Captions here
please

Community Summer Study

SNOWMASS

July 17-26 2022, Seattle

Large Experiments/Facilities

Rare Processes and Precision Measurements Frontier

Marina Artuso, Robert Bernstein, Alexey A. Petrov
Syracuse U FNAL WSU/USC

RPF: frontier-wide issues

★ There are several fundamental physics questions addressed by RPF

- the origin of flavor, generations, and quark and lepton mass hierarchies
- the exploitation of flavor decays as precision probes of all the sectors of the Standard Model and windows to new physics
- the motivation underlying discrete SM symmetries and mechanisms for symmetry breaking
- the origin of baryon and lepton number violation and connections to the baryon asymmetry of the universe
- probe the physics of the dark sector available at high-intensity machines
- develop a deeper understanding of non-perturbative QCD using the rich landscape of conventional and exotic hadrons

★ Most of those questions are studied with small and medium-sized experiments

see B. Bernstein's talk

RPF science drivers and experiments

★ The exact definition of the "size" of the experiment affects classification in RPF

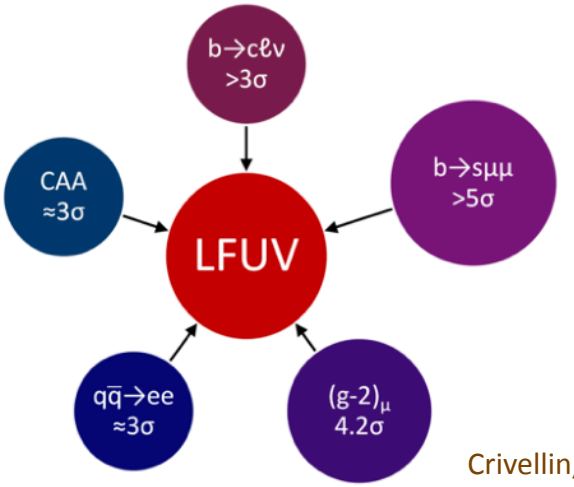
- physical size? cost (include operations? computing? personnel?)?

	Physics Driver
1	New physics in flavor/flavor problem
2	Probes of spacetime symmetries and gravity
3	Electric Dipole Moments
4	Baryon-lepton number violation
5	Charged Lepton Flavor Violation
6	Dark Sector Probe
7	QCD at work in hadron spectroscopy

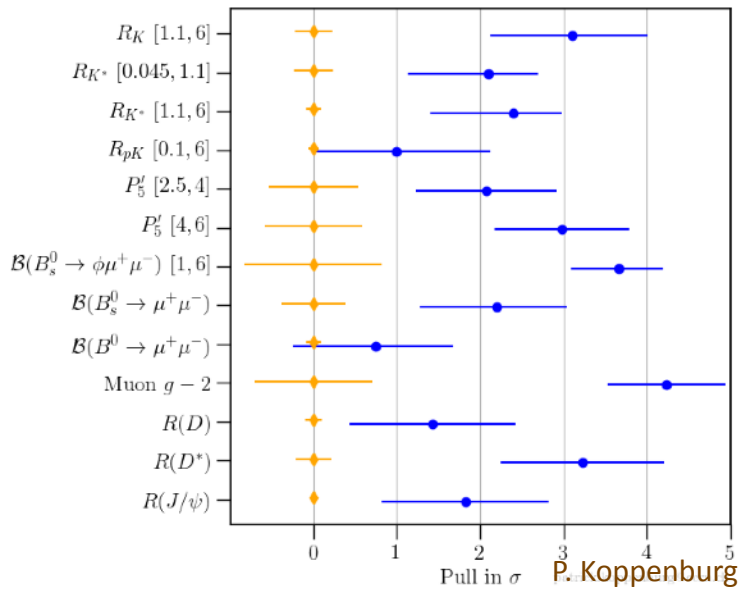
Experiment	Status	Time Scale	Driver	
LHCb, LHCb Upgrade 2 [ATLAS, CMS for some modes]	LHCb U2 now in CERN baseline program	Now-midterm	1,2,6,7	medium see B. Bernstein's talk
Belle II and its upgrades		Now-midterm	1,2,6,7	medium
BESIII/STCF		Now-midterm	1,2,6,7	see B. Bernstein's talk
FCCee/CEPC	Proposed	Post HL-LHC	1,2,6,7	
Rare K decay experiments	Now/proposed	Now-midterm	2	medium
η,η' factories	Now/proposed	2030's	1	small/medium
N-Nbar, MAGE, table-top experiments on quantum-gravity interface	Proposed	late 2020's-2030's	2,4	small
Storage ring EDMs	Proposed	2030-2040	1,2,3,6	medium
Rare muon decay experiments/ Mu2e-II+advanced muon facility at FNAL	Now/proposed	2030-2040	4,5,6	AMF: large
Dark Matter New Initiative	Proposed	late 2020's	6	small/medium

Muons as tools to discover New Physics

★ Many experimental anomalies involve interactions of muons



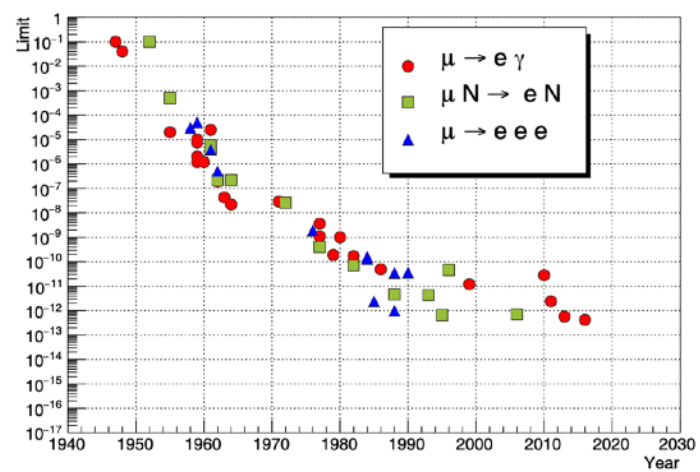
Crivellin, Hoferichter



P. Koppenburg

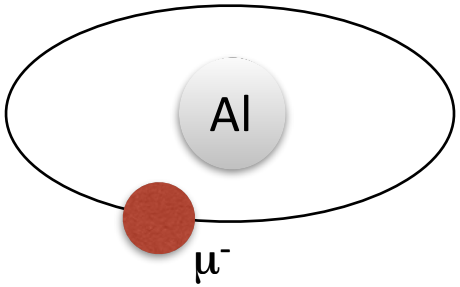
LORENZO CALIBBI and GIOVANNI SIGNORELLI

- other lepton-flavor conserving processes
  - magnetic properties: muon g-2
    - currently a discrepancy theory/exp
  - electric properties: muon EDM
    - probes CP-violation in leptons
  - muonic hydrogen
    - proton size/QED/New Physics



Muon conversion: basic idea

★ Basic idea for a muon conversion experiment



★ take low energy muons (~ 30 MeV) and stop them in a target A(Z,A-Z): muons cascade to atomic 1s state

★ Binding energy and orbit radius for muonic hydrogen-like state

$$E_b = -\frac{Z^2 m e^4}{8n^2} \sim \frac{Z^2 m}{n^2}$$

$$r = \frac{n^2}{Z\pi m e^2} \sim \frac{n^2}{Zm}$$

muonic atom is 200x stronger bound
radius is 200x smaller

★ Radial wave function for hydrogen-like system: $R_{nl} \sim r^\ell Z^{3/2}$
overlap probability: $p \sim r^{2\ell} Z^3$

large overlap for an s-wave and high-Z nucleus

Measure $$R_{\mu e} = \frac{\Gamma\left[\mu^- + (A,Z) \to e^- + (A,Z)\right]}{\Gamma\left[\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)\right]}$$ to probe NP

Bound states: muon conversion

★ Examples of nuclei suitable for muon conversion experiments

Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound lifetime	Atomic Bind. Energy(1s)	Conversion Electron Energy	Prob decay >700 ns
Al(13,27)	1.0	.88 μs	0.47 MeV	104.97 MeV	0.45
Ti(22,~48)	1.7	.328 μs	1.36 MeV	104.18 MeV	0.16
Au(79,~197)	~0.8-1.5	.0726 μs	10.08 MeV	95.56 MeV	negligible

J. Miller, 2006

★ The experiment is tricky

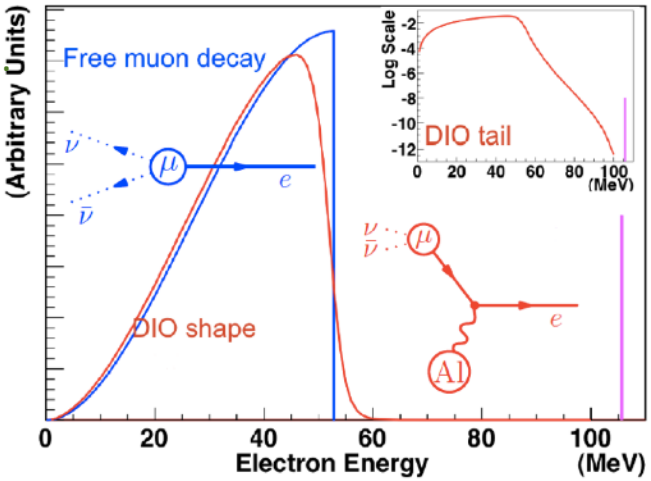
✓ Muon conversion gives monoenergetic electrons...

✓ ... yet, there are other sources of electrons as well!

$$\begin{cases} \mu^- \to e^- + \bar{\nu}_e + \nu_\mu & \text{- decay (40\%)} \\ \mu^- + Al \to X + \nu_\mu & \text{- capture (60\%)} \\ \mu^- + Al \to e^- + Al & \text{- conversion} \end{cases}$$

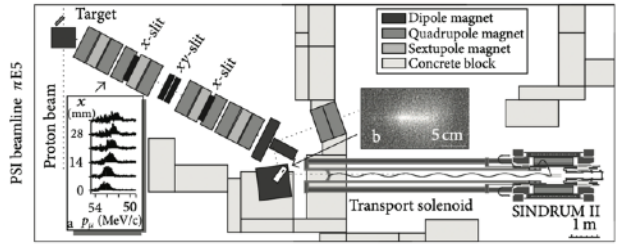
SINDRUM II (PSI), 2006 : $R_{\mu e} < 7 \times 10^{-13}$

M2e goal : $R_{\mu e} <$ a few $\times 10^{-17}$



Czarnecki, Marciano, Tormo

Muon experiments

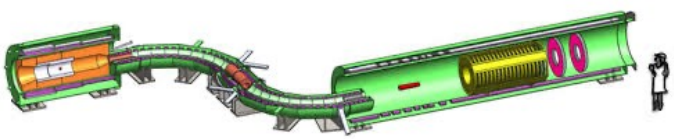


SINDRUM II: $R_{\mu e} < 7 \times 10^{-13}$

current upper limit
probing mass scales ~ 10^4 TeV

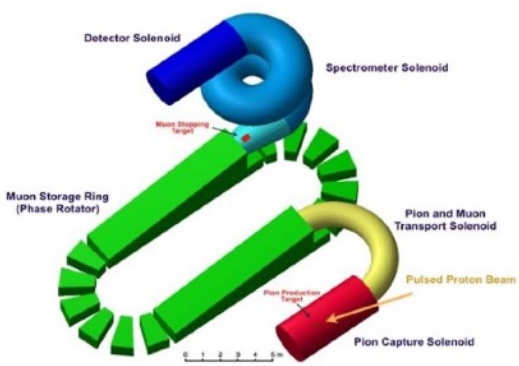
Mu2e: $R_{\mu e} < 8 \times 10^{-17}$

or 10^{-4} SINDRUM II



Mu2e II: $R_{\mu e} < \text{a few} \times 10^{-18}$

or 10^{-5} SINDRUM II



Advanced Muon Facility (AMF) at PIP-II: all muon channels at one facility:

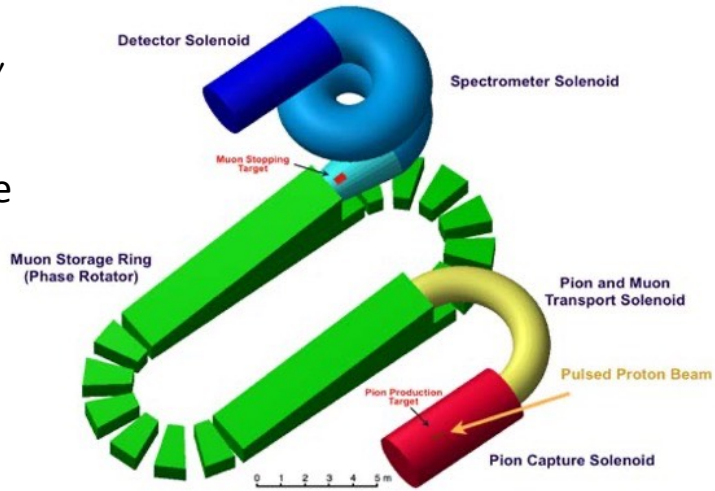
AMF: $R_{\mu e} < \text{a few} \times 10^{-19}$

or 10^{-6} SINDRUM II

Advanced Muon Facility (AMF) at FNAL

★ The Advanced Muon Facility would employ PIP-II to enable

- CLFV in all three muon modes ($\mu N \to eN, \mu \to e\gamma, \mu \to 3e$): a world-leading facility
  - two new small rings for $\mu^- N \to e^- N$ and $\mu^- N \to e^+ N'$ at high-Z and additional x100 in rate
  - x100-1000 more beam for $\mu \to e\gamma$ and $\mu \to 3e$ than are possible at PSI
  - a possible DM experiment
- possible muonium-antimuonium oscillation experiment
- possible atomic physics studies with muonia
- possible muon EDM experiment

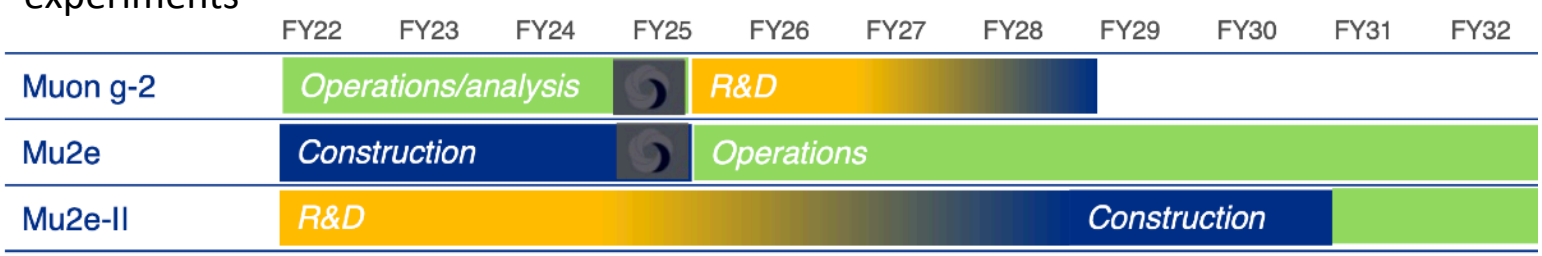


see arXiv: 2203.08278 [hep-ex]

★ Technical challenges directly related to muon collider R&D

- PIP-II, compressor ring, fixed-field alternating gradient ring, experiments

L. Merminga



AMF

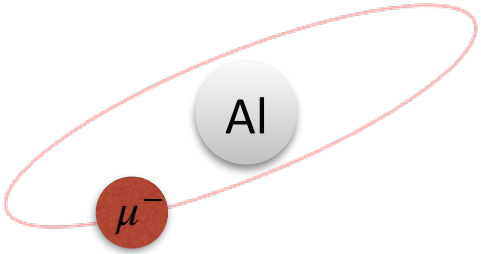
R&D and construction: late 30's

The Evening
EXTRA!

Muon conversion

- How effective is this approach compared to scattering?
  - let's compute effective luminosity
  - recall that

$$L = \Phi \rho_T \ell = N \rho_T \frac{\ell}{t} = N \rho_T v$$



  - in this "experiment" the probability density is given by the 1s wave function
  - … and we need to take into account the fact that muon decays
  - Then luminosity = (density)(velocity)(flux of muons)(lifetime)

$$L_{\rm eff} = |\psi(0)|^2 \times \alpha Z \times \Phi_\mu \times \tau_\mu = \frac{m_\mu^3 Z^4 \alpha^4}{\pi} \Phi_\mu \tau_\mu$$

  - For Al target (Z=13), flux of $\Phi_\mu = 10^{10}$ muons/sec and $\tau_\mu = 2\ \mu$sec

$$L_{\rm eff} = 10^{48} {\rm cm}^{-2}\ {\rm sec}^{-1}$$

Bernstein, Czarnecki

Muon facilities

- A possibility of using muon beams at CMP facilities

Jian Tang, talk at RPPM meeting (Snowmass 2021)

	Proton driver [MW]	Surface muons			Decay muons		
		Intensity [1E6/s]	Polarization [%]	Spread [%]	energy [MeV/c]	Intensity [1E6/s]	Spread [%]
PSI	1.3	420	90	10	85-125	240	3
ISIS	0.16	1.5	95	<15	20-120	0.4	10
RIKEN/RAL	0.16	0.8	95	<15	65-120	1	10
JPARC	1	100	95	15	33-250	10	15
TRIUMF	0.075	1.4	90	7	20-100	0.0014	10
EMuS	0.005	83	50	10	50-450	16	10
Baby EMuS	0.005	1.2	95	10			

×5 CSNS-II upgrade

Facility	Source Type	Intensity (μ+/sec)*
ISIS	pulsed	1.5×10^{6}
J-PARC	continuous	1.8×10^{6}
PSI	continuous	7.0×10^{4}
TRIUMF	pulsed	5.0×10^{6}
SEEMS	pulsed	1.9×10^{8}

- Muonium Antimuonium Conversion Experiment (MACE) EMuS at CSNS

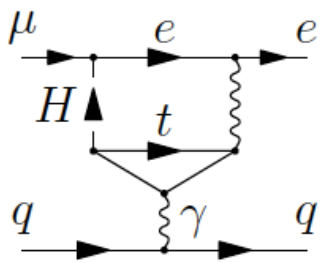
Muon conversion: high energy vs low energy

★ Leptonic FCNC could be generated by New Physics

★ Ex.1 FCNC Higgs decays H → μe, τe, etc.: $Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$ Harnik, Kopp, Zupan

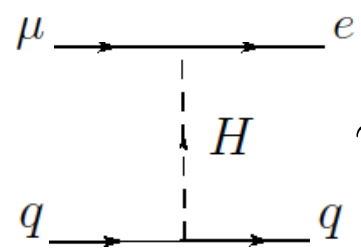
★ FCNC Higgs model & muon conversion/quarkonium decays

e.g.



$\sim \mathcal{O}(\alpha^2)$

Barr-Zee type



$\sim \mathcal{O}(m_u \text{ or } m_d)$

tree level
(note suppression of light quark couplings)

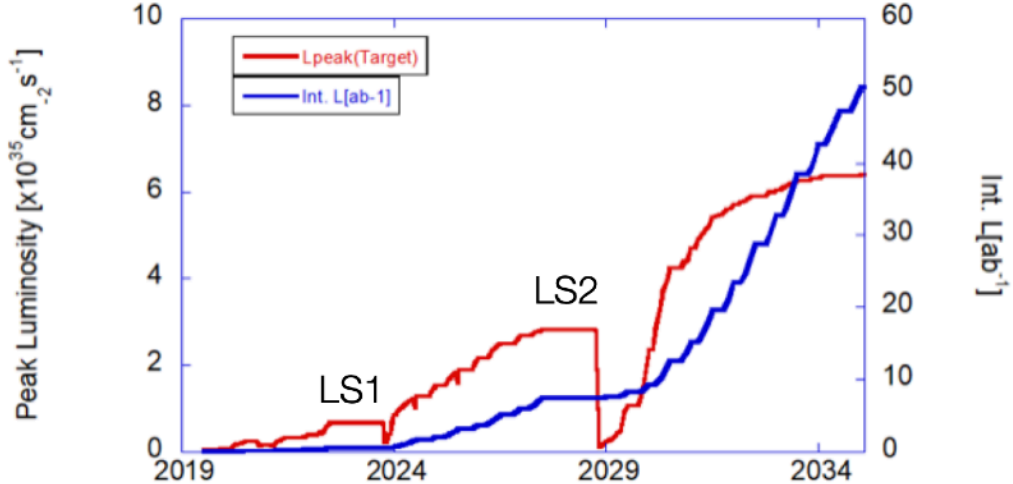
★ Ex.2 Exceptional couplings of (flavor-diagonal) NP to third generation $\mathcal{H}_{\rm NP} = G\bar{b}'_L\gamma^\lambda b'_L\bar{\tau}'_L\gamma_\lambda\tau'_L$ flavor "anomalies" Glashow, Guadagnoli, Lane

★ Ex.3 Leptoquarks -> flavor "anomalies"

Number of possible models > number of model builders

Belle II status and plans

- Running since 2019. Achieved
  peak $L = 4.7\times10^{34}\text{cm}^{-2}\text{s}^{-1}$
  int. $L = 430\ \text{fb}^{-1}$
- Now in LS1 (till ~end of 2023), mainly to replace an incomplete vertex detector



- International task force of accelerator experts formed in 2021 to help define the path towards target $L = 6.5\times10^{35}\ \text{cm}^{-2}\text{s}^{-1}$ and target int. $L = 50\ \text{ab}^{-1}$ by mid-2030s
  - Upgrade SuperKEKB in LS2 (~2027-2029) to reach target peak L (QCS, lattice?)
  - Upgrade vertex detector to accommodate the new interaction-region design, and other sub-detectors to improve robustness against increasing machine background

Di Canto, Meinel

Proposals beyond current Belle II program

- Beam polarization to perform precision electroweak (and τ-physics) measurements
  - Could begin while SuperKEKB completes its program of delivering 50ab^{-1} to Belle II and continue afterwards
- Running at ultra-high luminosities ($L > 10^{36}\,\text{cm}^{-2}\text{s}^{-1}$) and integrate $\sim 250\text{ab}^{-1}$
  - Such an upgrade may effectively complement the heavy-flavor program of the LHC experiments. However, the feasibility from the accelerator perspective is still unclear, and so is the upgrade timeline

Di Canto, Meinel

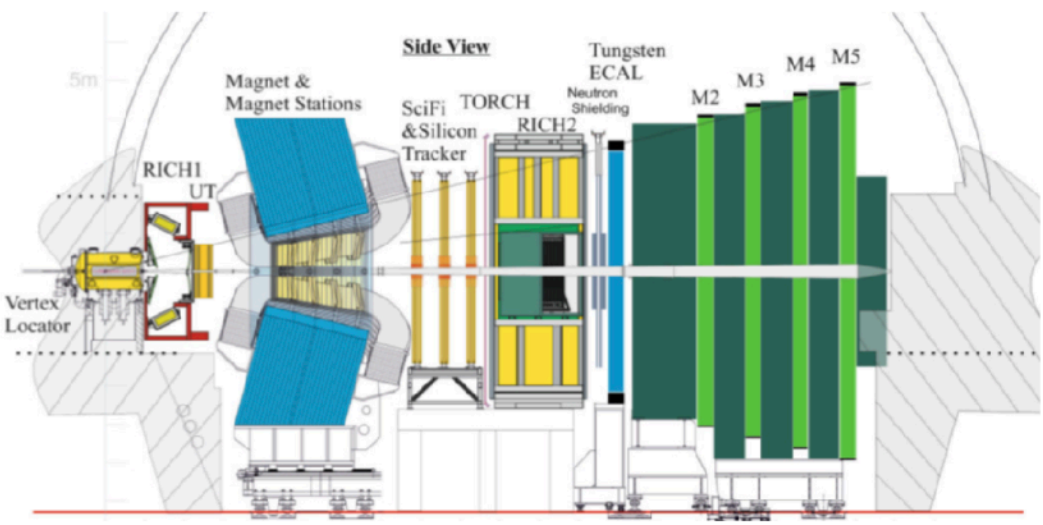
LHCb status and plans

- Collected about 9fb^{-1} during Run 1 and 2
- Upgrade I detector just started taking data and plans to get 50fb^{-1} by 2032
  - Considering the enhanced online-selection efficiency, the yield of beauty and charm hadrons available for analyses will increase by factors up to 10 (depending on the final states) compared to Run 2
- Upgrade II during LS4 (2033-2034) to run at L = 2×10^{34}cm^{-2}s^{-1} (10× Upgrade I) and collect 300fb^{-1} by end of Run 6 (early 2040s)
  - Now part of the baseline HL-LHC plan
  - Some preparatory work (Upgrade Ib) can be performed already during LS3 (2026-2028) to also benefit the physics performance during Run 4, beyond what has been projected for Upgrade I

Di Canto, Meinel

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 $L = 2\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ with 40x larger pile-up
- Extremely challenging upgrade, currently in early planning [LHCb-TDR-023]: options available, dedicated R&D needed, estimated cost of ~175MCHF for baseline option



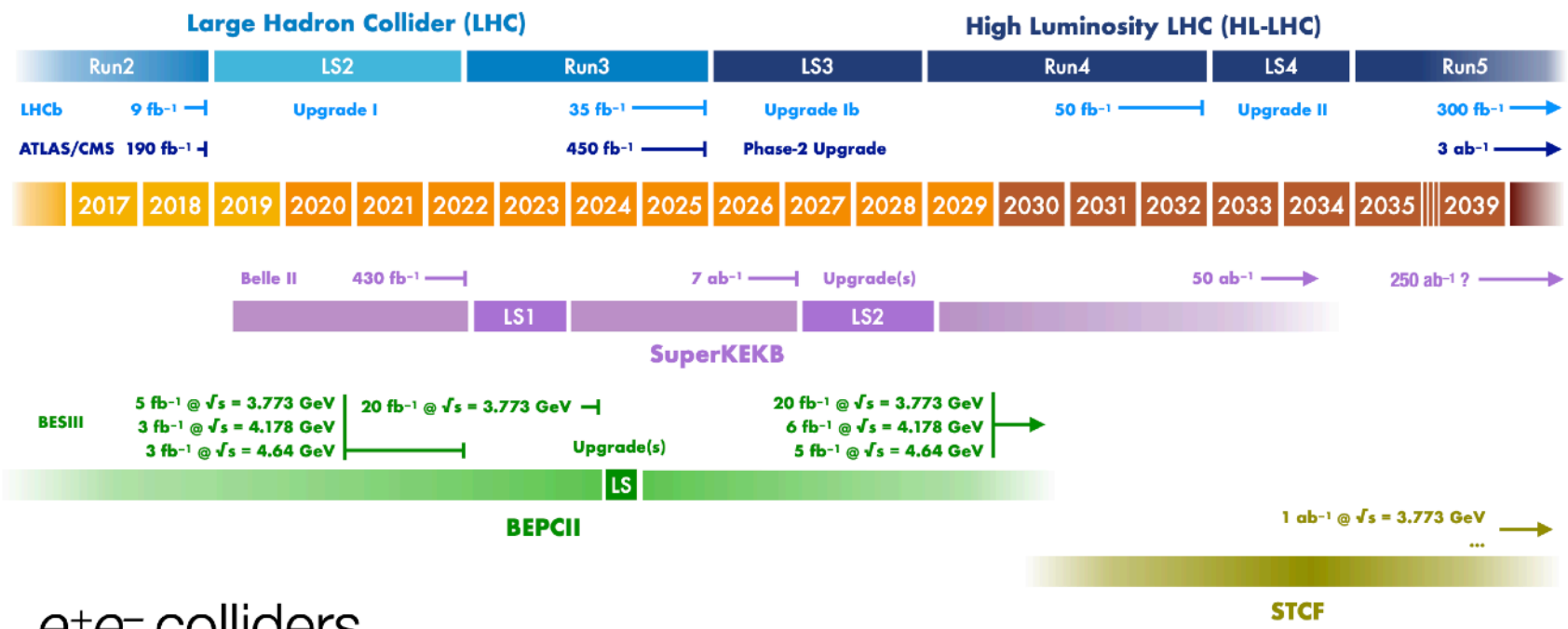
- Key ingredients:
  - High granularity
  - Fast timing (tens of ps)
  - Radiation hardness (up to few $10^{16}\, n_{eq}/\text{cm}^2$)
- DAQ and trigger:
  - Full detector readout at 30 MHz
  - Offline-quality reconstruction at trigger level for real-time analysis

Di Canto, Meinel

Heavy flavor factories: medium size, large scope

Timeline of heavy-flavor experiments

hadron colliders



e^+e^- colliders

Di Canto, Meinel