CKM measurements at the Belle II experiment

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On behalf of Belle II Collaboration

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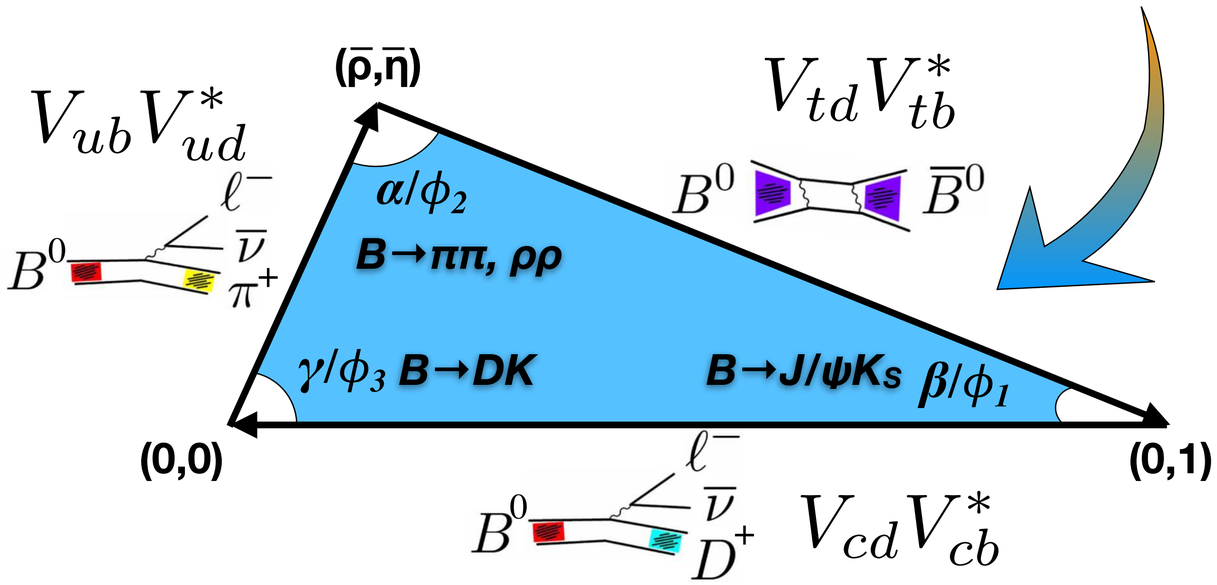
CKM matrix and unitarity triangle (UT)

$$V=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}=\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A^2\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}+O(\lambda^4)$$

Complex phase cause CP violation

$V^\dagger V = 1$ → ***b*** row ***d*** column →

$$\underset{\lambda^3\cdot 1}{V_{ub}^* V_{ud}}+\underset{\lambda^2\cdot\lambda}{V_{cb}^* V_{cd}}+\underset{1\cdot\lambda^3}{V_{tb}^* V_{td}}=0$$



$$\phi_1=\arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\phi_2=\arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

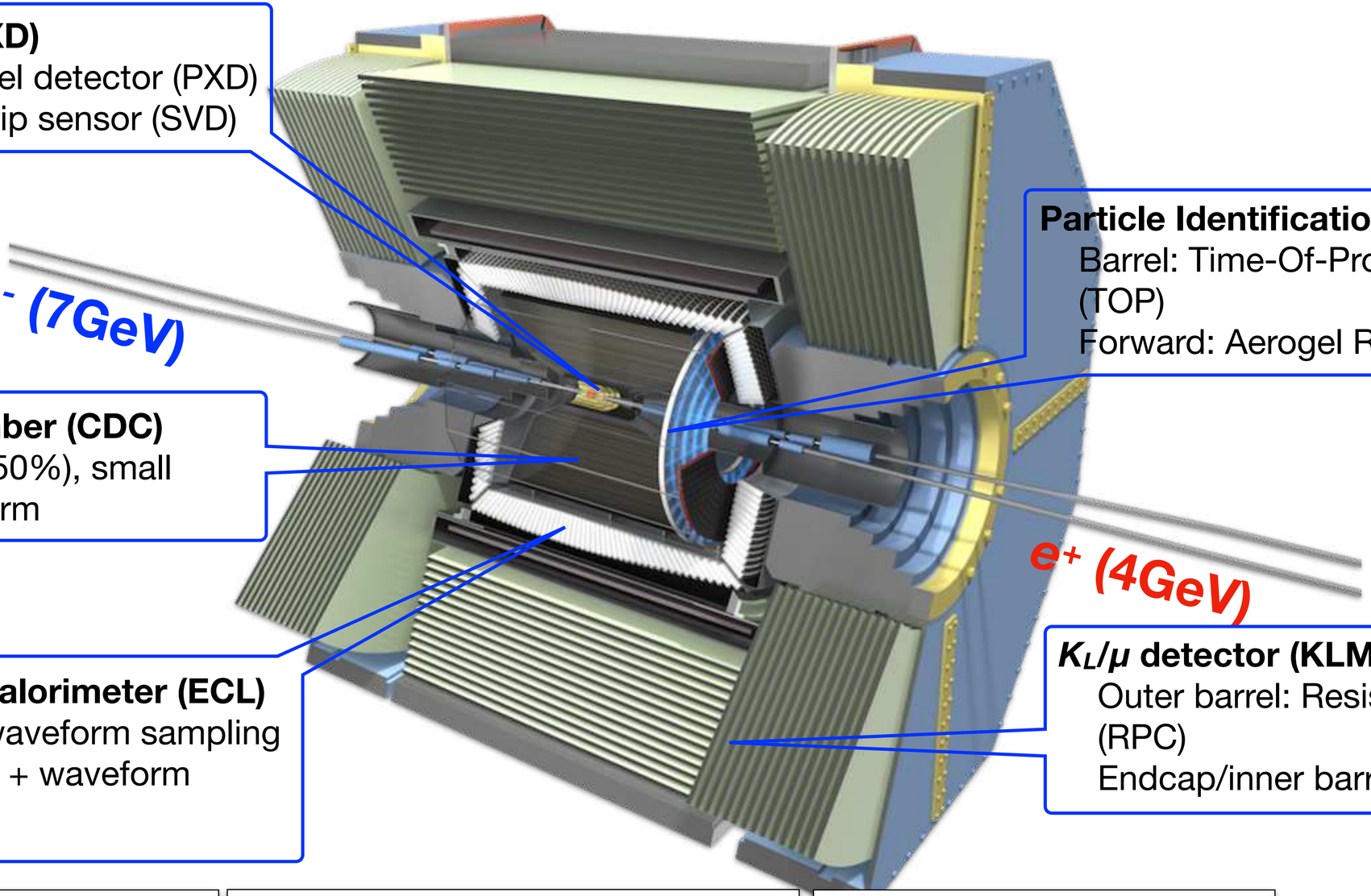
$$\phi_3=\arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- Search for NP with different processes (tree, loop diagrams) by precise measurement of UT
- Comprehensive test (only Belle II)
  - Measure all sides and angles

The Belle II detector

Vertex detector (VXD)
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)

Particle Identification
Barrel: Time-Of-Propagation counters (TOP)
Forward: Aerogel RICH (ARICH)



Central Drift Chamber (CDC)
He (50%), C_2H_6 (50%), small cells, long lever arm

ElectroMagnetic Calorimeter (ECL)
Barrel: CsI(Tl) + waveform sampling
Endcap: pure CsI + waveform sampling

***K_L/μ* detector (KLM)**
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

Level-1 trigger system
CDC+ECL+TOP+KLM
L1 trigger latency 5 μsec

Data acquisition (DAQ) system
Maximum 30 kHz L1 trigger
1MB/event

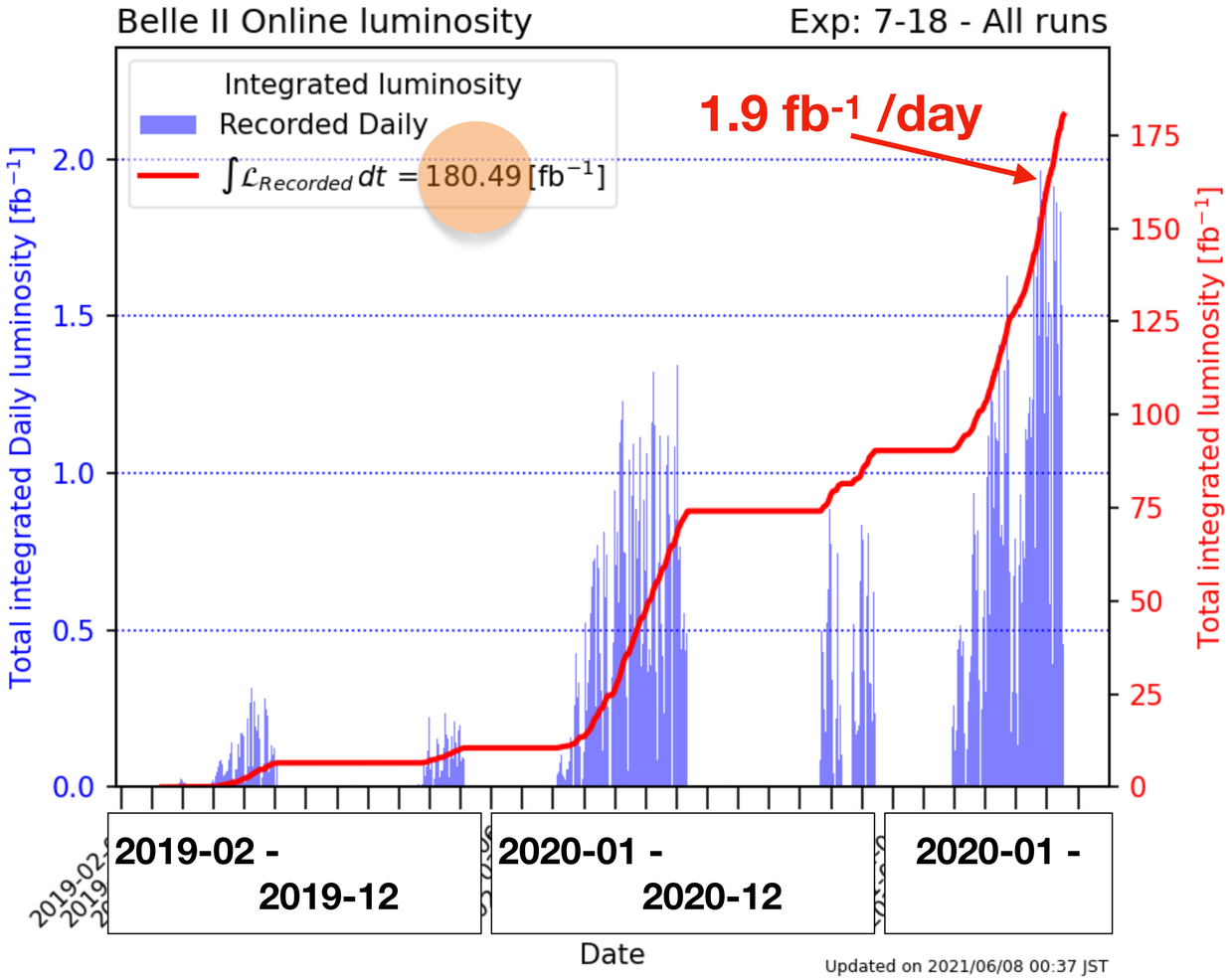
Computing system
GRID
Tens of PB / year

This talk focus on: measurements of $|V_{cb}|$, $|V_{ub}|$ and ϕ_1, ϕ_3

Data-set used for the analyses present in this talk:

- 34.6 fb^{-1} ($|V_{cb}|$, $|V_{ub}|$, ϕ_1)
- 62.8 fb^{-1} (ϕ_3)

Belle II data taking efficiency = 88.8%
Oct. 19 - Dec. 18, 2020



ϕ_1 : details in Radek Zlebcik's talk "Rediscovery of the decays for the CP violation measurements at Belle II" on 10 June

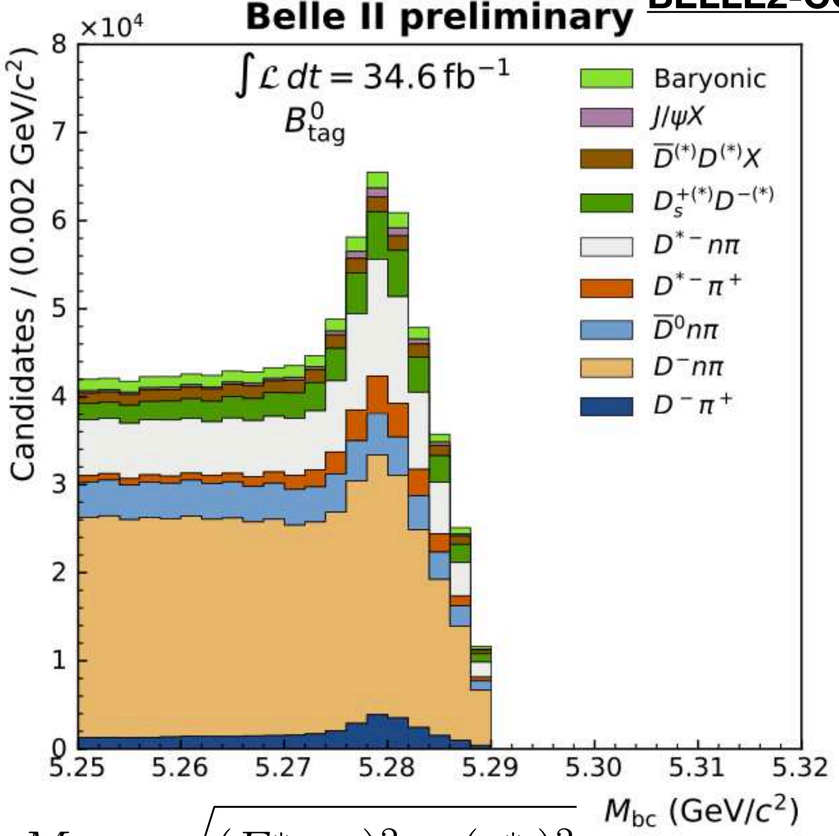
ϕ_2 : Ching-hua Li 's talk "Charmless B decays at Belle II" on 10 June

B decay reconstruction at Belle II

Untag: only reconstruct signal *B* decay
Tag : reconstruct signal *B* decay, also the other side *B*

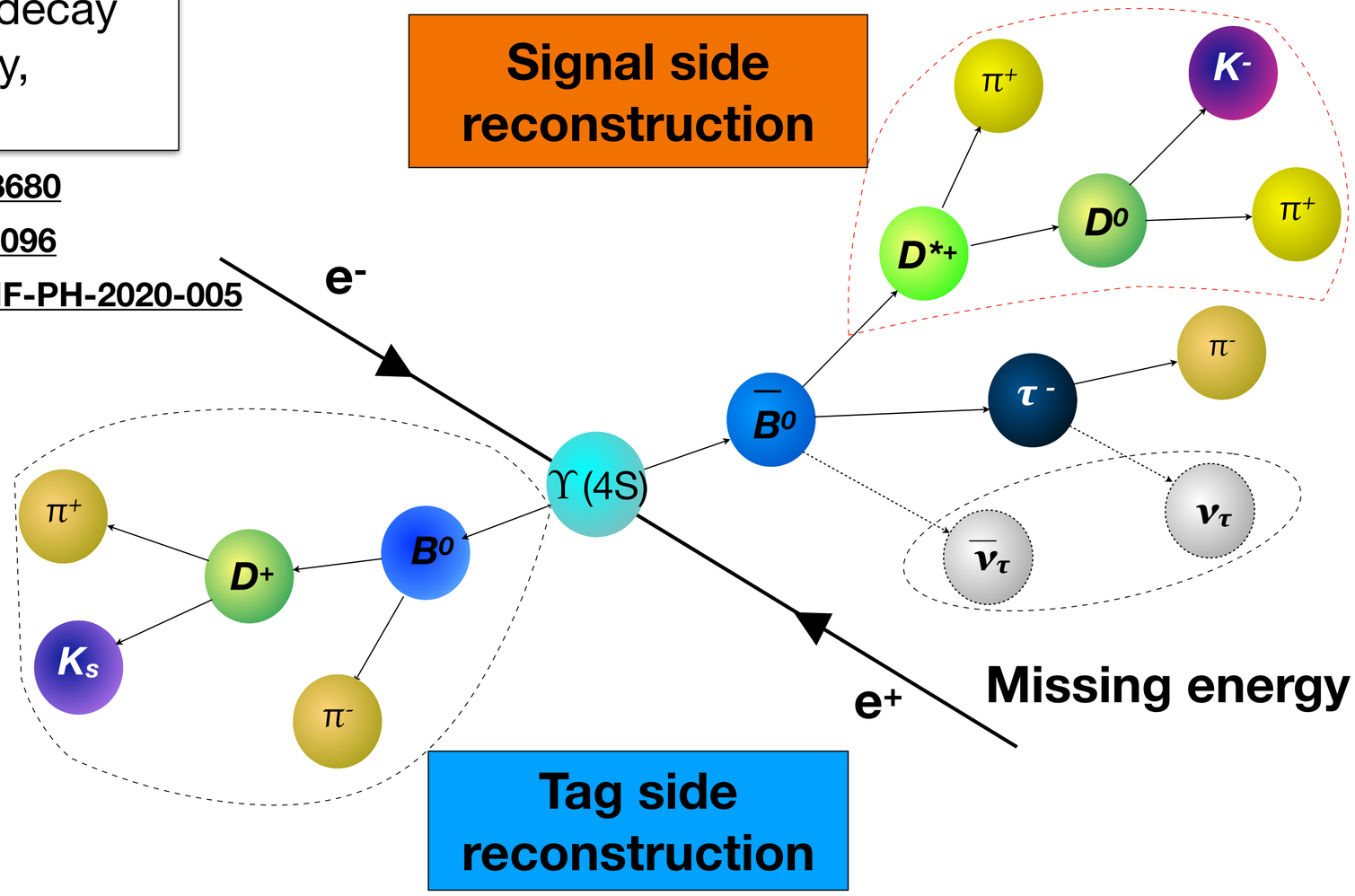
Data $\int \mathcal{L}dt = 34.6 fb^{-1}$

arXiv: 1807.08680
arXiv:2008.06096
BELLE2-CONF-PH-2020-005



$$M_{bc} = \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$

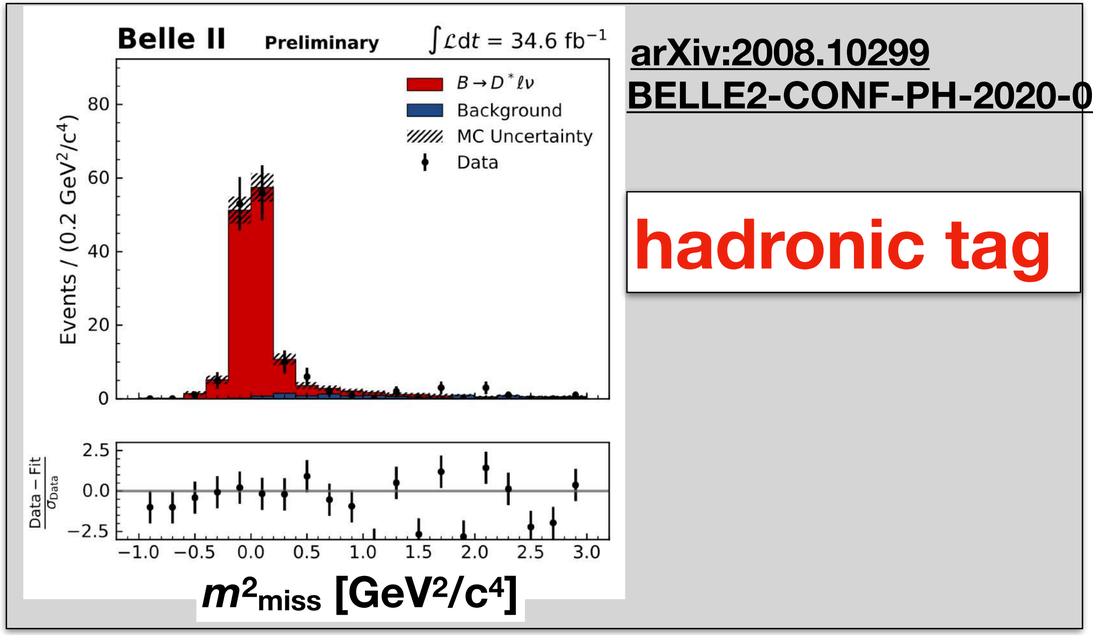
Signal side reconstruction



Tag side reconstruction

Reconstruct ~100 hadronic decay channels, ~10000 decay chains
- ε=0.47% for $B^\pm$ @ purity ~30%
- ε=0.29% for B^0 @ purity ~20%

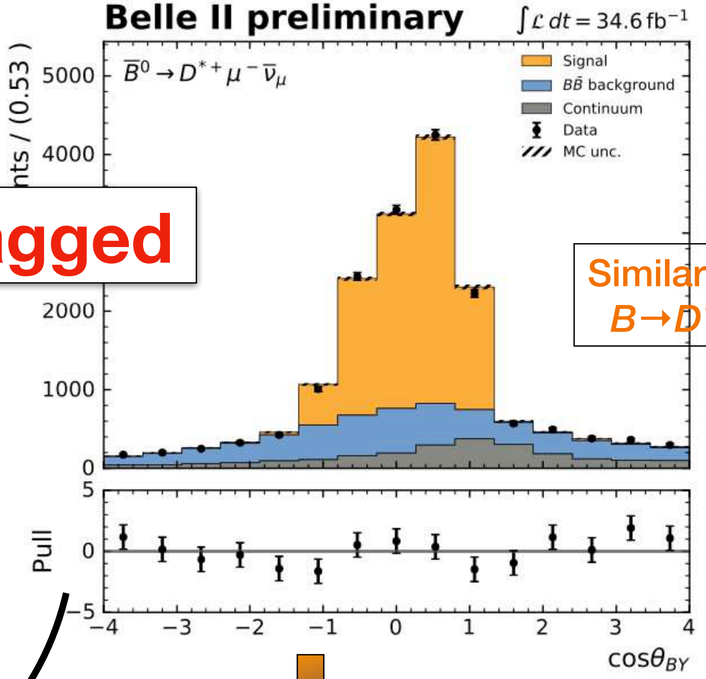
BF($B \to D^* l\nu$) for $|V_{cb}|$



arXiv:2008.10299
BELLE2-CONF-PH-2020-009

hadronic tag

untagged



arXiv:2008.07198
BELLE2-CONF-PH-2020-008

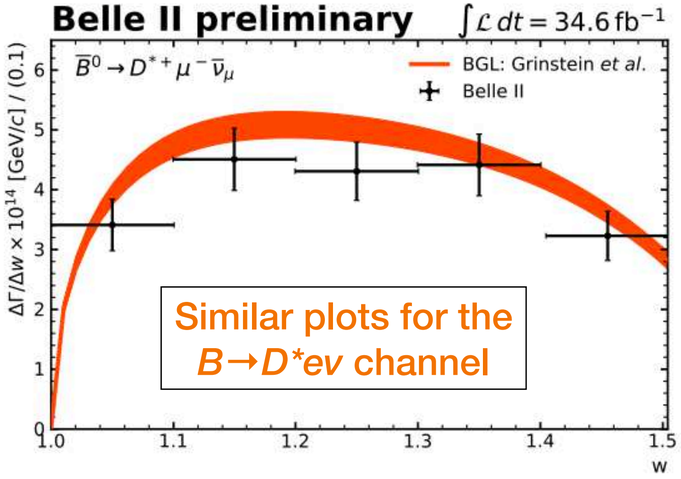
Similar plots for the $B \to D^* e\nu$ channel

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

$Y : D^* l \quad system$

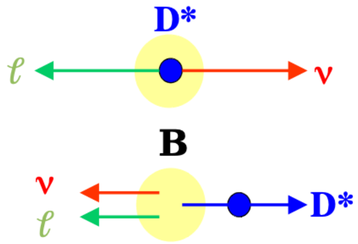
	$\mathcal{B}(\bar{B}^0 \to D^{*+} l^- \nu)$
had. tag	**(4.51 ± 0.41(stat) ± 0.27(sys) ± 0.45(π_s))%**
untag	**(4.60 ± 0.05(stat) ± 0.17(sys) ± 0.45(π_s))%**
PDG	**(5.05 ± 0.14)%**

Unfolded w spectrum to compare with BGL parameterization



Similar plots for the $B \to D^* e\nu$ channel

$$w = \frac{m_B^2 + m_{D^{*+}}^2 - q^2}{2 m_B m_{D^{*+}}}$$



$$\frac{d\Gamma}{d\omega} \propto |Vcb|^2 |\mathcal{F}(\omega)|^2$$

PLAN:
Form factor determination rely heavily on w = 1 (zero recoil)

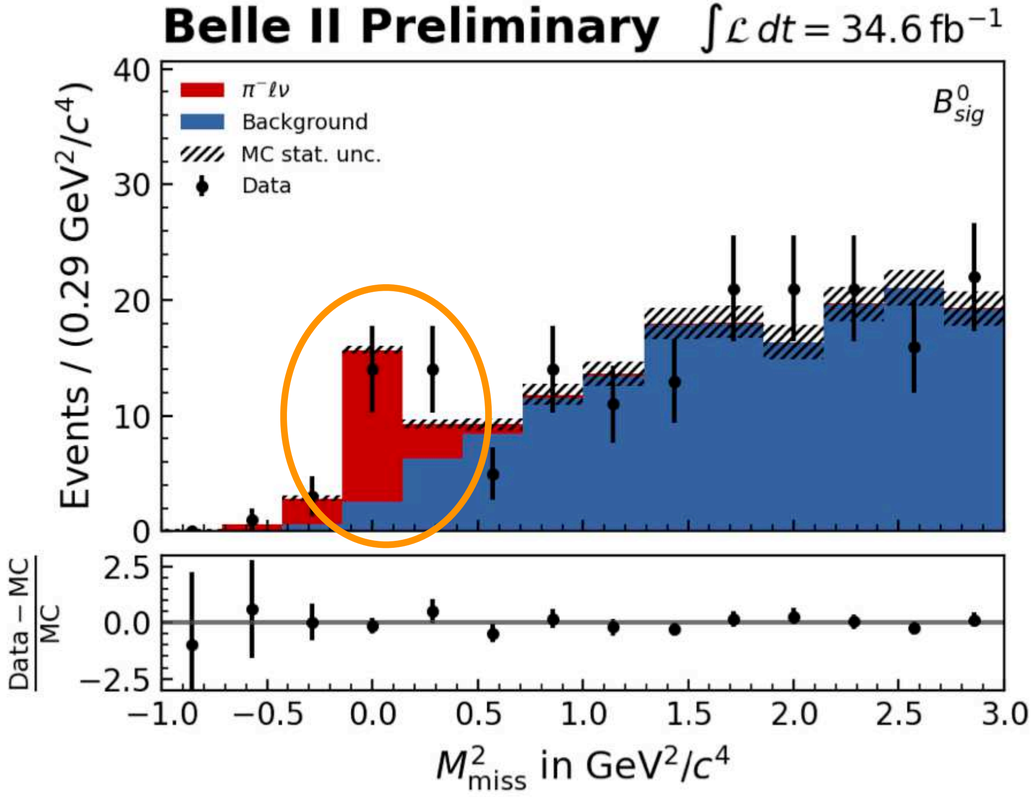
BF($B^0 \to \pi l \nu$) and BF($B \to X_u l \nu$) for $|V_{ub}|$

$|V_{ub}|$ determination from exclusive and inclusive measurements differ by ~2σ

Measurement of $\mathcal{B}(\bar{B}^0 \to \pi^- l \nu)$ based on hadronic tag

arXiv:2008.08819

BELLE2-CONF-PH-2020-007



$\mathcal{B}(\bar{B}^0 \to \pi^- l^+ \nu) = (\ 1.58 \pm 0.43(\text{stat}) \pm 0.07\ (\text{sys})\ ) \times 10^{-4}$

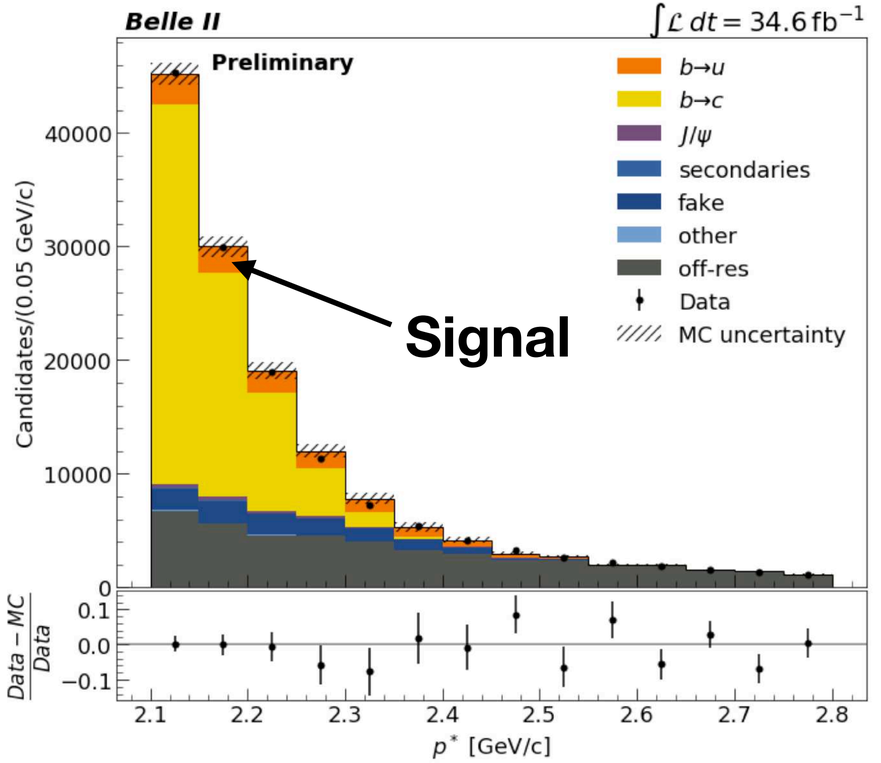
$\mathcal{B}(\bar{B}^0 \to \pi^- l^+ \nu) = (\ 1.50 \pm 0.06) \times 10^{-4}$ (PDG) **Agreement**

Next target: q^2 distribution for $|V_{ub}|$ determination

Untagged Inclusive $B \to X_u l \nu$ measurement

- lepton momentum endpoint
- less $B \to X_c l \nu$ (dominant background)

BELLE2-NOTE-PL-2020-026

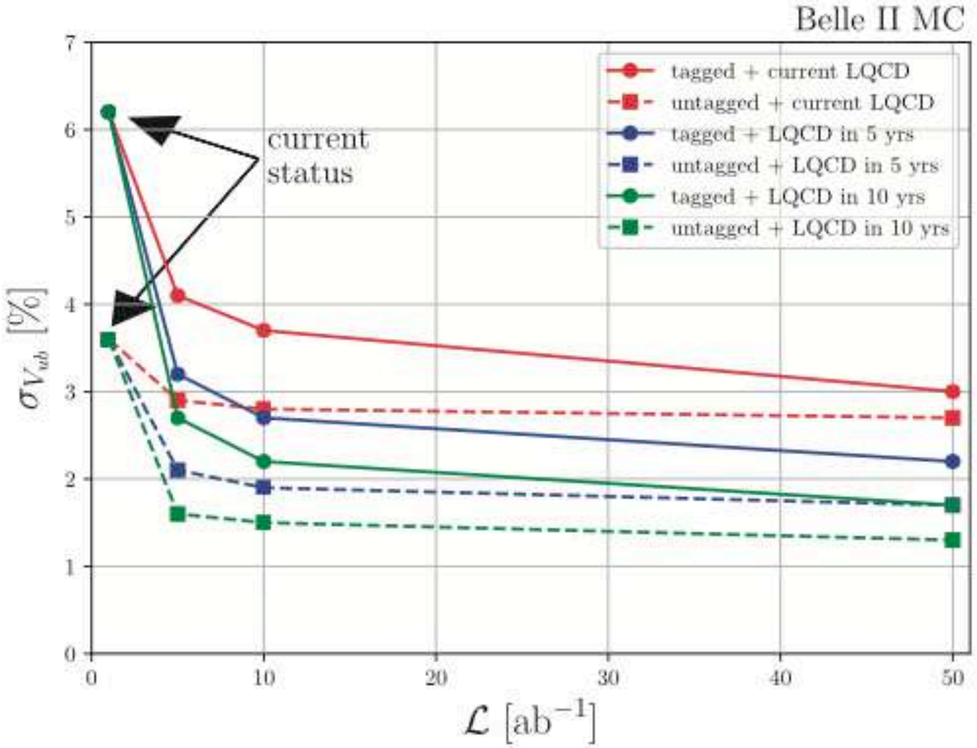


Capable of measuring $|V_{ub}|$ with more data

Prospects of $|V_{ub}|$ and $|V_{cb}|$

Side	Observable	Dominant uncertainties
$\|V_{td}\|$	Δm_d: $B\bar{B}$ mixing frequency	Lattice QCD ($\|V_{td}\|$ now is mainly limited by lattice QCD)
$\|V_{cb}\|$	$Br(b\to c l\nu)$	Exclusive: lattice QCD Inclusive: experiment vs. phenomenology
$\|V_{ub}\|$	$Br(b\to u l\nu)$	

The Belle II Physics Book, PTEP 2019, 123C01



Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\|V_{cb}\|$ incl.	$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$	1.2%	–
$\|V_{cb}\|$ excl.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\text{ex.}} \pm 1.4\%_{\text{th.}})$	1.8%	1.4%
$\|V_{ub}\|$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$	3.4%	3.0%
$\|V_{ub}\|$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\text{ex.}} \pm 3.0\%_{\text{th.}})$	2.4%	1.2%

Time dependent CPV - Flavor tagging

TDCPV measurement:
- Precise measurement of Δt
- B flavor tagger

arXiv: 2008.02707

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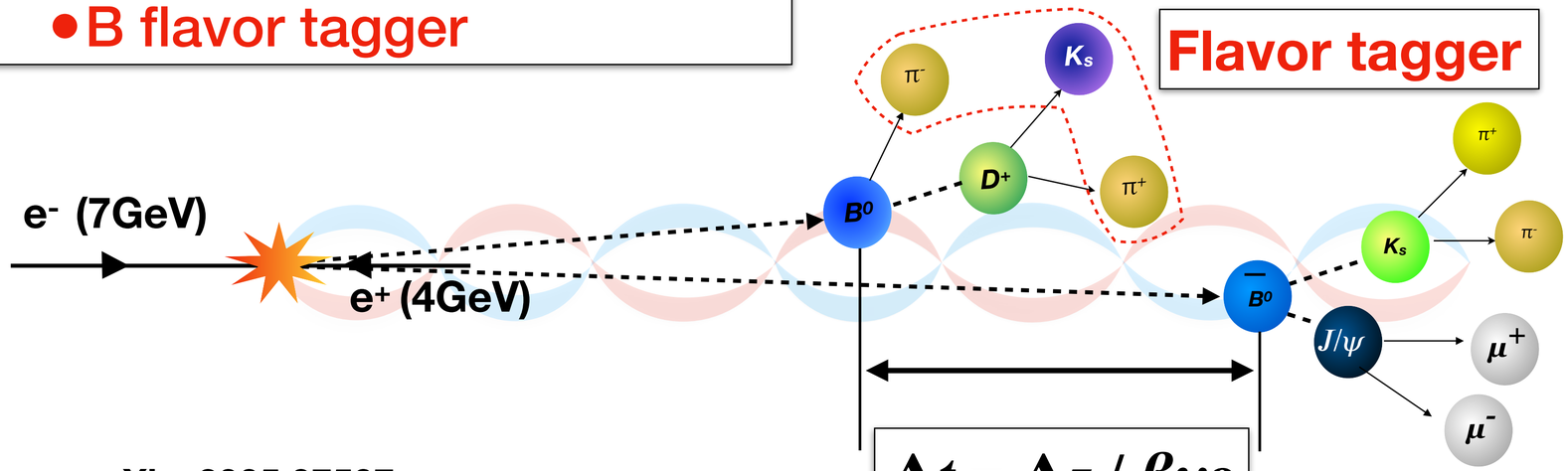
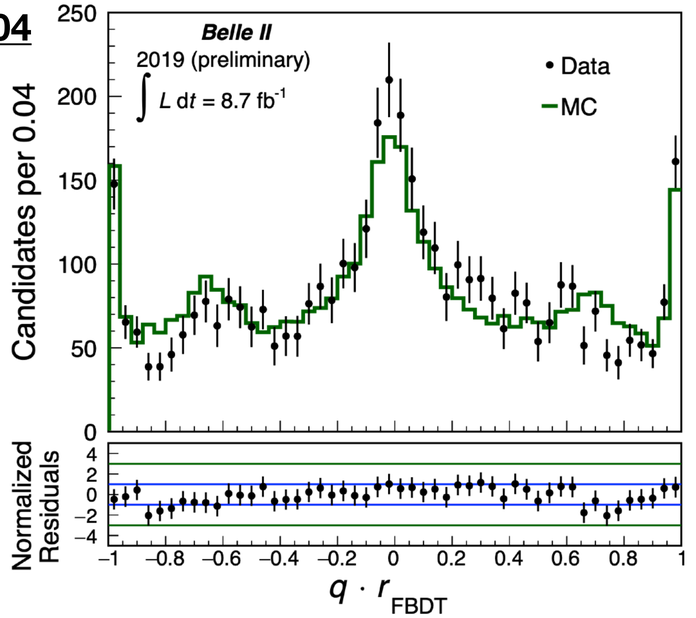


Flavor tagger

$\Delta t = \Delta z / \beta\gamma c$

$\Delta z \sim 130$ um

Flavor non-specific CP eigenstate



$\bar{B}$ ⟷ B

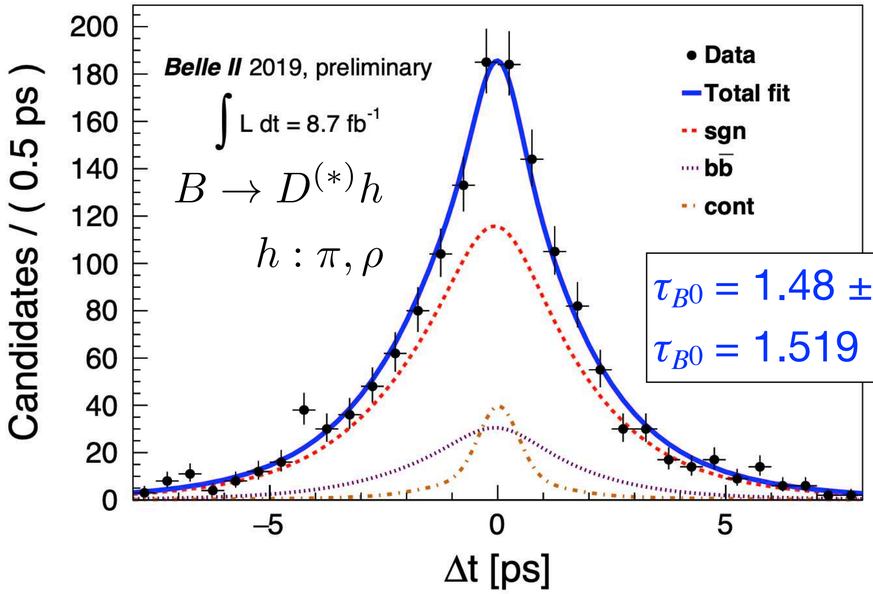
dilution factor r_{FBDT} = 1-2w

w: wrong tagging fraction

$$\varepsilon_{eff} = \sum_i \varepsilon_i \cdot (1 - 2w_i)^2$$

Effective flavor tagging efficiency:
- Belle II : (33.8 ± 3.9)%
- Belle : (30.1 ± 0.4)%
- Belle II MC : ~37%

arXiv: 2005.07507



τ_{B0} = 1.48 ± 0.28 ± 0.06 ps

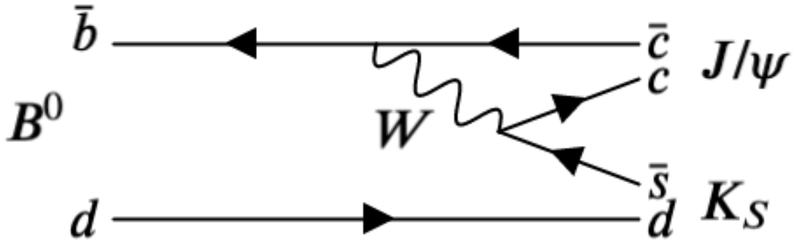
τ_{B0} = 1.519 ± 0.004 ps (PDG)

Details in Radek Zlebcik's "talk" on 10 June

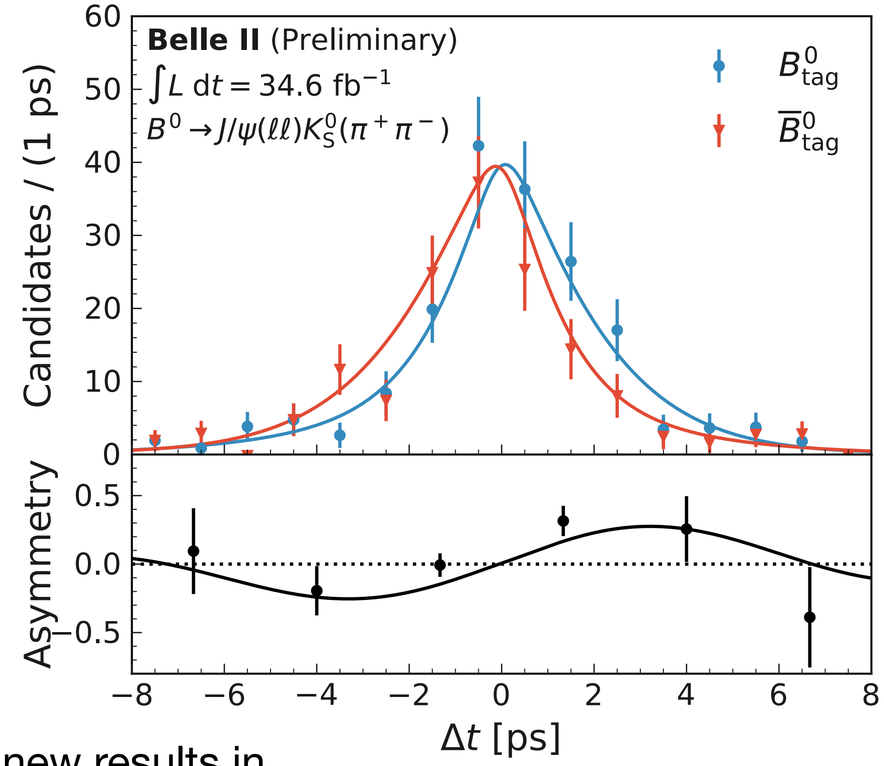
Measurement of sin(2ϕ_1)

- ***b→c*** **: tree diagram dominated golden modes *B^0→J/ψK^0*, *B^0→ψ(2S)K^0*…**
- **Theoretically and experimentally precise channel**

$$P(\Delta t, q) = \frac{e^{-|\Delta t|\tau_{B^0}}}{4\tau_{B^0}}(1 + (1-2\omega)q[S_f sin(\Delta m \Delta t) + A_f cos(\Delta m \Delta t)])$$



S_f : indirect (time dependent) CPV parameter
A_f : direct CP violating asymmetry assumed zero



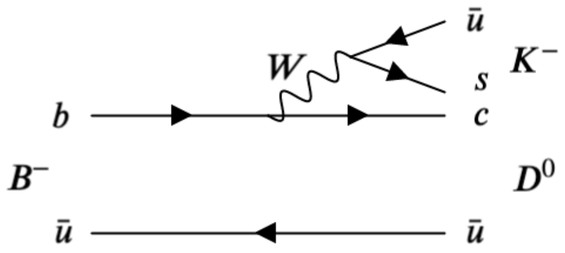
BELLE2-NOTE-PL-2020-011

$\sin(2\phi_1) \approx S_f = 0.55 \pm 0.21$ (stat.) ± 0.04 (syst.)
$\sin(2\phi_1) = 0.699 \pm 0.017$ (world average)

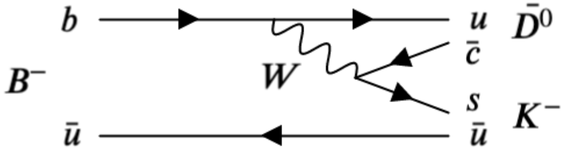
Precision aimed at Belle II for sin(2ϕ_1):
reduce uncertainty by factor ~5 to reach to 5%

ϕ_1 : details with more new results in Radek Zlebcik's "talk" on 10 June

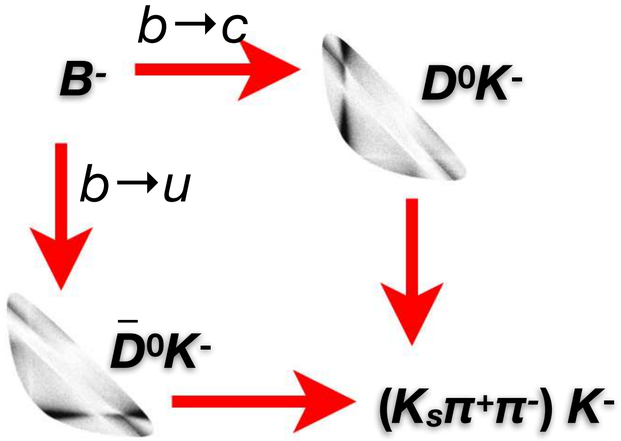
ϕ_3 measurement



Favored



Color suppressed



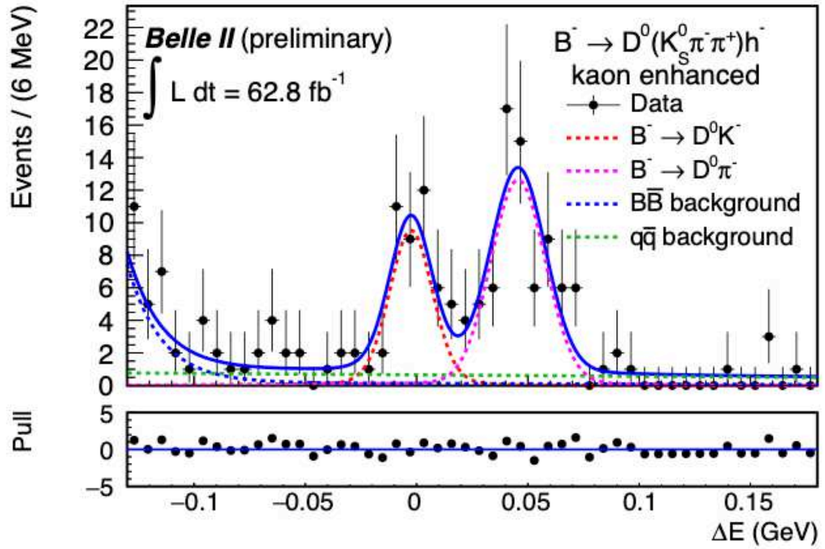
- **Interference between *b*→*c* and *b*→*u* (tree level)**

$$\frac{A^{suppr.}(B^- \to \bar{D}_0 K^-)}{A^{favor.}(B^- \to D_0 K^-)} = r_B e^{i(\delta_B - \phi_3)}$$

r_B : ratio of amplitude

δ_B : strong phase difference

arxiv: 2104.03628



- Model-independent binned Dalitz plot approach
- Rely on continuum suppression tool and particle identification technique at Belle II
- Different systematics w.r.t. the LHCb results

$$R^{(*)0} = \frac{\Gamma(B^- \to D^{(*)0} K^-)}{\Gamma(B^- \to D^{(*)0} \pi^-)}$$

$$R^{(*)+} = \frac{\Gamma(\bar{B}^0 \to D^{(*)+} K^-)}{\Gamma(\bar{B}^0 \to D^{(*)+} \pi^-)}$$

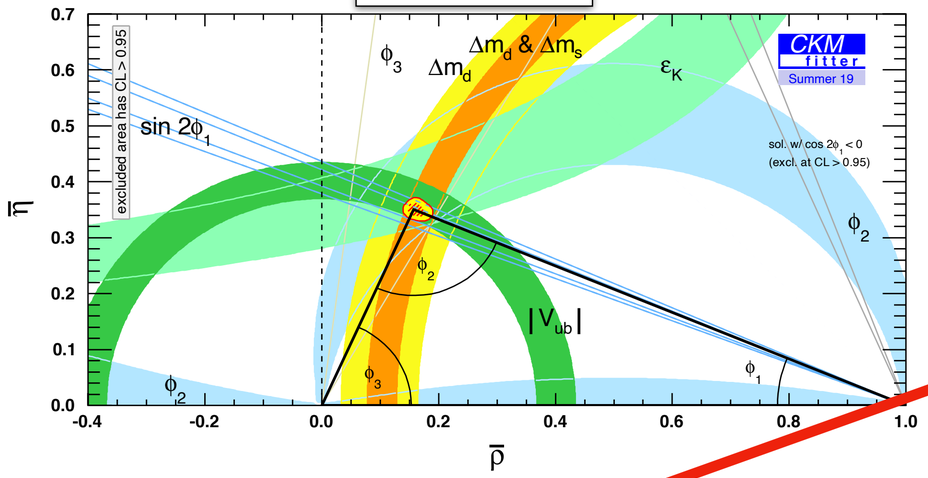
	$B^- \to D^0(K^-\pi^+)h^-$	$B^- \to D^0(K^0_S\pi^+\pi^-)h^-$	$\bar{B}^0 \to D^+h^-$
Belle II $R^{+/0}$ $(\times 10^{-2})$	$7.66 \pm 0.55\ ^{+0.11}_{-0.08}$	$6.32 \pm 0.81\ ^{+0.09}_{-0.11}$	$9.22 \pm 0.58 \pm 0.09$
LHCb $R^{+/0}$ $(\times 10^{-2})$	$7.77 \pm 0.04 \pm 0.07$	$7.77 \pm 0.04 \pm 0.07$	$8.22 \pm 0.11 \pm 0.25$

The Belle II Physics Book, PTEP 2019, 123C01

Foreseen precision of ϕ_3 is expected to be 1.6° with 50 ab^{-1} dataset

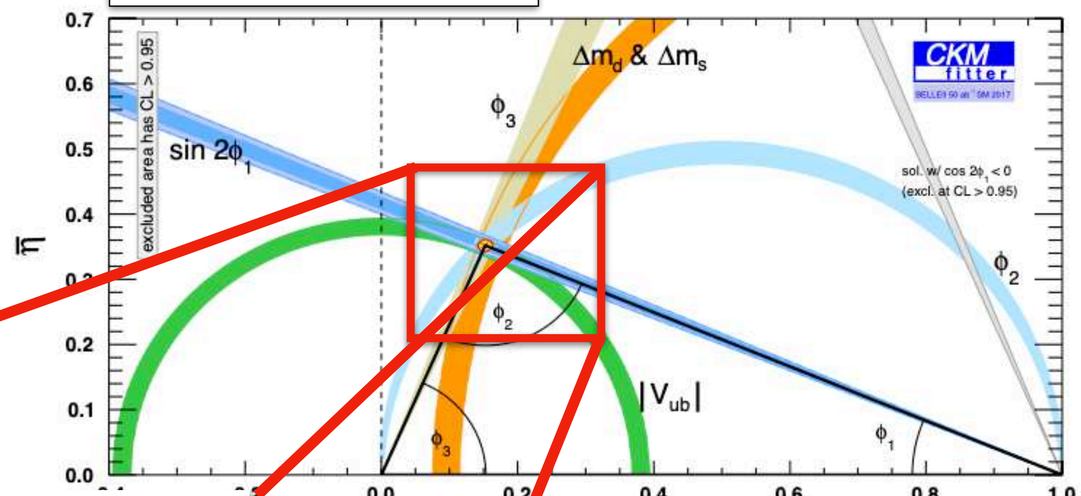
Unitarity Triangle fit extrapolation at Belle II

Current



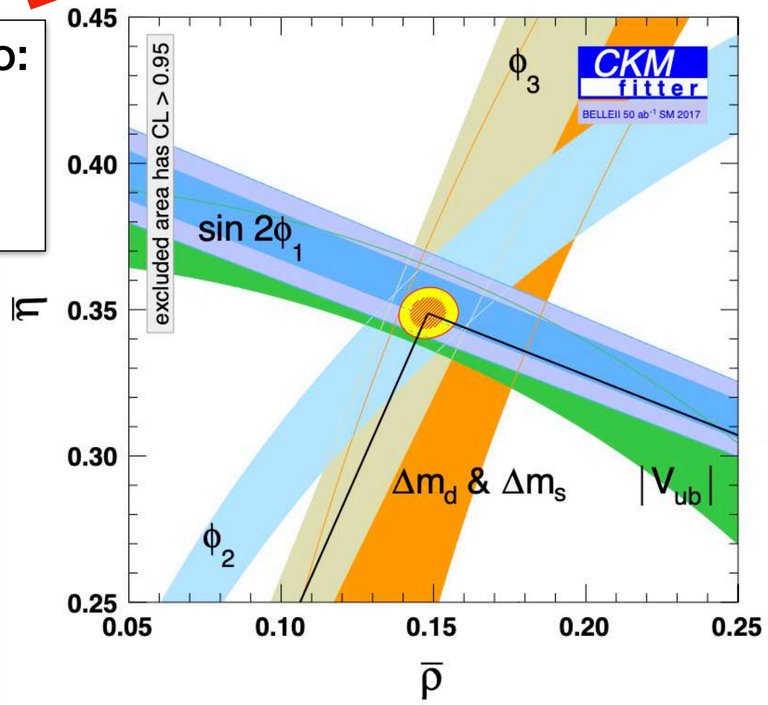
Belle II 50 ab^{-1}

The Belle II Physics Book, PTEP 2019, 123C01



Standard model (SM) scenario: the central values are chosen such that they satisfy the SM (closed UT)

Zoom



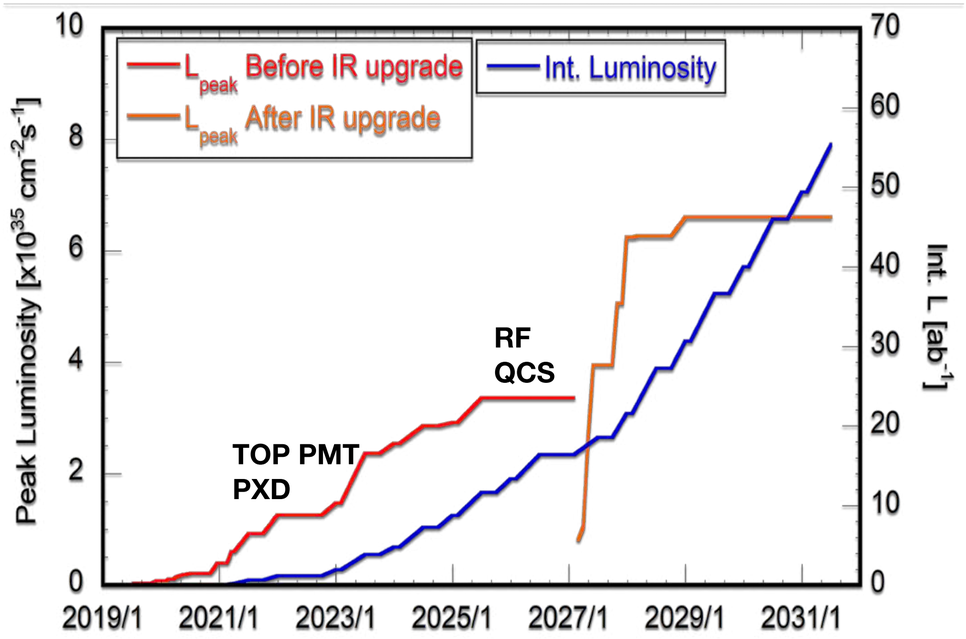
- Tensions existed on $|V_{ub}|$ and ϕ_1
  - UT can not close if keeping the central value for 50 ab^{-1}
- Differences between UT determined by tree ($|V_{ub}|$, ϕ_3) and loop (ϕ_1, ϕ_2) can be discriminated with 50 ab^{-1} data-set

Summary and prospects

- Super B-factory offers good probe for testing SM and searching for NP at luminosity frontier.

- Belle II will play a key role for CKM measurements.
  - First BF measurements of semileptonic B decays with had. tagged/untagged techniques for $|V_{cb}|$ and $|V_{ub}|$.
  - First sin2ϕ_1 result has agreement with W.A, aim 5% precision at Belle II.
  - Decay rate ratio of $B \to DK/B \to D\pi$ was performed for determination of ϕ_3.

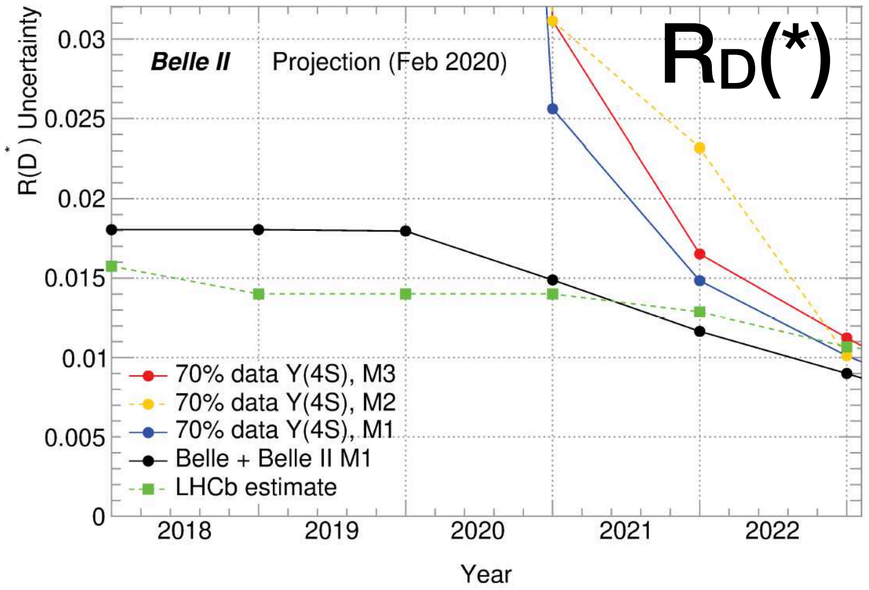
- Looking forward for more interesting results from Belle II.

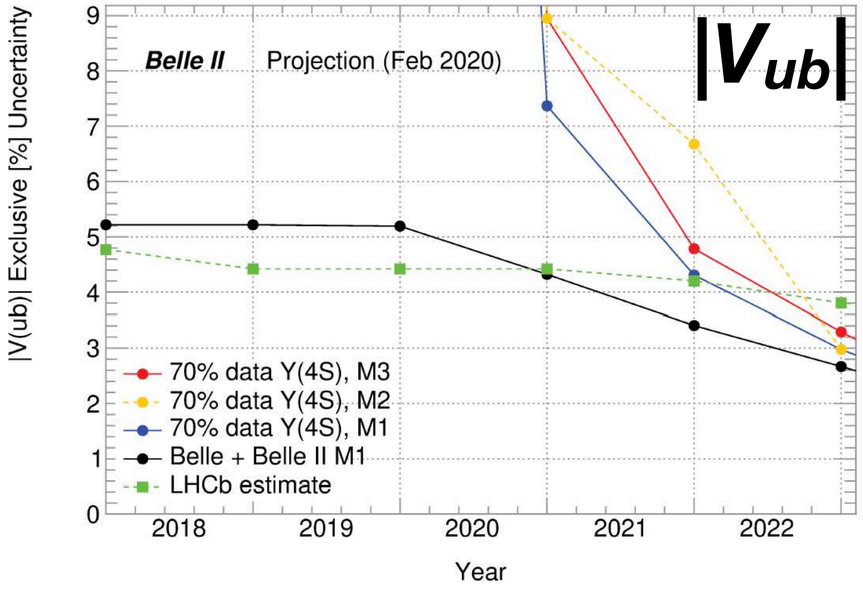


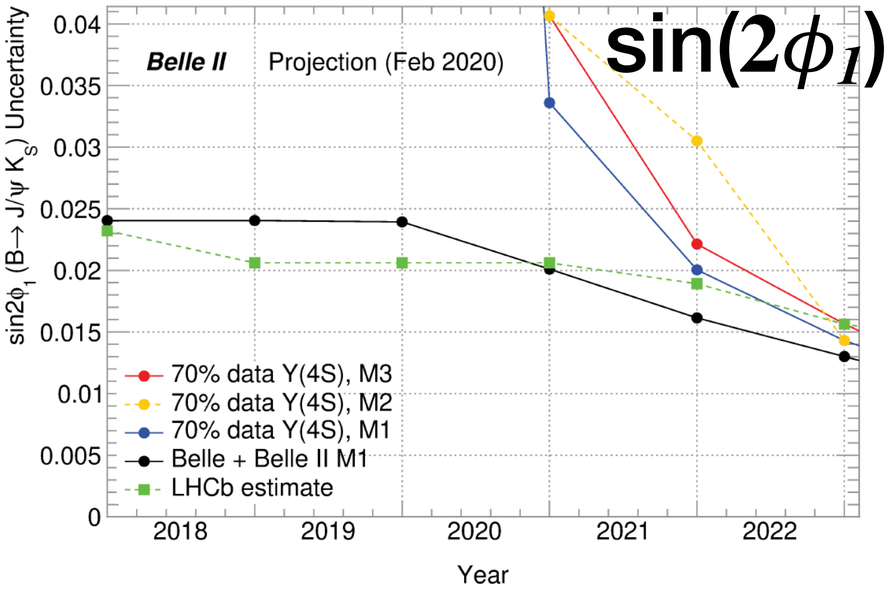
Stay tuned !

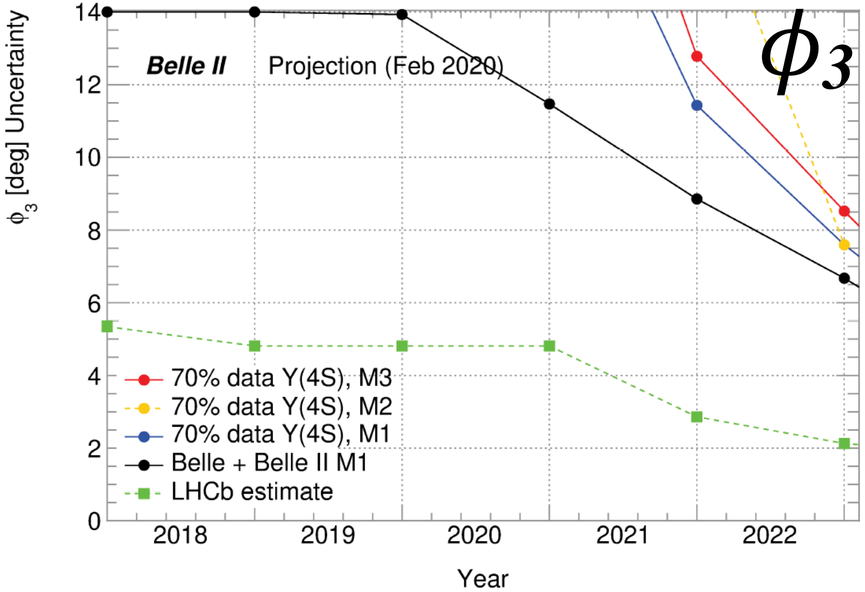
Backup

Belle II - LHCb comparison









$B \to X_c l \nu$ for $|V_{cb}|$

Hadronic mass moments of inclusive $B \to X_c l \nu$ with hadronic tag

arXiv:2009.04493

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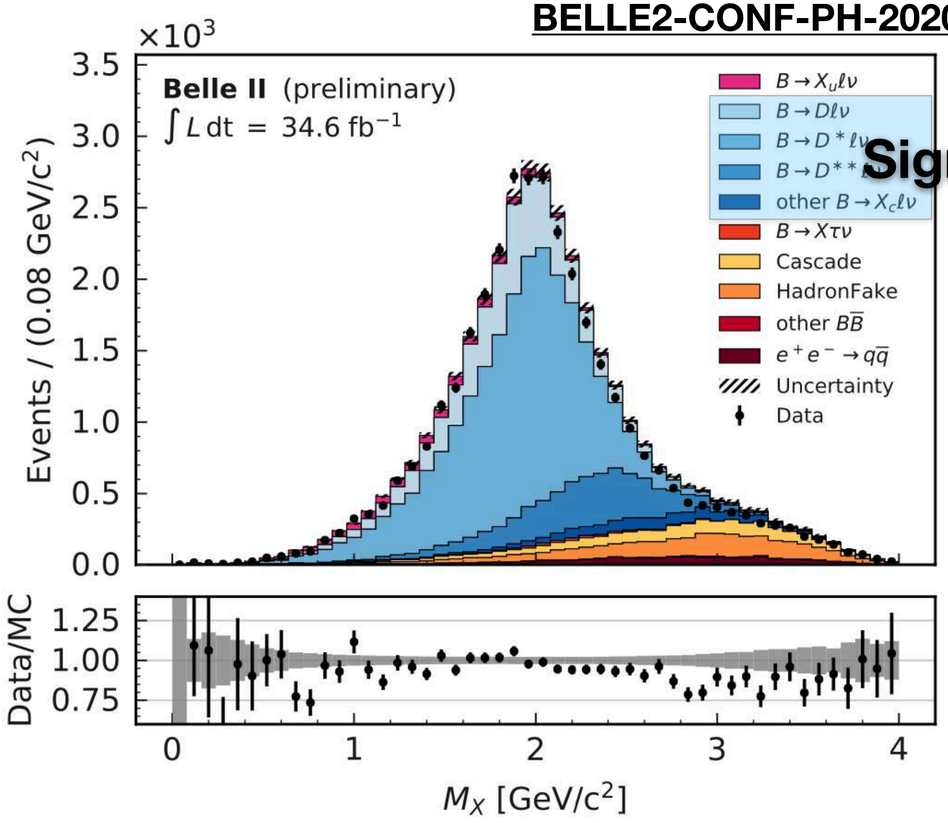
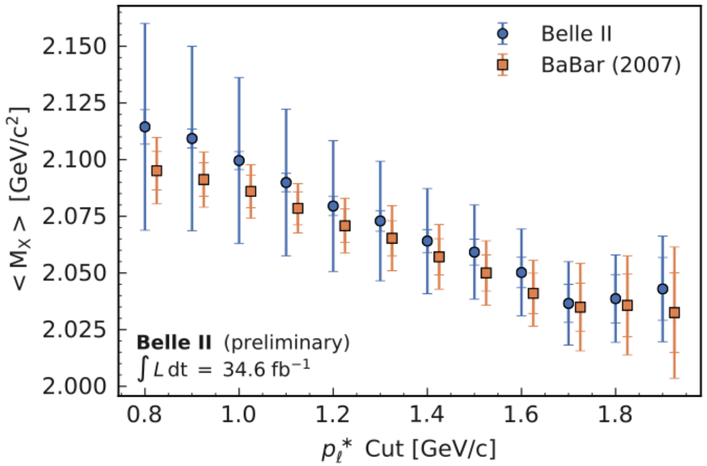
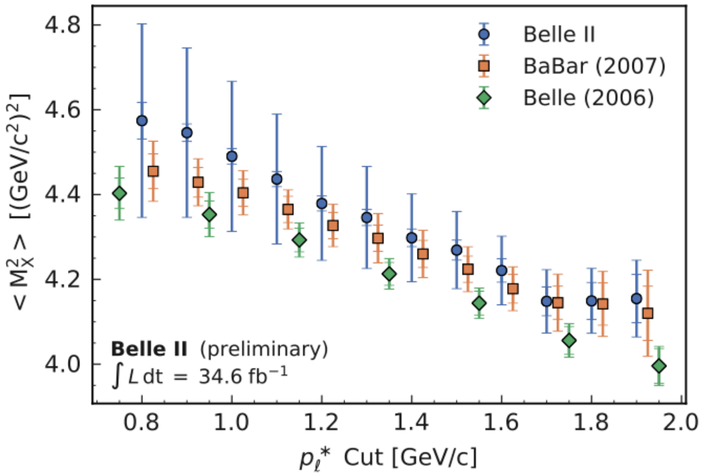
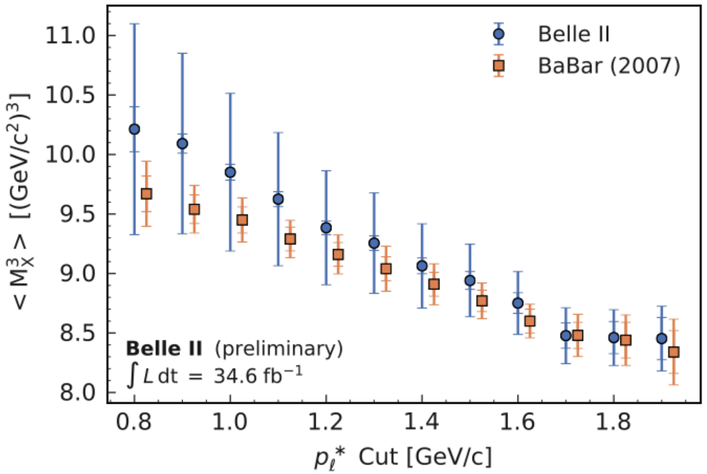
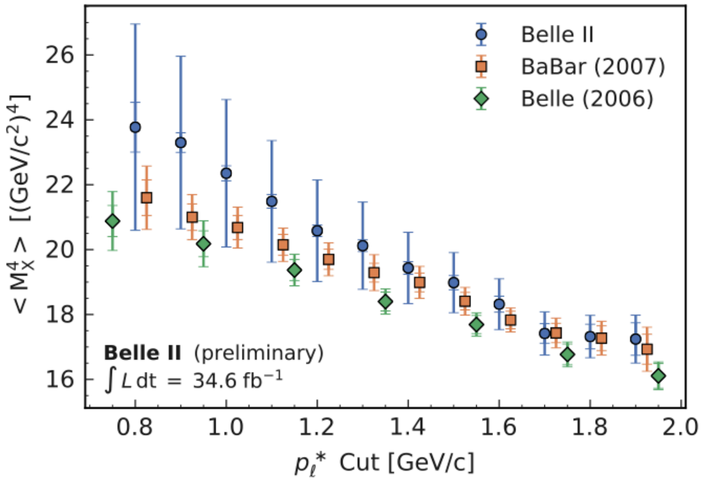


Signal









Moments dependence on the lepton momentum cut

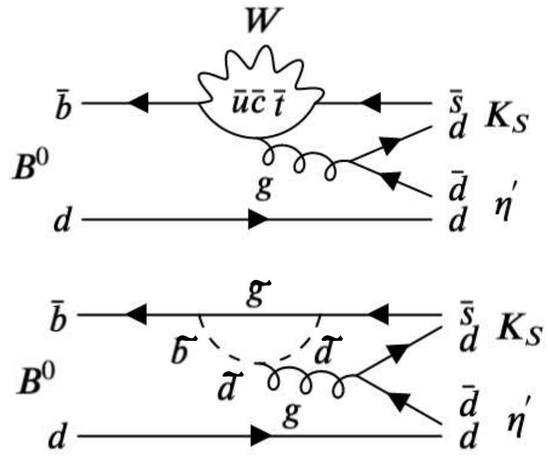
- **$|V_{cb}|$ calculated based on the parameters extracted from p^*l vs $\langle M^n_X \rangle$ distributions**
- **A new method proposed in JHEP02 (2019)177 to extract $|V_{cb}|$ from q^2 vs $\langle q^n_X \rangle$ distributions**
  - **Targeting a publication this summer**

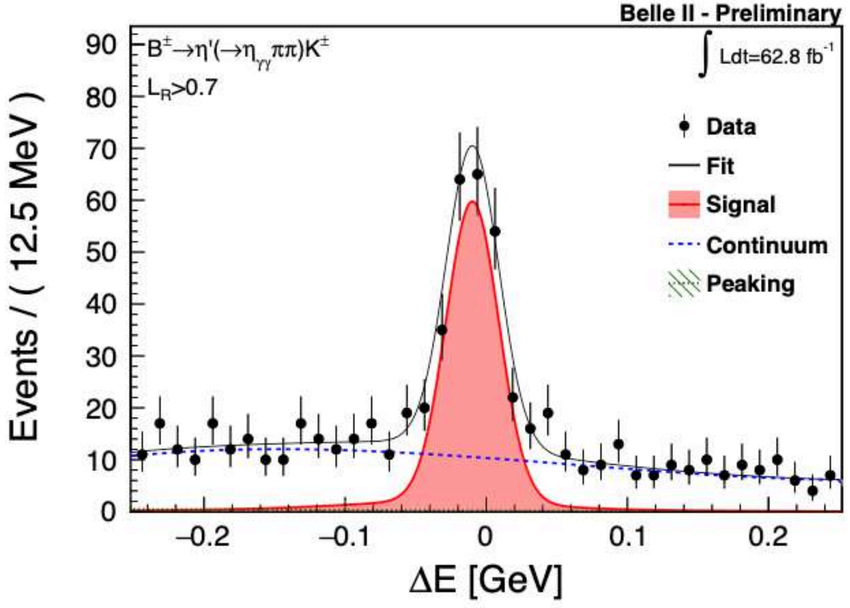
sin(2ϕ_1) with QCD penguin

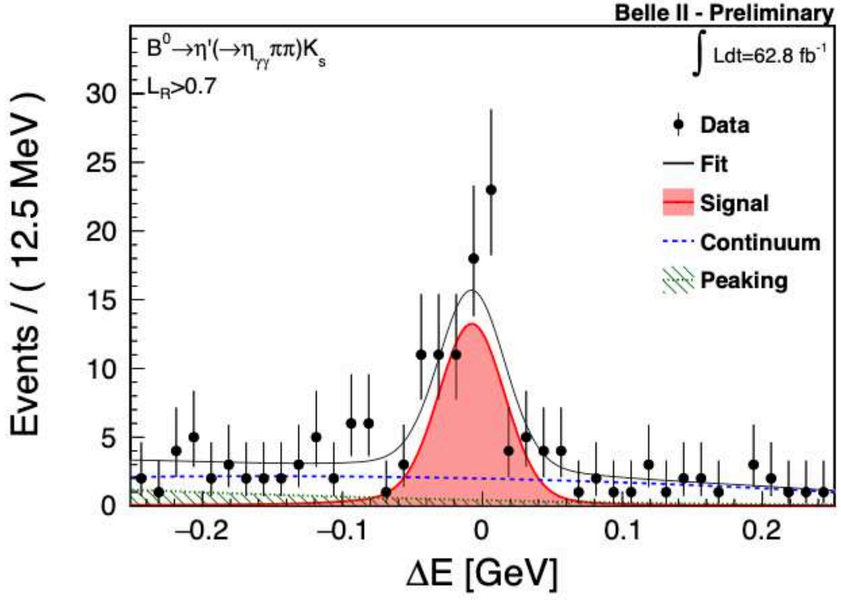
- **b→qqs : QCD penguin dominated contribution, sensitive to New Physics**
  - **Golden mode, e.g. *B→η'K* decays**
- **sin(2ϕ_1) measured by b→s and b→c processes used to have ~3.8σ tension, however now it was reduced to rather small**
- **Only rediscovery and BR measurement (CP measurement not done yet)**

B*$^{\pm}$→*η'K*$^{\pm}$ with *η'*→*ηπ*$^+$*π*$^-$ or *η'*→*ργ

$B^0 \to \eta' K_S$ with $\eta' \to \eta\pi^+\pi^-$ or $\eta' \to \rho\gamma$

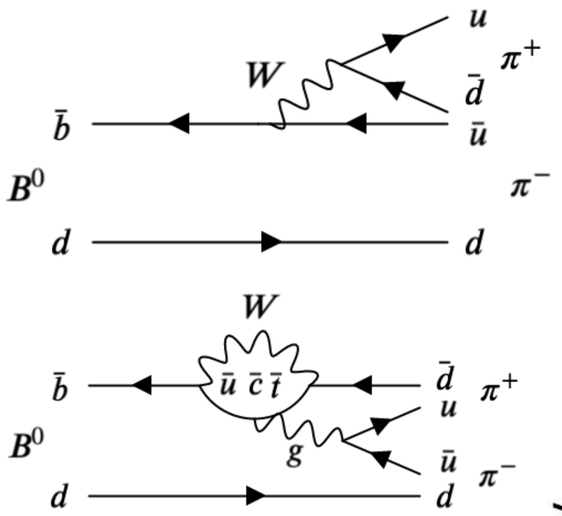






Channel	This analisis $\mathcal{B}$ ($\times 10^6$)	World average $\mathcal{B}$ ($\times 10^6$)
$B^{\pm} \to \eta' K$	$68.2\ ^{+3.6}_{-3.5}(\text{stat}) \pm 3.4(\text{syst})$	70.6 ± 2.5
$B^0 \to \eta' K^0$	$63.7\ ^{+5.9}_{-5.5}(\text{stat}) \pm 5.8(\text{syst})$	66 ± 4

ϕ_2 measurement ($B \to \pi\pi$)



Diagrams	$B^\pm \to \pi^\pm\pi^0$	$B^0 \to \pi^+\pi^-$	$B^0 \to \pi^0\pi^0$
Tree	✔	✔	
Color Suppress	✔		✔
Penguin		✔	✔

penguin pollution

Constraint for ϕ_2

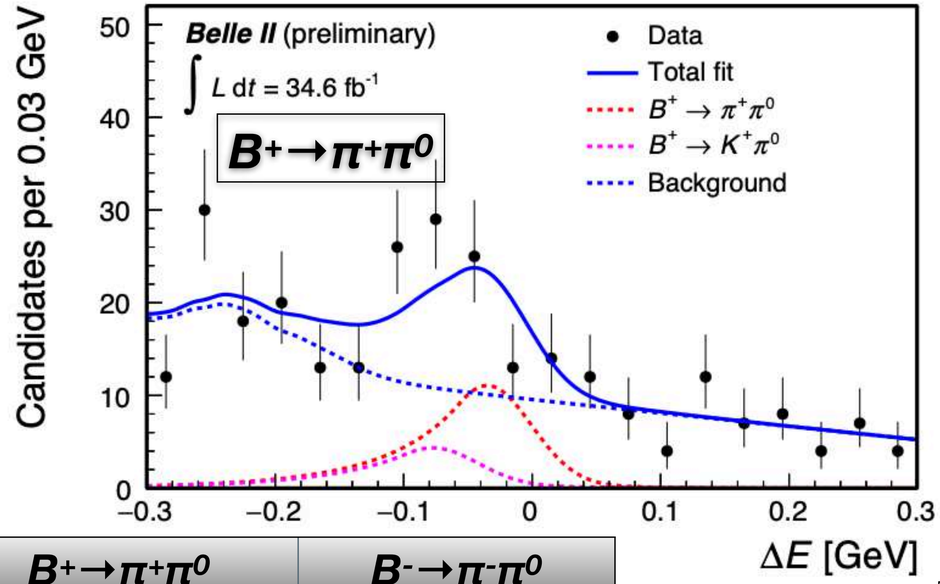
- **TDCPV parameter S_f and A_f**
- **Branch fraction of all $B \to \pi\pi$ ($\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$) modes**

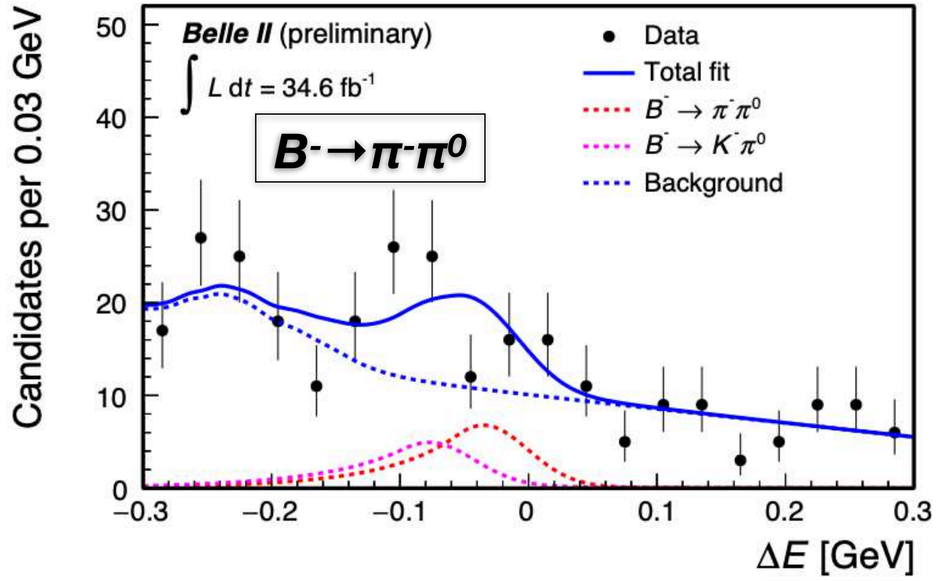
$$S_f = \sqrt{1 - A_f{}^2}\, sin(2\phi_2 + 2\Delta\phi_2)$$

Interference between tree and penguin

arXiv:2009.09452

BELLE2-CONF-PH-2020-012

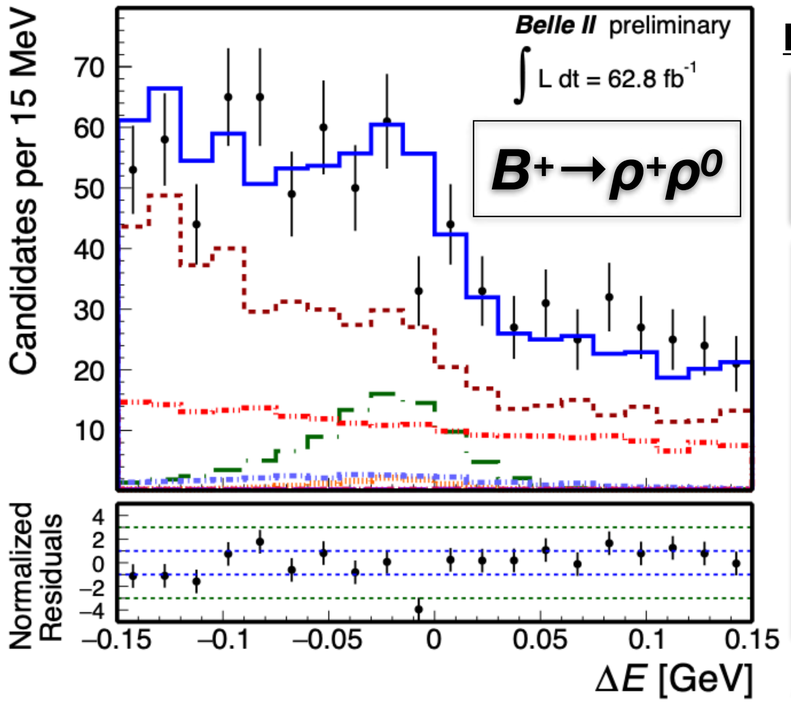




	$B^+ \to \pi^+\pi^0$	$B^- \to \pi^-\pi^0$
Yield	$43\ ^{+19}_{-20}$	$24\ ^{+13}_{-14}$
A_{CP}	$-0.268\ ^{+0.249}_{-0.322} \pm 0.123$	
A_{CP}(PDG)	0.03 ± 0.04	

- **$B \to \pi^0\pi^0$** analysis started at Belle II
  - 8-fold ambiguity of ϕ_2 can be reduced to 2-fold with TDCPV in $B^0 \to \pi^0\pi^0$

ϕ_2 measurement ($B \to \rho\rho$)



BELLE2-CONF-DRAFT-2021-005

$\int L\,dt = 62.8\ fb^{-1}$

Data
Fit result
Signal long
Signal trans
SxF
$B\bar{B}$ bkg
$B \to f_0 X$
$B \to \rho\pi\pi$
Continuum

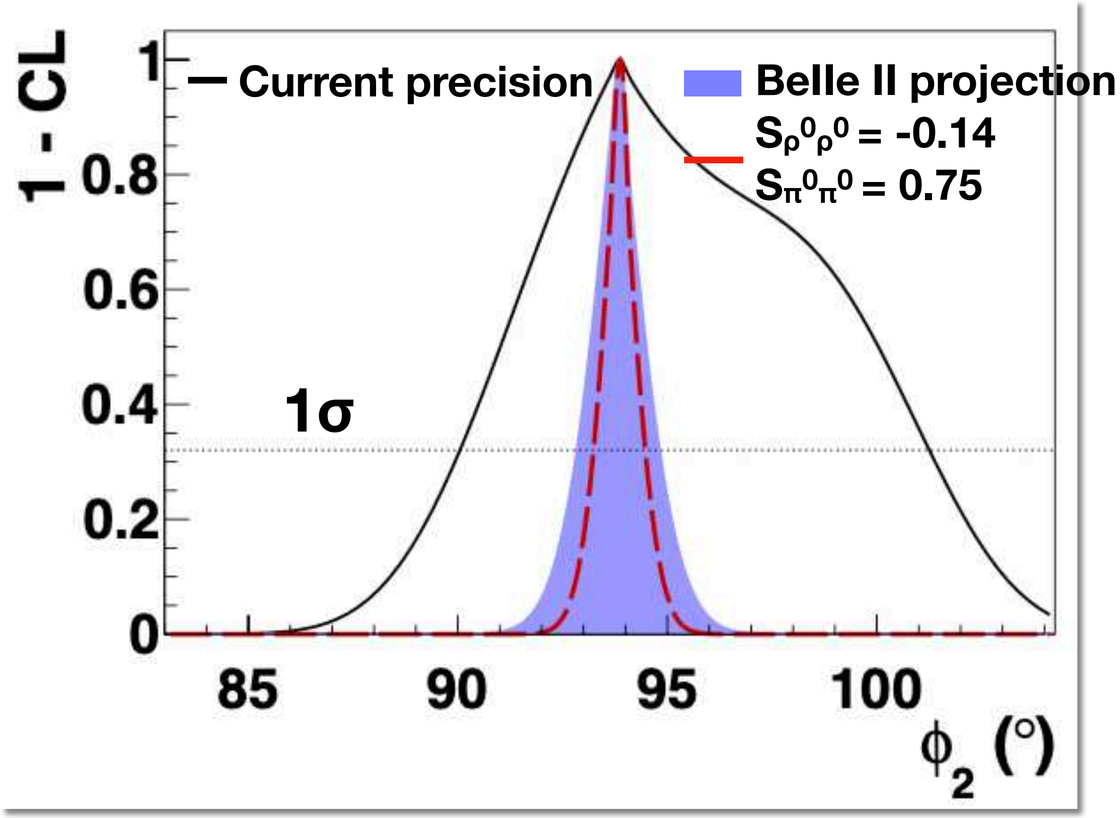
$\Delta E = E^*_B - E^*_{beam}$

	$B^+ \to \rho^+\rho^0$
Yeild	104 ± 16
$Br(10^{-6})$	20.6 ± 3.2 ± 3.1
PDG	24.0 ± 1.9
f_L	$0.936^{+0.049}_{-0.041}$ ± 0.021
f_L(PDG)	0.950 ± 0.016

f_L = fraction of longitudinally polarized events

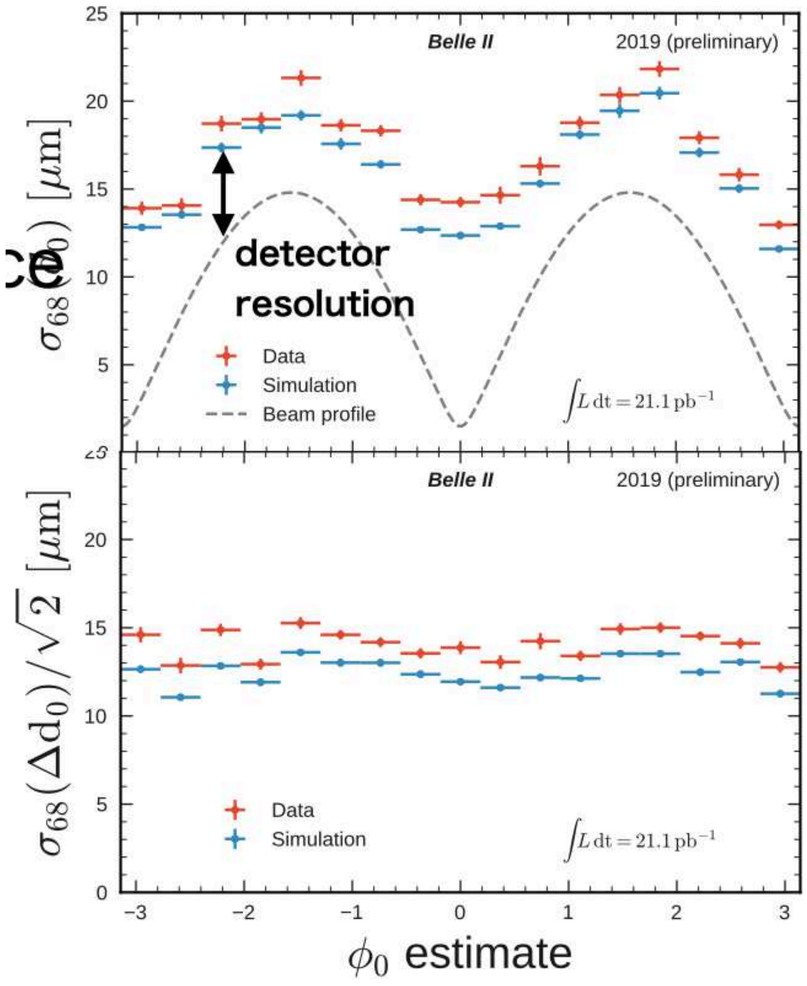
- **Compatible with PDG value**
- **Performance superior to early Belle results**

The Belle II Physics Book, PTEP 2019, 123C01



- **$\Delta\phi_2 \sim 0.6°$** (current 4.2°) with 50 fb^{-1} data
  - $B \to \pi\pi$, $B \to \rho\rho$ isospin analysis and $B \to \rho(\pi\pi)\pi$ Dalitz analysis of 3 body decays
  - **LHCb can not measure ϕ_2**

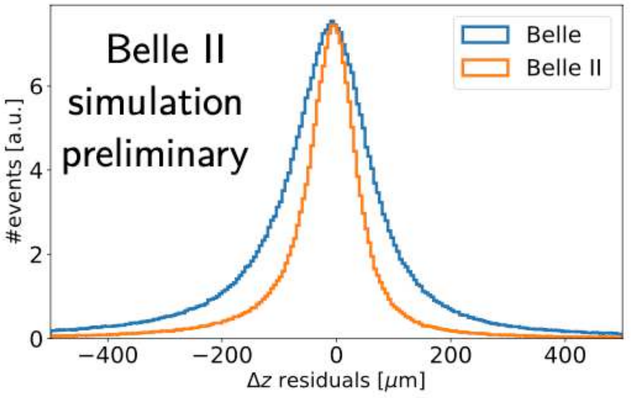
VXD position resolution

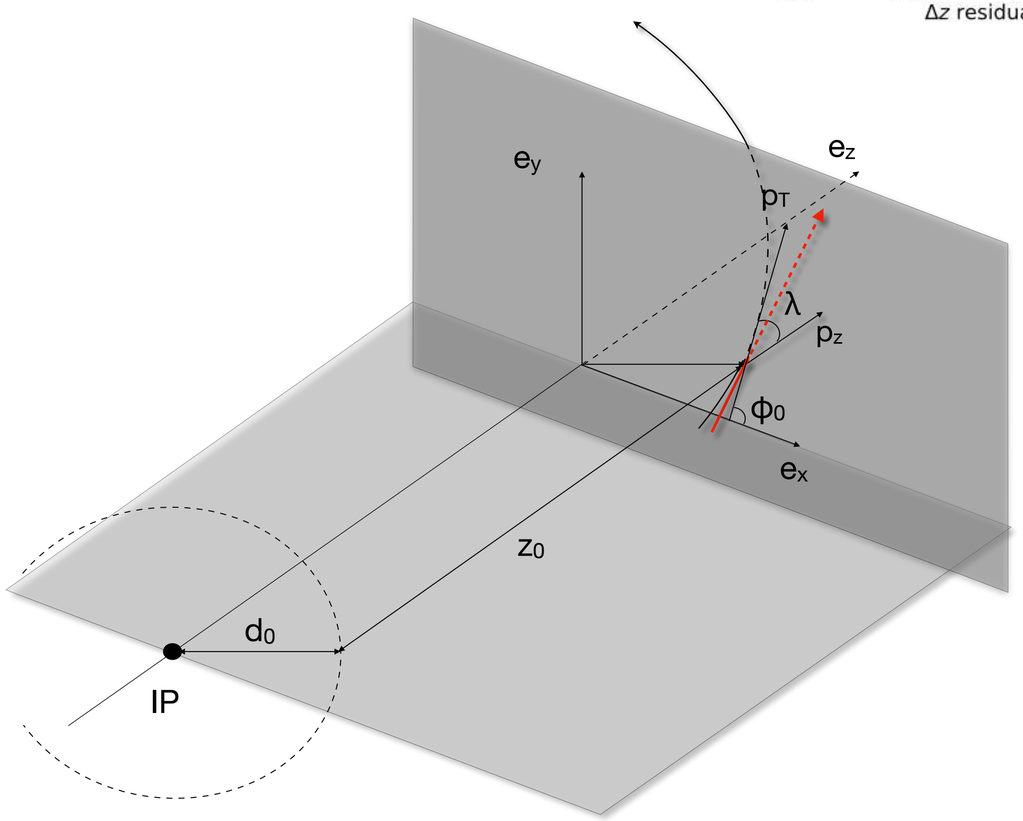


Detector resolution : difference between d_0 and beam profile

σ_x :14.8 μm

σ_y :1.5 μm





d_0 resolution:

14.2 ± 0.1 μm (Data)

12.5 ± 0.1 μm (Simulation)