New Physics in Tree-Level Decays and the CKM Angle γ

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in collaboration with

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based on [arXiv:1412.1446]

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Determination of γ

The CKM angle γ is measured in $B \to DK$ decays.

Current experimental value (LHCb):

$$\gamma = (73 \pm 10)^\circ$$

Expected sensitivity at Belle II:

$$\Delta\gamma = 1^\circ \quad \text{[arXiv:1011.0352]}$$

Theoretical uncertainty due to higher order electroweak corrections (in the SM):

$$\frac{\Delta\gamma}{\gamma} < 10^{-7} \quad \text{[JHEP 1401 (2014) 051]}$$

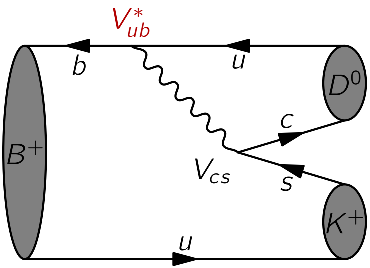
$\Rightarrow$ What about new physics?

GLW Method

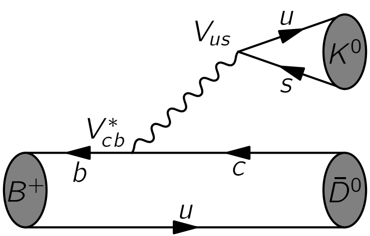
$$B^+ \to D^0 K^+,\ \bar{D}^0 K^+,\ D_1^0 K^+$$
$$B^- \to D^0 K^-,\ \bar{D}^0 K^-,\ D_1^0 K^-$$
$$D_1^0 = \frac{1}{\sqrt{2}}(D^0 + \bar{D}^0)$$

Decay rates into all three final states can be measured separately.

$B^+ \to D^0 K^+$



$B^+ \to \bar{D}^0 K^+$

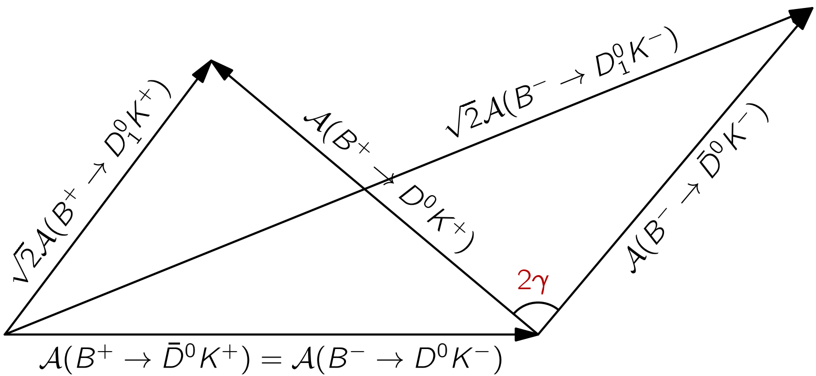


GLW Method

$$\arg \mathcal{A}(B^+ \to D^0 K^+) = \delta + \gamma \quad , \quad \arg \mathcal{A}(B^- \to \bar{D}^0 K^-) = \delta - \gamma$$

$$\mathcal{A}(B^+ \to \bar{D}^0 K^+) = \mathcal{A}(B^- \to D^0 K^-)$$

$$\sqrt{2}\mathcal{A}(B^\pm \to D_1^0 K^\pm) = \mathcal{A}(B^\pm \to D^0 K^\pm) + \mathcal{A}(B^\pm \to \bar{D}^0 K^\pm)$$



Weak Effective Hamiltonian

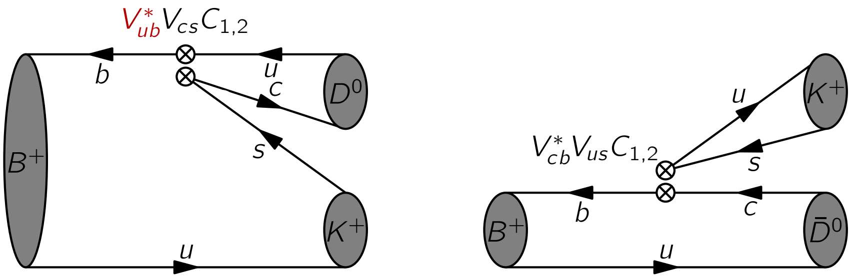
$$\mathcal{H}_{\text{eff}}^{\bar{u}_i u_j d_k} = \frac{G_F}{\sqrt{2}} V_{u_i b} V^*_{u_j d_k} [C_1^{\bar{u}_i u_j d_k} Q_1^{\bar{u}_i u_j d_k} + C_2^{\bar{u}_i u_j d_k} Q_2^{\bar{u}_i u_j d_k} + C_3^{\bar{u}_i u_j d_k} Q_3^{\bar{u}_i u_j d_k} + \ldots]$$

Tree level operators:

$$Q_1^{\bar{u}_i u_j d_k} = (\bar{u}_i^\alpha b^\beta)_{V-A} (\bar{d}_k^\beta u_j^\alpha)_{V-A} \quad ,$$
$$Q_2^{\bar{u}_i u_j d_k} = (\bar{u}_i^\alpha b^\alpha)_{V-A} (\bar{d}_k^\beta u_j^\beta)_{V-A}$$

In theories without FCNCs the penguin operators Q_3, Q_4, $\ldots$ are loop induced and absent for $i \neq j$.

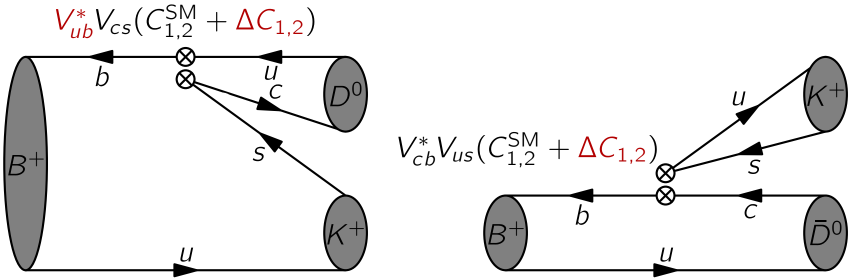
New Physics in γ Measurement



The determination of γ is unaffected by new physics as long as

- no penguin operators are induced by new physics and
- C_1 and C_2 are real.

New Physics in γ Measurement



The determination of γ is unaffected by new physics as long as

- no penguin operators are induced by new physics and
- C_1 and C_2 are real.

$\Rightarrow$ What do we really know about C_1 and C_2 experimentally?

Universality

Assume universal Wilson coefficients

$$C_1^{\bar{u}_i u_j d_k} \equiv C_1 \quad , \quad C_2^{\bar{u}_i u_j d_k} \equiv C_2 \quad \text{for all } i, j, k \in \{1, 2\}.$$

and use

$$b \to \bar{u}ud,\ \bar{c}ud,\ \bar{c}ud,\ \bar{c}cd, \ldots$$

transitions to constrain C_1 and C_2.

Most relevant observables are already discussed in [arXiv:1404.2531].

Observables (I)

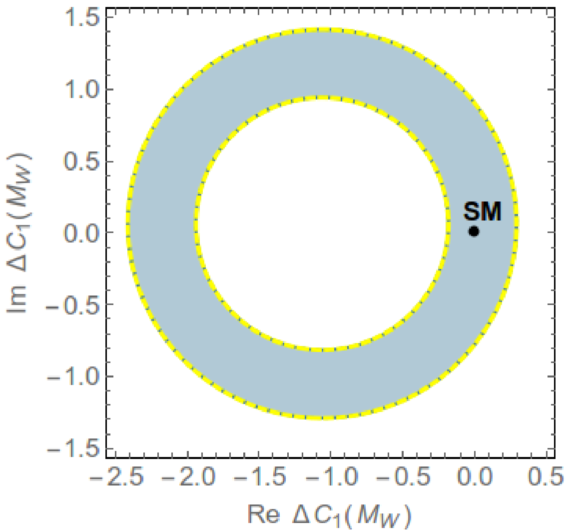
- $b \to \bar{u}ud$:
  - decay rates for $B \to \pi\pi,\ \rho\pi,\ \rho\rho$ ($R_{\pi^+\pi^0},\ R_{\rho^-\rho^0/\rho^+\rho^-}$),
  - mixing induced CP asymmetries in $B \to \pi\pi,\ \rho\pi$ ($S_{\pi^+\pi^-},\ S_{\rho\pi}$),
- $b \to \bar{c}ud, \bar{u}cd$:
  - decay rate for $B^0 \to D^{*+}\pi^-$ ($R_{D^{*+}\pi^-}$),
  - indirect CP asymmetries for $B^0 \to D^{(*)0}h^0$ ($S_{D^*h^0},\ h^0 = \pi^0, \eta, \omega$),

Theory formulae based on QCD factorisation.

Observables (II)

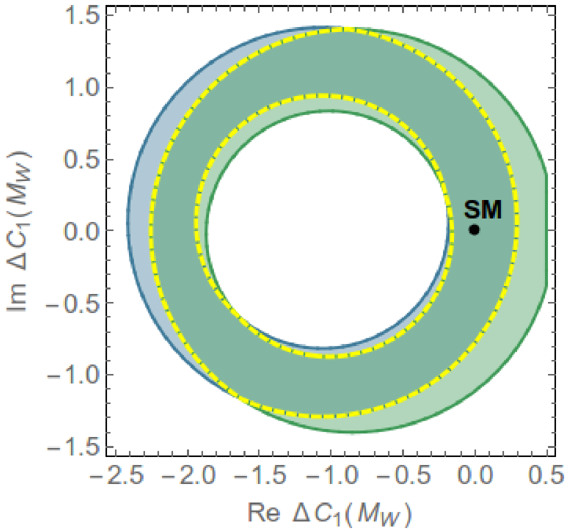
- $b \to \bar{c}cd$:
  - $\mathrm{Br}(B \to X_d\gamma)$,
  - $\sin(2\beta_d)$ from $B \to J/\psi K_S$,
  - semileptonic asymmetry a_{sl}^d,
- $b \to \bar{c}cs$:
  - $\mathrm{Br}(B \to X_s\gamma)$,
  - semileptonic asymmetry a_{sl}^s,
- $b \to$ anything:
  - total B meson lifetime $\Gamma_{B,\mathrm{tot}}$,
  - B_s lifetime difference $\Delta\Gamma_s$.

Constraints on C_1 (with $C_2 = 0$)



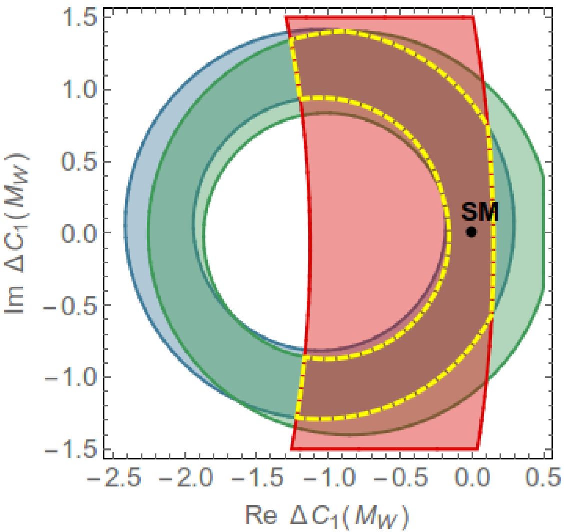
Constraint from $R_{\pi^+\pi^0}$

Constraints on C_1 (with $C_2 = 0$)



Constraint from $R_{\rho^-\rho^0/\rho^+\rho^-}$

Constraints on C_1 (with $C_2 = 0$)



Constraint from $R_{D^{*+}\pi^-}$

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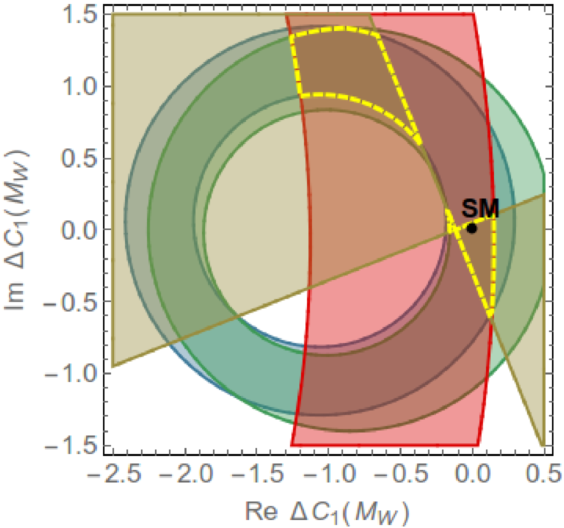

Constraint from $S_{D^* h^0}$

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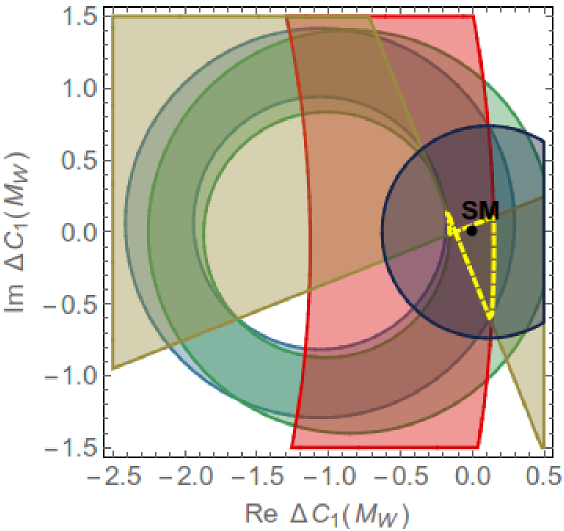
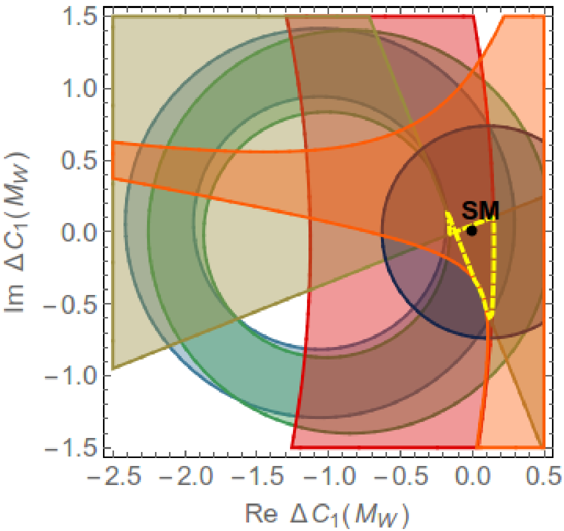


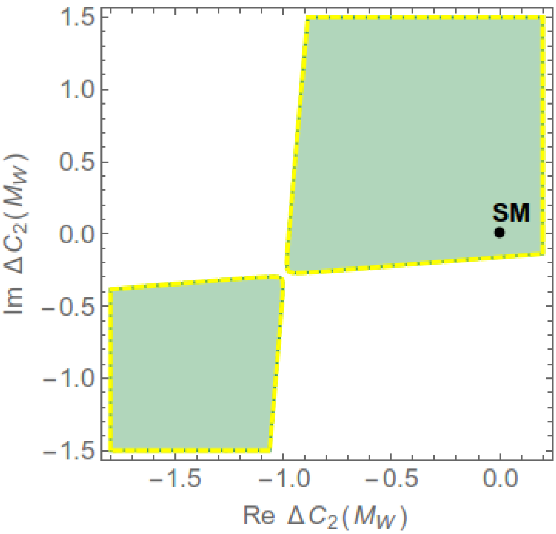
Constraint from $\Gamma_{B,\text{tot}}$

Constraints on C_1 (with $C_2 = 0$)



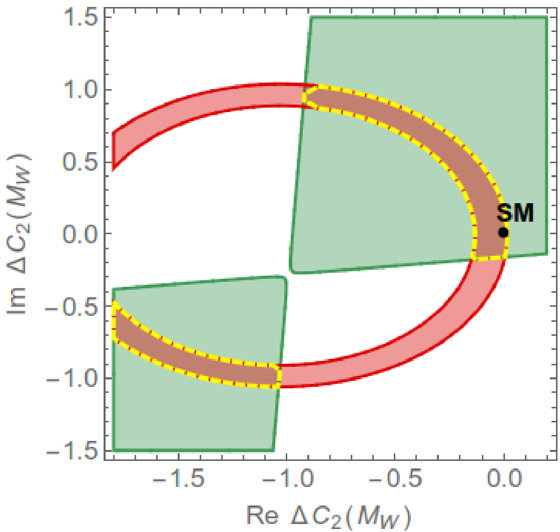
Constraint from $a_{\rm sl}^d$

Constraints on C_2 (with $C_1 = 0$)



Constraint from $S_{\pi^+\pi^-}$

Constraints on C_2 (with $C_1 = 0$)



Constraint from $R_{D^{*+}\pi^-}$

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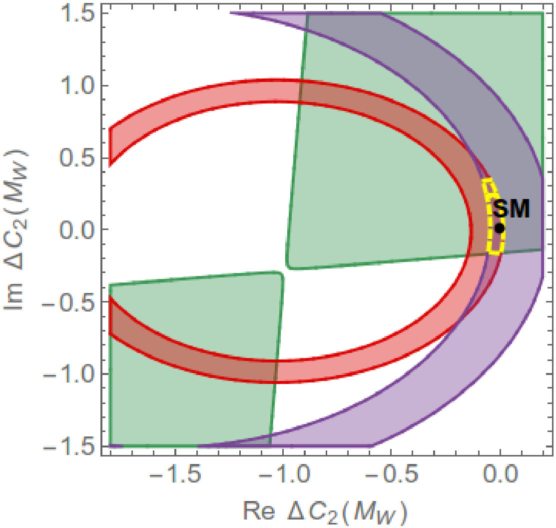
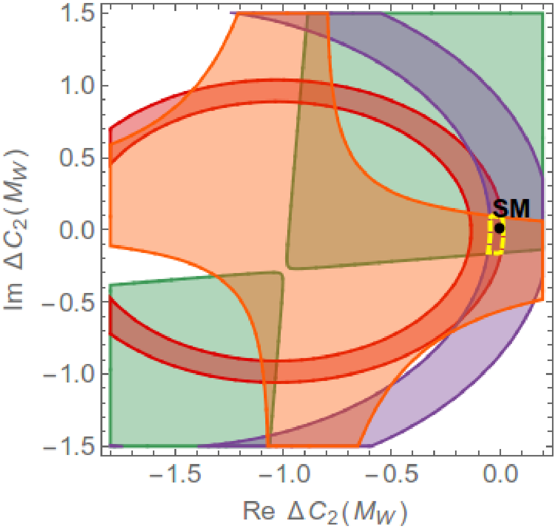


Constraint from $\mathrm{Br}(B \to X_s\gamma)$

Constraints on C_2 (with $C_1 = 0$)



Constraint from a_{sl}^d

Determination of γ

γ is determined from the amplitude ratio

$$\frac{\mathcal{A}(B^- \to \bar{D}^0 K^-)}{\mathcal{A}(B^- \to D^0 K^-)} = \left.\frac{\mathcal{A}(B^- \to \bar{D}^0 K^-)}{\mathcal{A}(B^- \to D^0 K^-)}\right|_{\mathrm{SM}} \cdot \left[1 + (r_{A'} - r_A)\frac{\Delta C_1}{C_2}\right]$$

with

$$r_A = \frac{\langle D^0 K^- | Q_1^{\bar{c}us} | B^- \rangle}{\langle D^0 K^- | Q_2^{\bar{c}us} | B^- \rangle} \quad , \quad r_{A'} = \frac{\langle \bar{D}^0 K^- | Q_1^{\bar{u}cs} | B^- \rangle}{\langle \bar{D}^0 K^- | Q_2^{\bar{u}cs} | B^- \rangle}$$

Consequently

$$\gamma_{\mathrm{exp}} = \gamma_{\mathrm{SM}} + (r_A - r_{A'})\frac{\mathrm{Im}\,\Delta C_1}{C_2} \equiv= \gamma_{\mathrm{SM}} + \delta\gamma$$

New Physics in γ

We don't know the value of $r_A - r_{A'}$ very well.

Colour counting:

$$r_A = \mathcal{O}(1) \quad , \quad r_{A'} = \mathcal{O}(3)$$

Naive factorisation:

$$r_A \approx \frac{f_D F_0^{B\to K}(0)}{f_K F_0^{B\to D}(0)} \approx 0.4 \quad , \quad r_{A'} = ??$$

Tentatively using $r_A - r_{A'} = -0.6$ we find allowed region for $\delta\gamma$:

$$|\delta\gamma| \lesssim 4^\circ$$

Conclusions

- The determination of γ can be "contaminated" by new physics in the Wilson coefficients C_1 and C_2.

$$\delta\gamma = (r_A - r_{A'})\frac{\mathrm{Im}\,\Delta C_1}{C_2}$$

- The hadronic ratios r_A and $r_{A'}$ have very large theoretical uncertainties.
- Current data from tree-level B decays still allows new physics effects in the Wilson coefficients C_1 and C_2 of the order of 10%.
- This corresponds to $|\delta\gamma| \approx 4^\circ$ (with a large theoretical uncertainty due to r_A and $r_{A'}$).

Global Fits with *my*Fitter

Definition of p-Values

- Consider model with parameters $\vec{\omega} \in \Omega$ and observables $\vec{x} \in \mathbb{R}^n$,
- described by probability density $f(\vec{x}, \vec{\omega})$.
- Null hypothesis: $\omega \in \Omega_0 \subset \Omega$.
- Define test statistic

$$\Delta\chi^2(\vec{x}) = -2 \ln \frac{\max_{\vec{\omega}\in\Omega_0} f(\vec{x}, \vec{\omega})}{\max_{\vec{\omega}\in\Omega} f(\vec{x}, \vec{\omega})} \quad .$$

- For observed data $\vec{x}_0$

$$\begin{aligned} p &= \max_{\vec{\omega}\in\Omega_0} \Pr(\Delta\chi^2(\vec{X}) > \Delta\chi^2(\vec{x}_0) | \vec{X} \sim f(\,\cdot\,, \vec{\omega})) \\ &= \max_{\vec{\omega}\in\Omega_0} \int d^n\vec{x} f(\vec{x}, \vec{\omega}) \theta(\Delta\chi^2(\vec{x}) - \Delta\chi^2(\vec{x}_0)) \quad . \end{aligned}$$

Wilks' Theorem

The asymptotic formula

$$p = Q(\tfrac{k}{2}, \tfrac{1}{2}\Delta\chi^2(\vec{x}_0))$$

holds exactly only for linear regression models, i.e.

$$f(\vec{x}, \vec{\omega}) \propto \exp[-\tfrac{1}{2}(\vec{\mu}(\vec{\omega}) - \vec{x})^\mathsf{T}\Sigma^{-1}(\vec{\mu}(\vec{\omega}) - \vec{x})]$$

with

- Σ fixed,
- $\vec{\mu}(\vec{\omega}) = C\vec{\omega} + \vec{b}$ and C, $\vec{b}$ fixed,
- $\Omega = \mathbb{R}^p$.

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with

- Σ fixed,
- $\vec{\mu}(\vec{\omega}) = C\vec{\omega} + \vec{b}$ and C, $\vec{b}$ fixed (never true in BSM fits),
- $\Omega = \mathbb{R}^p$ (not true in presence of theoretical constraints).

Non-nested Models: The Case of the SM4

- Add a sequential 4-th generation to the SM.
- Chiral fermions do not decouple.

$\Rightarrow$ SM is not a limiting case of SM4.

$\Rightarrow$ The parameter space Ω is not a vector space.

$$\Omega = \Omega_{\mathsf{SM}} \sqcup \Omega_{\mathsf{SM4}}$$

- The *p*-value is very small ($\mathcal{O}(10^{-7})$), mostly because of Higgs data.

Computing the p-Value

- Use the bootstrap p-value

$$\hat{p} = \int d^n\vec{x} f(\vec{x}, \hat{\vec{\omega}}_0)\theta(\Delta\chi^2(\vec{x}) - \Delta\chi^2(\vec{x}_0))$$

$\hat{\vec{\omega}}_0$: maximum likelihood estimate of $\vec{\omega}$ under the null hypothesis $\vec{\omega} \in \Omega_0$

- Compute the integral numerically with importance sampling method.
- Choose sampling density $\rho(\vec{x})$ which samples the linearised model perfectly.

$\Rightarrow$ Speeds up the computation for the SM4 by factor 100 to 1000.

*my*Fitter

This method is implemented in the public code *my*Fitter, which

- is a model-independent framework for maximum likelihood fits and numerical p-value computations,
- supports parallelised integration,
- is available in a C++ version (complete with a manual and examples)
- and a Python version with better support for non-linear constraints (documentation is work in progress).

More details in [arXiv:1207.1446] and on

`http://myfitter.hepforge.org`

Conclusions (p-Values)

- $p = Q(\frac{k}{2}, \frac{1}{2}\Delta\chi^2)$ is an approximation.
- The approximation can be very bad in realistic BSM models (especially for non-decoupling models).
- Toy simulations become unfeasible for small p-values.
- Importance sampling techniques as implemented in *my*Fitter can speed things up considerably.