Charm tagging

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Belle II Physics Week

Disclaimers

Some were asking why **I’m** giving a talk on **charm tagging**?

This talk is not on charm **flavor** tagging!
(a.k.a. charm tagger)

This is what I also wonder… :)
(lack of real experts, ccbarFEI dev. in Ljubljana)

→ anyway I hope to bring this topic a bit more into light @ Belle II

Outline

→ intro
→ charm tagging idea
→ learn from examples @ Belle:
- D_s^+
- D^0
- Λ_c^+

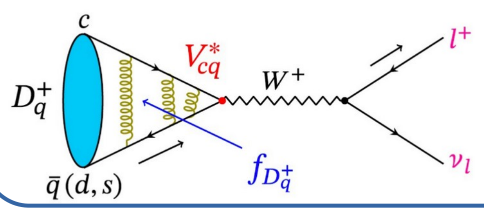
→ ccbarFEI
→ conclusions

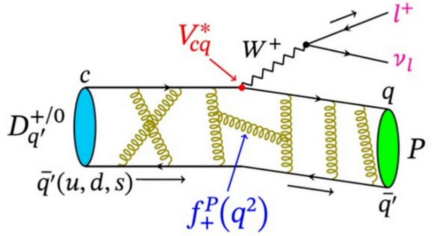
Why and who can do charm

→ tomorrow do not miss (11:30):
Charm decays with missing energy (NP and SM) by H.Gisbert!

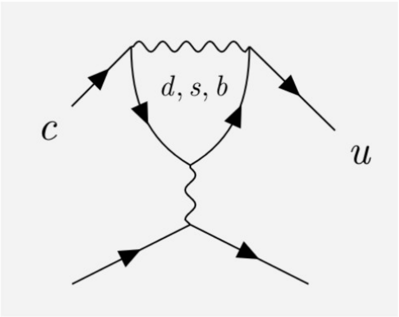
→ many unique opportunities for probing strong and weak interactions in the SM and beyond: CP violation, $D^0 - \bar{D}^0$ mixing, (semi)leptonic decays, rare and forbidden decays, etc.

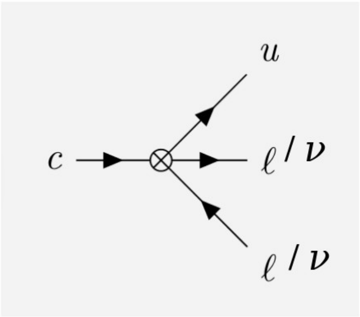
→ charm tagging @ B-factories is relevant from the context of measuring decays with missing energy and more generally in measuring absolute branching fractions





→ determine decay constants, form factors
→ determine $|V_{cq}|$
→ LFU tests





FCNC process, e.g.
$D \to \pi\nu\nu$ sensitive probe for NP contributions:
→ basically null test of the SM
→ unique in the up-type sector
→ poorly exp. explored!

Most of charm Br are measured relatively to normalization mode

$$\mathcal{B}(X \to Y) = \frac{N(X \to Y)}{N_X}$$

→ in B decays N_B from B counting

→ in charm N_X unknown

→ tagging provides a way for inclusive reconstruction
$N_X \to N_{\text{incl}}$

Experiment	Machine	Operation	C.M.	Luminosity	N_{prod}	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	2010-2011 (2021-) 2016-2019 2014+2020	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	2.9 (8 $\rightarrow$ 20) fb^{-1} 7.3 fb^{-1} 4.5 fb^{-1}	$D^{0,+}$: $10^7 (\rightarrow 10^8)$ D_s^+: 5×10^6 Λ_c^+ : 0.8×10^6 ★☆	$\sim$ 10-30% ★★★	☺ extremely clean environment ☺ quantum coherence ☺ pure D-beam, almost no background ☹ no CM boost, no time-dept analyses
Belle II	SuperKEKB (e^+e^-)	2019-	10.58 GeV	0.4 ($\rightarrow$ 50) ab^{-1}	D^0: 6×10^8 $(\rightarrow 10^{11})$ $D^+_{(s)}$: 10^8 $(\rightarrow 10^{10})$ Λ_c^+: 10^7 $(\rightarrow 10^9)$	$\mathcal{O}$(1-10%)	☺ clear event environment ☺ high trigger efficiency ☺ good-efficiency detection of neutrals ☺ time-dependent analysis ☹ smaller cross-section than LHCb
Belle	KEKB (e^+e^-)	1999-2010	10.58 GeV	1 ab^{-1}	D: 10^9 Λ_c^+: 10^8 ★★☆	★★	
LHCb	LHC (pp)	2011,2012 2015-2018 (2022-2025,2029-)	7+8 TeV 13 TeV	1+2 fb^{-1} 6 fb^{-1} ($\rightarrow$ 23 $\rightarrow$ 50)	5×10^{12} 10^{13} ★★★★	$\mathcal{O}$(0.1%) ★	☺ very large production cross-section ☺ large boost ☺ excellent time resolution ☹ dedicated trigger required

→ each of experiments has their advantages for different charm studies

→ at present BESIII may be hard to compete in many missing energy measurements

→ nonetheless, even at present (and especially in near future) Belle II has a great potential to produce competitive and leading results (especially with clever ideas and novel reconstruction techniques)

B tagging (B factories beloved)

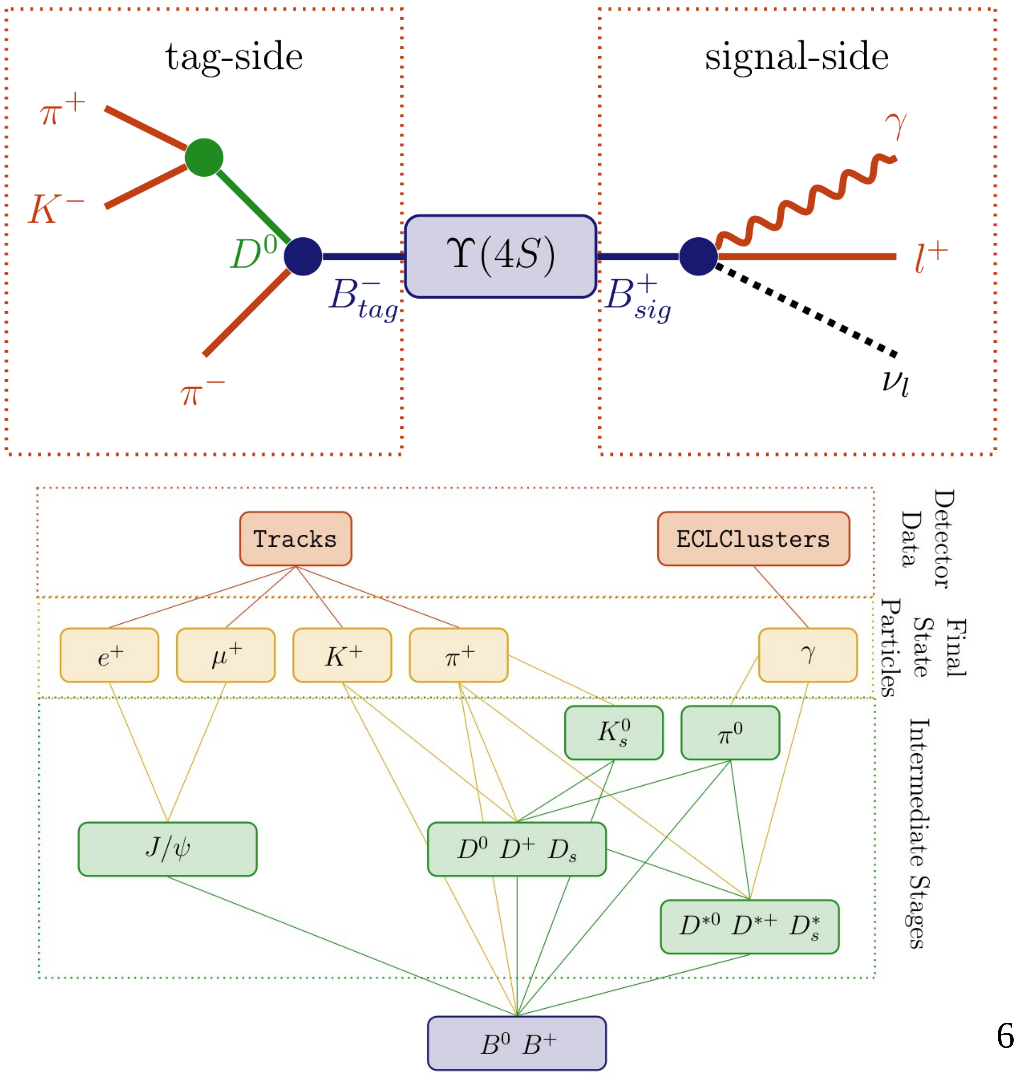
→ K. Trabelsi will tell you everything and more about it tomorrow

→ exactly two B mesons produced

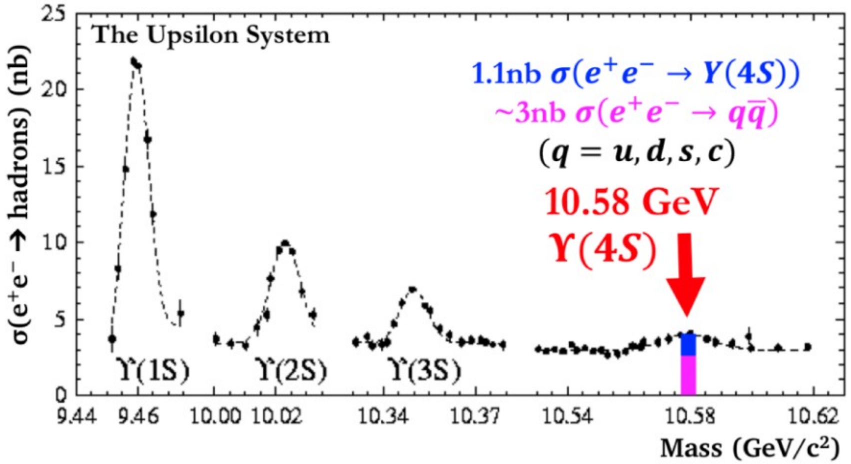
→ fully reconstructing one of the B's in an event gives you particles and kinematics of the other B

→ enables to identify final states with one or more neutrinos in the final state

→ Full Event Interpretation (FEI) algorithm is nominally used to reconstruct B_{tag}'s with "high" efficiency



What about charm



→ @ Belle II charmed hadrons are produced in B decays and in $e^+e^- \to c\bar{c}$ $(\sigma \sim 1.3\text{nb})$

→ while charm from B can also be used for charm studies ccbar events are our interest $e^+e^- \to c\bar{c}$

→ following the B tagging idea let's consider

$$e^+e^- \to c\bar{c} \to \boxed{X_{\text{tag}}} D_{\text{sig}}$$

need to reconstruct

→ if X_{tag} is correctly reconstructed in its RestOfEvent we will find only decay products of $D_{sig} \to f$ along with kinematic constraint $\vec{p}_{D_{sig}} = \vec{p}_{miss}$ $(\vec{p}_{miss} = \vec{p}_{e^+} + \vec{p}_{e^-} - \vec{p}_{X_{tag}})$

→ if we do not put any requirement on RestOfEvent and look at

$M_{miss} = \sqrt{p^2_{miss}}$ $(p_{miss} = p_{e^+} + p_{e^-} - p_{X_{tag}})$ correctly reconstructed events will peak at $M(D_{sig})$

→ the number of peaking events give the total number of D_{sig}'s in the sample (inclusive) which can is then used for absolute branching fraction calculation

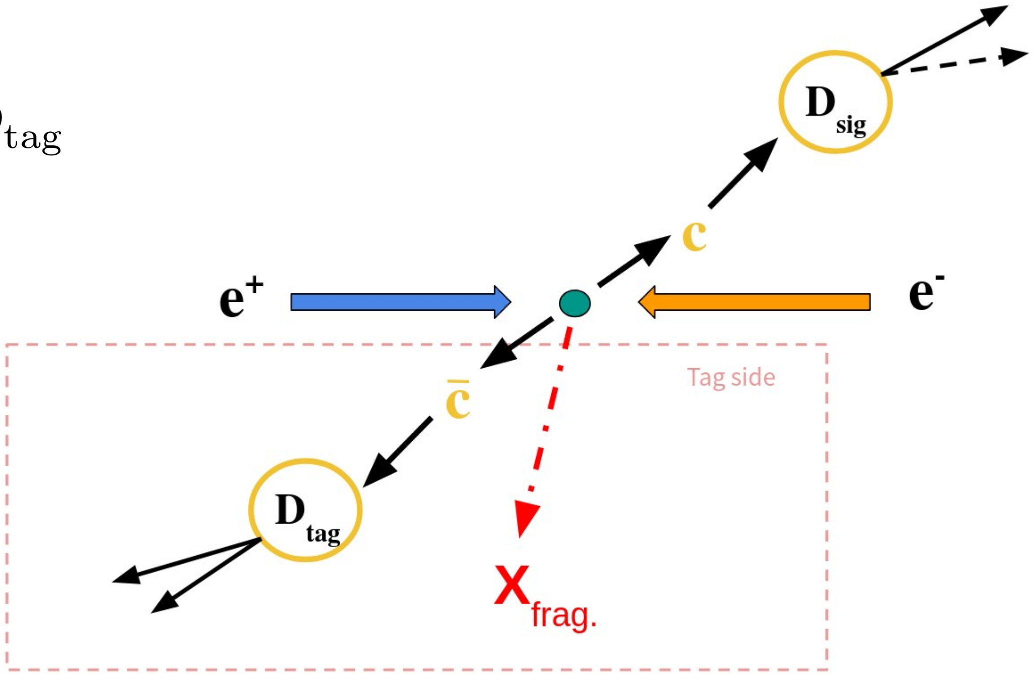
What is in $X_{\rm tag}$?

charge, charmness, strangeness, baryon number of $X_{\rm tag} + D_{sig}$ must each add up to 0!

→ since there is plenty of energy available, $X_{\rm tag}$ contains additional particles next to $\bar{D}_{\rm tag}$ (fragmentation particles)

→ for each $D_{\rm sig}$ type of interest a collection of valid $X_{\rm tag}$ ‘s can be used

→ ideally as many tag modes as possible are used as it determines size of inclusive $D_{\rm sig}$ sample



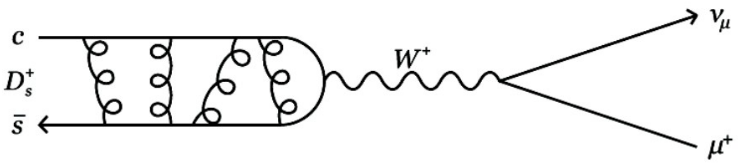
Examples

Branching fractions of leptonic and hadronic D_s^+ decays at Belle

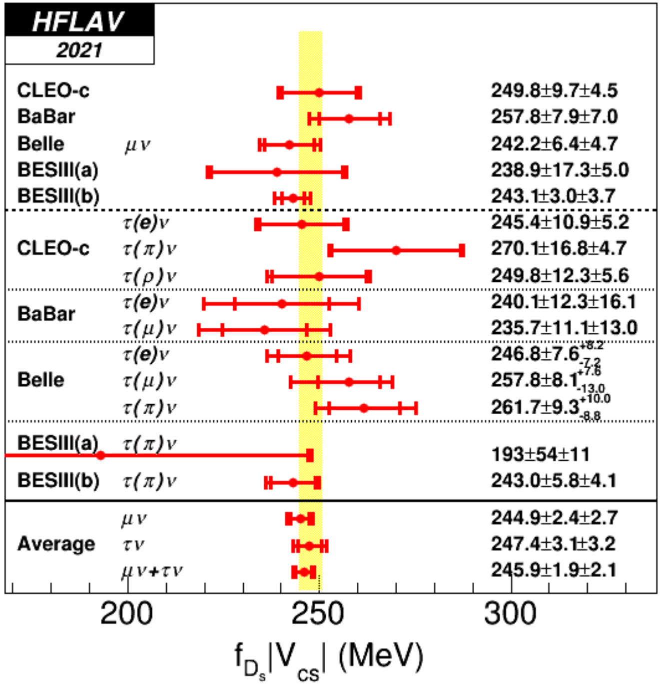
→ this measurement is prime example of charm tagging technique at B-factories

→ references: arxiv:1307.6240, BelleNote (A. Zupanc)

→ main aim was determination of D_s decay constant f_{D_s}



$$\mathcal{B}(D_s^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} f_{D_s}^2 |V_{cs}|^2 \tau_{D_s} M_{D_s} m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{D_s}^2}\right)^2$$



→ in addition to $D_s^+ \to \ell\nu$ few hadronic decay modes were considered

Method overview

→ reconstruct events of form $e^+e^- \to c\bar{c} \to \overline{D}_{\mathrm{tag}} K X_{\mathrm{frag}} D_s^{*+}$

$D_s^{*+} \to D_s^+\gamma$

→ two steps: → inclusive D_s^+ reconstruction (no constraints on D_s^+) for Br normalization

→ within the inclusive D_s^+ sample search for $D_s^+ \to f$ of interest

Inclusive D_s^+ reconstruction

→ D_{tag} modes considered:

MVAs (NeuroBayes) trained to improve selection for each mode

→ Kaon to conserve strangeness
$K = K^\pm,\ K_S^0$

→ for $D_{tag} = \Lambda_c$ additional proton required in event

D^0 modes	$\mathcal{B}$ [%]
$K^-\pi^+$	3.9
$K^-\pi^+\pi^0$	13.9
$K^-\pi^+\pi^+\pi^-$	8.1
$K^-\pi^+\pi^+\pi^-\pi^0$	4.2
$K_S^0\pi^+\pi^-$	2.9
$K_S^0\pi^+\pi^-\pi^0$	5.4
Sum	38.4

D^+ modes	$\mathcal{B}$ [%]
$K^-\pi^+\pi^+$	9.4
$K^-\pi^+\pi^+\pi^0$	6.1
$K_S^0\pi^+$	1.5
$K_S^0\pi^+\pi^0$	6.9
$K_S^0\pi^+\pi^+\pi^-$	3.1
$K^+K^-\pi^+$	1.0
Sum	28.0

Λ_c^+ modes	$\mathcal{B}$ [%]
$pK^-\pi^+$	5.0
$pK^-\pi^+\pi^0$	3.4
pK_S^0	1.1
$\Lambda\pi^+$	1.1
$\Lambda\pi^+\pi^0$	3.6
$\Lambda\pi^+\pi^+\pi^-$	2.6
Sum	16.8

+ $D^{*+} \to D^0\pi^+,\ D^+\pi^0;\ D^{*0} \to D^0\pi^-,\ D^0\gamma$

$$e^+e^- \to c\bar{c} \to \overline{D}_{\text{tag}} K X_{\text{frag}} D_s^{*+}$$

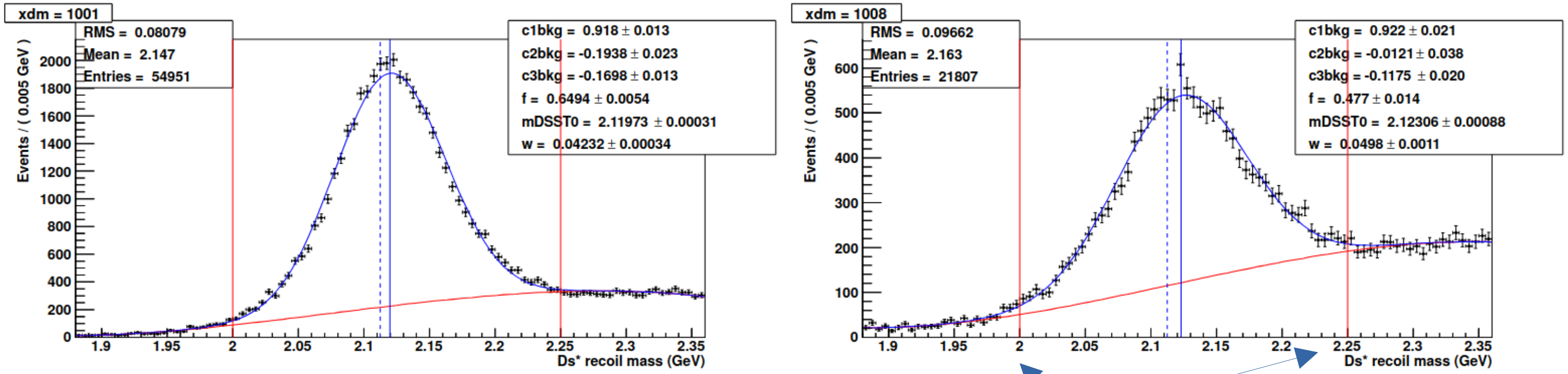
$$D_s^{*+} \to D_s^+\gamma$$

Method overview

→ fragmentation system: $X_{\text{frag}} = \text{nothing},\ \pi^\pm,\ \pi^0,\ \pi^\pm\pi^\pm,\ \pi^\pm\pi^0,\ \pi^\pm\pi^\pm\pi^\pm,\ \pi^\pm\pi^\pm\pi^0$

→ inclusive D_s^* : calculate $M_{\text{miss}}(D_{\text{tag}}K_{\text{frag}}X_{\text{frag}}) = \sqrt{|p_{e^+} + p_{e^-} - p_{D_{\text{tag}}} - p_{K_{\text{frag}}} - p_{X_{\text{frag}}}|^2}$

$X_{\text{frag}} = \pi^\pm$ (Signal MC) $X_{\text{frag}} = \pi\pi\pi^0$



→ select one D_s^* candidate in event: closest to true D_s^* mass and cut

→ mass constrained vertex fit is performed to $D_{tag}KX_{frag}$ system with $M_{miss}(D_{tag}KX_{frag})$ constrained to $m_{D_s^*}$

→ greatly improves the mass resolution of inclusive D_s peak!

$e^+e^- \to c\bar{c} \to \overline{D}_{\rm tag} K X_{\rm frag} D_s^{*+}$

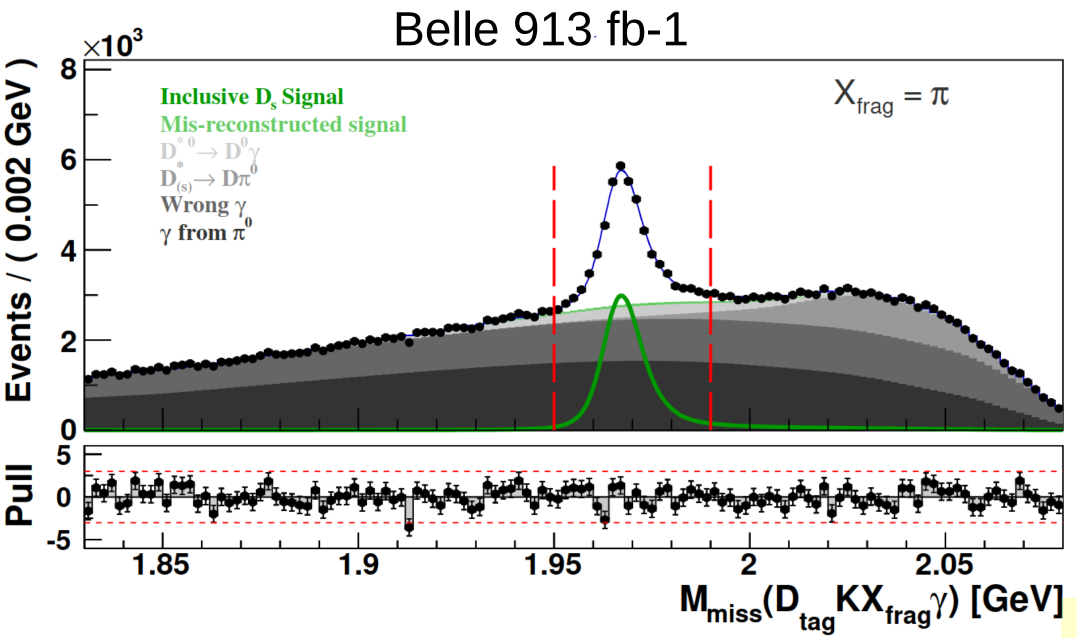
$D_s^{*+} \to D_s^+\gamma$

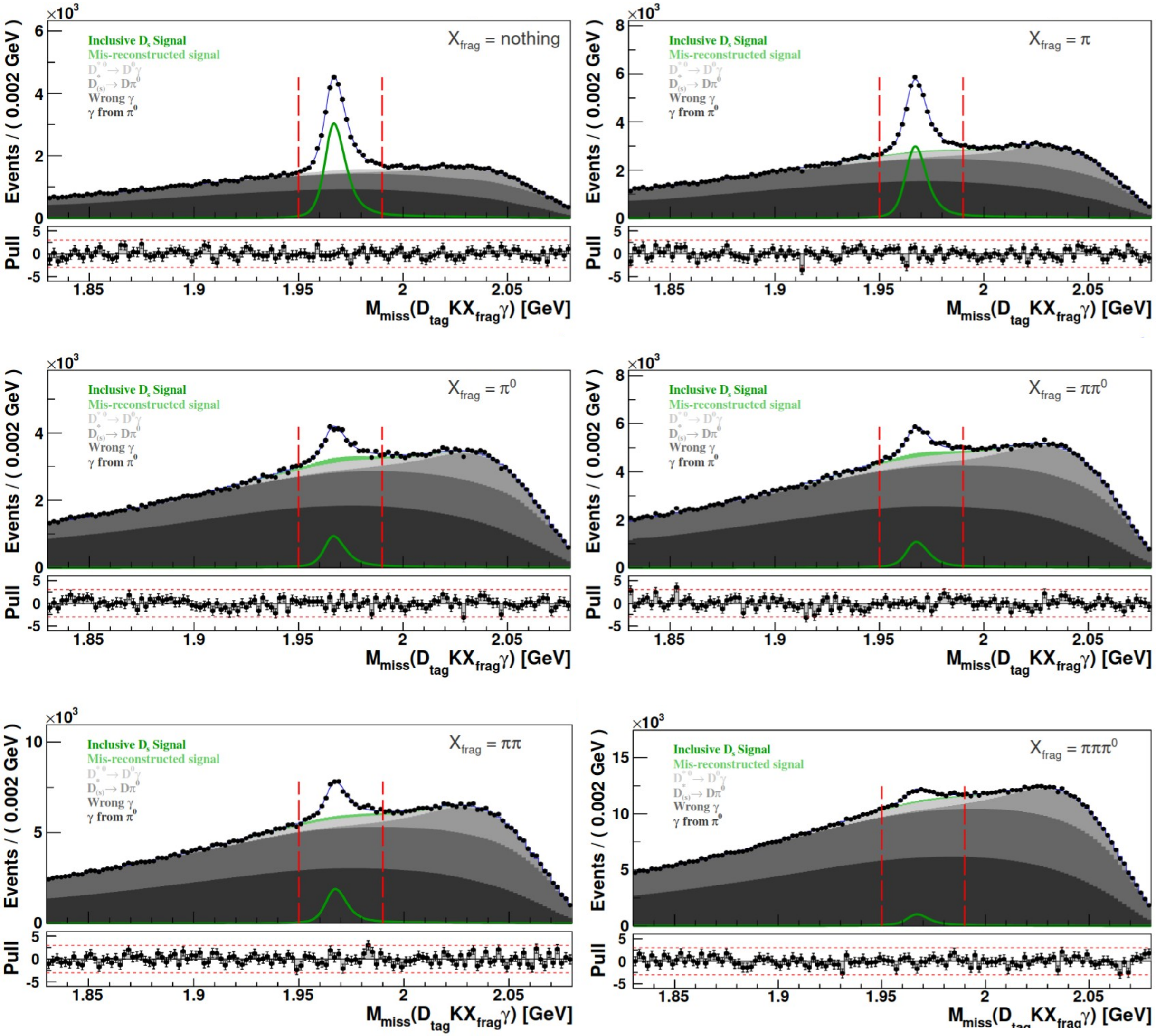
Method overview

→ **inclusive D_s :** - search for γ $(E_\gamma > 0.12\ GeV)$ outside of $D_{tag} K X_{frag}$

- require $p_{miss}(D_{tag} K X_{frag} \gamma) > 2.8$ GeV

- evaluate and plot $M_{miss}(D_{tag} K X_{frag} \boxed{\gamma})$ → note the γ





Fit to $M_{\mathrm{miss}}(D_{\mathrm{tag}} K X_{\mathrm{frag}} \gamma)$ for each X_{frag}:

- Histogram MC templates (6 categories)
- Peak resolution calibrated using real data
- Good description of the observed distributions achieved

Summed all together

$$N_{D_s}^{\mathrm{inc}} = 94360 \pm 1310(\mathrm{stat.}) \pm 1450(\mathrm{syst.})$$

Reconstruction of exclusive D_s final states and branching fraction determination

→ within the reconstructed inclusive sample we try to identify and count $D_s \to f$ decays from the tracks and clusters in the RestOfEvent of $D_{tag}KX_{frag}\gamma$

→ nominally only events in $M_{miss}(D_{tag}KX_{frag}\gamma)$ signal window (red lines on previous slide) are considered

→ after $N(D_s^+ \to f)$ in inculsive sample is determined Branching fraction is obtained as

$$\mathcal{B}(D_s^+ \to f) = \frac{N(D_s^+ \to f)}{N_{D_s}^{\rm inc} \cdot \boxed{f_{\rm bias}} \cdot \boxed{\varepsilon(D_s^+ \to f|\text{incl. } D_s^+)}}$$

rec. eff. for $D_s^+ \to f$ given correct inclusive D_s^+

From MC one can see that inclusive D_s^+ rec. eff. (i.e. correct $D_{tag}KX_{frag}\gamma$ reconstruction) depends on f

→ inclusive sample is therefore not truly inclusive!

Correction factor

"tag" efficiency in $D_s \to f$ events

$$f_{\rm bias} = \frac{\boxed{\varepsilon^{incl}_{D_s \to f}}}{\boxed{\sum_i \mathcal{B}(D_s \to i)\varepsilon^{incl}_{D_s \to f}}}$$

average inclusive efficiency

→ determined from MC

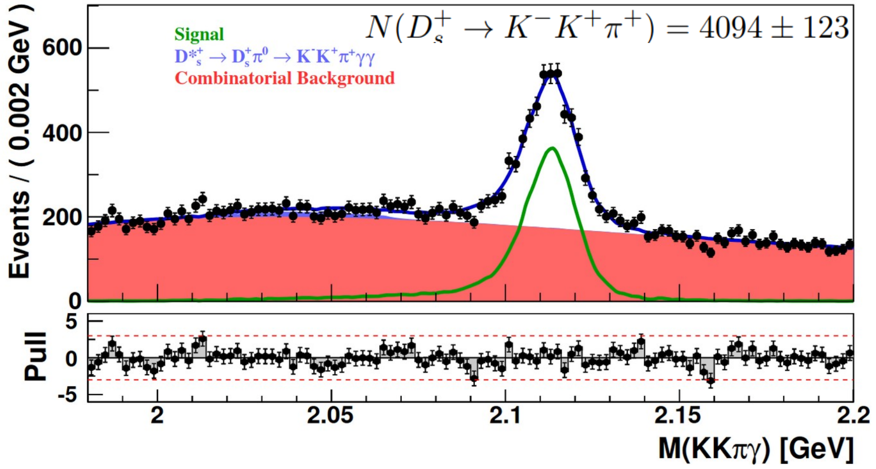
$$D_s^+ \to K^+K^-\pi^+$$

→ require exactly 3 tracks in tag ROE + PID

→ fit to exclusive D_s^* invariant mass $M(KK\pi\gamma)$

$$\mathcal{B}(D_s^+ \to K^-K^+\pi^+) = (5.06 \pm 0.15(\text{stat.}) \pm 0.21(\text{syst.})) \times 10^{-2}$$

→ now superseded by BESIII measurement (2403.19256)



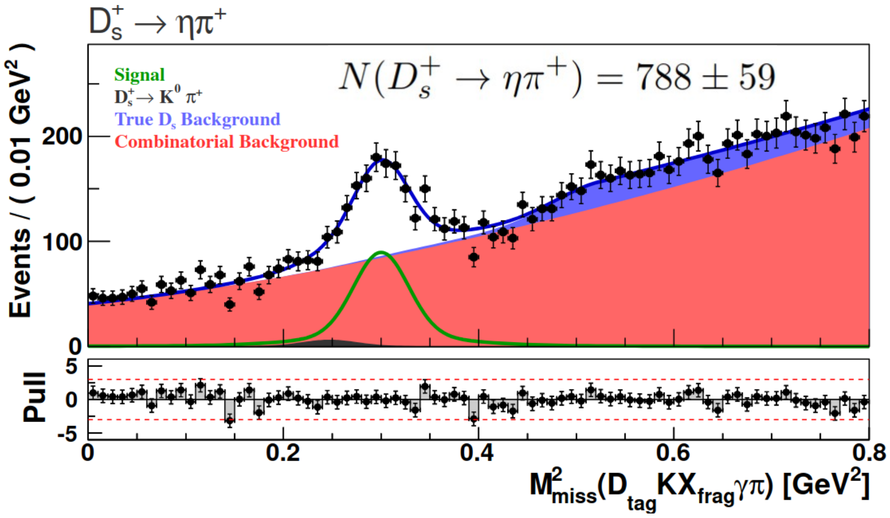
$$D_s^+ \to \eta\pi^+$$

→ singe pion required in tag ROE

→ fit $M^2_{miss}(D_{tag}KX_{frag}\gamma\pi)$

→ do not reconstruct η explicitly → increase efficiency

$$\mathcal{B}(D_s^+ \to \eta\pi^+) = (1.82 \pm 0.14(\text{stat.}) \pm 0.07(\text{syst.})) \times 10^{-2}$$

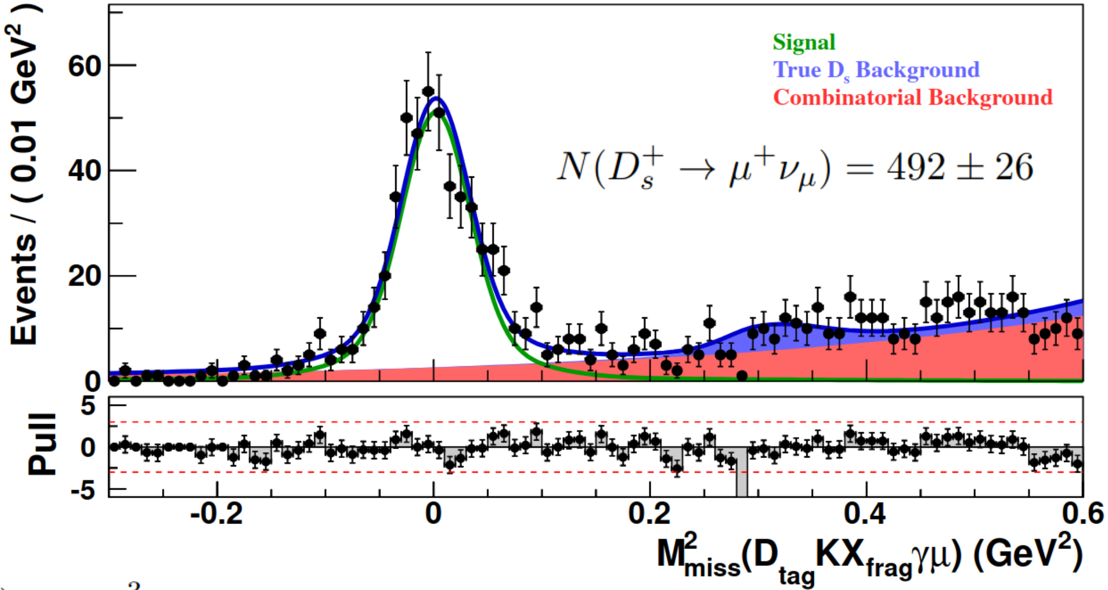


$D_s^+ \to \ell^+ \nu_\ell$

→ require 1 charged track in tag ROE with muon/electron PID selection

→ fit $M^2_{miss}(D_{tag} K X_{frag} \gamma \ell^{\pm})$

→ since single missing ν signal should peak at $M^2_{miss}{=}0$



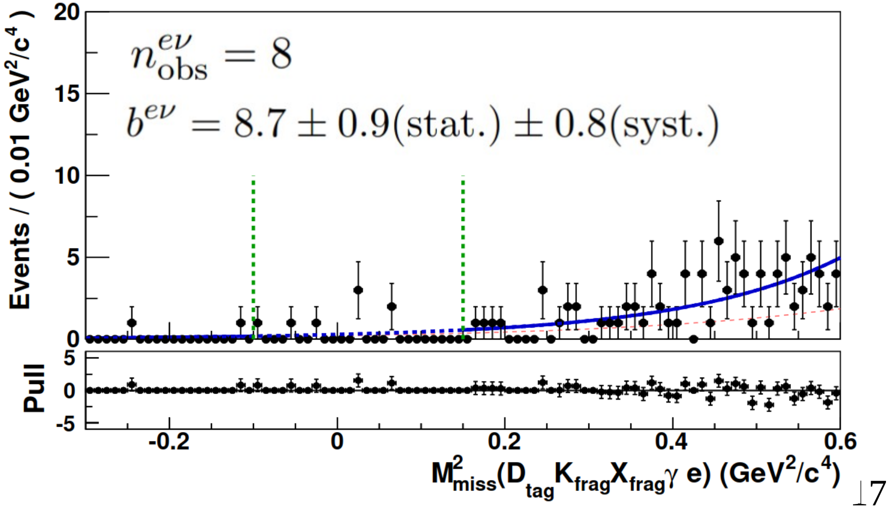
$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.31 \pm 0.28(\text{stat.}) \pm 0.20(\text{syst.})) \times 10^{-3}$$

Superseded by BESIII (2307.14585)

$$\mathcal{B}_{D_s^+ \to \mu^+\nu_\mu} = (0.5294 \pm 0.0108)\% \; (N_{sig} \sim 2500)$$

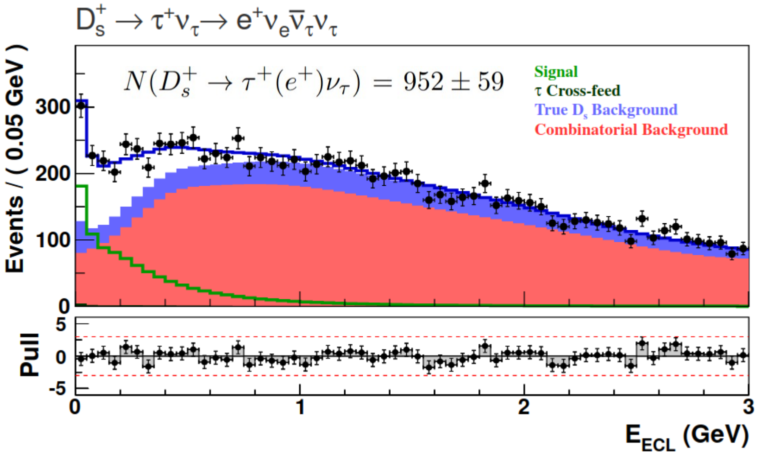
$$\mathcal{B}(D_s^+ \to e^+\nu_e) < 1.0 \; (0.83) \times 10^{-4} \text{ at } 95 \; (90)\% \text{ C.L.}$$

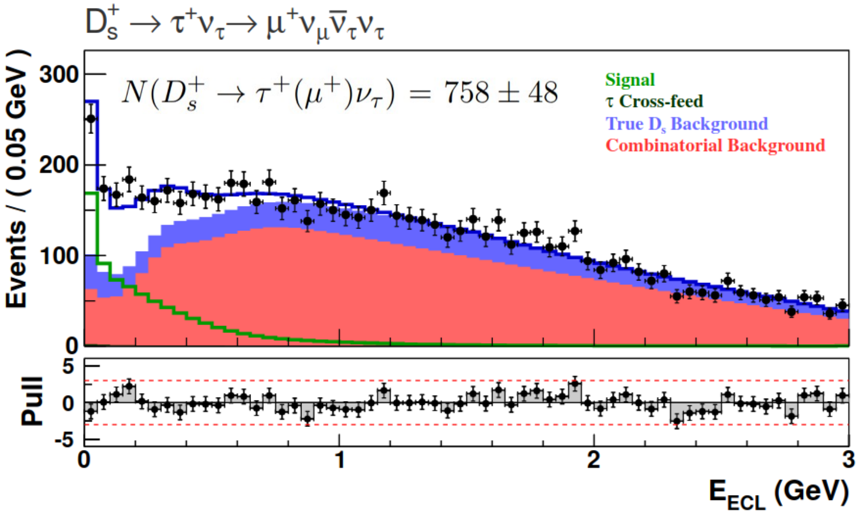
(still best UL; ~3x better than BaBar)

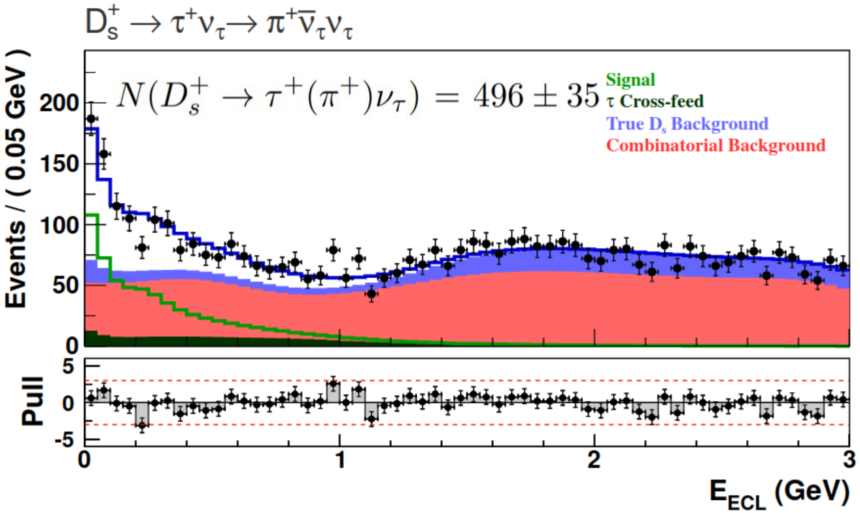


$D_s^+ \to \tau^+\nu_\tau$

- → τ reconstructed in 3 decay modes:
  $\tau \to \mu\nu\nu,\ \tau \to e\nu\nu,\ \tau \to \pi\nu$ (46% of total)
- → one track in tag ROE with corresponding PID
- → due to multiple $\nu's$ these events do not peak at 0!
- → fit on E_{ECL} is performed instead using templates from MC







$D_s^+ \to \tau^+\nu_\tau$

→ obtained branching fractions:

τ decay mode	$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$ [$\times 10^{-2}$]
$e\nu\nu$	$5.37 \pm 0.33^{+0.35}_{-0.30}$
$\mu\nu\nu$	$5.88 \pm 0.37^{+0.34}_{-0.58}$
$\pi\nu$	$5.96 \pm 0.42^{+0.45}_{-0.39}$
Combination	$5.70 \pm 0.21^{+0.31}_{-0.30}$

→ largest systematics originates from the E_{ECL} templates, e.g. peaking backgrounds $D_s^+ \to \overline{K}^0\ell^+\nu_\ell$ with K_L that deposits little or no energy in ECL etc.

→ extraction of D_s decay constant

$$f_{D_s} = \frac{1}{G_F m_\ell \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)|V_{cs}|}\sqrt{\frac{8\pi\mathcal{B}(D_s^+ \to \ell^+\nu_\ell)}{m_{D_s}\tau_{D_s}}}$$

$$f_{D_s} = (255.5 \pm 4.2(\text{stat.}) \pm 4.8(\text{syst.}) \pm 1.8(\tau_{D_s}))\ \text{MeV}$$

→ LFU test $R^{D_s}_{\tau/\mu} = 10.73 \pm 0.69(\text{stat.})^{+0.56}_{-0.53}(\text{syst.})$ $(R^{SM} \sim 9.75)$

→ these are also superseded by BESIII measurements (2303.12600) $\mathcal{B}_{D_s^+\to\tau^+\nu_\tau} = (5.32 \pm 0.07 \pm 0.07)\%$

→ many syst. uncert. will improve with larger stat. @ Belle II

$D^0 \to$ invisible **at Belle (II)**

- In SM, heavy (B or D) decays to $\nu\bar{\nu}$ is helicity suppressed with an expected branching fraction of $\mathrm{Br}(\mathrm{D}^0 \to \nu\bar{\nu}) = 1.1 \cdot 10^{-30}$, which is beyond the reach of current collider experiments.

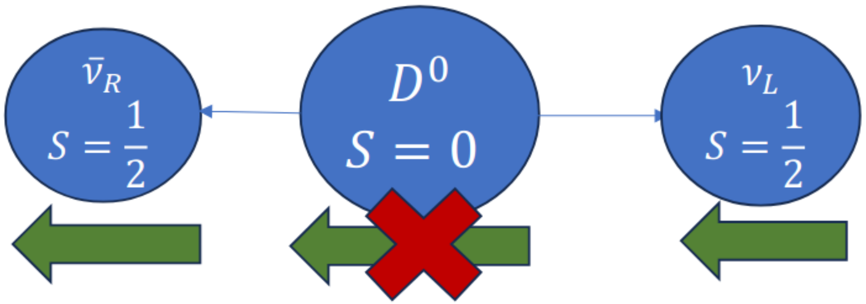


Figure1: Scheme of helicity suppressing

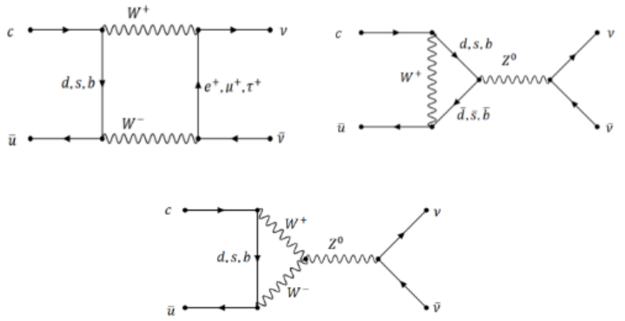


Figure2: Feynman diagram for $D^0 \to \nu\bar{\nu}$

- Therefore, search for $D^0 \to$ invisible final states is sensitive to new physics

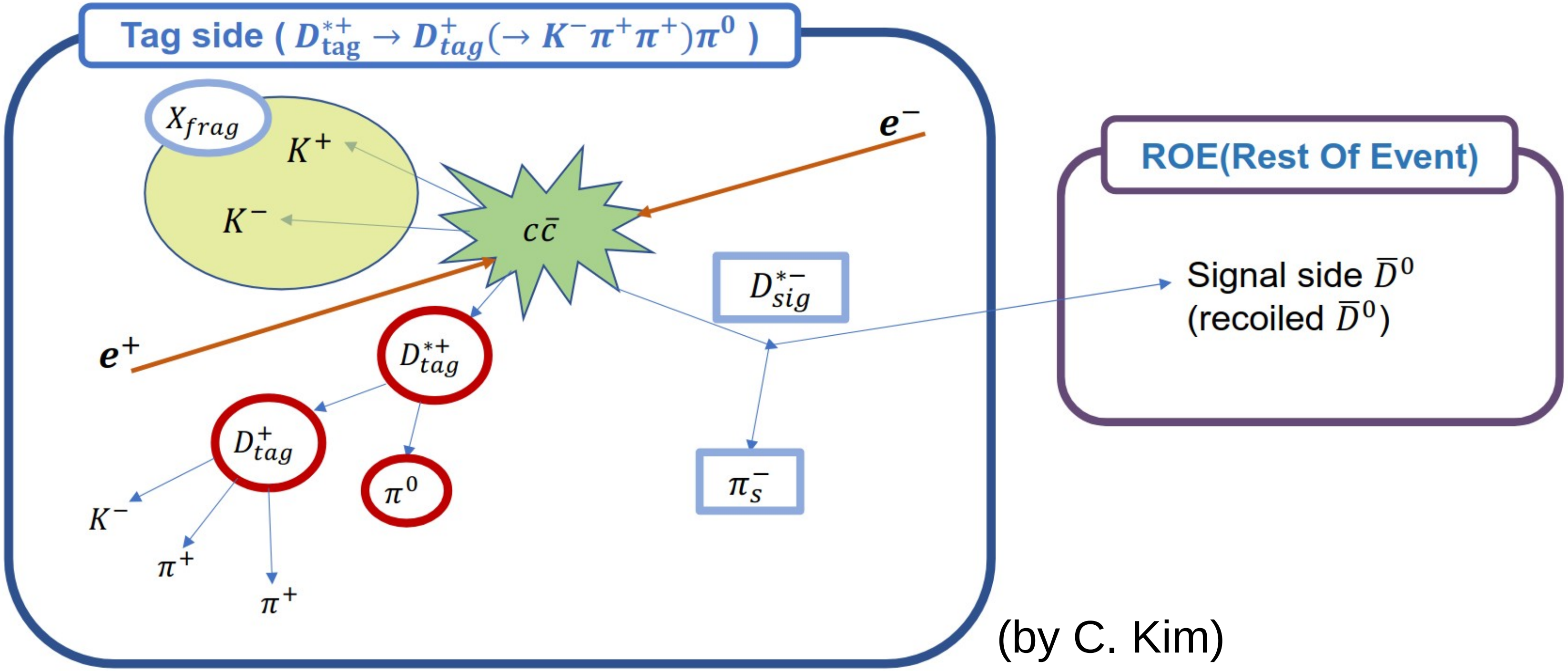
(by C. Kim)

→ published Belle result from 2017 (Y.-T. Lai): 1611.09455, BN

→ ongoing Belle II effort by C. Kim (Yonsei): BELLE2-NOTE-PH-2025-003

Measurement strategy

$$e^+e^- \rightarrow c\bar{c} \rightarrow D^{(*)}_{\rm tag} X_{\rm frag} \overline{D}^{*-}_{\rm sig} \text{ with } \overline{D}^{*-}_{\rm sig} \rightarrow \overline{D}^{0}_{\rm sig} \pi^-_s$$



(by C. Kim)

$D_{tag}^{(*)}$ modes

D^0 decay	p^* (GeV/c)	D^+ decay	p^* (GeV/c)
$K^-\pi^+$	> 2.3	$K^-\pi^+\pi^+$	> 2.3
$K^-\pi^+\pi^0$	> 2.5	$K^-\pi^+\pi^+\pi^0$	> 2.5
$K^-\pi^-\pi^+\pi^+$	> 2.3	$K^0_S\pi^+$	> 2.3
$K^-\pi^-\pi^+\pi^+\pi^0$	> 2.5	$K^0_S\pi^+\pi^0$	> 2.4
$K^0_S\pi^+\pi^-$	> 2.3	$K^0_S\pi^+\pi^+\pi^-$	> 2.4
$K^0_S\pi^+\pi^-\pi^0$	> 2.5	$K^+K^-\pi^+$	> 2.3

Λ_c^+ decay	p^* (GeV/c)	D_s^+ decay	p^* (GeV/c)
$pK^-\pi^+$	> 2.3	$K^+K^-\pi^+$	> 2.3
$pK^-\pi^+\pi^0$	> 2.5	$K^0_SK^+$	> 2.3
pK^0_S	> 2.3	$K^0_SK^0_S\pi^+$	> 2.3
$\Lambda\pi^+$	> 2.3	$K^+K^-\pi^+\pi^0$	> 2.5
$\Lambda\pi^+\pi^0$	> 2.5	$K^0_SK^-\pi^+\pi^+$	> 2.4
$\Lambda\pi^+\pi^+\pi^-$	> 2.3		

$+D^*$ from D + (π^+, π^0, γ)

X_{frag} modes

$D^{(*)+}$	$D^{(*)0}$
nothing(K^+K^-)	$\pi^+(K^+K^-)$
$\pi^0(K^+K^-)$	$\pi^+\pi^0(K^+K^-)$
$\pi^+\pi^-(K^+K^-)$	$\pi^+\pi^-\pi^+(K^+K^-)$
$\pi^+\pi^-\pi^0(K^+K^-)$	

Λ_c^+	$D_s^{(*)+}$	
$\pi^+\overline{p}$	K^0_S,	$\pi^0K^0_S$
$\pi^+\pi^0\overline{p}$	π^+K^-,	$\pi^+\pi^0K^-$
$\pi^+\pi^-\pi^+\overline{p}$	$\pi^+\pi^-K^0_S$,	$\pi^+\pi^-\pi^0K^0_S$
	$\pi^+\pi^-\pi^+K^-$	

→ standard selections are applied (PID, π^0 , $D_{(s)}$ inv. masses)
+ for $D^*_{(s)}$ tags mass difference $|M(D^*_{(s)}) - M(D_{(s)})| < 3\sigma_{res}$

→ for each $D_{tag}X_{frag}$ combination the missing mass

$$M_{miss}(D_{tag}X_{frag}) = \sqrt{|p_{e^+} + p_{e^-} - p_{D_{tag}} - p_{X_{frag}}|^2}$$

is required to be within the selected window of D^{*-} mass

→ this is a sample of recoiling D^{*-}

→finally π_s^- is searched for outside of the $D_{tag}X_{frag}$ system and

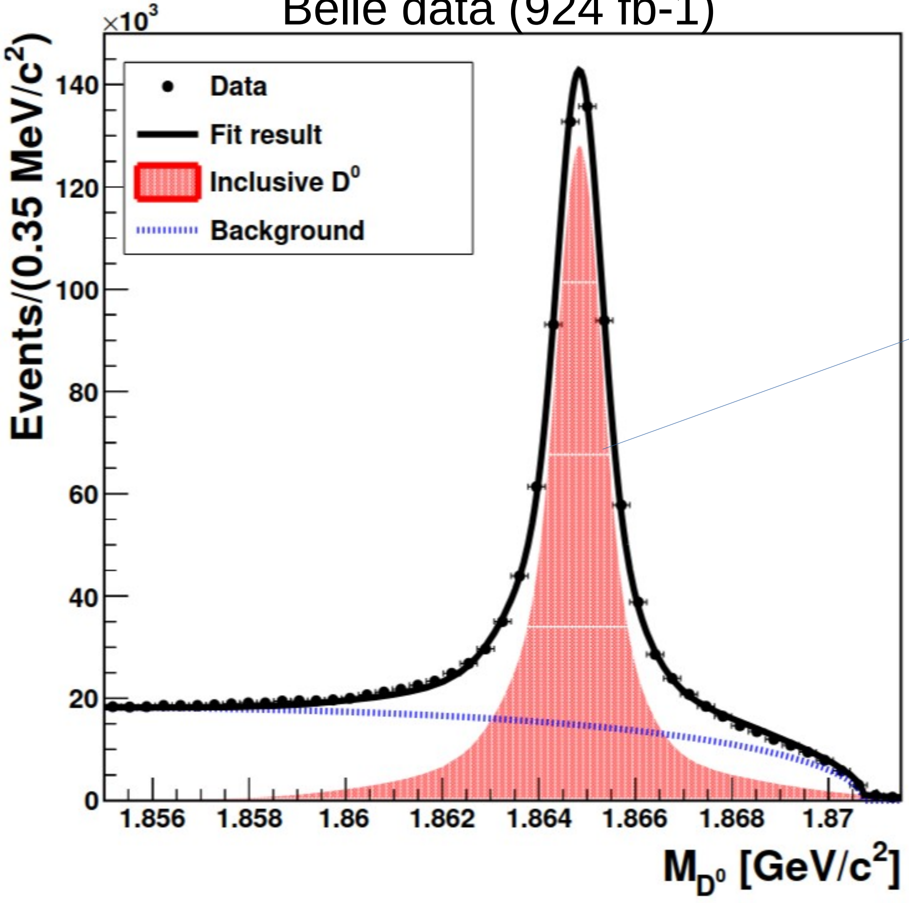
$$M_{miss}(D_{tag}X_{frag}\pi_s^-) = \sqrt{|p_{e^+} + p_{e^-} - p_{D_{tag}} - p_{X_{frag}} - p_{\pi_s^-}|^2}$$

is obtained from kinematic fit where $M_{miss}(D_{tag}X_{frag})$ is constrained to $m_{D^{*-}}$

→ events with D^0 recoiling from $D_{tag}X_{frag}\pi_s^-$ will form a sharp peak around m_{D^0}

Inclusive D^0 sample

Belle data (924 fb-1)



Notice the
$\sigma_M \sim 1\ \mathrm{MeV}$

694667^{+1494}_{-1563} inclusive D^0 decays

Search for $D^0 \to invisible$ signal

→ in events from inclusive D^0 sample, no remaining final state particles (out of $D_{tag}X_{frag}\pi_s^-$) are required (events with charged tracks, π^0, K_L are vetoed)

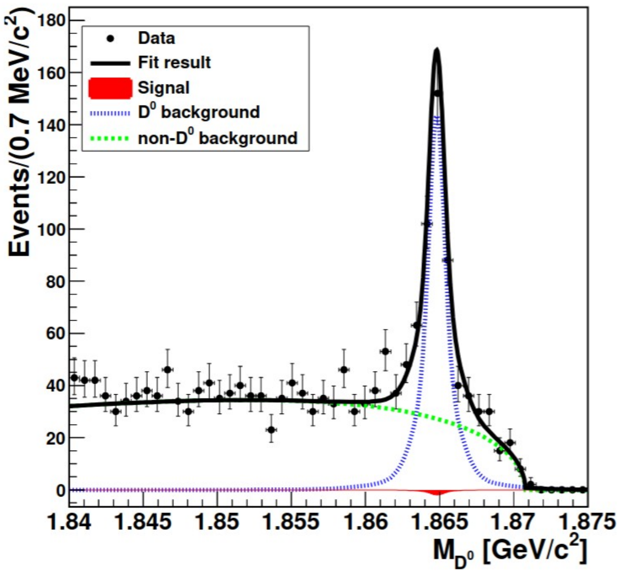
→ for the remaining 2D ML fit is performed in M_{D^0}, E_{ECL} to determine signal yield

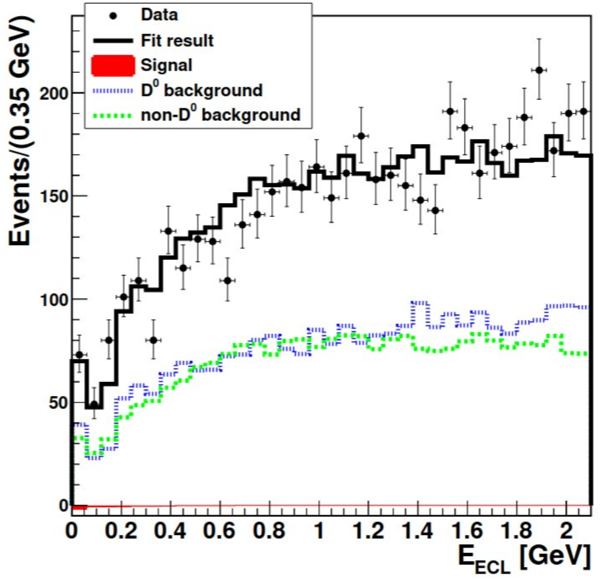
→ in addition to signal, background with true D^0 and non-D^0 background are considered

→ E_{ECL} templates are obtained from MC, while M_{D^0} peak shape is fixed form inclusive fit

$$N_{sig} = -6.3^{+22.5}_{-21.0}$$

$$\mathcal{B} = \frac{N_{\text{sig}}}{\epsilon \times N_{D^0}^{\text{incl.}}}$$





→ rec. efficiency is $(62.4^{+3.2}_{-3.1})\%$
(this is effectively eff. of the vetoes)

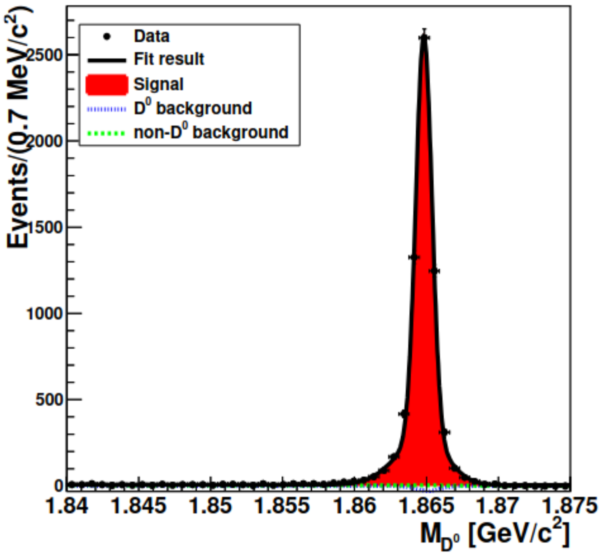
→ calibrated on the sample with
$D^0 \to K^-\pi^+$

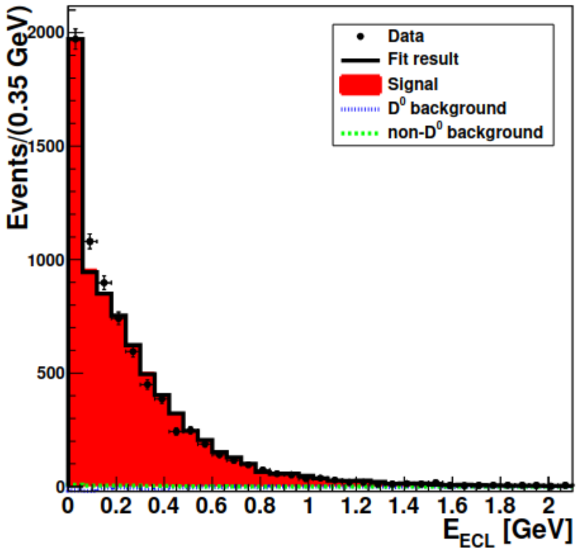
→ upper limit is determined by

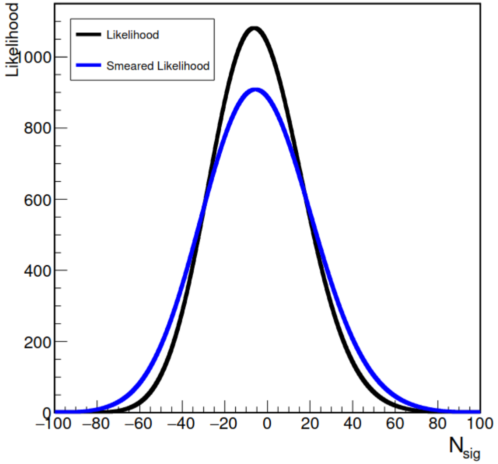
$$\int_0^{\mathcal{B}_{UL}} \mathcal{L}(\mathcal{B})d\mathcal{B} = 0.9 \int_0^1 \mathcal{L}(\mathcal{B})d\mathcal{B}$$

$$\mathcal{L}_{\rm smear}(\mathcal{B}) = \int_0^1 \mathcal{L}(\mathcal{B}')\frac{e^{-\frac{(\mathcal{B}-\mathcal{B}')^2}{2\Delta\mathcal{B}^2}}}{\sqrt{2\pi}\Delta\mathcal{B}}d\mathcal{B}'$$

$\Delta\mathcal{B}$ - total systematics on $\mathcal{B}$







The dominant systematics comes from E_{ECL} modeling of backgrounds

$$\mathcal{B}(D^0 \to invisible) < 9.4 \times 10^{-5} \text{ @ } 90\%\text{C.L.}$$

PRL 113, 042002 (2014)

Belle note (A.Zupanc et al.)

Measurement of absolute branching fraction of $\Lambda_c^+ \to pK^-\pi^+$

→ this channel is often reference mode for measurements of Λ_c^+ branching fractions (to any mode)

→ in addition it is most often used mode in measurements of b-flavored mesons in baryons to final states containing Λ_c^+

→ similarly as before absolute Br is determined from $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = \frac{N(\Lambda_c^+ \to pK^-\pi^+)}{N_{\rm inc}^{\Lambda_c} f_{\rm bias}\varepsilon(\Lambda_c^+ \to pK^-\pi^+)}$

→ where $e^+e^- \to c\bar{c} \to D^{(*)}X_{frag}\bar{p}\Lambda_c^+$ is used to obtain the inclusive Λ_c sample

D^-, D^{*-}

In principle any even number of K + any number of $\pi's$ → only one π^+ actually used

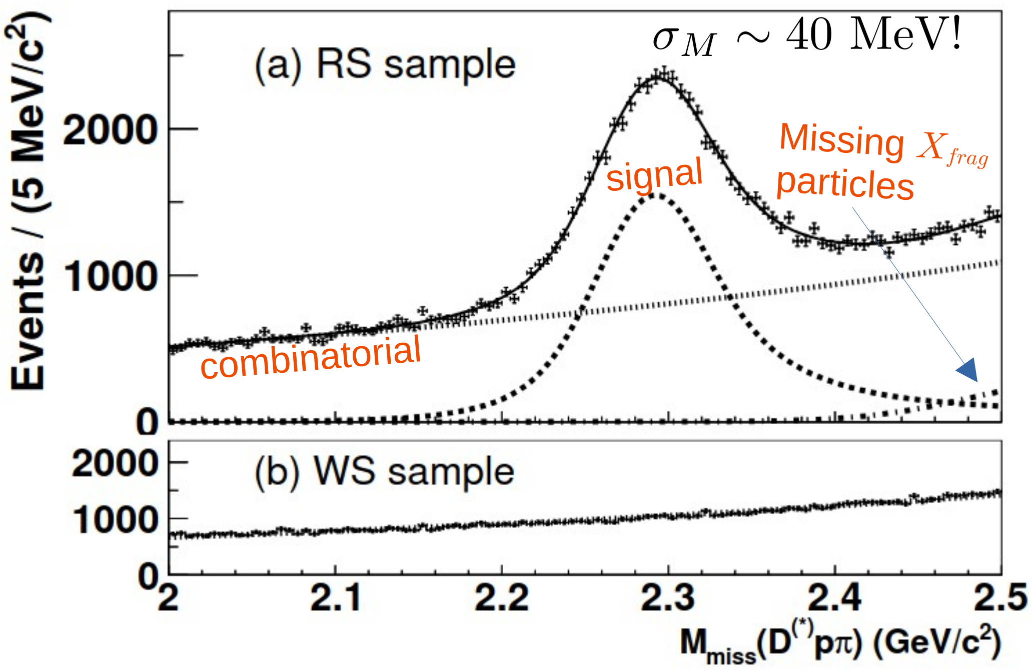
→ kinematic fit is performed to each $D^{(*)}\pi p$ which constrains particle to originate from common point in IP region and D mass is constrained to its nominal value

→ events are split into

right sign (RS) $D^{(*)-}\bar{p}\pi^+$

wrong sign (WS) $D^{(*)-}p\pi^-$ and $D^{(*)+}\bar{p}\pi^-$

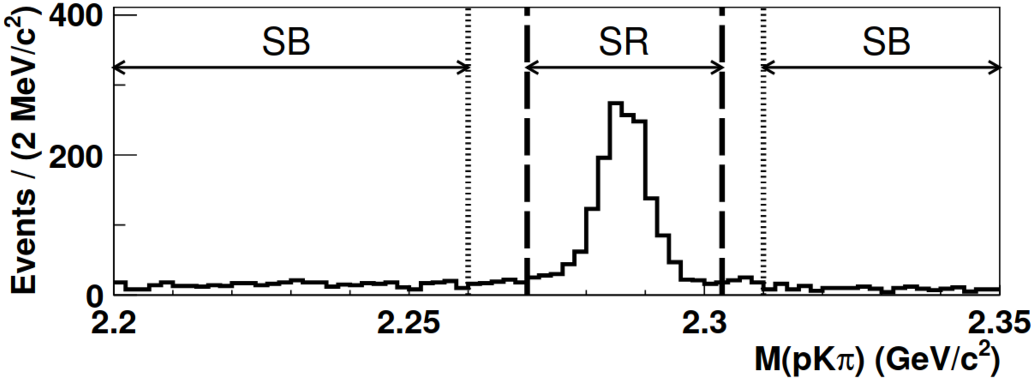
Cannot contain correct Λ_c!
(zero charge sum + baryon + charm consv.)



→ tail in signal distribution (hi end) from
$e^+e^- \to c\bar{c}\gamma_{ISR} \to D_{\text{tag}}X_{\text{frag}}p\Lambda_c^-\gamma_{ISR}$

$$N_{\text{incl}}^{\Lambda_c} = 36447 \pm 432$$

→ in tag ROE exactly 3 tracks are required and $\Lambda_c^+ \to pK^-\pi^+$ is reconstructed

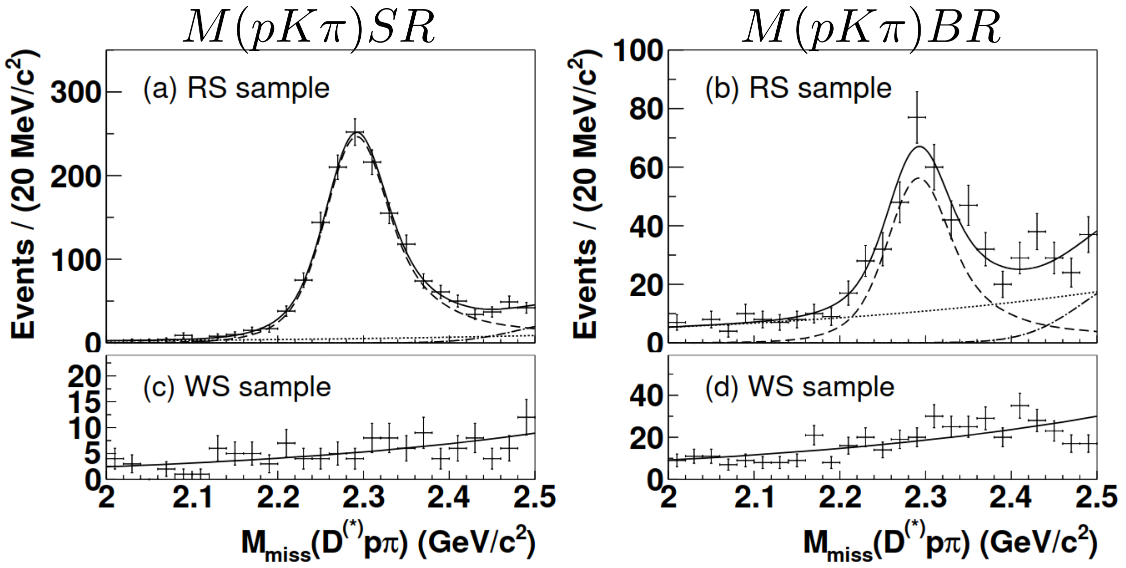


→ rather than fitting $M(pK\pi)$,
$M_{miss}(D^{(*)}p\pi)$ is fitted for events in
$M(pK\pi)$ signal and sideband regions

→ these fits are performed in the same way and with same parametrisations as for inclusive sample, which largely cancels related fit systematics

→ finally number of events peaking in both $M(pK\pi)$ and $M_{miss}(D^{(*)}p\pi)$ is obtained by sideband subtraction

$$N(\Lambda_c^+ \to pK^-\pi^+) = 1359 \pm 45$$



→ taking into account $\Lambda_c^+ \to pK^-\pi^+$ rec. eff. and $N_{incl}^{\Lambda_c}$

$$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24(\text{stat.})^{+0.21}_{-0.27}(\text{syst.}))\%$$

Source	Uncertainty [%]
Tracking	1.1
Proton ID	0.4
Efficiency	1.1
Dalitz model	1.1
f_{bias}	1.5
Bkg. subtraction	$^{+0.5}_{-0.9}$
Fit Model	$^{+1.7}_{-2.9}$
Total	$^{+3.0}_{-3.9}$

→ still on par and in slight tension with BESIII

$5.84 \pm 0.27 \pm 0.23$	6.3k	ABLIKIM	2016	BES3	$e^+ e^- \to \Lambda_c \bar{\Lambda}_c$, 4.599 GeV
$6.84 \pm 0.24\ ^{+0.21}_{-0.27}$	1.4k	[1] ZUPANC	2014	BELL	$e^+ e^- \to D^{(*)-}\bar{p}\pi^+$ recoil

ccbarFEI

ccbarFEI

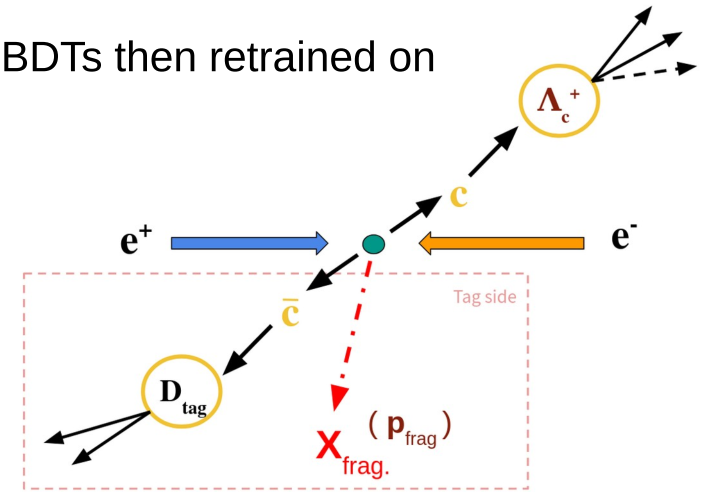
→ FEI is existing tool that is trained to efficiently reconstruct hadronic B decays.

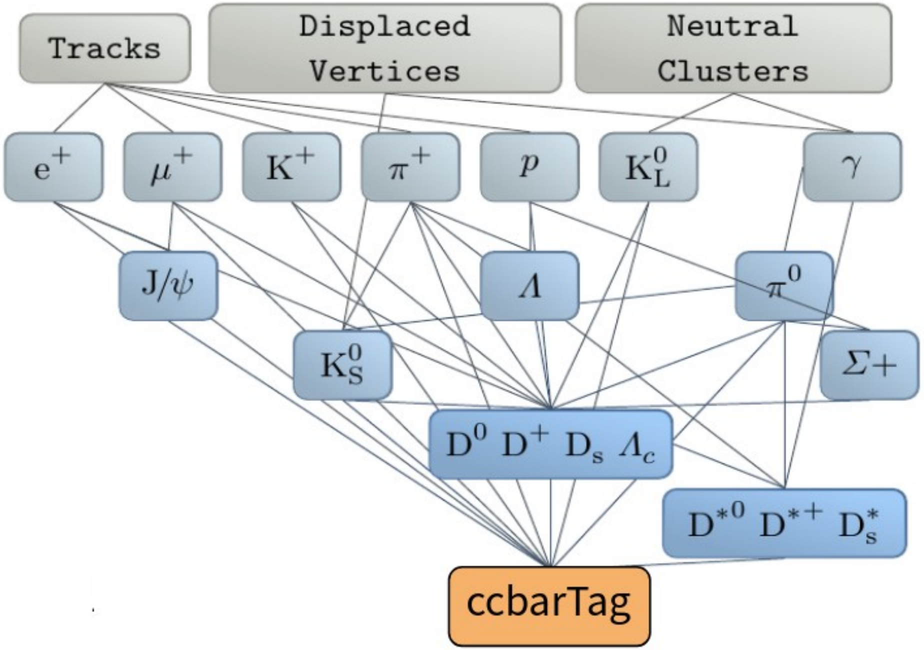
→ in the chain it is already reconstructing various charm states

→ idea of ccbarFEI is to adjust FEI to reconstruct charm tags (the recoil of which is a single $D_{(s)}, \Lambda_c,$ etc.)

→ target B modes in the last step of FEI are replaced with a list of target ccbar tags (specific for $D_{(s)}, \Lambda_c,$ etc. inclusive samples)

→ all stages of BDTs then retrained on ccbar events

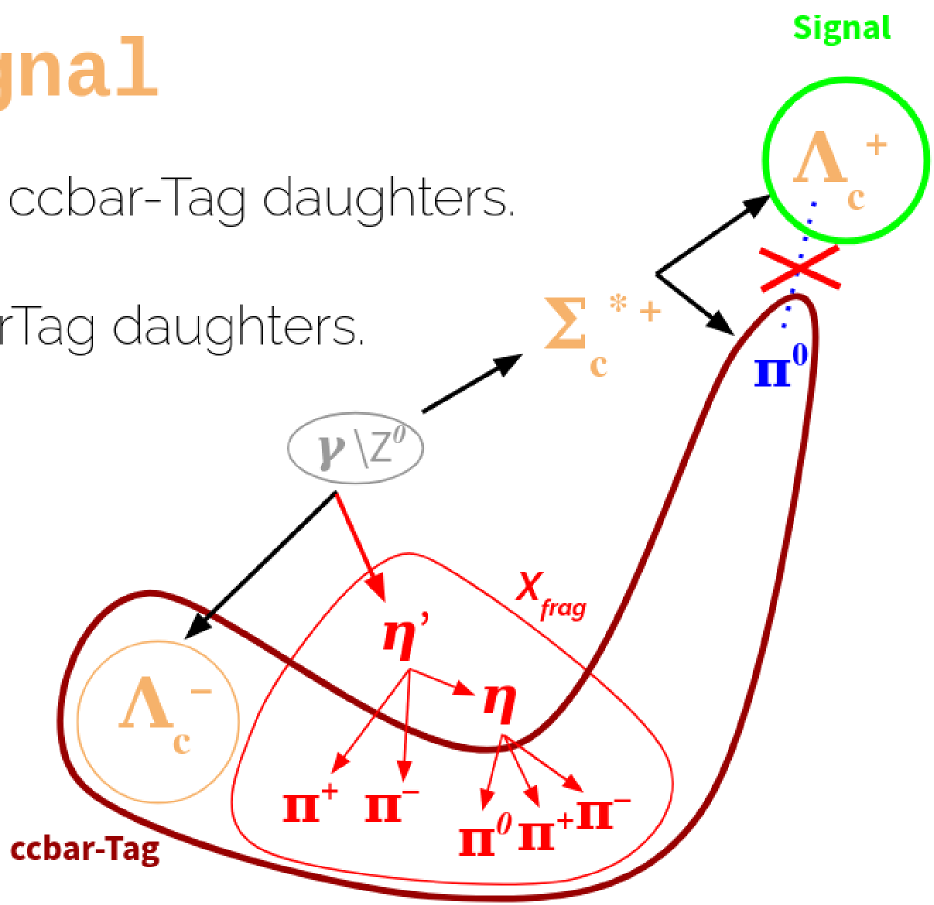




FEI adjustments: `ccbarTagSignal`

1. Check `isSignal` and `mcErrors` for ccbar-Tag daughters.
2. Check that Λ_c is not ancestor of ccbarTag daughters.
3. Check that all ccbarTag daughters have the same "All Mother" $\gamma \backslash Z^0$.
4. Count $\gamma \backslash Z^0$ descendants which are explicitly rec. by FEI (ignore rad. photons)

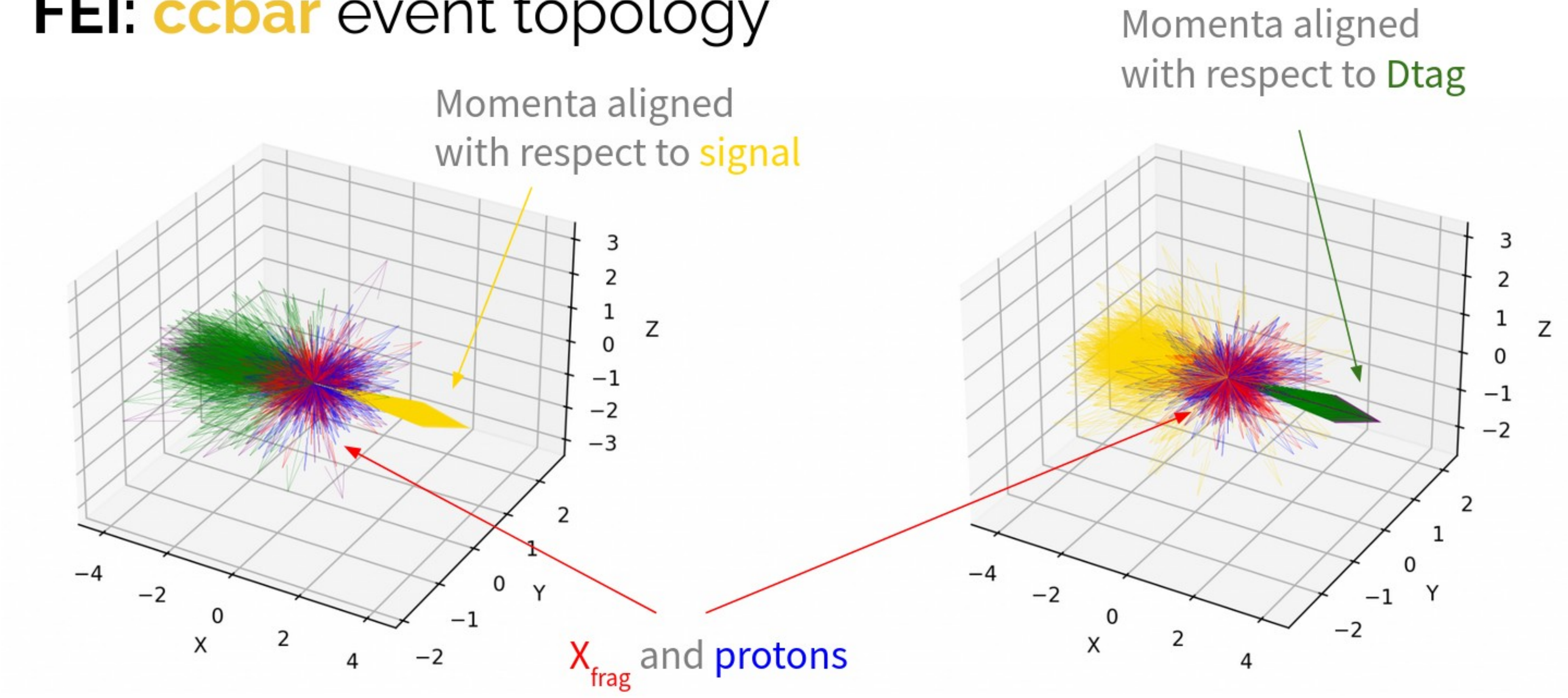
$$\mathrm{nDaug}_{\gamma/Z} = 1 + \mathrm{nDaug}_{\mathrm{ccbarTag}}$$
$$N(\Lambda_c)_{\gamma/Z} = 1 + N(\Lambda_c)_{\mathrm{ccbarTag}}$$



→ BDT performance for signal/background separation mostly relies on product of signal probabilities of reconstructed particles in ccbar tag

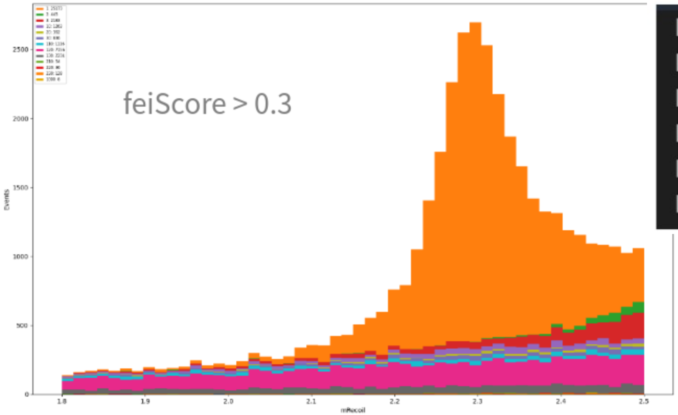
→ some additional observables, e.g. angle between D_{tag} momentum and $\vec{p}_{\mathrm{miss}}$ are included

FEI: ccbar event topology



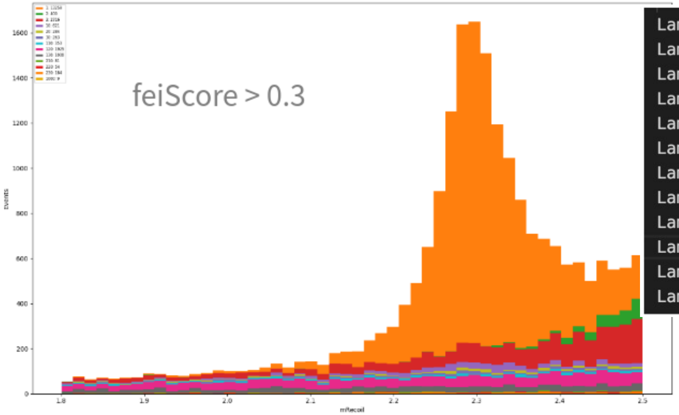
$M_{miss}(\mathrm{tag}_{\Lambda_c})$ for various types of tag_{Λ_c}

default modes




```
LambdaCTag.addChannel(['D0', 'p+'])
LambdaCTag.addChannel(['D*0', 'p+'])
LambdaCTag.addChannel(['D+', 'p+', 'pi-'])
LambdaCTag.addChannel(['D*+', 'p+', 'pi-'])
LambdaCTag.addChannel(['D_s+', 'p+', 'K-'])
LambdaCTag.addChannel(['D_s*+', 'p+', 'K-'])
```

added charged




```
LambdaCTagCharged.addChannel(['D0', 'p+', 'pi+', 'pi-'])
LambdaCTagCharged.addChannel(['D*0', 'p+', 'pi+', 'pi-'])
LambdaCTagCharged.addChannel(['D+', 'p+', 'pi-', 'pi+', 'pi-'])
LambdaCTagCharged.addChannel(['D*+', 'p+', 'pi-', 'pi+', 'pi-'])
LambdaCTagCharged.addChannel(['D_s+', 'p+', 'K-', 'pi+', 'pi-'])
LambdaCTagCharged.addChannel(['D_s*+', 'p+', 'K-', 'pi+', 'pi-'])
LambdaCTagCharged.addChannel(['D0', 'p+', 'K+', 'K-'])
LambdaCTagCharged.addChannel(['D*0', 'p+', 'K+', 'K-'])
LambdaCTagCharged.addChannel(['D+', 'p+', 'pi-', 'K+', 'K-'])
LambdaCTagCharged.addChannel(['D*+', 'p+', 'pi-', 'K+', 'K-'])
LambdaCTagCharged.addChannel(['D0', 'p+', 'p+', 'anti-p-'])
LambdaCTagCharged.addChannel(['D*0', 'p+', 'p+', 'anti-p-'])
```

additional Λ_c

```
LambdaCTagExtra.addChannel(['Lambda_c+', 'gamma'])
LambdaCTagExtra.addChannel(['Lambda_c+', 'gamma', 'gamma'])
LambdaCTagExtra.addChannel(['Lambda_c+', 'gamma', 'gamma', 'gamma'])
LambdaCTagExtra.addChannel(['Lambda_c+', 'pi0', 'gamma'])
LambdaCTagExtra.addChannel(['Lambda_c+', 'pi0', 'gamma', 'gamma'])
LambdaCTagExtra.addChannel(['Lambda_c+', 'pi+', 'pi-'])
LambdaCTagExtra.addChannel(['Lambda_c+', 'pi+', 'pi-', 'gamma'])
LambdaCTagExtra.addChannel(['Lambda_c+', 'pi+', 'pi-', 'gamma', 'gamma'])
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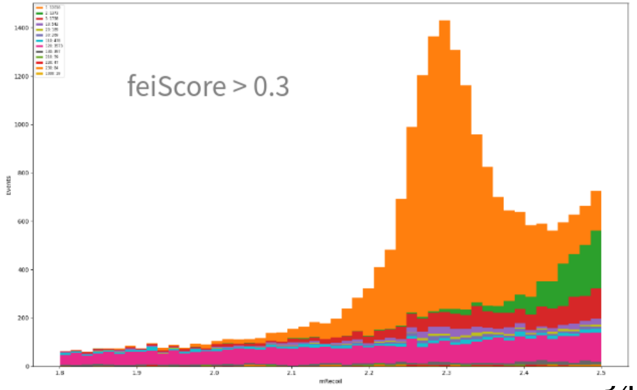
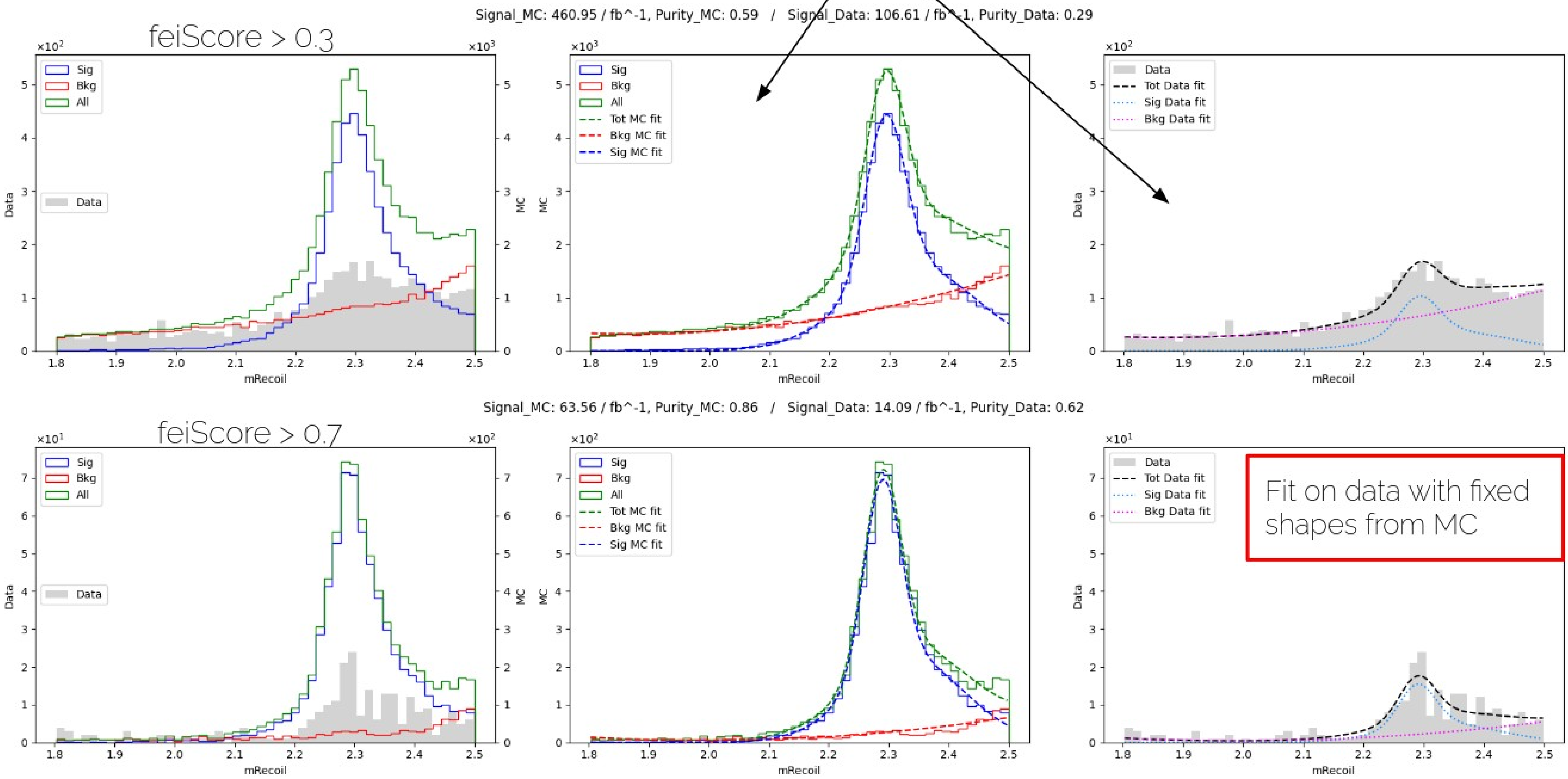
LambdaCTagExtra.addChannel(['Lambda_c+', 'pi+', 'pi-', 'pi0', 'gamma'])
LambdaCTagExtra.addChannel(['Lambda_c+', 'p+', 'anti-p-'])
LambdaCTagExtra.addChannel(['Lambda_c+', 'p+', 'anti-p-', 'pi0'])
```



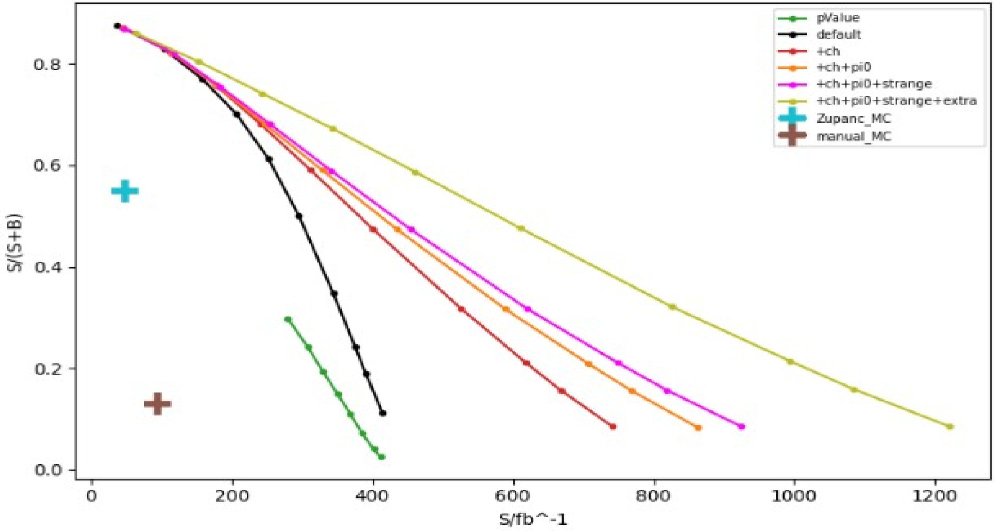
ccbarFEI: Data VS MC all modes

- MC15ri generic (validation 100 fb^{-1})
- 10 fb^{-1} Bucket37, 4S, rel-08-01-08, DB3224,

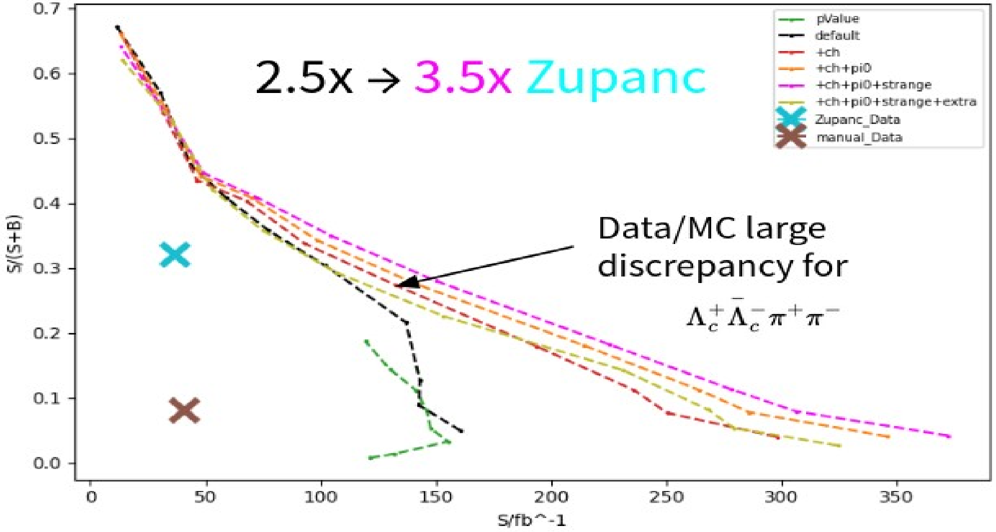


Comparison with ccbar tag reconstruction from previous measurements

MC



DATA



	Yield MC	Purity MC	Yield Data	Purity Data
Zupanc	48	55 %	36	33 %
Kristof	94	13 %	41	8 %
ccbarFEI > 0.2 > 0.5	 295 (455) 159 (183)	 50 (47) % 77 (75) %	 102 (150) 44 (50)	 30 (28) % 46 (45) %

→ there is ~ factor 4 difference in the inclusive Λ_c yield between data and MC

→ still yield is improved compared to Zupanc analysis for 2.5x using “simple” modes only, and 3.5x using more modes (at same purity)

Data / MC discrepancy

→ total number of Λ_c / fb-1 in ccbar MC agrees well with data

→ contributions from individual fragmentation modes can be vastly different
- training on more data like sample (calibrate MC to represent data better)

→ BDT input distributions for signal and backgrounds might differ greatly
- careful selection of BDTs input features (study data/mc discrepancies)

→ a lot of technical work has been done to have ccbarFEI in basf2, now it is time to focus on physics, data/mc understanding, optimizations etc.

→ **GREAT potential** for further significant improvements of performance in data
(in MC ccbarFEI inclusive yield is 10x larger than in Belle analyses!)

ccbarFEI present overall picture

→ **Goal**: have a tool that produces inclusive samples of charmed mesons and baryons and is available to anyone in a similar way as B meson FEI is!

→ **ccbarFEI** is already **fully part of basf2** since light-2507-europa

→ preliminary payloads with training weights are available for Λ_c and $D^{+,0}$ tags

→ usage is same as for FEI (find example steerings at /group/belle2/group/physics/FEI/kspenko/sandbox)

```
configuration = fei.config.FeiConfiguration(prefix='FEI_TEST', training=False, monitor=False)
feistate = fei.get_path(particles, configuration)
main.add_path(feistate.path)
```

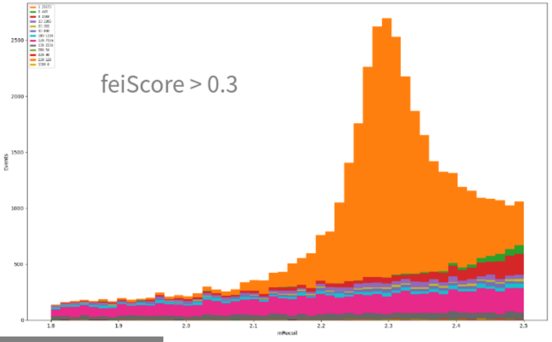
```
particles = get_ccbarLambdaC_channels(
        specific=False,
        addPi0=True,
        addCharged=True,
        addStrangness=True,
        usePIDNN=False)
```

```
for plist in ['Lambda_c+:ccbarTag', 'Lambda_c+:ccbarTagCharged', 'Lambd          ange', 'Lambd
    ma.matchMCTruth(plist, path=main)
    ma.variablesToNtuple(
        plist,
        variables=[
            'extraInfo(SignalProbability)',
            'extraInfo(decayModeID)',
            'daughterProductOf(extraInfo(SignalProbability))',
            'pValueCombinationOfDaughters(extraInfo(SignalProbability))',
            'ccbarTagSignal',
            'ccbarTagSignalSimplified',
            'ccbarTagEventStatus',
            'ccbarTagSignalBinary',
            'mRecoil'],
```

created tag lists

store tag side related variables

you can e.g. reproduce such plot easily



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Get in touch with us (Kristof, me) if you are interested in contributing to these efforts (kristof.spenko@ijs.si, luka.santelj@ijs.si)

```
configuration = fei.config.FeiConfiguration( …                                  …itor=False)
feistate = fei.get_path(particles, configuration)
main.add_path(feistate.path)
```

```
pa…
        sp…
        addPi0=Tru…
        addCharged=True,
        addStrangness=True,
        usePIDNN=False)
```

```
for plist in [ Lambda_c+:ccbarTag', 'Lambda_c+:ccbarTagCharged', 'Lambd
    ma.matchMCTruth(plist, path=main)
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            'ccbarTagSignal',
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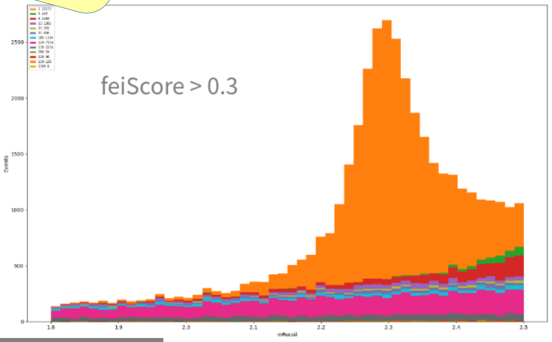
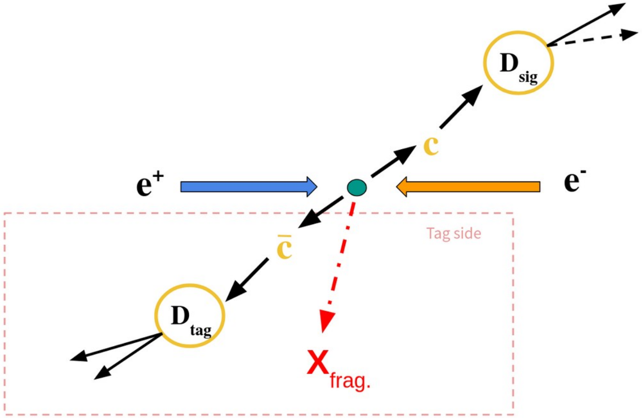


Conclusions



→charm tagging is wonderful technique that enables charm measurements to final states with missing energy and to measure absolute branching fractions

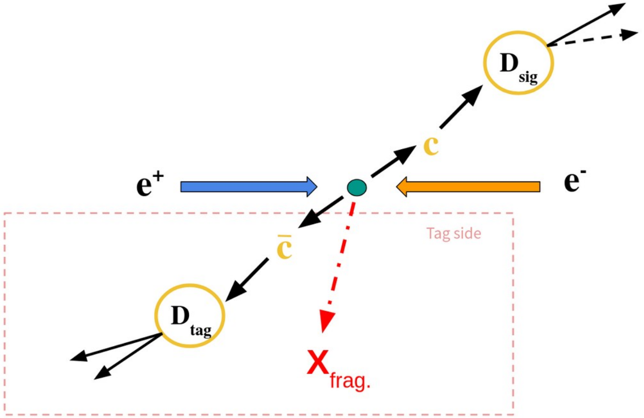
→successfully exploited @ Belle (but somehow under the radar @ Belle II so far)

→ with more and more data in hand it will become increasingly important to have a general charm tagger tool that is maintained and improved in collaboration wide effort (as FEI)

→ccbarFEI is a step in this direction, and it shows potential for big improvements in performance w.r.t. methods used at Belle

→ if interested in charm tagging please get in touch with ccbarFEI developers (kristof.spenko@ijs.si)

Conclusions



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→ccbarFEI is a step in this direction, and it shows potential for big improvements in performance w.r.t. methods used at Belle

→ if interested in charm tagging please get in touch with ccbarFEI developers

May I also give you one last bit of advice: Never say that you'll give a talk unless you know clearly what you're going to talk about and more or less what you're going to say.

(Feynman's commencement speech at Caltech (1974); it's a wonderful text, find it here)

Source	$K^-K^+\pi^+$ [%]	$\overline{K}^0K^+$ [%]	$\eta\pi^+$ [%]	$e^+\nu_e$ [%]	$\mu^+\nu_\mu$ [%]	$\tau^+\nu_\tau$ [%]
Normalization	±2.1	±2.1	±2.1	±2.1	±2.1	±2.1
Tag bias	±1.4	±1.4	±1.4	±1.4	±1.4	±1.4
Tracking	±1.1	±0.4	±0.4	±0.4	±0.4	±0.4
Particle ID	±2.6	±0.8	±1.1	±1.9	±2.0	±1.7
Efficiency	±0.7	±0.7	±1.4	±4.3	±1.8	±0.8
Dalitz model	±1.1	–	–	–	–	–
Fit model	±0.8	±0.8	±2.2	–	±0.2	$^{+3.3}_{-2.9}$
D_s^+ background	–	±0.6	±0.7	–	±0.8	±2.8
τ cross-feed	–	–	–	–	–	±0.9
$\mathcal{B}(\tau \to X)$	–	–	–	–	–	±0.2
Total syst.	±4.1	±2.9	±3.9	±5.4	±3.8	$^{+5.4}_{-5.2}$

Table 5. Summary of systematic uncertainties for the branching fraction measurements of D_s^+ decays. The total systematic error is calculated by summing the individual uncertainties in quadrature.

	Estimated background yields		
Background Source	$\tau^+(e^+)\nu_\tau$	$\tau^+(\mu^+)\nu_\tau$	$\tau^+(\pi^+)\nu_\tau$
$D_s^+ \to \eta\ell^+\nu_\ell$	911.0 ± 102.3	768.7 ± 86.4	–
$D_s^+ \to \eta'\ell^+\nu_\ell$	49.5 ± 12.0	35.1 ± 8.6	–
$D_s^+ \to \phi\ell^+\nu_\ell$	307.8 ± 20.7	188.0 ± 13.3	–
$D_s^+ \to \overline{K}^0\ell^+\nu_\ell$	242.6 ± 66.3	175.7 ± 48.1	–
$D_s^+ \to \overline{K}^{*0}\ell^+\nu_\ell$	26.0 ± 10.5	13.9 ± 5.8	–
$D_s^+ \to K\overline{K}\ell^+\nu_\ell$	59.2 ± 14.5	33.1 ± 8.0	–
$D_s^+ \to \mu^+\nu_\mu$	–	10.0 ± 1.4	26.2 ± 3.7
$D_s^+ \to \overline{K}^0 K^+$	18.5 ± 2.5	40.5 ± 4.9	132.3 ± 9.2
$D_s^+ \to \phi\pi^+$	11.2 ± 2.1	14.8 ± 2.5	–
$D_s^+ \to K^{*+}K^0$	32.4 ± 8.3	41.7 ± 10.6	–
$D_s^+ \to \eta\pi^+$	–	–	398.2 ± 24.2
$D_s^+ \to \rho^0 K^+$	–	–	185.1 ± 34.9