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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Belle II

Belle II: second generation B-factory (I)

Main experiments at B-factories of the past:

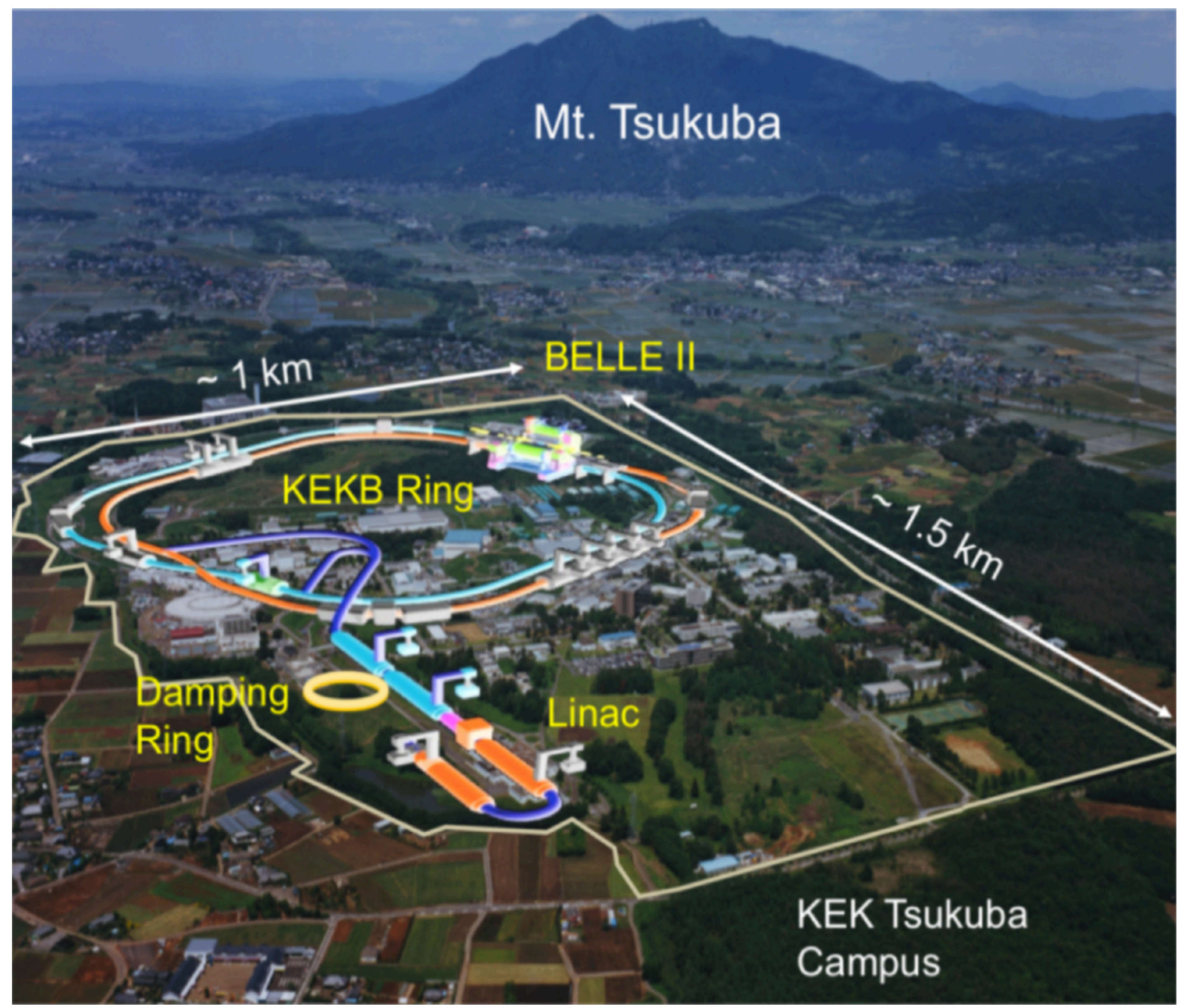
- Belle (KEK Laboratory, Japan)
- BaBar (SLAC Laboratory, California)

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

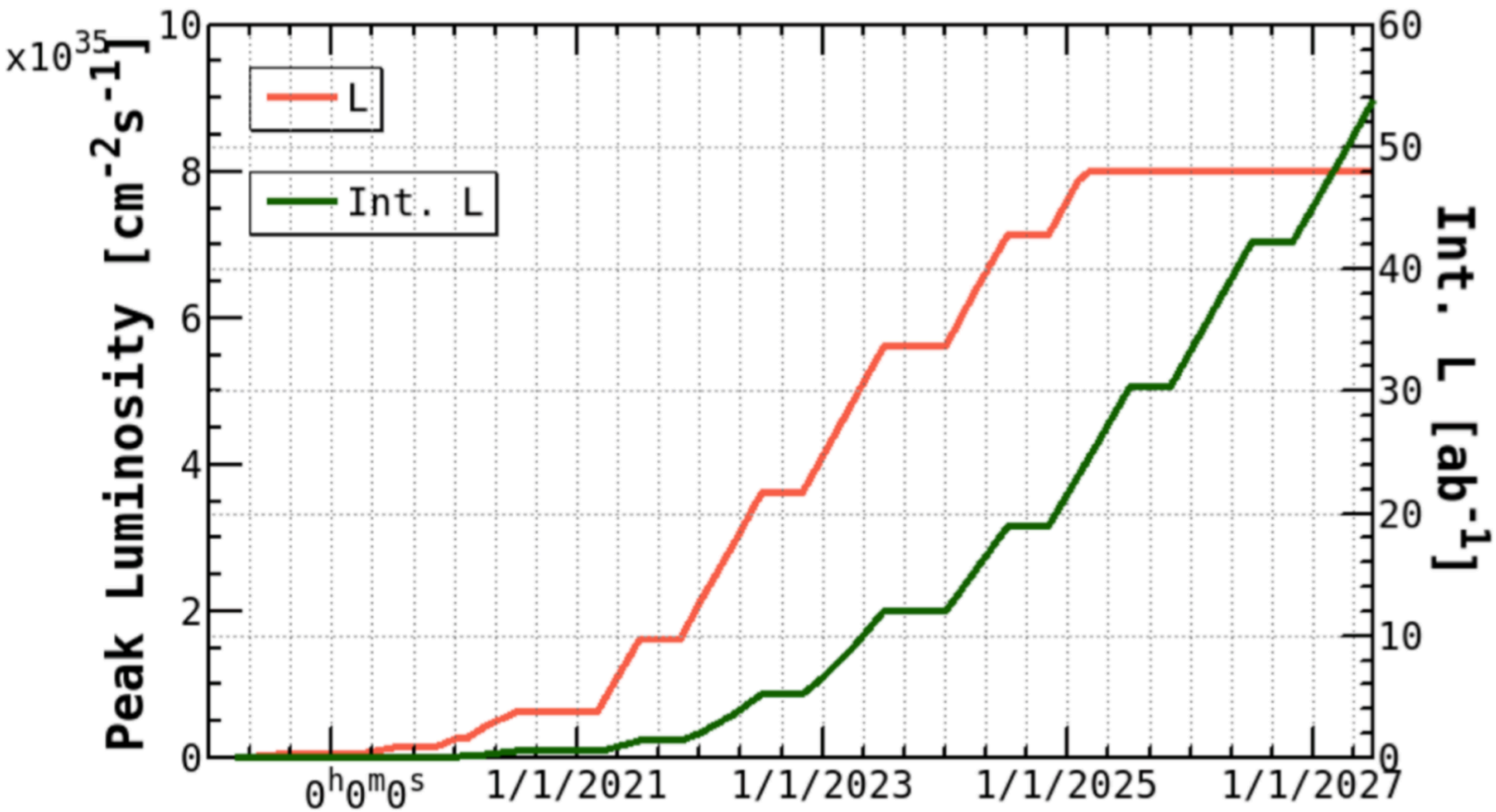
Main problem:
statistics collected by KEKB and PEP-II colliders was not sufficient to analyse some rare decays, SM validations and other highly precise measurements

↓

Belle II: usage of the improved collider SuperKEKB



Belle II: second generation B-factory (II)



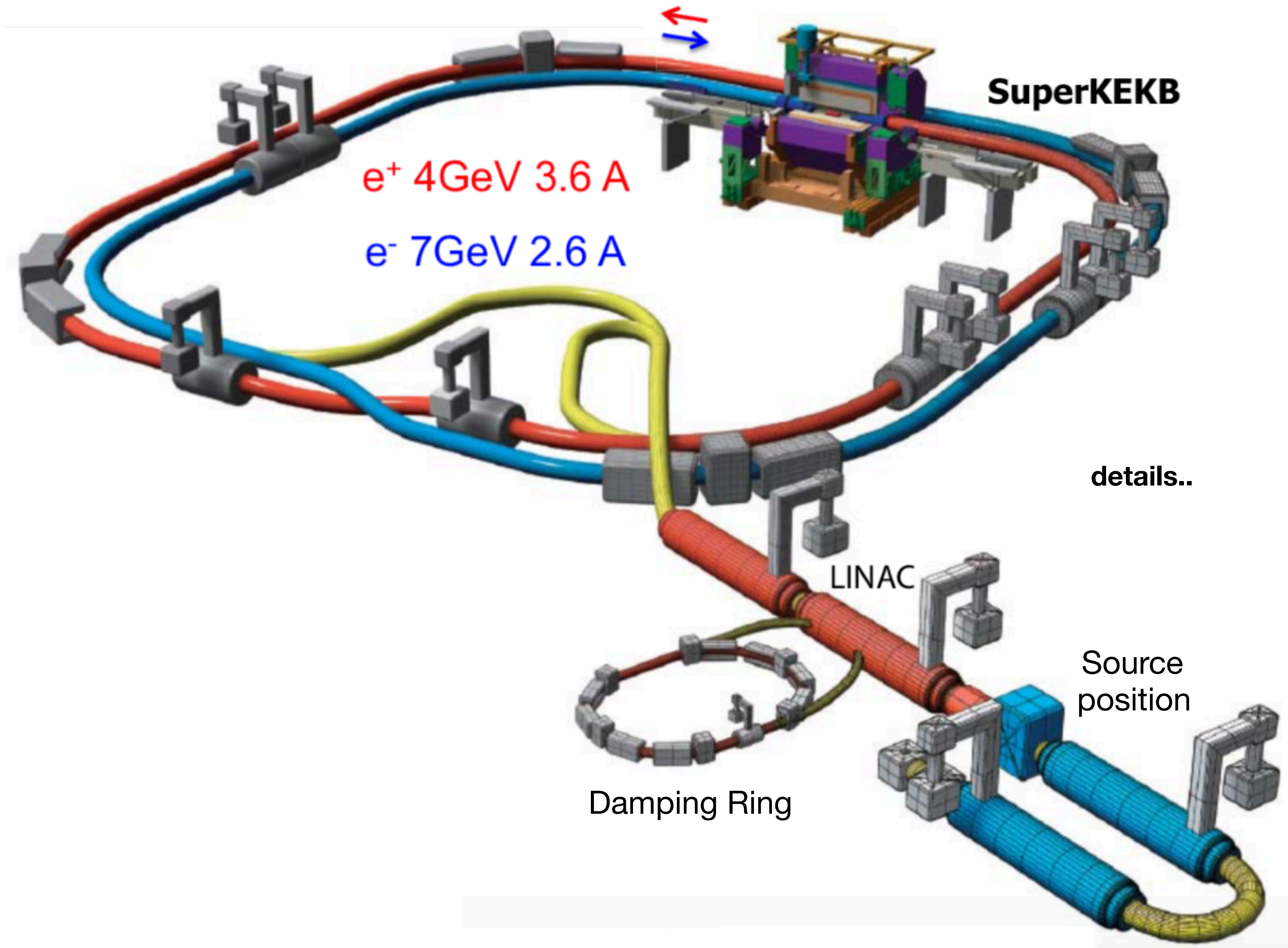
Improved detector performances

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

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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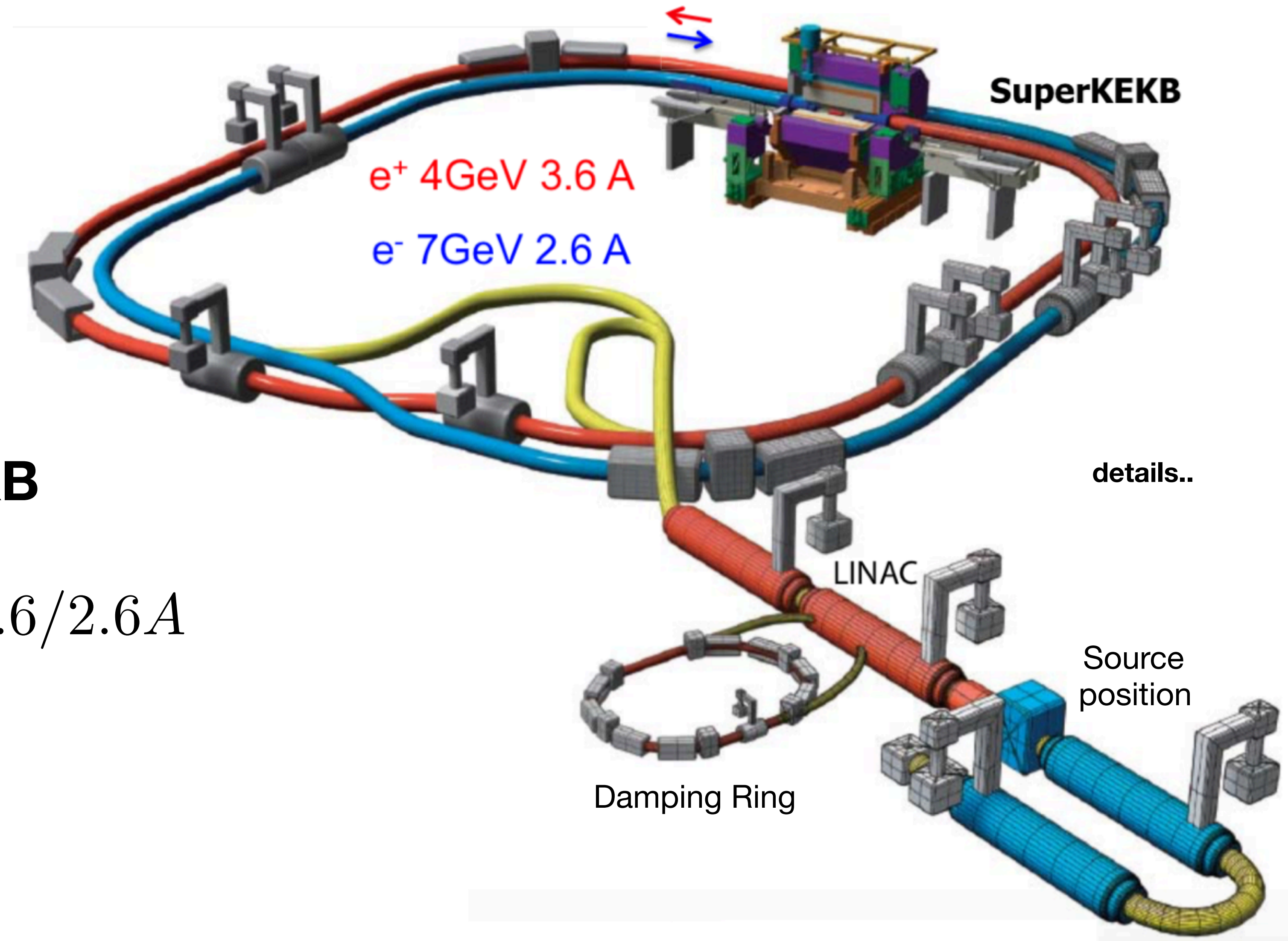

KEKB

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

SuperKEKB

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

Collider SuperKEKB

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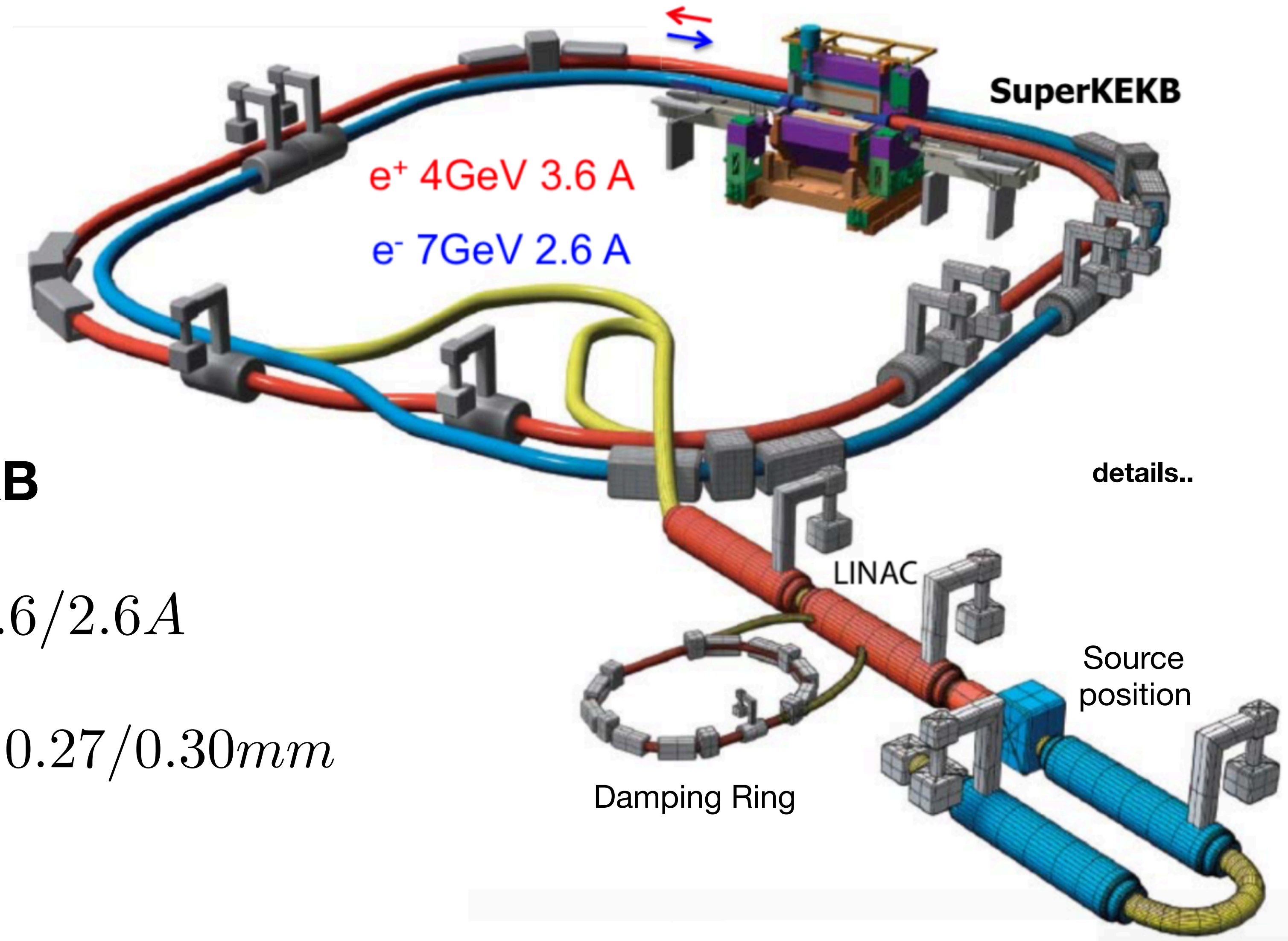

KEKB	**SuperKEKB**
$I_{e^+/e^-} = 1.64/1.19A$	$I_{e^+/e^-} = 3.6/2.6A$
$\beta^*_{y\ e^+/e^-} = 5.9/5.9mm$	$\beta^*_{y\ e^+/e^-} = 0.27/0.30mm$

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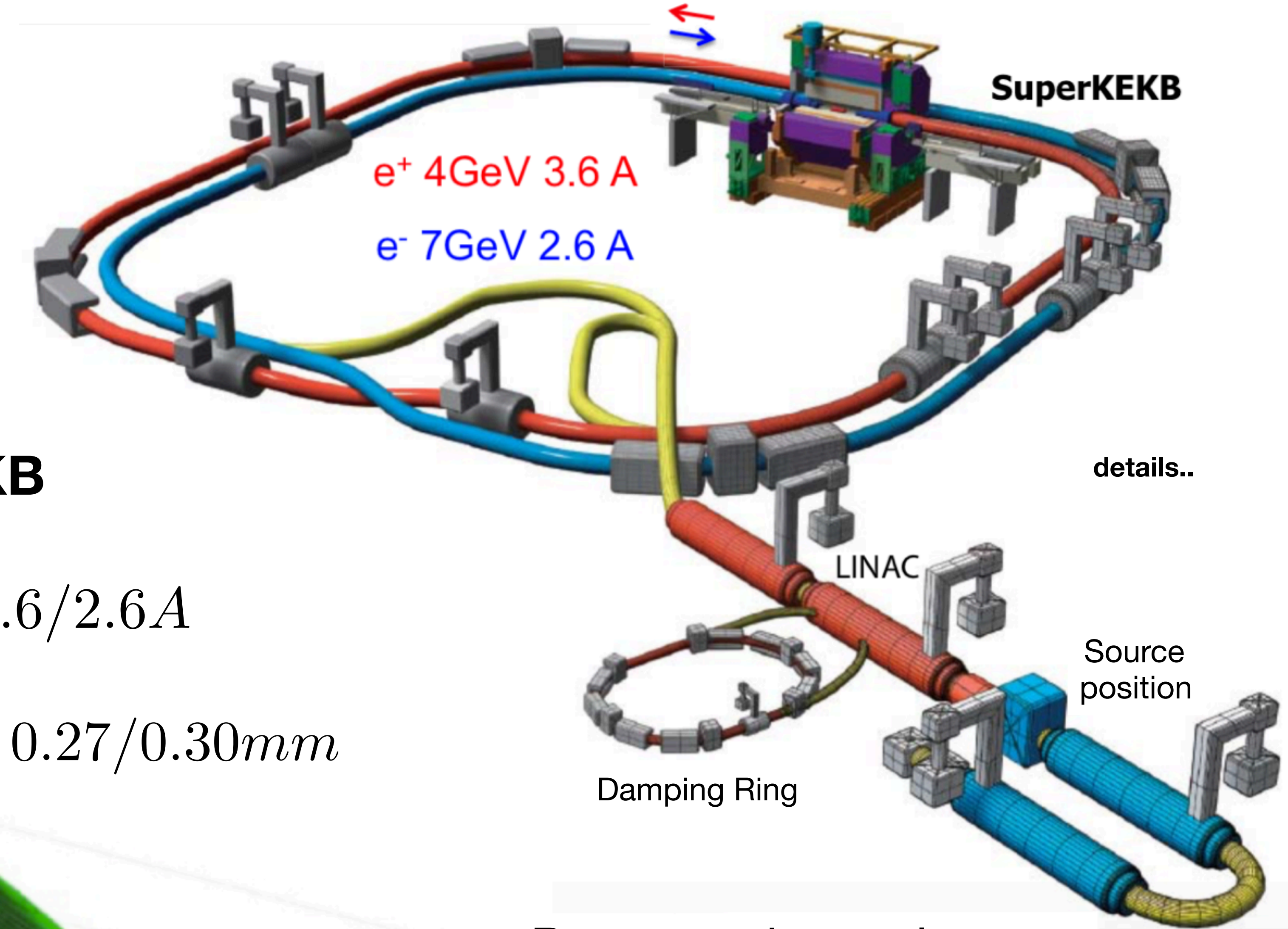

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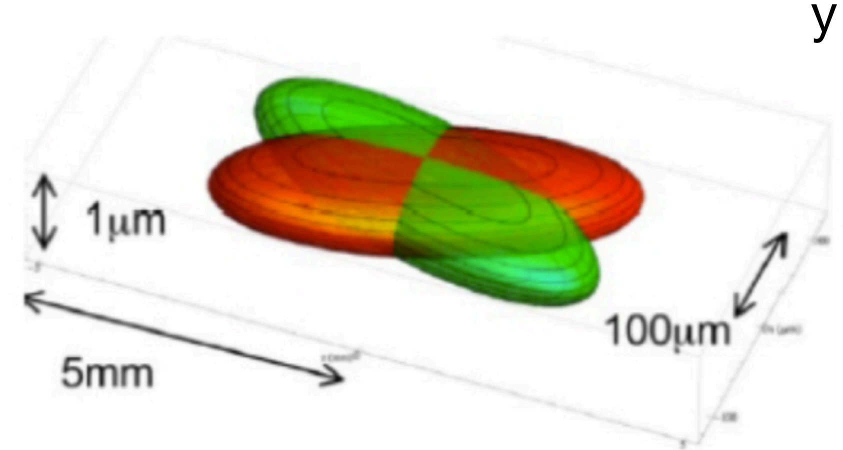

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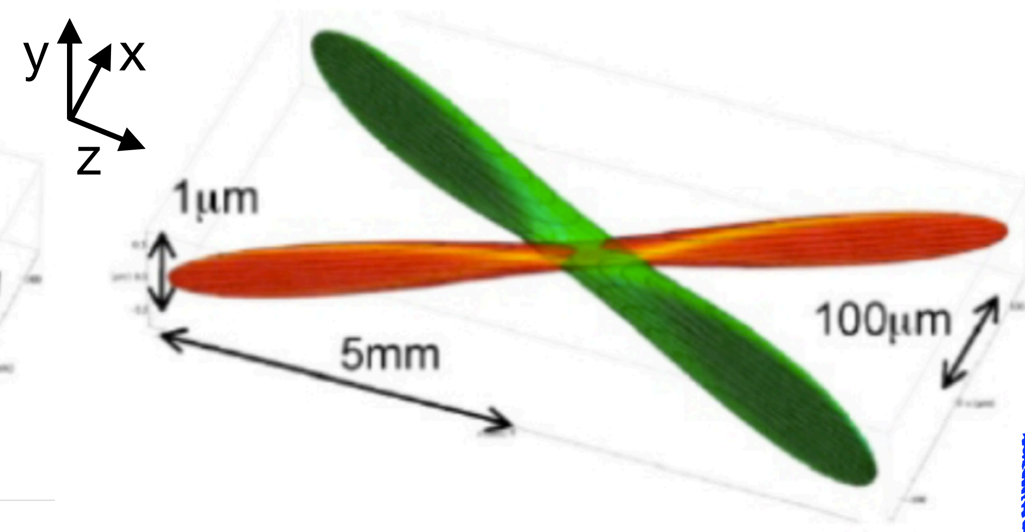
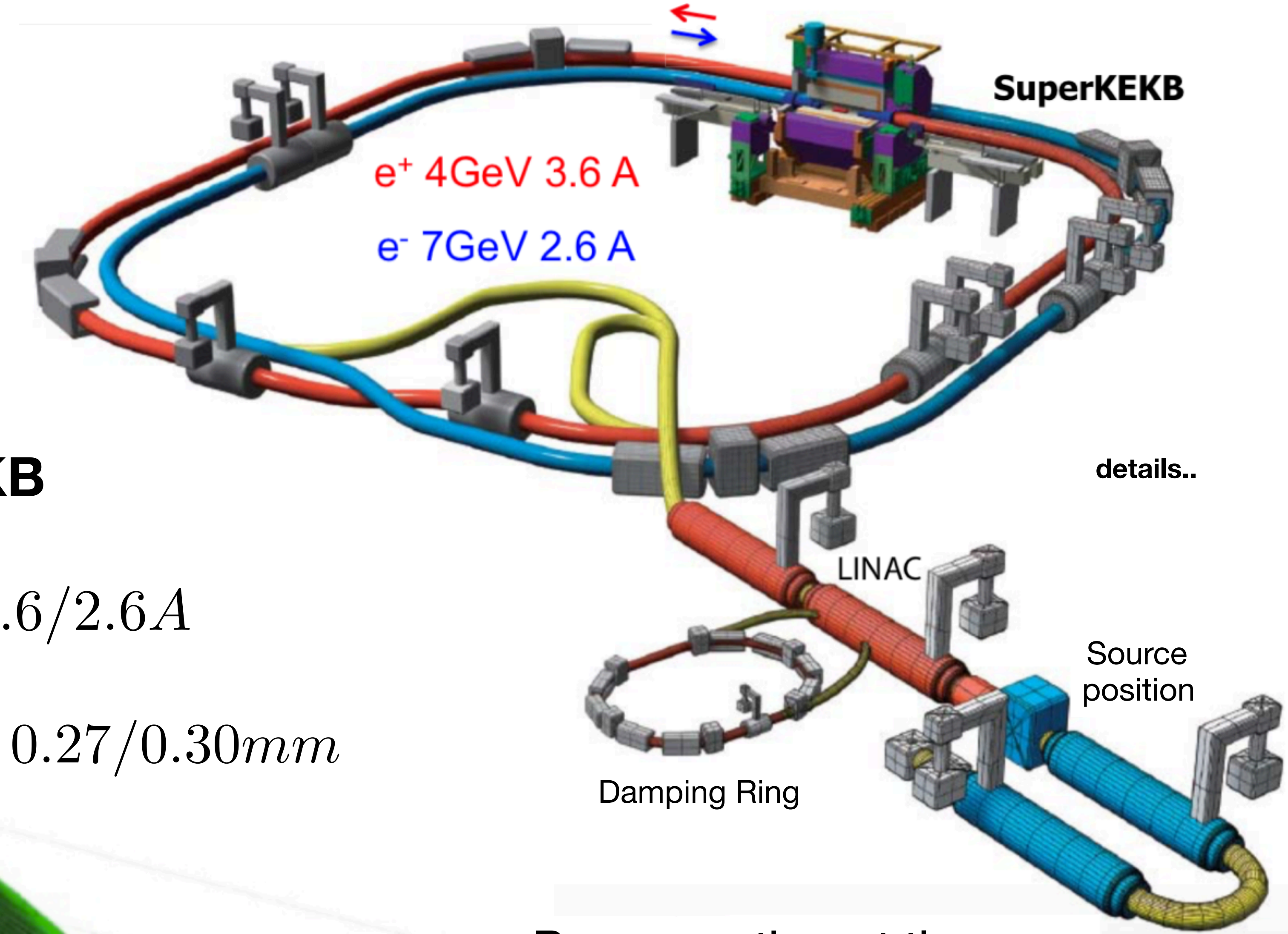


Beam section at the interaction point:
~42 nm in y
~6 μm in x

Nano-beam scheme

Collider SuperKEKB

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



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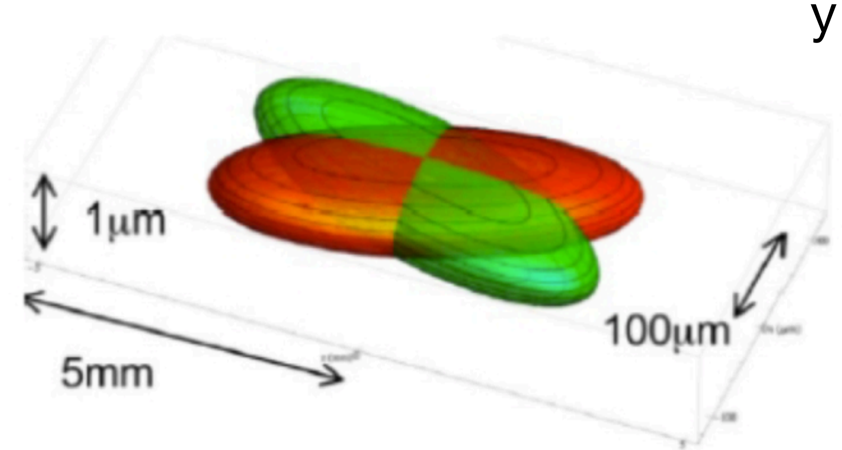

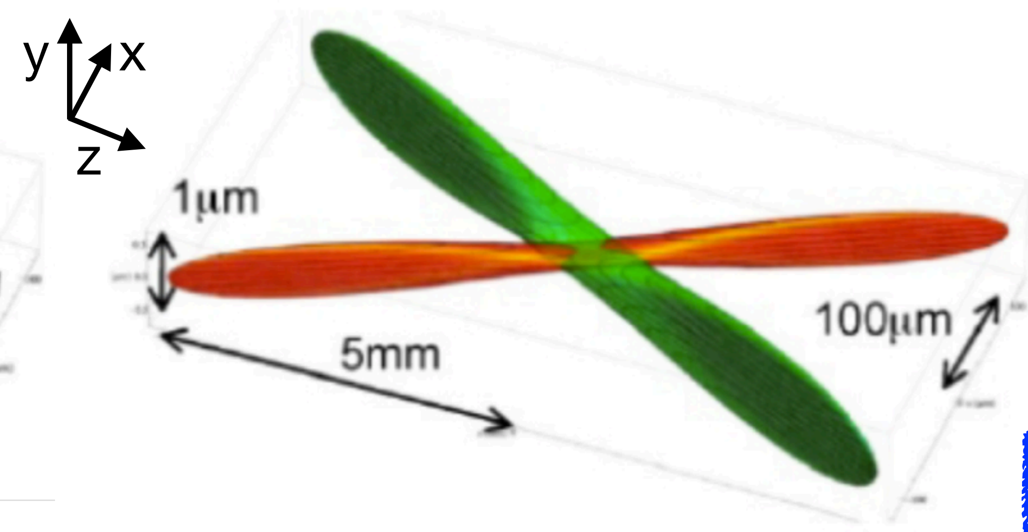

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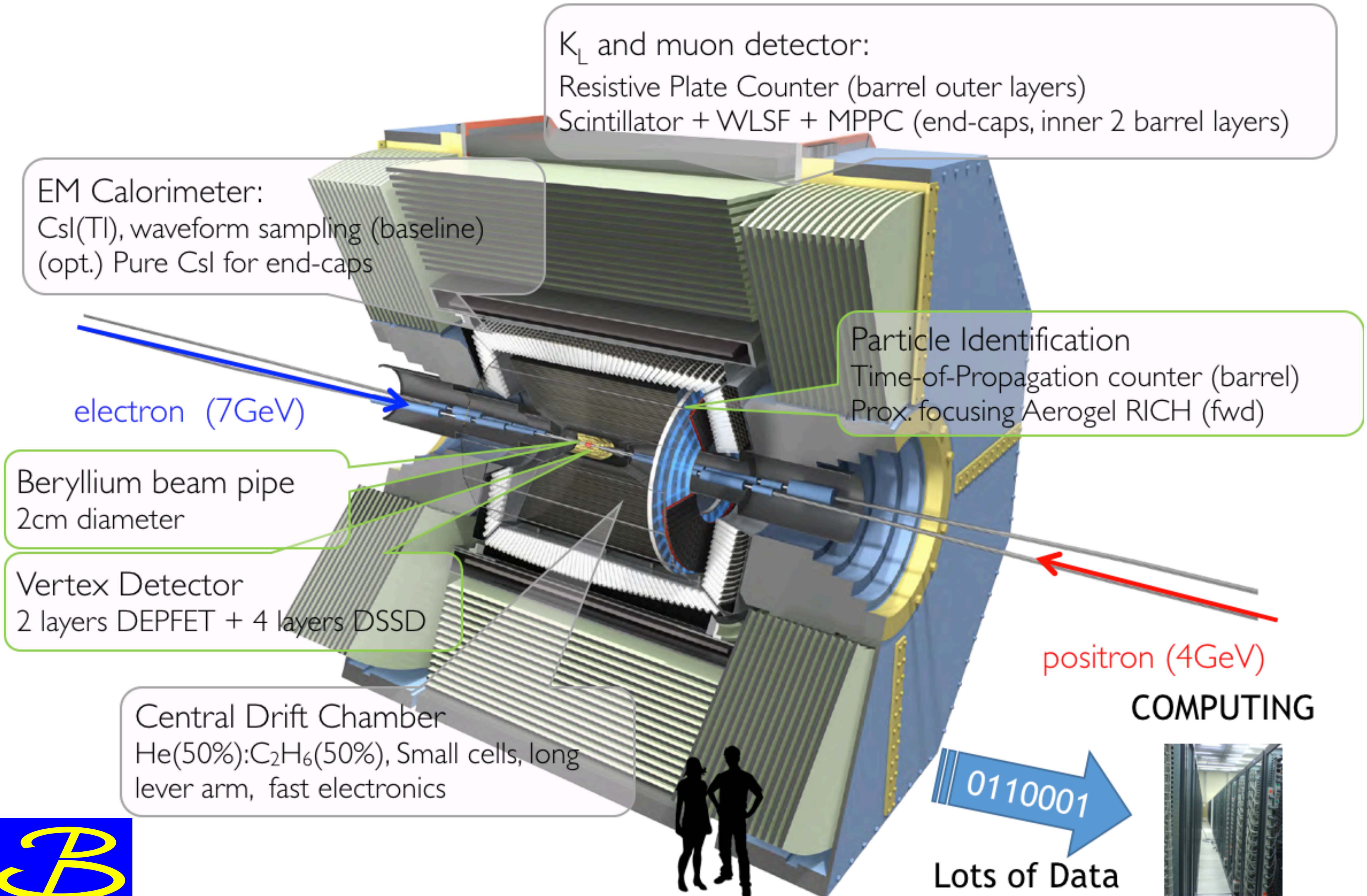
Nano-beam scheme

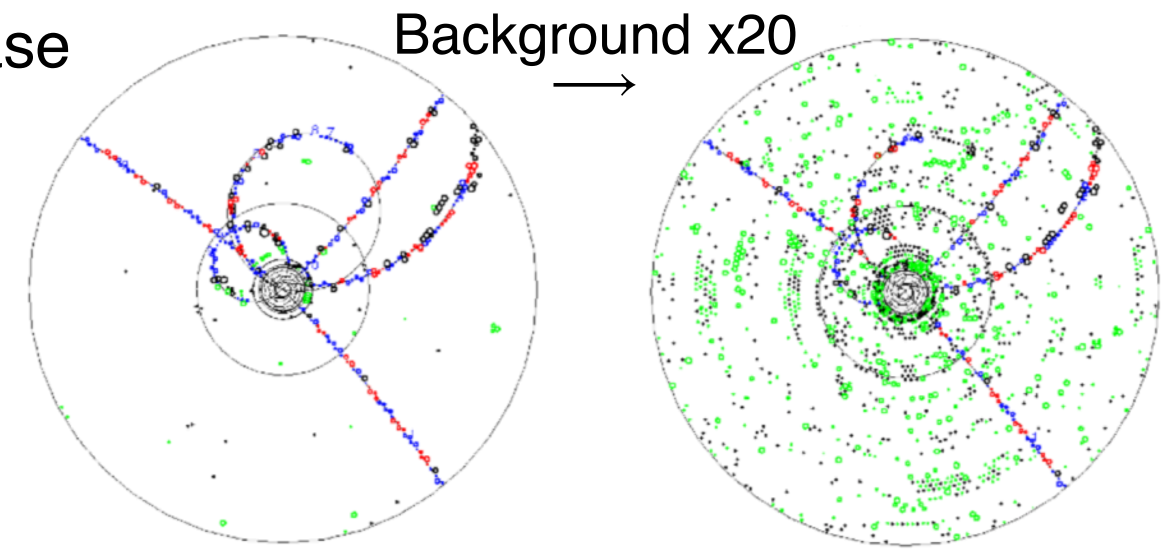
Expected improvement of integrated luminosity of a factor ~50 w.r.t. Belle: **50 ab^{-1}**

Belle II detector (I)



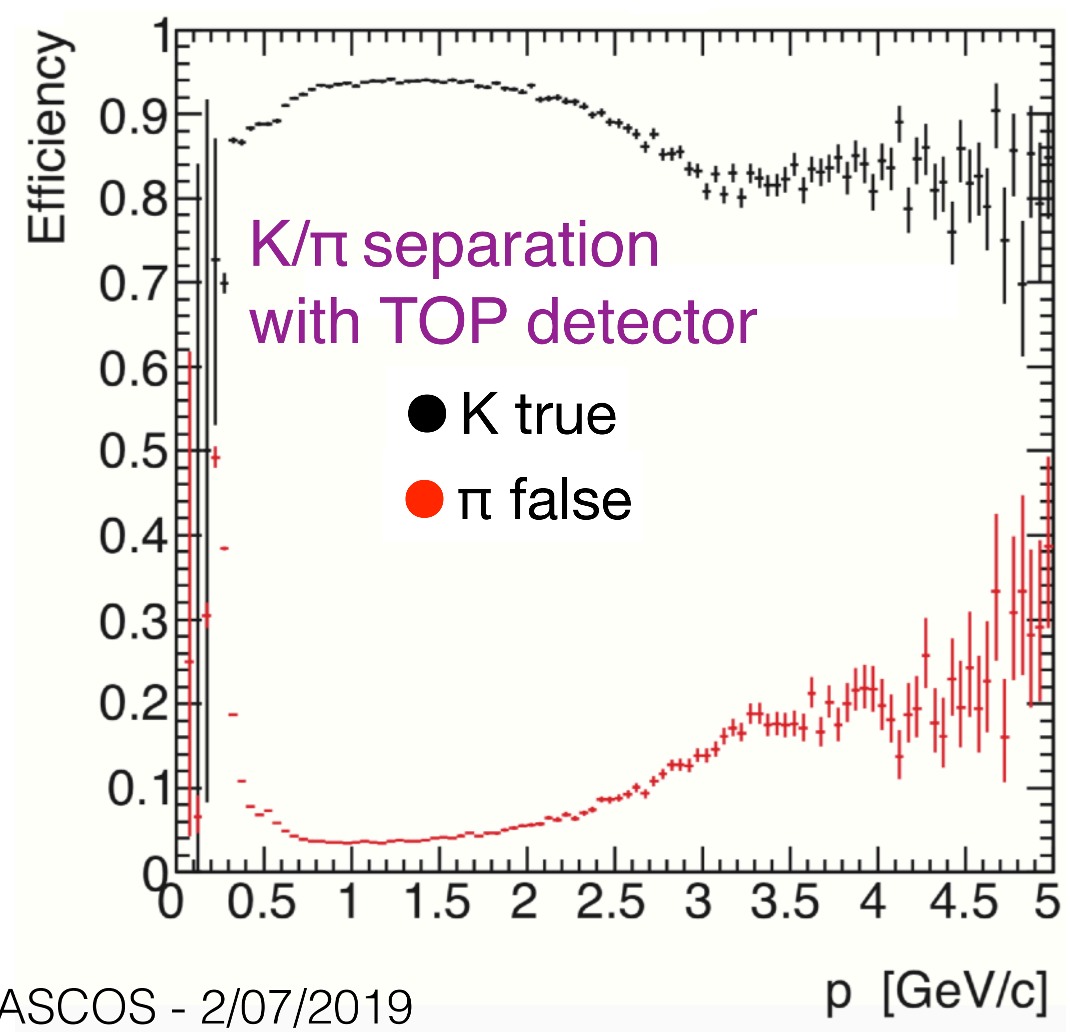
Belle II detector (II)

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 sampling in the e.m. calorimeter (to reduce pileup);
- 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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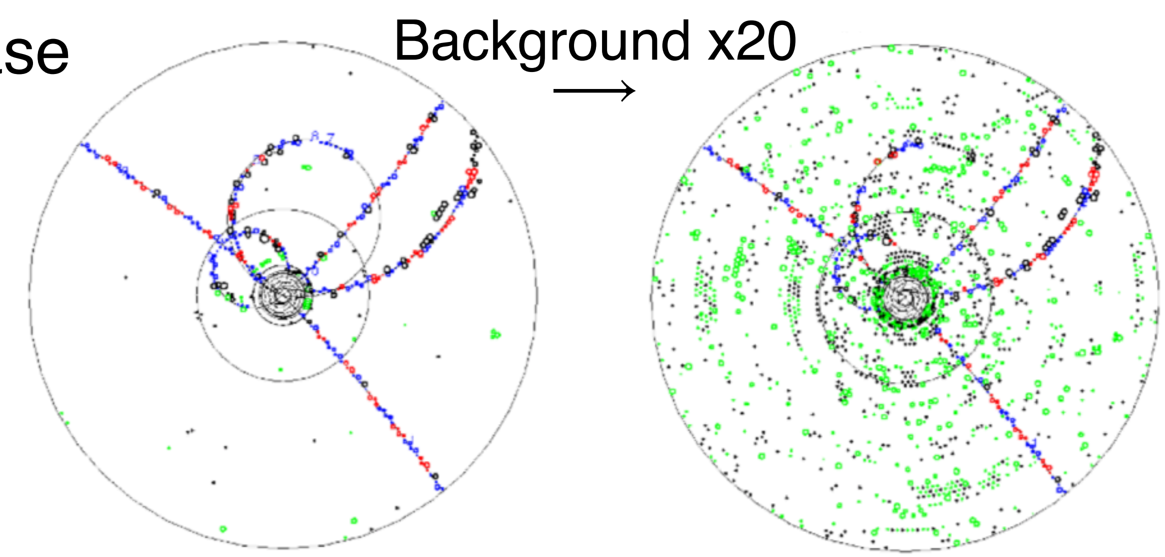

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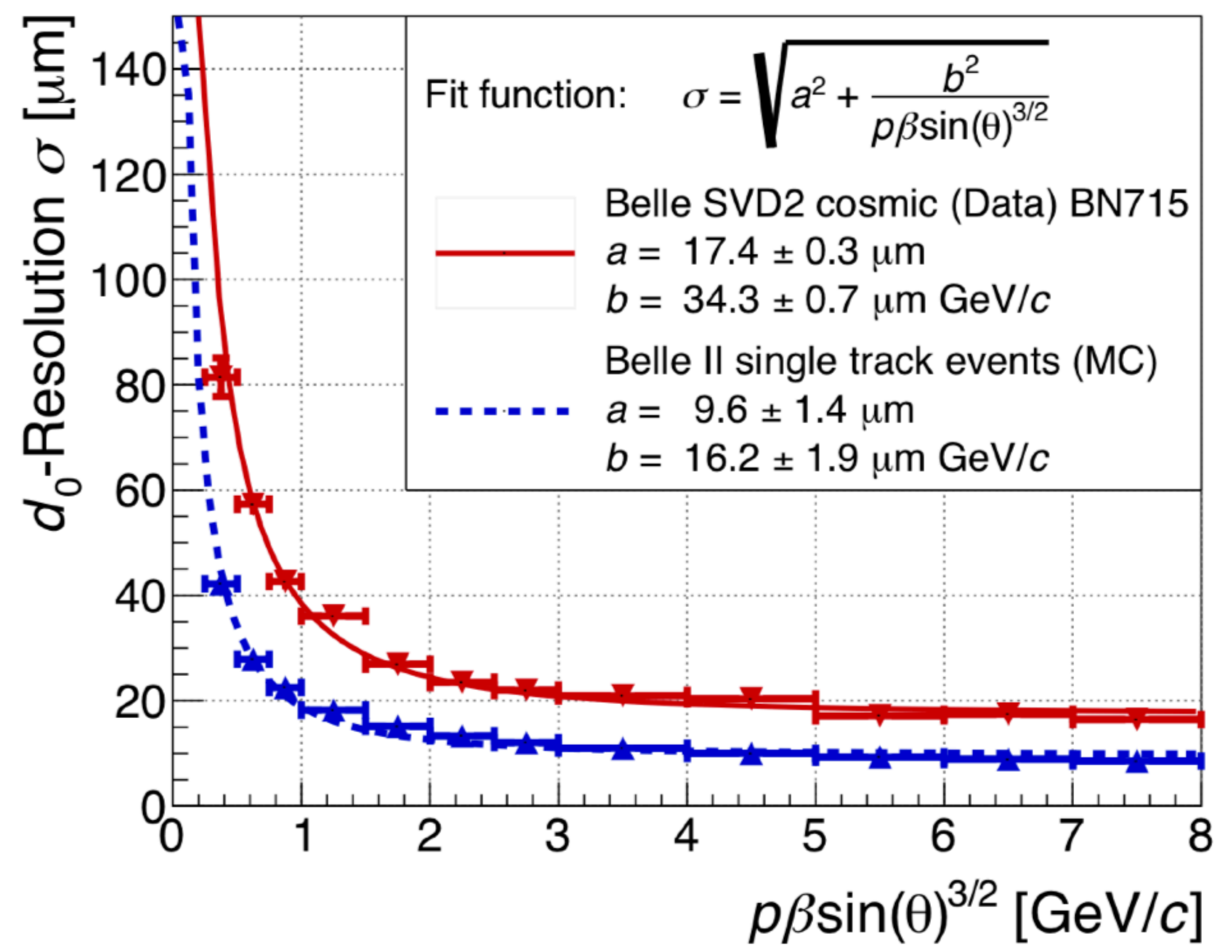
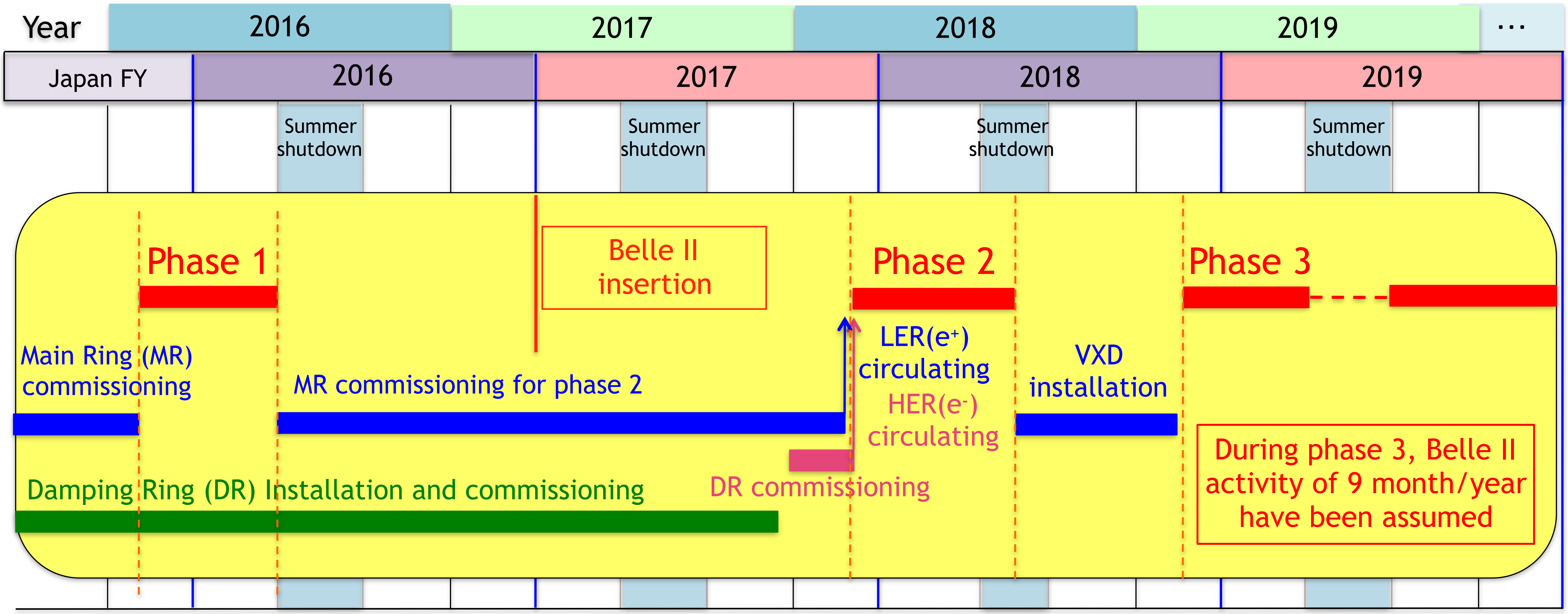


Belle II operation status and plan (I)

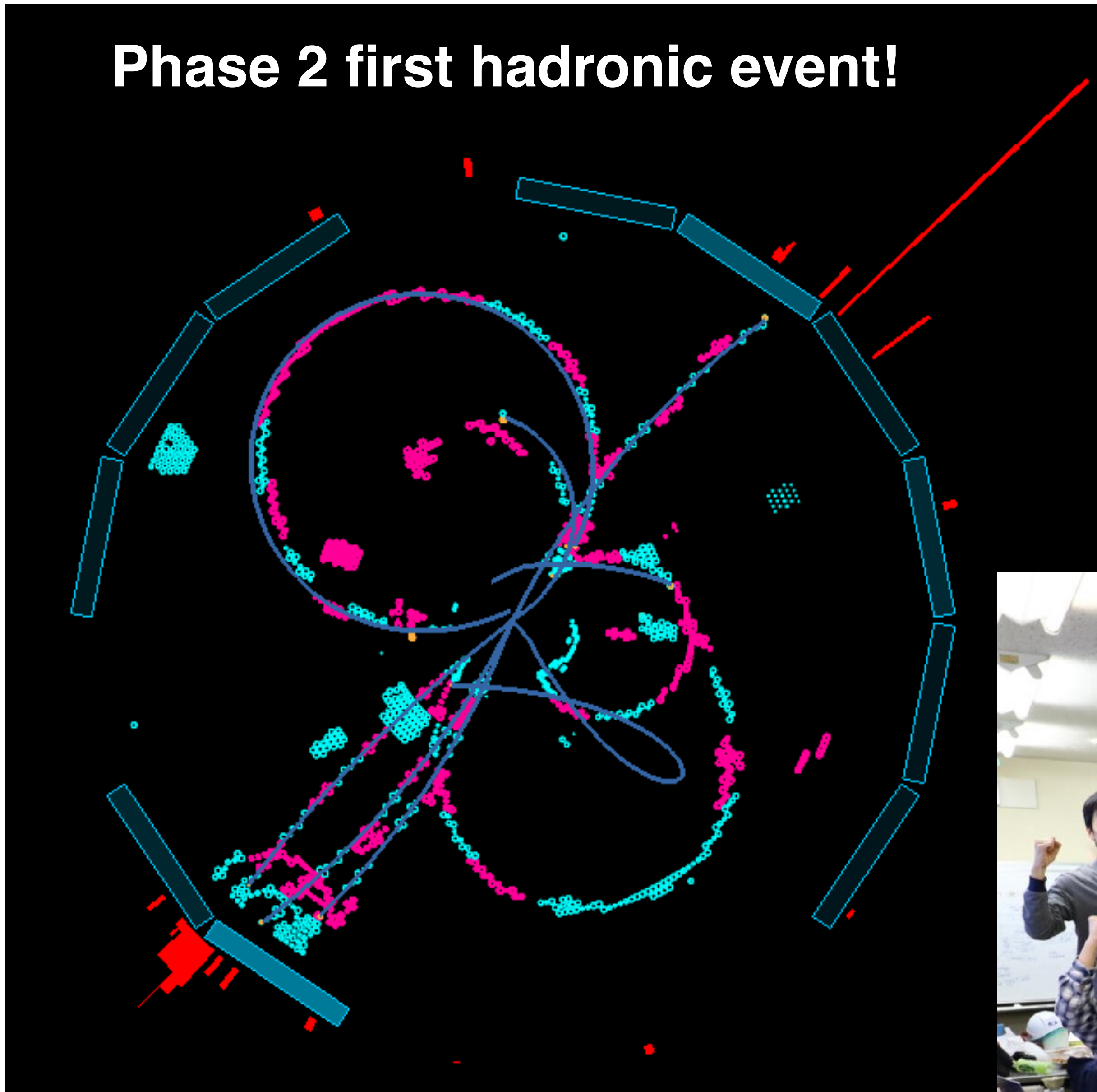


Phase 1: SuperKEKB commissioning & background estimation **Completed**

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

Phase 3: Data taken with the whole detector installed, ongoing! **March 2019**

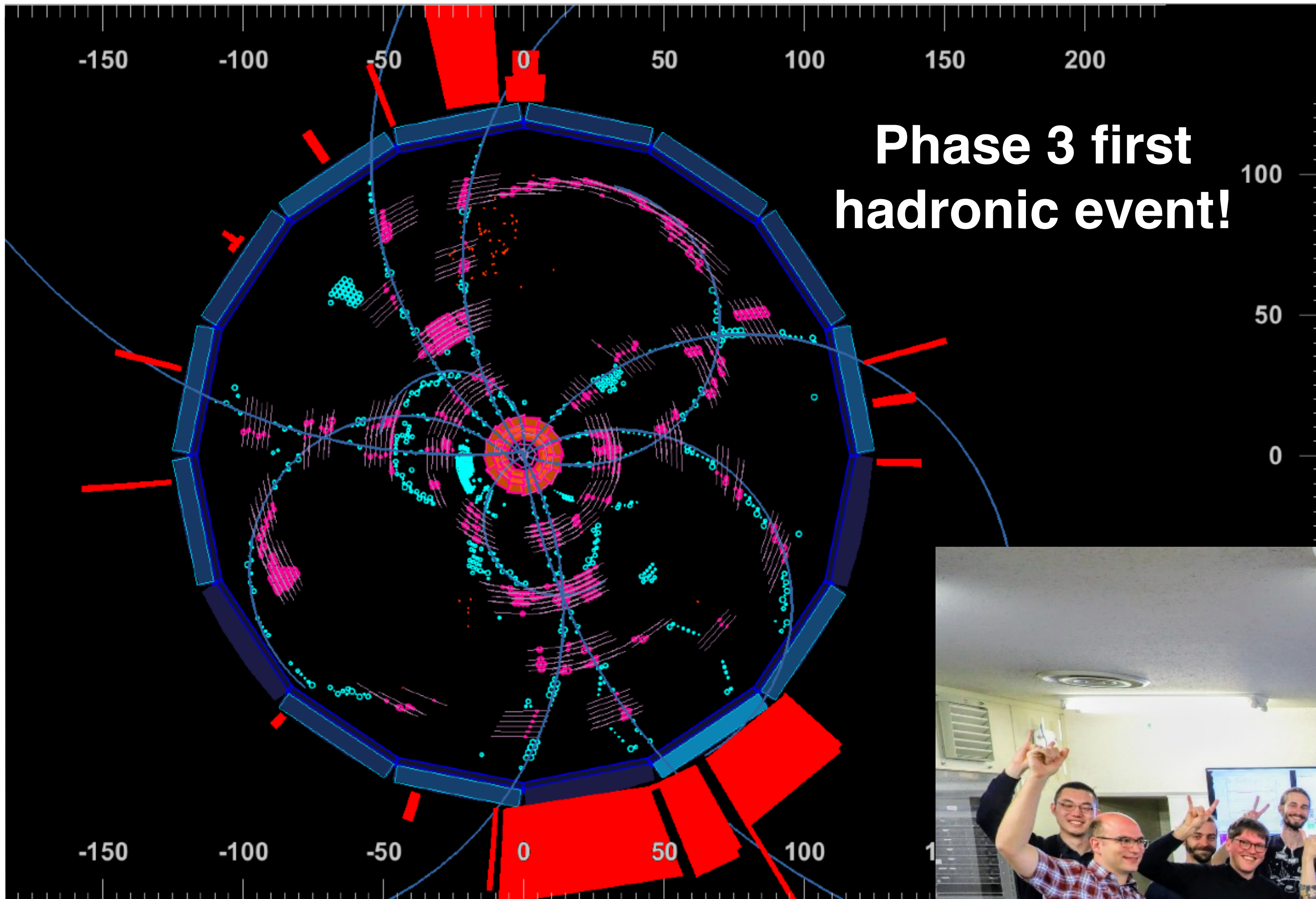
Belle II first event display: phase 2



25 April 2018
Belle II control room

Belle II

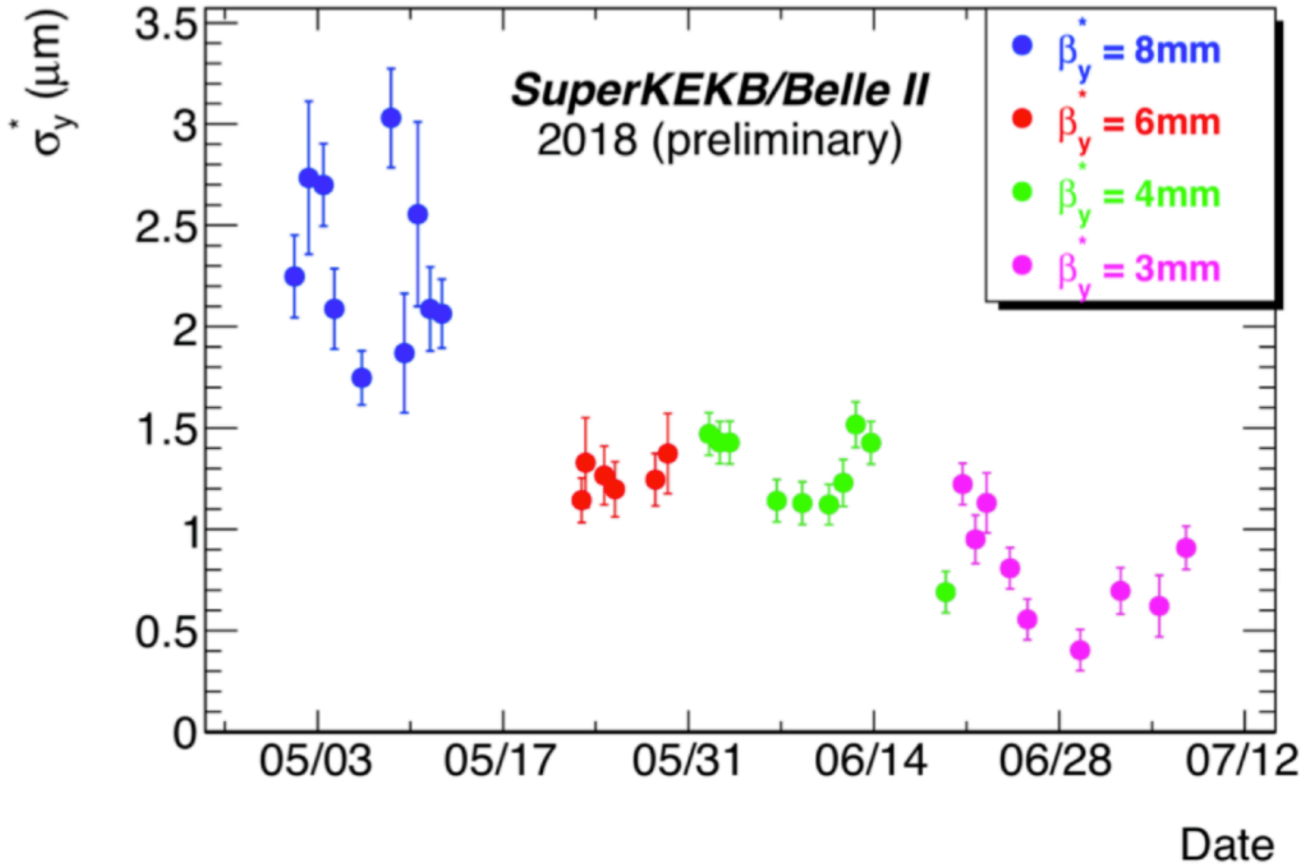
Belle II first event display: phase 3



25 March 2019
Belle II control room

Belle II first results (I)

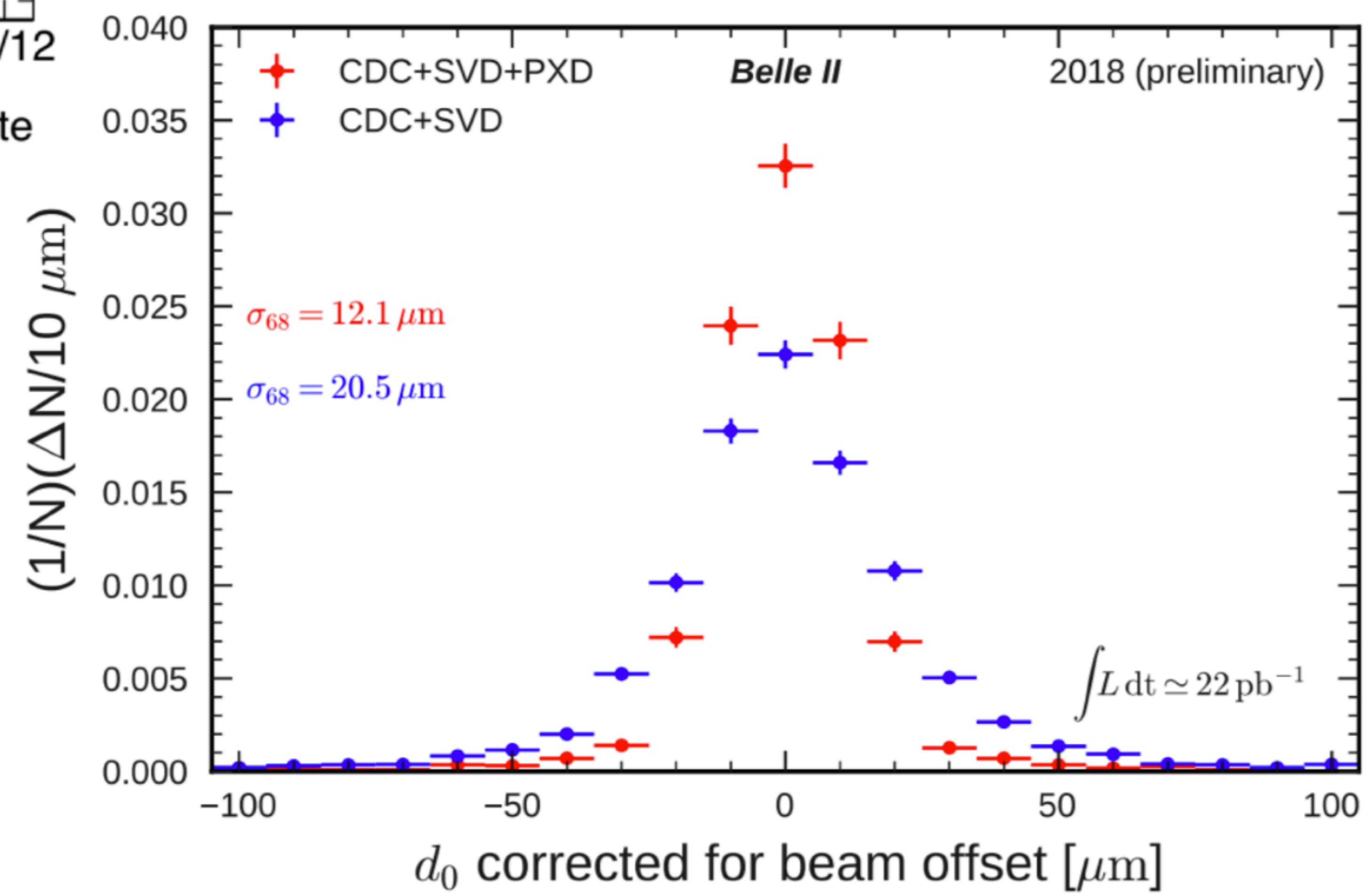
Vertical beam size σ_y^* as a function of the date



Integrated luminosity collected so far by SuperKEKb: ~6.5 fb^{-1}

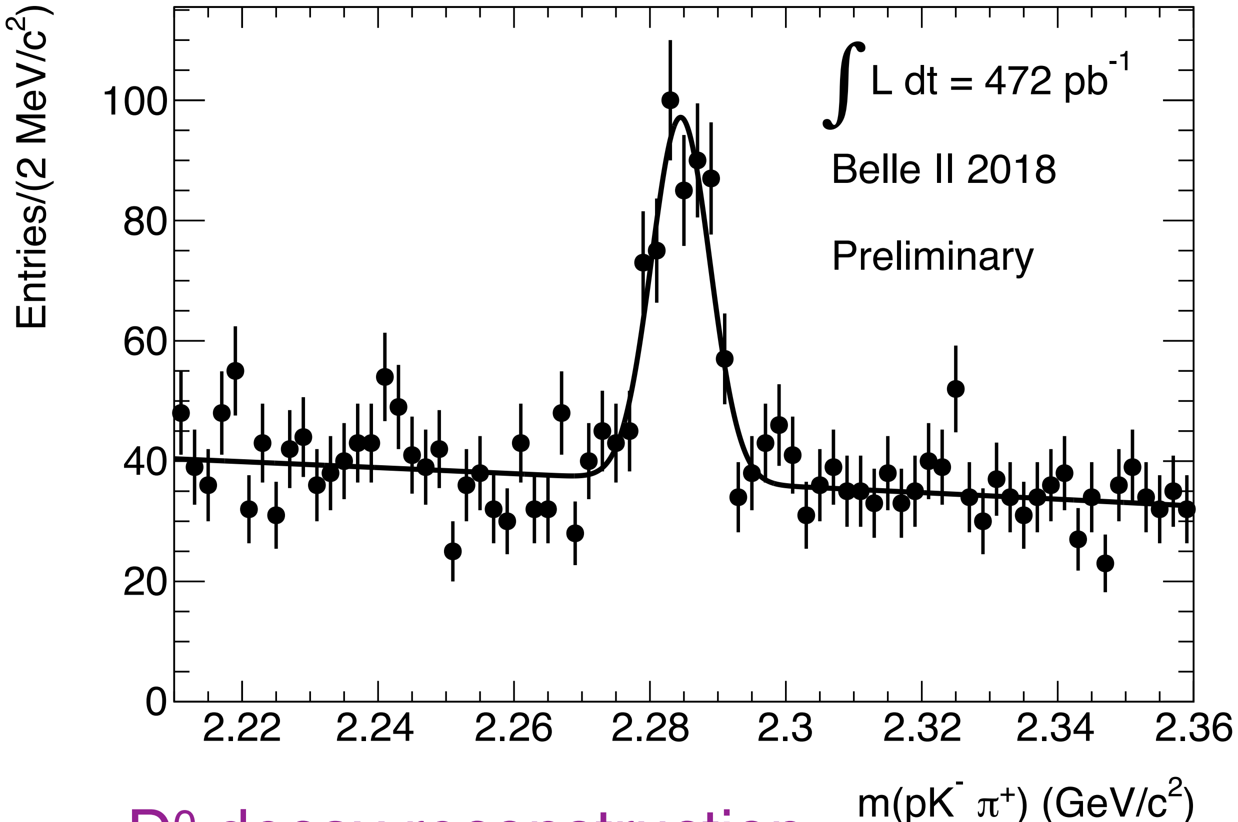
Instant luminosity reached so far by SuperKEKb ~10^{34} cm^{-2} s^{-1}

Transverse impact parameter resolution

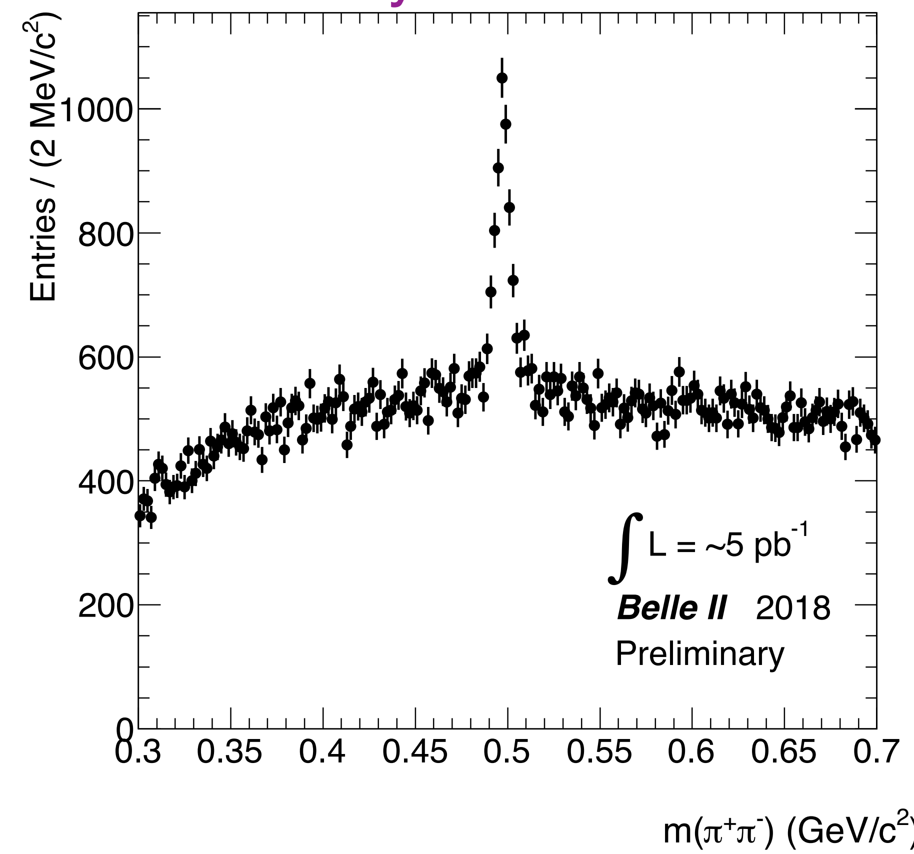


Belle II first results (II)

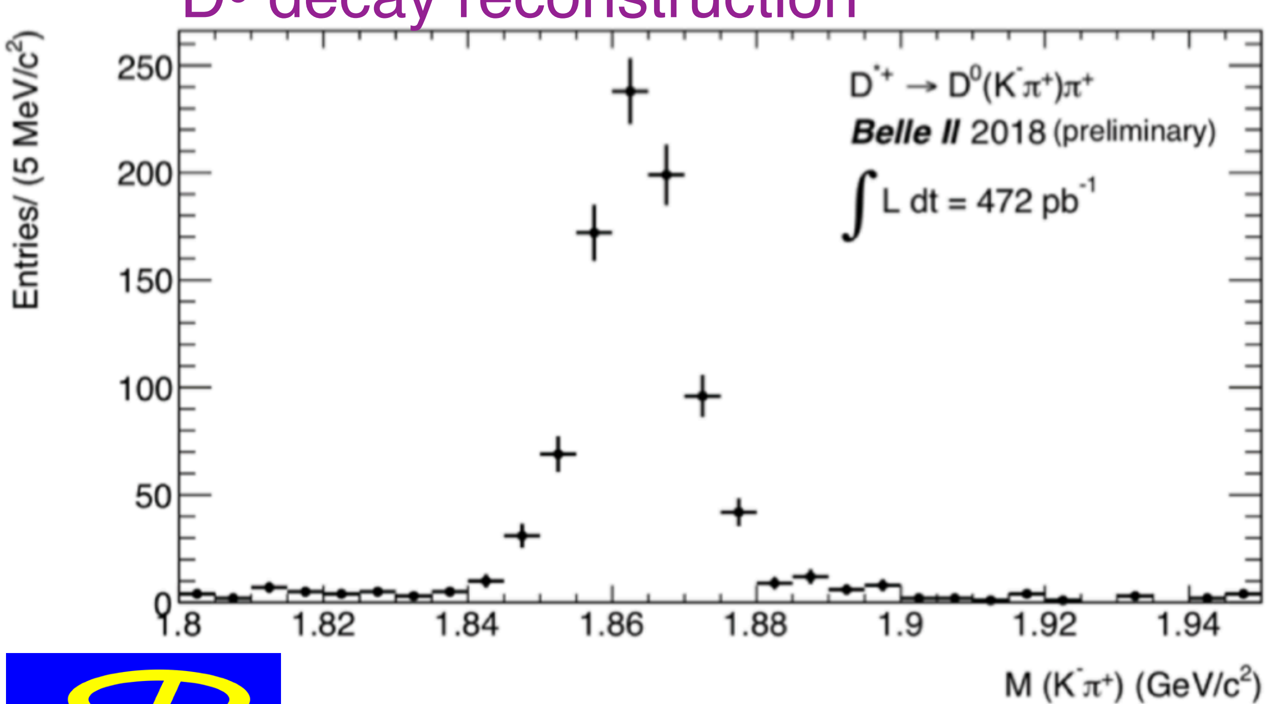
Λ^+_c decay reconstruction



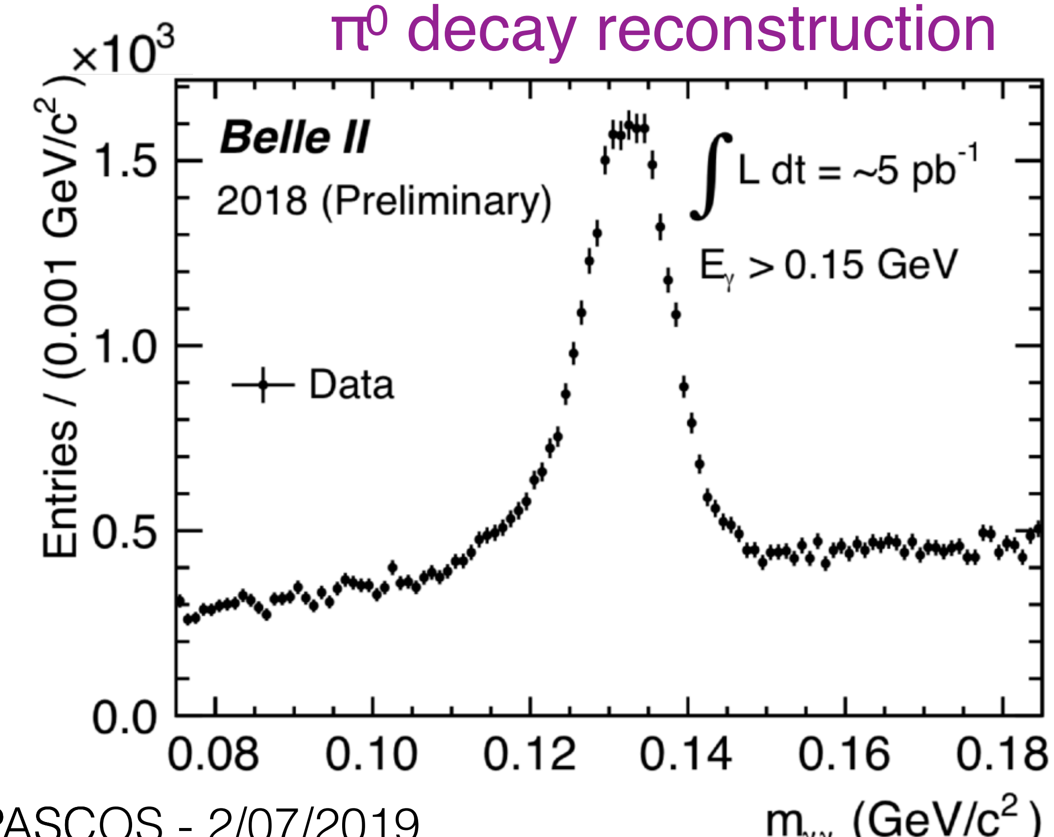
K⁰ decay reconstruction



D⁰ decay reconstruction

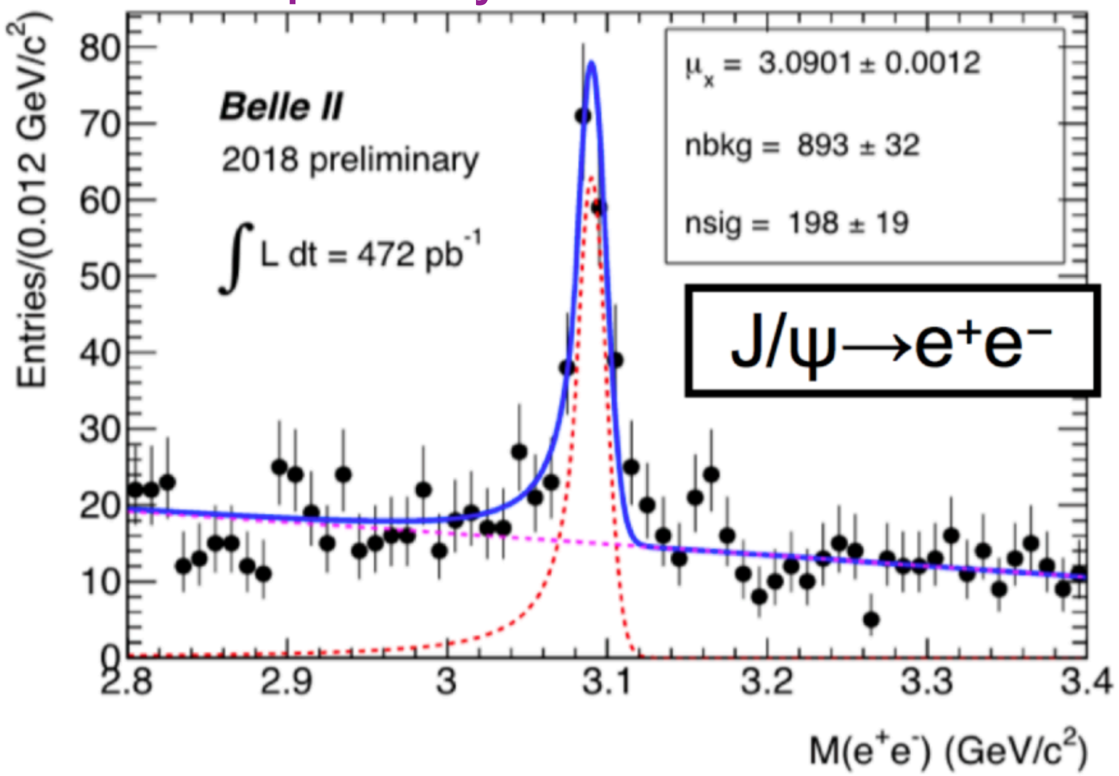


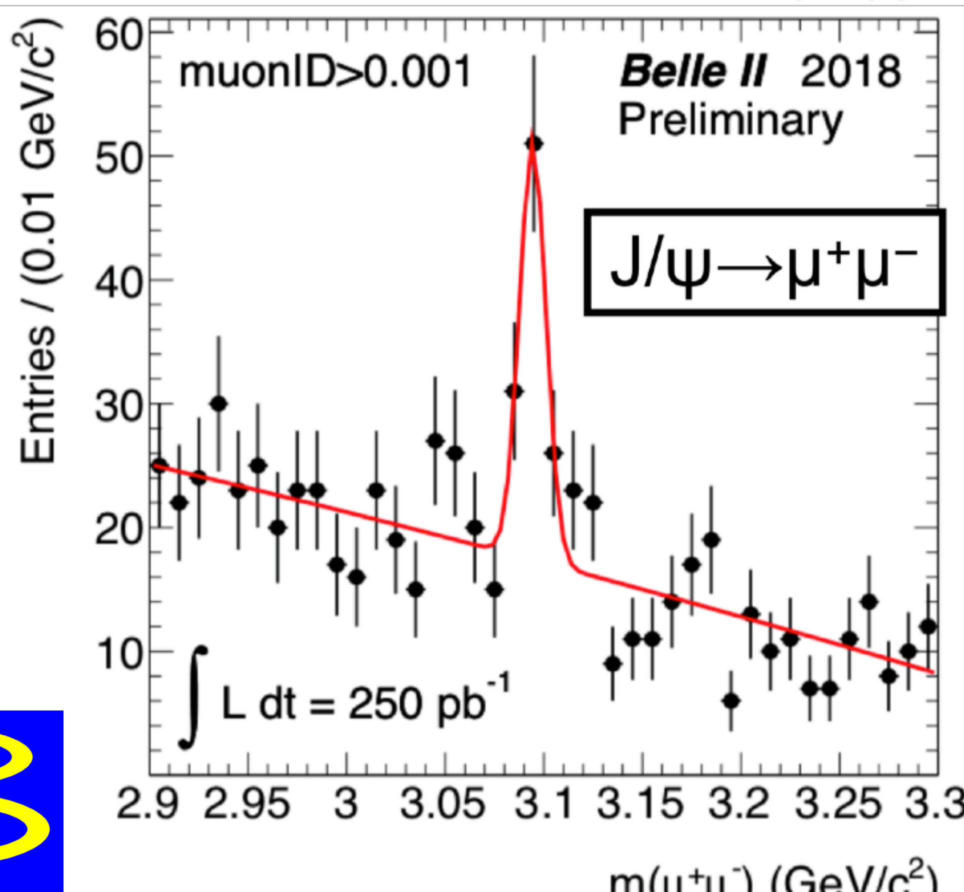
π⁰ decay reconstruction



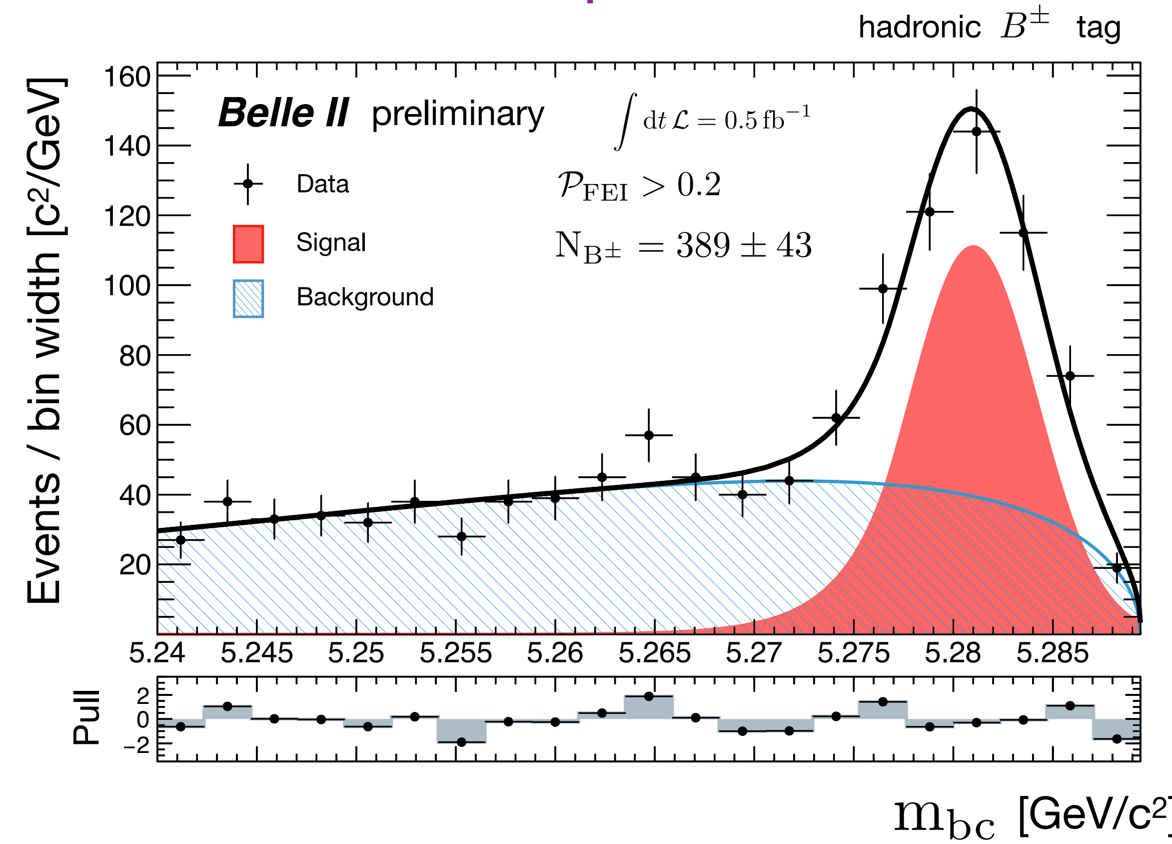
Belle II first results (II)

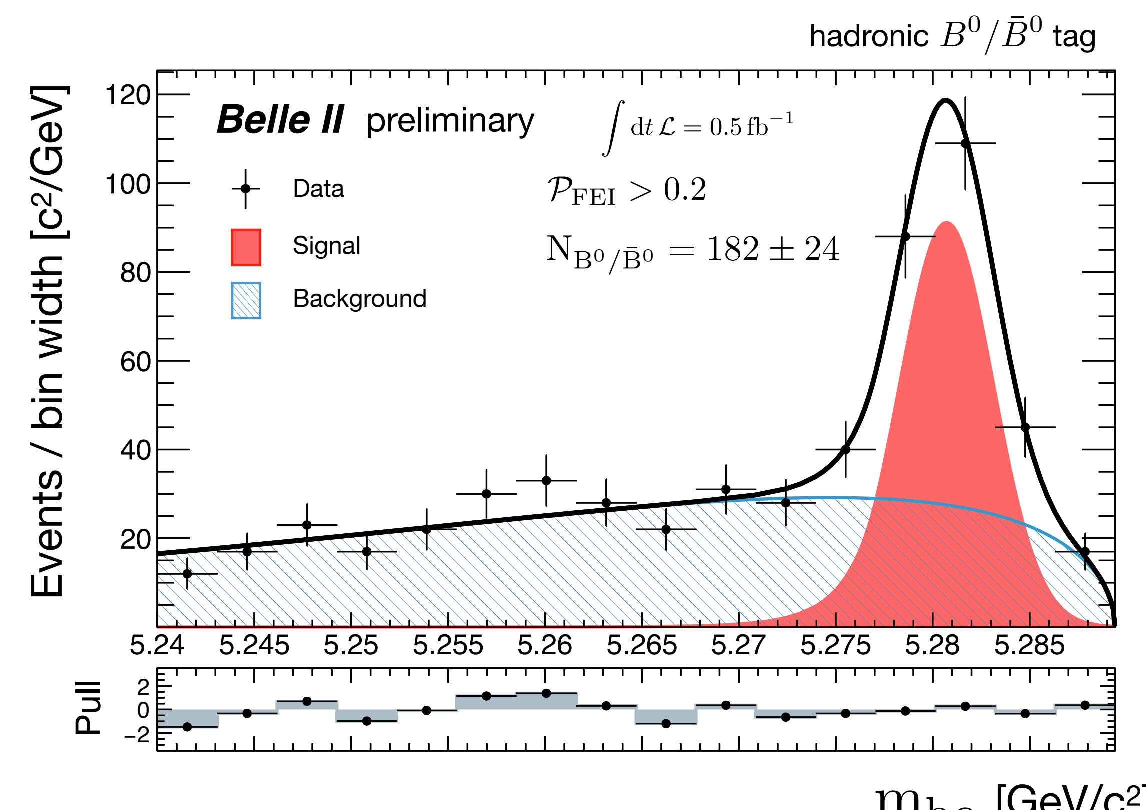
J/ψ decays reconstruction





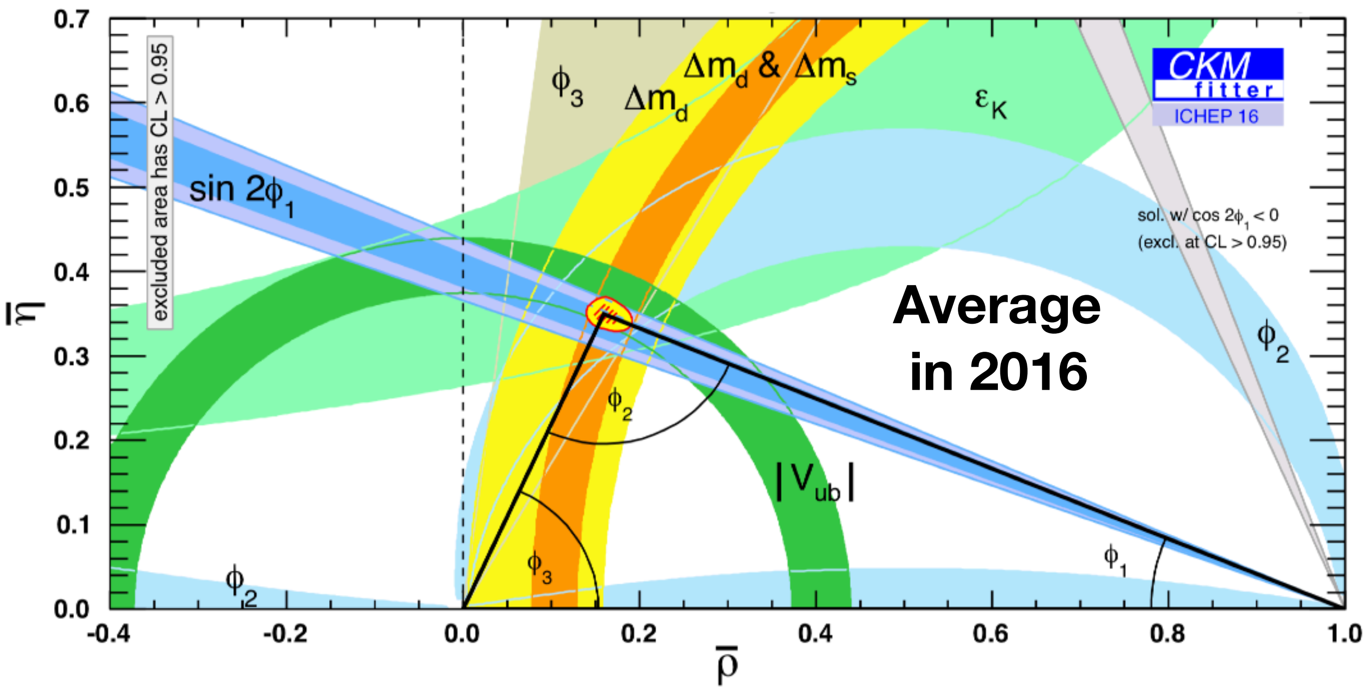
Full event interpretation results

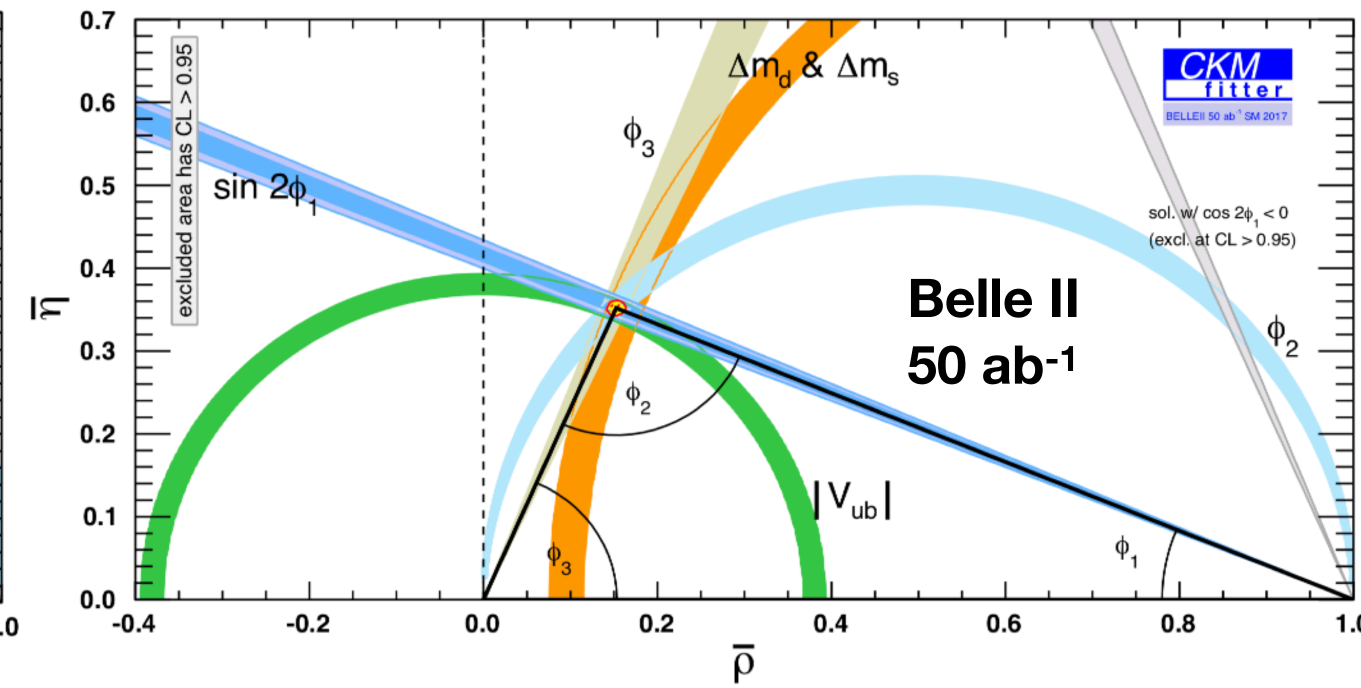




Physics program

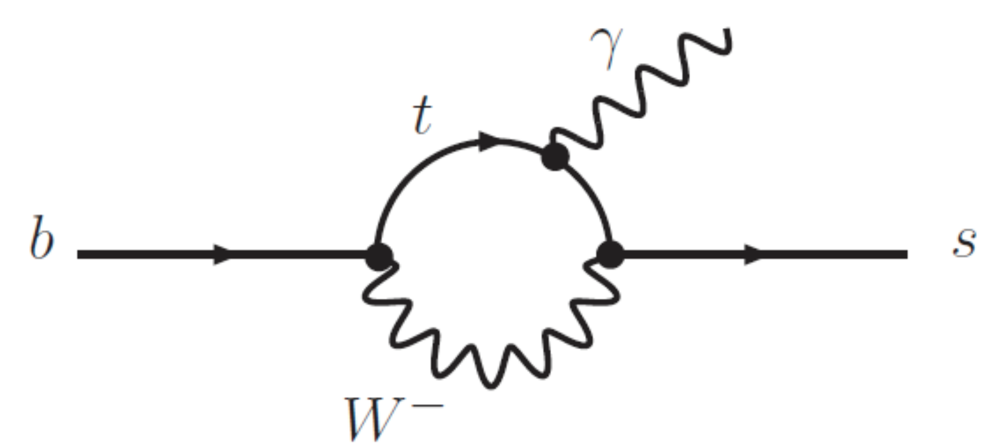
- Precision measurement of the Unitarity Triangle angles and CKM matrix elements.





- 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

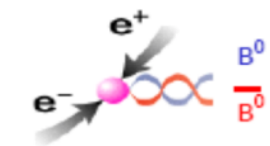
summary…



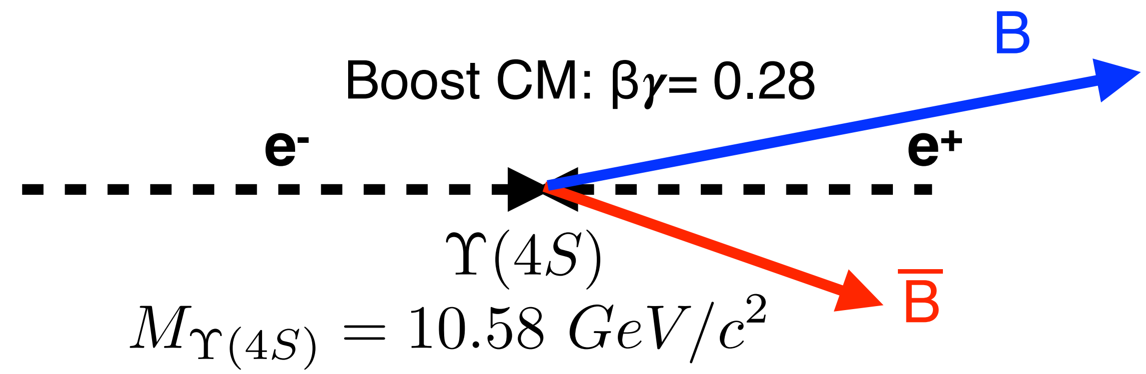
Belle II

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..

Belle II exclusive advantages

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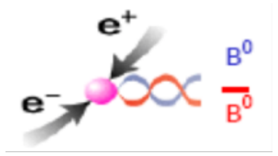

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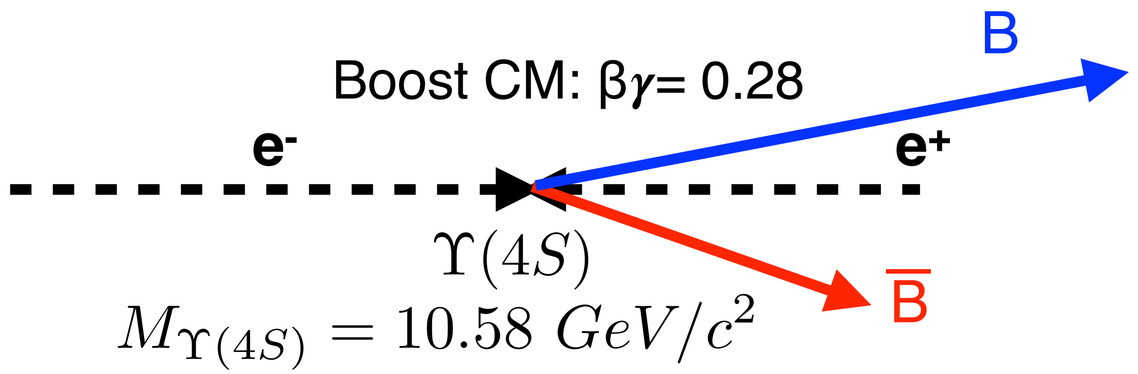
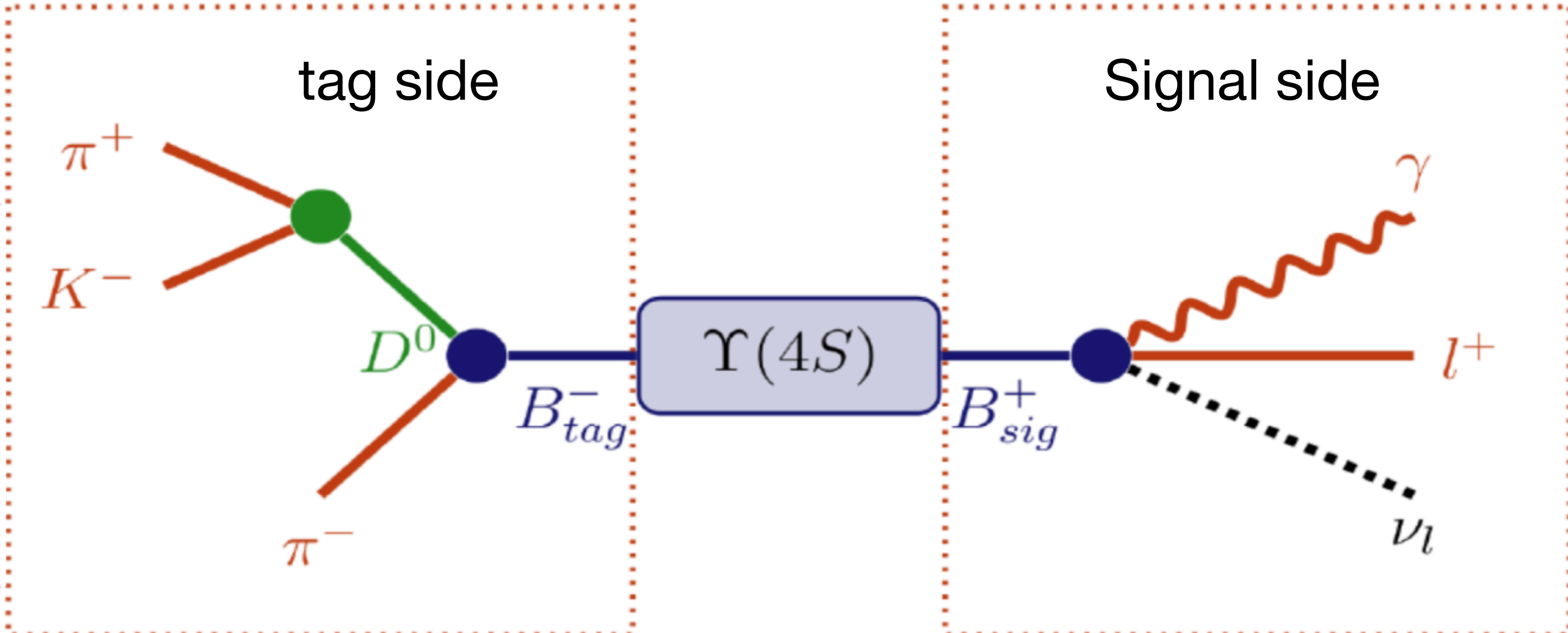


Full Event Interpretation (FEI)

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:

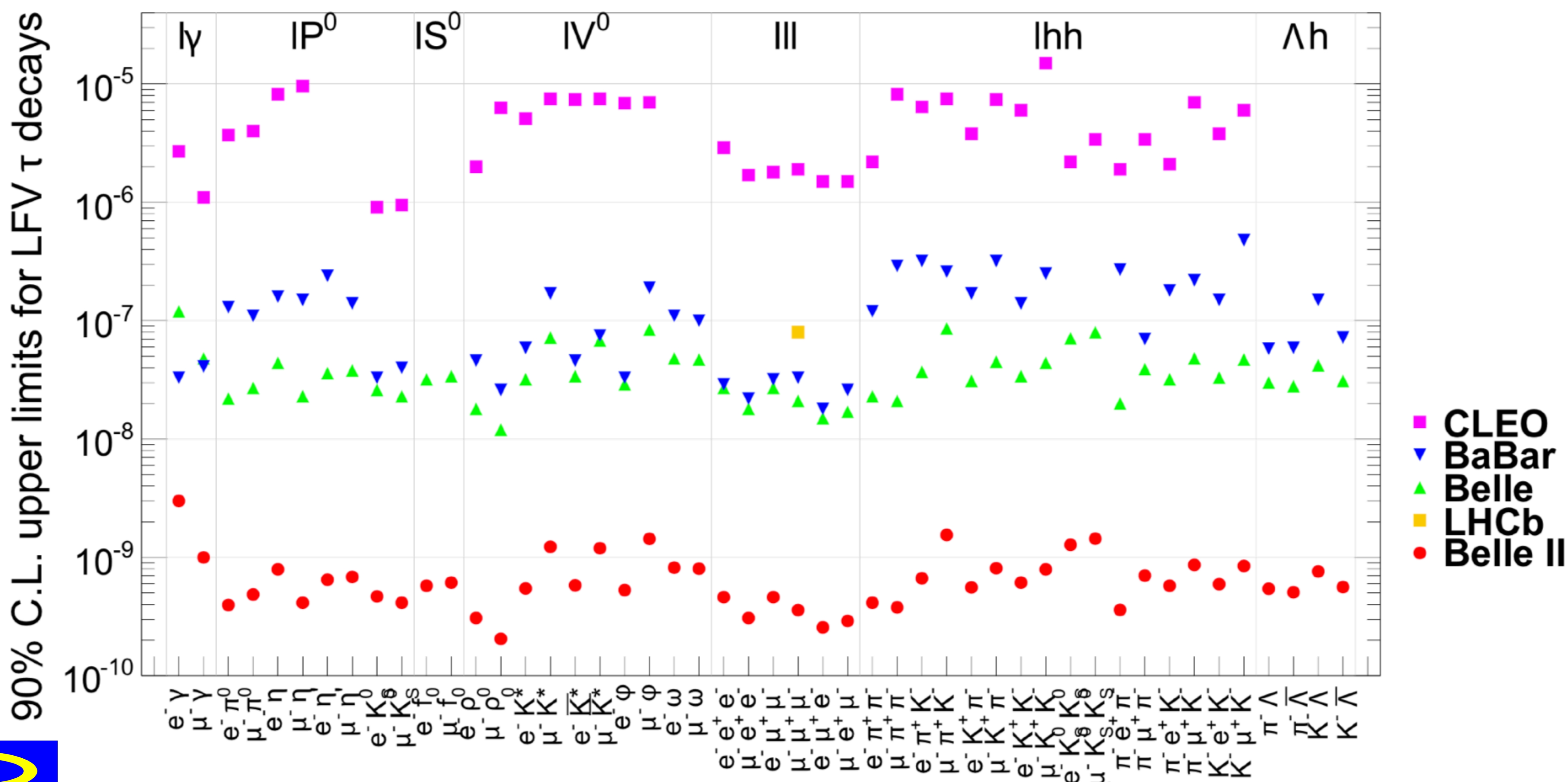
- 1.5% semi-leptonic tag: more efficient but less precise
- 0.3% hadronic tag: less efficient but more precise



Lepton flavour violation in τ decays (II)

Belle II expectations:

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

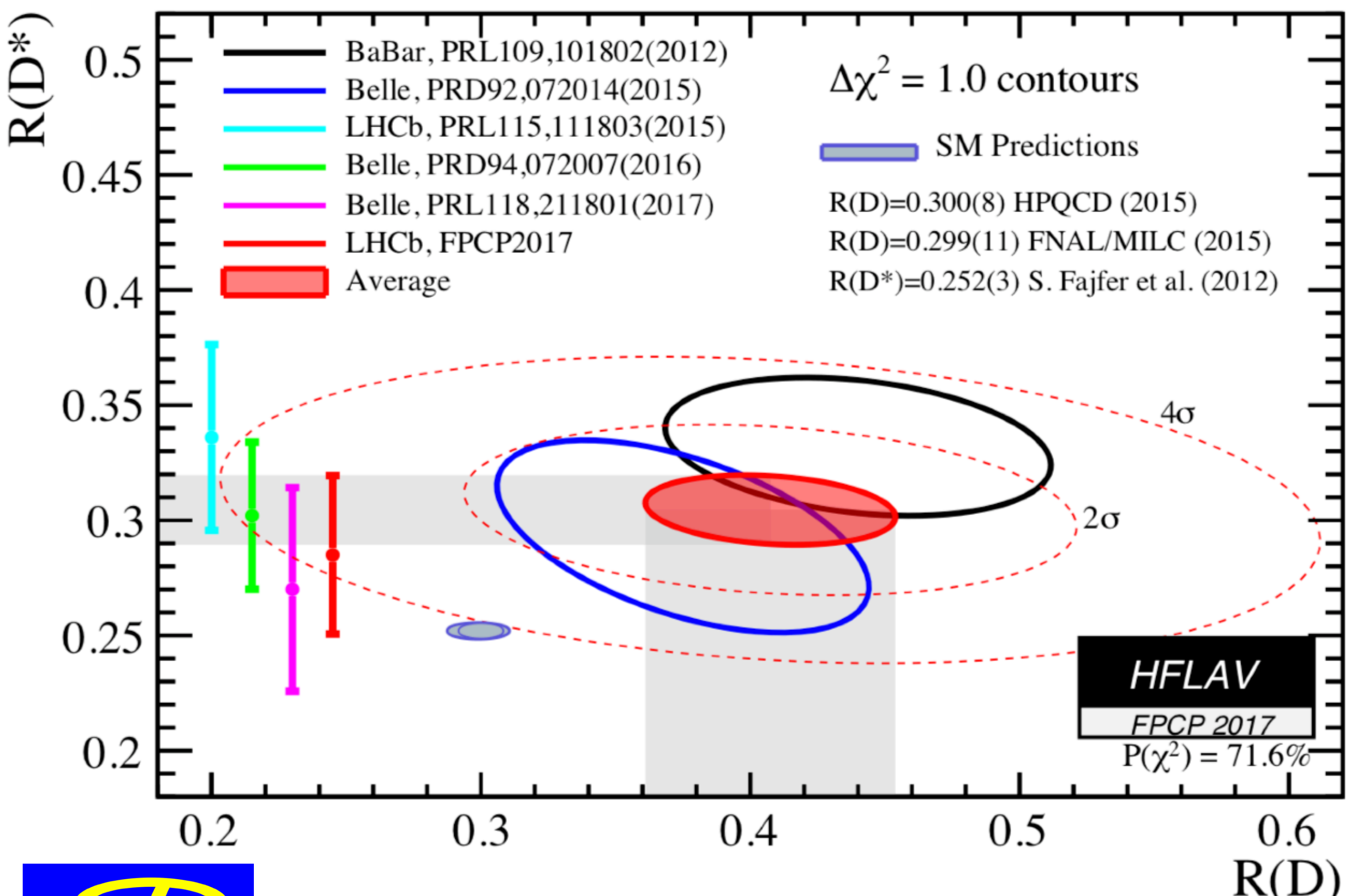


Flavour anomalies in R(D*) and R(D)

Observables:

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

4.1σ SM disagreement



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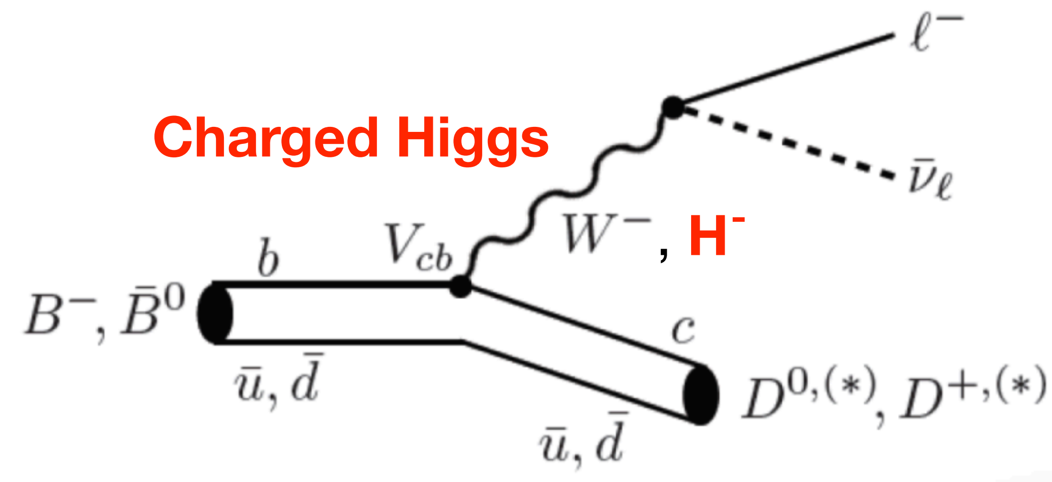
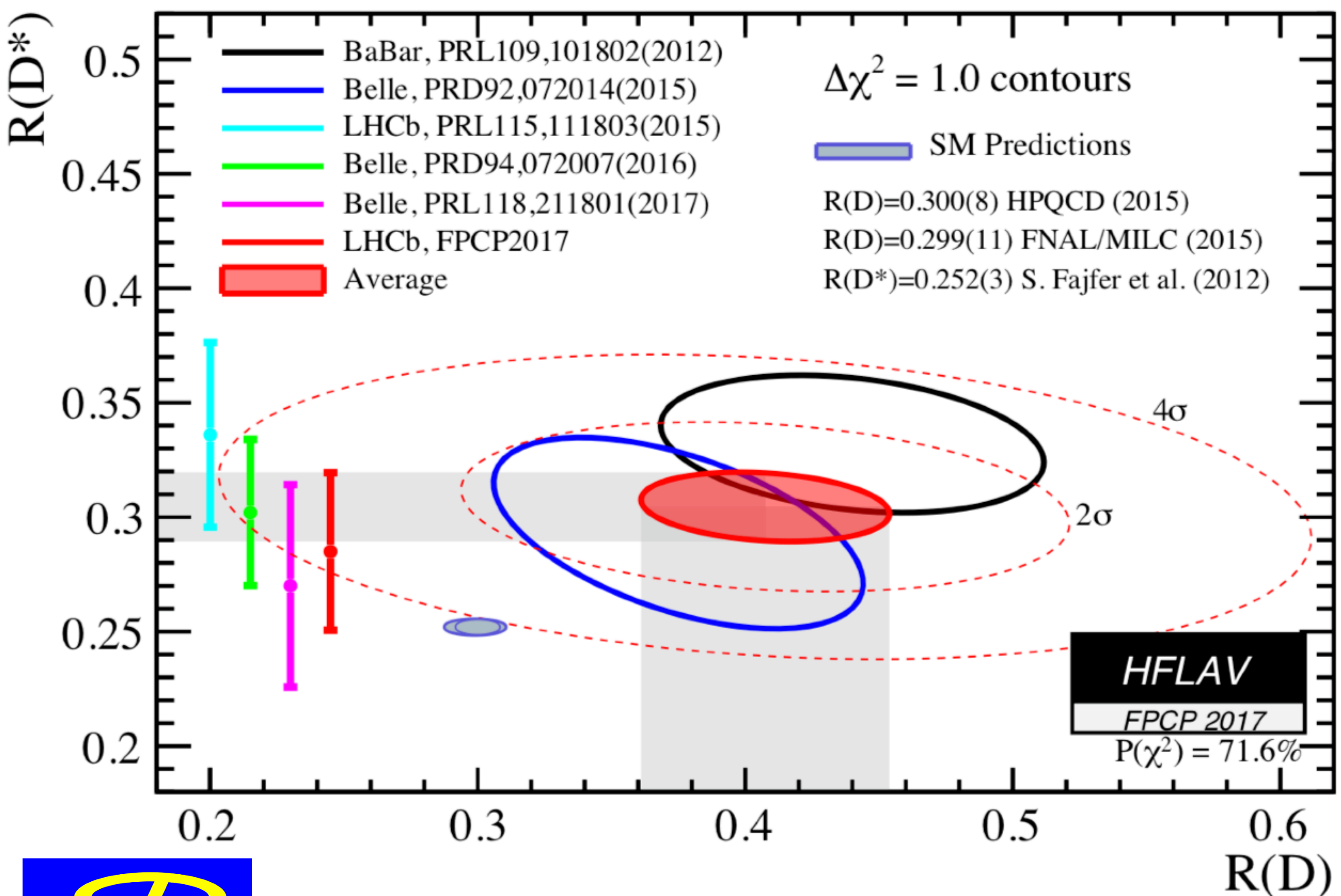
Charged Higgs





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

Complementary to LHCb

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\|V_{us}\|$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\|V_{cb}\|$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\|V_{ub}\|$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K_S^0]$	***	$8 \cdot 10^{-3}$	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
$S(B_d \to K^*(\to K_S^0\pi^0)\gamma))$	***	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
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	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
$\|q/p\|_D$	***	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.

B. Golob, KEK FF Workshop, Feb. 2012

Conclusions

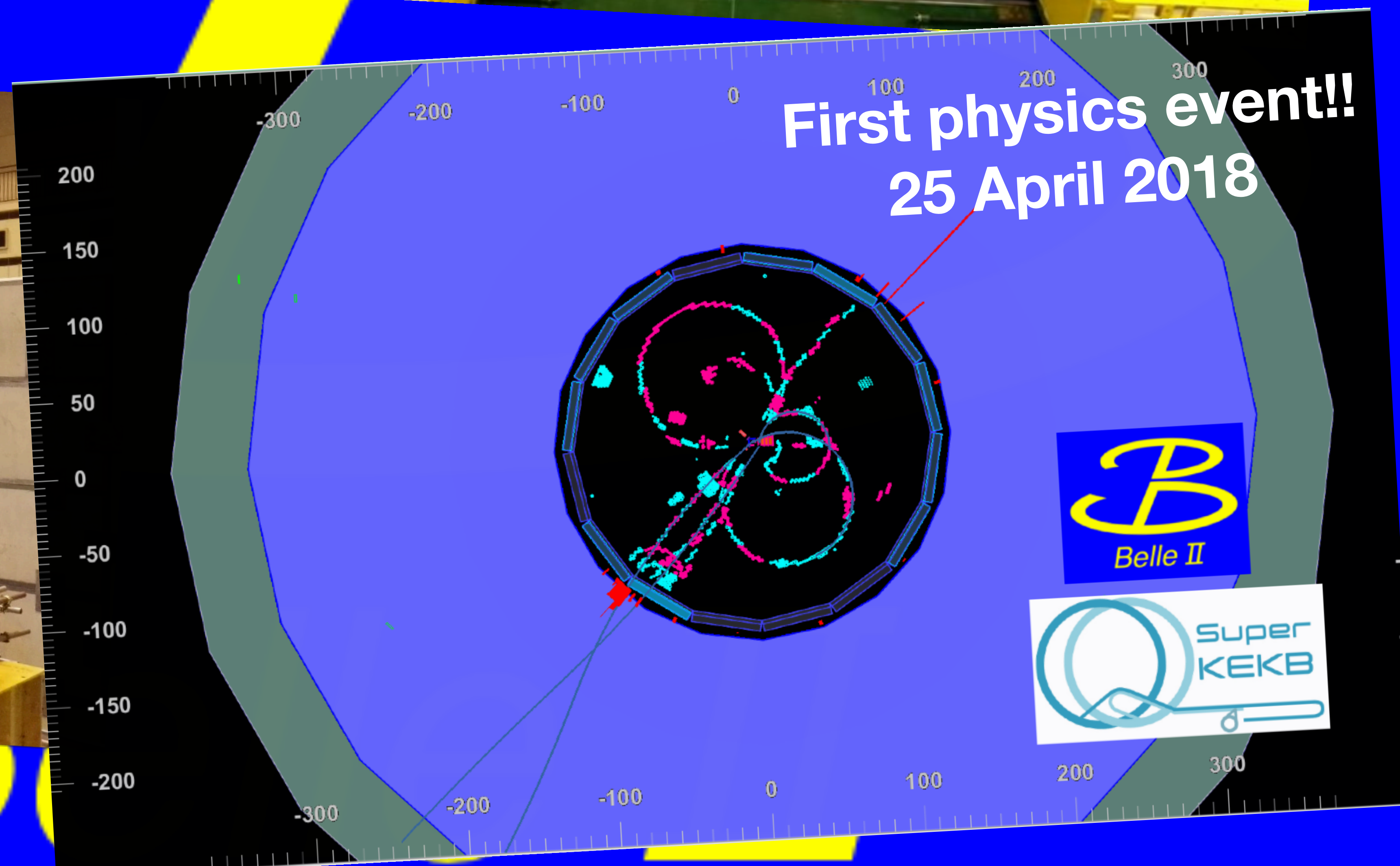
- New collider SuperKEKB → $\mathscr{L}^{int} = 50\ ab^{-1}$ before 2027
- Improved detector performances: good neutral particle reconstruction, resonances, decay vertices and events with high missing energy.
- Fundamental physics studies: CKM matrix, CPV, LFV, FCNC, dark sector.

- Installation and insertion of the detector: 11 April 2017
- Current status:
  - Phase 2 first data will be used for publications soon.
  - Phase 3: data taking is ongoing and ~6.5 fb^{-1} has been already collected

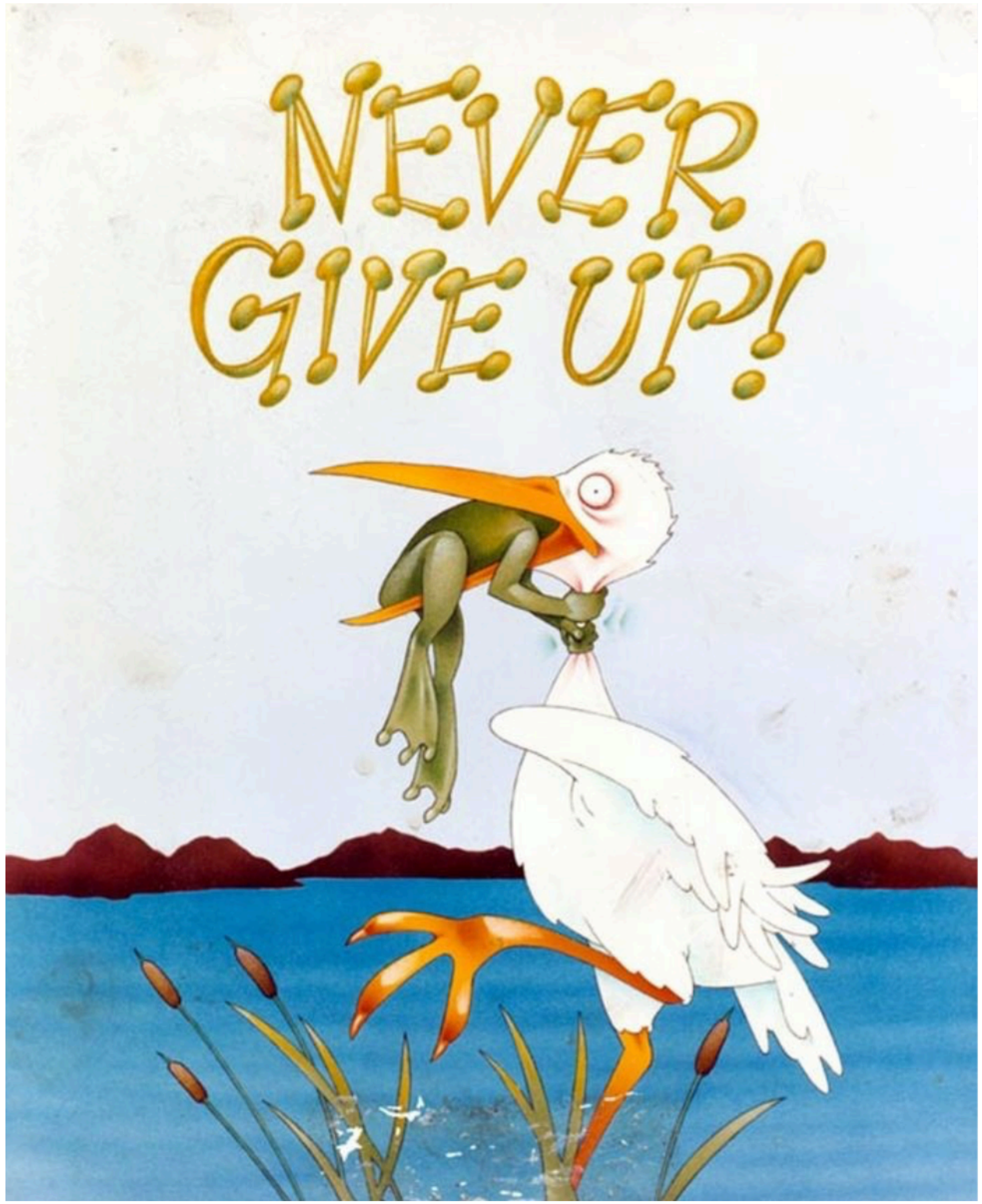

Top installation
May 2016


Belle II insertion
11 April 2017


CDC installation
October 2016


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

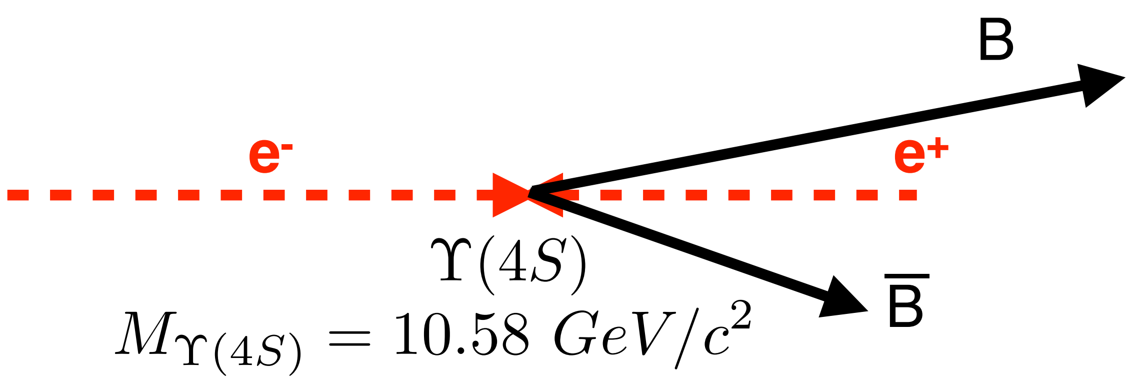
[a] Rate is pre-scaled by a factor 1/100

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

Total event rate: 30 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.

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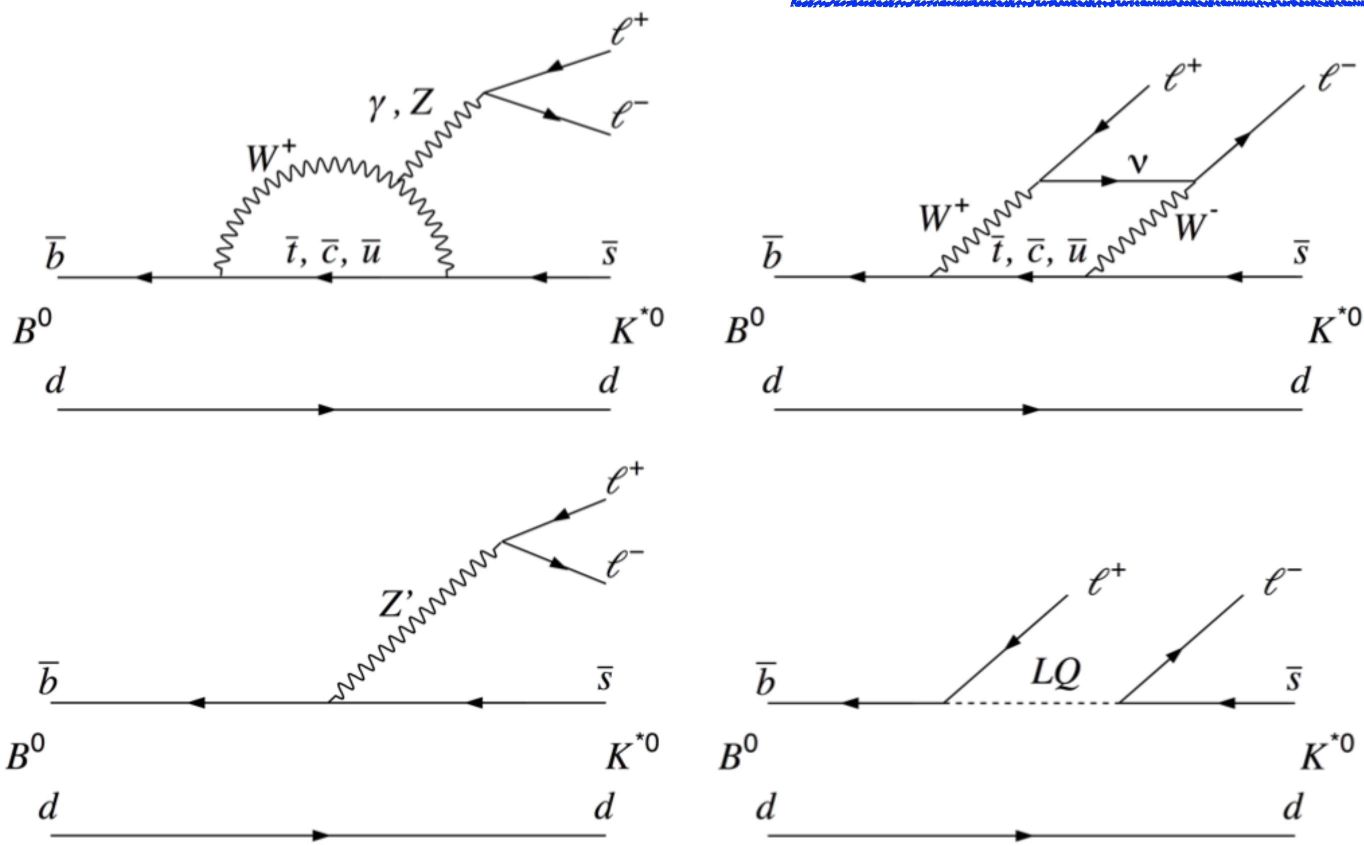
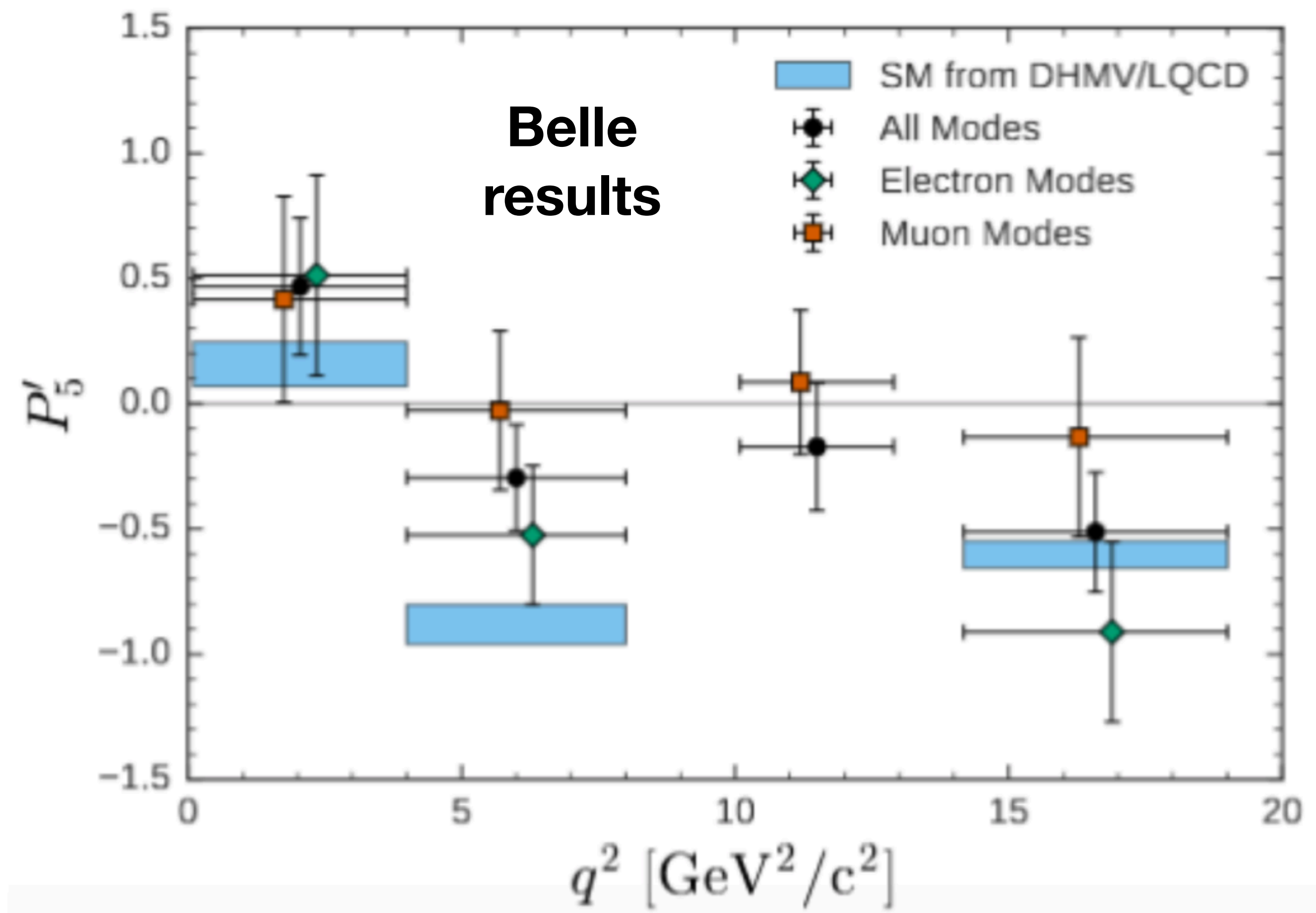
$B^0 \longrightarrow K^{*0}\mu^+\mu^-$

FCNC: b → s transitions Possible New Physics



Angular analysis (using $P_5^{'}$) chosen to reduce theoretical uncertainties

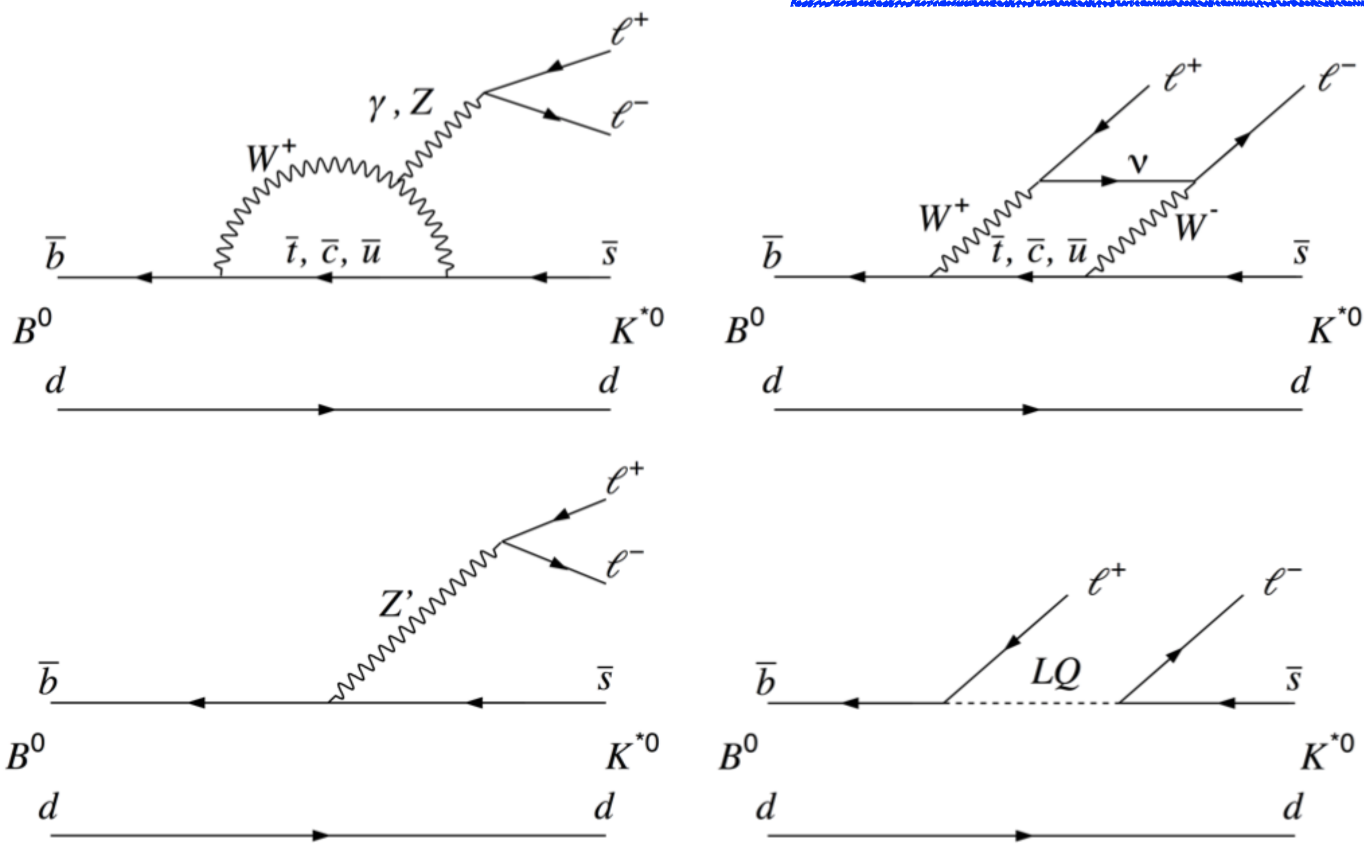


Previous analysis done by the Belle experiment shows a discrepancy of P_5' parameter within a certain q^2 range of ~2.6σ in the SM→ **comparable results with LHCb analysis.**

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

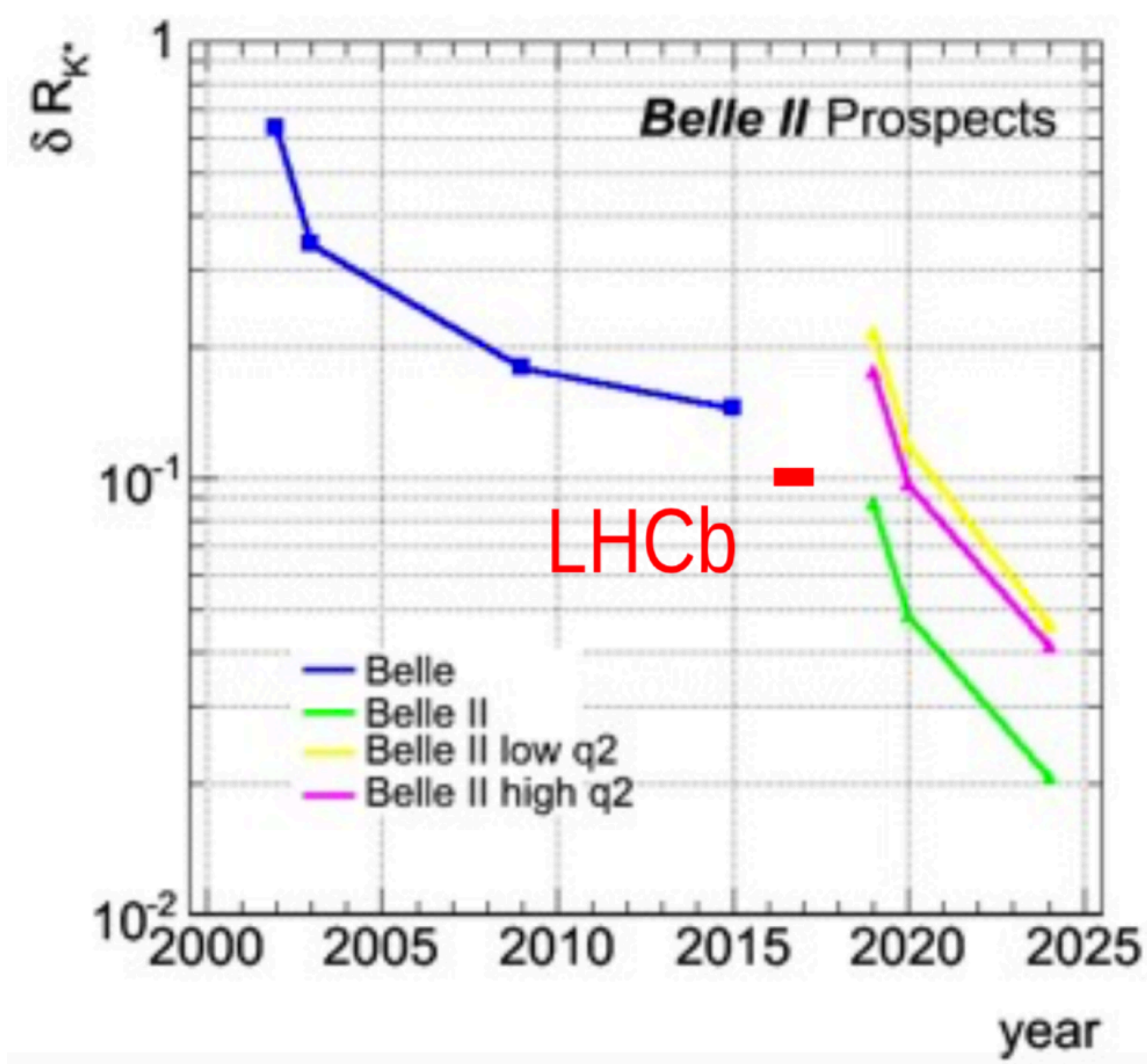
FCNC: b → s transitions

Possible New Physics



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

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

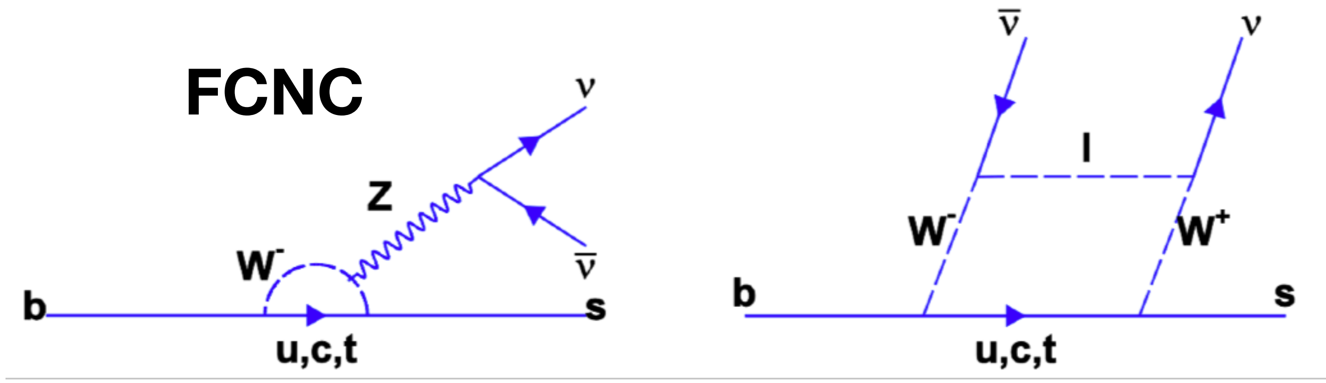


Belle II experiment contribution will be crucial for that measurement!

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

SM prediction box diagram + penguin:

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



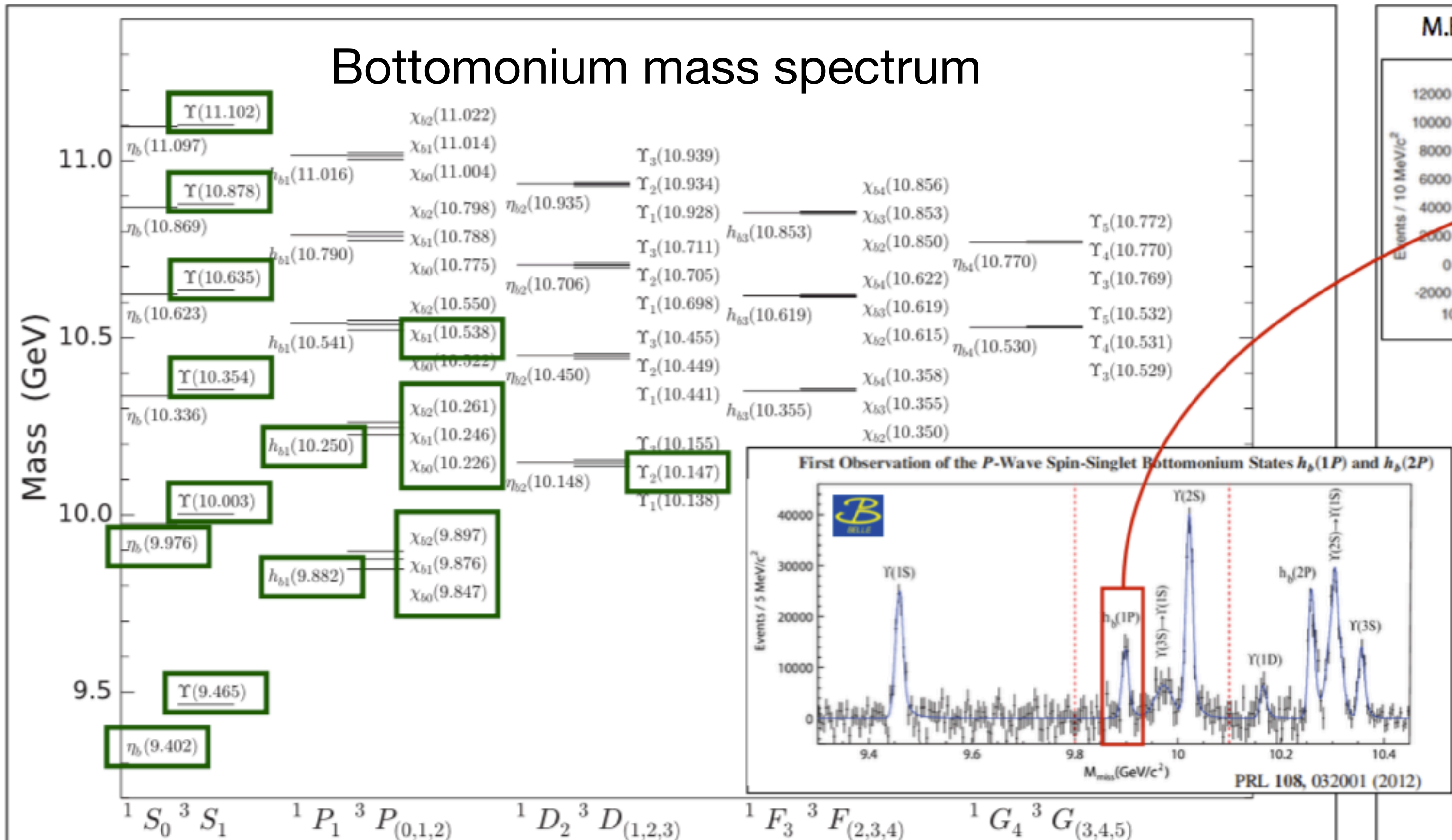
Upper limit measured at Belle:

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

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}

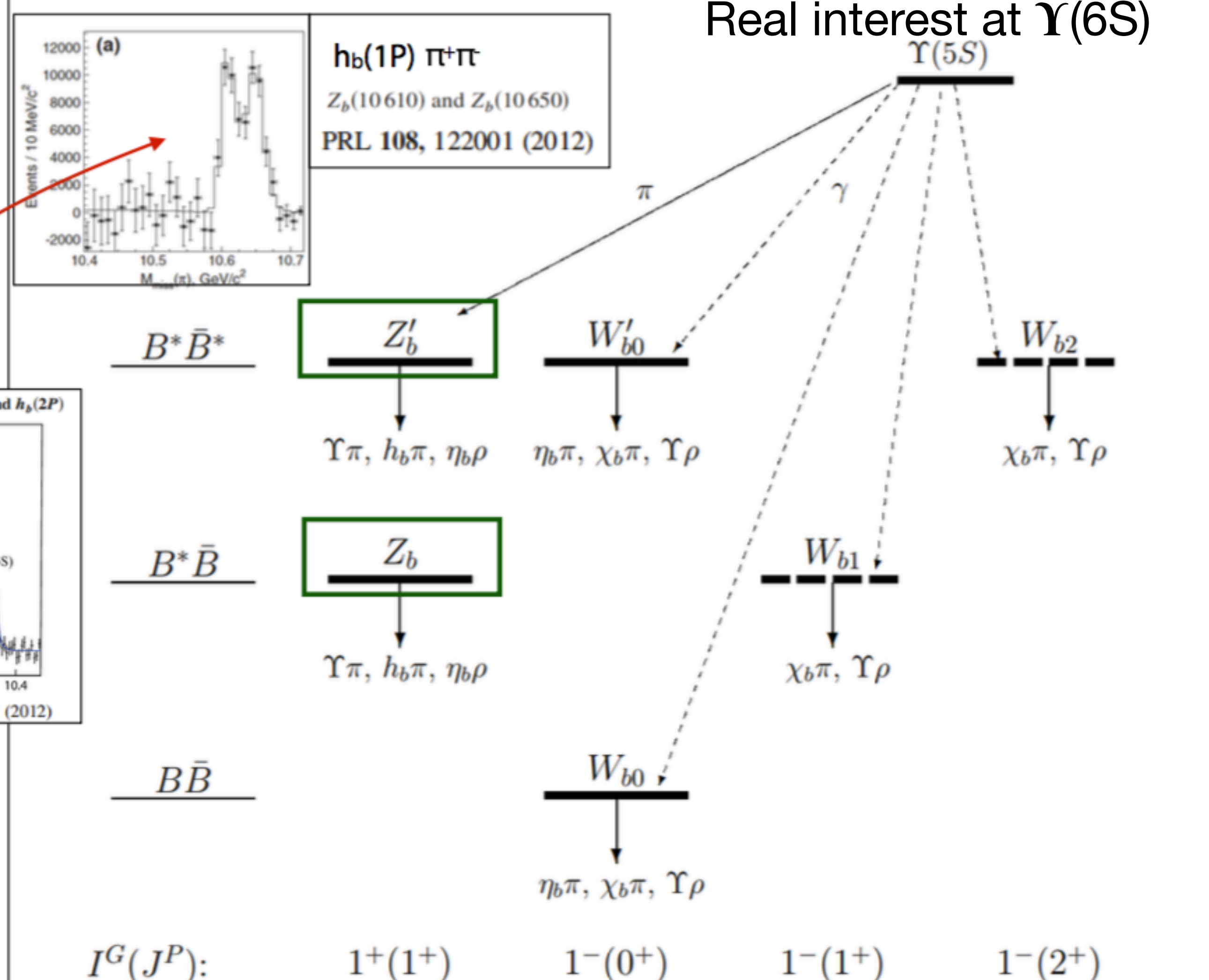
Hadronic spettroscopy



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)



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.

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