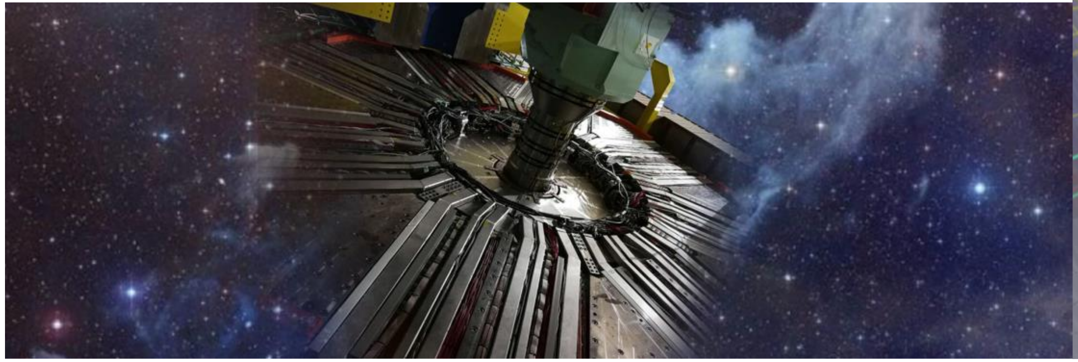
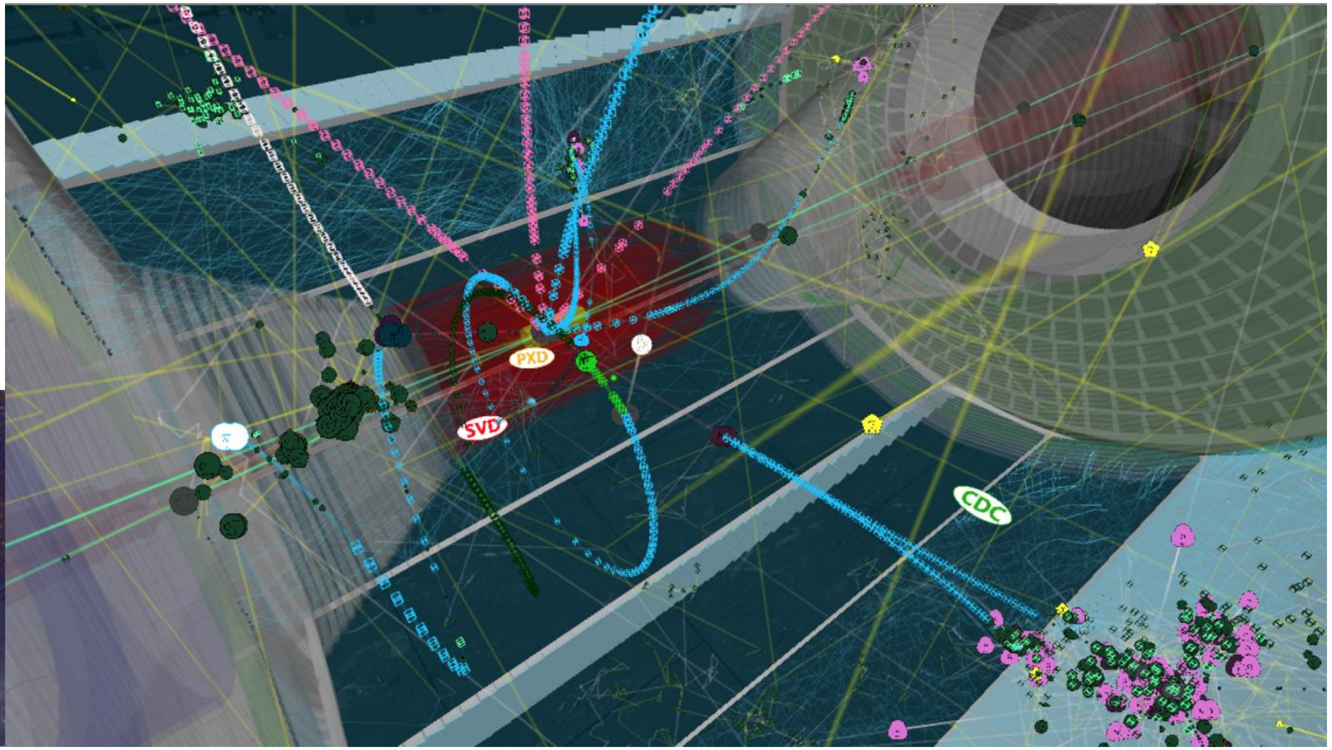
Belle II实验上的CKM矩阵和CP破坏研究

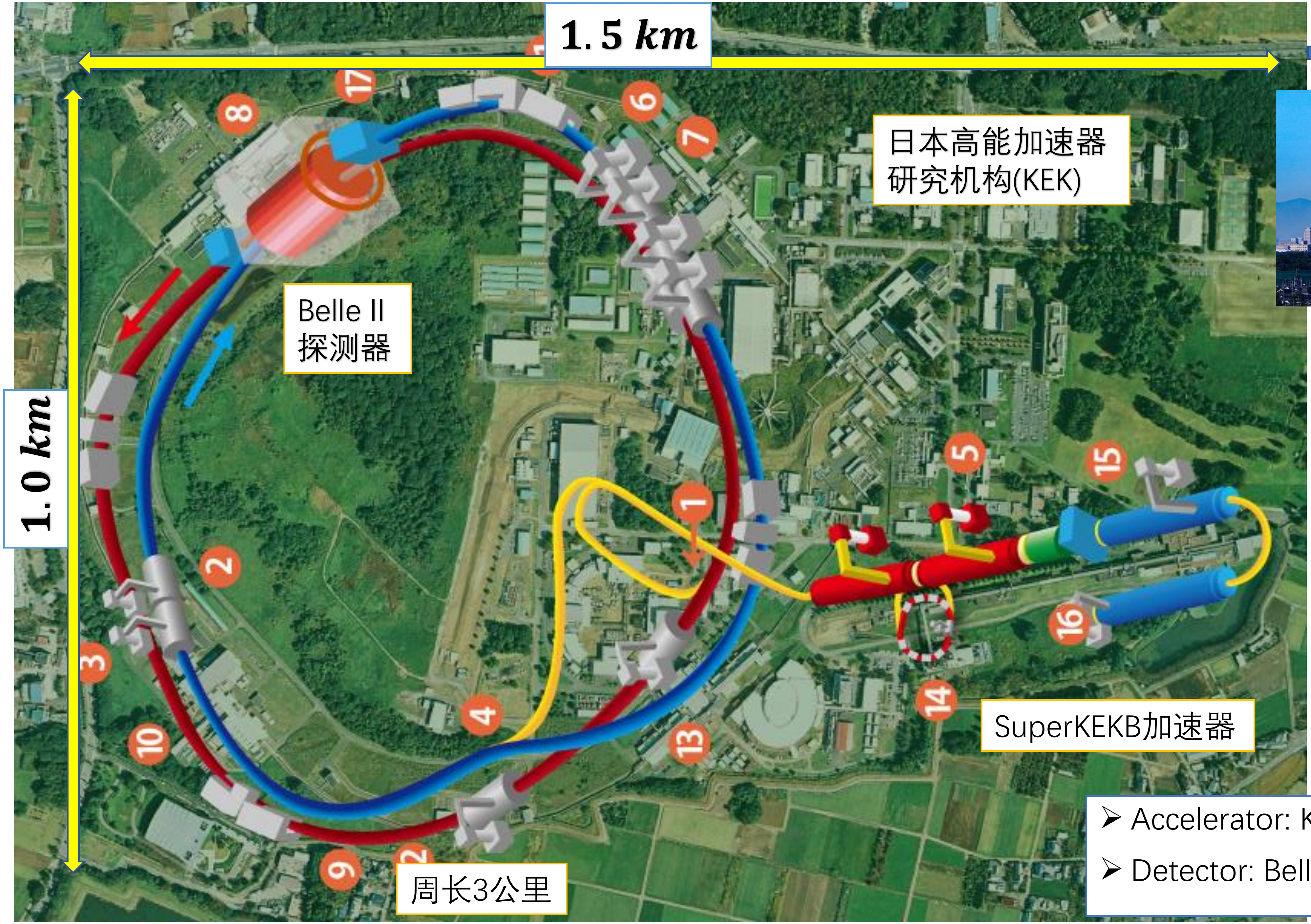
王小龙 复旦大学

味物理讲座

2022年3月24日







东京

北

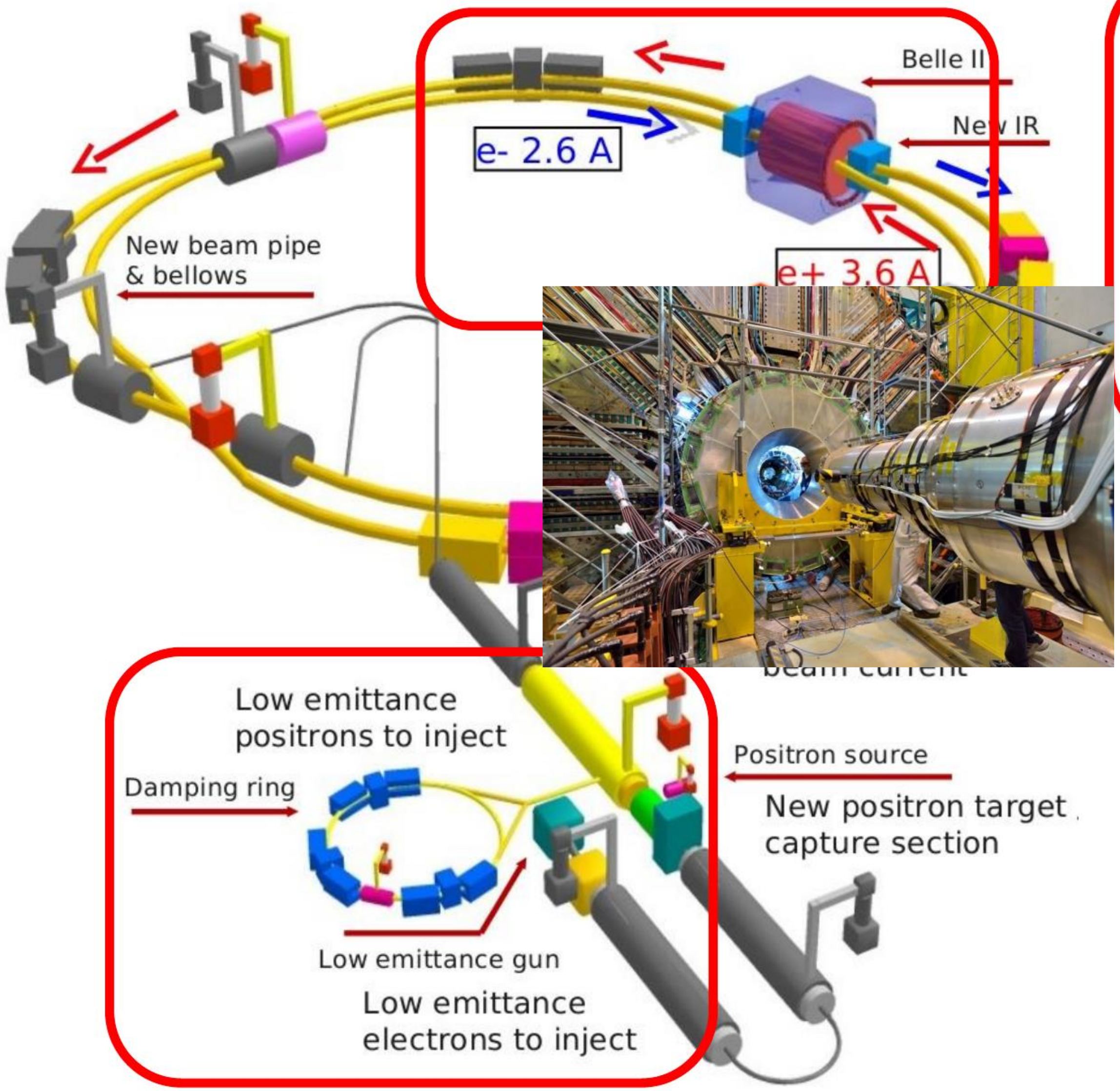
南

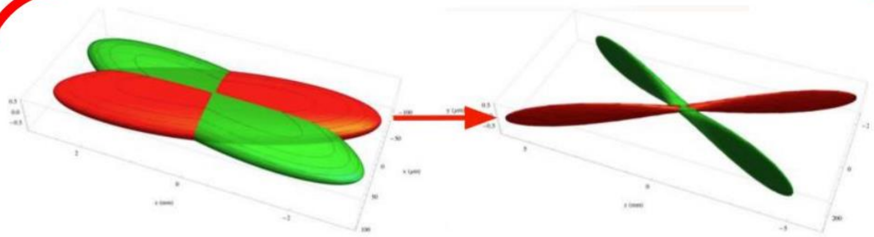
筑波市：
日本的科学城

KEK:
著名高能物理
中心之一

- Accelerator: KEKB → SuperKEKB
- Detector: Belle → Belle II

SuperKEKB accelerator





"nano-beam" scheme

Beam squeezing: x20 smaller at IR

x2

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

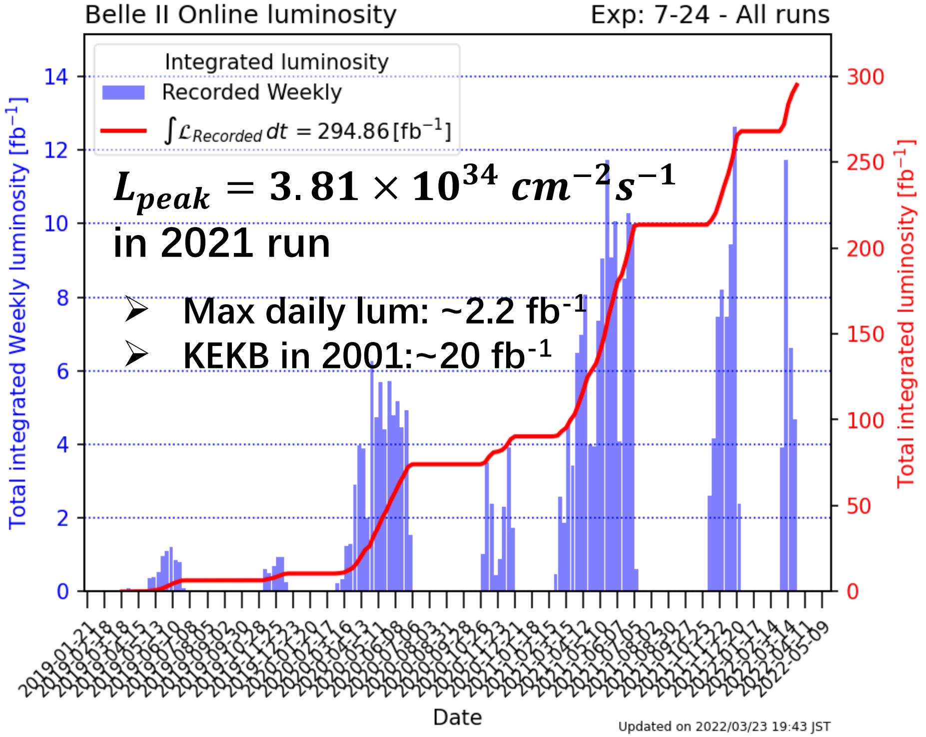
X1/20

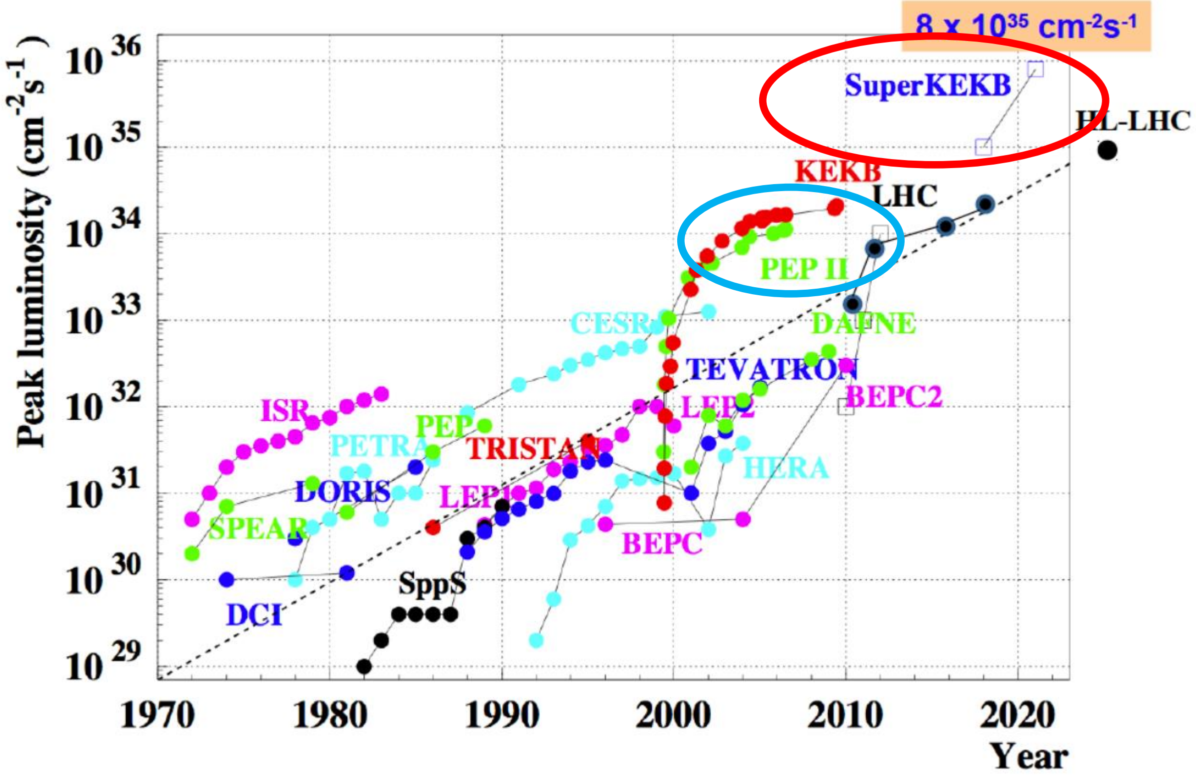
Target luminosity: $8\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

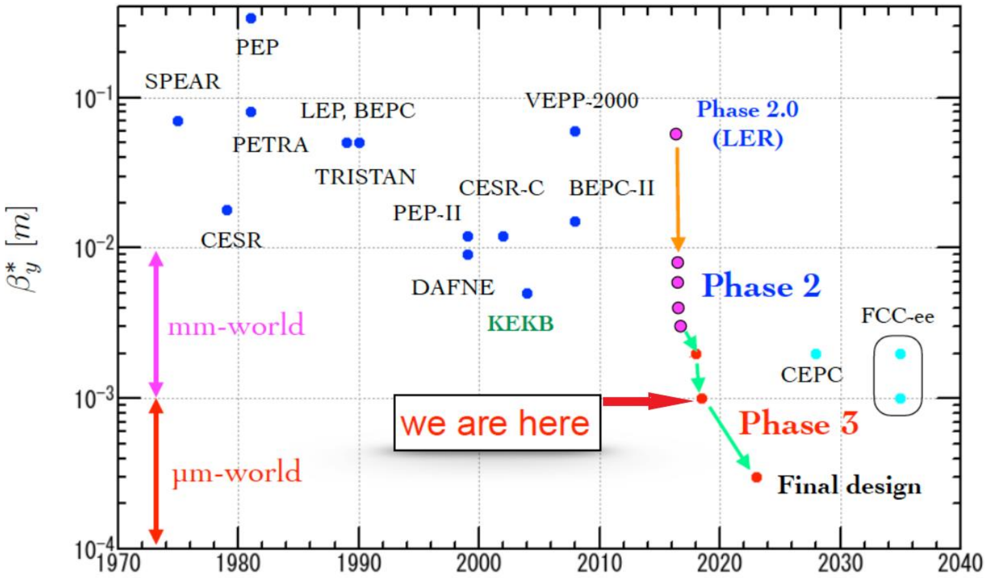
KEKB x 40!

Designed luminosity of SKB

- Came back to the game in March 2019.
- First time to use the Nano-beam scheme, verify it!
- Lum. record in 2021 run: 3.81×10^{34}.
- Expect to achieve $\mathbf{10^{35}\ cm^{-2}s^{-1}}$ in 2022.

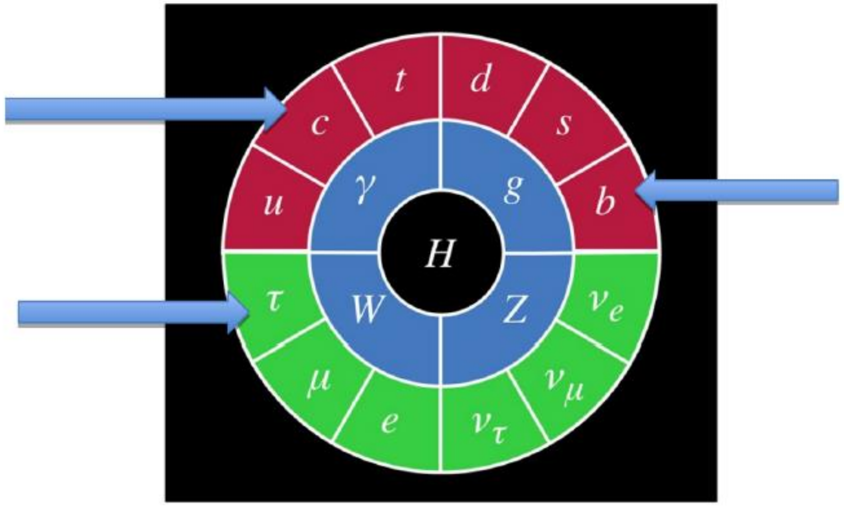






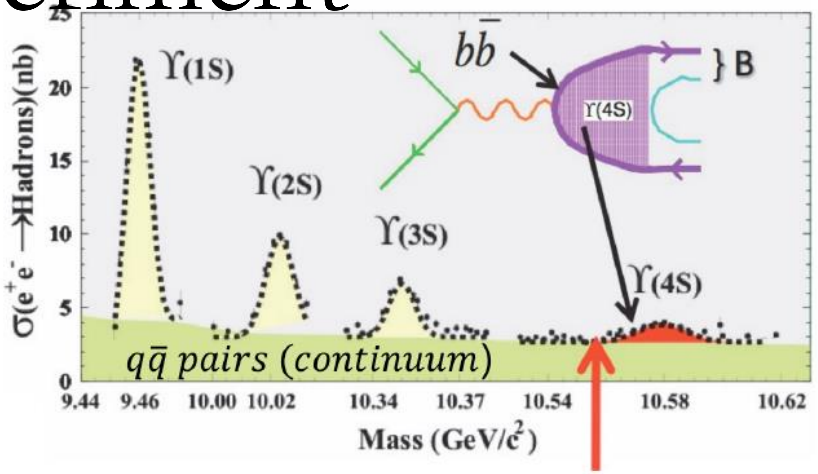
Capability of the Belle II experiment

17种基本粒子

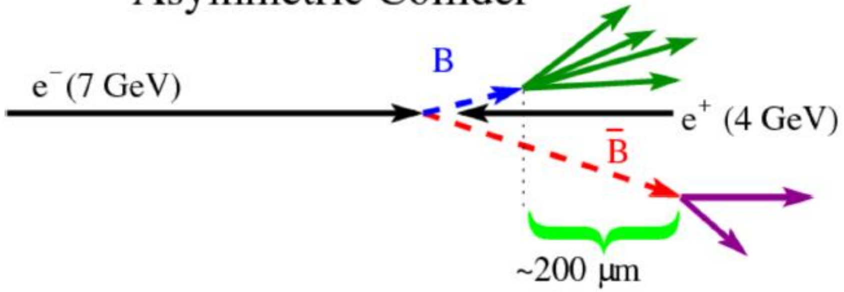


Physics process	Cross section [nb]
$\Upsilon(4S)$	1.110 ± 0.008
$u\bar{u}(\gamma)$	1.61
$d\bar{d}(\gamma)$	0.40
$s\bar{s}(\gamma)$	0.38
$c\bar{c}(\gamma)$	1.30

First super B factory

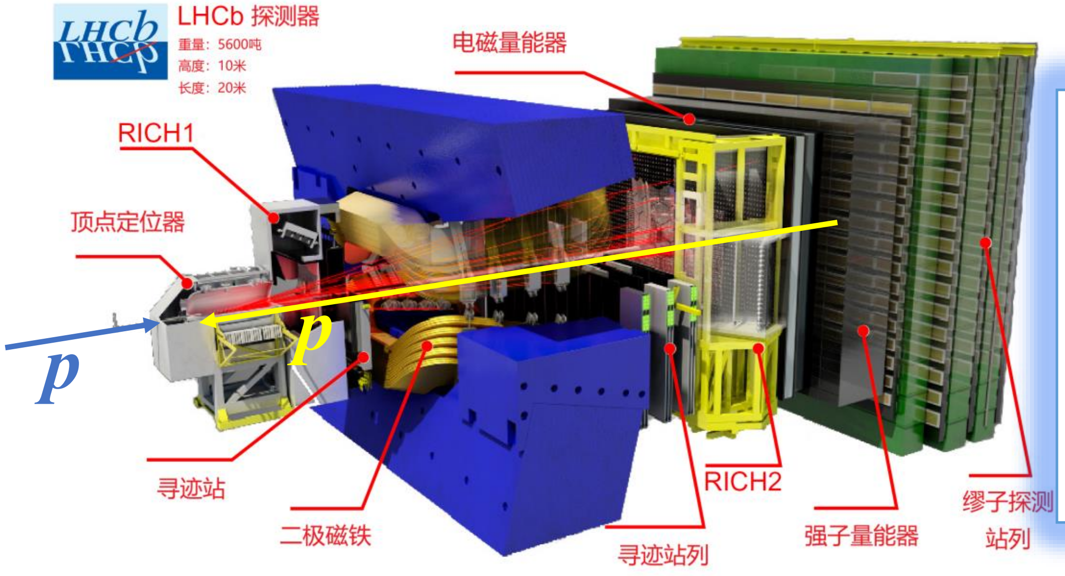


Asymmetric Collider



- B-factory: 10^9 pairs/ab^{-1};
- $\tau^+\tau^-$, $c\bar{c}$: 10^9 pairs/ab^{-1}.
- Expected Belle II data sample: $50 - 70$ ab^{-1}.
- Meanwhile, Belle II is considering the upgrade: $\mathcal{L} \times 5$

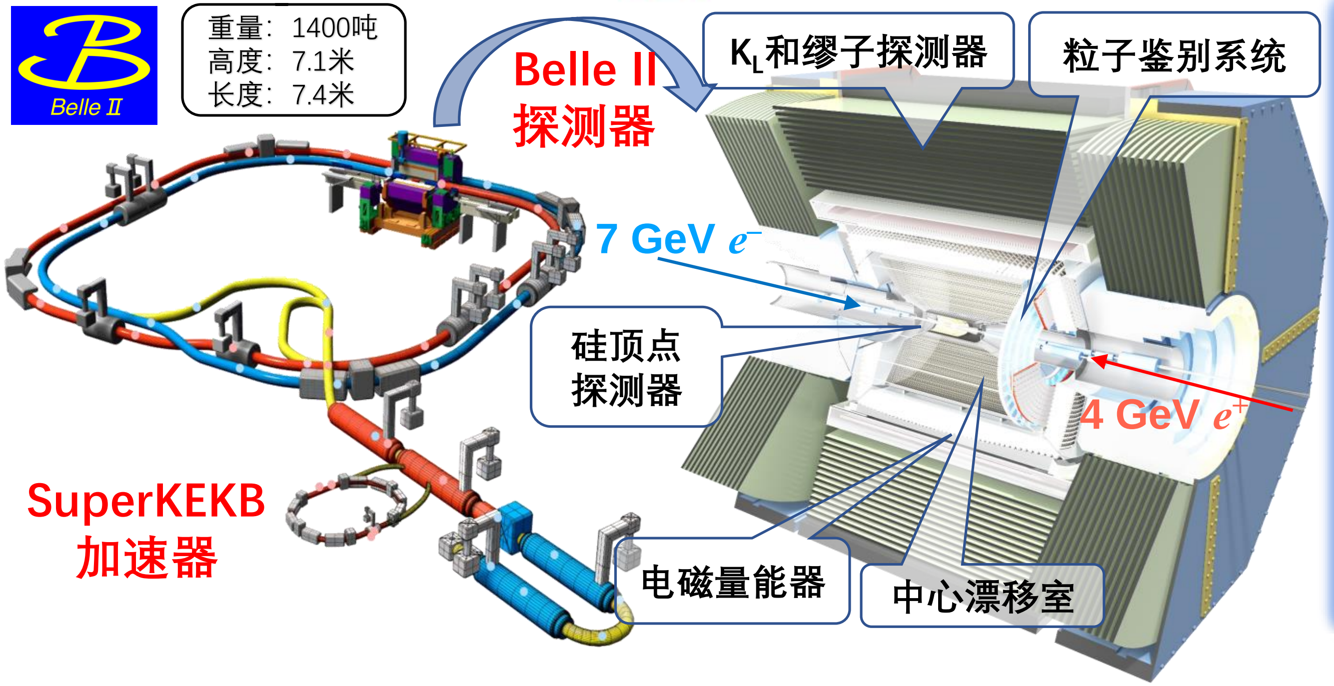
国际前沿重味物理探测器：LHCb和Belle II



世界上两个最先进的探测器！

LHCb探测器

- ➢ 质子-质子对撞，信号产额大！
- ➢ 单臂式探测器，重点探测前冲角度；
- ➢ 大量的硅探测器，顶点和径迹重建性能非常好；
- ➢ 对纯带电末态测量有优势。



Belle II探测器

- ➢ 正负电子对撞，本底水平低！
- ➢ 超导聚焦磁场将束流尺寸压低到纳米量级；
- ➢ 全覆盖立体角探测器，可探测中性粒子；
- ➢ 可利用对撞质心系；
- ➢ 对含中性粒子末态测量有优势。

Belle II Physics

Belle II Theory Interface Platform (B2TIP) Workshop series, 2015-2018:

WG1
Semileptonic & Leptonic B decays

WG2
Radiative & Electroweak Penguins

WG3
α/φ_2 β/φ_1

WG4
γ/φ_3

WG5
Charmless Hadronic B Decay

WG6
Charm

WG7
Quarkonium(-like)

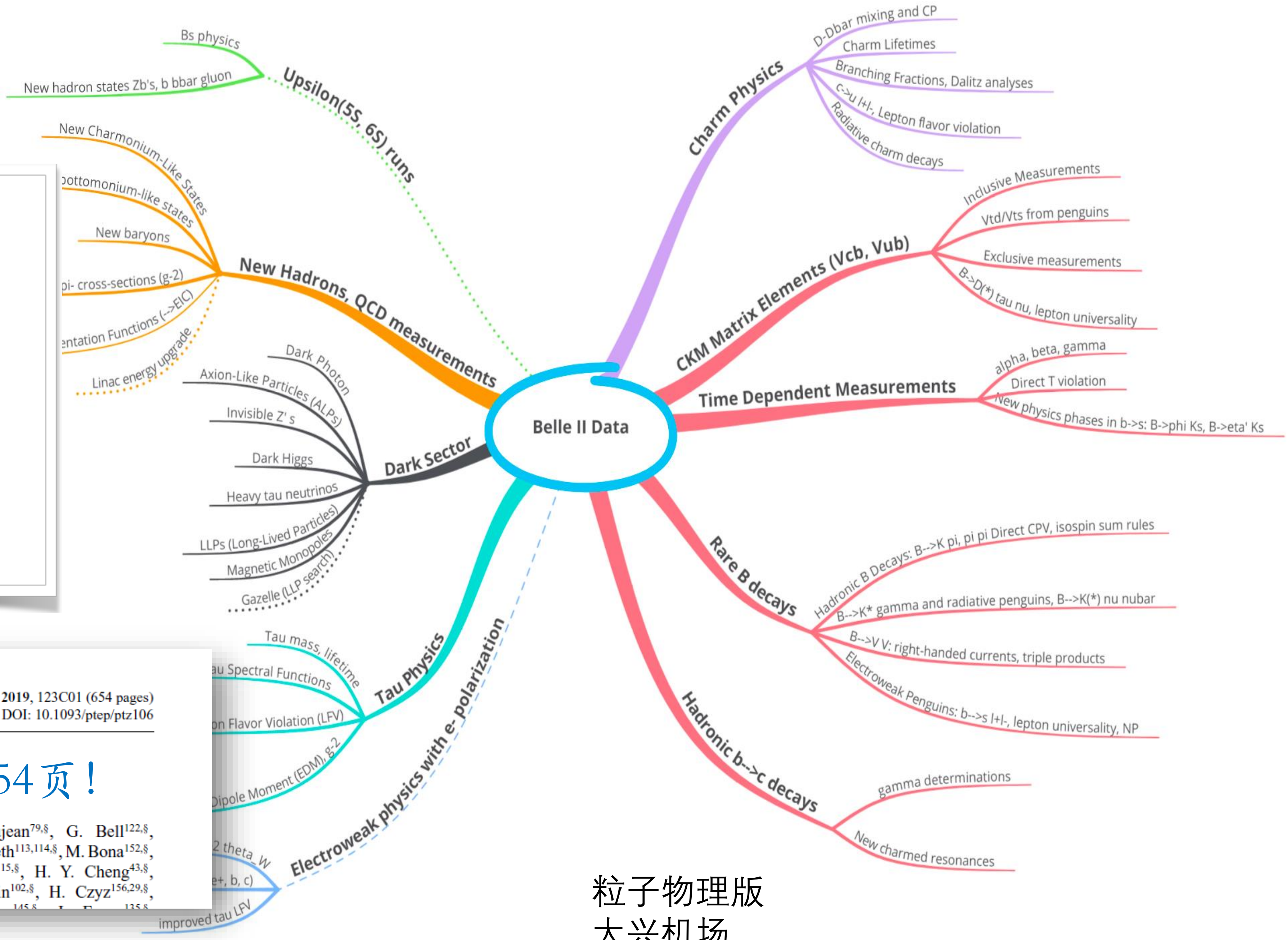
WG8
Tau, low multiplicity

WG9
New Physics

PTEP
Prog. Theor. Exp. Phys. 2019, 123C01 (654 pages)
DOI: 10.1093/ptep/ptz106

The Belle II Physics Book   654页！

E. Kou[75,*,§,†], P. Urquijo[145,‡,†], W. Altmannshofer[135,§], F. Beaujean[79,§], G. Bell[122,§], M. Beneke[114,§], I. I. Bigi[148,§], F. Bishara[150,16,§], M. Blanke[49,51,§], C. Bobeth[113,114,§], M. Bona[152,§], N. Brambilla[114,§], V. M. Braun[50,§], J. Brod[112,135,§], A. J. Buras[115,§], H. Y. Cheng[43,§], C. W. Chiang[92,§], M. Ciuchini[59,§], G. Colangelo[128,§], A. Crivellin[102,§], H. Czyz[156,29,§],



粒子物理版
大兴机场

物理研究内容十分丰富！

标准模型中的味物理机制：CKM矩阵

夸克间带电流相互作用的拉格朗日量：

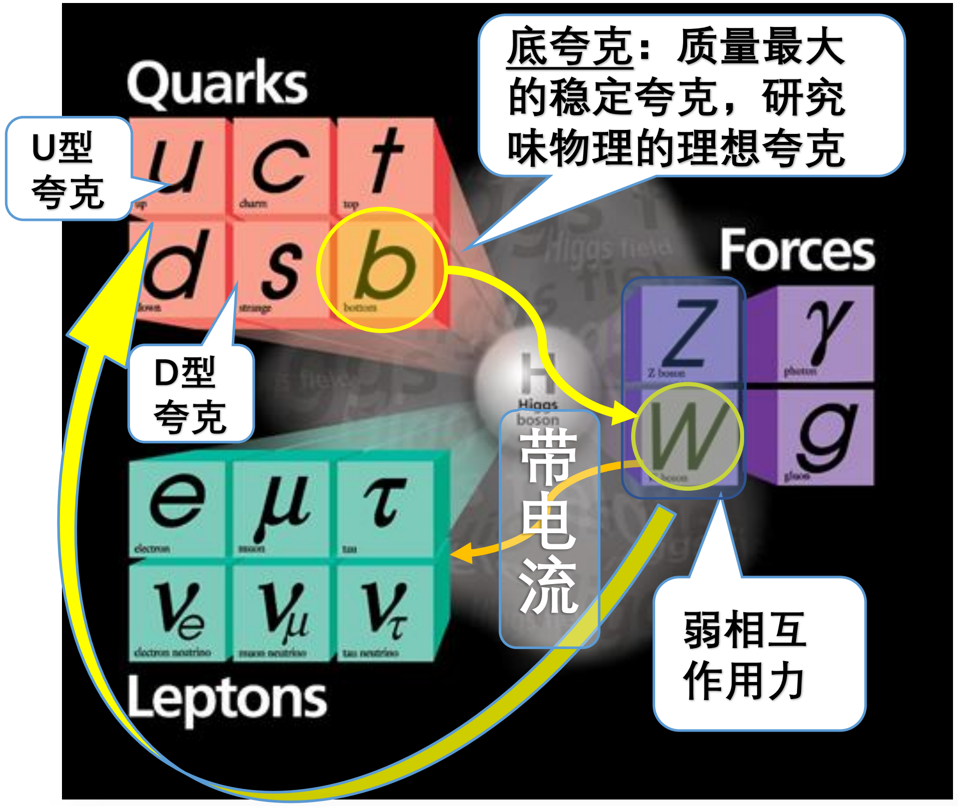
$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}}\overline{U}_i\gamma^\mu\frac{1-\gamma^5}{2}(V_{CKM})_{ij}D_jW_\mu^+ + h.c.$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

弱作用本征态　　CKM矩阵　　质量本征态

Wolfenstein参数化形式

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3\left[1-(\rho+i\eta)\left(1-\frac{1}{2}\lambda^2\right)\right] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix},$$

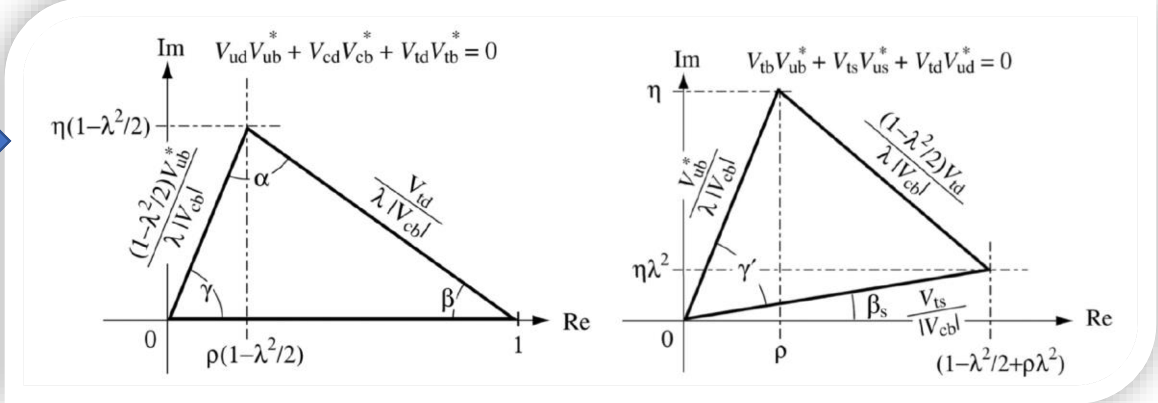


CKM矩阵的幺正性：

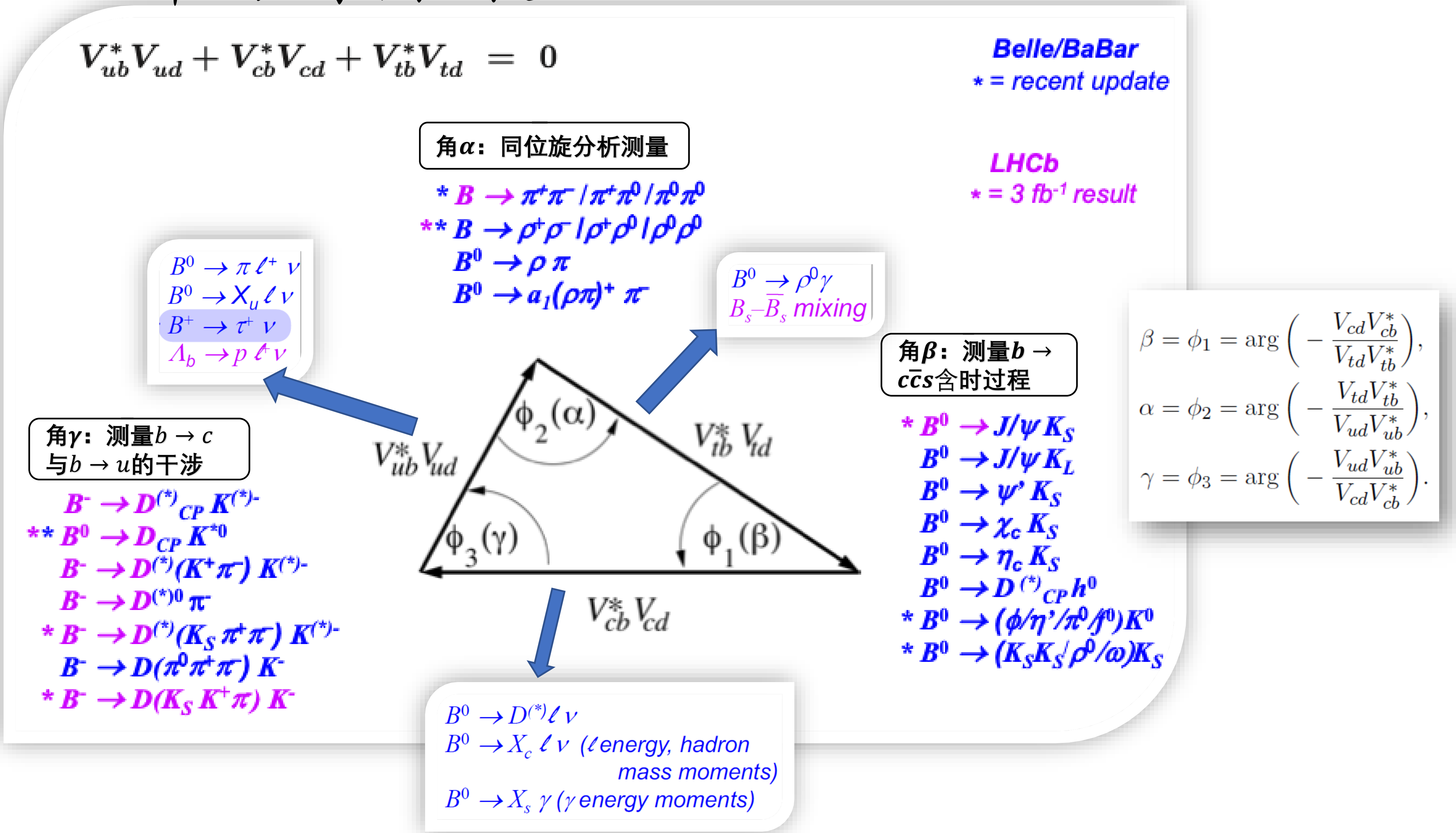
$$V_{CKM}V_{CKM}^\dagger = I$$

- 得出六个幺正三角形，其中两个$O(\lambda^3)$级别
- 幺正性是CKM测量的主要内容，对寻找和研究新物理的贡献十分敏感！
- Jarlskog参数：衡量CP破坏的大小

$$J_{CP} = \lambda^6A^2\eta$$



CKM矩阵的精确测量



$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$
Belle/BaBar
* = recent update
LHCb
* = 3 fb-1 result
角α：同位旋分析测量
* $B \to \pi^+\pi^- / \pi^+\pi^0 / \pi^0\pi^0$
** $B \to \rho^+\rho^- / \rho^+\rho^0 / \rho^0\rho^0$
$B^0 \to \rho\pi$
$B^0 \to a_1(\rho\pi)^+ \pi^-$
$B^0 \to \pi \ell^+ \nu$
$B^0 \to X_u \ell \nu$
$B^+ \to \tau^+ \nu$
$\Lambda_b \to p \ell^+ \nu$
$B^0 \to \rho^0 \gamma$
B_s–$\overline{B}_s$ mixing
角β：测量$b \to c\bar{c}s$含时过程
* $B^0 \to J/\psi K_S$
$B^0 \to J/\psi K_L$
$B^0 \to \psi' K_S$
$B^0 \to \chi_c K_S$
$B^0 \to \eta_c K_S$
$B^0 \to D^{(*)}_{CP} h^0$
* $B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$
* $B^0 \to (K_S K_S/\rho^0/\omega)K_S$
角γ：测量$b \to c$与$b \to u$的干涉
$B^- \to D^{(*)}_{CP} K^{(*)-}$
** $B^0 \to D_{CP} K^{*0}$
$B^- \to D^{(*)}(K^+\pi^-) K^{(*)-}$
$B^- \to D^{(*)0} \pi^-$
* $B^- \to D^{(*)}(K_S \pi^+\pi^-) K^{(*)-}$
$B^- \to D(\pi^0\pi^+\pi^-) K^-$
* $B^- \to D(K_S K^+\pi^-) K^-$
$V_{ub}^* V_{ud}$
$V_{tb}^* V_{td}$
$V_{cb}^* V_{cd}$
$\phi_2(\alpha)$
$\phi_3(\gamma)$
$\phi_1(\beta)$
$B^0 \to D^{(*)}\ell\nu$
$B^0 \to X_c \ell \nu$ (ℓ energy, hadron mass moments)
$B^0 \to X_s \gamma$ (γ energy moments)
$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$,
$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$,
$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$.

CKM当前的测量精度

$|V_{cb}|$：对$B \to X_c l\nu$的测量

- 单举过程：

$$|V_{cb}|_{in} = (42.2 \pm 0.8) \times 10^{-3}$$

- 遍举过程：

$$|V_{cb}|_{D^{*}\ell\nu} = (39.05 \pm 0.47_{\rm exp} \pm 0.58_{\rm th}) \times 10^{-3},$$

$$|V_{cb}|_{D\ell\nu} = (39.18 \pm 0.94_{\rm exp} \pm 0.36_{\rm th}) \times 10^{-3}.$$

$|V_{ub}|$：对$B \to X_u l\nu$的测量

- 单举过程：

$$|V_{ub}|_{in} = (3.67 \pm 0.09 \pm 0.12) \times 10^{-3}$$

- 遍举过程：

$$|V_{ub}|_{ex} = (4.49 \pm 0.16^{+0.16}_{-0.17} \pm 0.17) \times 10^{-3}$$

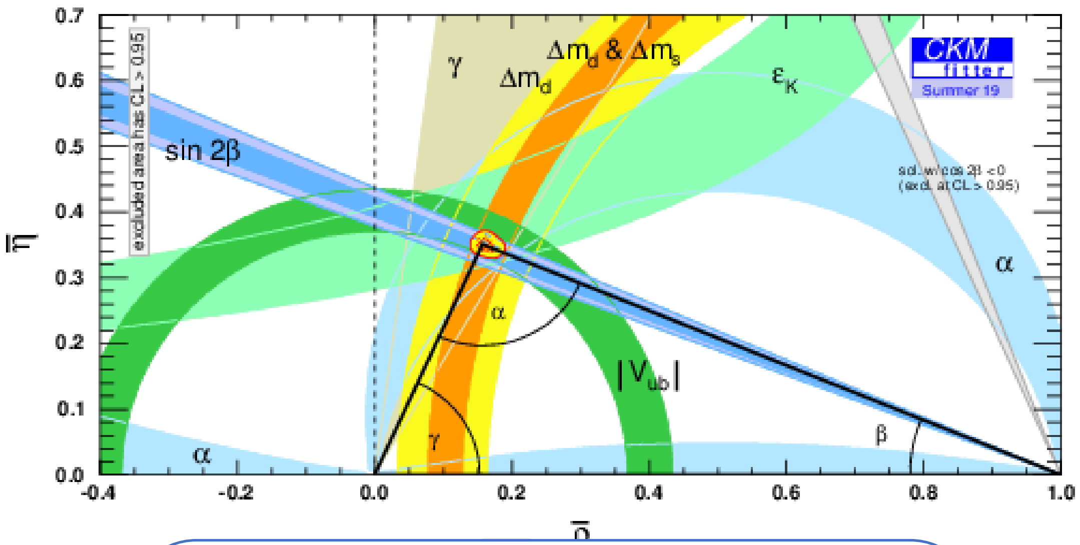
- $|V_{ub}|_{ex}$与$|V_{ub}|_{in}$的差别超过3σ！

$|V_{td}|$和$|V_{ts}|$：通过$B - \overline{B}$震荡等

$$|V_{td}| = (8.1 \pm 0.5) \times 10^{-3}$$

$$|V_{ts}| = (39.4 \pm 2.3) \times 10^{-3}$$

CKM矩阵有很大的研究空间，LHCb和Belle II实验正在使之进入精确测量的新阶段，具有发现新物理的重大潜力！



幺正三角形内角：

$$\alpha = (86.2^{+4.4}_{-4.0} \cup 178.4^{+3.9}_{-5.1})^{\circ}$$

$$\beta = (22.14^{+0.69}_{-0.67})^{\circ}, \qquad \gamma = (71.1^{+4.6}_{-5.3})^{\circ}$$

LHCb对相角ϕ_s的测量：

$$\phi_s^{\overline{d}ds} = (-0.10 \pm 0.13 \pm 0.14)\ rad$$

$$\phi_s^{\overline{s}ss} = (-0.073 \pm 0.115 \pm 0.027)\ rad$$

Wolfenstein参数化：

$$\lambda = 0.22453 \pm 0.00044, \quad A = 0.836 \pm 0.015$$

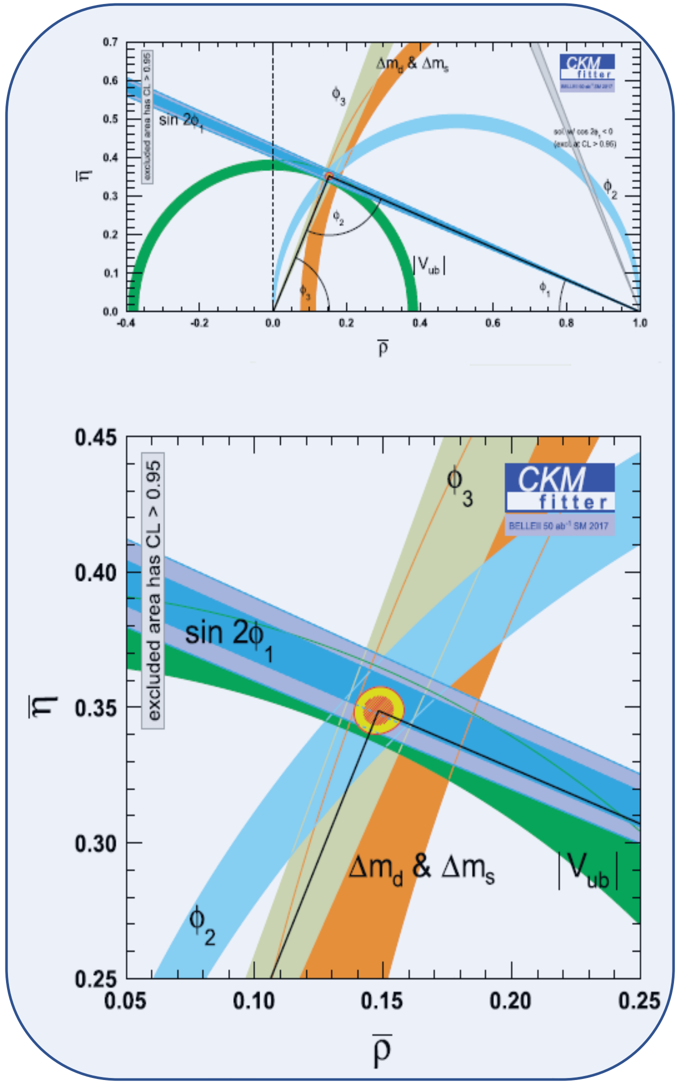
$$\overline{\rho} = 0.122^{+0.018}_{-0.017}, \quad \overline{\eta} = 0.355^{+0.012}_{-0.011}$$

- 衡量CP破坏的$Jarlskog$参数：

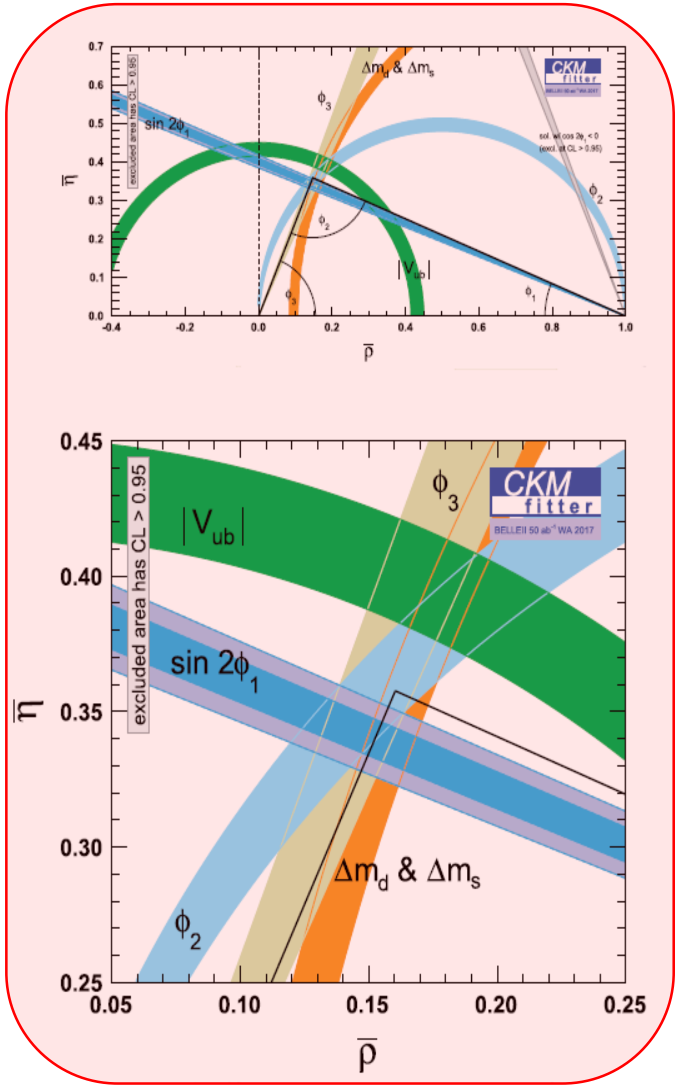
$$J_{CP} = (3.18 \pm 0.15) \times 10^{-5}$$

Belle II和LHCb预期达到的测量精度

预期精度：
- α: 0.6°
- β: 0.4°
- γ: 1.5°
- $|V_{cb}|$: $1-1.5\%$
- $|V_{ub}|$: $2-3\%$



标准模型的预期



根据现有测量的预期

精度大幅提高以后，CKM幺正性是否继续保持？

精确测量CKM矩阵是发现新物理贡献的可靠途径。

Expected achievements by Belle II

Observables	Expected the. 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	LHCb/Belle II
$\lvert V_{cb}\rvert$ 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
CP Violation			
$S(B \to \phi K^0)$	***	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
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb

☞ From Belle II physics book

arXiv:1808.10567 (to appear in PTEP)

Precision CKM metrology

Direct and mixing-induced CP violation in B decays

(Semi-)leptonic B decays

Radiative & electroweak penguins

2025???

$|V_{ub}|$ and $|V_{cb}|$ at Belle (II)

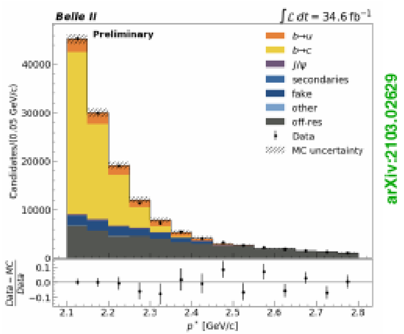
Inclusive and Exclusive $b \to (c,u)\ell\nu$ Branching Fractions

M.Merola: Towards first Vub and Vcb measurements at the Belle II experiment

- A large variety of different analysis strategies will help to resolve the remaining discrepancies
- Alternative approaches, such as the recently proposed use of inclusive q^2-moments, are expected to further enhance sensitivity to V_{cb}

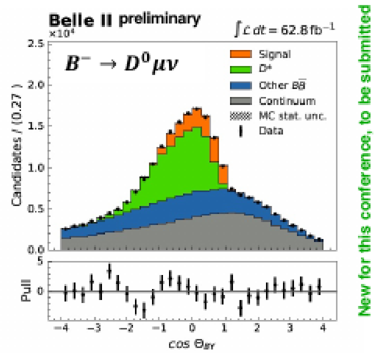
M. Merola / C. Niebuhr, EPS 2021

Untagged inclusive $X_u \ell \nu$



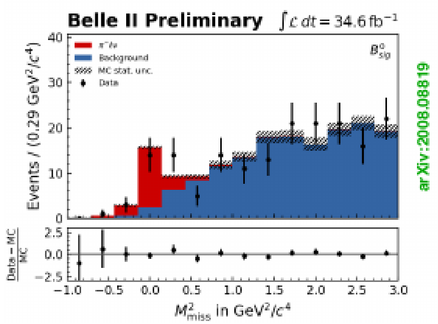
3σ significance for b-u

Untagged exclusive $B \to D^0 \ell \nu$



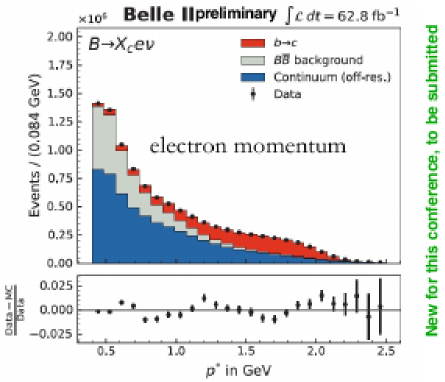
$\mathcal{B}(B^- \to D^0 \ell^- \bar{\nu}_l) = (2.293 \pm 0.053_{\rm stat} \pm 0.084_{\rm syst})\%$

FEI hadronic tag excl. $B^0 \to \pi^- \ell \nu$



$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell)$ $(1.58 \pm 0.43_{\rm stat} \pm 0.07_{\rm sys}) \times 10^{-4}$

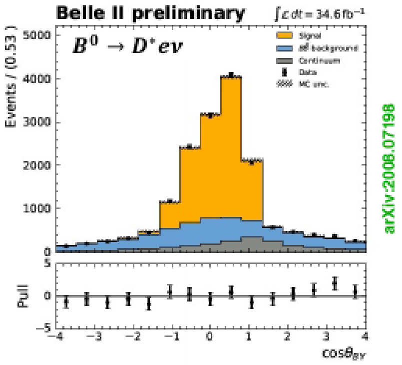
Untagged inclusive $X_c \ell \nu$



$\mathcal{B}(B \to X_c \ell \nu) = (9.75 \pm 0.03(stat) \pm 0.47(syst))\%$

Lepton momentum p* in the CMS

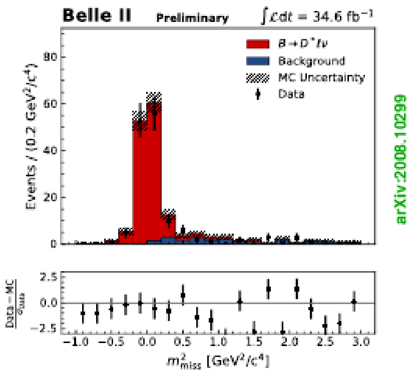
Untagged exclusive $B^0 \to D^* \ell \nu$



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

θ_{BY} angle between B and $D\ell$ system

FEI hadronic tag excl. $B^0 \to D^* \ell \nu$

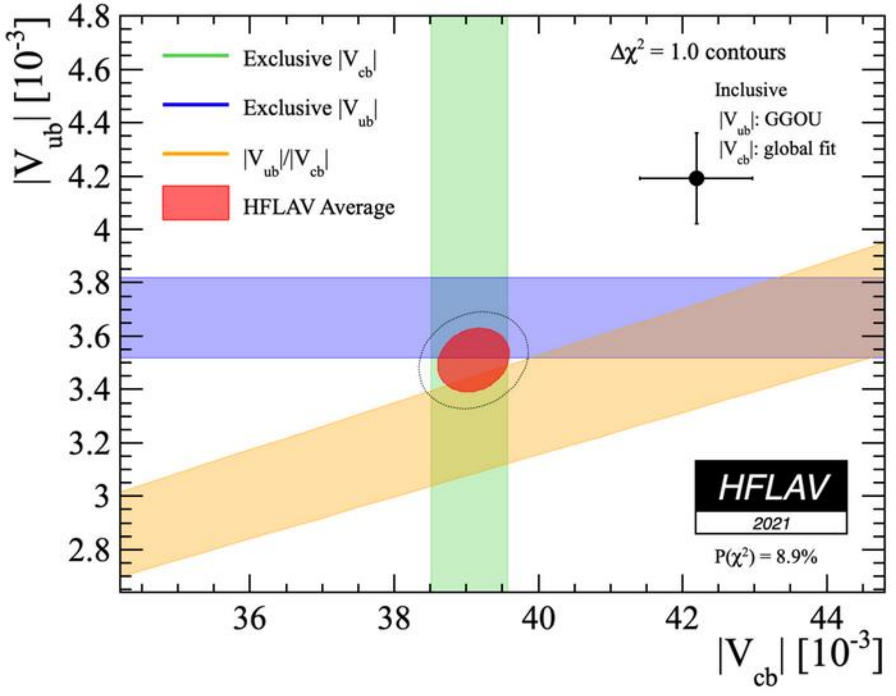


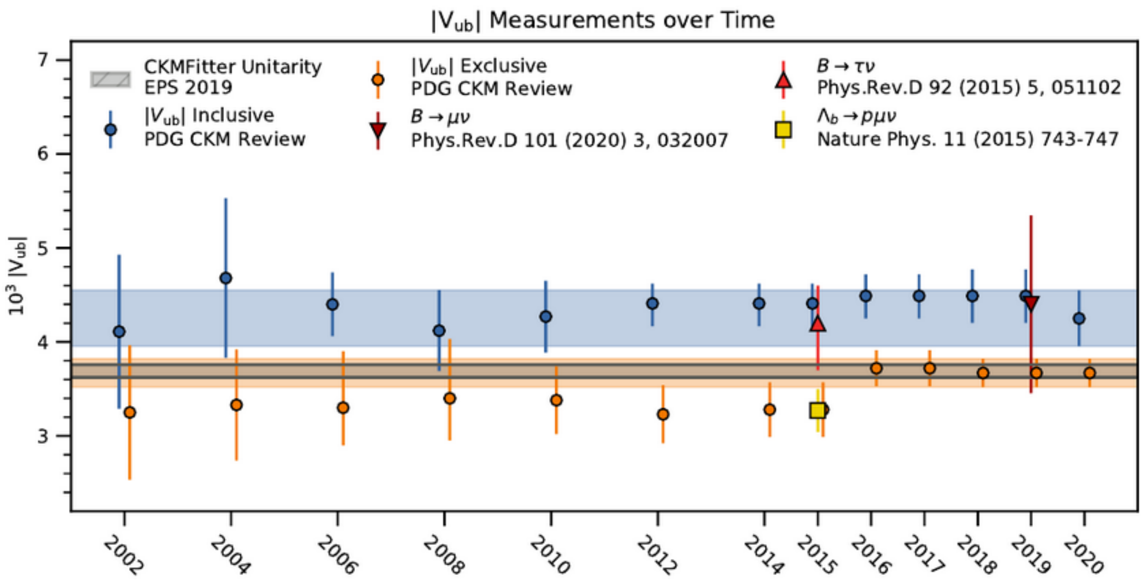
$\mathcal{B}(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_l) = (4.51 \pm 0.41_{\rm stat} \pm 0.27_{\rm syst} \pm 0.45_{\pi_s})\%$

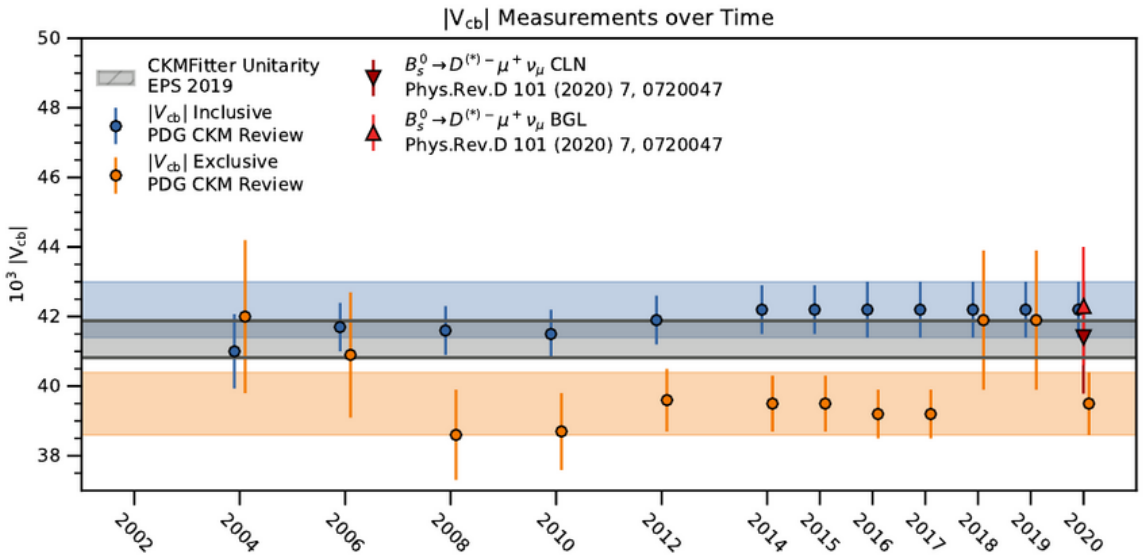
$$m_{\rm miss}^2 = \left(p_{e^+e^-} - p_{B_{\rm tag}} - p_{D^*} - p_\ell\right)^2$$

Inclusive vs exclusive V_{xb}

Long standing tension between inclusive and exclusive V_{xb} determinations:





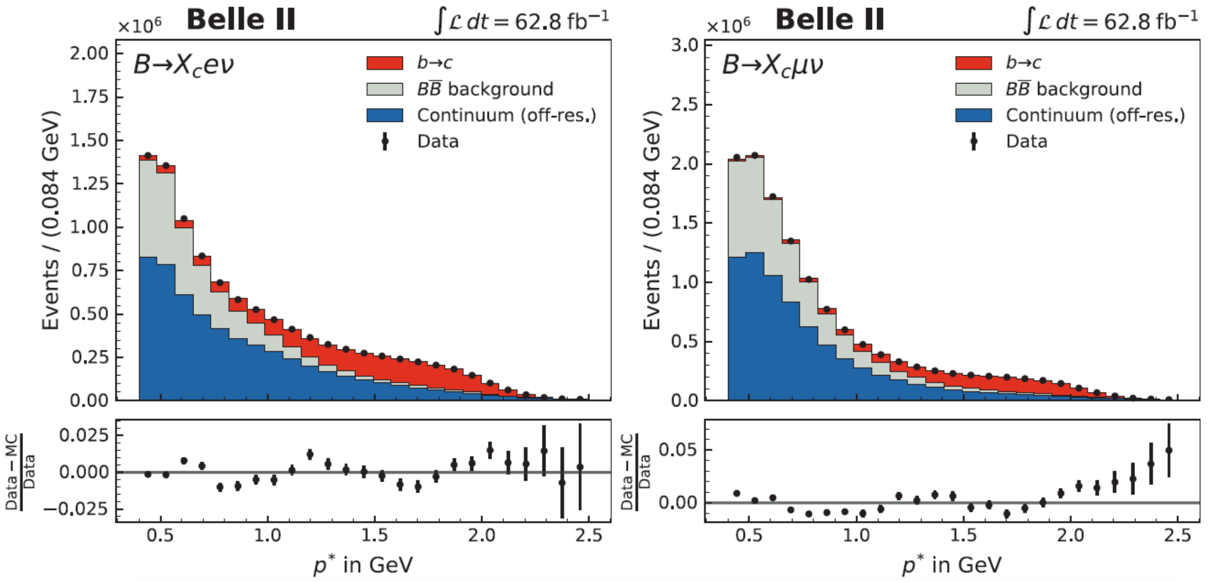


What's the contributions due to Kaon (veto) in inclusive V_{xb}? Especially the neutral K_L?

M. Bauer, HQL 2021

Inclusive and exclusive $B \to X_c l\nu$

Inclusive $B \to X_c l\nu$:



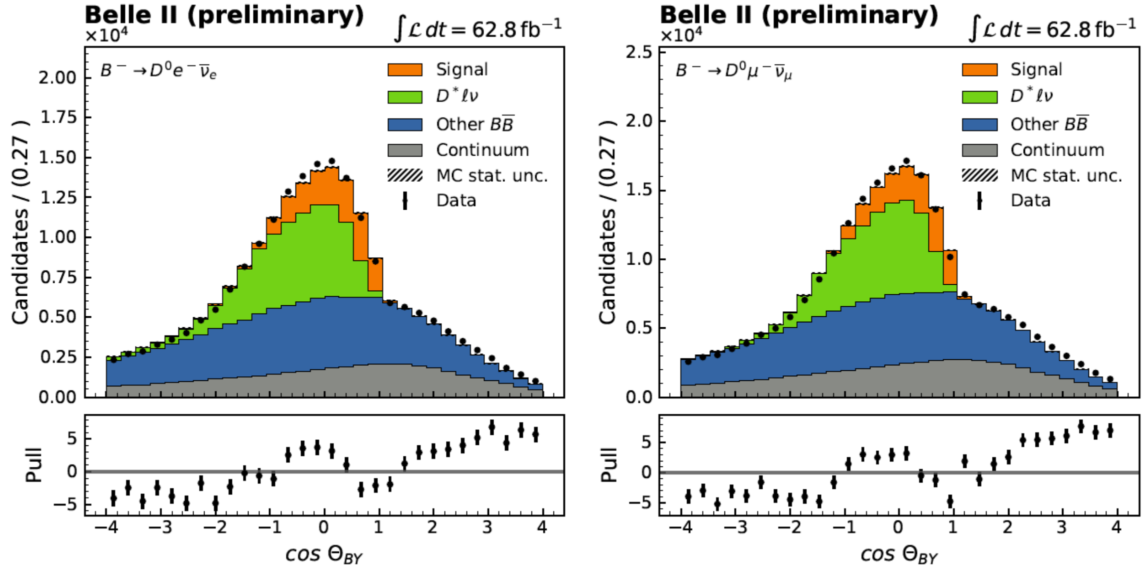
$$\mathcal{B}(B \to X_c e \nu_e) = (9.97 \pm 0.03(\mathrm{stat}) \pm 0.38(\mathrm{sys}))\%$$
$$\mathcal{B}(B \to X_c \mu \nu_\mu) = (9.47 \pm 0.05(\mathrm{stat}) \pm 0.45(\mathrm{sys}))\%$$

Dominant systematics from continuum modeling, lepton ID, and signal shape.

arXiv: 2111.09405 [hep-ex]

Branching ratio of $B^- \to D^0 l^- \nu$:

$$\cos\theta_{BY} = \frac{2\,E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|} \qquad Y = D^0\ell$$



$$\mathcal{B}(B^- \to D^0 e^- \bar{\nu}_e) = (2.34 \pm 0.08_{\mathrm{stat}} \pm 0.07_{\mathrm{syst}})\%$$
$$\mathcal{B}(B^- \to D^0 \mu^- \bar{\nu}_\mu) = (2.24 \pm 0.08_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}})\%$$

arXiv: 2110.02648 [hep-ex]

$|V_{cb}|$ from q^2 moments

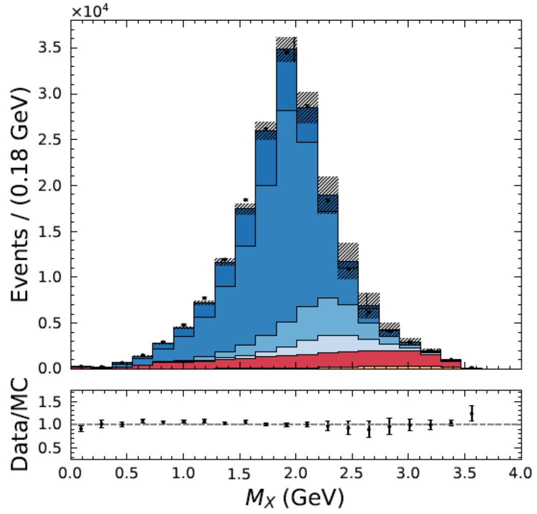
Measurement of the q^2 moments, that allows the extraction of $|V_{cb}|$, utilizing the method proposed in JHEP 02 (2019) 177:

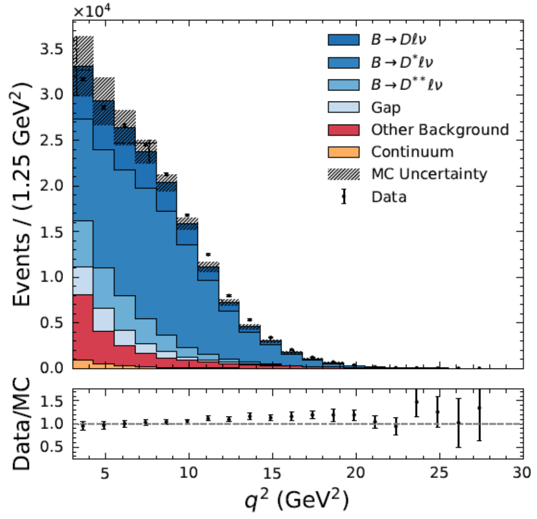
Belle, full data set (711 fb^{-1})
arXiv: 2109.01685 [hep-ex]

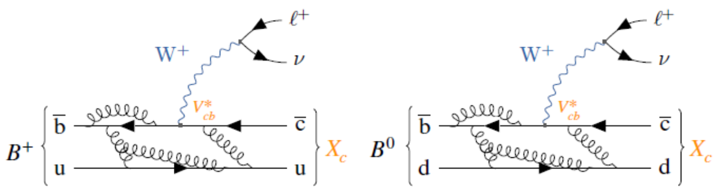
q^2 of the B meson system to the X_c system.

Analysis performed on the recoil of a fully reconstructed B meson (**Hadronic Tagging**)

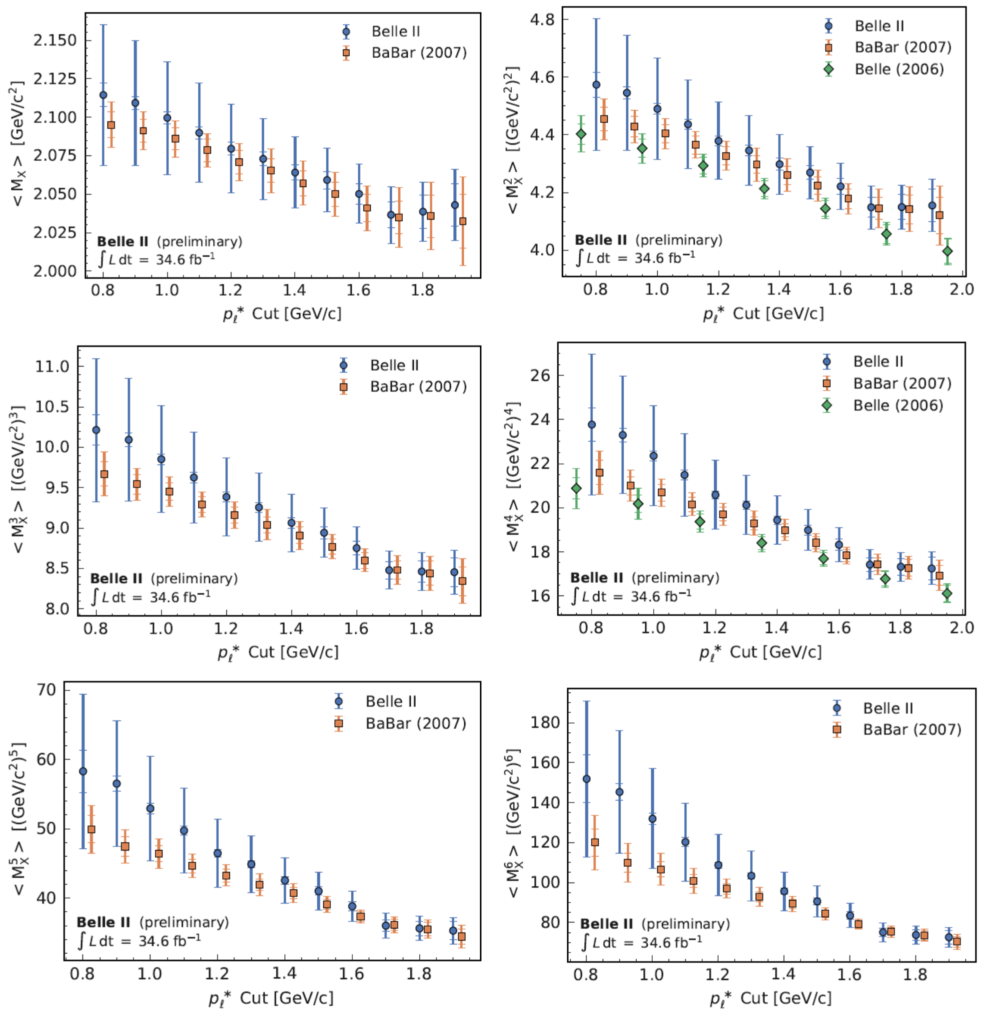
The measured moments will serve as input for a new $|V_{cb}|$ determination.







Belle II: arXiv: 2009.04493 [hep-ex]



Measurements of hadronic mass moments $< M_X^n >$ in $B \to X_c l\nu$, which can be used to determine $|V_{cb}|$ together with other observables of inclusive B decays.

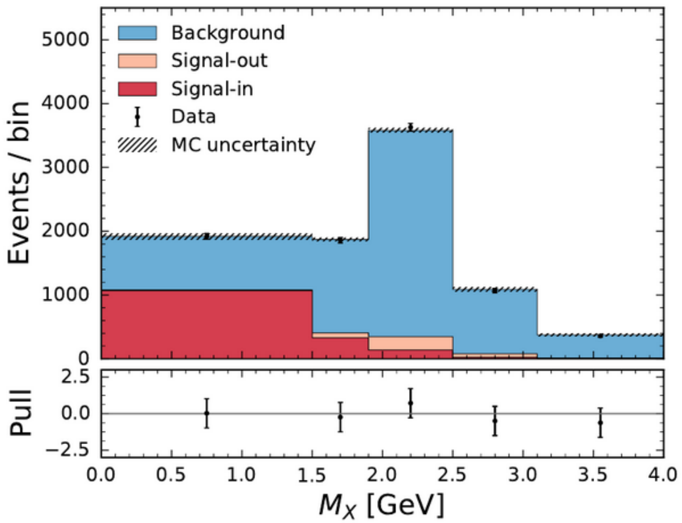
Exclusive $|V_{ub}|$ at Belle

arXiv: 2104.13354 [hep-ex]

Inclusive $B \to X_u l \nu$:

Phys. Rev. D104, 012008 (2021)

The $B \to X_c l \nu$ background is strongly suppressed with the use of a BDT.



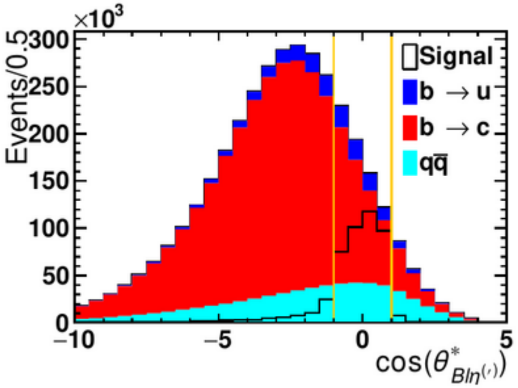
$$\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell) = (1.09 \pm 0.05 \pm 0.08) \times 10^{-3}$$

$$|V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3}$$

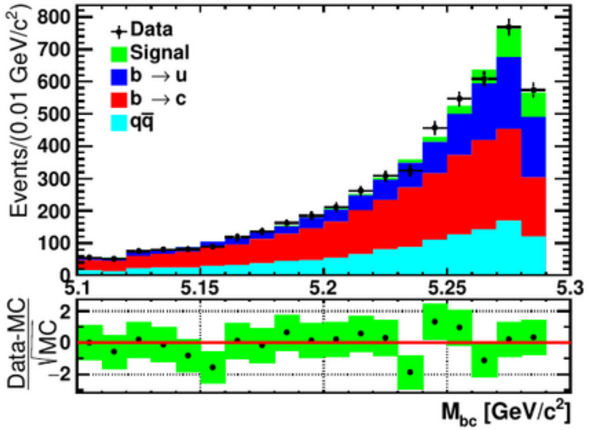
Branching ratios of $B^- \to \eta^{(\prime)} l^- \nu$:

$711\ fb^{-1}$

Signal-side only reconstruction to increase the efficiency.



$$\cos(\theta^\star_{B\ell\eta^{(\prime)}}) = \frac{2E^\star_B E^\star_{\ell\eta^{(\prime)}} - m_B^2 c^4 - m^2_{\ell\eta^{(\prime)}} c^4}{2|\vec{p}^\star_B||\vec{p}^\star_{\ell\eta^{(\prime)}}|c^2}$$



(a) $M_{\rm bc}(\eta \to \gamma\gamma)$

No restriction on the q^2 range, to reduce the model uncertainty.

$$q^2 = (p_B - p_{\eta^{(\prime)}})^2$$

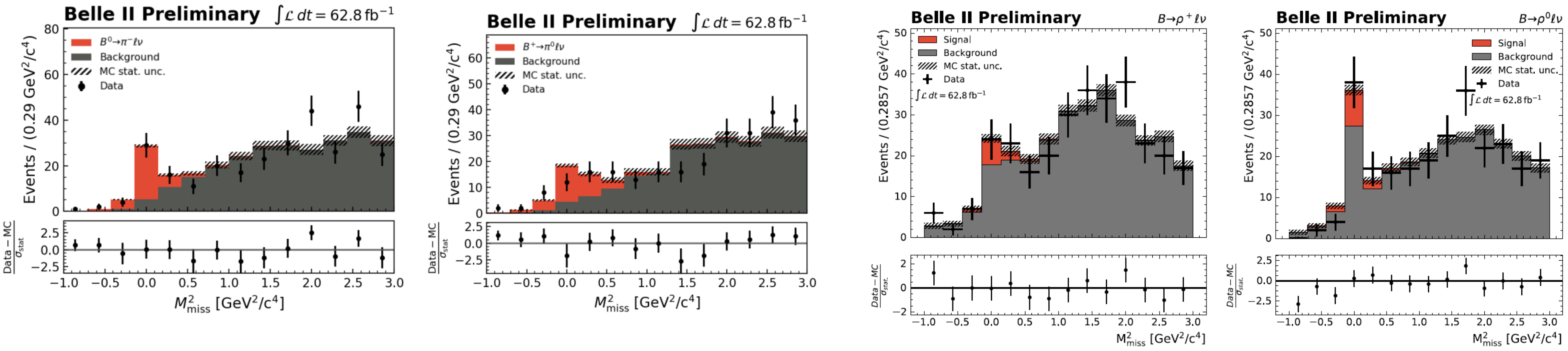
$$\mathcal{B}(B^+ \to \eta \ell^+ \nu_\ell) = (2.83 \pm 0.55_{(\rm stat.)} \pm 0.34_{(\rm syst.)}) \times 10^{-5}$$

$$\mathcal{B}(B^+ \to \eta' \ell^+ \nu_\ell) = (2.79 \pm 1.29_{(\rm stat.)} \pm 0.30_{(\rm syst.)}) \times 10^{-5}$$

Exclusive $|V_{ub}|$ at Belle II

arXiv: 2111.00710 [hep-ex]

"Golden modes" for $|V_{\mathrm{ub}}|$, measured on the recoil of fully reconstructed B mesons:



	Measured	Significance	PDG Values
$\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell)$	$(1.47 \pm 0.29_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}}) \times 10^{-4}$ (*)	6.2σ	$(1.50 \pm 0.06) \times 10^{-4}$
$\mathcal{B}(B^- \to \pi^0 \ell^- \bar{\nu}_\ell)$	$(8.29 \pm 1.99_{\mathrm{stat}} \pm 0.46_{\mathrm{syst}}) \times 10^{-5}$	7.7σ	$(7.80 \pm 0.27) \times 10^{-4}$
$\mathcal{B}(\bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell)$	$(9.26 \pm 6.33_{\mathrm{stat}} \pm 0.38_{\mathrm{syst}}) \times 10^{-5}$ Upper limit: $< 3.37 \times 10^{-4}$ (95% CL)	1.4σ	$(2.94 \pm 0.21) \times 10^{-4}$
$\mathcal{B}(B^- \to \rho^0 \ell^- \bar{\nu}_\ell)$	$(1.51 \pm 1.13_{\mathrm{stat}} \pm 0.09_{\mathrm{syst}}) \times 10^{-5}$ Upper limit: $< 1.97 \times 10^{-4}$ (95% CL)	1.5σ	$(1.58 \pm 0.11) \times 10^{-4}$

(*) Sum of three q^2 bins

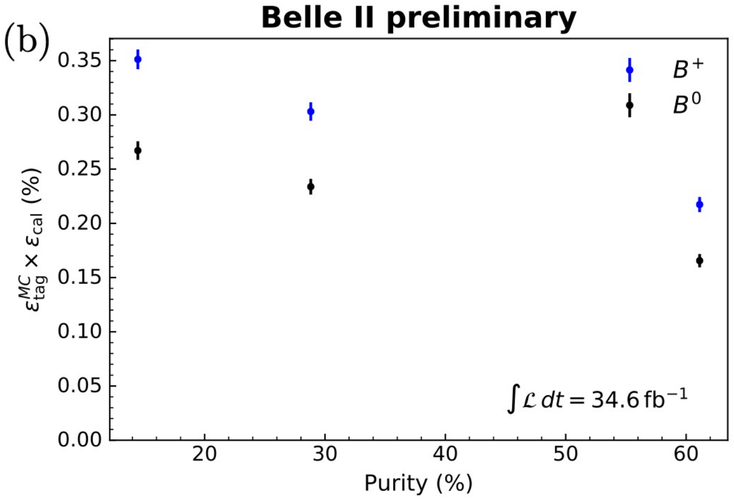
Consistent with the world average

Full-event-interpretation (FEI) tagging at Belle II

Full Event Interpretation (FEI): Comp. and Soft. For Big Sci. **3**, 6 (2019)
Multivariate algorithm for exclusive tagging of one B meson in a $\Upsilon(4S)$ decay using hierarchal approach.

Over 100 B meson decay channels and over 10,000 decay cascades

Improved efficiency up to 50% relatively with respect to conventional approaches!



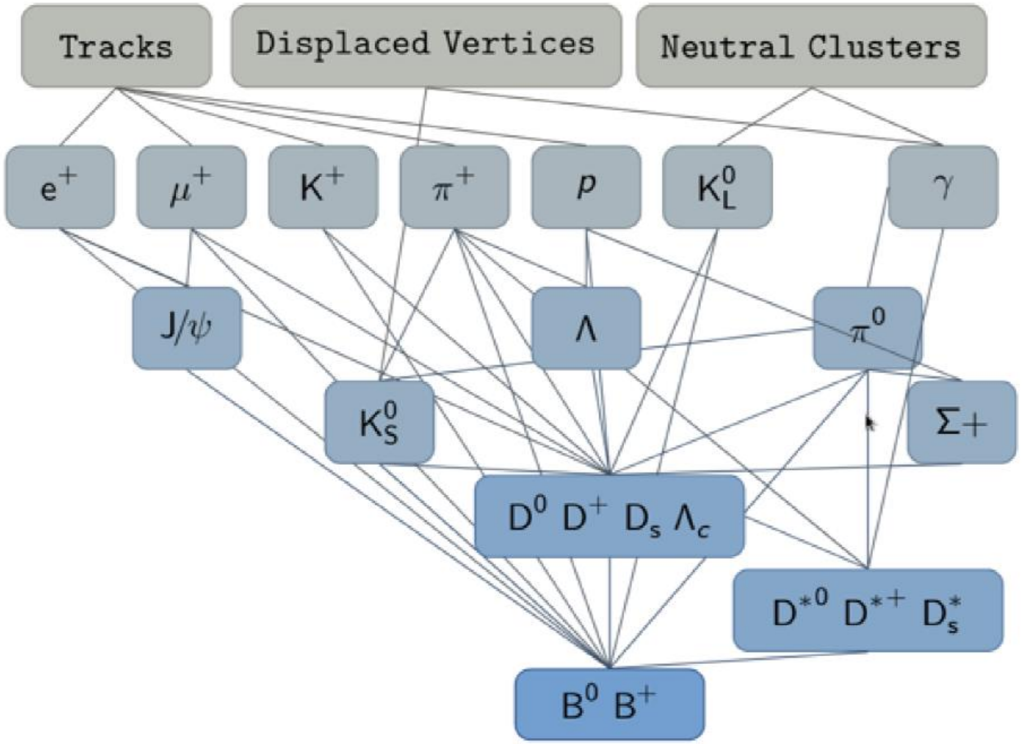
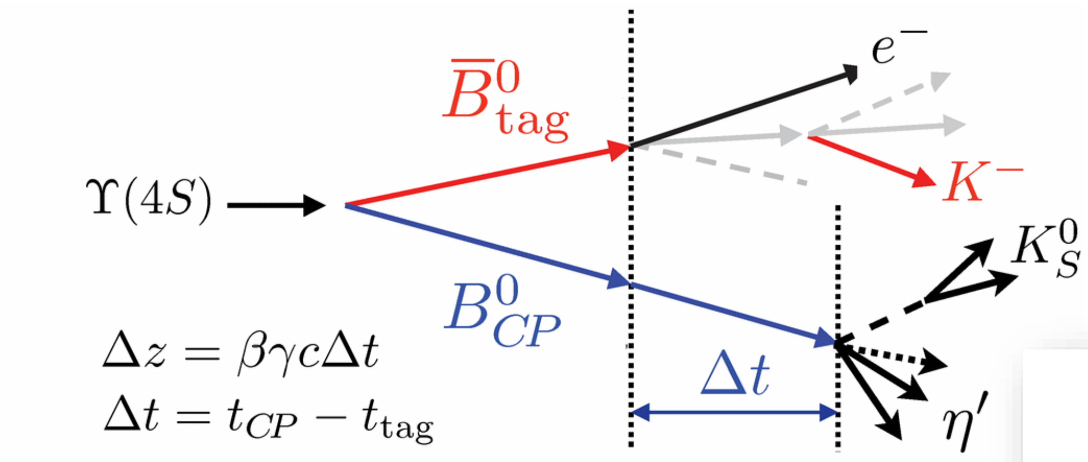


FIG. 1: Hierarchical structure of the full-event-interpretation tagging algorithm.

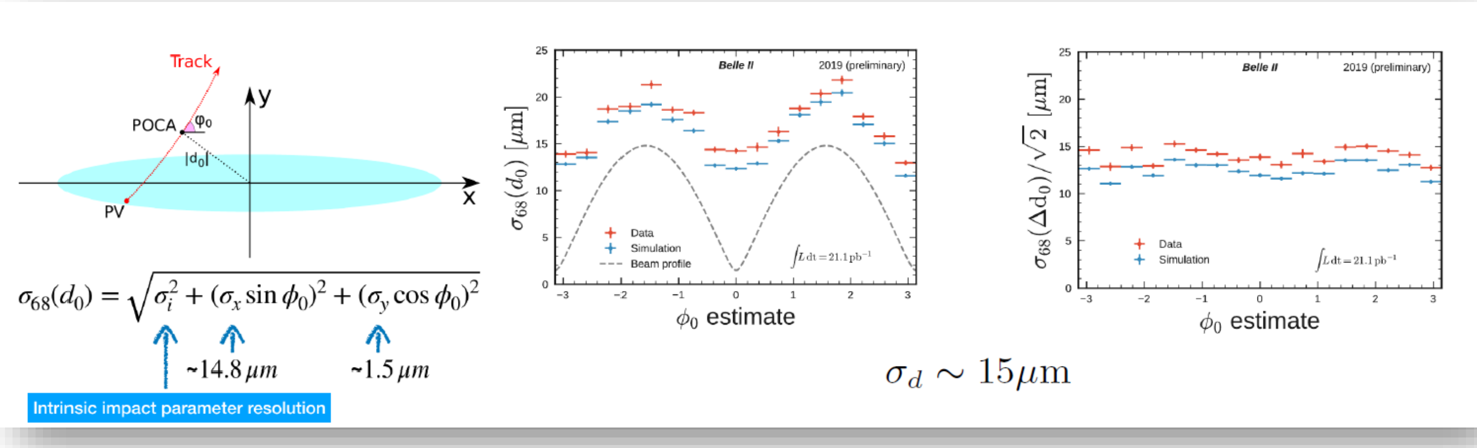
arXiv:2008.06096

Time dependent CPV in B decays



$$\mathcal{A}_f(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)}{\Gamma(\overline{B}^0(\Delta t) \to f) + \Gamma(B^0(\Delta t) \to f)} = S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t)$$

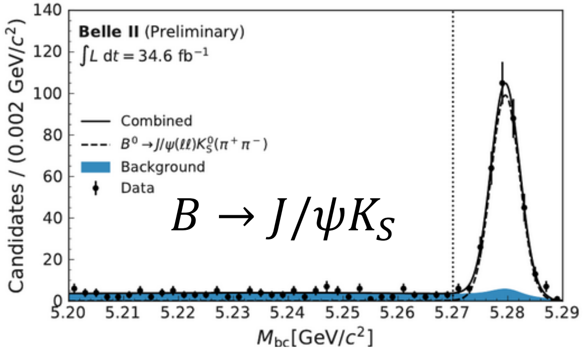
$< \Delta z > \sim 130\ \mu m$ at Belle II

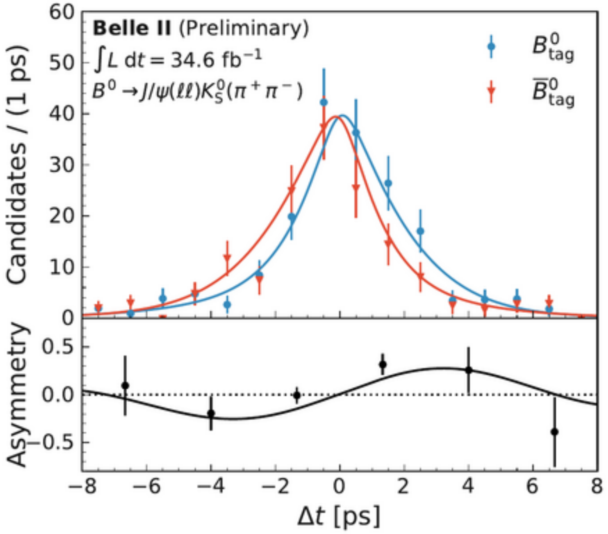


$\sin(2\beta)$ is still a fundamental input for the CKM UT fit, it will be a golden channel at Belle II until the end of data taking.

$\sin(2\beta/\phi_1)$ from $B \to J/\psi K^0$

BELLE2-NOTE-PL-2020-011





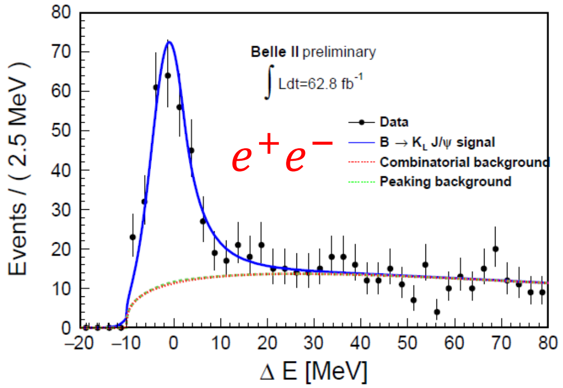
$\sin(2\beta)$ = 0.55 ± 0.21 ± 0.04
(significance ~ 2.7σ)

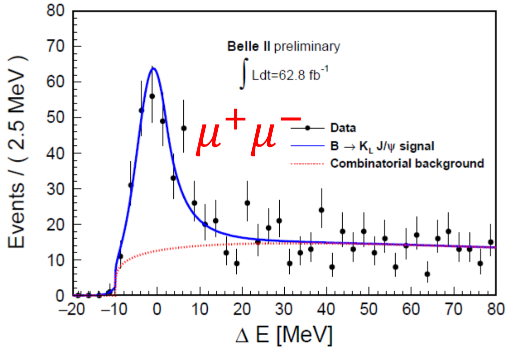
WA: $\sin(2\beta)$ = 0.699 ± 0.017

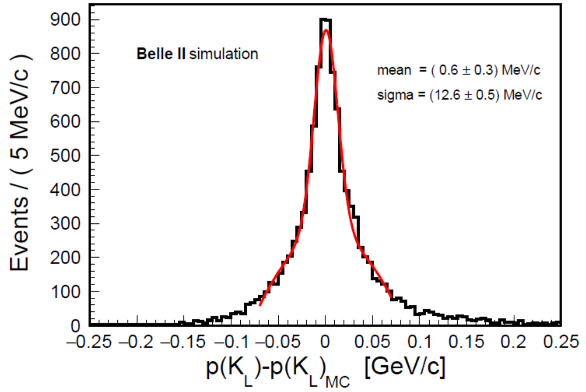
$B \to J/\psi K_L$ arXiv: 2106.13547 [hep-ex]

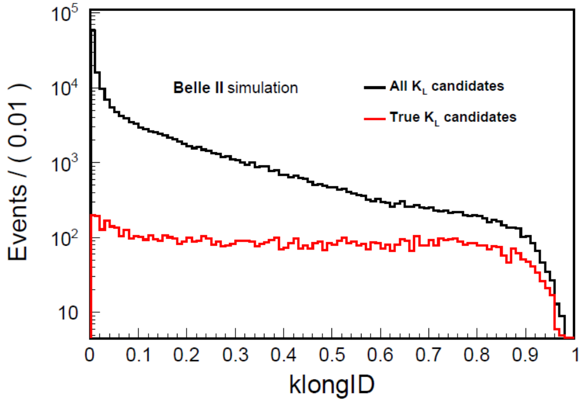
K_L reconstruction:

- Get direction of K_L according to cluster in KLM.
- $J/\psi \to e^+e^-$ or $\mu^+\mu^-$
- Mass constraint of $J/\psi K_L$ to get the P_4 of K_L.









- $N^{sig}(e^+e^-) = 226 \pm 20$, $N^{sig}(\mu^+\mu^-) = 267 \pm 21$
- In good agreement with Belle.
- But the systematic uncertainties related to peaking background is relatively large.
- $\Delta N_{peaking}(e^+e^-) = 31$, $\Delta N_{peaking}(\mu^+\mu^-) = 28$

B Flavor Tagger

arXiv: 2110.00790 [hep-ex], submitted to EPJC

- The algorithms provide essential inputs for measurements of quark-favor mixing and CPV.
- The flavor (B or B) of the unreconstructed B in the eveCnt is determined by combining information from:
  - Charged leptons;
  - Charged kaons and pions;
  - Presence of K_S, Λ^0, $\cdots$
- Effective FT efficiency:
  - For a category-based algorithm:

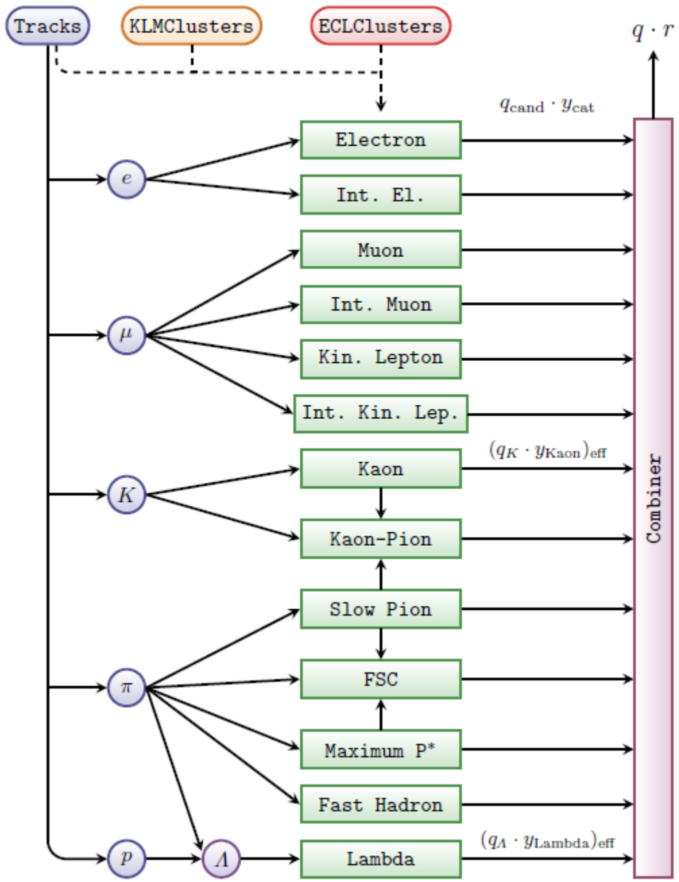
    $\varepsilon_{\rm eff} = (30.0 \pm 1.2({\rm stat}) \pm 0.4({\rm syst}))\%$ $\quad B^0$

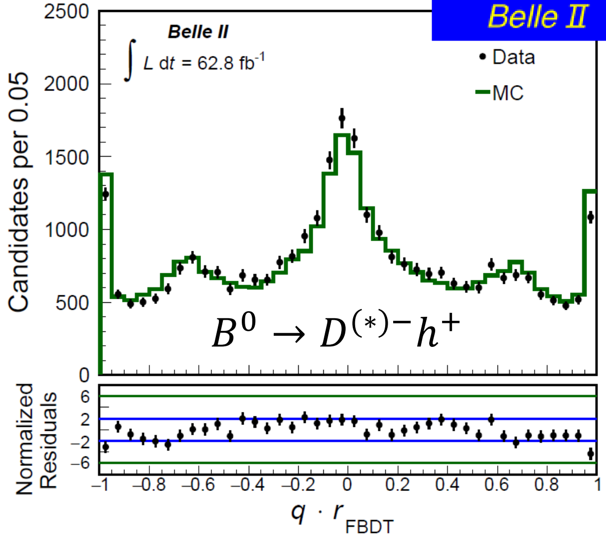
    $\varepsilon_{\rm eff} = (37.0 \pm 0.6({\rm stat}) \pm 0.2({\rm syst}))\%.$ $\quad B^\pm$
  - For a deep-learning algorithm:

    $\varepsilon_{\rm eff} = (28.8 \pm 1.2({\rm stat}) \pm 0.4({\rm syst}))\%$ $\quad B^0$

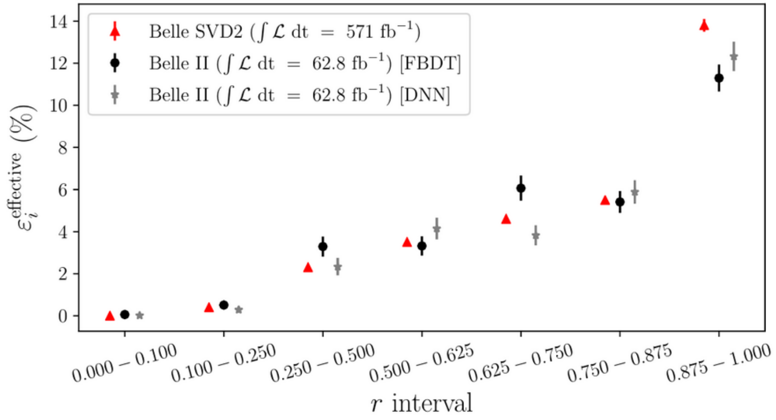
    $\varepsilon_{\rm eff} = (39.9 \pm 0.6({\rm stat}) \pm 0.2({\rm syst}))\%.$ $\quad B^\pm$

category-based flavor tagger





DNN flavor tagger based on a deep-learning multi-layer perceptron (MLP)



$r = 1 - 2w$, where w is the wrong tag fraction

$\sin(2\beta/\phi_1)$ outlook

- $\sin(2\beta/\phi_1)$ from $J/\psi K^0$ with $50\ ab^{-1}$ data will be systematics dominated.
- Irreducible systematic uncertainties from alignment of the vertex detector and Doubly Cabibbo Suppress Decays on the tag side.

Belle II Physics Book

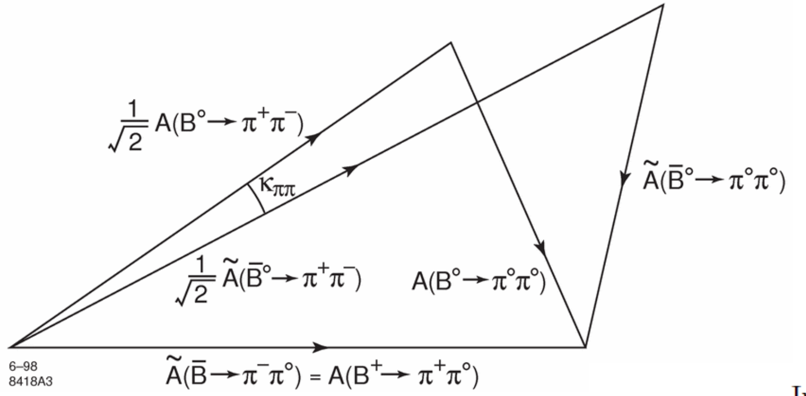
	No improvement	Vertex improvement	Leptonic categories
$S_{c\bar{c}s}$ ($50\ \text{ab}^{-1}$) time dependent CP parameter			
stat.	0.0027	0.0027	0.0048
syst. reducible	0.0026	0.0026	0.0026
syst. irreducible	0.0070	0.0036	0.0035
$A_{c\bar{c}s}$ ($50\ \text{ab}^{-1}$) direct CP asymmetry			
stat.	0.0019	0.0019	0.0033
syst. reducible	0.0014	0.0014	0.0014
syst. irreducible	0.0106	0.0087	0.0035

- Penguin pollution can no longer be ignored and must be constraint from $B \rightarrow J/\psi\pi^0$ and other SU(3) related channels.

α/ϕ_2 at Belle (II)

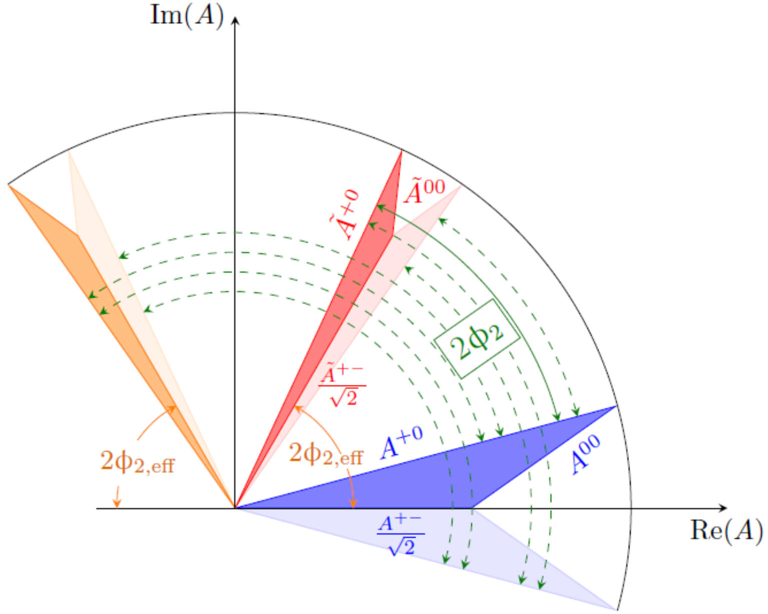
- The measurement of ϕ_2 from $B \to \pi\pi$ (or $\rho\rho$) is from isospin analysis:

$$\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$$
$$\frac{1}{\sqrt{2}}\tilde{A}^{+-} + \tilde{A}^{00} = \tilde{A}^{+0}$$
$$A^{+0} = \tilde{A}^{+0}$$



Gronau and London, PRL 65 (1990), 3381

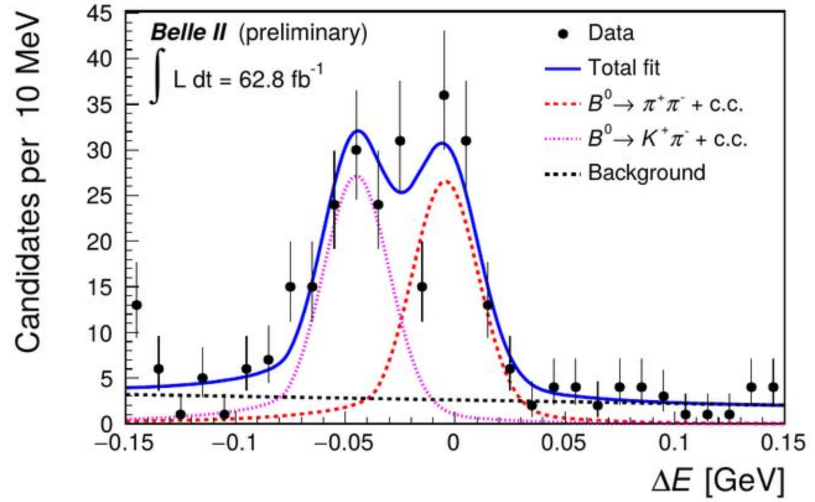
- Observables:
    - ➢ Branching fractions: $\pi^{\pm}\pi^{0}, \pi^{+}\pi^{-}, \pi^{0}\pi^{0}$
    - ➢ Direct CP (time-independent) asymmetries: C^{+-}, C^{00}
    - ➢ Time-dependent CP asymmetries: S^{+-}, S^{00}
    - ➢ We expect to push the sensitivity to $\Delta\alpha \sim 1^{o}$.



α related measurements at Belle II

arXiv:2106.03766 [hep-ex]

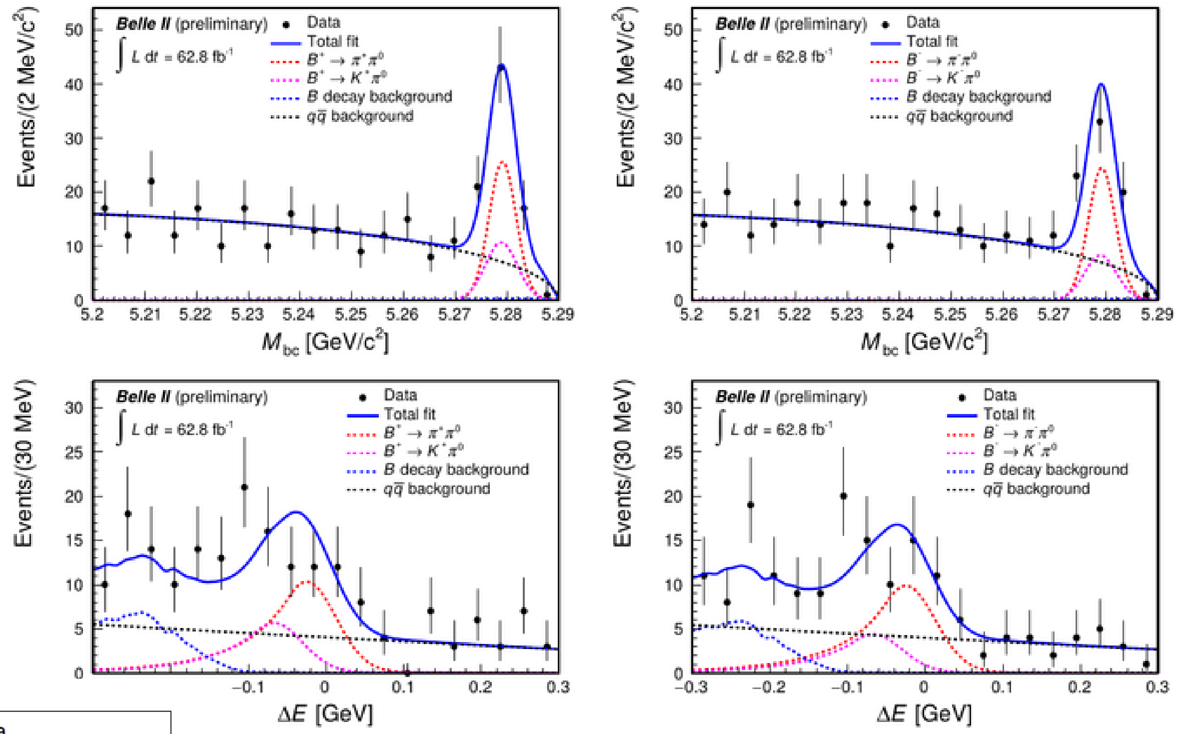
Measurements of $B^0 \to h^+\pi^-$, $B^+ \to K_S\pi^+$



$$\mathcal{B}(B^0 \to \pi^+\pi^-) = [5.8 \pm 0.7(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-6}$$

arXiv:2105.04111 [hep-ex]

Measurement of $B^\pm \to h^\pm\pi^0$



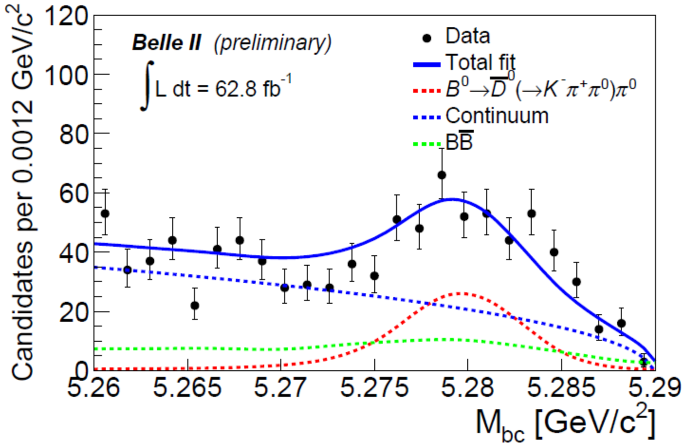
$$\mathcal{B}(B^+ \to \pi^+\pi^0) = [5.5^{+1.0}_{-0.9}(\text{stat}) \pm 0.7(\text{syst})] \times 10^{-6}$$

$$\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})$$

arXiv:2107.02373 [hep-ex]

First evidence of $B^0 \to \pi^0\pi^0 (3.4\sigma)$

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.98^{+0.48}_{-0.39} \pm 0.27) \times 10^{-6}$$



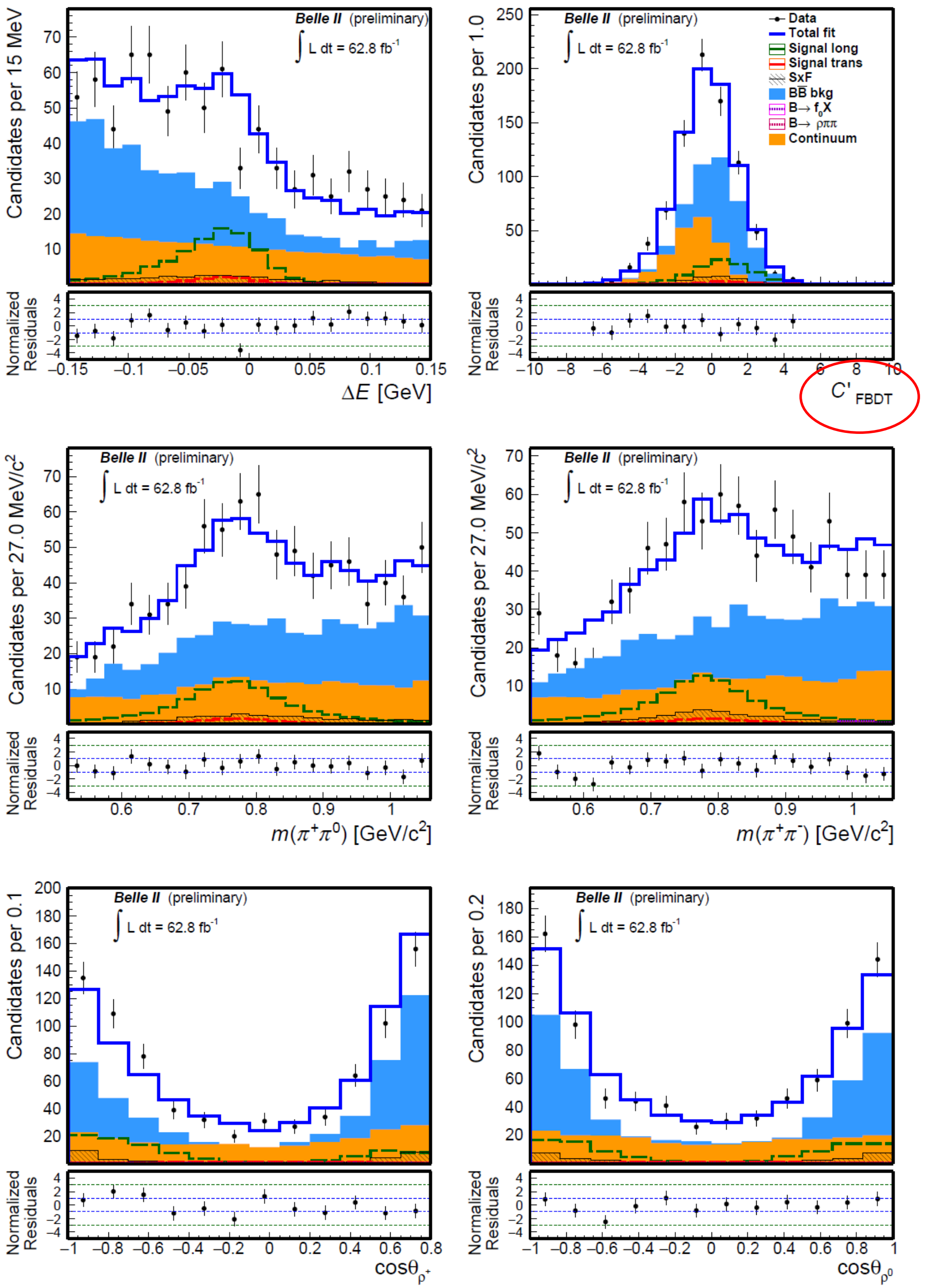
$B \to \rho^+\rho^0$ at Belle II

arXiv:2109.11456 [hep-ex]

- $\rho^+ \to \pi^+\pi^0(\to \gamma\gamma), \rho^0 \to \pi^+\pi^-$
- $B \to \rho\rho$ ispospin analysis comes with the additional complication that it needs the longitudinal polarization fraction $f_L$of the decay (as the CP eigenvalues depend on the helicity state);
- A complex, multi-dimensional analysis is mandatory for this kind of final states;
- The branching ratio and f_L are compatible with the WA;
- Also on this case we see better performance compared to Belle.

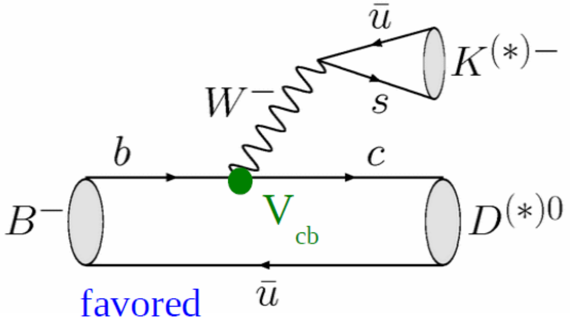
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [20.6 \pm 3.2(\text{stat}) \pm 3.1(\text{syst})] \times 10^{-6}$$

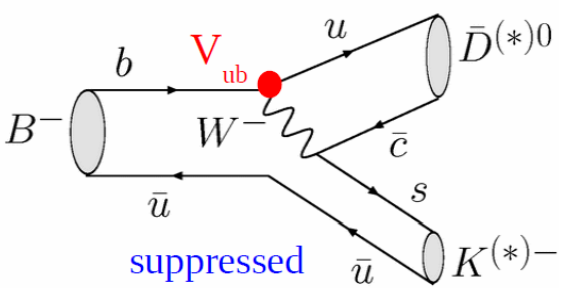
$$f_L(B^+ \to \rho^+\rho^0) = 0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst})$$

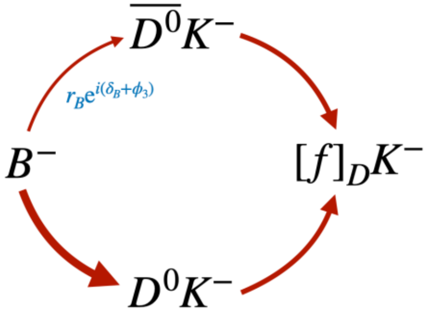


γ/ϕ_3 at Belle II

- Most difficult angle to compete with LHCb, but the importance of this input for the CKM fit fully justifies the effort;
- ϕ_3 is the phase between $b \to u$ and $b \to c$ quark transitions.
- Sensitivity comes mostly from time integrated measurements of $B^- \to \bar{D}^0 K^-$ and $D^0 K^-$.







$$\frac{A^{\text{suppr.}}(B^- \to \overline{D^0}K^-)}{A^{\text{favor.}}(B^- \to D^0K^-)} = r_B e^{i(\delta_B+\phi_3)}$$

- Several methods exist to extract the weak phase: GLW, ADS, BPGGSZ
- Belle II will have unique sensitivity to modes with neutrals in the final state:
  - ➢ GLW: $K_S\pi^0$, $K_S\eta$;
  - ➢ ADS using $D^{*0} \to D^0\gamma$, $D^0\pi^0$;
  - ➢ BPGGSZ of $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $\cdots$

(From Niharika Rout)

GLW *Phys. Lett. B* **253**, 483

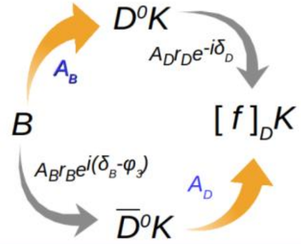
- CP eigenstates such as $K^+K^-, \pi^+\pi^-$ (CP-even) or $K_S^0\pi^0, K_S^0\eta$ (CP-odd)
- Four observables: $R_{CP}^{\pm}, A_{CP}^{\pm}$
- No external charm factory inputs are required

$$R_{CP}^{\pm} = \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D^0K^-) + \mathcal{B}(B^+ \to \bar{D}^0K^+)} = 1 + r_B^2 \pm 2r_B\cos(\delta_B)\cos(\phi_3)$$

$$A_{CP}^{\pm} = \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)} = \pm 2r_B\sin(\delta_B)\sin(\phi_3)/R_{CP}^{\pm}$$

ADS *Phys. Rev. Lett.* **78**, 3257

- *D* from a favoured amplitude decays to a doubly-Cabibbo-suppressed state
- Two observables: R_{ADS}, A_{ADS}
- External inputs: r_D, δ_D



BPGGSZ *Phys. Rev. D* **68**, 054018

- Self-conjugate multi body final states : $K_S^0\pi\pi, K_S^0KK, K_S^0\pi\pi\pi^0$
- Sensitivity to ϕ_3 by comparing *D* Dalitz plot distributions of B^+ and B^-
- Fit D Dalitz plot with full Amplitude model

$$A_{B^+} = \bar{A}(m_-^2, m_+^2) + r_B e^{i(\delta_B-\phi_3)}A(m_-^2, m_+^2)$$

$m_\pm^2$ = squared invariant mass of $K_S^0h^\pm$: *D* Dalitz plot variable

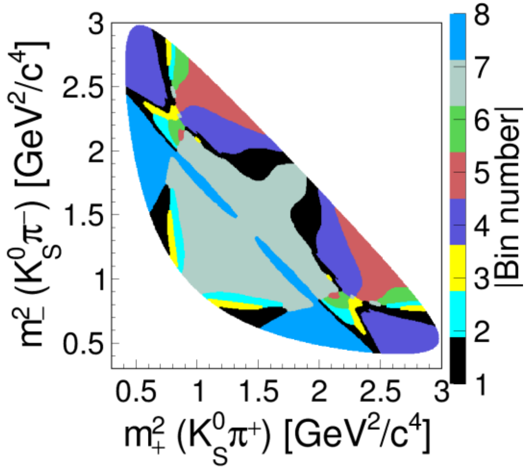
BPGGSZ at Belle (II)

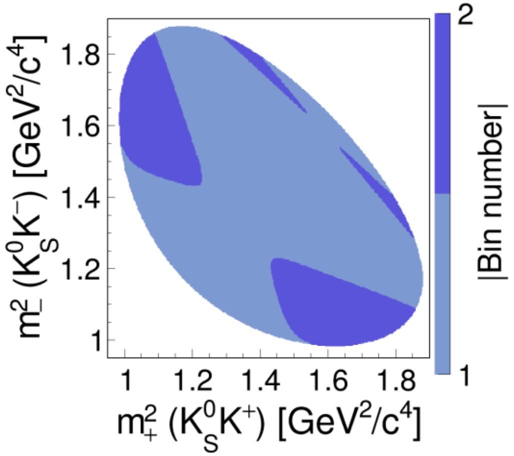
model independent

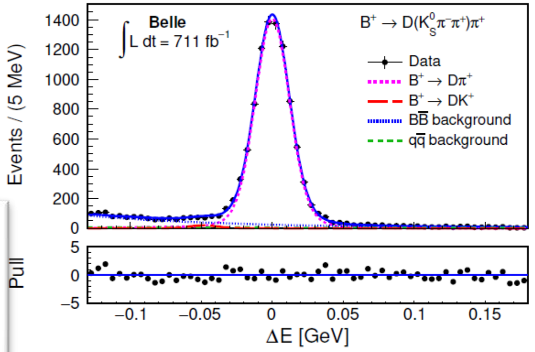
F. Abudinén et al, Belle + Belle II

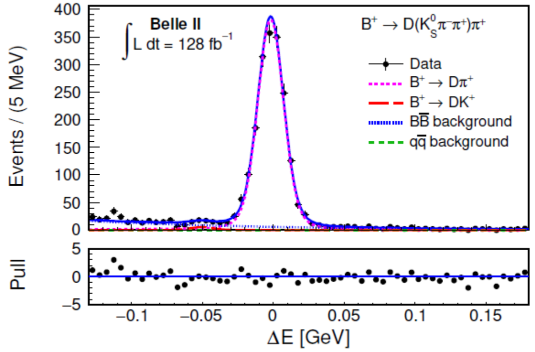
JHEP02(2022)063

- First analysis on the combined Belle ($711\ fb^{-1}$) + Belle II ($128\ fb^{-1}$) data set;
- Final states: $B^+ \rightarrow D^0(K_S h^+ h^-)h^+, h = \pi, K$;
- Full re-optimization of selection and continuum suppression;
- Model-dependent uncertainty is avoided through D Dalitz plot binning;
- 40% increase in signal yield compared to previous Belle analysis.
- New inputs from BESIII on strong-phase has significant impact on systematic uncertainty.





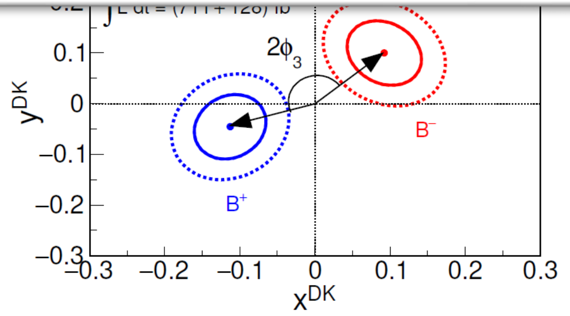


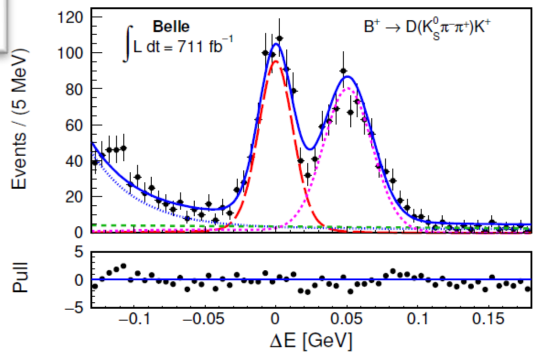


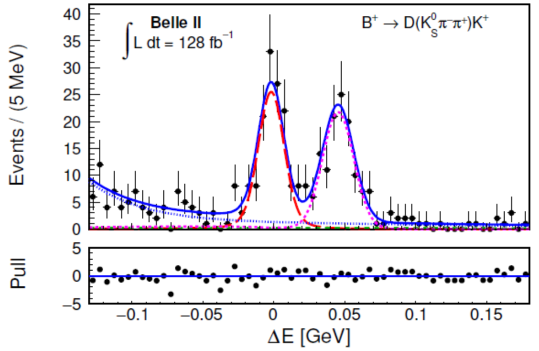
$\delta_B(°)$	124.8 ± 12.9 (stat.) ± 0.5 (syst.) ± 1.7 (ext. input)
r_B^{DK}	0.129 ± 0.024 (stat.) ± 0.001 (syst.) ± 0.002 (ext. input)
$\phi_3(°)$	78.4 ± 11.4 (stat.) ± 0.5 (syst.) ± 1.0 (ext. input)

Belle previous results: *PRD **85**, 112014 (2012)*

$$\phi_3(°) = 77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3$$



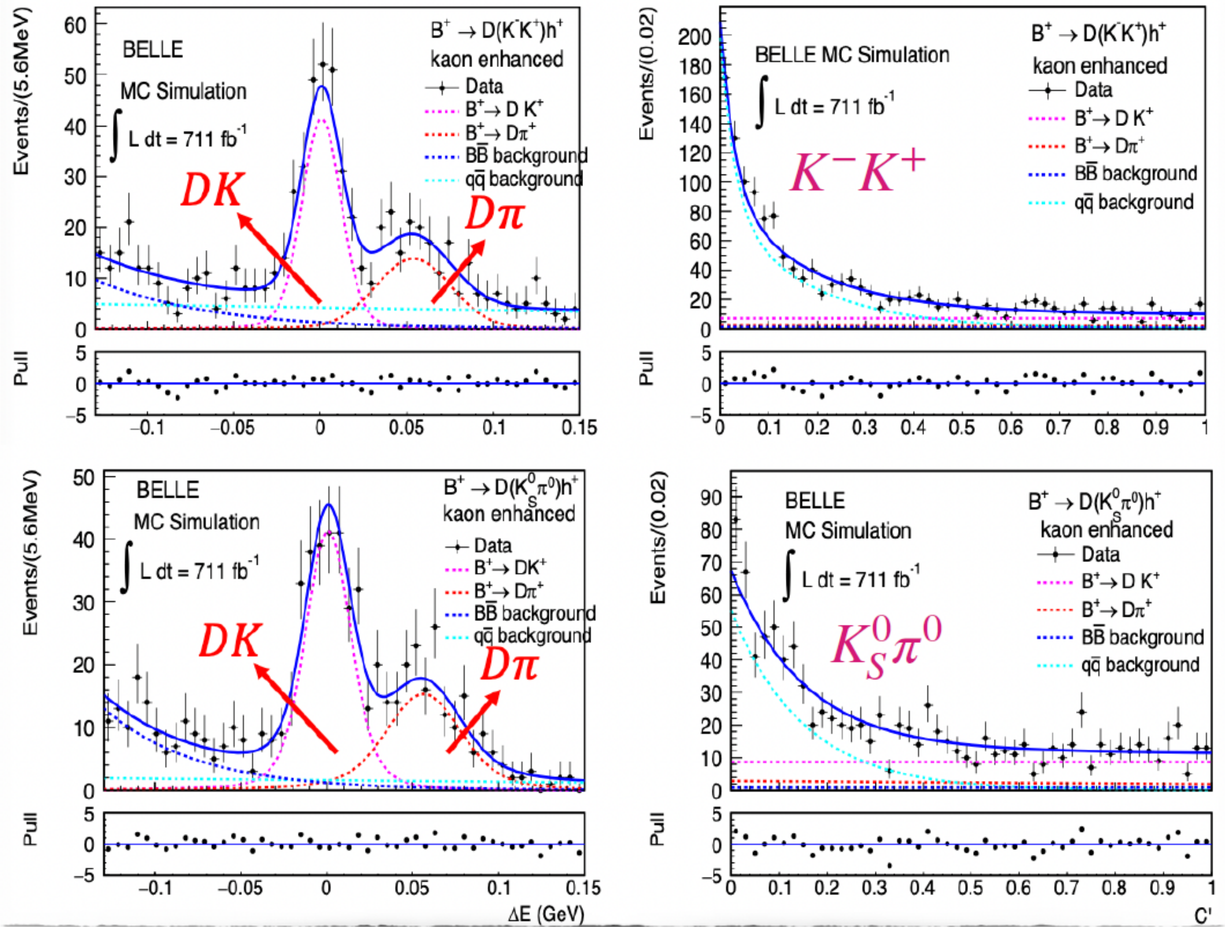


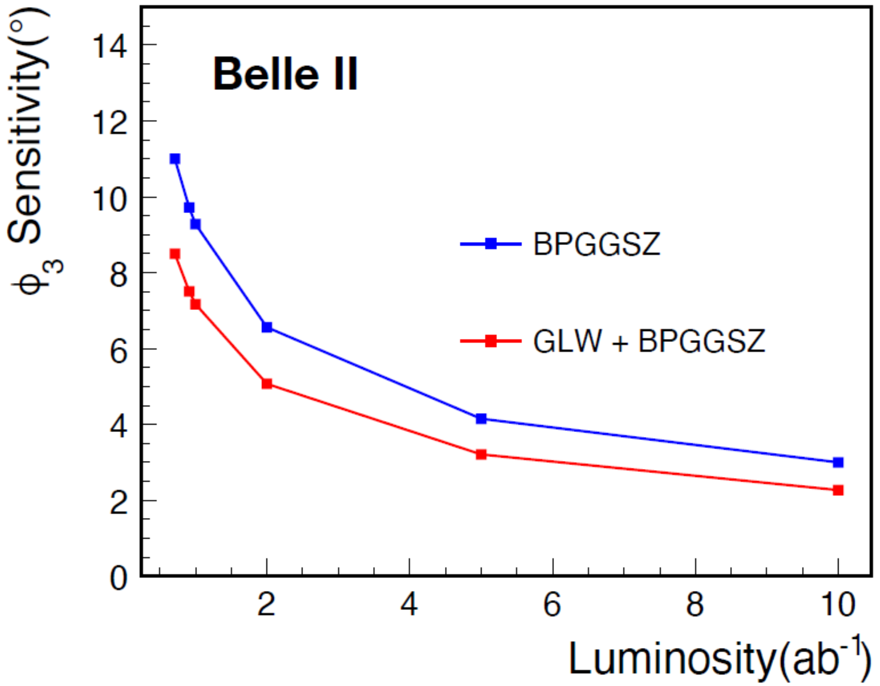


Future prospects

Ongoing sensitivity studies with $D_{CP\pm}$ final states:

Belle + Belle II: *previously performed with 275 fb^{-1} Belle data set*





- Expected uncertainty with $10\ ab^{-1}$ data set is $< 3^{o}$.
- Many other multi-body final states and $K_S hh$ from inclusive $D^{*0(+)}$are ongoing.

R&D for Belle II KLM upgrade

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass Whitepaper:
The Belle II Detector Upgrade Program

Belle II Collaboration

March 23, 2022

Abstract

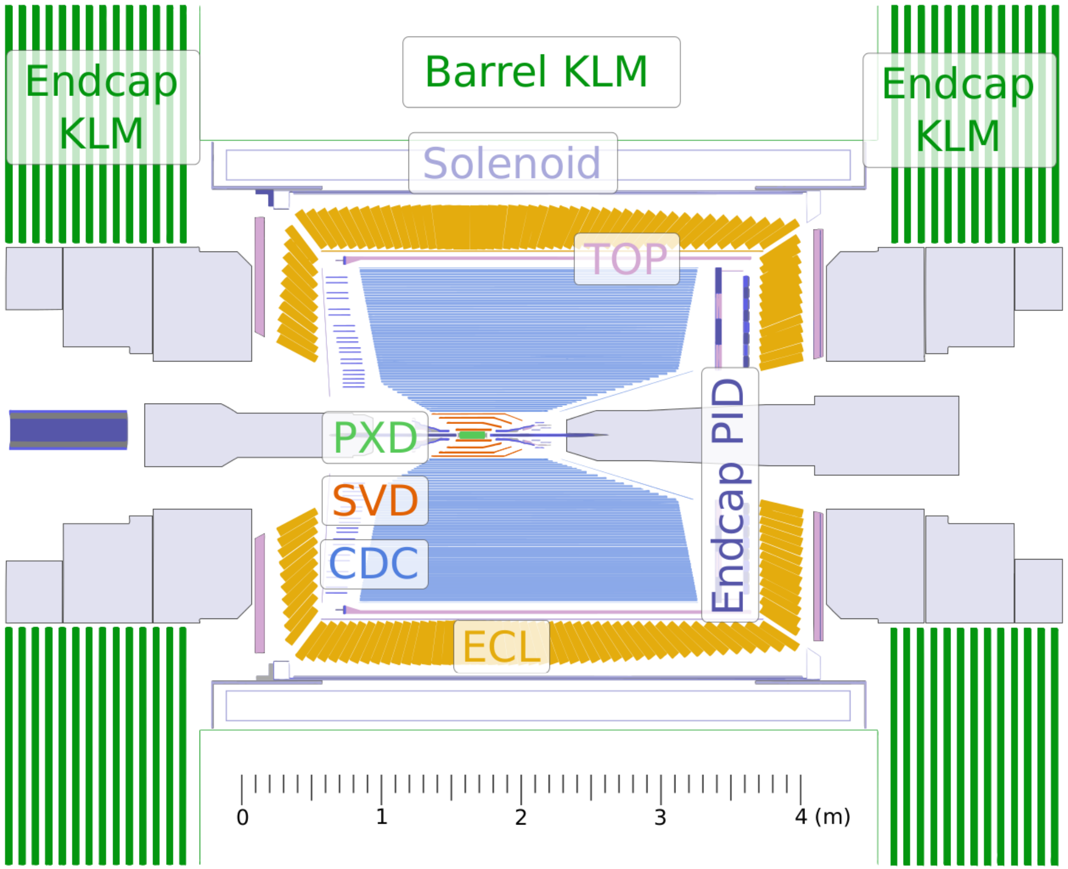
We describe the planned near-term and potential longer-term upgrades of the Belle II detector at the SuperKEKB electron-positron collider in Tsukuba, Japan. These upgrades will allow increasingly sensitive searches for possible new physics beyond the Standard Model in flavor, tau, electroweak and dark sector physics that are both complementary to and competitive with the LHC and other experiments. We encourage the instrumentation-frontier community to contribute and study upgrade ideas as part of the Snowmass process.

arXiv:2203.11349v1 [hep-ex]

8 KLM

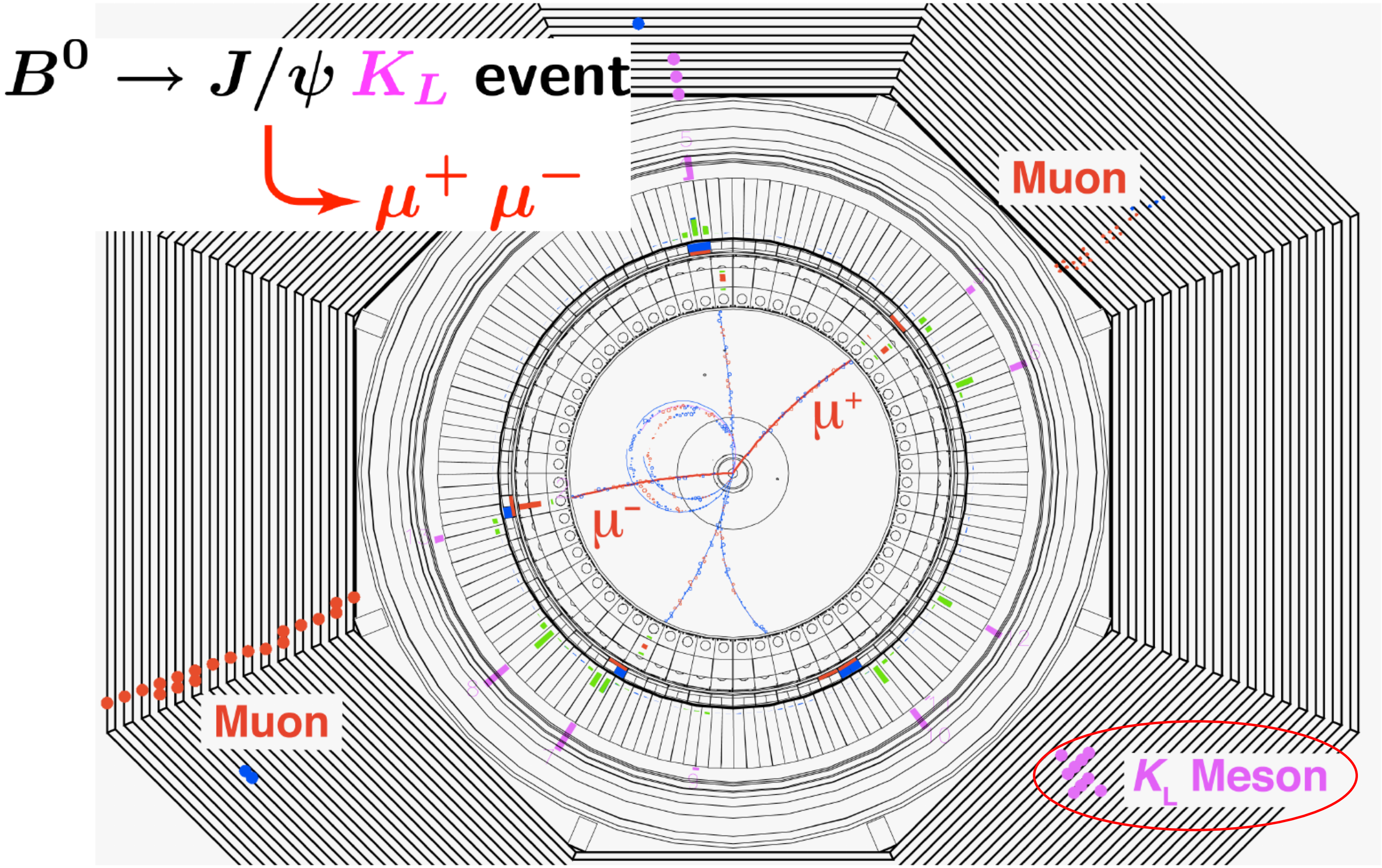
L. Piilonen, X. Wang, G. Varner

A performance upgrade has been proposed for the Belle II KLM subdetector, which identifies K_L mesons and muons with momenta up to about 4.5 GeV/c, to add the capability of energy measurement for the K_L mesons via a time-of-flight measurement. This is described in Sec. 8.2.



Performance Requirements

- Detect K_L mesons and muons (≈1 per event) with high efficiency and purity



To upgrade the Belle II detector

Subdector	Function	2022 upgrade	2026 upgrades proposed to date
PXD	Vertex Detector	2 layer upgrade	1) New DEPFET 2) SOI 3) CMOS monolithic sensors
SVD	Vertex Detector	—	1) Thin, double-sided strips, w/ new frontend 2) Merge PXD and SVD, CMOS monolithic sensors
CDC	Tracking	Upgrade FE if ready	1) Keep current detector, upgrade FE electronics 2) Replace with TPC w/ MPGD readout
TOP	PID, barrel	Repl. conv. MCP-PMTs	1) Replace not-life-extended ALD MCP-PMTs 2) Partial "STOPGAP" (see below)
ARICH	PID, forward	—	1) Replace HAPPD with Silicon PhotoMultipliers 2) Replace HAPPD with Large Area Picosecond Photodetectors
ECL	γ, e ID	—	1) Add pre-shower detector in front of ECL 2) Replace ECL PiN diodes with APDs
KLM	K_L, μ ID	—	1) Replace 13 barrel layers of legacy RPCs with scintillators 2) On-detector upgraded scintillator readout 3) Timing upgrade for K-long momentum measurement
Trigger		Firmware improvements	~~Not defined yet, depend on detector upgrades~~
DAQ		1) 2021: PCIe40 readout upgrade 2) Add 1300 cores to HLT	Add 1900 cores to HLT

Snowmass whitepaper

Expected precision with Belle II upgrade

Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	Belle-II 250 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005	0.002
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°	0.8°
α/ϕ_2 (WA)	4°	2°	0.6°	0.3°
$\lvert V_{ub}\rvert$ (Exclusive)	4.5%	2%	1%	< 1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	0.03	0.015	0.007
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	0.07	0.025	0.018
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035	0.015
$R(B \to K^* \ell^+ \ell^-)^\dagger$	0.26	0.09	0.03	0.01
$R(B \to D^* \tau \nu)$	0.018	0.009	0.0045	<0.003
$R(B \to D \tau \nu)$	0.034	0.016	0.008	<0.003
$\mathcal{B}(B \to \tau \nu)$	24%	9%	4%	2%
$B(B \to K^* \nu \bar{\nu})$	–	25%	9%	4%
$\mathcal{B}(\tau \to \mu \gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}	3.1×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	0.073×10^{-9}

arXiv:2203.11349v1 [hep-ex]

Why to upgrade KLM

- K^0_L detection.
  - K^0_L mesons are identified via their interactions in the first few layers of the KLM, and through low energy hadronic showers in the ECL. Without detector upgrades, K^0_L detection efficiencies will adversely suffer, which is a significant loss to the physics program. K^0_L mesons are difficult to detect at LHCb.
  - In addition to time dependent CP violation measurements of CP eigenstate modes, improved K^0_L detection is critical to step change improvements in background suppression in semileptonic, leptonic, electroweak penguin di-neutrino, and dark sector analyses.

Rare and leptonic decay searches such as $B \to \tau\nu$ and $B \to K^{(*)}\nu\bar{\nu}$ rely on $b \to c \to s$ background suppression based on the presence of zero extra tracks in the event, and minimal excess energy in the calorimeter. These analyses often require the detection and veto of K^0_L mesons (in the ECL and KLM), as the majority the remaining background in analyses of this type contains undetected K^0_L. Taking into account potential tracking efficiency loss, impacts of higher beam background in the calorimeter, and losses to KLM hit efficiencies, such analyses would have greatly reduced reach without detector upgrades. The effect could imply a further reduction of approximately 50% in statistical power, leading to total losses of order 75%.

2.3 Physics channels

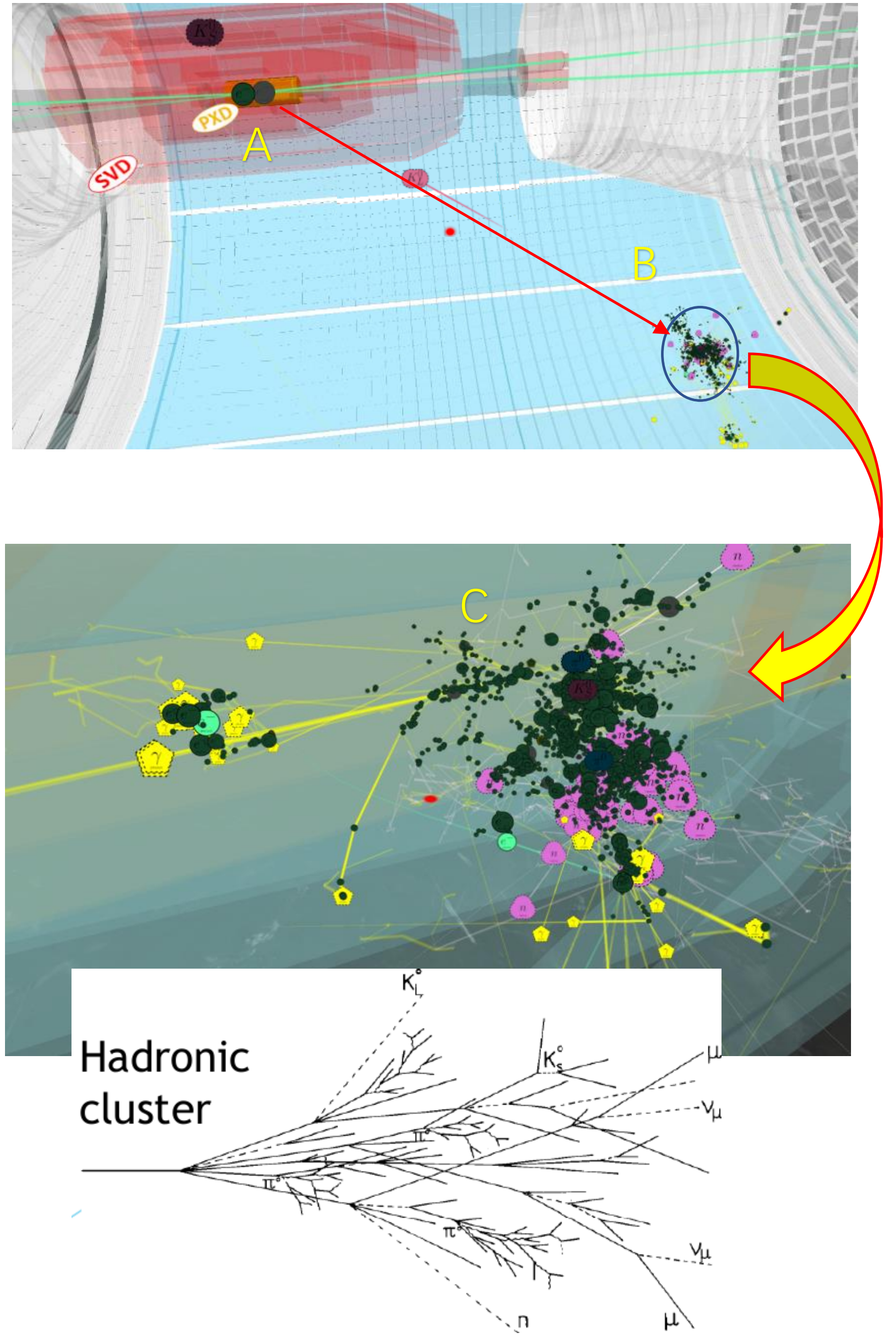
There are numerous flagship physics channels that would stand to benefit from the Belle II upgrade scenarios, summarised in Table 4 and discussed in detail below.

Topic	VXD	CDC (incl. Trigger)	PID	PID Ω	ECL	KLM
$\mathcal{B}(B \to \tau\nu, B \to K^{(*)}\nu\bar{\nu})$	✓			✓	✓	✓
$\mathcal{B}(B \to X_u \ell\nu)$	✓		✓	✓		✓
R, Polarisation$(B \to D^{(*)}\tau\nu)$	✓				✓	
FEI	✓	✓		✓		
$S_{\rm CP}, C_{\rm CP}(B \to \pi^0\pi^0, K^0_S\pi^0)$	✓	✓			✓	
$S_{\rm CP}, C_{\rm CP}(B \to \rho\gamma)$		✓	✓		✓	
$S_{\rm CP}, C_{\rm CP}(B \to J/\psi K^0_S, \eta' K^0_S)$	✓	✓				
Flavour tagger	✓		✓			
τ LFV		✓			✓	
Dark sector searches		✓			✓	✓

Table 4: Selected key physics channels and high-level analysis algorithms with the sub-detector upgrades that would make substantial impacts to measurement reach. The symbol Ω refers to solid angle coverage of the particle identification systems.

How to measure the momentum of a neutral hadron???

- Stable particles detected in collision experiments: γ、$e^{\pm}$、$\mu^{\pm}$、π、 Kaon、$p/\bar{p}$ and neutron.
- It’s always very difficult to measure a neutral hadron: K_L and neutron.
  - Charge = 0, no track in a general detector.
  - HCAL designed for energy measurement, but too much energy leakage due to π^0, neutrino, etc.
  - HCAL typically doesn’t have a good performance in measuring the deposited energy, due to the cost.
- But, if we can measure the flight time…



If KLM can perform like a TOF,

- There are many hits in a hadronic cluster, which is mainly produced in strong interaction with nuclear in the KLM. Fast time information is expected. If we can measure the stop time precisely, the time of flight can be determined, since the start time from Interaction Point (IP) has a precision of less than 30 ps.
  - The relationship between the mass m, the momentum p, the distance L and the time of flight T:

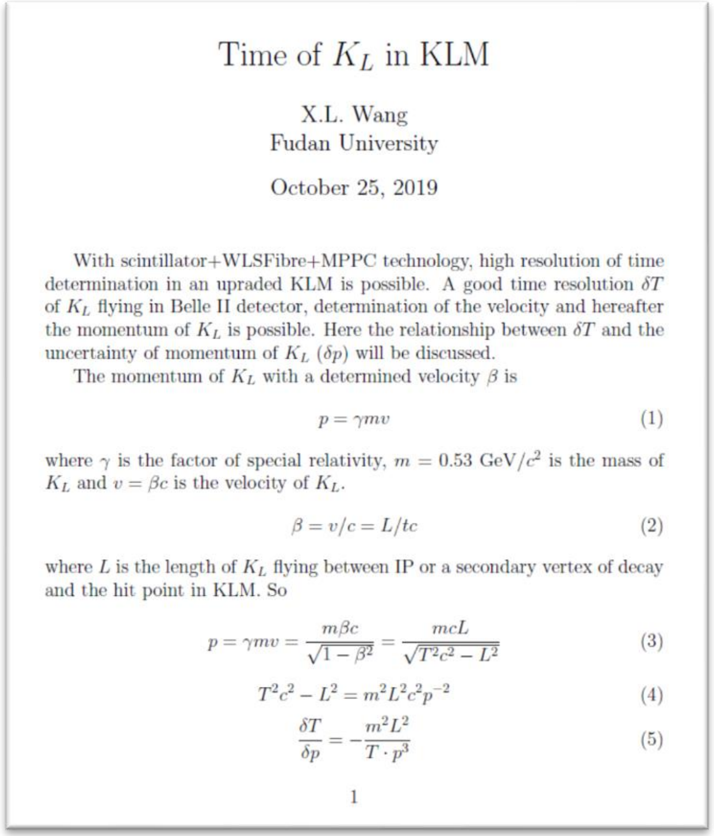
$$T^2c^2 - L^2 = m^2L^2c^2p^{-2},$$

  - The relationship between the precisions:

$$\delta p = \frac{Tp^3}{m^2L^2}\delta T$$

- For example: in Belle II detector, a 1.5 GeV/c K_L with flies L = 2 m before creating a cluster in KLM, if the KLM has a performance of $\delta T = 100\,ps$, then, T = 7.07 ns and $\delta p = 0.19$ GeV/c. Therefore, $\frac{\delta p}{p} = 13\%$!
- Neutron has a large mass than K_L.

Introduced this idea at the 34th Belle II General Meeting (B2GM)。


Time of K_L in KLM

X.L. Wang
Fudan University

October 25, 2019

With scintillator+WLSFibre+MPPC technology, high resolution of time determination in an upraded KLM is possible. A good time resolution δT of K_L flying in Belle II detector, determination of the velocity and hereafter the momentum of K_L is possible. Here the relationship between δT and the uncertainty of momentum of K_L (δp) will be discussed.

The momentum of K_L with a determined velocity β is

$$p = \gamma m v \quad (1)$$

where γ is the factor of special relativity, m = 0.53 GeV/c^2 is the mass of K_L and $v = \beta c$ is the velocity of K_L.

$$\beta = v/c = L/tc \quad (2)$$

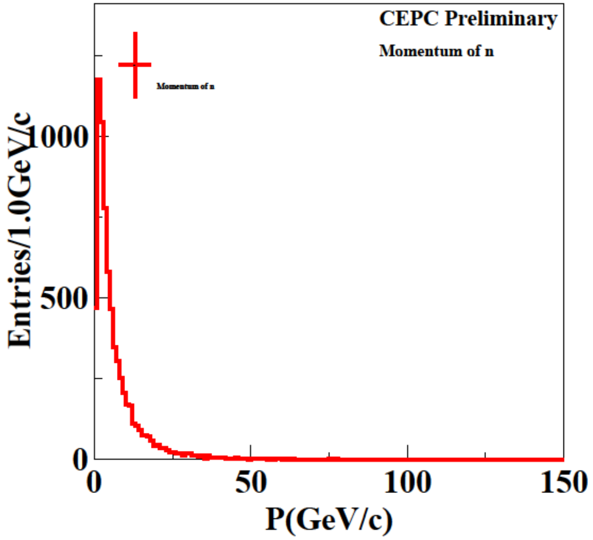
where L is the length of K_L flying between IP or a secondary vertex of decay and the hit point in KLM. So

$$p = \gamma m v = \frac{m\beta c}{\sqrt{1-\beta^2}} = \frac{mcL}{\sqrt{T^2c^2 - L^2}} \quad (3)$$

$$T^2c^2 - L^2 = m^2L^2c^2p^{-2} \quad (4)$$

$$\frac{\delta T}{\delta p} = -\frac{m^2L^2}{T \cdot p^3} \quad (5)$$

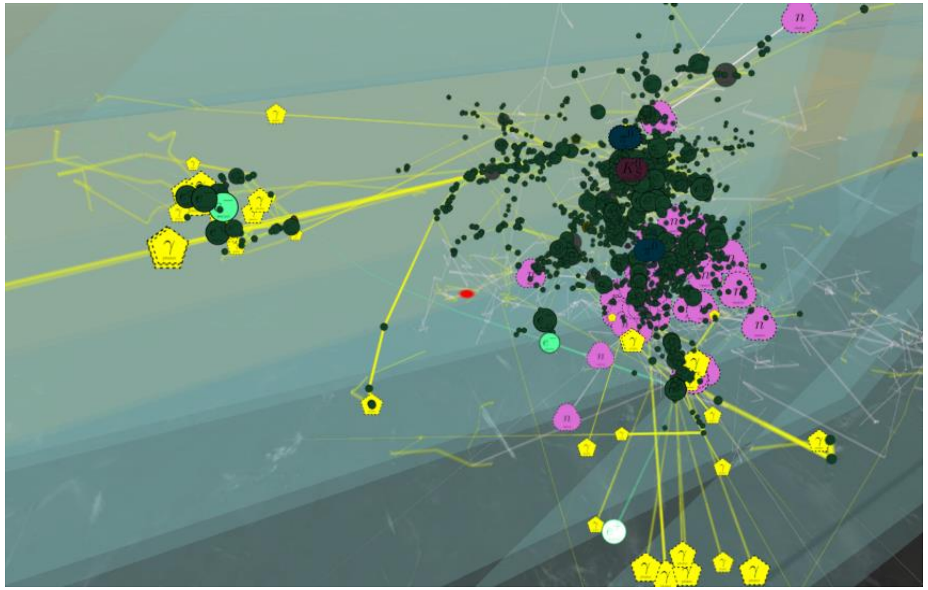
1



The original idea for the detector

Use the original design for KLM, scint+WLS fibre+SiPM, and improve the time resolution.

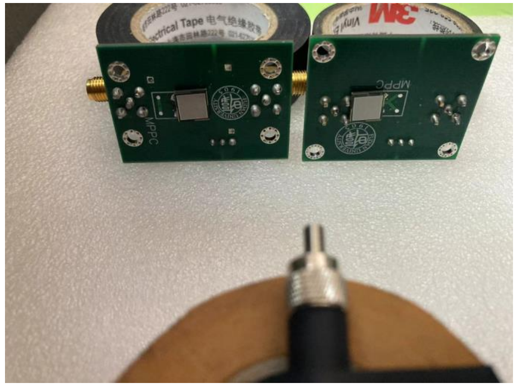
- Start time:
  - IP for the collider, $\delta T < 30\,ps$
  - For most of the know stable particles, such as B meson, D meson and some baryons, the life time $\tau < 10\,ps$.
- Stop time:
  - The time when a hadron cluster is created,
  - Combine time information from multiple hits.
  - The lower dE threshold, the more hits.
- Typically, resolution of TOF: $< 100\,ps$
  - Good reference for us



高精度前端电子学的设计

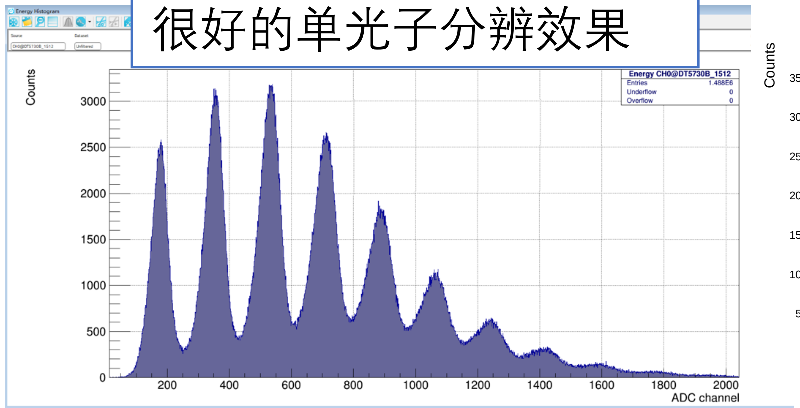
- 基于高精度的三极管开发各种读出电子学，开展低噪声高速前放的设计。
- 设计方案可针对不同类型（滨松，国产NDL）以及数量的SiPM。
- 实现很高的时间精度，33 ps！

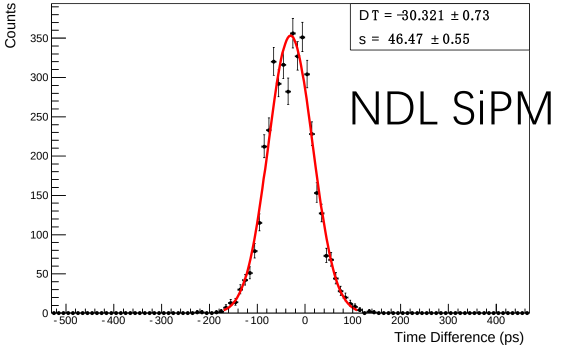
激光器测试SiPM时间分辨



100ps多路激光器

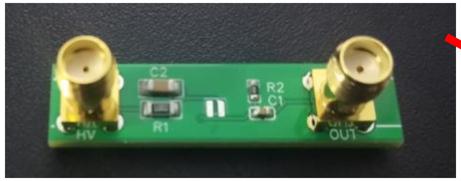
很好的单光子分辨效果

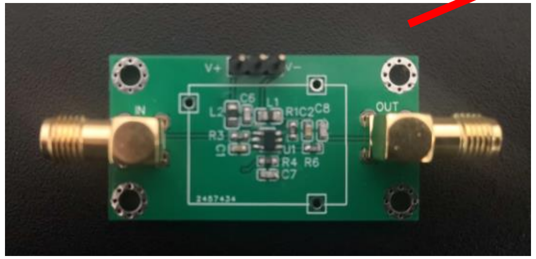


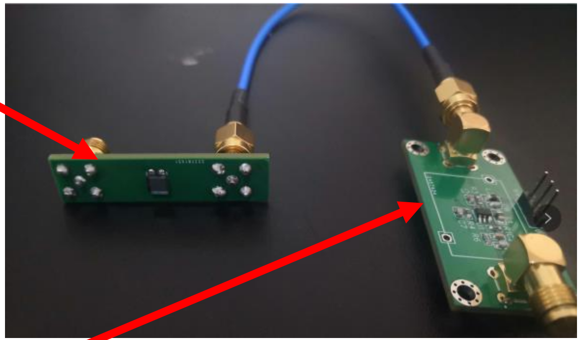


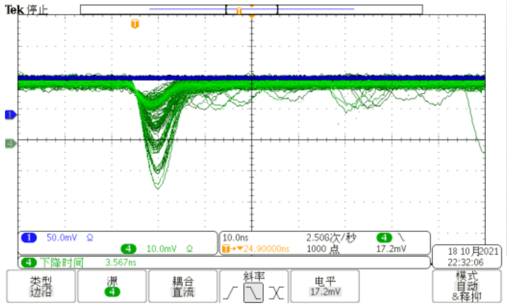
NDL SiPM

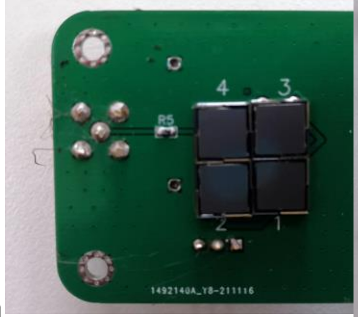
$\delta T=$ （32.5±0.4） ps







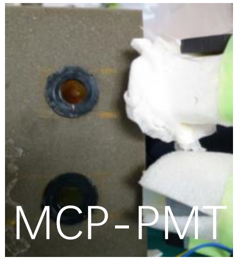




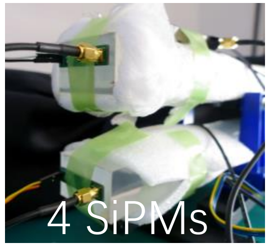
完整的塑闪探测条

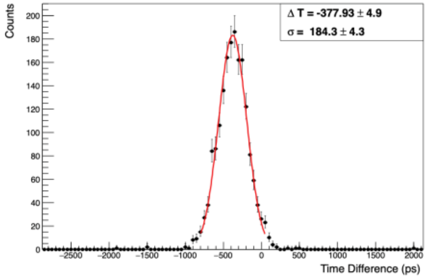
塑闪+SiPM探测原型机

- 研究实现了建造探测器的**各个关键环节**：塑闪（国产），SiPM（国产NDL，滨松），读出电子学（自行设计）
- 制作了完整的探测道，宇宙线测试结果显示优异性能：
  - **时间分辨：达到128ps，与MCP-PMT和圣戈班塑闪的性能一致！**
  - **稳定的ADC分布，使得探测器有可能用于dEdx的测量。**
- 研究表明，探索出来的探测器方案具有很好的性能，优于部分预期！

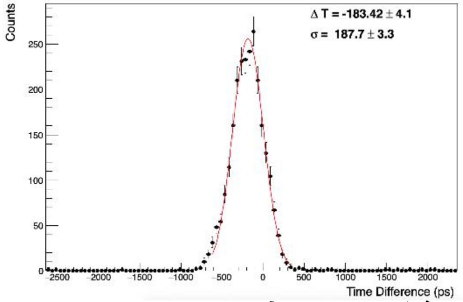


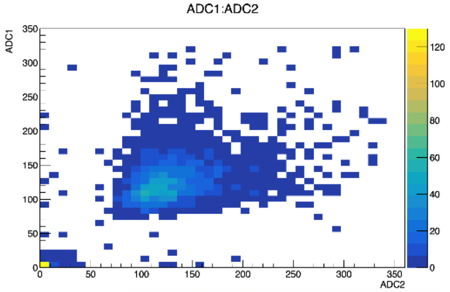
高能所进口塑闪：$3cm \times 5cm \times 1m$





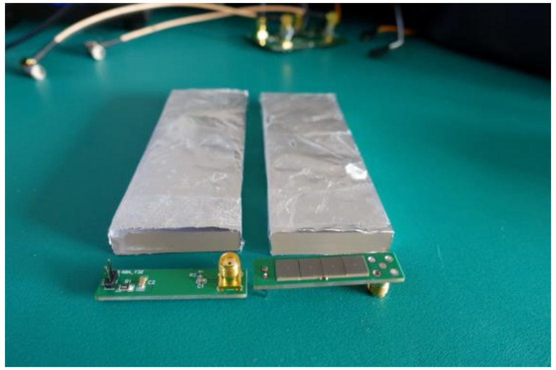
MCP-PMT测量

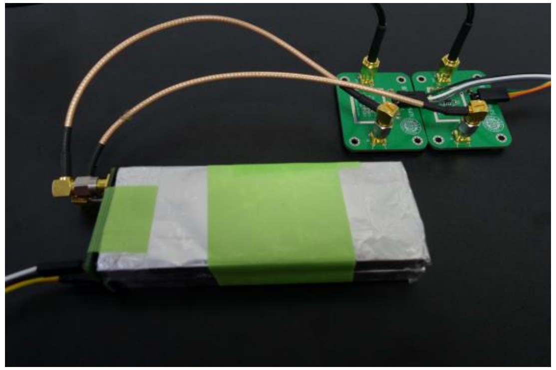


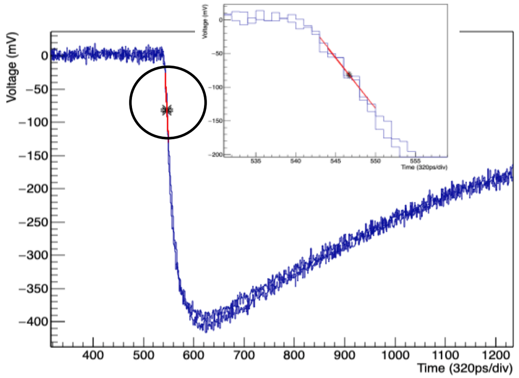


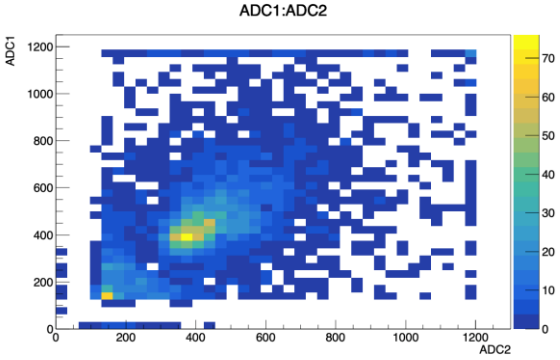
4片SiPM并联测量

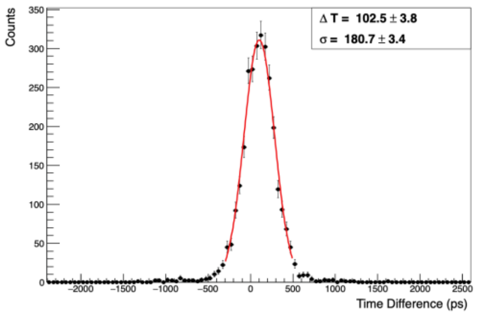
国产塑闪尺寸： $4cm \times 1cm \times 10cm$



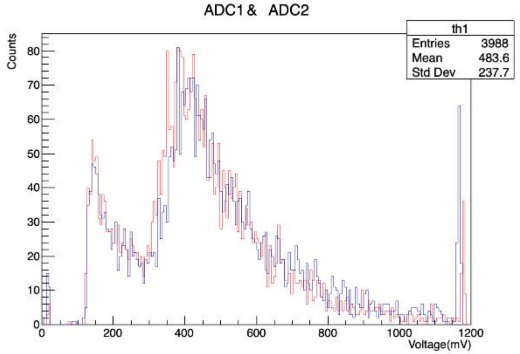








单个探测道时间精度：128ps！



不同探测道的ADC分布非常接近！

Summary

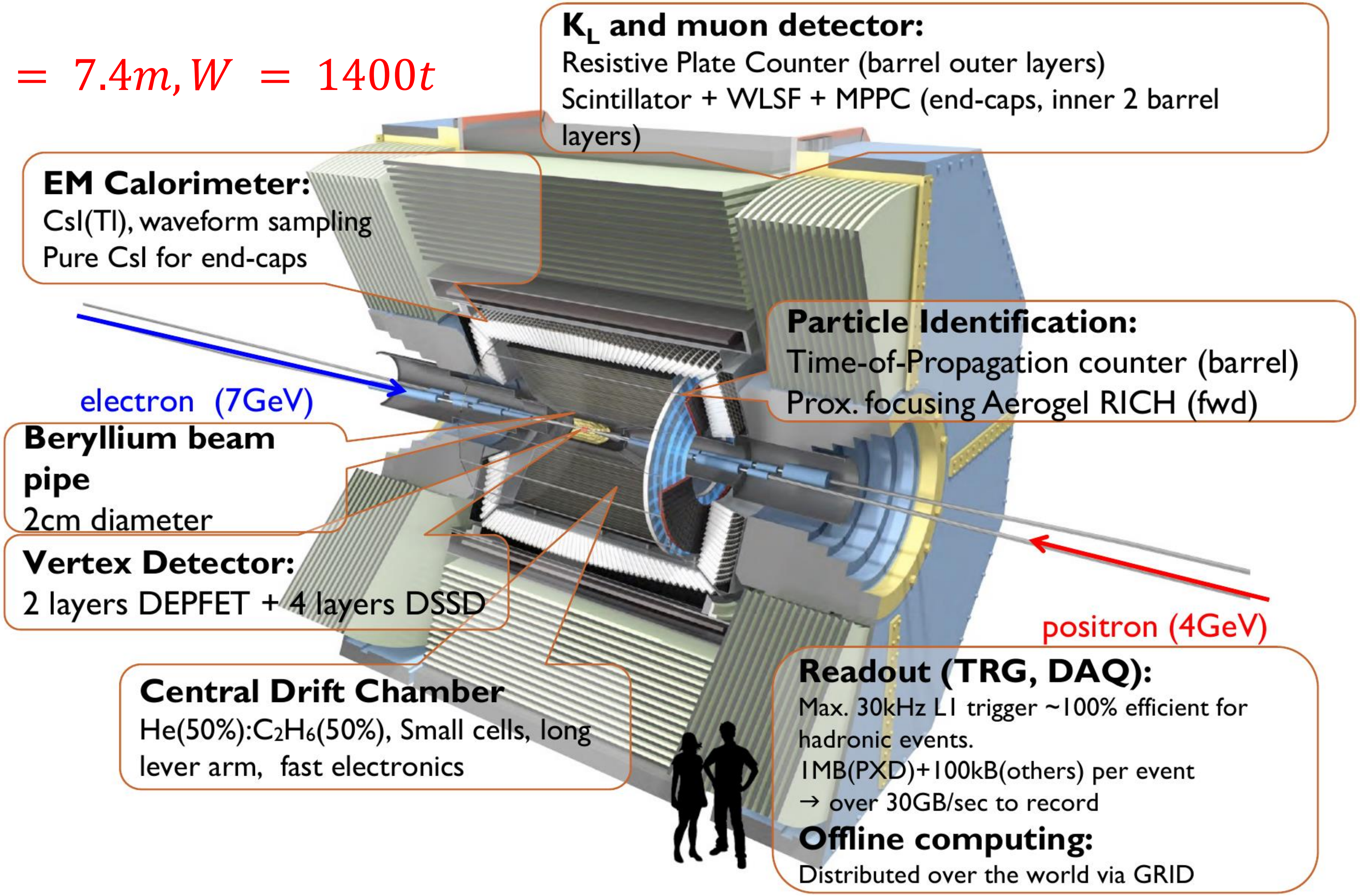
- The start of the Belle II Experiment was slower than expected, but there are coming competitive measurements.
- Complex and ambitious analyses have been shown already, more will come in the near future.
- Belle II Physics Program will cover most of the inputs relevant for the CKM UT analysis.
- The snowmass whitepaper of Belle II upgrade has been submitted.
- The R&D for Belle II KLM upgrade is ongoing at Fudan.

Thank you!

Backup

Belle II detector

$H = 7.1m, L = 7.4m, W = 1400t$

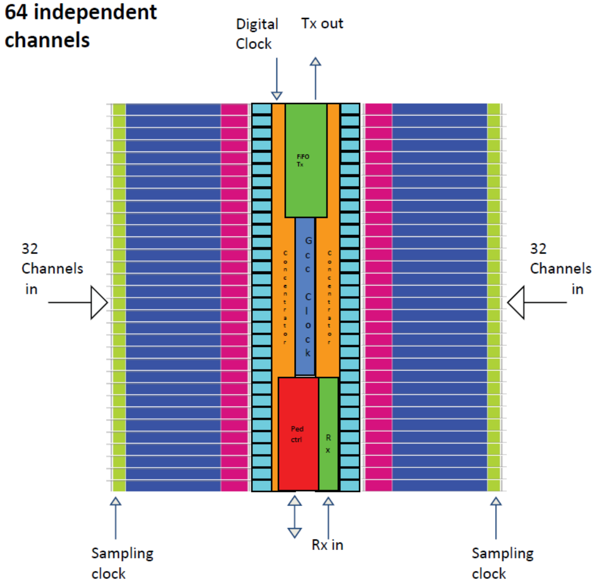


KLM readout upgrade at Belle II

TARGET ASIC upgrade

Nalu Scientific
Data Acquisition Systems

HdSoC Floorplan:
64 independent channels

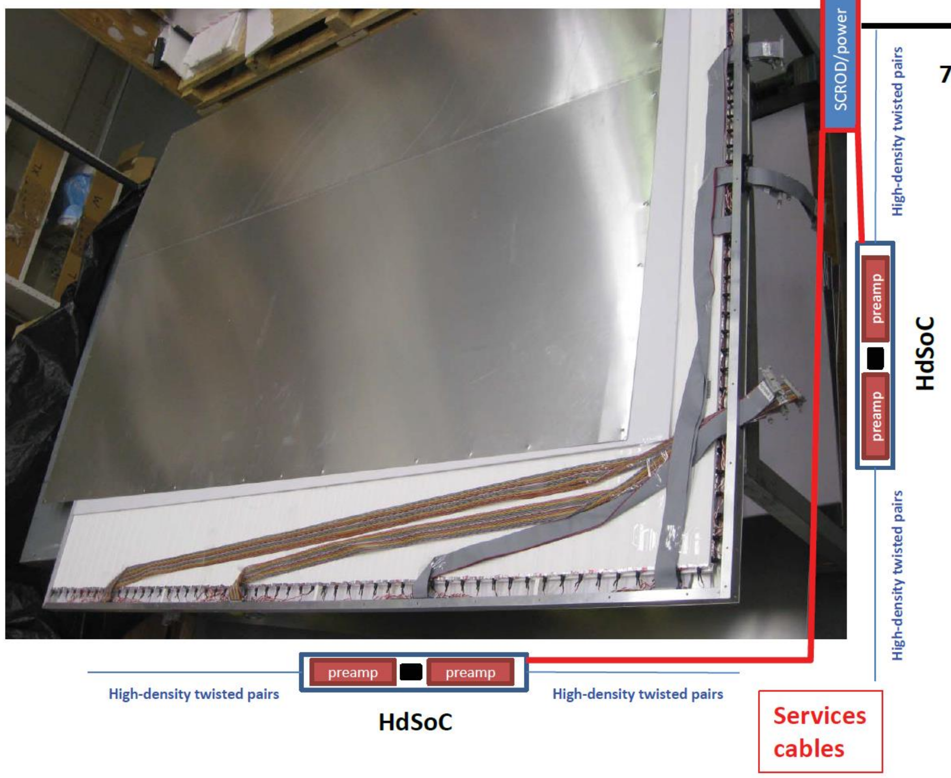


Parameter	Specification
Channel no.	64
Sample rate	1-2 GSa/s
Bandwidth	1 GHz
No. bits	12
Supply Voltage	2.5V
Input noise	1mV
Gain stages	TBD -
Analog buffer length/channel	2048
Power/channel	20-40mW
Integration	SoC

- 4x integration
- Compact power/signal cabling to SCROD
- System on Chip (signal processing), reduce SCROD processing load
- "Data push" possible (reduces need for depth since don't wait for L1 trigger)
- Possibility to integrate amplification, Si-PM overbias adjustment
- Prototypes available early 2021

Minimize cables, board size

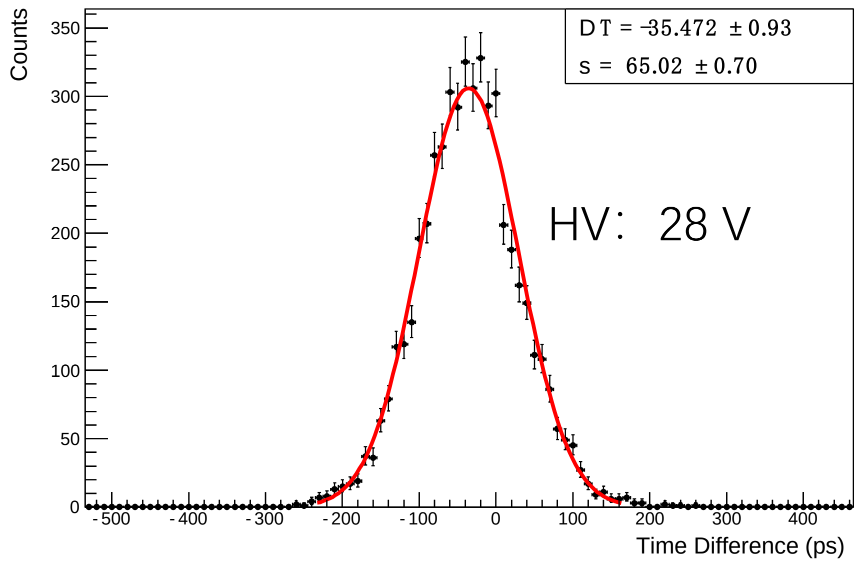
2x CAT-7
Fiber optic
Power (48V?)

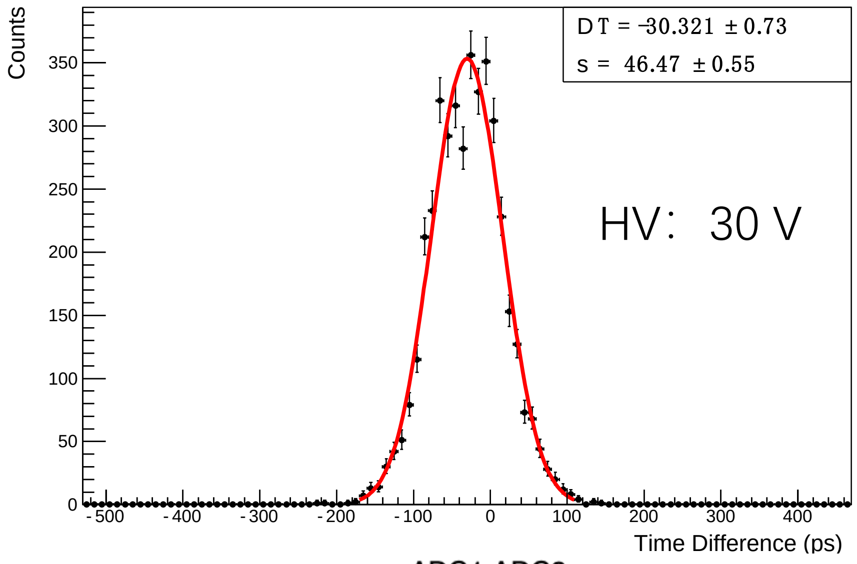


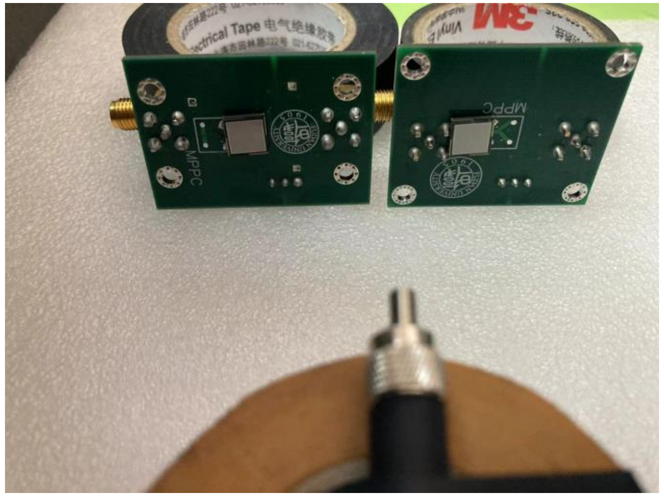
7-series FPGA (Zynq?)

- 2 separate ASIC cards
- #z channels always same; wrap phi channels as needed
- 8 sectors * 15 layers * 2 FW/BW * 2 ASICs = 480 ASICs, ASIC cards
- 240 SCROD

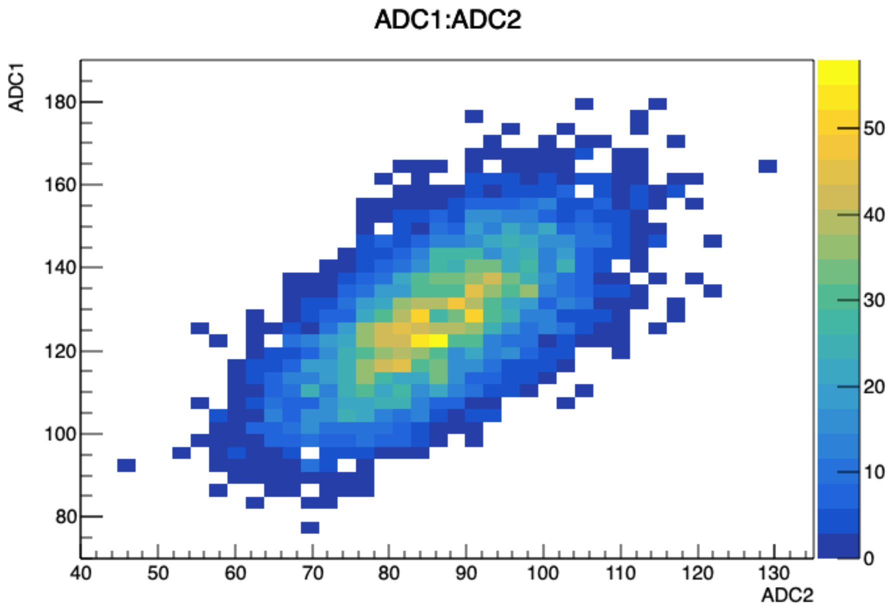
New NDL SiPM with $6mm \times 6mm$

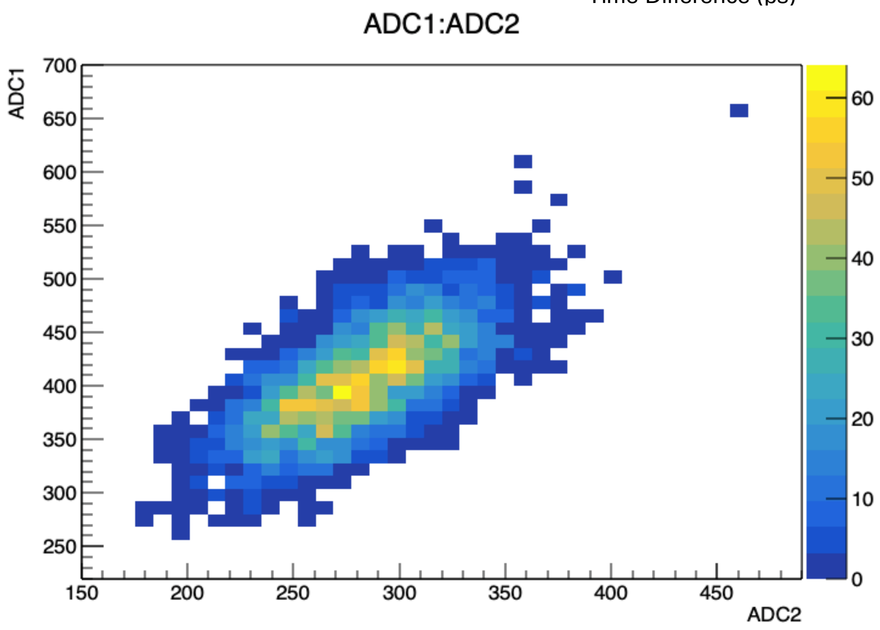






Keep laser constant

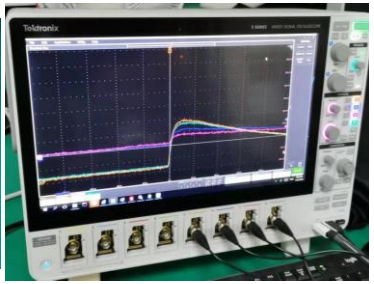




HV/ V	Pedestal	ADC	σ of time difference
28	1.2	140, 90	65
30	2.9	400,270	46

Time resolution = $\sigma/\sqrt{2}$

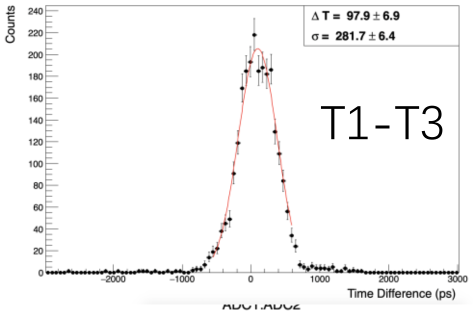
Effect from the velocity of cosmic rays!

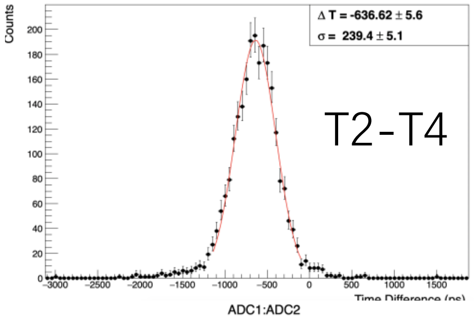


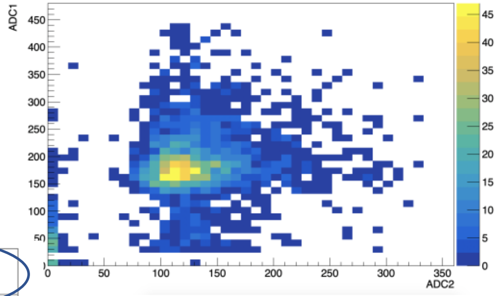
T1, T4

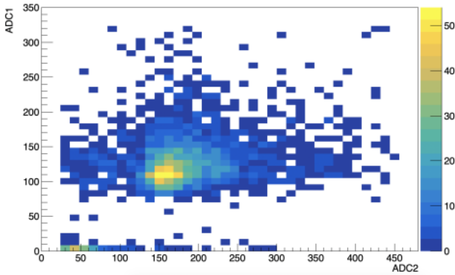
T2 and T3 with distance of $\sim 4cm$
T1 and T4 with distance of $\sim 10cm$

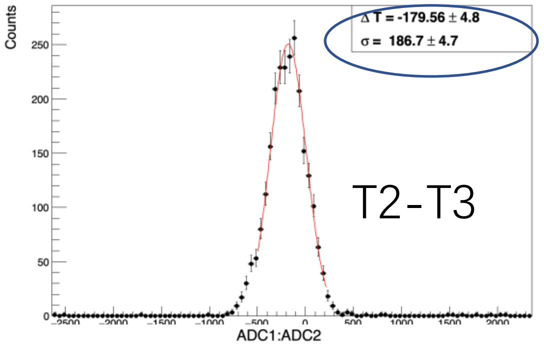
T1 close to T2, T4 close to T3

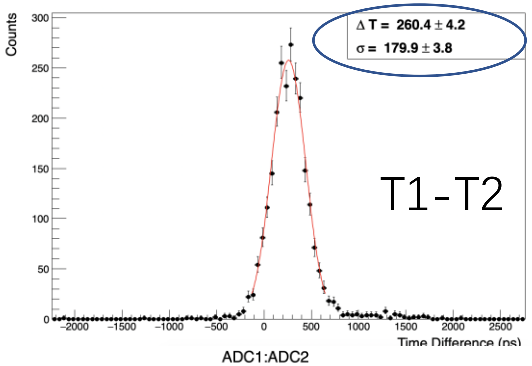


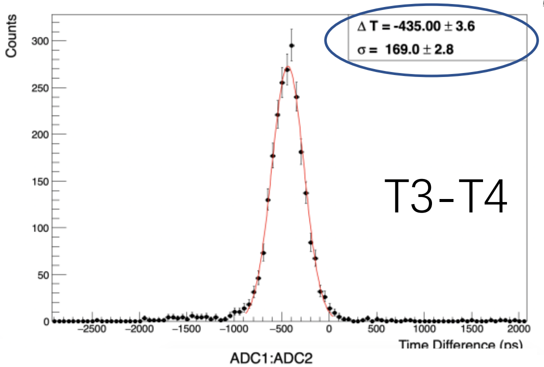


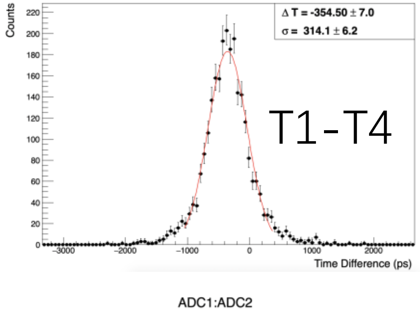


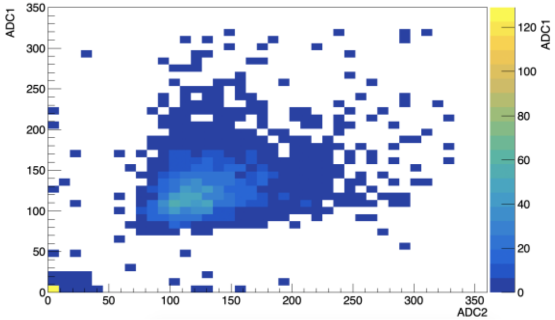


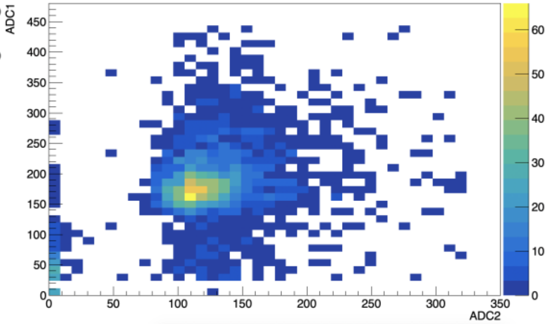


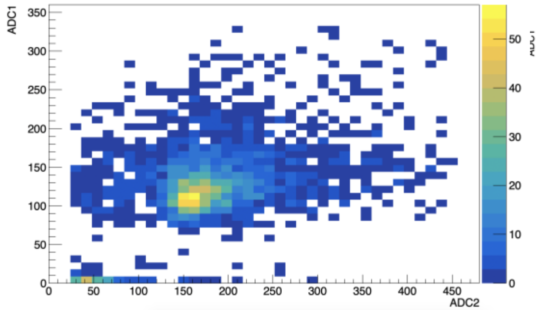


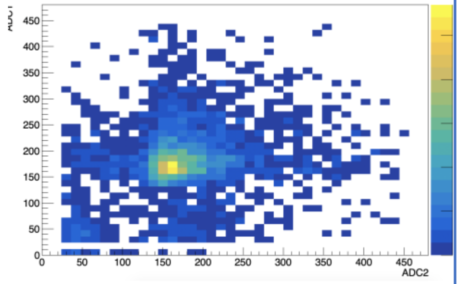












Time resolutions:

T2,T3: $132.0 \pm 3.3ps$

T1,T2: $127.2 \pm 2.7ps$

T3,T4: $119.5 \pm 2.0ps$

T1,T3: $199.2 \pm 4.5ps$

T2,T4: $169.3 \pm 3.6ps$

T1,T4: $222.1 \pm 4.4ps$

- Increase of time resolution is due to the velocity of CR.
- Velocity of CR should be taken into account.