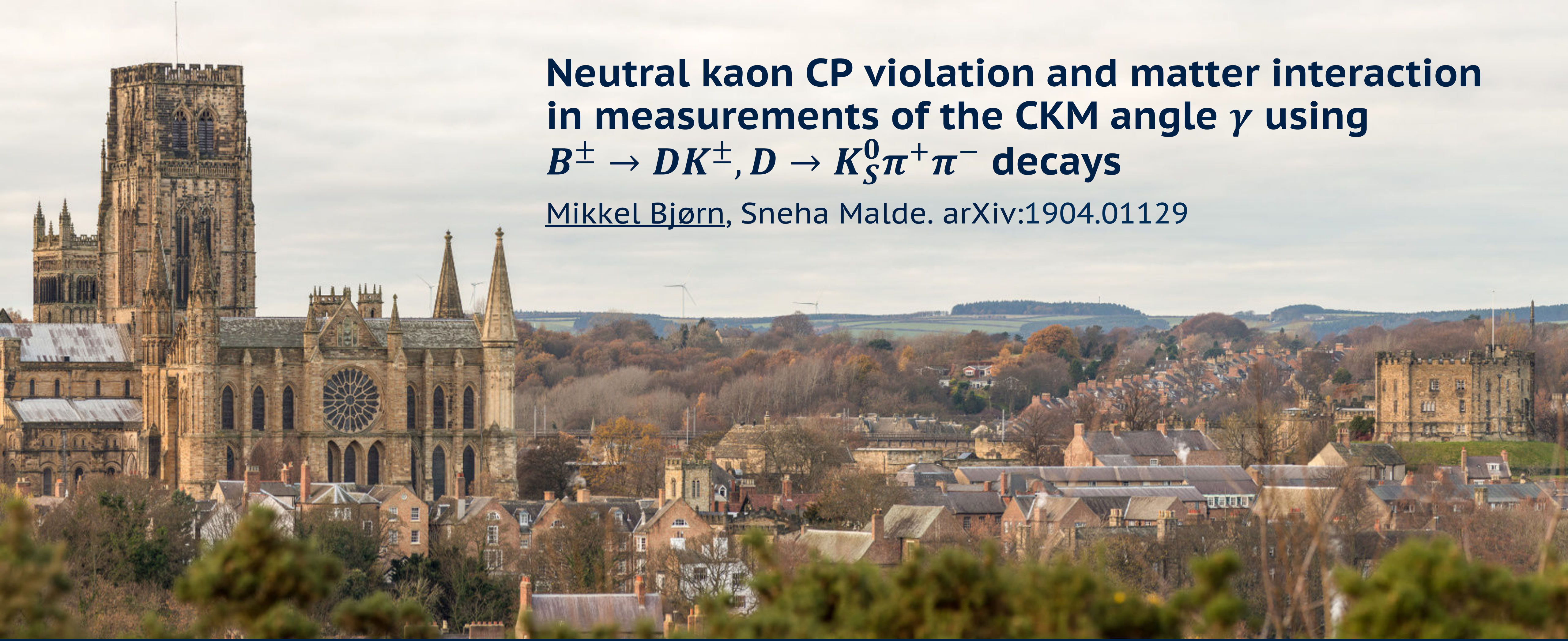
Neutral kaon CP violation and matter interaction in measurements of the CKM angle γ using $B^{\pm} \to DK^{\pm}, D \to K_S^0\pi^+\pi^-$ decays

Mikkel Bjørn, Sneha Malde. arXiv:1904.01129



Towards the Ultimate Precision in Flavour Physics
University of Durham
3 April • 2019

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Precision in GGSZ

Sensitivity to γ from interference between $B \to D^0 K$ and $B \to \bar{D}^0 K$ decays

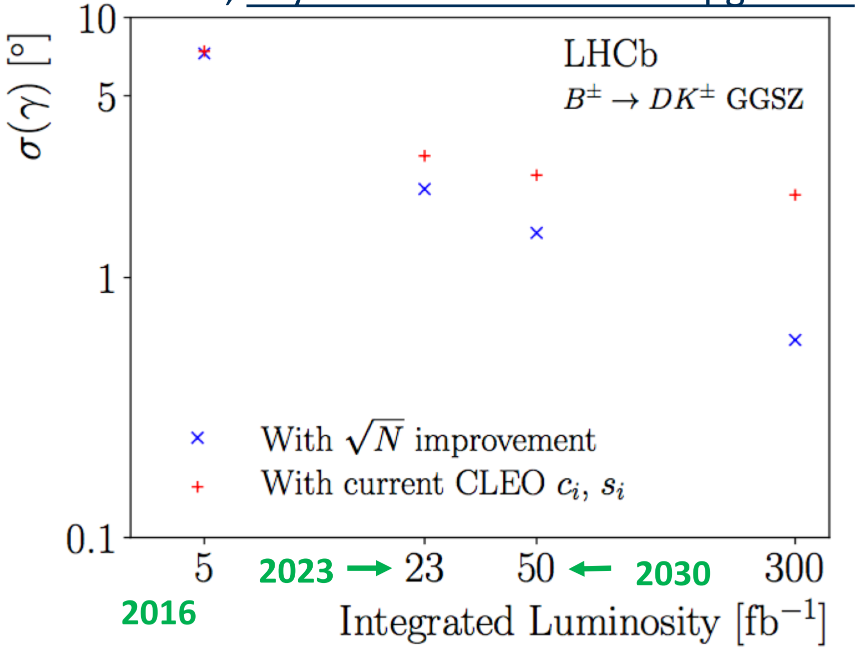
A Golden Mode at Belle II and LHCb:

$$B^{\pm} \to D(\to K_S^0 \pi^+ \pi^-) K^{\pm}$$

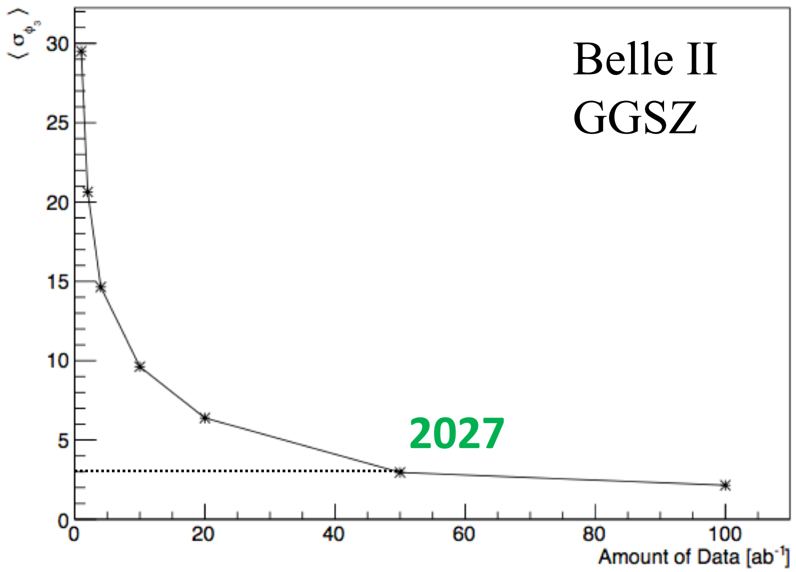
- Sensitivity to γ via Dalitz-plot-distribution analysis: the **GGSZ** method [hep-ph/0303187]

Both LHCb and Belle II will reach precision of **a few degrees** in GGSZ analyses

LHCb, Physics case for an LHCb Upgrade II



Belle II, The Belle II Physics Book



Neutral kaon CPV as a source of systematic uncertainty

$$B^{\pm} \to D(\to K_S^0 \pi^+ \pi^-) K^{\pm}$$

Neutral Kaon CPV → source of bias

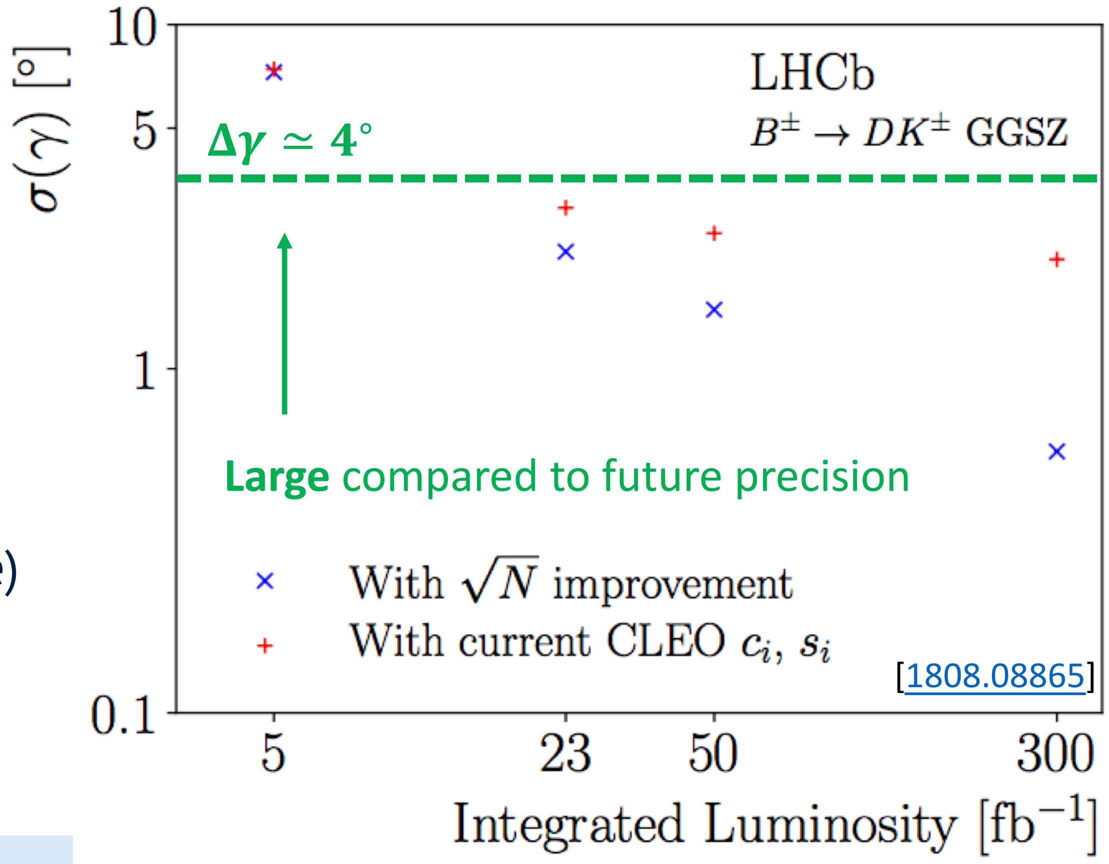
Grossman & Savastio [1311.3575] estimate impact on γ measurements

- $\Delta\gamma/\gamma = O(|\epsilon|/r_B) = \%$ level
- Valid for GLW measurements ($D \to CP$ eigenstate)
- Rough estimate: $\Delta\gamma \simeq 4^{\circ}$

Large compared to future precision

We present detailed further studies

- for current experimental procedure
- including kaon regeneration
- with bias estimates for LHCb and Belle II



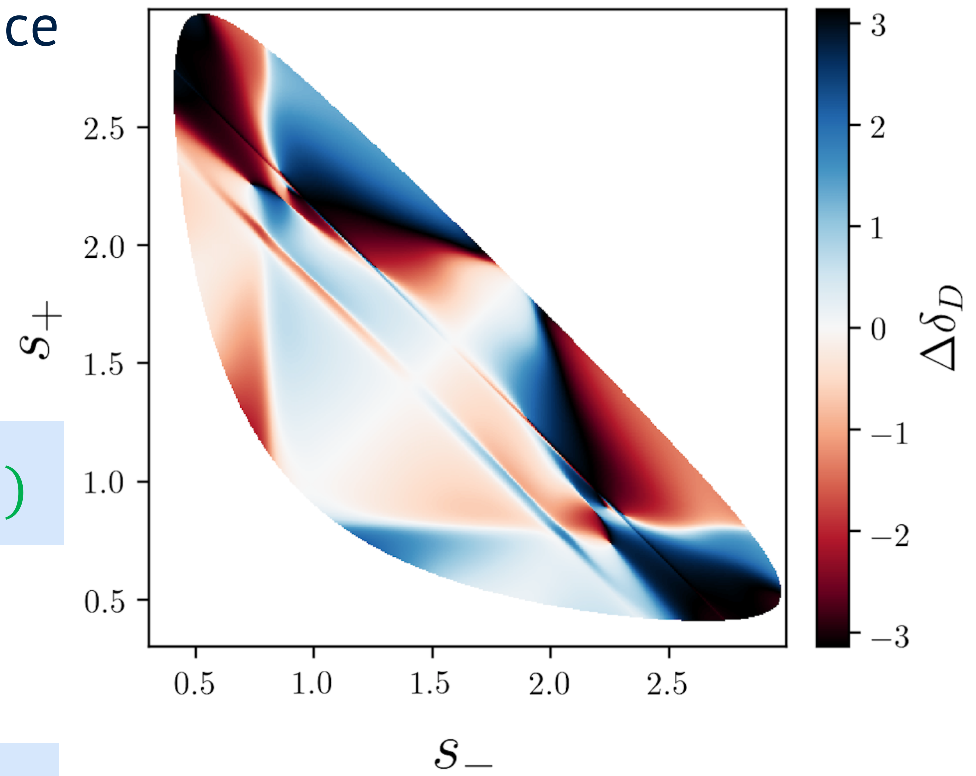
$|\epsilon| \simeq 2\times10^{-3}$
$r_B^{DK} \simeq 10^{-1}$

The GGSZ analysis method

Rich structure of $D \to K_S^0 \pi^+ \pi^-$ amplitude over phase-space
→ $D^0 - \bar{D}^0$ interference varies over Dalitz-plot
→ CP asymmetry varies over Dalitz-plot

K_S^0 is (almost) a CP eigenstate
→ $K_S^0 \pi^+ \pi^-$ is self-conjugate → $\boldsymbol{A_S^{\bar{D}}(s_-, s_+) = A_S^D(s_+, s_-)}$

- $A_S^D = A\left(D^0 \to K_S^0 \pi^+ \pi^-\right) = \left|A_S^D\right| e^{i\delta_D}$
- $\Delta\delta_D = \delta_D(s_-, s_+) - \delta_D(s_+, s_-)$



$$d\Gamma^{B^\pm} \propto \left|A_S^D(s_\mp, s_\pm)\right|^2 + r_B^2 \left|A_S^D(s_\pm, s_\mp)\right|^2 + 2r_B \left|A_S^D(s_\pm, s_\mp)\right| \left|A_S^D(s_\mp, s_\pm)\right| \cos[\Delta\delta_D + \delta_B \pm \gamma]$$

Model-independent GGSZ measurements in practice

Total normalisation **independent** of (x, y) and between B^+ and B^-
→ measurement unaffected by overall production/detection asymmetry

Measured observables are:
$\boldsymbol{x}_\pm + i\boldsymbol{y}_\pm = r_B \exp[i(\delta_B \pm \gamma)]$

Better fit stability than directly fitting γ

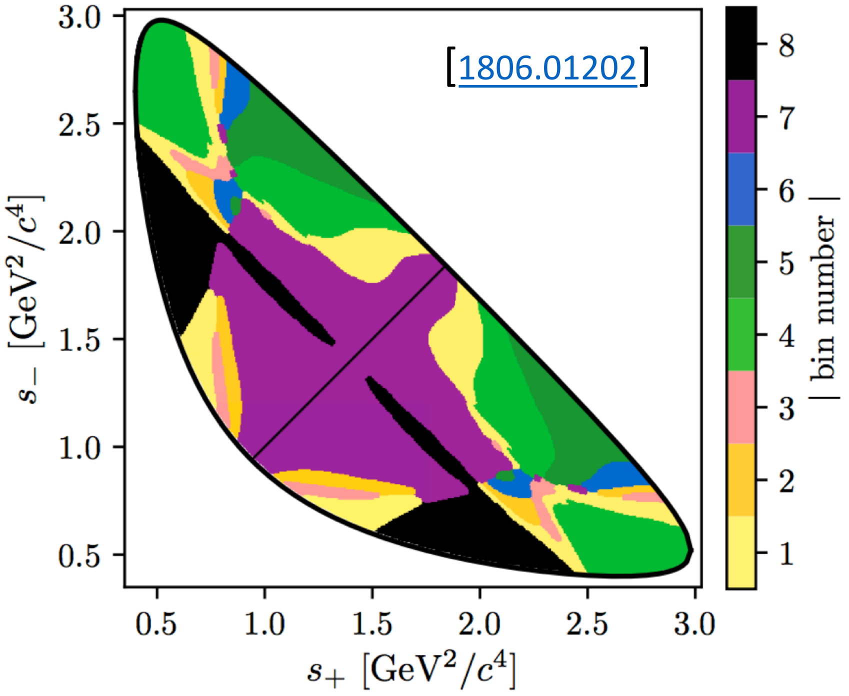
$$N_{\pm i}^{B^-} = h^- \{K_{\pm i} + (x_-^2 + y_-^2) K_{\mp i} + 2\sqrt{K_i K_{-i}} (x_- c_{\pm i} + y_- s_{\pm i})\}$$
$$N_{\pm i}^{B^+} = h^+ \{K_{\mp i} + (x_+^2 + y_+^2) K_{\pm i} + 2\sqrt{K_i K_{-i}} (x_+ c_{\pm i} - y_+ s_{\pm i})\}$$

F_i : Fractional yield of flavour tagged D^0 into bin i

Measured in **control-channel with flavour tagged D^0 & $\bar{D}^0$**

c_i/s_i : Strong phase difference of $D^0 - \bar{D}^0$ decays

External input from CLEO-c/BES III measurement [1010.2817]



Neutral Kaon CP Violation

CP violation in the kaon sector changes GGSZ equations → $\boldsymbol{A^{D}(s_-, s_+) \neq A^{\bar{D}}(s_+, s_-)}$!

$$d\Gamma \propto |\psi_S(t, s_-, s_+) + \epsilon \cdot \psi_L(t, s_-, s_+)|^2$$

K_S^0 is not an exact CP eigenstate

$$A_S^D(s_-, s_+) \propto A_S^{\bar{D}}(s_+, s_-) + 2\epsilon A_2^{\bar{D}}(s_+, s_-)$$

Contribution from $K_S^0 - K_L^0$ interference

$$A_L^D(s_-, s_+) \propto -A_L^{\bar{D}}(s_+, s_-) - 2\epsilon A_1^{\bar{D}}(s_+, s_-)$$

Corrected yields simple to calculate in terms of $A_{1/2}^D = A\left(D^0 \to K_{1/2}\pi^+\pi^-\right)$

$$A_1^D(s_-, s_+) = A_1^{\bar{D}}(s_+, s_-)$$

$$A_2^D(s_-, s_+) = -A_2^{\bar{D}}(s_+, s_-)$$

$$A_S^D \propto A_1^D - \epsilon A_2^D$$

$$A_L^D \propto A_2^D - \epsilon A_1^D$$

$$\frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = \epsilon,$$

$$\epsilon \simeq (2.2 \times 10^{-3}) e^{0.24\pi i}$$

$$\widehat{CP}\ K_1 = K_1 \qquad \widehat{CP}\ K_2 = -K_2$$

$$i\partial_t\psi = \mathcal{H}_{vac}\begin{pmatrix}K^0\\ \overline{K}^0\end{pmatrix} + \begin{pmatrix}\chi & 0\\ 0 & \bar{\chi}\end{pmatrix}_{matter}\begin{pmatrix}K^0\\ \overline{K}^0\end{pmatrix}$$

χ ($\bar{\chi}$) is proportional to K^0 ($\overline{K}^0$) forward scattering amplitude in material

Kaon regeneration in matter introduces further dependence on $A\left(D \to K_L^0\pi^+\pi^-\right)$:

Non-zero $K_L^0 \leftrightarrow K_S^0$ transition amplitudes in matter

To lowest order in $r_\chi = \frac{1}{2}\frac{\chi-\overline{\chi}}{(m_L-m_S)+i/2(\Gamma_L-\Gamma_S)}$ [Z.Phys.C.72.543]

$$\psi_S(t) = e^{-i/2(\chi+\overline{\chi})t}\left((\psi_S^0 - r_\chi\psi_L^0)e^{i\lambda_S t}+r_\chi\psi_L^0 e^{i\lambda_L t}\right)$$

For LHCb and Belle II:

$< r_\chi > \simeq 10^{-3}$

The A1 and A2 amplitude relations

The amplitudes $A_1 = A(D^0 \to K_1\pi^+\pi^-)$ and $A_2 = A(D^0 \to K_2\pi^+\pi^-)$ are related under the assumption that they are well described by isobar-like models [1010.2817]

$$A_2^D(s_-, s_+) = -A_1^D(s_-, s_+) + \boldsymbol{r_A \Delta A(s_-, s_+)}, \qquad \boldsymbol{r_A \simeq \tan^2 \theta_C}$$

$$A_1^D = \alpha^0 + \sum_{CF} \alpha_i A(K^{*-}\pi^+) + \sum_{DCS} \alpha_j A(K^{*+}\pi^-) + \sum_{\pi\pi} \alpha_k A(K_1\pi^+\pi^-)$$

$\to \bar{K}^0$: relative " $-$ "

$\to K^0$: relative " $+$ "

$\to \bar{K}^0$ & K^0: but K^0 coupling is DCS

$$A_2^D = \alpha^{0\prime} - \sum_{CF} \alpha_i A(K^{*-}\pi^+) + \sum_{DCS} \alpha_j A(K^{*+}\pi^-) + \sum_{\pi\pi} -(1 - 2r_k e^{i\delta_k})\alpha_k A(K_1\pi^+\pi^-)$$

$K^0 \propto K_1 + K_2$

$\bar{K}^0 \propto K_1 - K_2$

Where the DCS amplitudes satisfy : $\alpha_{DCS}/\alpha_{CF} \simeq r_k \simeq \tan^2 \theta_C \simeq 0.05$

Modified Dalitz bin yields

$$N_{\pm i}^{B^-} = h^-(1 + \Gamma_S/\Gamma_L|\epsilon + r_\chi|^2 + \boldsymbol{\Delta h})\{\hat{K}_{\pm i} + (x_-^2 + y_-^2)\hat{K}_{\mp i} + 2\sqrt{\hat{K}_i\hat{K}_{-i}}(x_-\hat{c}_{\pm i} + y_-\hat{s}_{\pm i}) + \boldsymbol{O(r\epsilon)}\}$$

$$N_{\pm i}^{B^+} = h^+(1 + \Gamma_S/\Gamma_L|\epsilon + r_\chi|^2 - \boldsymbol{\Delta h})\{\hat{K}_{\pm i} + (x_-^2 + y_-^2)\hat{K}_{\mp i} + 2\sqrt{\hat{K}_i\hat{K}_{-i}}(x_-\hat{c}_{\pm i} + y_-\hat{s}_{\pm i}) + \boldsymbol{O(r\epsilon)}\}$$

Dalitz-plot distribution is only changed at $\boldsymbol{O(r\epsilon)}$

→ **expected impact on GGSZ measurements is $\boldsymbol{O(r\epsilon/r_B)}$ = permille level**

→ need to look at higher order terms to assess bias

$O(r\epsilon) =$

$O(r_A\epsilon) + O(r_A r_\chi)$

$+(r_B\epsilon) + O(r_B r_\chi)$

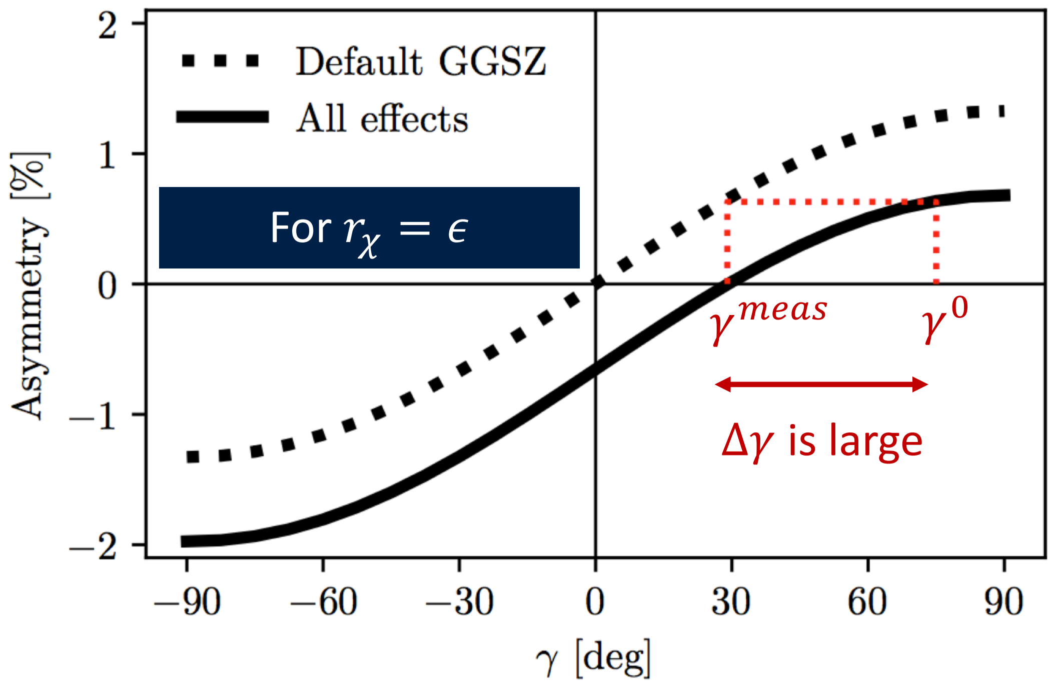
Well known overall yield asymmetry [eg. 1110.3790]

- Here shown for infinite time-acceptance
- And including contribution from material interaction

$$\Delta h(\epsilon, r_\chi) = 2\mathrm{Re}[\epsilon + r_\chi]\left(1 - 2\frac{\Gamma_S}{\Gamma_S + \Gamma_L}\frac{1 + \mu \cdot \mathrm{Im}[\epsilon + r_\chi]/\mathrm{Re}[\epsilon + r_\chi]}{1 + \mu^2}\right) + O(r\epsilon), \qquad \mu = \frac{2\Delta m}{\Gamma_S + \Gamma_L}$$

Bias on γ measurements from the integrated-yield asymmetry

$$A = \frac{N^- - N^+}{N^- + N^+} = \frac{2\sum c_i\sqrt{K_iK_{-i}}r_B \sin\delta_B \sin\gamma + \Delta h(\epsilon, r_\chi)}{1 + r_B^2 + r_B \cos\delta_B \cos\gamma}$$



$K_S^0\pi^+\pi^-$ is not a CP eigenstate

Non-trivial phase $\Delta\delta_D(s_-, s_+)$

→ $\sum c_i\sqrt{K_iK_{-i}} \simeq 0.1 \ll 1$

→ $\Delta\gamma = O(|\epsilon|/(0.1 \times r_B))$ = **10's of degrees**

Corrections are possible, but

- $\Delta h(\epsilon, r_\chi)$ depends significantly on experimental time acceptance [1110.3790]
- $\Delta h(\epsilon, r_\chi)$ depends on experiment material budget and geometry
- Terms of $O(r_A r_\chi)$ and $O(r_A \epsilon)$ lead to % level biases and must be included

Not an issue in current experiments: overall asymmetry is not used to determine γ

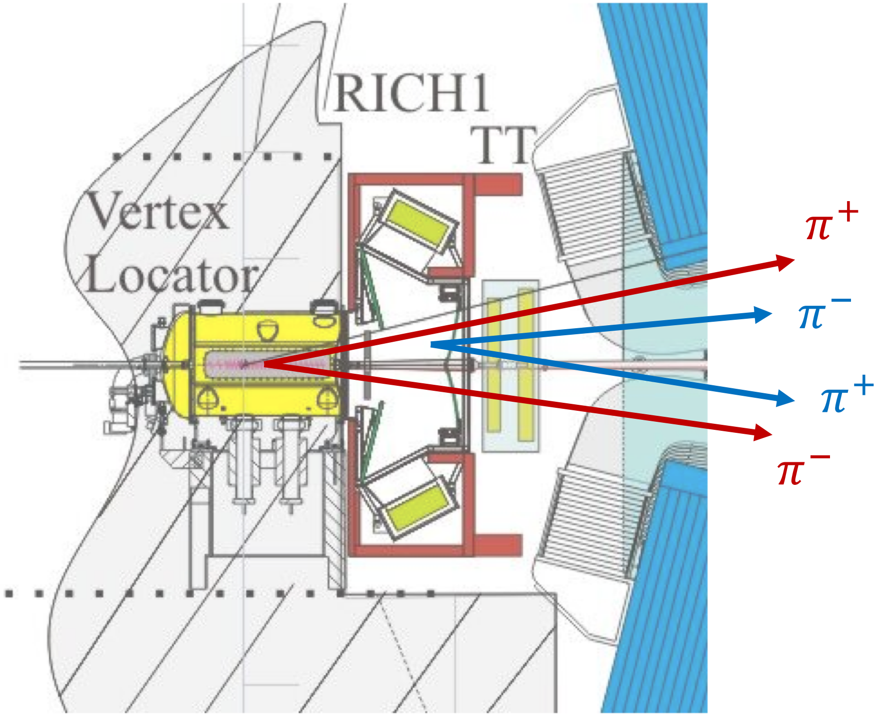
To assess impact on actual GGSZ measurements

- Higher orders of r_A, r_B, r_χ, and ϵ needed
- Realistic time-acceptance and material-interaction assumptions

Numerical studies performed for

- The Belle II detector
- The **LL** and **DD** data categories at LHCb

All orders of r, ϵ included in numerical evaluations



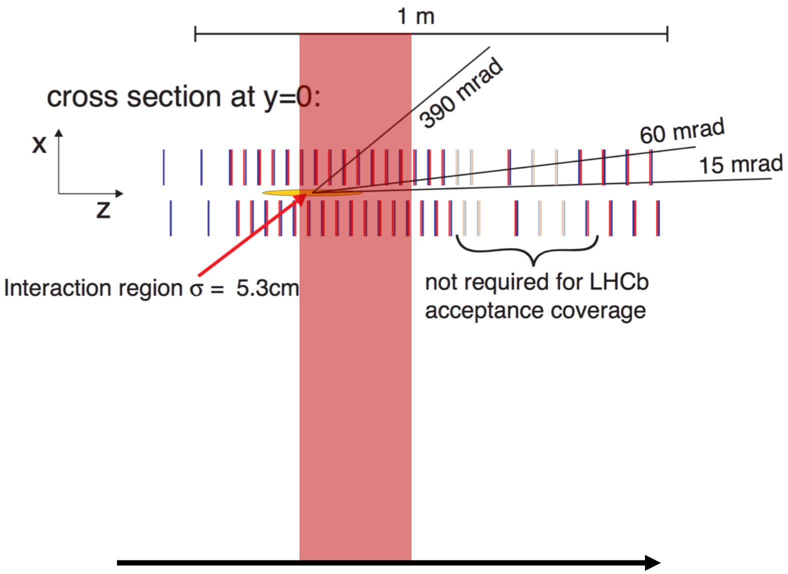
LL: both kaon decay product tracks reconstructed in VELO and downstream

DD: kaon decay product tracks only reconstructed downstream

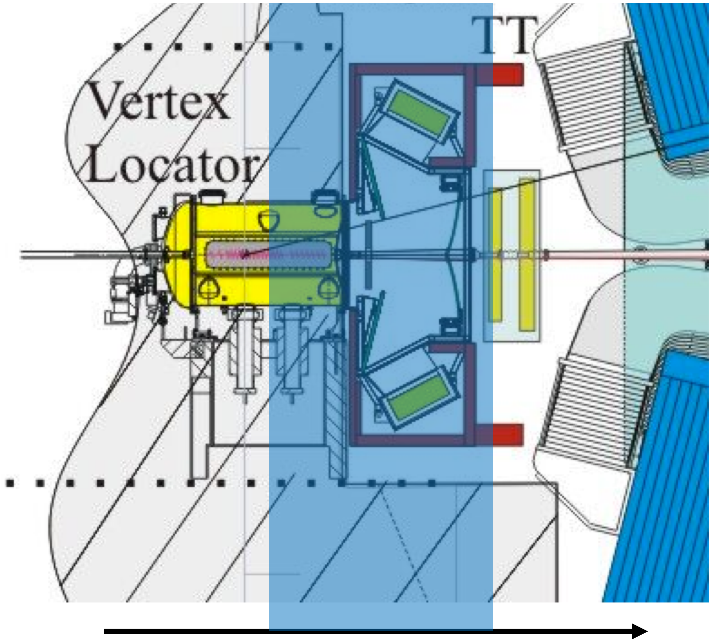
(Simplified) Experimental time-acceptance

Time-acceptance ($\tau_{\mathrm{decay}} \in [\tau_1, \tau_2]$) for kaon with $p = (p_z, p_T)$ determined by geometry

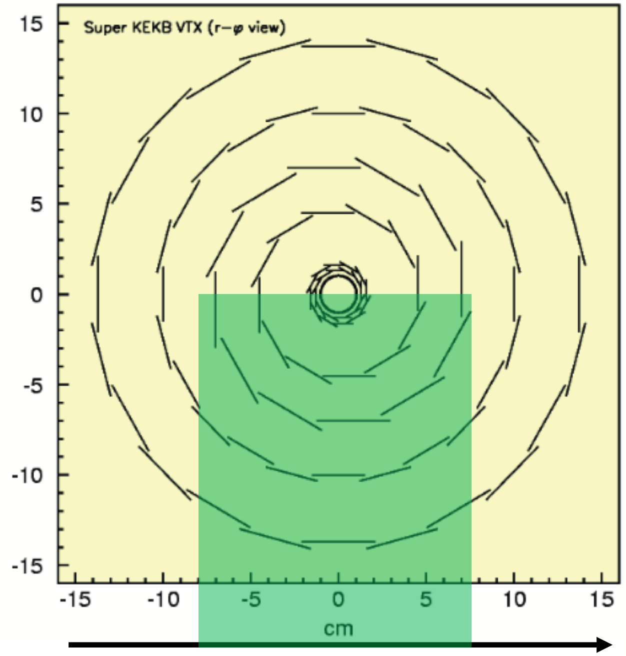
- **LL LHCb**/**Belle II**: require kaon decay products to cross at least 3 vertex detector segments
- **DD LHCb**: require kaon decay before the TT tracking station



$z_{LL} \in [0, 280]$ mm
$< \tau_{LL} > \simeq 0.1\tau_{K_S^0}$



$z_{DD} \in [280, 2350]$ mm
$< \tau_{DD} > \simeq 0.8\tau_{K_S^0}$



$r_{Belle\ II} \in [0, 80]$ mm
$< \tau_{Belle\ II} > \simeq 0.7\tau_{K_S^0}$

Calculation procedure and input requirements

1. Model for $A_1(s_-, s_+)$ used to get $A_2(s_-, s_+)$ and then $A_{S(L)}^{D(\overline{D})}(s_-, s_+)$
2. $\psi_{S/L}^{\pm}(t, s_-, s_+)$ calculated keeping all orders of $r_{A,B,\chi}$ and ϵ
   - For inputs $(\gamma^0, r_B^0, \delta_B^0)$
3. $N_i^{\pm}$ from integrating $\mathrm{d}\Gamma^{\pm}$ over
   - experimental time-acceptance
   - Dalitz-plot bins
4. Fit $(x_\pm, y_\pm)$ with default GGSZ eq.
5. Interpret $(x_\pm, y_\pm)$ in terms of (γ, r_B, δ_B)
   $\rightarrow \quad \Delta\gamma = \gamma - \gamma^0$

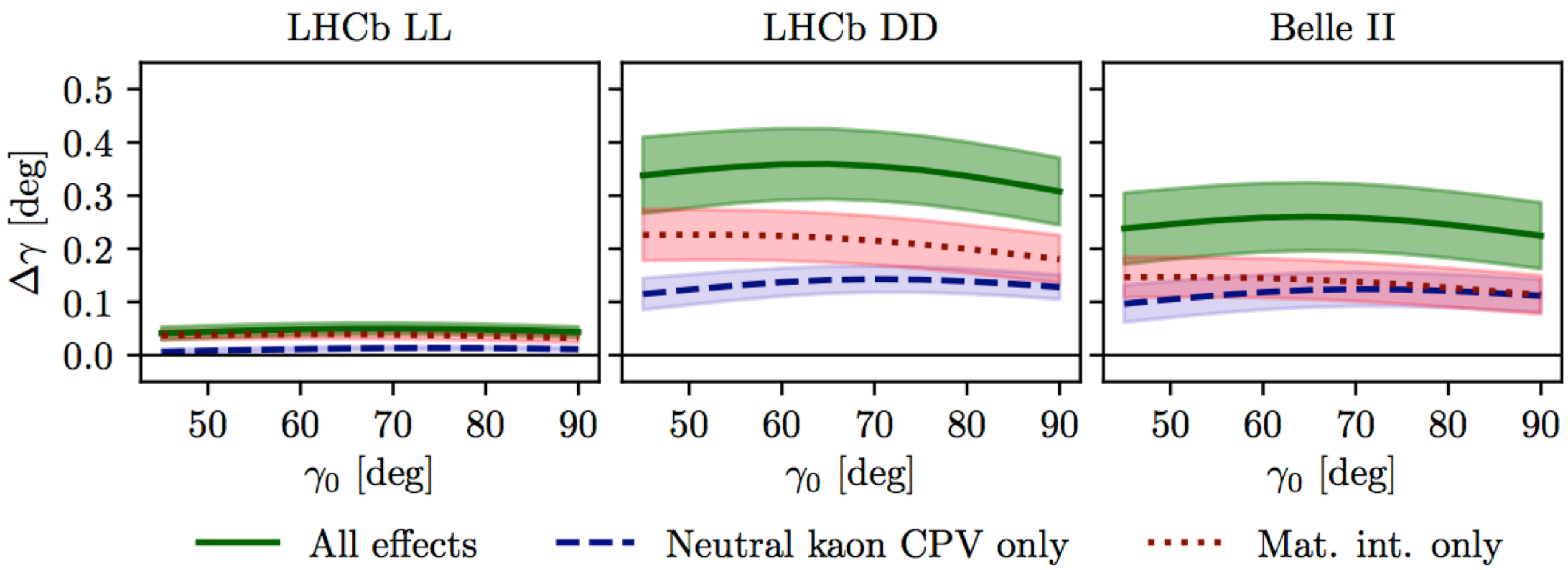
Belle 2018 model [1804.06153] used to represent A_1

Material parameter $\Delta\chi$ from average material budget cf. technical design reports

$\Delta\chi$ and (t_1, t_2) depend on momentum distribution, estimated using RapidSim [1612.07489]

Time acceptance(t_1, t_2) from detector geometry and p_K

Results



$\Delta\gamma < 0.4^\circ \rightarrow \Delta\gamma/\gamma = O(r\epsilon/r_B) = O(\epsilon)$ as expected

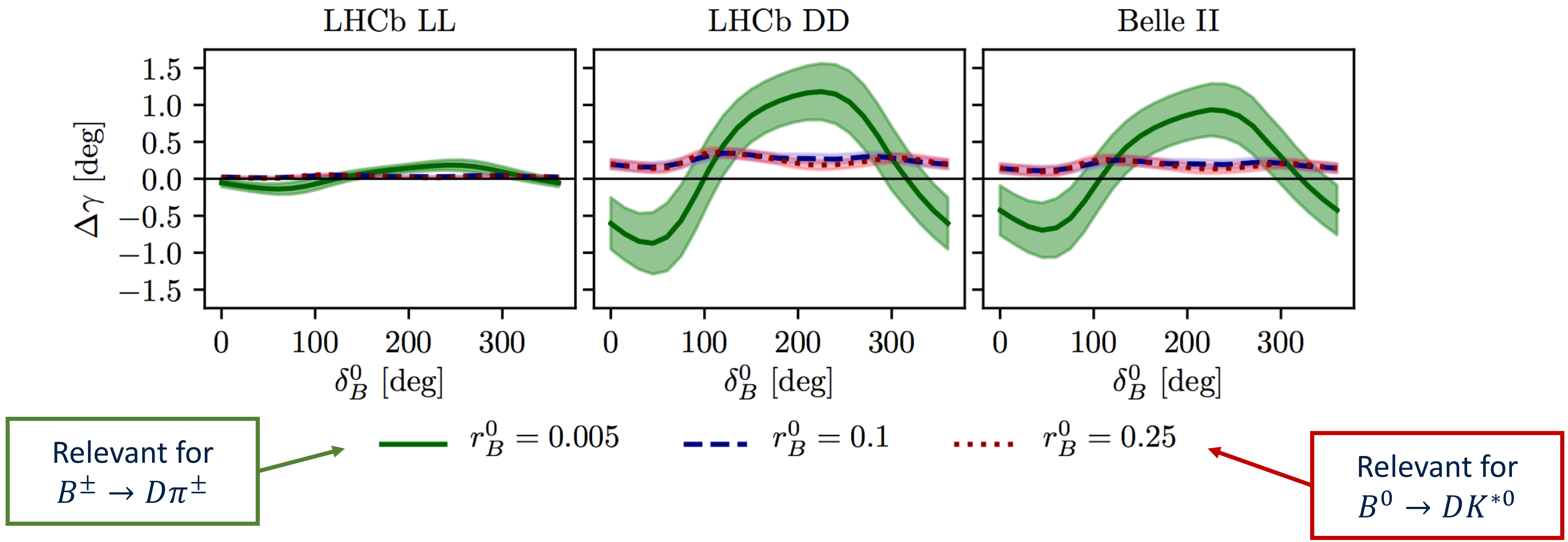
Material interaction and kaon CPV equally important

$\Delta\gamma$ small in LL LHCb: when $(t_1, t_2) < \tau_S$: K_S^0-CPV and $K_S^0 - K_L^0$ interference approximately cancels [1110.3790]

Uncertainty bands

- Vary material density ± 10 %
- Vary time-acceptance ± 10 %
- 50 different (r_k, δ_k) in $A_1 \rightarrow A_2$
- Vary resolution in $p(K)$ average
- EvtGen/Belle (2010) as alternative amplitude models for A_1

Results: other B decay modes



$\Delta\gamma/\gamma$ large for $B^{\pm} \to D\pi^{+}$ because $O(r_A\epsilon/r_B^{D\pi}) \simeq \mathbf{4}$ %

For $r_B \in \{0.1, 0..25\}$ the $O(r_B\epsilon/r_B) = O(\epsilon)$ terms dominate bias

Other D decay modes

For **Dalits-plot based** measurements all arguments are **equally valid** for $D \to K_S^0 K^+ K^-$ and $D \to K_S^0 \pi^+ \pi^- \pi^0$

$\to$ hence $\Delta\gamma/\gamma = O(\epsilon)$

The **global yield asymmetry from CPV in B decay** is larger in $D \to K_S^0 \pi^+ \pi^- \pi^0$ because it is dominantly CP-odd [1710.10086]

$\to$ hence GLW-type measurements only suffer $\Delta\gamma/\gamma = O(\epsilon/r_B)$ biases

The studies here should be repeated for more precise estimates, with suitable **amplitude models and binning schemes** in place

Bias corrections

Bias **corrections** following procedure outlined here are possible

- For both Dalitz-plot and global-asymmetry based measurements

But it is important that they

- Must include matter interaction
- Must include $O(r\epsilon)$ terms
- Must be made with full detector simulation

At the sub-degree level other effects become important as well

Conclusions

Material interaction and neutral kaon CPV of equal importance in γ measurements in $B^{\pm} \to D(\to K_S^0 \pi^+ \pi^-) K^{\pm}$ decays

Measurements from global-yield asymmetries suffer γ biases of 10's of degrees

Bias in $B \to DK$ GGSZ measurements at LHCb and Belle II estimated to be **less than $\mathbf{0.5^\circ}$**

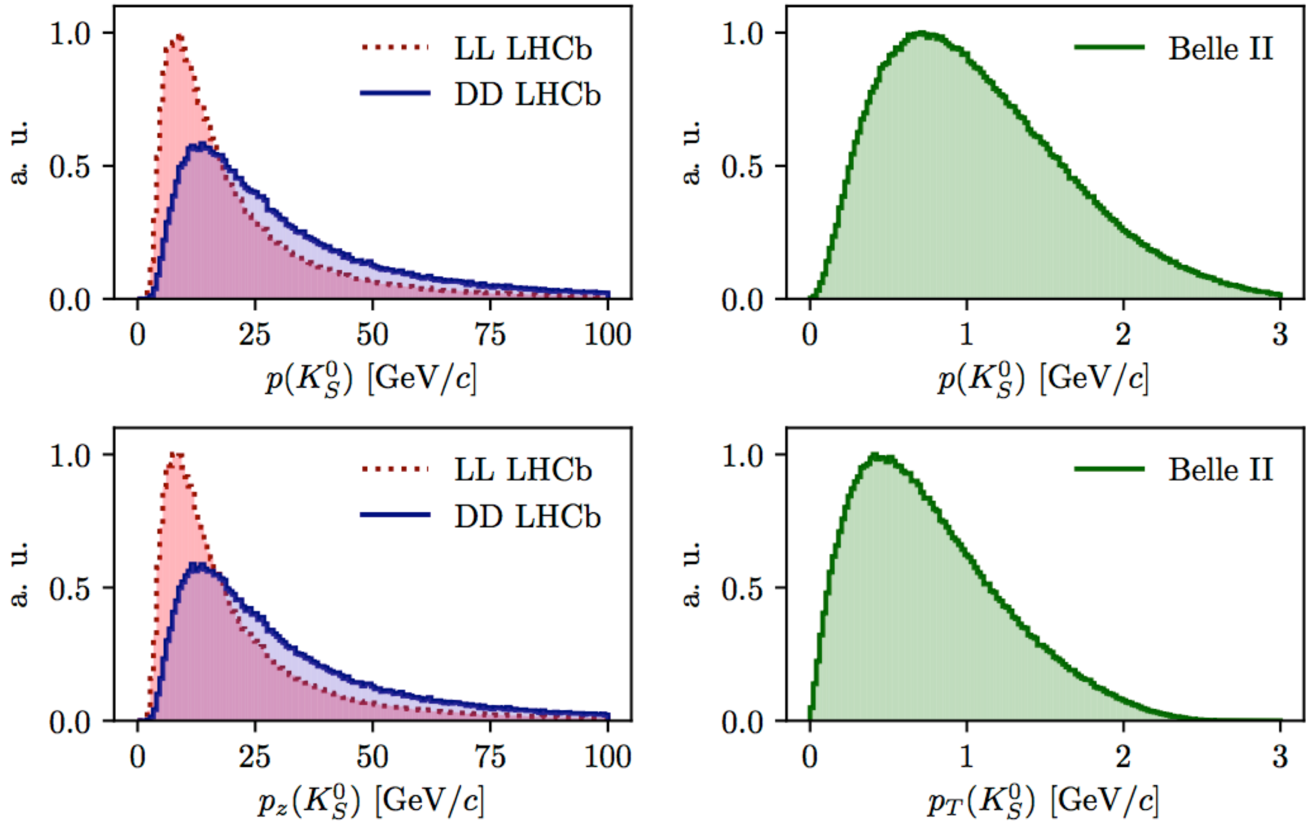
- Can be treated as (small) systematic uncertainty in upcoming measurements

Backup Slides

Momentum distributions

Momentum distributions estimated via RapidSim (phase-space generator)

- Can generate with LHCb kinematics/acceptance
- Can decay $B^{\pm}$ with $\gamma\beta = 0.28$ corresponding to Belle II (with minor tweaking)



Average material properties

Material interaction is governed by

$$\Delta\chi = -\frac{2\pi\mathcal{N}}{m_K}(f - \bar{f})$$

Simple calculation: constant average scattering centre density $\mathcal{N}$ used

Estimated from material budgets in TDR's

The difference in forward-scattering amplitudes of K^0 and $\bar{K}^0$ has been measured [PhysRevLett.42.13]

$$\left|\frac{f - \bar{f}}{p_K}\right| = 2.23 \frac{A^{0.758}}{p_K^{0.614}(\mathrm{GeV}/c)}\ \mathrm{mb}$$

$$\arg \Delta f = -\frac{\pi}{2}(2 - 0.614)$$

Using average momentum

- $|r_\chi|(\mathrm{LL}) = 2.7{\times}10^{-3}$
- $|r_\chi|(\mathrm{DD}) = 2.2{\times}10^{-3}$
- $|r_\chi|(\mathrm{Belle\ II}) = 1.5{\times}10^{-3}$

Phase-space dependent momentum

Kaon momentum in lab is correlated with $m^2(\pi^+\pi^-)$

Averages taken over momentum distribution for each point in phase-space

Phase-space dependence of (τ_1, τ_2) and r_χ can affect GGSZ measurements