Les Rencontres de Physique de la Vallée d'Aoste
La Thuile, Aosta Valley, Italy
March 10 -16, 2019

THE BELLE II EXPERIMENT: STATUS AND PROSPECTS

CLAUDIA CECCHI

UNIVERSITA' DI PERUGIA & INFN-PG

FLAVOR PHYSICS: A STORY OF SUCCESS

DISCOVERY OF FLAVOR EXPERIMENTS

CPV in K^0 system discovered in 1964 → CKM mechanism and 3rd quark generation

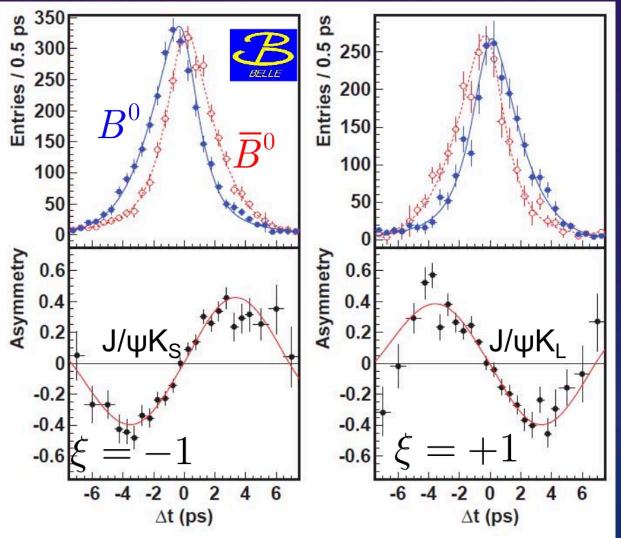
Neutral kaon oscillation predicted in 1955 and established in 1960 and only in 1987 observed in B^0 system → charm and top quark masses

K^0_L → $\mu^+\mu^-$ suppression → GIM

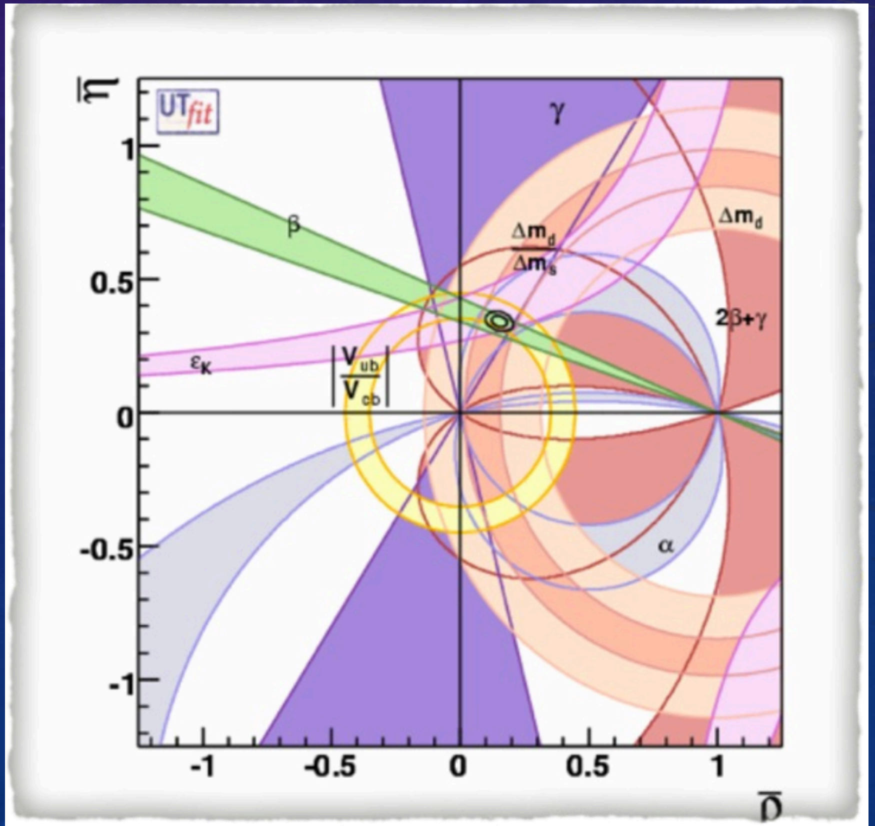
V_{ud}	β-decay	$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$	$\cos\vartheta_C$
V_{us}	K-decay	$K^+ \to \pi^0 + \ell^+ + \nu_\ell$ $K^0 \to \pi^- + \ell^+ + \nu_\ell$	$\sin\vartheta_C$
V_{cd}	ν-production of c's	$\nu_\ell + d \to \ell^- + c$	$\cos\vartheta_C$
V_{cs}		$D^\pm \to K^0 + \ell^\pm + \nu_\ell$	$\sin\vartheta_C$
V_{ub}	B-decay	$b \to u + \ell^- + \bar{\nu}_\ell$	
V_{cb}		$b \to c + \ell^- + \bar{\nu}_\ell$	
V_{td}	Δm in B^0-$\bar{B}^0$		

$B^0_d \to J/\Psi K_S$	$\sin 2\beta$
$B^0_d \to \pi^+\pi^-$	$\sin 2\alpha$
$B^0_s \to D_s^\pm K^\mp$	$\sin 2\gamma$

PRECISION MEASURMENTS OF CKM ELEMENTS

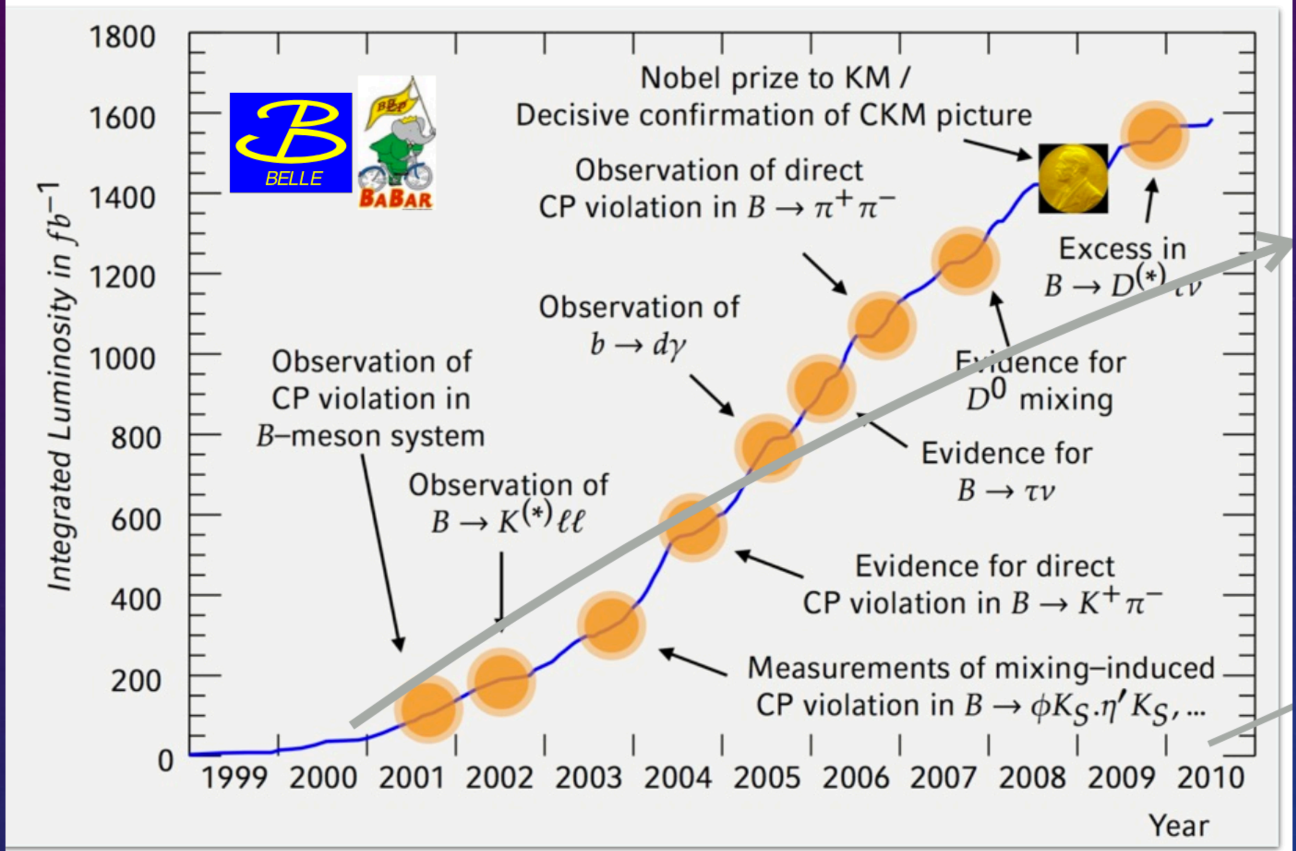


$\sin 2\varphi_1 = 0.667 \pm 0.023 \pm 0.012$
$A_f = 0.006 \pm 0.016 \pm 0.012$
PRL108,171802 (2012)



B FACTORIES AND THE INTENSITY FRONTIER

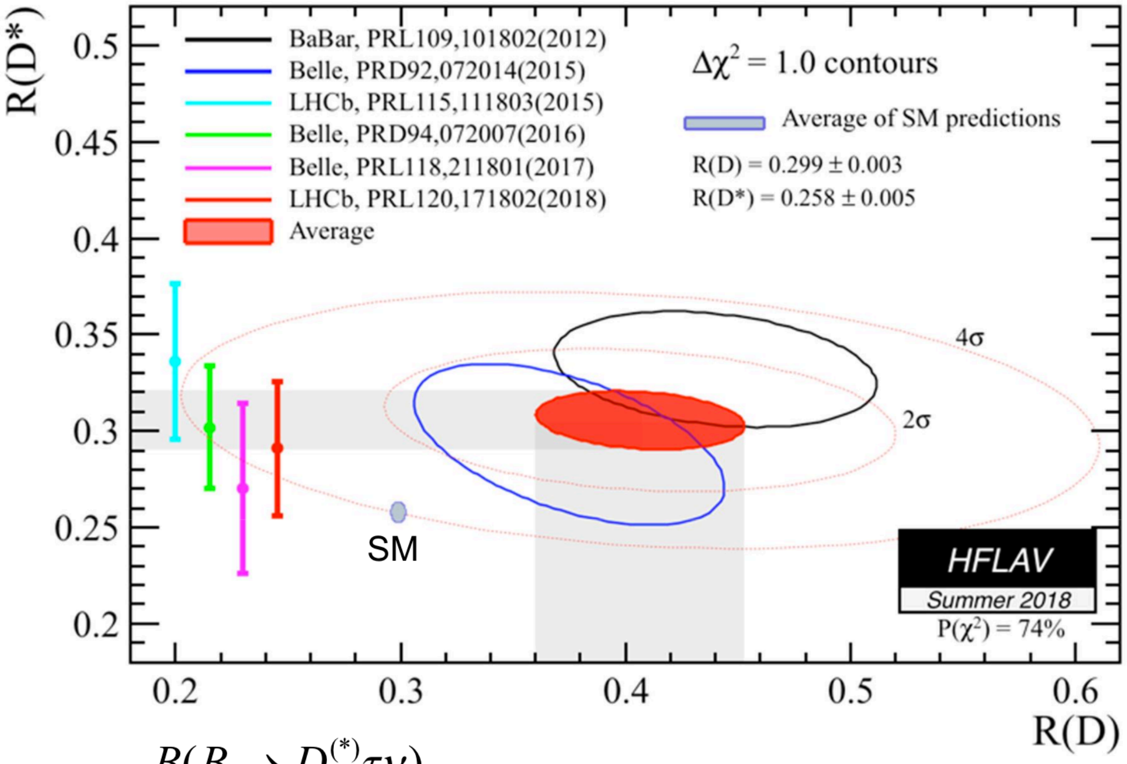
BaBar (PEPII@SLAC) and **Belle** (KEKB@KEK)



Physics of the B Factories
Ed. A.J. Bevan, B. Golob, Th. Mannel, S. Prell, and B.D. Yabsley,
Eur. Phys. J. C74 (2014) 3026,
arXiv:1406.6311 [hep-ex]

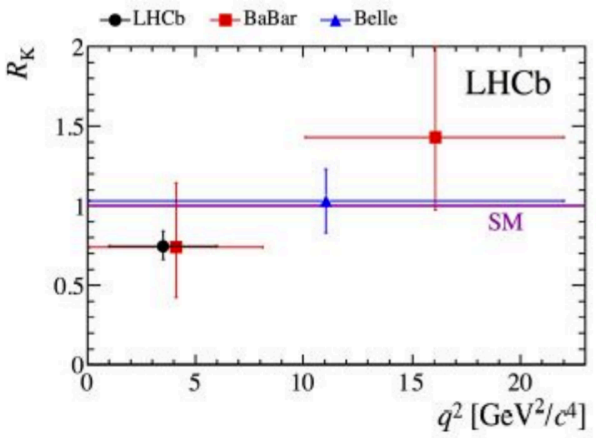
OPEN QUESTIONS

Summer 2018 ICHEP:
World Average is still ~4σ from the Standard Model

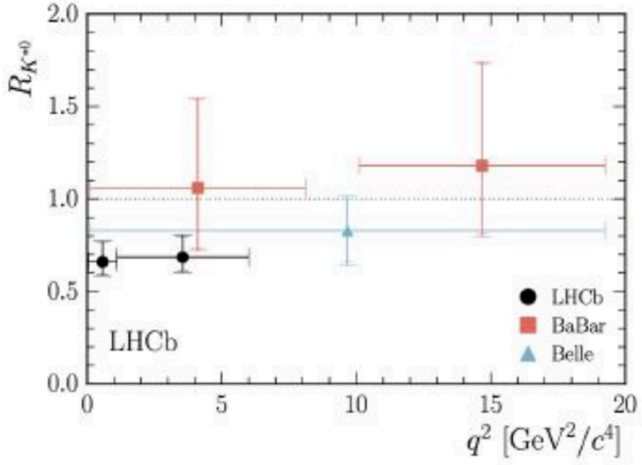


$$R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}l\nu)}$$

l = μ, e LHCB only μ



R_K is ~2.6σ from the SM

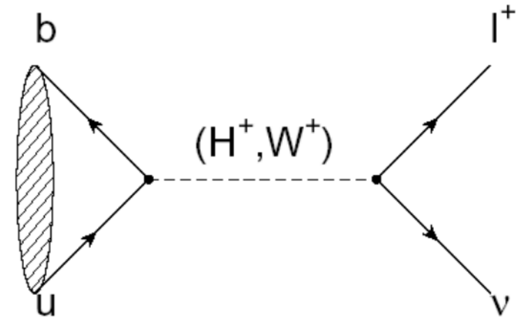


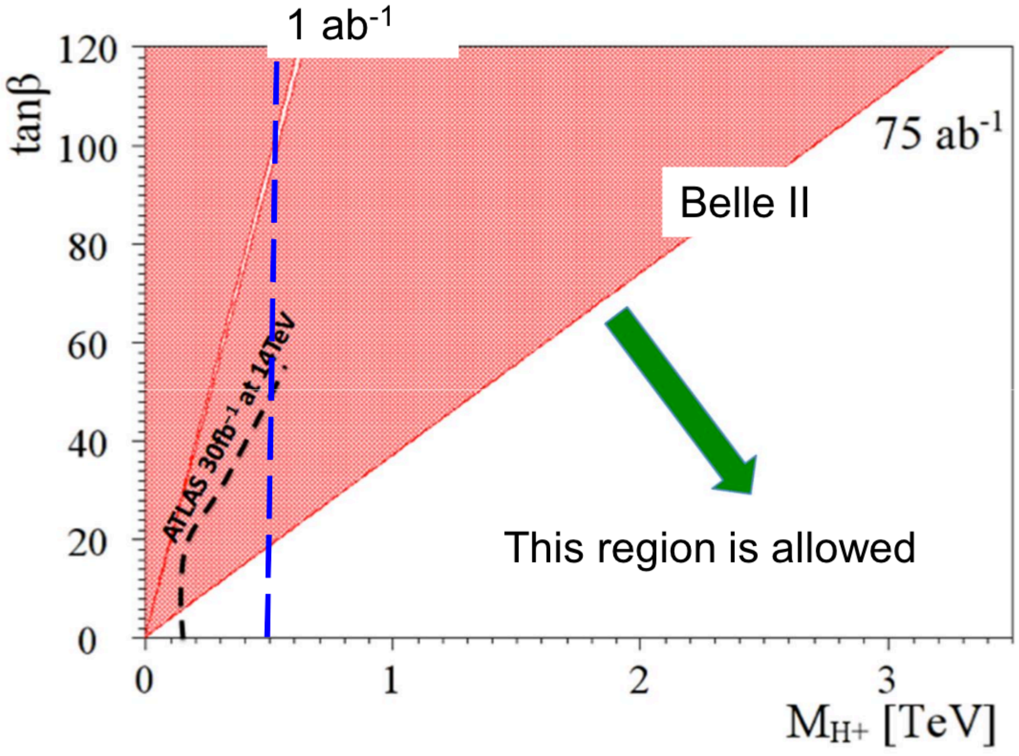
R_{K^*} ~2.1σ (low bin), 2.5σ (central bin)

$$R_{K^{(*)}}(q^2) = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}$$

COMPLEMENTARITY e+e- AND LHC

The current combined B→τυ limit places a stronger constraint than direct searches from LHC exps. for the next few years.





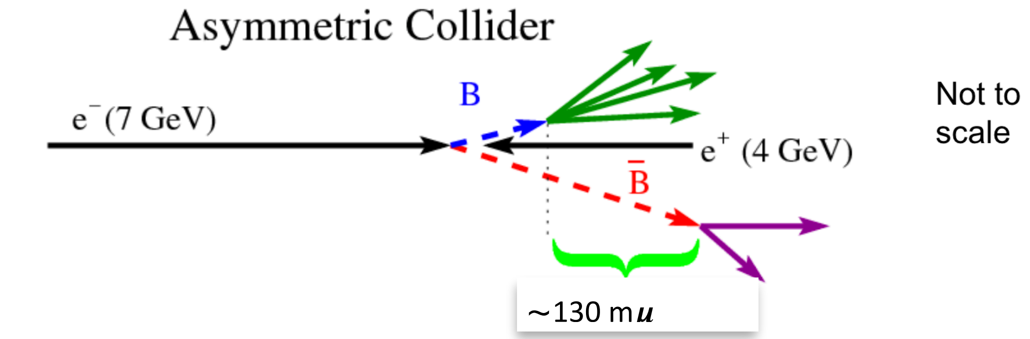
$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

Currently inclusive b→sγ rules out m_{H+} below ~480 GeV/c^2 range at 95% CL (independent of tanβ), M. Misiak et al. (assuming no other NP)

http://arxiv.org/abs/1503.01789

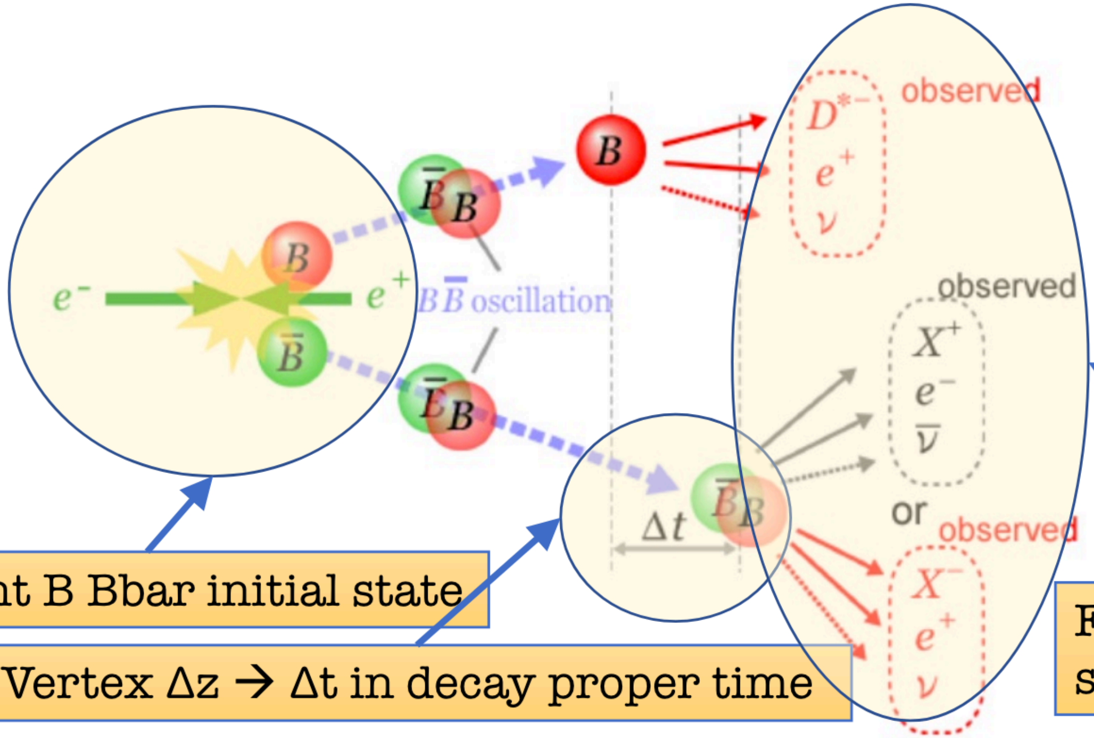
For more detail see a dedicated talk at this conference by D. Tonelli

WHAT IS THE GAME AT ASYMMETRIC e^+e^- FACTORIES



The beam energies are asymmetric (7 on 4 GeV)

The decay distance is increased by around a factor ~7



Coherent B Bbar initial state

Vertex $\Delta z \rightarrow \Delta t$ in decay proper time

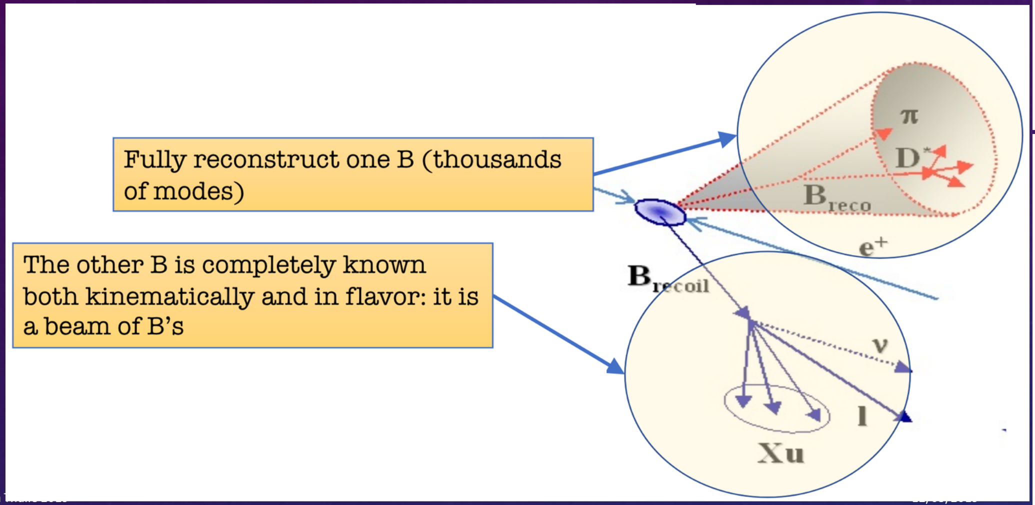
Final state can identify flavor, or select CP eigenstate

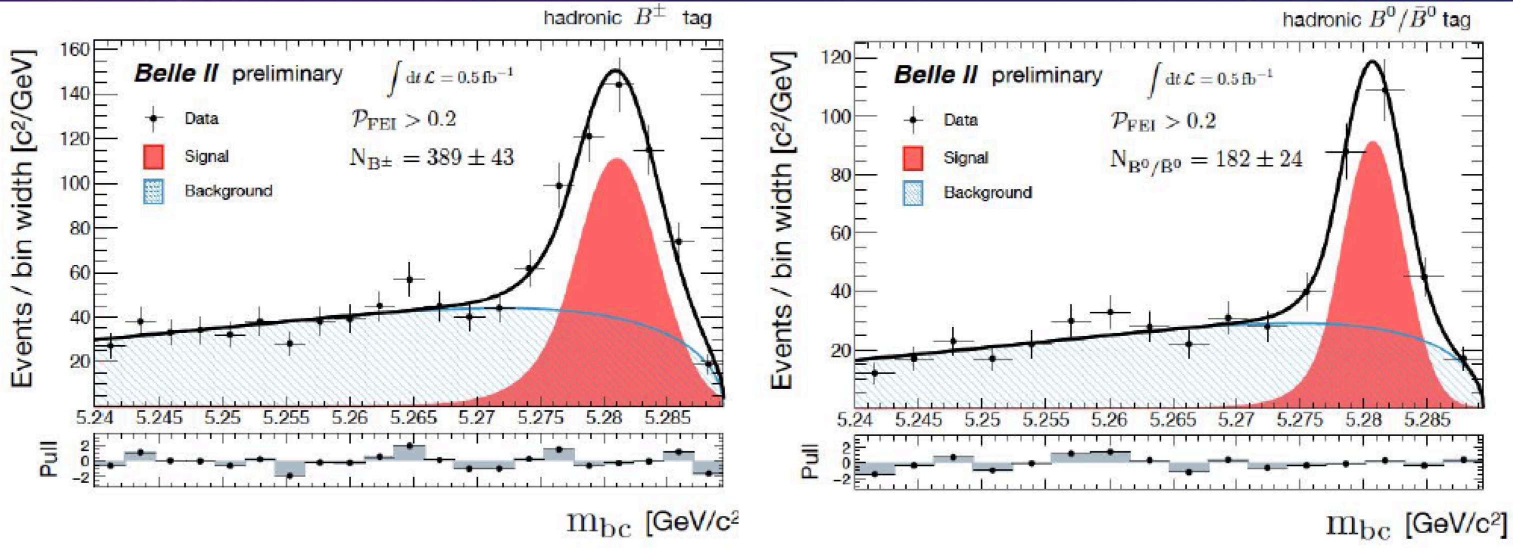
But also some difficulties:

- e^+e^- cross section about 1000 smaller than hadronic production
- Production of only B_d and B_u, B_s is possible at smaller rate, B_c unreachable

FULL EVENT INTERPRETATION

Now use the full Phase 2 pilot run dataset and apply the FEI (Full Event Interpretation) technique based on boosted decision trees (BDTs, a machine learning technique)





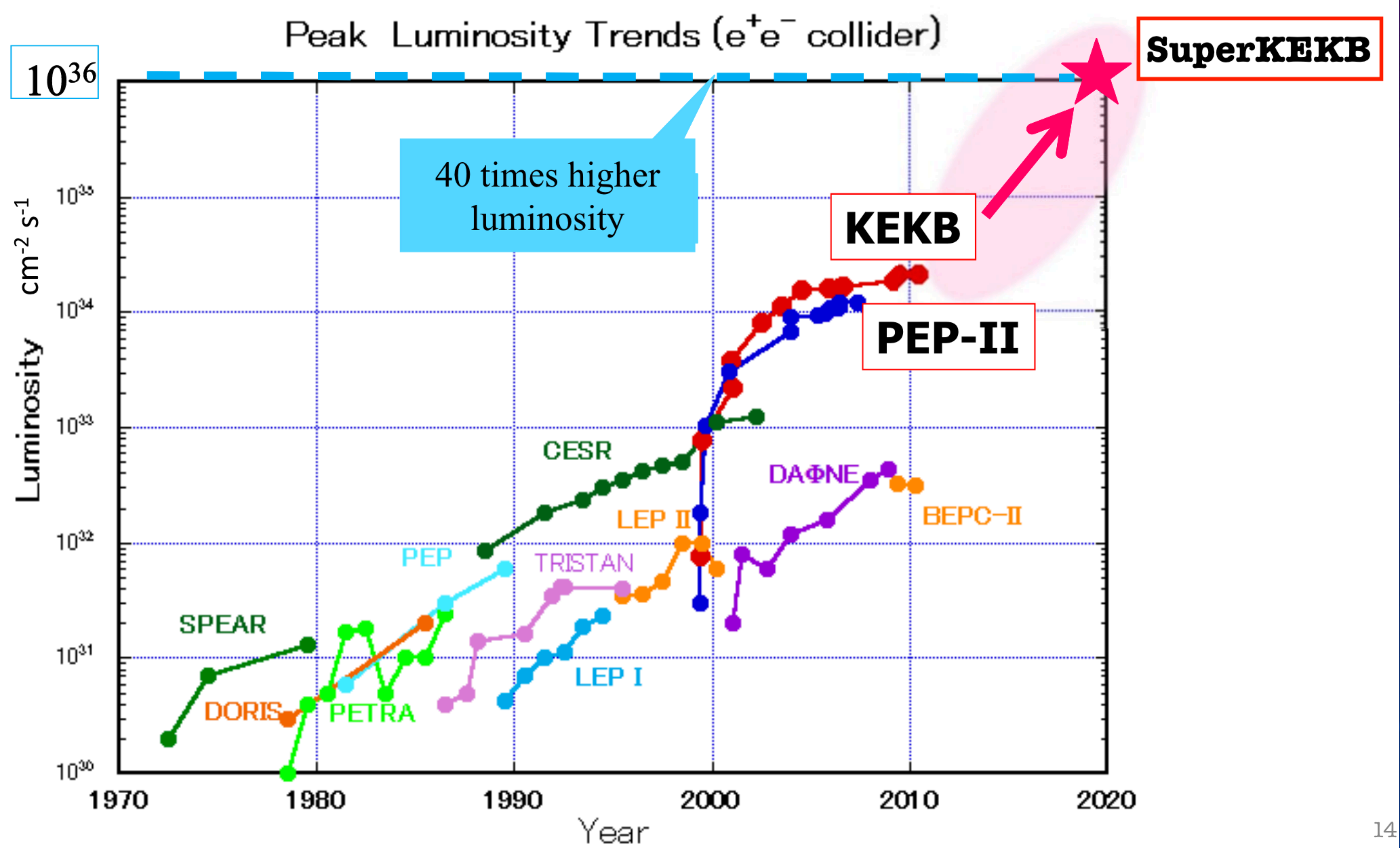
We now observe ~571 fully reconstructed B mesons (389+182) or an improvement of a factor of ~O(3.6) in overall efficiency by using this advanced analysis method that covers many more decay channels.

Belle II Notes: Approved plots

Plots for Full Event Interpretation Reconstruction Performance with 500 pb-1 of Phase II data

William Sutcliffe ; Florian Bernlochner

INTENSITY FRONTIER



NANO BEAM SCHEME TO INCREASE LUMINOSITY

Beam-beam parameter

Lorentz factor

Beam current

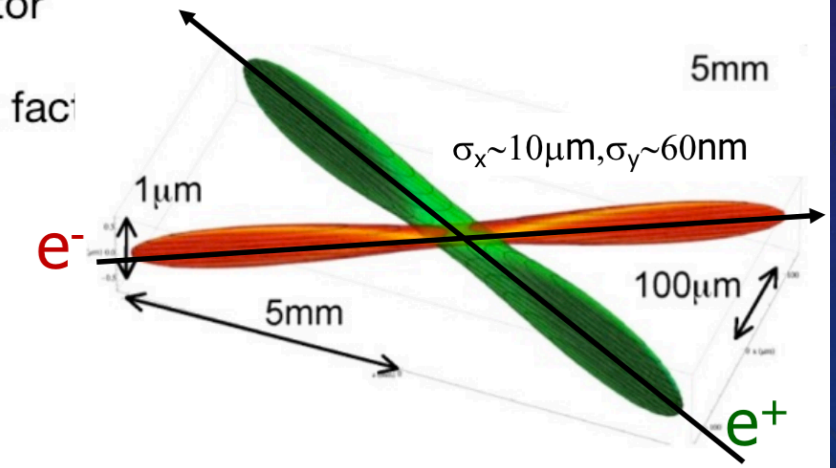
$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Classical electron radius

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

Vertical beta function@IP

Lumi. reduction factor (crossing angle)&
Tune shift reduction fac (hour glass effect)
0.8 - 1
(short bunch)



(1) Smaller β_y^*

(2) Increase beam currents

(3) Increase ξ_y

"Nano-Beam" scheme

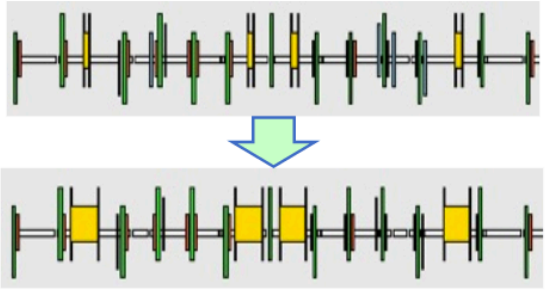
$$\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$$

Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB

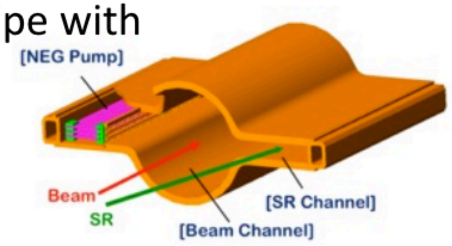
KEKB → SuperKEKB

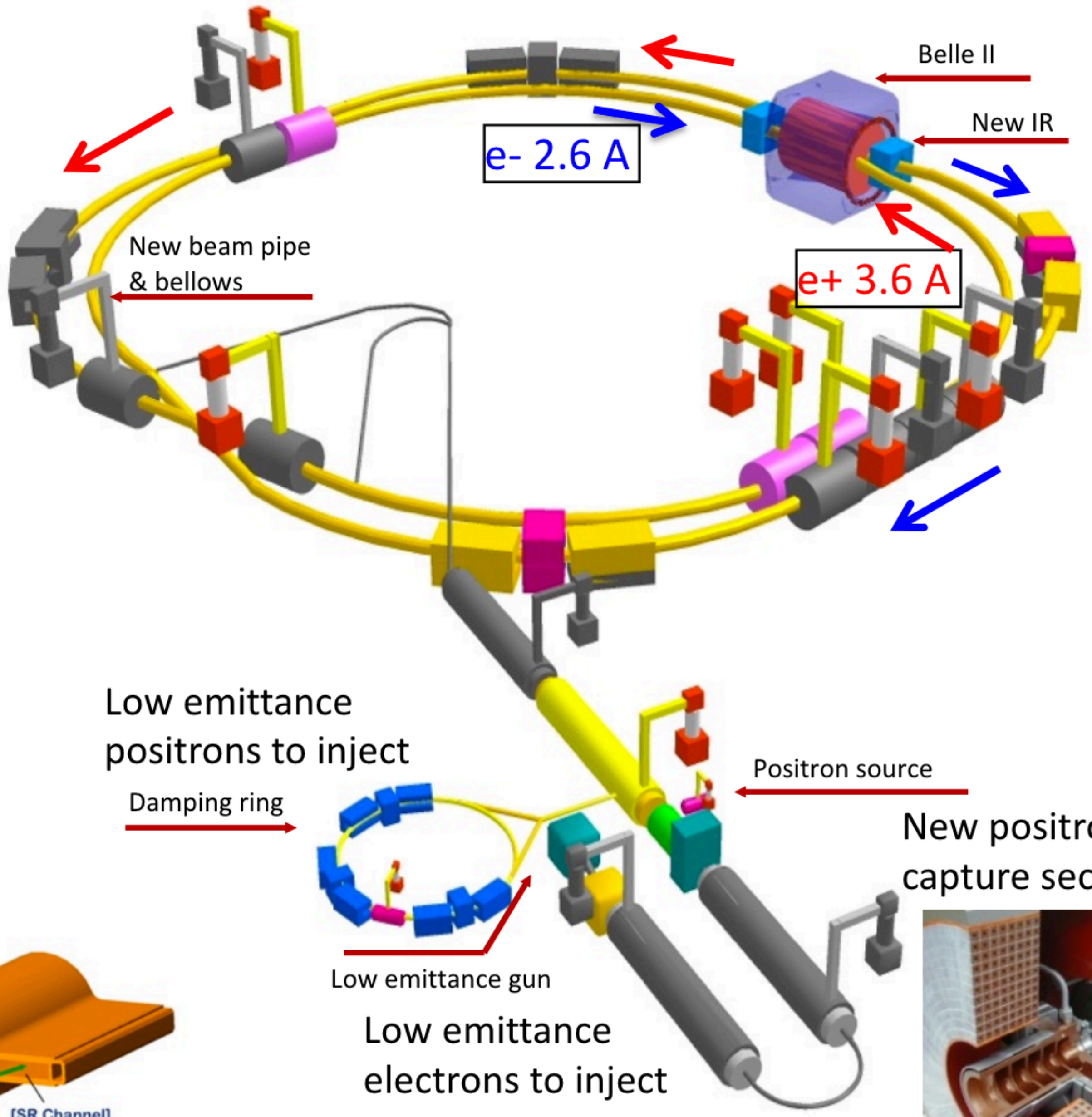
Replace short dipoles with longer ones (LER)

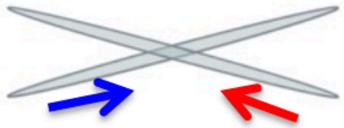


Redesign the lattices of HER & LER to squeeze the emittance

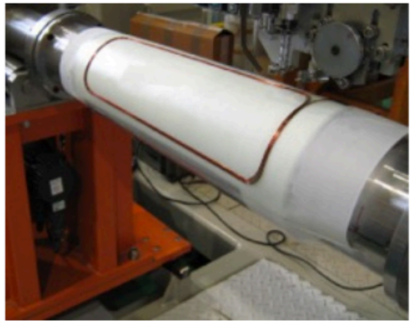
TiN-coated beam pipe with antechambers



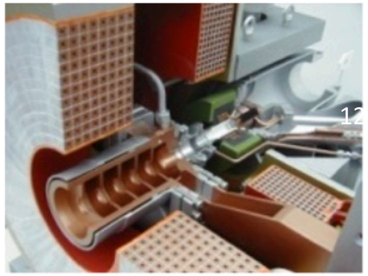




New superconducting /permanent final focusing quads near the IP

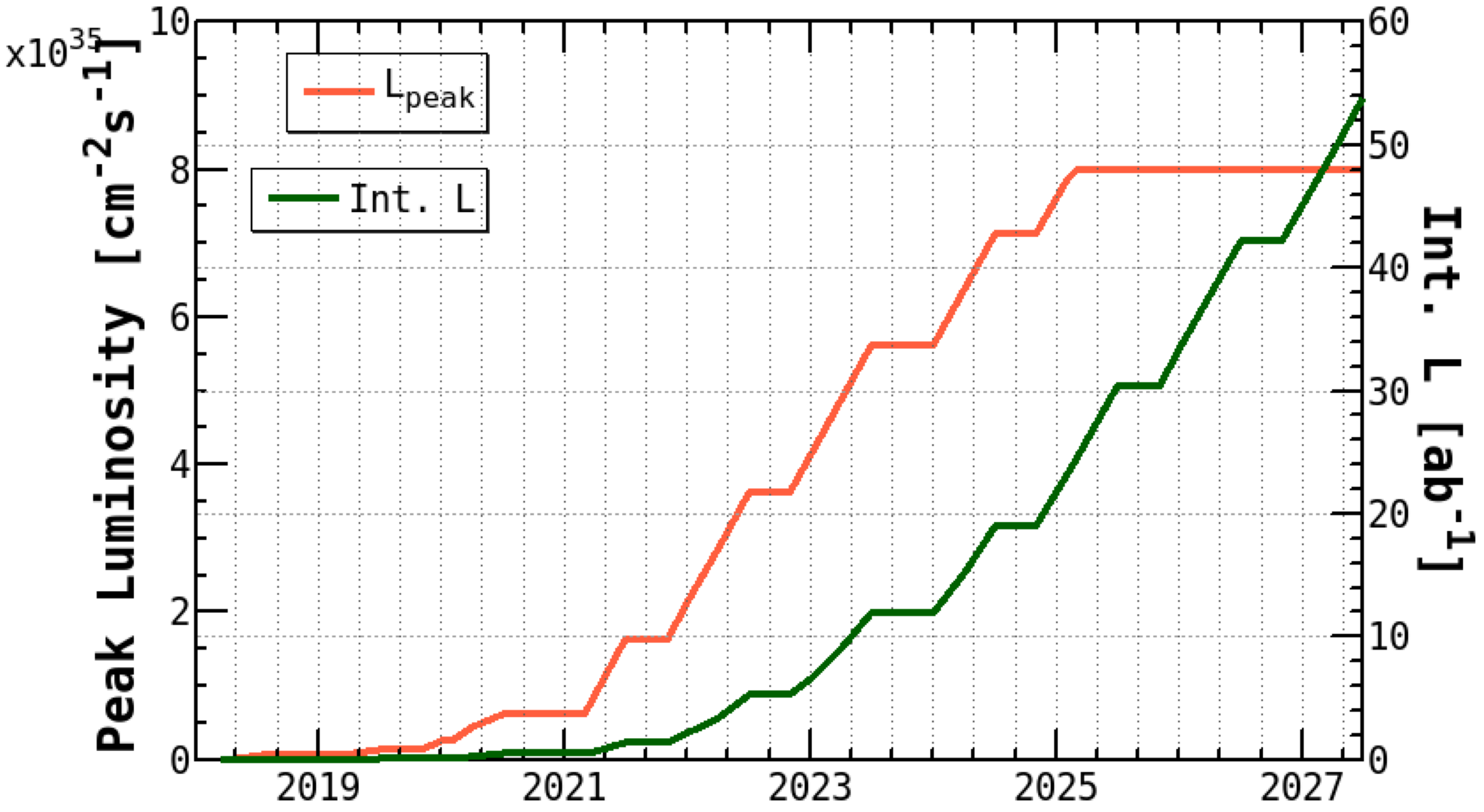


New positron target / capture section



Add / modify RF systems for higher beam current

LUMINOSITY PROFILE



Phase I (Feb – June 2016)

- Background commissioning detectors (diamo TPC’s, diodes, crystals…)
- Circulated both beams but no collisions;
- Tune accelerator optics, etc.; vacuum scrubbing

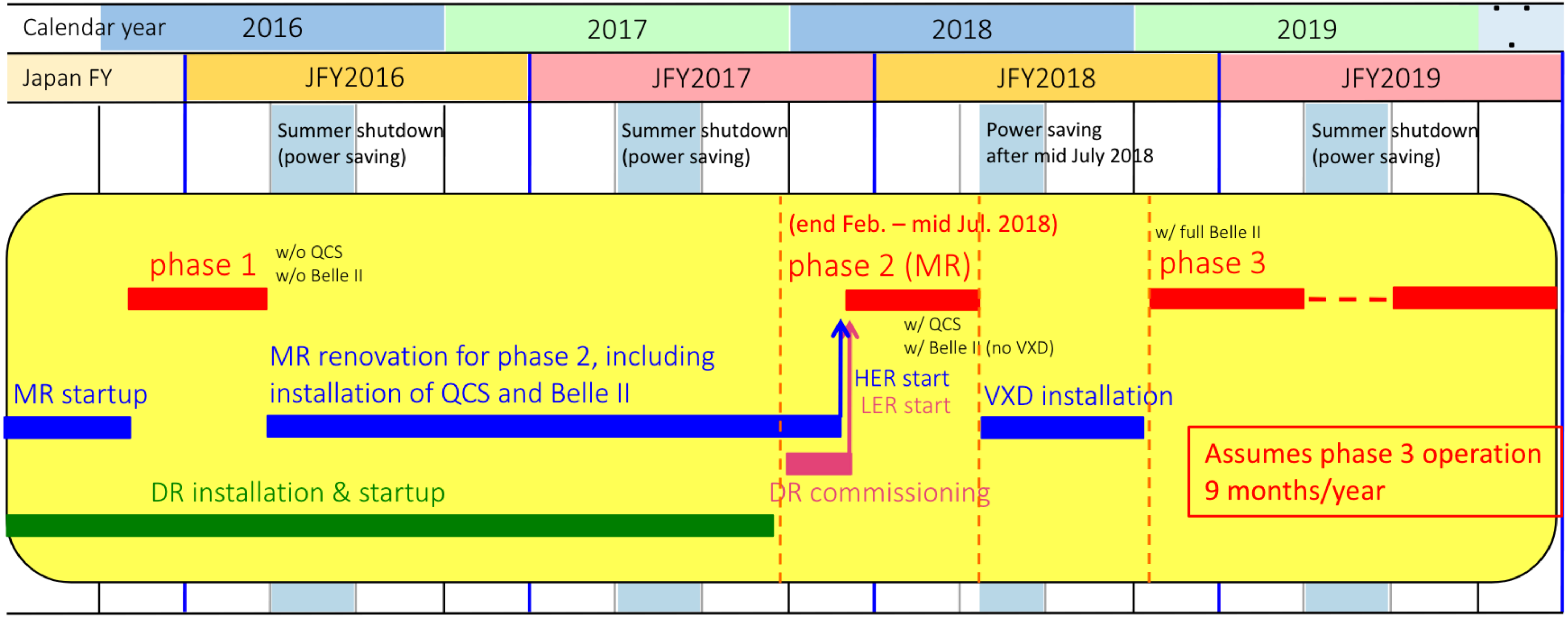
Phase II (2018)

- First collisions!
- Beam Commissioning
- Background measurements with BEAST II/2
- Full Belle II outer detector without Vertex Detector

Phase III (2019 →)

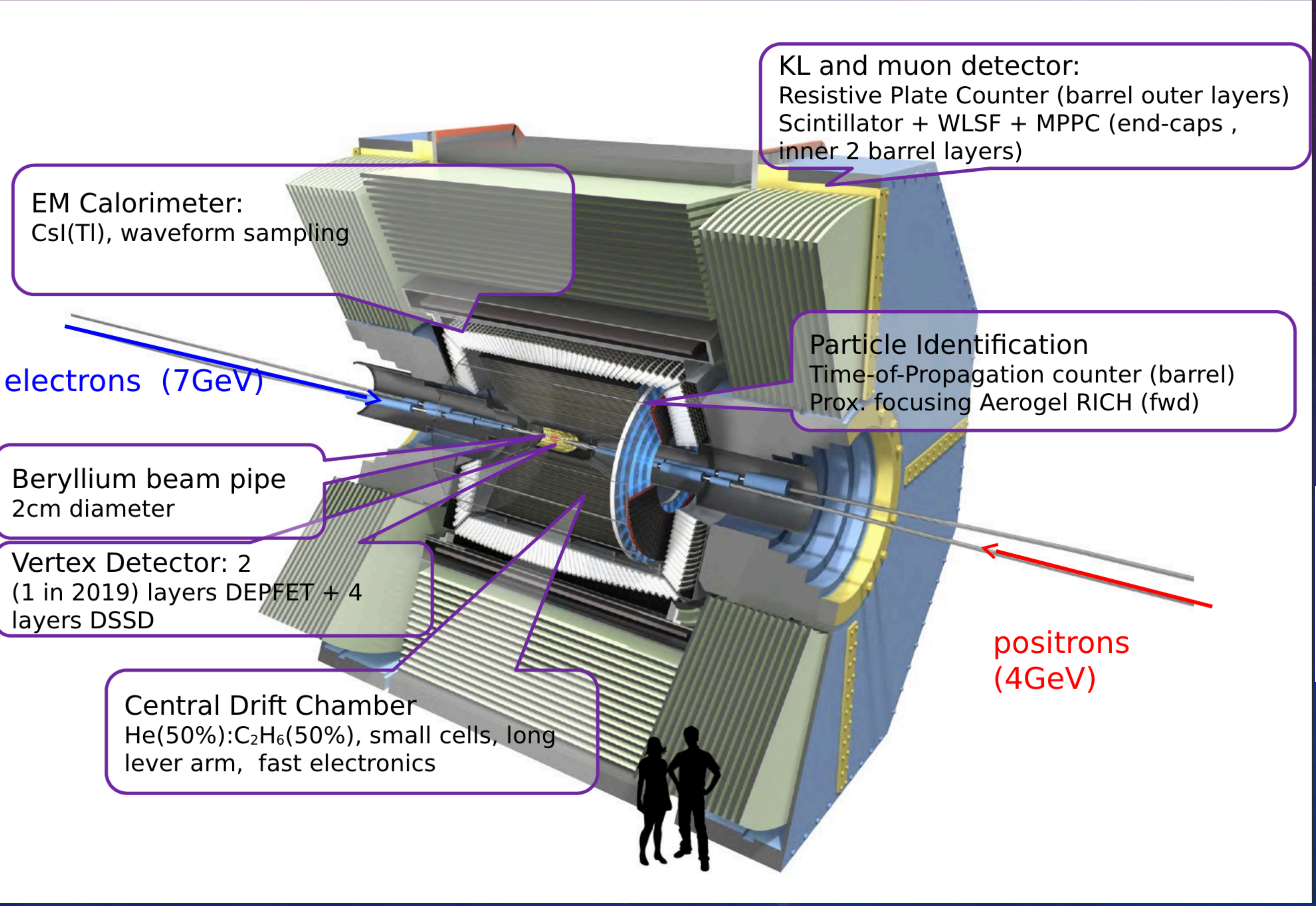
- Physics run

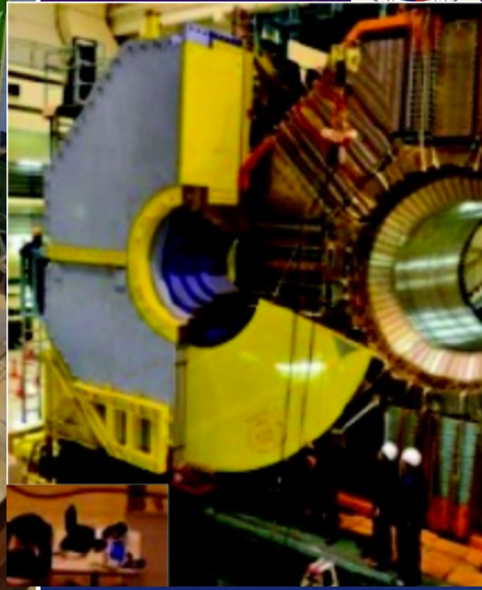
SCHEDULE



- First collision April 26th 2018
- Phase 3 has started March 11th THE SHOW MUST GO ON!!!!

BELLE II DETECTOR





SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, lor
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

BELLE II COLLABORATION

>800 members
101 institution
25 countries

PHASE2 FIRST COLLISION!

Apr 26, 2018

First collisions on April 26

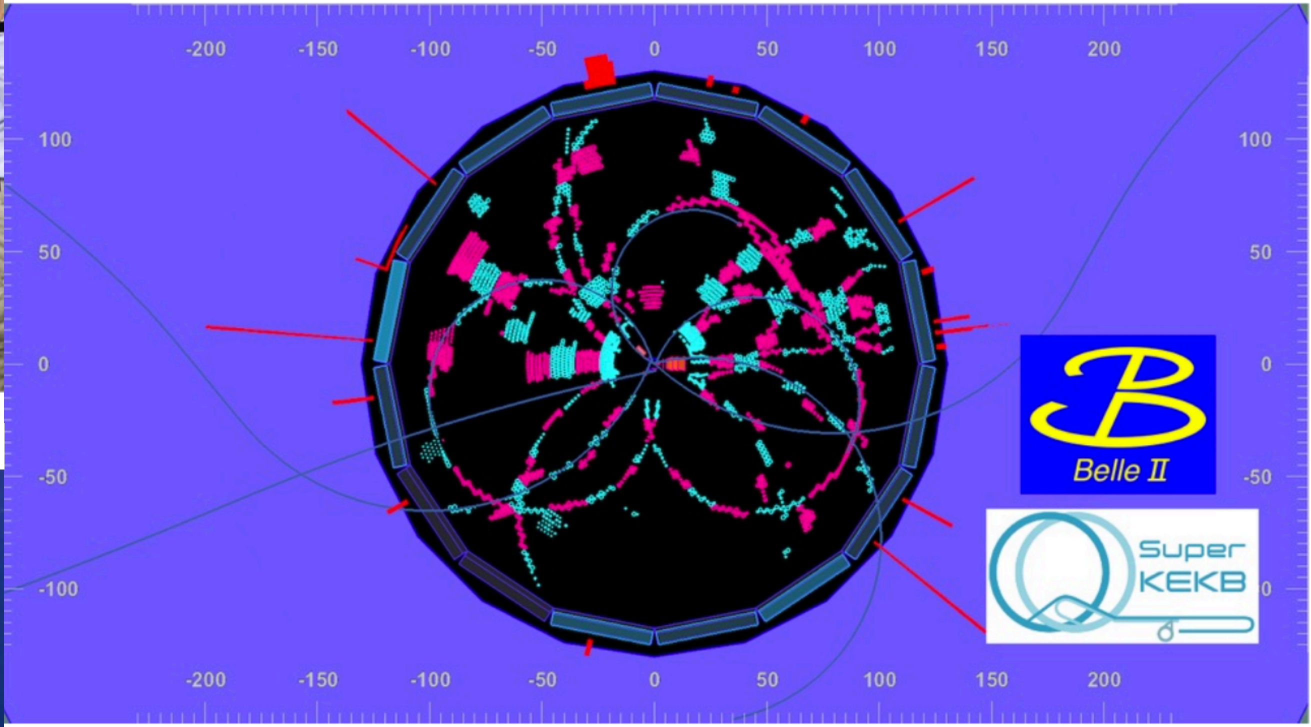
β^* successfully squeezed down to β^*=2mm

L = 5.54 x 10^{33} $cm^{-2}s^{-1}$

L_{spec} = 2 x 10^{31} $cm^{-2}s^{-1}$

Integrated Luminosity (online): 500 pb^{-1}

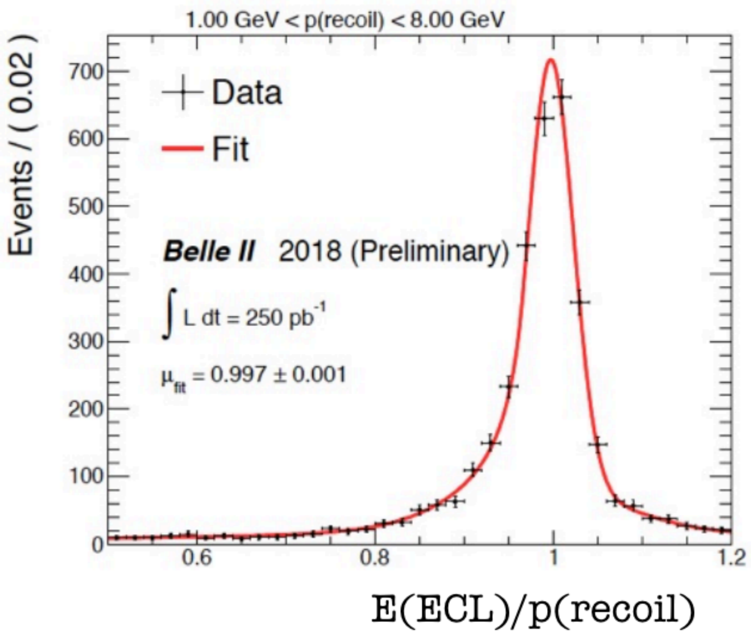
$$e^+e^- \to \gamma^* \to B\bar{B}$$



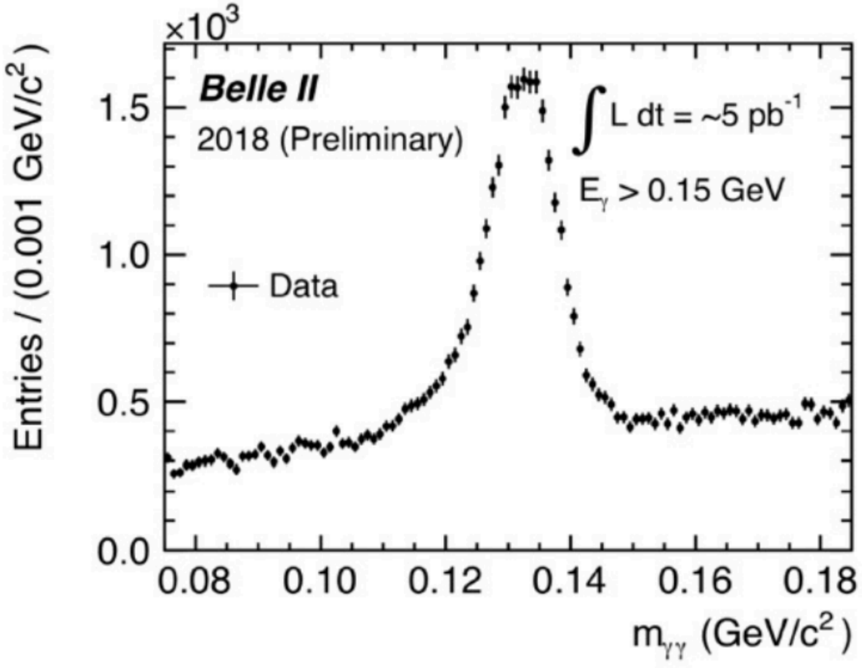
A potential e+ e- →B anti-B candidate

PHASE2: PHOTON RECONSTRUCTION

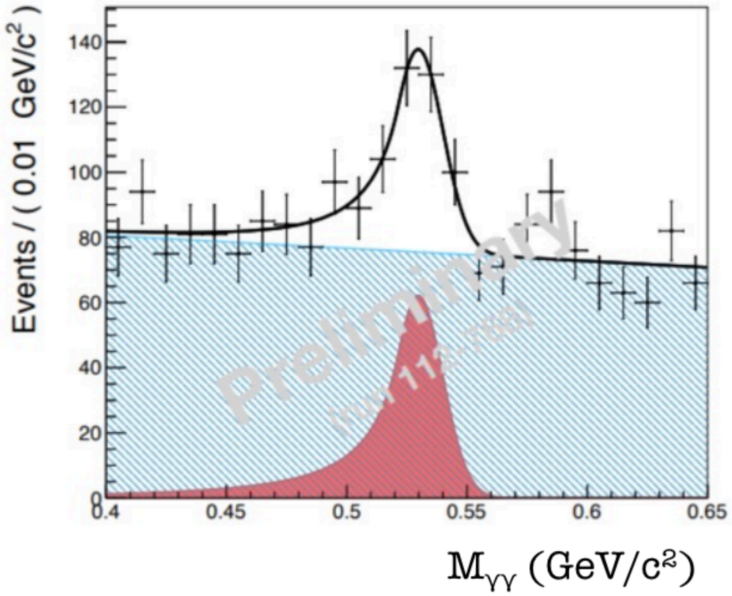
$e^+e^- \to \mu^+\mu^-\gamma$



$\pi^0 \to \gamma\gamma$



$\eta \to \gamma\gamma$



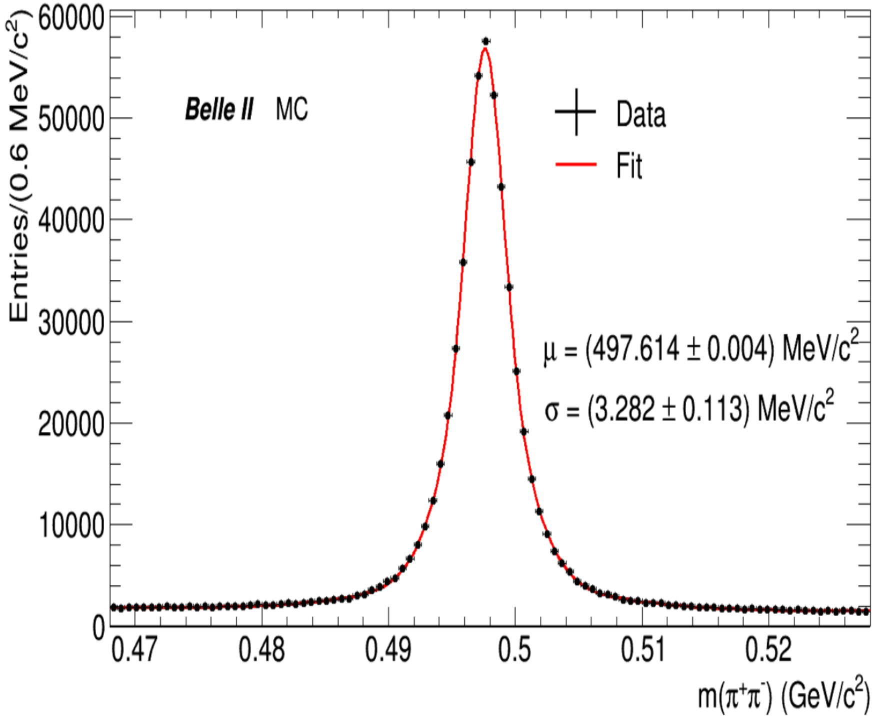
- Good reconstruction of both single photons and pairs
- Ready for the "dark sector" – single photons

$$e^+e^- \to \gamma X$$

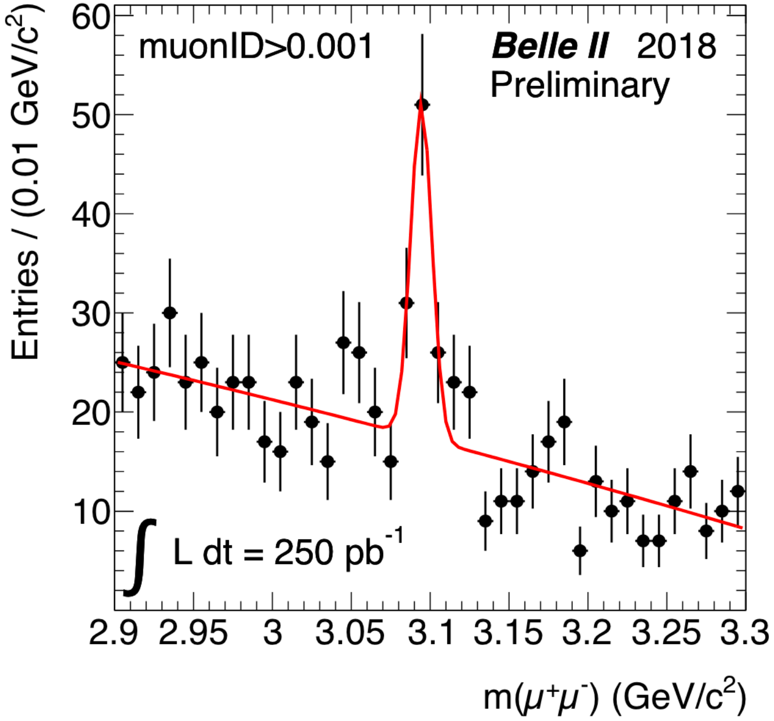
$$e^+e^- \to \gamma\, ALP \to \gamma(\gamma\gamma)$$

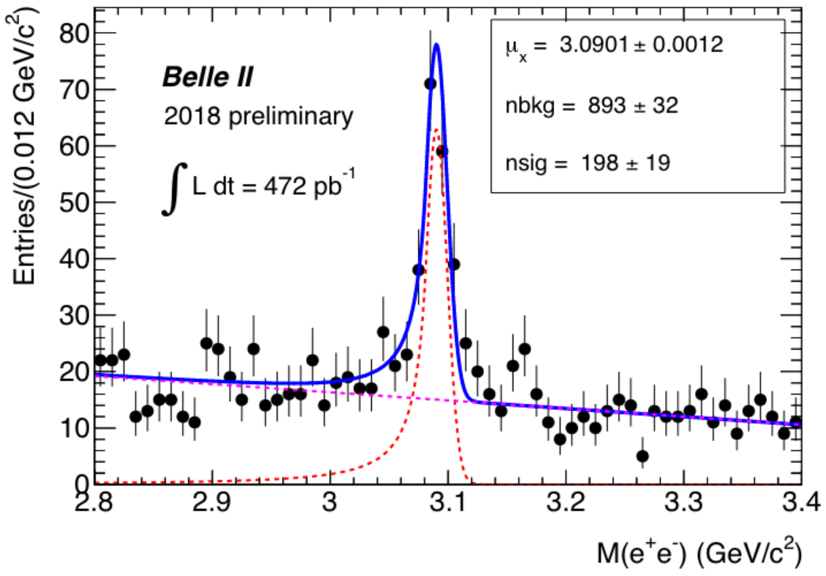
PHASE2: TRACKING

$K_S \to \pi^+\pi^-$



$J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$



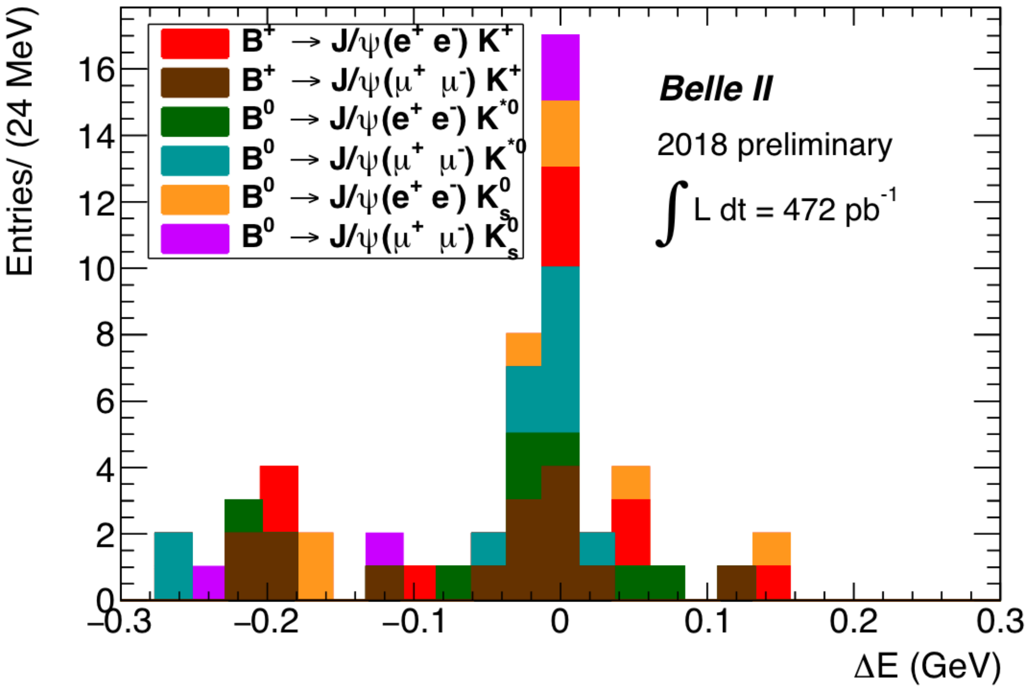


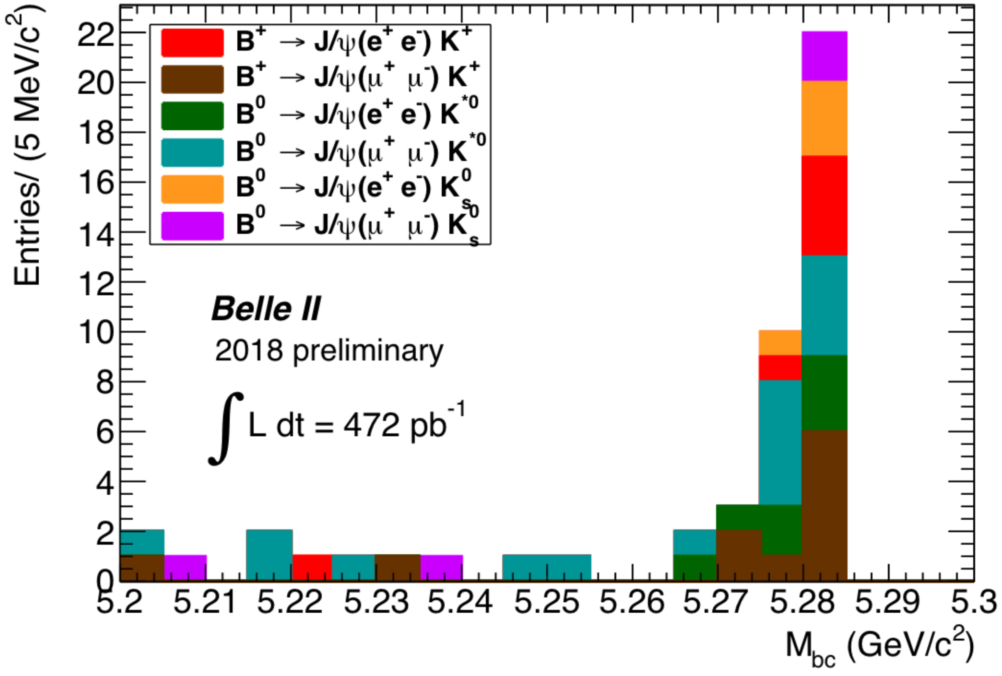
- Good tracking efficiency.

PHASE2: RE-DISCOVERY OF B MESONS

$$\Delta E = E_{cm}/2 - E_{recon}$$

$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p^2_{recon}}$$





History 1983:

VOLUME 50, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1983

Observation of Exclusive Decay Modes of *b*-Flavored Mesons $40.7\ \mathrm{pb}^{-1}$

B-meson decays to final states consisting of a D^0 or $D^{*\pm}$ and one or two charged pions have been observed. The charged-B mass is $5270.8 \pm 2.3 \pm 2.0$ MeV and the neutral-B mass is $5274.2 \pm 1.9 \pm 2.0$ MeV.

PHYSICS: EARLY PHASE3

- Luminosity will depend on machine and detector performance
- Let's assume 10 fb^{-1} by summer 2019

SEMILEPTONIC

B→ $\pi l\nu$ and $\rho l\nu$ untagged (CLEO saw a signal with 2.66 fb^{-1})

TIME DEPENDENT CP VIOLATION AND CHARM

D lifetimes (2 fb^{-1})

$D^0 \to K^+\pi^-$, $D^0 \to K^+\pi^-\pi^0$ (10 fb^{-1})

B lifetimes (2-10 fb^{-1})

Time dependent B mixing (10 fb^{-1})

RADIATIVE ELECTROWEAK PENGUINS

B → $K^*\gamma$ (2fb^{-1}) rediscovery penguins

B→ $X_s\gamma$ (10 fb^{-1})

HADRONIC B DECAYS

B → $K\pi$(10 fb^{-1})

B → ϕK (10 fb^{-1})

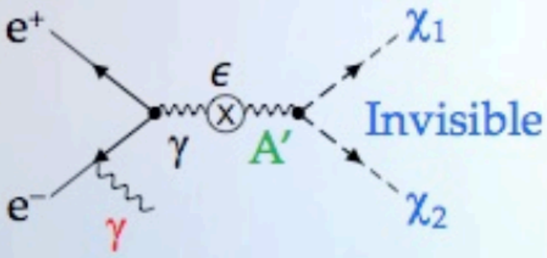
B → $J/\psi K$ (2-10 fb^{-1})

Time dependent B mixing (10 fb^{-1})

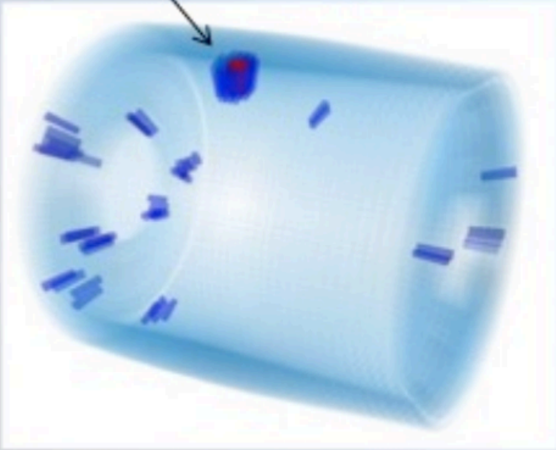
DARK SECTOR physics publications!

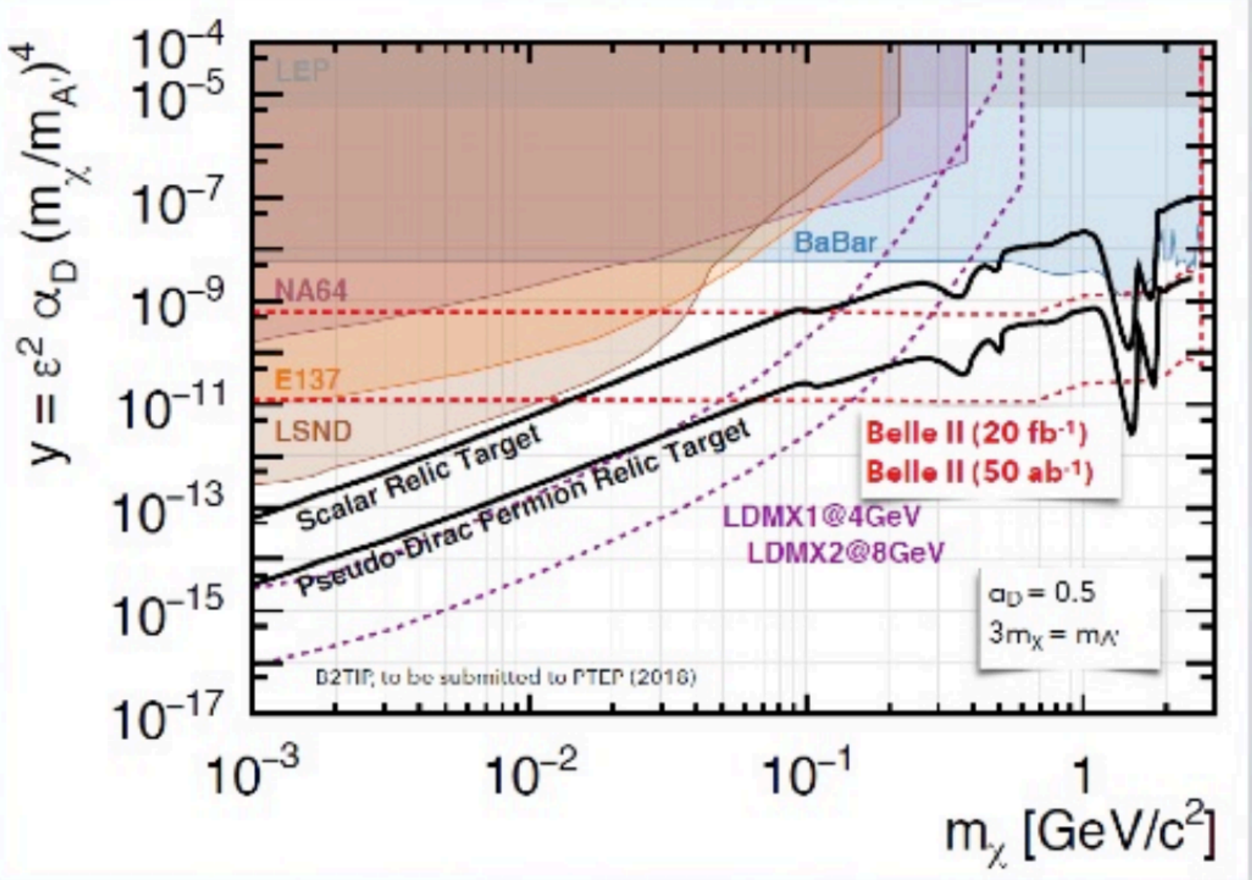
PHYSICS PHASE3 → DARK SECTOR

- New triggers will be used in Belle II to search for dark matter and dark photons.
  - Single photon trigger with ~1 GeV threshold to search for dark photon decaying into light dark matter



$$E_\gamma = \frac{E_{CM}^2 - M_{A'}^2}{2E_{CM}}$$





For more details see dedicated talk at this conference by G. Inguglia

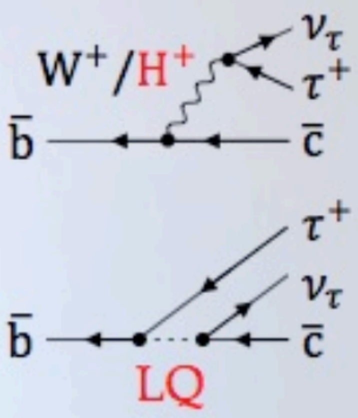
PHYSICS PHASE3: B→D(*)$\tau\nu$

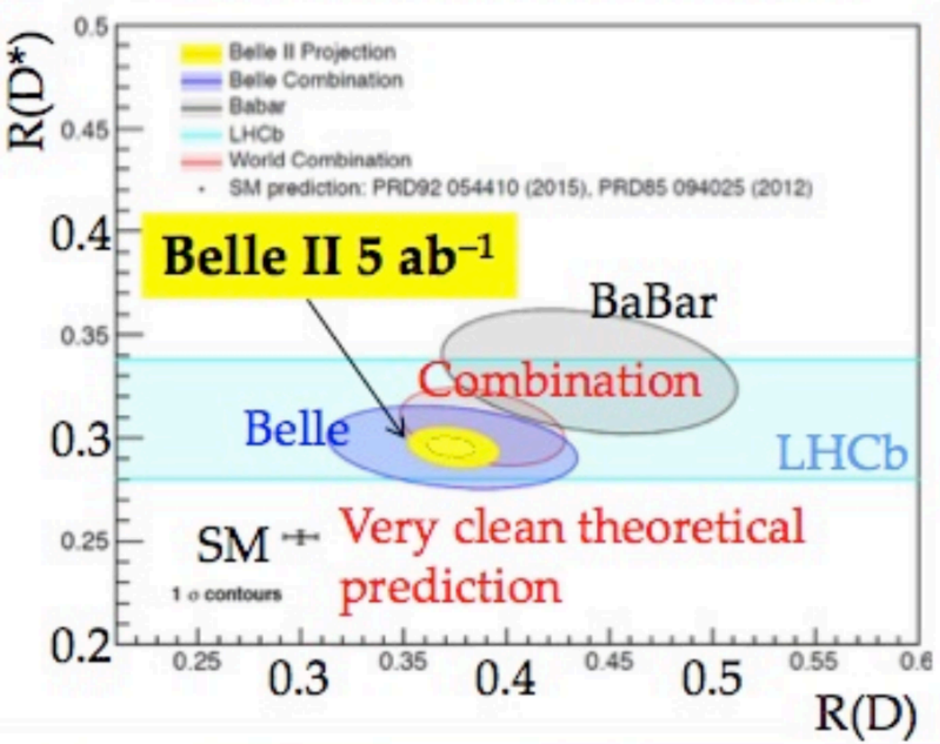
$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)} \quad (\ell = \text{e or } \mu)$$

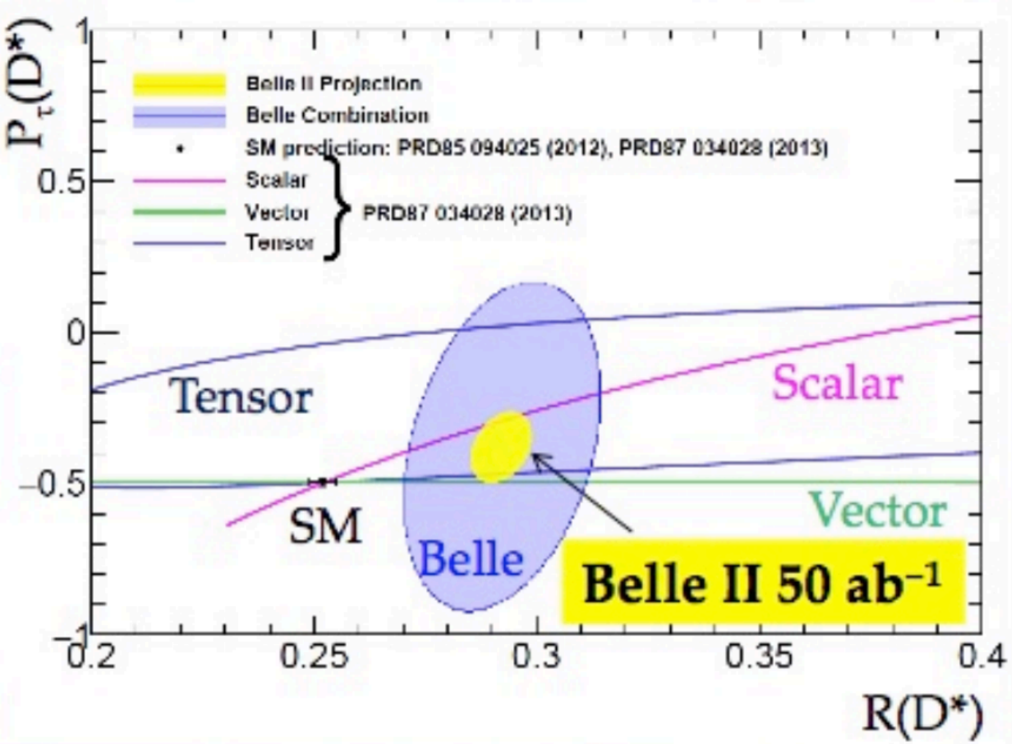
- Partial cancellation of theoretical uncertainties related to hadronic effects and measurement systematics.

$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \quad (\Gamma^\pm\text{: decay rate of } \pm\tau\text{-helicity})$$

- Another probe of New Physics



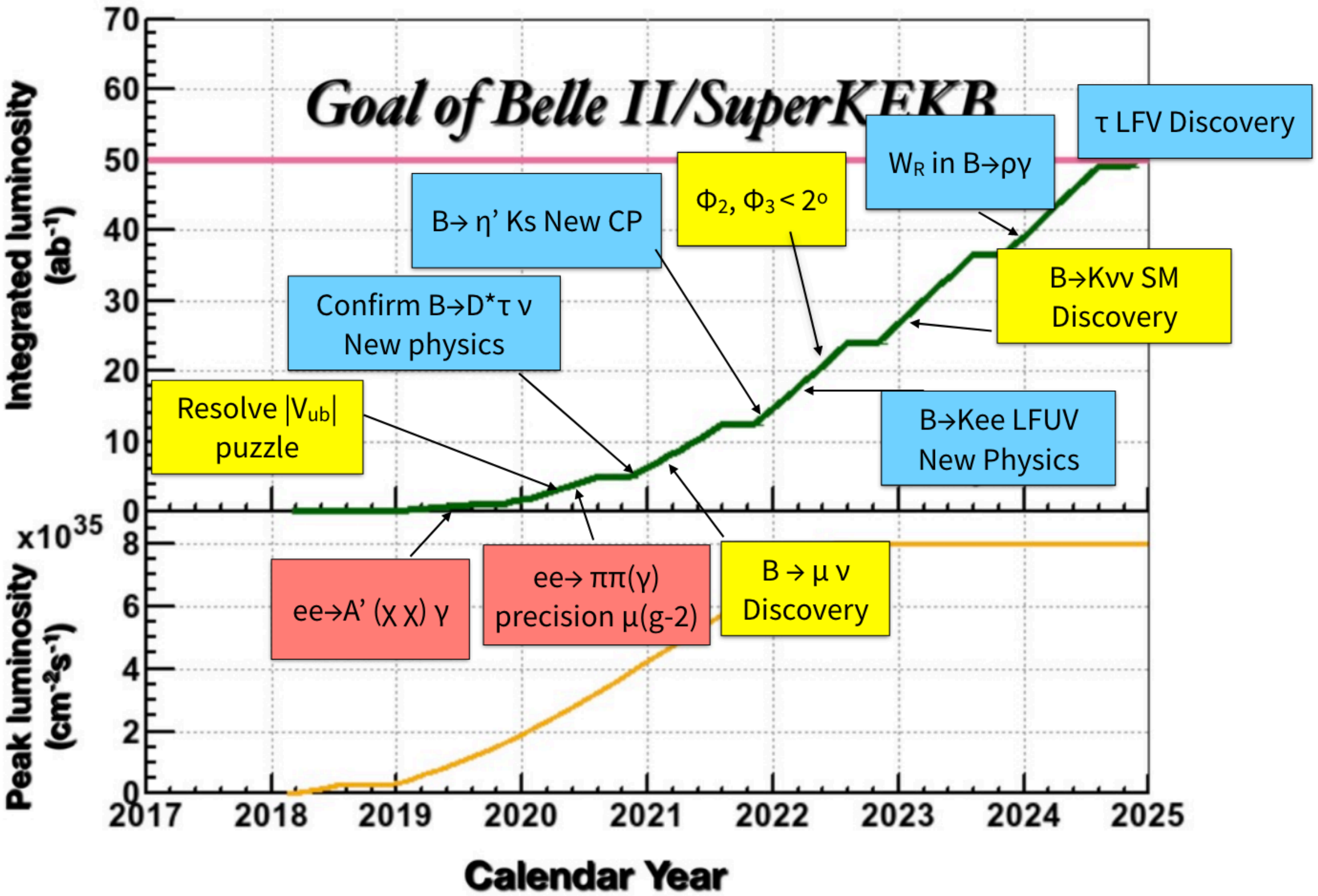




PHASE3 PHYSICS PERSPECTIVES

- B2TIP: Belle2 Theory Interface Platform
- A series of joint workshops with theorists
- Belle II Physics book submitted to PTEP

https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/



Ultimate precision

Observables	Expected the. accuracy	Expected exp. uncertainty		Facility (2025)
UT angles & sides				
ϕ_1 [°]	***	0.4	CKM	Belle II
ϕ_2 [°]	**	1.0		Belle II
ϕ_3 [°]	***	1.0		LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%		Belle II
$\|V_{cb}\|$ excl.	***	1.5%		Belle II
$\|V_{ub}\|$ incl.	**	3%		Belle II
$\|V_{ub}\|$ excl.	**	2%		Belle II/LHCb
CP Violation				
$S(B \to \phi K^0)$	***	0.02	CPV	Belle II
$S(B \to \eta' K^0)$	***	0.01		Belle II
$\mathcal{A}(B \to K^0 \pi^0)[10^{-2}]$	***	4		Belle II
$\mathcal{A}(B \to K^+ \pi^-)$ $[10^{-2}]$	***	0.20		LHCb/Belle II
(Semi-)leptonic			LEPT	
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%		Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	SL	Belle II
$R(B \to D\tau\nu)$	***	3%	LFUV	Belle II
$R(B \to D^*\tau\nu)$	***	2%		Belle II/LHCb

Radiative & EW Penguins				
$\mathcal{B}(B \to X_s\gamma)$	**	4%	EWP	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005		Belle II
$S(B \to K_S^0 \pi^0 \gamma)$	***	0.03		Belle II
$S(B \to \rho\gamma)$	**	0.07		Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3		Belle II
$\mathcal{B}(B \to K^* \nu\overline{\nu})$ $[10^{-6}]$	***	15%		Belle II
$\mathcal{B}(B \to K \nu\overline{\nu})$ $[10^{-6}]$	***	20%		Belle II
$R(B \to K^* \ell\ell)$	***	0.03		Belle II/LHCb
Charm				
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	CHARM	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%		Belle II
$A_{CP}(D^0 \to K_S^0 \pi^0)$ $[10^{-2}]$	**	0.03		Belle II
$\|q/p\|(D^0 \to K_S^0 \pi^+ \pi^-)$	***	0.03		Belle II
$\phi(D^0 \to K_S^0 \pi^+ \pi^-)$ [°]	***	4		Belle II
Tau				
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	LFV	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100		Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3		Belle II/LHCb

- Very rich physics program in the next few years

CONCLUSIONS

- Belle II has completed the initial data taking (Phase 2)
  - Understanding the machine and the backgrounds
  - Detector and software checkout
  - Initial physics

- Belle II will explore New Physics on the Intensity Frontier in a complementary way w.r.t. LHC high p_T experiments, in a healthy competition with LHCb

- We are ready to start a long physics run in the Super Factory mode (Phase 3) from yesterday!
This requires high-efficiency data-taking by Belle II and extensive running by Super KEK-B, soon to be the world's highest luminosity accelerator.

- Particle Physics community is waiting for our results → first at LP2019

BACKUP

SUPERKEKB DESIGN PARAMETERS

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	ϕ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.37	0.40	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0881	0.0807	
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

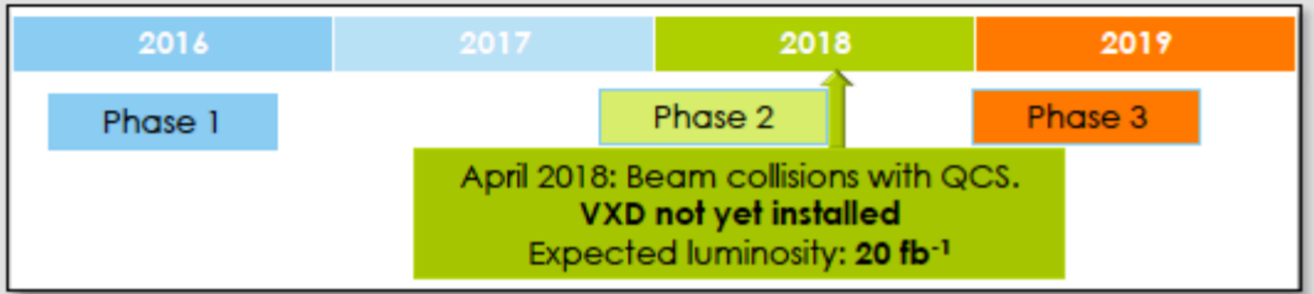
- **Nano-beams and a factor of two more beam current** to increase luminosity
- **Large crossing angle**

- **Change beam energies** to solve the problem of short lifetime for the LER
- Consequence βy: decrease 0.42 → 0.28

Physics Competition and Complementarity

2019–2020	2021–2023	2024–2026	2026–2029	2030–2031	2032–203+
	Run III		Run IV		Run V
LS2		LS3		LS4	
LHCb 40 MHz **UPGRADE I**	$L = 2 \times 10^{33}$	**LHCb** **Consolidate: Upgr Ib**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb** **UPGRADE II**	$L = 1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$
ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	**ATLAS** **Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 \times 10^{34}$
CMS Phase I Upgr	$300\ fb^{-1}$	**CMS** **Phase II UPGRADE**		**CMS**	$3000\ fb^{-1}$
Belle II $5\ ab^{-1}$	$L = 8 \times 10^{35}$	$50\ ab^{-1}$	LHC schedule: Frederick Bordry, Jun 2015		

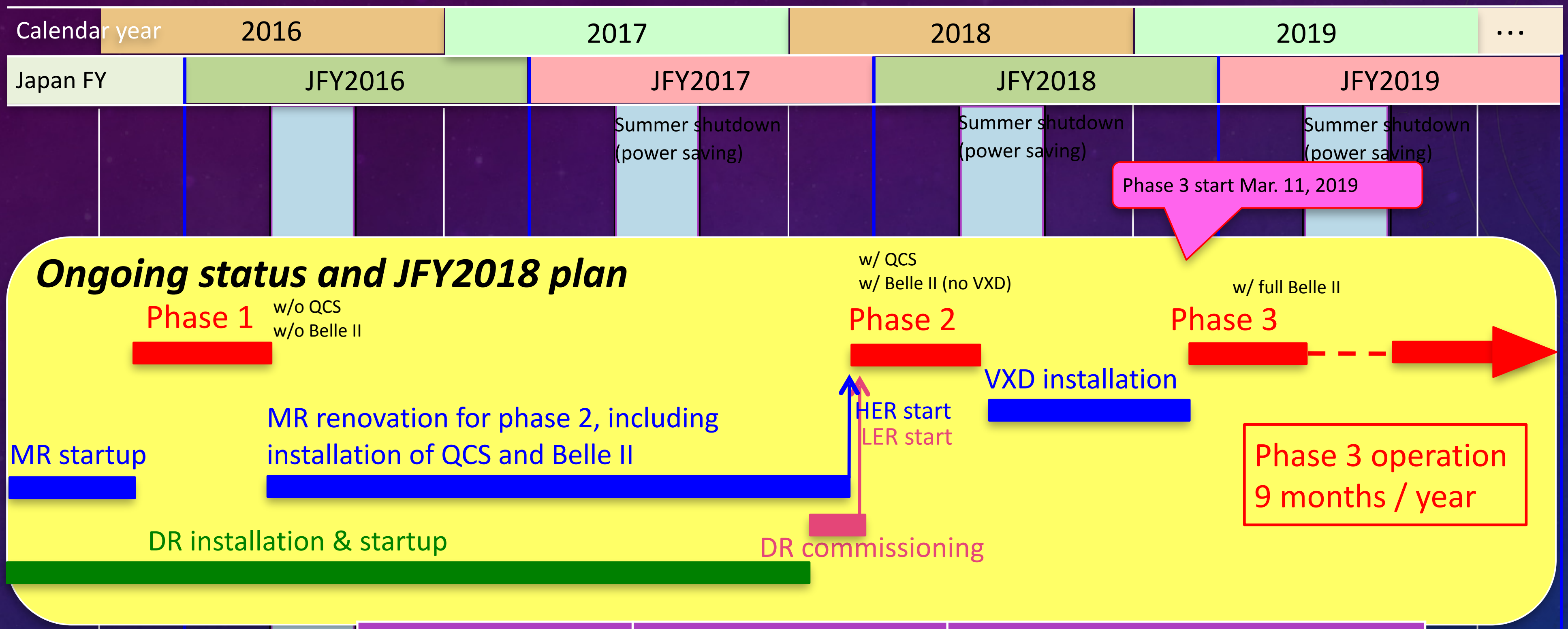
- Belle II
  - $L=5\times10^{33}\ cm^{-2}s^{-1}$ achieved!
  - Physics with VXD in 2019



R. Cheaib, Moriond, 12 Mar 2018, arXiv:1802.01366

GLOBAL SCHEDULE

as of Dec. 2018



Phase2 started April 26, 2018

	Start	End
Operation	Mar. 11, 2019	9:00 Jul. 1, 2019
Summer shutdown	Jul. 1, 2019	Early autumn 2019 (end Sep-Oct)
Operation	Early autumn 2019	~Christmas
Winter shutdown	~Christmas	Early 2020 (Jan-Feb)
Operation	Early 2020 (Jan-Feb)	9:00 Jul. 1, 2020
Shutdown 2020	Jul. 1, 2020	Depending on the amount of Belle II/ superKEKB consolidation works

E+E- CROSS SECTIONS

Cross section @ Υ(10580)

$e^+e^- \to$	Cross-section (nb)
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	~ 40