Heavy-quark flavors at Snowmass

ECFA WG1-FLAV: 1st Meeting — June 29, 2022

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What is Snowmass?

https://www.snowmass21.org/start

Snowmass 2021

DPF Community Planning Exercise

Search SEARCH

- Announcements
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Organization

- Snowmass Steering Group
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Snowmass Frontiers

- Energy Frontier
- Neutrino Physics Frontier
- Rare Processes and Precision
- Cosmic Frontier
- Theory Frontier
- Accelerator Frontier
- Instrumentation Frontier
- Computational Frontier

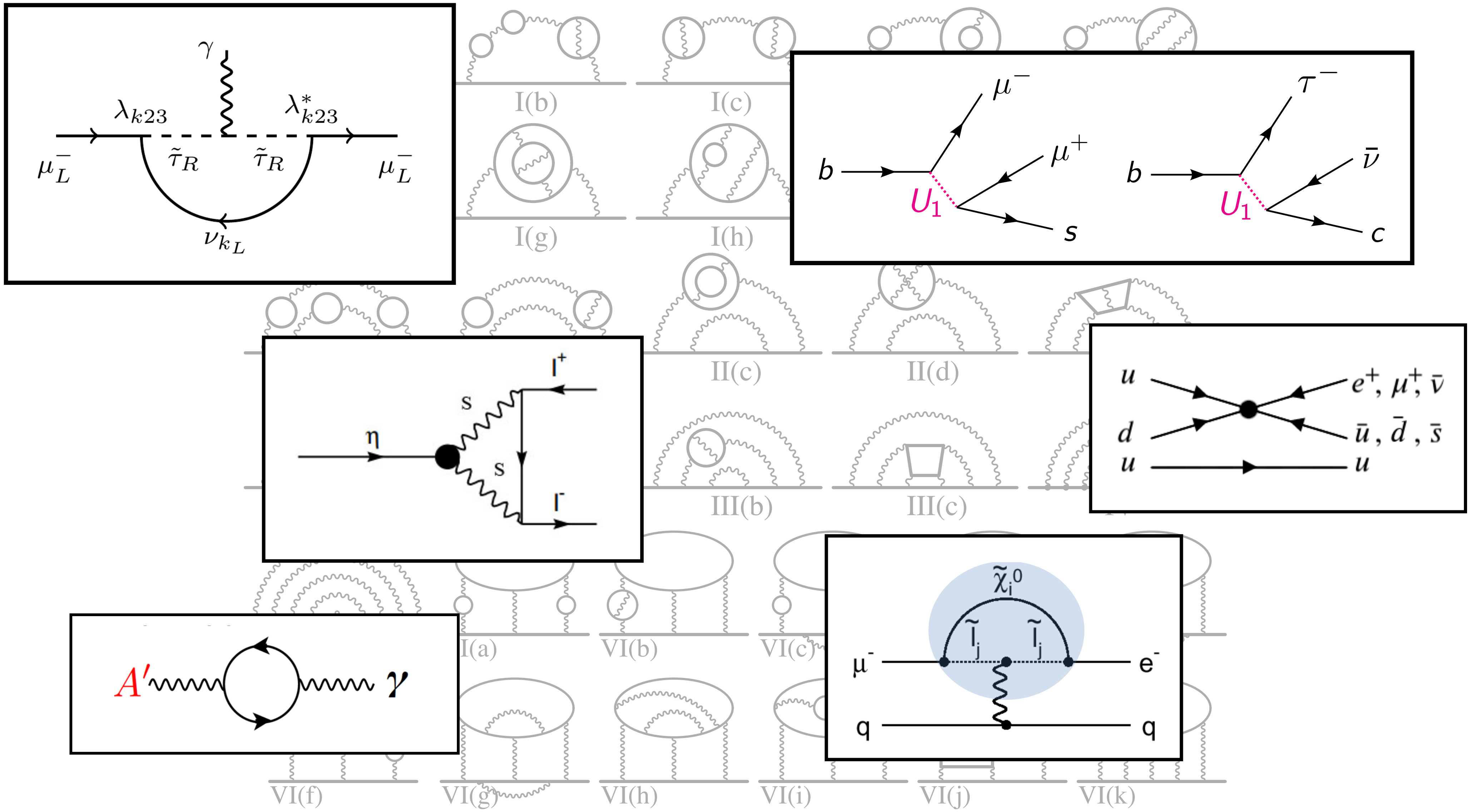
Trace: • conveners • **start**

Welcome to Snowmass

The Snowmass Community Planning Exercise, which was delayed in January 2021 due to the COVID-19 pandemic, resumed full activity in September 2021. It will culminate in July with the Community Summer Study Workshop. For details and updates, please see the announcement at https://snowmass21.org/announcements. The ongoing activities and updates from the individual frontiers can be found on their frontier Wiki pages. We encourage you to participate in the activity by signing up to the research frontiers at their Wiki pages, accessible from the side menu if you haven't already done so.

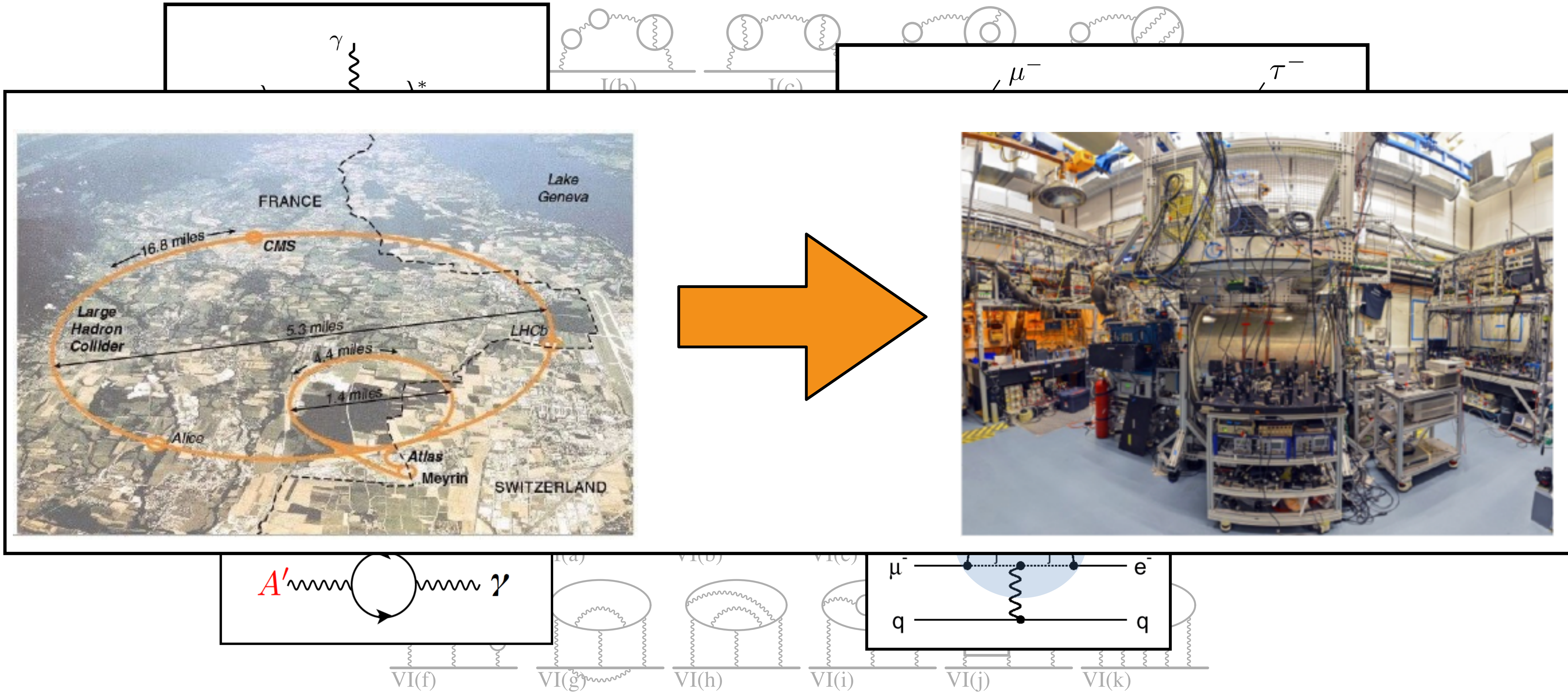
The Particle Physics Community Planning Exercise (a.k.a. "Snowmass") is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. Snowmass will define the most important questions for the field of particle physics and identify promising opportunities to address them. (Learn more about the history and spirit of Snowmass here "How to Snowmass" written by Chris Quigg). The P5, Particle Physics Project Prioritization Panel, will take the scientific input from Snowmass and develop a strategic plan for U.S. particle physics that can be executed over a 10 year timescale, in the context of a 20-year global vision for the field.

Rare Processes and Precision Measurements



Probing beyond-standard-model physics with precision measurements and rare/forbidden processes from as many directions as possible

Rare Processes and Precision Measurements



Experimental efforts range from from (big) collider-based experiments to "table-top" experiments. Need intense sources and ultra-sensitive detectors.

Rare Processes and Precision Measurements

- Frontier conveners: M. Artuso, R. Bernstein, A. Petrov
- Topical groups:

RF1: Weak decays of b and c quarks — A. Di Canto, S. Meinel

RF2: Weak decays of strange and light quarks — E. Goudzovski, E. Passemar

RF3: Fundamental Physics in Small Experiments — P. Winter, T. Blum

RF4: Baryon and Lepton Number Violating Processes — P. Fileviez Perez, A. Pocar

RF5: Charged Lepton Flavor Violation — B. Echenard, S. Davidson

RF6: Dark Sector Studies at High Intensities — M. Williams, S. Gori

RF7: Hadron Spectroscopy — T. Skwarnicki, R. Lebed

- Liaisons with other frontiers:

Energy: M. Franco Sevilla

Neutrino: R. Bernstein

Cosmic: S. Gardner

Theory: A. Petrov

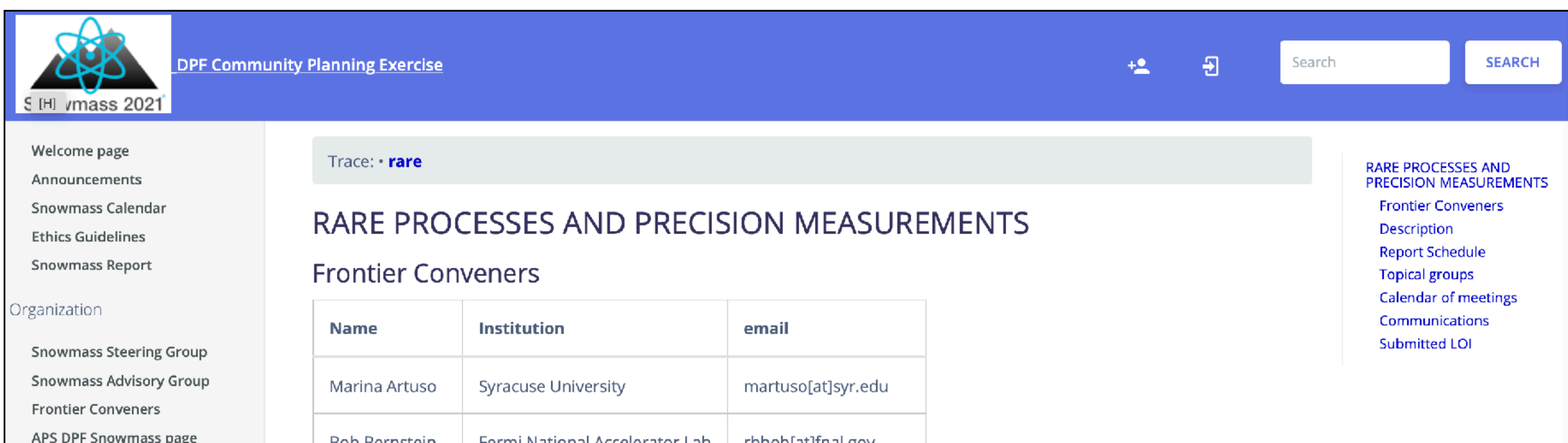
Accelerator: R. Bernstein

Instrumentation: M. Artuso

Computational: M. Williams

Community Engagement: S. Middleton

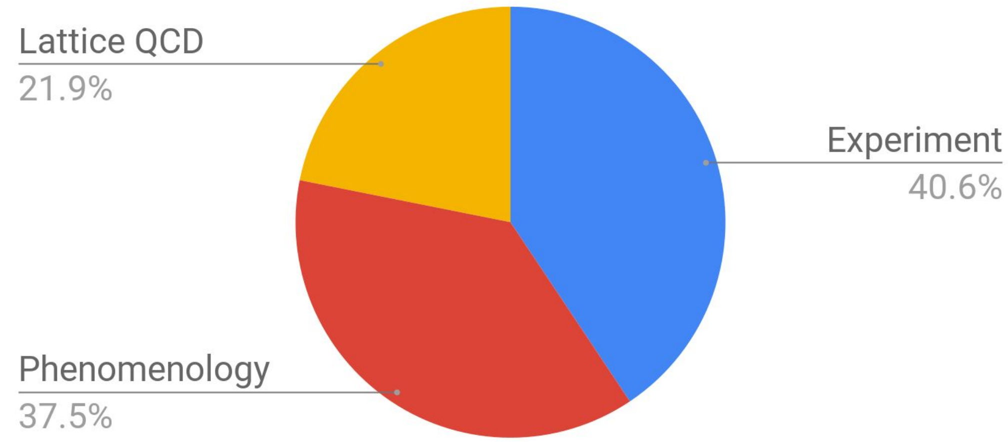
https://www.snowmass21.org/rare/start



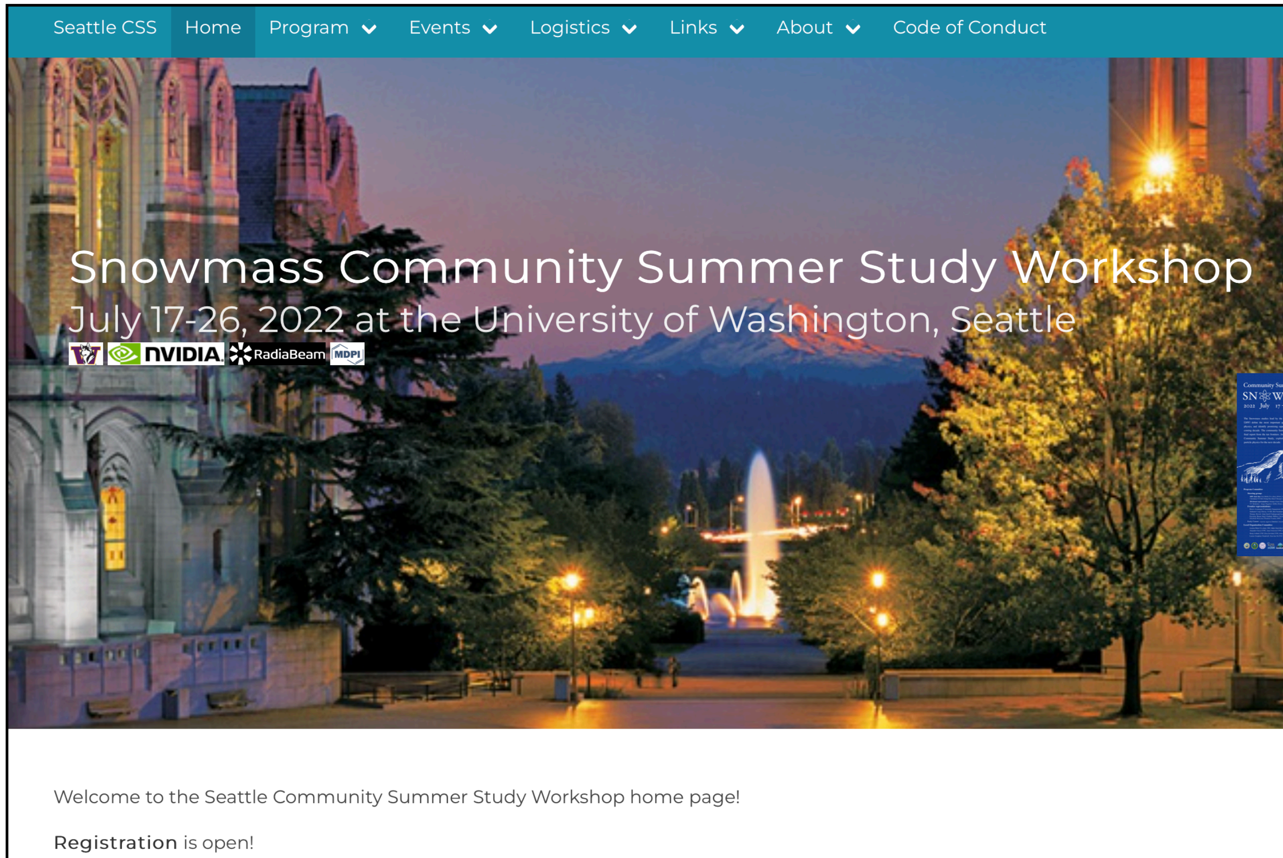
RF1: weak decays of *b* and *c* quarks

- One of the largest/most participated RF topical groups
- Received 28 LOIs at the start of Snowmass, with healthy mix of theory and experimental topics. Most of them converted into contributed (white) papers
- Organized two workshops before the Covid-19 pause of activities:
  - Sept 28-29, 2020 “Lepton flavor violation and lepton universality violation in meson and baryon decays” (with RF5) https://indico.fnal.gov/event/44442/
  - Jan 11-12, 2021 “Theory meets experiment on $|V_{ub}|$ and $|V_{cb}|$” (with TF05 and TF06) https://indico.fnal.gov/event/46246/
- And a successful frontier meeting in Cincinnati
  - May 16-19, 2022 “RF Spring meeting” https://indico.fnal.gov/event/51844/
- Now working on the topical group report and organization of the final CSS workshop in Seattle

RF1 LOIs split by topics



http://seattlesnowmass2021.net



RF1 white papers

- White papers received/expected so far

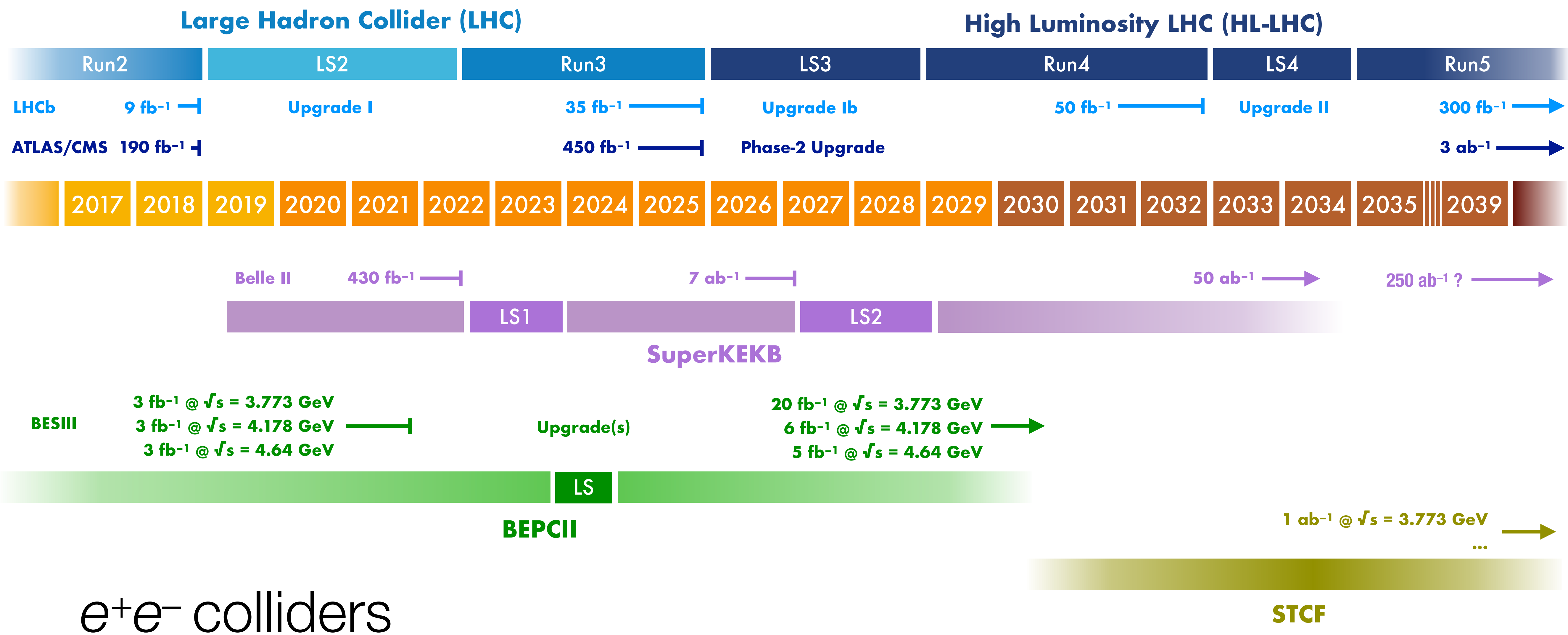
Whitepaper	Authors	Status
Charm Physics in the High-Luminosity Super τ-Charm Factory	H.-Y. Cheng, X.-R. Lyu, Z.-Z.	arXiv:2203.03211
Belle II physics reach and plans for the next decade and beyond	Belle II collaboration	Snowmass website
The Belle II detector upgrade program	Belle II collaboration	arXiv:2203.11349
Belle II executive summary	D. M. Asner et al.	arXiv:2203.10203
Future physics potential of LHCb	LHCb collaboration	LHCb-PUB-2022-012
Physics with the Phase-2 ATLAS and CMS detectors	ATLAS and CMS collaborations	ATL-PHYS-PUB-2022-018
Physics in the τ-charm region at BESIII	BESIII collaboration	arXiv:2204.08943
A New Tool for Detecting BSM Physics in $B \to K^*ll$ Decays	A. Sibidanov et al.	arXiv:2203.06827
A New Tool to Search for Physics Beyond the Standard Model in $B \to D^*l$	B. Bhattacharya et al.	arXiv:2203.07189
A lattice QCD perspective on weak decays of b and c quarks	O. Witzel et al.	In preparation
USQCD perspectives on the role of lattice gauge theory in HEP	A. Kronfeld et al.	In preparation
New physics in B meson mixing: future sensitivity and limitations	J. Charles et al.	arXiv:2006.04824
$b \to s\tau^+\tau^-$ Physics at Future Z Factories	L. Li, T. Liu	arXiv:2012.00665
The Future Circular Collider: a Summary for the US 2021 Snowmass	G. Bernardi et al.	arXiv:2203.06520
Japan's strategy for Future Projects in High Energy Physics	M. Enddo et al.	arXiv:2203.13979
Flavor model building	W. Altmannshofer, J. Zupan	arXiv:2203.07726
The Physics potential of the CEPC	H. Cheng et al.	arXiv:2205.08553

- In addition, we have solicited the following white papers to give an overview of the physics discovery potential and questions that can be addressed from both theory and experiments points of view

Topic	Editor (Experiment)	Editor (Theory)	Status
High precision in CKM unitarity tests in b and c decays	S. Monteil	A. Lenz	In preparation
Searches for CP violation in b and c decays	D. Tonelli	Y. Grossman	In preparation
Lepton-flavor violation and lepton-flavor-universality violation in b and c decays	P. Koppenburg	D. Guadagnoli	In preparation
Rare decays of b and c hadrons	F. Archilli	W. Altmannshofer	arXiv:2206.11331

Timeline of heavy-flavor experiments

hadron colliders



e^+e^- colliders

Complementarity

LHCb

- Huge advantage in production rate, but large backgrounds results in lower efficiencies (advantage remains mostly for charged final states)
- Larger boost and superior decay-time resolution for time-dependent measurements
- Access to all *b*-hadron species

Belle II

- Cleaner environment allows for more generous selections — milder efficiency effects
- Unique access to fully neutral final states and decays with invisible particles
- Quantum-correlated $B\bar{B}$ production allows efficient determination of production flavor for time-dependent *CP*-violation measurements

ATLAS/CMS

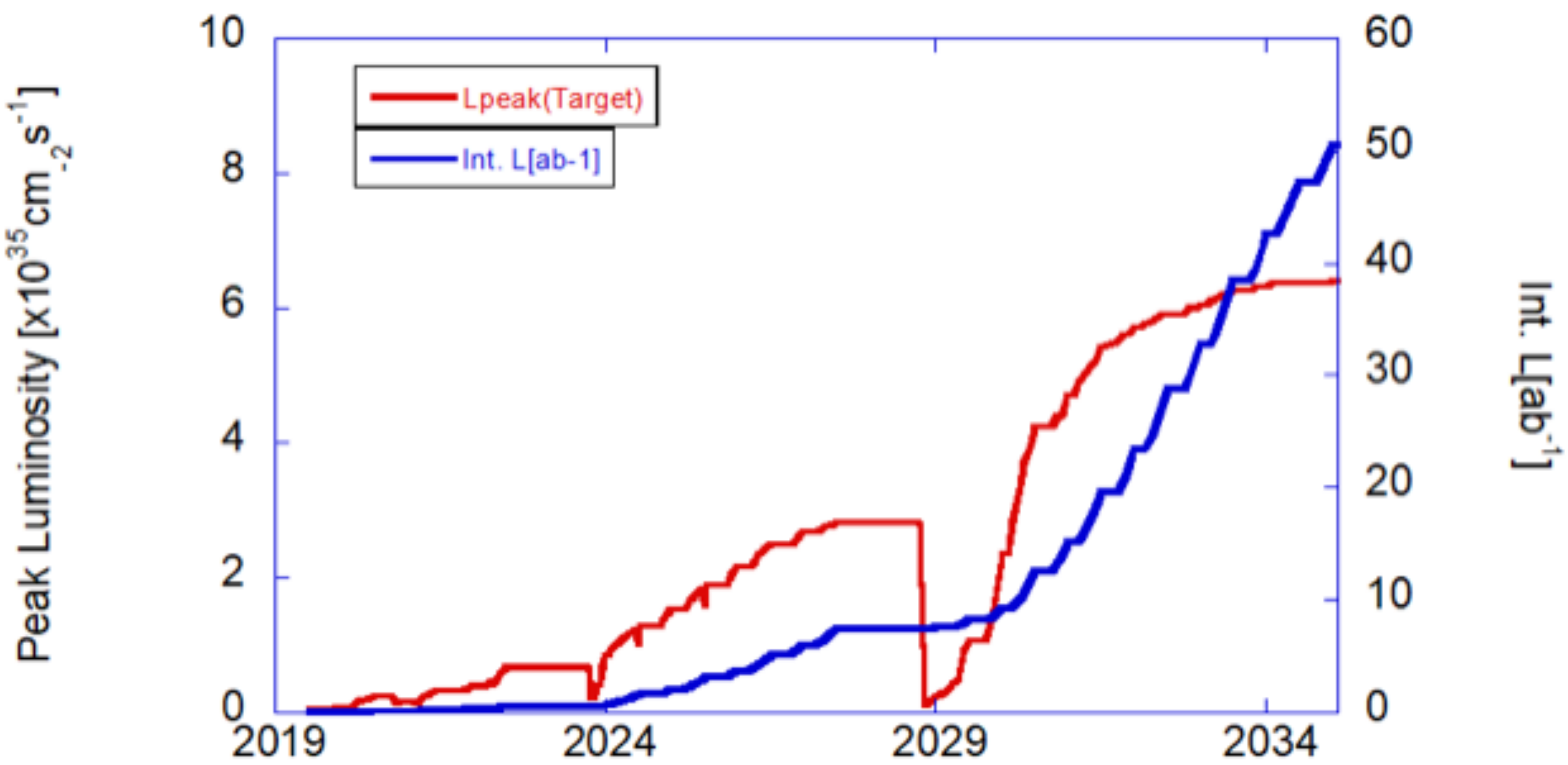
- Larger inst. lumi. than LHCb, access limited to final states with dimuons

charm-τ factories (BESIII/STCF)

- Unique access to quantum-correlated $D^0\bar{D}^0$ pairs

Belle II status and plans

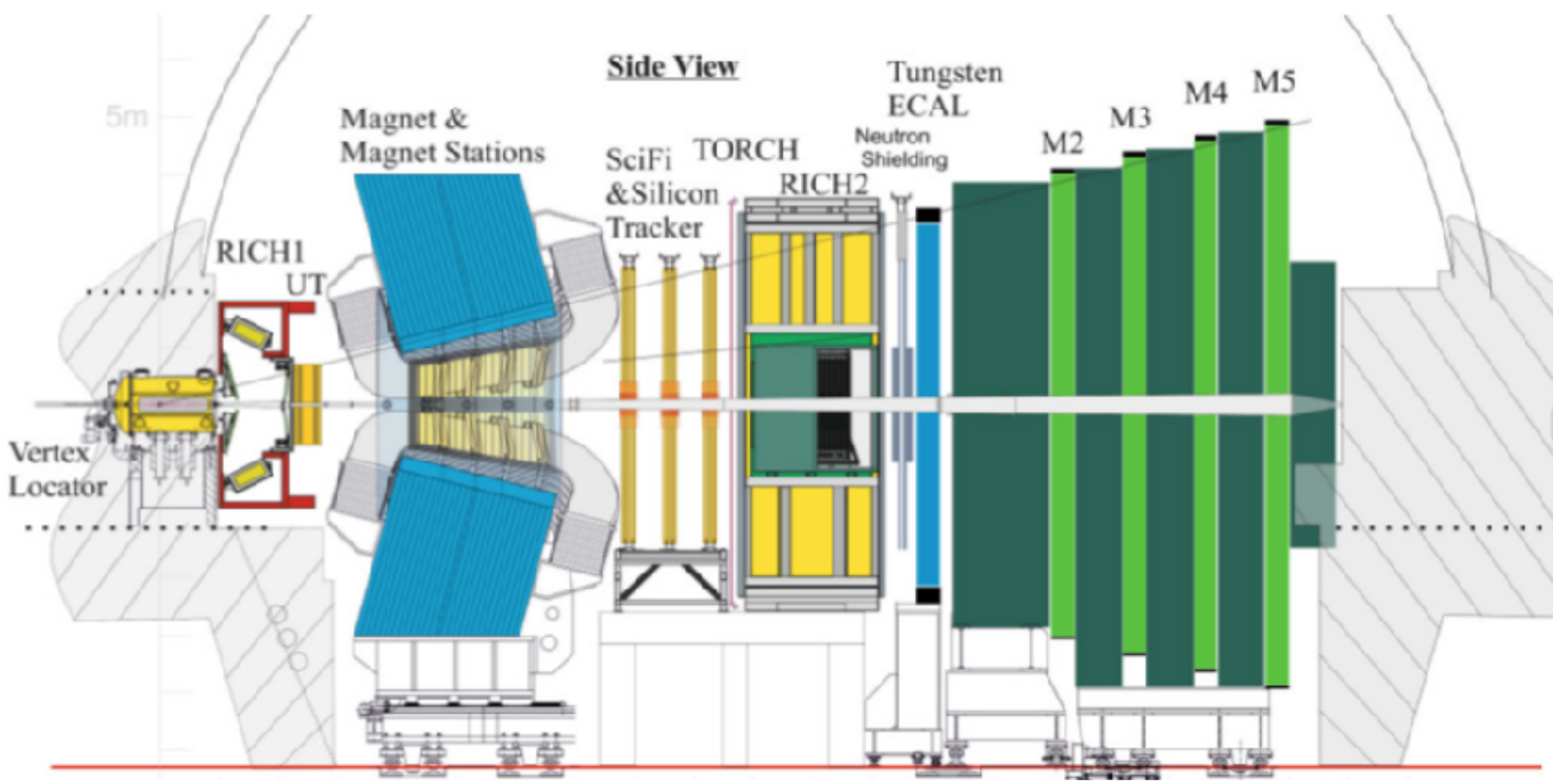
- Running since 2019:
  peak $L = 4.7\times10^{34}$ cm^{-2}s^{-1},
  int. L = 430 fb^{-1}
  - Now in LS1 (till ~end of 2023): mainly to replace PXD
- International task force of accelerator experts formed in 2021 to establish SuperKEKB's path towards target $L = 6.5\times10^{35}$ cm^{-2}s^{-1} and target int. L = 50 ab^{-1} by mid-2030s
  - LS2 (~2027-2029): upgrade SuperKEKB (QCS, lattice), to reacl target L, and parts of the detector, to improve robustness against machine backgrounds



- Upgrades beyond the currently planned program
  - Concrete proposal for beam polarization to perform precision electroweak (and τ-physics) measurements
  - Speculative proposal for running at ultra-high luminosities ($L > 10^{36}$ cm^{-2}s^{-1}) and integrate ~250 ab^{-1}

LHCb Upgrade II

- LHCb physics program limited by the detector (and not by the LHC)
- Baseline target: keep same performance as in Run 2, but run at $L = 2\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with 40x larger pile-up
- Extremely challenging upgrade, currently in early planning: options available, dedicated R&D needed, estimated cost of ~175MCHF for baseline option



- Key ingredients:
  - High granularity
  - Fast timing (tens of ps)
  - Radiation hardness (up to few $10^{16}\, n_{eq}/\mathrm{cm}^2$)
- DAQ and trigger:
  - Full detector readout at 30 MHz
  - Offline-quality reconstruction at trigger level for real-time analysis

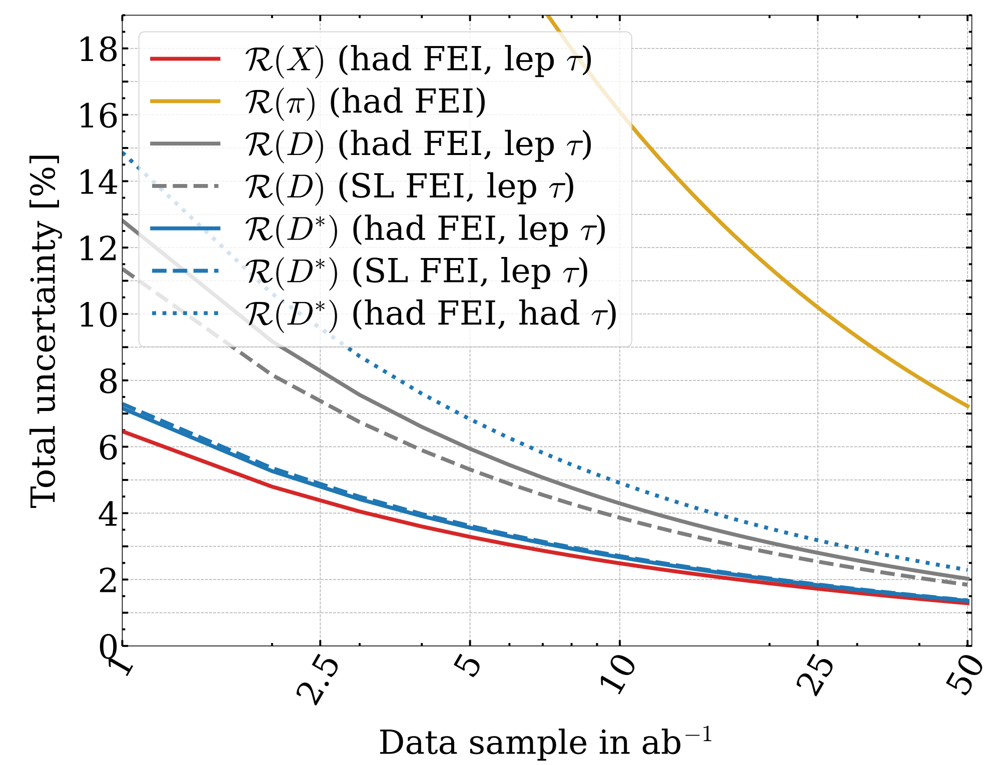
Expected progress on (some) key observables

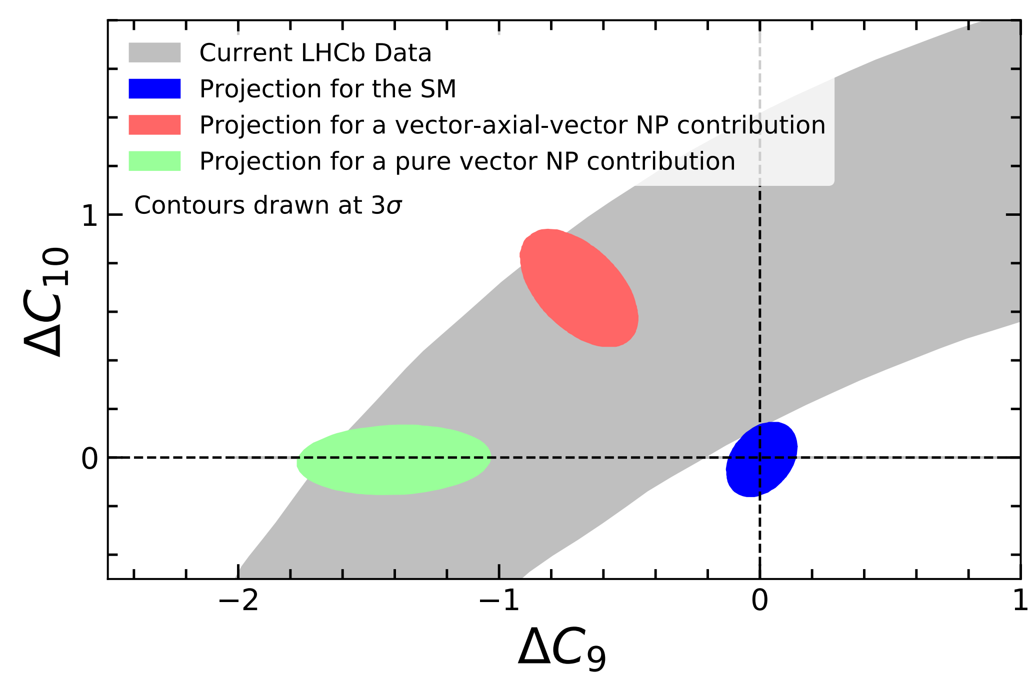
Observable	Current best	Belle II $50\,\mathrm{ab}^{-1}$	Belle II $250\,\mathrm{ab}^{-1}$	LHCb $50\,\mathrm{fb}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$	ATLAS $3\,\mathrm{ab}^{-1}$	CMS $3\,\mathrm{ab}^{-1}$	BESIII $20\,\mathrm{fb}^{-1}$ $(*)$	STCF $1\,\mathrm{ab}^{-1}$ $(*)$
Lepton-flavor-universality tests									
$R_K(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.044 [31]	0.036	0.016	0.017	0.007				
$R_{K^*}(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.12 [32]	0.032	0.014	0.022	0.009				
R_D	0.037 [33]	0.008	< 0.003	na	na				
R_{D^*}	0.018 [33]	0.0045	< 0.003	0.005	0.002				
Rare decays									
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ $[10^{-9}]$	0.46 [34, 35]			na	0.16	0.46–0.55	0.39		
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.69 [34, 35]			0.27	0.11	na	0.21		
$\mathcal{B}(B^0 \to \overline{K}^{*0}\tau^+\tau^-)$ UL $[10^{-3}]$	2.0 [36, 37]	0.5	na						
$\mathcal{B}/\mathcal{B}_{\mathrm{SM}}(B^+ \to K^+\nu\overline{\nu})$	1.4 [38, 39]	0.08–0.11	na						
$\mathcal{B}(B \to X_s\gamma)$	10% [40, 41]	2–4%	na						
CKM tests and *CP* violation									
α	5° [42]	0.6°	0.3°						
$\sin 2\beta(B^0 \to J/\psi\, K^0_{\mathrm{S}})$	0.029 [43]	0.005	0.002	0.006	0.003				
γ	4° [44]	1.5°	0.8°	1°	0.35°			0.4° (†)	$< 0.1°$ (†)
$\phi_s(B_s^0 \to J/\psi\,\phi)$	32 mrad [45]			10 mrad	4 mrad	4–9 mrad	5–6 mrad		
$\lvert V_{ub}\rvert(B^0 \to \pi^-\ell^+\nu)$	5% [46, 47]	2%	$< 1\%$	na	na				
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert(\Lambda_b^0 \to p\mu^-\overline{\nu})$	6% [48]			2%	1%				
$f_{D^+}\lvert V_{cd}\rvert(D^+ \to \mu^+\nu)$	2.6% [49]	1.4%	na					1.0%	0.15%
$S_{CP}(B^0 \to \eta' K^0_{\mathrm{S}})$	0.08 [50, 51]	0.015	0.007	na	na				
$A_{CP}(B^0 \to K^0_{\mathrm{S}}\pi^0)$	0.15 [50, 52]	0.025	0.018	na	na				
$A_{CP}(D^+ \to \pi^+\pi^0)$	11×10^{-3} [53]	1.7×10^{-3}	na	na	na			na	na
$\Delta x(D^0 \to K^0_{\mathrm{S}}\pi^+\pi^-)$	18×10^{-5} [54]	na	na	4.1×10^{-5}	1.6×10^{-5}			na	na
$A_\Gamma(D^0 \to K^+K^-, \pi^+\pi^-)$	11×10^{-5} [55]	na	na	3.2×10^{-5}	1.2×10^{-5}			na	na

Table 1-1. *Projected uncertainties (or 90% CL upper limits) in several key heavy-flavor observables over the next two decades. A missing entry means that the observable cannot be measured, the abbreviation na means that, although the observable can be measured, the projected uncertainty is not available. Projections are taken from Refs. [17, 19, 56] (Belle II), Refs. [57, 28] (LHCb), Ref. [23] (ATLAS and CMS), Refs. [25, 30] (BESIII and STCF). $(*)$ Integrated luminosity at $\sqrt{s} = 3.773$. (†) Projected uncertainties on γ resulting from BESIII/STCF measurements of the D strong-phase differences, which will contribute as external inputs to the Belle II and LHCb measurements.*

Lepton-flavor-universality tests

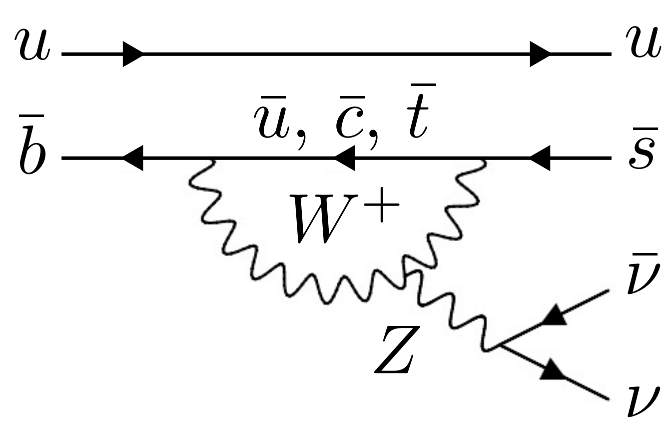
- Measurements of LFU observables in $b \to s\ell^+\ell^-$ and $b \to c\tau^-\bar{\nu}$ decays will reach 1%-level uncertainties in the next decade, a precision sufficient to establish or reject the level of LFU violation seen in the current measurements
- LHCb Upgrade II will then open new avenues with sensitivity to even cleaner theoretically observables, such as the difference between the values of C_9 and C_{10} for $b \to se^+e^-$ and $b \to s\mu^+\mu^-$ transitions, crucial to distinguish between different NP models

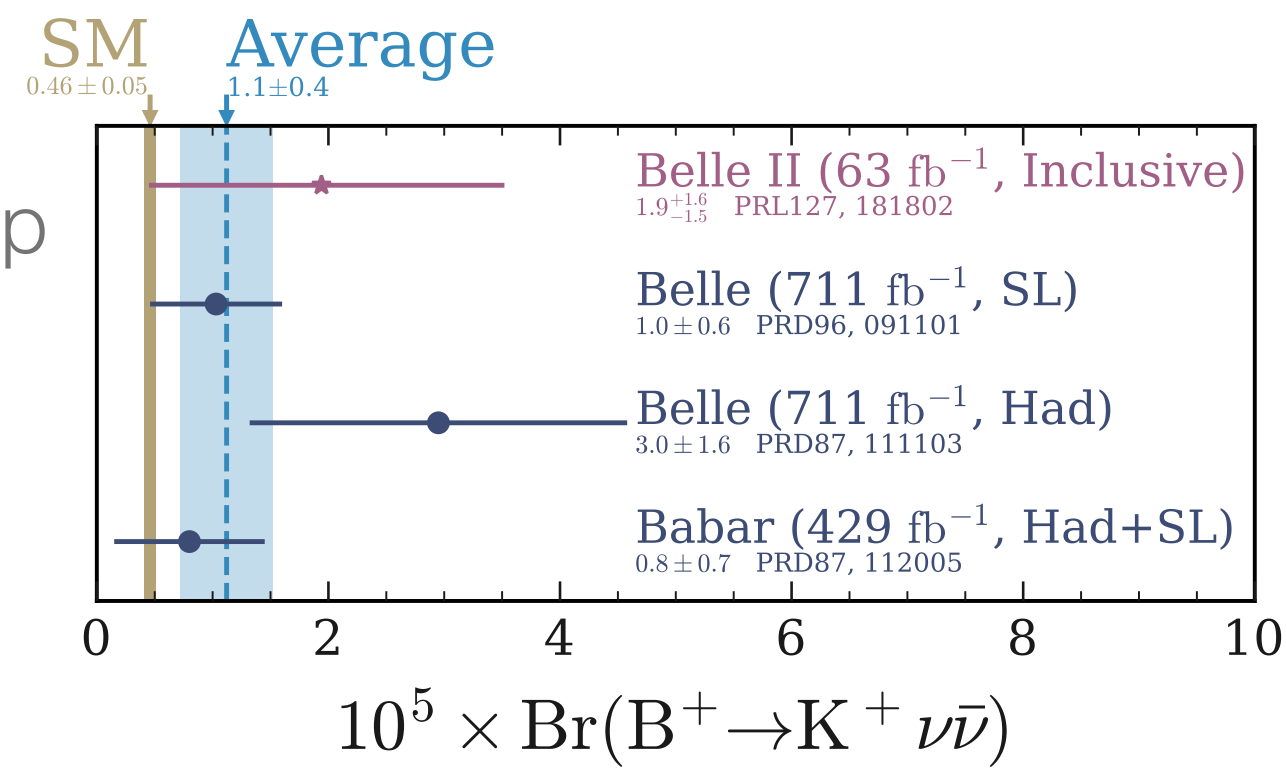




Rare decays: $B \to K^{(*)} \nu\bar{\nu}$

- Complementary to $b \to s\ell^+\ell^-$ transitions, but with no charm-loop contamination (theoretically clean)



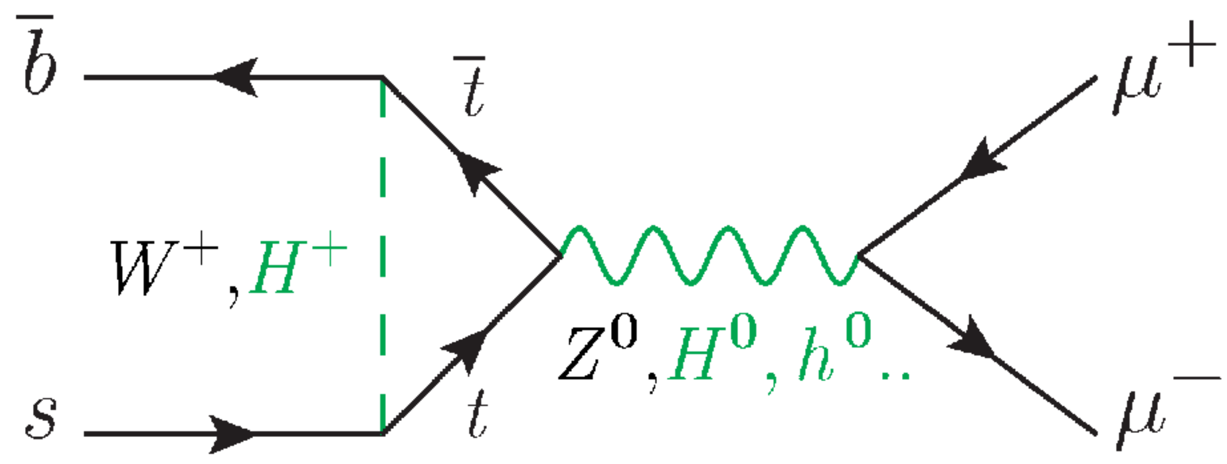


- Accessible only at Belle II
  - SM rate of $B^+ \to K^+ \nu\bar{\nu}$ can be measured at >3σ with 5/ab

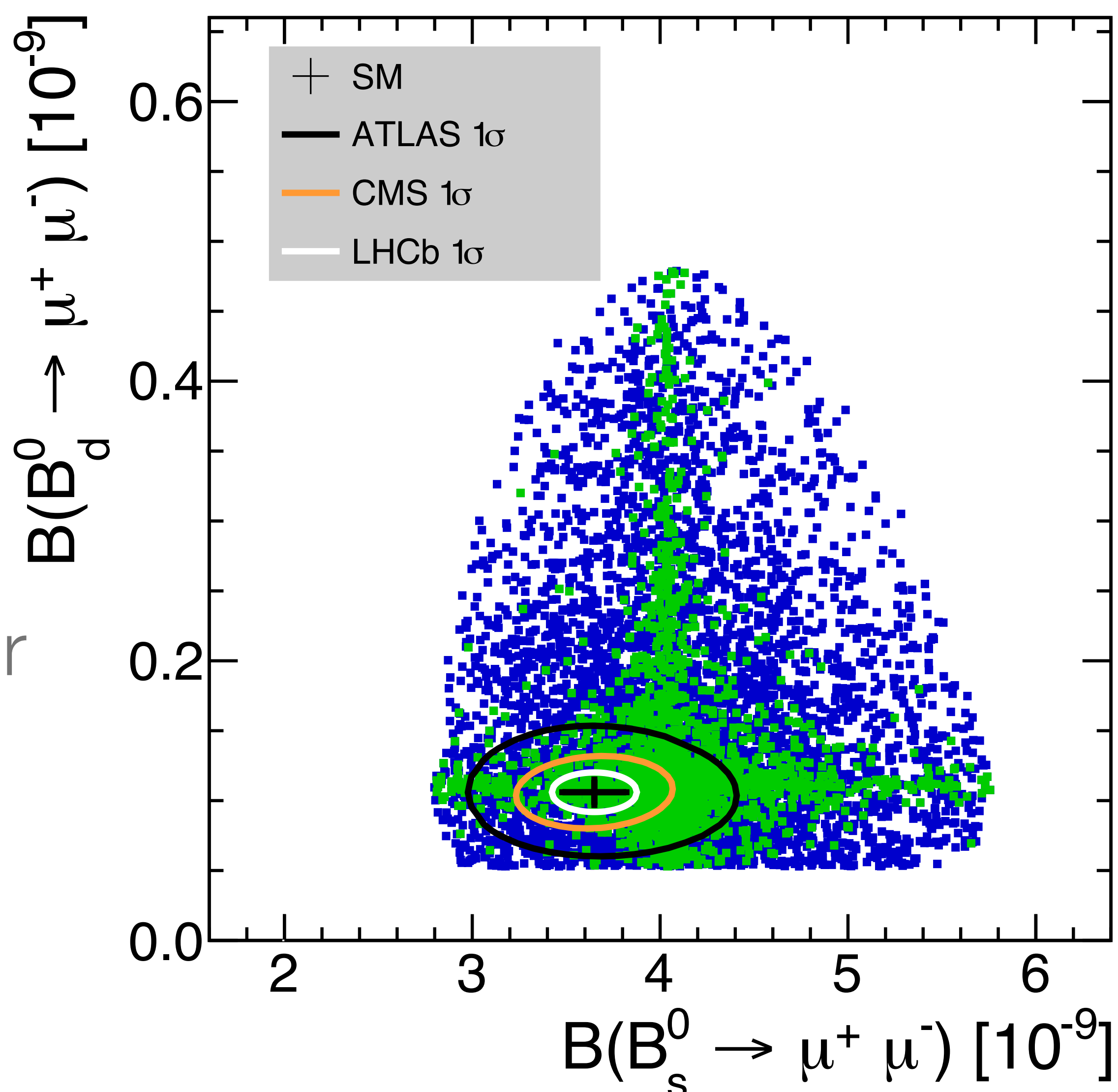
Baseline (improved) uncertainties on rate relative to SM

Decay	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 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)

Rare decays: $B_{(s)} \to \mu^+\mu^-$ decay



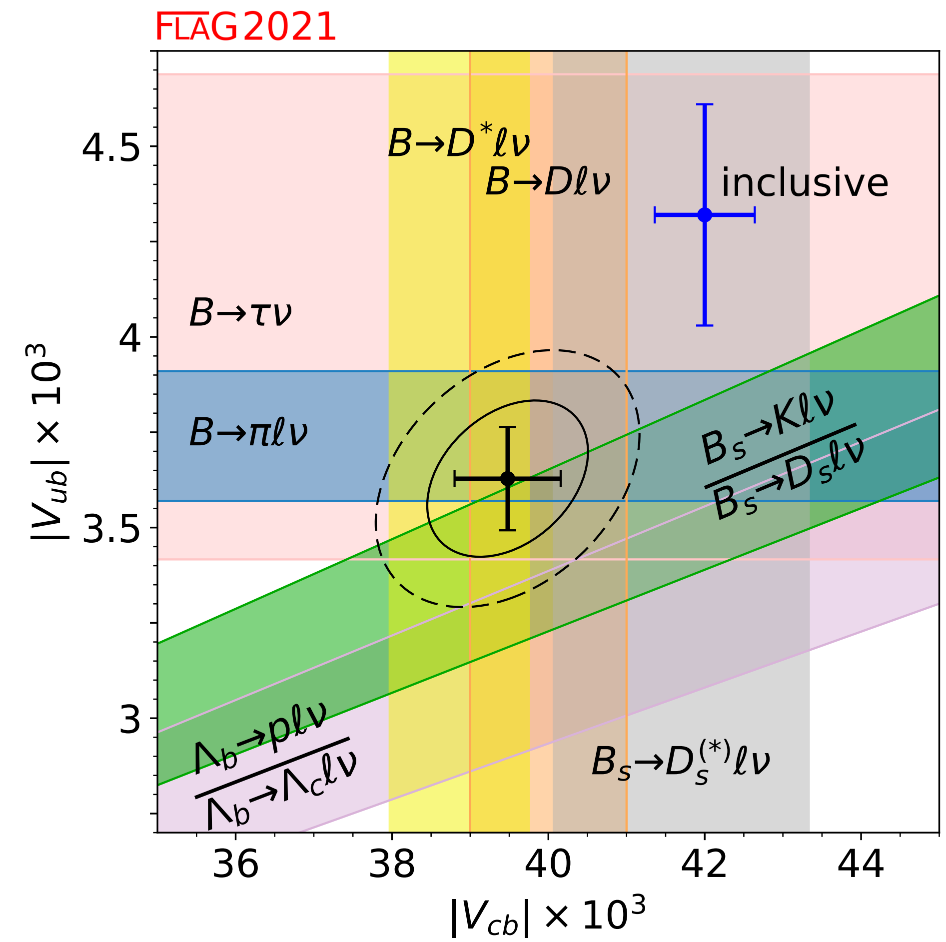
- Powerful probe of the SM gauge sector
- LHCb Upgrade II will approach SM uncertainty (currently limited by CKM matrix elements, B_s decay constant)
- Effective lifetime and time-dependent *CP* asymmetry are additional NP probes that will become accessible during HL-LHC

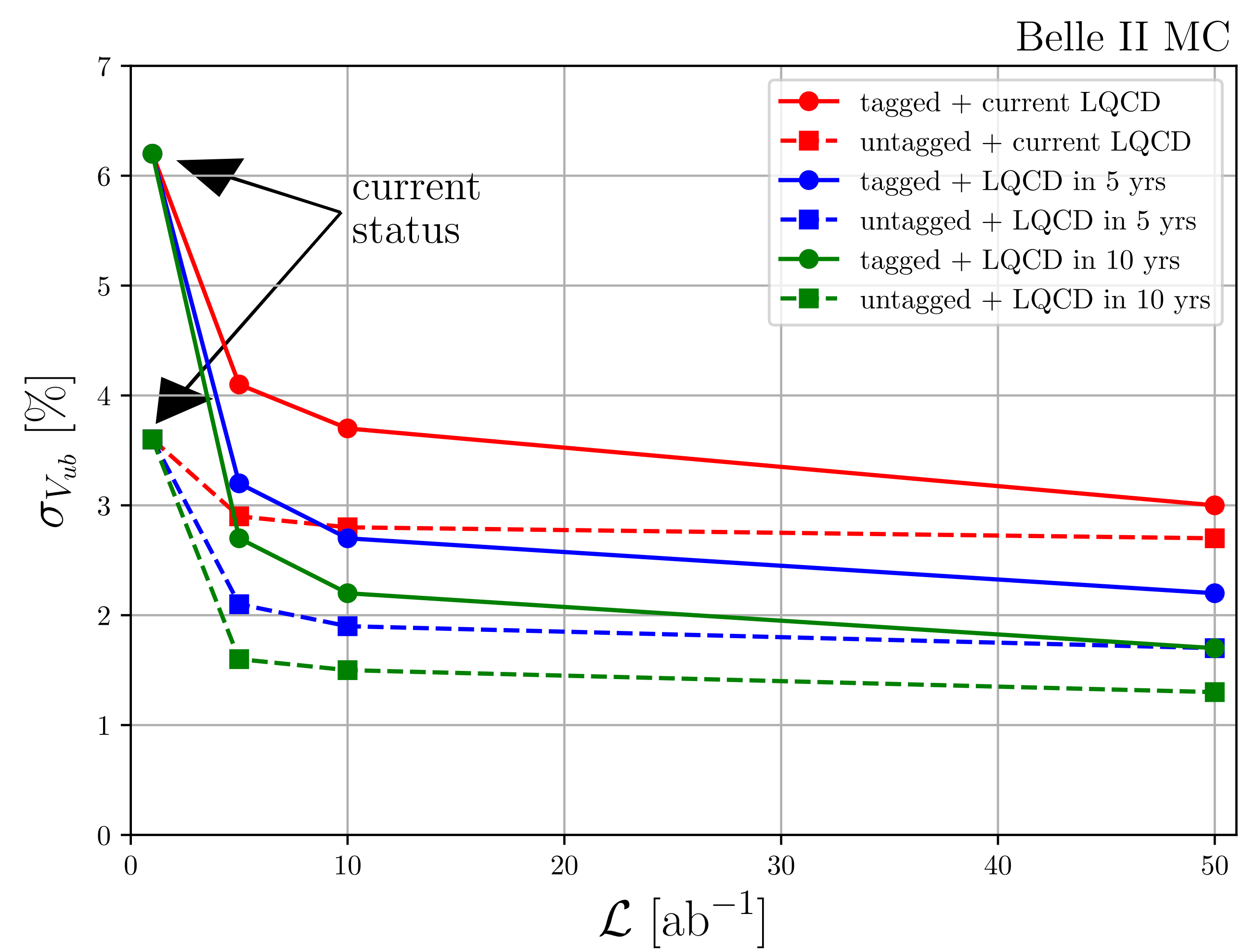


SUSY allowed
\+ other exp. constraints

CKM tests: V_{ub}, V_{cb}

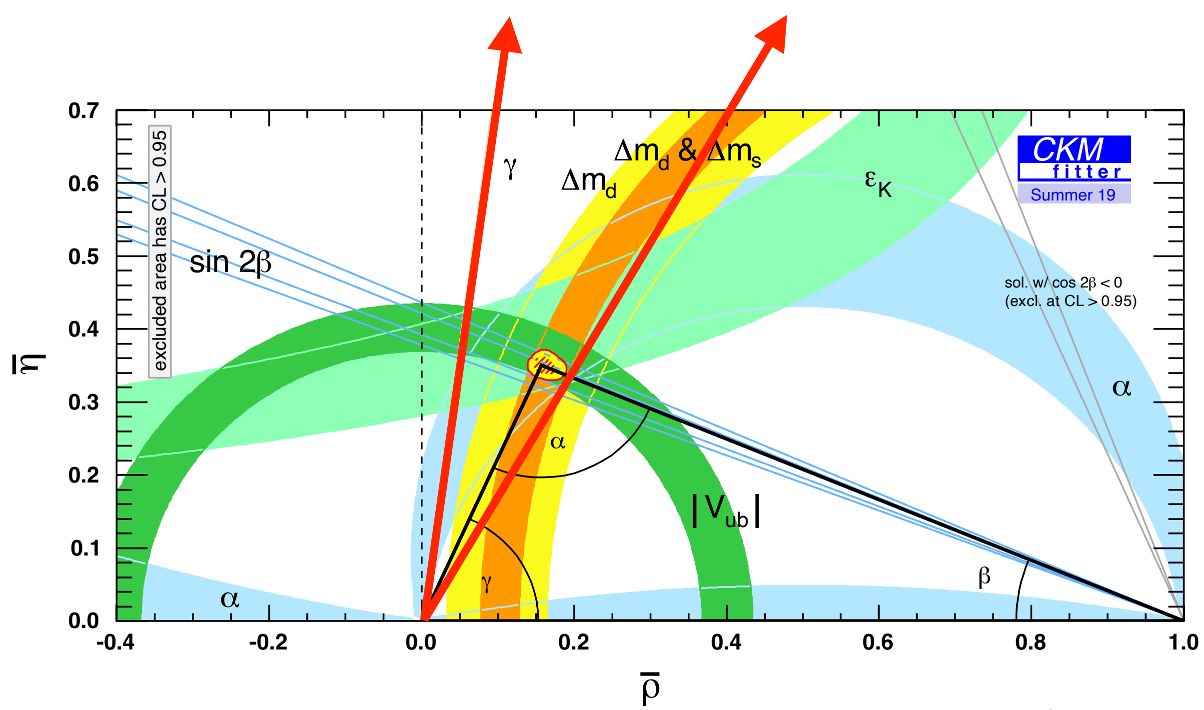
- Long-standing discrepancy between exclusive and inclusive determinations. Resolving the tension is a high priority that will require a combined experiment-theory effort
- Belle II will drive the global experimental progress throughout the next decade
- LHCb can achieve competitive sensitivity on the ratio $|V_{ub}|/|V_{cb}|$ using Λ_b and B_s decays
- Not obvious that data and theory improvements will solve discrepancy — if keep doing the same, why would we get different results? Opportunity (and challenge) is to innovate

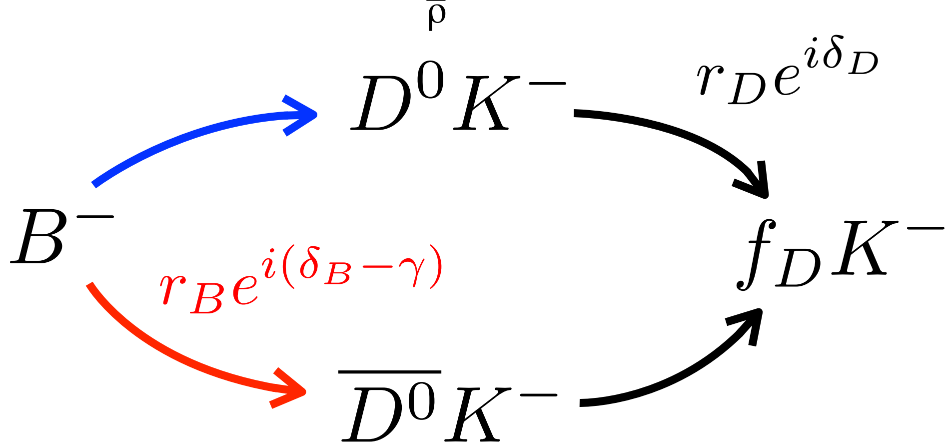




CKM tests: γ

- The only *CP*-violation parameter that can be measured from tree-level decays (negligible theory prediction)





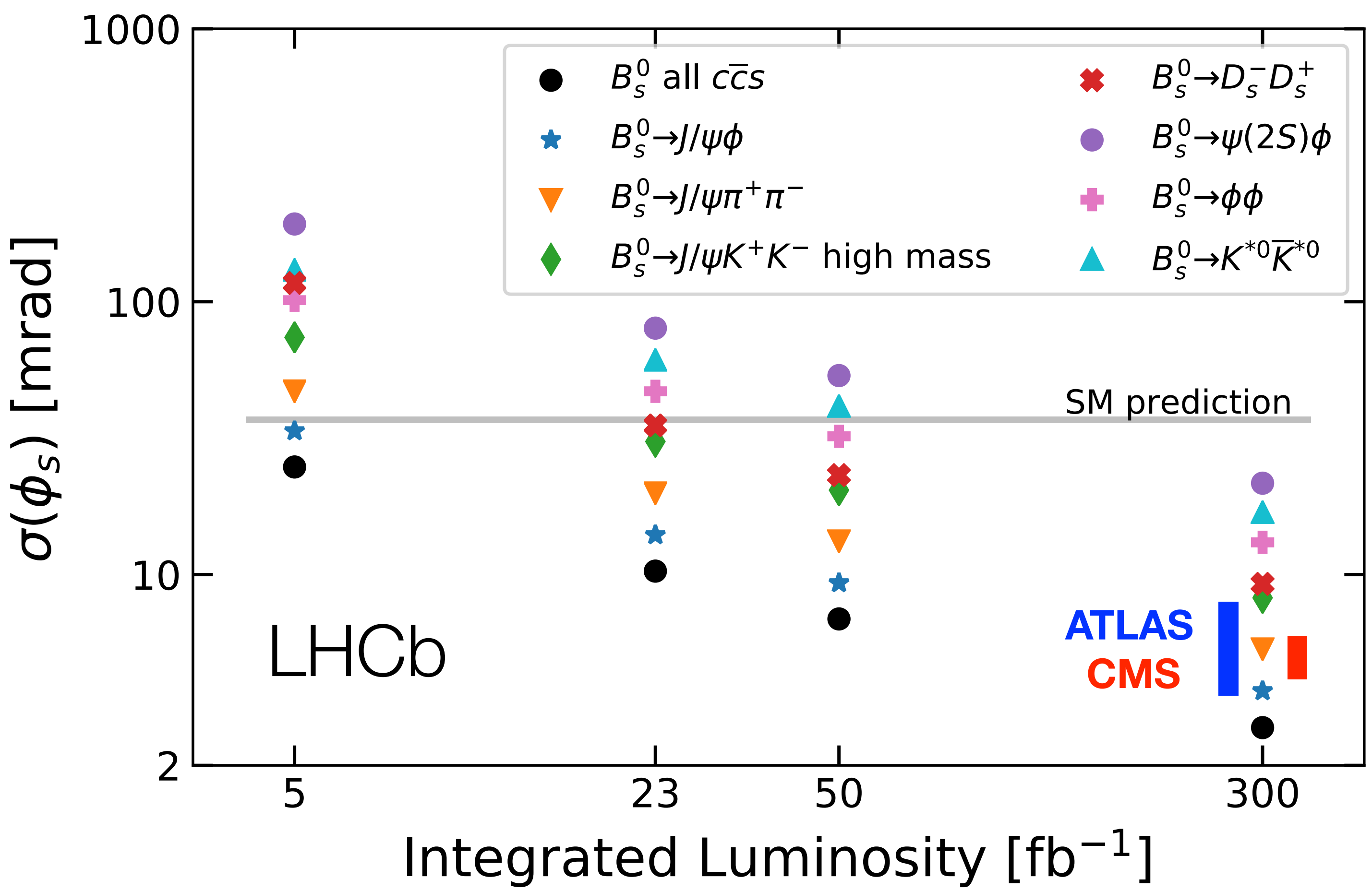
	Precision
Now	4°
Belle II (50/ab)	1.5°
LHCb (50/fb)	1°
Belle II (250/ab)	0.8°
LHCb (300/fb)	0.35°

Complementarity is trilateral: inputs from coherent $D^0\bar{D}^0$ data instrumental to reach the asymptotic precision. Current ~1.5° contribution (CLEO+BESIII) expected to shrink to ~0.4° (BES III after 2024) and to ~0.1° (STCF)

CP violation in the B_s system

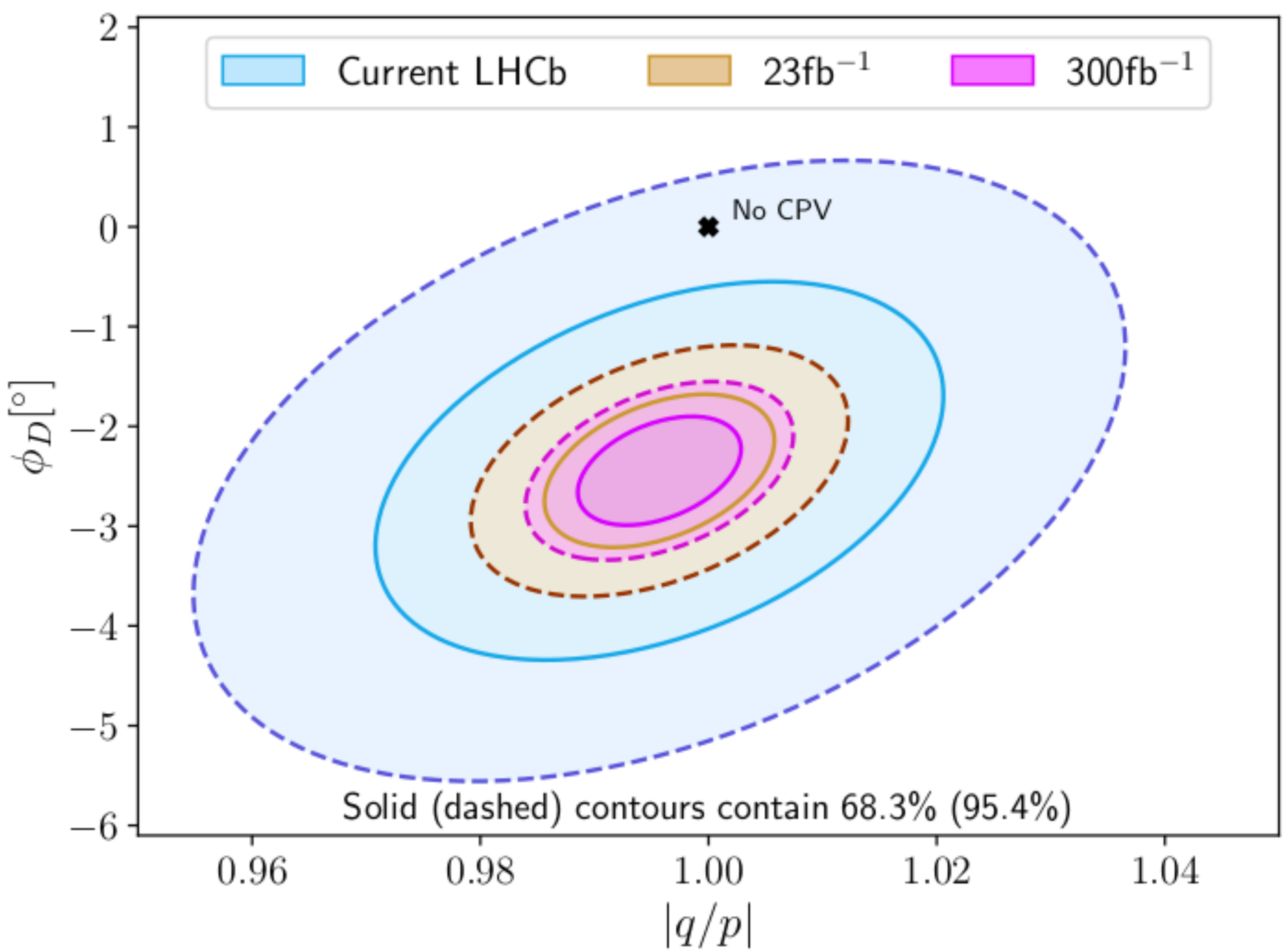
- Mixing phase very small and precisely predicted in the SM, ideal probe for new sources of *CP* violation

- Limited by experimental (statistical) uncertainties. During HL-LHC precision with $B_s \to J/\psi\phi$ will be ~4 mrad, well below SM value



- Will either expose NP or provide precise reference for non-SM searches in gluonic-penguin channels

Mixing-induced *CP* violation in charm



- Compelling access to beyond-SM physics. Precise predictions are hard, but LHCb's sensitivity to ~x10 enhancements with respect to naive SM predictions offers unique discovery potential

Conclusive (forward looking) remarks

- The next two decades offer an unique, probably unrepeatable, opportunity: for the first time, several experiments with complementary capabilities will pursue a highly synergistic and diverse program of heavy-flavor measurements
    - Potential to probe NP at energy scales more than doubled that of present indirect searches. A substantial advancement compared to the incremental reach of direct searches at the energy frontier
- Further into the future:
    - The identification of the next collider will be mostly motivated by the need to understand the mechanism behind the electroweak-symmetry breaking, the important role of heavy-quark physics should still be considered as key for a broad and rich HEP program
    - The great potential to disclose indications of NP, or severely constrain its nature, in the next decades means that quark-flavor physics is likely to provide crucial inputs about what should be the next energy-frontier facility