γ angle measurement in $B^{\pm} \to D^0(\to K_s^0\pi^+\pi^-\pi^0)h^{\pm}$ decays using BPGGSZ method, at LHCb

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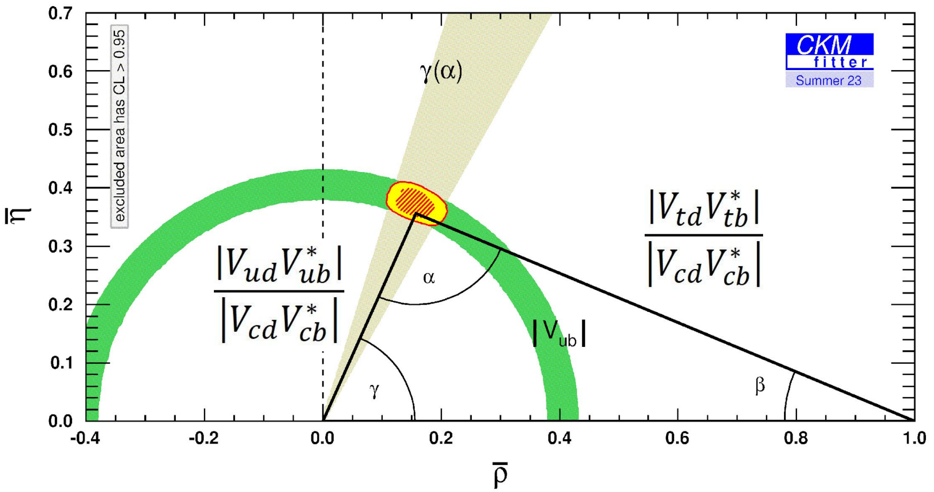
Université Clermont-Auvergne, LPC

GDR-Inf Annual Workshop

Cabourg - 06-08 November 2024

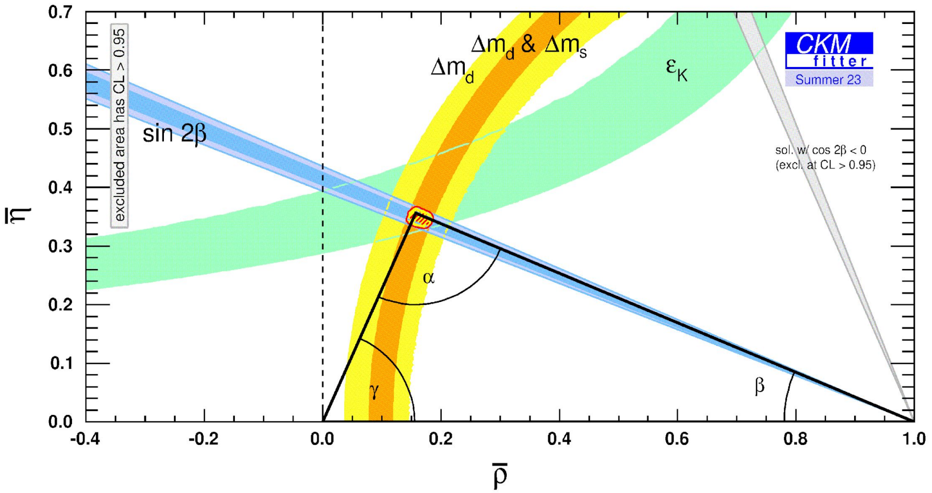
Introduction



Tree-level only (direct measurement):

$\gamma = (64.6 \pm 2.8)^\circ$ (LHCb)

LHCb-CONF-2024-004



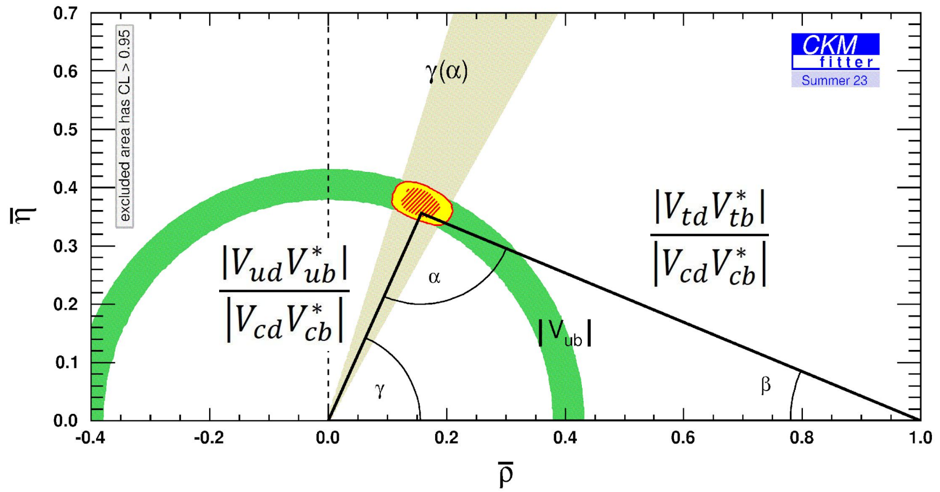
Loop-level only (indirect measurement):

$\gamma = (66.29^{+0.72}_{-1.86})^\circ$ (CKMfitter)

- Direct γ measurements at tree levels is a "standard-candle" for SM ->Statistically limited
- To be compared with indirect measurements (with potential new physics in loop level) -> Possible BSM sensitivity in case of discrepancy
- A 1° precision on direct measurements -> Test the global validity of CKM formalism up to at least 17 TeV Phys.Rev.D 89 (2014) 3, 033016

$$\gamma \equiv arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}) \equiv arg(\bar{\rho} + i\bar{\eta})$$ = CKM Matrix complex phase = **The parameter to access CPV !**

Introduction



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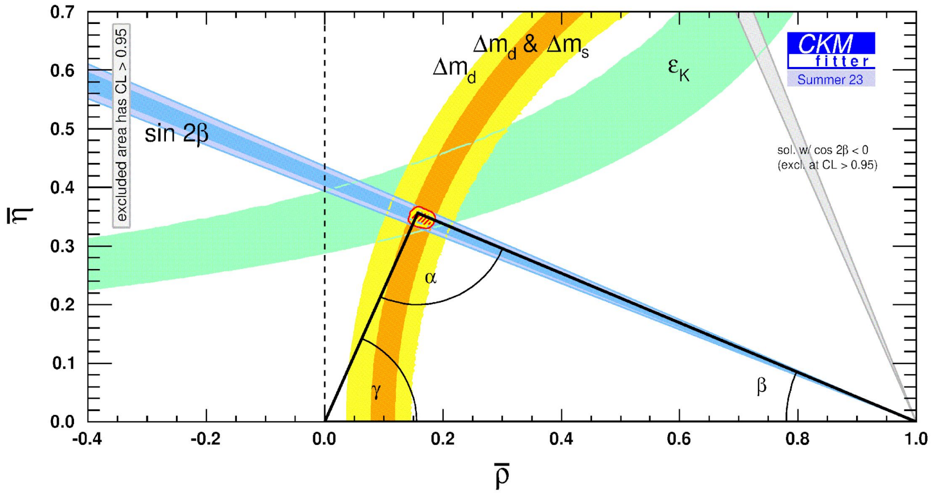

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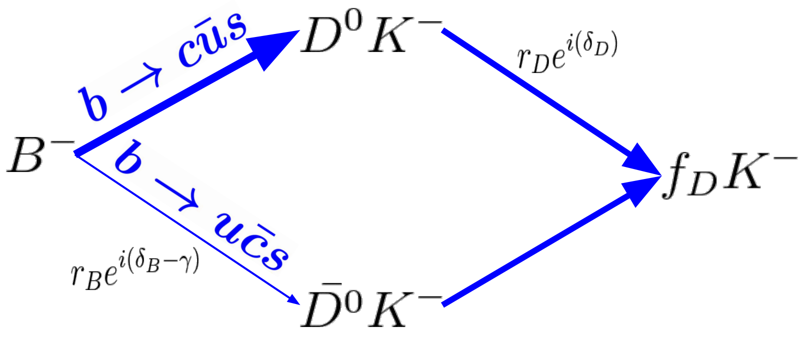
- Directly measurable in interference between $b \to u\bar{c}s$ and $b \to c\bar{u}s$ processes (golden channel is $B^\pm \to D^0 K^\pm$).



$$r_B^{DK} = (9.72^{+0.22}_{-0.21})\%$$

Generalized BPGGSZ formalism

γ measurement depends on $\Delta\delta_D$, the strong phase difference between $D^0 \to f\ (\delta_D)$ and $\bar{D}^0 \to f\ (\delta_{\bar{D}})$

Varies on Phase-Space of the 4-body decay $D^0 \to K_s^0\pi^+\pi^-\pi^0$

Similar method to the one in JHEP 01 (2019) 82 (Belle, from Resmi P.K thesis)

-> Binned map of strong phase from JHEP 10 (2018) 178 (Resmi P.K, J. Libby, S. Malde, & G. Wilkinson-CLEO-c)
(with 0.82fb^{-1} $\Psi(3770)$ dataset)

Exclusively defined

Bin	Bin region	m_L (GeV/c^2)	m_U (GeV/c^2)
1	$m_{\pi^+\pi^-\pi^0} \approx m_\omega$	0.762	0.802
2	$m_{K_S^0\pi^-} \approx m_{K^{*-}}$ &	0.790	0.994
	$m_{\pi^+\pi^0} \approx m_{\rho^+}$	0.610	0.960
3	$m_{K_S^0\pi^+} \approx m_{K^{*+}}$ &	0.790	0.994
	$m_{\pi^-\pi^0} \approx m_{\rho^-}$	0.610	0.960
4	$m_{K_S^0\pi^-} \approx m_{K^{*-}}$	0.790	0.994
5	$m_{K_S^0\pi^+} \approx m_{K^{*+}}$	0.790	0.994
6	$m_{K_S^0\pi^0} \approx m_{K^{*0}}$	0.790	0.994
7	$m_{\pi^+\pi^0} \approx m_{\rho^+}$	0.610	0.960
8	$m_{\pi^-\pi^0} \approx m_{\rho^-}$	0.610	0.960
9	Remainder	-	-

Generalized BPGGSZ formalism

One can then deduce $N_i^{\pm}$, the measured yields (cf paper LHCb-PAPER-2020-019):

- $F_i = \frac{\int_{\mathcal{D}_i} P\eta d\mathcal{D}}{\sum_j \int_{\mathcal{D}_j} P\eta d\mathcal{D}}$ are fractions of $D^0/\bar{D}^0$ in bin i (η = efficiency at a given point in phase-space $\mathcal{D}$)
- $f\pm$ is a normalisation factor
- $r_B = \frac{|A_{B\to \bar{D}^0 K}|}{|A_{B\to D^0 K}|}$ ← **Drives statistical precision on γ**
- $c_i = \frac{\int_{\mathcal{D}_i} |A||\bar{A}| C d\mathcal{D}}{\sqrt{\int_{\mathcal{D}_i} |A|^2 d\mathcal{D} \int_{\mathcal{D}_i} |\bar{A}|^2 d\mathcal{D}}}$ ← $C = cos(\Delta\delta_D)$, $S = sin(\Delta\delta_D)$
- $x_\pm = r_B cos(\delta_B \pm \gamma)$
- $y_\pm = r_B sin(\delta_B \pm \gamma)$

$$\begin{cases} N^-_{i,DK} = f^-_{DK}(F_i + r_B^{DK^2}\overline{F_i} + 2\sqrt{F_i\overline{F_i}}(c_i x_-^{DK} + s_i y_-^{DK})) \\ N^+_{i,DK} = f^+_{DK}(\overline{F_i} + r_B^{DK^2}F_i + 2\sqrt{F_i\overline{F_i}}(c_i x_+^{DK} - s_i y_+^{DK})) \\ N^-_{i,D\pi} = f^-_{D\pi}(F_i + r_B^{D\pi^2}\overline{F_i} + 2\sqrt{F_i\overline{F_i}}(c_i x_-^{D\pi} + s_i y_-^{D\pi})) \\ N^+_{i,D\pi} = f^+_{D\pi}(\overline{F_i} + r_B^{D\pi^2}F_i + 2\sqrt{F_i\overline{F_i}}(c_i x_+^{D\pi} - s_i y_+^{D\pi})) \end{cases}$$

= "Cartesian coordinates" or "CP-observables"

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$F_i^{DK} = F_i^{D\pi}$ **if**

- $B^{\pm} \to D^0\pi^{\pm}$ and $B^{\pm} \to D^0K^{\pm}$ have a similar selection and efficiency mapping through $\mathcal{D}$
- PID cut efficiency is the same for all of the 9 bins
- 9×9 Migration matrix is similar between $B^{\pm} \to D^0\pi^{\pm}$ and $B^{\pm} \to D^0K^{\pm}$

All those hypothesis have been tested and validated !

Strategy

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➡ **Simultaneous fit on 36 categories :**
- **2 channels**
- **2 charges**
- **9 bins**

➡ c_i and s_i are taken as inputs from CLEO-c paper JHEP 10 (2018) 178

➡ $N_i^{\pm}$ are observables measured in LHCb

➡ $x_{\pm}, y_{\pm}$ **are CP-observables fitted** with the simultaneous fit

➡ F_i & $\bar{F}_i$ are free independent parameters in the simultaneous fit

➡ $r_B^+ = \sqrt{x_+^2 + y_+^2}$, $r_B^- = \sqrt{x_-^2 + y_-^2}$

Note : In principle $r_B^+ \equiv r_B^-$ but left independent in Simultaneous fit

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➡ **Simultaneous fit on 36 categories :**
- 2 channels
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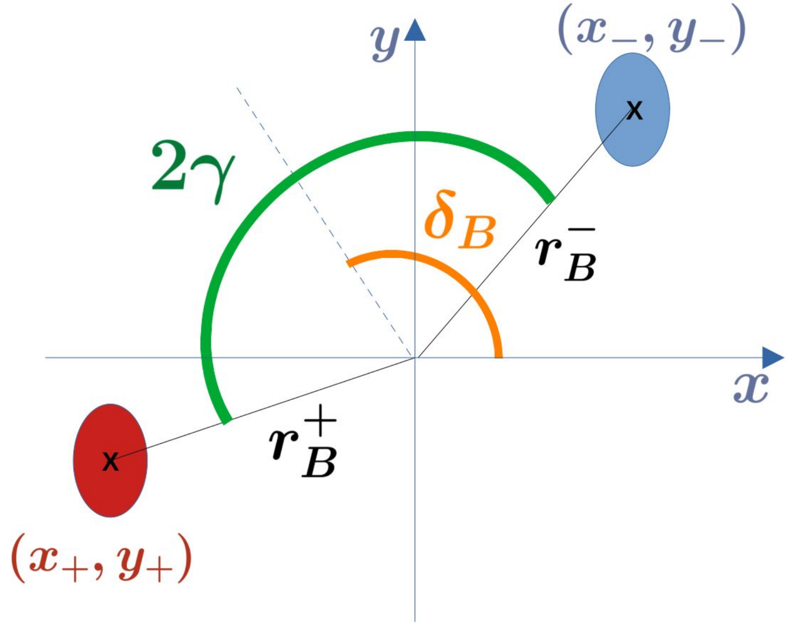
➡ **Extraction of physics parameters from $x_\pm$, $y_\pm$**



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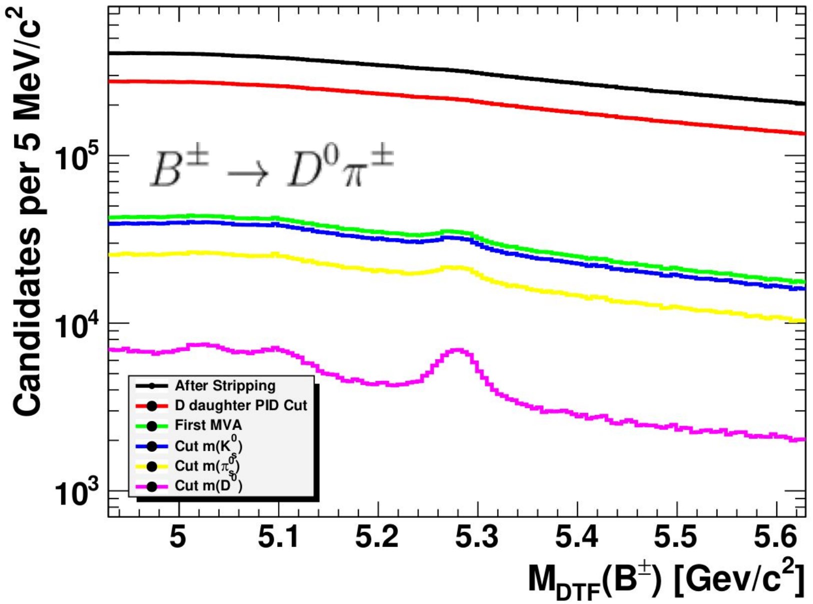
Sketch the selection steps for this measurement

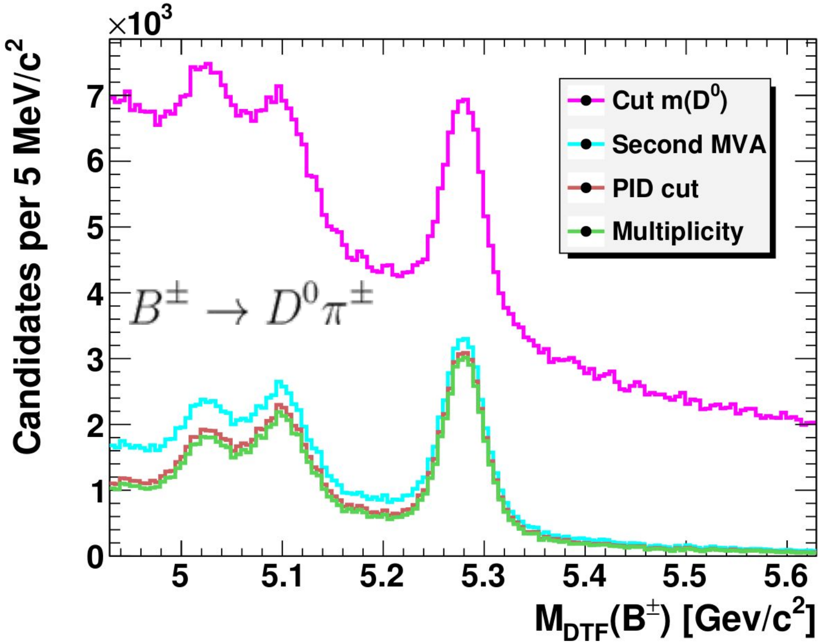
- Use of the **reference mode** $B^{\pm} \to D^0\pi^{\pm}$ that is topologically identical, statistically more interesting and less sensible to CP asymmetry

$$\mathcal{B}(B^{\pm} \to D^0\pi^{\pm}) = (12.67 \pm 0.43) \times \mathcal{B}(B^{\pm} \to D^0K^{\pm}) = (4.61 \pm 0.10) \times 10^{-3}$$

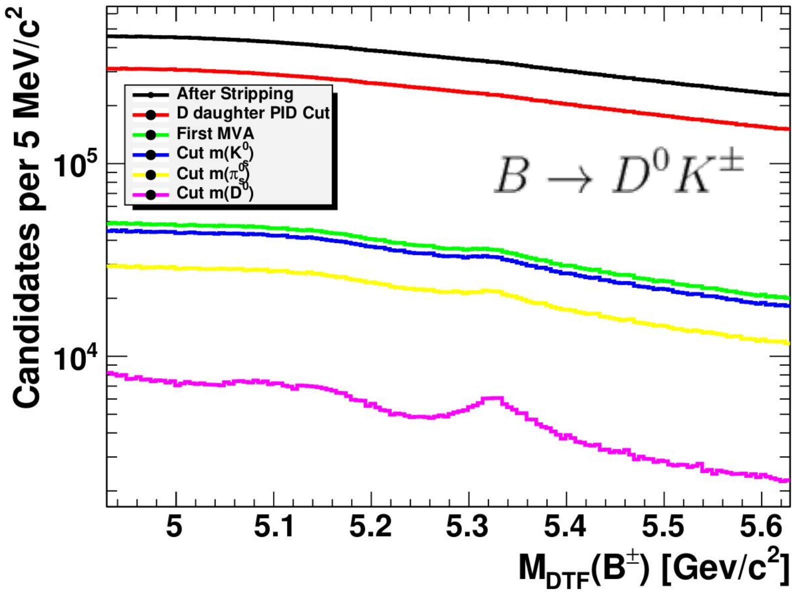
- Selection adapted for Runs 1 vs 2 and for K_S^0DD vs LL
- Selection based on **2 Multivariate-Analysis** and **unidimensional cuts on particle masses** :
  - First MVA : MLP method on geometrical and topological variables from D and its daughters (impact parameters, vertex quality, vertex relative position, photons identification, etc)
  - Unidimensional cuts on K_S^0, π^0 and D^0 masses
  - Second MVA : MLP method on geometrical and topological variables from B decay
- Cut on **PID likelihood** difference to limit bachelor track misID
- Choosing the best candidate in case of multiplicity (mainly due to π^0), thanks to a MVA trained on MC, discriminating true signal events

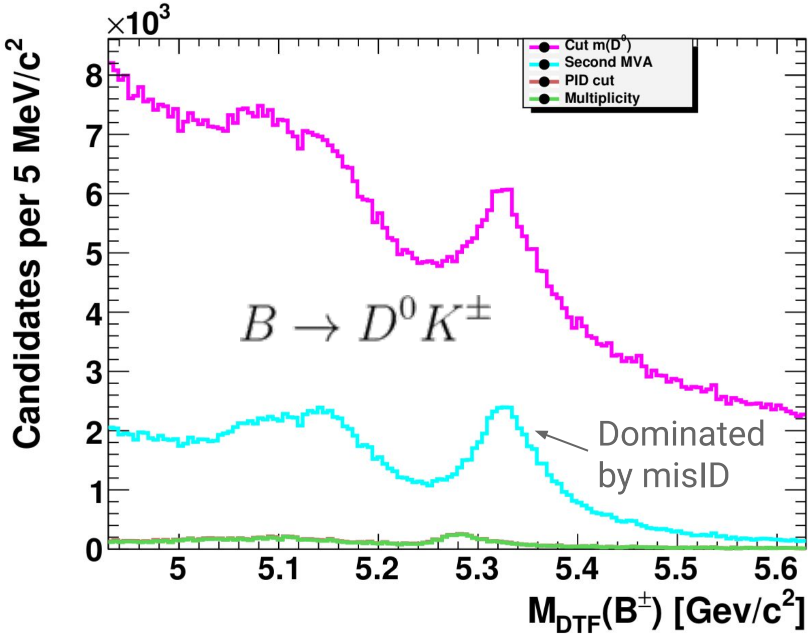
Selection : Summary

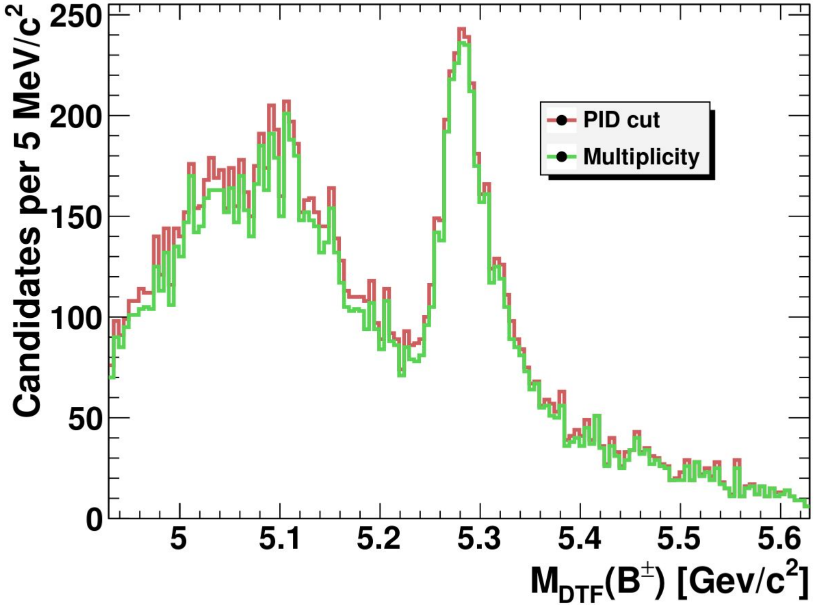




10^3 to 10^4 rejection factor on background







Background Study

A complete study of physical background has been processed, using **full simulation of >20 modes**

Here is a list of studied backgrounds. **Non-negligeable ones are surrounded** for $B^\pm \to D^0\pi^\pm$ and $B \to D^0 K^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\pi^0]\pi^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\gamma]\pi^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\pi^0]K^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\gamma]K^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\pi^0]\rho^\pm(\to \pi^\pm\pi^0)$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\gamma]\rho^\pm(\to \pi^\pm\pi^0)$

$B^\pm \to D^0(\to K_s\pi\pi)\rho^\pm(\to \pi^\pm\pi^0)$

$B^\pm \to D^0(\to K_s\pi\pi)K^{*\pm}(\to K^\pm\pi^0)$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\pi^0]\pi^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\gamma]\pi^\pm$

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$B^0 \to D^{*\pm}[\to D^0(\to K_s\pi\pi\pi^0)\pi^\pm]\pi^\mp$

$B^0 \to D^{*\pm}[\to D^0(\to K_s\pi\pi\pi^0)\pi^\pm]K^\mp$

$B_s^0 \to D^0(\to K_s\pi\pi\pi^0)K^\mp\pi^\pm$

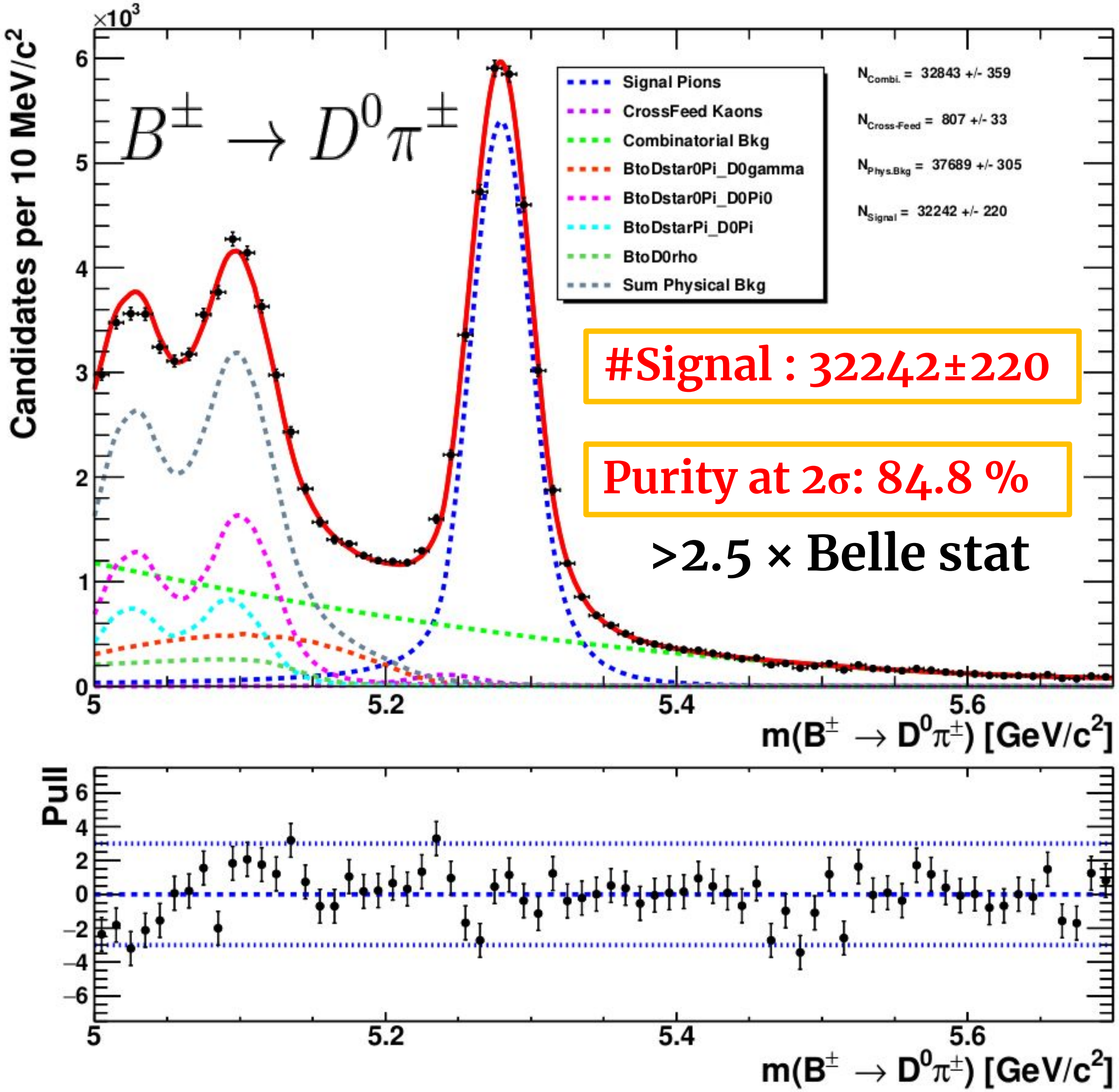
MC produced in Square-Dalitz + **weighted with Laura++** to account for resonances (LHCb amplitude model LHCb-PAPER-2014-036)

No peaking background !

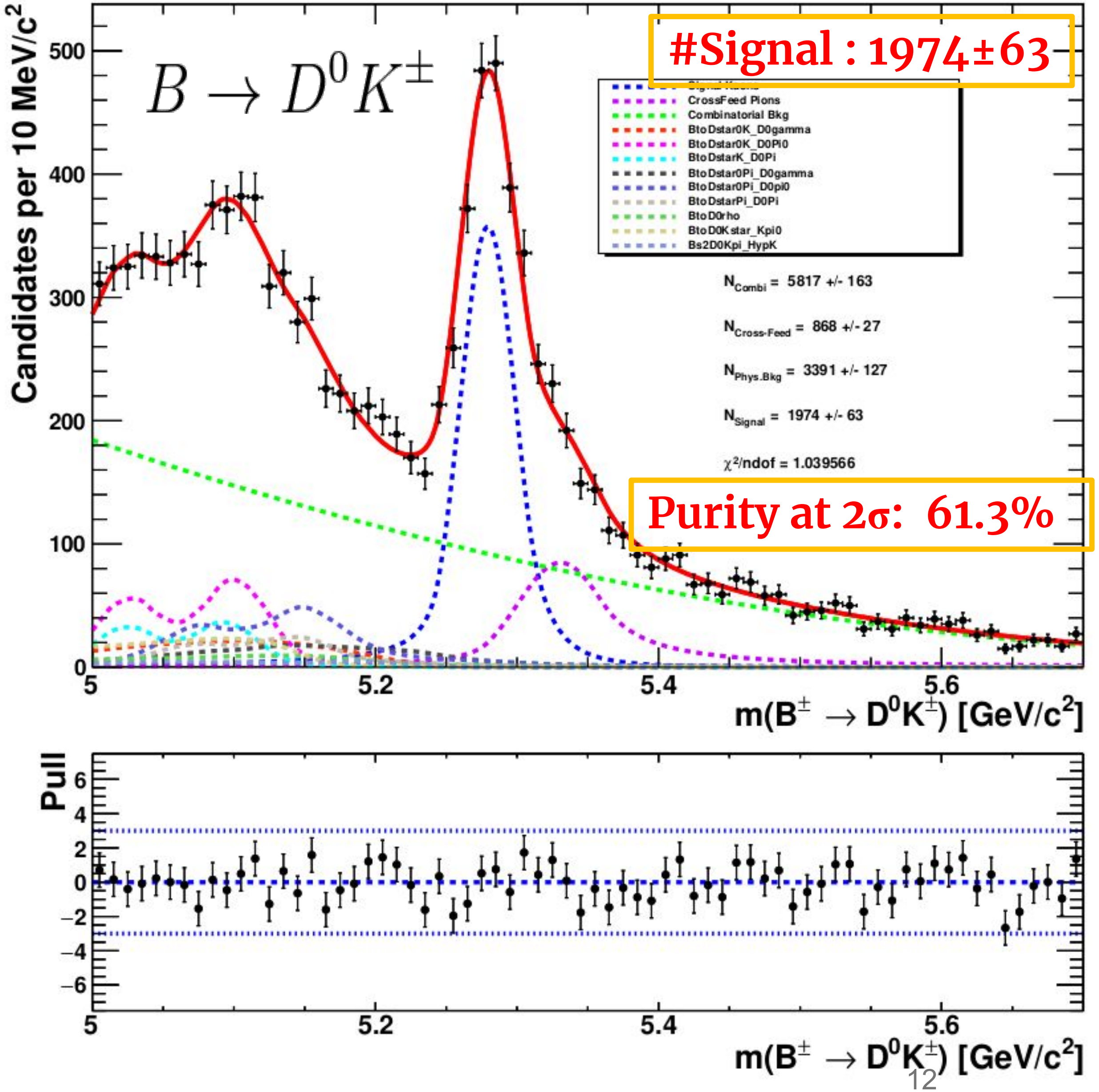
- Additional study has been made in K_S^0 and D^0 sidebands, **limiting impact of K$_s$-less and charm-less backgrounds** to less than 0.66% and 0.15% on the signal respectively at 90% CL.

- Background components are included in global mass fit through parametric PDFs "**RooKeyPDF**" **objects** (after a smearing to adapt MC to DATA signal width)

Global Fit



$B^\pm \to D^0\pi^\pm$
Candidates per 10 MeV/c²
×10³
Signal Pions
CrossFeed Kaons
Combinatorial Bkg
BtoDstar0Pi_D0gamma
BtoDstar0Pi_D0Pi0
BtoDstarPi_D0Pi
BtoD0rho
Sum Physical Bkg
$N_{Combi.}$ = 32843 +/- 359
$N_{Cross-Feed}$ = 807 +/- 33
$N_{Phys.Bkg}$ = 37689 +/- 305
N_{Signal} = 32242 +/- 220
#Signal : 32242±220
Purity at 2σ: 84.8 %
>2.5 × Belle stat
m(B± → D⁰π±) [GeV/c²]
Pull

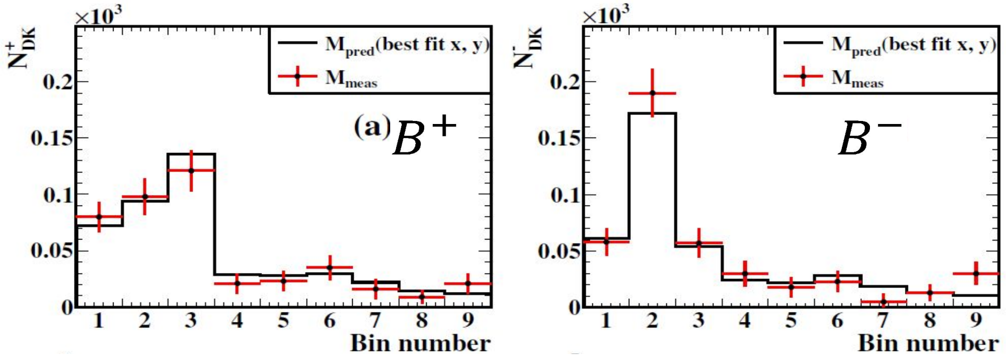


$B \to D^0K^\pm$
Candidates per 10 MeV/c²
#Signal : 1974±63
CrossFeed Pions
Combinatorial Bkg
BtoDstar0K_D0gamma
BtoDstar0K_D0Pi0
BtoDstarK_D0Pi
BtoDstar0Pi_D0gamma
BtoDstar0Pi_D0pi0
BtoDstarPi_D0Pi
BtoD0rho
BtoD0Kstar_Kpi0
Bs2D0Kpi_HypK
N_{Combi} = 5817 +/- 163
$N_{Cross-Feed}$ = 868 +/- 27
$N_{Phys.Bkg}$ = 3391 +/- 127
N_{Signal} = 1974 +/- 63
χ²/ndof = 1.039566
Purity at 2σ: 61.3%
m(B± → D⁰K±) [GeV/c²]
Pull

Run simultaneous unbinned minos CP-fit on DATA (**36 categories**):

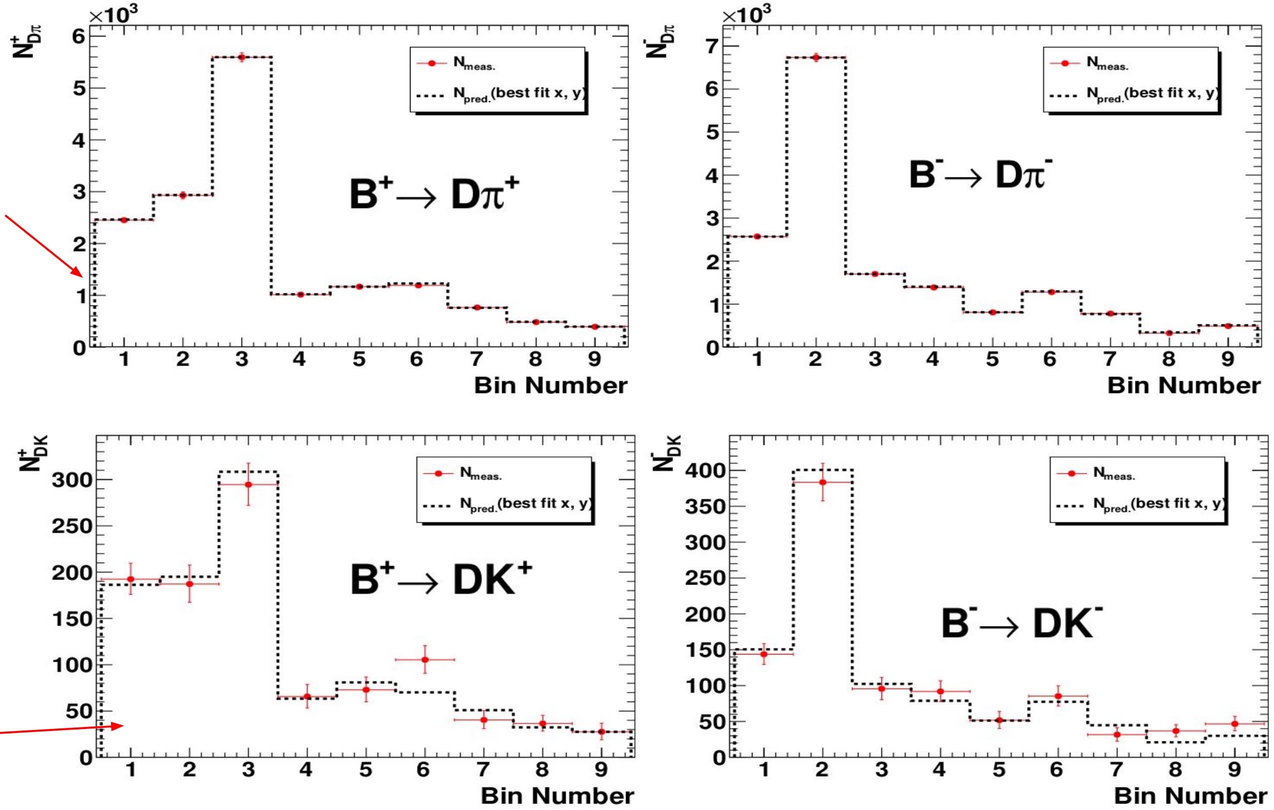
- **All shapes fixed** by global fits (signal, physical and combinatorial backgrounds, cross-feed)
- **Sum of the yields** (integrated over bins) **constrained** to the yields in the global fits
- **For fit stability**, CP-observables $x_\pm^{D\pi}$ and $y_\pm^{D\pi}$ are fixed for $B \to D\pi$ channel, according to LHCb combination (-> systematic uncertainty)
- Consider two separate values for $r_B^{DK,-} = \sqrt{(x_-^{DK})^2 + (y_-^{DK})^2}$ and $r_B^{DK,+} = \sqrt{(x_+^{DK})^2 + (y_+^{DK})^2}$
- **Fit method validated by Toy Study**

Reminder, for BELLE :



$\Sigma = 32242 \pm 220$

$\Sigma = 1974 \pm 63$



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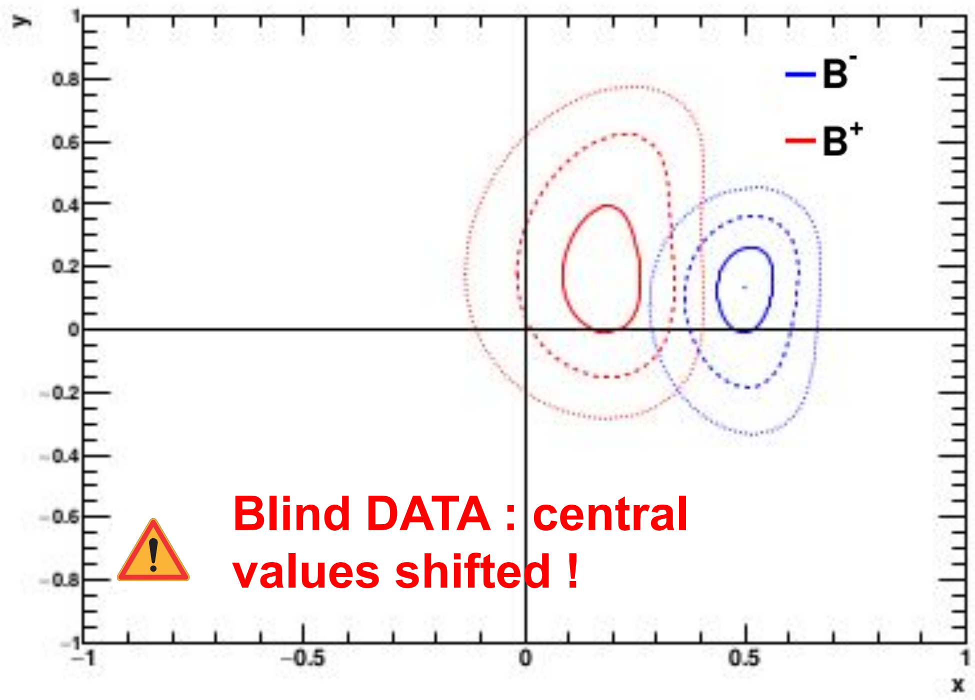


$$x_-^{DK} = XX^{+0.063}_{-0.066}$$
$$y_-^{DK} = XX^{+0.125}_{-0.148}$$
$$x_+^{DK} = XX^{+0.084}_{-0.092}$$
$$y_+^{DK} = XX^{+0.225}_{-0.178}$$

Statistical uncertainty only

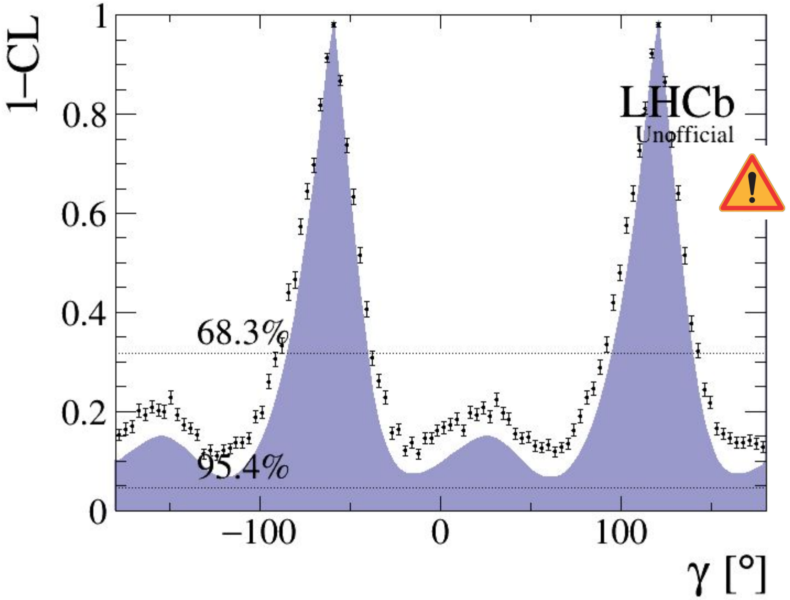
For Comparison, see Belle results:

x_-	y_-	x_+	y_+
0.095 ± 0.121	$0.354^{+0.144}_{-0.197}$	-0.030 ± 0.121	$0.220^{+0.182}_{-0.541}$

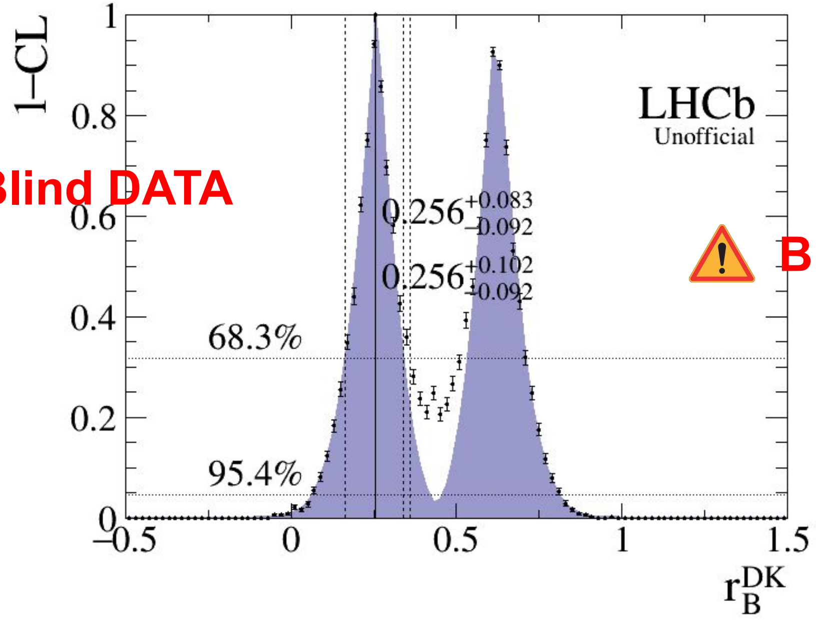
- Interpretation (GammaCombo – Prob and plugin methods)
- Statistical uncertainty only ⚠

Prob = minimization of global χ^2

Plugin = frequency computed on simulated toys (1k toys per value)



⚠ Blind DATA



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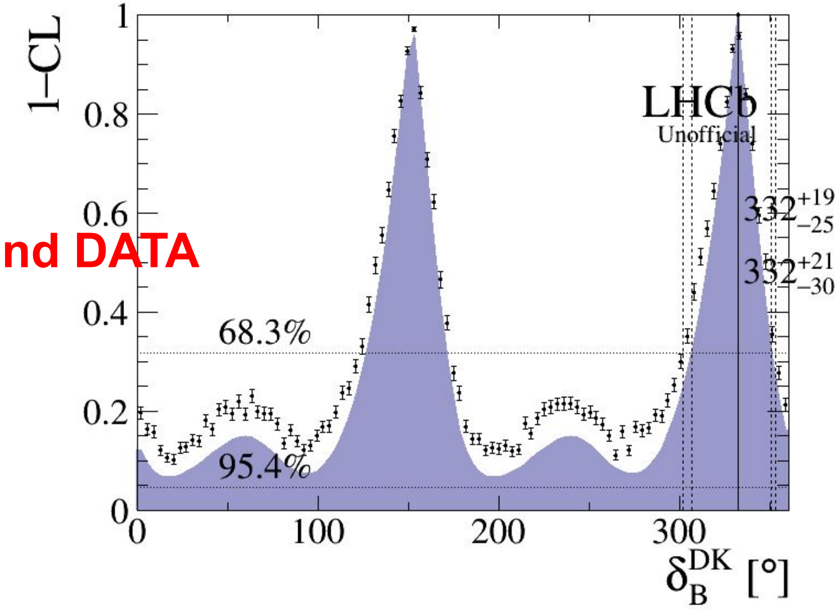


Prob :

$$\gamma = (XX^{+19}_{-25})^\circ$$
$$r_B^{DK} = XX^{+0.083}_{-0.092}$$
$$\delta_B^{DK} = (XX^{+19}_{-25})^\circ$$

Plugin :

$$\gamma = (XX^{+22}_{-30})^\circ$$
$$r_B^{DK} = XX^{+0.102}_{-0.092}$$
$$\delta_B^{DK} = (XX^{+21}_{-30})^\circ$$

- Precision on r_B improved by ~30% wrt Belle (2019)

The latest LHCb combination (Summer 2024) :

Parameter	Value	68.3 % CL Uncertainty	68.3 % CL Interval	95.4 % CL Uncertainty	95.4 % CL Interval
γ[°]	64.6	± 2.8	[61.8, 67.4]	$^{+5.5}_{-5.7}$	[58.9, 70.1]
r_B^{DK} [%]	9.73	$^{+0.21}_{0.20}$	[9.53, 9.94]	$^{+0.42}_{-0.40}$	[9.33, 10.15]
δ_B^{DK} [°]	127.4	$^{+2.8}_{-3.0}$	[124.4, 130.2]	$^{+5.6}_{-6.2}$	[121.2, 133.0]

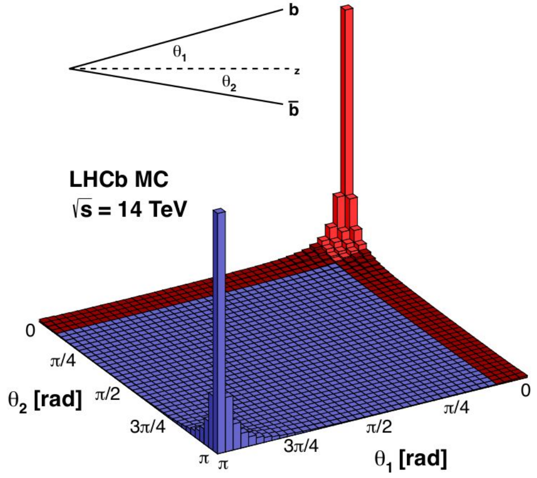
Conclusion and perspectives

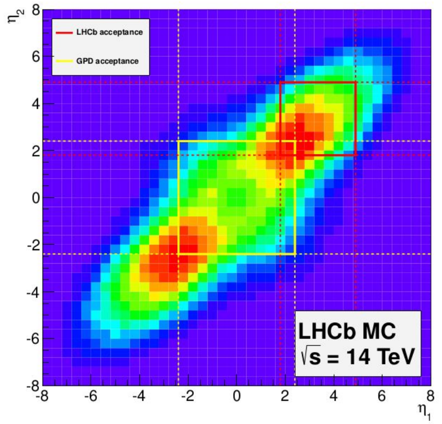
- Most of the analysis is now done (selection, background analysis, global fit, CP-fit, most cross-checks and systematics, etc)
- >2.5× Belle statistics -> A statistical sensitivity of about 20°
- An Analysis Note under WG review + Presented as blinded results in a plenary talk at LHCb June 2024 week in Glasgow -> **First steps towards the journal publication for this pioneer measurement in LHCb**
- Expect improvements with the upcoming BESIII strong-phase measurement (20fb^{-1} dataset on tape at $\Psi(3770)$ resonance) -> Planned collaboration with Oxford team to update this analysis with Run 3 and BESIII inputs
- This mode can also be used later to participate to an Amplitude Analysis of this D^0 decay (good purity)
  - Foreseen analysis combined with measurements using decay $B \rightarrow D^*(2010)^+ \mu^- X$
  - Quick and dirty feasibility study for BR measurement of $D^0 \rightarrow K^{*-}\rho^+$ already made
  - Not measured since Mark III in 1994 ... 30 years ago !
  - Possible model-dependent analysis following the amplitude model

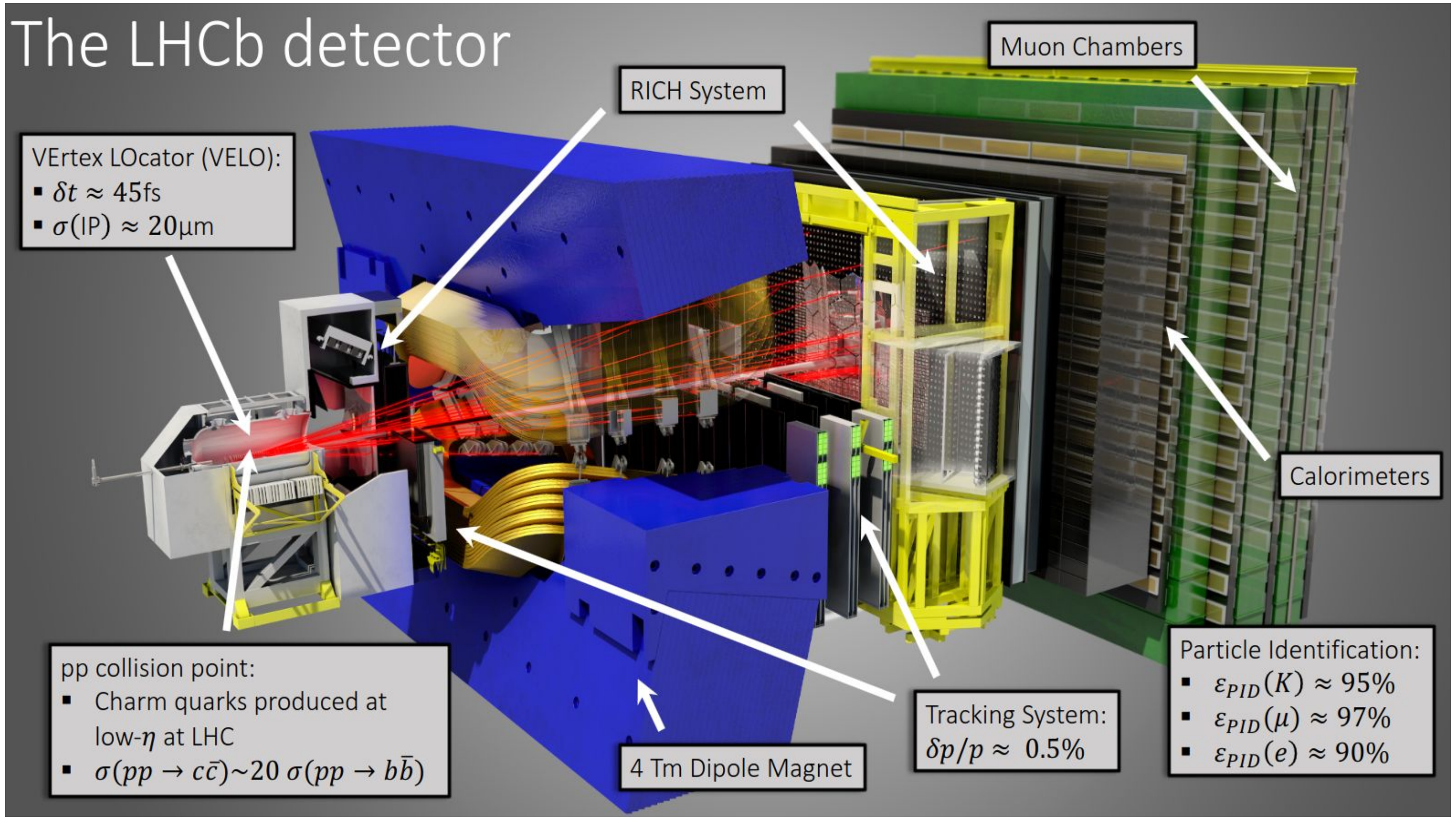
BACKUP

LHCb Experiment

- **One of the four main experiments** at LHC (with ATLAS, CMS and ALICE)
- 20m forward spectrometer ($2<\eta<5$) : general detector specialized in **beauty and charm study**
- Physics program involves flavour physics, **CP violation measurements**, EW, exotic particles, heavy ion physics, …
  -> Initially designed to study CPV and rare decays in beauty and charm sectors -> **Extended program**
- Excellent vertexing, tracking, momentum resolution and particle identification (**K vs π**)+photons reconstruction

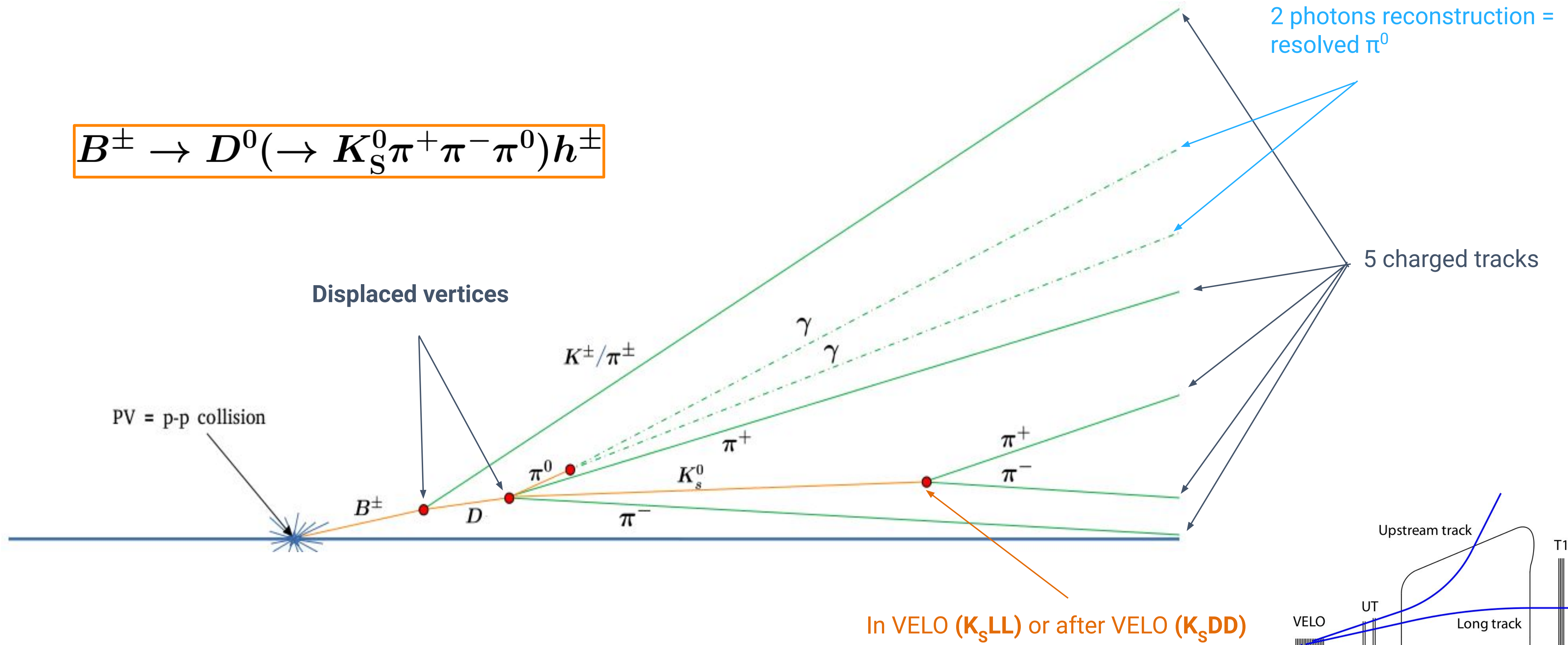


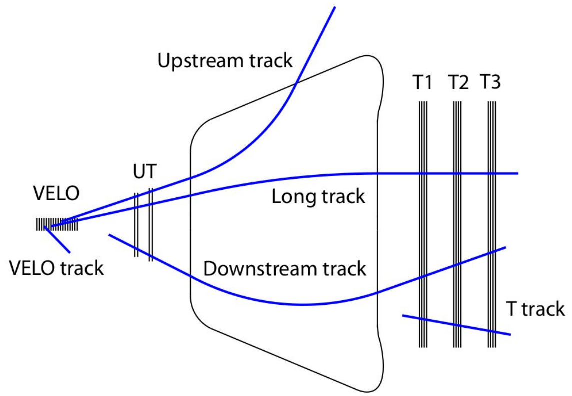




→ **Almost all the sub-detectors are useful for my complicated mode**

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

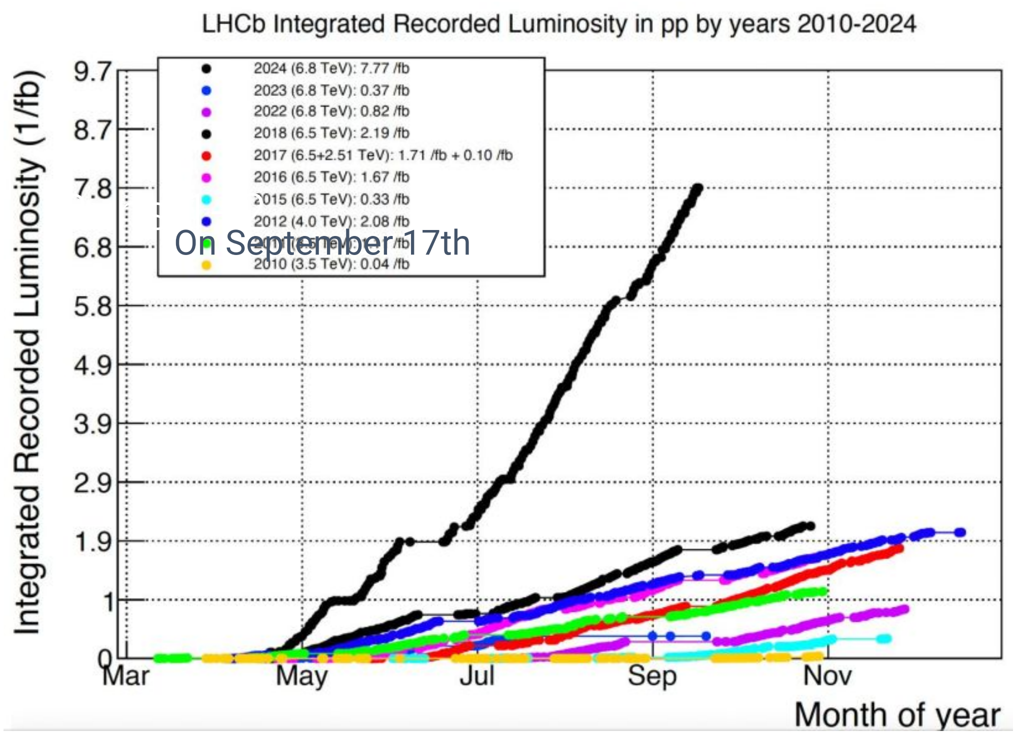


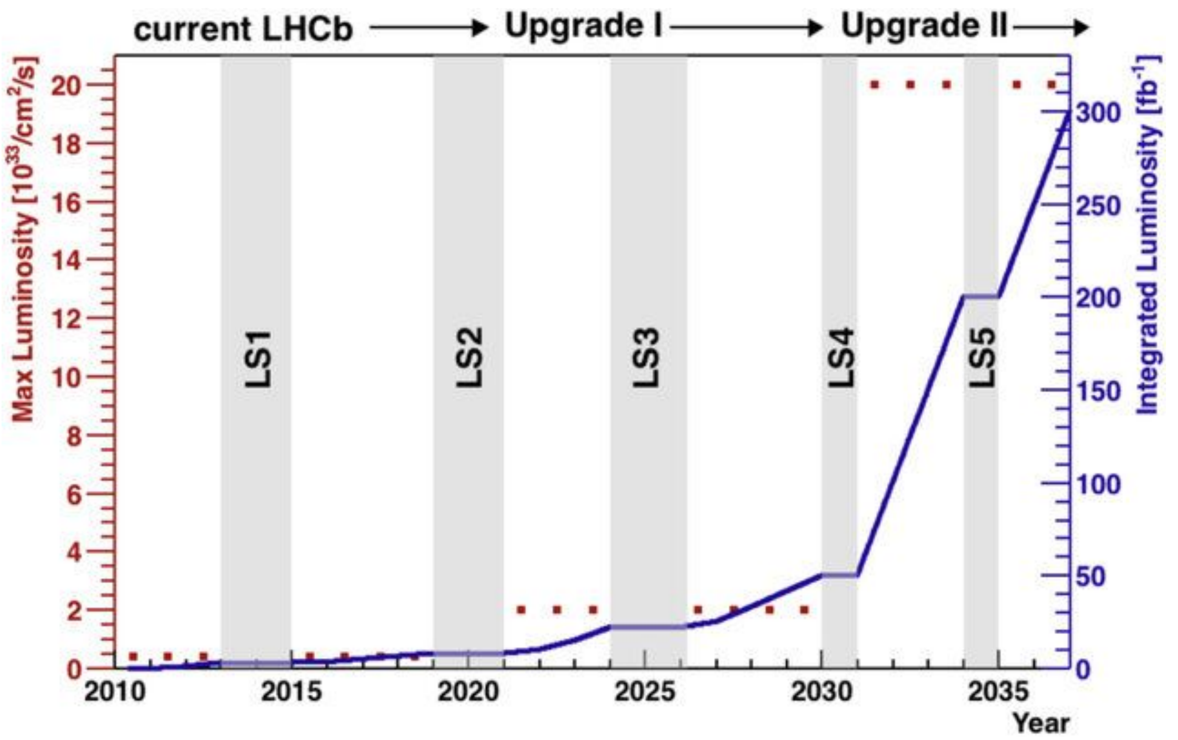


→ **Almost all the sub-detectors are useful for my complicated mode**

LHCb Experiment

- **9 fb^{-1}** integrated luminosity during Runs 1+2 -> **More to come with run 3+4 (50 fb^{-1}) and HL-LHC (300 fb^{-1})**
- Already **~8 fb^{-1}** in 2024
- High statistics for high precision measurements

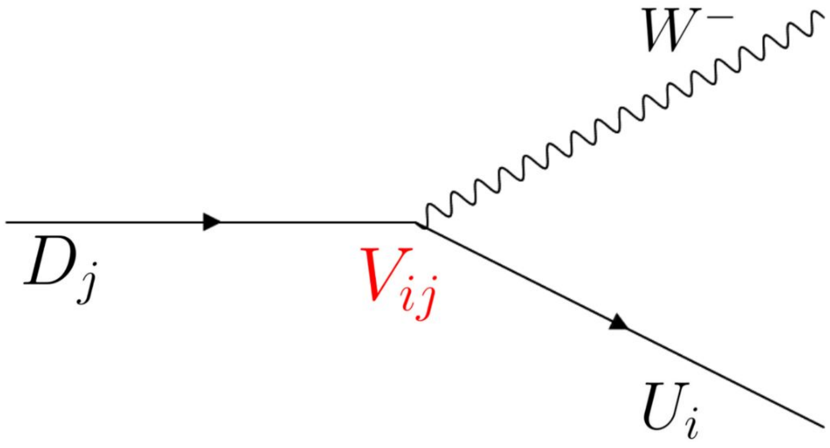




The CKM Matrix, the Unitary Triangle and ɣ angle

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

- CKM Matrix describes transition between quarks through weak interaction -> **the source of CPV in SM**
  + Predicts 3 families of quarks ('73) ! → (‘08)
- Its elements can been determined from experiment -> Parameterization with 4 independent parameters



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The CKM Matrix, the Unitary Triangle and ɣ angle

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitary equations and triangle : $\boldsymbol{V V^\dagger = I_3}$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- CKM Matrix describes transition between quarks through weak interaction -> **the source of CPV in SM**

  + Predicts 3 families of quarks (‘73) ! →  **(‘08)**
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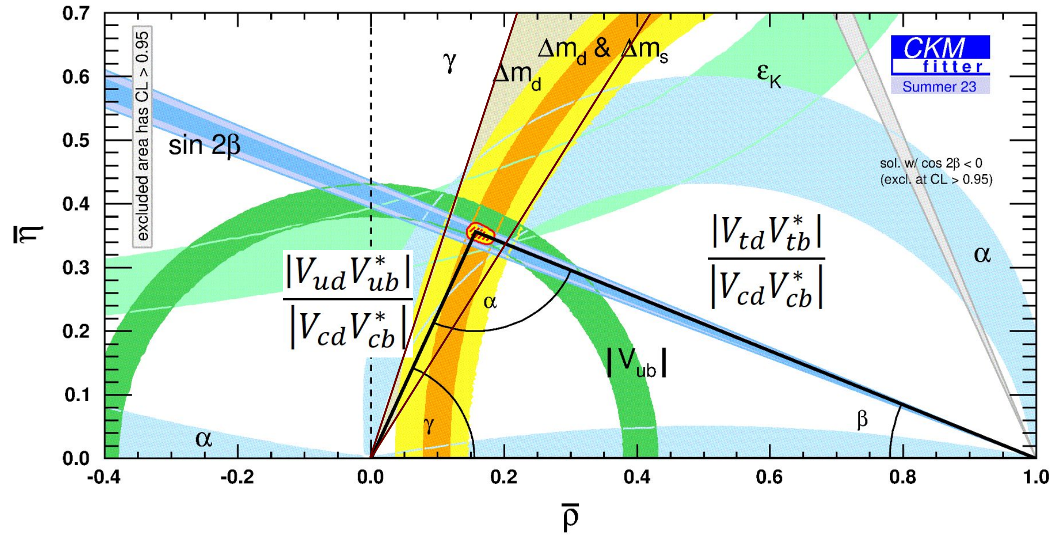

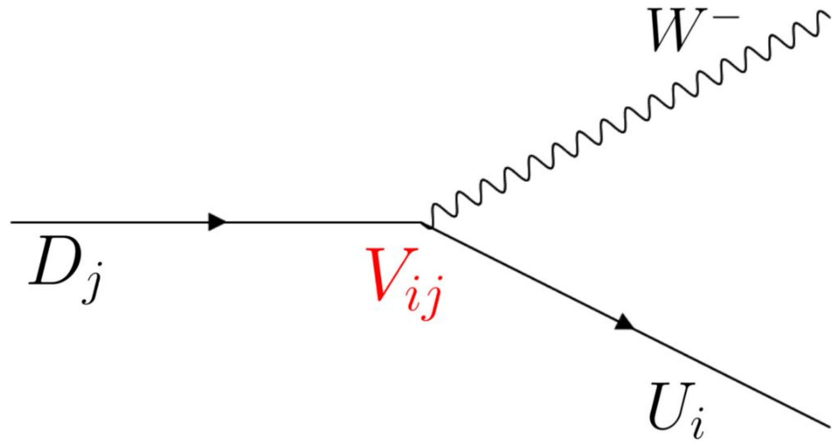

$$\gamma \equiv arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}) \equiv arg(\bar\rho + i\bar\eta)$$

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The CKM Matrix, the Unitary Triangle and ɣ angle

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitary equations and triangle : $\boldsymbol{VV^\dagger = I_3}$

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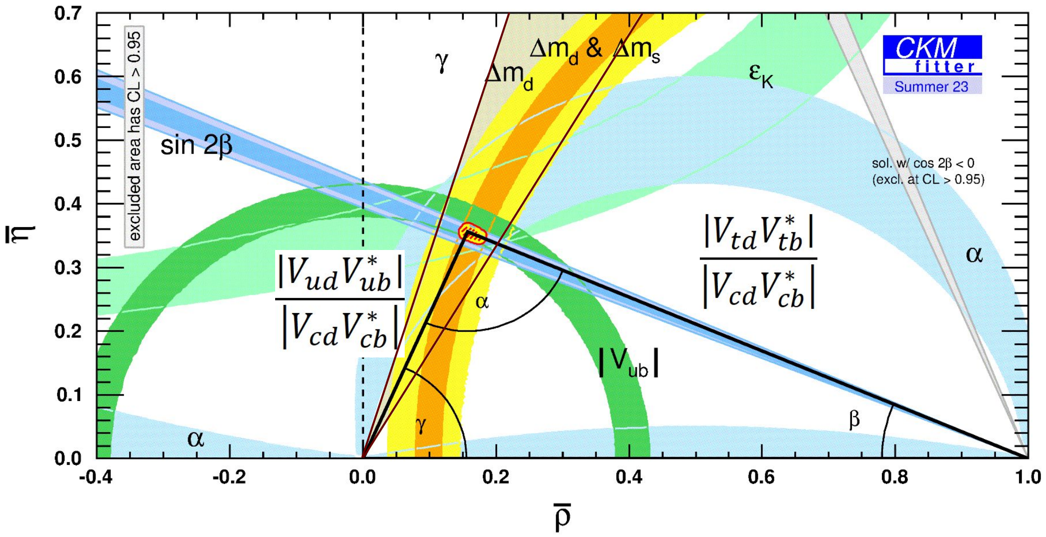

- CKM Matrix describes <u>transition between quarks</u> through weak interaction -> **the source of CPV in SM**
  + Predicts 3 families of quarks ('73) ! → ('08)
- Its elements can been determined from experiment -> Parameterization with 4 independent parameters
- Goal : **Sensitivity to BSM effects** if unitarity triangle is broken by discrepancy between direct and indirect measurements
- The current state of ɣ measurements (LHCb-CONF-2024-004) :

Direct : $\gamma = (64.6 \pm 2.8)^\circ$ -> Tree Level = standard candle

Indirect : $\gamma \overset{\text{CKMfitter}}{=} (66.3^{+0.7}_{-1.9})^\circ$ -> Loops / Penguin diagrams

$$\gamma \equiv arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \equiv arg(\bar{\rho}+i\bar{\eta})$$ = CKM Matrix complex phase **= <u>The parameter to access CPV !</u>**

The CKM Matrix, the Unitary Triangle and γ angle

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	B_s mixing
$\|C_{ij}\| = \|V_{ti}V_{tj}^*\|$	tree level	17	19
(CKM-like)	one loop	1.4	1.5
$\|C_{ij}\| = 1$	tree level	2×10^3	5×10^2
(no hierarchy)	one loop	2×10^2	40

TABLE II. The scale of the operator in Eq. (2) probed by B_d and B_s mixings at Stage II (if the NP contributions to them are unrelated). The impact of CKM-like hierarchy of couplings and/or loop suppression is indicated.

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-> Test of global validity of the CKM formalism in tree level diagrams

- CKM Matrix describes transition between quarks through weak interaction -> **the source of CPV in SM**
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- Its elements can been determined from experiment
  -> Parameterization with 4 independent parameters
- Goal : **Sensitivity to BSM effects** if unitarity triangle is broken by discrepancy between direct and indirect measurements
- The current state of γ measurements (LHCb-CONF-2024-004) :

Direct : $\gamma = (64.6 \pm 2.8)^\circ$ -> Tree Level = standard candle

CKMfitter

Indirect : $\gamma = (66.3^{+0.7}_{-1.9})^\circ$ -> Loops / Penguin diagrams

- According to CKMfitter group, a sub-degree precision on direct measurement would test SM up to dozens of TeV energy scales
  -> **Only possible in association of multiple analysis**

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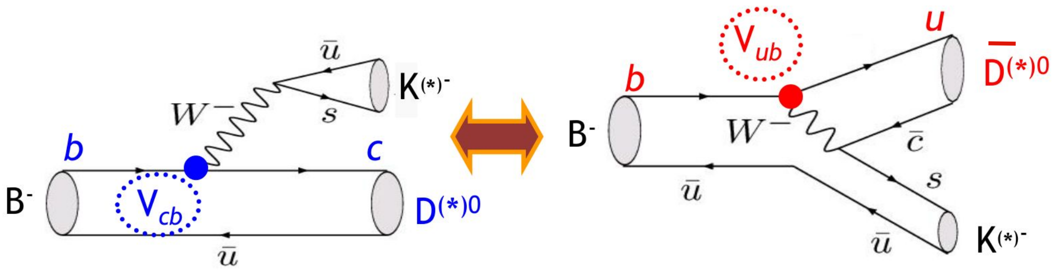
The golden channel to measure ɣ angle

- Relative weak phase ɣ measured in the interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions by amplitude modulation

- Golden channel = $B^{\pm} \to D^0 K^{\pm}$

Same final state $\tilde{D}^0 \equiv [D^0/\bar{D}^0]$



$$\gamma \equiv arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$$

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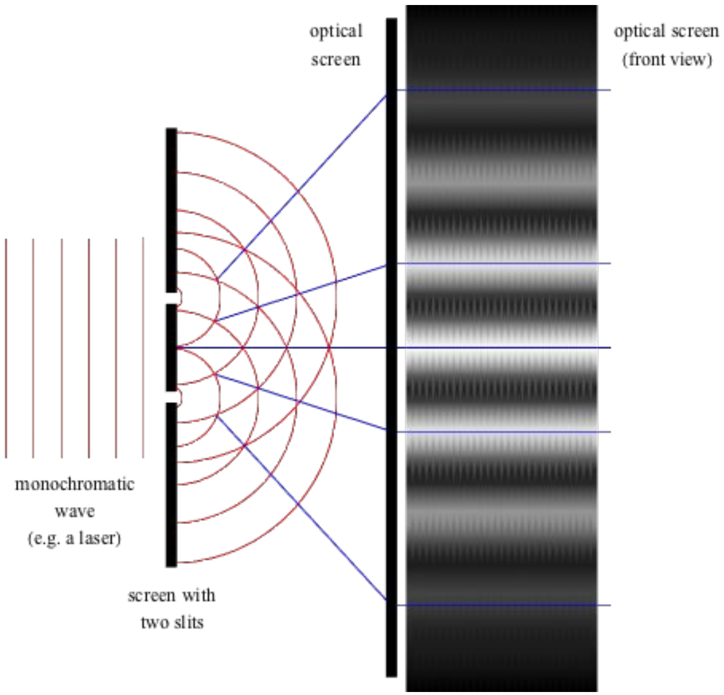
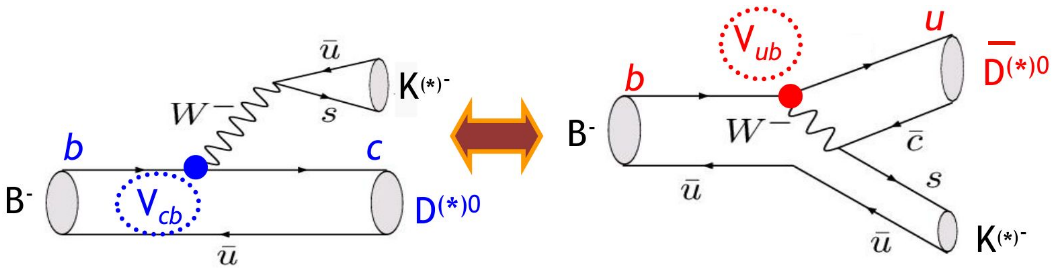
The golden channel to measure ɣ angle

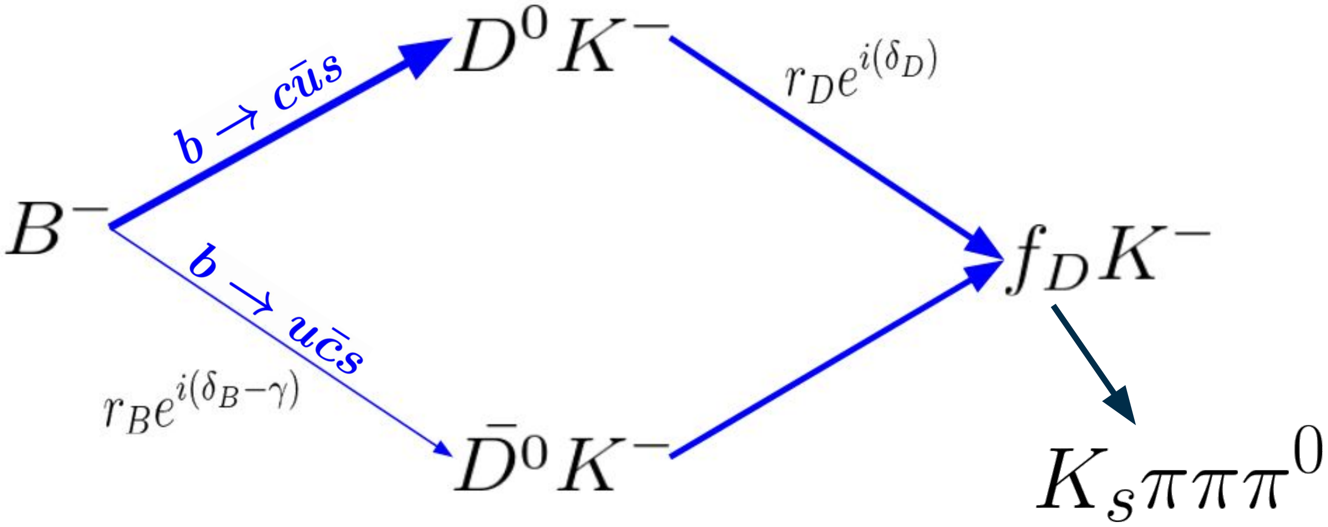
- Relative weak phase ɣ measured in the interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions by amplitude modulation
- Golden channel = $B^{\pm} \to D^0 K^{\pm}$
- Possible analogy with Young slits with a slit thinner than the other



Same final state $\tilde{D}^0 \equiv [D^0/\bar{D}^0]$



$$\gamma \equiv arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$$



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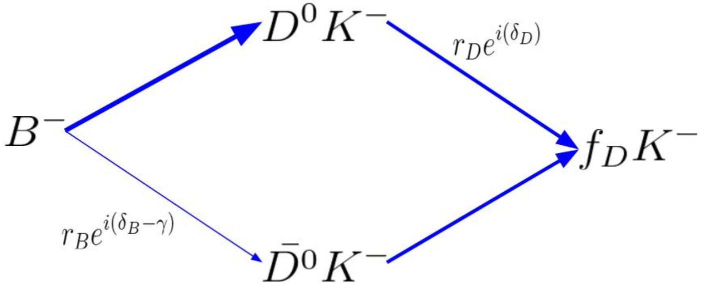
Generalized BPGGSZ* formalism

*BPGGSZ = Bondar, Poluektov (Eur. Phys. J. C 55 (2008) 51)
Giri, Grossman, Soffer, Zupan (Phys. Lett. B 253 (1991) 483)



The Amplitude $\boldsymbol{A_B}$ for the decay from $\boldsymbol{B^+}$ to final state (at a given point in the D decay phase-space Ɗ) is :

$$A_B = \bar{A} + r_B e^{i(\delta_B+\gamma)} A \quad (1)$$

-> δ_B = strong-phase difference between $\boldsymbol{B^\pm \to D^0K^\pm}$ and $\boldsymbol{B^\pm \to \bar{D}^0K^\pm}$

-> A (resp $\bar{A}$) = Amplitudes for $D^0 \to f$ (resp $\bar{D}^0 \to f$)

-> $r_B = \frac{|A_{B\to\bar{D}^0K}|}{|A_{B\to D^0K}|}$ → **Drives statistical precision on ɣ**

The probability density for a decay at a point in Ɗ : $P_B = |A_B|^2 = |\bar{A}|^2 + r_B^2|A|^2 + 2r_B\Re[\bar{A}^*Ae^{i(\delta_B+\gamma)}]$

As $\bar{A}^*A = |\bar{A}||A|e^{i\Delta\delta_D}$, we obtain : $P_B = \bar{P} + r_B^2 P + 2\sqrt{P\bar{P}}[x\_C - y\_S]$ (2)

With :

- $y_\pm = r_B sin(\delta_B \pm \gamma)$
- $x_\pm = r_B cos(\delta_B \pm \gamma)$

- $C = cos(\Delta\delta_D)$
- $S = sin(\Delta\delta_D)$

- $P = |A|^2$
- $\bar{P} = |\bar{A}|^2$

= “Cartesian coordinates” or “CP-observables”

Similar formalism for B^-, with : $A \leftrightarrow \bar{A}$ and $\gamma \leftrightarrow -\gamma$

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Generalized BPGGSZ formalism

γ measurement depends on $\Delta\delta_D$, the strong phase difference between $D^0 \to f\ (\delta_D)$ and $\bar{D}^0 \to f\ (\delta_{\bar{D}})$

Varies on Phase-Space of the 4-body decay $D^0 \to K_s^0\pi^+\pi^-\pi^0$

Similar method to the one in JHEP 01 (2019) 82 (Belle, from Resmi P.K thesis)

-> Binned map of strong phase from JHEP 10 (2018) 178 (Resmi P.K, J. Libby, S. Malde, & G. Wilkinson-CLEO-c)

(with 0.82fb^{-1} $\Psi(3770)$ dataset)

Exclusively defined

Bin	Bin region	m_L (GeV/c^2)	m_U (GeV/c^2)
1	$m_{\pi^+\pi^-\pi^0} \approx m_\omega$	0.762	0.802
2	$m_{K_S^0\pi^-} \approx m_{K^{*-}}$ &	0.790	0.994
	$m_{\pi^+\pi^0} \approx m_{\rho^+}$	0.610	0.960
3	$m_{K_S^0\pi^+} \approx m_{K^{*+}}$ &	0.790	0.994
	$m_{\pi^-\pi^0} \approx m_{\rho^-}$	0.610	0.960
4	$m_{K_S^0\pi^-} \approx m_{K^{*-}}$	0.790	0.994
5	$m_{K_S^0\pi^+} \approx m_{K^{*+}}$	0.790	0.994
6	$m_{K_S^0\pi^0} \approx m_{K^{*0}}$	0.790	0.994
7	$m_{\pi^+\pi^0} \approx m_{\rho^+}$	0.610	0.960
8	$m_{\pi^-\pi^0} \approx m_{\rho^-}$	0.610	0.960
9	Remainder	-	-

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Generalized BPGGSZ formalism

γ measurement depends on $\Delta\delta_D$, the strong phase difference between $D^0 \rightarrow f\ (\delta_D)$ and $\bar{D}^0 \rightarrow f\ (\delta_{\bar{D}})$

Varies on Phase-Space of the 4-body decay $D^0 \rightarrow K_s^0\pi^+\pi^-\pi^0$

$$\Gamma_i^- = h\left(K_i + r_B^2\overline{K}_i + 2\sqrt{K_i\overline{K}_i}(c_i x_- + s_i y_-)\right)$$

$$\Gamma_i^+ = h\left(\overline{K}_i + r_B^2 K_i + 2\sqrt{K_i\overline{K}_i}(c_i x_+ - s_i y_+)\right)$$

Similar method to the one in JHEP 01 (2019) 82 (Belle, from Resmi P.K thesis)

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(with 0.82fb^{-1} $\Psi(3770)$ dataset)

- K_i and $\bar{K}_i$ are fractions of $D^0/\bar{D}^0$ in bin i
- h is a normalisation factor
- $r_B = \dfrac{|A_{B\rightarrow\bar{D}^0K}|}{|A_{B\rightarrow D^0K}|}$ ← **Drives statistical precision on γ**
- $c_i = \dfrac{\int_{\mathcal{D}_i}|A||\bar{A}|C d\mathcal{D}}{\sqrt{\int_{\mathcal{D}_i}|A|^2 d\mathcal{D}\int_{\mathcal{D}_i}|\bar{A}|^2 d\mathcal{D}}}$ ← $C = cos(\Delta\delta_D)$, $S = sin(\Delta\delta_D)$
- $x_\pm = r_B cos(\delta_B \pm \gamma)$
- $y_\pm = r_B sin(\delta_B \pm \gamma)$

= "Cartesian coordinates" or "CP-observables"

Bin	Bin region	m_L (GeV/c^2)	m_U (GeV/c^2)
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4	$m_{K_S^0\pi^-} \approx m_{K^{*-}}$	0.790	0.994
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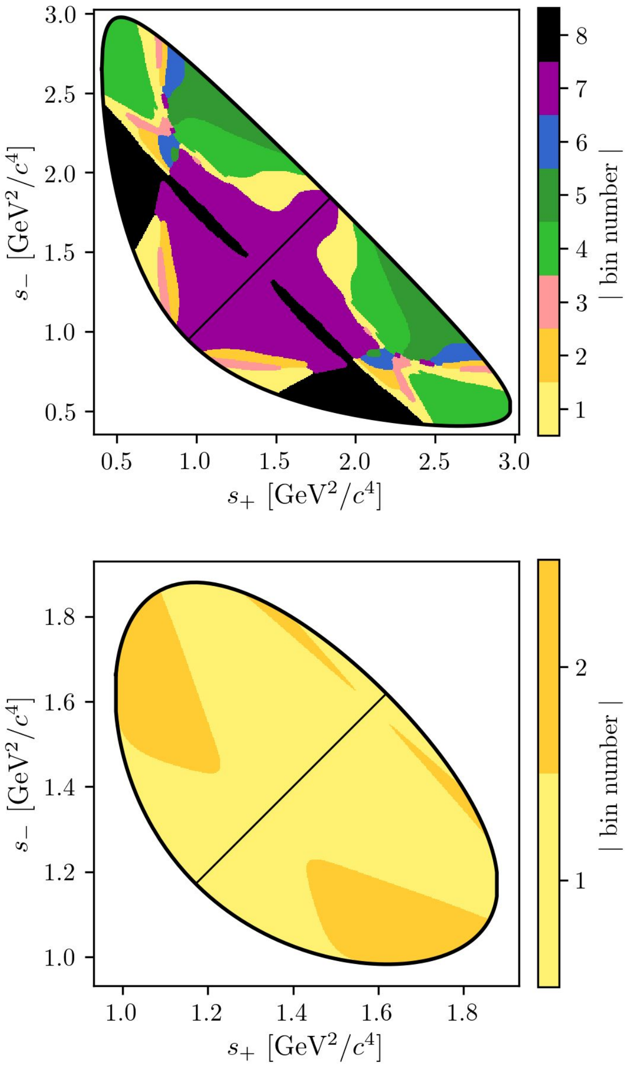
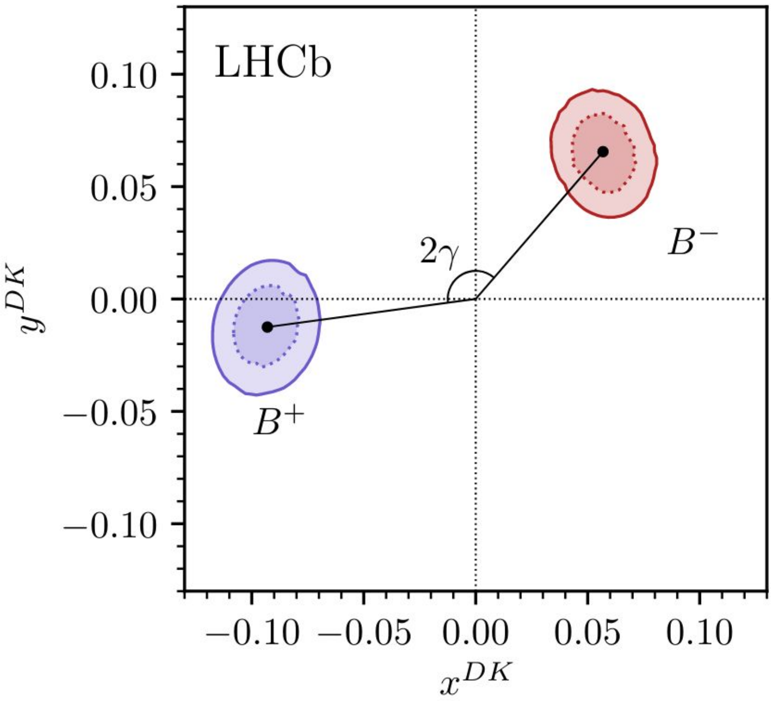
6	$m_{K_S^0\pi^0} \approx m_{K^{*0}}$	0.790	0.994
7	$m_{\pi^+\pi^0} \approx m_{\rho^+}$	0.610	0.960
8	$m_{\pi^-\pi^0} \approx m_{\rho^-}$	0.610	0.960
9	Remainder	-	-

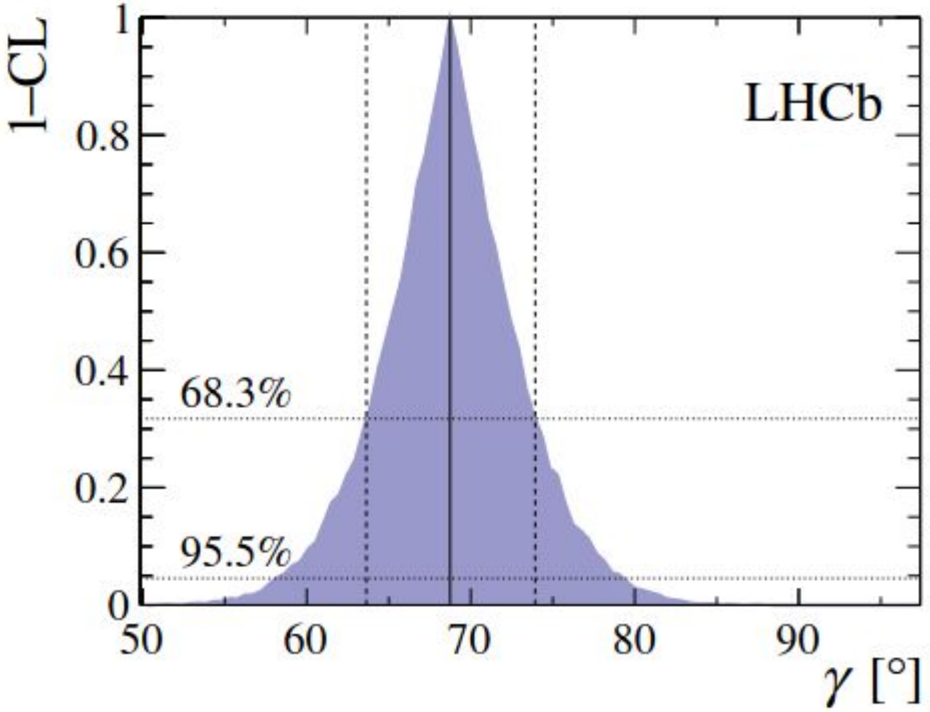
- The 3-body decay mode used in BPGGSZ, with Run 1+2 dataset is currently the most precise γ measurement. The 4-body decay with π^0 still not measured in LHCb

$$B^{\pm} \to D^0(K_s^0 h^+ h^-)h^{\pm}$$

$$\gamma = (68.7^{+5.2}_{-5.1})^{\circ}$$







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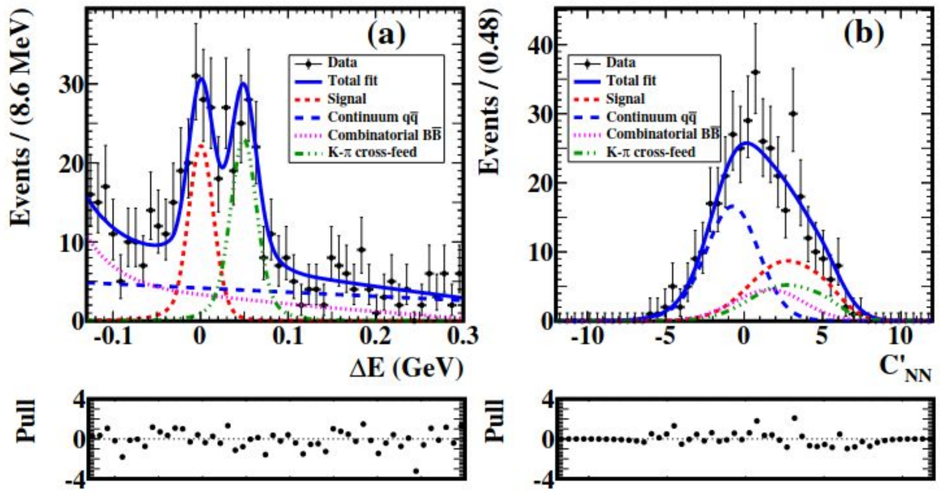
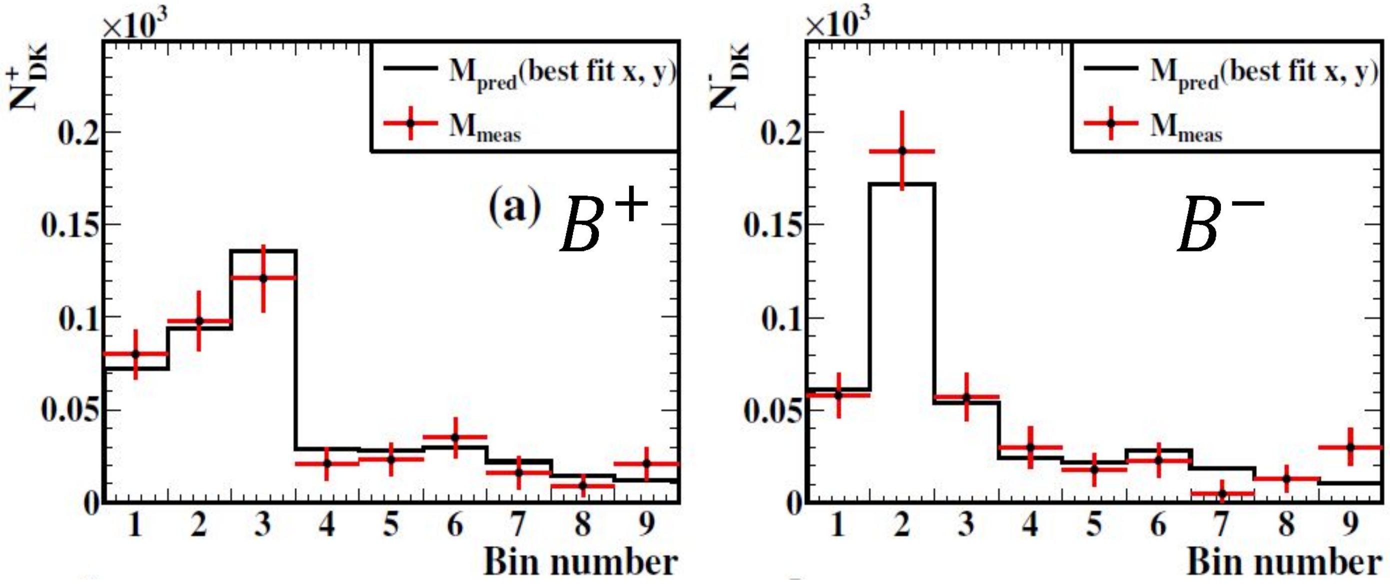


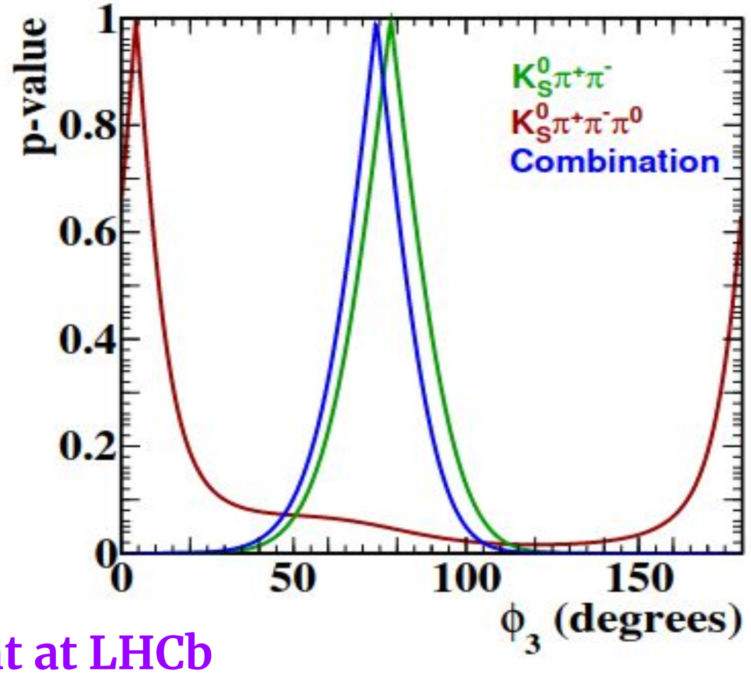
- In $B^{\pm} \to D^0 K^{\pm}$: 815±51 events with ~60% purity at 2σ

$$\gamma = (5.7^{+10.2}_{-8.8} \pm 3.5 \pm 5.7)^{\circ}$$

- 95% Confidence level : $\gamma \in (-29.7, 109.5)^{\circ}$
- $r_B^{DK} = (32.3 \pm 14.7 \pm 2.3 \pm 5.1)\%$

-> Compatible with LHCb combination at 2σ, given the large error
-> Uncertainty dominated by statistics





→ **Aim of this thesis** : Perform equivalent pioneer measurement at LHCb

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Strategy

One can then deduce $N_i^{\pm}$, the measured yields (cf paper LHCb-PAPER-2020-019):

$$\begin{cases} N^-_{i,DK} = f^-_{DK}(F_i + r_B^{DK^2}\overline{F_i} + 2\sqrt{F_i\overline{F_i}}(c_i x_-^{DK} + s_i y_-^{DK})) \\ N^+_{i,DK} = f^+_{DK}(\overline{F_i} + r_B^{DK^2}F_i + 2\sqrt{F_i\overline{F_i}}(c_i x_+^{DK} - s_i y_+^{DK})) \\ N^-_{i,D\pi} = f^-_{D\pi}(F_i + r_B^{D\pi^2}\overline{F_i} + 2\sqrt{F_i\overline{F_i}}(c_i x_-^{D\pi} + s_i y_-^{D\pi})) \\ N^+_{i,D\pi} = f^+_{D\pi}(\overline{F_i} + r_B^{D\pi^2}F_i + 2\sqrt{F_i\overline{F_i}}(c_i x_+^{D\pi} - s_i y_+^{D\pi})) \end{cases}$$

- $F_i = \frac{\int_{\mathcal{D}_i} P\eta d\mathcal{D}}{\sum_j \int_{\mathcal{D}_j} P\eta d\mathcal{D}}$
- η = efficiency at a given point in phase-space
- Hypothesis : $F_i^{DK} = F_i^{D\pi}$

$F_i^{DK} = F_i^{D\pi}$ **if**

- $B^{\pm} \to D^0\pi^{\pm}$ and $B^{\pm} \to D^0K^{\pm}$ have a similar selection and efficiency mapping through $\mathcal{D}$
- PID cut efficiency is the same for all of the 9 bins
- 9×9 Migration matrix is similar between $B^{\pm} \to D^0\pi^{\pm}$ and $B^{\pm} \to D^0K^{\pm}$

All those hypothesis have been tested and validated !

Sketch the selection steps for this measurement

- Use of the **reference mode** $B^{\pm} \to D^0\pi^{\pm}$ that is topologically identical, statistically more interesting and less sensible to CP asymmetry

$$\mathcal{B}(B^{\pm} \to D^0\pi^{\pm}) = (12.67 \pm 0.43) \times \mathcal{B}(B^{\pm} \to D^0K^{\pm}) = (4.61 \pm 0.10) \times 10^{-3}$$

- Selection adapted for Runs 1 vs 2 and for K_S^0DD vs LL
- Selection based on **2 Multivariate-Analysis** and **unidimensional cuts on particle masses** :
  - First MVA : MLP method on geometrical and topological variables from D and its daughters (impact parameters, vertex quality, vertex relative position, photons identification, etc)
  - Unidimensional cuts on K_S^0, π^0 and D^0 masses
  - Second MVA : MLP method on geometrical and topological variables from B decay
- Cut on **PID likelihood** difference to limit bachelor track misID
- Choosing the best candidate in case of multiplicity (mainly due to π^0), thanks to a MVA trained on MC, discriminating true signal events

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Stripping selection

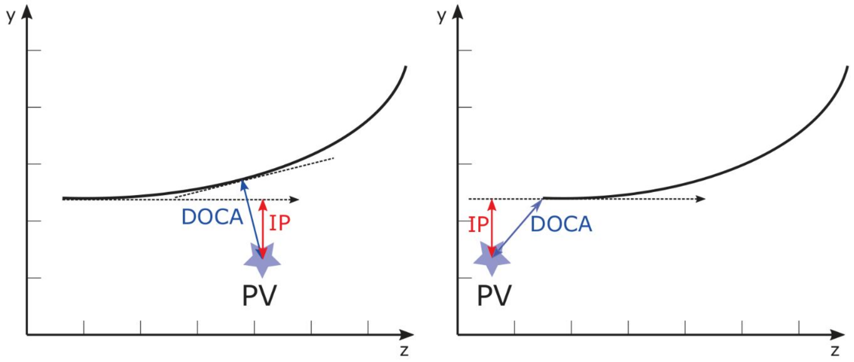
Table 7.6: Stripping selections of B2D0PiD2KSPi0HHLLResolvedBeauty2CharmLine, B2D0KD2KSPi0HHLLResolvedBeauty2CharmLine, B2D0PiD2KSPi0HHDDResolvedBeauty2Char B2D0KD2KSPi0HHDDResolvedBeauty2CharmLine lines.

Particle	Quantity	Criteria
Event	#PV	> 0
	#long tracks	< 500
	HLT2IncPhi	True
or	HLT2Topo(2‖3‖4)Body	True
$B^{\pm}$	Invariant Reconstructed Mass	$\in [4750, 7000]\,\mathrm{MeV}/c^2$
	Σp_{T}	$> 5000\,\mathrm{MeV}/c$
	Vertex : $\chi^2/nDof$	< 10
	τ	$> 0.2\,\mathrm{ps}$
	$cos(\theta_{DIRA})$(BPVDIRA)	> 0.999
	BPVIPCHI2	< 25
At least one daughter	HasTrack	= True
	p_{T}	$> 1700\,\mathrm{MeV}/c$
	p	$> 10000\,\mathrm{MeV}/c$
	Track : $\chi^2/nDof$	< 4.0
	Min IPχ^2	> 16
	Min IP	$> 0.1\,\mathrm{mm}$
Bachelor π/K	HasTrack	= True
	Track : $\chi^2/nDof$	< 4.0
	p_{T}	$> 500\,\mathrm{MeV}/c$
	p	$> 5000\,\mathrm{MeV}/c$
	Min IPχ^2	> 4.0
D^0	Σp_{T}	$> 1800\,\mathrm{MeV}/c$
	Reconstructed Mass	$\in [1614.84, 2114.84]\,\mathrm{MeV}/c^2$
	DOCA	$< 0.5\,\mathrm{mm}$
	Vertex : $\chi^2/nDof$	< 10
	BPVVDCHI2	> 36
	$cos(\theta_{DIRA})$(BPVDIRA)	> 0
π^+/π^-	p_{T}	$> 100\,\mathrm{MeV}/c$
	p	$> 1000\,\mathrm{MeV}/c$
	Track : $\chi^2/nDof$	< 4.0
	Min IPχ^2	> 4.0
π^0	Mass	$\in [105, 165]\,\mathrm{MeV}/c^2$
	p_{T}	$> 500\,\mathrm{MeV}/c$
	p	$> 1000\,\mathrm{MeV}/c$
K^0_{S}	Mass	$\in [467, 527]\,\mathrm{MeV}/c^2$
	p_{T}	$> 250\,\mathrm{MeV}/c$
	$p(\pi^+)$	$> 2\,\mathrm{GeV}/c$
	π^+ : Min IPχ^2	$> 9.$ (case LL) $> 4.$ (DD)
	CL photon 12	> 0.25
At least one daugther...	p_{T}	$> 500\,\mathrm{MeV}/c$
	p	$> 5000\,\mathrm{MeV}/c$
...with either...	IsBasic & HasTrack	= True
...and...	Track : $\chi^2/nDof$	< 4.0
...or...	Is_Ks0	= True
...and	BPVVDCHI2	> 1000

Quantity	Description
#PV	Number of Primary Vertices in the beam collision (Pile-up)
#long tracks	Number of tracks reconstructed in the whole tracking system
HLT2IncPhi	Trigger line reconstructing vertices that can originate from a ϕ meson
HLT2Topo(2‖3‖4)Body	Trigger line on multi-body topology (based on BDT classifier)
Σp_{T}	Sum of daughters transverse momentum
Vertex : $\chi^2/nDof$	Control the quality of the vertex
BPVDIRA	Angle between particle momentum and topological direction
BPVIPCHI2‖MinIPχ^2	χ^2 of the impact parameter with primary vertex (see Fig. 8.3)
Track : $\chi^2/nDof$	Control the quality of the reconstructed track
DOCA	Distance of closest approach with primary vertex
BPVCDCHI2	χ^2 while determining distance between PV and decaying vertex
CL photon	Confidence level for the particle to be a photon
IsBasic	return True if the particle doesn't have children

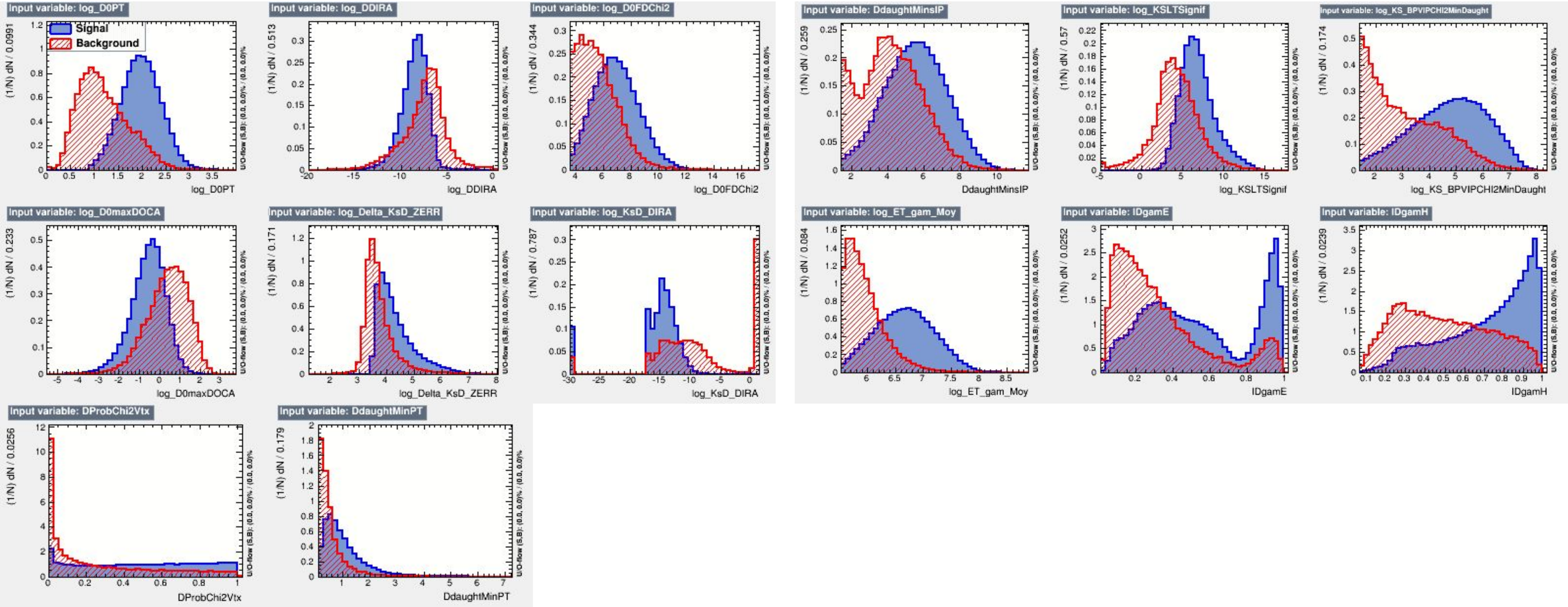
Selection

MVA1	
Variable name	**Description**
Log_D0PT	D^0 transverse momentum
Log_DDIRA	Alignment between D^0 flight direction (from $B^\pm$ and D^0 vertices position) and reconstructed momentum
Log_D0FDChi2	Statistical significance of the distance between D^0 vertex and PV
Log_D0maxDOCA	Maximum distance of the closest approach to the PV for all possible pairs of daughters
Log_Delta_KsD_ZERR	Distance between D^0 and K^0_s vertices along the beam axis
Log_KsD_DIRA	Alignment between K^0_s flight direction and reconstructed momentum
DdaughtMinsIP	Minimal Impact parameter of D^0 daughters
Log_KsLTSignif	Statistical significance of K^0_s life-time
Log_KS_BPVIPCHI2MinDaught	Minimal Impact parameter of K^0_s daughters
Log_ET_gam_Moy	Mean transverse energy of photons from π^0
IdgamE et IDgamH	Probability for both photons not to be electrons (resp, hadrons)
DProbChi2Vtx	D^0 vertex quality
DDaughtMinPT	Minimal transverse momentum of charged pions in D^0 decay



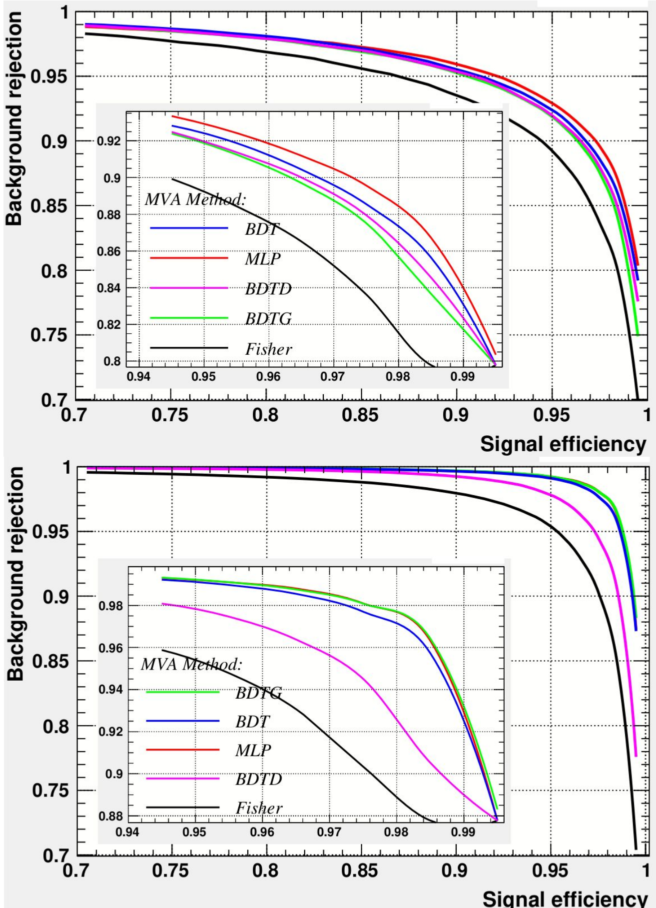
Selection : First MVA

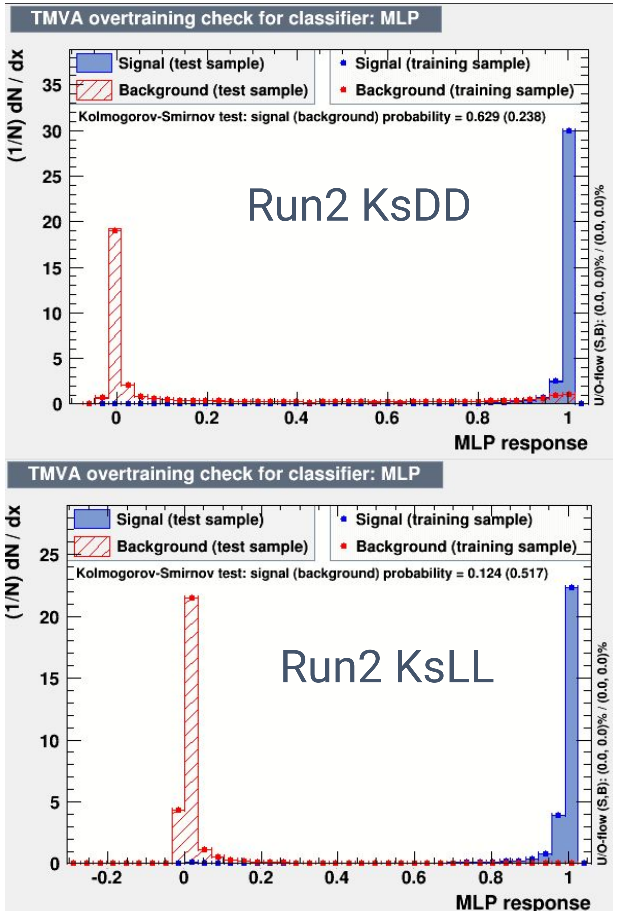
- First MVA on D decay geometrical and topological parameters using a MLP method
  - **Signal** = Simulated phase-space signal with $\mathtt{BKGCAT} \in \{0, 10\}$ + meson masses conditions
  - **Background** = Data events in m($B^{\pm}$) upper side-band and neutral mesons side-bands
- 4 independent categories : Run1/2 with KsLL/KsDD samples



Selection : First MVA

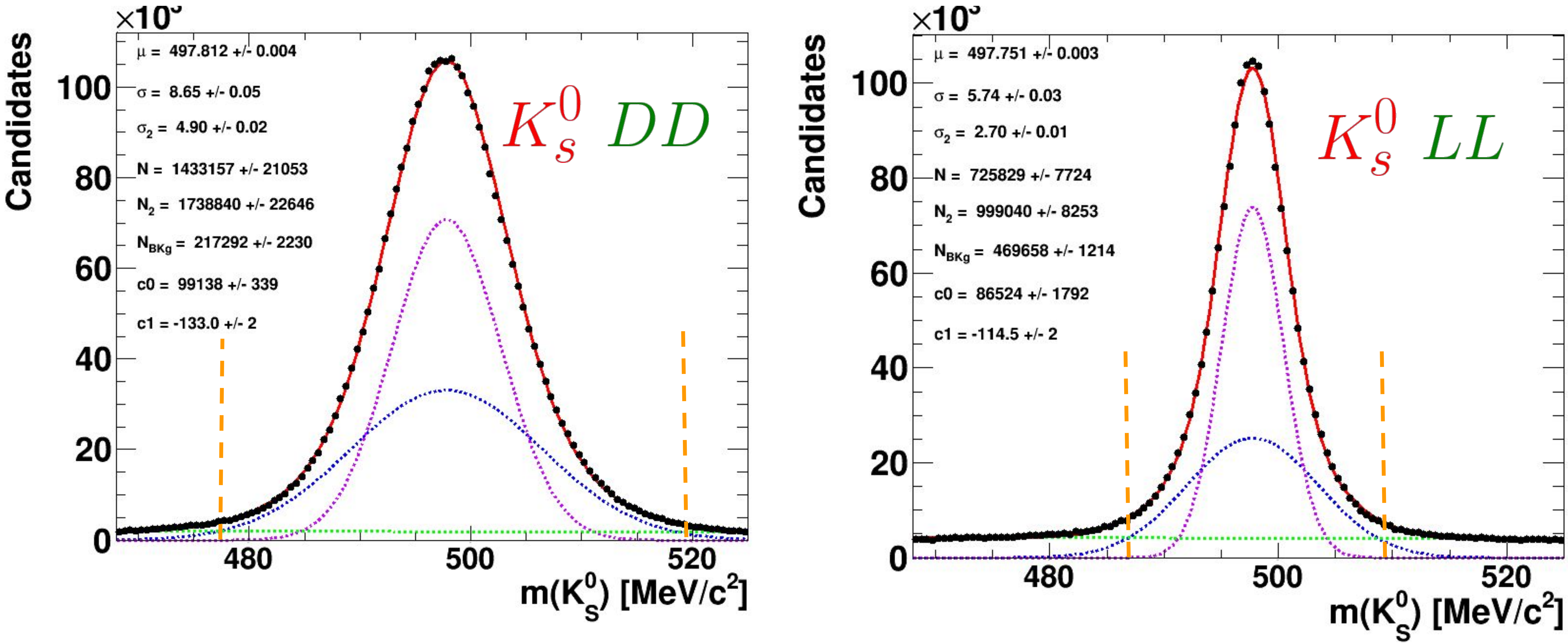
- First MVA on D decay geometrical and topological parameters using a MLP method
  - **Signal** = Simulated phase-space signal with $\texttt{BKGCAT} \in \{0, 10\}$ + meson masses conditions
  - **Background** = Data events in m($B^{\pm}$) upper side-band and neutral mesons side-bands
- 4 independent categories : Run1/2 with KsLL/KsDD samples
- Tested 5 methods : Fisher, MLP, BDT, BDTD, BDTG -> retained MLP





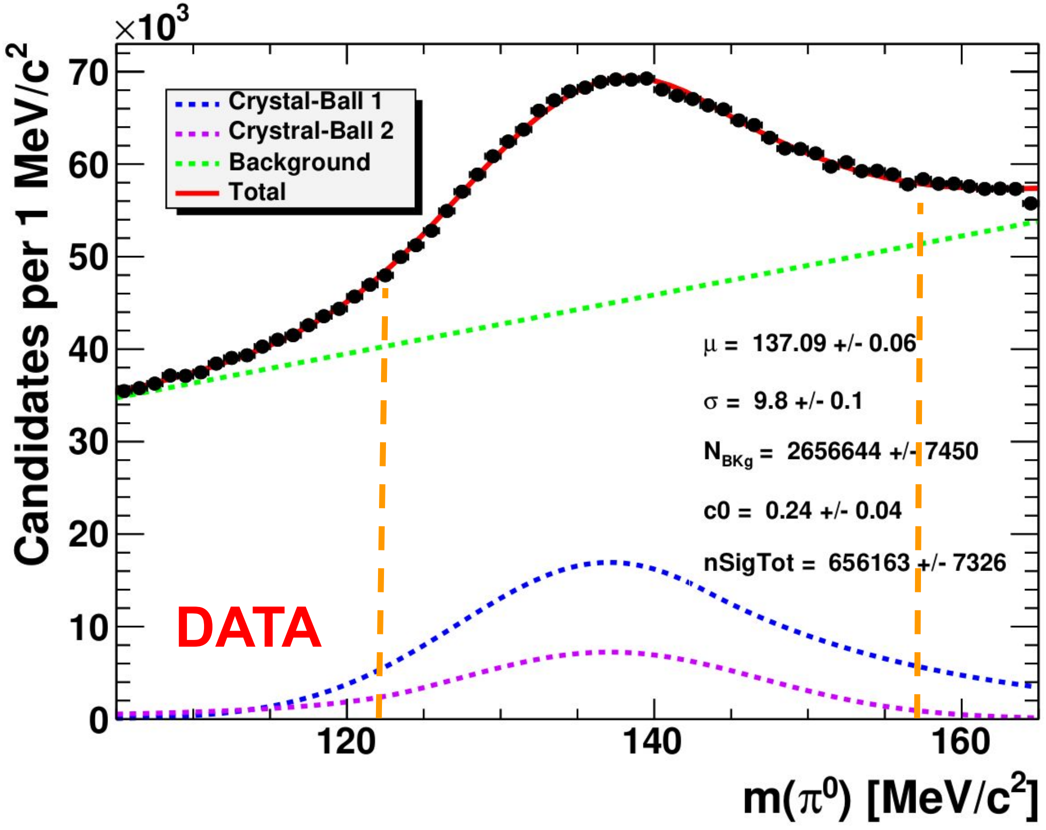
Category	Selection	Signal efficiency (%)	Background rejection (%)
Run1 DD	MLP > 0.938	97.0	91.7
Run1 LL	MLP > 0.319	98.0	97.7
Run2 DD	MLP > 0.885	97.0	90.5
Run2 LL	MLP > 0.301	98.0	97.5

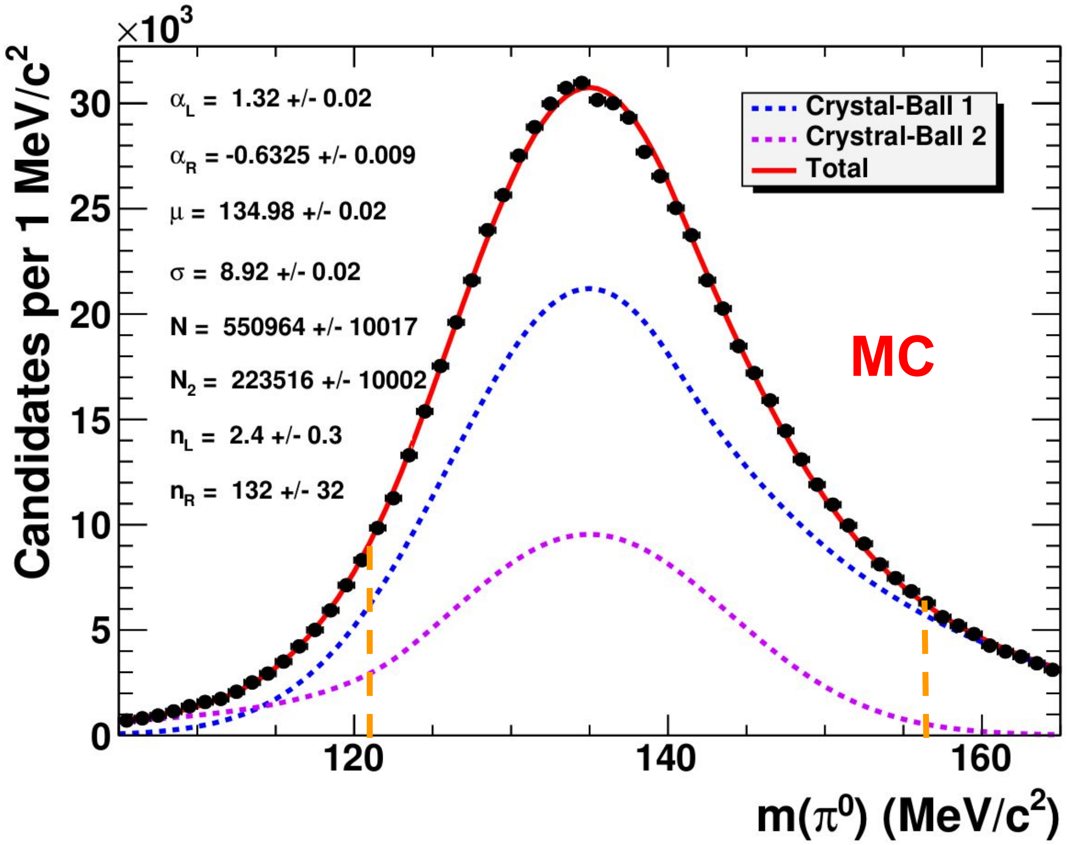
- $m(K_s^0)$ selection by optimisation of $\frac{S}{\sqrt{S+B}}$ in left and right sides of the peak on DATA



- $m(\pi^0)$ selection by optimisation of $S/\sqrt{S+B}$ in left and right sides of the peak on DATA
  Combinatorial Background modelled with a technique where signal PDF is driven by MC

Exemple with Run 2 KsDD (Similar in other categories) :

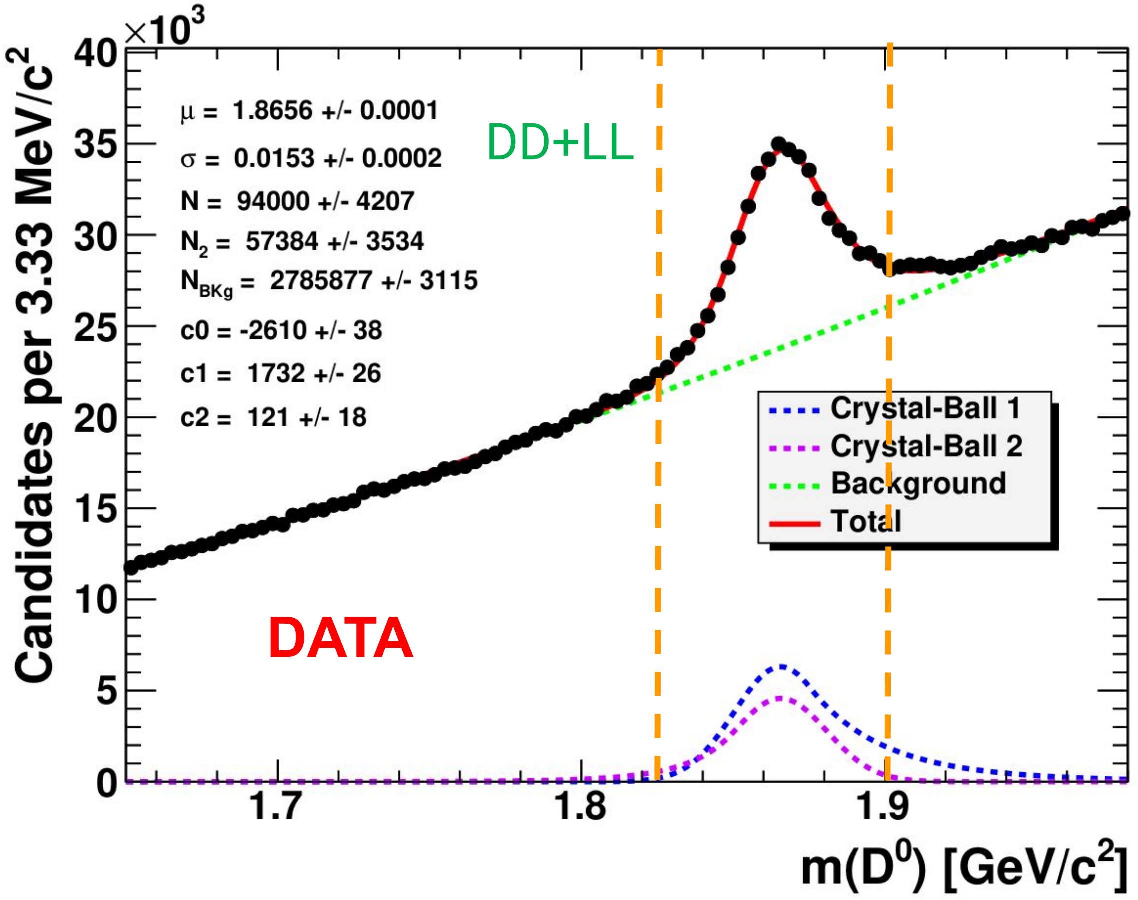


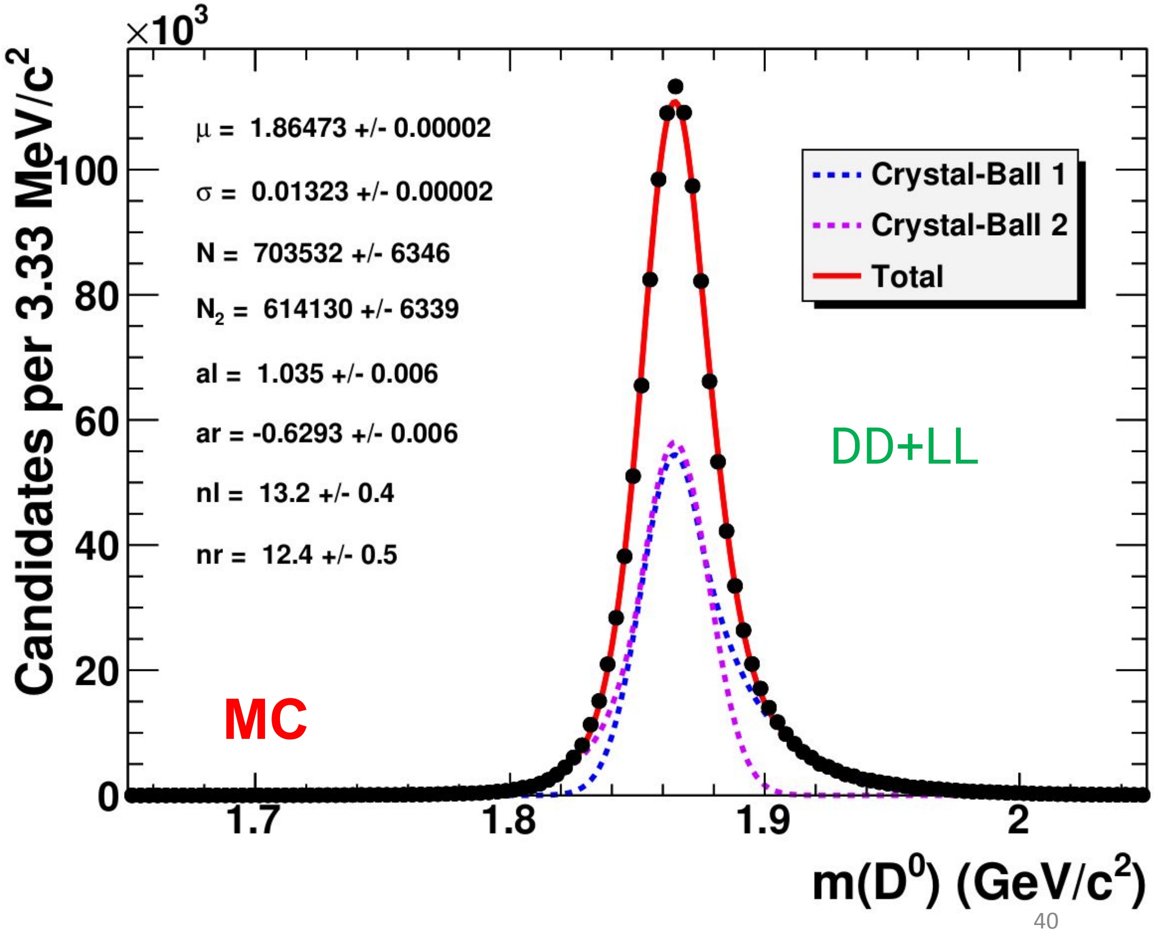


Selection : mass cuts

- $m_{DTF}(D^0)$ selection by optimisation of $\frac{S}{\sqrt{S+B}}$ in right side on DATA (arbitrary cut at 2.5σ for left side, with test on tighter cuts)

  Sum over the 4 categories :

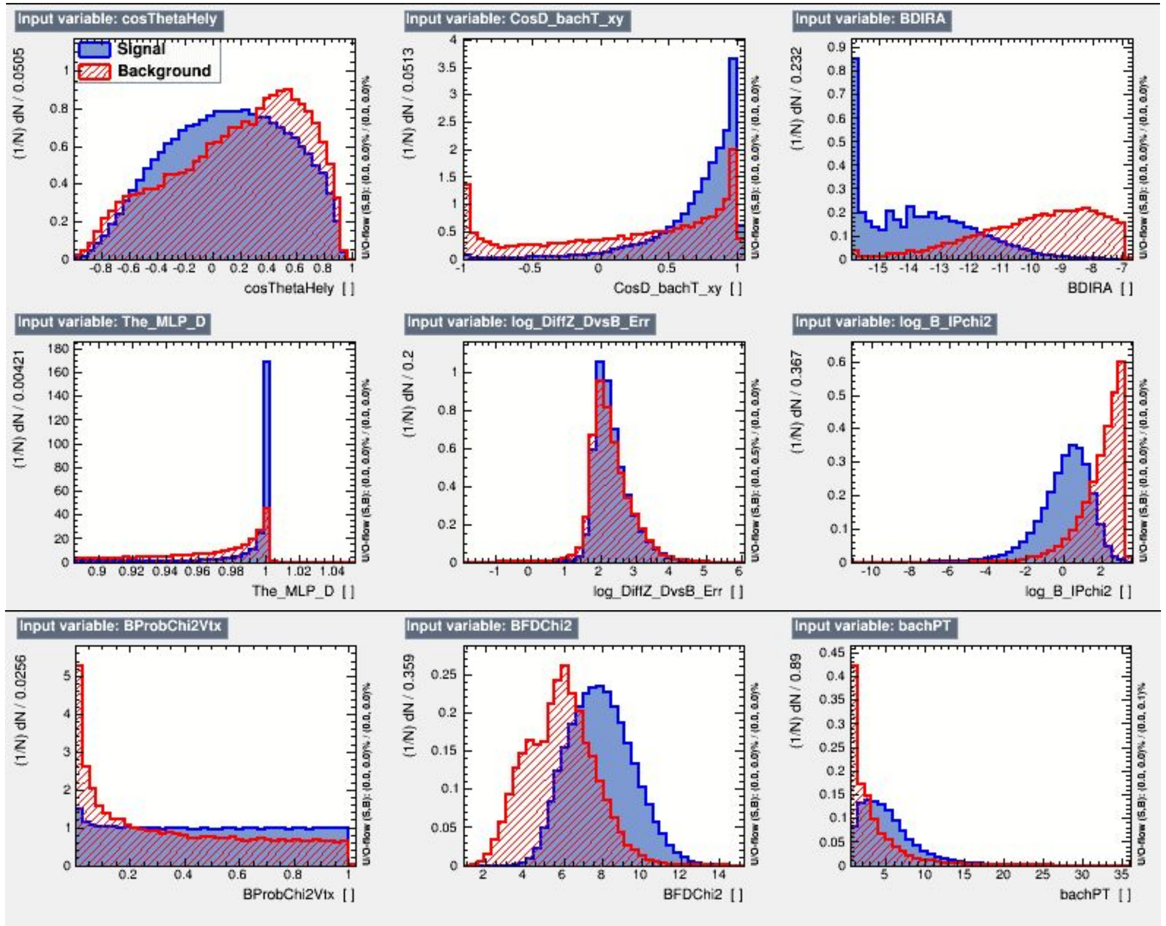


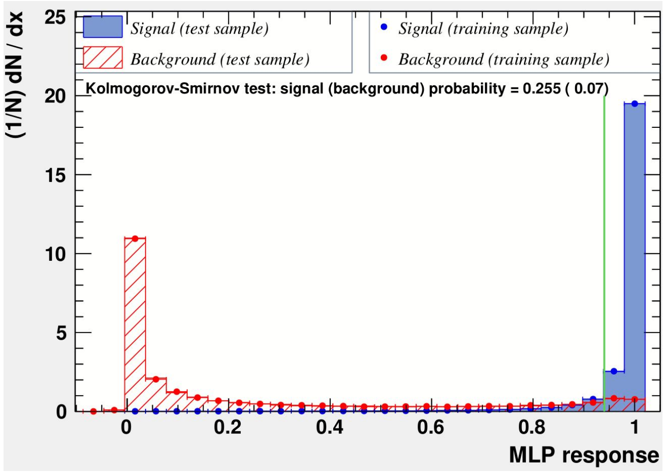


MVA2	
Variable name	**Description**
cosThetaHely	Helicity angle between $B^{\pm}$ and D^{0} in $B^{\pm}$ rest-frame
CosD_bachT_xy	Angle between D^{0} and bachelor track in transverse plan
BDIRA	Alignment between $B^{\pm}$ flight direction and reconstructed momentum
The_MLP_D	Output ofthe first MVA
log_DiffZ_DvsB_Err	Distance between $B^{\pm}$ and D^{0} vertices along the beam axis
log_B_IPchi2	χ^{2} of the $B^{\pm}$ impact parameter
BProbChi2Vtx	$B^{\pm}$ vertex quality
BFDChi2	Statistical significance of the distance between PV and $B^{\pm}$ vertex
bachPT	Transverse momentum of the bachelor track

Selection : Second MVA

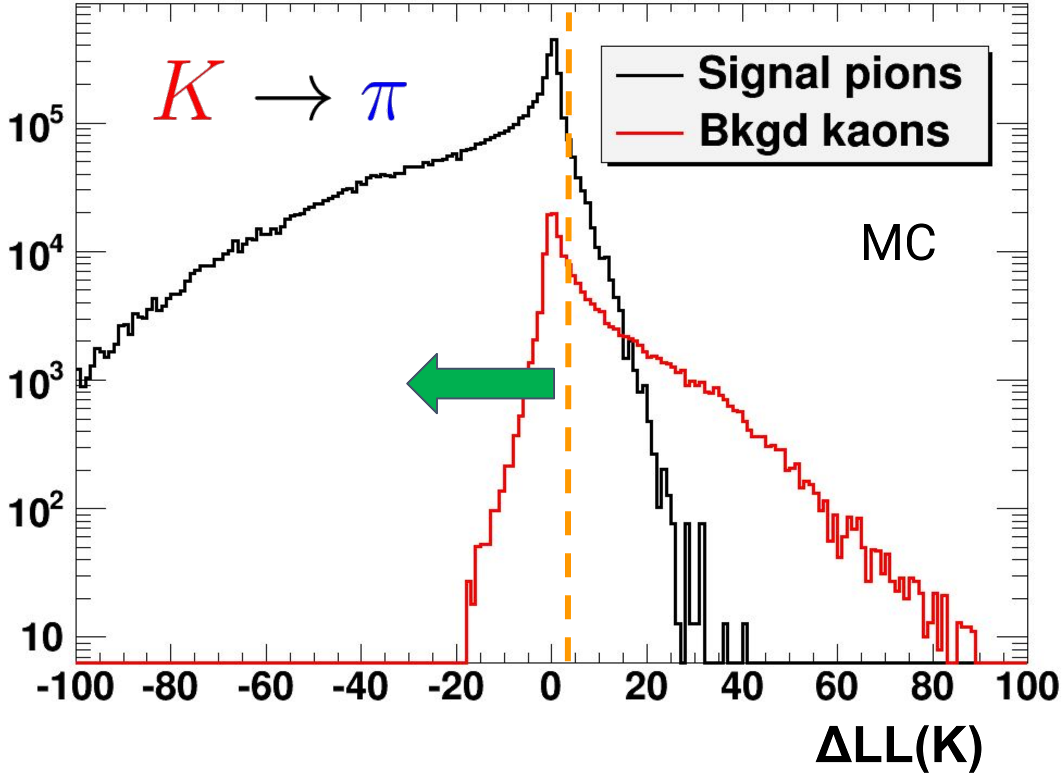
- Second MVA on B decay geometrical and topological parameters using a MLP method
  - **Signal** = Simulated phase-space signal with BKGCAT $\in \{0, 10\}$ + m($B^{\pm}$) within 50 MeV around PDG value
  - **Background** = Data events in m($B^{\pm}$) upper side-band
- Cut position chosen to maximize the statistical significance

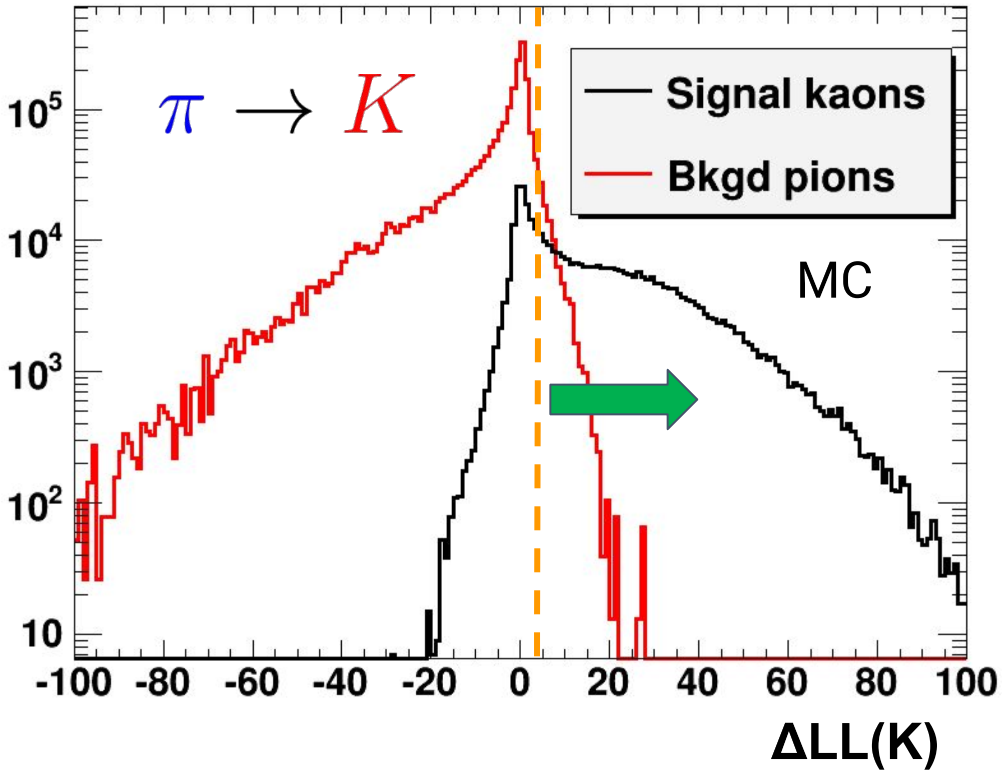




Category	Selection	Signal efficiency (%)	Background efficiency (%)
Run1 DD	MLP > 0.985	86.1	8.0
Run1 LL	MLP > 0.948	89.0	7.7
Run2 DD	MLP > 0.940	90.2	6.3
Run2 LL	MLP > 0.927	90.8	6.1

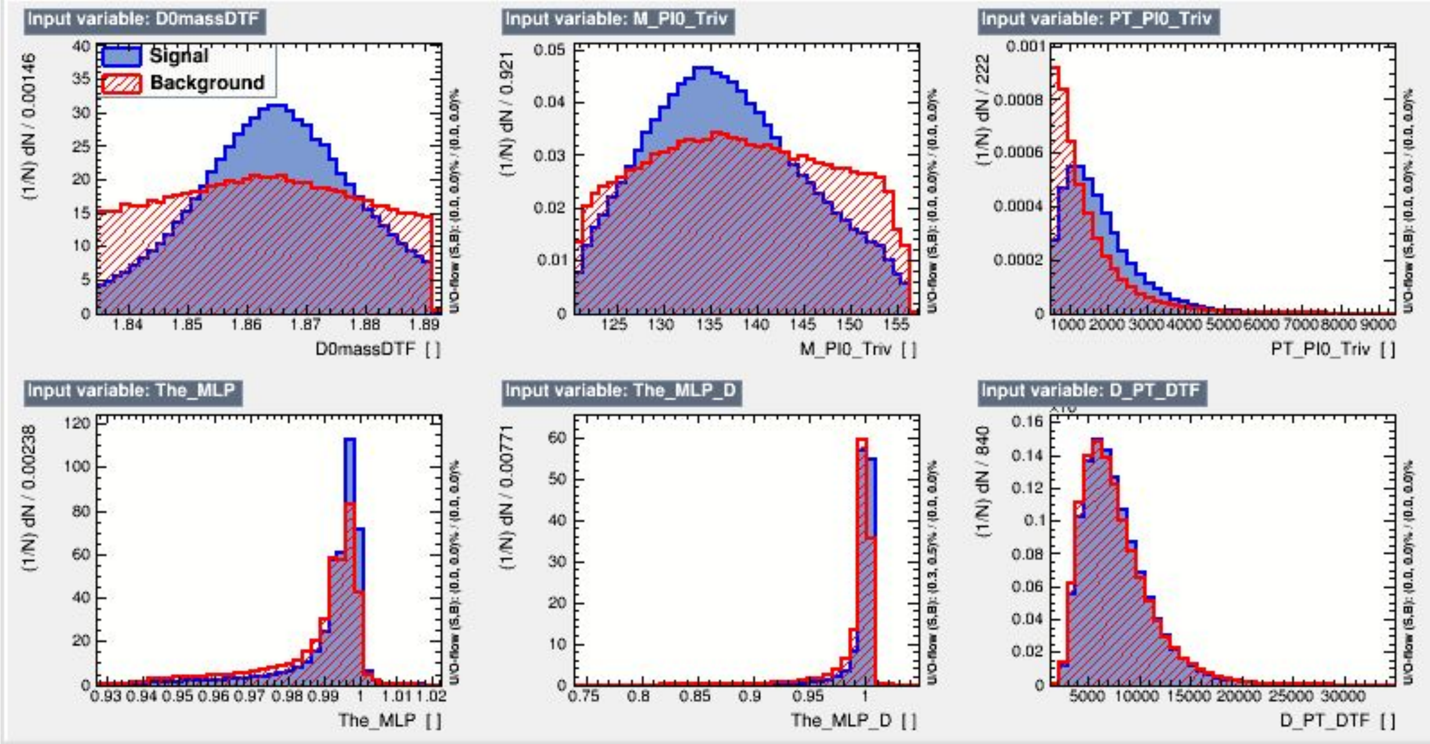
Selection : bachelor PID

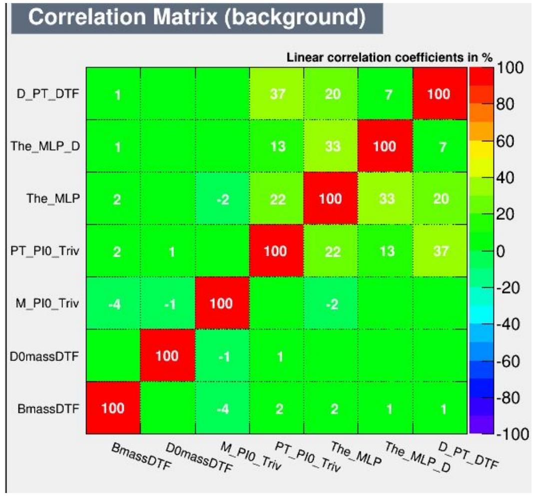


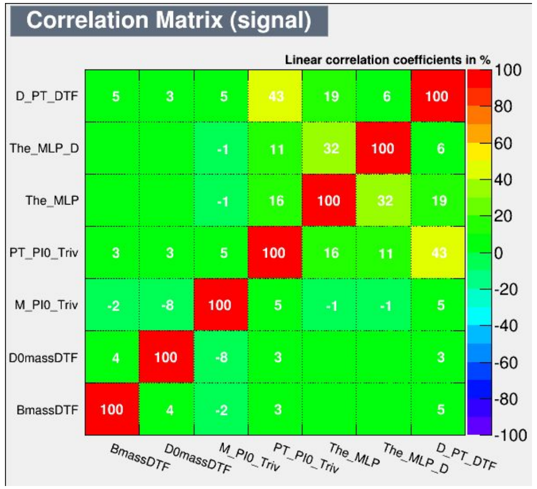


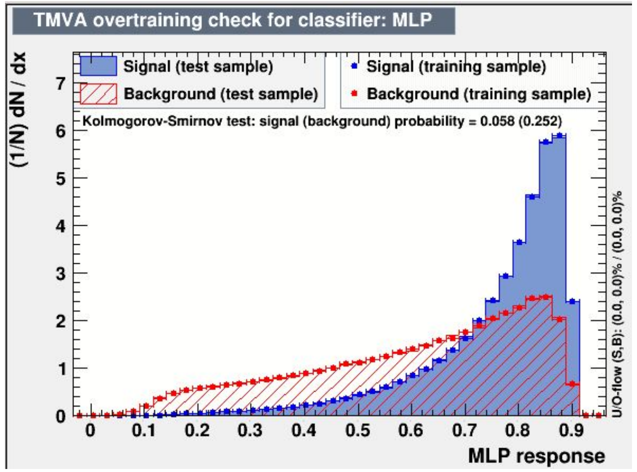
- To limit misidentification of the bachelor track, we discriminate using a PID Likelihood Difference
- ~70.7% signal efficiency / ~2.6% misidentification efficiency for $B \to D^0 K^{\pm}$
- For MC, ΔLL(K) variable corrected with PIDcorr tool

Selection









- Multiple candidates (~6%) are filtered, choosing the best candidate thanks to a MVA trained on MC, discriminating BKGCAT=0 and BKGCAT>0 (Variables uncorrelated to B mass)

Selection

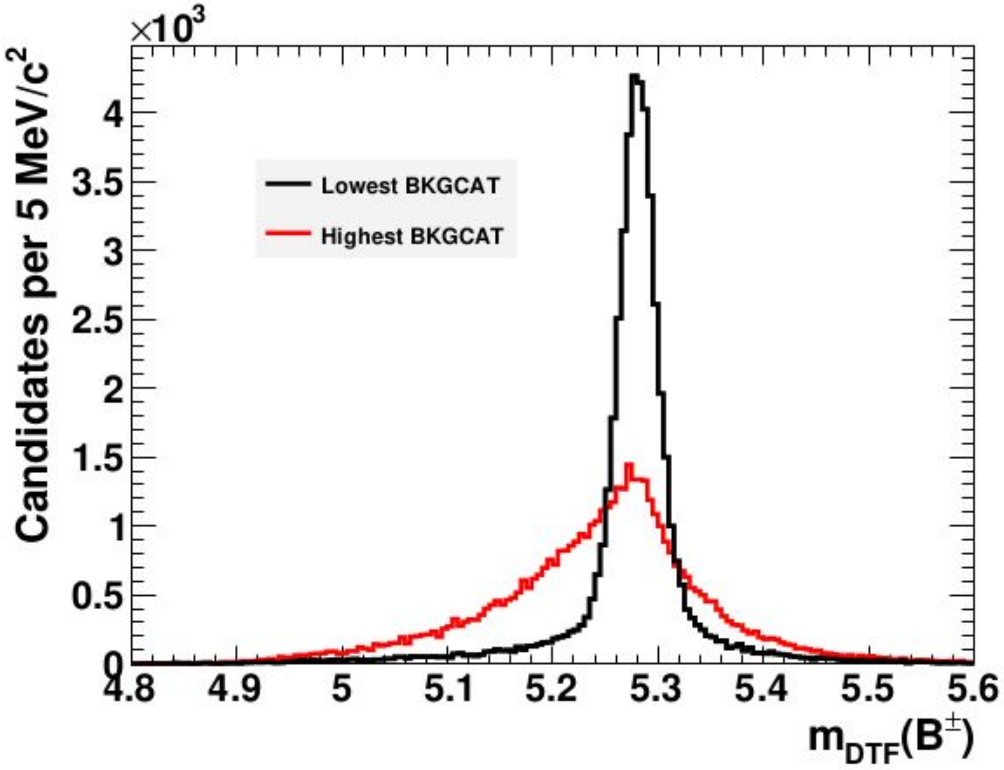


Figure 8.41: Distributions of $m_{DTF}(B^{\pm})$ for the lowest (black) and highest (red) `BKGCAT` for simulated events with multiplicity.

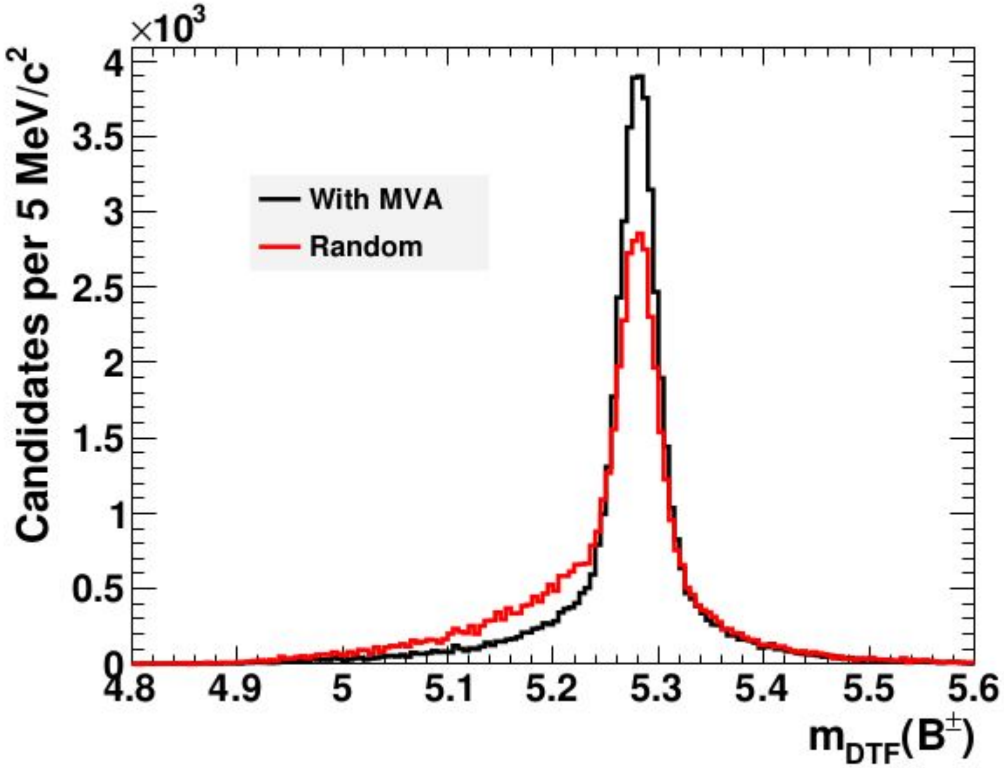
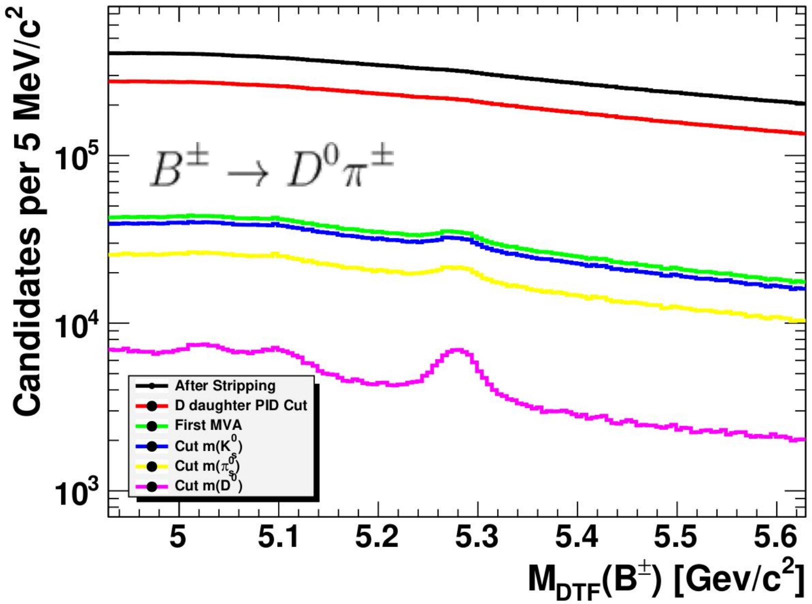
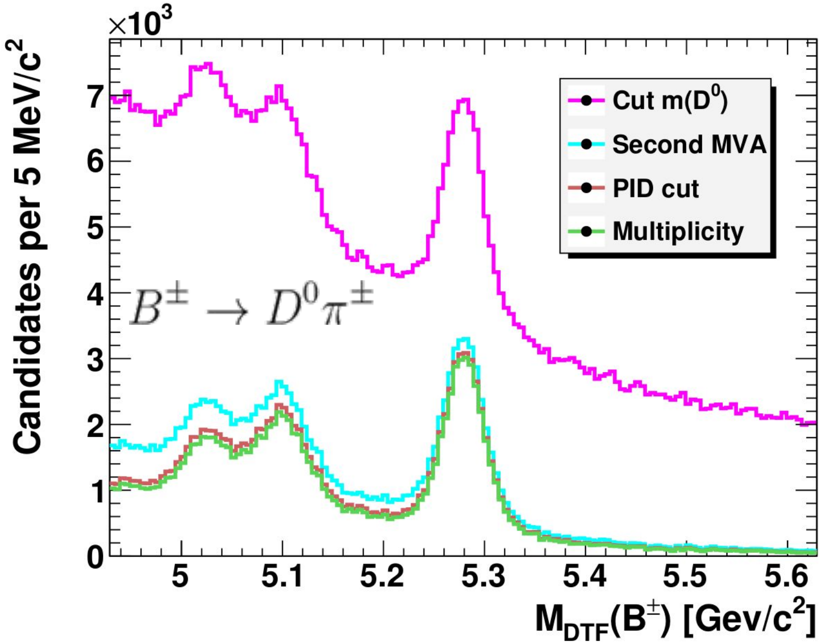


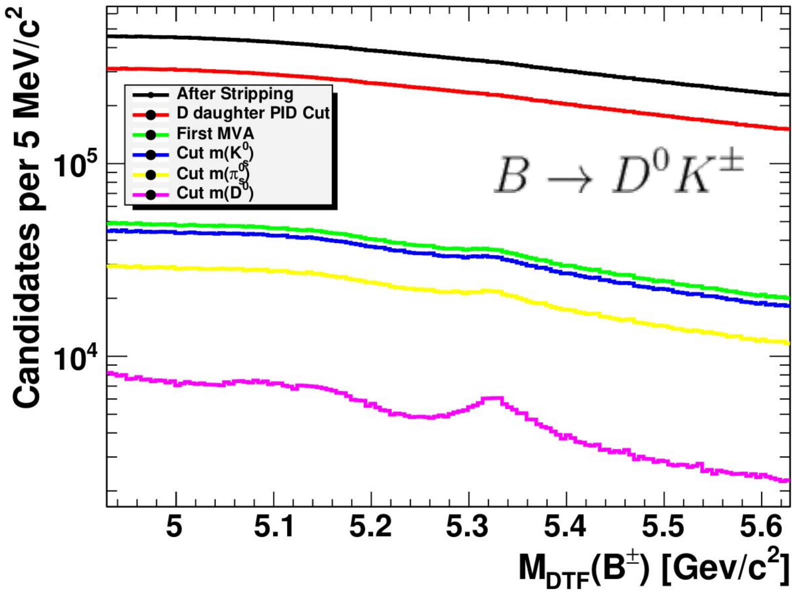
Figure 8.42: Distributions of $m_{DTF}(B^{\pm})$ for simulated events with multiplicity. Best candidates are selected by the `MVA` method (black) or randomly (red).

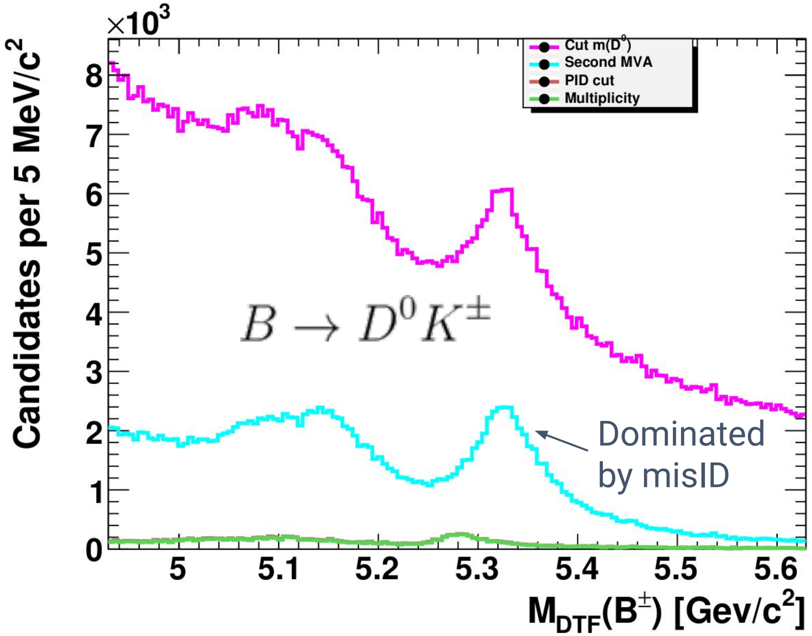
Selection : Summary

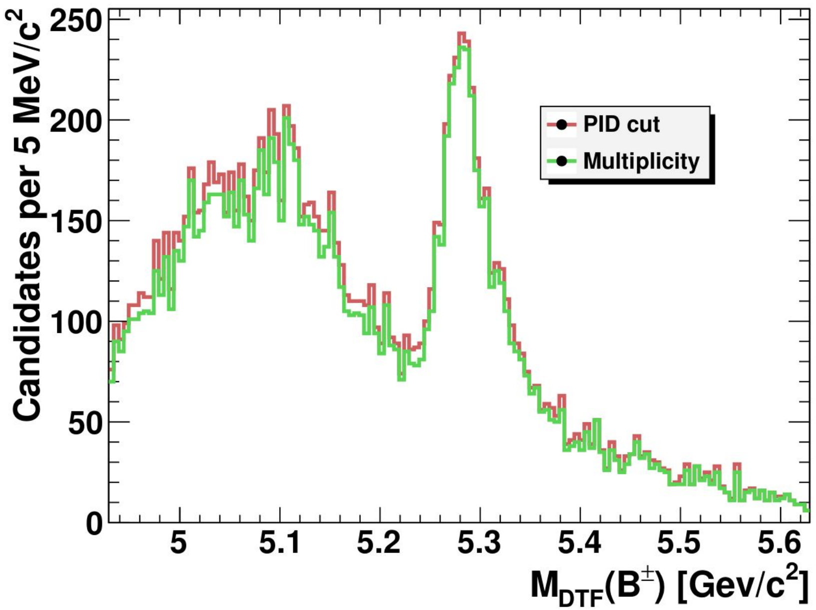




10³ to 10⁴ rejection factor on background







Background Study

A complete study of physical background has been processed, using **full simulation of >20 modes**

Here is a list of studied backgrounds. **Non-negligeable ones are surrounded** for $B^\pm \to D^0\pi^\pm$ and $B \to D^0 K^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\pi^0]\pi^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\gamma]\pi^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\pi^0]K^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\gamma]K^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\pi^0]\rho^\pm(\to \pi^\pm\pi^0)$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi)\gamma]\rho^\pm(\to \pi^\pm\pi^0)$

$B^\pm \to D^0(\to K_s\pi\pi)\rho^\pm(\to \pi^\pm\pi^0)$

$B^\pm \to D^0(\to K_s\pi\pi)K^{*\pm}(\to K^\pm\pi^0)$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\pi^0]\pi^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\gamma]\pi^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\pi^0]K^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\gamma]K^\pm$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\pi^0]\rho^\pm(\to \pi^\pm\pi^0)$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\gamma]\rho^\pm(\to \pi^\pm\pi^0)$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\pi^0]K^{*\pm}(\to K^\pm\pi^0)$

$B^\pm \to D^{*0}[\to D^0(\to K_s\pi\pi\pi^0)\gamma]K^{*\pm}(\to K^\pm\pi^0)$

$B^\pm \to D^0(\to K_s\pi\pi\pi^0)\rho^\pm(\to \pi^\pm\pi^0)$

$B^\pm \to D^0(\to K_s\pi\pi\pi^0)K^{*\pm}(\to K^\pm\pi^0)$

$B^0 \to D^{*\pm}[\to D^0(\to K_s\pi\pi\pi^0)\pi^\pm]\pi^\mp$

$B^0 \to D^{*\pm}[\to D^0(\to K_s\pi\pi\pi^0)\pi^\pm]K^\mp$

$B_s^0 \to D^0(\to K_s\pi\pi\pi^0)K^\mp\pi^\pm$

MC produced in Square-Dalitz + **weighted with Laura++** to account for resonances (LHCb amplitude model LHCb-PAPER-2014-036)

No peaking background !

- Additional study has been made in K_S^0 and D^0 sidebands, **limiting impact of K_s-less and charm-less backgrounds** to less than 0.66% and 0.15% on the signal respectively at 90% CL.

- Background components are included in global mass fit through parametric PDFs "**RooKeyPDF**" **objects** (after a smearing to adapt MC to DATA signal width)

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Charm-less background

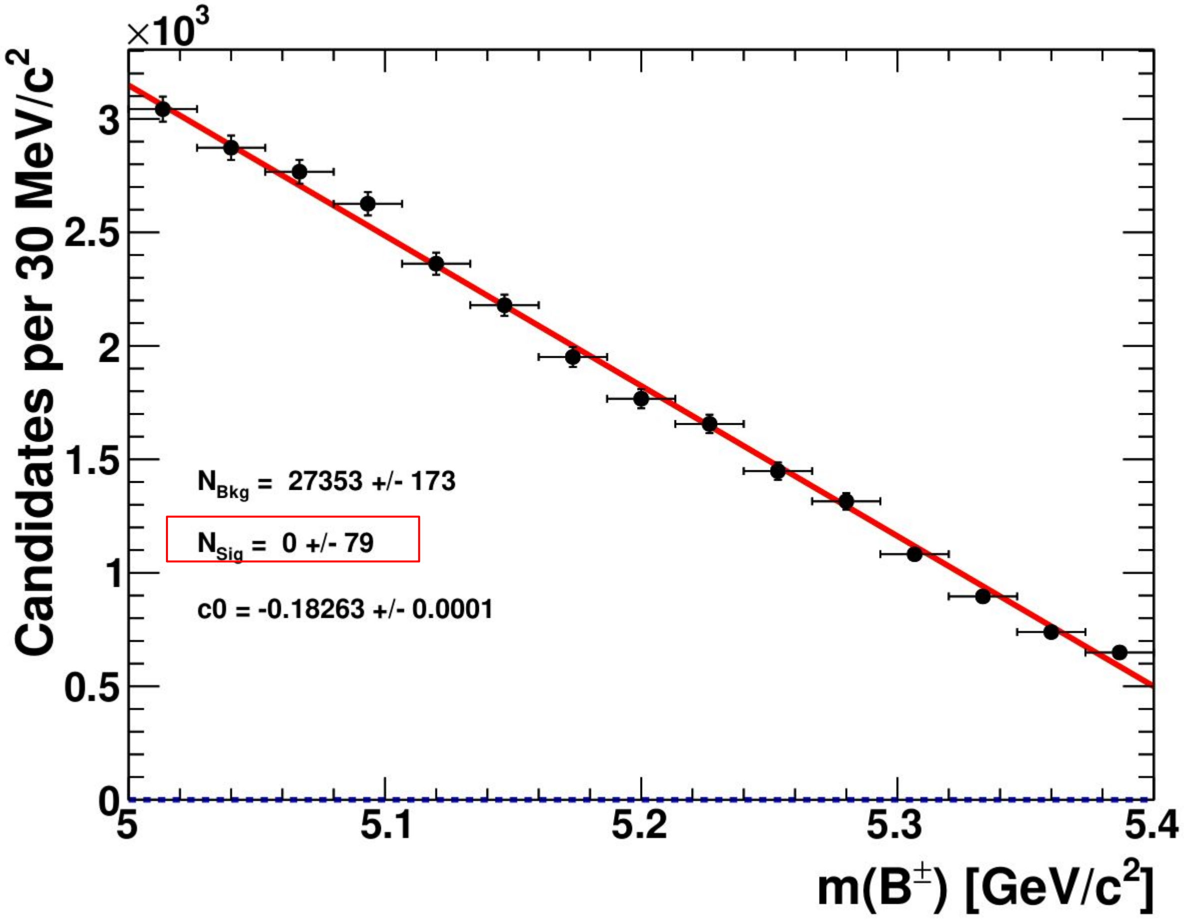
Charmless background has been studied :

→ Tested on $B \to D\pi$ sample

→ In D° side-band ($m_{DTF}(D^0) < 1.8\,\mathrm{GeV}/c^2$)

→ With $Z_{vtx}(B) - Z_{vtx}(D) < 3\sigma$

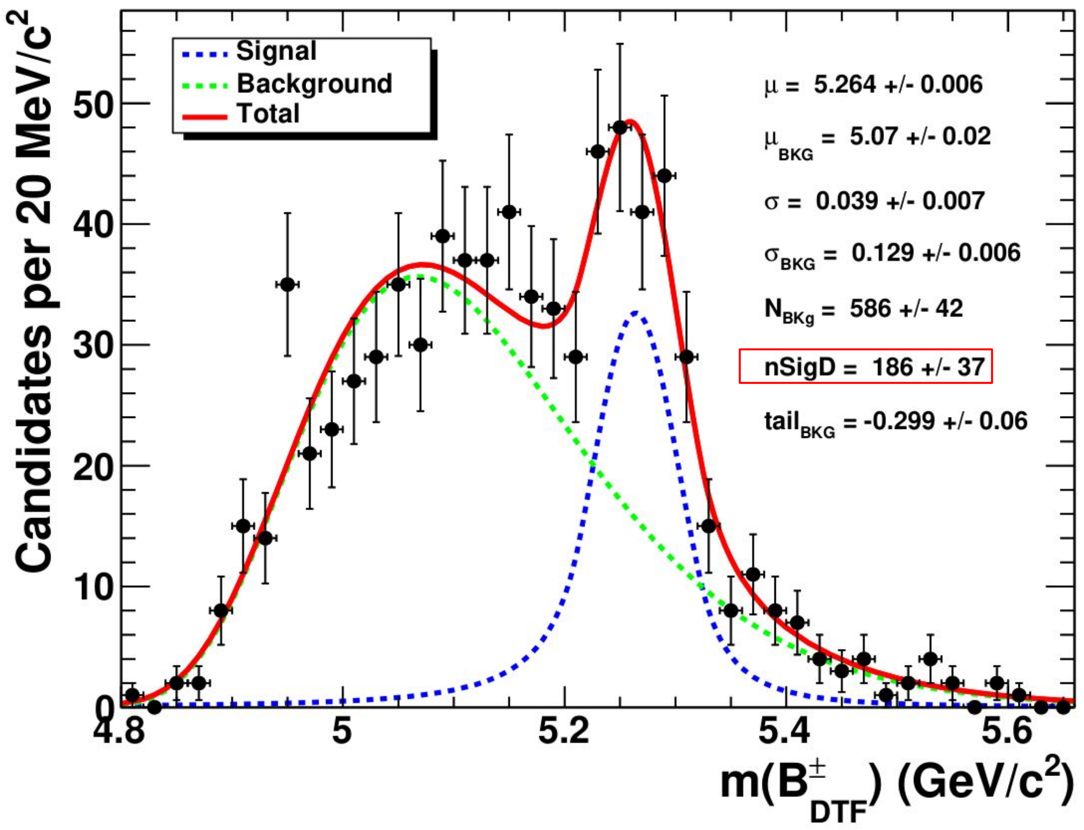
→ Once renormalised on selected signal, limit at 90% CL to 62 events in B->Dπ -> 0.19% of signal



Ks-less background

→ Only for $K_s^0 LL$ (D^0 and K_s^0 vertexes are mingled -> K_s^0 candidate vertex in VELO)

→ Measured in K_s^0 sidebands ($m(K_s^0) \notin [480, 515] MeV/c^2$) with $\boldsymbol{Z_{vtx}(K_s^0) - Z_{vtx}(D^0) < 3\sigma}$



→ A portion of this peak (~4 evts) is residual signal (estimated from MC signal)

→ Counting for this, there still is a significant Ks-less background

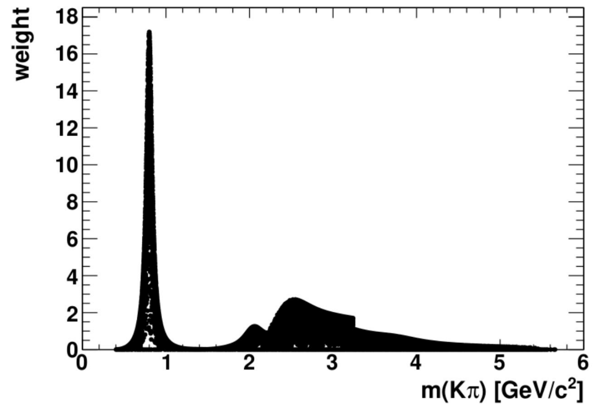
→ Renormalising with the side-band width and to the total data sample (including $K_s^0 DD$), this leads to a proportion of signal of :

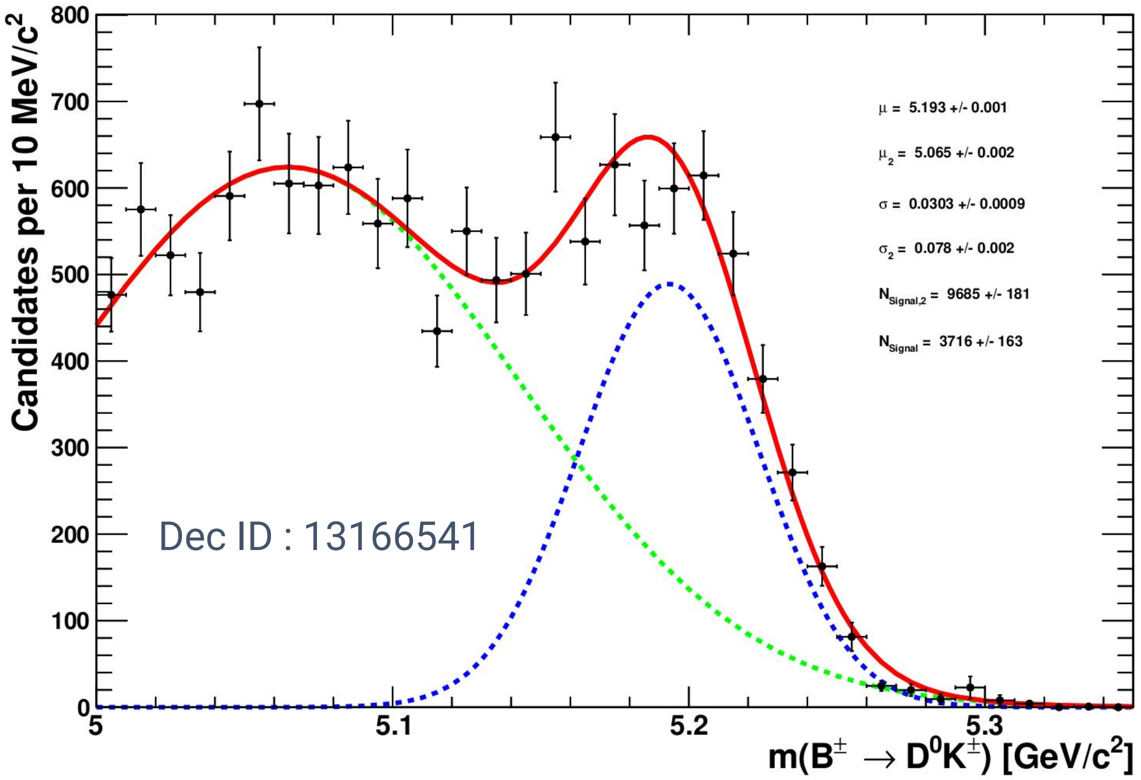
$$\mathbf{0.52 \pm 0.11\ \%}$$

→ Small enough not to be considered -> Only in systematics

$B_s^0 \to D^0 K \pi$ background

-> MC produced in Square-Dalitz + **weighted with Laura++** for resonances





→ Not a peaking background

→ Has to be considered in the partially reconstructed backgrounds

→ For nominal fit, yield will be fixed compare to signal yield. The ratio between both has been calculated taking into account efficiency ratio and BF ratio.

→ Fixed yield to 4.82+-0.9% of signal yield

Global Fit

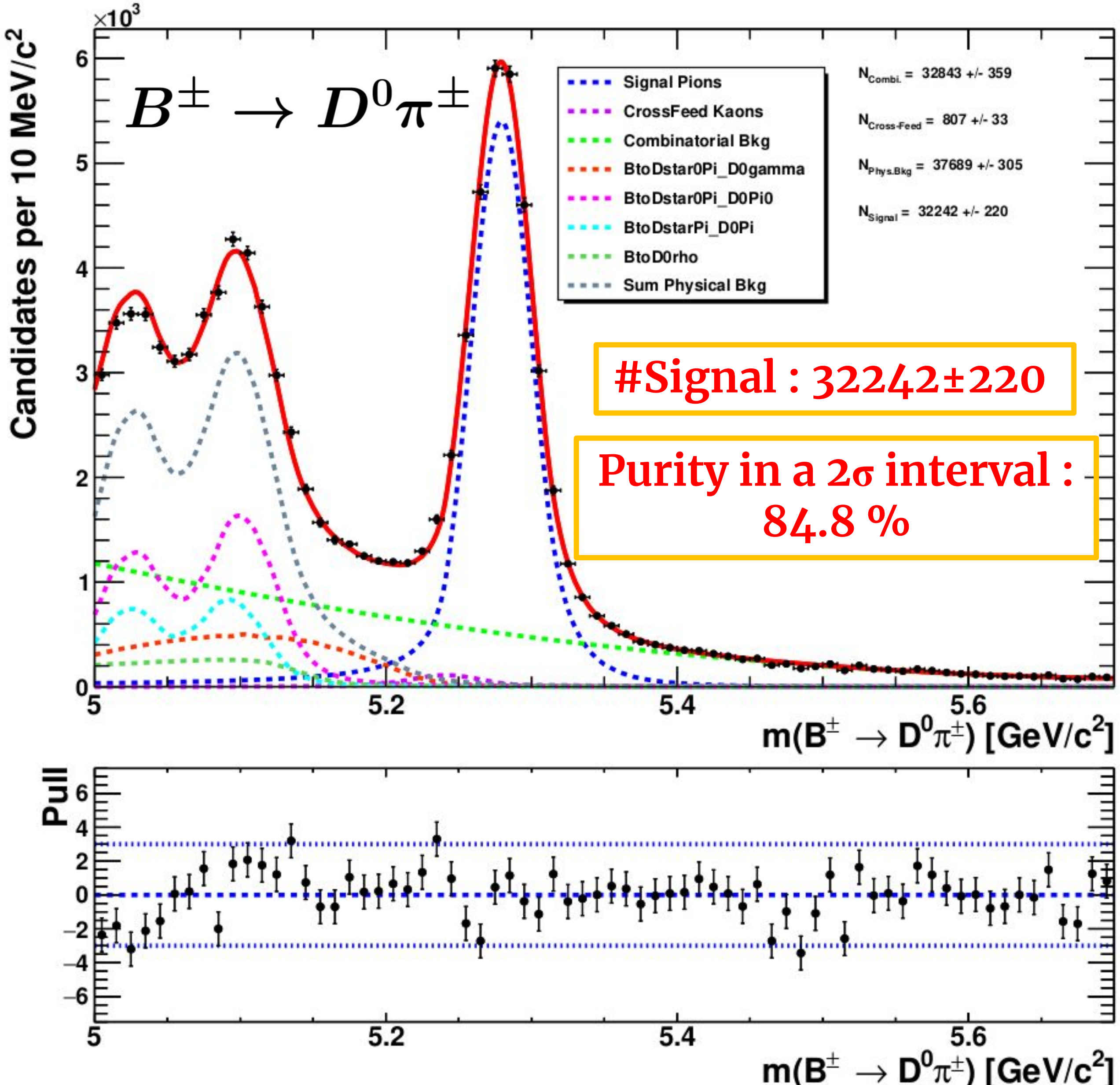
- **Signal** : double-sided Crystal-Ball function
  - Left tail fixed from MC
  - Right tail, mean, width are free

- **Combinatorial** : free Chebychev polynomial of order 2

- **Cross-Feed** : Shape from MC (RooKeyPdf)
  - Yield constrained from $B \to DK$ signal yield (see next slide)

- **Partially-reconstructed backgrounds** : Shape from parametric PDFs (“RooKeyPDFs”) to MC
  - Most of individual components yields constrained one to the other from relative BRs and selection efficiencies

-> Validated with toy simulation studies !



Reminder : 9981±134 events at Belle
→ Statistics ×3

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Global Fit

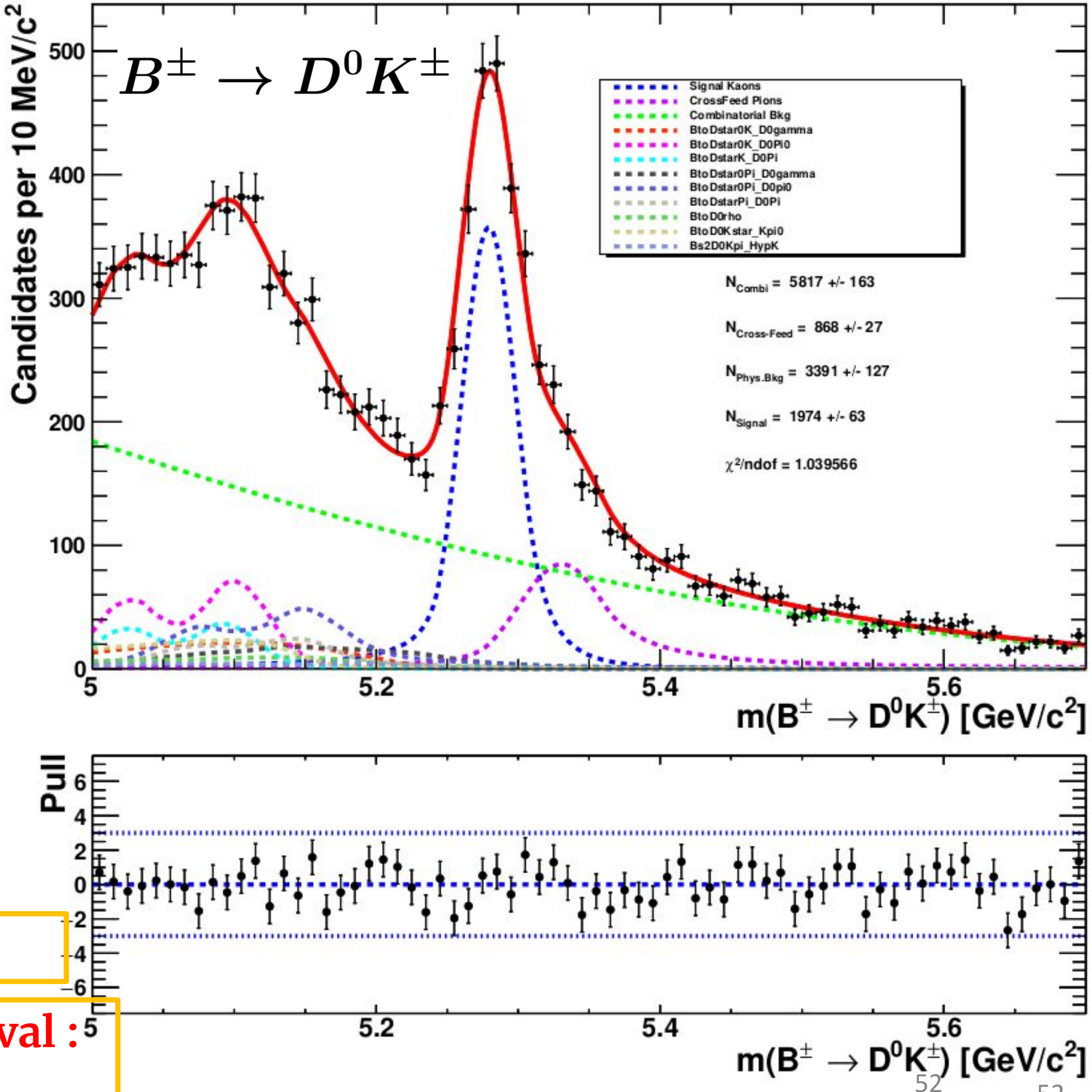
- **Signal** : double-sided Crystal-Ball function
  - Parameters fixed to $B \to D\pi$ fit ones

- **Cross-feed** :
  - Shape from $B \to D\pi$ data sample with misID mass hypothesis
  - Yield constrained from $B \to D\pi$ signal yield and MC efficiencies

- **Combinatorial** : free Chebychev polynomial of order 2

- **Partially-reconstructed background** :
  - Shapes from parametric PDFs on MC
  - Relative yields constrained from BRs and efficiencies

-> Validated with toy simulation studies !



<u>Reminder</u> : 815±51 events at Belle
→ Statistics ×2.5

#Signal : 1974±63

Purity in a 2σ interval : 61.3%

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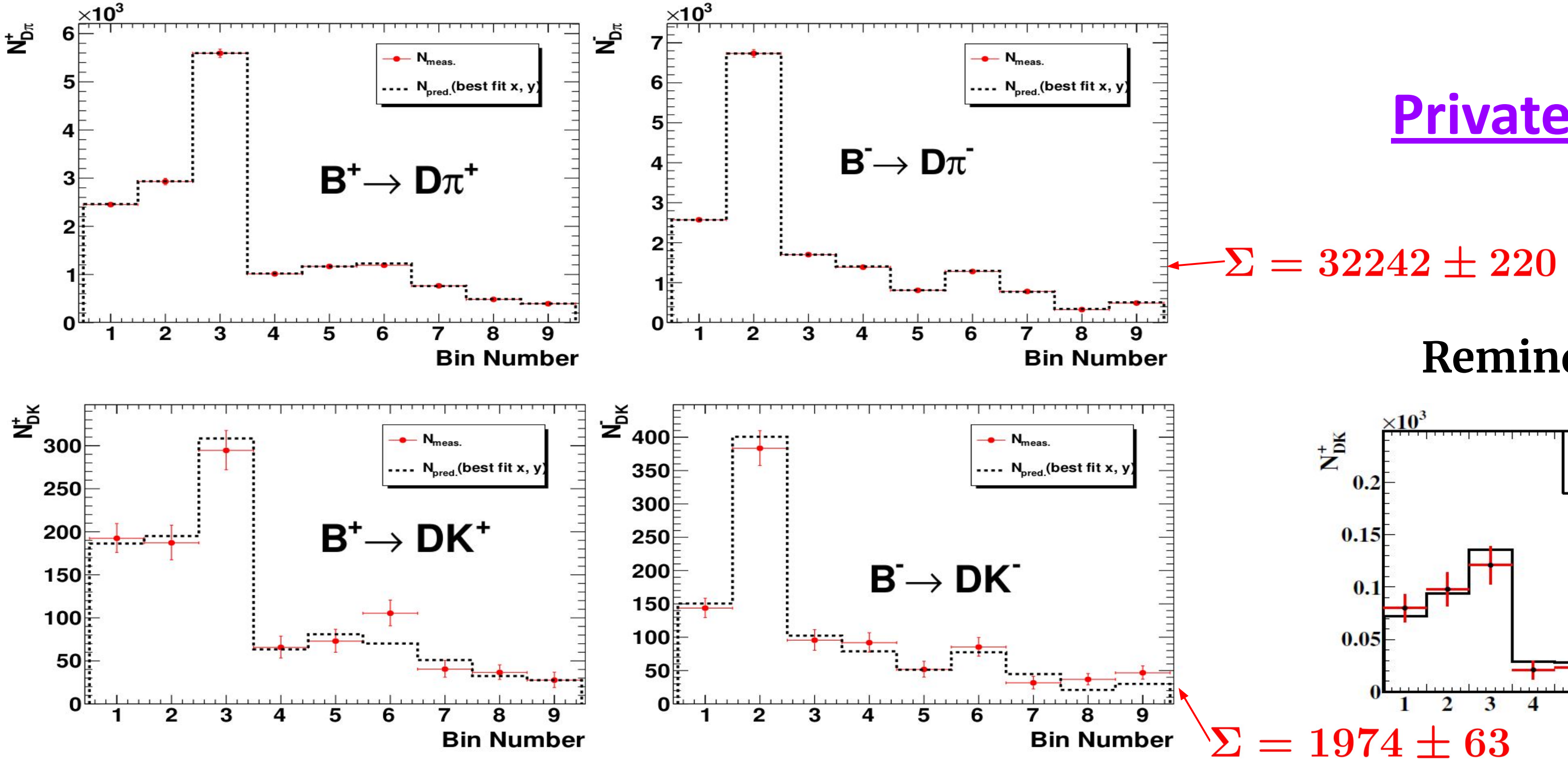
CP-fit on DATA

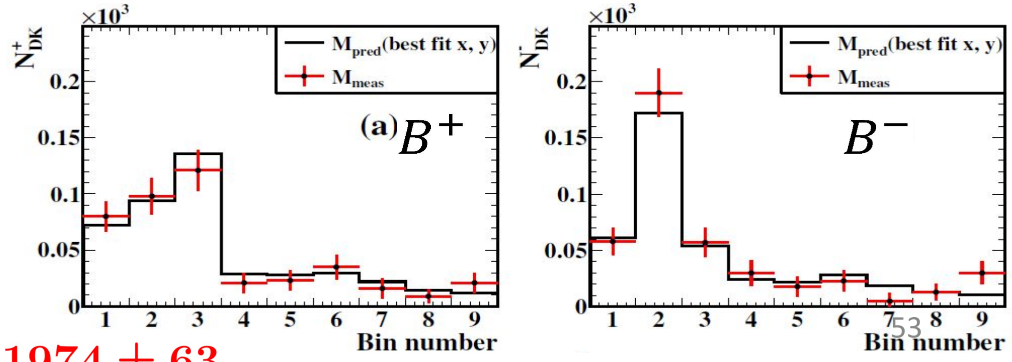
Run simultaneous unbinned minos CP-fit on DATA (**36 categories**):

- **All shapes fixed** by global fits (signal, physical and combinatorial backgrounds, cross-feed)
- **Sum of the yields** (integrated over bins) **constrained** to the yields in the global fits
- **For fit stability**, CP-observables $x_\pm^{D\pi}$ and $y_\pm^{D\pi}$ are fixed for $B \to D\pi$ channel, according to LHCb combination (-> systematic uncertainty)
- Consider two separate values for $r_B^{DK,-} = \sqrt{(x_-^{DK})^2 + (y_-^{DK})^2}$ and $r_B^{DK,+} = \sqrt{(x_+^{DK})^2 + (y_+^{DK})^2}$



Private authorized unblinding

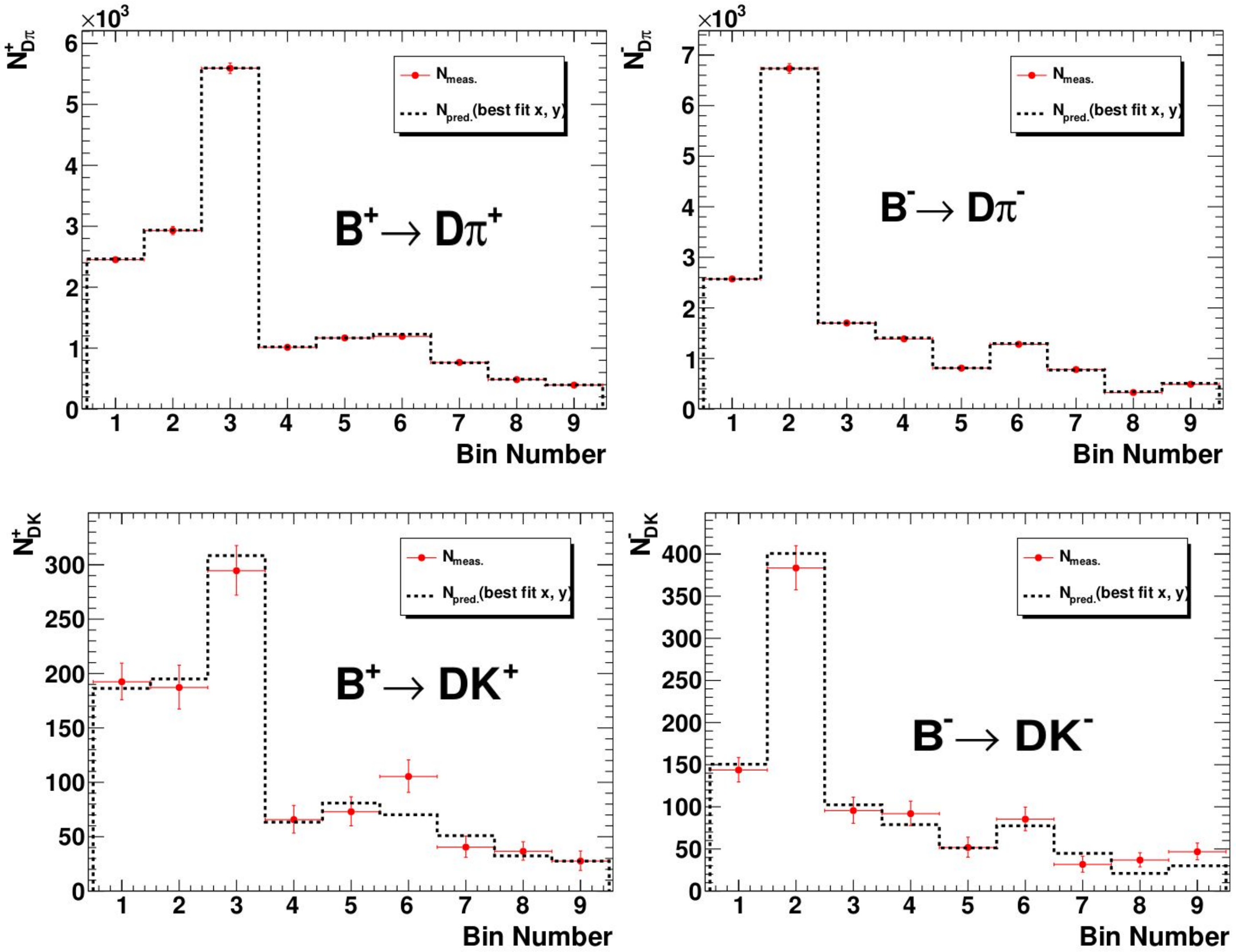
Reminder, for BELLE :



Cross-Check : Yields per category in DATA

Cross-check : measure the yields in each bin in DATA through **individual fits per bins**

- Shapes are taken from global fit
- Free signal yields



$$
\begin{cases}
N^{-}_{i,DK} = f^{-}_{DK}\left(F_i + {r_B^{DK}}^2 \overline{F_i} + 2\sqrt{F_i\overline{F_i}}\,(c_i x_-^{DK} + s_i y_-^{DK})\right) \\
N^{+}_{i,DK} = f^{+}_{DK}\left(\overline{F_i} + {r_B^{DK}}^2 F_i + 2\sqrt{F_i\overline{F_i}}\,(c_i x_+^{DK} - s_i y_+^{DK})\right) \\
N^{-}_{i,D\pi} = f^{-}_{D\pi}\left(F_i + {r_B^{D\pi}}^2 \overline{F_i} + 2\sqrt{F_i\overline{F_i}}\,(c_i x_-^{D\pi} + s_i y_-^{D\pi})\right) \\
N^{+}_{i,D\pi} = f^{+}_{D\pi}\left(\overline{F_i} + {r_B^{D\pi}}^2 F_i + 2\sqrt{F_i\overline{F_i}}\,(c_i x_+^{D\pi} - s_i y_+^{D\pi})\right)
\end{cases}
$$

→ Expected yield computed from formalism

- \+ $\boldsymbol{x}_{\pm}$ and $\boldsymbol{y}_{\pm}$ from CP-fit
- \+ F_i from CP-fit (led by $B^{\pm} \to D^0\pi^{\pm}$)

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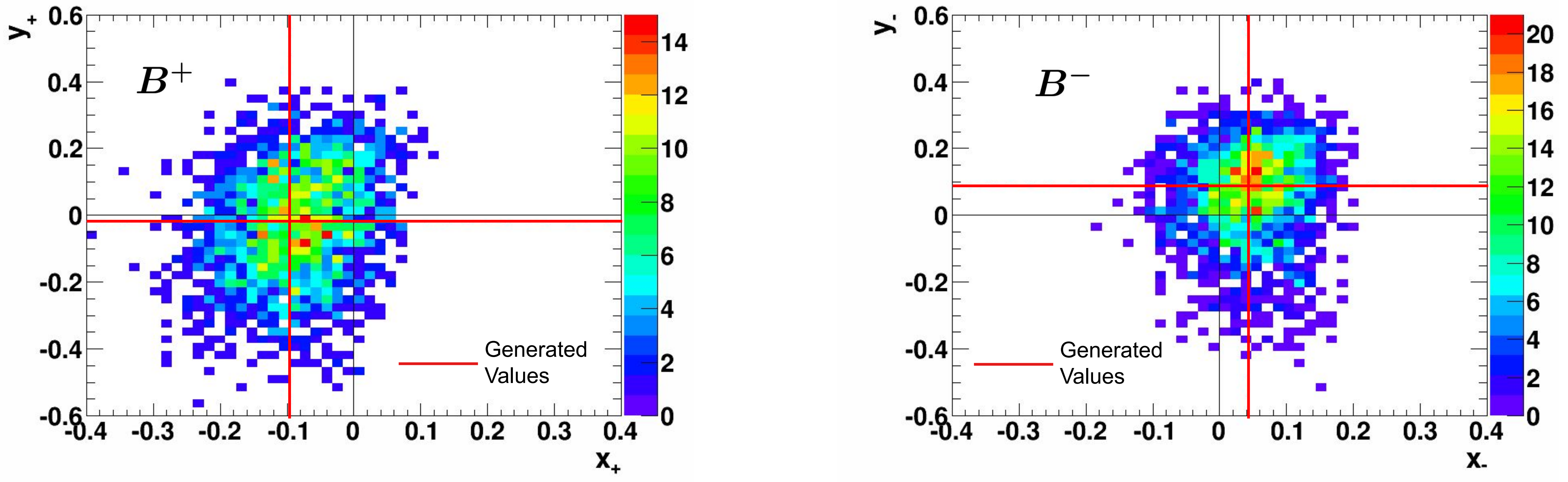
CP-fit Toy Study

Toy study on 2000 pseudo-experiments to test the extraction of **CP-observables $x_{\pm}$, $y_{\pm}$** from simultaneous fit to the **36 categories**

- Pseudo-experiments signal yields generated from the formalism **with inputs from LHCb combination** CONF-2022-003-001.
  - F_i fractions from first estimation on $B \to D\pi$ data sample
- Combinatorial yields according to estimation in $B \to D\pi$ data sample
- Partially reconstructed BKG yields to follow F_i fractions.



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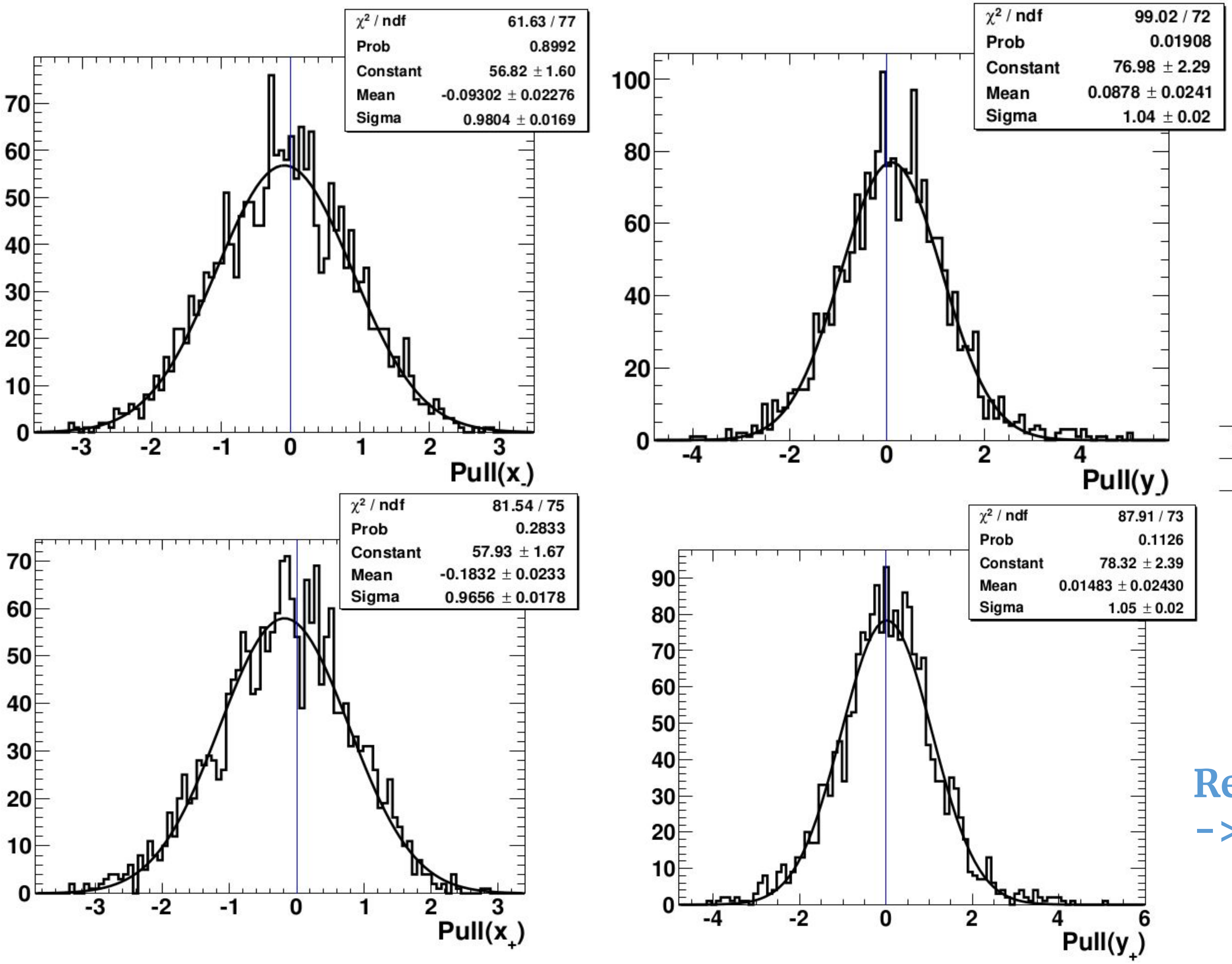
CP-fit Toy Study



- **Pull distributions are Gaussian, as expected**
- **Relatively small biases** (reduced in asymptotic regime)
- **Well-estimated uncertainties**

Parameter	Mean bias (%)	Mean pull (%)	Pull width (%)
	With nominal statistics		
x_-	0.51 ± 0.14	-9.31 ± 2.28	98.04 ± 1.69
y_-	-1.53 ± 0.33	8.78 ± 2.41	104 ± 2
x_+	1.18 ± 0.17	-18.32 ± 2.33	96.56 ± 1.78
y_+	-0.61 ± 0.38	1.48 ± 2.43	105 ± 2

Reminder : $x_\pm$, $y_\pm$ are the main parameters
-> They are used to set the combination !

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Systematic uncertainties

- **c_i/s_i inputs** -> Measured with 2000 pseudo-experiments : <20% of statistical uncertainty on $x_\pm$ and $y_\pm$

  Should be the main systematic

- c_i/s_i from CLEO-c are efficiency corrected -> **we have effective c_i/s_i** due to efficiency variation across phase-space ! -> To be computed
  - In standard GGSZ : measured using amplitude model -> **very small uncertainty**
  - Can use first amplitude model version from Tomaso Pajero (CERN fellow) with $B \to D^*(2010)^+\mu^- X$

- $B \to D\pi$ **physics input** ($r_B^{D\pi}$, $\delta_B^{D\pi}$, γ) -> << statistical uncertainty (~1%)

- Uncertainty on **first bin redefinition** (detector resolution) -> To be computed

- Uncertainty on **bias correction** (see Pull study)

- **CPV and matter regeneration** for K_S^0 meson system -> negligible in similar studies with low statistics

- **Mass-shape parameterisation** for signal and backgrounds

  → Measured at first level using a bootstrapping procedure -> a few % of stat. unc.

  → Impact from the shape variation between bins to be studied

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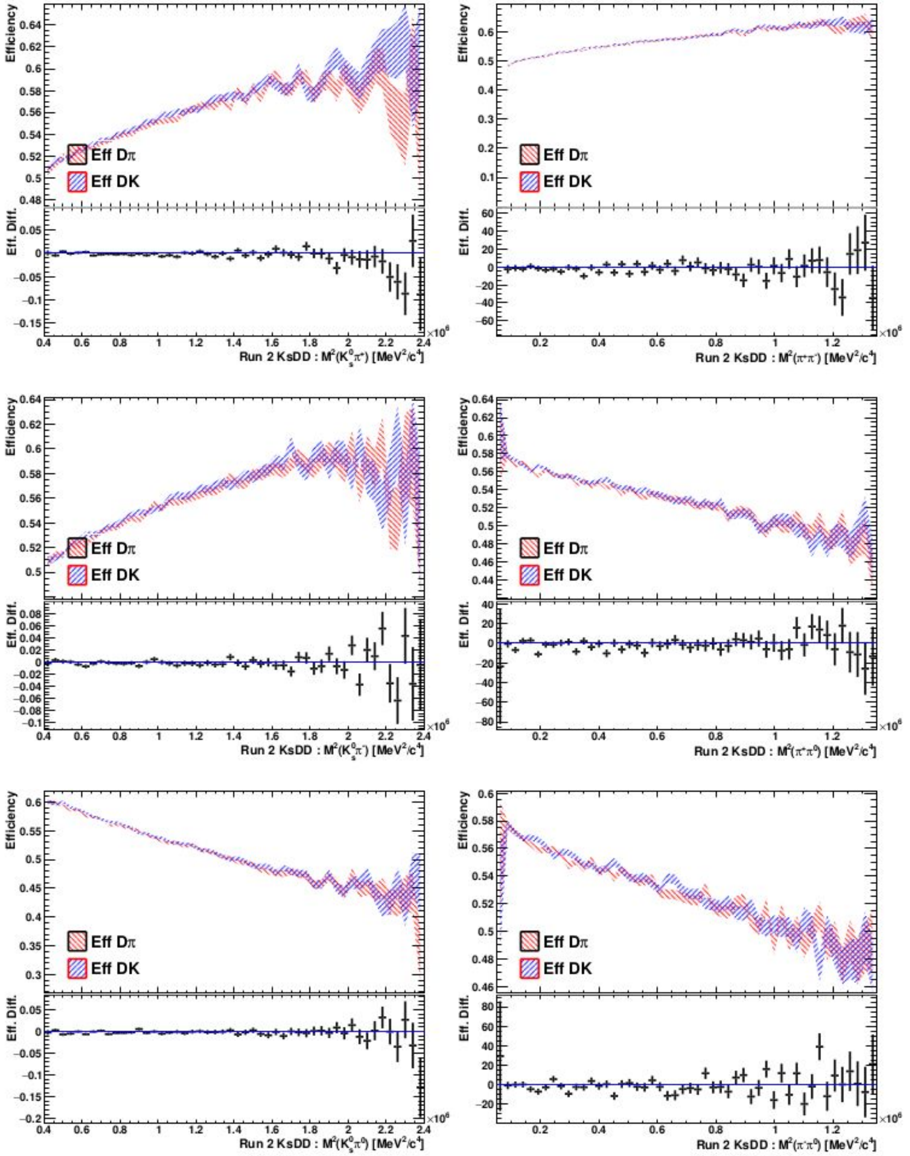
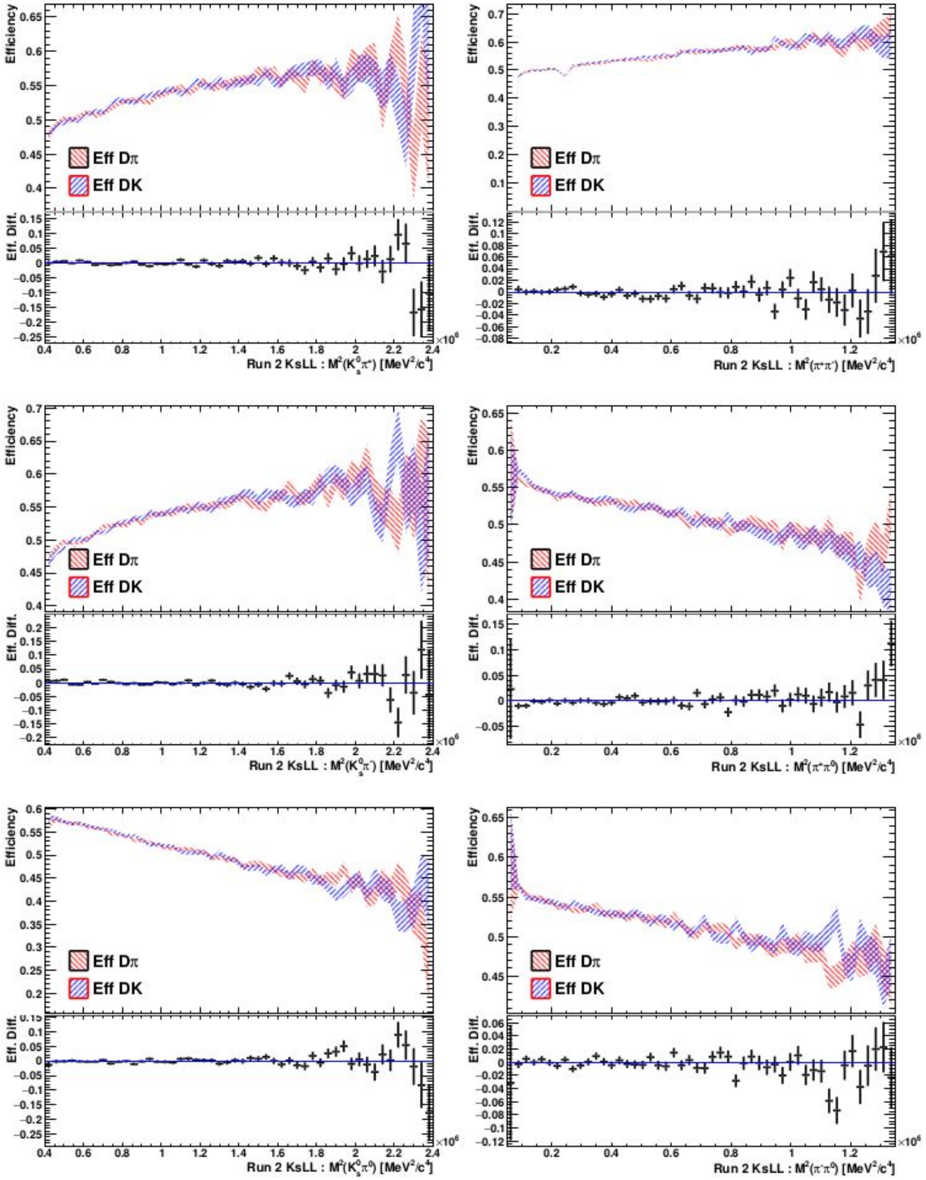
Selection efficiency consistency

-> Project efficiency on each phase-space dimension for both channels :

Run 2
DD



Run 2
LL



c_i/s_i input uncertainties

- Generate 2000 toys in signal only (10000 events B->DK / 164000 events B->Dπ per toy), with physics parameters set to the LHCb combination while varying c_i/s_i input (Correlation taken into account with Cholesky method)
- Toys fitted with the nominal simultaneous fit (fixed CLEO-c c_i/s_i)
- Smaller uncertainty than the one estimated by BELLE analysis

Remainder Stat :

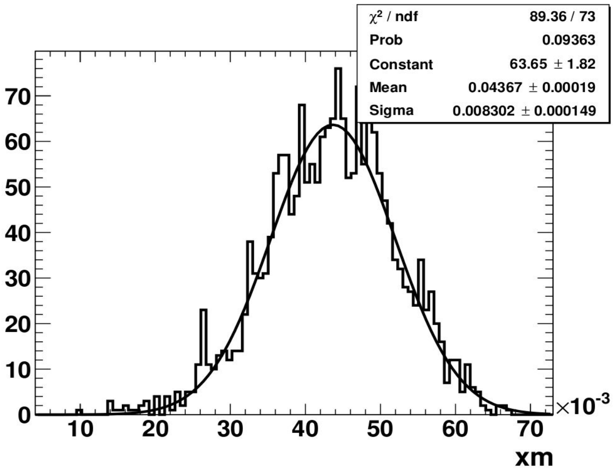
$$x_-^{DK} = XX^{+0.063}_{-0.066}$$
$$y_-^{DK} = XX^{+0.125}_{-0.148}$$
$$x_+^{DK} = XX^{+0.084}_{-0.092}$$
$$y_+^{DK} = XX^{+0.225}_{-0.178}$$

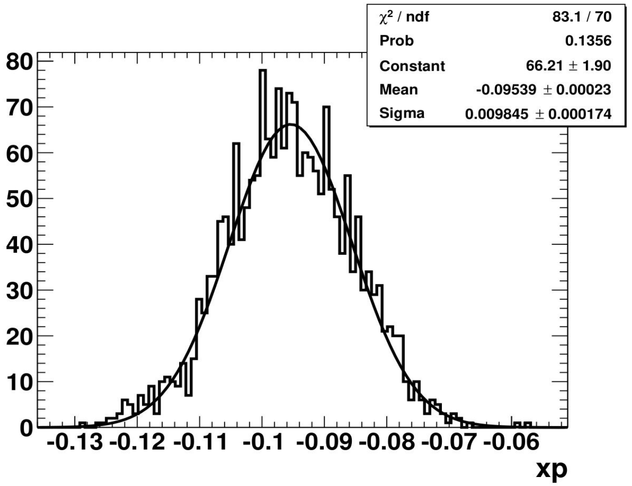
Parameter	Mean	Mean error	Sigma	Sigma Error
xm	0.0436745	0.000194079	0.00830159	0.000148708
xp	-0.0953942	0.000227879	0.00984546	0.000174369
ym	0.0880574	0.000795734	0.0343804	0.00060065
yp	-0.0199105	0.000491541	0.0210182	0.000396295

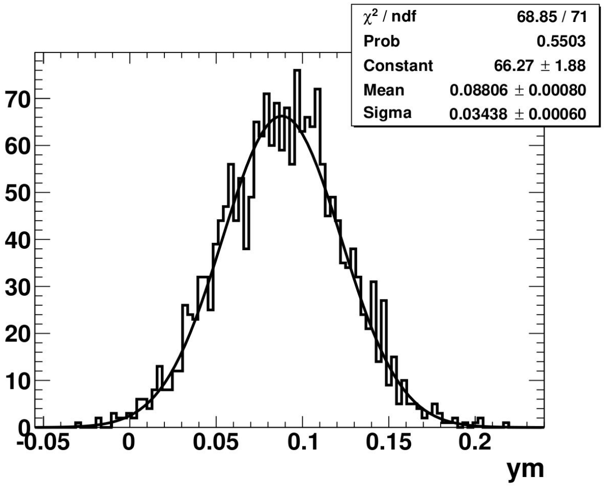
< Statistics

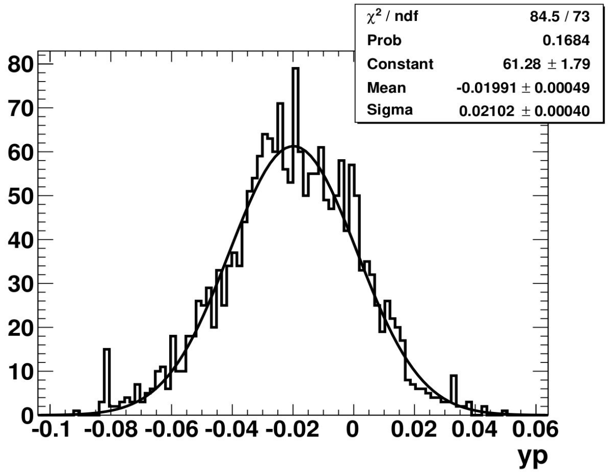
Correlation matrix :

1	-0.489463	-0.146204	-0.285719
-0.489463	1	0.0627223	0.334292
-0.146204	0.0627223	1	-0.178205
-0.285719	0.334292	-0.178205	1









Systematic from physics input to $B^{\pm} \to D^0\pi^{\pm}$ decay

- Generate 2000 toys in signal only (10000 events B->DK / 164000 events B->Dπ per toy), with physics parameters set to the LHCb combination while varying Dπ physics input (Correlation taken into account with Cholesky method)

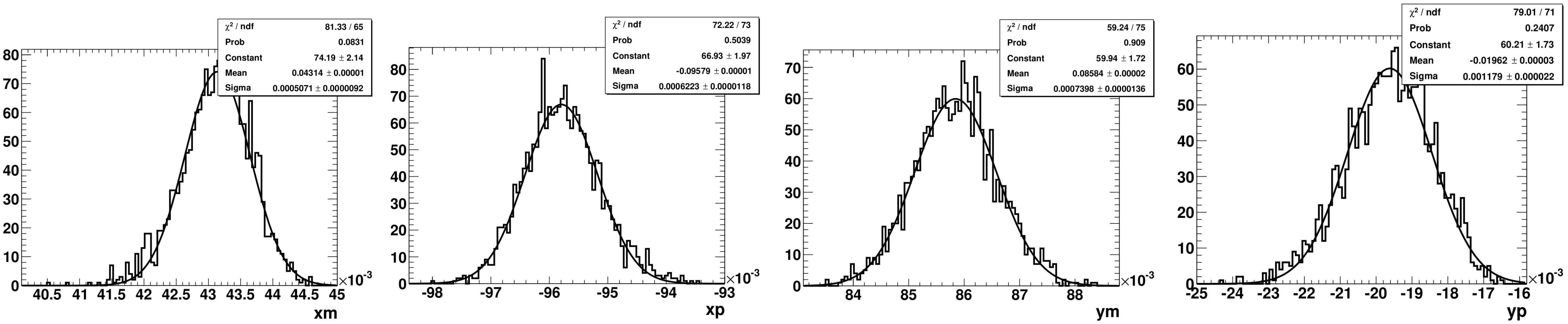
- Toys fitted with the nominal simultaneous fit (fixed Dπ physics inputs)

Parameter	Mean	Mean error	Sigma	Sigma Error
xm	0.0431416	1.19166e-05	0.000507137	9.16551e-06
xp	-0.0957948	1.45436e-05	0.000622265	1.17844e-05
ym	0.0858445	1.71341e-05	0.000739769	1.35529e-05
yp	-0.0196209	2.84873e-05	0.00117878	2.17046e-05

<< Statistics

Correlation matrix :

1	-0.0205235	-0.533831	0.629314
-0.0205235	1	-0.818923	0.529908
-0.533831	-0.818923	1	-0.784929
0.629314	0.529908	-0.784929	1



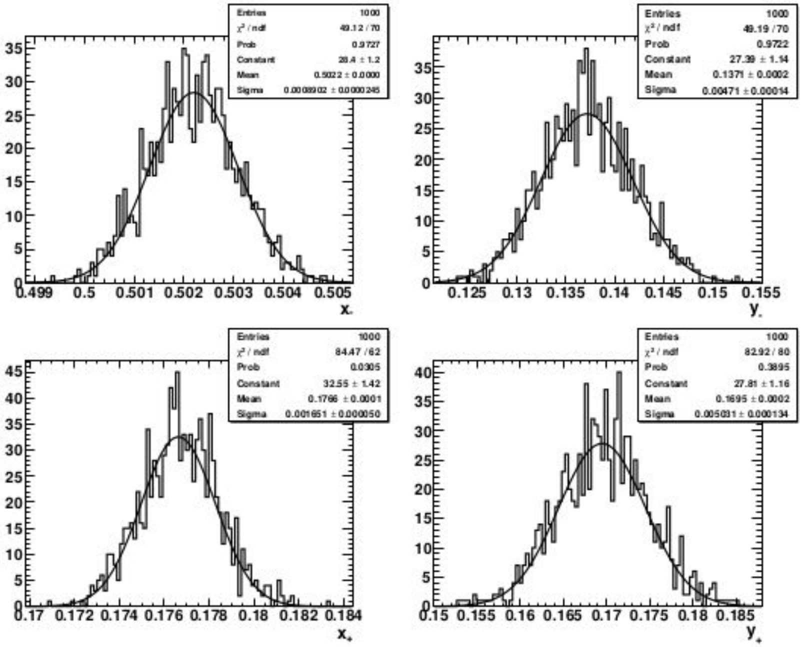


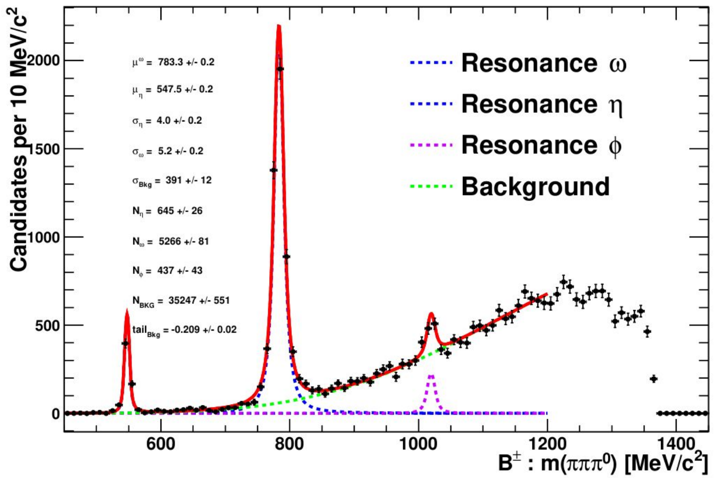
Figure 12.7: Distribution of the CP observables fitted for the bootstrap procedure repeated 1000 times.

	Uncertainty ($\times 10^{-2}$)			
	x_-^{DK}	y_-^{DK}	x_+^{DK}	y_+^{DK}
σ	0.09	0.47	0.17	0.50
	Correlations			
	x_-^{DK}	y_-^{DK}	x_+^{DK}	y_+^{DK}
x_-^{DK}	1.000	0.488	0.037	-0.610
y_-^{DK}		1.000	-0.369	-0.754
x_+^{DK}			1.000	-0.115
y_+^{DK}				1.000

Table 12.7: Systematic uncertainties due to the mass-shape parameterisation and corresponding correlation matrix.

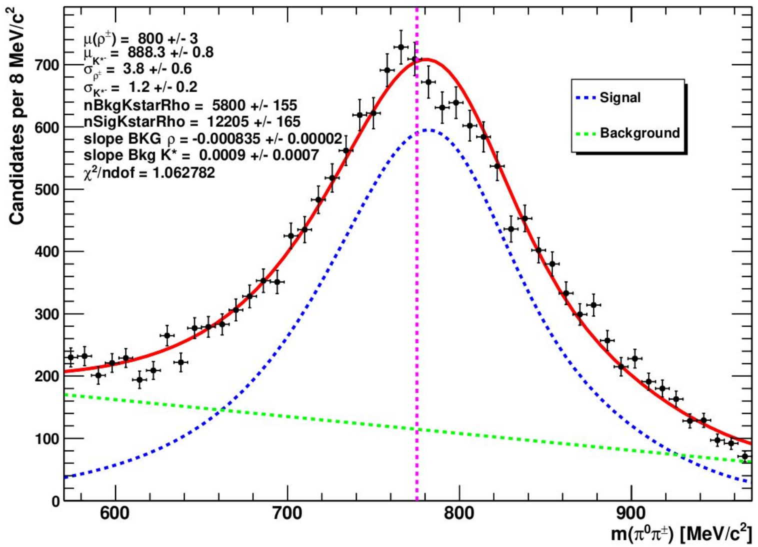
- sPlot method (statistical subtraction) to project signal from global fit into two or three bodies mass resonances
- Use $D^0 \to K^0_S\omega$ as normalisation channel

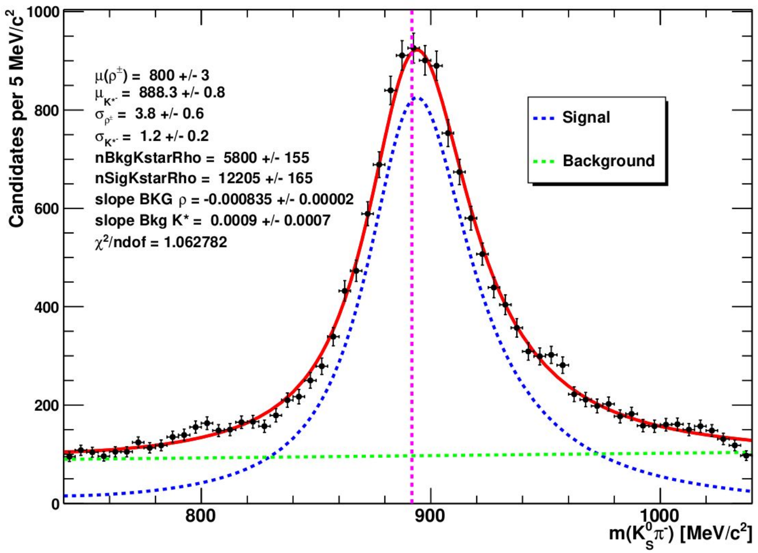
$$\mathcal{B}(D^0 \to K^{*-}\rho^+) = \frac{N(K^{*-}(\to K^0_S\pi^-)\rho^+(\to \pi^+\pi^0))}{N(K^0_S\omega(\to \pi^+\pi^-\pi^0))} \times \mathcal{B}(D^0 \to K^0_S\omega(\to K^0_S\pi^+\pi^-\pi^0)) \times \frac{1}{\epsilon(\text{cut on } m(K^0_S\pi^\pm) \text{ and } m(\pi^\mp\pi^0))} \times \frac{1}{\mathcal{B}(K^{*-} \to K^0\pi^-) \times \mathcal{B}(K^0 \to K^0_S)}$$




Quick & Dirty
+ Stat only

$$\boldsymbol{\mathcal{B}(D^0 \to K^{*-}\rho^+) = (7.43 \pm 0.48)\,\%}$$



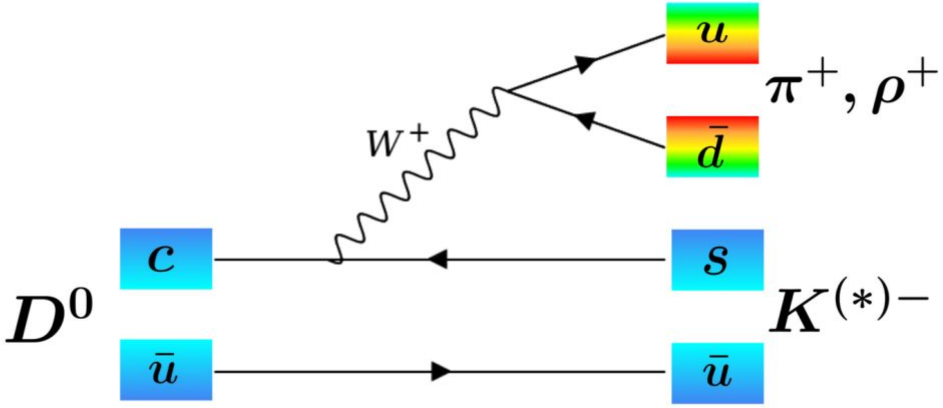


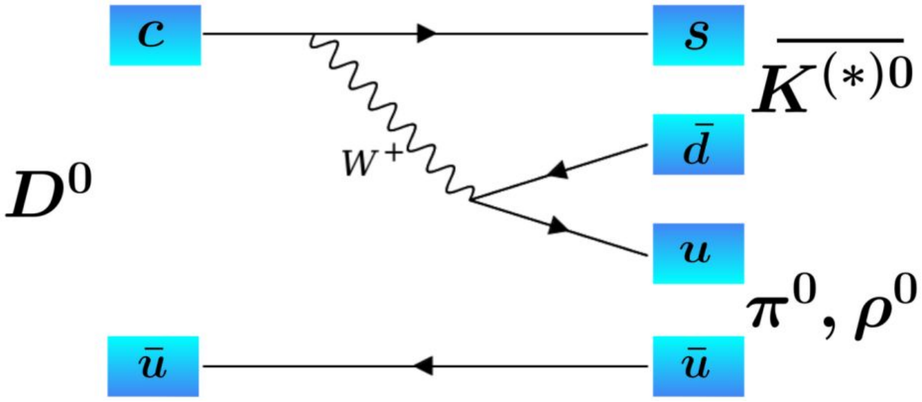
MARK III @1992 : (6.2±2.3±2.0) %

It impresses me very much to measure a hadronic D decay BF @7% 44 years after that the D meson was discovered at SLAC in MARK I by G. Goldhaber and F. Pierre.

$$\mathcal{B}(D^0 \to K^{*-}\rho^+) = (7.43 \pm 0.48)\,\%$$

Troubles with Non-leptonic Charm Decays (H. Lipkin 1980, i.e colours suppressed/favoured D decays)





$$\frac{\mathcal{B}(D^0 \to \bar{K}^0\pi^0)}{\mathcal{B}(D^0 \to K^-\pi^+)}_{Lipkin} = \frac{1}{8} = 12.5\,\%$$

≅9 (3 colors)

$$\frac{\mathcal{B}(D^0 \to \bar{K}^0\pi^0)}{\mathcal{B}(D^0 \to K^-\pi^+)}_{PDG} = (56 \pm 1)\,\%$$

$$\frac{\mathcal{B}(D^0 \to \bar{K}^{*0}\rho^0)_{PDG}}{\mathcal{B}(D^0 \to K^{*-}\rho^+)_{this\ meas.}} = (20 \pm 2)\,\%$$

The $D \to K^*\rho$ systems seems to have less final state interactions, as expected due to the larger masses