Belle II: status and prospects

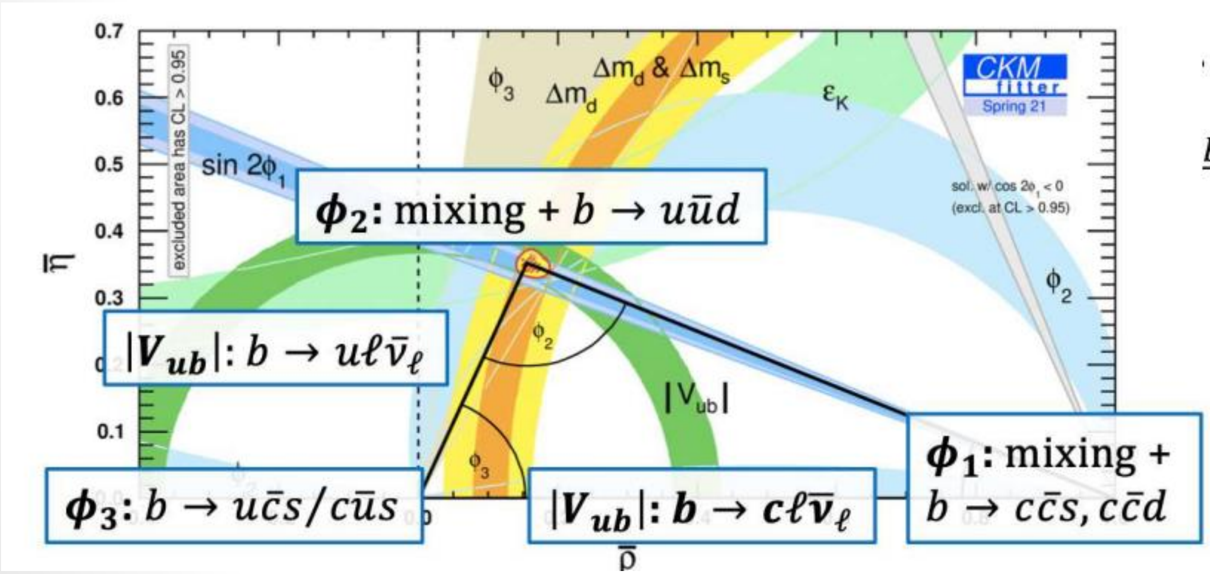
Jim Libby (IIT Madras)

Overview

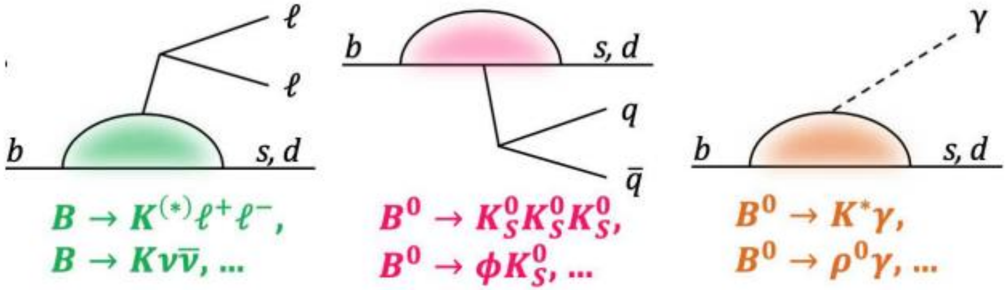
- Introduction to Belle II
- Some recent(-ish) highlights
  - CP violation
  - Anomalies
  - Beyond Bs – dark sector searches
- Prospects

Why Belle II?

- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ provides a source of B meson decays in a **low multiplicity** and **kinematically constrained** environment
- Belle and BABAR collected 1.5 ab^{-1} of such data → **Belle II to collect 30 times more**
- **Approximately one billion B pairs per ab^{-1}**



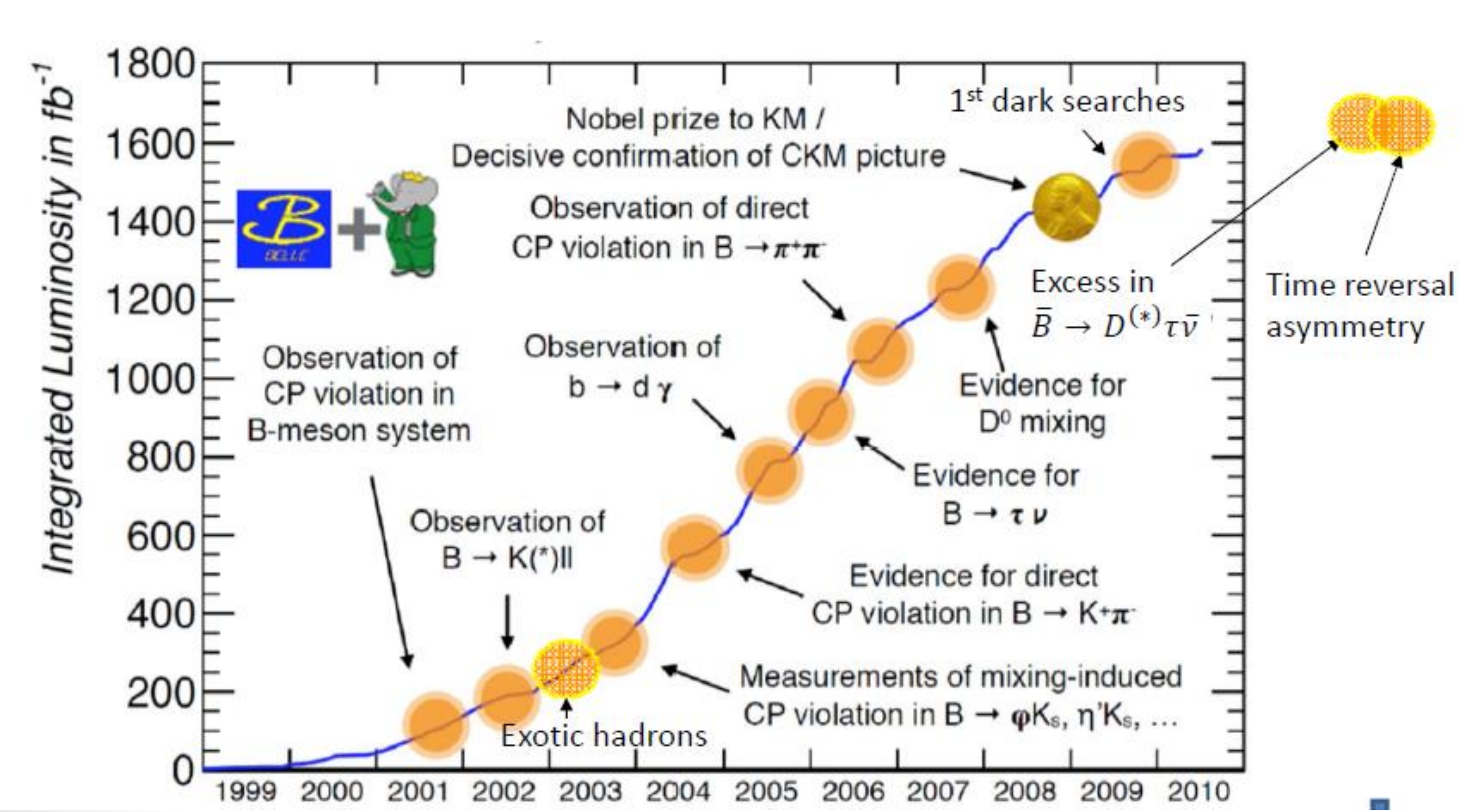
1) **Further exploration of KM mechanism**



2) **Penguins a plenty**

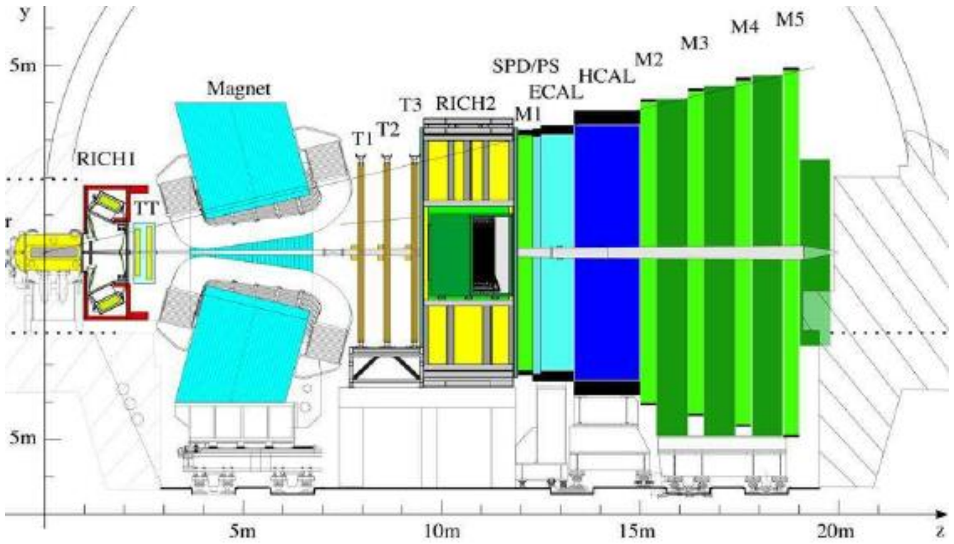
3) Not just Bs
- $\sigma(b\bar{b}) \approx \sigma(c\bar{c}) \approx \sigma(\tau^+\tau^-)$
- quarkonium
- **dark sector** and
- $e^+e^- \to \pi^+\pi^-\gamma$ for $g_\mu - 2$

Belle and BABAR achievements

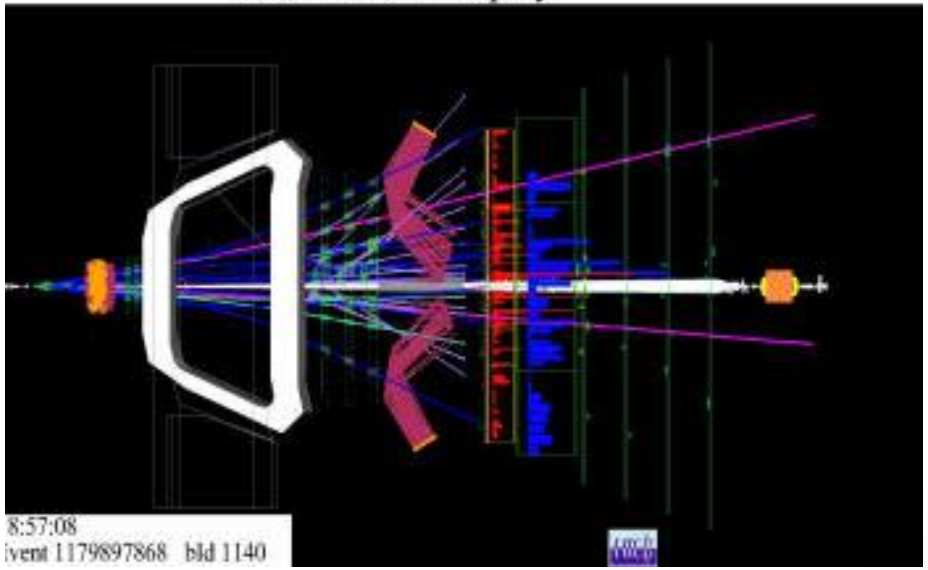


Belle II's rival LHCb in a slide

- 13 TeV pp collisions
  - trillion bb/2 fb^{-1}
  - 6 fb^{-1} @ 13 TeV
  - + 3 fb^{-1} @ 7/8 TeV
- Forward geometry gets both *b* quarks in acceptance and boosted – exploit *b* lifetime to separate background
- RICHes for π/K separation
- Full trigger bandwidth for *B* physics
- Has been driving flavour physics for the past decade so you might ask….



LHCb Event Display

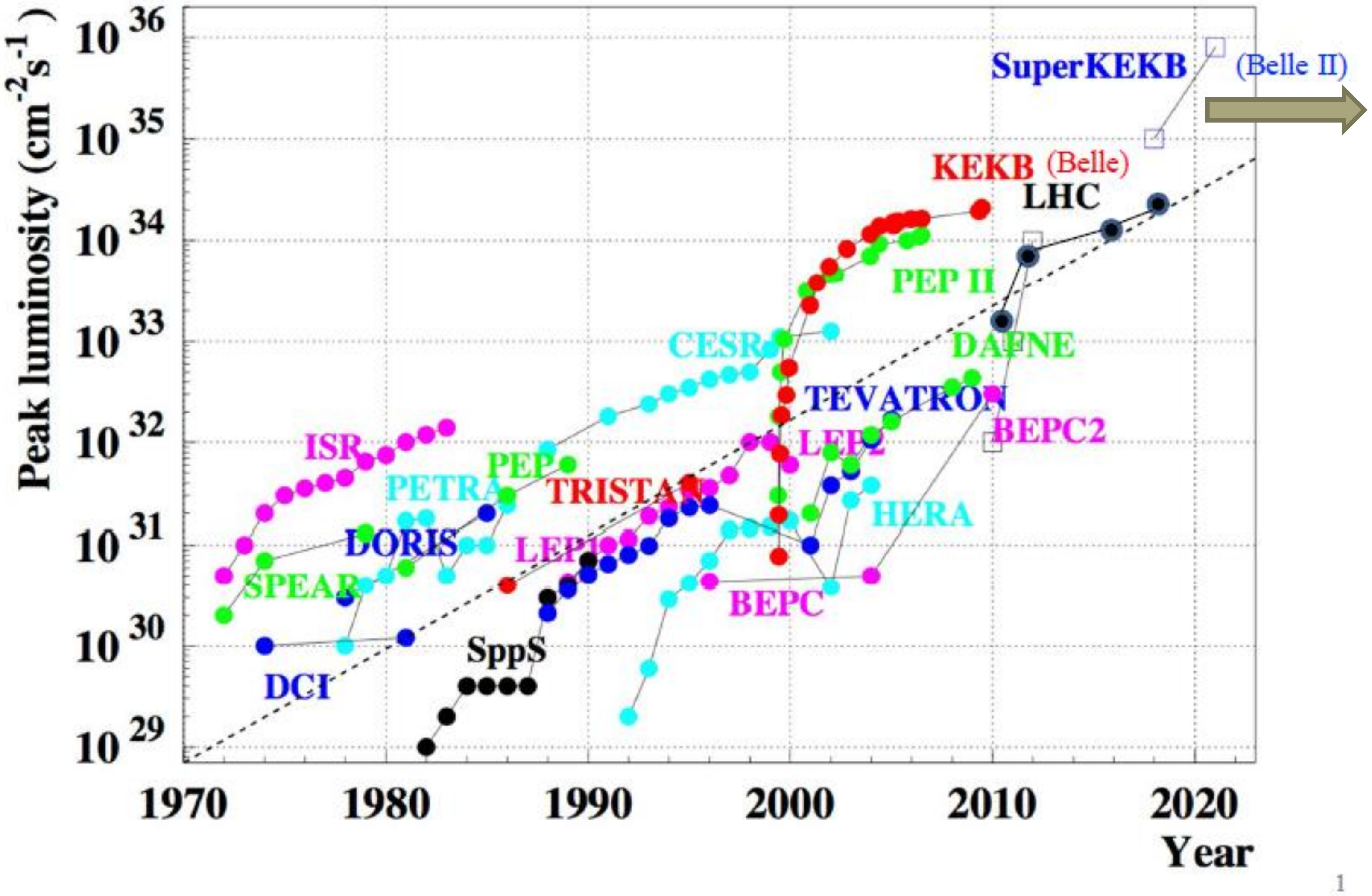


But isn't LHCb doing everything already?

Complementarity

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

“Moore’s” Law of Luminosity



The path to higher luminosity

Beam-beam parameter $\xi \propto \sqrt{\frac{\beta^*}{\varepsilon}}$

Lorentz factor

Beam current

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

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

Classical electron radius

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

Vertical beta function@IP

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

The path to higher luminosity

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

Lorentz factor

Beam current

Beam-beam parameter

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

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

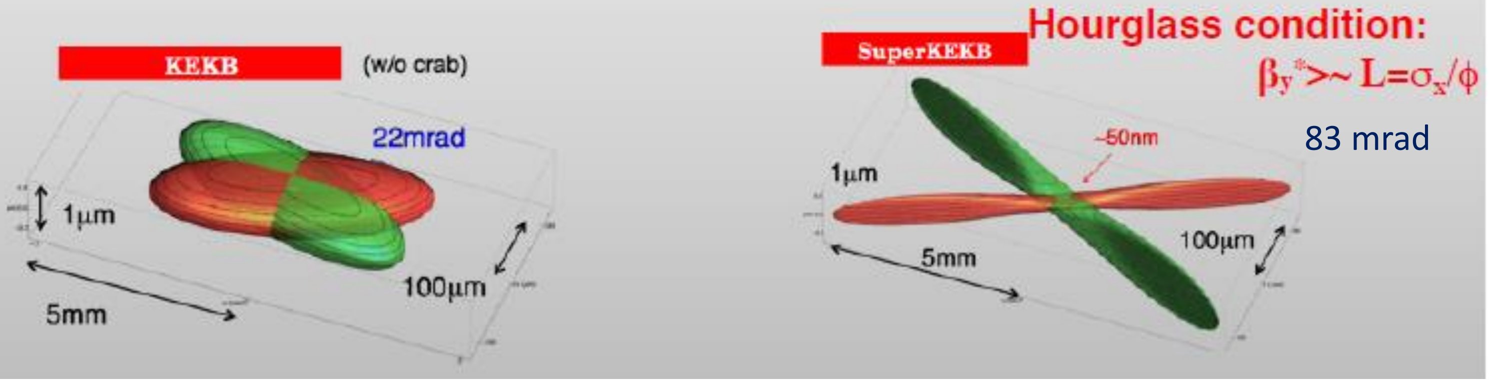
Classical electron radius

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

Vertical beta function@IP

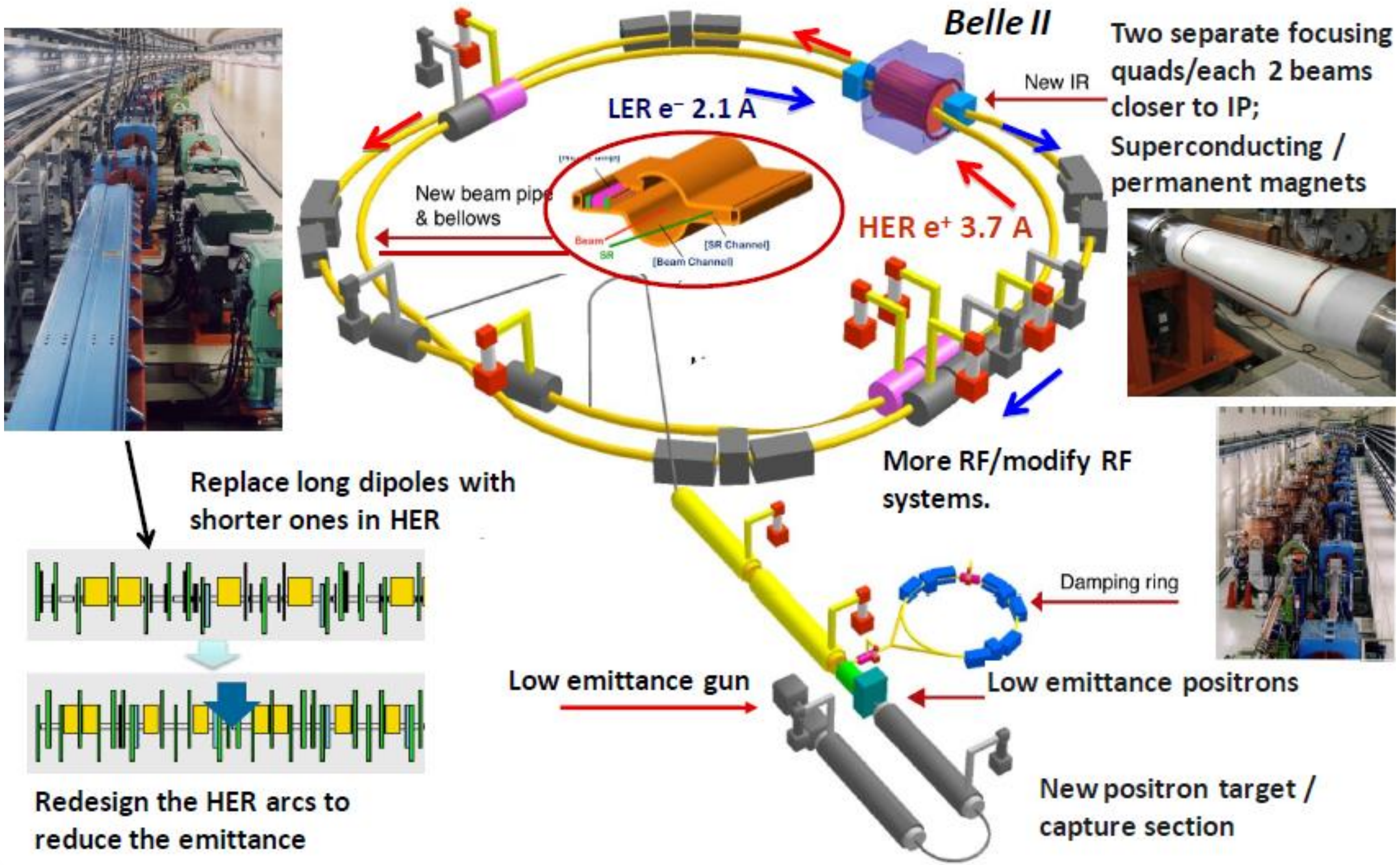
(1) Smaller β_y^* (20 x)

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

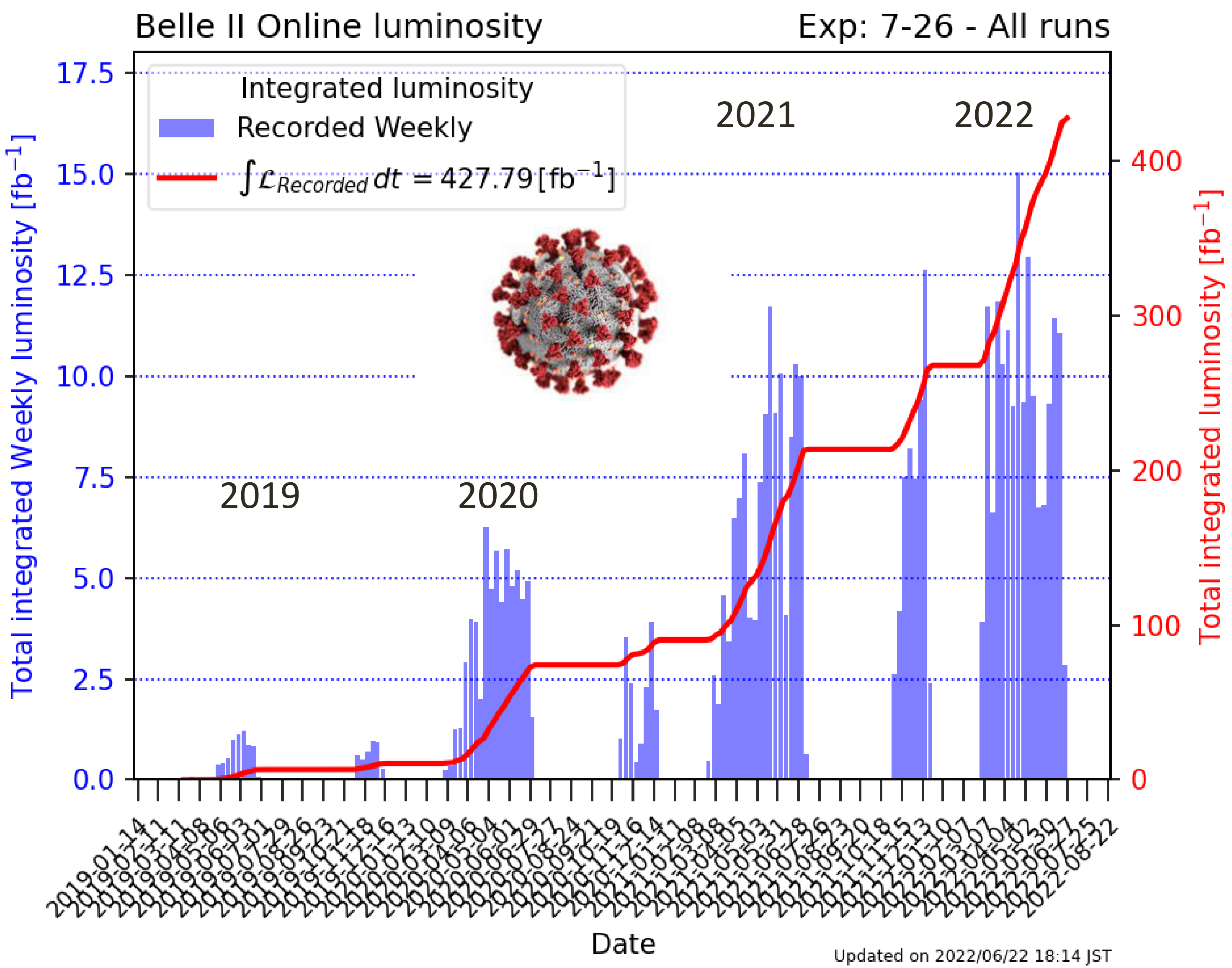


SUPERKEKB

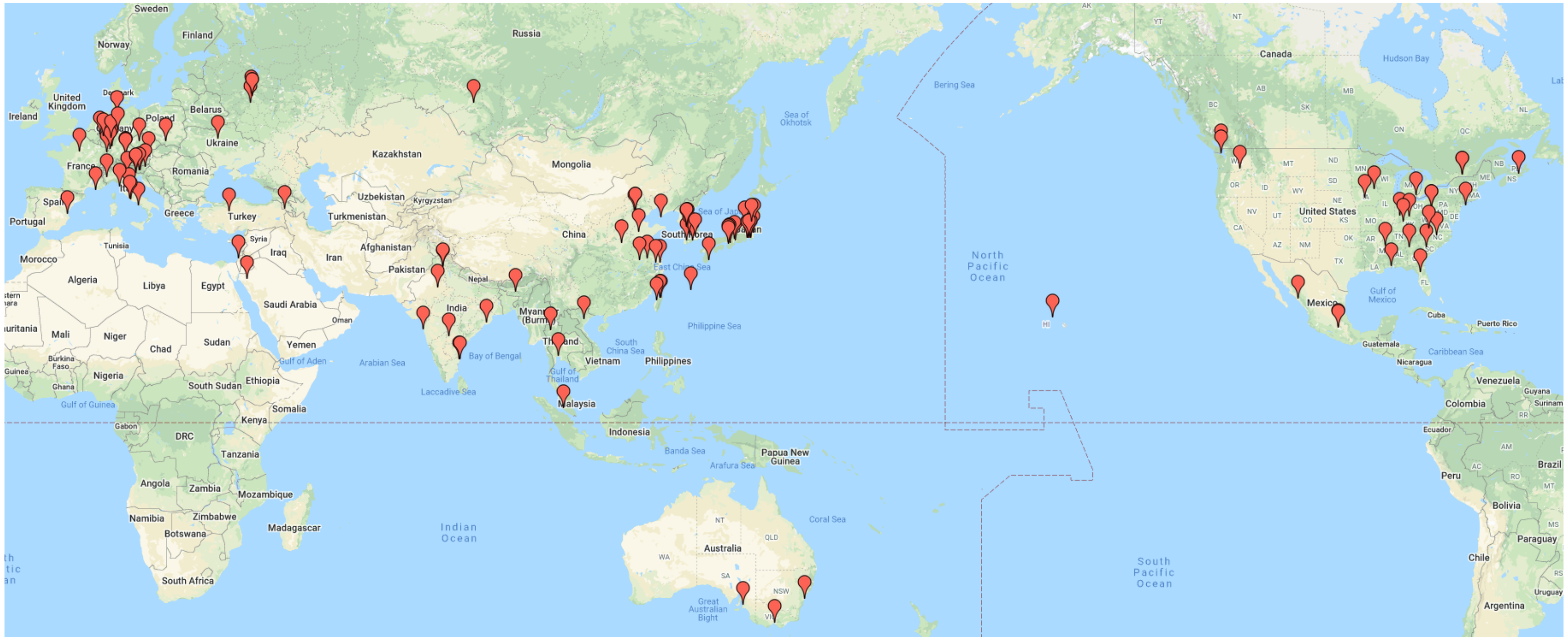
Asymmetric energy: 8 GeV electron 3 GeV positron



Integrated luminosity – so far

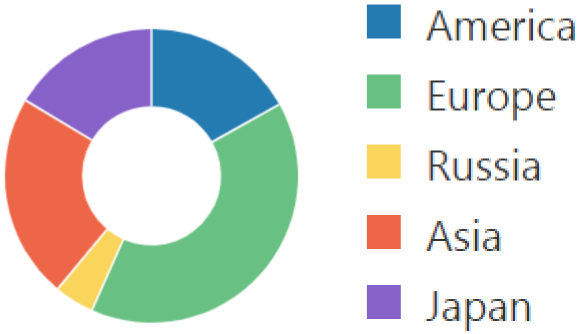


Belle II Collaboration

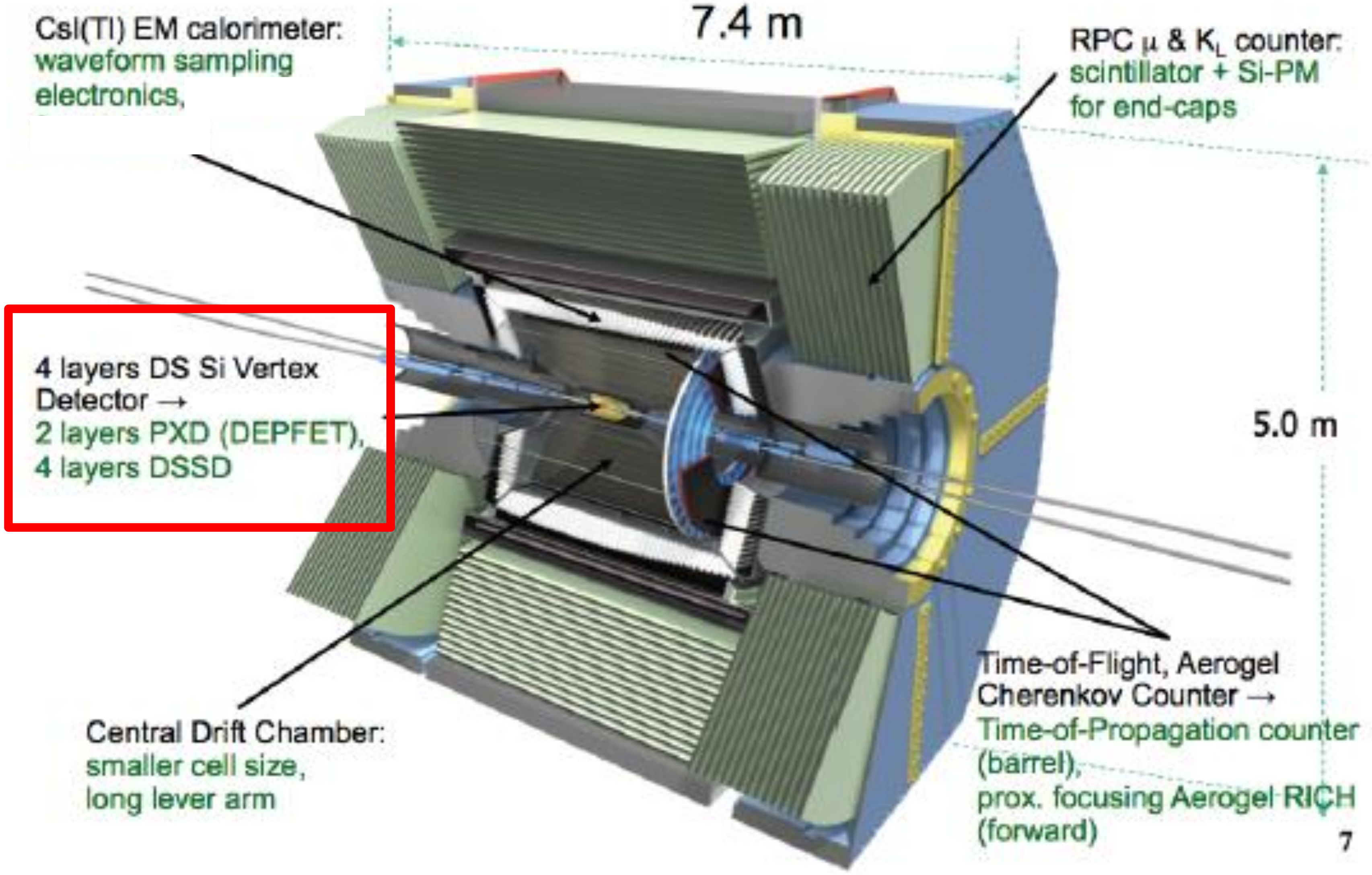


O(1000) physicists from 26 countries

India: ~50 at IITX (X=M, H, G, BBS), MNIT, IISER Mohali, TIFR, PU, PAU, UPES

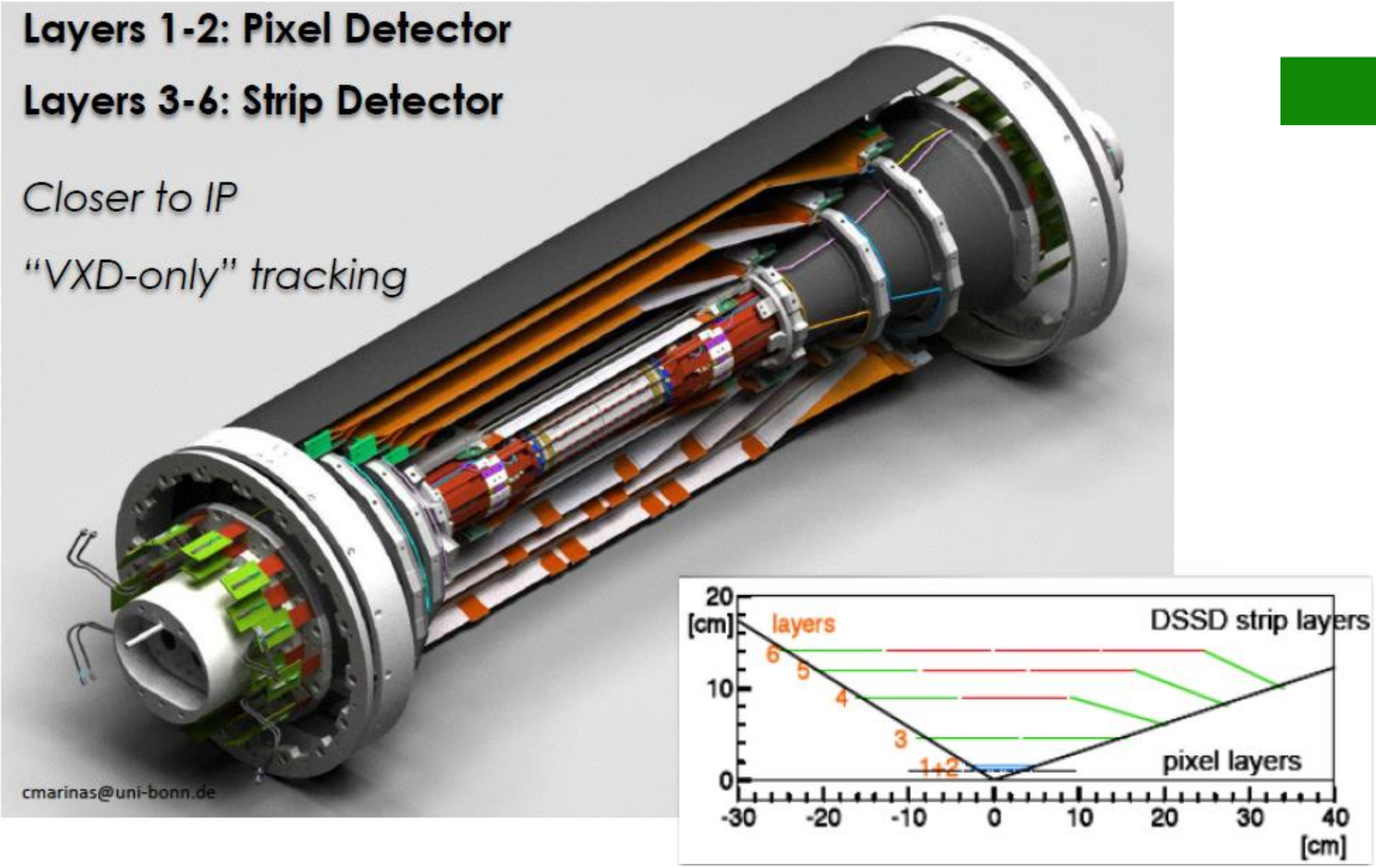


The detector

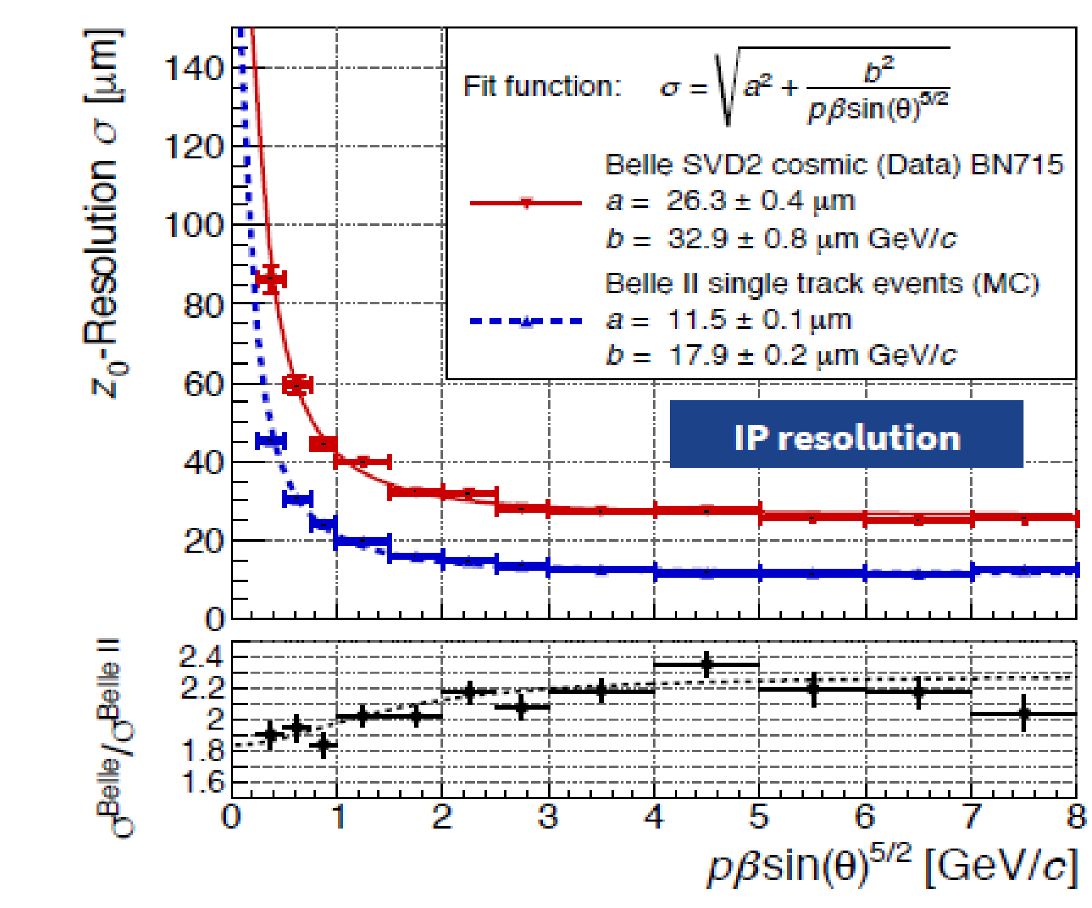


Belle II – Silicon Vertex Detector

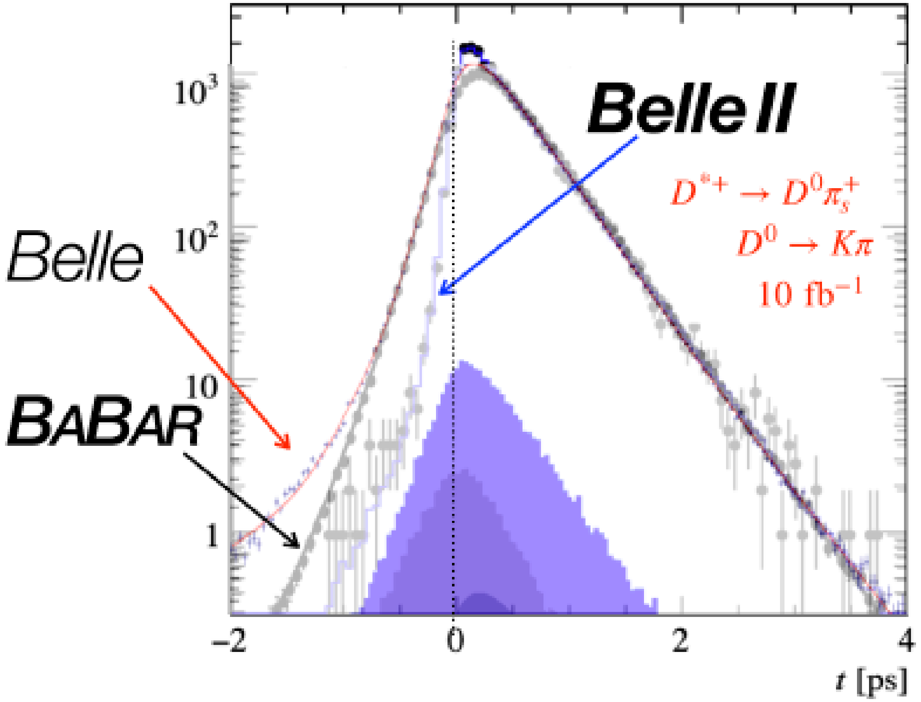
Only one layer of pixels for Phase III



SVD performance



PRL **127**, 211801 (2021)



Belle II decay time resolution nearly twice as better as Belle's

Belle a factor two worse than **Belle II**

	Belle II	World Average Value
$\tau(D^0)$ =	(410.5 ± 1.1 ± 0.8) fs	(410.1 ± 1.5) fs
$\tau(D^+)$ =	(1030.4 ± 4.7 ± 3.1) fs	(1040 ± 7) fs

RECENT RESULT: CP VIOLATION

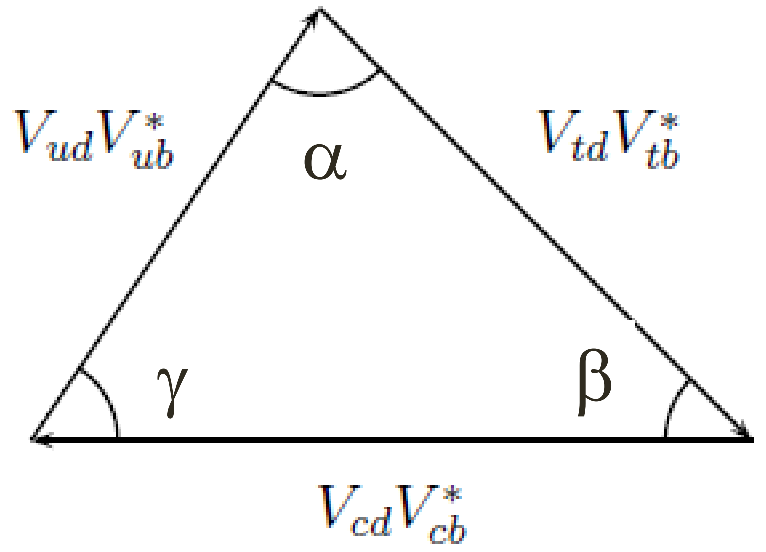
Visualising CP violation: the unitarity triangle

$\lambda = \sin\theta_c = 0.22$

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

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

3)

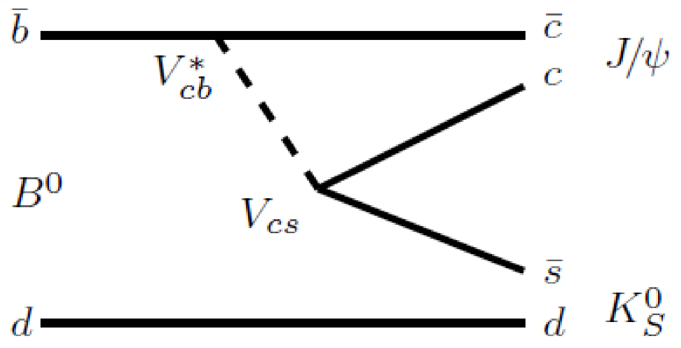


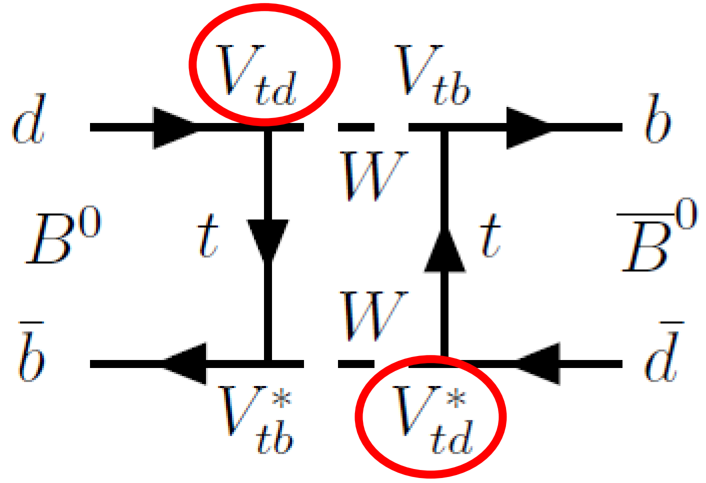
$$\phi_1 = \beta$$
$$= \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$
$$\simeq \arg\left(\frac{1}{1-\rho-i\eta}\right)$$

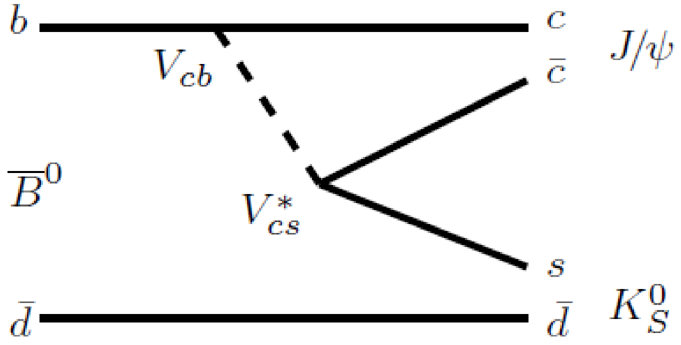
The Golden Mode

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

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







CP violation in the 'interference of mixing and decay amplitudes' – decay time dependent

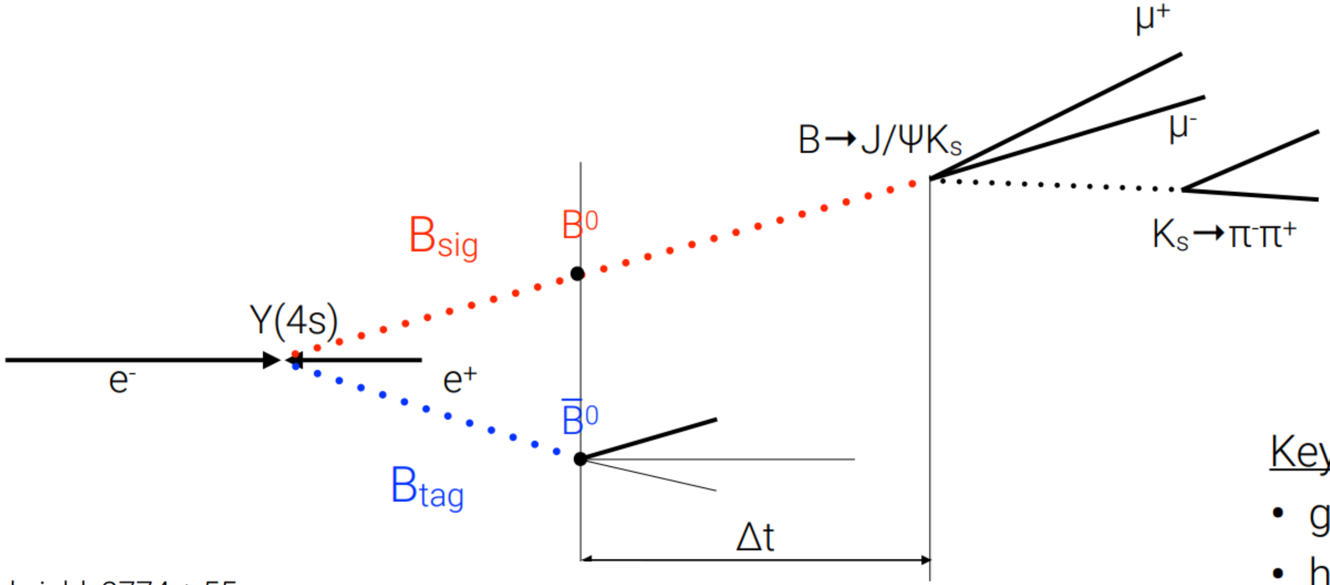
$$A_{CP}(\Delta t) = \frac{\Gamma\left[\overline{B}^0(\Delta t) \to f\right] - \Gamma\left[B^0(\Delta t) \to f\right]}{\Gamma\left[\overline{B}^0(\Delta t) \to f\right] + \Gamma\left[B^0(\Delta t) \to f\right]} = S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)$$

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

Time-dependent CPV violation

Chiara La Licata ICHEP
Conference note in preparation

7-GeV electrons on 4-GeV positrons produce Υ(4S) that decays promptly in a quantum-coherent $B\bar{B}$ pair



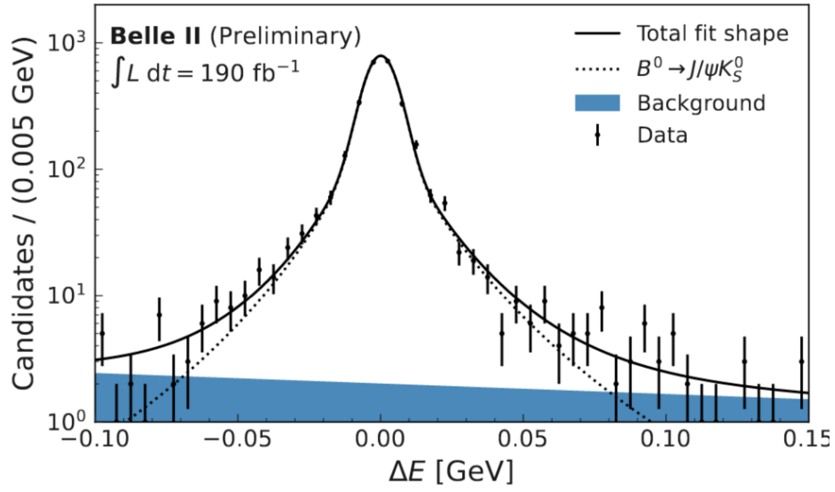
B_{sig} => fully reconstructed in a final state f_{CP} common to B^0 and $\bar{B}^0$

B_{tag} ⇒ only flavor information + vertex position

Key aspects:

- good vertex resolution
- high tagging efficiency

Signal yield: 2774 ± 55



ε_{eff}(Belle II) = (30.0 ± 1.2 ± 0.4)%

$\Delta E = E_B - E_{beam}$ (in c.m. frame)

$\sin 2\phi_1$ results

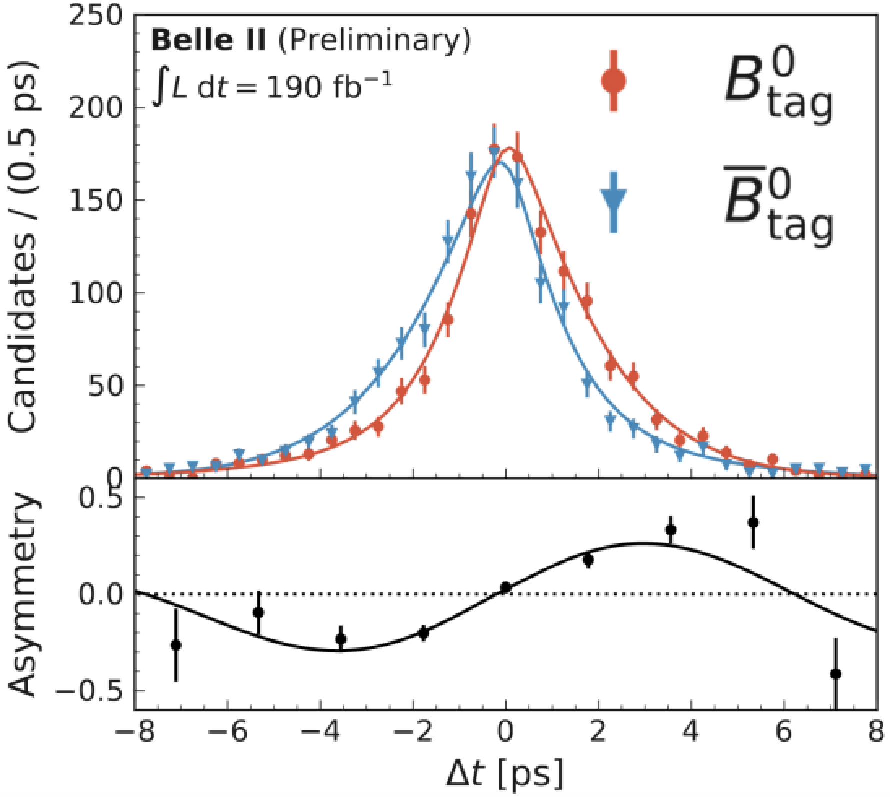
Apply analysis to $B^0 \to J/\psi K_s^0$ sample

Source	$\sigma(S_{CP})$	$\sigma(A_{CP})$
Statistical	0.0622	0.0439
$B^0 \to D^{(*)-}\pi^+$ sample size	0.0111	0.0093
Analysis bias	0.0080	0.0020
Signal charge asymmetry	0.0027	0.0126
$w_6^+ = 0$ limit	0.0014	0.0001
Resolution function parametrization	0.0039	0.0008
τ_{B^0}, Δm_d	0.0007	0.0002
Alignment	0.0020	0.0042
Beam spot	0.0024	0.0020
Momentum scale	0.0005	0.0013
$\sigma_{\Delta t}$ binning	0.0050	0.0051
Multiple candidates	0.0005	0.0008
Tag-side interference	0.0020	$^{+0.0380}_{-0.000}$
Total systematic	0.0159	$^{+0.0418}_{-0.0173}$

Milestone: tools are ready for an impactful $\sin 2\phi_1$ measurement

NEW

Signal yield: 2774 ± 55



$S_{CP} = 0.720 \pm 0.062\ (\text{stat.}) \pm 0.016\ (\text{syst.})$

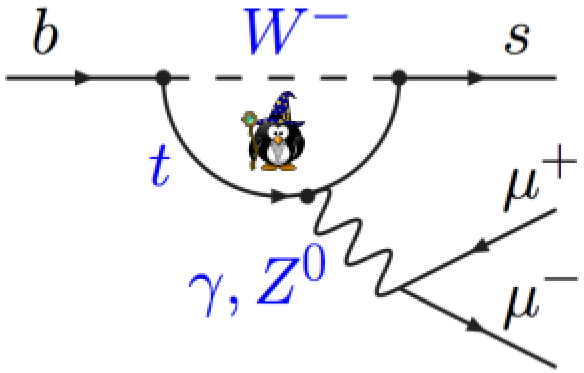
$A_{CP} = 0.094 \pm 0.044\ (\text{stat.})\ ^{+0.042}_{-0.017}\ (\text{syst.})$

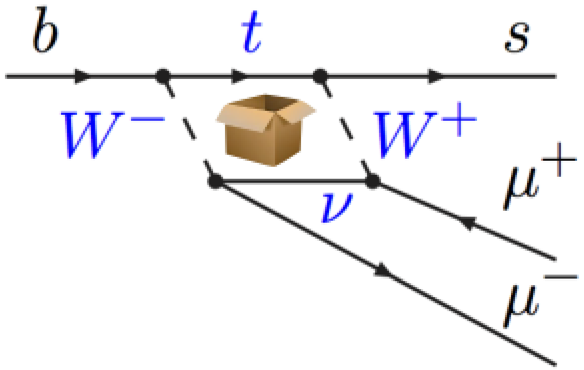
What next? Gluonic penguin modes $B^0 \to \phi K_S^0$ and $B^0 \to \eta' K_S^0$ - BSM physics can shift S_{CP} and A_{CP}

RECENT-ISH RESULT: ANOMALY RELATED

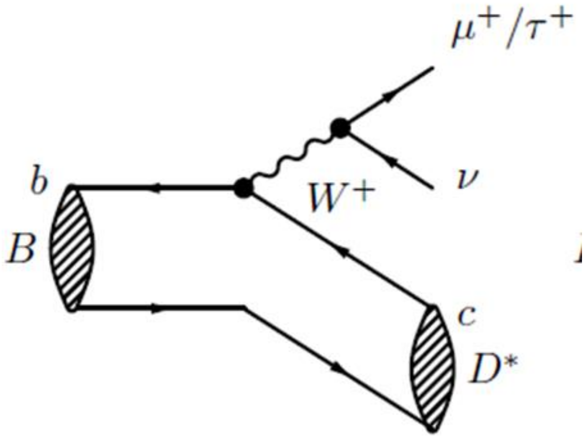
Overview of modes with anomalies

- Flavour changing neutral current *b*→*sll* at loop level only



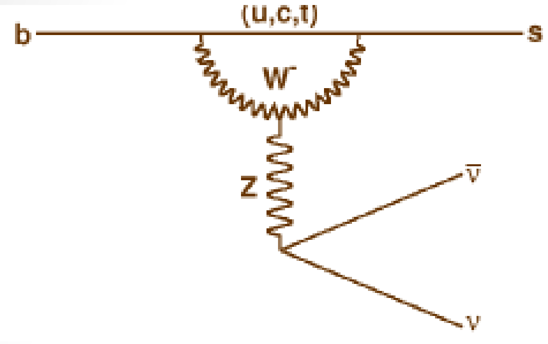


- Tree level *b*→*c*$\tau\nu$ semileptonic

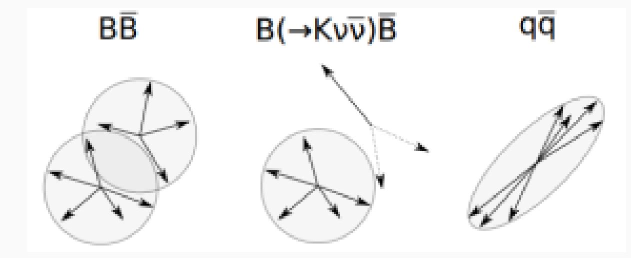


	Pro	Con
b→sll	New physics reach O(10 TeV)	One experiment
b→cτν	Three experiments	New physics near the EW scale

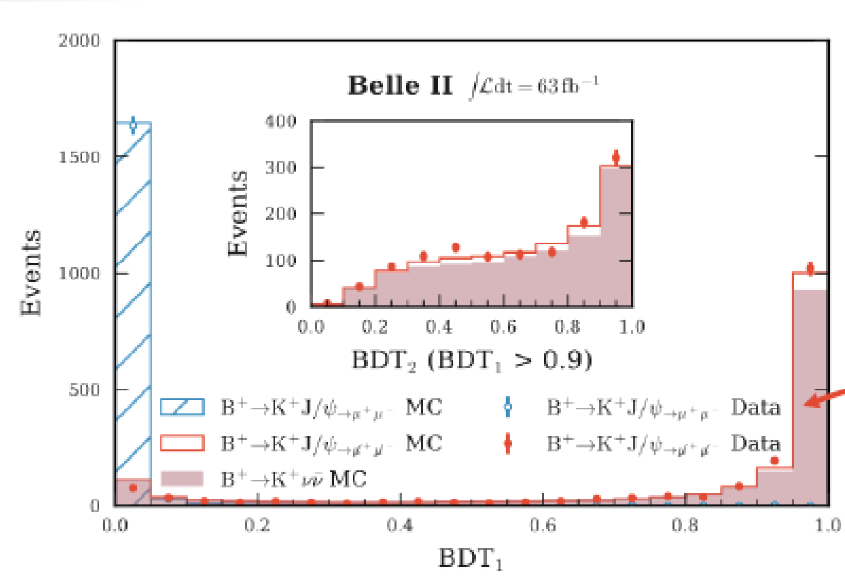
$b \to s\nu\nu$ - PRL **127**, 181802 (2021)



- Transition mediates by a virtual Z-boson.
- SM prediction for the BF[$B \to K^+\nu\nu]_{SM}$ is $(4.6 \pm 0.5) \times 10^{-6}$ **[B2TIP, PTEP 2019, 123C01].**

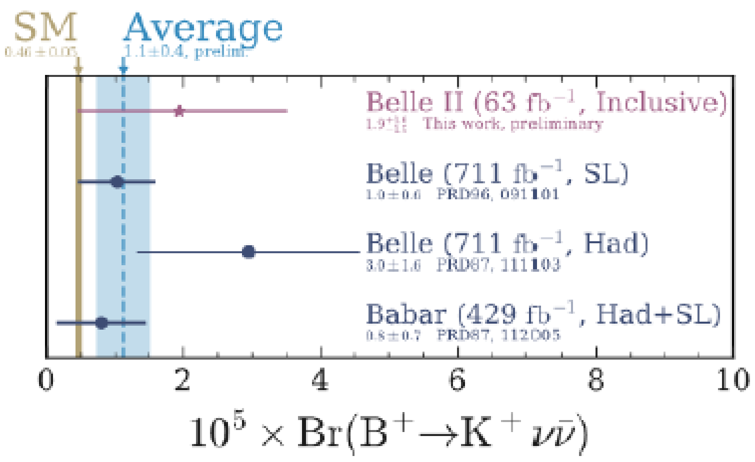


- **Inclusive tagging approach** : nested statistical-learning discriminators exploits efficiently topology allowing for sizeable signal (4%) while controlling large backgrounds.



- Validate with $B^+ \to K^+ J/\psi\ [\to \mu^+\mu^-]$

- $\mu^+\mu^-$ ignored
- K^+ momentum modified
  2-body → 3 body



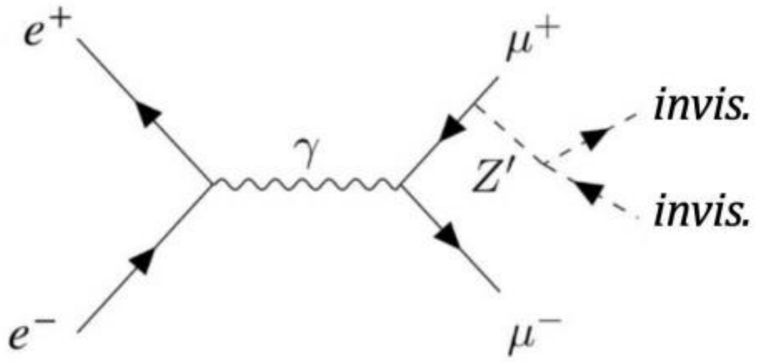
Sensitivity with just 63 fb^{-1} data is already close to previous searches with significantly large data-set.

RECENT RESULT: DARK SECTOR

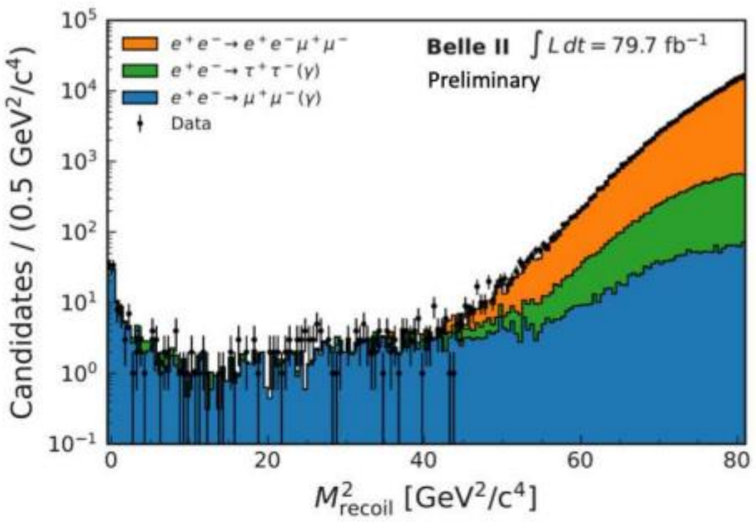
Z’ → invisible – to be submitted to PRL

$L_\mu - L_\tau$ gauge boson Z' couples only to 2nd and 3rd generation leptons

- Avoids stringent existing limits on electron and quark couplings
- Could explain $(g\text{-}2)_\mu$ and other flavour anomalies, e.g. $R_{D^{(*)}}$, $R_{K^{(*)}}$
- $Z' \to \nu\bar{\nu}$ process (mostly relevant for $m_{Z'} < 2m_\mu$). More generally Z' could be mediator to dark sector, coupling to dark χ via $Z' \to \chi\bar{\chi}$



$e^+ e^- \to \mu^+ \mu^- + E_{miss}$



Z' produced by “Z' -strahlung” process from final-state muon

- Previous limits by BABAR and Belle on $Z' \to \mu^+\mu^-$

Z' reconstructed in recoil of di-muon pair

- 2-track trigger w/ muon $p_T^\mu > 0.4$ GeV/c
- No extra energy (γ, π^0) present in the event

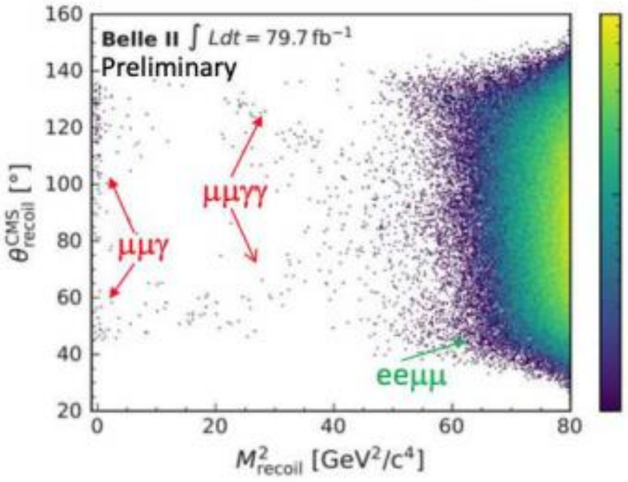
Z’ → invisible – to be submitted to PRL

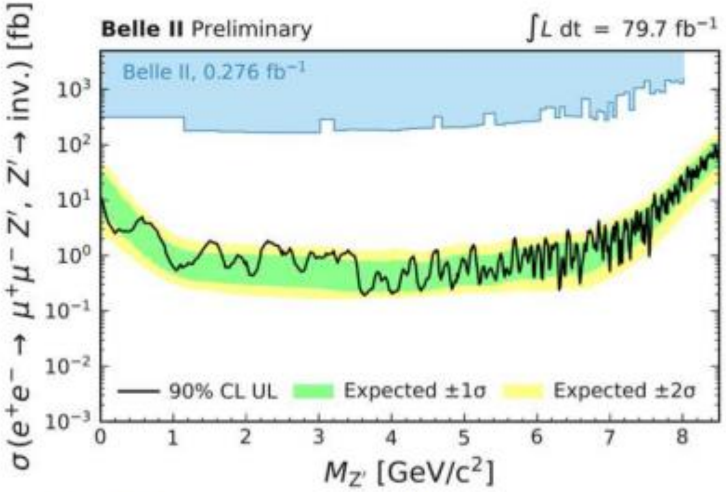
Backgrounds originate from QED processes which mimic the $\mu^+\mu^-$ + E_{miss} final state, typically due to detector acceptance effects:

- $e^+e^- \rightarrow \mu^+\mu^-\gamma\ (\gamma)$ undetected photon(s)
- $e^+e^- \rightarrow \tau^+\tau^-\ (\gamma)$ muonic τ decays and mis-ID
- $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ missing e^+e^-

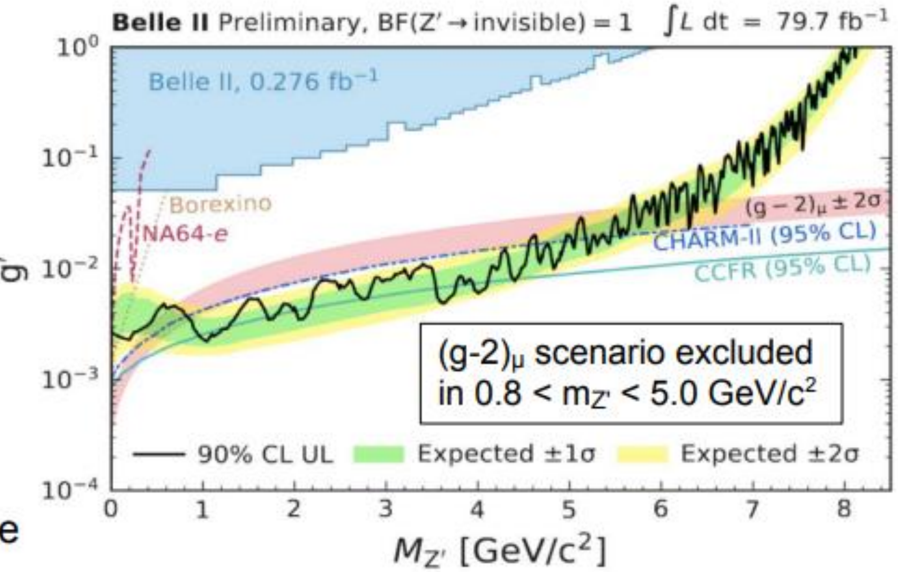
Neural Net based on kinematic variables optimized for background suppression

Based on 79.7 fb^{-1}





No significant excess seen within signal mass range



(g-2)$_\mu$ scenario excluded in 0.8 < $m_{Z'}$ < 5.0 GeV/c^2

16 new results for ICHEP

BELLE II PROSPECTS

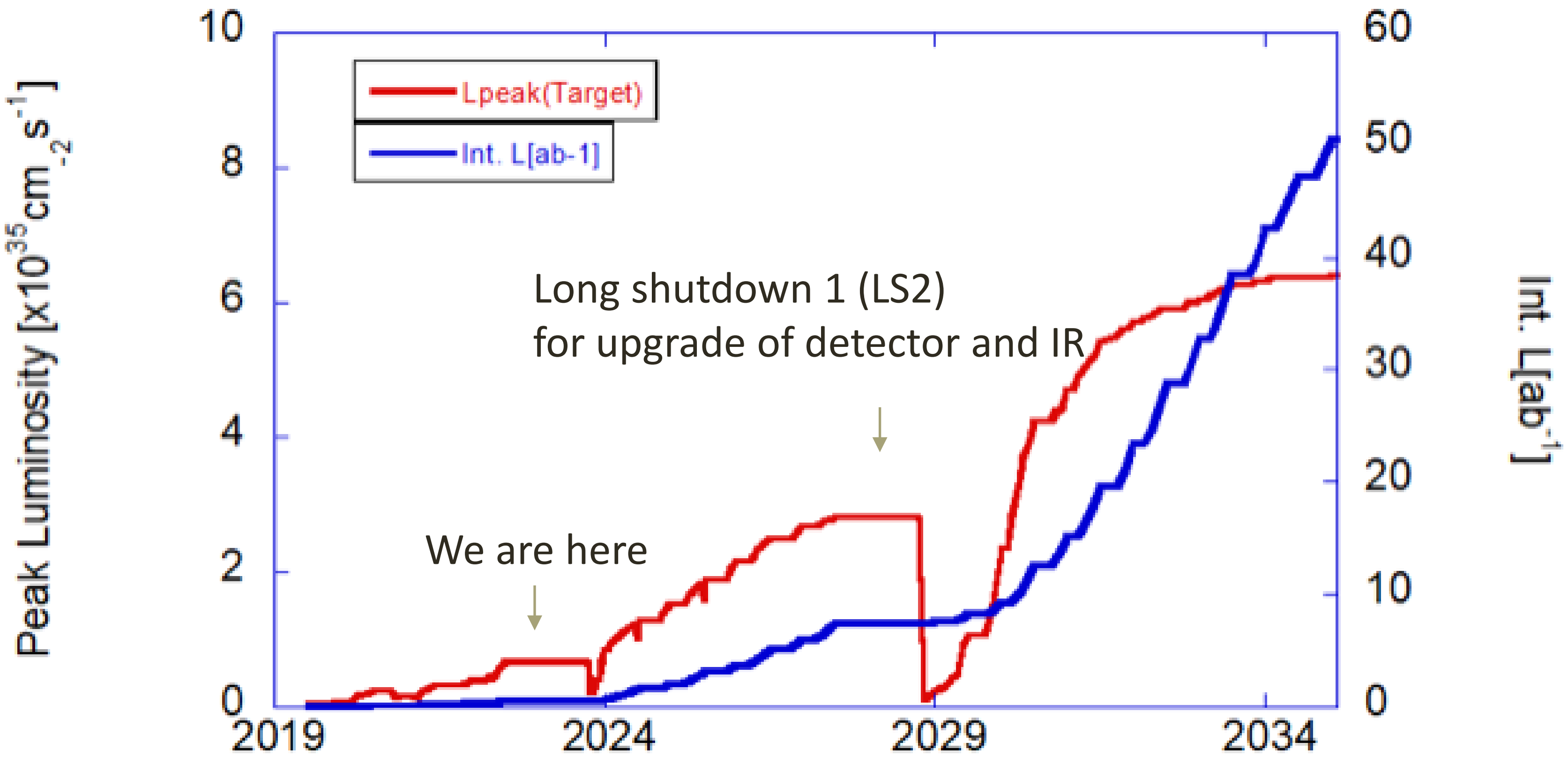
Belle II data taking plan

High backgrounds from the beams have made stable running at high luminosity difficult

We have not accumulated data at the rate anticipated

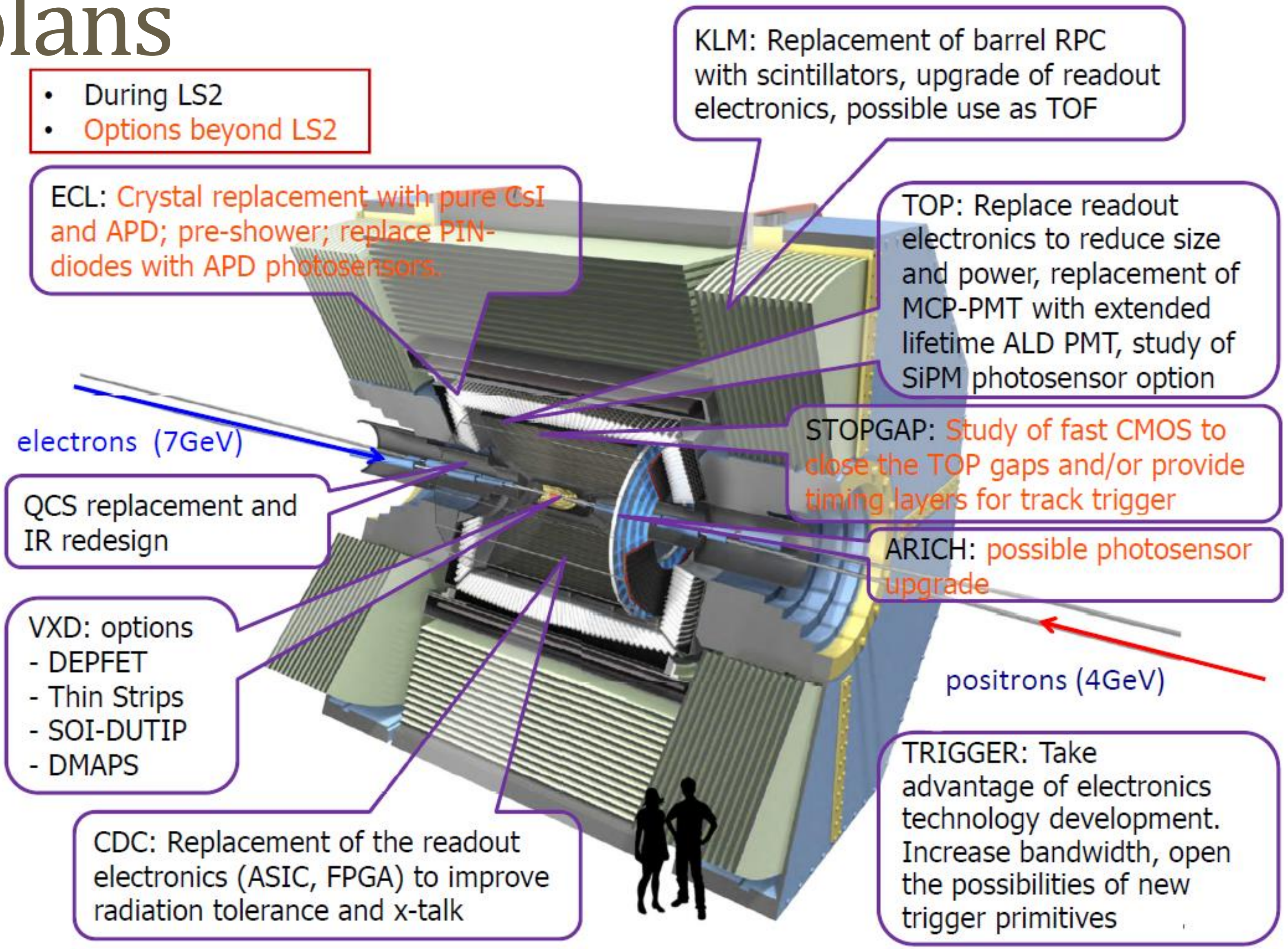
Long shutdown ongoing: accelerator and detector improvements

Path to 2 x 10^{35} $cm^{-2}s^{-1}$ but thereafter more work required



Upgrade plans

- Many plans and possibilities
  - + polarized beams for $\sin^2\theta_W$
- Work on a Conceptual Design Report begun to be delivered in 2023
- Followed by a Technical Design Report in 2024
- Shutdown end of 2026 or 2027 for installation



Conclusions

https://arxiv.org/pdf/2207.06307.pdf - Belle II Snowmass
Nitty gritty and up to date predictions of what we can acheive

- Belle II is up and running since 2019
- First significant results are coming in B, charm, tau, dark sector and spectroscopy
- We have a BABAR sized data set in hand to do much more in the next year of shutdown
  - Measurements are benefiting from improved techniques, e.g., machine learning
- Then onward to 10^{35} $cm^{-2}s^{-1}$ and a few ab^{-1} data set by 2026
  - Unique reach for missing energy, neutral, tau and dark sector
- Path to 50 ab^{-1} unclear but active upgrade programme underway so this can be delivered by the middle of the next decade