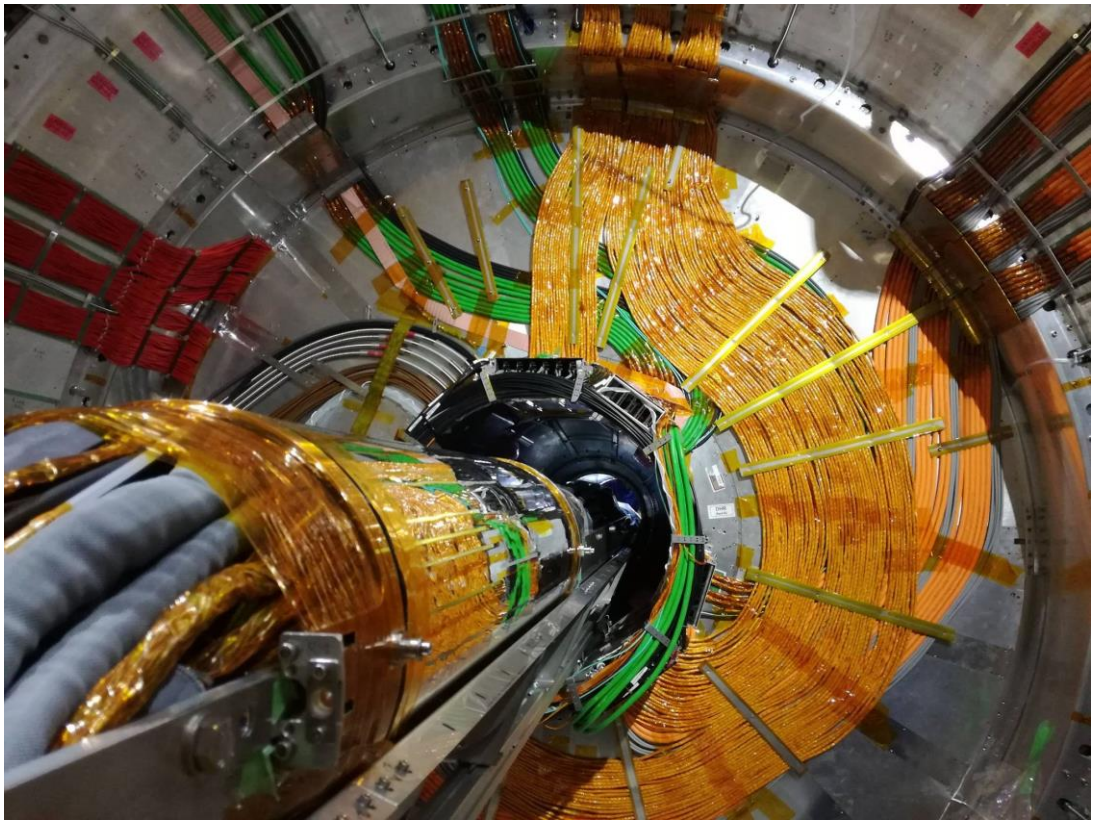
CP-violation measurements



(Laura Zani)

Martin Sevior,
University of Melbourne

CP-Violation

Sakharov Conditions:

- Baryon number violation
- ***CP* violation**
- Interactions out of thermal equilibrium

Measured $\frac{n_b}{n_\gamma} \approx 6 \times 10^{-10}$

SM. Electroweak Baryogenesis limits this to 10^{-26} => $\frac{n_{\bar{b}}}{n_\gamma} \approx 0$

What causes this additional CPV?

CPV in the Standand Model

_CP_ Violation Through Mixing: $\Gamma(P^0 \to \bar{P}^0) \neq \Gamma(\bar{P}^0 \to P^0)$

$$P^0 \to \bar{P}^0 \to \bar{f} \quad \neq \quad \bar{P}^0 \to P^0 \to f$$

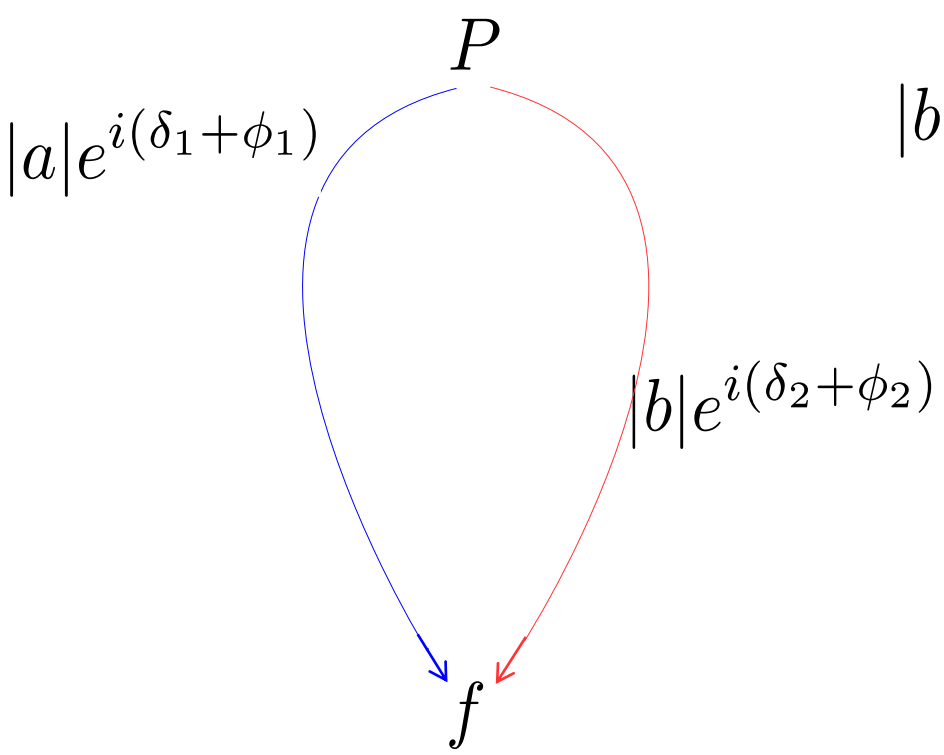
_CP_ Violation Through Interference: $\Gamma(P^0 \to f)(t) \neq \Gamma(\bar{P}^0 \to f)(t)$

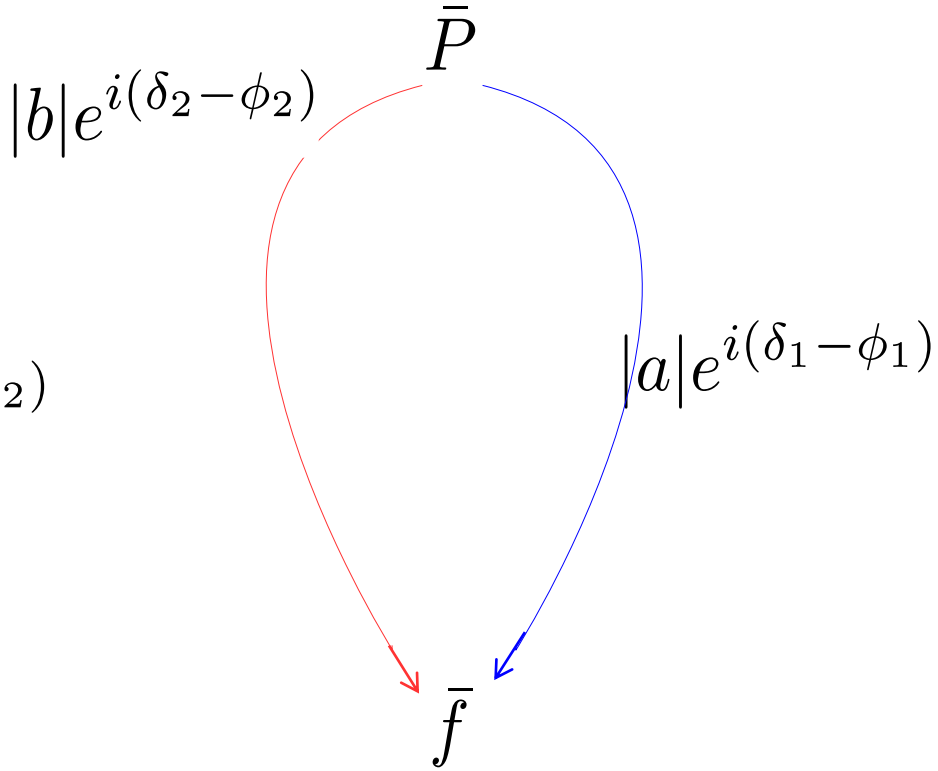
$$\begin{matrix} P^0 \to f \\ \bar{P}^0 \to f \end{matrix} \quad + \quad \begin{matrix} \bar{P}^0 \to \bar{P}^0 \to f \\ \bar{P}^0 \to \bar{P}^0 \to f \end{matrix}$$

Direct _CP_ Violation: $\Gamma(P \to f) \neq \Gamma(\bar{P} \to \bar{f})$

CP-violation

Direct *CP* Violation: $\Gamma(P \to f) \neq \Gamma(\bar{P} \to \bar{f})$



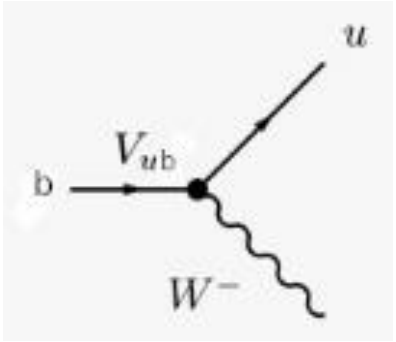


$$|A_f|^2 = |a|^2 + |b|^2 + 2|a||b|\cos(\Delta\delta + \Delta\phi)$$

$$|\bar{A}_{\bar{f}}|^2 = |a|^2 + |b|^2 + 2|a||b|\cos(\Delta\delta - \Delta\phi)$$

CKM Matrix

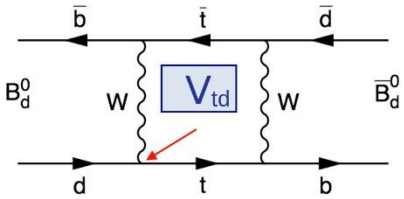
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Charmless B-decays

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$B\bar{B}$ mixing

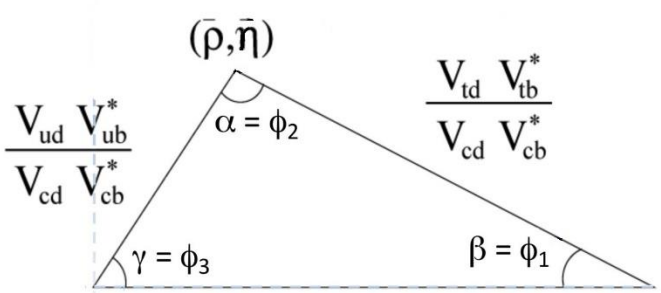


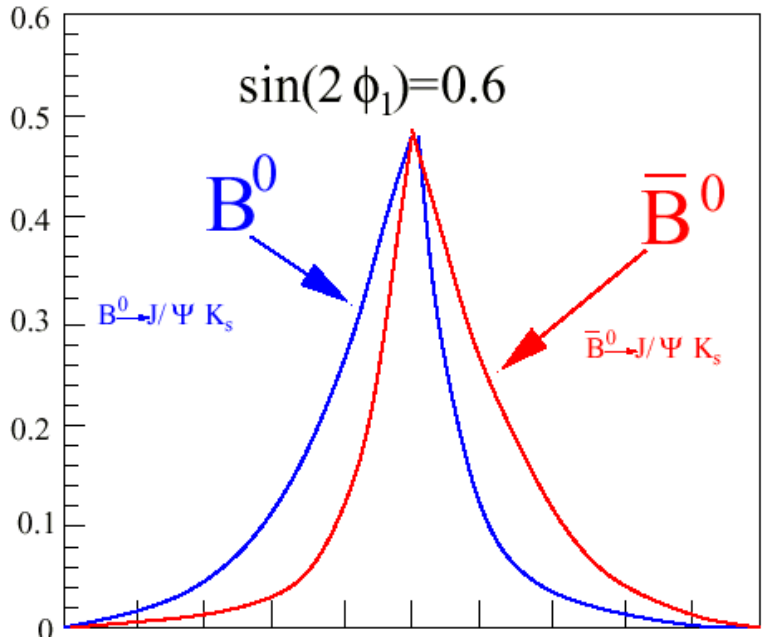
$$V_{ub} << V_{cb}$$

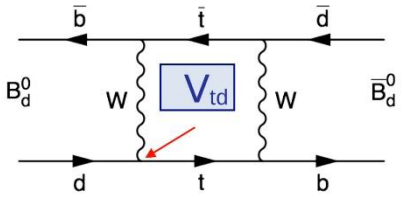
Time Dependent CP-Violation

Look for interference between mixing and decay amplitudes.

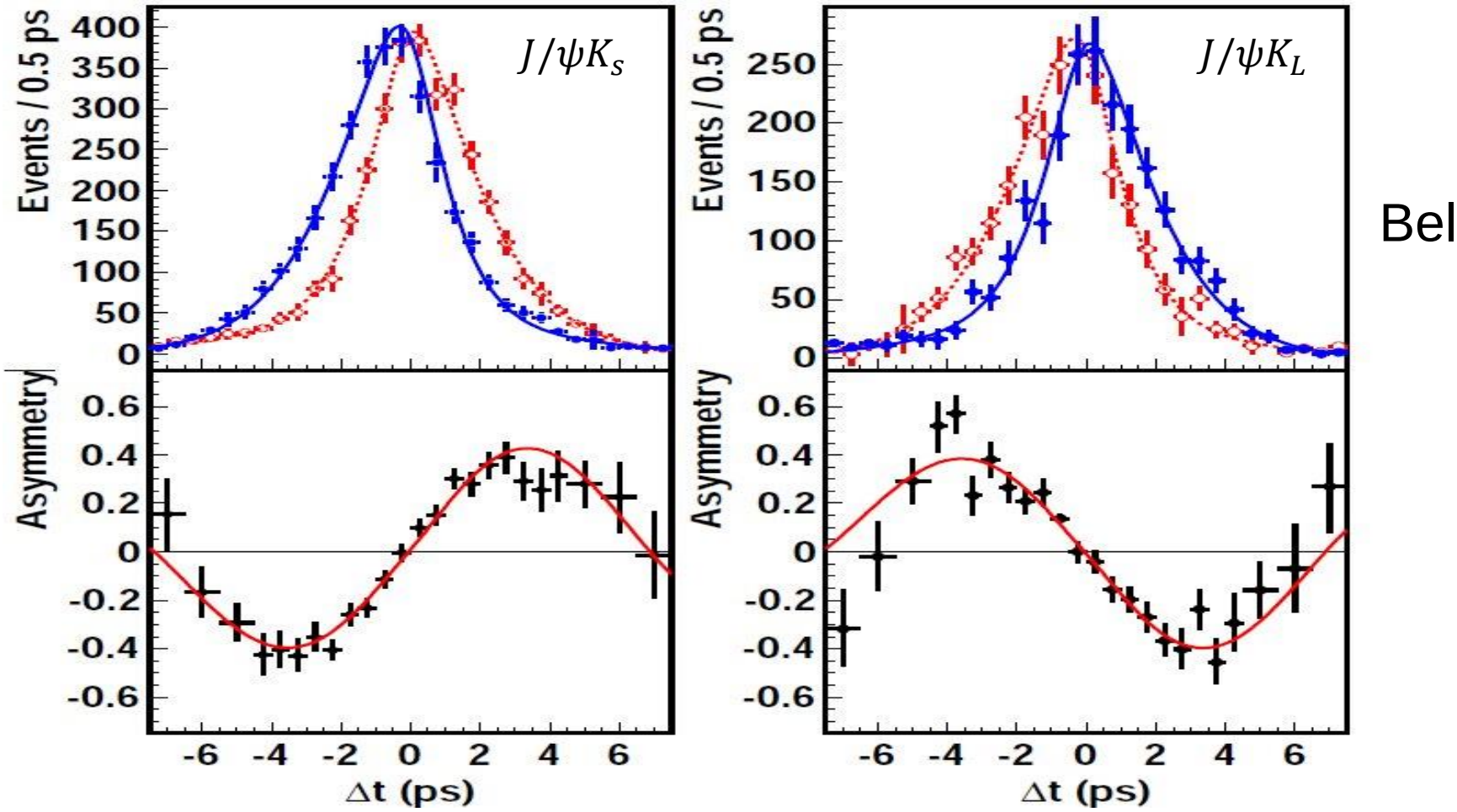
$$A(t) = \frac{\Gamma(\overline{B^0} \to f_{cp}) - \Gamma(B^0 \to f_{cp})}{\Gamma(\overline{B^0} \to f_{cp}) + \Gamma(B^0 \to f_{cp})} = -\xi_f sin(2\phi_1) sin(\Delta m t)$$







Measurement of TDCPV for $B \to J/\Psi K^0$



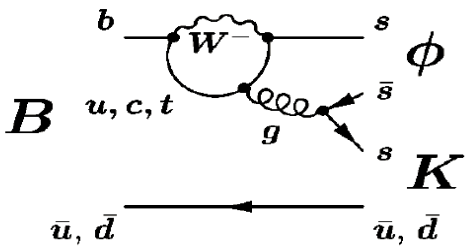
Belle

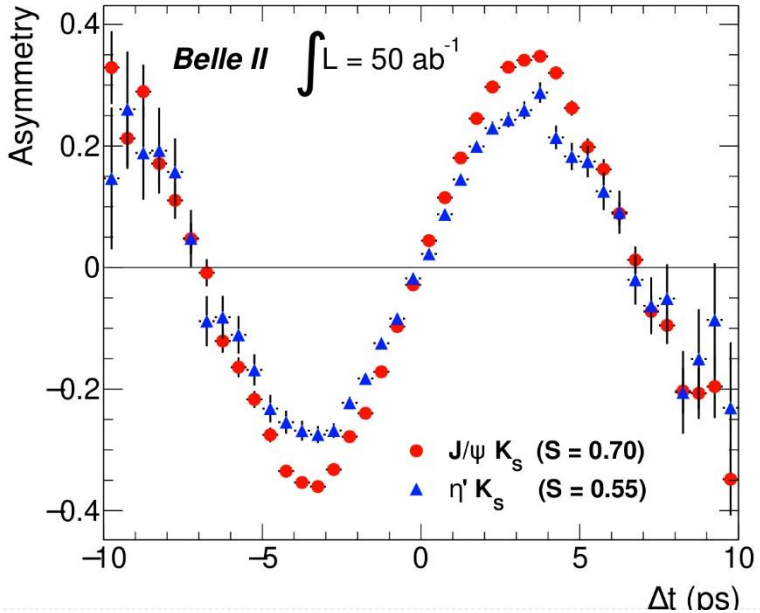
PDG 2018, $\sin(2\Phi_1) = 0.691 \pm 0.017$

New Physics hiding in $b \to ss\bar{s}$?

Hunting for phases from new physics

Example:





In the SM, $\sin(2\varphi_1)^{\text{eff}} = \sin(2\varphi_1)$ ($B \to \psi K_S$)

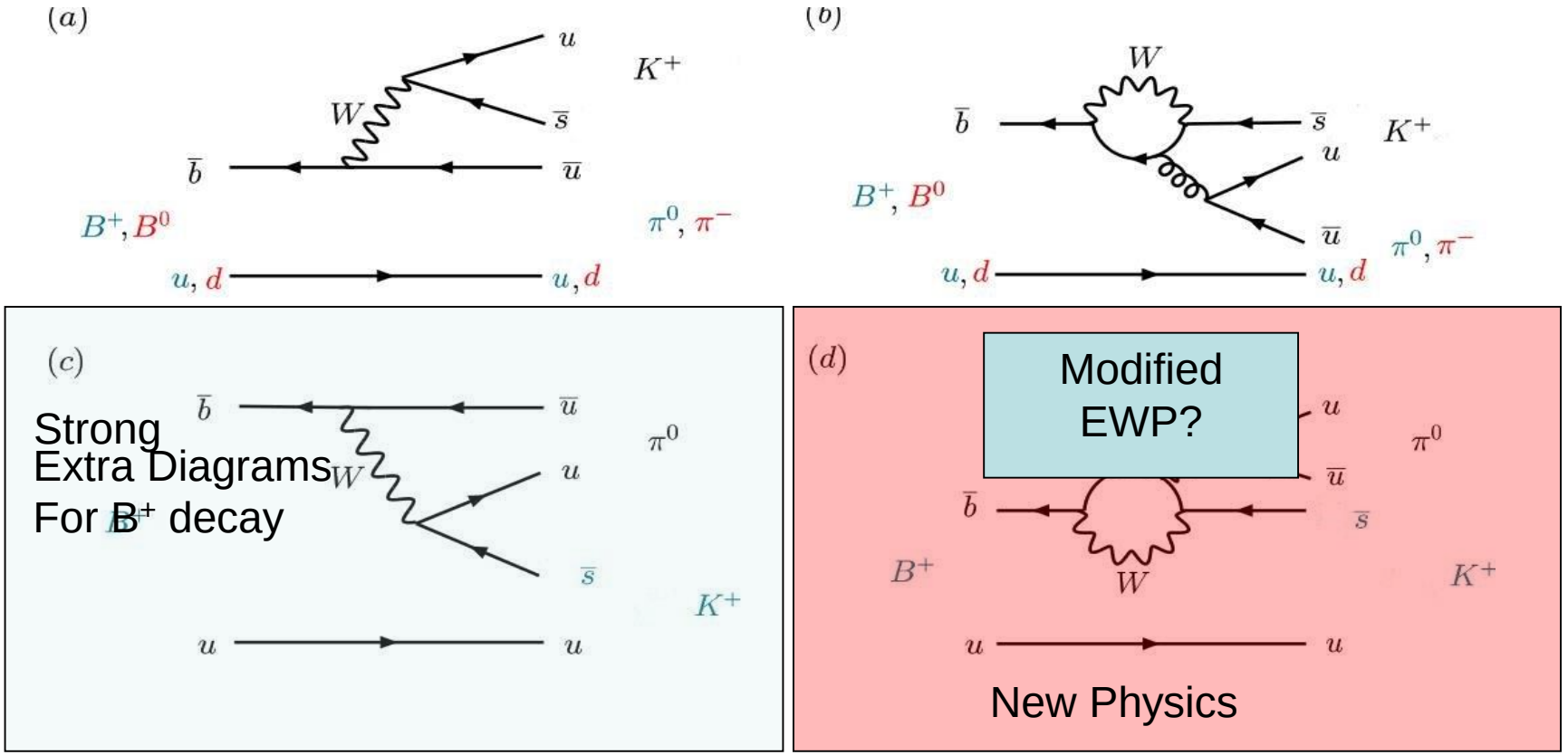
Mode	Shift from $\sin(2\Phi_1)$	Theoretical Uncertainty	Data
$B \to \eta' K_s$	0.01	0.01	-0.05±0.06
$B \to \Phi K_s$	0.02	0.01	-0.06±0.12
$B \to \eta K_s$	0.10	0.09	
$B \to \varpi K_s$	0.13	0.08	0.03+-0.21

$B \to K\pi$ Puzzle

Unexpected results in BR & Direct CP violation for $B \to K\pi$ modes

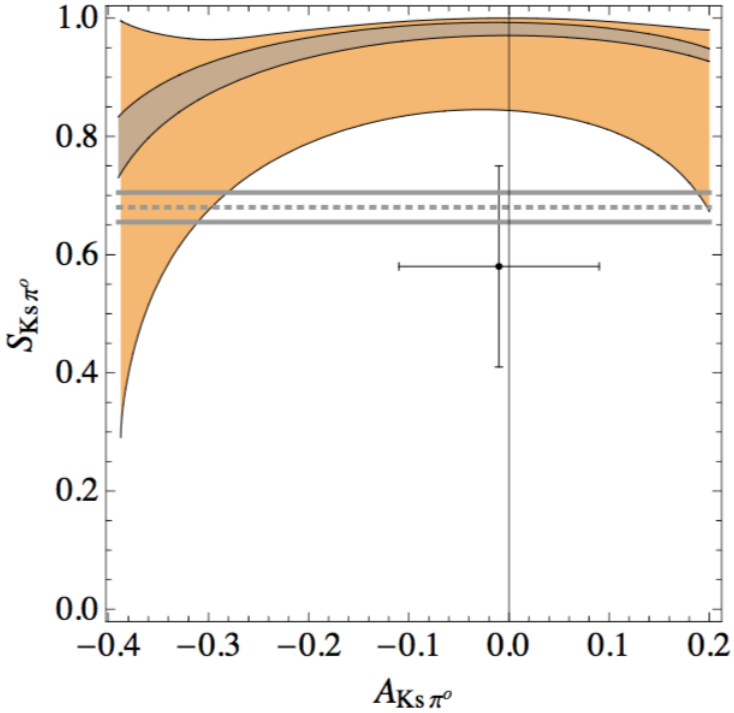
$$A_{CP}\left(B \to K^{\pm}\pi^{\mp}\right) = -0.0.82 \pm 0.006$$

$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{0}) = +0.037 \pm 0.021$$

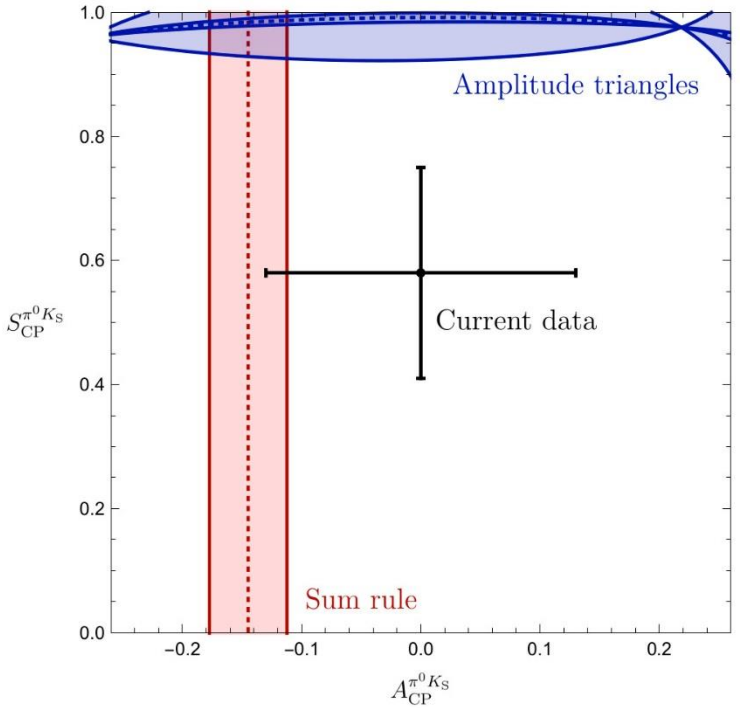


Theory Predictions for $B^0 \to K_s\pi^0$

2008 → Smaller uncertainties on Φ_3 → 2018



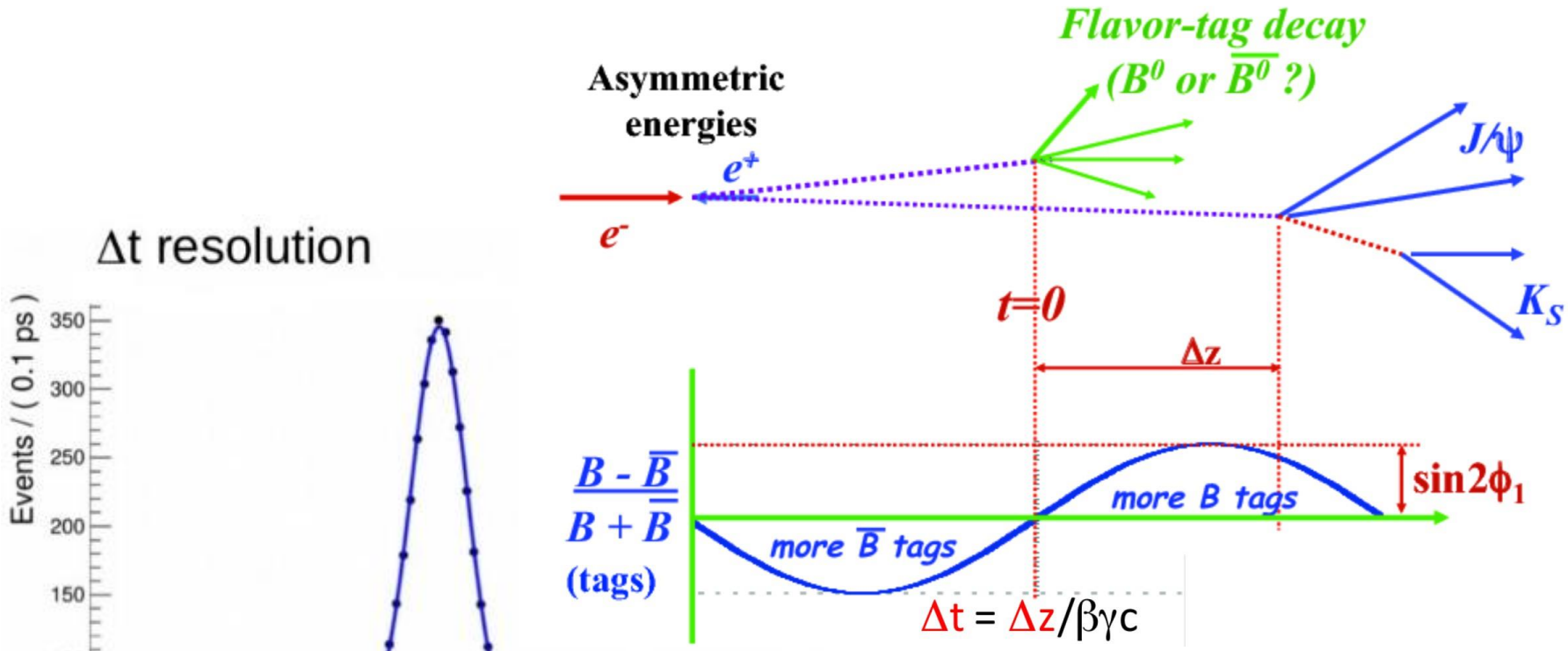
[R. Fleischer, S. Jäger, D. Pirjol, J. Zupan (2008)]



R. Fleischer, R. Jaarsma, and K. K. Vos;
PLB 785 (2018) 525;
R. Fleischer, R. Jaarsma, E. Malami, and K. K. Vos;
arXiv:1806.08783 [hep-ph]

2.2σ discrepancy now

Δt Determination at B-factories

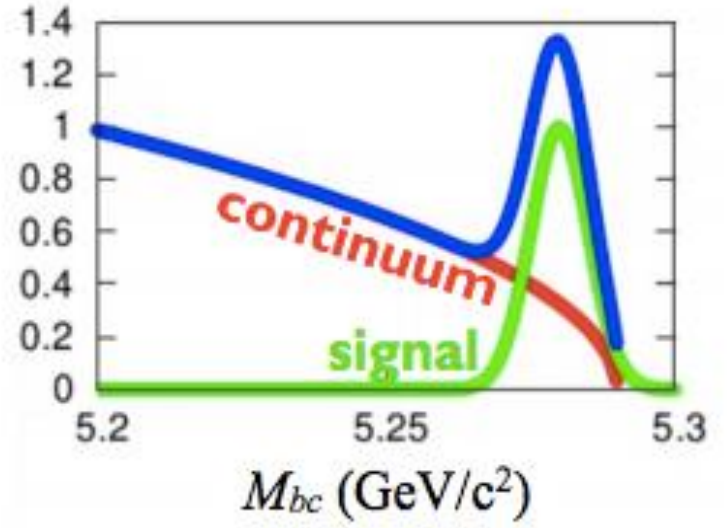


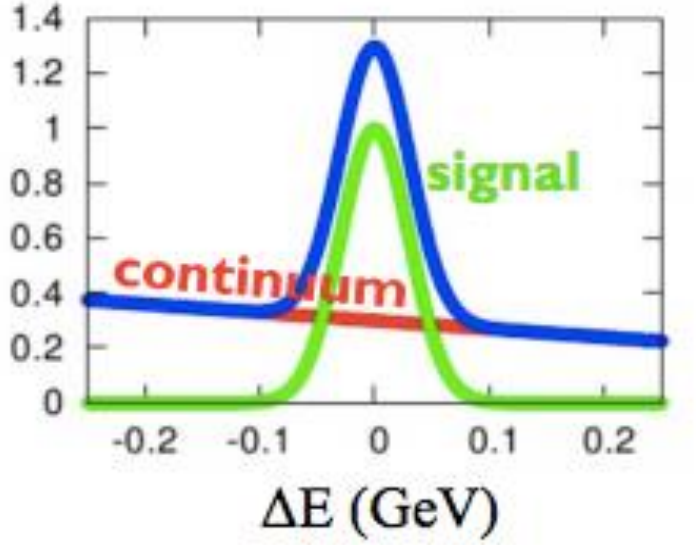
Belle II Flavour tag eff = 37% - 40%
Belle Flavour tag eff = 30%

Kinematic Variables in B-Factory measurements

$$M_{\mathrm{bc}} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

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

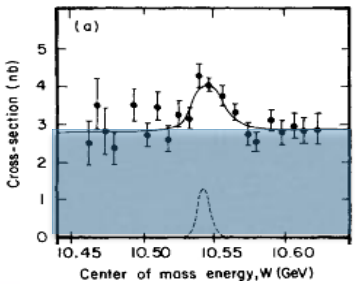


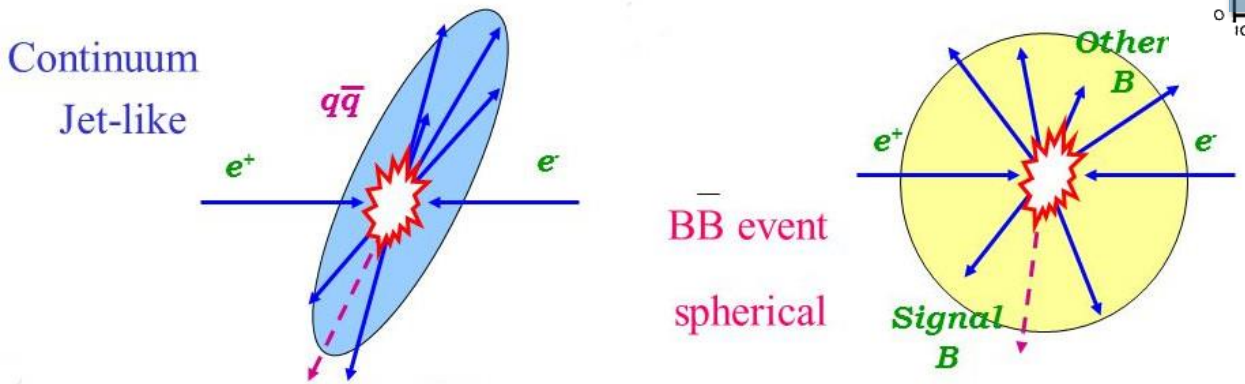


M_{bc} peaks at B mass for fully reconstructed signal
ΔE peaks at zero for fully reconstructed signal

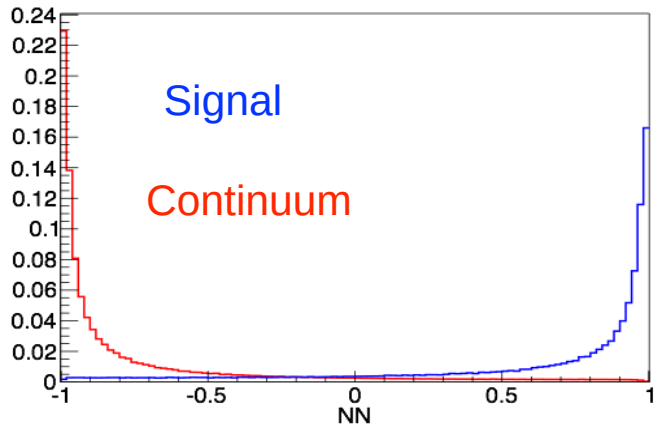
Continuum Background

- Continuum background($e^+e^- \rightarrow q\bar{q}(u,d,s,c)$):
  - Dominant background
  - Event topology differs from BB decays

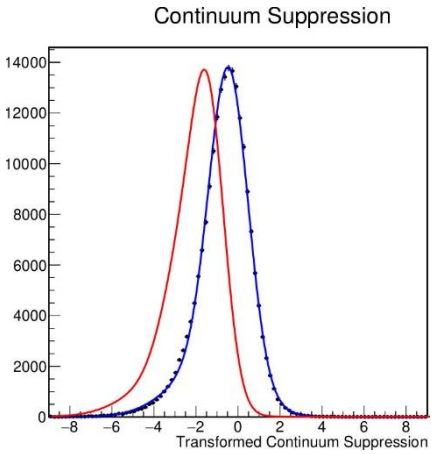




  - Combined variables describing the event topology in an artificial neural network.



$$\log\left(\frac{N - N_{cut}}{N_{max} - N}\right)$$



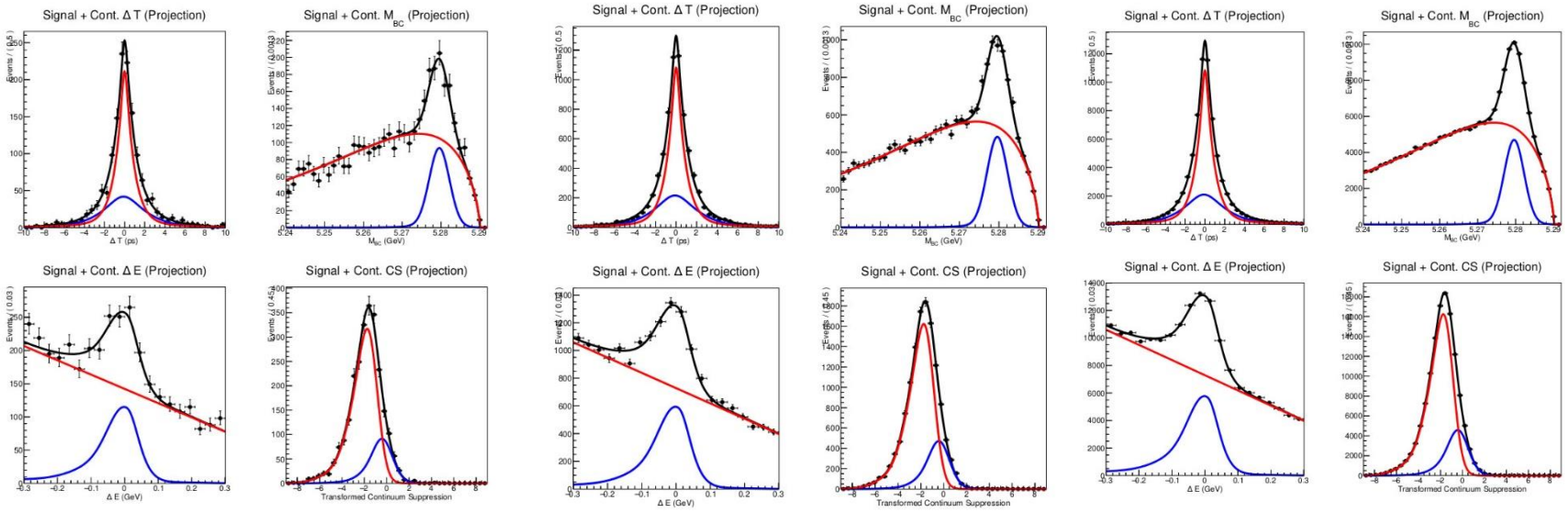
Belle II prospects for $B \to K_s \pi^0$

(Melbourne analysis of Belle II MC)

Continuum background

Signal

Timing resolution for K_s ~ 1.17 ps
(All charged tracks 0.77 ps)

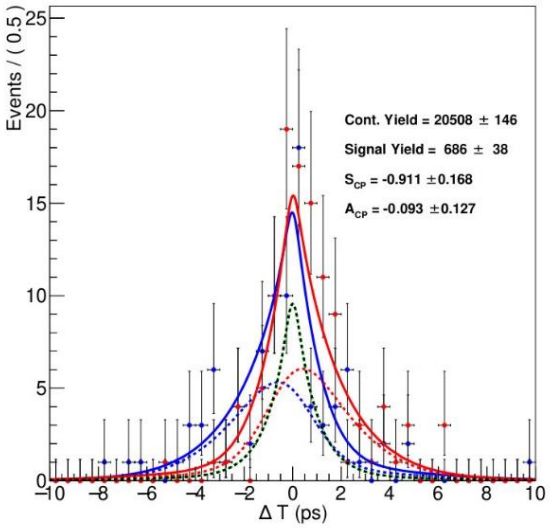


1 ab^{-1} 5 ab^{-1} 50 ab^{-1}

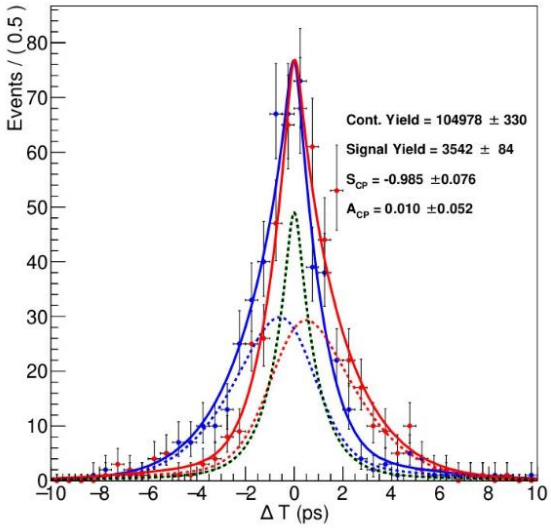
Time-Dependent CPV for $B \to K_s \pi^0$

$\overline{B^0}$ decays

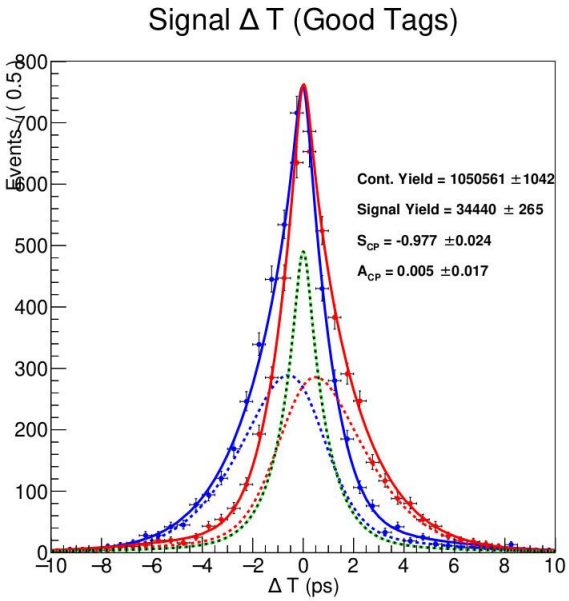
B^0 decays



1 ab^{-1}



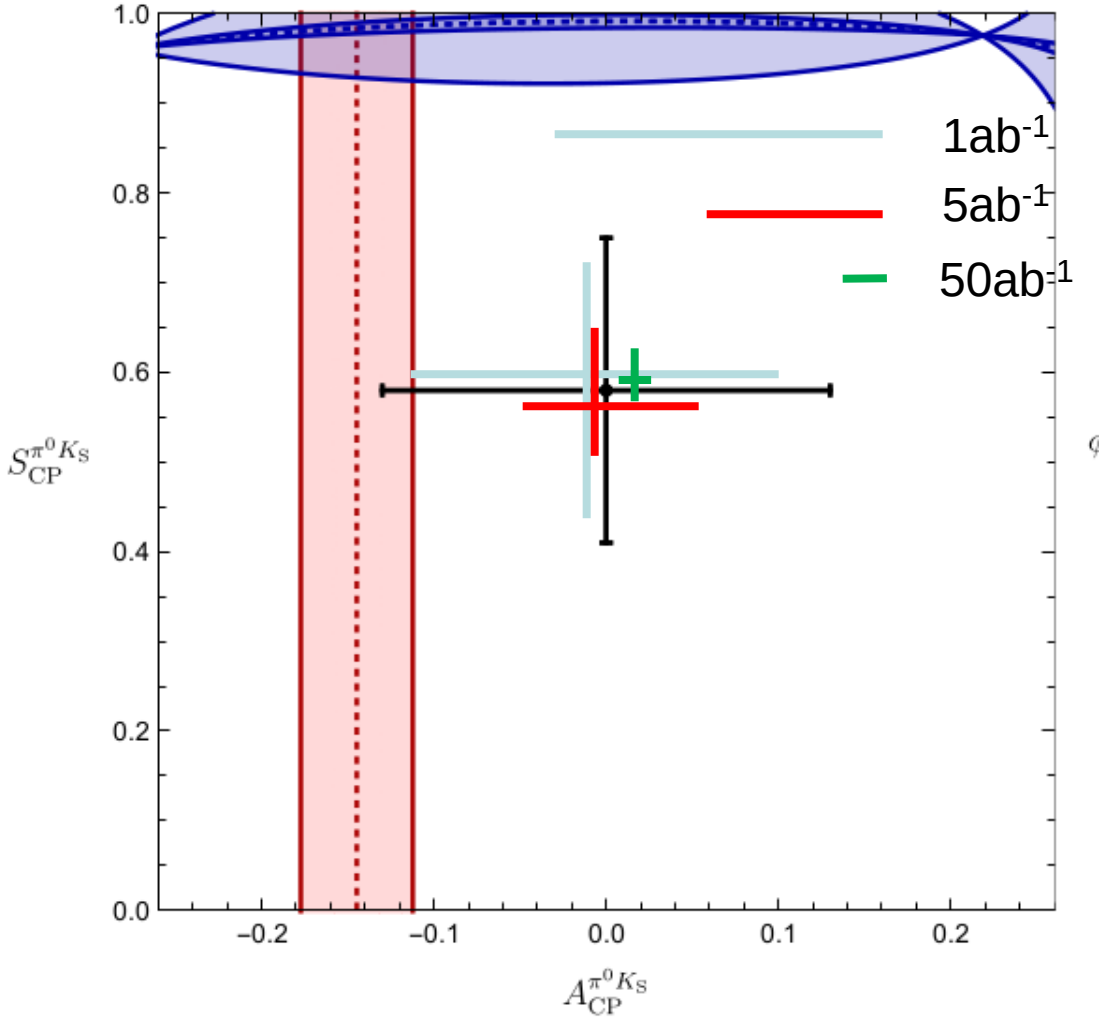
5 ab^{-1}



50 ab^{-1}

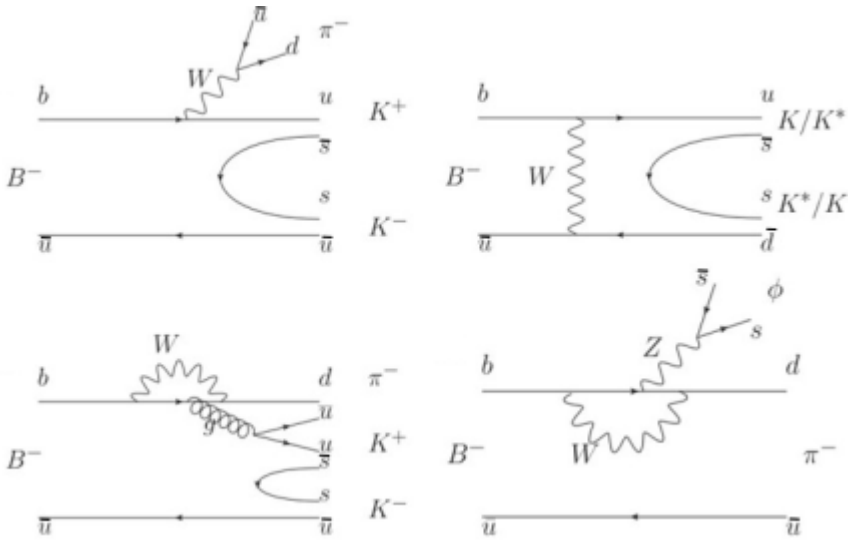
S_{CP} and A_{CP} $B \to K_s\pi^0$ at Belle II

If S_{CP} and A_{CP} hold their central values we have >5σ deviation with 5 ab^{-1}



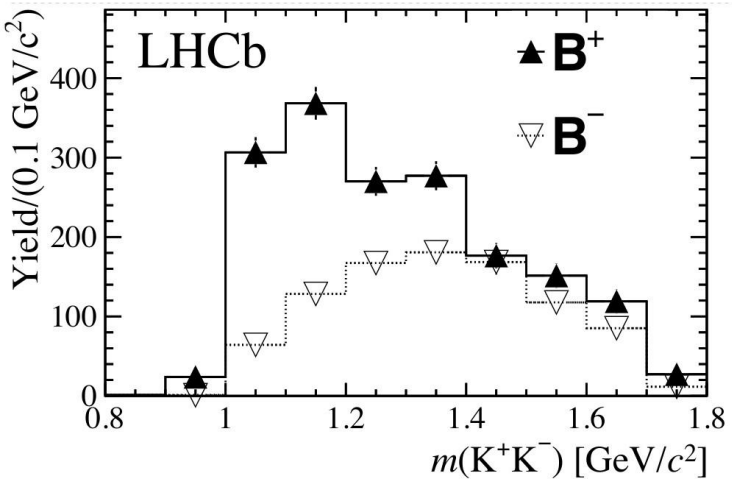
A_{CP} for $B^{\pm} \rightarrow K^{+}K^{-}\pi^{\pm}$

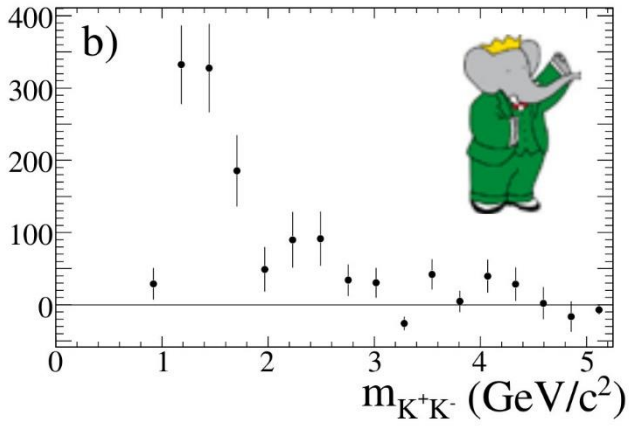
Cabibbo and color suppressed tree
And Penguin diagrams



Br($B^{\pm} \rightarrow K^{-}K^{+}\pi^{\pm}$) = $(5.0 \pm 0.5 \pm 0.5) \times 10^{-6}$
PRL 99, 221801 (2007) BaBar

A_{CP} = 0.123 ± 0.017 ± 0.012 ± 0.007
PRD 90, 112004 (2014) LHCb

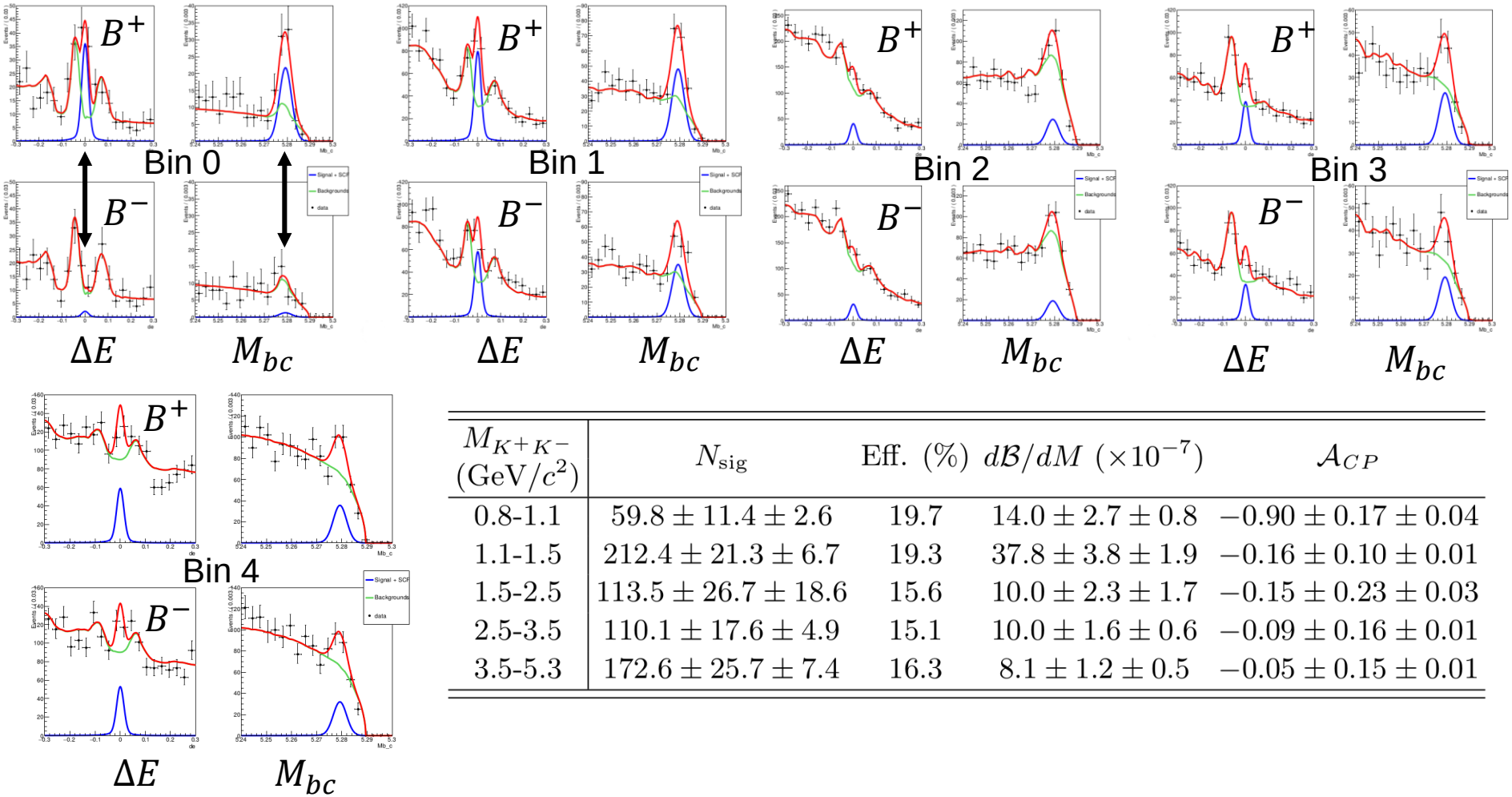




Fit for $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ in M_{KK} Bins

Signal — Sum

Backgrounds • Data



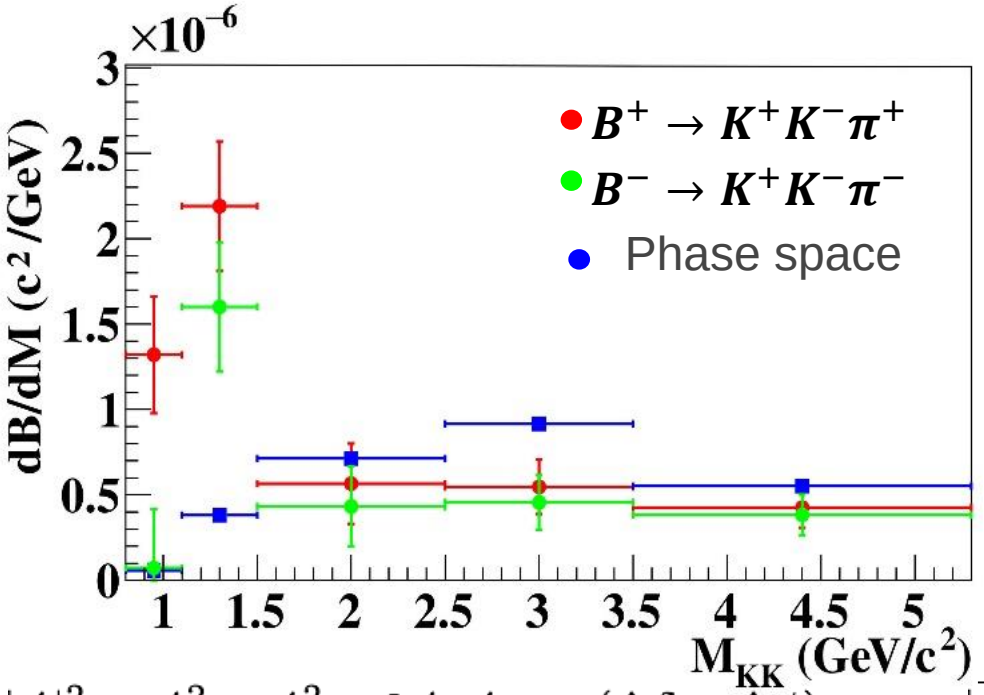
$M_{K^+K^-}$ (GeV/c^2)	$N_{\rm sig}$	Eff. (%)	$d\mathcal{B}/dM$ ($\times 10^{-7}$)	$\mathcal{A}_{CP}$
0.8-1.1	$59.8 \pm 11.4 \pm 2.6$	19.7	$14.0 \pm 2.7 \pm 0.8$	$-0.90 \pm 0.17 \pm 0.04$
1.1-1.5	$212.4 \pm 21.3 \pm 6.7$	19.3	$37.8 \pm 3.8 \pm 1.9$	$-0.16 \pm 0.10 \pm 0.01$
1.5-2.5	$113.5 \pm 26.7 \pm 18.6$	15.6	$10.0 \pm 2.3 \pm 1.7$	$-0.15 \pm 0.23 \pm 0.03$
2.5-3.5	$110.1 \pm 17.6 \pm 4.9$	15.1	$10.0 \pm 1.6 \pm 0.6$	$-0.09 \pm 0.16 \pm 0.01$
3.5-5.3	$172.6 \pm 25.7 \pm 7.4$	16.3	$8.1 \pm 1.2 \pm 0.5$	$-0.05 \pm 0.15 \pm 0.01$

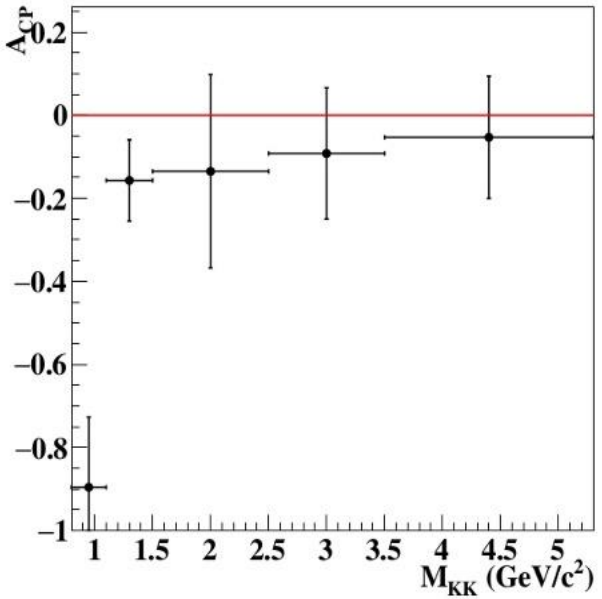
$B^{\pm} \to K^{+}K^{-}\pi^{\pm}$

Total $\mathcal{B}$ = (5.38 ± 0.40 ± 0.35) × 10 $^{-6}$

A_{CP} = −0.170 ± 0.073 ± 0.017

C.-L.Hsu et al. Phys. Rev. D96, 031101(R) (2017)





$$|A|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\delta + \Delta\phi) \qquad |\overline{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\delta - \Delta\phi)$$

Unusual dynamics showing a large enhancement and very large direct CP-violation

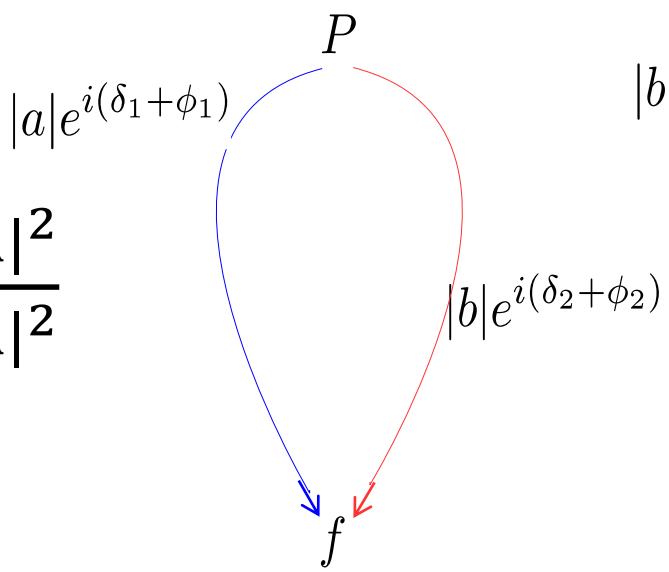
A_{CP} = -0.9 ±0.17 ± 0.03 at M_{KK} < 1.1 GeV (4.8 σ)

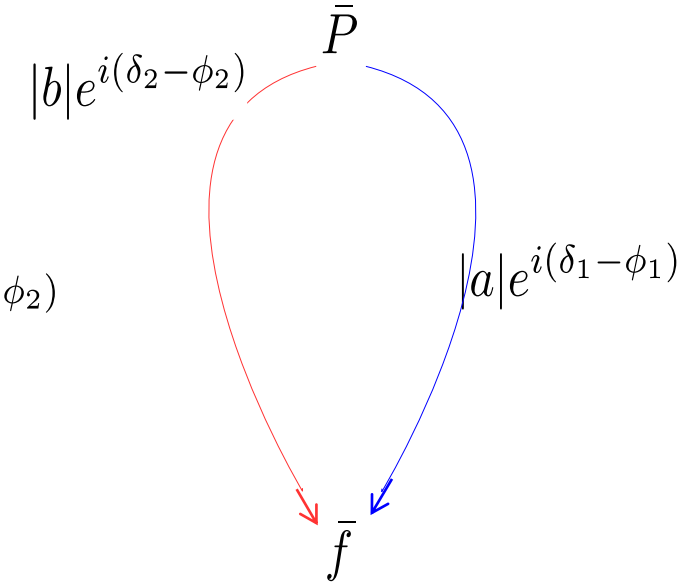
Hard to make a model do both.

Challenge to Theory for $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$

Recall

$$A_{CP} = \frac{|\overline{A}|^2 - |A|^2}{|\overline{A}|^2 + |A|^2}$$





$$|A_f|^2 = |a|^2 + |b|^2 + 2|a||b|\cos(\Delta\delta + \Delta\phi)$$

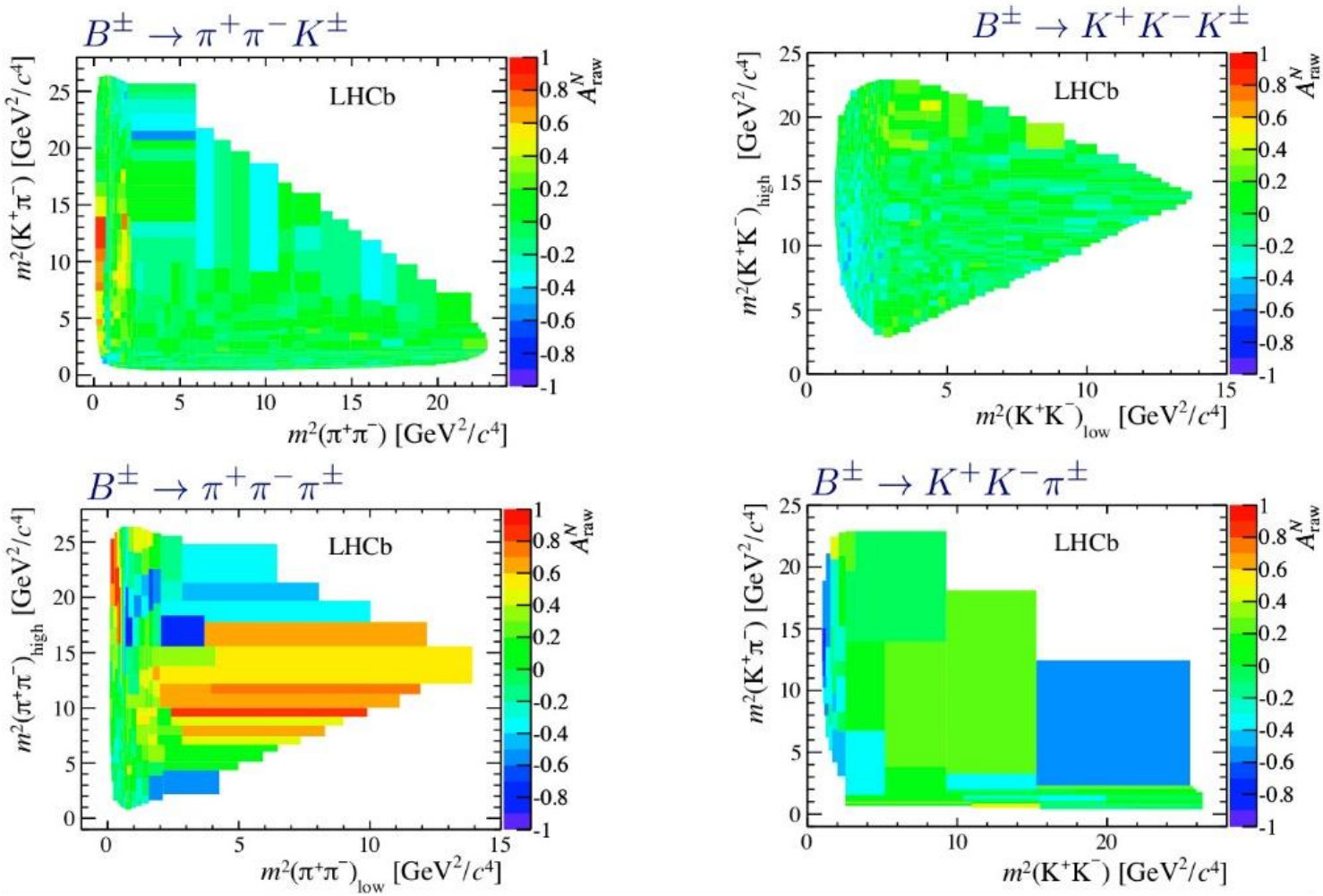
$$|\bar{A}_{\bar{f}}|^2 = |a|^2 + |b|^2 + 2|a||b|\cos(\Delta\delta - \Delta\phi)$$

Need an order of magnitude increase in EW Tree diagram
And an order of magnitude increase in Penguin diagram
Both in 0.99 GeV < M_{KK} < 1.1 GeV

The Full Challenge in 3-body decays

Results from LHCb

Distributions of A_{CP} PRD **90**, 112004



Regions of phase space where $A_{CP} = \pm 1$

Conclusions

- Many interesting challenges for Theory and experiment in CPV studies.
- For 2-body modes Theory precision is a few percent.
- Will be challenged by new experimental results over the next decade
- 2.2 σ discrepancy in $B^0 \to K_s \pi^0$ targeted by Belle II
- Order of magnitude challenge to theory in $\mathrm{B}^{\pm} \to \mathrm{K}^{+}\mathrm{K}^{-}\pi^{\pm}$ DCPV
- Many interesting challenges in DCPV in 3-body modes.

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Thank you!

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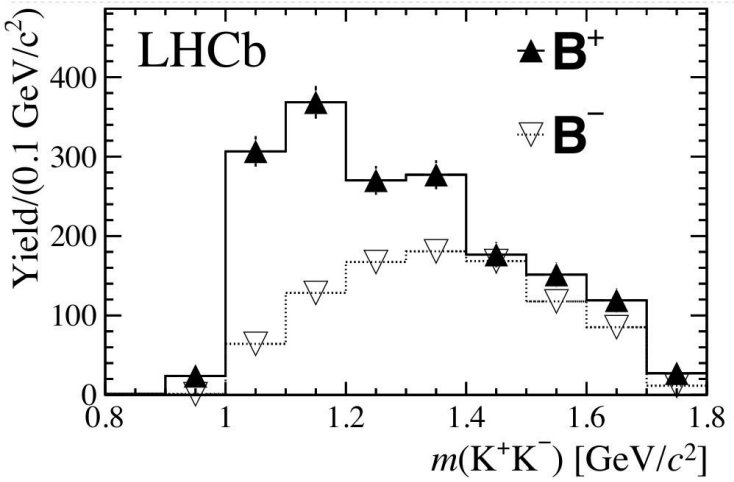
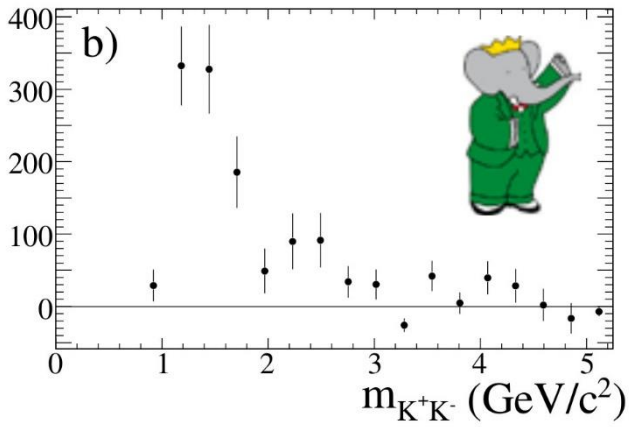
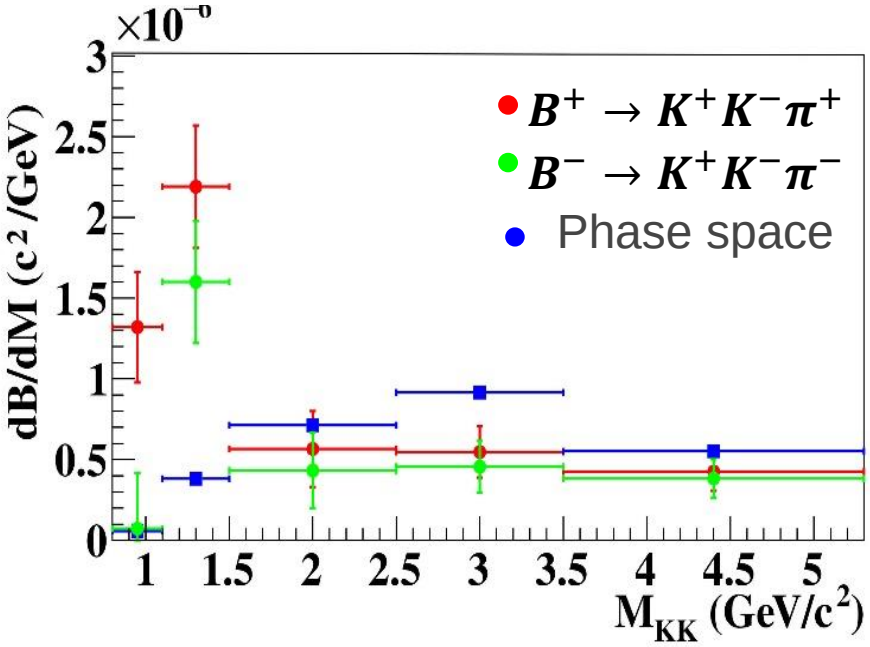
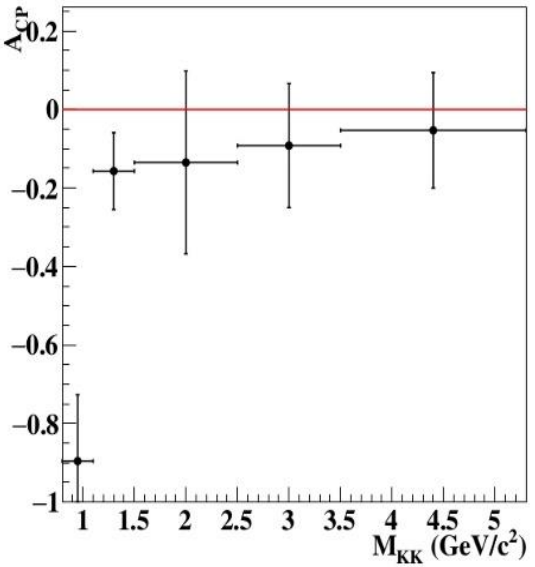
Backup

$B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ comparison









Belle