# First look at CKM parameters from Belle II

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

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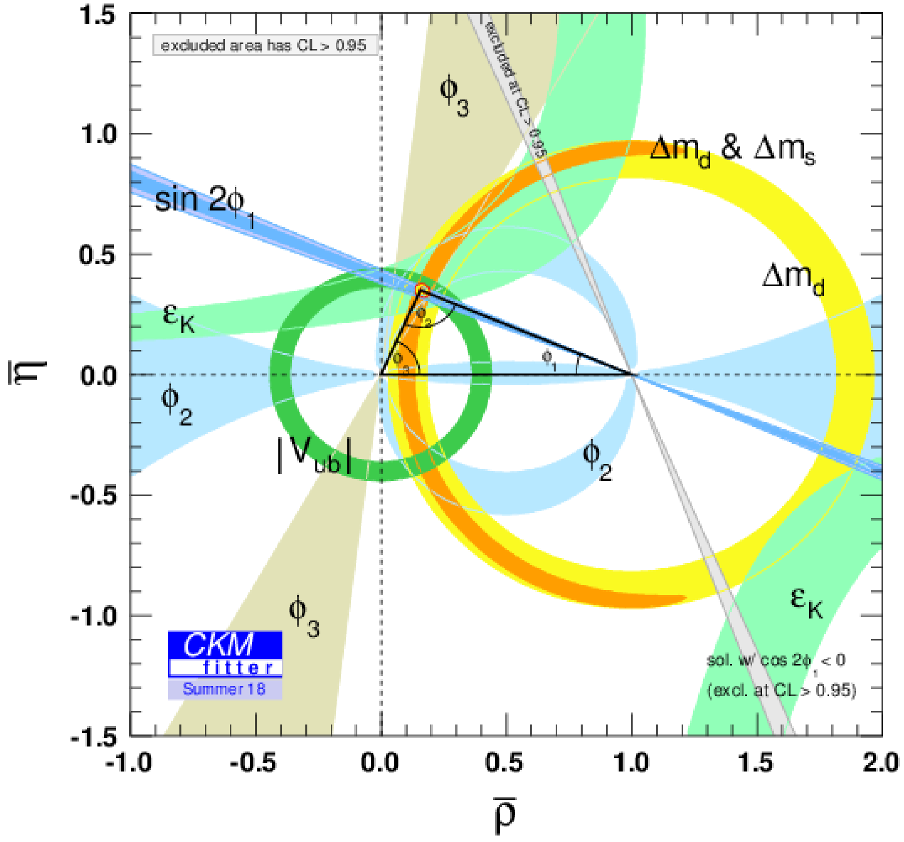
on behalf of the Belle II Collaboration

"Intensity frontier in Particle Physics:
Flavor, CP Violation and Dark Physics"

Taipei, October 4th 2019

# Flavor Physics Today

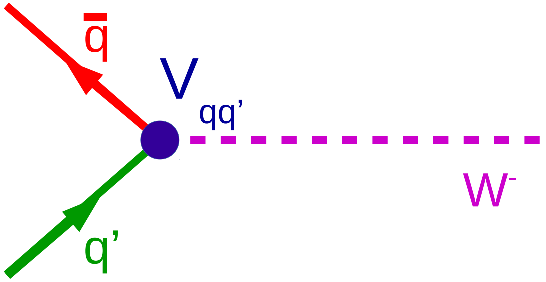
- Tremendous progress in Flavor Physics in the last 20 years:
  - Discovery of direct CP violation in K decays (NA48, KTEV);
  - Discovery of CP violation in B mesons (BaBar, Belle);
  - Discovery of D° oscillations (BaBar, Belle);
  - Discovery of CP violation in Charm (LHCb);
  - …
- The fit of the Unitarity Triangle is a big (though not whole) part of the story;
- Overall this testifies the success of the CKM paradigm: one single weak phase can account for all the observed phenomena;
- We are ready to test whether this will survive the next step in precision.

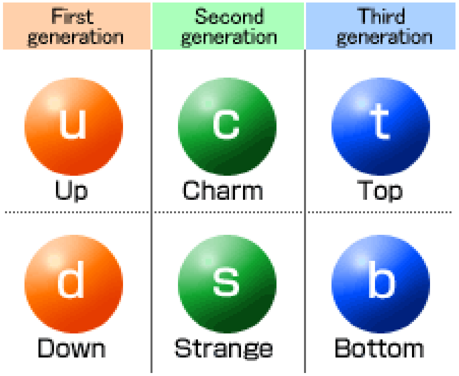


**Status of the CKM Unitarity Triangle fit, as of Summer 2018**

# The CKM Matrix

- The coupling of the quarks via the charged weak current





$$q = +\frac{2}{3}$$

$$q = -\frac{1}{3}$$

is described by the Cabibbo-Kobayashi-Maskawa matrix:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- The CKM Matrix is a 3x3 complex matrix;
- The condition that the Matrix must be unitarity and the freedom to redefine the complex phase of five out of six quark fields, reduces the number of degrees of freedom to 4 (not predicted by the Theory).

# The CKM Matrix

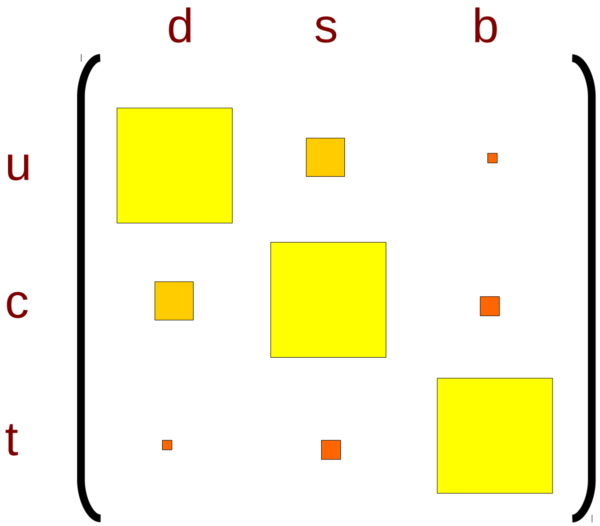
- The CKM Matrix can be parameterized as:

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parameterization

λ: expansion parameter, aka sine of Cabibbo angle,

λ ~ 0.22



- Strong hierarchical structure: the coupling between quarks of different generations is suppressed;
- There can be a weak phase, affecting only the smallest elements of the Matrix, at first order;
- This weak phase is the origin of all CP Violating phenomena we have observed so far in the quark sector.

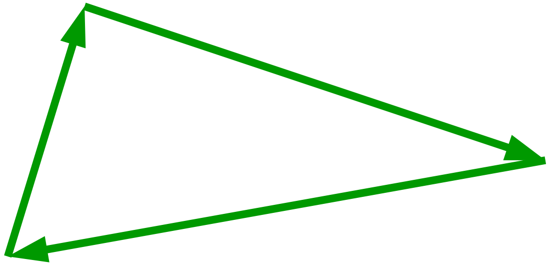
# The CKM unitarity triangle(s)

Six (only three are independent) of the unitarity conditions of the CKM Matrix define triangles on the complex plane:

$$\boxed{V_{CKM}V_{CKM}^{\dagger} = \mathbb{1}}$$

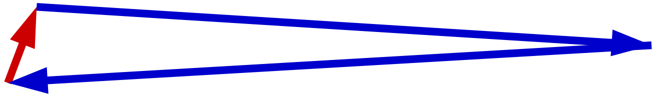
1) $$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

$O(\lambda^3)$ $O(\lambda^3)$ $O(\lambda^3)$



2) $$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$

$O(\lambda^4)$ $O(\lambda^2)$ $O(\lambda^2)$



3) $$V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0$$

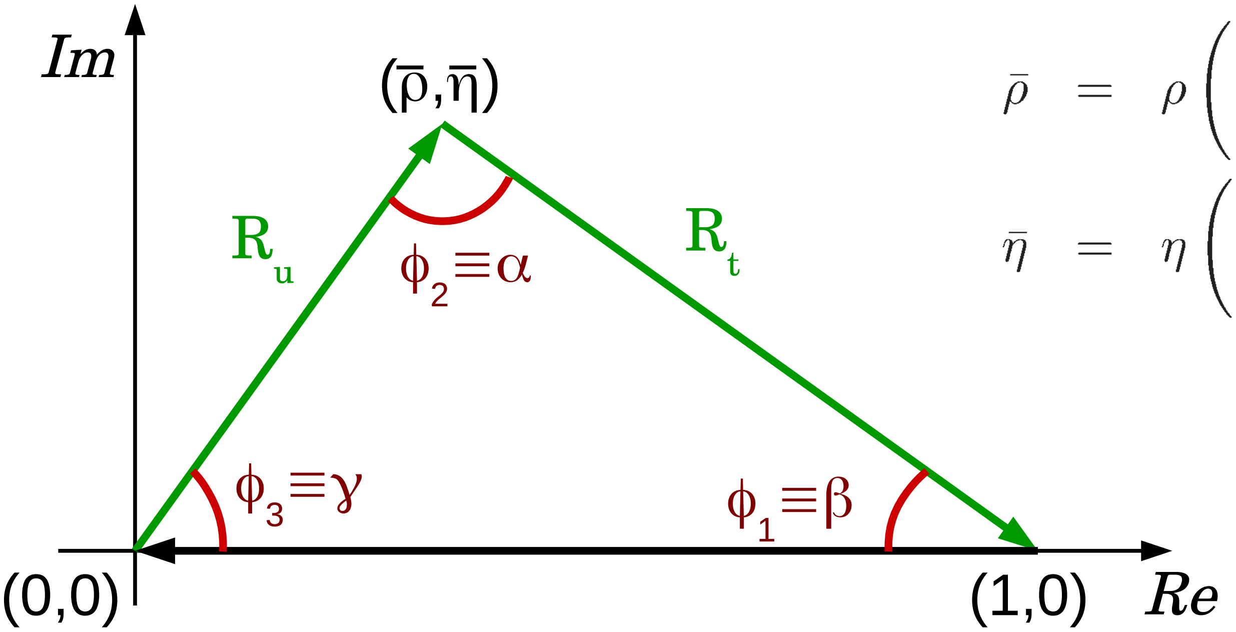
$O(\lambda)$ $O(\lambda)$ $O(\lambda^5)$

# The CKM Unitarity Triangle

- Dividing 1) by $V_{cd}V^*_{cb}$, we obtain:

$$\boxed{\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} + 1 + \frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}} = 0}$$

which defines the “standard” CKM Unitarity Triangle:



$$\bar\rho = \rho\left(1 - \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4)\right)$$

$$\bar\eta = \eta\left(1 - \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4)\right)$$

- We can (over)constrain the position of the apex $(\bar\rho, \bar\eta)$, by performing independent measurements of the magnitude of the sides $R_u$ and $R_t$, and of the angles $\phi_1$, $\phi_2$, and $\phi_3$.

# Outline

- Motivations;
- The Belle II Experiment @ SuperKEKB;
- The Belle II Physics Book;
- Measurements of the UT sides:
  - ➔ $R_t$ from $B\bar{B}$ oscillations;
  - ➔ $R_u$ from measurement of semileptonic B decays;
- Measurements of UT angles:
  - ➔ $\sin(2\phi_1)$ from $B \to J/\psi K^0, \eta' K^0, \phi K^0$;
  - ➔ $\phi_2$ from isospin analysis of $B \to \pi\pi$ and $B \to \rho\rho$;
  - ➔ $\phi_3$ from $B^+ \to D^0 K^+$ decays;
- Outlook.

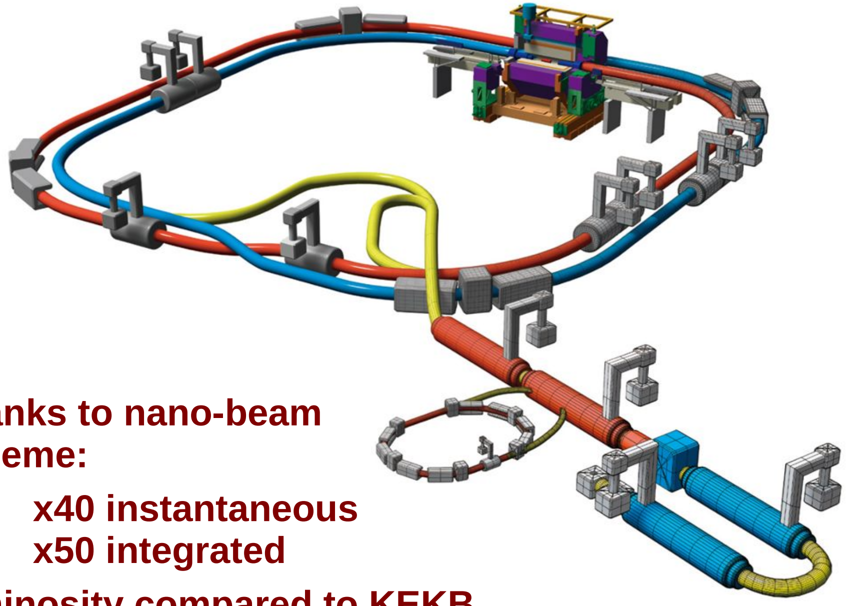
# Motivations

- The parameters that define the CKM Matrix are fundamental quantities of the Standard Model that cannot be predicted by the theory;
- Improving the **precision** on all the accessible quantities and constrain even more the position of the tip of the UT Triangle is the starting point...
- ... but we really want to find some **inconsistency** on the whole CKM picture, signaling the presence of New Physics;

- Key point: with this approach, no single measurement can stand as a smoking gun for New Physics: the sensitivity comes from the combination of many different observables;
- General guiding principle:
  - decays that dominantly proceed through **tree level** amplitudes are free from New Physics contributions;
  - **loop amplitude** dominated decays instead might be significantly influenced by New Physics contributions.

# The Belle II Experiment @ SuperKEKB

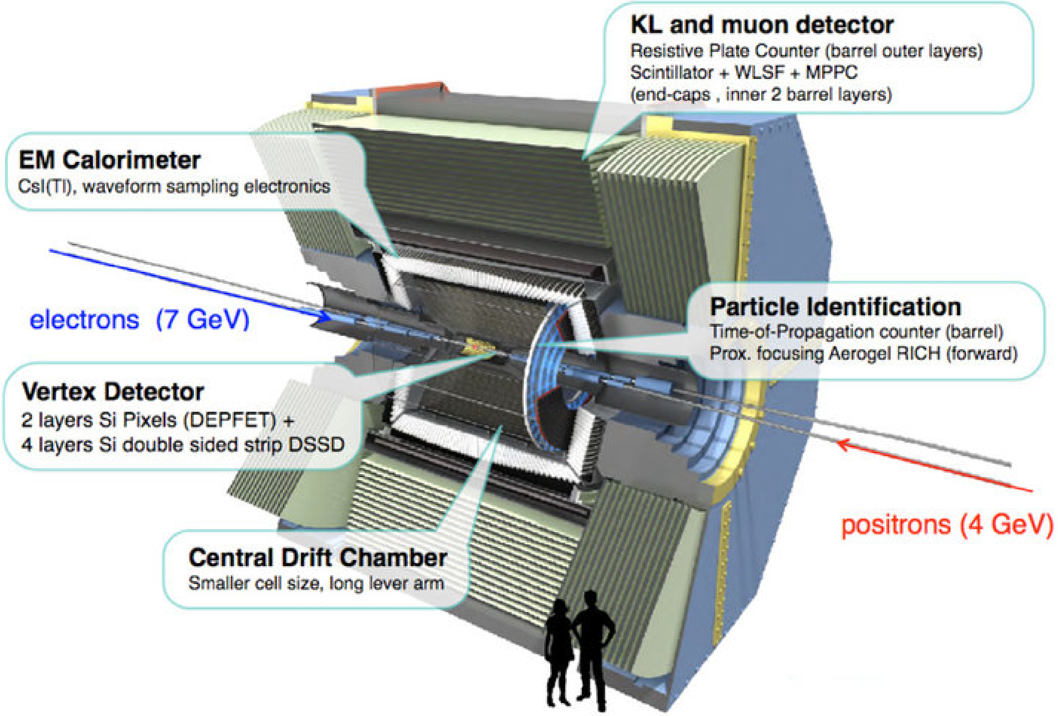
The Belle II experiment at the SuperKEKB $e^+e^-$ collider has recently started operations



**Thanks to nano-beam scheme:**

**x40 instantaneous**
**x50 integrated**

**luminosity compared to KEKB**



**KL and muon detector**
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC
(end-caps , inner 2 barrel layers)

**EM Calorimeter**
CsI(Tl), waveform sampling electronics

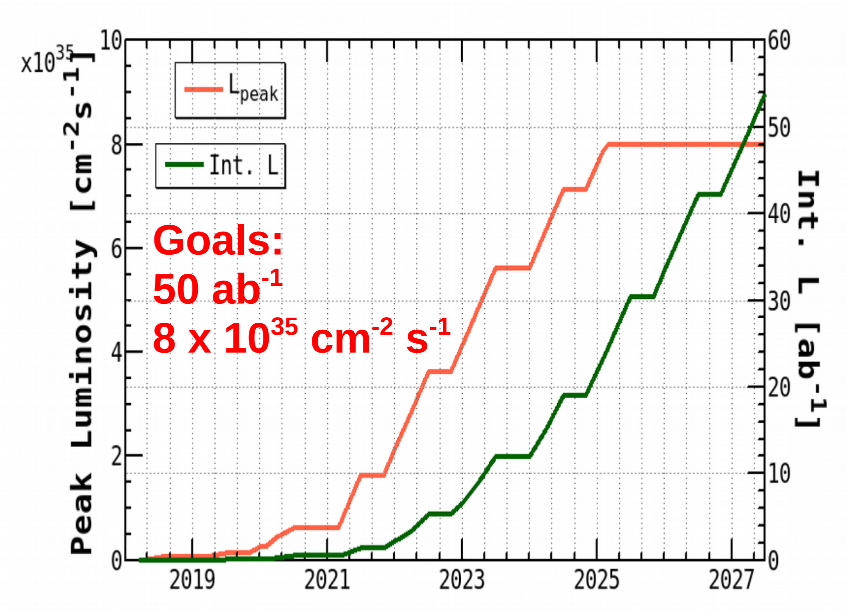
electrons (7 GeV)

**Particle Identification**
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

**Vertex Detector**
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

positrons (4 GeV)

**Central Drift Chamber**
Smaller cell size, long lever arm



**Goals:**
**50 ab$^{-1}$**
**8 x 10$^{35}$ cm$^{-2}$ s$^{-1}$**

Extensive detector upgrade:

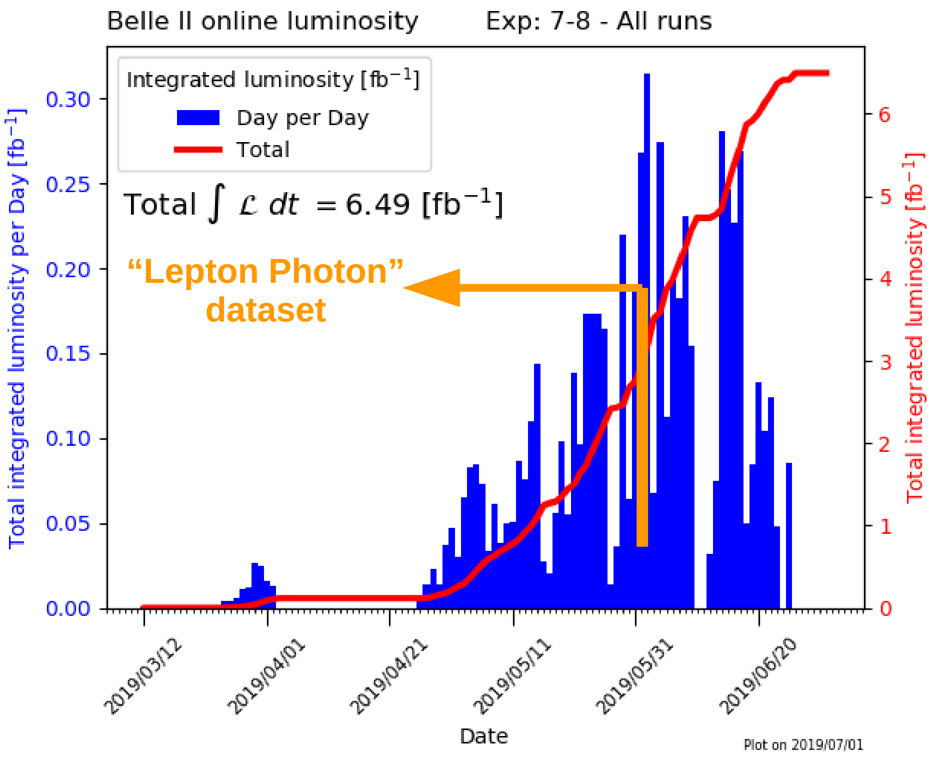
- improved vertexing resolution and $K_S$ reconstruction efficiency;
- enhanced K/π separation;
- more efficient analysis tools, thanks to widespread use of multivariate algorithms.

A. Gaz

See talk by
A. Soffer

# Dataset

- First Physics Run with the complete detector;
- From April to July, we integrated ~6.5 fb$^{-1}$, ~0.8 fb$^{-1}$ of which were taken 50 MeV below the $\Upsilon(4S)$ resonance, to study the non-$B\bar{B}$ components;
- Maximum instantaneous luminosity: ~6 x 10$^{33}$ (12 x 10$^{33}$) cm$^{-2}$ s$^{-1}$, with the detector ON (OFF). The current limiting factor is given by beam-gas interactions, expected to improve with time;
- Many of the results I will show today are based on the first ~3.5 fb$^{-1}$ collected by the experiment;
- This is < 1% of what was collected by the first generation of B-factory experiments: this is mostly a preview of a vast Physics program.

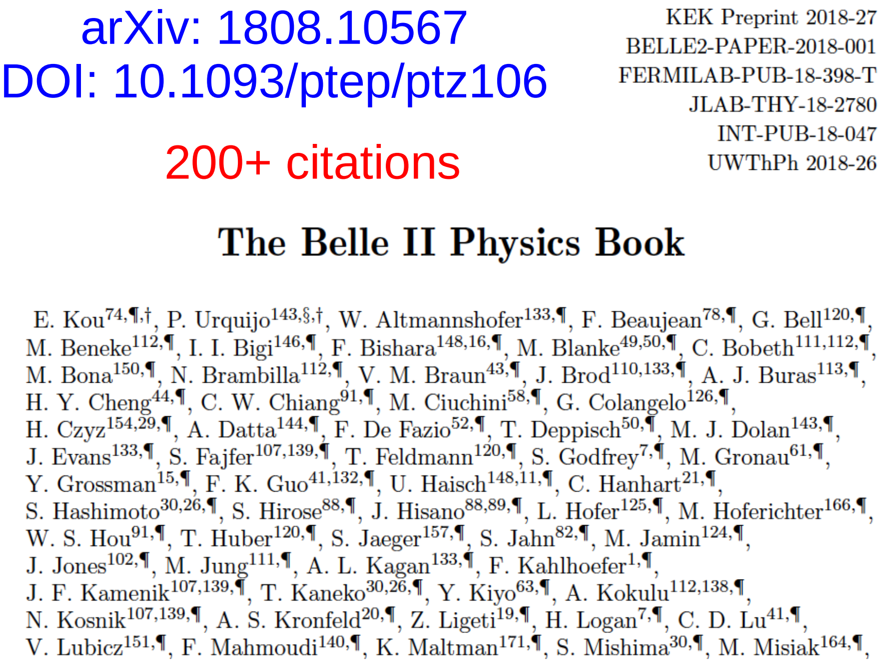


# The Belle II Physics Book

- The "Belle II Physics Book" has been recently accepted for publication by PTEP;
- This is the results of several years of collaboration between Belle II and the Theory Community;
- Sensititivity estimates on the golden (and silver) channels are given.

arXiv: 1808.10567
DOI: 10.1093/ptep/ptz106

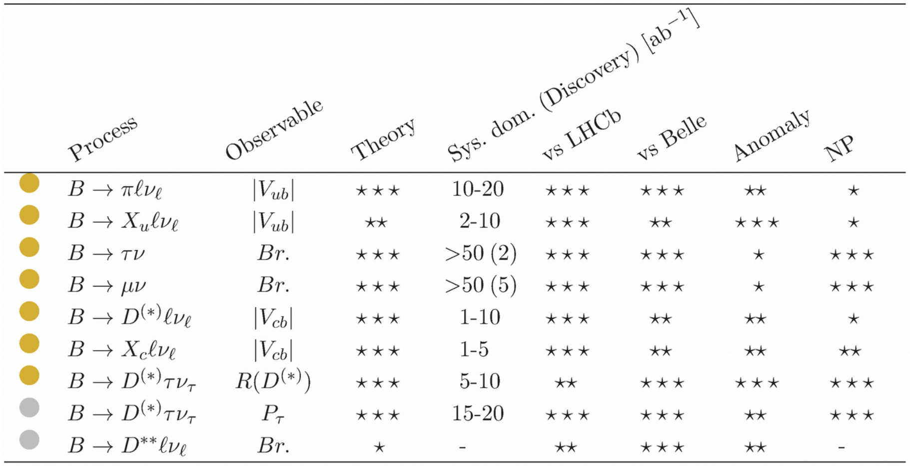
200+ citations



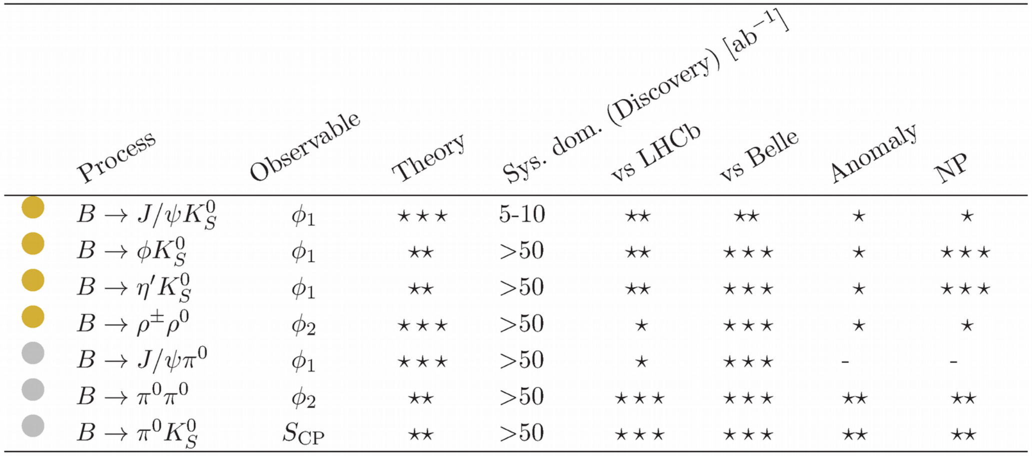
KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

**The Belle II Physics Book**

E. Kou[74,¶,†], P. Urquijo[143,§,†], W. Altmannshofer[133,¶], F. Beaujean[78,¶], G. Bell[120,¶], M. Beneke[112,¶], I. I. Bigi[146,¶], F. Bishara[148,16,¶], M. Blanke[49,50,¶], C. Bobeth[111,112,¶], M. Bona[150,¶], N. Brambilla[112,¶], V. M. Braun[43,¶], J. Brod[110,133,¶], A. J. Buras[113,¶], H. Y. Cheng[44,¶], C. W. Chiang[91,¶], M. Ciuchini[58,¶], G. Colangelo[126,¶], H. Czyz[154,29,¶], A. Datta[144,¶], F. De Fazio[52,¶], T. Deppisch[50,¶], M. J. Dolan[143,¶], J. Evans[133,¶], S. Fajfer[107,139,¶], T. Feldmann[120,¶], S. Godfrey[7,¶], M. Gronau[61,¶], Y. Grossman[15,¶], F. K. Guo[41,132,¶], U. Haisch[148,11,¶], C. Hanhart[21,¶], S. Hashimoto[30,26,¶], S. Hirose[88,¶], J. Hisano[88,89,¶], L. Hofer[125,¶], M. Hoferichter[166,¶], W. S. Hou[91,¶], T. Huber[120,¶], S. Jaeger[157,¶], S. Jahn[82,¶], M. Jamin[124,¶], J. Jones[102,¶], M. Jung[111,¶], A. L. Kagan[133,¶], F. Kahlhoefer[1,¶], J. F. Kamenik[107,139,¶], T. Kaneko[30,26,¶], Y. Kiyo[63,¶], A. Kokulu[112,138,¶], N. Kosnik[107,139,¶], A. S. Kronfeld[20,¶], Z. Ligeti[19,¶], H. Logan[7,¶], C. D. Lu[41,¶], V. Lubicz[151,¶], F. Mahmoudi[140,¶], K. Maltman[171,¶], S. Mishima[30,¶], M. Misiak[164,¶],



| | Process | Observable | Theory | Sys. dom. (Discovery) [ab$^{-1}$] | vs LHCb | vs Belle | Anomaly | NP |
|---|---|---|---|---|---|---|---|---|
| 🟡 | $B \to \pi \ell \nu_\ell$ | $\|V_{ub}\|$ | ⋆⋆⋆ | 10-20 | ⋆⋆⋆ | ⋆⋆⋆ | ⋆⋆ | ⋆ |
| 🟡 | $B \to X_u \ell \nu_\ell$ | $\|V_{ub}\|$ | ⋆⋆ | 2-10 | ⋆⋆⋆ | ⋆⋆ | ⋆⋆⋆ | ⋆ |
| 🟡 | $B \to \tau \nu$ | $Br.$ | ⋆⋆⋆ | >50 (2) | ⋆⋆⋆ | ⋆⋆⋆ | ⋆ | ⋆⋆⋆ |
| 🟡 | $B \to \mu \nu$ | $Br.$ | ⋆⋆⋆ | >50 (5) | ⋆⋆⋆ | ⋆⋆⋆ | ⋆ | ⋆⋆⋆ |
| 🟡 | $B \to D^{(*)} \ell \nu_\ell$ | $\|V_{cb}\|$ | ⋆⋆⋆ | 1-10 | ⋆⋆⋆ | ⋆⋆ | ⋆⋆ | ⋆ |
| 🟡 | $B \to X_c \ell \nu_\ell$ | $\|V_{cb}\|$ | ⋆⋆⋆ | 1-5 | ⋆⋆⋆ | ⋆⋆ | ⋆⋆ | ⋆⋆ |
| 🟡 | $B \to D^{(*)} \tau \nu_\tau$ | $R(D^{(*)})$ | ⋆⋆⋆ | 5-10 | ⋆⋆ | ⋆⋆⋆ | ⋆⋆⋆ | ⋆⋆⋆ |
| ⚪ | $B \to D^{(*)} \tau \nu_\tau$ | $P_\tau$ | ⋆⋆⋆ | 15-20 | ⋆⋆⋆ | ⋆⋆⋆ | ⋆⋆ | ⋆⋆⋆ |
| ⚪ | $B \to D^{**} \ell \nu_\ell$ | $Br.$ | ⋆ | - | ⋆⋆ | ⋆⋆⋆ | ⋆⋆ | - |



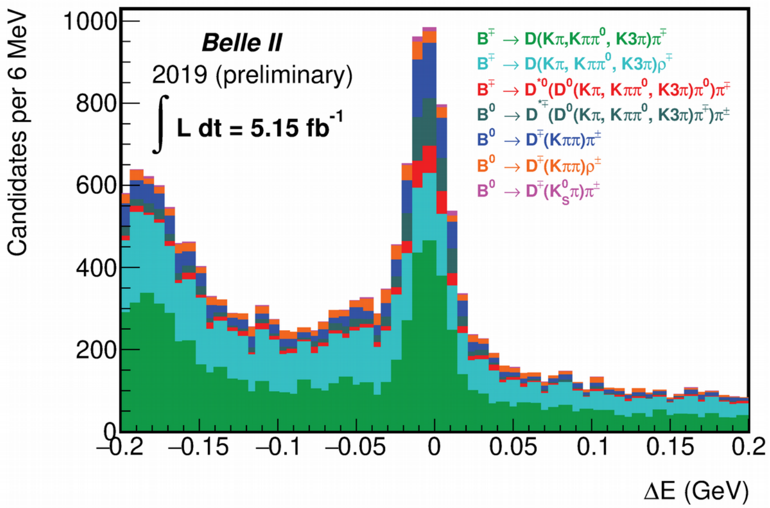
| | Process | Observable | Theory | Sys. dom. (Discovery) [ab$^{-1}$] | vs LHCb | vs Belle | Anomaly | NP |
|---|---|---|---|---|---|---|---|---|
| 🟡 | $B \to J/\psi K_S^0$ | $\phi_1$ | ⋆⋆⋆ | 5-10 | ⋆⋆ | ⋆⋆ | ⋆ | ⋆ |
| 🟡 | $B \to \phi K_S^0$ | $\phi_1$ | ⋆⋆ | >50 | ⋆⋆ | ⋆⋆⋆ | ⋆ | ⋆⋆⋆ |
| 🟡 | $B \to \eta' K_S^0$ | $\phi_1$ | ⋆⋆ | >50 | ⋆⋆ | ⋆⋆⋆ | ⋆ | ⋆⋆⋆ |
| 🟡 | $B \to \rho^\pm \rho^0$ | $\phi_2$ | ⋆⋆⋆ | >50 | ⋆ | ⋆⋆⋆ | ⋆ | ⋆ |
| ⚪ | $B \to J/\psi \pi^0$ | $\phi_1$ | ⋆⋆⋆ | >50 | ⋆ | ⋆⋆⋆ | - | - |
| ⚪ | $B \to \pi^0 \pi^0$ | $\phi_2$ | ⋆⋆ | >50 | ⋆⋆⋆ | ⋆⋆⋆ | ⋆⋆ | ⋆⋆ |
| ⚪ | $B \to \pi^0 K_S^0$ | $S_{\rm CP}$ | ⋆⋆ | >50 | ⋆⋆⋆ | ⋆⋆⋆ | ⋆⋆ | ⋆⋆ |

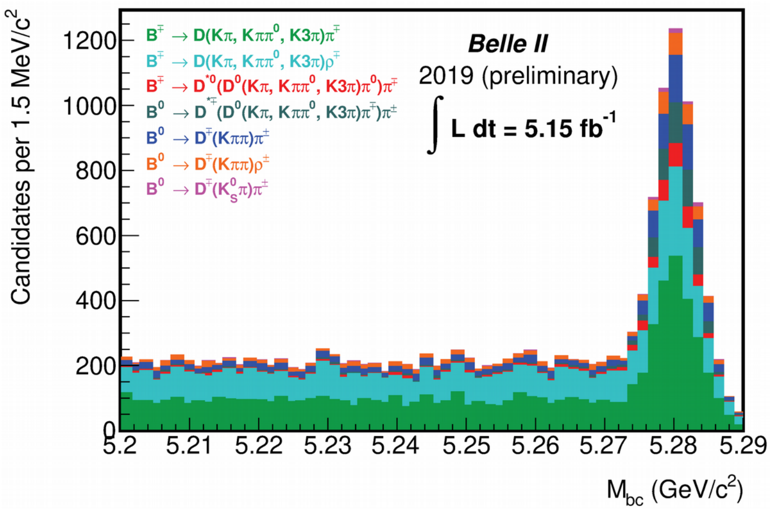
# B-factory jargon

Two variables are extremely useful to discriminate against background for fully reconstructed final states:

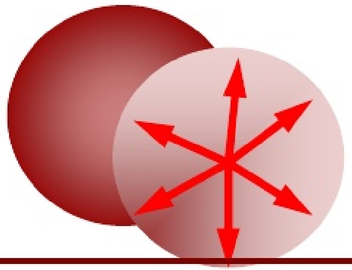
$$\boxed{\Delta E = E_B^* - \frac{\sqrt{s}}{2}}$$

$$\boxed{M_{bc} = \sqrt{\frac{s}{4} - p_B^{*2}}}$$

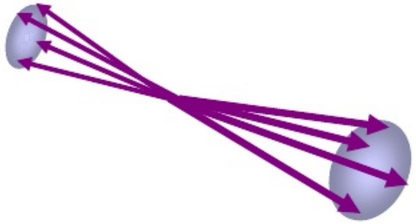




For many final states, the dominant source of background is the ‘continuum’, which is suppressed based on the different topology with respect to $B\overline{B}$ events:



**Spherical BB events**

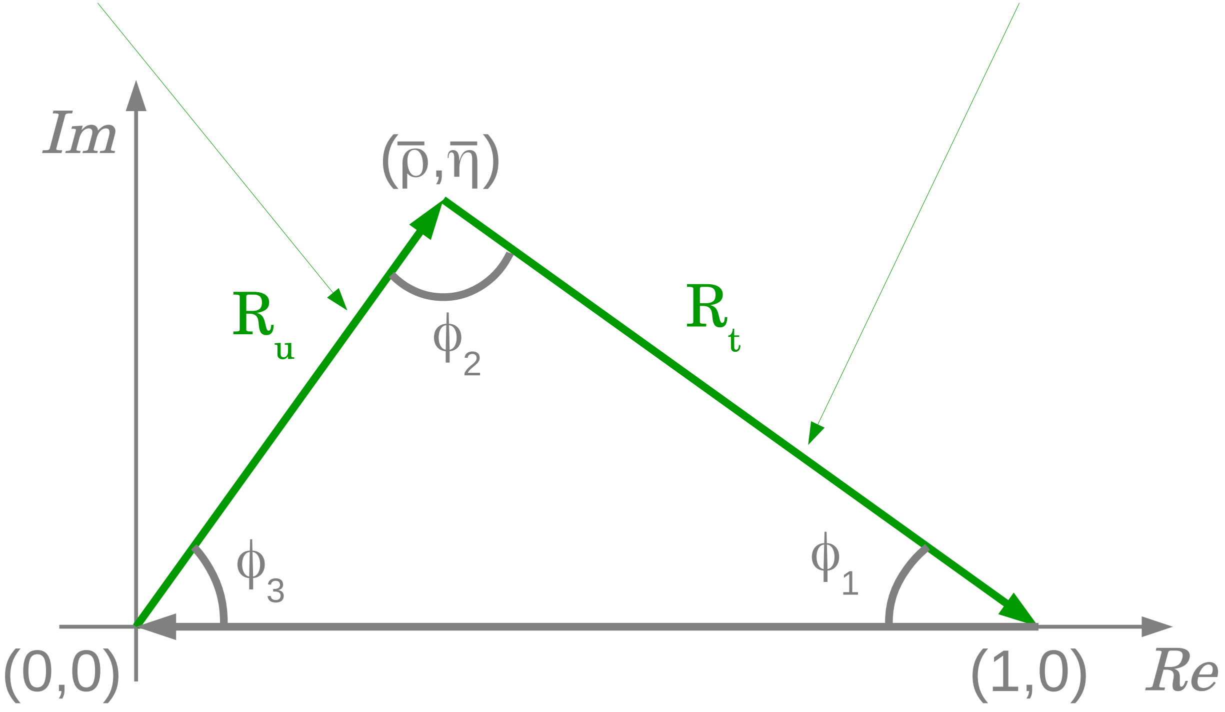


**Jet-like qq events**

# Determination of the UT Sides

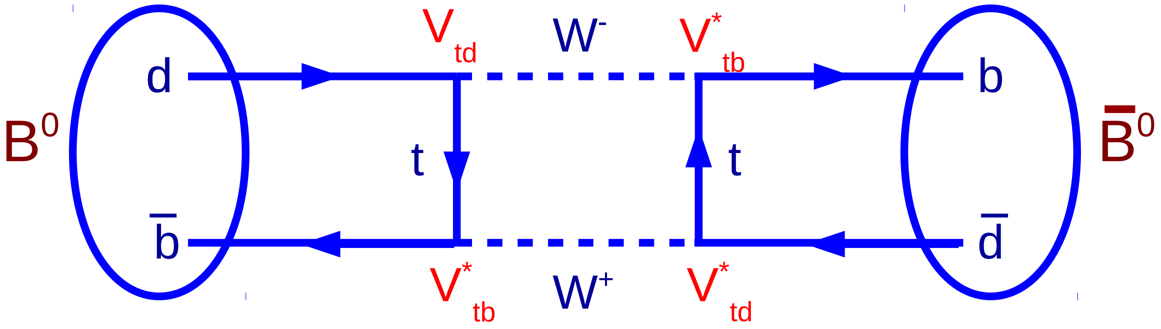
$$R_u \equiv \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$$

$$R_t \equiv \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$$

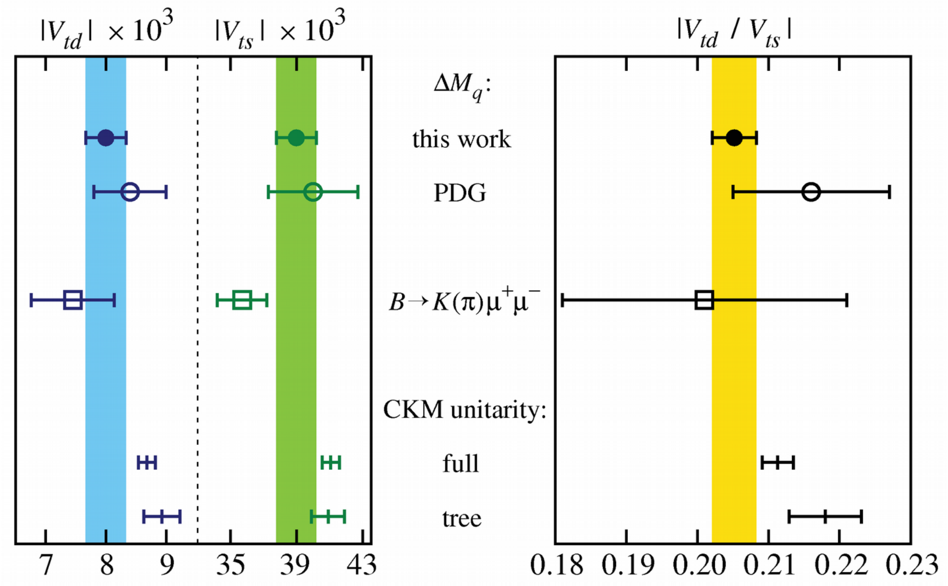


# Sides: $R_t$

$$R_t \equiv \left| \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \right|$$



- $R_t$ mostly comes from the $B\bar{B}$ oscillation frequencies $\Delta m_d/\Delta m_s$ (systematics cancel in the ratio);
- The experimental measurements are close to being systematics dominated, the focus is on Lattice QCD, which computes the relevant hadronic quantities;
- Some tension with the CKM fit!



FERMILAB LATTICE and MILC Collaborations,
Phys.Rev. D93 (2016) 11, 113016

# Sides: $R_t$ - Experiments

- Current experimental situation:

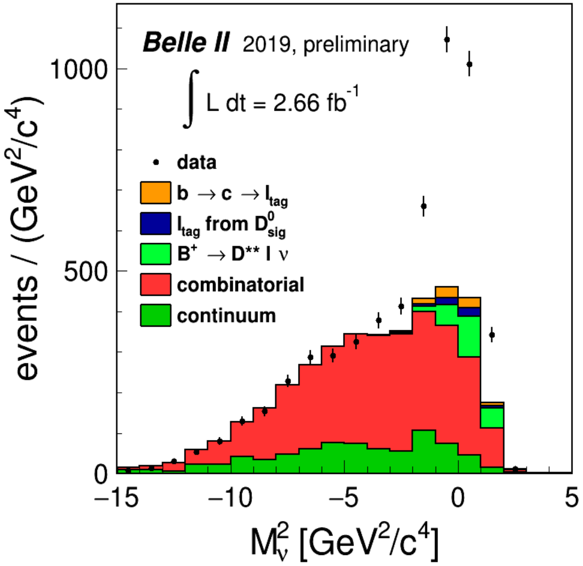
| | Result ($ps^{-1}$) | Dataset | Reference |
|---|---|---|---|
| $\Delta m_d$ | $0.511 \pm 0.007 \pm 0.007$ | 81 $fb^{-1}$ | BaBar: Phys. Rev. D73 (2006) 012004 |
| | $0.511 \pm 0.005 \pm 0.006$ | 140 $fb^{-1}$ | Belle: Phys. Rev. D71 (2005) 072003 |
| | $0.5050 \pm 0.0021 \pm 0.0010$ | 3.0 $fb^{-1}$ | LHCb: Eur. Phys. J C76 (2016) 412 |
| $\Delta m_s$ | $17.768 \pm 0.023 \pm 0.006$ | 1.0 $fb^{-1}$ | LHCb: New J. Phys. 15 (2013) 053021 |

- LHCb is now dominating the field, but the previous B-factories did not fully exploit their datasets;
- Belle II should try to catch up quickly!
- In fact, the rediscovery of the $B\overline{B}$ oscillations was one of the first milestones to demonstrate the physics capabilities of the experiment.

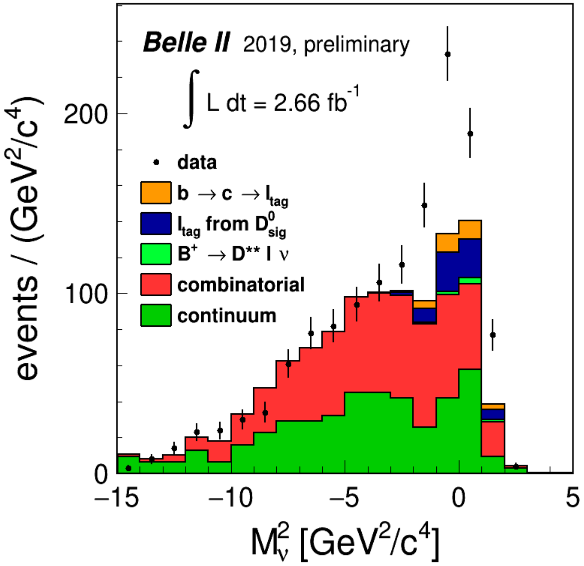
# Observation of $B\bar{B}$ mixing at Belle II

- Target: $B^\circ \to D^{*-} l^+ \nu$ decays, with $D^{*-} \to D^\circ \pi^-_{soft}$;
- Large branching fraction and clean B-flavor tagging from the leptons;
- Proper decay time difference $\Delta t$ estimated from displacement of the B decay vertices along the boost axis: $\Delta t = \Delta z/(\beta\gamma c)$

Unmixed ($l^\pm l^\mp$)

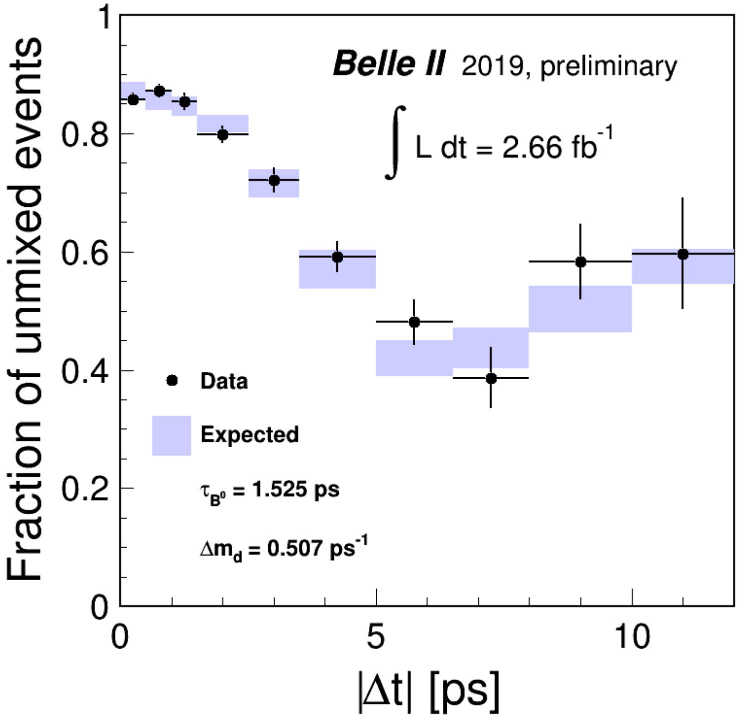


Mixed ($l^\pm l^\pm$)



Fraction of mixed events $\chi_d = (17.2 \pm 3.6)\%$

(World Average = 18.6%)

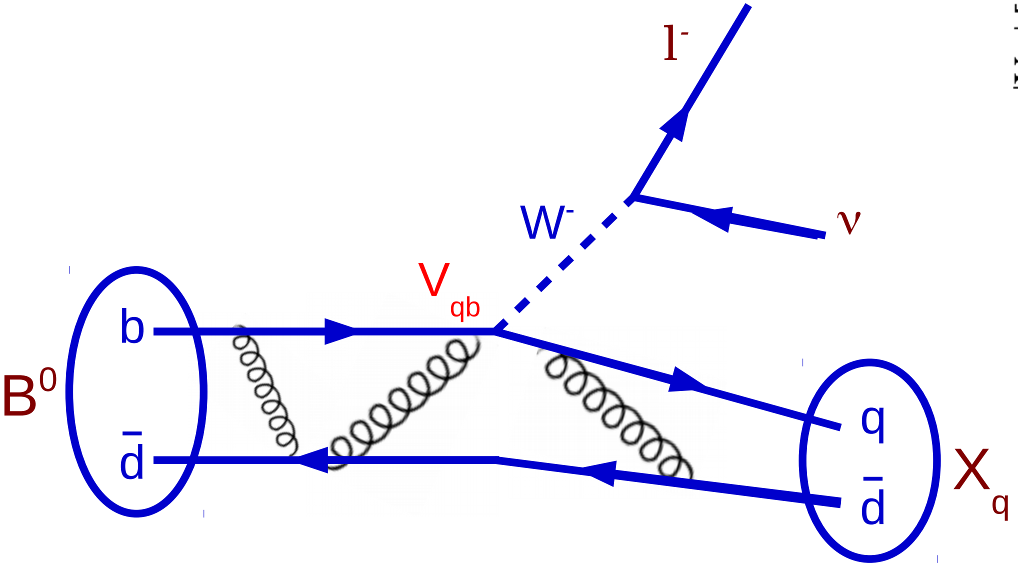


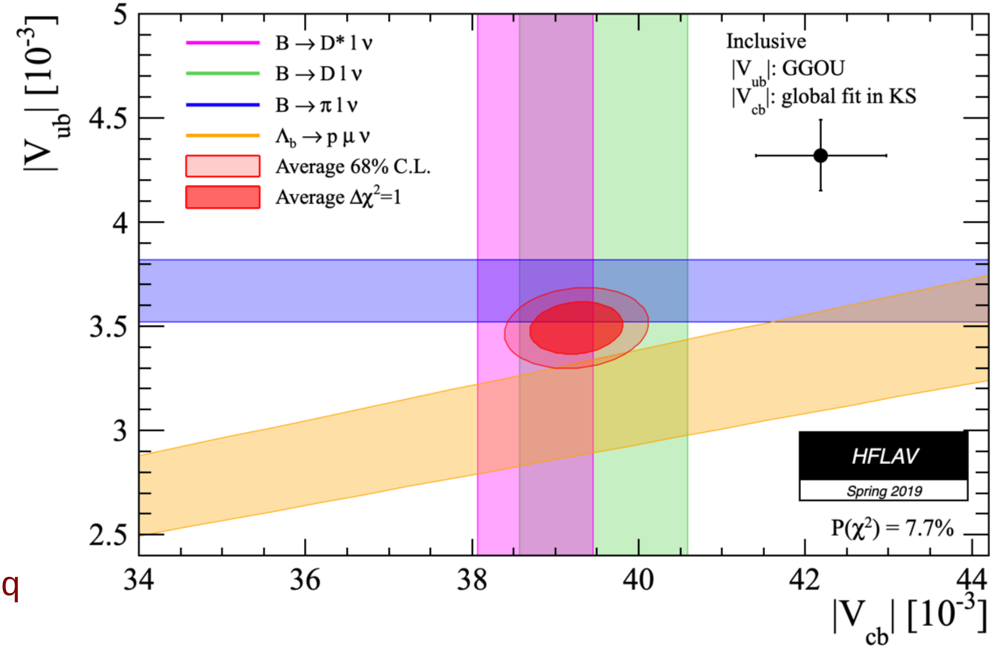
|Δt| dependent behavior of the fraction of unmixed events consistent with the expectations

# Sides: $R_u$

$$R_u \equiv \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$$

- The precision on $R_u$ is dominated by $V_{ub}$ and $V_{cb}$;
- Experimentally, these parameters are measured from semileptonic decays of B mesons (hadrons);
- Tree level transitions: fundamental inputs for the CKM fit!





Tension between different determinations, still to be fully understood

# Sides: $R_u$ – status and prospects

- Current precision: < 2% for $|V_{cb}|$, 5-6% for $|V_{ub}|$;

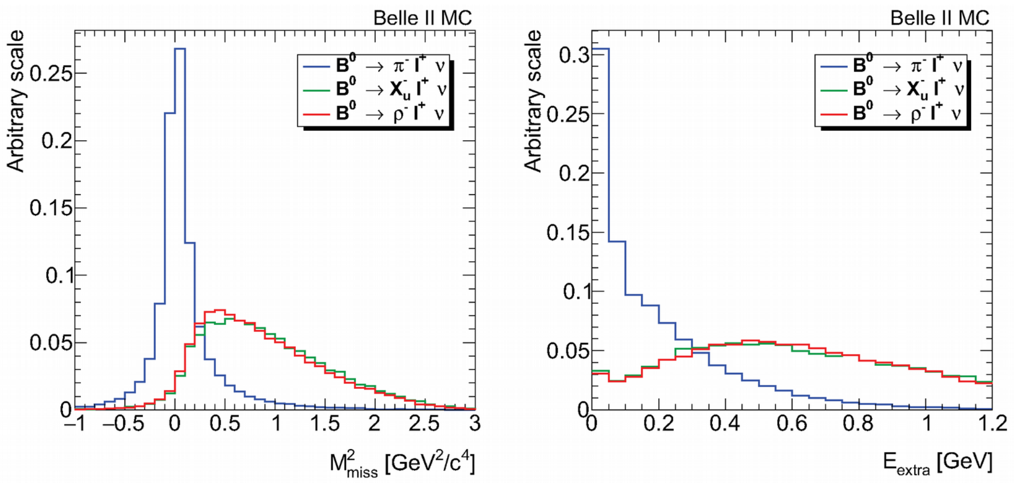
HFLAV World Average

- $|V_{cb}|$: progress will be driven by exclusive $B \to D^{(*)} l \nu$ decays thanks to better understanding of the form factors from Lattice QCD;

(conservatively assuming no progress on inclusive $|V_{cb}|$ )

- $|V_{ub}|$: big improvement driven by Lattice QCD, exclusive determinations will dominate the average!

Tagged $B \to \pi l \nu$ analysis

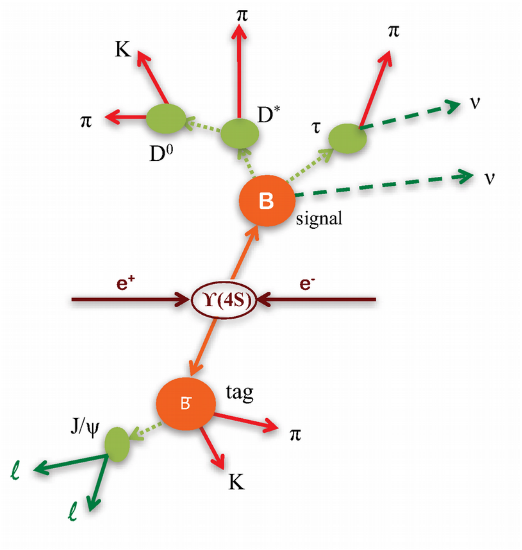


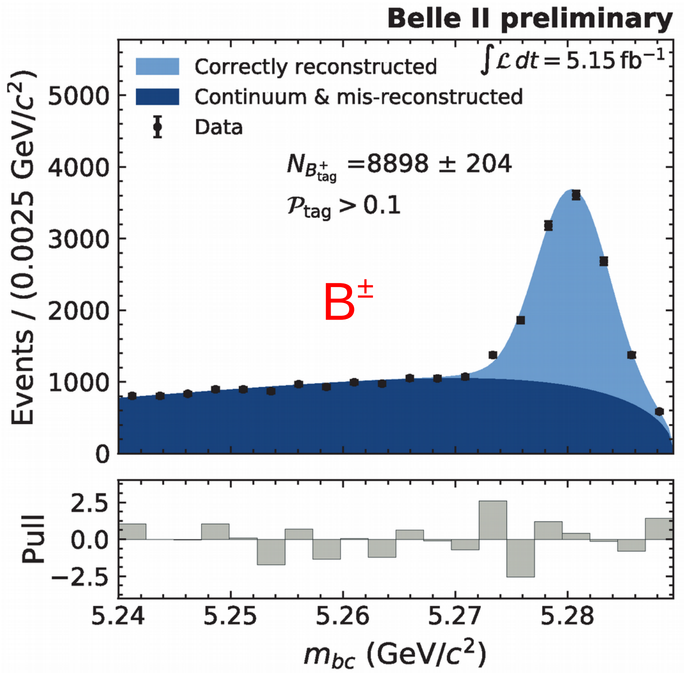
**Projected errors: (Experiment ⊕ Theory)**

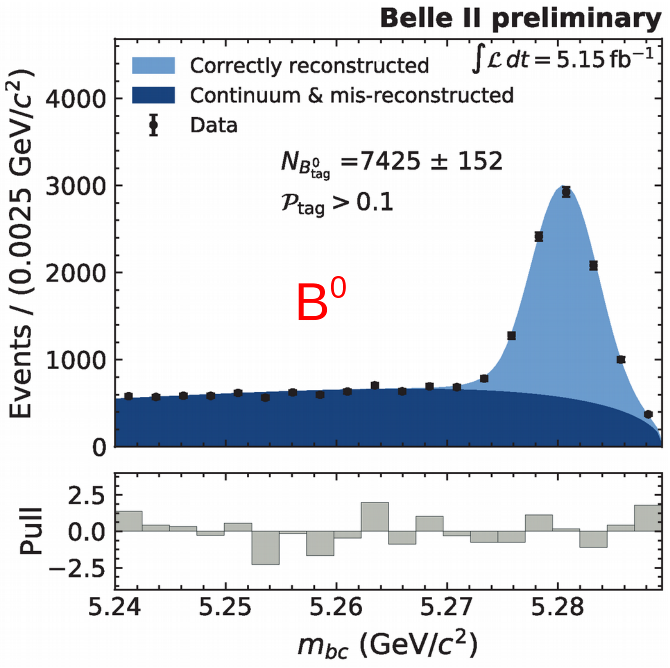
| | **Belle** | **Belle II 5 $ab^{-1}$** | **Belle II 50 $ab^{-1}$** |
|---|---|---|---|
| $|V_{ub}|$ exclusive (tagged) | $(3.8 \oplus 7.0)\%$ | $(1.8 \oplus 1.7)\%$ | $(1.2 \oplus 0.9)\%$ |
| $|V_{ub}|$ exclusive (untagged) | $(2.7 \oplus 7.0)\%$ | $(1.2 \oplus 1.7)\%$ | $(0.9 \oplus 0.9)\%$ |
| $|V_{ub}|$ inclusive | $(6.0 \oplus 2.5\text{-}4.5)\%$ | $(2.3 \oplus 2.5\text{-}4.5)\%$ | $(1.7 \oplus 2.5\text{-}4.5)\%$ |

# Full Event Interpretation

- Experimental challenge: SL decays involve at least one neutrino in the final state;
- In order to control the backgrounds we need good understanding of the event kinematics: great advantage of an experiment at an $e^+e^-$ collider!
- Only at a B-factory: employ MVA's to reconstruct both B mesons (signal and tag side) in the event:







- In general: very wide range of measurements (techniques and final states) will take advantage of this technique.

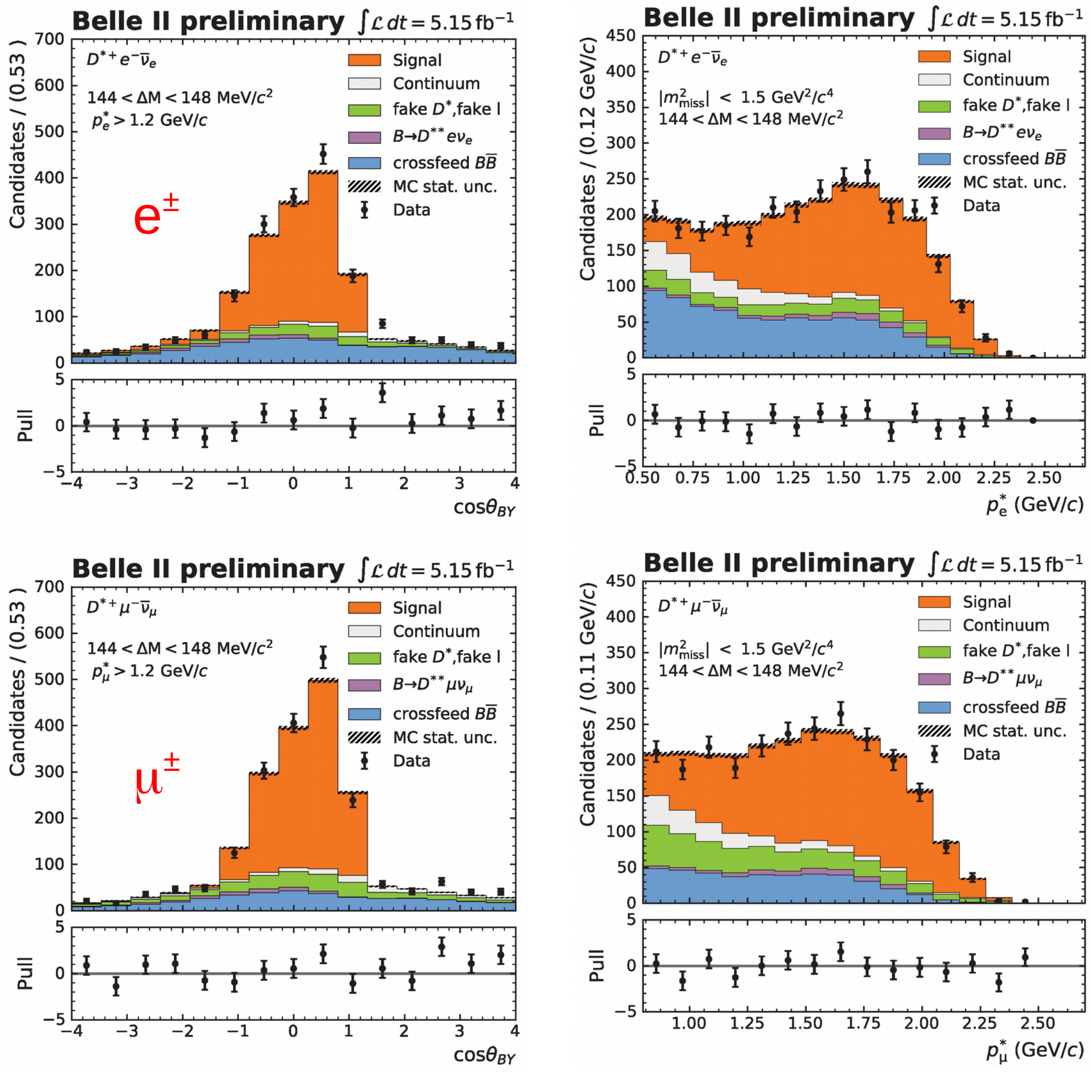
arXiv: 1807.08680 [hep-ex]
Comput. Softw. Big Sci. 3 (2019) no.1, 6

# Untagged $B^0 \rightarrow D^{*-} l^+ \nu$

- Flagship decay channel for the measurement of $|V_{cb}|$;
- Fully reconstruct $D^{*-} \rightarrow D^{\circ}\pi^-$, with $\overline{D}^{\circ} \rightarrow K^+\pi^-$;
- Key variable: cosine of the angle between the B flight direction and the direction of the (D*l) system (Y):

$$\cos\theta_{BY} = \frac{2E^*_B E^*_Y - M^2_B - m^2_Y}{2p^*_B p^*_Y}$$

- Full scale test of Belle II's Lepton ID capabilities!



**> 1000 events for both e and μ channels!**

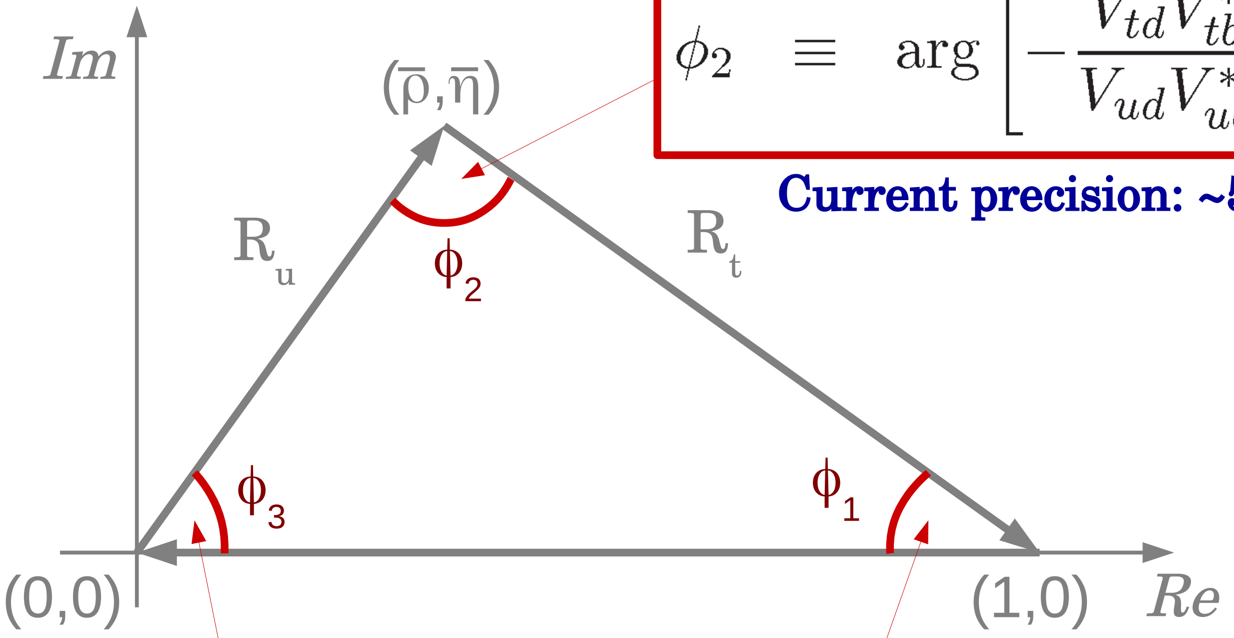
# Determination of the Angles

alternative nomenclature:

$\phi_1 = \beta$

$\phi_2 = \alpha$

$\phi_3 = \gamma$



$$\phi_2 \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

**Current precision: ~5°**

$$\phi_3 \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

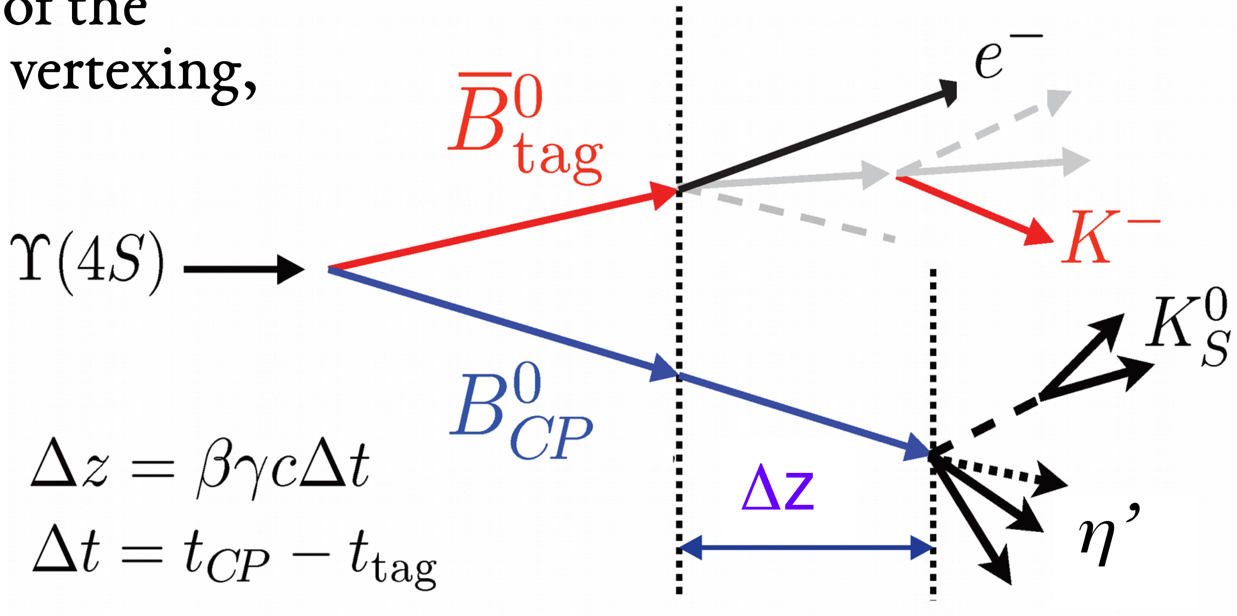
**Current precision: ~5°**

$$\phi_1 \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

**Current precision: ~0.7°**

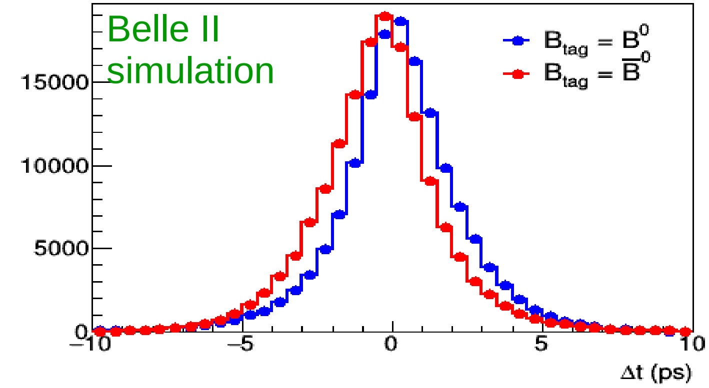
# $\sin 2\phi_1$: overview

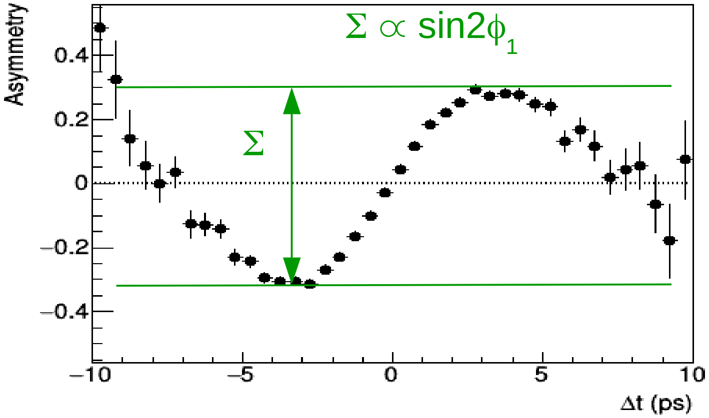
- Flagship analysis of the first generation of B-factories, exploiting the fact that the B's are produced in an entangled state;
- Severe test for all the aspects of the experiment (reconstruction, vertexing, PID, background rejection).



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

$$\Delta t = t_{CP} - t_{\rm tag}$$





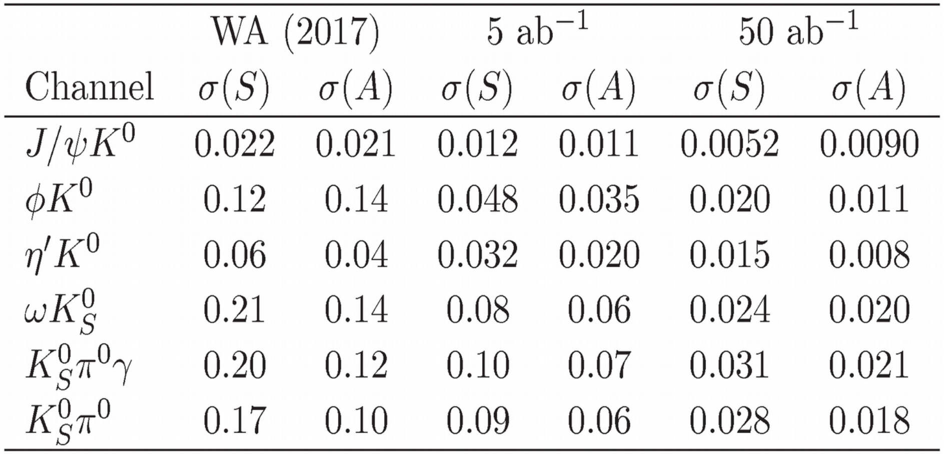
<Δz> ~ 130 μm at Belle II

$$\boxed{\begin{aligned} \mathcal{A}_f(\Delta t) &= \frac{\Gamma(\overline{B}^0(\Delta t) \to \eta' K^0_S) - \Gamma(B^0(\Delta t) \to \eta' K^0_S)}{\Gamma(\overline{B}^0(\Delta t) \to \eta' K^0_S) + \Gamma(B^0(\Delta t) \to \eta' K^0_S)} \\ &= S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t) \end{aligned}}$$

# sin2$\phi_1$: status and motivations

- On the golden modes ($B^0 \to c\bar{c}\, K^0$) we are definitely in the precision era (soon will be limited by systematics):

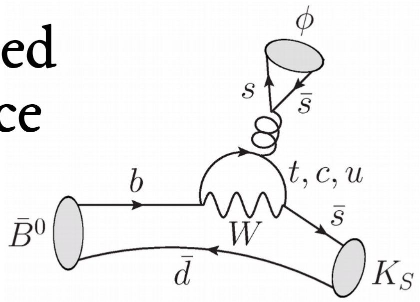
HFLAV Average: S = 0.691 ± 0.017



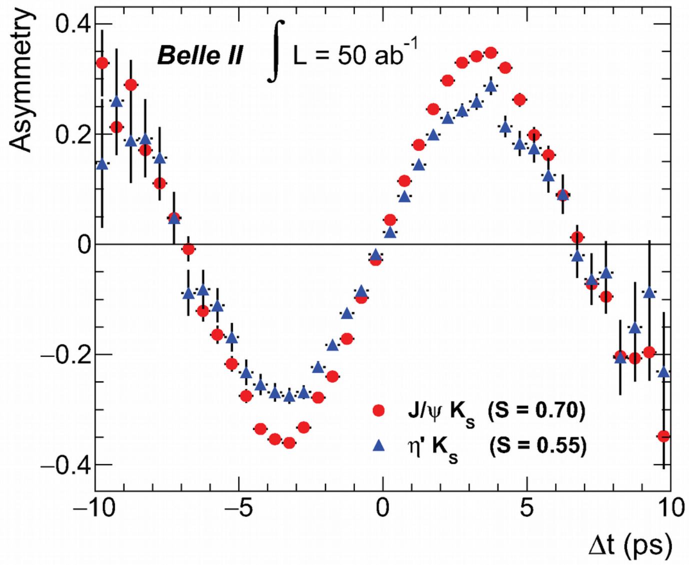
|  | WA (2017) |  | 5 ab$^{-1}$ |  | 50 ab$^{-1}$ |  |
|---|---|---|---|---|---|---|
| Channel | $\sigma(S)$ | $\sigma(A)$ | $\sigma(S)$ | $\sigma(A)$ | $\sigma(S)$ | $\sigma(A)$ |
| $J/\psi K^0$ | 0.022 | 0.021 | 0.012 | 0.011 | 0.0052 | 0.0090 |
| $\phi K^0$ | 0.12 | 0.14 | 0.048 | 0.035 | 0.020 | 0.011 |
| $\eta' K^0$ | 0.06 | 0.04 | 0.032 | 0.020 | 0.015 | 0.008 |
| $\omega K^0_S$ | 0.21 | 0.14 | 0.08 | 0.06 | 0.024 | 0.020 |
| $K^0_S \pi^0 \gamma$ | 0.20 | 0.12 | 0.10 | 0.07 | 0.031 | 0.021 |
| $K^0_S \pi^0$ | 0.17 | 0.10 | 0.09 | 0.06 | 0.028 | 0.018 |

- Challenge both for the **experiment** and for the **theory**: no longer possible to neglect penguin pollution – can be controlled experimentally by SU(3) related modes, e.g. $B^0 \to J/\psi\, \pi^0$;

- Additional motivation: compare the time-dependent asymmetry between tree- and loop-dominated modes, New Physics could produce a sizable shift.

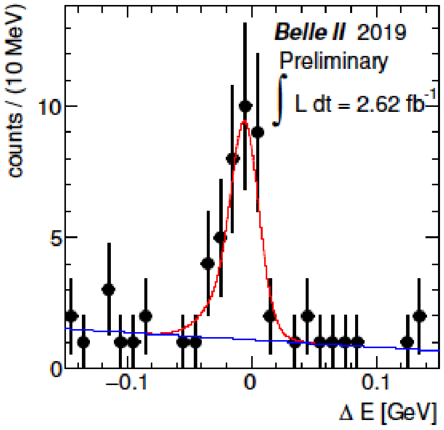


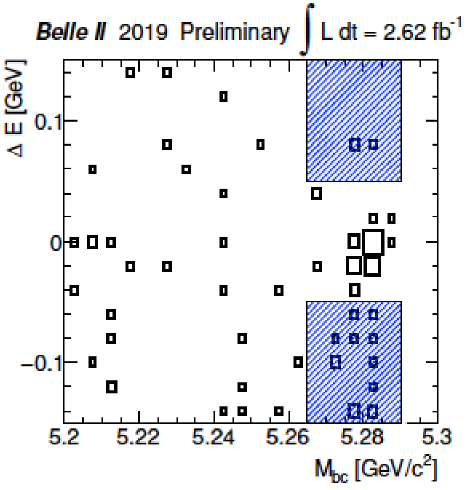
Simulation: dream scenario!



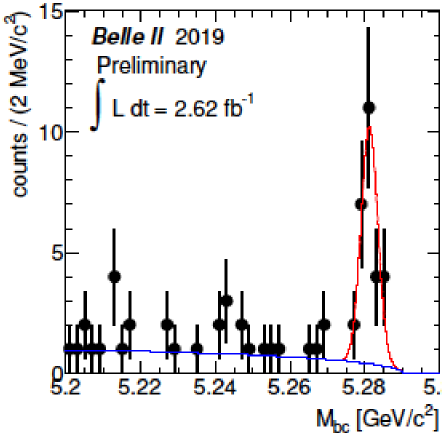
# Rediscovery of $B^0 \rightarrow J/\psi\, K^{(*)}$

## $B^0 \rightarrow J/\psi\, K^0_s,\ K^0_s \rightarrow \pi^+\pi^-$

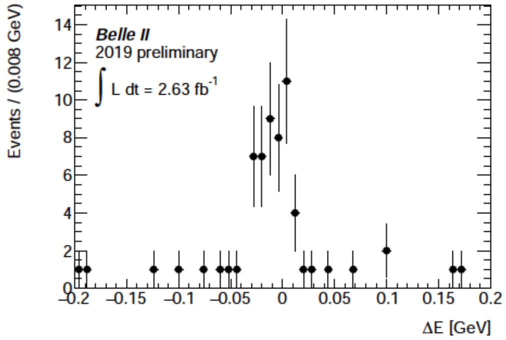


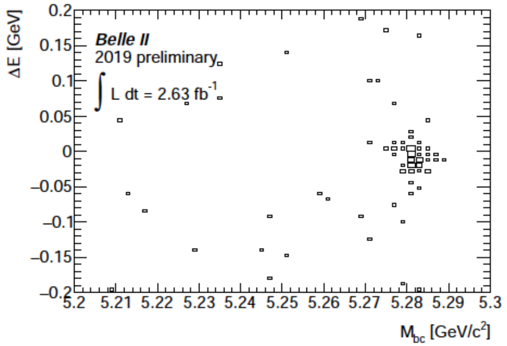


$N_{sig} = 26.9 \pm 5.2$

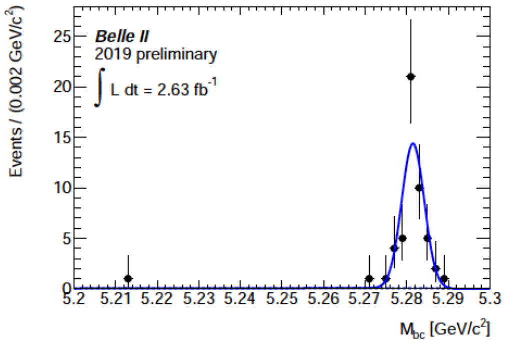


## $B^0 \rightarrow J/\psi\, K^{*0},\ K^{*0} \rightarrow K^-\pi^+$





$N_{sig} = 48.6 \pm 7.0$



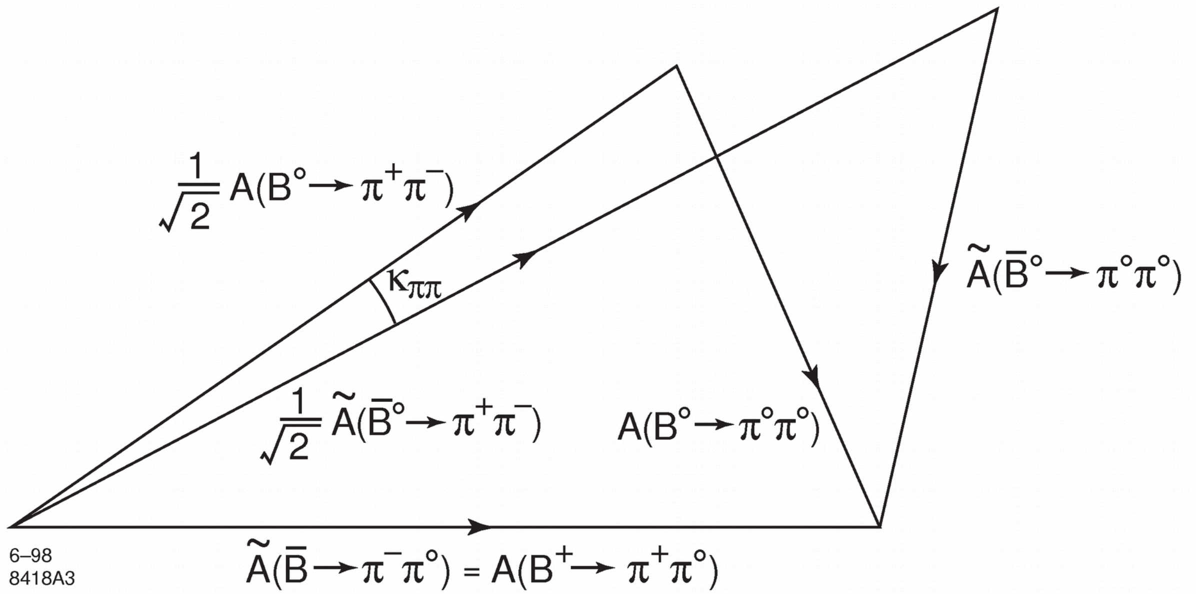
Not useful for measuring CP violation, but very useful to study vertexing resolution (comparing the J/ψ and the K* vertices)

# Measurements of $\phi_2$

- The measurement of $\phi_2$ from B → ππ (or B → ρρ) final states comes from an isospin analysis:

The following equalities hold:

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



see e.g. Eur. Phys. J. C77 (2017) no. 8, 574

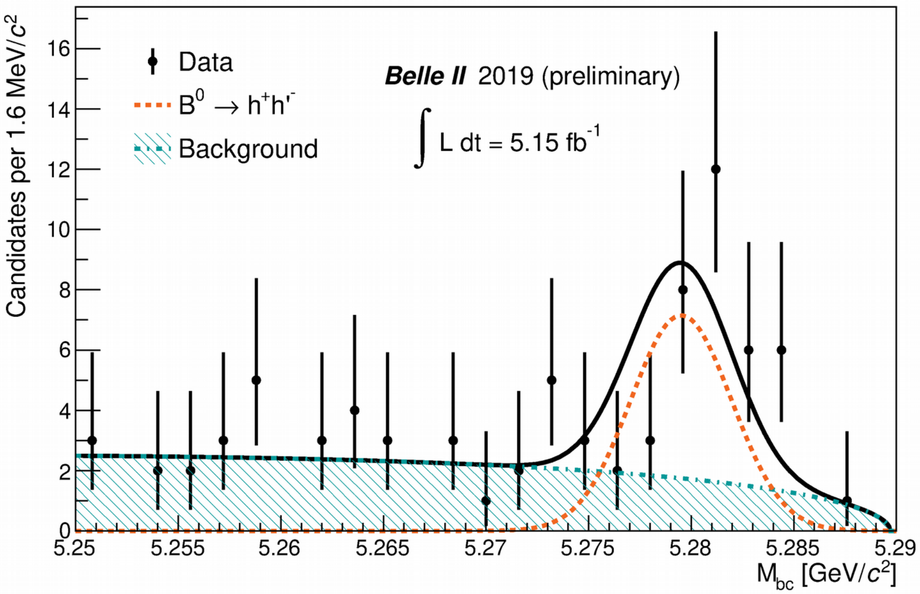
- Observables (for e.g. B → ππ):
  - branching fractions of: $B^\circ \to \pi^+\pi^\circ, \pi^+\pi^-, \pi^\circ\pi^\circ$;
  - direct (time independent) CP asymmetries: $C^{+-}$, $C^{\circ\circ}$;
  - time dependent CP asymmetries: $S^{+-}$, $S^{\circ\circ}$.

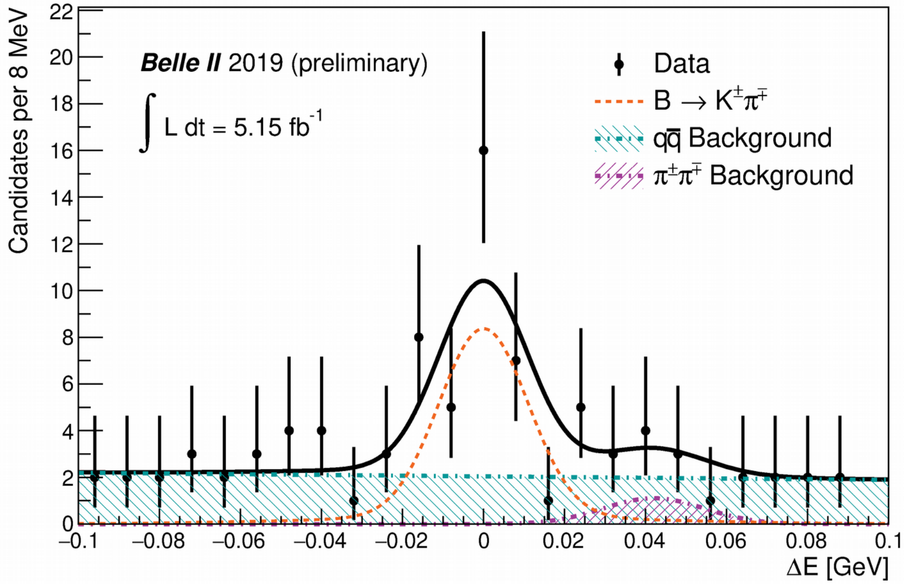
This will be measured for the first time at Belle II

- LHCb will make precise measurements of $B^\circ \to \pi^+\pi^-$ and $B^\circ \to \rho^\circ\rho^\circ$, but won't be able to make a full isospin analysis.

# Rediscovery of $B \to h^+h'^-$

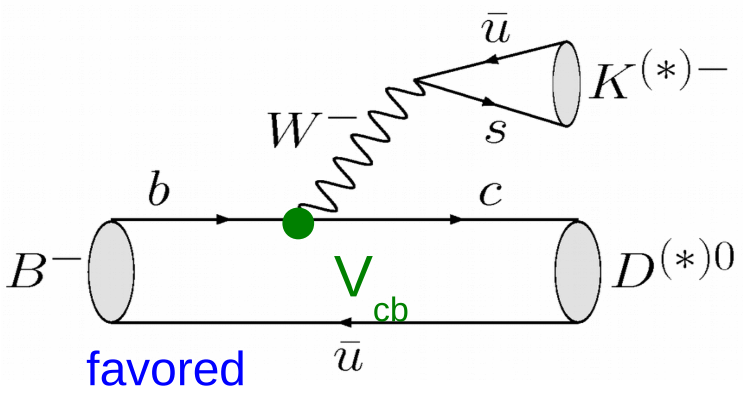
- First milestone for the measurement of $\phi_2$: rediscovery of the charmless $B \to h^+h'^-$ decays;
- Continuum background is suppressed using a BDT classifier utilizing variables sensitive to the event topology;
- Only very loose PID requirements on the final state particles;
- A clear signal (~25 events) is observed for the $K^+\pi^-$ mode;
- More statistics will be needed to observe the more elusive $\pi^+\pi^-$ signal.



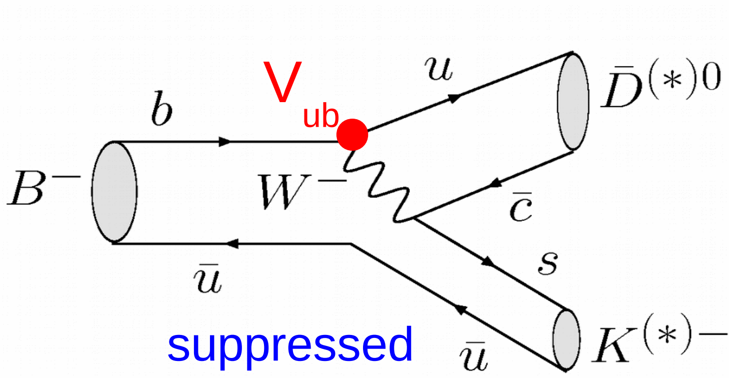


# Measurements of $\phi_3$

- The most powerful way to measure $\phi_3$ is through the time integrated analysis of $B^- \to \bar{D}^\circ K^-$ decays, exploiting the interference:



favored

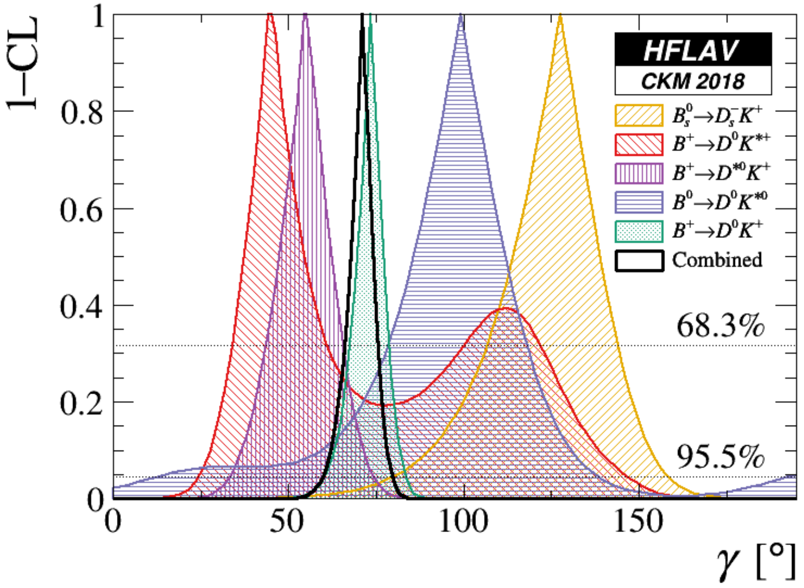


suppressed

**Key parameter:**

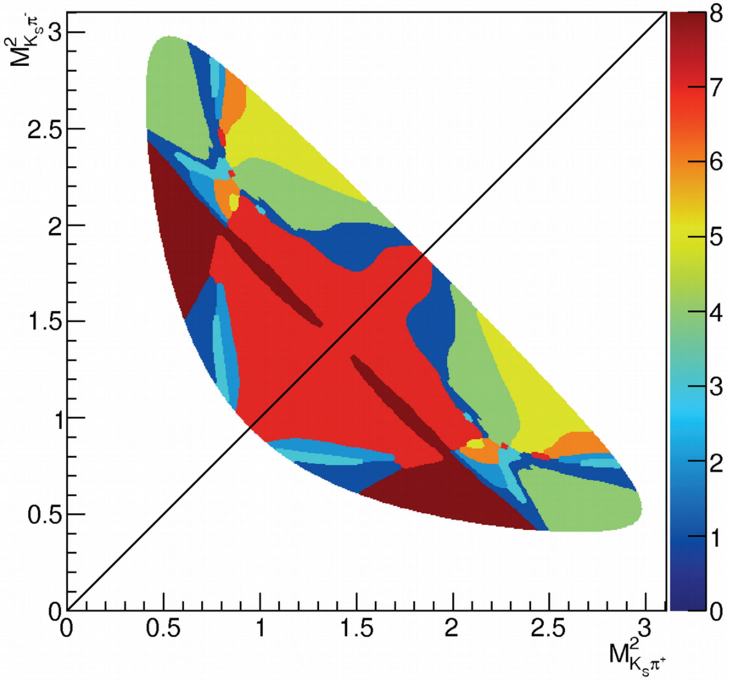
$$\boxed{r_B = \left|\frac{A(b \to u)}{A(b \to c)}\right|}$$

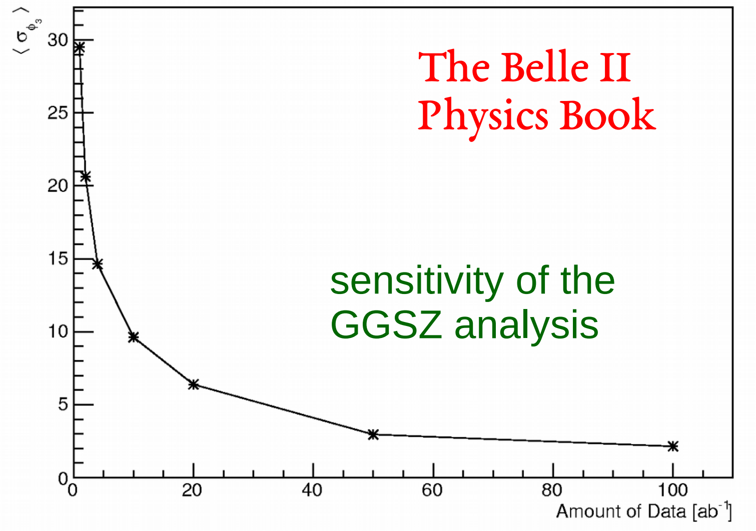
- Fundamental input for the CKM fit: this comes from tree level transitions;
- $\phi_3$ can also be measured from time dependent analyses of $B^\circ \to D^\pm\pi^\mp$ and $B_s \to D_s^{\pm}K^\mp$;
- LHCb is leading the competition (a lot of ground to recover for Belle II!).



# $\phi_3$ at Belle II

- Most sensitive method: GGSZ(*) analysis of the $D^\circ \rightarrow K_S\pi^+\pi^-$ Dalitz Plot, exploiting the large strong phases across the plane to enhance the sensitivity;
- Dominant systematics for the first BaBar and Belle measurements: choice of amplitude model (~9°);
- This can be overcome with a model independent DP (already pioneered at Belle and LHCb) and with strong phase measurements from BESIII;
- The sensitivity can be enhanced by including also the $K^+K^-K_S$, $K_S\pi^+\pi^-\pi^0$, $K_L\pi^+\pi^-$ and $D^{*\circ} \rightarrow D^\circ\gamma$ and $D^{*\circ} \rightarrow D^\circ\pi^\circ$ modes;
- Ultimate precision at Belle II (when all methods are combined): ~1°.





The Belle II Physics Book

sensitivity of the GGSZ analysis

(*) Giri, Grossman, Soffer, Zupan Phys. Rev. D68 (2003) 054018

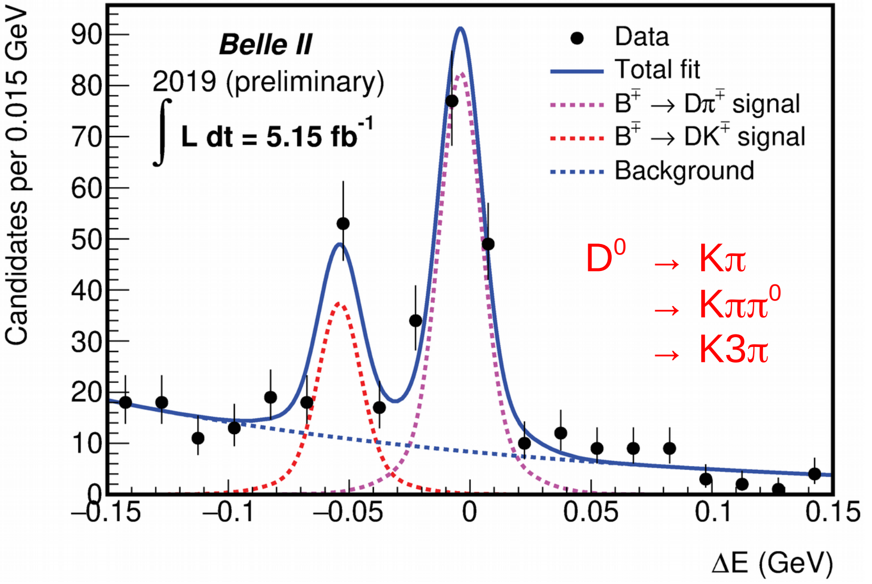
# Rediscovery of B → DK at Belle II

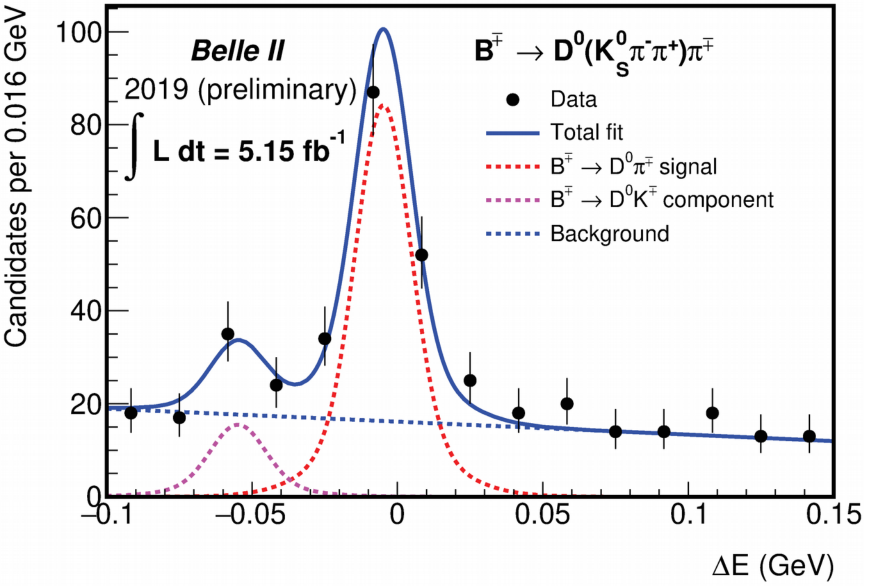
- Major milestone: rediscover the $B^+ \to D^\circ K^+$ signal, next to the higher branching fraction mode $B^+ \to D^\circ \pi^+$;
- Multivariate discriminator suppresses continuum background;
- Tight PID criteria for the $D^\circ \to K\pi$, $K\pi\pi^\circ$, $K3\pi$ modes:

pionID (bachelor hadron) < 0.4

(53 ± 9 B → DK signal events)

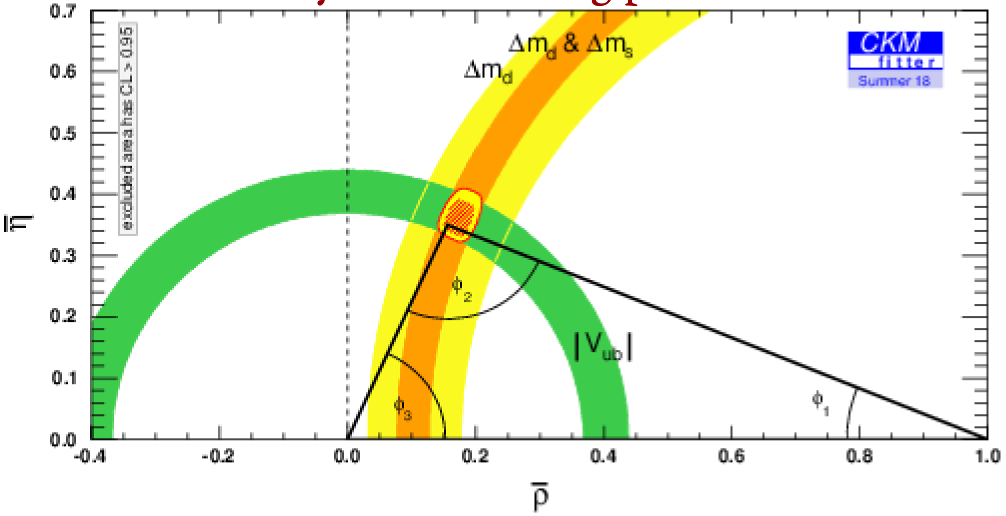
- Also the golden mode for the GGSZ analysis ($D^\circ \to K_S\pi^+\pi^-$) is starting to show up (new since Lepton Photon!).



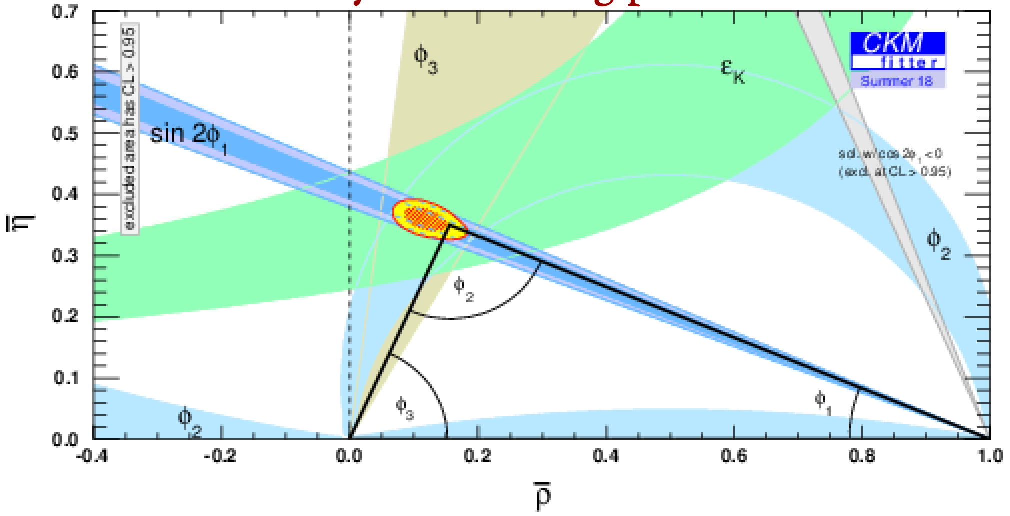


# CKM UT: status

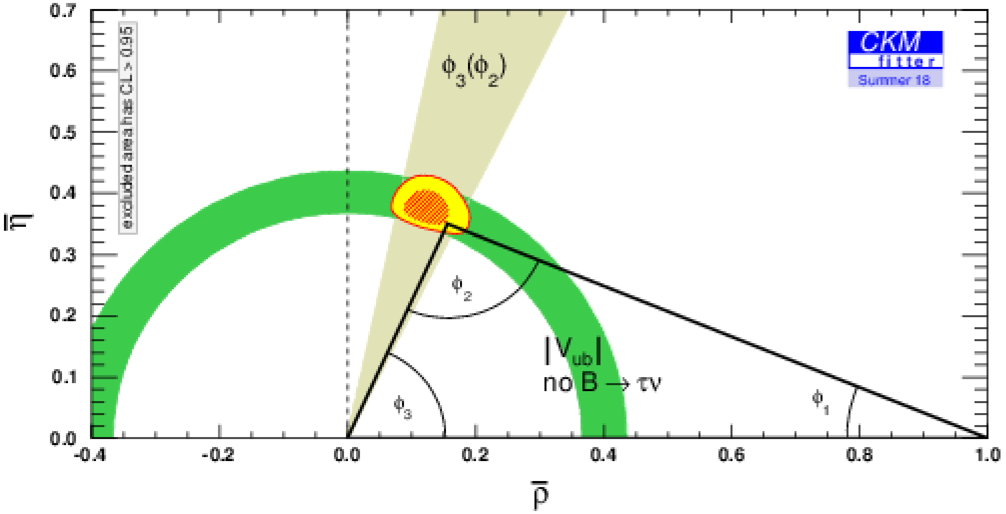
only CP conserving processes



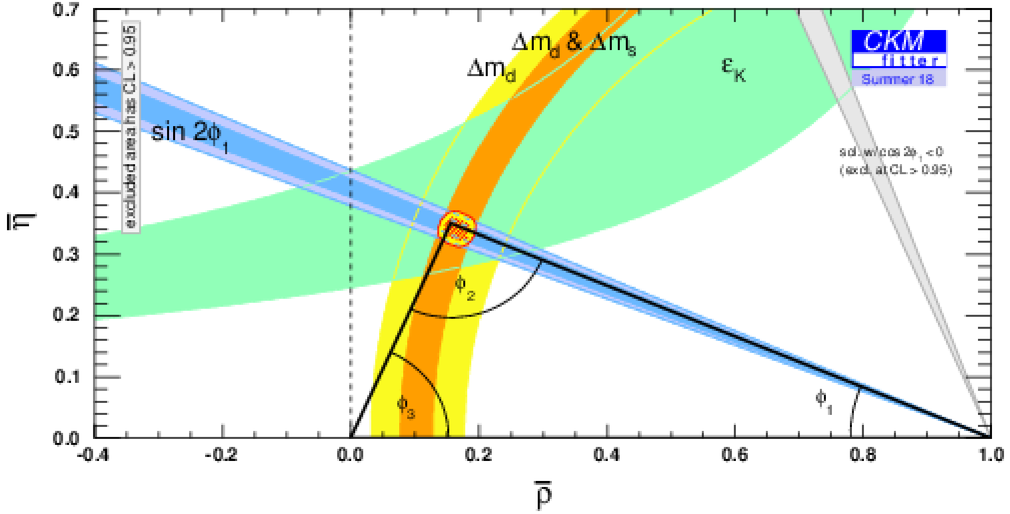
only CP violating processes



only tree processes



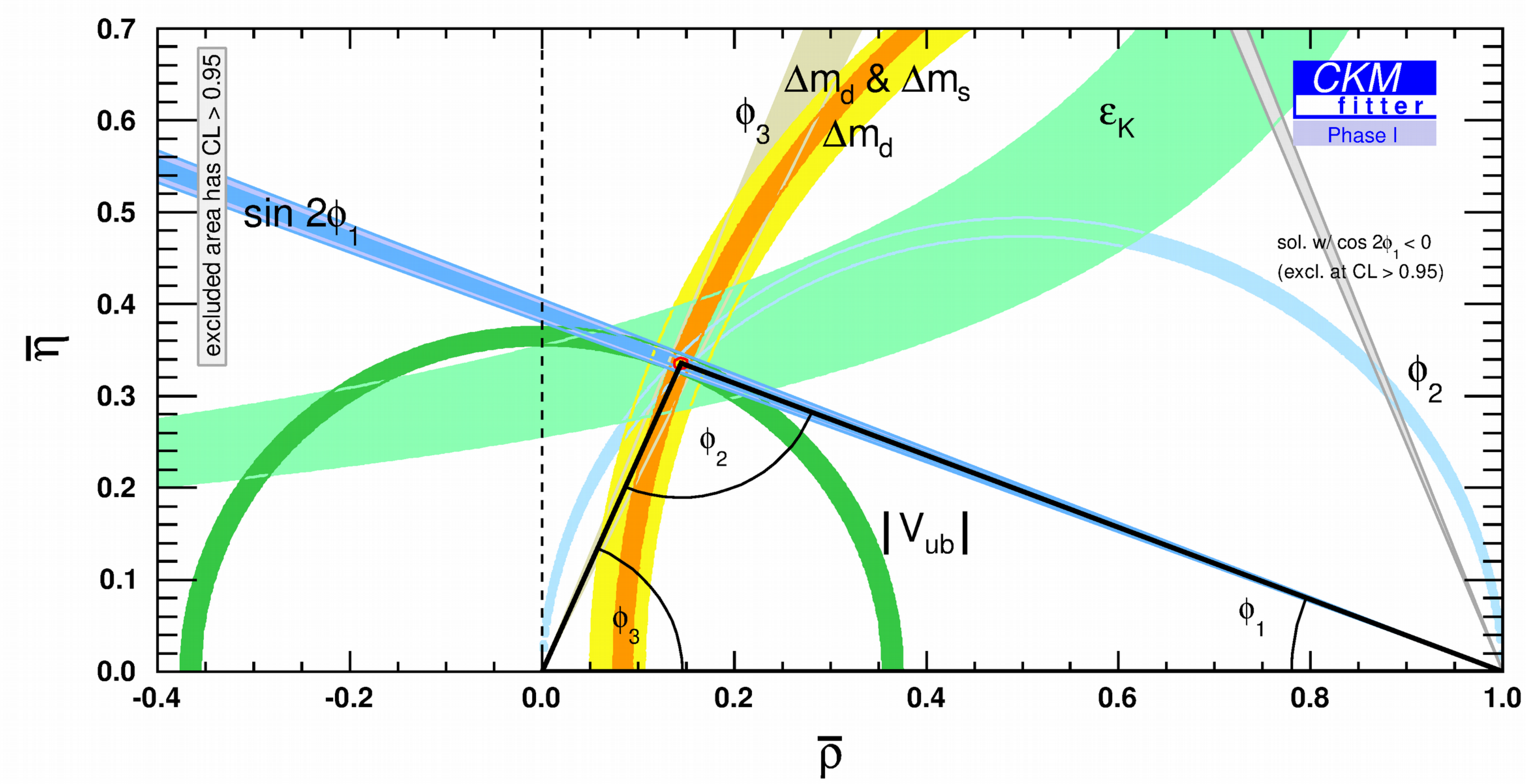
only loop processes



Some tensions here and there: maybe statistical fluctuations, maybe not...

# CKM UT: outlook

CKM Unitarity Triangle ~8 years from now:



Assumptions: Belle II 50 ab$^{-1}$, LHCb 23 fb$^{-1}$

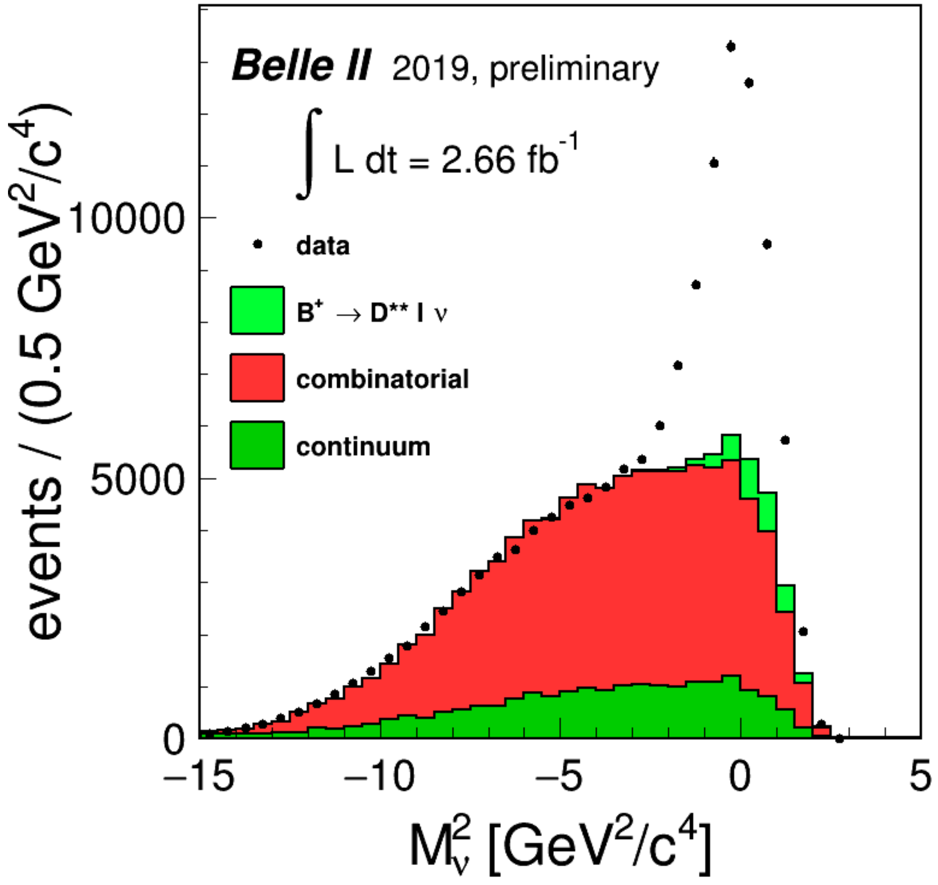
# Conclusions

- The complete Belle II detector successfully started its physics program;
- The dataset is still too small to make a dent on the current picture of the CKM Unitarity Triangle but:
  - ➔ the detector is working mostly as expected;
  - ➔ we will enter the real game very soon: we expect to have ~1 $ab^{-1}$ by Summer 2021;
- Belle II will give critical contributions to:
  - ➔ solving the inclusive vs exclusive $|V_{ub}|$ / $|V_{cb}|$ puzzle;
  - ➔ measuring the CKM angles $\phi_1$ and $\phi_2$ on a large number of channels…
- … and will be competitive/complementary to LHCb on many other areas;
- We are looking forward to one decade of big progress in Flavor Physics!

# Backup Slides

# Rediscovery of $B\bar{B}$ mixing

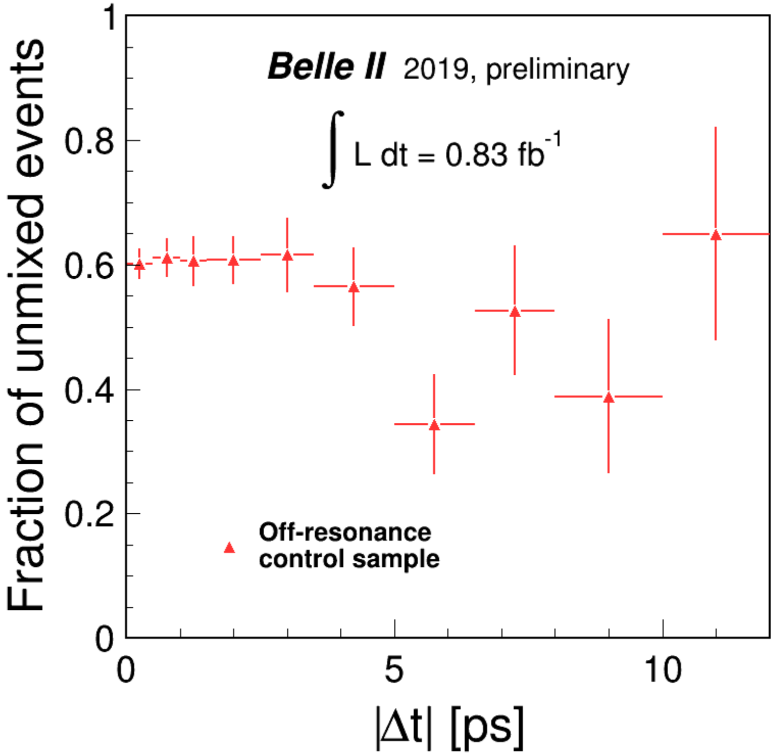
- One partially reconstructed $B^0 \to D^{*-} l^+ \nu$ candidate in the event is required;
- Major background: $B\bar{B}$ combinatorial, estimated from the data using same-sign ($\pi_s$, $l$) pairs, and normalizing to the $M^2_\nu < -3$ GeV$^2$ sideband;
- Continuum is taken from the off-resonance sample (taking into account the integrated luminosity ratio with the on-resonance);
- The fraction of peaking backgrounds within the peaking component is taken from the simulation.



**~35k peaking $B^0$ events**

# Rediscovery of $B\overline{B}$ mixing

| Channel | Data |
|---|---|
| Untagged $e$ only | $18514 \pm 1128$ |
| Untagged $\mu$ only | $16625 \pm 1111$ |
| Untagged ($e$ or $\mu$) | $35492 \pm 2209$ |
| Tagged unmixed ($N_U$) | $1642 \pm 133$ |
| Tagged mixed ($N_M$) | $253 \pm 45$ |
| ($\varepsilon_U/\varepsilon_M$) correction factor | $1.35 \pm 0.10$ |
| $\chi_d$ (fraction of mixed events) | $\boxed{(17.2 \pm 3.6)\%}$ |



$\chi^2$ probability of a fit with a flat line: ~13%

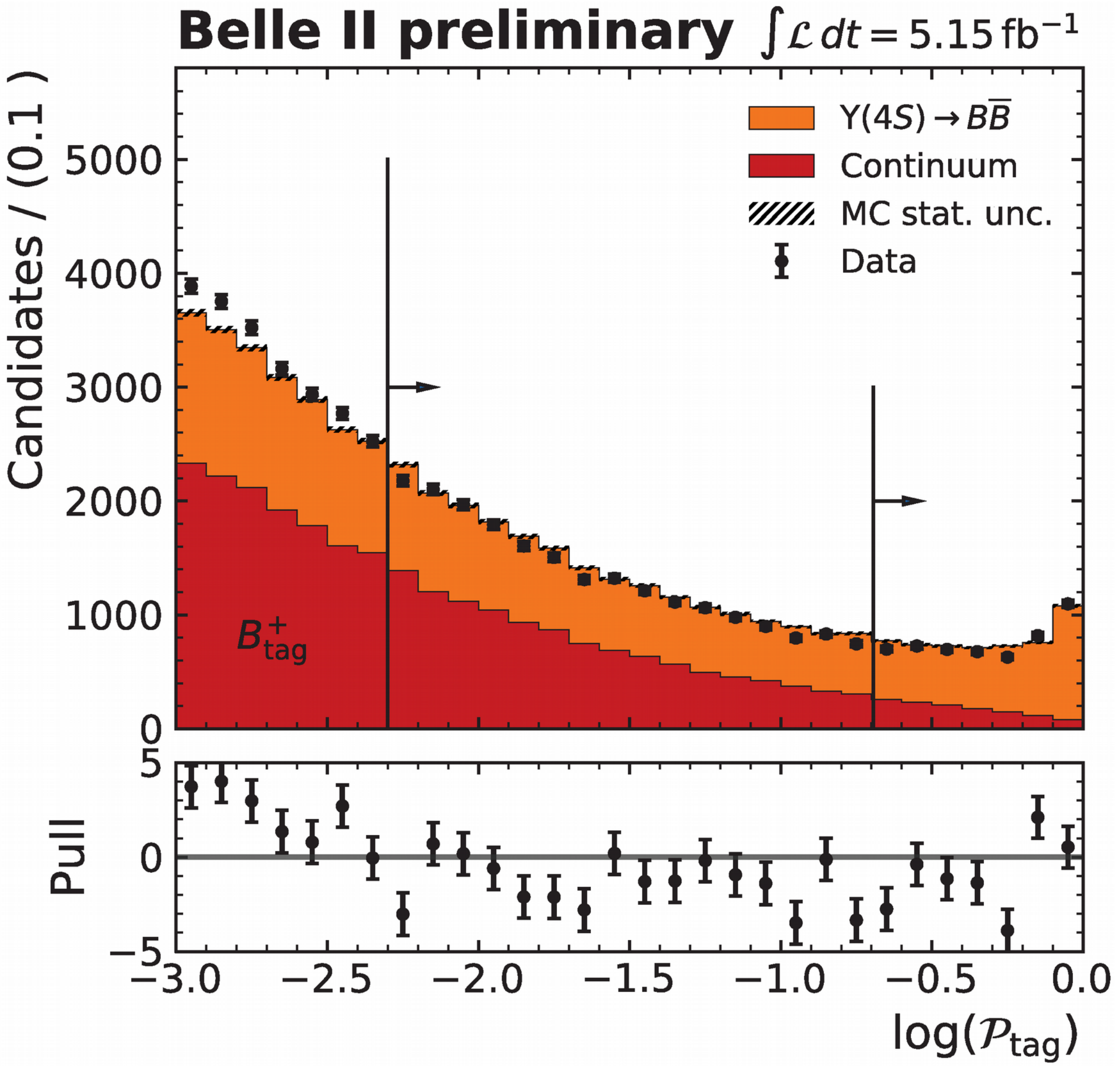
**Experimentally:**

$$\chi_d = \frac{N_M/\varepsilon_M}{N_U/\varepsilon_U + N_M/\varepsilon_M} = \frac{N_M \cdot \left(\frac{\varepsilon_U}{\varepsilon_M}\right)}{N_U + N_M \cdot \left(\frac{\varepsilon_U}{\varepsilon_M}\right)}$$

**Connection with $\tau_B$ and Δm:**

$$\chi_d = \frac{\tau_{B^0}^2 \Delta m^2}{2(1 + \tau_{B^0}^2 \Delta m^2)}$$

# FEI probability



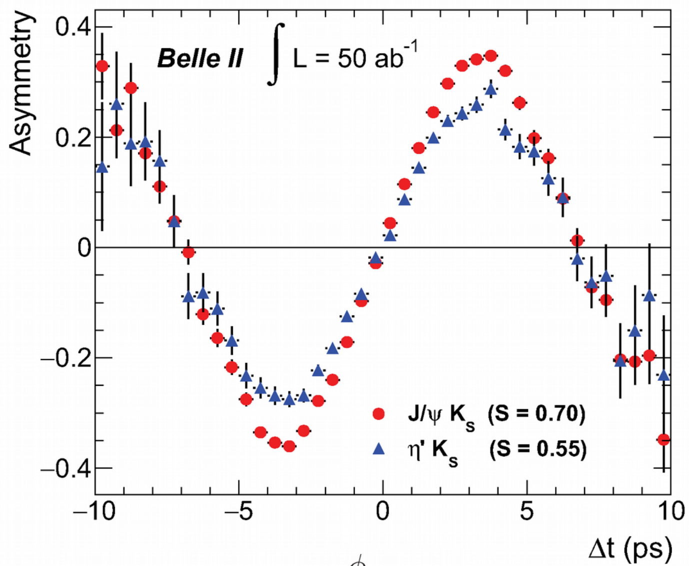
# $\sin 2\phi_1$: status and motivations

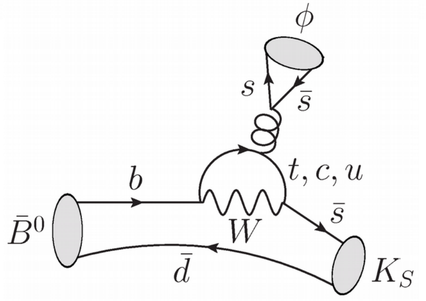
- On the golden modes ($B^\circ \to c\bar{c}\, K^\circ$) we are definitely in the precision era:

| | | | |
|---|---|---|---|
| Int. lumi: 426 $fb^{-1}$ | BaBar: | $S = 0.687 \pm 0.028 \pm 0.012$ | PRD **79**, 072009 (2009) |
| Int. lumi: 711 $fb^{-1}$ | Belle: | $S = 0.667 \pm 0.023 \pm 0.012$ | PRL **108**, 171802 (2012) |
| Int. lumi: 3.0 $fb^{-1}$ | LHCb: | $S = 0.731 \pm 0.035 \pm 0.020$ | PRL **115**, 031601 (2015) |

HFLAV Average: $S = 0.691 \pm 0.017$

- Challenge both for the **experiment** (the measurement will be systematics dominated) and for the **theory** (no longer possible to neglect penguin pollution);
- Additional motivation: compare the time-dependent asymmetry between tree- and loop-dominated modes, New Physics could produce a sizable shift.





# $\sin 2\phi_1$: projections

- Breakdown of systematics:

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

Two major irreducible systematics:

1) vertex detector alignment;

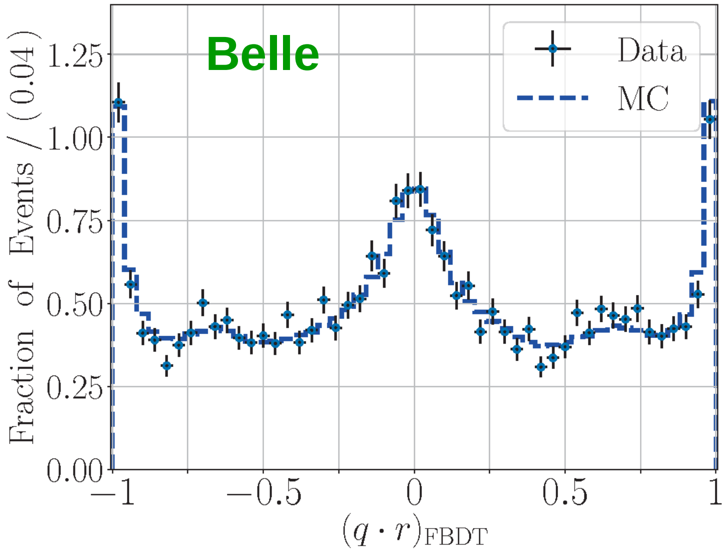
2) Doubly Cabibbo Suppressed decays on tag-side (does not affect leptonic categories)

- Prospects on the golden channels: Belle II will lead on most penguin dominated modes.

| | WA (2017) | | 5 $\text{ab}^{-1}$ | | 50 $\text{ab}^{-1}$ | |
|---|---|---|---|---|---|---|
| Channel | $\sigma(S)$ | $\sigma(A)$ | $\sigma(S)$ | $\sigma(A)$ | $\sigma(S)$ | $\sigma(A)$ |
| $J/\psi K^0$ | 0.022 | 0.021 | 0.012 | 0.011 | 0.0052 | 0.0090 |
| $\phi K^0$ | 0.12 | 0.14 | 0.048 | 0.035 | 0.020 | 0.011 |
| $\eta' K^0$ | 0.06 | 0.04 | 0.032 | 0.020 | 0.015 | 0.008 |
| $\omega K_S^0$ | 0.21 | 0.14 | 0.08 | 0.06 | 0.024 | 0.020 |
| $K_S^0 \pi^0 \gamma$ | 0.20 | 0.12 | 0.10 | 0.07 | 0.031 | 0.021 |
| $K_S^0 \pi^0$ | 0.17 | 0.10 | 0.09 | 0.06 | 0.028 | 0.018 |

# Belle II Flavor Tagger

We can test the performance of the new Flavor Tagger on Belle data converted to Belle II format:



FBDT Combiner

| $r$- Interval | $\varepsilon_i$ | $w_i \pm \delta w_i$ | $\varepsilon_{{\rm eff},i} \pm \delta\varepsilon_{{\rm eff},i}$ |
|---|---|---|---|
| 0.000 – 0.100 | 15.49 | $47.61 \pm 0.04$ | $0.035 \pm 0.002$ |
| 0.100 – 0.250 | 15.81 | $41.42 \pm 0.06$ | $0.465 \pm 0.014$ |
| 0.250 – 0.500 | 19.88 | $31.57 \pm 0.09$ | $2.695 \pm 0.066$ |
| 0.500 – 0.625 | 10.68 | $21.87 \pm 0.06$ | $3.375 \pm 0.110$ |
| 0.625 – 0.750 | 11.52 | $15.68 \pm 0.06$ | $5.416 \pm 0.169$ |
| 0.750 – 0.875 | 9.68 | $9.39 \pm 0.07$ | $6.372 \pm 0.219$ |
| 0.875 – 1.000 | 16.77 | $2.32 \pm 0.05$ | $15.226 \pm 0.382$ |
| Total | $\varepsilon_{\rm eff} = \sum_i \varepsilon_i \cdot \langle 1 - 2w_i \rangle^2 = 33.6 \pm 0.5$ | | |

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

effective tagging efficiency

efficiency of category i

mis-tagging probability of category i

**Summary**

Old FT - Belle data: $\varepsilon_{\rm eff} = (30.1 \pm 0.4)\%$

New FT - Belle data: $\varepsilon_{\rm eff} = (33.6 \pm 0.5)\%$

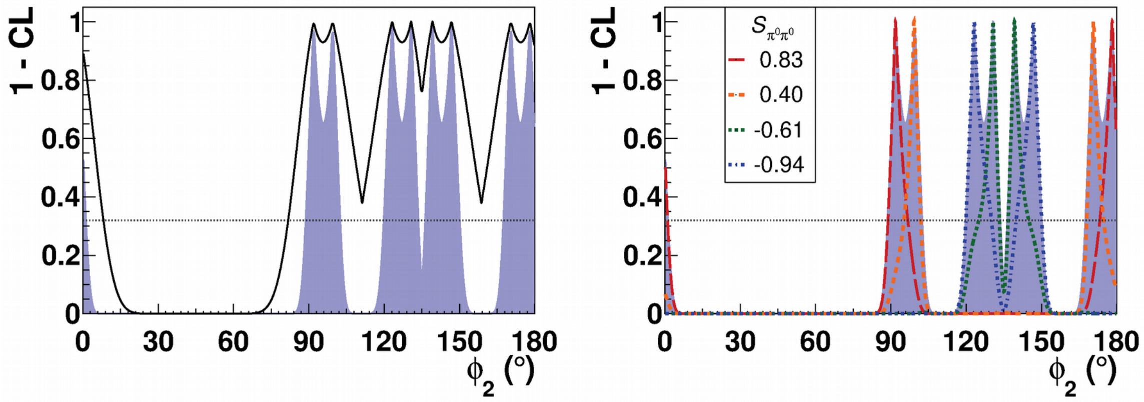
New FT - Belle MC: $\varepsilon_{\rm eff} = (34.18 \pm 0.03)\%$

New FT - Belle II MC: $\varepsilon_{\rm eff} = (37.16 \pm 0.03)\%$

More than 10% relative improvement on the same dataset!

# TD CPV analysis of $B^0 \to \pi^0\pi^0$

- Only at Belle II: TD CPV of $B^0 \to \pi^0\pi^0$, exploiting $\pi^0$ Dalitz decays and $\gamma$ conversions;
- Expect ~270 signal events with full dataset;
- Predicted error on $S^{00}$ ~ 0.28;
- This would reduce the ambiguity on $\phi_2$ by a factor 2 or 4 (depending on central value);

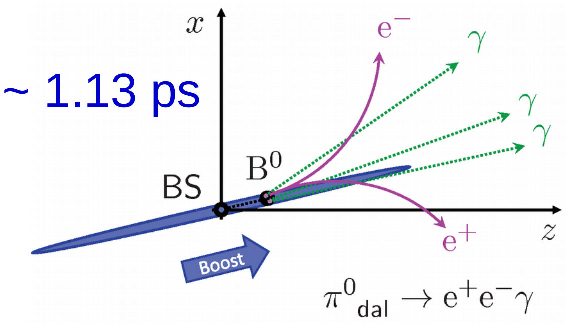


Filled area: extrapolation of Belle results to Belle II sensitivity.

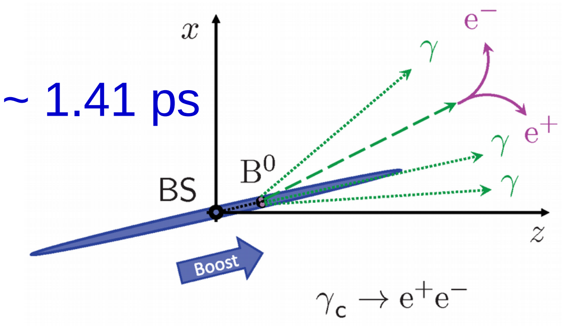
Dashed line: same as above, but adding $S^{00}$.

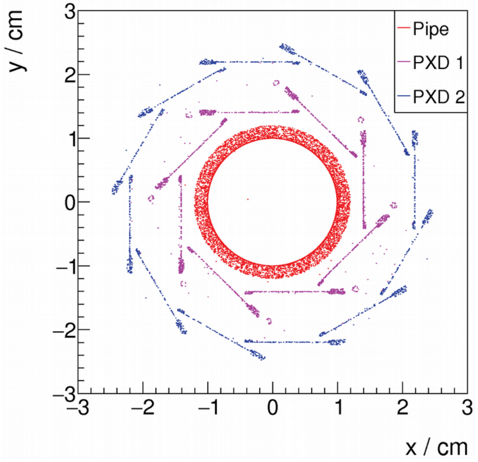
- Final precision at Belle II (50 $ab^{-1}$) from $B \to \pi\pi$ and $B \to \rho\rho$: $\sigma(\phi_2)$ ~ 0.6°.

$\Delta t_{res}$ ~ 1.13 ps



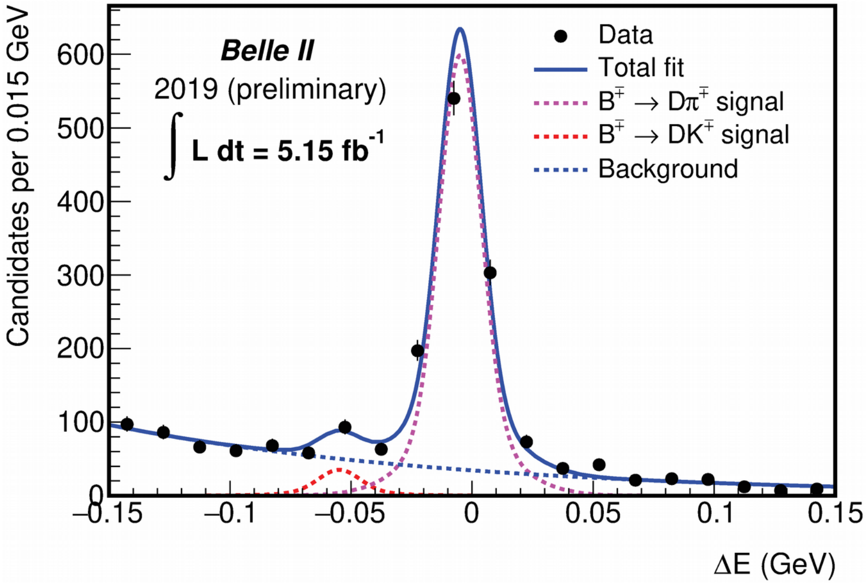
$\Delta t_{res}$ ~ 1.41 ps

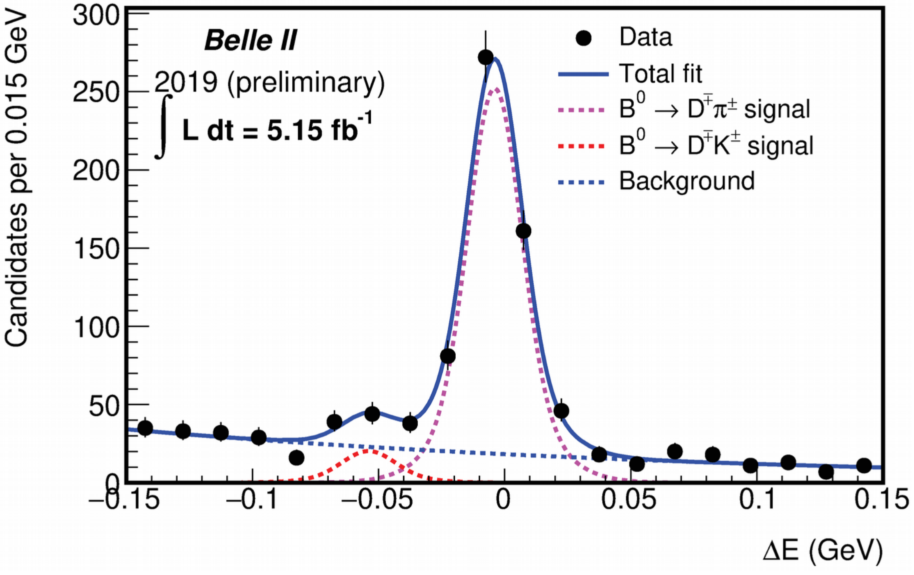




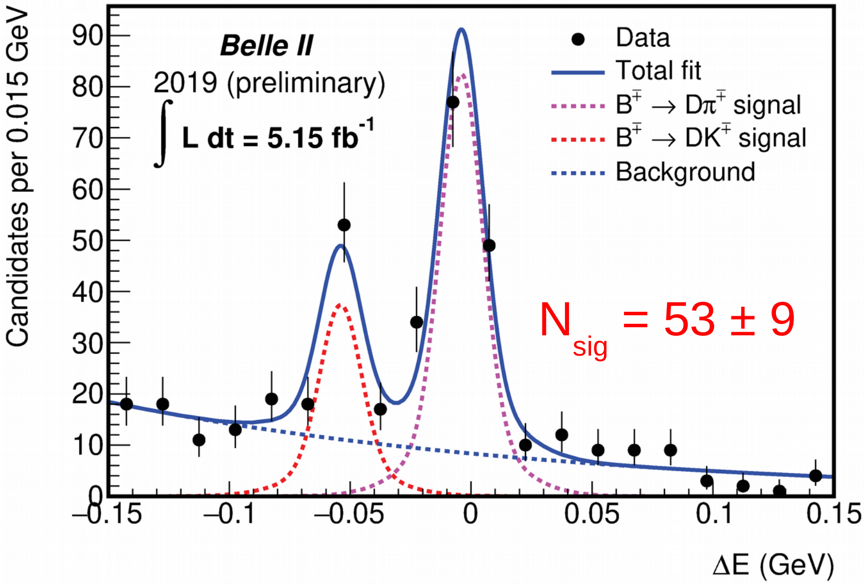
# Rediscovery of $B \to DK$

## No PID on bachelor hadron





## PID requirement on bachelor hadron



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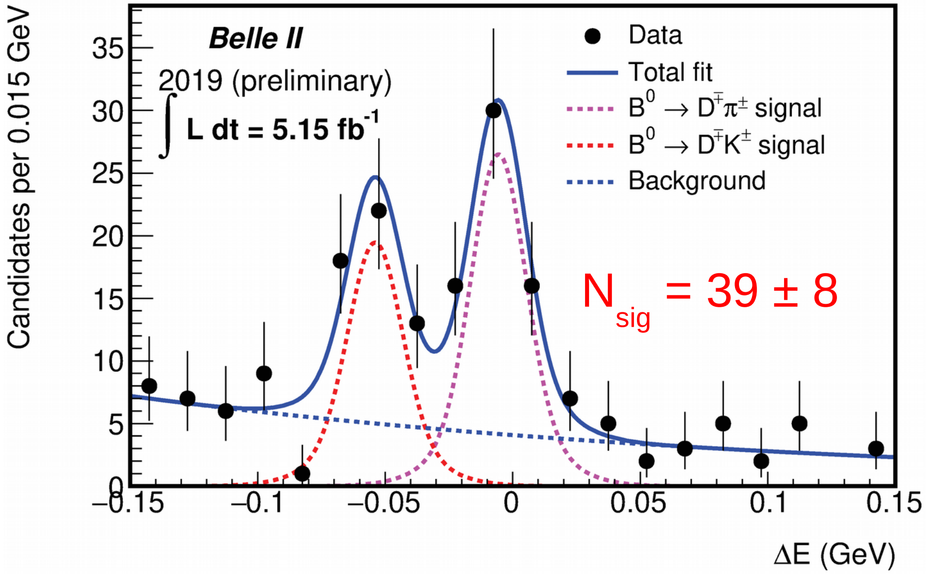

# Beam Energy Spread