Charmingly Direct CPV

Charm Flavor Tagger - v1.0

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Intro

CPV in charm

$$A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

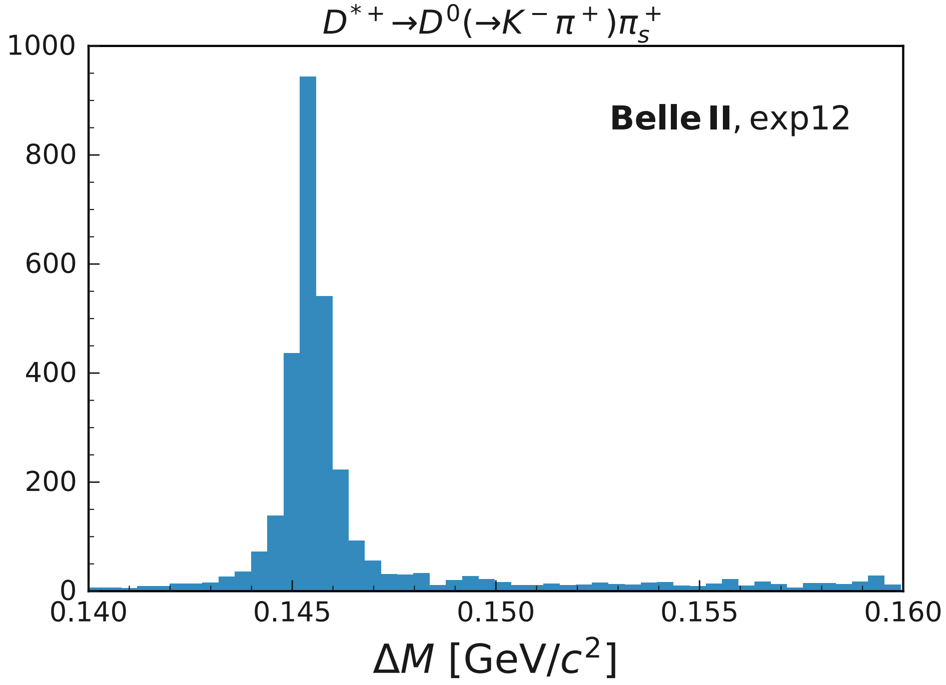
- CPV in charm is expected to be small and challenging to observe
  - effects are suppressed by $\mathcal{O}(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 0.1\,\%$
- direct CPV has been established in (LHCb, link):
  - $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-0.154 \pm 0.029)\,\%$
- while observed value is consistent with SM, challenges first principles calculations and raises the question whether the signal is due to NP
- recent measurement from LHCb indicates direct CP violation in $D^0 \to \pi^+\pi^-$at 3.8σ (link)
- particularly interested in complementary channels at Belle II
  - focus on $D^+ \to \pi^+\pi^0$, $D^0 \to \pi^0\pi^0$
- isospin sum rule relating all decays will provide further clarification

$$\boxed{R = \frac{A_{CP}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} - \frac{A_{CP}(D^+ \to \pi^+\pi^0)}{1 + \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}}$$

D* Tagging

slow pion: $M(D^{*+}) - M(D^0) \approx 145\,\mathrm{MeV}/c^2$

- main ingredient is to determine the D^0 flavor at time of production
- standard approach: reconstruct strong decay $D^{*+} \to D^0 \pi_s^+$, where charge of "slow" pion determines flavor
- major drawbacks:
  - inefficient reconstruction of slow=low momentum pion
  - loss in statistics (only ~25% of all charm quarks hadronize into $D*$)

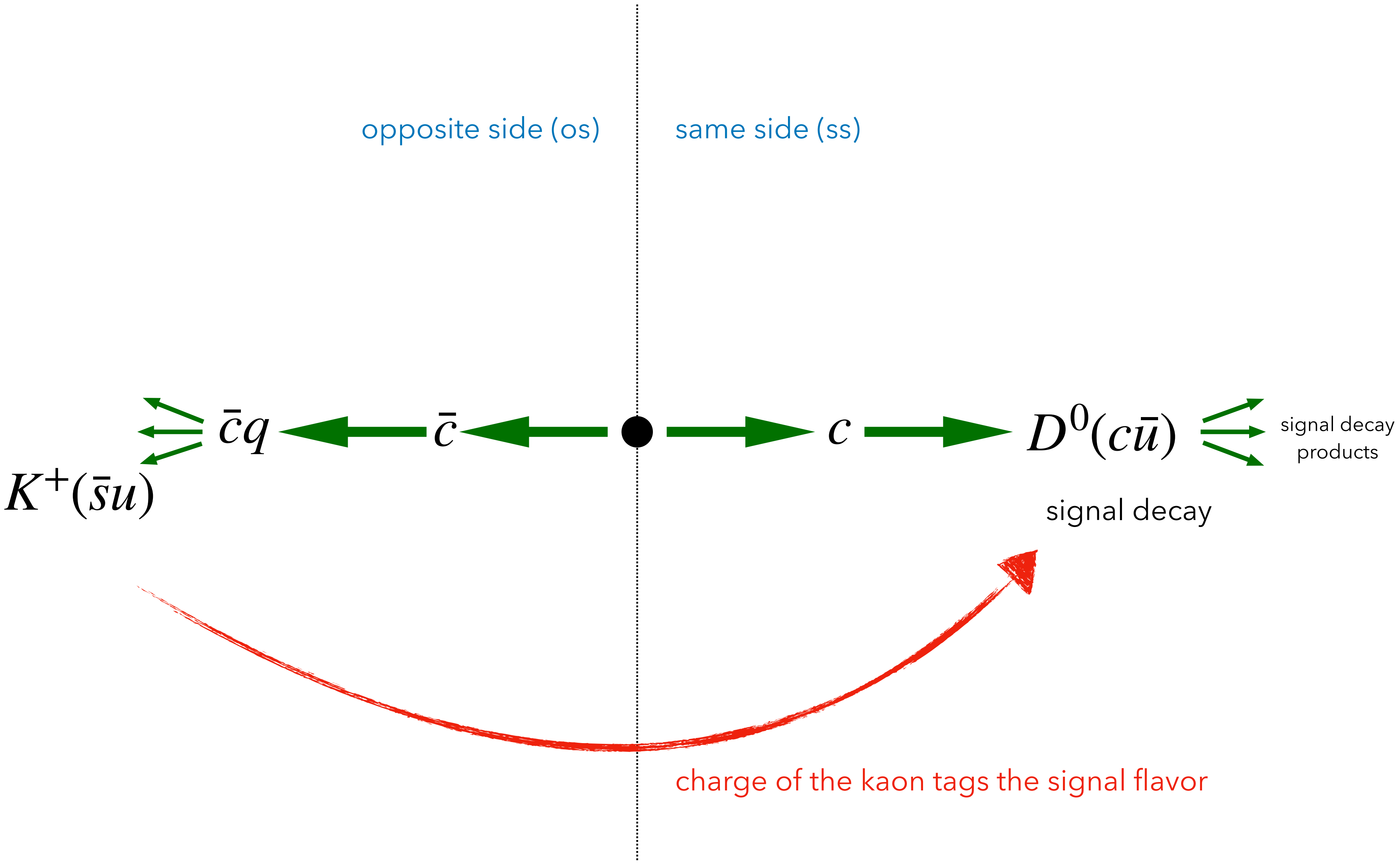


The ROE Flavor Tag

- perform flavor tag with information from the rest of the event (ROE)
- ROE : every track and cluster not related to signal decay
- inclusive approach in which single tracks are reconstructed in the ROE and their charge provides the tag
- this approach could
  - compensate loss in statistics of D* tag,
  - reduce combinatorial background (charged mesons)
- inspired by:
  - ROE method for flavor tagging (by Giulia and Giacomo, link)
  - B-flavor tagging algorithms at Belle II (category-based and deep-learning tagger, link)

The Tagger

The tagging principle



opposite side (os)

same side (ss)

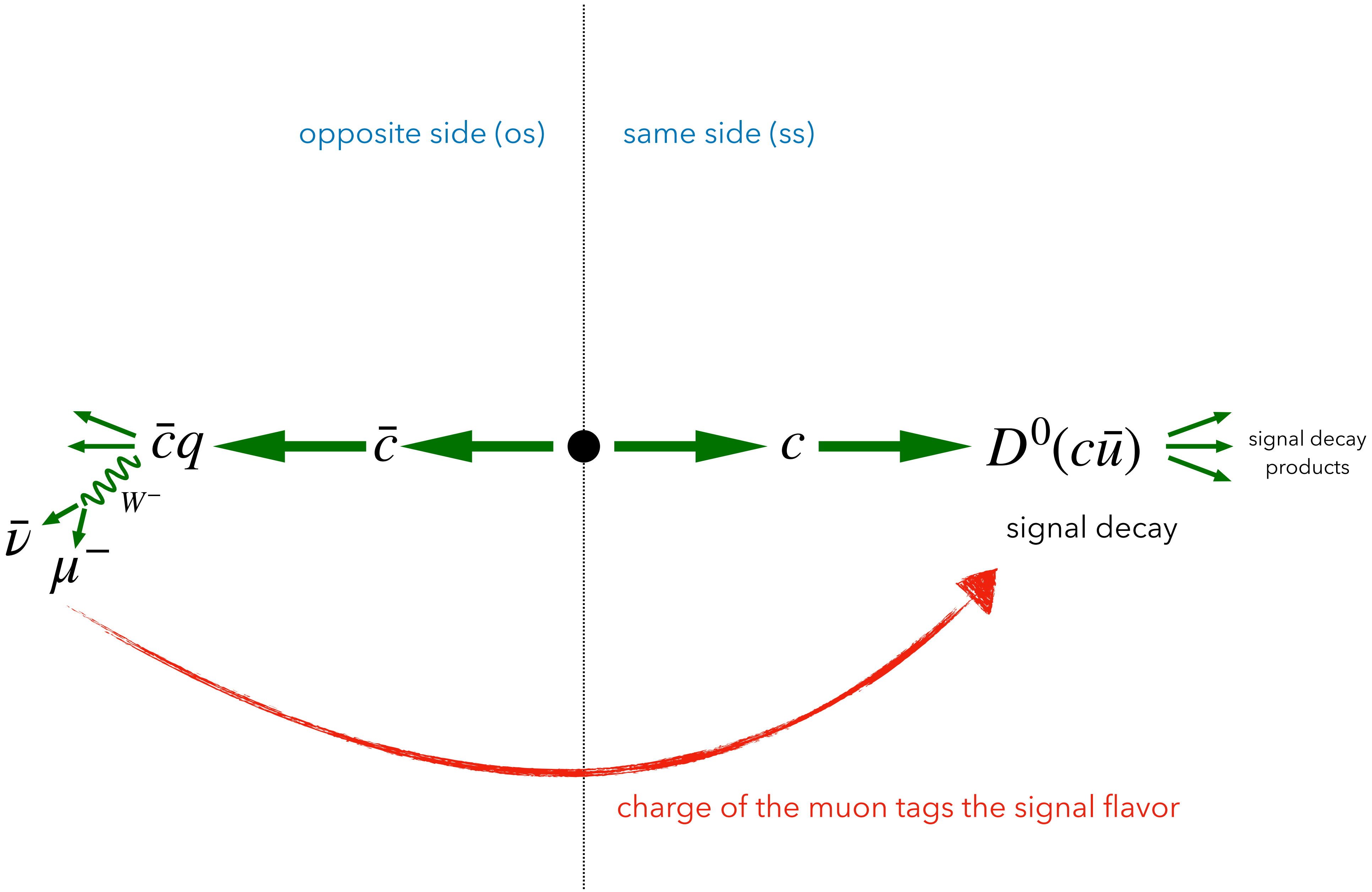
$K^+(\bar{s}u)$ $\bar{c}q$ $\bar{c}$ c $D^0(c\bar{u})$

signal decay products

signal decay

charge of the kaon tags the signal flavor

The tagging principle



opposite side (os)

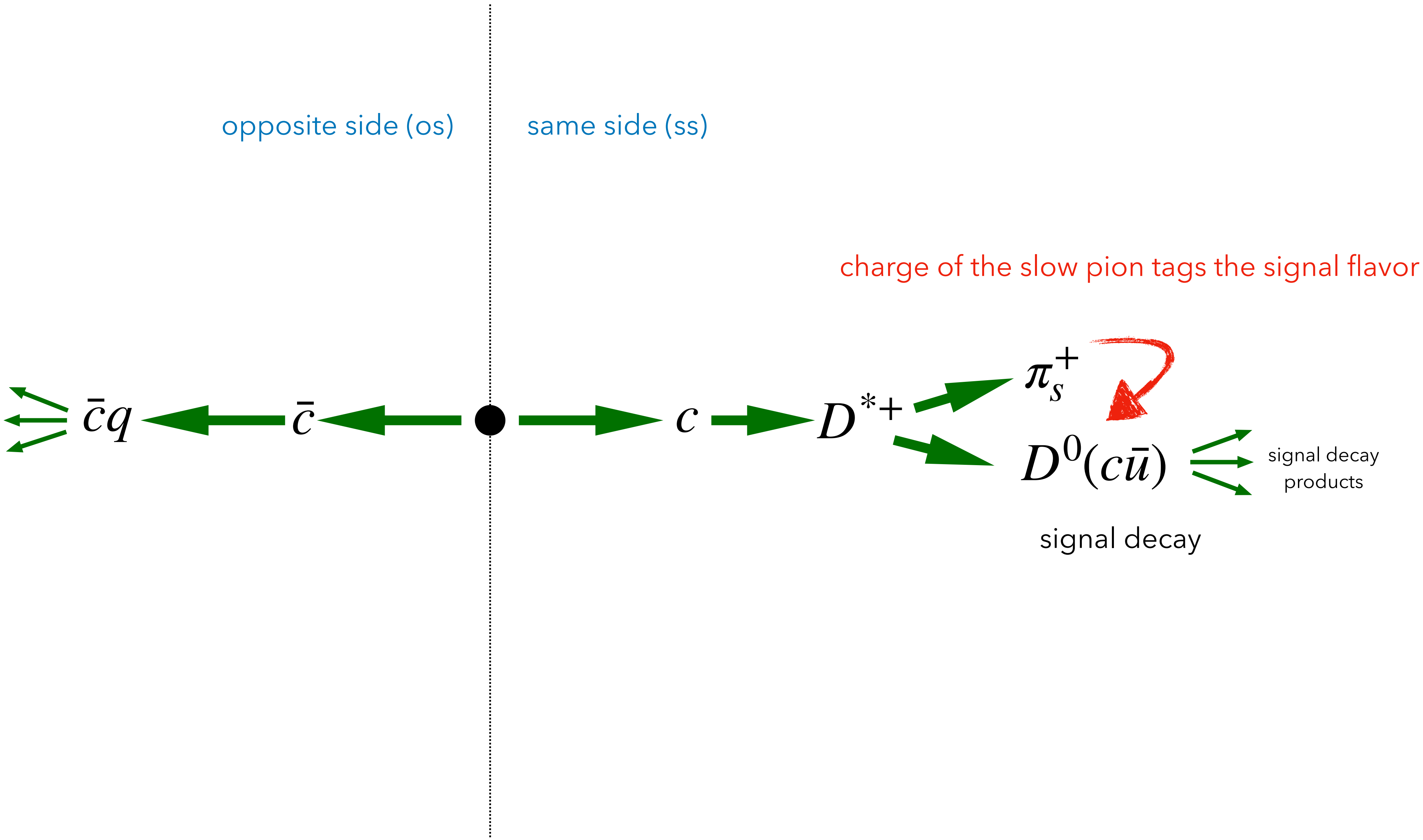
same side (ss)

signal decay products

signal decay

charge of the muon tags the signal flavor

The tagging principle



opposite side (os)

same side (ss)

charge of the slow pion tags the signal flavor

signal decay

Samples and Reconstruction

- samples used (light-2205-abys)
  - MC15ri_a
    - charged,mixed,qqbar (1 ab^{-1})
  - proc13-chunk2 (exp12)
    - 54.6 fb^{-1}
- signal reconstruction of $D^0 \to K^-\pi^+$ cand.:
  - K, π: thetainCDCAcceptance, dr<1cm, |dz|<3cm, globalPID>0.5
  - D^0: 1.78<InvM<1.92, p*>2.0
- ROE reconstruction:
  - all track candidates with: dr<1cm, |dz|<3cm

The algorithm

Step 1: reconstruct ROE candidates for every signal D0 candidate

event_1	D0_cand_1	ROE_cand_1 ROE_cand_2 ROE_cand_3 ROE_cand_4 …
	D0_cand_2	ROE_cand_1 ROE_cand_2 ROE_cand_3 ROE_cand_4 …
	…	…
event_2	…	…

The algorithm

Step 2: split ROE list by candidate charge

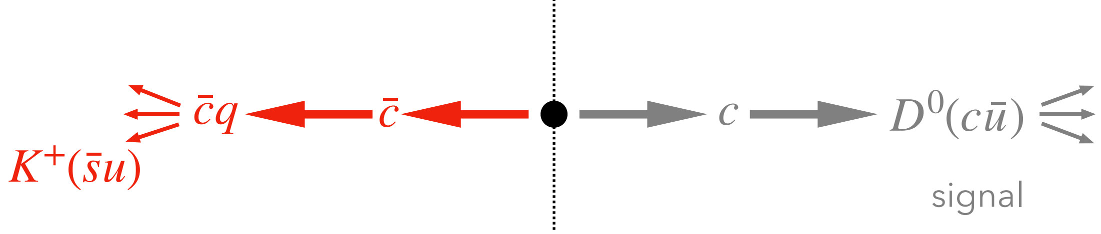
event_1	D0_cand_1	ROE_cand_1_p ROE_cand_2_p …	ROE_cand_1_n ROE_cand_2_n …
	D0_cand_2	ROE_cand_1_p ROE_cand_2_p …	ROE_cand_1_n ROE_cand_2_n …
	…	…	…
event_2	…	…	…

The algorithm

Step 3: rank ROE lists by opening angle (between D^0 and ROE cand.) and keep first three candidates per charge (6 tracks in total)

event_1	D0_cand_1	ROE_rank_1_p ROE_rank_2_p ROE_rank_3_p	ROE_rank_1_n ROE_rank_2_n ROE_rank_3_n
	D0_cand_2	ROE_rank_1_p ROE_rank_2_p ROE_rank_3_p	ROE_rank_1_n ROE_rank_2_n ROE_rank_3_n
	…	…	…
event_2	…	…	…

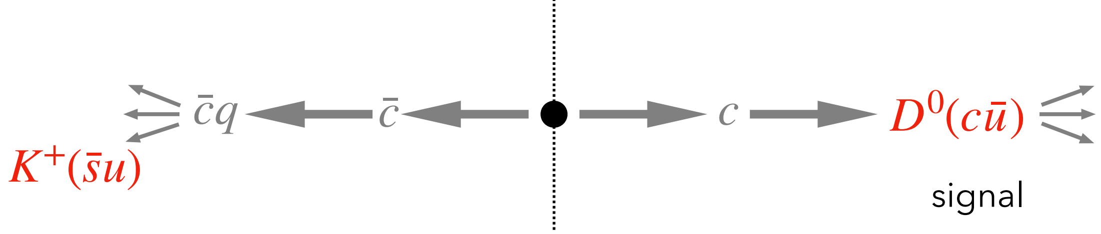
The algorithm



Step 4a: assign ROE candidate tracks into tag categories with generator information

tag category	requirements		
	track hypothesis	allowed parent	or grandparent
Kaon tag	K	$D^0, D^+, D_s^+, \Lambda_c^+$	$D^0, D^+, D_s^+, \Lambda_c^+$
Slow pion (ss)	π	D^{*+}	/
Slow pion (os)	π	D^{*+}	/
Muon tag	μ	$D^0, D^+, D_s^+, \Lambda_c^+$	$D^0, D^+, D_s^+, \Lambda_c^+, D^{*+}$
Electron tag	e	$D^0, D^+, D_s^+, \Lambda_c^+$	$D^0, D^+, D_s^+, \Lambda_c^+, D^{*+}$
Proton tag	p	$\Lambda_c^+, \Sigma_c^{++}, \Sigma_c^+, \Sigma_c^0, \Sigma_c^{*++}, \Sigma_c^{*+}, \Sigma_c^{*0}, \Xi_c^+, \Xi_c^0$	$\Lambda_c^+, \Sigma_c^{++}, \Sigma_c^+, \Sigma_c^0, \Sigma_c^{*++}, \Sigma_c^{*+}, \Sigma_c^{*0}, \Xi_c^+, \Xi_c^0$
Generic tag	/	$D^0, D^+, D_s^+, \Lambda_c^+$	$D^0, D^+, D_s^+, \Lambda_c^+$

The algorithm



Step 4b: check charge correlation and assign ROE tag charge (=q)

Signal	Tag particles	
	same side	opposite side
D^0	π_s^+	$K^+, \mu^-, e^-, \pi_s^-, \bar{p}$
$\bar{D}^0$	π_s^-	$K^-, \mu^+, e^+, \pi_s^+, p$

if at least one of 6 tracks fulfills this criteria

Signal	**q**
D^0	1
anti-D^0	-1
no tag	0

Training details

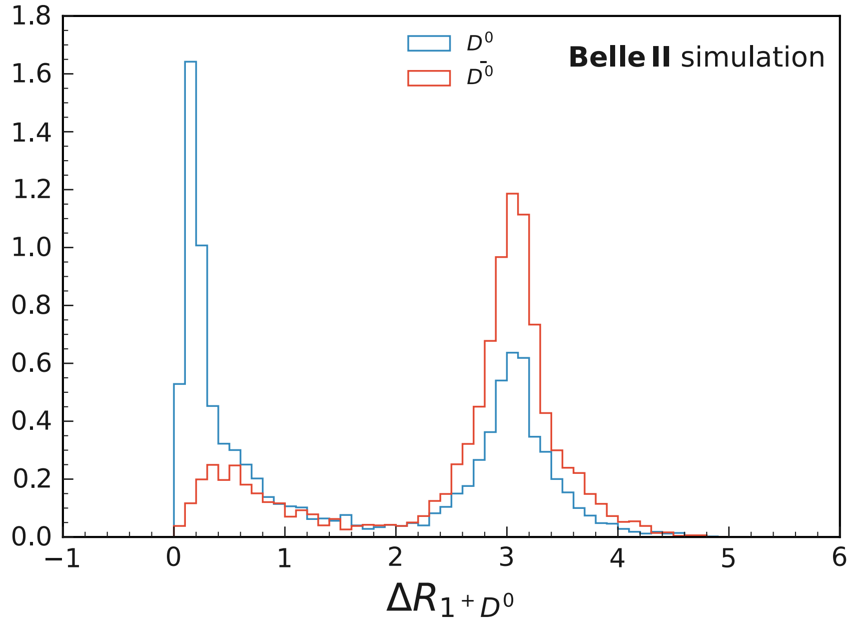
- use $D^0 \rightarrow K^- \pi^+$ events (340k)
- label events by determining q
    - -1:anti-D^0 (34%), 1:D^0 (35%), 0:no tag (31%)
- train on events with $|q|>0$
- sample size: 240k events (180k for training, 60k for testing)
- BDT from sklearn library (HistGradientBoostingClassifer)

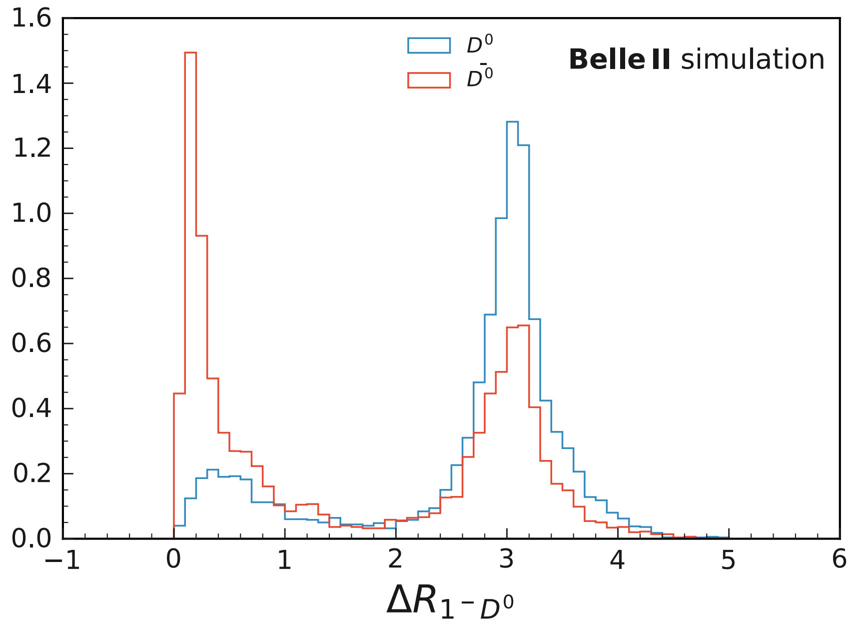
BDT features

event variables	$\#\text{Kaons}_{\text{ROE}}$	
ROE candidate variables	kaonID	for each of the 6 ROE candidates
	mRecoil (only for $1^\pm$ cand.)	
	$\Delta R(i, D^0)$	

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

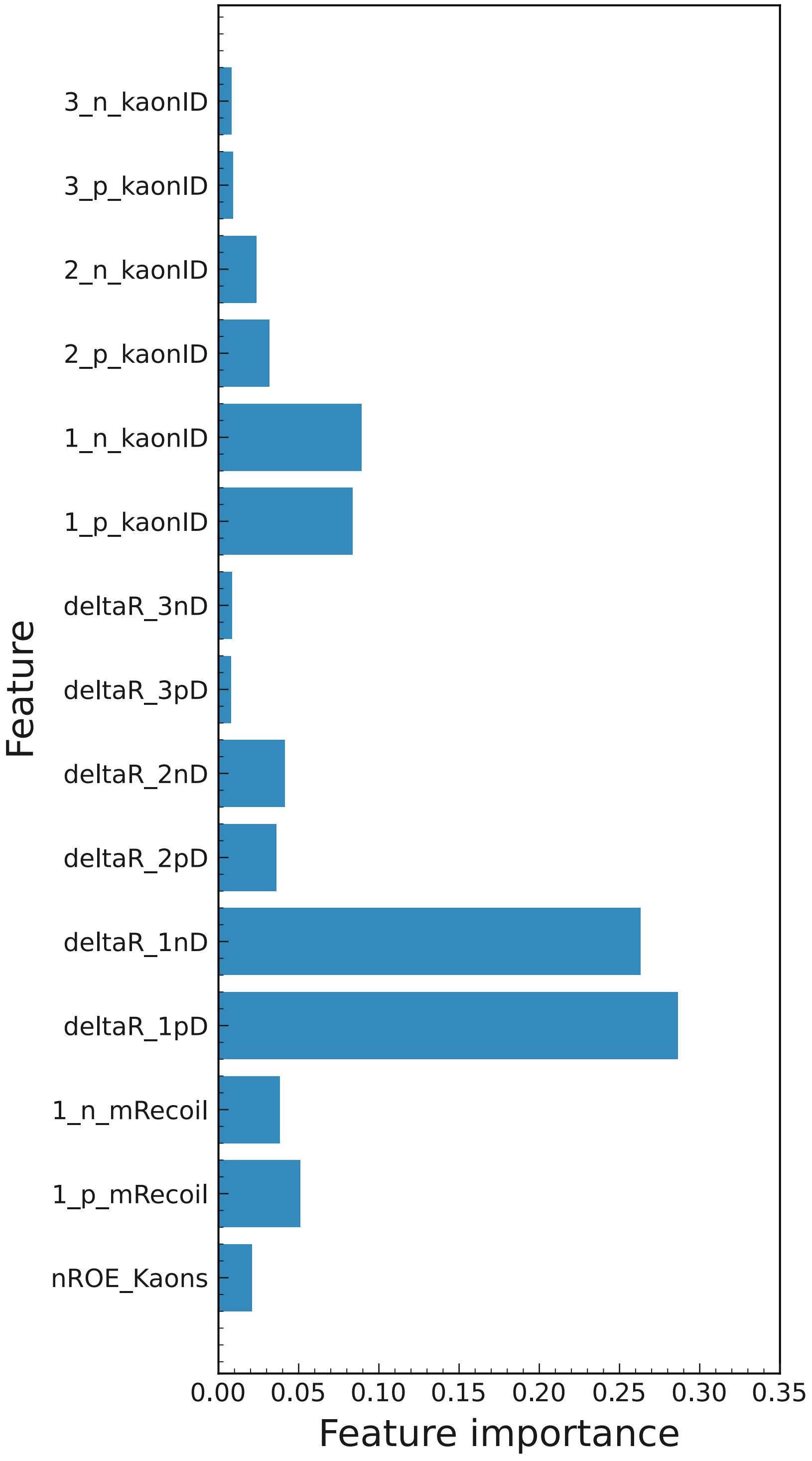
$$\text{kaonID} = \frac{\mathscr{L}_K}{\mathscr{L}_K + \mathscr{L}_\pi + \mathscr{L}_e + \mathscr{L}_\mu + \mathscr{L}_p + \mathscr{L}_d}$$

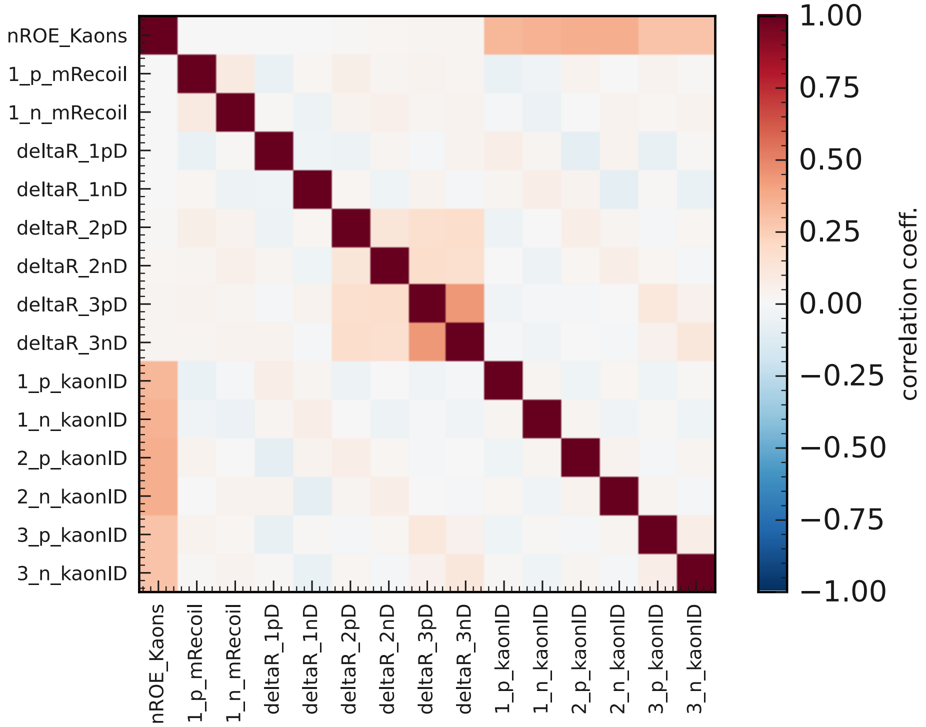




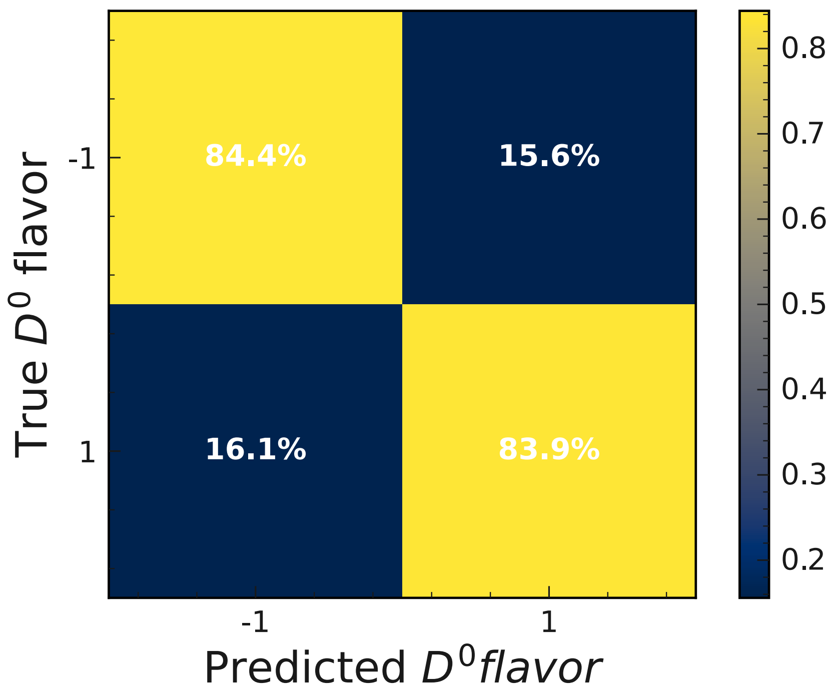
BDT performance

BDT performance





Confusion matrix for test set



BDT performance on test sample	**D0**	**anti-D0**
precision	85%	84%
recall	84%	84%
accuracy	84%	
accuracy (train sample)	85%	

$$\text{recall}=\text{sensitivity}=\frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FN}}$$

$$\text{precision}=\frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FP}}$$

Evaluation

Tagging metrics and BDT output

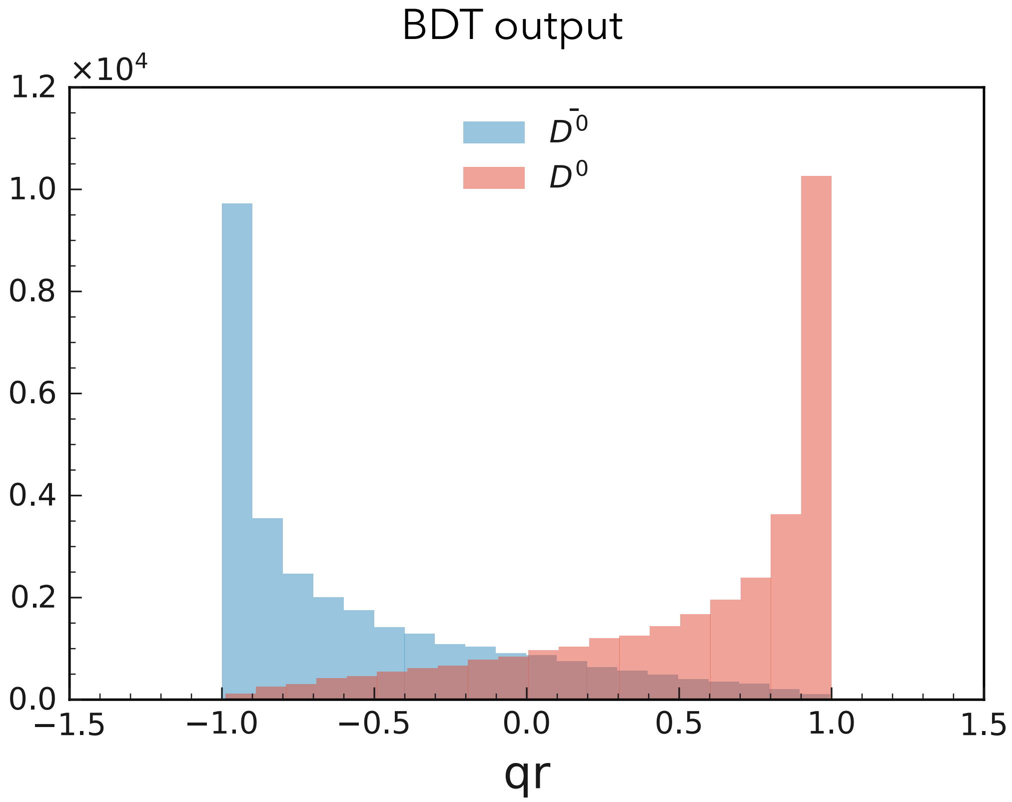
tagging efficiency: $\epsilon_{tag} = \frac{R+W}{R+W+U}$

mistag fraction: $\omega = \frac{W}{R+W}$

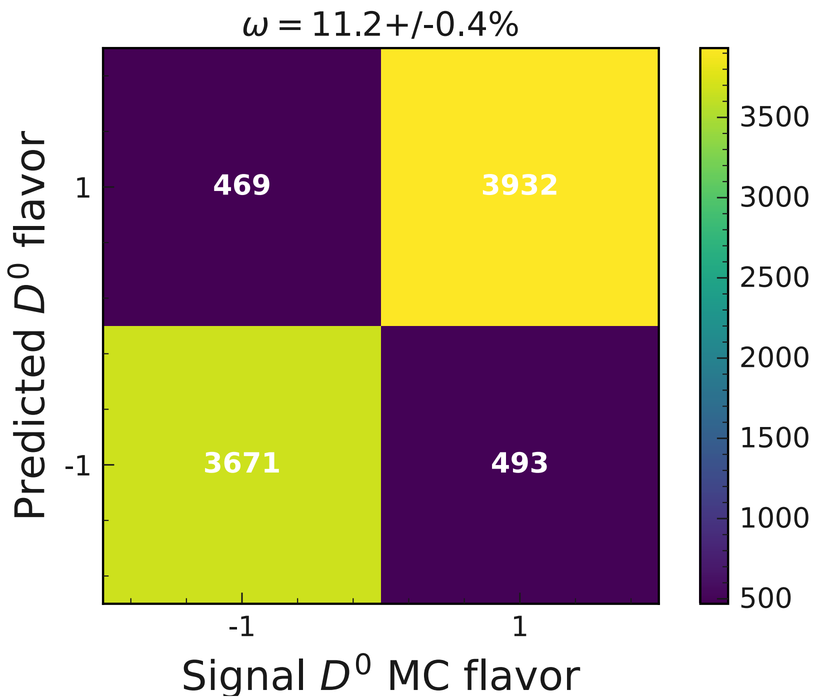
dilution: $r = |1-2\omega|$

tagging power: $\epsilon_{eff} = \epsilon_{tag}(1-2\omega)^2$

R (W), U: rightly (wrongly) tagged, untagged D^0 candidates



Tagging power (MC and data)



|qr|>0.4

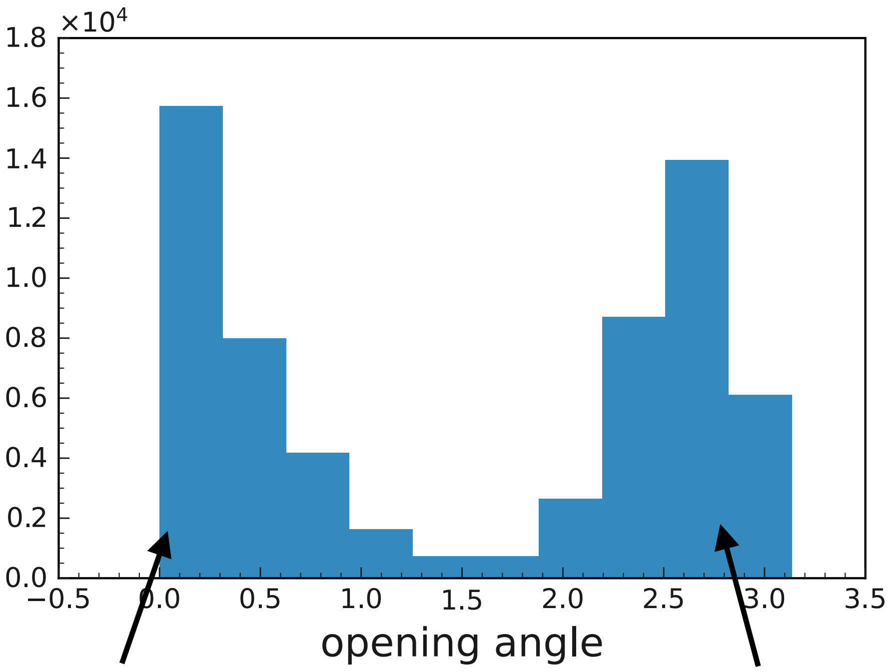
Sample ($D^0 \to K^- \pi^+$)	signal yield	tagging efficiency	mistag fraction	tagging power
MC15	11,700±100	73±1%	11.2±0.4%	44±1%
exp12(proc13)	12,900±100	72±1%	12.5±0.4%	40±1%

Conclusion

- first working version of the Charm Tagger looks promising
- available data set can be increased by 50% w.r.t to only using D^* tag
- open tasks:
  - explore different features
  - use $D^0 \rightarrow$invisible training sample
  - evaluate on different final states

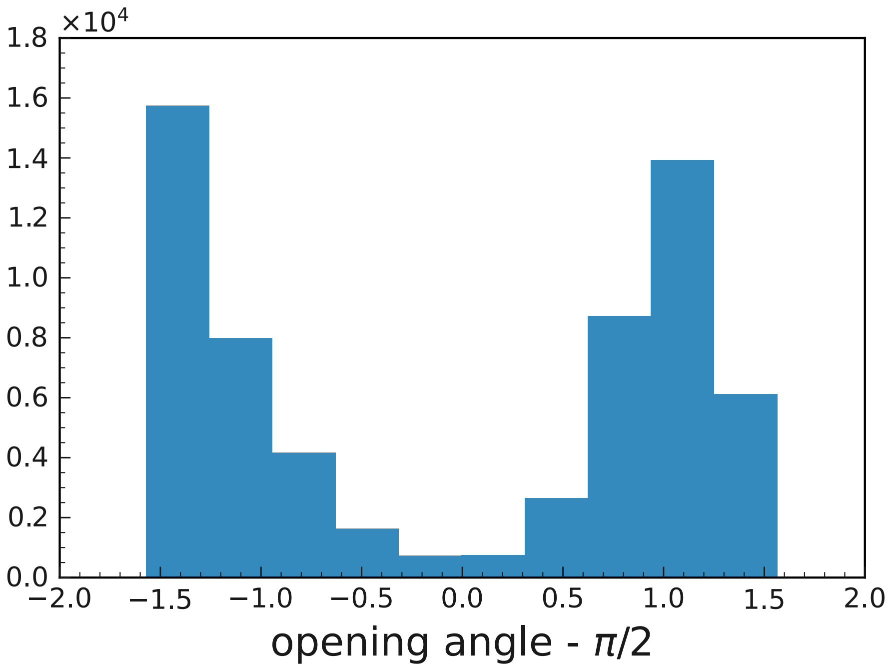
Backup

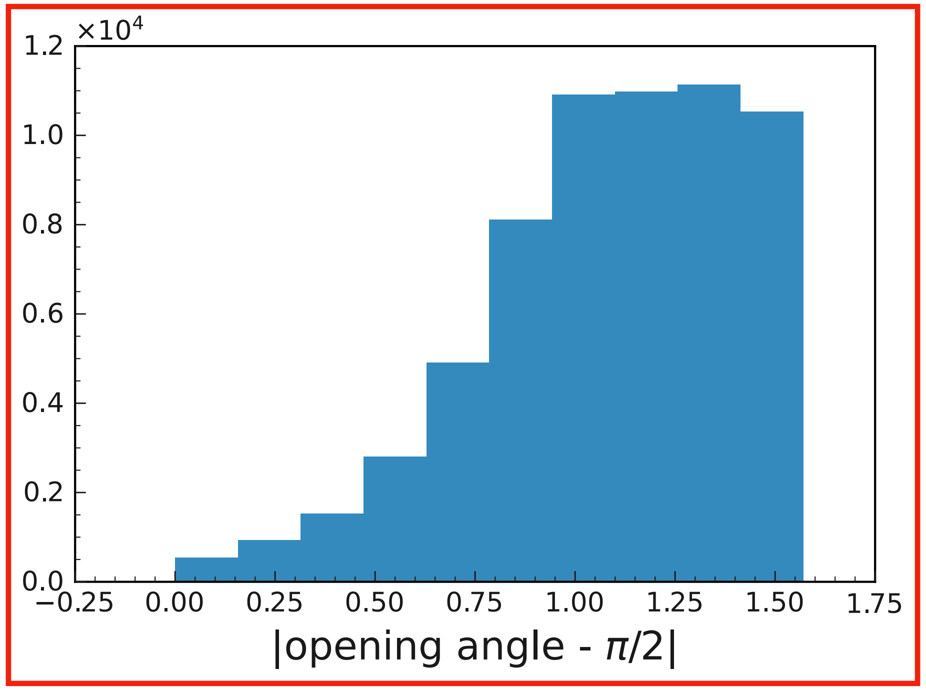
Intermezzo : ranking variable



slow pions from same side

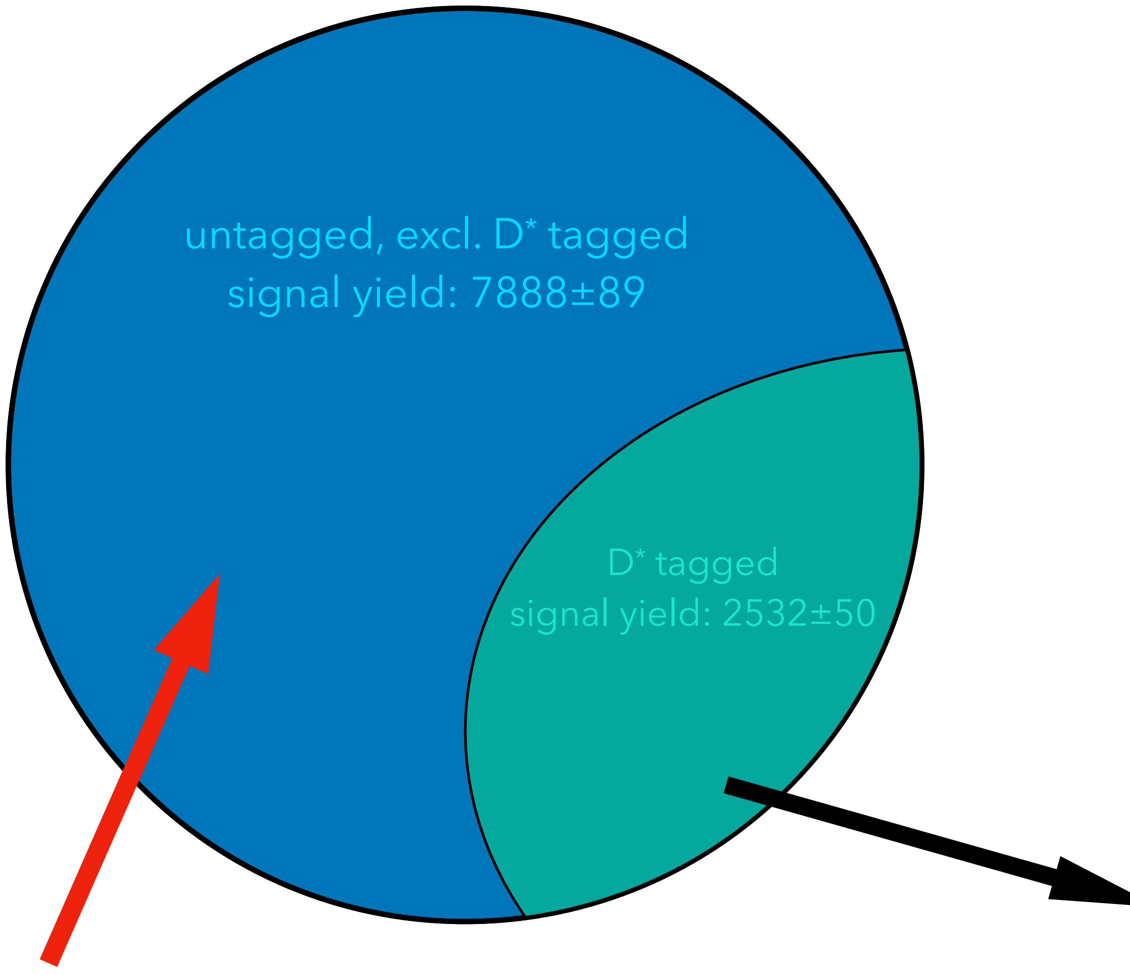
kaons, muons from opposite side





How much does it add?

untagged $D^0 \to K\pi$ sample
signal yield: 10383±102

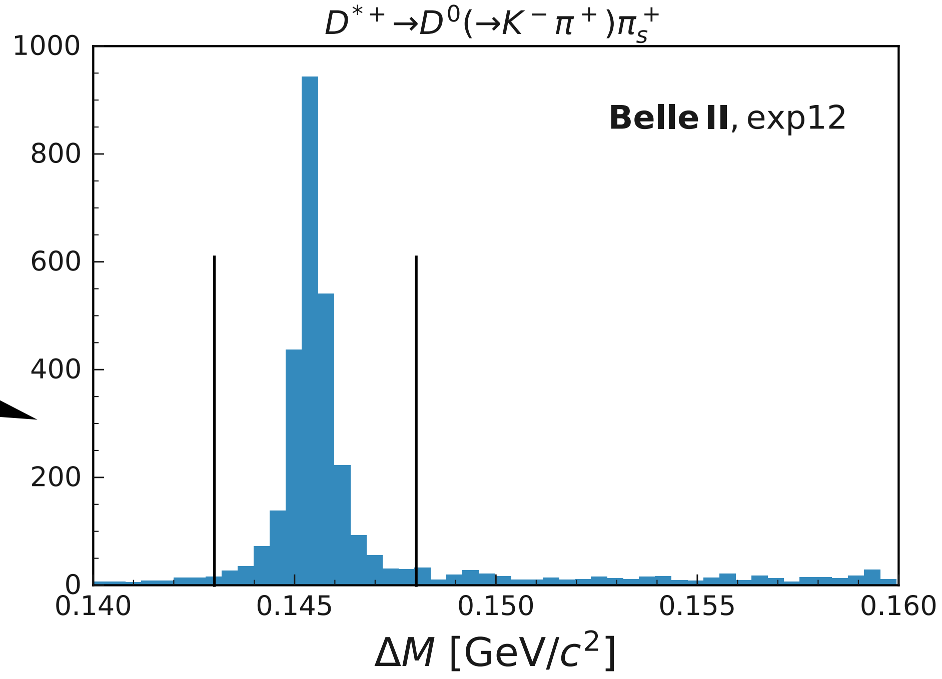


untagged, excl. D^* tagged
signal yield: 7888±89

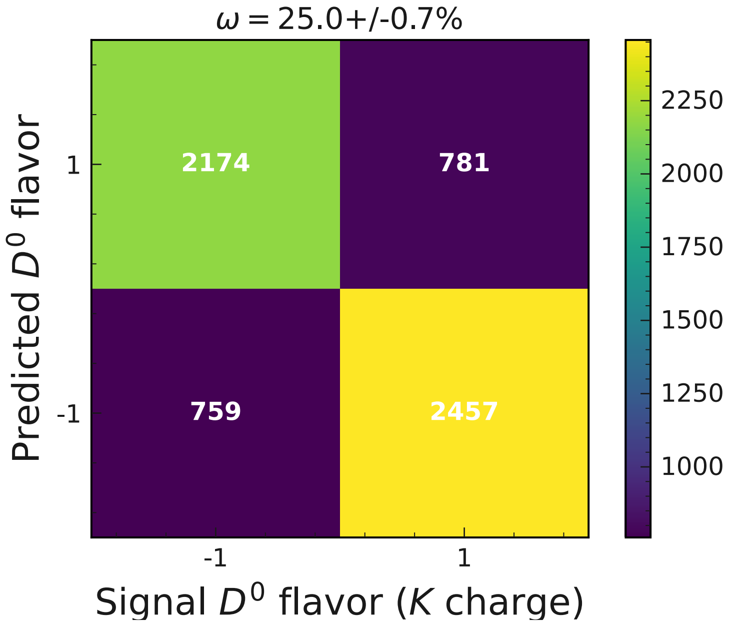
D^* tagged
signal yield: 2532±50

How much of this can we tag?

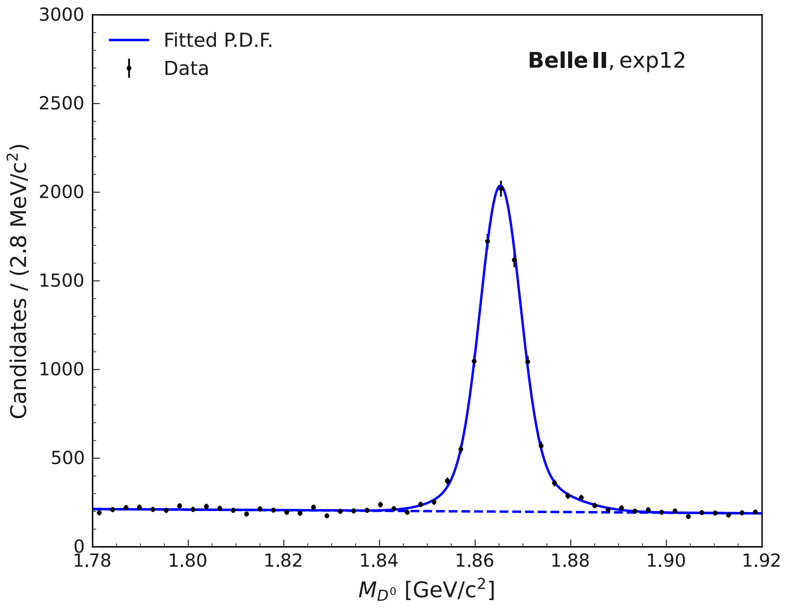
D^* selection:
$0.143<\Delta M<0.148$
globalPID>0.9 for D^0 daughters



Performance in exp12 data (without D* tag)

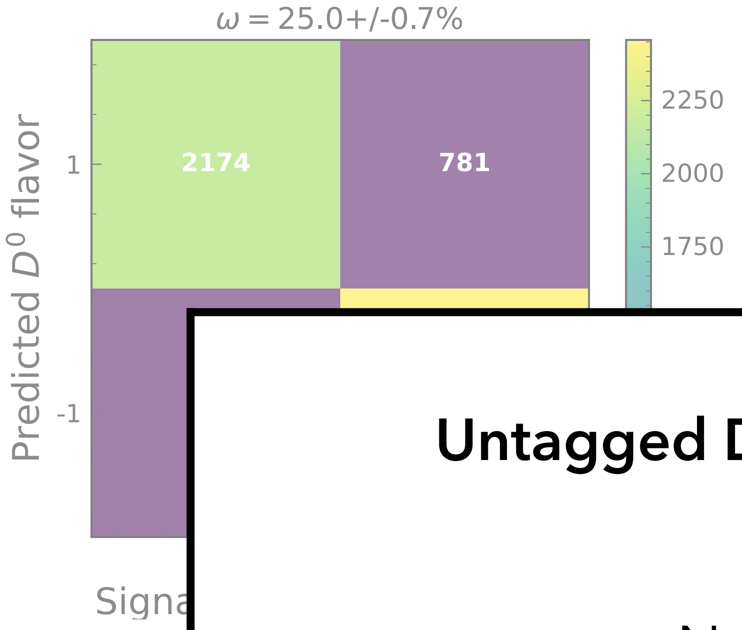


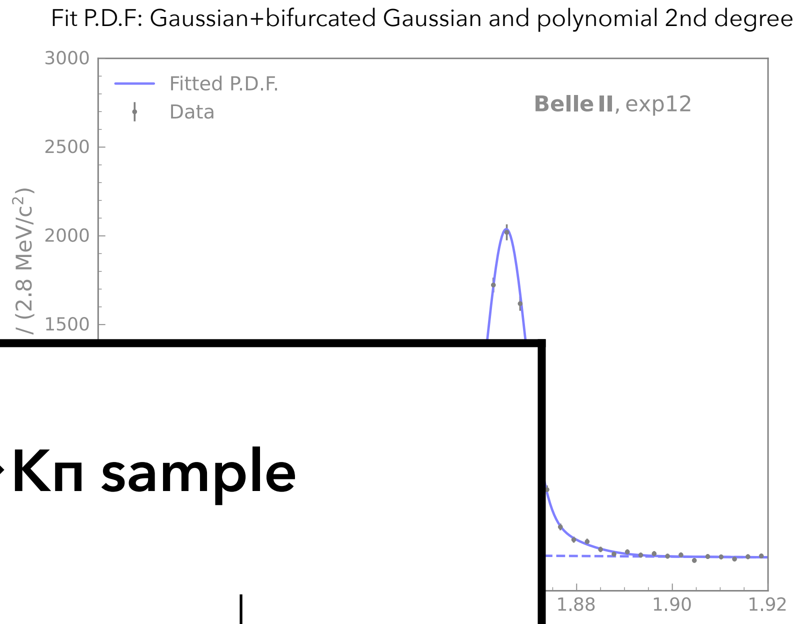
Fit P.D.F: Gaussian+bifurcated Gaussian and polynomial 2nd degree



- validate on exp12 data:
  - select events with globalPID>0.9 for D^0 daughters
  - exclude events from D* tagged sample
  - apply BDT
  - evaluate for sweighted D^0,
    - signal yield: 7888±89
    - 78.2±1.3% tagging efficiency
    - mistag fraction:25.0±0.7% (24.1±0.8% and 25.9±0.8% for D^0, anti-D^0 resp.)
    - tagging power: **19.6±1.1%**

Performance in exp12 data (without D* tag)



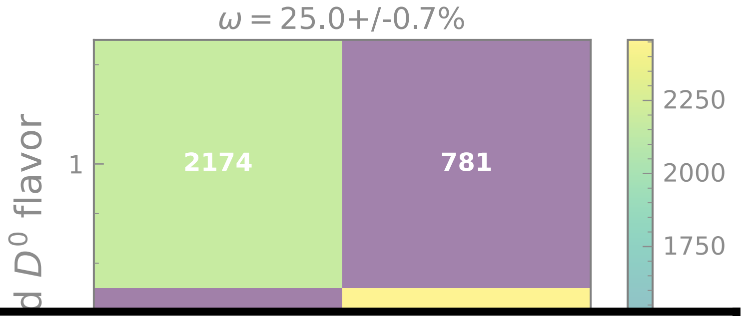

Fit P.D.F: Gaussian+bifurcated Gaussian and polynomial 2nd degree

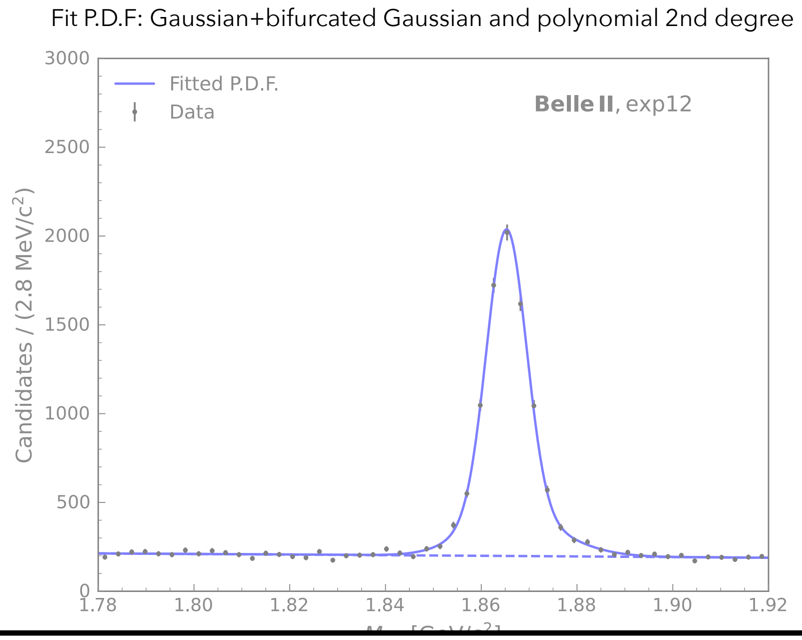
- validate on
  - select e
  - exclude
  - apply B
  - evaluate
    - sign
    - 78.2
    - mis $-D^0$ resp.)
    - tag

Untagged D0→Kπ sample

		D* tag	
		No Tag	Tag
Charm Flavor Tagger	No Tag	6342	278
	Tag	1546	2254

Performance in exp12 data (without D^* tag)





Untagged D0→Kπ sample

		D^* tag	
		No Tag	Tag
Charm Flavor Tagger	No Tag	6342	278
	Tag	1546	2254

In the untagged D^0 sample:

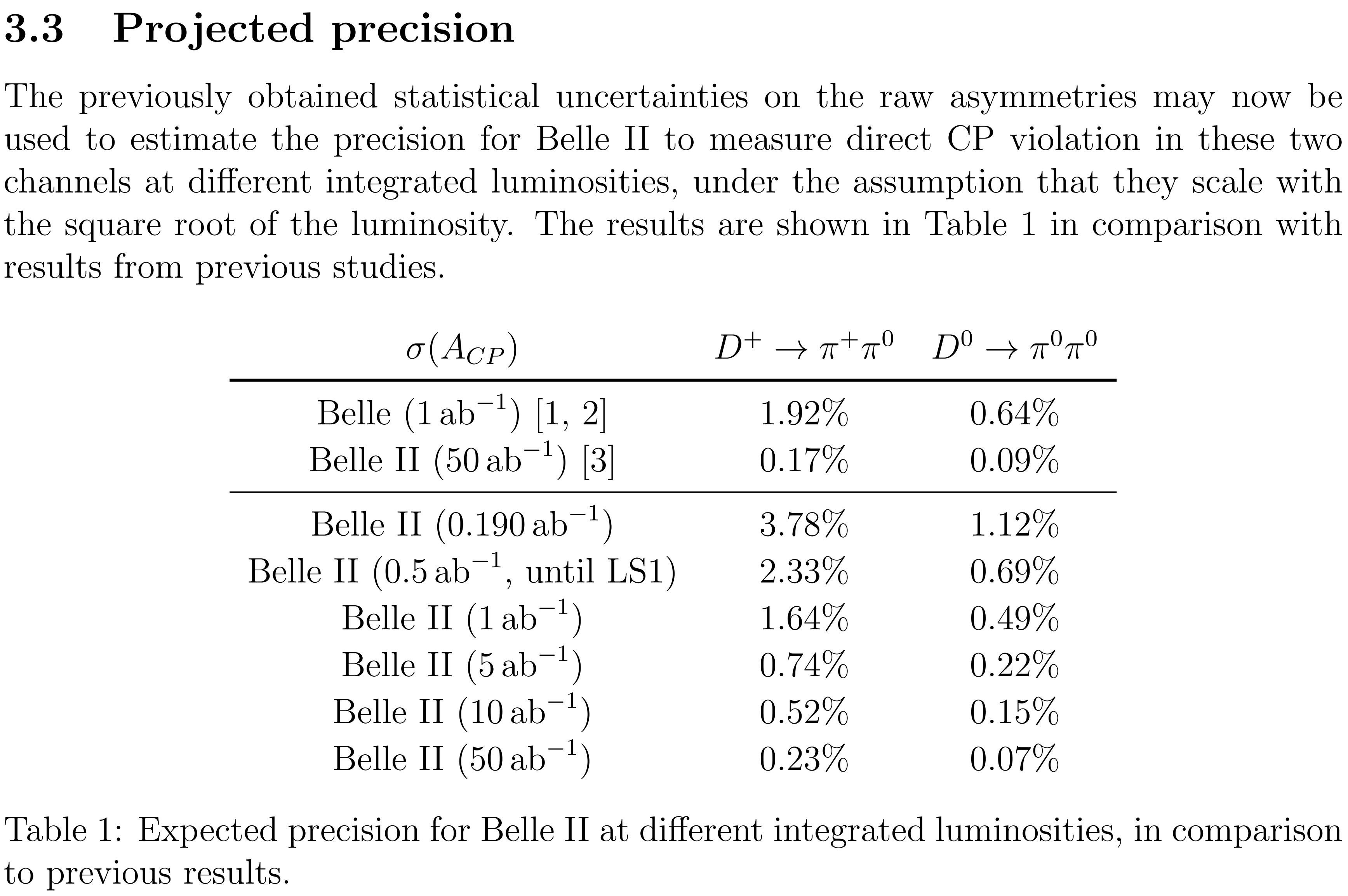
D^* tag: 2532

Charm Flavor Tagger: 3800

→**50% increase of the data sample**

±0.8% and 25.9±0.8% for D^0, anti-D^0 resp.)

Acp predictions



3.3 Projected precision

The previously obtained statistical uncertainties on the raw asymmetries may now be used to estimate the precision for Belle II to measure direct CP violation in these two channels at different integrated luminosities, under the assumption that they scale with the square root of the luminosity. The results are shown in Table 1 in comparison with results from previous studies.

$\sigma(A_{CP})$	$D^+ \to \pi^+\pi^0$	$D^0 \to \pi^0\pi^0$
Belle ($1\,\mathrm{ab}^{-1}$) [1, 2]	1.92%	0.64%
Belle II ($50\,\mathrm{ab}^{-1}$) [3]	0.17%	0.09%
Belle II ($0.190\,\mathrm{ab}^{-1}$)	3.78%	1.12%
Belle II ($0.5\,\mathrm{ab}^{-1}$, until LS1)	2.33%	0.69%
Belle II ($1\,\mathrm{ab}^{-1}$)	1.64%	0.49%
Belle II ($5\,\mathrm{ab}^{-1}$)	0.74%	0.22%
Belle II ($10\,\mathrm{ab}^{-1}$)	0.52%	0.15%
Belle II ($50\,\mathrm{ab}^{-1}$)	0.23%	0.07%

Table 1: Expected precision for Belle II at different integrated luminosities, in comparison to previous results.