Flavour physics and tests of fundamental interactions

GT2 – Symposium ESPPU

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20 January 2025

The intensity frontier

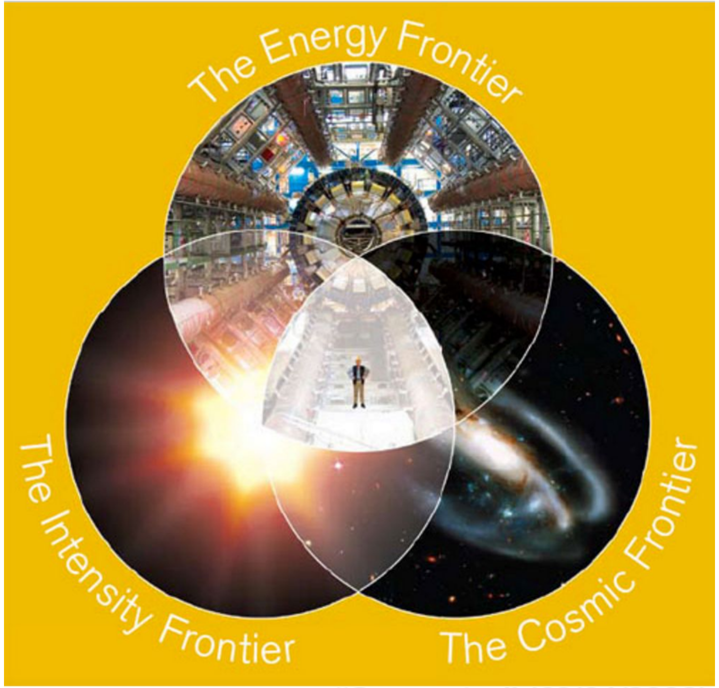
INTENSITY frontier GDR-InF

Probe New Physics pushing the experiment's luminosity rather than the energy scale

Strategy:

- Look for deviations from theory predictions in precise measurements of SM processes
- Search for hugely suppressed or forbidden processes in SM

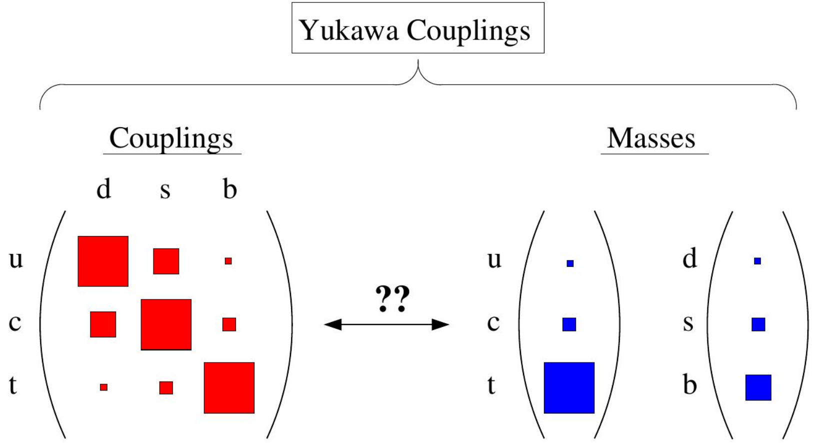
Require large datasets and precise measurements



"Symmetry" (08/01/2008)

Why the flavour sector

- Majority of SM parameters
- Unexplained patterns and hierarchies in masses and CKM elements
- Accidental symmetries (baryon and lepton numbers)
- Indirect measurements are powerful prediction and discovery tool
  - Predicted half the quarks before their direct discovery!
  - Strong constraints on masses of c, t, H before their discovery



Link to open questions

- Matter/antimatter imbalance
- Strong CP problem
- Dark matter

Inputs to GT2

- 11 direct contributions on esppu.in2p3.fr about
  - Current and proposed future experiments (Belle II, LHCb, n2EDM, GrAHal, PIONEER)
  - Precision measurements at FCC-ee
  - Theory (Phenomenology and lattice QCD)
  - Challenges in an heterogeneous computing environment with exabytes of data
  - New-physics searches with radioactive ions beams
- Dedicated discussion at GDR-InF annual workshop (indico.in2p3.fr/event/33443/)

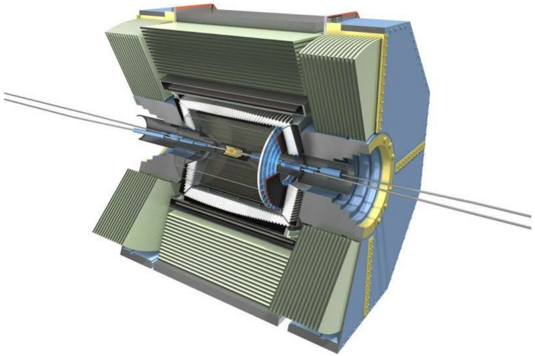
Amhis	Yasmine	IJCLab	GT2 GT4	Nouvelle expérience, Saveurs, QCD	⇨ Intérêt de la communauté française pour une participation au programme de physique et aux améliorations du détecteur LHCb pour la période 2035 - 2041 (LHCb Upgrade II)
Blossier	Benoît	IJCLab Orsay	GT2 GT4	Théorie/Phénoménologie, Calcul et données, BSM / Nouvelle physique, Saveurs, QCD	⇨ QCD sur réseau, texte en anglais
DELAHAYE	Pierre	GANIL, CAEN, France	GT2 GT1	Physique sur accélérateurs, Physique hors-accélérateurs, R&D détecteurs, Nouvelle expérience, BSM / Nouvelle physique, Physique électrofaible, Saveurs	⇨ "PIONEER: A Next-Generation Pion Decay Experiment at PSI"
Delmastro	Marco	LAPP Annecy	GT1 GT2	Physique sur accélérateurs, Higgs, Physique électrofaible, Saveurs	⇨ Expression d'Intérêt pour les mesures de précision au FCC-ee
Farget	Fanny	GANIL	GT2	Physique hors-accélérateurs, BSM / Nouvelle physique	⇨ Radioactive Ion Beams opportunities to reach Physics Beyond the Standard Model
Farget	Fanny	GANIL	GT5 GT2	Physique hors-accélérateurs, BSM / Nouvelle physique	⇨ Exploring physics beyond the Standard Model with the new DESIR facility at GANIL
Gligorov	Vladimir	LPNHE	GT5 GT2	Physique sur accélérateurs, Physique hors-accélérateurs, R&D détecteurs, Calcul et données, Développement durable	⇨ Reflection sur les défis technologique dans calcul et données
Lefort	Thomas	LPC Caen	GT2 GT5	Physique hors-accélérateurs, BSM / Nouvelle physique	⇨ neutron EDM
NORTIER	Florian	IP2I Lyon	GT1 GT2	Physique sur accélérateurs, Théorie/Phénoménologie, Higgs, BSM / Nouvelle physique, Physique électrofaible, Saveurs	⇨ Contribution of the IP2I Theory Group to the ESPPU 2025
Pugnat	Pierre	LNCMI, CNRS, Grenoble	GT2	Physique hors-accélérateurs, Nouvelle expérience, Nouveau champ expérimental, BSM / Nouvelle physique	⇨ Grenoble Axion Haloscopes: From BabyGrAHal to GrAHal for Axion Dark Matter Search
Serrano	Justine	CPPM	GT2	Physique sur accélérateurs, R&D détecteurs, BSM / Nouvelle physique, Saveurs	⇨ The Belle II experiment and its upgrade

Two-pillars strategy

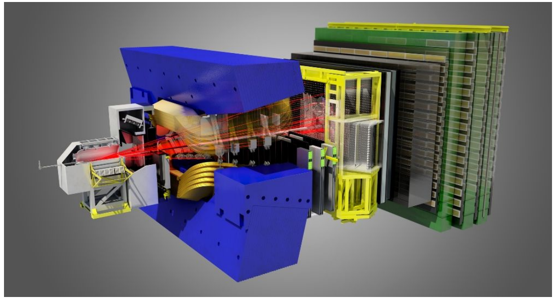
- Big experiments with a large physics program
- Smaller experiments dedicated to
  - Measurement of crucial observables (EDM, g-2, LFV experiments)
  - Dedicated searches for long-lived particles (Axion, ALPs, …)

Big experiments with a large physics program

Big experiments with a large physics program



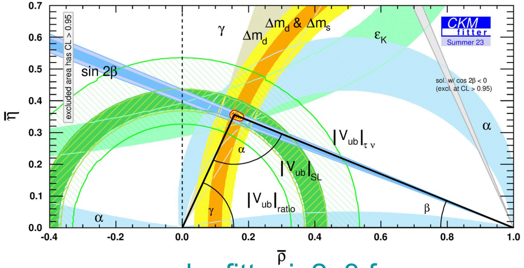
- Hermetic detector
  - Allow inclusive and missing energy analyses
- Asymmetric e^+e^- collider at $\Upsilon(4S)$
  - Clean environment
  - Entangled B pair
  - ~100% trigger efficiency for BB events
  - Similar BB, cc and $\tau\tau$ production x-section
  - Good efficiency for photons and neutral particles



- General purpose detector in the forward region
- pp collisions
  - Large bb and cc production cross section
  - All B-hadron produced
  - Large boost
- Complementary program of QCD and EW measurements
- Fully software trigger since Run 3

Main physics interests

1. CP violation and unitary triangle
2. Rare B decays sensitive to New Physics
3. Tests of lepton flavour violation and lepton flavour universality violation
4. Charm and tau physics
5. Spectroscopy
6. …



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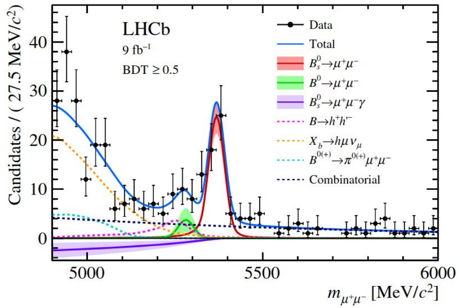
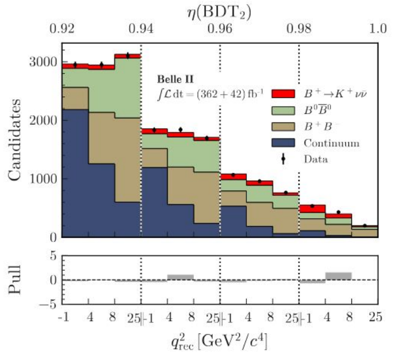
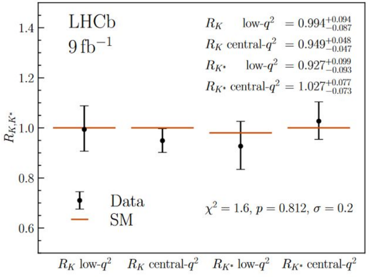


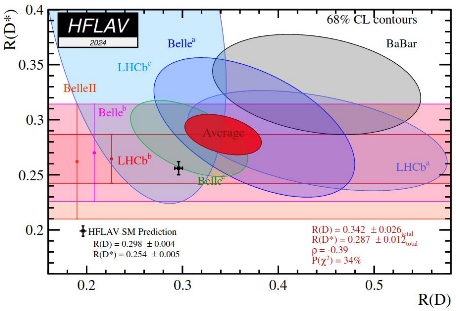
PRL 128 041801



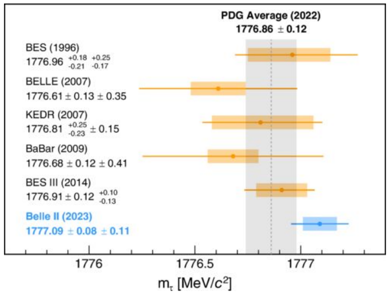
PRD 109 112006



PRL 131 051803



arXiv:2411.18639



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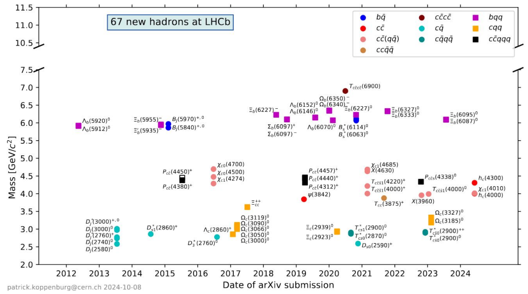


koppenburg.ch/particles

Upgrade opportunities

- Without upgragrades expect 50 fb^{-1} for LHCb (2041) and 5-10 ab^{-1} for Belle II (2032)
- Most of key observables still statistically limited
- Calls for larger datasets
  - Increase instantaneous luminosity
  - Upgrade detectors and acquisition systems to cope with increased luminosity

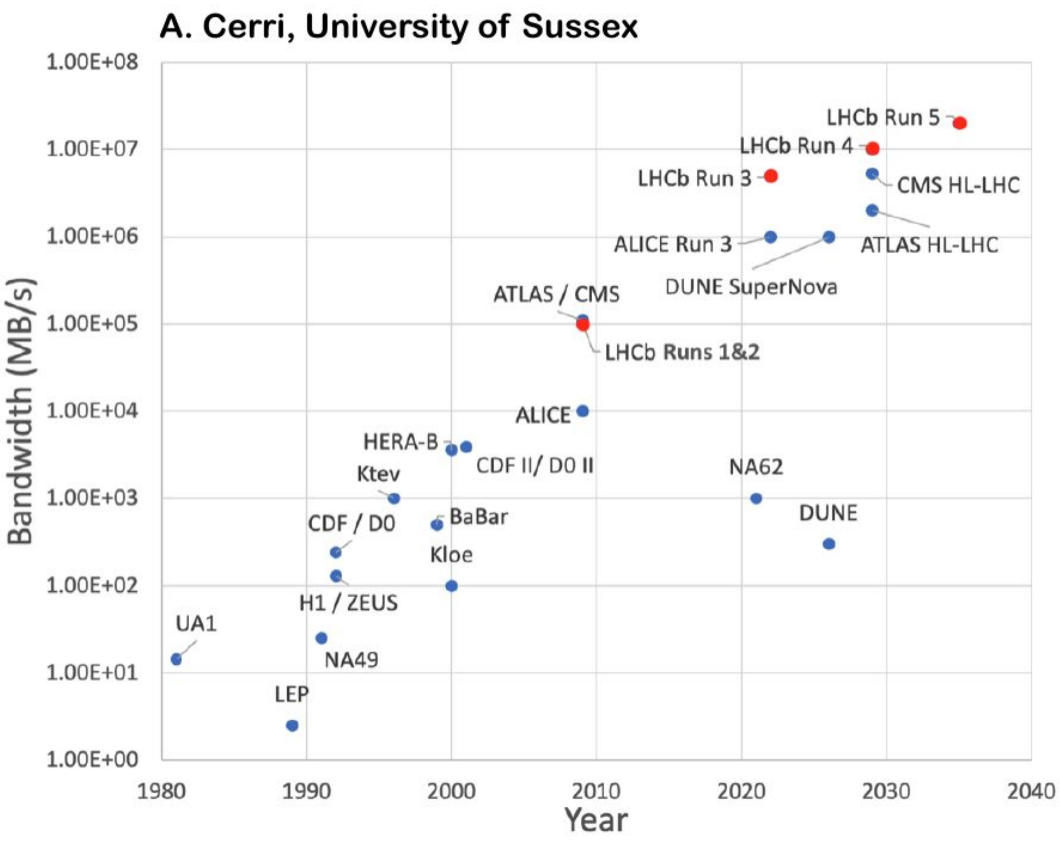
Belle II

- Goal: 50 ab^{-1}
- When: ~ 2032
- More robust against beam background
- Improved performances
- Possibly polarised e^- beam for precise measurements of electroweak and τ parameters

LHCb

- Goal: 300 fb^{-1}
- When: 2034 (Long Shutdown 4), some already in 2027 (Long Shutdown 3)
- Precise timing and high granularity essential to reduce pileup
- Heterogeneous trigger
- Probe a 90% higher new physics mass scale for fixed couplings

Computing challenges



- Flavour physics at the forefront of the Exascale computing
- Need for highly efficient and energy-saving heterogeneous high performance computing
- Need for interdisciplinary teams of physicists and computer engineers

Longer term wish: Tera-Z + Giga-W on a e^+e^- machine with a suitable detector

INTENSITY frontier GDR-InF

- A Tera-Z factory has several advantages of LHCb and Belle II combined
- W^+W^- run allows direct access to CKM elements

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

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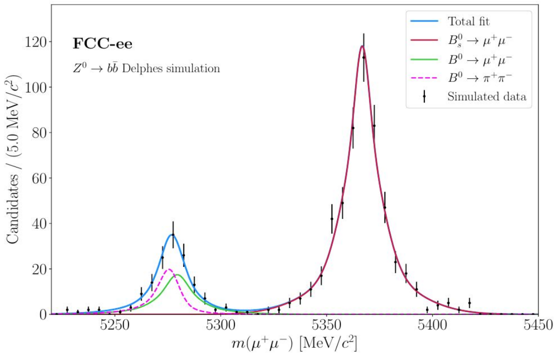
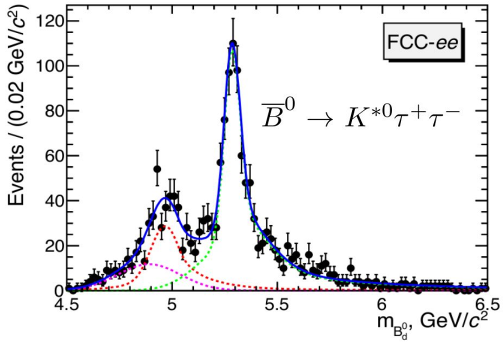
- Preferred option is a circular e^+e^- collider
    - A smaller number of Z from a linear collider will clearly provide less opportunities for World-leading measurements (considering the available samples after Belle II and LHCb)
    - Multiple collision points allow for an experiment optimized for the needs of flavour physics

Opportunities at Tera-Z + Giga-W

- Improved precision on CKM parameters (angles and sides Unitarity triangle, Φ_s; direct access to V_{cb} from W decays)
- Unique sensitivity to very rare FCNC B decays ($B_{(s)} \to \mu\mu$, $B_s \to \tau\tau$, $b \to s(d)ll$, $b \to s(d)\tau\tau$, $b \to s(d)\nu\nu$) and challenging B_c decays ($B_c \to \mu\nu$, $B_c \to \tau\nu$) sensitive to possible new physics
- Improve measurement of τ properties and reach for LFV decays
- Opportunities in charm physics, heavy flavour spectroscopy





arXiv:2203.06520

A suitable detector for flavour physics

- Good momentum resolution down to 100 MeV
- Good vertex resolution to separate secondary vertices and perform time-dependent measurements
- pion/kaon/proton separation across full kinematical range
- Electromagnetic calorimeter with good resolution and granularity (transverse and longitudinal) down to low energies
- Good efficiency and precision in reconstructing K_S and Λ

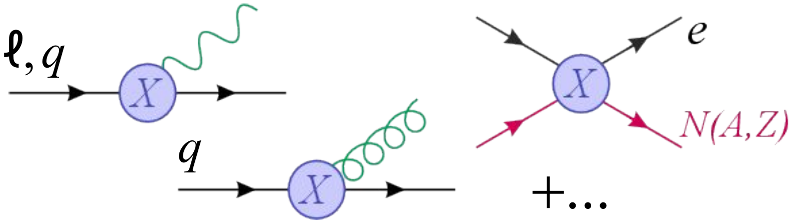
Smaller dedicated experiments

Smaller dedicated experiments

INTENSITY frontier GDR-InF

CP violation: Very constrained in the SM : - Only one phase in the CKM matrix,
- Strong CP violation is (puzzlingly) tiny.

Tiny EDMs (leptons, nucleons, atomic), nuclear CP asymmetries,...
Does not suffice to induce the baryon asymmetry of the universe,



Most BSM bring many new CP-violating phases and break this pattern.

Scales up to O(100 TeV) can be probed.

n2EDM@PSI for the neutron EDM,
Ultra cold neutrons, comagnetometer.

DESIR@GANIL for asymmetries,
Beta decay spectra, radioactive ion beams.

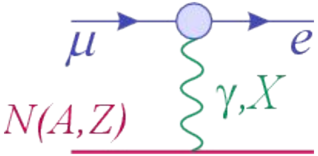
Smaller dedicated experiments

INTENSITY frontier GDR-InF

Lepton flavor violation: In the SM, charged leptonic flavors appear essentially conserved.

Many tests using B, D, K, τ decays + dedicated experiments for μ.

COMET experiment (COherent Muon to Electron Transition) at JPARC



Sensitivity up to 1000 TeV.

COMET J-PARC

Many other initiatives (conversion, $\mu \to e\gamma$, $\mu \to eee$)

Lepton flavor universality: In the SM, gauge interactions do not care about flavors.

Again, many tests both heavy meson decay, or directly via EW-scale colliders.

Dedicated experiment for the pion: $\dfrac{\pi \to \mu\nu}{\pi \to e\nu}$ @ PIONEER

Smaller dedicated experiments

INTENSITY frontier GDR-InF

Vud: It is the only ‘naturally occurring’ CKM element, best measured at low energy

Precise test of the unitarity of CKM: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$.

Nuclear (superallowed):

Spiral2 DESIR

Pion decay $\pi \to \ell\nu$:

PIONEER

Baryon and lepton numbers: Accidentally but exactly conserved in the SM Lagrangian.

	ΔB	ΔL
Proton decay	-1	$\pm 1, \pm 3$
$0\nu\beta\beta$	0	± 2
$n-\bar{n}$ oscillations	± 2	0
Dinucleon trans.	-2	x

These are flavored transitions,

but mostly addressed by the GT3-neutrinos.

Smaller dedicated experiments

New light particle: Are we sure nothing else exists at low energy?

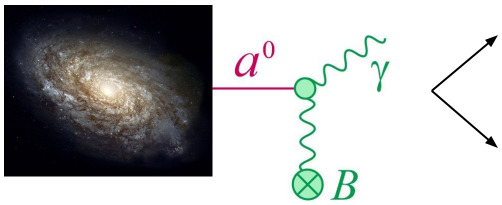
Dark matter is presumably made of particles!

A whole dark sector may exist with dark fermions, photons, (pseudo)scalars,…

Generalist searches (e.g. beam dump, nuclear recoil, colliders, …)

Precision observables: $\frac{1}{(many\,TeV)^n} \rightarrow \frac{(very\,small)}{(\leq GeV)^n}$

Many searches for axions as solutions to the strong CP puzzle (including n2EDM).



MADMAX: Dielectric disks for interference + resonance

GrAHal: RF resonant cavity in a large 42T hybrid magnet @LNCMI

Lattice QCD

INTENSITY frontier GDR-InF

Most flavor observables involve light hadrons:

Observables ~ | (SD physics, calculable) x (hadronic matrix element) |^2

Lattice calculations are crucial to match the experimental precision

Challenges to attain the percent level accuracy:

Needs to control QED and $m_u \neq m_d$ effects,
(directly on fine lattice and/or indirectly via low-energy EFT)

Road to inclusiveness requires dealing with many hadron states,

Developments for nuclear observables (from Vud to $0\nu\beta\beta$ or proton decay).

Past few decades have seen great achievements,

...but the next generation experiments ask to push even further!

Priorities

Short-medium term

- Fully exploit LHCb and Belle II and support their proposed upgrades
- Support smaller dedicated experiments (n2EDM, COMET, GrAHal, MADMAX, Gbar, …)
- Pursue synergy with NuPECC for precise measurements at the boundary between particle and nuclear physics (e.g. with DESIR at GANIL)

Long-term

- Tera-Z + Giga-W on a e^+e^- machine with a well designed detector
- Important to continue investing in smaller dedicated experiments with potential high-impact discoveries (including probes for a possible dark sector)

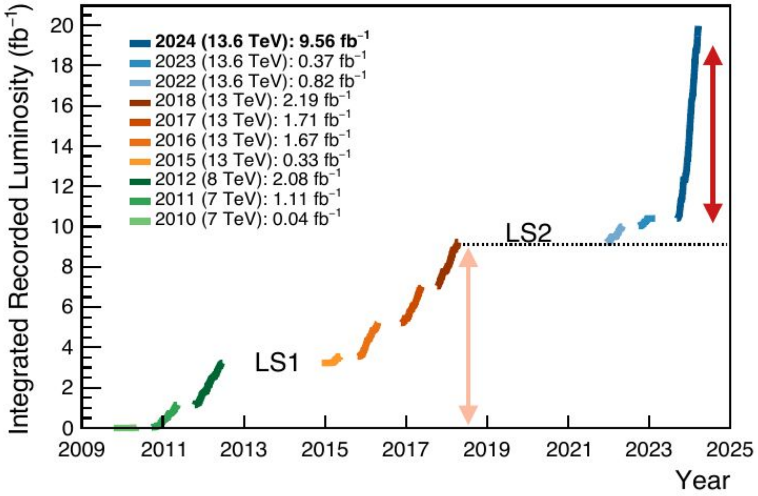
Specific needs from Theory, Detector and Computing

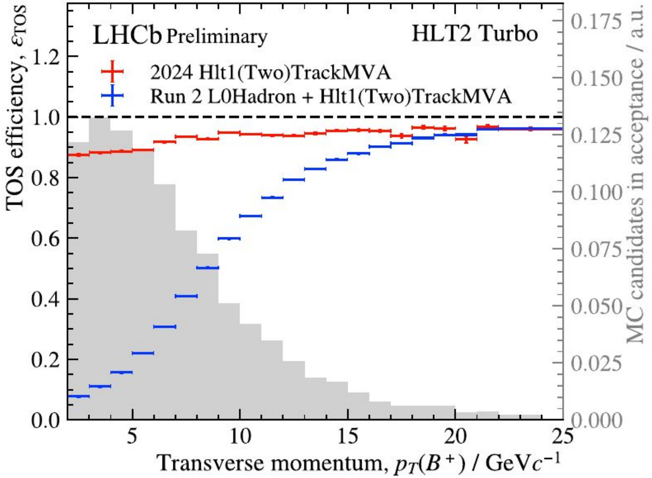
BACKUP

Discussion items

-

LHCb Upgrade I





- 5 time larger instantaneous luminosity
- Greatly improved tracker & PID granularity, 30 MHz detector readout & GPU tracking trigger
- More than doubled the efficiency for hadronic signals

LHCb-U2 physics opportunities

INTENSITY frontier GDR-InF

Observable	Old LHCb (up to $9\,\text{fb}^{-1}$)		LHCb Upgrade 2 Scoping Document: Upgrade I ($23\,\text{fb}^{-1}$)	Upgrade I ($50\,\text{fb}^{-1}$)	Upgrade II ($300\,\text{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	$2.8°$	[18, 19]	$1.3°$	$0.8°$	$0.3°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	[22]	12 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[55, 56]	3%	2%	1%
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[25]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[29]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[57]	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%	[30, 31]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[58]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[59]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[60]	0.148	0.097	0.038

Comparison expected yields

INTENSITY frontier GDR-InF

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

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Current and planned b-factories

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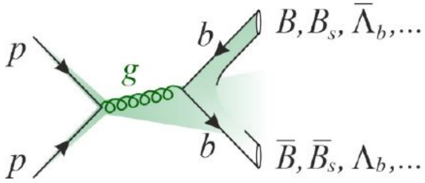
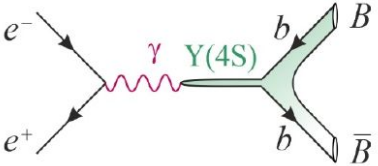
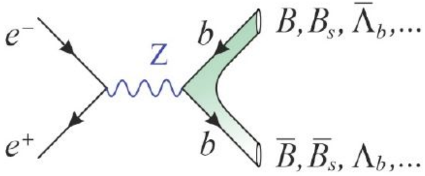


All b hadrons
Large production rate



Clean environment
Entanglement
Neutral decay products
Hermiticity (neutrinos)
τ factory



Many of the advantages of LHCb and Belle II

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