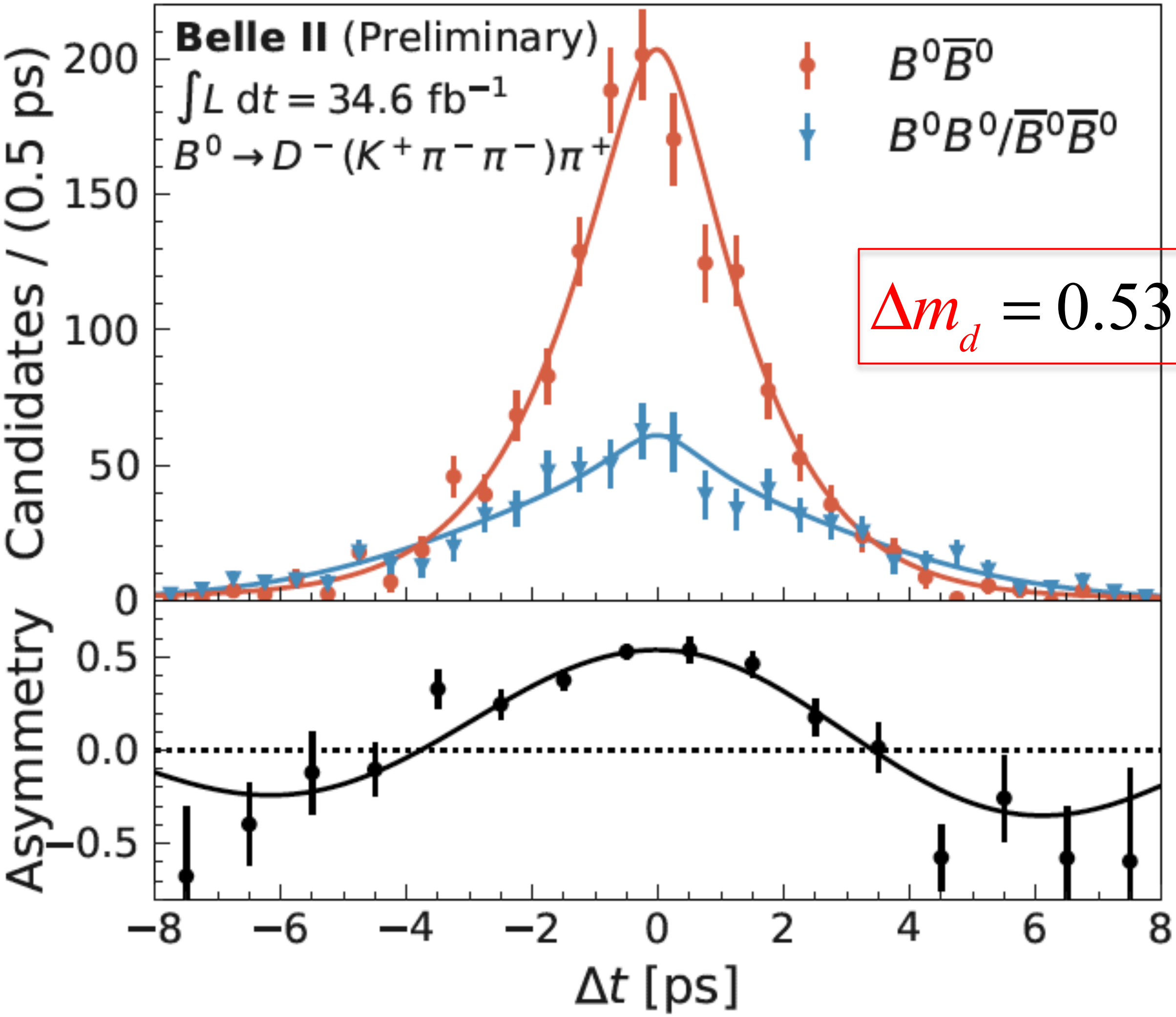


Start with a B^0 (wait a while, ~a few x 10^{-12} sec).

There is a large probability that the B^0 will turn into its anti-particle, an anti-B^0 (discovered by ARGUS at DESY in 1987)

The variable on the x-axis is beam-constrained mass (CM energy/2 or beam energy is used instead of reconstructed energy

Time Dependent Mixing asymmetry (not CPV)



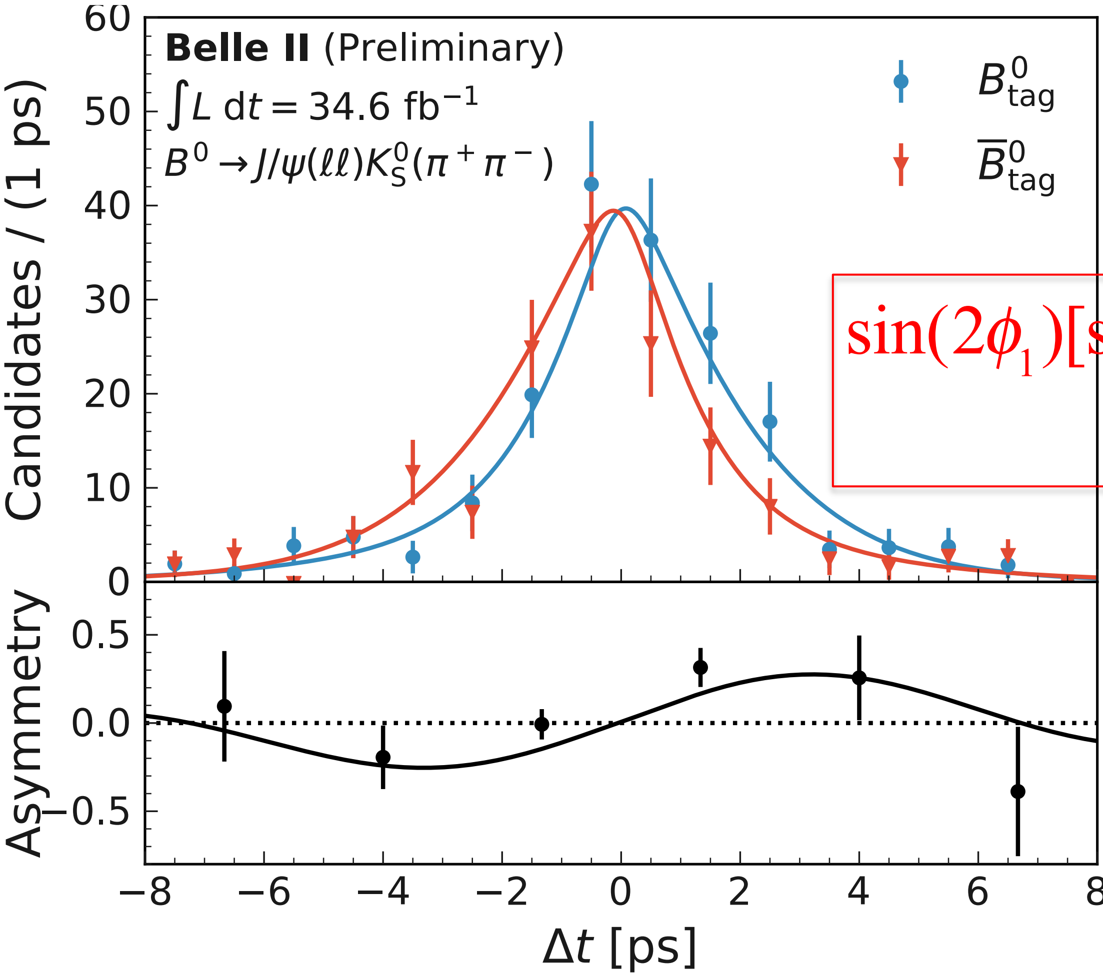
$$\boxed{\Delta m_d = 0.531 \pm 0.046 \pm 0.013\, ps^{-1}}$$

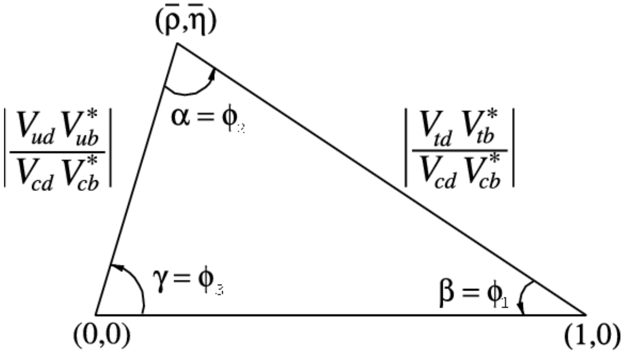
(WA=0.5065 ±0.019 ps^{-1})

$$Asym(mixing) = \frac{OF - SF}{OF + SF}$$

$$N_{SF/OF} \sim \frac{\exp(-|\Delta t|/\tau)}{4\tau}[1 \pm (1-2w)\cos(\Delta m_d \Delta t)] \otimes R(\Delta t)$$

Hint of time-dependent CPV from Belle II (2.7σ significance)





$$\sin(2\phi_1)[\sin(2\beta)] = 0.55 \pm 0.21 \pm 0.04$$

(WA=0.685±0.019)

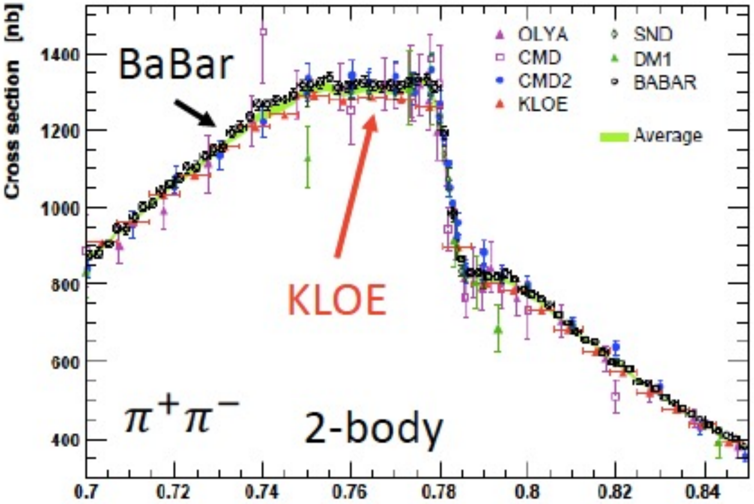
Based on the QM interference of

$$B^0 \to f_{CP}\ ;\ B^0 \to \overline{B^0} \to f_{CP}$$

Expect updates in summer 2022 (x6 more data)

$$N_{+/-} \sim \frac{\exp(-|\Delta t|/\tau)}{4\tau}\left\{1 \pm (1-2w)\sin(2\phi_1)\sin(\Delta m_d \Delta t)\right\} \otimes R(\Delta t)$$

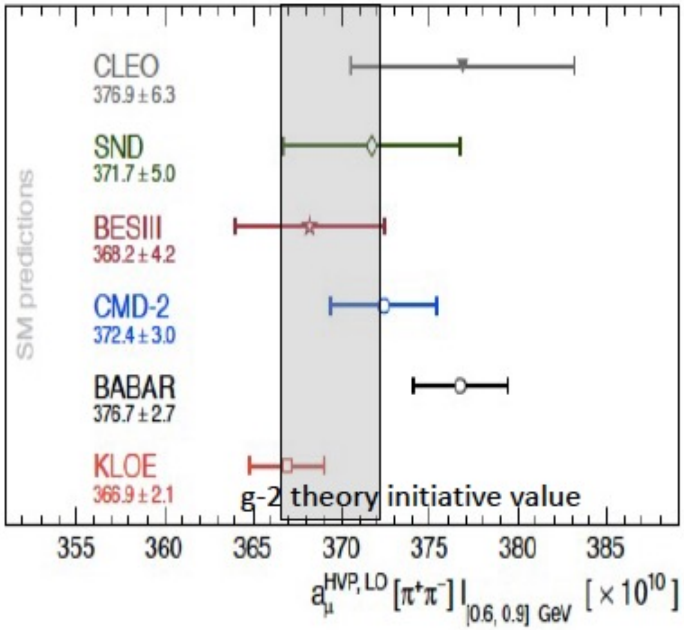
Gold Standard: $e^+e^- \rightarrow hadrons$



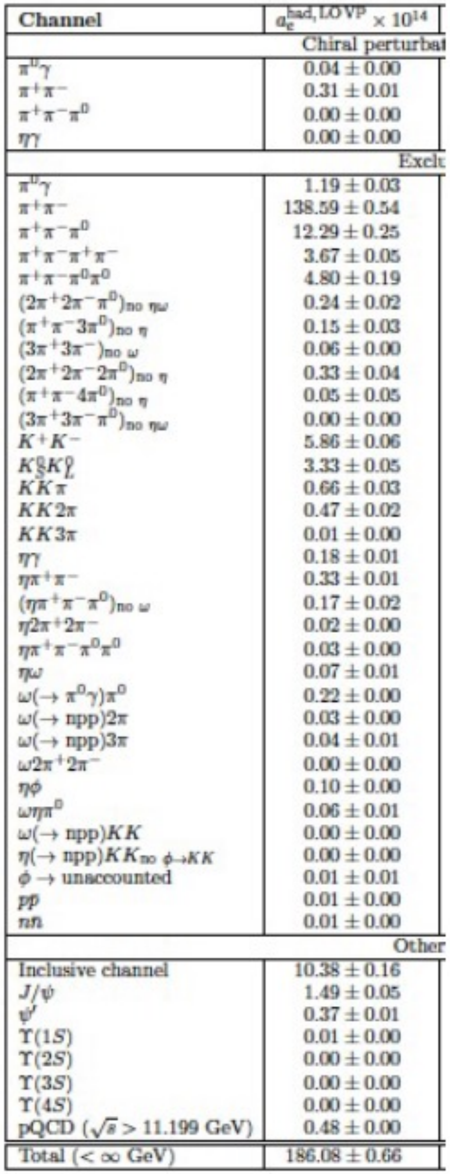
BaBar

KLOE

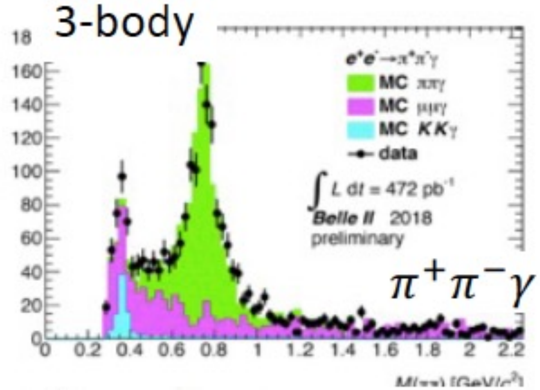
$\pi^+\pi^-$ 2-body



g-2 theory initiative value

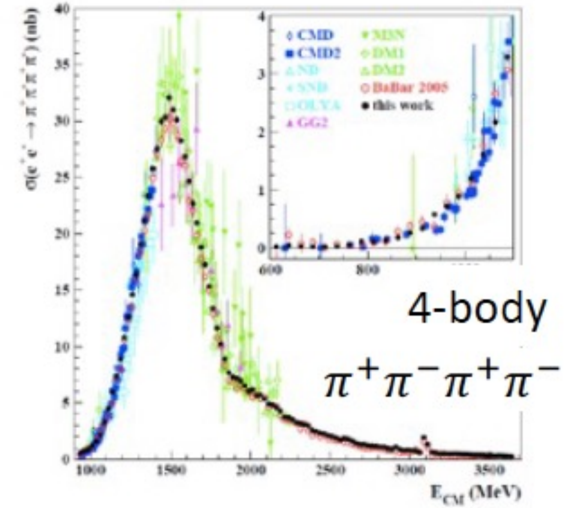


Channel	$a_e^{\mathrm{had,LOVP}} \times 10^{14}$
	Chiral perturbat
$\pi^0\gamma$	0.04 ± 0.00
$\pi^+\pi^-$	0.31 ± 0.01
$\pi^+\pi^-\pi^0$	0.00 ± 0.00
$\eta\gamma$	0.00 ± 0.00
	Exclu
$\pi^0\gamma$	1.19 ± 0.03
$\pi^+\pi^-$	138.59 ± 0.54
$\pi^+\pi^-\pi^0$	12.29 ± 0.25
$\pi^+\pi^-\pi^+\pi^-$	3.67 ± 0.05
$\pi^+\pi^-\pi^0\pi^0$	4.80 ± 0.19
$(2\pi^+2\pi^-\pi^0)_{\mathrm{no}\ \eta\omega}$	0.24 ± 0.02
$(\pi^+\pi^-3\pi^0)_{\mathrm{no}\ \eta}$	0.15 ± 0.03
$(3\pi^+3\pi^-)_{\mathrm{no}\ \omega}$	0.06 ± 0.00
$(2\pi^+2\pi^-2\pi^0)_{\mathrm{no}\ \eta}$	0.33 ± 0.04
$(\pi^+\pi^-4\pi^0)_{\mathrm{no}\ \eta}$	0.05 ± 0.05
$(3\pi^+3\pi^-\pi^0)_{\mathrm{no}\ \eta\omega}$	0.00 ± 0.00
K^+K^-	5.86 ± 0.06
$K^0_S K^0_L$	3.33 ± 0.05
$KK\pi$	0.66 ± 0.03
$KK2\pi$	0.47 ± 0.02
$KK3\pi$	0.01 ± 0.00
$\eta\gamma$	0.18 ± 0.01
$\eta\pi^+\pi^-$	0.33 ± 0.01
$(\eta\pi^+\pi^-\pi^0)_{\mathrm{no}\ \omega}$	0.17 ± 0.02
$\eta 2\pi^+2\pi^-$	0.02 ± 0.00
$\eta\pi^+\pi^-\pi^0\pi^0$	0.03 ± 0.00
$\eta\omega$	0.07 ± 0.01
$\omega(\rightarrow \pi^0\gamma)\pi^0$	0.22 ± 0.00
$\omega(\rightarrow \mathrm{npp})2\pi$	0.03 ± 0.00
$\omega(\rightarrow \mathrm{npp})3\pi$	0.04 ± 0.01
$\omega 2\pi^+2\pi^-$	0.00 ± 0.00
$\eta\phi$	0.10 ± 0.00
$\omega\eta\pi^0$	0.06 ± 0.01
$\omega(\rightarrow \mathrm{npp})KK$	0.00 ± 0.00
$\eta(\rightarrow \mathrm{npp})KK_{\mathrm{no}\ \phi\rightarrow KK}$	0.00 ± 0.00
$\phi \rightarrow$ unaccounted	0.01 ± 0.01
$p\bar{p}$	0.01 ± 0.00
$n\bar{n}$	0.01 ± 0.00
	Other
Inclusive channel	10.38 ± 0.16
J/ψ	1.49 ± 0.05
ψ'	0.37 ± 0.01
$\Upsilon(1S)$	0.01 ± 0.00
$\Upsilon(2S)$	0.00 ± 0.00
$\Upsilon(3S)$	0.00 ± 0.00
$\Upsilon(4S)$	0.00 ± 0.00
pQCD ($\sqrt{s} > 11.199$ GeV)	0.48 ± 0.00
Total ($< \infty$ GeV)	186.08 ± 0.66



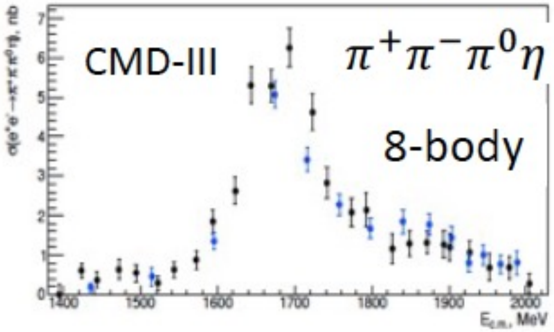
3-body

$\pi^+\pi^-\gamma$



4-body

$\pi^+\pi^-\pi^+\pi^-$

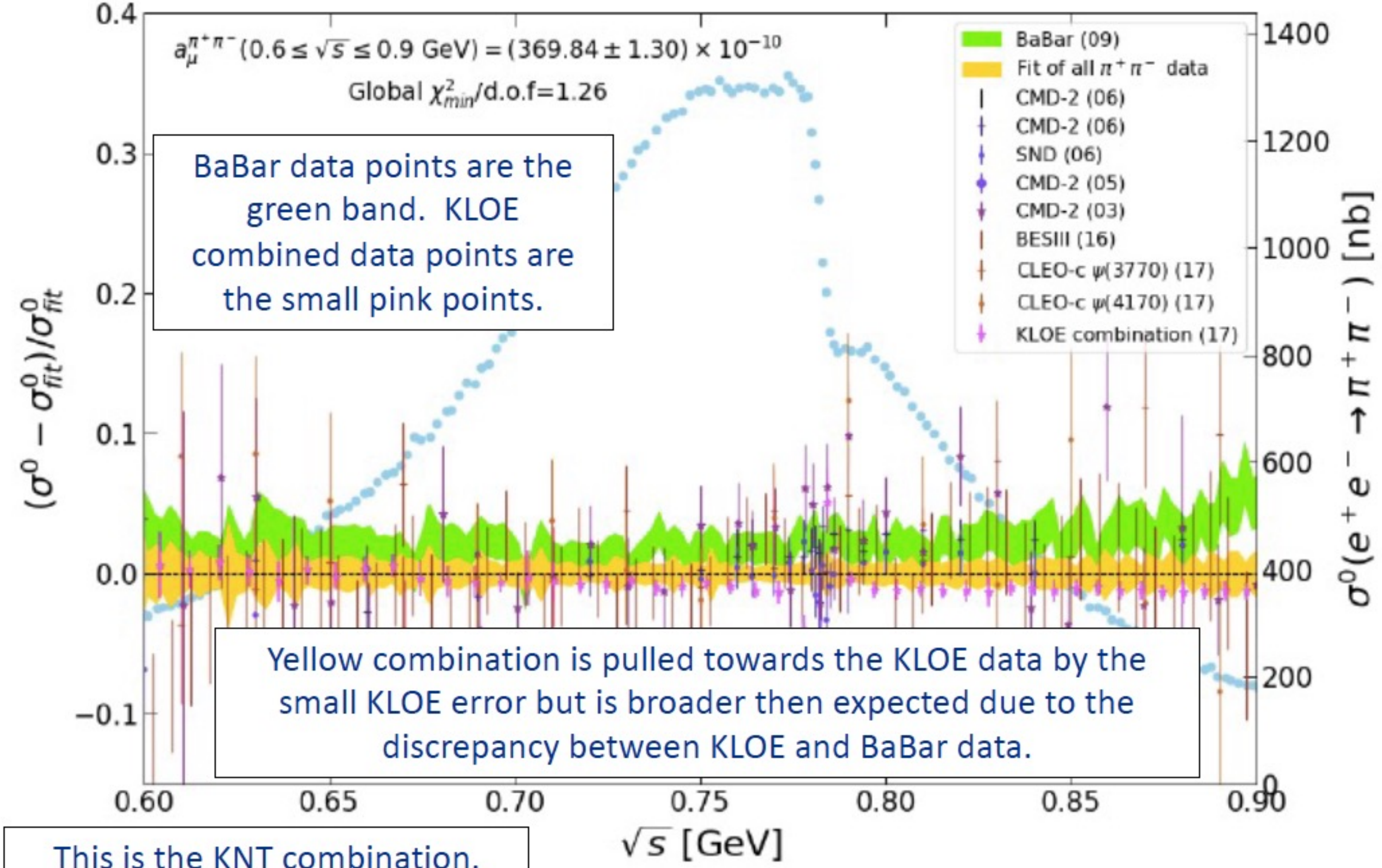


CMD-III

$\pi^+\pi^-\pi^0\eta$

8-body

$e^+e^- \rightarrow \pi^+\pi^-$

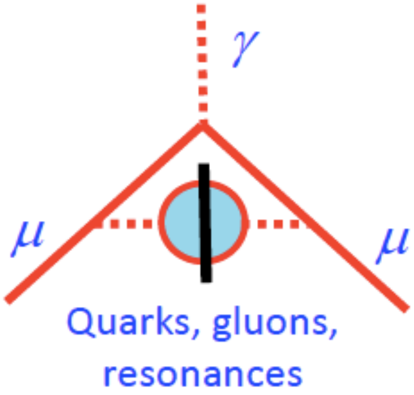


BaBar data points are the green band. KLOE combined data points are the small pink points.

Yellow combination is pulled towards the KLOE data by the small KLOE error but is broader then expected due to the discrepancy between KLOE and BaBar data.

This is the KNT combination. The white paper combination has about a 60% boarder error.

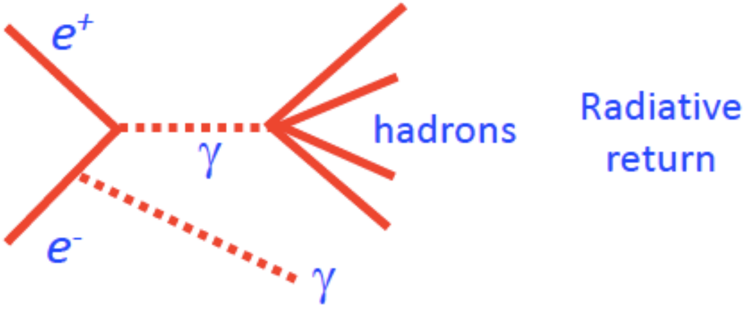
Leading order QCD: HVP



The leading order QCD contribution comes from Hadronic Vacuum Polarization

This can be taken directly from data by the measurement of the differential cross section $e^+e^- \rightarrow hadrons$.

The assumptions are analyticity and the optical theorem.



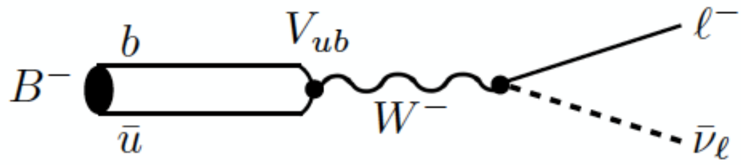
This is considered the gold standard and the Muon g-2 Theory initiative only uses this data in their prediction.

The $^1/_s$ scaling puts significant weight to the two-pion low energy region around the ρ and ω but data from all regions and all final states needs to be included.

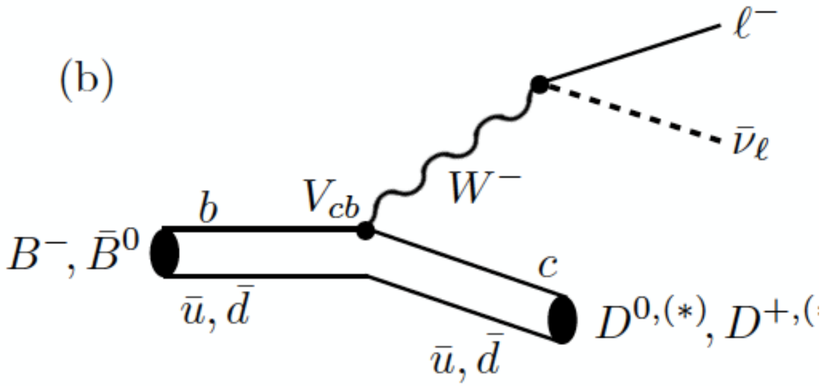
$$\frac{g-2}{2}HVP = \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}R(s)K_l(s)$$

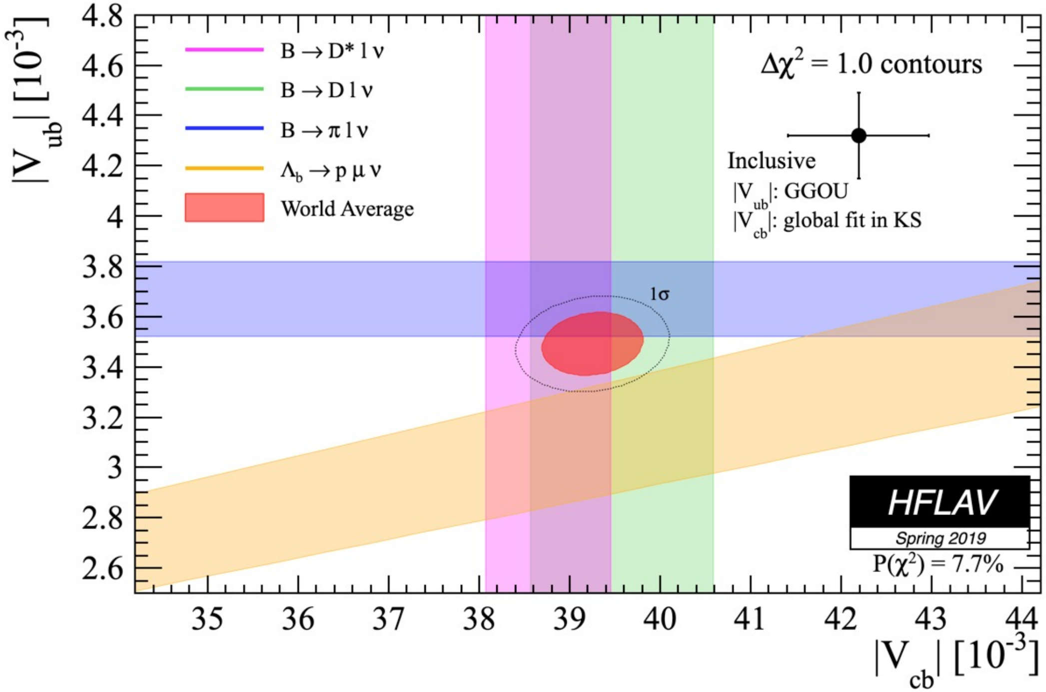
Motivation for semileptonic decays: V_{cb} , V_{ub}

(a)



(b)





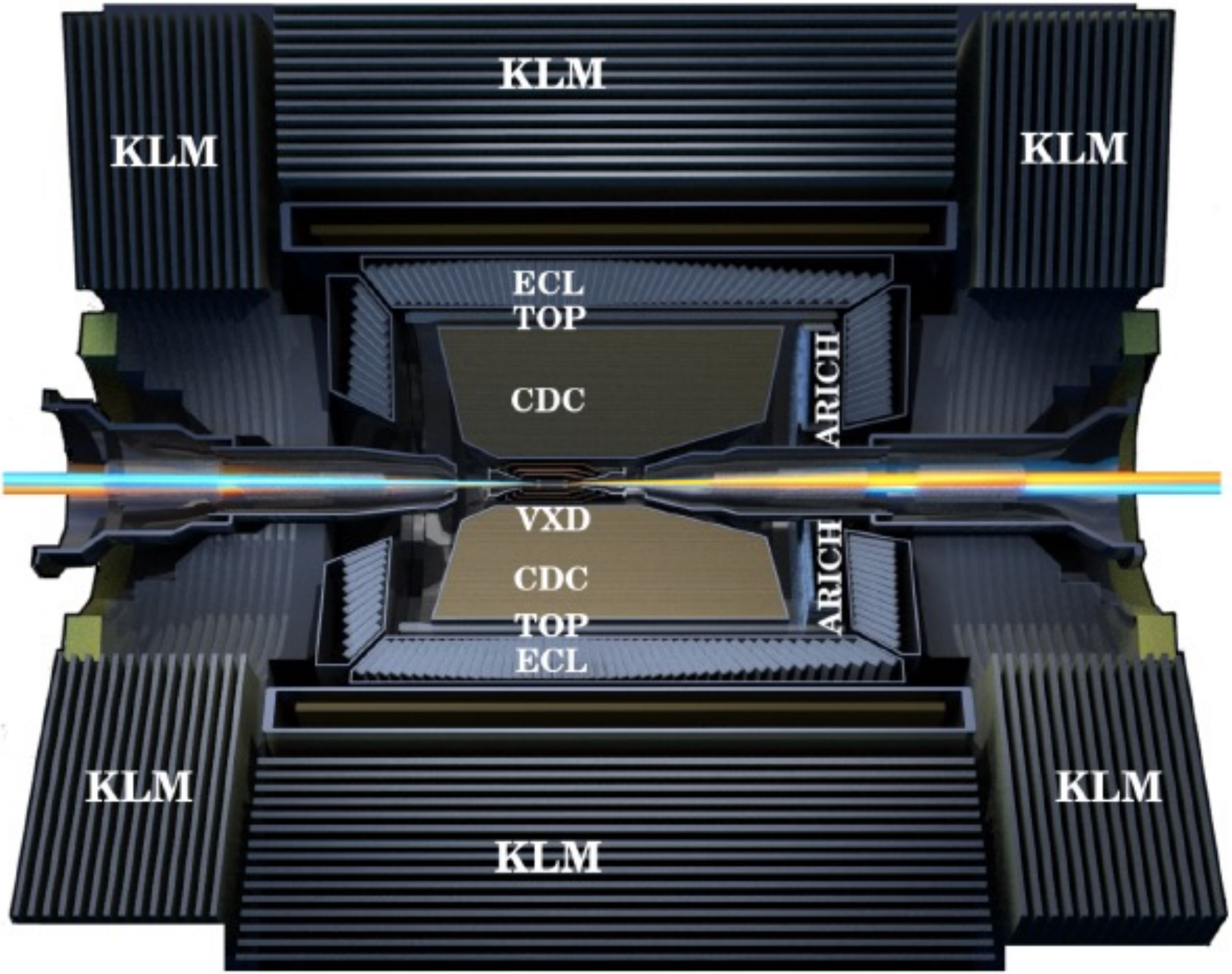
a) Purely leptonic decays e.g. $B^+ \rightarrow \tau^+ \nu$

b) Semileptonic decays e.g. $B \rightarrow D^{(*)} \tau\nu$ or $B \rightarrow D^{(*)}\, l\, \nu$

Tensions persist between exclusive and inclusive (e+e-) measurements of fundamental CKM elements $|V_{cb}|$, $|V_{ub}|$

Figure credit:

https://www.nature.com/articles/nature22346


KLM
KLM
KLM
ECL
TOP
CDC
ARICH
VXD
ARICH
CDC
TOP
ECL
KLM
KLM
KLM

$B \to K^* l^+ l^- (q^2)$ bootcamp at B2TIP

Angular dependence

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^3(\Gamma\pm\bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi}\left[\begin{aligned} &\frac{3}{4}(1-F_L)\sin^2\vartheta_K + F_L\cos^2\vartheta_K \\ &+\frac{1}{4}(1-F_L)\sin^2\vartheta_K\cos 2\vartheta_L \\ &-F_L\cos^2\vartheta_K\cos 2\vartheta_L + S_3\sin^2\vartheta_K\sin^2\vartheta_L\cos 2\phi \\ &+S_4\sin 2\vartheta_K\sin 2\vartheta_L\cos\phi + \\ &+ \qquad\qquad + S_7\sin 2\vartheta_K\sin\vartheta_L\sin\phi \\ &+ \end{aligned}\right]$$

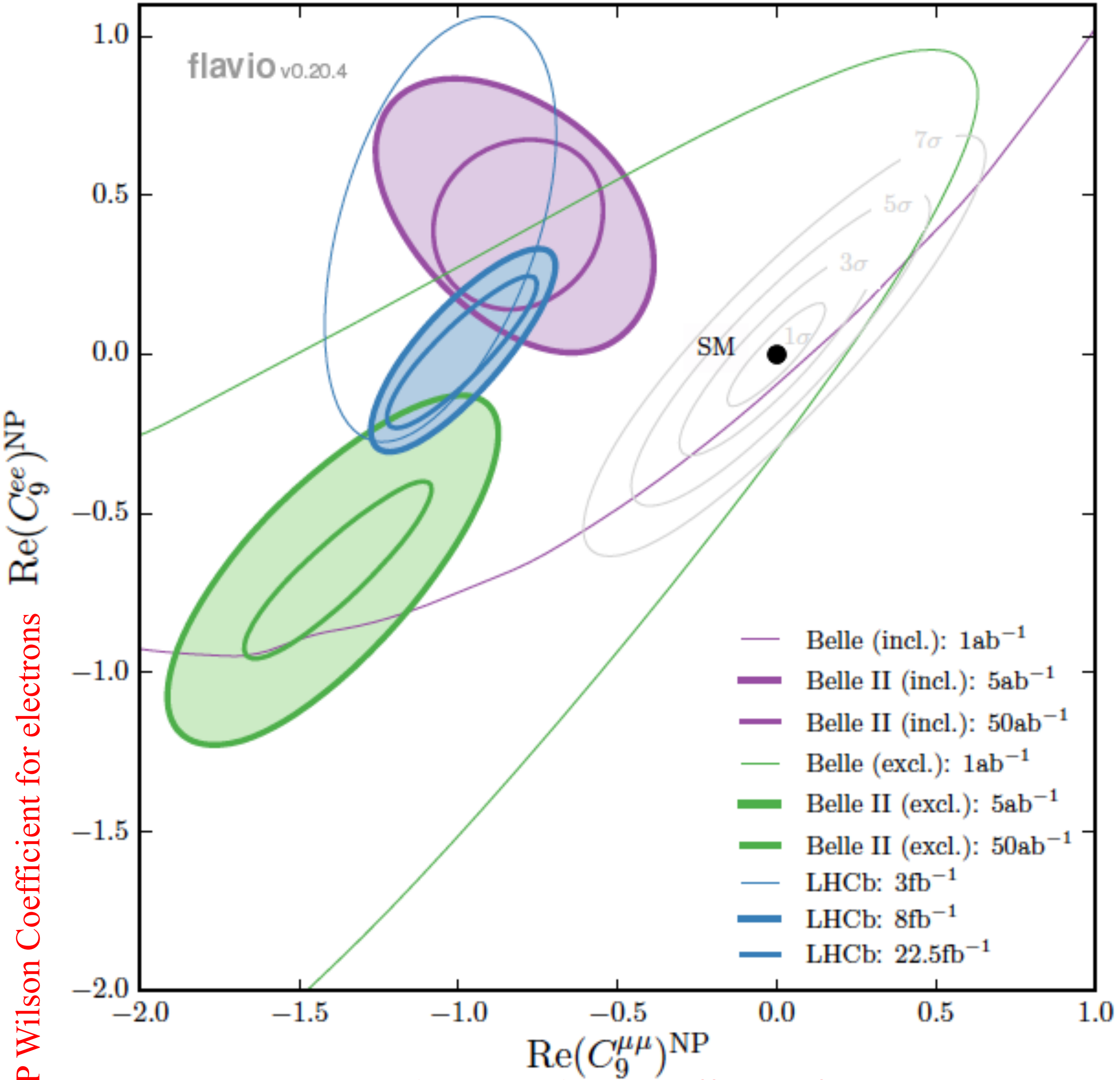
F_L is the longitudinal polarization fraction.

(-) means the term is only in $\Gamma - \bar{\Gamma}$

Introduce $P_{4,5}' = S_{4,5}/\mathrm{sqrt}[F_L(1-F_L)]$ to reduce dependence on form factors

Thanks to Rahul Sinha

NP in b→s l^+l^-



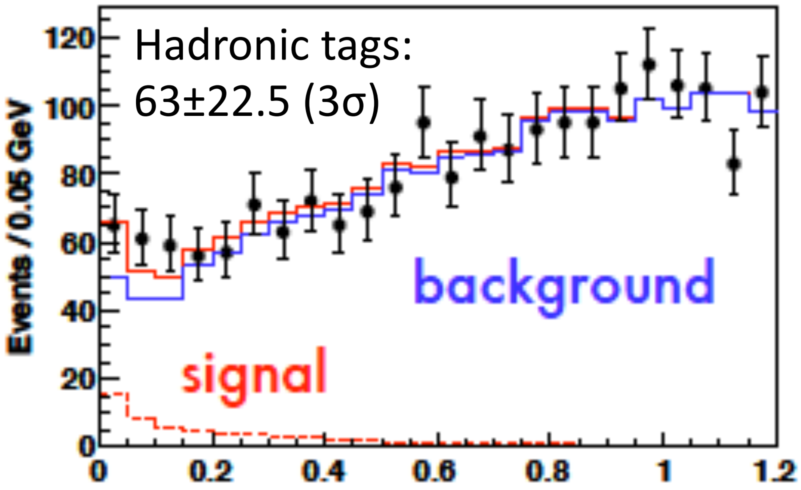
NP Wilson Coefficient for electrons

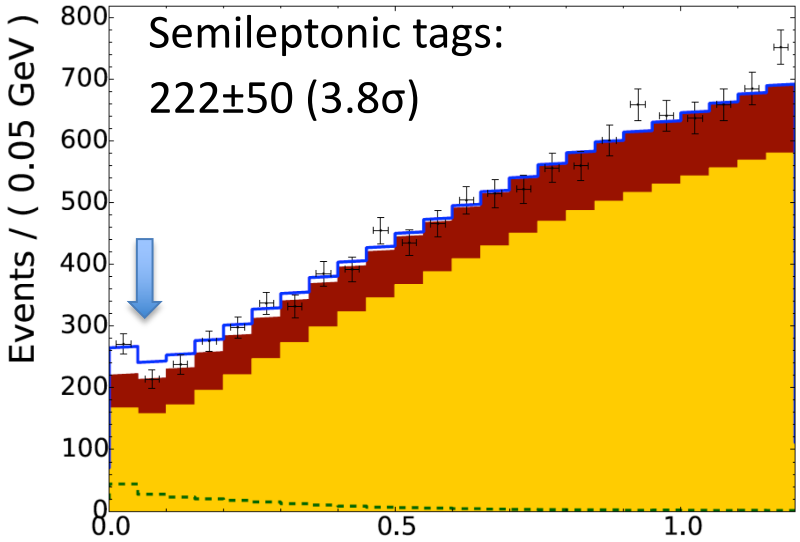
New Physics Wilson Coefficient for muons

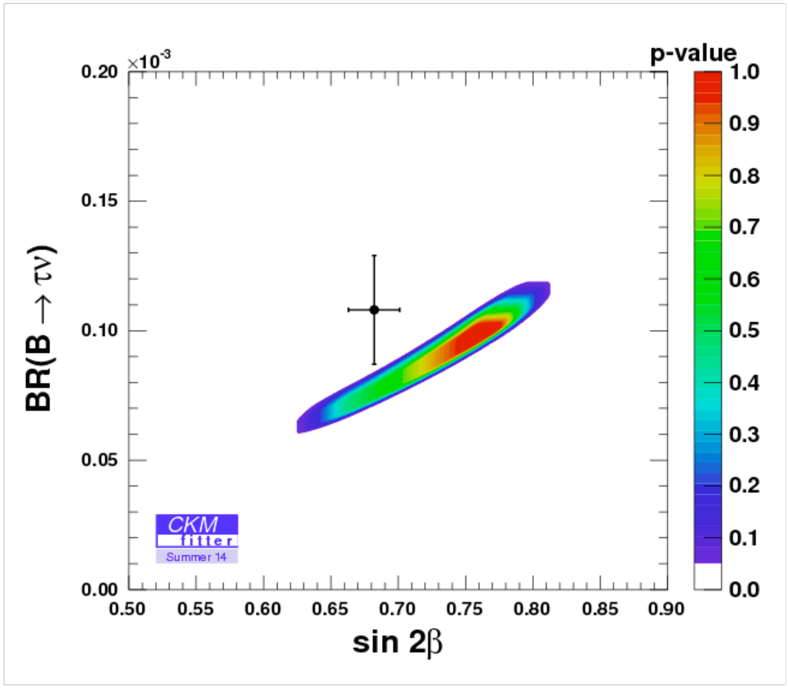
Prepared by D. Straub et al. for the Belle II Physics Book (edited by P. Urquijo and E. Kou)

Belle II can do both <u>inclusive</u> and exclusive. Equally strong capabilities for electrons and muons.

Example: old Belle B→τν results with full *reprocessed* data sample: either hadronic or semileptonic tags (PRD 92, 051102 (2015))



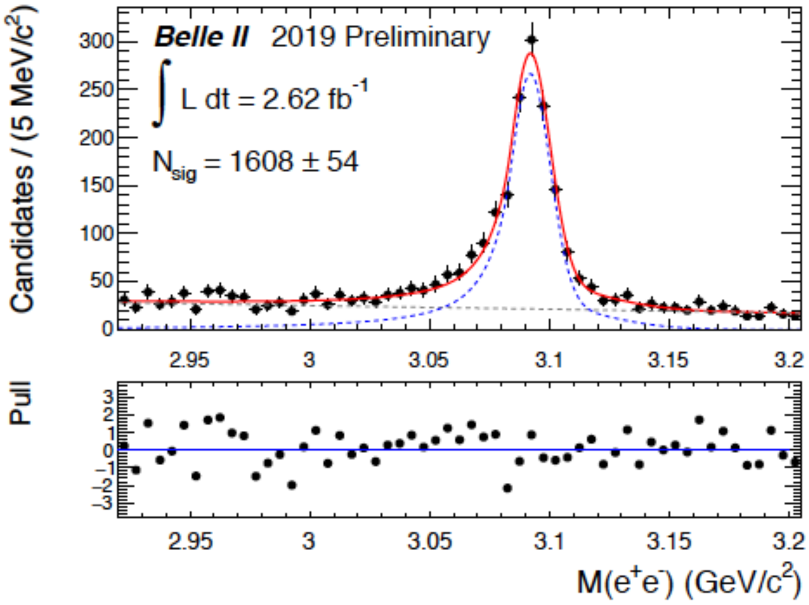


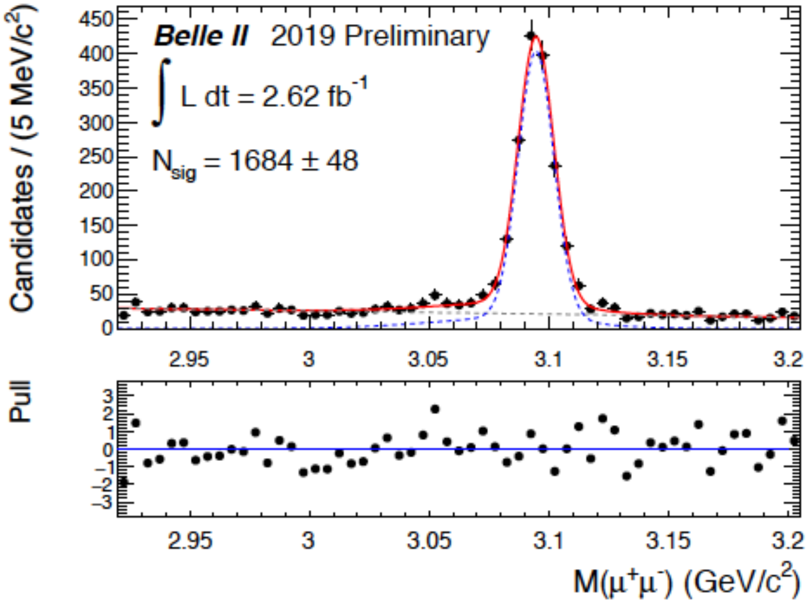


With the full B factory statistics only “evidence”. No single observation from either Belle or BaBar.

➔The horizontal axis is the “Extra Calorimeter Energy” or E_{ECL}

Signals for B→J/ψ X in Phase 3 data





Clear signals for B→J/ψ X in ~1/2 of Phase 3 data. Note the small radiative tail on the di-electrons (does include bremsstrahlung recovery).

→*Belle II has equally strong capabilities for electrons and muons.*