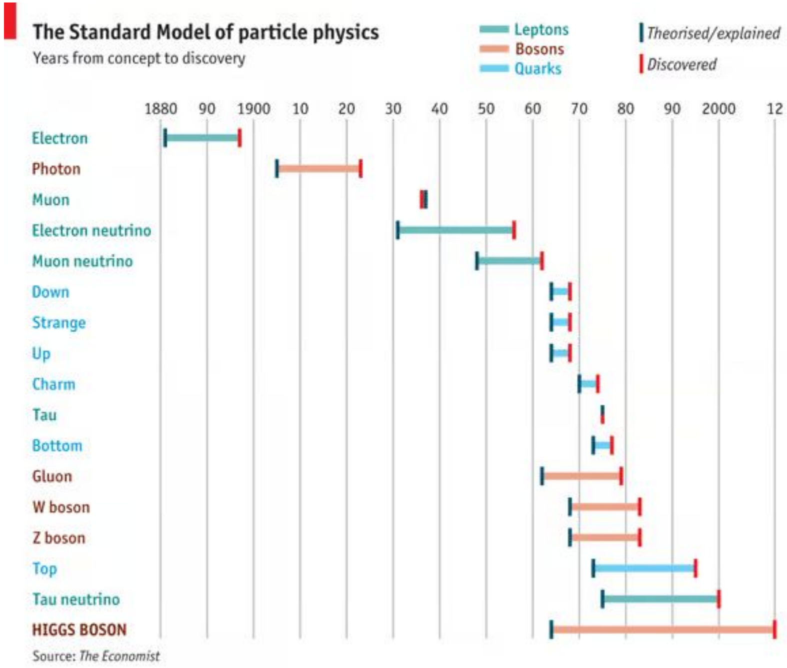
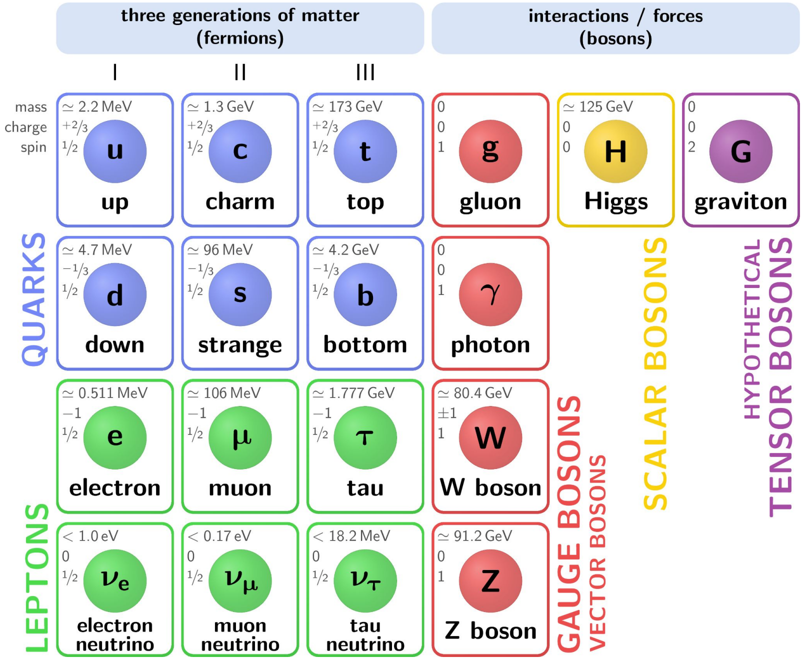
Flavor physics - mid and long term

Radek Žlebčík

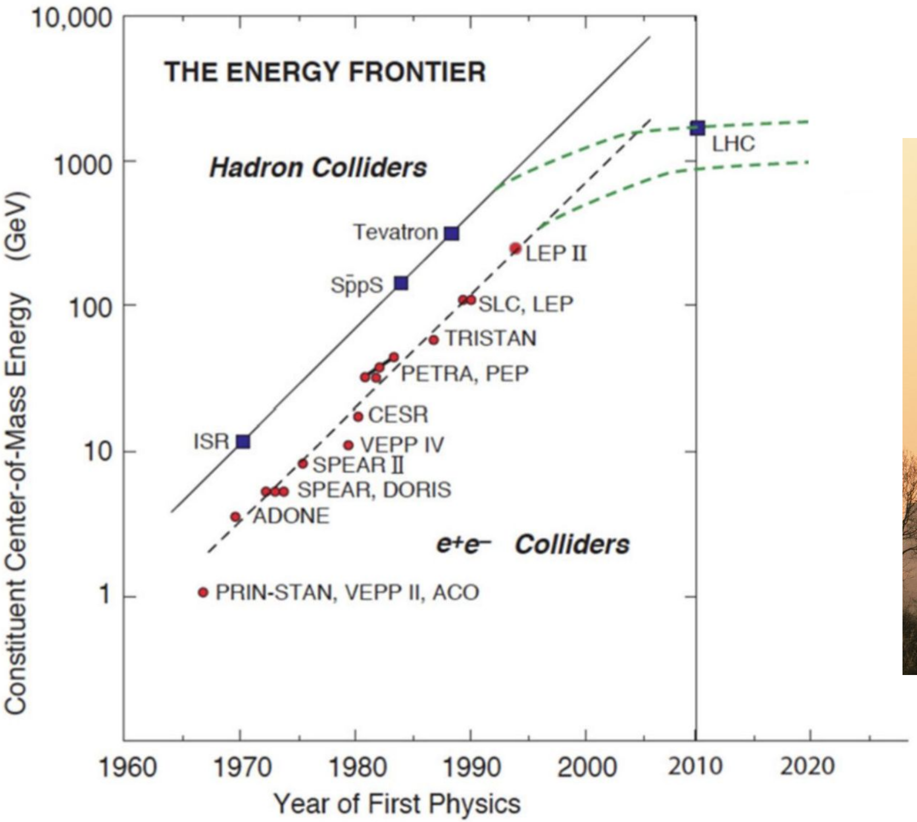
European Strategy Update Trieste meeting, November 20, 2024

Direct discoveries – a 120 years success story





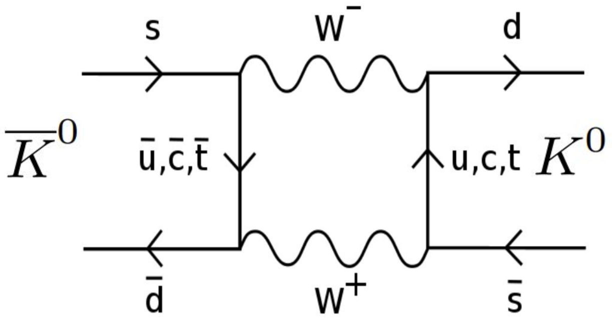
Energy crisis?



FCC (~2060)

[R. Harlander, at al., Eur.Phys.J.H 48 (2023)](#)

Indirect searches - a possible (the only?) way forward



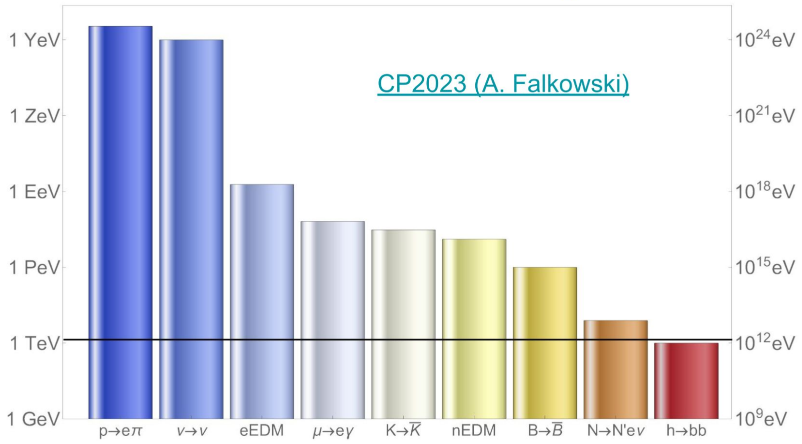
Top-quark (175 GeV): an important contributor to K amplitude (0.5 GeV)

Virtual particles of arbitrarily high mass may be exchanged affecting physics at lower, observable energies

- **Rare processes**, where SM contributions are suppressed
- **Precise measurements and predictions** to overconstrain models → Most of SM degrees of freedom associated with flavor

Expanding the SM

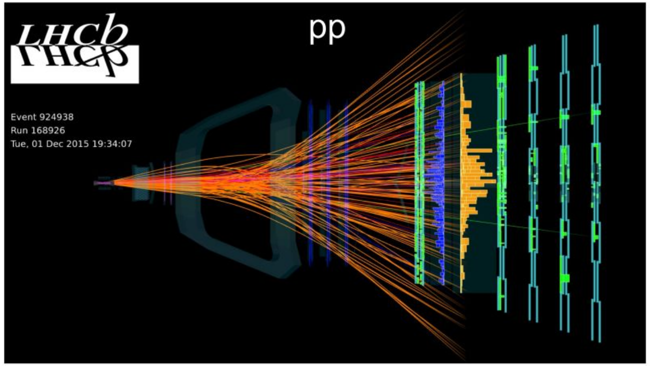
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i$$



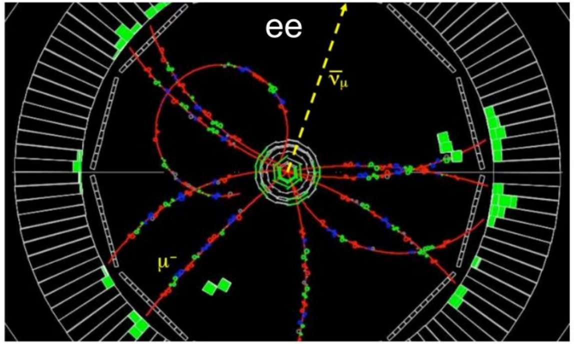
Sensitivity to higher energy scales than in direct LHC searches for new particles
(different processes probe different Wilson coefficients C_i)

- One of 4 large LHC experiments (27 km ring)
- pp collisions at 14 TeV
- ~ 100k B mesons / s
- >100 tracks per collision

- e^+e^- SKEKB accelerator (3 km ring)
- e^+e^- collisions at 10.6 GeV
- ~ 50 BB mesons / s
- ~10 tracks per collision



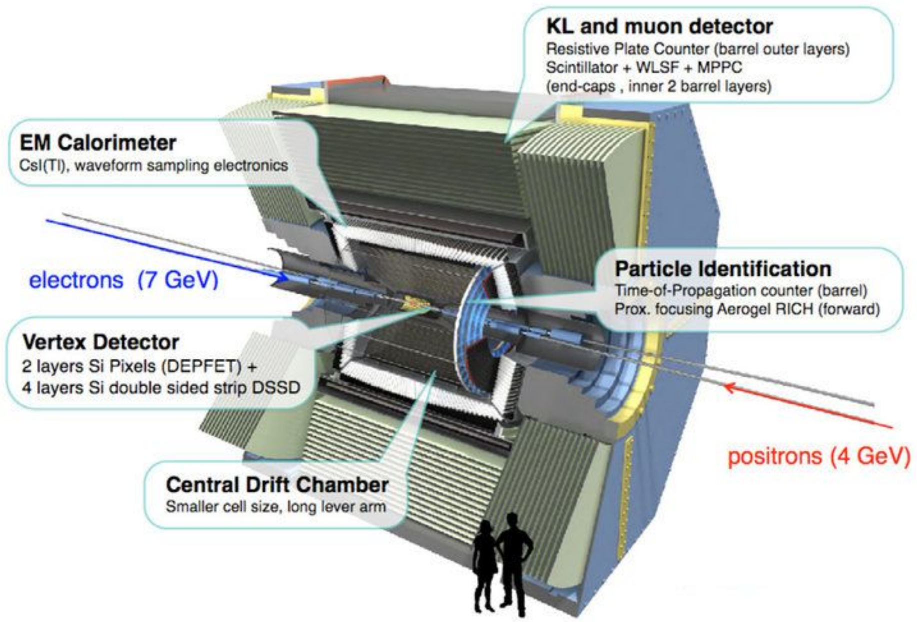
Huge samples.



Known initial state + hermetic detector

Belle II detector

- Hermetic coverage and known initial states:
  → Good reconstruction of final states with multiple neutrinos
- Barrel geometry + good calorimeter:
  → Good reconstruction of final state photons

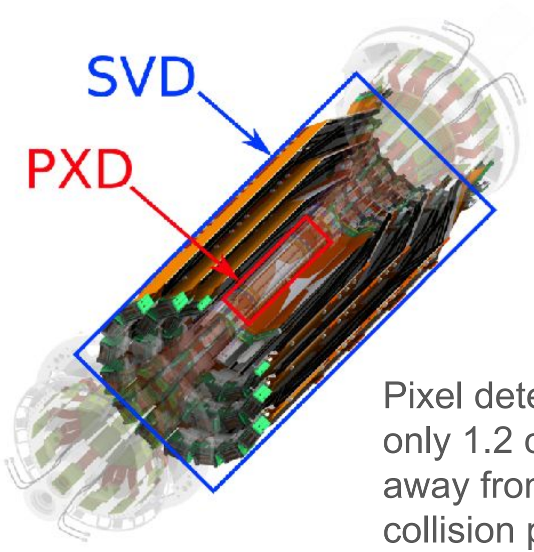


These features offer Belle II unique access to a number of channels that are considered superbly promising for indirect searches

It takes two to tango…

SuperKEKB has had a very troubled start up.
After 5 years still 20x below design performance.

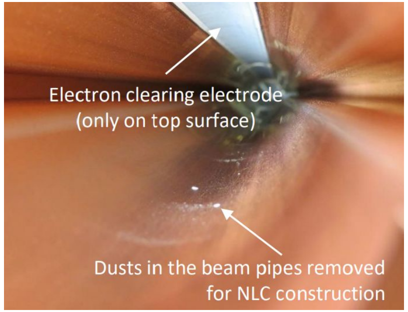
Recent example: sudden beam instabilities at high beam currents
→ Frequent uncontrolled beam aborts (These can and have damaged our pixel detector)



Pixel detector only 1.2 cm away from collision point

A lot of run time dedicated to machine studies

- Dust thought as the most likely cause of the problems
  → 15 pipes turned upside down

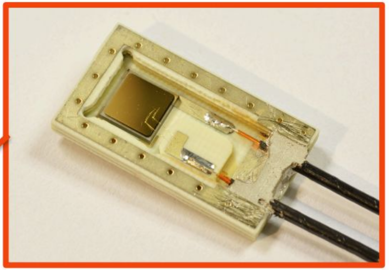


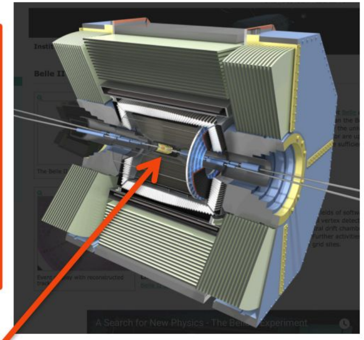
Key role for Trieste’s diamonds

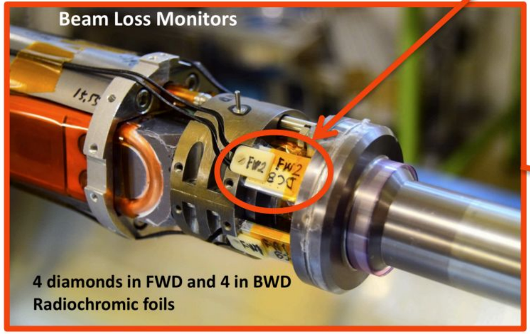
- Only defense against unstable beams are rapid beam aborts
- Diamond sensors developed at Trieste trigger beam aborts to keep detector safe
- Keep improving the system to make it faster

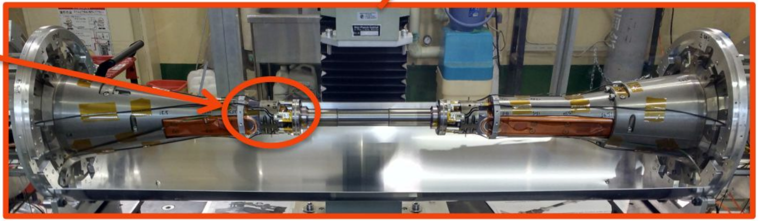
Nucl.Instrum.Meth.A 997 (2021)

Small (4.5 x 4.5 x 0.5) mm^3 artificial diamond crystals



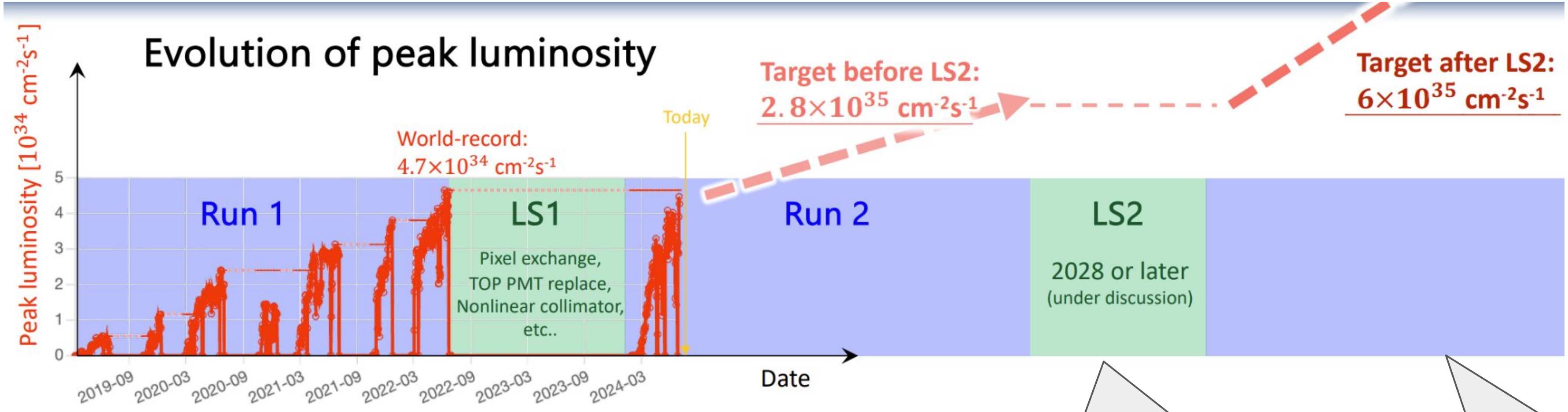






SuperKEKb & Belle II prospects

ICHEP2024



What was achieved:

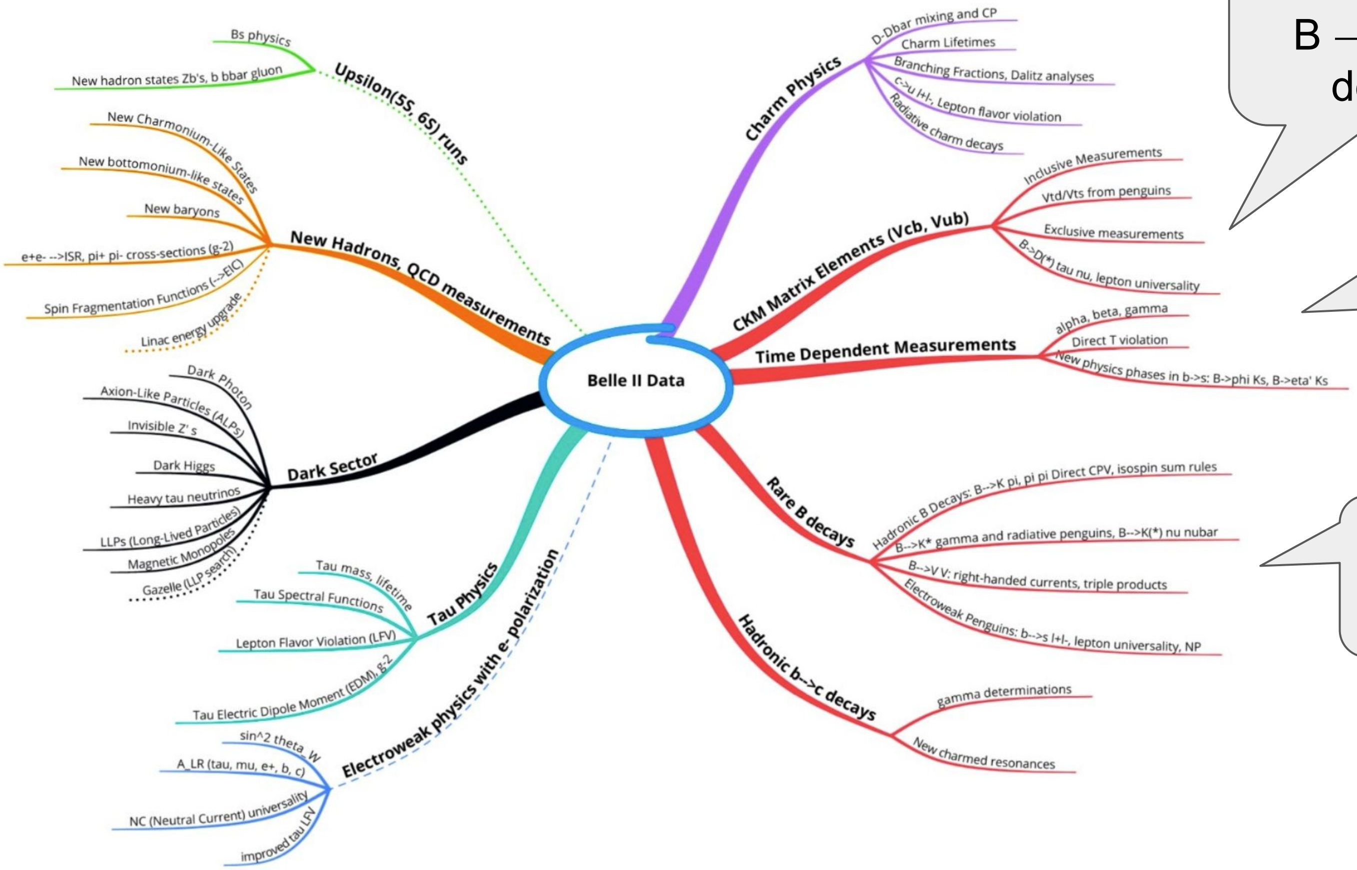
- Instantaneous luminosity: 5×10^{34} cm^{-2} s^{-1}
  target: 60×10^{34} cm^{-2} s^{-1}
- Integrated luminosity: 0.55 ab^{-1}
  target: 50 ab^{-1}

Mid-term upgrade
Replacing PXD
Upgrade of L1 Trigger
…

Long-term upgrade
Upgrade of interaction region
Polarized beams?

arXiv:2406.19421

Belle II physics



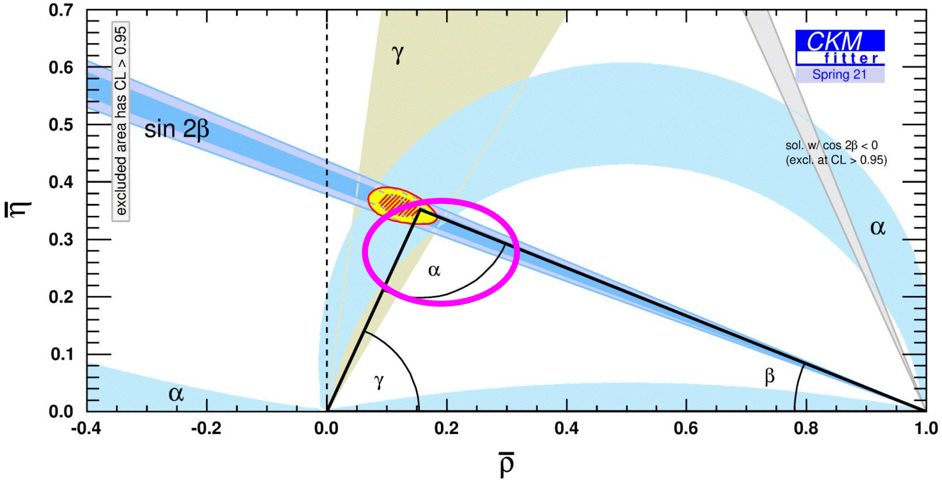
Lepton universality in $B \to D^{(*)} \tau \nu$ decays

Angle α of Unitarity Triangle

Rare decays
$B \to K \nu \nu$
$B \to K \tau \tau$

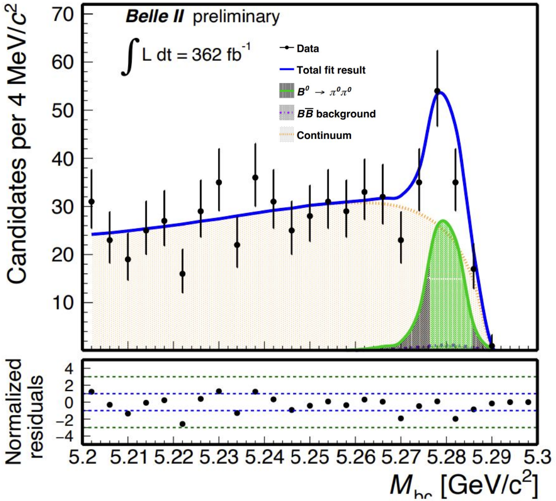
Angle α: Demonstrating the unicity of Belle II CPV program

α = (84±4)°:
e.g. $B^0 \to \pi^0 \pi^0$



A Trieste enterprise

- Angle α determined from BRs & A_{CP} of all charge combinations of $B \to \pi\pi$
- Very difficult for LHCb, due to 4 photon event signature and no track
- Graph neural network Flavor Tagger to determine flavor of the other B meson (+30% performance gain over Belle/BaBar)



Belle II measurement:
BR = $(1.26 \pm 0.20 \pm 0.11)\ 10^{-6}$

Belle & BaBar avg.
α = (88±5)°

World avg.
α = (84.1±4.2)°

Single Belle II result better than world average $(1.59 \pm 0.26)\ 10^{-6}$ despite the sample size

The Belle II Snowmass expectation ($50\ ab^{-1}$) is ±1° precision for α.

Made in Trieste

The first Belle II highlight: $B^+ \rightarrow K^+ \nu \nu$

PRD 109, 112006 (2024)

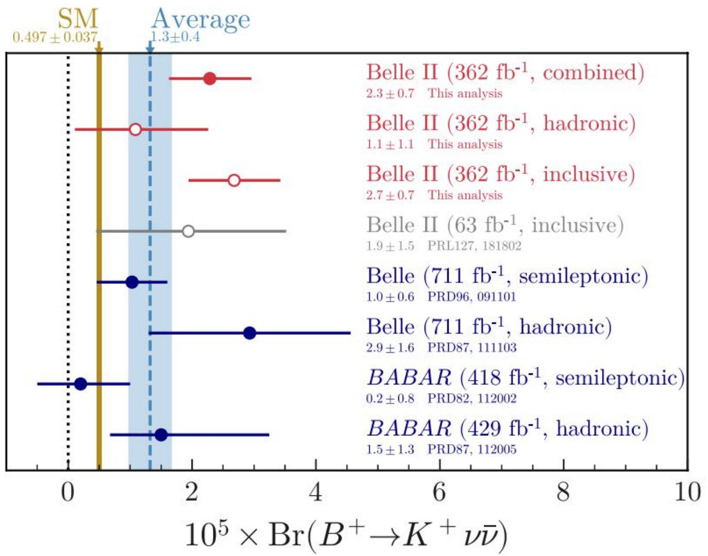
- A rare FCNC b→s decay
- Theoretically “clean” due to only 1 or 0 charged particles in the final state
- Belle II territory, too large BG in pp
- Possibility to also study decays with K_S or K^* instead of K^+

$$\mathbf{B}(B^+ \rightarrow K^+ \nu\bar{\nu}) = \left(2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right) \times 10^{-5}$$

(SM prediction: 0.6×10^{-5}, $\mu = 3.8 \pm 1.2$)

Projections of μ unc.:

Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \rightarrow K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \rightarrow K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)

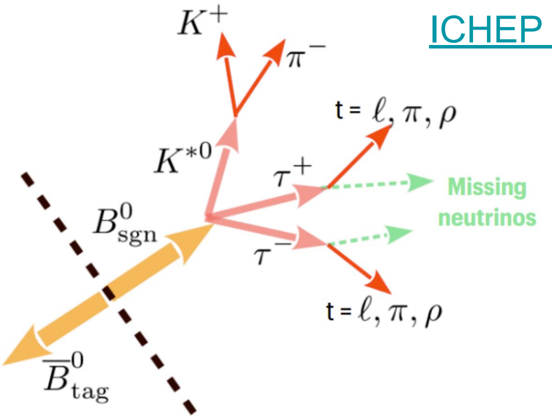


A 2.7σ excess w.r.t. the SM prediction to be probed with more data

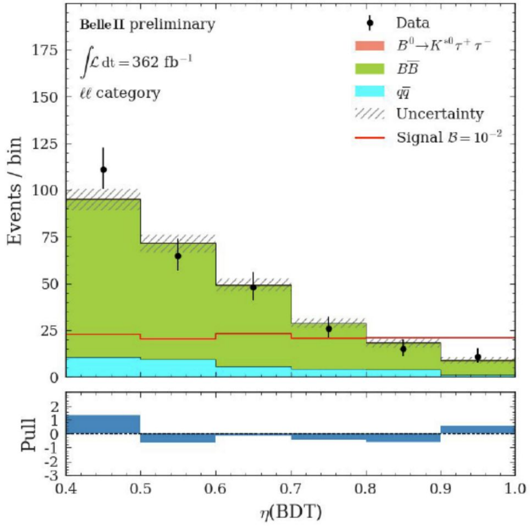
Another Belle II highlight: $B^0 \to K^{*0} \tau \tau$

ICHEP 2024

- A rare (10^{-7}) b→s decay that probes lepton universality
- Hard to measure in pp due to final state ν's



$$BF(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3} \text{ at 90\% CL}$$



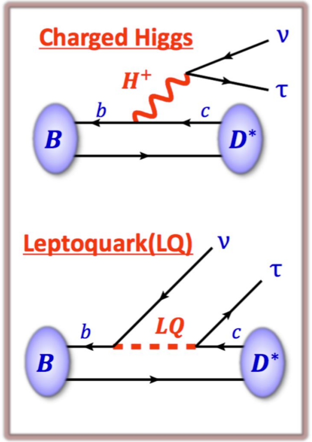
Exclusion limit dominated by stat. precision.
The full Belle II statistics should allow 5×10^{-4}

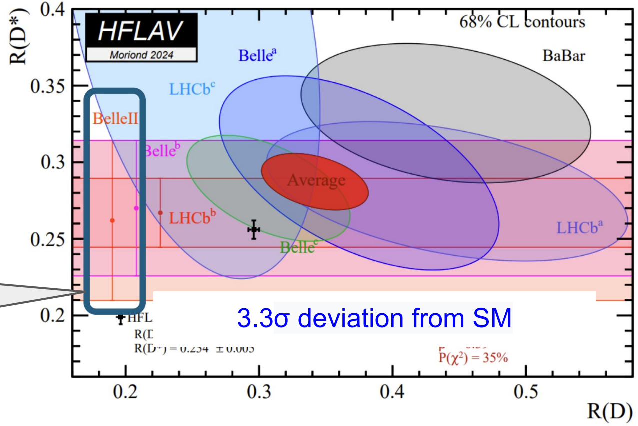
In Trieste we measure associated $B^+ \to K^+ \tau \tau$ channel

Lepton flavor universality in b→c transitions

- Long-standing b→c tau excess in b→c ell transitions
- Observed by three experiments. Reached 3 sigma
- Points to few GeV tree-level physics (leptoquarks?)
- Belle results are the most precise
- Belle II better than Belle at same luminosity
- Clearly one of the flagships in the next decade

Possibly different BSM contribution for D and D*





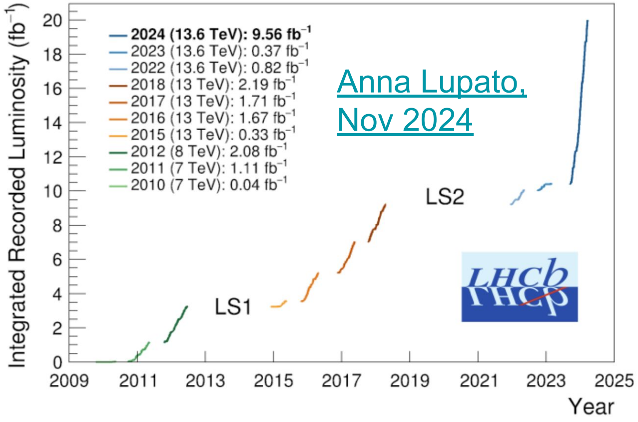
Based only on 0.2 ab^{-1}

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

Will the anomaly persist?

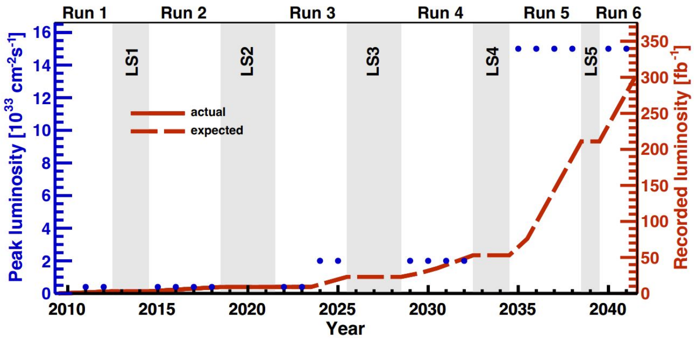
LHCb prospects

- Hardware level-zero trigger removed in 2022, full transition to software-based triggering. Impressive hike in data size



Anna Lupato, Nov 2024

- TDR for HL-LHCb recently approved
- Expected 30x higher luminosity than in Run 1+2



Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

1 fb^{-1} in pp ~ 1 ab^{-1} in ee

Conclusions

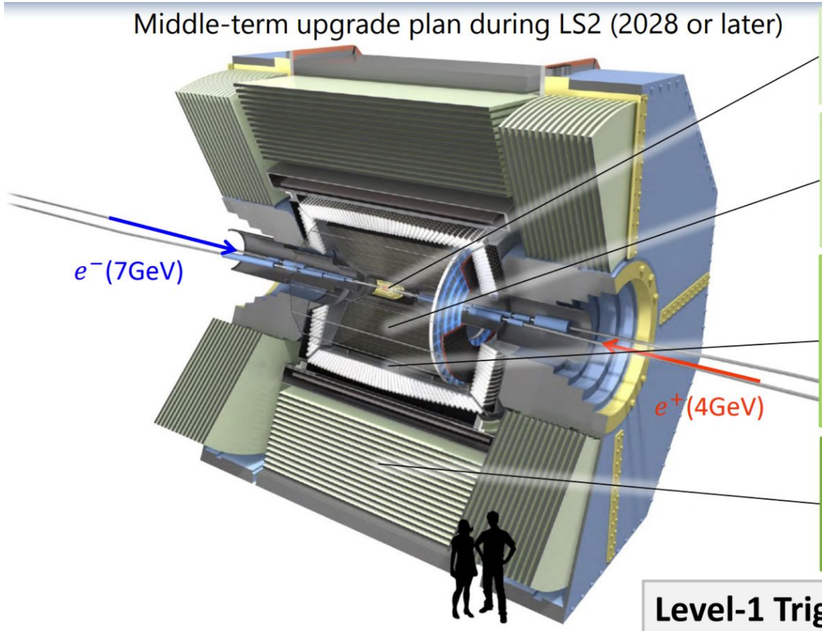
- Indirect searches for new interactions allow to look much above 1 TeV LHC energy scale
- After a 30-year exploration, quark flavor sector still offers several sensitive and reliable probes.
- And many are unique to Belle II
  - Measurements of the B^0 mixing phase using gluonic penguin processes.
  - Searches for rare processes yielding multiple neutrinos in the final states
  - Settling the long-standing anomalies observed in b⟶ tau excess
- It will be an exciting ride, in competition and synergy with similar measurements done by LHCb and CMS/ATLAS

https://indico.phys.nthu.edu.tw/event/109/

Backup

Possible Belle II upgrades

ICHEP2024 arXiv:2406.19421



Vertex detector
- Fully-pixelated CMOS DMAPS detector

Drift chamber (CDC)
- New front-end electronics (less cross-talk, better radiation hardness, and less power)

Particle identification
Barrel: Time-Of-Propagation counters (TOP)
- Replace w/ life-extended PMTs
- New front-end electronics (less power)

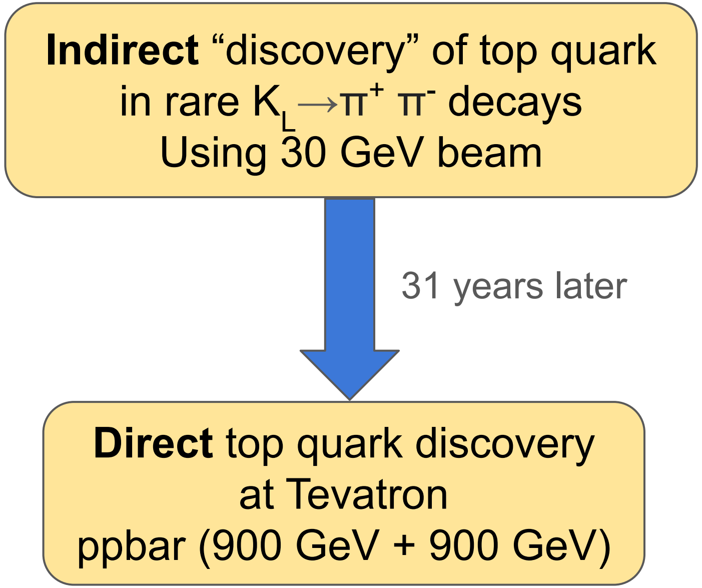
K_L/μ detector (RPC + scintillator)
- Option 1: Replace RPC w/ scintillator
- Option 2: RPC avalanche mode operation

Level-1 Trigger
- Replace electronics with latest technology to allow more sophisticated ML algorithm and more data bandwidth

Some of the long-term plans:
- Redesigning interaction region (new QCS) → to increase luminosity
- Polarized beams → e.g. for tau (g-2) measurement

CP violation was an early success story

- **1964:** CP violation observed in the K^0-K^0bar system (at that time 3 quarks known)
- **1973:** Kobayashi, Maskawa realize that we need 6 quarks for CP in SM
- **1974**: Charm quark discovery
- **1977:** Bottom quark discovery
- **1995:** Top quark discovery

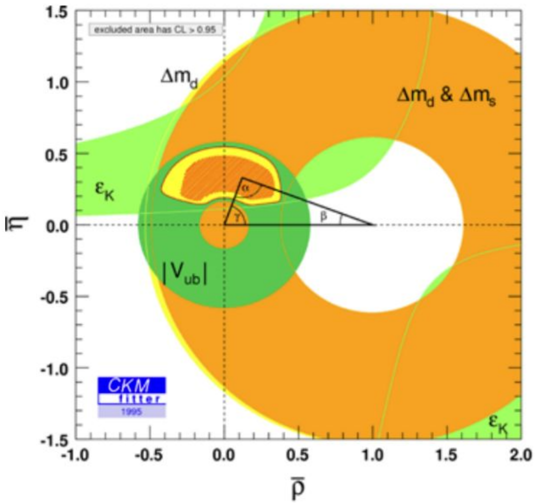


Indirect discovery of 3 new quark flavors happened 30 years earlier with 30 times smaller beam energy.

(Somewhat provocatively: lack of non-SM physics at the LHC "predicted" by SM-like flavor results at Babar/Belle/CDF a decade earlier)

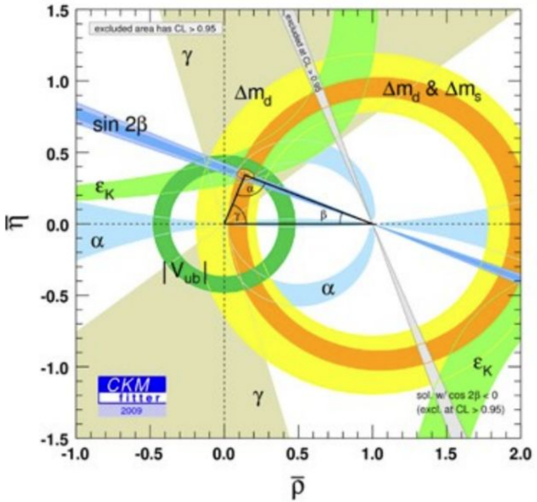
Exploring CPV: a 30-year tour de ~~force~~ precision

1995



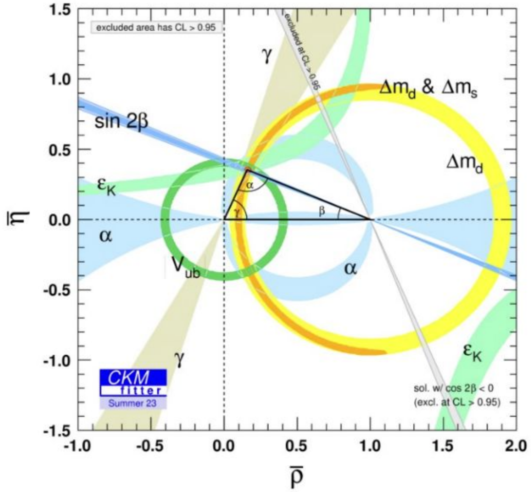
Pre 1st generation *B* factories

2009



Post 1st generation *B* factories
+ CDF B_s mixing

2023

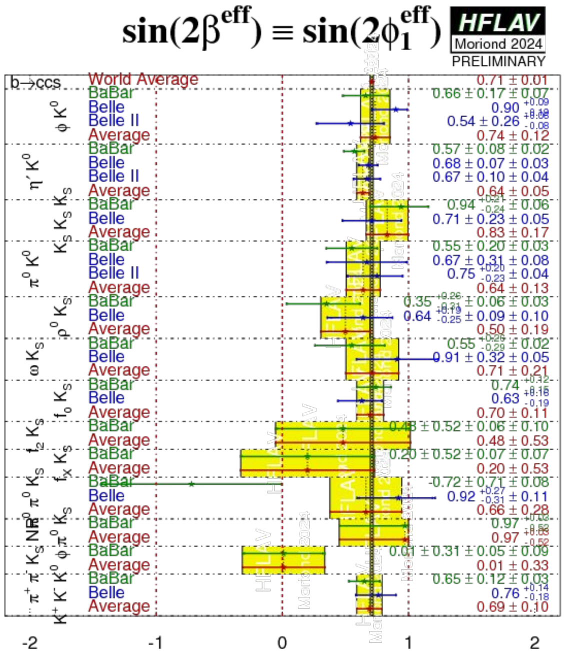


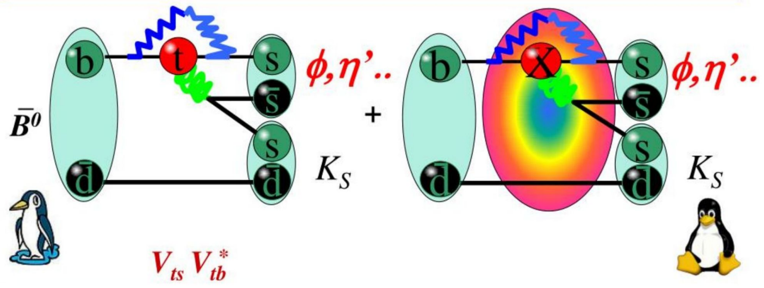
Today
+ LHCb and improved theory

All looks consistent with the SM -- within a remaining 10% uncertainty.
Non-SM physics will be either visible in suppressed processes or blind to flavor.

CP violation in rare b→s decays

- New physics can impact the phase of the amplitude of rare b→s decays (e.g. $B^0 \to \eta' K^0_s$) changing the CKM Unitarity Triangle angle sin 2β
  →Hunting for deviations wrt
  tree-level b→c channels
- Measurements have been performed only at B factories





$\beta_{b\to c}$=(22.6 ±0.5)°

$\beta_{b\to s}$=(20.4 ±1.4)°

Expected ±0.4° $\beta_{b\to s}$ precision with full BII data.

Consistent within 1.5σ

Belle II prospects for rare B→ K ν ν & B→ K τ τ decays

- The Snowmass Belle II unc. projections:

Signal strength (relative unc. wrt SM)

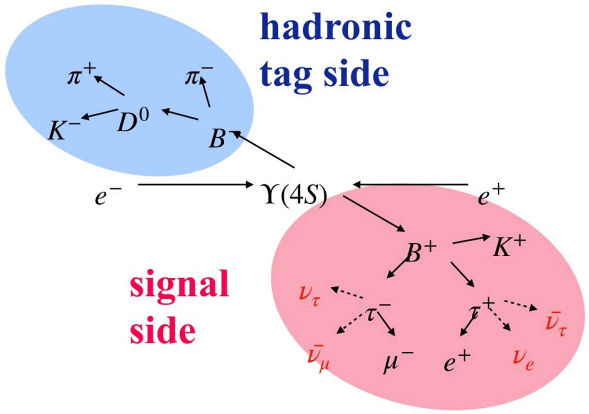
Decay	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$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

Probing observed 2.7σ deviation with higher statistics…

Currently 0.31 for $B^+ \to K^+\nu\nu$

	$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)	
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

Currently 1.8×10^{-3}



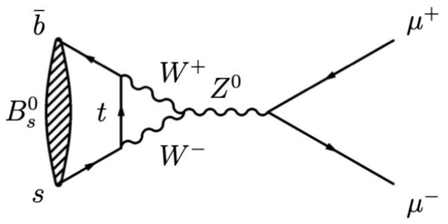
In Trieste we measure associated $B^+ \to K^+\tau\tau$ channel

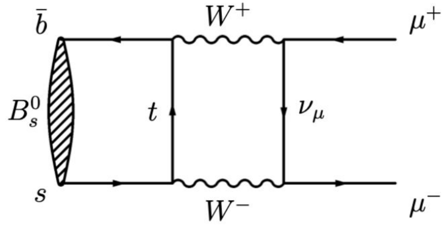
The LHCb highlight: $B_{(s)} \to \mu^+\mu^-$

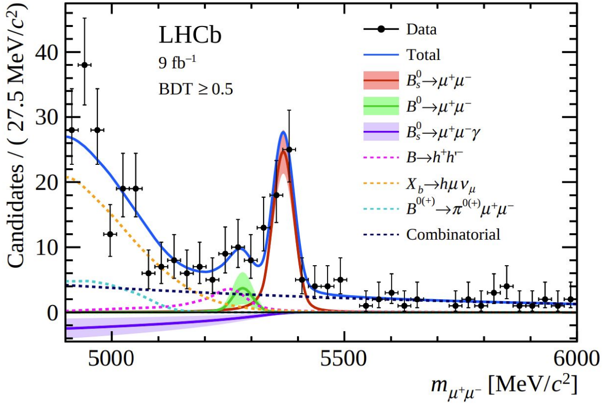
Phys.Rev.Lett. 128 (2022) 4, 041801

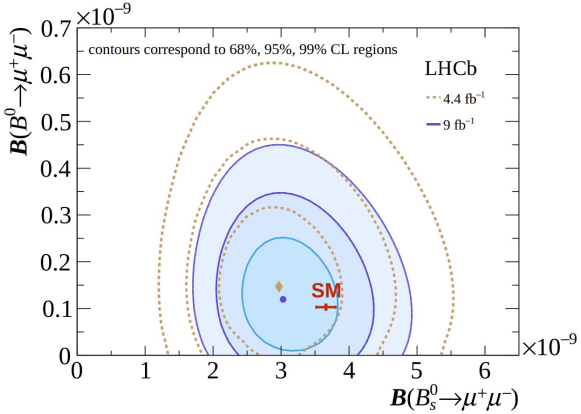
- A very rare helicity-suppressed decay
  (at Belle II we have too few B mesons to see it)
- BRs predicted by Standard Model:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$









Sensitive to Z', leptoquarks, non-SM higgs…

Decay rates compatible with SM so far…

Trouble with (theoretical particle) Physics

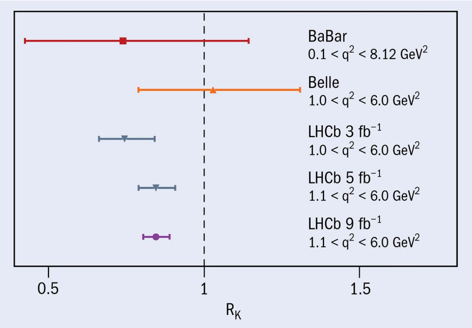
- The Standard Model persists from 1970s although there are several unexplained phenomena
- Too many BSM theories that are not falsifiable by current experiments

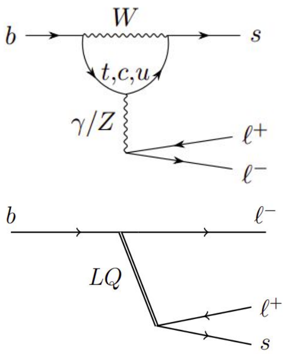
Prospects for rare b→s decays

BR(b → s $\mu^+\mu^-$) / BR(b → s e^+e^-)

- LHCb has advantage of higher statistics
- At Belle II electron & muons efficiencies almost the same*
  →better sys. cancellation in the ratio

TODO
Find newer review plot with the fix





*Remember Dec 2022 disappearance of LHCb R_K anomaly

BR(b → s ν ν)

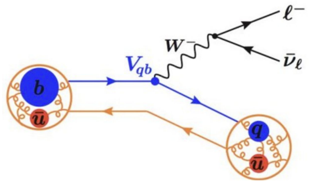
- This is a Belle II territory
  → too large BG in pp
- Theoretically cleaner due to only 1 or 0 charged particles in the final state
- Chance to further probe 2.7σ deviation in B($B^+ \to K^+ \nu\nu$) and also look at modes with K_S or K*

$$\mathbf{B}(\boldsymbol{B^+ \to K^+ \nu\bar{\nu}}) = \left(\mathbf{2.3 \pm 0.5(stat)^{+0.5}_{-0.4}\,(syst)}\right) \times \mathbf{10^{-5}}$$

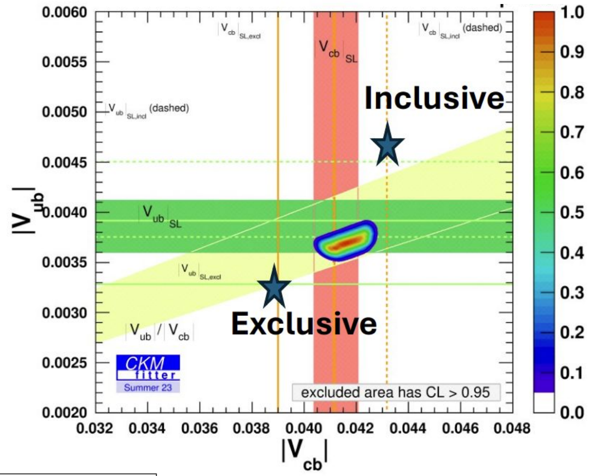
2.7σ deviation wrt SM (0.6x10^{-5})

BII also searches for b→s $\tau^+\tau^-$

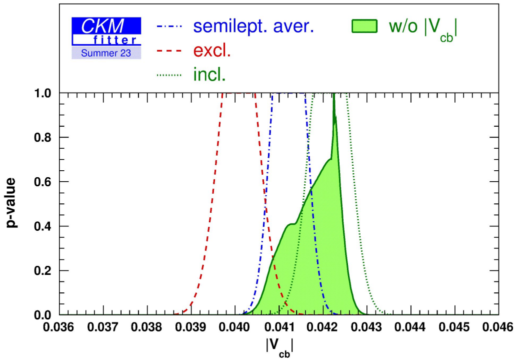
$|V_{cb}|$ and $|V_{ub}|$: Inclusive vs Exclusive puzzle



- A long standing difference between: inclusive (i.e. $B \to X_c \, l \, \nu$) exclusive (e.g. $B \to D^* \, l \, \nu$) determination of $|V_{cb}|$ (and $|V_{ub}|$)
- The bias can come from theory and/or suboptimal analysis technique
- Disagreement deteriorates the power to overconstrain the CKM elements



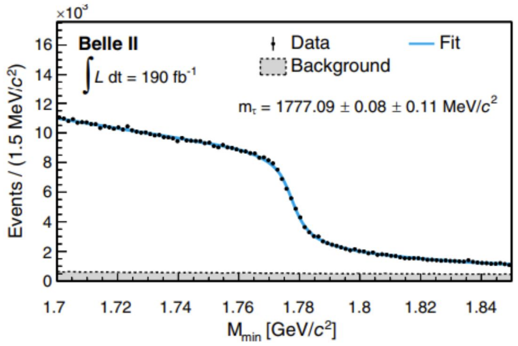
New exclusive $|V_{cb}|$ results taking into account full differential information:
BaBar: $(41.1 \pm 1.2)\ 10^{-3}$
Belle: $(41.0 \pm 0.7)\ 10^{-3}$
Just between old excl. & incl. results



Both LHCb and Belle II expect to reduce unc. by several times.

Highlights from Belle II

- About 50 published measurements so far
- Some of them are world best although Run 1 luminosity (0.4 ab^{-1}) is about half of the Belle experiment

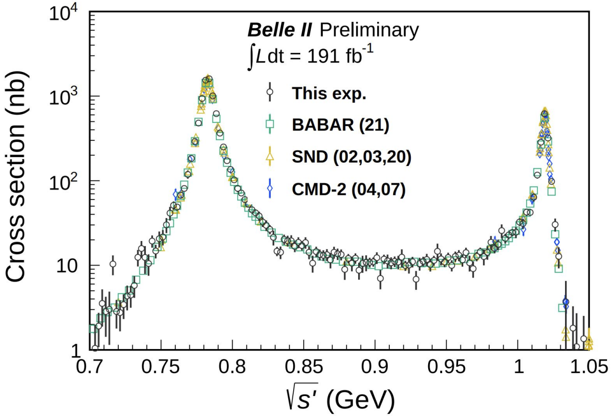


World best tau mass

PRD 108, 032006 (2023)

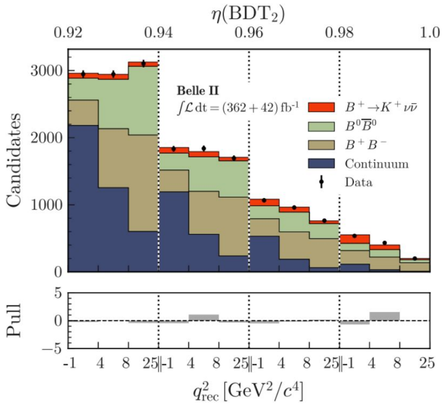
$e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$

(input for g-2 predictions)



2.5σ deviation from BaBar

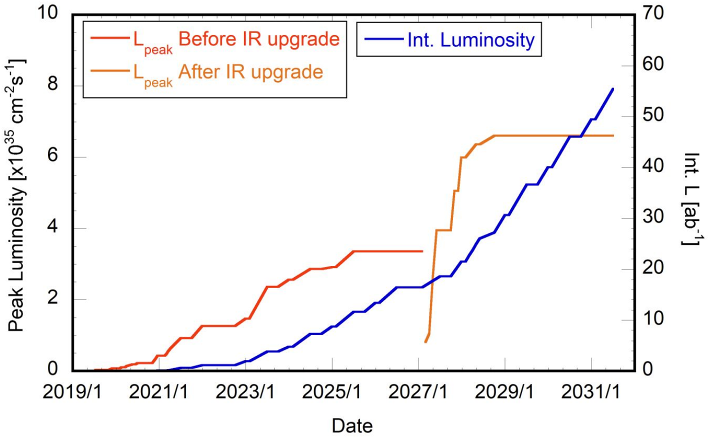
$$\mathbf{B}(B^+ \rightarrow K^+ \nu\bar{\nu}) = \left(2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})\right) \times 10^{-5}$$



2.7σ “tension” with SM

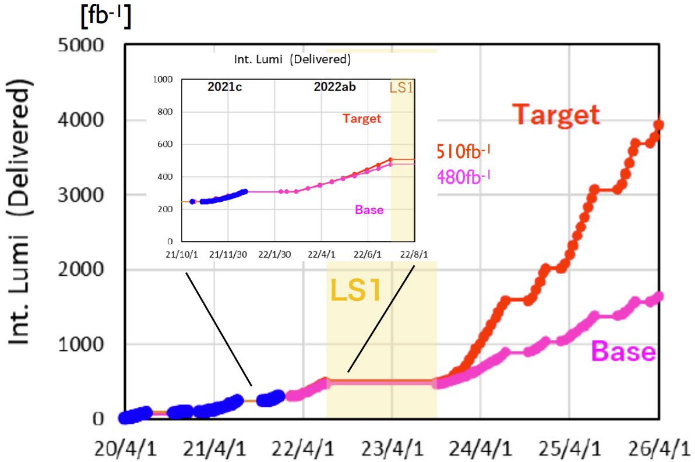
Belle II luminosity expectations

2020 projection



8 ab^{-1} by today

2022 projection

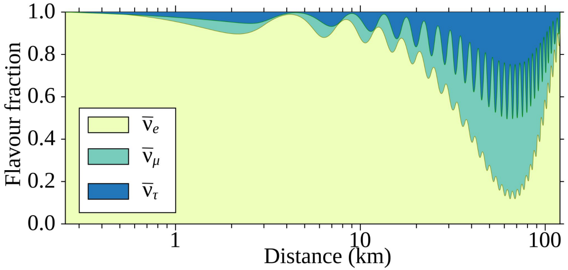


Target: 1.6 ab^{-1} by today
Base: 1.0 ab^{-1} by today

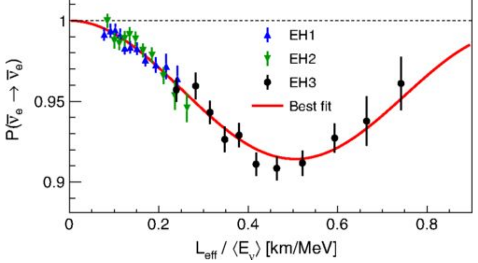
In reality 0.55 ab^{-1} by today, hopefully surpassing Belle in ~1.5year

Observations challenging the Standard Model

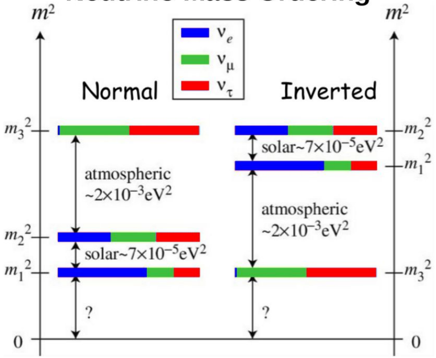
Neutrino masses



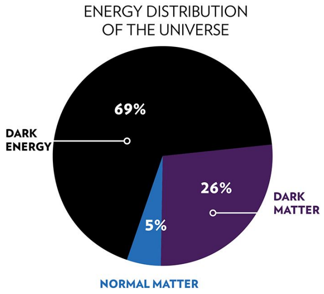
Daya Bay experiment
(Phys. Rev. Lett. 115 (2015))

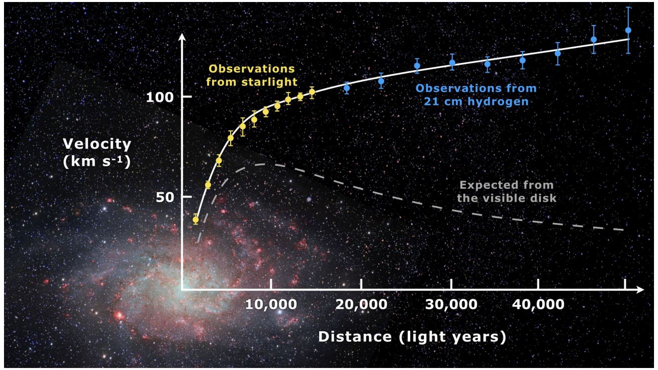


Neutrino Mass Ordering



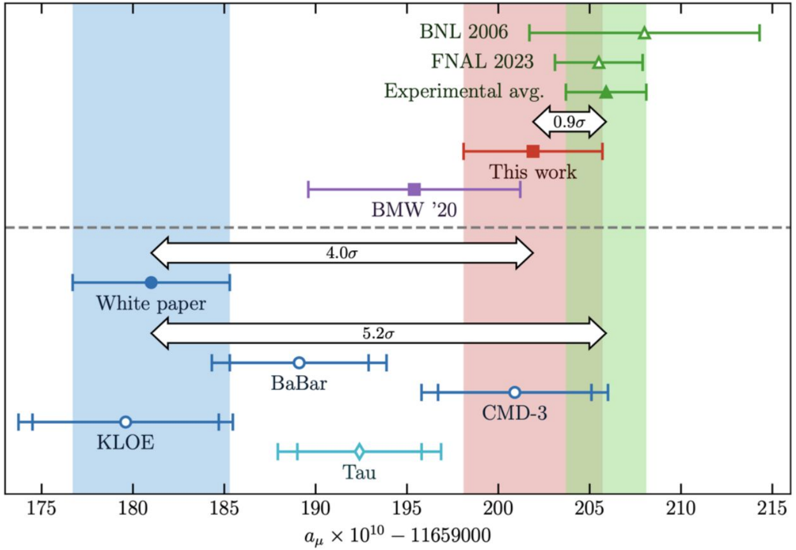
Dark Matter



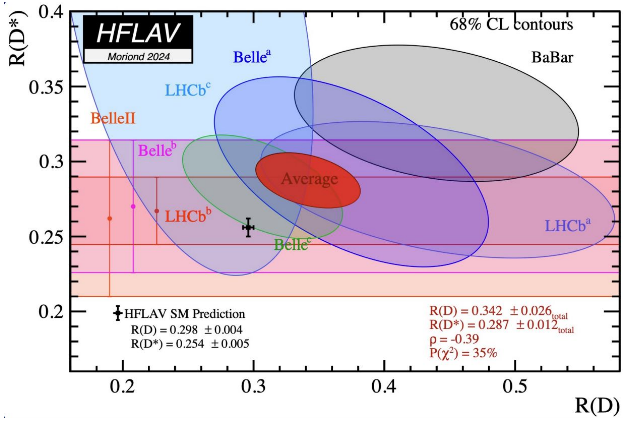


Observations in the “gray” area

g-2



B anomalies



These are not at the energy frontier…