CKM angle γ in open charm B decays

Halime Sazak
LPC, Clermont

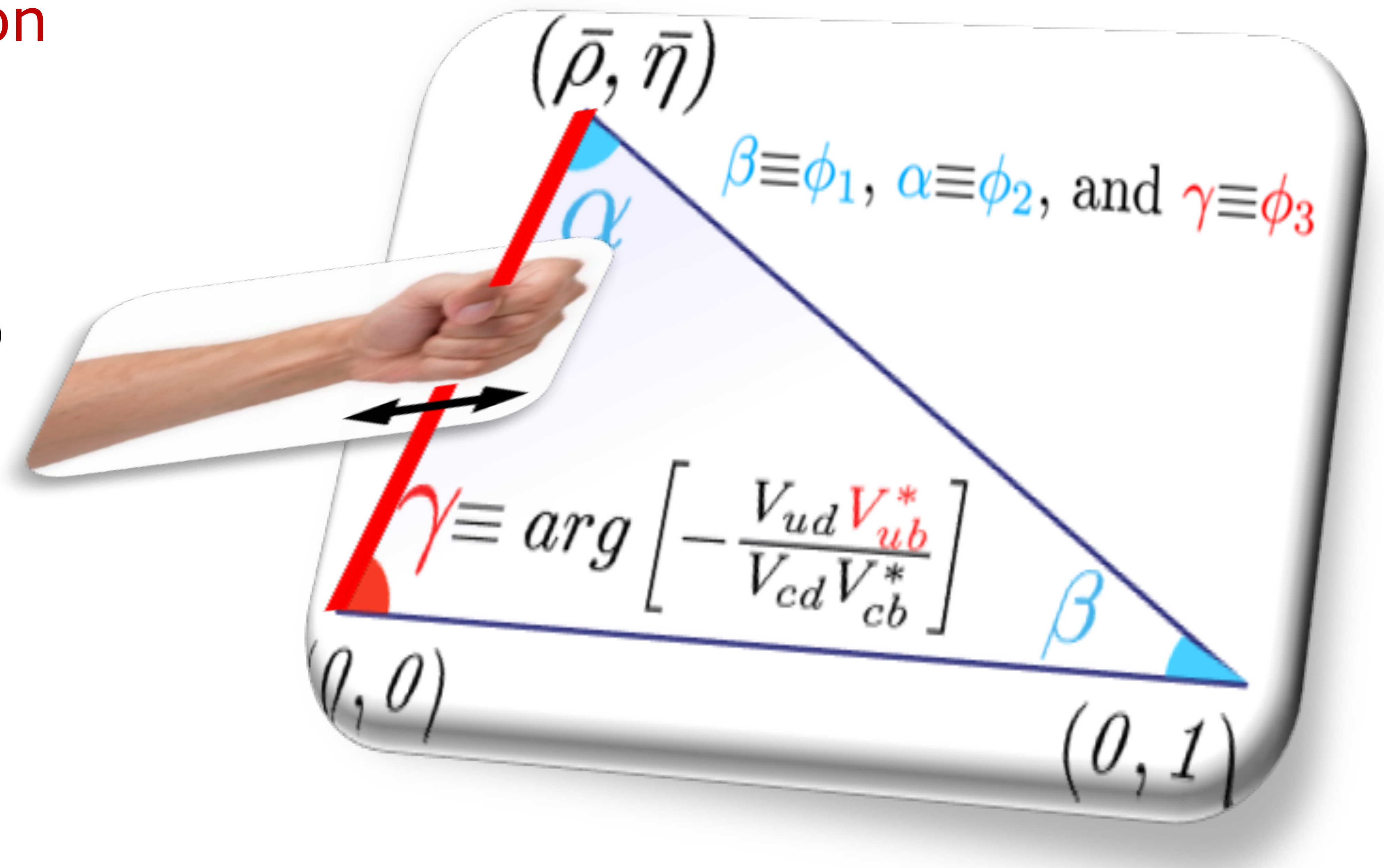
GDR-InF Annual Workshop 2022
2 – 4 November

Contents

- Physics motivation – CKM matrix and Unitarity Conditions
- Analysis
  - CKM angle γ measurement in $\boldsymbol{B_s^0} \rightarrow \boldsymbol{\bar{D}^{(*)0}\phi(KK)}$ decay
  - CKM angle γ measurement in $\boldsymbol{B^-} \rightarrow \boldsymbol{DK^{*-}(K^-\pi^0)}$ decay
- Conclusions

Physics motivation: CKM matrix and Unitarity Conditions

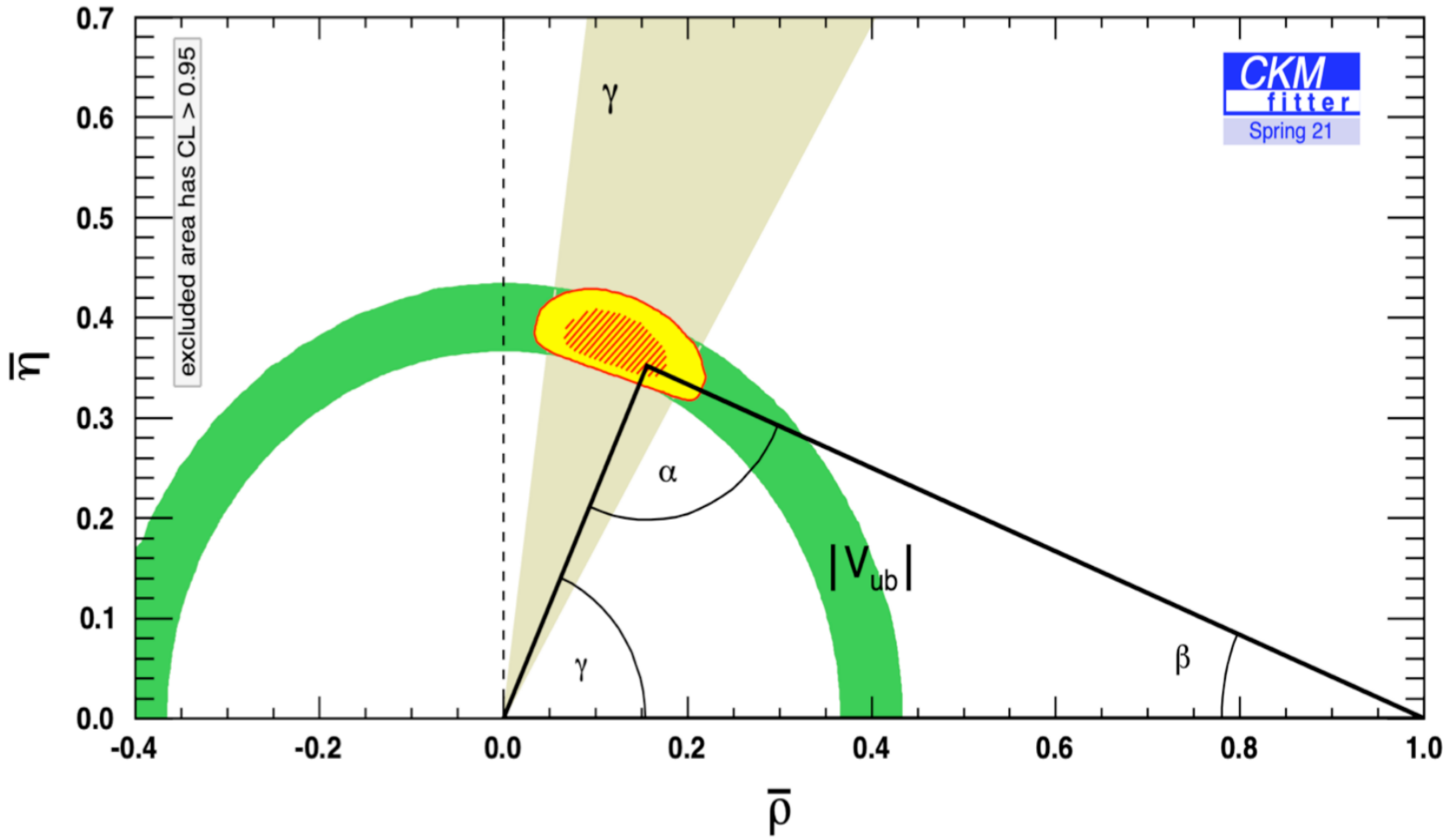
- In order to verify the unitarity of the CKM matrix
  - Complex phase $\gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$ which is source of CP violation can be measured from the processes mediated
    - Only angle accessible at **Tree-level** (direct measurement)
      - theoretically clean
      - "**Standard Candle**" of the Standard Model
      - Interference between b→c and b→ u quark transitions
  - Precise measurements of the magnitudes of the CKM matrix elements : mixing, branching fractions
  - Sub-degree level of measurements to be compared with the CKMfitter global fit to challenge the Standard Model



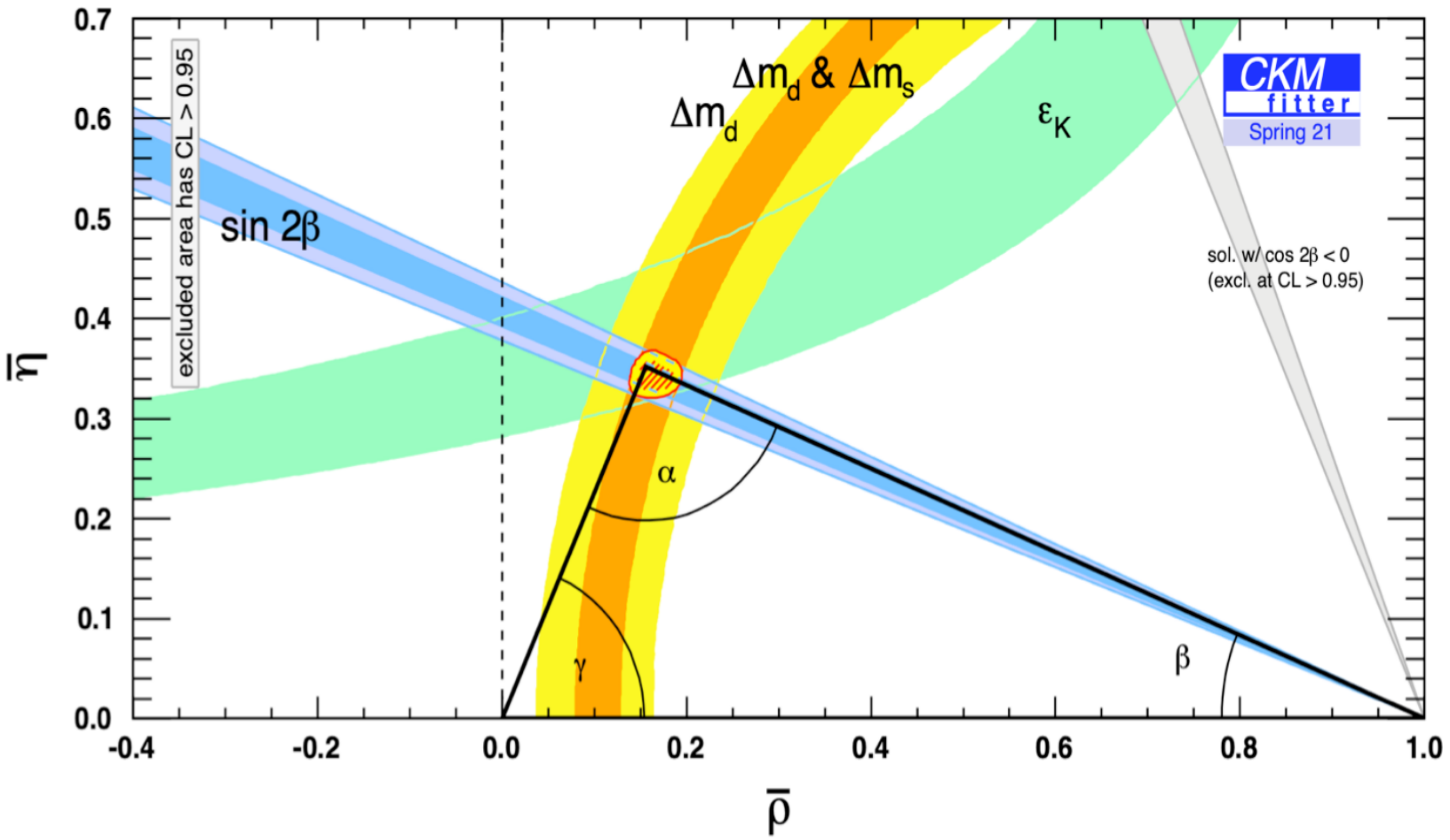
- **Loop-level** (indirect measurement) – sensitive to New Physics (NP)

Physics motivation : Unitarity triangle

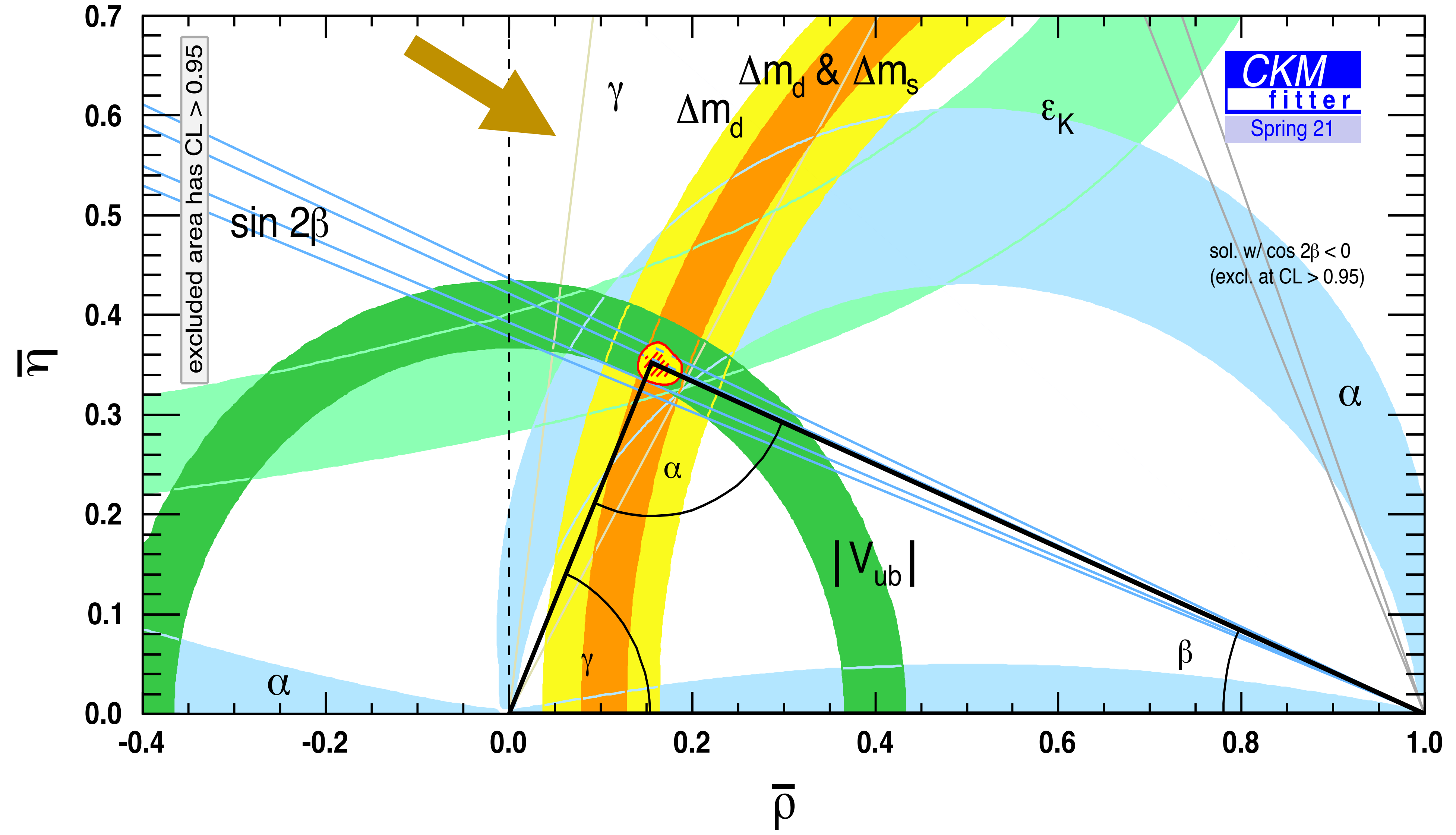
- Discrepancy between these will indicate "**New Physics**"
- Many different channels used to measure the angles and sides of the triangle



Direct measuments
(Pure SM like)



Indirect measurements
(Possible sensitivity to NP)



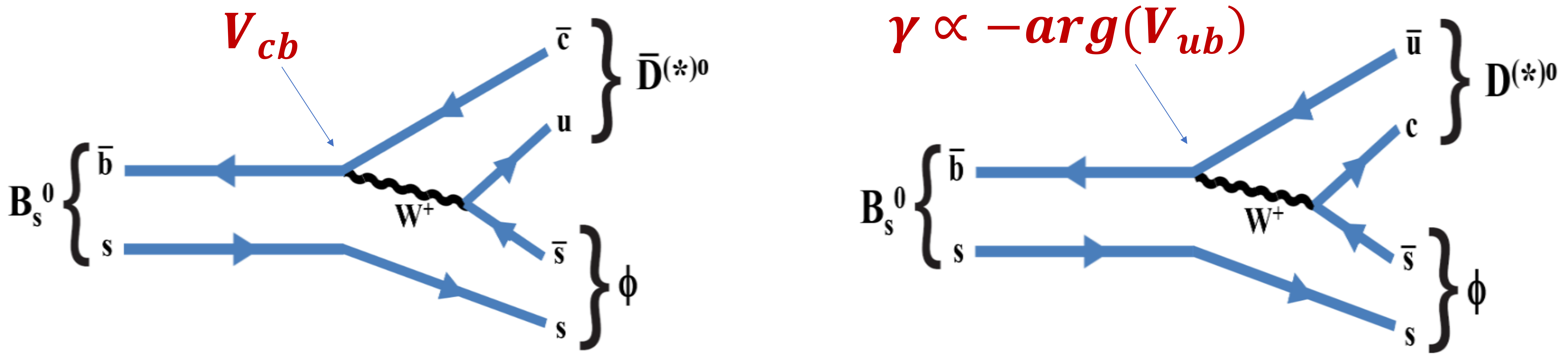
CKM angle γ in $B_s^0 \to \overline{D}^{(*)0}\phi(KK),\ D^{(*)0} \to K^-\pi^+\pi^0$

- Analysis based on Run1+Run2 data sample corresponding to an integrated luminosity of $9fb^{-1}$

The CKM angle γ in $B_s^0 \to D^{(*)0}\phi(KK)$ decays

Motivations

- Another accessible measurement in B_s^0 decays
- Time-integrated untagged analysis in various neutral D meson sub-decays [Phys.Rev.D.69.113003-2004] ; J. Zupan, [Phys. Lett. B 649 (2007) 61]; S. Ricciardi,[LHCb-PUB-2010-005, CERN-LHCb-PUB-2010-005.]
- Relying on external input on QCD parameters on D decays
- Already observed in R. Aaij et al. [LHCb Collaboration], [Phys. Rev. D 98 (2018) 071103.]
- In those decays the access to γ proceed through the two interfering color-suppressed Feynman diagrams, whose amplitudes are comparable in size (r_B from 20% to 50%) [Phys. Rev. D 102 (2020) 056017.]



- Experimentally clean final states with the narrow mass resonances ϕ and D^0
- Decay modes considered in this analysis: $K\pi, K\pi\pi\pi, K\pi\pi^0, KK, \pi\pi$

The CKM angle γ in $B_s^0 \to D^{(*)0}\phi(KK)$ decays

[Chinese Phys. C 45 023003 (2021)]

- Yields used in sensitivity study

- The sensitivity analysis relies on rough extrapolation based on the analysis that was not developed for $B_s^0 \to D^{(*)0}\phi(KK)$ but for the $B_s^0 \to \bar{D}^0 K^+K^-$. [Phys. Rev. D 98 (2018) 071103.]

- The projections for sub-decay modes: $\boldsymbol{K\pi, KK, \pi\pi, K\pi\pi\pi, K\pi\pi^0}$ are extrapolated from other published gamma papers in LHCb.

Goal: Optimize the selections for the various $B_s^0 \to D^{(*)0}\phi$ channels to obtain a very high purity and the most abundant signal of $B_s^0 \to D^0\phi$ to achieve the best sensitivity on $\boldsymbol{\gamma}$

	Expect. yield (Run 1 only)	
$B_s^0 \to \tilde{D}^0(K\pi)\phi$	577 (132 ± 13 [18])	
$B_s^0 \to \tilde{D}^0(K3\pi)\phi$	218	
$B_s^0 \to \tilde{D}^0(K\pi\pi^0)\phi$	58	
$B_s^0 \to \tilde{D}^0(KK)\phi$	82	
$B_s^0 \to \tilde{D}^0(\pi\pi)\phi$	24	
$B_s^0 \to \tilde{D}^0(K_S^0\pi\pi)\phi$	54	
$B_s^0 \to \tilde{D}^0(K_S^0KK)\phi$	8	
$B_s^0 \to \tilde{D}^{*0}\phi$ mode	$D^0\pi^0$	$D^0\gamma$
$B_s^0 \to \tilde{D}^{*0}(K\pi)\phi$	337	184
	(119 [18])	
$B_s^0 \to \tilde{D}^{*0}(K3\pi)\phi$	127	69
$B_s^0 \to \tilde{D}^{*0}(K\pi\pi^0)\phi$	34	18
$B_s^0 \to \tilde{D}^{*0}(KK)\phi$	48	26
$B_s^0 \to \tilde{D}^{*0}(\pi\pi)\phi$	14	8

The CKM angle γ in $B_s^0 \to D^{(*)0}\phi(KK)$ decays

[Chinese Phys. C 45 023003 (2021)]

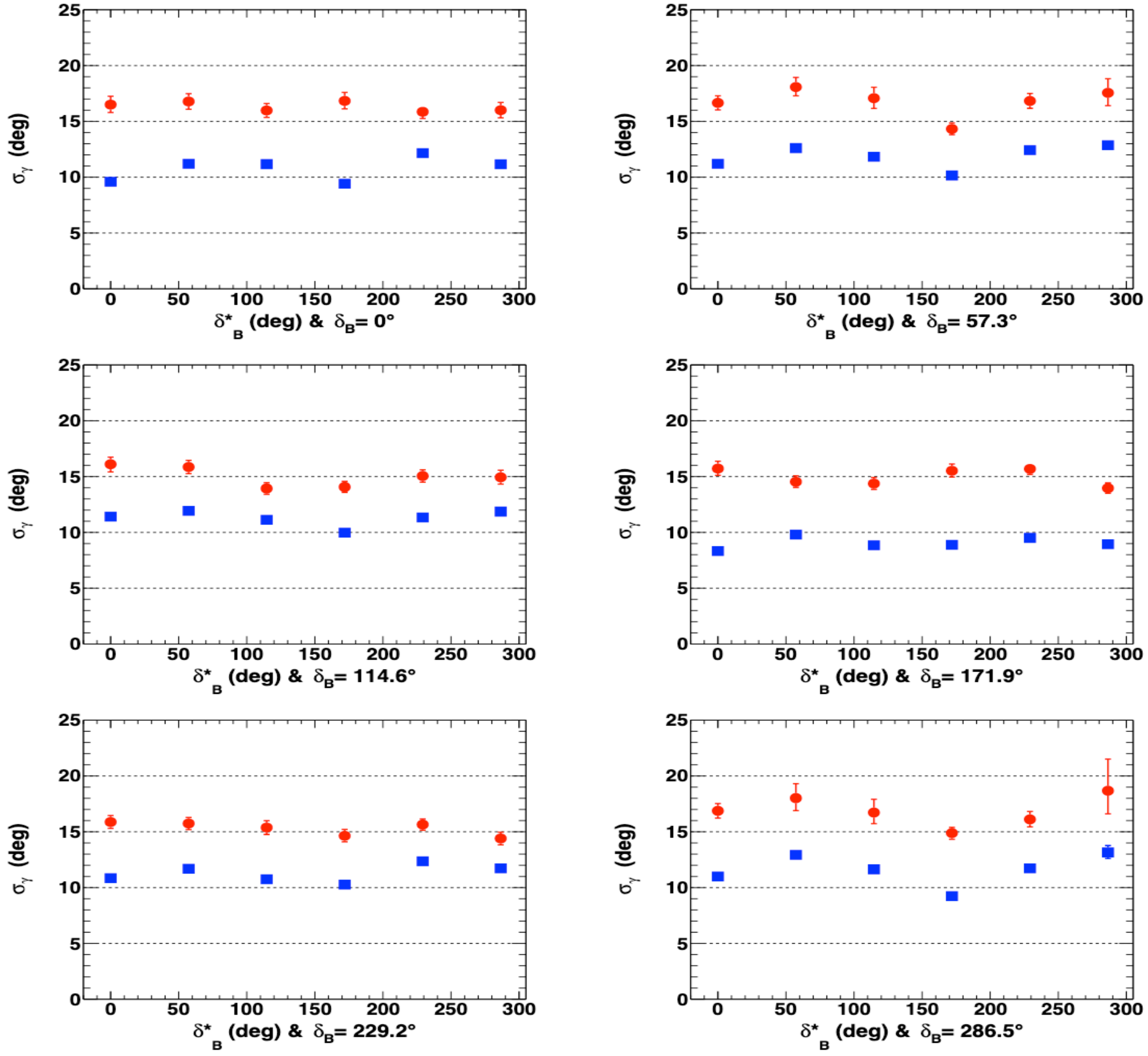
- The study was performed while varying the unknown nuisance strong interaction parameters: r_B, δ_B, r_B^*, δ_B^*

- Extrapolate the yield of signals from [Phys. Rev. D 98 (2018) 071103.]

- The sensitivity on $\boldsymbol{\gamma}$ obtained $\boldsymbol{\sim 8^\circ}$ **to** $\boldsymbol{19^\circ}$ with Run1 & Run2 dataset(similar sensitivity as in $B_s^0 \to D_s^\mp K^\pm(\pi\pi)$ decays)

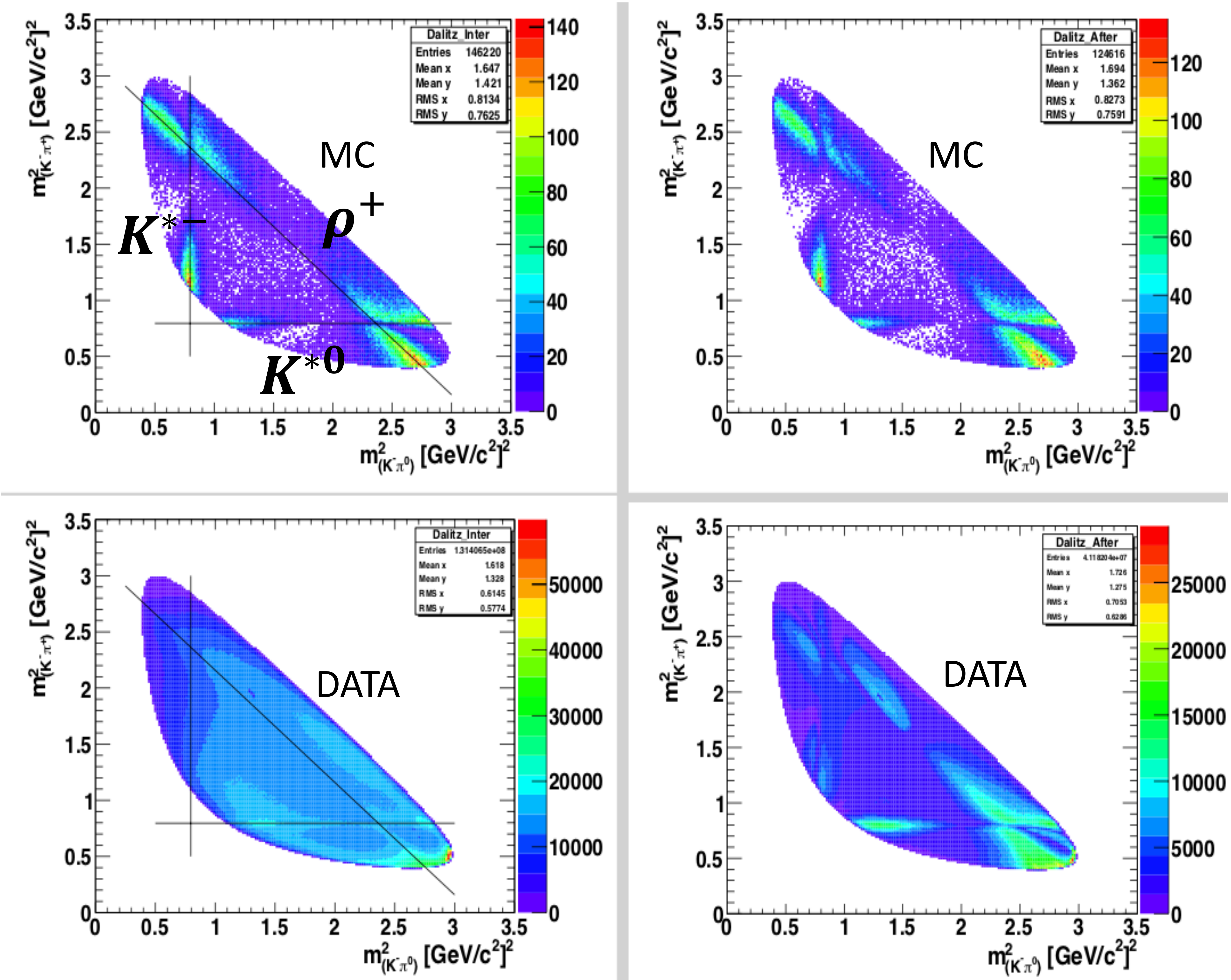
- In the absence of $B_s^0 \to D^*\phi$, the sensitivity to $\boldsymbol{\gamma}$ is 15 to 20% worse

- Projection for future LHCb upgrades have also been studied in this paper



$B_s^0 \to D^{(*)0}\phi$ analysis – optimization example for the "most challenging" mode $D^0 \to K^-\pi^+\pi^0$

- Selection of sub-decay mode $D^0 \to K^-\pi^+\pi^0$ is complicated because of neutral pion π^0
  - Large backgrounds studied: Resolved $\pi^0 \to \gamma\gamma$ separately in ECAL
- **MC simulation:**
  - Amplitude model from E691 Experiment and confirmed by CLEO-C Experiment
  - Relative distribution of the strong phase is not effecting. Data is adjusted according to the Dalitz amplitude model.
  - MVA sculpts the 2D distribution without biasing the strong $D^0 \to K^-\pi^+\pi^0$ phase
  - involving resonant Spin-1 particles (K^{*0} (horizontal), K^{*-} (vertical), ρ^+ (anti-diagonal))
- **MVA Method: BDT to select π^0 (discriminating variables)**
  - Dalitz weight, photon asymmetry, photon tranverse energy, probability for photons to be not electrons or hadrons to reduce the background
- **Optimization of the π^0**
  - Signal Efficiency 85%
  - Background Rejection 80%



Resonance R	m_R (MeV/c^2)	Γ_R (MeV)	C_R	Φ_R	Fraction (Γ_i/Γ)
$K^{*0}(892) \to K^-\pi^+$	896.10	50.70	3.19	$-13°$	$(1.95 \pm 0.24)\%$
$K^{*-}(892) \to K^-\pi^0$	891.66	50.80	2.96	$68°$	$(4.8 \pm 2.2) \times 10^{-3}$
$\rho^+(770) \to \pi^+\pi^0$	766.50	150.2	8.56	$40°$	$(8.2 \pm 1.8) \times 10^{-3}$

Γ_R: width of the resonant particle
C_R: amplitude
Φ_R: phase

http://dx.doi.org/10.1093/ptep/ptaa104

The CKM angle γ – optimisation of the pre-selections for $B_s^0 \to D^{(*)0}\phi(KK)$

- **Pre-selections** inherited from $\overline{D}^0 K^+ K^-$ analysis re-optimized on $B_s^0 \to D^{(*)0}\phi$ to improve the statistical significance and to reduce the background [Phys. Rev. D 98, 071103(R)(2018)]

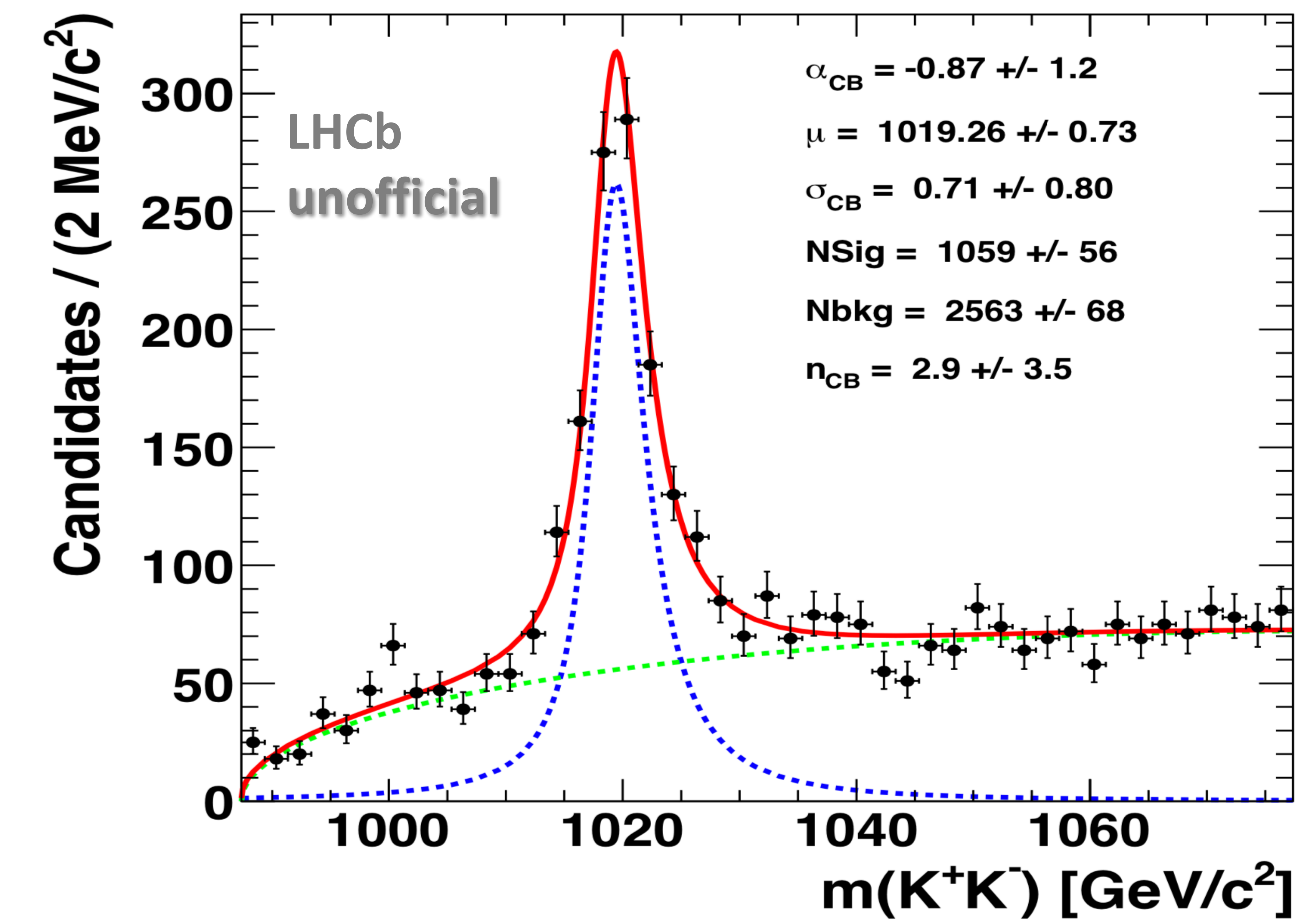
- Final selection studied for with MVA giving the best optimization suppresses the combinatorial background

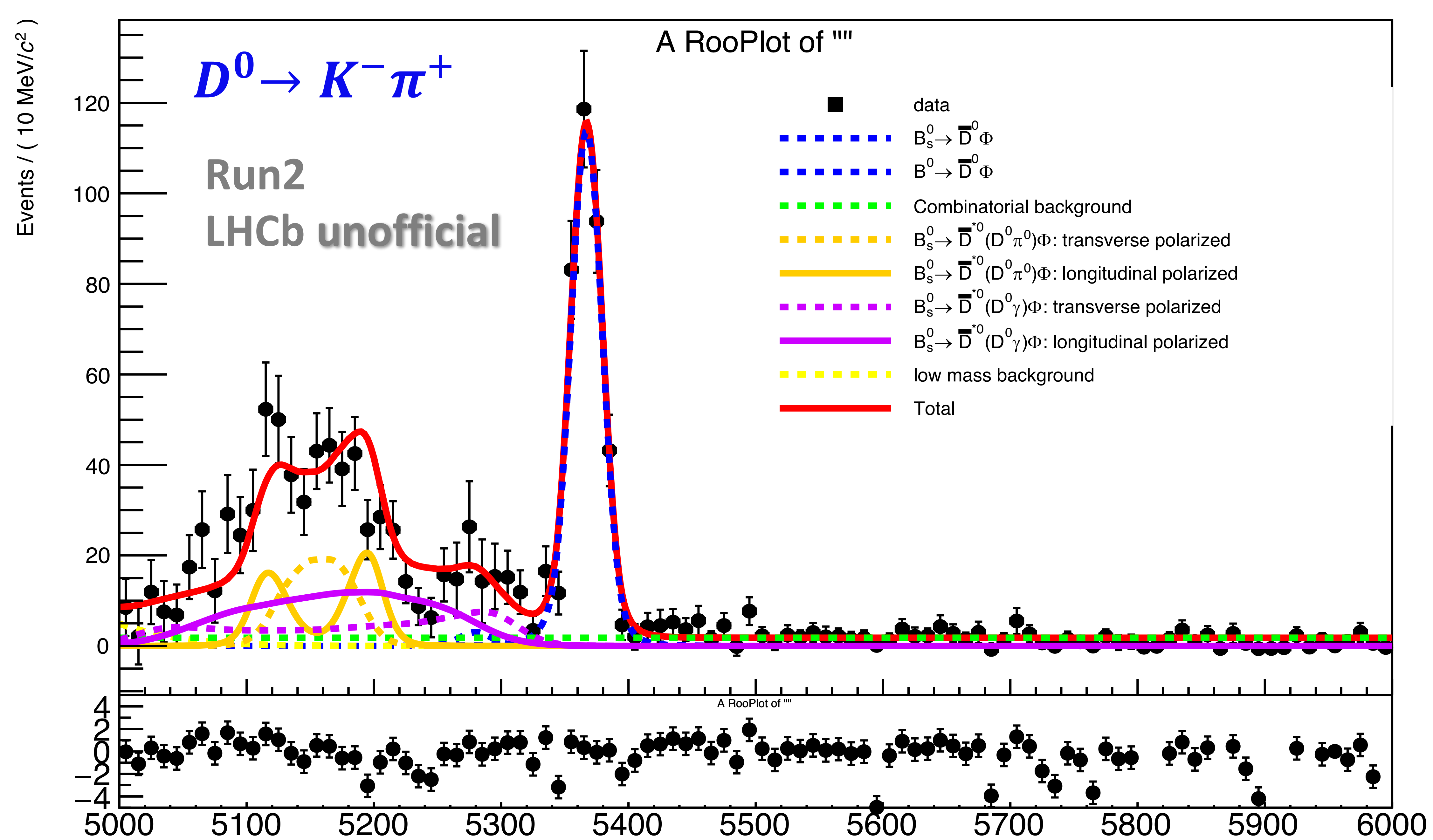
  - Topological and kinematic variables to discriminate the signal against the background used for
    - $D^0 \to h^- h^+ (K\pi,\ KK, \pi\pi\ ),\ D^0 \to K^-\pi^-\pi^+\pi^+$ (Fisher)
    - $D^0 \to K^-\pi^+\pi^0$ (MLP classifier)

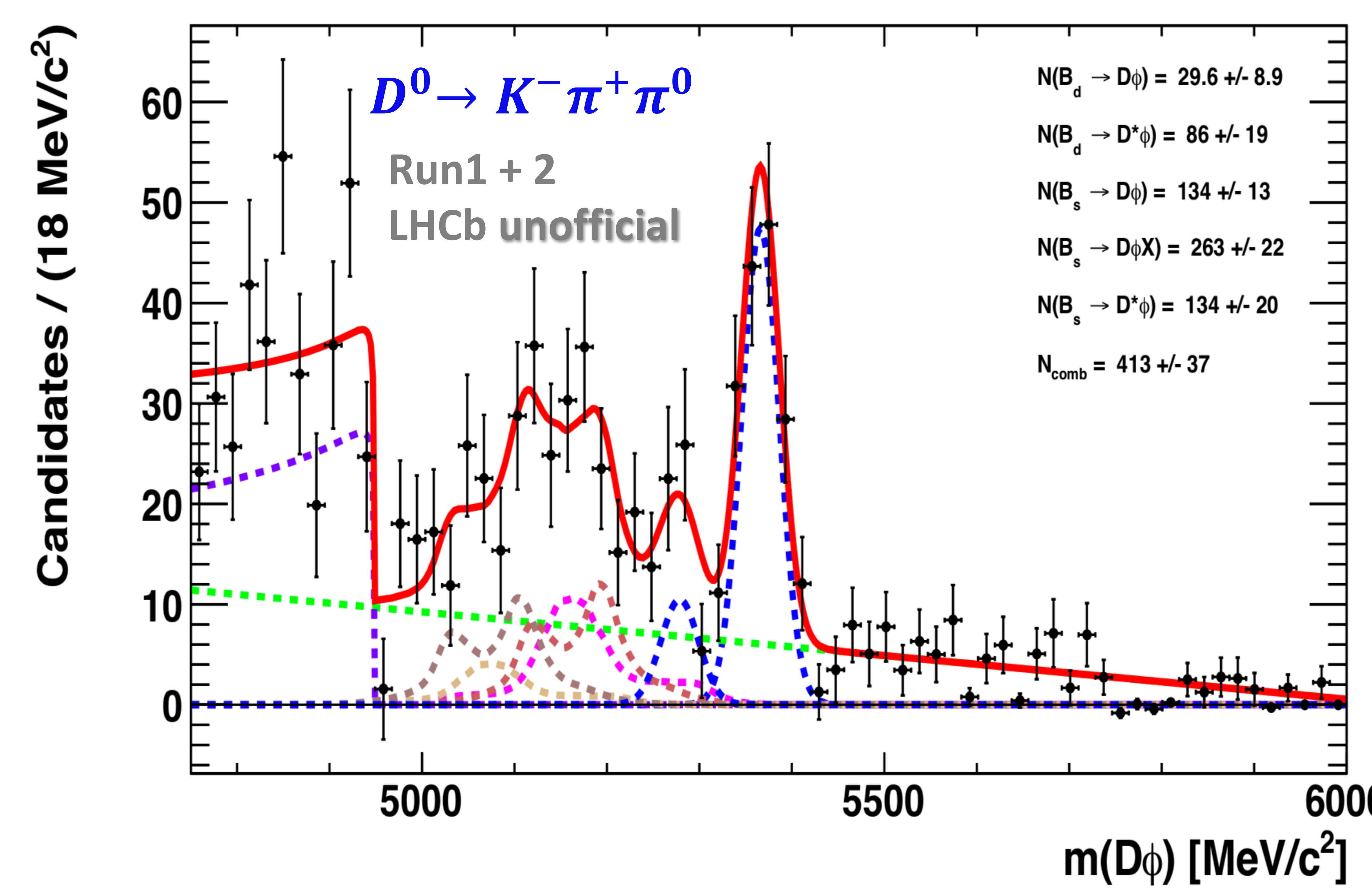
Candidates		Criteria	
D^0	Invariant mass	[1765.0 , 1965.0] MeV/c²	
B^0	Invariant mass	[5.1 , 6.0] GeV/c²	
π^0		[116.0 , 160.0] MeV/c²	
D^0	Vertex χ^2 / nDof	< 6 to < 4	
	BPVIPCHI2	> 20	
D^0	SDB = $\frac{z_D - z_B}{\sqrt{\sigma_{z\,D}^2 + \sigma_{z\,B}^2}}$	> 3 to ~ 1.25 (RUN1) > 3 to ~ 1.05 (RUN2)	Charmless decay
B^0	Vertex χ^2 / nDof BPVIPCHI2 $\cos(\theta_{dira})$(BPVDIRA)	< 4 < 4 > 0.99995	
D^{*-} (2010) veto		$m_{D_\pi} - m_D \notin$ [140.621 , 150.221] MeV/c²	
PID requirements for D^0 daughters (RICHs Identification)			
* π	ProbNN$_\pi$ x (1 – ProbNN$_K$)x (1 – ProbNN$_p$)	2%	
* K.	ProbNN$_K$ x (1 – ProbNN$_\pi$)x (1 – ProbNN$_p$)	0.02% to 5%	

The CKM angle – mass distribution and fit to the $B_s^0 \to D^{(*)0}\phi(KK)$

- sPlot technique performed to distinguish ϕ from non- ϕ background
- Signal shape modelled $m(KK)$: Breit-wigner function convoluted with Crystal-Ball resolution function
- Extended unbinned maximum likelihood fit performed to the invariant mass of m(KK) on $B_s^0 \to D^{(*)0}\phi$ candidates in the mass range $m_{DKK} \in [4750{,}6000]\text{MeV/c}^2$





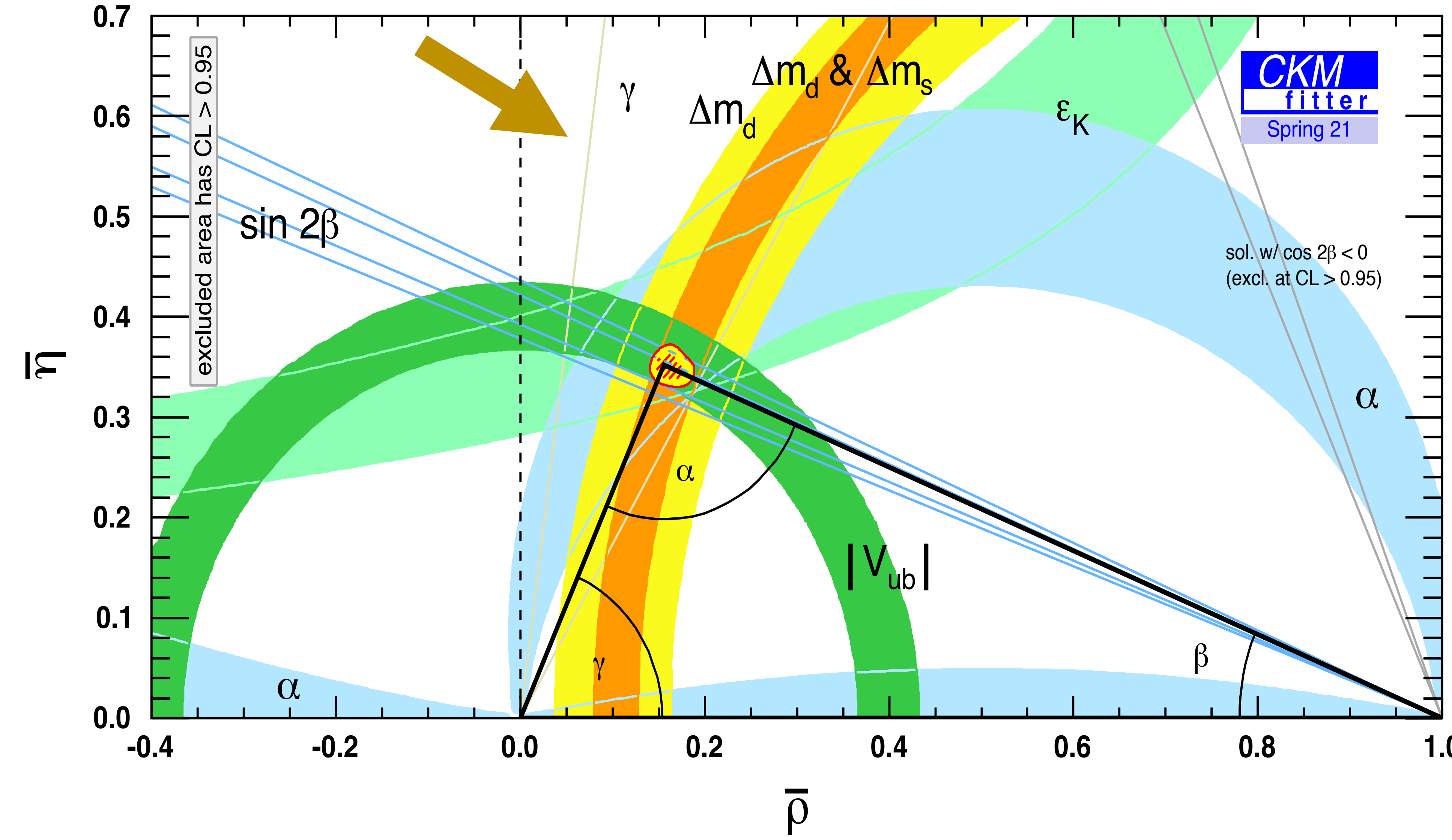


The CKM angle – mass distribution and fit to the $B_s^0 \to D^{(*)0}\phi(KK)$

- The yields are extracted by fitting the invariant mass of $B_s^0 \to D^{(*)0}\phi$ with Gaussian for the signal and combination of Chebyshev PDF are performed for the combinatorial background.
- The signal rate is improved by almost factor of 2

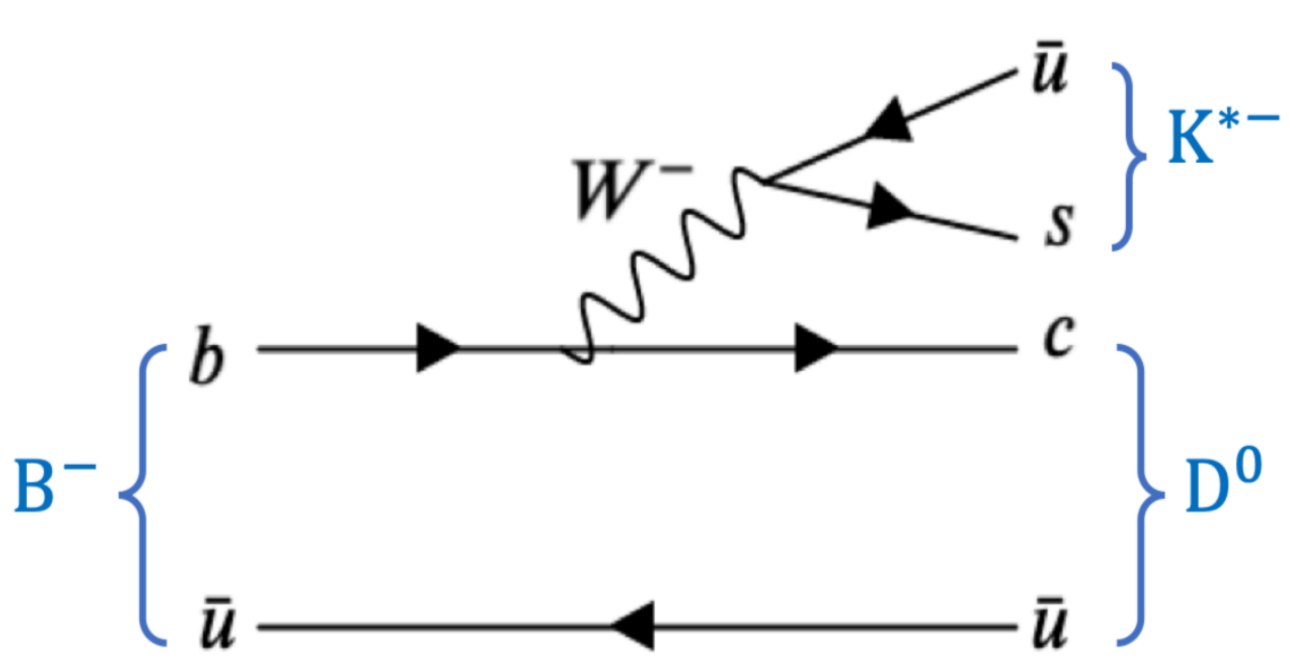
D^0 sub decay modes	$K\pi$	$K\pi\pi^0$
$B_s \to D^0\phi$ [Chinese Phys. C 45 023003 (2021)]	577	58
$B_s \to D^0\phi$ LHCb Run1+Run2	935 ± 32	134 ± 13
$B_s \to D^{*0}\phi$ longitudinal [Chinese Phys. C 45 023003 (2021)]	521	52
$B_s \to D^{*0}\phi$ LHCb Run1+Run2 (with $f_L = 0.5 \sim 0.7$)	1106 ± 45	137 ± 20

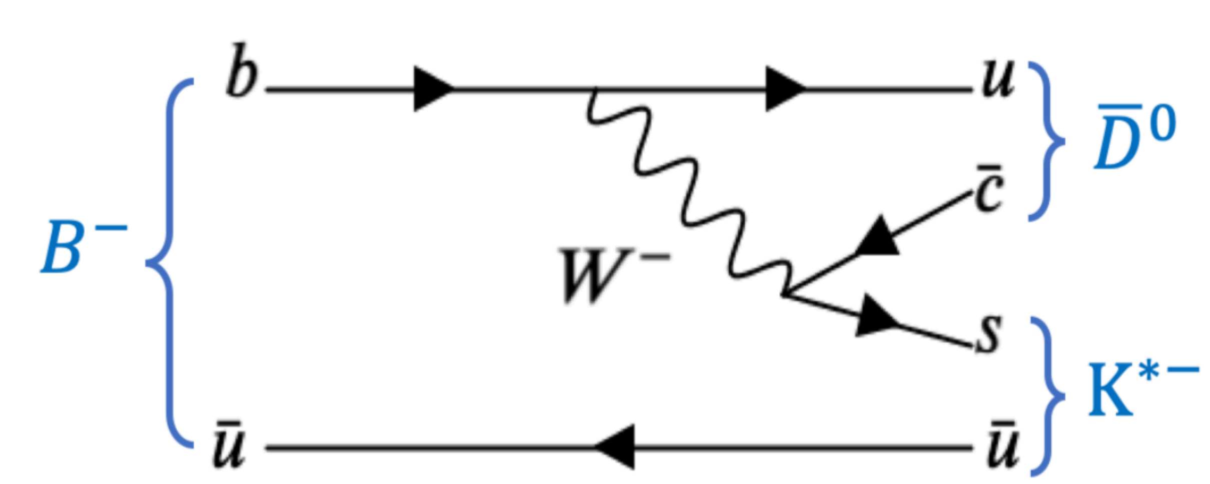
- Uncertainty of yields are assumed to be $\sqrt{N}$ in sensitivity study
- Relative uncertainty reduced 10%~30% , expect even better sensitivity on γ



CKM angle γ in $B^{\pm} \to \overline{D}^0 K^{*\pm}$ with $K^{*-} \to K^- \pi^0$

- Sensitivity to γ determined by the interference between the favoured b→c and suppressed b→u quark transitions in the tree level
- Analysis based on Run1+Run2 data sample corresponding to an integrated luminosity of $9 fb^{-1}$





δ_B , r_B $\quad \sigma(\gamma) \propto \frac{1}{r_B^2}$

Motivations

- Analysis on more conventional decay of $\mathbf{B^{\pm} \to D^0 K^{*\pm}}$ and $\mathbf{K^{*-} \to K_s \pi^-}$ has been done with RunI & RunII (2015 & 2016) data by A. Nandi & S. Malde (Oxford) & V. Tisserand [LHCb-PAPER-2017-030]

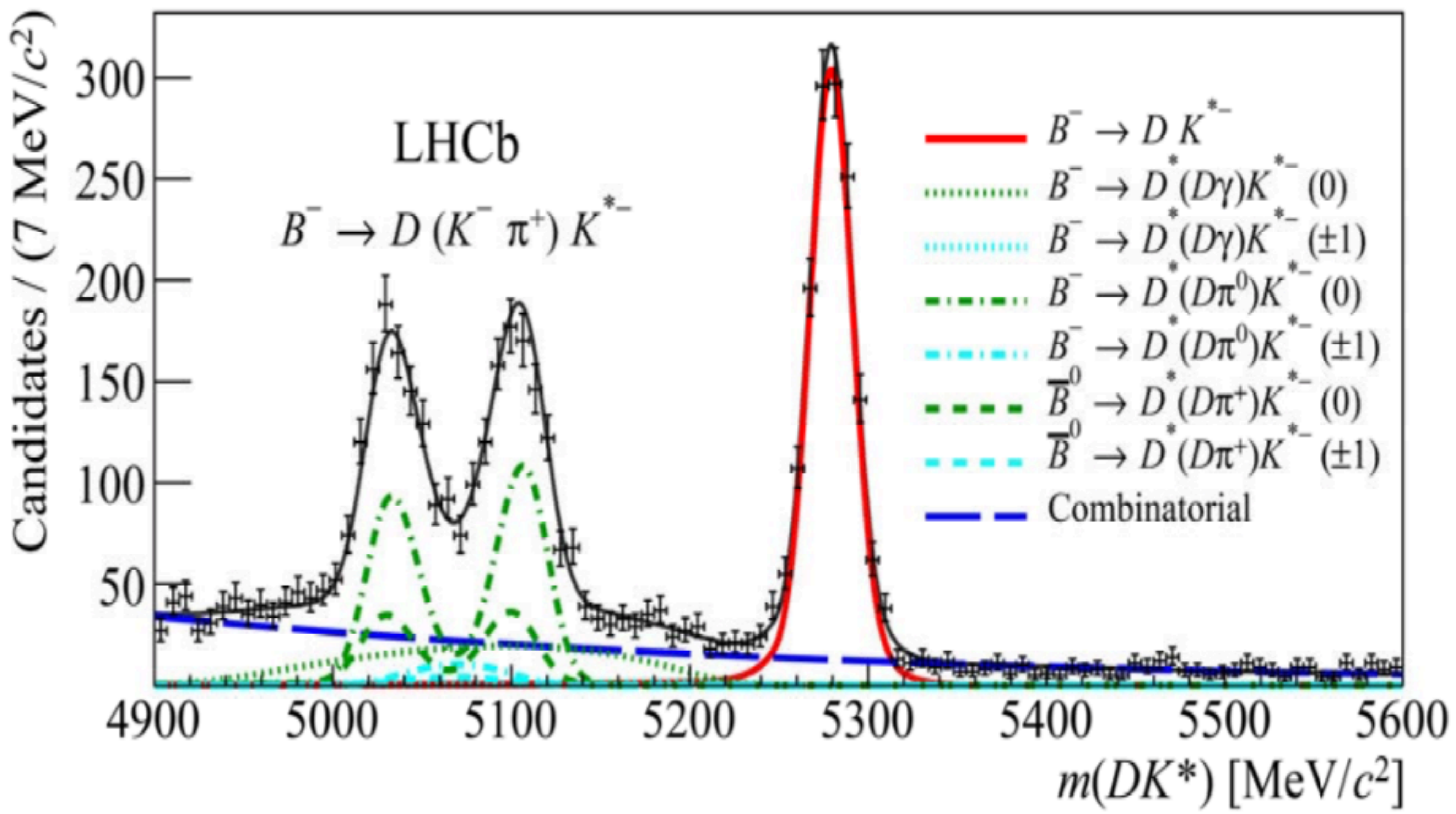
- $\mathbf{B^- \to D^0 K^{*-}}$ **with** $\mathbf{K^{*-} \to K^- \pi^0}$ same decay, another sub-decay using the full dataset RunI & RunII

$$\mathcal{BF}(K^{*-} \to K^0_S(\pi^+\pi^-)\pi^-) \approx \frac{2}{3} \times BF(K^{*-} \to K^-\pi^0)$$

  - Only difference dealing with $\mathbf{\pi^0}$ (reconstruction efficiency much lower)

  - Direct observation of the $\mathbf{B^- \to D^0 K^{*-}}$ decay, where D^0 meson is reconstructed in four different final states: CP-even eigenstates $K^-K^+, \pi^-\pi^+$ referred as GLW decay modes and flavour eigenstates $K^-\pi^+$ and $K^+\pi^-$ referred as ADS decay modes.

- **With current analysis to be used and improved**
  - **Full datasets**
  - **Same physics, i.e.** $\mathbf{r_B}$, $\mathbf{\delta_B}$
  - **Selection optimisation(Pre-selections, PID, MVA)**
  - **Efficieny measurement**
  - **Systematics**



[LHCb-PAPER-2017-030]

Decay mode	B^- yield	B^+ yield
$B^{\pm} \to D(K^{\pm}\pi^{\mp})K^{*\pm}$	996 ± 34	1035 ± 35
$B^{\pm} \to D(K^+K^-)K^{*\pm}$	134 ± 14	121 ± 13
$B^{\pm} \to D(\pi^+\pi^-)K^{*\pm}$	45 ± 10	33 ± 9
$B^{\pm} \to D(K^{\mp}\pi^{\pm})K^{*\pm}$	1.6 ± 1.9	19 ± 7

$$R_{CP+} = 1.18 \pm 0.08 \pm 0.01$$
$$A_{CP+} = 0.08 \pm 0.06 \pm 0.01$$

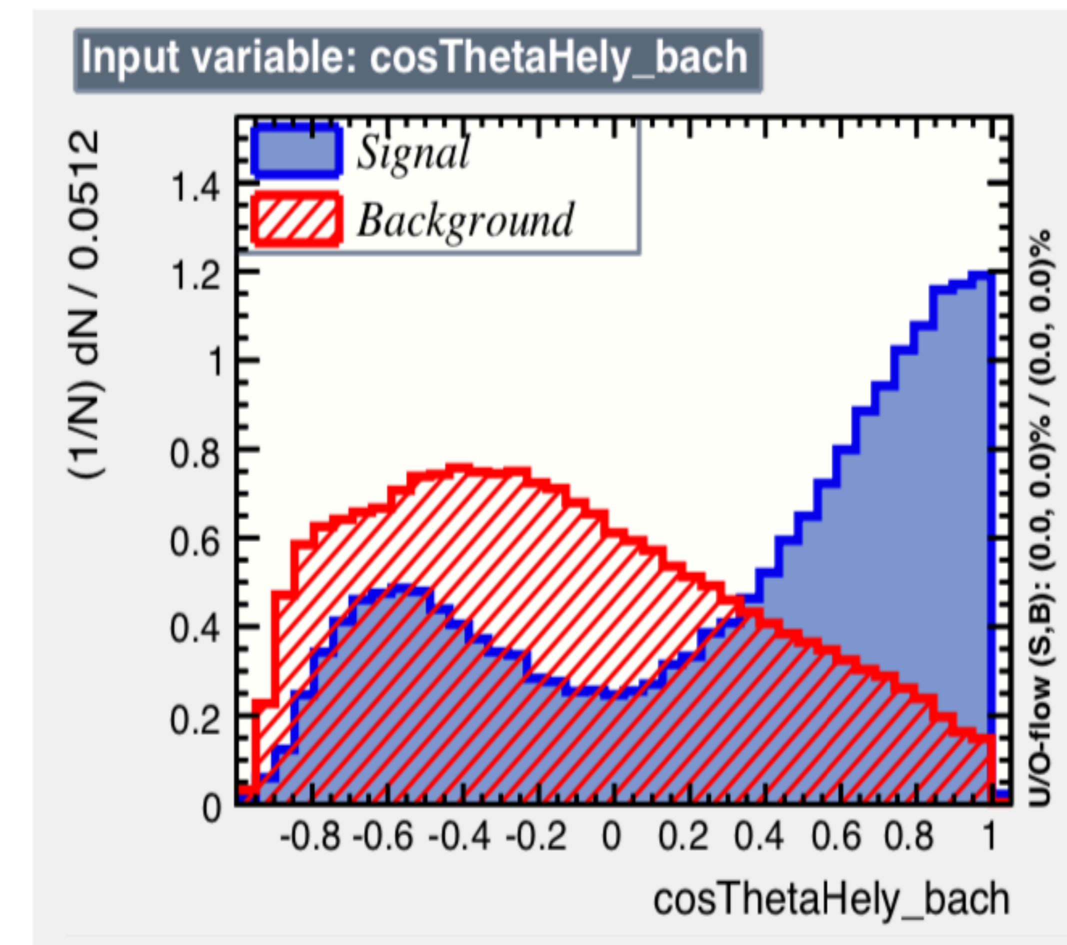
Statistical significance
4.2σ
[LHCb-PAPER-2017-030]

3 steps of MVAs (MLP)

In order to fight against the combinatorial background the strategy is to use the particles (D and K*) sidebands

→ 1) Bkgd with sideband m($\mathbf{K^-\pi^0}$) in [1.1, 1.3] Gev/c^2

1 MVA on the π^0 and K^* discriminating variables using signal MC and data



to suppress the most abundant combinatorial background originated. from π^0.

- **m(π^0) in [117.5, 159] Mev/c^2**
- **m(K^*)** mass region within the mass range $\pm$ **300 Mev/c^2** PDG mass.
- Discriminating variable i.e. cosThetaHely_bach: $\mathbf{K^*}$ is a vector V → SS

The signal distribution $cos^2 theta$ and the asymmetry is due to the stripping cuts on the p_T of the π^0 and K track.

→2) **1 MVA on the D discriminating variables.** Using **MC in RED** and **data in Blue.** (see graphics right)

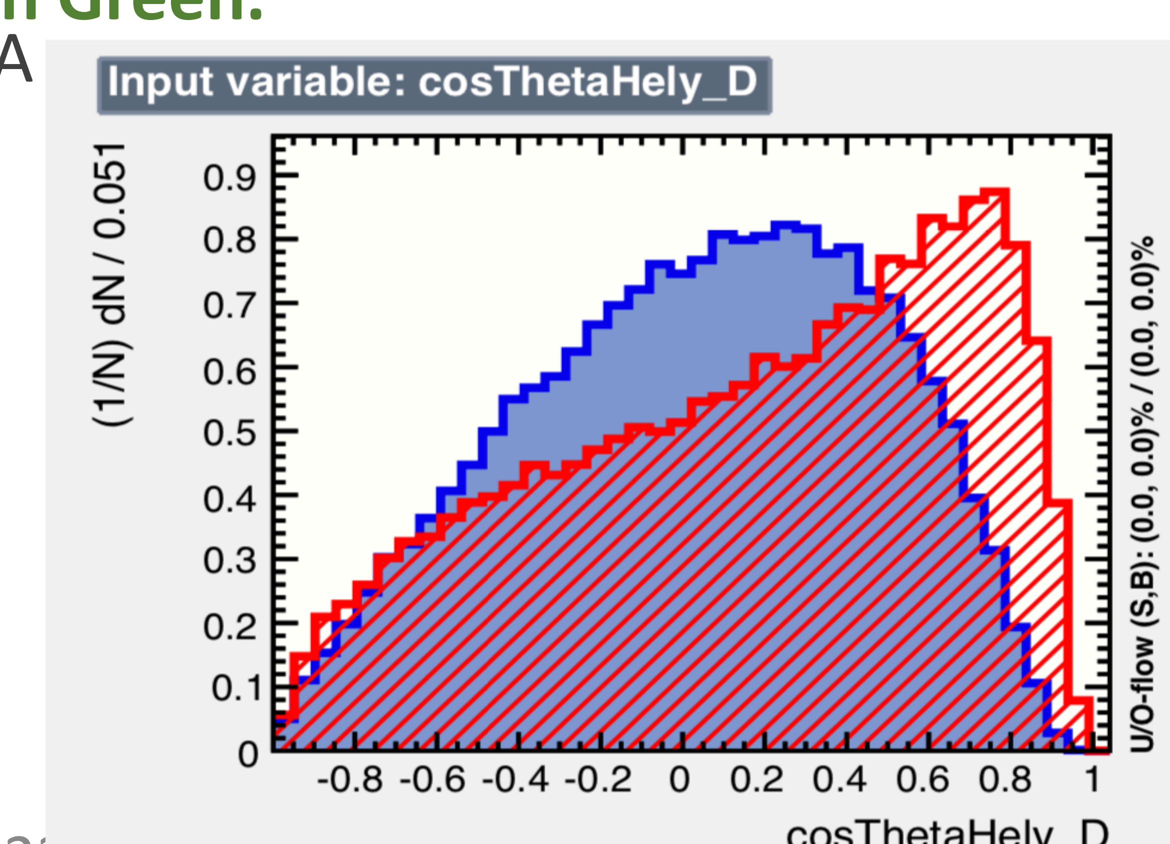
Cut on the mass range **m(D) within $\pm$105 Mev/c^2** PDG mass. (keep sideband for the later use)

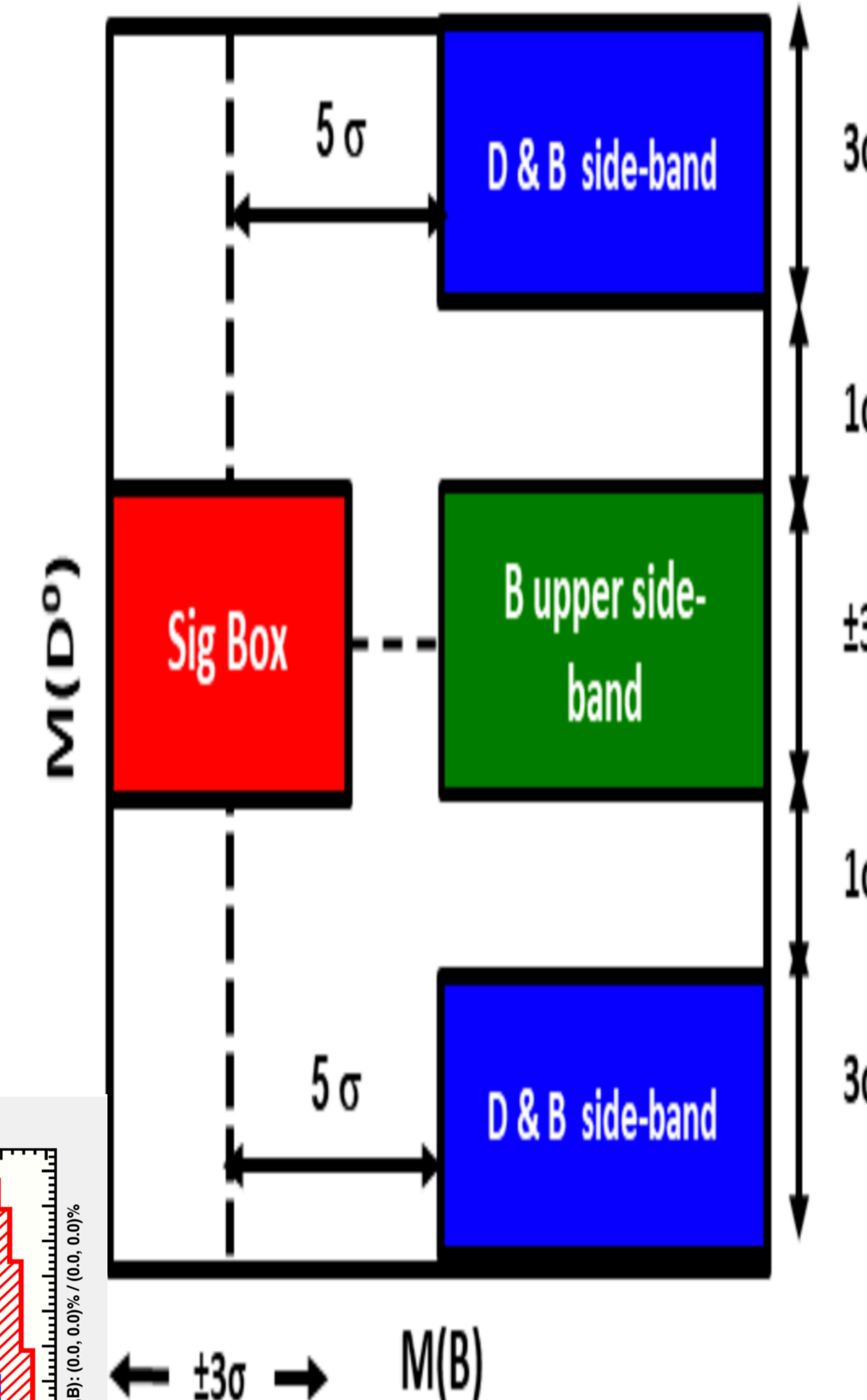
→3) **1 MVA on the second B discriminating variables** using **MC in RED** and **Data in Green.** (see graphics right) on the $\mathbf{K^{*-}}$ and MVA on the **D** used as inputs for the last MVA

- Discriminating variable i.e. cosThetaHely_D: the angle between the momentum

of the D and B mesons. The signal shape is 1- $cos^2 theta$ since $\mathbf{B^-} \to \mathbf{D^0 K^{*-}}$ is

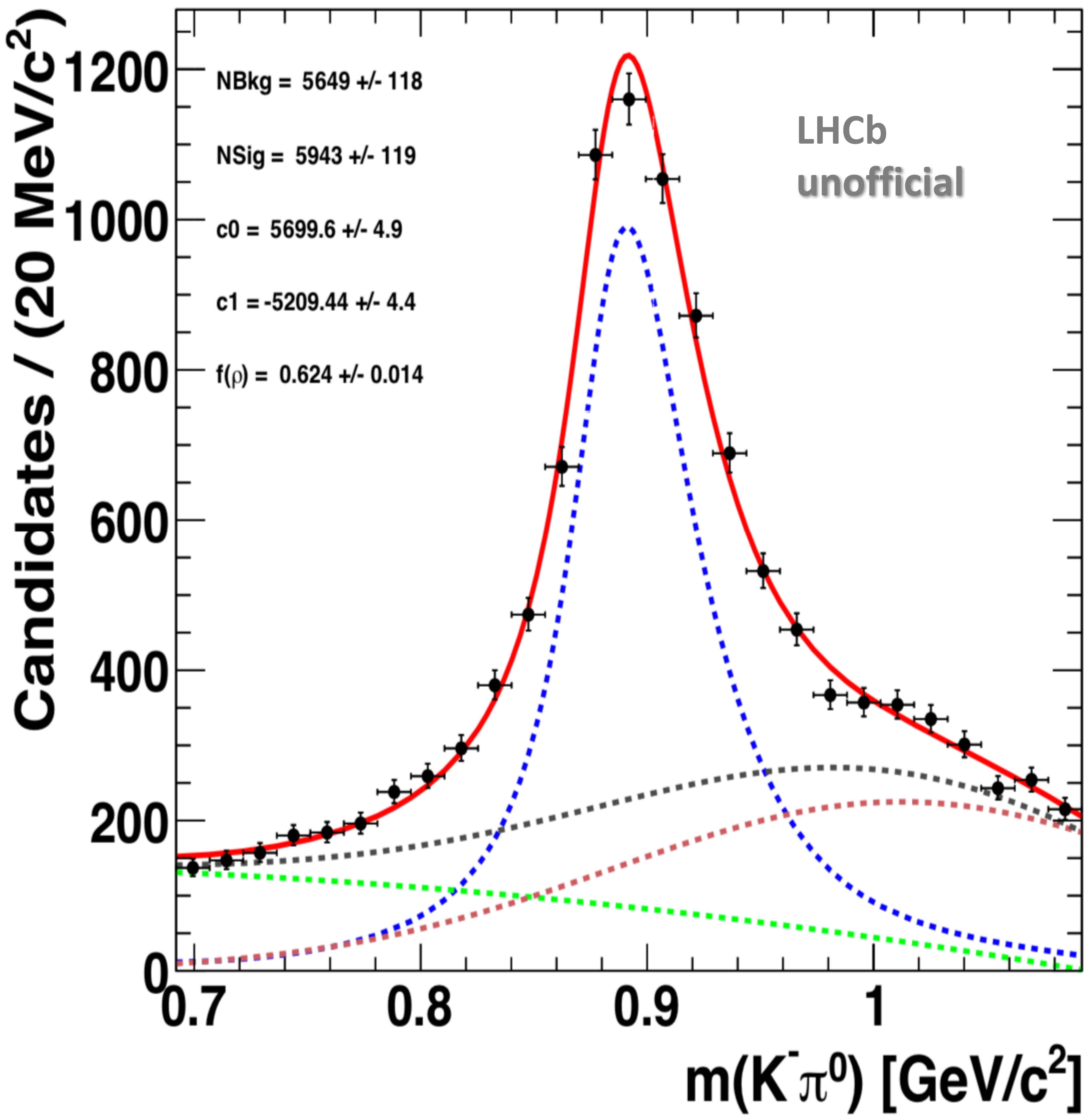
S → S+V





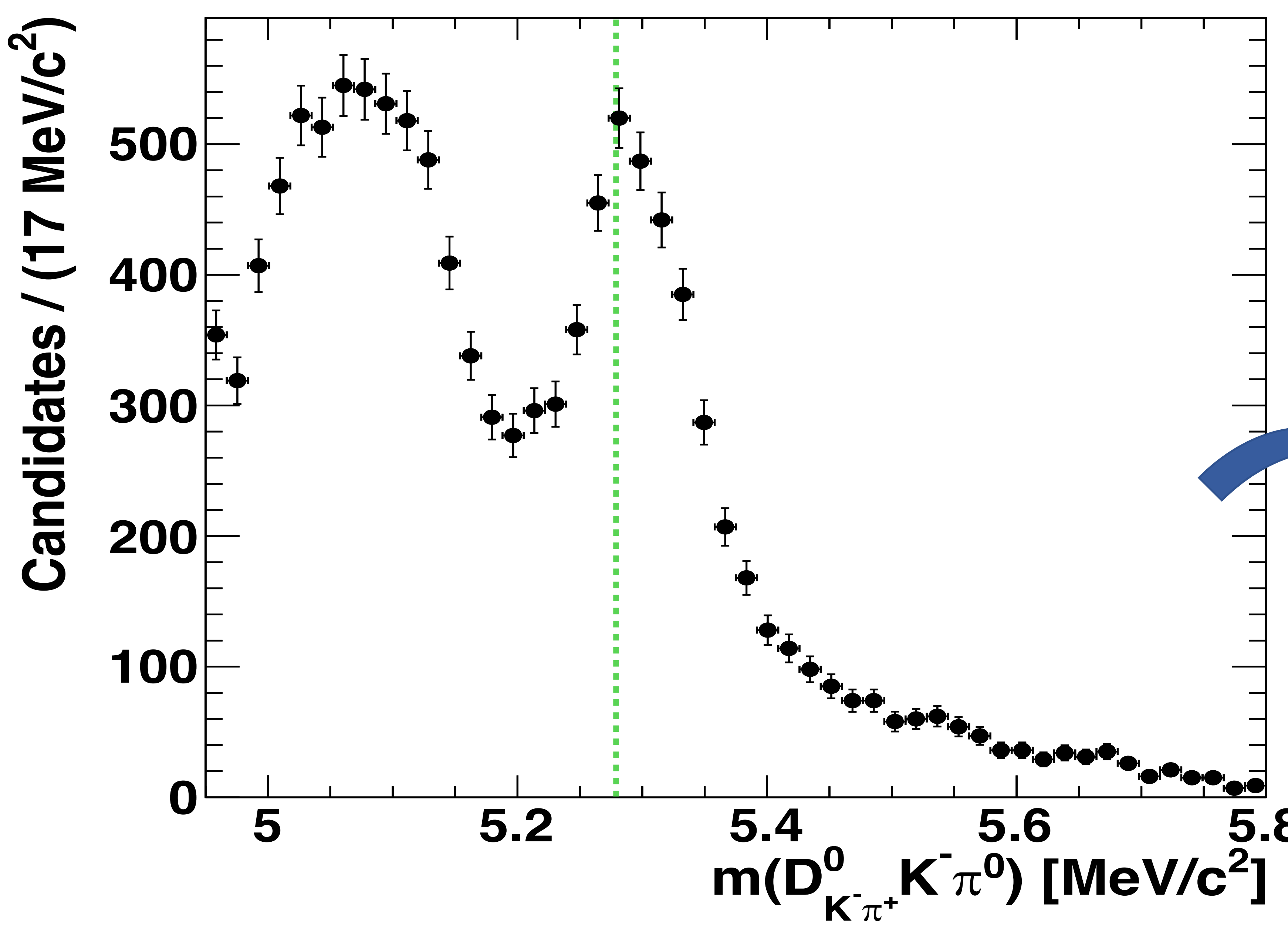
The CKM angle γ in $B^{\pm} \to \bar{D}^0 K^{*\pm}$

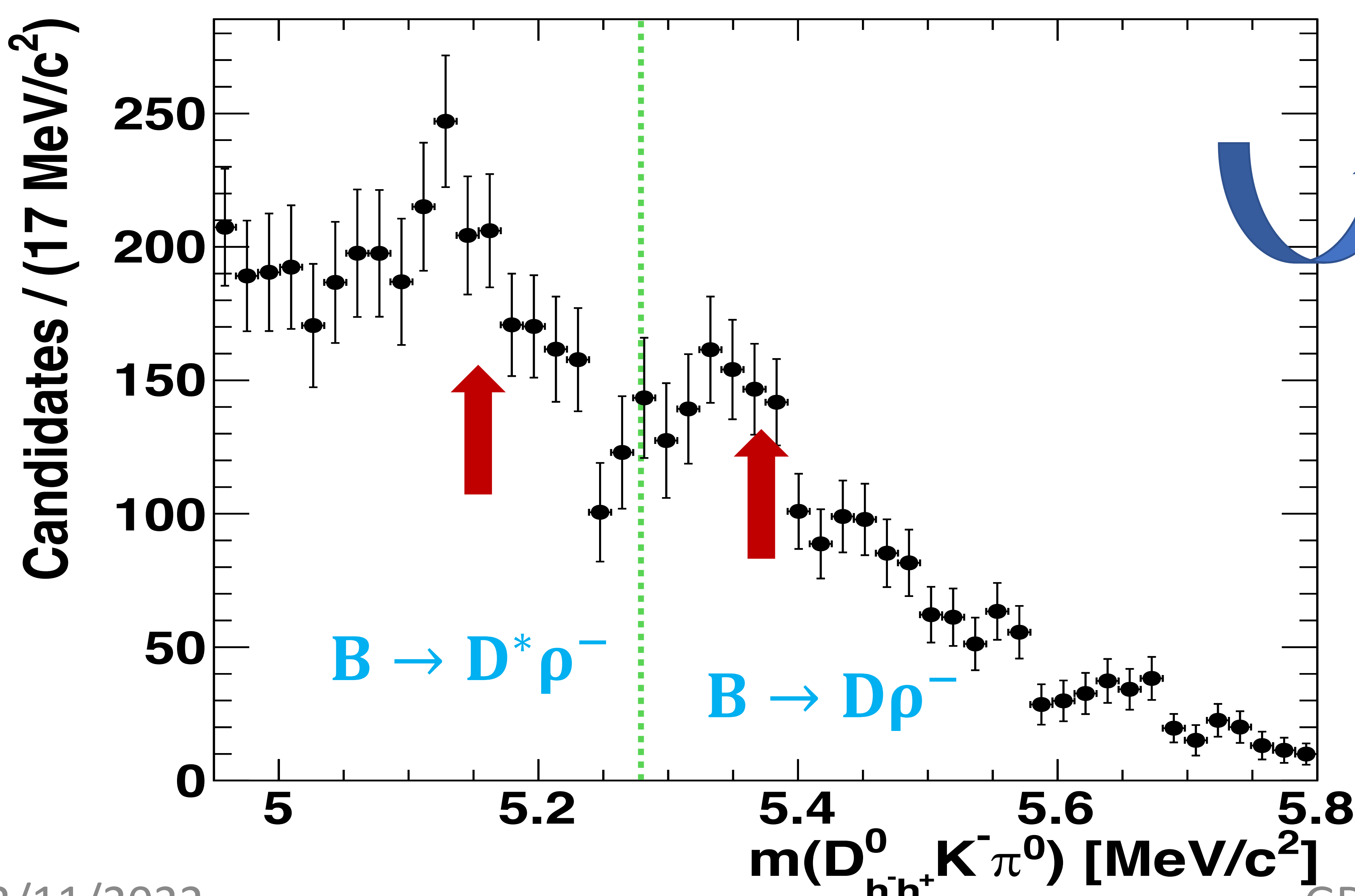
- Various background sources contribute to the invariant mass fit
  - ✓ Charmless decays : $B^- \to K^+K^-K^{*-}$, $B^- \to \pi^+\pi^-K^{*-}$, $B^- \to \pi^+K^-K^{*-}$, $B^- \to \pi^-K^+K^{*-}$
  - ✓ Partially reconstructed decays $B^- \to D^{*0}[D^0\pi^0]K^{*-}$, $B^- \to D^{*0}[D^0\gamma]K^{*-}$, $B^- \to D^{*+}[D^0\pi^+]K^{*-}$
  - ✓ Background from $B^0 \to D^{*+}[D^0\pi^+]\rho^-[\pi^-\pi^0]$ and $B^- \to D^{(*)0}\rho^-[\pi^-\pi^0]$
  - ✓ Combinatorial background
- After all selections deployed, to remove the remaining non-K^* background (i.e. $B \to D^{0(*)}\rho$) lies below the signal peak, we follow two steps:
- **First:** A fit to the K^{*-} mass is performed on top of the combinatorial background and the mis-identified $\rho^- \to \pi^-\pi^0$
- Retain only $K^{*-} \to K^-\pi^0$ candidates in the mass range of $[0.692, 1.092]\mathrm{GeV/c^2}$
- Signal shape modelled $m(K^-\pi^0)$: Breit-wigner function convoluted with two Novosibirsk PDFs



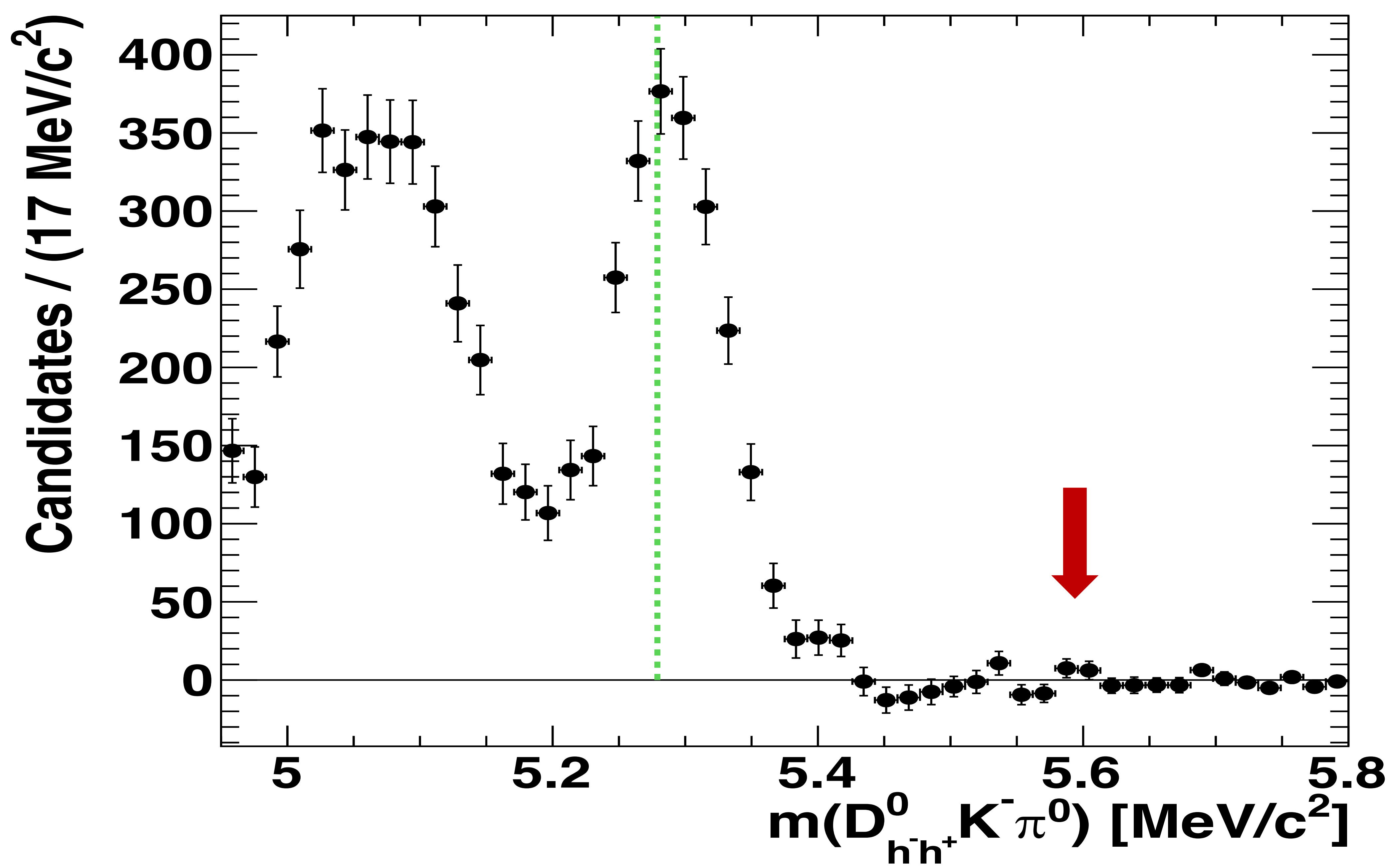
$B^{\pm} \to \overline{D}^0 K^{*\pm}$ analysis -- sPlot subtraction of non-K^* background

- sPlot technique which provides a statistical subtraction is used to distinguish to remove the non-K^* background

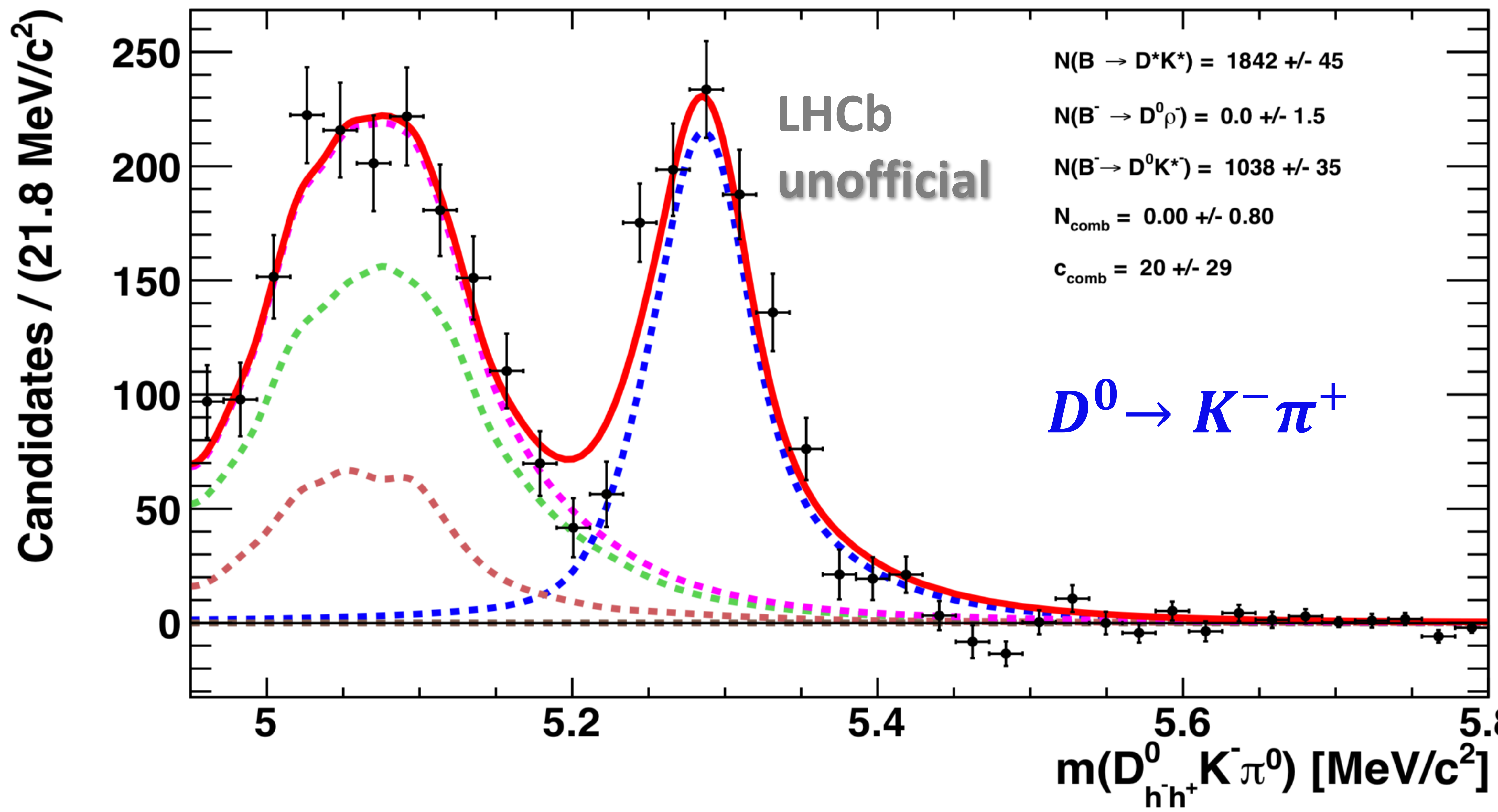


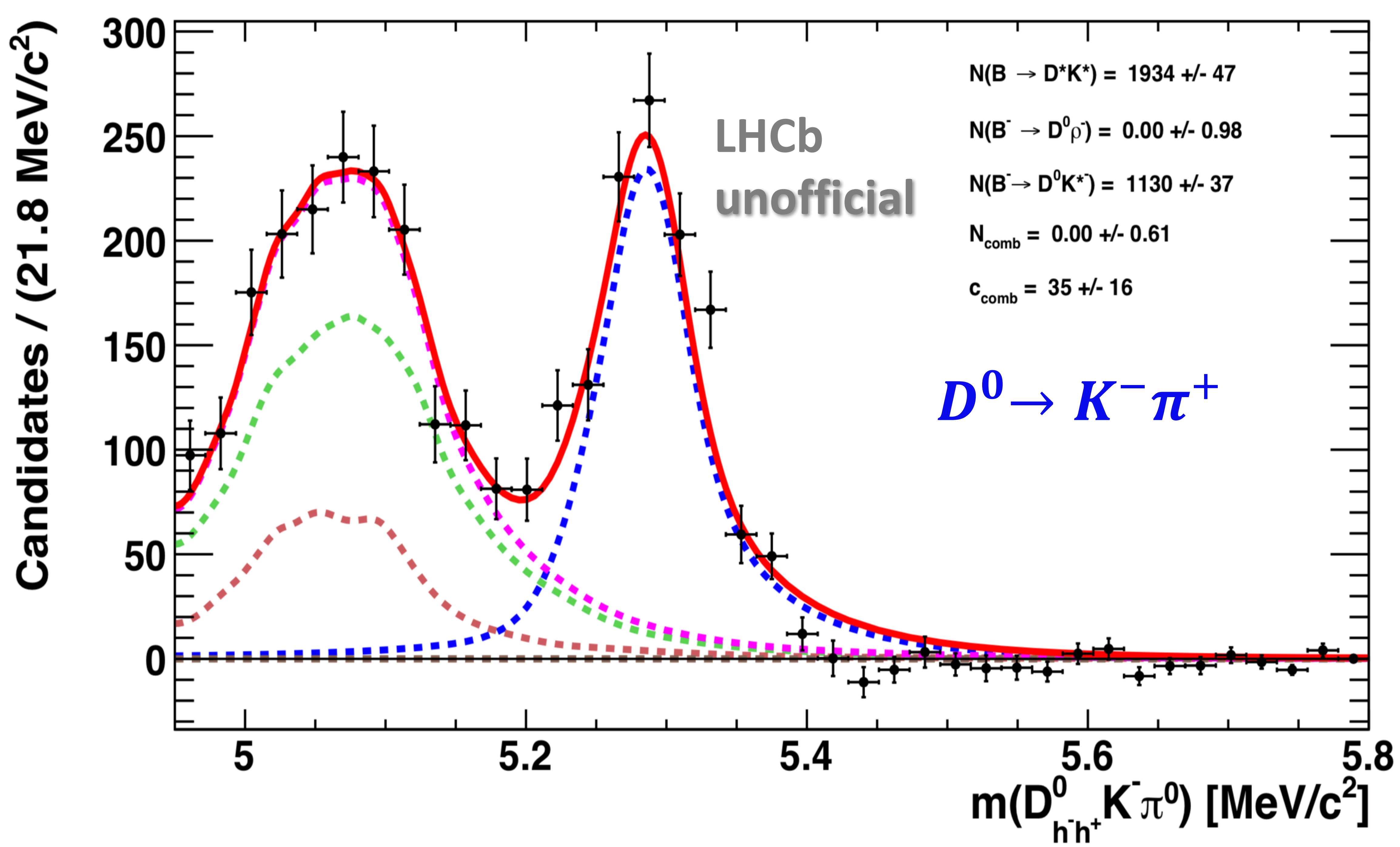


- **Second:** From the fit to the K^{*-}, sWeight is determined to project into the m(DK^{*-}) B mass plot with only the K^{*-} candidates.
- Combinatorial background and $D^{0(*)}\rho$ contamination almost fully removed.



Mass distribution and fit to the $B^{\pm} \to \overline{D}^0 K^{*\pm}$





- After the sPlot subtraction an extended unbinned maximum likelihood fit performed to the invariant mass of on $\mathbf{B}^- \to \mathbf{D}^0\mathbf{K}^{*-}$ candidates in the mass range $m_{DK\pi^0} \in [4950, 5800]\mathrm{MeV/c}^2$

- Signal yields extracted from the fit to the invariant mass of $\mathbf{B}^- \to \mathbf{D}^0\mathbf{K}^{*-}$, where $\mathbf{D}^0$ decays to $K^-\pi^+$ and for $\mathbf{B}^-$ and $\mathbf{B}^+$ candidates.

➢ $A_{K\pi} = (-1.3 \pm 3.2 \pm 0.2)\%$ obtained after corrections and systematics and it is compatible with zero as expected

➢ There is no asymmetry observed.

➢ The result is comparable with the reference published analysis $B^- \to D^0K^{*-}$ with $K^{*-} \to K_s\pi^-$ correspond to $A_{K\pi} = (-0.4 \pm 2.3 \pm 0.8)\%$ [LHCb-PAPER-2017-030]

Mass distribution and fit to the $B^{\pm} \to \bar{D}^0 K^{*\pm}$

- After the sPlot subtraction an extended unbinned maximum likelihood fit performed to the invariant mass of on $\mathbf{B^-} \to \mathbf{D^0 K^{*-}}$ candidates in the mass range $m_{DK\pi^0} \in [4950, 5800]\text{MeV/c}^2$

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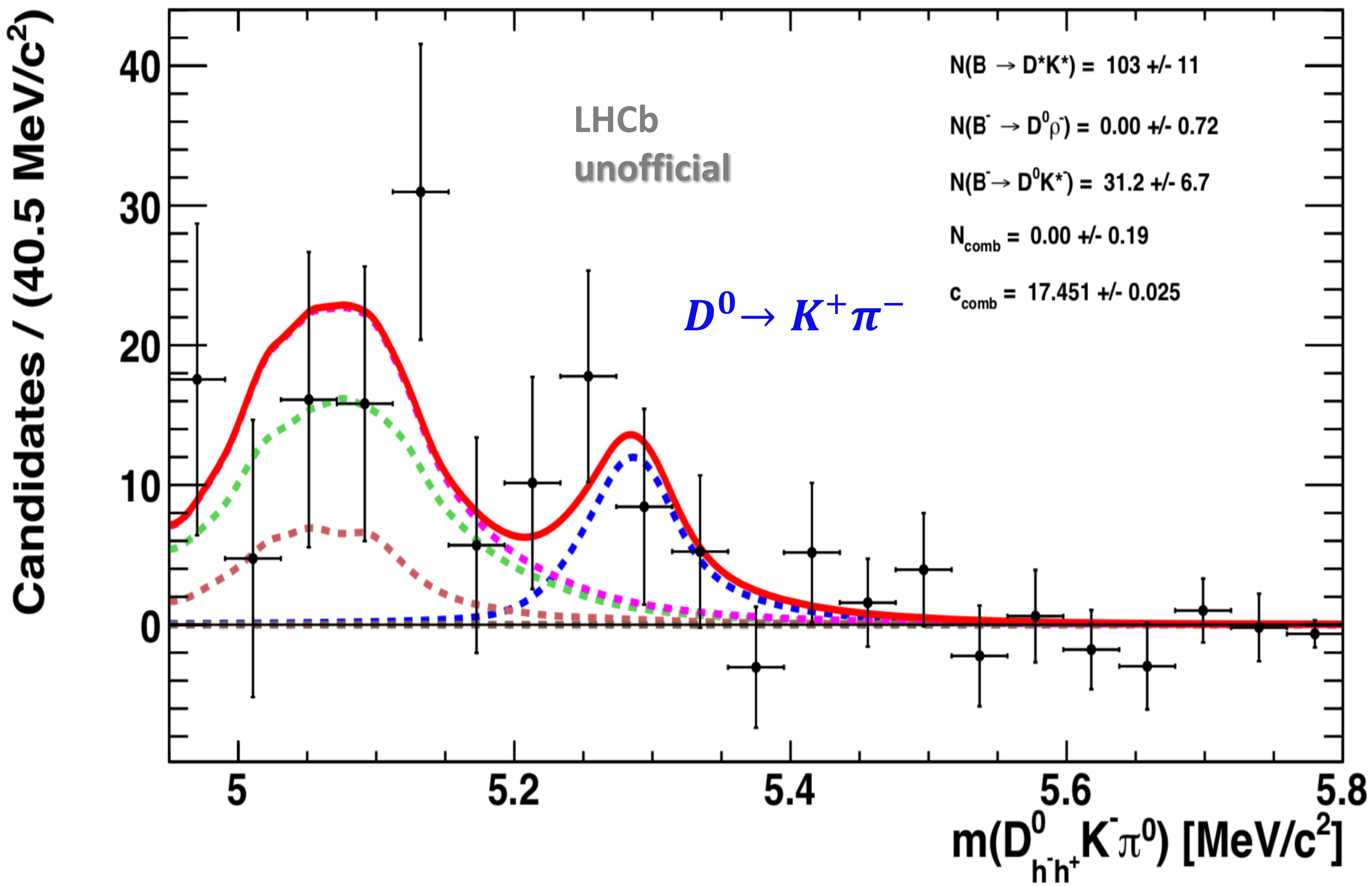

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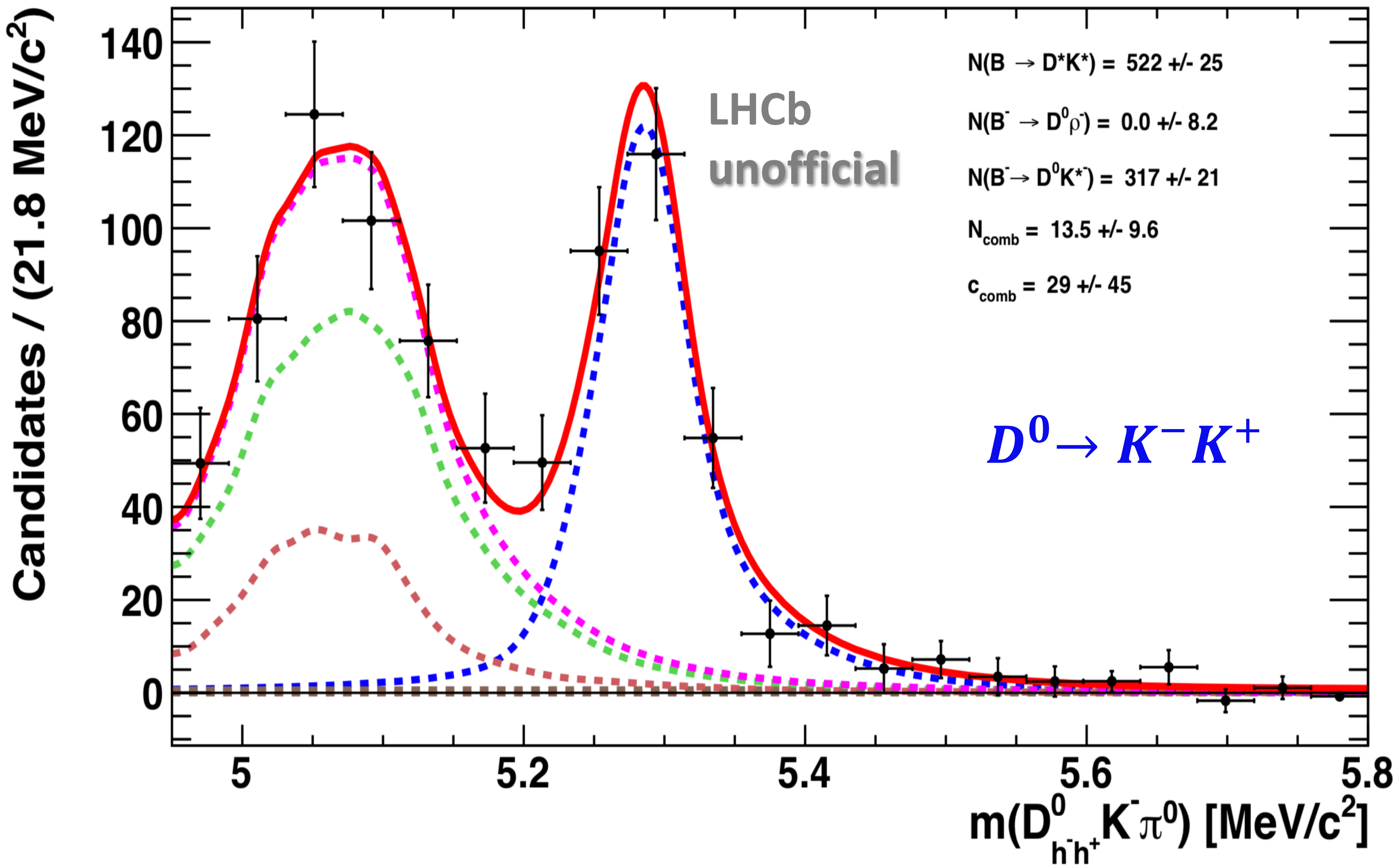

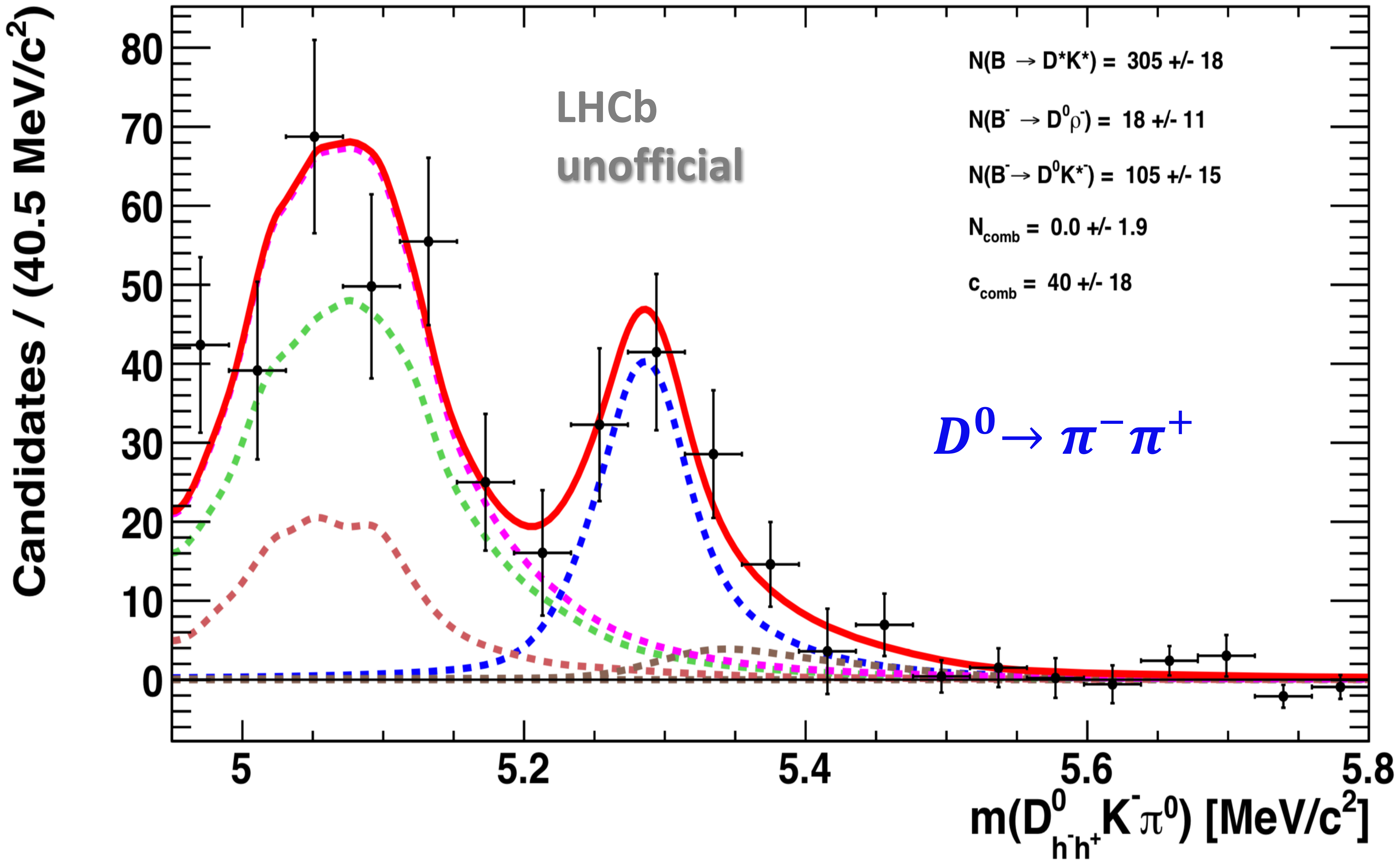

Conclusion

- Analysis for the CKM angle γ measurements are presented
  - $\boldsymbol{B_s^0 \to D^{(*)0}\phi(KK)}$ decay, where $\boldsymbol{D^0}$ to $\boldsymbol{K^-\pi^+\pi^0}$
  - $\mathrm{B^- \to D^0K^{*-}}$ decay, where $\boldsymbol{D^0}$ to $\boldsymbol{K^-\pi^+}$, $\boldsymbol{K^-K^+}$, $\boldsymbol{\pi^-\pi^+}$, $\boldsymbol{K^+\pi^-}$

- The CKM angle γ is constrained with the modes of $\boldsymbol{B_s^0 \to D^{(*)0}\phi(KK)}$, where $\boldsymbol{D^0}$ reconstructed in $K\pi$, KK, $\pi\pi$, $K3\pi$, $K\pi\pi^0$.
- The asymmetry $\boldsymbol{A_{K\pi} = (-1.3 \pm 3.2 \pm 0.2)\%}$ is obtained compatible with zero and this result is compatible with the reference analysis $B^- \to D^0K^{*-}$ with $K^{*-} \to K_s\pi^-$ published by LHCb $\boldsymbol{A_{K\pi} = (-0.4 \pm 2.3 \pm 0.8)\%}$

- The results will be improved with the better statistics will be reached by the LHCb Run 3

Thank you for your attention!