INFN ROMA TRE
Istituto Nazionale di Fisica Nucleare
Sezione di Roma Tre

ROMA TRE
UNIVERSITÀ DEGLI STUDI

The Belle II Experiment: status and prospects

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IX Edition of the International Workshop on QCD theory and experiment, Matera, 26 June 2018

Belle II

Belle II: second generation B-factory (I)

Main experiments at B-factories of the past:

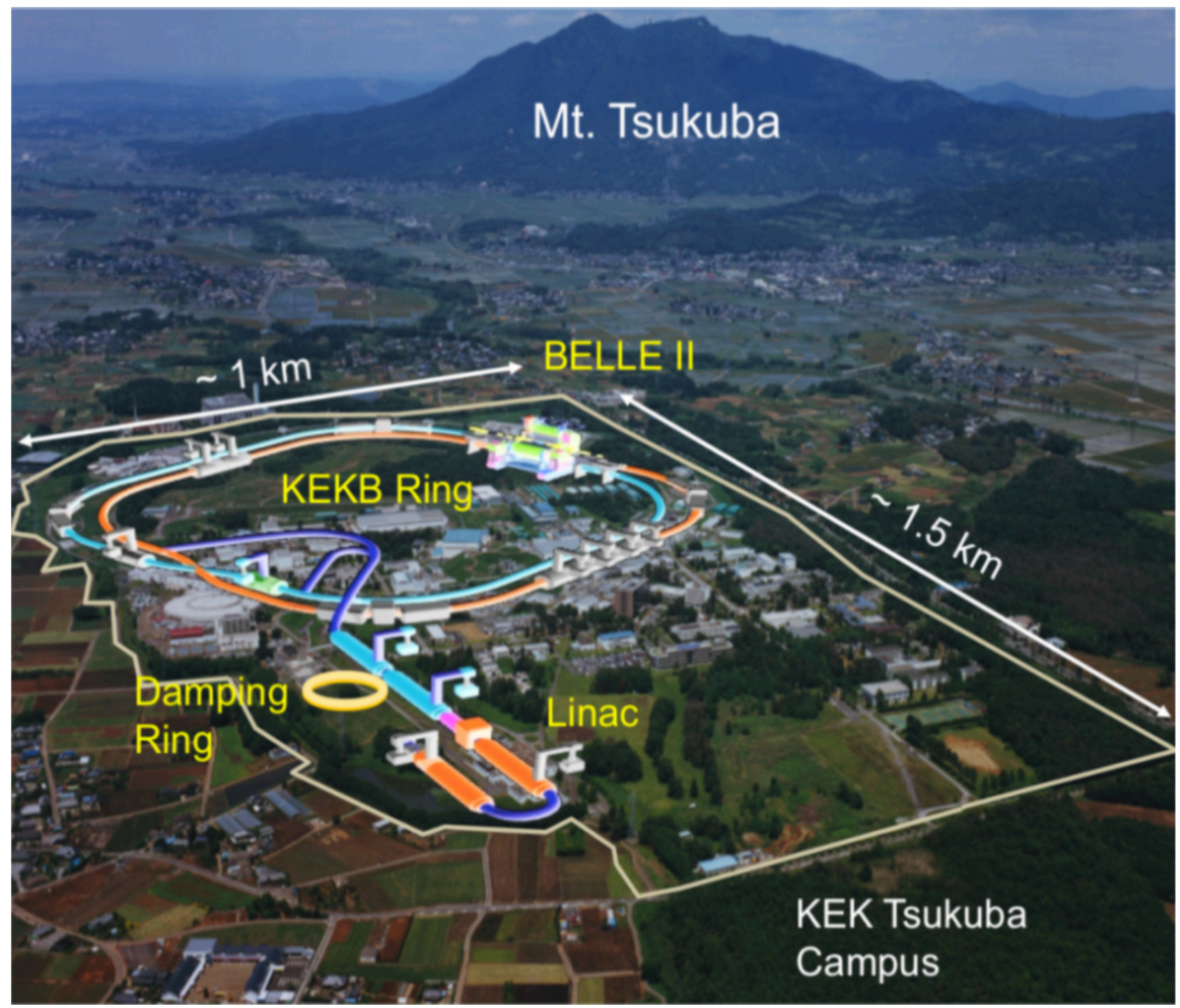
- Belle (KEK Laboratory, Japan)
- BaBar (SLAC Laboratory, California)

→ Important results: confirmation of the CKM mechanism in the SM, CP violation observation in the B meson system etc..

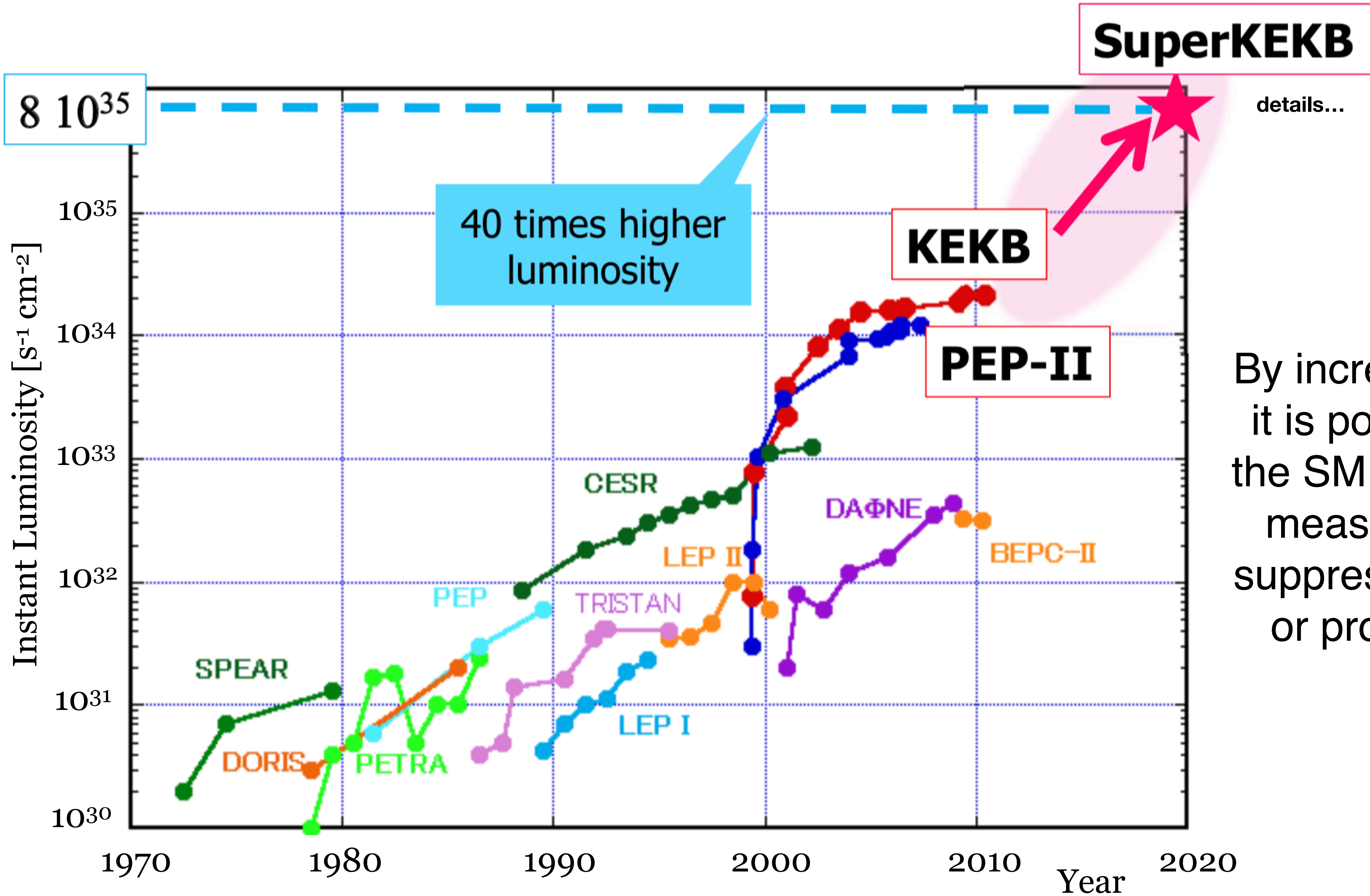
Main problem:
statistics collected by KEKB and PEP-II colliders was not sufficient to analyse some rare decays, SM validations and other highly precise measurements

↓

Belle II: usage of the improved collider SuperKEKB



Belle II: second generation B-factory (II)

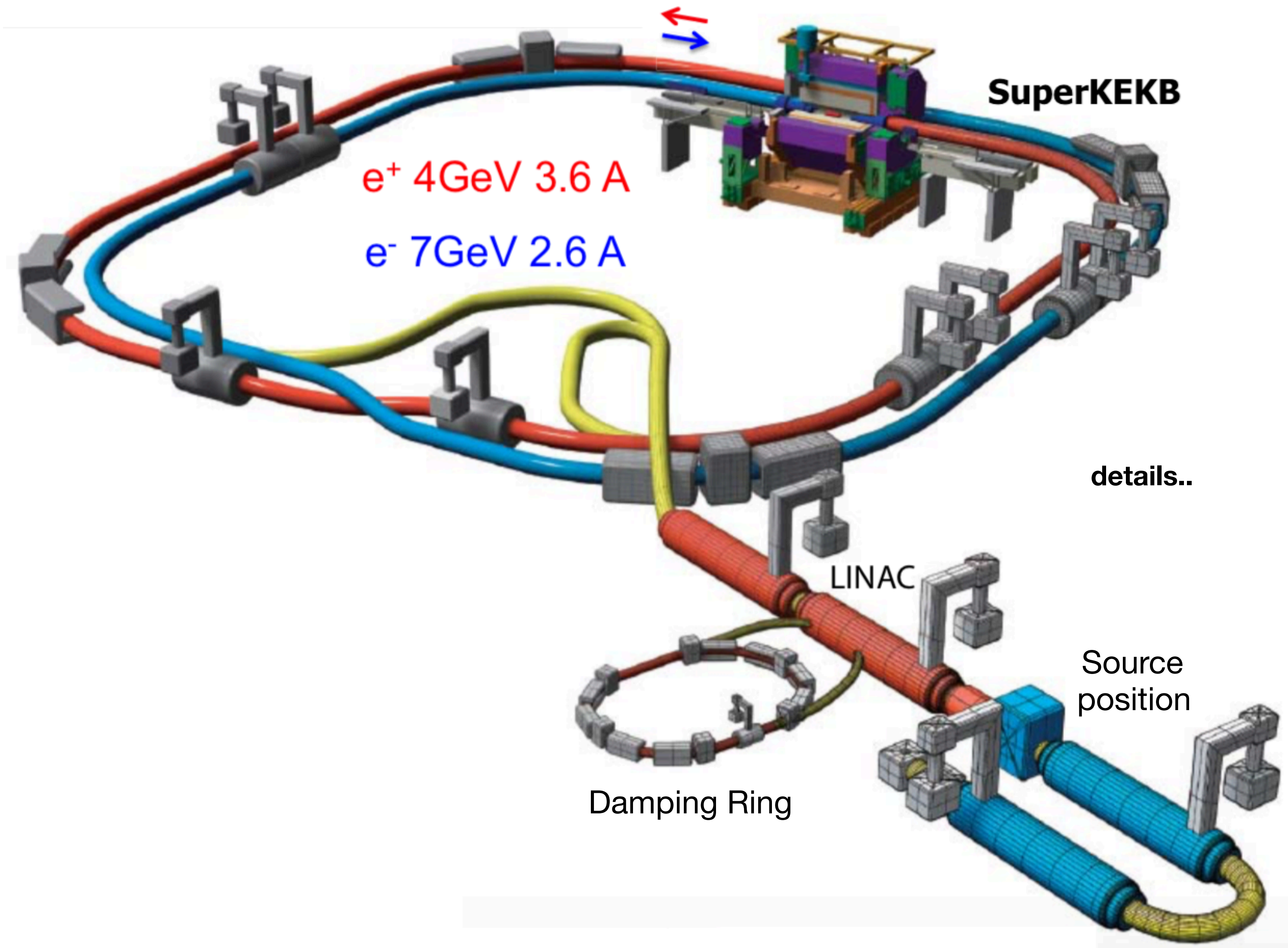


By increasing the luminosity it is possible to investigate the SM through high precise measurements for highly suppressed, highly accurate or prohibited processes.

Improved detector performances → New Physics possibility!

Collider SuperKEKB

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



details..

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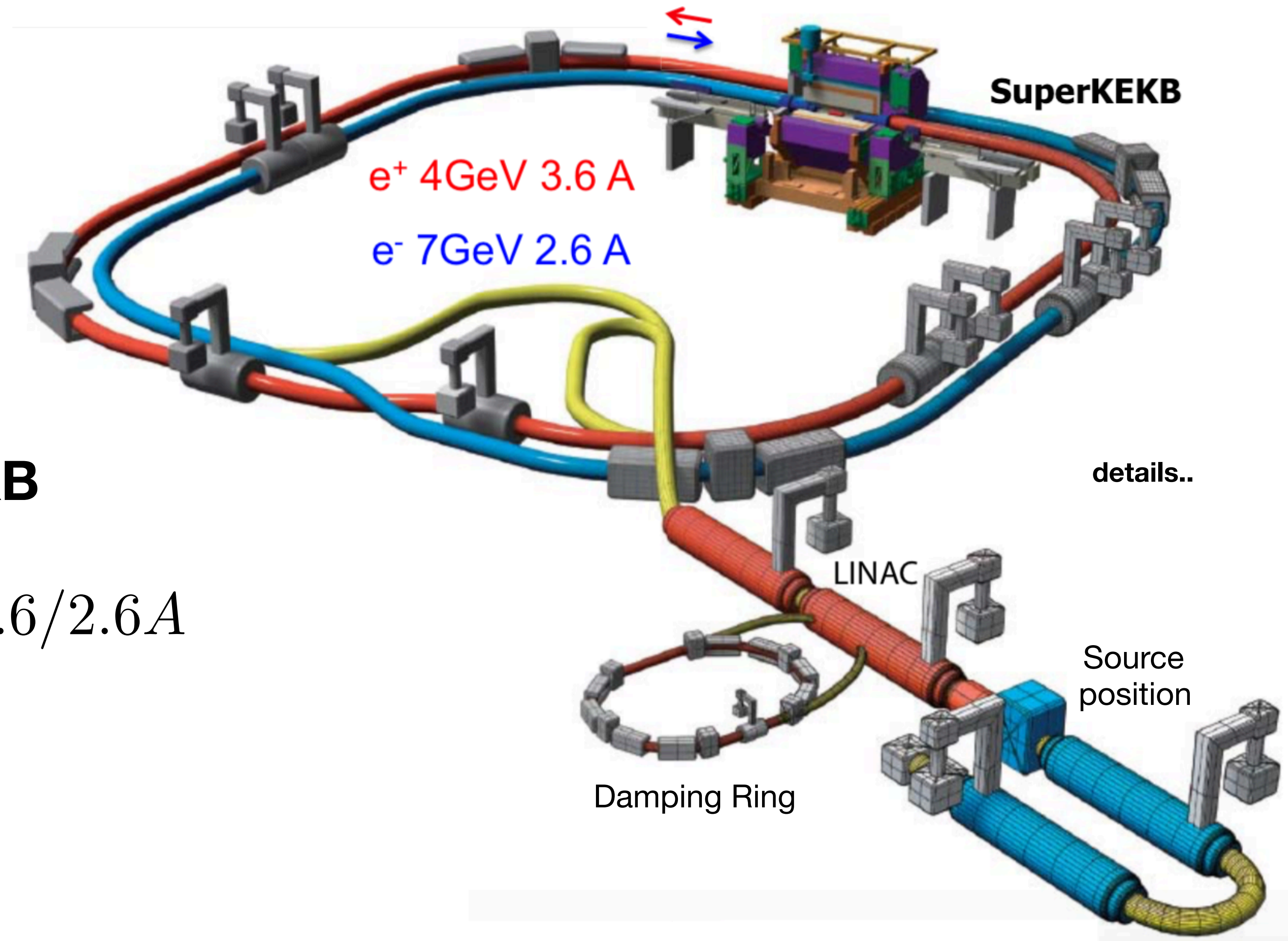

KEKB

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

SuperKEKB

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

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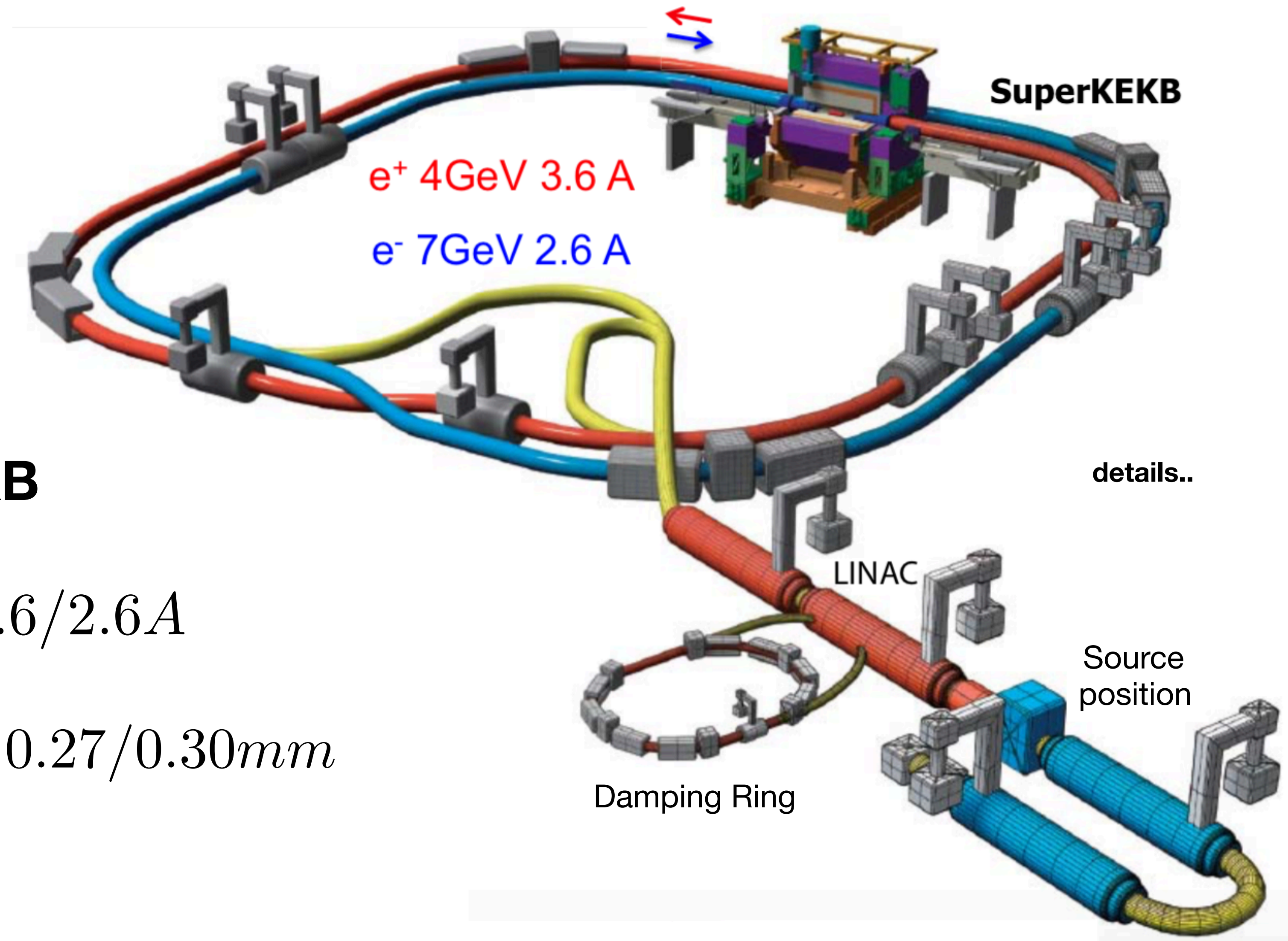

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$$\beta_{y\ e^+/e^-}^* = 5.9/5.9mm$$

SuperKEKB

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

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

Collider SuperKEKB

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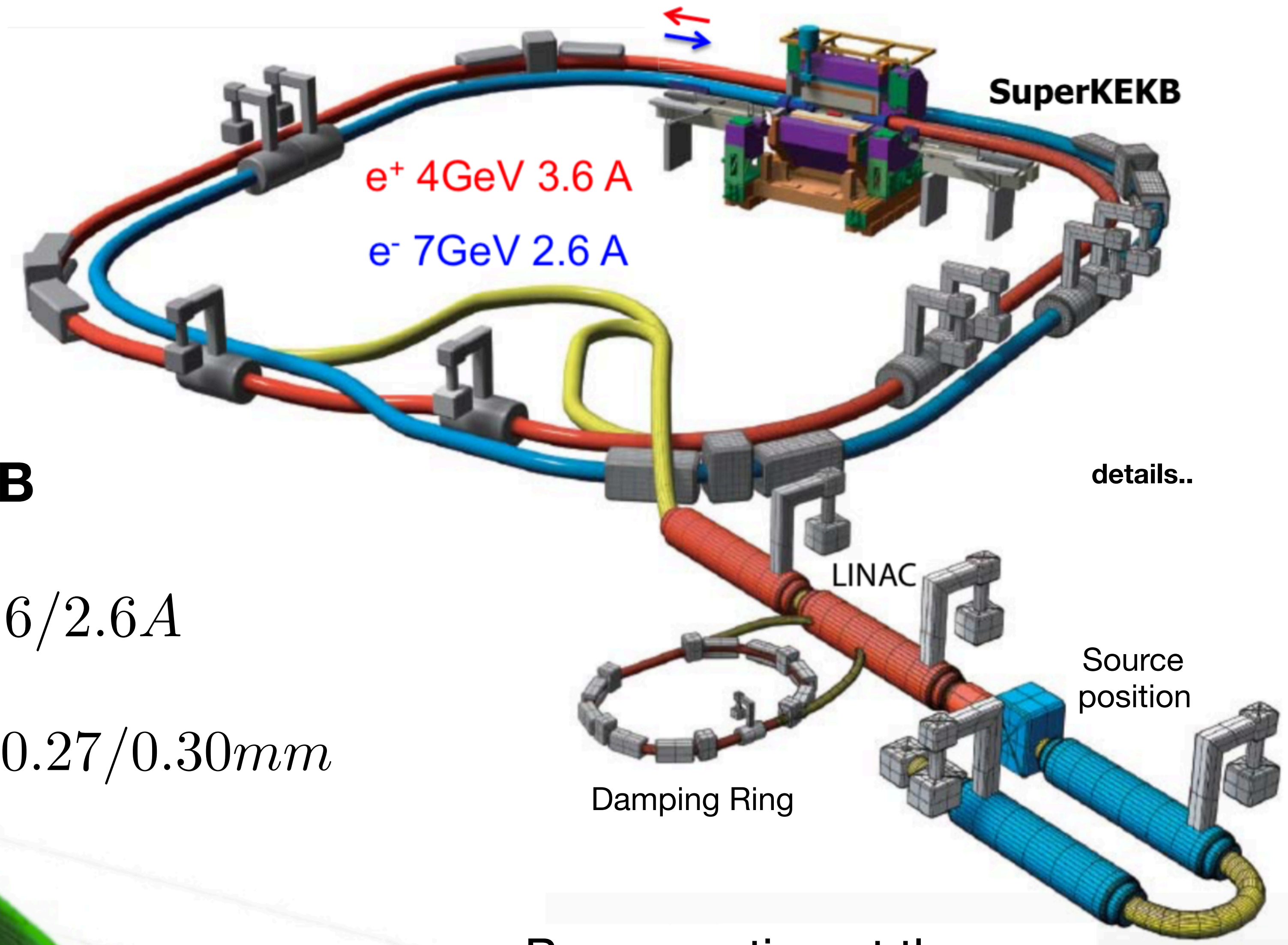

KEKB	**SuperKEKB**
$I_{e^+/e^-} = 1.64/1.19A$	$I_{e^+/e^-} = 3.6/2.6A$
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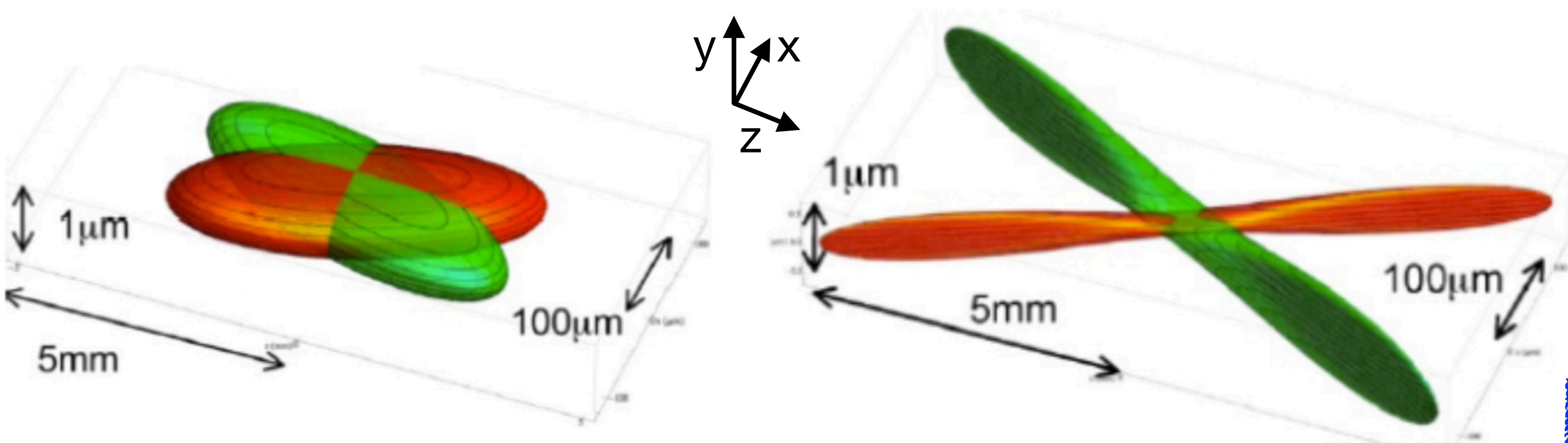

Beam section at the interaction point:
~42 nm in y
~6 μm in x

Nano-beam scheme

Collider SuperKEKB

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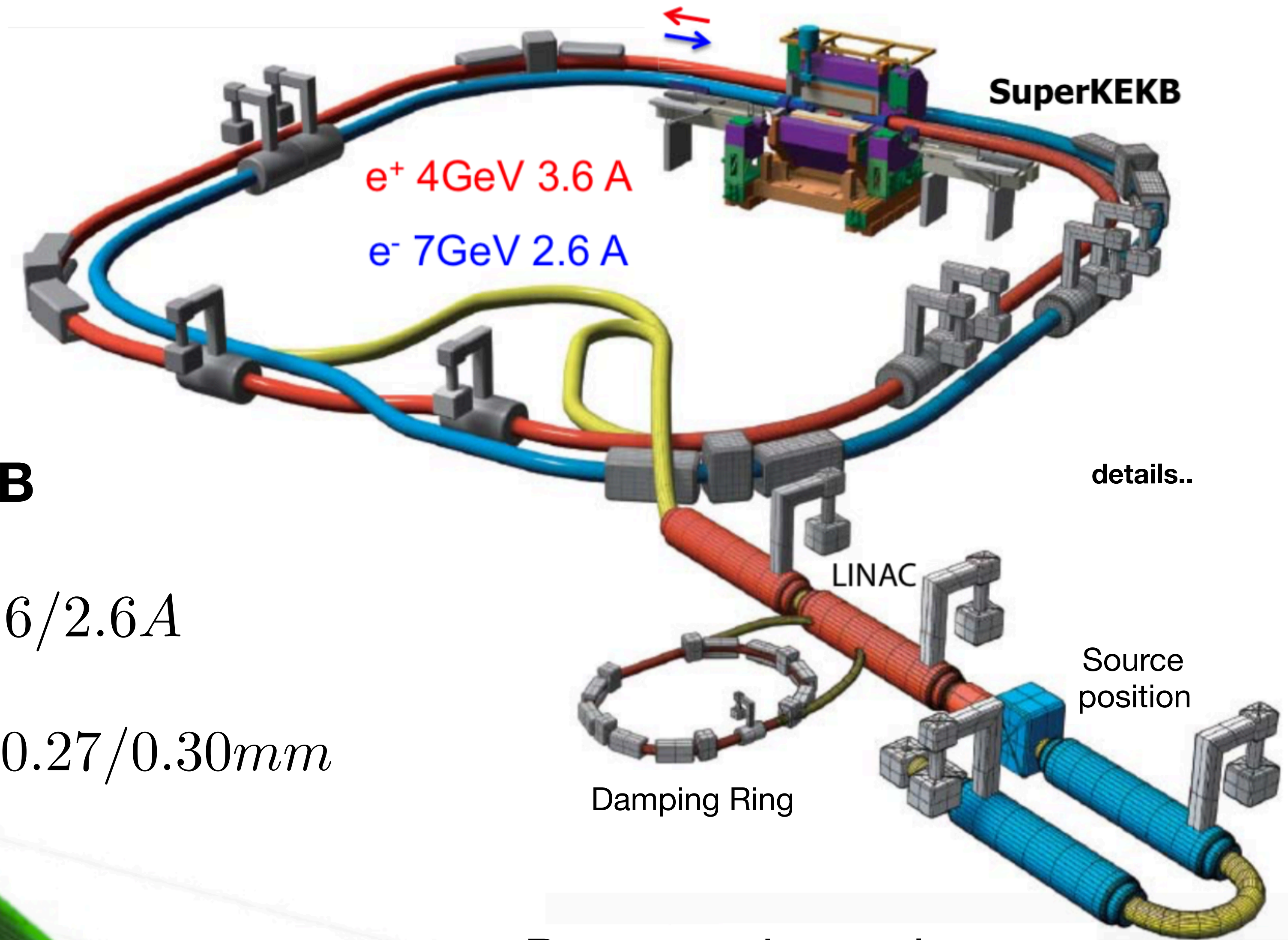

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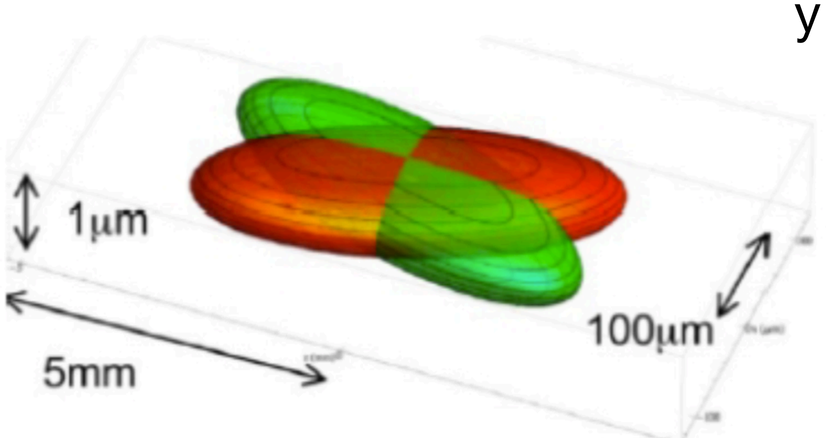

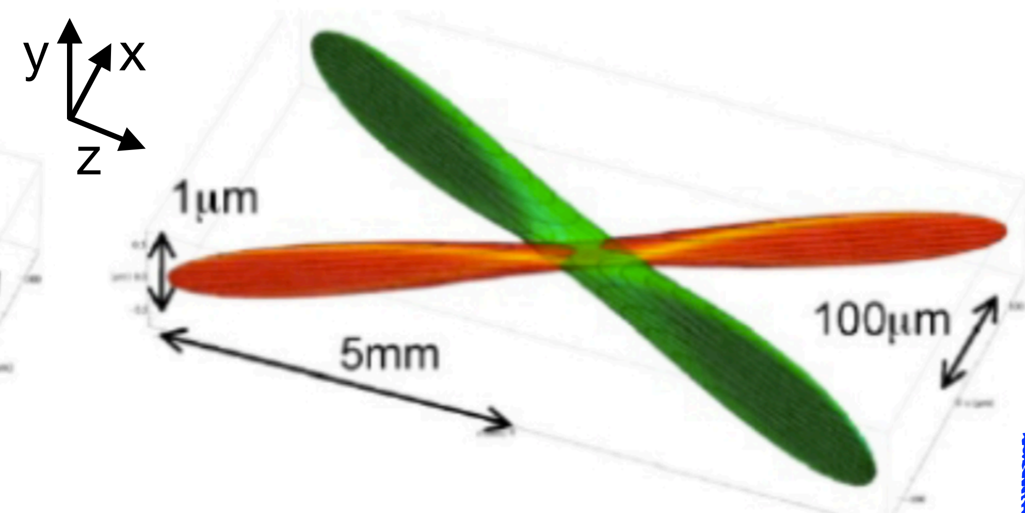

Beam section at the interaction point:
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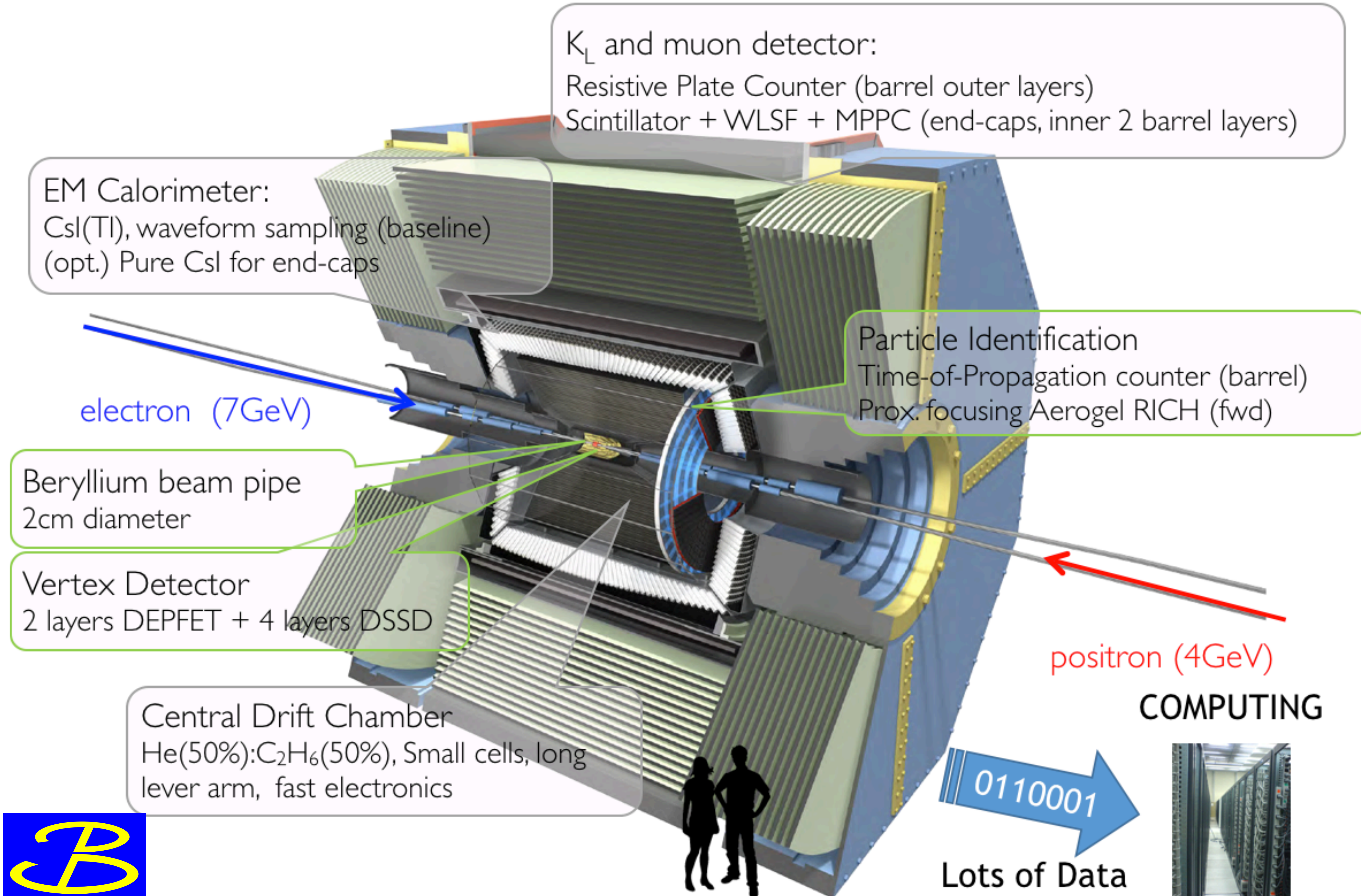
Nano-beam scheme

Expected improvement of integrated luminosity of a factor ~50 w.r.t. Belle: **50 ab^{-1}**

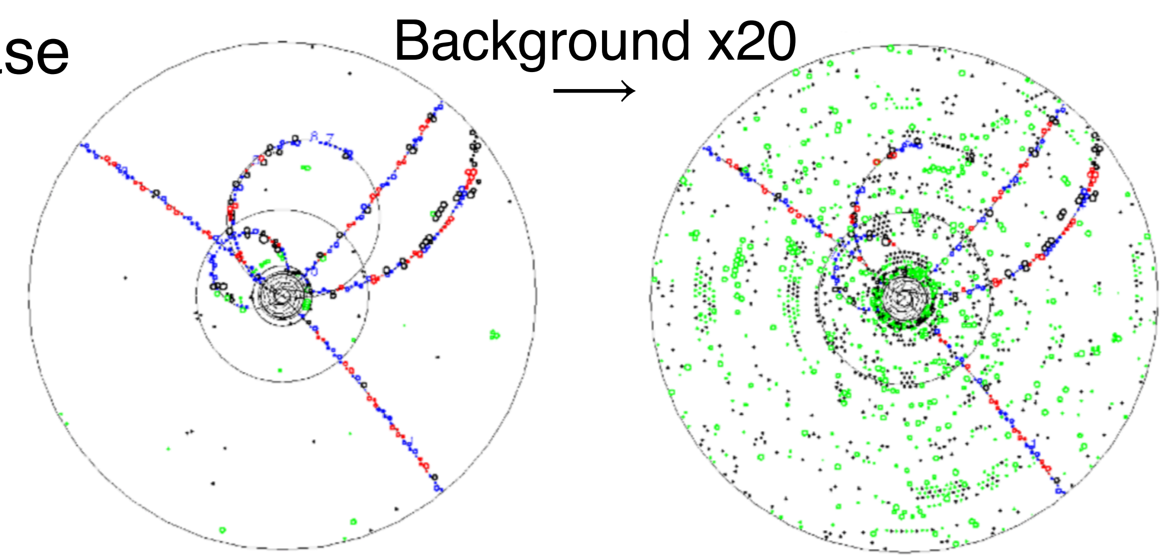
Belle II detector (I)



Belle II

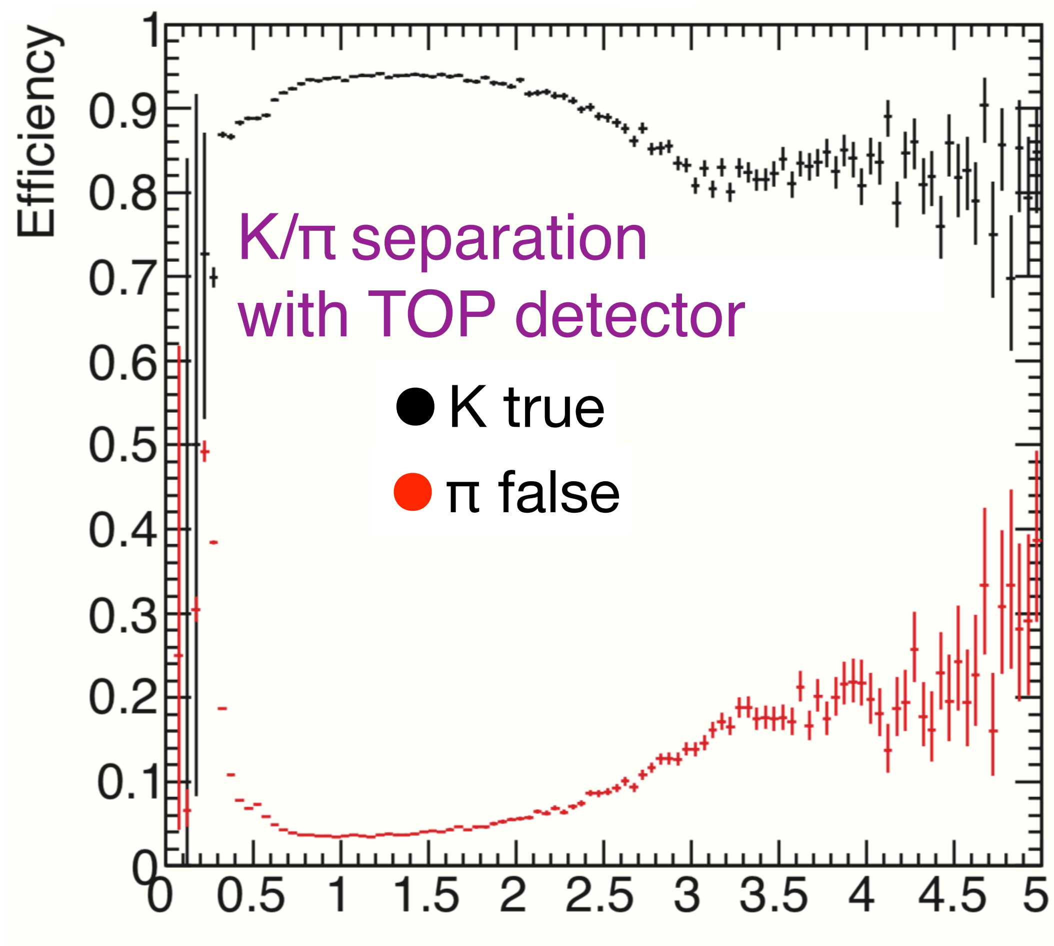
Belle II detector (II)

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



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).



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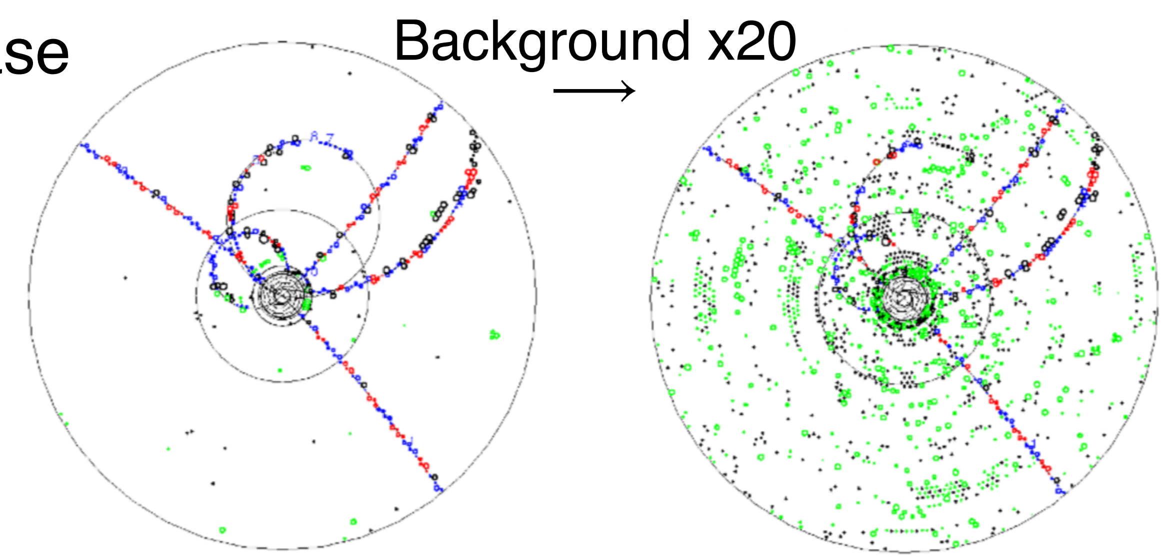

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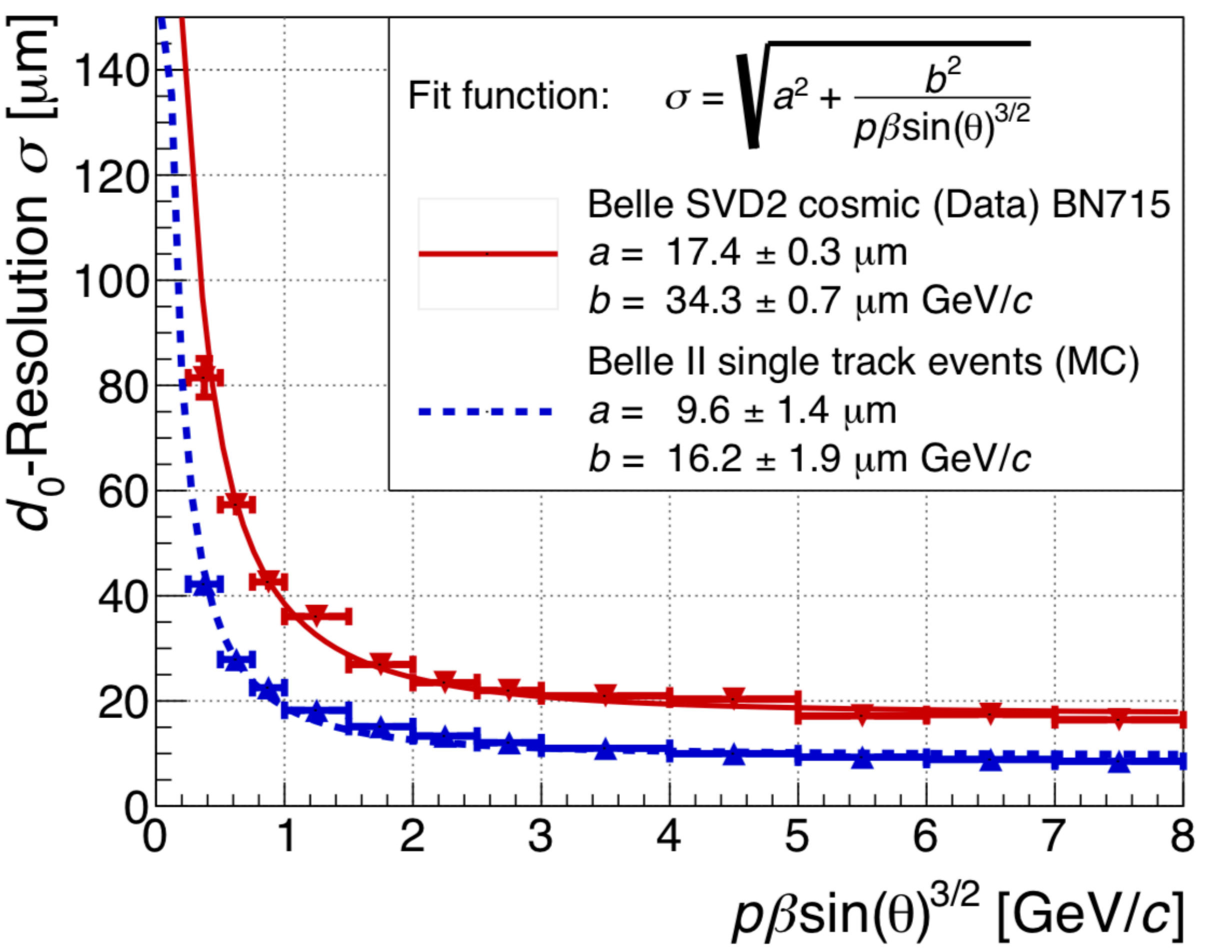
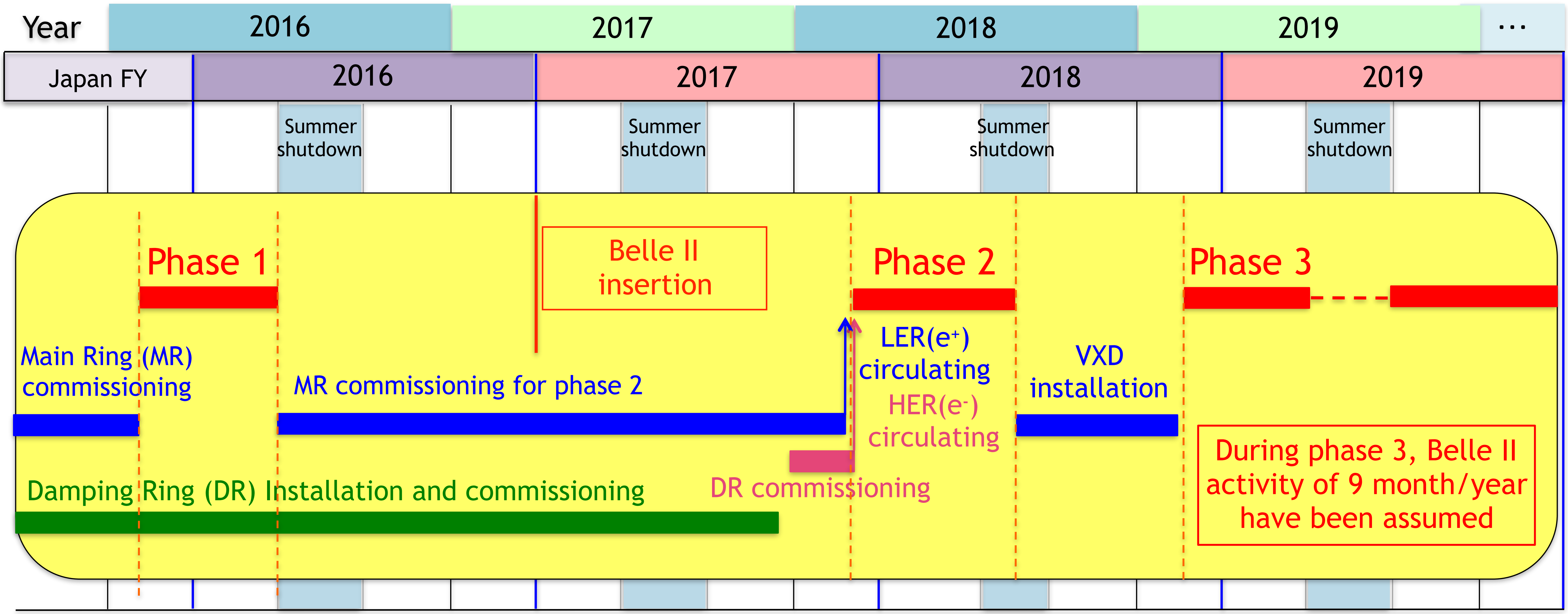


Belle II status and plan



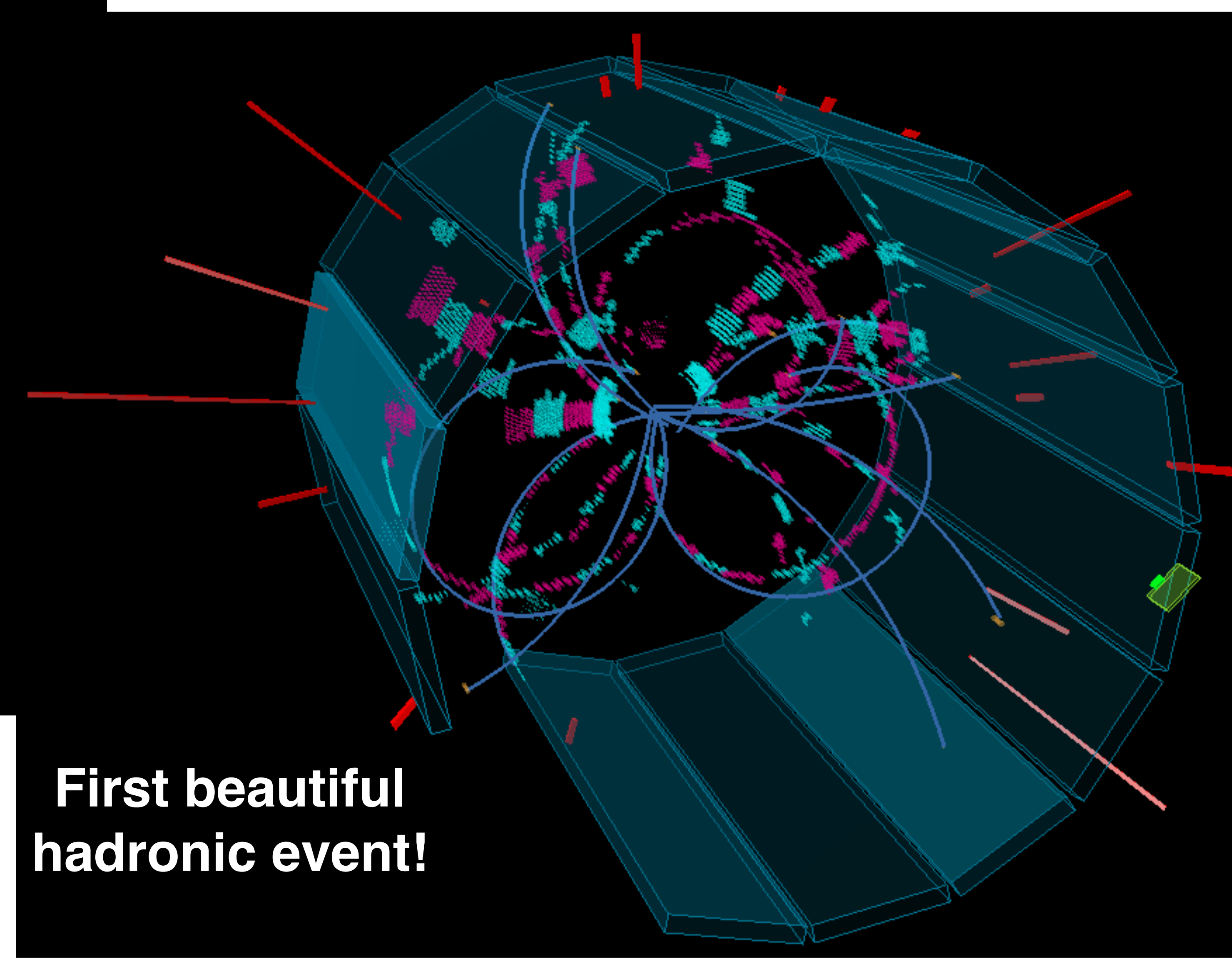
Phase 1: SuperKEKB commissioning & background estimation — **Completed**

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**

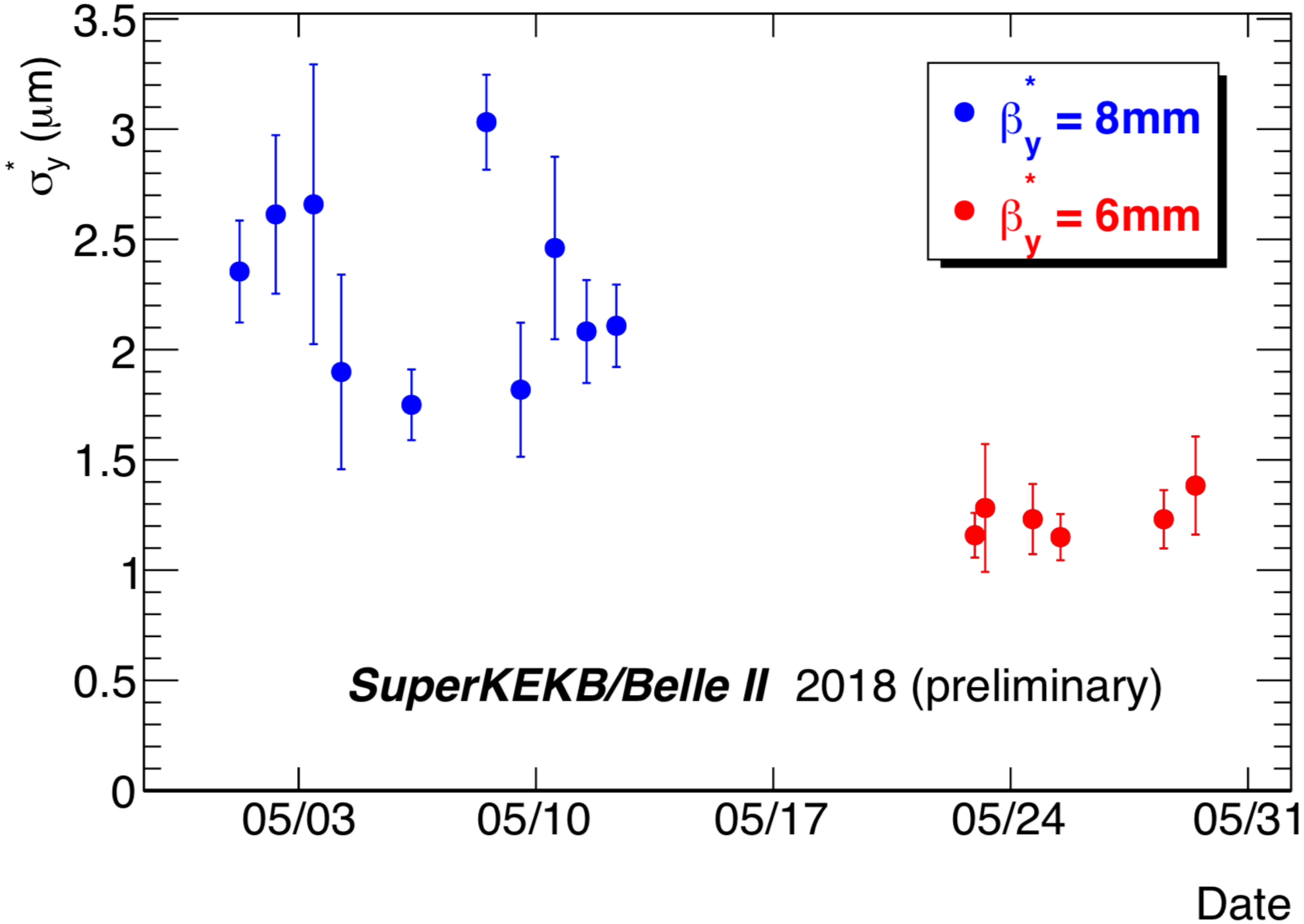
Belle II first event displays

Phase 2 first hadronic physics event!

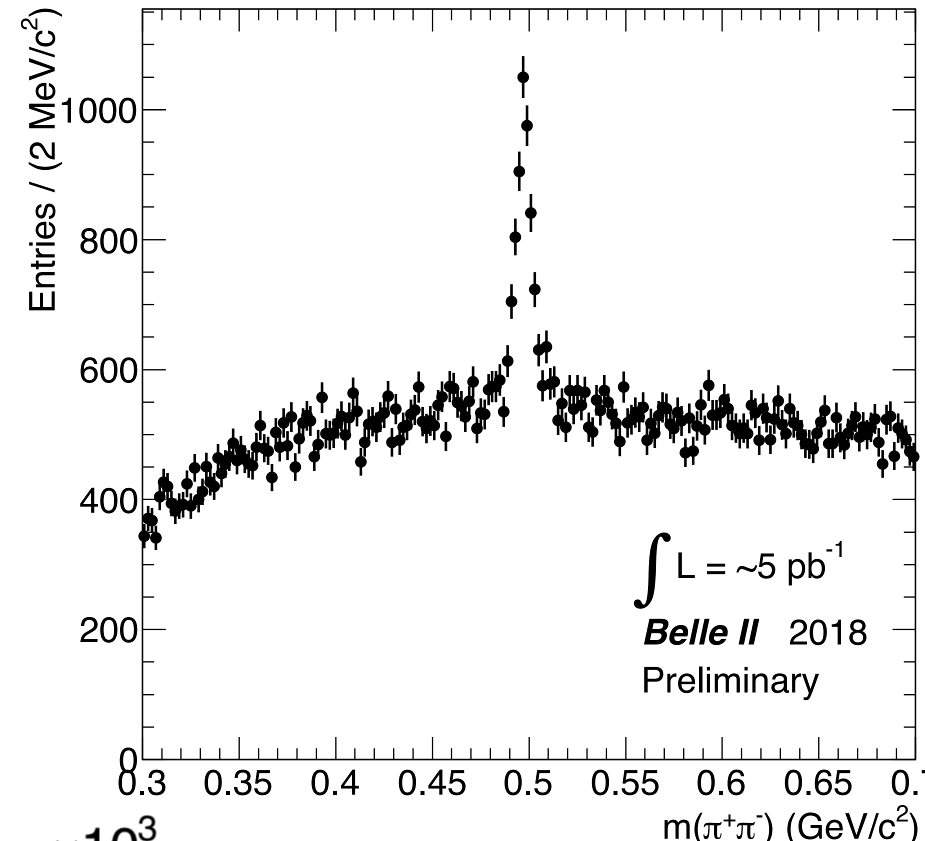


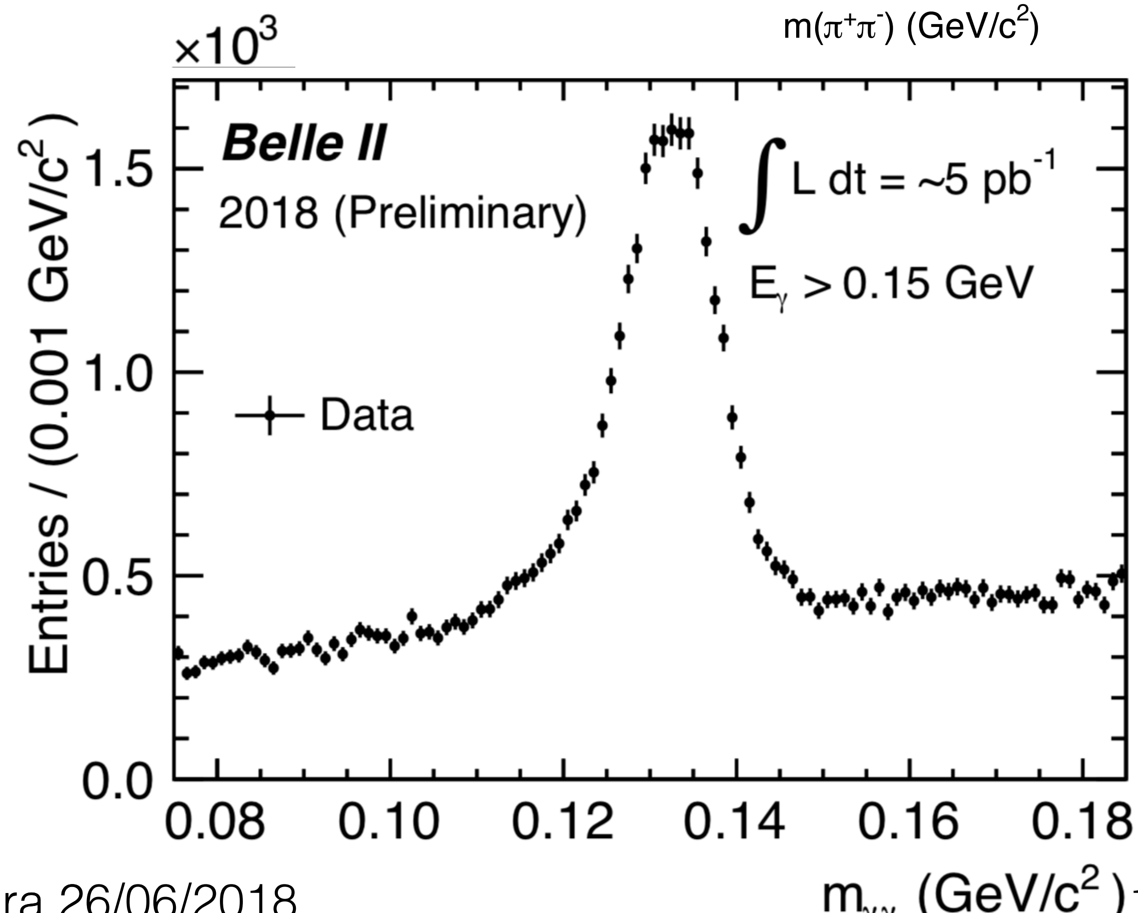
Belle II first results

Vertical beam size σ_y^* as a function of the date



First kaon & π^0 mass reconstruction plots

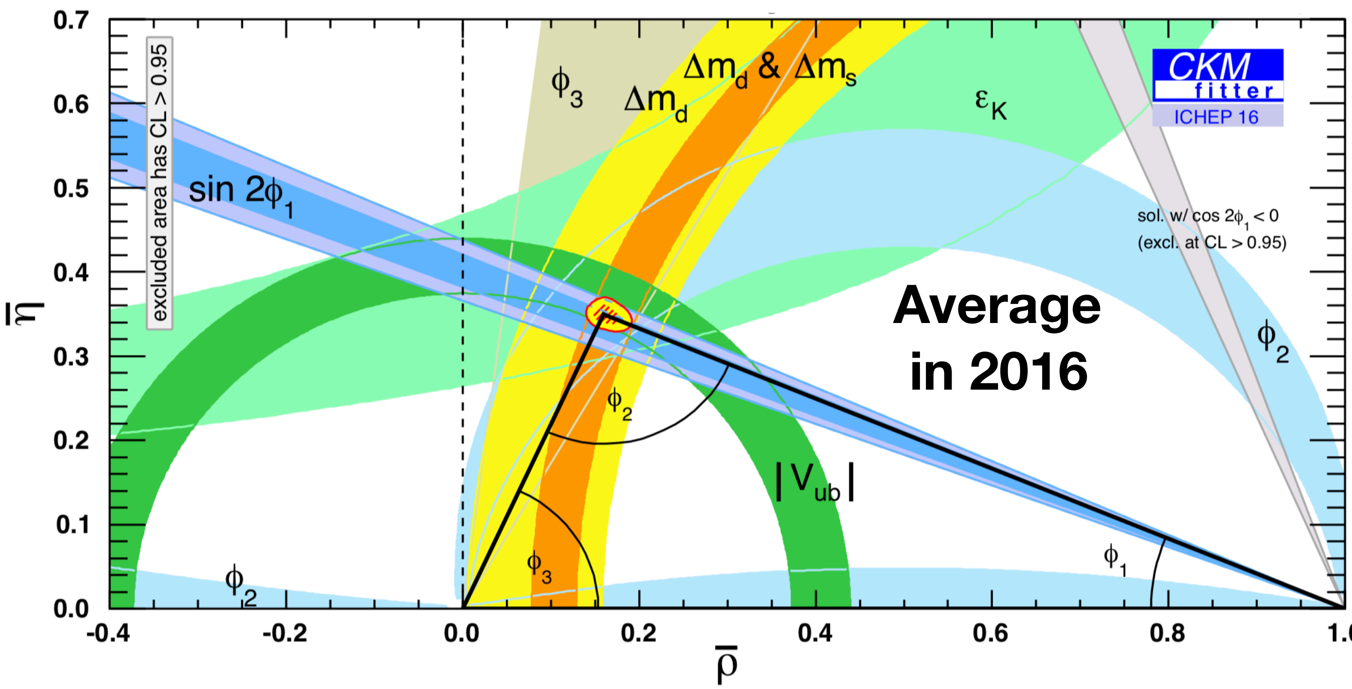


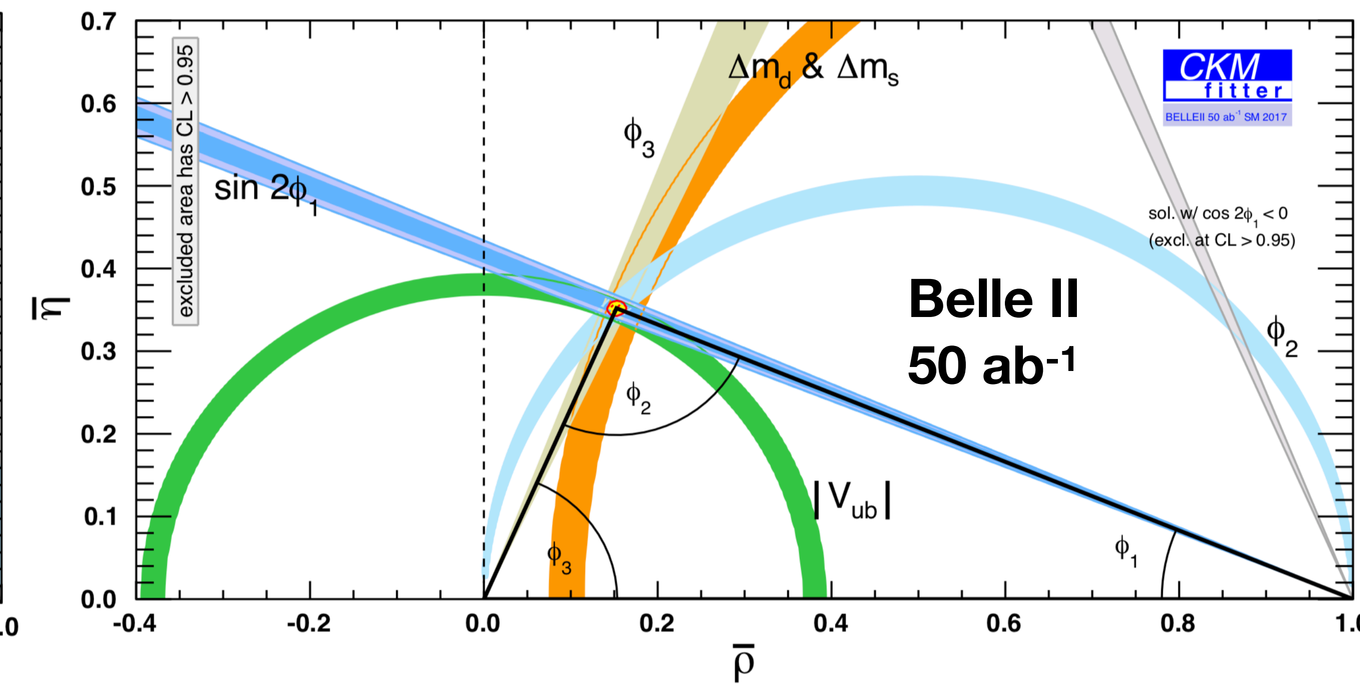


Instant luminosity reached so far by SuperKEKb ~10^{33} cm^{-2} s^{-1}

Physics program

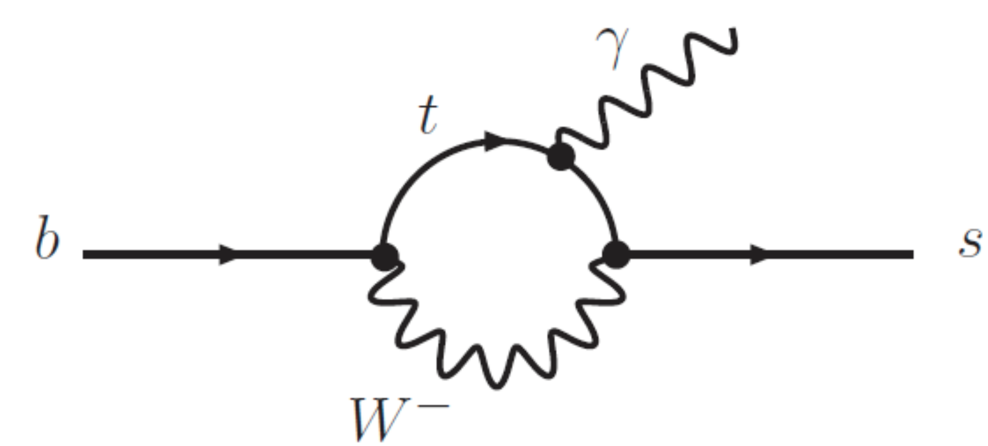
- Precision measurement of the Unitarity Triangle angles and CKM matrix elements.





- 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

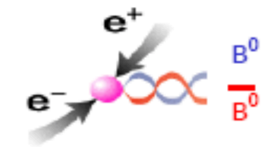
summary…



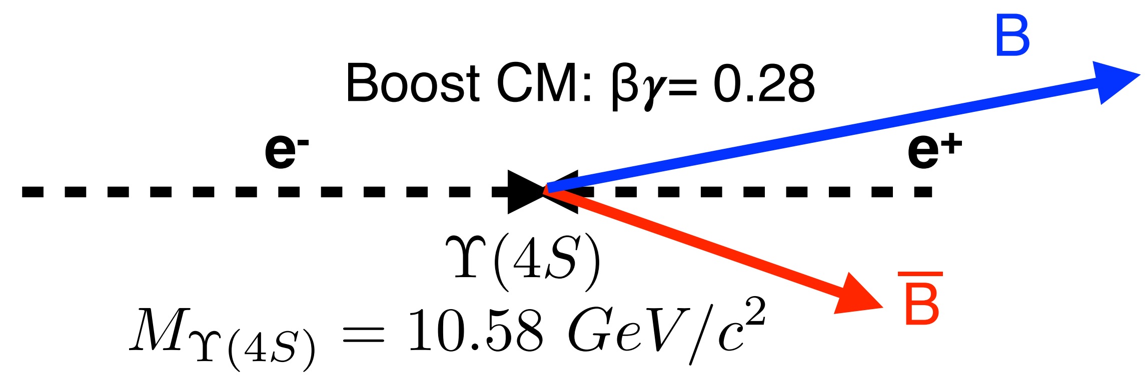
Belle II

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



details..

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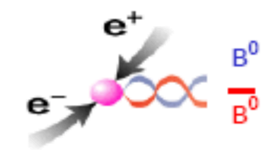
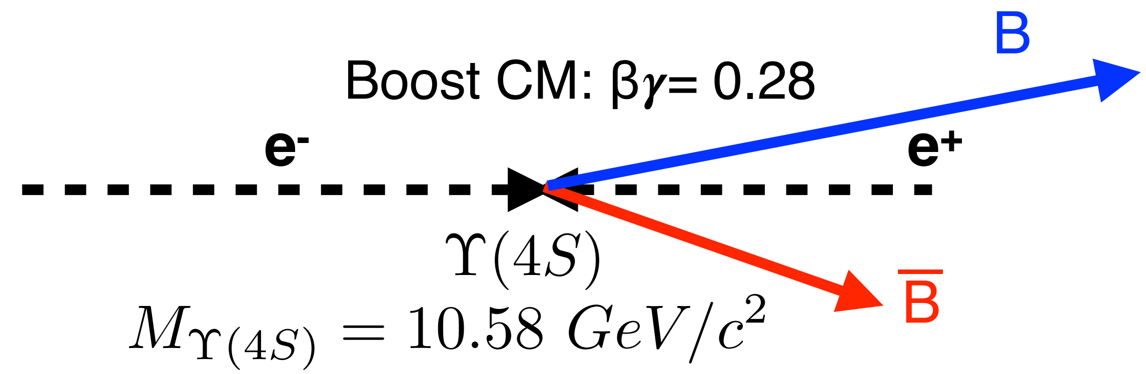


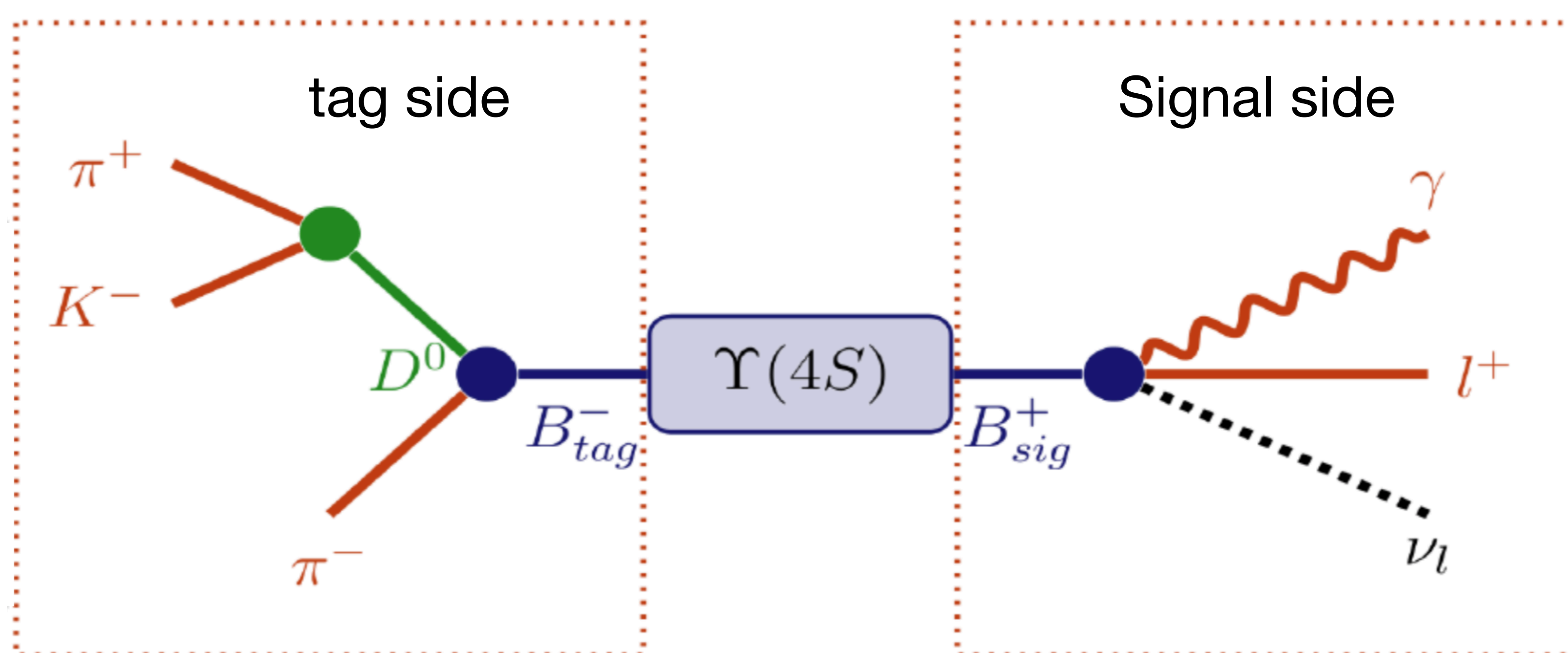


Full Event Interpretation (FEI)

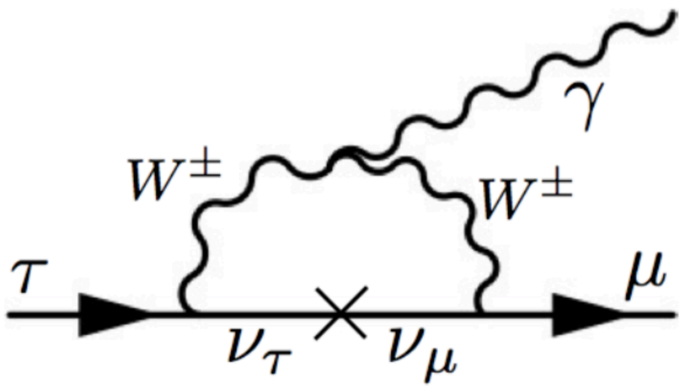
Full reconstruction of one B meson decay (B_{tag}) → determination of the flavour of the other B (B_{sig}) and isolation of particles coming from the signal side → (large advantages in analysis with missing energy/mass)

Reconstruction efficiency:

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



Lepton flavour violation in τ decays (I)

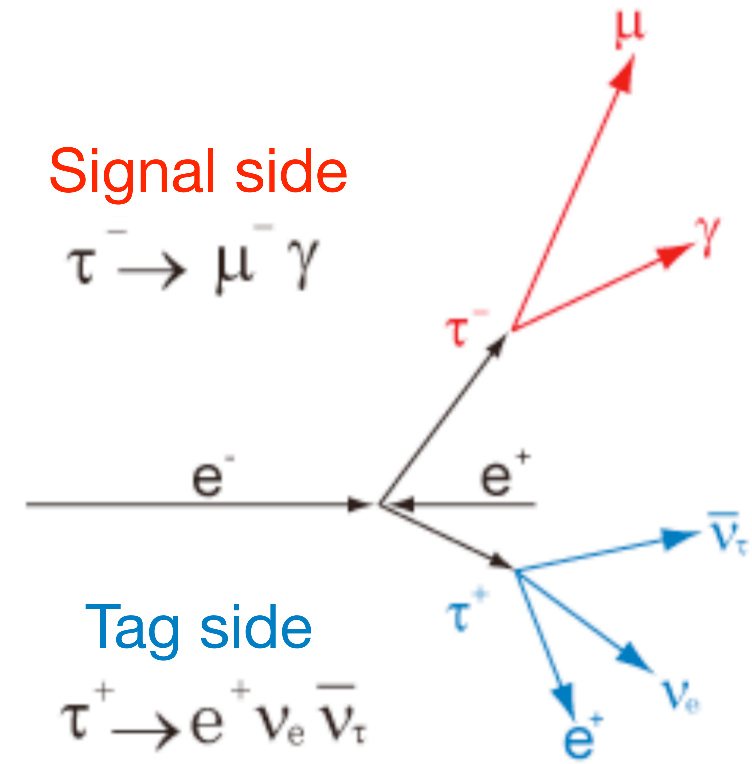


SM prediction:
$$BF(\tau \to l\gamma) \sim 10^{-40}$$

Studied <u>only</u> at the B-factory

LHCb not competitive

details..



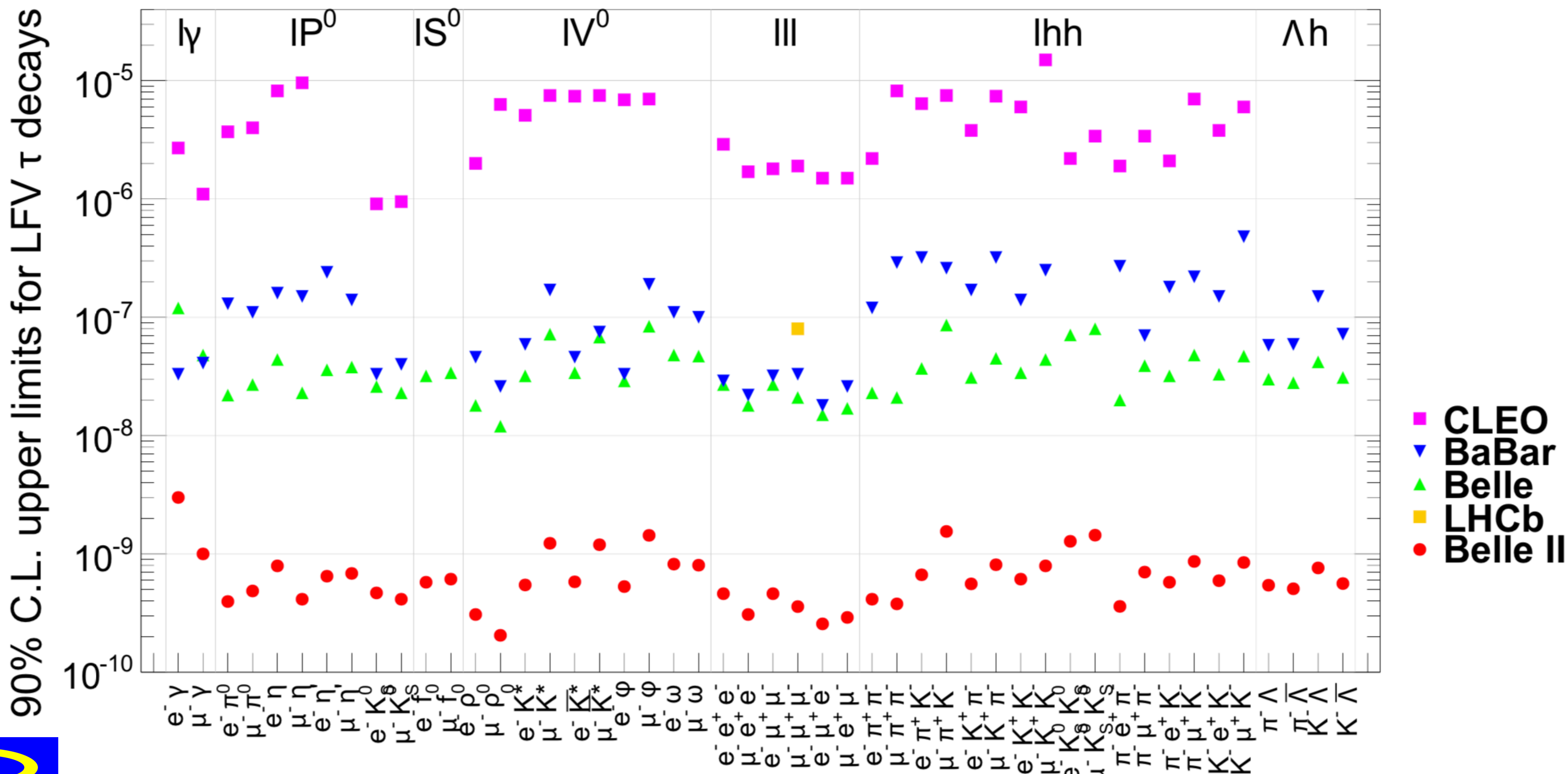
Ratios of BFs of τ LFV decays allow to discriminate NP models!

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

Lepton flavour violation in τ decays (II)

Belle II expectations:

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



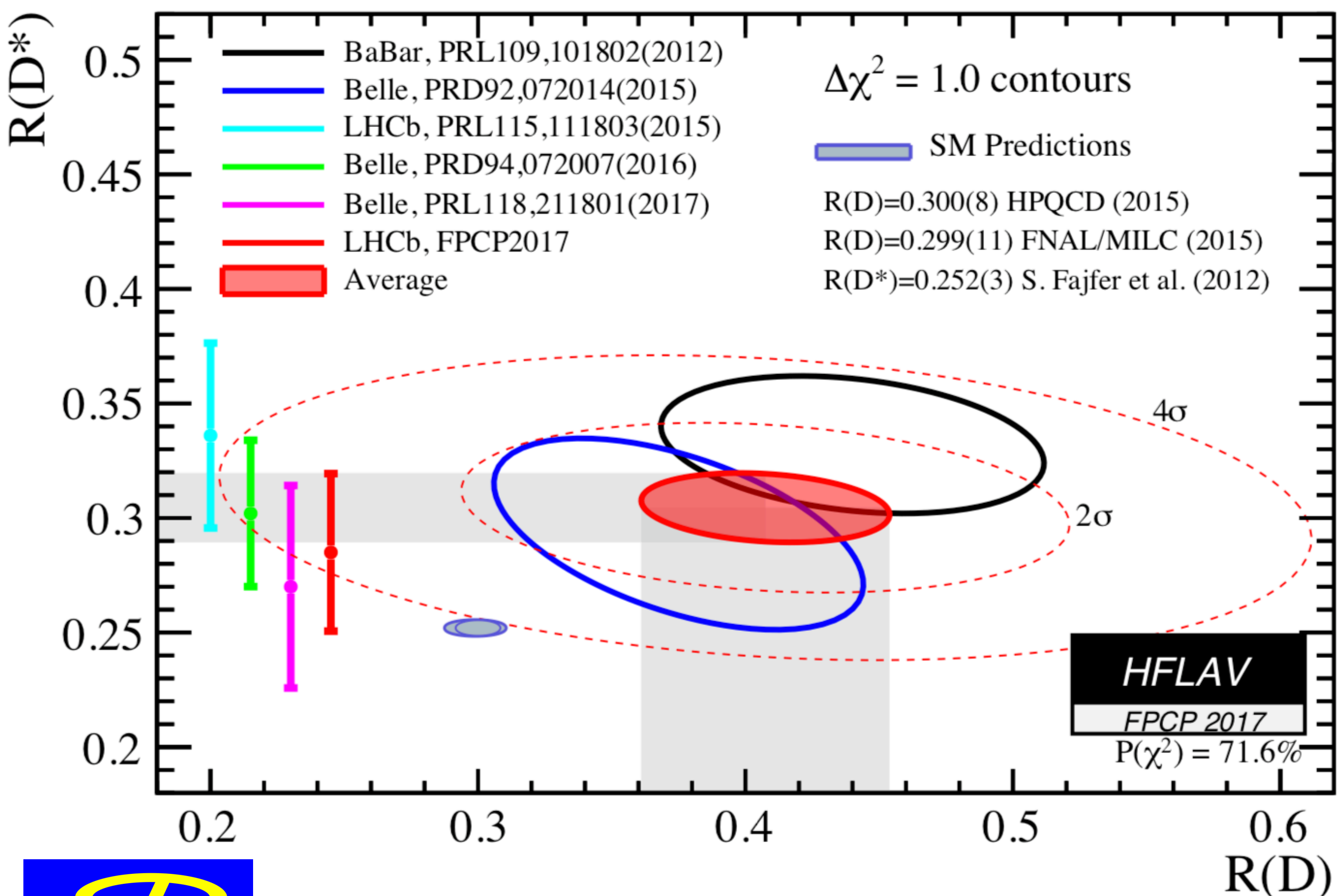
Belle II

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



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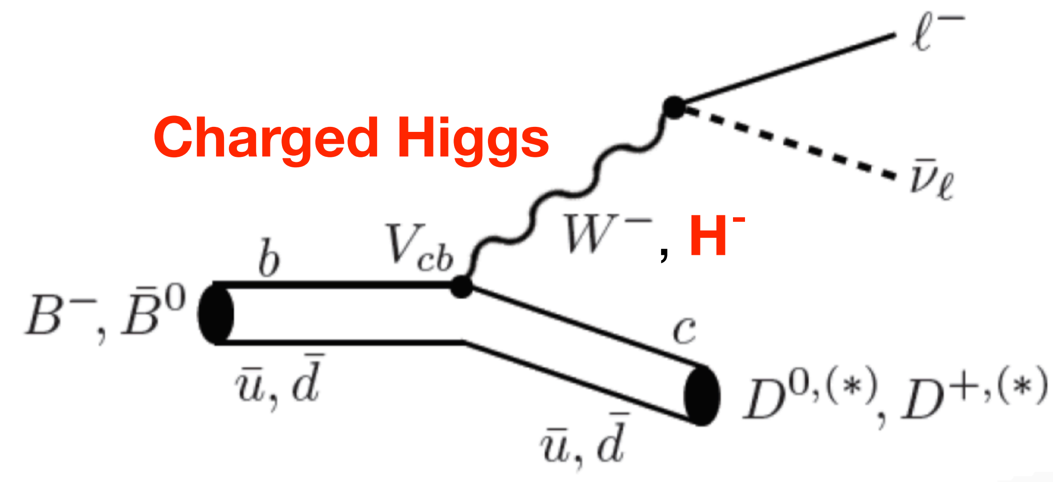
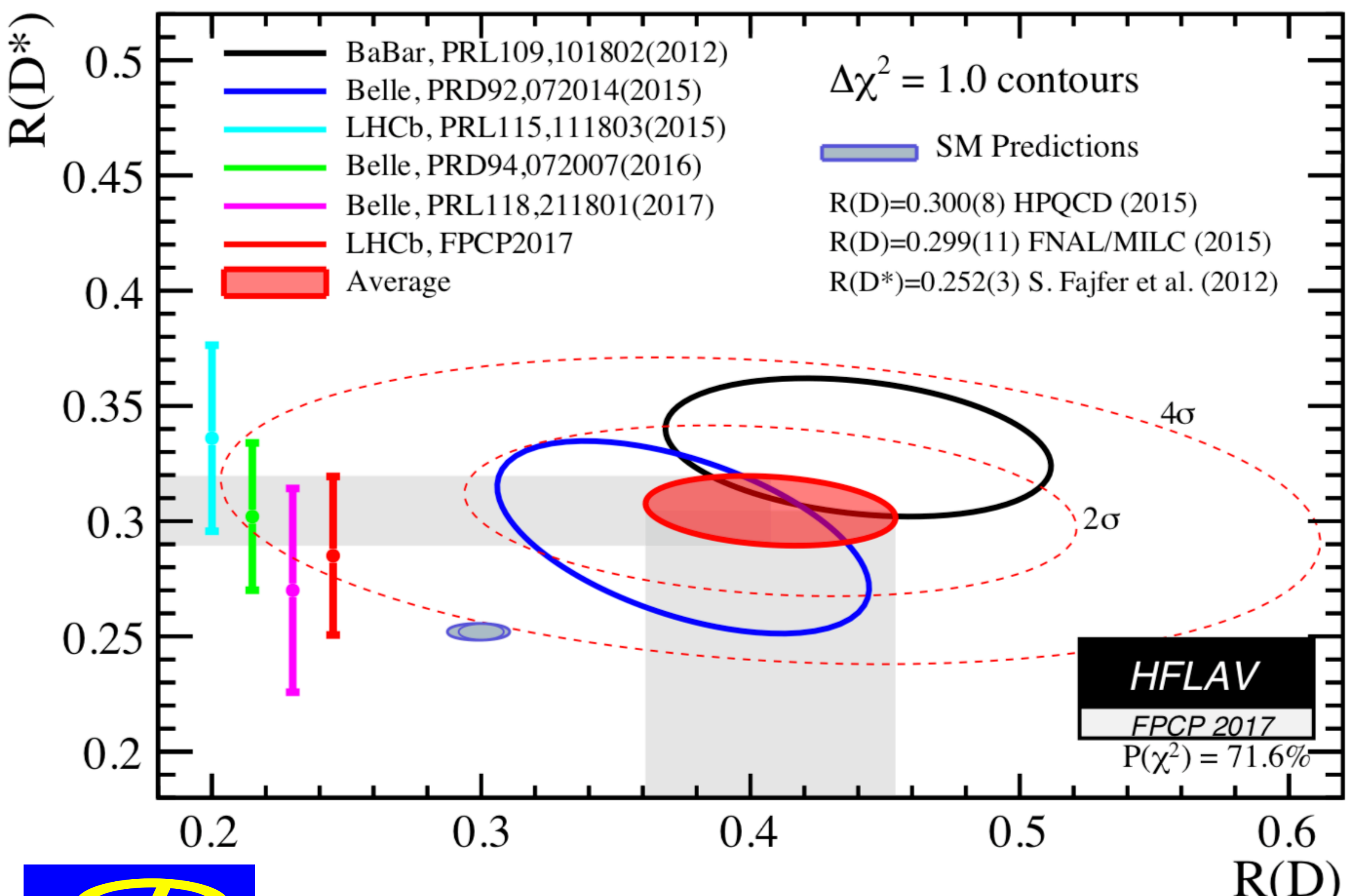
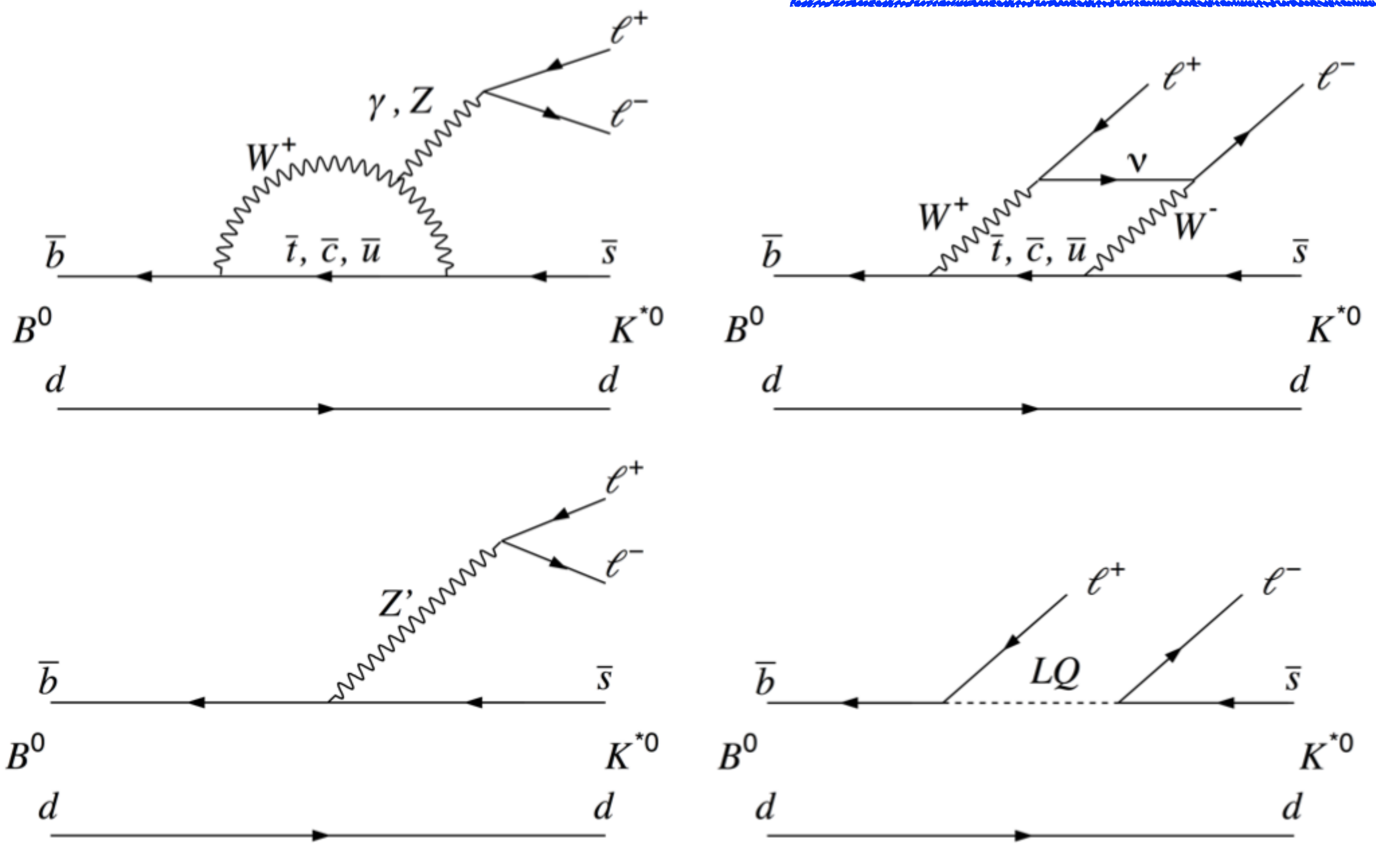




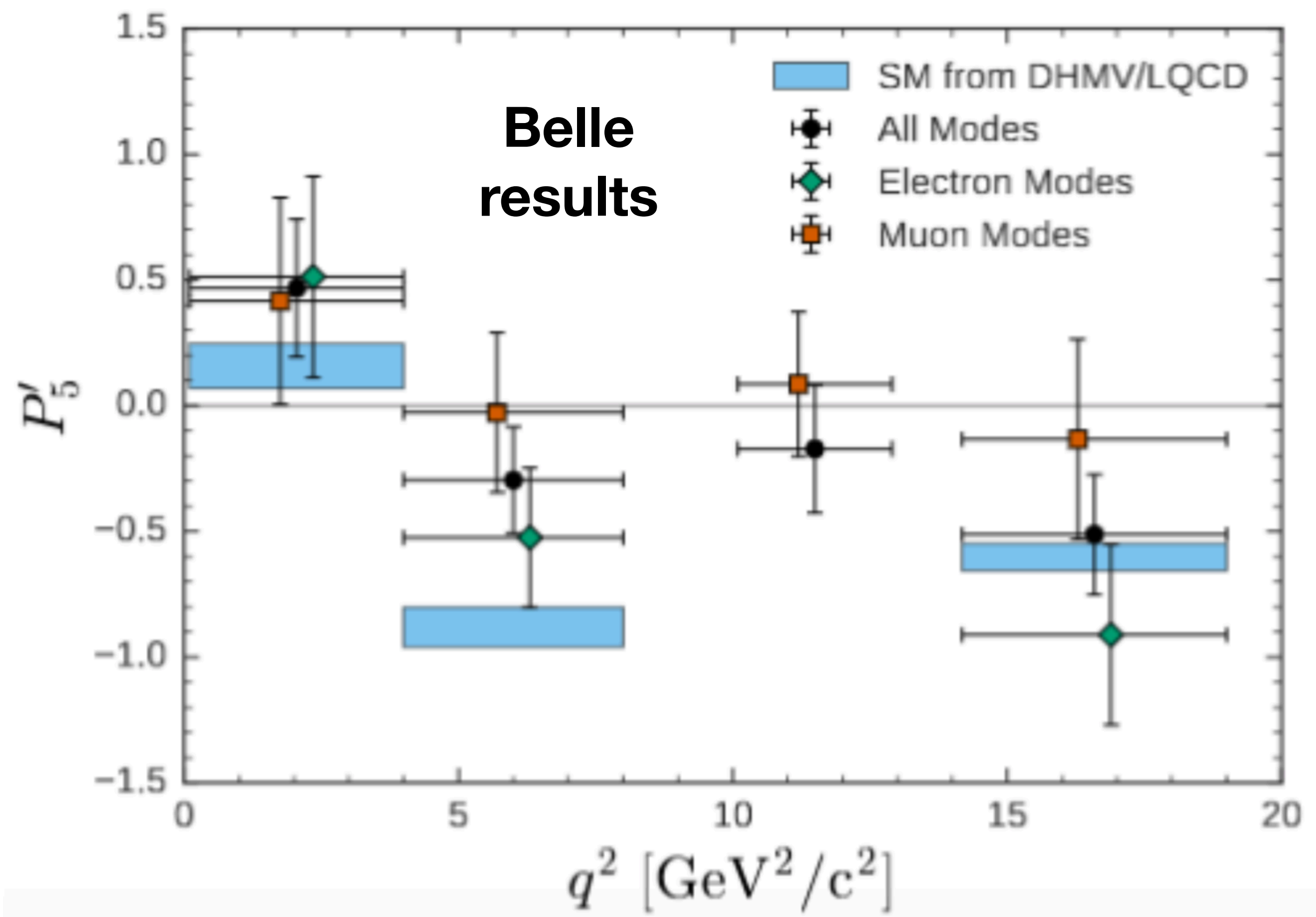
It could be explained through the existence of charged Higgs or other New Physics models

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

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 P_5' parameter within a certain q^2 range of ~2.6σ in the SM→ **comparable results with LHCb analysis.**

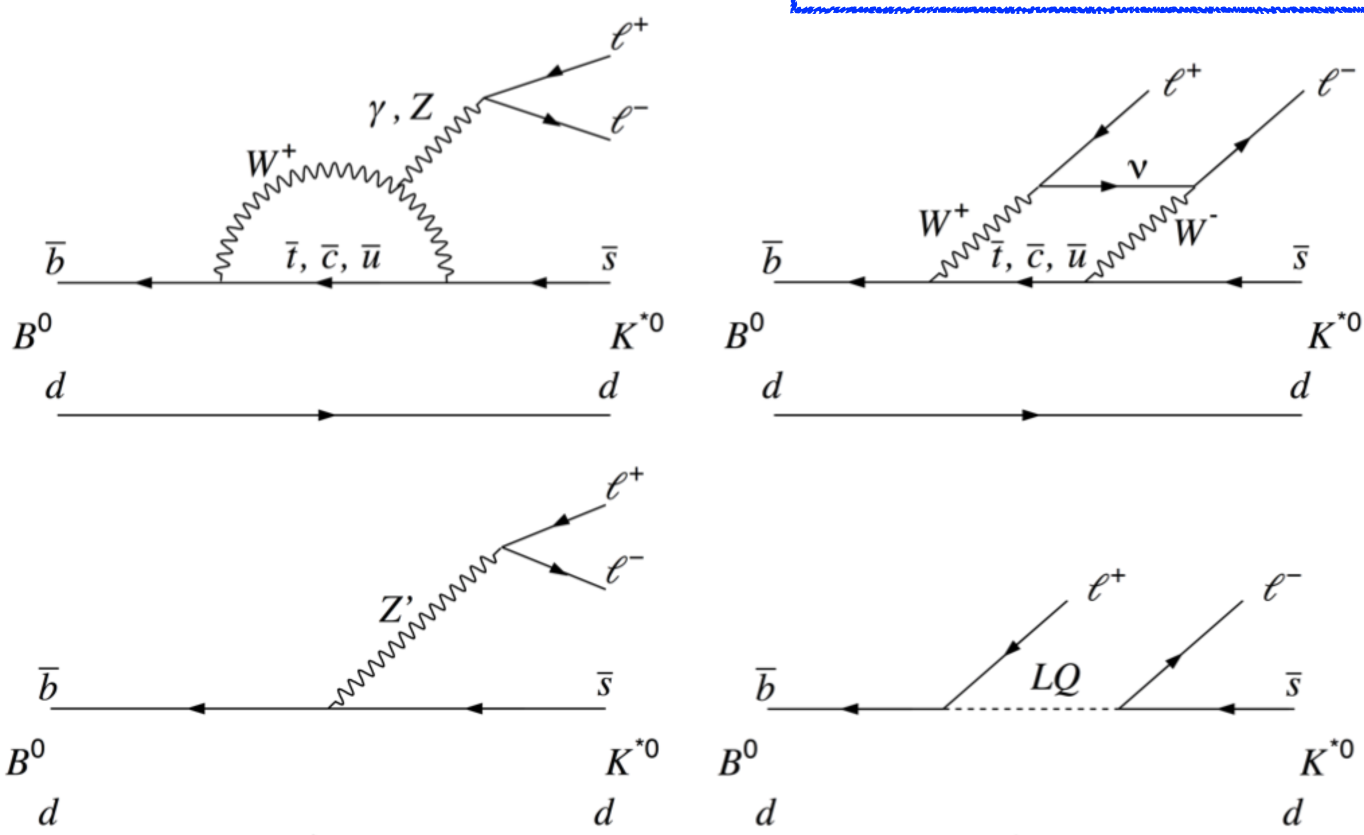
more..

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

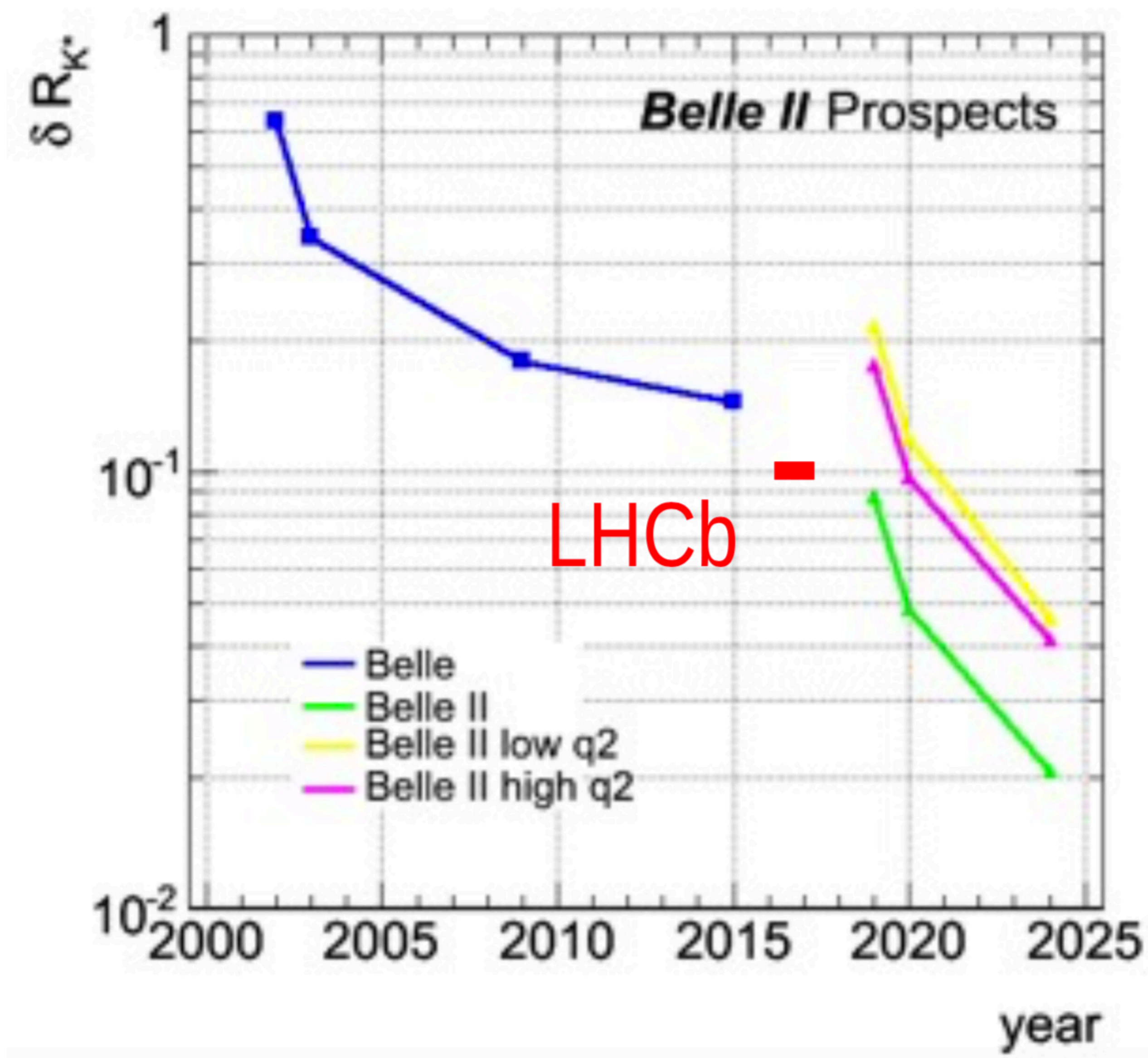
$R_{K^{(*)}} = BR(B \to K^{(*)}\mu\mu)/(B \to K^{(*)}ee) \overset{SM}{\simeq} 1$

FCNC: b → s transitions

Possible New Physics

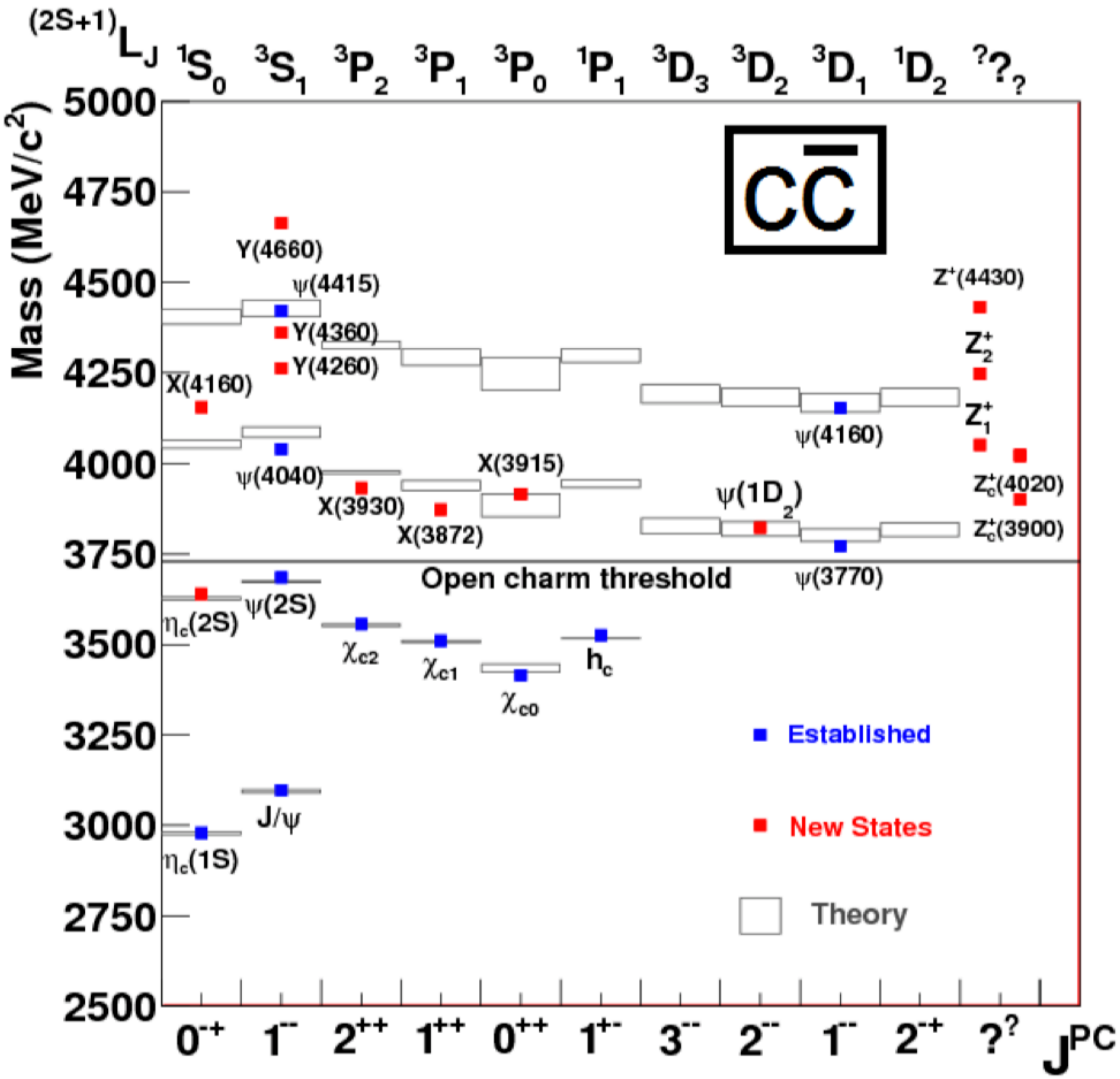


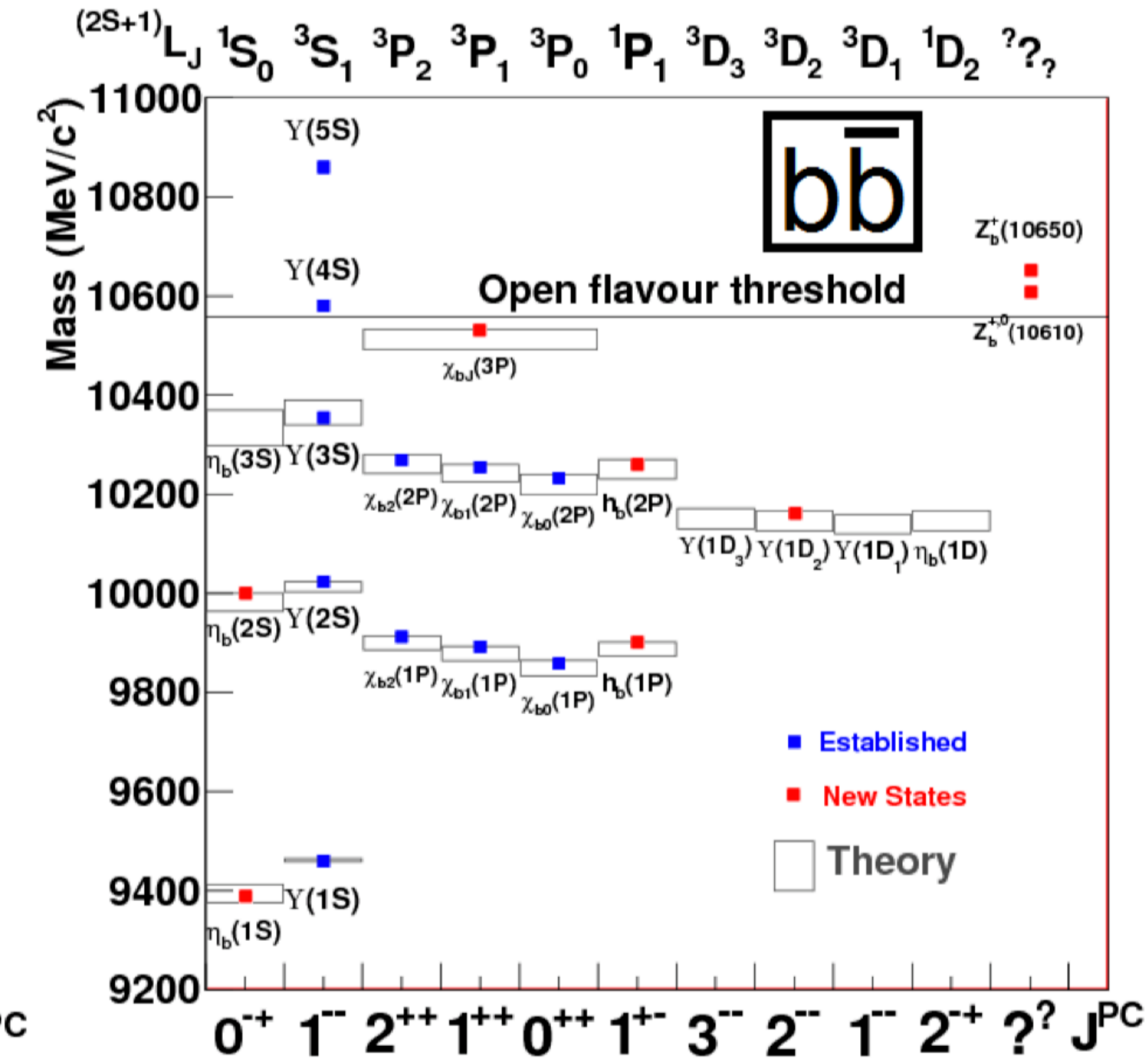
Belle II projection sensitivity on R_{K^*}:



Belle II experiment contribution will be crucial for that measurement!

Spectroscopy status





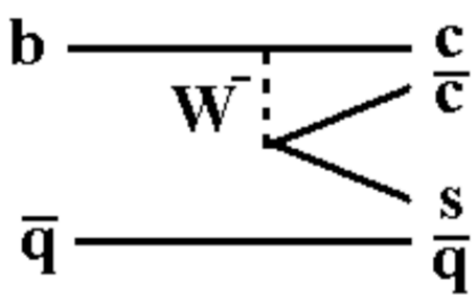
Many intermediate states have been already discovered

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

Belle II

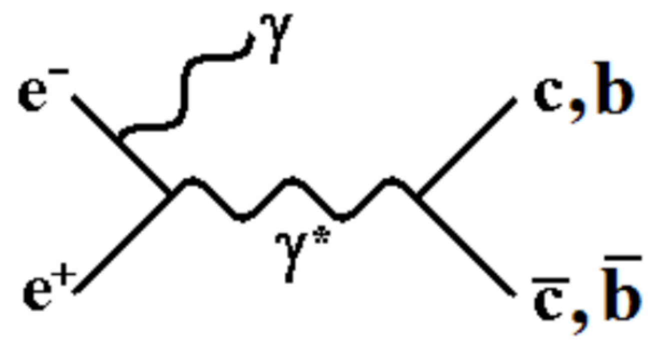
Quarkonium production at B-factory

B decays



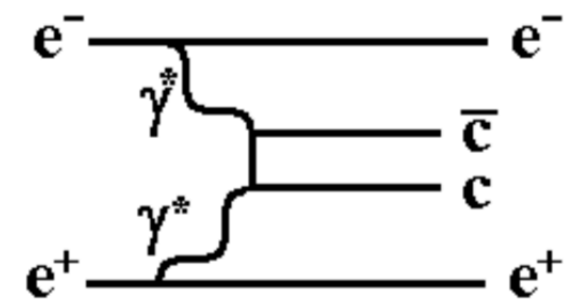
All quantum numbers available

Initial State Radiation (ISR)



$J^{PC}=1^{--}$

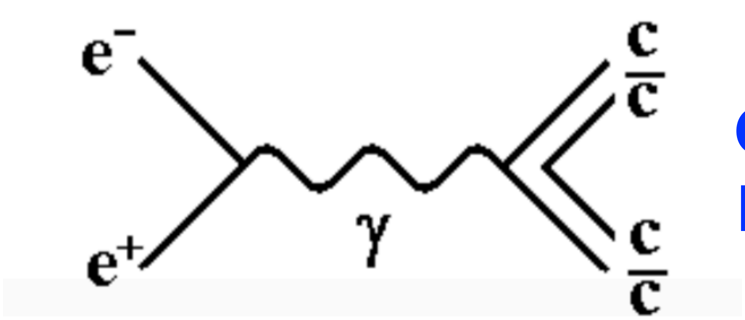
Two-photon interaction



Only at Belle II

$J^{PC}=0^{-+}, 0^{++}, 2^{++}$

Double charmonium production

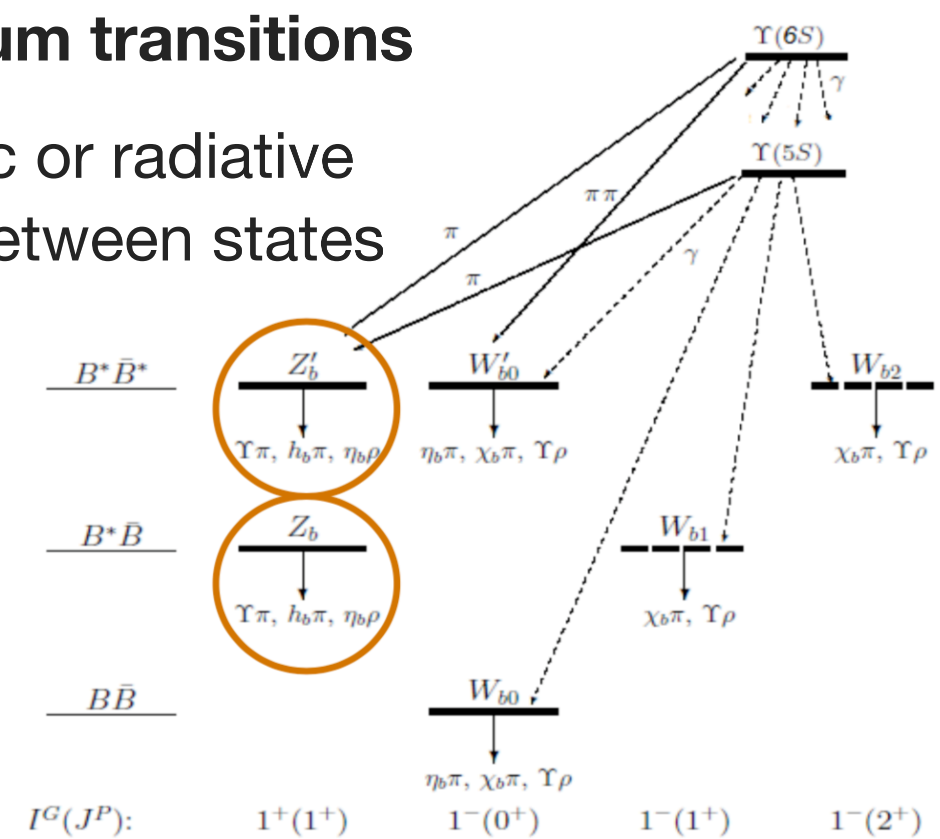


Only at Belle II

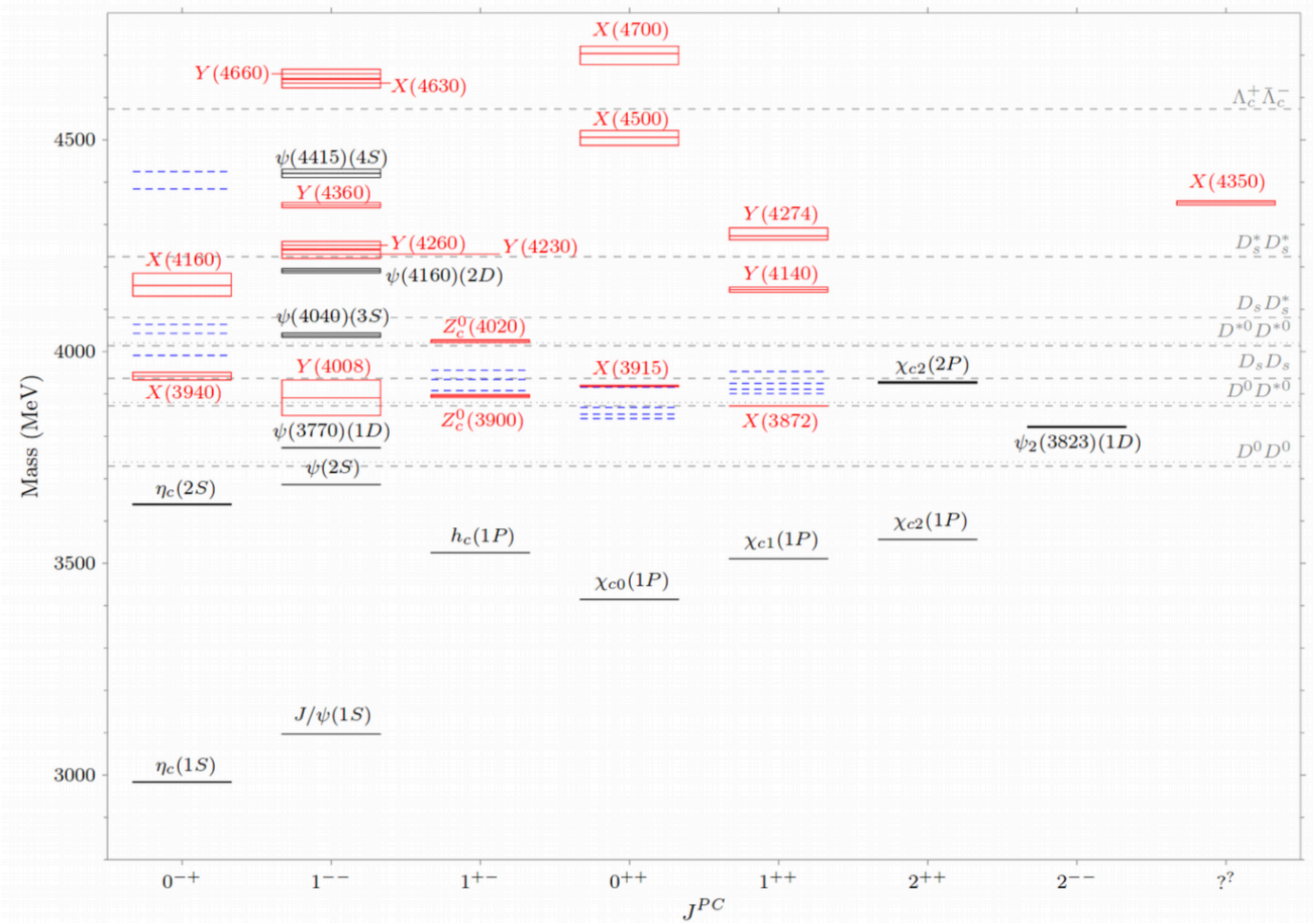
$J^{PC}=1^{--}$ (J/Ψ, Ψ(2S)) & J=0

Quarkonium transitions

Hadronic or radiative decays between states



Charmonium status



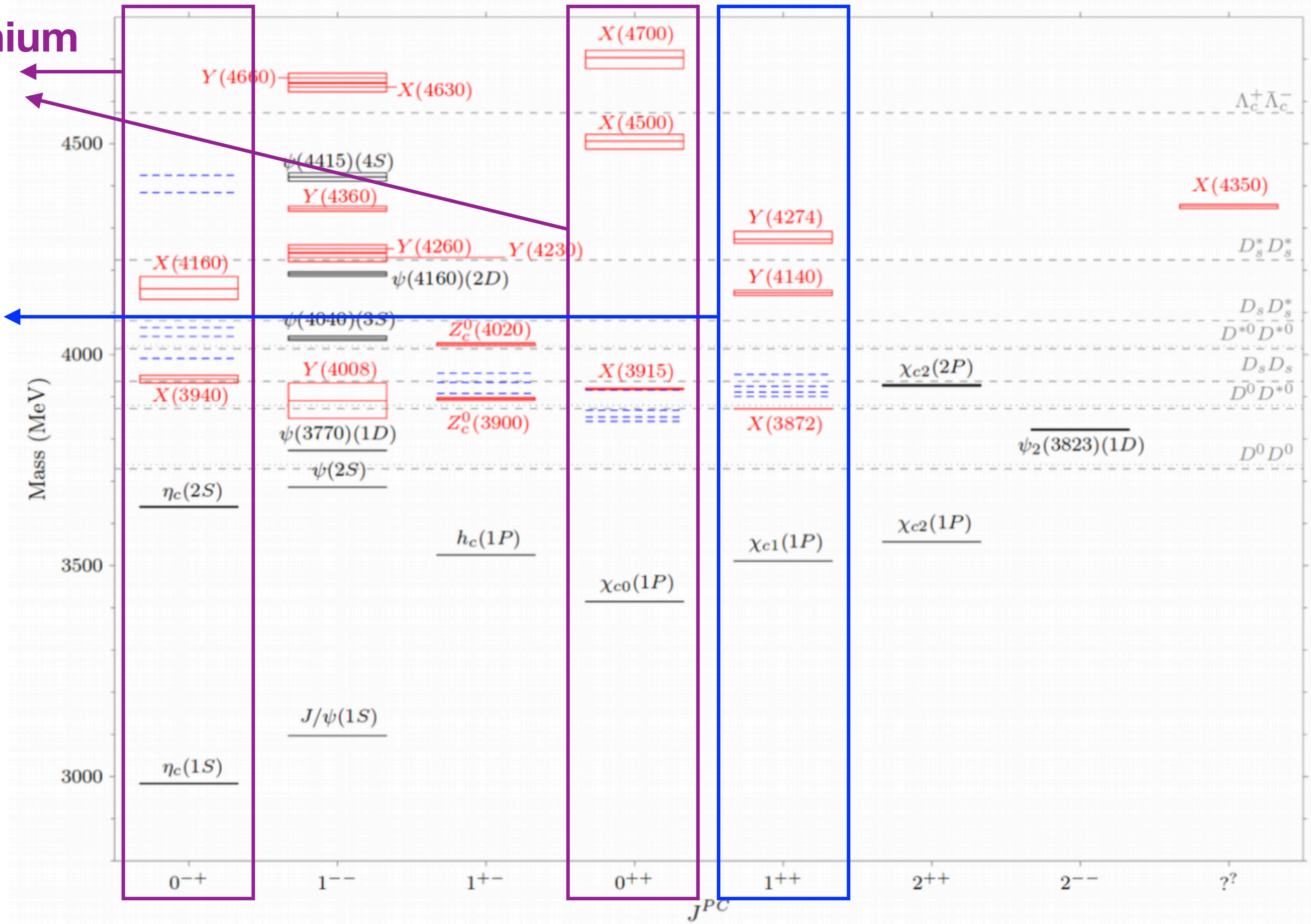
Current state:

- Many states and overpopulation
- Several states have been seen in one process only
- Limited statistics

Charmonium status

Double charmonium production

2 photon interaction



Current state:

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Belle II contribution

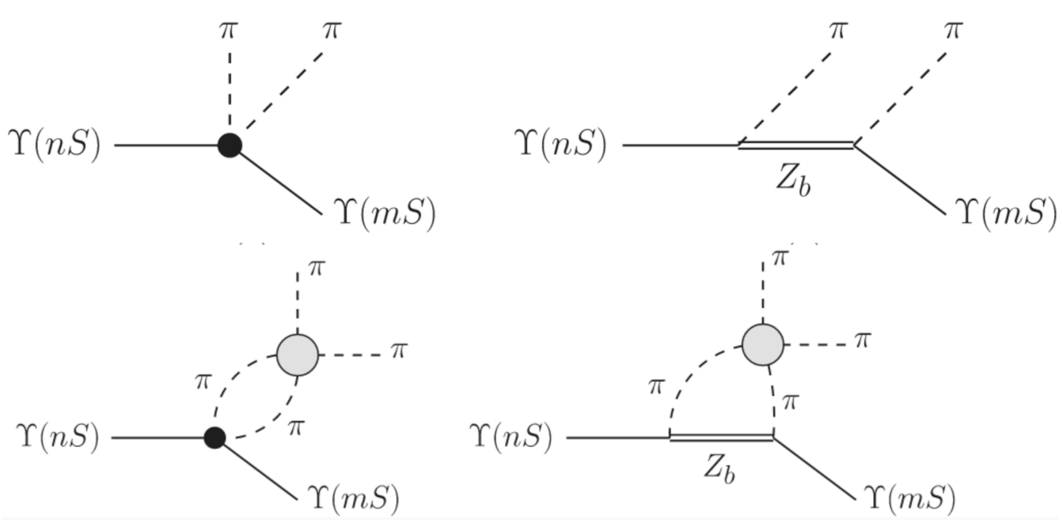
- Exploit unique production methods: double charmonium, two-photon;
- Large statistics samples to improve LHCb and BESIII sensitivity;
- Not necessarily restricted by E_{CM} (double charmonium, 2γ and ISR).

Bottomonium status

Current samples in fb^{-1} (millions of events), and the proposal for Belle II

Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
BelleII	-	-	300 (1200)	5×10^4 (5.4×10^4)	1000 (300)	100+400(scan)	3.6%

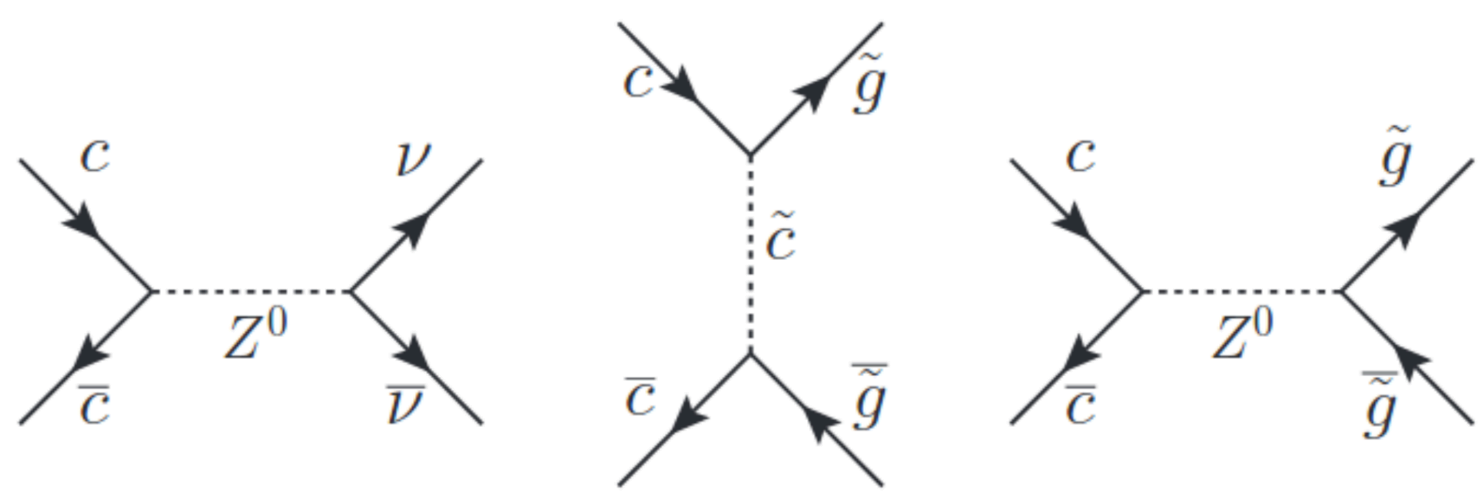
Y(3S) search for exotica in transitions



Belle II main goals:

- Y(3S) → ππ Y(1S) and search for missing ππ/η transitions;
- Y(3S): rare χ_b decays. $\chi_b(2P) \to \tau\tau$ is sensitive to the presence of a CP-even light Higgs;
- Y(1S) → invisible, SM confirmation and NP contributions;

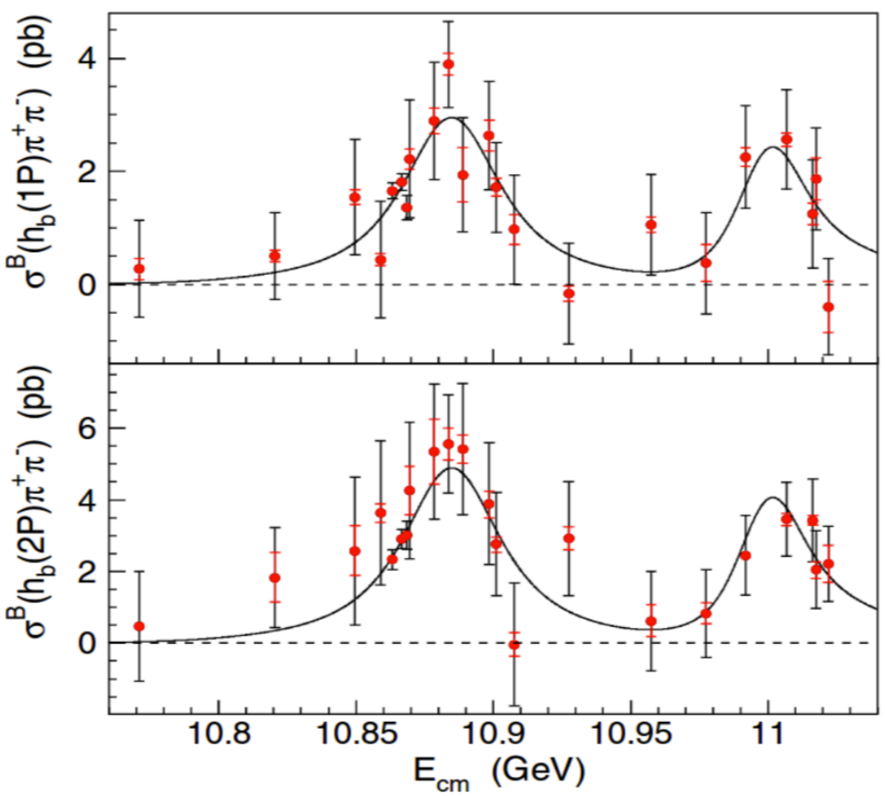
Non-SM contributions from Y(1S) → χχ



Bottomonium status

Current samples in fb^{-1} (millions of events), and the proposal for Belle II

Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
BelleII	-	-	300 (1200)	5×10^4 (5.4×10^4)	1000 (300)	100+400(scan)	3.6%



Accelerator requirement: E_{CM} = ~11.02 GeV, just above Y(6S)

Belle II main goals:

- Determine the Zb mass wrt the open flavour threshold;
- Search for new predicted resonances;
- Use both single transitions and double cascades;
- Y(5S)-Y(6S) scan → Investigate the presence of a broad resonance at 10.750 GeV and settle the nature of Y(5).

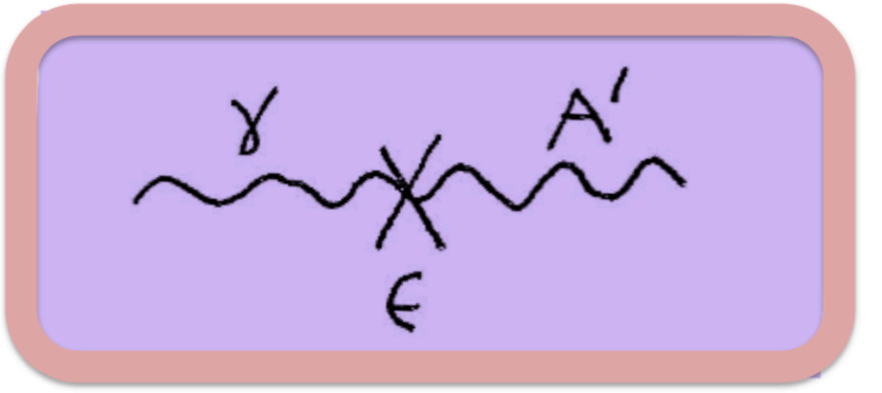
Name	L	S	J^{PC}	Emitted hadrons [Threshold, GeV/c^2]
$\eta_b(3S)$	0	0	0^{-+}	ω [11.12], ϕ [11.36]
$h_b(3P)$	1	0	1^{+-}	$\pi^+\pi^-$ [10.82], η [11.09], η' [11.50]
$\eta_{b2}(1D)$	2	0	2^{-+}	ω [10.93], ϕ [11.17]
$\eta_{b2}(2D)$	2	0	2^{-+}	ω [11.23], ϕ [11.47]
$\Upsilon_J(2D)$	2	1	$(1,2,3)^{--}$	$\pi^+\pi^-$ [10.73], η [11.00], η' [11.41]
$h_{b3}(1F)$	3	0	3^{+-}	$\pi^+\pi^-$ [10.63], η [10.90], η' [11.31]
$\chi_{bJ}(1F)$	3	1	$(2,3,4)^{++}$	ω [11.14], ϕ [11.38]
$\eta_{b4}(1G)$	4	0	4^{-+}	ω [11.31], ϕ [11.55]
$\Upsilon_J(1G)$	4	1	$(3,4,5)^{--}$	$\pi^+\pi^-$ [10.81], η [11.08], η' [11.49]

Belle II

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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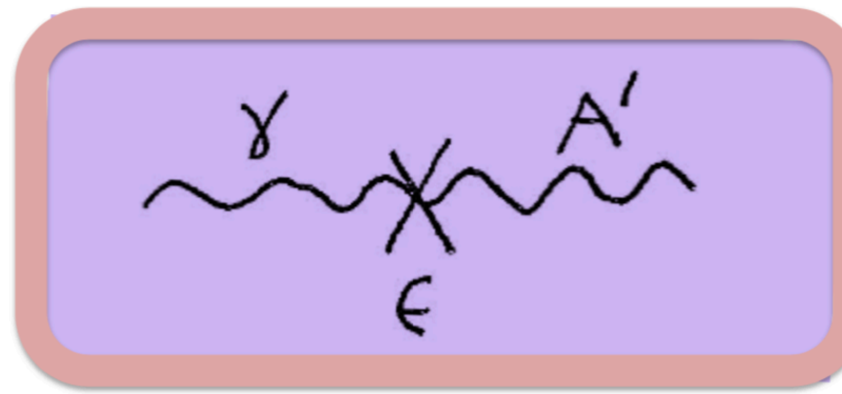
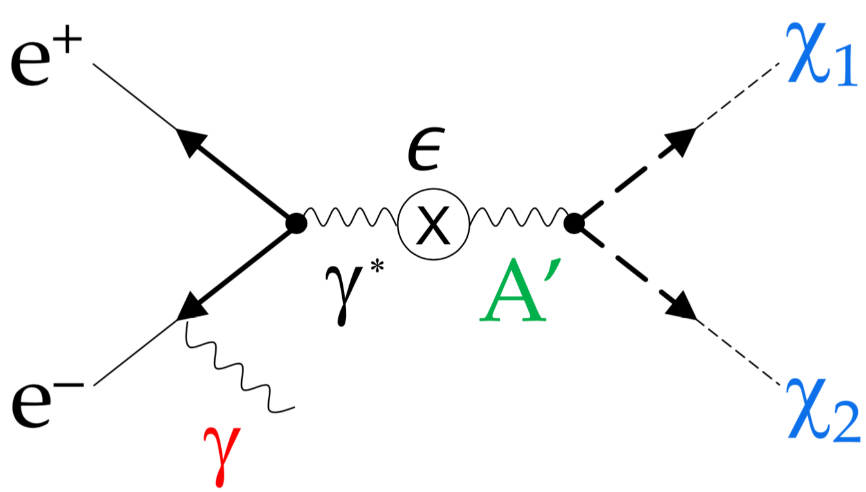
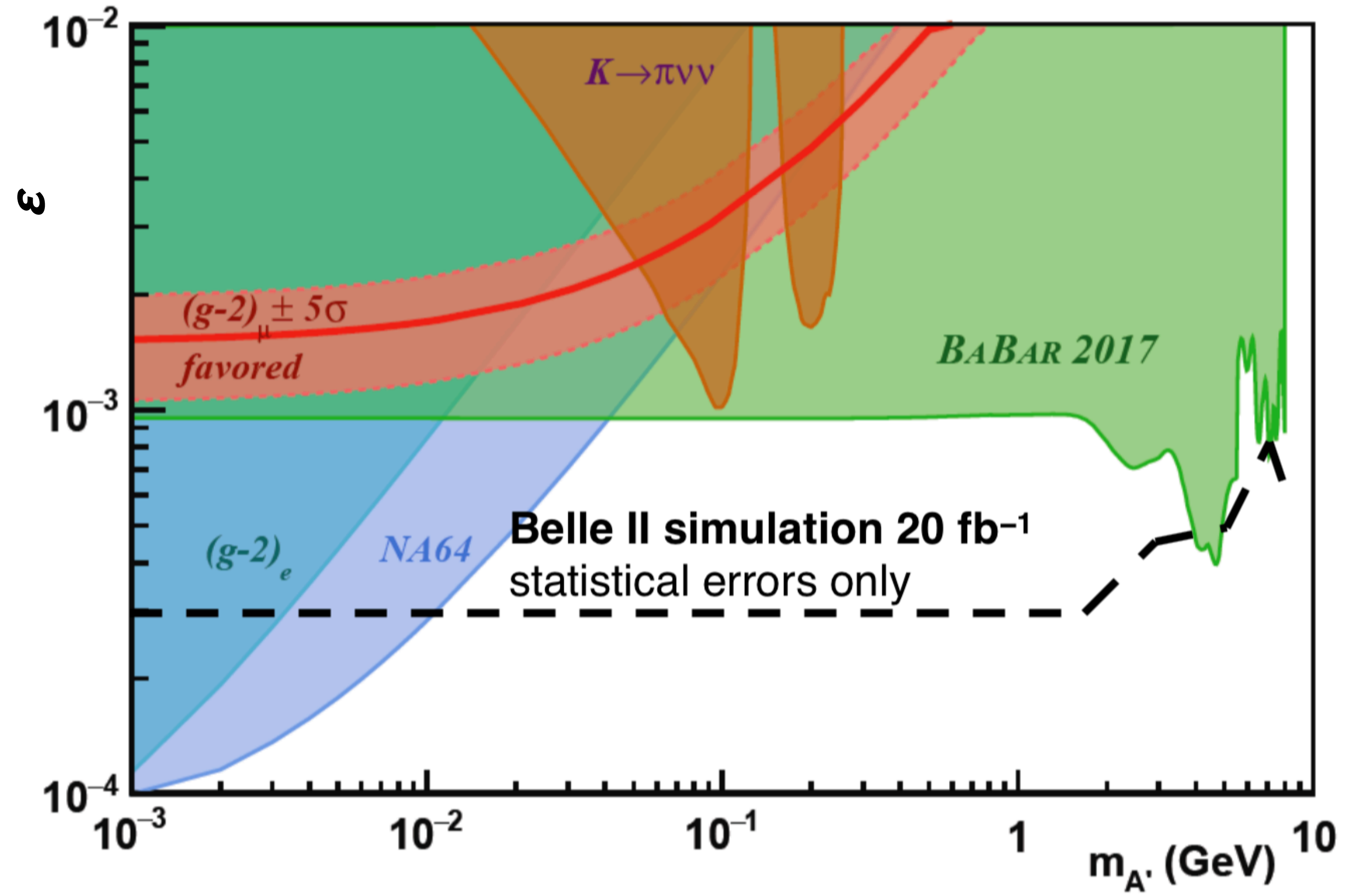
- $\chi_{1,2}$: dark matter particles



A' decay into invisible states



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



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

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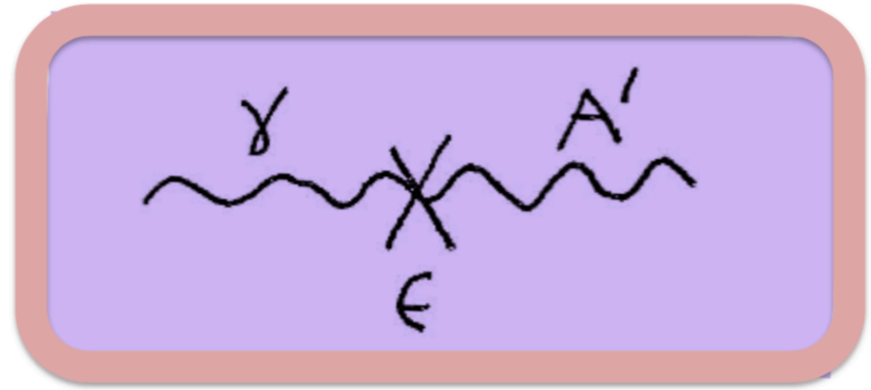

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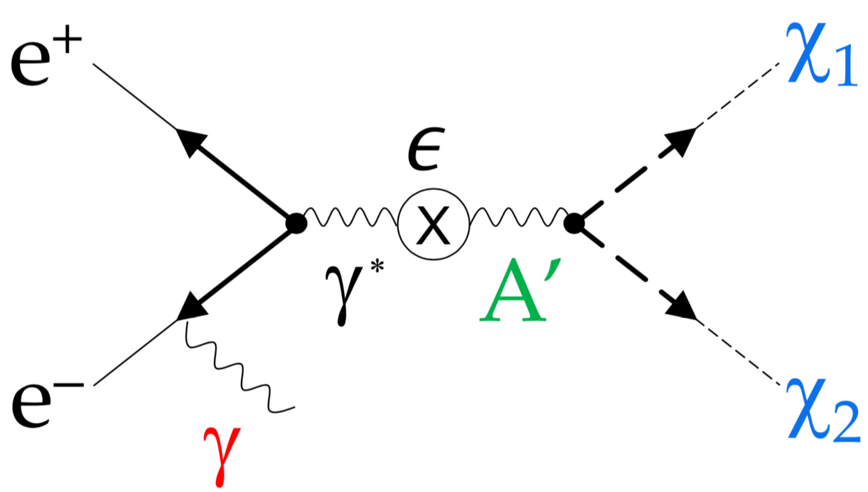

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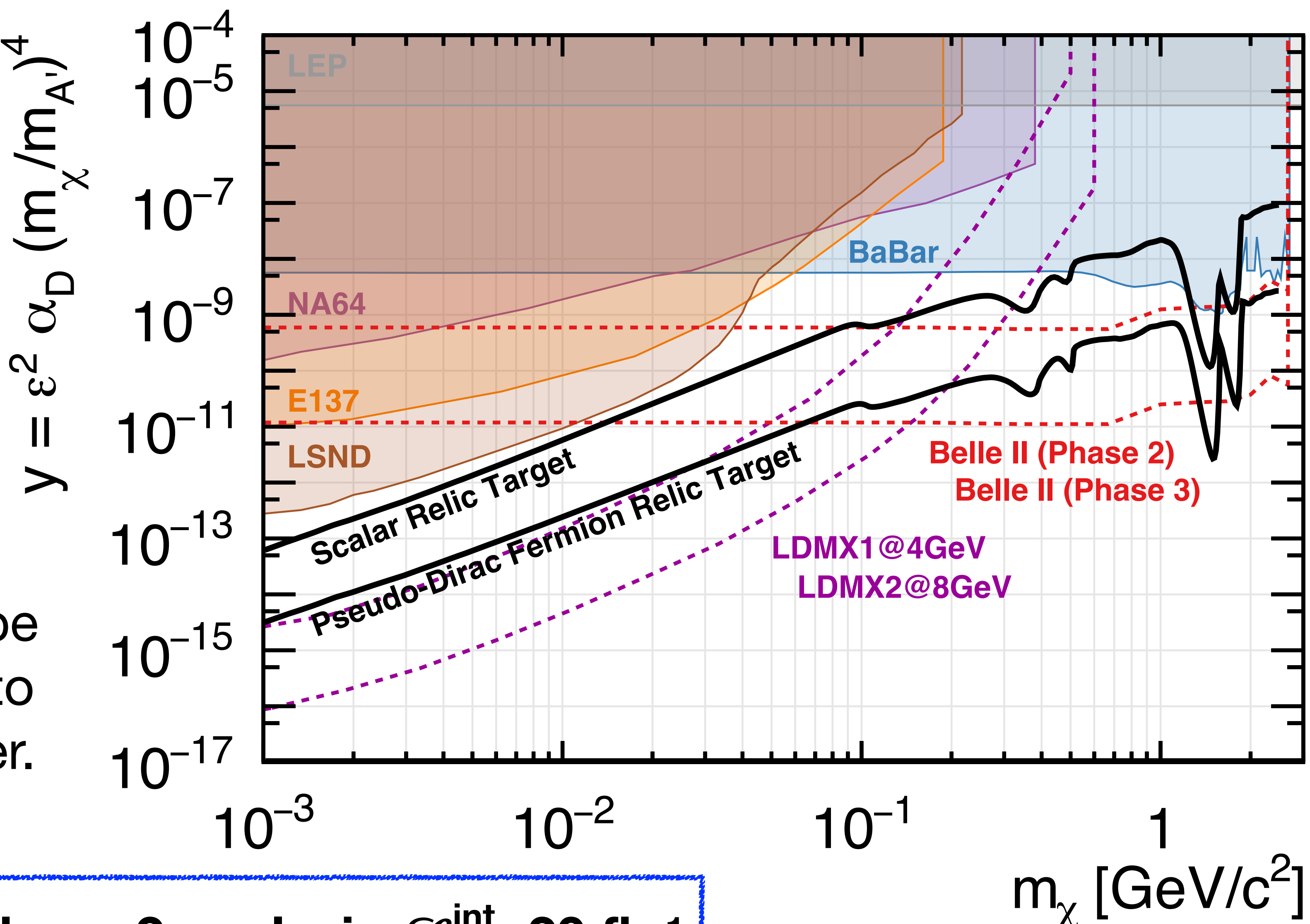


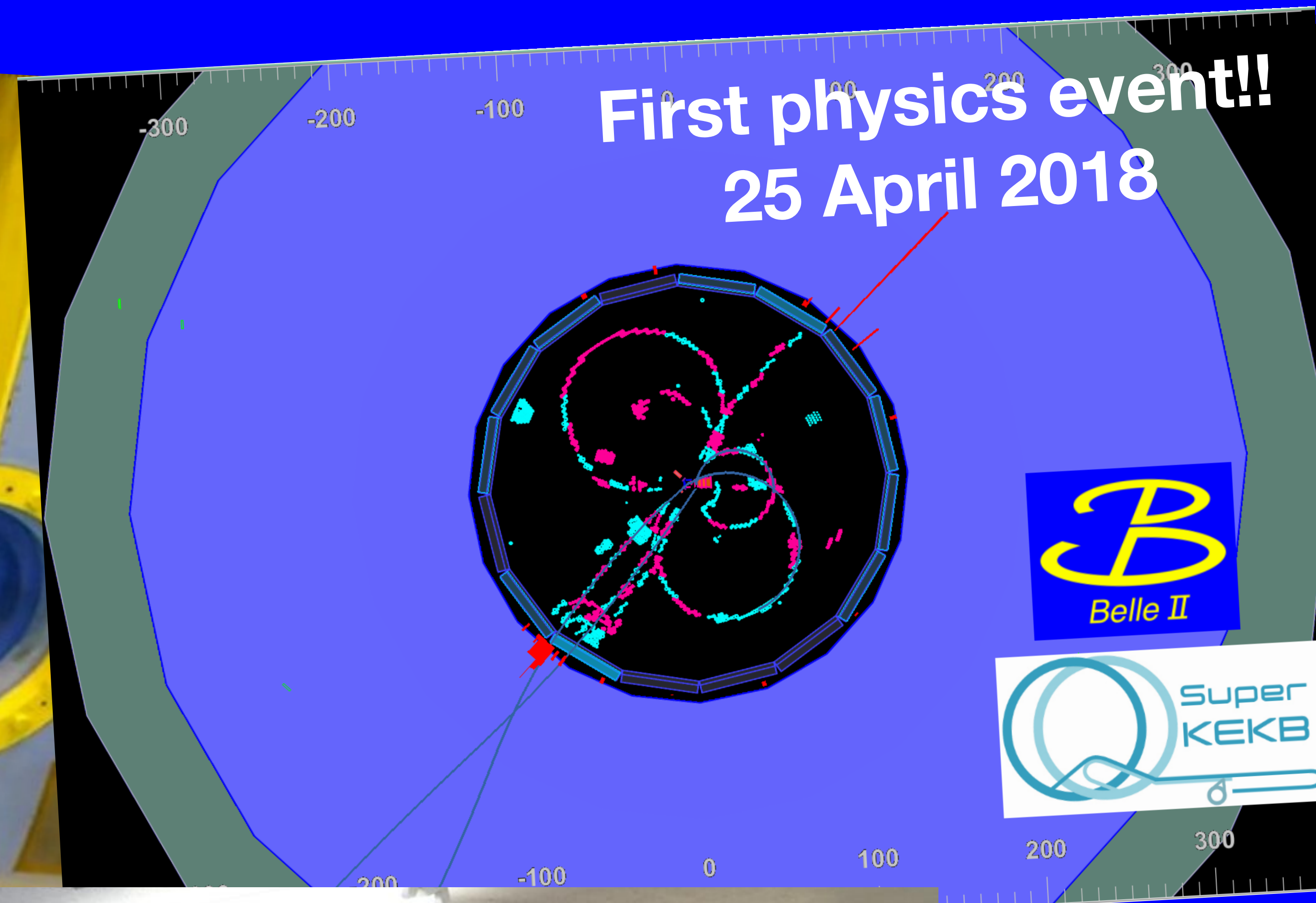
Possible phase 2 analysis $\mathscr{L}^{int}$=20 fb^{-1}

Conclusions

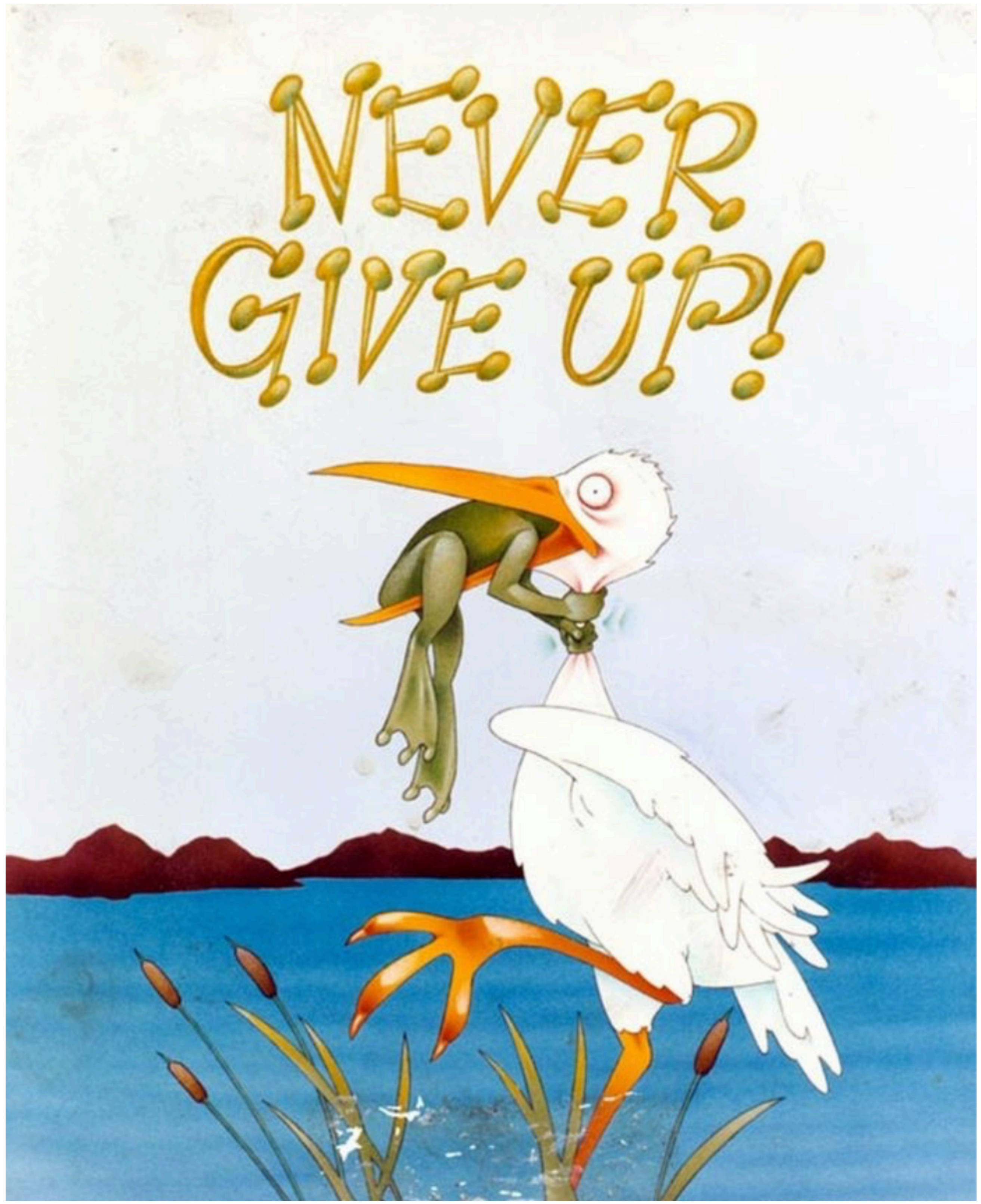
- New collider SuperKEKB → $\mathscr{L}^{int} = 50\ ab^{-1}$ before 2026
- Improved detector performances: good neutral particle reconstruction, resonances, decay vertices and events with high missing energy.
- Fundamental physics studies: CKM matrix, CPV, LFV, FCNC, dark sector.
- Installation and insertion 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

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

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$ $\Upsilon(4S)$	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}

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

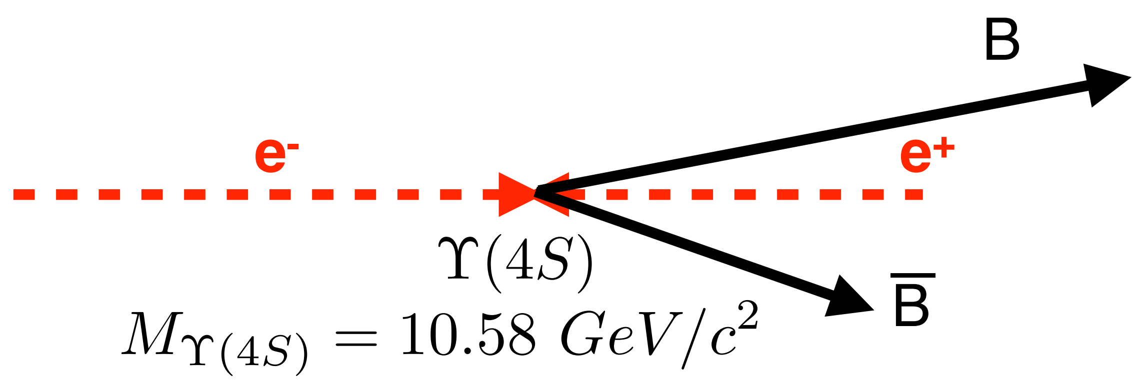
[a] Rate is pre-scaled by a factor 1/100

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

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

back..

CM boost



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

- E_{CM} at the resonance of $\Upsilon(4S)$
- Center of mass boost: $\beta\gamma = 0.28$

Symmetric beams:

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

↓

Decay vertex can not be resolve.

Asymmetric beams:

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

↓

Decay vertex can be resolved.

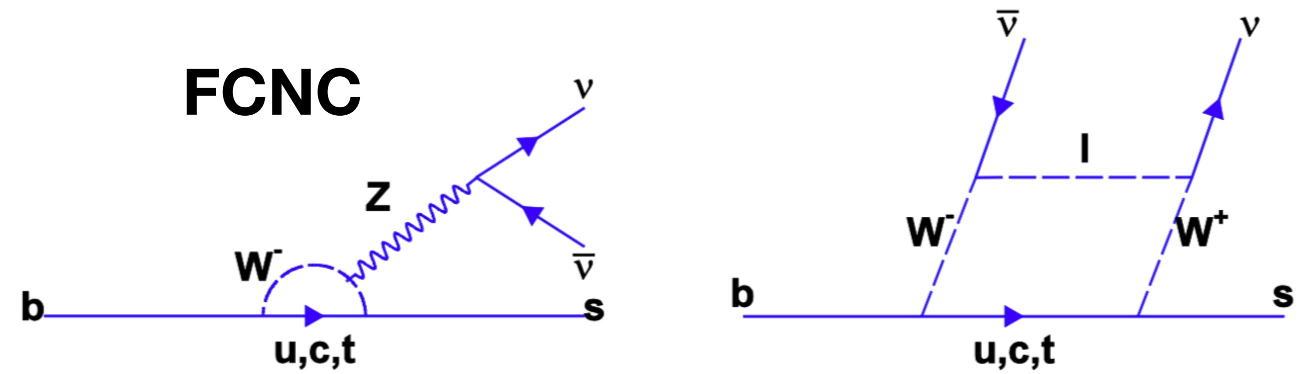
Belle CM boost: $\beta\gamma = 0.425$ → more separation but less luminosity.

back..

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

SM prediction box diagram + penguin:

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



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}

Complementary to LHCb

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\vert V_{us}\vert$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\vert V_{cb}\vert$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\vert V_{ub}\vert$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K^0_S]$	***	$8 \cdot 10^{-3}$	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
$S(B_d \to K^*(\to K^0_S\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A^d_{SL}	***	0.001	LHCb
A^s_{SL}	***	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
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	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			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\vert q/p\vert_D$	***	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.

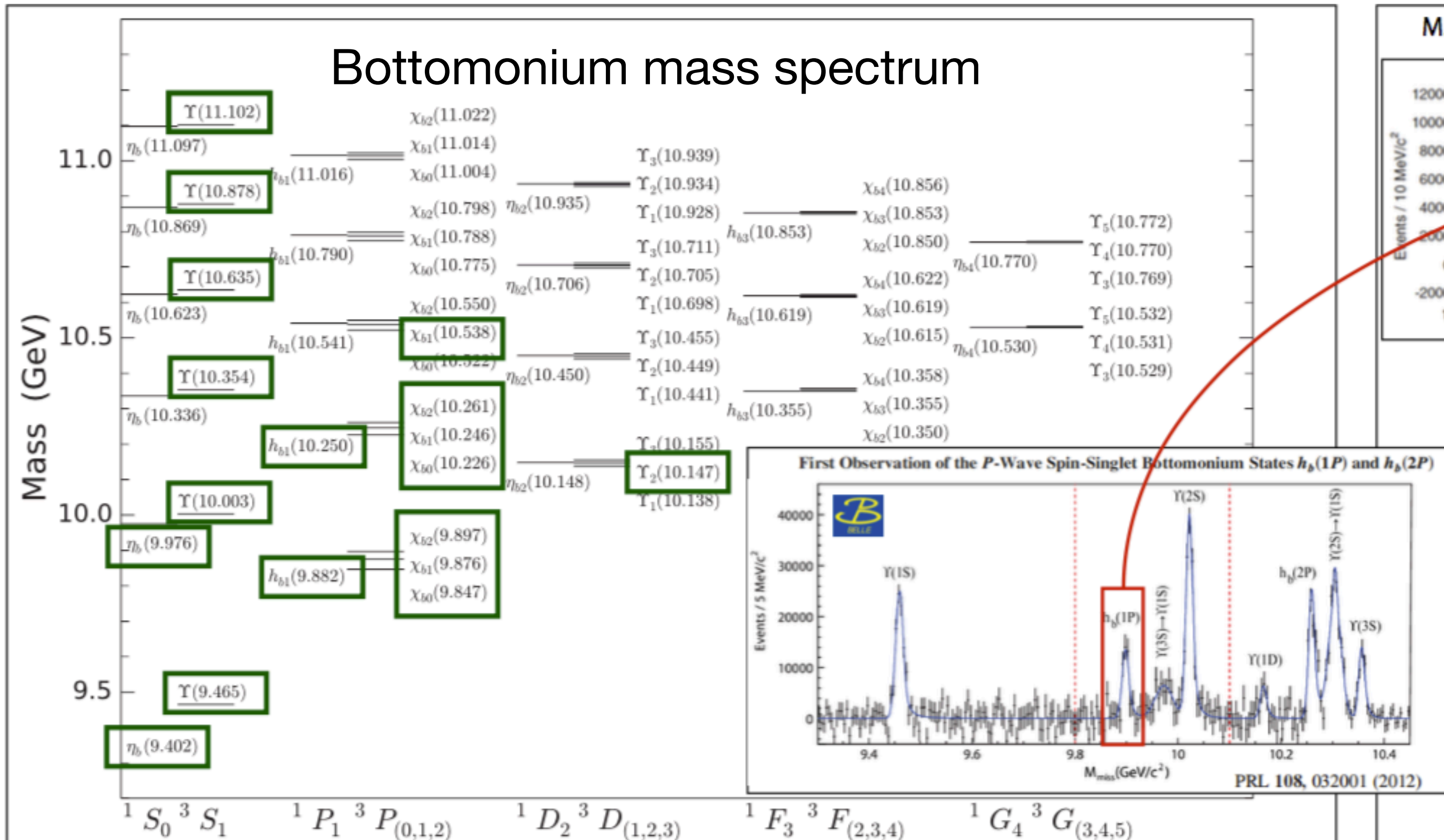
Belle II:

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

back..

B. Golob, KEK FF Workshop, Feb. 2012

Hadronic spettroscopy

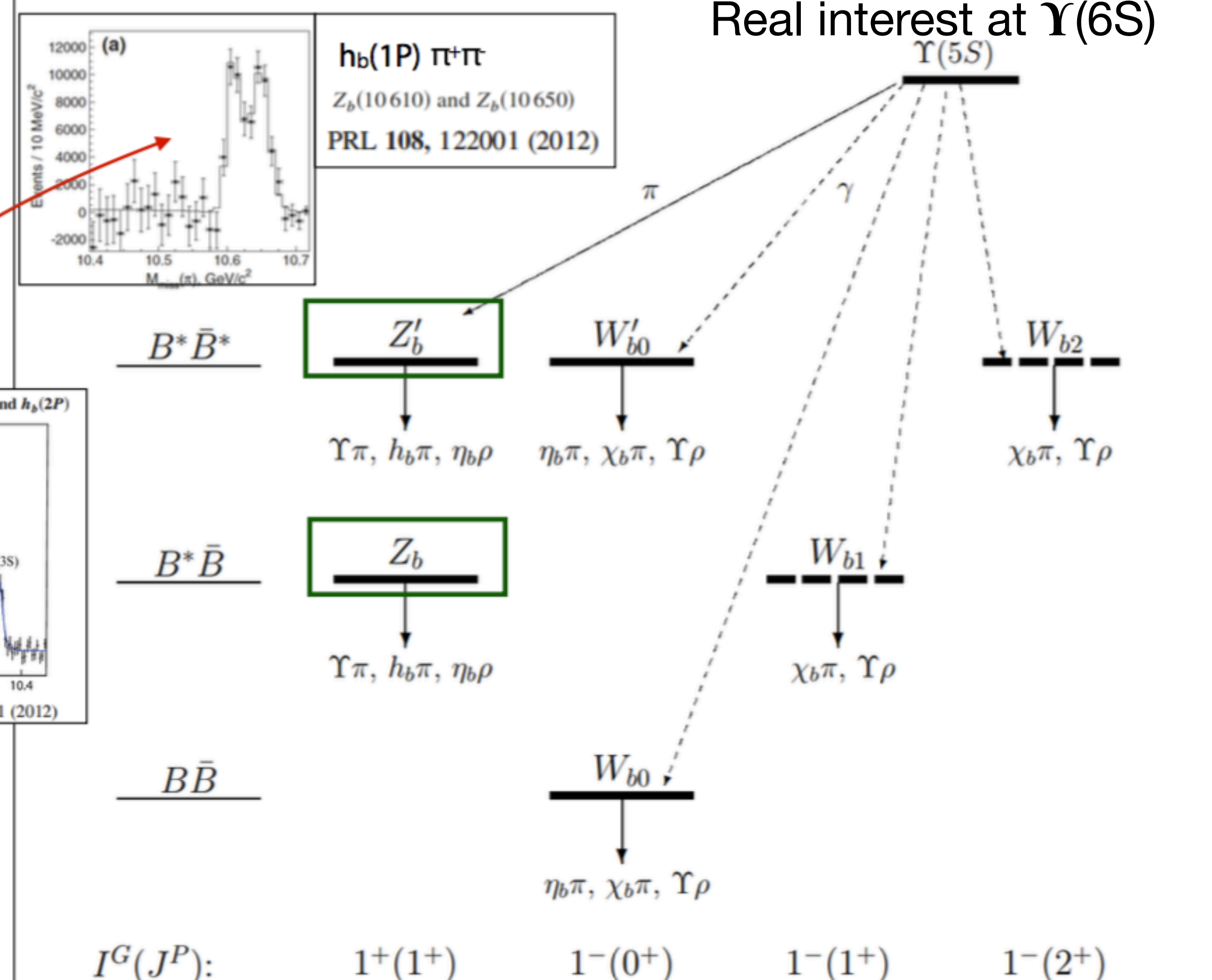


S. Godfrey and K. Moats, Bottomonium mesons and strategies for their observation, Phys. Rev. D 92, 054034 (2015)
S. Godfrey and N. Isgur, Mesons in a relativized quark model with chromodynamics, Phys. Rev. D 32, 189 (1985).

Many intermediate states have been observed and many others have not

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

Real interest at Υ(6S)

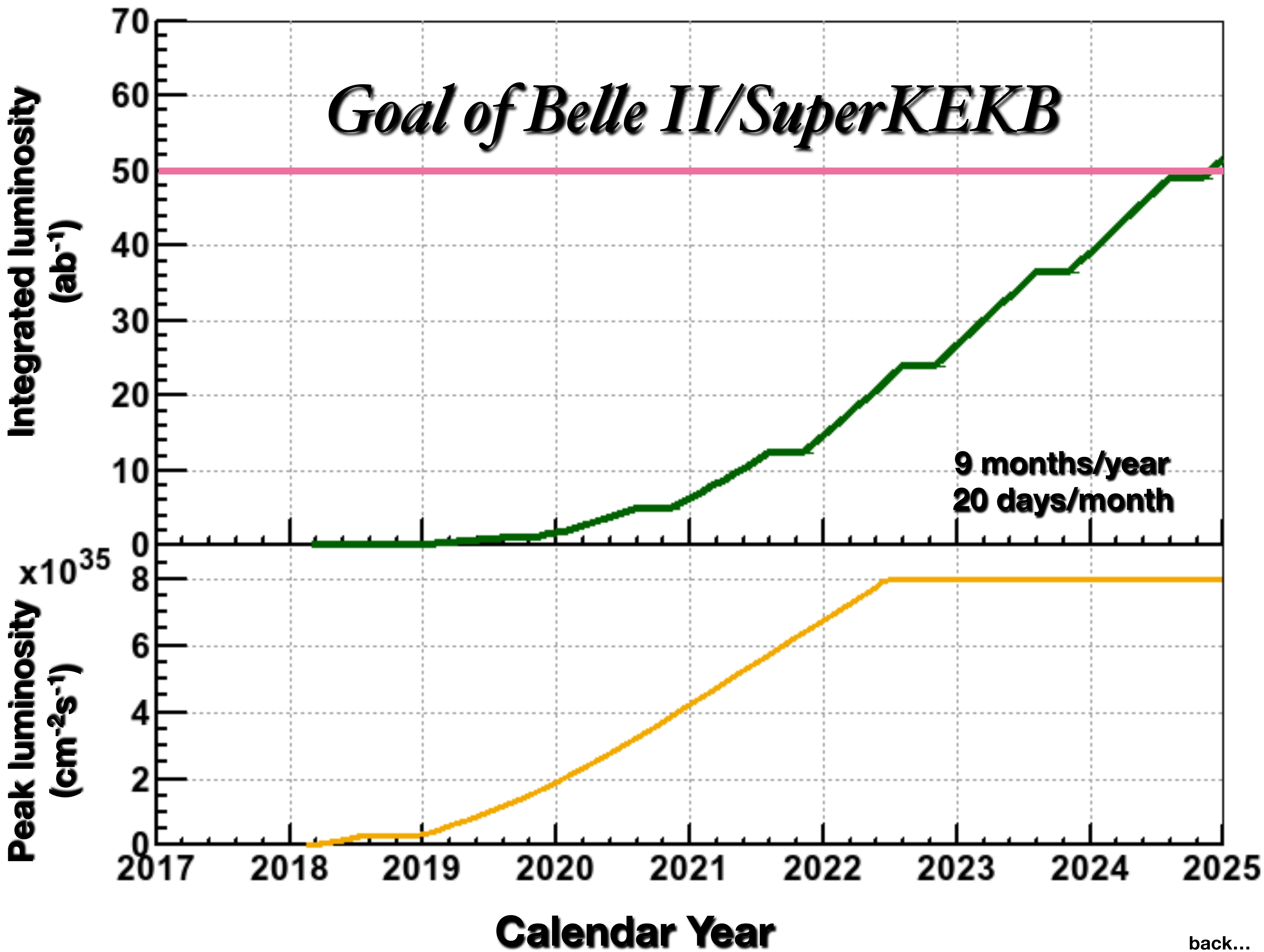


The heavy quark spin symmetry implies that in addition to the recently observed $Z(10610)$ and $Z(10650)$ molecular resonances with $I^G = 1^+$, there should exist two or four molecular bottomonium-like states with $I^G = 1^-$. Properties of these G-odd states are considered, including their production in the radiative transitions from Υ(5S), by applying the same symmetry to the Υ(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.

back..

SuperKEKB luminosity projection

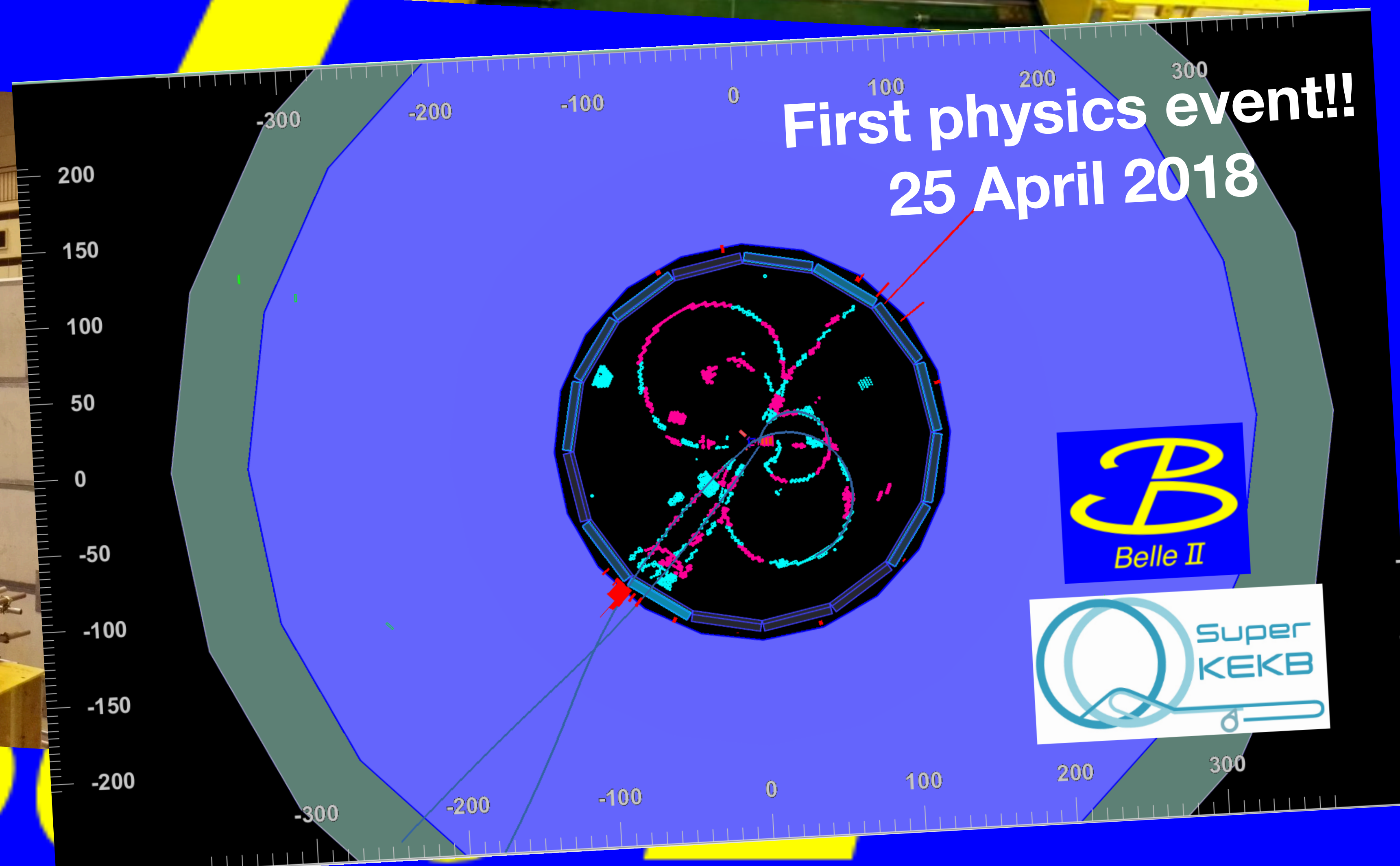


back...


Top installation
May 2016


Belle II insertion
11 April 2017


CDC installation
October 2016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