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Prospects for data-driven analyses of the decay $B \to K^* ll$

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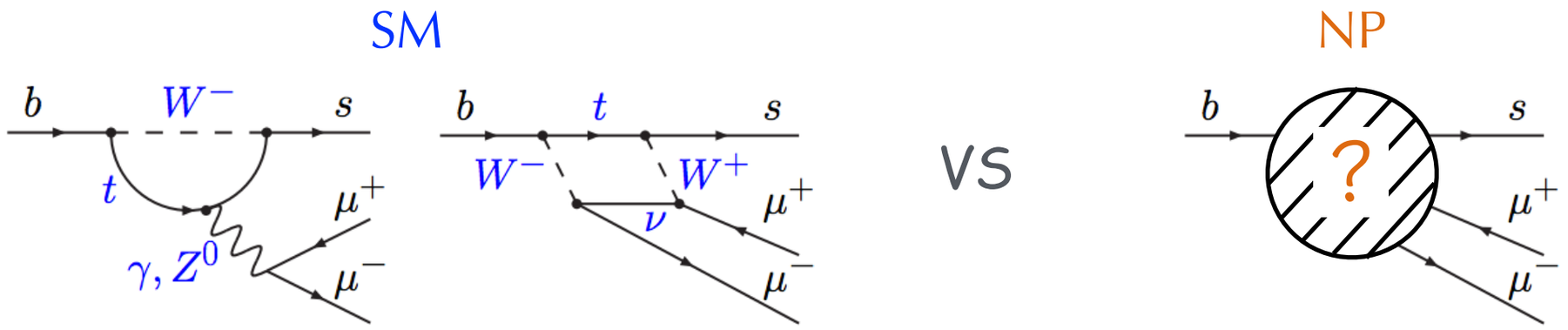
Implications of LHCb measurements and future prospects (CERN)

Introduction: the $B \to K^*\mu\mu$ decay

- Historically a key channel for indirect search for NP



- $\mathcal{B}r$ below SM expectation [JHEP 06 (2014) 133, JHEP 09 (2015) 179, JHEP 06 (2015) 115]
  - coherently in all $b \to s\mu\mu$ decay modes
- P_5' anomaly [JHEP 1308 (2013) 131, JHEP 02 (2016) 104, PRL 118 (2017)11, 111801]

Are these hints of NP...? or is there a problem with the understanding of QCD?

In this talk we present prospects for present and future experiments to disantangle the two effects!

Controlling the charm loop

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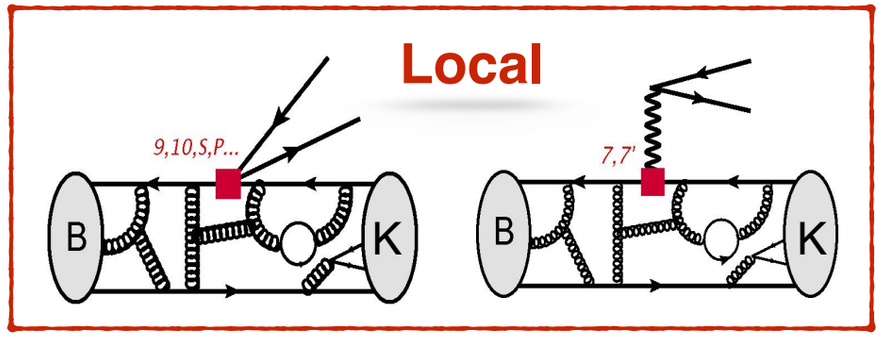
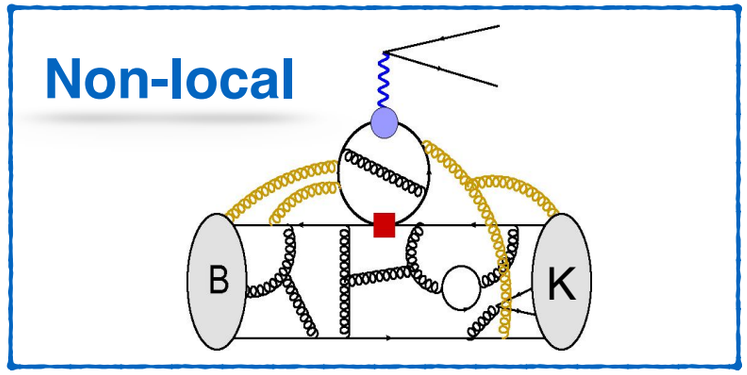
- EFT → general model-independent parametrization of NP

$$\mathcal{L} = \mathcal{L}_{QCD} + \mathcal{L}_{QED} + \frac{4G_F}{\sqrt{2}} \sum_i \mathcal{C}_i(\mu)\mathcal{O}_i(\mu)$$

  - possible sources of NP included in C_i
  - Non-local hadronic contribution from SM
    - difficult to reliably quantify from first principles





- Parametrization introduced in **arxiv:1707.07305v1** **[see talk by J. Virto]**
  - The angular distributions can be described by the q^2-dependent K^* amplitudes $(\lambda = \perp, \parallel, 0)$

$$\mathcal{A}_\lambda^{L,R} = N_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

Wilson coeff. **Non-local contribution** → **both will be extracted from data…**

[see talk by J. Virto]

The parametrization (in a nutshell)

How to parametrize the correlator $\mathcal{H}$?

- Taylor expansion around $z = 0$ [after mapping: $q^2 \to z(q^2)$]
- Extract the poles: $\mathcal{H}_\lambda(z) = \dfrac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \dfrac{1 - z z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z)$

  $\hat{\mathcal{H}}_\lambda(z)$ analytic within unit circle $|z| = 1$ $\longrightarrow$ $\hat{\mathcal{H}}_\lambda(z) = \left[\sum_k \alpha_k^{(\lambda)} z^k \right] \mathcal{F}_\lambda(z)$

What do we know about the correlator $\mathcal{H}$?

- Experimental constraints:
  - $B \to K^*\{J/\psi, \psi(2S)\}$ branching ratio by Belle and angular observables by BaBar and LHCb
- Theory constraints:
  - the ratios $\mathcal{H}_\lambda(q^2)/\mathcal{F}_\lambda(q^2)$ are theoretically computed for $q^2<0$: {-1, -3, -5, -7} GeV^2

TABLE I. Mean values and standard deviations (in units of 10^{-4}) of the prior PDF for the parameters $\alpha_k^{(\lambda)}$.

k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–

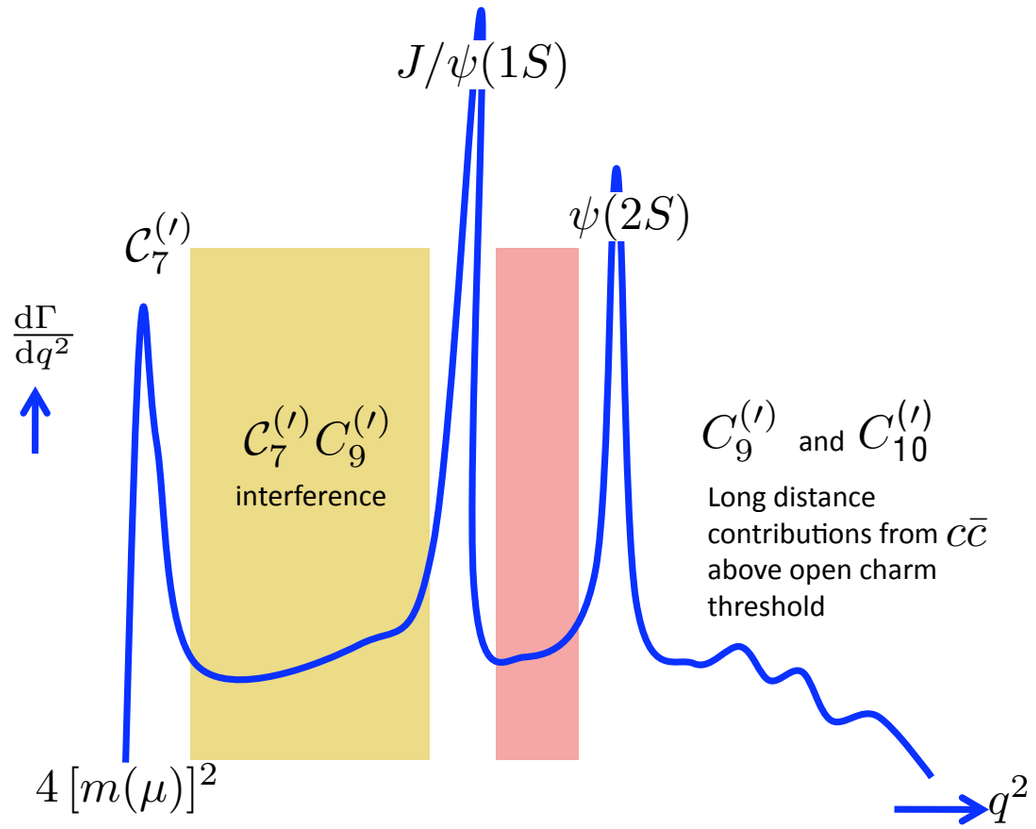
We can use these information as priors for the $\alpha_\lambda{}^{(k)}$ parameters in our fit

Amplitude fit

We perform a q^2-unbinned amplitude fit:

- signal $p.d.f. = \dfrac{1}{\Gamma}\dfrac{d^4\Gamma}{dq^2\, d\Omega}$
- Cut hadronic expansion at order z^2:
  - 8 complex parameters $\alpha^{(0)}_{\perp,\parallel,0}$, $\alpha^{(1)}_{\perp,\parallel,0}$, $\alpha^{(2)}_{\perp,\parallel}$ ($\hat{\mathcal{H}}_0$ must vanish for $q^2 = 0$)
- two q^2 ranges: [1.1, 9.0] & [10.0, 13.0] GeV^2
  - also tried [1.1, 8.0] & [11.0, 12.5] GeV^2

current analysis ranges:
- LHCb: [1.1, 8.0] & [11, 12.5] GeV^2 [1]
  [1.1, 8.8] & [10.1, 12.9] GeV^2 [2]
- Belle: [1.1, 8.0] & [10.1, 12.9] GeV^2 [3]



[1] JHEP02(2016)104
[2] PRL111(2013)191801
[3] PRL118(2017)11,111801
[4] JHEP 04 (2017) 142
[5] JHEP 08, 098 (2016)
[6] JHEP0610,081(2006)

Additional constraints to the fit:

- the BR is gaussian constrained separately in the two regions [4]: $\dfrac{d\Gamma}{dq^2} = \sum_{\chi=L,R}\sum_{\lambda=\perp,\parallel,0}|A_{\lambda,\chi}|^2$
- multi-variate gaussian priors on $\alpha_\lambda{}^{(k)}$
- multi-variate gaussian priors on form factors [5]
- gaussian constraint to CKM parameters [6]

39 nuisance parameters + free-floating C_i

NP sensitivity

We define a “BenchMark-Point” (BMP) scenario for NP: $C_9^{BMP} = C_9^{SM} - 1$

- C_7 and C_{10} fixed at their SM values
- generate $4k$ toys and perform the fit
- extract the sensitivity to non-SM C_9 for present and future experiments (LHCb and Belle-II)
  - no experimental effects (resolution*, efficiency…)
  - no S-wave pollution
    [see Langenbruch et al.’s work, arXiv:1708.04474v1]

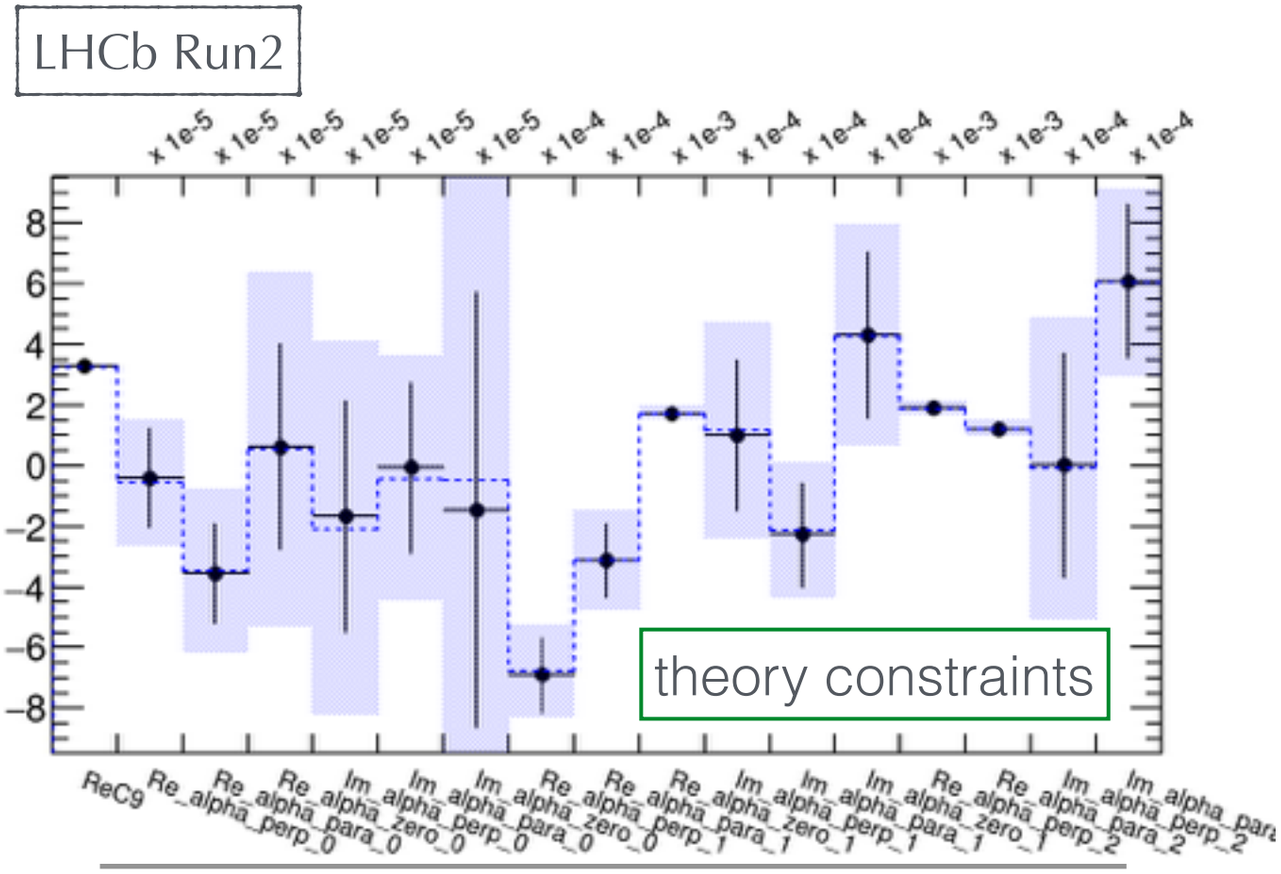
→ Sensitivity to be understood as upper bound (stat. only)

*assuming a “naive” constant resolution for $\sqrt{q^2}$ of 9 MeV [PRD95,071101(2017)]
has a negligible impact on the sensitivity

Prior knowledge on the $\alpha_\lambda{}^{(k)}$ parameters

So far we used theoretical and experimental prior knowledge on the $\alpha_\lambda{}^{(k)}$ parameters

- When using priors the fit is able to extract additional information
  - uncertainties a-posteriori are smaller than a-priori



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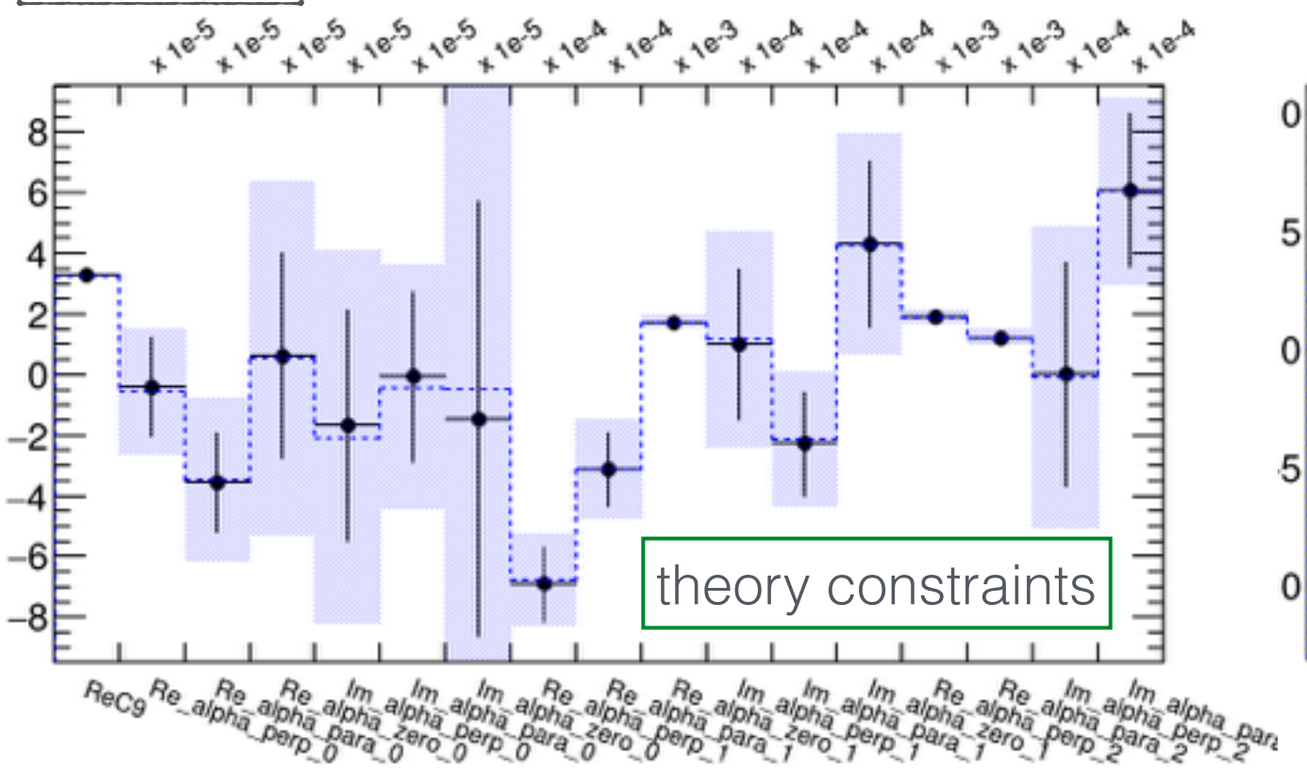
Can we perform the analysis without any prior?

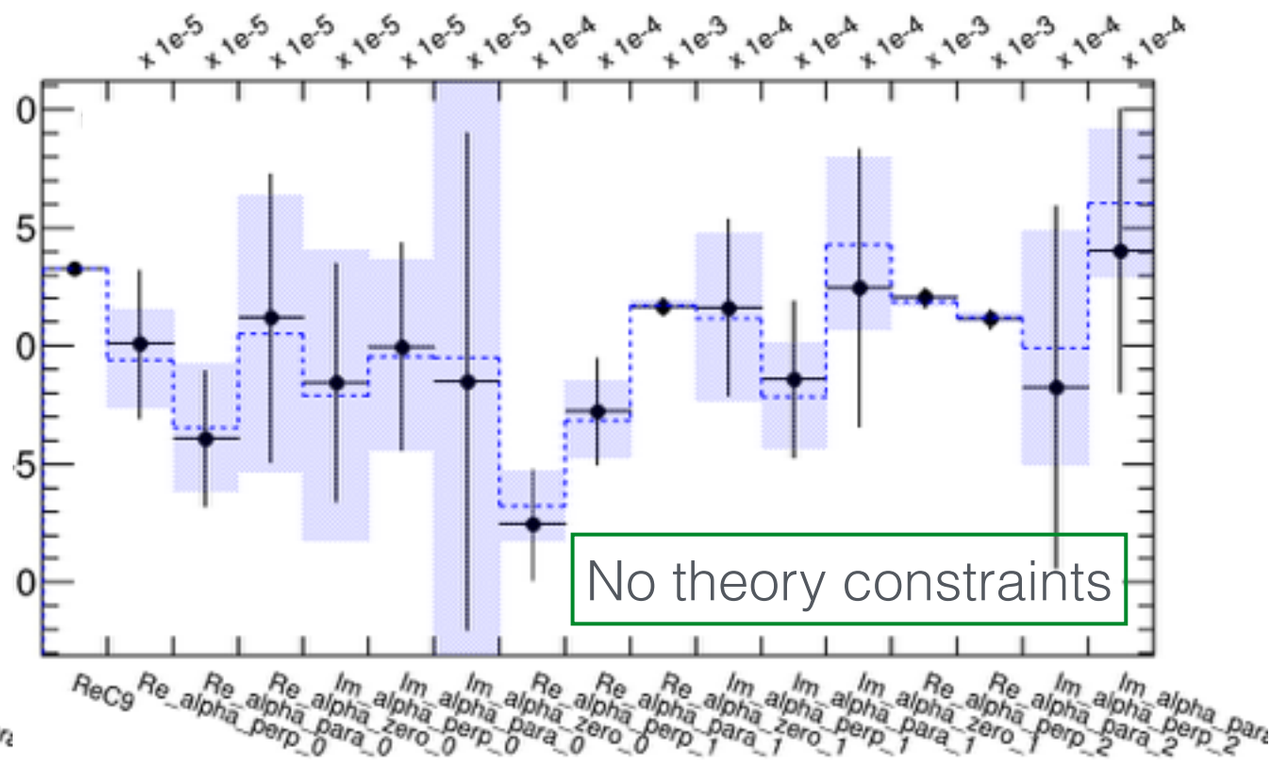
Yes!

When removing the priors the fit converges and
we are still able to disantangle hadronic from NP effects

with priors	without priors
$\sigma(C_9) = 0.13$	$\sigma(C_9) = 0.19$

LHCb Run2





Sensitivity to higher order in z

So far we cut the expansion of $\hat{\mathcal{H}}_\lambda(z)$ after z^2

- This introduces a model dependence
- Priors for z^3 would require complete NP analysis

Still we try to study effects of expansion up to z^3:

- Toys genereted with $\alpha_\lambda{}^{(3)} = 0$ ⟶ but $\alpha_\lambda{}^{(3)}$ free-floating in the fit
- Fitted **without theory** priors on $\alpha_\lambda{}^{(k)}$

We find:

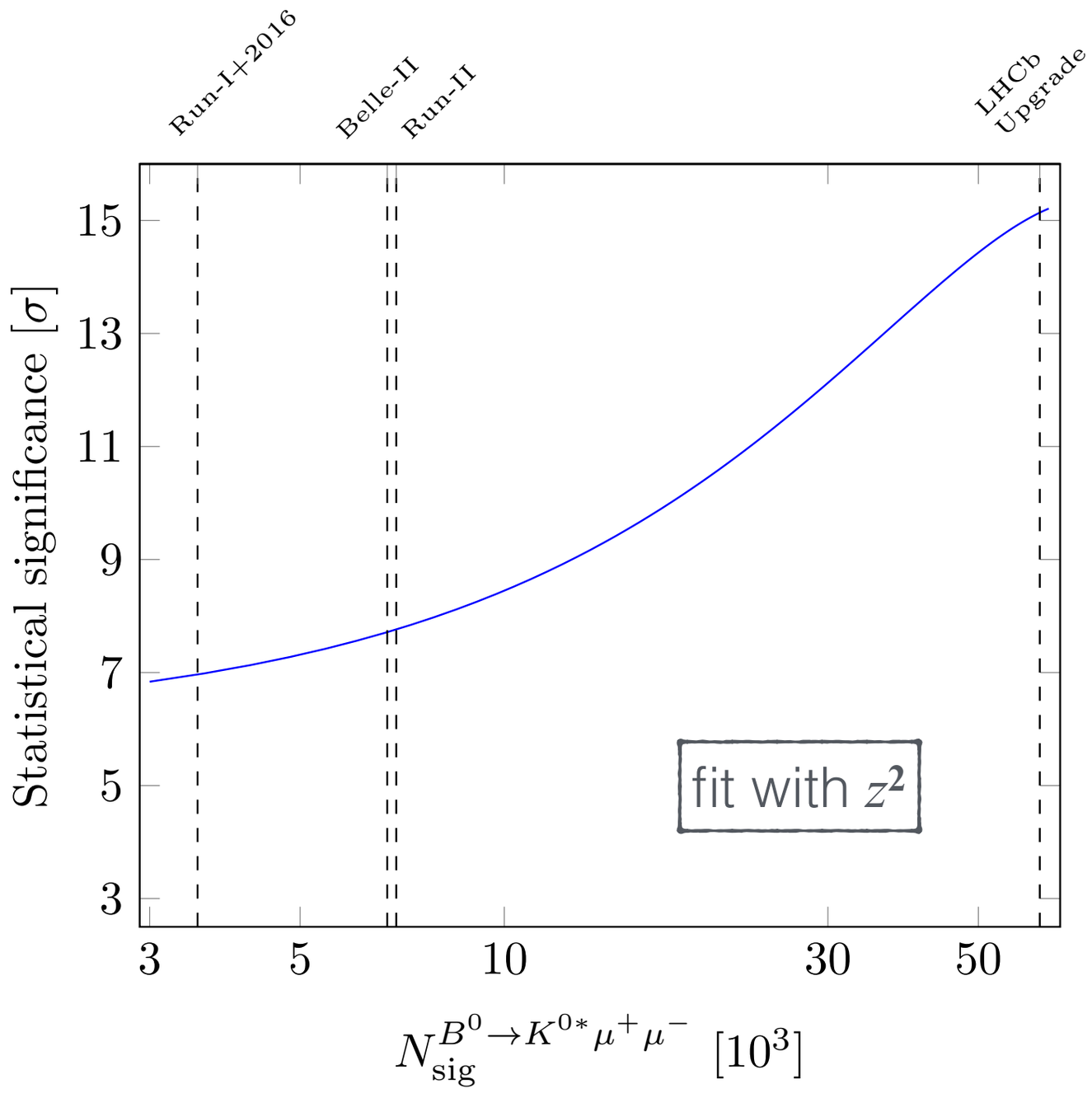
- $\sigma(\alpha_\lambda^3) \sim 5 \cdot 10^{-3}$ ⟶ No sensitivity for $\alpha_\lambda{}^{(3)} < 5 \cdot 10^{-3}$

- $\mathcal{C}_9\big|_{z^3} - \mathcal{C}_9\big|_{z^2} = 0.17$
- $\sigma(\mathcal{C}_9)\big|_{z^3} = 0.69 \quad \text{vs} \quad \sigma(\mathcal{C}_9)\big|_{z^2} = 0.17$

C_9 resolution worsen by a factor 3 with the z^3 terms

Possible solution: combined NP analysis of theory results, hadronic decays and $B \to K^* \mu\mu$

NP sensitivity: projection



Assuming the parametrization of [arxiv:1707.07305] is good description of nature

Motivation to perform combined theory+experimental analysis in LHCb/Belle-II soon

Crucial to study higher order of z in data

Lepton Flavour Universality test

- Recent non-standard measurements of LFU ratios (R_K, R_{K*}) suggest a possible LFU violating NP explanation to $b \to s\mu\mu$ anomalies
- LFUV, if exist, must be observed also in angular analysis
- We can perform a simultaneous fit to muons & electrons
  - all parameters shared except for Wilson coefficients

We define: $\Delta C9 = C9^{(\mu)} - C9^{(e)}$

What are the prospects for a measurement of a LFU violating $\Delta C9$?

We investigate the NP scenario:

$C9^{(\mu)} + 1 = C9^{(e)} = C9^{SM}$ (NP only in muons)

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$B \to K^* ee$ decay:

- worse experimental resolution due to bremsstrahlung

LHCb
- analysis limited to the q^2 range: [1.1, 7.0] GeV^2

Belle-II
- optimistic case:
  - same number of μ and e in the region between J/ψ and $\psi(2S)$
- pessimistic case:
  - no e in the region between J/ψ and $\psi(2S)$
  - sensitivity lowered by ~1.5σ at 50 ab^{-1}

ΔC_9: LHCb/Belle-II sensitivity

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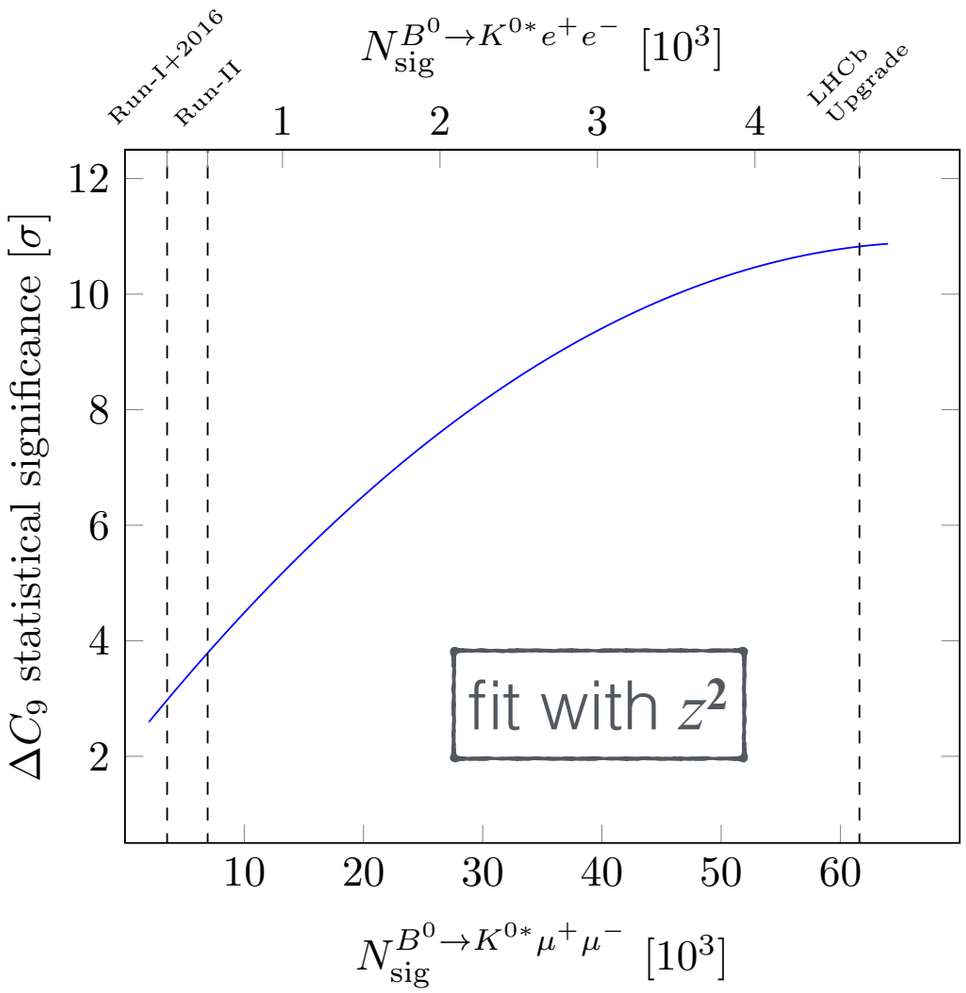
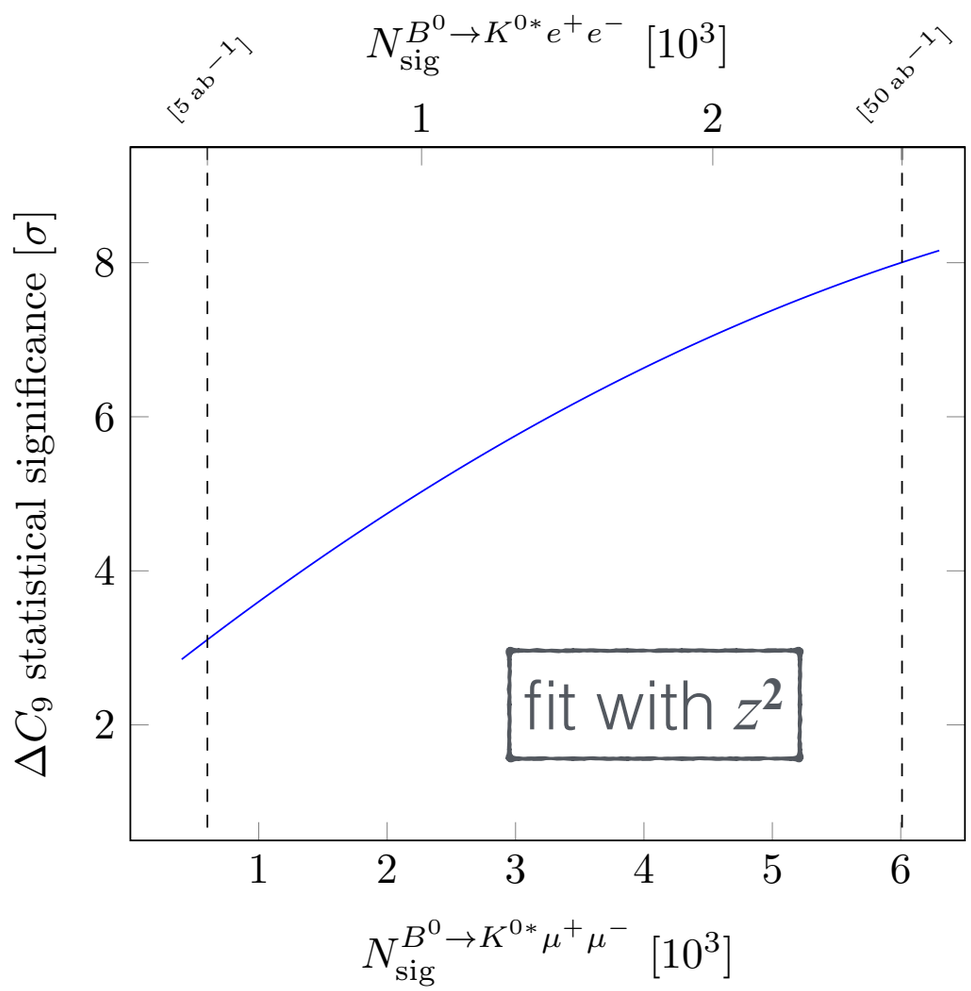
LHCb: $\varepsilon_e \sim 1/10\ \varepsilon_\mu$



- Smearing of electron resolution (compatible with [JHEP 08, 055 (2017)])
  - results in a shift of the value of $C_9^{(e)}$ but doesn't affect ΔC_9 resolution

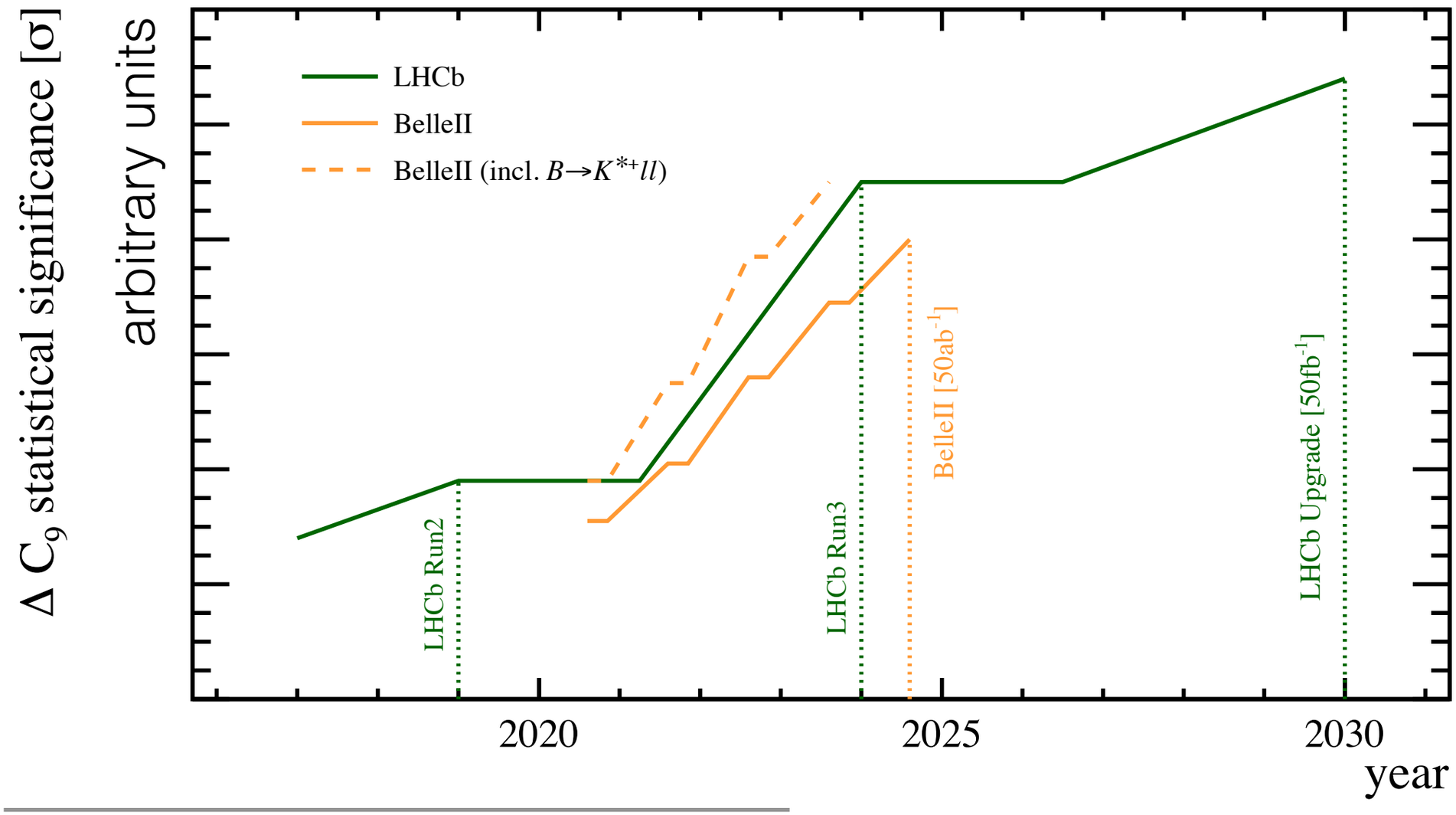
Belle-II: $\varepsilon_e \sim \varepsilon_\mu$



Sensitivity of fit with z^3 under investigation

ΔC_9: future prospect

- Prospect for $\Delta C9$ based on $B \to K^*\mu\mu$ and $B \to K^*ee$ expected yield in LHCb and Belle-II
  - Belle-II dashed line assumes the inclusion of $B \to K^{*\pm}ll$ decays (roughly double the number of events)

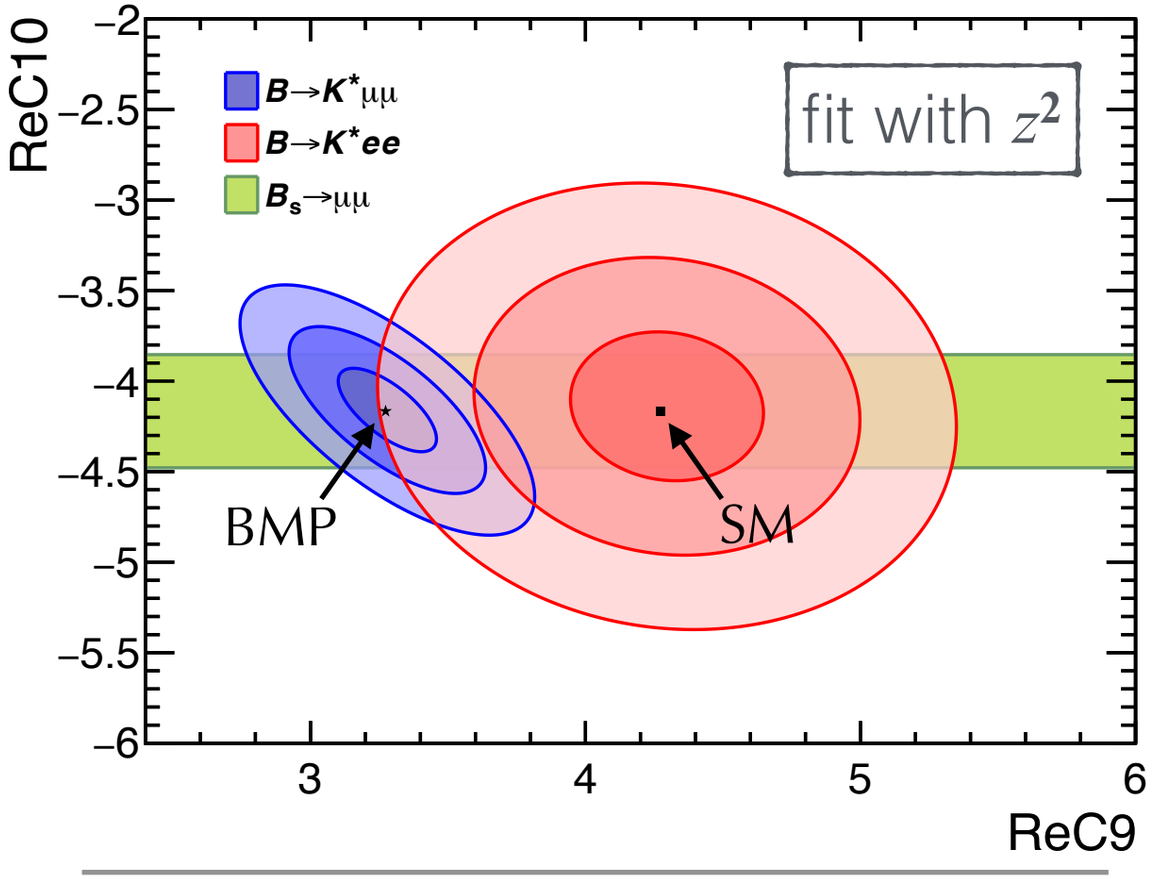


fit with z^2

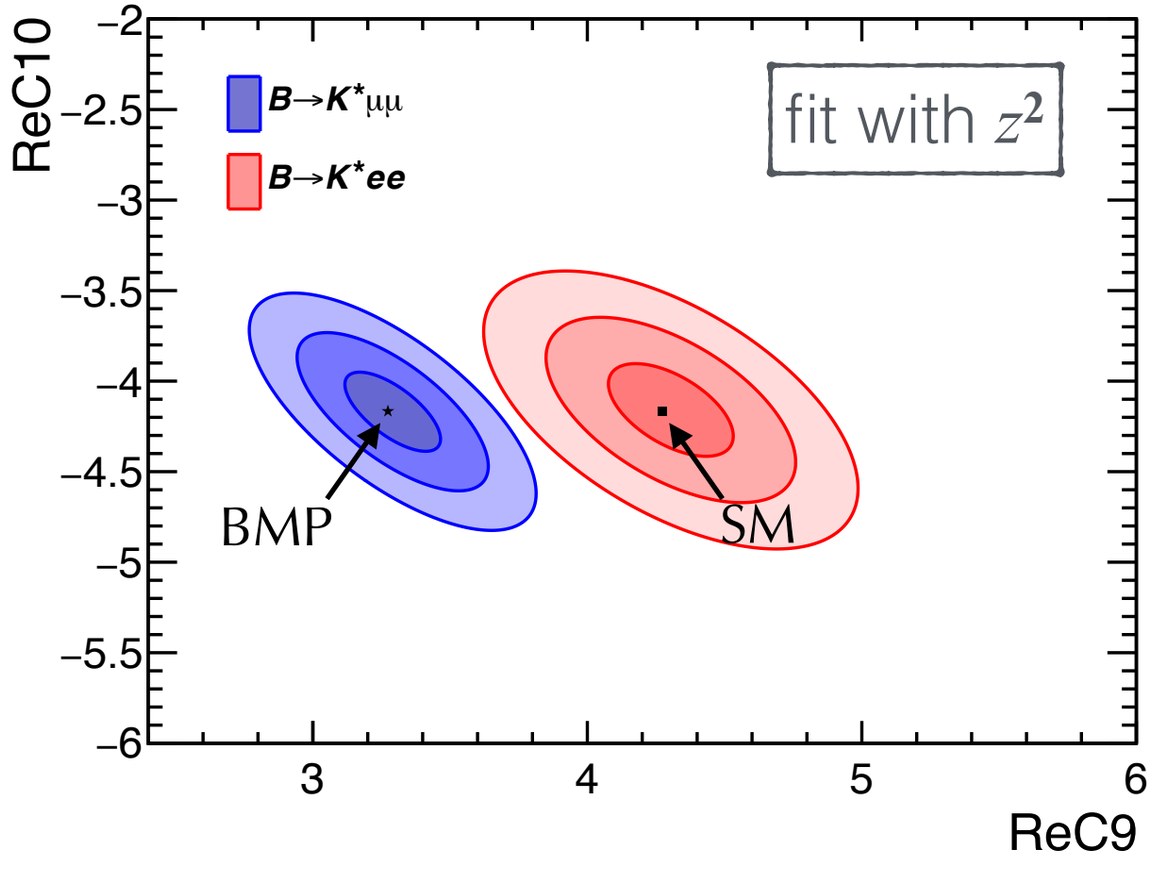
Combined C_9, C_{10} fits

- Many model allow NP contribution in both C_9 and C_{10}
- Prospect for a combined fit to C_9, C_{10} using (only) the $B \to K^*\mu\mu$ and $B \to K^*ee$ expected yield for LHCb-RunII and Belle-II
  - projected C_{10} sensitivity to $B_s \to \mu\mu$ is overlaid as reference
- Assumption: NP only in $C_9^{(\mu)}$

LHCb Run-II



Belle-II [50ab^{-1}]



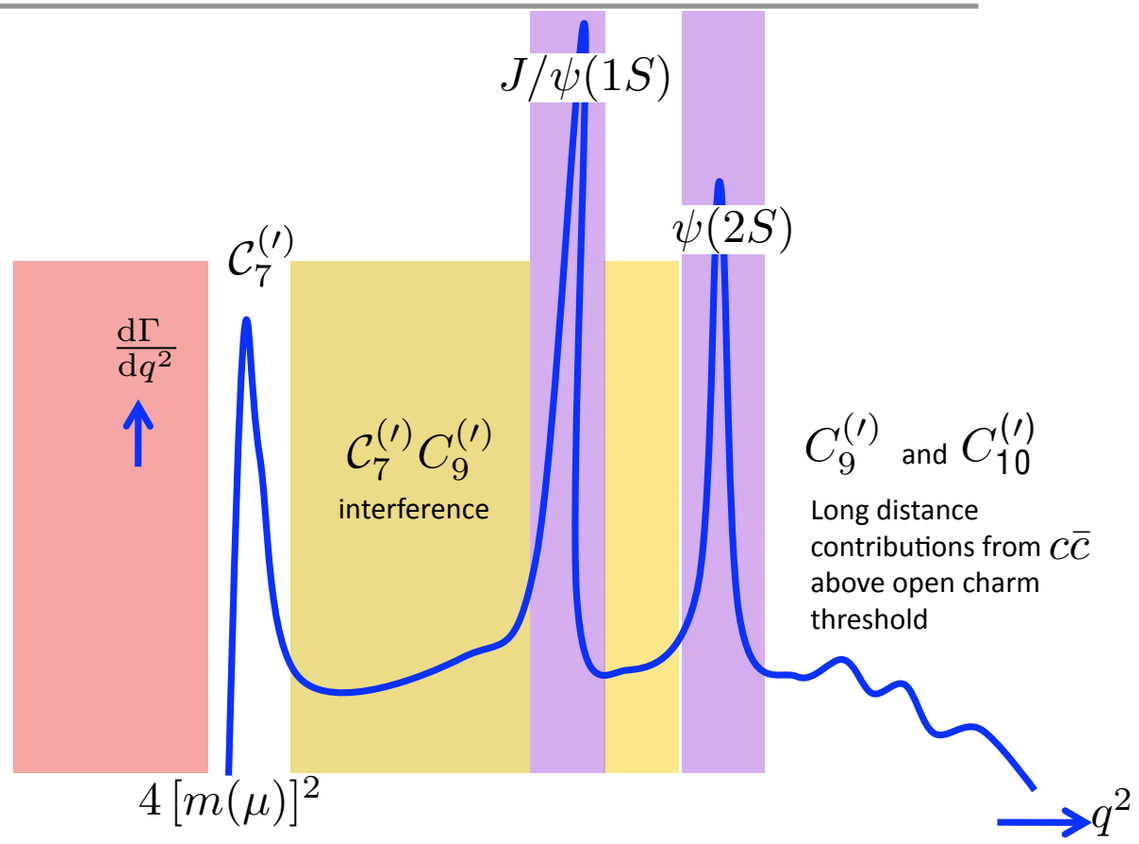
Conclusion

- We presented the prospects for future simultaneous determinations of NP shifts to $C9$ and non-local hadronic effects in the decay $B \to K^* \mu\mu$
  - Results crucially dependent on present knowledge of hadronic correlator from arxiv:1707.07305
  - The current dataset available at the LHCb experiment might provide a large statistical significance to NP, assuming our NP scenario
    - Capability of extracting information on the hadronic correlators from data-only, without any priors
- Motivation to perform combined theory+experimental analysis in LHCb/Belle-II soon
- Simultaneous fit to $B \to K^* \mu\mu$ and $B \to K^* ee$ decays can allow to explore LFU breaking hypothesis

backup

Problem with priors for z^3 coefficients

- theory at q2 < 0
- $B \to K^* \mu\mu$ data (C9 dependent)
- $B \to K^* \{J/\psi,\ \psi(2S)\}$



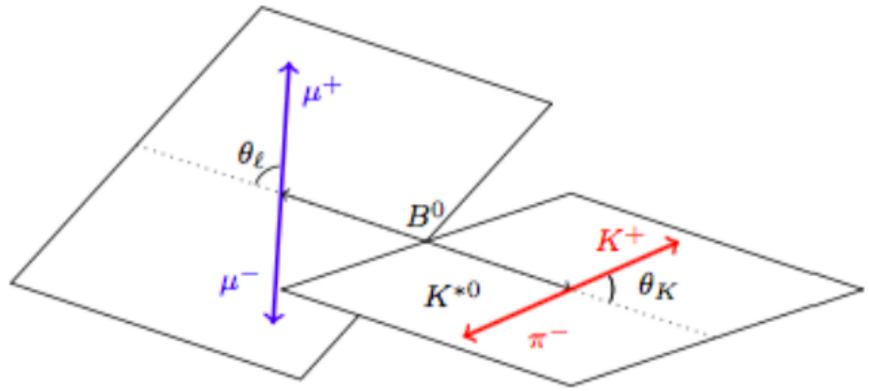
- priors for z^2 are constructed from:
  - theory
  - hadronic
- NP independent

- priors for z^3 are constructed from:
  - theory
  - hadronic
  - $B \to K^* \mu\mu$
- NP dependent

Intro: parametrization

- The differential decay rate can be expressed by separating the angular and q^2 dependencies

$$\frac{8\pi}{3}\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} =$$
$$(J_{1s} + J_{2s}\cos 2\theta_\ell + J_{6s}\cos\theta_\ell)\sin^2\theta_K$$
$$+(J_{1c} + J_{2c}\cos 2\theta_\ell + J_{6c}\cos\theta_\ell)\cos^2\theta_K$$
$$+(J_3\cos 2\phi + J_9\sin 2\phi)\sin^2\theta_K\sin^2\theta_\ell$$
$$+(J_4\cos\phi + J_8\sin\phi)\sin 2\theta_K\sin 2\theta_\ell$$
$$+(J_5\cos\phi + J_7\sin\phi)\sin 2\theta_K\sin\theta_\ell\,,$$



- The angular observable can be described by the q^2-dependent K^* amplitudes ($\lambda = \perp, \parallel, 0$)

Wilson coeff. **Non-local contribution**

$$\mathcal{A}_\lambda^{L,R} = N_\lambda \left\{ (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[C_7\mathcal{F}_\lambda^T(q^2) - 16\pi^2\frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]\right\}$$

Normalization **Form factors**

Amplitudes

$$\frac{4}{3}J_{1s} = \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}\right)$$
$$+ 4\,\beta_\ell^2\left(|A_{0\perp}|^2 + |A_{0\parallel}|^2\right) + 4\,(4-3\beta_\ell^2)\left(|A_{t\perp}|^2 + |A_{t\parallel}|^2\right)$$
$$+ 8\sqrt{2}\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}\left[(A_\parallel^L + A_\parallel^R)A_{t\parallel}^* + (A_\perp^L + A_\perp^R)A_{t\perp}^*\right],$$

$$\frac{4}{3}J_{1c} = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\,\mathrm{Re}(A_0^L A_0^{R*})\right] + \beta_\ell^2|A_S|^2$$
$$+ 8\,(2-\beta_\ell^2)|A_{t0}|^2 + 8\,\beta_\ell^2|A_{\parallel\perp}|^2 + 16\,\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}\Big[(A_0^L + A_0^R)A_{t0}^*\Big],$$

$$\frac{4}{3}J_{2s} = \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R) - 16\left(|A_{t\perp}|^2 + |A_{t\parallel}|^2 + |A_{0\perp}|^2 + |A_{0\parallel}|^2\right)\right],$$

$$\frac{4}{3}J_{2c} = -\beta_\ell^2\left[|A_0^L|^2 + |A_0^R|^2 - 8\left(|A_{t0}|^2 + |A_{\parallel\perp}|^2\right)\right],$$

$$\frac{4}{3}J_3 = \frac{\beta_\ell^2}{2}\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + (L\to R) + 16\left(|A_{t\parallel}|^2 - |A_{t\perp}|^2 + |A_{0\parallel}|^2 - |A_{0\perp}|^2\right)\right],$$

$$\frac{4}{3}J_4 = \frac{\beta_\ell^2}{\sqrt{2}}\mathrm{Re}\left[A_0^L A_\parallel^{L*} + (L\to R) - 8\sqrt{2}\left(A_{t0}A_{t\parallel}^* + A_{\parallel\perp}A_{0\parallel}^*\right)\right],$$

$$\frac{4}{3}J_5 = \sqrt{2}\beta_\ell\,\mathrm{Re}\Big[A_0^L A_\perp^{L\,*} - (L\to R) - 2\sqrt{2}A_{t\parallel}A_S^* - \frac{m_\ell}{\sqrt{q^2}}\Big([A_\parallel^L + A_\parallel^R]A_S^*$$
$$+ 4\sqrt{2}\,A_{0\parallel}A_t^* - 4\sqrt{2}\,[A_0^L - A_0^R]A_{t\perp}^* - 4\,[A_\perp^L - A_\perp^R]A_{t0}^*\Big)\Big],$$

$$\frac{4}{3}J_{6s} = 2\,\beta_\ell\,\mathrm{Re}\Big[A_\parallel^L A_\perp^{L\,*} - (L\to R) + 4\sqrt{2}\,\frac{m_\ell}{\sqrt{q^2}}\Big([A_\perp^L - A_\perp^R]A_{t\parallel}^* + [A_\parallel^L - A_\parallel^R]A_{t\perp}^*\Big)\Big],$$

$$\frac{4}{3}J_{6c} = 4\,\beta_\ell\,\mathrm{Re}\Big[2\,A_{t0}A_S^* + \frac{m_\ell}{\sqrt{q^2}}\left[(A_0^L + A_0^R)A_S^* + 4\,A_{\parallel\perp}A_t^*\right]\Big],$$

$$\frac{4}{3}J_7 = \sqrt{2}\beta_\ell\,\mathrm{Im}\Big[A_0^L A_\parallel^{L\,*} - (L\to R) + 2\sqrt{2}A_{t\perp}A_S^* + \frac{m_\ell}{\sqrt{q^2}}\Big([A_\perp^L + A_\perp^R]A_S^*$$
$$+ 4\sqrt{2}\,A_{0\perp}A_t^* + 4\sqrt{2}\,[A_0^L - A_0^R]A_{t\parallel}^* - 4\,[A_\parallel^L - A_\parallel^R]A_{t0}^*\Big)\Big],$$

$$\frac{4}{3}J_8 = \frac{\beta_\ell^2}{\sqrt{2}}\,\mathrm{Im}\Big[A_0^L A_\perp^{L\,*} + (L\to R))\Big],$$

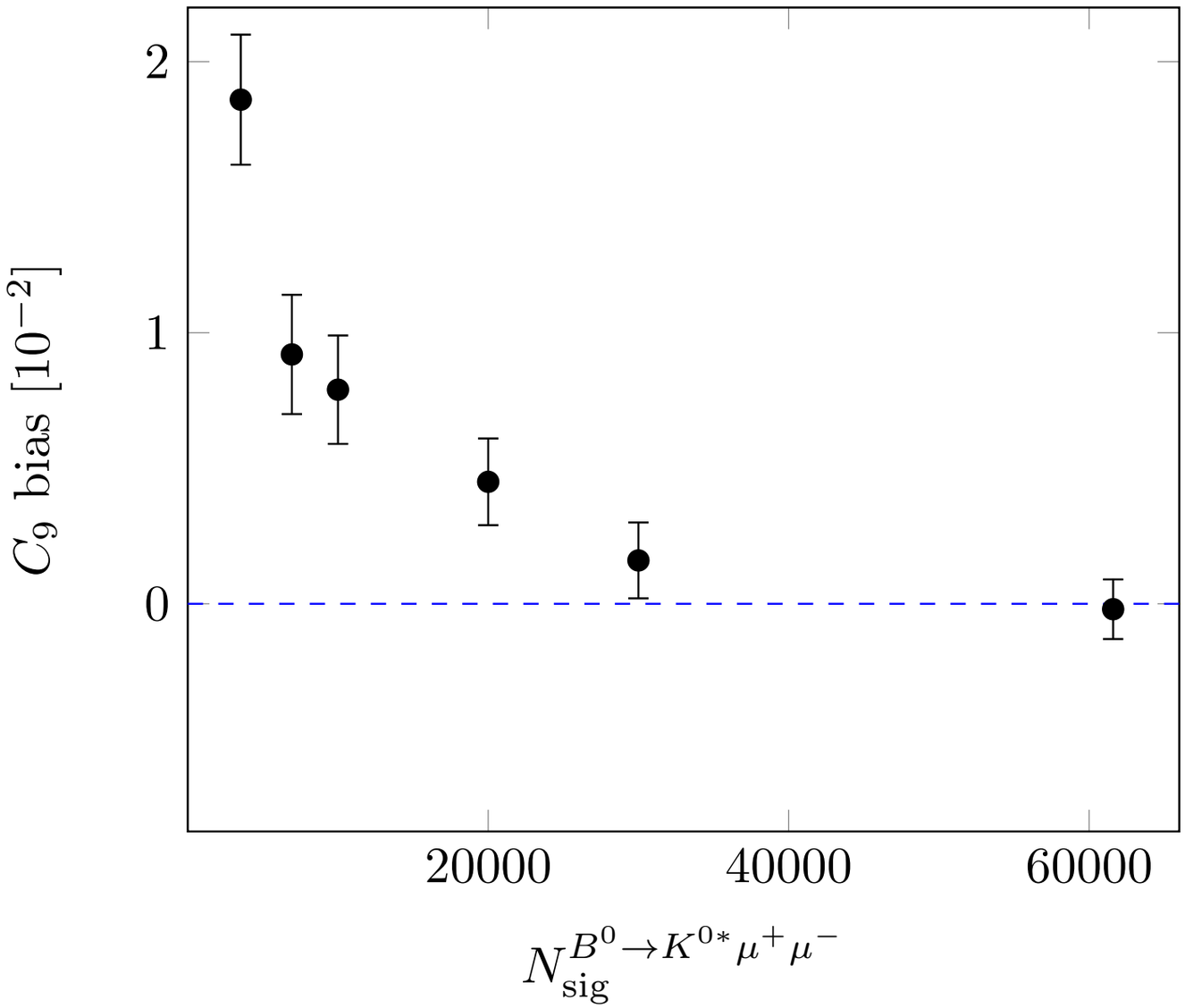
$$\frac{4}{3}J_9 = \beta_\ell^2\,\mathrm{Im}\Big[A_\perp^L A_\parallel^{L\,*} + (L\to R))\Big],$$

Projected number of events

LHCb	Muons		Electrons	
	$[1.1, 9.0]$ GeV^2	$[10.0, 13.0]$ GeV^2	$[1.1, 7.0]$ GeV^2	$[10.0, 13.0]$ GeV^2
Run1 + 2016	2330	1200	265	-
Run2	4570	2360	520	-
Upgrade	40620	20980	4660	-

Belle-II	Muons		Electrons	
	$[1.1, 9.0]$ GeV^2	$[10.0, 13.0]$ GeV^2	$[1.1, 7.0]$ GeV^2	$[10.0, 13.0]$ GeV^2
5 ab-1	425	175	160	100
12 ab-1	1020	420	390	245
24 ab-1	2045	840	780	490
36 ab-1	3070	1260	1170	740
50 ab-1	4260	1750	1625	1025

C_9 bias



Prior knowledge on the $\alpha_\lambda{}^{(k)}$ parameters

So far we used prior theoretical and experimental knowledge on the on the $\alpha_\lambda{}^{(k)}$ parameters

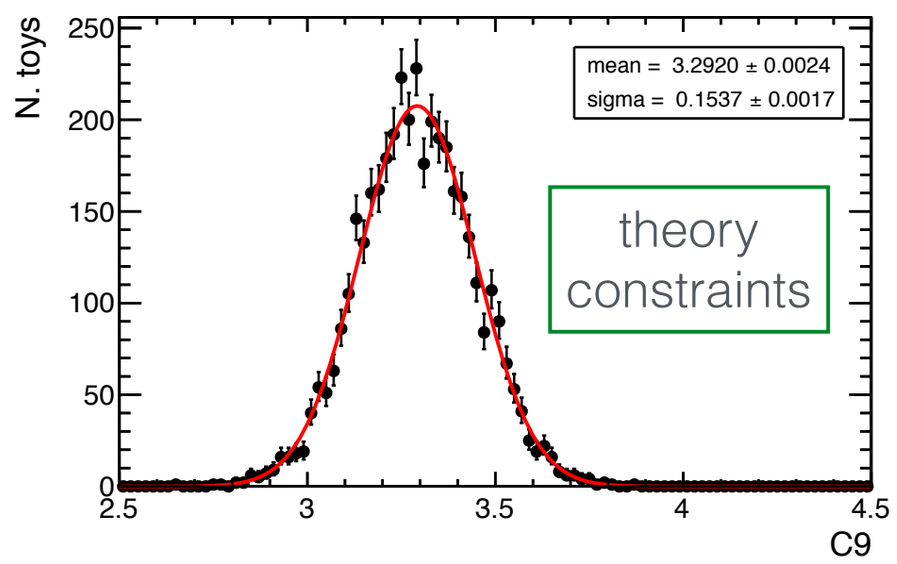
↳ *Can we perform the analysis without any prior?*

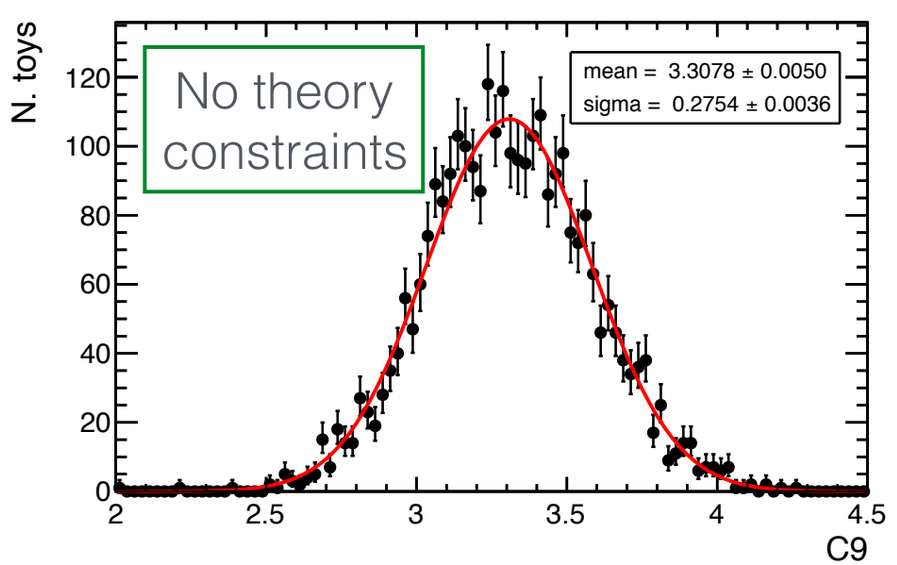
Yes!

- When using the theory priors the fit is able to extract additional information → uncertainties a-posteriori are smaller than a-priori
- When removing the priors the fit converges and we are still able to disantangle hadronic from NP effects

Of course we got a worse resolution in C9

LHCb Run1 + 2016 dataset





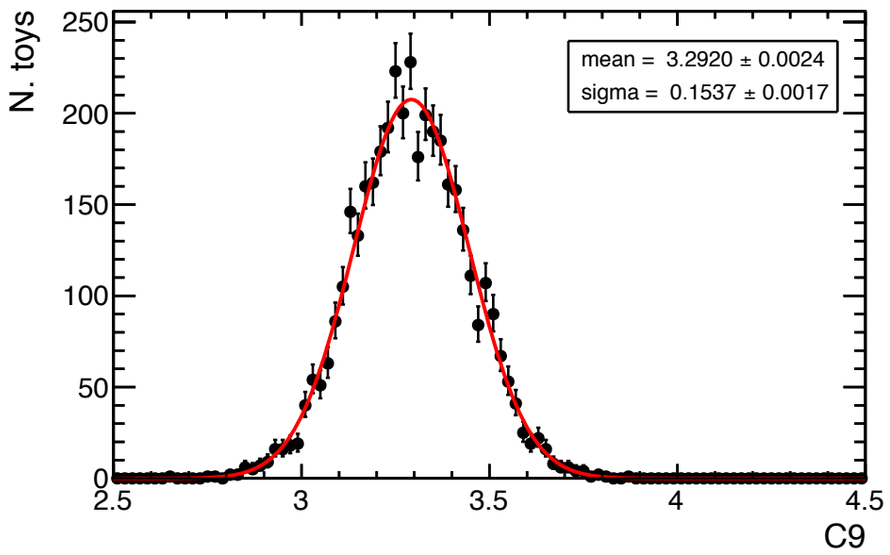
Prior knowledge on the $\alpha_\lambda{}^{(k)}$ parameters

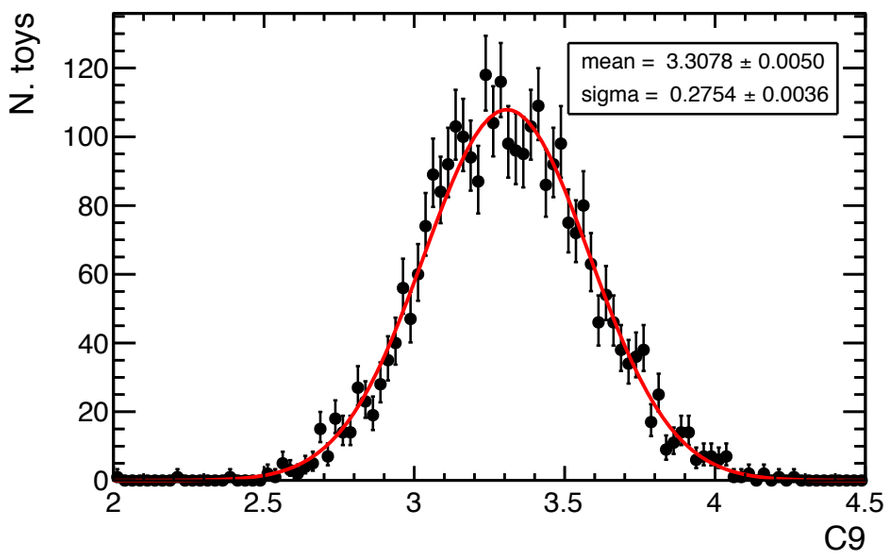
Universität Zürich[UZH]

Theory constraints

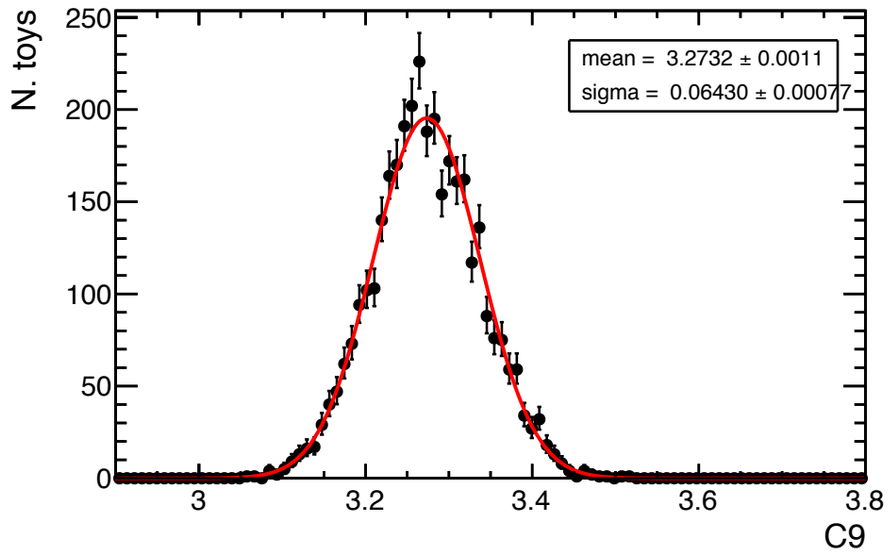
No theory constraints

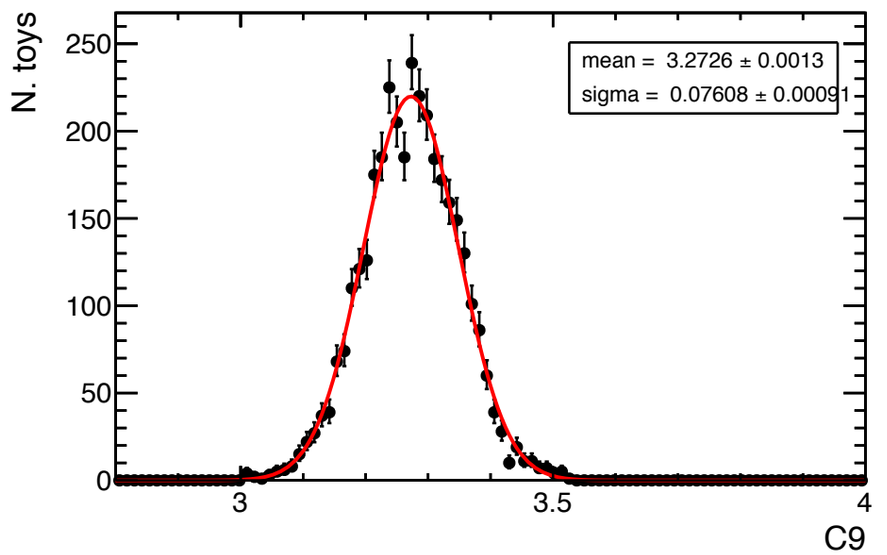
LHCb Run1 + 2016 dataset



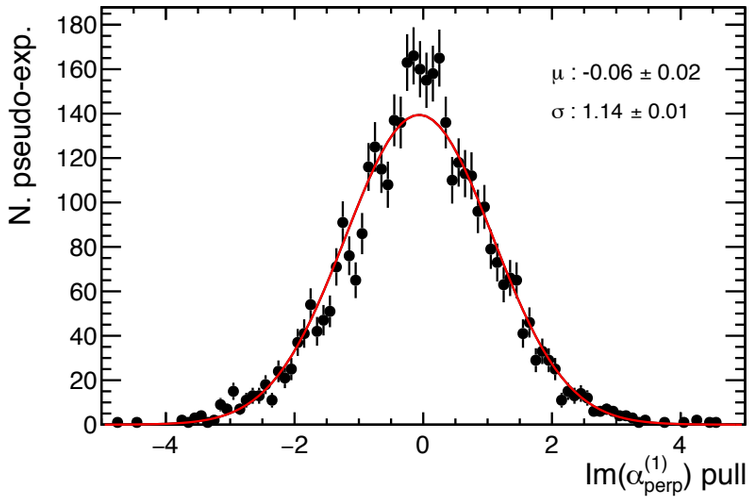


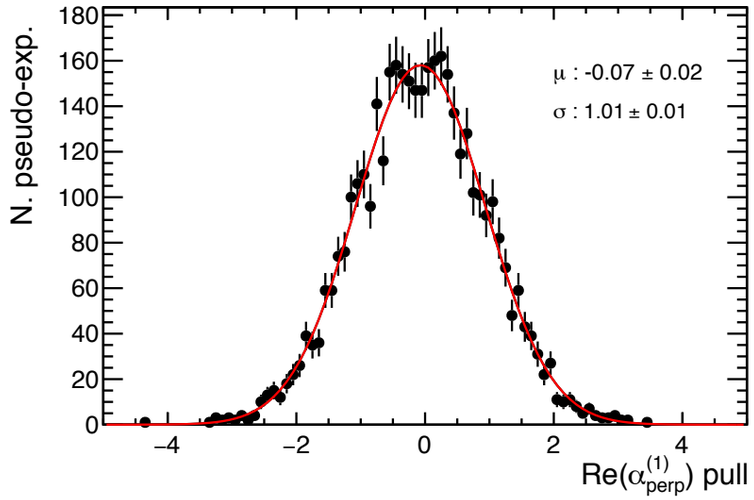
LHCb Upgrade

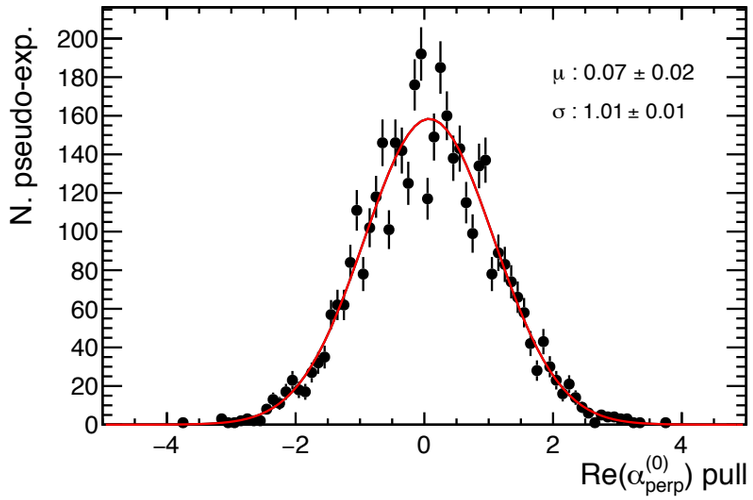


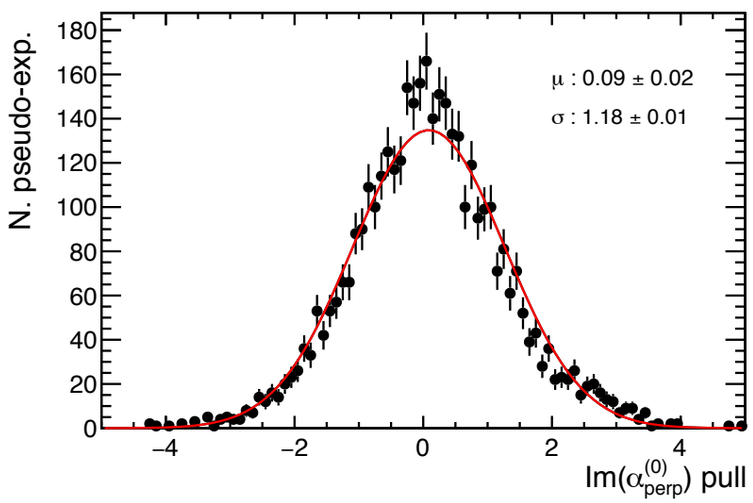


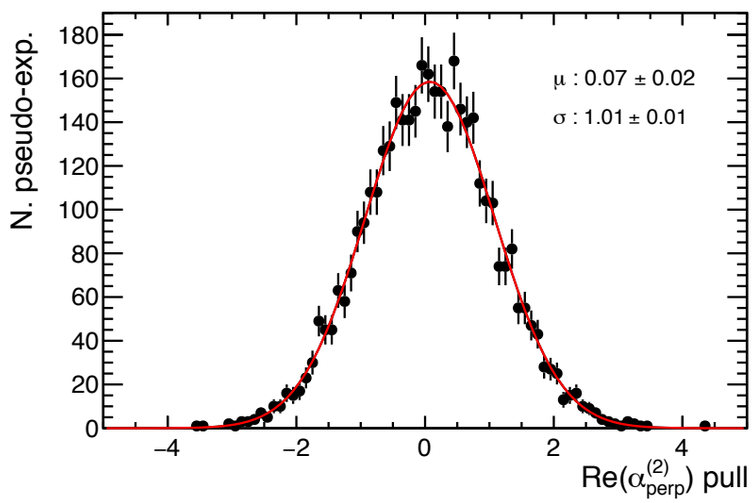
pull of alpha parameters

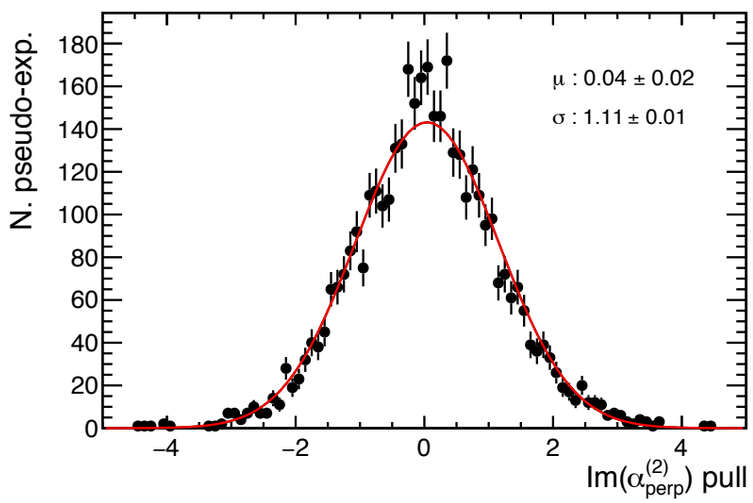




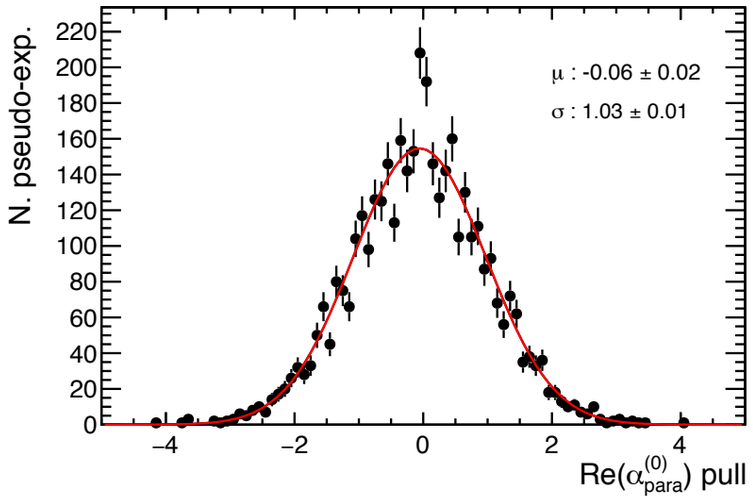


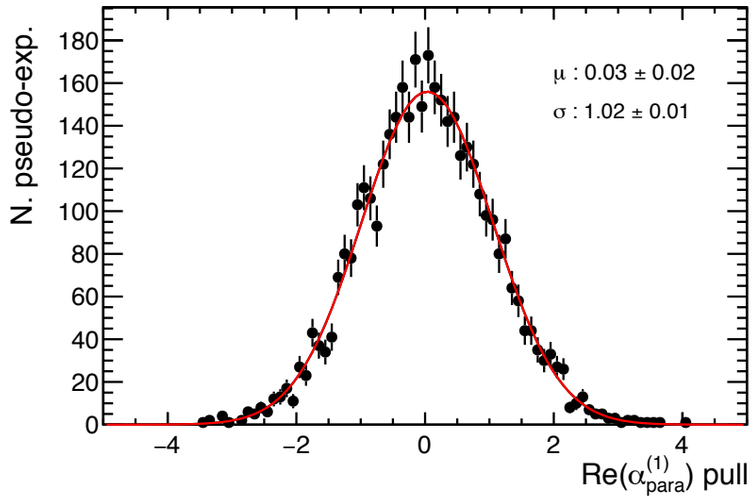


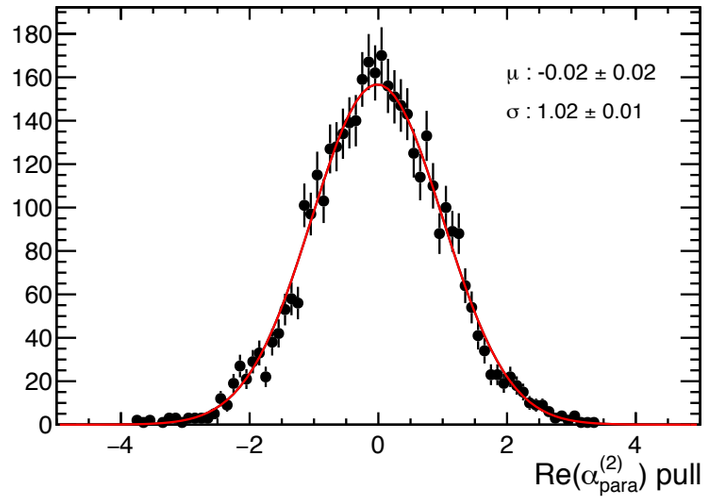


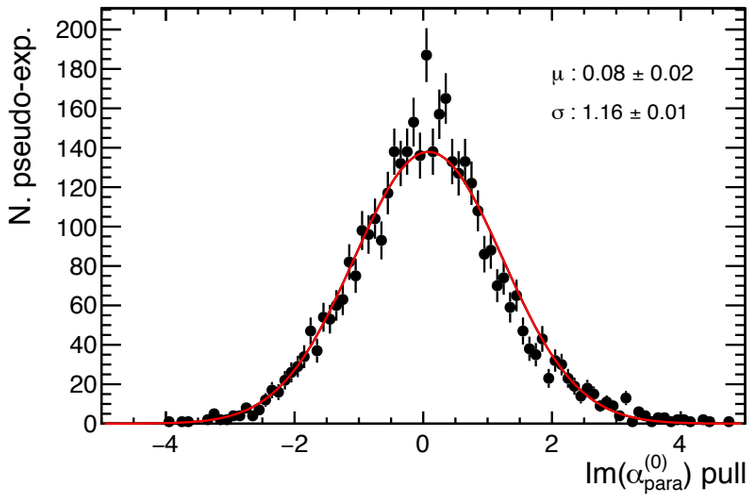


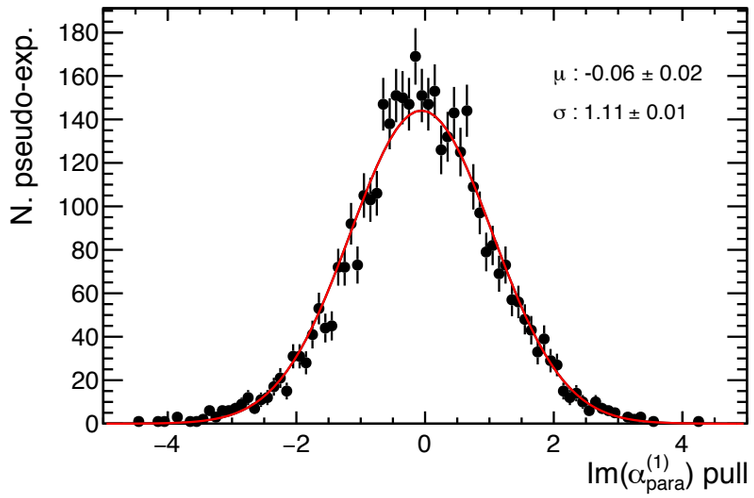
pull of alpha parameters

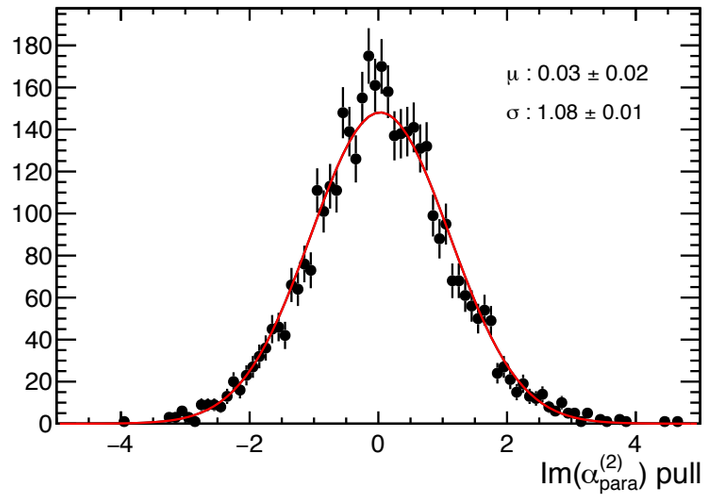
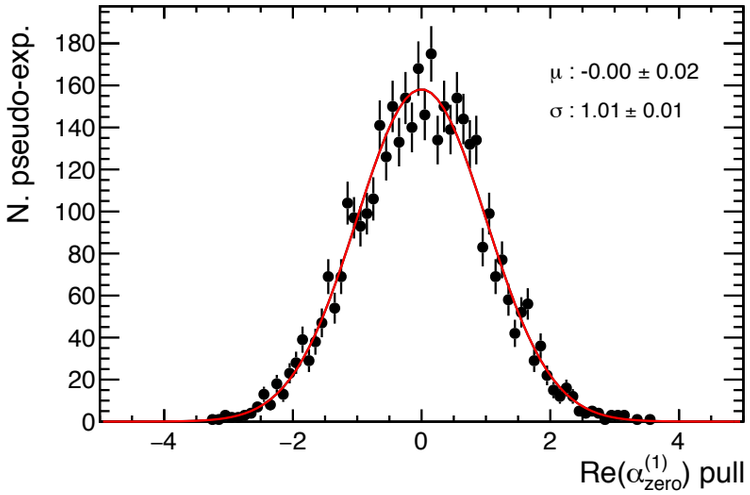
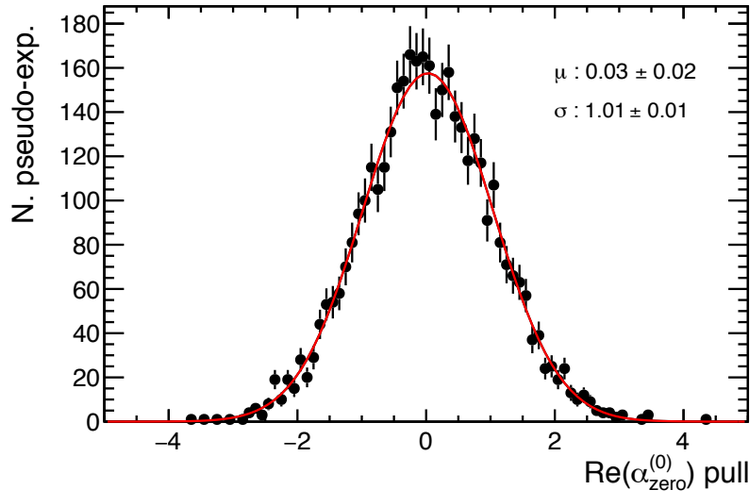
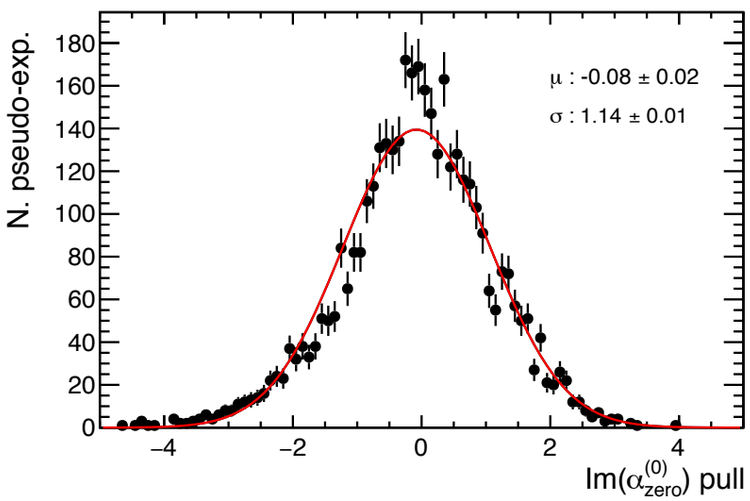
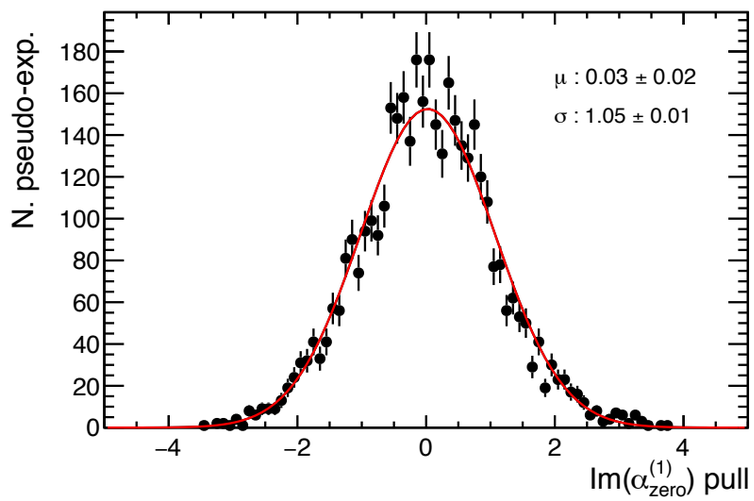












pull of alpha parameters