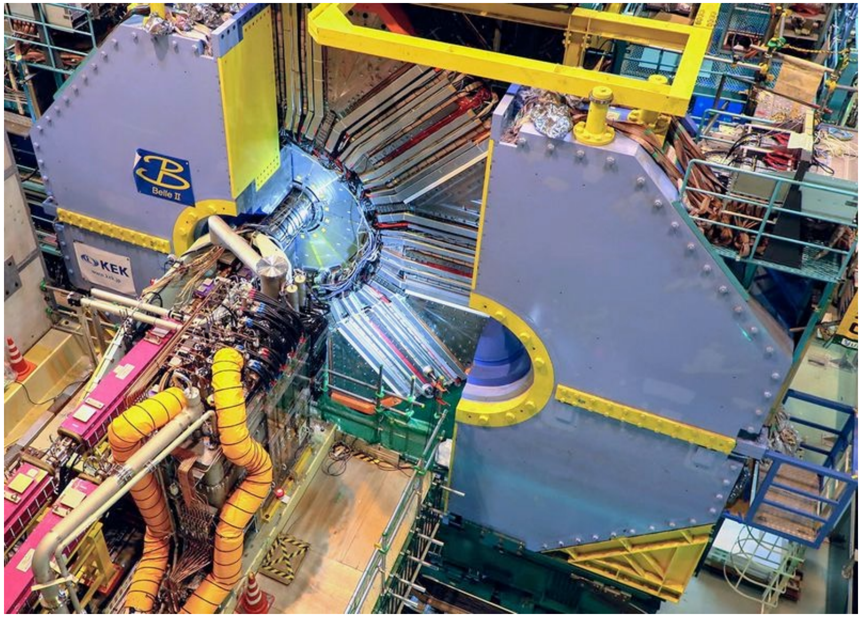
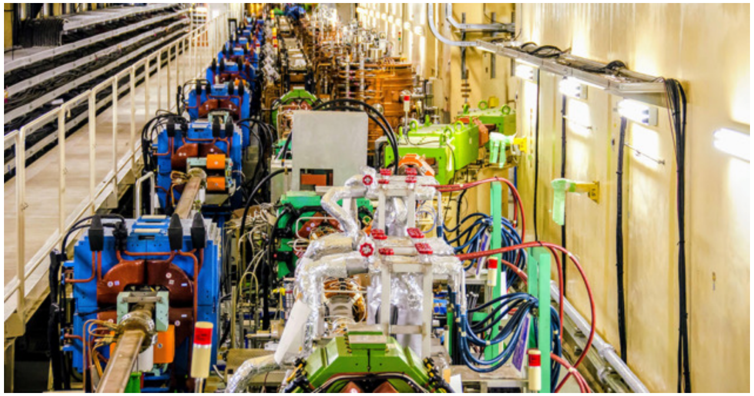
Potential for BSM discoveries in b→c and b→s with *Belle II@SuperKEKB*

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

Introduction and Snowmass 2022 recap. Belle II@50 ab^{-1} and 250 ab^{-1}

Three areas where BSM discoveries *may* be possible:

1. Angular distributions in B→D^* l nu and Δ observables
https://arxiv.org/abs/2206.11283 (PRD)

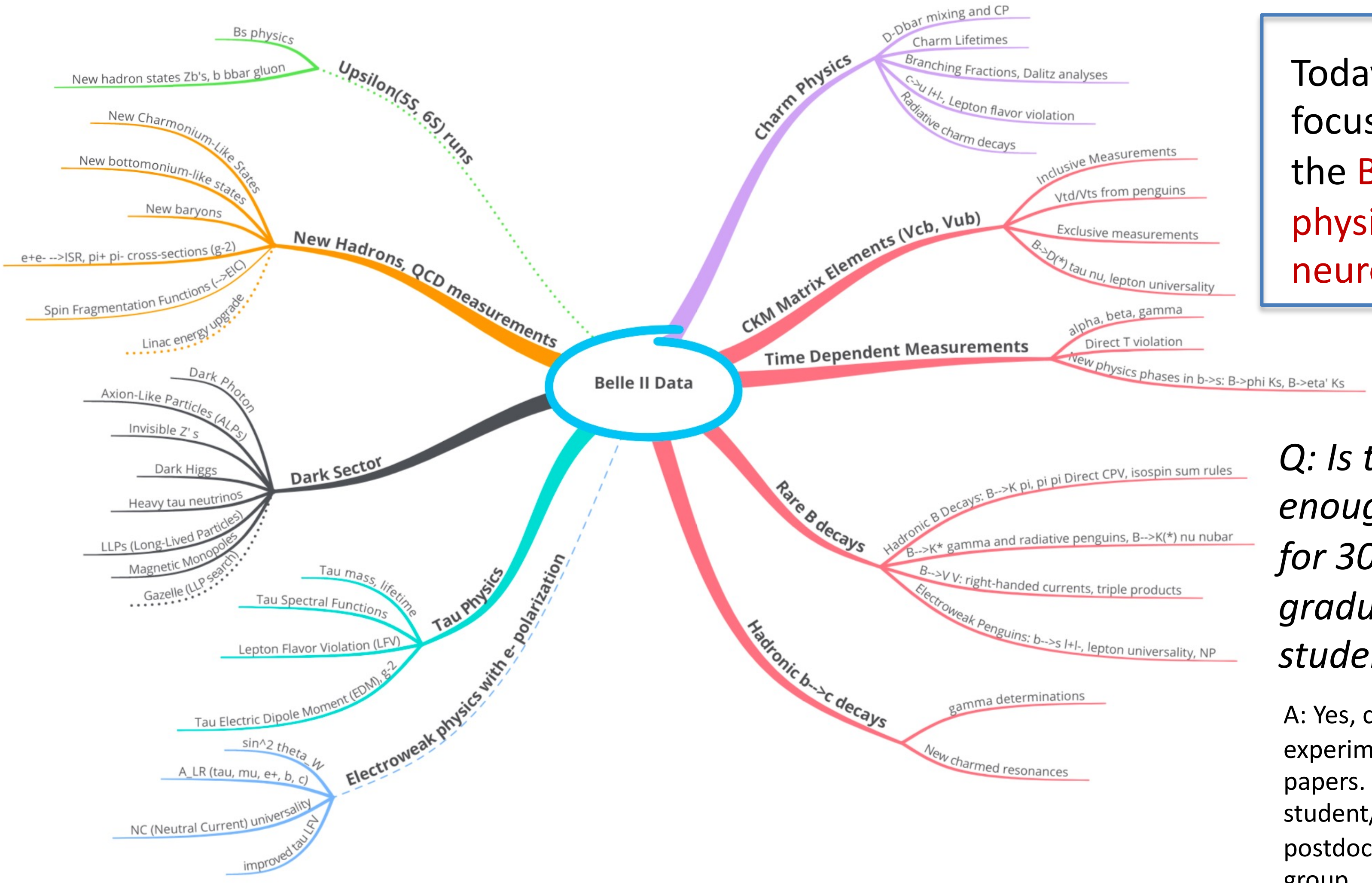
2. Angular distributions in B→K^* l^+ l^- and Δ observables
https://arxiv.org/abs/2203.06827
(submitted to PRD)

3. Clean NP mode, B→K *ν vbar*
https://arxiv.org/abs/2107.01080 (PRD)

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

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 300 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

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 *alternate* route to going beyond the SM.

Younger theorists: Dark Sector may be another path.

The “Vision Thing” for Belle II/SuperKEKB

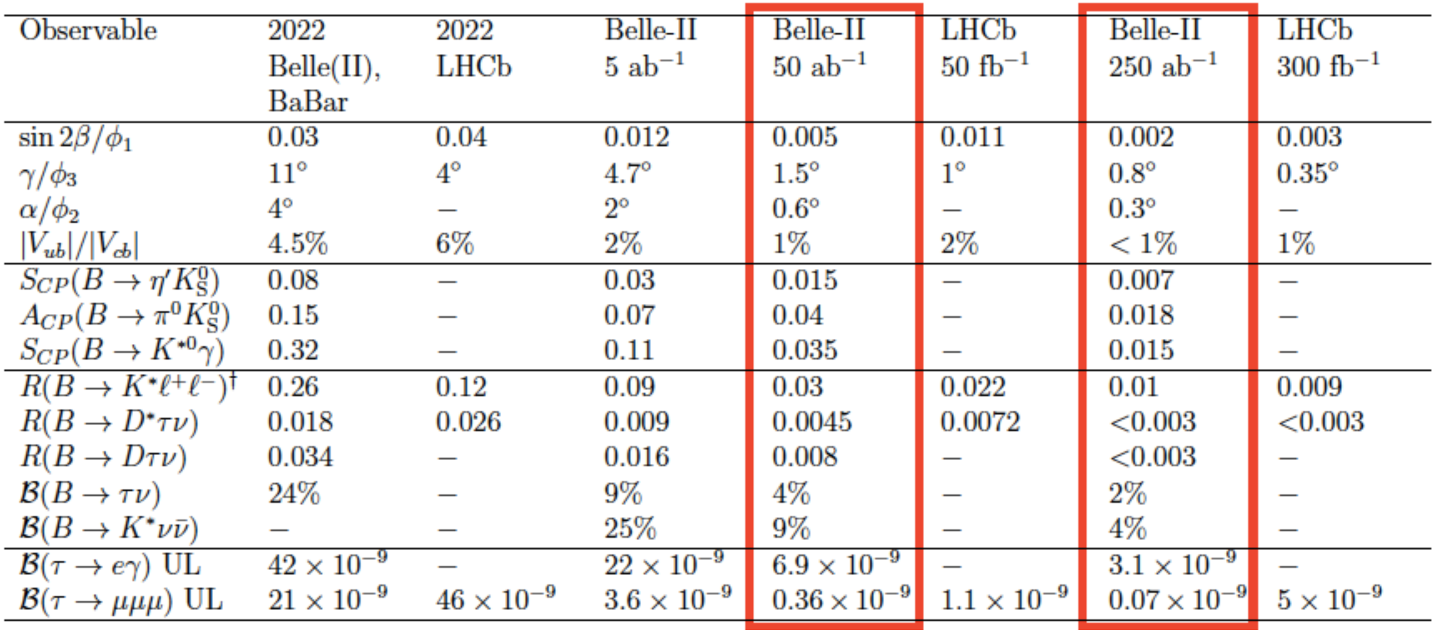
What happens beyond 50 ab^{-1} ?

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.

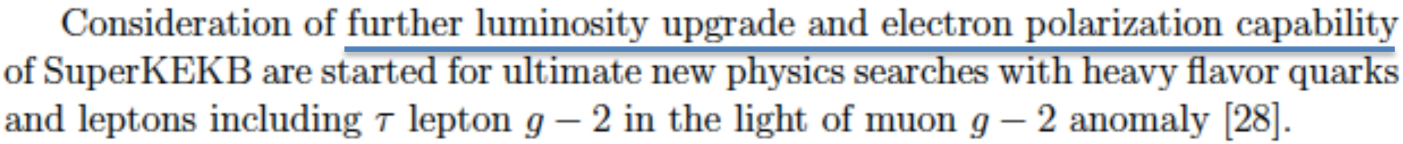
Upgrades
Most key channels will be stats. limited (not theory or syst.).



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



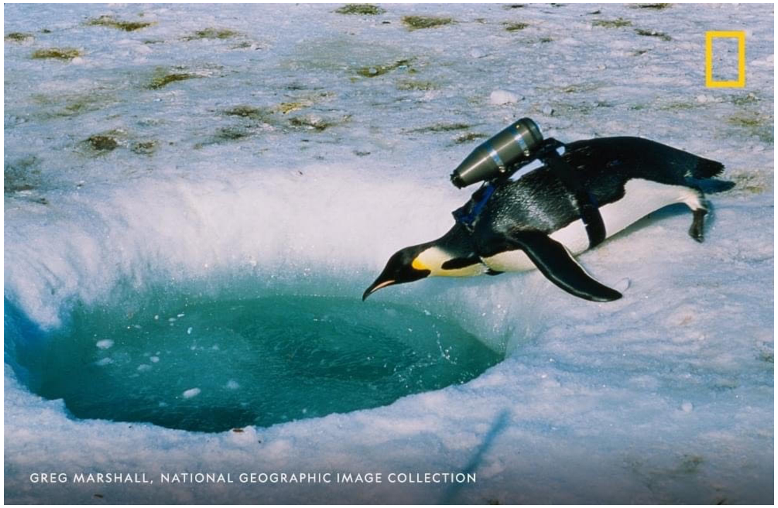
Consideration of further luminosity upgrade and electron polarization capability of SuperKEKB are started for ultimate new physics searches with heavy flavor quarks and leptons including τ lepton $g-2$ in the light of muon $g-2$ anomaly [28].

Backup slides on e- polarization and electroweak measurements.

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

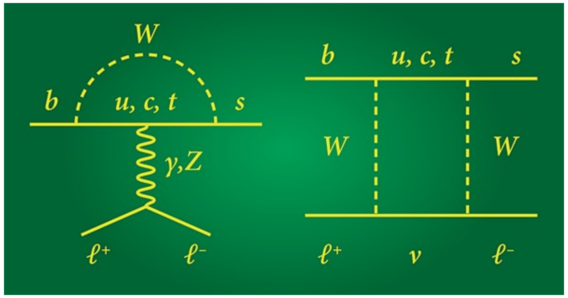
Research penguin

Photo Credit: National Geographic



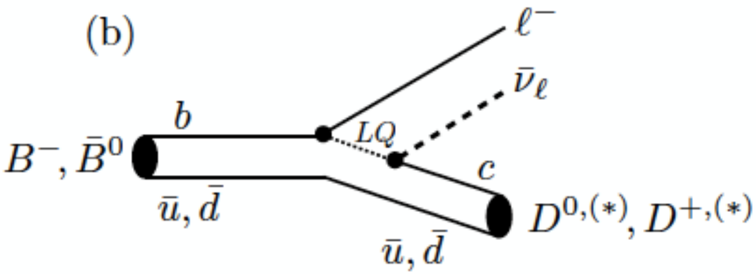
GREG MARSHALL, NATIONAL GEOGRAPHIC IMAGE COLLECTION

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



Sequoia National Forest

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



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

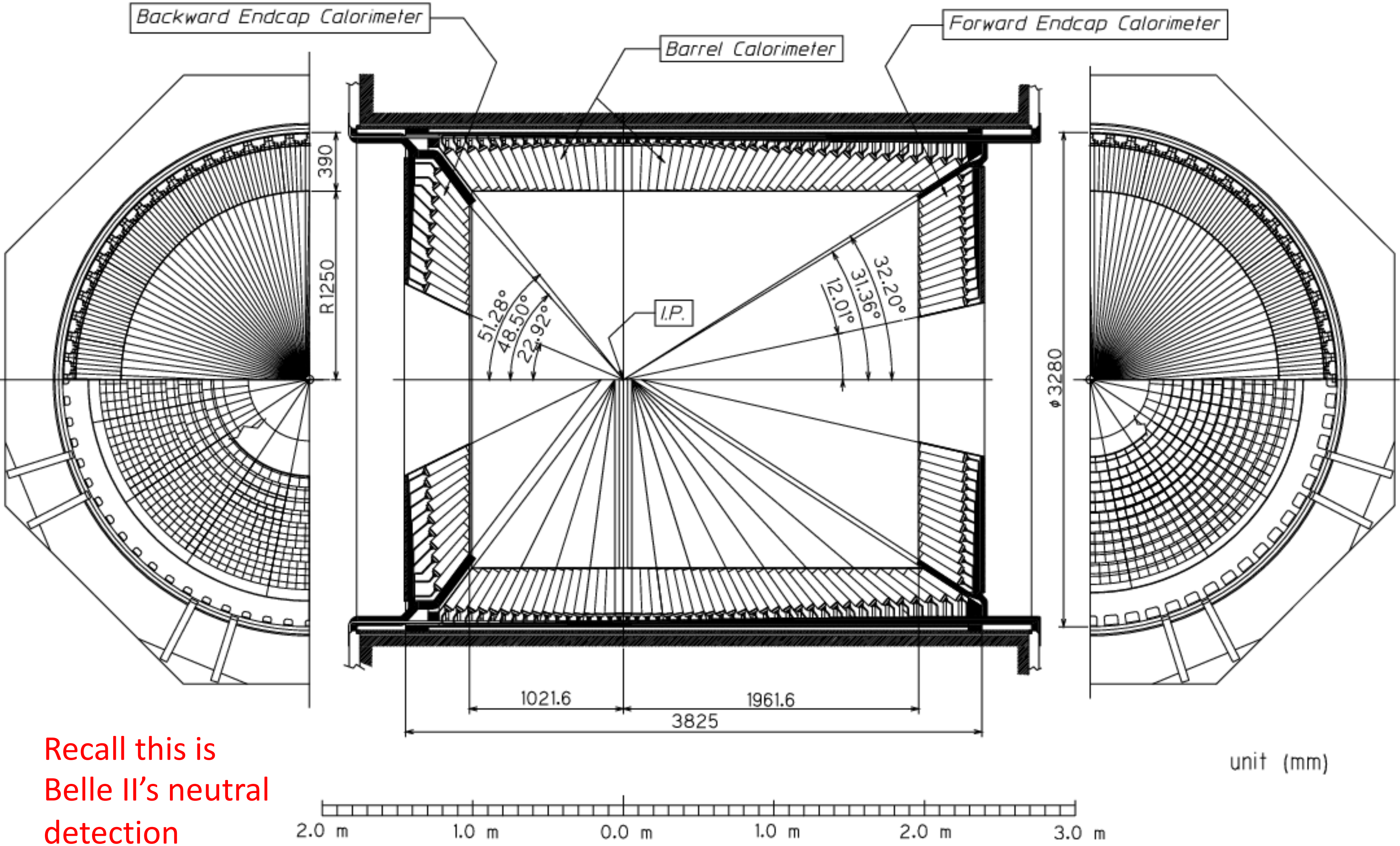
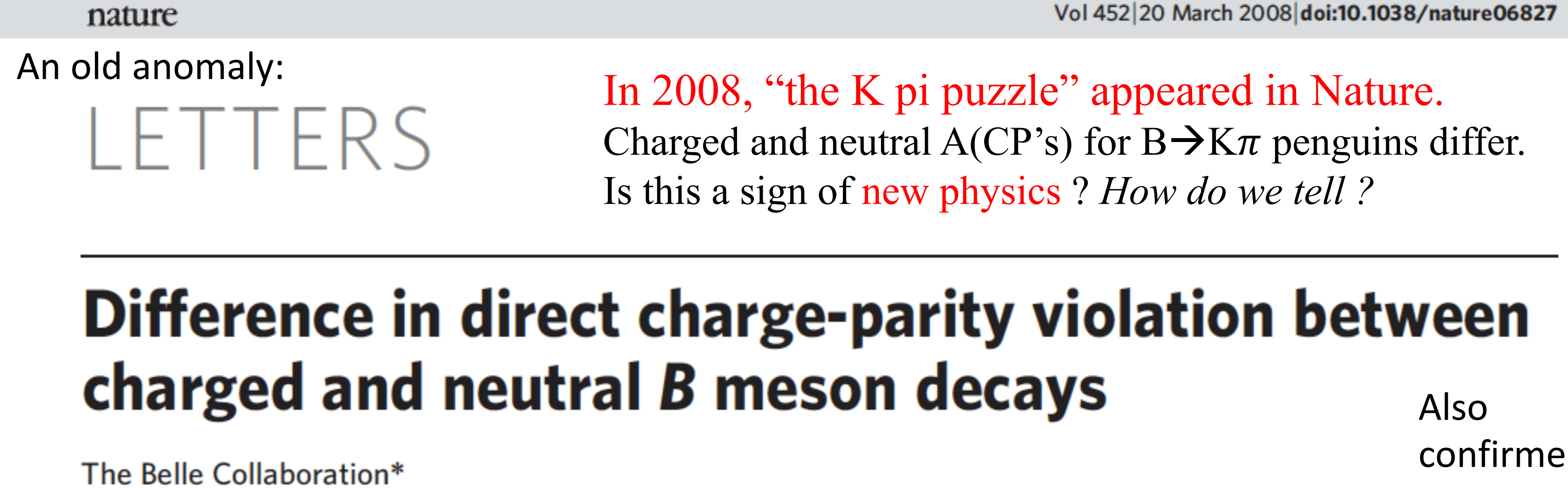


Fig. 69. Overall configuration of ECL.

Recall this is Belle II’s neutral detection superpower

An old anomaly:



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

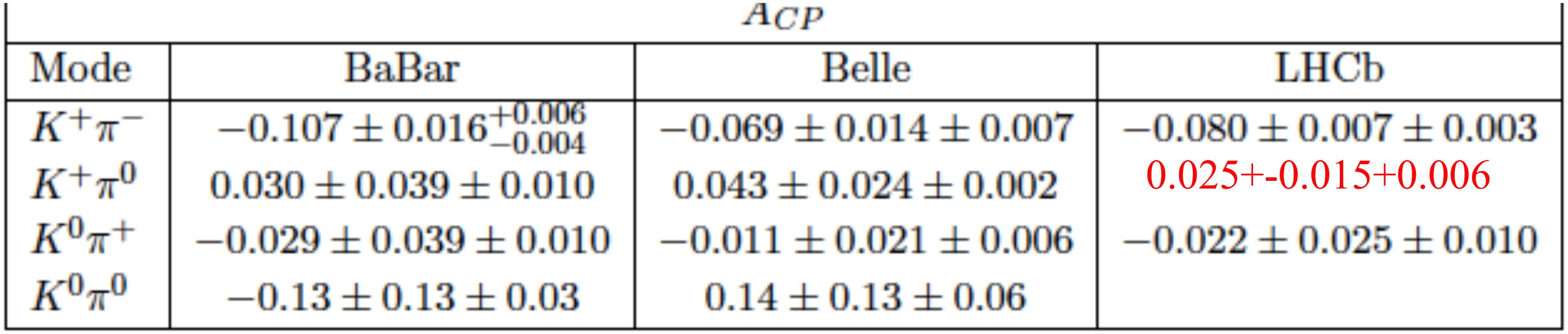
LETTERS

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 ? *How do we tell ?*

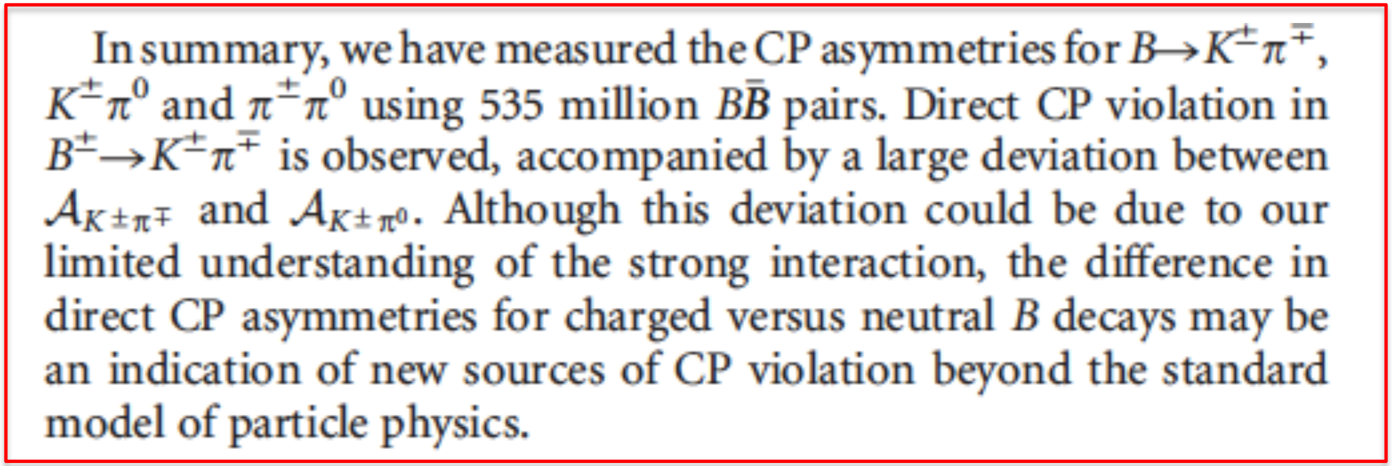
Difference in direct charge-parity violation between charged and neutral *B* meson decays

The Belle Collaboration*

Also confirmed by BaBar



	$\mathcal{A}_{CP}$		
Mode	BaBar	Belle	LHCb
$K^+\pi^-$	$-0.107\pm0.016^{+0.006}_{-0.004}$	$-0.069\pm0.014\pm0.007$	$-0.080\pm0.007\pm0.003$
$K^+\pi^0$	$0.030\pm0.039\pm0.010$	$0.043\pm0.024\pm0.002$	0.025+-0.015+0.006
$K^0\pi^+$	$-0.029\pm0.039\pm0.010$	$-0.011\pm0.021\pm0.006$	$-0.022\pm0.025\pm0.010$
$K^0\pi^0$	$-0.13\pm0.13\pm0.03$	$0.14\pm0.13\pm0.06$	



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.

The isospin sum rule in the next decade.

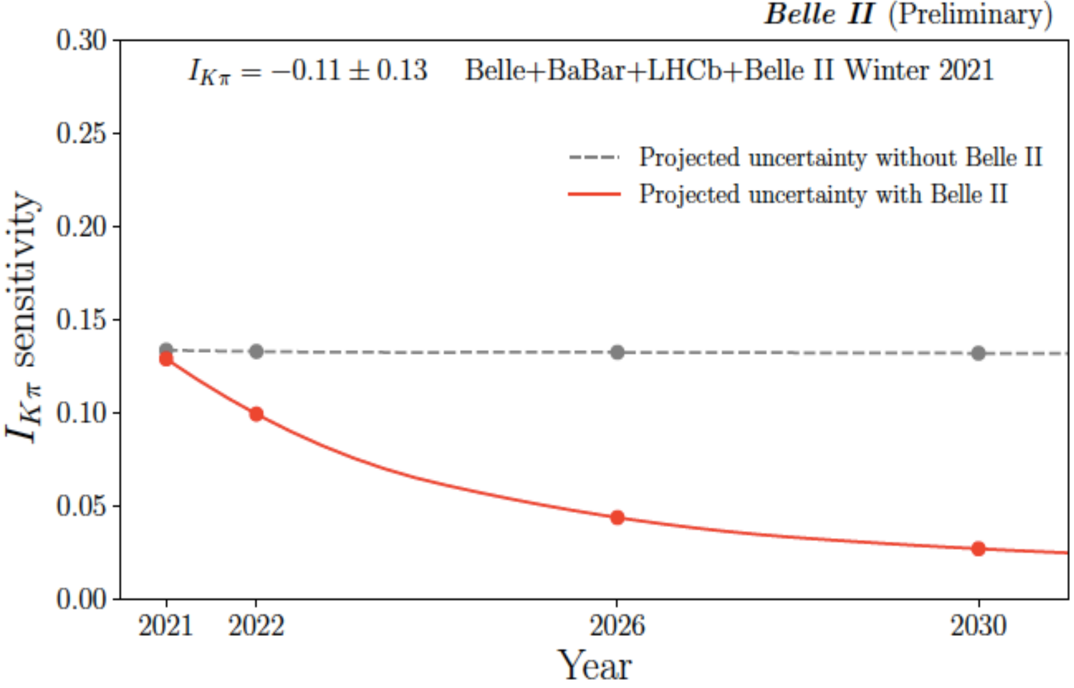
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

https://arxiv.org/abs/2104.14871

Michael Gronau

The isospin sum rule detects enhanced NP electroweak penguins in B→K π

Requires neutrals *and* flavor tagging.



With Belle II@250 ab^{-1}, expect a sensitivity of ~0.018

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

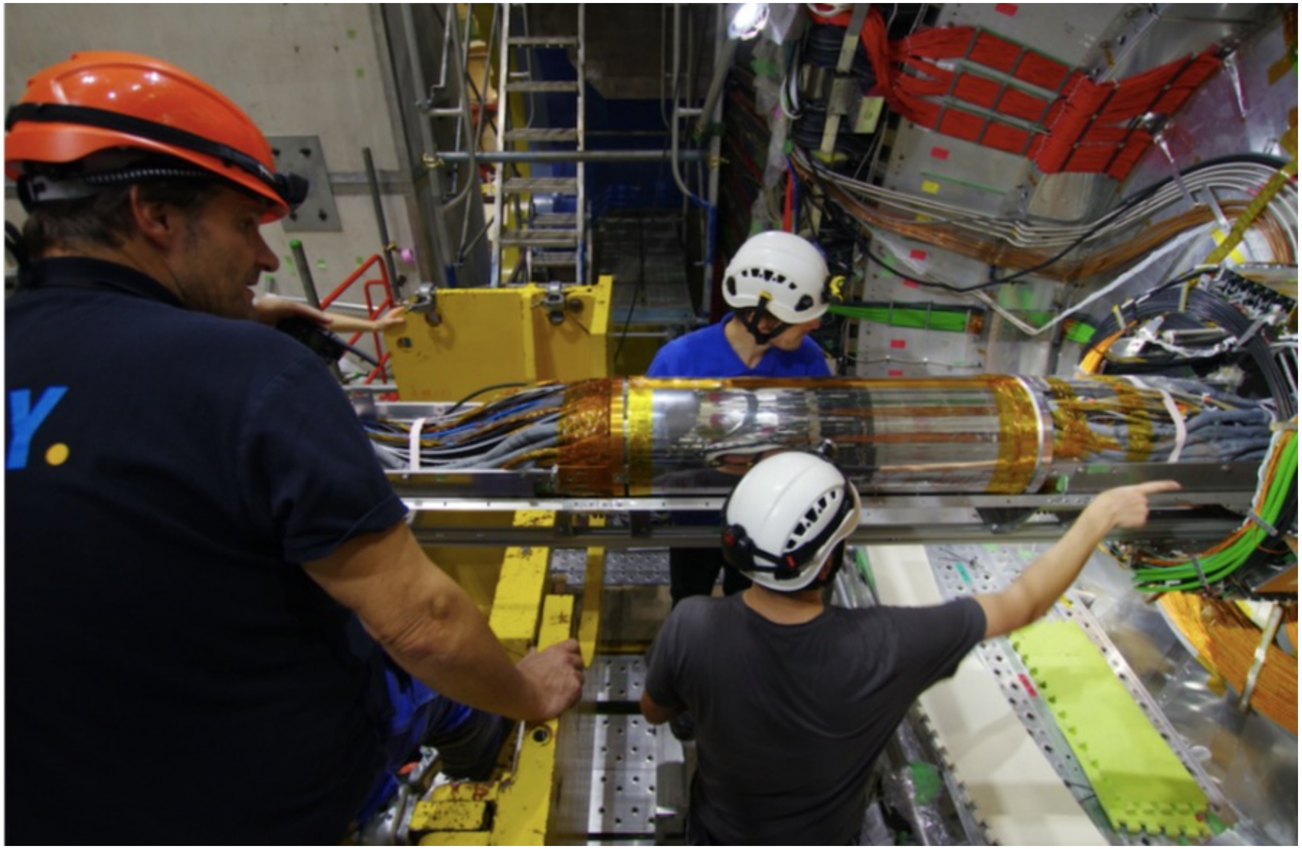
FIG. 4. The projected uncertainty on $I_{K\pi}$ with and without Belle II inputs. The inputs for $I_{K\pi}$ are averages of the estimated updates from ongoing LHCb and Belle II experiments with current world averages [10]. The red curve shows a projection when updates on the complete set of $K\pi$ measurements 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.

LaThuile 2023: Belle II will report a new result on the B-->h h isospin sum rule.

Time Dependent Measurements at Belle II

"Pain et beurre" (i.e .bread and butter) for the B factories.

"misoshiro and gohan" ?



Belle II VXD installed on Nov 21, 2018. (PXD L1 and two ladders of L2. and the SVD (4 layers))

LS1: A VXD upgrade is in progress

Recent time-dependent measurements from Belle II:

https://arxiv.org/abs/2302.12898 (CPV in b-->c cbar s)

https://arxiv.org/abs/2302.12791 (B-Bbar mixing)

More time-dependent papers on CPV in B→ϕ Ks, Ks π0, Ks Ks Ks at LaThuile/Moriond 2023. (See Iijima-san's talk at this workshop).

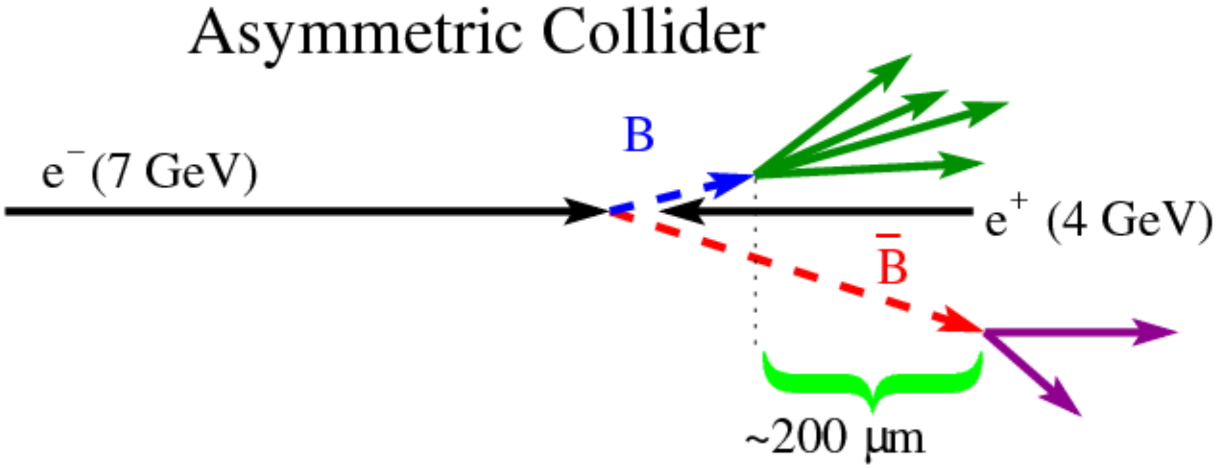
The B^0-anti B^0 meson pairs at the Upsilon(4S) are produced in a coherent, *entangled* **quantum mechanical state**.

(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

Reminder: Quantum Mechanical Entanglement

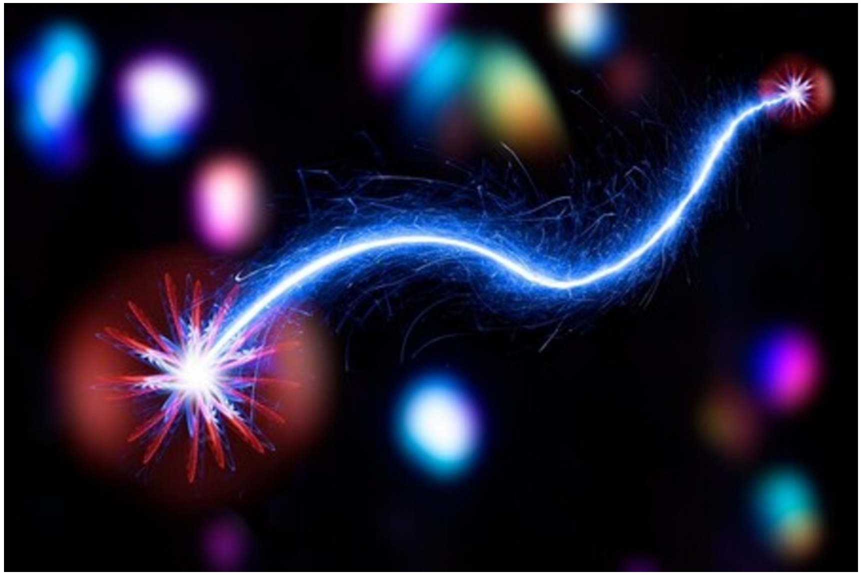
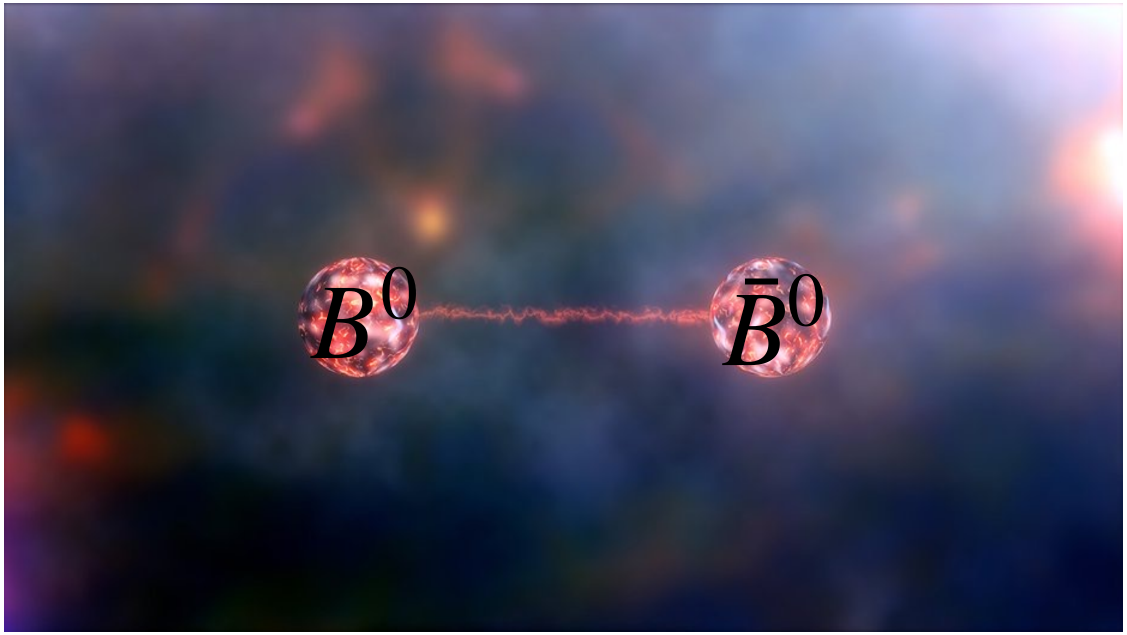


Figure credit: V. de Schwanberg/sciencesource.com



Original from Caltech outreach

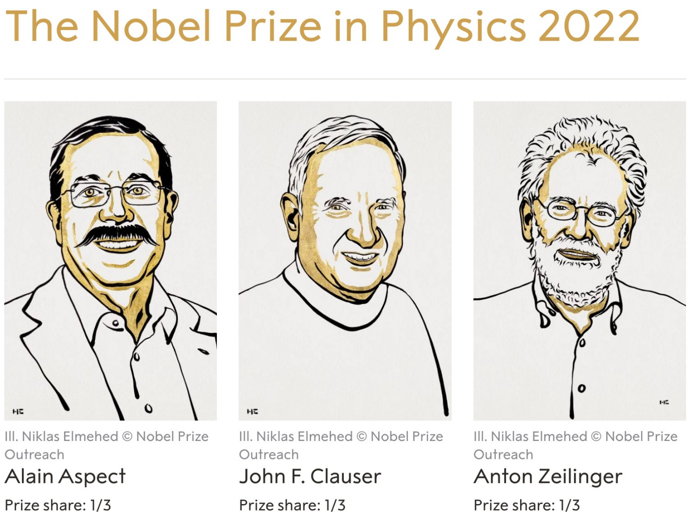
The B^0-anti B^0 meson pairs at the Upsilon(4S) are produced in a coherent, *entangled* **quantum mechanical state**.

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

Ans: C=-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) [Ans: otherwise the overall wavefunction is zero]



The Nobel Prize in Physics 2022

Ill. Niklas Elmehed © Nobel Prize Outreach
Alain Aspect
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach
John F. Clauser
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach
Anton Zeilinger
Prize share: 1/3

Nobel Prize for “QM Entanglement”

Each B^0-anti B^0 pair is an Einstein-Podolsky-Rosen (EPR) experiment.

Belle checked for the breakdown of QM in https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.99.131802
https://arxiv.org/abs/quant-ph/0702267

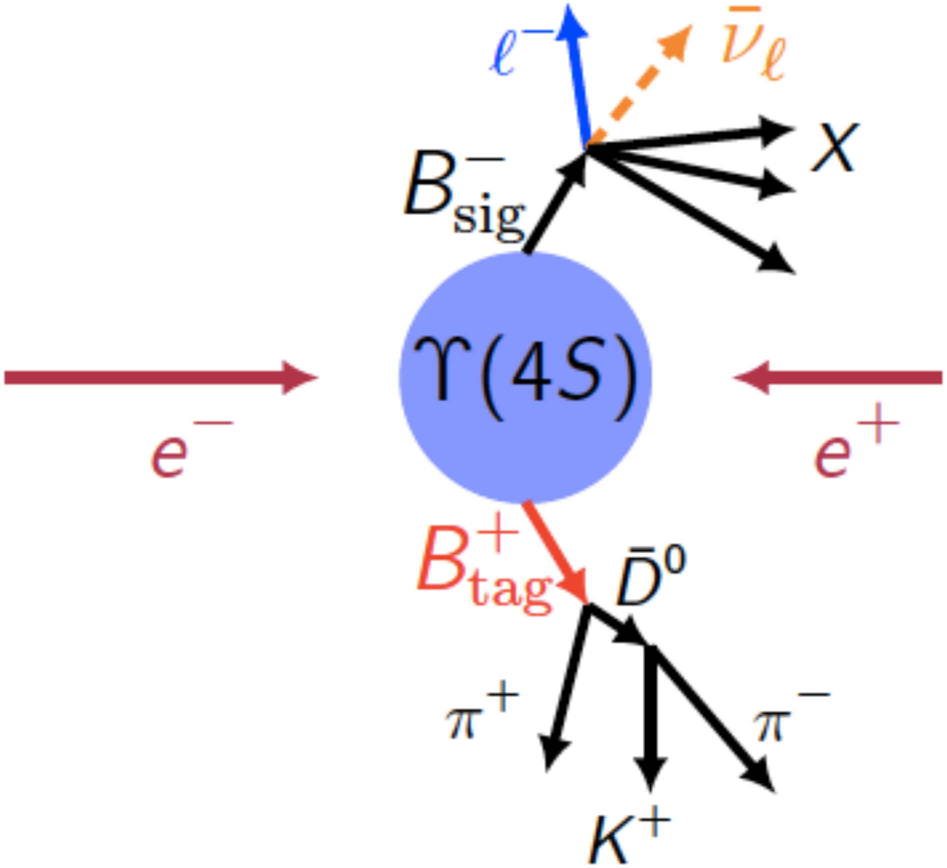
Q: Can Belle II do more on QM entanglement ?

Let's review 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).

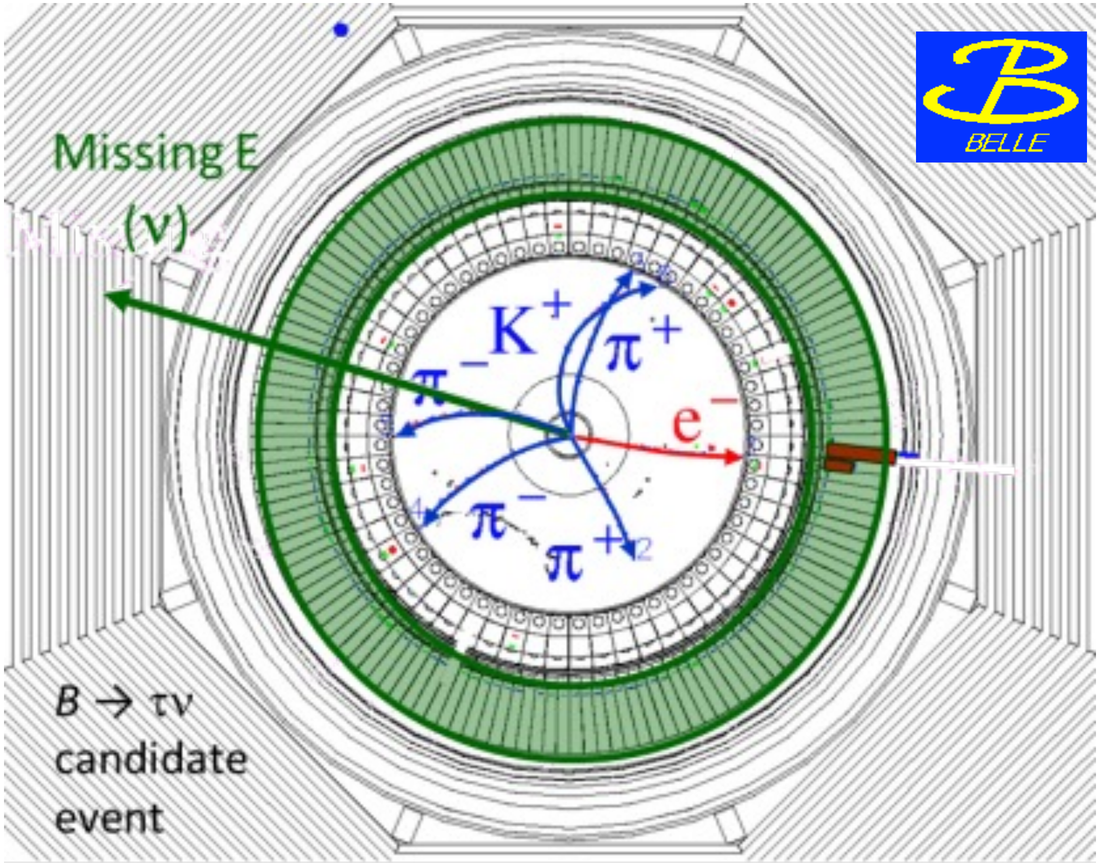
$Clean\ but\ efficiency\ \varepsilon \sim 0.5\%$

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

Example of a Missing Energy Decay ($B \rightarrow \tau\nu$) *in old Belle Data* (recorded before 2010)

$$B^+ \rightarrow \overline{D}^0 \pi^+ \quad (\rightarrow K\pi^-\pi^+\pi^-)$$

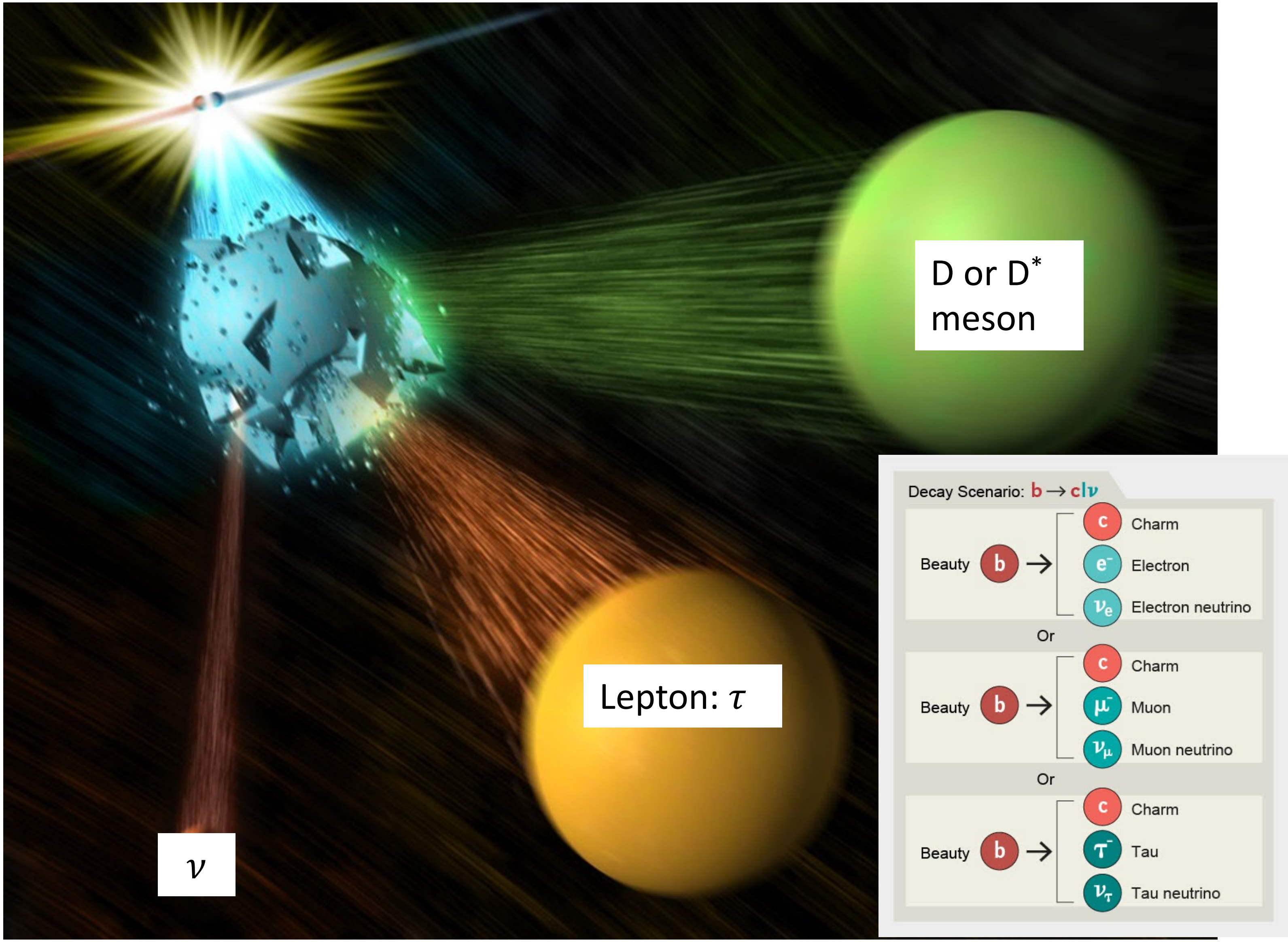
$$B^- \rightarrow \tau(\rightarrow e\nu\bar{\nu})\nu$$



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

SLAC
Outreach

Possible breakdown of lepton universality in B→D$^{(*)}$ τ υ

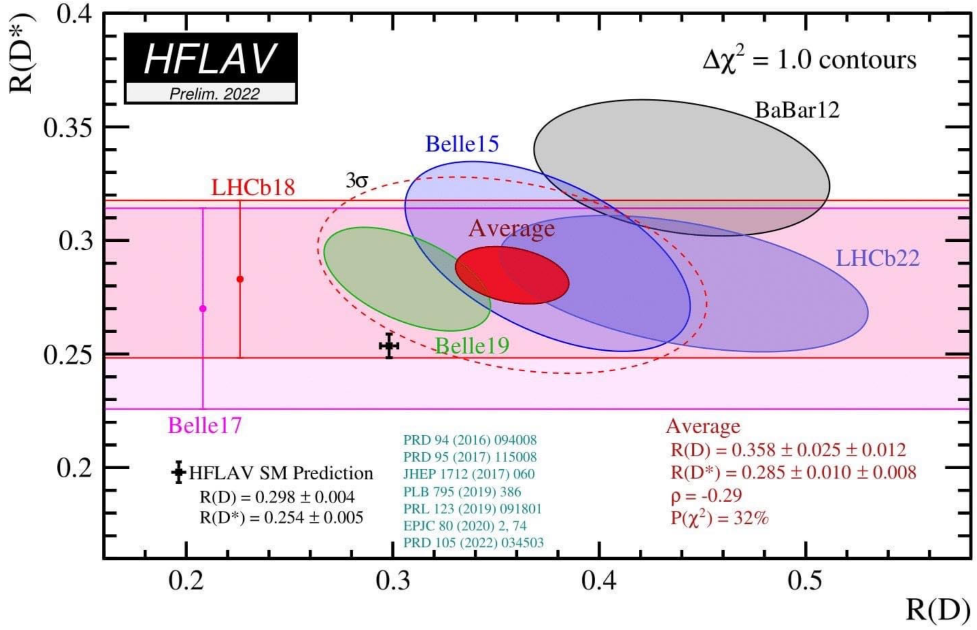


Let’s try to understand this picture of the production process (EM) and a weak decay

B→D$^{(*)}$ τ υ, possible breakdown of lepton universality

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

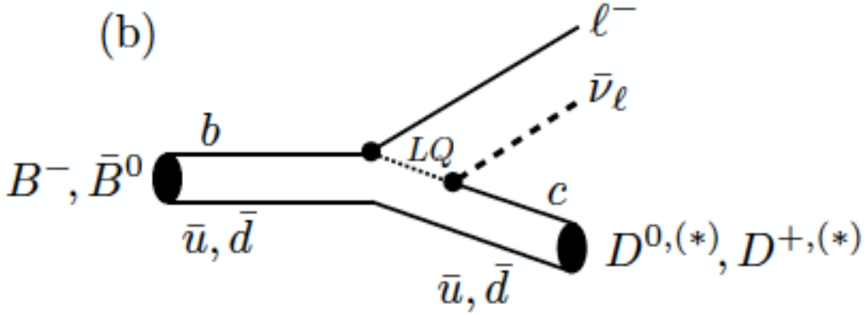
This may be BSM in the weak b→c charged current



Normally mediated by virtual W charged current.

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

See talks by Sevilla, Cornella



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

LHCb update(2022, 2023)→3.2σ→ 3.0σ

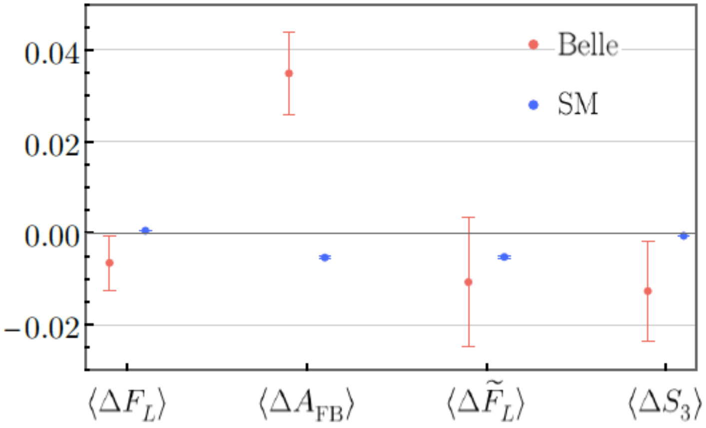
	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

Future: Look at q², angular distributions

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

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

Be careful: Require $q^2 > 1.15\ \mathrm{GeV}^2$



~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)).

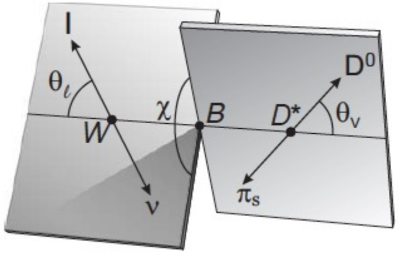
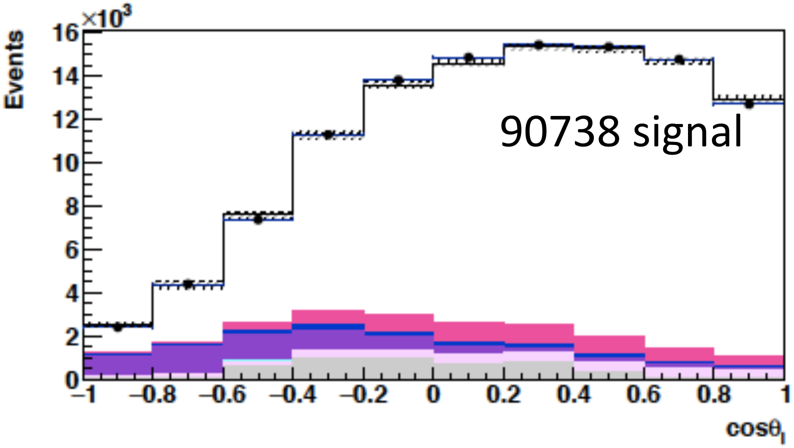
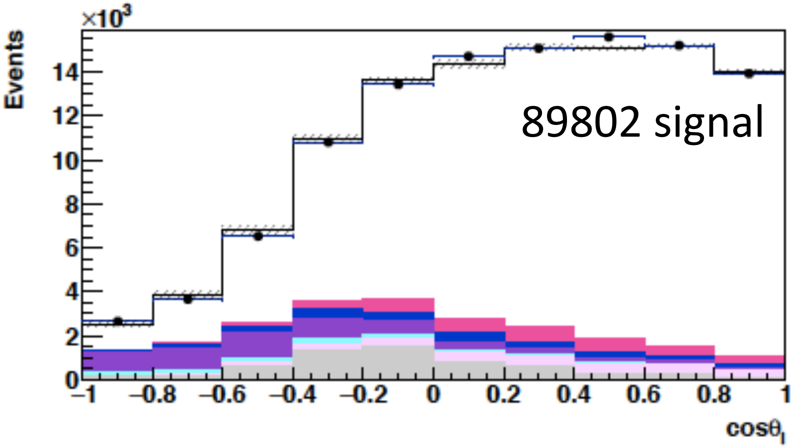


FIG. 3. Definition of the angles θ_ℓ, θ_ν and χ for the decay

“untagged”, no FEI used.



90738 signal



89802 signal

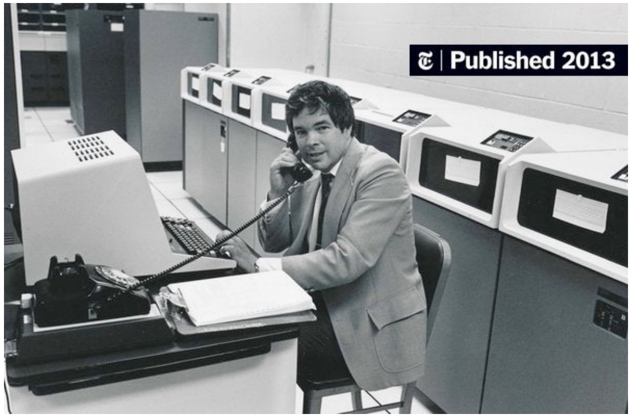
Evidence for BSM couplings in b→cμν ?

We need new tools to explore BSM physics couplings

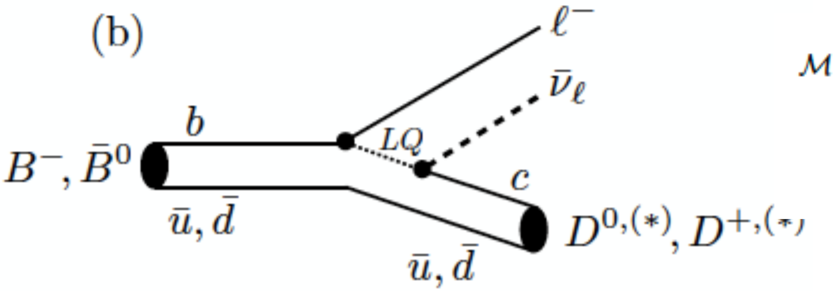
Monte Carlo Generators for B→D* l nu and B→K* l+ l- that allow for SM and BSM physics in Wilson coefficients.
This will allow for new and powerful experimental analyses of angular dependences.

Feynman and his diagrams

Paradigm shift



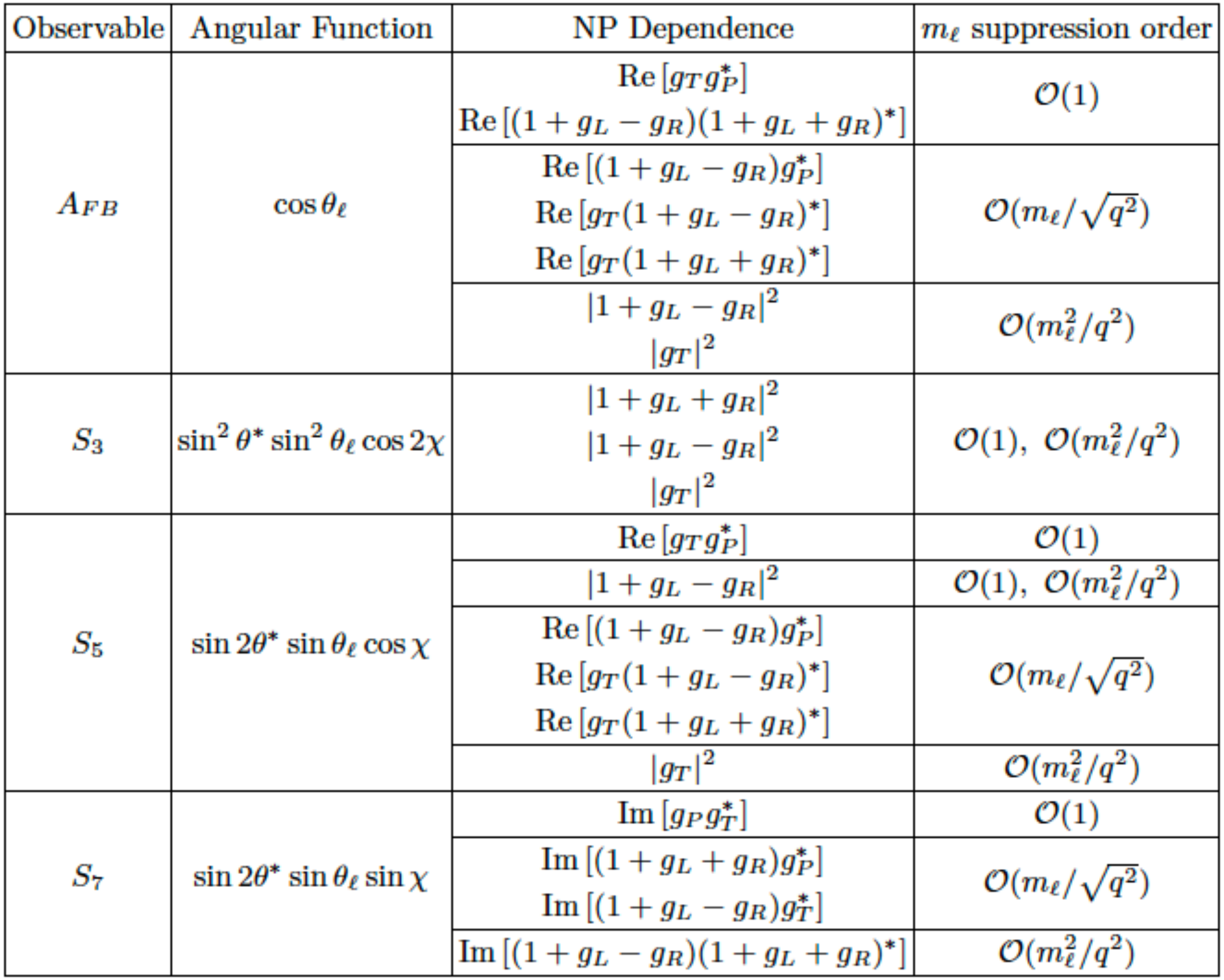
Wilson and his Coefficients in Effective Field Theories



$$\mathcal{M} = \frac{4 G_F V_{cb}}{\sqrt{2}} \Big\{ \langle D\pi | \bar{c}\gamma^\mu \left[(1+g_L)P_L + g_R P_R\right] b | \overline{B} \rangle \left(\bar{\ell}\gamma_\mu P_L \nu\right) + \langle D\pi | \bar{c}\left(g_{S_L} P_L + g_{S_R} P_R\right) b | \overline{B} \rangle \left(\bar{\ell} P_L \nu\right) + g_T \langle D\pi | \bar{c}\sigma^{\mu\nu} b | \overline{B} \rangle \left(\bar{\ell}\sigma_{\mu\nu} P_L \nu\right) \Big\}$$

Can MC this matrix element for any value of g_L, g_R, g_{SL}, g_{SR}

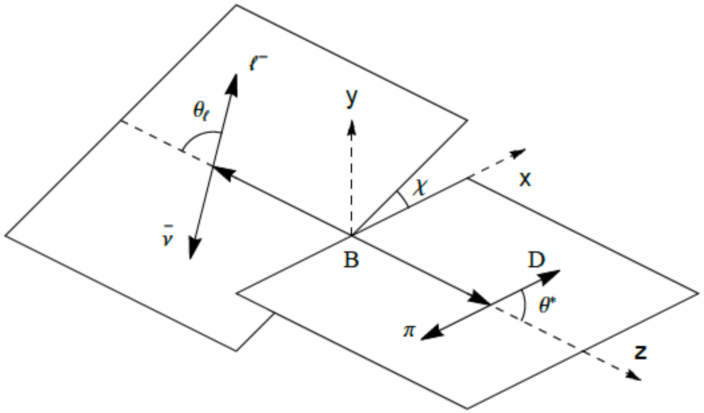
How the BSM couplings manifest in B→D* l nu, l=e, μ



Observable	Angular Function	NP Dependence	m_ℓ suppression order
A_{FB}	$\cos\theta_\ell$	$\mathrm{Re}\,[g_T g_P^*]$ $\mathrm{Re}\,[(1+g_L-g_R)(1+g_L+g_R)^*]$	$\mathcal{O}(1)$
		$\mathrm{Re}\,[(1+g_L-g_R)g_P^*]$ $\mathrm{Re}\,[g_T(1+g_L-g_R)^*]$ $\mathrm{Re}\,[g_T(1+g_L+g_R)^*]$	$\mathcal{O}(m_\ell/\sqrt{q^2})$
		$\|1+g_L-g_R\|^2$ $\|g_T\|^2$	$\mathcal{O}(m_\ell^2/q^2)$
S_3	$\sin^2\theta^*\sin^2\theta_\ell\cos 2\chi$	$\|1+g_L+g_R\|^2$ $\|1+g_L-g_R\|^2$ $\|g_T\|^2$	$\mathcal{O}(1),\ \mathcal{O}(m_\ell^2/q^2)$
S_5	$\sin 2\theta^*\sin\theta_\ell\cos\chi$	$\mathrm{Re}\,[g_T g_P^*]$	$\mathcal{O}(1)$
		$\|1+g_L-g_R\|^2$	$\mathcal{O}(1),\ \mathcal{O}(m_\ell^2/q^2)$
		$\mathrm{Re}\,[(1+g_L-g_R)g_P^*]$ $\mathrm{Re}\,[g_T(1+g_L-g_R)^*]$ $\mathrm{Re}\,[g_T(1+g_L+g_R)^*]$	$\mathcal{O}(m_\ell/\sqrt{q^2})$
		$\|g_T\|^2$	$\mathcal{O}(m_\ell^2/q^2)$
S_7	$\sin 2\theta^*\sin\theta_\ell\sin\chi$	$\mathrm{Im}\,[g_P g_T^*]$	$\mathcal{O}(1)$
		$\mathrm{Im}\,[(1+g_L+g_R)g_P^*]$ $\mathrm{Im}\,[(1+g_L-g_R)g_T^*]$	$\mathcal{O}(m_\ell/\sqrt{q^2})$
		$\mathrm{Im}\,[(1+g_L-g_R)(1+g_L+g_R)^*]$	$\mathcal{O}(m_\ell^2/q^2)$

Even with NP, it is small.

Guiding idea: angular distributions and q^2 are the key to finding BSM couplings in B→D* l nu



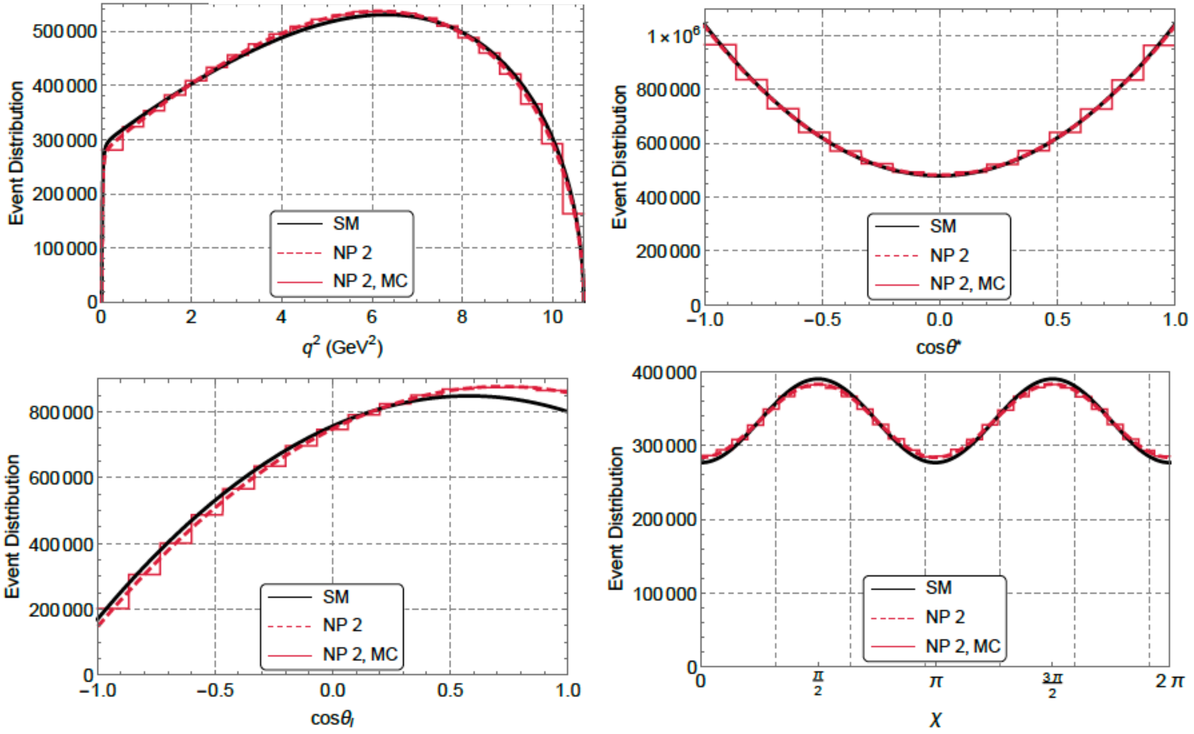


FIG. 2. Distribution of $\overline{B} \to D^* \ell^- \bar{\nu}$ events as functions of (clockwise from top left) q^2, $\cos\theta^*$, χ, and $\cos\theta_\ell$. Theory predictions are shown for the SM (solid black curve) and for NP Scenario 2 (dashed red curve). EvtGen data are shown for NP Scenario 2 (solid red histogram). Each plot is fully integrated over three of the four kinematic variables. The q^2 range is divided into 23 equal bins, to reflect the expected resolution of experimental measurements. The angular bins are chosen to be sufficiently fine to compare MC data to the theory. The $\cos\theta$ ranges are divided into 15 equal bins, and the χ range, being twice as large as the θ ranges, is divided into twice as many bins.

Distributions in MC integrated over all q^2

What BSM signatures could Belle II see in B→D* l nu at 50 ab^{-1} ?

+ correlated angular asymmetries@50 ab^{-1}

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

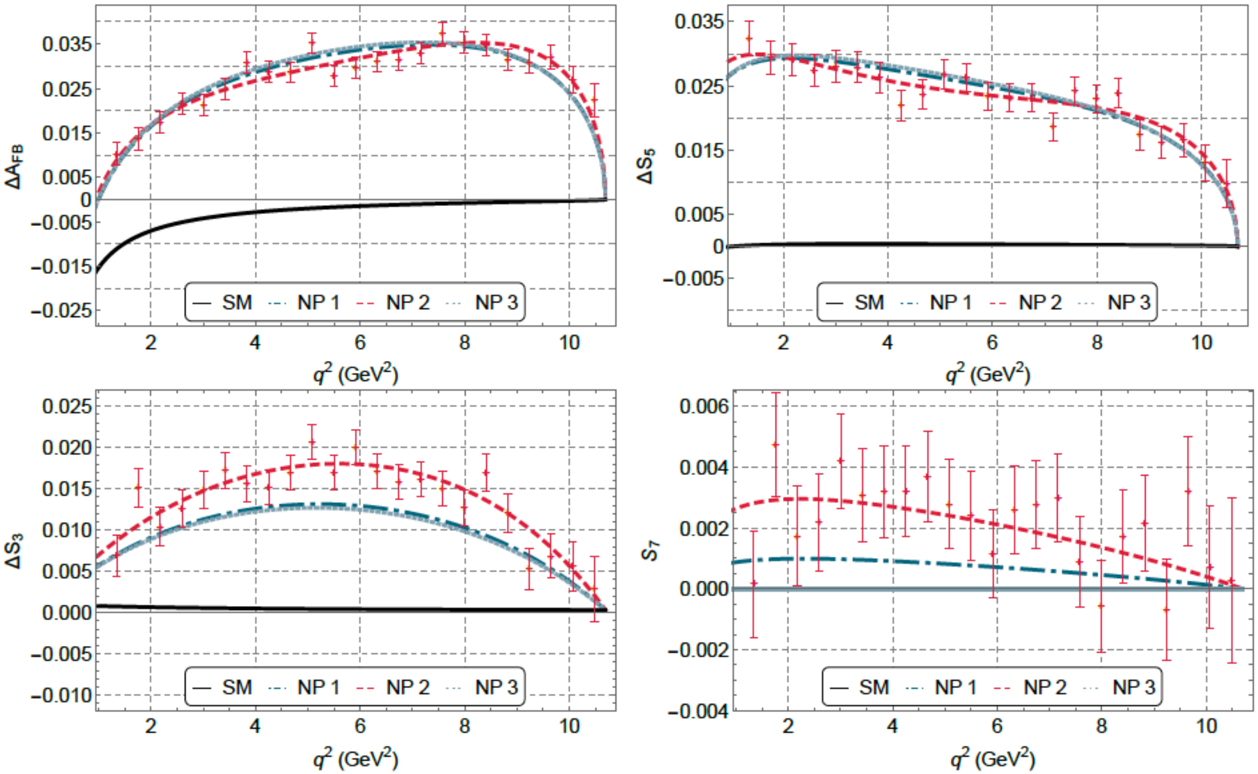


FIG. 4. ΔA_{FB}, ΔS_5, ΔS_3, and S_7 plotted as functions of q^2 for different values of NP coefficients. Here we have used the CLN parameterizations of the FFs. The NP parameters were chosen so that the ratio of semi-leptonic branching fractions is constrained to be within 3% of unity, as well as the ΔA_{FB} for the full q^2 range is within the interval 0.0349 ± 0.0089. EvtGen data for NP Scenario 2 ($g_L = 0.08$, $g_R = 0.09$, $g_P = 0.6i$) generated with 10^7 events (anticipated Belle II statistics) are shown as points with error bars. Theory curves are presented for all three NP Scenarios: Scenario 1 is dot-dashed blue, Scenario 2 is dashed red and Scenario 3 is dotted blue.

Using Δ *observables*
eliminates dependences on hadronic form factors

Sensitivities in Δ Observables for Belle II in B→D* l nu up to 250 ab^{-1}

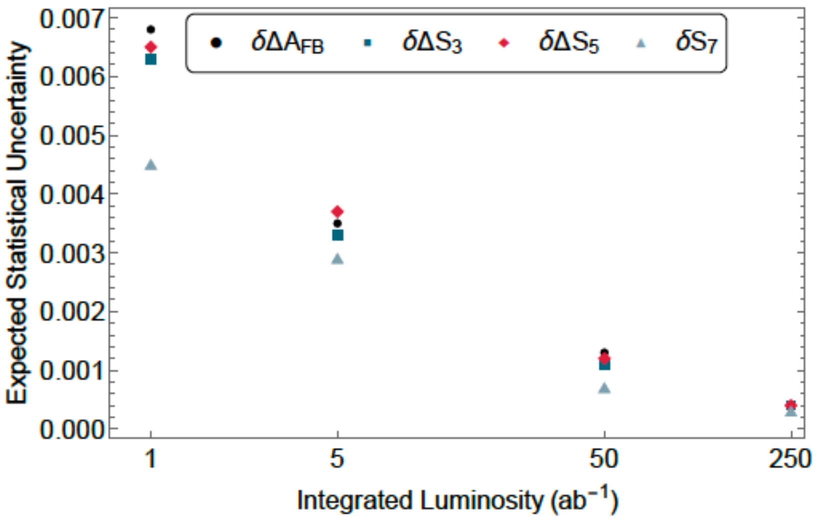
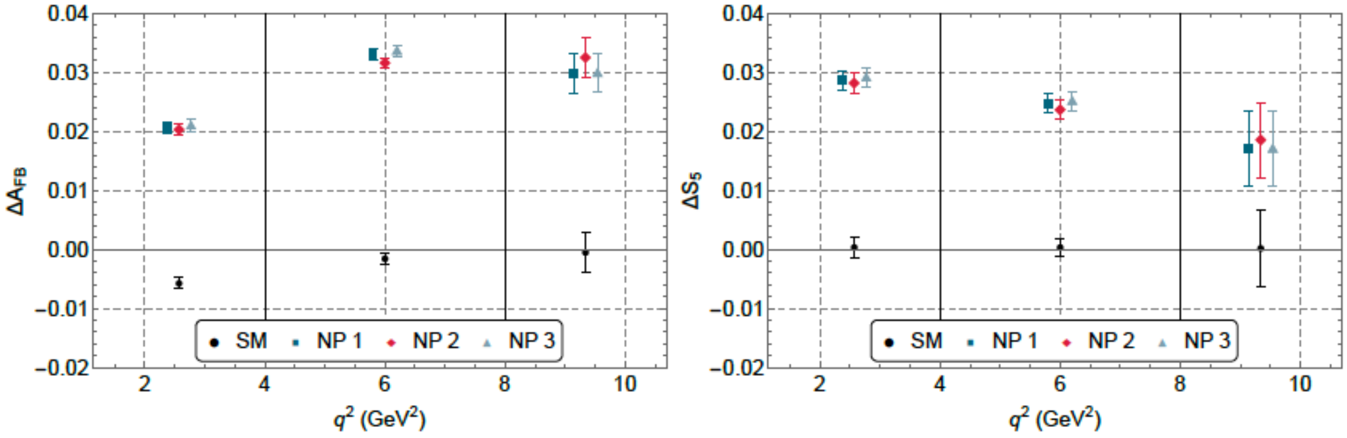


FIG. 6. Expected statistical uncertainties for the four observables at 1, 5, 50, and 250 ab^{-1} of Belle II data. These expected uncertainties were found using the BTODSTARLNUNP MC simulation.



Correlations between angular asymmetries in B→D* l nu

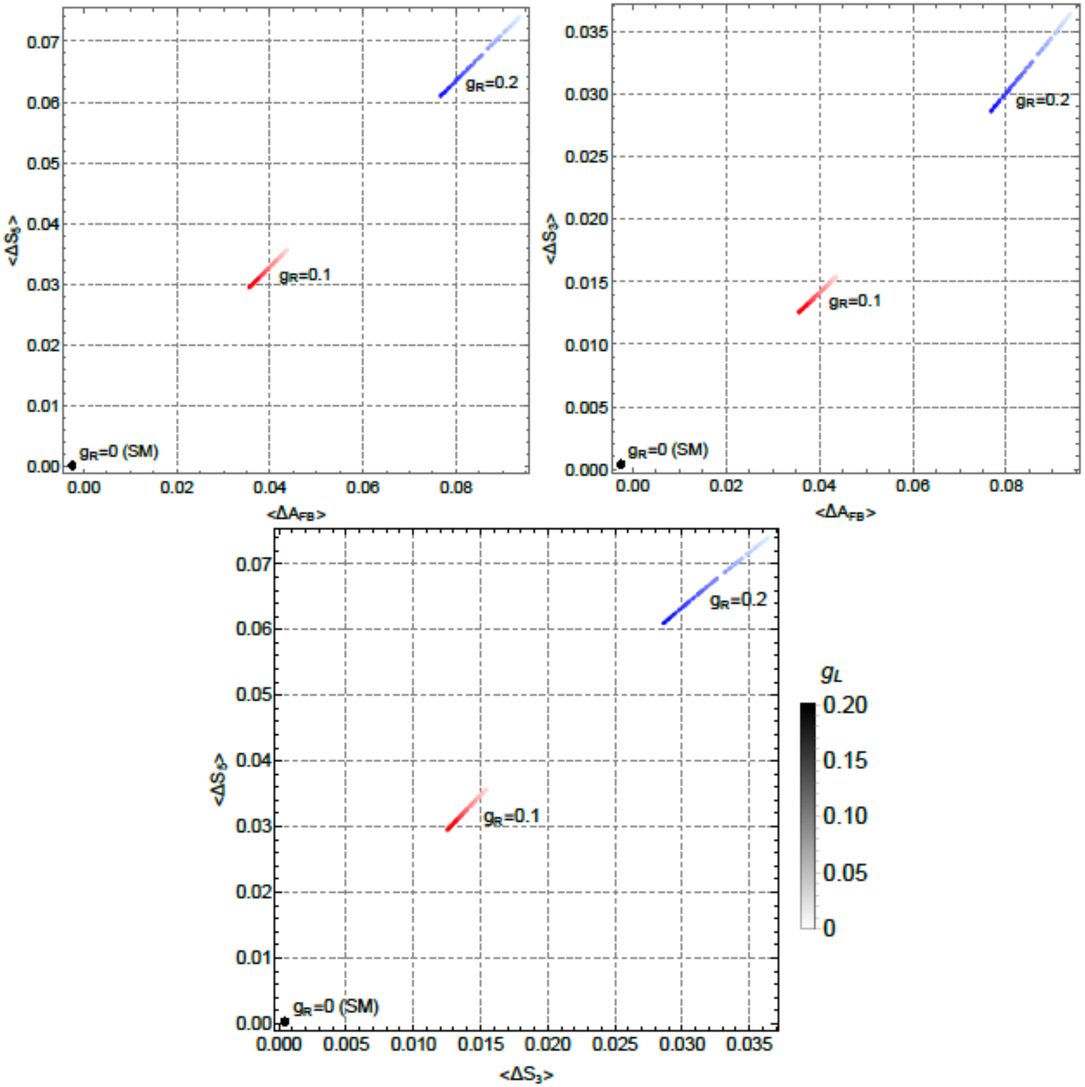


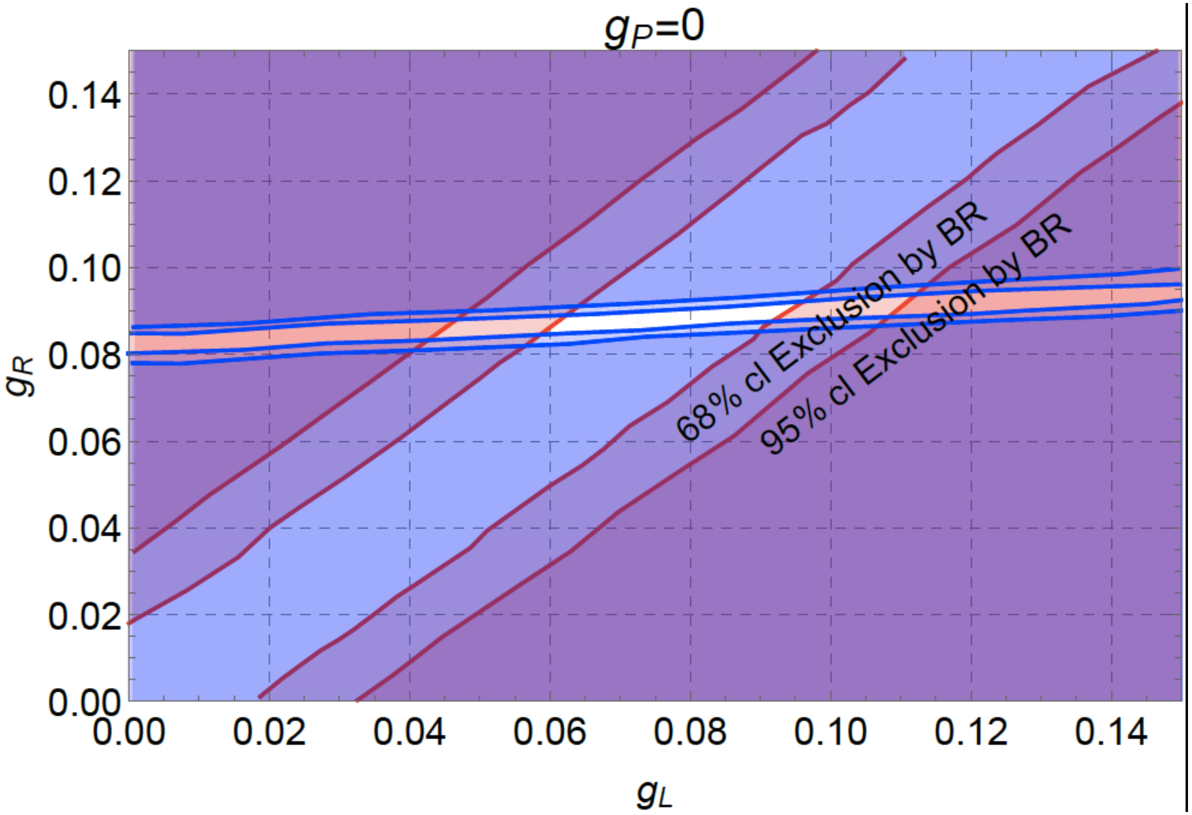
FIG. 8. Correlations between $\langle \Delta A_{FB} \rangle$, $\langle \Delta S_3 \rangle$, and $\langle \Delta S_5 \rangle$ in NP scenarios. For each point, g_L is varied between 0 and 0.2 (light to dark in the color scale as depicted in the bar legend; applies for each value of g_R), with $g_R = 0$, 0.1, or 0.2, which are representative values in the allowed range, and $g_P = 0$. All points for which only g_L is non-zero return the SM values of the three observables.

An important illustration of constraints on BSM couplings (g_R and g_L)

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

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

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



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

Note that the LFV in the ratio of B→D* l nu branching fractions to muons and electrons is already well constrained (<2%)

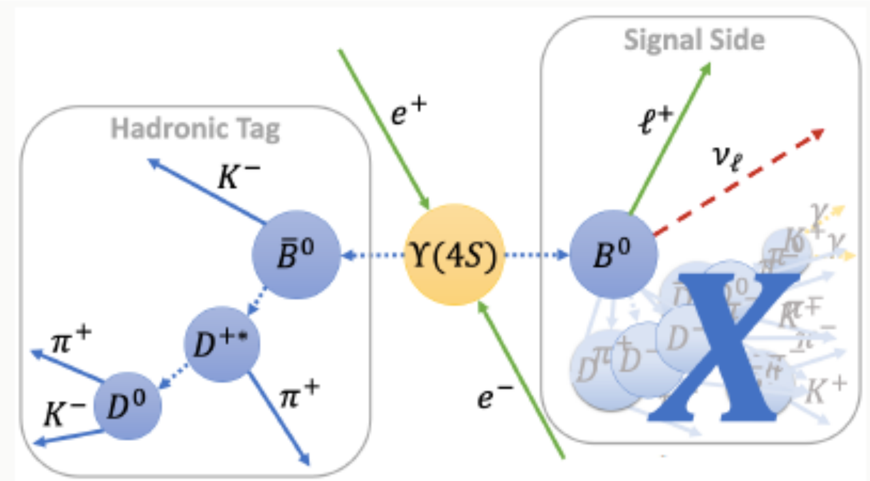
https://arxiv.org/abs/2203.07189

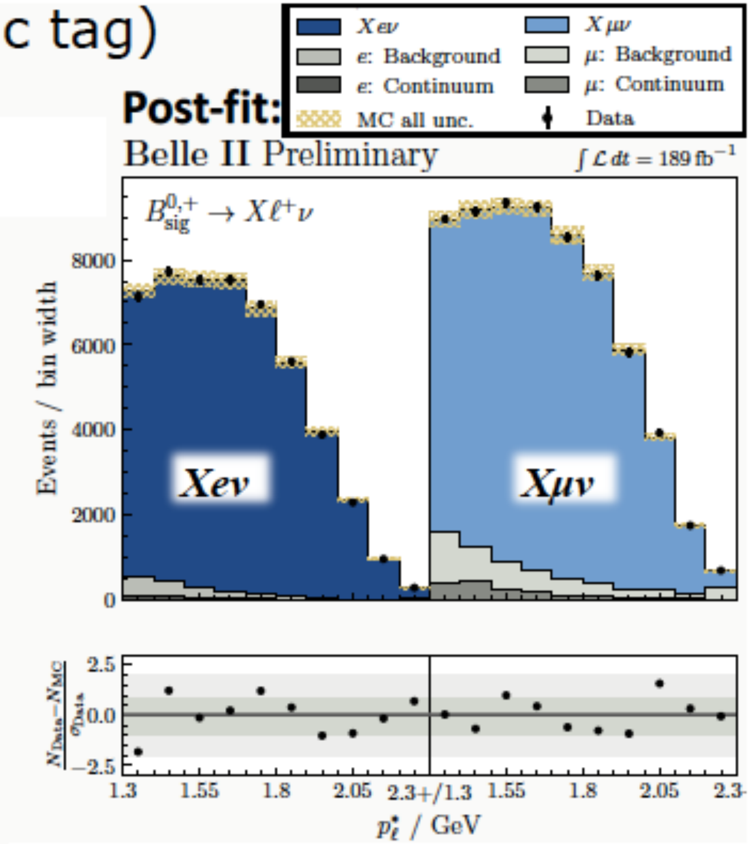
Plots: Quinn Campagna (Ole Miss)

Test of e/μ universality (Belle II)

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

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





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

- ➢ Most precise LFU test in b→cl⁻ν to date
  - ➢ precursor to an inclusive *B*→*X*τν / *B*→*Xl*ν measurement

https://arxiv.org/abs/2301.08266, submitted to PRL

Lepton Universality Tests in $b \to s\ l^+ l^-$ transitions

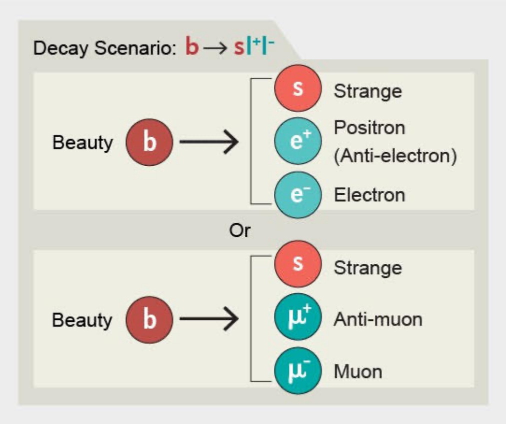
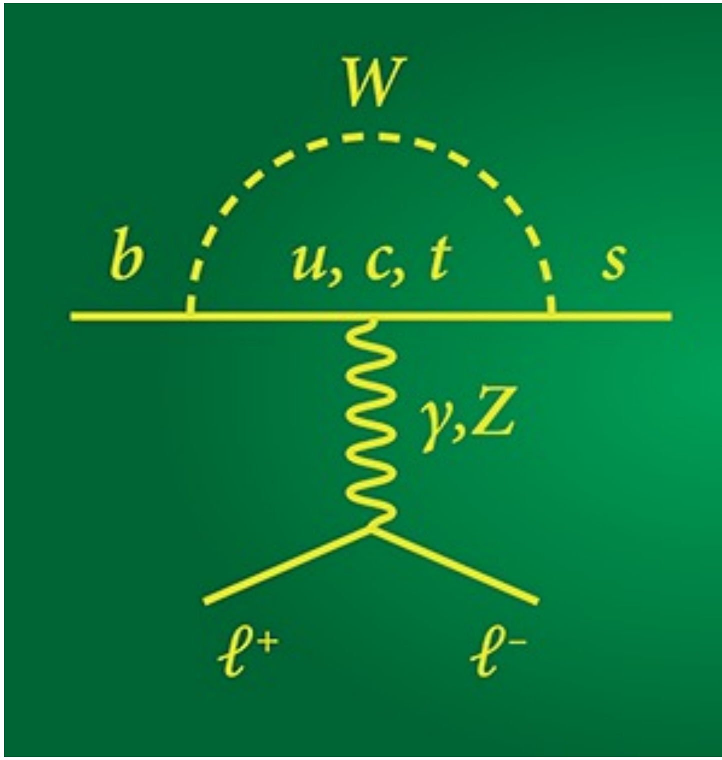
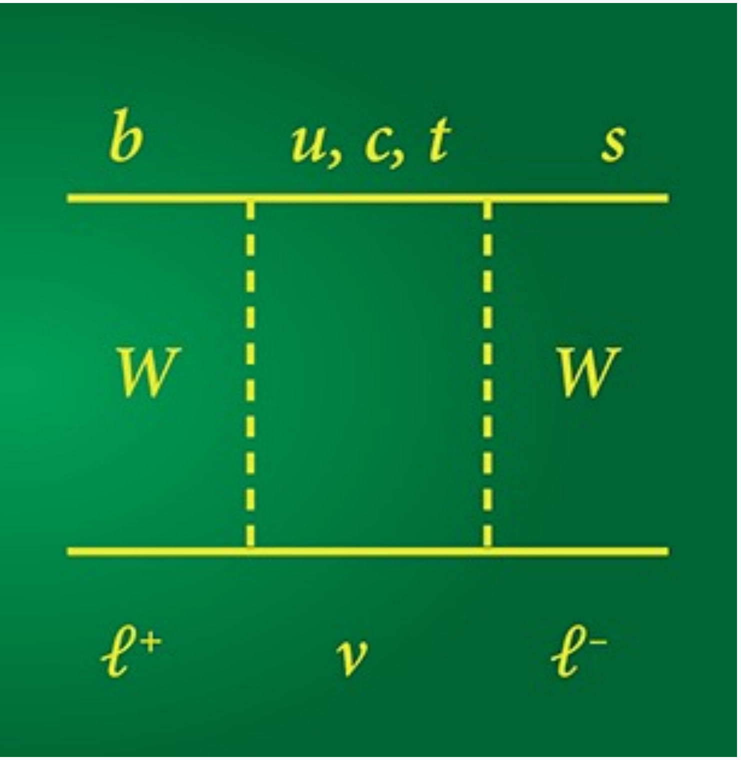


Figure credit: Scientific American



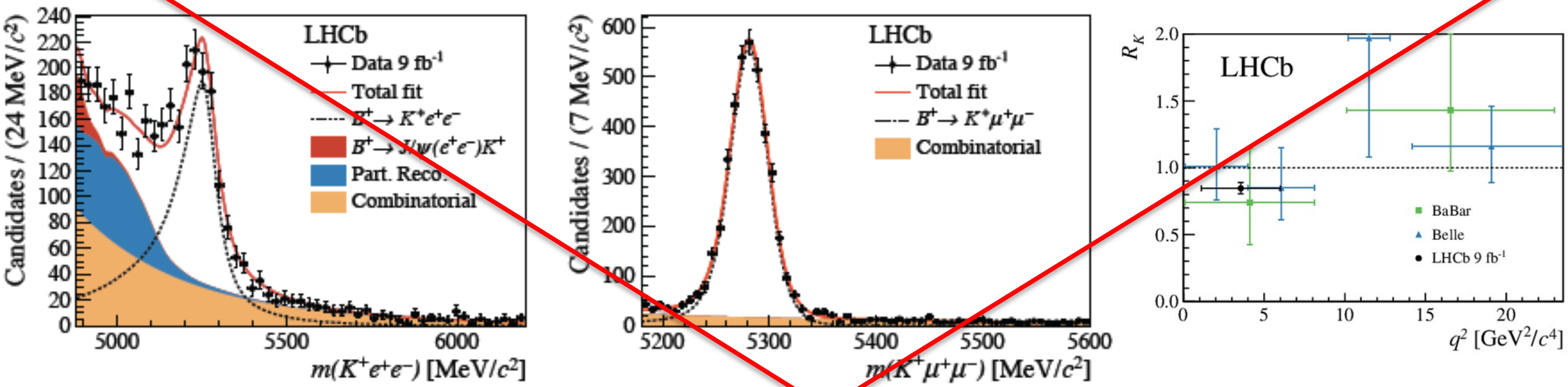
“Electroweak Penguin”



“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



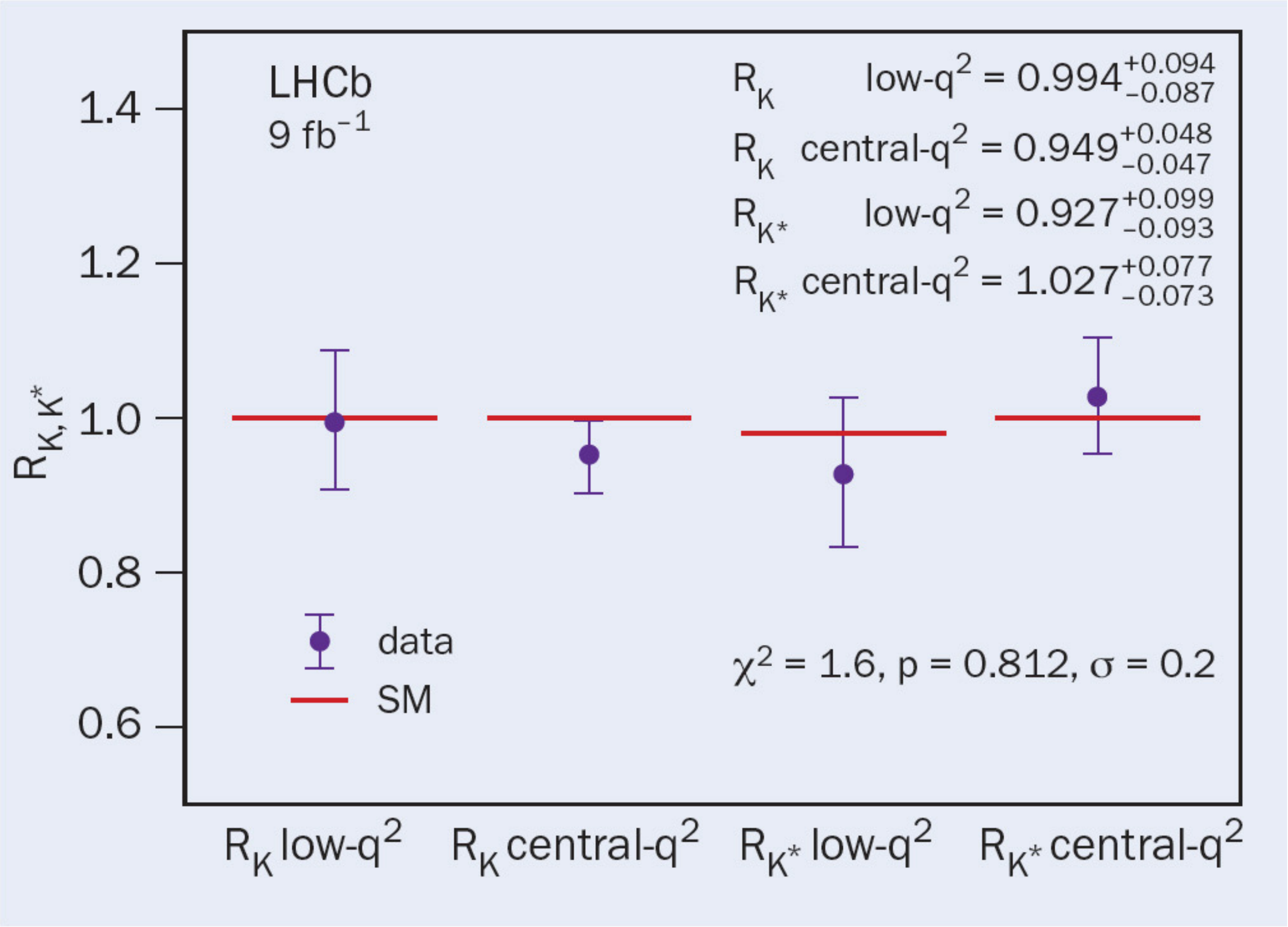
$$R_K = \frac{BF(B^+ \to K^+\mu^+\mu^-)}{BF(B^+ \to J/\psi(\to \mu^+\mu^-)K^+} \Big/ \frac{BF(B^+ \to K^+e^+e^-)}{BF(B^+ \to J/\psi(\to e^+e^-)K^+}$$

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

<1 (lepton universality prediction)

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

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



See talk by Mitesh Patel at this workshop for details.

Details in https://arxiv.org/abs/2212.09153

“Although a component of this shift can be attributed to statistical effects, it is understood that this change is primarily due to systematic effects,” explains LHCb spokesperson Chris Parkes of the University of Manchester. “The systematic shift in R(K) in the central q^2 region compared to the 2021 result stems from an improved understanding of misidentified hadronic backgrounds to electrons, due to an underestimation of such backgrounds and the description of the distribution of these components in the fit. New datasets will allow us to further research this interesting topic, along with other key measurements relevant to the flavour anomalies.” –CERN Courier Dec 2021

Time for a shift in thinking:

Look for lepton universality violation in $B \to K^* l^+ l^-$ (and $B \to D^* l \nu$) angular distributions.

Use "Delta" Δ observables (comparing electron and muon angular distributions) to fit for BSM Wilson coefficient contributions

https://arxiv.org/abs/2203.06827

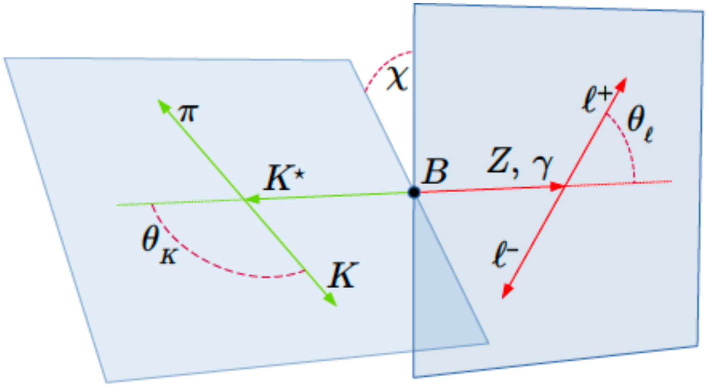
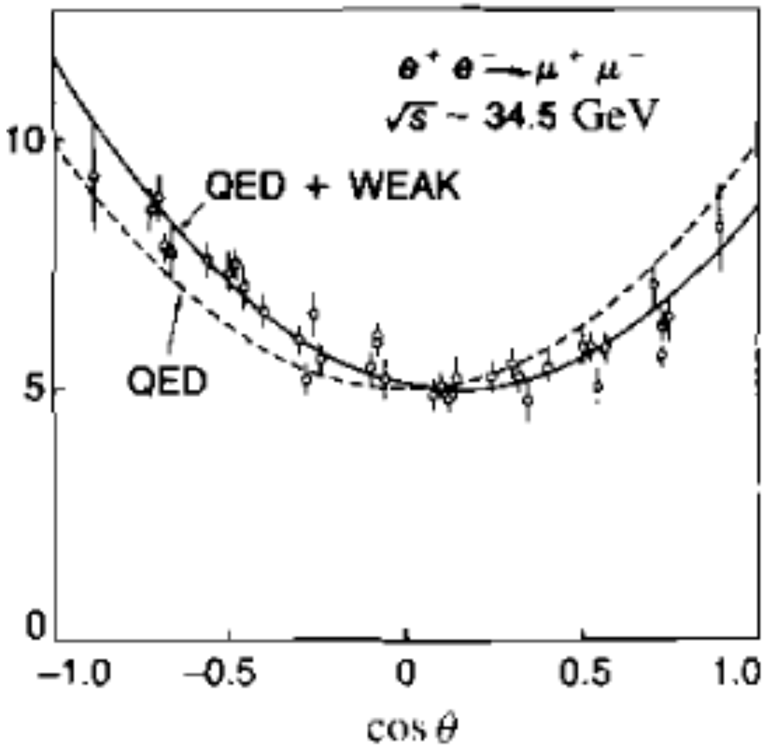
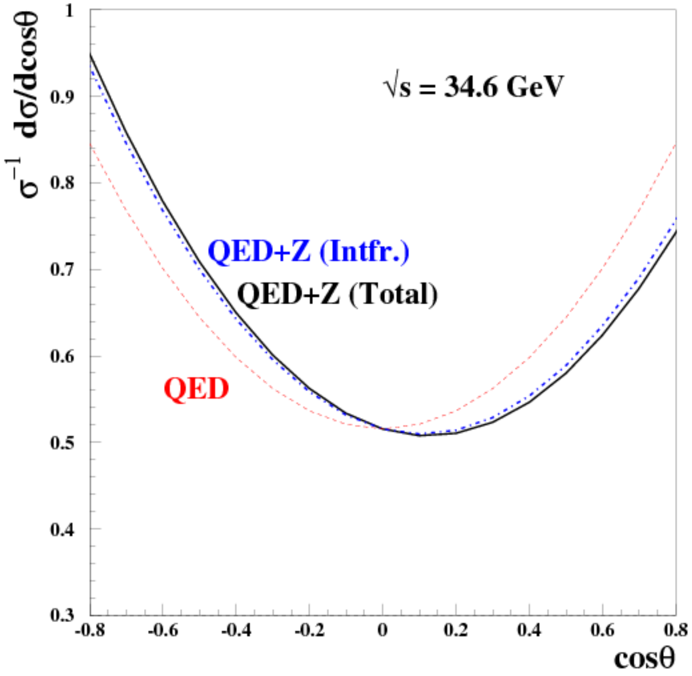


FIG. 1. The $B \to K^* \ell^+ \ell^-$ decay and the subsequent $K^* \to K\pi$ decay kinematic parameters.

Equally strong detection capabilities for electrons and muons. Already publishing a number of lepton universality tests. Ideally suited for this mission.

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

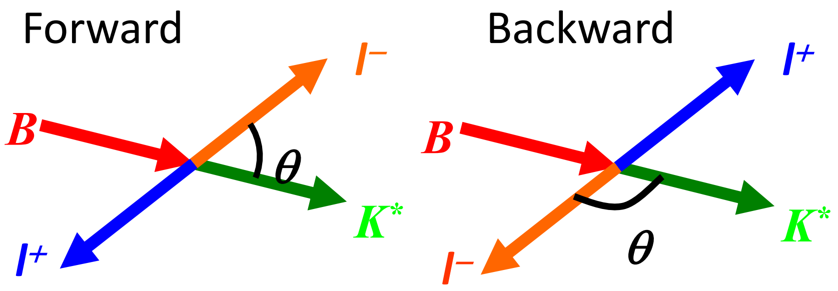


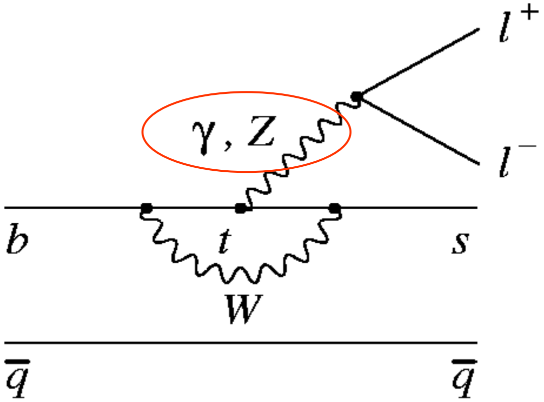


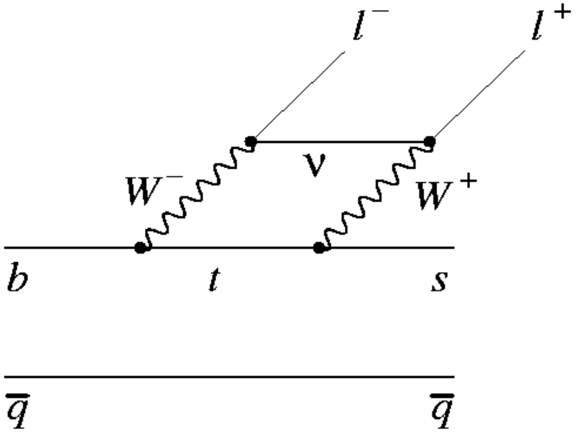
Conclusion from this angular distribution: There is a Z boson at higher energy even though colliders of the time did not have enough $\sqrt{s}$ to produce it ($|A|^2 + |B|^2 + 2A^*B$)

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

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





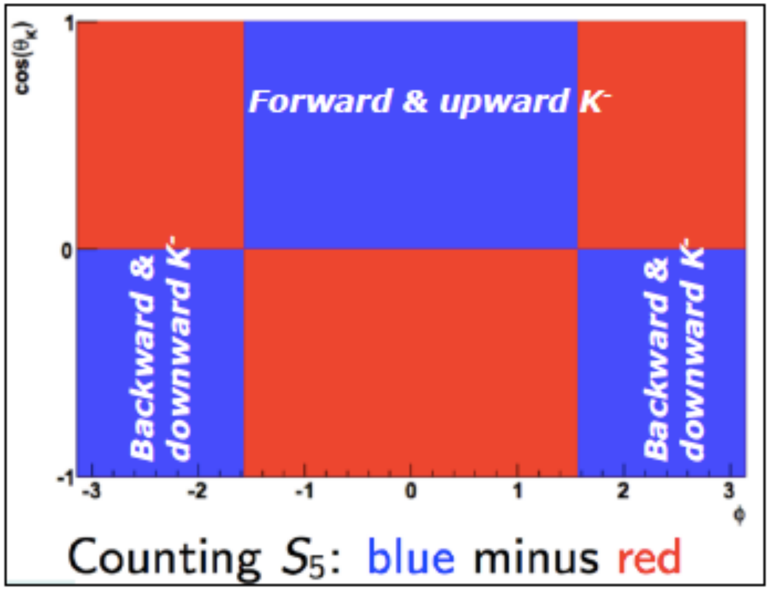


Note that all the heavy particles of the SM (W, Z, top) enter in this decay.

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

Can in effect vary √s for NP

More on angular asymmetries, A_{FB} , $S_5(q^2)$



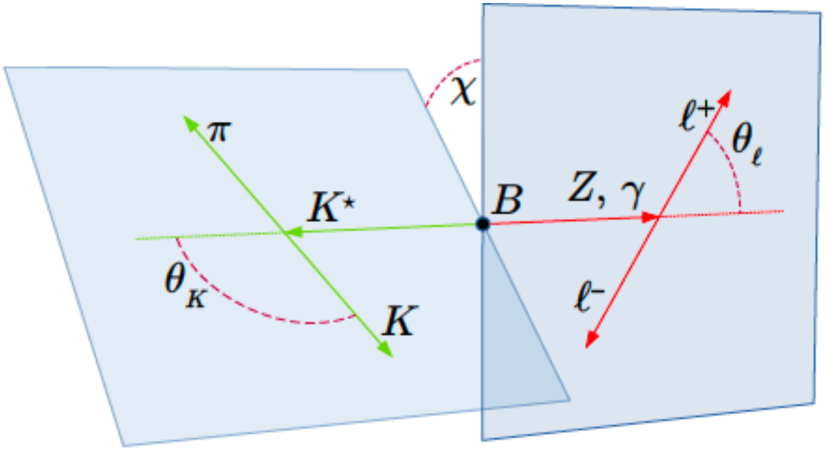
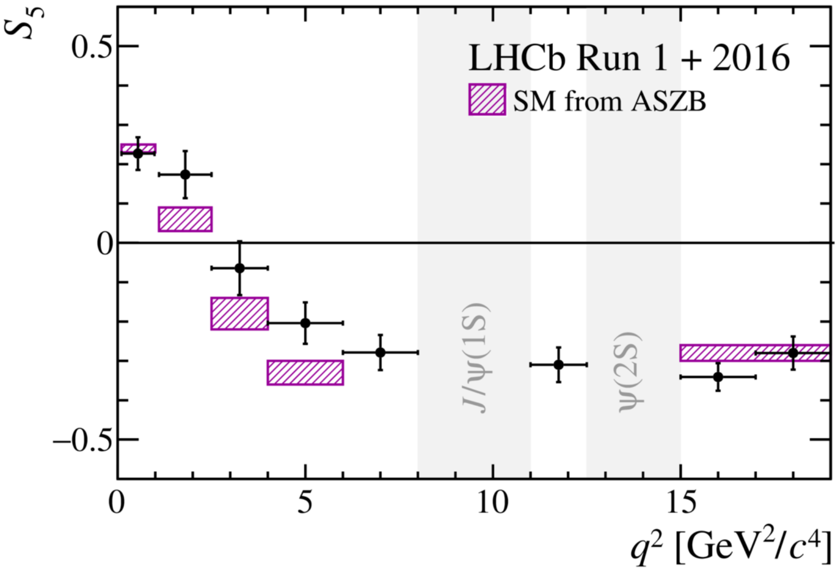


FIG. 1. The $B \to K^* \ell^+ \ell^-$ decay and the subsequent $K^* \to K\pi$ decay kinematic parameters.

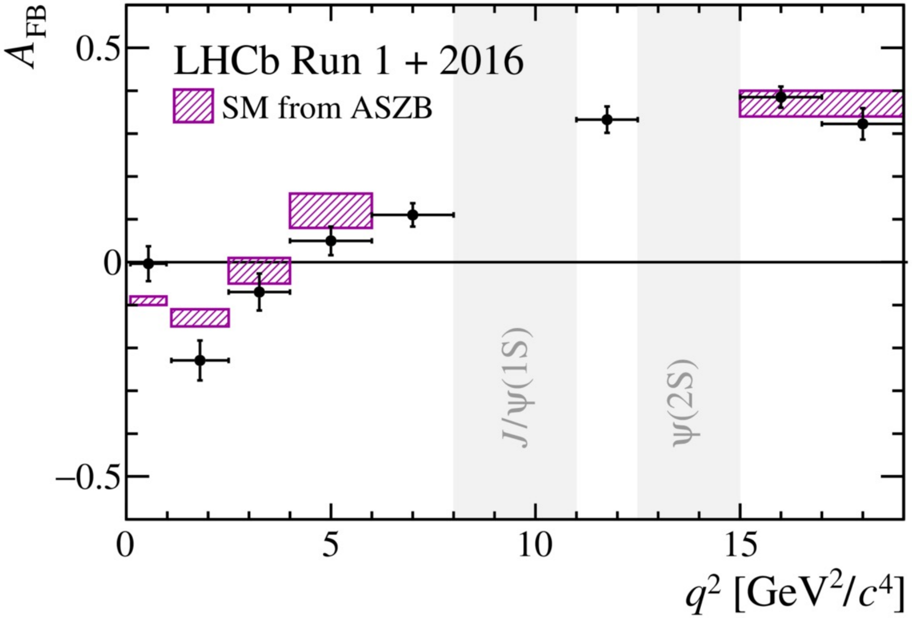
Expect correlated *angular asymmetries* with sensitivity to BSM physics.

Published LHCb 5 fb^{-1} results on $B \rightarrow K^* \mu^+\mu^- (q^2)$

A different angular asymmetry, involving χ



Forward-backwards asymmetry



“The P_5’ measurements <u>are only compatible with the SM prediction at a level of 3.7σ</u>…..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” (LHCb 2015 conference paper)

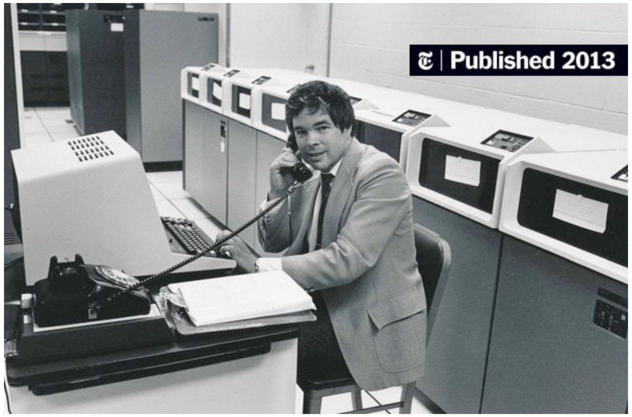
These angular asymmetries persist in 2023

Feynman Diagrams and Model Building

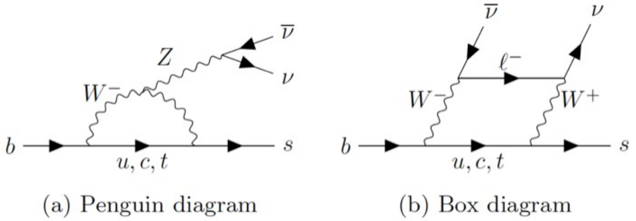
Effective Field Theory →Wilson Coefficients

Feynman family and diagrams

Paradigm shift



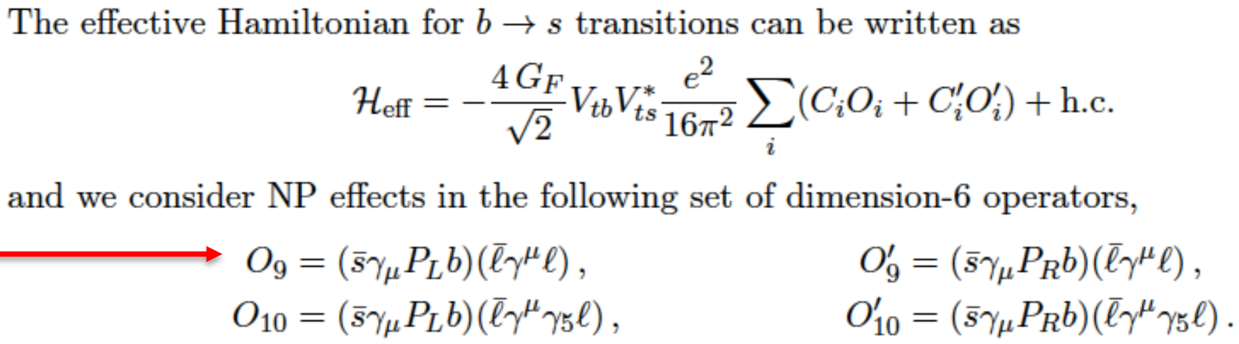
Ken Wilson ("Wilson coefficients")



(a) Penguin diagram (b) Box diagram

C_7, C_9, C_{10}

New Physics/BSM 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,

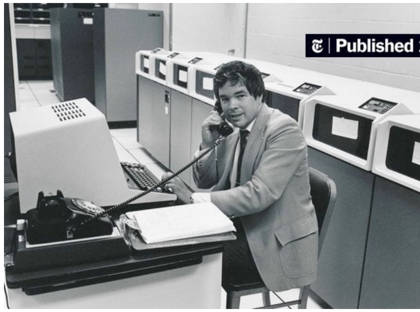
$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

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

The primes are NP right-handed couplings.

New Physics Couplings in b→s

Feynman
family and
diagrams



Ken Wilson

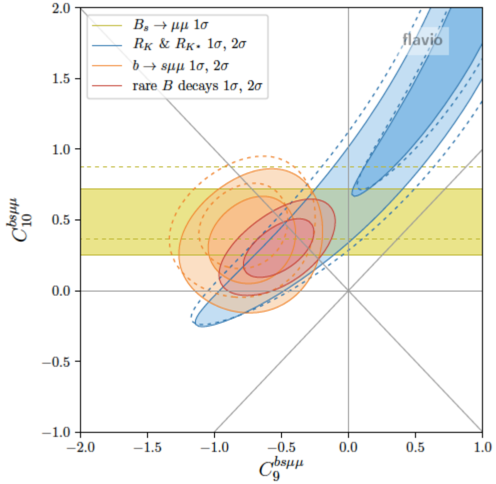
The effective Hamiltonian for $b \to s$ transitions can be written as

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

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 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 : ~3.4σ from the SM

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

Traditional approach to $B \rightarrow K^* l+ l-$: in data: look at A_{FB} and S_5 in coarse bins of q^2

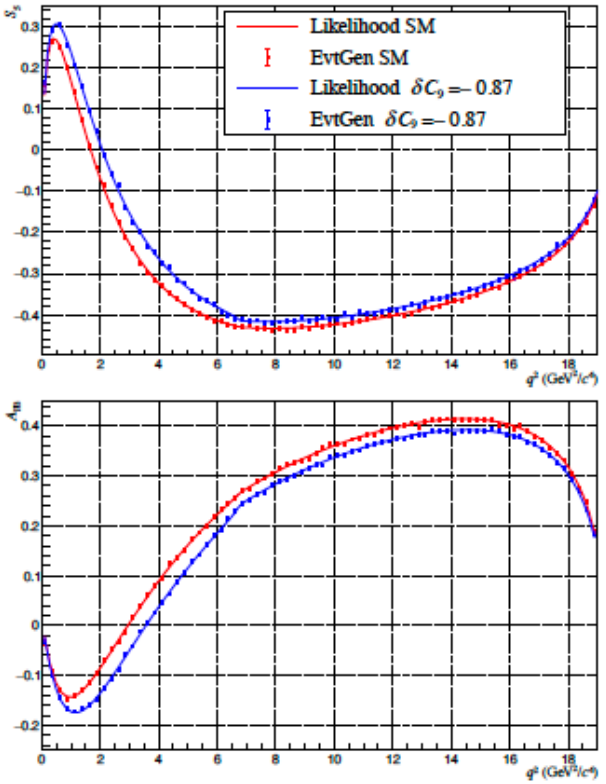


FIG. 6. Comparison of S_5 (top plot) and A_{FB} (bottom plot) observables with BSM $\delta C_9 = -0.87$ and SM $\delta C_9 = 0$ in the di-muon mode. The points are generated with the BSM **EvtGen** simulation while the curves are the results of integrating the four-dimensional likelihood function.

"No one-bin wonders". Shifts of A_{FB} are correlated with shifts in S_5 (physics correlation) and vice versa.

Let's dig in deeper to the possible BSM contributions to $B \rightarrow K^*$ l l using our new BSM MC physics generator

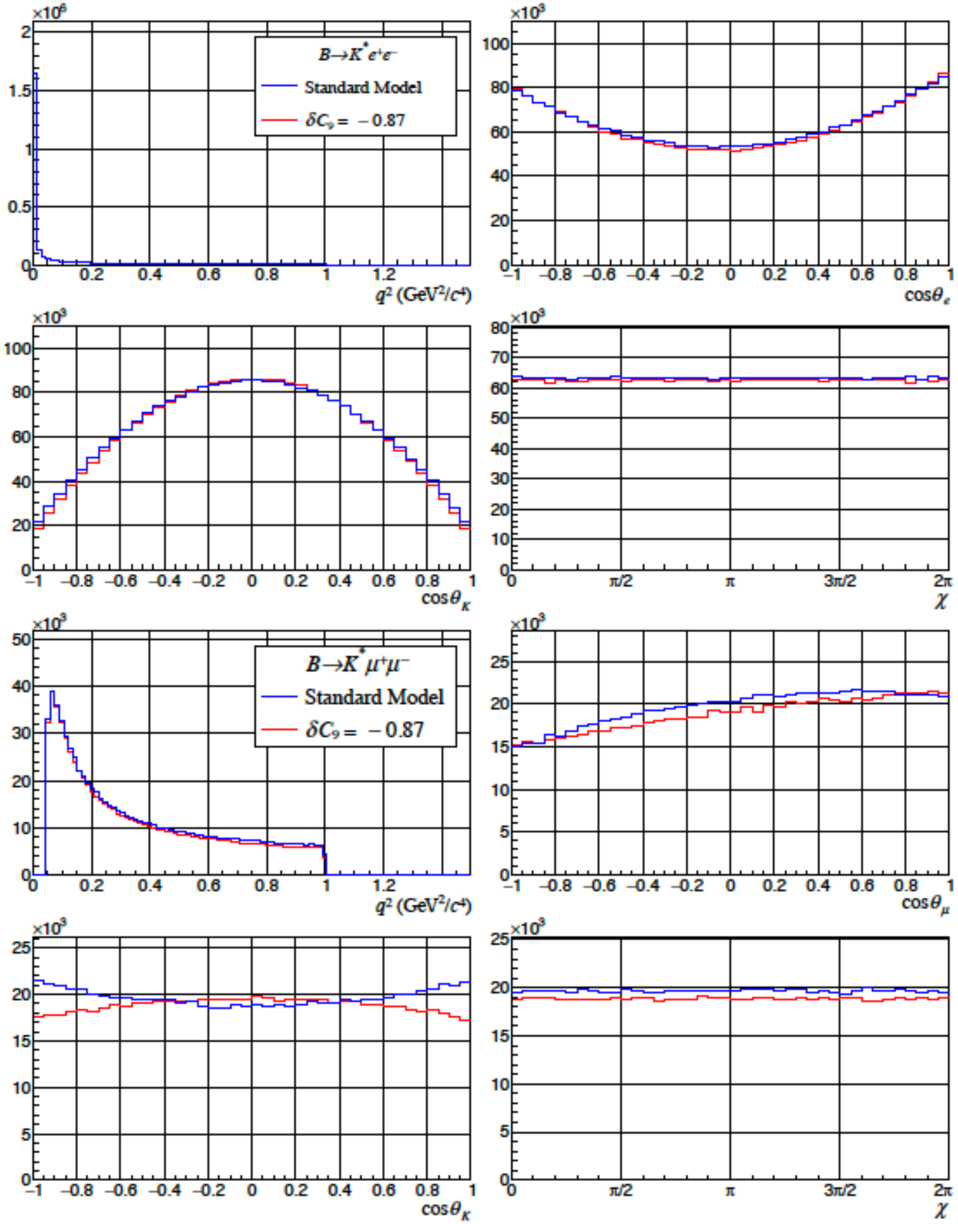
MC

$B \to K^*$ l+ l- @Low q^2 (<1 GeV^2): dielectrons vs dimuons

dielectrons

The “photon pole” dominates so effects are small

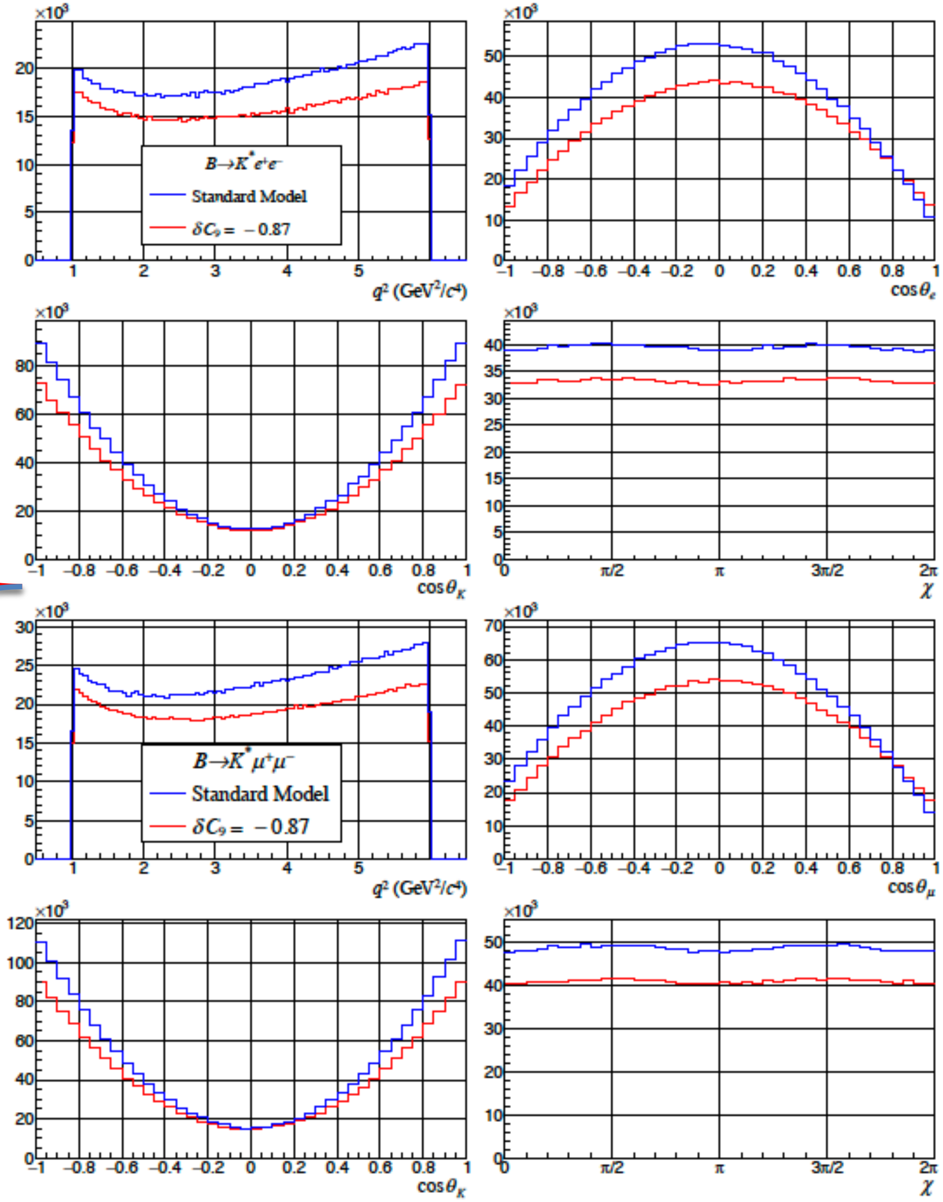
dimuons



Hunting for $\delta C_9 = -0.87$

MC $B \to K^*$ l+ l- @Mid q^2 ([1-6] GeV^2): dielectrons vs dimuons

dielectrons



Now the effects in di-electrons and dimuons are similar

dimuons

Hunting for

$$\delta C_9 = -0.87$$

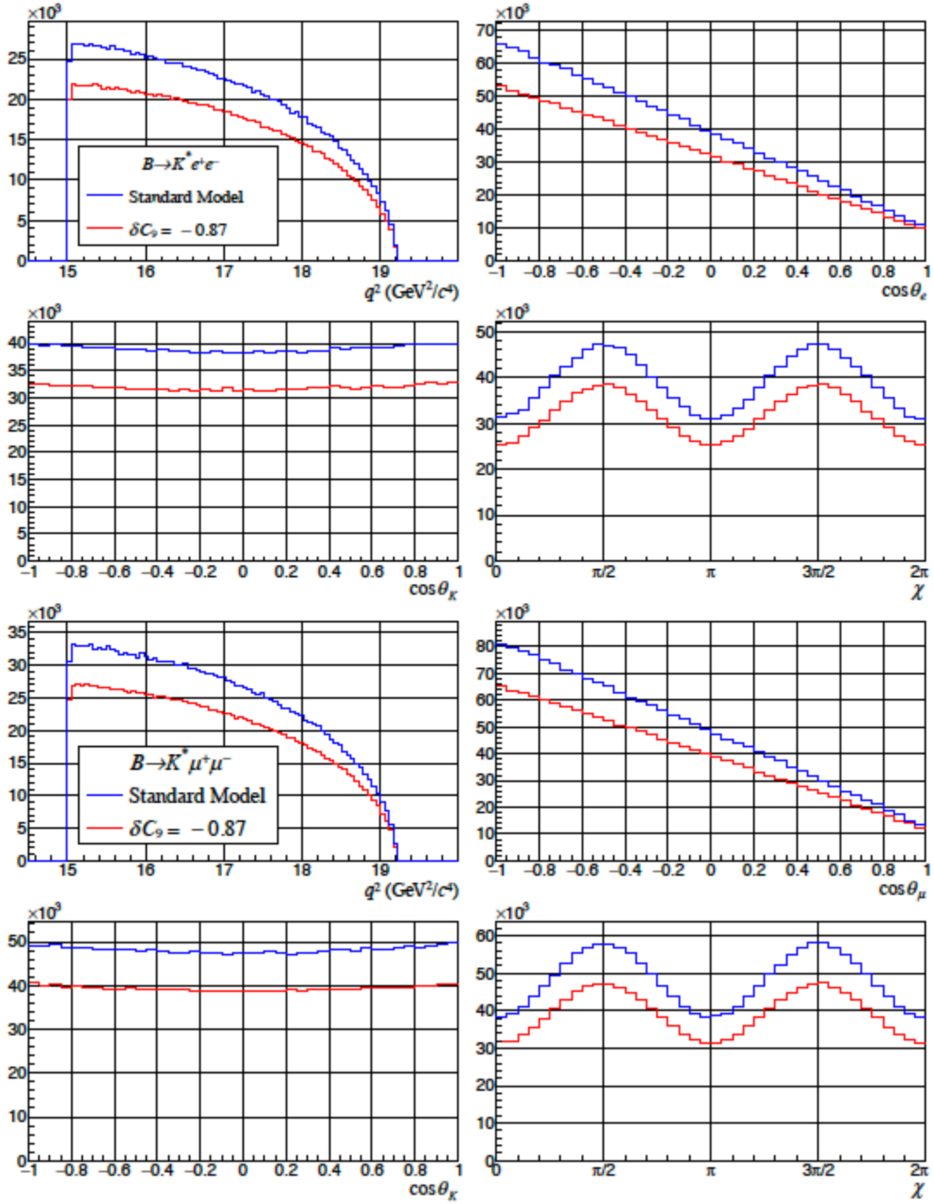
Multiple differences in angles and q^2

MC

$B \rightarrow K^*$ l+ l- @high q^2 ([>15] GeV^2): dielectrons vs dimuons

dielectrons

dimuons



Hunting for

$$\delta C_9 = -0.87$$

Multiple differences in cos θ(lepton) and q^2

Skip if time is short

Hunting for BSM C_7 and BSM C_7'

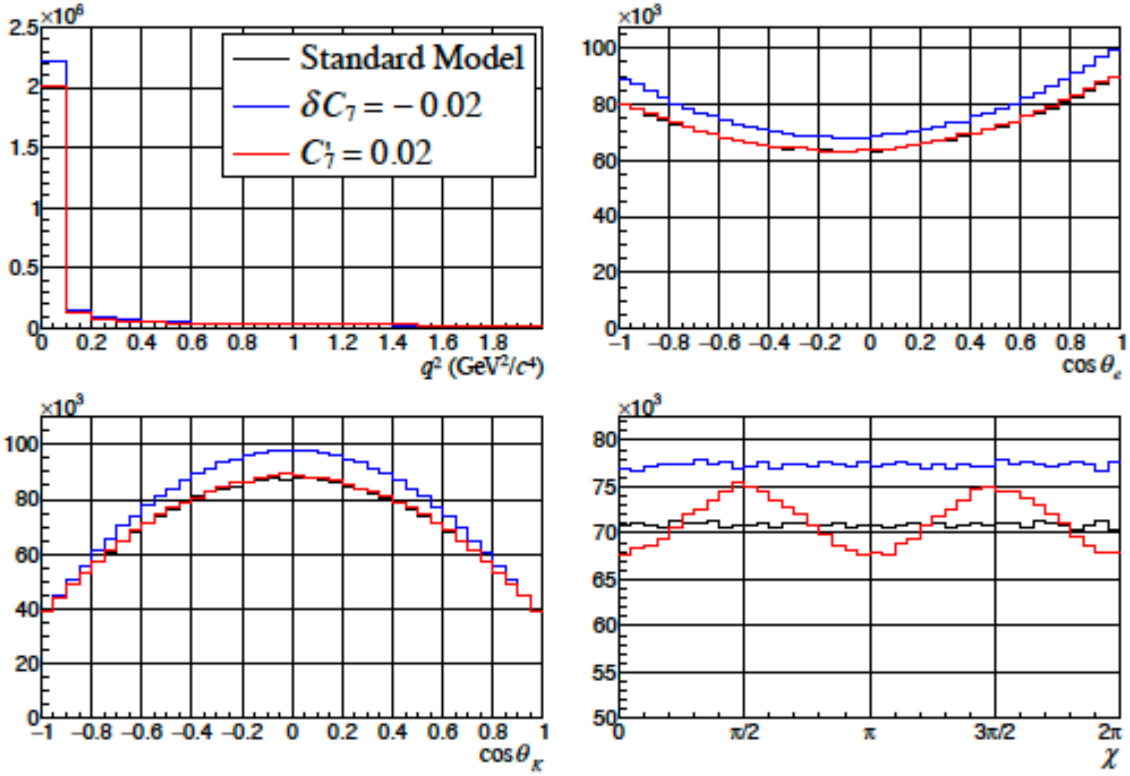
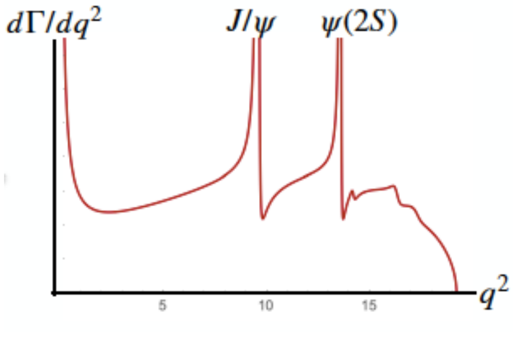


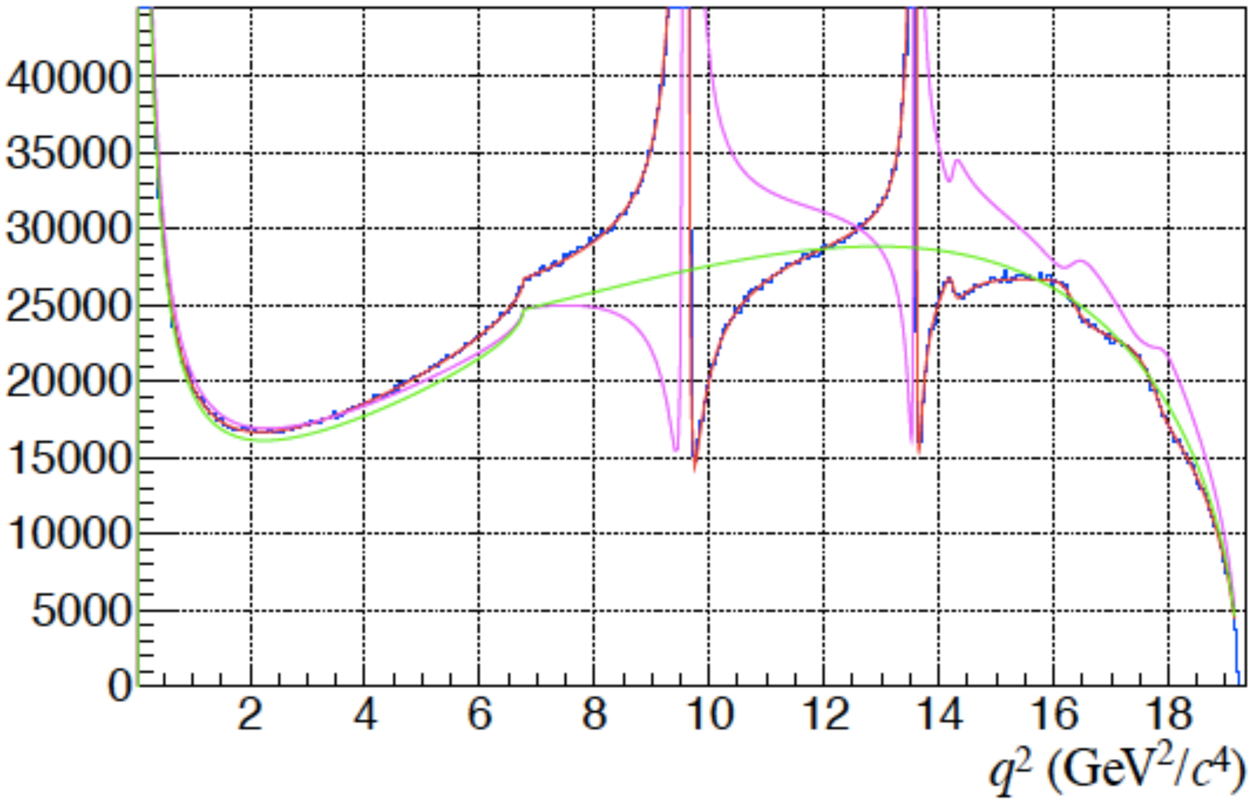
FIG. 3. The effect of C_7' and δC_7 on angular distributions in the Sibidanov Monte Carlo generator in the $B \to K^* e^+ e^-$ decay mode for $q^2 < 2\, GeV^2/c^4$. There is a striking modulation in the χ angle distribution due to a right-handed BSM physics contribution as well as clear left-handed BSM signatures at low q^2 and in cosθ_K.



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

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

Alexei Sibidanov



https://arxiv.org/abs/2203.06827

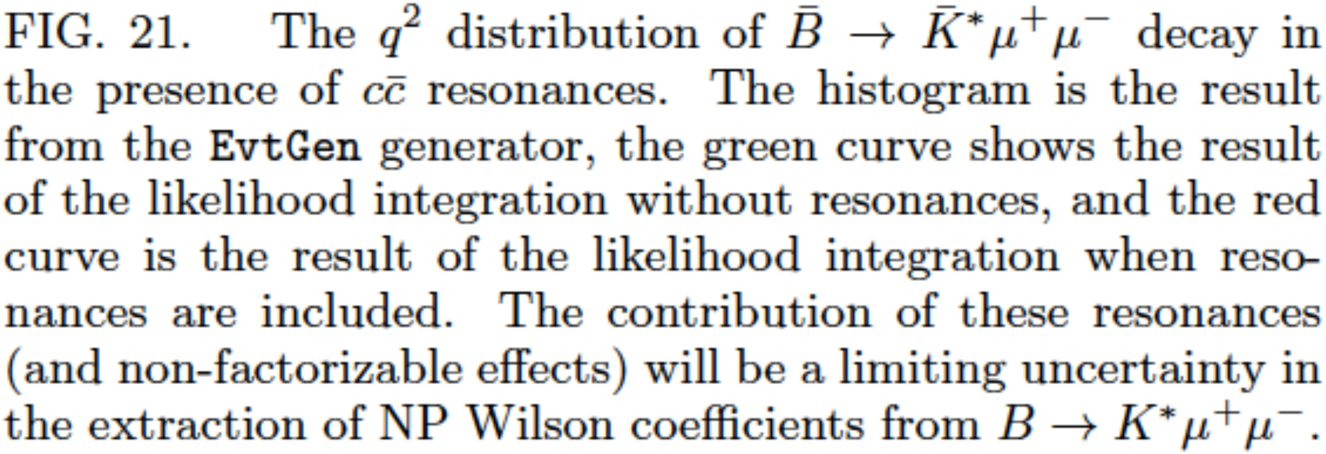
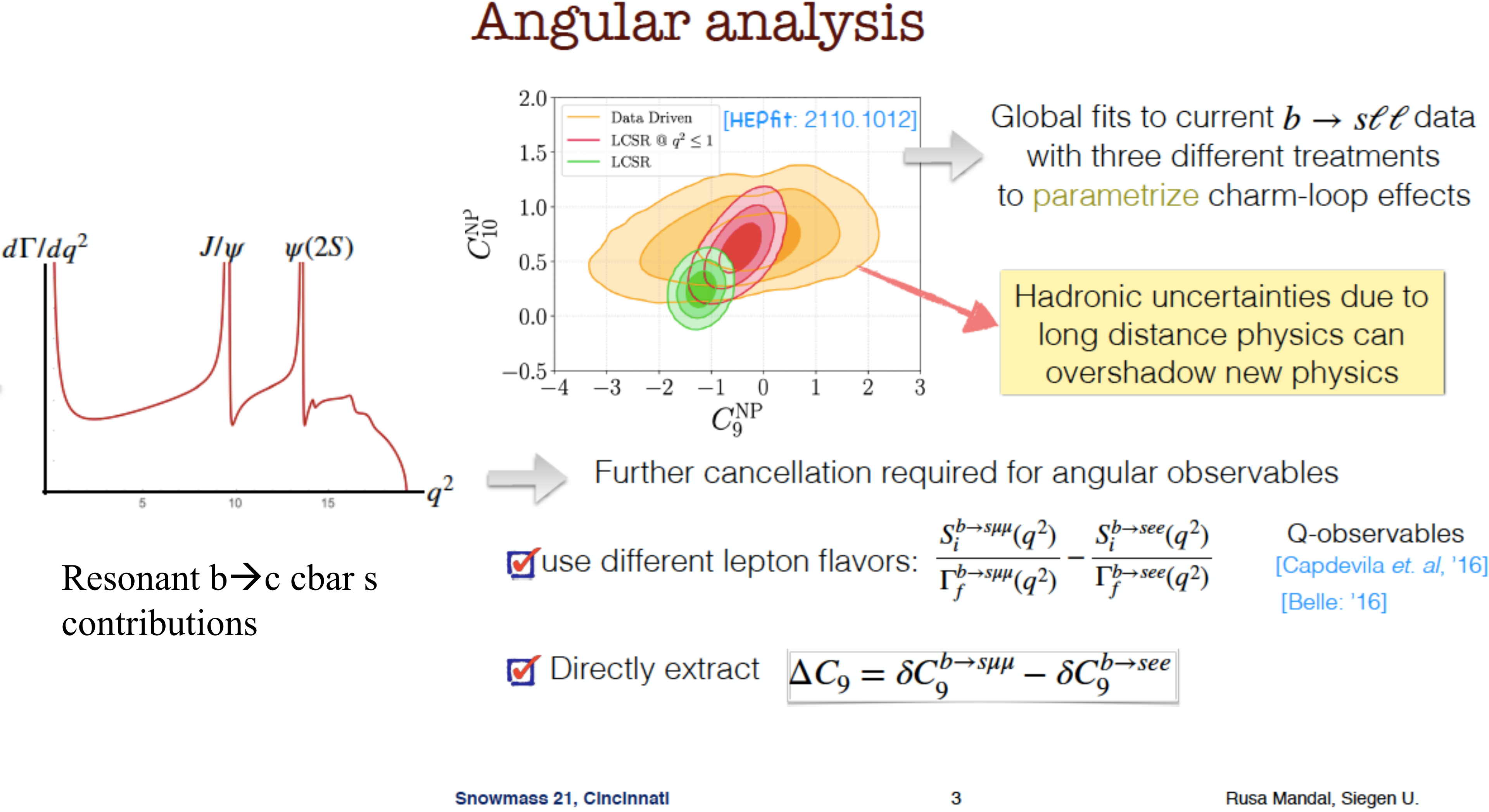


FIG. 21. The q^2 distribution of $\bar{B} \to \bar{K}^* \mu^+ \mu^-$ decay in the presence of $c\bar{c}$ resonances. The histogram is the result from the **EvtGen** generator, the green curve shows the result of the likelihood integration without resonances, and the red curve is the result of the likelihood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

A Snowmass Highlight:



Angular analysis

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

Resonant b→c cbar s contributions

☑ 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 of strong interaction uncertainties is the Delta (Δ) Observables.

https://arxiv.org/abs/2203.06827

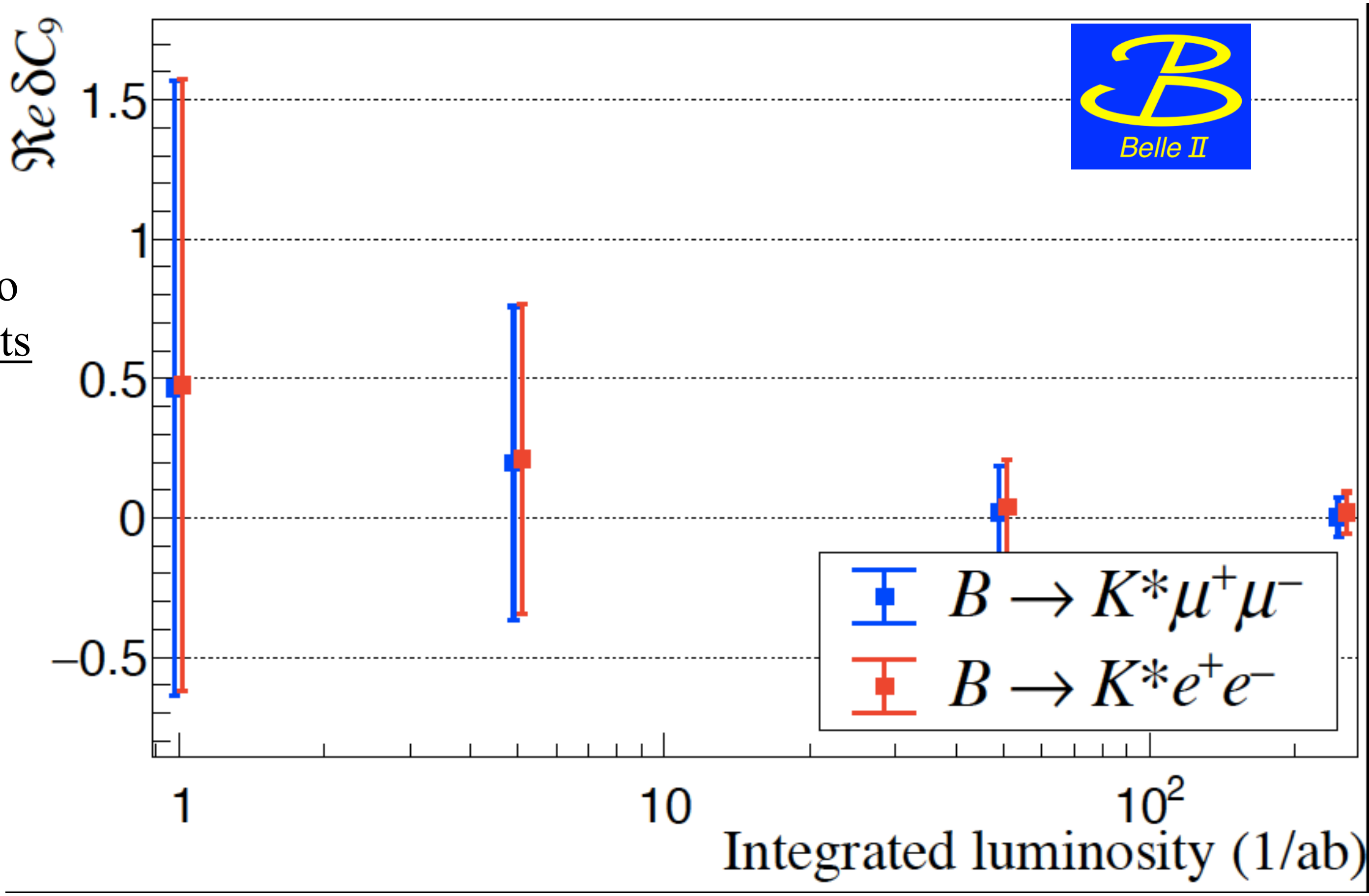
Reminder and Motivation:

C_9 : Global fit to world b→s data still gives a 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.

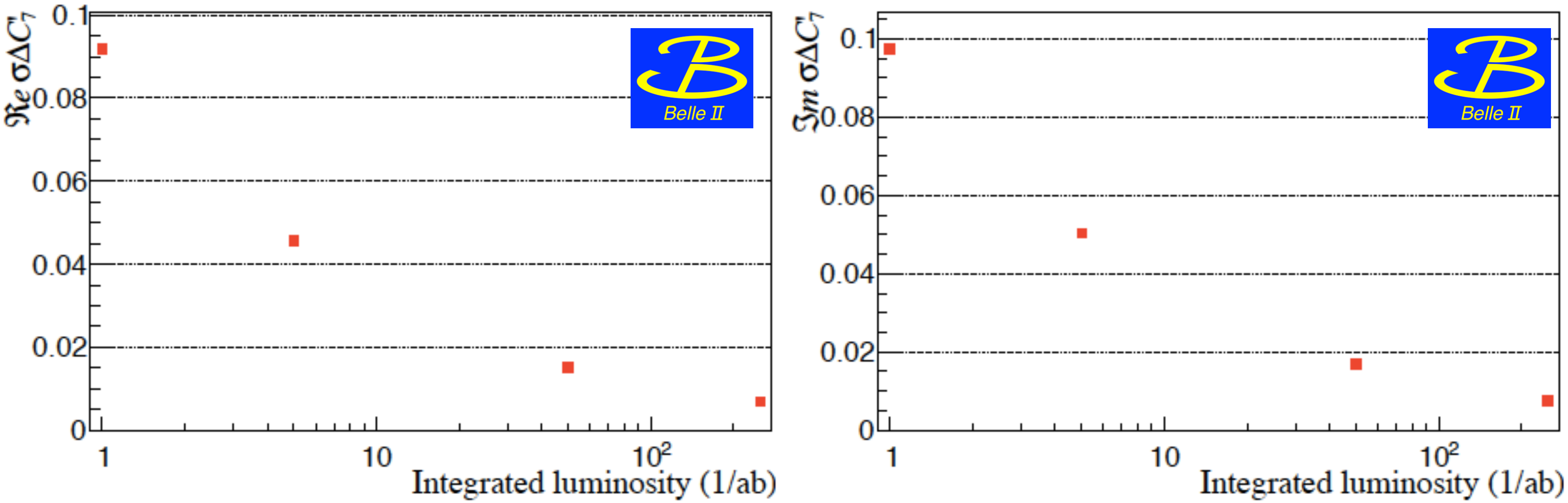
https://arxiv.org/abs/2203.07189

Apres-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.

Skip if time is short

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

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



Apres-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.

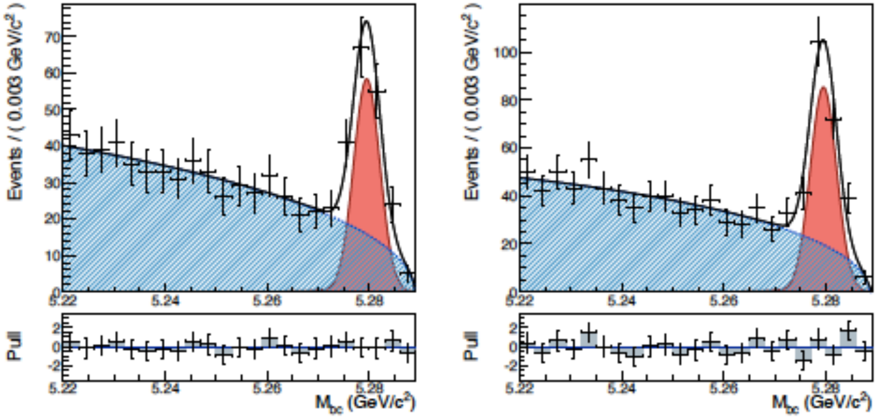


FIG. 1. Distribution of the beam-energy constrained mass for selected $B \to K^* e^+ e^-$ (left) and $B \to K^* \mu^+ \mu^-$ (right). Combinatorial background (shaded blue), signal (red filled) and total (solid) fit functions are superimposed on the data points

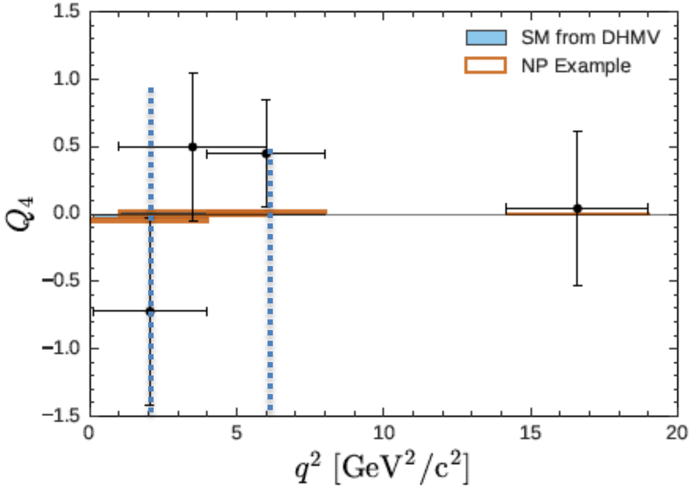
$$\Delta P_4' = P_4'(B \to K^* \mu^+ \mu^-) - P_4'(B \to K^* e^+ e^-)$$

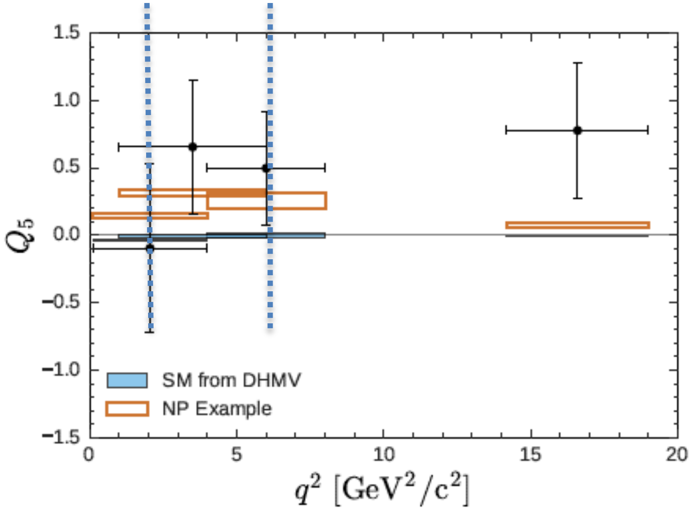
a.k.a. Q_4

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

a.k.a. Q_5

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

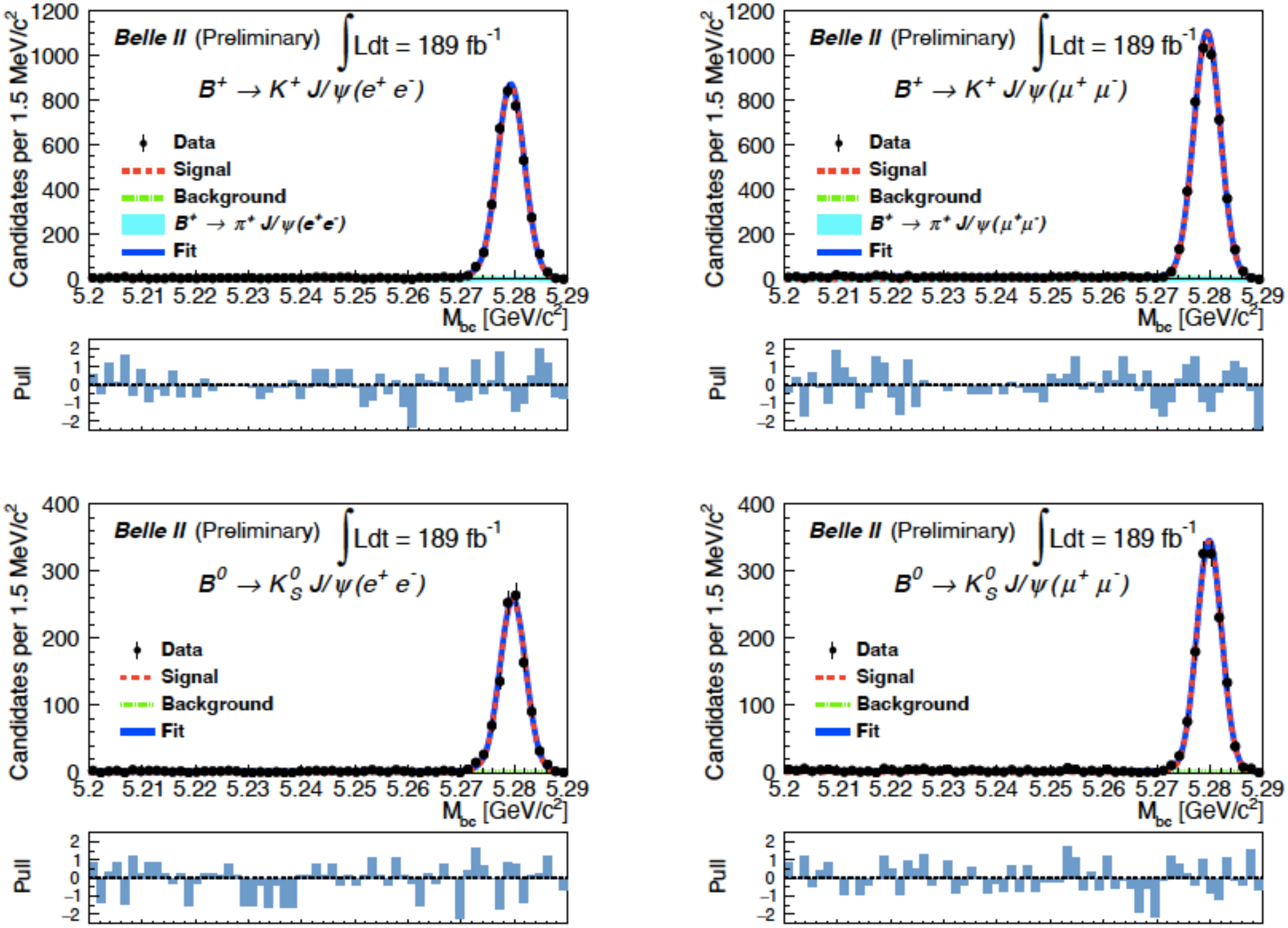




S. Wehle, C. Niebuhr, S. Yashchenko, et al.
(Belle Collaboration), PRL118, 111801 (2017)

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

Includes brems recovery for electrons



https://arxiv.org/abs/2207.11275

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

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

Still work in progress

AI/ML and BSM Wilson coefficients

Idea: instead of 4-d max L fitting, convert the 4d distribution into an image and use CNNs to extract the BSM Wilson coefficient

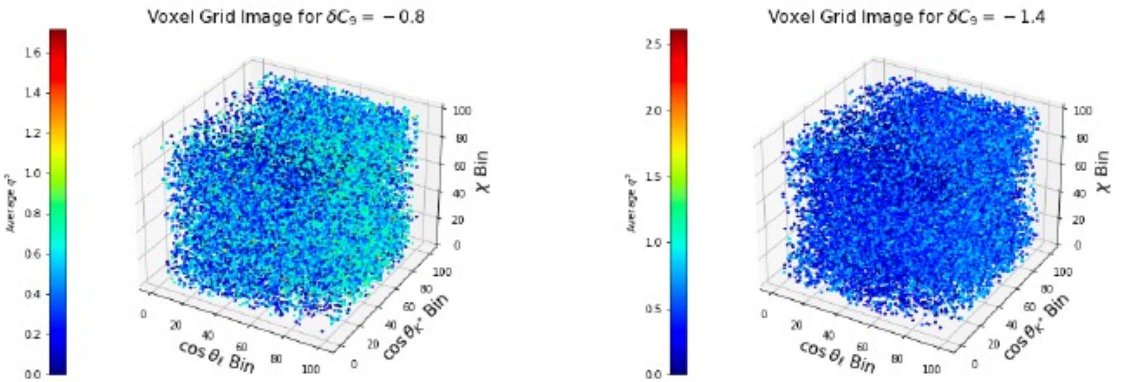
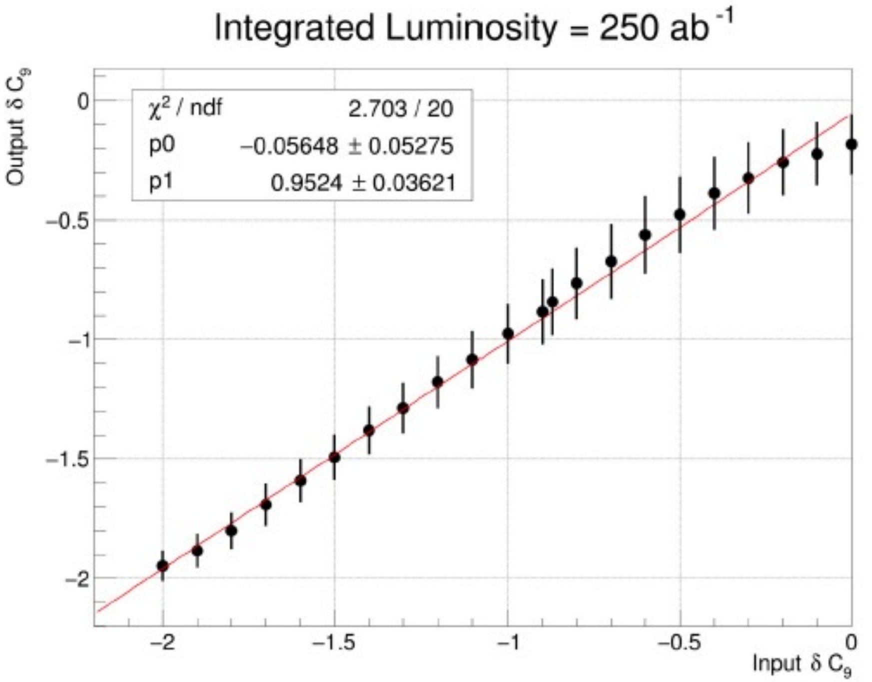


FIG. 8. The "images" of $B \to K^* \ell^- \ell^+$ angular observable data for two values of NP contributions to the operator C_9. Dubey and Browder are using a CNN (Convolutional Neural Net) to fit for δC_9 and BSM signals.

Technical point: Can add a background image from an Mbc sideband to the image.

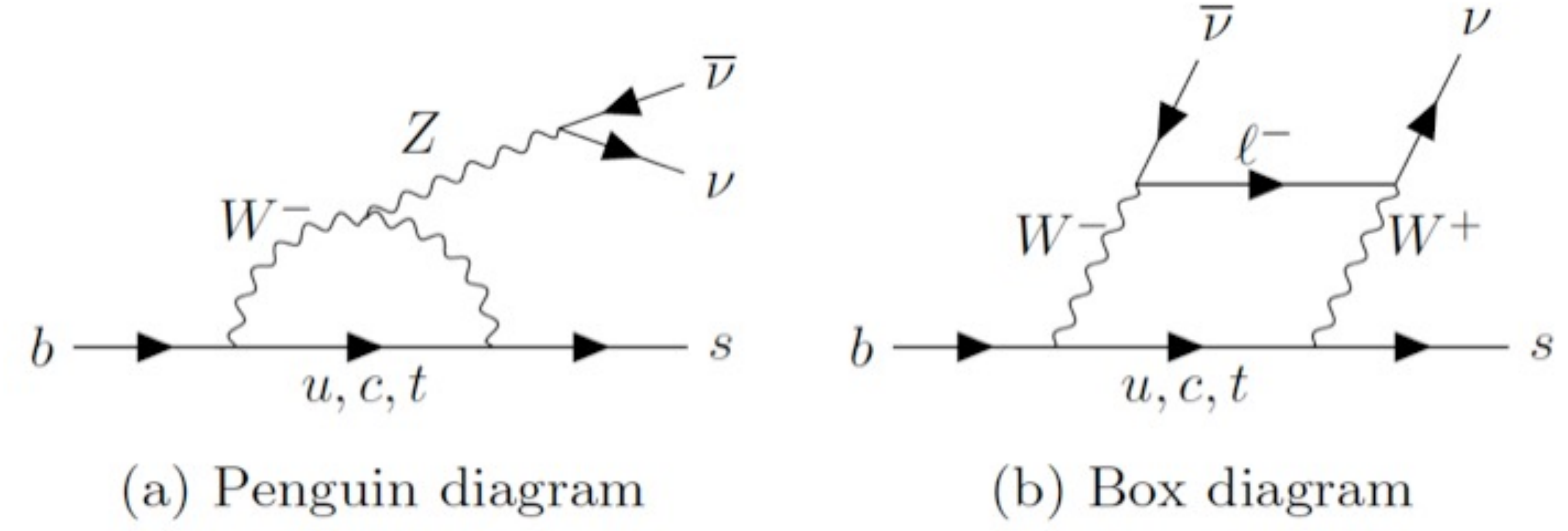


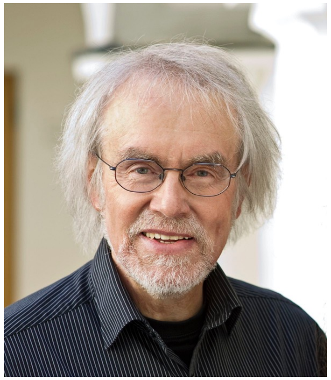
Regression via a convolutional neural network (CNN).

This is regression not classification (i.e. "dog vs cat")

S. Dubey et al.

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





Andrezj
Buras

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

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

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

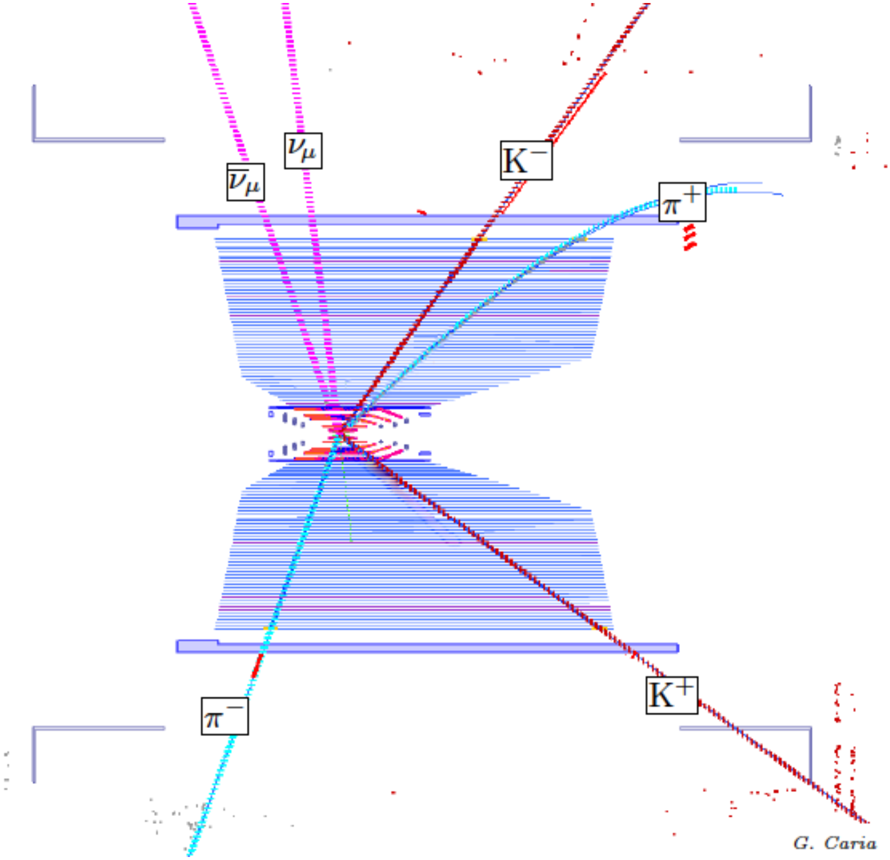
Realizing “Buras’ clean dream” in Belle II ?

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

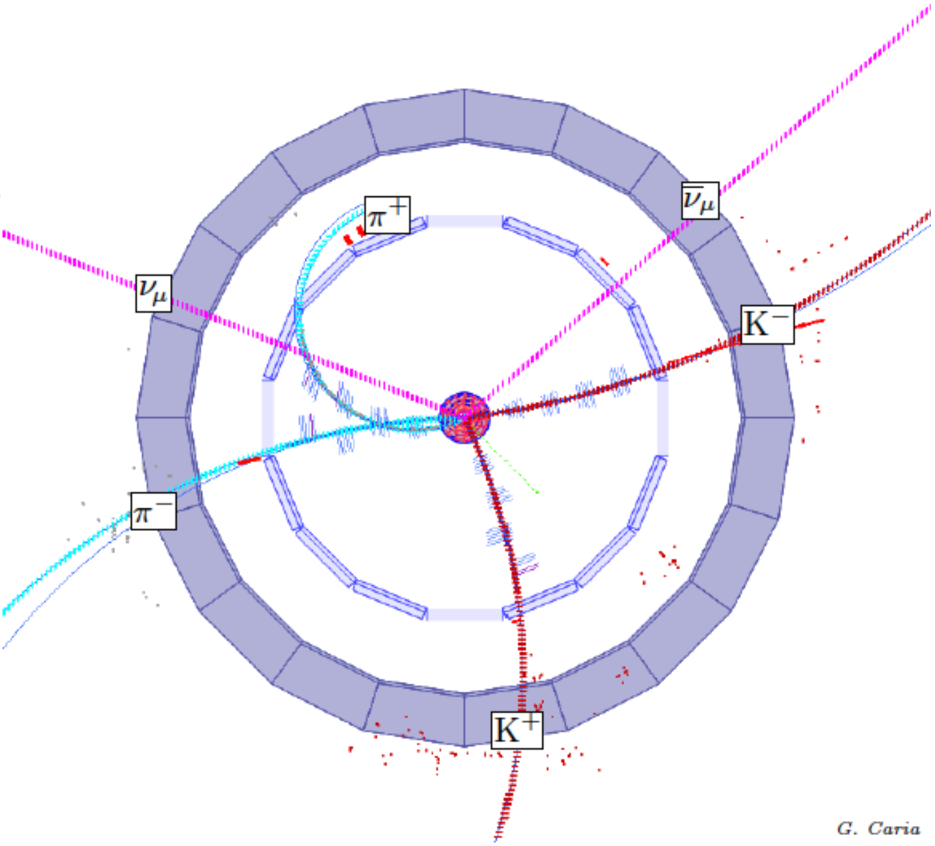
Signal: B→K ν ν

tag mode: B→Dπ; D→Kπ

View in r-z



Zoomed view of the vertex region in r--phi



B→K ν νbar: NP without hadronic uncertainties

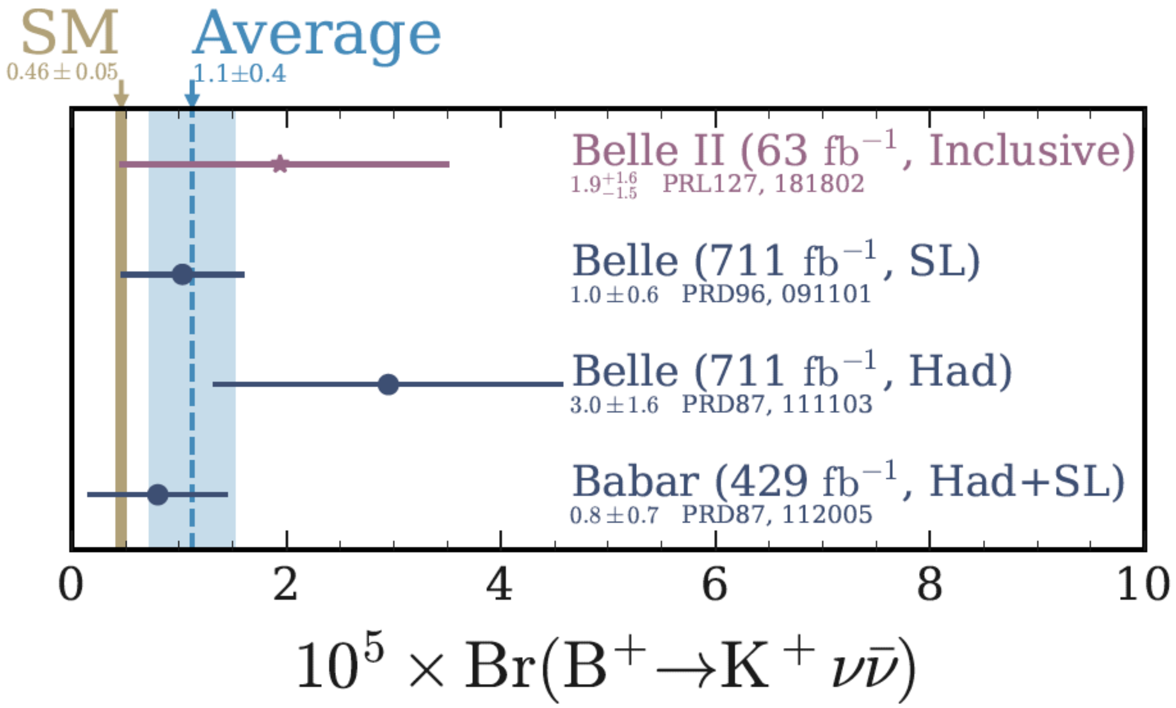
An emerging anomaly ???

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

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

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

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



It is quite possible that NP shows up in b→s nu nubar and not b→s l+ l- or vice-versa

Dark matter could also play a major role.

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

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

Belle II sensitivities to B→K(*) nu nubar at Snowmass

Snowmass proceedings: https://arxiv.org/abs/2207.06307

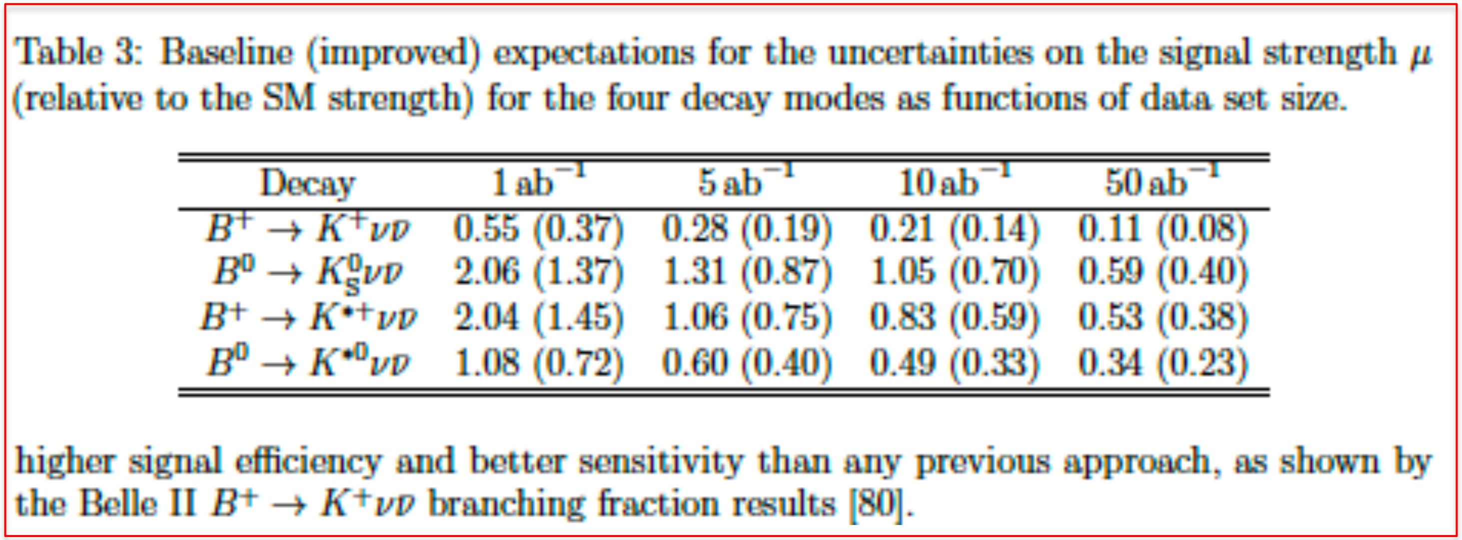


Table 3: Baseline (improved) expectations for the uncertainties on the signal strength μ (relative to the SM strength) for the four decay modes as functions of data set size.

Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

higher signal efficiency and better sensitivity than any previous approach, as shown by the Belle II $B^+ \to K^+\nu\bar{\nu}$ branching fraction results [80].

Should be able to measure K nu nubar, K* nu nubar, q^2 spectra and K^* polarization.

See talk by Prof. Rusa Mandal at this workshop for theoretical aspects.

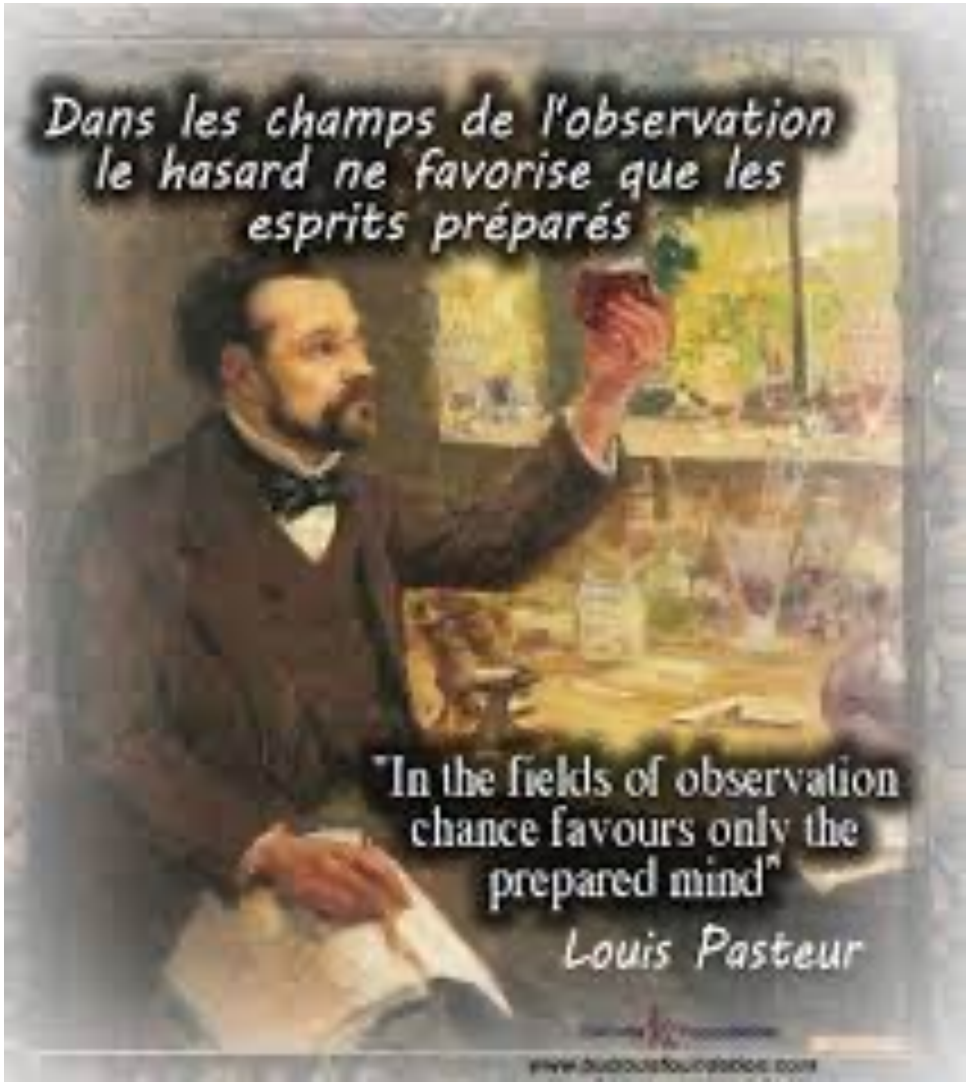
Opportunities for BSM Physics Discoveries with Belle II@SuperKEKB

- Quantum mechanics, entanglement, symmetry and *symmetry breaking* are at the heart of the particle physics in Belle II
- Belle II is exploring BSM Physics on the Luminosity or Intensity Frontier. *This is different from the LHC high pT program*
- *Will BSM physics appear in angular asymmetries in $B \to D^{*} l \nu$ or $B \to K^{*} l+ l-$ and/or perhaps in $B \to K(*) \nu$ vbar ?*

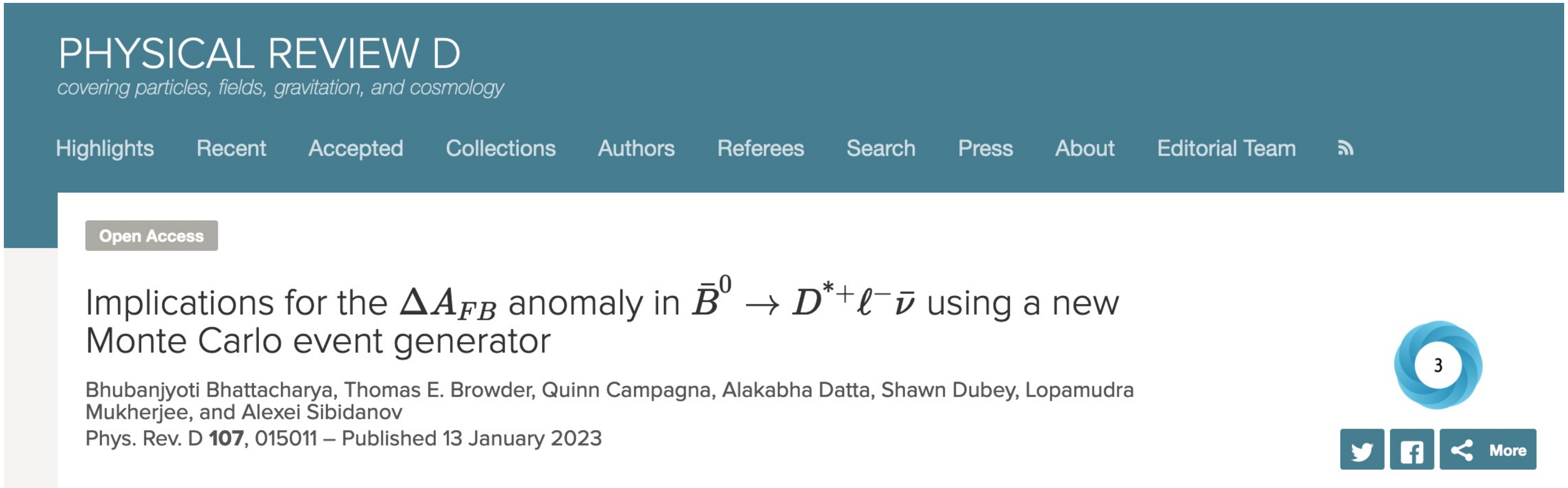
Belle II Executive Summary for Snowmass (high energy physics for the next decade) https://arxiv.org/abs/2203.10203

Some new ideas for BSM discoveries at Belle II
https://arxiv.org/abs/2107.01080 (PRD)
https://arxiv.org/abs/2203.06827 (submitted to PRD)
https://arxiv.org/abs/2206.11283 (PRD)

Backup slides



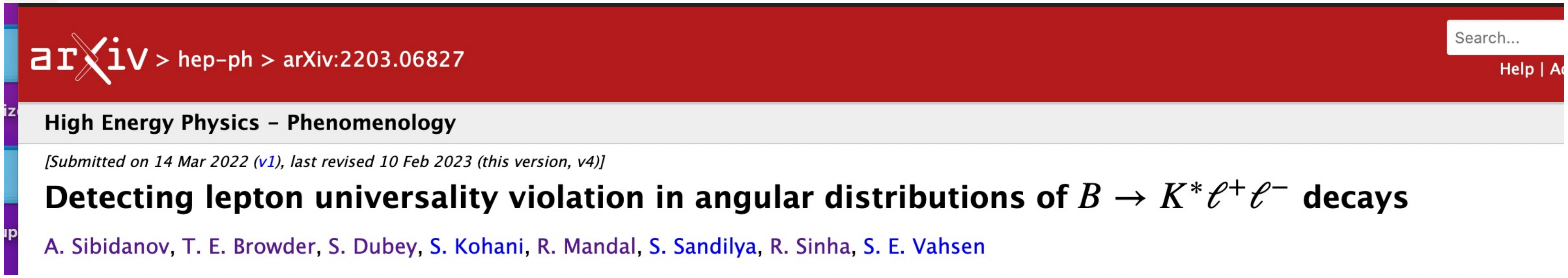
Acknowledgments:



Implications for the ΔA_{FB} anomaly in $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ using a new Monte Carlo event generator

Bhubanjyoti Bhattacharya, Thomas E. Browder, Quinn Campagna, Alakabha Datta, Shawn Dubey, Lopamudra Mukherjee, and Alexei Sibidanov

Phys. Rev. D **107**, 015011 – Published 13 January 2023



[Submitted on 14 Mar 2022 (v1), last revised 10 Feb 2023 (this version, v4)]

Detecting lepton universality violation in angular distributions of $B \to K^*\ell^+\ell^-$ decays

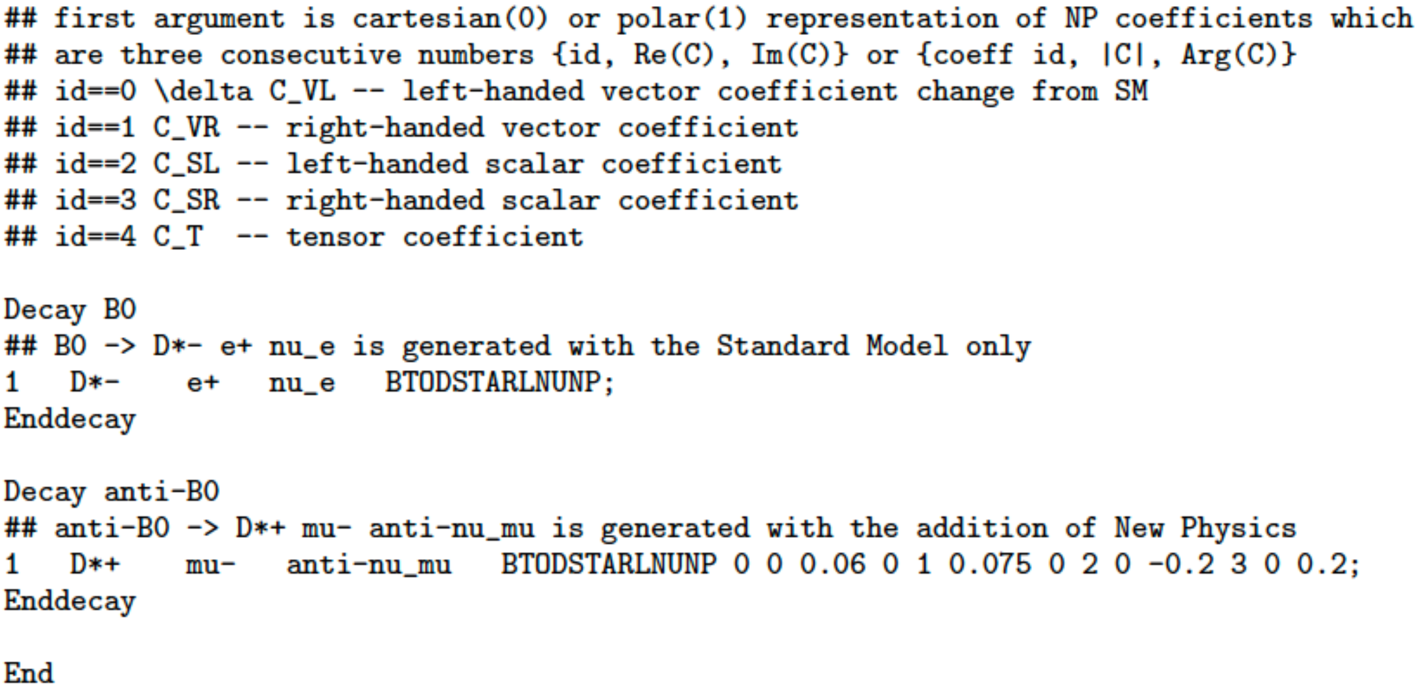
A. Sibidanov, T. E. Browder, S. Dubey, S. Kohani, R. Mandal, S. Sandilya, R. Sinha, S. E. Vahsen

Impact of $B \to K\nu\bar{\nu}$ measurements on beyond the Standard Model theories

Thomas E. Browder, Nilendra G. Deshpande, Rusa Mandal, and Rahul Sinha

Phys. Rev. D **104**, 053007 – Published 23 September 2021

EVTGEN input for B→D* l nu MC



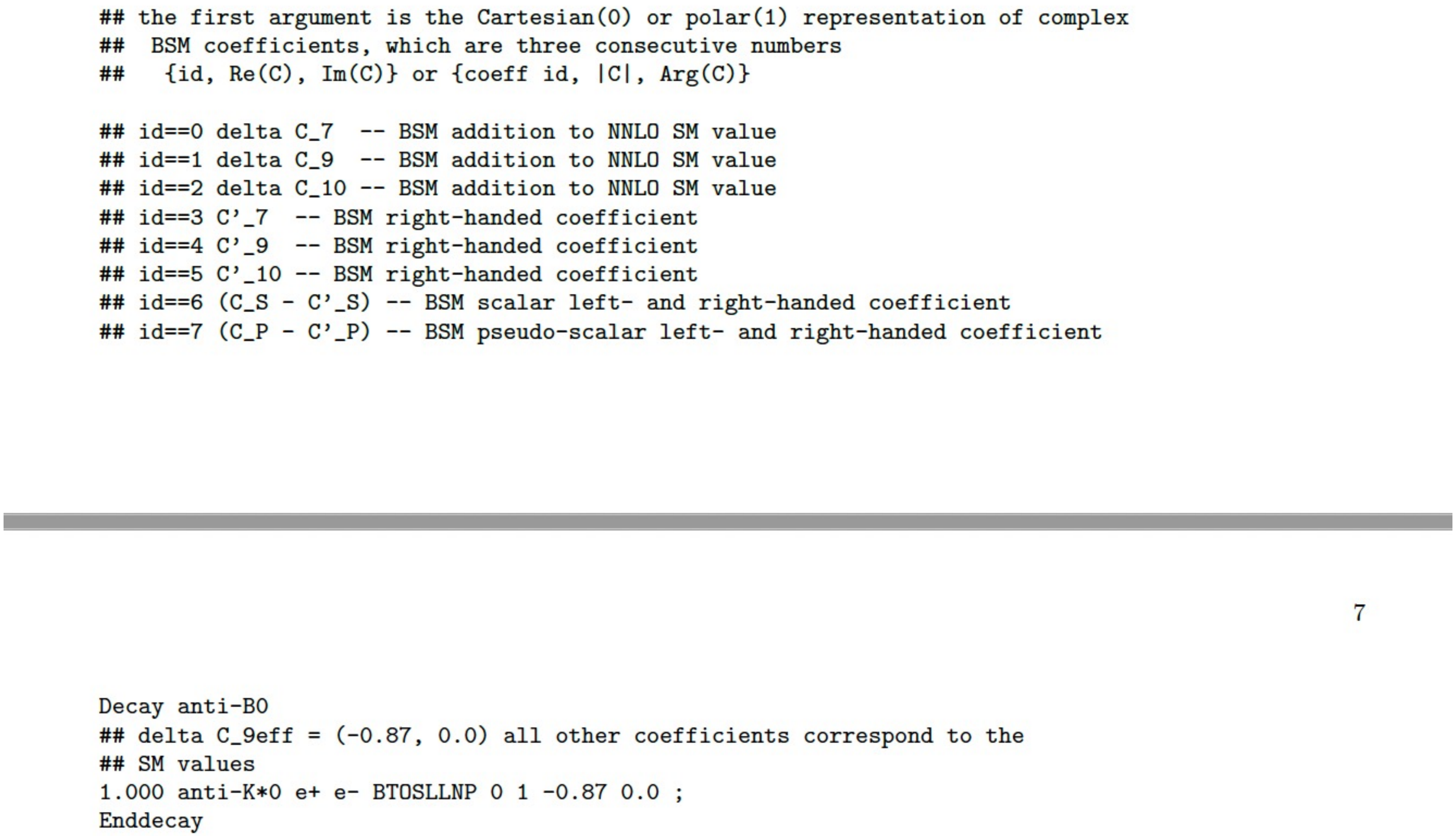
```
## first argument is cartesian(0) or polar(1) representation of NP coefficients which
## are three consecutive numbers {id, Re(C), Im(C)} or {coeff id, |C|, Arg(C)}
## id==0 \delta C_VL -- left-handed vector coefficient change from SM
## id==1 C_VR -- right-handed vector coefficient
## id==2 C_SL -- left-handed scalar coefficient
## id==3 C_SR -- right-handed scalar coefficient
## id==4 C_T  -- tensor coefficient

Decay B0
## B0 -> D*- e+ nu_e is generated with the Standard Model only
1   D*-    e+   nu_e   BTODSTARLNUNP;
Enddecay

Decay anti-B0
## anti-B0 -> D*+ mu- anti-nu_mu is generated with the addition of New Physics
1   D*+    mu-   anti-nu_mu   BTODSTARLNUNP 0 0 0.06 0 1 0.075 0 2 0 -0.2 3 0 0.2;
Enddecay

End
```

EVTGEN input for B→K* l+ l- MC



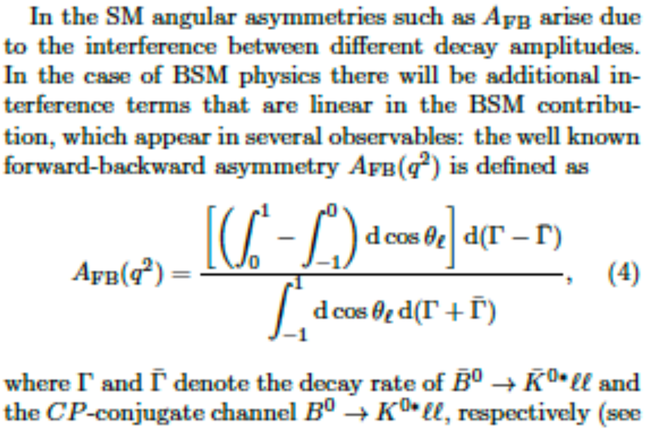
```
## the first argument is the Cartesian(0) or polar(1) representation of complex
##  BSM coefficients, which are three consecutive numbers
##   {id, Re(C), Im(C)} or {coeff id, |C|, Arg(C)}

## id==0 delta C_7  -- BSM addition to NNLO SM value
## id==1 delta C_9  -- BSM addition to NNLO SM value
## id==2 delta C_10 -- BSM addition to NNLO SM value
## id==3 C'_7  -- BSM right-handed coefficient
## id==4 C'_9  -- BSM right-handed coefficient
## id==5 C'_10 -- BSM right-handed coefficient
## id==6 (C_S - C'_S) -- BSM scalar left- and right-handed coefficient
## id==7 (C_P - C'_P) -- BSM pseudo-scalar left- and right-handed coefficient
```

7

```
Decay anti-B0
## delta C_9eff = (-0.87, 0.0) all other coefficients correspond to the
## SM values
1.000 anti-K*0 e+ e- BTOSLLNP 0 1 -0.87 0.0 ;
Enddecay
```

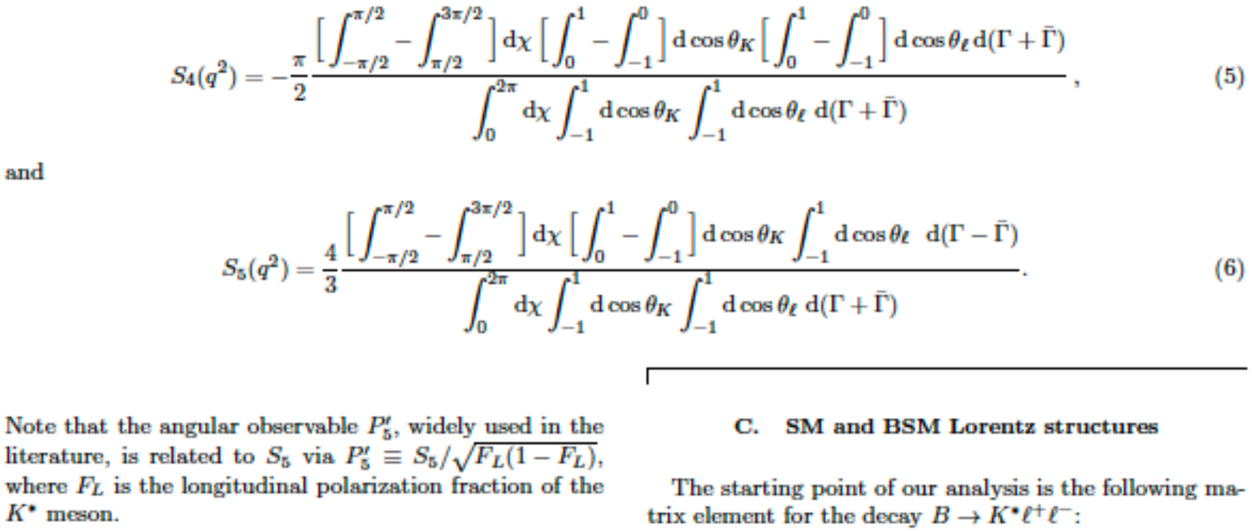
Definitions of asymmetries in B→K* l+ l-



In the SM angular asymmetries such as $A_{\rm FB}$ arise due to the interference between different decay amplitudes. In the case of BSM physics there will be additional interference terms that are linear in the BSM contribution, which appear in several observables: the well known forward-backward asymmetry $A_{\rm FB}(q^2)$ is defined as

$$A_{\rm FB}(q^2) = \frac{\left[\left(\int_0^1 - \int_{-1}^0\right) \mathrm{d}\cos\theta_\ell\right] \mathrm{d}(\Gamma - \bar{\Gamma})}{\int_{-1}^1 \mathrm{d}\cos\theta_\ell \, \mathrm{d}(\Gamma + \bar{\Gamma})}, \quad (4)$$

where Γ and $\bar{\Gamma}$ denote the decay rate of $\bar{B}^0 \to \bar{K}^{0*}\ell\ell$ and the CP-conjugate channel $B^0 \to K^{0*}\ell\ell$, respectively (see



$$S_4(q^2) = -\frac{\pi}{2} \frac{\left[\int_{-\pi/2}^{\pi/2} - \int_{\pi/2}^{3\pi/2}\right] \mathrm{d}\chi \left[\int_0^1 - \int_{-1}^0\right] \mathrm{d}\cos\theta_K \left[\int_0^1 - \int_{-1}^0\right] \mathrm{d}\cos\theta_\ell \, \mathrm{d}(\Gamma + \bar{\Gamma})}{\int_0^{2\pi} \mathrm{d}\chi \int_{-1}^1 \mathrm{d}\cos\theta_K \int_{-1}^1 \mathrm{d}\cos\theta_\ell \, \mathrm{d}(\Gamma + \bar{\Gamma})}, \quad (5)$$

and

$$S_5(q^2) = \frac{4}{3} \frac{\left[\int_{-\pi/2}^{\pi/2} - \int_{\pi/2}^{3\pi/2}\right] \mathrm{d}\chi \left[\int_0^1 - \int_{-1}^0\right] \mathrm{d}\cos\theta_K \int_{-1}^1 \mathrm{d}\cos\theta_\ell \, \mathrm{d}(\Gamma - \bar{\Gamma})}{\int_0^{2\pi} \mathrm{d}\chi \int_{-1}^1 \mathrm{d}\cos\theta_K \int_{-1}^1 \mathrm{d}\cos\theta_\ell \, \mathrm{d}(\Gamma + \bar{\Gamma})}. \quad (6)$$

Note that the angular observable P_5', widely used in the literature, is related to S_5 via $P_5' \equiv S_5/\sqrt{F_L(1-F_L)}$, where F_L is the longitudinal polarization fraction of the K^* meson.

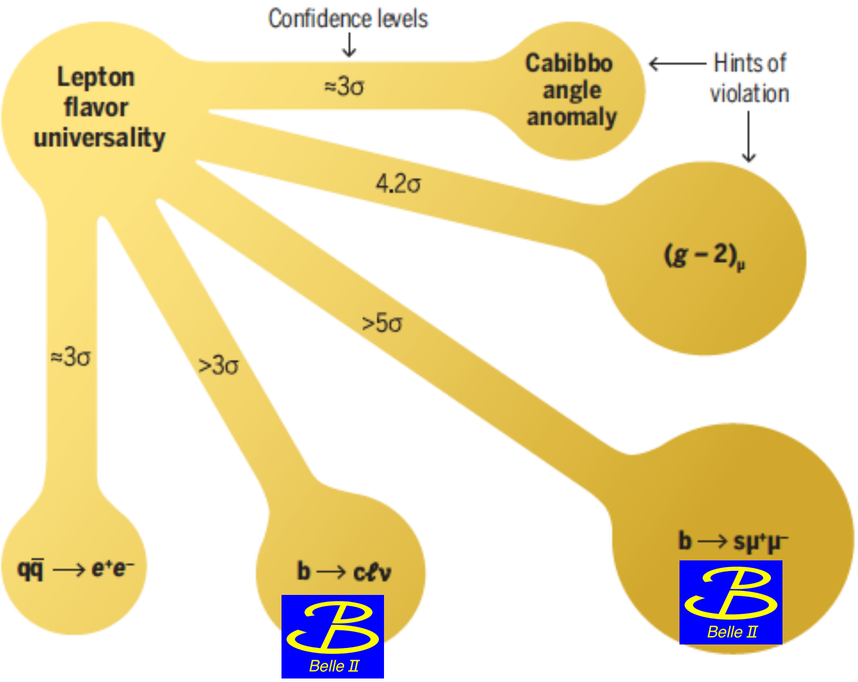
C. SM and BSM Lorentz structures

The starting point of our analysis is the following matrix element for the decay $B \to K^*\ell^+\ell^-$:

Conclusion I: Here are some examples of how Belle II might find BSM 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.

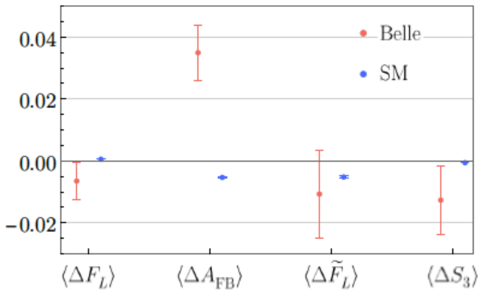


From December 2021 SCIENCE magazine article by A. Crivellin and M. Hoferichter.

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})

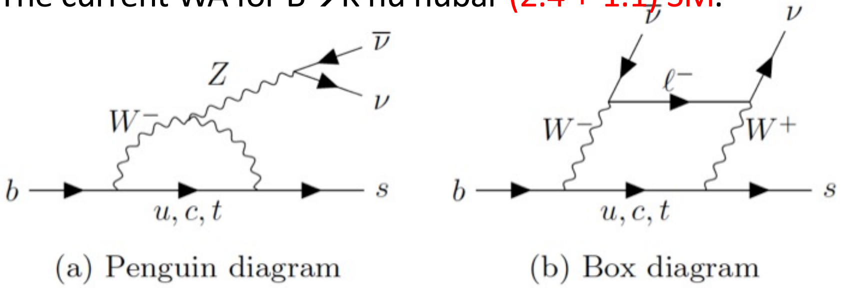


Eur. Phys. J.C. 81 (2021).

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).

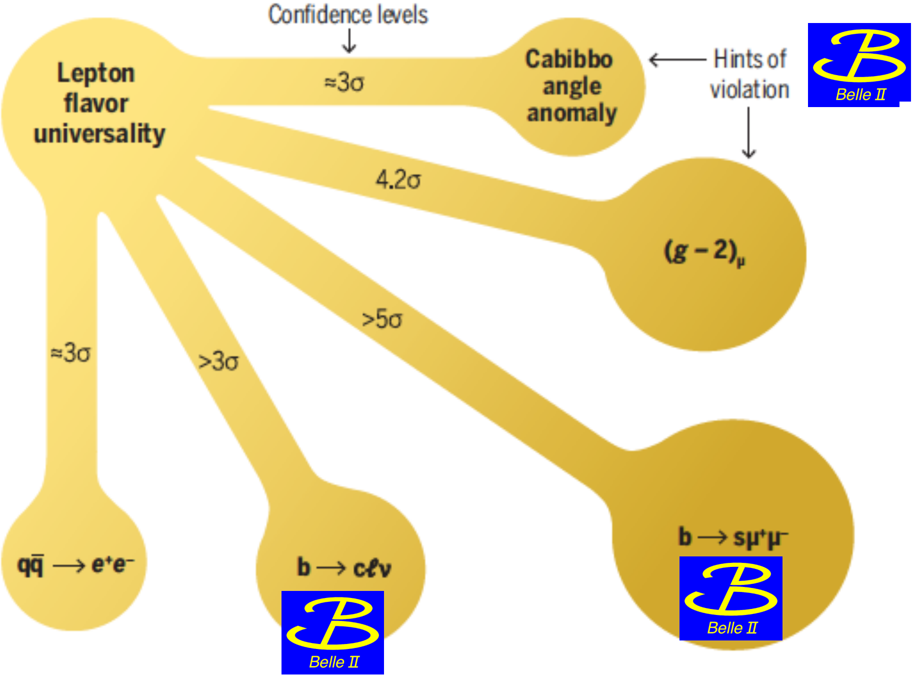
But these modes require lots of data…."There is no royal road to new physics" (to paraphrase Euclid).

But wait there's more…..

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

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.

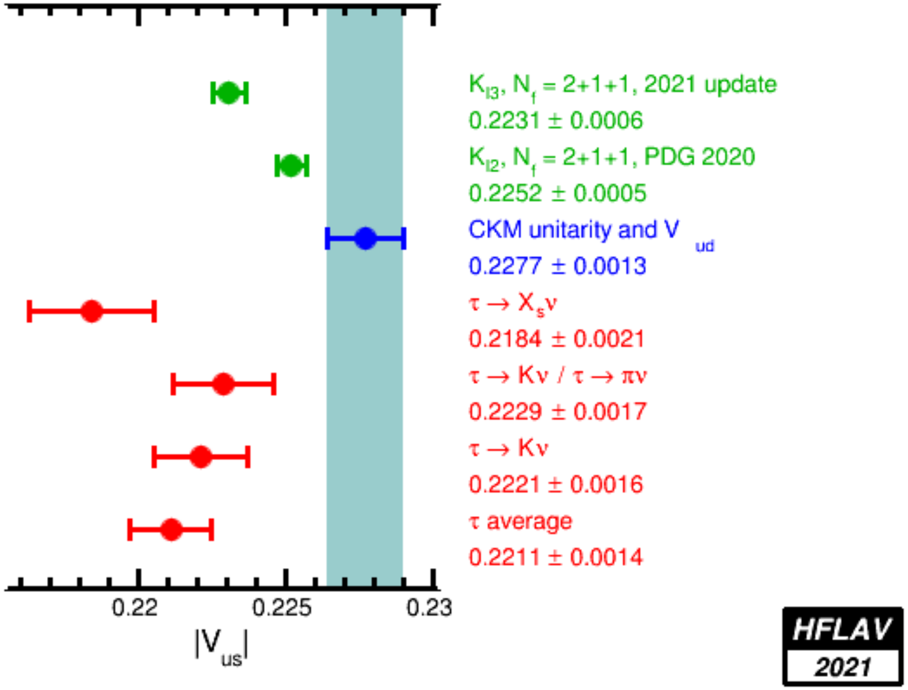


From December 2021 SCIENCE magazine article by A. Crivellin and M. Hoferichter.

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

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



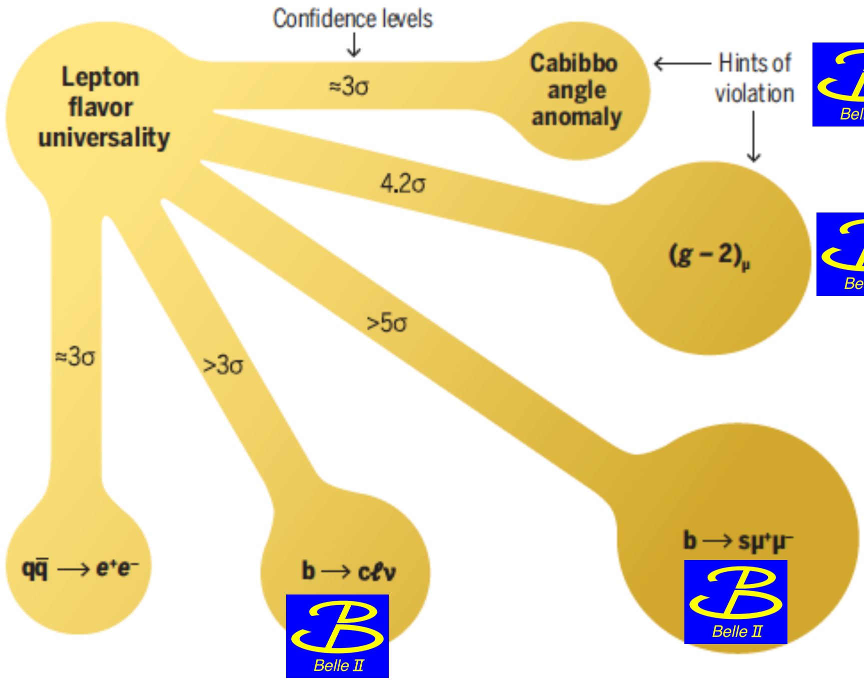
The CAA could be another hint of lepton flavor universality violation

+But wait there's still more…..

Belle II can contribute to g-2 (See talk by A. Vossen)

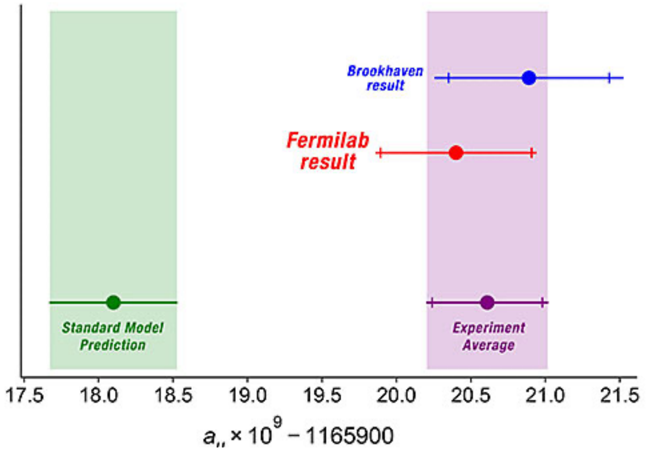
Possible violations of lepton flavor universality are getting harder to ignore

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.

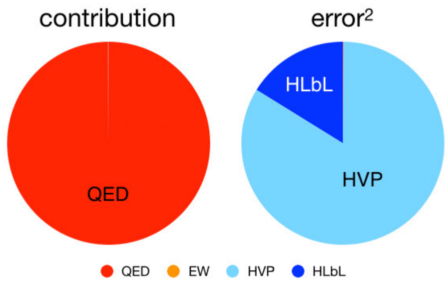


From December 2021 SCIENCE magazine article by A. Crivellin and M. Hoferichter.

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



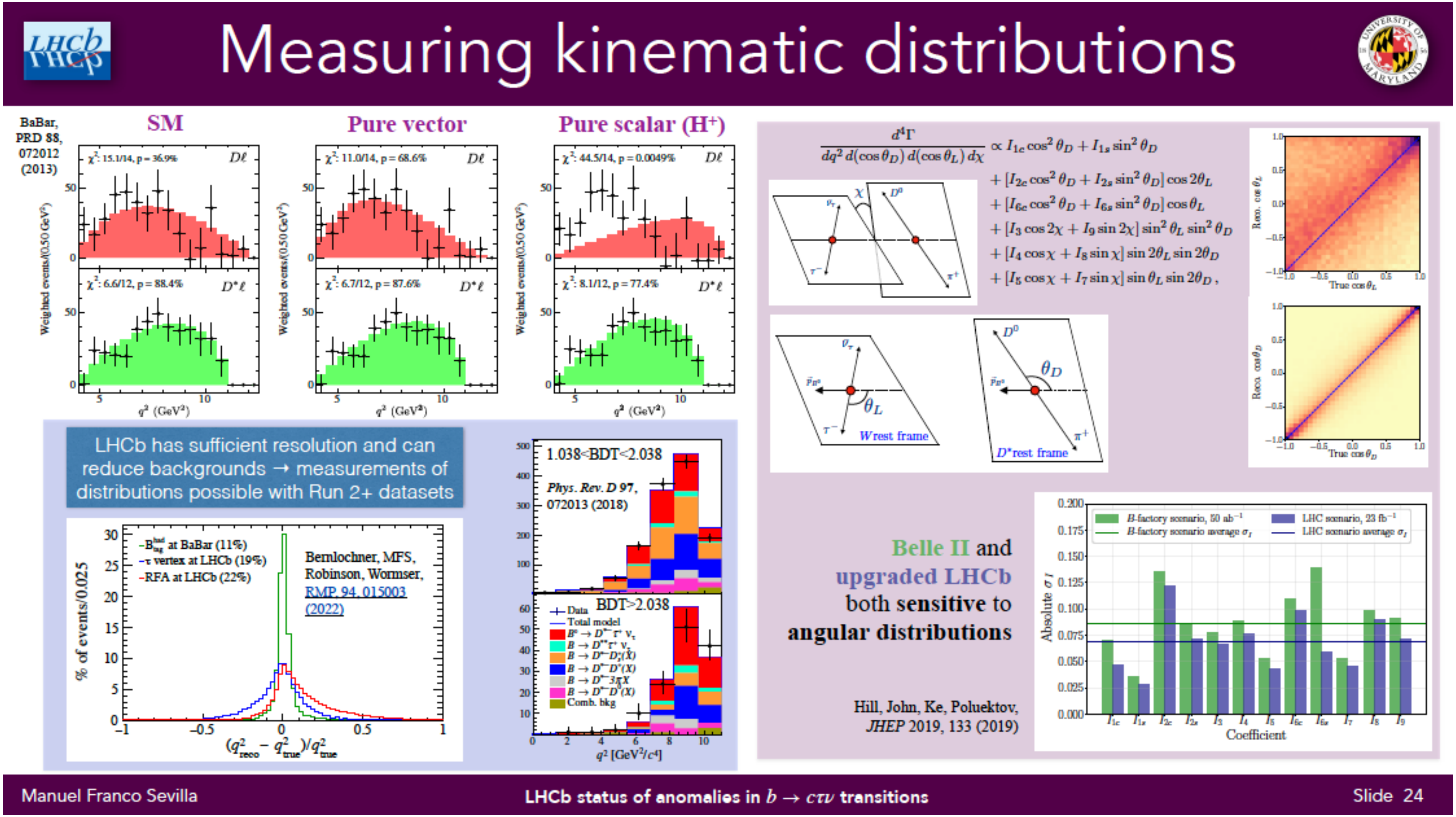
Standard Model theory



KLOE and BaBar data disagree

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

Example from BaBar



Measuring kinematic distributions

BaBar, PRD 88, 072012 (2013)

LHCb has sufficient resolution and can reduce backgrounds → measurements of distributions possible with Run 2+ datasets

Bernlochner, MFS, Robinson, Wormser, RMP 94, 015003 (2022)

Phys. Rev. D 97, 072013 (2018)

$$\frac{d^4\Gamma}{dq^2\,d(\cos\theta_D)\,d(\cos\theta_L)\,d\chi} \propto I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D$$
$$+ [I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D]\cos 2\theta_L$$
$$+ [I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D]\cos\theta_L$$
$$+ [I_3\cos 2\chi + I_9\sin 2\chi]\sin^2\theta_L\sin^2\theta_D$$
$$+ [I_4\cos\chi + I_8\sin\chi]\sin 2\theta_L\sin 2\theta_D$$
$$+ [I_5\cos\chi + I_7\sin\chi]\sin\theta_L\sin 2\theta_D\,,$$

Belle II and **upgraded LHCb** both **sensitive** to **angular distributions**

Hill, John, Ke, Poluektov, *JHEP* 2019, 133 (2019)

Manuel Franco Sevilla　　LHCb status of anomalies in $b \to c\tau\nu$ transitions　　Slide 24

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

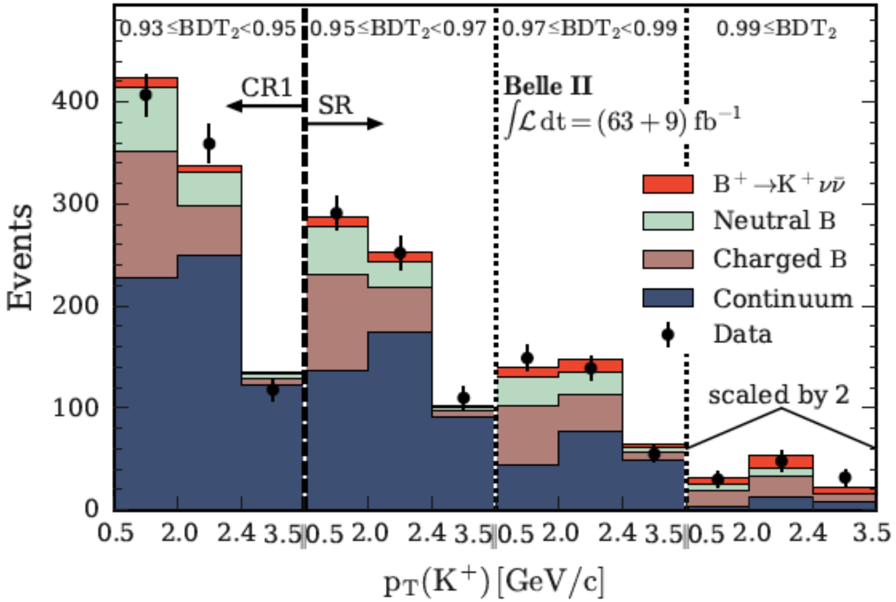


FIG. 3: Yields in on-resonance data and as predicted by the simultaneous fit to the on- and off-resonance data, corresponding to an integrated luminosity of 63 fb^{-1} and 9 fb^{-1}, respectively. The predicted yields are shown individually for charged and neutral *B*-meson decays and the sum of the five continuum contributions. The leftmost three bins belong to CR1 with $\text{BDT}_2 \in [0.93, 0.95]$ and the other nine bins correspond to the SR, three for each range of $\text{BDT}_2 \in [0.95, 0.97, 0.99, 1.0]$. 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

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

Snowmass 2022 (*International* Physics Rodeo)

To plan the high energy physics discoveries for the next decade.

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.

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

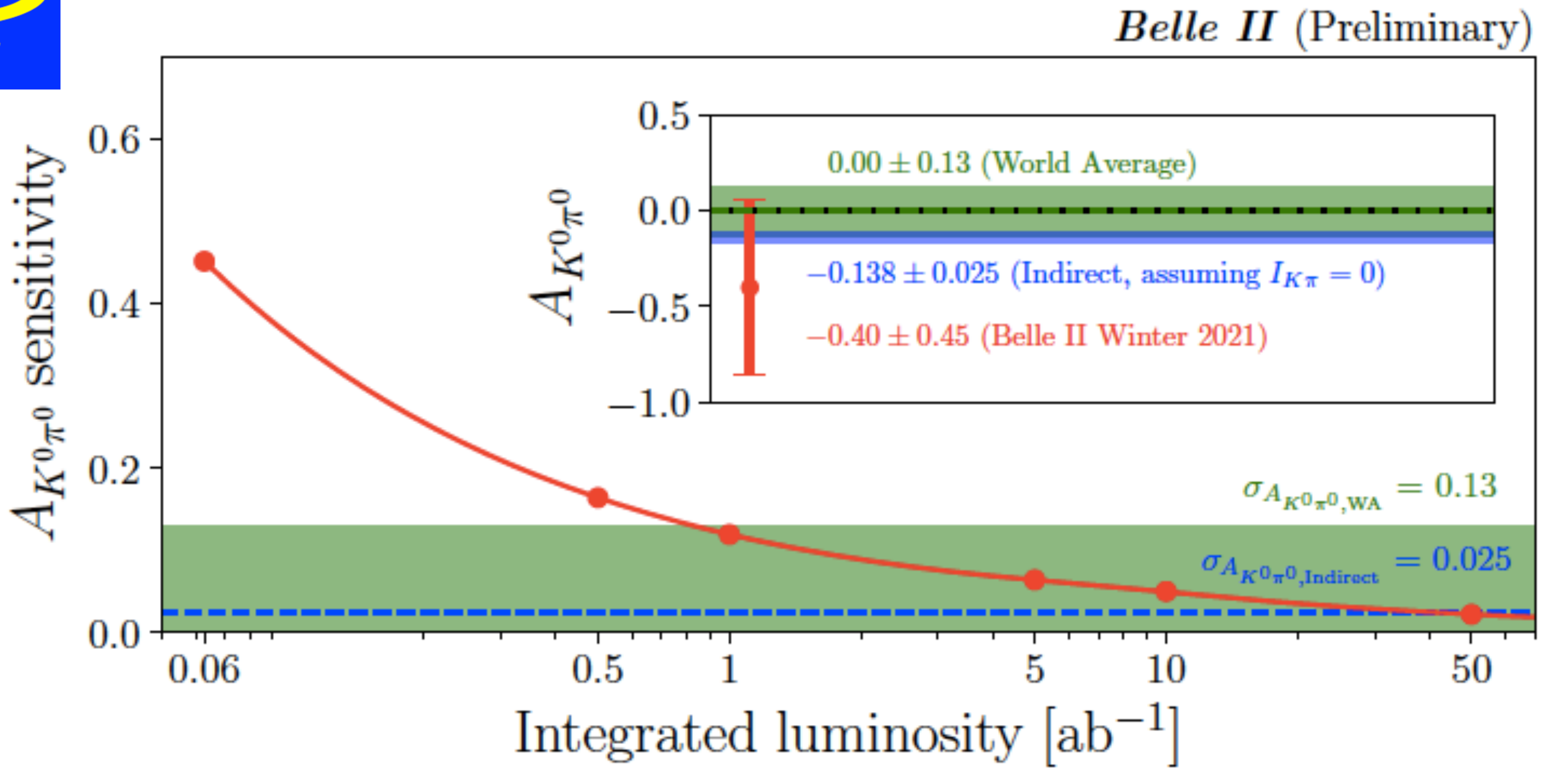
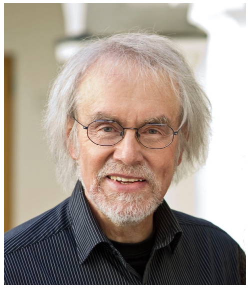


FIG. 5. The projected uncertainty on $\mathcal{A}_{K^0\pi^0}$ measurement. The inset panel shows the comparison of (red marker) the measurement reported here with (green band) the world average value, and (blue band) the indirect determination from Eq. 1 assuming $I_{K\pi} = 0$ and world average values 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

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

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

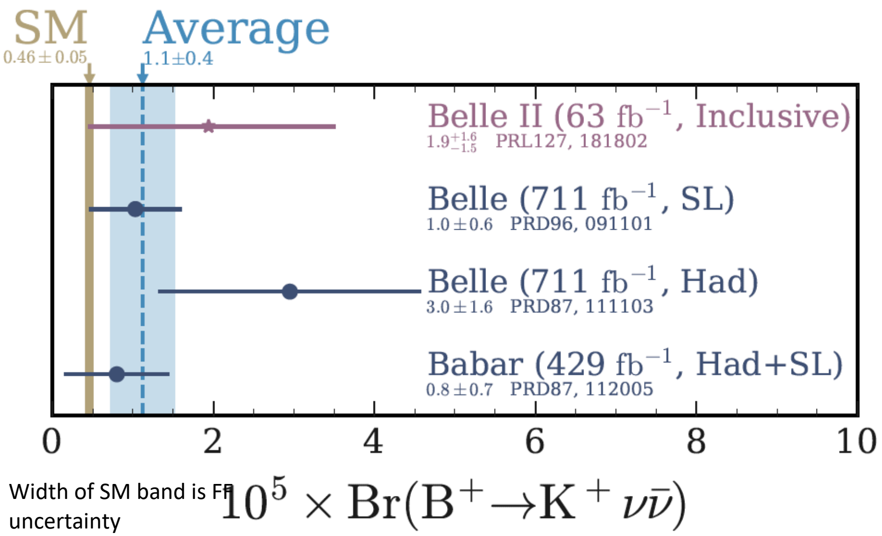


Andrezj
Buras

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

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

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



Width of SM band is FF uncertainty

"Note there are no charm loops here"- Wolfgang A.

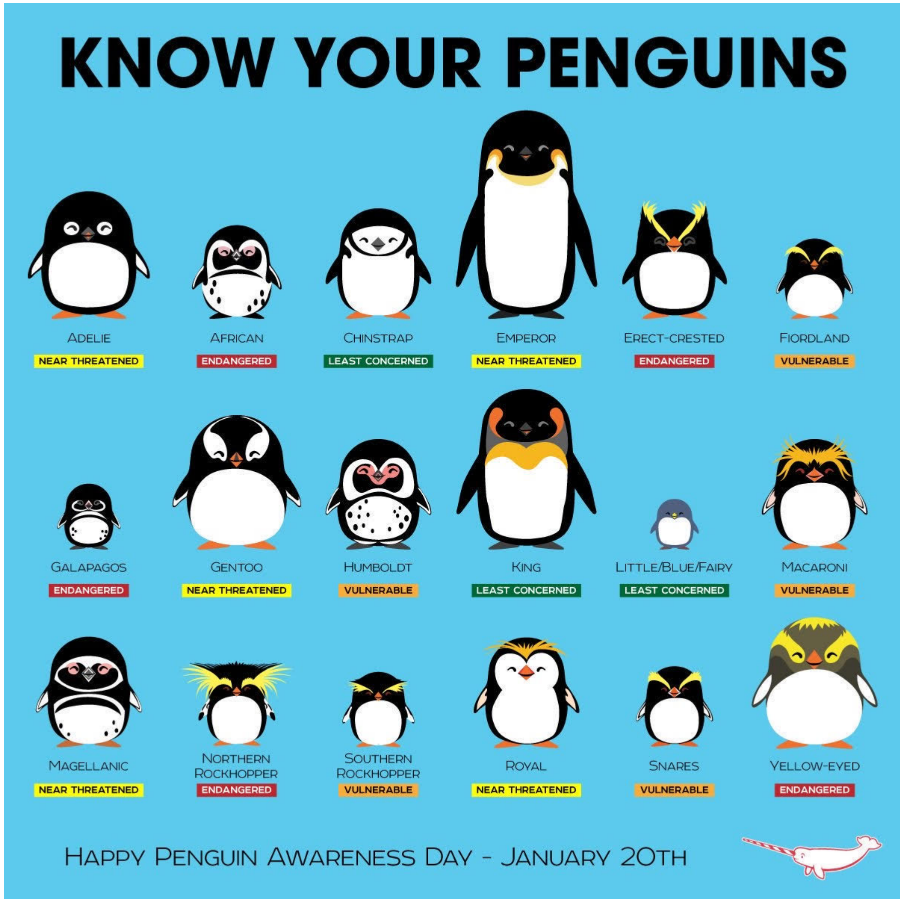
An emerging anomaly ???

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.

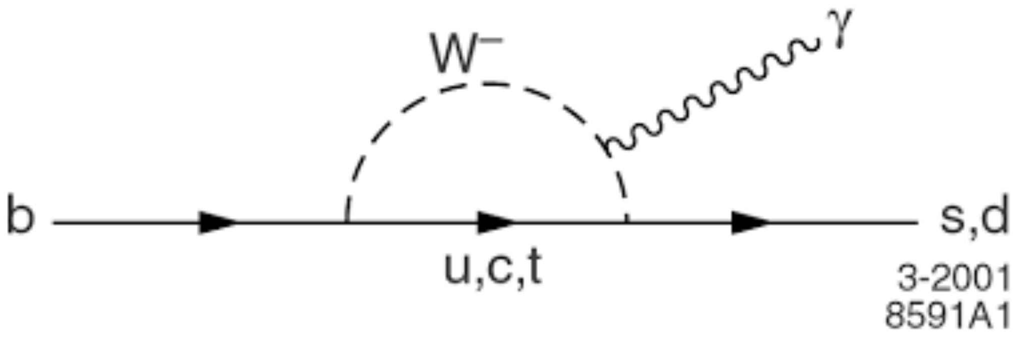
This is one way that Belle II could discover New Physics soon. For example: https://arxiv.org/abs/2107.01080, Phys. Rev. D. 104, 053007 (2021)

Dark matter could also play a major role.

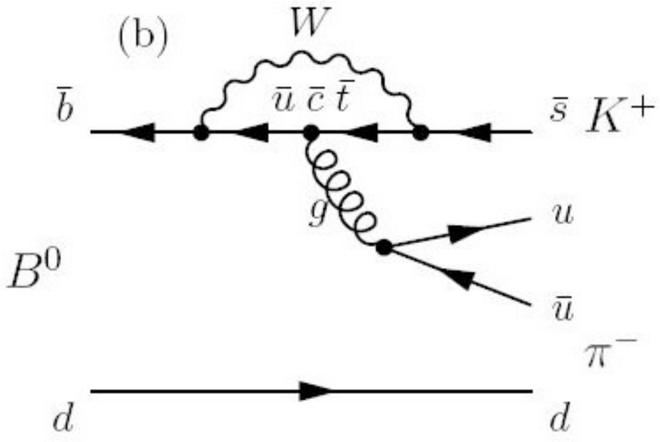
Recap:



"Radiative Penguin"



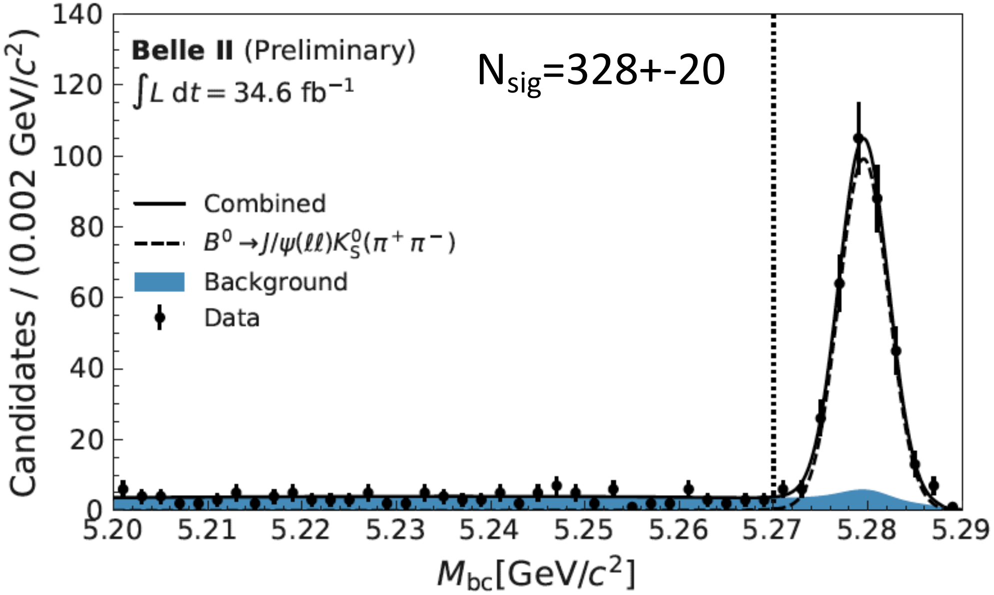
"Gluonic Penguin"



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

A "Golden" CP Eigenstate

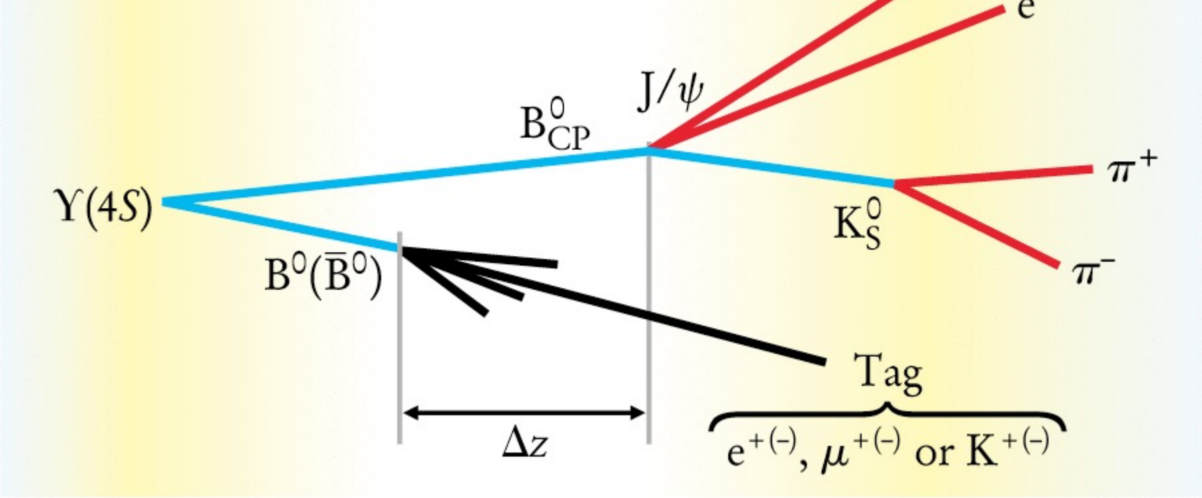
Test with 17% of the Phase 3 data sample.



Now apply a *simplified analysis:*

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

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

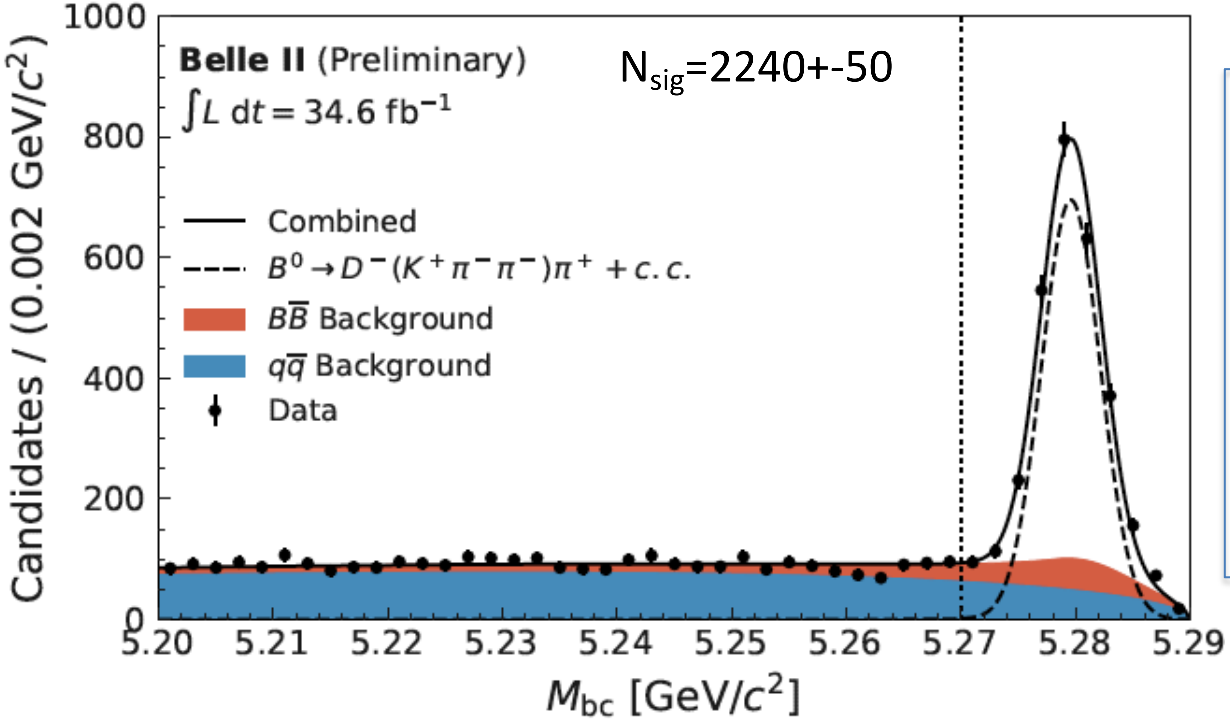


$$\Delta t \approx \frac{\Delta z}{\beta\gamma}$$

Figure credit: Physics Today

This is a flavor-specific B decay mode with a charged track topology similar to the $B \rightarrow J/\psi K_S$ signal.

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

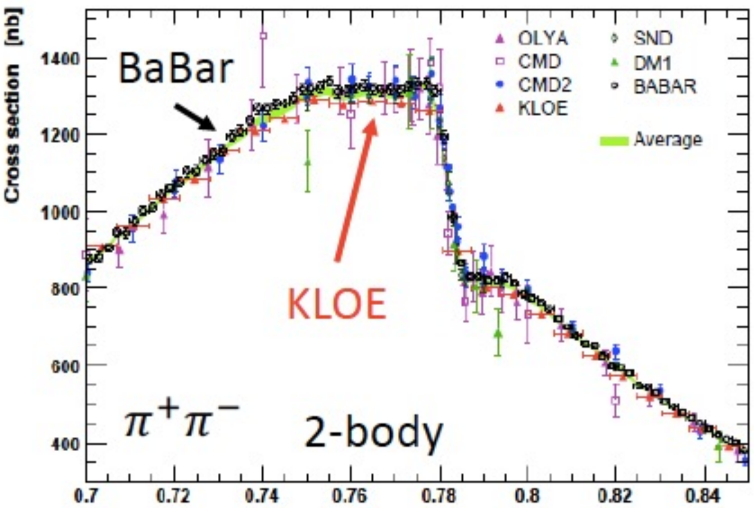


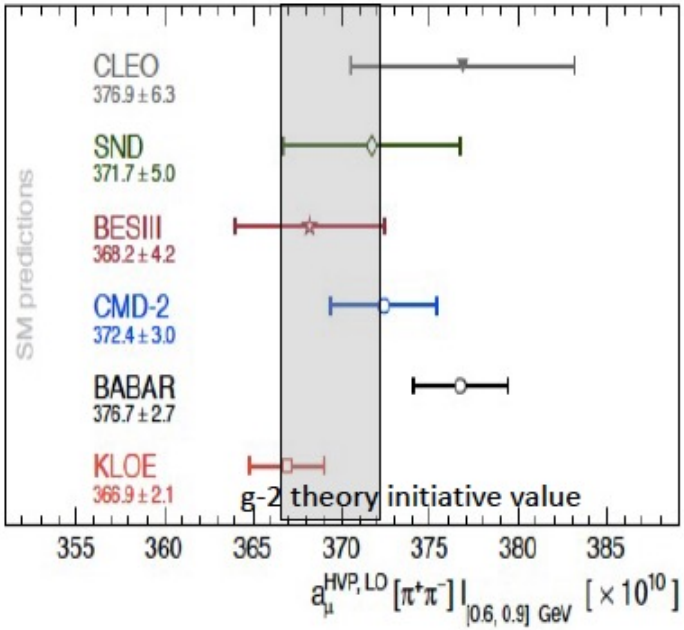
Start with a B^0 (wait a while, ~a few x 10^{-12} sec).

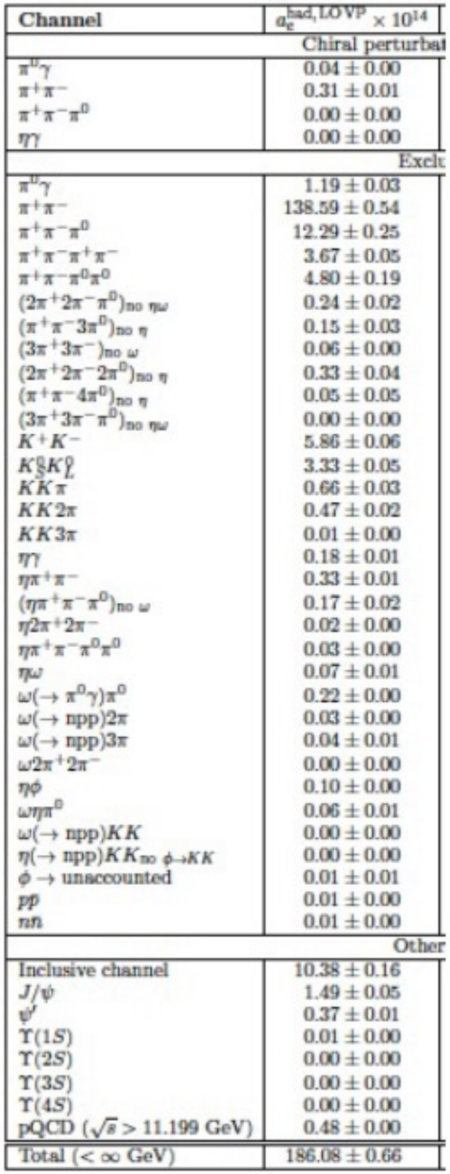
There is a large probability that the B^0 will turn into its anti-particle, an anti-B^0 (discovered by ARGUS at DESY in 1987)

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

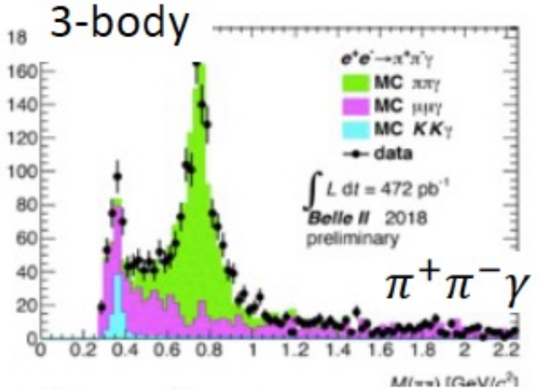
Gold Standard: $e^+e^- \rightarrow hadrons$

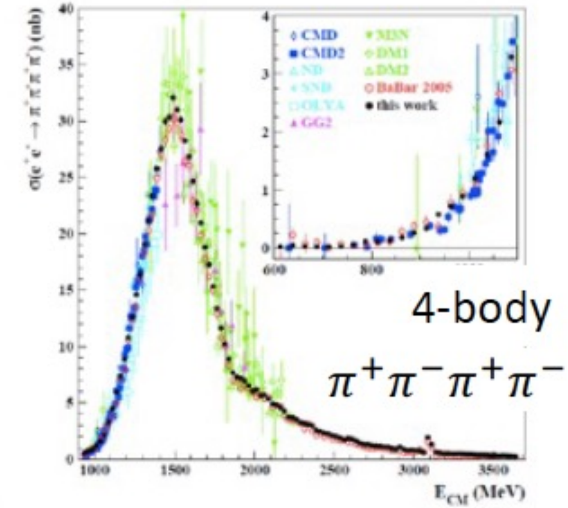


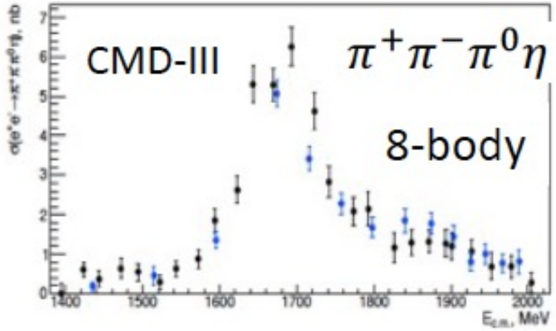




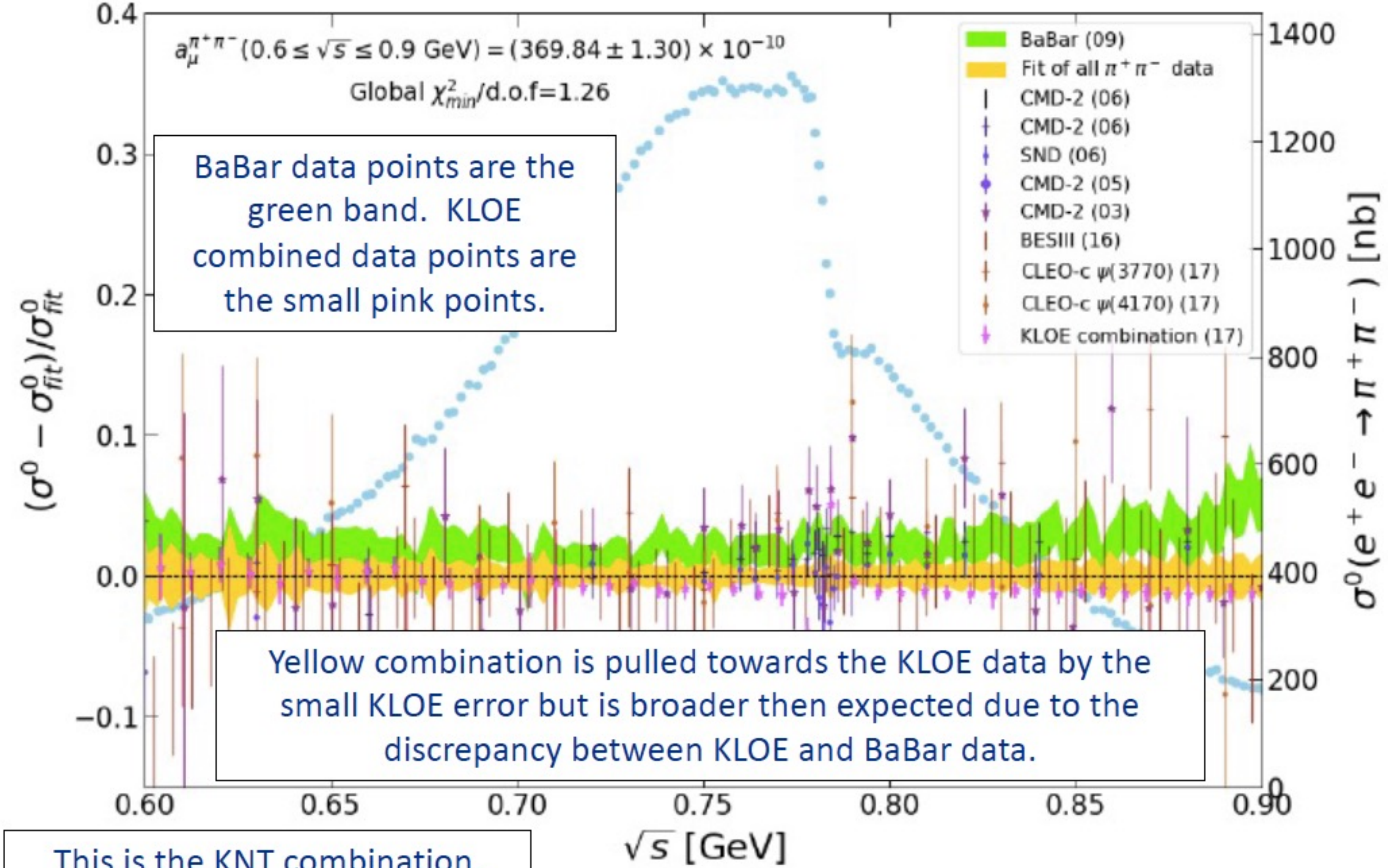
Channel	$a_e^{\mathrm{had,\,LOVP}} \times 10^{14}$
	Chiral perturbat
$\pi^0\gamma$	0.04 ± 0.00
$\pi^+\pi^-$	0.31 ± 0.01
$\pi^+\pi^-\pi^0$	0.00 ± 0.00
$\eta\gamma$	0.00 ± 0.00
	Excl
$\pi^0\gamma$	1.19 ± 0.03
$\pi^+\pi^-$	138.59 ± 0.54
$\pi^+\pi^-\pi^0$	12.29 ± 0.25
$\pi^+\pi^-\pi^+\pi^-$	3.67 ± 0.05
$\pi^+\pi^-\pi^0\pi^0$	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
$K_S^0K_L^0$	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
$\omega(\to \pi^0\gamma)\pi^0$	0.22 ± 0.00
$\omega(\to \mathrm{npp})2\pi$	0.03 ± 0.00
$\omega(\to \mathrm{npp})3\pi$	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
$\omega(\to \mathrm{npp})KK$	0.00 ± 0.00
$\eta(\to \mathrm{npp})KK_{\mathrm{no}\ \phi\to KK}$	0.00 ± 0.00
$\phi \to$ 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







$e^+e^- \to \pi^+\pi^-$



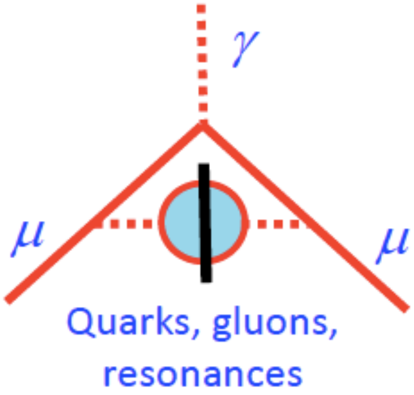
BaBar data points are the green band. KLOE combined data points are the small pink points.

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.

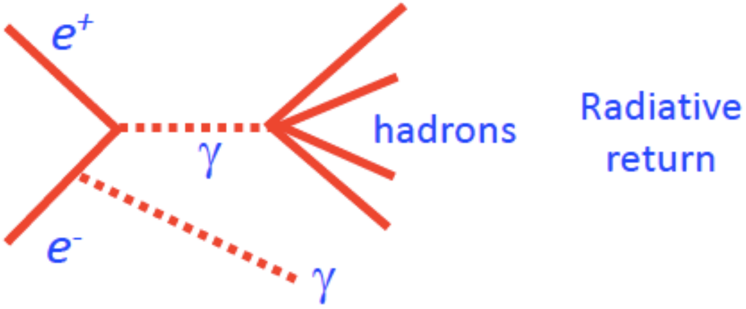
Leading order QCD: HVP

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.



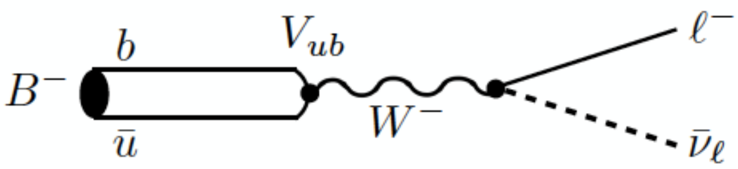
This is considered the gold standard and the Muon g-2 Theory initiative only uses this data in their prediction.

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.

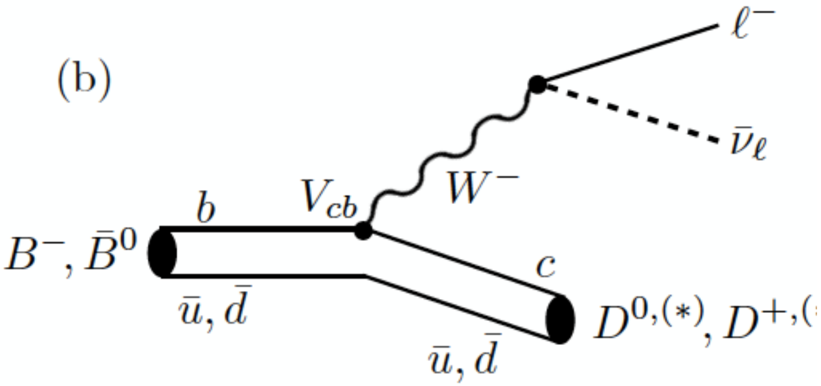
$$\frac{g-2}{2}HVP = \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}R(s)K_l(s)$$

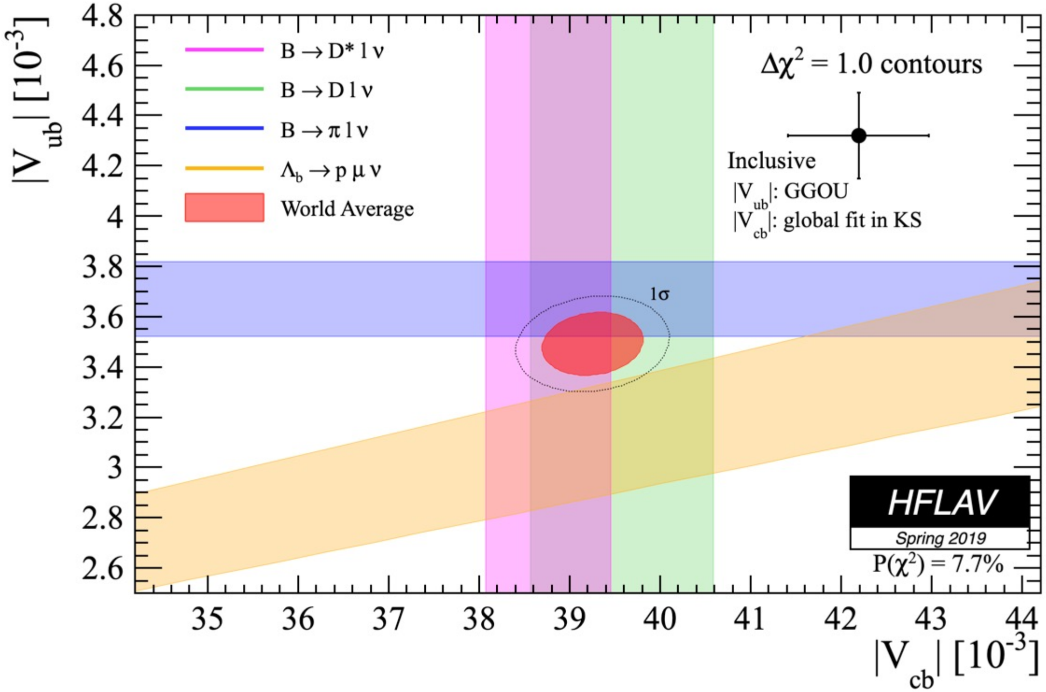
Motivation for semileptonic decays: V_{cb} , V_{ub}

(a)



(b)





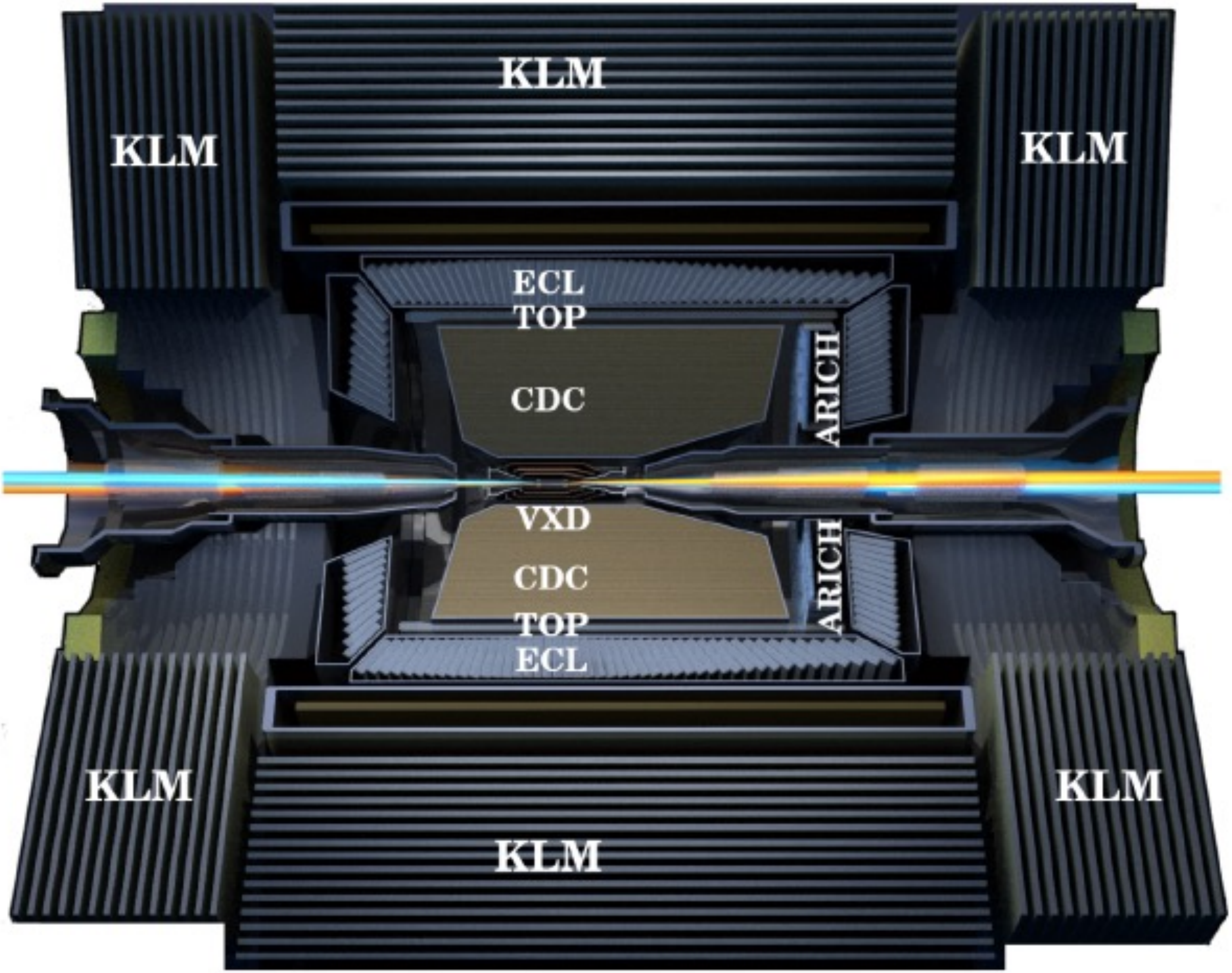
a) Purely leptonic decays e.g. $B^+ \rightarrow \tau^+ \nu$

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

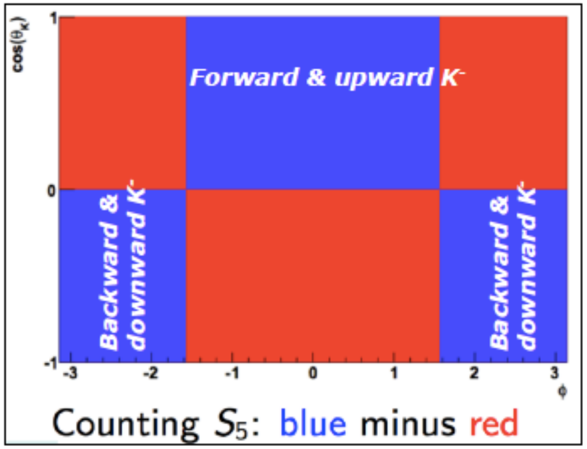
Tensions persist between exclusive and inclusive (e+e-) measurements of fundamental CKM elements $|V_{cb}|$, $|V_{ub}|$

Figure credit:

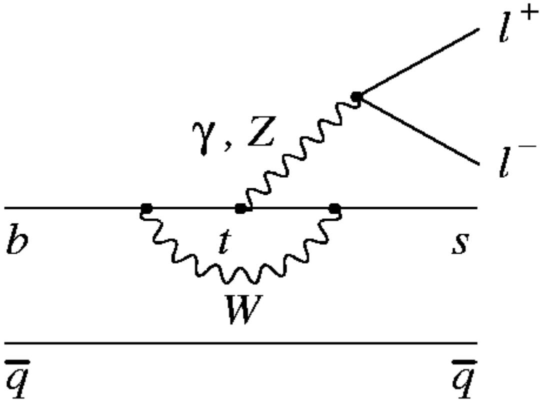
https://www.nature.com/articles/nature22346


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

More on angular asymmetries, A_{FB} , $S_5(q^2)$



Counting S_5: blue minus red



Can in effect vary √s for NP

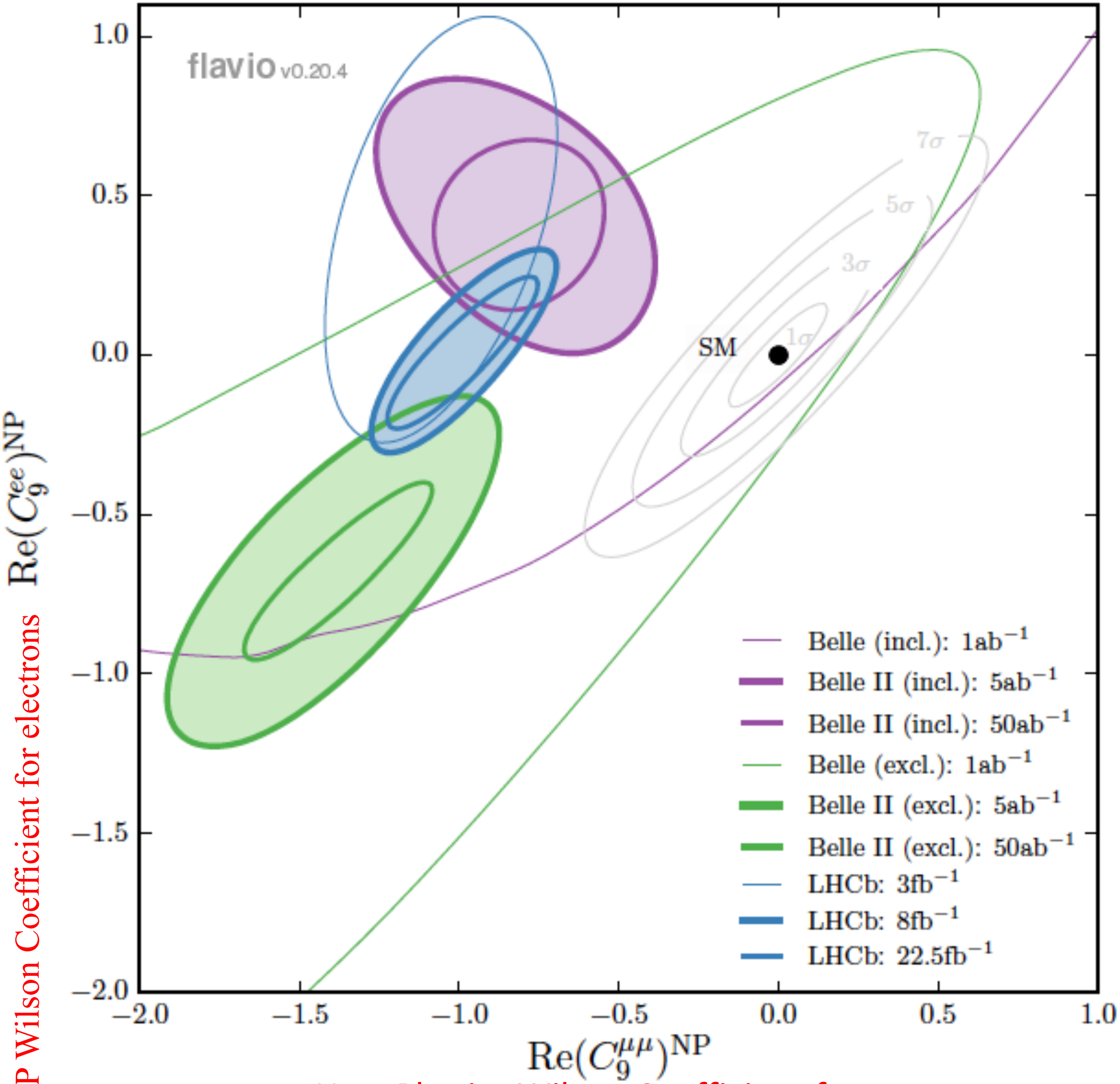
A_{FB} depends on $q^2 = M^2(l^+l^-)$

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

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.

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.

Upgrading SuperKEB with Polarized Electron Beams: "Chiral Belle" uses Belle II with L-R polarized SuperKEKB

- Goal is ~70% polarization with 80% polarized source (SLC had 75% polarization at the experiment)
- Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode (similar to SLC source)
- Inject vertically polarized electrons into the High Energy Ring (HER) - needs low enough emittance source to be able to inject.
- Rotate spin to longitudinal before IP, and then back to vertical after IP using solenoidal and dipole fields – recent studies have demonstrated feasibility
- Use Compton polarimeter to monitor longitudinal polarization with <1% absolute precision, higher for relative measurements (arXiv:1009.6178) - needed for real time polarimetry – similar to HERA and EIC technologies.
- Use tau decays to obtain absolute average polarization at IP – *BABAR* analysis demonstrates 0.5% precision (see C. Miller, Lake Louise Winter Institute 2022)

“Chiral Belle II” -> Left-Right Asymmetries

- •Measure *difference* between cross-sections with left-handed beam electrons and right-handed beam electrons
- •Same technique as SLD A_{LR} measurement at the Z-pole giving single most precise measurement of :

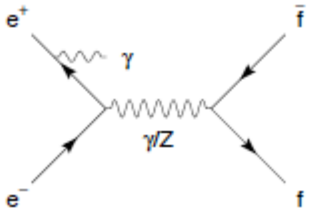
$$\sin^2\theta_{eff}^{lepton} = 0.23098 \pm 0.00026$$

- •At 10.58 GeV, polarized e^- beam yields product of the neutral axial-vector coupling of the electron and vector coupling of the final-state fermion via Z-γ interference:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right)\boxed{g_A^e g_V^f}\langle Pol\rangle$$

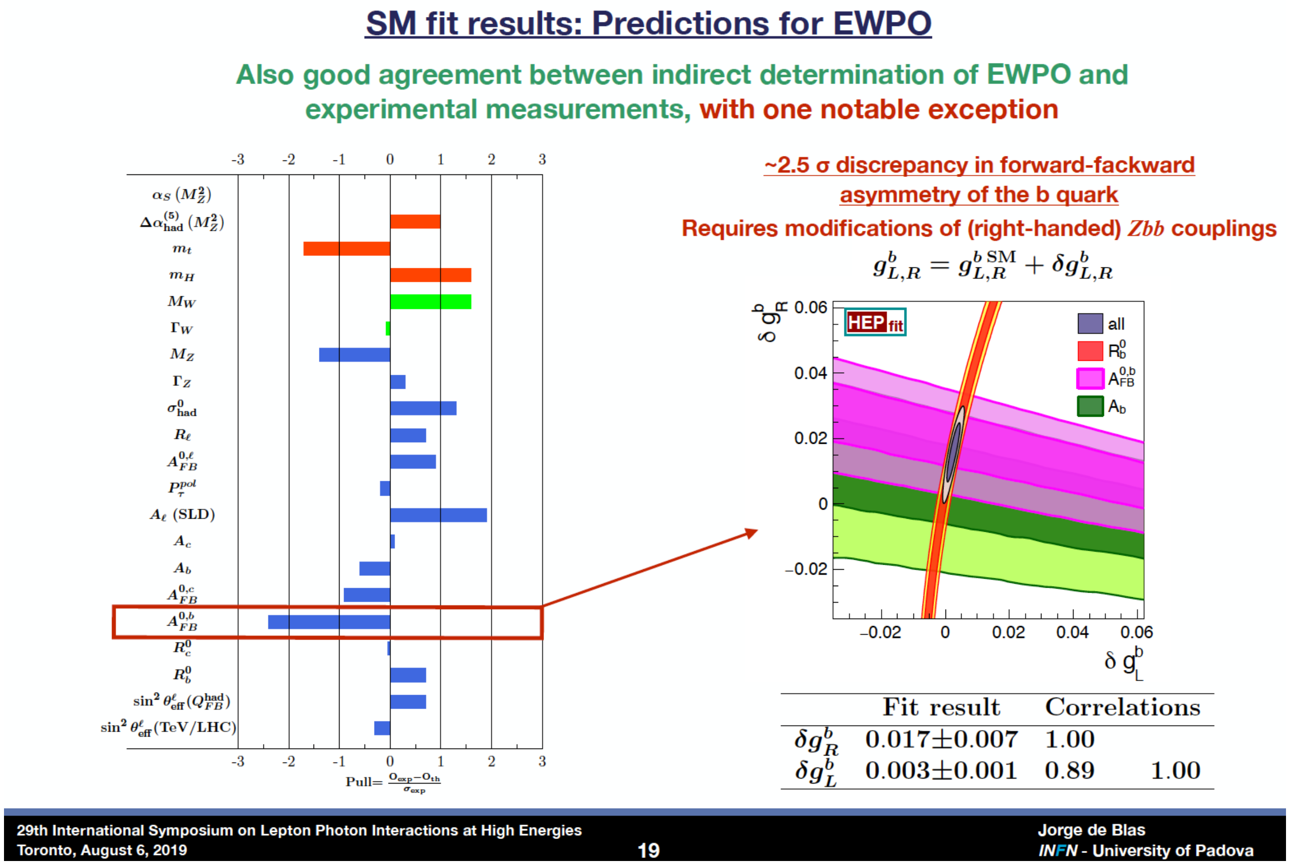
$$\propto T_3^f - 2Q_f \sin^2\theta_W$$

(for s-channel Born)



Belle II/SuperKEKB with a polarized e$^-$ beam can address this long-standing electroweak discrepancy and hint of NP

Warning: Does not include CDF 2022 W mass update.



SM fit results: Predictions for EWPO

Also good agreement between indirect determination of EWPO and experimental measurements, with one notable exception

~2.5 σ discrepancy in forward-fackward asymmetry of the b quark

Requires modifications of (right-handed) *Zbb* couplings

$$g^b_{L,R} = g^{b\,\mathrm{SM}}_{L,R} + \delta g^b_{L,R}$$

	Fit result	Correlations	
δg^b_R	0.017±0.007	1.00	
δg^b_L	0.003±0.001	0.89	1.00

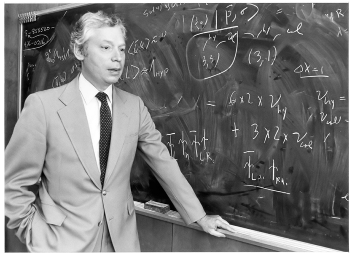
29th International Symposium on Lepton Photon Interactions at High Energies
Toronto, August 6, 2019

19

Jorge de Blas
INFN - University of Padova

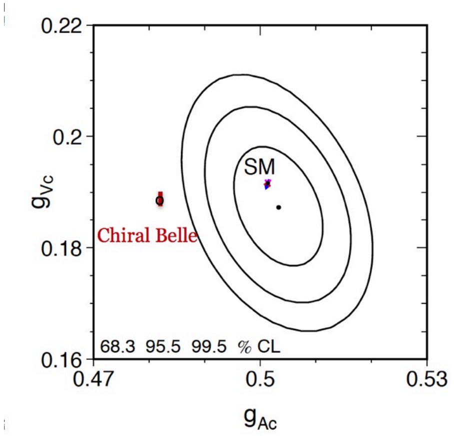
A New Path for Belle II Discovery in a *Precision Neutral Current Electroweak Program* with Heavy Quarks

- Left-Right Asymmetries (A_{LR}) yield high precision measurements of the *neutral current vector couplings* (g_V) to each of accessible fermion flavor, *f* :
  - beauty (D-type)   (as well as for 3 charged leptons and light quarks)
  - charm (U-type)

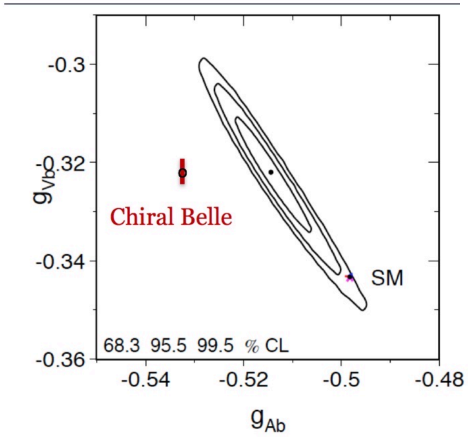


Steve Weinberg

c-quark:
Chiral Belle ~7 times more precise



b-quark:
Chiral Belle ~4 times more precise
with 20 ab^{-1}



$$\text{Recall: } g_V^f \text{ gives } \theta_W \text{ in SM} \begin{cases} g_A^f = T_3^f \\ g_V^f = T_3^f - 2Q_f \sin^2\theta_W \end{cases}$$

T_3 = -0.5 for charged leptons and D-type quarks
+0.5 for neutrinos and U-type quarks

Unique Access to New Physics in bottom-to-charm Neutral Current Vector Coupling Universality Ratio via A_{LR} (b-bbar)/ A_{LR} (c-cbar)

Projections of b-quark and c-quark Neutral Current Vector Coupling Sensitivities with 70% polarized e^- beam

UNPRECEDENTED PRECISION

Final State Fermion	SM	World Average[1]	Chiral Belle 20 ab^{-1}	Chiral Belle 50 ab^{-1}	Chiral Belle 250 ab^{-1}
	g_V^f (M_Z)	g_V^f (M_Z)	σ (g_V^f) or σ(g_V^b/ g_V^c)	σ (g_V^f) or σ(g_V^b/ g_V^c)	σ (g_V^f) or σ(g_V^b/ g_V^c)
b-quark	-0.3437	-0.322	±0.0003(stat) ±0.0017(sys)	±0.0002(stat) ±0.0017(sys)	±0.00009(stat) ±0.0017(sys)
(eff.=0.3)	± .00049	±0.0077	±0.0017(total)	±0.0017(total)	±0.0017(total)
		2.8σ tension	**Improves x 4**	Improves x 4	Improves x 4
c-quark	0.192	0.1873	±0.0006(stat) ±0.0009(sys)	±0.00035(stat) ±0.0009(sys)	±0.00016(stat) ±0.0009(sys)
(eff.=0.3)	± .0002	±0.0070	±0.0011(total)	±0.0010(total)	±0.0009(total)
			Improves x 7	Improves x 7	Improves x 8

Get stuck at ~20 ab^{-1}

bottom-to-charm UNIVERSALITY RATIO Beam Polarization (dominant systematic) cancels in the ratio

g_V^b /g_V^c	-1.7901	-1.719	±0.0058 (stat ~ total)	±0.0034 (stat ~ total)	±0.00015 (stat ~ total)
Ratio	± .0005	± .082	**Improve x 14**	**Improve x 24**	**Improve x 53**
Relative error:	0.18%	4.8%	**0.32%**	**0.19%**	**0.09%**

Use the ratio

$\sin^2\Theta_W$ - all LEP+SLD measurements combined WA = 0.23153 ± 0.00016

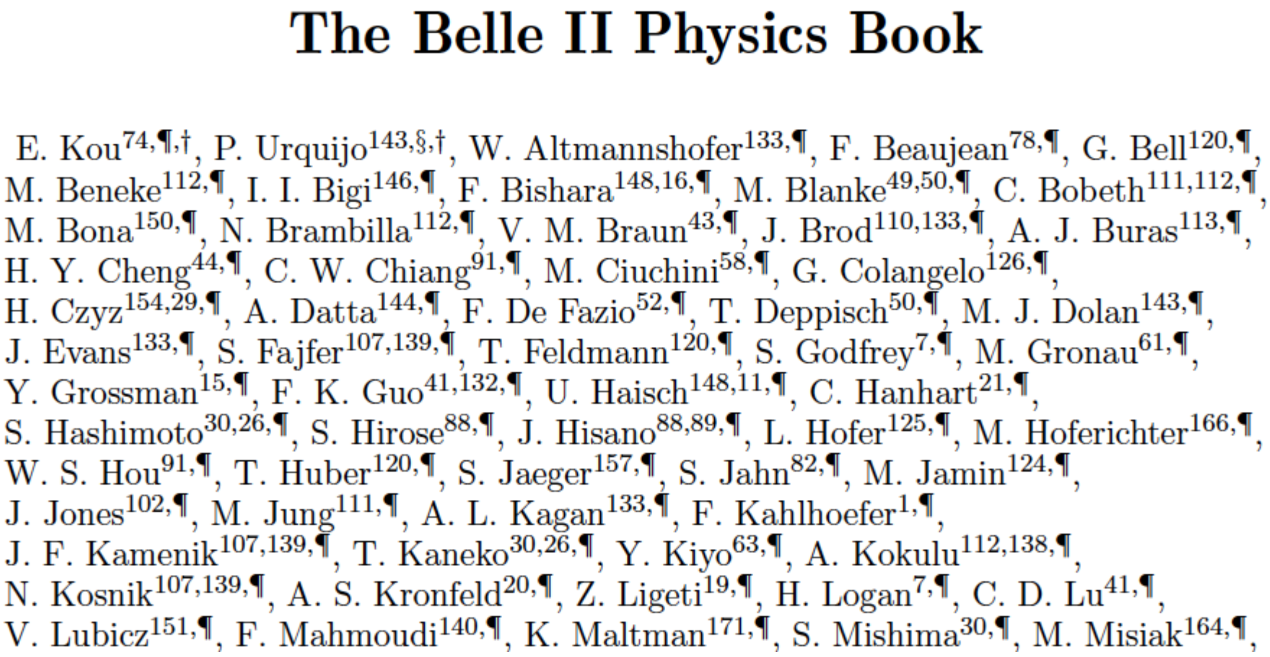
$\sin^2\Theta_W$ - Chiral Belle combined leptons with 40 ab^{-1} have error ~current WA https://arxiv.org/abs/1808.10567

Outcome of the B2TIP (Belle II Theory Interface) Workshops (2014-2018)

Emphasis is on New Physics (NP) reach.

Strong participation from theory community,
lattice QCD community and Belle II experimenters.
689 pages, published by Oxford University Press

Some updates in
Belle II Physics Program White Paper
https://www.slac.stanford.edu/~mpeskin/Snowmass2021/BelleIIPhysicsforSnowmass.pdf



The Belle II Physics Book

E. Kou[74,¶,†], P. Urquijo[143,§,†], W. Altmannshofer[133,¶], F. Beaujean[78,¶], G. Bell[120,¶], M. Beneke[112,¶], I. I. Bigi[146,¶], F. Bishara[148,16,¶], M. Blanke[49,50,¶], C. Bobeth[111,112,¶], M. Bona[150,¶], N. Brambilla[112,¶], V. M. Braun[43,¶], J. Brod[110,133,¶], A. J. Buras[113,¶], H. Y. Cheng[44,¶], C. W. Chiang[91,¶], M. Ciuchini[58,¶], G. Colangelo[126,¶], H. Czyz[154,29,¶], A. Datta[144,¶], F. De Fazio[52,¶], T. Deppisch[50,¶], M. J. Dolan[143,¶], J. Evans[133,¶], S. Fajfer[107,139,¶], T. Feldmann[120,¶], S. Godfrey[7,¶], M. Gronau[61,¶], Y. Grossman[15,¶], F. K. Guo[41,132,¶], U. Haisch[148,11,¶], C. Hanhart[21,¶], S. Hashimoto[30,26,¶], S. Hirose[88,¶], J. Hisano[88,89,¶], L. Hofer[125,¶], M. Hoferichter[166,¶], W. S. Hou[91,¶], T. Huber[120,¶], S. Jaeger[157,¶], S. Jahn[82,¶], M. Jamin[124,¶], J. Jones[102,¶], M. Jung[111,¶], A. L. Kagan[133,¶], F. Kahlhoefer[1,¶], J. F. Kamenik[107,139,¶], T. Kaneko[30,26,¶], Y. Kiyo[63,¶], A. Kokulu[112,138,¶], N. Kosnik[107,139,¶], A. S. Kronfeld[20,¶], Z. Ligeti[19,¶], H. Logan[7,¶], C. D. Lu[41,¶], V. Lubicz[151,¶], F. Mahmoudi[140,¶], K. Maltman[171,¶], S. Mishima[30,¶], M. Misiak[164,¶],