Bundesministerium
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Prospects for measuring the CKM angle γ with the decays $B^0 \to D^\mp \pi^\pm$ and $B^0 \to \overline{D}^0 K^0_\mathrm{S}$

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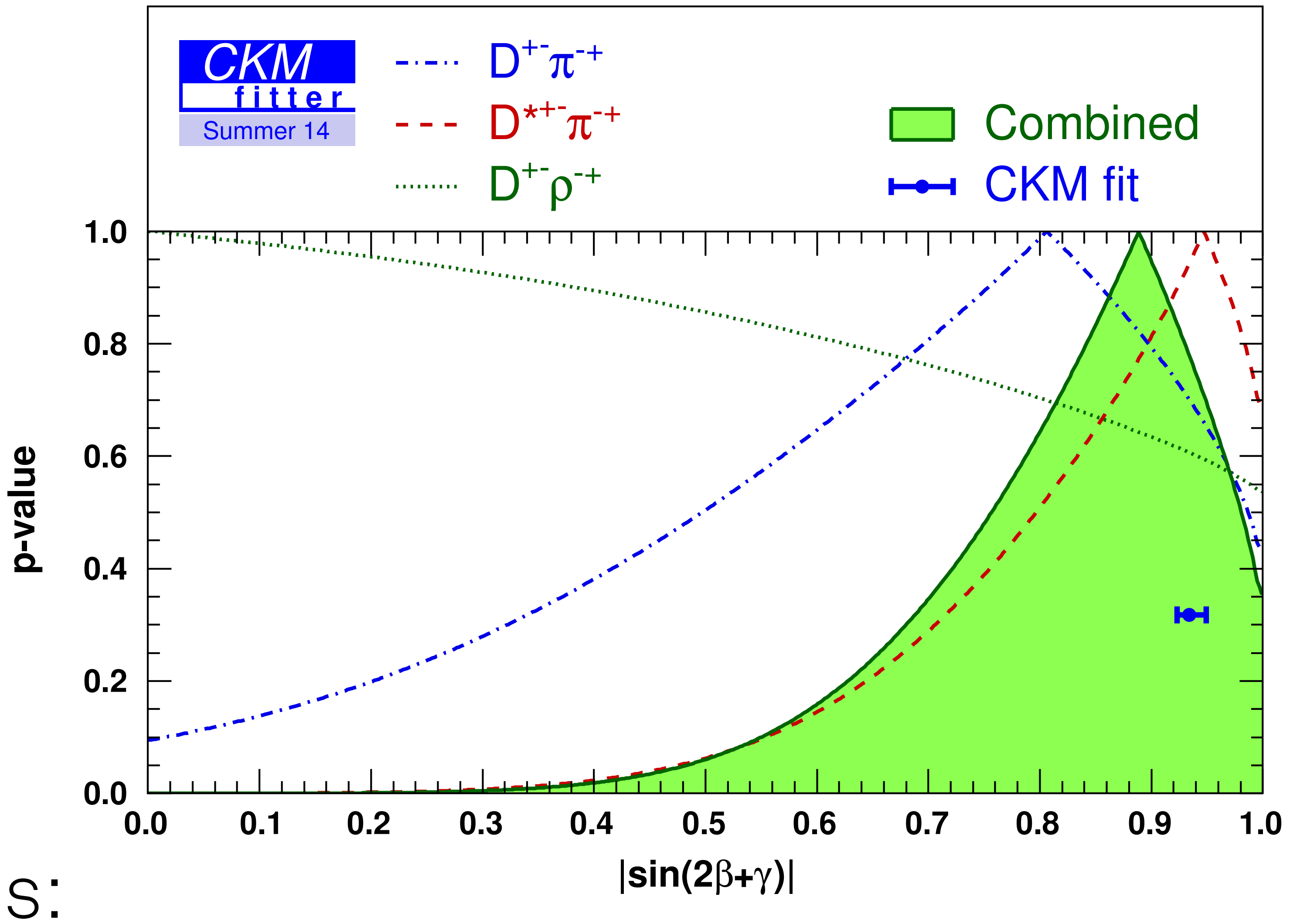
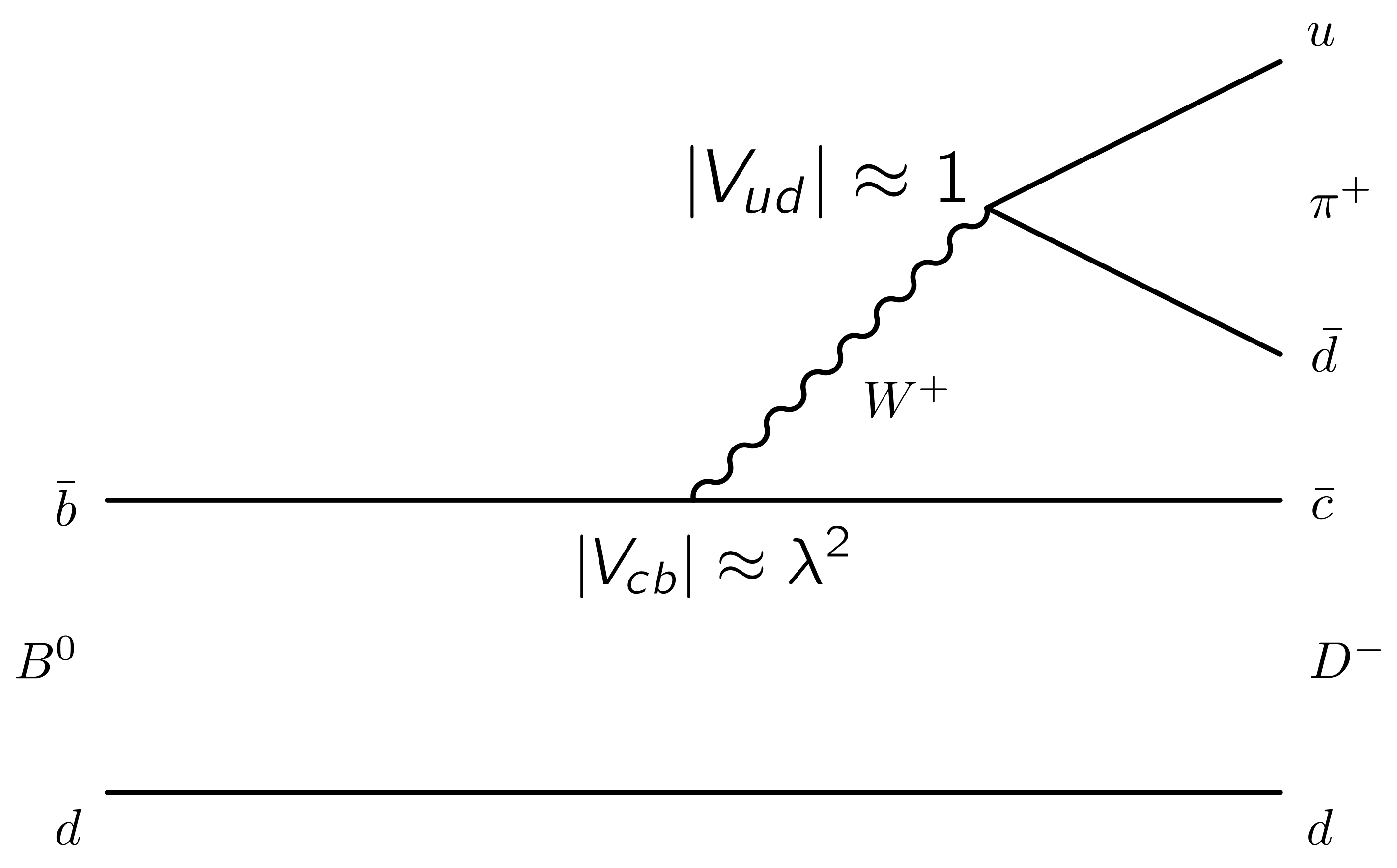
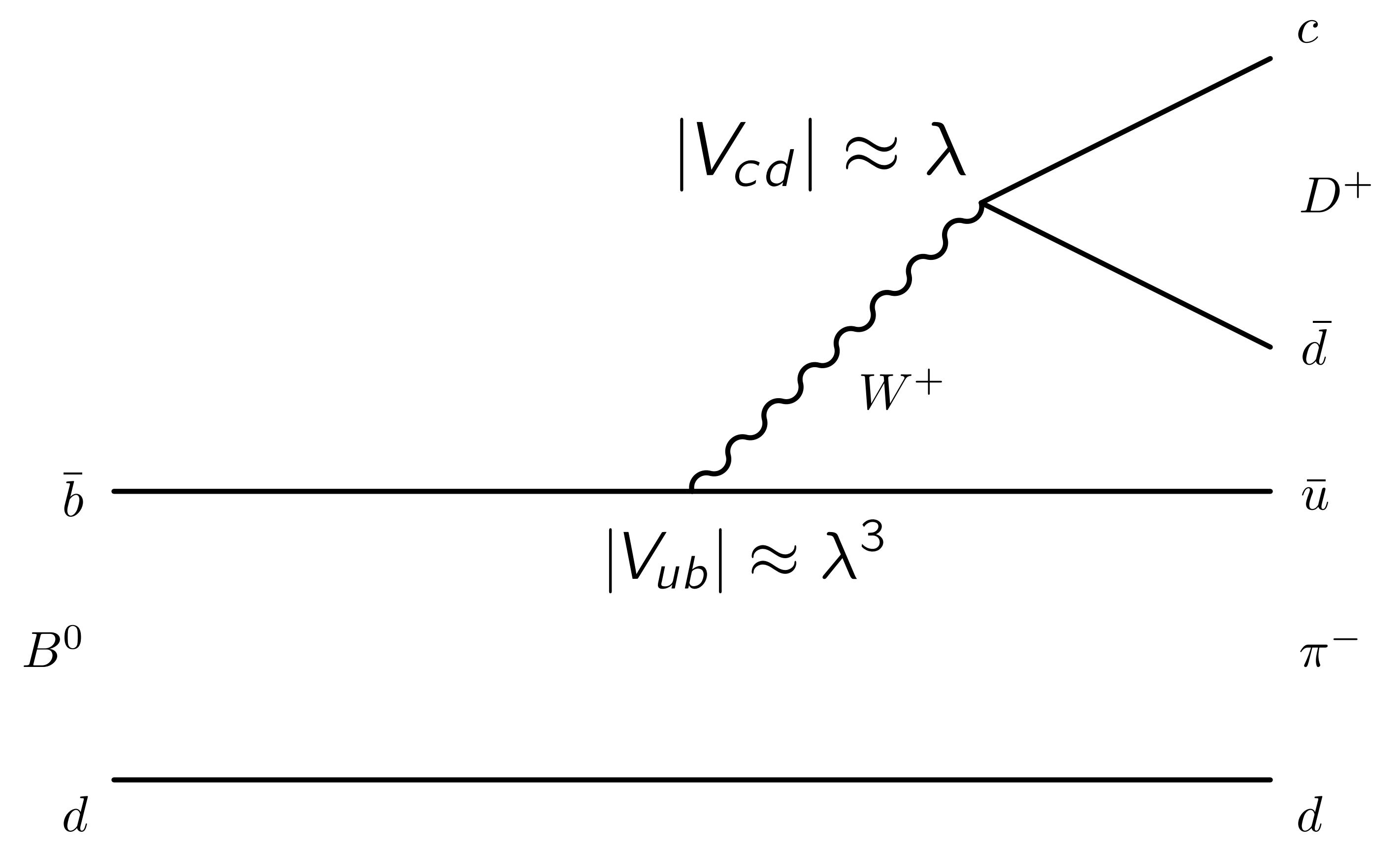
on behalf of the LHCb collaboration

Motivation

- $B^0 \to D^{\mp}\pi^{\pm}$ provides theoretically clean measurement of CKM angle γ
  - measure *CP* violation in interference of mixing and decay







- advantages:
  - B^0system: low oscillation frequency ($\Delta m \approx 0.51\,\text{ps}^{-1}$)
  - high statistics channel (expect ≈500,000 signal candidates)
- disadvantage:
  - decay amplitudes different ($O(\lambda^2)$ vs $O(\lambda^4)$)
    → interference at the percent level

Decay rates

- time-dependent analysis of four decay amplitudes: $B^0 \to D^{\mp}\pi^{\pm}$ and $\overline{B}^0 \to D^{\mp}\pi^{\pm}$

$$\Gamma\left(B^0 \to D^-\pi^+\right)(t) \propto e^{-\frac{t}{\tau}}\left(1 + D_f \sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm C_f \cos(\Delta m t) \mp S_f \sin(\Delta m t)\right)$$

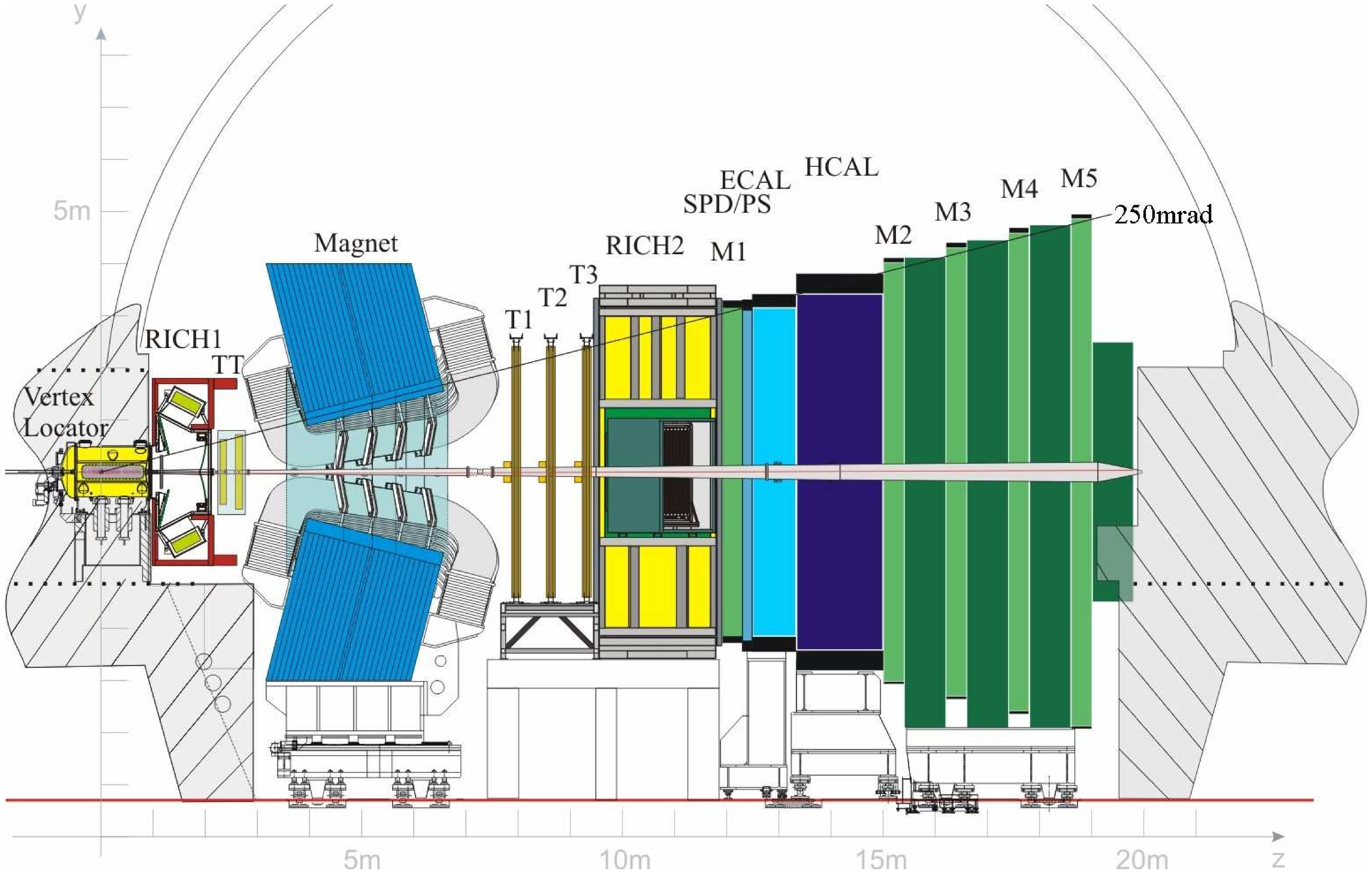
$$\Gamma\left(B^0 \to D^+\pi^-\right)(t) \propto e^{-\frac{t}{\tau}}\left(1 + D_{\overline{f}} \sinh\left(\frac{\Delta\Gamma t}{2}\right) \mp C_{\overline{f}} \cos(\Delta m t) \pm S_{\overline{f}} \sin(\Delta m t)\right)$$

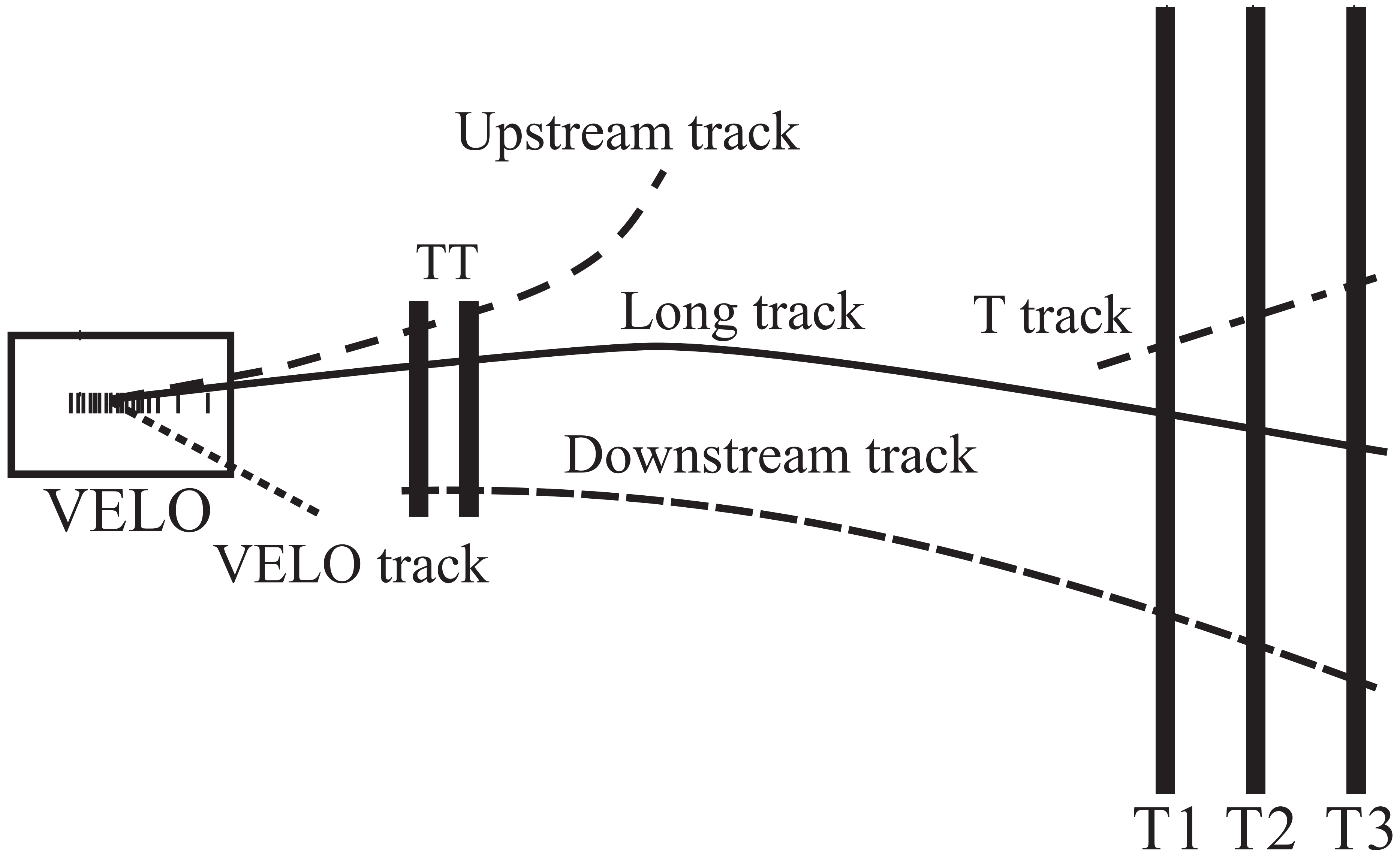
with $C_f = C_{\overline{f}} = \frac{1-r^2}{1+r^2}, S_f = \frac{-2r\sin(2\beta+\gamma-\delta)}{1+r^2}, S_{\overline{f}} = \frac{2r\sin(2\beta+\gamma+\delta)}{1+r^2}$

and $r = \frac{\left|\mathcal{A}\left(\overline{B}^0 \to D^-\pi^+\right)\right|^2}{\left|\mathcal{A}\left(B^0 \to D^-\pi^+\right)\right|^2} = \frac{\left|\mathcal{A}\left(B^0 \to D^+\pi^-\right)\right|^2}{\left|\mathcal{A}\left(\overline{B}^0 \to D^+\pi^-\right)\right|^2}$

- for B^0system: term of sinh vanishes because of$\Delta\Gamma \approx 0$
- sensitivity to C/S observables only from events with tagged production flavour
  - small value of $r \to$ no sensitivity on C
- for γ determination: external input of r and β necessary
  - two possible γ solutions due to ambiguity of sine function

LHCb





- pseudorapidity range: $2 < \eta < 5$
- different track types:
  - long track: decay products traversing all tracking detectors
  - downstream: decay products not traversing VELO

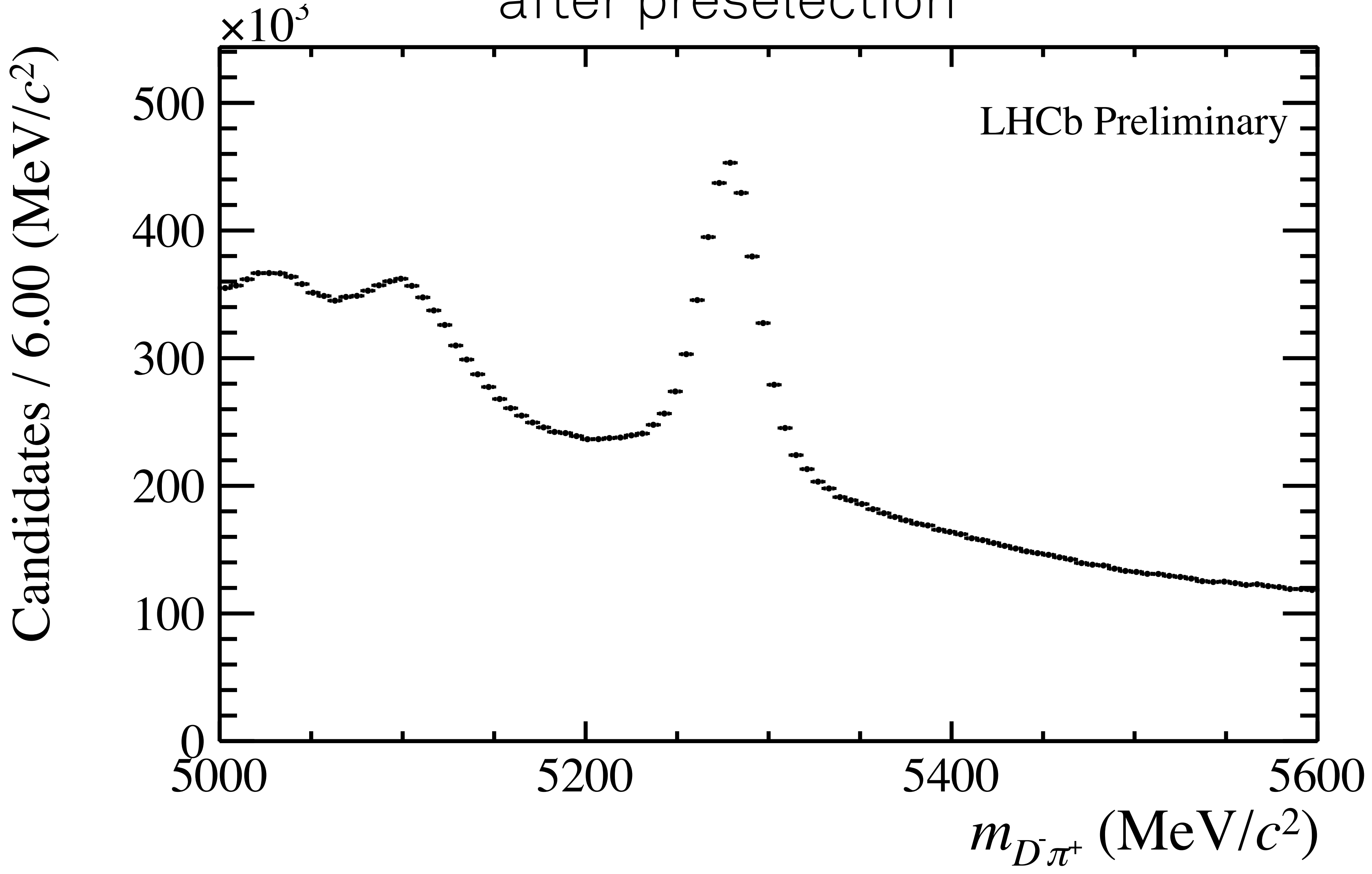
JINST 3 (2008) S08005

Selection of $B^0 \to D^{\mp}\pi^{\pm}$ decays

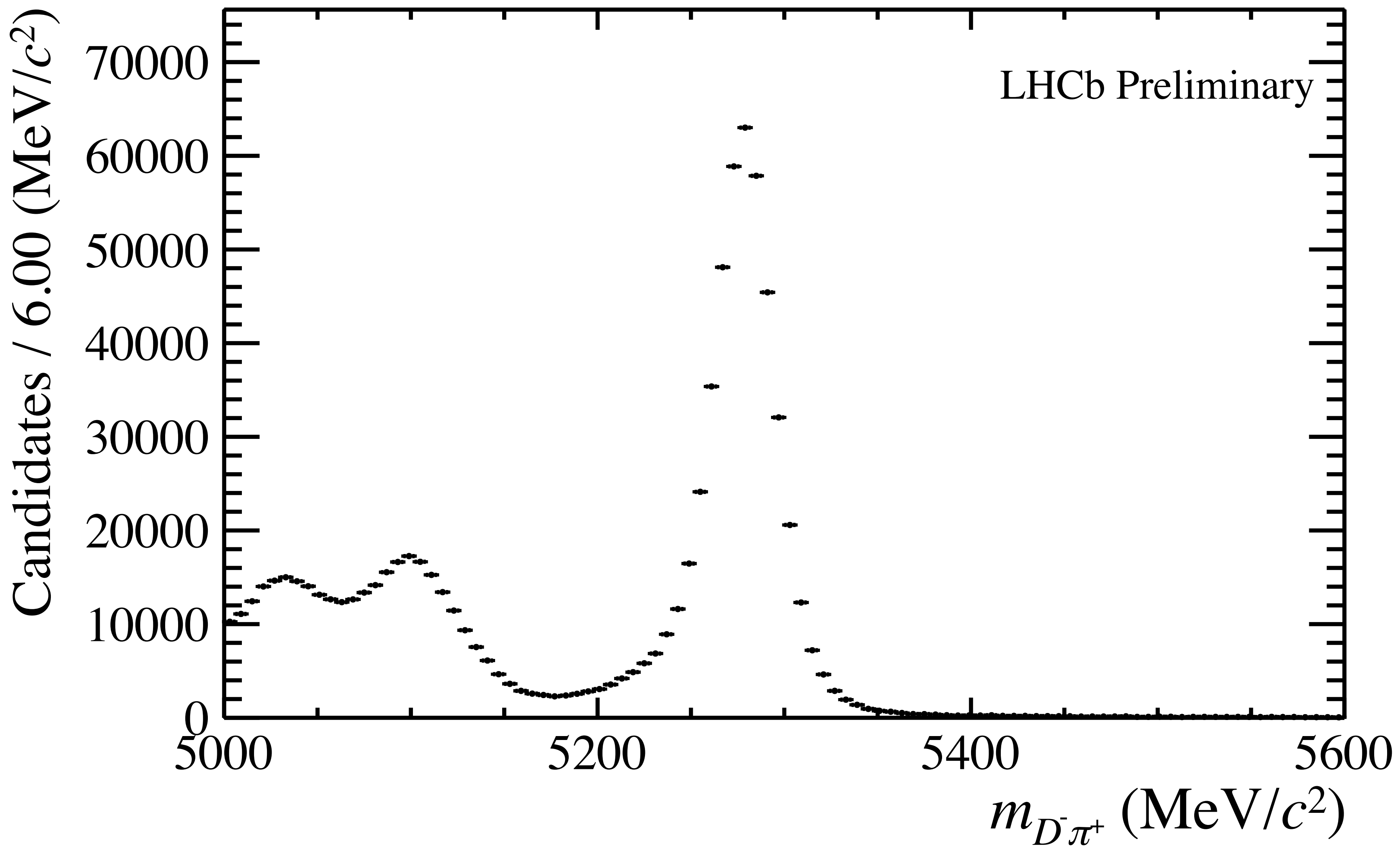
- loose preselection
- main offline selection of all (B,PV) pairs:
  - vetoing physical backgrounds
  - reduction of combinatorial background with a BDT
- random candidate selection
- FoM: statistical uncertainty on *CP* violation parameters
  - apply selection
  - perform massfit to extract yields
  - generate toy samples
  - perform decay time fit to extract uncertainties

- overall signal efficiency: 70.1±0.1%
- combinatoric background rejection: 99.911±0.002%

after preselection

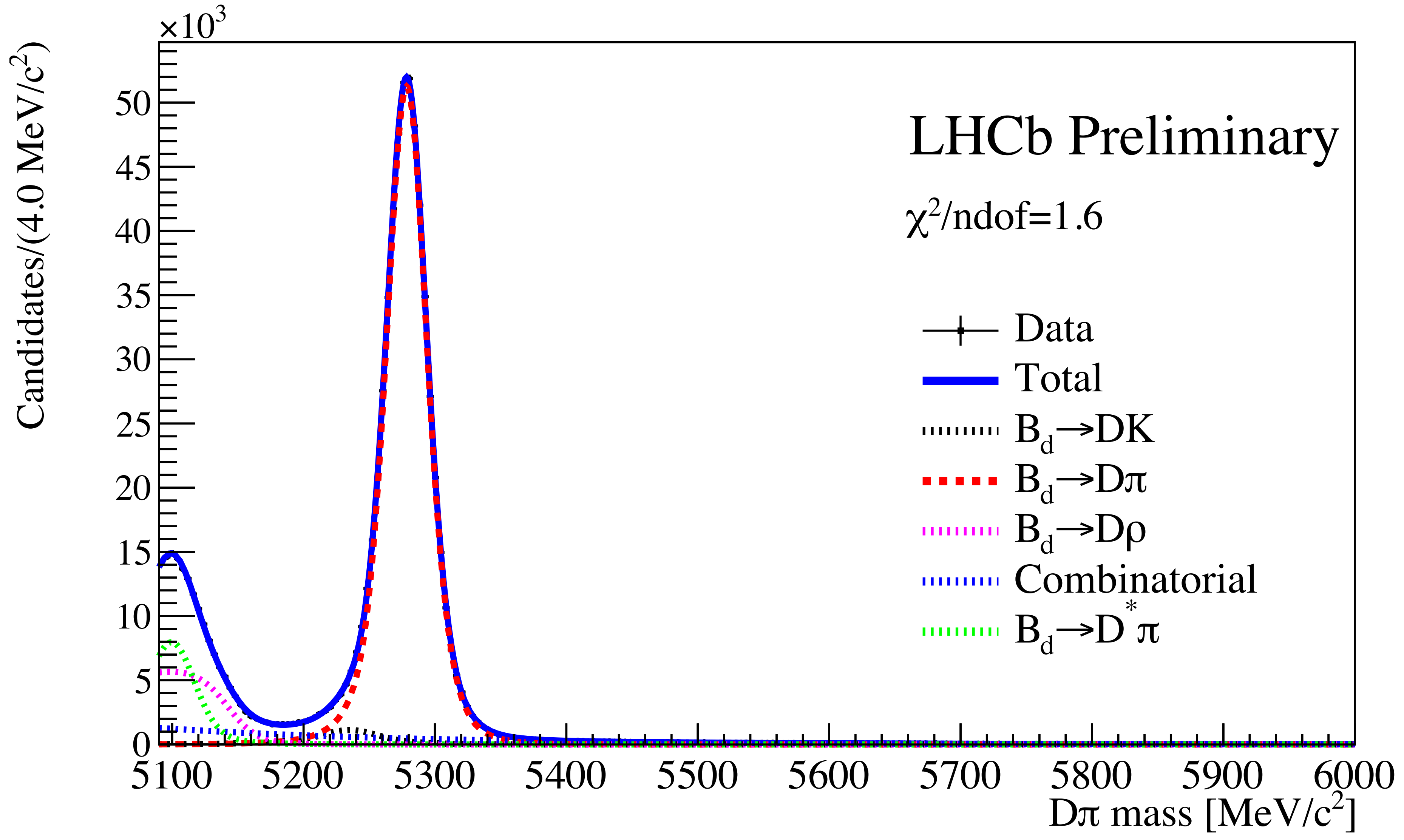


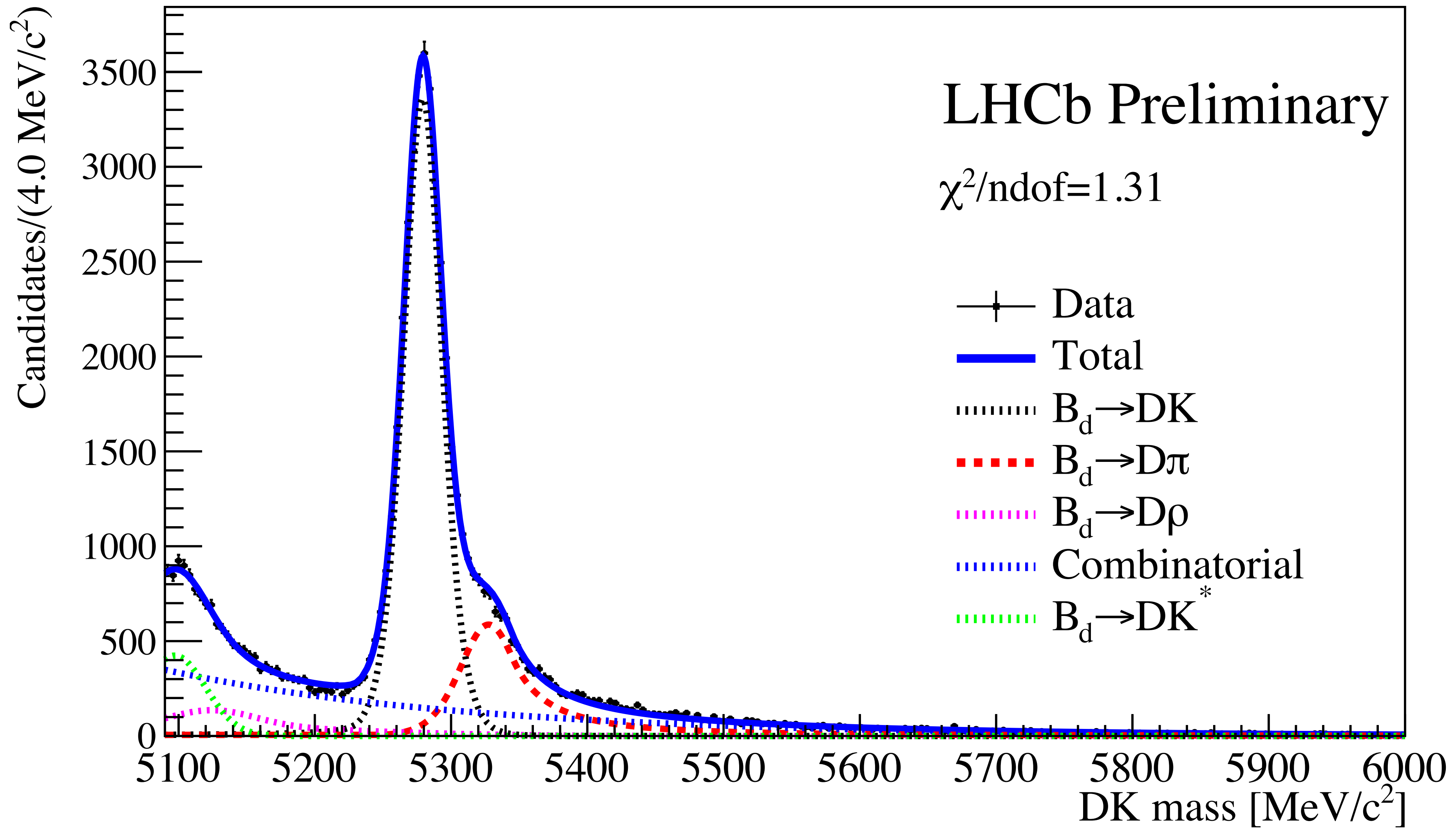
after full selection



Massfit

- split dataset into two disjoint subsets according to PID information
  - genuine $B^0 \to D^{\mp}\pi^{\pm}$ decays with small cross-feed from $B^0 \to D^{\mp}K^{\pm}$
  - genuine $B^0 \to D^{\mp}K^{\pm}$ with a fraction of cross-feed $B^0 \to D^{\mp}\pi^{\pm}$
- pion and kaon samples are fitted simultaneously
- fit range from 5090 MeV/c^2 to 6000 MeV/c^2
- yields of all components floating in the fit
- cross-feed decays in both samples are constrained to that of the corresponding signal sample
- yields in range from 5220 MeV/c^2 to 5600 MeV/c^2:
  - signal yield: 540,500 ± 800
  - background yield: 39,190 ± 330

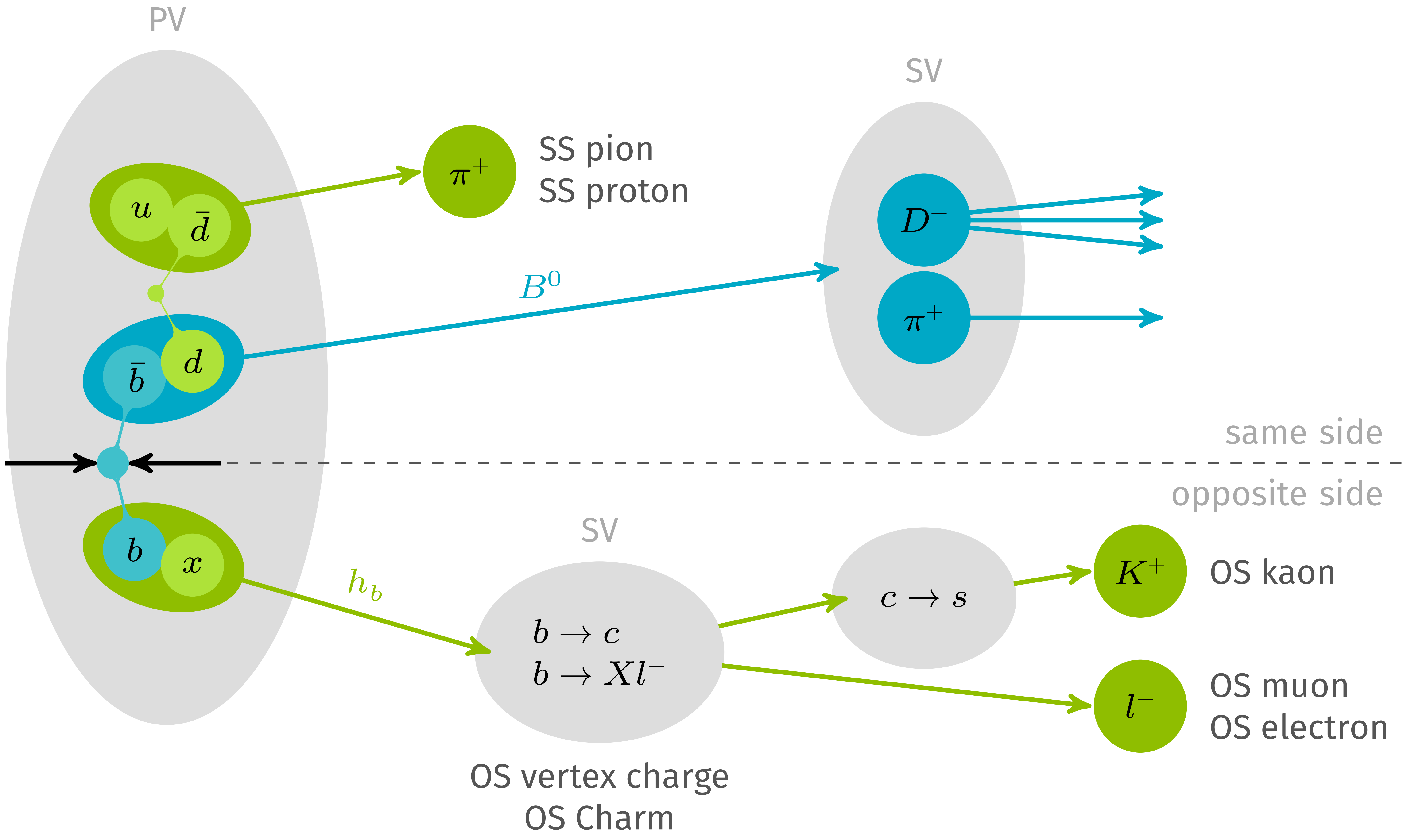




Flavour tagging

- using both SS taggers:
- train both taggers on $B^0 \to J/\psi\, K^{*0}$
- expected performance:
  - tagging efficiency: $\varepsilon_{\text{tag}} = (79.40 \pm 0.23)\,\%$
  - tagging power: $\varepsilon_{\text{eff}} = (2.11 \pm 0.11)\,\%$

LHCb-Paper-2016-039



- using full set of available OS taggers:
  - single track taggers: OSμ, OSe, OSk
  - OS vertex charge
  - OS charm
- expected performance:
  - tagging efficiency: $\varepsilon_{\text{tag}} = (27.3 \pm 0.2)\,\% + (4.11 \pm 0.03)\,\%$
  - tagging power: $\varepsilon_{\text{eff}} = (2.1 \pm 0.1)\,\% + (0.40 \pm 0.02)\,\%$

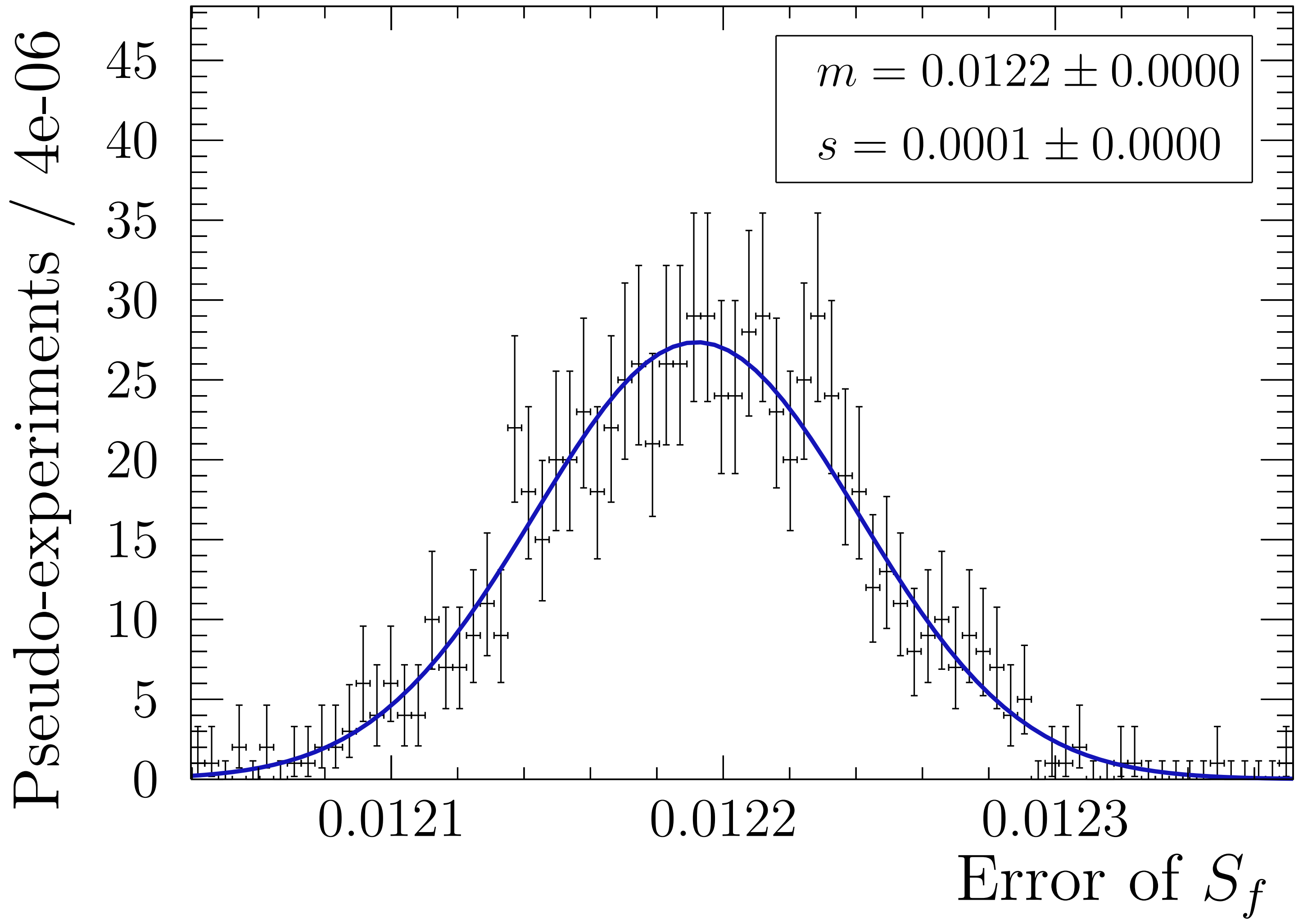
LHCb-Paper-2011-027 & LHCb-Paper-2015-027

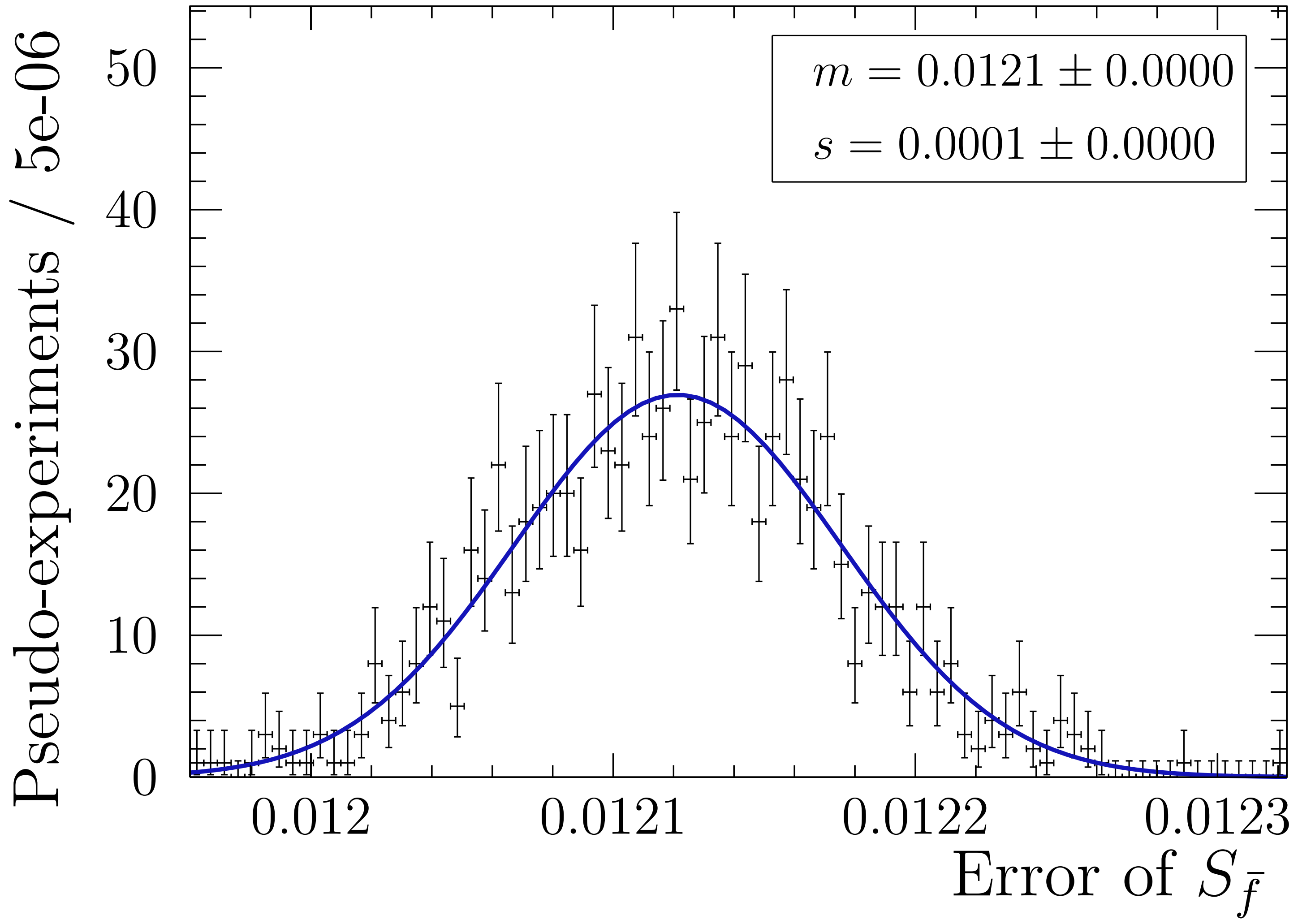
Prospects

- time-independent analysis steps done
- decay time fit
  - acceptance floated
  - decay time constrained to HFAG WA (1.52 ps) arXiv:1412.7515v1
- toy studies using
  - ≈80% tagging efficiency for SS
  - ≈35% tagging efficiency for OS
  - mass/time shapes from data
  - statistical sensitivity: $\sigma\left(S_f\right) = \sigma\left(S_{\bar{f}}\right) \approx 0.012$
- current uncertainties:

	Belle	BaBar	WA
S_f	0.030(stat) ± 0.012(syst)	0.048(stat) ± 0.014(syst)	0.027
$S_{\bar{f}}$	0.029(stat) ± 0.012(syst)	0.048(stat) ± 0.014(syst)	0.027

arXiv:1412.7515v1

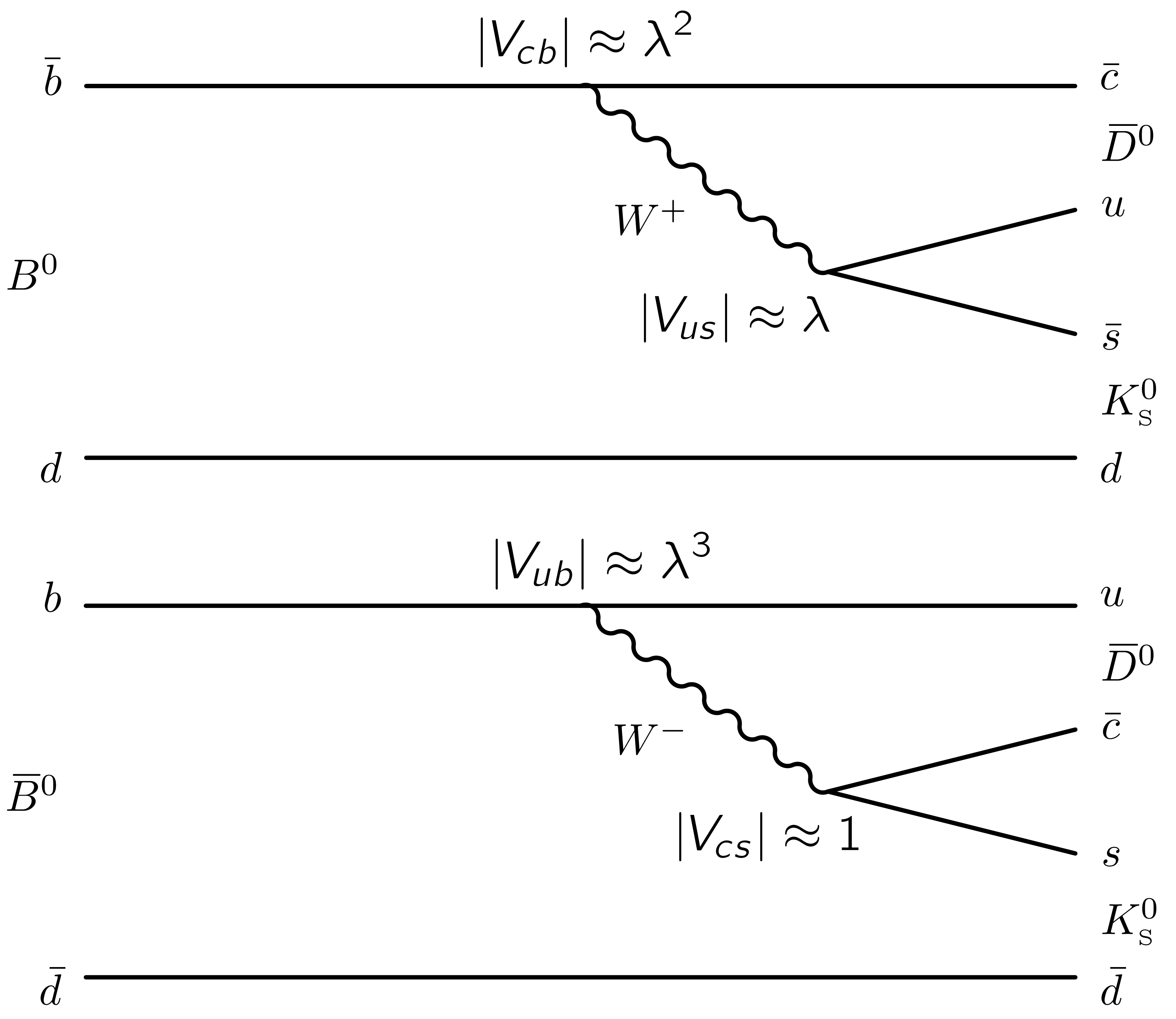




Prospects with $B^0 \rightarrow D^{*\mp}\pi^{\pm}$ and $B^0 \rightarrow D^{\mp}\pi^{\pm}$ in Run II

- already recorded ~2 fb^{-1} in Run II
  - higher $b\overline{b}$ cross section due to higher centre-of-mass energy
- still two years of data taking ahead
- expected number of $B^0 \rightarrow D^{\mp}\pi^{\pm}$ candidates for Run II: 1,300,000 (5 fb^{-1}, 13 TeV)
- statistical sensitivities
  - Run II standalone: $\sigma\left(S_f\right) = \sigma\left(S_{\overline{f}}\right) \approx 0.007$
  - Run I + Run II: $\sigma\left(S_f\right) = \sigma\left(S_{\overline{f}}\right) \approx 0.006$
- adding decays into excited $D^{*\pm}$ mesons
  - including decay modes $D^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$
  - expect $\mathcal{O}\left(0.5 \times N_{B^0 \rightarrow D^{\mp}\pi^{\pm}}\right)$ for $B^0 \rightarrow D^{*\mp}\pi^{\pm}$ PRD 87, 071101(R) (2013)
  - Run I + Run II: $\sigma\left(S_f\right) = \sigma\left(S_{\overline{f}}\right) \approx 0.005$
- sensitivity on γ depends heavily on values for r and δ

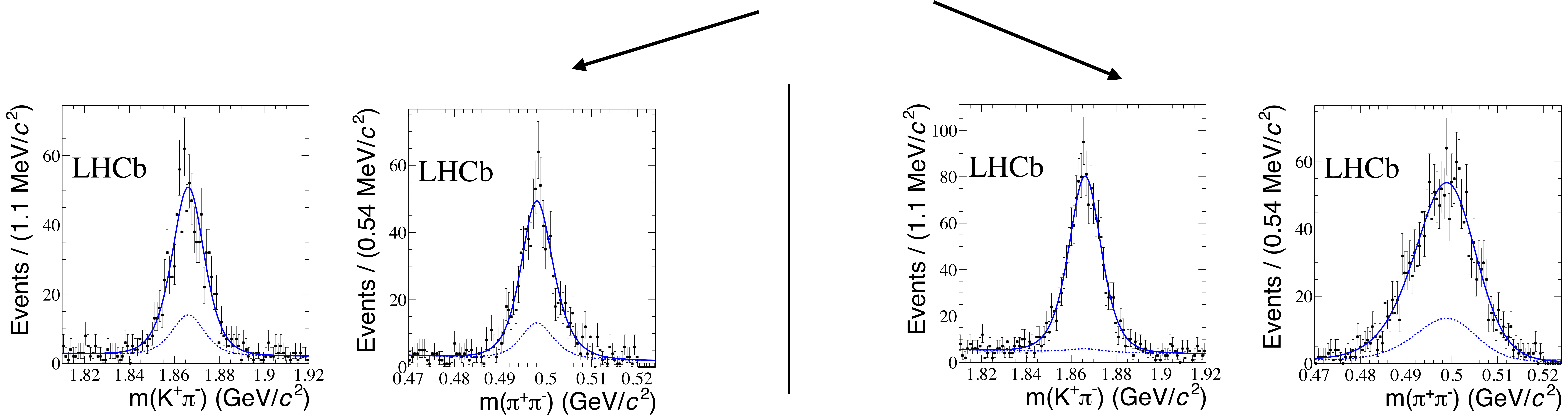
Prospects with $B^0 \to \overline{D}^0 K^0_S$ and $B^0_s \to \overline{D}^0 K^0_S$



- $B^0 \to \overline{D}^0 K^0_S$ has similar decay mechanism as $B^0 \to D^\mp \pi^\pm$
  - sensitivity on $2\beta + \gamma$
  - interfering amplitudes have similar size ($\mathcal{O}(\lambda^3)$)
- $B^0_s \to \overline{D}^0 K^0_S$ shares same Feynman diagrams as $B^0_s \to J/\psi \phi$
  - possible decay channel to measure ϕ_s
- branching fractions expected at $\mathcal{O}\left(5 \times 10^{-4}\right)$
- first: measurement of $B^0_s \to \overline{D}^0 K^0_S$ branching fractions normalised to $B^0 \to \overline{D}^0 K^0_S$
- $\overline{D}^0$ candidates formed from combinations of a kaon and pion candidate
- K^0_S candidates built out of two pions
  - using long track and downstream kaons

Yield determination

ML fit simultaneously in long and downstream K_s^0 samples



four fit components:

correctly reconstructed *D* and *K* candidates

correctly reconstructed *D* candidates with two random pions

correctly reconstructed *K* candidates with random pion and kaon

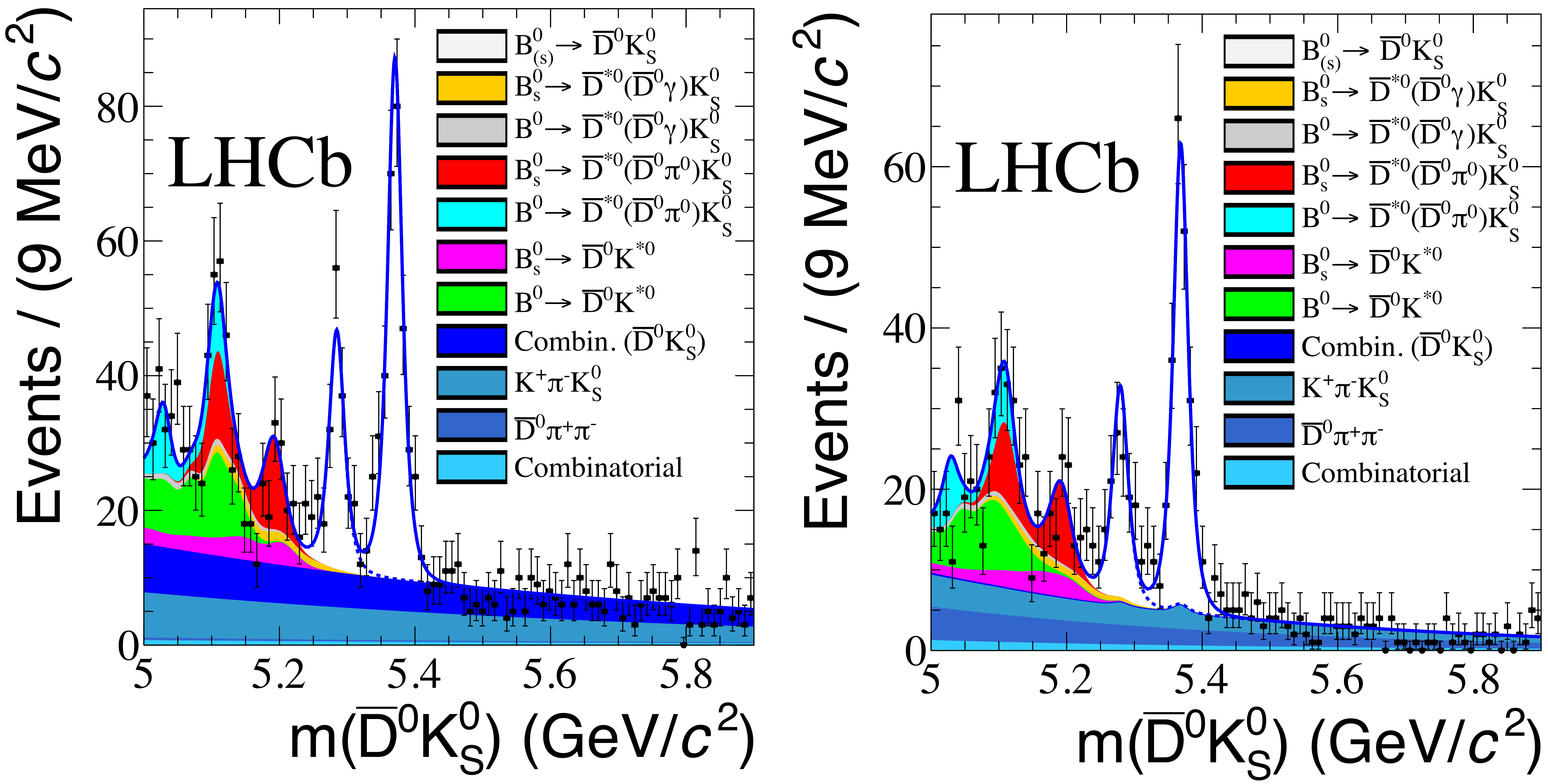
random combination of all four daughter particles

LHCb-PAPER-2015-050

Yield determination

- mass shape categories :
  - signal for B^0 and B_s^0
  - peaking structures at lower masses: photon or pion not reconstructed
  - combinatorial background

- shared parameters between PDF's for long and downstream samples
- gaussian constraints to branching fractions increase fit stability:
  - $\mathcal{B}\left(B_s^0 \to \bar{D}^0 K^{*0}\right) / \left[\mathcal{B}\left(B^0 \to \bar{D}^0 K^{*0}\right) + \mathcal{B}\left(B_s^0 \to \bar{D}^0 K^{*0}\right)\right]$
  - $\mathcal{B}\left(B_{(s)}^0 \to \bar{D}^{*0}\left(\bar{D}^0\pi^0\right) K^0\right) / \left[\mathcal{B}\left(B_{(s)}^0 \to \bar{D}^{*0}\left(\bar{D}^0\gamma\right) K^0\right) + \mathcal{B}\left(B_{(s)}^0 \to \bar{D}^{*0}\left(\bar{D}^0\pi^0\right) K^0\right)\right]$



- determined signal yields: $N\left(B^0 \to \bar{D}^0 K_S^0\right) = 219 \pm 21$ $N\left(B_s^0 \to \bar{D}^0 K_S^0\right) = 471 \pm 26$ $N\left(B_s^0 \to \bar{D}^{*0} K_S^0\right) = 258 \pm 83$

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Branching fraction determination

- using ratio to determine branching fraction

$$\mathcal{B}\left(B_s^0 \to \overline{D}^{(*)0}\overline{K}^0\right) = \mathcal{R}^{(*)} \times \left[\mathcal{B}\left(B^0 \to \overline{D}^0 K^0\right) + \mathcal{B}\left(\overline{B}^0 \to \overline{D}^0 \overline{K}^0\right)\right]$$

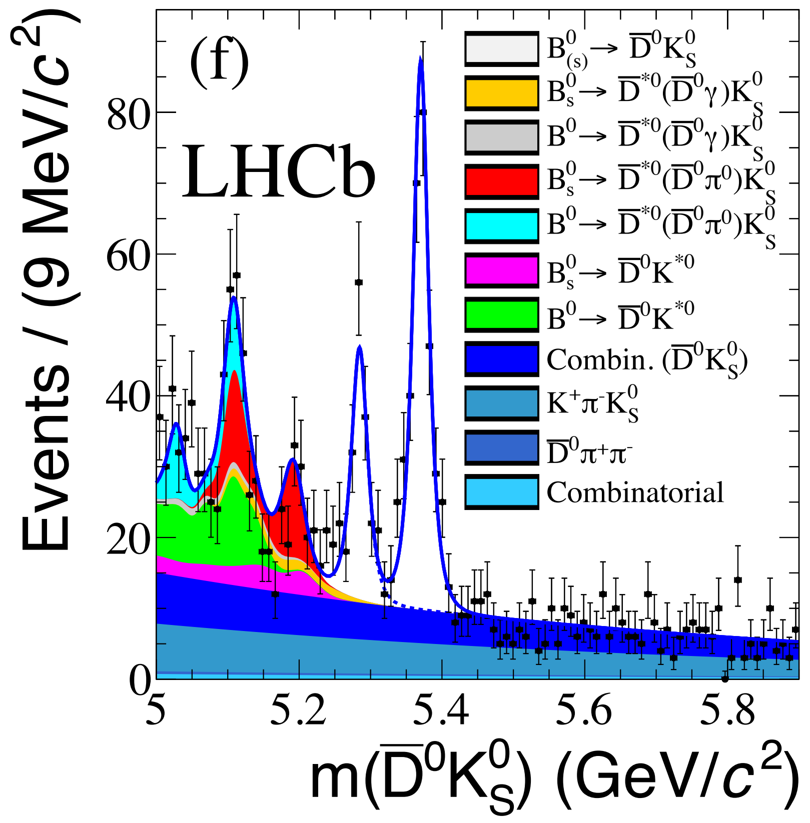
with $\mathcal{R}^{(*)} = \frac{f_d}{f_s} \frac{N\left(B_s^0 \to \overline{D}^{(*)0} K_S^0\right)}{N\left(B^0 \to \overline{D}^0 K_S^0\right) + N\left(\overline{B}^0 \to \overline{D}^0 K_S^0\right)} \frac{\epsilon_{B^0}}{\epsilon_{B_s^0}}$

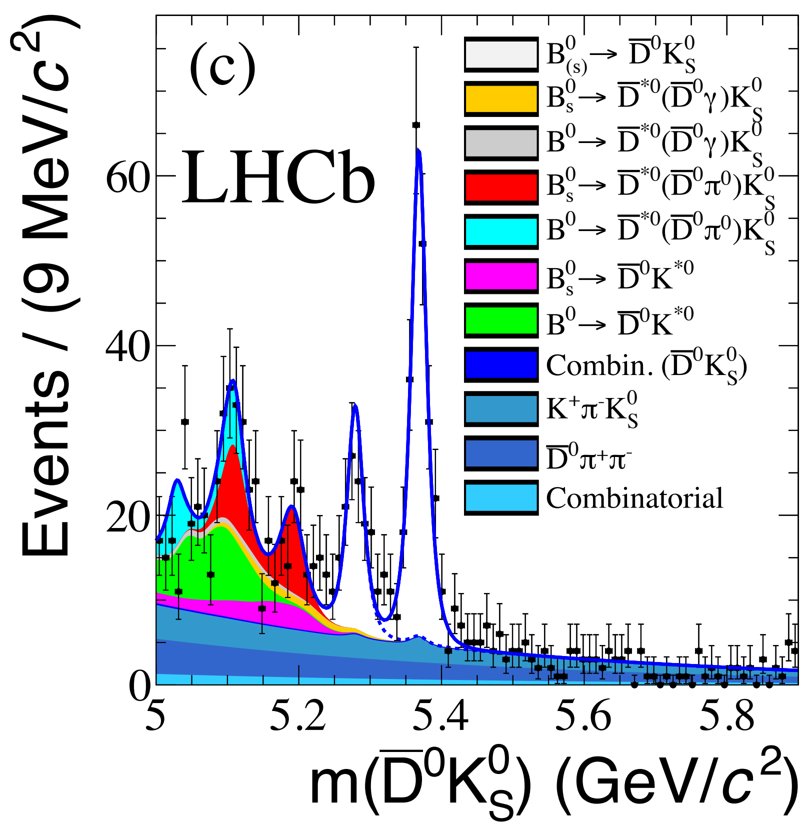
obtained from simulated samples

previous LHCb measurement

JHEP 04 (2013) 001
LHCb-CONF-2013-011

parameters in the fit





Results

- resulting signal yields with systematic uncertainties:
  - $N\left(B^0 \to \overline{D}^0 K^0_\mathrm{S}\right) = 219 \pm 21(\mathrm{stat}) \pm 11(\mathrm{syst})$
  - $N\left(B^0_s \to \overline{D}^0 K^0_\mathrm{S}\right) = 471 \pm 26(\mathrm{stat}) \pm 25(\mathrm{syst})$
  - $N\left(B^0_s \to \overline{D}^{*0} K^0_\mathrm{S}\right) = 258 \pm 83(\mathrm{stat}) \pm 30(\mathrm{syst})$

first observation of $B^0_s \to \overline{D}^0 K^0_\mathrm{S}$
evidence of $B^0_s \to \overline{D}^{*0} K^0_\mathrm{S}$

- ratios of branching fractions: $\mathcal{R}^{(*)} = \frac{f_d}{f_s} \frac{N\left(B^0_s \to \overline{D}^{(*)0} K^0_\mathrm{S}\right)}{N\left(B^0 \to \overline{D}^0 K^0_\mathrm{S}\right) + N\left(\overline{B}^0 \to \overline{D}^0 K^0_\mathrm{S}\right)} \frac{\epsilon_{B^0}}{\epsilon_{B^0_s}}$

$$\mathcal{R} = 8.3 \pm 0.9(\mathrm{stat}) \pm 0.5(\mathrm{syst}) \pm 0.5(\mathrm{frag})$$
$$\mathcal{R}^* = 5.4 \pm 2.0(\mathrm{stat}) \pm 0.7(\mathrm{syst}) \pm 0.3(\mathrm{frag})$$

- branching fractions:

$$\mathcal{B}\left(B^0_s \to \overline{D}^0 \overline{K}^0\right) = (4.3 \pm 0.5(\mathrm{stat}) \pm 0.3(\mathrm{syst}) \pm 0.3(\mathrm{frag}) \pm 0.6(\mathrm{norm})) \times 10^{-4}$$
$$\mathcal{B}\left(B^0_s \to \overline{D}^{*0} \overline{K}^0\right) = (2.8 \pm 1.0(\mathrm{stat}) \pm 0.3(\mathrm{syst}) \pm 0.2(\mathrm{frag}) \pm 0.4(\mathrm{norm})) \times 10^{-4}$$

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Prospects for $B^0 \to \overline{D}^0 K_\mathrm{S}^0$

- Run I + Run II expectations: O(1,000) $B^0 \to \overline{D}^0 K_\mathrm{S}^0$ candidates
- reminder:

$$r_{D\pi} \approx \left| \frac{V_{ub}V_{cd}^*}{V_{cb}^*V_{ud}} \right| \approx 0.02$$

- for $B^0 \to \overline{D}^0 K_\mathrm{S}^0$:

$$r_{\overline{D}^0 K_\mathrm{S}^0} \approx \left| \frac{V_{ub}V_{cs}^*}{V_{cb}^*V_{us}} \right| \approx 0.4$$

- number of B's needed to make measurement: $N_B \propto \dfrac{1}{\mathcal{B}\left(B^0 \to f\right) r_f^2}$
- about 4 times less B's needed with $B^0 \to \overline{D}^0 K_\mathrm{S}^0$
- expected sensitivity with $B^0 \to \overline{D}^0 K_\mathrm{S}^0$: $\sigma\left(S_f\right) = \sigma\left(S_{\overline{f}}\right) \approx 0.1$
- but: uncertainty from $\overline{D}^0$ tag (DCS decay of $\overline{D}^0 \to K^-\pi^+$)
  - alternative: using self tagged excited D^0 state

Conclusion

- huge progress in time dependent measurement of *CP* violation in $B^0 \to D^{\mp}\pi^{\pm}$
  - time-independent parts of analysis completed
  - expected statistical sensitivity: $\sigma\left(S_f\right) = \sigma\left(S_{\overline{f}}\right) \approx 0.012$
- prospects with $B^0 \to D^{\mp}\pi^{\pm}$ and $B^0 \to D^{*\mp}\pi^{\pm}$:
  - uncertainty on S_f and $S_{\overline{f}}$ can be reduced to 0.005 with the combined Run I and Run II data
- $B^0 \to \overline{D}^0 K_{\mathrm{S}}^0$ gives sensitivity to same CKM matrix elements as $B^0 \to D^{\mp}\pi^{\pm}$
  - advantage: interfering amplitudes are similar
  - disadvantage: much lower statistics + DCS $\overline{D}^0 \to K^-\pi^+$ decays

Backup

Systematic uncertainties for $B_s^0 \to \overline{D}^0 K_S^0$

- tested following sources of systematic uncertainties:
  - fit model (only systematic on number of signal candidates)
  - efficiency determination from simulated samples
  - impact of selection → no systematic applied
  - effect due to random removal of random candidates → no systematic applied
  - repeated measurement for different magnet polarities/long& downstream samples → no systematic applied

Source	$B_s^0 \to \overline{D}^0 K_S^0$	$B_s^0 \to \overline{D}^{*0} K_S^0$
Fit model	5.4%	11.9%
$\epsilon_{B^0}/\epsilon_{B_s^0}$	2.4%	2.5%
f_s/f_d	5.8%	
$\mathcal{B}_{\text{sum}}$	13.5%	

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