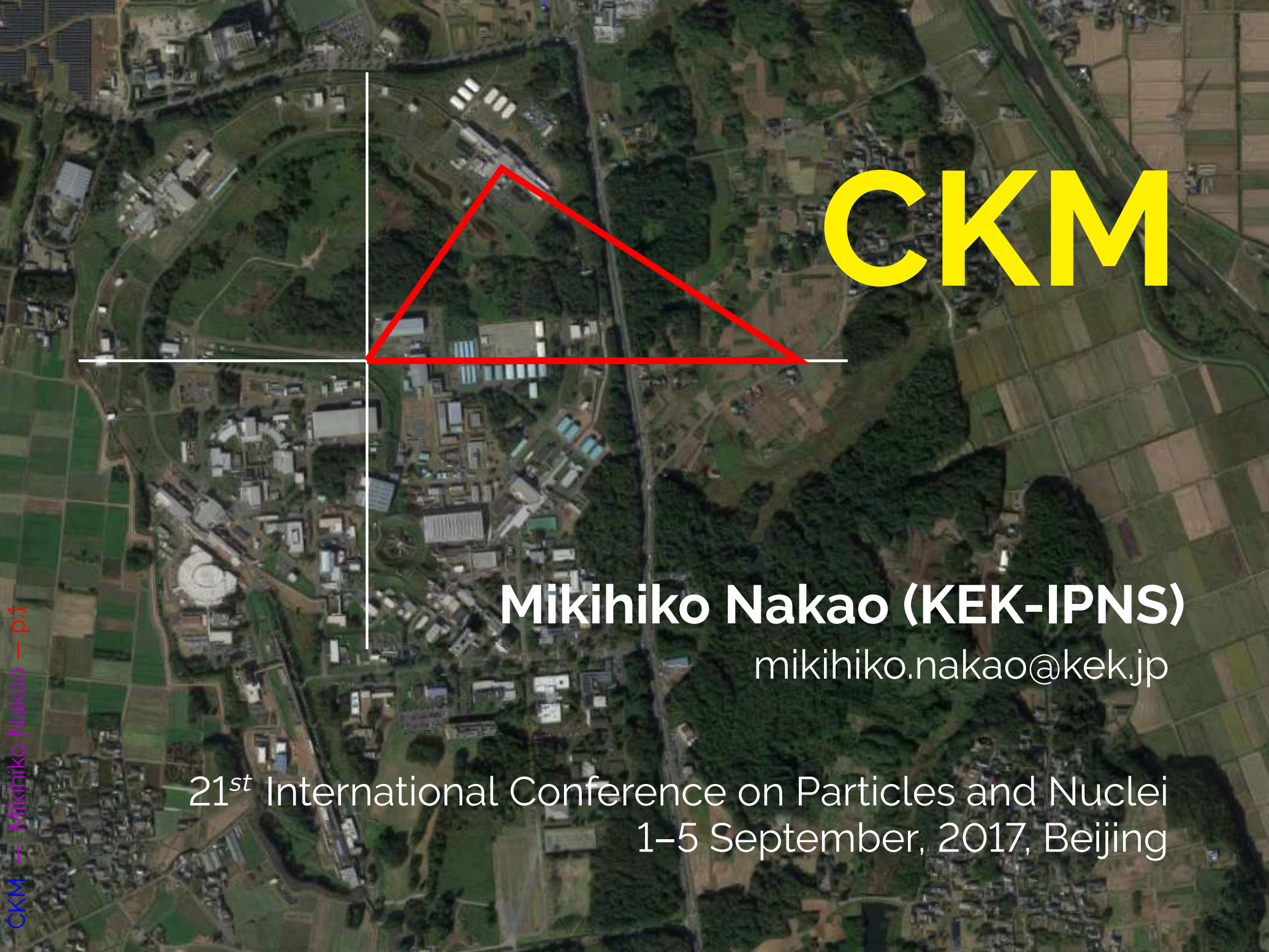
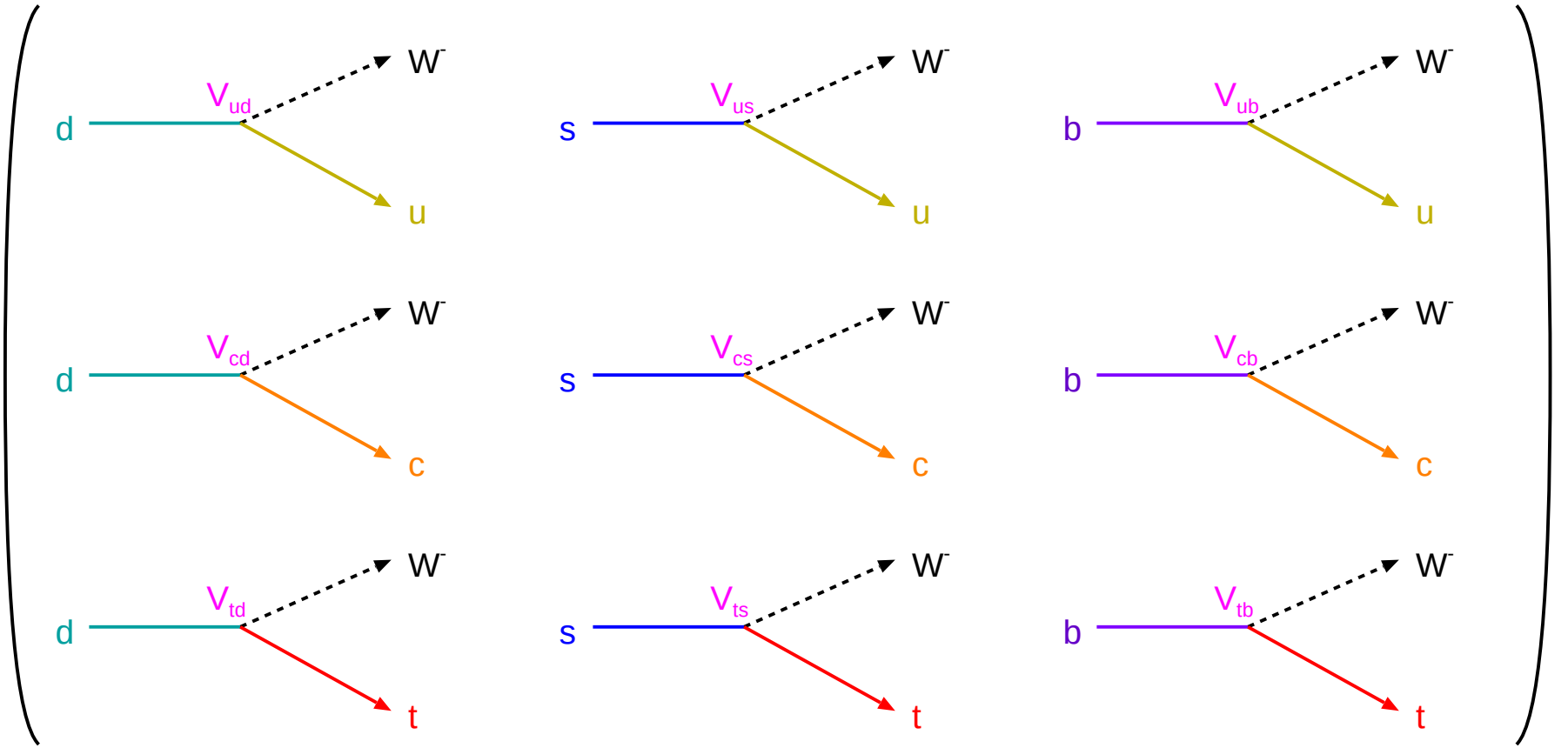


CKM

Mikihiko Nakao (KEK-IPNS)
mikihiko.nakao@kek.jp

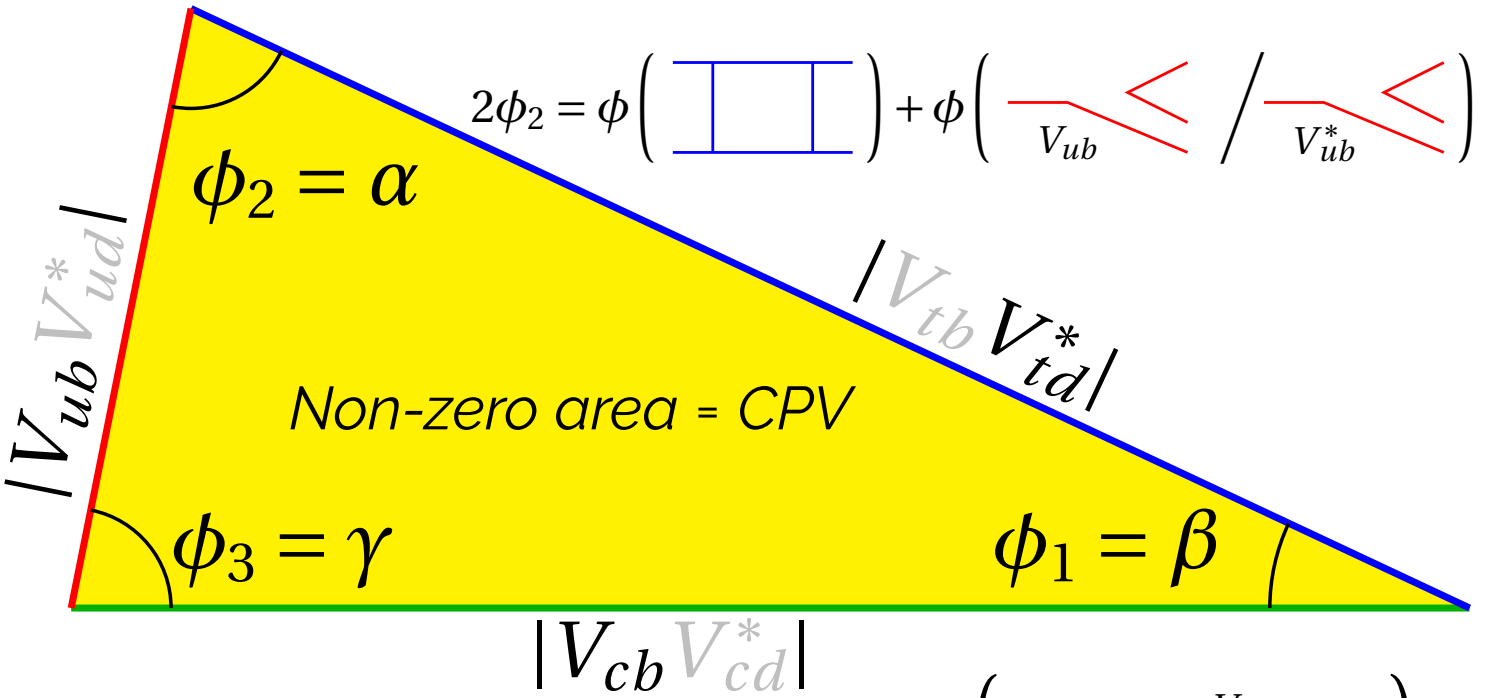
21st International Conference on Particles and Nuclei
1–5 September, 2017, Beijing

$V_{\text{Cabibbo}-\text{Kobayashi}-\text{Maskawa}} =$



Simple 3×3 complex matrix of tree-level quark transitions, loop and box diagrams give a rich structure, including CPV

Unitarity Triangle



$$\phi_3 = \phi\left(\quad\right)$$ V_{ub}

$$2\phi_1 = \phi\left(\quad\right)$$ $\overline{B}^0$ B^0 V_{td} V_{td}

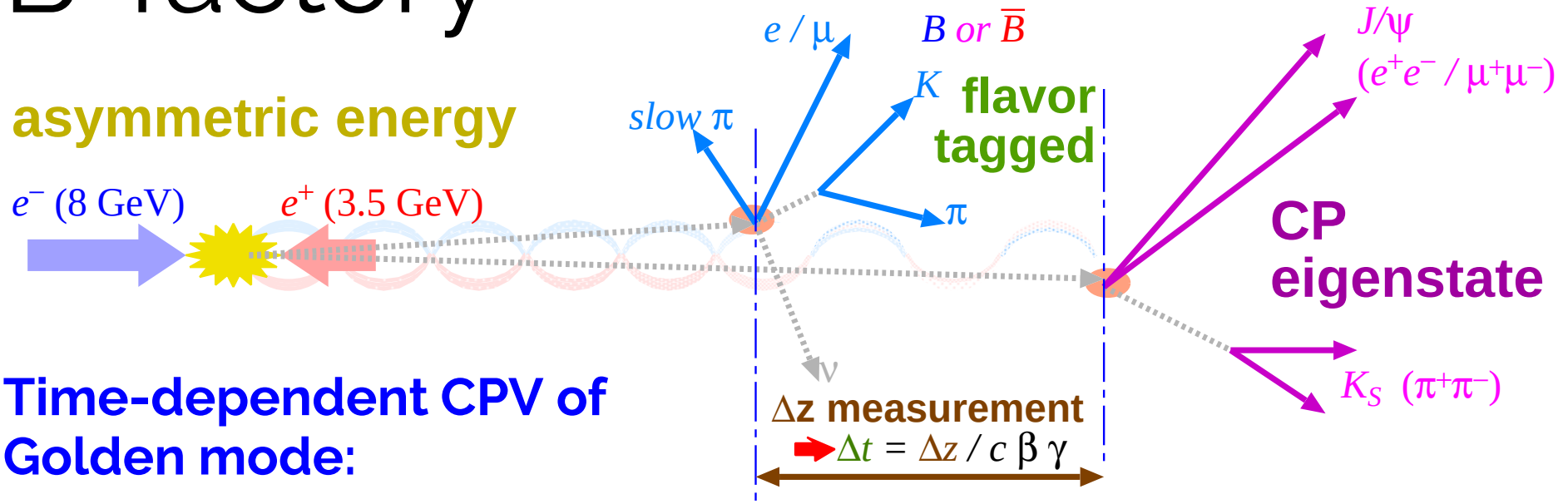
$$|V_{ub}|^2 \propto \left|\quad\right|^2 \text{ or } \left|\quad\right|^2$$ V_{ub} V_{ub}

$$|V_{cb}|^2 \propto \left|\quad\right|^2$$ V_{cb}

+ Hadronic uncertainties…

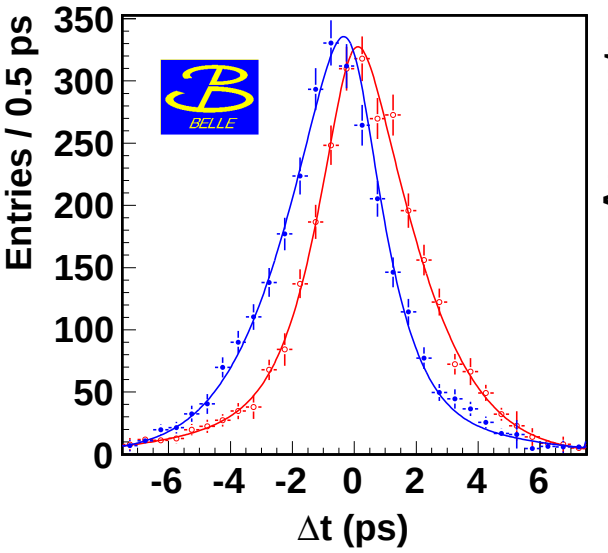
B-factory

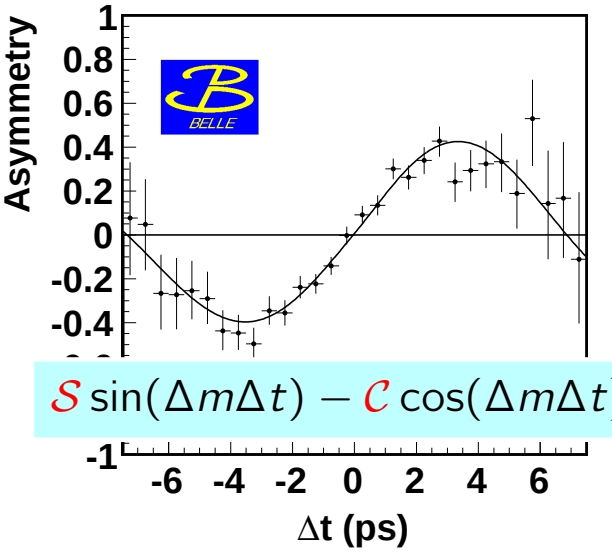
asymmetric energy



Time-dependent CPV of Golden mode:

- ✔ $B^0 \to J/\psi K_S$
- ✔ flavor tag
  $\epsilon_{\text{effective}} \sim 30\%$
- ✔ $\sigma(\Delta z) \sim 100\ \mu\text{m}$
  $\Leftrightarrow \langle \Delta z \rangle \sim 200 \mu\text{m}$

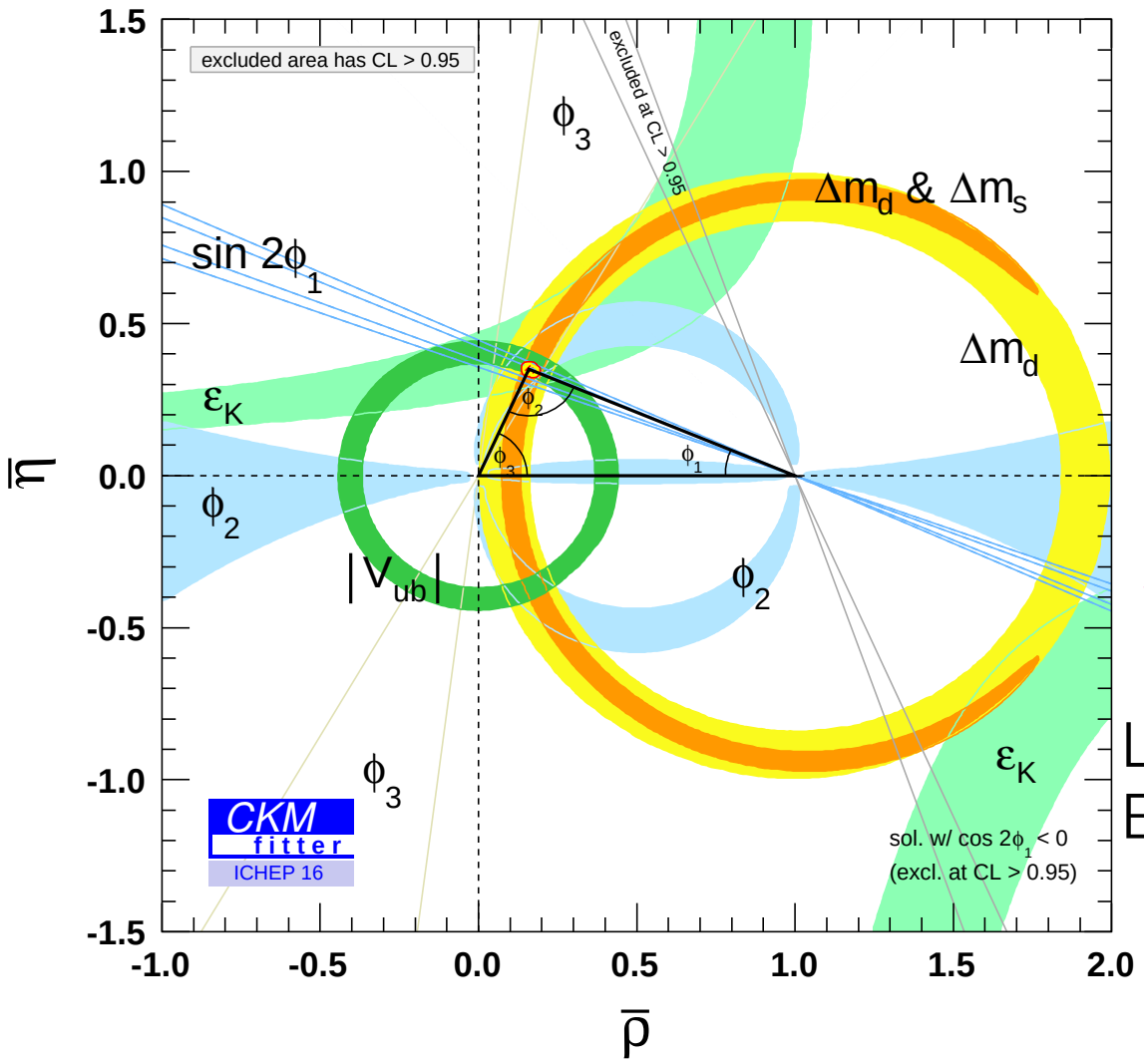




$\mathcal{S}\sin(\Delta m \Delta t) - \mathcal{C}\cos(\Delta m \Delta t)$

$\mathcal{S}_{c\bar{c}s} = \sin 2\phi_1 = +0.667 \pm 0.023 \pm 0.013$ PRL 108, 171802 (2012)

$\mathcal{S}_{c\bar{c}s} = \sin 2\beta = +0.687 \pm 0.028 \pm 0.012$ PRD 79, 072009 (2009)

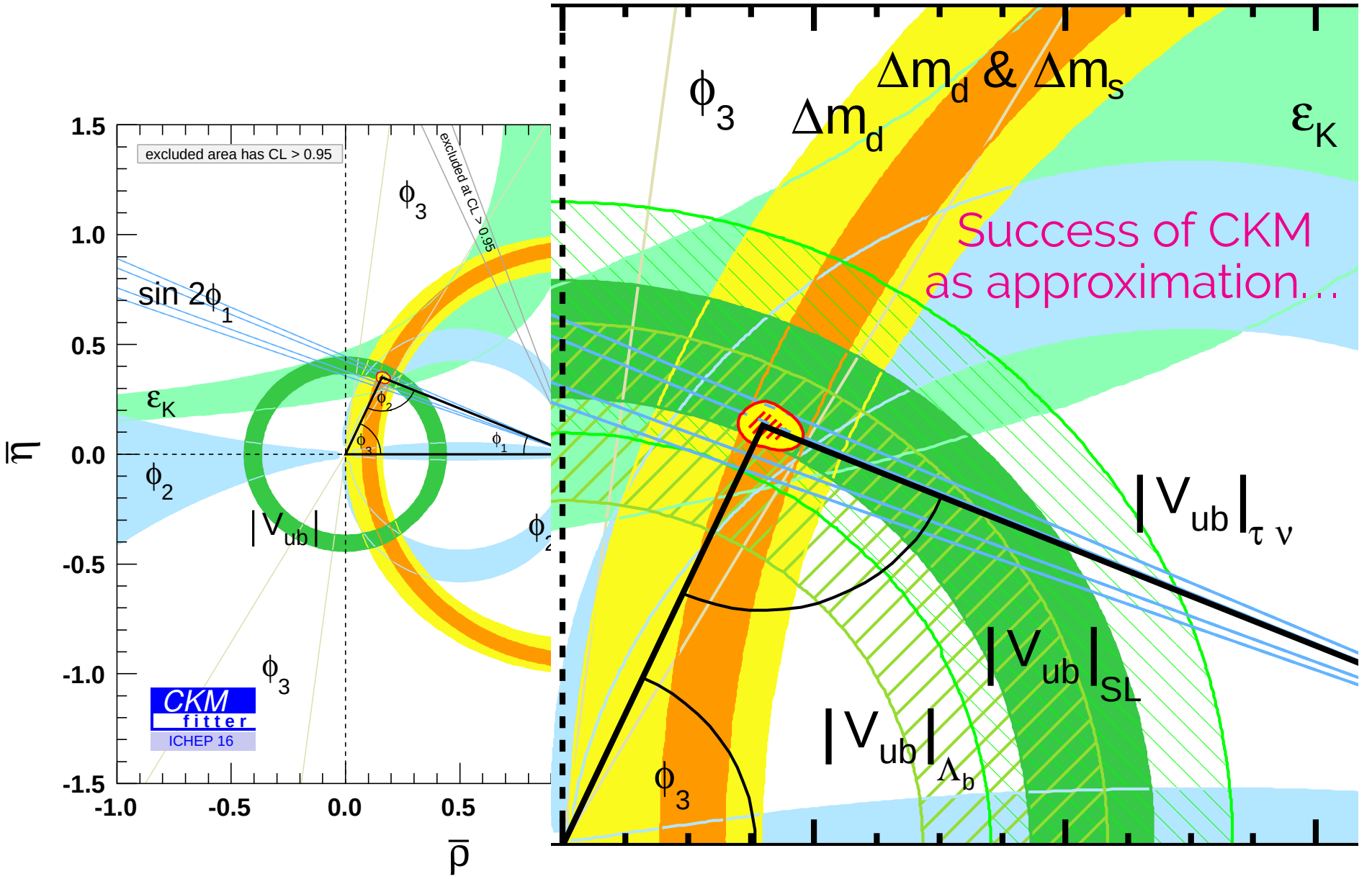


- All sides and angles
- Trees and loops
- Overconstraints

Success of CKM

Legacy of first generation B-factories (+LHCb)

2008 Nobel Prize to Kobayashi and Maskawa

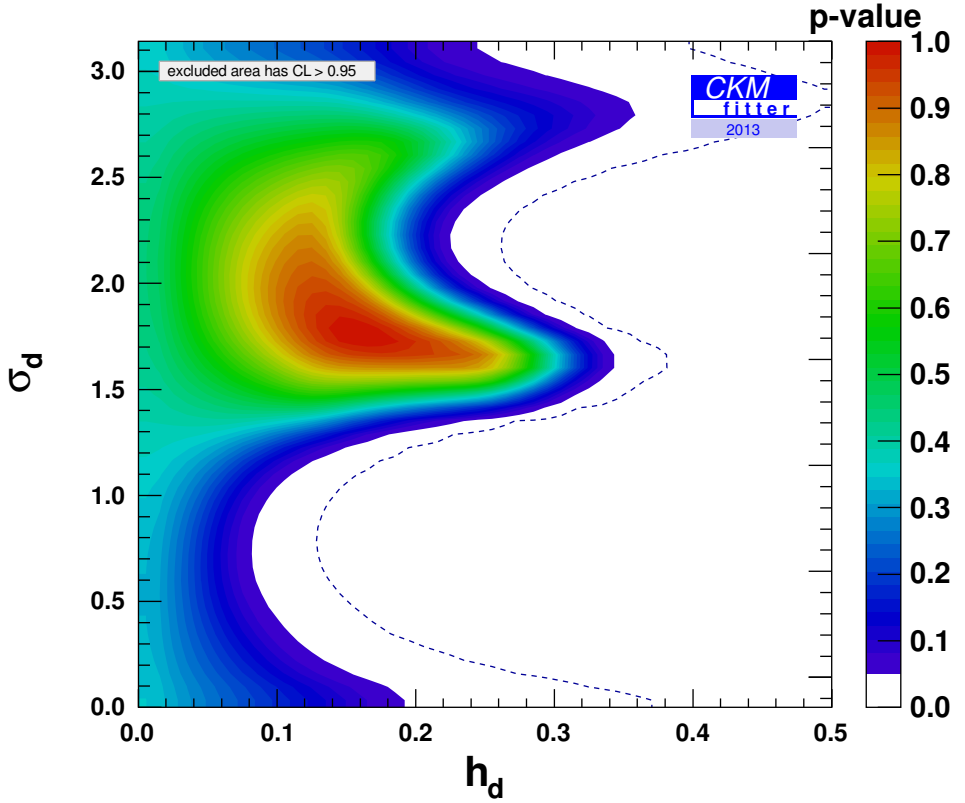


- Problems in $|V_{ub}|$, most likely in measurements + SM theory
- **No constraint for O(10%) new physics contributions!**

Quark transitions in NP modify the Unitarity Triangle

Deviation of **loop (ϕ_1 and V_{td})** from **tree (ϕ_3 and V_{ub})** as a clear sign of NP, parametrized in a model independent way

$$M_{12} = M_{12}^{\mathrm{SM}}(1 + h_d e^{2i\sigma_d})$$



[Ligeti arxiv:1704.02938]

Scale of new physics

$$h_d \simeq \frac{|C_d^{\mathrm{NP}}|^2}{|V_{tb}^* V_{td}|^2} \left(\frac{4.5\ \mathrm{TeV}}{\Lambda_{\mathrm{NP}}}\right)^2$$

If NP coupling is similar to CKM (=MFV), Λ_{NP} is already larger than 8 TeV

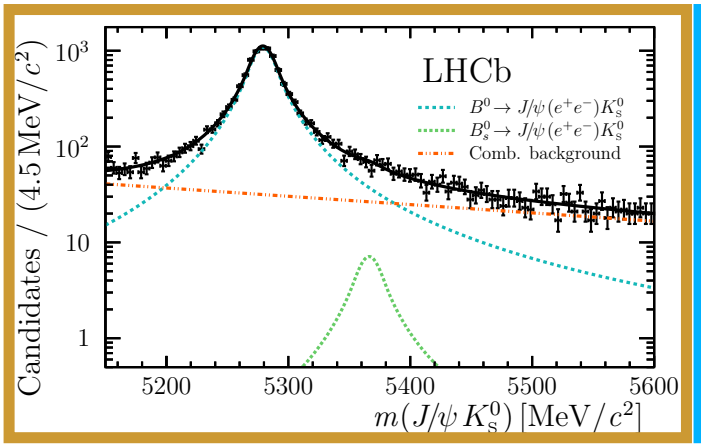
Recent progress — outline of this talk

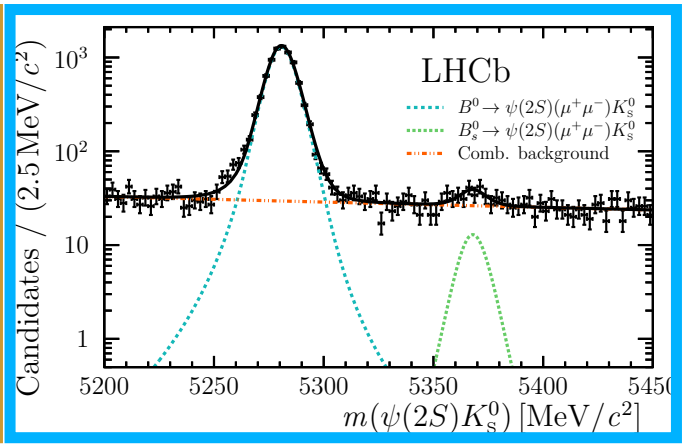
- ϕ_1/β — addition of $\psi(2S)$ and electron modes (LHCb)
  — from time-dependent Dalitz analysis (Belle)
- ϕ_2 — new results on $B^0 \to \pi^0\pi^0$ (Belle)
- γ — new results (LHCb)
- V_{cb} — recent progress on form factor (Belle)
- V_{ub} — inclusive electron spectrum of $B \to X_u e\nu$ (BaBar)
  — measurement of $B \to \mu\nu$ (Belle)

Disclaimer: some of the recent topics are not included: such as ϕ_s measurement (LHCb), $B \to \eta'\ell\nu$ (Belle), CPV in b-baryons (LHCb), CPV in $B \to KK\pi$ (Belle), ...

LHCb: $B \to (c\bar{c})K_S$

[G.Cowan LP'17, LHCb-PAPER-2017-029 in preparation]

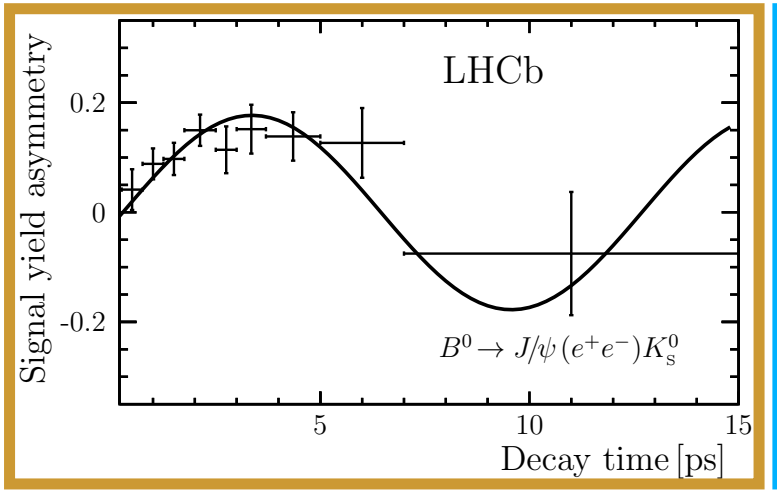


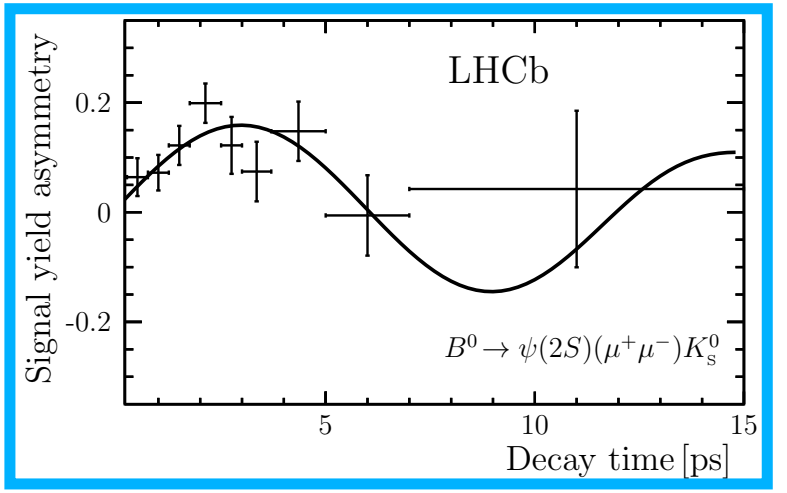


preliminary

- Huge signal samples, penalty in small flavor tag efficiency
- **New:** $B \to J/\psi(\to e^+e^-)K_S$ and $B \to \psi(2S)(\to \mu^+\mu^-)K_S$
  [dominant mode: $B \to J/\psi(\to \mu^+\mu^-)K_S$, PRL115,031601(2015)]

time dependent fit: $A_{CP}(t) = \mathcal{S}\sin(\Delta m t) - \mathcal{C}\cos(\Delta m t)$, $\mathcal{S} = \sin 2\beta$

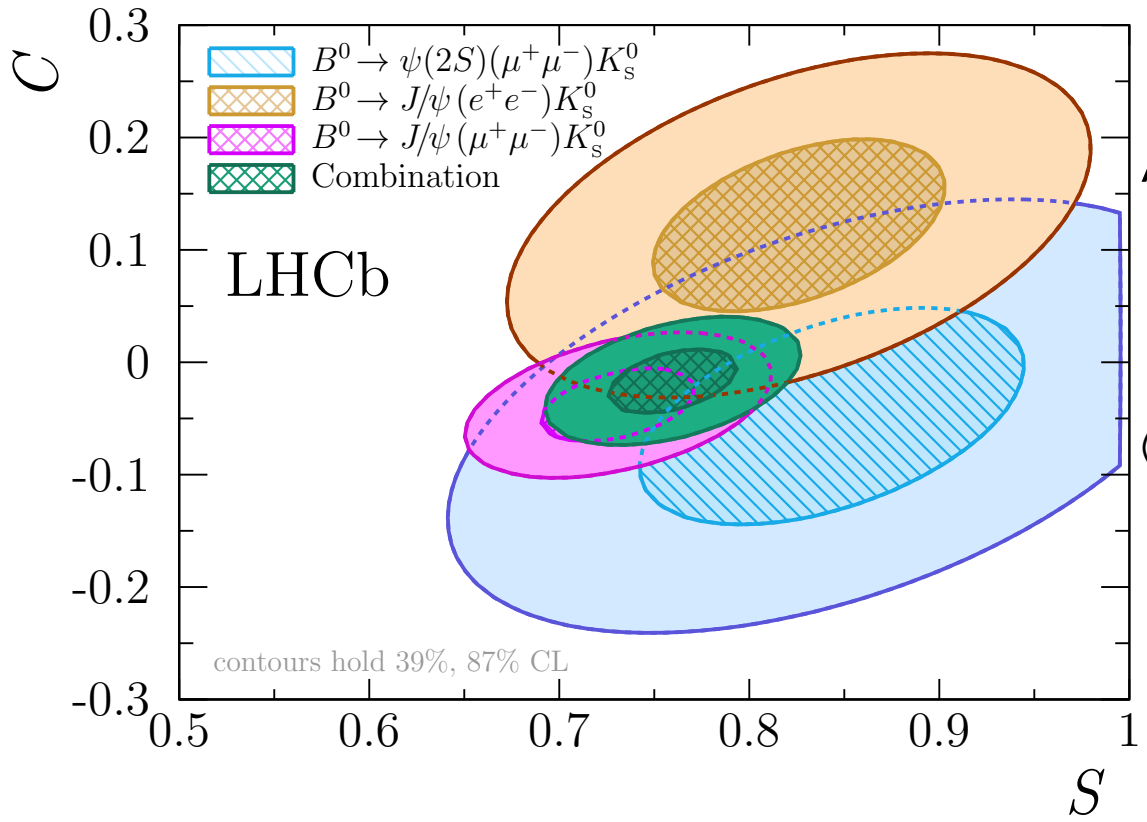




LHCb: sin2β

[G.Cowan LP'17, LHCb-PAPER-2017-029 in preparation]

preliminary



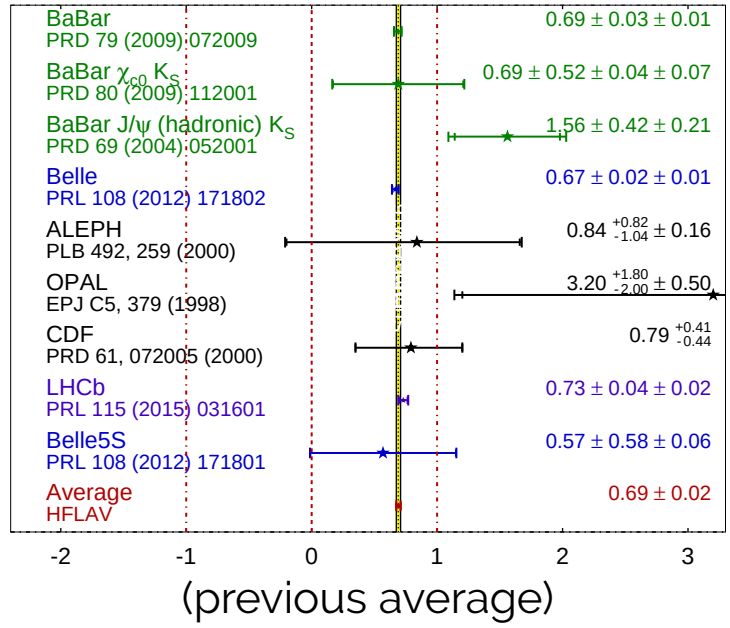
All combined:

$$\mathcal{S} = +0.760 \pm 0.034$$
$$\mathcal{C} = -0.017 \pm 0.029$$

(Belle $\delta\mathcal{S} = 0.026$, BaBar $\delta\mathcal{S} = 0.030$)

- ✔ New modes help to reduce error
- ✔ Only a little behind the B-factories
- ✔ Contribution to the world average

sin(2β) ≡ sin(2φ$_1$) HFLAV Summer 2016



time-dependent Dalitz: $B \to D^{(*)} h^0$ ($h^0 = \pi^0, \eta, \eta', \omega$)

$$N_i(\Delta t, \phi_1) = h_2 e^{-\frac{|\Delta t|}{\tau_B}} \left[1 + Q_B \frac{K_i - K_{-i}}{K_i + K_{-i}} \cos(\Delta m_B \Delta t) \right.$$
$$\left. + 2 Q_B \xi_{h^0} (-1)^l \frac{\sqrt{K_i K_{-i}}}{K_i + K_{-i}} \sin(\Delta m_B \Delta t)(S_i \cos 2\phi_1 + C_i \sin 2\phi_1) \right]$$

Integrated $|\text{amplitude}|^2$

$K_i = \int |\mathcal{A}_D(m_-^2, m_+^2)|^2 d\mathcal{D}$

from $B^- \to D^0 \pi^-$ (flavor specific)

Integrated strong phase

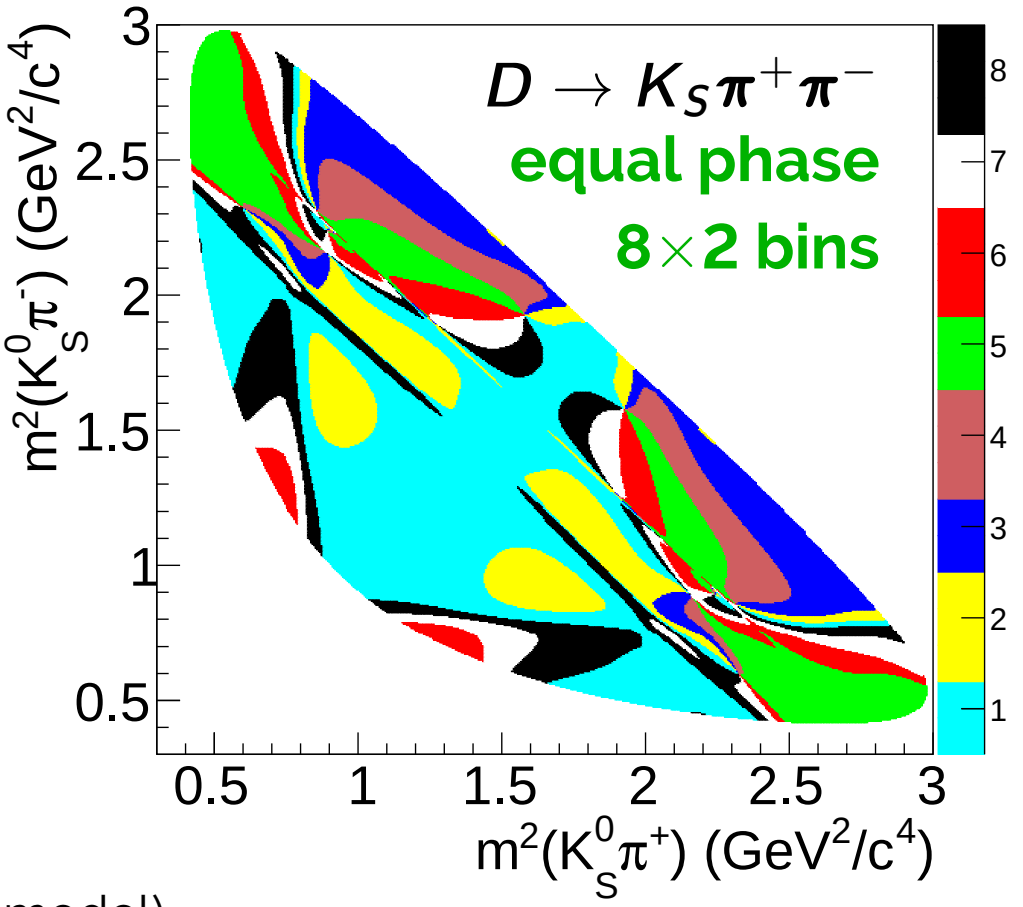
$$S_i = \frac{\int |\mathcal{A}_D||\overline{\mathcal{A}}_D| \sin \Delta\delta_D \, d\mathcal{D}}{\sqrt{K_i K_{-i}}},$$

$$C_i = \frac{\int |\mathcal{A}_D||\overline{\mathcal{A}}_D| \cos \Delta\delta_D \, d\mathcal{D}}{\sqrt{K_i K_{-i}}}$$

from coherent $D^0\overline{D}^0$ by CLEO

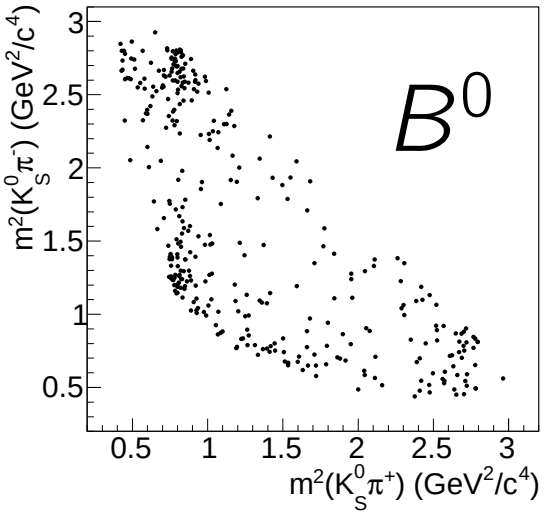
Measured in 8×2 bins

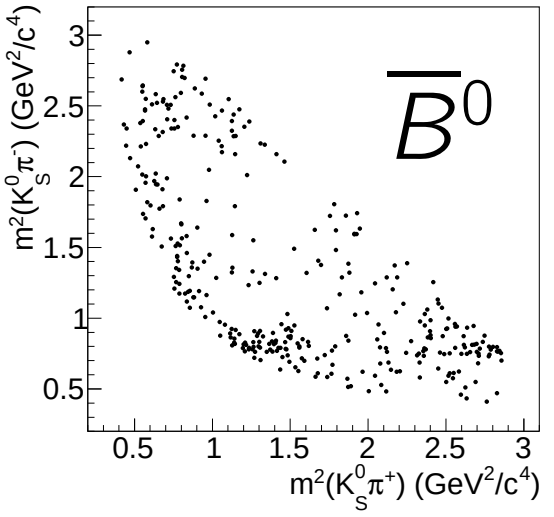
(binning based on a realistic resonant model)

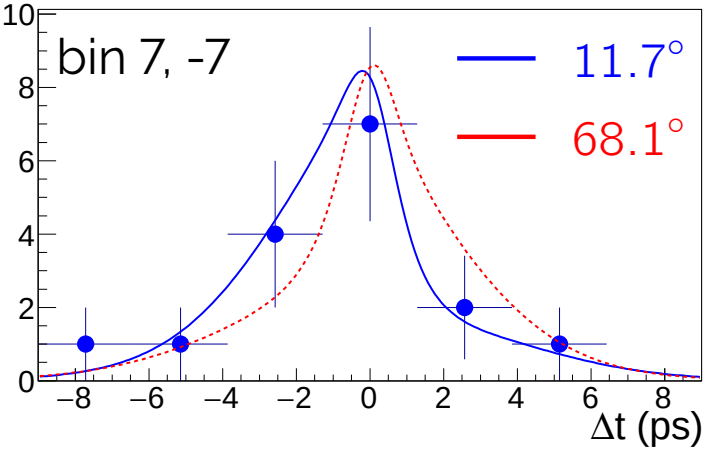


Belle: ϕ_1 from Dalitz

[Belle PRD94,052004(2016)]







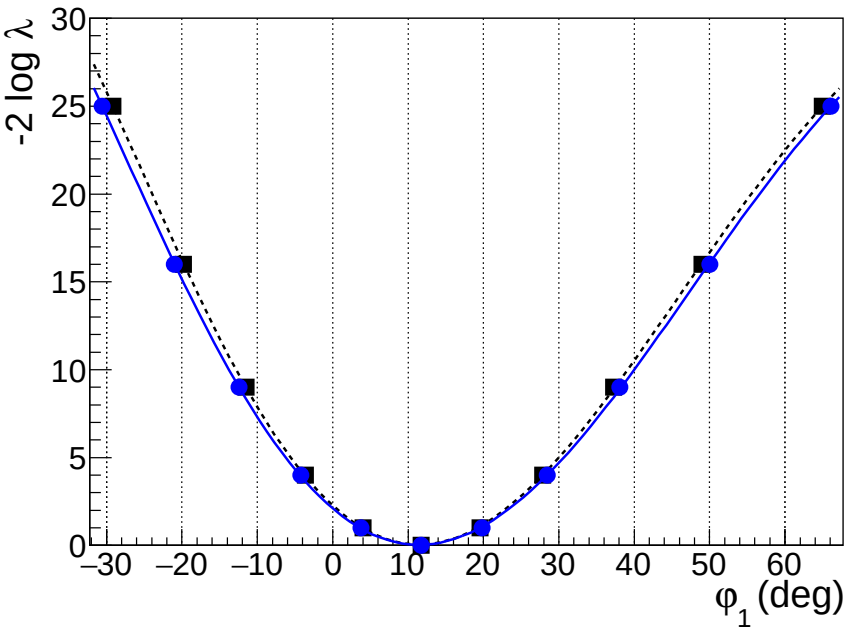
time-dependent Dalitz fit of $B \to D^{(*)} h^0$

$\phi_1 = 11.7° \pm 7.8° \pm 2.1°$

$\Leftrightarrow$ two solutions from $B \to [c\bar{c}]K^0$

$\phi_1 = 21.9°$ (1.3σ away)

$\phi_1 = 68.1°$ **(5.1σ away)**

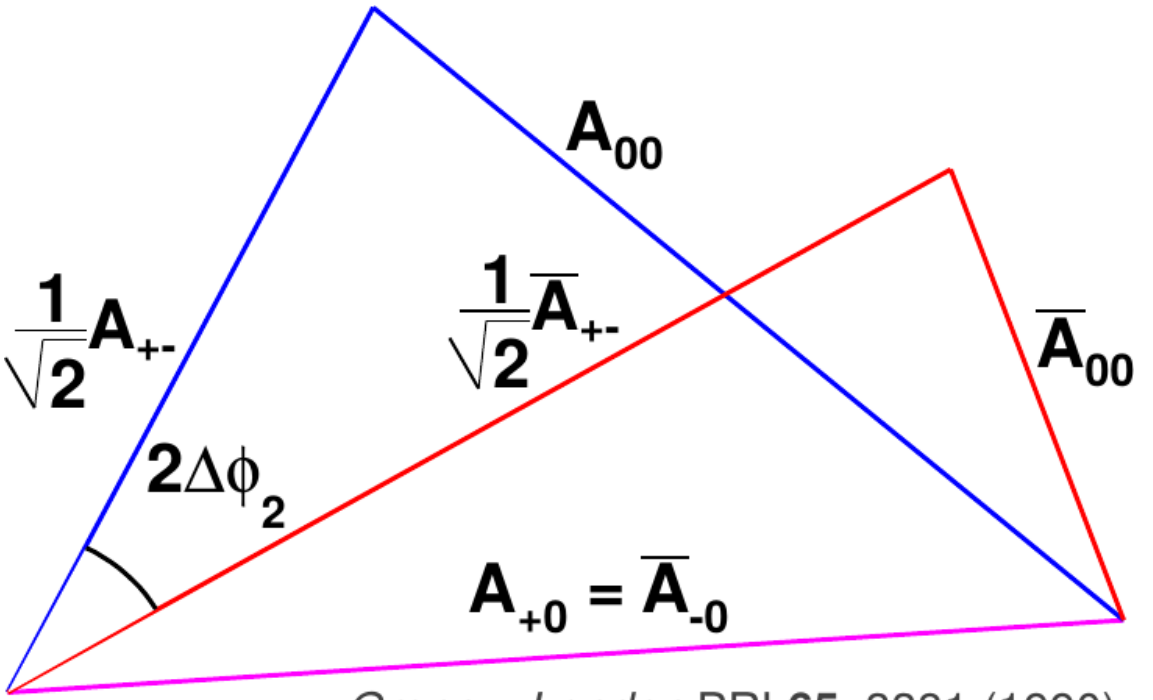


second ϕ_1 solution is definitely excluded (and no more needed in the CKMfitter UT plot)

ϕ_2/β: isospin analysis

- $\sin 2\phi_2$ from $B \to \pi^+\pi^-$ need to resolve "penguin pollution"
- $\mathcal{S} = \sqrt{1-\mathcal{A}^2}\sin 2(\phi_2 + \Delta\phi_2)$,
  where $\Delta\phi_2$ from 3 branching fractions and 2 direct CPV

A_{+-}: $B^0 \to h^+h^-$
$\overline{A}_{+-}$: $\overline{B}^0 \to h^+h^-$
A_{00}: $B^0 \to h^0h^0$
$\overline{A}_{00}$: $\overline{B}^0 \to h^0h^0$
A_{+0}: $B^+ \to h^+h^0$
($h = \pi,\ \rho$)

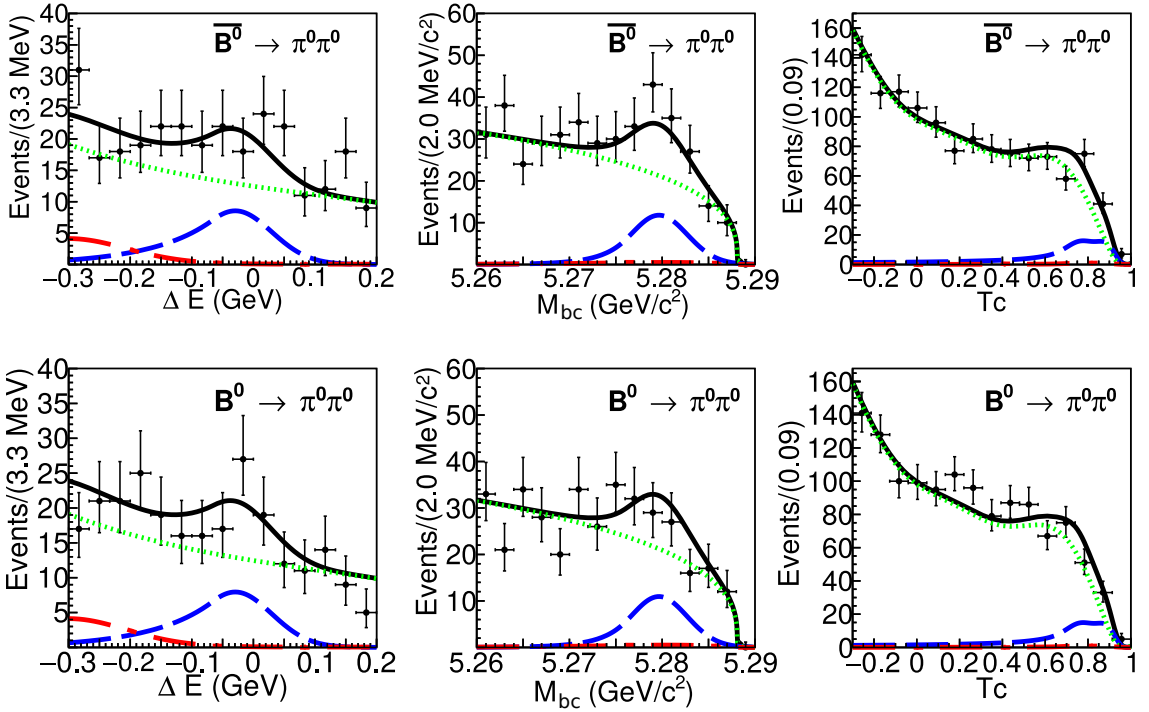


Gronau, London PRL**65**, 3381 (1990)

- $B \to \pi^+\pi^-$ and $B \to \pi^+\pi^0$ have been precisely measured, but it took long time for Belle to finalize $B \to \pi^0\pi^0$
  [No charged track, need precise timing info for photon clusters]

Belle: $B \to \pi^0\pi^0$ and ϕ_2

[arXiv:1705.02083 to appear in PRD]



(previous results)

$\mathcal{B}(B \to \pi^0\pi^0)\ (10^{-6})$

PDG: 1.91 ± 0.22

BaBar(2013): 1.83 ± 0.25

Belle(2005): 2.3 ± 0.5

SM: < 1.0 **???**

3D-fit: $M_{\rm bc}$, ΔE, T_c

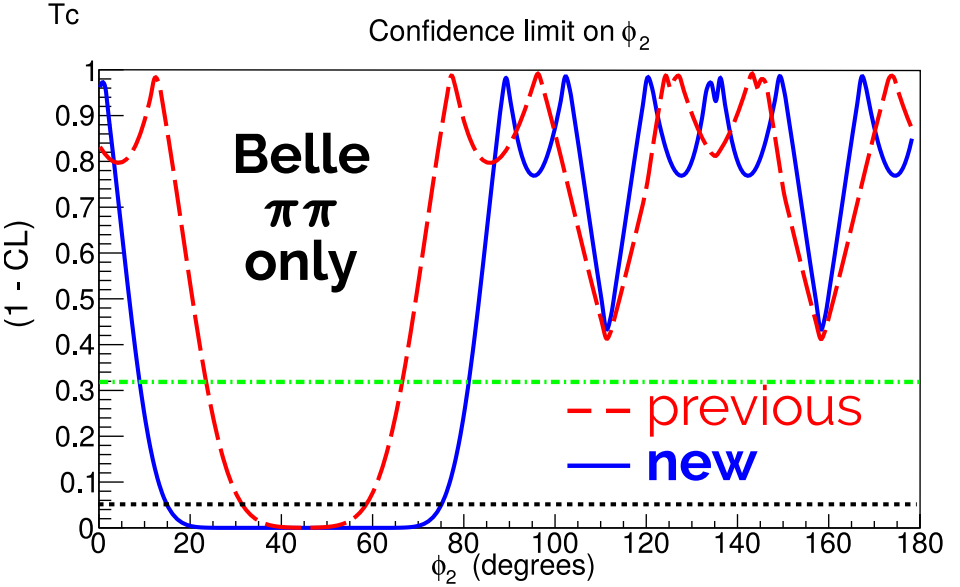
(Tc: continuum suppression variable)

$\mathcal{B} = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$

$A_{CP} = 0.14 \pm 0.36 \pm 0.10$

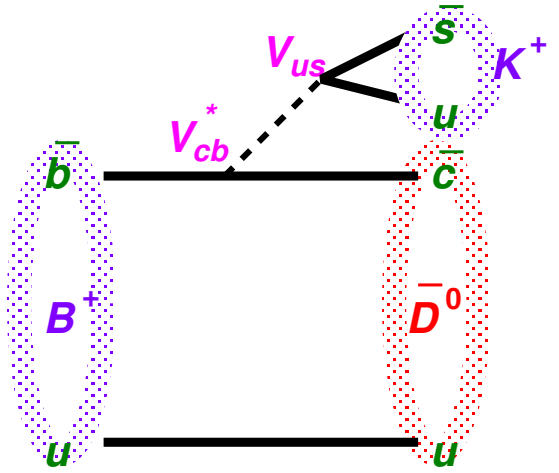
ϕ_2 excluded from the range:

$15.5° < \phi_2 < 75.0°$ at 2σ

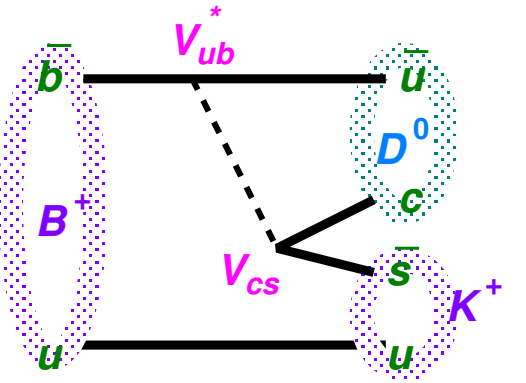


ϕ_3/γ measurement

$A(B^- \to D^0 K^-) \propto \lambda^3$



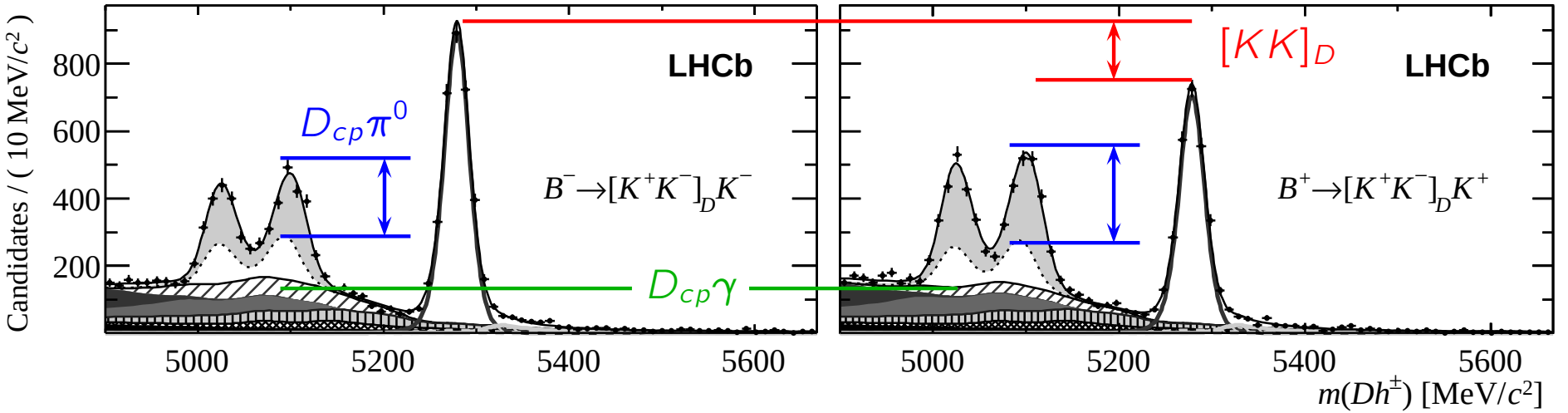
$A(B^- \to \overline{D}^0 K^-) \propto \lambda^3(\rho + i\eta)$



- Two interfering diagrams have the same order in λ and weak phase difference ϕ_3/γ (and unknown strong phase difference δ)
- $r = |A(\overline{D}^0 K^-)/A(D^0 K^-)| \sim 0.2$ for color suppression ($r^2 \sim 0.04$)
- ϕ_3/γ extraction methods
  - **GLW** — $D^0 \to f_{CP}$, e.g., K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$
  - **ADS** — $D^0 \to$ doubly-cabibbo-suppressed, e.g., $K^+\pi^-$
  - **GGSZ** — $D^0 \to K_S\pi^+\pi^-$, using Dalitz plot

LHCb: γ from $B \to D^{(*)0}K$

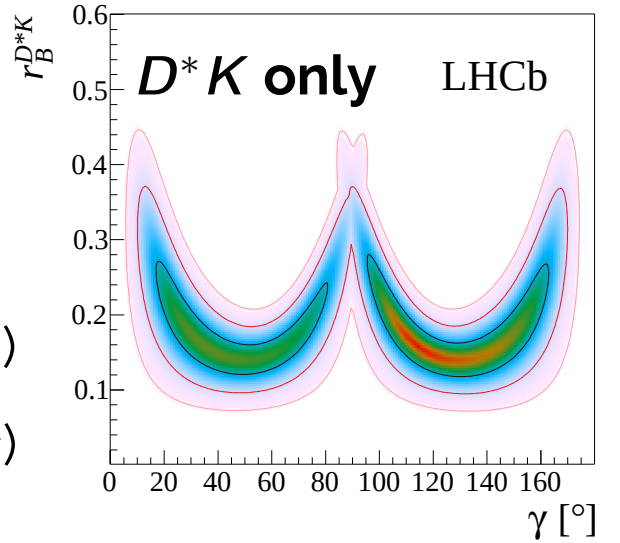
[arXiv:1708.06370 submitted to PLB]



- GLW method using $D_{CP} = K^+K^-$ and $\pi^+\pi^-$
- Partial reco of $D^* \to D^0\pi^0$ and $D^0\gamma$ (soft π^0/γ not reconstructed)

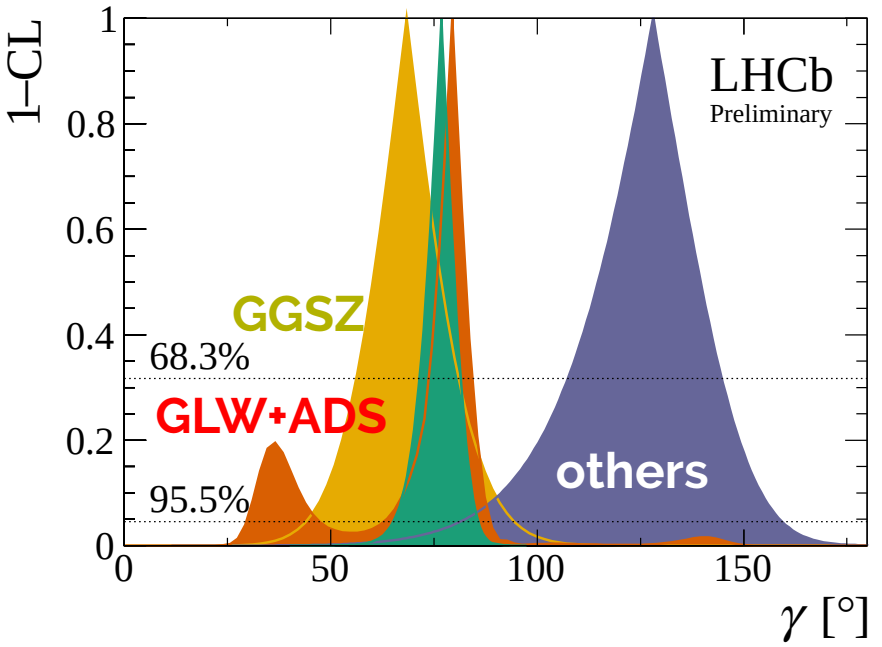
Results

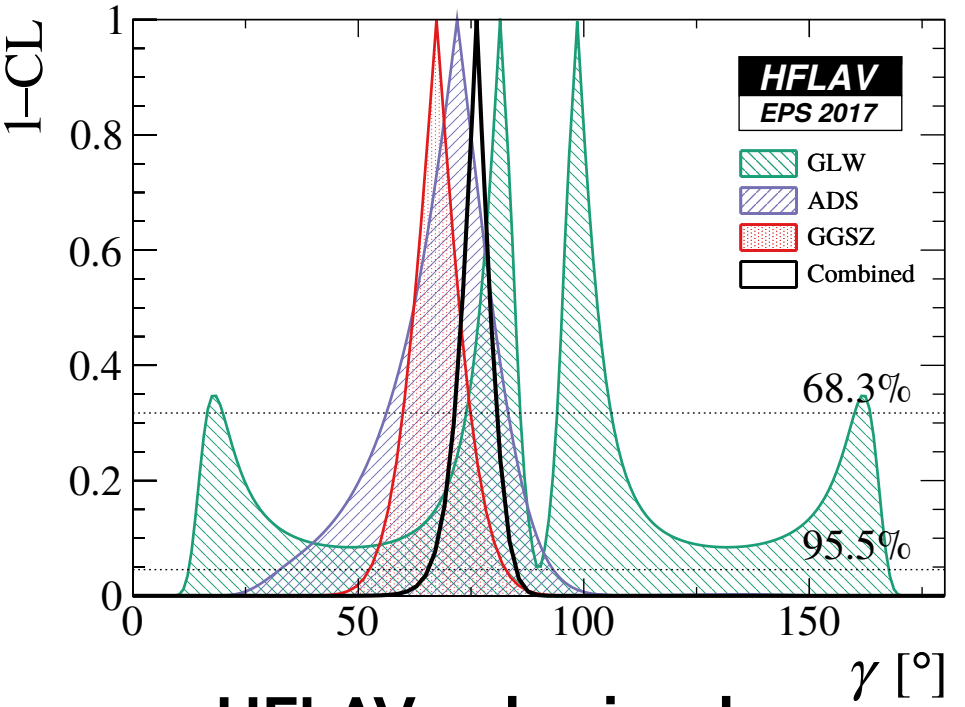
$[KK]_DK$	$A_{CP} = +0.126 \pm 0.014 \pm 0.002$
$[\pi\pi]_DK$	$A_{CP} = +0.115 \pm 0.025 \pm 0.007$
$[D_{CP}\pi^0]_{D^*}K$	$-A_{CP} = +0.151 \pm 0.033 \pm 0.011$ (4.3σ)
$[D_{CP}\gamma]_{D^*}K$	$A_{CP} = +0.276 \pm 0.094 \pm 0.047$ (2.4σ)



γ/ϕ_3: average

[LHCb-CONF-2017-004, HLFAV]





LHCb cobmined

$$\gamma = (76.8\,^{+5.1}_{-5.7})^\circ$$

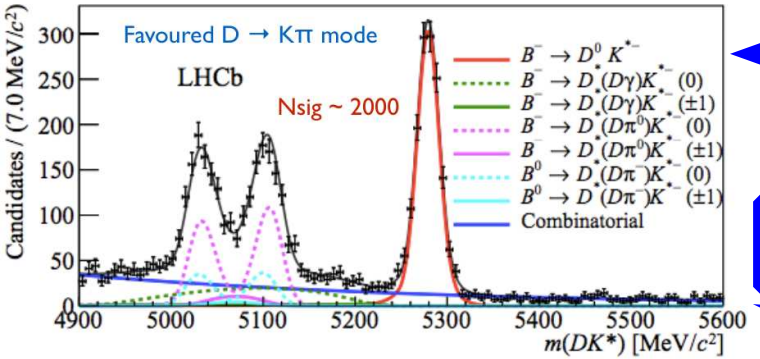
HFLAV cobmined

$$\gamma = (76.2\,^{+4.7}_{-5.0})^\circ$$

- γ measurement is dominated by LHCb, who provides 85 observables and 37 parameters
- World average is better than 5°
- More to come from LHCb…

LHCb: γ from $B \to D^0 K^*$

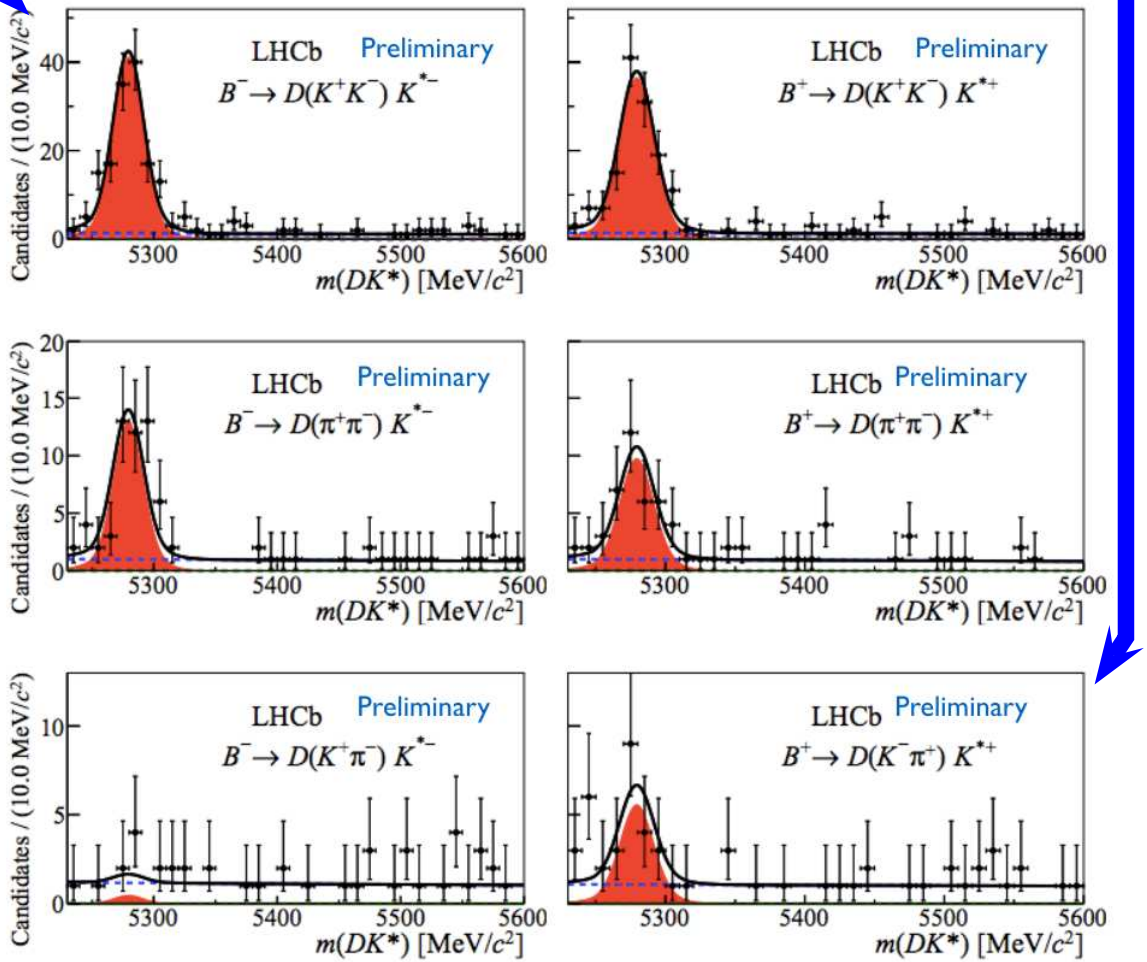
[G.Cowan LP'17, LHCb-PAPER-2017-030 in preparation]



Large signal for **favored** $D^0 \to K^-\pi^+$

GLW: clean CP modes $D^0 \to K^+K^-/\pi^+\pi^-$

4.2σ evidence for wrong sign $K^-\pi^+$: **ADS**

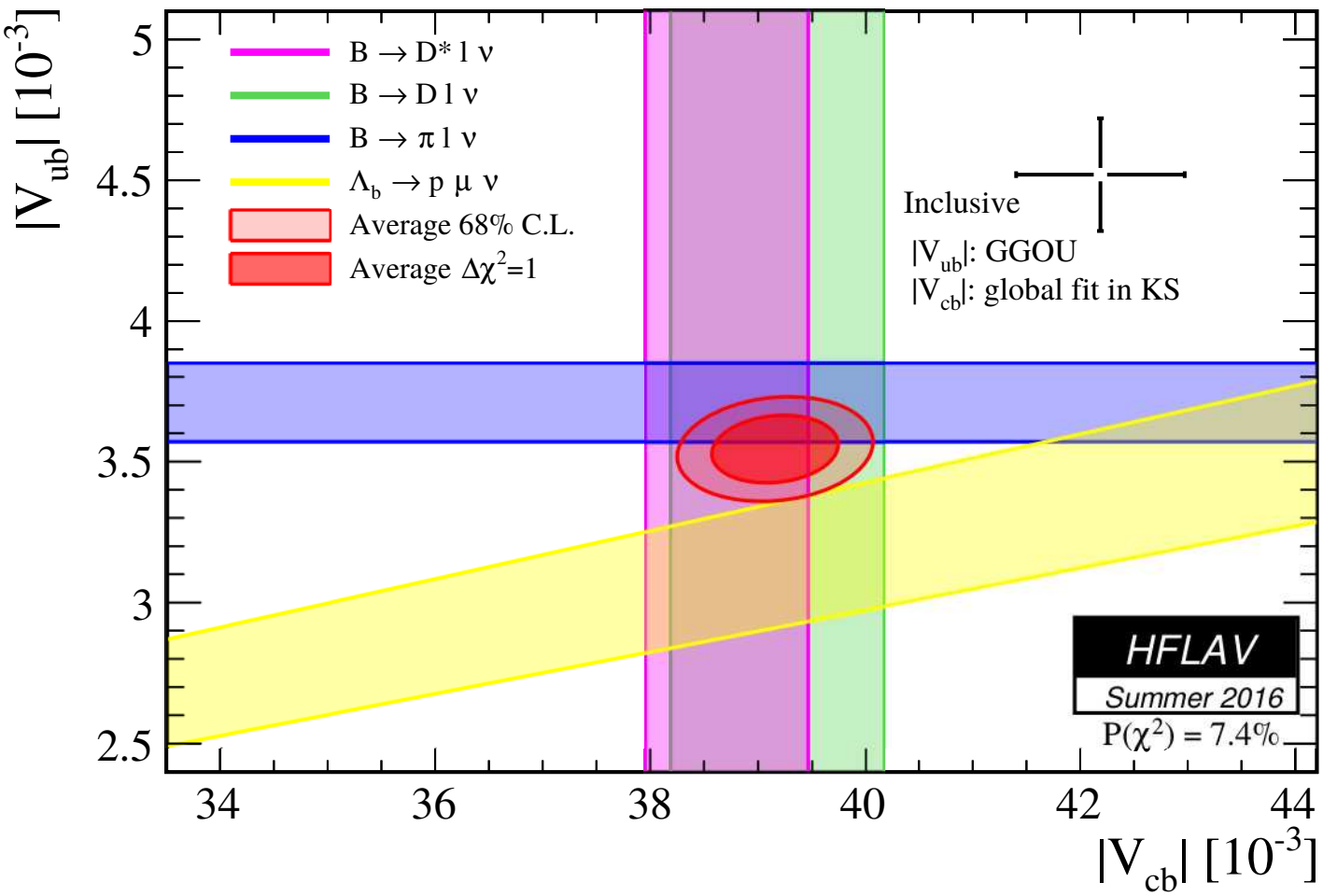


Rates and asymmetries provide constraints on r, δ and γ

Not in average yet

preliminary

V_{ub} and V_{cb}, inclusive and exclusive



Both V_{ub} and V_{cb} suffer from discrepancy between **inclusive** and **exclusive** analyses by 2–3σ

$|V_{cb}|(D^*\ell\nu) = (39.05 \pm 0.47 \pm 0.58) \times 10^{-3}$ $\quad$ $|V_{ub}|(\pi\ell\nu) = (3.67 \pm 0.15) \times 10^{-3}$

$|V_{cb}|(\text{incl}) = (42.19 \pm 0.78) \times 10^{-3}$ $\quad$ $|V_{ub}|(\text{incl}) = (4.52 \pm 0.15 \pm 0.13) \times 10^{-3}$

Belle: $B \to D^* \ell \nu$ hadronic tag

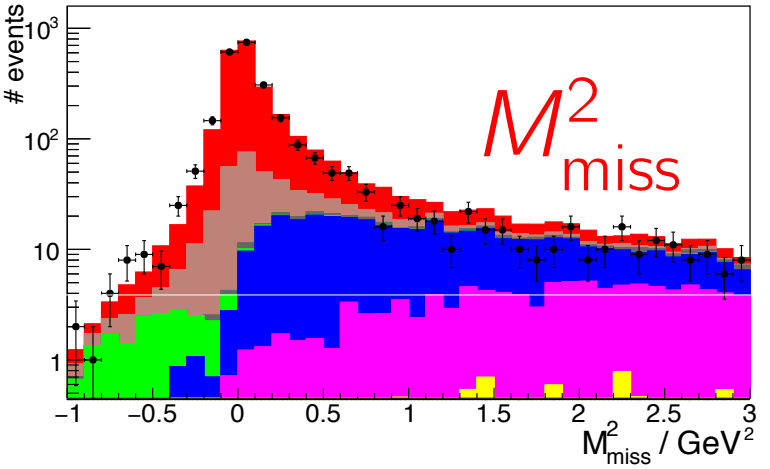
[arXiv:1702.01521 preliminary]

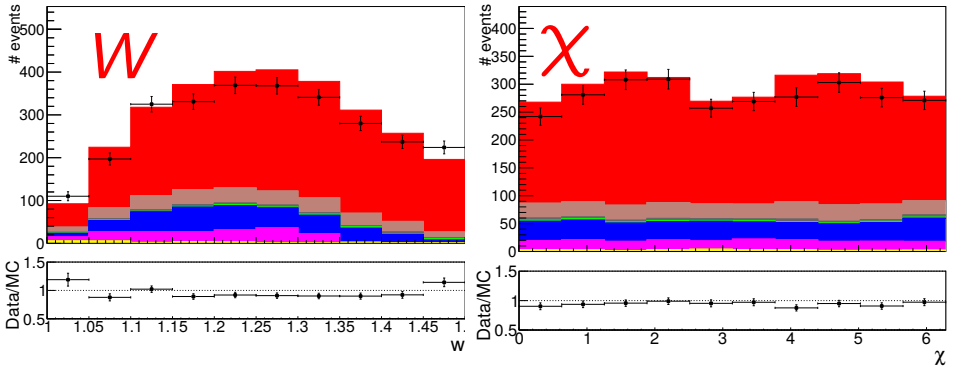
Standard method: CLN form factor

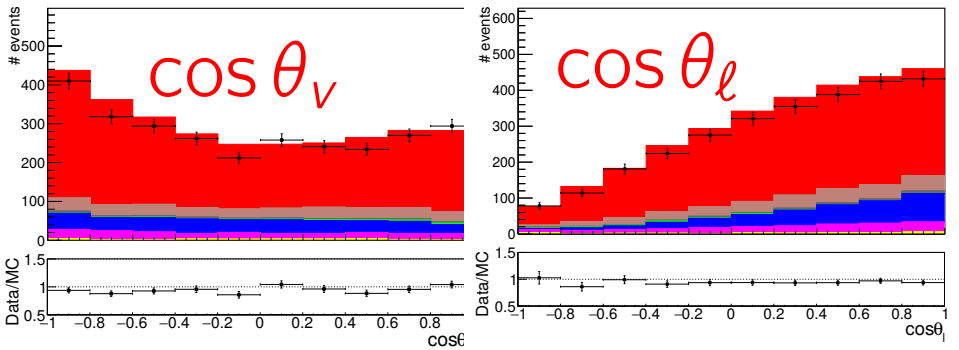
3-angles (θ_v, θ_ℓ, χ) and w ($= \frac{m_B^2 - m_{D^*} - q^2}{m_B m_{D^*}}$)

$$\frac{d^4\Gamma(B \to D^* \ell \nu)}{dw\, d\cos\theta_v\, d\cos\theta_\ell\, d\chi} = f(|V_{cb}|^2, \rho_D^2, R_1, R_2)$$

FF parameters determined from fit







preliminary

$$|V_{cb}| = (37.4 \pm 1.2) \times 10^{-3}$$

$$\Leftrightarrow |V_{cb}|_{\mathrm{WA}} = (39.2 \pm 0.7) \times 10^{-3}$$

not filling the gap between inclusive / exclusive

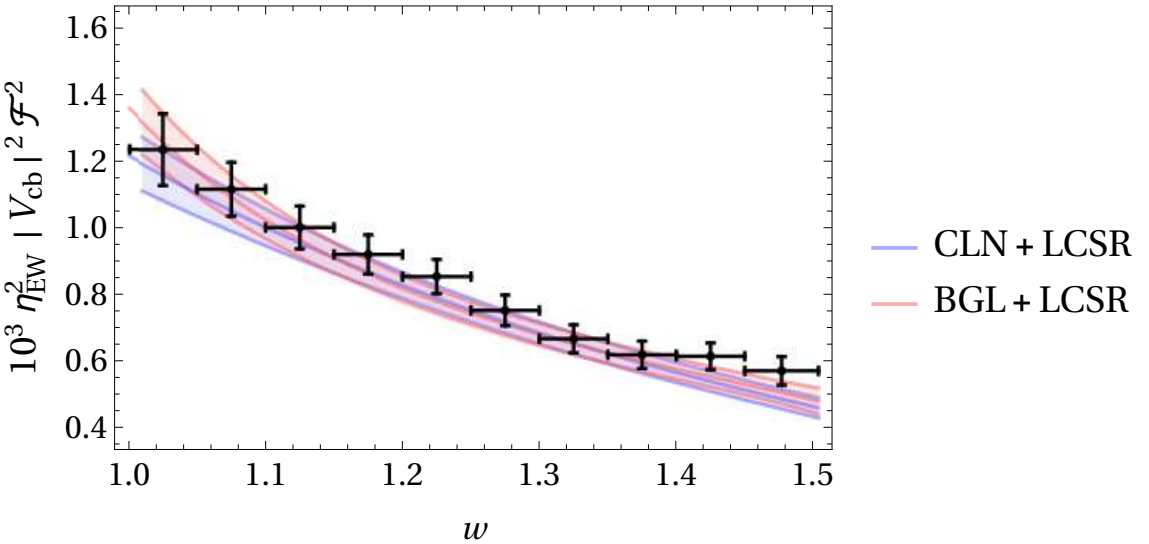
FF refit: BGL vs CLN

Alternative FF: BGL instead of CLN

Boyd-Grinstein-Lebed PRD56,6895(1997), Caprini-Lellouch-Neubert NPB530,153(1998)

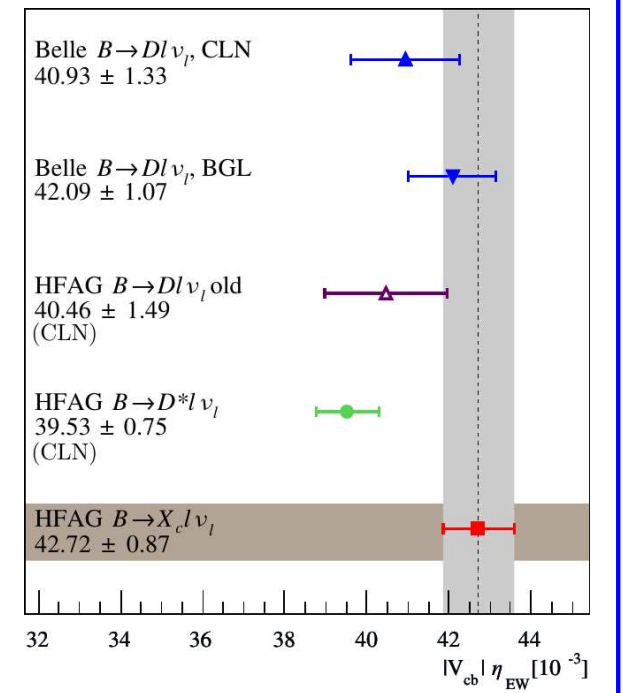
Refit of Belle data

by Bigi-Gambino-Schacht PLB769,441(2017), also by Grinstein Kobach PLB771,359(2017)



$$|V_{cb}|(\text{BGL}) = (40.4\,^{+1.6}_{-1.7}) \times 10^{-3}$$

$$|V_{cb}|(\text{CLN}) = (38.2 \pm 1.4) \times 10^{-3}$$

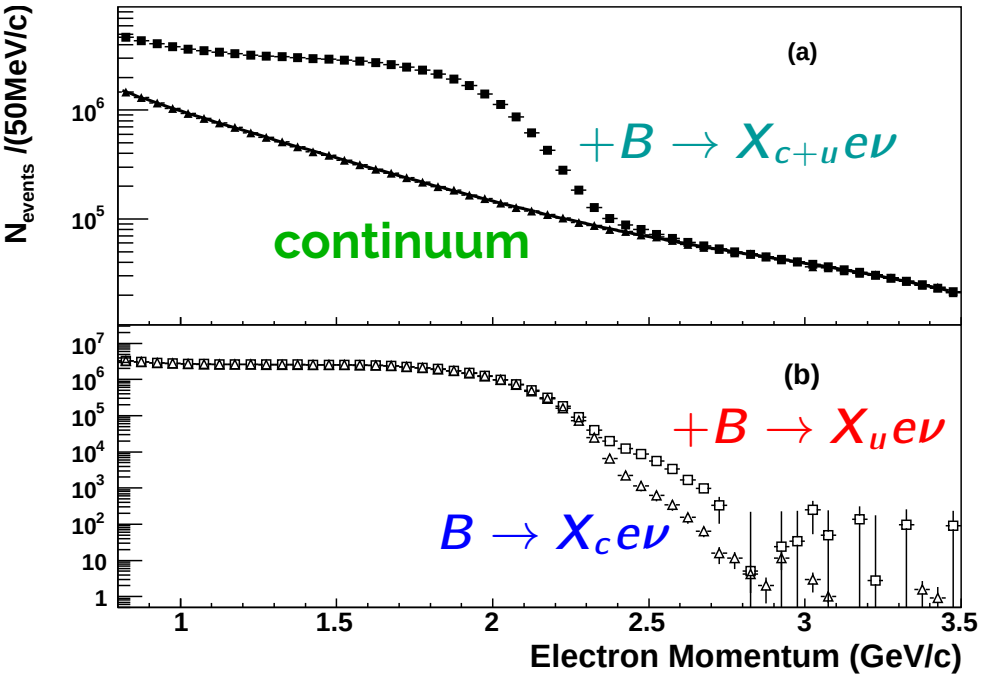


Also in $B \to D\ell\nu$
(old plot from 2015)

Reconciliation of inclusive-exclusive?

BaBar: $B \to X_u e\nu$ inclusive

[PRD95,072001 (2017)]

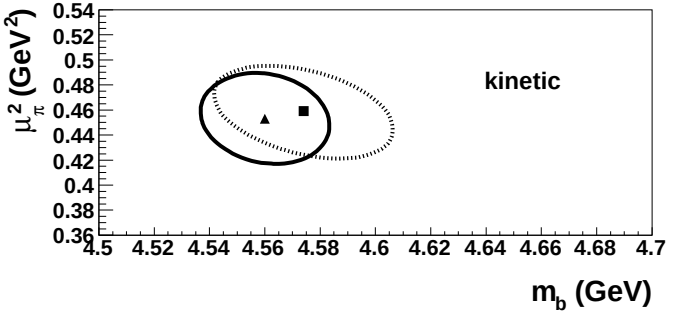


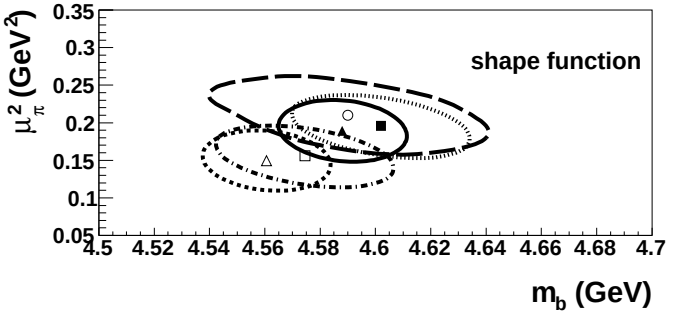
Endpoint analysis single bin: 2.1–2.7 GeV

4 different models to extrapolate the spectrum (shape function)

- DN (1999)
- BLNP (2004)
- GGOU (2007)
- DGE (2006)

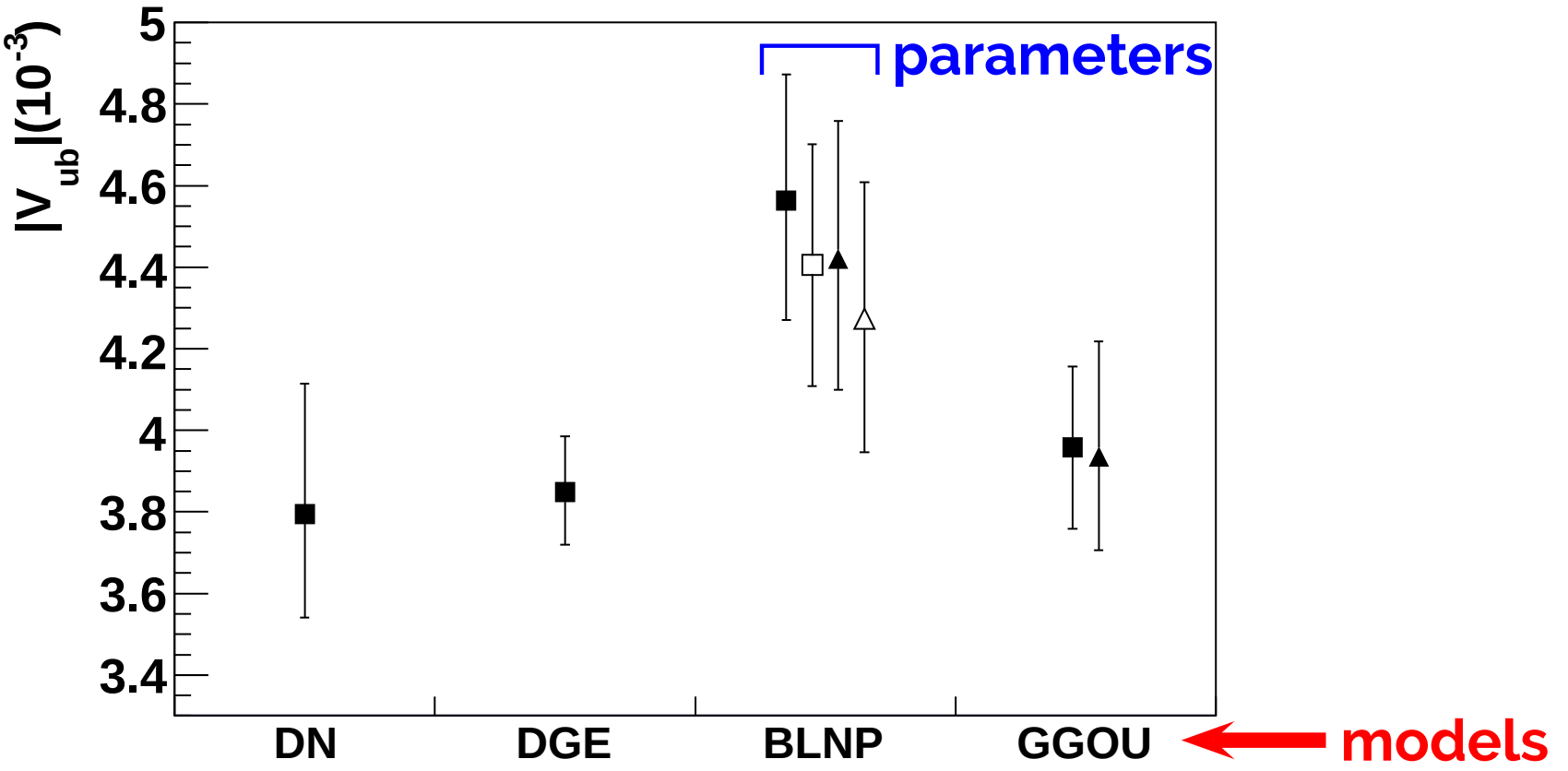
HQE parameters from latest HFLAV fit





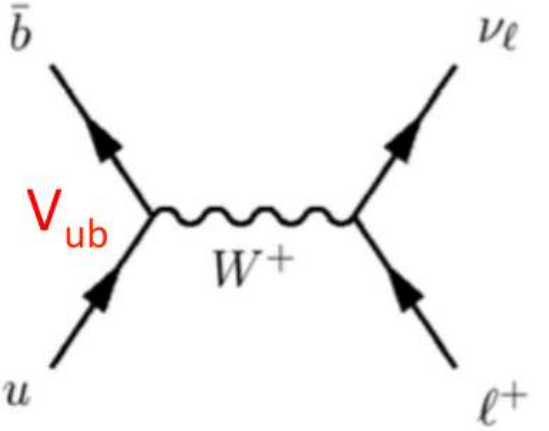
BaBar: $|V_{ub}|$

[PRD95,072001 (2017)]

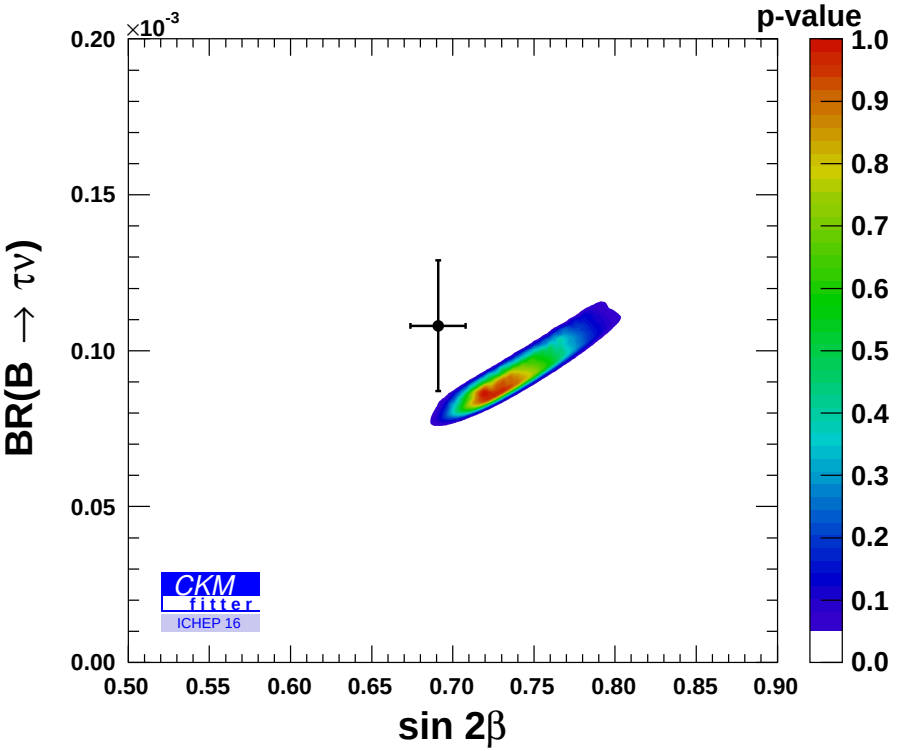


- Lower (= closer to the exclusive) in 3 models
- Variation of shape function parameters do not affect much
- Model dependence = limitation of single bin extrapolation

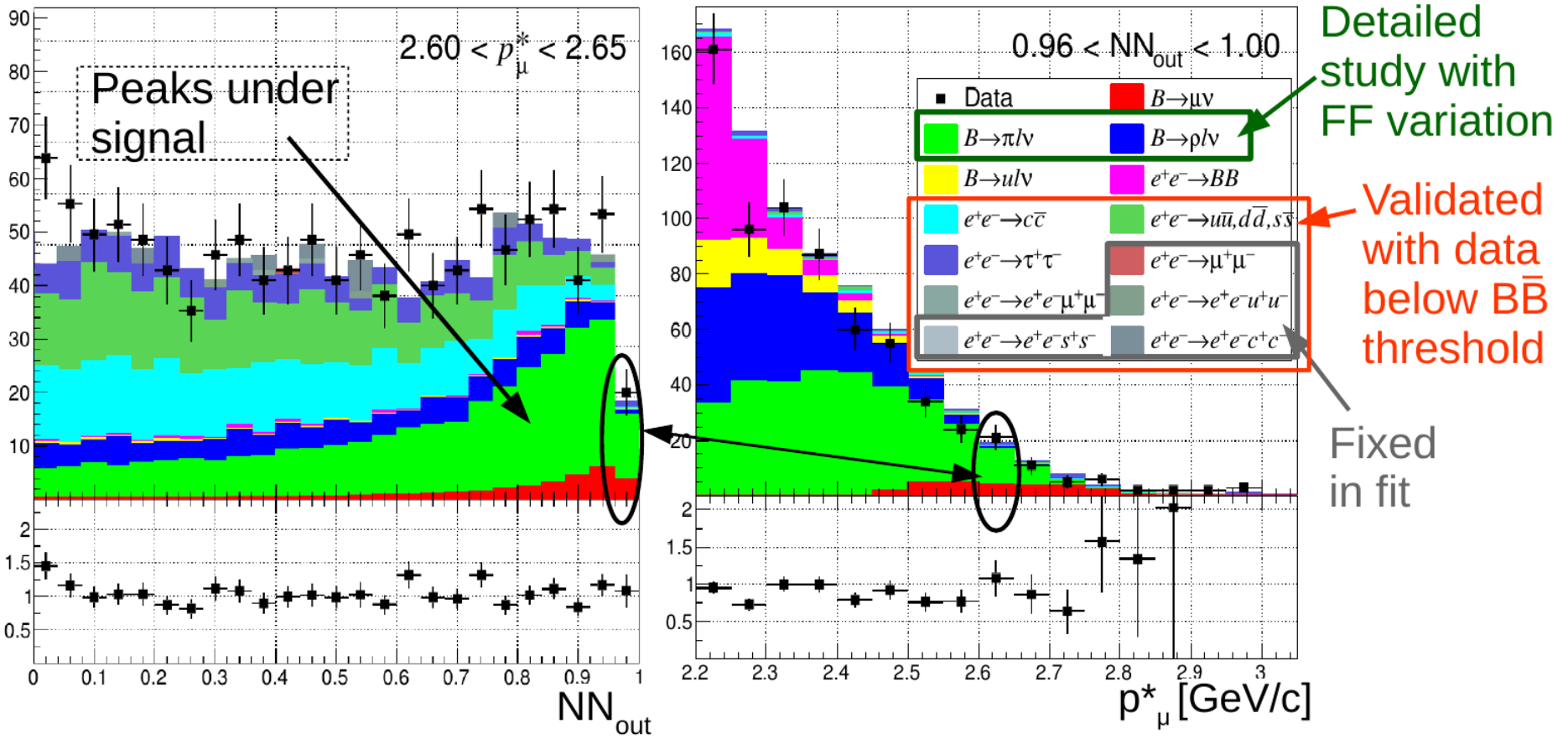
$B^+ \to \ell^+ \nu$ and CKM



- **Purely leptonic decay** is proportional to $f_B^2 |V_{ub}|^2$ (in SM),
  (also sensitive to type-II 2HDM charged Higgs)
- However, f_B is not precisely known
  (only from Lattice)
- Instead, **more reliable constraint** using Δm_d and other CKM
  (then no direct constraint to $|V_{ub}|$)
- $B \to \tau\nu$ has been measured,
  but no single 5σ signal yet
  (and previous tension is no more significant)
- $B \to \mu\nu$ **result is wanted**
  (lepton universality test is of great interest now)



Belle: $B^+ \to \mu^+\nu$



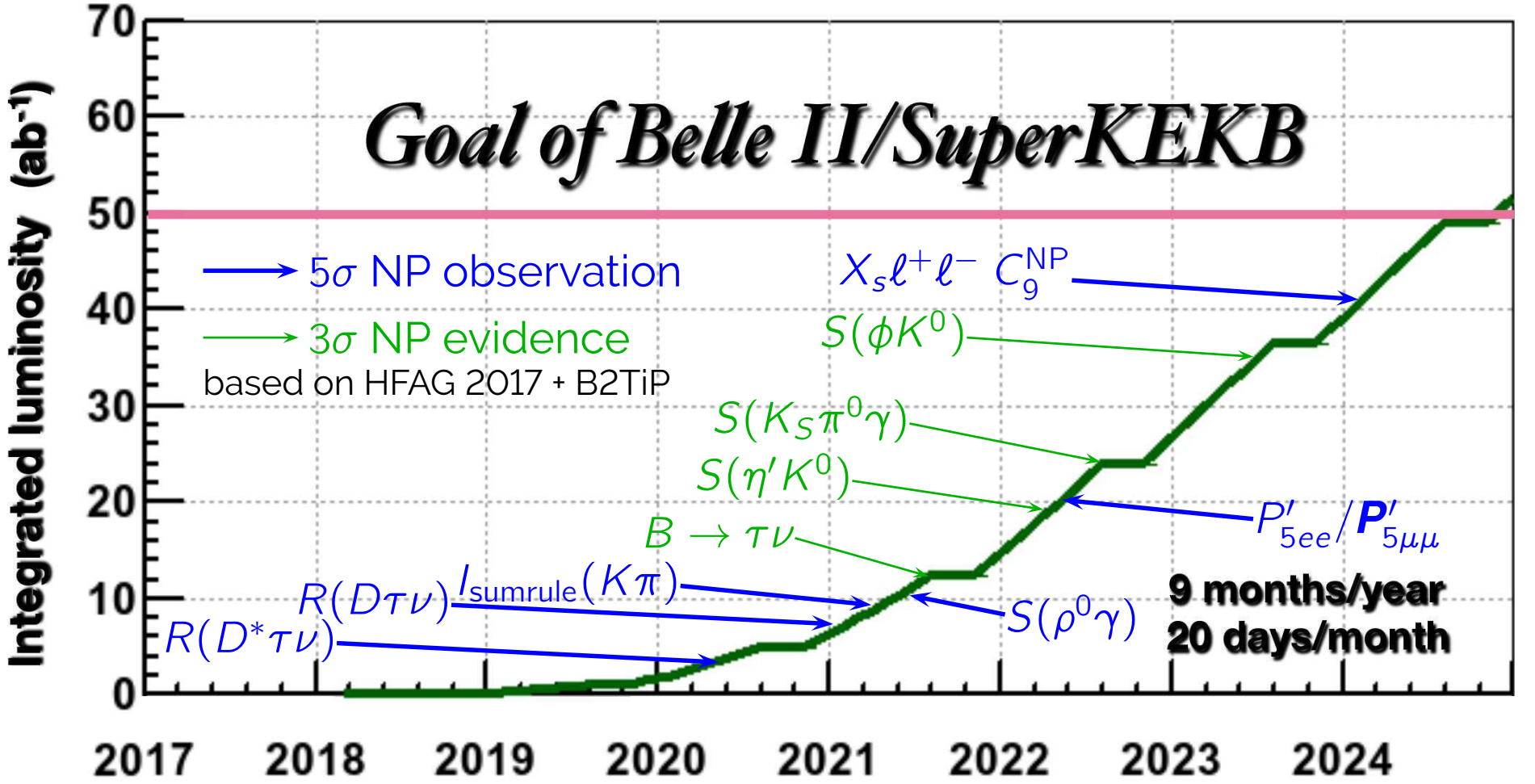
Untagged analysis, neural network output, efficiency = 38%

$\mathcal{B}(B \to \mu\nu) = (6.5 \pm 2.2 \pm 1.6) \times 10^{-7} \in [2.9,\ 10.7] \times 10^{-7}$ (90%CL)

- 2.4σ from null, consistent with $\mathcal{B}_{\mathrm{SM}} = (3.8 \pm 0.3) \times 10^{-7}$
- One of anticipated early Belle II hot topics (!)

Belle II at SuperKEKB coming soon

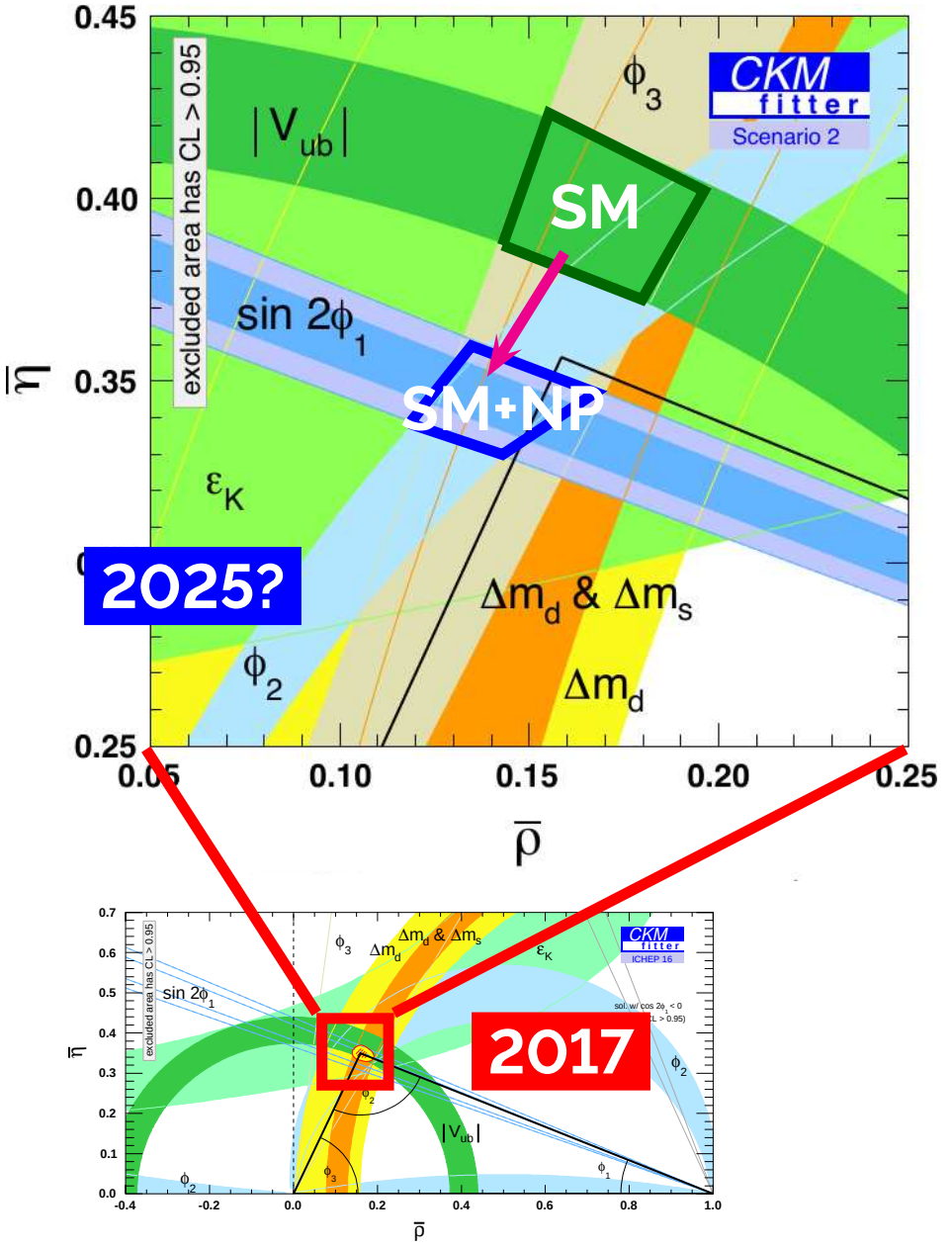
- Forward endcap installation — very soon
- **Phase II** operation (no VXD, limited physics) — 2018.2.–
- **Phase III** full physics run — (late 2018 or) 2019–



Rich physics ahead!

- ✔ Current inconclusive NP "hints" → "5σ-observed" (?)
- ✔ Topics involving neutrals and inclusive: $\tau\nu$, $\rho\gamma$, $K\nu\bar{\nu}$, $X_s\gamma$, ...
- ✔ LHCb upgrade plan covered in the next talk

CKM prospects



- All angles are measured with ~1% precision
- V_{ub} inconsistency has to be resolved
- Chance to find the clear NP signal (!)

New paradigm of quark transition is coming (!?)

Summary

- Belle and BaBar are finalizing the analysis of CKM
- LHCb pushing down γ, now WA with 5° precision
- V_{ub} internal inconsistency has to be resolved
- Major progress by startup of Belle II and LHCb upgrade