# Future Prospects for Heavy Flavor Measurements


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Madrid, Spain, 8.04.2014

HELMHOLTZ
ASSOCIATION

DESY

# Outline

> Introduction

> Physics Highlights from LHCb and Belle

> Experimental Status and Plans

- LHCb Upgrade
- Belle2

> Summary

# Introduction

> LHC discovered a Higgs

> No New Physics observed

- Direct: no BSM particles or decays
- Indirect: measured deviations from the SM are small

> Important

- Joint efforts in energy and intensity frontier
- High experimental precision
- Theoretical cleanliness

# Heavy Flavor Physics at LHCb and Belle II

> LHCb
- Great B and charm statistics
- Very good charged particle reconstruction

> Complimentary to direct searches for New Physics at LHC

> Need precise theoretical predictions

## Key observables (*arXiv:1311.1076*)

| Type | Observable | Current precision | LHCb 2018 | Upgrade ($50\,\mathrm{fb}^{-1}$) | Theory uncertainty |
|---|---|---|---|---|---|
| $B_s^0$ mixing | $2\beta_s\ (B_s^0 \to J/\psi\ \phi)$ | 0.10 [9] | 0.025 | 0.008 | $\sim 0.003$ |
| | $2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$ | 0.17 [10] | 0.045 | 0.014 | $\sim 0.01$ |
| | $A_{\mathrm{fs}}(B_s^0)$ | $6.4 \times 10^{-3}$ [18] | $0.6 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | $0.03 \times 10^{-3}$ |
| Gluonic penguin | $2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$ | – | 0.17 | 0.03 | 0.02 |
| | $2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ | – | 0.13 | 0.02 | $< 0.02$ |
| | $2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$ | 0.17 [18] | 0.30 | 0.05 | 0.02 |
| Right-handed currents | $2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$ | – | 0.09 | 0.02 | $< 0.01$ |
| | $\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$ | – | 5 % | 1 % | 0.2 % |
| Electroweak penguin | $S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$ | 0.08 [14] | 0.025 | 0.008 | 0.02 |
| | $s_0\,A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$ | 25 % [14] | 6 % | 2 % | 7 % |
| | $A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$ | 0.25 [15] | 0.08 | 0.025 | $\sim 0.02$ |
| | $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ | 25 % [16] | 8 % | 2.5 % | $\sim 10$ % |
| Higgs penguin | $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ | $1.5 \times 10^{-9}$ [2] | $0.5 \times 10^{-9}$ | $0.15 \times 10^{-9}$ | $0.3 \times 10^{-9}$ |
| | $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ | – | $\sim 100$ % | $\sim 35$ % | $\sim 5$ % |
| Unitarity triangle angles | $\gamma\ (B \to D^{(*)}K^{(*)})$ | $\sim 10$–$12°$ [19, 20] | $4°$ | $0.9°$ | negligible |
| | $\gamma\ (B_s^0 \to D_s K)$ | – | $11°$ | $2.0°$ | negligible |
| | $\beta\ (B^0 \to J/\psi\ K_S^0)$ | $0.8°$ [18] | $0.6°$ | $0.2°$ | negligible |
| Charm *CP* violation | $A_\Gamma$ | $2.3 \times 10^{-3}$ [18] | $0.40 \times 10^{-3}$ | $0.07 \times 10^{-3}$ | – |
| | $\Delta A_{CP}$ | $2.1 \times 10^{-3}$ [5] | $0.65 \times 10^{-3}$ | $0.12 \times 10^{-3}$ | – |

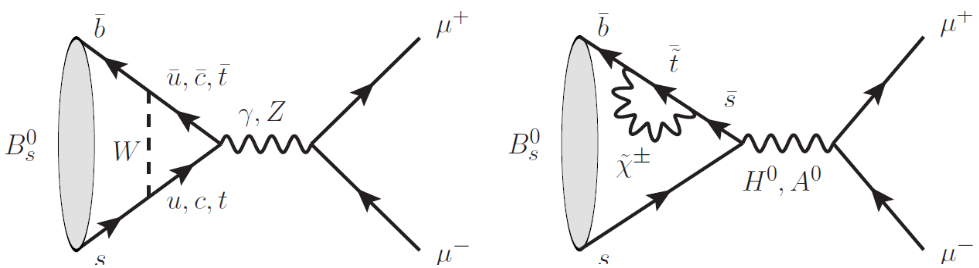
# Heavy Flavor Physics at LHCb and Belle II

- Belle II
  - Well-defined initial state
  - Ability to reconstruct final states with photons, $\pi^0$s and neutrinos
- Complimentary to direct searches for New Physics at LHC
- Need precise theoretical predictions

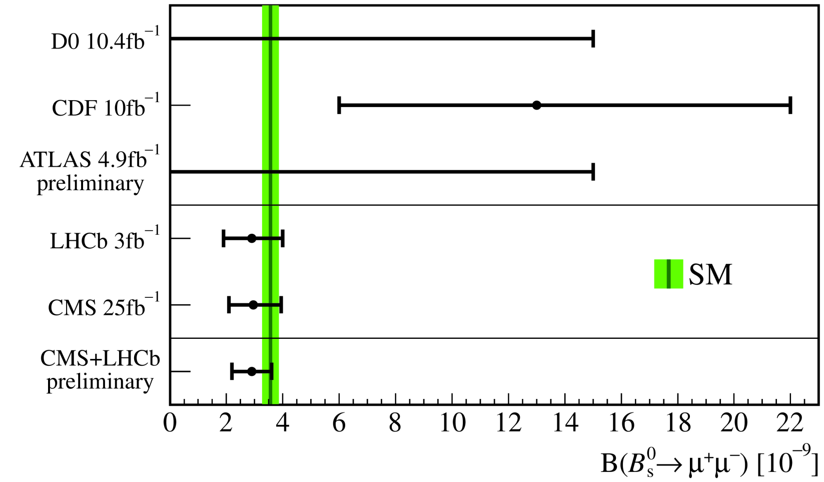
## Key observables (*arXiv:1311.1076*)

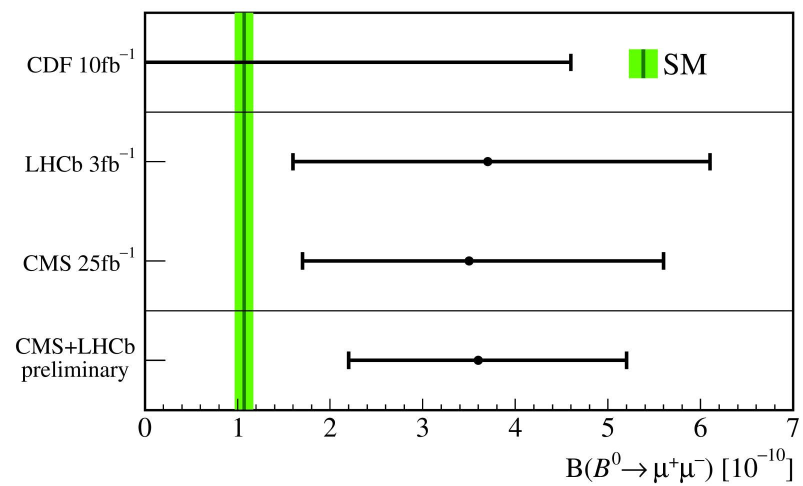
| Observable | SM theory | Current measurement (early 2013) | Belle II ($50\,\mathrm{ab}^{-1}$) |
|---|---|---|---|
| $S(B \to \phi K^0)$ | 0.68 | $0.56 \pm 0.17$ | $\pm 0.03$ |
| $S(B \to \eta' K^0)$ | 0.68 | $0.59 \pm 0.07$ | $\pm 0.02$ |
| $\alpha$ from $B \to \pi\pi, \rho\rho$ | | $\pm 5.4°$ | $\pm 1.5°$ |
| $\gamma$ from $B \to DK$ | | $\pm 11°$ | $\pm 1.5°$ |
| $S(B \to K_S \pi^0 \gamma)$ | $< 0.05$ | $-0.15 \pm 0.20$ | $\pm 0.03$ |
| $S(B \to \rho\gamma)$ | $< 0.05$ | $-0.83 \pm 0.65$ | $\pm 0.15$ |
| $A_{\mathrm{CP}}(B \to X_{s+d}\,\gamma)$ | $< 0.005$ | $0.06 \pm 0.06$ | $\pm 0.02$ |
| $A^d_{\mathrm{SL}}$ | $-5 \times 10^{-4}$ | $-0.0049 \pm 0.0038$ | $\pm 0.001$ |
| $\mathcal{B}(B \to \tau\nu)$ | $1.1 \times 10^{-4}$ | $(1.64 \pm 0.34) \times 10^{-4}$ | $\pm 0.05 \times 10^{-4}$ |
| $\mathcal{B}(B \to \mu\nu)$ | $4.7 \times 10^{-7}$ | $< 1.0 \times 10^{-6}$ | $\pm 0.2 \times 10^{-7}$ |
| $\mathcal{B}(B \to X_s\gamma)$ | $3.15 \times 10^{-4}$ | $(3.55 \pm 0.26) \times 10^{-4}$ | $\pm 0.13 \times 10^{-4}$ |
| $\mathcal{B}(B \to K\nu\bar{\nu})$ | $3.6 \times 10^{-6}$ | $< 1.3 \times 10^{-5}$ | $\pm 1.0 \times 10^{-6}$ |
| $\mathcal{B}(B \to X_s\ell^+\ell^-)$ $(1 < q^2 < 6\,\mathrm{GeV}^2)$ | $1.6 \times 10^{-6}$ | $(4.5 \pm 1.0) \times 10^{-6}$ | $\pm 0.10 \times 10^{-6}$ |
| $A_{\mathrm{FB}}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing | 7% | 18% | 5% |
| $\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ $(q^2 > 16\,\mathrm{GeV}^2)$ | 9% → 2% | 11% | 2.1% |

# Search for Rare $B^0_{(s)} \rightarrow \mu^+\mu^-$ Decays




- > Flavor Changing Neutral Current (FCNC), suppressed in the SM
- > Sensitive to NP contributions
- > LHCb found first evidence for rare decay $B^0_s \rightarrow \mu^+\mu^-$
  *Phys. Rev. Lett.* ***110****, 021801 (2013)*
- > Combining CMS (25 $fb^{-1}$) and updated LHCb (3 $fb^{-1}$) results
  *Phys. Rev. Lett.* ***111****, 101804, 101805 (2013)* → first observation of $B^0_s \rightarrow \mu^+\mu^-$

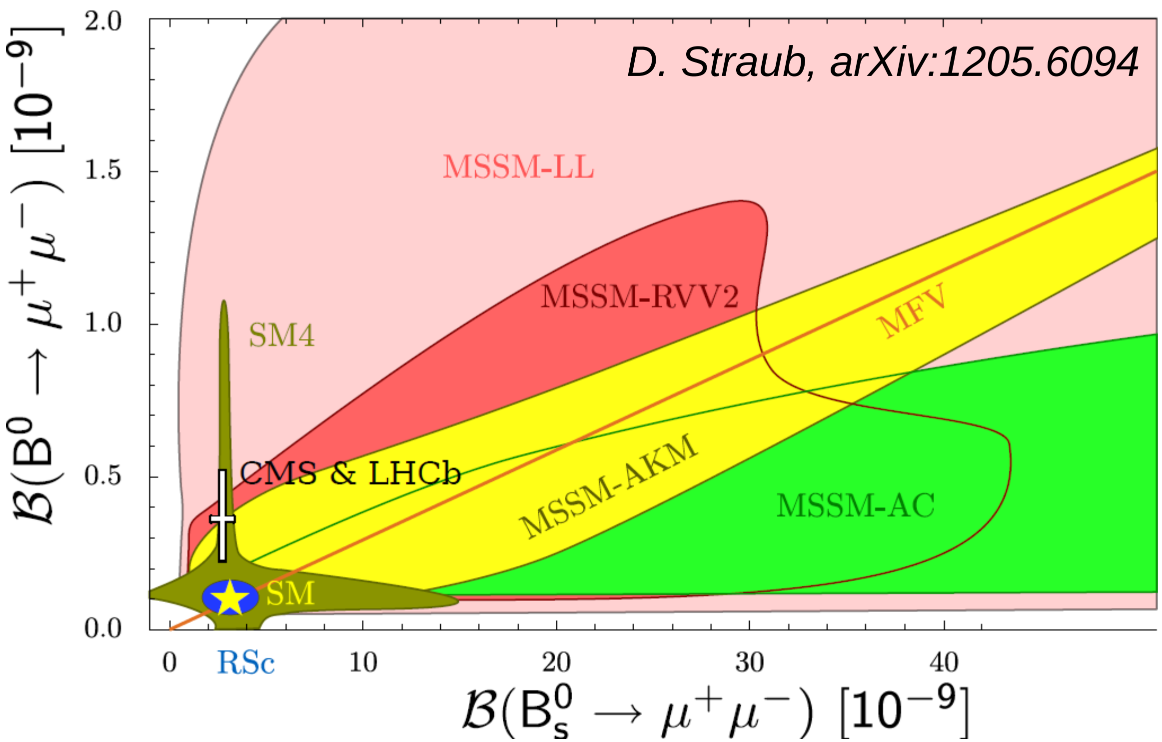



*CMS-PAS-BPH-13-007; LHCb-CONF-2013-012*

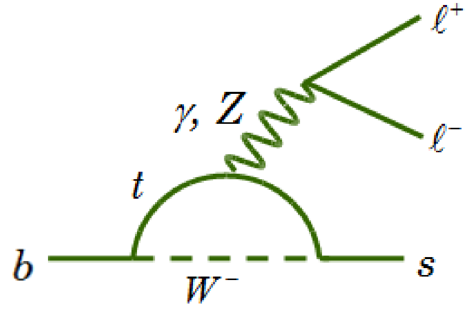
# Comparison with the SM and Its Extensions

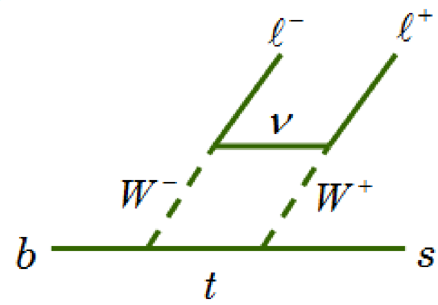
- Constraints on New Physics models
- The current SM BR($B^0_s \to \mu^+\mu^-$) has about 10% uncertainty, important to improve theoretical errors



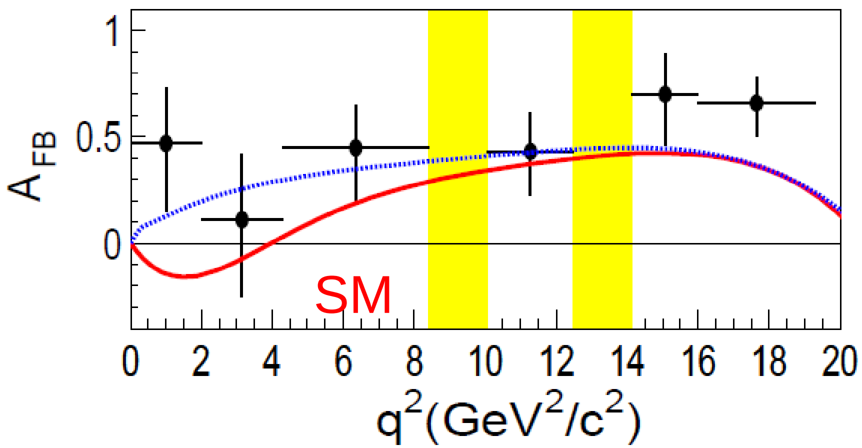
# Electroweak Penguin $b \to s\, l^+ l^-$

- Electroweak penguin (or box) diagram
- Rich set of observables
  - Branching fraction, CP Asymmetry, isospin asymmetry, $q^2 = |M(l^+l^-)|^2$, $FL$, forward-backward asymmetry, ratio of $\mu$ mode and $e$ mode

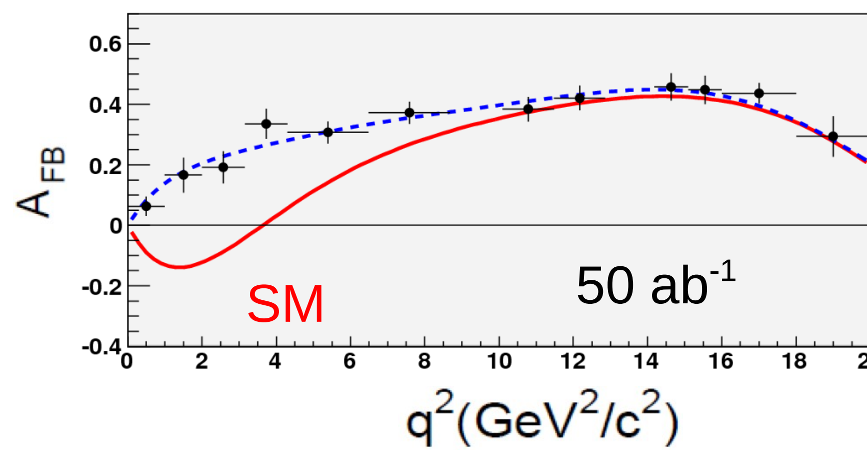



- Belle measurement of the forward-backward asymmetry in $B \to K^* l^+ l^-$, indication of New Physics?



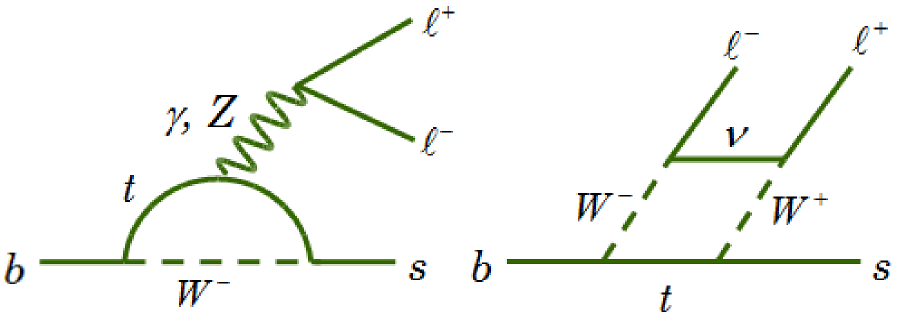

*Phys. Rev. Lett.* ***103***, *171801 (2009)*




*Projection for Belle II planned luminosity*

# Electroweak Penguin $b \to s\, l^+ l^-$

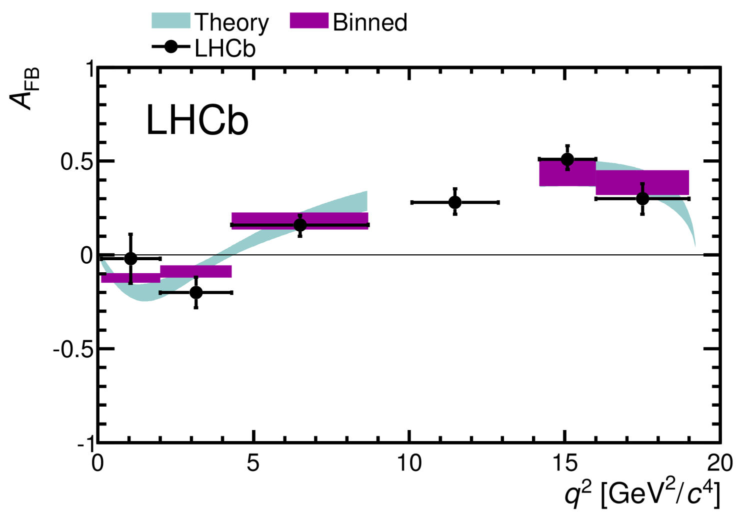
> Electroweak penguin (or box) diagram



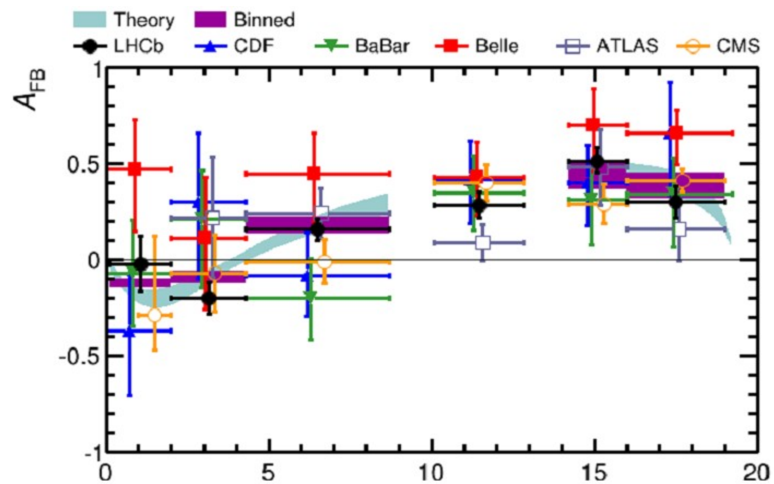

> Rich set of observables

- Branching fraction, CP Asymmetry, isospin asymmetry, $q^2 = |M(l^+l^-)|^2$, *FL*, forward-backward asymmetry, ratio of $\mu$ mode and *e* mode

> Other experiments including LHCb are consistent with the SM




*JHEP 1308 (2013) 131*



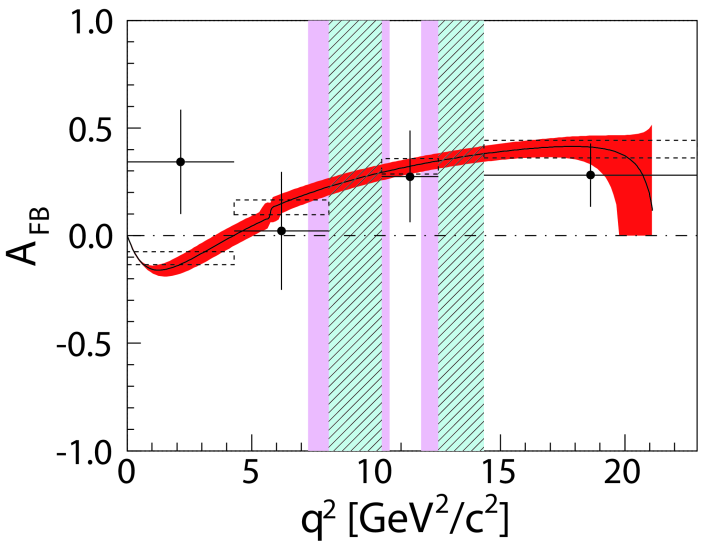
# Inclusive $B \to X_s l^+l^-$

- LHCb will further improve the measurement on the exclusive $\mu$ mode
- B factory experiments advantages
  - Ratio of muon mode and electron mode
  - Inclusive (sum-of-exclusive) analysis
- Measurement of the forward-backward asymmetry in $B \to X_s l^+l^-$ at Belle
  - Semi-inclusive reconstruction (sum-of-exclusive) method
  - $X_s l^+l^-$ is reconstructed from 36 (18x2) exclusive modes

$X_s = K^\pm/K_S$ + up to four $\pi$ (at most one $\pi^0$)

| | |
|---|---|
| [ $K$ ] | $K$, $K_S$ |
| [ $K\pi$ ] | $K\pi$, $K_S\pi$, $K\pi^0$, $K_S\pi^0$ |
| [ $K2\pi$ ] | $K2\pi$, $K_S2\pi$, $K\pi\pi^0$, $K_S\pi\pi^0$ |
| [ $K3\pi$ ] | $K3\pi$, $K_S3\pi$, $K2\pi\pi^0$, $K_S2\pi\pi^0$ |
| [ $K4\pi$ ] | $K4\pi$, $K_S4\pi$, $K3\pi\pi^0$, $K_S3\pi\pi^0$ |

$l^+l^- = e^+e^-$ or $\mu^+\mu^-$

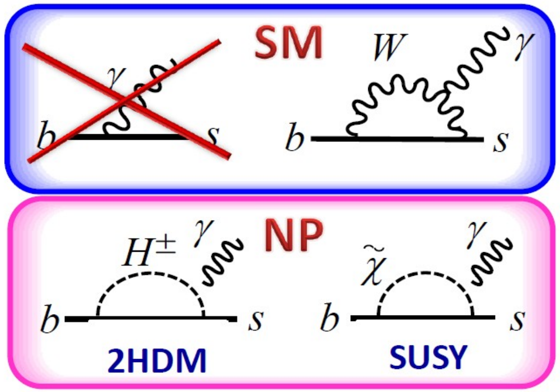



*arXiv:1402.7134*

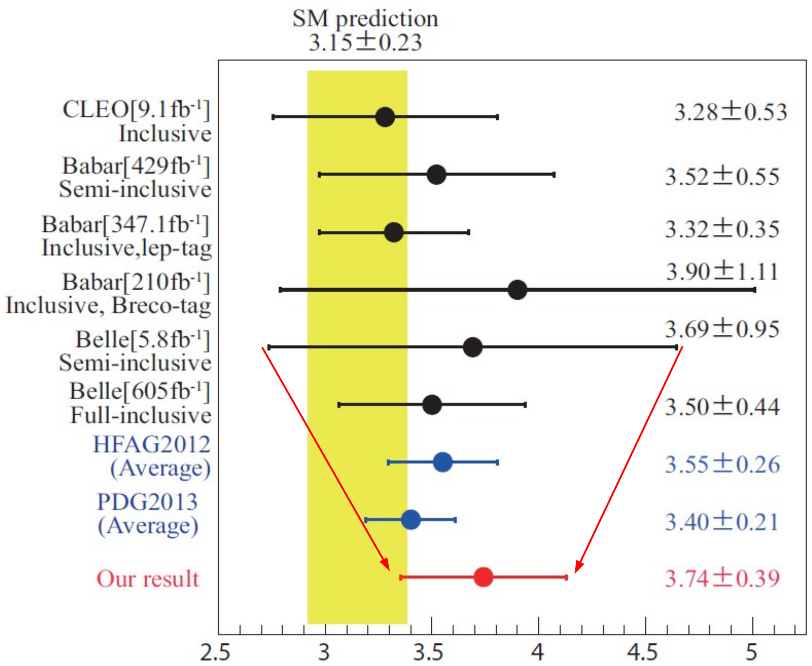
- Smaller uncertainties of theoretical calculations than in exclusive case
- One of the key measurements at Belle II

# Inclusive $B \to X_s \gamma$

- $b \to s\,\gamma$ transition: FCNC
- Forbidden at tree level in the SM, proceeds via loop diagrams
- Inclusive branching fraction sensitive to new particles in the loop

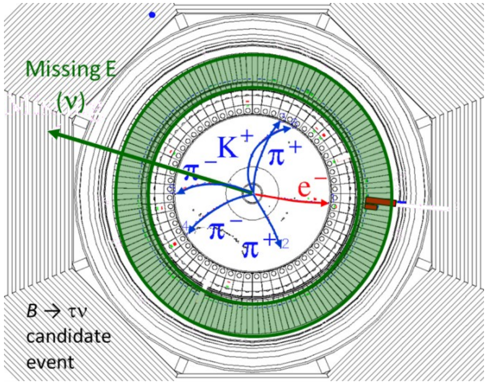



- Preliminary results from Belle
  *T. Saito, Moriond EW, La Thuile, 17.03.2014*
  *https://indico.in2p3.fr/conferenceDisplay.py?confId=9116*
- Semi-inclusive (sum-of-exclusive) approach
- Consistent with the SM
- Key measurement at Belle II
- Improvements in theoretical calculations important



# Unique Capabilities of $e^+e^-$ B Factories

- Clean event environment
- Detection of neutral particles
- Example: full reconstruction method



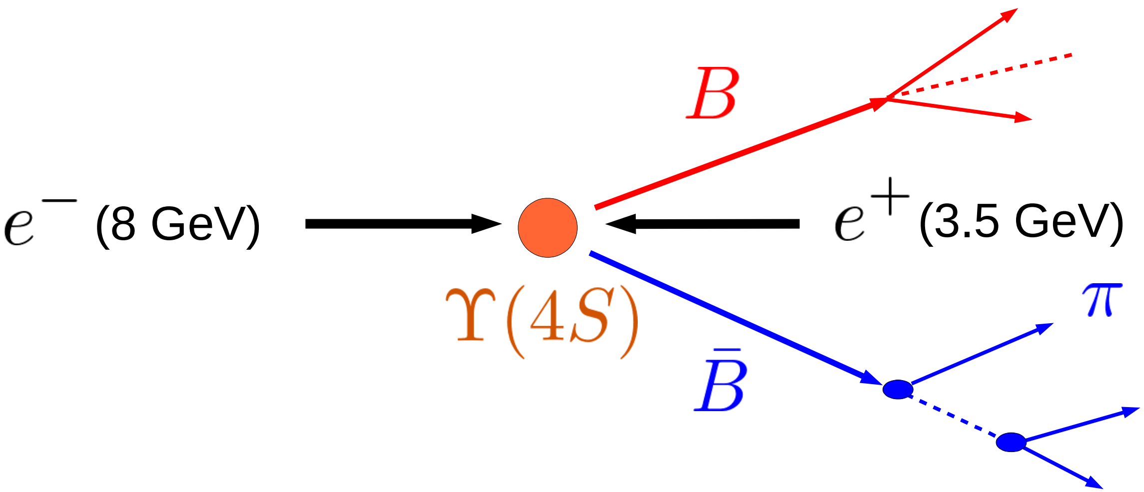

Decays of interest

$B \to \tau\nu,\ D\tau\nu$

$B \to X_u l\nu$

$B \to K\nu\nu$

$\ldots$




Full reconstruction

$B \to D\pi\ etc$

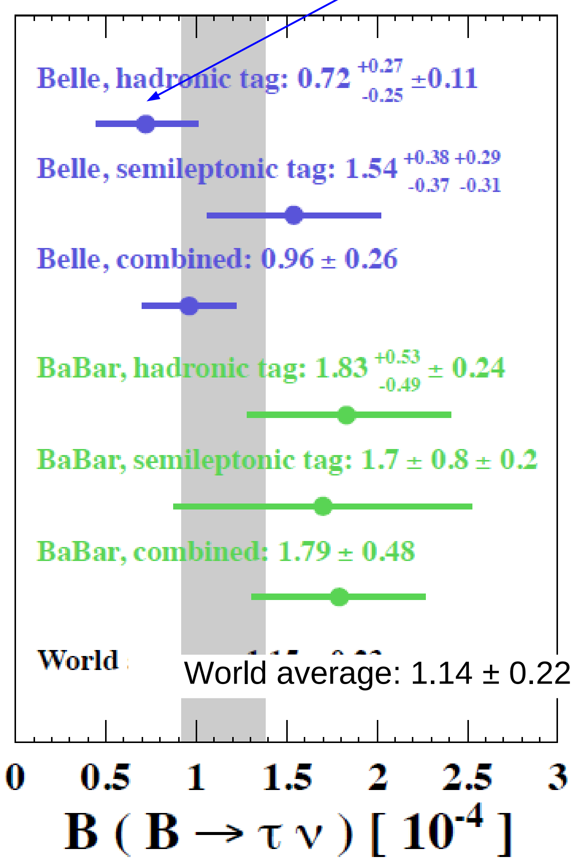
(0.1–0.3%)

Semileptonic tagging

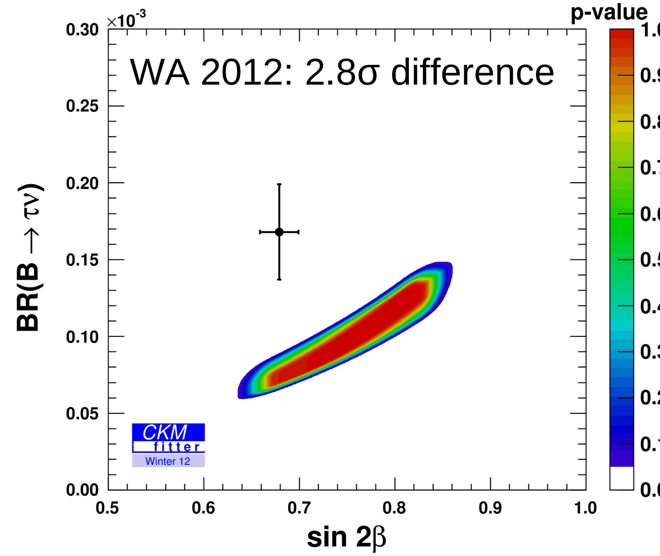
- Effective offline B meson beam

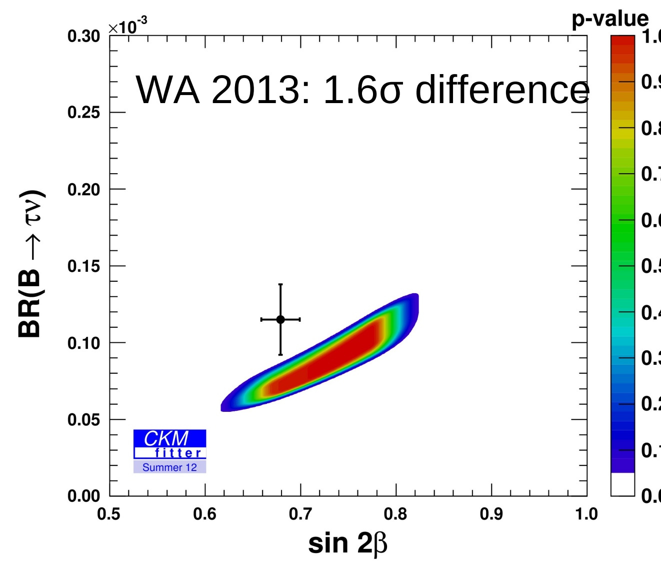
# Belle: B Decays with Tau Lepton

- $B \to \tau\nu$ using full reconstruction method with hadronic tag *PRL 110, 131801 (2013)*

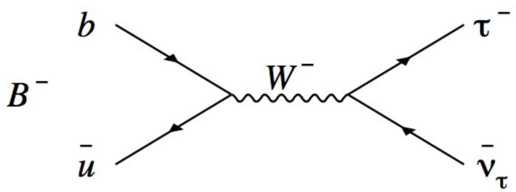


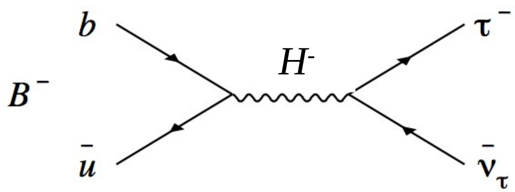

- Aim to measure $B \to \tau\nu$ at Belle II with precision of 3-5%



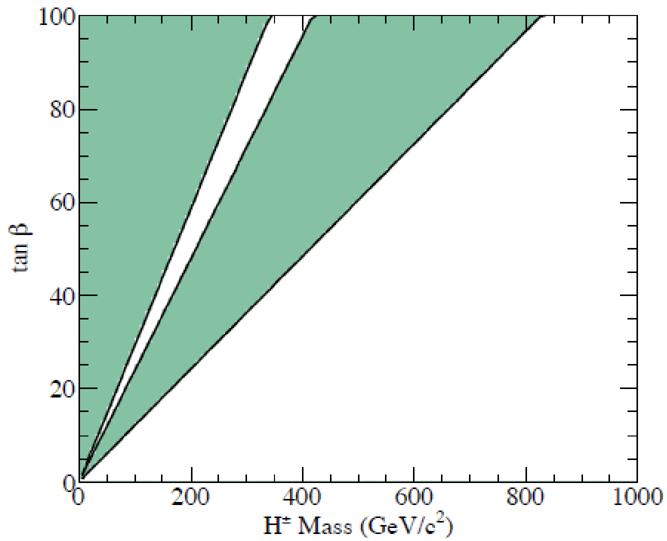
# Belle: B Decays with Tau Lepton



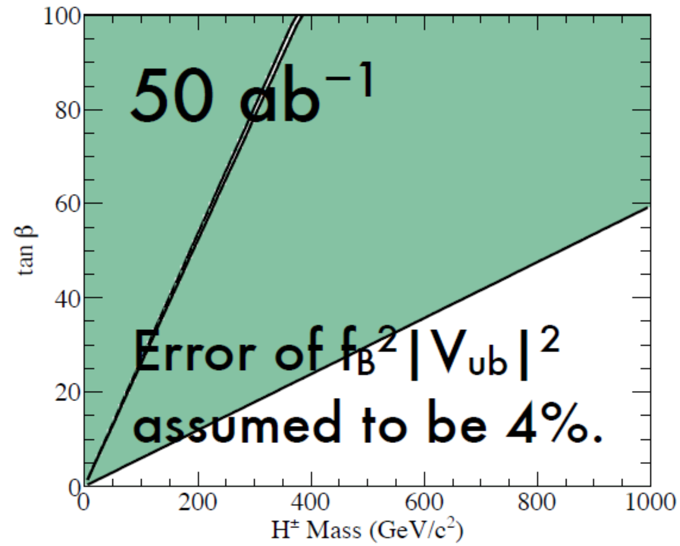




SM 2HDM(TypeII)

$$\mathcal{B} = \underbrace{\frac{G_F^2}{8\pi}\tau_B f_B^2 |V_{ub}|^2 m_B^3 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left(\frac{m_\tau}{m_B}\right)^2}_{\equiv \mathcal{B}^{SM}} \times \underbrace{\left(1 - m_B^2 \frac{\tan^2\beta}{m_{H\pm}^2}\right)^2}_{\equiv r_H}$$




B Factory exclusion plot



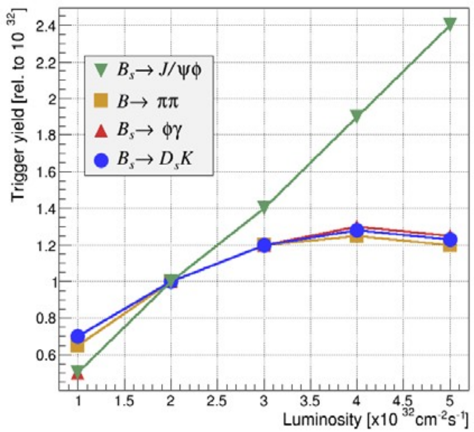

Super B Factory exclusion plot

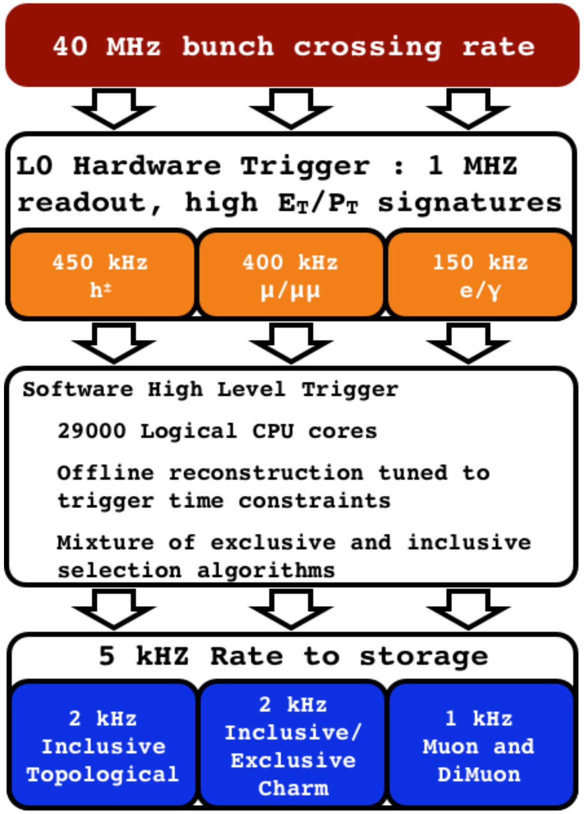
# LHCb and Belle II: Why Upgrade?

- LHC experiments and B factories collected a lot of data
- Most of the results compatible with the Standard Model
- Measured deviations from the Standard Model are small
- Many measurements still limited in statistics
- Systematic uncertainties can be reduced with more data
- Some parameters of theoretical calculations can be better constrained using high-statistics data

# LHCb Current Limitations

- Hardware trigger and DAQ
- Rate limited by bandwidth to 1.1 MHz
- Yield saturation: factor ~2 between di-muon events and fully hadronic decays

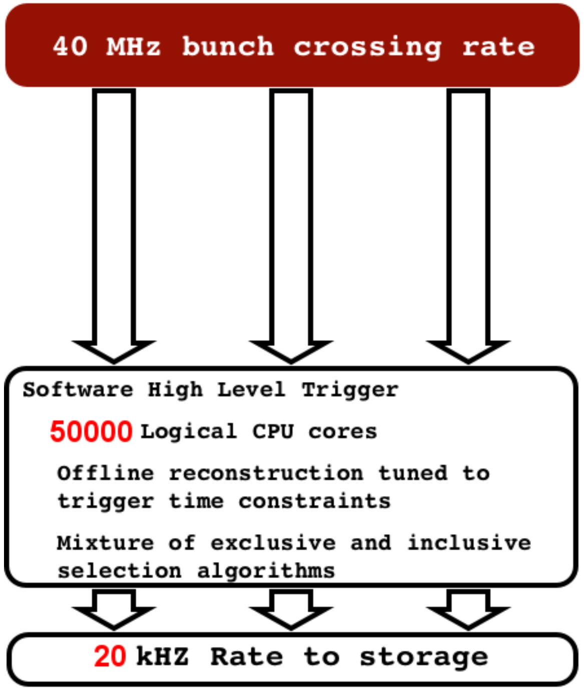


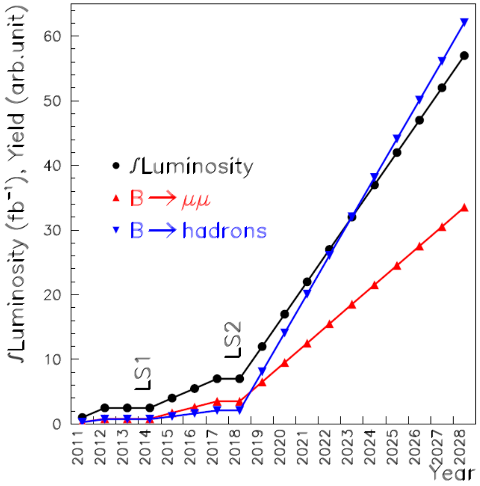




- At high luminosities
  - Harsher cuts on $p_T$ and $E_T$
  - More pile-up: reconstruction more difficult
  - Detector aging and degradation for no real gain in statistics

# LHCb Upgrade Strategy

- Efficient selection requires IP and $p_T$ of tracks
  - Remove L0
- Readout every LHC bunch crossing: 40 MHz instead of 1.1 MHz
  - Trigger-less Front-End electronics
  - Multi-Tbit/s readout network
- Fully software flexible trigger (HLT)
  - Output bandwidth ~20kHz
- Readout conditions
  - Design upgraded sub-detectors to sustain instantaneous luminosity up to $20 \times 10^{32}$ $cm^{-2}s^{-1}$ (pile up=5.2, 2622 bunches, 25 ns, 14 TeV)
- Goal: collect ≥ 50 $fb^{-1}$ over 10 years (increase of luminosity and trigger efficiency)



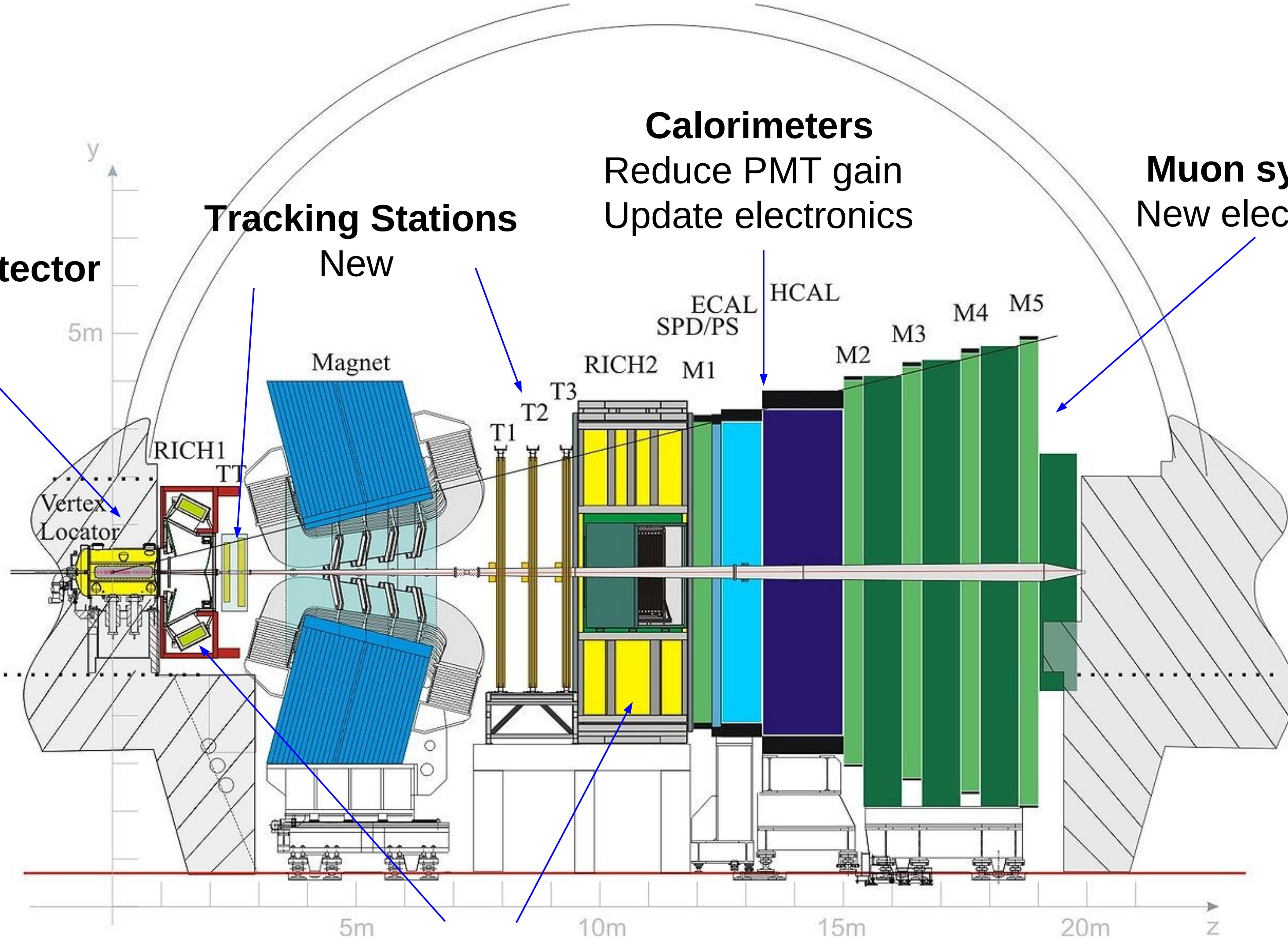
# LHCb Detector Upgrade

**Vertex Detector**
New

**Tracking Stations**
New

**Calorimeters**
Reduce PMT gain
Update electronics

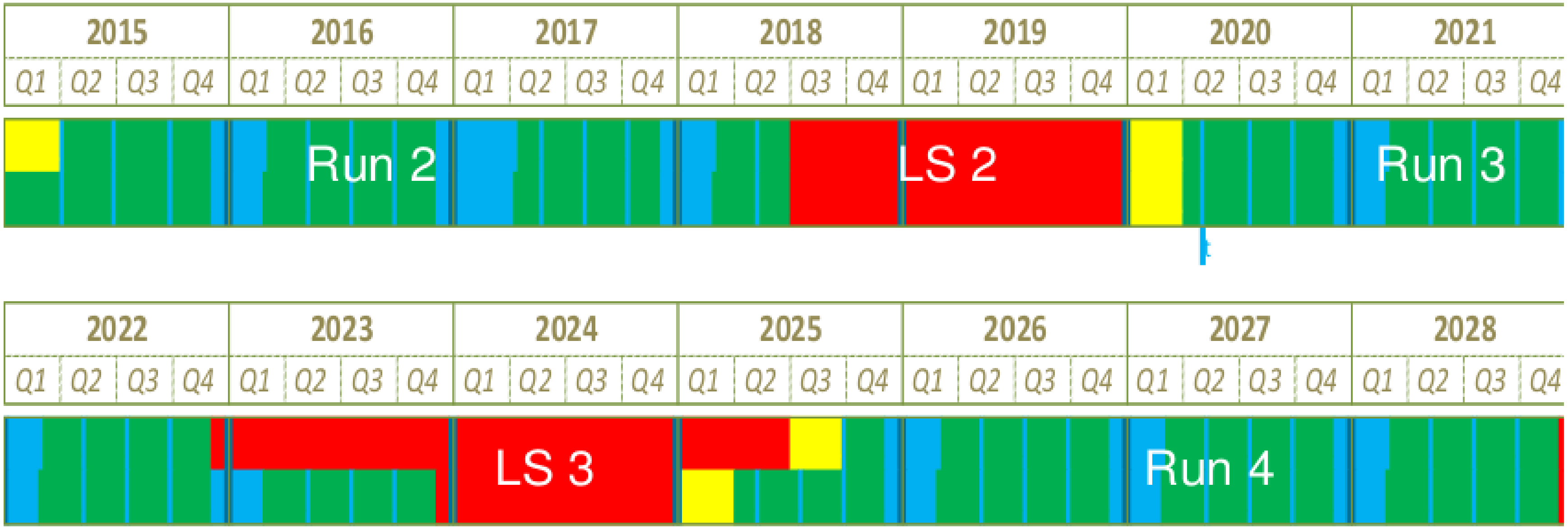
**Muon system**
New electronics



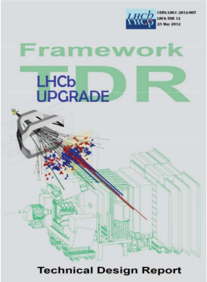

**RICH Detectors**
Replace HPDs
New electronics

Replace all readout boards
and DAQ network

# LHC Schedule After the Long Shutdown 1




- Run 2: LHCb should collect an additional 5-7 $fb^{-1}$ of data
- LS 2: upgrade of LHCb (18 months shutdown)
- Then take data: collect ≥ 50 $fb^{-1}$ within about 10 years

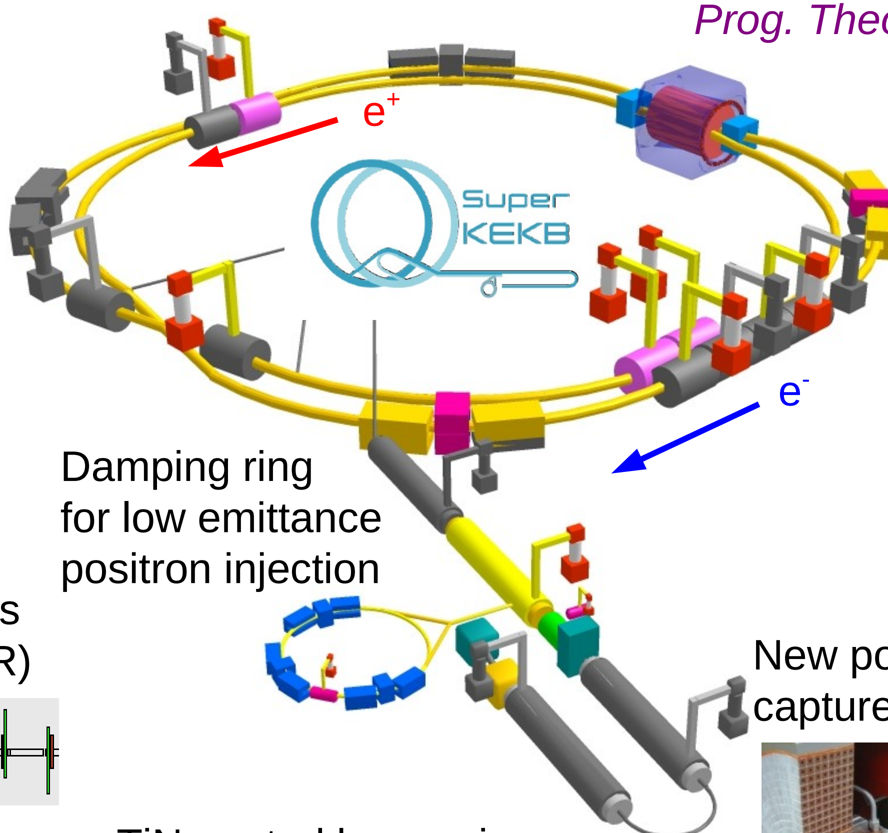




*http://cds.cern.ch/record/1333091/files/LHCC-I-018.pdf*
*http://cds.cern.ch/record/1443882/files/LHCB-TDR-012.pdf*

# SuperKEKB: Accelerator Design

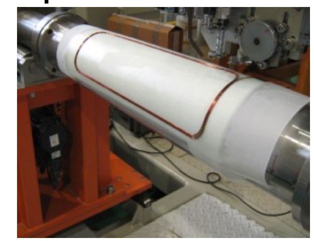
*Prog. Theor. Exp. Phys. 2013, 03A011*

Low emittance lattice

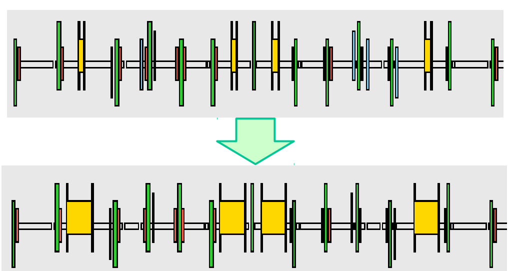



Damping ring
for low emittance
positron injection

New superconducting/
permanent final focusing
quadrupole near the IP

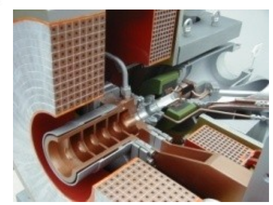


Replace short dipoles
with longer ones (LER)

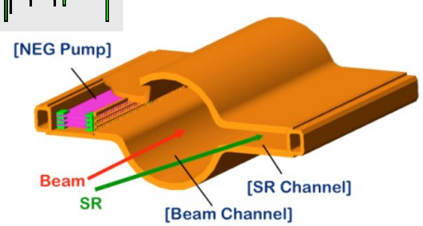


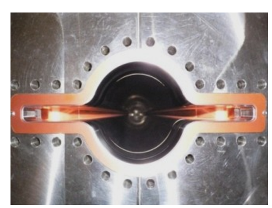
Add RF systems for
higher beam current

New positron
capture section

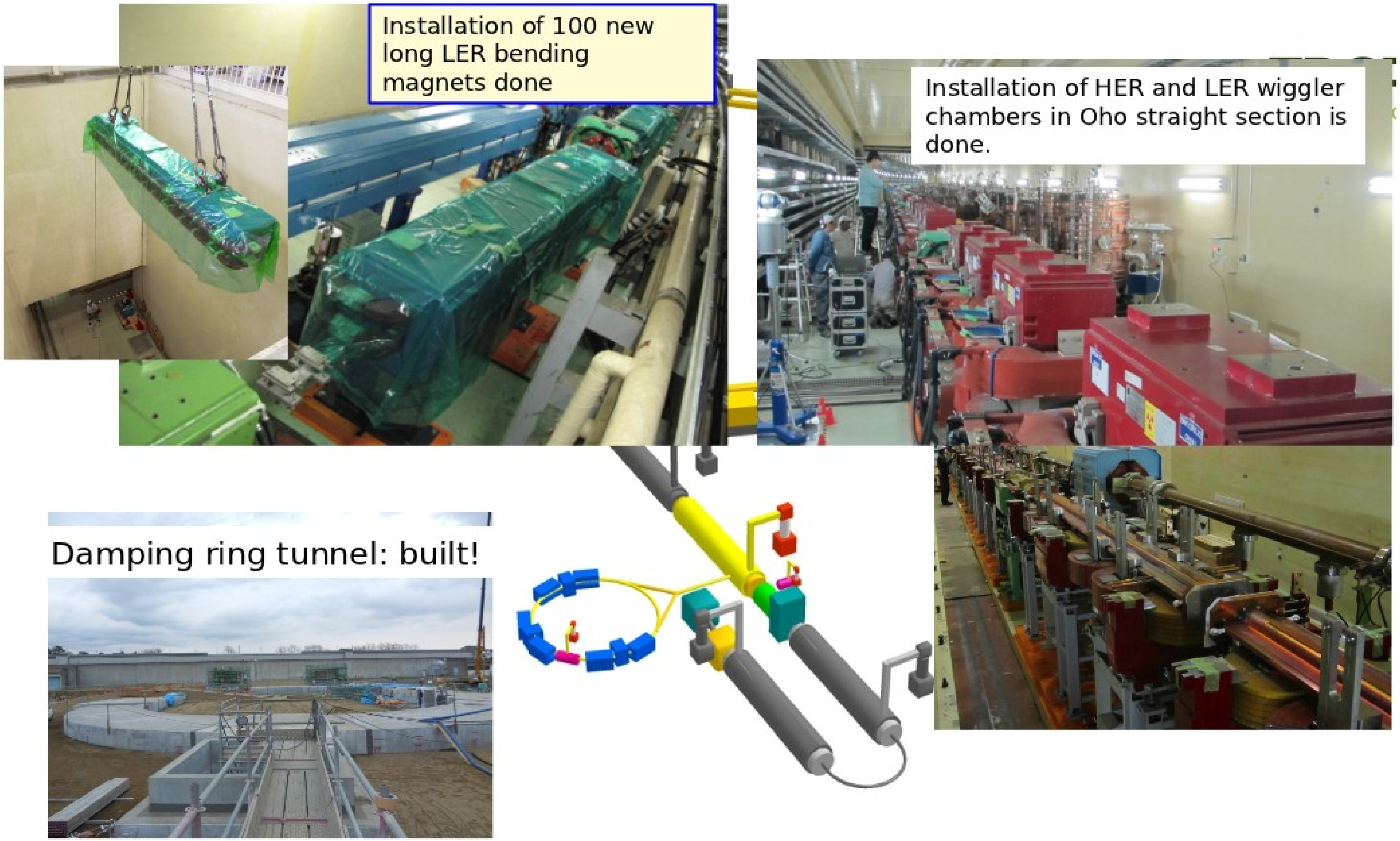


TiN-coated beam pipe
with antechambers



# SuperKEKB: Progress



# Strategy for SuperKEKB

Lorentz factor

Beam current

Beam-beam parameter

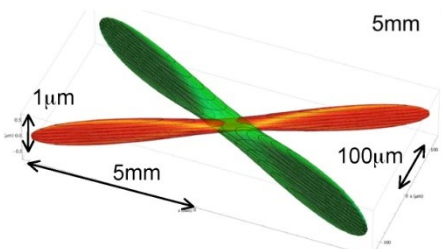
$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Geometrical reduction factors (crossing angle, hourglass effect)

Classical electron radius

Beam size ratio at IP 1-2% (flat beam)

Vertical beta function at IP




Nano-beam scheme:

*P. Raimondi for SuperB*

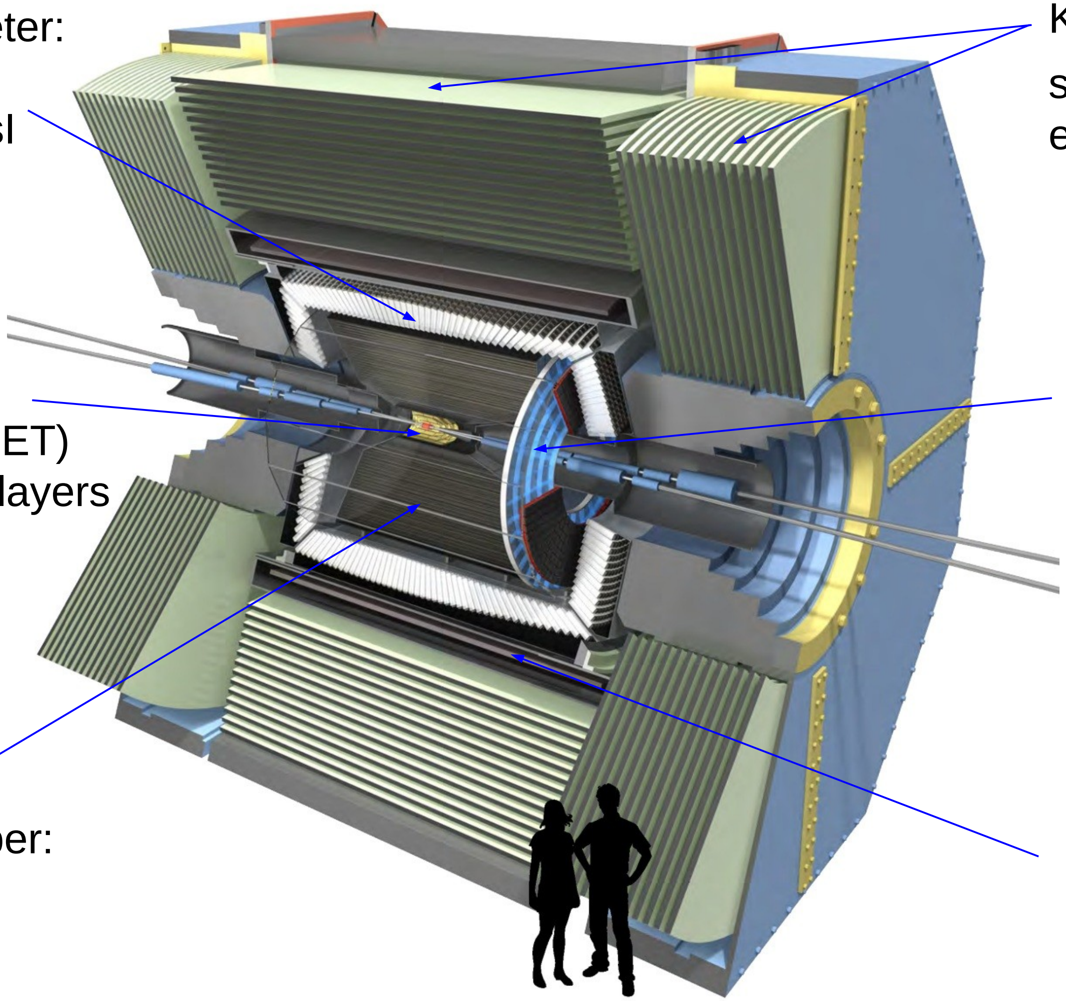
*http://www.lnf.infn.it/conference/superb06/talks/raimondi1.ppt*

| | E (GeV) LER/HER | $\beta^*_y$ (mm) LER/HER | $\beta^*_x$ (cm) LER/HER | φ (mrad) | I (A) LER/HER | L ($cm^{-2}s^{-1}$) |
|---|---|---|---|---|---|---|
| KEKB | 3.5/8.0 | 5.9/5.9 | 120/120 | 11 | 1.6/1.2 | $2.1 \times 10^{34}$ |
| SuperKEKB | 4.0/7.0 | 0.27/0.30 | 3.2/2.5 | 41.5 | 3.6/2.6 | $80 \times 10^{34}$ |

# Belle II Detector

CsI(Tl) EM calorimeter:
waveform sampling
electronics, pure CsI
for endcaps

$K_L$ and muon counter:
scintillator + Si-PM for
endcaps



Vertex detector:
2 pixel layers (DEPFET)
4 double-sided strip layers

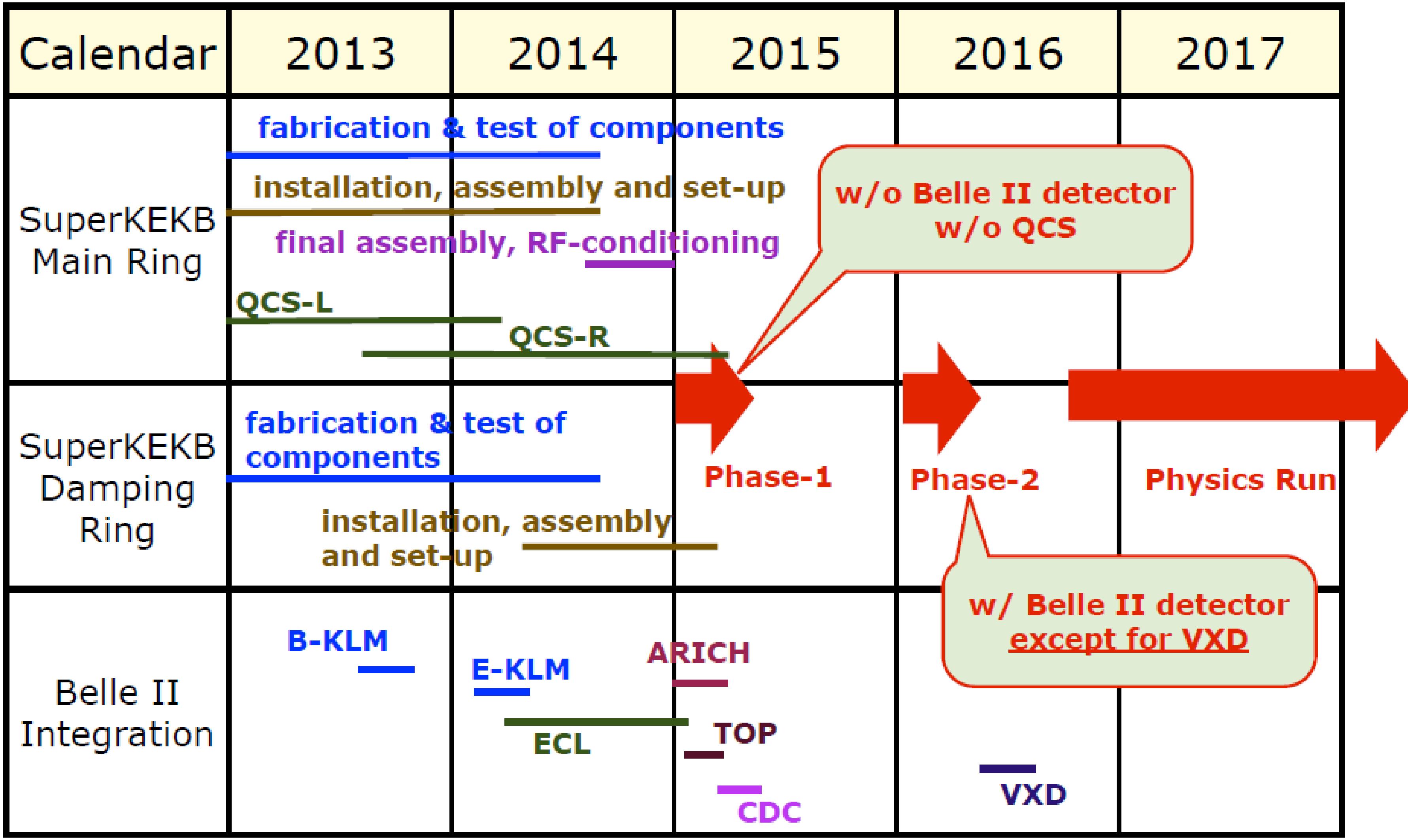
Aerogel RICH
(forward)

Central drift chamber:
longer lever arm
smaller cell size

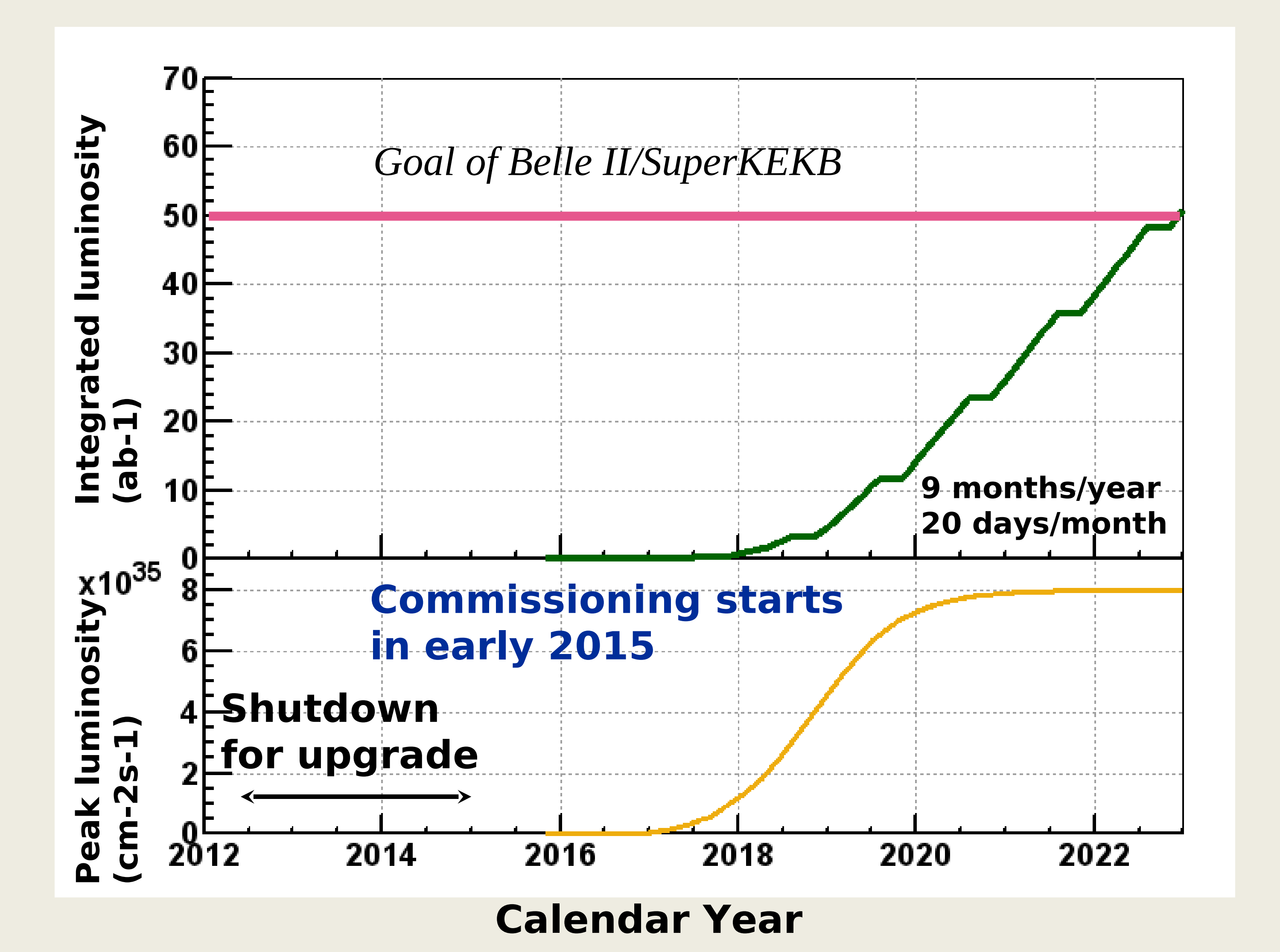
Time-of-propagation
(barrel)

Details in TDR *arXiv:1011.0352*

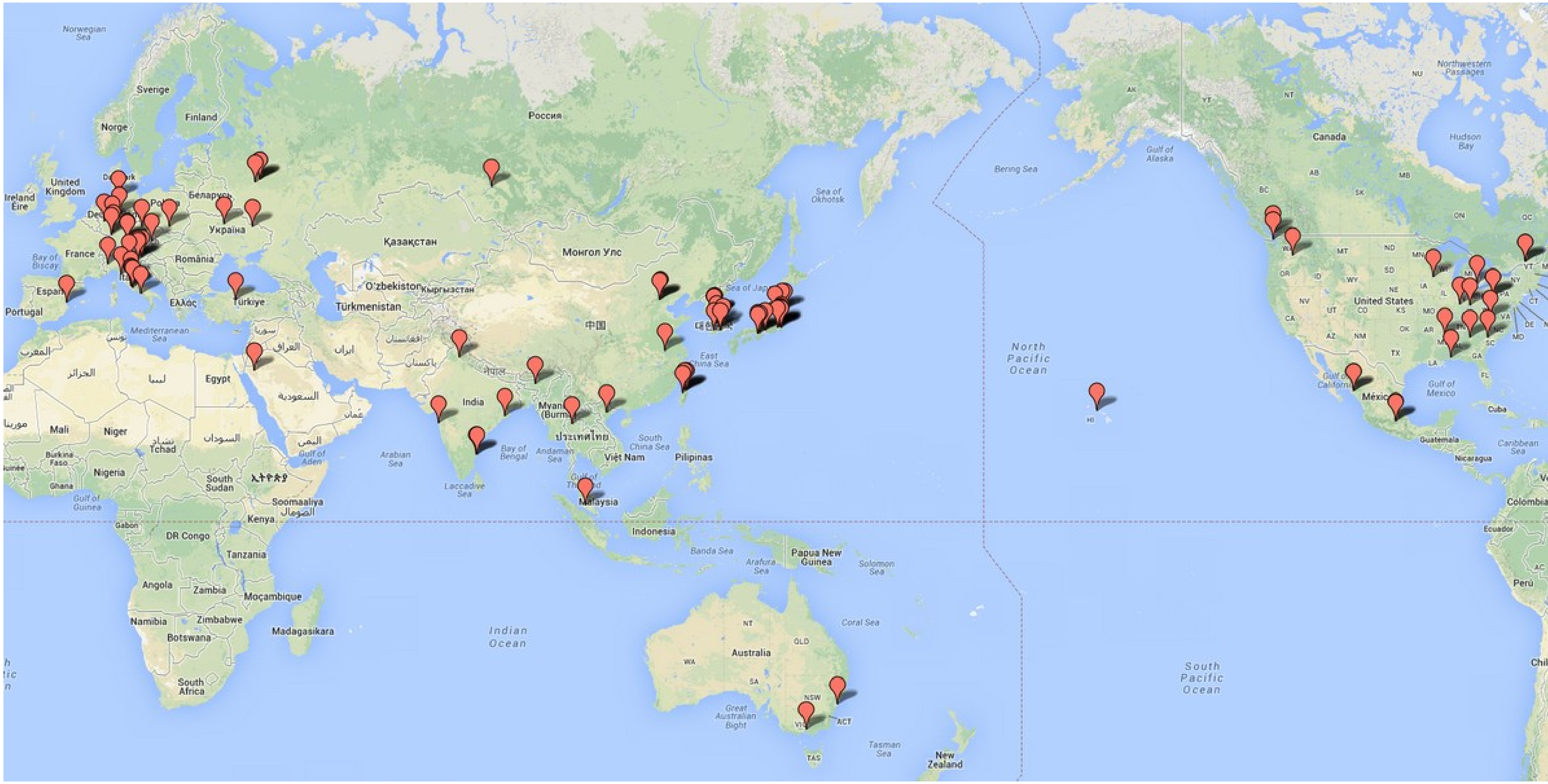
# SuperKEKB and Belle II Schedule



# Goal and Timelines of SuperKEKB / Belle II



# Belle II Collaboration



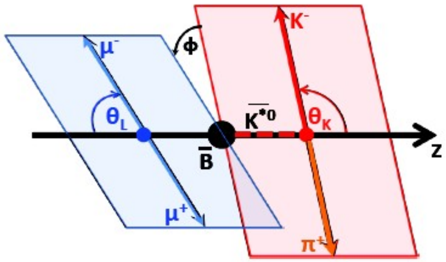

23 countries, 97 institutions, ~600 collaborators

# Summary

- During next decades Belle II at SuperKEKB and LHCb will collect high-statistics data on Heavy Flavor
- Complementary to direct searches for New Physics at LHC
- Experimental sensitivity will be comparable to or better than current theoretical uncertainties
- Essential progress of theoretical developments during last years was crucial to understand current experimental results
- Further theoretical developments are very important to fully benefit from future measurements

# Backup Slides

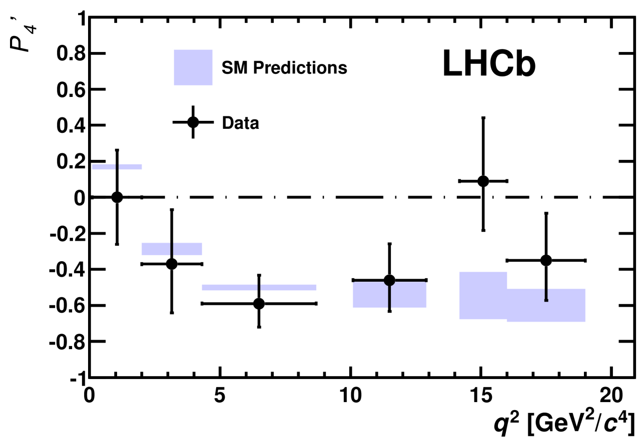
# More Observables in $B \to K^{(*)}\mu^+\mu^-$ from LHCb

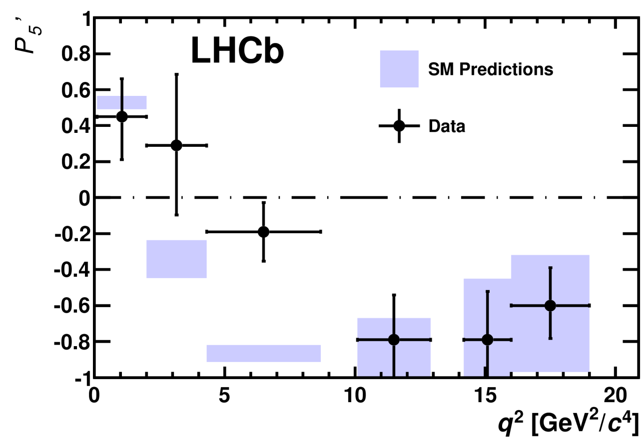



$$
\begin{aligned}
d\Gamma \sim\ & \frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l \\
& - F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\
& + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi \\
& + S_6\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi \\
& + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi
\end{aligned}
$$

- Observables with reduced theoretical uncertainty from hadronic form factors (*Descotes-Genon, Matias, Virto, JHEP 05 (2013) 137*)

$$P_i' = S_i/\sqrt{F_L(1-F_L)}$$



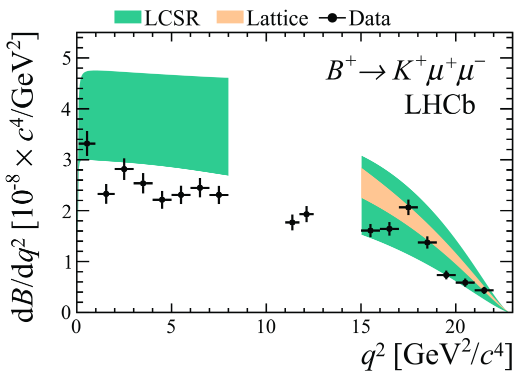



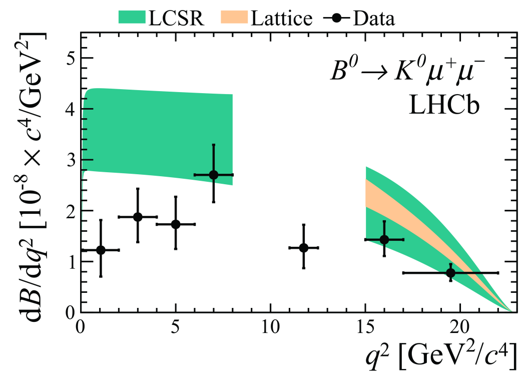

*Phys. Rev. Lett.* ***111***, *191801 (2013)*, $1\text{fb}^{-1}$

- 3.7 sigma discrepancy between the measurement and SM predictions
- 2.8 sigma significance considering 24 independent measurement

# $B \rightarrow K^{(*)}\mu^+\mu^-$ from LHCb (3 $fb^{-1}$)

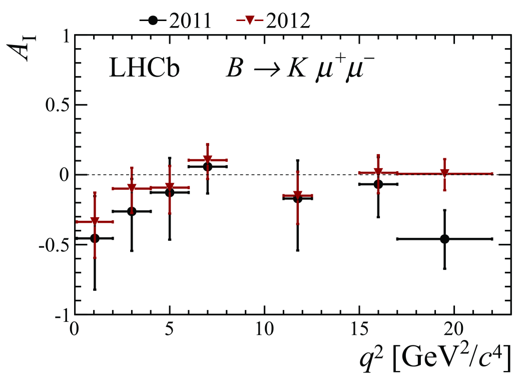
- $B^+ \rightarrow K^+\mu^+\mu^-$ and $B^0 \rightarrow K^0\mu^+\mu^-$ decays also consistent with SM but slightly below the theoretical predictions

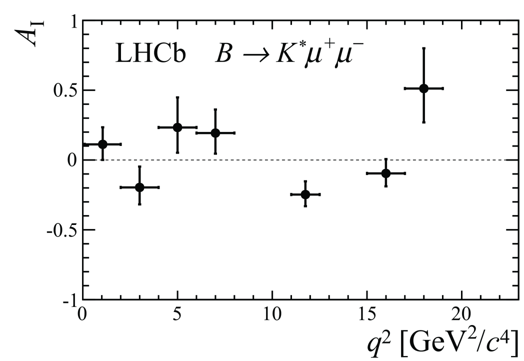



*arXiv:1403.8044*

- Analysis of 1 $fb^{-1}$ data from 2011:
  - $A_I$ consistent with zero for $K^*$ modes and 4.4σ below zero for $K$ modes
- Recent $A_I$ results based on 3 $fb^{-1}$ consistent with the SM

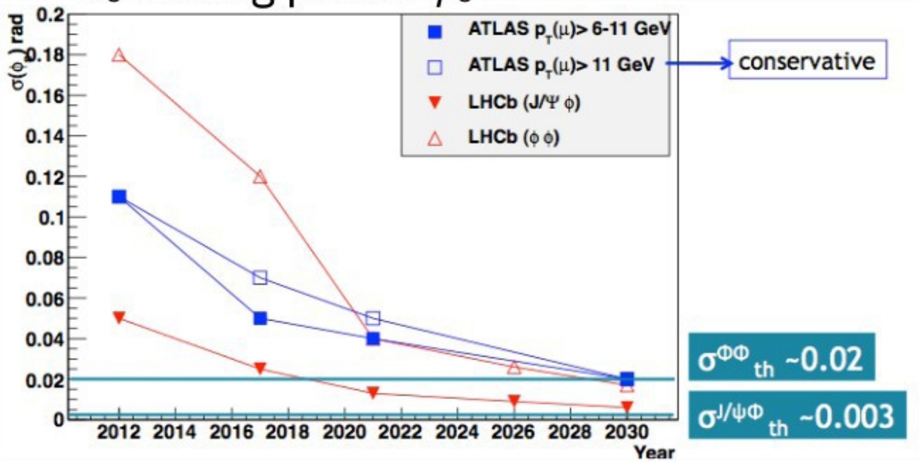


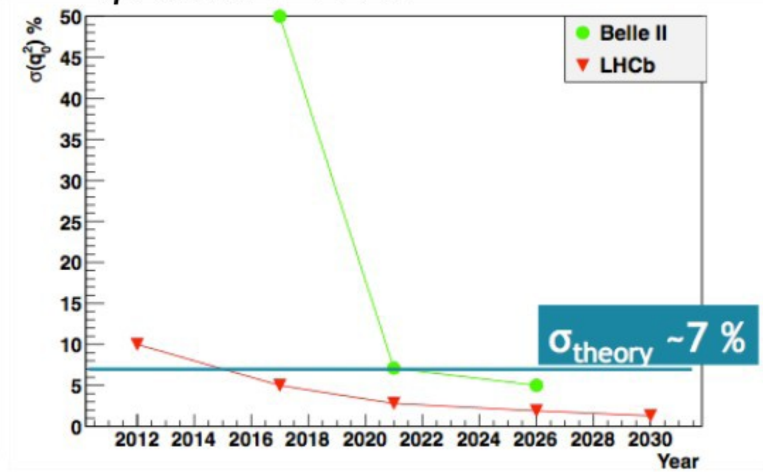

*arXiv:1403.8044*

# Prospects of LHCb, Belle II and Other Experiment

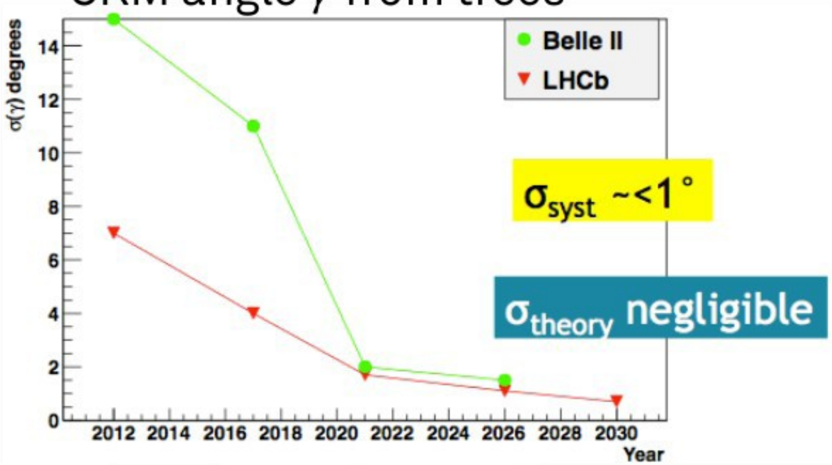
### $B_s$ mixing phase $\phi_s$



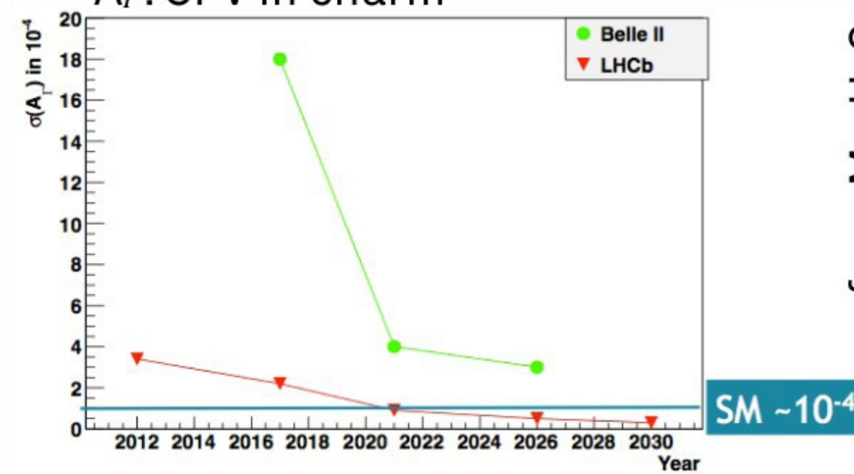

### $q_0$ from $B \to K^* ll$




### CKM angle $\gamma$ from trees

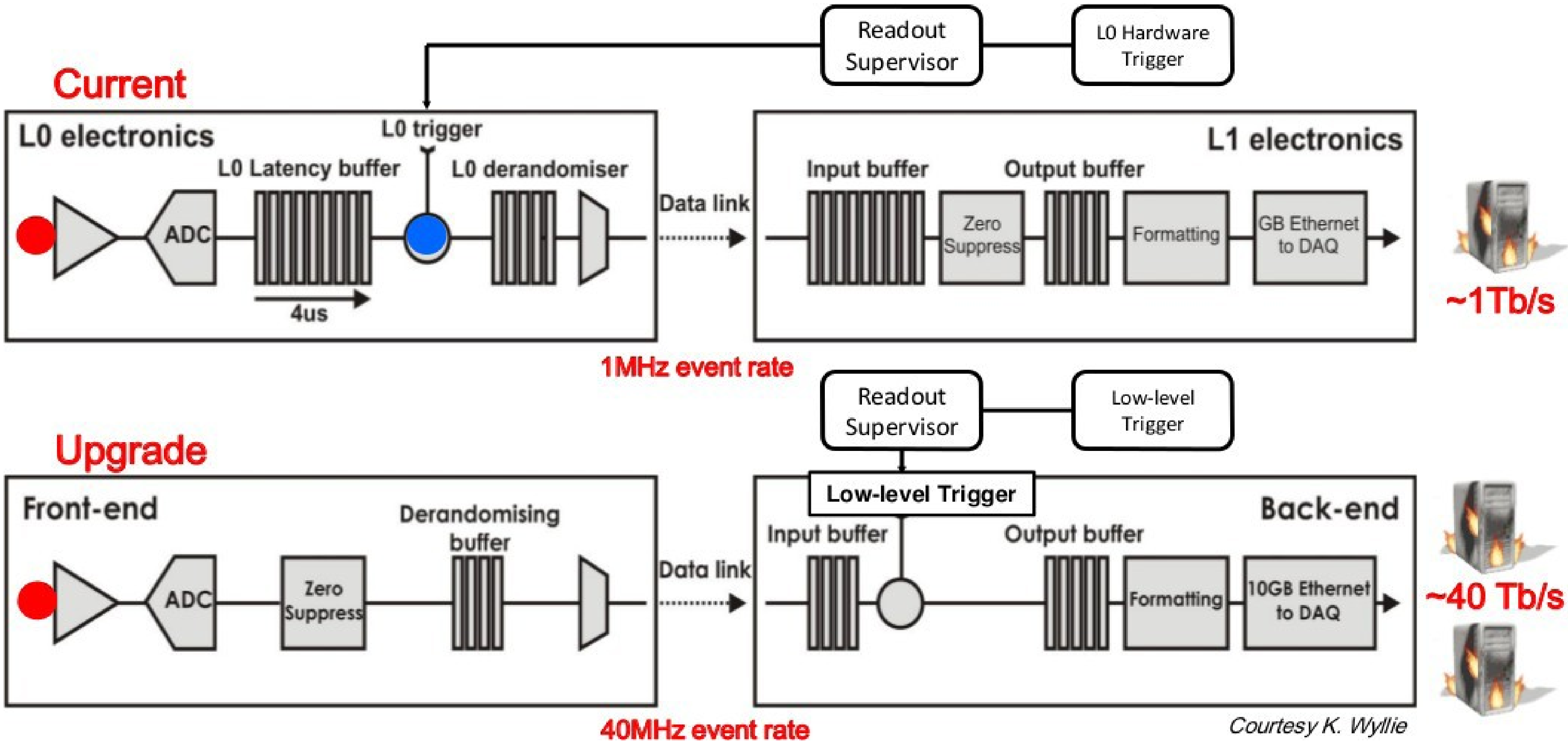



### $A_\Gamma$: CPV in charm




from M. -H. Schune @ECFA HL-LHC 2013

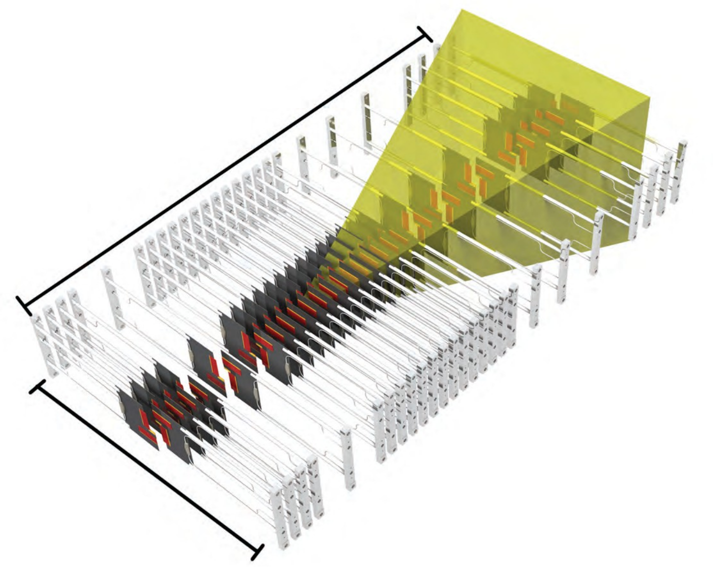
# LHCb Upgraded Readout Architecture

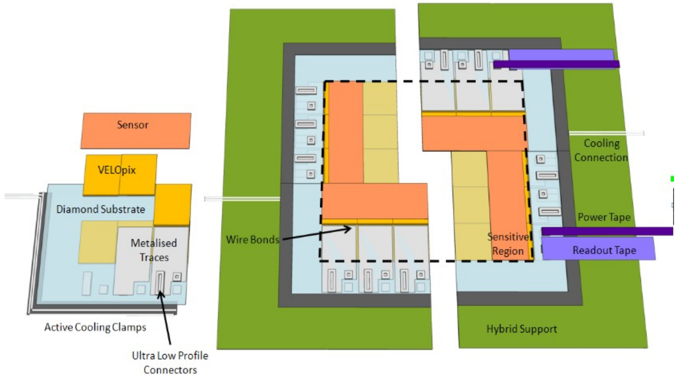


# LHCb Vertex Detector Upgrade

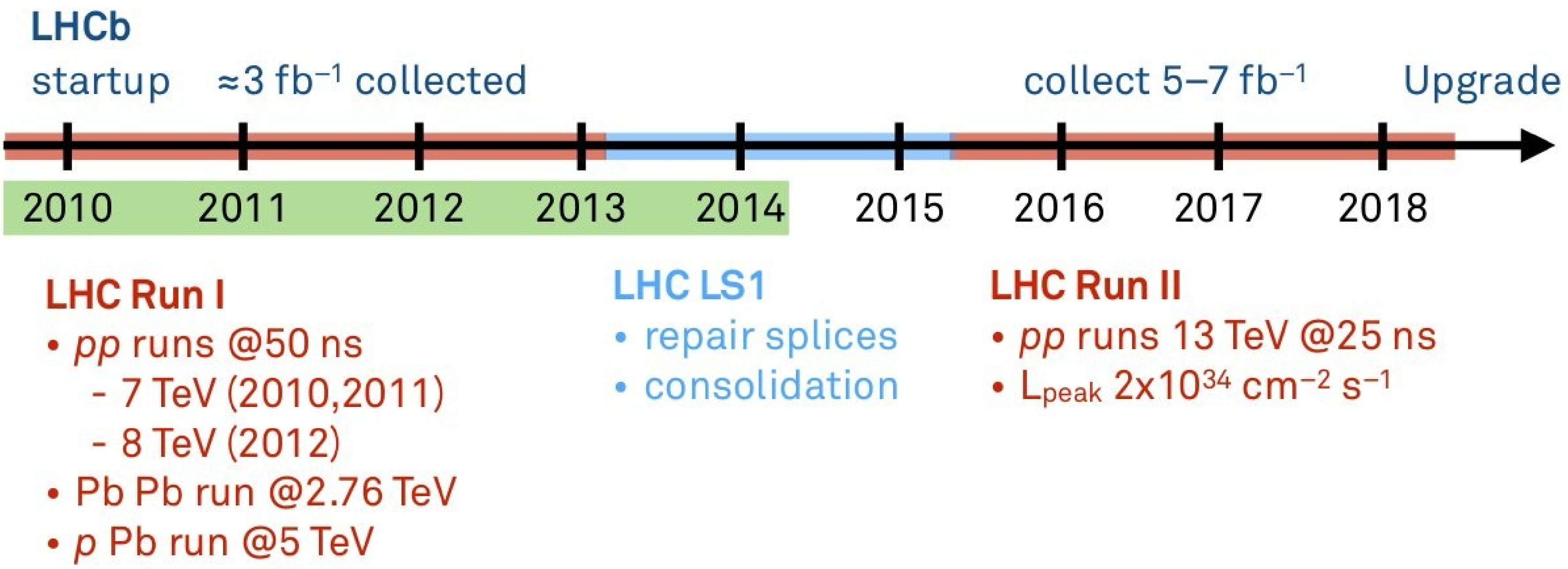
> Perform equal or better in harsher conditions
  - Cope with radiation damage and occupancies
  - Low material budget
  - Fast and efficient reconstruction at hardware level

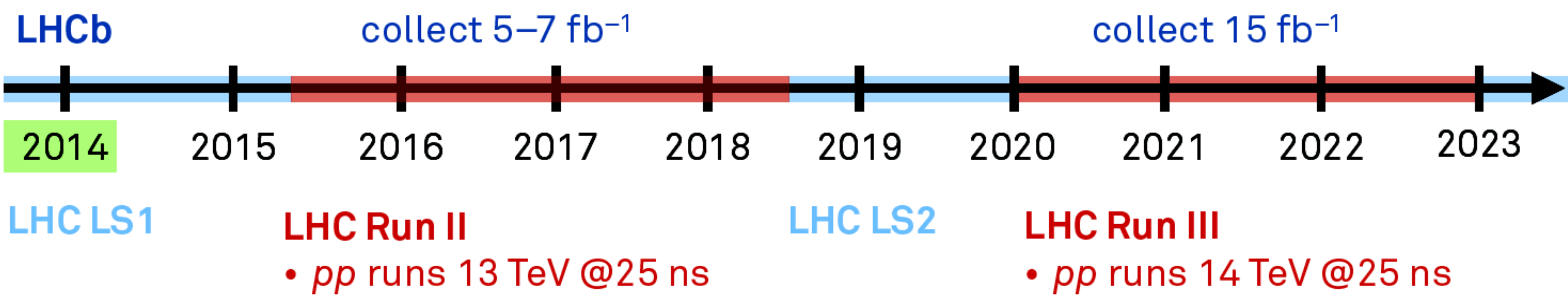
> Choice
  - Silicon-pixel detector
  - Micro-channel cooling (<-20°C)
  - Closer to the beam (3.5 mm)





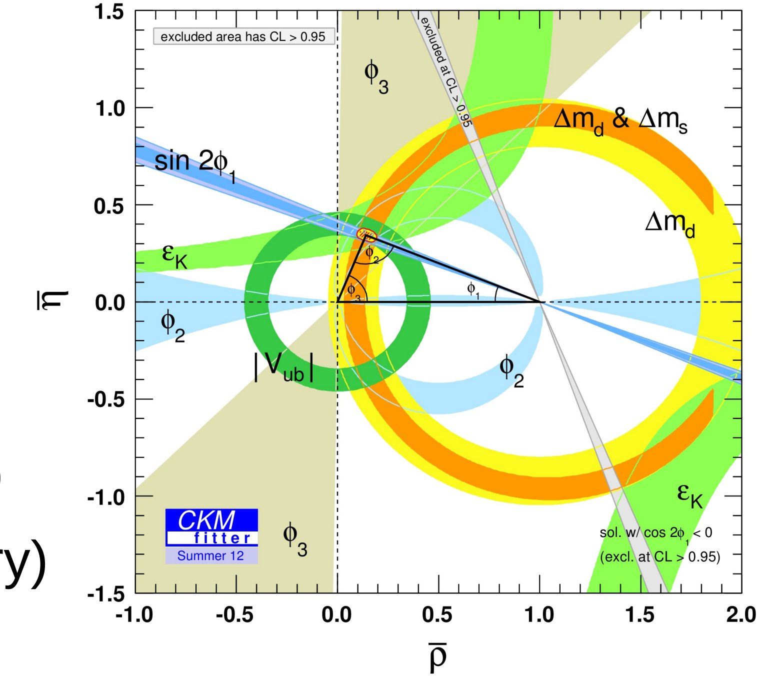
# LHCb Upgrade Plan



# Achievements of $e^+e^-$ B Factories

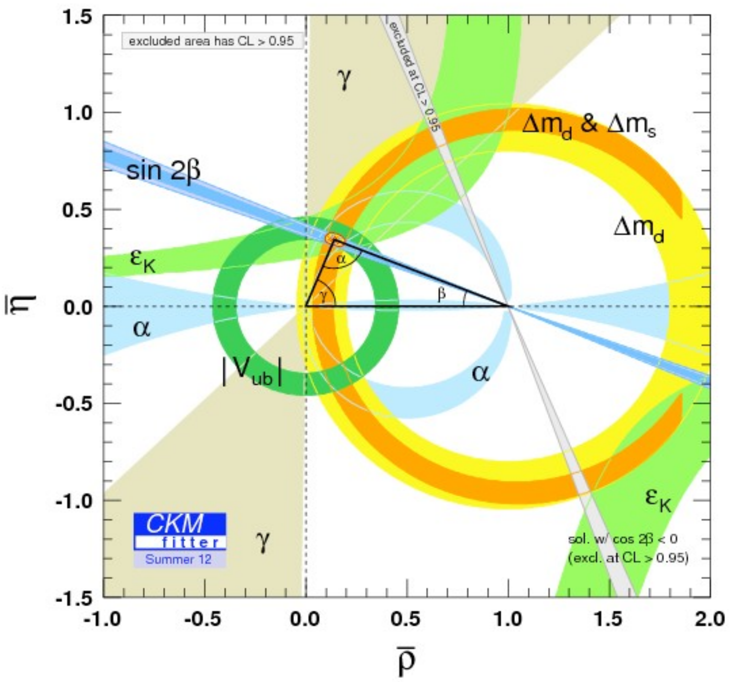
- $e^+e^-$ B Factories: Belle at KEKB and BaBar at PEP-II
- Successful confirmation of Kobayashi-Maskawa mechanism of CP violation in the Standard Model
  - Nobel Prize for Kobayashi and Maskawa in 2008
- Precise measurements of CKM elements and angles of UT
- Much more
  - Measurements of rare B-decay modes
  - b → s transitions: new sources of CPV
  - Observation of D mixing (charm factory)
  - Searches for LFV tau decays (tau factory)
  - Observation of exotic hadrons



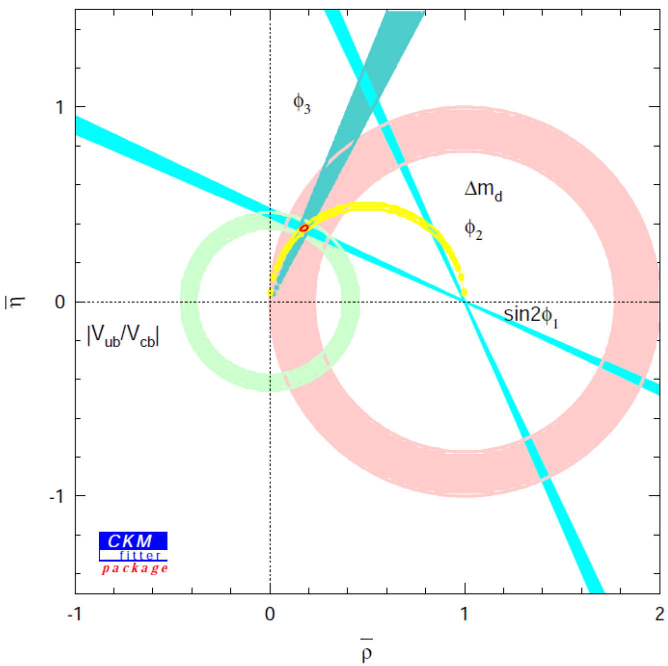
# Precision Tests of CKM

- Much more improved measurements
- Overconstrain Unitarity Triangle
- Discrepancy between measurements → new physics?

2012 (~1000 $fb^{-1}$ at Belle and BaBar)

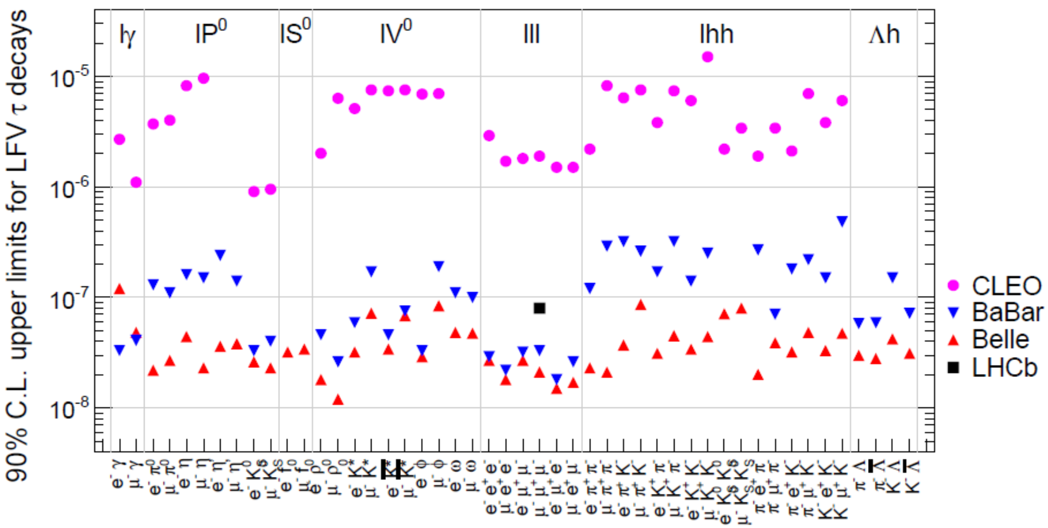



Expected constraint at 50 $ab^{-1}$

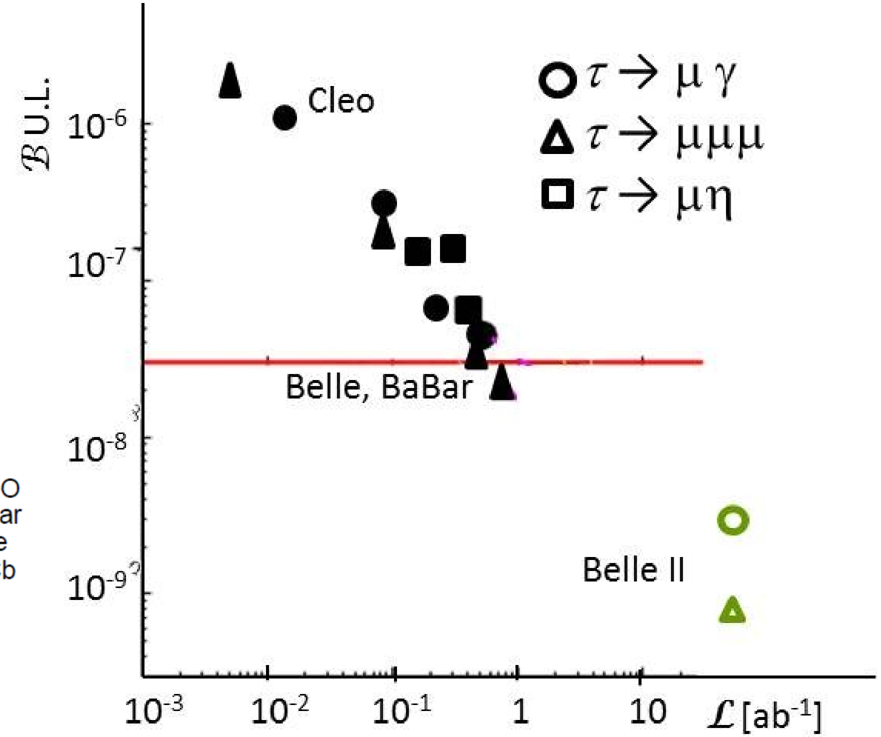


# Search for New Physics: LFV in Tau Decays

- Strongly suppressed in SM
  Br ~ $10^{-53}$-$10^{-49}$
- In New Physics models LFV up to $O(10^{-9}$-$10^{-7})$
- Current limits from B factories




- With 50ab$^{-1}$ sensitivity will reach $O(10^{-9})$



# Broad Physics Program at Belle II

| Observable | SM prediction | Theory error | Present result | Future error | Future Facility |
|---|---|---|---|---|---|
| $\lvert V_{us}\rvert$ $[K \to \pi \ell \nu]$ | input | $0.5\% \to 0.1\%_{\rm Latt}$ | $0.2246 \pm 0.0012$ | 0.1% | $K$ factory |
| $\lvert V_{cb}\rvert$ $[B \to X_c \ell \nu]$ | input | 1% | $(41.54 \pm 0.73) \times 10^{-3}$ | 1% | Super-$B$ |
| $\lvert V_{ub}\rvert$ $[B \to \pi \ell \nu]$ | input | $10\% \to 5\%_{\rm Latt}$ | $(3.38 \pm 0.36) \times 10^{-3}$ | 4% | Super-$B$ |
| $\gamma$ $[B \to DK]$ | input | $< 1^\circ$ | $(70^{+27}_{-30})^\circ$ | $3^\circ$ | LHCb |
| $S_{B_d \to \psi K}$ | $\sin(2\beta)$ | $\lesssim 0.01$ | $0.671 \pm 0.023$ | 0.01 | LHCb |
| $S_{B_s \to \psi \phi}$ | 0.036 | $\lesssim 0.01$ | $0.81^{+0.12}_{-0.32}$ | 0.01 | LHCb |
| $S_{B_d \to \phi K}$ | $\sin(2\beta)$ | $\lesssim 0.05$ | $0.44 \pm 0.18$ | 0.1 | LHCb |
| $S_{B_s \to \phi\phi}$ | 0.036 | $\lesssim 0.05$ | — | 0.05 | LHCb |
| $S_{B_d \to K^* \gamma}$ | few $\times$ 0.01 | 0.01 | $-0.16 \pm 0.22$ | 0.03 | Super-$B$ |
| $S_{B_s \to \phi \gamma}$ | few $\times$ 0.01 | 0.01 | — | 0.05 | LHCb |
| $A^d_{\rm SL}$ | $-5 \times 10^{-4}$ | $10^{-4}$ | $-(5.8 \pm 3.4) \times 10^{-3}$ | $10^{-3}$ | LHCb |
| $A^s_{\rm SL}$ | $2 \times 10^{-5}$ | $< 10^{-5}$ | $(1.6 \pm 8.5) \times 10^{-3}$ | $10^{-3}$ | LHCb |
| $A_{CP}(b \to s\gamma)$ | $< 0.01$ | $< 0.01$ | $-0.012 \pm 0.028$ | 0.005 | Super-$B$ |
| $\mathcal{B}(B \to \tau\nu)$ | $1 \times 10^{-4}$ | $20\% \to 5\%_{\rm Latt}$ | $(1.73 \pm 0.35) \times 10^{-4}$ | 5% | Super-$B$ |
| $\mathcal{B}(B \to \mu\nu)$ | $4 \times 10^{-7}$ | $20\% \to 5\%_{\rm Latt}$ | $< 1.3 \times 10^{-6}$ | 6% | Super-$B$ |
| $\mathcal{B}(B_s \to \mu^+\mu^-)$ | $3 \times 10^{-9}$ | $20\% \to 5\%_{\rm Latt}$ | $< 5 \times 10^{-8}$ | 10% | LHCb |
| $\mathcal{B}(B_d \to \mu^+\mu^-)$ | $1 \times 10^{-10}$ | $20\% \to 5\%_{\rm Latt}$ | $< 1.5 \times 10^{-8}$ | [?] | LHCb |
| $A_{\rm FB}(B \to K^* \mu^+\mu^-)_{q_0^2}$ | 0 | 0.05 | $(0.2 \pm 0.2)$ | 0.05 | LHCb |
| $B \to K \nu \bar\nu$ | $4 \times 10^{-6}$ | $20\% \to 10\%_{\rm Latt}$ | $< 1.4 \times 10^{-5}$ | 20% | Super-$B$ |
| $\lvert q/p\rvert_{D-\rm mixing}$ | 1 | $< 10^{-3}$ | $(0.86^{+0.18}_{-0.15})$ | 0.03 | Super-$B$ |
| $\phi_D$ | 0 | $< 10^{-3}$ | $(9.6^{+8.3}_{-9.5})^\circ$ | $2^\circ$ | Super-$B$ |
| $\mathcal{B}(K^+ \to \pi^+ \nu\bar\nu)$ | $8.5 \times 10^{-11}$ | 8% | $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ | 10% | $K$ factory |
| $\mathcal{B}(K_L \to \pi^0 \nu\bar\nu)$ | $2.6 \times 10^{-11}$ | 10% | $< 2.6 \times 10^{-8}$ | [?] | $K$ factory |
| $R^{(e/\mu)}(K \to \pi \ell \nu)$ | $2.477 \times 10^{-5}$ | 0.04% | $(2.498 \pm 0.014) \times 10^{-5}$ | 0.1% | $K$ factory |
| $\mathcal{B}(t \to c\, Z, \gamma)$ | $\mathcal{O}(10^{-13})$ | $\mathcal{O}(10^{-13})$ | $< 0.6 \times 10^{-2}$ | $\mathcal{O}(10^{-5})$ | LHC (100 fb$^{-1}$) |

| | | |
|---|---|---|
| $B(B \to Xs\gamma)$ | 6% | Super-B |
| $B(B \to Xd\gamma)$ | 20% | Super-B |
| $S(B \to \rho\gamma)$ | 0.15 | Super-B |
| $B(\tau \to \mu\gamma)$ | $3 \cdot 10^{-9}$ | Super-B (90% U.L.) |
| $B(B+ \to D\tau\nu)$ | 3% | Super-B |
| $B(Bs \to \gamma\gamma)$ | $0.25 \cdot 10^{-6}$ | Super-B (5 ab-1) |
| $\sin 2\theta W$ @ $Y(4S)$ | $3 \cdot 10^{-4}$ | Super-B |

- Physics at Super B factory:
  *arXiv:1002.5012*
  *arXiv:1008.1541*
- Belle II and LHCb will provide complementary information

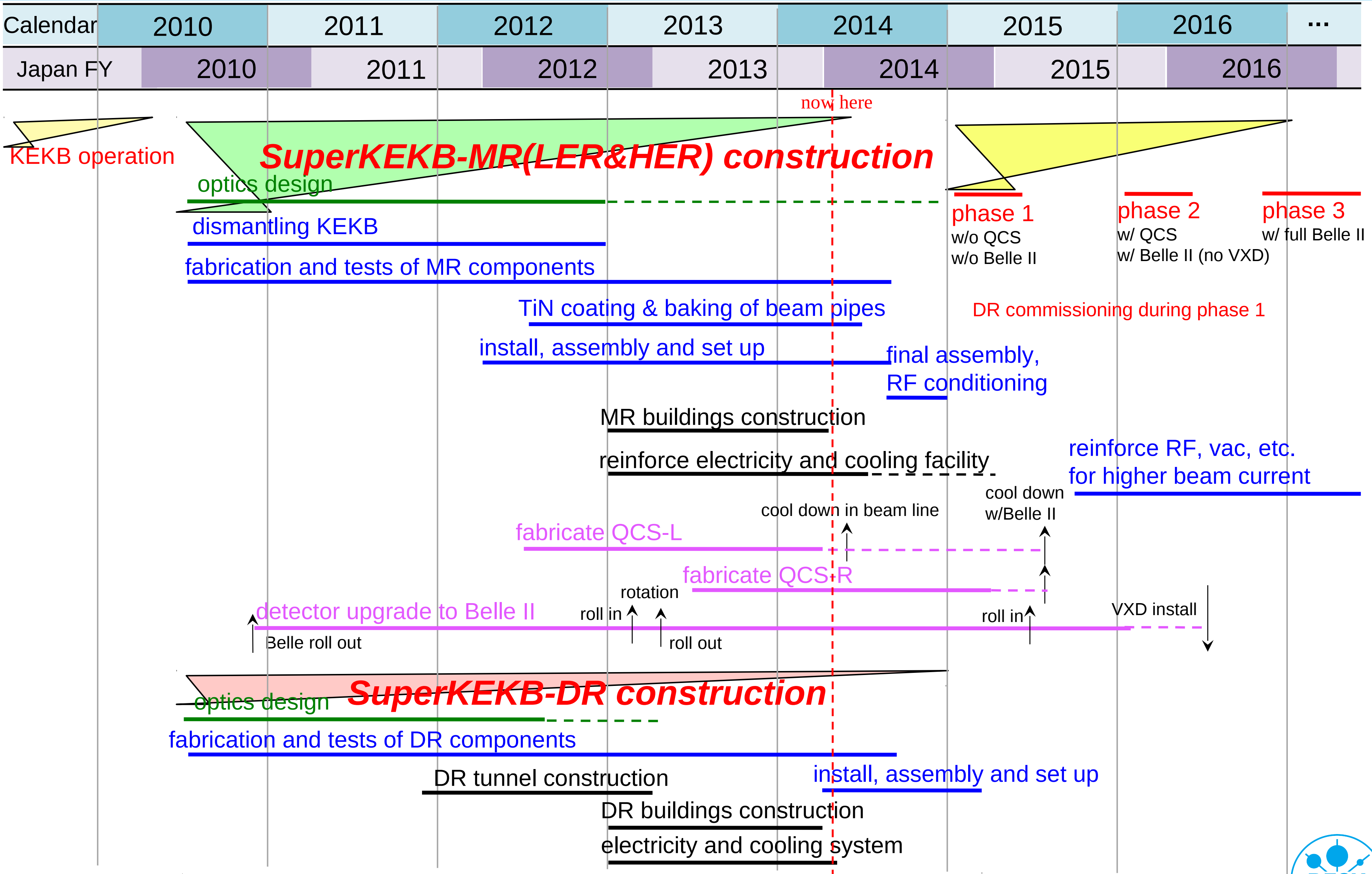
Adopted from *G. Isidori et al., Ann.Rev.Nucl.Part.Sci. 60, 355 (2010)*

Super B factory

LHCb

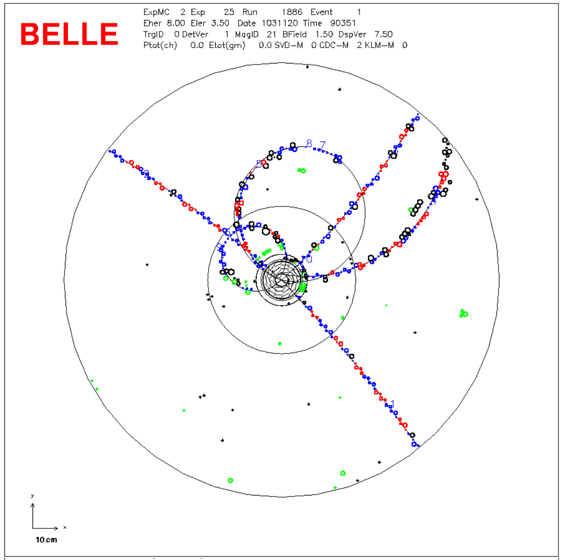
K experiments

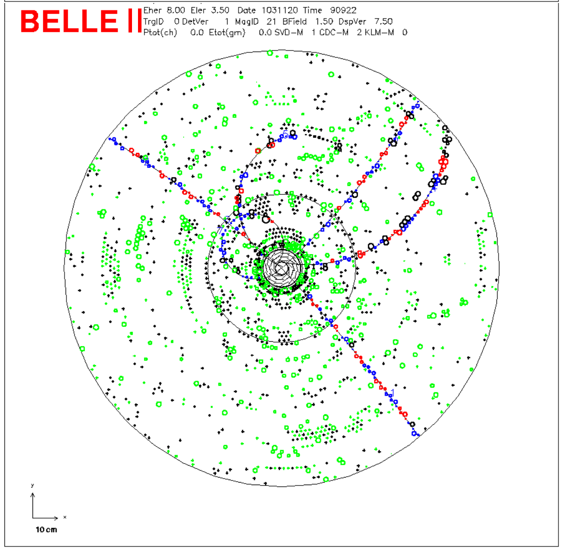
# SuperKEKB Schedule



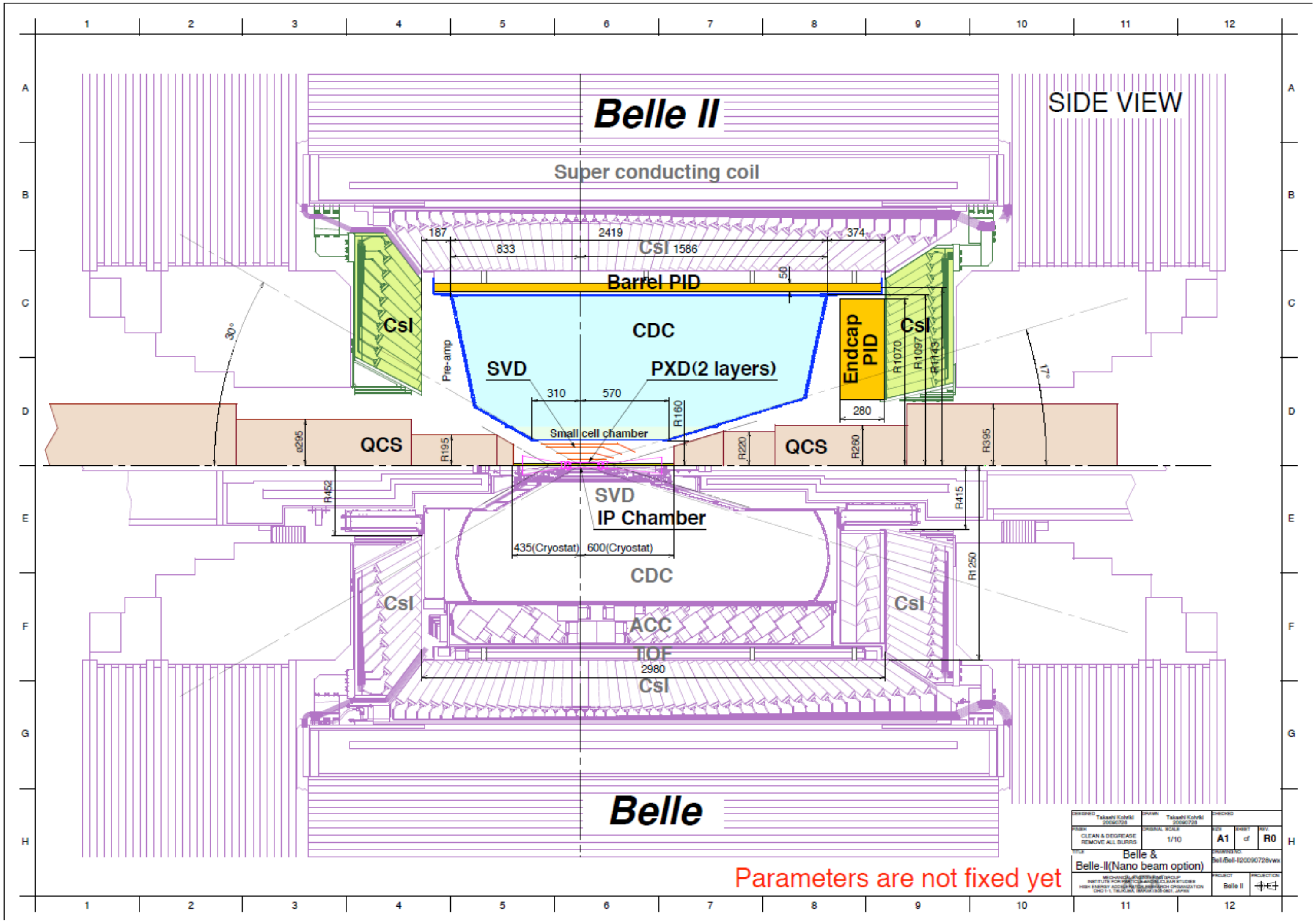
# Experimental Challenges at High Luminosity

- High background (10-20 times higher than at Belle)
  - Fake hits, pile up, radiation damage
- Higher trigger rate
  - Typical Level1 trigger rate: 20kHz
  - High performance DAQ
- Important improvements
  - Hermeticity for full reconstruction analyses
  - IP and secondary vertex resolution
  - $K_S$ and $\pi^0$ identification efficiency
  - Improve Kaon/pion separation
- Details in TDR *arXiv:1011.0352*



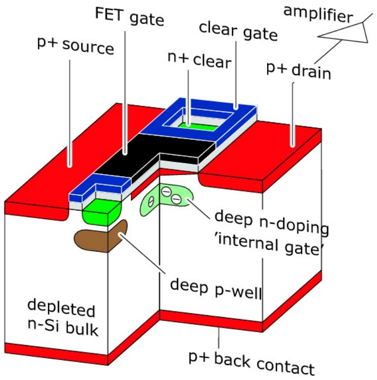



# Belle II in Comparison with Belle

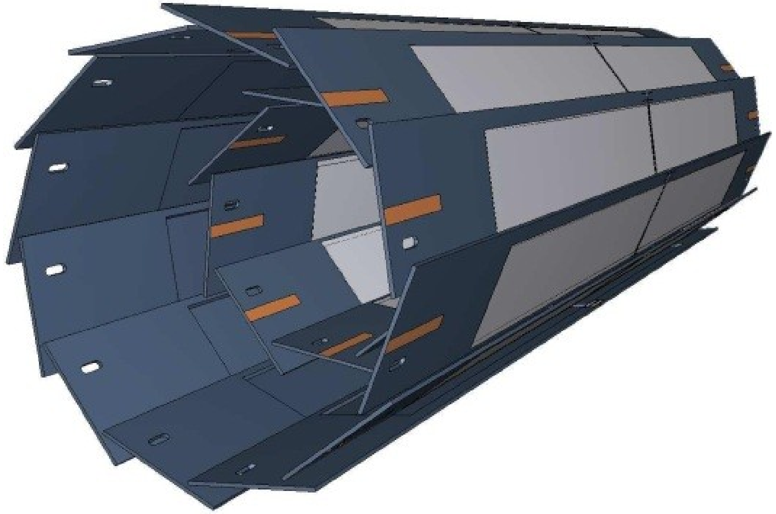


# Pixel Vertex Detector (PXD)

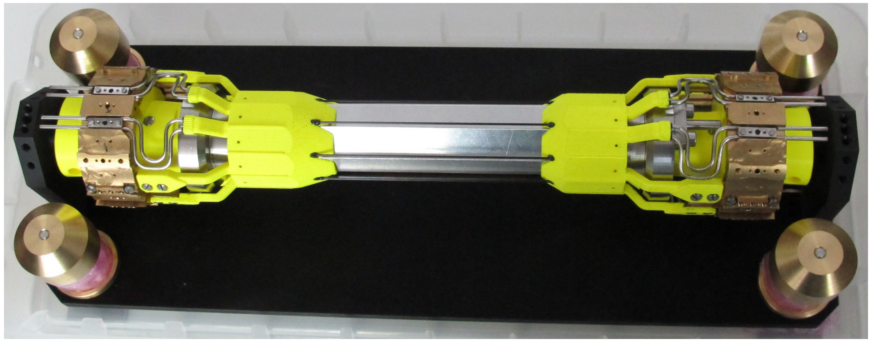
- DEPFET technology: thin (75µm) sensors
- Work in high occupancy close to the interaction region
- Fast readout




PXD design



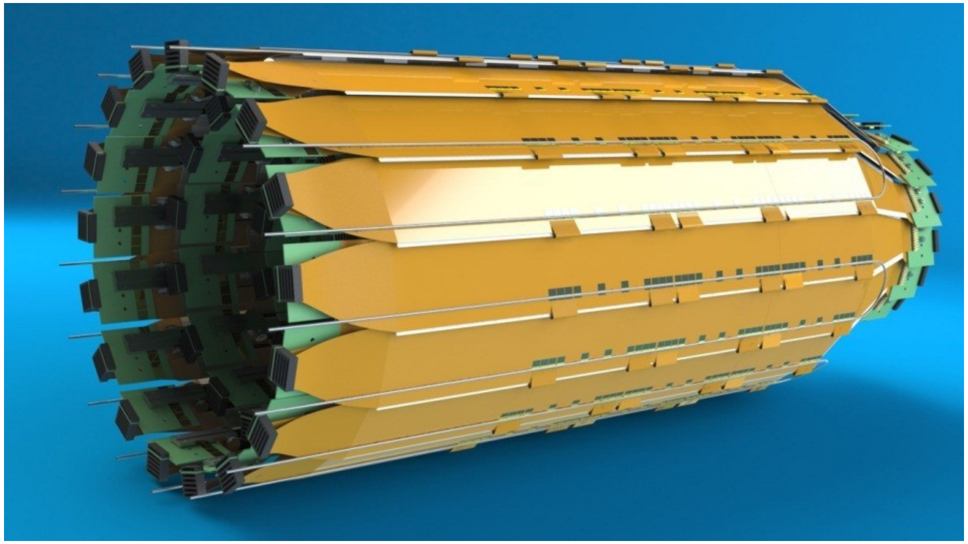
PXD mockup



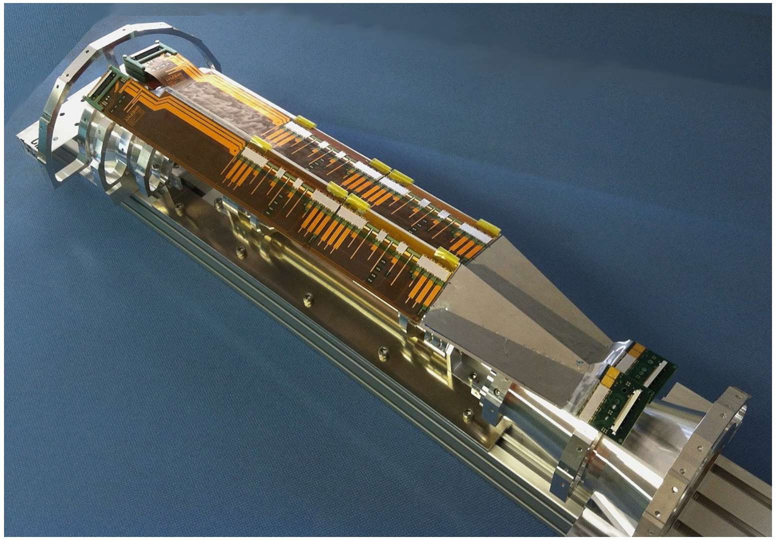
# Silicon Vertex Detector (SVD)

- Double-sided silicon strip detectors
- Pipelined readout to reduce dead time, pile-up rejection
- Larger acceptance (by 30%) for detection of pions from $K_S$ decay → significant improvement in $\delta S(K_S\pi^0\gamma)$

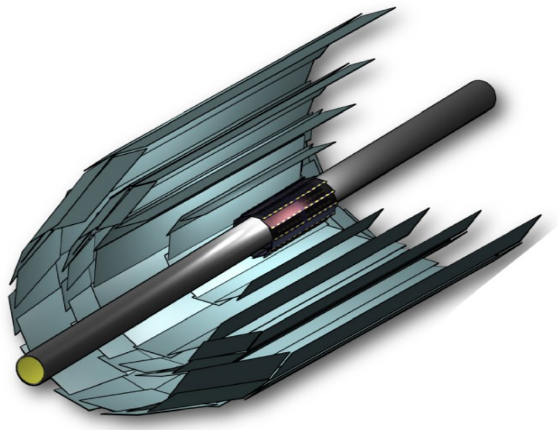
SVD design

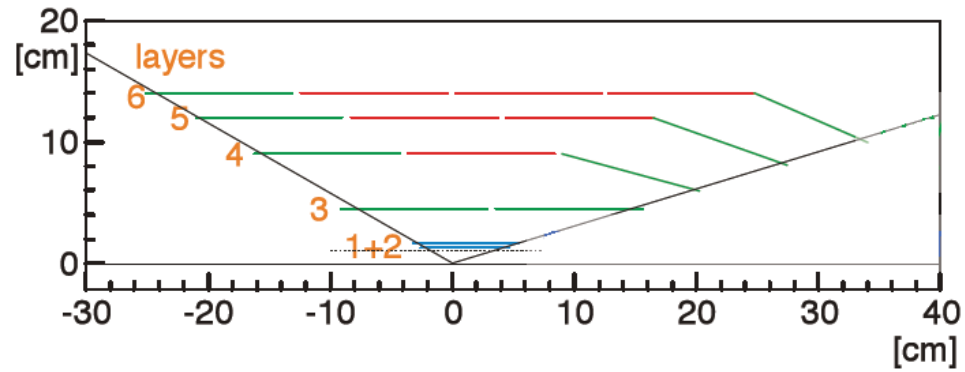


SVD mockup



# Vertex Detector: PXD+SVD

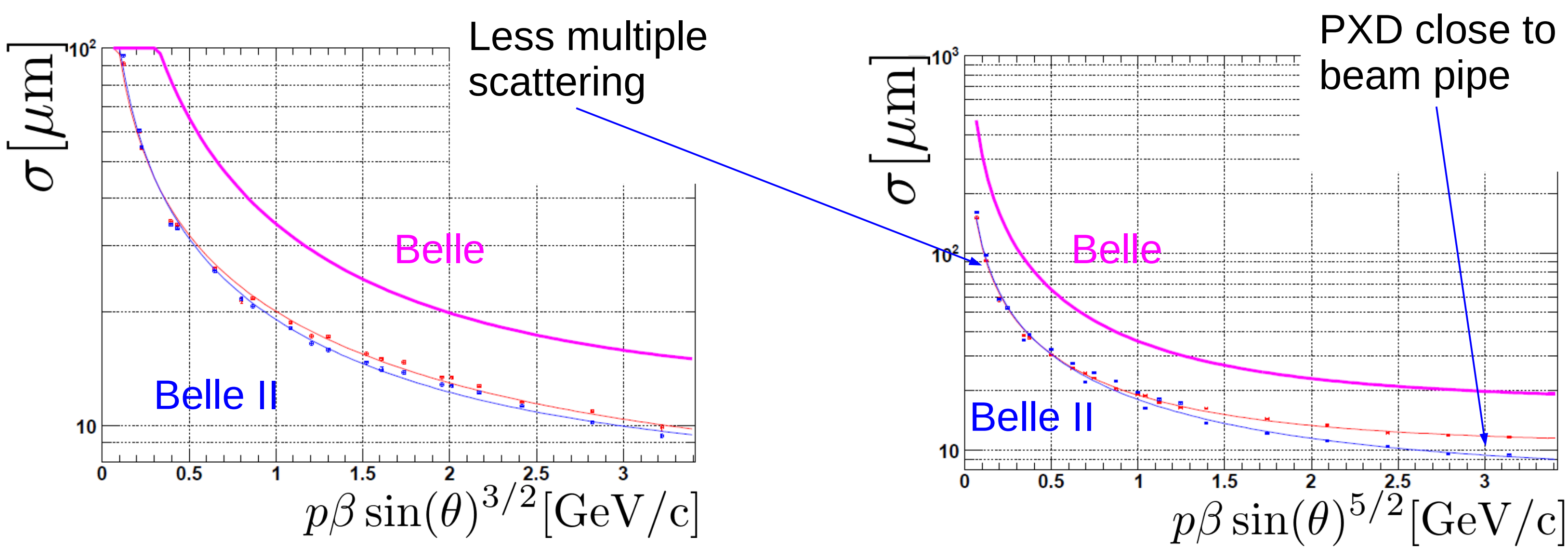




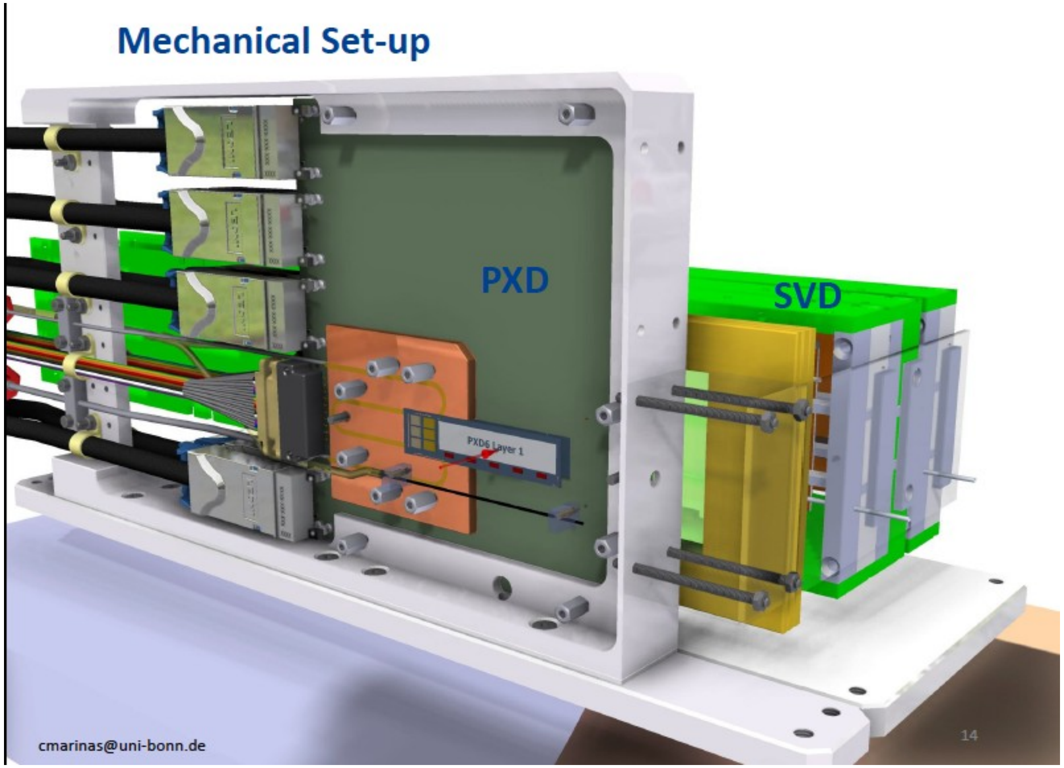

> Significant improvement in IP resolution

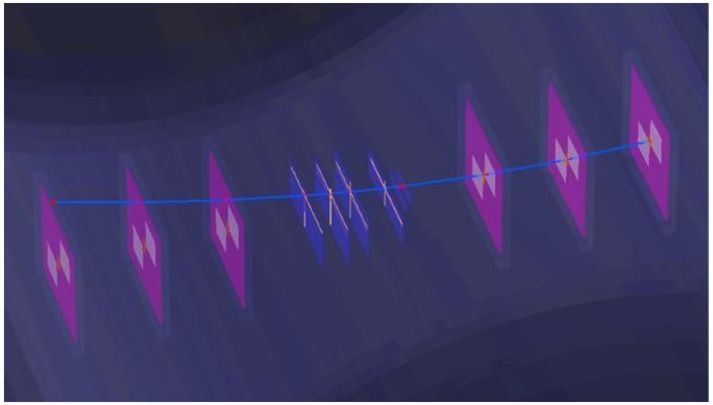
Closest approach resolution

Z resolution



# Vertex Detector: DESY Beam Test in January 2014



> Read out "Region Of Interest" scheme in PXD works

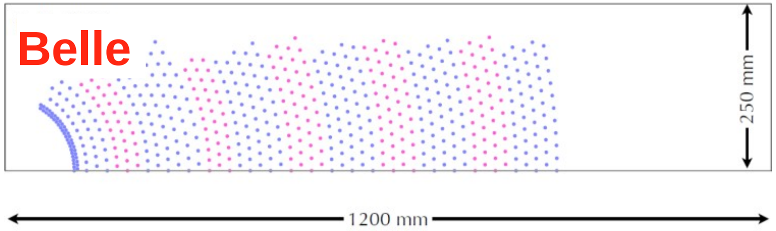
(In order to reduce the Gbit/s data volume from pixels)

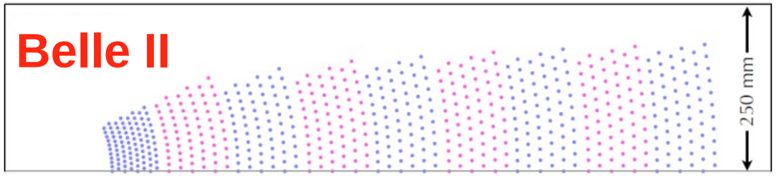
# Central Drift Chamber (CDC)

- Smaller cells near beam pipe
- Extended outer radius for better momentum resolution
- Faster readout electronics to reduce dead time

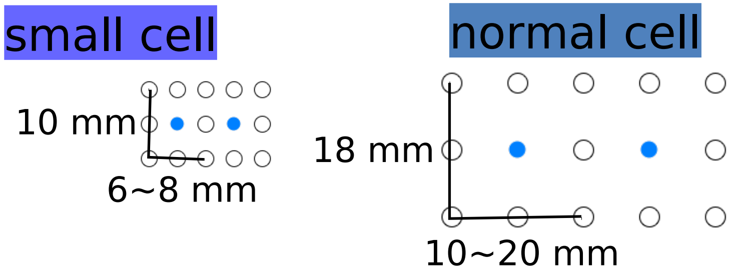
$\sigma_p/p \sim 0.3\% + 0.1\% \times p(\mathrm{GeV})$ in $B = 1.5\mathrm{T}$

$\sigma(\mathrm{d}E/\mathrm{d}x) \sim 6\%$



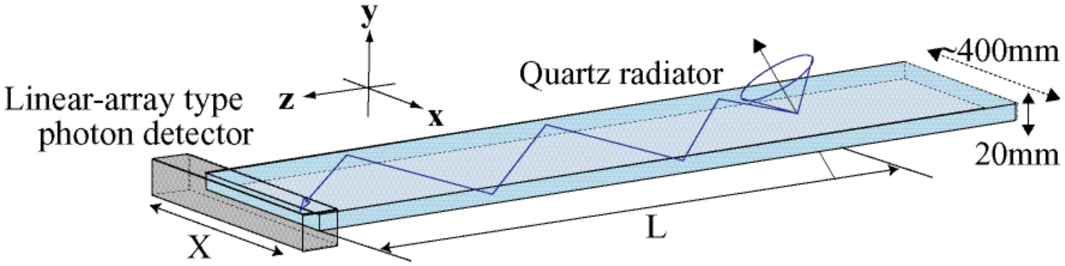



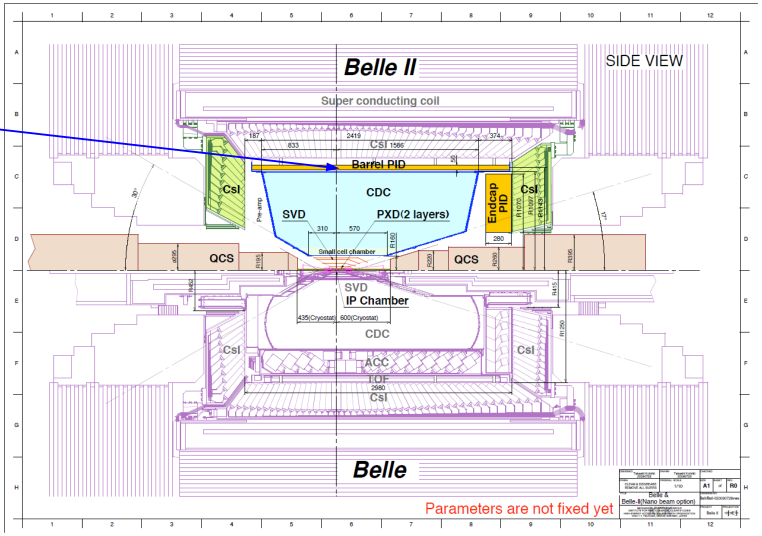

| | Belle | Belle II |
|---|---|---|
| Innermost sense wire | R=88mm | R=168mm |
| Outermost sense wire | R=863mm | R=1111.4mm |
| Number of layers | 50 | 56 |
| Total number of sense wires | 8400 | 14336 |
| Gas | He : $C_2H_6$ | He : $C_2H_6$ |
| Sense wires | W(Ø30μm) | W(Ø30μm) |
| Field wires | Al(Ø120μm) | Al(Ø120μm) |

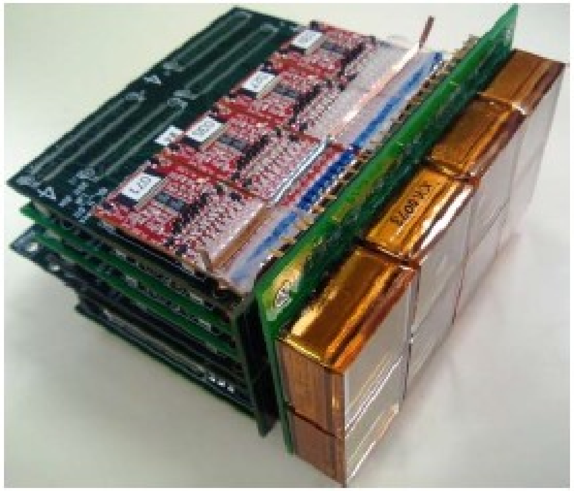


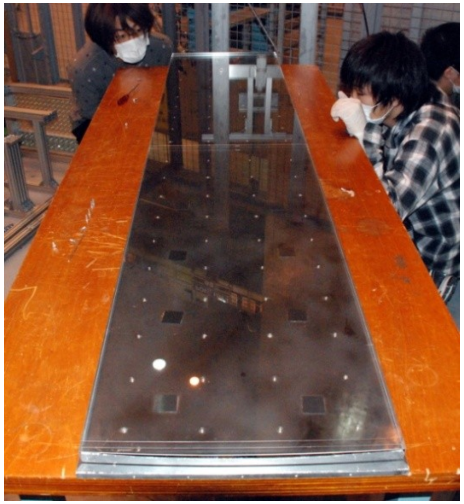
# Barrel PID: Time of Propagation Detector (TOP)

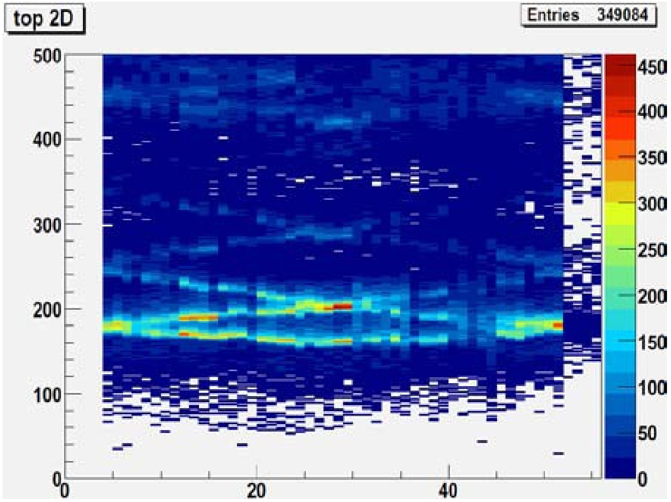
- Compact design
- Improved K/π separation



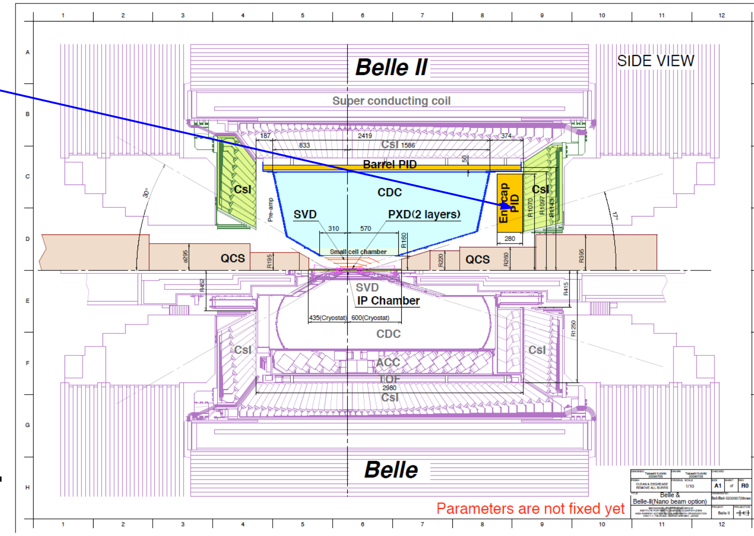



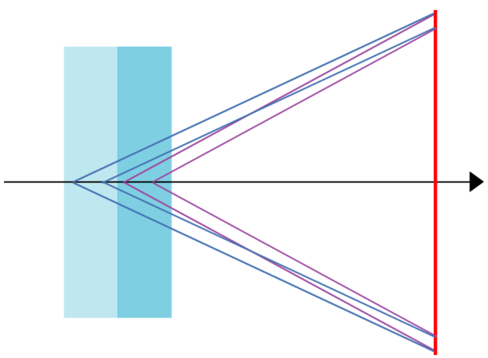




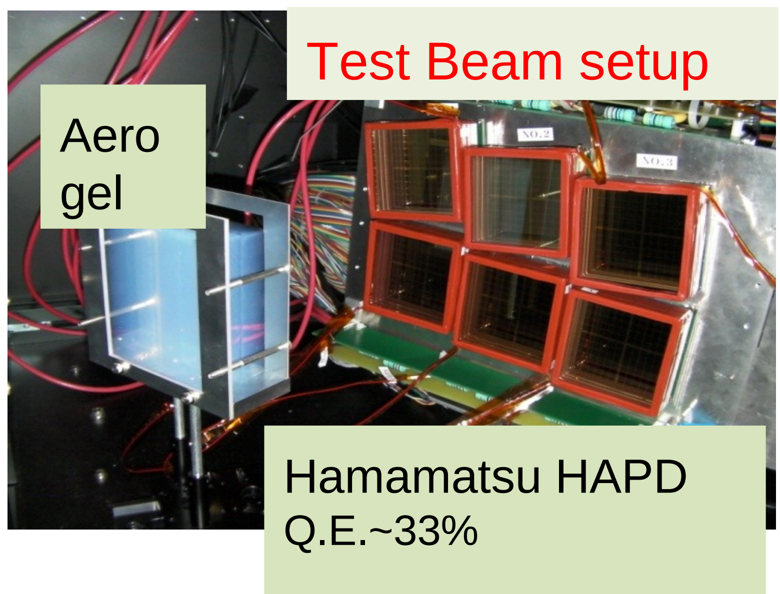
# Endcap PID: Aerogel RICH

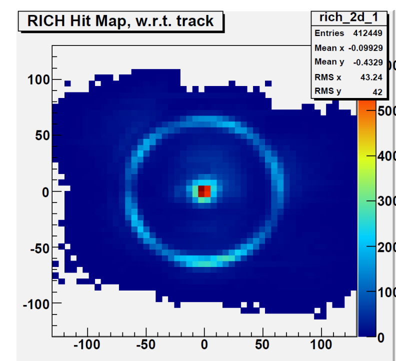
- Novel proximity-focusing two-layer radiator
- Employ multiple layers with different refractive indices
- Cherenkov images from individual layers overlap on the photon detector



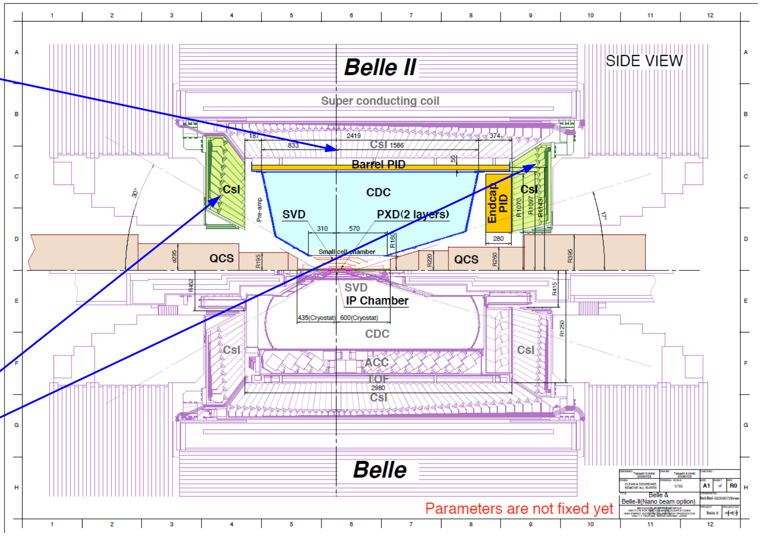
*NIM A548 (2005) 383*



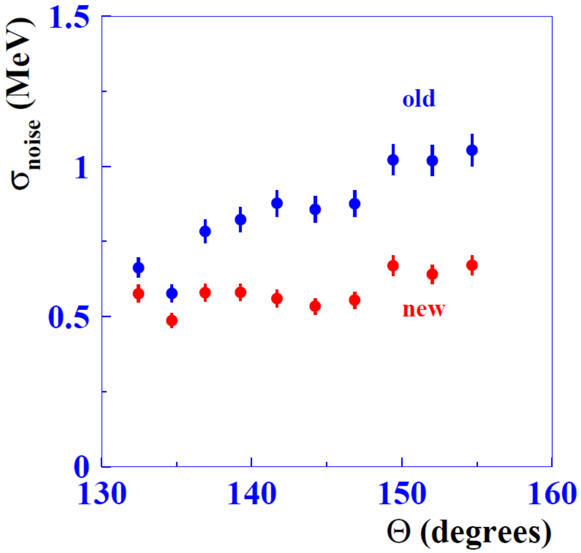



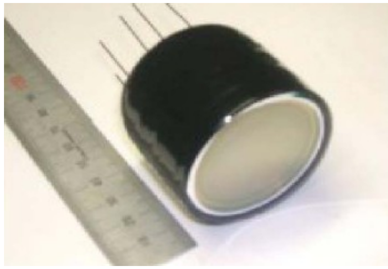
# Electromagnetic Calorimeter

- Barrel: reuse existing CsI(Tl)
- Readout electronics:
  - Upgrade to 2 MHz waveform sampling
  - Online signal processing
- Endcaps: considering upgrade to pure CsI
- Better performance & radiation hardness
- Improved energy resolution



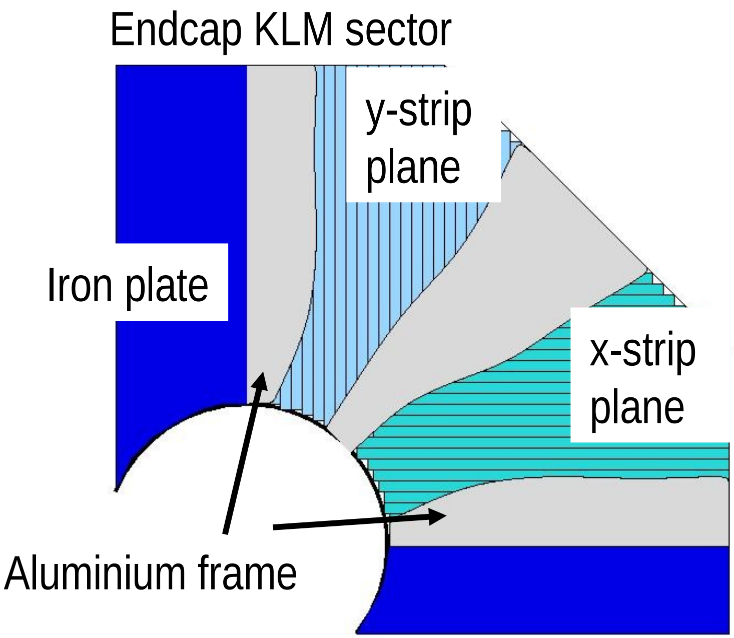

Better signal-to-background separation

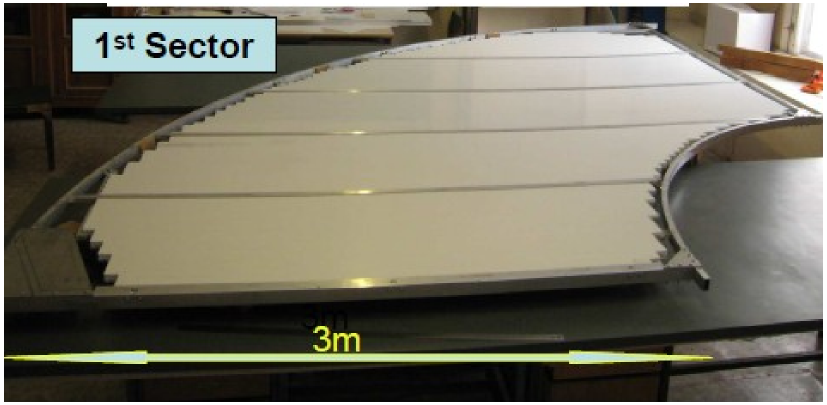


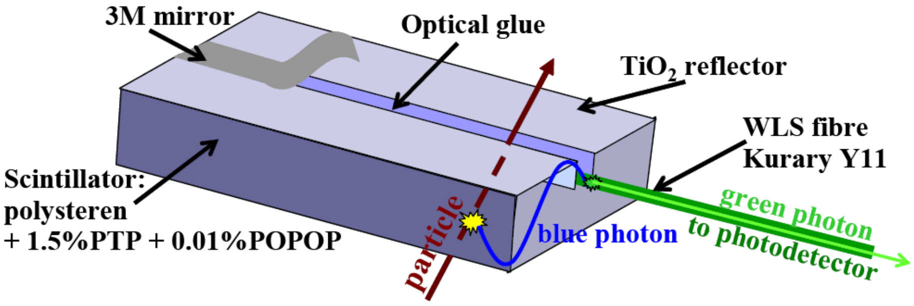



# $K_L$ and μ Detection (KLM)

- End-caps upgrade: Resistive Plate Chambers → scintillator-based KLM
- Scintillators + SiPM → better beam-background tolerance
- Barrel KLM: some RPC layers may be replaced as background increases with luminosity



# Software Upgrade

- New framework with dynamic module loading, parallel processing, python steering, root I/O, and use of GRID
- Full detector simulation with Geant4
- Tracking with GenFit
- Alignment with Millepede II