Belle II Status and Prospects

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for the ***Belle II Collaboration***

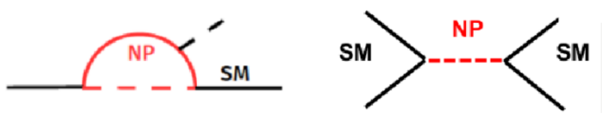
Lake Louise Winter Institute 2020

Lake Louise, Calgary, Canada
February 9 – 15, 2020

The hunt for New Physics

Intensity / precision frontier

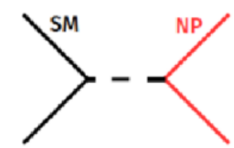
New virtual particles in loops/trees transitions, deviation from SM expectations (B factories, LHCb)

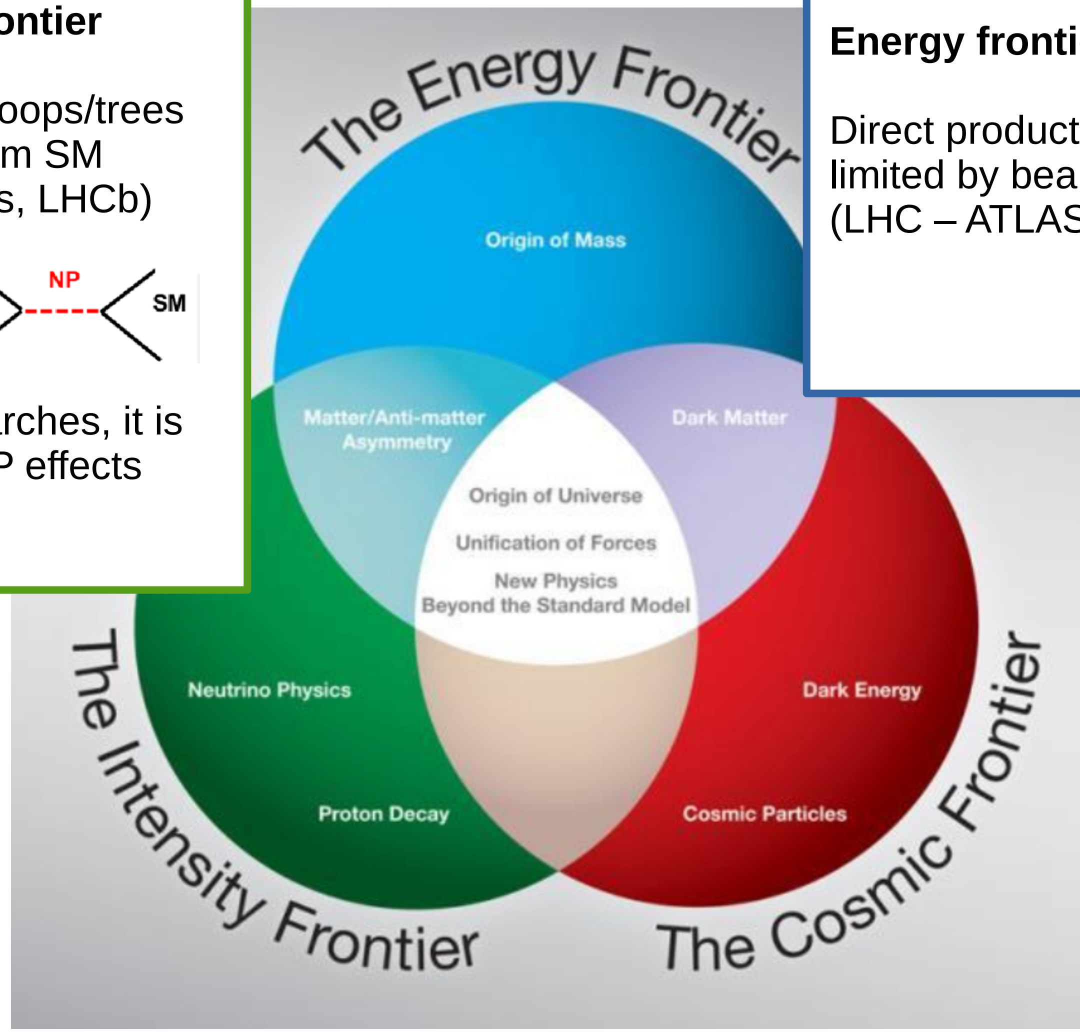


If NP found in direct searches, it is reasonable to expect NP effects in *B, D, tau* decays

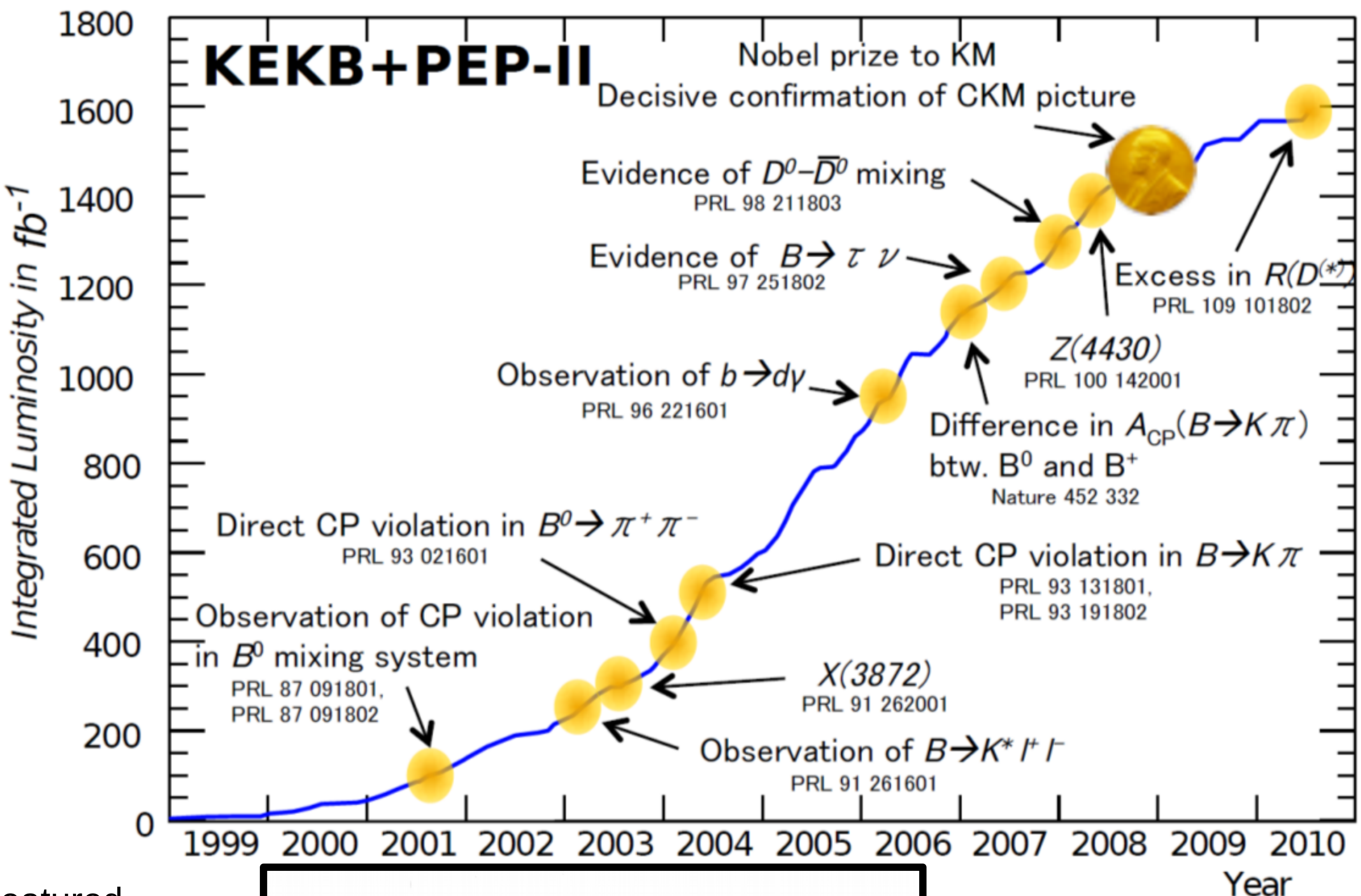
Energy frontier

Direct production of new particles - limited by beam energy
(LHC – ATLAS, CMS)





Rich legacy of B-Factories



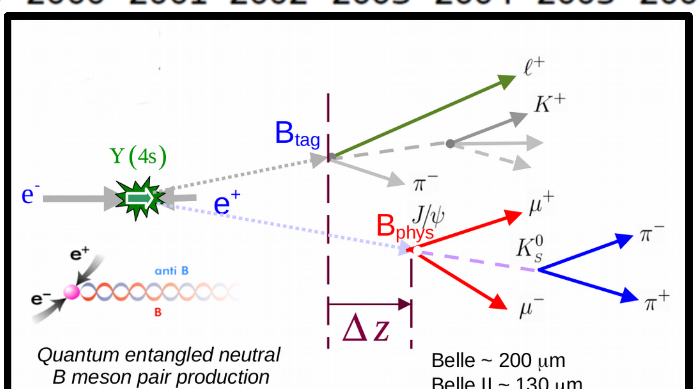
Analyses still continuing...

Belle talks on Tuesday:

- **Measurement of time-dependent CP violation in $B^0 \to K_S K_S K_S$ decays at Belle**
  by **Kookhyun Kang**
- **New Results on D-Mixing and CP Violation from Belle**
  by **David Cinabro**

Featured physics goal:

Precise time-dependent CP-violation measurements



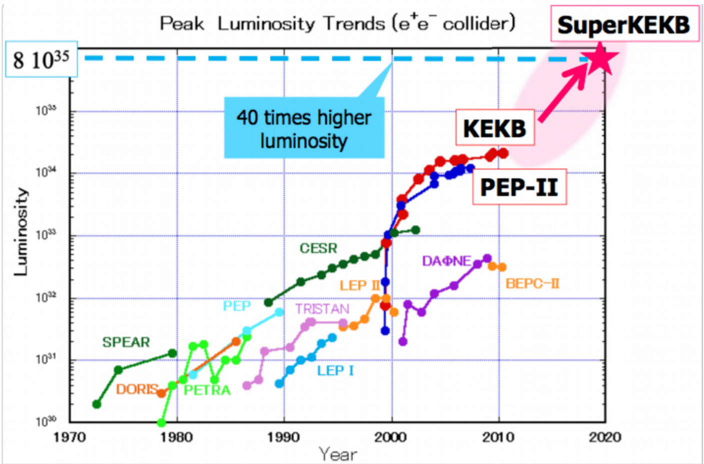
Collider requirements: extreme luminosity
Detector requirements – need for excellent:
- particle ID
- vertex resolution (reduced boost)
- radiation hardness
- DAQ/software… (high data rates, backgrounds)

Belle II

The next generation Super-B-Factory: SuperKEKB

$\mathcal{L}_{peak} = 2\cdot10^{34} \rightarrow 8\cdot10^{35}/cm^2s$

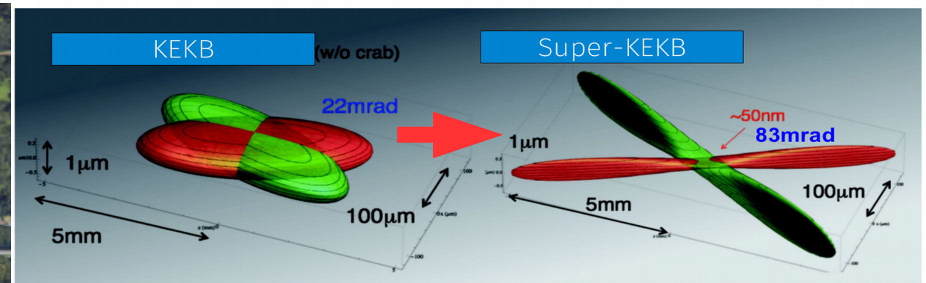
40 x KEKB luminosity: **Nano-beam**



beam current

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

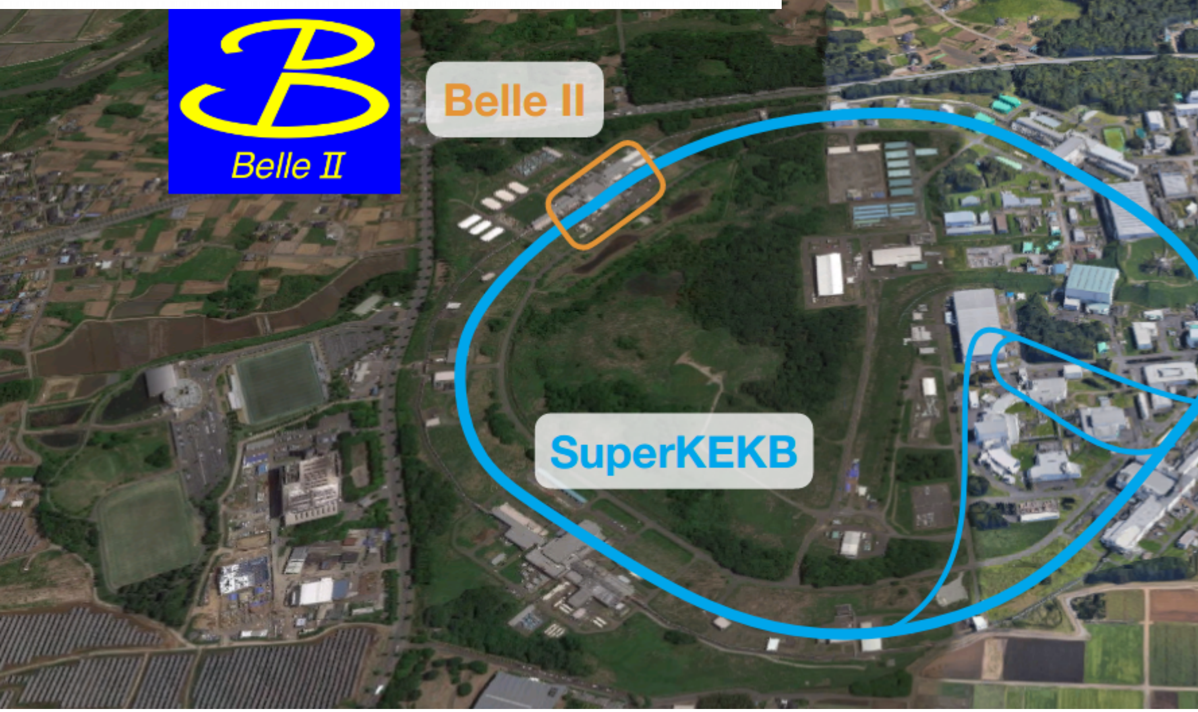
vertical beta function at IP



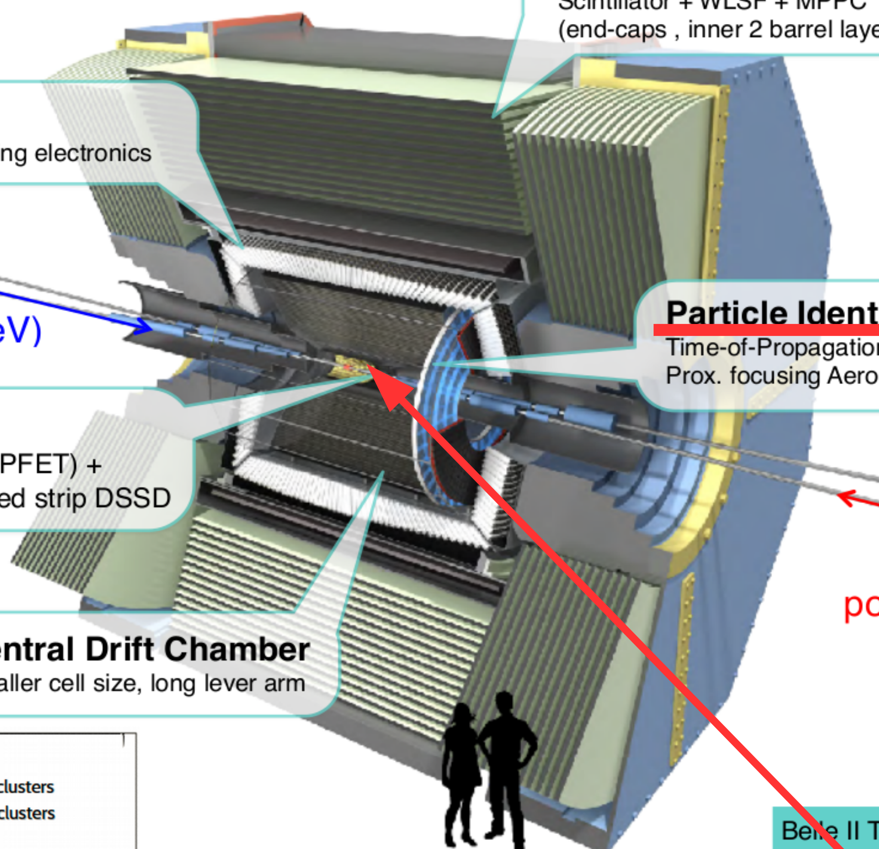
	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm⁻²s⁻¹)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20

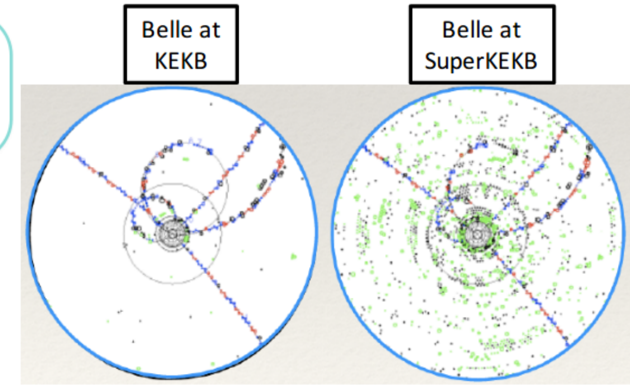
factor 2-3



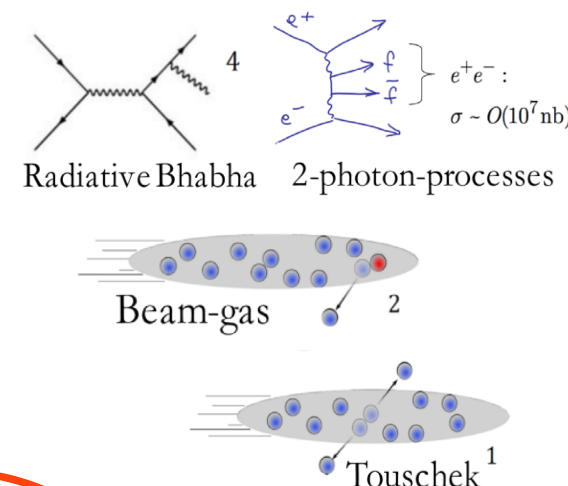
Belle → Belle II

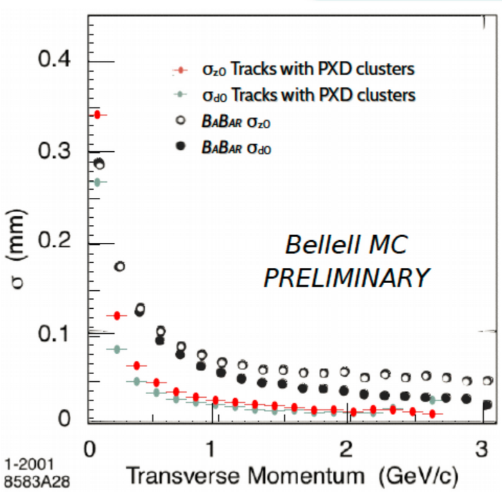


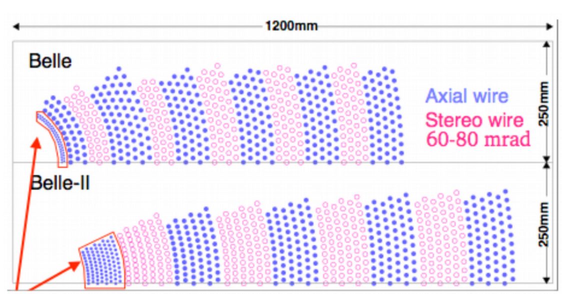
Belle II TDR, arXiv:1011.0352

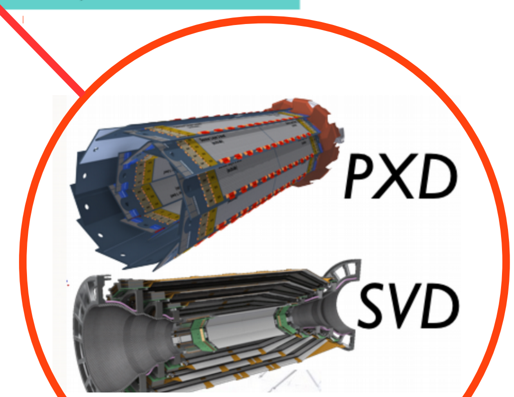


Higher backgrounds









Belle II Physics Prospects: Overview

Only selection of examples
(Sorry if I did not include your favourite)

With 50 ab^{-1} of e^+e^- collisions at (or close to) Y(4S) we have/can:

- (Super) B-Factory (~ 1.1 x 10^9 $B\bar{B}$ pairs / ab^{-1})
- (Super) Charm-Factory (~ 1.3 x 10^9 $c\bar{c}$ pairs / ab^{-1})
- (Super) Tau-Factory (~ 0.9 x 10^9 tau pairs / ab^{-1})

- Exploit the clean e^+e^- environment to probe existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, …
- Scan $e^+e^- \to$ light hadrons cross-section in range [0.5 – 10] GeV

Well defined initial state – Belle II can handle:

- neutral final states $\pi^0\pi^0$, $K_S\pi^0(\gamma)$, $K_SK_SK_S$
- final states with missing energy $\tau\nu$, $D^{(*)}\tau\nu$
- inclusive modes, e.g. $B \to X_s\gamma$, $B \to X_s l^+l^-$

Next talk: Rare B decays at Belle II
by **Ming-Chuan Chang**

- **CPV in B decays** ($B \to J/\psi K^0$, $K^0\pi^0\gamma$, $K\pi$)
- **(Semi)leptonic B decays** ($B \to D^{(*)}l\nu$, $\pi l\nu$, $\tau\nu$, $\mu\nu$)
- **Rare B decays** ($B \to K^{(*)}\nu\nu$, $K^{(*)}ll$, $X_s\gamma$, X_sll, $\gamma\gamma$)
- **Charm physics** ($D \to l\nu$, mixing, CPV)
- **LFV** tau decays ($\tau \to 3l$, $l\gamma$)
- **Dark Sector, Spectroscopy** (also early physics)

Thursday: First results on DM searches at Belle II by **Michael De Nuccio**

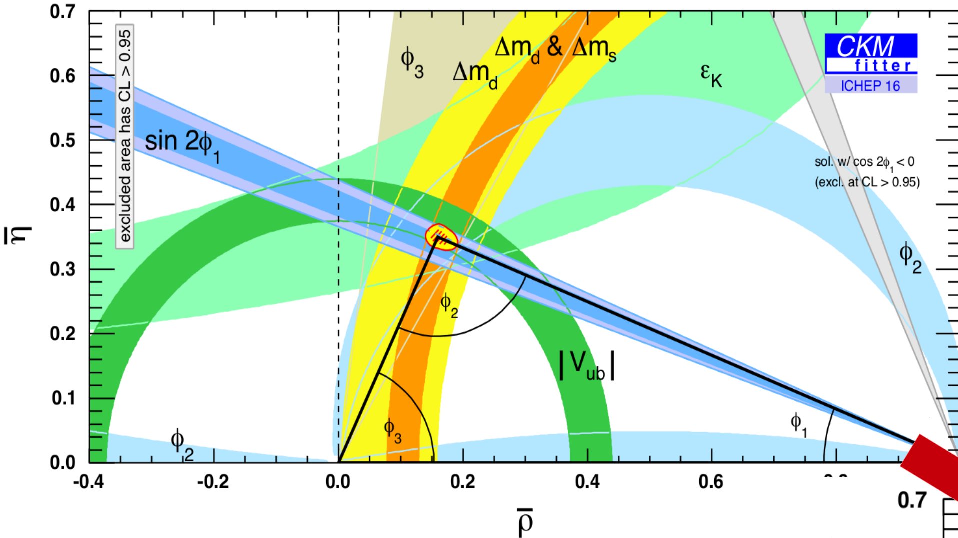
Tuesday: Semileptonic and leptonic B decays at Belle II by **Andreas Warburton**

*Belle II **complementary** to LHCb on indirect searches, but also **competitive** in some studies*

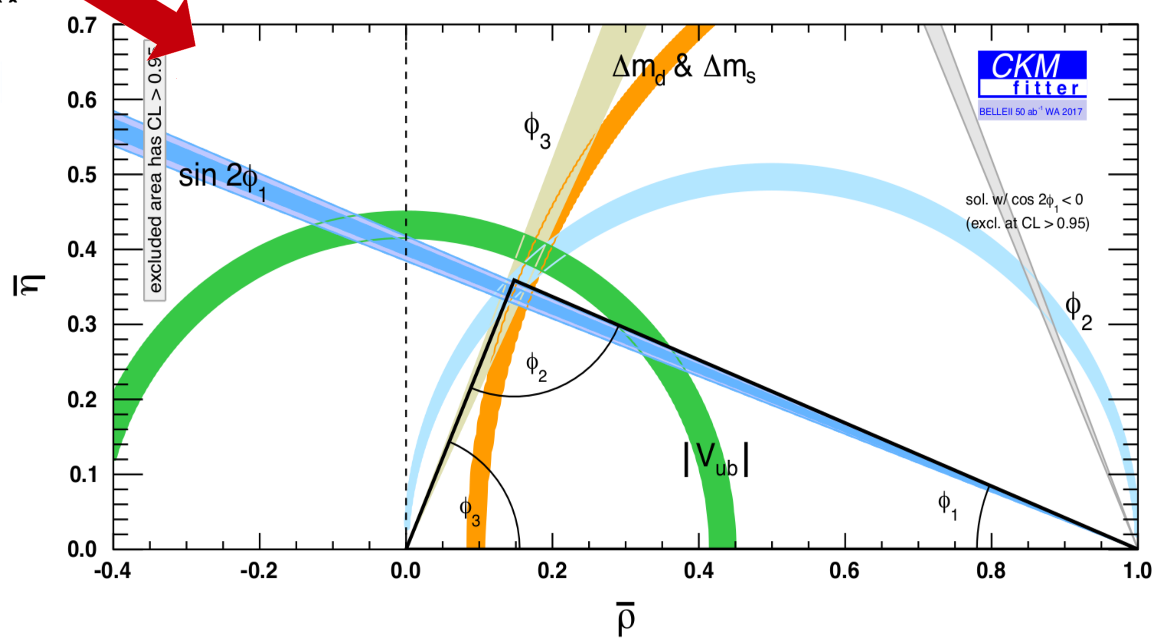
The Belle II Physics Book, arXiv:1808.10567
Prog. Theor. Exp. Phys. **2019**, 123C01 (2019)

Unitarity Triangle in the precision era

Enhanced precision of UT parameters (sides, angles)

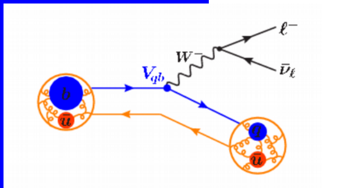


UT angles with ~ 1% uncertainty for 50 ab^{-1}



Inconsistency between angles or/and sides → New Physics

Semileptonic B decays



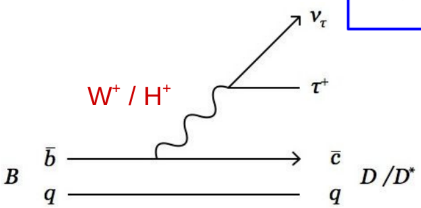
$B \to D^{(*)} \tau \nu$

Hot topic: Ratios R(D(*))

- **Lepton universality** test
- Very clean theory prediction
- Tension with SM

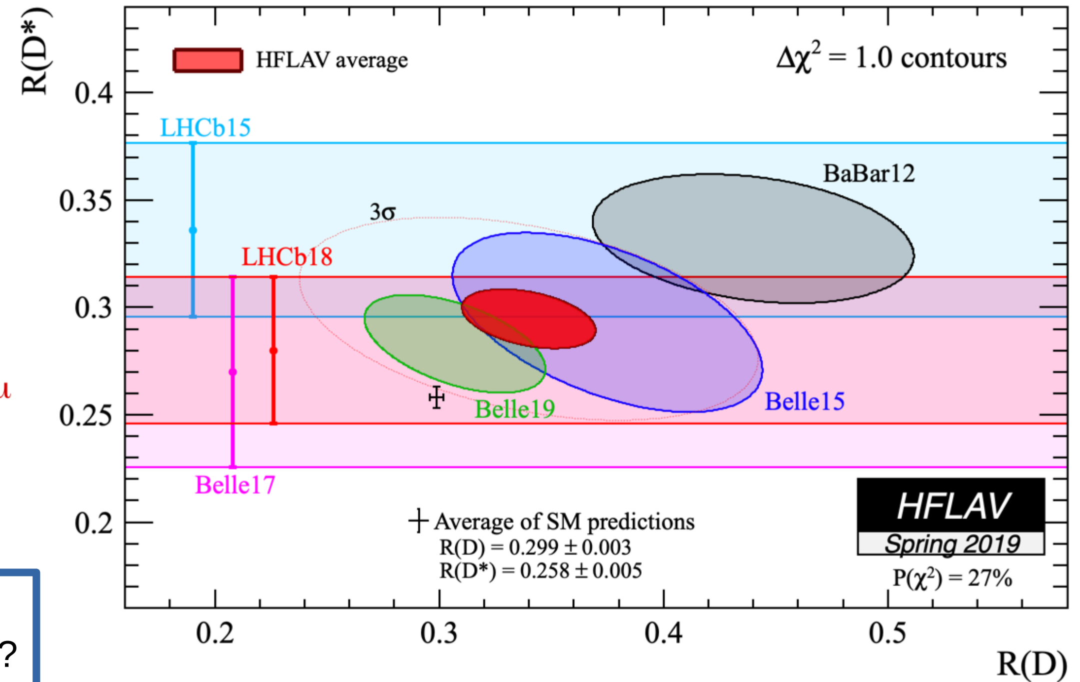
$$R(D^{(*)}) \equiv \frac{\Gamma(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to \bar{D}^{(*)}\ell^+\nu_\ell)}$$

l = e, μ



sensitive to charged scalars (ex. charged Higgs)
→ *BF modification*

Belle II can reach 3% sensitivity for R(D(*)) → NP?



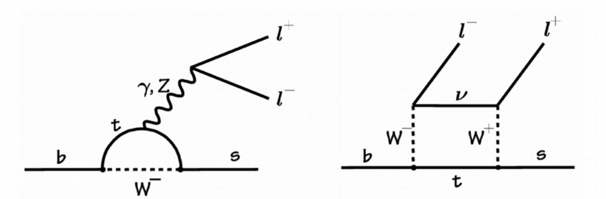
Tuesday: Semileptonic and leptonic B decays at Belle II by **Andreas Warburton**

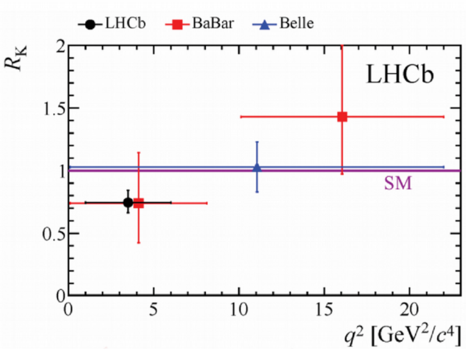
Electroweak Penguins

Lepton Flavor Universality violation in $B^+ \to K^+ l^+ l^-$?

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+\to K^+\mu^+\mu^-]}{dq^2}\,dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+\to K^+e^+e^-]}{dq^2}\,dq^2} \approx 1$$

Confirmation from Belle II will be crucial (good efficiency for electrons and muons in wide q^2 range)





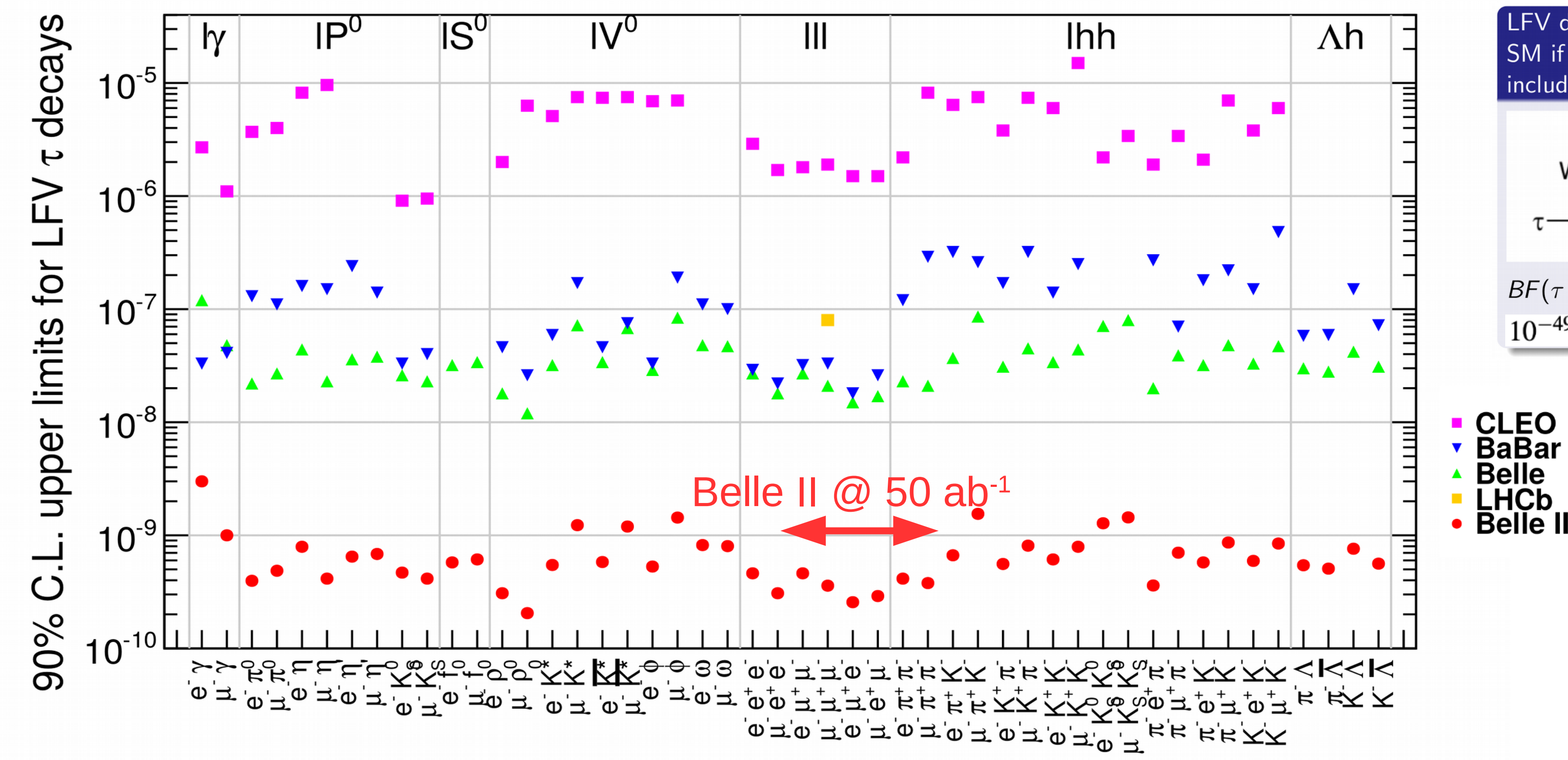
2.6σ tension from latest LHCb measurement

Tau Physics

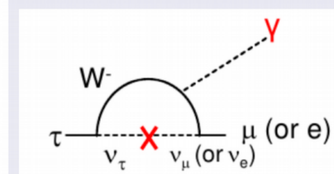
Lepton Flavour Violation in τ decays

- In the SM, lepton flavour violating decays, like $\tau \to \mu\,\gamma$, are forbidden/highly supressed, while NP could enhance their BF's significantly
- Belle II can access final states with neutrals $(\gamma, \pi^0, \eta^{(\prime)}, \ldots)$
- Control of beam backgrounds crucial

Physics models	$B(\tau \to \mu\gamma)$	$B(\tau \to \mu\mu\mu)$
SM + ν mixing	$10^{-49} \sim 10^{-52}$	$10^{-53} \sim 10^{-56}$
SM+heavy Majorana ν_R	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY SO(10)	10^{-8}	10^{-10}
mSUGRA + seesaw	10^{-7}	10^{-9}
SUSY Higgs	10^{-10}	10^{-7}



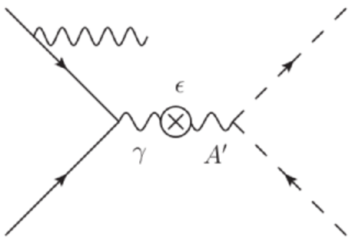
LFV decay only allowed in SM if neutrino mixing included



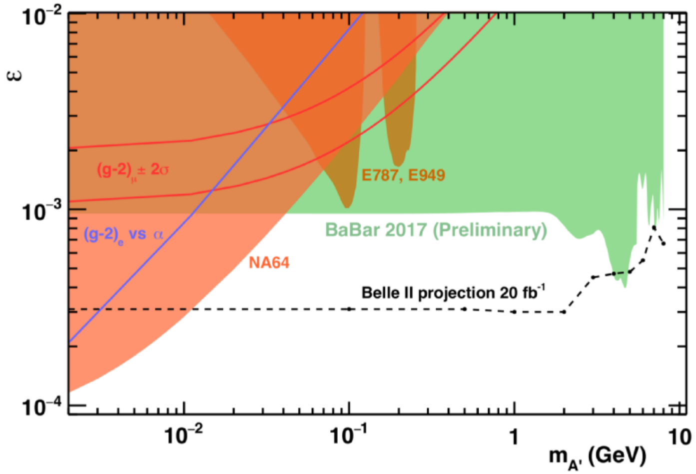
$$BF(\tau \to \ell\gamma) \approx \left(\frac{\Delta m^2_\nu}{m^2_W}\right)^2 \approx 10^{-49} \sim 10^{-52}$$

$e^+e^- \rightarrow$ light hadrons, dark things, spectroscopy, exotic states...

Dark Photon Search



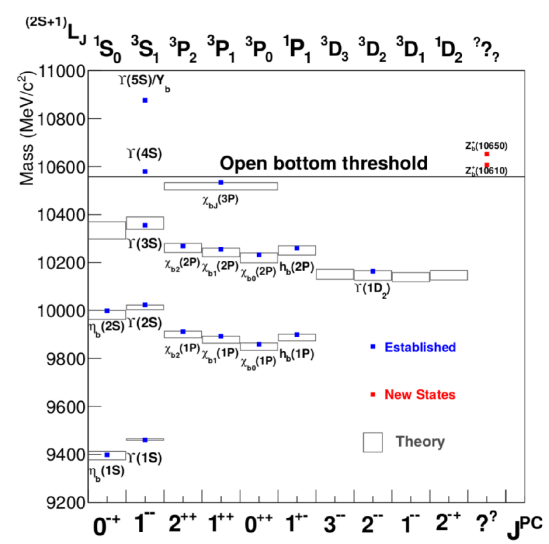
Special single photon trigger required



Early Physics

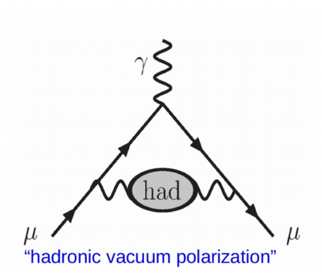
Thursday: First results on DM searches at Belle II by **Michael De Nuccio**

Bottomonium States

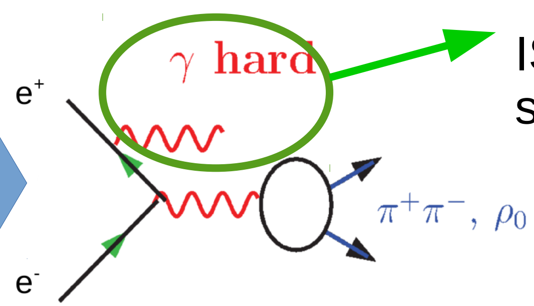


$e^+e^- \rightarrow$ light hadrons

- Long standing discrepancy between theory and experiment in the $(g-2)_\mu$ (3.5 sigma)
- Most of the uncertainity in the theory comes from the hadronic contribution:



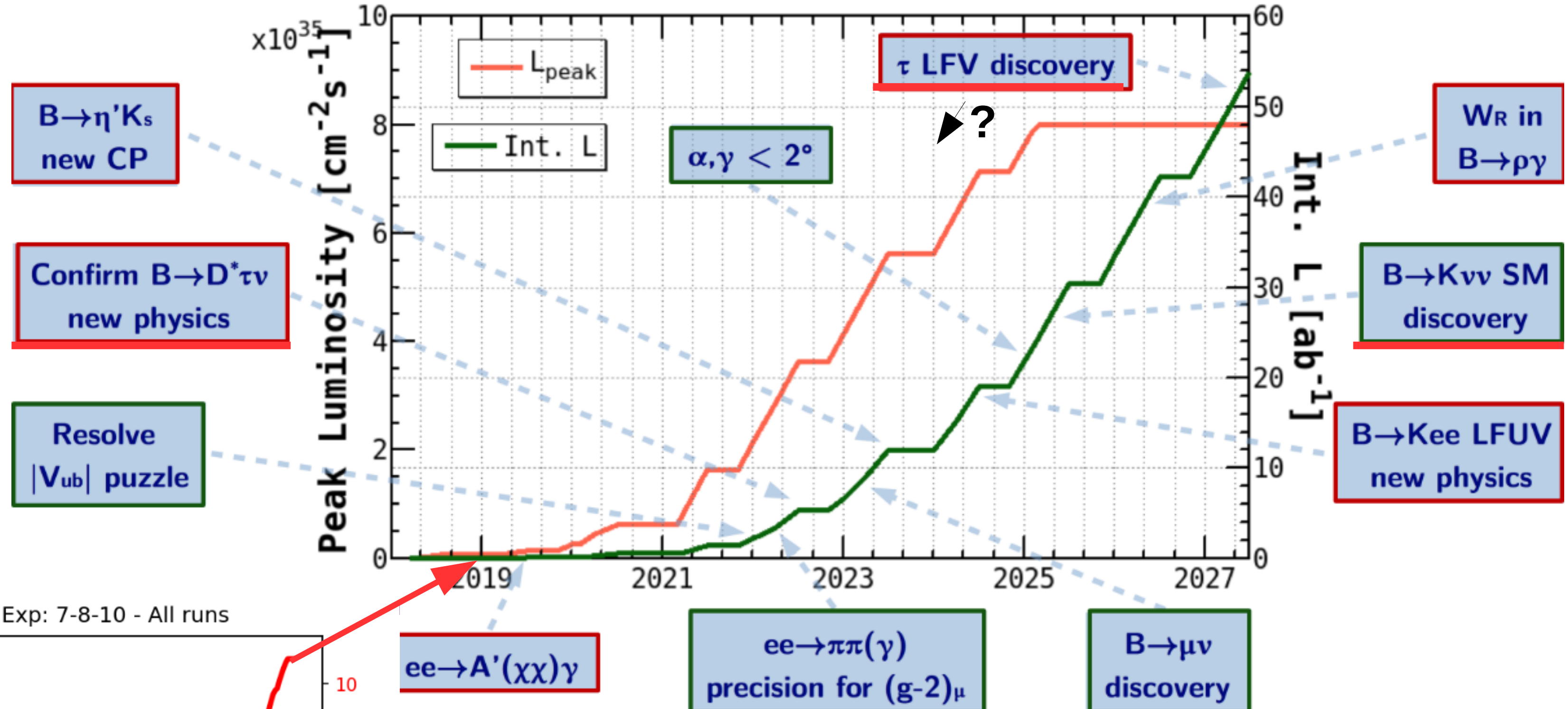
Optical Theorem

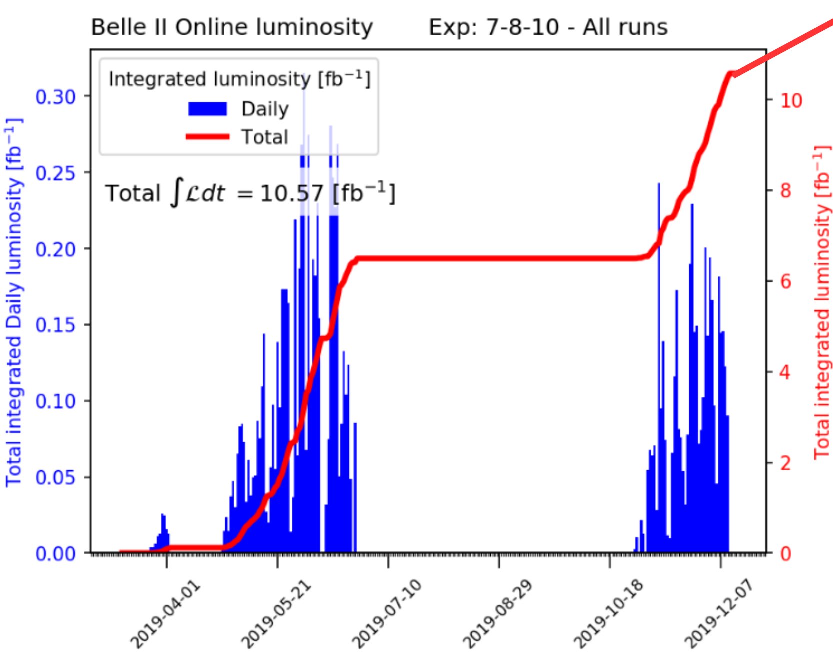


ISR: Energy scan

SuperKEKB/Belle II Status and Vistas

Now
(2019)





- 1 ab^{-1} (= Belle) in 2021
- 5 ab^{-1} in 2022
- 10 ab^{-1} by mid 2023

Sure shot
Wish list

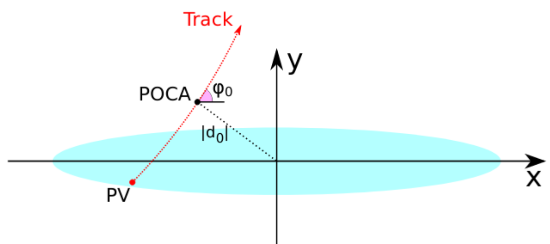
Future
(Data taking restart:
March 2020)

Belle II Performance: Vertex Resolution & D^0 Lifetime

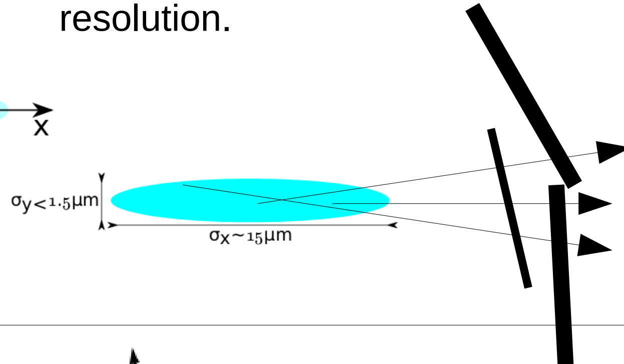
Vertex fit of 2-track events (~Bhabha) selecting "good" tracks with PXD, SVD and CDC hits

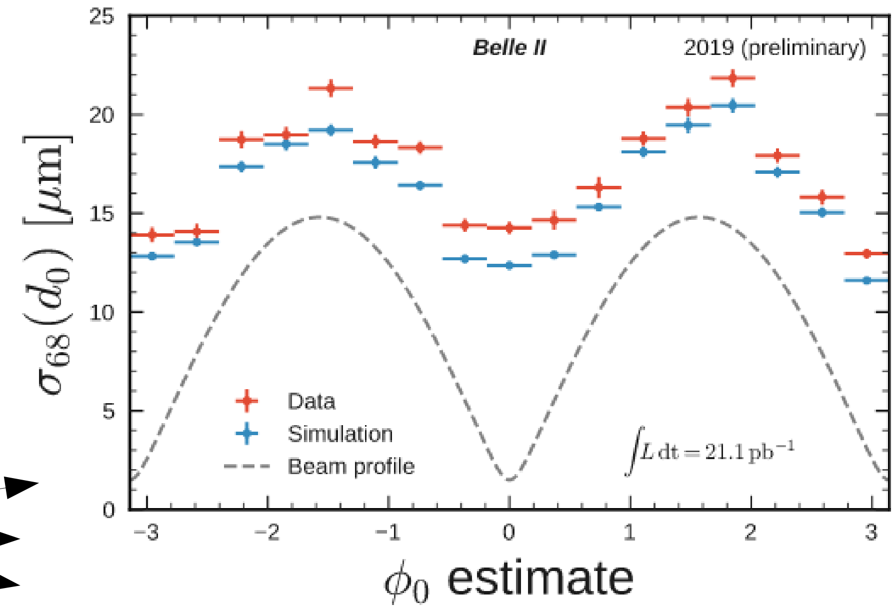
14.1±0.1 (stat) μm resolution

2x better than Belle



Vertical beamspot size < 1.5 μm →
Tracks @ $\varphi_0 = 0, \pm\pi$ measure tranverse impact parameter resolution.

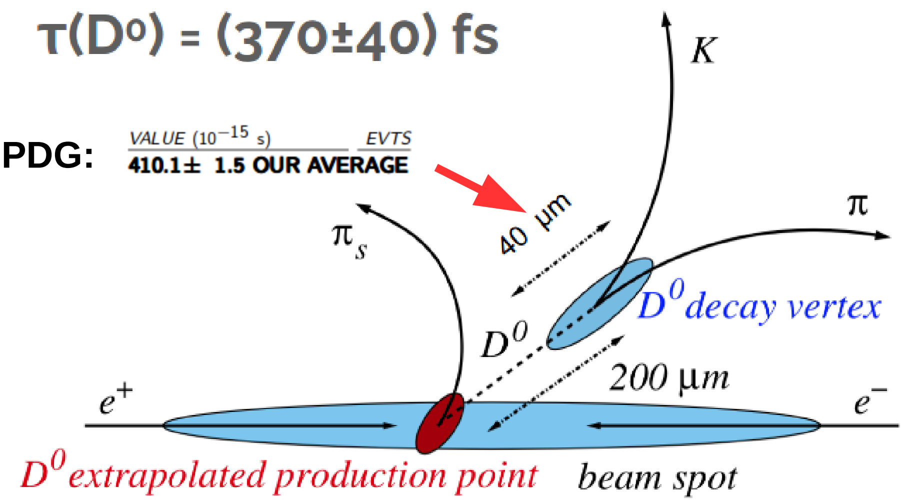


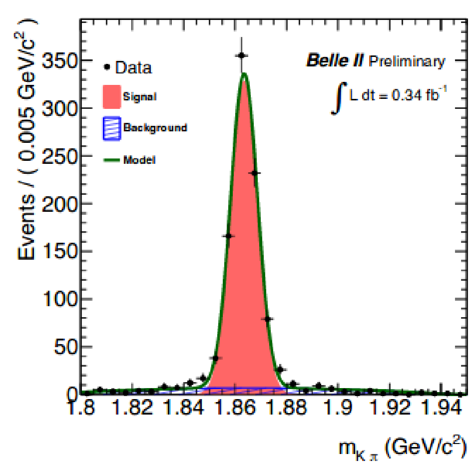


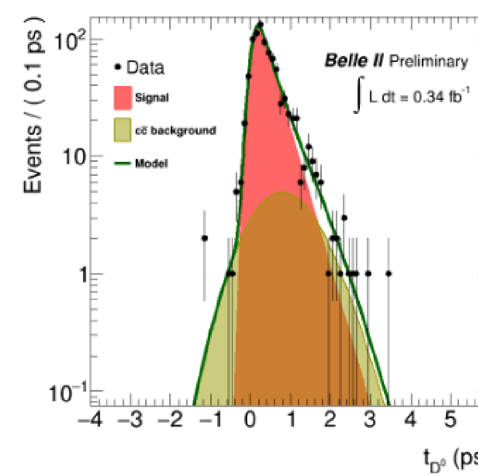
$\tau(D^0)$ = (370±40) fs

PDG:

VALUE $(10^{-15}$ s)	*EVTS*
410.1± 1.5 OUR AVERAGE	







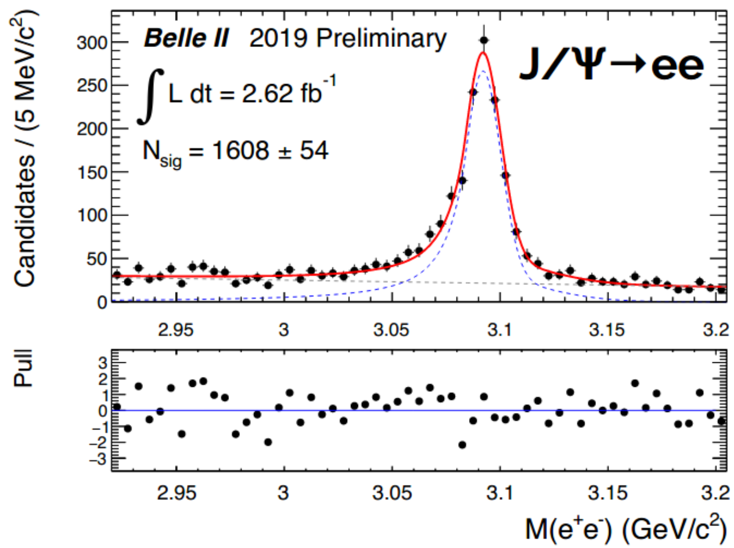
Powerful test of vertex fitting performance. Using global decay-chain fit (TreeFitter).
Shortlived D* constrained to beamspot region.

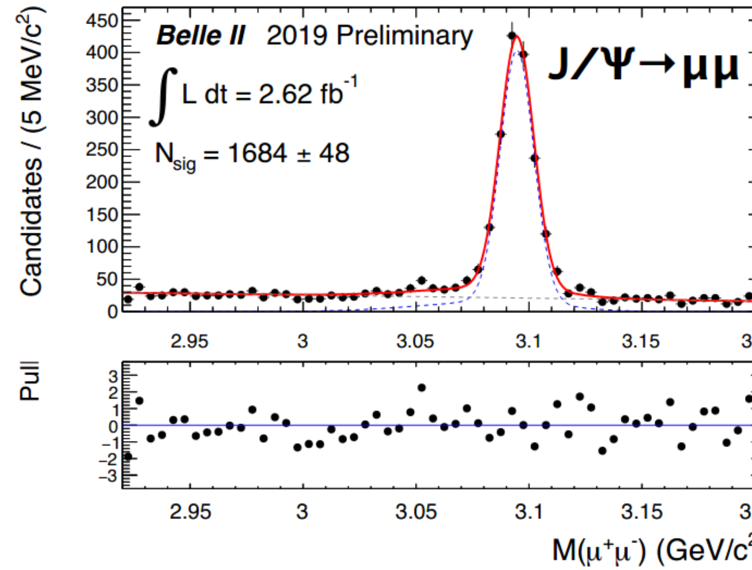
First physics @ $o(10\ \mathrm{fb}^{-1})$

Lepton identification:

Muons & electrons

(Mostly calorimeter + muon system)



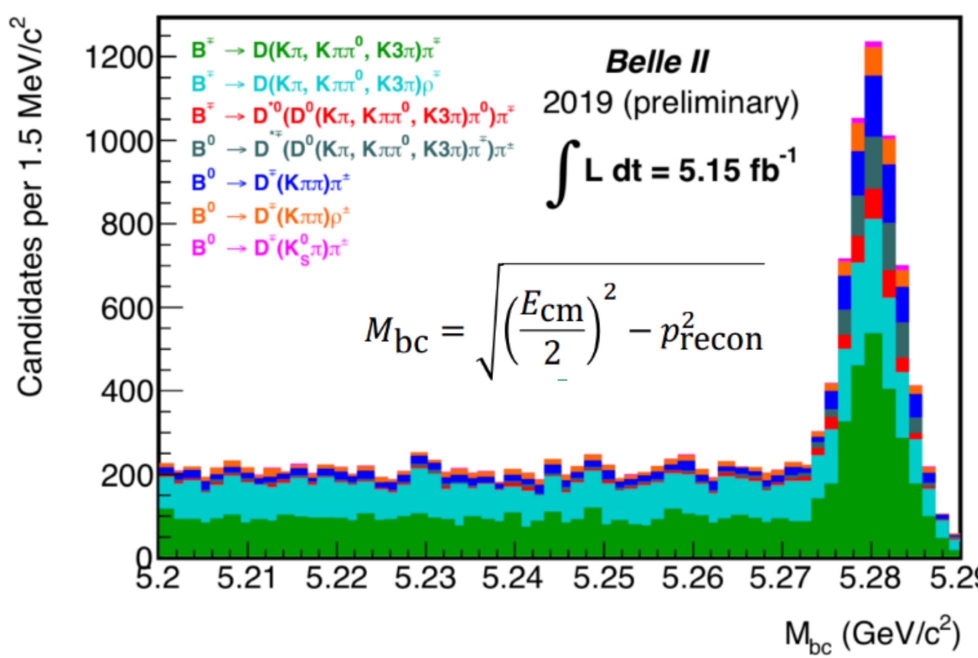


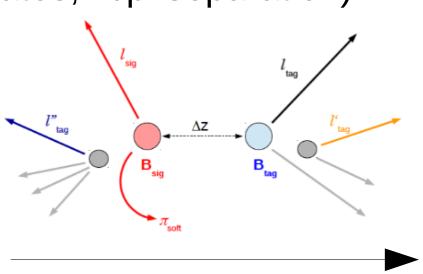
Rediscovery of B-mesons:

Modes with neutrals efficiently reconstructed along with all-charged final states with kaons and pions

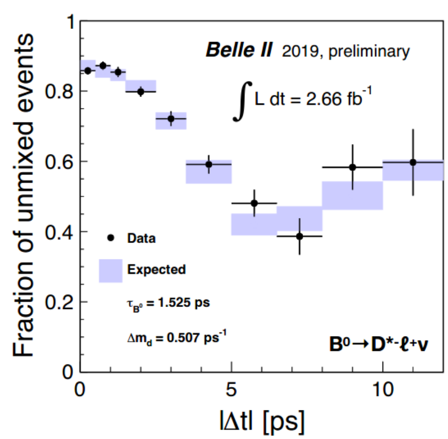
(Demonstration of Belle II capabilities – neutrals in final states, K/pi separation)

BELLE2-NOTE-PL-2019-028





Rediscovery of $B\bar{B}$ **mixing**:

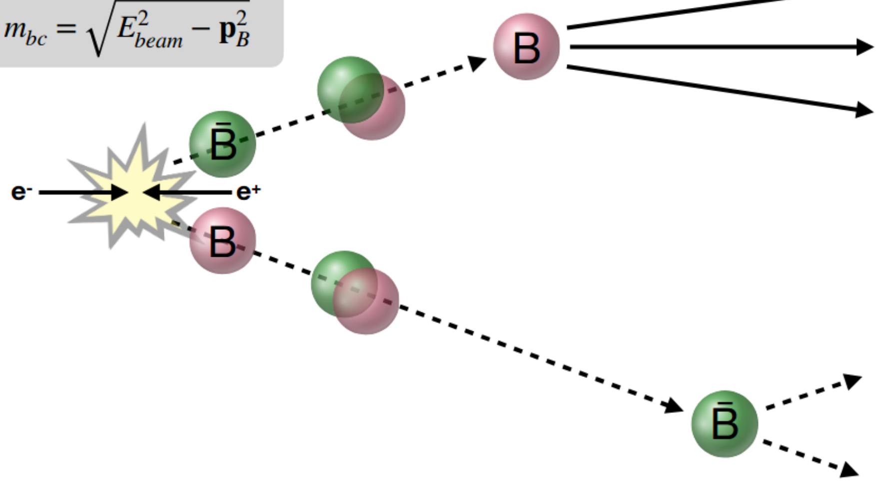


Full Event Interpretation (new @ Belle II)

arXiv:1807.08680; Comput. Softw. Big Sci. (2019) 3:6

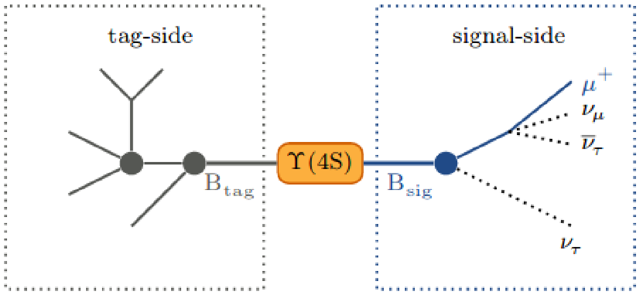
Initial four-momentum exactly known:

$$m_{bc} = \sqrt{E_{beam}^2 - \mathbf{p}_B^2}$$



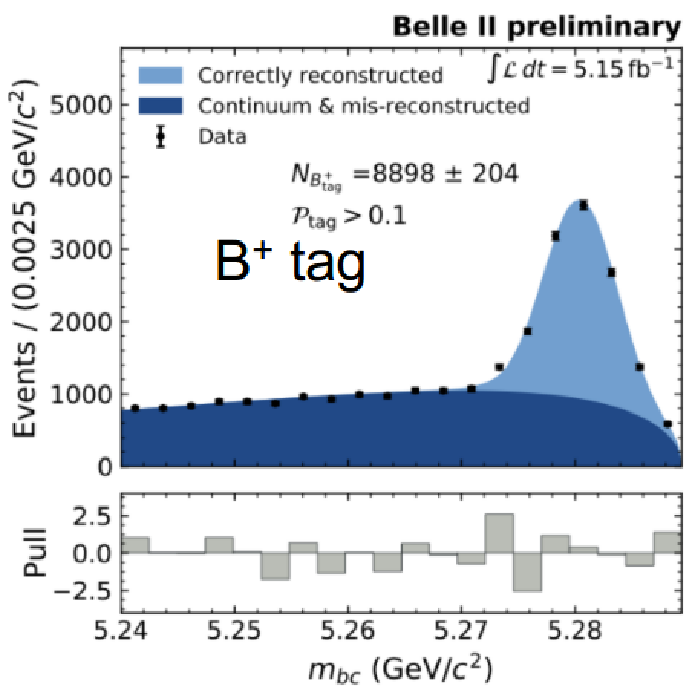
Fully reconstruct one of the B mesons: **FEI**

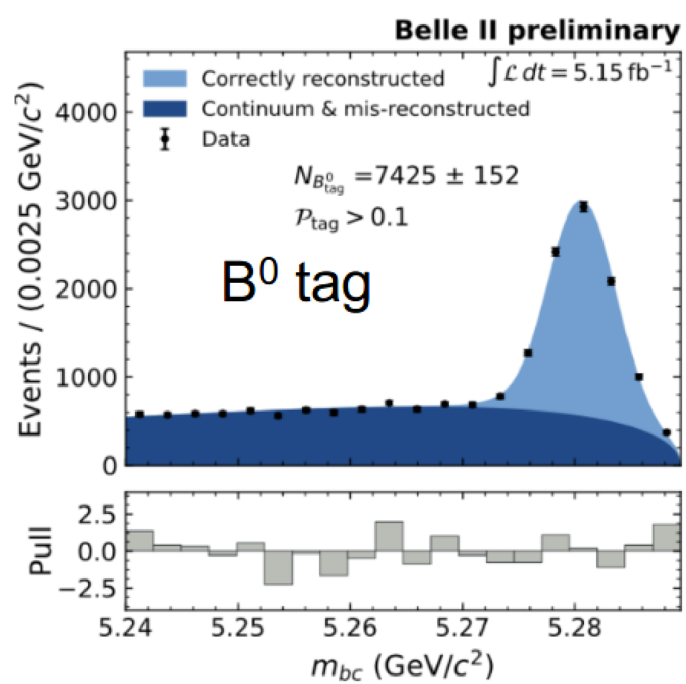
Overconstrain second B meson: Neutrino(s) in the final state, …



O(100) channels reconstructed

- Initial state known
- Fully reconstructed event
- Access to missing energy/momentum – final states with neutrinos

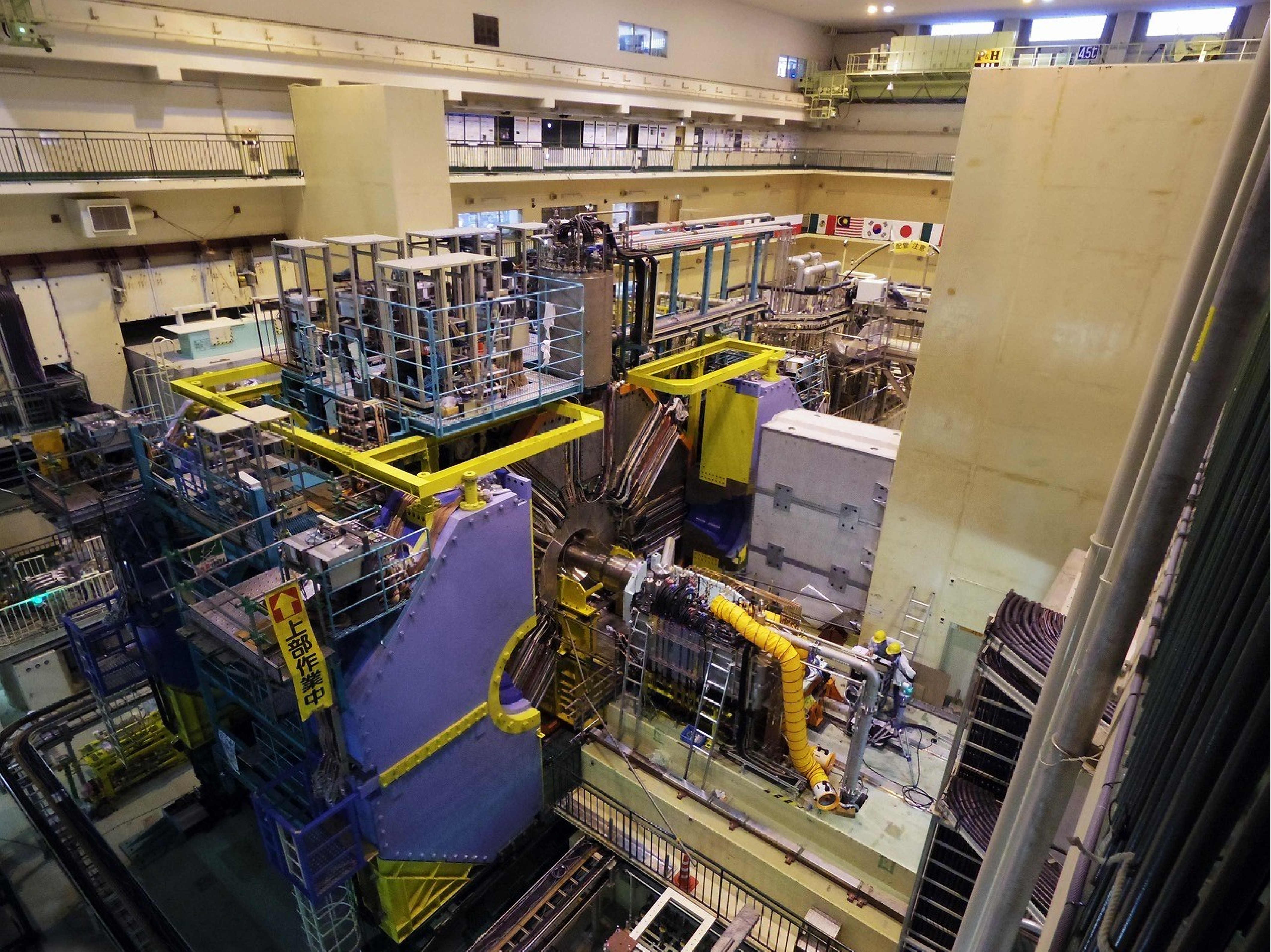




Summary

- First data from new generation Super-B-factory!
- Belle II will join LHCb in the hunt for New Physics just in time – competitive but also complementary
- Several tensions in SM known, Belle II can give definitive resolution
- If NP found at LHC, Belle II could reveal its flavour structure and/or weak phases. If not, precision measurements at Belle II even more important
- Physics run continues from March 2020 – goal of $O(100\ fb^{-1})$ for summer conferences

Thank you for your attention!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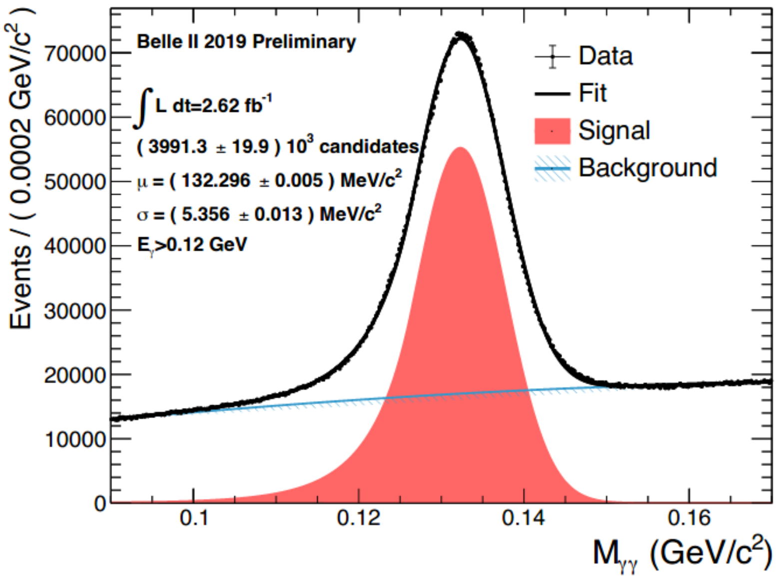
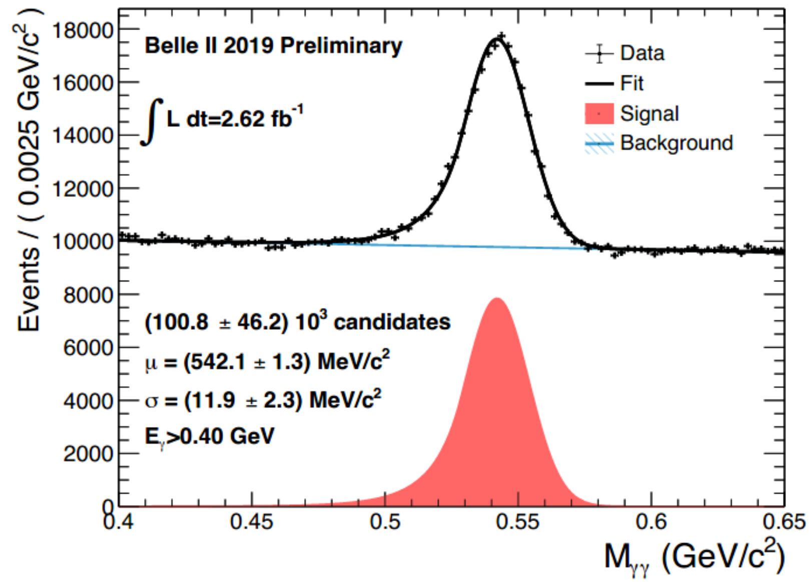
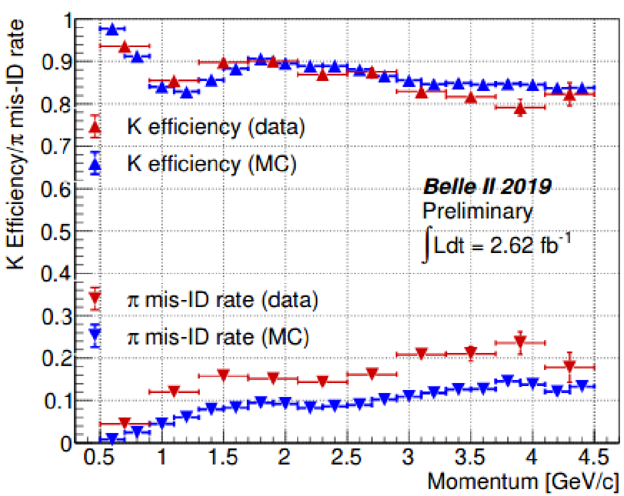
Belle II Performance: Reconstruction of neutrals, hadron PID (K/p

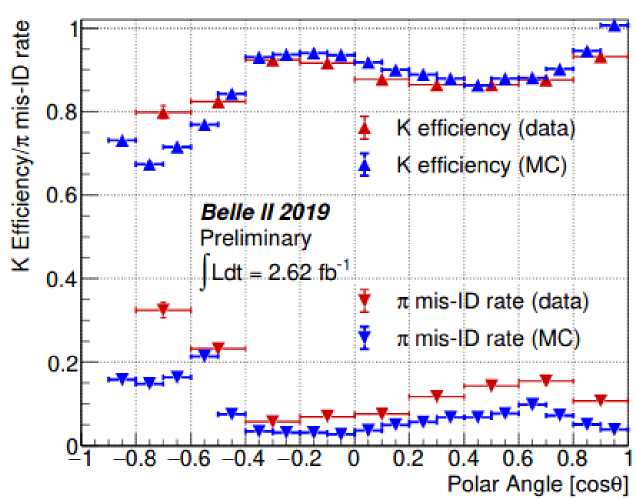
$\pi^0 \to \gamma\gamma$



$\eta \to \gamma\gamma$







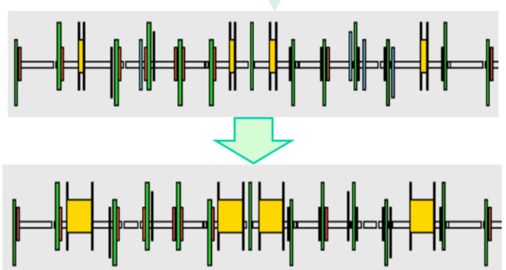
CDC, TOP (barrel) and ARICH (endcap)

Select $D^* \to D^0(K\pi)\,\pi_s$

Tag (Kπ) charge via slow pion charge

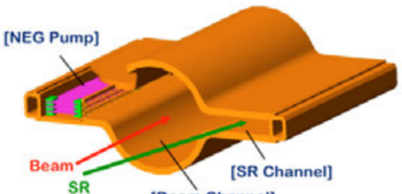
KEKB → SuperKEKB

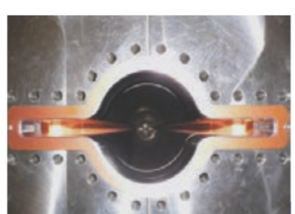
Replace short dipoles with longer ones (LER)

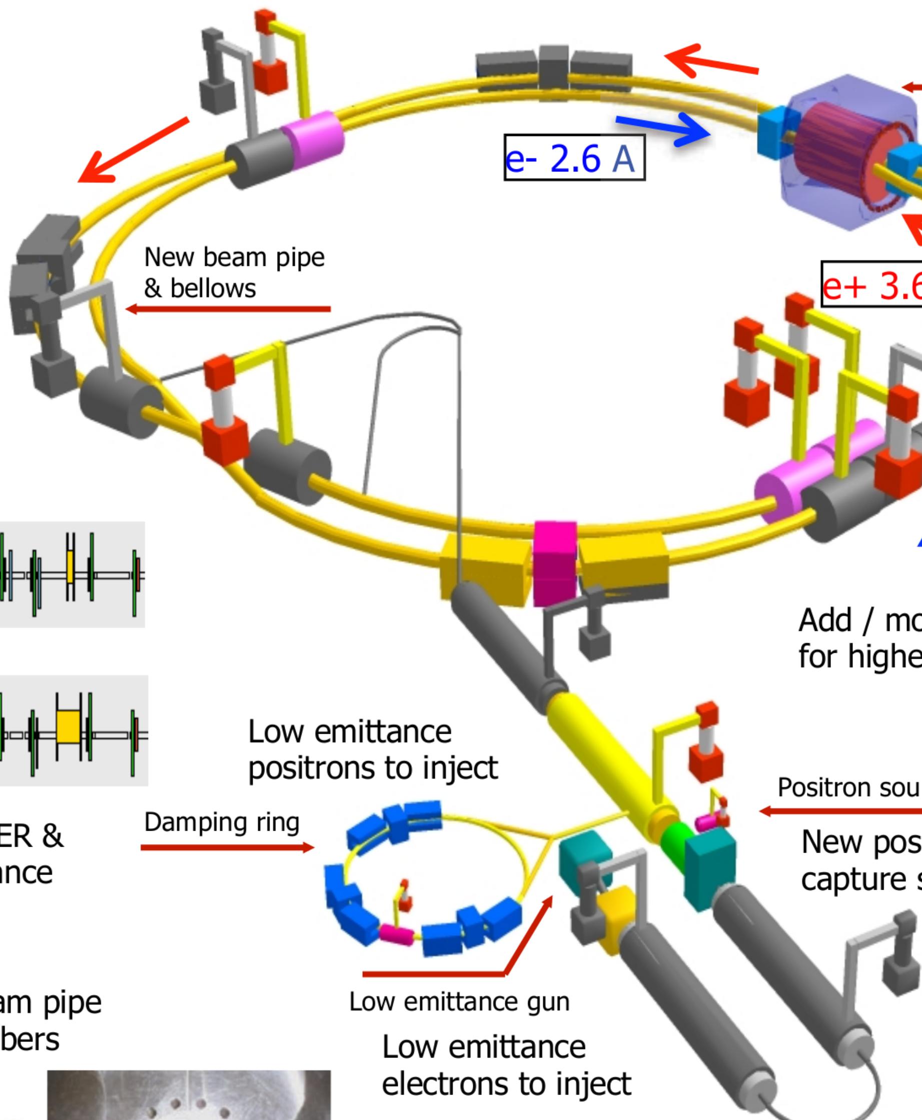


Redesign the lattices of HER & LER to squeeze the emittance

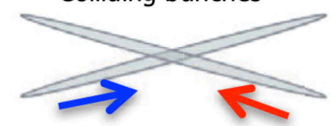
TiN-coated beam pipe with antechambers







Colliding bunches



New superconducting / permanent final focusing quads near the IP

Add / modify RF systems for higher beam current

New positron target / capture section

Belle II & LHCb

Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II
$\lvert V_{ub}\rvert$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	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			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	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

	Observables	Belle or LHCb* (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 2018	LHCb 50 fb^{-1}
Charm Rare	$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$	2.9%	0.9%		
	$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$	3.5%	2.3%		
	$\mathcal{B}(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5	30%	25%		
Charm CP	$A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	$-32 \pm 21 \pm 9$	11	6		
	$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-3}]$	3.4*			0.5	0.1
	A_Γ $[10^{-2}]$	0.22	0.1	0.03	0.02	0.005
	$A_{CP}(D^0 \to \pi^0\pi^0)$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$	0.29	0.09		
	$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	$-0.21 \pm 0.16 \pm 0.09$	0.08	0.03		
Charm Mixing	$x(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	0.14	0.11		
	$y(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	0.08	0.05		
	$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	0.10	0.07		
	$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	$-6 \pm 11 \pm {}^{4}_{5}$	6	4		
Tau	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45	< 14.7	< 4.7		
	$\tau \to e\gamma$ $[10^{-9}]$	< 120	< 39	< 12		
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0	< 3.0	< 0.3		

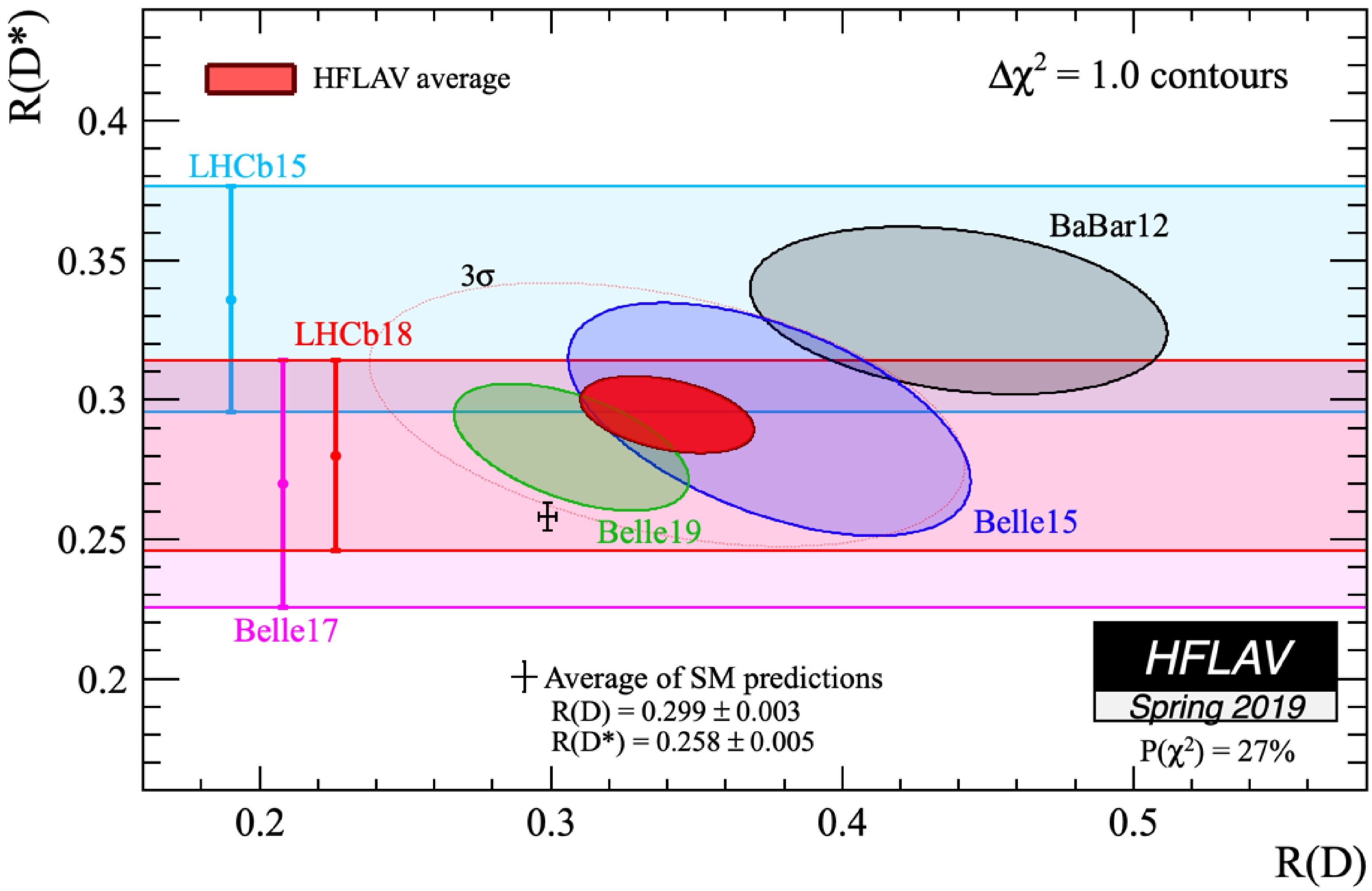
Phase 2 Physics

WG	Mode	Description	Benchmark study or Unique measurement?
Semileptonic	B→X l ν	Benchmark analysis in Υ(4S)	Benchmark
Semileptonic	B(s)→X l ν in Υ(6S), Di-leptons	B and B_s counting in Υ(6S)	Unique
EWP	B→K*γ	Benchmark analysis in Υ(4S)	Benchmark
BtoCharm	B → Dπ. D*π, D → hh, K_S X	Benchmark analysis in Υ(4S)	Benchmark
Bottomonium	Υ(6S) → ππ + Υ(nS)/hb	Zb substructure	Unique
Bottomonium	Υ(6S) cross section, R_b	Cross section measurement and Rb decomposition at Υ(6S)	Unique
Bottomonium	π π Υ(pS)	ECM 10.75 GeV decay → π π Υ(pS)	Unique
Low-multiplicity	ee → γ A', A'→ missing	Dark matter via dark photon	Unique
Low-multiplicity	ee → γ A'→ γ γ	Axion like dark sector for large A' masses (tri-photon final state)	Unique

Expected data sample @ full luminosity

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

assuming 100% running at each energy



HFLAV average
Δχ² = 1.0 contours
R(D*)
0.4
0.35
0.3
0.25
0.2
LHCb15
BaBar12
3σ
LHCb18
Belle19
Belle15
Belle17
HFLAV
Spring 2019
P(χ²) = 27%
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
0.2
0.3
0.4
0.5
R(D)

Expected SuperKEKB Backgrounds

Phase I (no collisions)

Touschek scattering:

- intra-bunch scattering process
- dominant with highly compressed beams
- 20 times higher

Beam-gas scattering:

- Bremsstrahlung (negligible) & Coulomb interactions (up to 100 times higher) with residual gas atoms & molecules

Synchrotron radiation:

- emission of photons by charged particles (e^+e^-) when deflected in *B*-field

Phase 2 (collisions)

Radiative Bhabha process:

photon emission prior or after *Bhabha* scattering
interaction with iron in the magnets leads to neutron background

Two photon process:

- very low momentum e^+e^- pairs via $e^+e^- \rightarrow e^+e^-e^+e^-$
- increased hit occupancy in inner detectors

Injection Background:

- covered later in the talk