CP VIOLATION IN THE CHARM SECTOR IN THE SM AND BEYOND

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- Introduction
- CP violation in D decays
- CPV in mixing: present and future
- Conclusions

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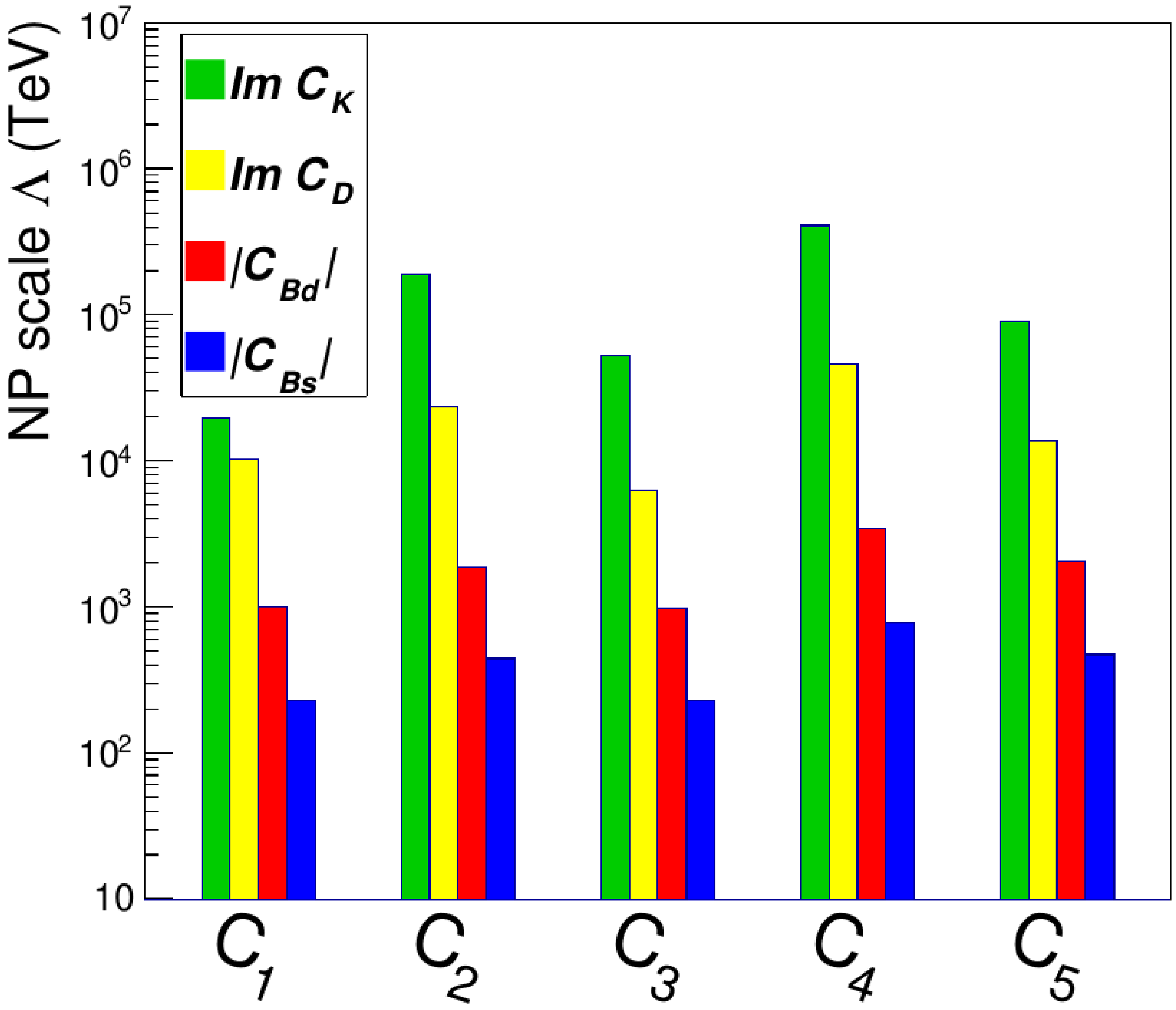
INTRODUCTION



Bounds on NP effective scale (Λ/√C) from ΔF=2 processes

INTRODUCTION

- No tree-level Flavour Changing Neutral Current in the SM
  - FCNC processes are finite and computable (at least in principle)
  - in the SM they arise at the loop level
    - New Physics can compete with SM
  - predictable once quark masses and Cabibbo-Kobayashi-Maskawa mixing matrix known
    - CKM matrix can be extracted from tree-level processes

INTRODUCTION

- CKM matrix is unitary, 3 angles and 1 phase
  - CKM phase generates CP violation in weak int.
- CKM matrix has hierarchical structure
  - can be expanded in a small parameter λ

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = 0.2255 \pm 0.0005$$

$$A = 0.826 \pm 0.012$$

$$\bar\rho = 0.148 \pm 0.013$$

$$\bar\eta = 0.348 \pm 0.010$$

$$\bar\rho = \rho\left(1-\frac{\lambda^2}{2}\right), \qquad \bar\eta = \eta\left(1-\frac{\lambda^2}{2}\right)$$

INTRODUCTION

- CKM unitarity implies GIM cancellation of SM loop contributions to FCNCs:
  - $\mathcal{A}(u_i \to u_j) \propto \sum_k V_{jk} V_{ik}^* f\left(\frac{m_{d_k}^2}{m_W^2}\right)$
- For c→u transitions:
  - $V_{ud}V_{cd}^* \sim \lambda$ and $m_d \ll m_D$ (long-distance)
  - $V_{us}V_{cs}^* \sim \lambda$ and $m_s \ll m_D$ (long-distance)
  - $V_{ub}V_{cb}^* \sim \lambda^5$ and $m_b \gg m_D$ (short-distance)

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  - ~~$V_{ub}V_{cb}^* \sim \lambda^5$ and $m_b \gg m_D$ (short-distance)~~

Negligible

INTRODUCTION

- short-distance contribution of bottom quarks negligible in c ↔ u transitions
- effectively a two-generation theory with slightly non-unitary mixing matrix:
  - $\lambda_d + \lambda_s = - \lambda_b$, where $\lambda_q = V_{cq}{}^* V_{uq}$
  - CP violation arises at $O(\lambda^4)$, suppressed by $r_{CKM} = \mathrm{Im}(\lambda_b/\lambda_{d,s}) \approx 6.5\ 10^{-4}$
  - GIM cancellation ⇔ s↔d ⇔ U-spin subgroup of SU(3) flavour symmetry of strong interactions

INTRODUCTION

- Charm weak interactions described by the $\Delta C=1$ effective Hamiltonian:

$$\mathcal{H}_{\rm eff}^{\Delta C=1} = \frac{4G_F}{\sqrt{2}} \sum_{i,j=1,2} V^*_{cd_i} V_{ud_j} \left(C_1 Q_1^{ij} + C_2 Q_2^{ij} \right) \qquad Q_{1,2}^{ij} \sim \bar{d}_i \gamma^\mu P_L c \bar{u} \gamma_\mu P_L d_j$$

- Cabibbo Allowed ($\propto V_{cs}^* V_{ud}$) and Doubly Cabibbo-Suppressed ($\propto V_{cd}^* V_{us}$) decays: real CKM factor up to $O(\lambda^5)$
- Singly Cabibbo Suppressed decays: CKM imaginary part at $O(\lambda^5)$, $r_{CKM} \approx 6.5\ 10^{-4}$
- $\Delta C=2$ processes generated by two insertions of $\Delta C=1$

CPV IN SCS DECAYS

- effective Hamiltonian for SCS decays:

$$\mathcal{H}_{\rm eff}^{\rm SCS} = \frac{2G_F}{\sqrt{2}}\Big\{ (\lambda_d - \lambda_s)\, C_1\left(Q_1^{dd} - Q_1^{ss}\right) + C_2\left(Q_2^{dd} - Q_2^{ss}\right) \qquad \Delta U=1$$

$$-\lambda_b\, C_1\left(Q_1^{dd} + Q_1^{ss}\right) + C_2\left(Q_2^{dd} + Q_2^{ss}\right)\Big\} \qquad \Delta U=0$$

- to get CPV in decay, i.e. $|A(D\to f)|\neq|A(\overline{D}\to \overline{f})|$, need λ_b and **strong phase difference δ** between contribution of ΔU=1 and ΔU=0 terms:

$$A_{CP} = r_{CKM}\,\langle\Delta U=0\rangle/\langle\Delta U=1\rangle\,\sin\delta$$

$\Delta I = \frac{1}{2}$ IN D DECAYS?

- Perform isospin analysis of $D \to \pi\pi$ decays:
  - $|A_0| \sim 2\,|A_2|$
  - $\mathrm{Arg}(A_0/A_2) \sim 90°$

Franco, Mishima & L.S. '12

- No $\Delta I = \frac{1}{2}$ rule, but maximal FSI effects
  - extremely tough for nonperturbative methods: no quark-hadron duality on the resonance

Khodjamirian & Petrov '17;

Chala et al '19

  - no dynamical assumption ⇔ no prediction

Muller, Nierste & Schacht '15; ...

ΔA_{CP}

- To cancel systematics (initial pp state), LHCb measures $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$

Franco, Mishima & L.S. '12

- Natural expectations in the SM:
  - $A_{CP}(KK) \sim -A_{CP}(\pi\pi) \sim O(r_{CKM} \langle\Delta U=0\rangle/\langle\Delta U=1\rangle \sin\delta) \sim r_{CKM}$
  - $\Delta A_{CP} \sim 2\, r_{CKM} \sim 0.13\ \%$

Brod, Kagan & Zupan '11

Franco, Mishima & L.S. '12

- LHCb result:
  - $\Delta A_{CP} = (-15.6 \pm 2.9)\, 10^{-4}$

CAN ΔA_{CP} BE NP?

- Need

$$\frac{C_{\rm NP}}{M_{\rm NP}^2} \sim \frac{4G_F}{\sqrt{2}}\lambda_b \Rightarrow \frac{M_{\rm NP}}{\sqrt{C_{NP}}} \sim 10^4\,{\rm GeV}$$

- A double insertion of the NP ΔC=1 operator generates a ΔC=2 transition with amplitude

$$\left(\frac{C_{\rm NP}}{M_{\rm NP}^2}\right)^2 \frac{\Lambda^2}{16\pi^2} \sim 10^{-19}\Lambda^2\,{\rm GeV}^{-4}$$

- The bound from CPV in D mixing requires

$$10^{-19}\Lambda^2{\rm GeV}^{-4} \leq 10^{-14}\,{\rm GeV}^{-2} \implies \Lambda \leq 200\,{\rm GeV}$$

MOVING FORWARD FROM ΔA_{CP}: THEORY

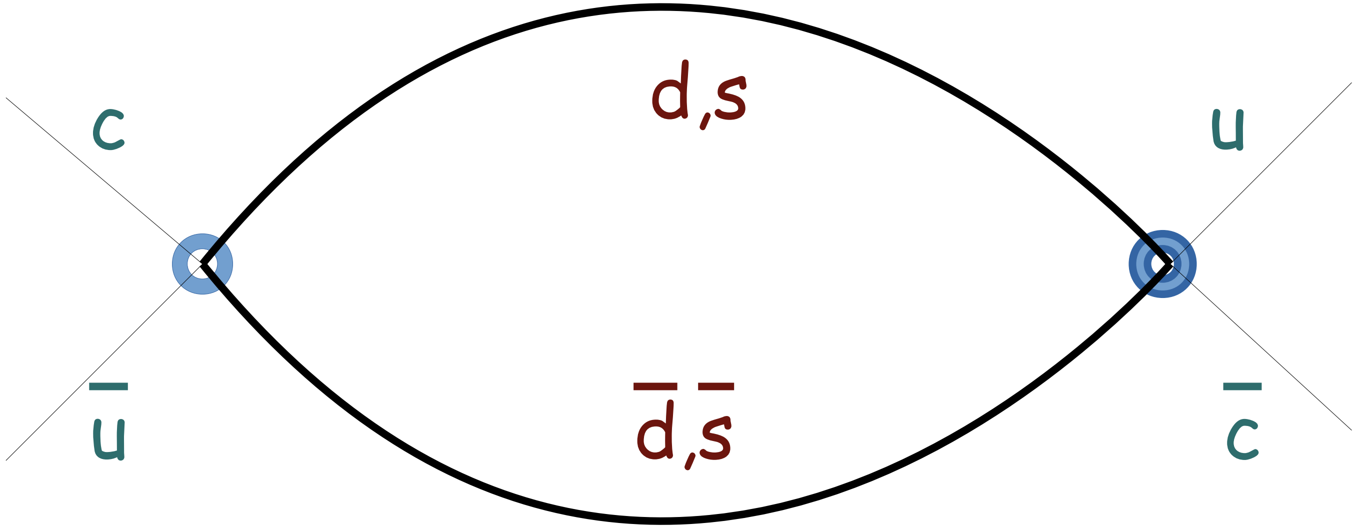
- LHCb obtained a fantastic observation of ΔA_{CP} in the ballpark of the SM expectation
- Not yet clear which theory approach can do best; most promising ones imho:
  - assume FSI dominance + dynamical info on rescattering
  - assume SU(3) + hierarchy in SU(3)-breaking
  - get some dynamical info from LQCD

MOVING FORWARD FROM ΔA_{CP}: EXPERIMENT

- All SCS channels give precious information:
  - on SU(3) breaking
  - on FSI and strong dynamics
- individual $A_{CP}(\pi^+\pi^-)$, $A_{CP}(K^+K^-)$ and $A_{CP}(K_SK_S)$ crucial
- all PP, PV and VV relevant for phenomenological description of CPV in mixing

$D-\bar{D}$ MIXING

- D mixing is described by the T-product of two $\Delta C=1$ Hamiltonians:



D-$\bar{D}$ MIXING

- Dispersive D-$\bar{D}$ amplitude M_{12} (off-shell intermediate states):
  - SM: long-distance dominated, not calculable
  - NP: short-distance, calculable on the lattice
- Absorptive D-$\bar{D}$ amplitude Γ_{12} (on-shell intermediate states):
  - SM: long-distance, not calculable
  - NP: negligible
- Observables: M_{12}, Γ_{12}, $\Phi_{12}=\arg(\Gamma_{12}/M_{12})$

Discussion based on Grossman, Kagan, Ligeti, Perez, Petrov & LS, arXiv:19xx.xxxxx

APPROXIMATE UNIVERSALITY

- CPV effects in $\Delta C=2$ amplitudes enhanced by $1/\varepsilon$ (factor of 3-5)
- No enhancement expected (confirmed by ΔA_{CP}) for CPV in $\Delta C=1$ amplitudes
- Work at leading order in r_{CKM}/ε: take all decay amplitudes real, but allow for CPV in $\Delta C=2$, with SM~1/8° plus NP in M_{12} only

APPROXIMATE UNIVERSALITY

- Working at linear order in r_{CKM}/ϵ, two different sources of CPV arise:
  - "dispersive CPV", measured by $\Phi_M = \arg(M_{12})$, sensitive to NP in $\Delta C=2$;
  - "absorptive CPV", measured by $\Phi_\Gamma = \arg(\Gamma_{12})$, sensitive to CPV in decay amplitudes thanks to the U-spin enhancement;
- Can we disentangle the two phases? Can we test approximate universality?

UNIVERSALITY AT WORK

- Define $|D_{S,L}| = p|D^0| \pm q|D^0|$, $\delta_{CP} = (1-|q/p|^2)/(1+|q/p|^2)$, $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$
- For small CP violation ($\delta_{CP} \ll 1$) one has
  - $\Delta m \sim 2|M_{12}|$
  - $\Delta\Gamma \sim 2|\Gamma_{12}|$
  - $\delta_{CP} \sim xy/(x^2 + y^2) \sin \Phi_{12}$

UNIVERSALITY AT WORK

- For D^0 decays to a CP eigenstate final state f, "direct" and "mixed" amplitudes interfere: relevant parameter is $\lambda_f = q/p\ \bar{A}_f/A_f$
- Introduce final-state dependent $\phi_f=\arg(\lambda_f)=\arg(q/p\ \bar{A}_f/A_f)$
- Taking all decay amplitudes real, $\phi_f=\phi=\arg(q/p)$

UNIVERSALITY AT WORK

- At zeroth order in r_{CKM}/ϵ, one has $\Phi_\Gamma=0$, $\Phi_{12}=\arg(\Gamma_{12}/M_{12})=-\Phi_M$, $\phi_f=\phi=\arg(q/p)$
- The relation $\Phi_\Gamma+\phi=\arg(y+i\delta_{CP}x)$ becomes $\phi=\arg(y+i\delta_{CP}x)$: everything depends on x, y and δ_{CP} only
- Perform a universal fit for x,y and $|q/p|$, or equivalently for $|M_{12}|$, $|\Gamma_{12}|$ and Φ_{12}

Cluchini et al '07
Kagan, Sokoloff '09

CURRENT FIT RESULTS w. UNIVERSALITY

- Combine all available experimental data assuming no CPV in decay amplitudes. For decays to CP eigenstates one has

$$\begin{aligned} \Gamma(D^0(t) \to f) &\propto \exp[-\hat{\Gamma}_{D^0\to f}\; t] & \hat{\Gamma}_{D^0\to f} &= \Gamma_D[1+\eta_f^{\rm CP}\;|q/p|\,(y\cos\phi - x\sin\phi)] \\ \Gamma(\overline{D^0}(t) \to f) &\propto \exp[-\hat{\Gamma}_{\overline{D^0}\to f}\; t] & \hat{\Gamma}_{\overline{D^0}\to f} &= \Gamma_D[1+\eta_f^{\rm CP}\;|p/q|\,(y\cos\phi + x\sin\phi)] \end{aligned}$$

$$A_\Gamma = \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\frac{y}{2}\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\frac{x}{2}\sin\phi$$

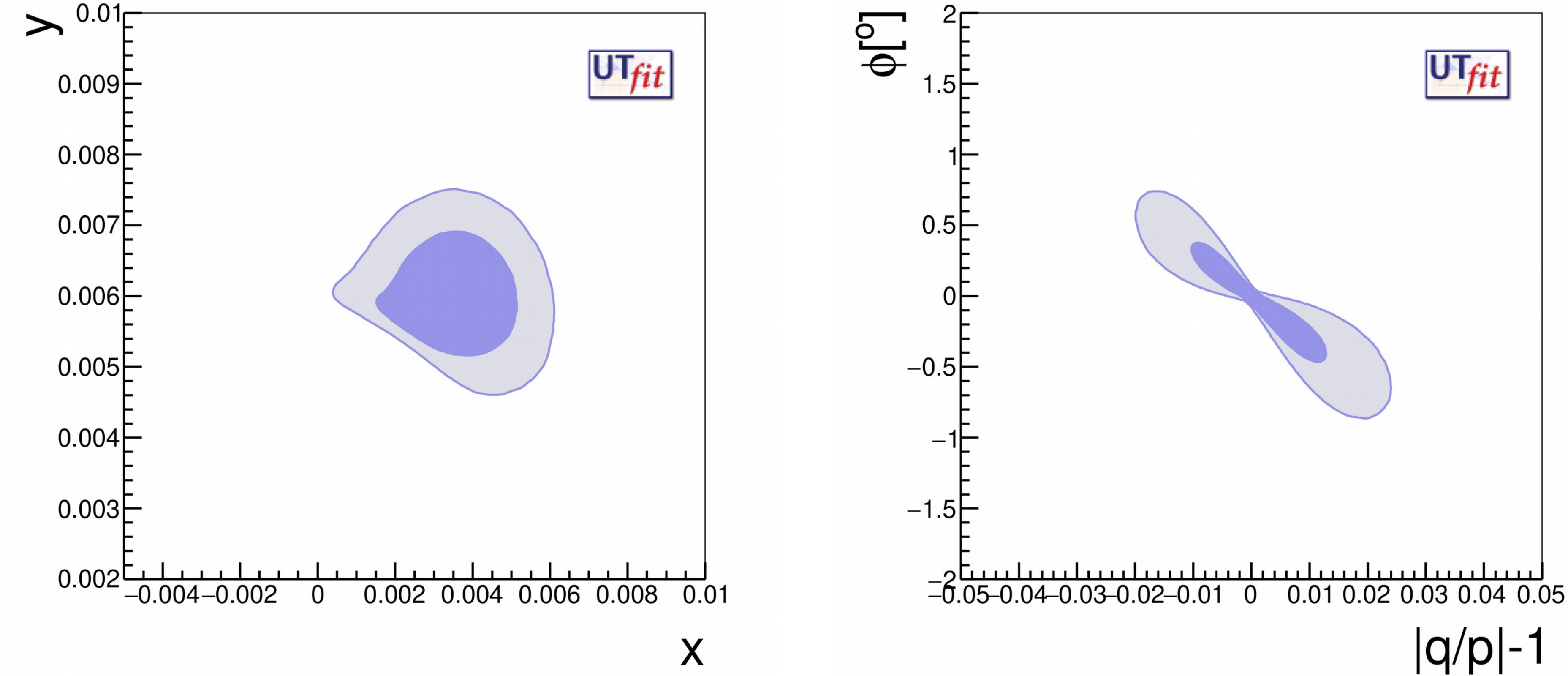
- New LHCb result presented at FPCP last week:

$$A_\Gamma(K^+K^- + \pi^+\pi^-,\ 2011\text{–}2016) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}$$

CURRENT FIT RESULTS w. UNIVERSALITY

- Combine all available experimental data assuming no CPV in decay amplitudes:
  - y_{CP} and A_Γ world average
  - $D^0 \to K_s\pi\pi$ from BaBar, Belle and LHCb
  - CLEO-c quantum correlated $D\to K\pi$
  - $D\to K\pi$ from BaBar, Belle, CDF and LHCb
  - $D\to K\pi\pi\pi$ from LHCb

CURRENT FIT RESULTS w. UNIVERSALITY



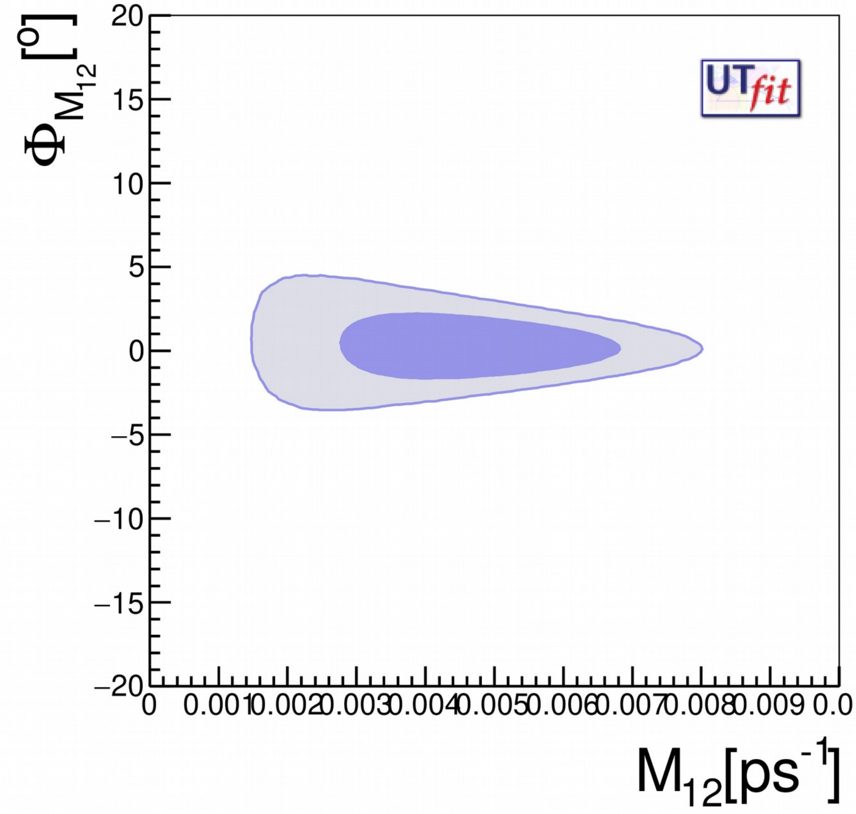
$x = (3.6 \pm 1.1)\ 10^{-3}$, $y = (6.02 \pm 0.57)\ 10^{-3}$,

$\phi = (-0.06 \pm 0.30)°$, $|q/p|-1 = (2 \pm 9)\ 10^{-3}$

CURRENT FIT RESULTS w. UNIVERSALITY

$M_{12} = (4.4 \pm 1.4)\ 10^{-3}\ ps^{-1}$

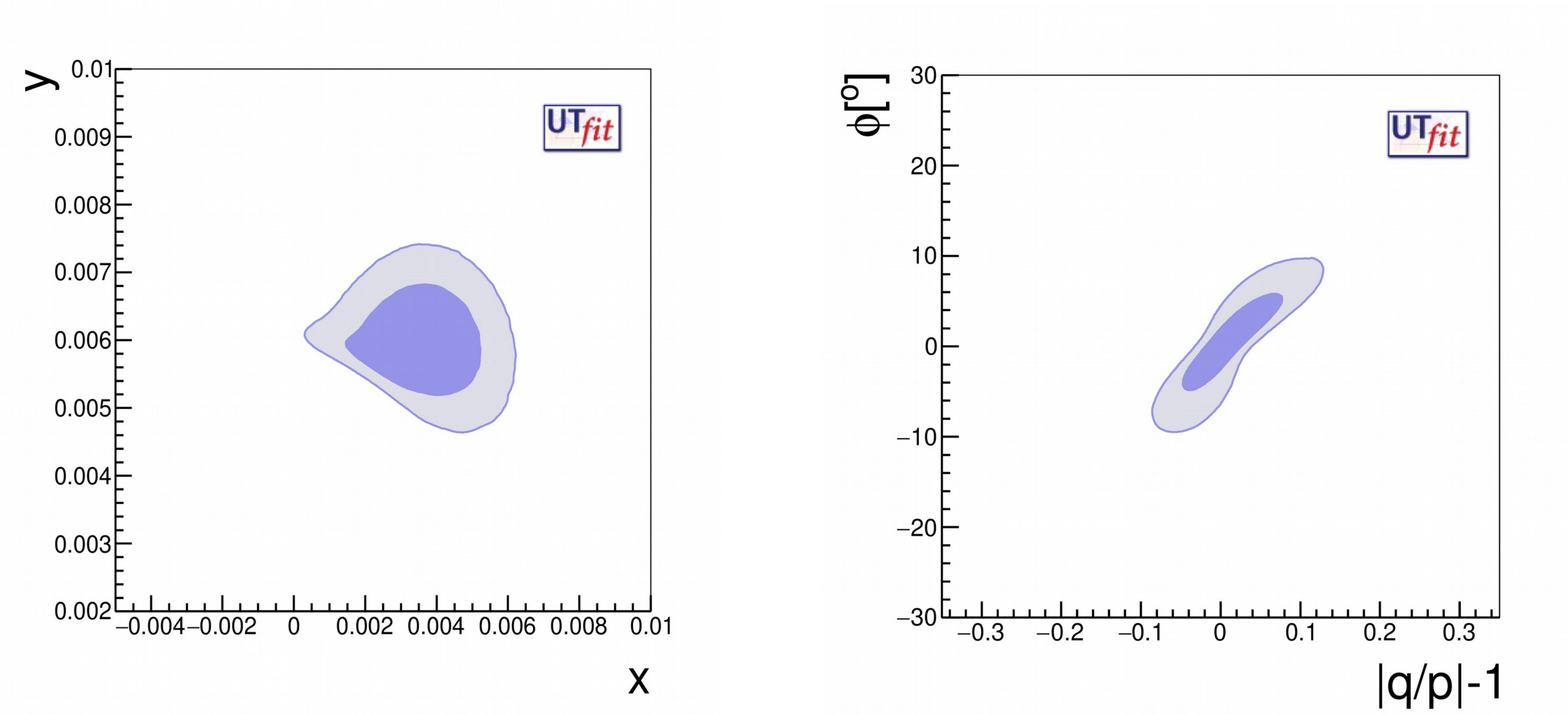
$\phi_{12} = (0.2 \pm 1.3)^\circ$



APPROXIMATE UNIVERSALITY AT WORK

- At linear order in r_{CKM}/ϵ, one has $\Phi_\Gamma \neq 0$, $\Phi_{12} = \arg(\Gamma_{12}/M_{12}) = \Phi_\Gamma - \Phi_M$, but still $\phi_f = \phi = \arg(q/p)$
- Clever piece of work by A. Di Canto et al. : define and measure CP-averaged x_{CP}, y_{CP} and CP-violating differences Δx and $\Delta y = A_\Gamma$
- At this order,
  - $\Delta x \propto |\Gamma_{12}| \sin \Phi_\Gamma$, $\Delta y = A_\Gamma \propto |M_{12}| \sin \Phi_M$

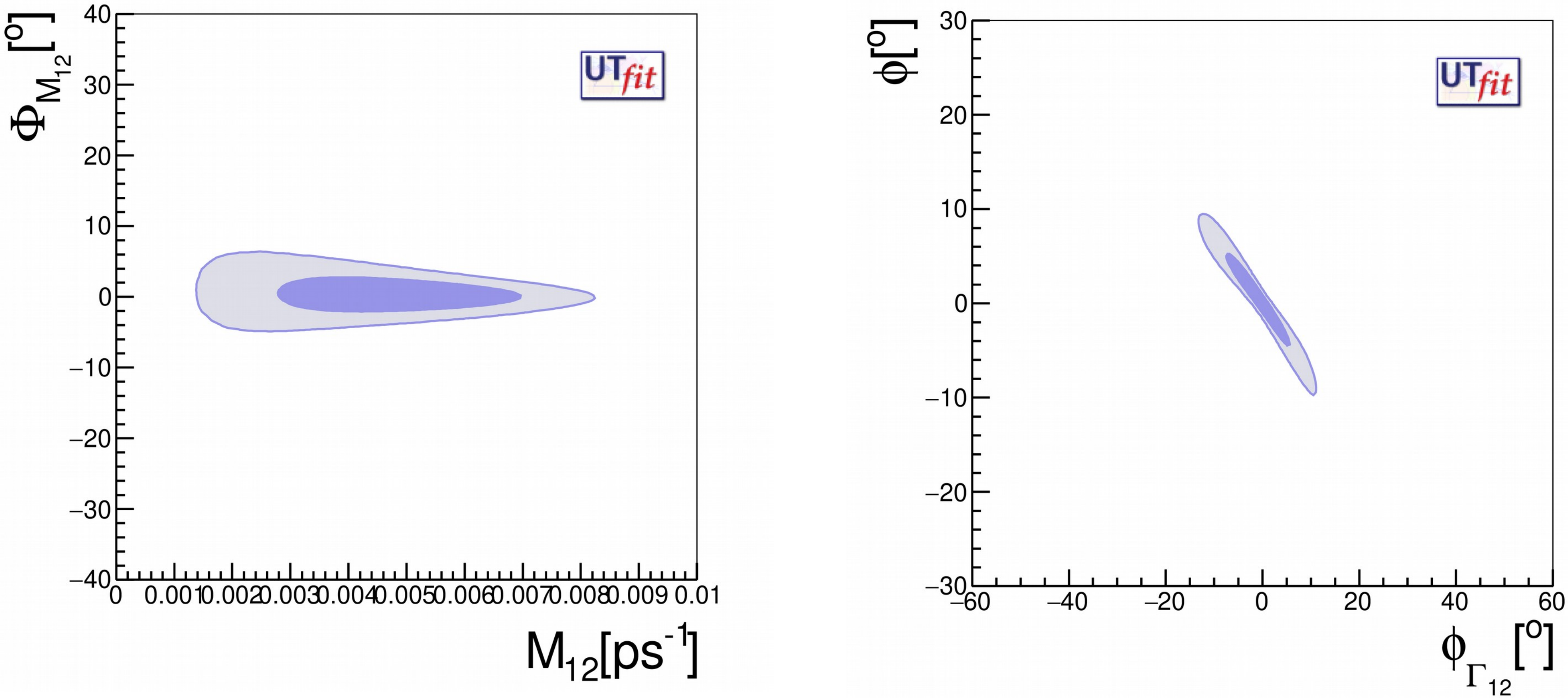
CURRENT FIT RESULTS w. APPROXIMATE UNIVERSALITY



$x = (3.7 \pm 1.1)\ 10^{-3}$, $y = (6.0 \pm 0.5)\ 10^{-3}$,

$\phi = (0.8 \pm 3.9)^\circ$, $|q/p|-1 = (0.9 \pm 3.9)\ 10^{-2}$

CURRENT FIT RESULTS w. APPROXIMATE UNIVERSALITY



$\phi_M = (0.2 \pm 1.6)^\circ$ to compare w. $\phi_{12} = (0.2 \pm 1.3)^\circ$

$\phi_\Gamma = (-1.0 \pm 5.3)^\circ$ for $\phi_\Gamma = 0$

CURRENT FIT RESULTS w. APPROXIMATE UNIVERSALITY

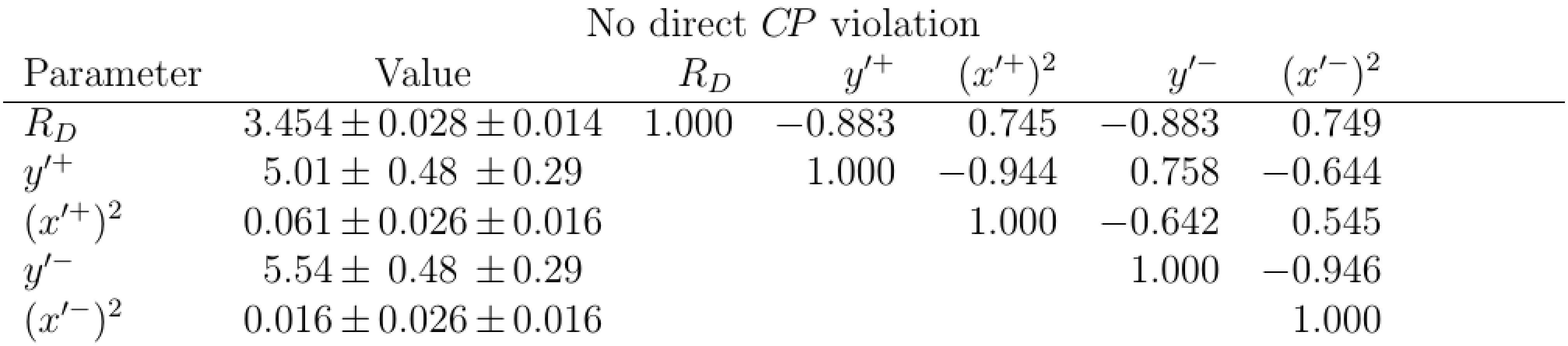
- Remarkable improvement: stringent constraints on the NP-sensitive Φ_M even when allowing for nonvanishing Φ_Γ!!
- We are now ready to switch to approximate universality!
- What will be the impact of LHCb upgrade II?

ASSESSING THE IMPACT OF LHCb UPGRADE II

- Consider foreseen experimental improvements
- Determine global sensitivity to CPV parameters Φ_M and Φ_Γ

EXP. INPUTS: D→Kπ

- LHCb analysis for no direct CPV scaled by luminosity, correlation matrix kept fixed:



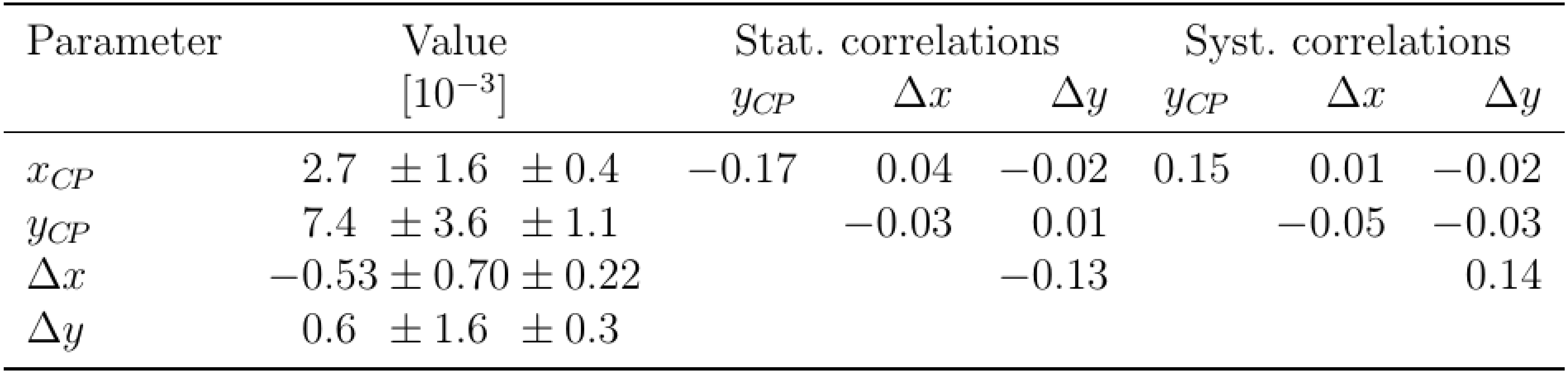
No direct CP violation

Parameter	Value	R_D	y'^+	$(x'^+)^2$	y'^-	$(x'^-)^2$
R_D	$3.454 \pm 0.028 \pm 0.014$	1.000	−0.883	0.745	−0.883	0.749
y'^+	$5.01 \pm 0.48 \pm 0.29$		1.000	−0.944	0.758	−0.644
$(x'^+)^2$	$0.061 \pm 0.026 \pm 0.016$			1.000	−0.642	0.545
y'^-	$5.54 \pm 0.48 \pm 0.29$				1.000	−0.946
$(x'^-)^2$	$0.016 \pm 0.026 \pm 0.016$					1.000

Phys. Rev. D97 (2018) 031101

EXP. INPUTS: $D \to K_S \pi\pi$

- Latest LHCb result scaled by luminosity, correlation matrix kept fixed (statistical errors only)

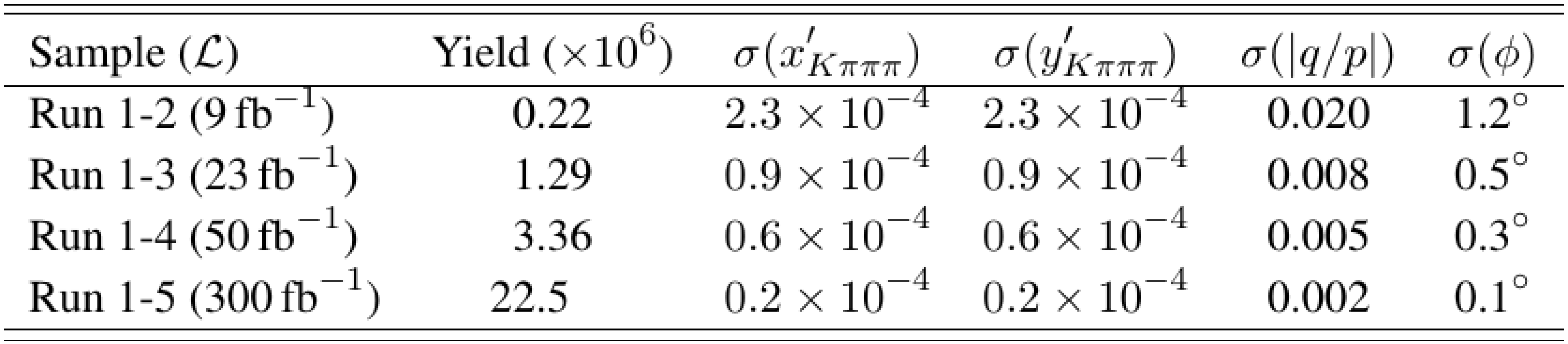


Parameter	Value $[10^{-3}]$	Stat. correlations y_{CP}	Stat. correlations Δx	Stat. correlations Δy	Syst. correlations y_{CP}	Syst. correlations Δx	Syst. correlations Δy
x_{CP}	$2.7 \pm 1.6 \pm 0.4$	-0.17	0.04	-0.02	0.15	0.01	-0.02
y_{CP}	$7.4 \pm 3.6 \pm 1.1$		-0.03	0.01		-0.05	-0.03
Δx	$-0.53 \pm 0.70 \pm 0.22$			-0.13			0.14
Δy	$0.6 \pm 1.6 \pm 0.3$						

arXiv:1903.03074

EXP. INPUTS: D→Kπππ

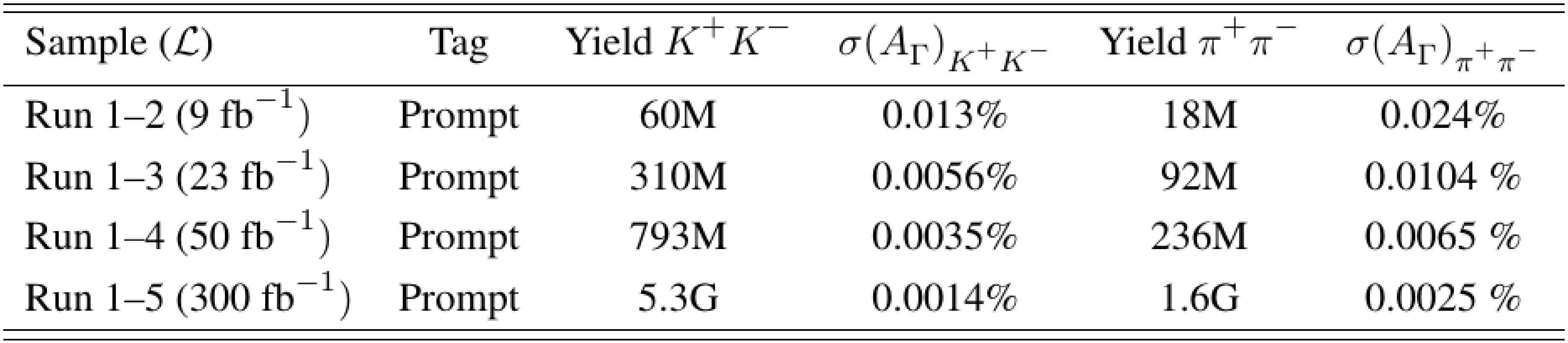
- Expected uncertainties from HL YR, correlation matrix invented due to lack of information (i.e. taken from CPV-allowed Belle $K_S\pi\pi$)



Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'_{K\pi\pi\pi})$	$\sigma(y'_{K\pi\pi\pi})$	$\sigma(\|q/p\|)$	$\sigma(\phi)$
Run 1-2 (9 fb^{-1})	0.22	2.3×10^{-4}	2.3×10^{-4}	0.020	1.2°
Run 1-3 (23 fb^{-1})	1.29	0.9×10^{-4}	0.9×10^{-4}	0.008	0.5°
Run 1-4 (50 fb^{-1})	3.36	0.6×10^{-4}	0.6×10^{-4}	0.005	0.3°
Run 1-5 (300 fb^{-1})	22.5	0.2×10^{-4}	0.2×10^{-4}	0.002	0.1°

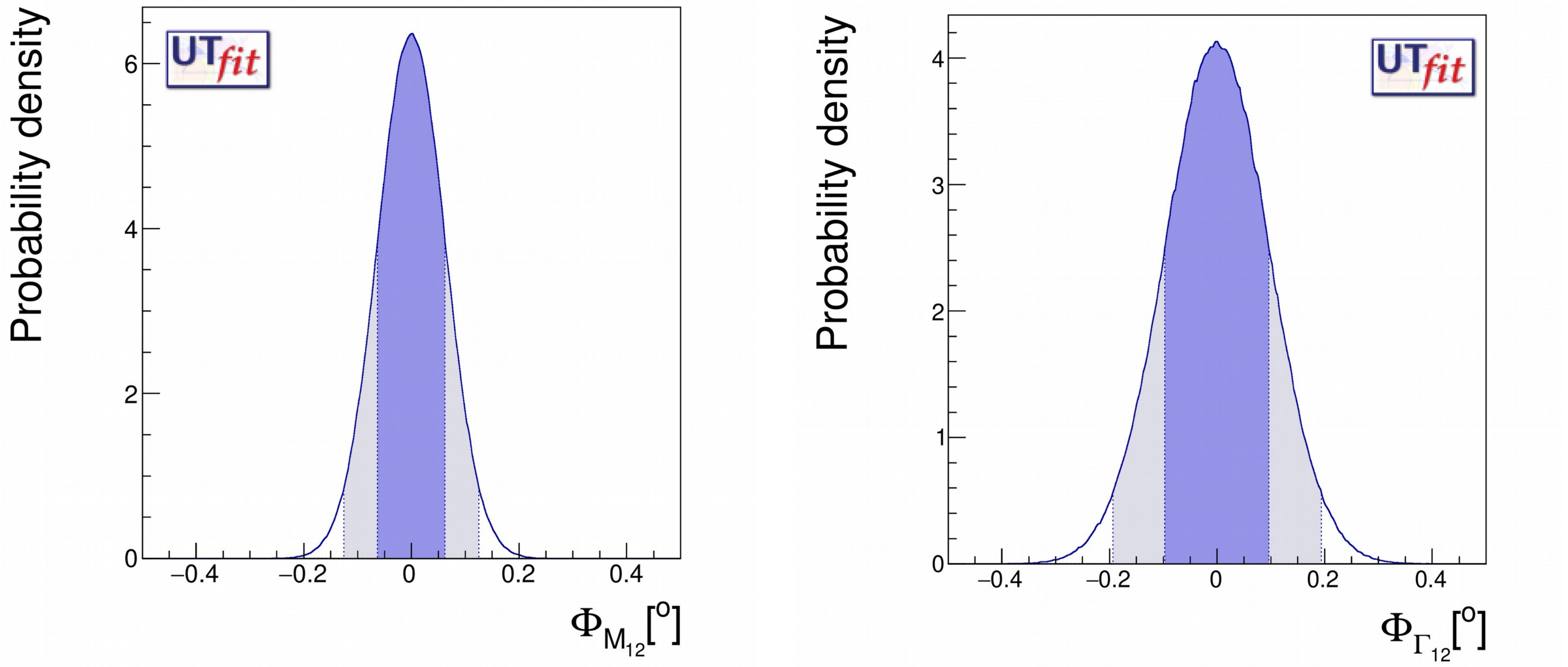
EXP. INPUTS: A_Γ

- Taken from HL YR:



Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)_{K^+K^-}$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)_{\pi^+\pi^-}$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

RESULTS FOR $\Phi_M=\Phi_\Gamma=0$



$\phi_M = (0.00 \pm 0.06)^\circ$, $\phi_\Gamma = (0.0 \pm 0.1)^\circ$

IMPACT OF INDIVIDUAL MEASUREMENTS

- All measurements:
  - $\delta(\phi_M) = 0.06°$, $\delta(\phi_\Gamma) = 0.1°$, $\delta(x) = 1.7\ 10^{-5}$, $\delta(y) = 1.9\ 10^{-5}$
- No $K_S\pi\pi$:
  - $\delta(\phi_M) = 0.06°$, $\delta(\phi_\Gamma) = 0.12°$, $\delta(x) = 2\ 10^{-5}$, $\delta(y) = 1.9\ 10^{-5}$
- No $K\pi\pi\pi$:
  - $\delta(\phi_M) = 0.07°$, $\delta(\phi_\Gamma) = 0.16°$, $\delta(x) = 3.7\ 10^{-5}$, $\delta(y) = 5.5\ 10^{-5}$

SUMMARY OF MIXING PROJECTIONS

- Successfully reconstruct the input value with $\delta\Phi_M = 0.06°$ and $\delta\Phi_\Gamma = 0.1°$
- LHCb Upgrade II will probe up to, and hopefully even into, the SM expectation!
- More than one order of magnitude for NP to show up in Φ_M!

CONCLUSIONS

- Amazing experimental progress in charm CPV recently achieved by LHCb:
  - observation of direct CPV in ΔA_{CP}, in the ballpark of the SM
  - improvements in the D mixing fit, now starting to be viable also with approximate universality

OUTLOOK

- Very bright prospects for LHCb Upgrade II:
  - at least one order of magnitude of NP contributions to CPV in mixing to be explored
  - SM order of magnitude in Φ_M and Φ_Γ within reach!
  - very nice interplay with measurements of direct CP violation:
    - check of SM estimates for Φ_Γ
    - very useful test of our understanding of D decay matrix elements

OUTLOOK II

- I'm sure that as always LHCb will do better than the most optimistic expectations
- Will be definitely difficult to keep the pace from the theory point of view
- With more data available, hopefully new ideas will allow us to find even more stringent tests of NP