The Belle II Experiment

천병구 (한양대)

On behalf of the Belle II Collaboration

KPS-DPF Workshop, Nov/3-4/2020

Why SuperKEKB/Belle II ?

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor		Mass GeV/c^2	Electric charge
ν_L	lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e	electron	0.000511	–1
ν_M	middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ	muon	0.106	–1
ν_H	heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ	tau	1.777	–1

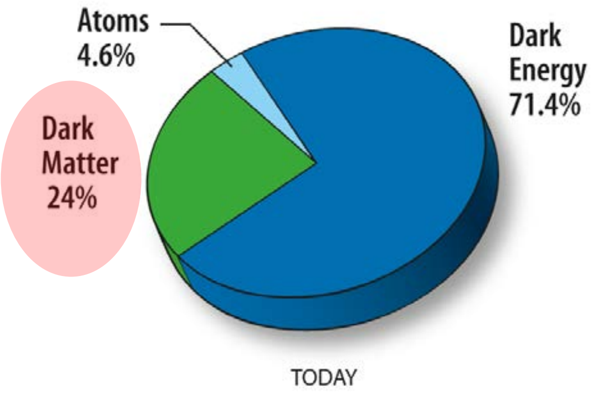
Quarks spin =1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.002	2/3
d	down	0.005	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	173	2/3
b	bottom	4.2	–1/3

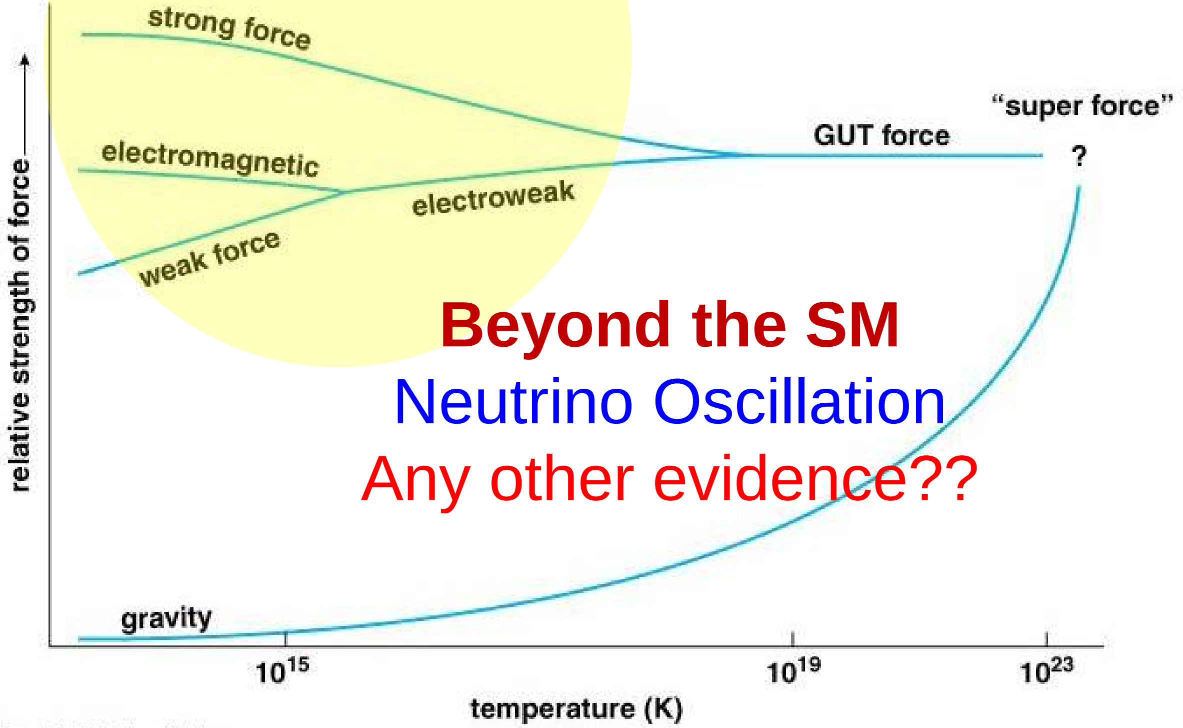
Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60



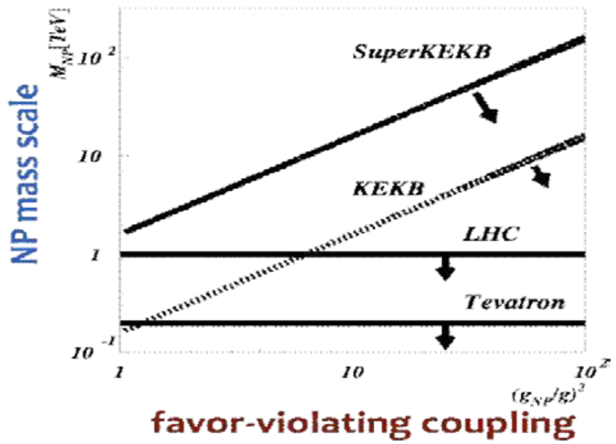
Standard Model
Higgs discovery
CPV in B decay



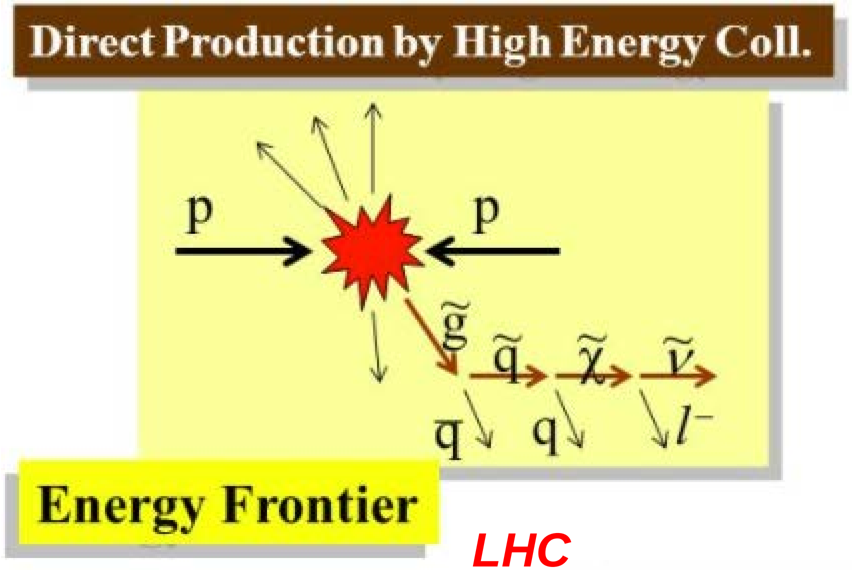
Beyond the SM
Neutrino Oscillation
Any other evidence??

Why SuperKEKB/Belle II ?

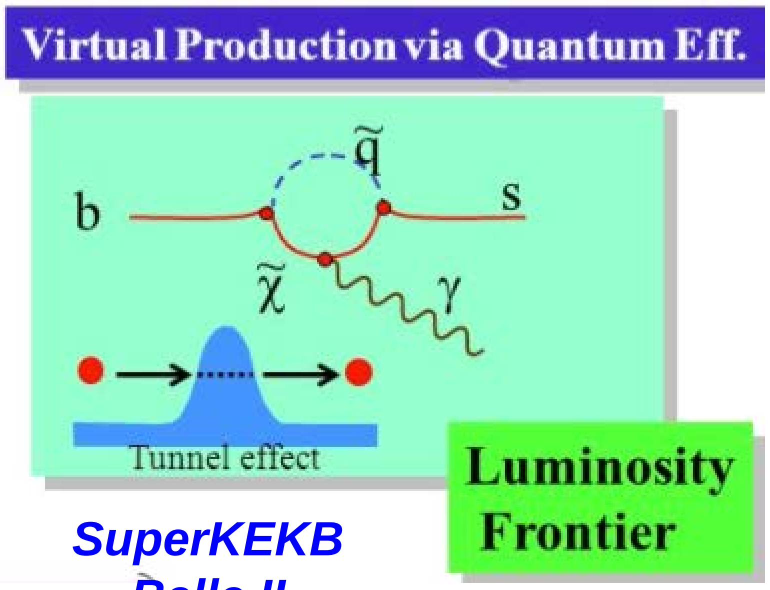
- No evidence of New Physics from LHC
  - After Higgs particle discovery in 2012
- New Physics beyond the Standard Model
  - Direct new particle production : ATLAS/CMS @LHC
  - Indirect new particle contribution : **Belle II @SuperKEKB**



LHC 실험과 Belle II 실험의 상보성



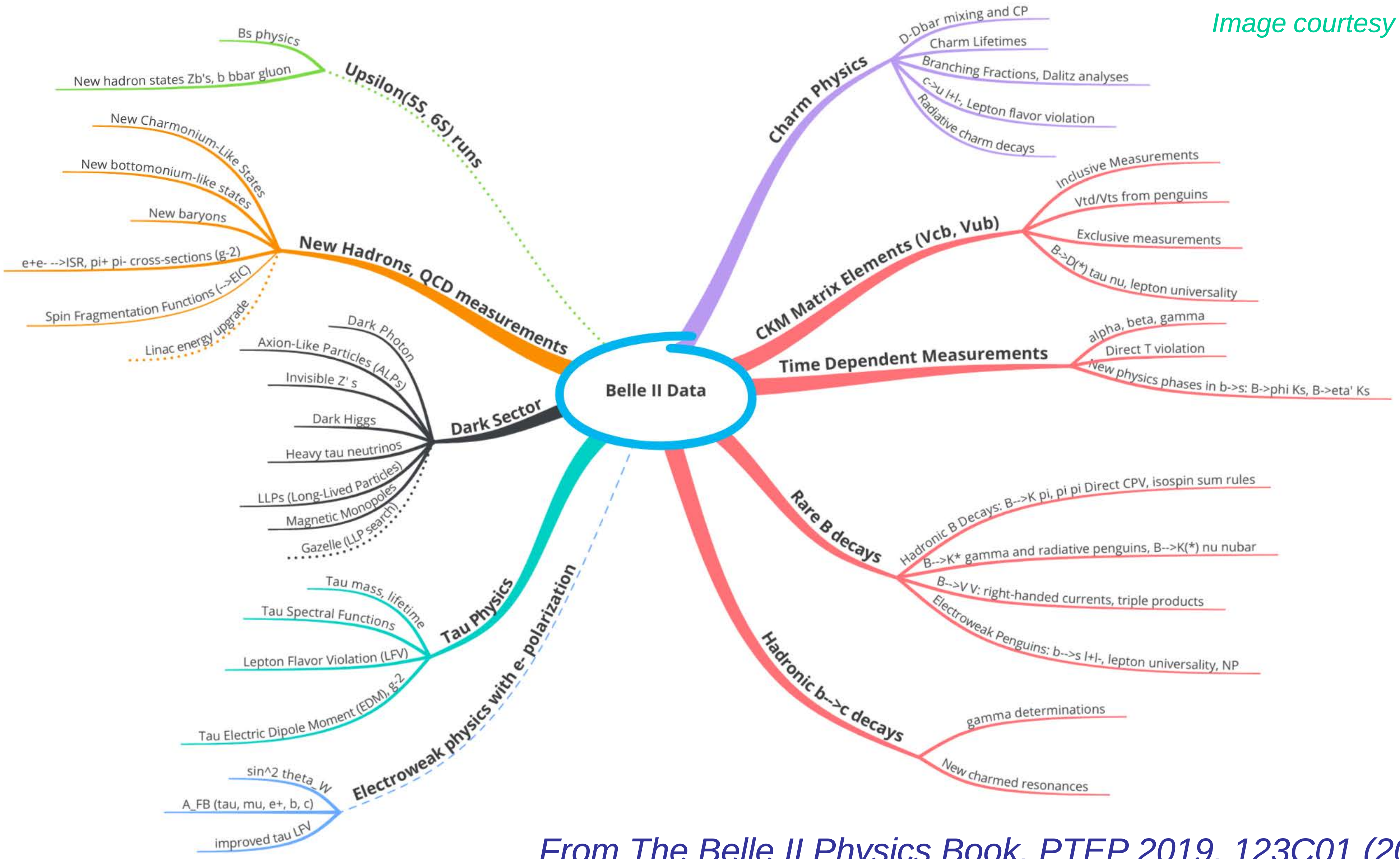
LHC
ATLAS,CMS



SuperKEKB
Belle II

Belle II Physics "Mind Map" for Snowmass-2021

Image courtesy of Tom Browder

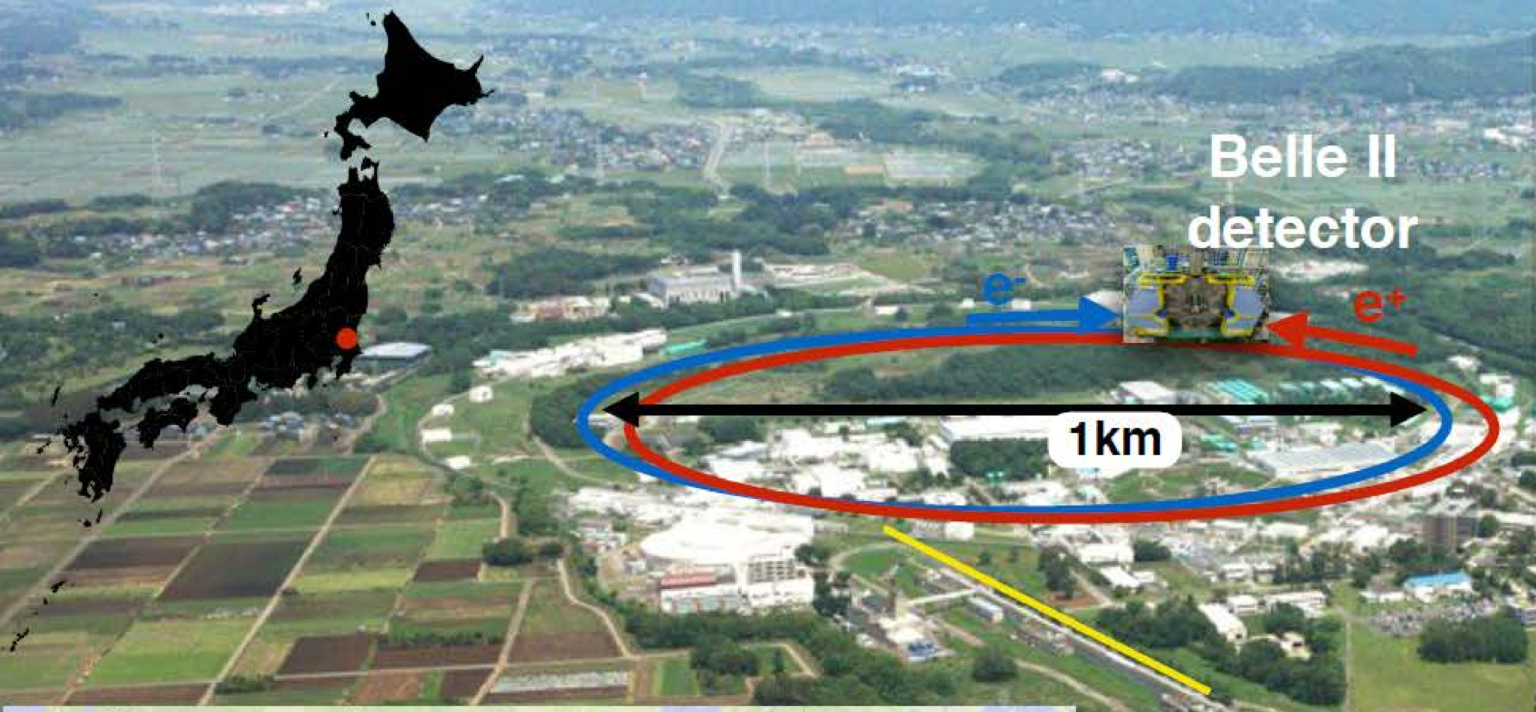


From The Belle II Physics Book, PTEP 2019, 123C01 (2019)

Belle II @ SuperKEKB

Belle II @ Super-KEKB

Intensity frontier B-factory experiment, Successor to Belle @KEKB (1999-2010)



7 GeV e^-, 4 GeV e^+

E_{CM} Y(4S) = 10.58 GeV + scans

Y(4S) → B anti-B

B + Charm + τ factory

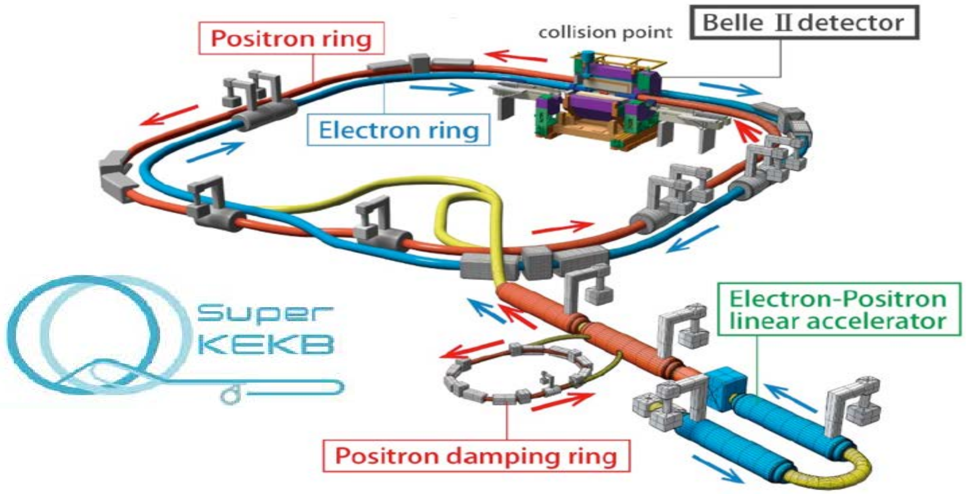
1050 Belle II collaborators
from 120 institutions in 26 countries

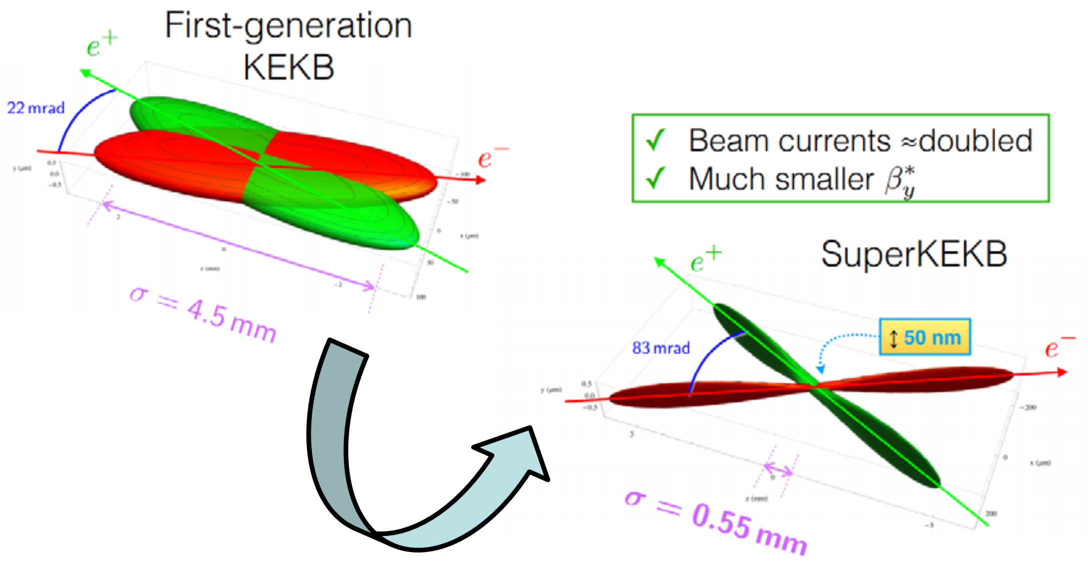
Belle II @ SuperKEKB

- Successor to Belle at KEKB (1.05 ab^{-1})
- No enough Belle data for **the New Physics beyond the SM**
- Plan to collect **50 ab^{-1}** of collisions at and near Υ(4S)
- SuperKEKB instantaneous luminosity goal is 8 x $10^{34}/cm^2/sec$

	E(GeV) e+ / e-	β^*_y e+ / e-	I(A) e+ / e-	Peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)
KEKB	3.5 / 8.0	5.9 / 5.9	1.6 / 1.2	2.1 × 10^{34}
SuperKEKB	4.0 / 7.0	0.27 / 0.30	3.6 / 2.6	**80 × 10^{34}**

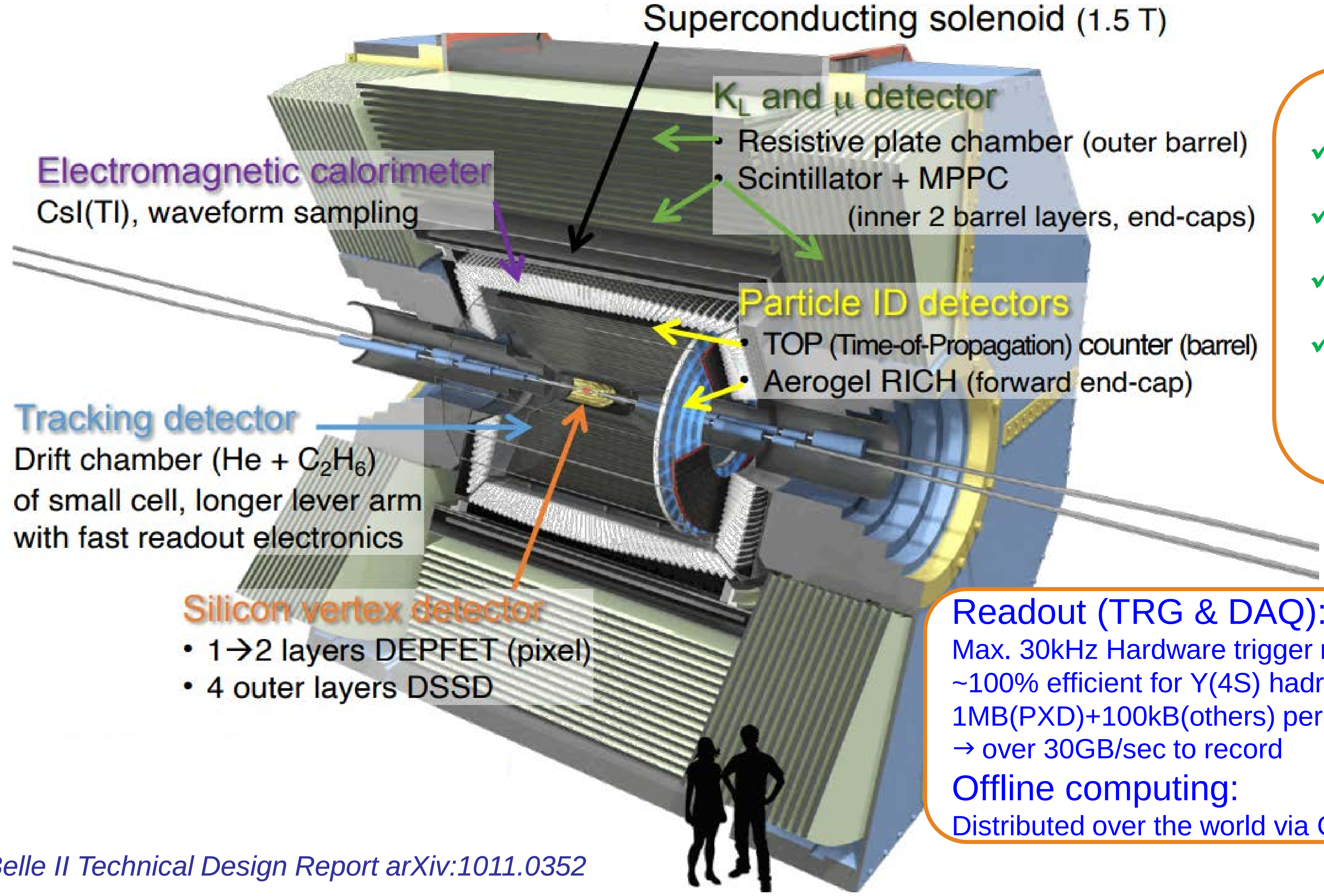
- Beam current: ×2 (High RF power)
- Beam size: 1/20 (Nano-beam; low emittance, compact and strong focusing quads; QCS)





Nano-beam scheme invented by Pantaleo Raimondi for Italian SuperB Factory

The Belle II detector



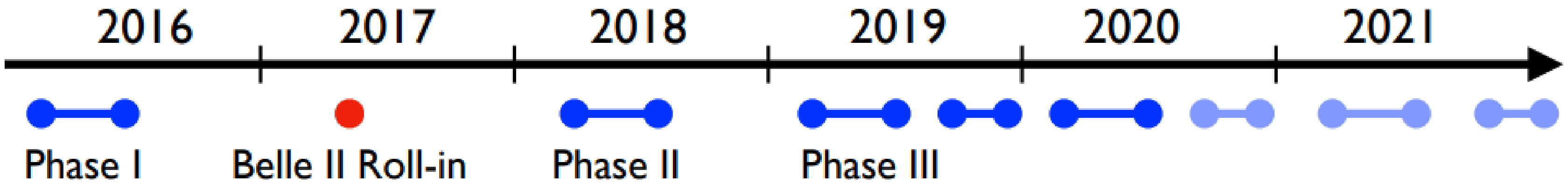
- ✓ Higher event rate :TRG/DAQ
- ✓ Improved vertexing/tracking
- ✓ Improved Particle-ID (K/π/p)
- ✓ Better beam background insensitivity

Readout (TRG & DAQ):
Max. 30kHz Hardware trigger rate
~100% efficient for Υ(4S) hadronic events.
1MB(PXD)+100kB(others) per event
→ over 30GB/sec to record
Offline computing:
Distributed over the world via GRID

Belle II Technical Design Report arXiv:1011.0352

Belle II Operation

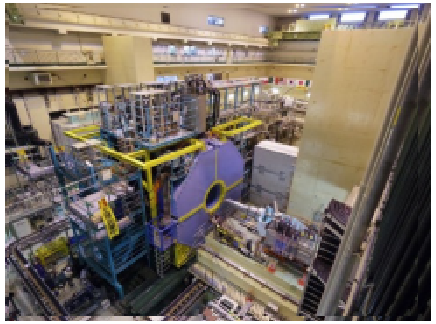
SuperKEKB/Belle II Operation History



Phase 1 (w/o QCS/Belle II)
- Accelerator tuning w/ single beams

Phase 2 (w/ QCS/Belle II but w/o VXD)
- Verification of nano-beam scheme
- Understand beam background
- Collision data w/o VXD

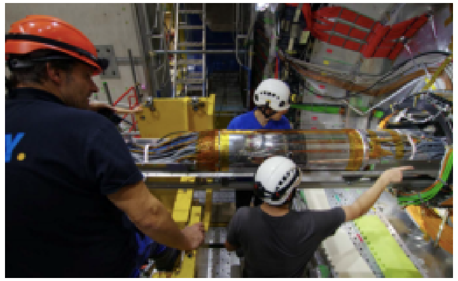
Phase 3 (w/ full detector)
- Production of physics data



Belle II roll-in (2017.4.17)

1st collision (2018.4.26)

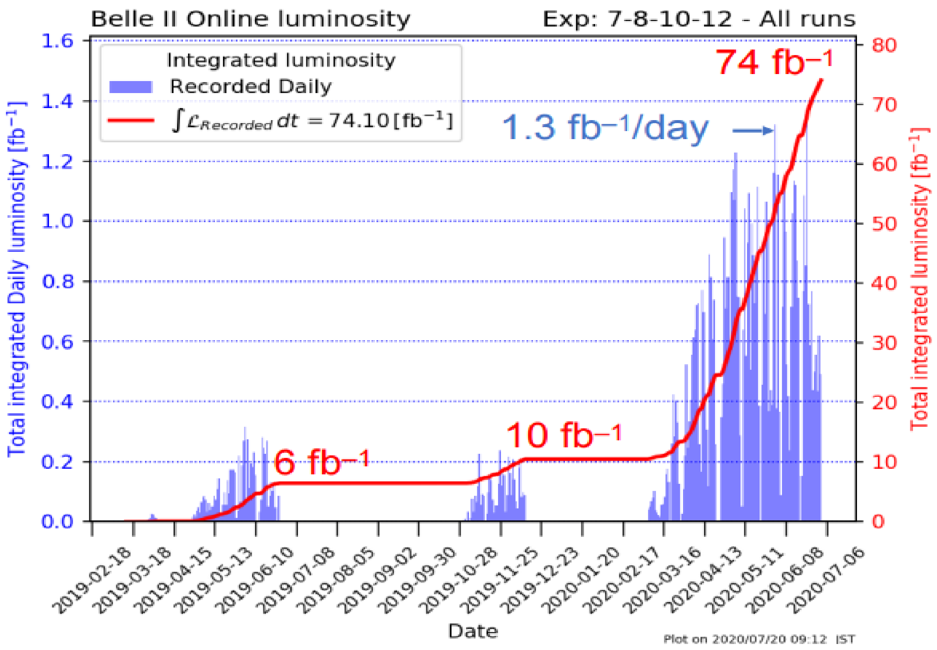
Installation of VXD

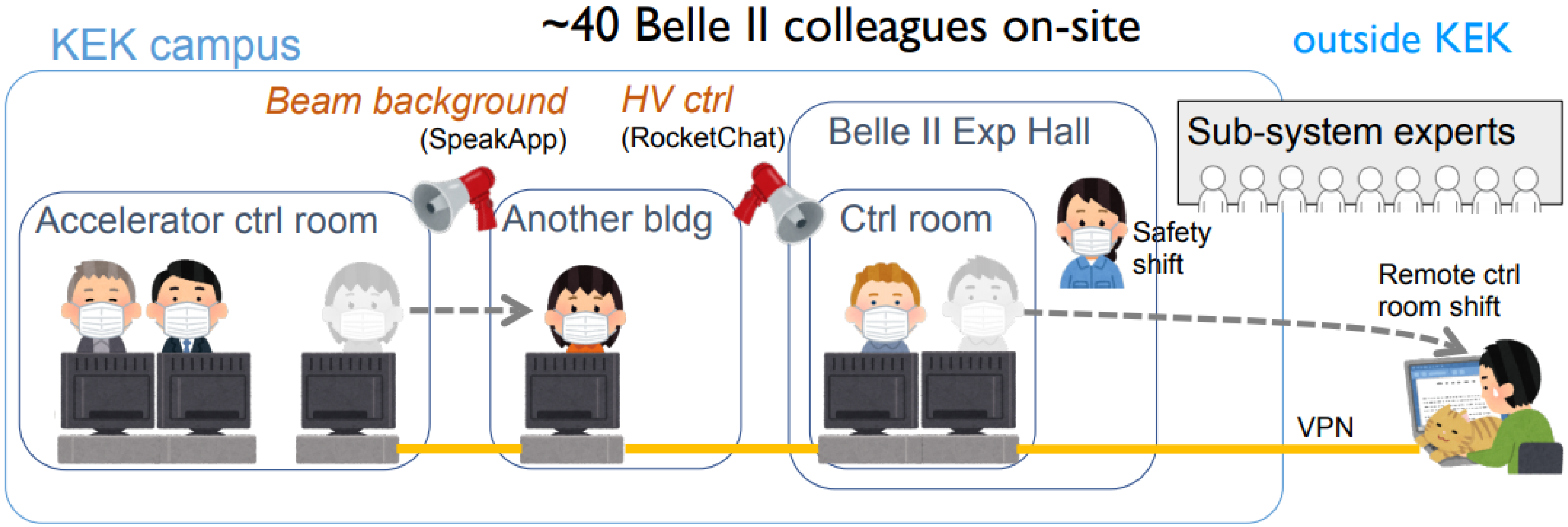


Phase 3 physics run (2019.3.25~)

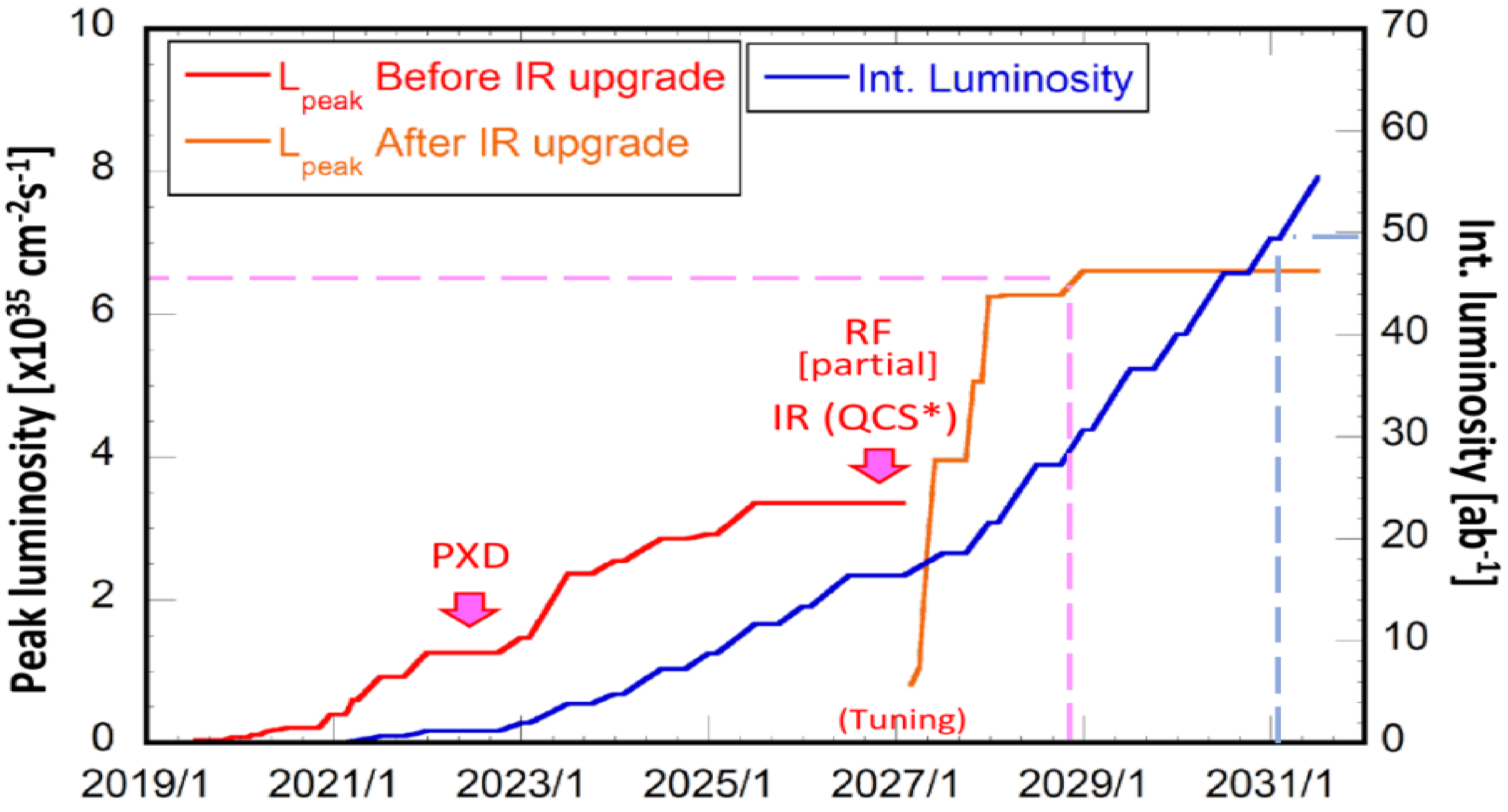
Belle II operation status

- Collected 74 fb^{-1} by last summer
- World record peak luminosity
  - 2.4×10^{34} /cm^2/sec (June 15th 2020)
- Data taking continued in 2020 against COVID-19 pandemic with caution
- Resumed Belle II operation in October
- Expect to collect 100 fb^{-1} by December
- Expect to collect ~ 1 ab^{-1} by JFY2021





Plan for the Long-term Operation



2 steps
+
2 steps

- Intermediate peak luminosity : (1-2 $\times 10^{35}$/cm^2/sec, 5 ab^{-1})
- High peak luminosity : (6.5 $\times 10^{35}$/cm^2/sec, 50 ab^{-1}) with a detector upgrade
- Beam polarization upgrade, advanced R&D
- Ultra high luminosity : (4 $\times 10^{36}$/cm^2/sec, 250 ab^{-1}), R&D project

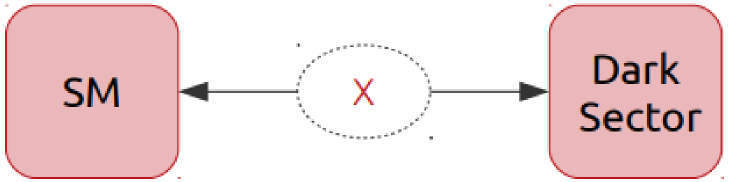
Belle II Results

Belle II Physics Results

- Many re-discoveries and performance studies on Phase 2 data
- 2 Dark Sector PRL publications on Phase 2 data in 2020
  - Search for an Invisibly Decaying Z' Boson at Belle II in $e^+e^- \rightarrow \mu^+\mu^-(e^+\mu^-)$ Plus Missing Energy Final States
  - Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II
- 12 spring/summer conference papers in 2020
- Getting ready to produce competitive results in B, charm, tau decays
- More information available here

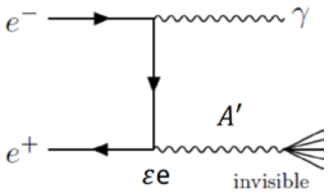
Dark sector search @ Belle II

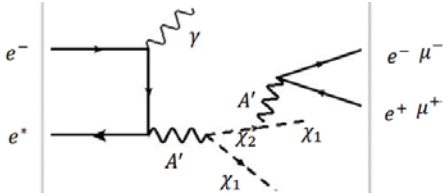
In recent years the possibility that both DM and the particles mediating its interactions to the Standard Model (SM) have a mass of MeV to GeV–scale has gained much attraction.

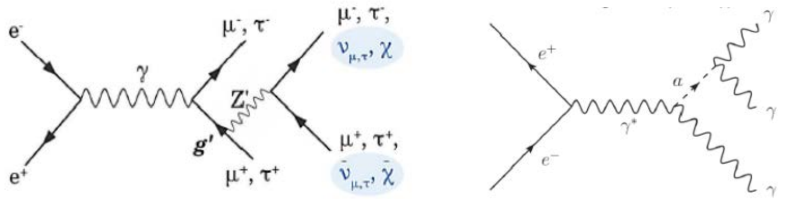


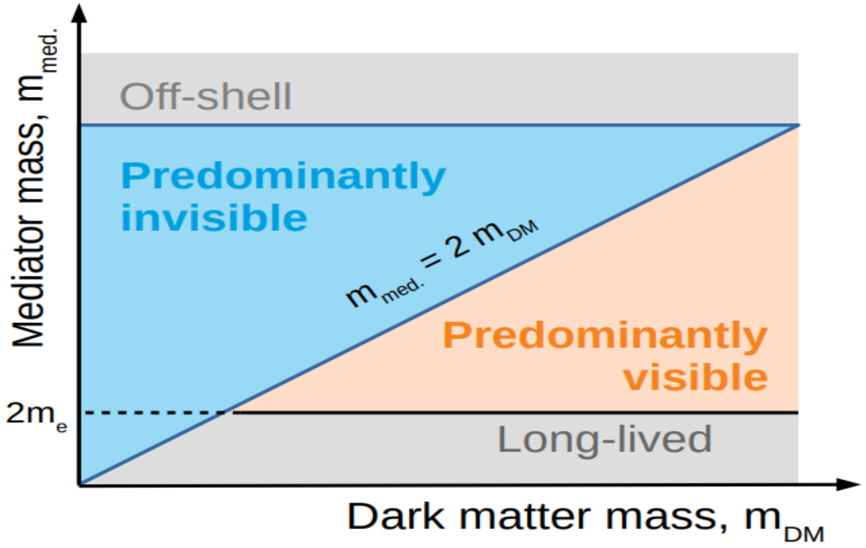
- There is a small number of possible portals between dark sector and standard model:

1) VECTOR PORTAL (dark photon A’, dark Z’, iDM);
2) PSEUDO-SCALAR PORTAL (Axion-Like particle);
3) SCALAR PORTAL (dark scalars, extended higgs model);
4) NEUTRINO PORTAL (sterile neutrino)









Belle II has a perfect environment where to search for dark matter or mediators :

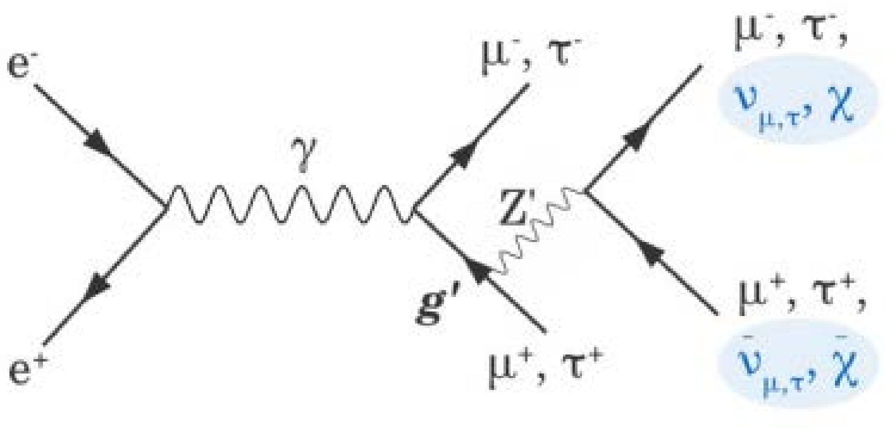
- ✓ Hermetic 4π-detector and well-known initial conditions;
- ✓ Minimal background from collision pile-up;
- ✓ Excellent PID;
- ✓ Dedicated triggers for low multiplicity events

Search for Z' → Invisible

L_μ - L_τ model* :

- suggest new light gauge boson Z' only interacting with the second and the third generation of leptons;
- would explain $(g\text{-}2)_\mu$ anomaly, $b \to s\mu\mu$ anomalies

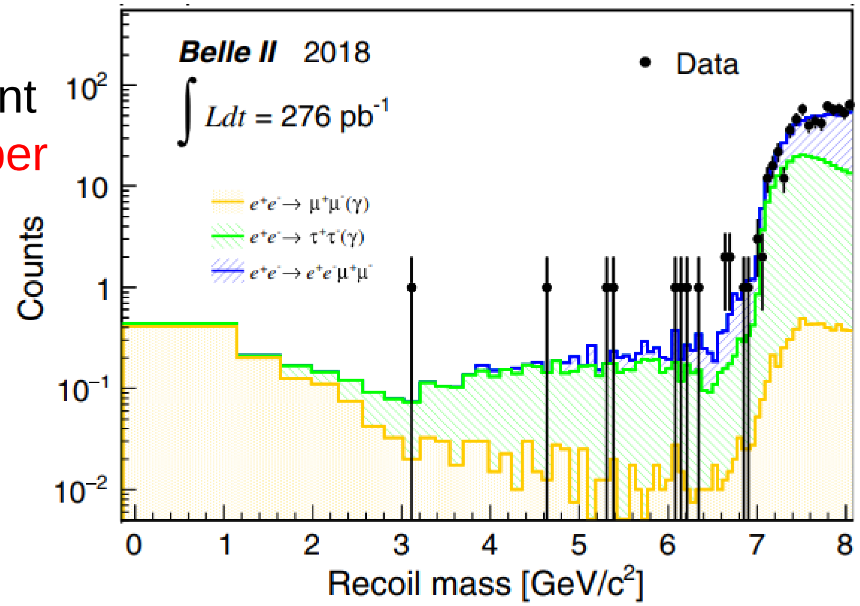
* Shuve et al. (2014), arXiv:1403.2727; Altmannshofer et al. (2016), arXiv: 1609.04026

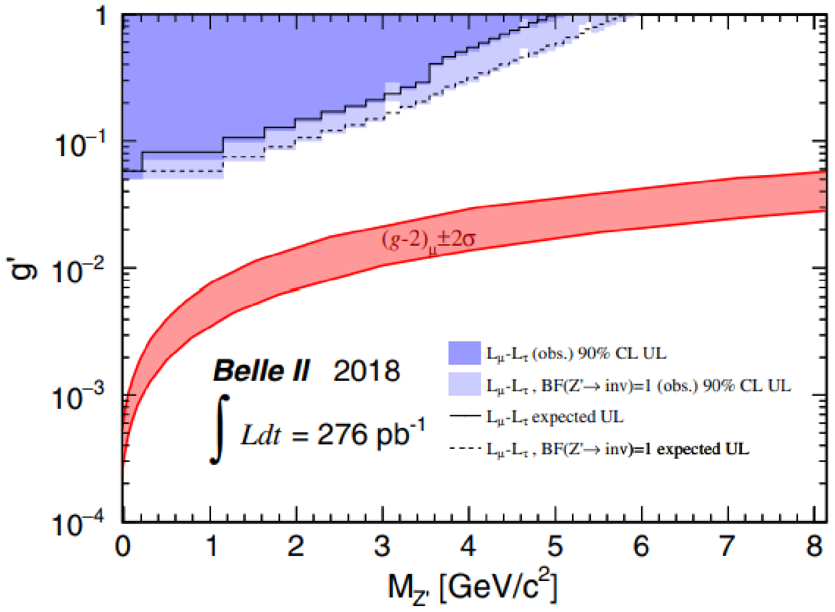


$e^+e^- \to \mu^+\mu^-\ Z'$; $Z' \to$ invisible

Experimental procedure :

- Used only 0.276 fb^{-1} of Phase 2 data
- Looking for a peak in the recoil mass distribution against $\mu\mu$ lepton pair
- Nothing else in the rest of the event
- No excess observed; 90% CL upper limit on coupling constant g': first result ever





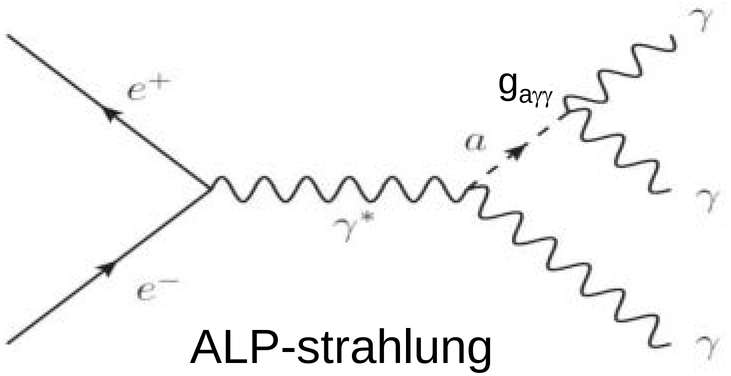
PRL124, 141801 (2020)

Belle II 1st physics paper

Search for Axion-Like Particle (ALP)

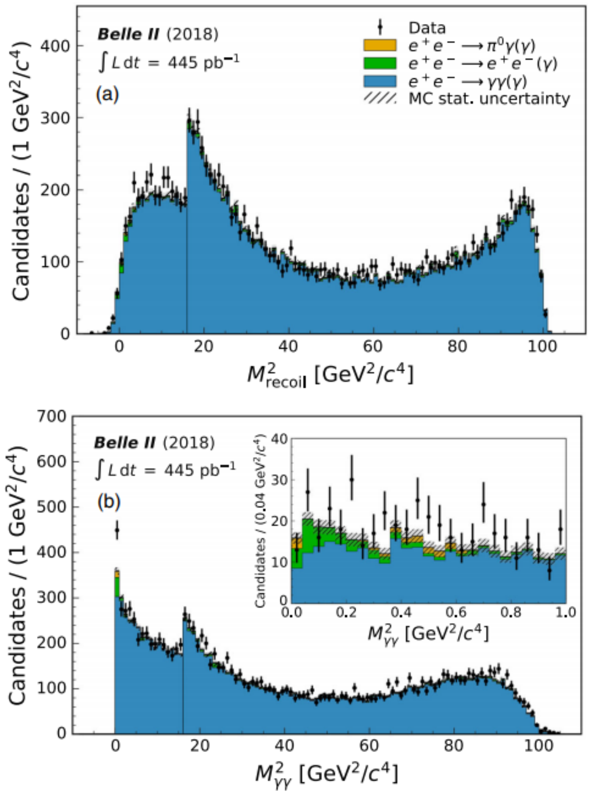
- ALPs are pseudo-scalars particles coupled with SM photons.
- Possible dark sector mediator and impact on $(g\text{-}2)_\mu$ if MeV-GeV range

- Used 0.445 fb^{-1} of Phase 2 data
- Looking for 3-photon final state via ALP-strahlung
- Search for a bump in recoil and di-photon mass distribution



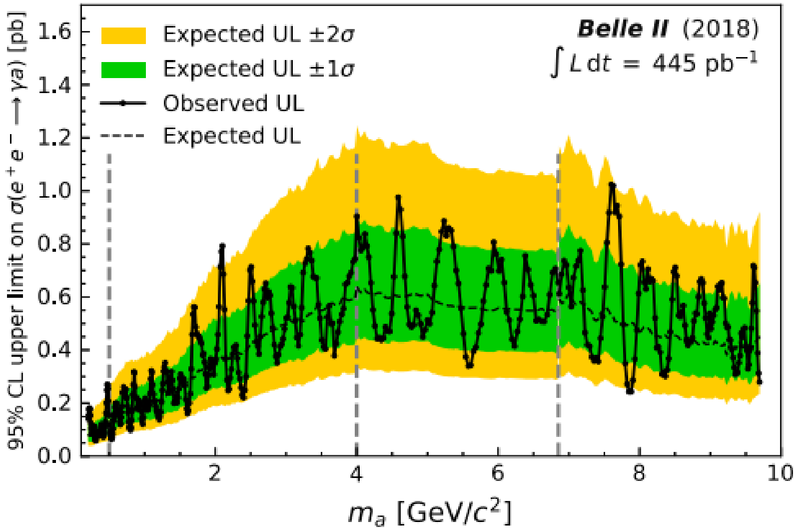
ALP-strahlung

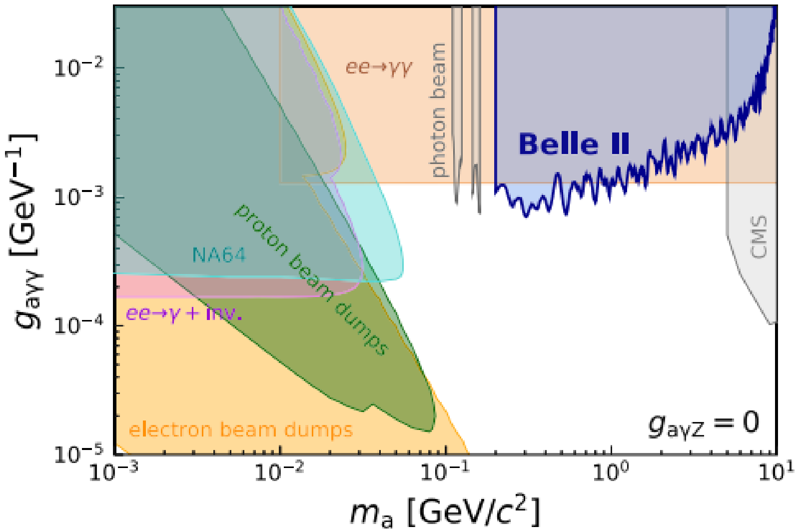
PRL 125, 161806 (2020)



- No excess observed, set 95% CL upper limit on the ALP-photon coupling
- Limit on $g_{a\gamma\gamma}$ assuming BF($a\rightarrow\gamma\gamma$) = 100%

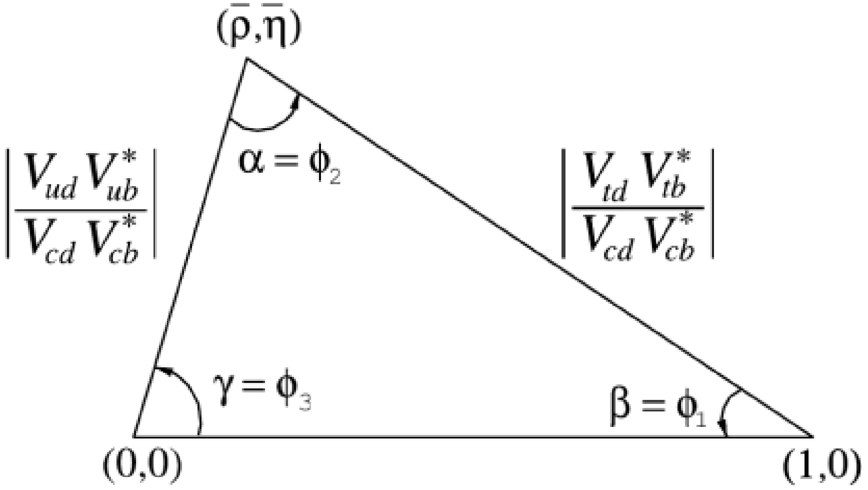
$$\sigma_a = \frac{g^2_{a\gamma\gamma}\alpha_{\rm QED}}{24}\left(1-\frac{m_a^2}{s}\right)^3$$





Measurement of CKM parameters

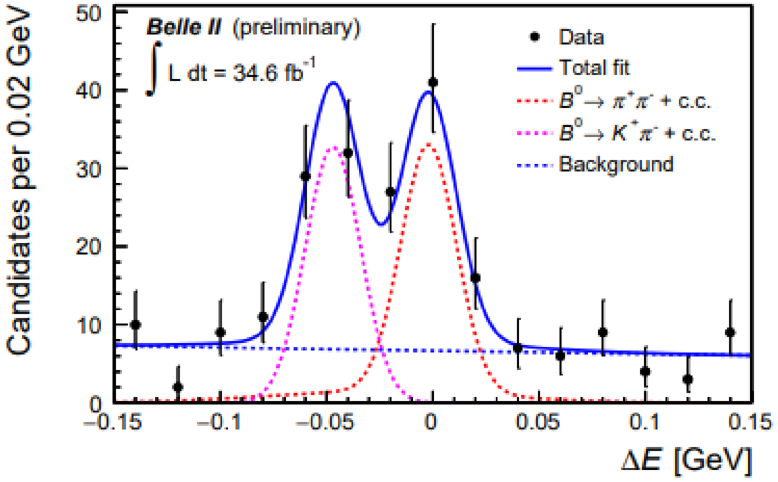
- In Standard model CP violation arises via a non zero phase of the CKM matrix
- Over-constraining unitarity triangle measuring both sides and angles is formidable test of Standard Model

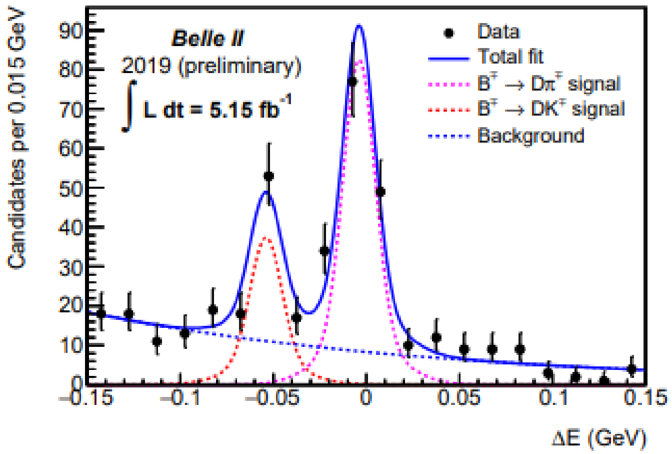


ϕ_2: $B^0 \to \pi^+\pi^-$

$$\Delta E = E_B^* - E_{\text{beam}}^*$$

ϕ_3: $B^0 \to DK$





[arXiv:2005.13559] [BELLE2-NOTE-PL-028]

CPV measurement

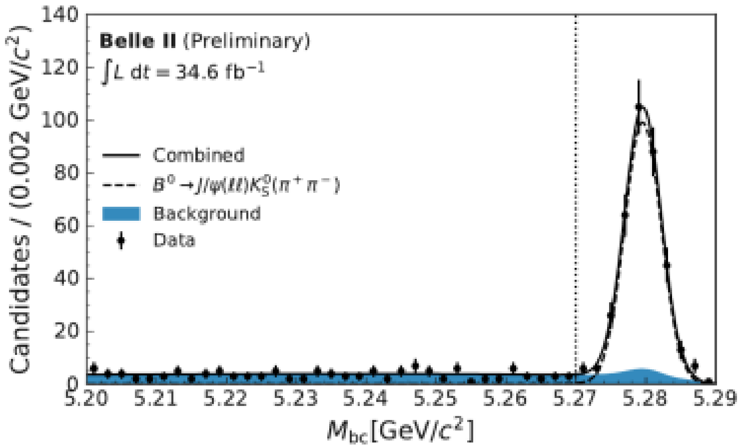
[BELLE2-NOTE-PL-2020-011]

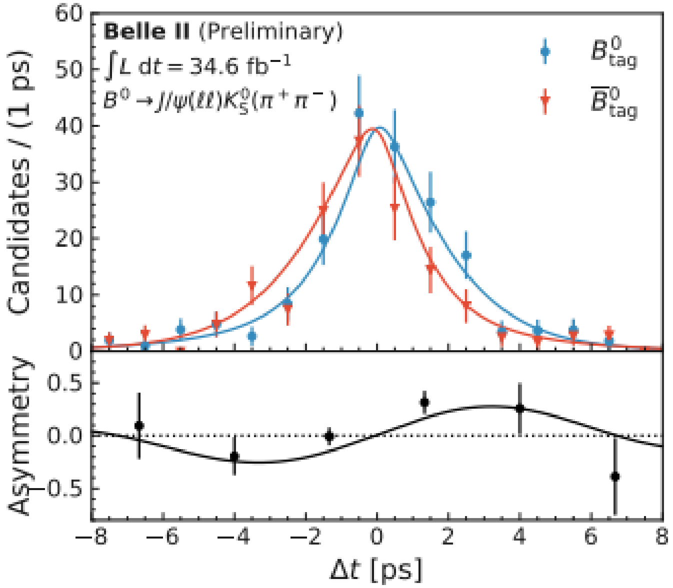
- Reconstruct $B^0 \to J/\psi K_S^0$ with $J/\psi \to \mu^+\mu^-, e^+e^-$
- use w from previous slide

$$sin(2\phi_1)sin(\Delta m_d \Delta t)(1-2w) * \mathcal{R}(\Delta_t) = \frac{N(B^0_{tag}) - N(\bar{B}^0_{tag})}{N(B^0_{tag}) + N(\bar{B}^0_{tag})}(\Delta t)$$

$$sin(2\phi_1) = 0.55 \pm 0.21 \pm 0.04$$

Belle II already able to see first 2.7σ hint for time-dependent CPV





Tau mass measurement

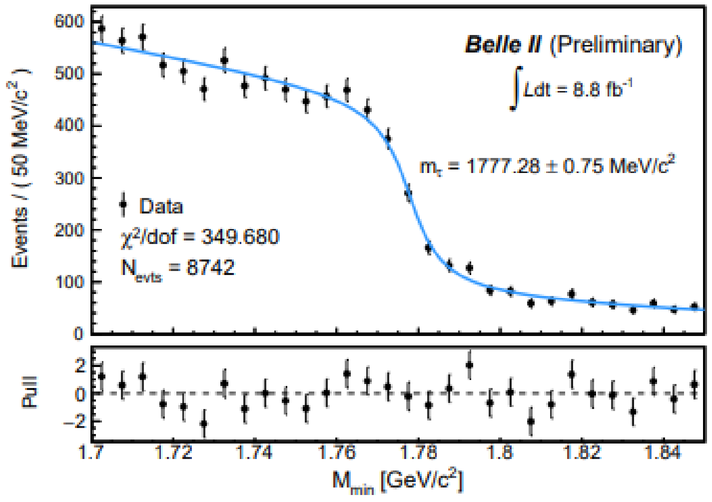
[axXiv:2008.04665]

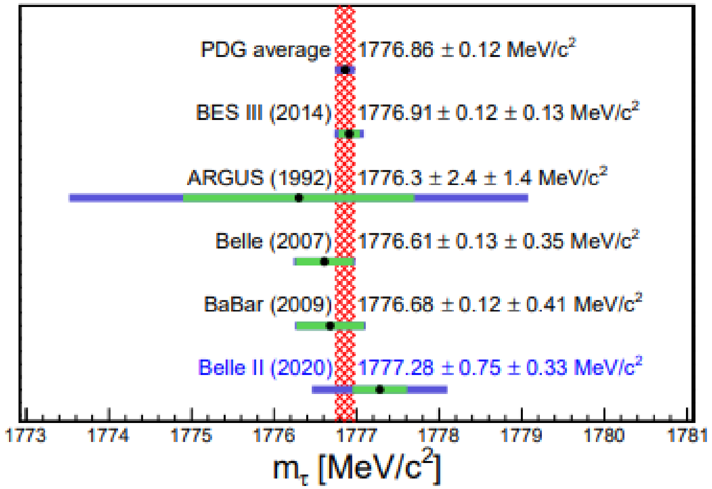
- Select $\tau \to 3\pi\nu$ decays in $e^+e^- \to \tau^+\tau^-$
- Estimate mass by fitting edge of the pseudo-mass

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(E^*_{\text{beam}} - E^*_{3\pi})(E^*_{\text{beam}} - P^*_{3\pi})}$$

$m_\tau = 1777.28 \pm 0.75 \pm 0.33$ MeV
(PDG: 1776.86 ± 0.12 MeV)

Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01





Belle II Korean Group

Belle II Korean Group

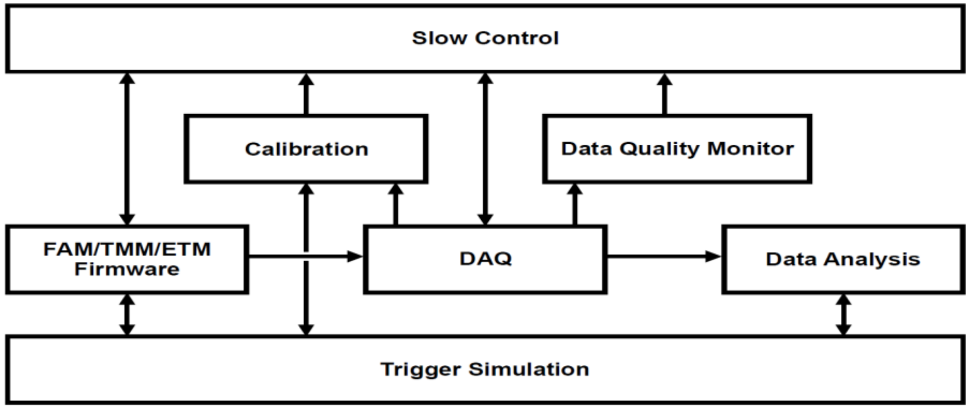
- 참여: 9개 기관 46명
  고려대,경북대,경상대,서울대,숭실대,연세대,전남대,한양대,KISTI

- 한국그룹 전체 미팅 : 2~3회/년

KB2GM
Nov/20/2020
전남대 주관

- **Belle II contribution :**
- ECL Calorimeter Trigger Construction
- CDC Track Trigger Firmware
- SVD Vertex Detector Assembly
- DAQ Slow Control
- Data Production and Geant4 validation
- Data Handling System using AMGA

Workflow of ECL trigger system



Belle II Korean Group

- **Belle II 분담금** : ~1억원/년 ; 연구재단 해외대형시설활용과제 수행

한국 SuperKEKB & Belle II 실험연구단

[세부 1] Belle II 실험의 전자기열량계 트리거 운용 연구 및 총괄지원 관리

[세부 2] Belle II 실험의 궤적트리거 운용 및 매혹입자 붕괴 연구

[세부 3] Belle II 실험의 실리콘검출기 운용 및 실험 데이터분석 연구

[세부 4] Belle II 실험의 시뮬레이션 소프트웨어 최적화 및 매혹입자 희귀붕괴 연구

[세부 5] SuperKEKB 충돌형 가속기의 빔 궤도 안정화 연구

[세부 6] Belle II 실험의 B 중간자 희귀붕괴 탐색과 암흑섹터 연구

[세부 7] Belle II 실험을 통한 XYZ 미지입자 연구

[세부 8] Belle II 실험을 통한 경입자 맛깔 구조 및 새로운 물리 탐색 연구

Summary

- Belle II aims to find the New Physics with ultimate precision measurement of heavy flavor decays, and dark matter search as well.
- Achieved
  - Nano-beam collision successfully
  - 74 fb^{-1} data collection by summer 2020
  - World highest peak luminosity record in June 2020
- Promising
  - World leading results for dark sector physics
  - To surpass Belle/BaBar data size by 2021
- Plan to accumulate 50 ab^{-1} around 2030

감사합니다.

Belle II Physics Results

2 Dark Sector PRL publications on Phase2 data:

- Search for an Invisibly Decaying Z′ Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States, PRL 124, 141801 (2020);
- Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II, PRL 125, 161806 (2020);

12 conference papers based on up to ~38 fb^{-1} of data:

Spring

- Charmless B decay reconstruction, arXiv:2005.13559 [hep-ex];
- Measurement of the branching fraction B(anti-$B^0 \to D^{*+} l^- \nu_l$), arXiv:2004.09066 [hep-ex];
- Measurement of the B^0 lifetime using fully reconstructed hadronic decays, arXiv:2005.07507 [hep-ex];

- Measurement of the branching ratios of $B^0 \to D^{(*)-} l^+ \nu$ (untagged analysis), arXiv:2008.07198 [hep-ex];
- Calibration of the Belle II hadronic Full Event Interpretation (FEI), arXiv:2008.06096 [hep-ex];
- Measurement of the hadronic mass moments of $B \to X_c l^+ \nu$ decays, arXiv:2009.04493 [hep-ex];
- Measurement of the branching ratios of $B^0 \to D^{*-} l^+ \nu$ (using the hadronic FEI), arXiv:2008.10299 [hep-ex];
- Rediscovery of $B^0 \to \pi^- l^+ \nu$ (using the hadronic FEI), arXiv:2008.08819 [hep-ex];
- Calibration of the Belle II B FlavorTagger, arXiv:2008.02707 [hep-ex];
- Rediscovery of $B \to \phi K^{(*)}$ decays, and measurement of the longitudinal polarization fraction of $B \to \phi K^*$, arXiv:2008.03873 [hep-ex];
- Branching ratios and direct CP asymmetries of $B \to$ Charmless decays, arXiv:2009.09452 [hep-ex];
- Measurement of the τ lepton mass, arXiv:2008.04665 [hep-ex];

Summer

We have a lot of analyses planned

Just to give you an idea

- ee → μμ Z'; { Z' → inv. | Z' → ℓℓ | Z' → 4μ }
- ee → μe Z'; { Z' → inv. | Z' → ℓℓ }
- ee → γ A'; { A' → inv. | A' → ℓℓ }
- ee → { γ a | ee a }; a → γγ
- ee → h' A'; A' → ℓℓ
- b → s { h' | a }
- ee → γ + DM; DM → A + inv.; A' → { ee | μμ | ππ }; "Inelastic dark matter".
- Dark QCD final states.
- Long lived (& very) long lived particles: generic displaced vertices.
- ee → $ee\pi^0$; light hadronic form factor
- ee → $\pi^+\pi^-(\gamma)$; for $(g-2)_\mu$
- ee → $e^\pm e^\pm \mu^\mp \mu^\mp$
- ee → τℓ
- ee → { μe | μτ } + missing

- b → s inv. (interpretation of b-physics golden channel B → $K^{(*)}\nu\nu$).
- B → Λ + inv.
- Υ(1S) → { inv. | γ + inv. }

Belle II vs LHCb

Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$\|V_{us}\|$ $[K \to \pi\ell\nu]$	input	$0.5\% \to 0.1\%_{\rm Latt}$	0.2246 ± 0.0012	0.1%	K factory
$\|V_{cb}\|$ $[B \to X_c\ell\nu]$	input	1%	$(41.54 \pm 0.73) \times 10^{-3}$	1%	Super-B
$\|V_{ub}\|$ $[B \to \pi\ell\nu]$	input	$10\% \to 5\%_{\rm Latt}$	$(3.38 \pm 0.36) \times 10^{-3}$	4%	Super-B
γ $[B \to DK]$	input	$< 1^\circ$	$(70^{+27}_{-30})^\circ$	3°	LHCb
$S_{B_d \to \psi K}$	$\sin(2\beta)$	$\lesssim 0.01$	0.671 ± 0.023	0.01	LHCb
$S_{B_s \to \psi\phi}$	0.036	$\lesssim 0.01$	$0.81^{+0.12}_{-0.32}$	0.01	LHCb
$S_{B_d \to \phi K}$	$\sin(2\beta)$	$\lesssim 0.05$	0.44 ± 0.18	0.1	LHCb
$S_{B_s \to \phi\phi}$	0.036	$\lesssim 0.05$	—	0.05	LHCb
$S_{B_d \to K^*\gamma}$	few $\times$ 0.01	0.01	-0.16 ± 0.22	0.03	Super-B
$S_{B_s \to \phi\gamma}$	few $\times$ 0.01	0.01	—	0.05	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	2×10^{-5}	$< 10^{-5}$	$(1.6 \pm 8.5) \times 10^{-3}$	10^{-3}	LHCb
$A_{CP}(b \to s\gamma)$	< 0.01	< 0.01	-0.012 ± 0.028	0.005	Super-B
$\mathcal{B}(B \to \tau\nu)$	1×10^{-4}	$20\% \to 5\%_{\rm Latt}$	$(1.73 \pm 0.35) \times 10^{-4}$	5%	Super-B
$\mathcal{B}(B \to \mu\nu)$	4×10^{-7}	$20\% \to 5\%_{\rm Latt}$	$< 1.3 \times 10^{-6}$	6%	Super-B
$\mathcal{B}(B_s \to \mu^+\mu^-)$	3×10^{-9}	$20\% \to 5\%_{\rm Latt}$	$< 5 \times 10^{-8}$	10%	LHCb
$\mathcal{B}(B_d \to \mu^+\mu^-)$	1×10^{-10}	$20\% \to 5\%_{\rm Latt}$	$< 1.5 \times 10^{-8}$	[?]	LHCb
$A_{\rm FB}(B \to K^*\mu^+\mu^-)_{q_0^2}$	0	0.05	(0.2 ± 0.2)	0.05	LHCb
$B \to K\nu\bar{\nu}$	4×10^{-6}	$20\% \to 10\%_{\rm Latt}$	$< 1.4 \times 10^{-5}$	20%	Super-B
$\|q/p\|_{D-\rm mixing}$	1	$< 10^{-3}$	$(0.86^{+0.18}_{-0.15})$	0.03	Super-B
ϕ_D	0	$< 10^{-3}$	$(9.6^{+8.3}_{-9.5})^\circ$	2°	Super-B
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	8.5×10^{-11}	8%	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	10%	K factory
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	2.6×10^{-11}	10%	$< 2.6 \times 10^{-8}$	[?]	K factory
$R^{(e/\mu)}(K \to \pi\ell\nu)$	2.477×10^{-5}	0.04%	$(2.498 \pm 0.014) \times 10^{-5}$	0.1%	K factory
$\mathcal{B}(t \to cZ, \gamma)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-13})$	$< 0.6 \times 10^{-2}$	$\mathcal{O}(10^{-5})$	LHC (100 fb^{-1})

- Belle II: clean environment: efficient detection of neutrals (γ,π^0,η)
- Belle II: quantum correlated $B^0\bar{B}^0$ pairs: flavor tagging is more efficient (34% vs 3%)
- Belle II: full reconstruction: b →u transition
- LHCb: large X-section

Belle II vs LHCb

Belle (II)

$e^+e^- \to \Upsilon(4S) \to b\bar{b}$

at $\Upsilon(4S)$: 2 B's (B^0 or B^+) and nothing else ⇒ clean events

(flavour tagging, B tagging, missing energy)

$\sigma_{b\bar{b}} \sim 1$ nb ⇒ 1 fb^{-1} produces 10^6 $B\bar{B}$

$\sigma_{b\bar{b}}/\sigma_{total} \sim 1/4$

LHCb

$pp \to b\bar{b}X$

production of B^+, B^0, B_s, B_c, Λ_b...

but also a lot of other particles in the event

⇒ lower reconstruction efficiencies

$\sigma_{b\bar{b}}$ much higher than at the $\Upsilon(4S)$

	$\sqrt{s}$ [GeV]	$\sigma_{b\bar{b}}$ [nb]	$\sigma_{b\bar{b}}/\sigma_{tot}$
HERA pA	42 GeV	~30	~10^{-6}
Tevatron	2 TeV	5000	~10^{-3}
LHC	8 TeV	~3×10^5	~ 5×10^{-3}
	14 TeV	~6×10^5	~10^{-2}

$b\bar{b}$ production cross-section at LHCb ~ 500,000 × BaBar/Belle !!

$\sigma_{b\bar{b}}/\sigma_{total}$ much lower than at the $\Upsilon(4S)$

⇒ lower trigger efficiencies

B mesons live relativey long

Belle (II): mean decay length $\beta\gamma c\tau \sim 200\ \mu m$

LHCb: **mean decay length $\beta\gamma c\tau \sim 7$ mm** (displaced vertices)

data taking period(s)

Belle (II): [1999-2010] = 1 ab^{-1}, [2019-...] = ...

LHCb: [run I: 2010-2012] = 3 fb^{-1}, [run II: 2015-2018] = 6 fb^{-1}

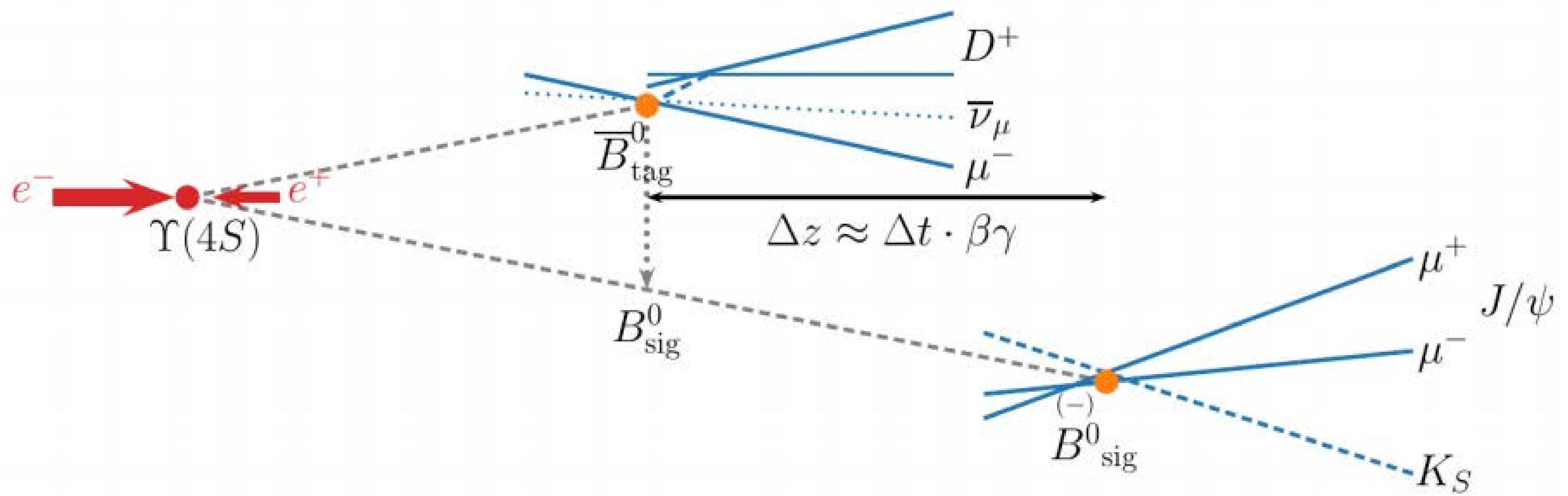
(near) future

Belle (II): [Belle II from 2019] → 50 ab^{-1}

LHCb: [LHCb upgrade from 2021]

Measurement of sin(2ϕ_1)

- Golden channel for Belle II
- $sin(2\phi_1) sin(\Delta m_d \Delta t)(1-2w) * \mathcal{R}(\Delta_t) = \frac{N(B^0_{tag}) - N(\bar{B}^0_{tag})}{N(B^0_{tag}) + N(\bar{B}^0_{tag})}(\Delta t)$



Key experimental requirements

- Precise Δt measurement
- Good flavour tagging performance