Gamma angle measurement in $B^- \to D^0(\to K_s\pi^+\pi^-\pi^0)K^-$ (Generalized GGSZ)

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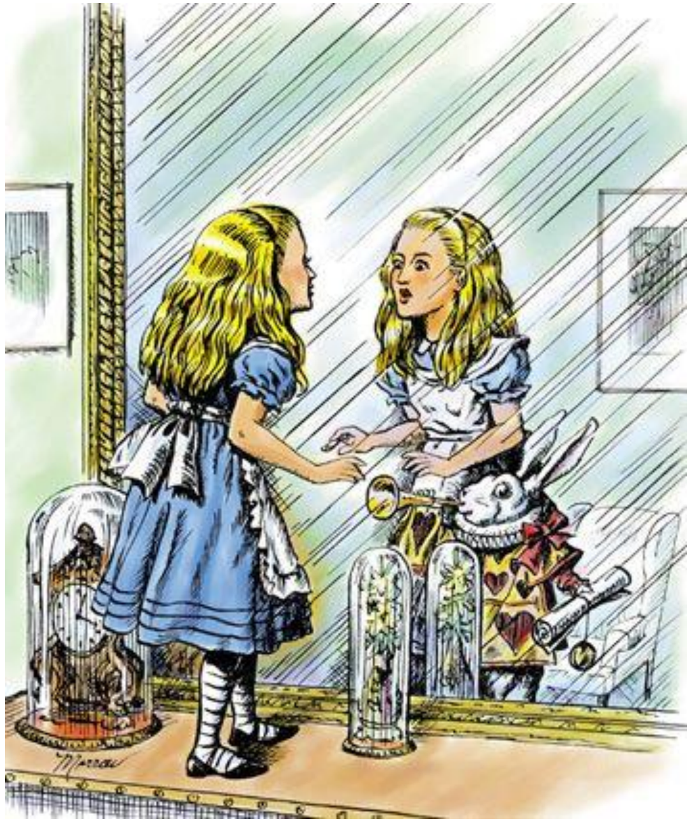
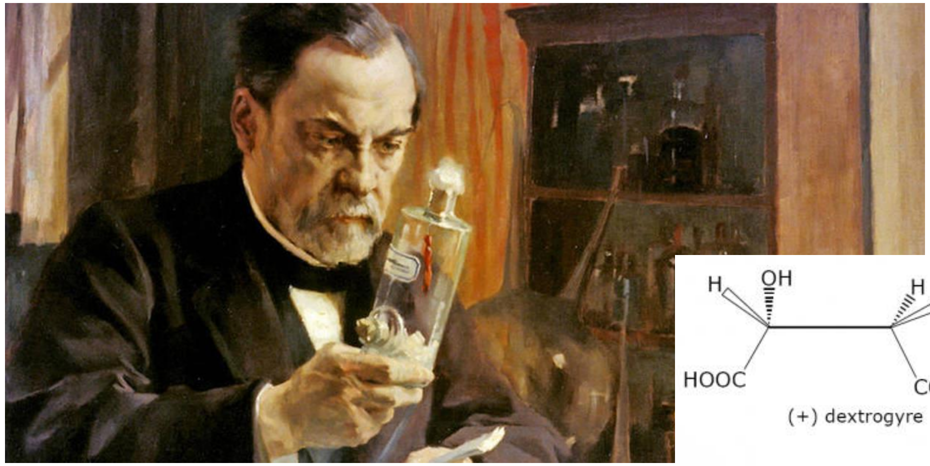
Journées de Rencontre des Jeunes Chercheurs
Saint-Jean-de-Monts – 22-28 October 2023

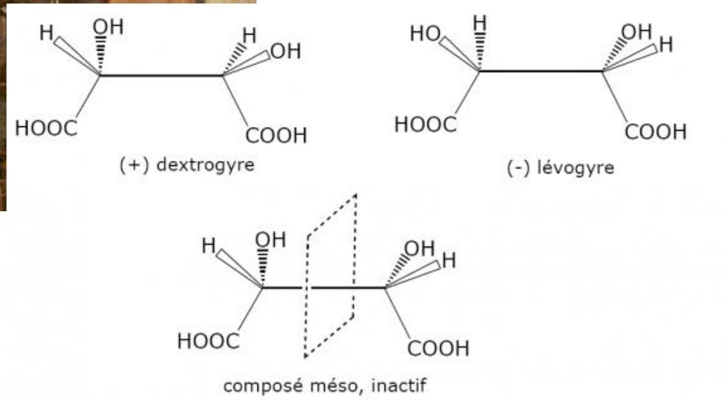
- **Parity:** is an event seen in a mirror as realistic as the original one?
- **Time reversal:** watching the film of an event backwards results in a realistic event?
- **Charge conjugation:** can we distinguish matter from antimatter?



Lewis Carroll (1871)
"Through the Looking-Glass, and What Alice Found There"

parity





Louis Pasteur and the [molecular chirality] (1847-1856)
[polarized light & crystallography]

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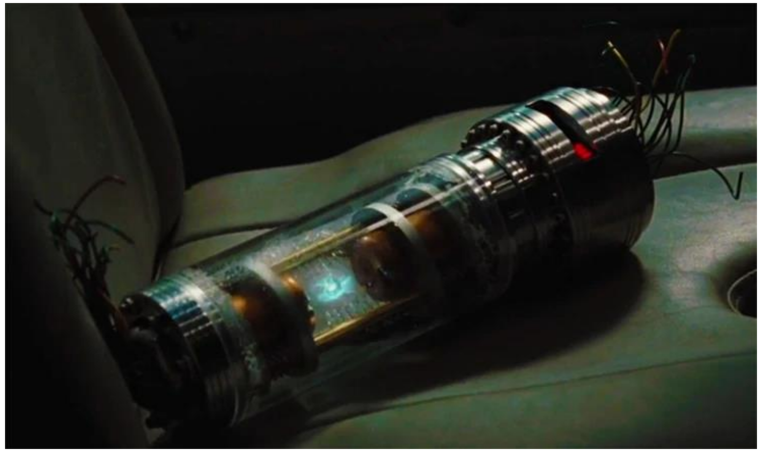
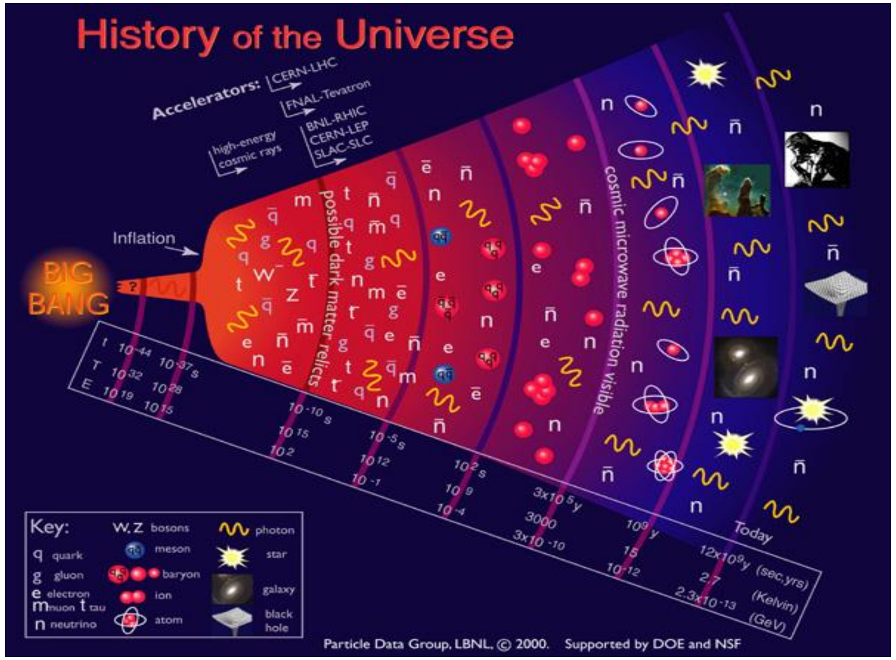
Anti-matter reactors/containers

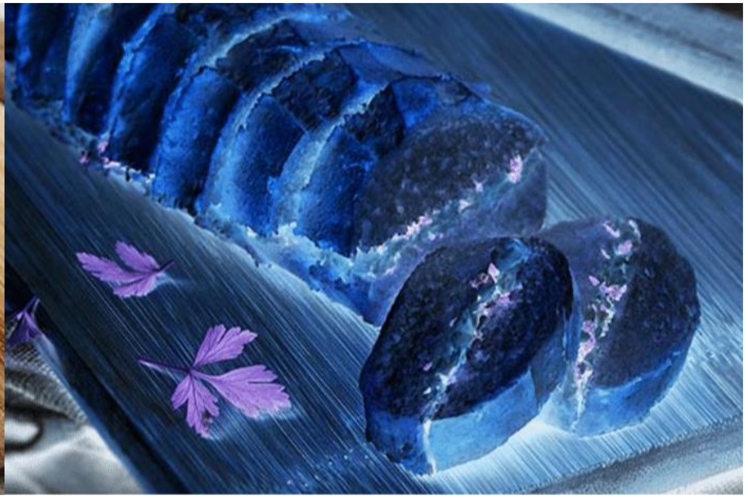


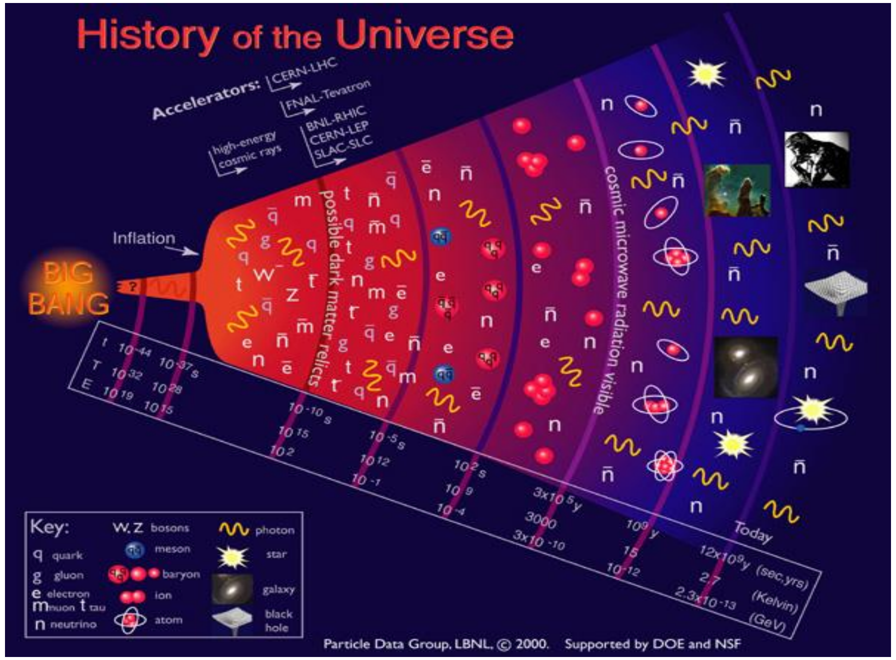
Time reversal machines

Matter / Antimatter Asymmetry



- BigBang : Préfou / Anti-Préfou symmetrically created
- Now : No More Antimatter : WHY ?



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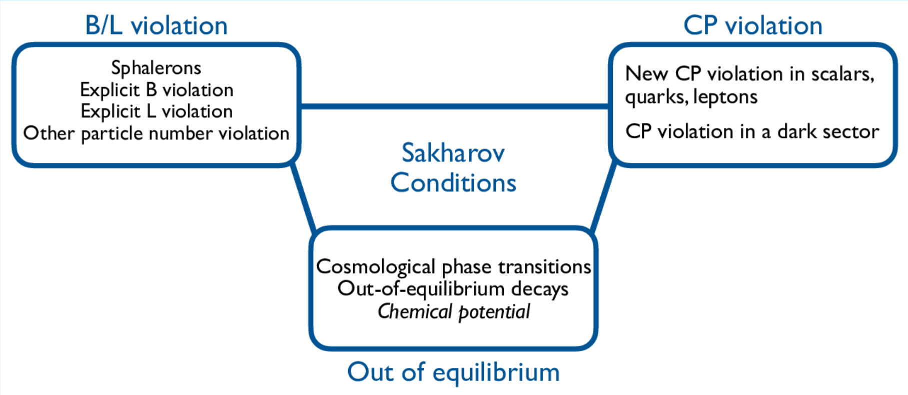
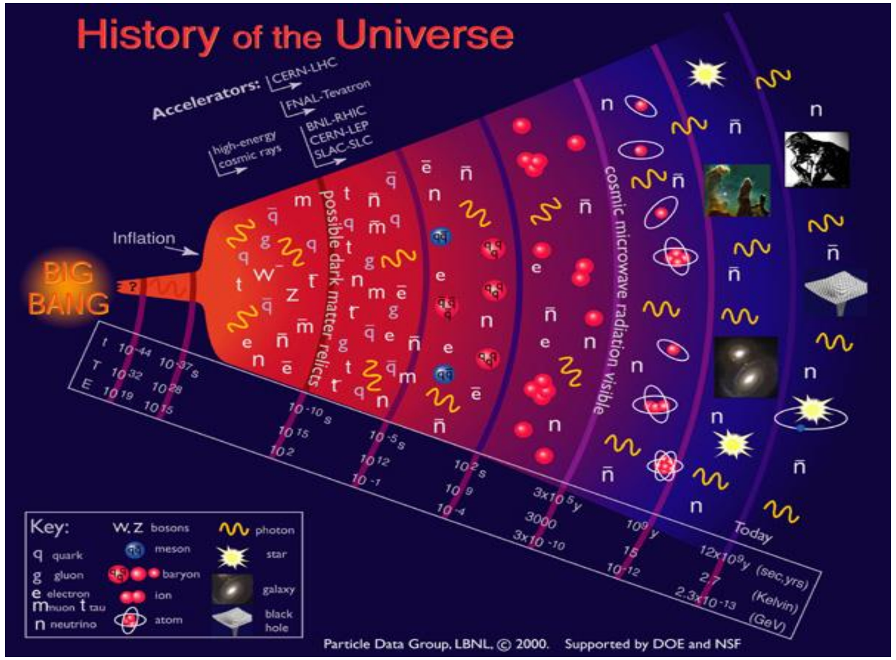


Matter / Antimatter Asymmetry



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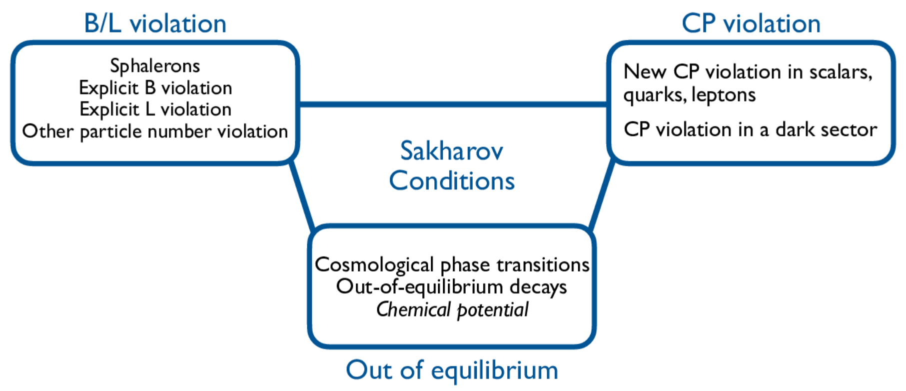
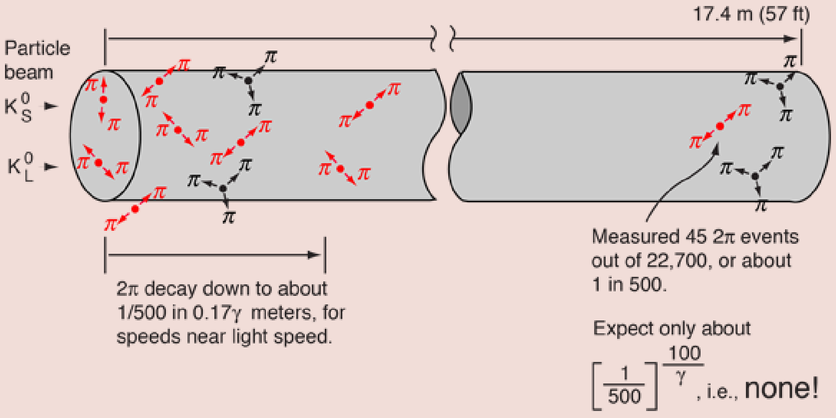
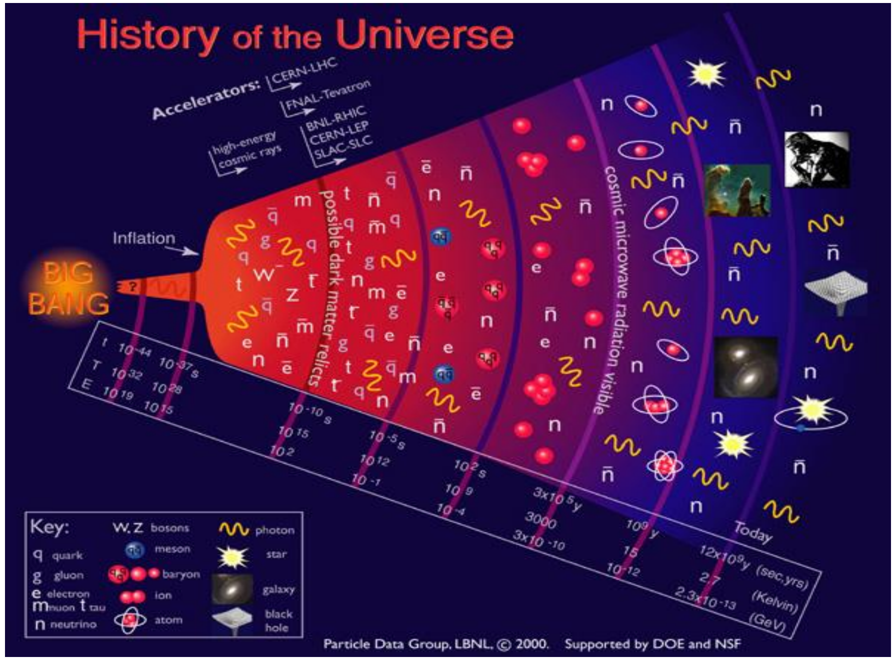


- CP Violation Observed in K mesons (1964, Cronin-Fitch)
- In B mesons (2000, B factories : BaBar, Belle)
- In D mesons (2019, LHCb)





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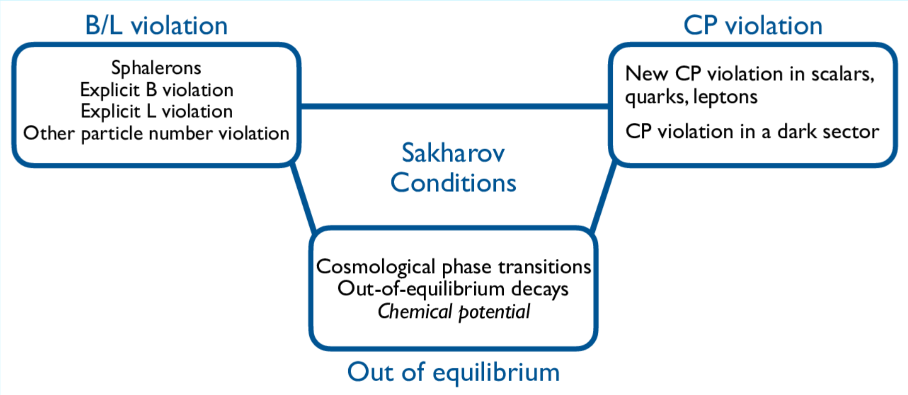

- **BUT** CP violation in standard model not sufficient to explain the absence of antimatter
  --> Is there a New Physics Beyond The Standard Model ?

The CKM Matrix, the Unitary Triangle and ɣ angle

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

- CKM Matrix describes transition between quarks through weak interaction -> **main CP contribution to SM in quark sector**
- Its elements can be determined from experiment
  -> Parameterization with 4 independent parameters

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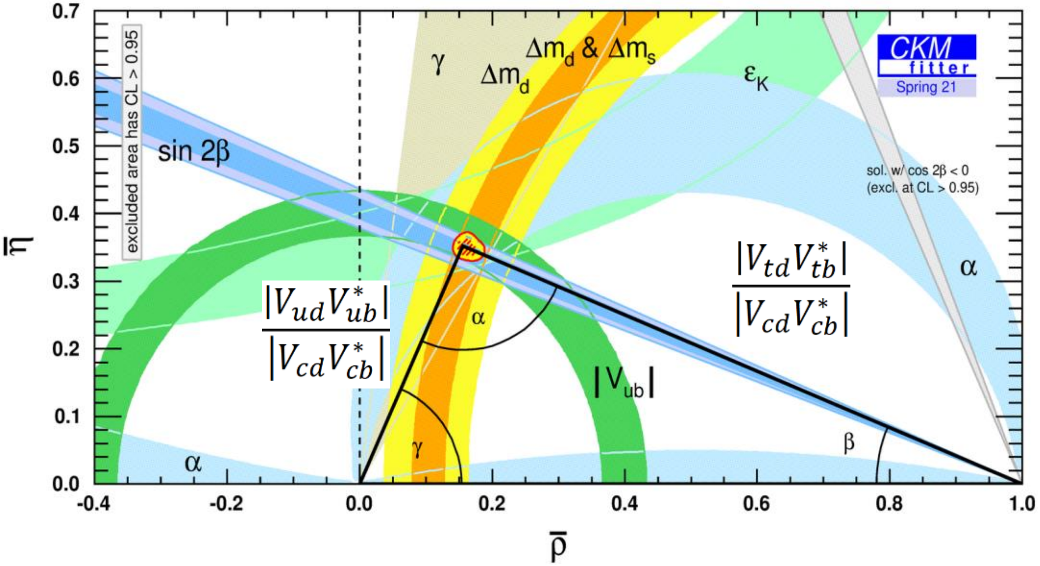
Unitary Equations and triangle :

$$\sum_{i=1}^{3} V_{ji}V_{ki}^* = \sum_{i=1}^{3} V_{ij}V_{ik}^* = 0$$



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- Goal : Sensitivity to BSM effects if Unitarity triangle different in direct and indirect measurements
- The current state of ɣ measurements (CONF-2022-003-001) :

Direct : $\gamma = (63.8^{+3.5}_{-3.7})^\circ$ -> Tree Level = Standard Candle

Indirect : $\gamma = (65.66^{+0.9}_{-2.65})^\circ$ -> Loops / Pinguin diagrams

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

The CKM Matrix, the Unitary Triangle and γ angle

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

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

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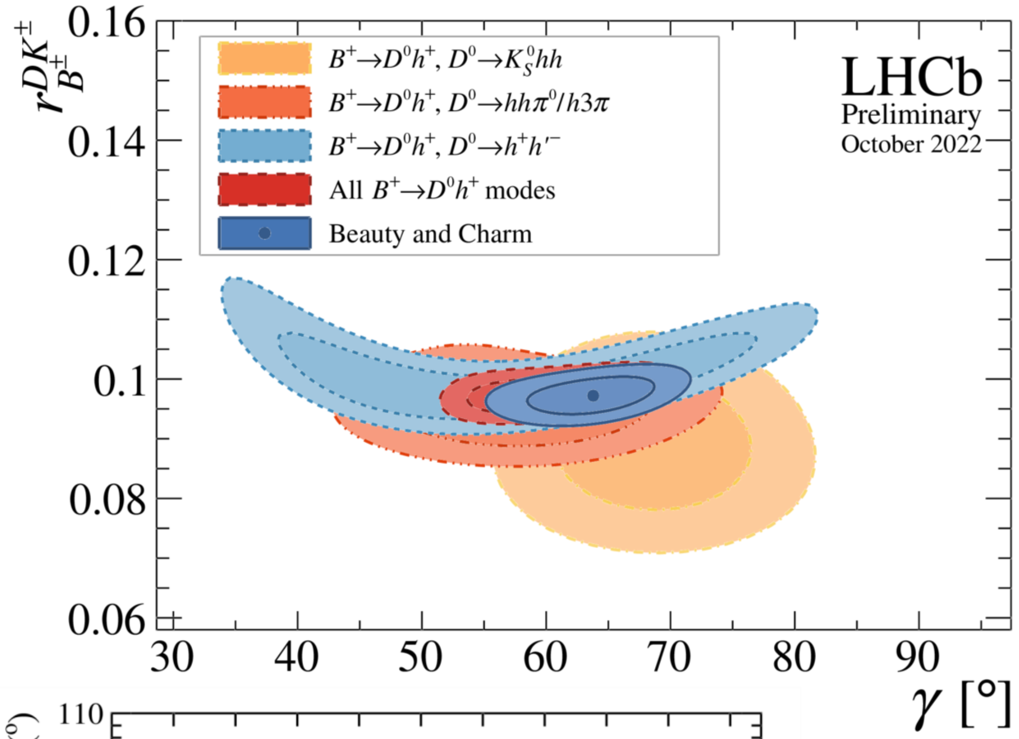
- According to CKMfitter group, a 1° precision on direct measurement **test SM up to dozens of TeV** energy scales -> **Only possible in association of multiple analysis**

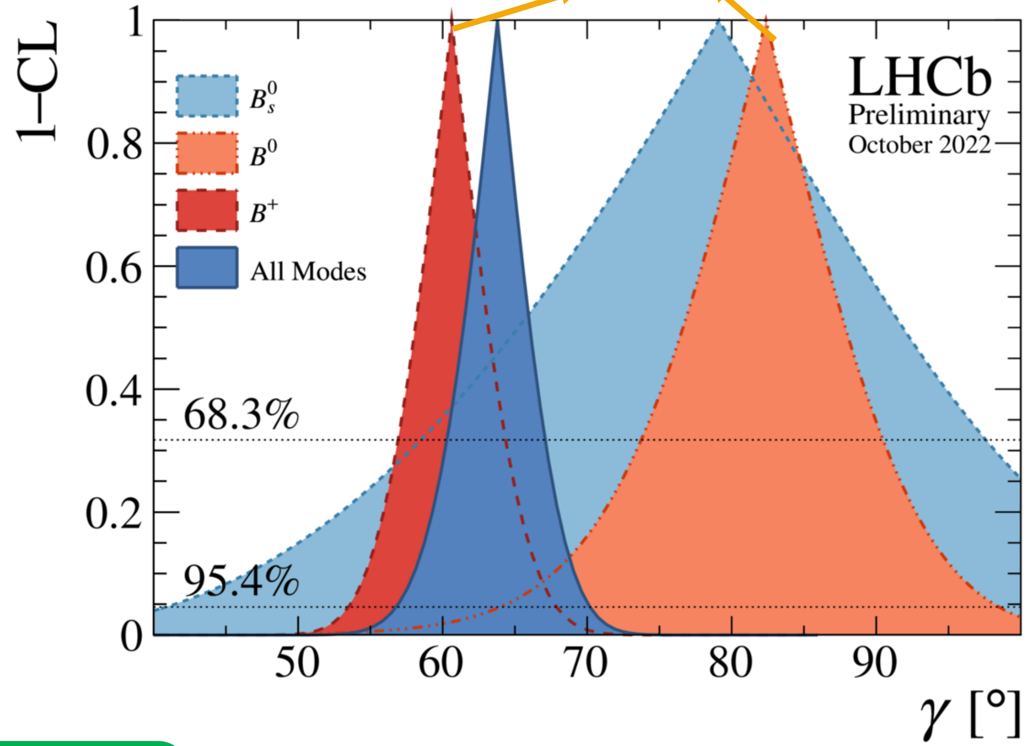
LHCb γ combination

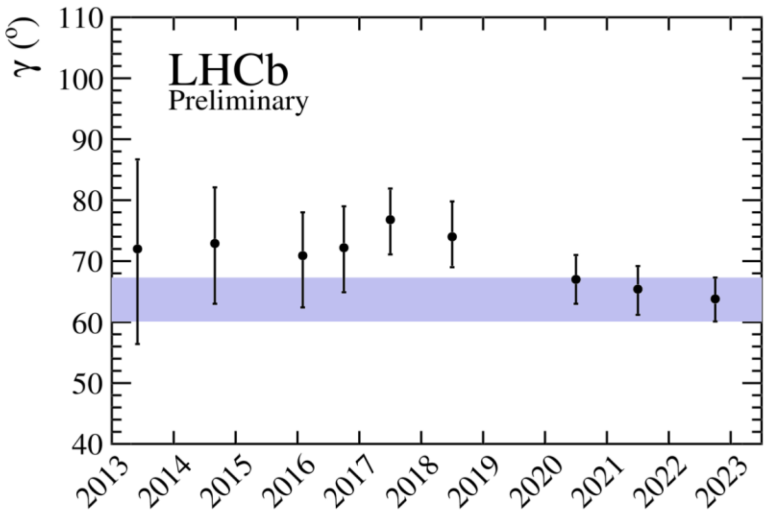
Further details of the statistical procedure can be found in JHEP 12 (2021) 141



B_s^0 = we enter in a luminosity era enabling more precision

Moderate tension (2.2σ) between B^+ and B^0 modes





$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

Compatible with the previous LHCb combination
In agreement with global CKM fit predictions

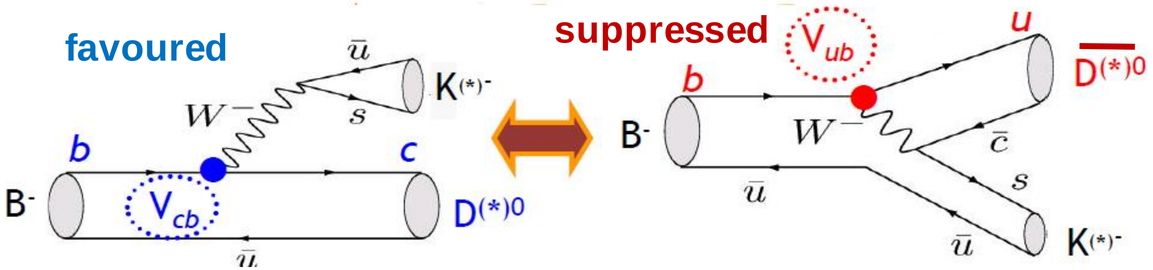
- Most precise determination of γ from a single experiment
- Uncertainties still in the regime of statistical dominance -> Systematic uncertainties account for ~1.4°
- Most precise measurement from a single analysis : arxiv:2010.08483

$B^\pm \to D^0 K^\pm$ with $D^0 \to K_s^0 \pi^+ \pi^-$

Measuring γ angle

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

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



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

Measuring γ angle

- Relative weak phase γ measured in the interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions by amplitude modulation
  -> Possible analogy with Young slits with a slit thinner than the other

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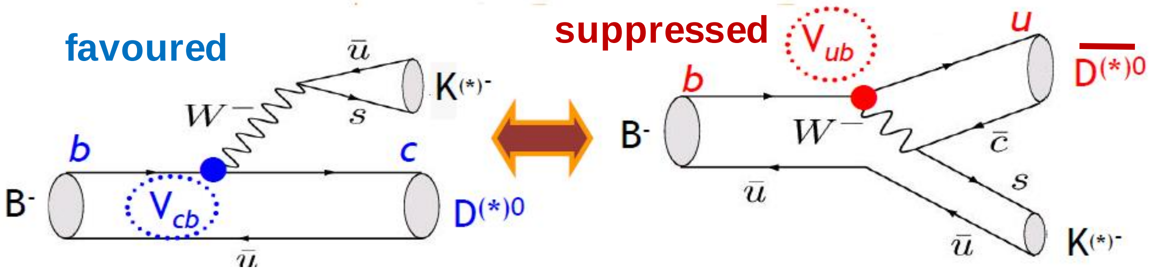

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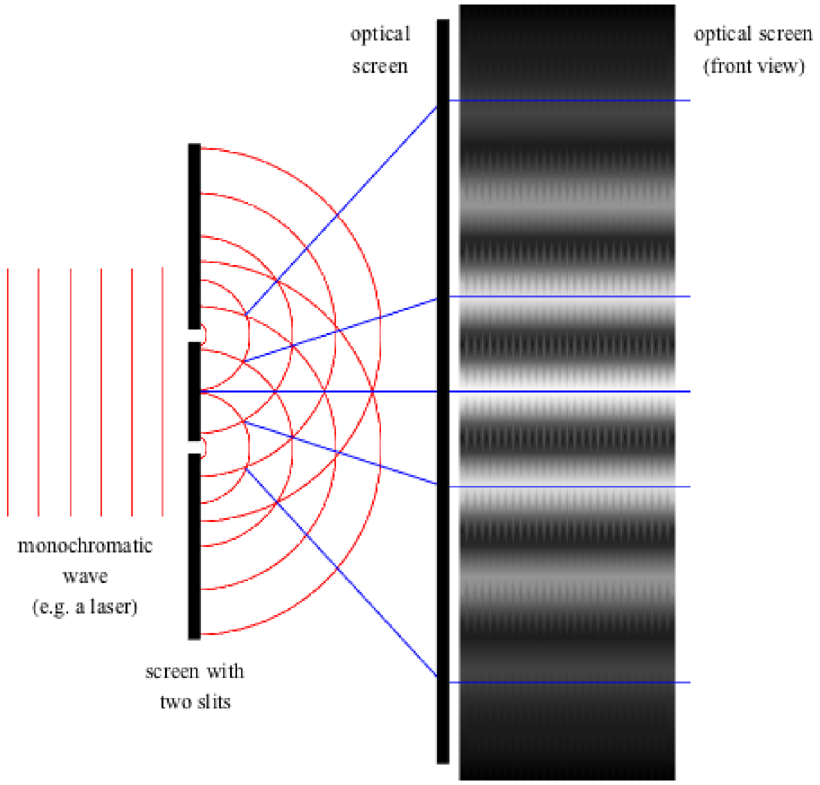
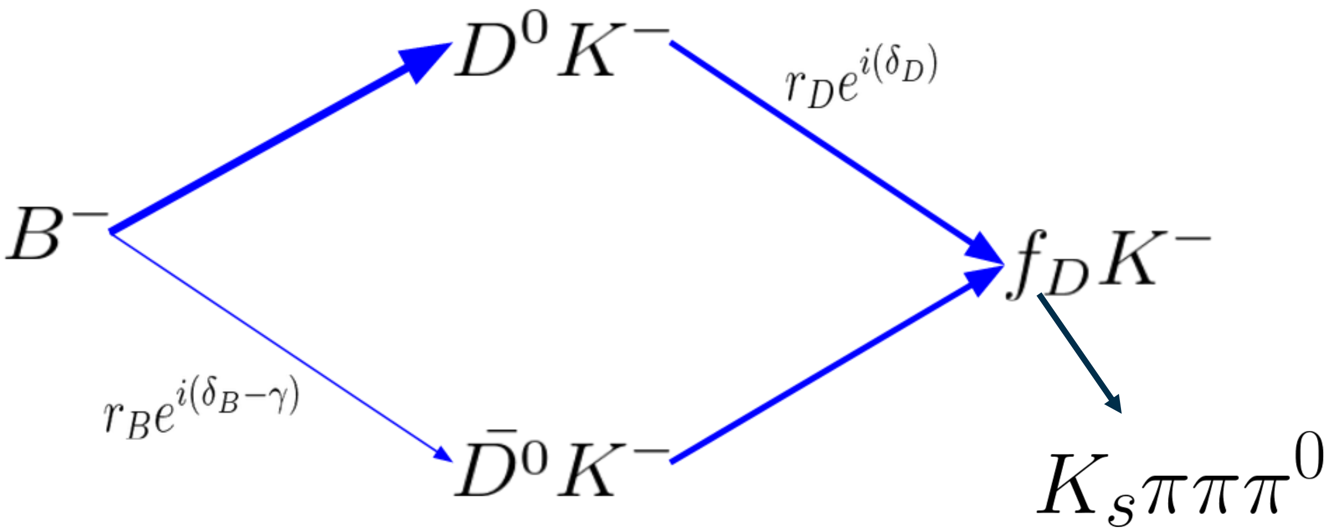
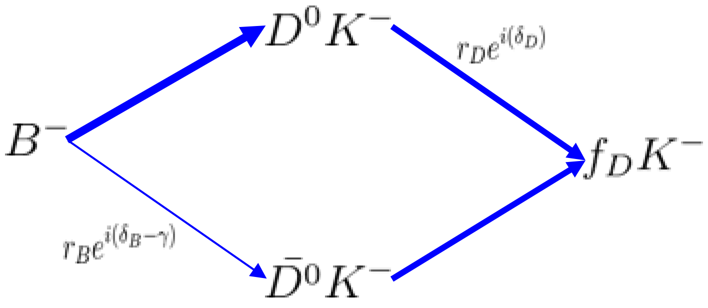




Generalized GGSZ formalism



The Amplitude A_B for the decay from 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 $B \to D^0K$ and $B \to \bar{D}^0K$

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

-> $r_B = \frac{|A_{B\to\bar{D}^0K}|}{|A_{B\to D^0K}|}$ → **Give sensibility to ɣ**

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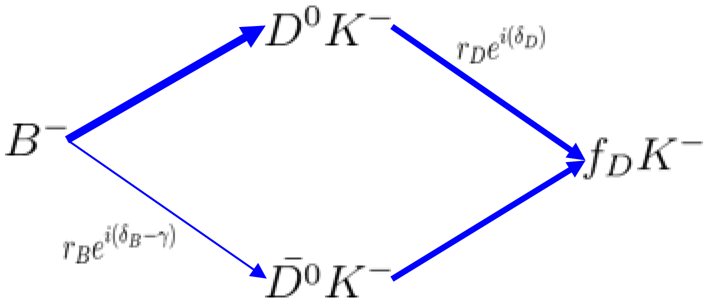

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The probability density for a decay at a point in Ɗ : $P_B = |A_B|^2 = |\bar{A}|^2 + r_B^2|A|^2 + 2r_B\Re[\bar{A}^*Ae^{i(\delta_B+\gamma)}]$

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 :
- $y_\pm = r_B sin(\delta_B \pm \gamma)$
- $x_\pm = r_B cos(\delta_B \pm \gamma)$
- $C = cos(\Delta\delta_D)$
- $S = sin(\Delta\delta_D)$
- $P = |A|^2$
- $\bar{P} = |\bar{A}|^2$

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

Generalized GGSZ formalism

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

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

I use a 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)

+ BES III measurements up to come !

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
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- h is a normalisation factor
- $r_B = \dfrac{|A_{B\to\bar{D}^0K}|}{|A_{B\to D^0K}|}$
- $c_i = \dfrac{\int_{\mathcal{D}_i}|A||\bar{A}|C d\mathcal{D}}{\sqrt{\int_{\mathcal{D}_i}|A|^2d\mathcal{D}\int_{\mathcal{D}_i}|\bar{A}|^2d\mathcal{D}}}$
- $x_\pm = r_B cos(\delta_B \pm \gamma)$
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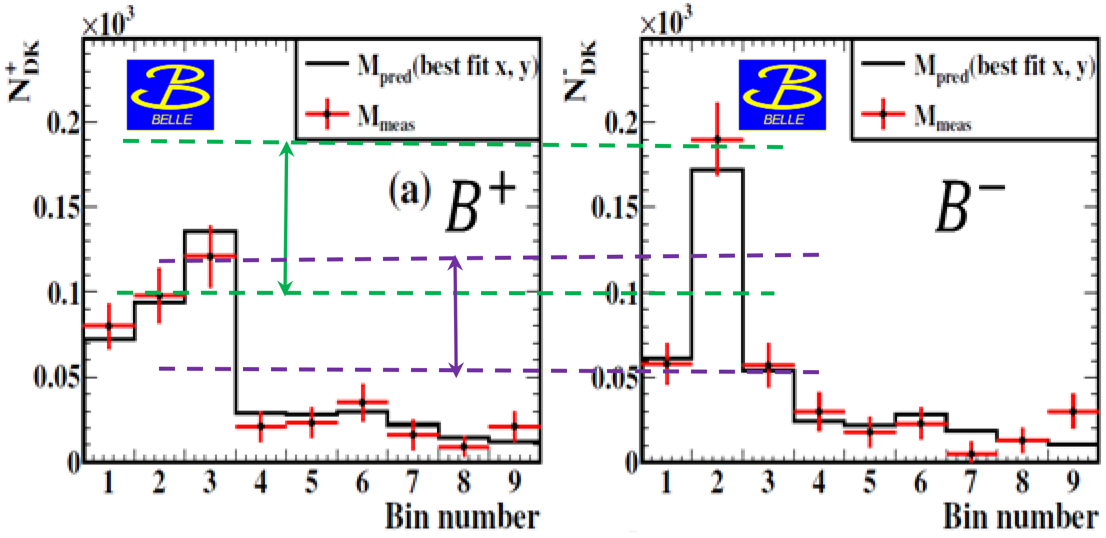

Selection

- Goal of the Selection : Keep the maximum efficiency on Signal while putting aside most of the Combinatorial and Physical background

- 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

$$BR(B^{\pm} \to D^0\pi^{\pm}) \approx 12.7 \times BR(B^{\pm} \to D^0K^{\pm})$$

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- Selection based on Uni or multi-dimensional dicriminating variables by comparing simulated Signal and background-only areas in DATA :
  - First MVA : MLP method on geometrical and topological variables from D decay
  - Unidimensional cuts on K^0s, π^0 and D^0 masses -> Optimized by maximization of the significance
  - Second MVA : MLP method on geometrical and topological variables from B decay

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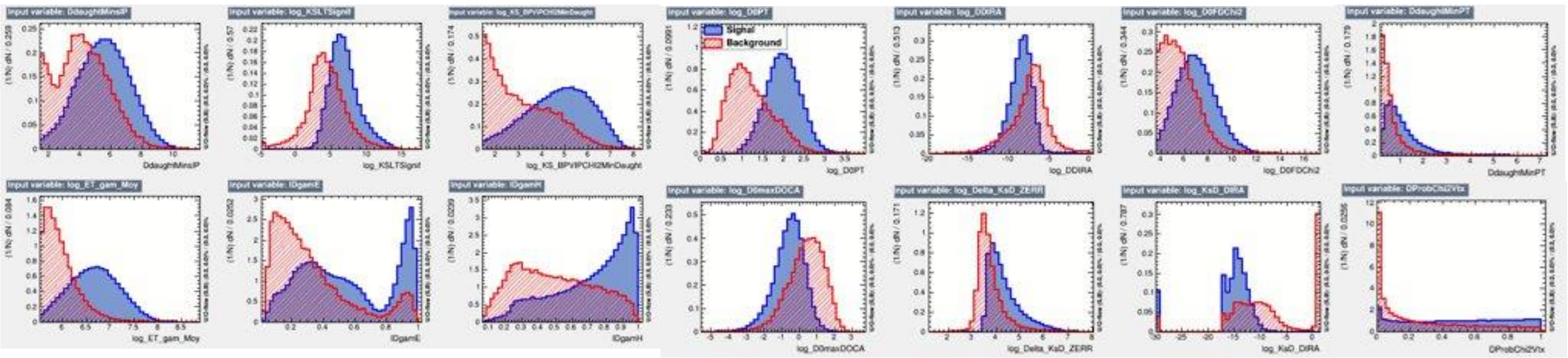
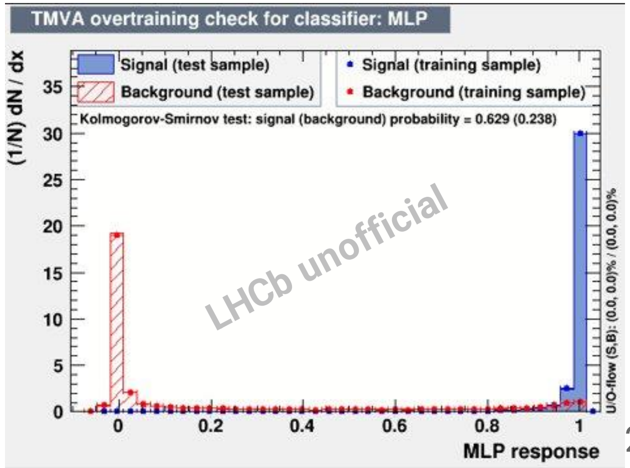
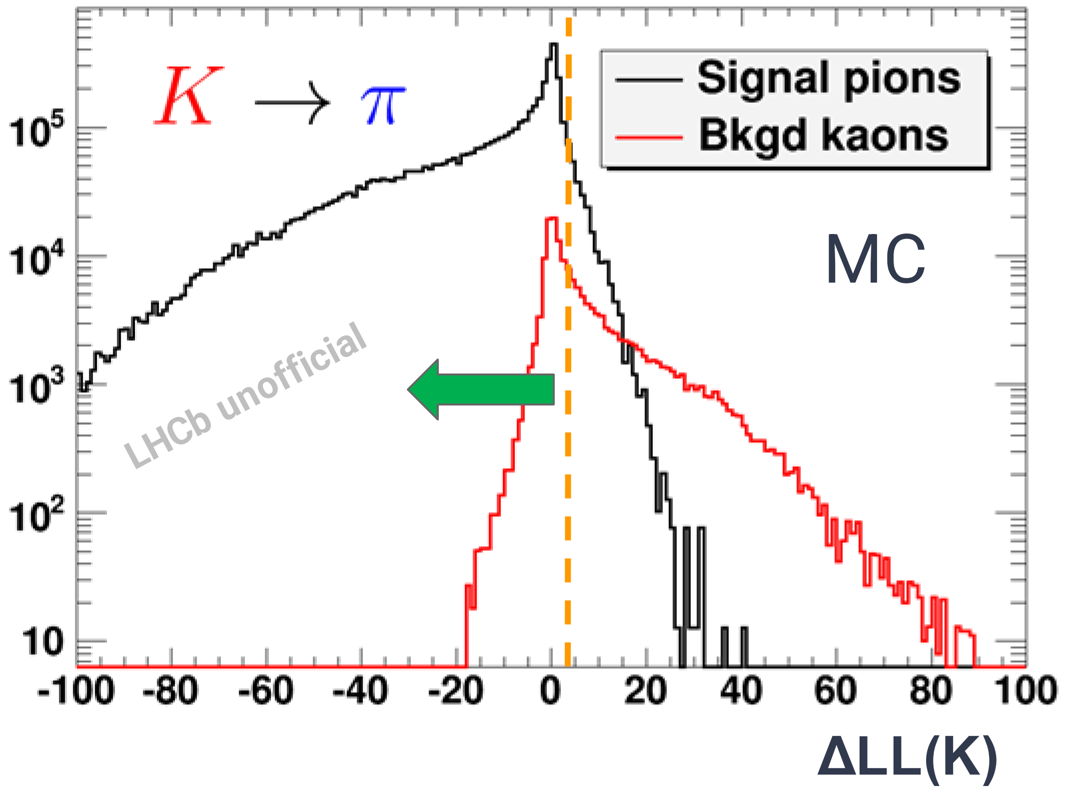
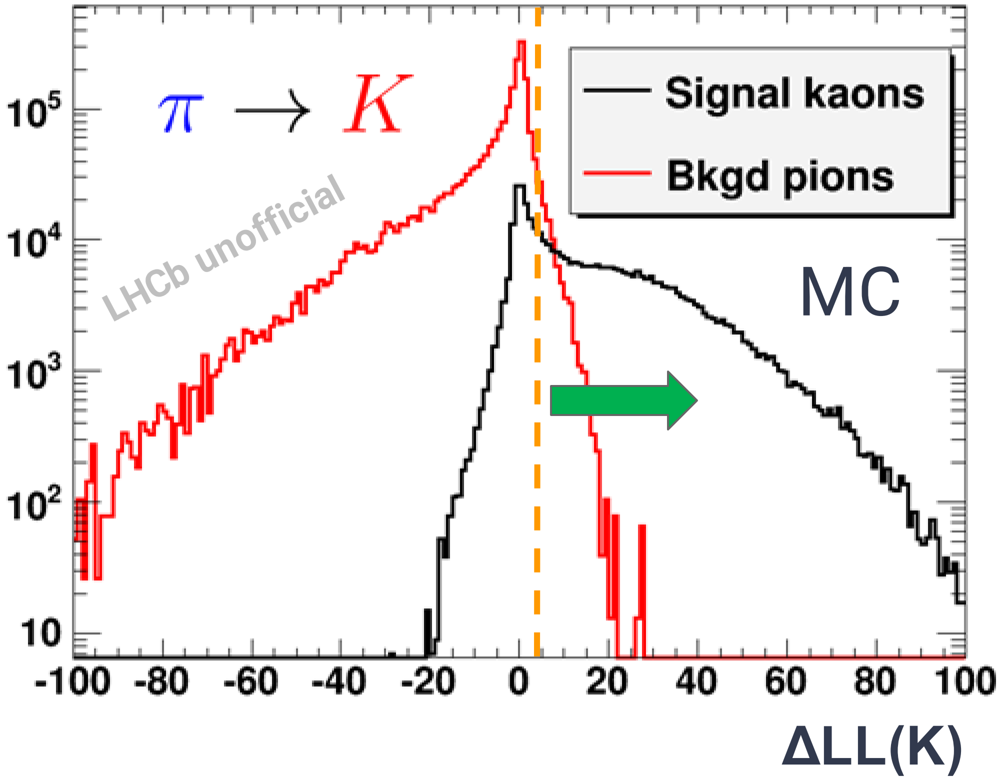
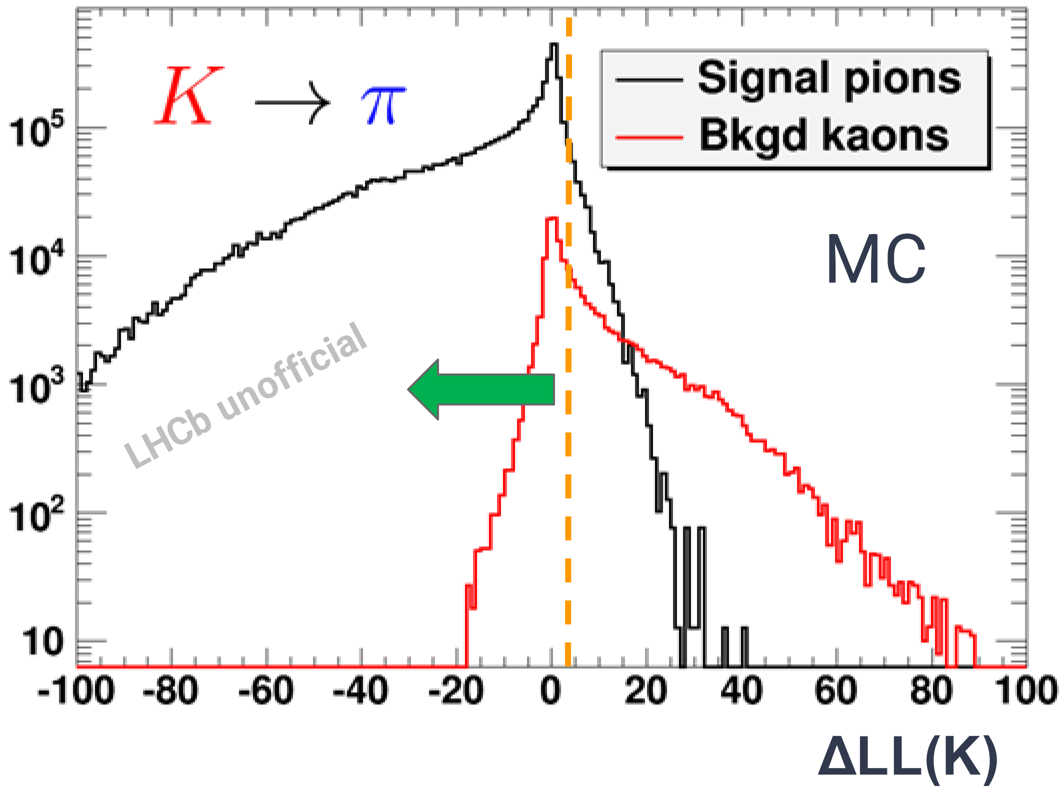


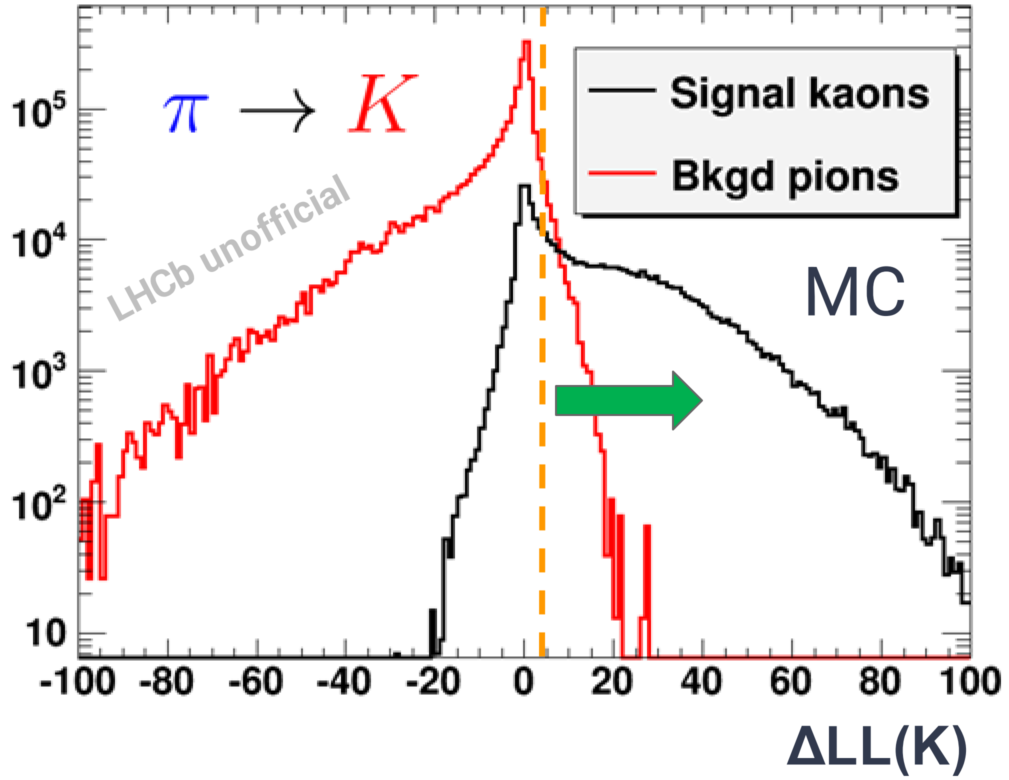






- To limit misidentification of the bachelor track, we discriminate using a PID Likelihood Difference
  - ~70.7% signal efficiency / ~2.6% misidentification efficiency for $B \rightarrow D^0 K^{\pm}$
  - For MC, ΔLL(K) variable corrected with PIDcorr tool

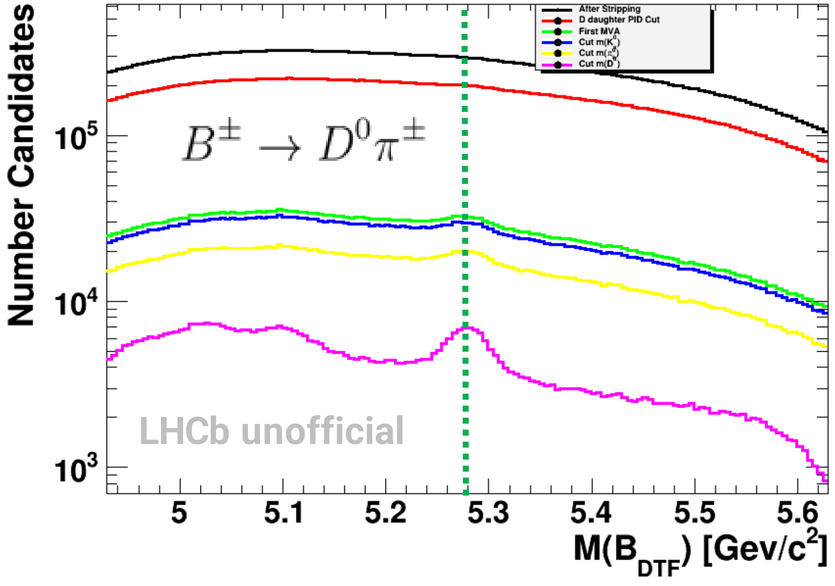


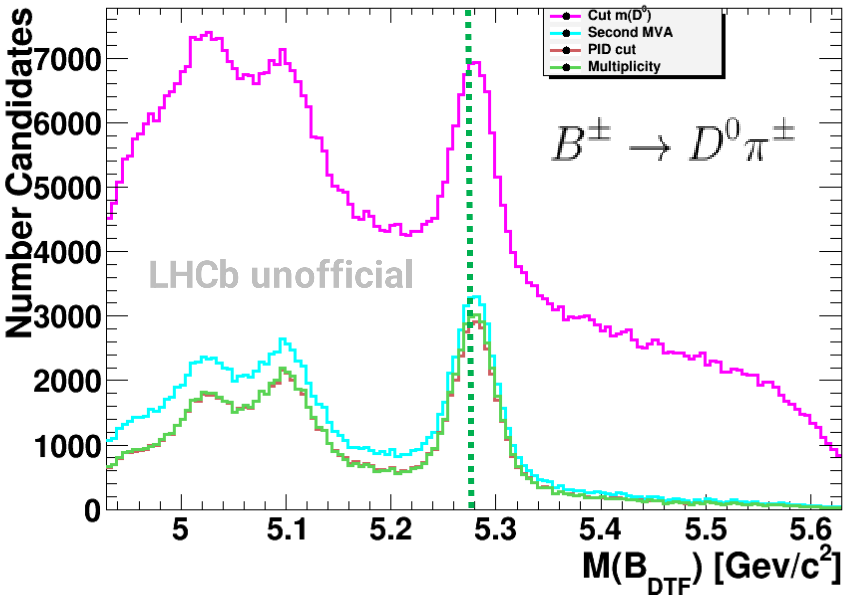


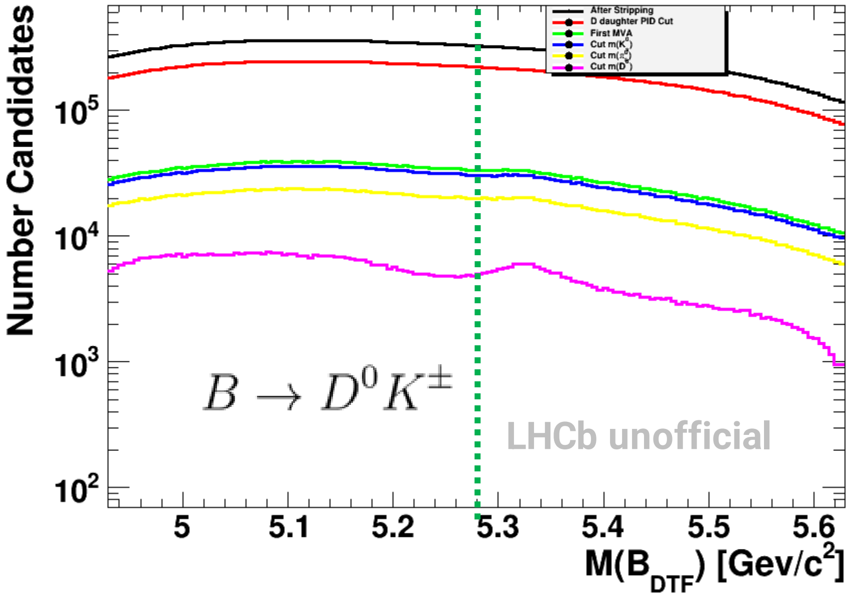
- To limit misidentification of the bachelor track, we discriminate using a PID Likelihood Difference
  - ~70.7% signal efficiency / ~2.6% misidentification efficiency for $B \to D^0 K^{\pm}$
  - For MC, ΔLL(K) variable corrected with PIDcorr tool

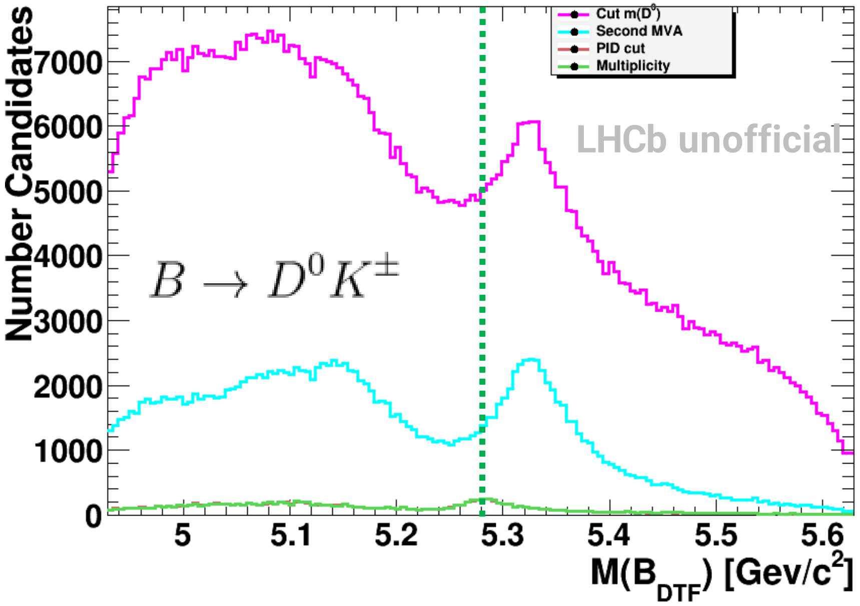
+ MVA to choose best candidates among multiple candidates (several selected candidates for a given collision)

Selection









10^3 to 10^4 rejection factor on background

Background Study

A complete study of physical background has been processed, using MC samples

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

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

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

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

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

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

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

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

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

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

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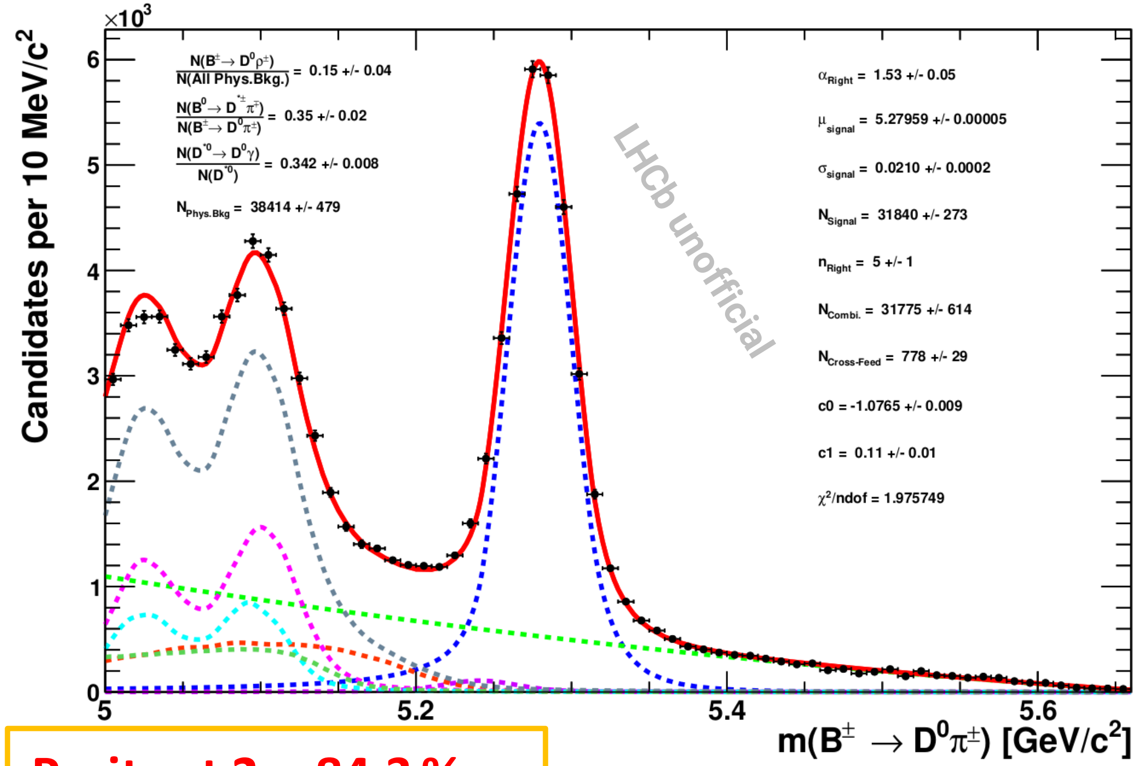
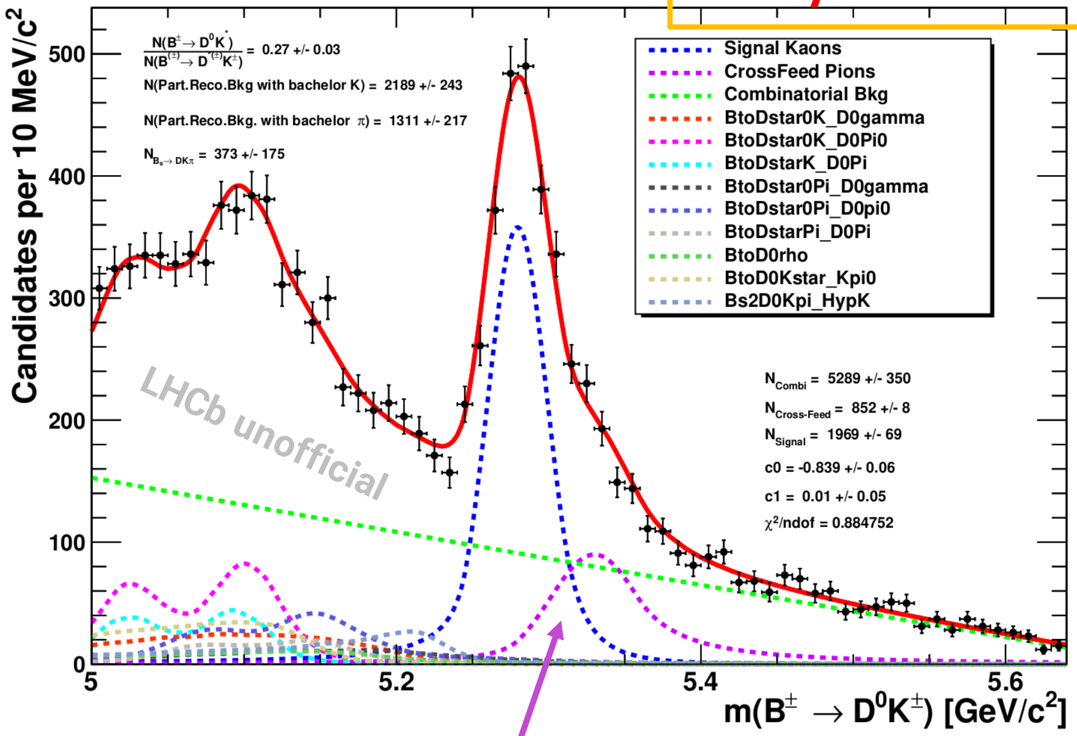
$B^0 \to D^{*\pm}[\to D^0(\to K_s\pi\pi\pi^0)\pi^{\pm}]K$

- 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 0.15% and 0.8% on the signal respectively.

B± mass fit



Purity at 2σ: 84.3 %



Purity at 2σ: 61.4 %

Reminder : $BR(B^\pm \to D^0\pi^\pm) \approx 12.7 \times BR(B^\pm \to D^0K^\pm)$

At 2σ :

#Signal	= 27191 ± 233
#CrossFeed	= 381 ± 14
#Combinatorial	= 4448 ± 86
#Phys. Bkg	= 219 ± 15

At ±2σ :

#Signal = 1623 ± 57

#Cross-feed = 208 ± 24

#Combinatorial background= 814 ± 32

#Phys. Bkg = 95 ± 5

Belle: 815±51 events
60% purity

Summary & Conclusion

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- CKM formalism is one of the main contribution to CP violation in the Standard Model
- A precise direct measurement of γ angle = standard candle of SM -> to be compared to indirect measurements with potential New Physics
- After Selection and Nominal Fit, next step is to extract physical parameters as γ angle from the Signal I obtained

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  - Participate to an Amplitude Analysis of D^0 decay
    - Continuous $\Delta\delta_D$ map -> redo γ measurement !
    - Measure $D^0 \to K^{*\pm}\rho^{\mp}$ branching ratio -> Not measured since Mark III ... 30 years ago !

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+ Work on Scintillating-Fiber LHCb tracker (SciFi) for Run 3 : Temperature monitoring, Geometry description in reconstruction algorithm, fine time-alignment, etc

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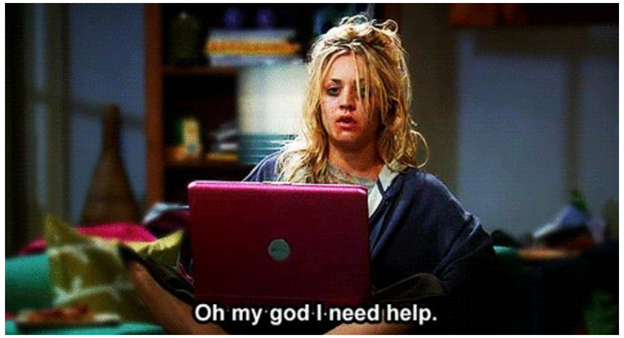
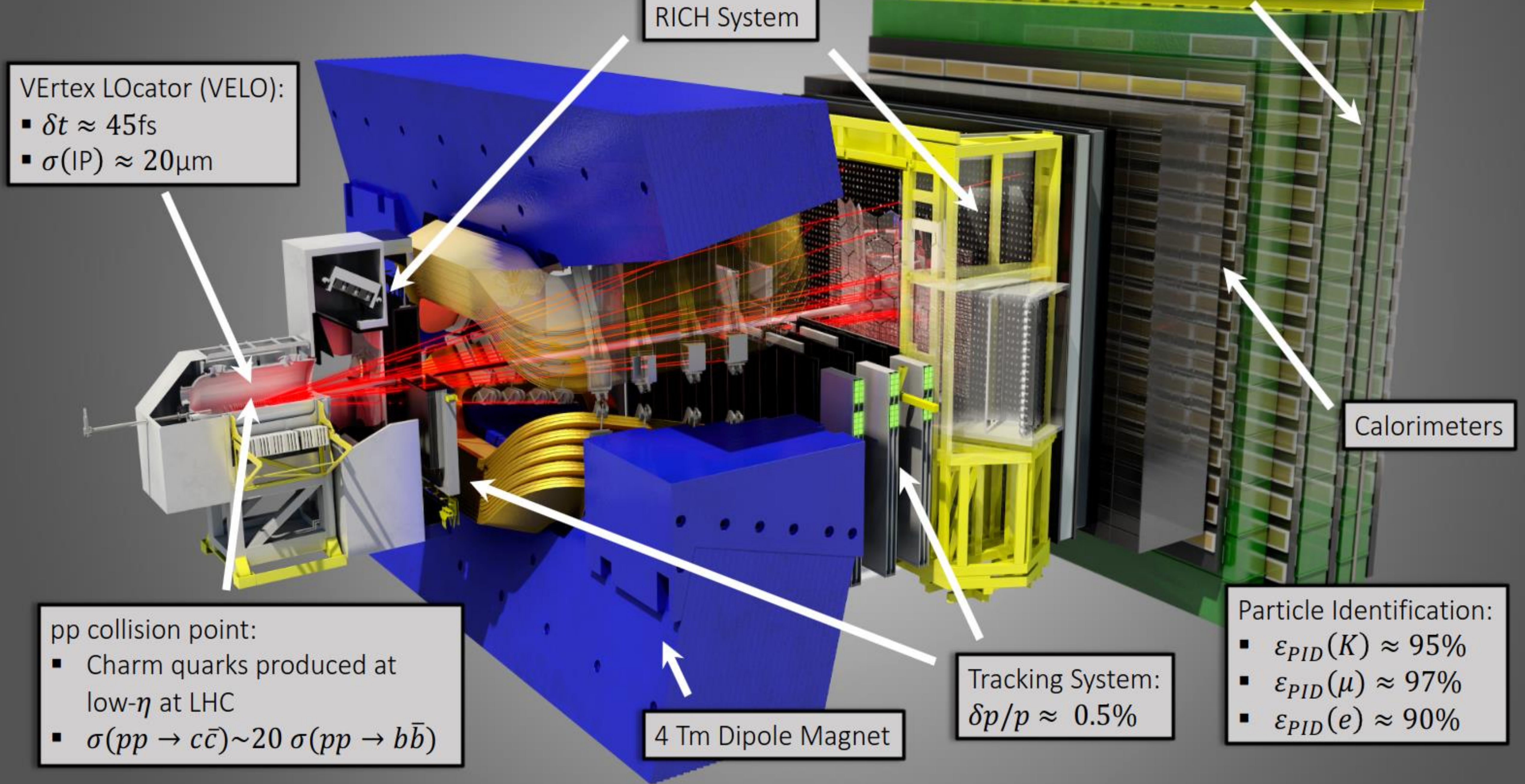


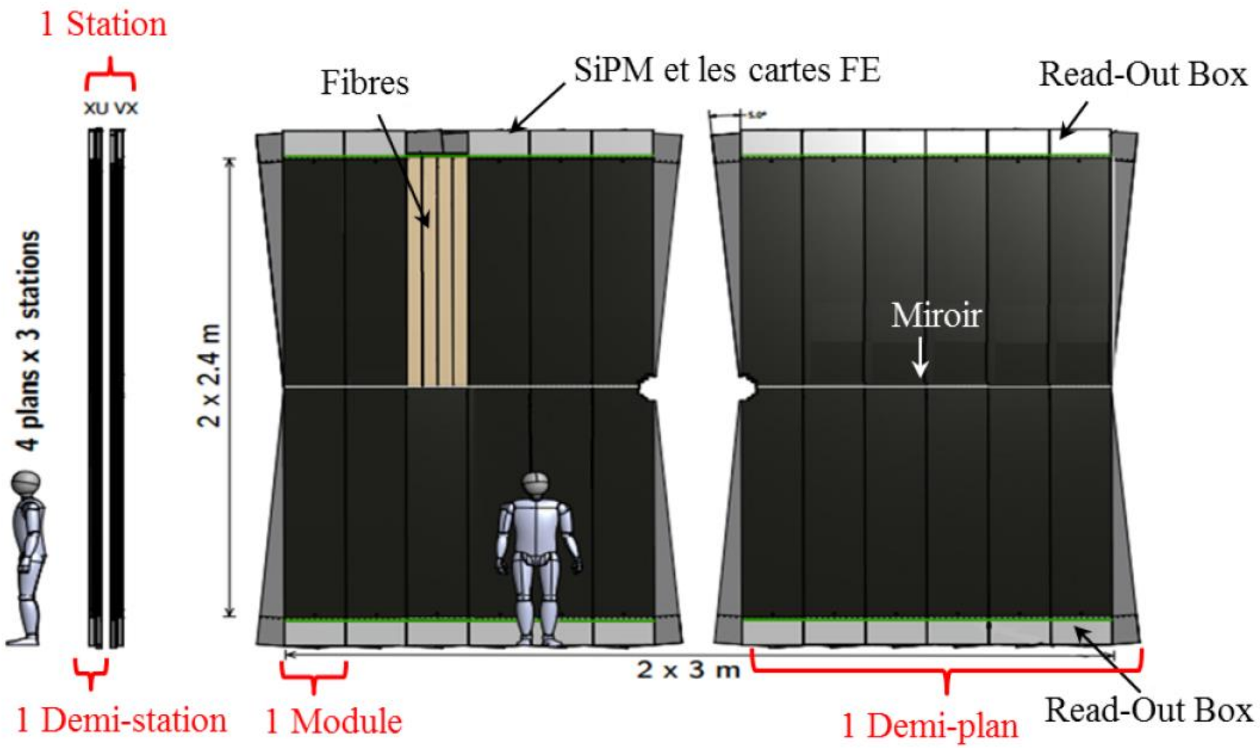
Thank you for your attention !!

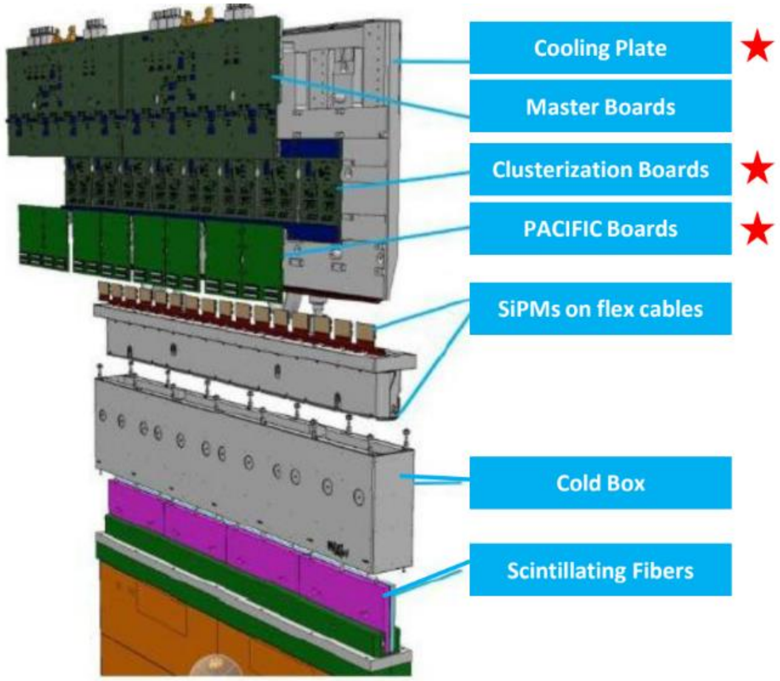
BACKUP

The LHCb detector



SciFi Tracker at LHCb





★ Important contribution from

The decay and formalism

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

$$\begin{cases} N^-_{i,DK} = h^-_{DK}[F_i + (r_B^{DK})^2\bar{F}_i + 2\sqrt{F_i\bar{F}_i}(c_i x_-^{DK} + s_i y_-^{DK})] \\ N^+_{i,DK} = h^+_{DK}[\bar{F}_i + (r_B^{DK})^2 F_i + 2\sqrt{F_i\bar{F}_i}(c_i x_+^{DK} - s_i y_+^{DK})] \\ N^-_{i,D\pi} = h^-_{D\pi}[F_i + (r_B^{D\pi})^2\bar{F}_i + 2\sqrt{F_i\bar{F}_i}(c_i x_-^{D\pi} + s_i y_-^{D\pi})] \\ N^+_{i,D\pi} = h^+_{D\pi}[\bar{F}_i + (r_B^{D\pi})^2 F_i + 2\sqrt{F_i\bar{F}_i}(c_i x_+^{D\pi} - s_i y_+^{D\pi})] \end{cases}$$

- $F_i = \dfrac{\int_{\mathcal{D}_i} P\eta d\mathcal{D}}{\sum_j \int_{\mathcal{D}_j} P\eta d\mathcal{D}}$
- 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 :

- $B \to D\pi$ and $B \to DK$ have a similar selection and then a similar efficiency mapping through $\mathcal{D}$
- PID cut efficiency is the same for all bins
- Multiplicity is the same for all bins
- $N_i^{\pm}$ is migration-corrected

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⟹ c_i and s_i are taken from Cleo-c paper JHEP 10 (2018) 178

⟹ $N_i^{\pm}$ will be measured in LHCb (current work)

⟹ $x_{\pm}$ and r_B are the parameters we want to extract

⟹ F_i are extracted from $B \to D\pi$ thanks to a simultaneous fit

Thanks to the common value of γ, one can use this alternate parameterization :

$$\xi^{D\pi} = \left(\frac{r_B^{D\pi}}{r_B^{DK}}\right)e^{i\delta_B^{D\pi} - i\delta_B^{DK}} \Longrightarrow \begin{cases} x_{\pm}^{D\pi} = x_{\xi} x_{\pm}^{DK} - y_{\xi}^{D\pi} y_{\pm}^{DK} \\ y_{\pm}^{D\pi} = x_{\xi} y_{\pm}^{DK} - y_{\xi}^{D\pi} x_{\pm}^{DK} \end{cases}$$

Selection

MVA 1	
Nom de la variable	*Description*
Log_D0PT	Impulsion transverse de D0
Log_DDIRA	Alignement de l'impulsion reconstruite et de la direction de vol du candidat D
Log_D0FDchi2	Signification statistique de la distance du vertex du candidat reconstruit D par rapport au Primary Vertex
Log_D0maxDOCA	Distance maximum des plus courtes approches pour toutes les paires possibles de particules filles de D
Log_Delta_KsD_ZERR	Distance entre les candidats D et Ks le long de l'axe du détecteur (le candidat Ks doit être détecté plus loin que le candidat D)
Log_KsD_DIRA	Alignement de l'impulsion reconstruite et de la direction de vol du candidat Ks.
DProbChi2Vtx	Qualité du Vertex du D
DdaughtMinsIP	Minimum des paramètres d'impact des particules filles de D
Log_KSLTSignif	Signification statistique de la durée de vie (longue) du candidat Ks. Débarrasse des paires de pions du Primary Vertex se faisant passer pour des Ks
Log_ET_gam_Moy	Energie transverse moyenne des photons issus du candidat π^0
IDgamE	Probabilité que les candidats photons ne soient pas des électrons
IDgamH	Probabilité que les candidats photons ne soient pas des hadrons
Log_KS_BPVIPCHI2MinDaught	Minimum des paramètres d'impact des particules filles de Ks^0
DdaughtMinPT	Minimum des moments transverses des pions chargés issus du D

MVA 2	
Nom de la variable	*Description*
cosThetaHely	Angle d'hélicité entre D et B
CosD_bachT_xy	Angle ϑ_{HvsD} entre D et la trace célibataire H (π^- ou K^-) dans le plan transverse
BDIRA	Alignement de l'impulsion reconstruite et de la direction de vol du candidat B
B_PTasy_cone15	Asymétrie de l'impulsion transverse de B dans un cône de 1.5 rad
The_MLP_D	Variable de sortie du MVA 1
log_B_IPchi2	Log de la Signification du paramètre d'impact du candidat reconstruit B par rapport au PV
log_DiffZ_DvsB_Err	Log de la distance entre les candidats D et B le long de l'axe du détecteur
BProbChi2Vtx	Qualité du vertex du B
BFDChi2	Signification statistique de la distance du vertex du candidat reconstruit B par rapport au PV
bachPT	Impulsion transverse du bachelor track