The Belle II Experiment: status and prospects

Alberto Martini

On behalf of the Belle II collaboration, University & INFN Roma Tre

Belle II: second generation B-factory (I)

Main experiments at B-factories of the past:

- Belle (KEK Laboratory, Japan)
- BaBar (SLAC Laboratory, California)

→ **Important results:** confirmation of the CKM mechanism in the SM, CP violation observation in the B meson system etc..
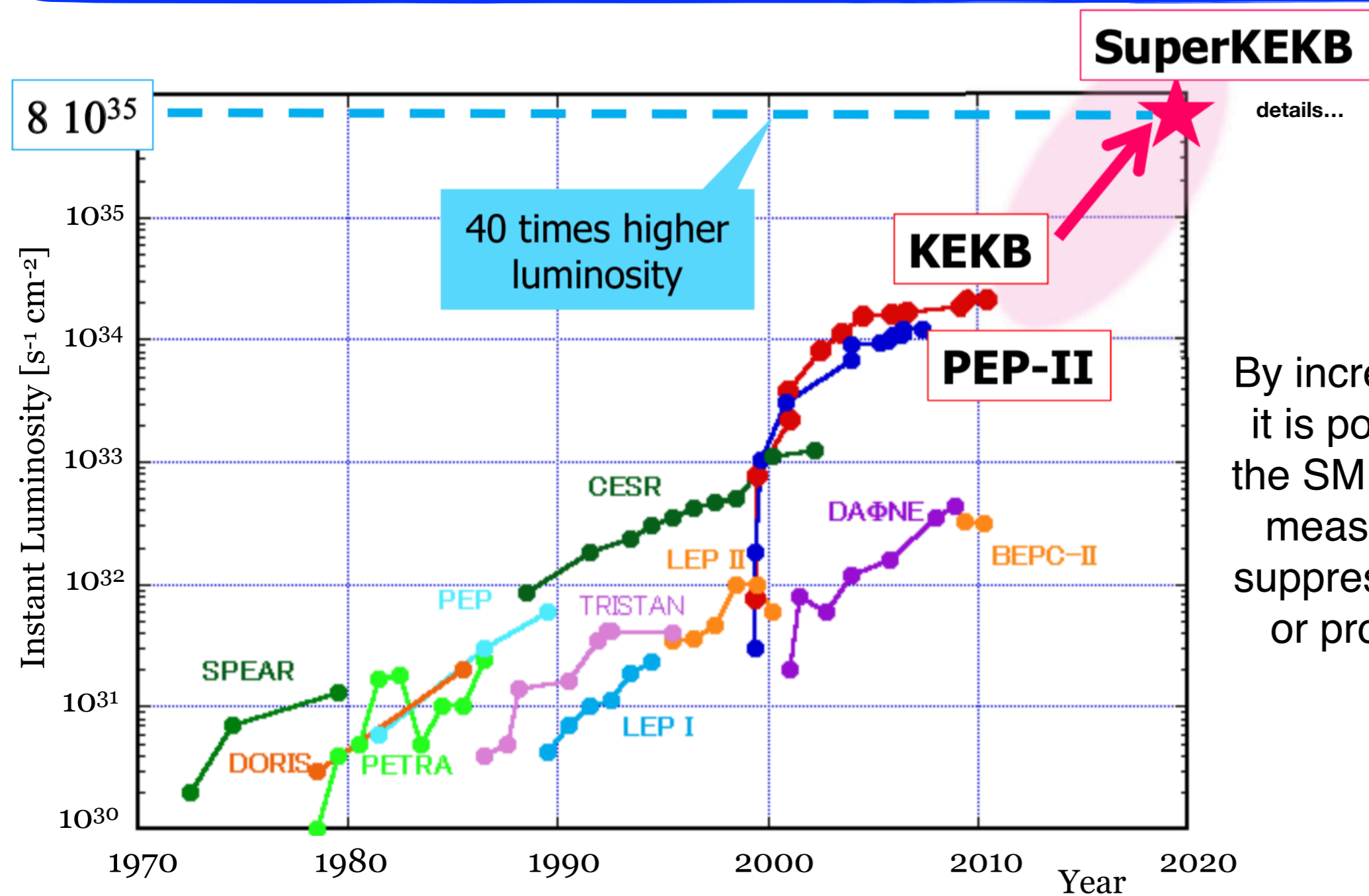
Main problem:
statistics collected by KEKB and PEP-II colliders was not sufficient to analyse some rare decays, SM validations and other highly precise measurements

↓

Belle II: usage of the improved collider SuperKEKB
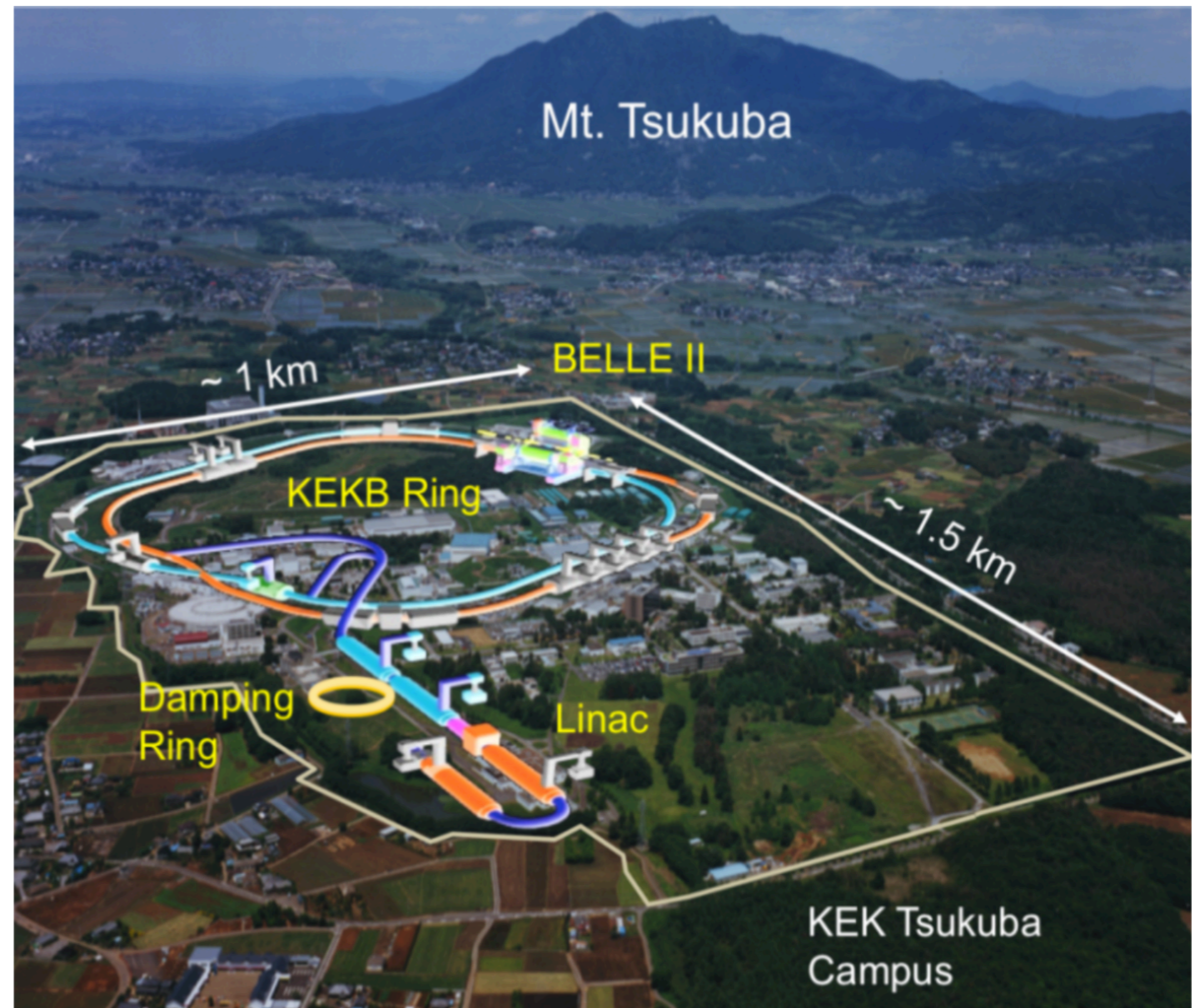
Belle II: second generation B-factory (II)

By increasing the luminosity it is possible to investigate the SM through high precise measurements for highly suppressed, highly accurate or prohibited processes.
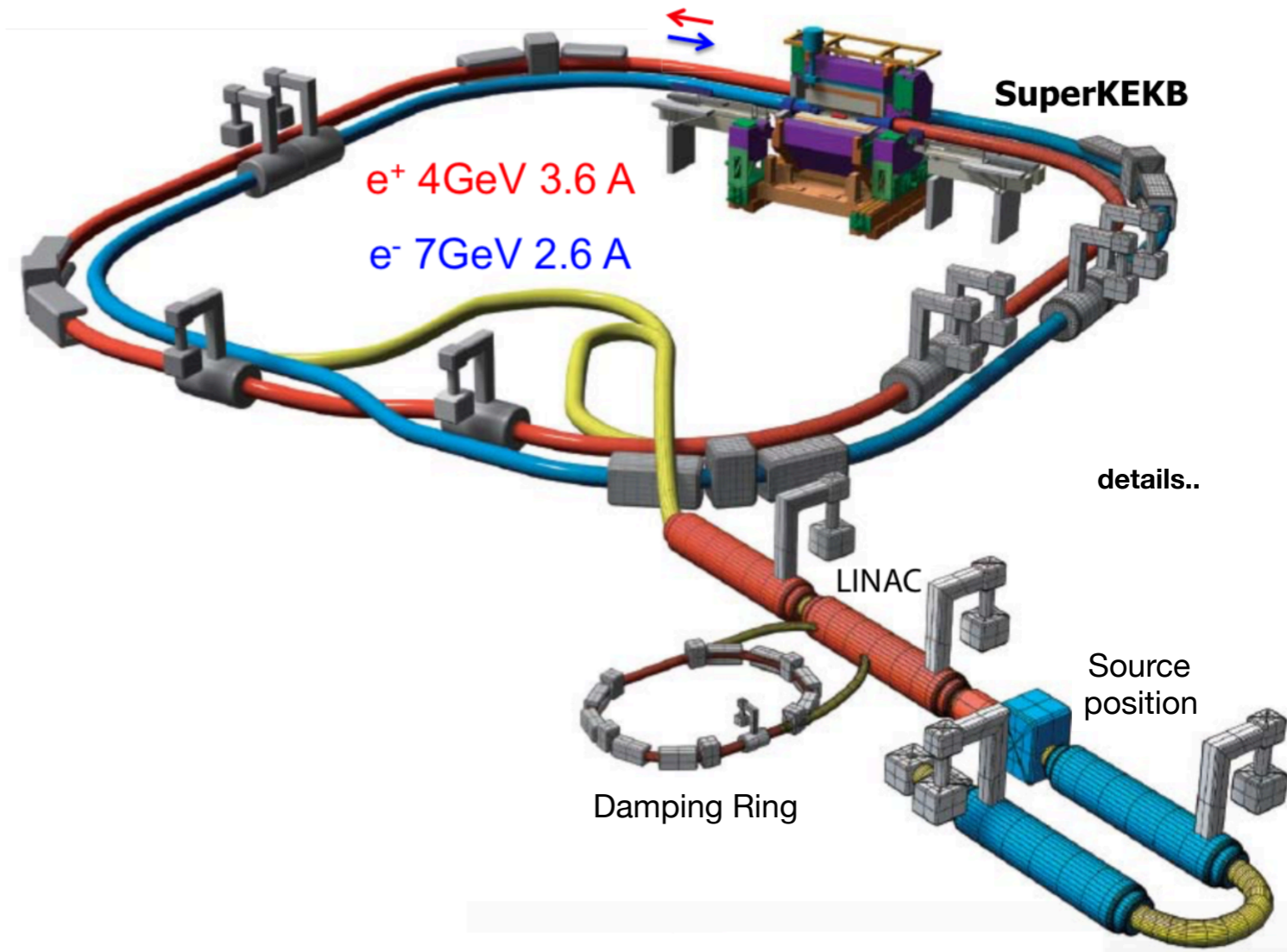
Improved detector performances → New Physics possibility!

Belle II

Collider SuperKEKB

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

SuperKEKB

e+ 4GeV 3.6 A

e- 7GeV 2.6 A
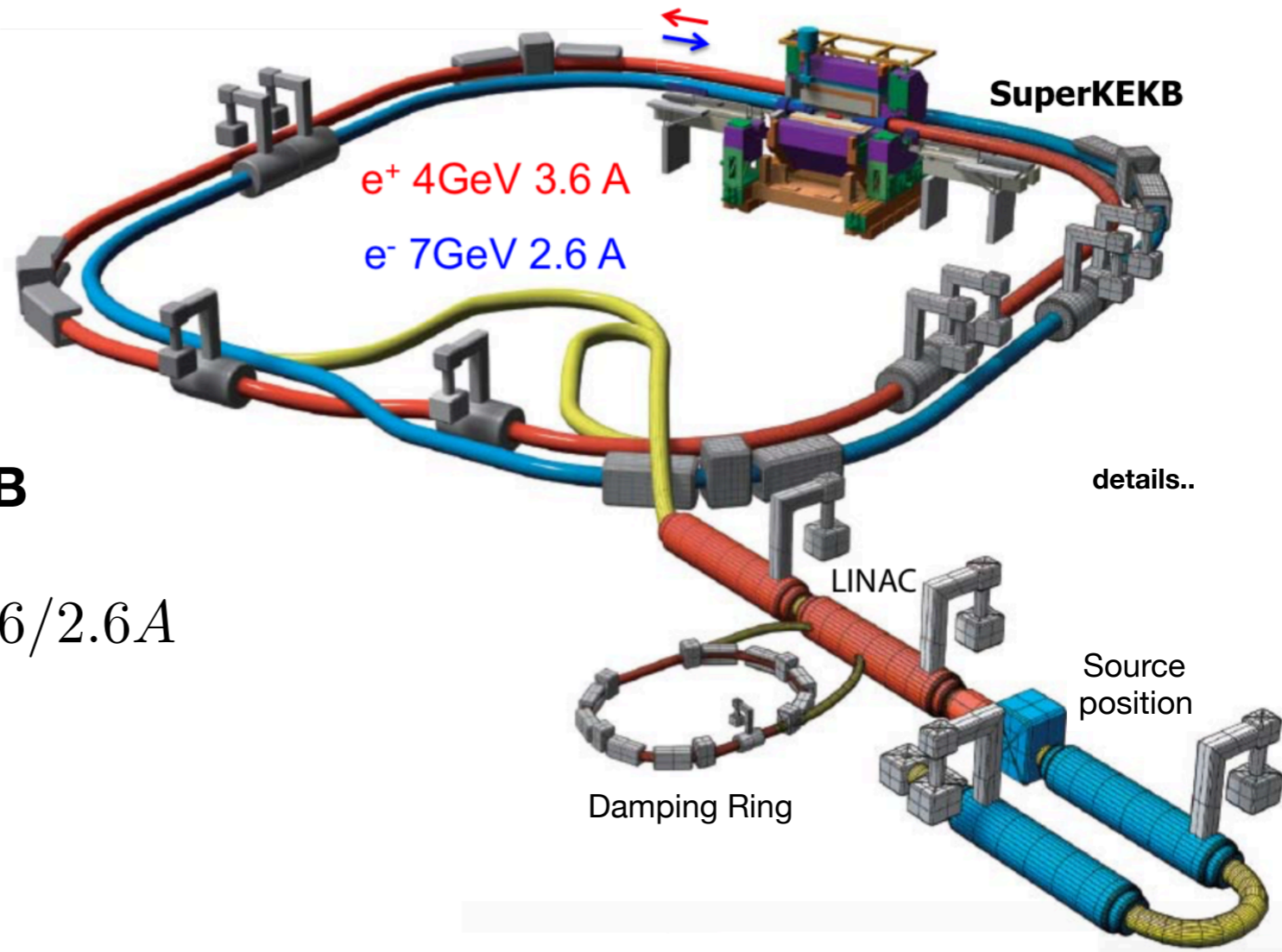
details..

LINAC

Source position

Damping Ring

Belle II

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KEKB

$$I_{e+/e-} = 1.64/1.19 A$$

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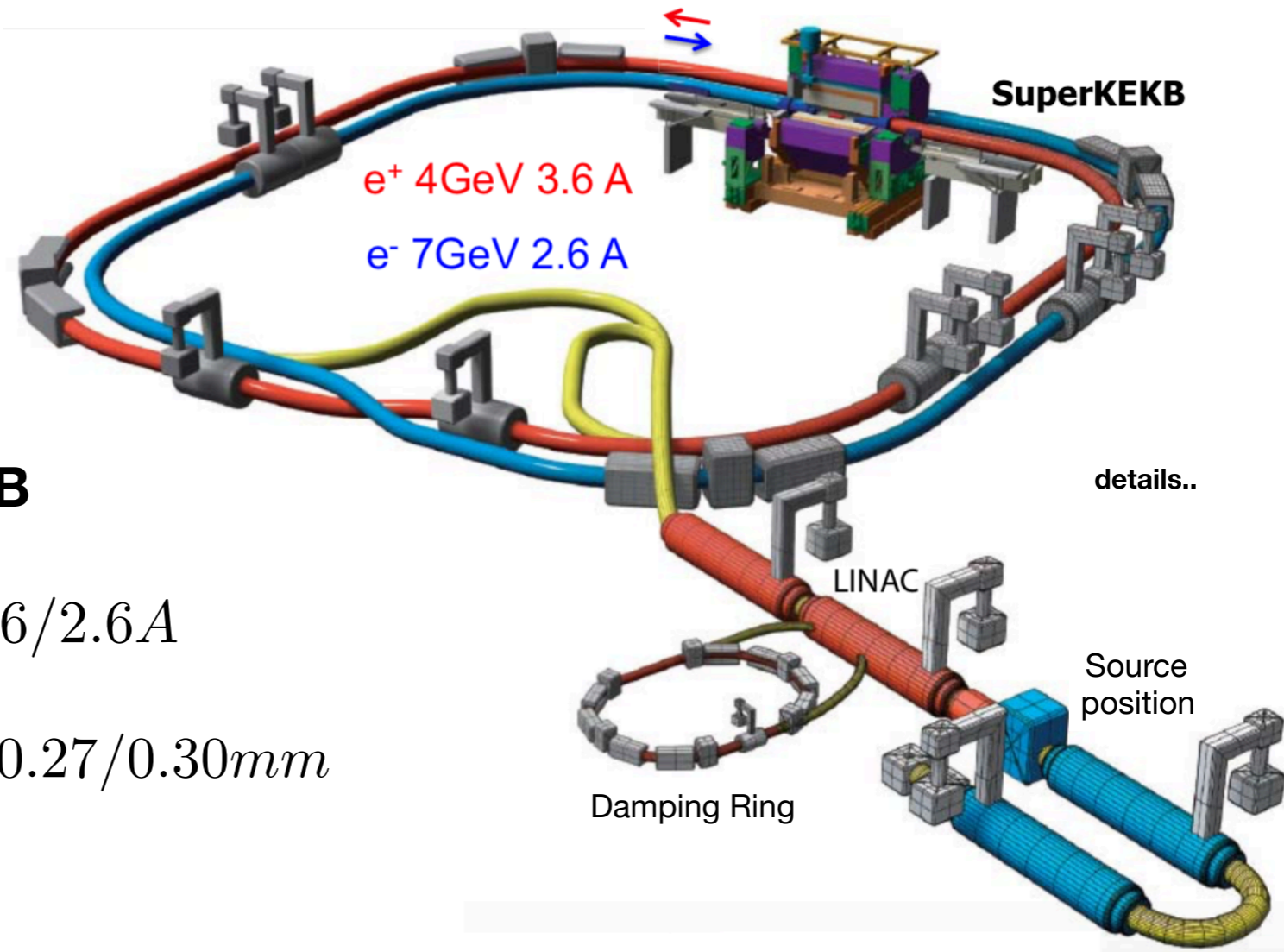
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Belle II

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details..

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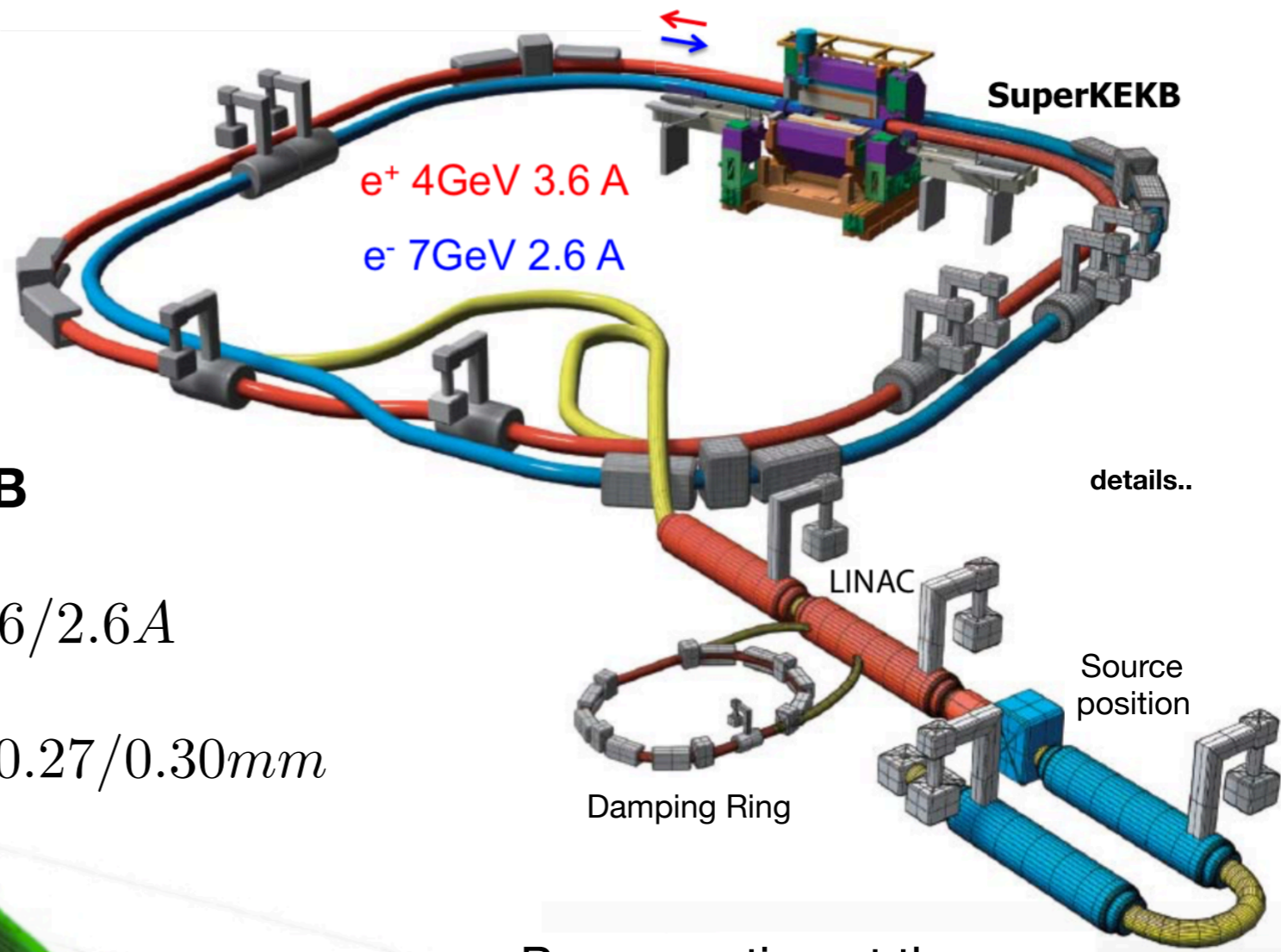
$\beta_{y\ e^+/e^-}^* = 5.9/5.9mm$

SuperKEKB

$I_{e^+/e^-} = 3.6/2.6A$

$\beta_{y\ e^+/e^-}^* = 0.27/0.30mm$

Belle II

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1μm

100μm

5mm

y x

z

1μm

5mm

100μm

Beam section at the interaction point:
~42 nm in y
~6 μm in x

Nano-beam scheme

Belle II

Collider SuperKEKB

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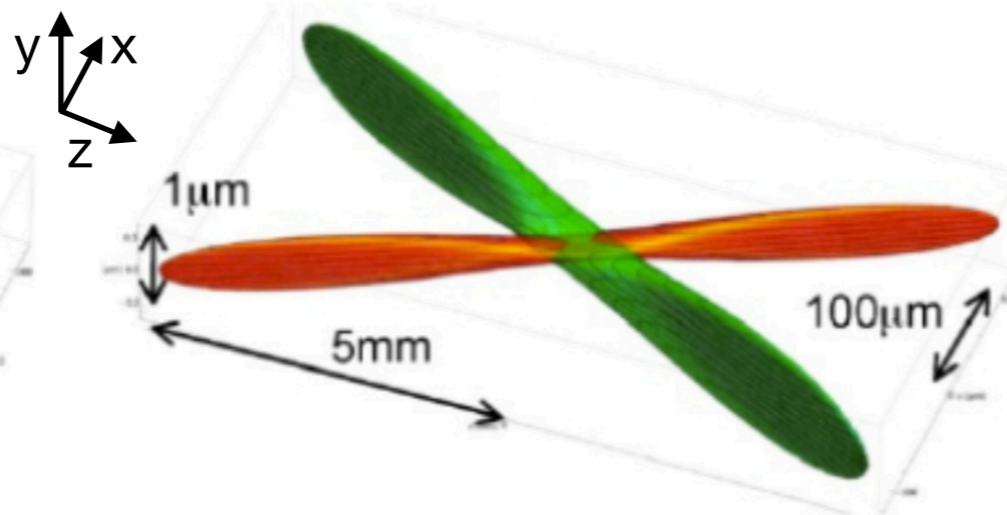

SuperKEKB
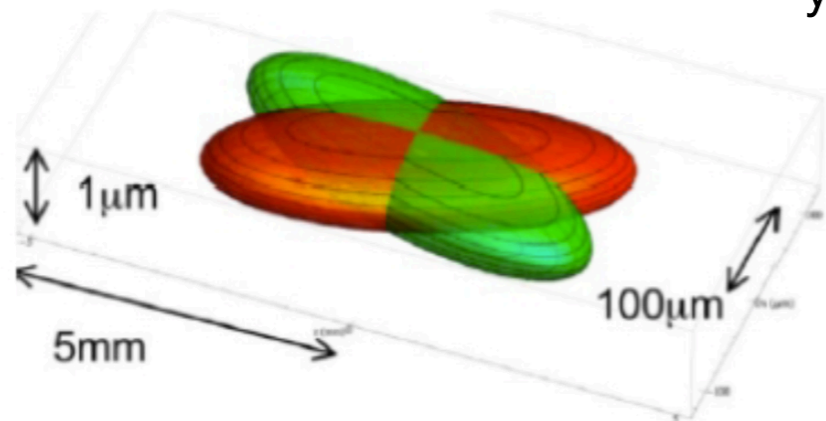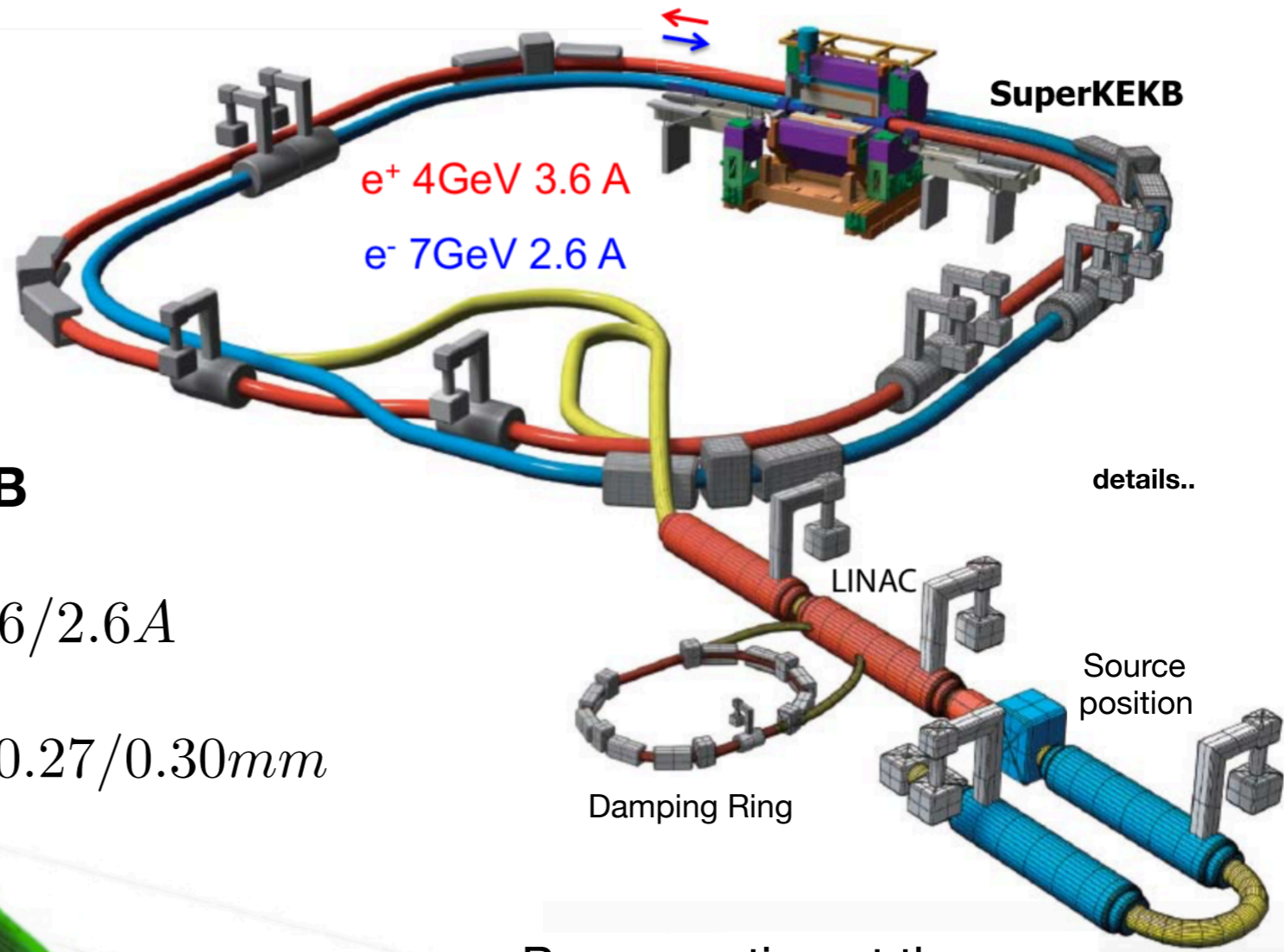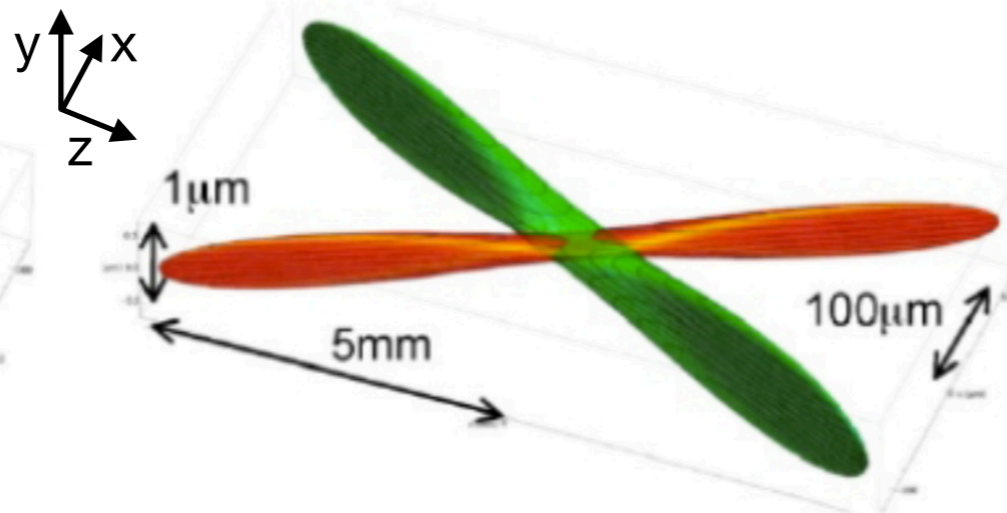
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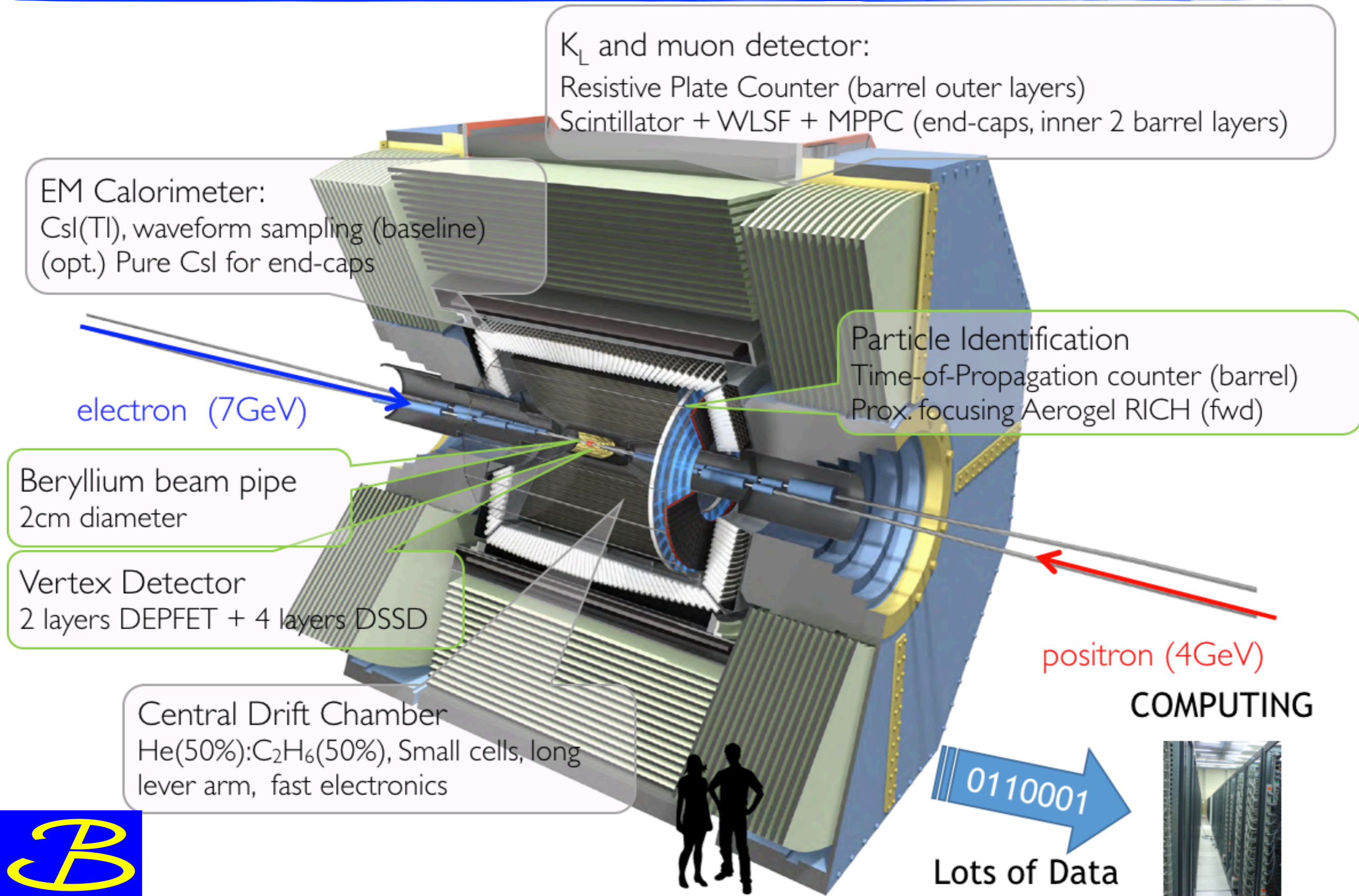
5mm

y x

z

1μm

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100μm

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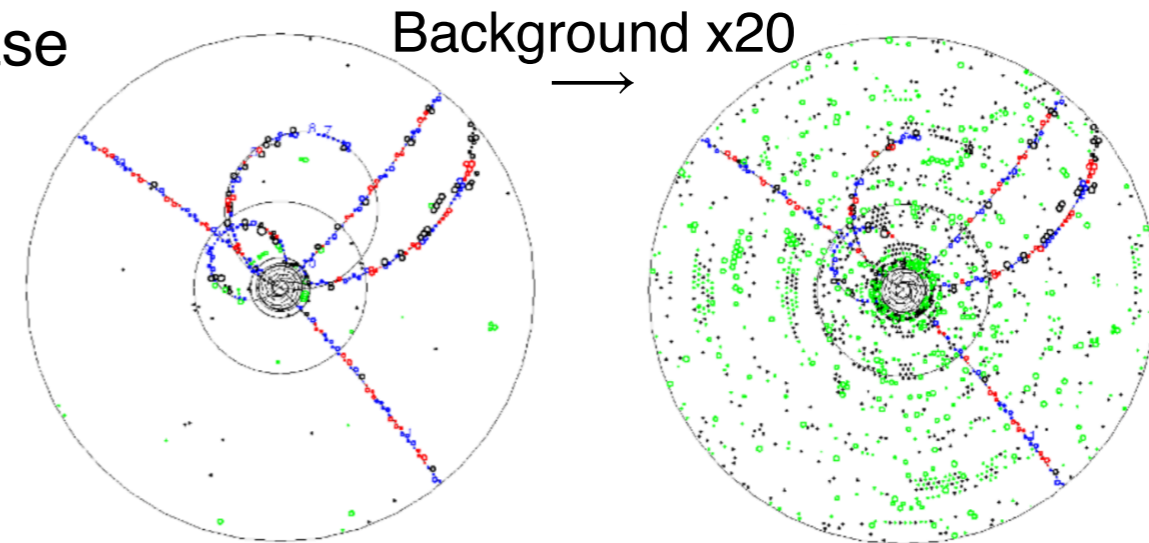
Expected improvement of integrated luminosity of a factor ~50 w.r.t. Belle: **50 ab⁻¹**

Belle II

Belle II detector (I)

K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (baseline)
(opt.) Pure CsI for end-caps

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electron (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positron (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long
lever arm, fast electronics

COMPUTING
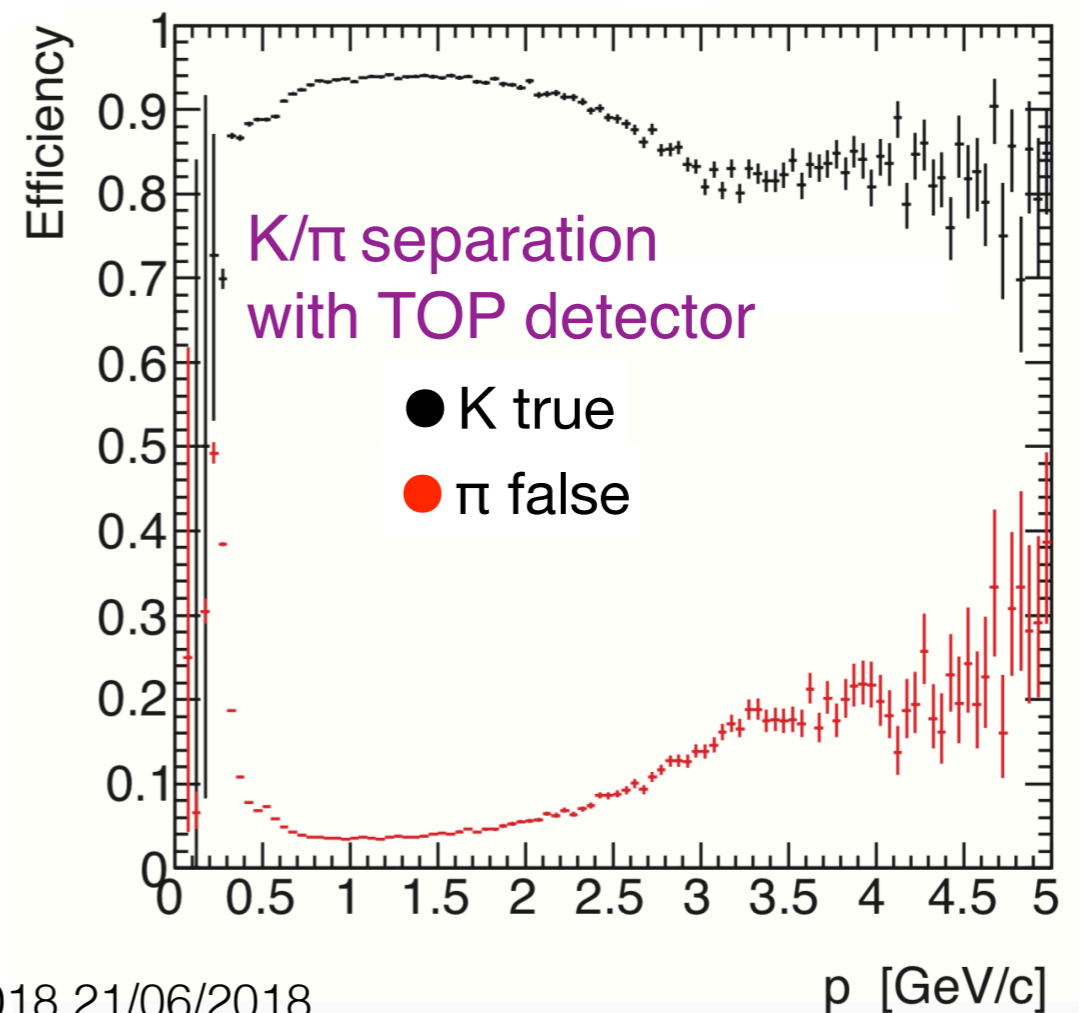
0110001

Lots of Data

Belle II

Belle II detector (II)

Increased luminosity → Higher occupancy, pile-up issues, more background hits
Higher trigger and DAQ rate
Radiation damage increase

Background x20 →

Improvements with respect to Belle:

- Signal readout speed and waveform fit in the e.m. calorimeter;
- K_S reconstruction efficiency (+30%);
- K/π separation (wrong ID probability reduced by a factor ~2.5);
- Primary and secondary vertices reconstruction (resolution x2).

K/π separation with TOP detector

● K true

● π false

Efficiency

p [GeV/c]

Belle II detector (II)

Increased luminosity → Higher occupancy, pile-up issues, more background hits
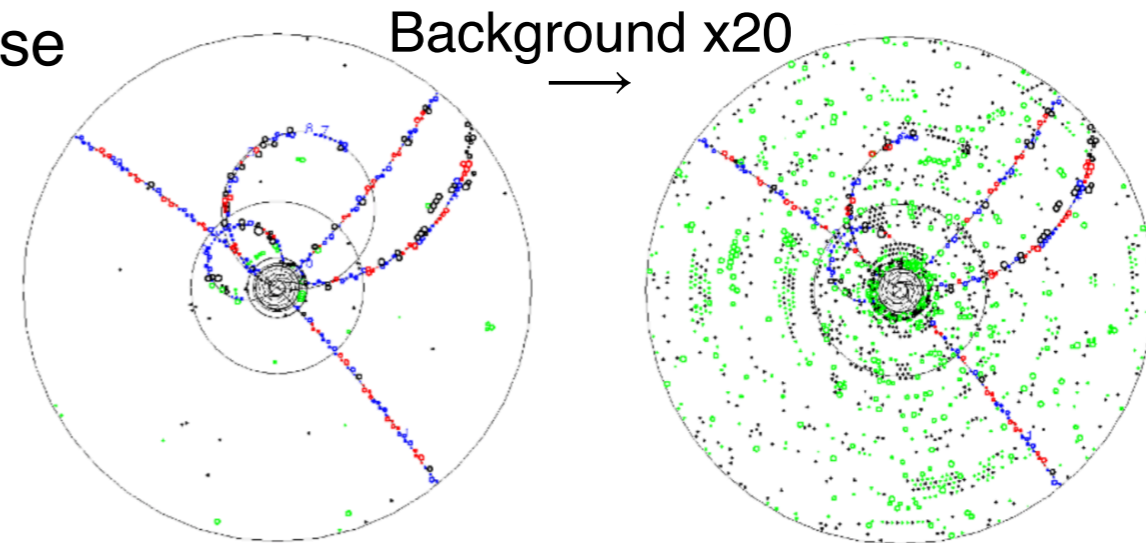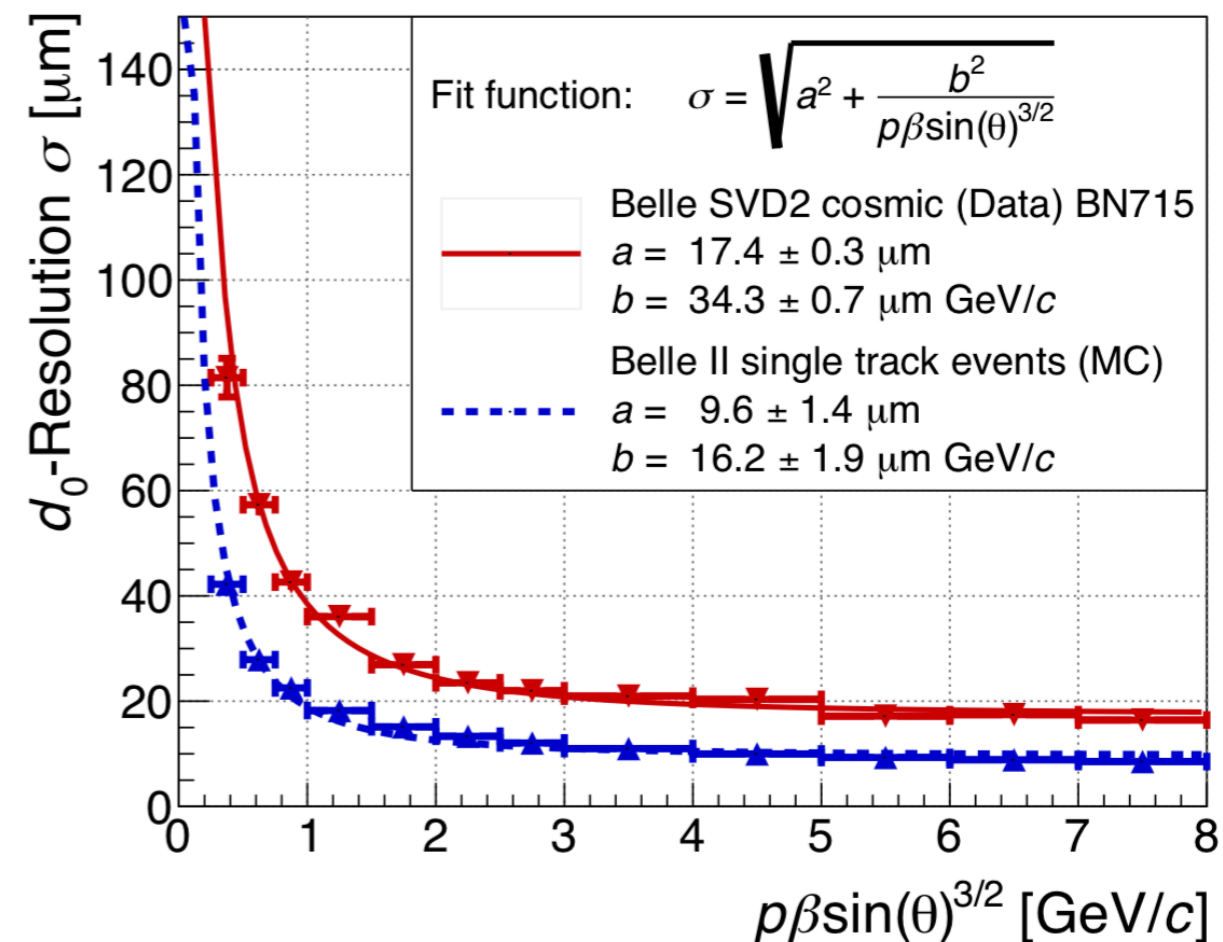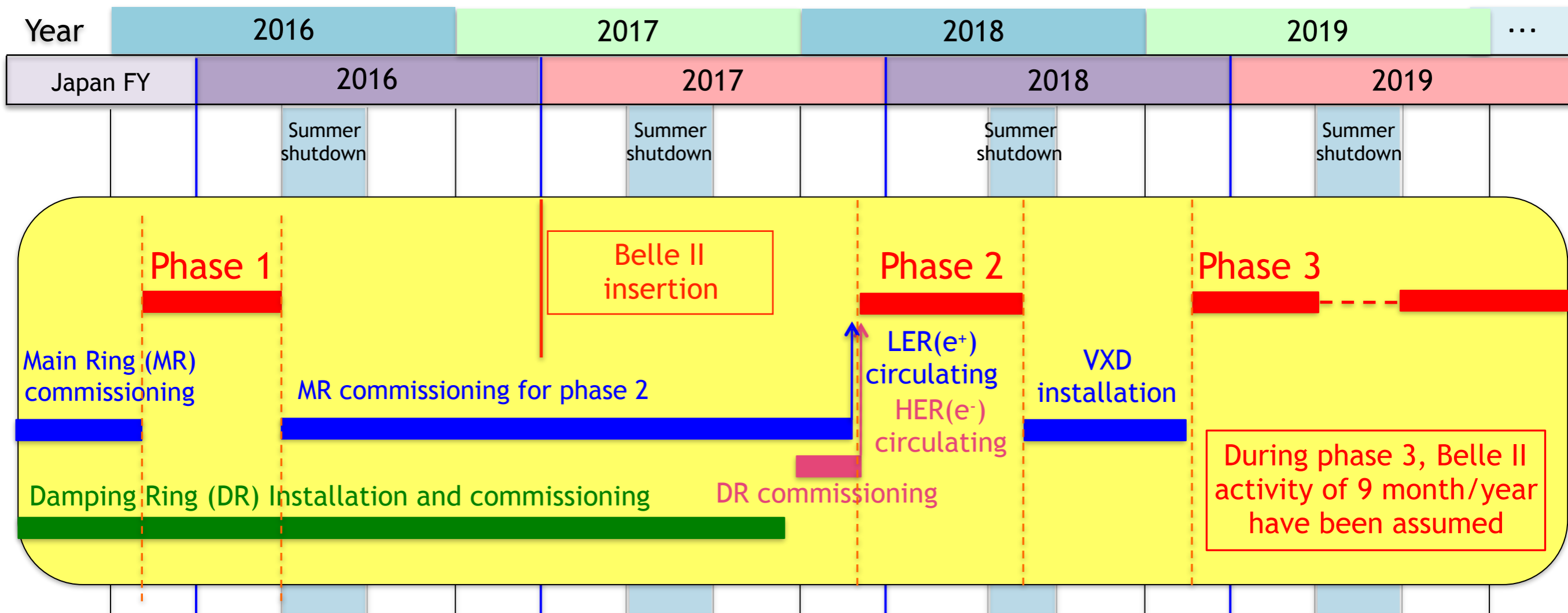Higher trigger and DAQ rate
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Fit function: $\sigma = \sqrt{a^2 + \dfrac{b^2}{p\beta\sin(\theta)^{3/2}}}$

Belle SVD2 cosmic (Data) BN715
$a = 17.4 \pm 0.3\ \mu m$
$b = 34.3 \pm 0.7\ \mu m\ GeV/c$

Belle II single track events (MC)
$a = 9.6 \pm 1.4\ \mu m$
$b = 16.2 \pm 1.9\ \mu m\ GeV/c$

d_0-Resolution σ [μm]

$p\beta\sin(\theta)^{3/2}$ [GeV/c]

Belle II status and plan

Year	2016	2017	2018	2019	...
Japan FY	2016	2017	2018	2019	

Summer shutdown   Summer shutdown   Summer shutdown   Summer shutdown

Phase 1   Belle II insertion   Phase 2   Phase 3

Main Ring (MR) commissioning   MR commissioning for phase 2   LER(e⁺) circulating   VXD installation

HER(e⁻) circulating

Damping Ring (DR) Installation and commissioning   DR commissioning

During phase 3, Belle II activity of 9 month/year have been assumed

Phase 1: SuperKEKB commissioning & background estimation   **Completed**

Phase 2: Collision runs with the detector installed partially, without the vertex detector → first physics data!   **Ongoing and almost finished!**

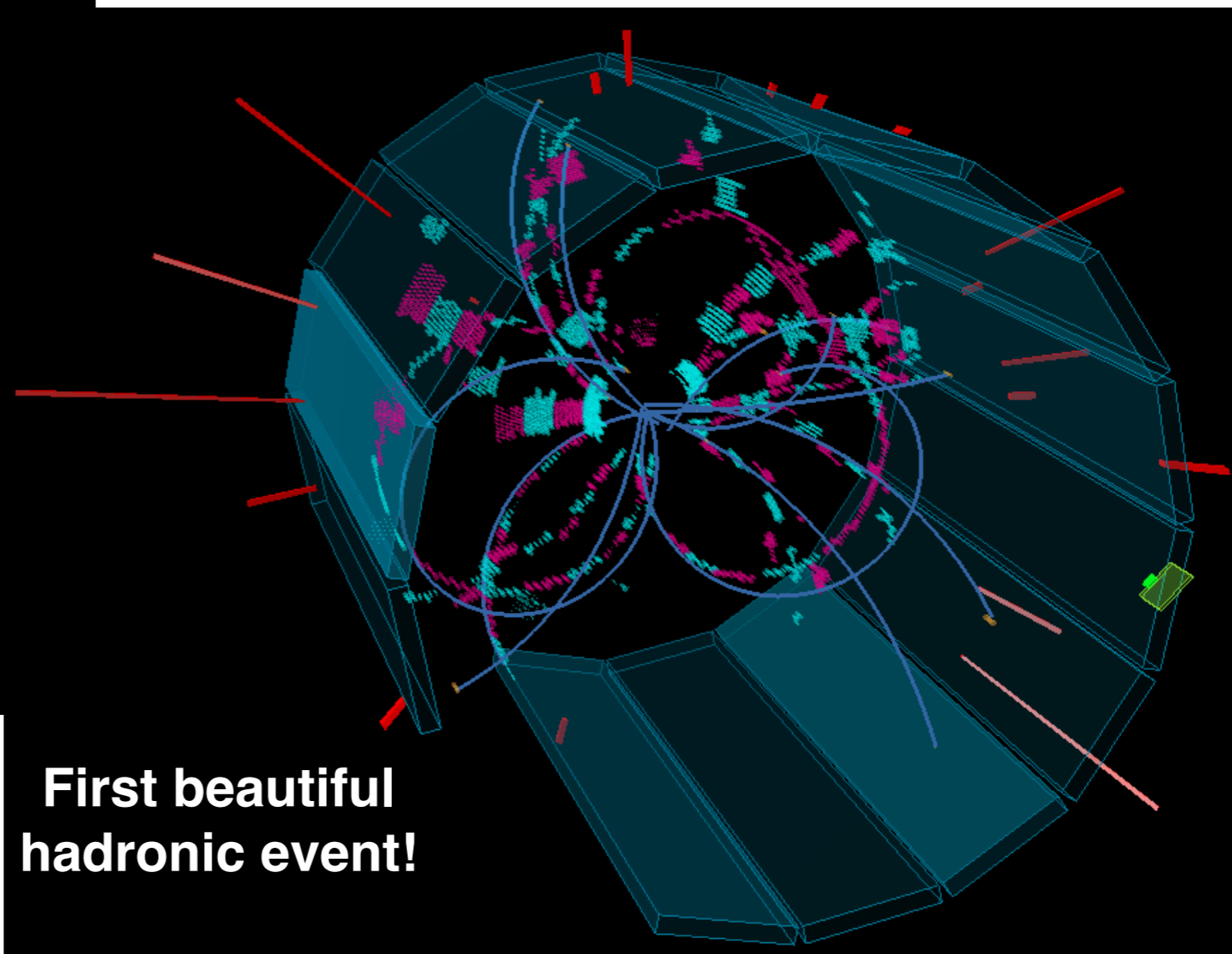**Phase 3:** Data taken with the whole detector installed   **February 2019**

Belle II

Belle II first event displays

First hadronic event!

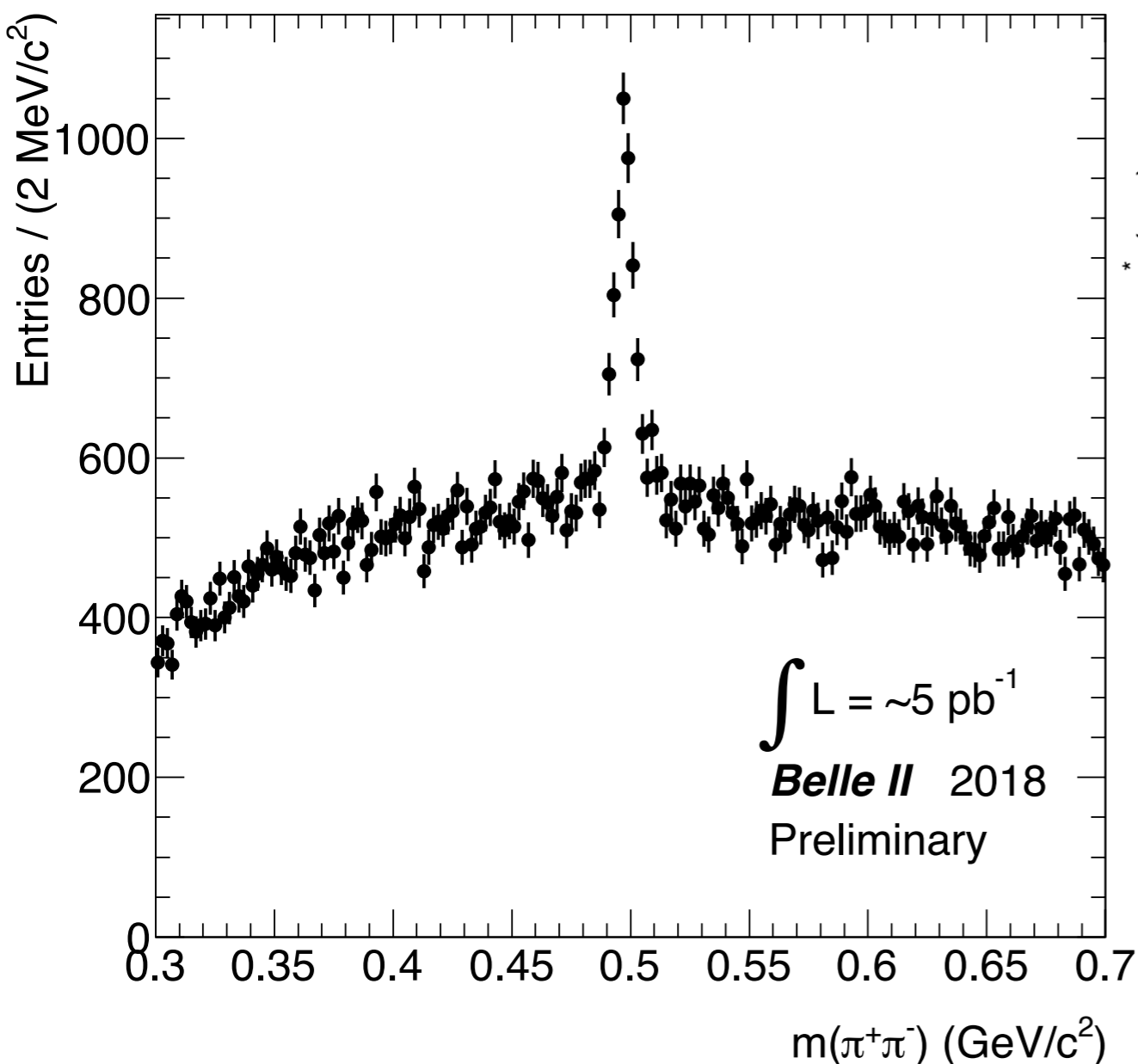**Phase 2 first hadronic physics event!**

First beautiful hadronic event!

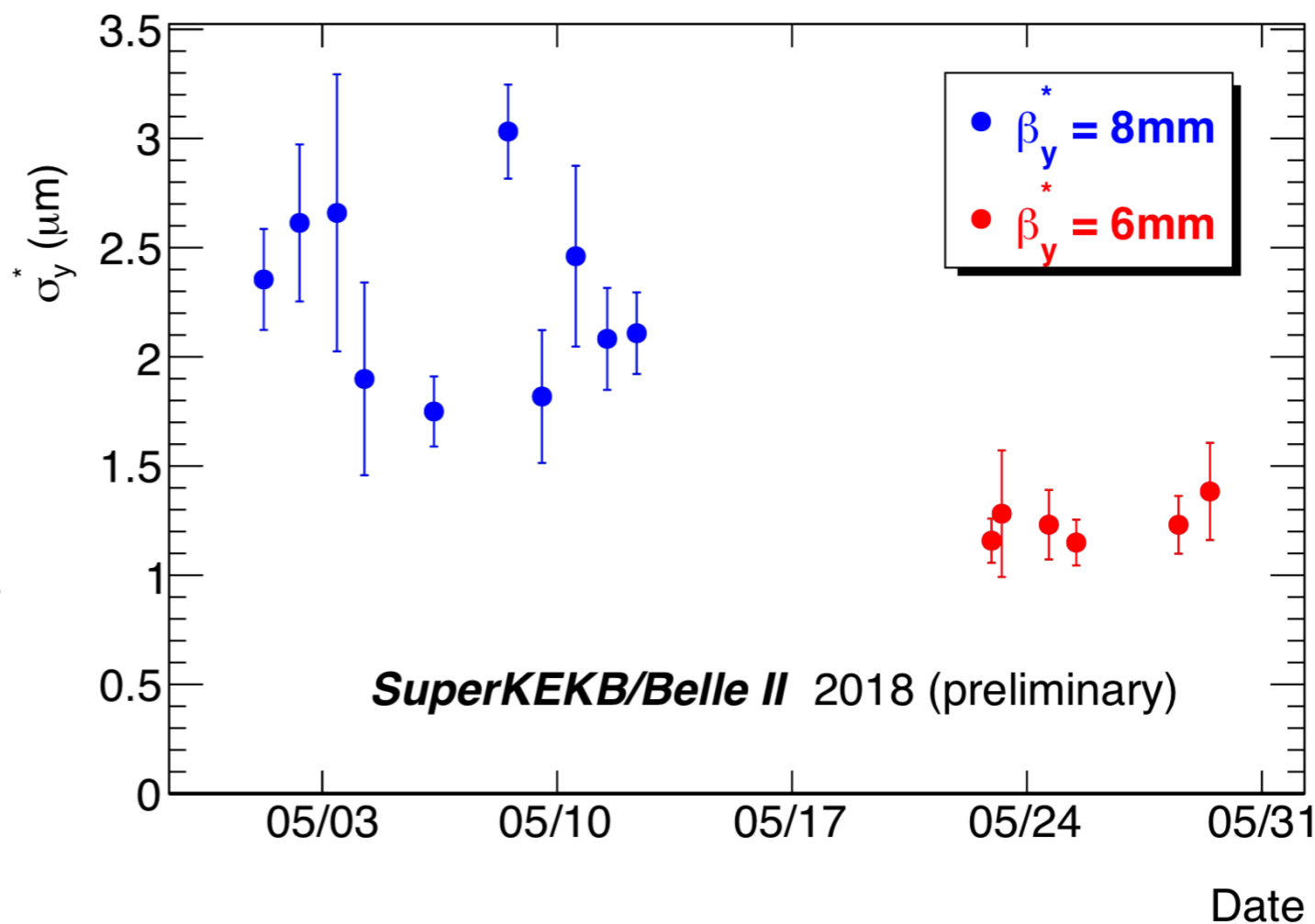Belle II

Belle II first results

First kaon mass reconstruction plot

Vertical beam size σ$_y$* as a function of the date

$\int L = \sim 5 \text{ pb}^{-1}$

Belle II 2018
Preliminary

$\beta_y^* = 8\text{mm}$

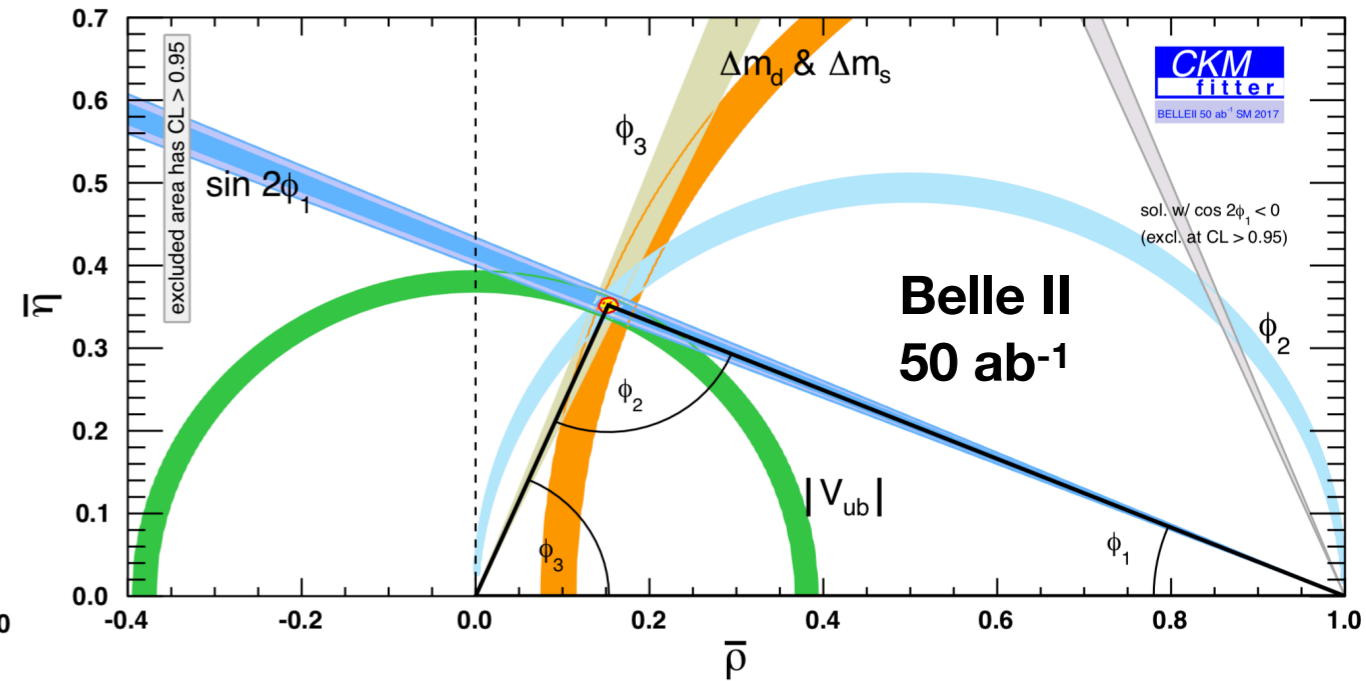$\beta_y^* = 6\text{mm}$

SuperKEKB/Belle II 2018 (preliminary)

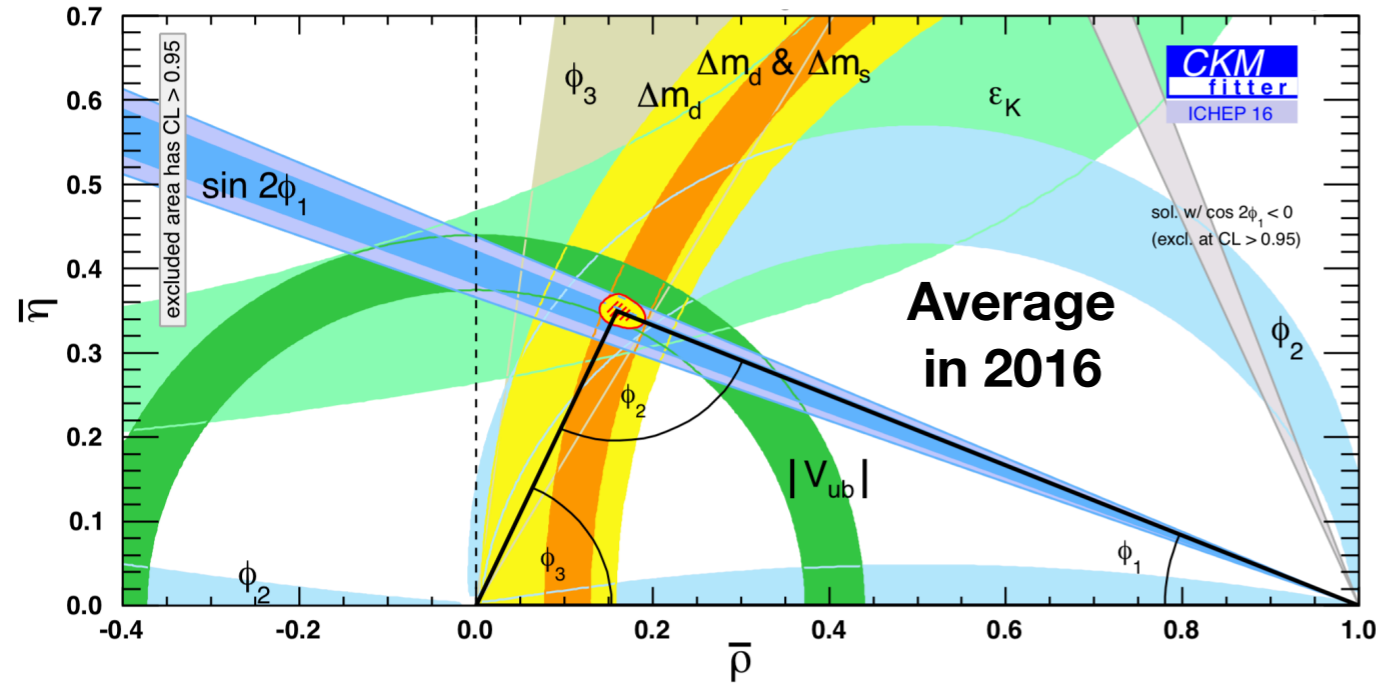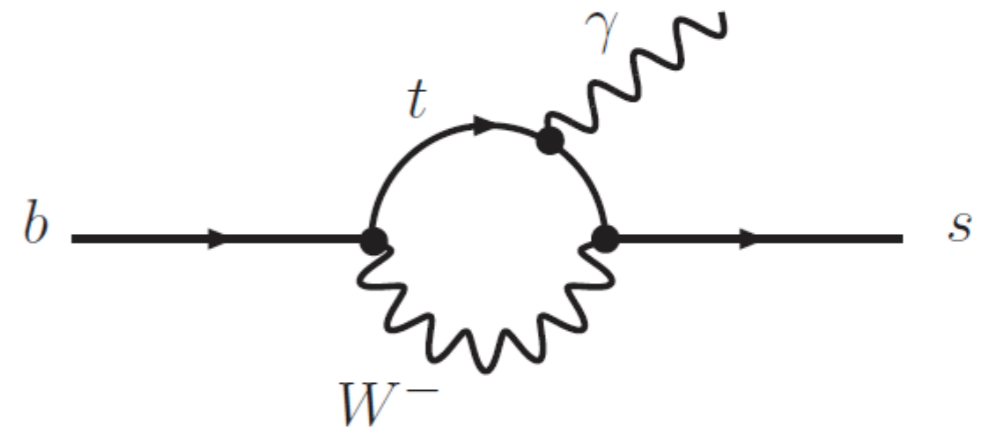**Instant luminosity reached so far by SuperKEKb ~10^{33} cm^{-2} s^{-1}**

Physics program

- Precision measurement of the Unitarity Triangle angles and CKM matrix elements.

- New CP violation sources through time-dependent/integrated asymmetry measurements.
- Flavour Changing Neutral Current (FCNC) studies
- Search for Lepton Flavour Violation (LFV)
- Dark sector investigation
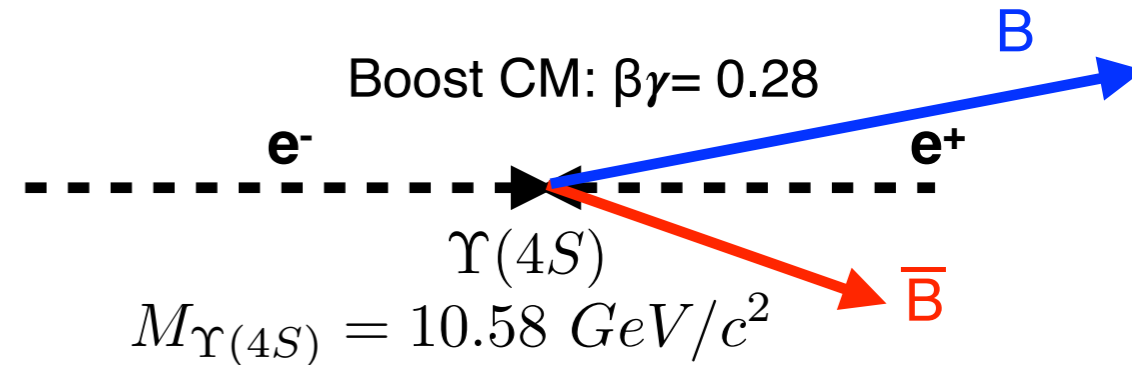- Hadronic spectroscopy and quarkonium studies

details…

Belle II exclusive advantages

- Coherent production of two B mesons from Y(4S) resonance
- "Clean" environment w.r.t. experiments using hadronic machine:
  - Large data samples with B, D and τ with low background
  - Analysis of decays with missing energy
- Good reconstruction efficiency and resolution for neutral particles as γ, K, π^0

coherent state

Boost CM: $\beta\gamma$ = 0.28

e⁻   e⁺

B

$\overline{B}$

$\Upsilon(4S)$

$M_{\Upsilon(4S)} = 10.58 \; GeV/c^2$

details..

Belle II

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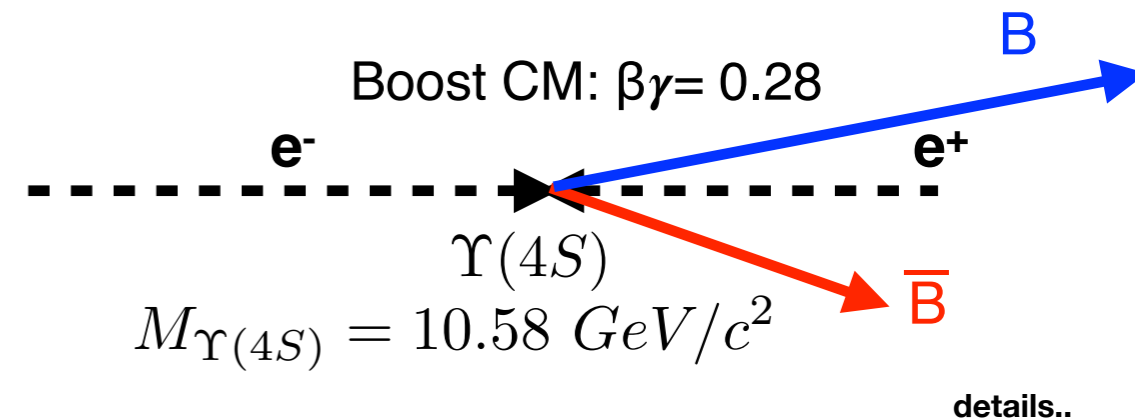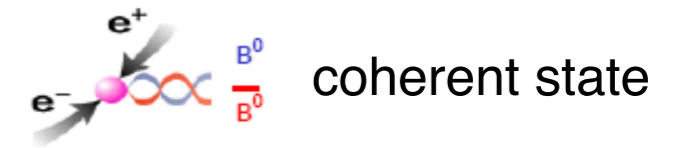
Full Event Interpretation (FEI)

Full reconstruction of one B meson decay (B_{tag}) → determination of the flavour of the other B (B_{sig}) and isolation of particles coming from the signal side → (large advantages in analysis with missing energy/mass)

Reconstruction efficiency:

- 1.5% semi-leptonic tag: more efficient but less precise
- 0.3% hadronic tag: less efficient but more precise

tag side

Signal side

π^+

K^-

D^0

B_{tag}^-

$\Upsilon(4S)$

B_{sig}^+

π^-

γ

l^+

ν_l
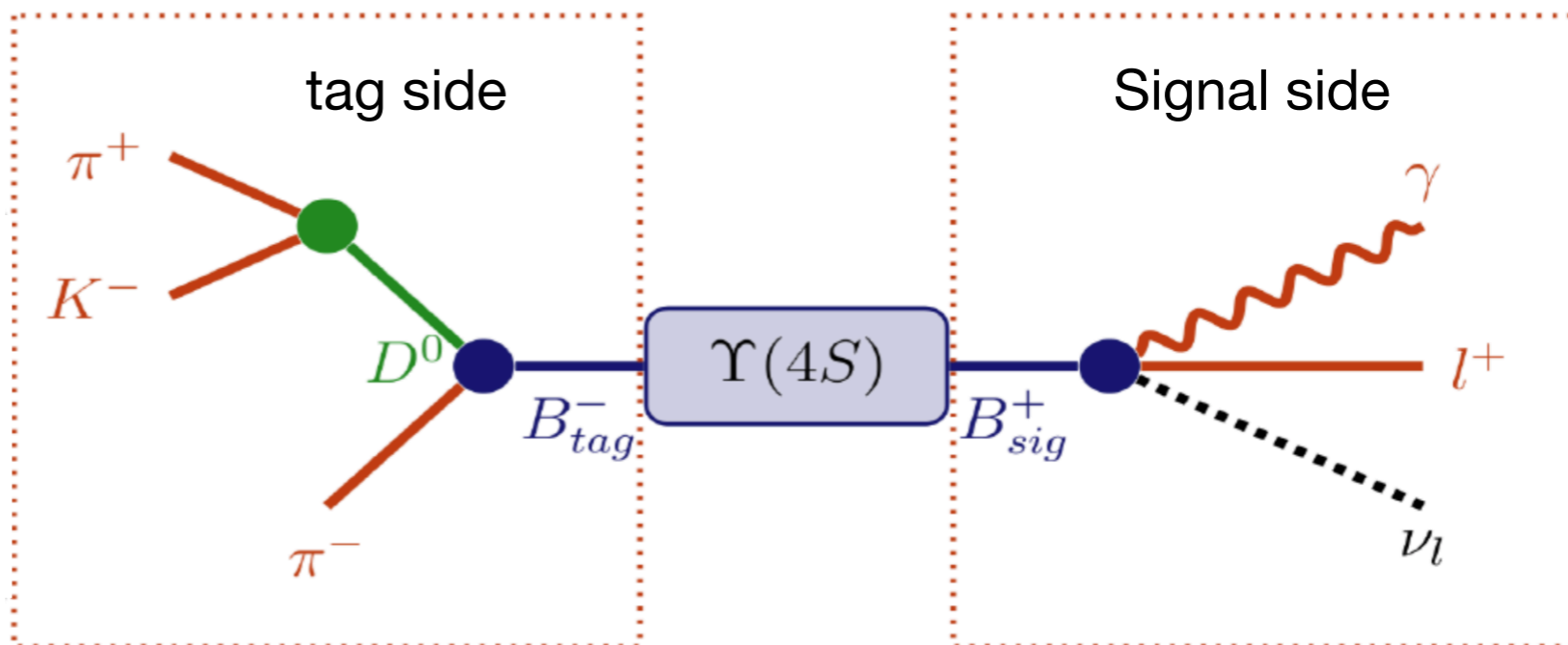
Lepton flavour violation in τ decays
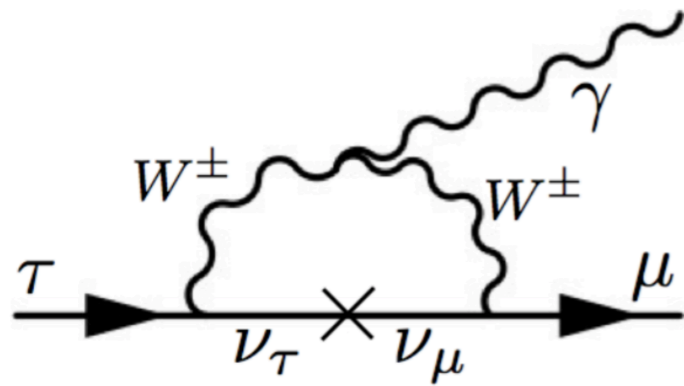
SM prediction:

$$BF(\tau \to l\gamma) \sim 10^{-40}$$

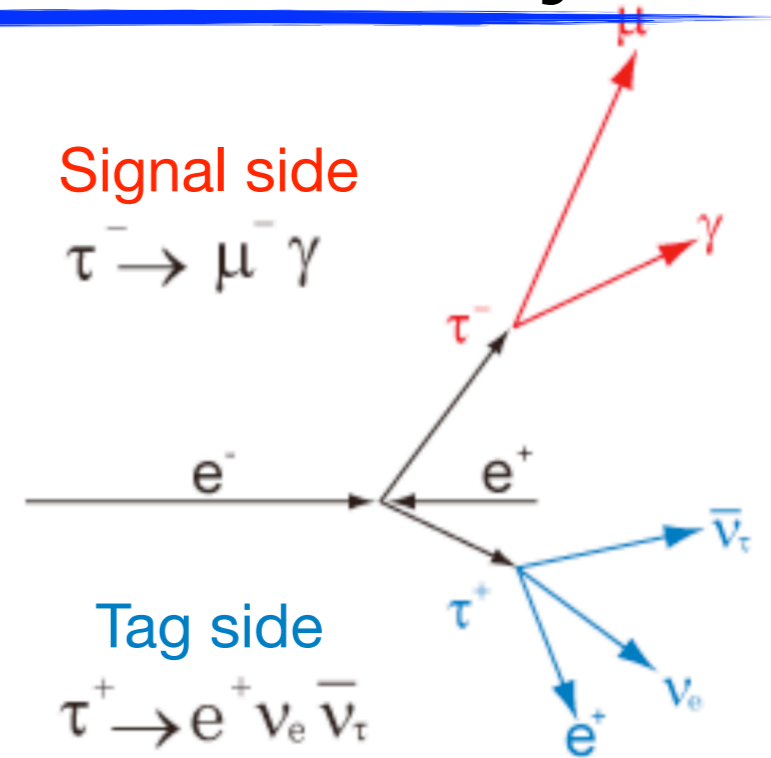**Studied only at the B-factory**

LHCb not competitive
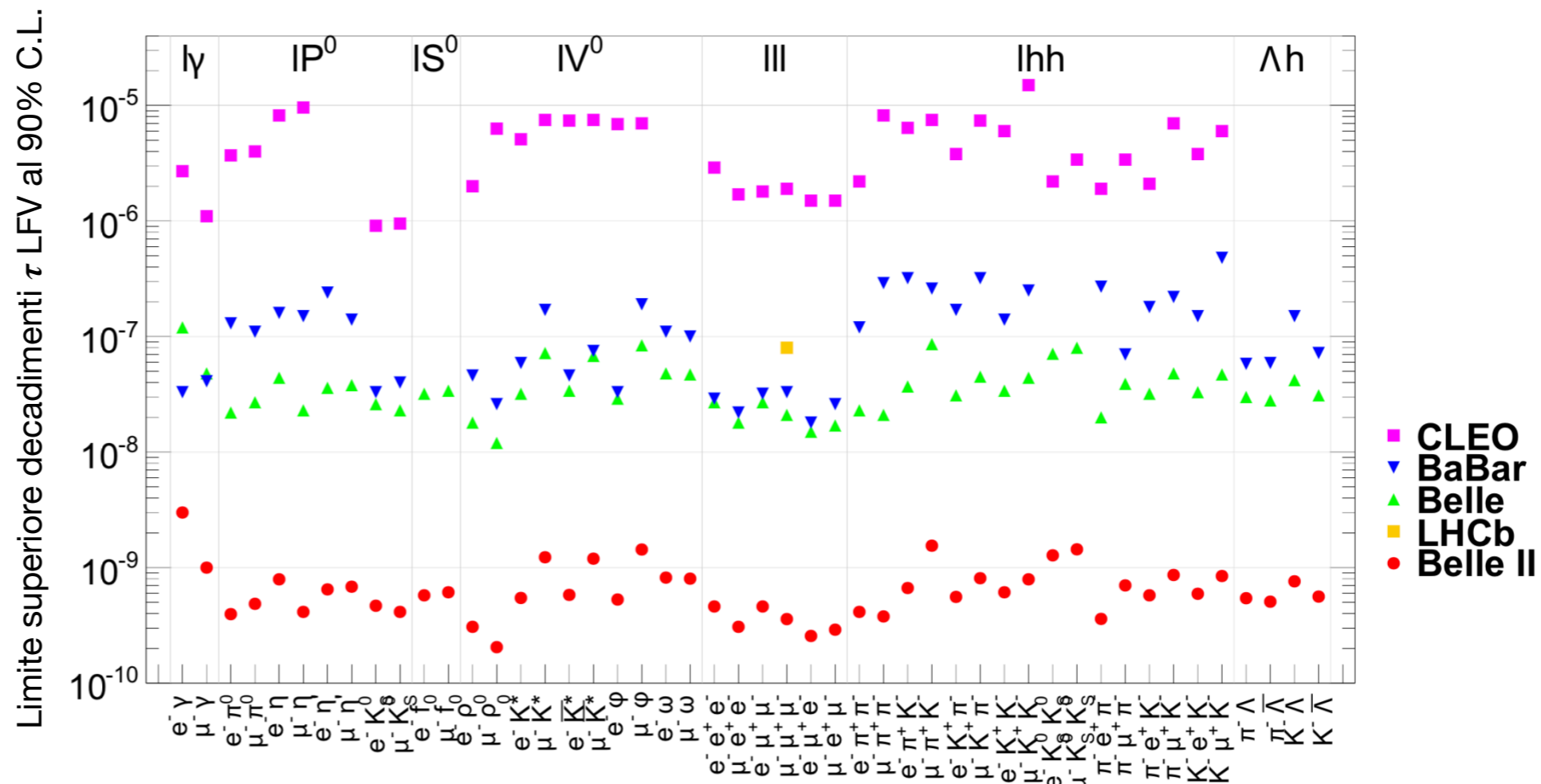
details..

Signal side

$$\tau^- \to \mu^- \gamma$$

Tag side

$$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$$

Belle II expectations:

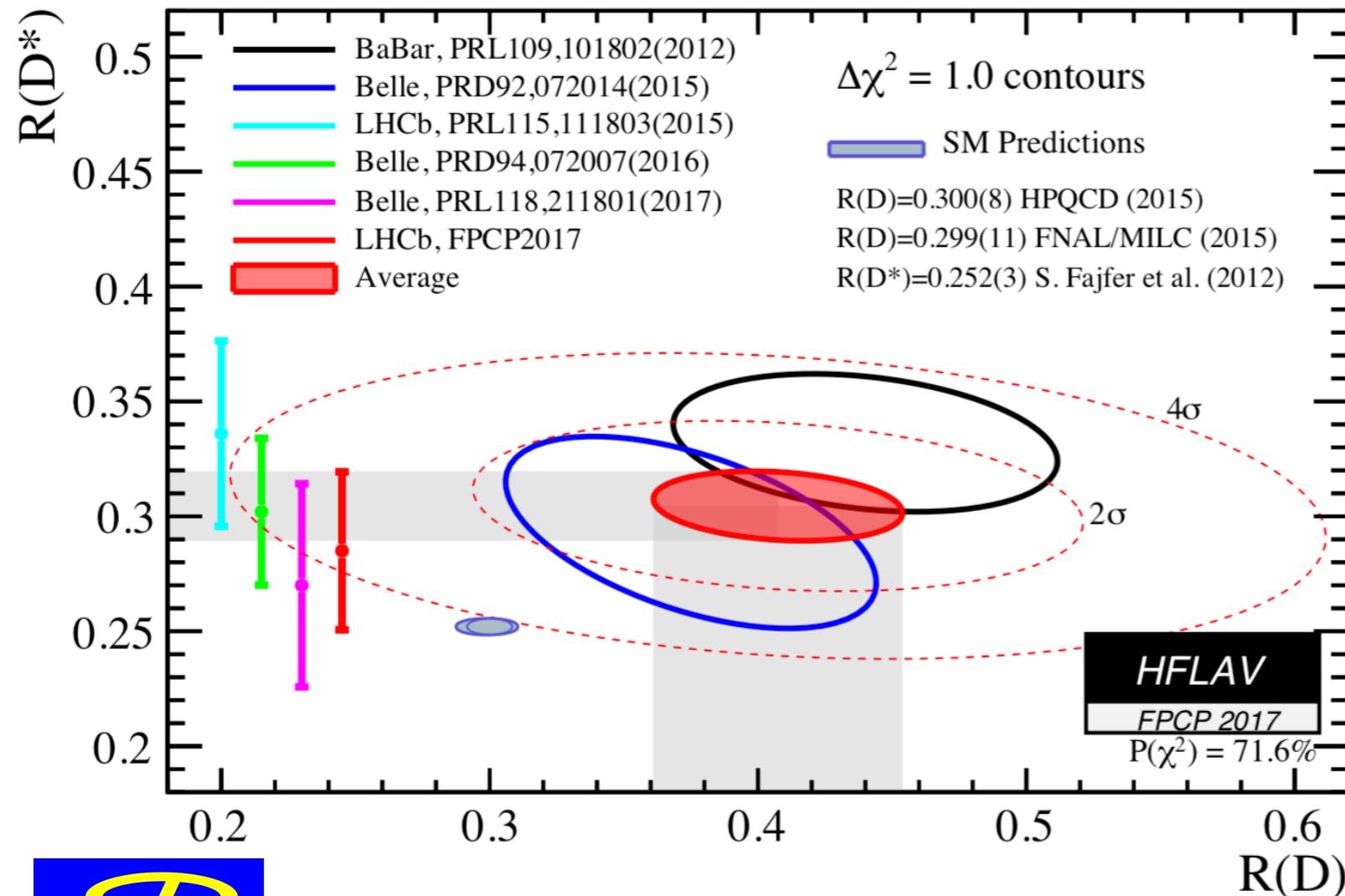Improvement of ≲2 order of magnitude w.r.t. the actual limits

Belle II

Flavour anomalies in R(D*) and R(D)

Observables:

$$R(D^*) = \frac{BF(B \to D^* \tau\ \nu)}{BF(B \to D^* \mu\ \nu)} \stackrel{SM}{=} 0.252 \pm 0.003$$

4.1σ SM disagreement

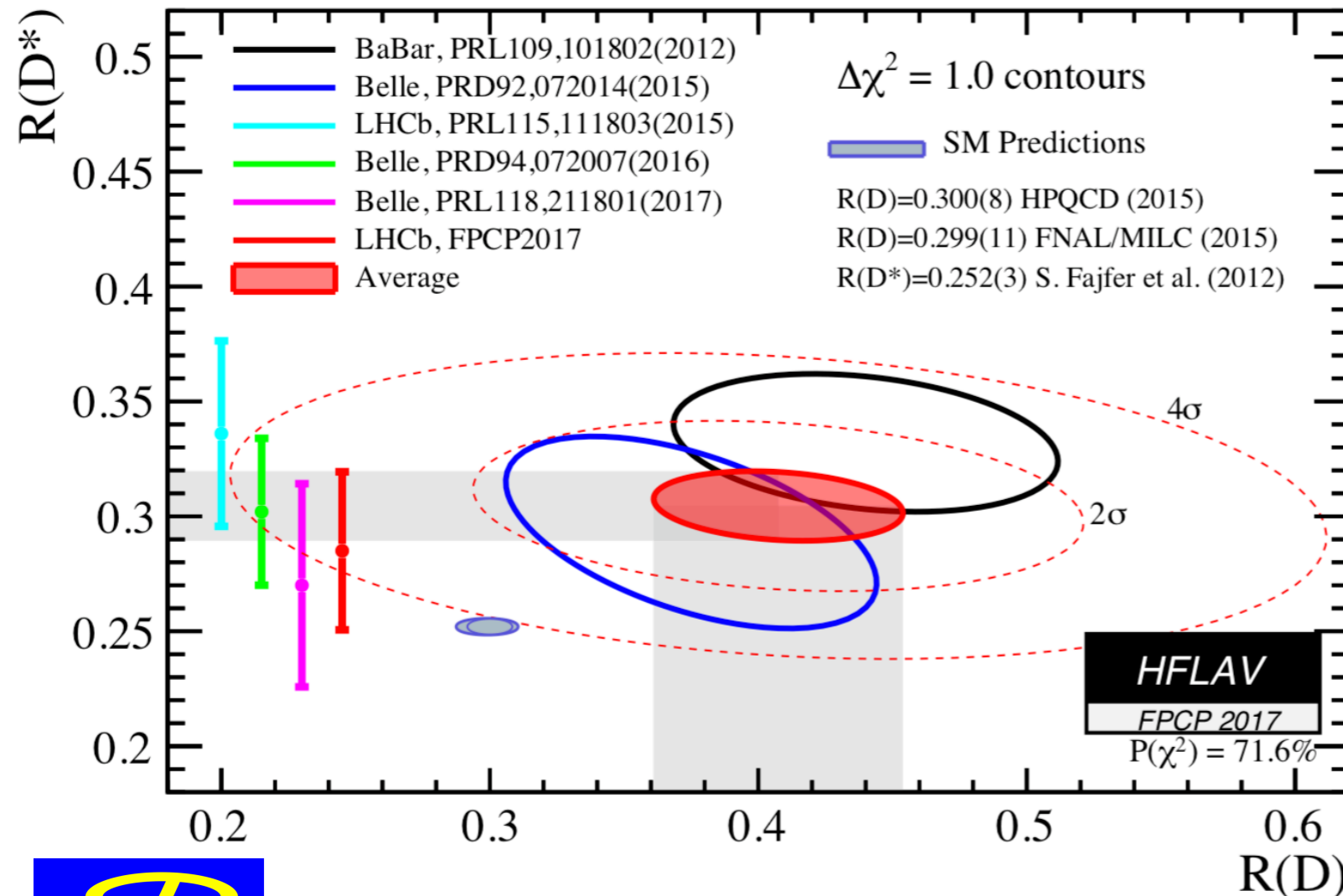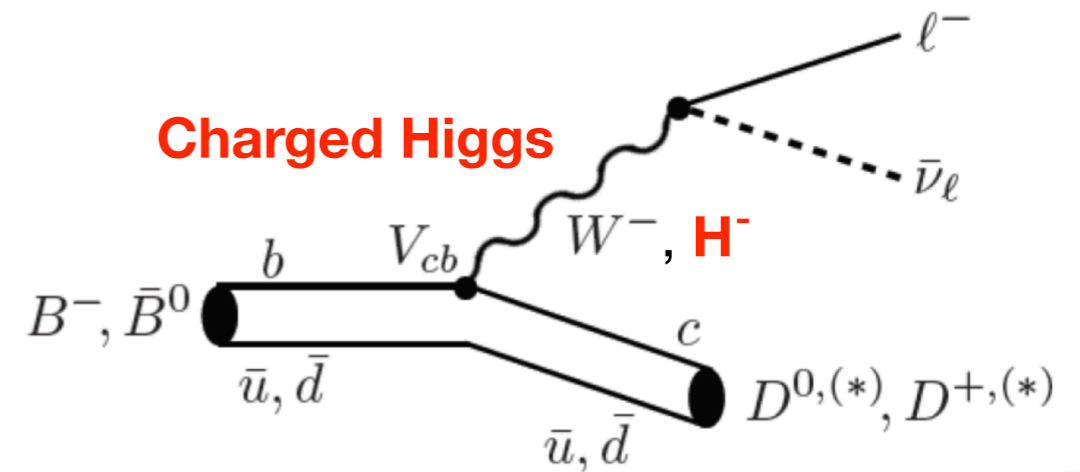# Flavour anomalies in R(D*) and R(D)

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Charged Higgs

4.1σ SM disagreement

It could be explained through the existence of charged Higgs or other New Physics models

More details in Mario Merola's talk

Belle II

more..

Dark sector

Minimal model introducing the dark interaction comprises:

- A': dark photon. Boson mediator of the dark interaction with mass $m_{A'}$ and spin 1
- ε: coupling parameter. It indicates the coupling intensity between the dark photon and the SM photon

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- ε: coupling parameter. It indicates the coupling intensity between the dark photon and the SM photon
- $\chi_{1,2}$: dark matter particles

A' decay into invisible states

At the moment, this analysis can be performed by Belle II thanks to the single photon dedicated trigger.
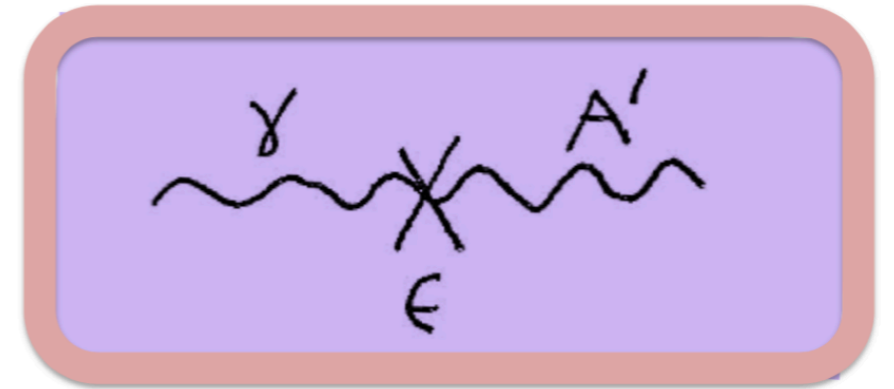

Possible phase 2 analysis $\mathscr{L}^{int}$=20 fb⁻¹

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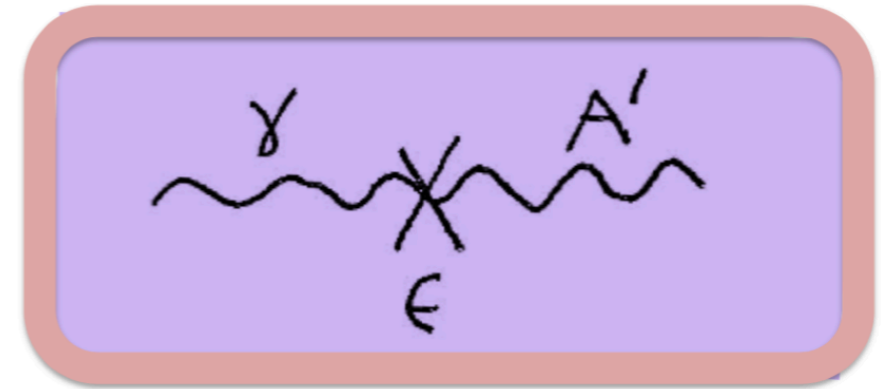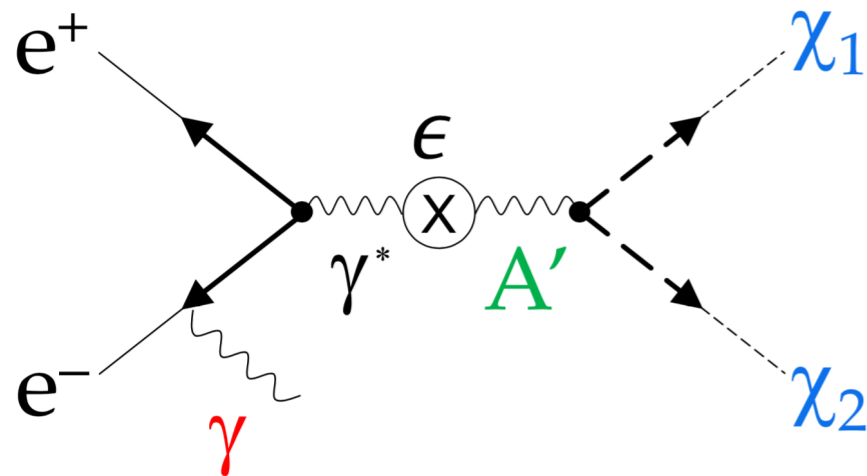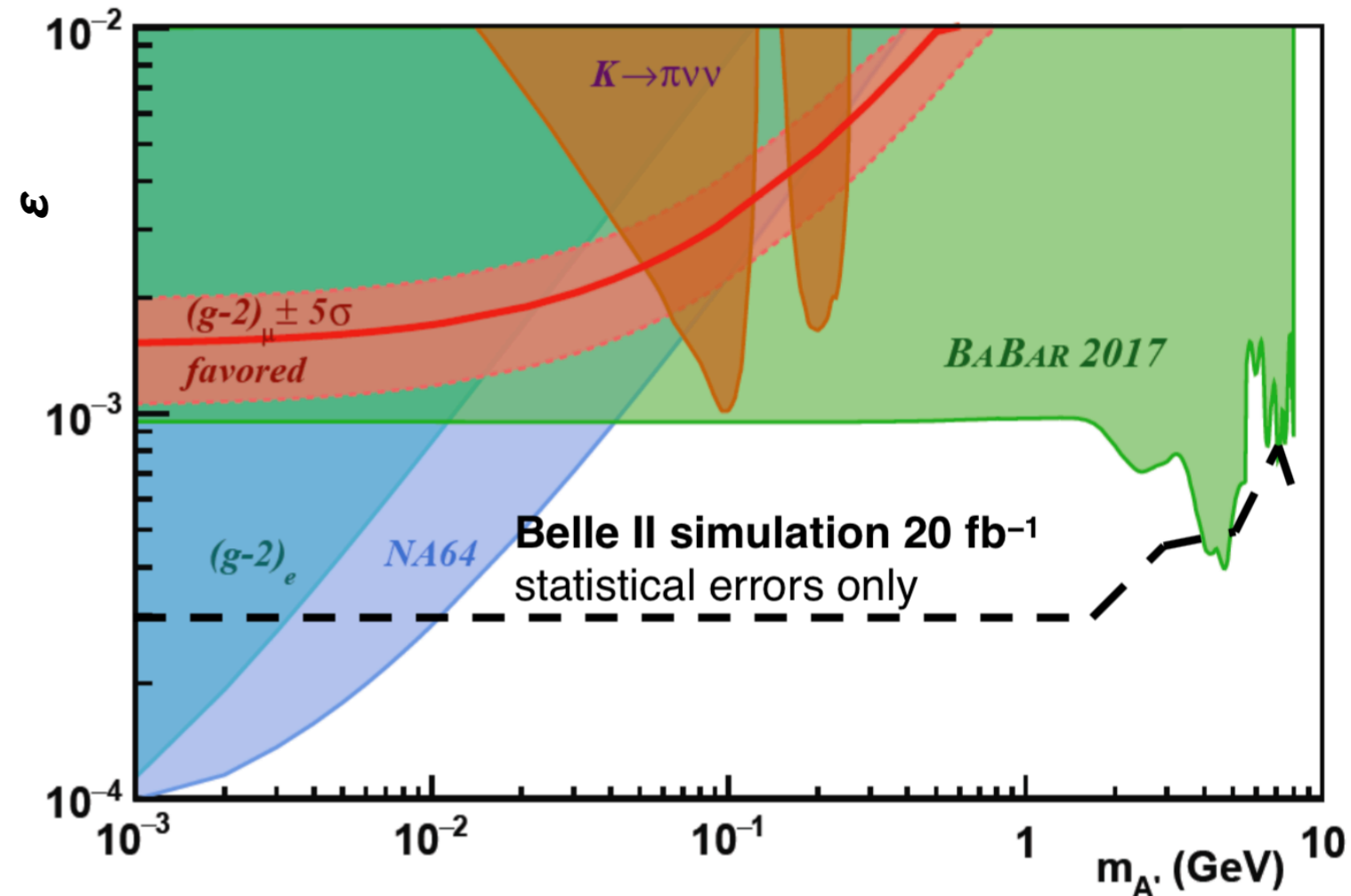
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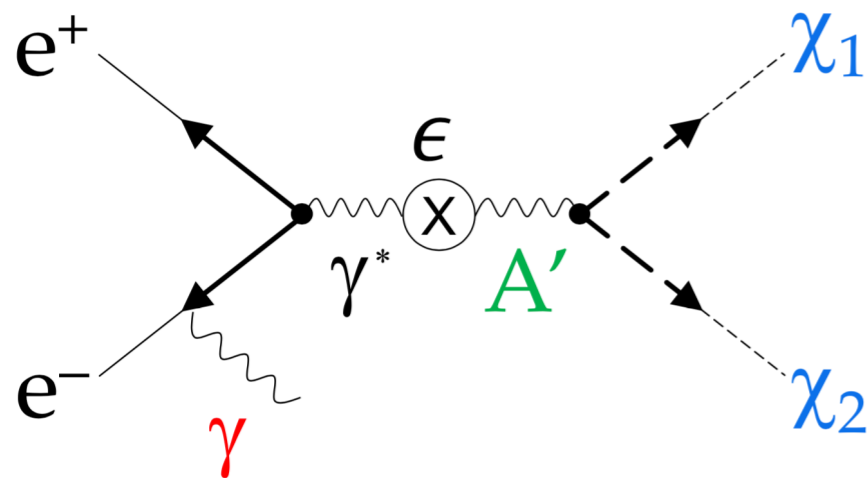
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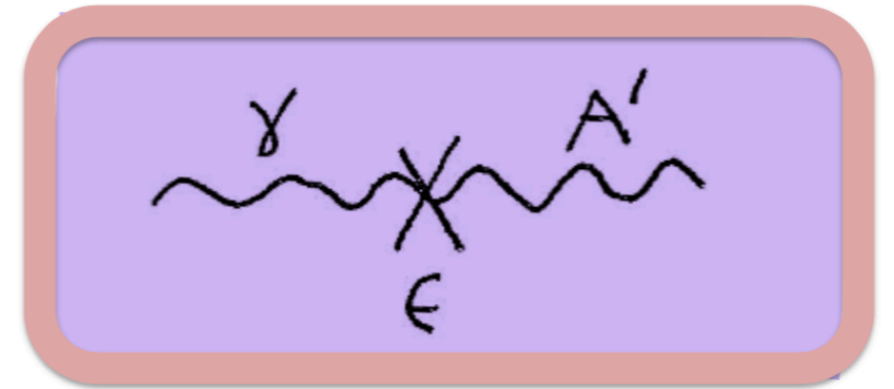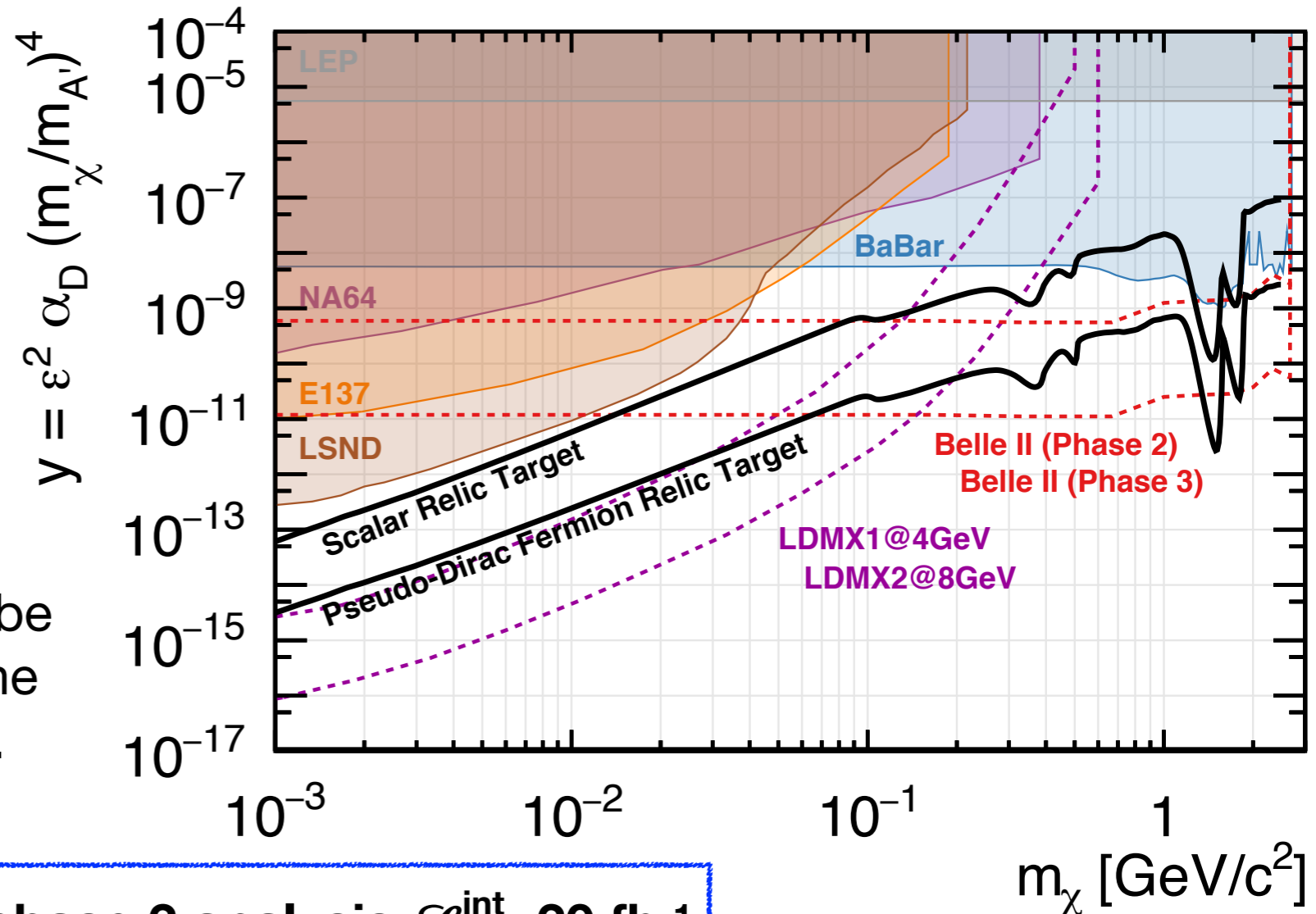
Possible phase 2 analysis $\mathscr{L}^{int}$=20 fb^{-1}

Conclusions

- New collider SuperKEKB $\rightarrow$ $\mathscr{L}^{int}$ = 50 ab^{-1} before 2026

- Improved detector performances: good neutral particle reconstruction, resonances, decay vertices and events with high missing energy.

- Fundamental physics studies: CKM matrix, CPV, LFV, FCNC, dark sector.

- Installation and insertion of the detector: 11 April 2017

- Current status, phase 2: first data analysed without vertex detector.

- Phase 3: data taking will start in February 2019 with the whole detector installed.

Belle II

Belle II insertion
11 April 2017

First physics event!!
25 April 2018

Belle II

Super KEKB
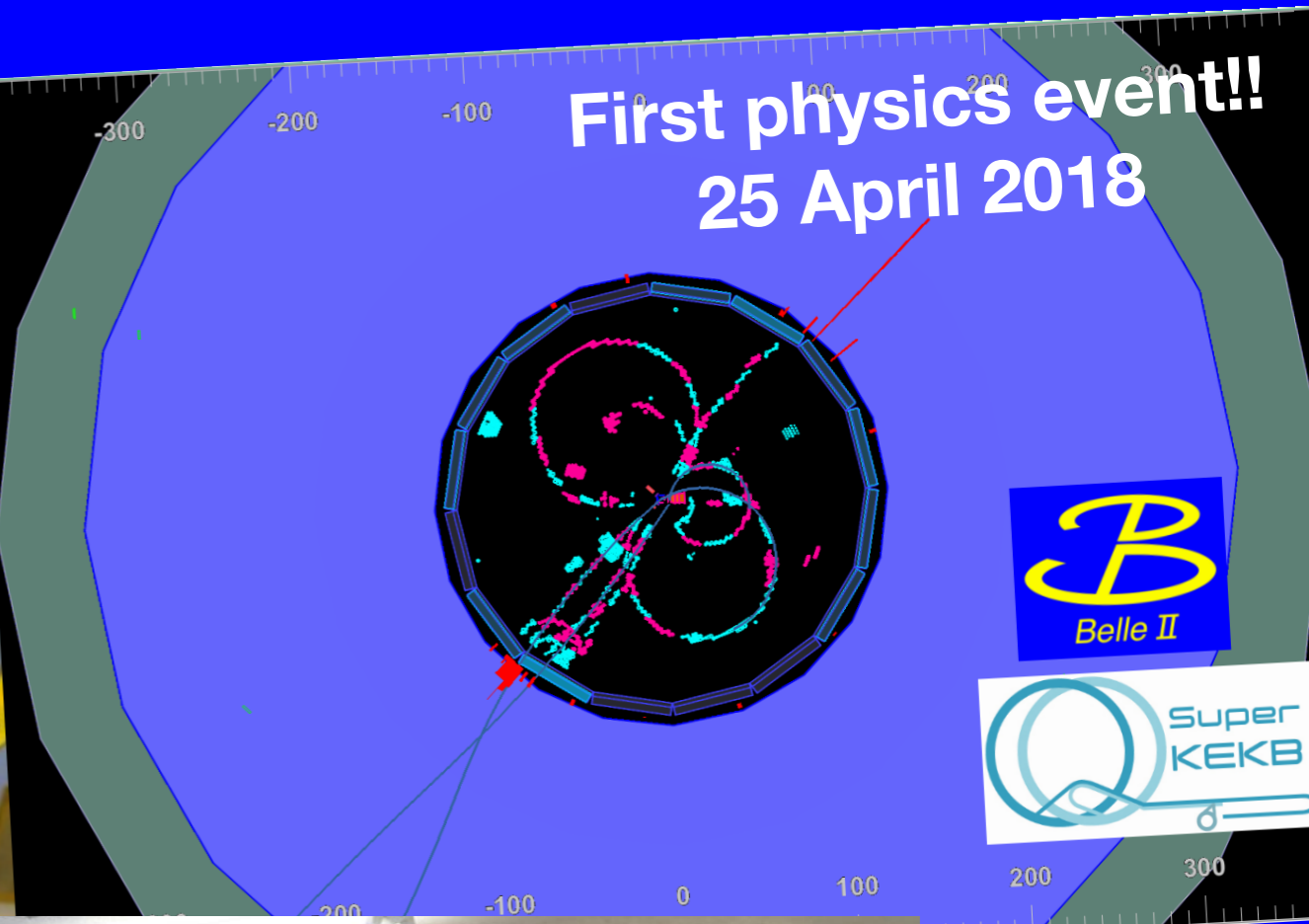
Emergency slides!!

Accessible channels and σ at Belle II

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$ Υ(4S)	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

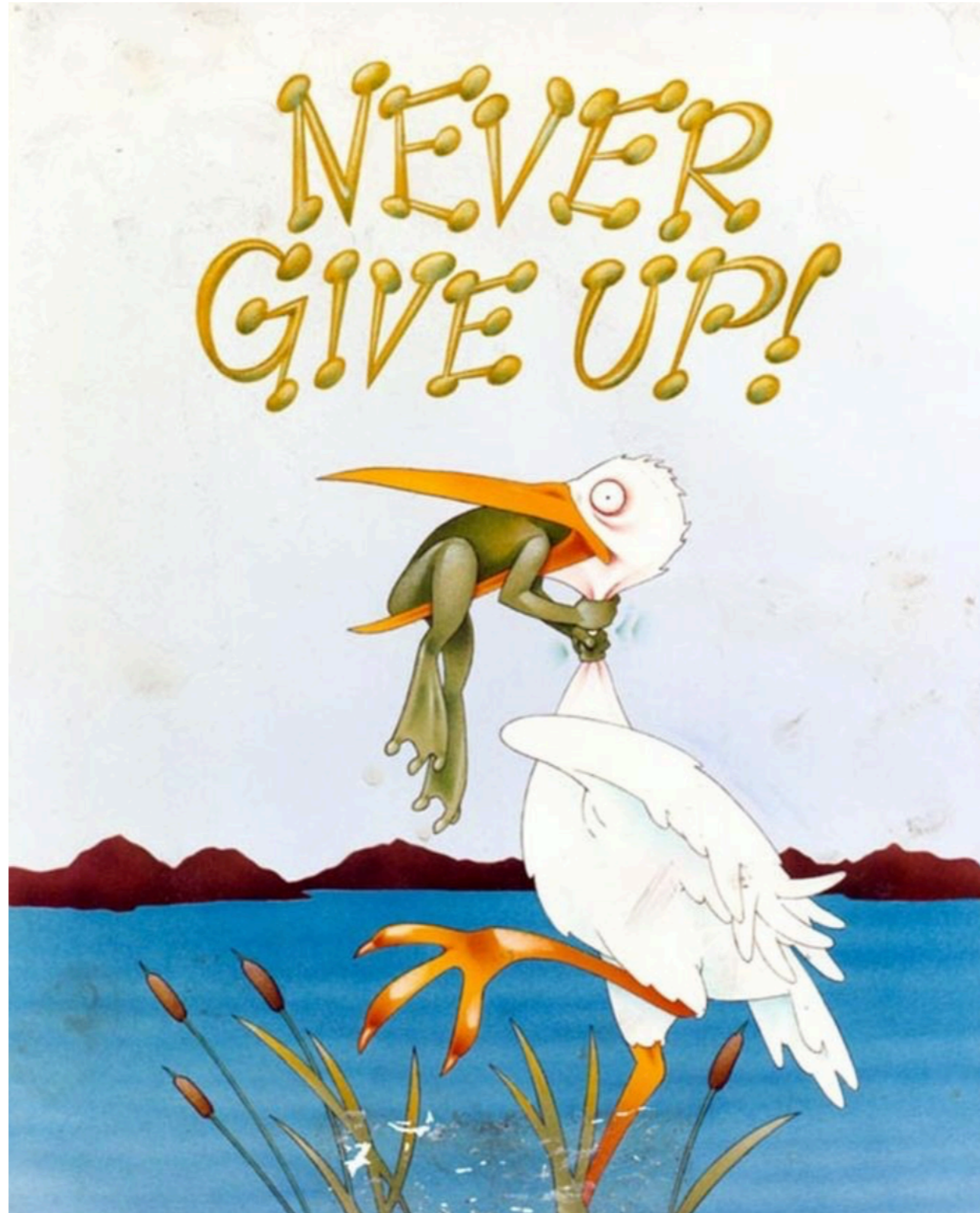Number of particles produced, assuming 100% of beam on each resonance.

Process	Cross section (nb)	Rate (Hz)
$\Upsilon(4S) \to B\bar{B}$	1.2	960
$e^+e^- \to$ continum	2.8	2200
$\mu^+\mu^-$	0.8	640
$\tau^+\tau^-$	0.8	640
Bhabha ($\theta_{\text{lab}} \geq 17°$)	44	350 [a]
$\gamma\gamma$ ($\theta_{\text{lab}} \geq 17°$)	2.4	19 [a]
2γ processes [b]	~ 80	~ 15000
Total	~ 130	~ 20000

Total event rate: 20 KHz allowed, thanks to improved detector system performances.

[a] Rate is pre-scaled by a factor 1/100

[b] $\theta_{\text{lab}} \geq 17°$, $p_t \geq 0.1 \text{GeV}/c$

back..

CM boost

B

$E_{e^+} \simeq 4GeV$
$E_{e^-} \simeq 7GeV$ $\Longrightarrow$

e⁻

e⁺

$\Upsilon(4S)$

$\overline{B}$

$M_{\Upsilon(4S)} = 10.58 \; GeV/c^2$
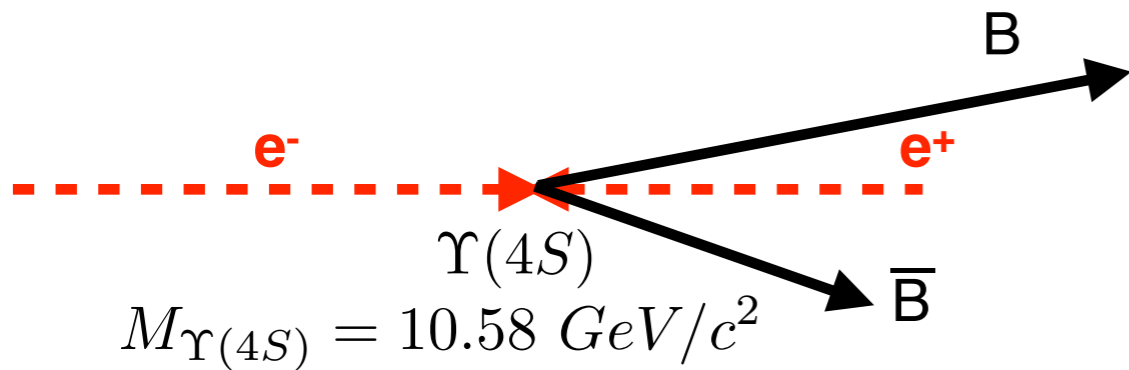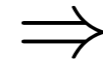
- E$_{CM}$ at the resonance of $\Upsilon(4S)$

- Center of mass boost:
  $\beta\gamma = 0.28$

Symmetric beams:

$\beta\gamma \simeq 0.06 \longrightarrow \Delta r \simeq 30\mu m$

Asymmetric beams:

$\beta\gamma \simeq 0.28 \longrightarrow \Delta z = \beta\gamma \cdot c \cdot \tau \simeq 130\mu m$

**Decay vertex can not
be resolve.**

**Decay vertex can be
resolved.**

Belle CM boost: $\beta\gamma = 0.425$ → more separation but less luminosity.

back..

Lepton flavour violation in τ decays (I)

Ratios of BFs of τ LFV decays allow to discriminate NP models!

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	Non-universal Z'
$\dfrac{\mathcal{B}(\tau \to \mu\mu\mu)}{\mathcal{B}(\tau \to \mu\gamma)}$	$\sim 2*10^{-3}$	0.06-0.1	0.4-2.3	~16
$\dfrac{\mathcal{B}(\tau \to \mu ee)}{\mathcal{B}(\tau \to \mu\gamma)}$	$\sim 1*10^{-2}$	$\sim 1*10^{-2}$	0.3-1.6	~16
$\mathcal{B}(\tau \to \mu\gamma)_{max}$	$<10^{-7}$	$<10^{-10}$	$<10^{-10}$	$<10^{-9}$

Belle II

$B \longrightarrow K^{*0}\nu\bar{\nu}$

SM prediction box diagram + penguin:

$$BF_{SM}(B \longrightarrow K^{*0}\nu\bar{\nu}) = (9.48 \pm 1.10) \cdot 10^{-6}$$
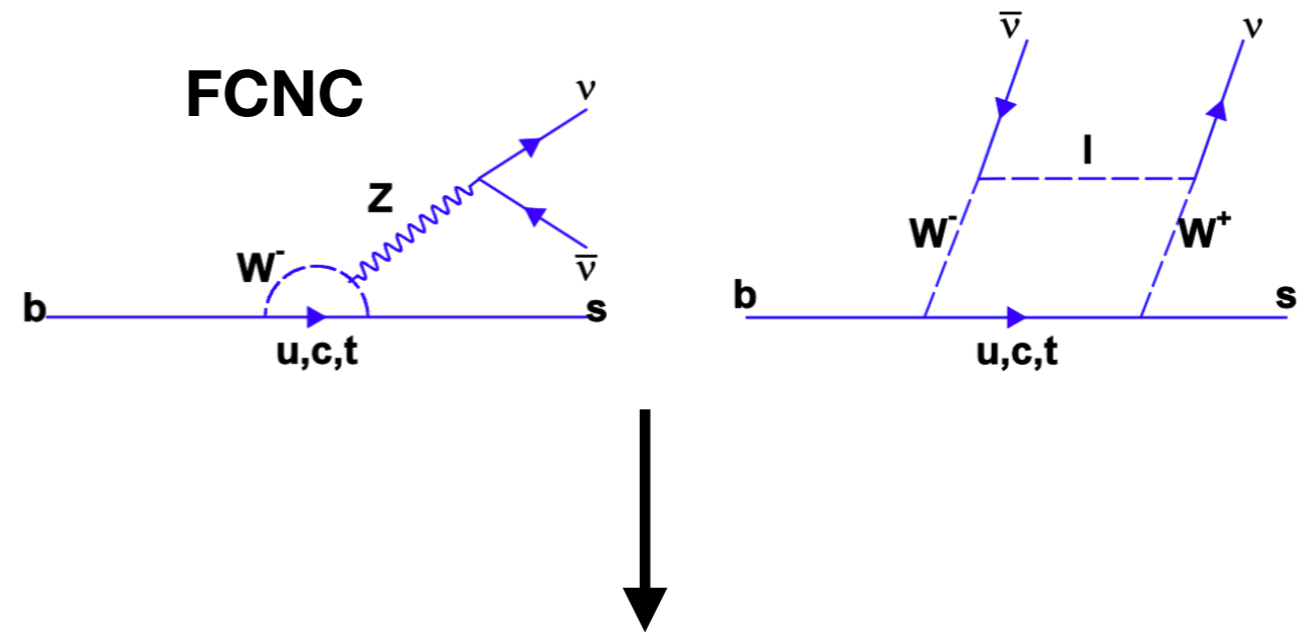
FCNC

Upper limit measured at Belle:

$$BF_{Belle}(B \longrightarrow K^{*0}\nu\bar{\nu}) < 5.5 \cdot 10^{-5}$$

Could lead to New Physics!

SM validity can be proved at 5σ through the decay rate
measurement using the whole Belle II statistic: $\mathscr{L}^{int}$=50 ab⁻¹

Belle II

$$B^0 \longrightarrow K^{*0}\mu^+\mu^-$$

FCNC: b → s transitions | Possible New Physics | Angular analysis (using P'_5) chosen to reduce theoretical uncertainties
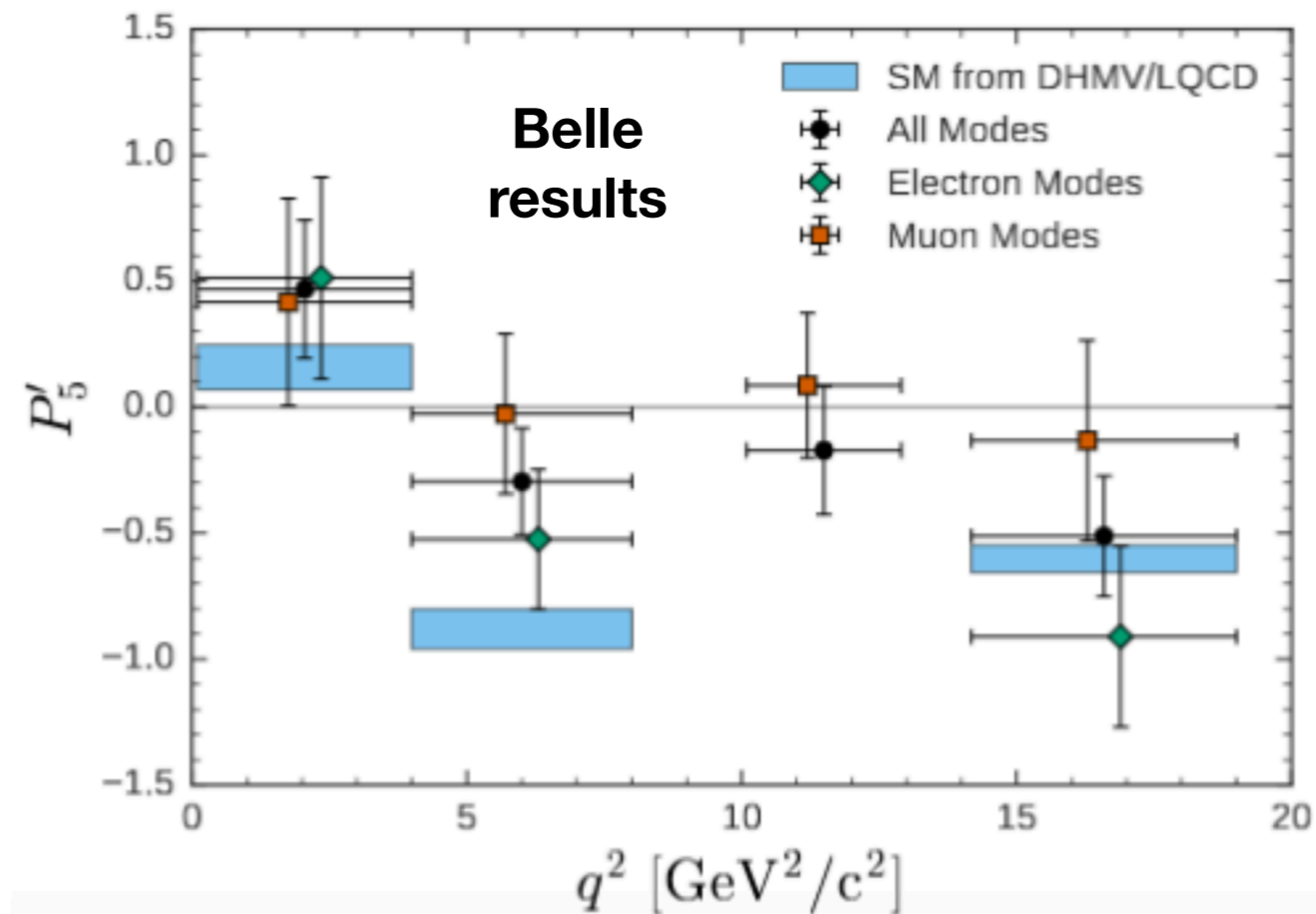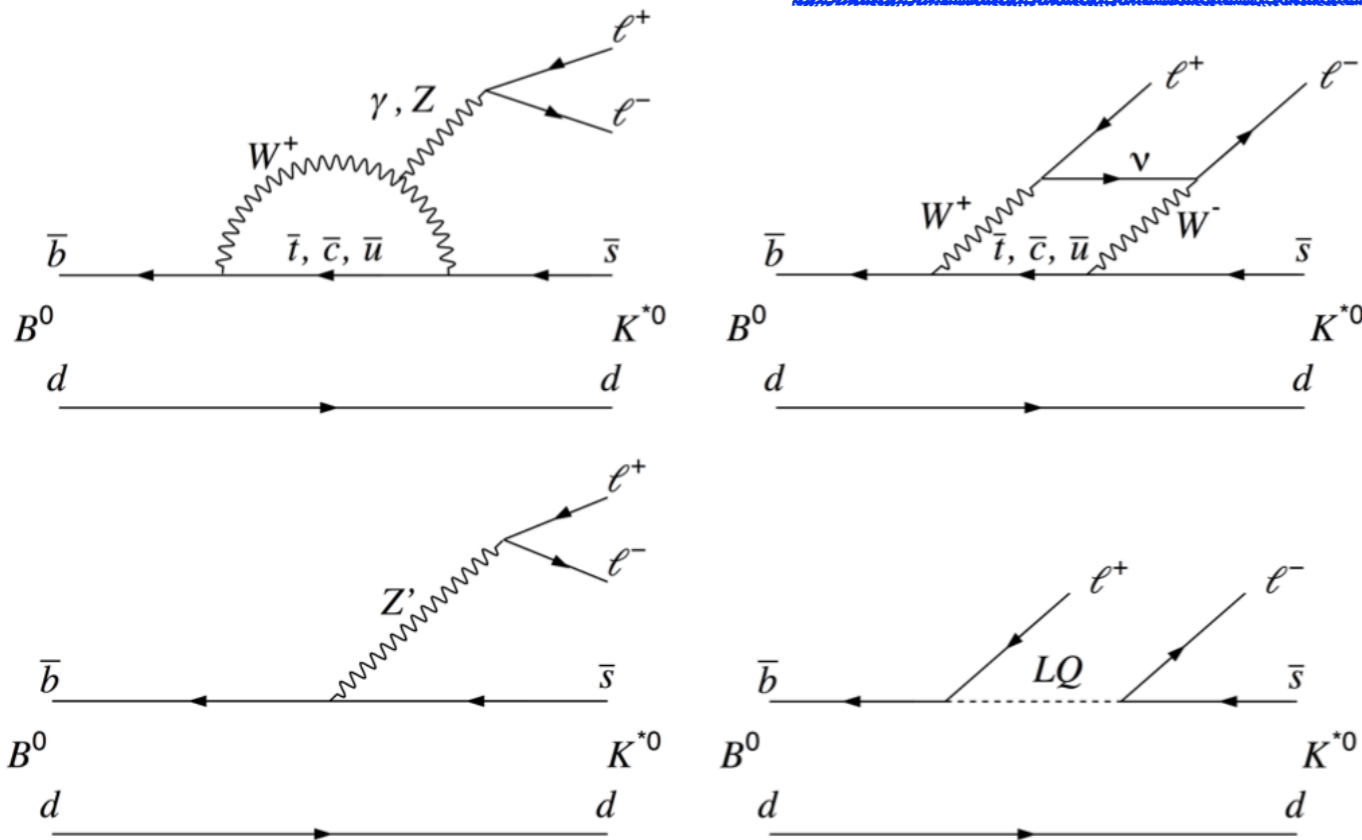
Previous analysis done by the Belle experiment shows a discrepancy of P₅' parameter within a certain q² range of ~2.6σ in the SM→ **comparable results with LHCb analysis.**

$B^0 \longrightarrow K^{*0}\mu^+\mu^-$

$$R_{K^{(*)}} = BR(B \to K^{(*)}\mu\mu)/(B \to K^{(*)}ee) \overset{SM}{\simeq} 1$$

FCNC: b → s transitions | Possible New Physics

Belle II projection sensitivity on R$_{K*}$:
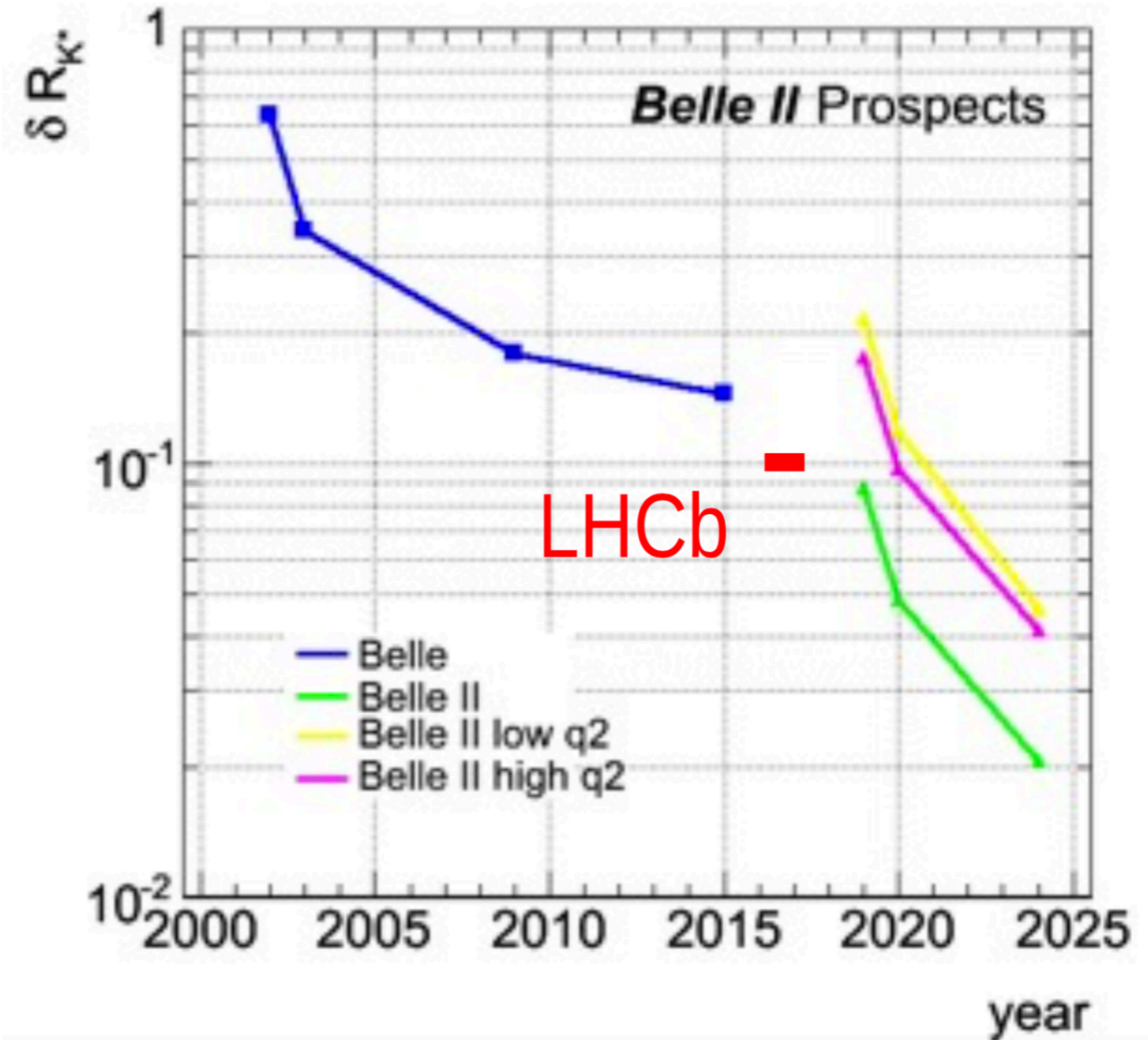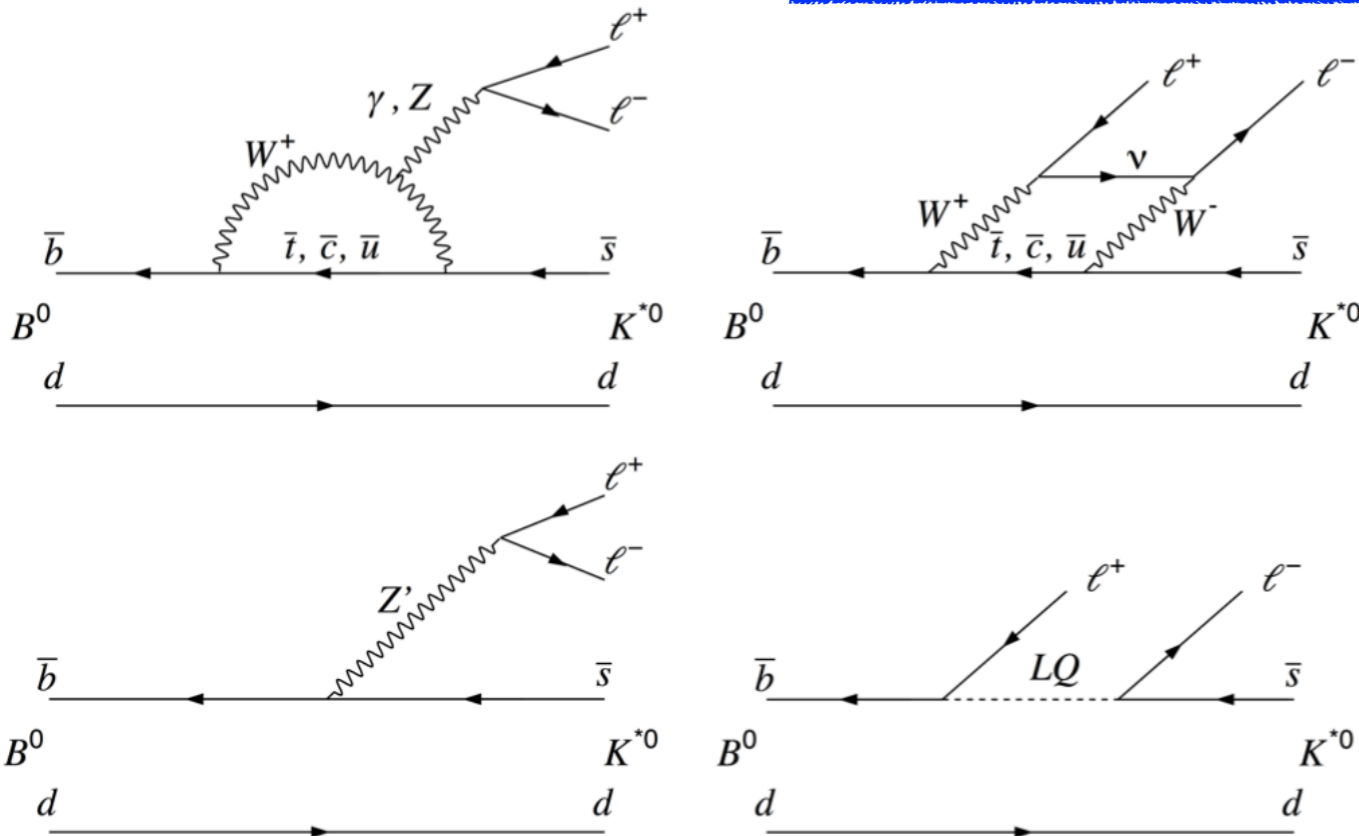
Belle II experiment contribution will be crucial for that measurement!

Hadronic spettroscopy

Bottomonium mass spectrum

Real interest at Υ(6S)

M.B. Voloshin, Radiative transitions from Y(5S) to molecular bottomonium, Phys. Rev. D 84, 031502(R) (2011)

h_b(1P) $\pi^+\pi^-$

Z_b(10610) and Z_b(10650)

PRL 108, 122001 (2012)

First Observation of the P-Wave Spin-Singlet Bottomonium States h_b(1P) and h_b(2P)

PRL 108, 032001 (2012)
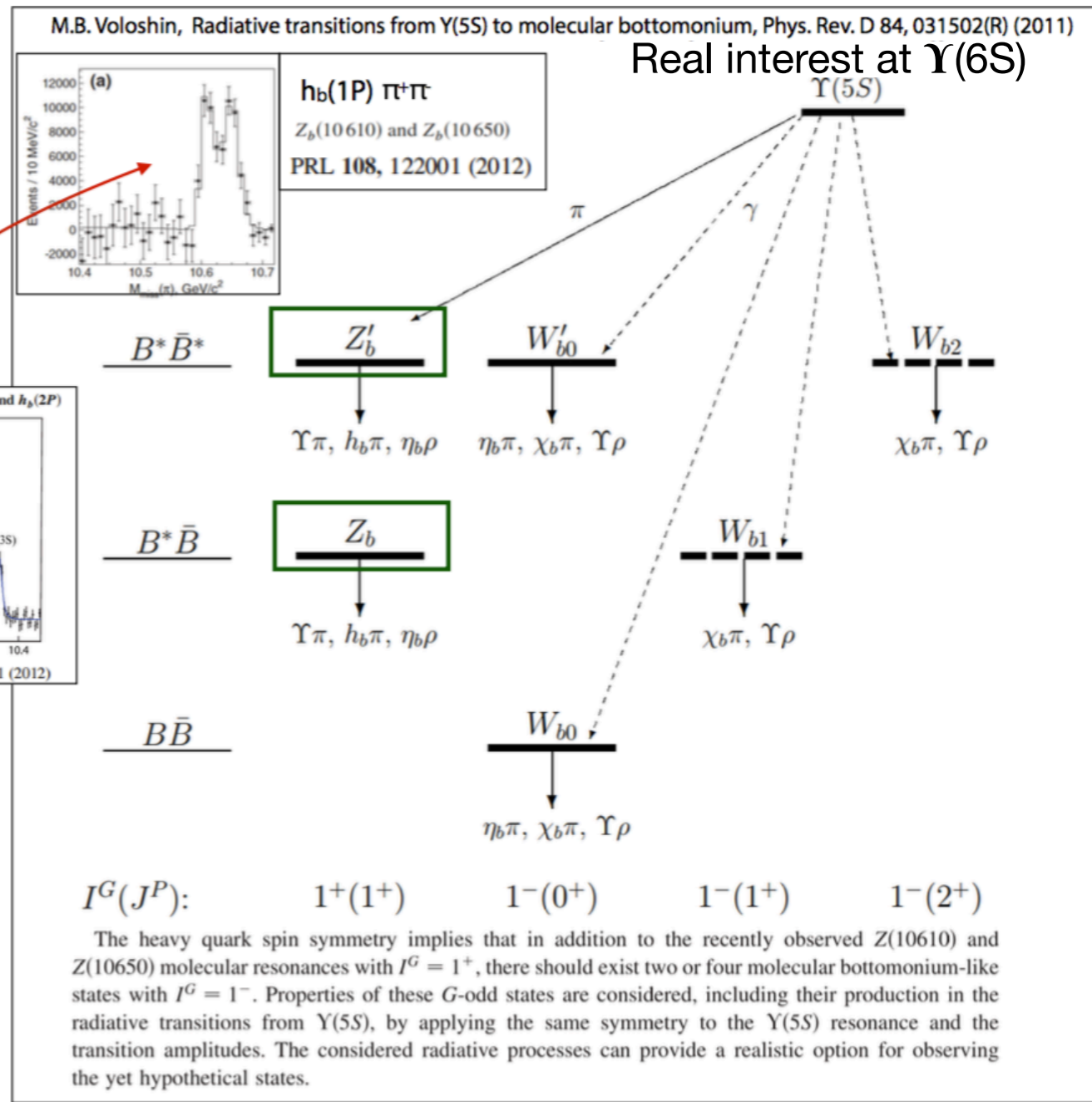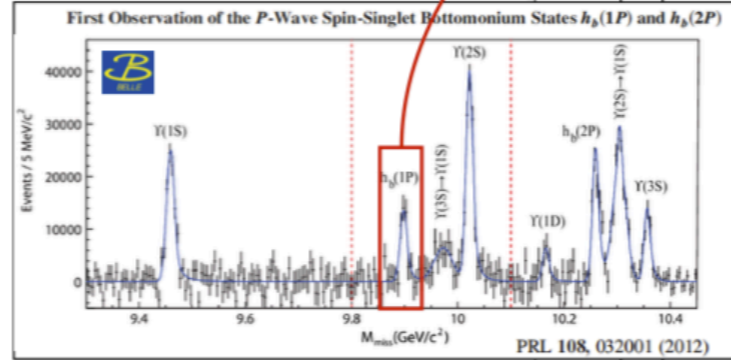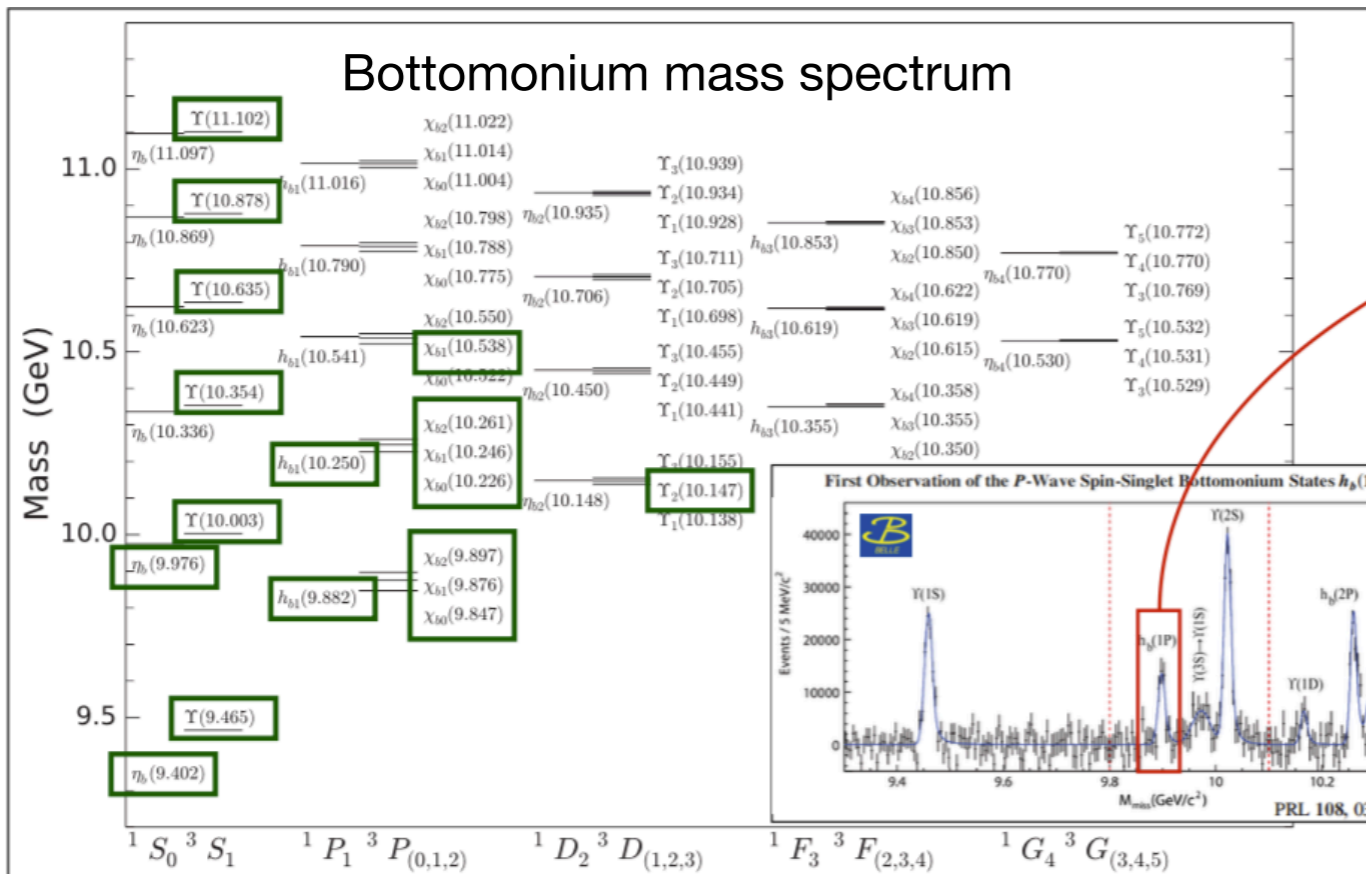
S. Godfrey and K. Moats, Bottomonium mesons and strategies for their observation, Phys. Rev. D 92, 054034 (2015)
S. Godfrey and N. Isgur, Mesons in a relativized quark model with chromodynamics, Phys. Rev. D 32, 189 (1985).

Many intermediate states have been observed and many others have not

$I^G(J^P)$: $1^+(1^+)$ $1^-(0^+)$ $1^-(1^+)$ $1^-(2^+)$

The heavy quark spin symmetry implies that in addition to the recently observed Z(10610) and Z(10650) molecular resonances with $I^G = 1^+$, there should exist two or four molecular bottomonium-like states with $I^G = 1^-$. Properties of these G-odd states are considered, including their production in the radiative transitions from Y(5S), by applying the same symmetry to the Y(5S) resonance and the transition amplitudes. The considered radiative processes can provide a realistic option for observing the yet hypothetical states.

QCD knowledge at low energies is needed to interpretate possible New Physics signals.

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Complementary to LHCb

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert\ [K\to\pi\ell\nu]$	**	0.1%	K-factory
$\lvert V_{cb}\rvert\ [B\to X_c\ell\nu]$	**	1%	Belle II
$\lvert V_{ub}\rvert\ [B_d\to\pi\ell\nu]$	*	4%	Belle II
$\sin(2\phi_1)\ [c\bar{c}K_S^0]$	***	$8\cdot10^{-3}$	Belle II/LHCb
ϕ_2		$1.5°$	Belle II
ϕ_3	***	$3°$	LHCb
CPV			
$S(B_s\to\psi\phi)$	**	0.01	LHCb
$S(B_s\to\phi\phi)$	**	0.05	LHCb
$S(B_d\to\phi K)$	***	0.05	Belle II/LHCb
$S(B_d\to\eta'K)$	***	0.02	Belle II
$S(B_d\to K^*(\to K_S^0\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s\to\phi\gamma))$	***	0.05	LHCb
$S(B_d\to\rho\gamma))$		0.15	Belle II
A_{SL}^d	***	0.001	LHCb
A_{SL}^s	***	0.001	LHCb
$A_{CP}(B_d\to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B\to\tau\nu)$	**	3%	Belle II
$\mathcal{B}(B\to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d\to\mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s\to\mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B\to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B\to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B\to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s\to\gamma\gamma)$		$0.25\cdot10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K\to\pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K\to e\pi\nu)/\mathcal{B}(K\to\mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau\to\mu\gamma)$	***	$3\cdot10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$\arg(q/p)_D$	***	$1.5°$	Belle II

Both LHCb and Belle II are needed to cover all the precision flavour physics aspects.

LHCb:
- Decay channels with charged particles in the final state.
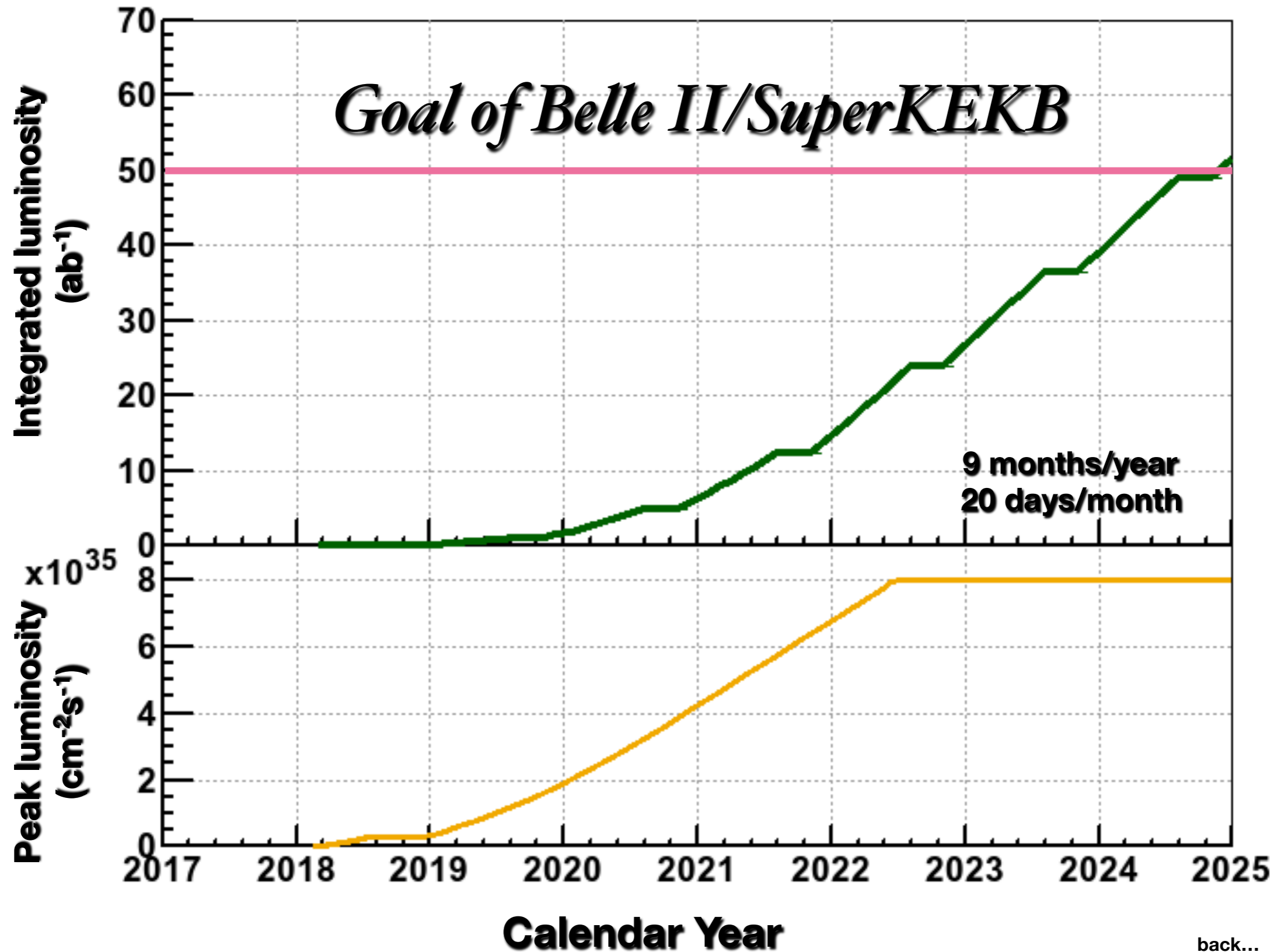
Belle II:
- Decay channels with some neutrinos or neutral particles in the final state;
- Inclusive decays;
- Decay channels involving long lived particles: K_S & K_L.

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B. Golob, KEK FF Workshop, Feb. 2012

SuperKEKB luminosity projection

Goal of Belle II/SuperKEKB

**9 months/year
20 days/month**

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Top installation
May 2016

Belle II insertion
11 April 2017

CDC installation
October 2016

First physics event!!
25 April 2018