



Strong-phase parameters in charm decays

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Transfer of status report, U. Oxford

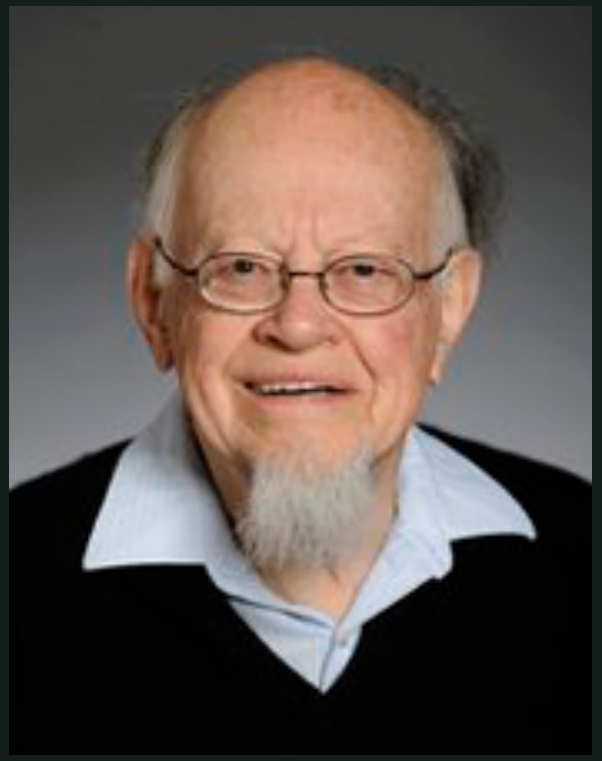
18 June 26

To find differences between matter and antimatter in the SM, CKM matrix is the ***only*** place.

Expand in small parameter $\lambda = \sin\theta_c$:

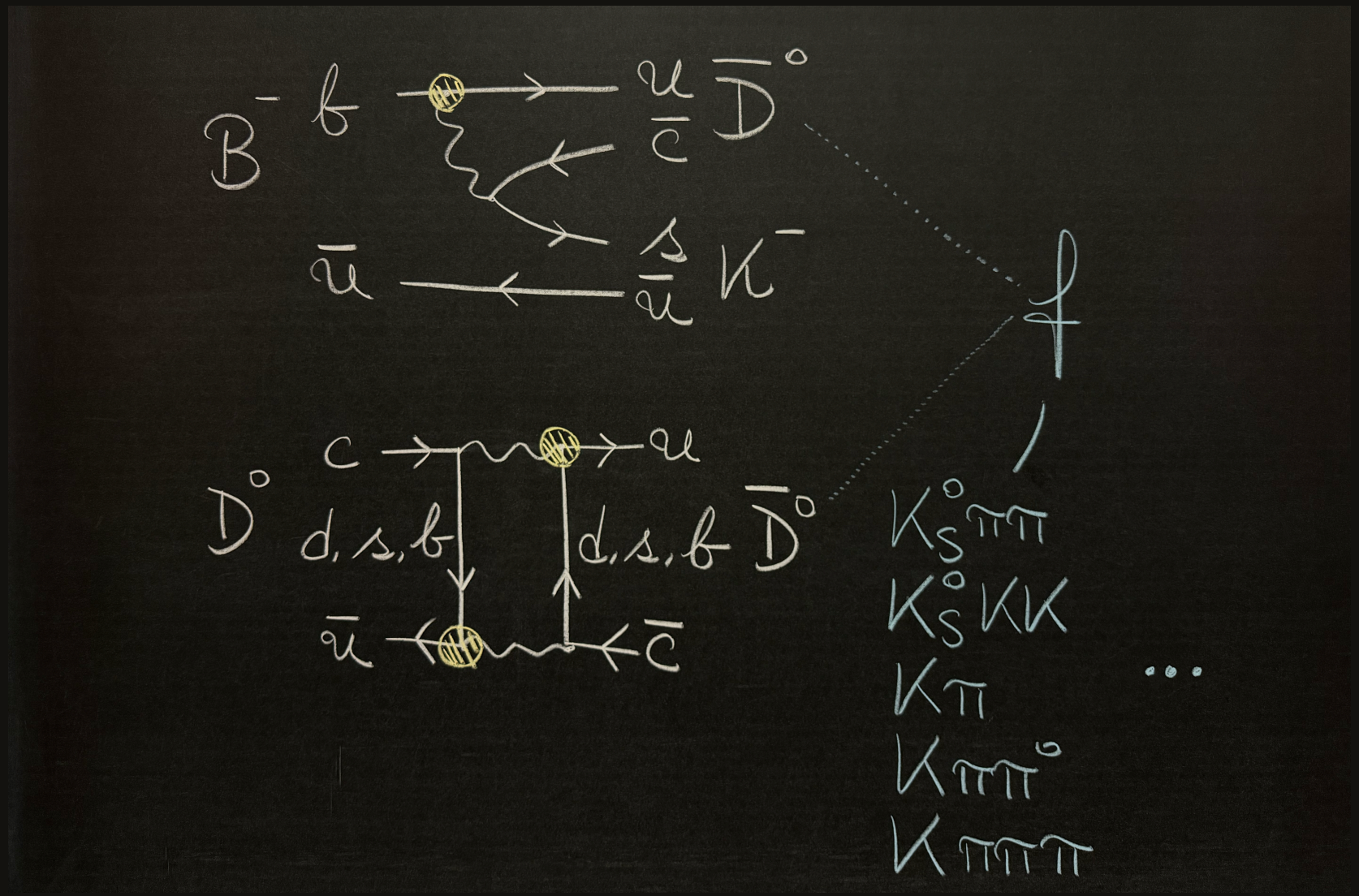
V_{ub}

$$V = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3 e^{-i\gamma} \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3\left(1 - e^{i\gamma}\right) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



Lincoln Wolfenstein

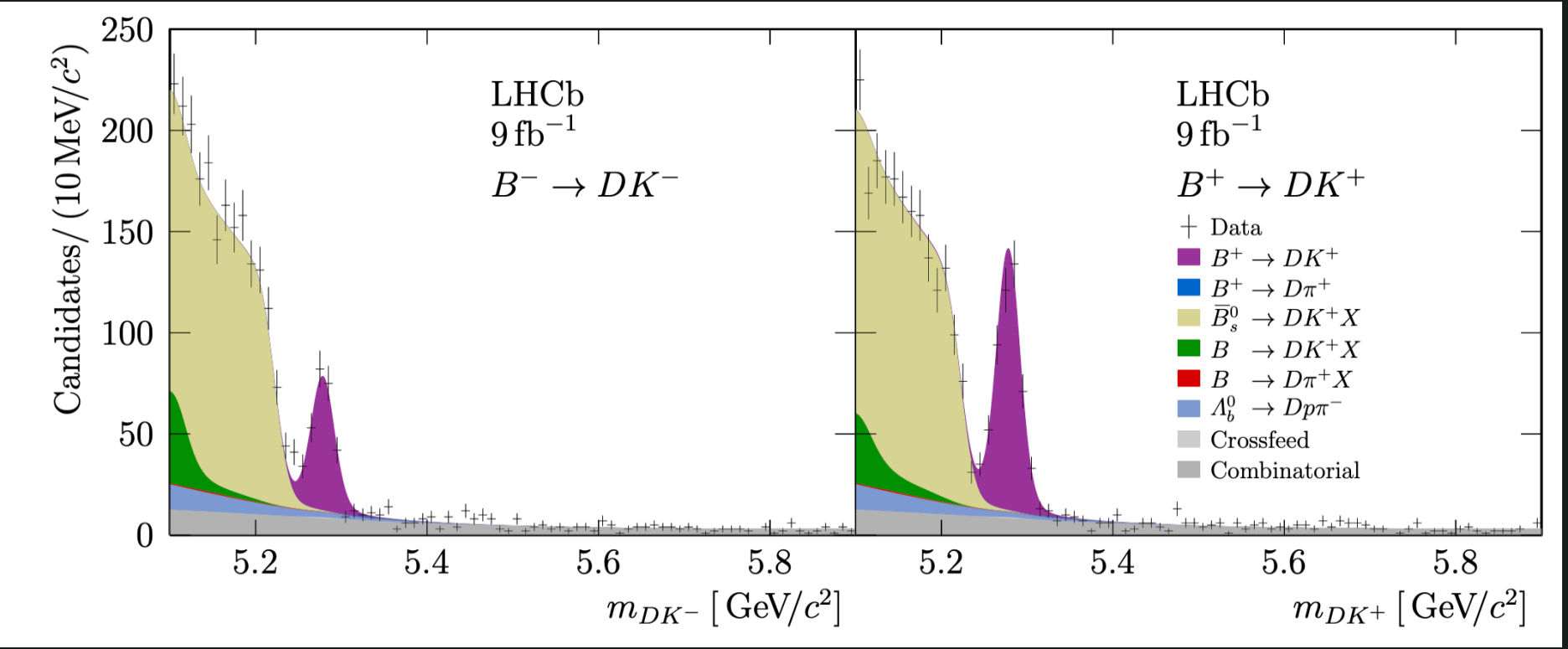
Matter-antimatter differences lie within $\arg V_{ub}$


B^-
b
u
$\bar{c}$
$\bar{D}^0$
$\bar{u}$
s
$\bar{u}$
K^-
D^0
c
u
d, s, b
d, s, b
$\bar{D}^0$
$\bar{u}$
$\bar{c}$
f
$K^0_S\pi\pi$
$K^0_S KK$
$K\pi$
$K\pi\pi^0$
$K\pi\pi\pi$
...

Difference between matter and antimatter …

$$N^{\pm} = \int \mathrm{d}\mathbf{z} \left| \left\langle K^{-}\pi^{+}\pi^{+}\pi^{-} \middle| B^{\pm} \right\rangle \right|^{2}$$

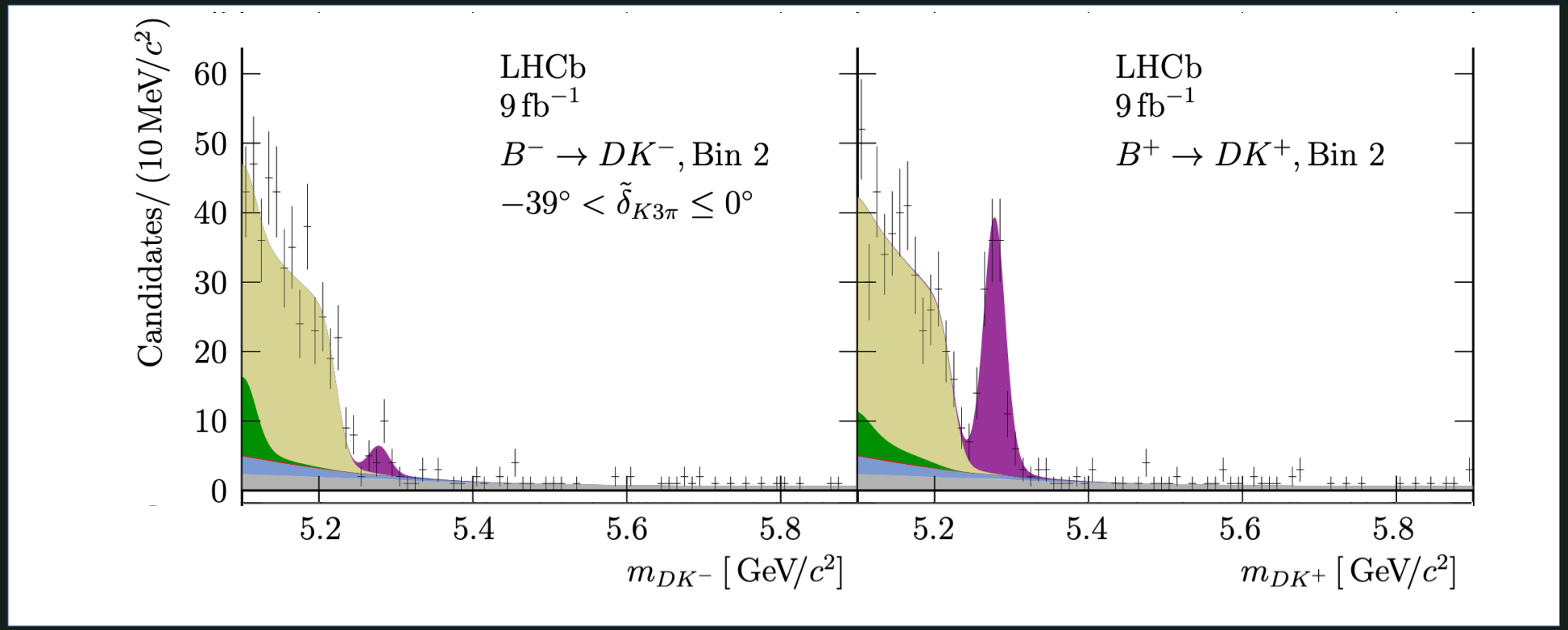
JHEP07(2023)138



… becomes larger after phase space binning!

$$N^{\pm}_{i=2} = \int_{i=2} \mathrm{d}\mathbf{z} \left| \left\langle K^-\pi^+\pi^+\pi^- \,|\, B^\pm \right\rangle \right|^2$$

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Binning = carefully grouping together regions of kaon and pion momenta

Strong-phase parameters

$$\left|\left\langle f|B^{\pm}\right\rangle\right|^2 = \left|\left\langle f|D^0\right\rangle\left\langle D^0|B^{\pm}\right\rangle + \left\langle f|\overline{D}^0\right\rangle\left\langle \overline{D}^0|B^{\pm}\right\rangle\right|^2$$

End-goal: measure phases carried by yellow

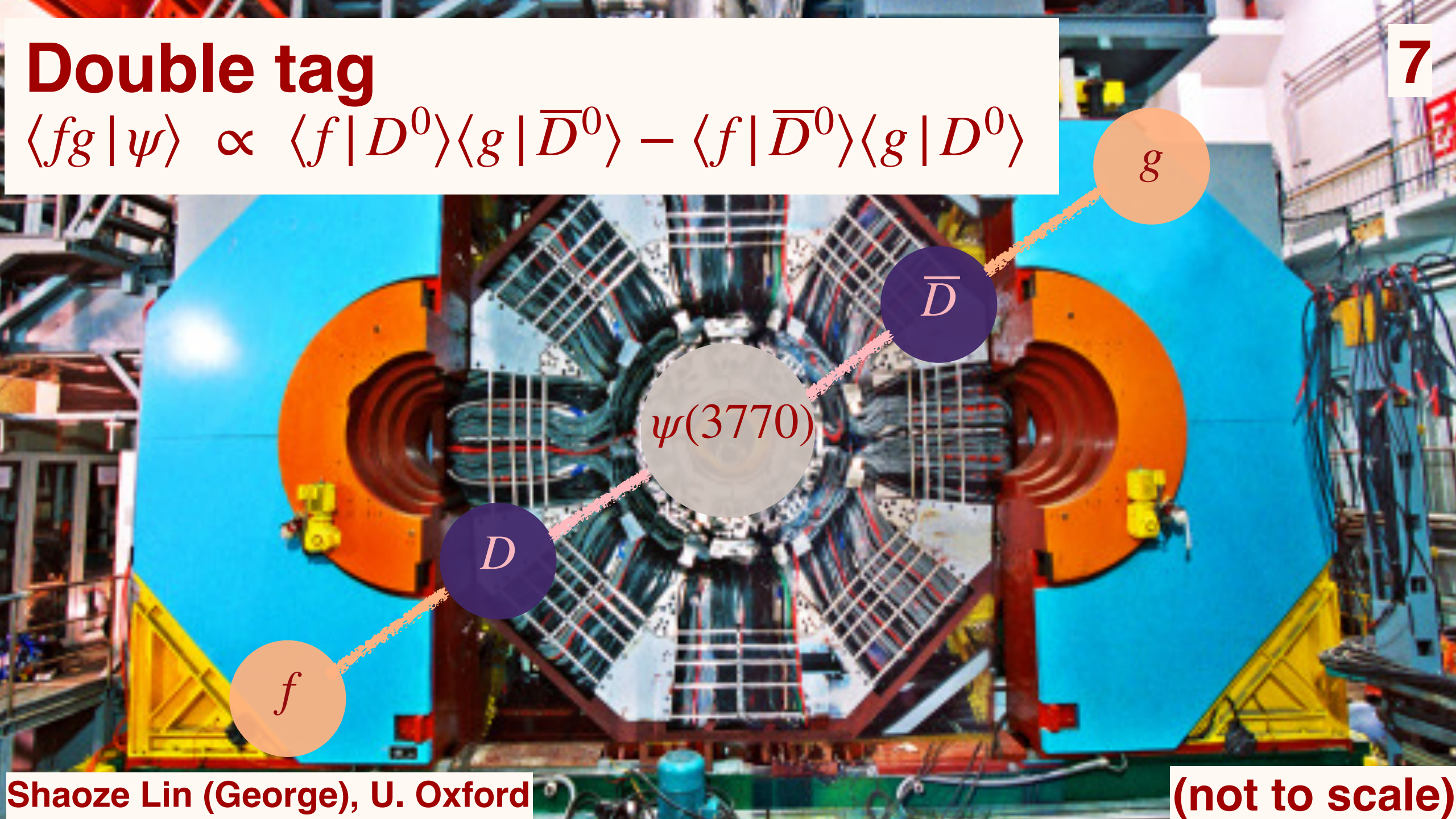
Measure binned $|$cyan$|^2$ in LHCb and use binned red as inputs

$$F_{f,i} \propto \int_i \mathrm{d}\mathbf{z} \left|\left\langle f|D^0\right\rangle\right|^2 \qquad c_{f,i} - \mathrm{i}s_{f,i} \propto \int_i \mathrm{d}\mathbf{z} \left\langle f|\overline{D}^0\right\rangle \left\langle f|D^0\right\rangle^*$$

Need a system of interference. **Enter BESIII!**

Double tag

$$\langle fg|\psi\rangle \propto \langle f|D^0\rangle\langle g|\overline{D}^0\rangle - \langle f|\overline{D}^0\rangle\langle g|D^0\rangle$$



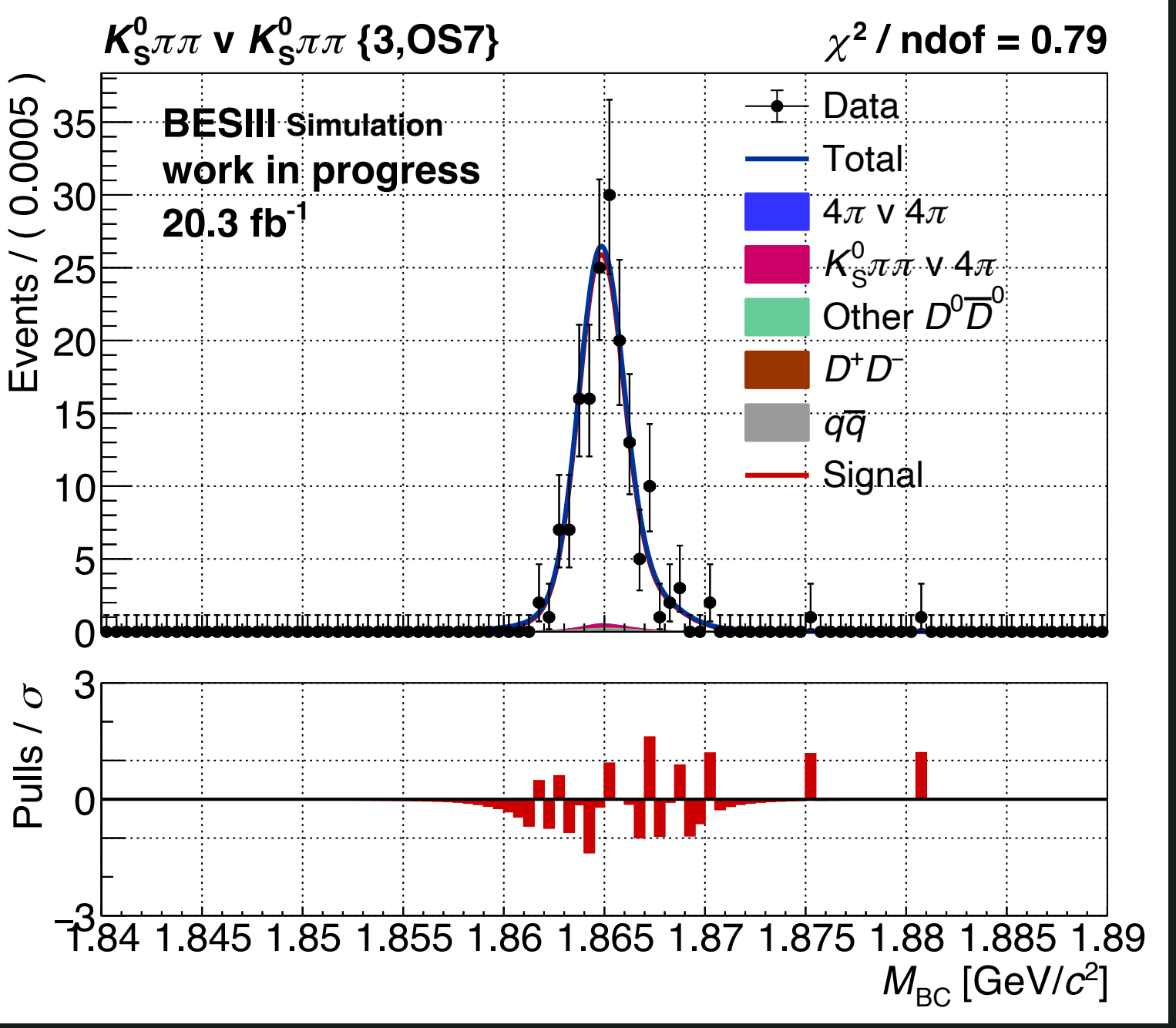
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(not to scale)

Quantum correlation

$$G_{fg,ij} = h_{fg}\left(F_{f,i}F_{g,-j} + F_{f,-i}F_{g,j} - 2\eta\sqrt{F_{f,i}F_{f,-i}F_{g,j}F_{g,-j}}\left(c_{f,i}c_{g,j} + s_{f,i}s_{g,j}\right)\right)$$

Yield is dependent on strong-phase parameters of both sides!



Very clean environment of e^+e^- machine!

However low statistics:

$8\,\text{fb}^{-1} \rightarrow 20\,\text{fb}^{-1}$

will be a **large** improvement

$S_{K^0_S\pi^+\pi^-,i}$

Bin	Stat Sys
1	$-0.741 \pm 0.090 \pm 0.015$
2	$-0.116 \pm 0.179 \pm 0.033$
3	$-0.622 \pm 0.168 \pm 0.030$
4	$-0.195 \pm 0.053 \pm 0.006$
5	$0.883 \pm 0.083 \pm 0.016$
6	$0.566 \pm 0.185 \pm 0.039$
7	$0.128 \pm 0.071 \pm 0.011$
8	$-0.197 \pm 0.096 \pm 0.012$

Stat dominated!

$8\,\text{fb}^{-1}$ BESIII

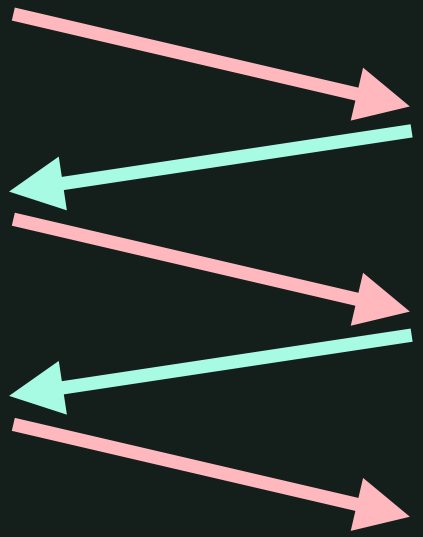
JHEP06(2025)086

Each endstate had their analyses …

$K^0_{S,L}\pi^+\pi^-$ CLEO $0.8\ \mathrm{fb}^{-1}$
PRD82 (2010) 112006

$K^0_{S,L}\pi^+\pi^-$ BESIII $3\ \mathrm{fb}^{-1}$
PRL124 (2020) 241802

$K^0_{S,L}\pi^+\pi^-$ BESIII $8\ \mathrm{fb}^{-1}$
JHEP06 (2025) 086



$K^-\pi^+\pi^+\pi^-$ CLEO $0.8\ \mathrm{fb}^{-1}$
PLB757 (2016) 520-527

$K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ BESIII $3\ \mathrm{fb}^{-1}$
JHEP05 (2021) 164

$K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ BESIII $8\ \mathrm{fb}^{-1}$
arXiv:2602.13002 [hep-ex]

$K^0_{S,L}\pi^+\pi^-$ v $K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$
signal v tag

$K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ v $K^0_{S,L}\pi^+\pi^-$
signal v tag

Sequential fits

$K^-\pi^+\pi^+\pi^-$

$K^-\pi^+\pi^0$



$K^0_S\pi^+\pi^-$

$K^-\pi^+$

Simultaneous fit



One fit to rule them all!

Correlations are not accounted for, this cannot continue! Instead:

$K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ v $K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ (In progress)

↓ Form multiplicative constraints on the likelihood

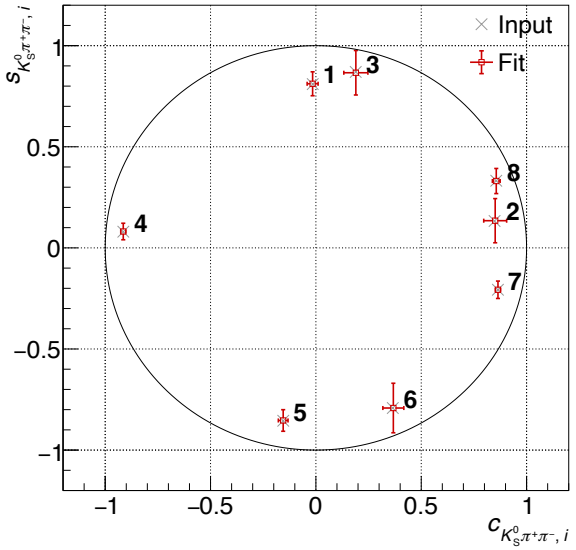
$K^0_{S,L}\pi^+\pi^-$ v $K^0_{S,L}\pi^+\pi^-, K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ (This work)

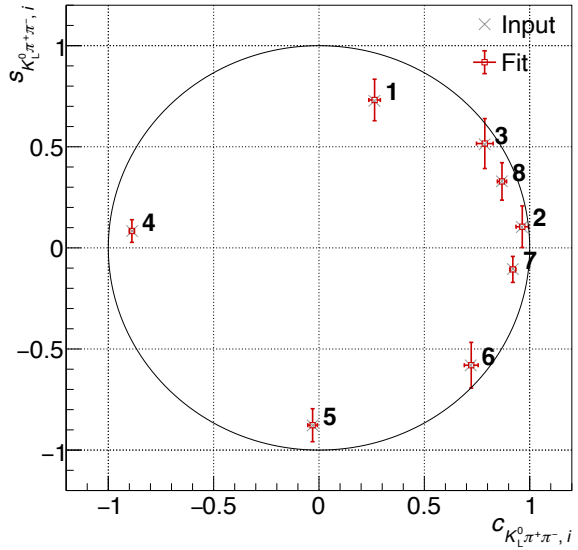
↓ Strong-phase parameters for ***everything***

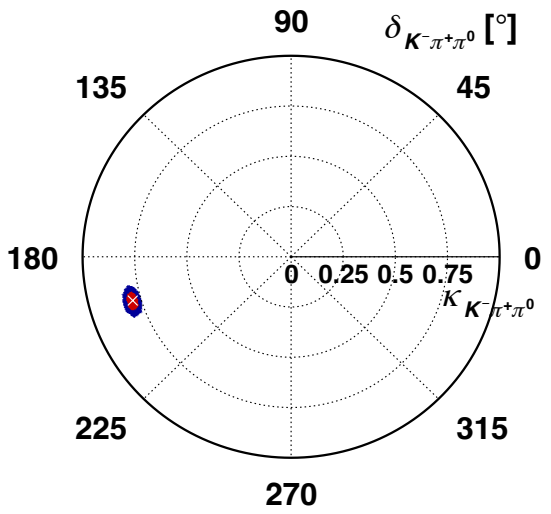
$s_{f,i}$

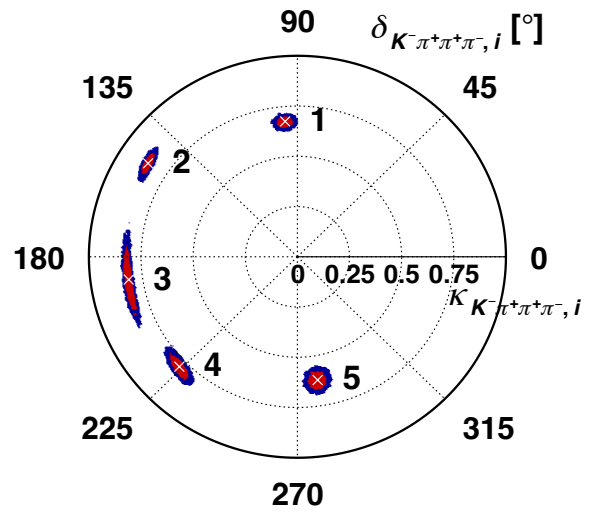
$c_{f,i}$

$K^0_S\pi^+\pi^-$ $K^0_L\pi^+\pi^-$ $K^-\pi^+\pi^0$ $K^-\pi^+\pi^+\pi^-$



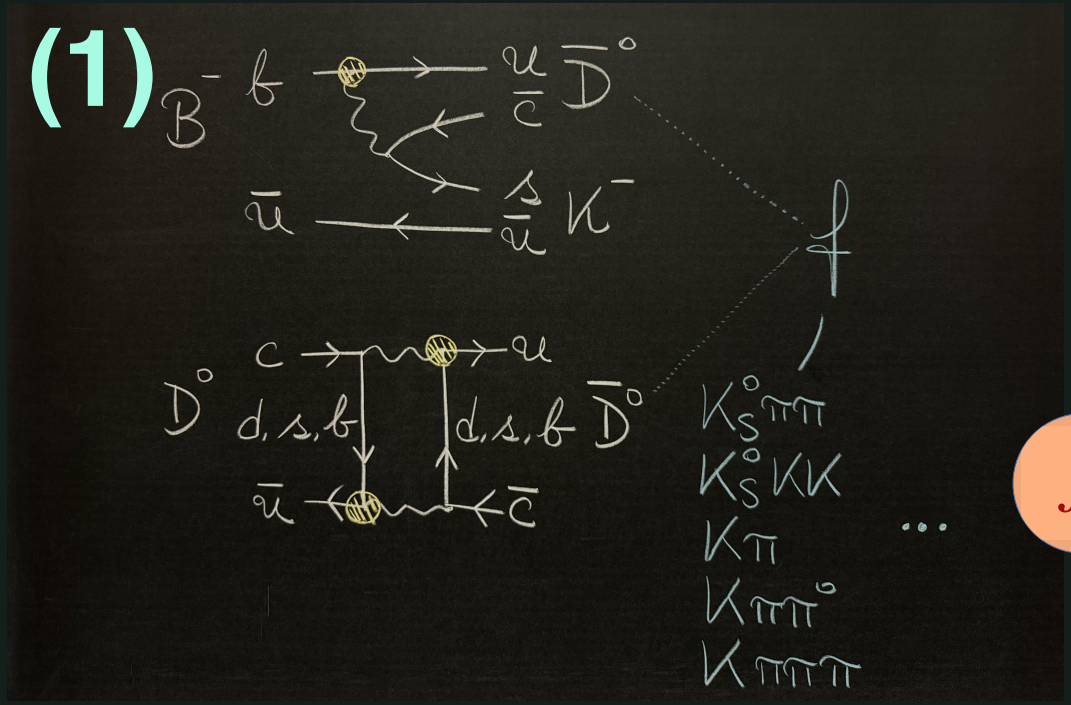




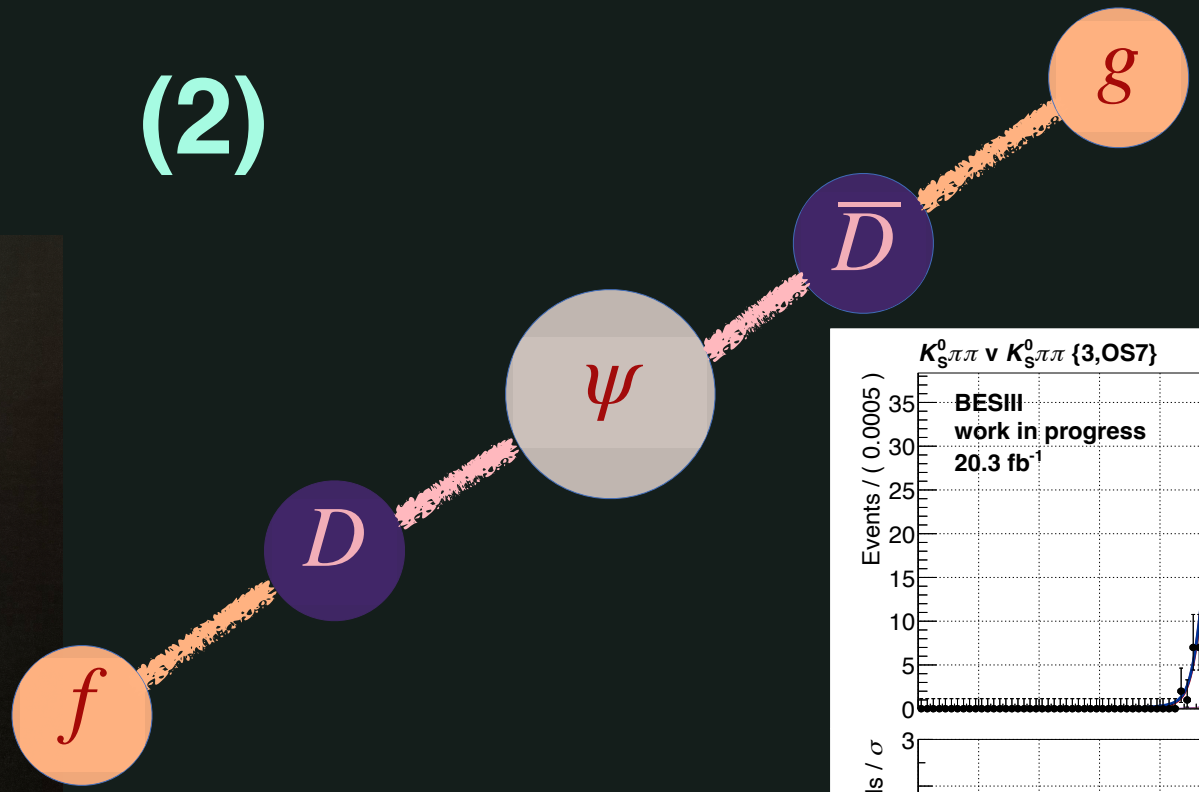


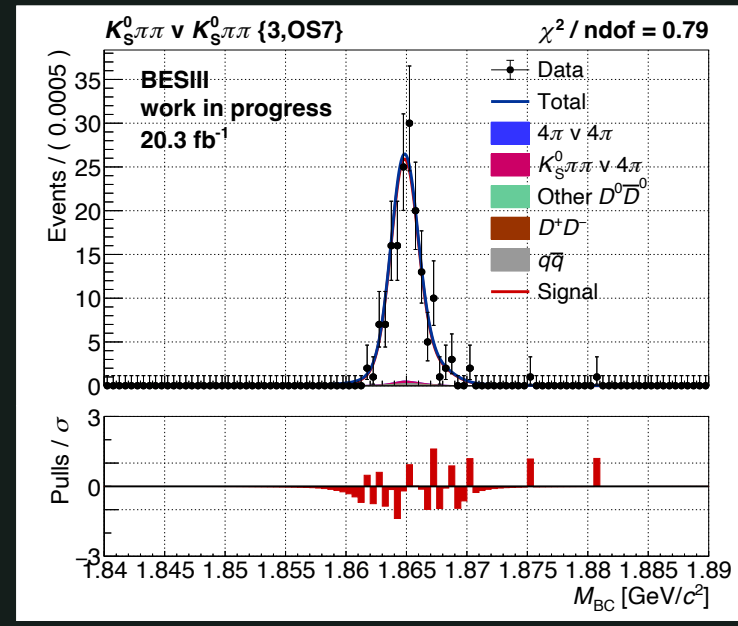
Summary

(1)



(2)





$K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ v $K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ (In progress)

↓ Multiplicative constraints on the likelihood

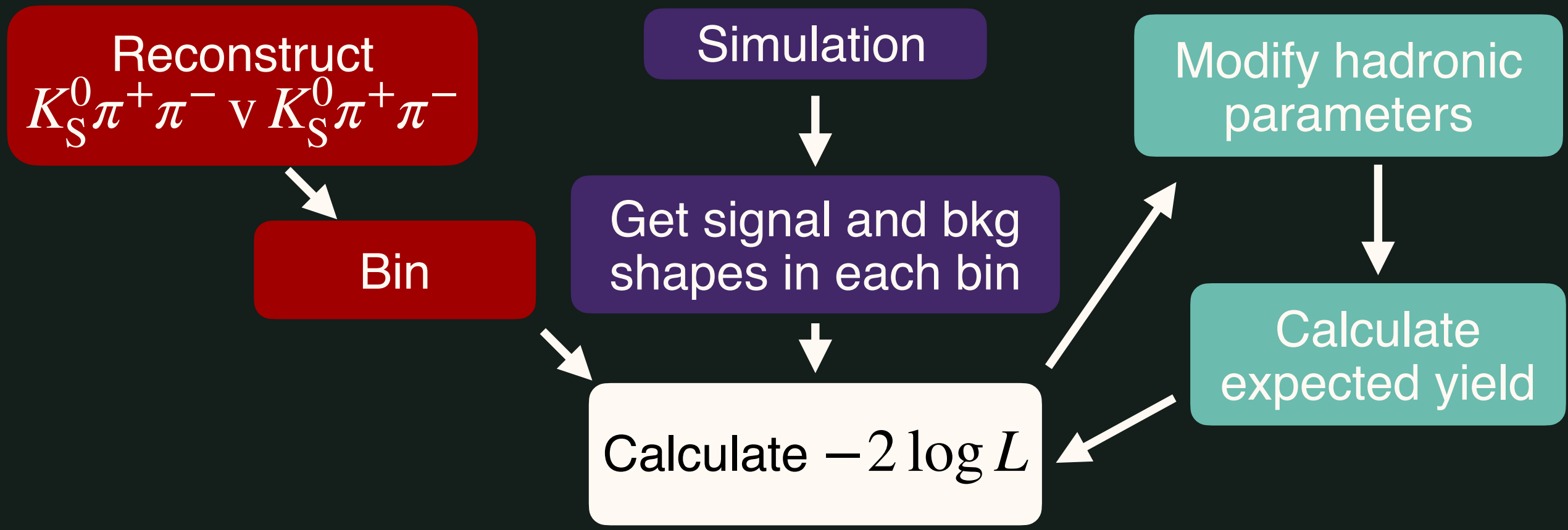
(3) $K^0_{S,L}\pi^+\pi^-$ v $K^0_{S,L}\pi^+\pi^-, K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ (This work)

Strong-phase parameters for ***everything***

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Quantum correlation

$$G_{fg,ij} = h_{fg}\left(F_{f,i}F_{g,-j} + F_{f,-i}F_{g,j} - 2\eta\sqrt{F_{f,i}F_{f,-i}F_{g,j}F_{g,-j}}\left(c_{f,i}c_{g,j} + s_{f,i}s_{g,j}\right)\right)$$

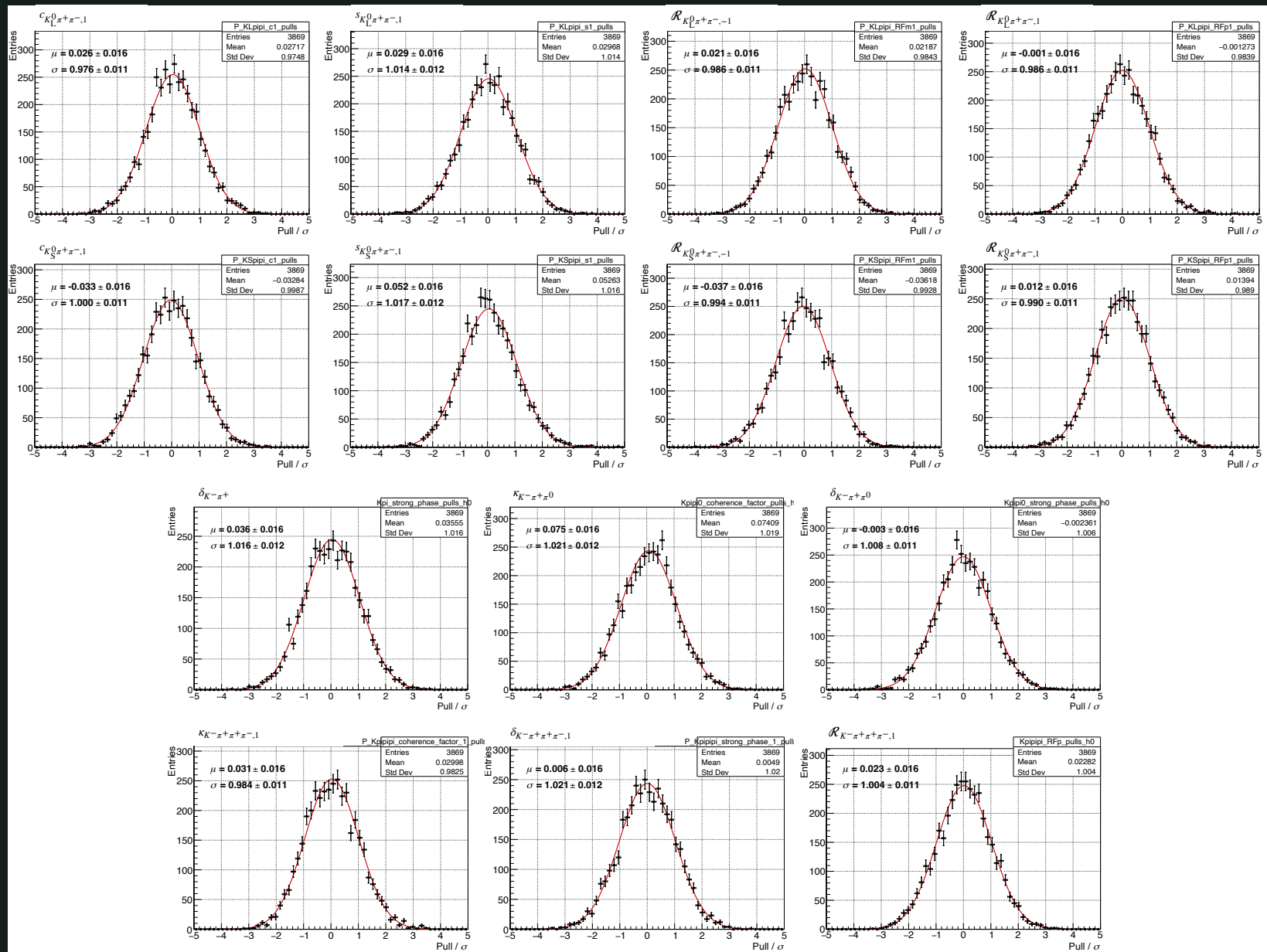


Backup: fitter validity

Psuedodatasets are generated, and no strong correlations observed.

Pull distributions for the parameters are examined.

No deviations from the standard normal distribution are observed.



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Backup: *CP* tags

$$G_{fg,ij} = h_{fg}\left(F_{f,i}F_{g,-j} + F_{f,-i}F_{g,j} - 2\eta\sqrt{F_{f,i}F_{f,-i}F_{g,j}F_{g,-j}}\left(c_{f,i}c_{g,j} + \cancel{s_{f,i}s_{g,j}}\right)\right)$$

States of well defined *CP*: $F_{f,0} = 1$, $c_{f,0} = 1$, $s_{f,0} = 0$, $\eta =$ *CP* eigenvalue

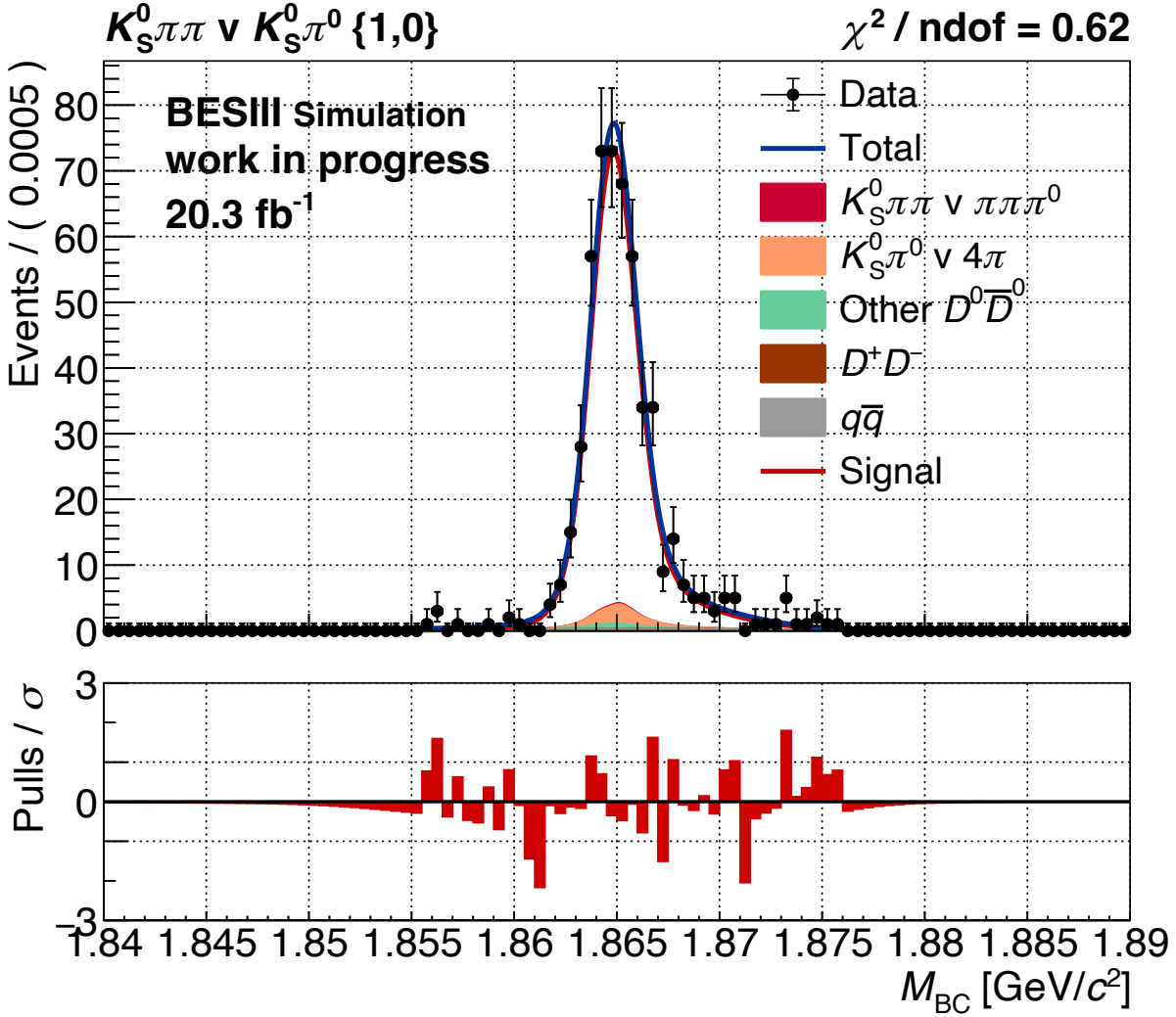
Therefore only constrains $c_{f,i}$, but **huge** number of channels!

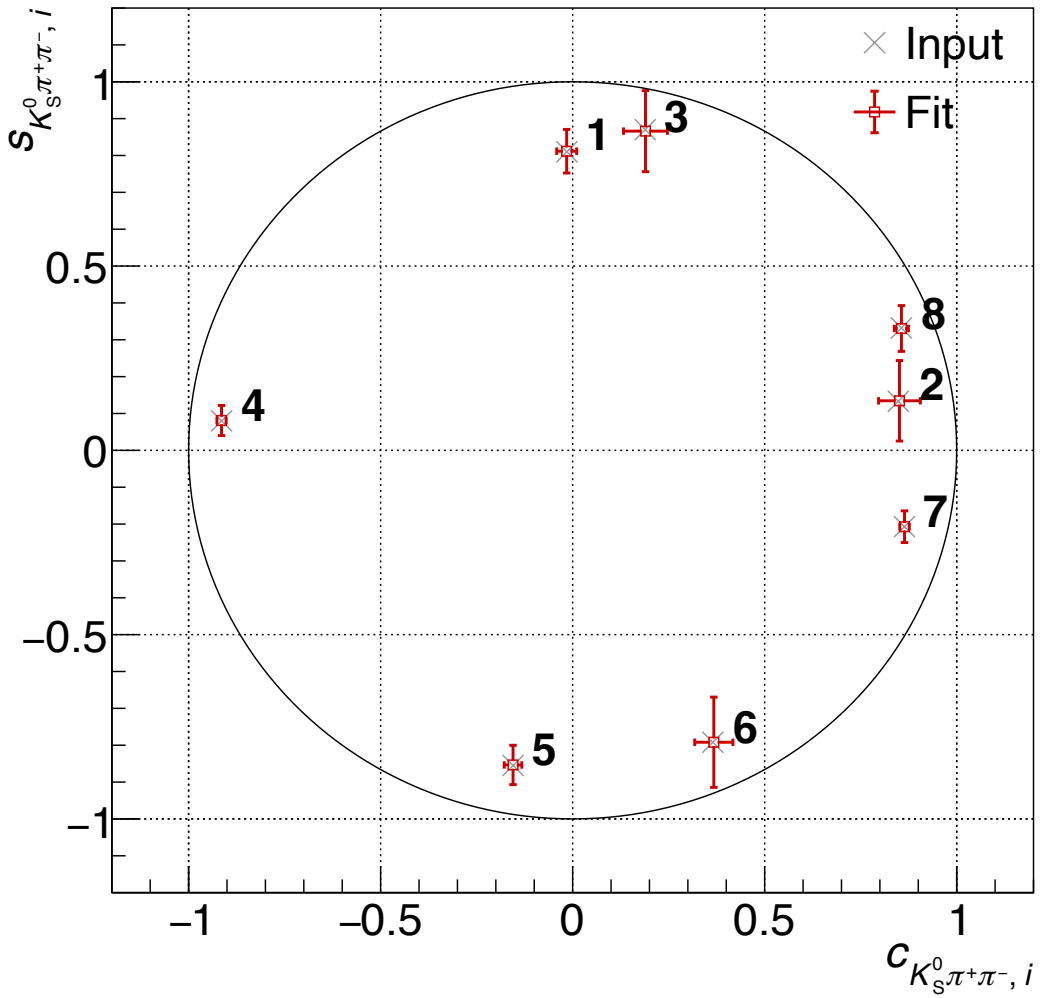
***CP* even**

$K^+K^-, \pi^+\pi^-, K^0_S\pi^0\pi^0, K^0_L\pi^0, K^0_L\pi^+\pi^-\pi^0, K^0_L\omega, K^0_L\eta_{\gamma\gamma}, K^0_L\eta_{\pi^+\pi^-\pi^0}, K^0_L\eta'_{\rho\gamma}, K^0_L\eta'_{\pi^+\pi^-\eta}$

***CP* odd**

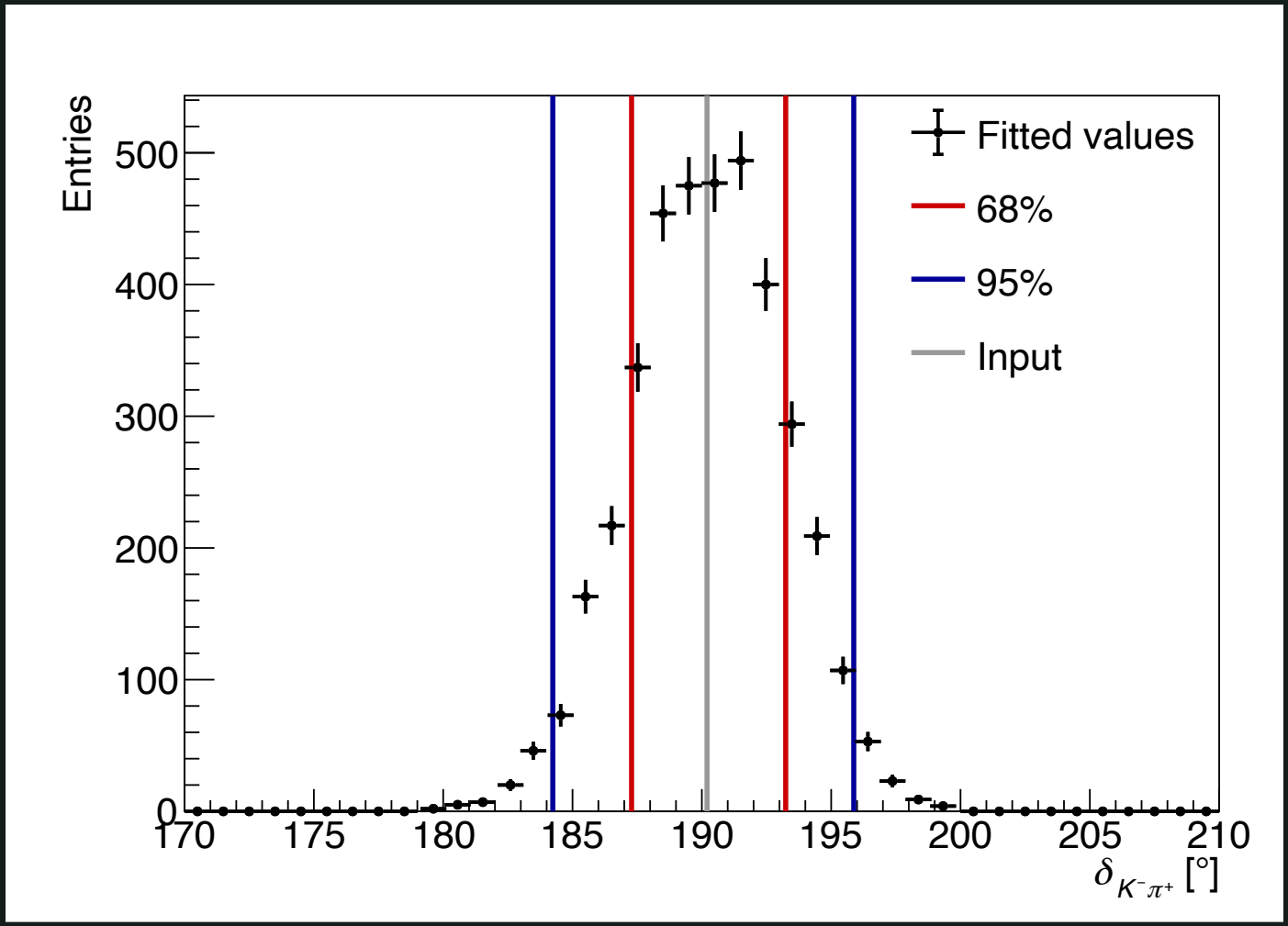
$K^0_L\pi^0\pi^0, K^0_S\pi^0, K^0_S\pi^+\pi^-\pi^0, K^0_S\omega, K^0_S\eta_{\gamma\gamma}, K^0_S\eta_{\pi^+\pi^-\pi^0}, K^0_S\eta'_{\rho\gamma}, K^0_S\eta'_{\pi^+\pi^-\eta}$



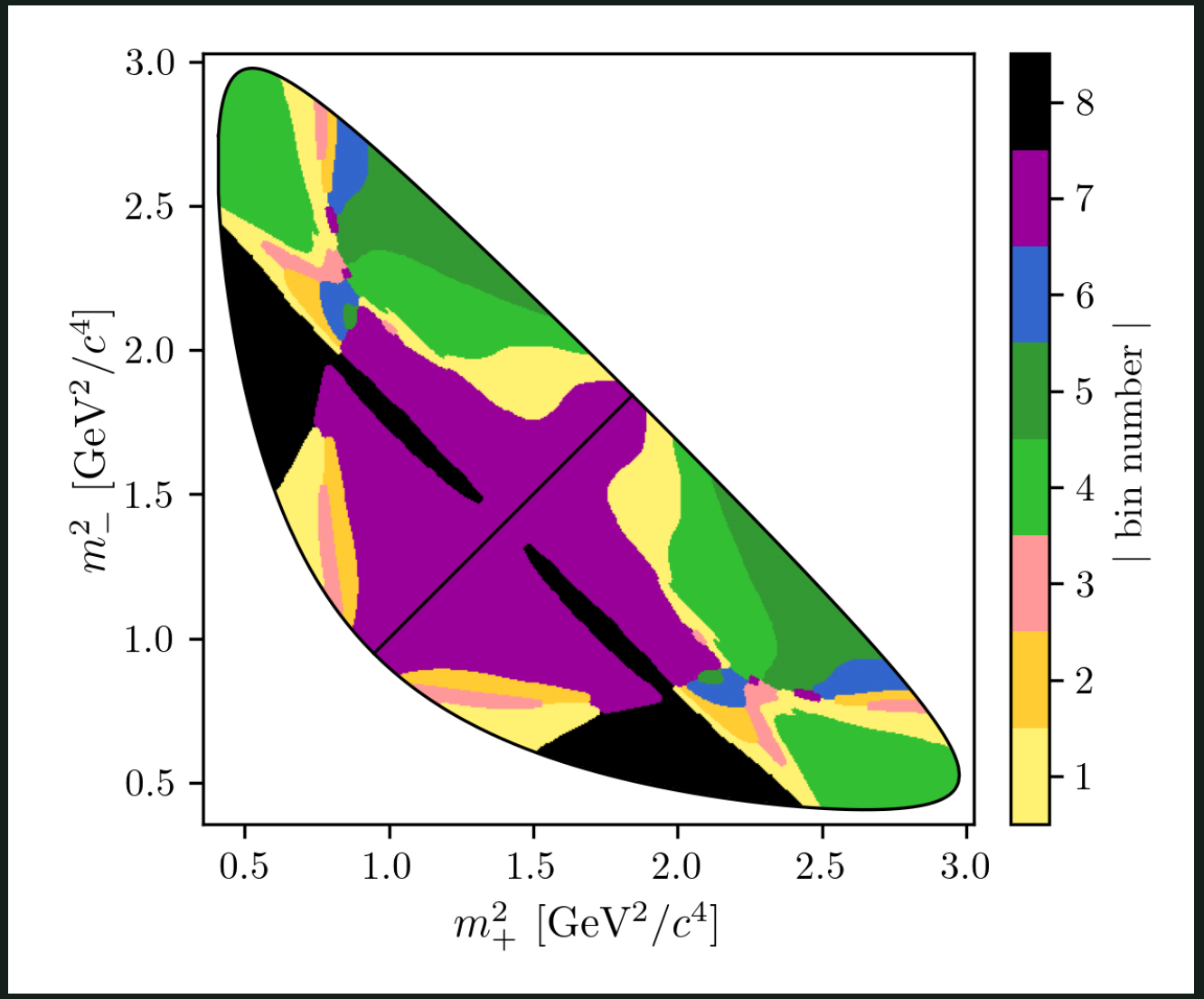


Result: including these channels constrains $c_{K^0_{S/L}\pi^+\pi^-,i}$ very well!

$K\pi$ toy fit result



Binning scheme



Backup: Observables

Partition the phase space of f into $2N$ bins, based on sensitivity.
Label bins by $-N, \ldots, N$ excluding zero, minus sign = *CP* on $|f\rangle$
The observables are

a) relative binned yields $$F_{f,i} \propto \int_i \mathrm{d}\mathbf{z} \left| \langle f | D^0 \rangle \right|^2$$

b) strong phases $$c_{f,i} - \mathrm{i}s_{f,i} \propto \int_i \mathrm{d}\mathbf{z} \langle f | \overline{D}^0 \rangle \langle f | D^0 \rangle^*$$

[$\mathrm{d}\mathbf{z}$: phase space element]

Goal: Measure these observables for all channels below in **one fit**

$$f = K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-, K^0_{\mathrm{S,L}}\pi^+\pi^-, K^0_{\mathrm{S,L}}K^+K^-$$

($K^0_{\mathrm{S,L}}K^+K^-$ work in progress)