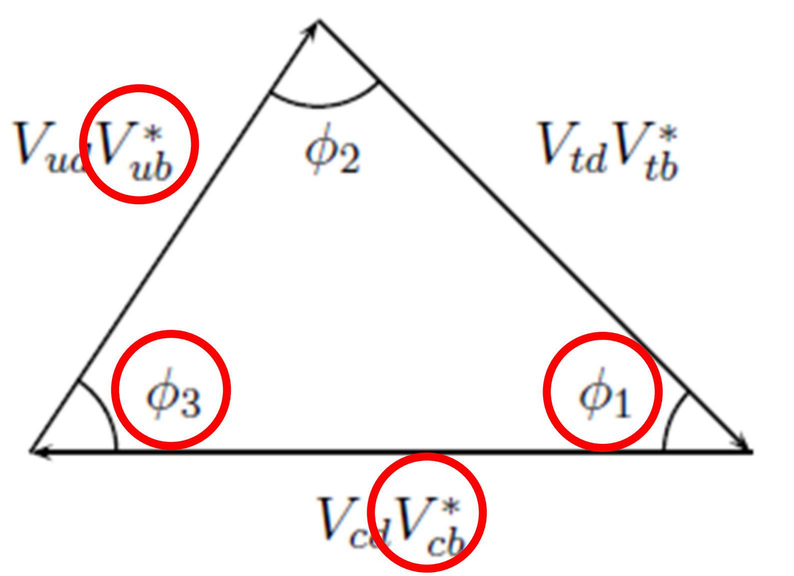
CKM physics at Belle II

Jim Libby (IIT Madras)
Anomalies 2019
18th July 2019

Overview

- Why CKM?
- SuperKEKB and Belle II
    - Current status
- CKM physics highlights
    - ϕ_1/β
    - ϕ_3/γ
    - $|V_{xb}|$
- Conclusion

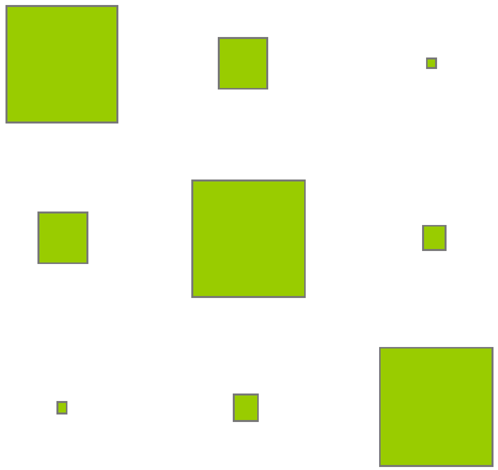


CKM matrix

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Two-by-two mixing matrix proposed by Cabibbo
  - Kobayashi-Maskawa proposed third generation to explain observed CP violation by Cronin and Fitch
- 3×3 unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase
- Intergenerational coupling disfavoured

Relative magnitude of elements



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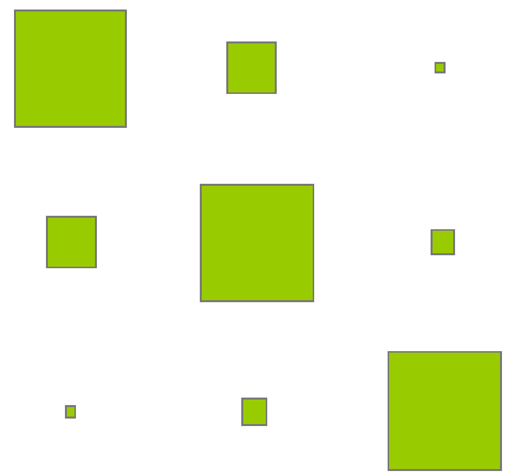

Responsible for CP violation

Visualising CP violation: the unitarity triangle

$$\lambda = \sin\theta_C = 0.22$$

1) $$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left[1-(\rho-i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

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2) Exploit unitarity (1st and 3rd col.) $$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

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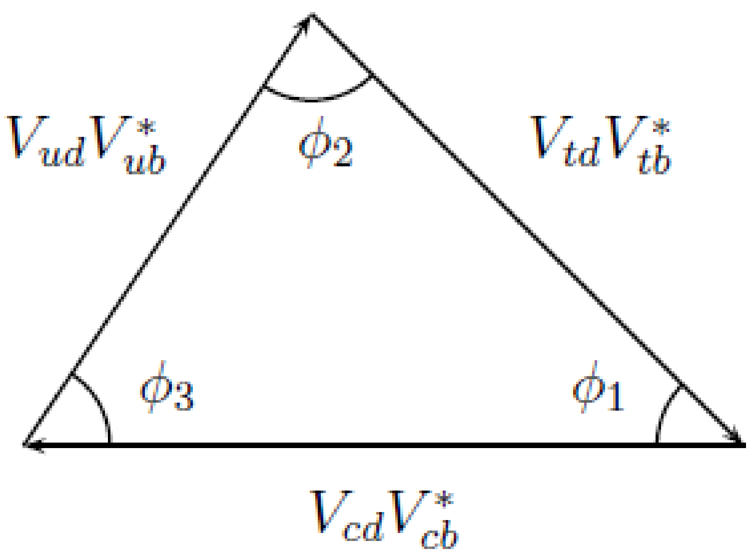
3)



$$\phi_1 = \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\simeq \arg\left(\frac{1}{1-\rho-i\eta}\right)$$

Visualising CP violation: the unitarity triangle

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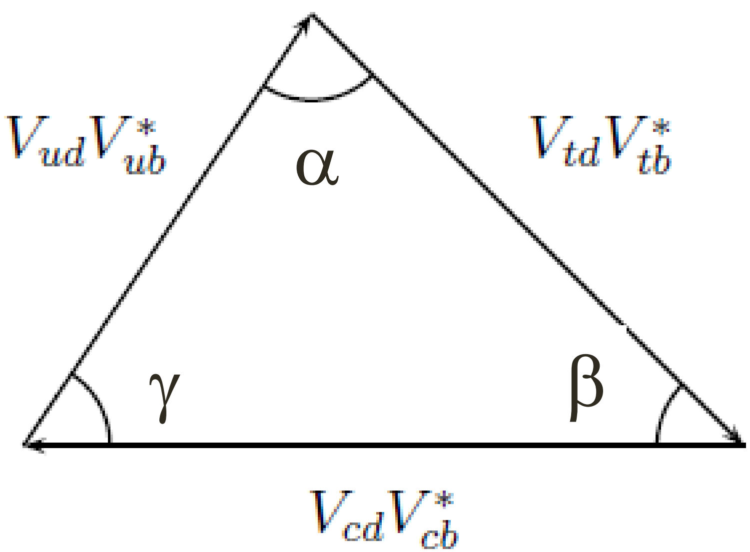

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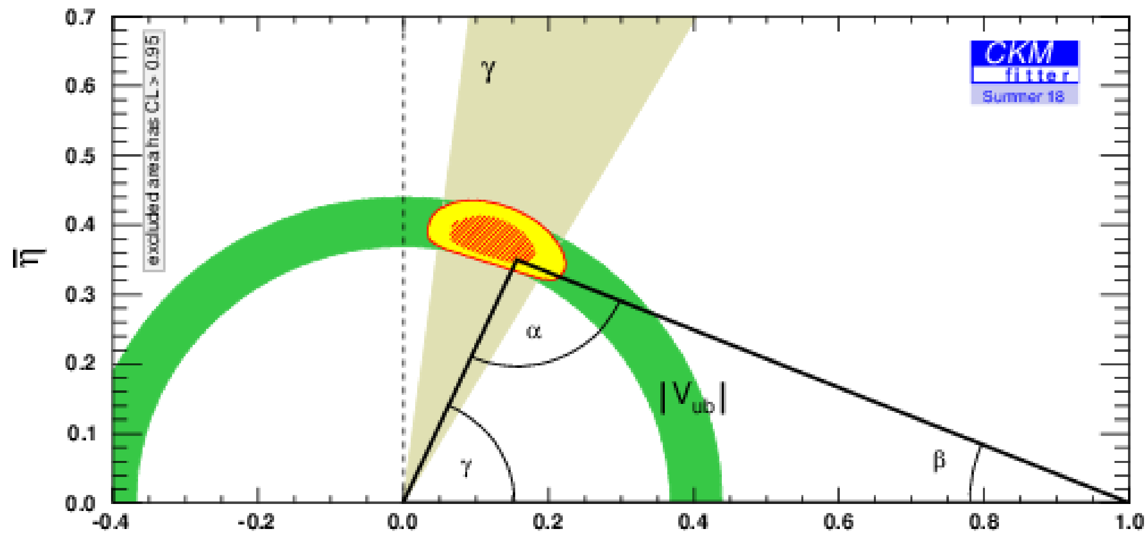
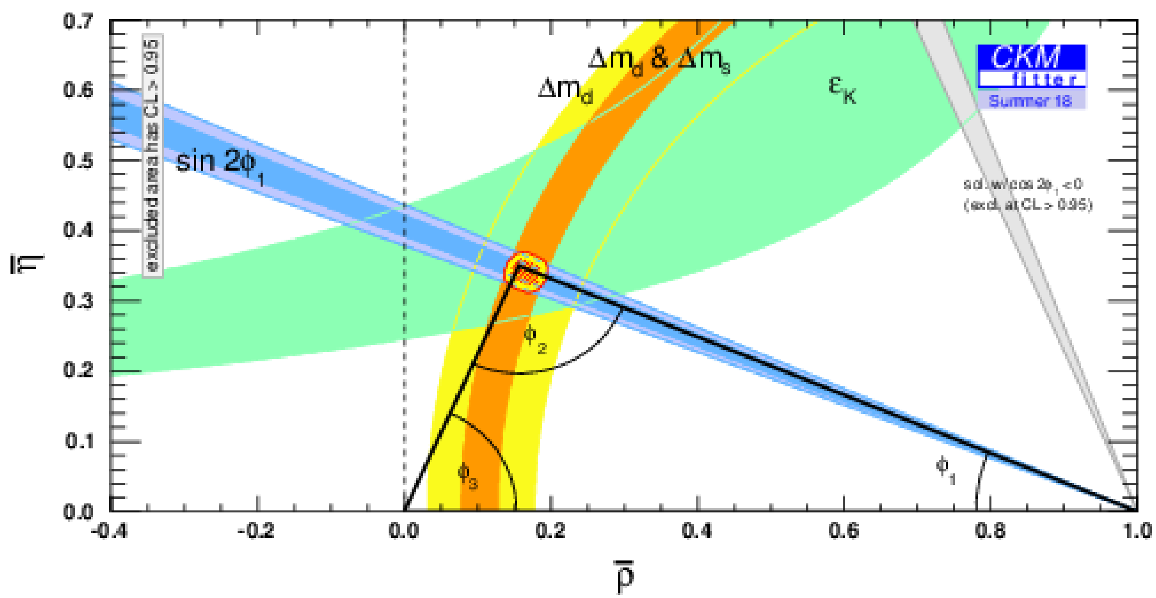
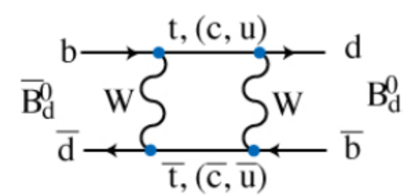
Over constraint



Tree level only



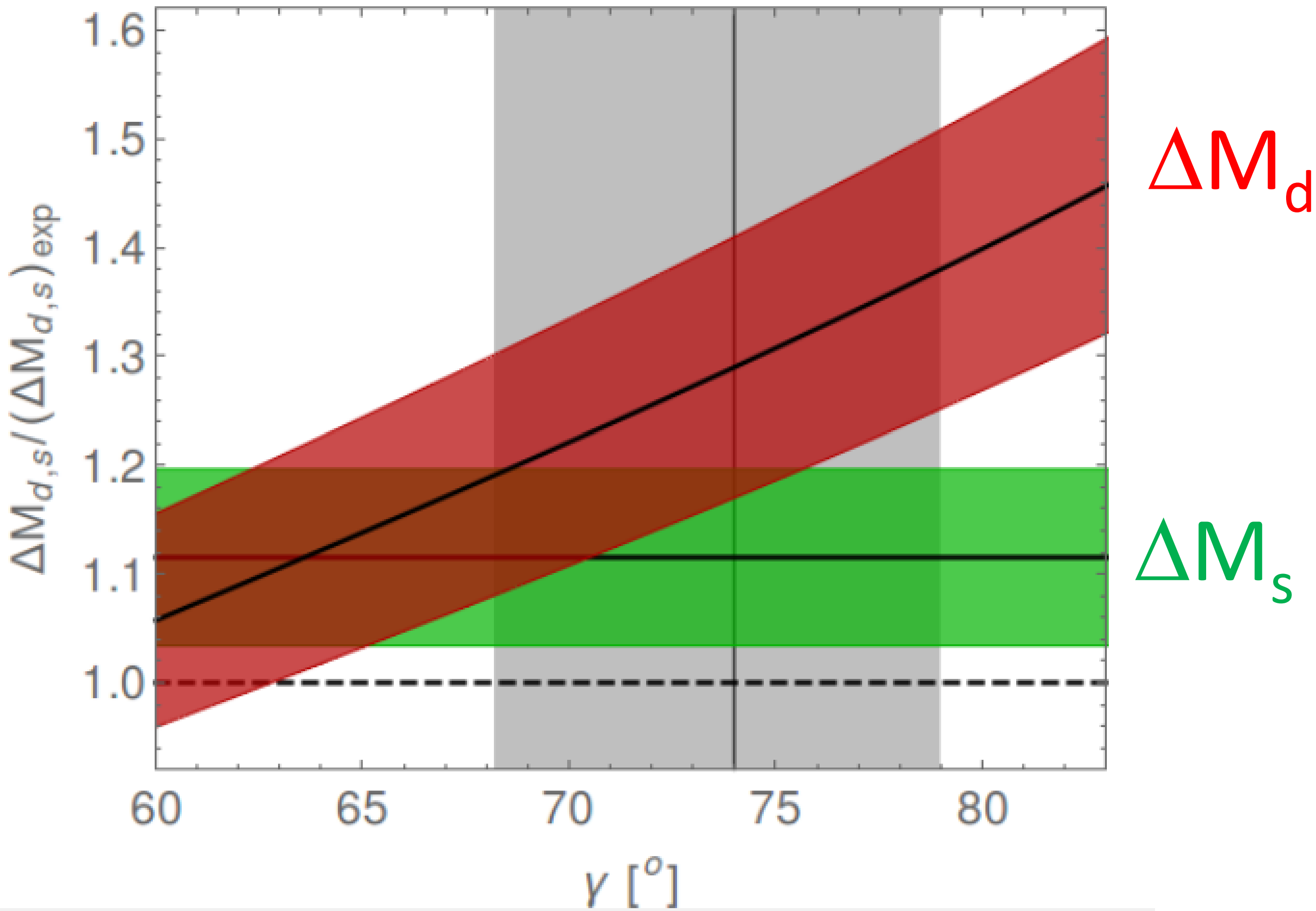
Loop-level only



NP at O(>TeV)?

Over constraint

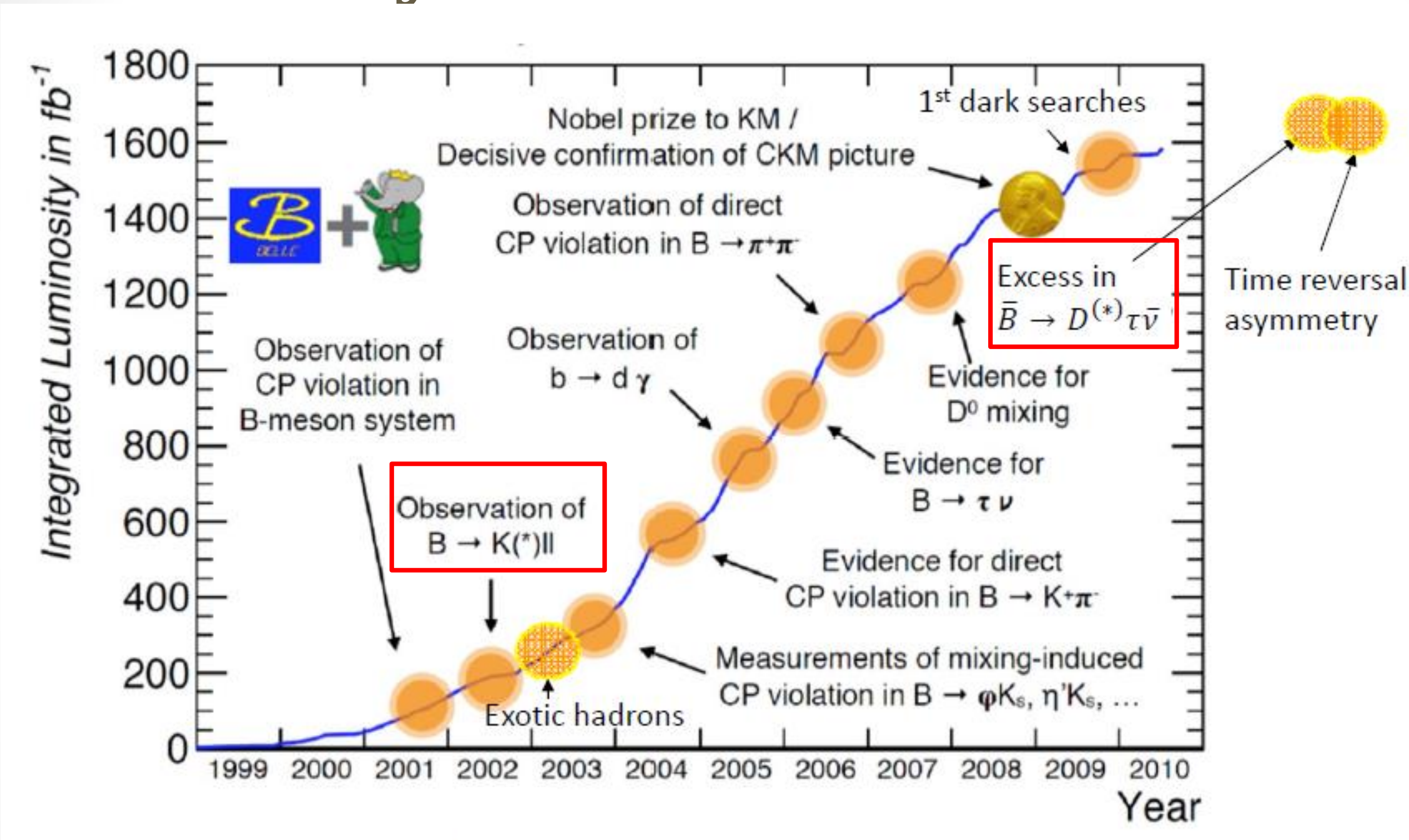
Blanke and Buras, Eur. Phys. J. **C79** (2019) no.2, 159



BELLE II AND SUPERKEKB

From Abi Soffer: HEPMAD

B-factory achievements

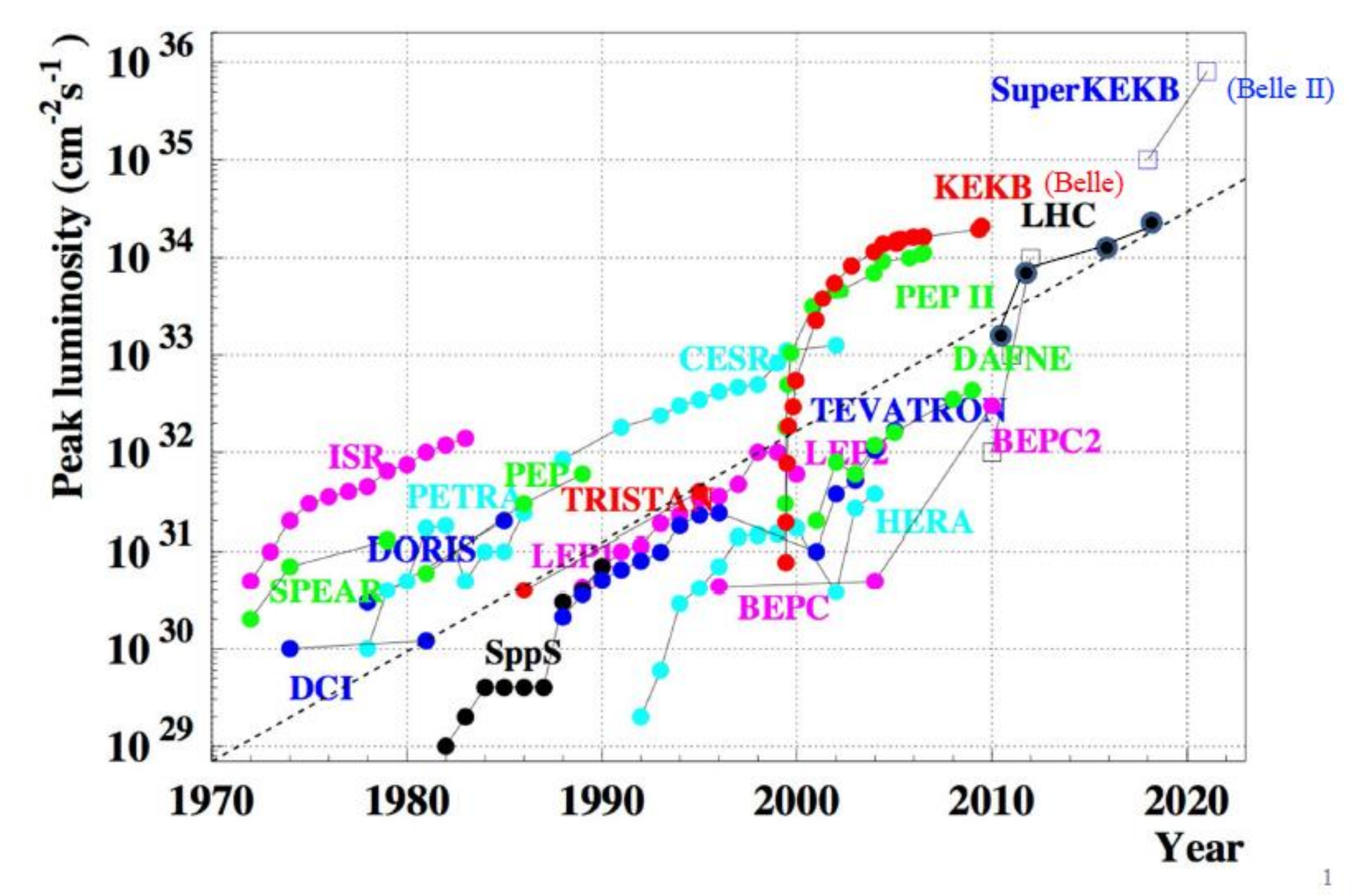


Belle II: can never have too much of a good thing (× 50 Belle)

- But isn't LHCb doing this already?

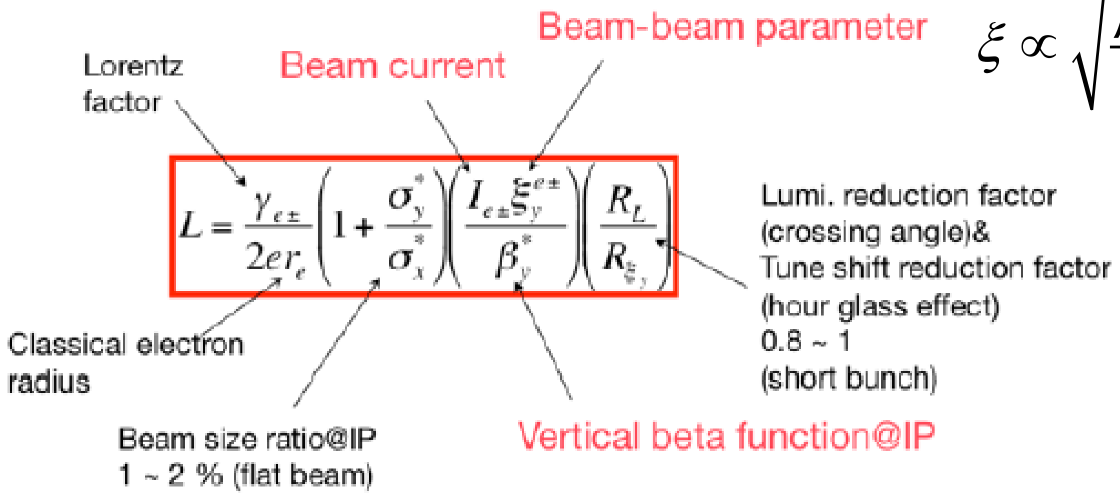
Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1}) by ~2024	~25	~50,000
Background level	Very high	Low
Typical efficiency	Low	High
π^0, K_S reconstruction	Inefficient	Efficient
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Very good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	36%

"Moore's" Law of Luminosity



The path to higher luminosity

$$\xi \propto \sqrt{\frac{\beta^*}{\varepsilon}}$$



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

Brute force: Increase beam currents by a factor of 5-10 ! Increase the beam-beam parameter by a factor of a few (crab cavities).
Too hard, too expensive (power, melt beam pipes)

The path to higher luminosity

$$\xi \propto \sqrt{\frac{\beta^*}{\varepsilon}}$$

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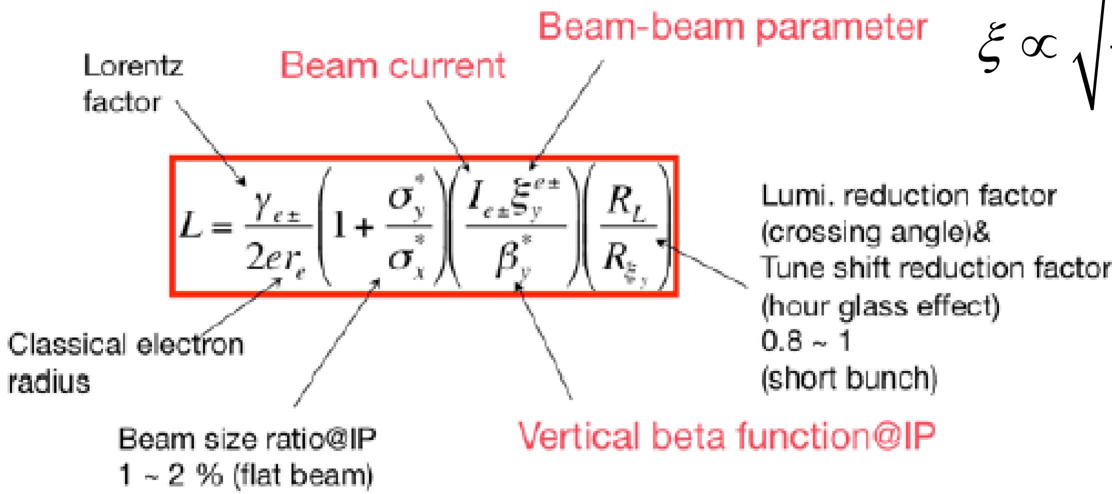
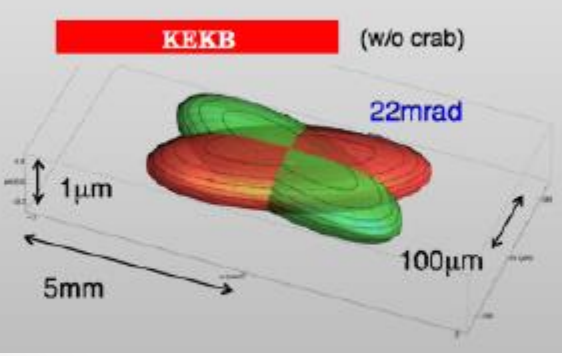
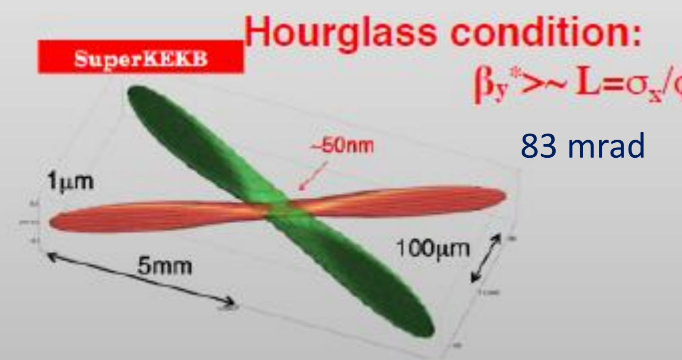


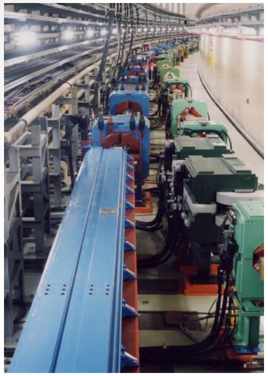
(1) Smaller β_y^* (20 x)

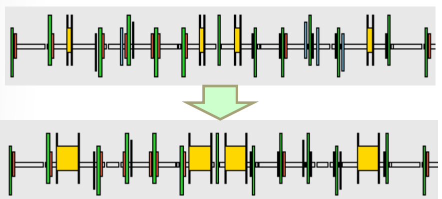
(2) Increase beam currents (~2-3x)



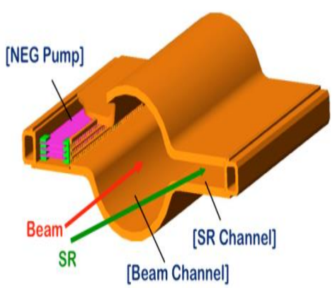


Replace short dipoles with longer ones (LER)

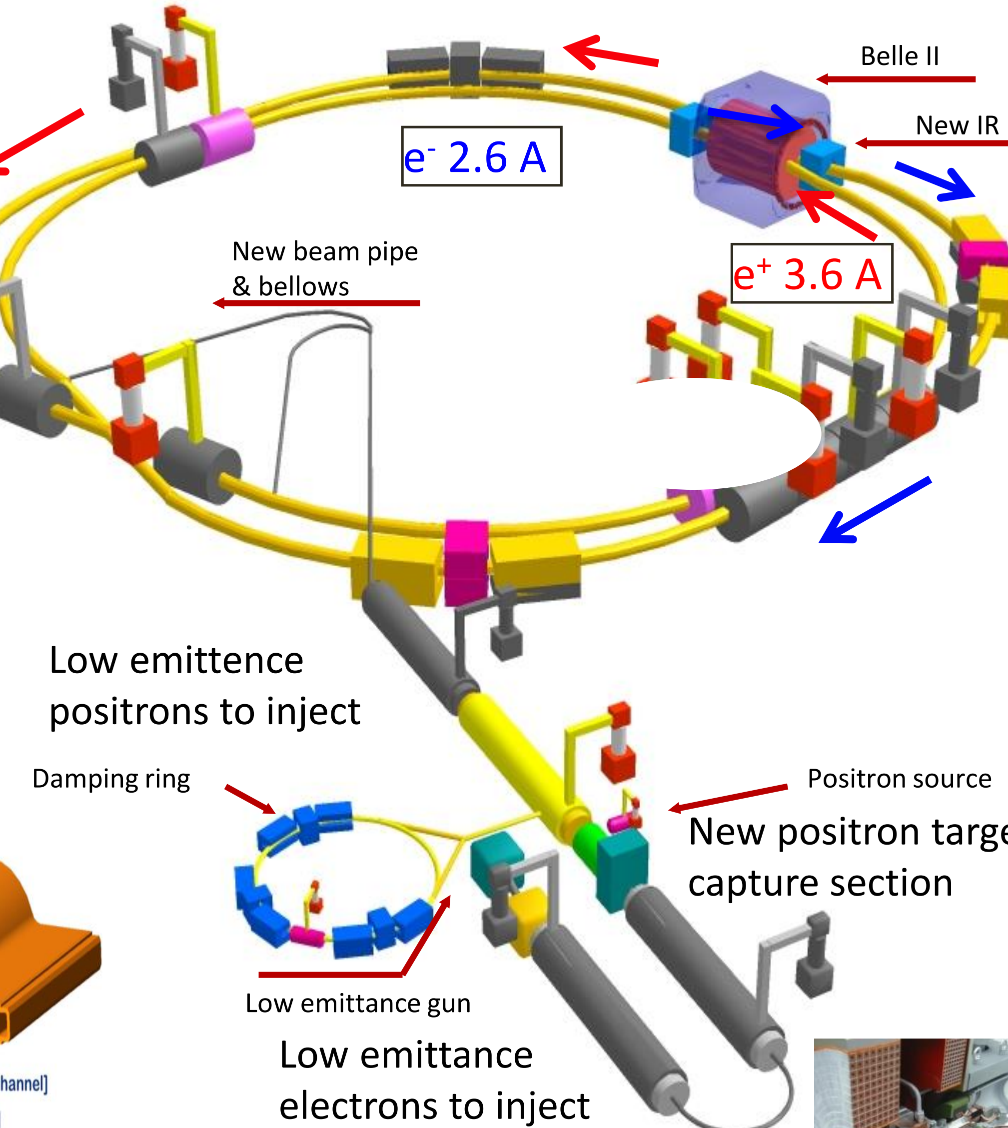




Redesign the lattices of HER & LER to squeeze the emittance



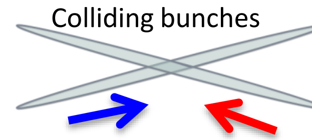
TiN-coated beam pipe with antechambers



Low emittence positrons to inject

New positron target / capture section

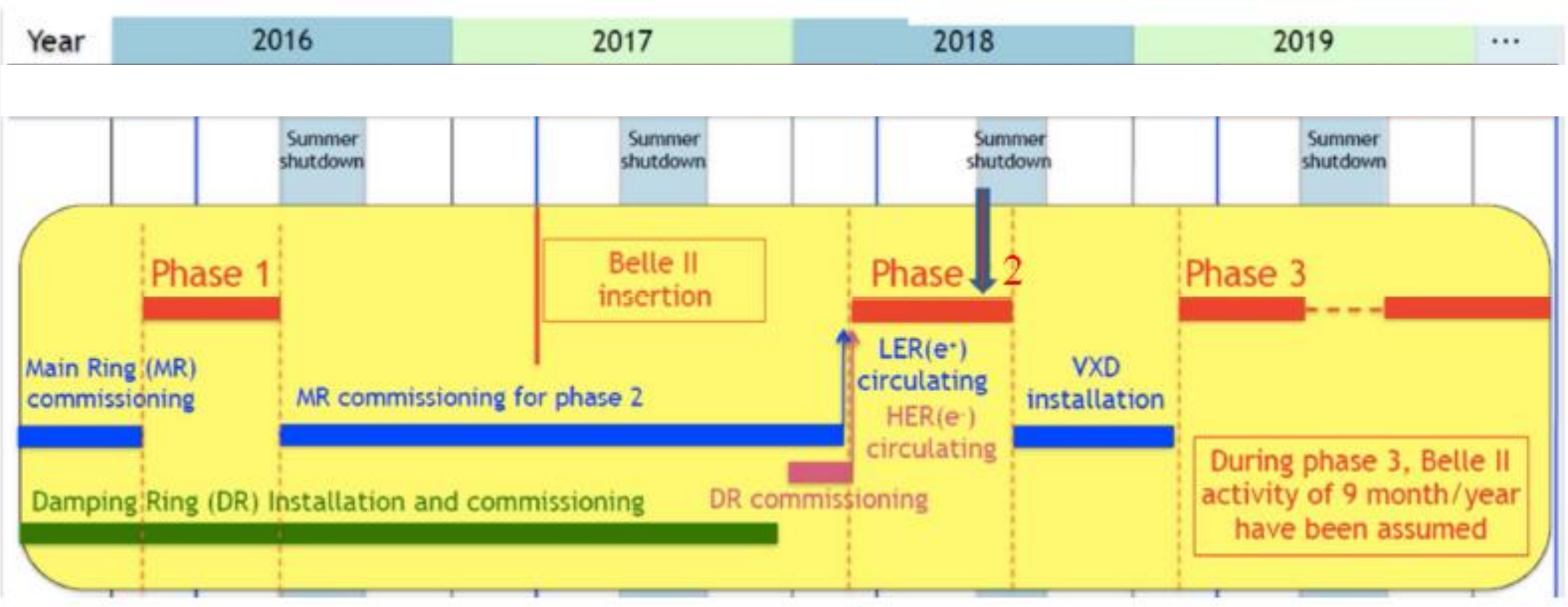
Low emittance electrons to inject



New superconducting /permanent final focusing quads near the IP

Add / modify RF systems for higher beam current

Schedule and status



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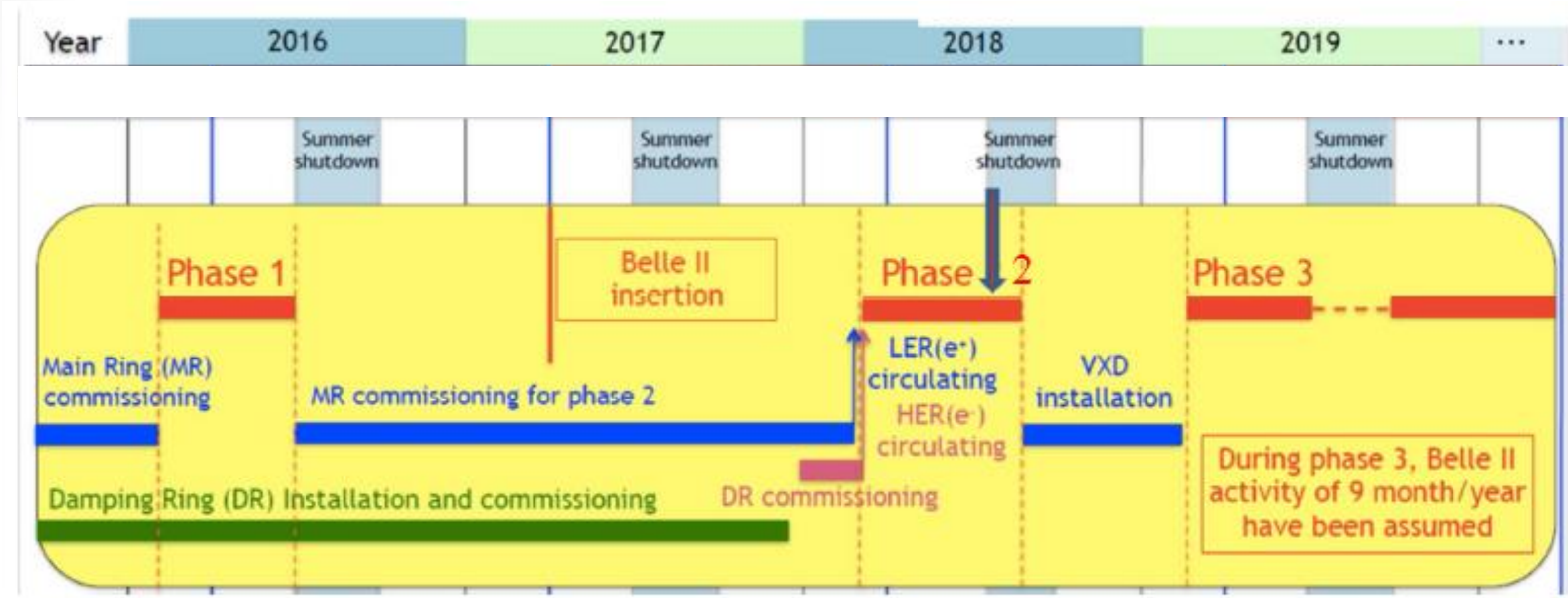
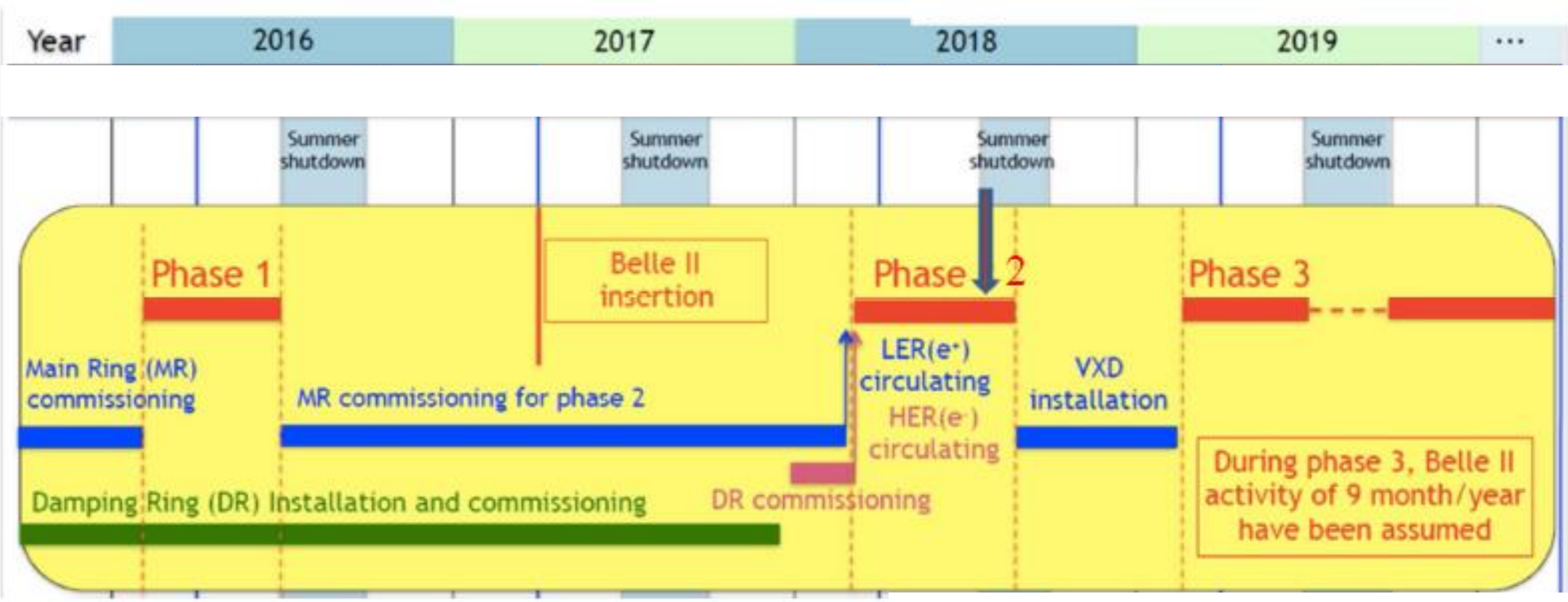
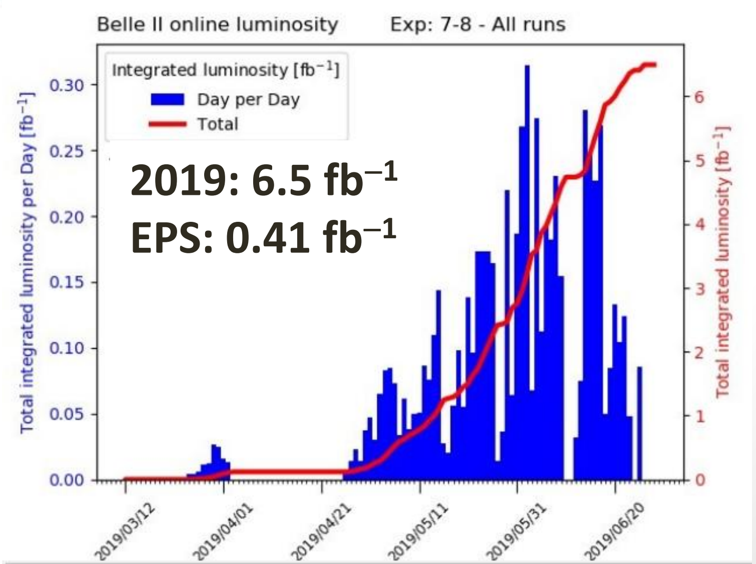


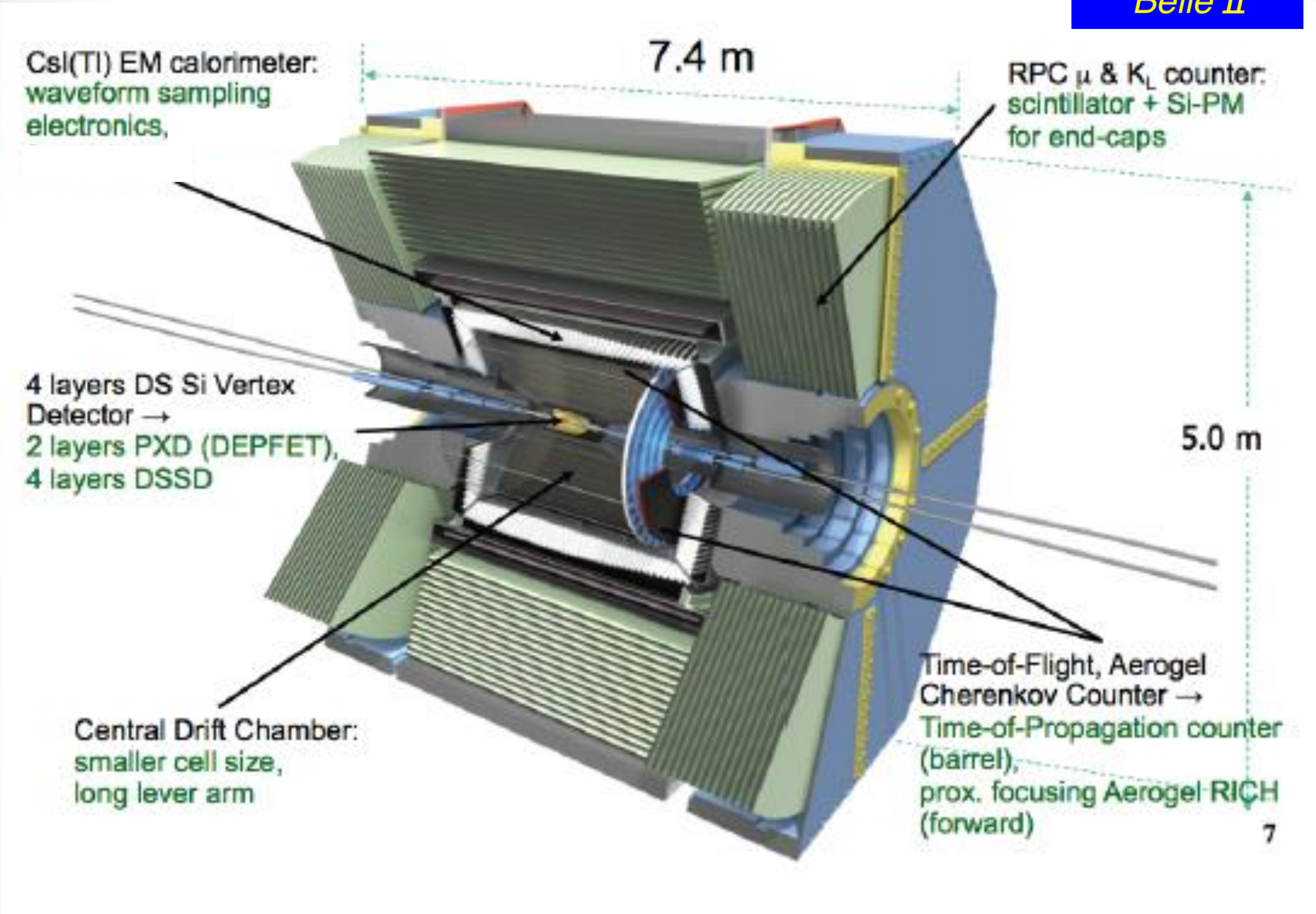
First collisions, 26 April, 2018

Schedule and status

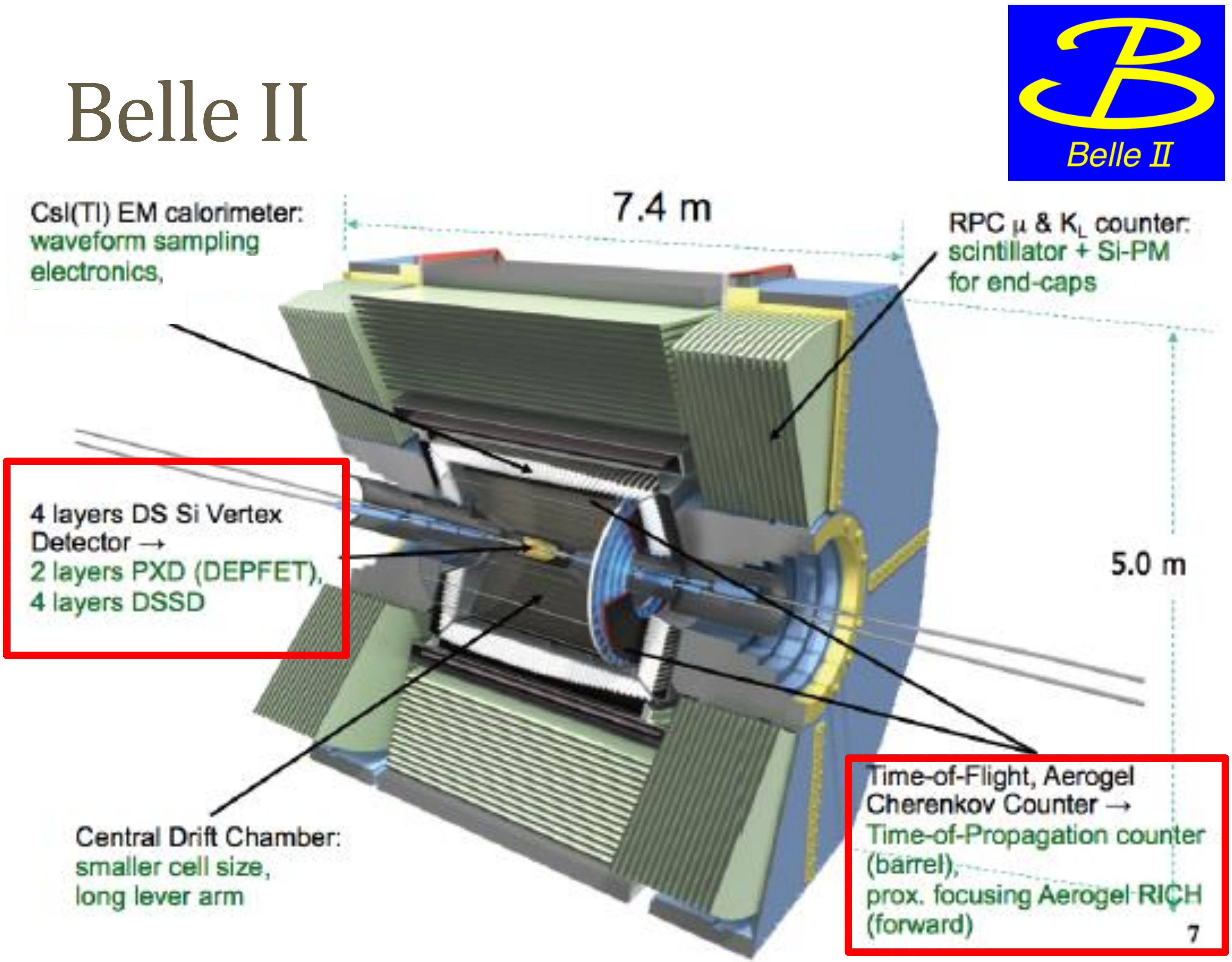




Belle II


7.4 m
5.0 m
CsI(Tl) EM calorimeter:
waveform sampling
electronics,
RPC μ & K$_L$ counter:
scintillator + Si-PM
for end-caps
4 layers DS Si Vertex
Detector →
2 layers PXD (DEPFET),
4 layers DSSD
Central Drift Chamber:
smaller cell size,
long lever arm
Time-of-Flight, Aerogel
Cherenkov Counter →
Time-of-Propagation counter
(barrel),
prox. focusing Aerogel RICH
(forward)
7

Belle II



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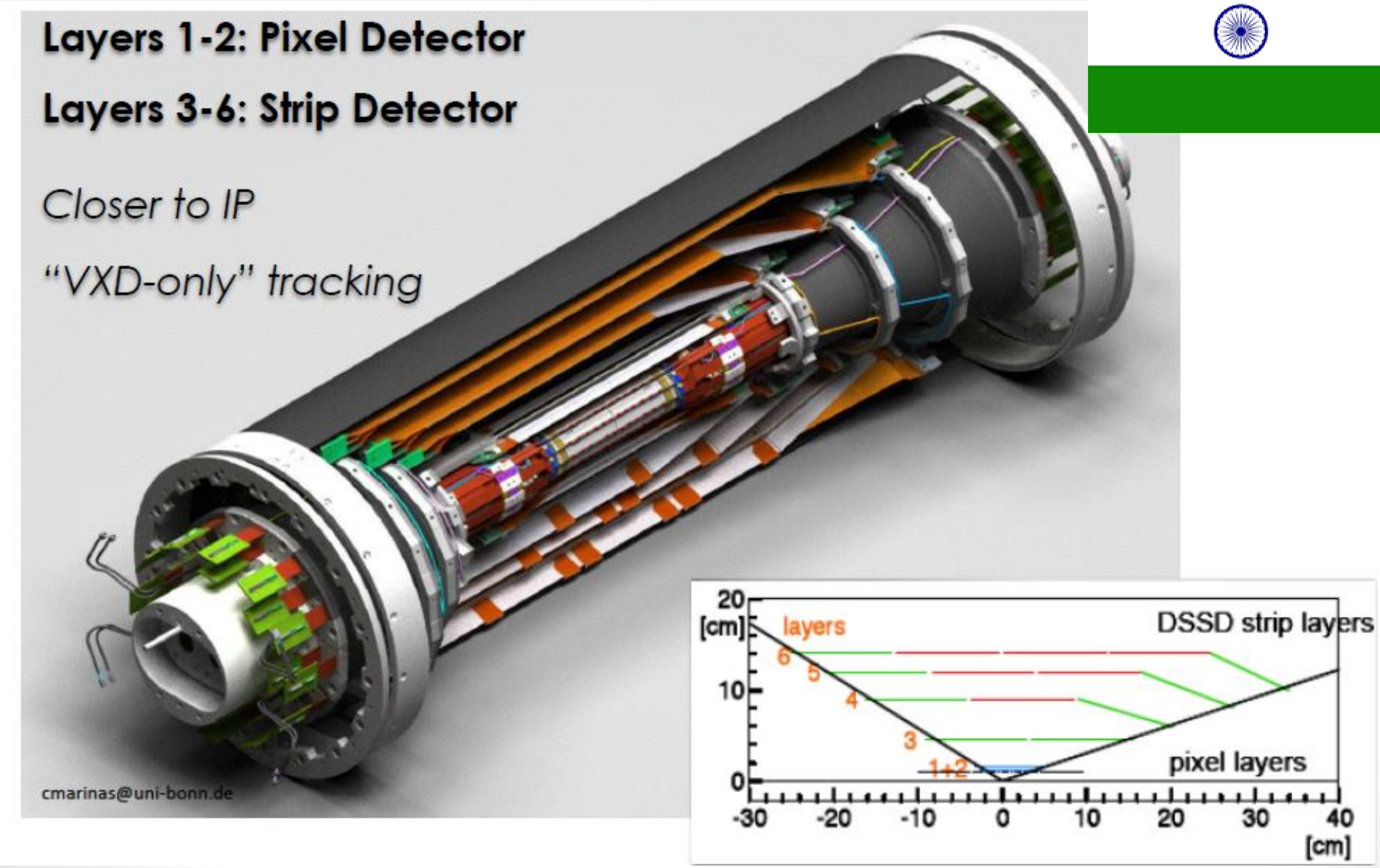
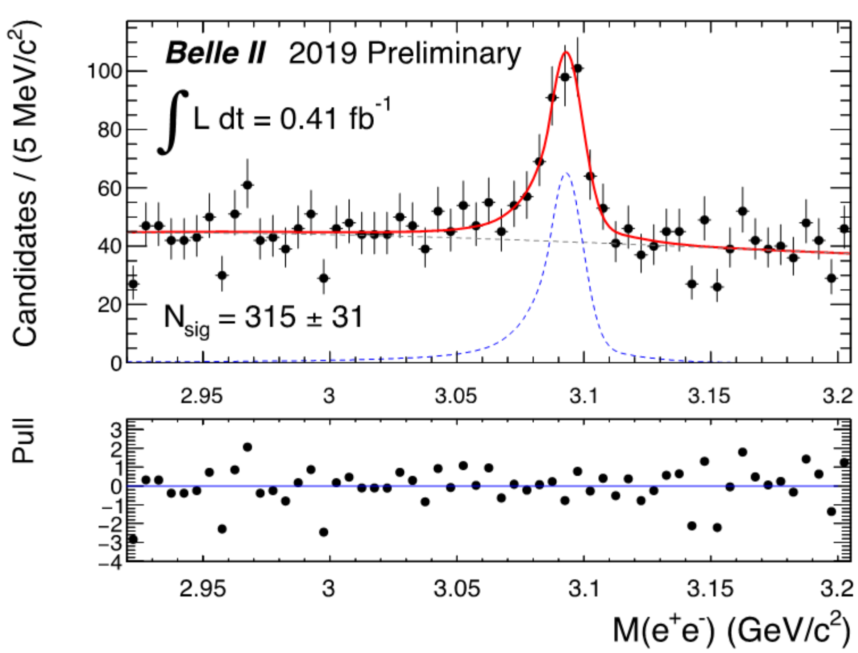
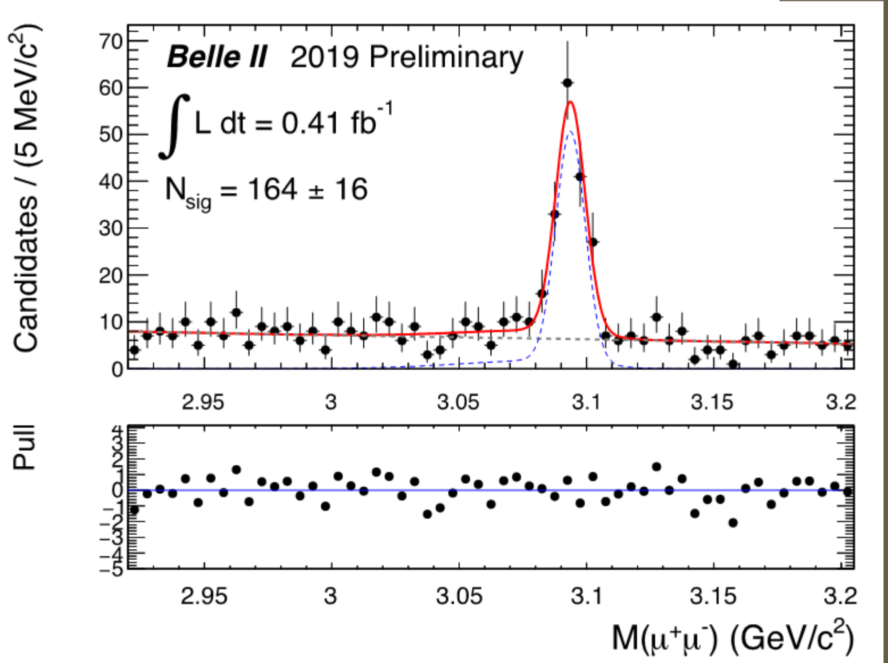
Belle II – Silicon Vertex Detector

1/8 for Phase II – only one layer of pixels for Phase III



Particle reconstruction – electrons and muons





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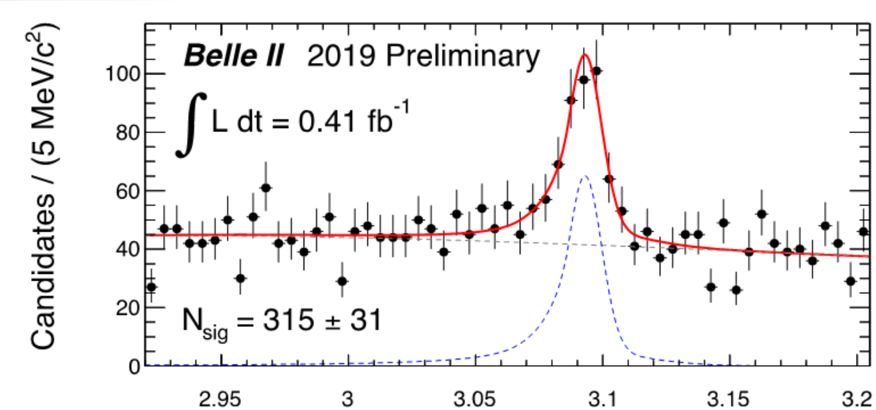
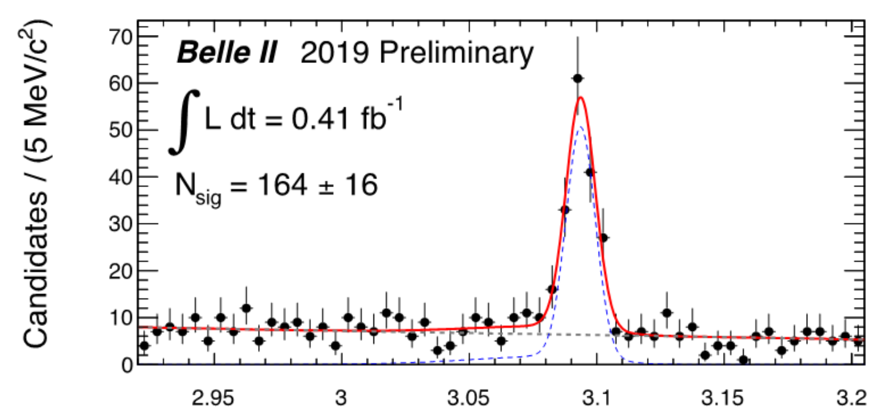
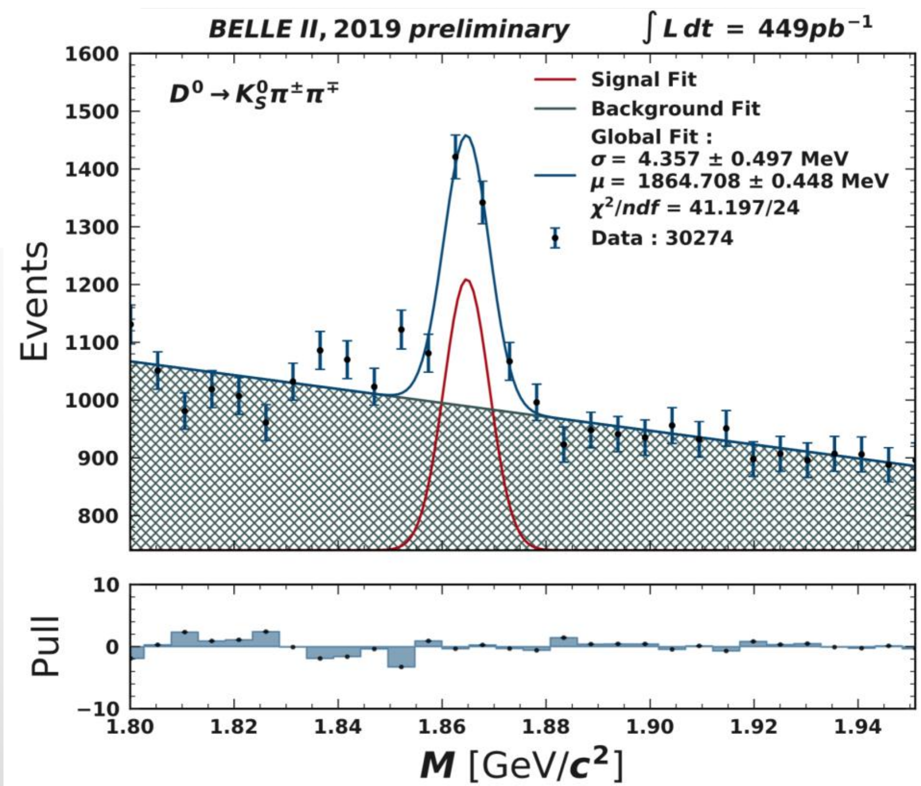
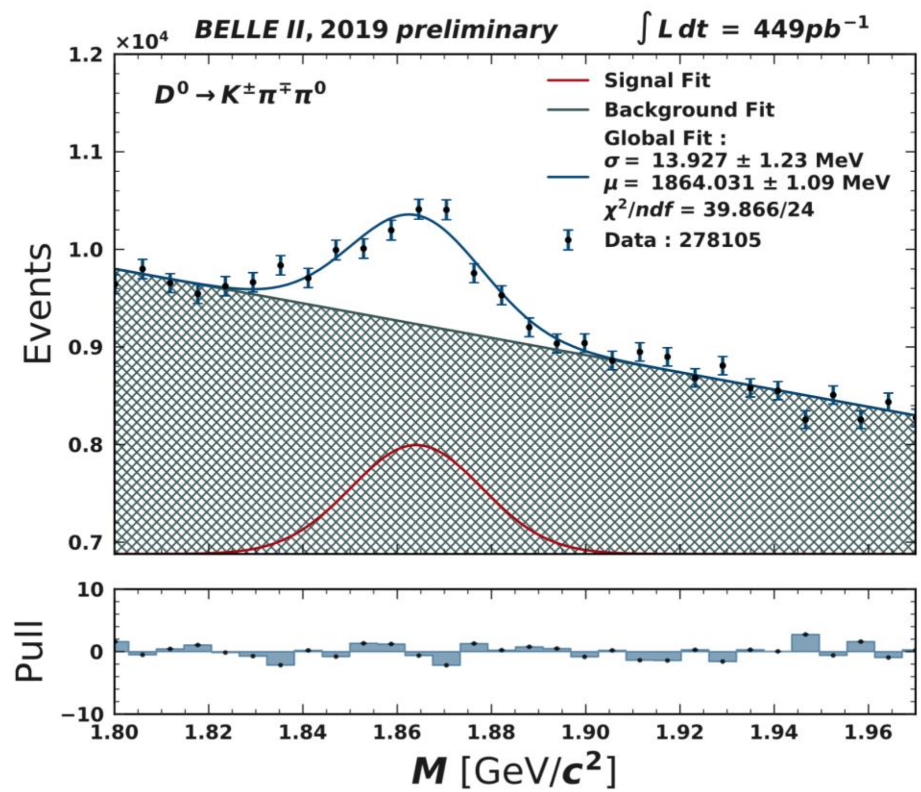


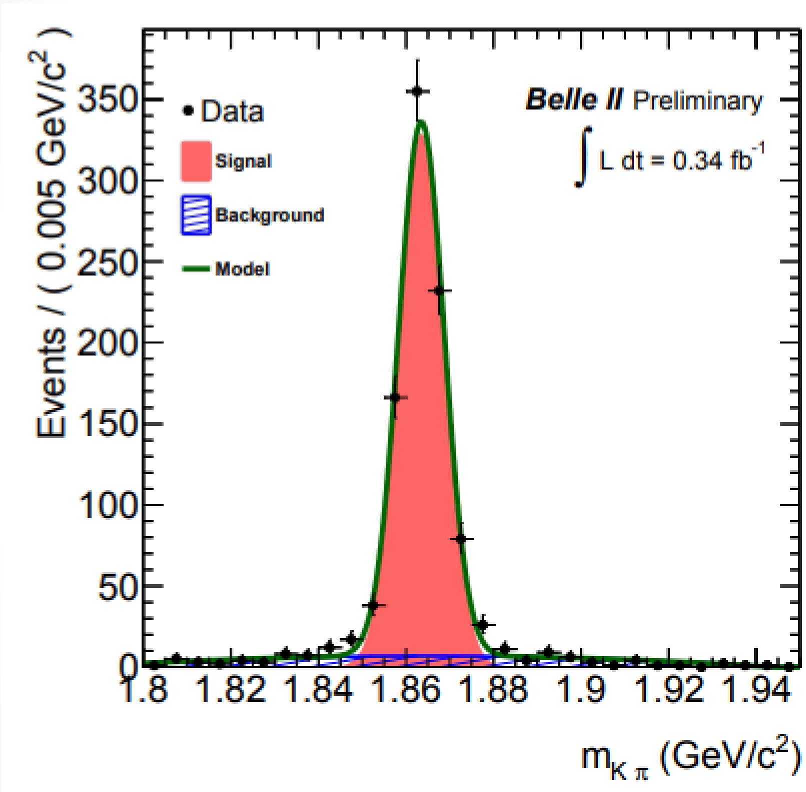




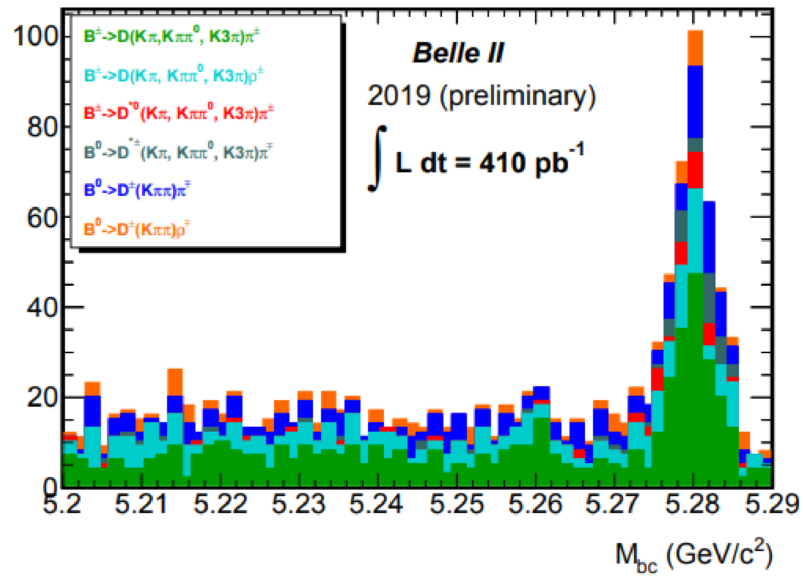


B and D meson reconstruction

$$M_{BC} = \sqrt{\left(\frac{E_{CM}}{2}\right)^2 - |\vec{\mathbf{p}}_B|^2}$$



$D^{*+} \to D^0 \pi^+,\ D^0 \to K^- \pi^+$



$B \to D^{(*)} h\ (h = \pi, \rho)$

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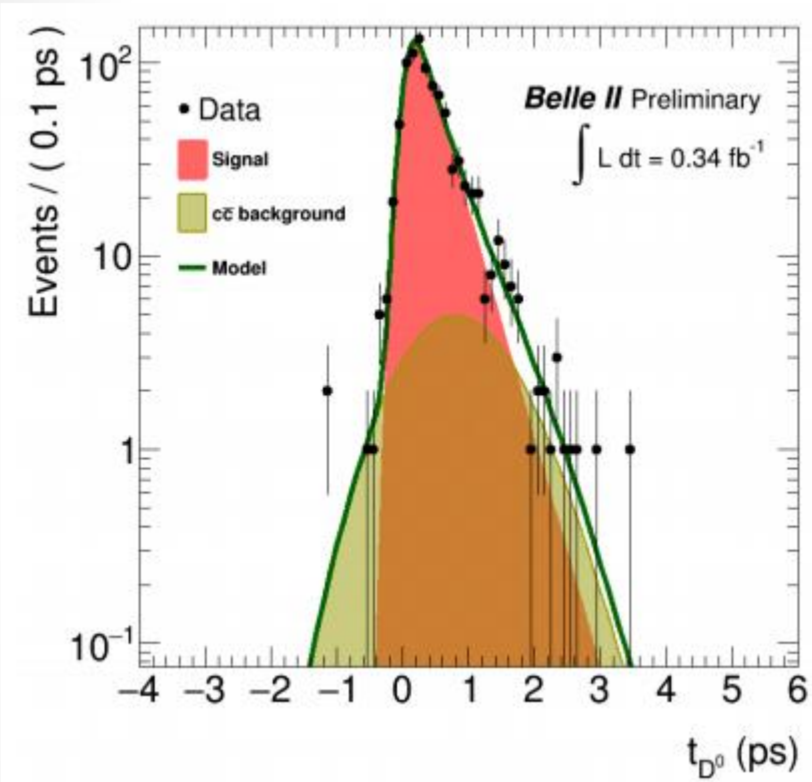
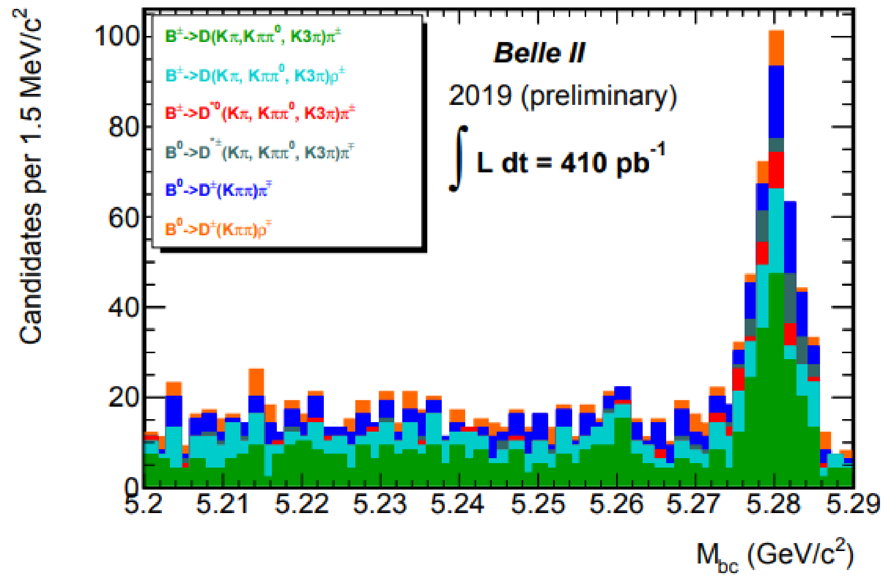




$D^{*+}\to D^0\,\pi^+,\ D^0\to K^-\pi^+$

$\tau = (370\pm40)$ fs

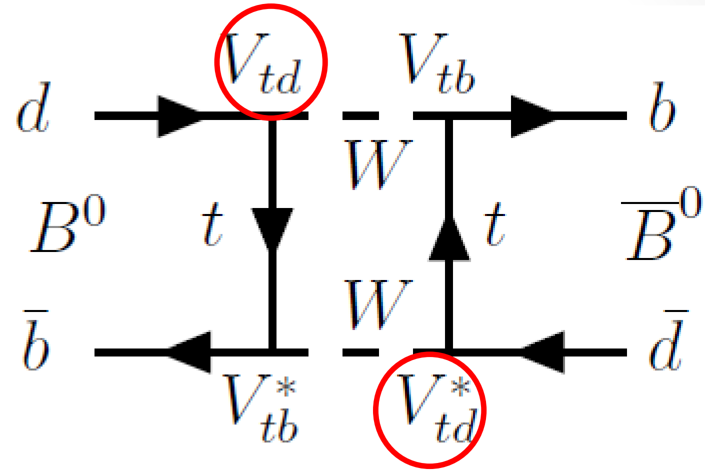
$B\to D^{(*)}h\ (h=\pi,\rho)$

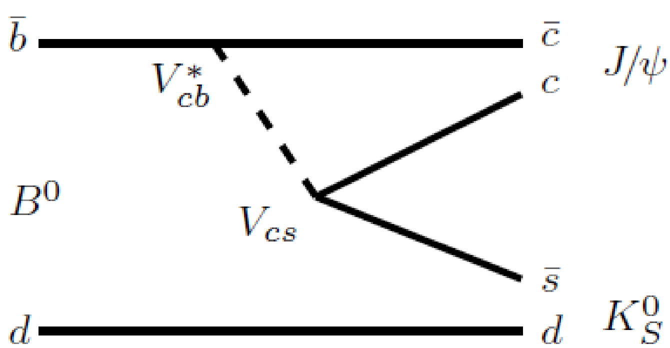
BELLE II PROSPECTS: ϕ_1

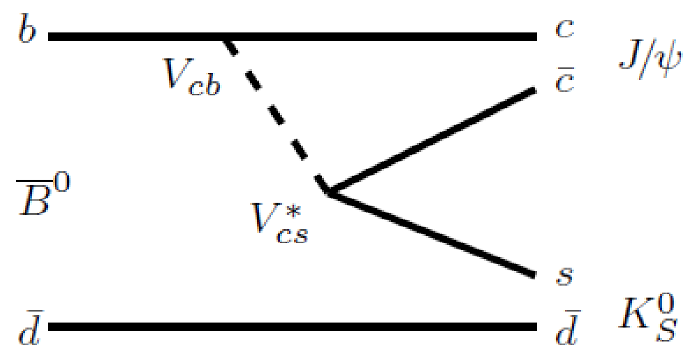
The Golden Mode

$B^0 \to J/\psi K_S^0$ sensitive to

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$







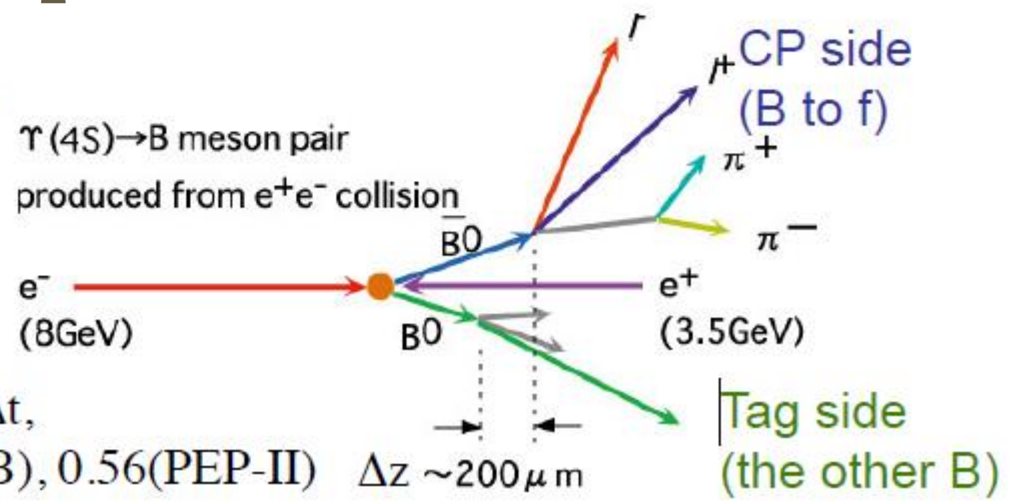
CP violation in the 'interference of mixing and decay amplitudes'

$$A_{CP}(\Delta t) = \frac{\Gamma\left[\bar{B}^0(\Delta t)\to f\right] - \Gamma\left[B^0(\Delta t)\to f\right]}{\Gamma\left[\bar{B}^0(\Delta t)\to f\right] + \Gamma\left[B^0(\Delta t)\to f\right]} = S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)$$

In SM $S_f = \sin 2\beta$ and $C_f = 0$ when no CPV in f

Time-dependent CPV violation

In order to see CPV by interference between decay and mixing.



$\Delta z = \beta\gamma c \Delta t$,

$\beta\gamma = 0.425$(KEKB), 0.56(PEP-II)

Time-dependent CPV violation

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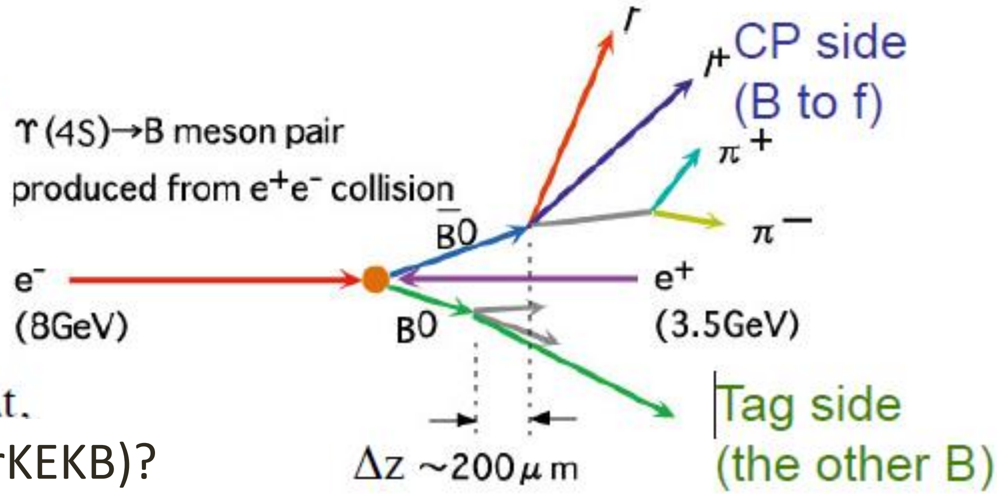

$\Delta z = \beta\gamma c \Delta t$.

$\beta\gamma$= 0.28 (SuperKEKB)?

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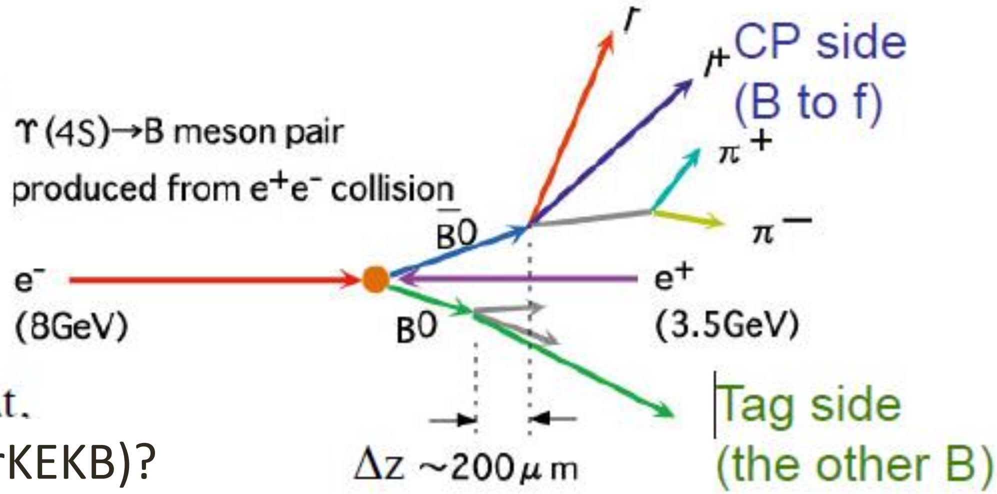

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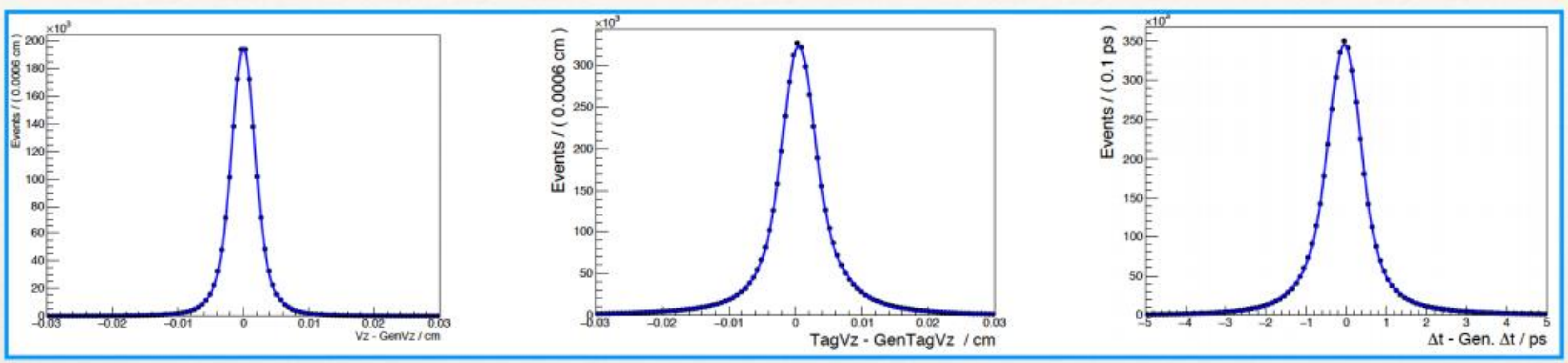


Δz resolution
$J/\psi \to \mu\mu$

Δz resolution
Tag Vertex

Δt resolution

Belle	Belle II	Belle	Belle II	Belle	Belle II
43 μm	26 μm	89 μm	53 μm	0.92 ps	0.77 ps

Flavour tagging

- Use leptons, kaons, pions and Λs not associated with signal
- Belle II more variables, MVA and leverage improved PID

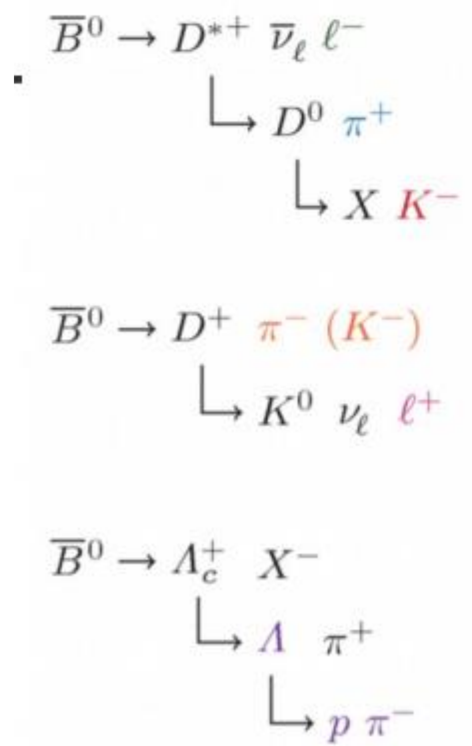
$$\overline{B}^0 \to D^{*+}\,\overline{\nu}_\ell\,\ell^-$$
$$\hookrightarrow D^0\,\pi^+$$
$$\hookrightarrow X\,K^-$$

$$\overline{B}^0 \to D^+\,\pi^-\,(K^-)$$
$$\hookrightarrow K^0\,\nu_\ell\,\ell^+$$

$$\overline{B}^0 \to \Lambda_c^+\,X^-$$
$$\hookrightarrow \Lambda\,\pi^+$$
$$\hookrightarrow p\,\pi^-$$

Flavour tagging

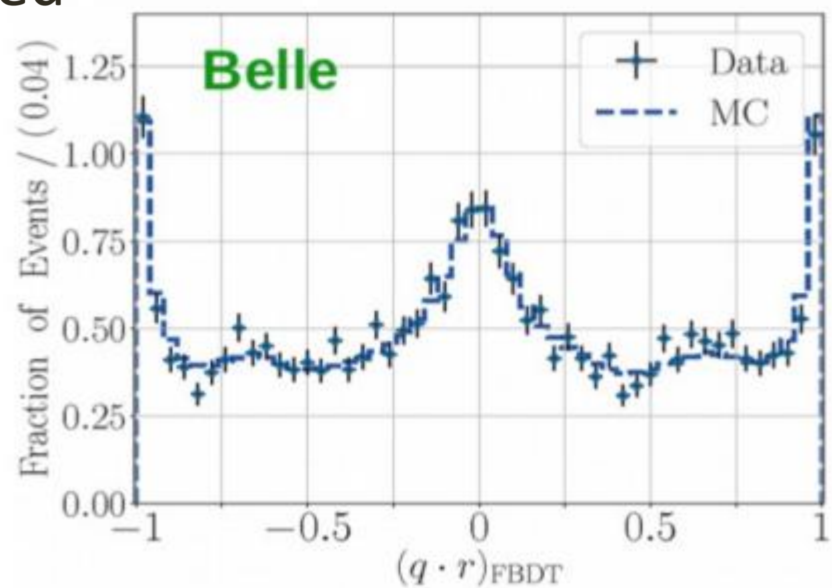
- Use leptons, kaons, pions and Λs not associated with signal
- Belle II more variables, MVA and leverage improved PID
- Validated on Belle data
- $\approx$ 20% improvement expected



$$\varepsilon_{eff} = \Sigma_i\, \varepsilon_i (1 - 2w_i)^2$$

effective tagging efficiency (ε_{eff}); efficiency of category i (ε_i); mis-tagging probability of category i (w_i)

Old FT - Belle data:	ε_{eff} = (30.1 ± 0.4) %
New FT - Belle data:	ε_{eff} = (33.6 ± 0.5) %
New FT - Belle MC:	ε_{eff} = (34.18 ± 0.03)%
New FT - Belle II MC:	ε_{eff} = (37.16 ± 0.03)%



Prospects

Phys. Rev. Lett. **108**, 171802 (2012)

	Belle (1 ab^{-1})		
Sample	Value	Stat. ($\times 10^{-3}$)	Syst. ($\times 10^{-3}$)
$B \to J/\psi K_S$	+0.67	29	13
$b \to c\bar{c}s$	+0.667	23	12

Prospects

Phys. Rev. Lett. **108**, 171802 (2012)

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$B \to J/\psi K_S$	+0.67	29	13
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Measurement becomes systematically limited

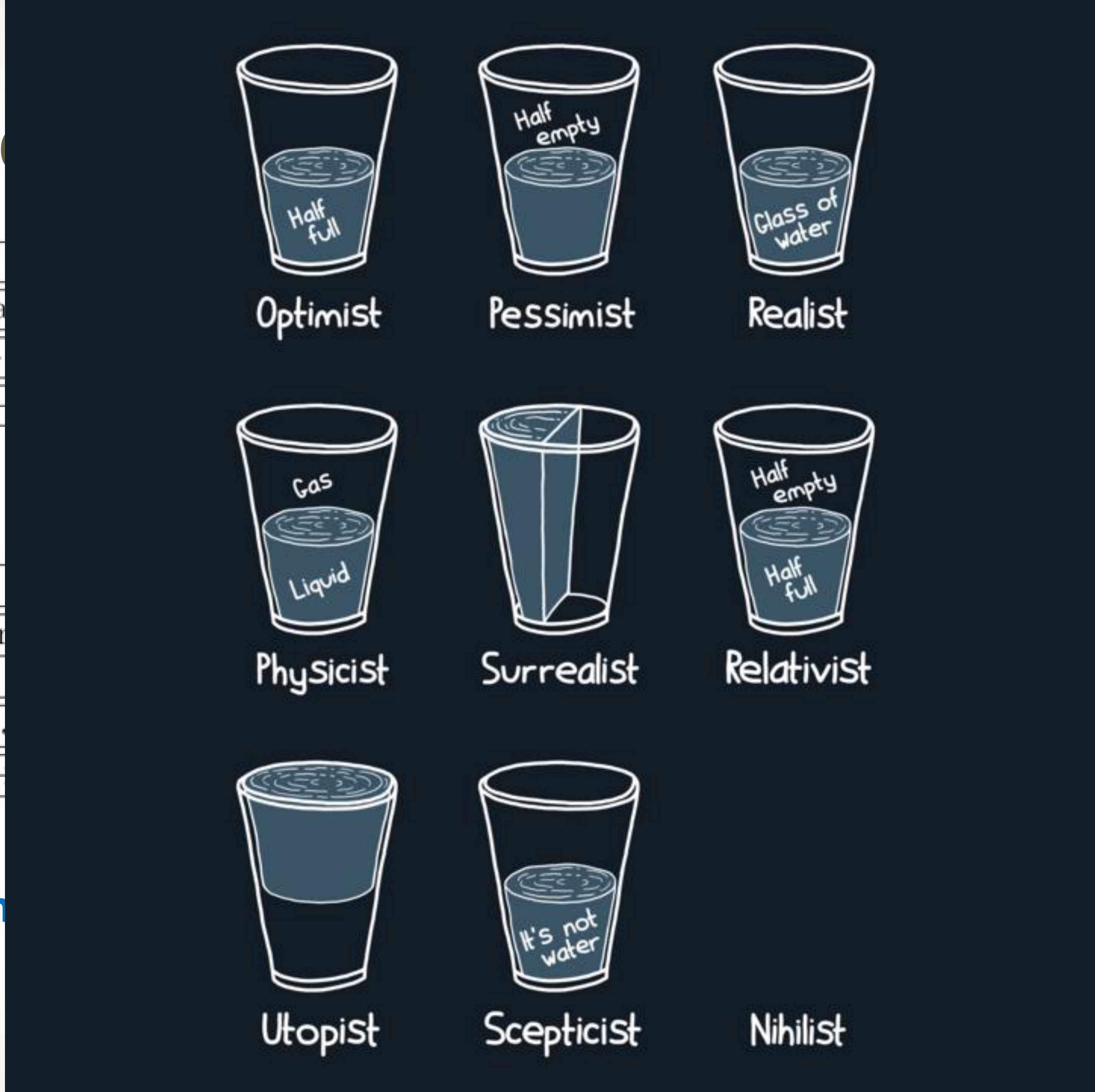
	Belle II (50 ab^{-1})				
Sample	Stat. ($\times 10^{-3}$)	Syst. (1) ($\times 10^{-3}$)		Syst. (2) ($\times 10^{-3}$)	
		Red.	Non-red.	Red.	Non-red.
$B \to J/\psi K_S$	3.5	1.2	8.3	1.2	4.4
$b \to c\bar{c}s$	2.7	2.6	7.0	2.6	3.6

Pr

Sa

$B \to$

b -



San

$B \to$

$b \to$

Half en

Half fu ... **ies**

Prospects

Phys. Rev. Lett. **108**, 171802 (2012)

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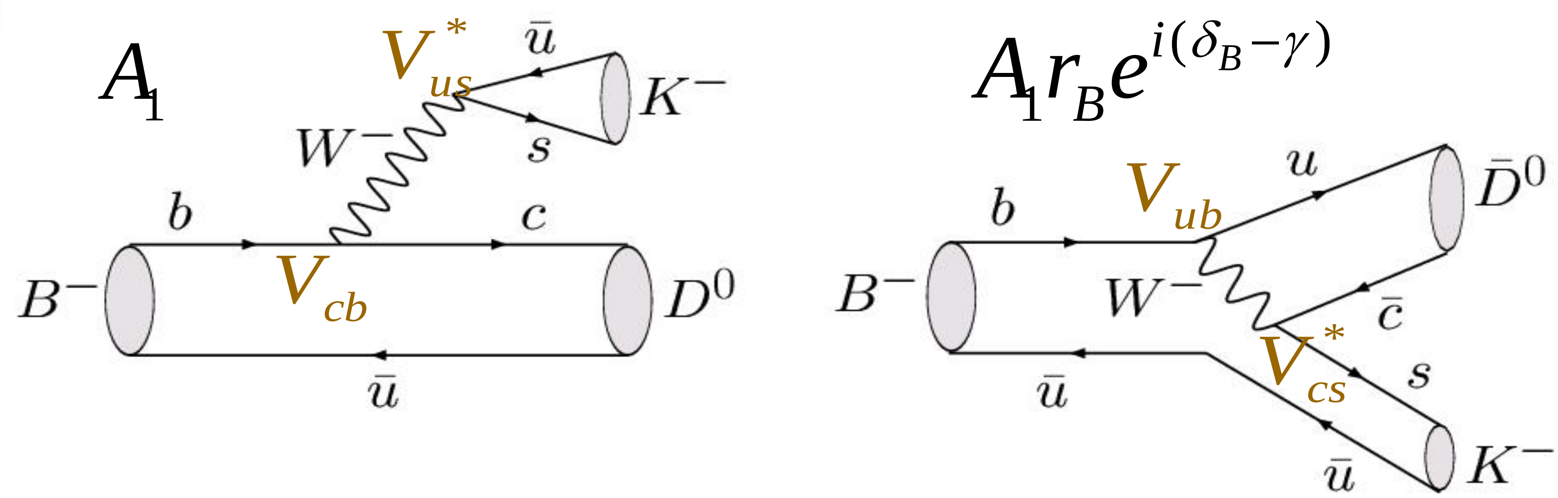
Half empty: no improvement in systematics

Half full: improvement in alignment and vertexing uncertainties

BELLE II PROSPECTS: ϕ_3

Measuring ϕ_3

- Tree-level determination γ

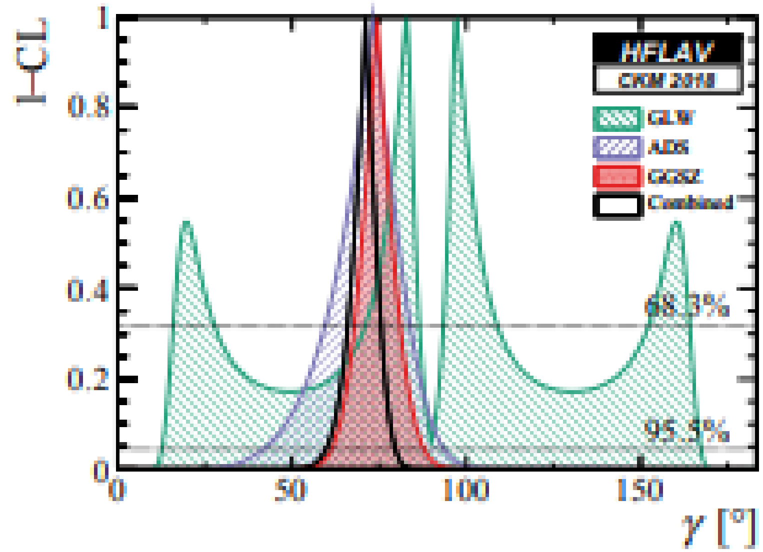


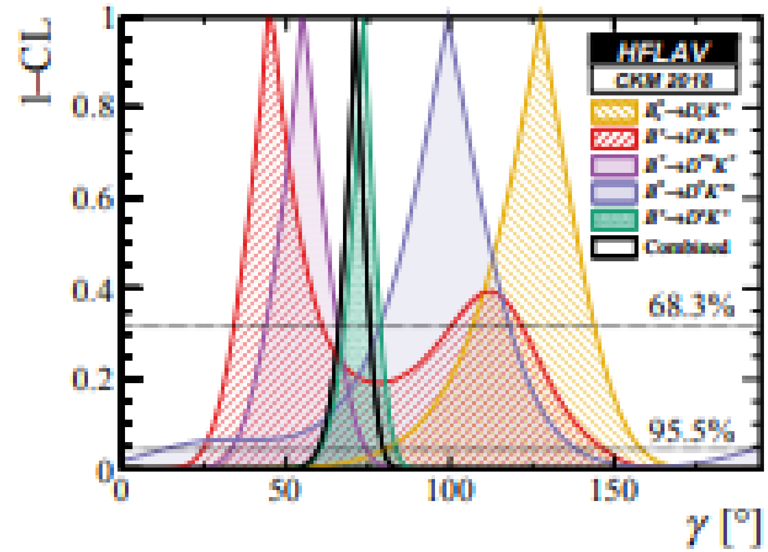
- Same final state for *D* and $\overline{D}$ $\Rightarrow$ interference $\Rightarrow$ **the possibility of DCPV**
- Four types of D final states generally used
  - **CP-eigenstates [GLW]**
    - Gronau & London, PLB **253**, 483 (1991), Gronau, & Wyler, PLB **265**, 172 (1991)
  - **K^+X^- ($X^-=\pi^-$, $\pi^-\pi^0$, $\pi^-\pi^-\pi^+$) - CF and DCS [ADS]**
    - Atwood, Dunietz & Soni, PRD **63**, 036005 (2001)
  - **Self-conjugate multibody states: $K_Sh^+h^-$ [Dalitz/GGSZ]**
    - Giri, Grossman, Soffer and Zupan, PRD **68**, 054018 (2003); Bondar (unpublished)
  - **None of the above (SCS): $K_SK^+\pi^-$ [GLS]**
    - Grossman, Ligeti and Soffer, Phys. Rev. D67 071301 (2003)

World averages

From all measurements of $B \to D^{(*)}K^{(*)}$ from GLW, ADS, and GGSZ

(Belle + BaBar + LHCb)





$$(\phi_3)^{\text{combined}} = (73.5^{+4.2}_{-5.1})^\circ \text{ [8]}$$

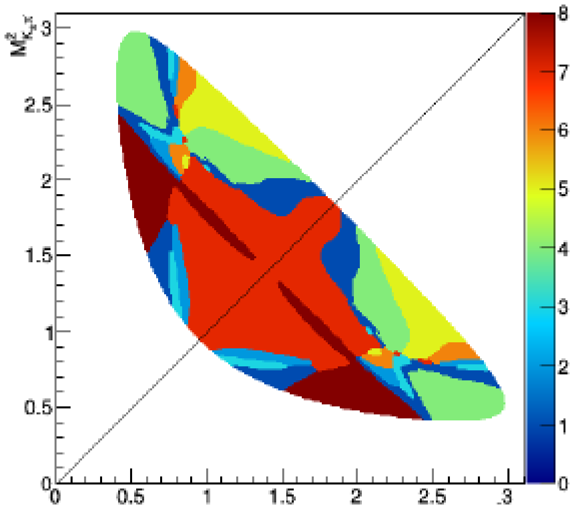
$$(\phi_3)^{\text{Belle}} = (73^{+13}_{-15})^\circ$$
$$(\phi_3)^{\text{BaBar}} = (69^{+17}_{-16})^\circ \text{ [6]}$$
$$(\phi_3)^{\text{LHCb}} = (74^{+5.0}_{-5.8})^\circ \text{ [7]}$$

[6] [PRD 87 052015 (2013)]

[7] [LHCb-CONF-2017-004]

[8] http://www.slac.stanford.edu/xorg/hflav/triangle/moriond2018/index.shtml

ϕ_3 at Belle II

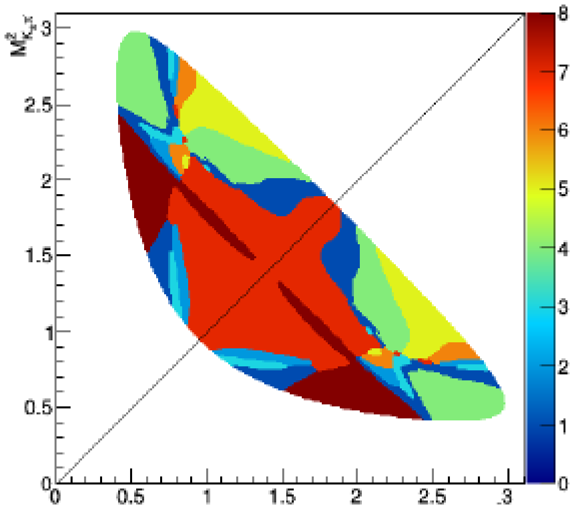


- GGSZ dominates the Belle average

$$\phi_3 = \left(73^{+13}_{-15}\right)^\circ$$

- Will continue to do so at Belle II

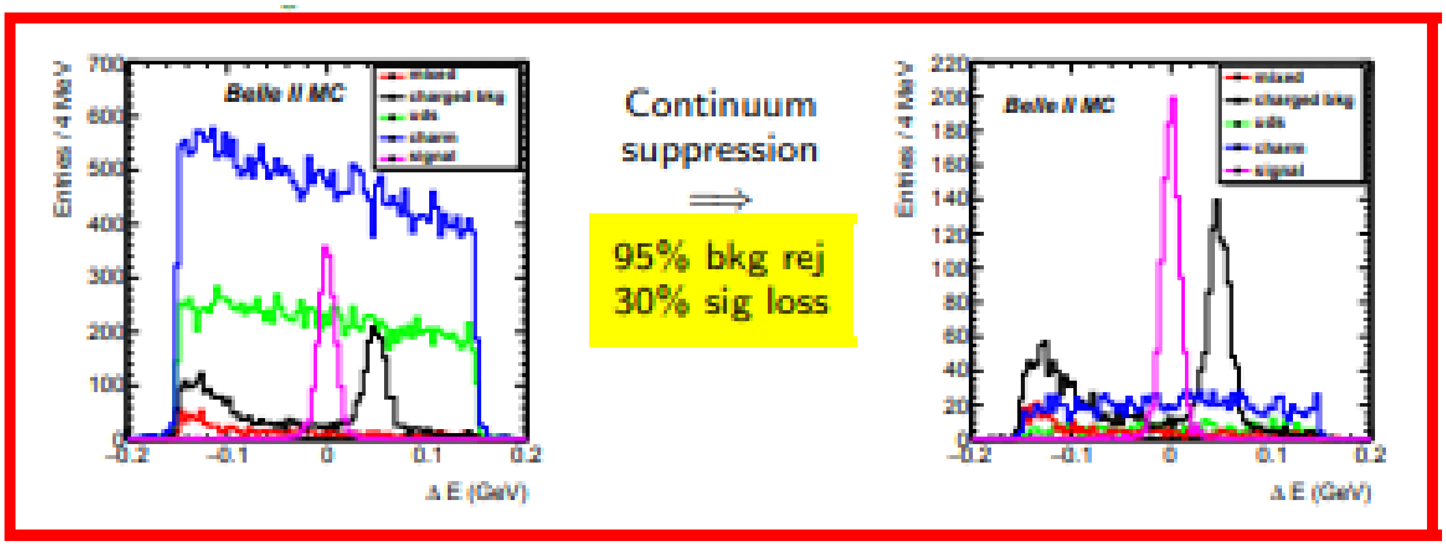
ϕ_3 at Belle II



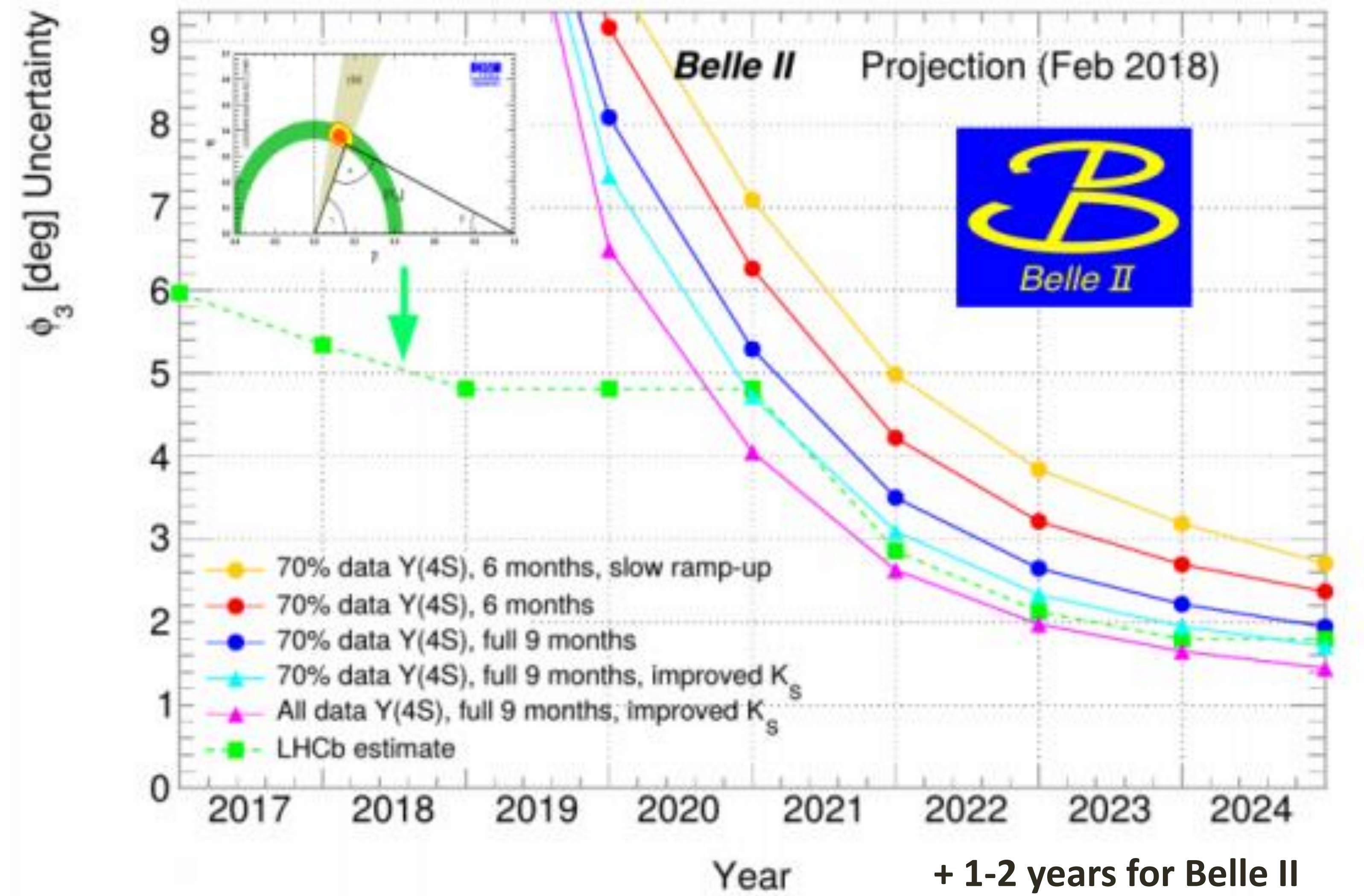
- GGSZ dominates the Belle average

$$\phi_3 = \left(73^{+13}_{-15}\right)^\circ$$

- Will continue to do so at Belle II
- PID and continuum suppression key



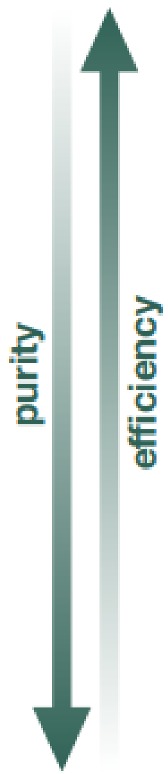
ϕ_3 at Belle II

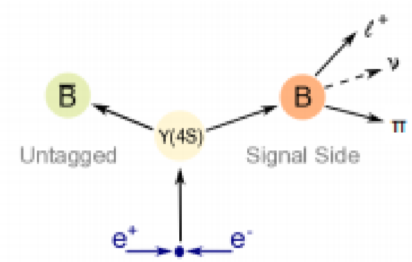


+ 1-2 years for Belle II

BELLE II PROSPECTS: V_{xb}

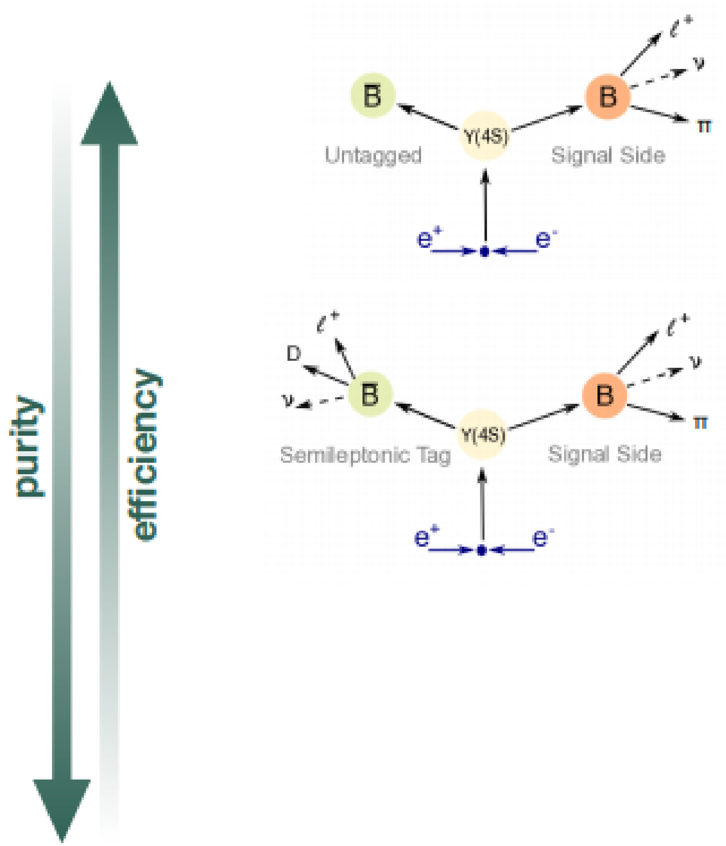
V_{xb}





- Untagged
  - Loose constraints on signal
  - Very large statistics, but also very large background
  - Efficiency $\epsilon \approx \mathcal{O}(100\%)$

V_{xb}



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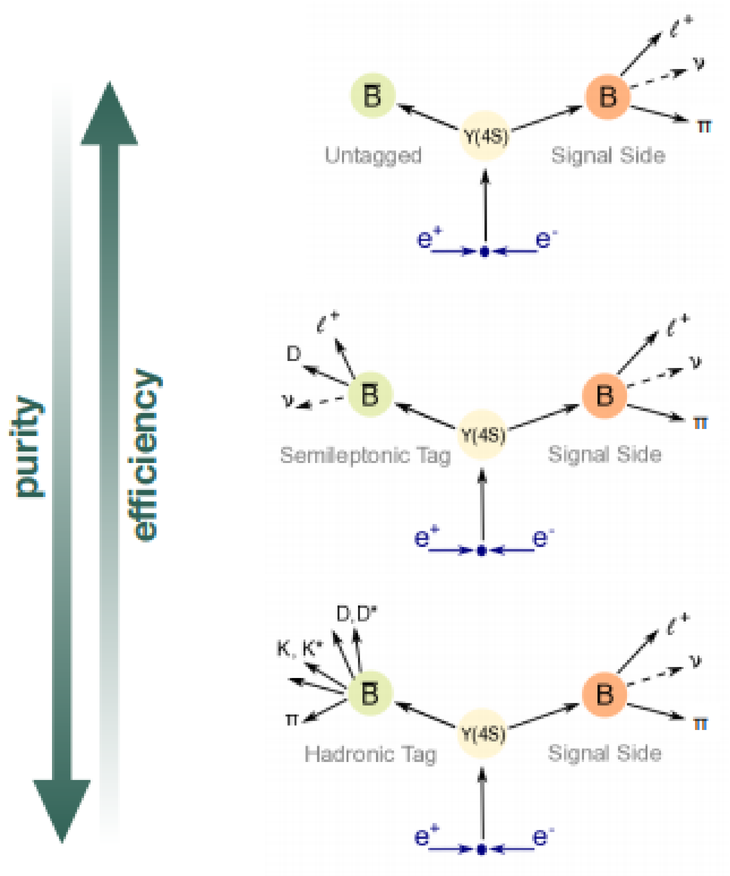
- Semileptonic tag
  - Mid-range reconstruction efficiency $\epsilon \approx \mathcal{O}(1\%)$
  - Due to multiple neutrinos, less information about B_{tag}

V_{xb}



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- Semileptonic tag
  - Mid-range reconstruction efficiency $\epsilon \approx \mathcal{O}(1\%)$
  - Due to multiple neutrinos, less information about B_{tag}

- Hadronic tag
  - Cleaner sample
  - Knowledge of $p(B_{sig})$
  - Low tag-side efficiency $\epsilon \approx \mathcal{O}(0.1\%)$

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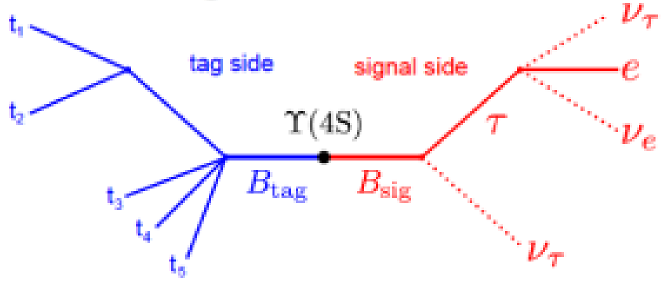
V_{xb}

New Full Event Interpretation (FEI) algorithm for tag-side reconstruction



- > 5000 B decays modes reconstructed
- O(200) particle decay channels for training
- Output is candidate-wise **signal probability**

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V_{xb}

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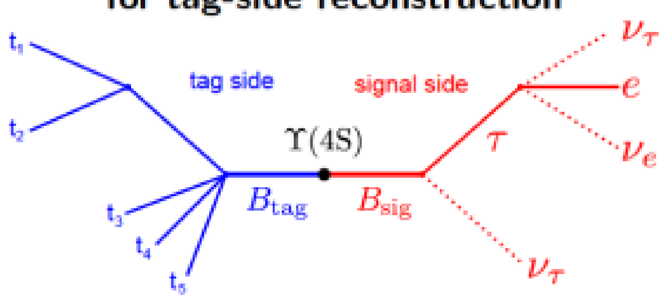

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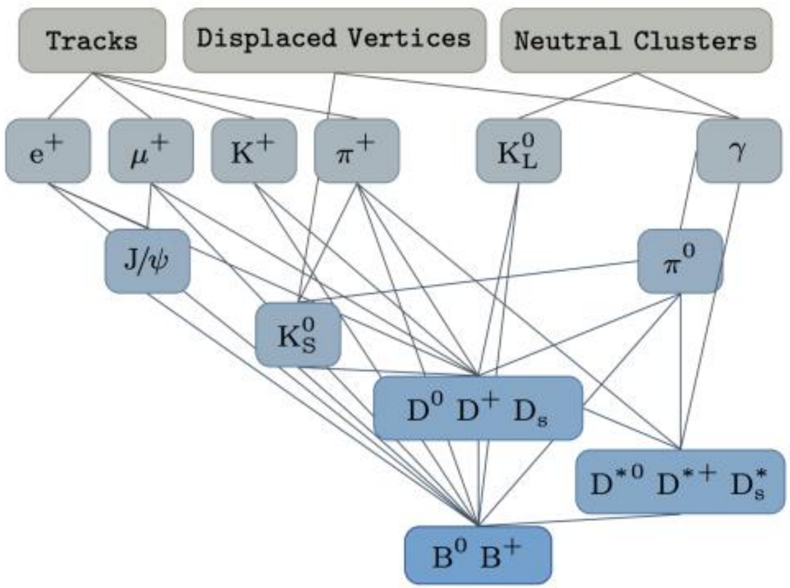

T.Keck, et al. Comput Softw. Big Sci (2019) 3: 6

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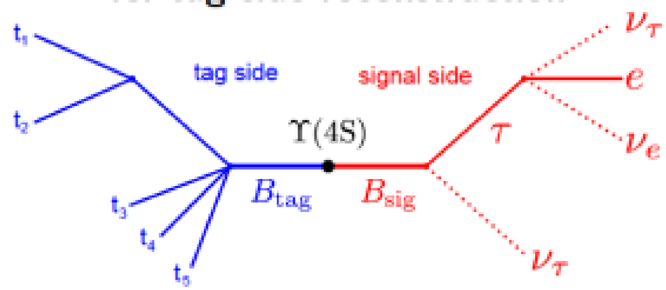

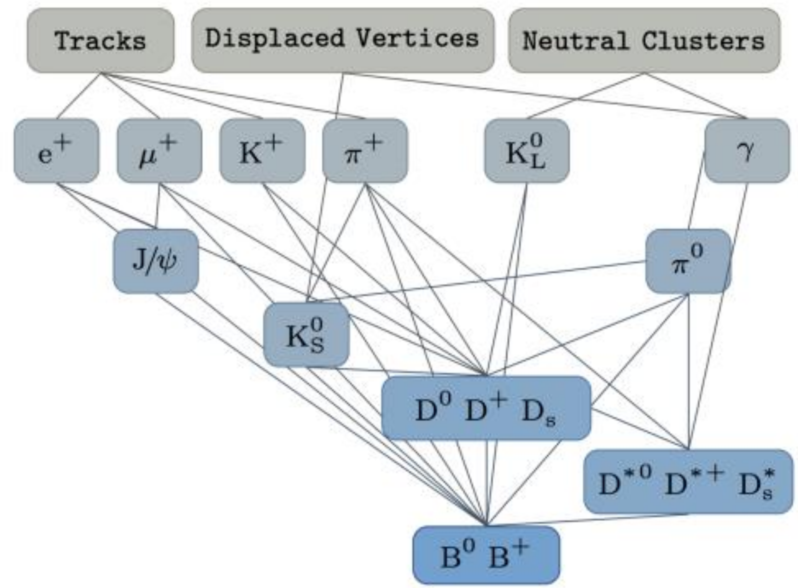

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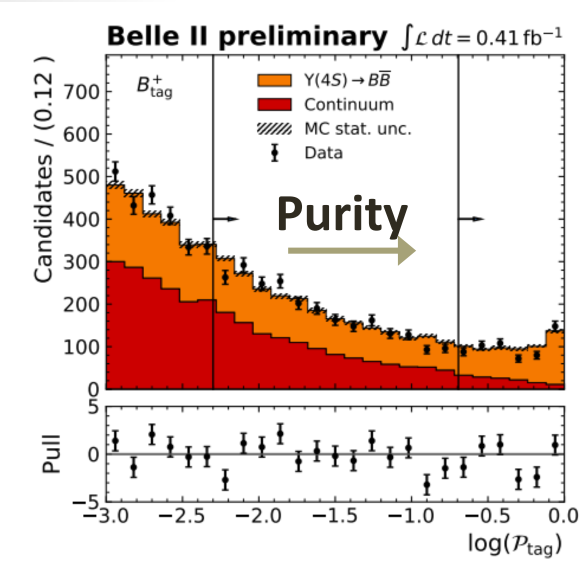
Tagging ε on MC

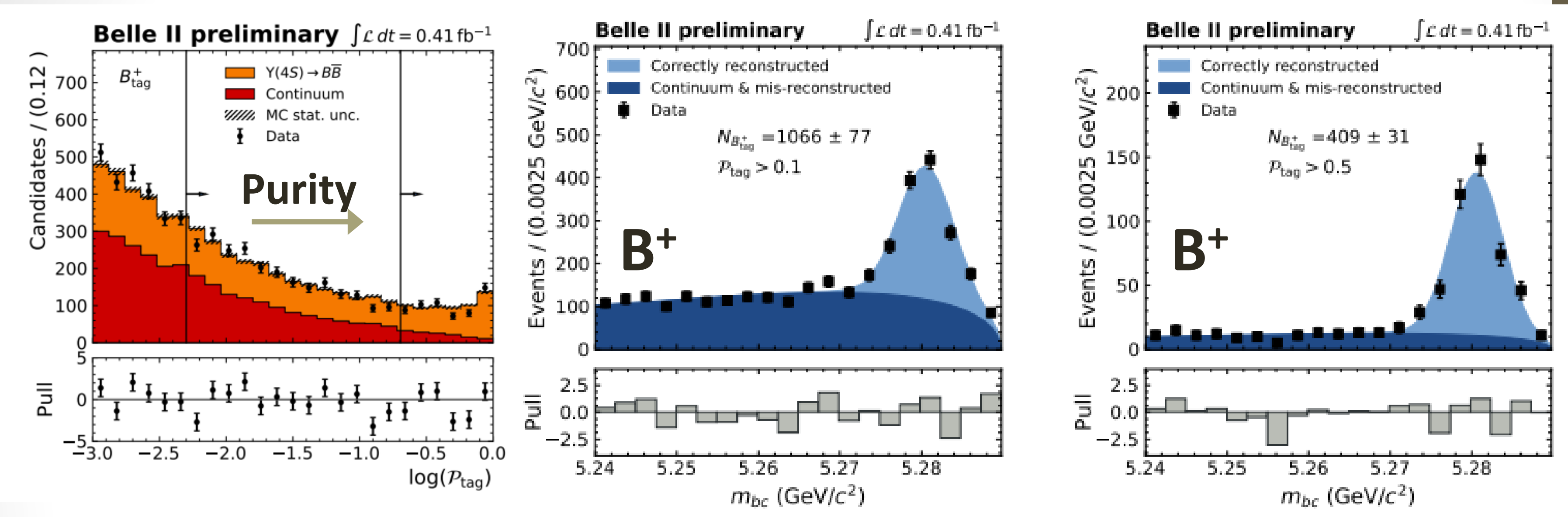
Tag	FR[1]	FEI Belle	FEI Belle II
Hadronic B^+	0.28%	0.76%	0.66%
SL B^+	0.67%	1.80%	1.45%
Hadronic B^0	0.18%	0.46%	0.38%
SL B^0	0.63%	2.04%	1.94%

[1] Belle Full Reconstruction algorithm.

FEI results in 2019



FEI results in 2019



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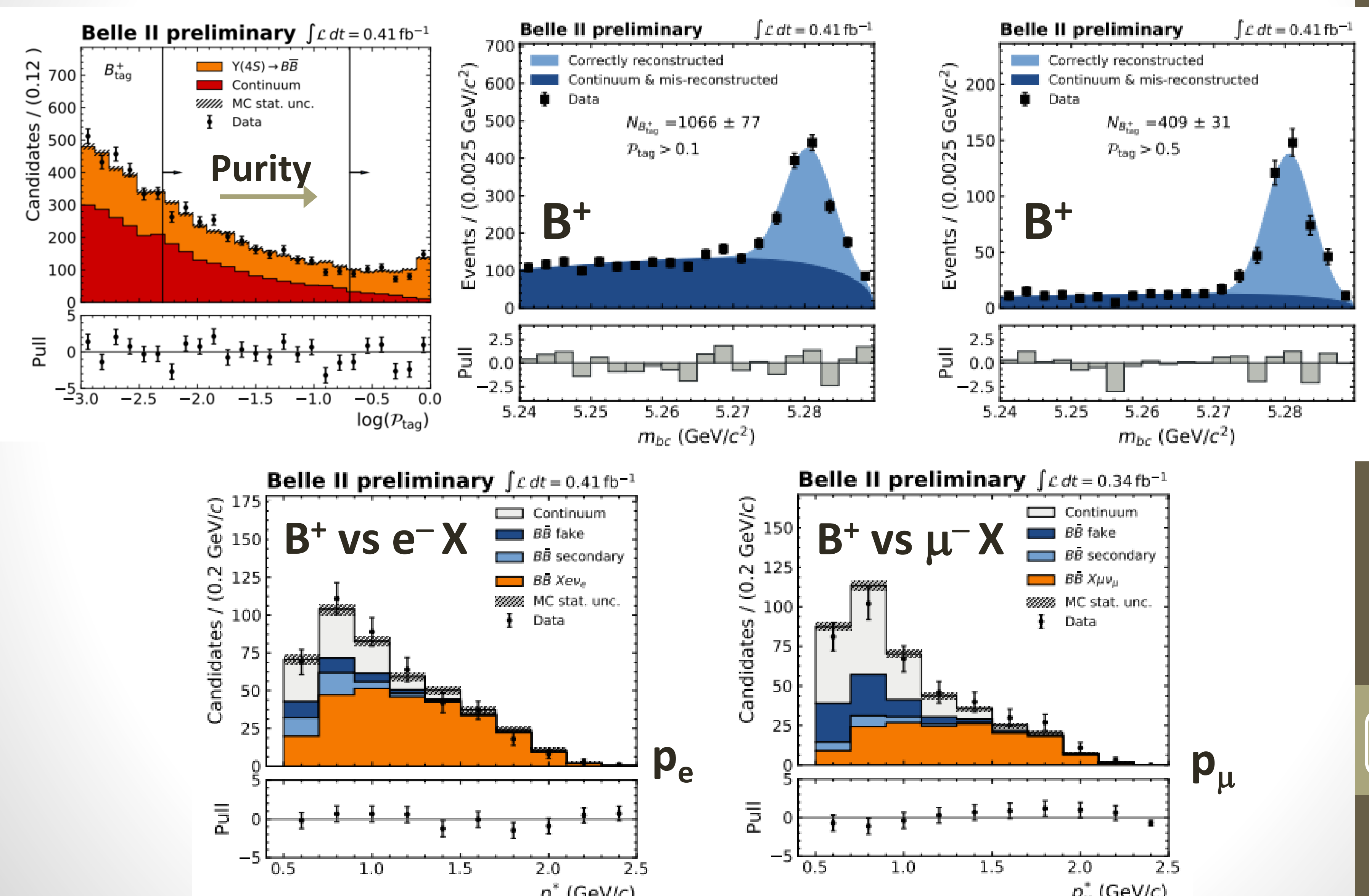

V_{xb}

Assume theory LQCD uncertainty improves

Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\lvert V_{cb}\rvert$ incl.	$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$	1.2%	–
$\lvert V_{cb}\rvert$ excl.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\text{ex.}} \pm 1.4\%_{\text{th.}})$	1.8%	1.4%
$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$	3.4%	3.0%
$\lvert V_{ub}\rvert$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\text{ex.}} \pm 3.0\%_{\text{th.}})$	2.4%	1.2%
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$91 \cdot (1 \pm 24\%)$	9%	4%
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	20%	7%

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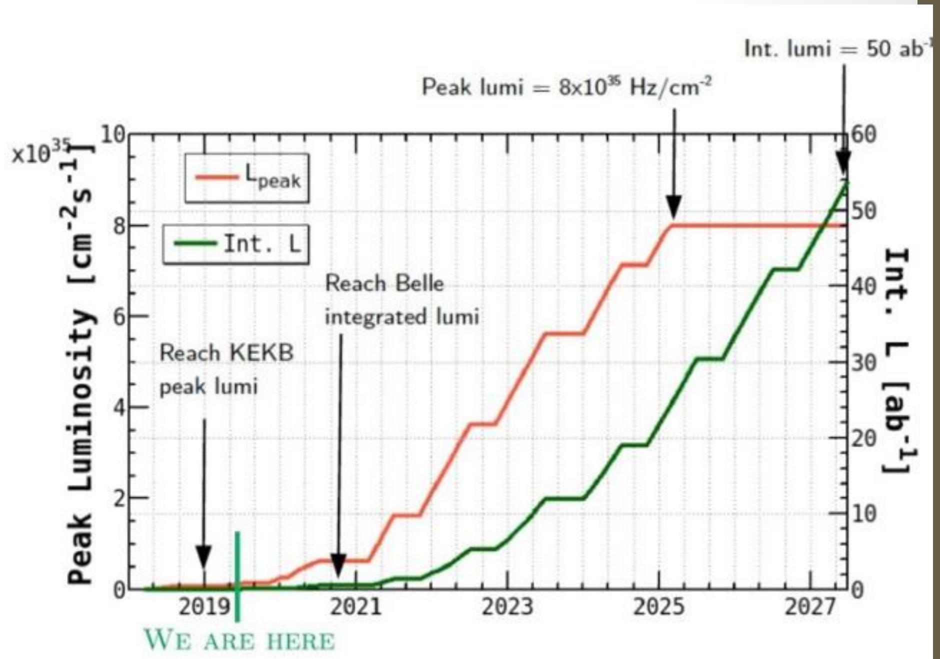
Aside from the overall constraint on the Unitarity Triangle these measurements will go some way to understand the long-standing tension between inclusive and exclusive measurements

Conclusion

- Belle II has begun but there is a long way to go to 50 ab^{-1}



Conclusion

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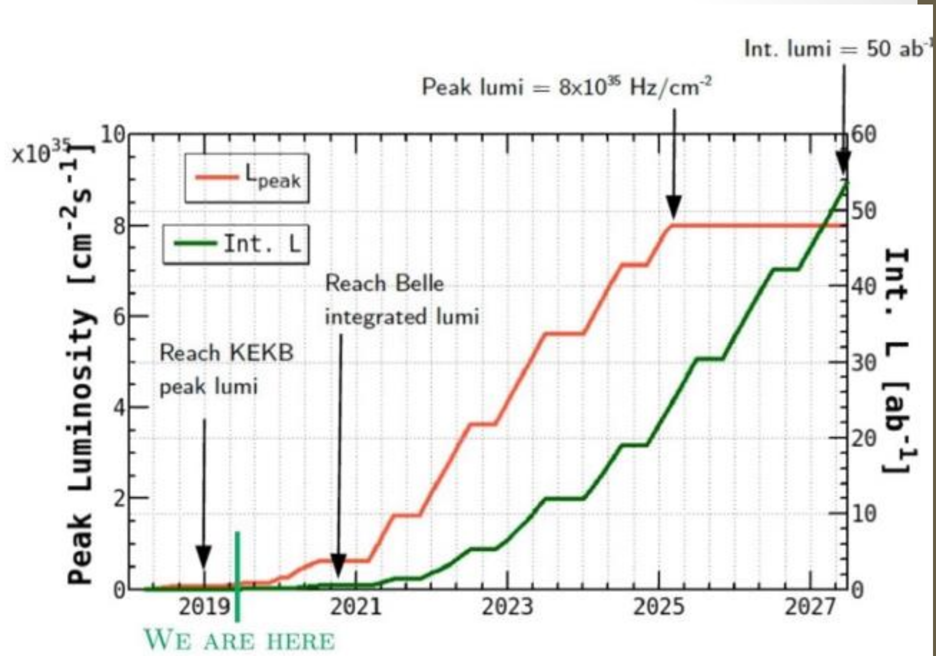
- Precise measurements of ϕ_1, ϕ_3 and V_{xb} will be made with sample
- Many interesting results to appear prior to that, once the Belle luminosity is crossed



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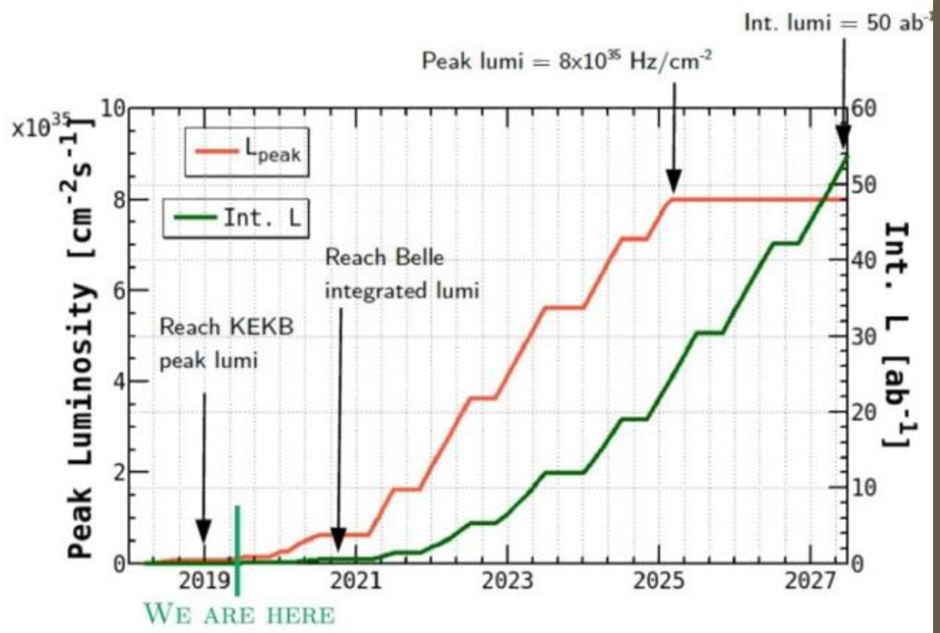
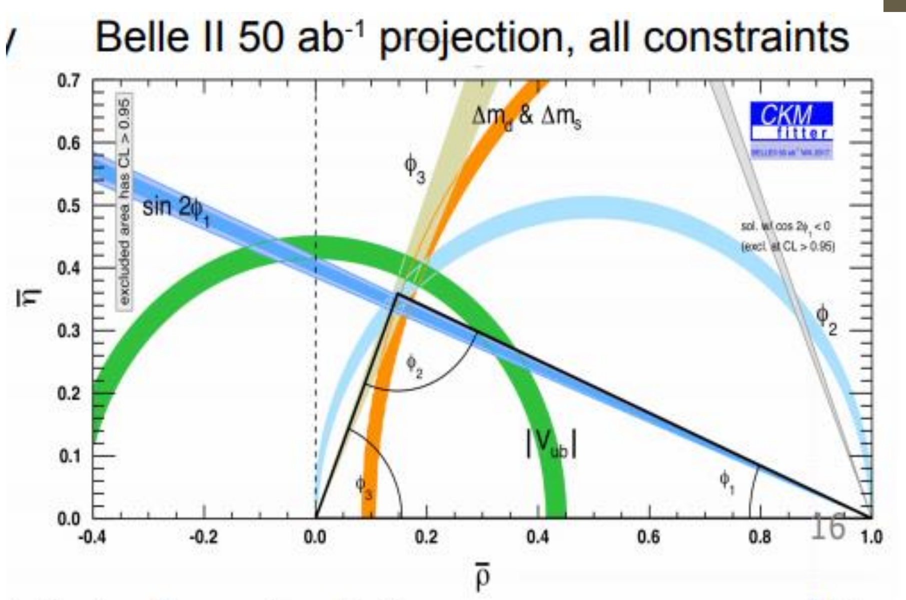
- What will the UT look like in 2027……

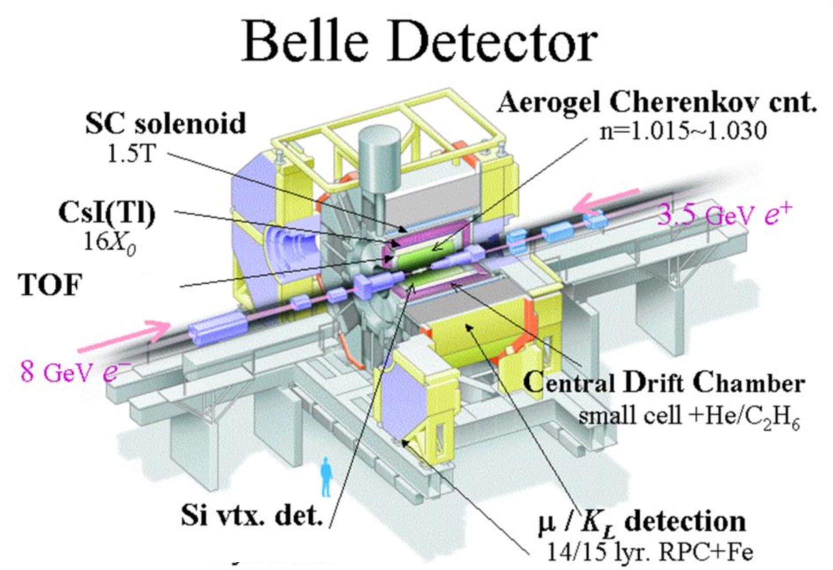


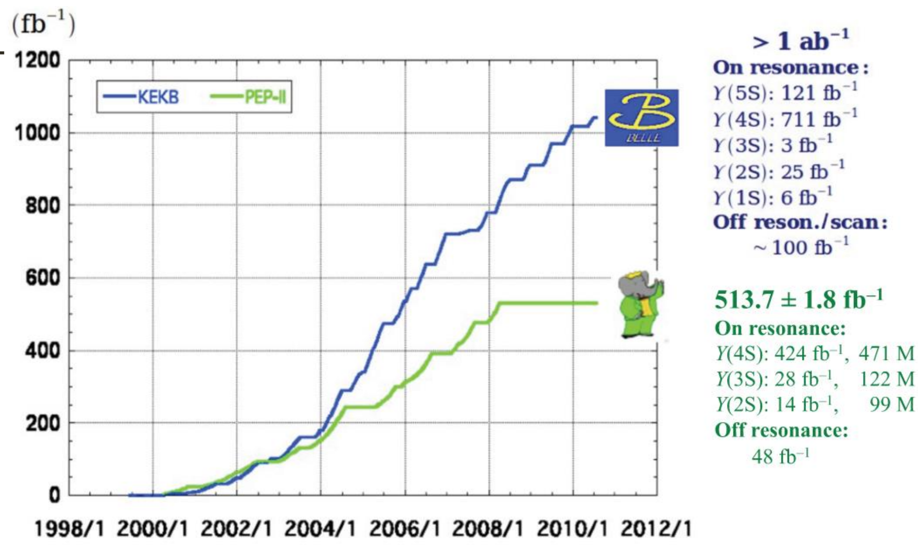


BACKUP

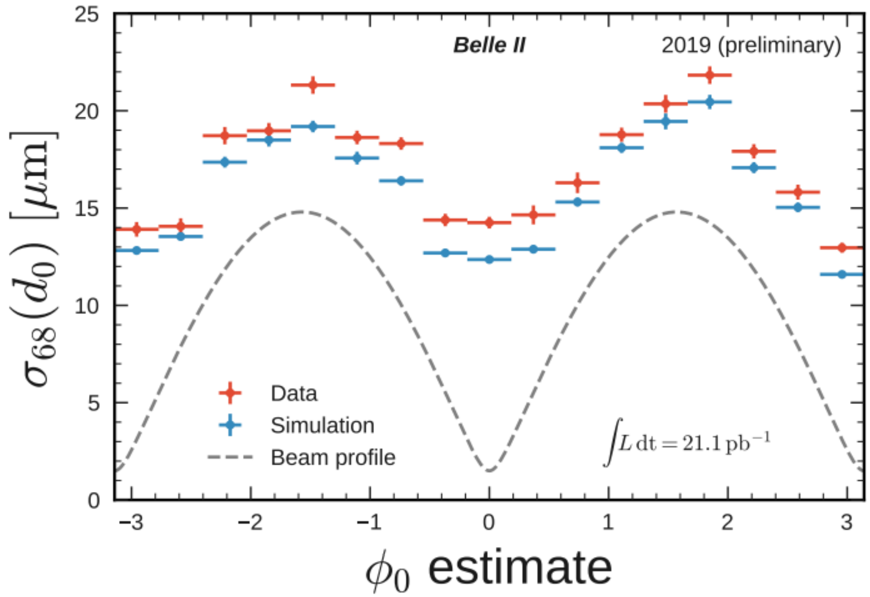
Belle

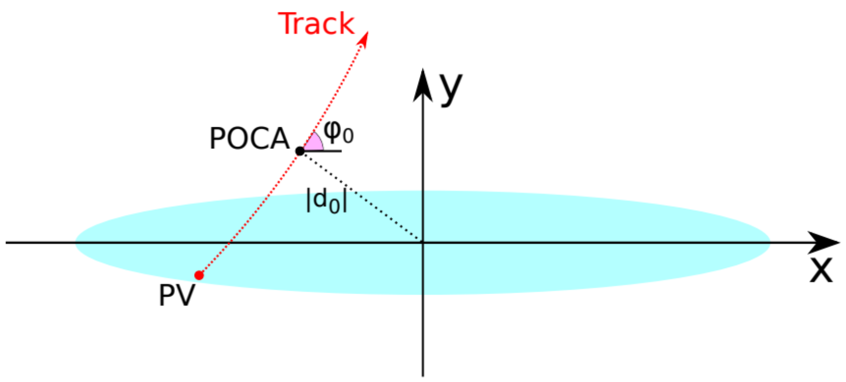
- Operation from 1999 to 2010
- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for CKM measurements
- Asymmetric energy to allow time-dependent measurements
- Coherent production of $B^0\overline{B^0}$
- Low multiplicity
- Detectors with good tracking, PID and calorimetry
  - plus hermeticity for full event reconstruction/tagging





Tracking performance - 2019





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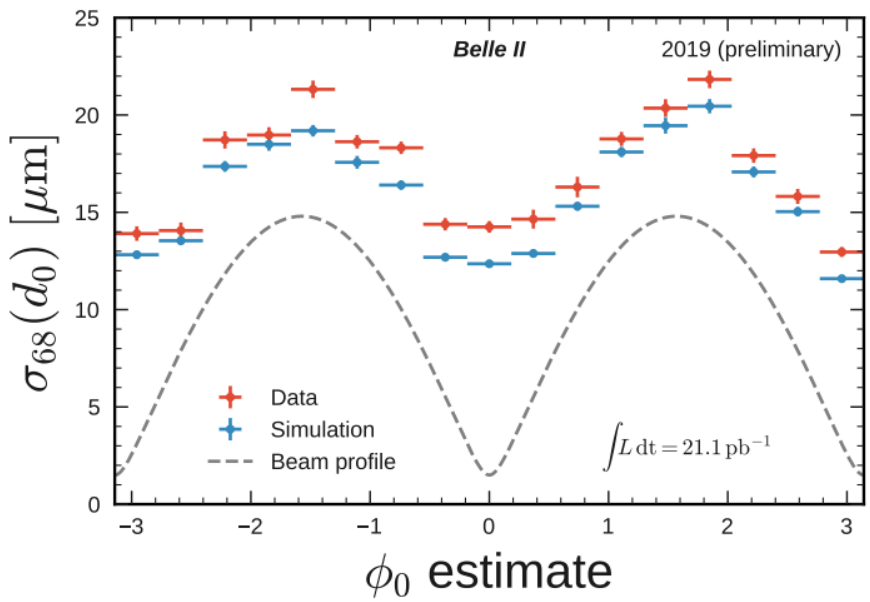

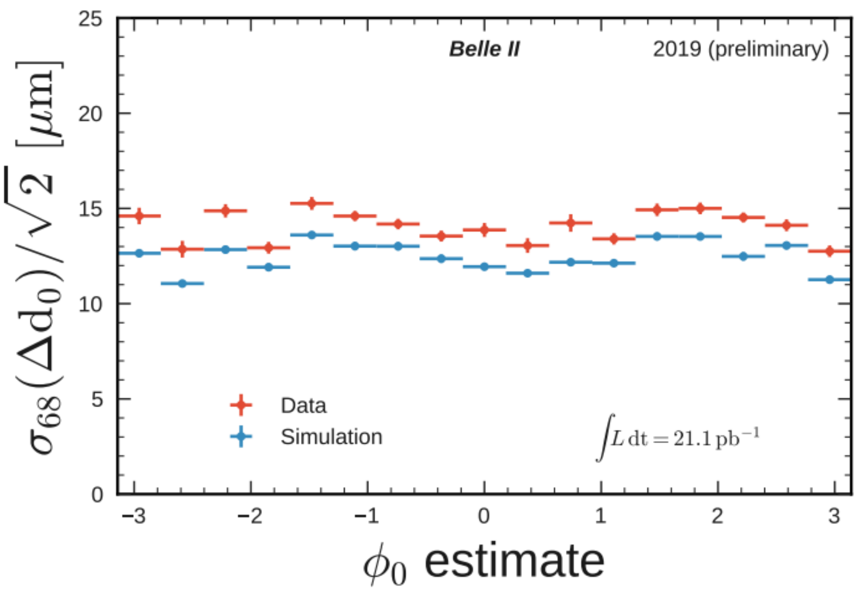

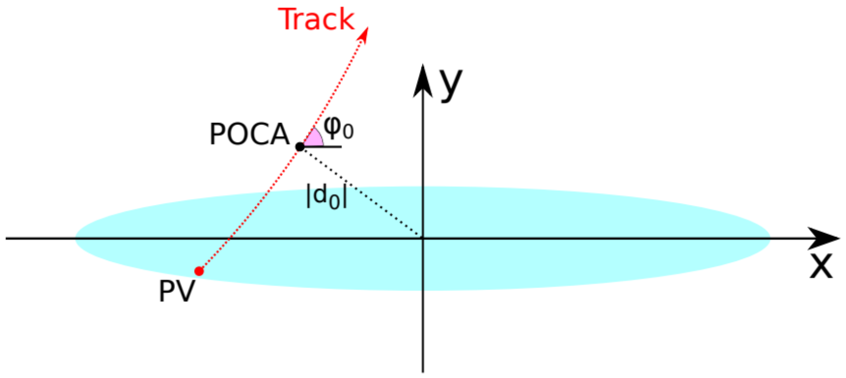

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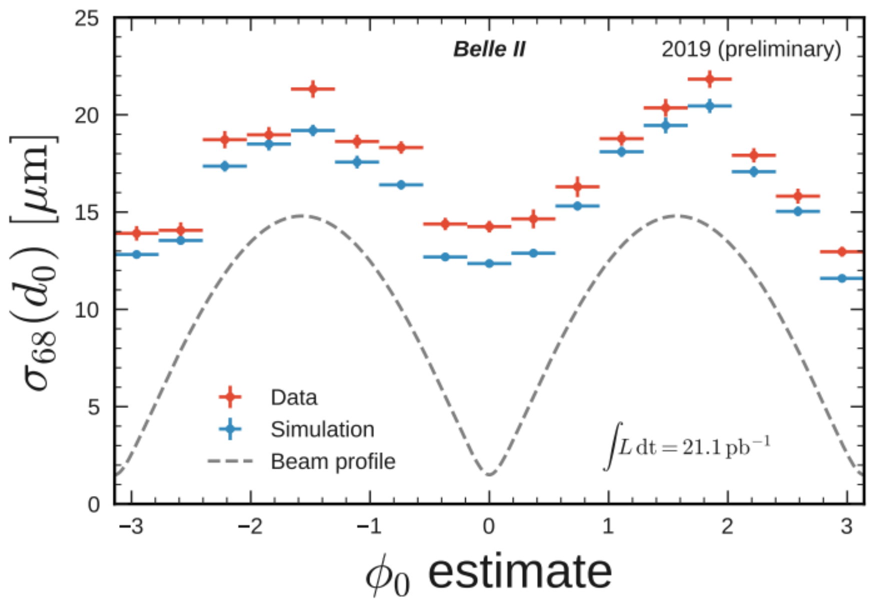

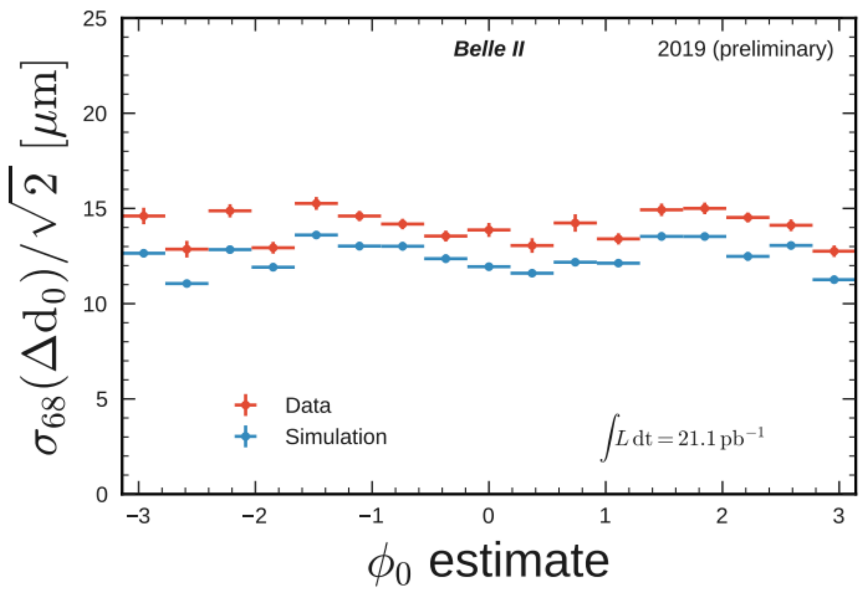

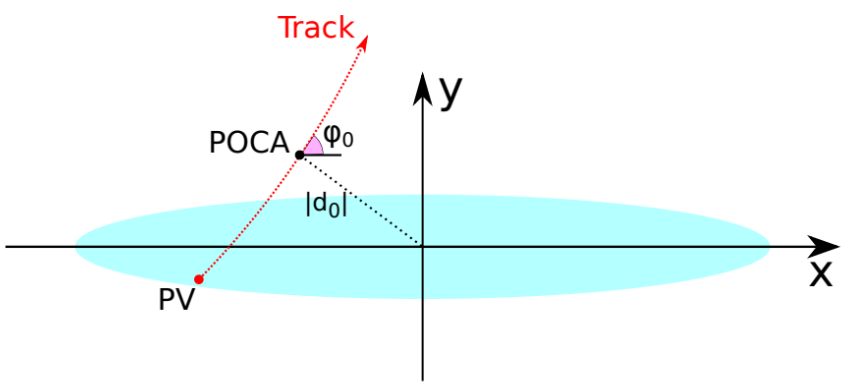

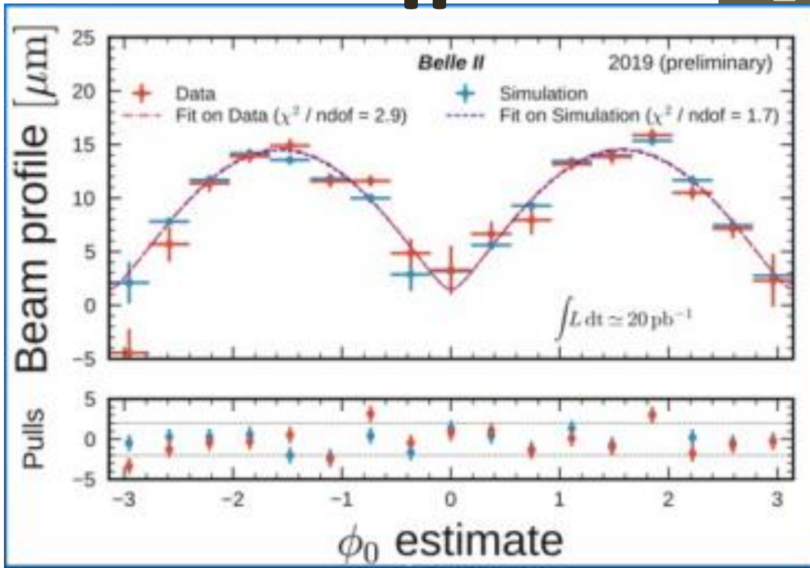

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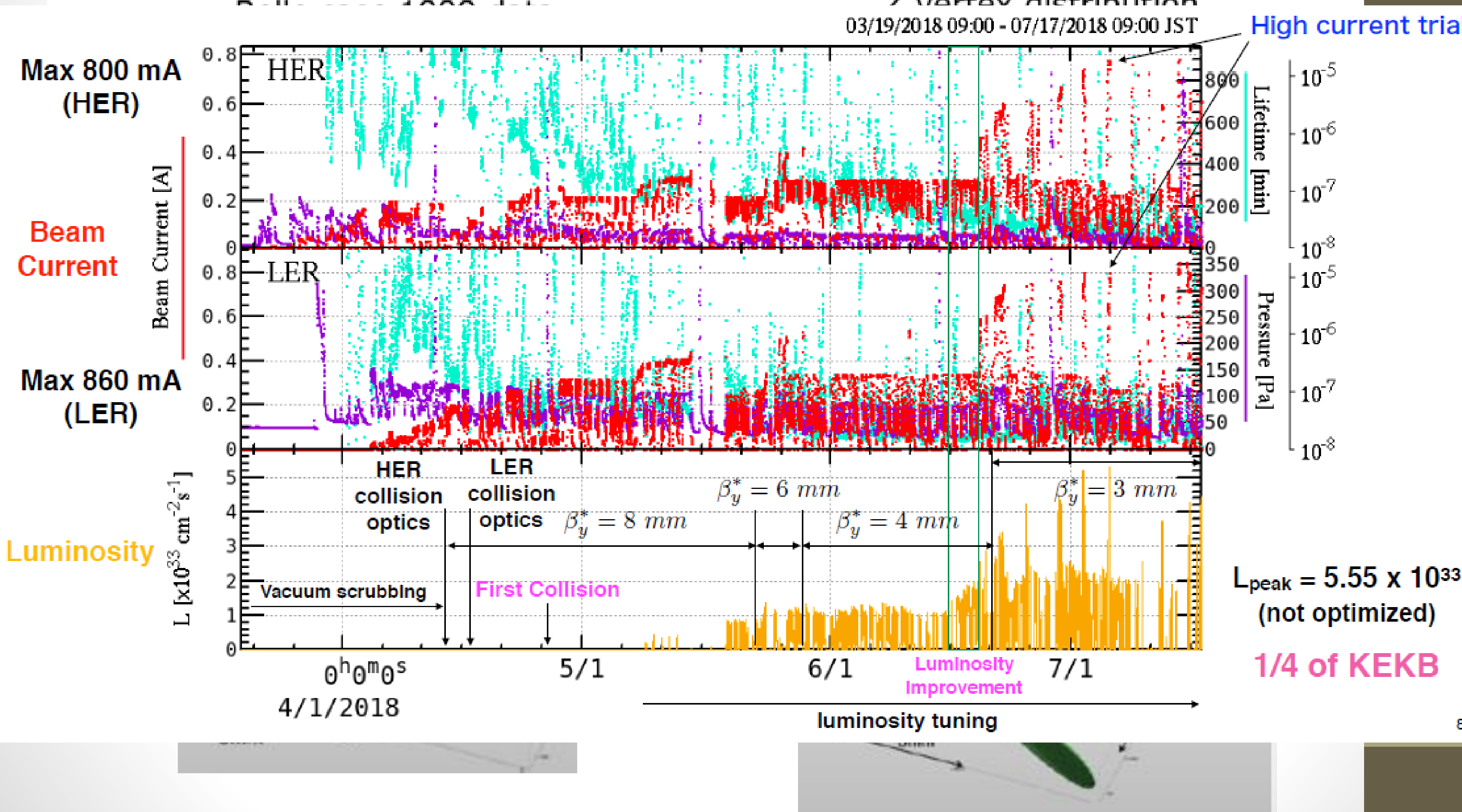
Super KEKB performance



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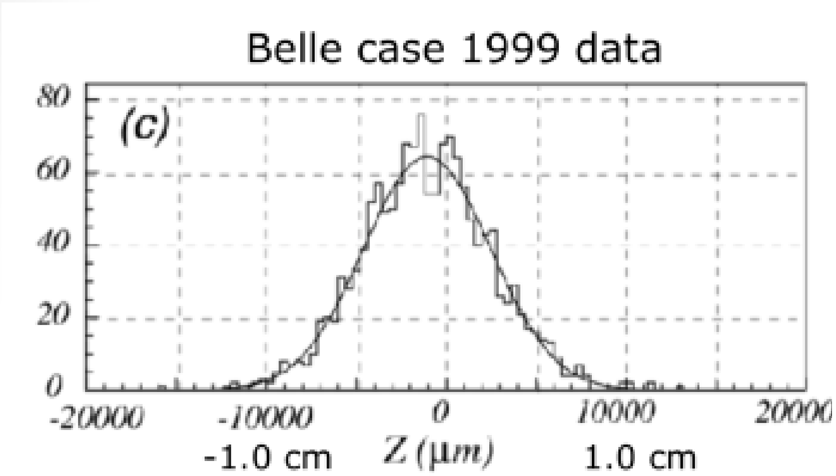
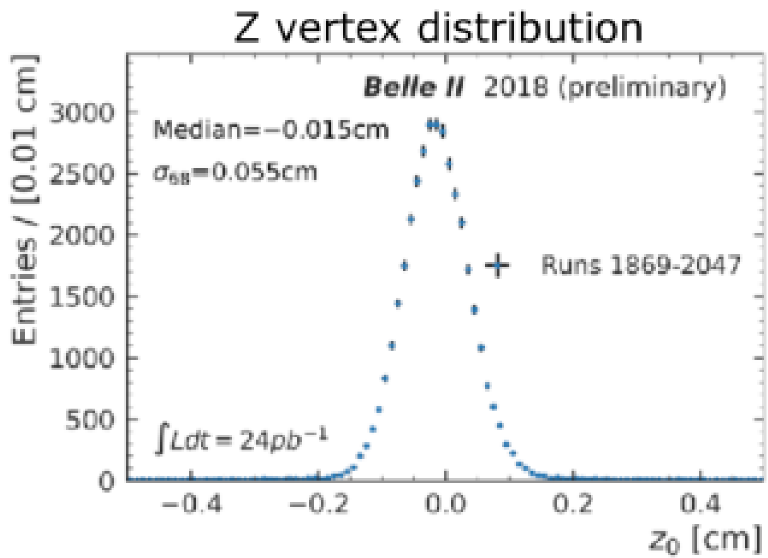
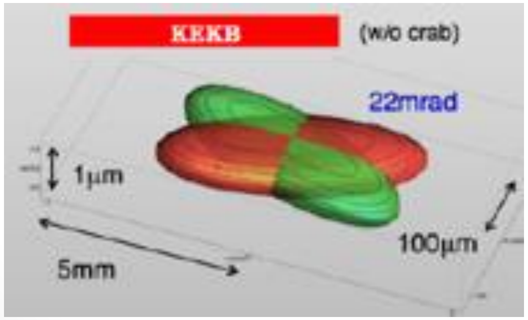


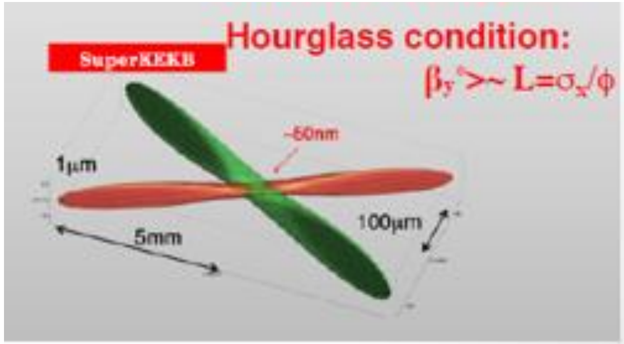


σ = 4.5 mm

σ = 550 μm

measurement at Belle II





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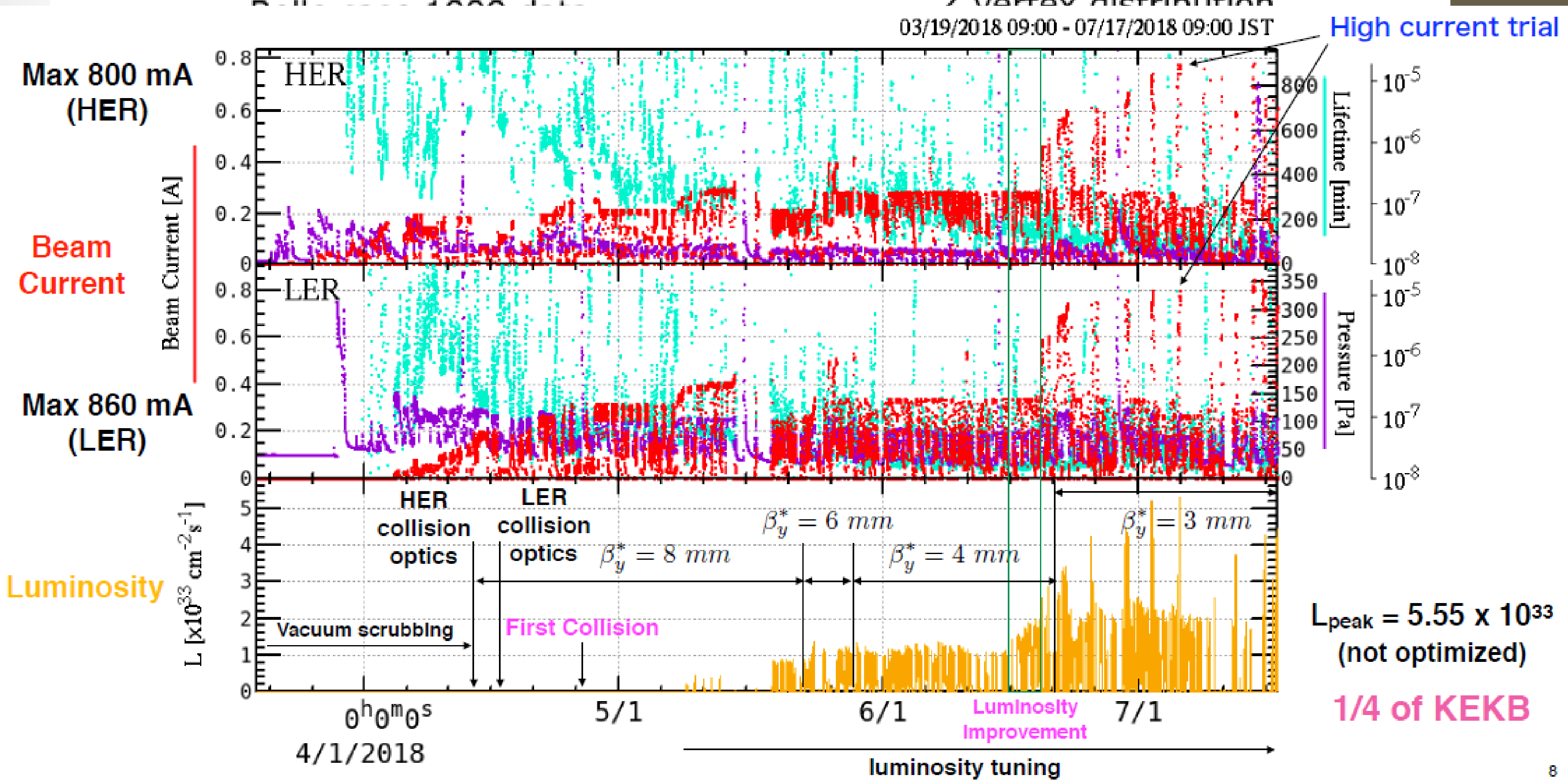

$L_{peak} = 5.55 \times 10^{33}$ (not optimized)

1/4 of KEKB