The Belle II Experiment: Status & Prospects

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for the Belle II collaboration

9th International Conference on New Frontiers in Physics (ICNFP 2020)

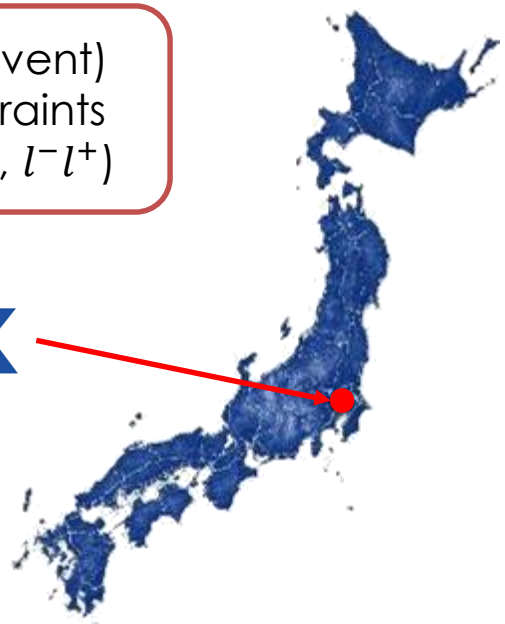
4-12 September 2020

A super B-factory?

- B factories (e^+e^- collisions at $\sqrt{s}$ = 10.58 GeV)
  - BaBar (PEPII) & Belle (KEKB) stopped in 2008/2010
  - accumulated ~ 1000 fb^{-1}
  - very successful analysis techniques

- Clean environment (few particles / event)
- Known initial state → kinematic constraints
- Final state always starts with pairs ($q\bar{q}$, l^-l^+)

- New inputs
  - ATLAS / CMS → Higgs but no non-SM particles
  - LHCb/B-factories intriguing tensions in flavour physics



- Motivations for a super B-factory
  - Complementary search for New Physics / LHC
  - Precision test of Standard Model
  - Direct search for new light particles
  - Hadronic physics

With billions of $B\bar{B}, c\bar{c}, \tau\bar{\tau}$ pairs

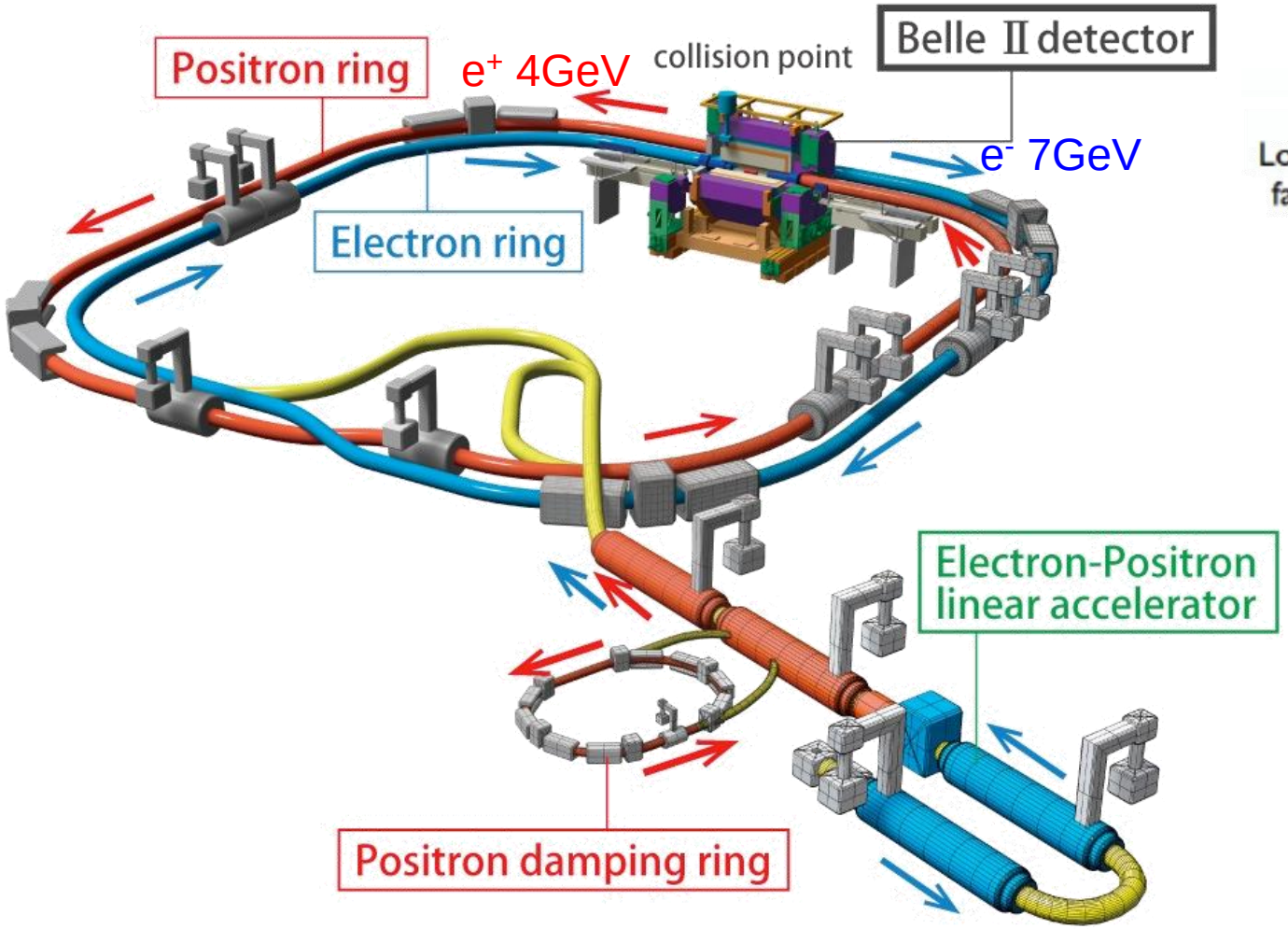
Luminosity frontier

⇒ The Belle II physics book
PTEP 12 (2019) 123C01

Outline

- The projects
  - SuperKEKB & Belle II
- Status
  - Luminosity, data taking & performance results
  - First results
- Prospects
  - Next expected results
  - SuperKEKB & Belle II in the next 10 years

SuperKEKB collider



- Recipe to high luminosity

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

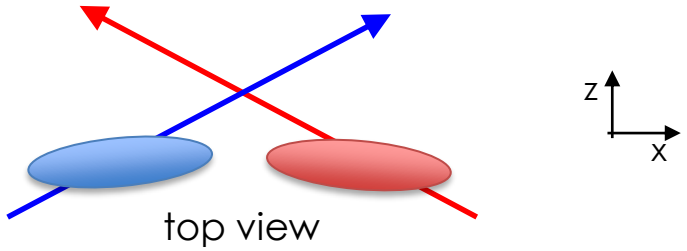
Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP

High currents: > 1A

Nano-scale beam size:
$\sigma_x \times \sigma_y$ ~ 10μm × 60 nm
B_y^*<< 1 mm

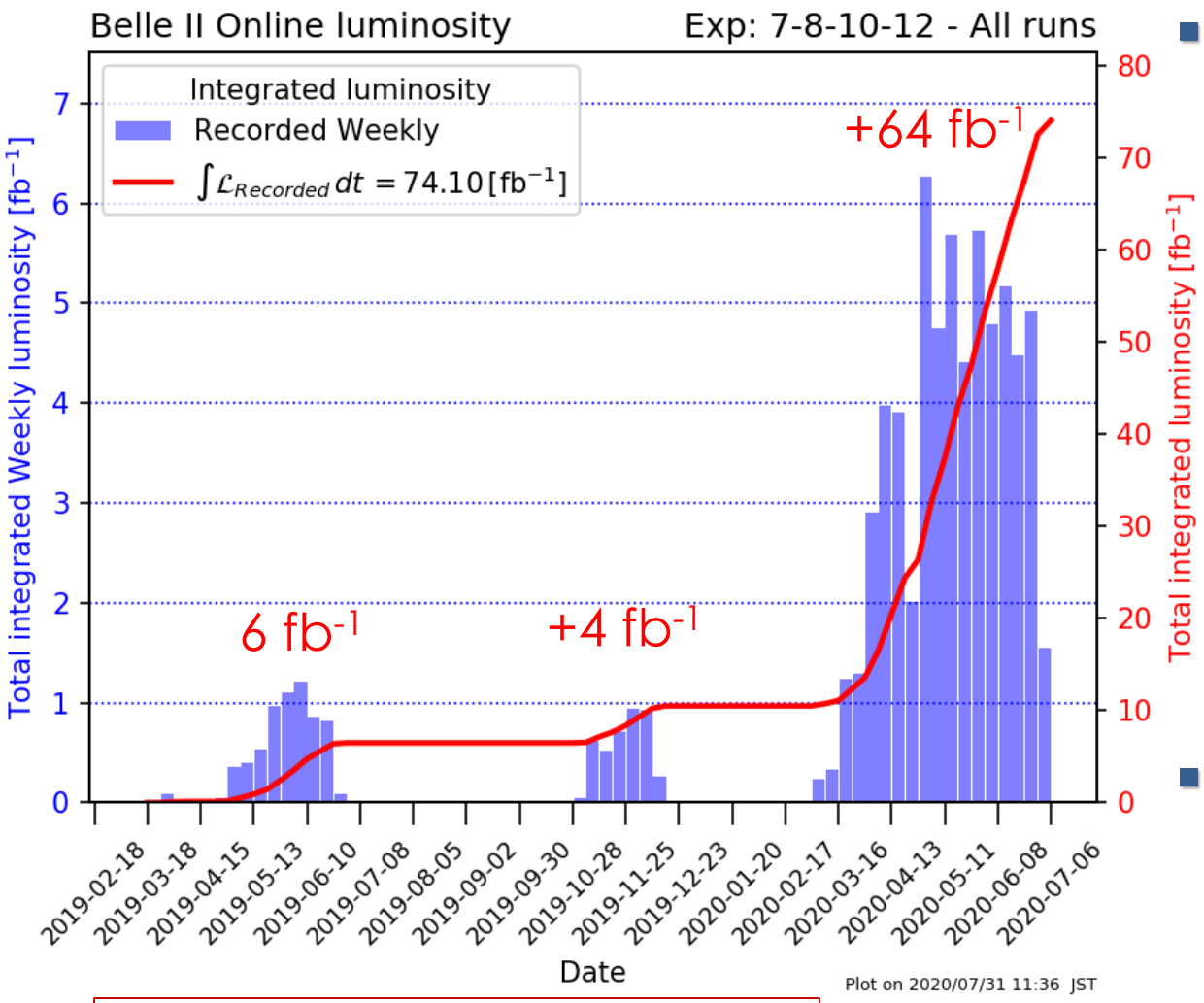
& specific beam crossing features

Crossing angle (83 mrad) + crab waist (80%)



⚠ Cost = severe beam induced background

SuperKEKB / Belle II Luminosity status



See ICHEP talk by **Yukiyoshi Onishi**
"Highlights from SuperKEKB..."

Machine progress

	KEKB	SuperKEKB	
		2020	Nominal
Energy (GeV) LER/HER	3.5 / 8	4 / 7	
Current (A) LER/HER	1.6/1.2	0.7/0.6	2.8 / 2.0
"Beam size" β_y* (mm)	5.9	0.8	0.3
Instant. Lumi. ($cm^{-2}.s^{-1}$)	2.1×10^{34} <	**2.4×10^{34}**	~6×10^{35}

First collisions April 2018

Final goal 50 ab^{-1}

Data taken

- On-resonance 74 fb^{-1}
  - Analysis ready in Summer 2020 exploit ~35 fb^{-1}
  - **Analysis ready in** Winter 2019-20 exploit < 10 fb^{-1}
- Off-resonance 6 fb^{-1} ($M_{\Upsilon(4S)}$ -60MeV)

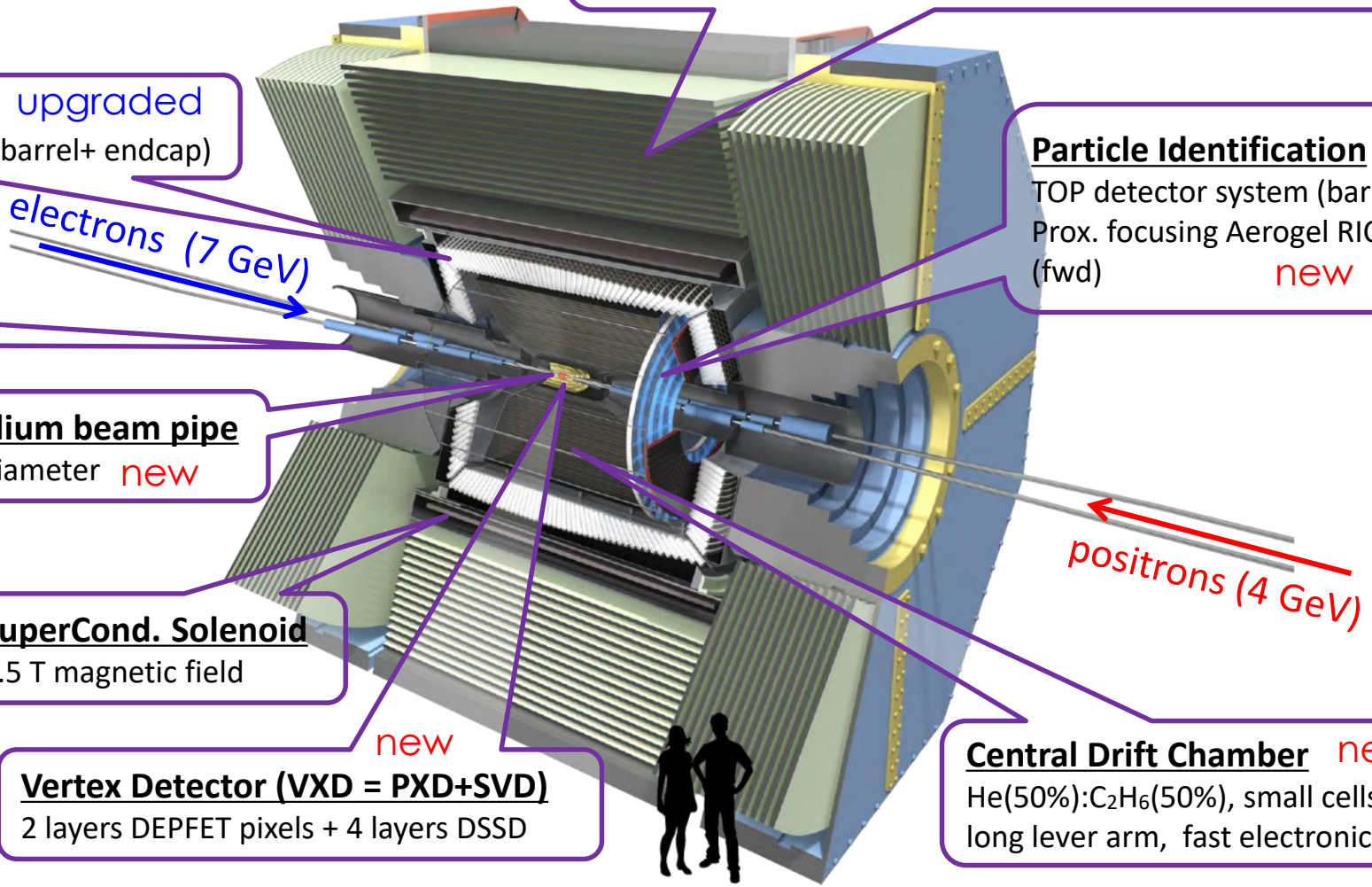
Belle II detector

- Planned for better performances / Belle under:
  - Higher beam-background rate
  - Higher trigger rate (30 kHz)

KLong and muon detector (KLM) upgraded
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's (end-caps , inner 2 barrel layers)

EM Calorimeter (CDC) upgraded
CsI(Tl), waveform sampling (barrel+ endcap)

Particle Identification
TOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd) new



Final focusing magnets new

Beryllium beam pipe
2cm diameter new

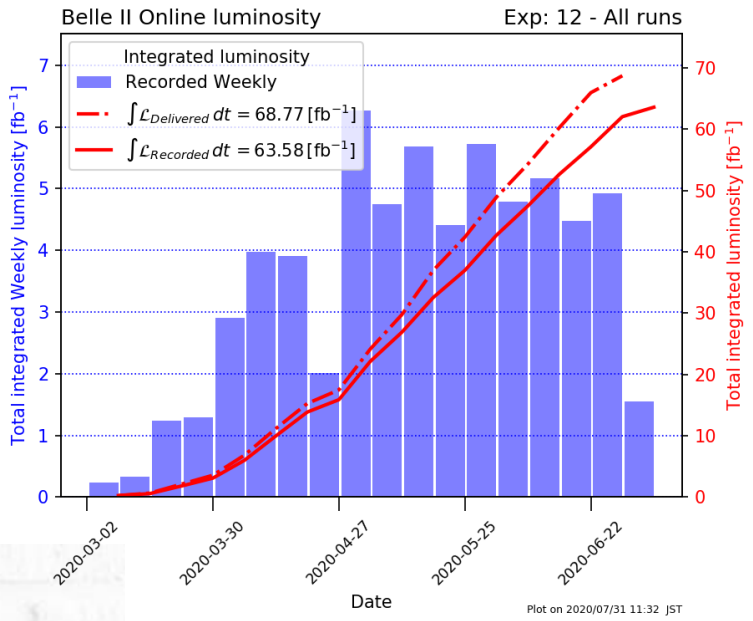
SuperCond. Solenoid
1.5 T magnetic field

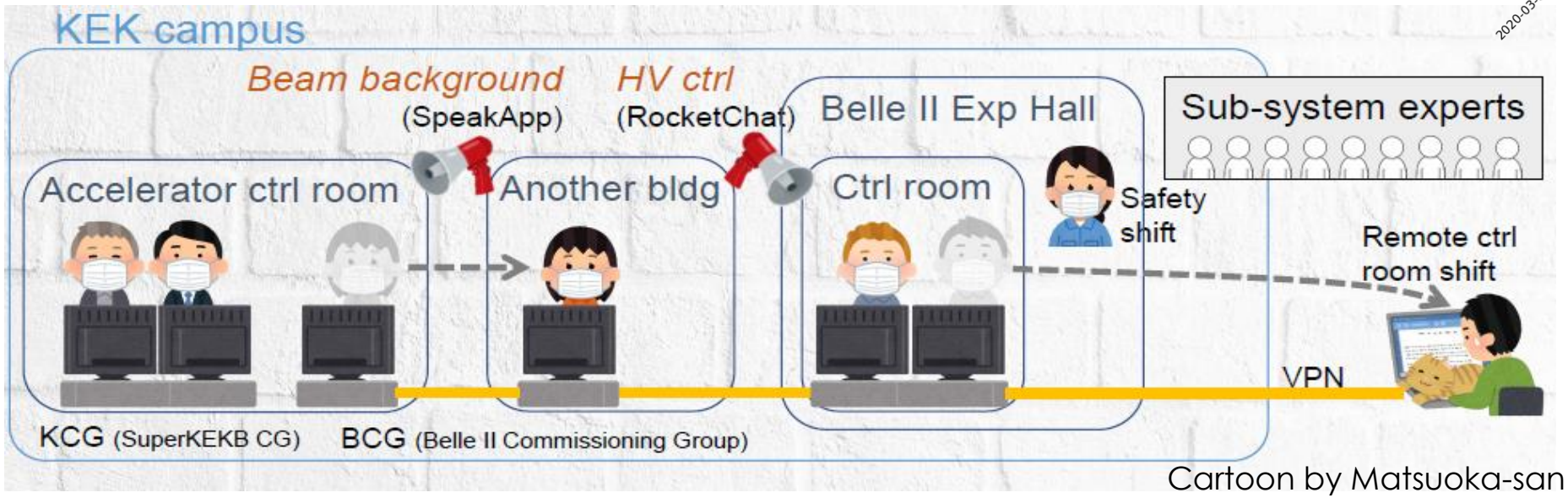
Vertex Detector (VXD = PXD+SVD) new
2 layers DEPFET pixels + 4 layers DSSD

Central Drift Chamber new
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

Special data taking conditions in 2020

- Non-stop operation with COVID-19 pandemic
  - Social distancing requirements
  - Strong developments for close to or fully remote sub-system operation
  - Huge commitment from Japanese colleagues & residents in Japan
    - Only 40 people on site from March to July





Cartoon by Matsuoka-san

Belle II data taking efficiency ~ 85%

(target for coming run 90%)

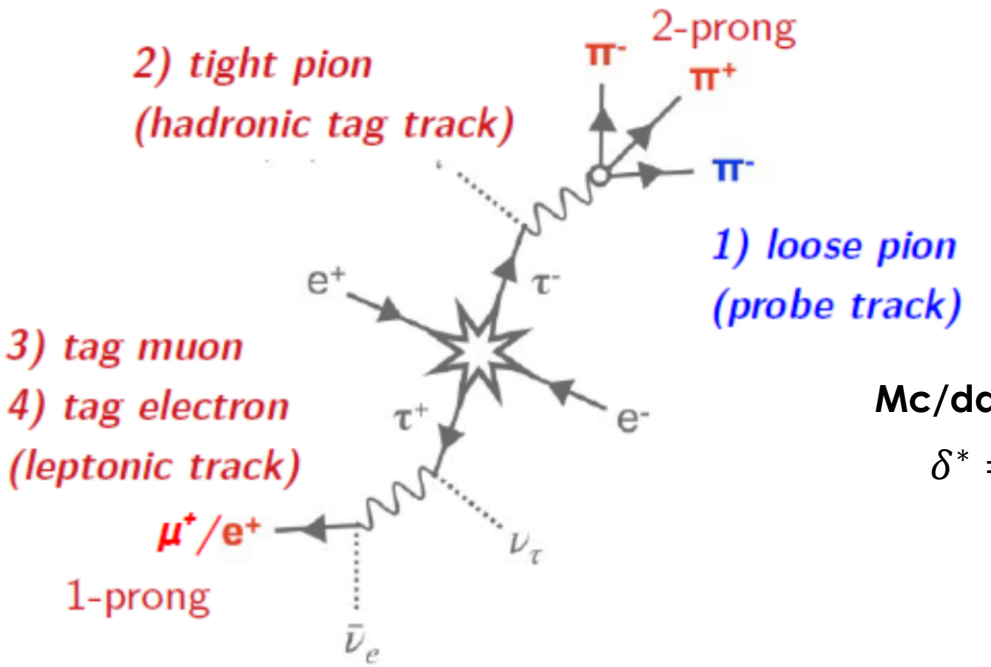
Tracking performance

- tag & probe technique with e+e- →τ+τ-
  - Lepton-ID tags the event
  - 3 prongs provide probe

} 4 charged tracks expected

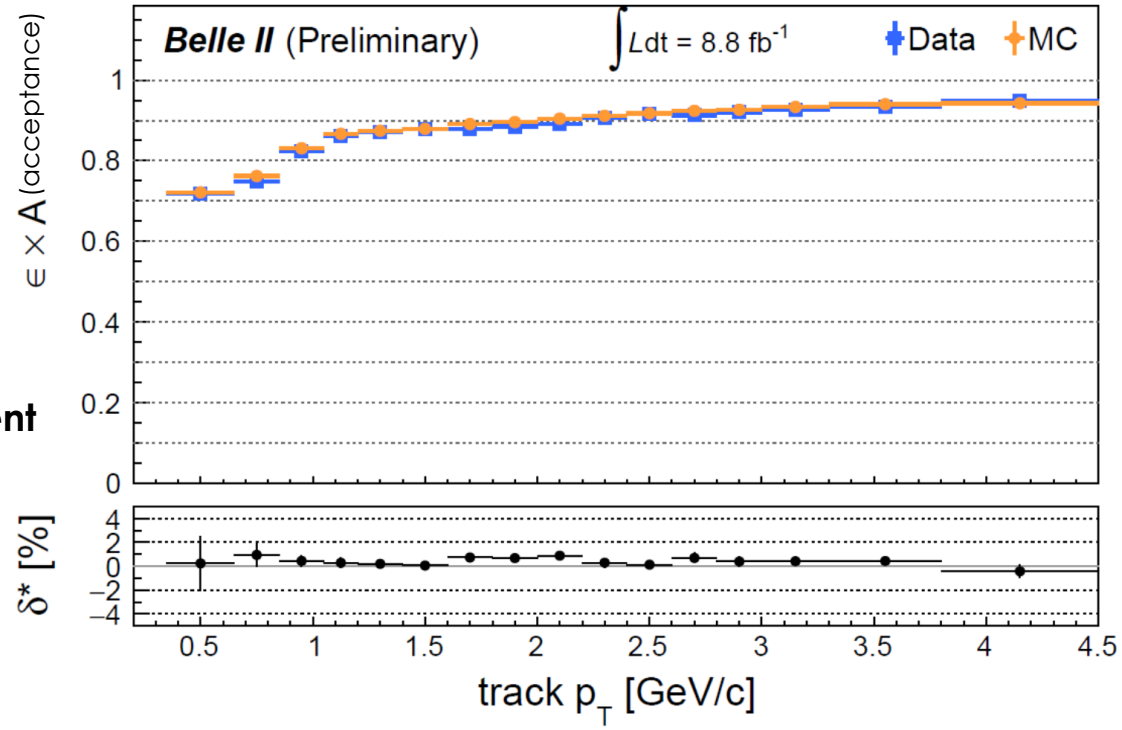
⇒ Track finding algo: BELLE2-PUB-TE-2020-001
⇒ BELLE2-NOTE-PL-2020-014

efficiency $\varepsilon = \frac{N_{\text{evts}}(4\text{tracks})}{N_{\text{evts}}(4\text{tracks}) + N_{\text{evts}}(3\text{tracks})}$



Mc/data agreement

$$\delta^* = 1 - \frac{\varepsilon_{\text{data}}}{\varepsilon_{\text{MC}}}$$



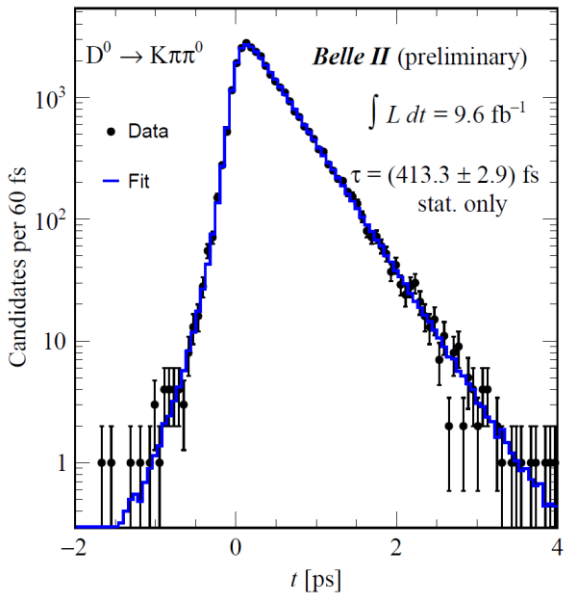
- Similar technique to evaluate **fake rate**/track: $r_{\text{fake}} = (0.97 \pm 0.34_{\text{stat}} \pm 0.06_{\text{syst}})\ \%$

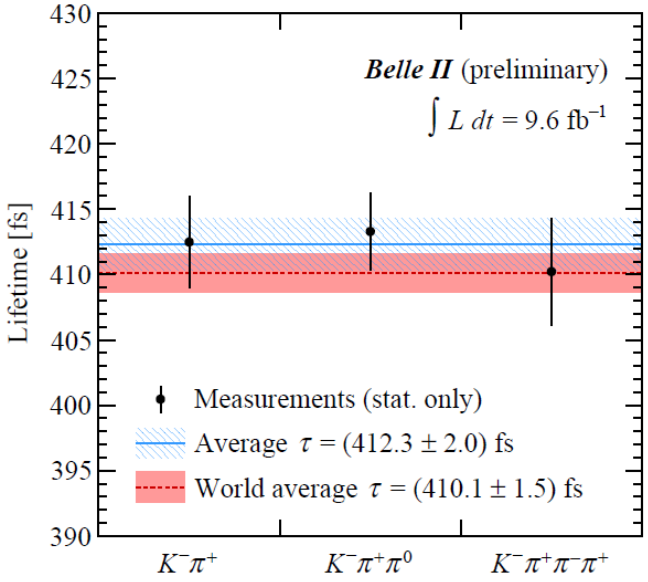
Vertexing performances

- D^0 lifetime
  - Measurement with 3 channels: $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
  - Estimated **vertex resolution ~40 μm**

$\Rightarrow \tau(D^0) = (412.3 \pm 2.0_{\text{stat}})$ fs

World Average (410.1±1.5) fs



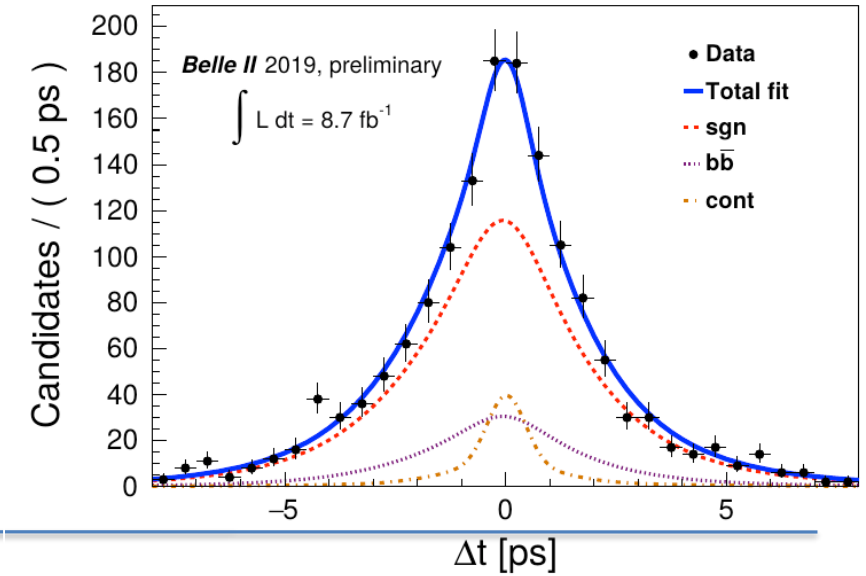


- B^0 lifetime
  - Smaller Υ(4S) boost: 0.42 (Belle) → 0.28 (Belle II)
  - Average distance between B-mesons 200μm → 130 μm
  - Hadronic channels $B \to D^{(*)-}\pi^+/\rho^+$
  - Estimated resolutions
    - Time: **Δt ~ 1 ps** ↔ Δt ~ 80 μm
    - Dominated by "tag"-side

⇒BELLE2-CONF-PH-2020-003

$\Rightarrow \tau(B^0) = (1.48 \pm 0.28_{\text{stat}} \pm 0.06_{\text{syst}})$ ps

World Average (1.519±0.004) ps



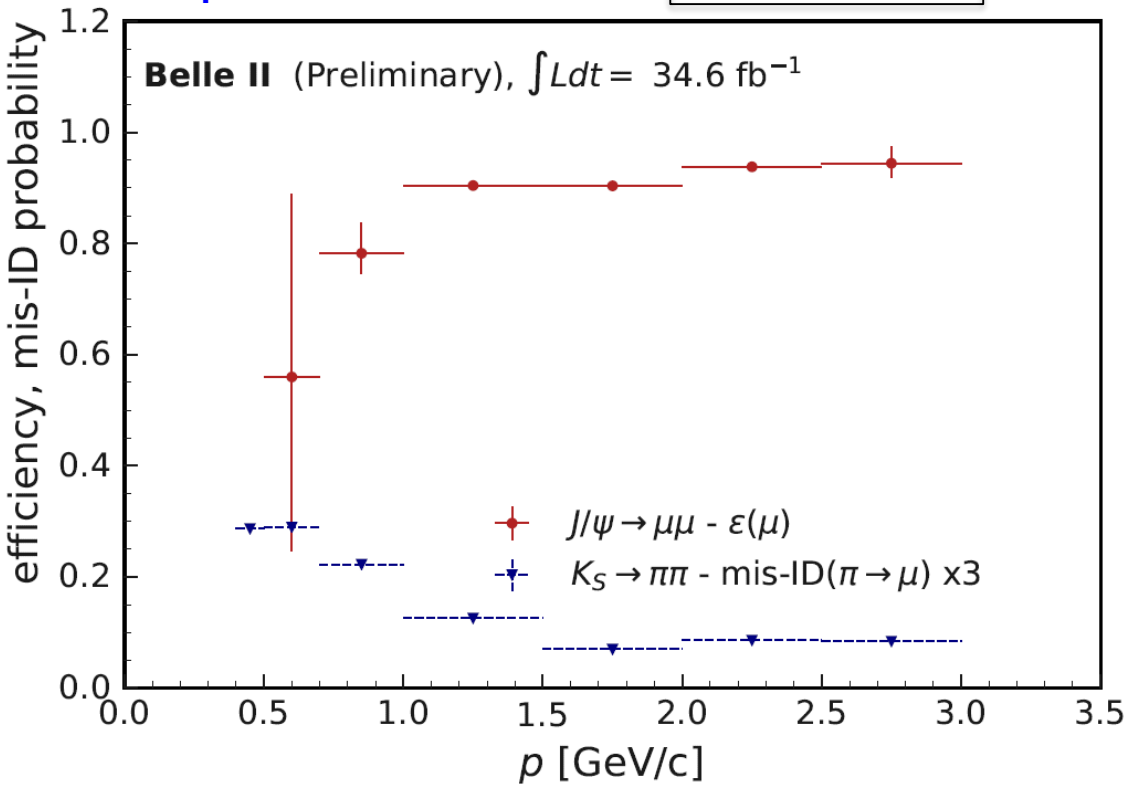
Particle identification: leptons

- Using fully reconstructed channels
  - Extract both efficiencies & mis-ID probability **from data**
  - For various leptonID & angular acceptance

$$\text{leptonID} = \frac{\mathcal{L}_{\text{lepton}}}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}$$

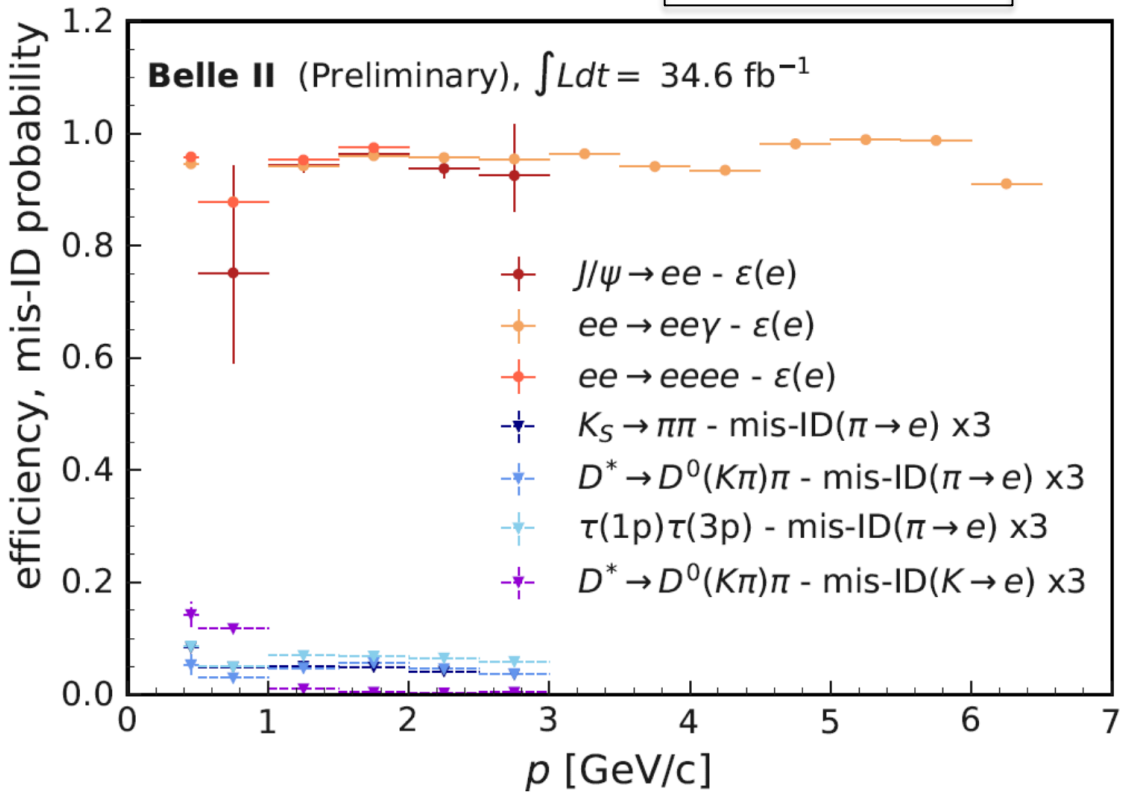
KLM

Total accept. $0.82 \leq \theta < 2.13$ rad, muonID > 0.9



ECL

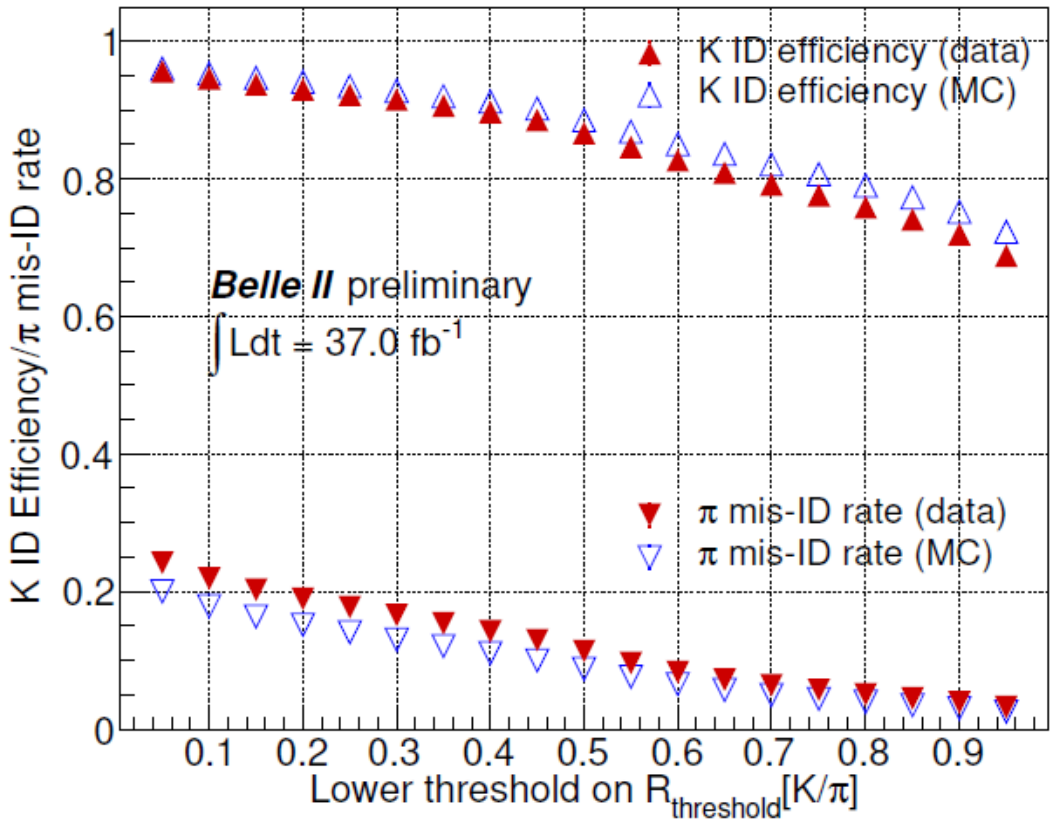
1 accept. bin $1.13 \leq \theta < 1.57$ rad, electronID > 0.9

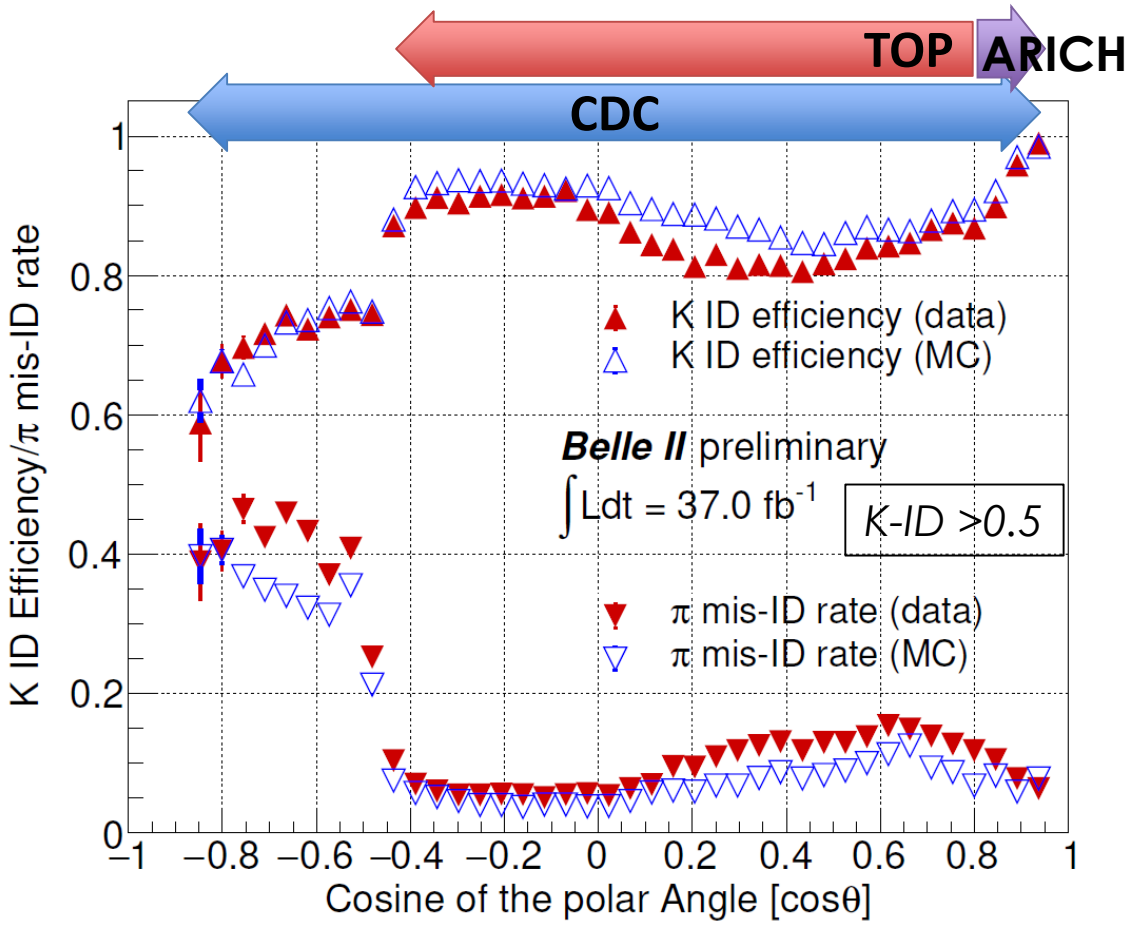


Particle identification: hadrons

- Using fully reconstructed channels
  - $D^{*+} \rightarrow D^0(K^-\pi^+)\ \pi^+$
  - Slow π from D^* tags D^0 flavour $\Rightarrow$ K & π identified **in data**

$$K/\pi\text{–ID} = \frac{\mathcal{L}_{K/\pi}}{\mathcal{L}_K + \mathcal{L}_\pi}$$

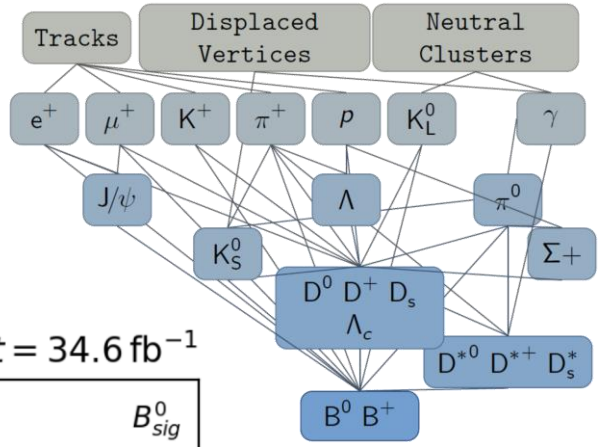




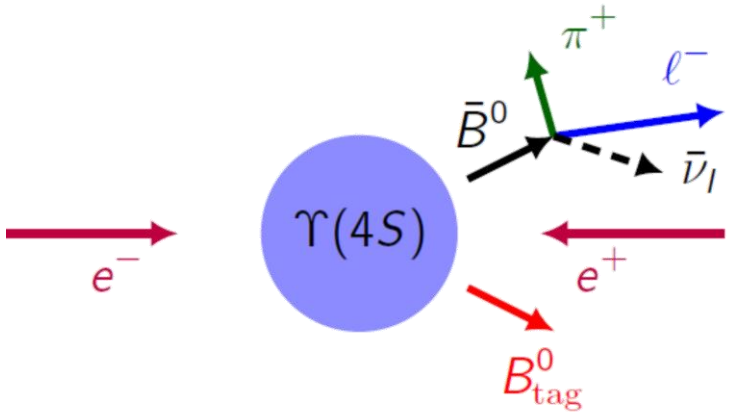
Full Event Interpretation

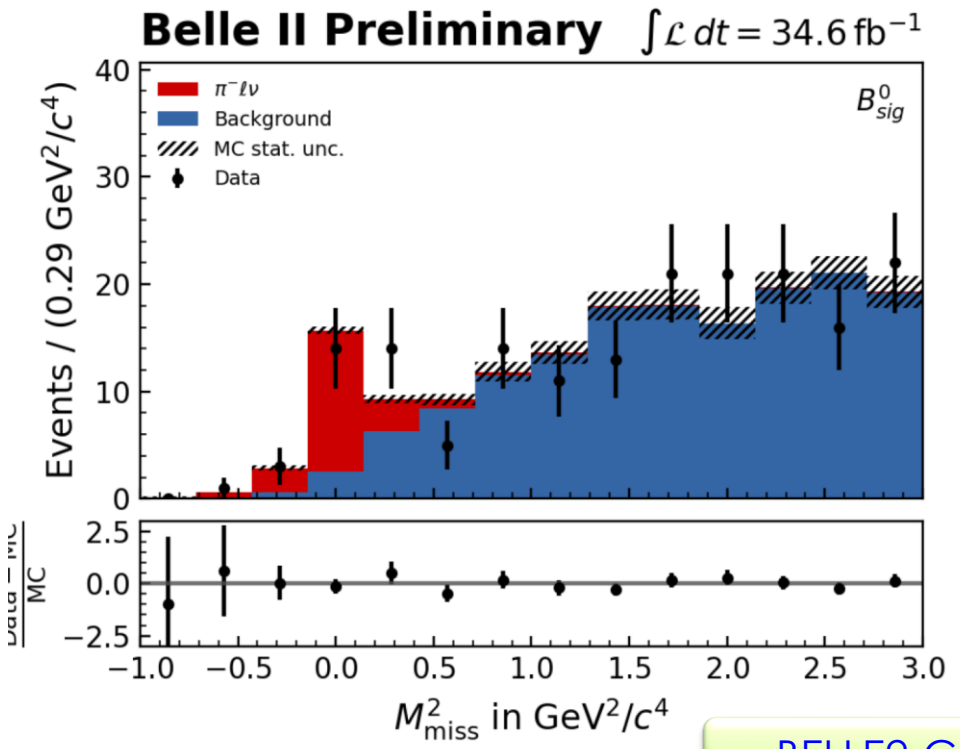
- B exclusive reconstruction in tag-side
  - **Critical tool** for signal channels with missing particles
  - 10^4 channels identified via successive (200) Boosted Decision Trees
    - Provides classifier $\wp_{\text{tag}}$ with eff-purity calibrated on data
  - Tag side with **fully hadronic or semileptonic decays**

⇒BELLE2-CONF-PH-2020-005



- Rediscovery of charmless B decay
  - Missing 4-momenta ⇒ M^2_{miss}





$\Rightarrow \mathcal{B}(B^0 \to \pi^- l^+ \nu_l) = (1.58 \pm 0.43_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-4}$

World Average (1.50± 0.06) x10^{-4}

⇒BELLE2-CONF-PH-2020-007

Dark Matter searches

The Belle II way: **light dark sector access via light mediators**

⇒ implies New Physics & DM

⇒ already competitive measurements

First Belle II publi!

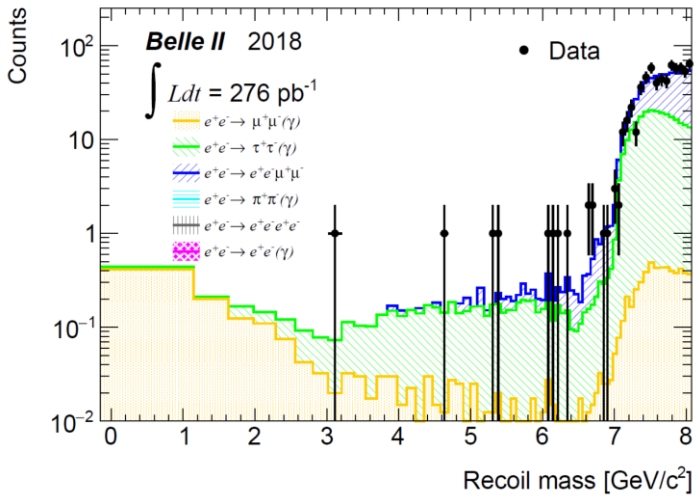
⇒ PRL 124 (2020) 141801

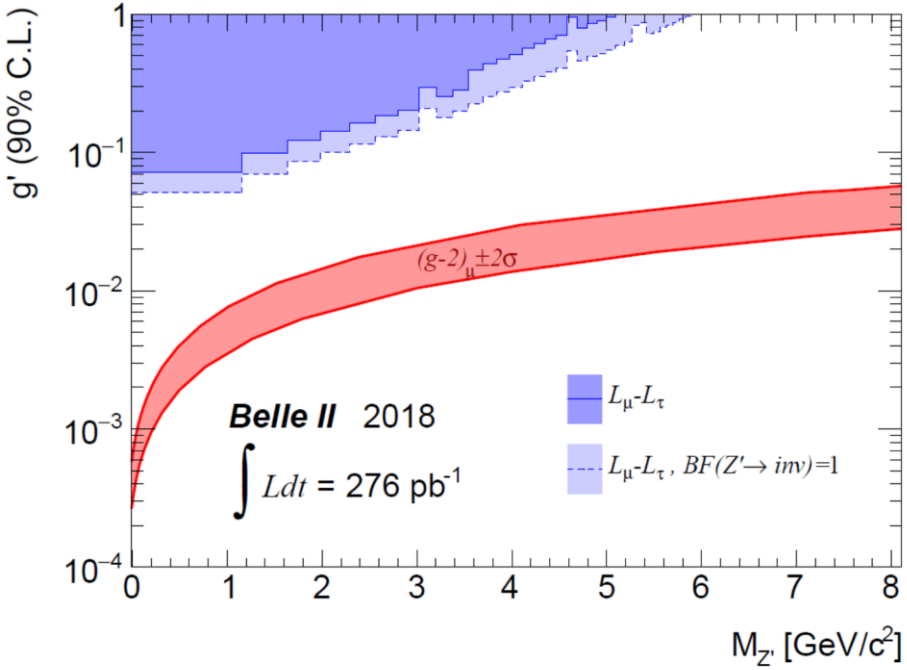
- New light Z'
  - Couples (g') both to SM particles & DM constituents
    - only 2nd & 3rd SM generations
  - Search for

$$e^+e^- \to \mu^+\mu^- Z'(\to \text{invisible DM})$$

$$e^+e^- \to e^\pm\mu^\mp Z'(\to \text{invisible DM})$$

  - Exploit recoil mass against *ll*-system





- Other searches on-going
  - Axion Like Particles
  - Dark photons

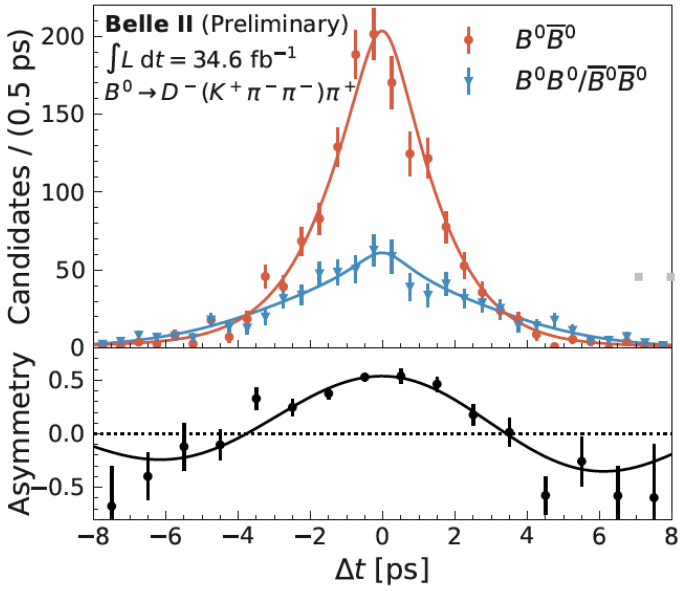
See Wednesday talk by **Marcello Campajola**
"Dark Sector first results at Belle II"

Time-dependent analysis for B-physics

- Major tool for
  - SM precision test, CP violation (φ_1)
  - NP sensitivity $b \to q\bar{q}s$ ($q = u, d, s$)
- Main analysis steps
  - **Time-resolution**: see lifetime measurement
  - **Flavour tagger**: effective efficiency~34 %

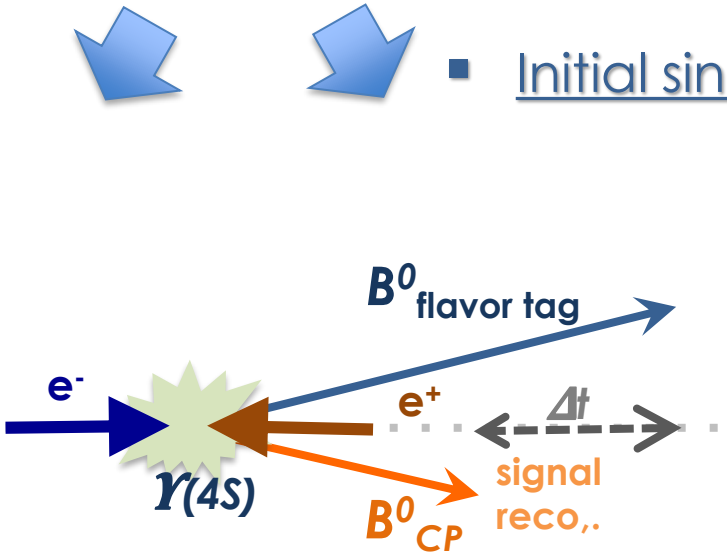
⇒ BELLE2-CONF-PH-2020-004

- Mixing $B^0 \to D^- \pi^+$

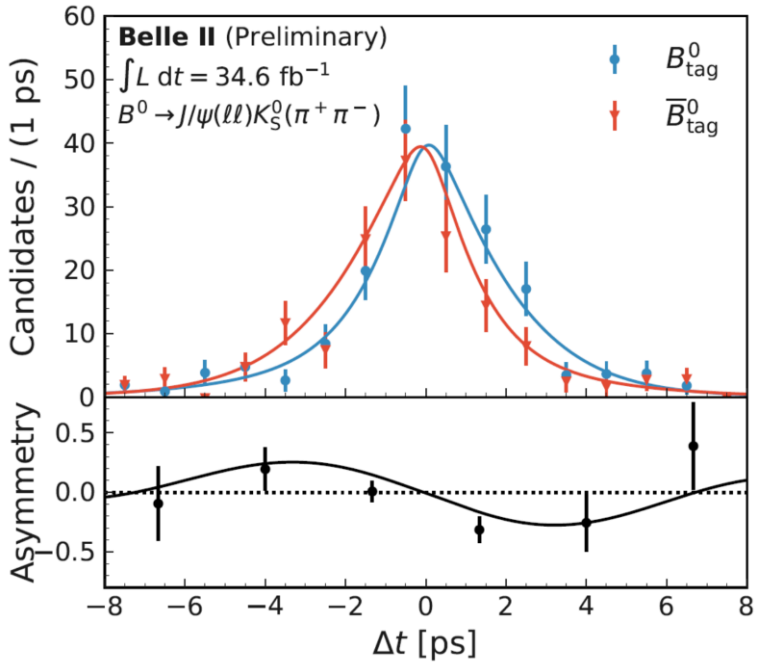


$\Rightarrow \Delta m_d(B^0) = (0.531 \pm 0.046_{\mathrm{stat}} \pm 0.013_{\mathrm{syst}})\mathrm{ps}$

World Average (0.5065± 0.019) ps



- Initial $\sin 2\varphi_1$ measurement $B^0 \to J/\psi K_S$



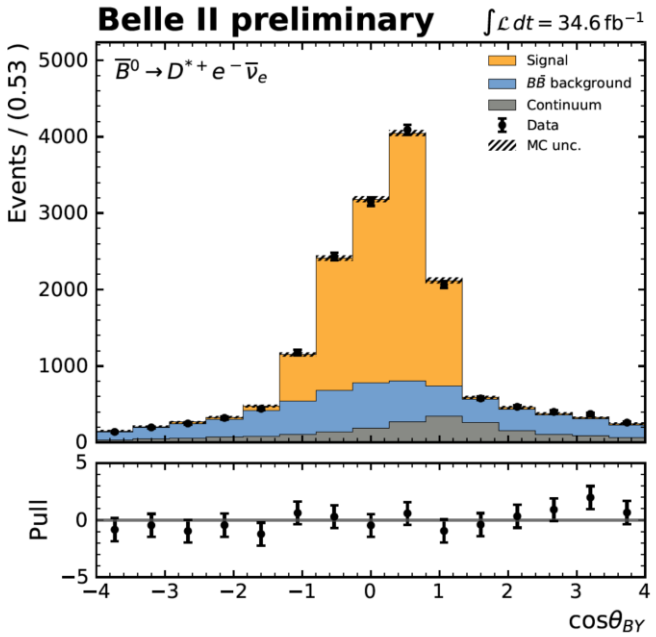
$\Rightarrow \sin 2\varphi_1 = 0.55 \pm 0.21_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$

World Average 0.685 ± 0.019

Semileptonic B-decays

- **Major tool for**
  - SM precision test, CKM elements $|V_{ub}|$, $|V_{cb}|$
  - Lepton Flavor Universality test

- Build *Y=D*l* system to separate signal/background

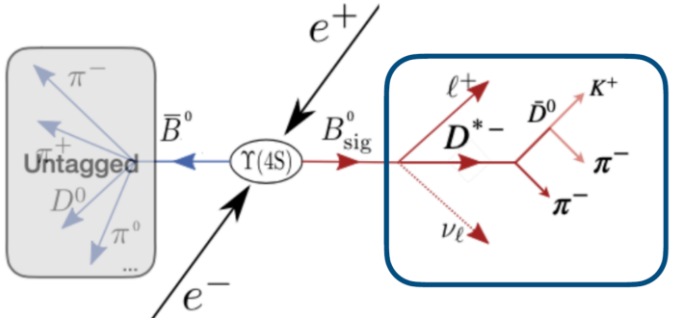


$\Rightarrow \mathcal{B}(\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l) = (4.60 \pm 0.05_{\mathrm{stat}} \pm 0.17_{\mathrm{syst}} + 0.45_{\pi_s})\%$

World Average 5.05± 0.14) %

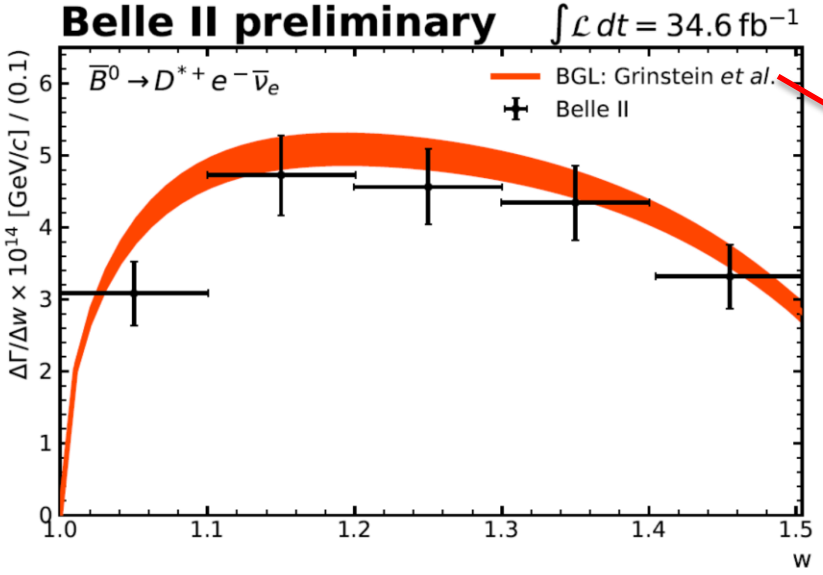
⇒ BELLE2-CONF-PH-2020-008

- **Untagged exclusive analysis**
  - 2 channels $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$ and $B^- \to D^0 l^- \bar{\nu}_l$



- Partial decay rates ΔΓ unfolded over

hadronic recoil parameter $w = \frac{m_B^2 + m_{D^*}^2 - (p_B - p_{D^*})^2}{2 m_B m_{D^*}}$



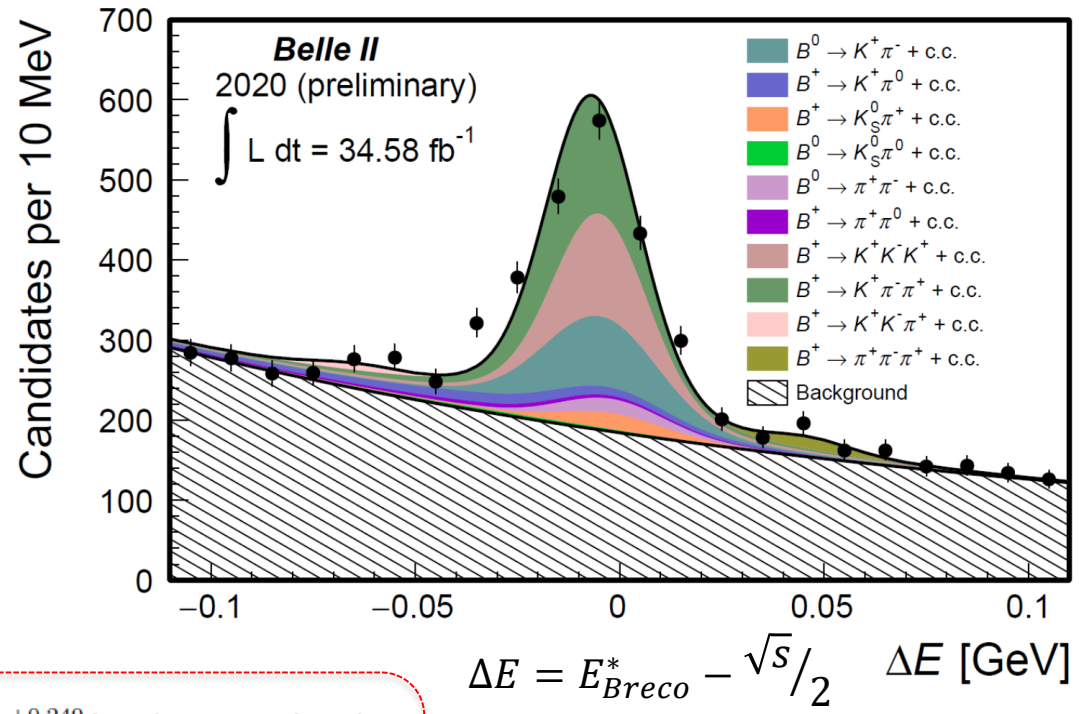
Prediction with hadronic form factor ⇒ $|V_{cb}|$ extraction

Charmless B-decays

- **Major tool for**
  - SM precision test: Unitarity Triangle φ_2, isospin sum rules
  - Sensitive to NP through loop contributions

- **Current focus**
  - Two- to Three- body decays with branching fractions ~ 10^{-6}
    - Reconstruction efficiency range =15-40%
  - Challenging $e^+e^- \to q\bar{q}$ background (continuum)
    - Boosted Decision Tree feed by 39 discriminating variable
  - For flavour-specific channels extract charge asymmetry
    → Probe direct CP-violation
    - Correction of instrumental-induced asymmetries with data

⇒ BELLE2-CONF-PH-2020-001
results below are updated



$$\Delta E = E^*_{Breco} - \sqrt{s}/2$$

$$\mathcal{A}(B^0 \to K^+\pi^-) = 0.029 \pm 0.065(\text{stat}) \pm 0.007(\text{syst}),$$

$$\mathcal{A}(B^+ \to K^+\pi^0) = 0.052^{+0.121}_{-0.119}(\text{stat}) \pm 0.022(\text{syst}),$$

$$\mathcal{A}(B^+ \to K^0_S\pi^+) = -0.072^{+0.109}_{-0.114}(\text{stat}) \pm 0.024(\text{syst}),$$

$$\mathcal{A}(B^+ \to \pi^+\pi^0) = -0.268^{+0.249}_{-0.322}(\text{stat}) \pm 0.123(\text{syst}),$$

$$\mathcal{A}(B^+ \to K^+K^-K^+) = -0.049 \pm 0.063(\text{stat}) \pm 0.022(\text{syst}),$$

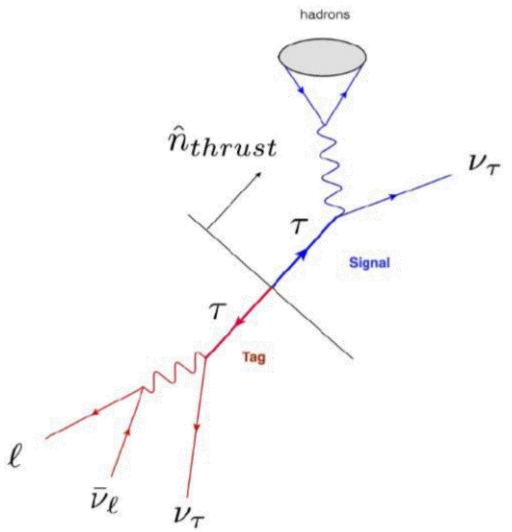
$$\mathcal{A}(B^+ \to K^+\pi^-\pi^+) = -0.063 \pm 0.081(\text{stat}) \pm 0.023(\text{syst})$$

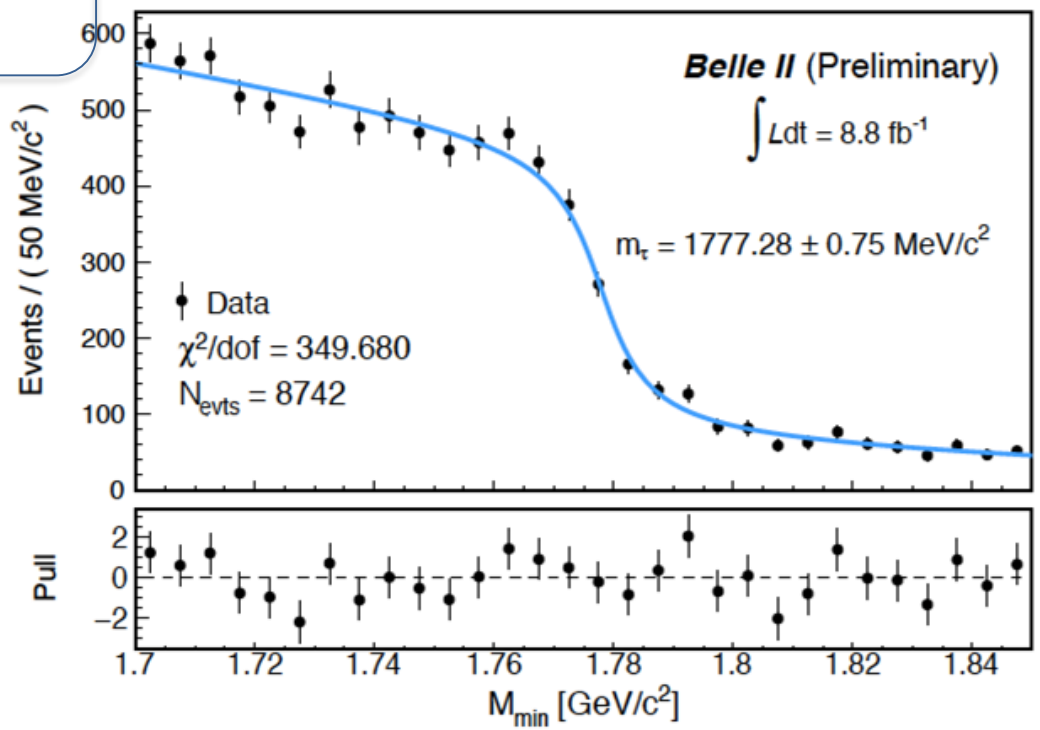
World average compatible

Tau physics

- Major tool for
  - Lepton Flavor Violation with various decays $\tau \to e\gamma, \mu\gamma, \mu\eta, l\alpha, lll$ …
  - SM precision test with τ characteristics

- Tau mass measurement
  - **Pseudomass** technique (←ARGUS)
  - Event selection: 3 charged-π / 1 prong (+π^0)





$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau$$

$\Rightarrow m(\tau) = 1777.28 \pm 0.75 \pm 0.33\ \text{MeV/c}^2$

World Average 1776.86 ± 0.12 MeV/c²

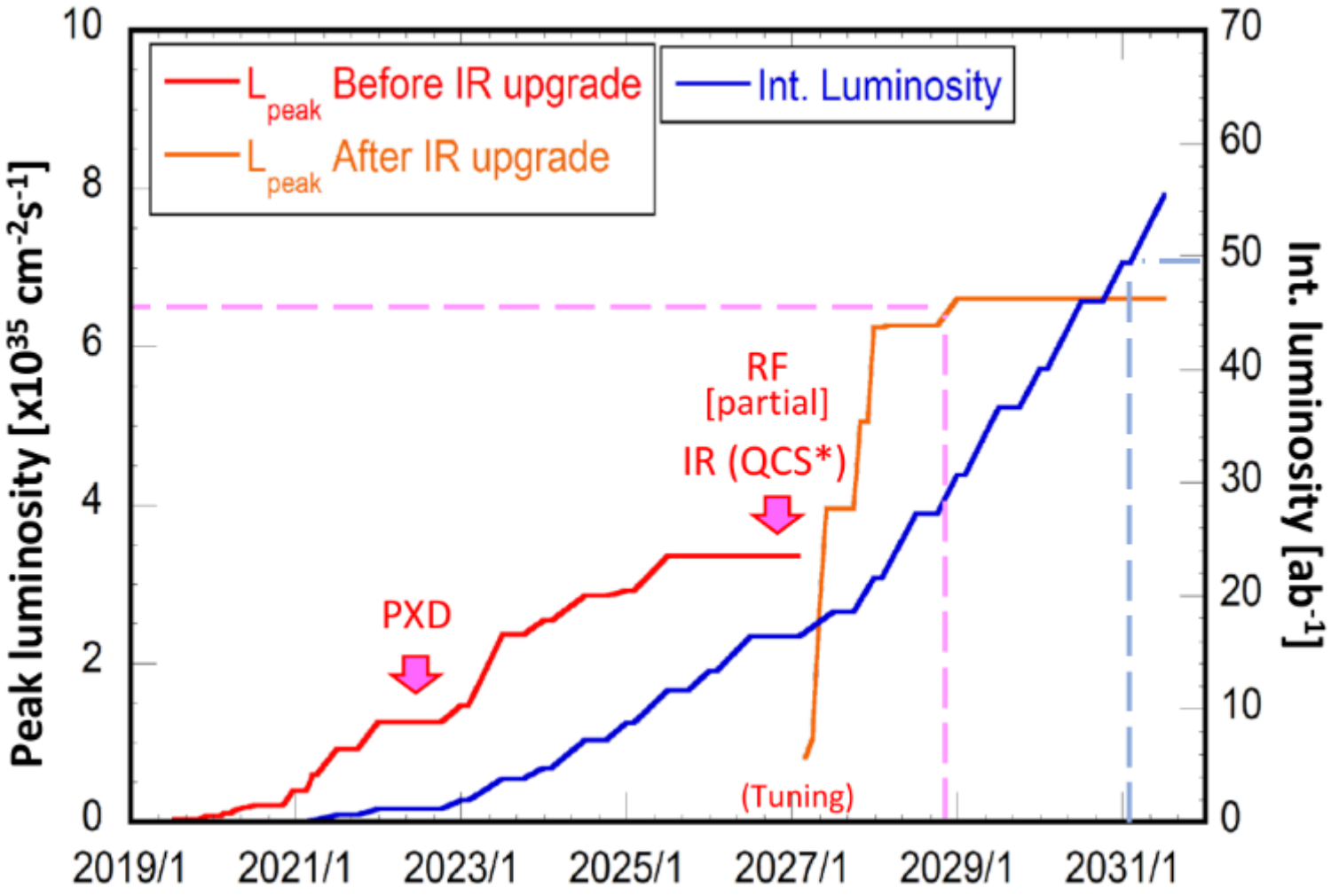
⇒ BELLE2-CONF-PH-2020-010

Prospects for SuperKEKB schedule overview

- Till 2026
  - Continuous machine tuning
    - Beam optics ($\beta_y^* \rightarrow 0.5$ mm)
  - **Beam background mitigation** (current limiting factor in 2020)
    - New collimators
- Upgrade foreseen in 2026
  - "Long" shutdown
  - **New final focussing magnets (QCS)**
  - New beam pipe for interact. region
  - Partial RF power upgrade

Nominal luminosity 6×10^{35} cm^{-2}.s^{-1}

L_{int} = 50 ab^{-1} after a few years



Prospects for Belle II

Continuous improvement with 2 major steps

- 2022 shutdown
  - On-going **DAQ** board replacement
  - Renew **PXD**: complete two inner layers
    with same DEPFET technology
    with new beam-pipe shielding (SR)
  - **TOP**-Photomultiplier replacement
    for longevity against beam-background
- 2026 shutdown
  - SuperKEKB requires long shutdown (see previous slides)
  - Opportunity for detector upgrades
    - Highest resilience against beam-background
    - Improve some performances
  - **Letter of intents** prepared this Fall
    - Vertexing / Tracking / PID / Calorimetry / Triggering

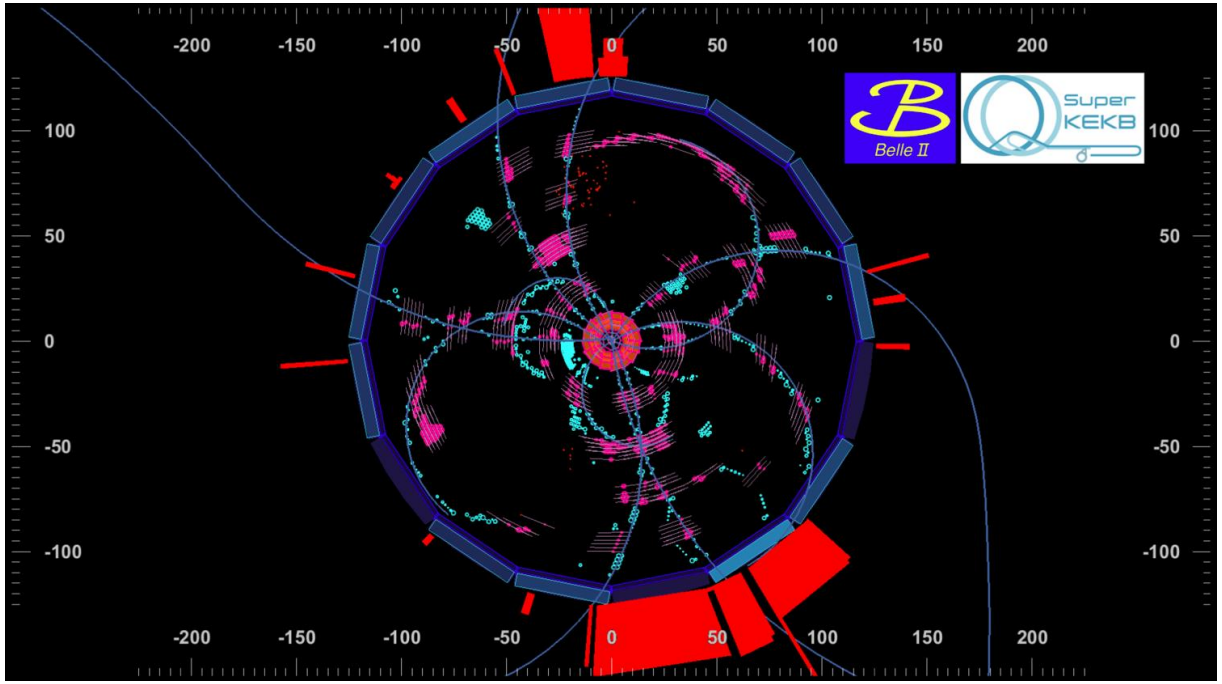
In the next 2 years

- Shortly expected analysis results
  - Combined Belle + Belle II measurement for φ_3
  - Radiative $b \to s\gamma$ transitions
  - Inclusive $B^+ \to K^+\nu\nu$
  - Inclusive (FEI tagged) $b \to s\gamma$
  - Dark sector:
    - Z' to visible, dark Higgsstrahlung, more ALPs search
  - Tau physics:
    - $\tau \to l\alpha$, lll
- Expected cumulated luminosity
  - March 2021 :140-240 fb^{-1}
  - July 2022: 1 ab^{-1} (BaBar / Belle L_{int} level)

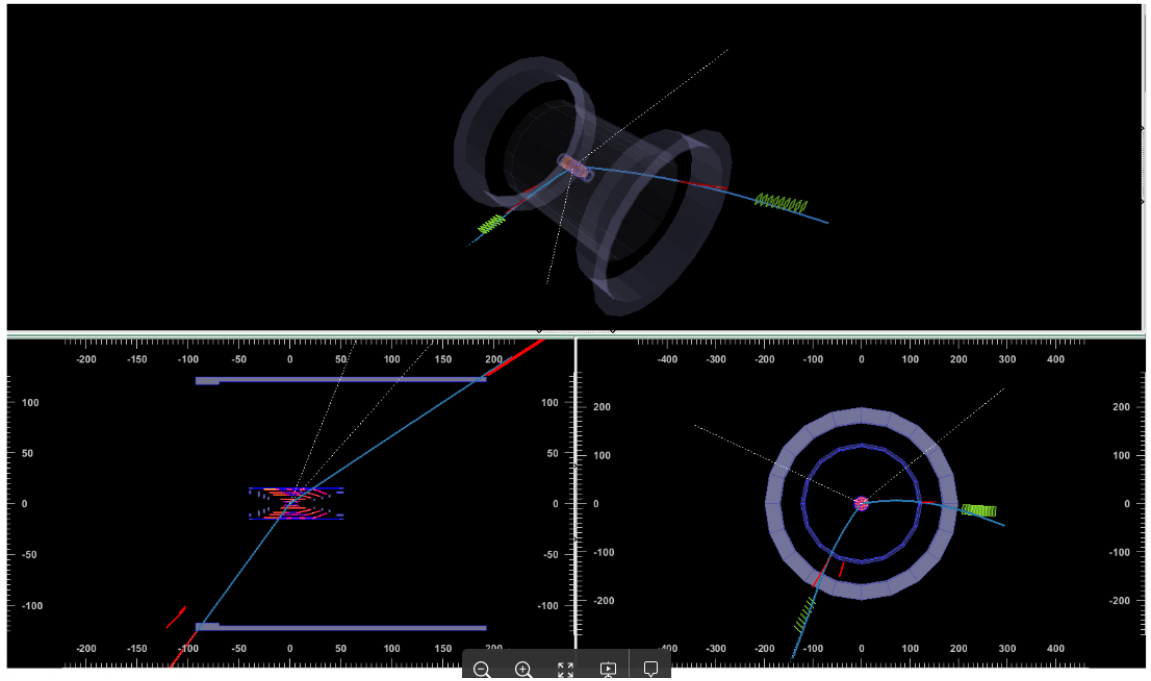
Conclusion

- SuperKEKB & Belle II have a clear plan to deliver & accumulate $L_{int} \sim 50$ ab^{-1}
- Current analysis performances similar or better than Belle
  → Many measurements delivered & on-going
- Already some competitive results

Opportunities for new ideas

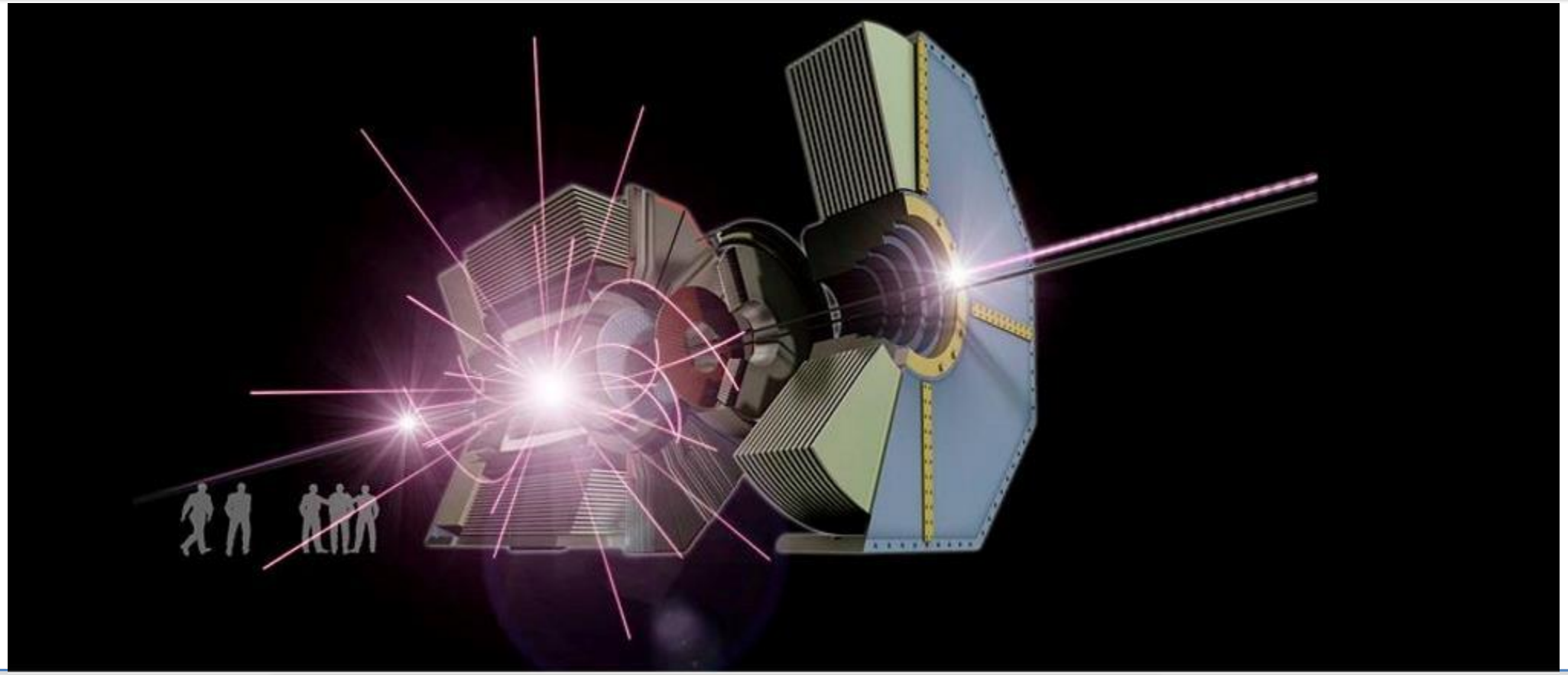


Real hadronic event



Monte-Carlo simulation with Z'→ invisible

SUPPLEMENTARY SLIDES



More results not covered

- Charmless B decays
  - Channels for φ2 measurement: $B^+ \to \phi K^+, B^+ \to \phi K^{*+}, B^+ \to \phi K_S^0$ ⇒ BELLE2-CONF-PH-2020-006
  - B → charmless BF's and A_CP's ⇒ BELLE2-CONF-PH-2020-001
- Semileptonic decays
  - Tagged (Full Event Interpretation) $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$ ⇒ BELLE2-CONF-PH-2020-009
  - Hadronic mass moments of $B \to X_c l \nu_l$ ⇒ ICHEP talk "First results on Vub and Vcb with Belle II"
- Radiative and electroweak Penguin B decays ⇒ ICHEP talk "Results and Prospects at Belle II "
- Charm physics ⇒ ICHEP talk "Charm potential at Belle II"
- Charmonia studies ⇒ ICHEP talk "First results from Belle II on exotic and conventional quarkonium"

The collider

e^+ 4GeV 3.6 A

e^- 7GeV 2.6 A

SuperKEKB

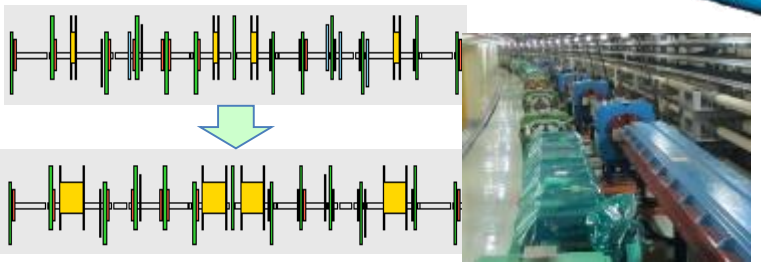
Target: L = $8\times10^{35}/cm^2/s$

New superconducting /permanent final focusing quads near the IP

New IR

Colliding bunches

Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

Add / modify RF systems for higher beam current

Positron source

New positron target / capture section

Damping ring

@1.1 GeV

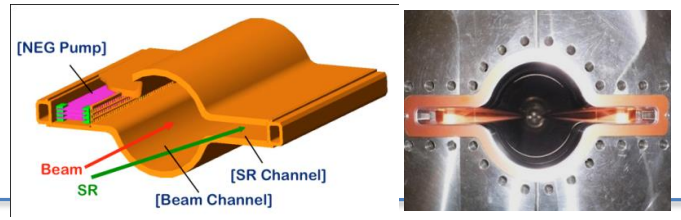
To inject low emittance positrons

Low emittance gun

To inject low emittance electrons

TiN-coated beam pipe with antechambers

Cu for wigglers and Al alloy for the rest

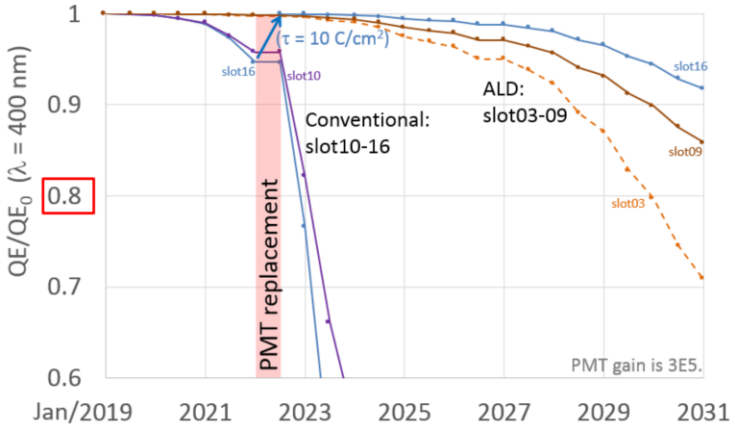


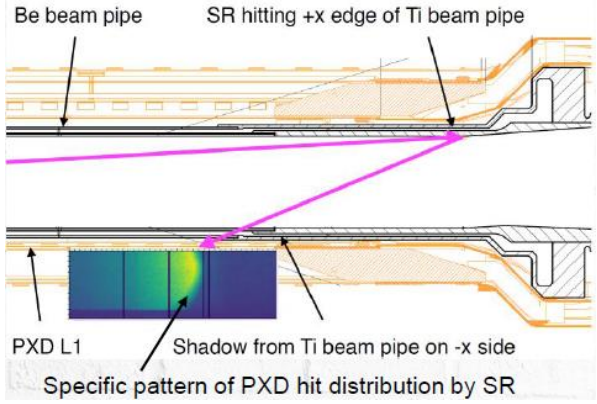
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm\xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

Beam induced background

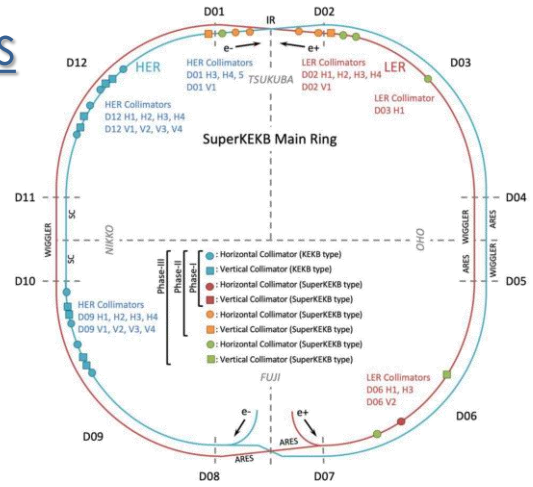
- **Various sources**
  - Single beam backgrounds
    - scale with I, I^2, 1/beam-size
  - Beam-Beam (QED) effects
    - scale with luminosity

- **Current main issues**
  - TOP MCP-PMT QE decrease with total charge
  - Synchrotron radiations in PXD





- **Mitigation measures**
  - Tuning
    - Injection
    - Beam geometry
  - Collimators
  - shielding



- **At luminosities > 10^{35} cm^{-2}.s^{-1}**
  - Concern is occupancy
    - especially / inner layers → few % range
  - Predictions robust to a factor <5
    - From current data / MC rate ratio

  - Opportunity for detector upgrades
    - Get safer by lowering occupancy
    - Get better performances for physics