FEASABILITY STUDY OF $D^0 \rightarrow \pi^+\pi^-\nu\bar{\nu}$ AT THE FCC-ee

TABEA HACHENEY[1], DOMINIK MITZEL[1], LARS RÖHRIG[1,2], STÉPHANE MONTEIL[2], ANGELO DI CANTO[3], MICHEL BERTEMES[4]

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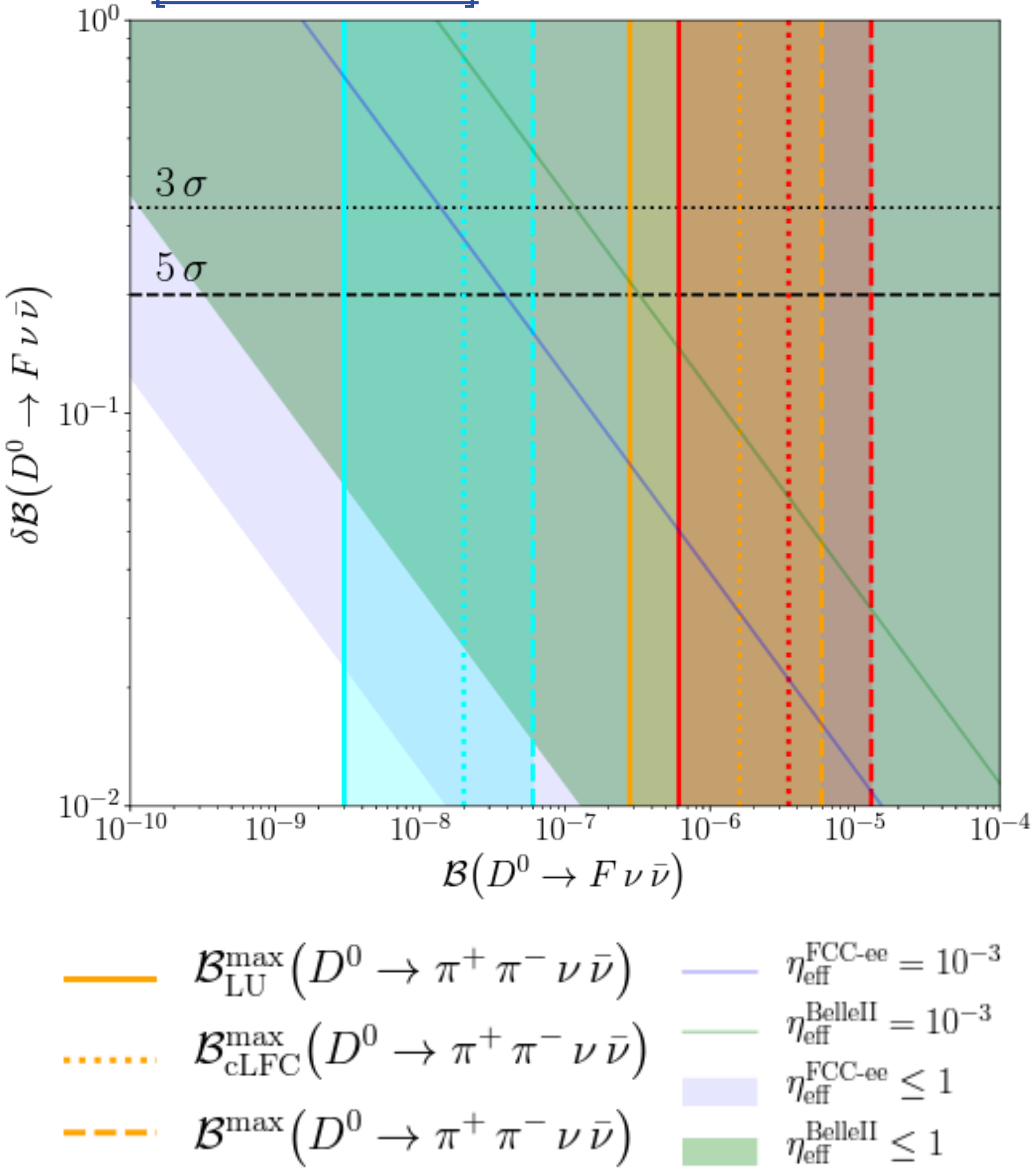
[1]Department of Physics - TU Dortmund University
[2]Laboratoire de Physique de Clermont - Université Clermont-Auvergne
[3]Physics Department - Brookhaven National Laboratory
[4]HEPHY - Austrian Academy of Sciences

tabea.hacheney@tu-dortmund.de

MOTIVATION

- $\mathscr{B}_{SM}\left(D^0 \to \pi^+\pi^-\nu\bar{\nu}\right)$ below experimental sensitivity → null test
  - Large enhancements possible for NP, with size depending on charged lepton flavor structure
- Recent interest in measurement of $B^+ \to K^+\nu\bar{\nu}$ [2311.14647]
- Existing study for $b \to s\nu\bar{\nu}$ at FCC-ee [2309.11353]
- **Goal**: sensitivity estimate at FCC-ee for a given number of Z events

[2010.02225]



tabea.hacheney@tu-dortmund.de

OVERVIEW

Signal and background datasets

Candidate reconstruction

Overview on most relevant variables

BDT ∧ Preselection

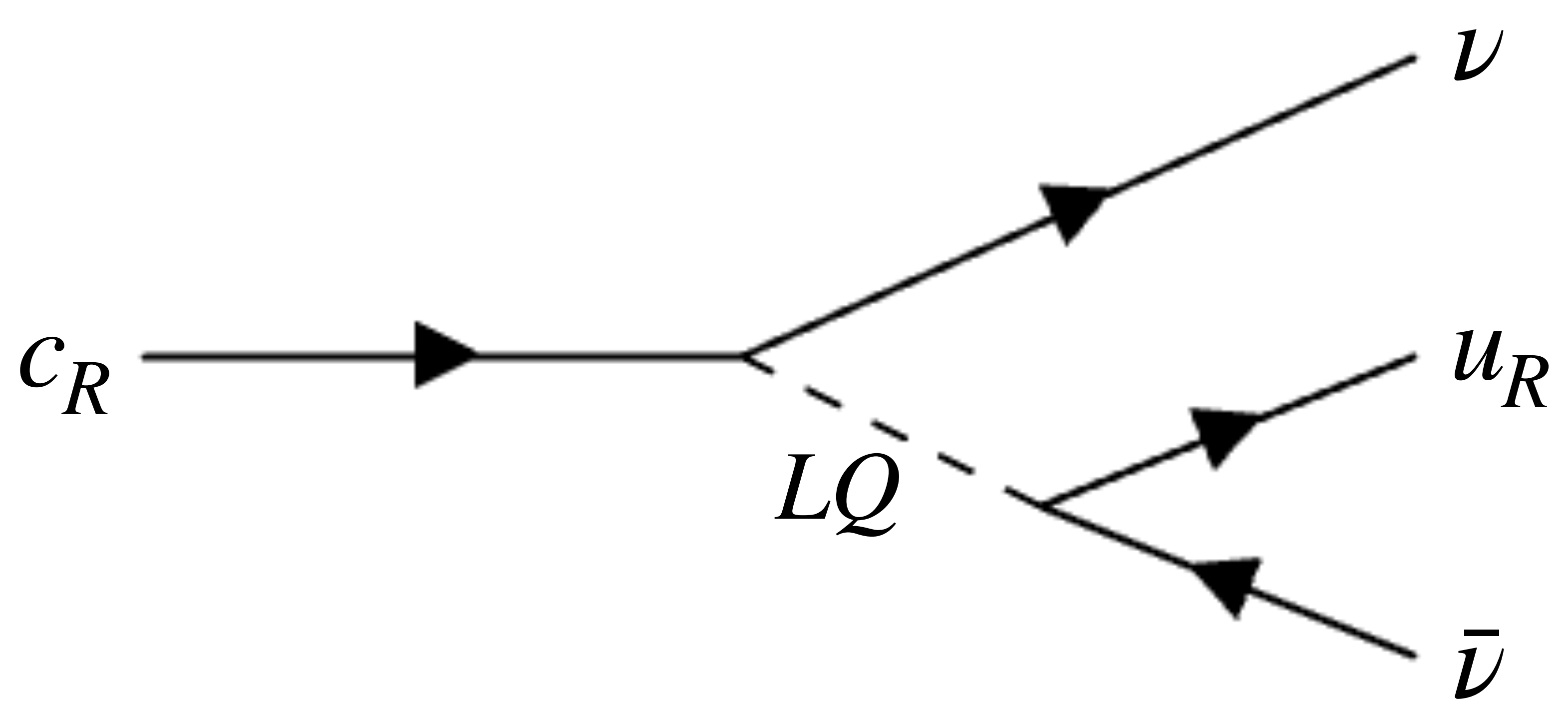
Estimating sensitivity

tabea.hacheney@tu-dortmund.de

SIGNAL

- Simulate inclusive $Z \to c\bar{c}$ with PYTHIA8
- Generate $D^0 \to \pi^+\pi^-\nu\bar{\nu}$ using PHSP model in EvtGen
  (no resonances in $m(\pi^+\pi^-)$)

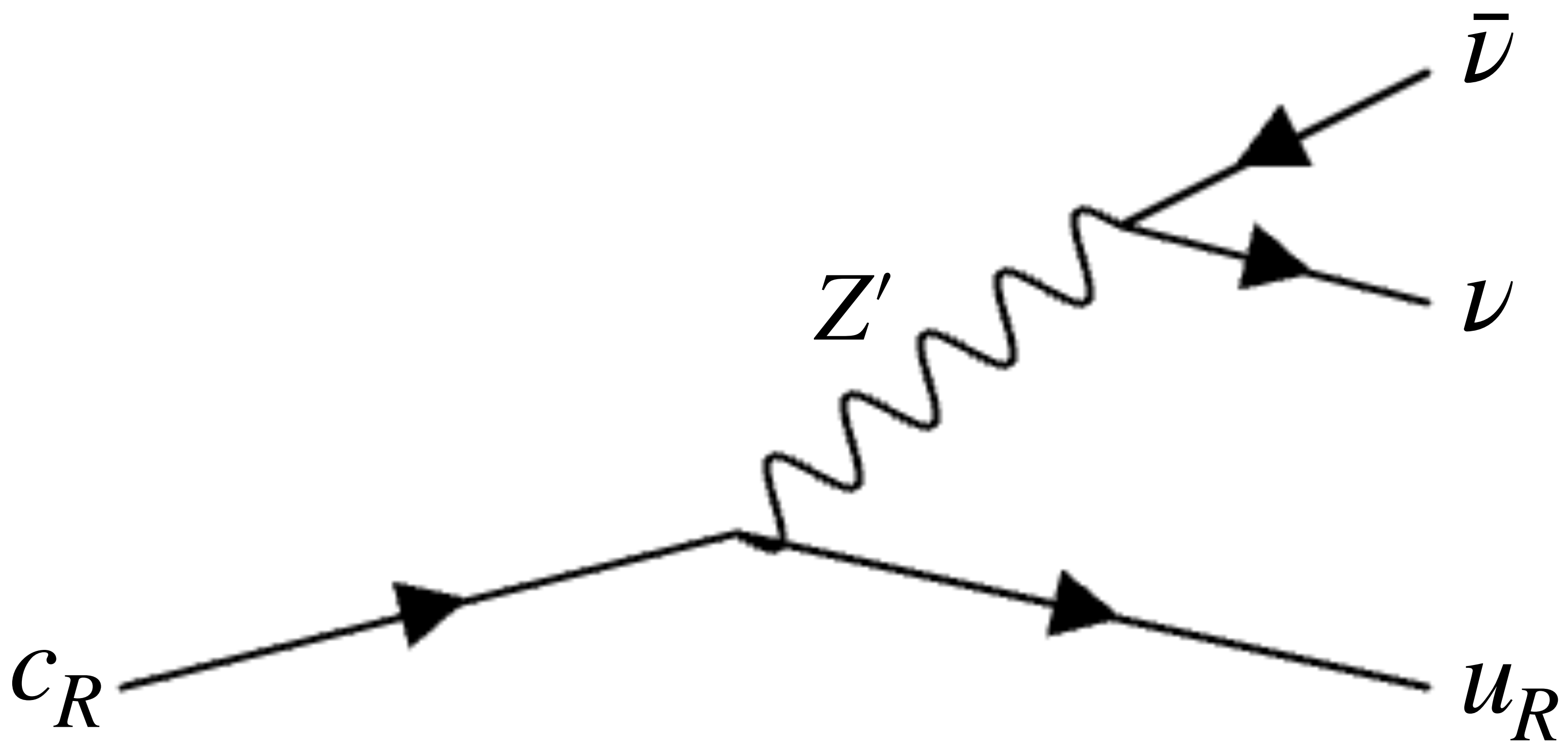
  $\Rightarrow 10^6$ signal events



BACKGROUND

- Inclusive $Z \to q\bar{q}$ IDEA samples from Winter 2023
- 100×10^6 of each quark flavor $(u/d, s, c, b)$

  $\Rightarrow 400 \times 10^6$ events



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EXCLUSIVE BACKGROUNDS

- Potentially risky decays not included in incl. sample due to small $\mathscr{B}$
- Similar signature in detector than signal → large missing p
- Signal channels from $b \to s\nu\bar{\nu}$ study [2309.11353v2]
  - $B_s \to \phi(\to K^+K^-)\nu\bar{\nu}$
  - $B^0 \to K_S(\to \pi^+\pi^-)\nu\bar{\nu}$
  - $B^0 \to K^*(\to K^+\pi^-)\nu\bar{\nu}$

→ 2×10^6 samples each

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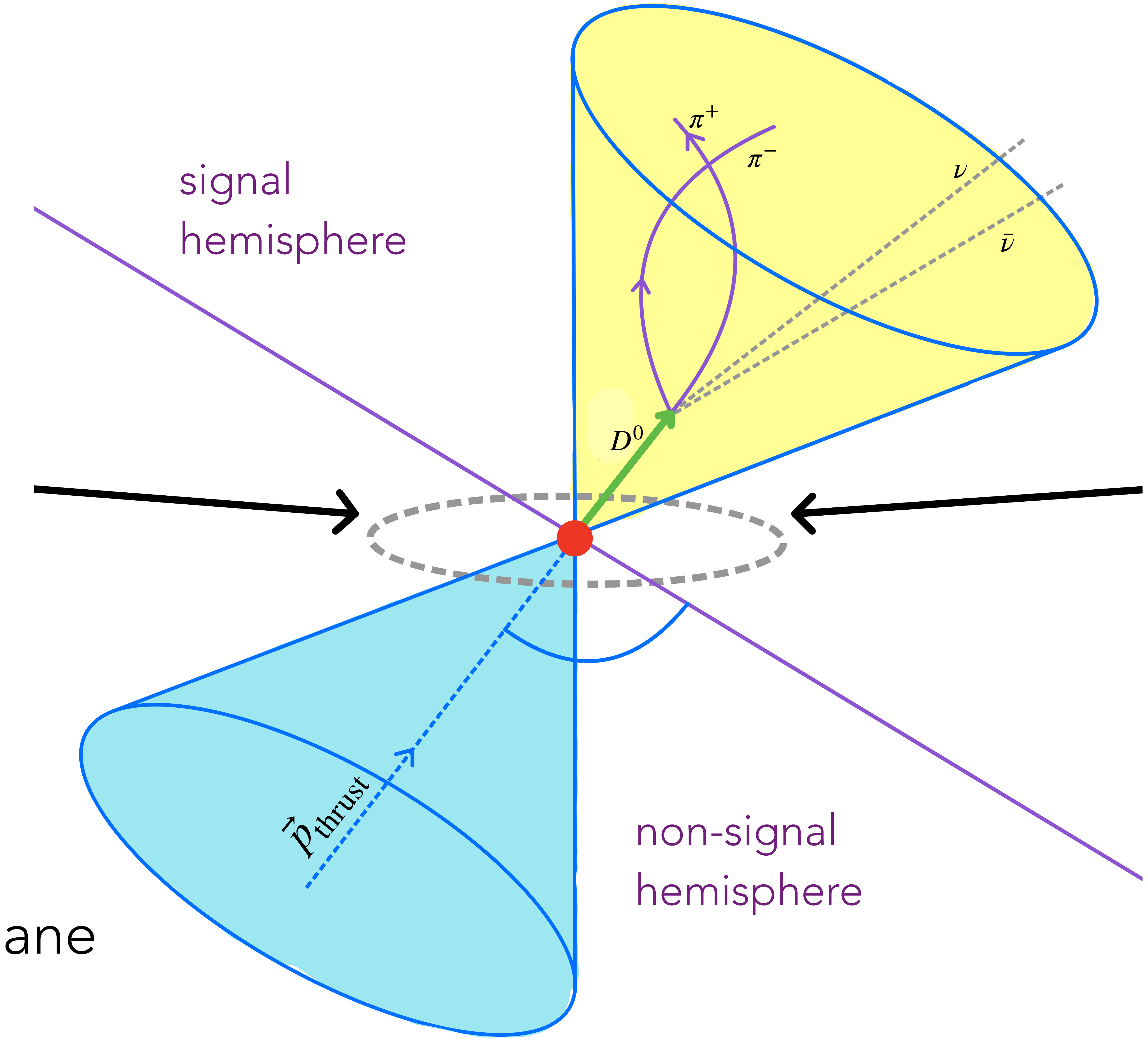
RECONSTRUCTING SIGNAL CANDIDATES

- Hemispheres normal to thrust of rec. event momenta and rel. to signal candidate

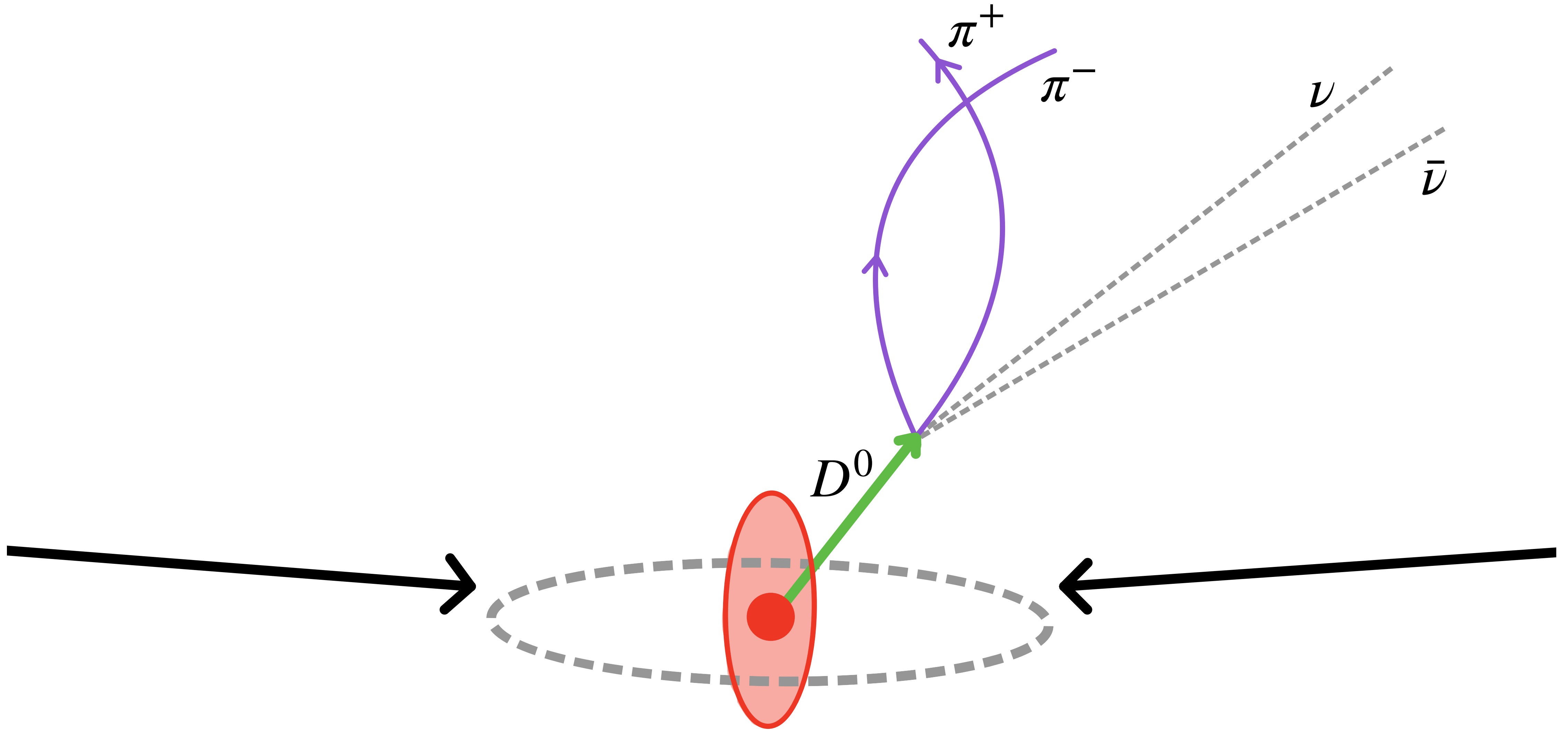


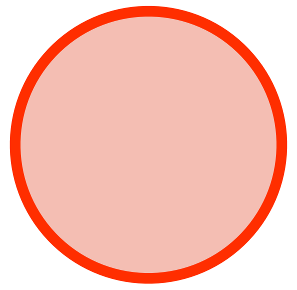
thrust ⊥ hem. plane

tabea.hacheney@tu-dortmund.de

RECONSTRUCTING SIGNAL CANDIDATES

- Define tracks originating from Luminous Region (LR)
  - PV reconstruction, as used in other studies, inefficient due to limited flight distance of charm hadrons ($\epsilon_{\text{reco}} \sim 36\,\%$)
  - Ellipse condition around $(0,0,0)$: ($\epsilon_{\text{reco}} \sim 50\,\%$)

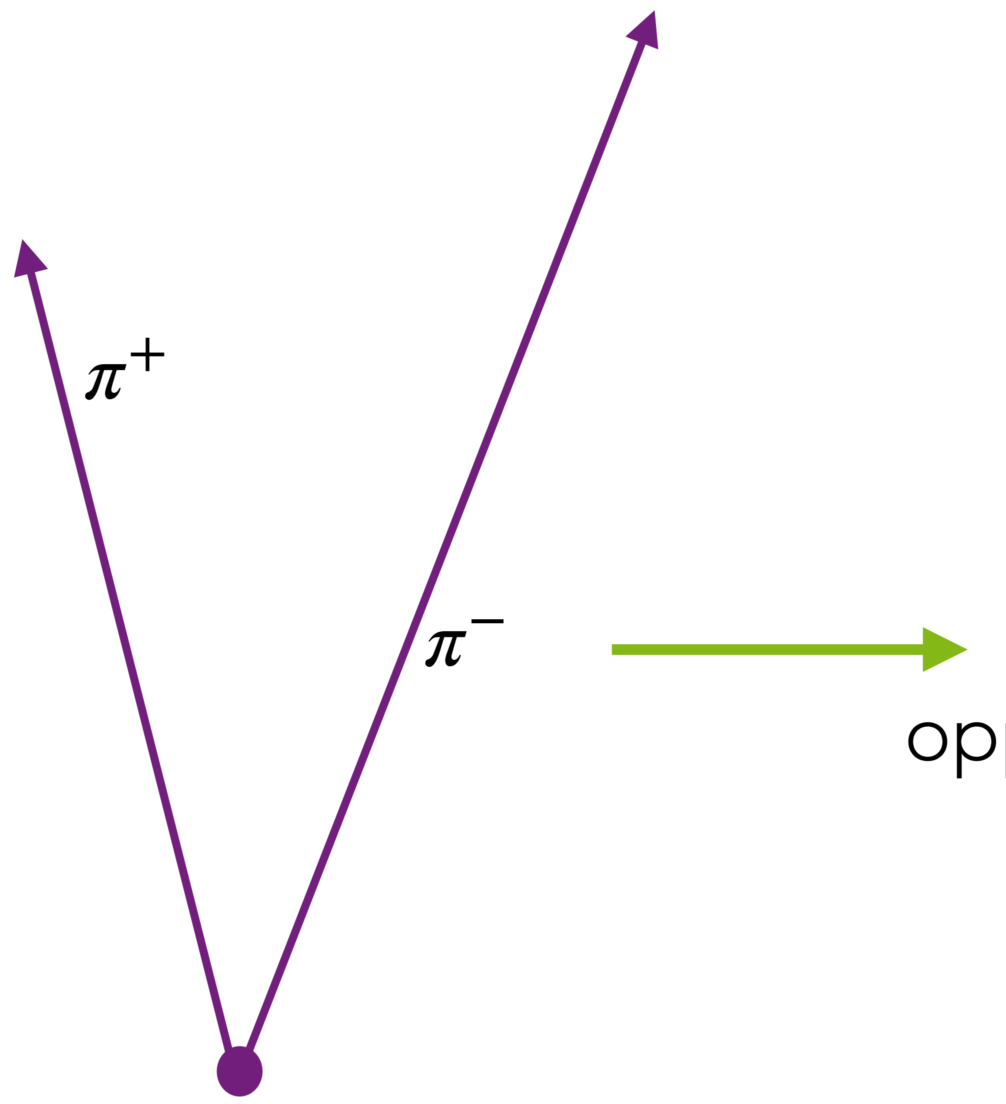


 $: \dfrac{s_x^2}{s^2} + \dfrac{s_y^2}{s^2} \leq 1$

$$\rightarrow s_x = \frac{d_{0x}}{\sqrt{\sigma^2_{d_{0x}} + \sigma^2_x}},\; s_y = \frac{d_{0y}}{\sqrt{\sigma^2_{d_{0y}} + \sigma^2_y}}$$

tabea.hacheney@tu-dortmund.de

RECONSTRUCTING SIGNAL CANDIDATES

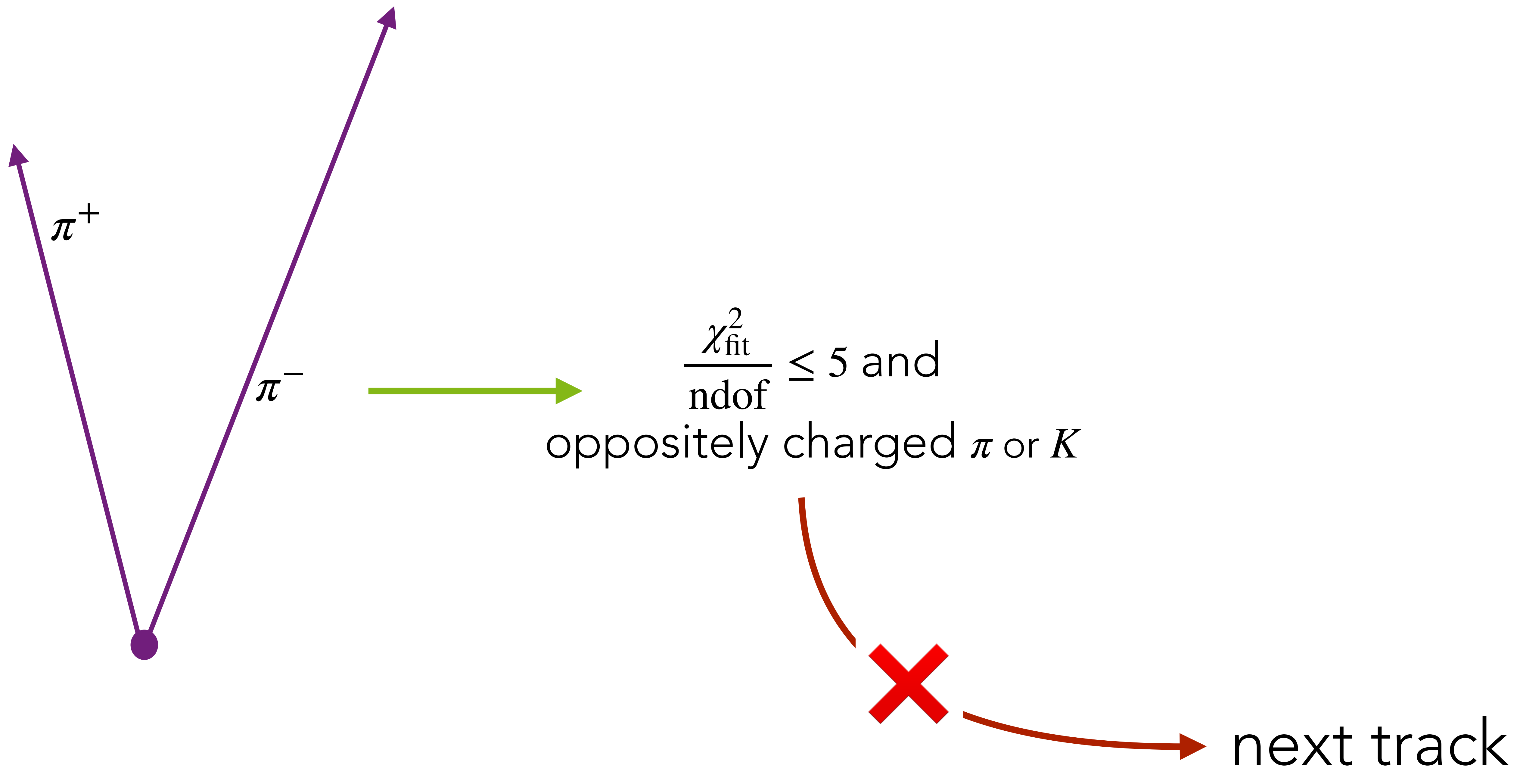


$\frac{\chi^2_{\text{fit}}}{\text{ndof}} \leq 5$ and
oppositely charged π or K

$\Rightarrow$ Select vertices with two oppositely charged hadrons $\in [\pi^+\pi^-, K^\pm\pi^\mp, K^+K^-]$ assuming $K \leftrightarrow \pi$ separation from Ref [Eur. Phys. J. Spec. Top., 228 (2019)]

tabea.hacheney@tu-dortmund.de

RECONSTRUCTING SIGNAL CANDIDATES



⇒ Select vertices with two oppositely charged hadrons $\in [\pi^+\pi^-, K^\pm\pi^\mp, K^+K^-]$ assuming $K \leftrightarrow \pi$ separation from Ref [Eur. Phys. J. Spec. Top., 228 (2019)]

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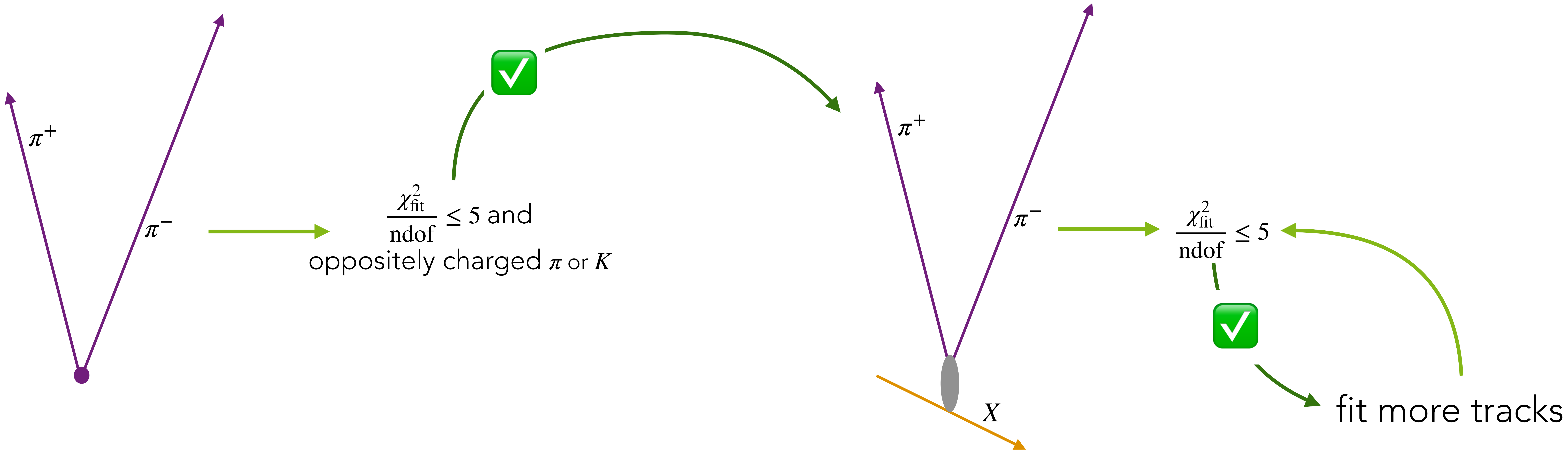

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tabea.hacheney@tu-dortmund.de

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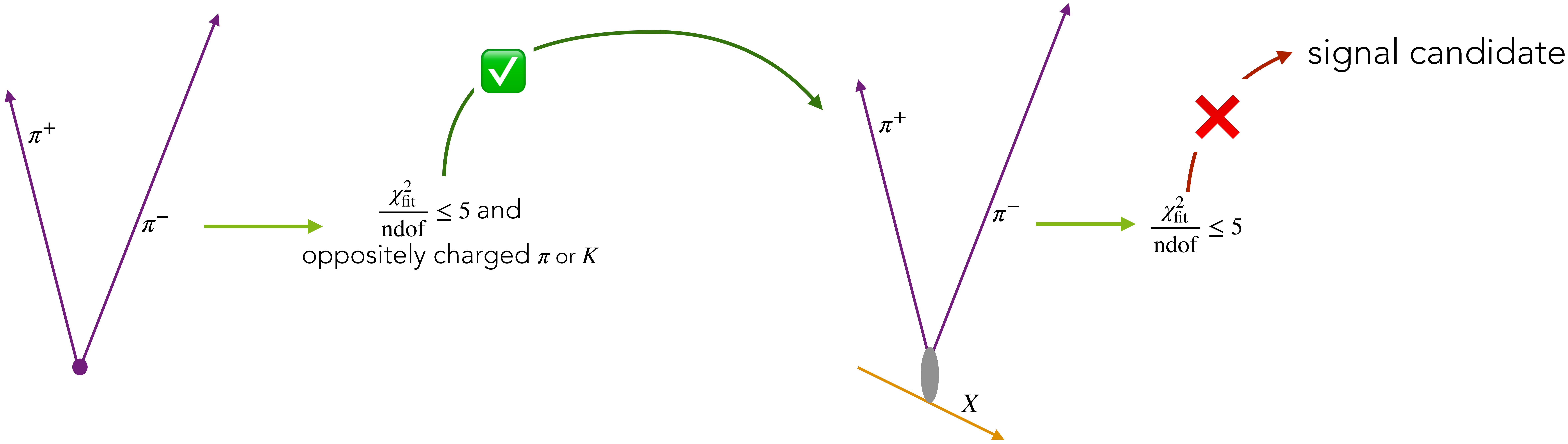

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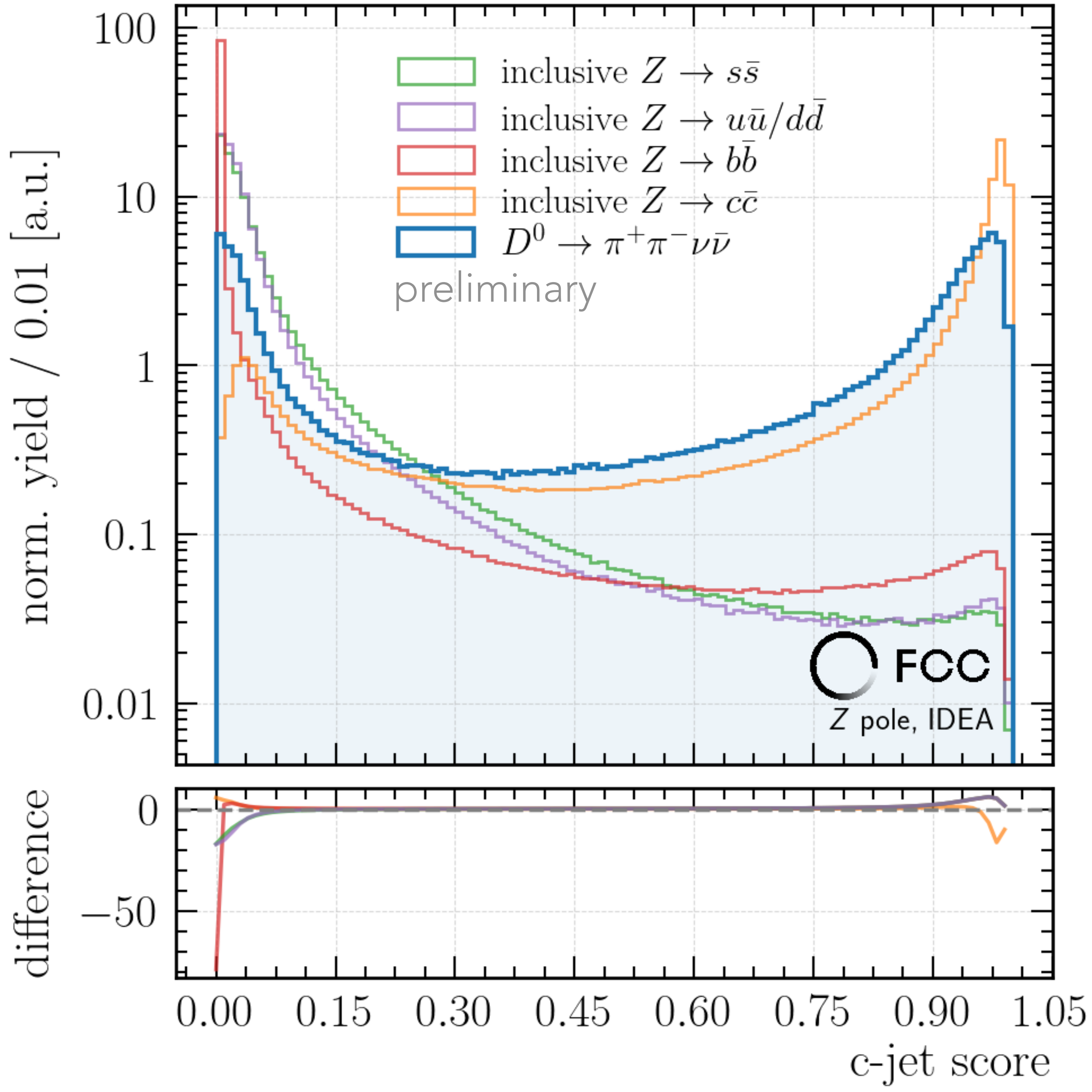
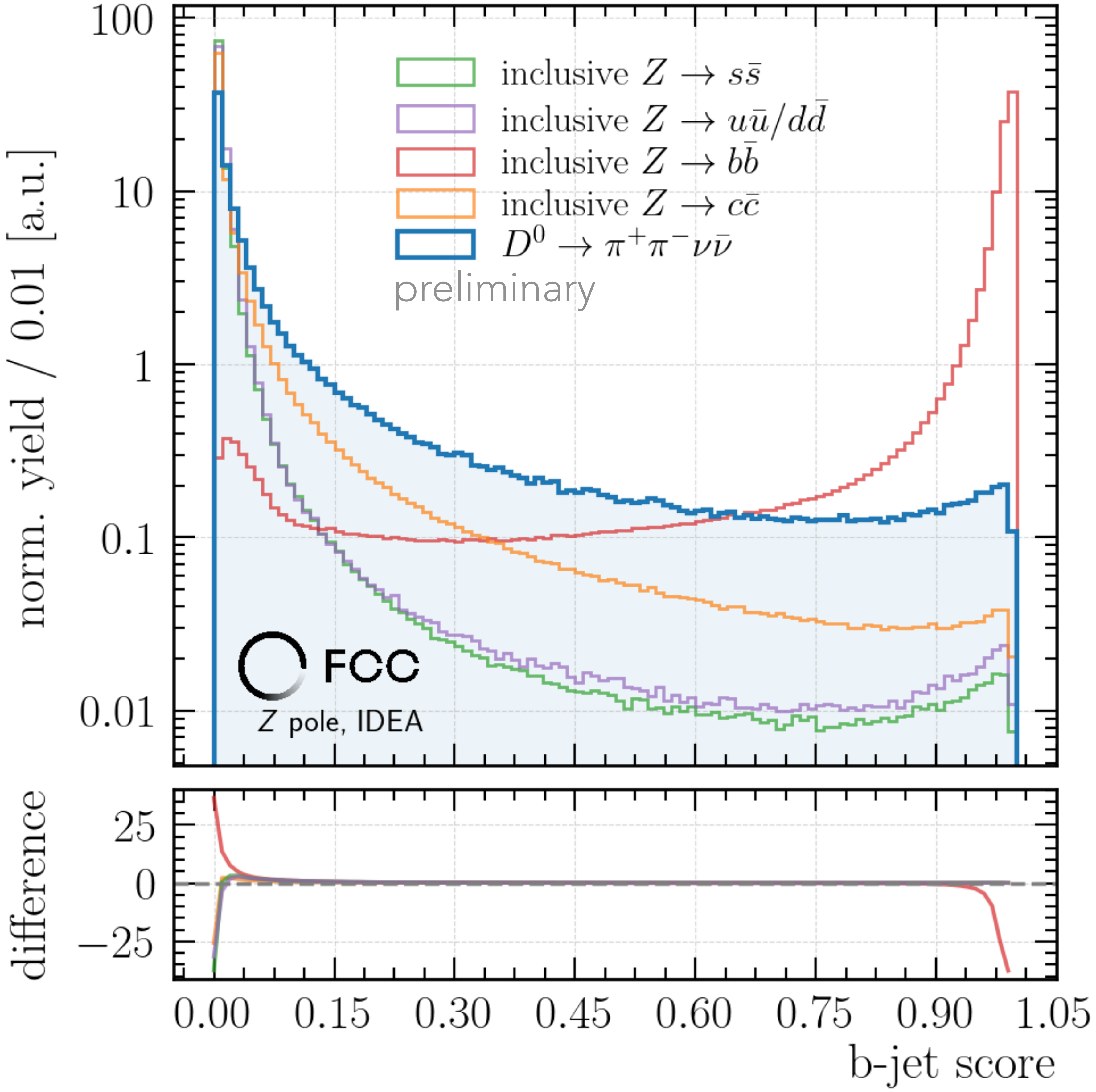
JET FLAVOR SCORE

- FCC-ee jet flavor tagger response [2202.03285]





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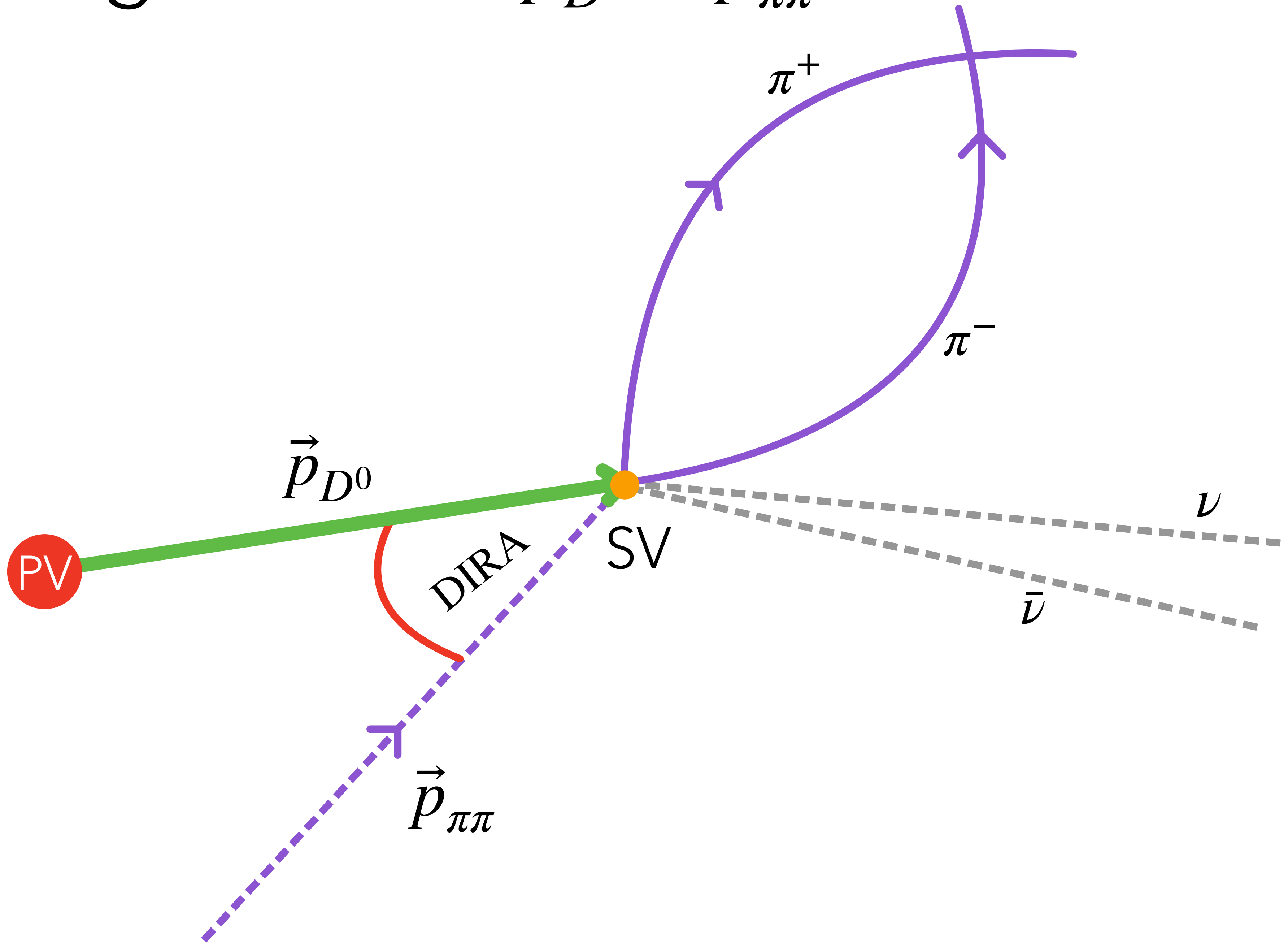
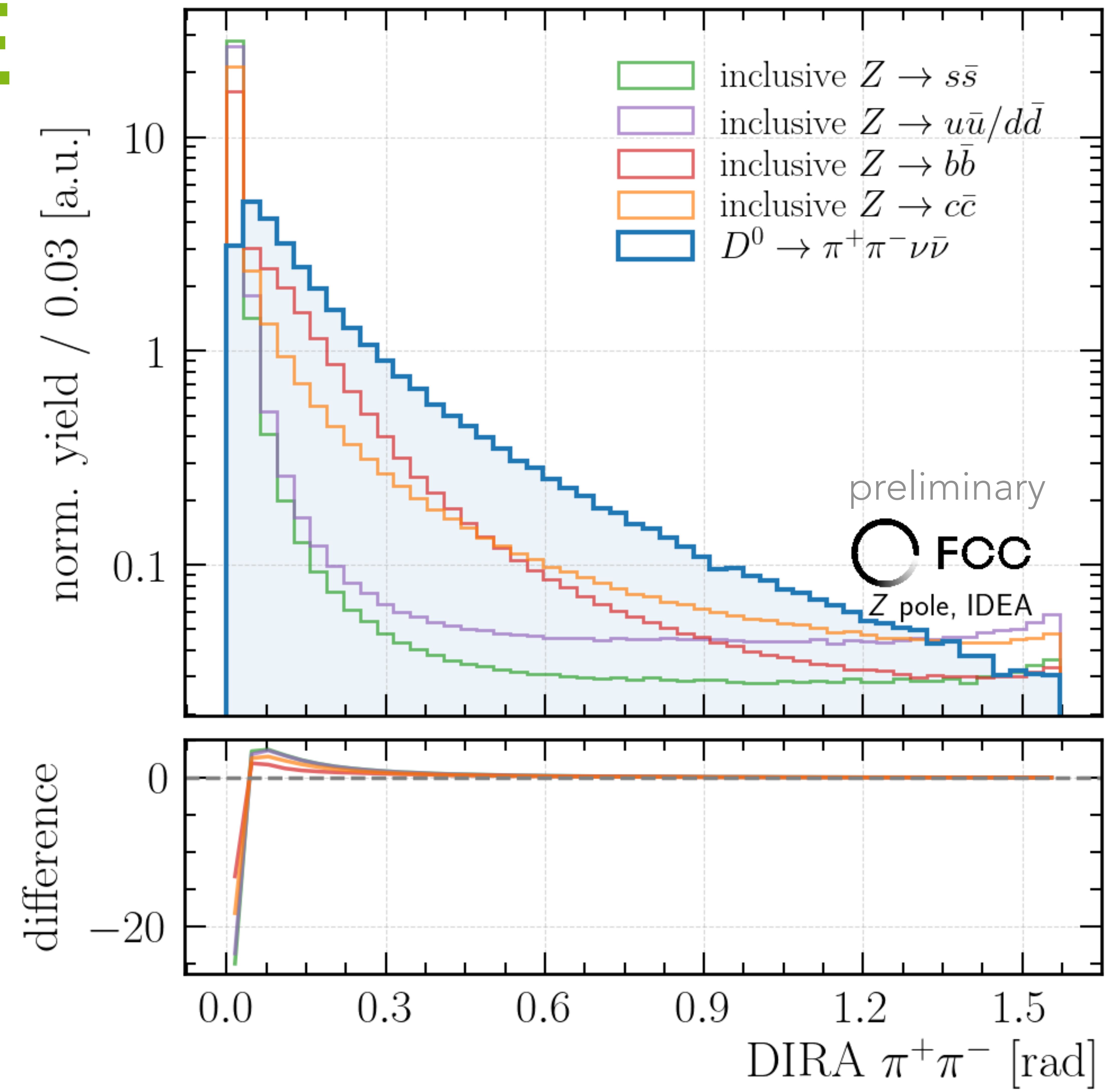
DIRECTION ANGLE

- Direction angle of reconstructed signal candidate
  - Better alignment if $\vec{p}_{D^0} \sim \vec{p}_{\pi\pi}$

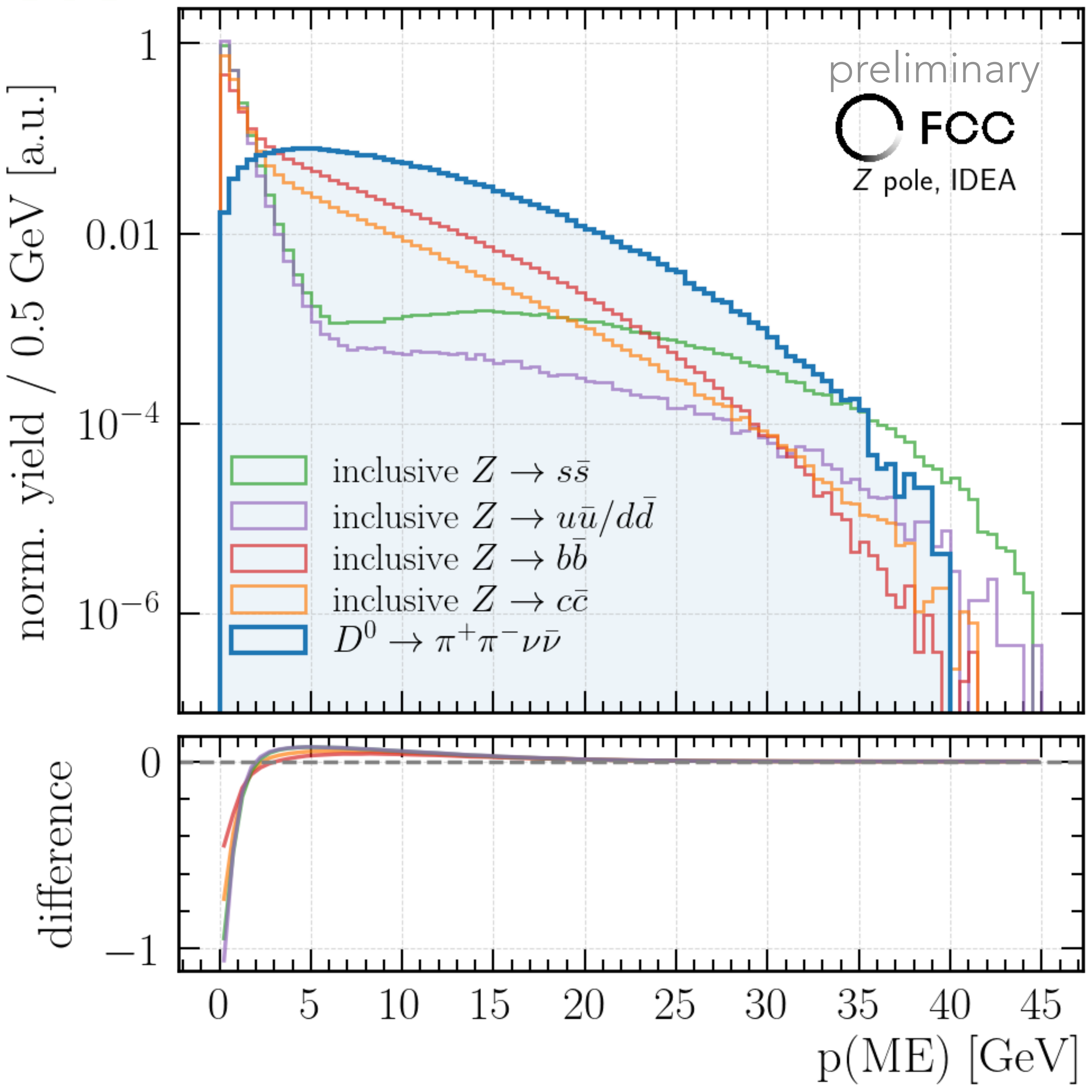




MISSING MOMENTUM

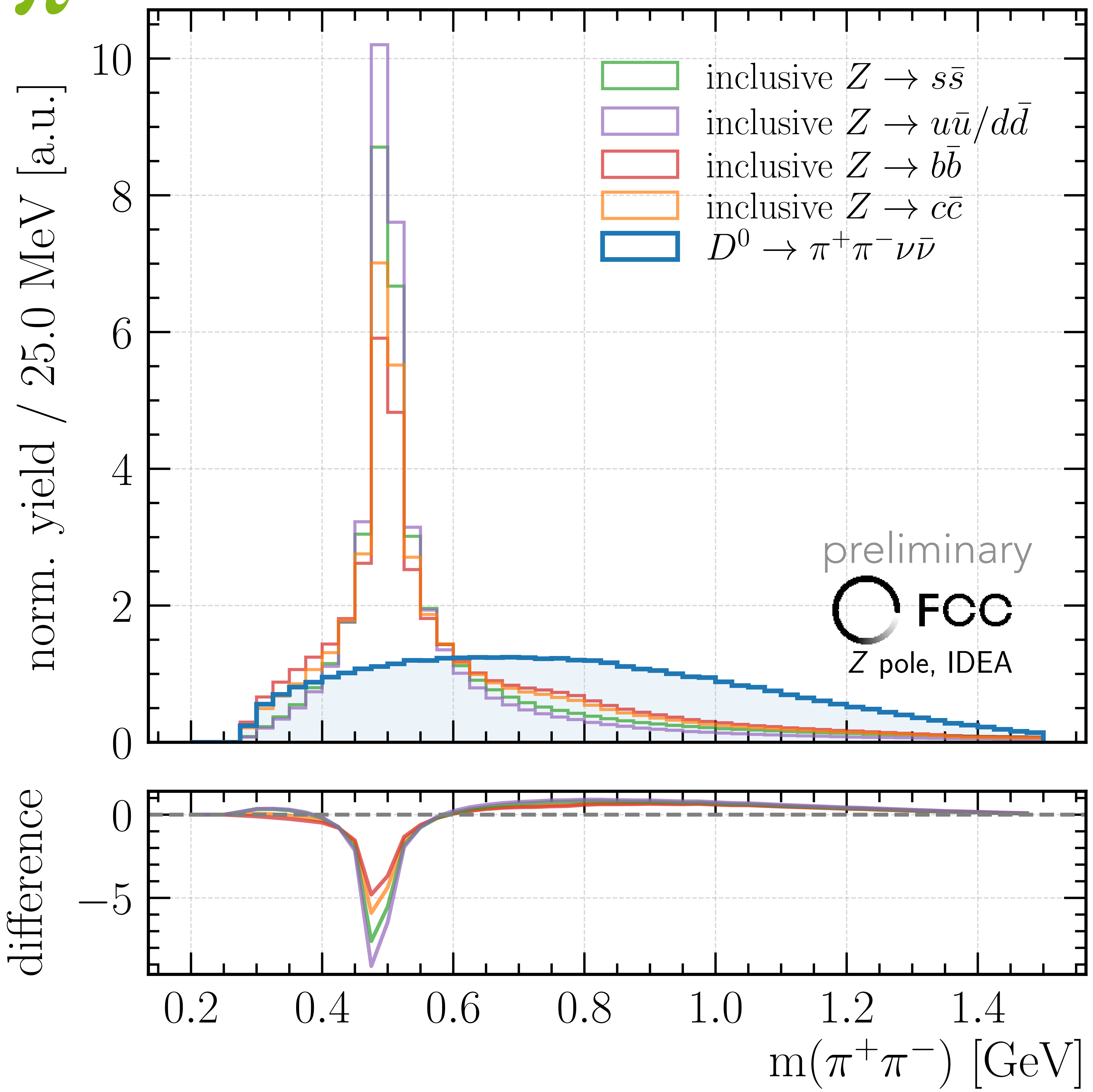
- Magnitude of missing momentum vector inferred from momentum conservation

- $\sqrt{s} = 91\,\mathrm{GeV} = \vec{p}_{\mathrm{detected}} + \vec{p}_{\mathrm{missing}}$



INVARIANT MASS $\pi^+\pi^-$

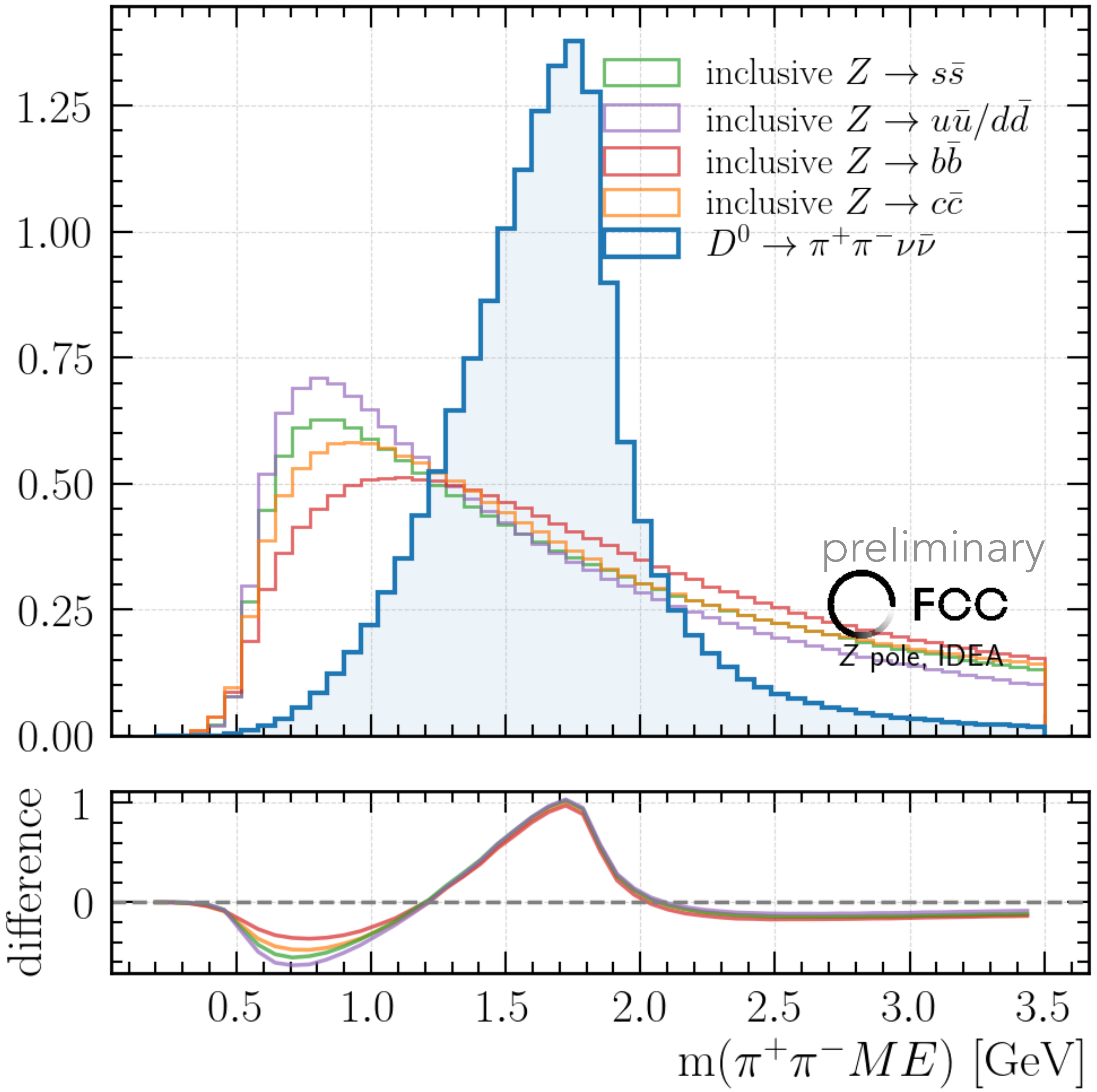
- Background dominated by K_S resonances
- Signal simulation without resonances
  - Planning on using a more sophisticated model



tabea.hacheney@tu-dortmund.de

INVARIANT MASS $\pi^+\pi^-$ + ME

- Rec. inv. mass of $\pi^+\pi^-$ together with the missing momentum
- Peaking structure around $m_{D^0} = 1865\,\mathrm{MeV}$ [PDG]
- Potentially extract candidats via fit
  - Currently doing simple event counting



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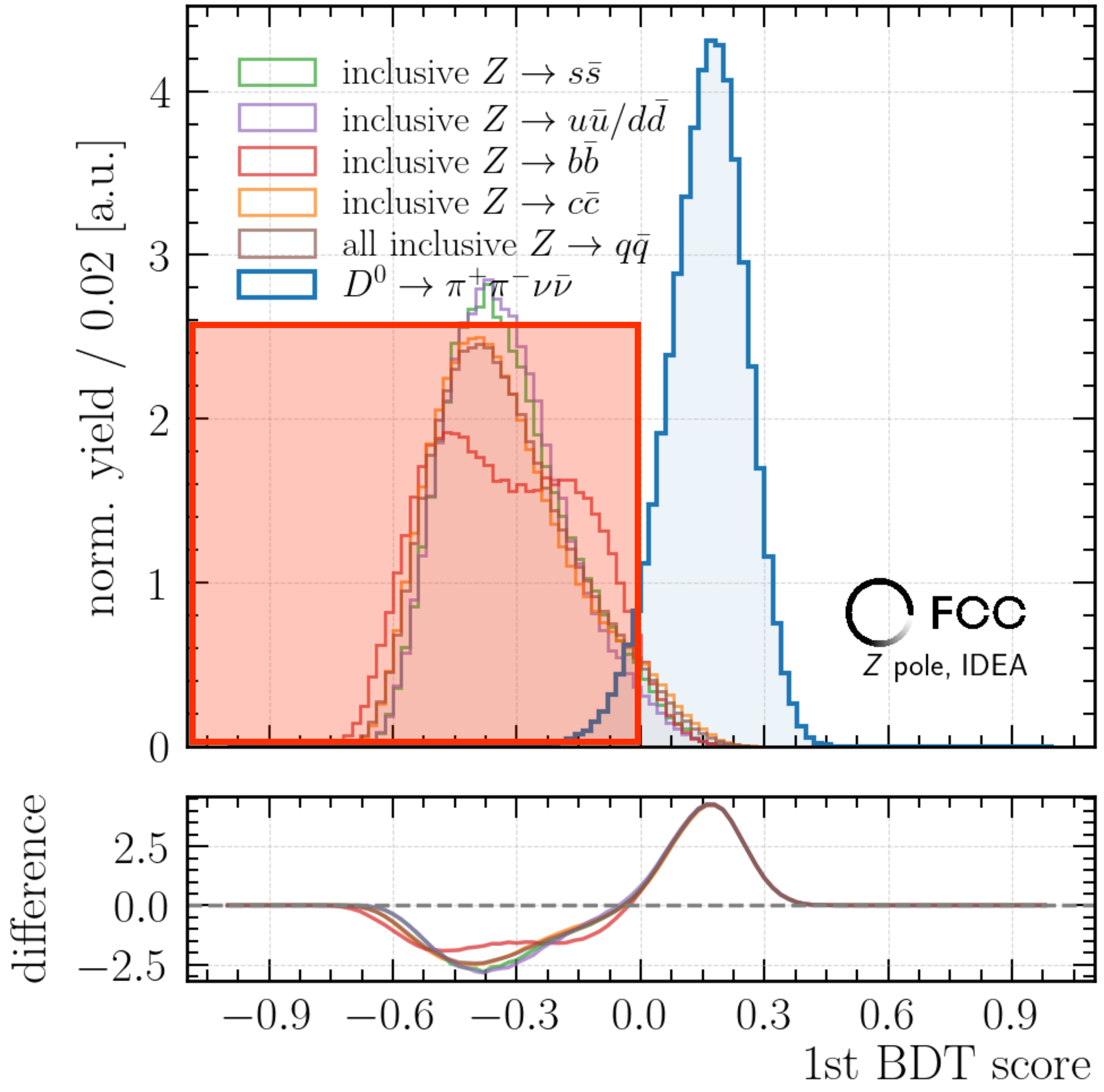
TWO-STAGE BDT

- Deploy two BDTs
  - BDT1 trained with events after preselection
    - $\epsilon_{\text{pre}}(\text{sig}\,(\text{backgr})) : \sim 80.7\,\%\,(\sim 0.8\,\%)$



tabea.hacheney@tu-dortmund.de

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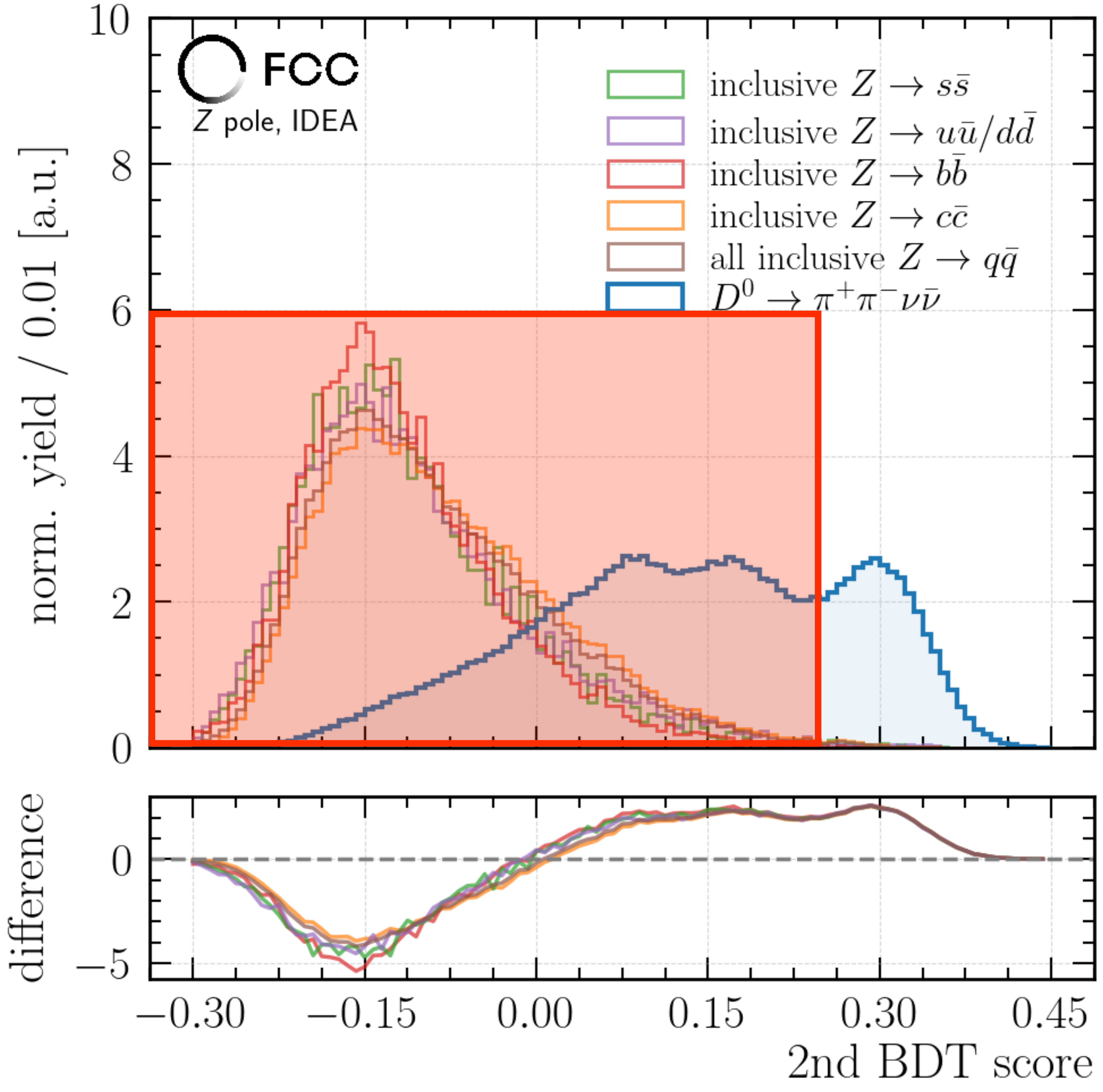
  - BDT2 with events left after cut on BDT1
- BDT2 has higher focus on difficult background



tabea.hacheney@tu-dortmund.de

TWO-STAGE BDT

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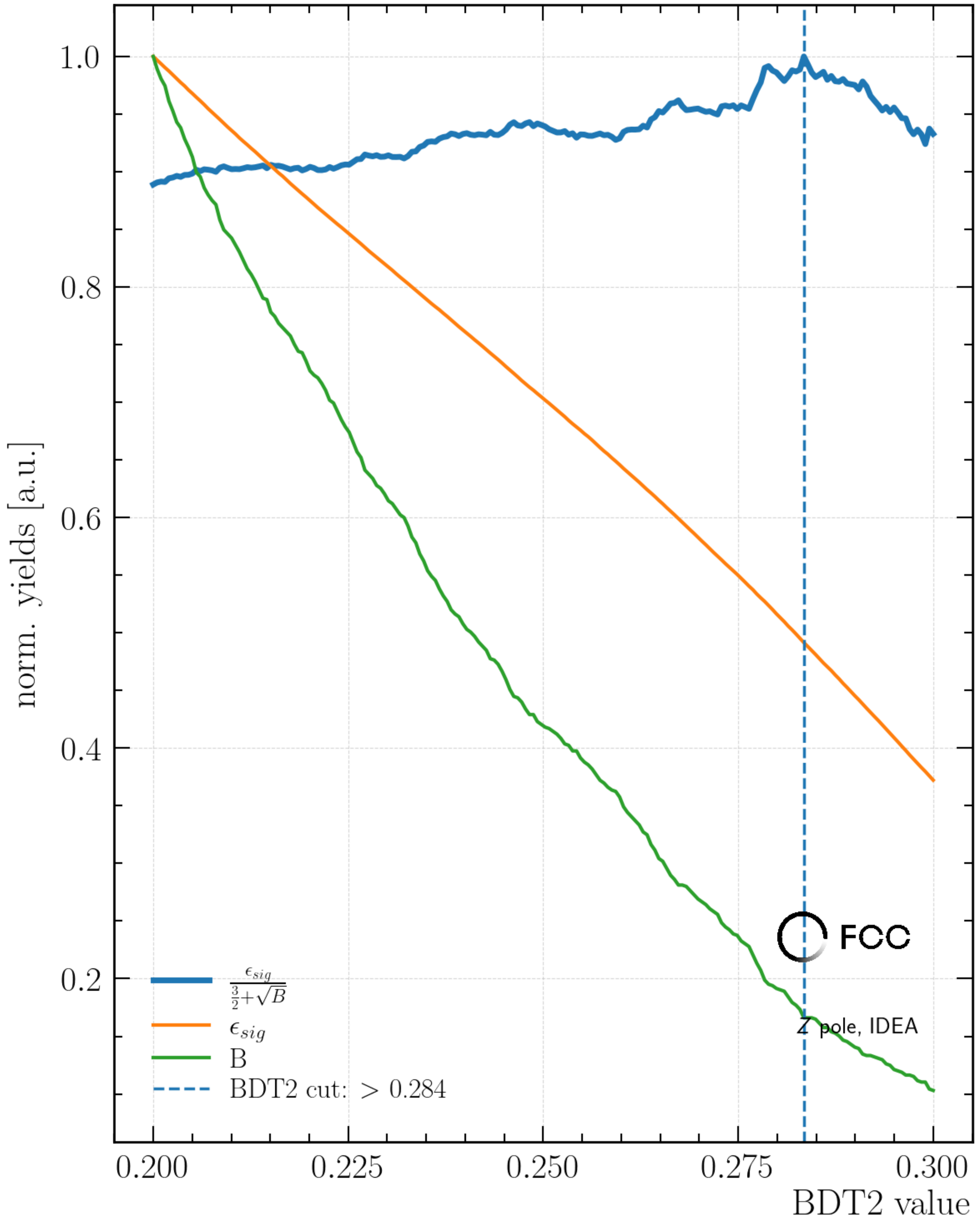
  - BDT2 with events left after cut on BDT1
- BDT2 has higher focus on difficult background
- Optimise cut with Punzi FOM: $$\frac{\epsilon_{sig}}{\frac{3}{2} + \sqrt{B}}$$
  (Optimising for 5σ results in same maximum)



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ESTIMATE SENSITIVITY

- Use efficiencies to compute expected number of background/signal

  - $\epsilon_{\text{total}} = \epsilon_{\text{reco}}\epsilon_{\text{pre}}\epsilon_{\text{BDT1}}\epsilon_{\text{BDT2}}\epsilon_{\text{misID}}$

- $S = 2 \times N_Z \times \mathcal{B}(Z \to c\bar{c}) \times 0.59 \times \mathcal{B}(D^0 \to \pi^+\pi^-\nu\bar{\nu}) \times \epsilon_{\text{total,s}}$

  $N_Z = 6 \times 10^{12}$

  0.59: f_{D^0} [1509.01061]

- $B = N_Z \left(\sum_{q=c,s,u/d} \mathcal{B}(Z \to q\bar{q})\epsilon_{\text{total,q}} + \mathcal{B}(Z \to b\bar{b})\left(\mathcal{B}_{\text{excl}}\epsilon_{\text{total,excl}} + (1 - \mathcal{B}_{\text{excl}})\epsilon_{\text{total,b}}\right) \right)$

  $\mathcal{B}_{\text{excl}} = 2 \times \sum_i \mathcal{B}_i f_i$

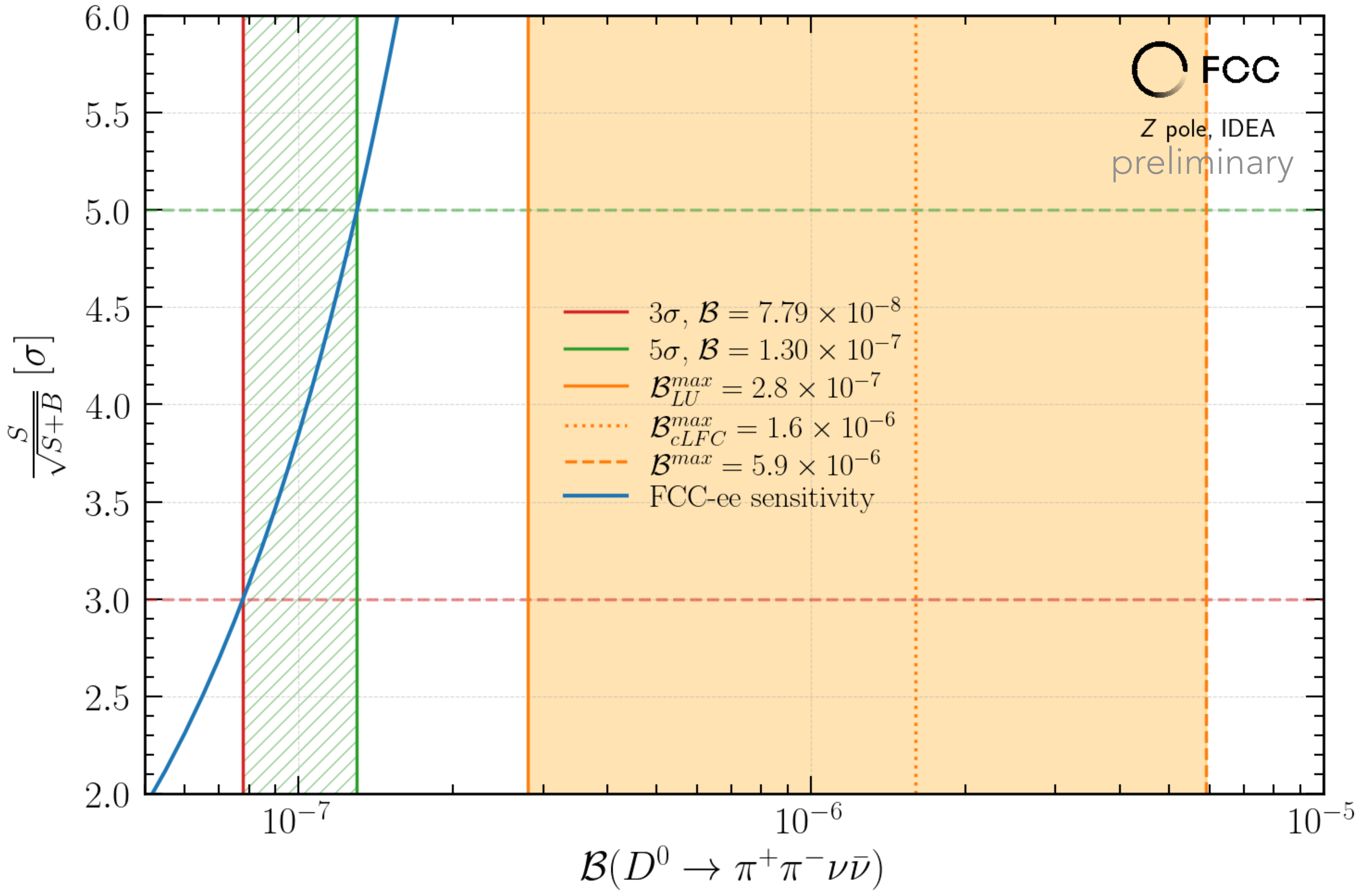
$\Rightarrow$ Estimate sensitivity with $\dfrac{S}{\sqrt{S+B}}$ for multiple $\mathcal{B}(D^0 \to \pi^+\pi^-\nu\bar{\nu})$

tabea.hacheney@tu-dortmund.de

ESTIMATE SENSITIVITY

- $B_{\text{total}} \sim 2 \times 10^6$
- $S_{3\sigma(5\sigma)} = 4\,435 \ (7\,397)$

	reco [%]	pres. [%]	BDTs	misID [%]	total
cc	79.9	2.5	10^{-4}	0.96	2×10^{-6}
bb	100.6	0.3	3×10^{-5}	0.80	7×10^{-8}
ss	62.6	0.3	10^{-4}	0.92	2×10^{-7}
ud	44.4	0.3	8×10^{-5}	0.99	10^{-7}
excl	99.2	2.9	10^{-4}	10^{-6}	5×10^{-12}
Signal	49.8	80.7	16.7 %	0.99	6.7 %



CONCLUSION

- Null test → any signal is sign of BSM physics
  - Preliminary FCC-ee sensitivity estimate better than BSM expectations

tabea.hacheney@tu-dortmund.de

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OUTLOOK

- Implement more realistic signal decay model [2010.02225]
- More excl. decay samples with high similarity to signal, but low $\mathscr{B}$
- Study implications of detector performance such as imperfect PID

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THANK YOU FOR YOUR ATTENTION!

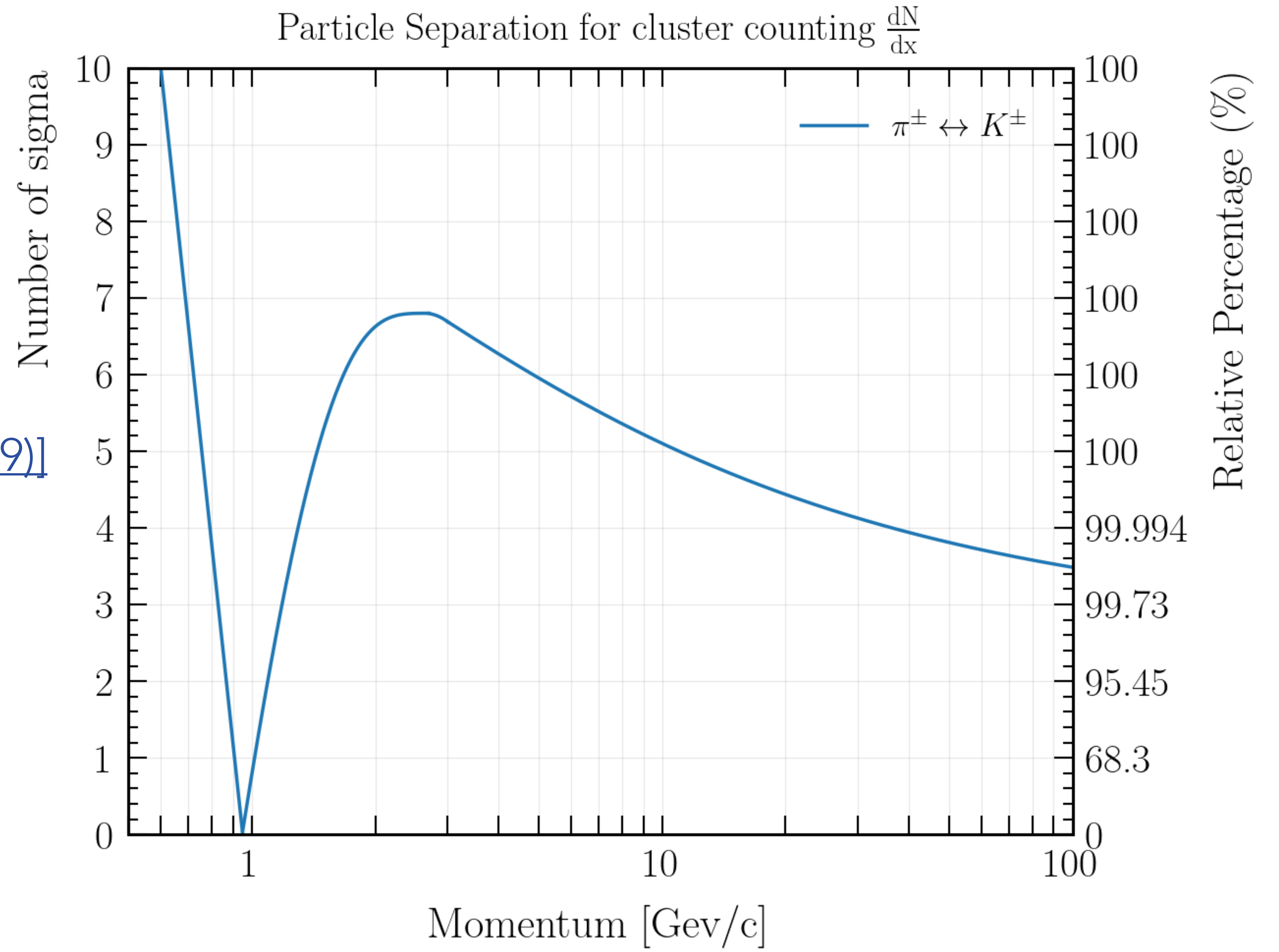
tabea.hacheney@tu-dortmund.de

BACKUP

tabea.hacheney@tu-dortmund.de

PID ASSUMPTIONS

- Select all 2 particle vertices including either K or $\pi \rightarrow \pi^+\pi^-, K^\pm\pi^\mp, K^+K^-$
- Assign misID chance to each track for p
  - Distribution inspired by conceptual design report vol. 2 [Eur. Phys. J. Spec. Top., 228 (2019)]
- Calculate efficiency for misID as $\pi^+\pi^-$



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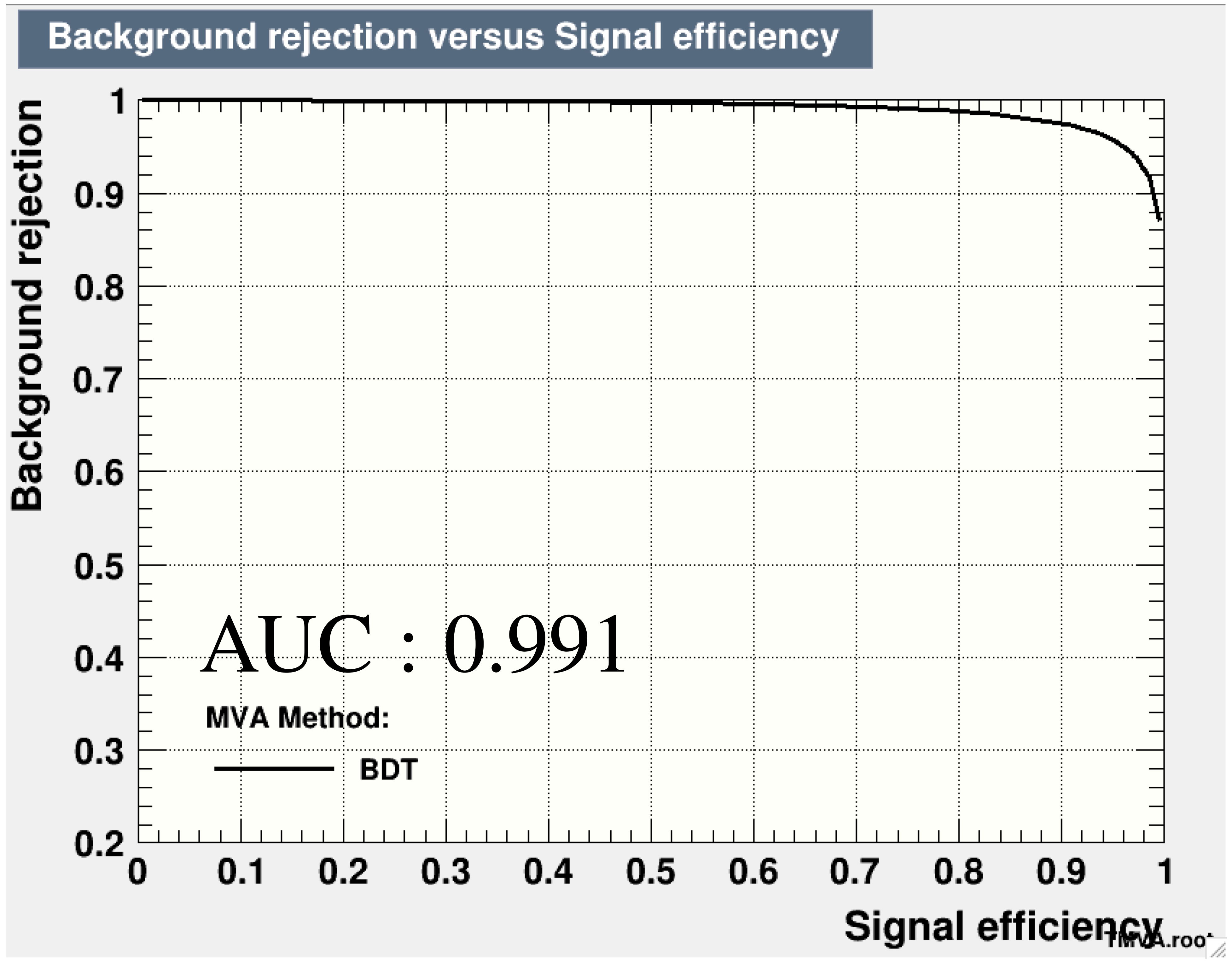
BDT 1

- AdaBoost with 31 input variables

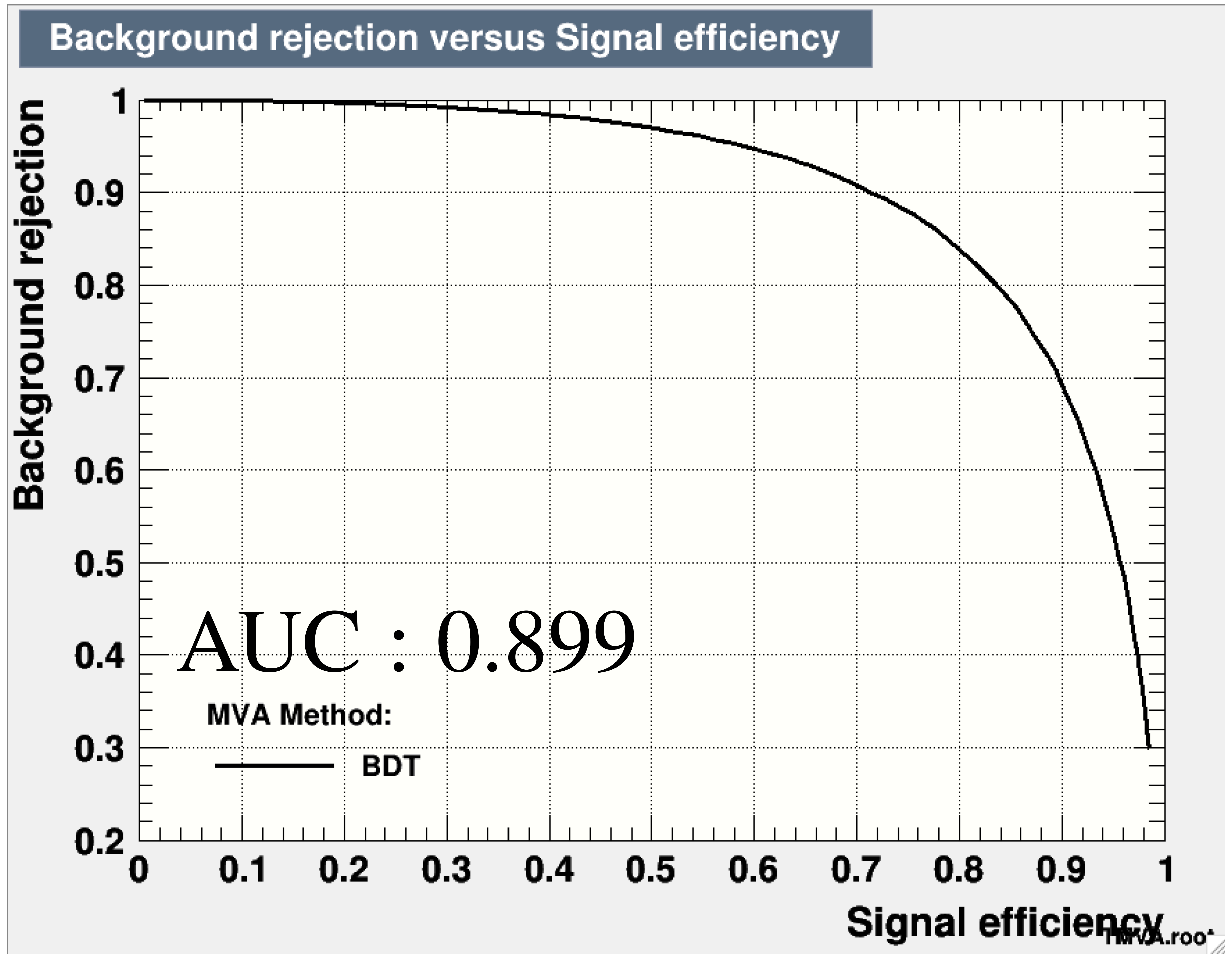


Rank	Variable	Separation power [%]	Variable importance [%]
1	E of particles in signal hemis.	53.10	5.558
2	Total rec. energy	52.01	5.810
3	Missing momentum	49.13	5.170
4	E asymmetry of hemis.	29.83	3.151
5	$m(\pi^+\pi^-\mathrm{ME})$	28.32	3.993
6	Number of tracks	22.87	3.797
7	Number of sec. vtx	22.50	3.012
8	Number of tracks around D0	20.83	2.641
9	$E(\pi^+\pi^-)$	20.46	4.440
10	$m(\pi^+\pi^-\mathrm{ME}) - m(\pi^+\pi^-)$	19.43	2.140

tabea.hacheney@tu-dortmund.de

BDT 2

- AdaBoost with 32 input variables
  - Additionally uses score of first BDT



Rank	Variable	Separation power [%]	Variable importance [%]
1	BDT1 score	36.10	10.87
2	Number of tracks	5.49	4.04
3	Number of Pi0	5.18	2.81
4	Number of particles	4.94	3.14
5	(b+s+u/d+g)-jet score	4.26	2.93
6	Number of tracks around D0	3.52	3.42
7	Total rec. energy	3.42	3.12
8	c-jet score	3.20	3.12
9	Missing momentum	3.16	3.23
10	$m(\pi^+\pi^-\text{ME})$	3.02	2.30

CHARGED LEPTON FLAVOR STRUCTURES

- $\mathscr{H}_{\text{eff}}^{\nu_i\bar{\nu}_j} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left(\mathscr{C}_L^{Uij}\mathscr{Q}_L^{ij} + \mathscr{C}_R^{Uij}\mathscr{Q}_R^{ij}\right) + \text{H.c.}$
- $\mathscr{H}_{\text{eff}}^{l_i l_j} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left(\mathscr{K}_L^{Uij}\mathscr{Q}_L^{ij} + \mathscr{K}_R^{Uij}\mathscr{Q}_R^{ij}\right) + \text{H.c.}$

$$\mathscr{K}^U_{L,R}(\text{LU})\begin{pmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{pmatrix} \qquad \mathscr{K}^U_{L,R}(\text{cLFC})\begin{pmatrix} k_e & 0 & 0 \\ 0 & k_\mu & 0 \\ 0 & 0 & k_\tau \end{pmatrix} \qquad \mathscr{K}^U_{L,R}(\text{general})\begin{pmatrix} k_e & k_{e\mu} & k_{e\tau} \\ k_{\mu e} & k_\mu & k_{\mu\tau} \\ k_{\tau e} & k_{\tau\mu} & k_\tau \end{pmatrix}$$

- Relation between $\mathscr{C}^{ij}_{L,R}$ and $\mathscr{K}^{ij}_{L,R}$ given in [2007.05001]

tabea.hacheney@tu-dortmund.de

FULL LIST OF BDT INPUT VARIABLES

1. $E(\pi^+\pi^-)$
2. $m(\pi^+\pi^-)$
3. $m(\pi^+\pi^-\mathrm{ME})$
4. $\mathrm{DOCA}(\pi^+\pi^-)$
5. E asymmetry of hemis.
6. E of tracks
7. E of tracks in signal hemis.
8. E of particles in signal hemis.
9. $\mathrm{FD}(\pi^+\pi^-)$
10. Missing momentum
11. Number of tracks
12. Number of particles
13. Number tracks around D^0
14. $m(\mathrm{LR})$
15. Total rec. energy
16. min. d(2 particle SV, LR)
17. $m(\pi^+\pi^-\mathrm{ME}) - m(\pi^+\pi^-)$
18. $\mathrm{DIRA}(\pi^+\pi^-) - \mathrm{DIRA}(\pi^+\pi^-\mathrm{ME})$
19. $\mathrm{IP}(\pi^+\pi^-) - \mathrm{IP}(\pi^+\pi^-\mathrm{ME})$
20. b-jet score
21. c-jet score
22. g-jet score
23. (b+s+u/d+g)-jet score
24. u/d-jet score
25. s-jet score
26. $\log(1 - \cos(\mathrm{DIRA}))$
27. $\log(1 - \cos(\angle(\pi^+, \pi^-)))$
28. $\log(1 - \cos(\angle(\mathrm{thrust})))$
29. Number 3 particle sec. vtx
30. Number of sec. vtx
31. Number of π^0
32. (BDT1 score)

tabea.hacheney@tu-dortmund.de

SEC TRACKS IN LR

	Sec. Tracks NOT in LR [%]	Sec. Tracks in LR [%]	LR Tracks NOT in LR [%]	LR Tracks in LR [%]
cc	73.9 ± 22.1	26.0 ± 22.1	12.2 ± 10.8	87.7 ± 10.9
bb	86.9 ± 14.2	13.1 ± 14.2	11.8 ± 12.6	86.8 ± 12.6
ss	62.4 ± 31.7	16.6 ± 28.4	13.2 ± 10.9	86.8 ± 12.6
ud	51.9 ± 35.2	20.0 ± 31.4	13.3 ± 10.8	86.7 ± 10.9
Signal	72.9 ± 30.0	26.9 ± 30.0	13.0 ± 11.3	86.6 ± 11.3

tabea.hacheney@tu-dortmund.de

BACKGROUND CONTRIBUTIONS

	Contribution [%]	Efficiency
cc	65.68	2×10^{-6}
bb	13.23	7×10^{-8}
ss	9.87	2×10^{-7}
ud	11.21	10^{-7}

$c\bar{c}$ backgr. decay contributions:

Inclusive	Contribution [%]
$D^0 \to \pi^+\pi^- X$	**29.94**
$K_S^0 \to \pi^+\pi^- X$	29.47
Combinatorial	23.45
$\omega \to \pi^+\pi^- X$	6.12
$\rho \to \pi^+\pi^- X$	5.43

Exclusive	Contribution [%]
$K_S^0 \to \pi^+\pi^-$	**29.47**
$D^0 \to K_S^0\pi^+\pi^-2\pi^0$	**9.88**
$D^0 \to K_L^0\pi^+\pi^-$	6.77
$\omega \to \pi^+\pi^-\pi^0$	6.01
$\rho \to \pi^+\pi^-$	5.43

tabea.hacheney@tu-dortmund.de

PRESELECTION

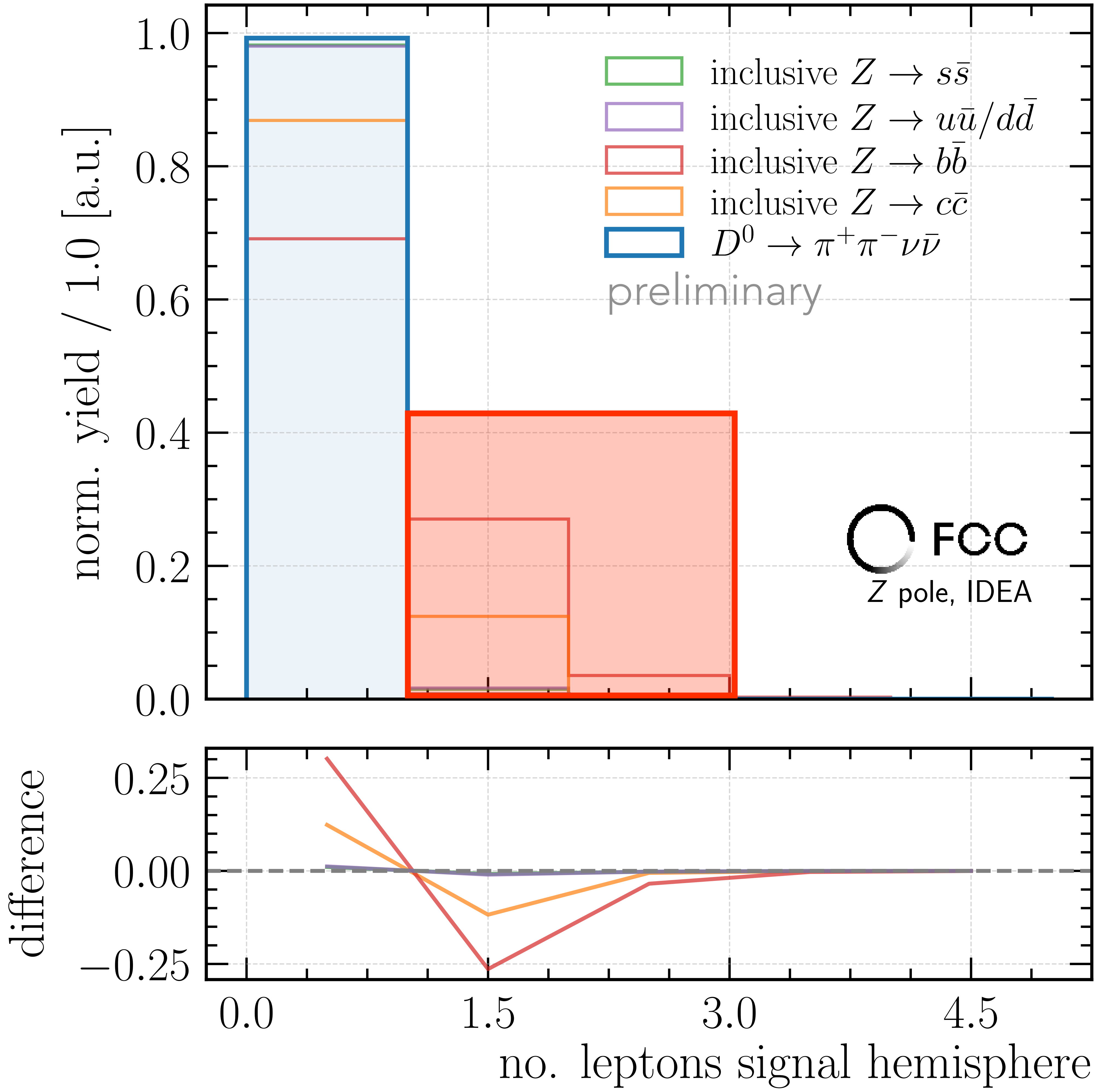
- Remove obvious background with cuts

Variable	Cut	Eff. Signal [%]	Eff. Background [%]
$\mathrm{IP}(\pi^+\pi^-) - \mathrm{IP}(\pi^+\pi^-\mathrm{ME})$	$> 0.5\,\mathrm{mm}$	99.48	23.96
$\max\left(\mathrm{IP}(\pi^\pm)\right)$	$< 2\,\mathrm{mm}$	99.75	25.54
$\mathrm{FD}\left(\pi^+\pi^-\right)$	$< 10\,\mathrm{mm}$	99.38	27.35
$\min\left(\mathrm{IP}(\pi^\pm\right)$	$< 1.5\,\mathrm{mm}$	99.98	32.06
$p(\mathrm{ME})$	$> 1.2\,\mathrm{GeV}$	96.43	33.64
$\ldots$	$\ldots$	$\ldots$	$\ldots$
$\prod$		**80.7**	**0.8**

tabea.hacheney@tu-dortmund.de

NUMBER OF LEPTONS

- Number of leptons on the hemisphere with the signal candidate
  - Potential source of missing energy from semileptonic decays
  - Preselection: $\mathrm{no\,.\,leptons} = 0$



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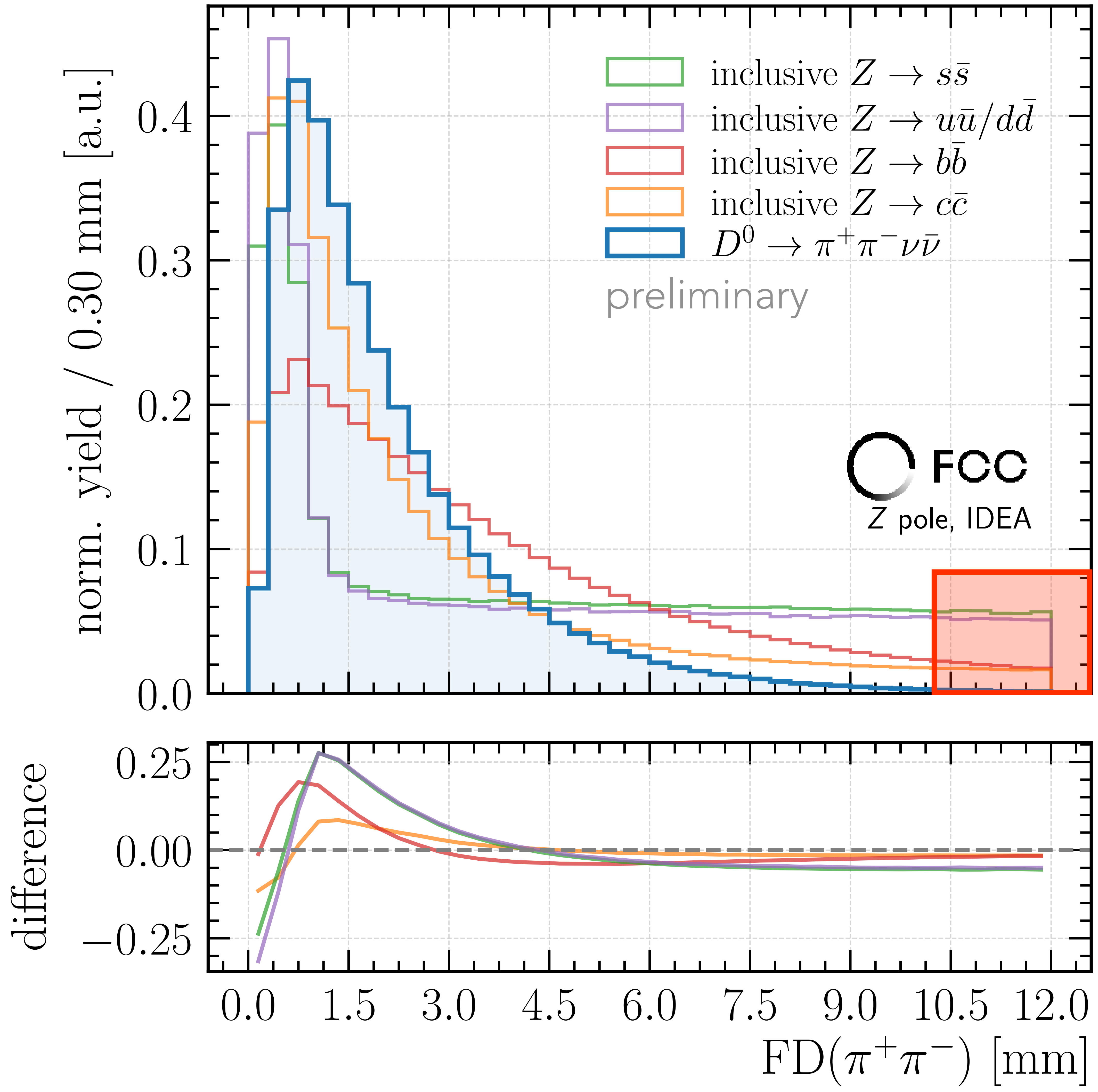
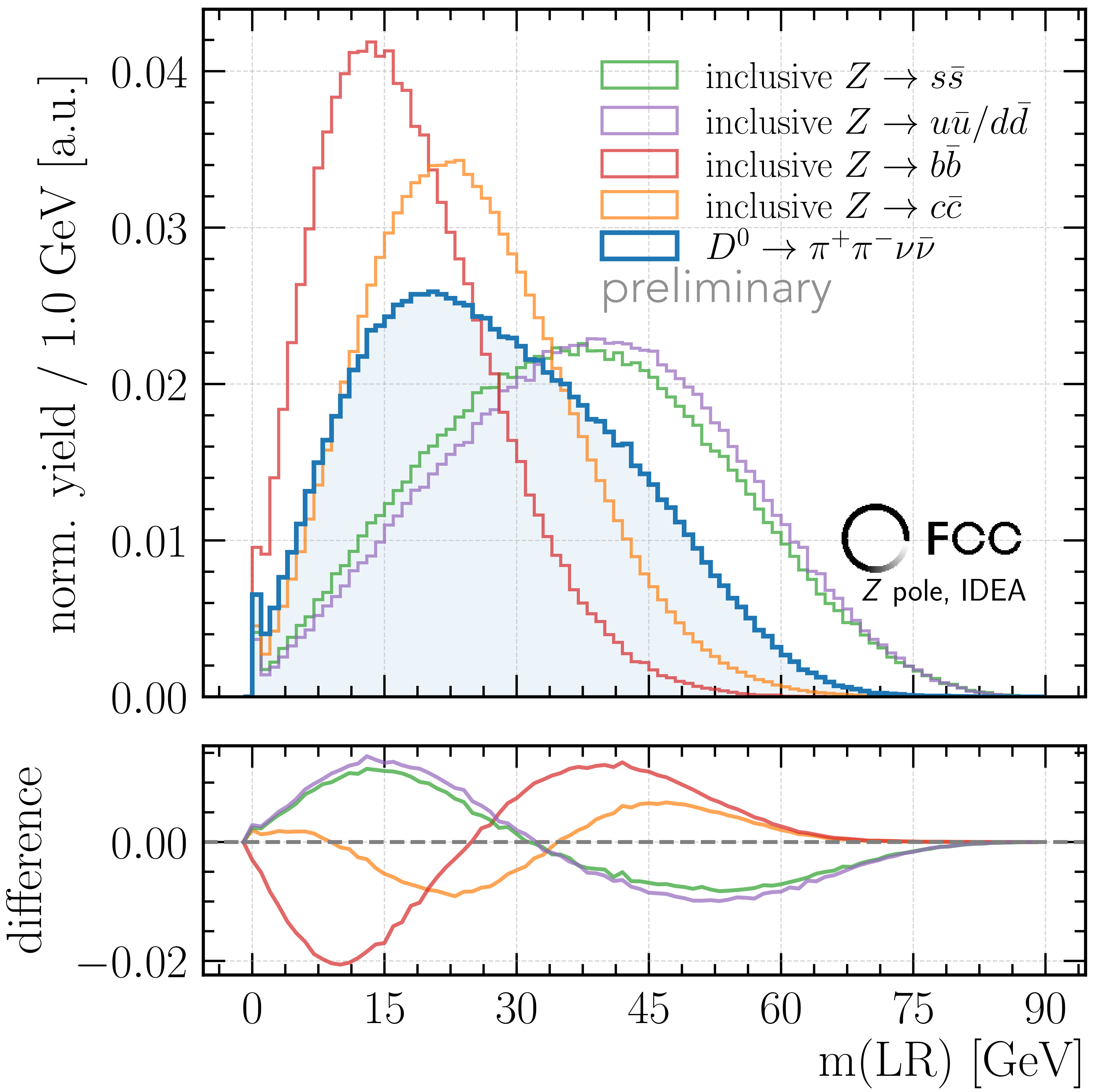
FLIGHT DISTANCE

- Flight distance of signal candidate
  - Discriminate between D-mesons and mesons with long lifetimes ($K_S \to \pi^+\pi^-$)
  - Preselection: $\mathrm{FD} < 10\,\mathrm{mm}$



MASS OF LUMINOUS REGION

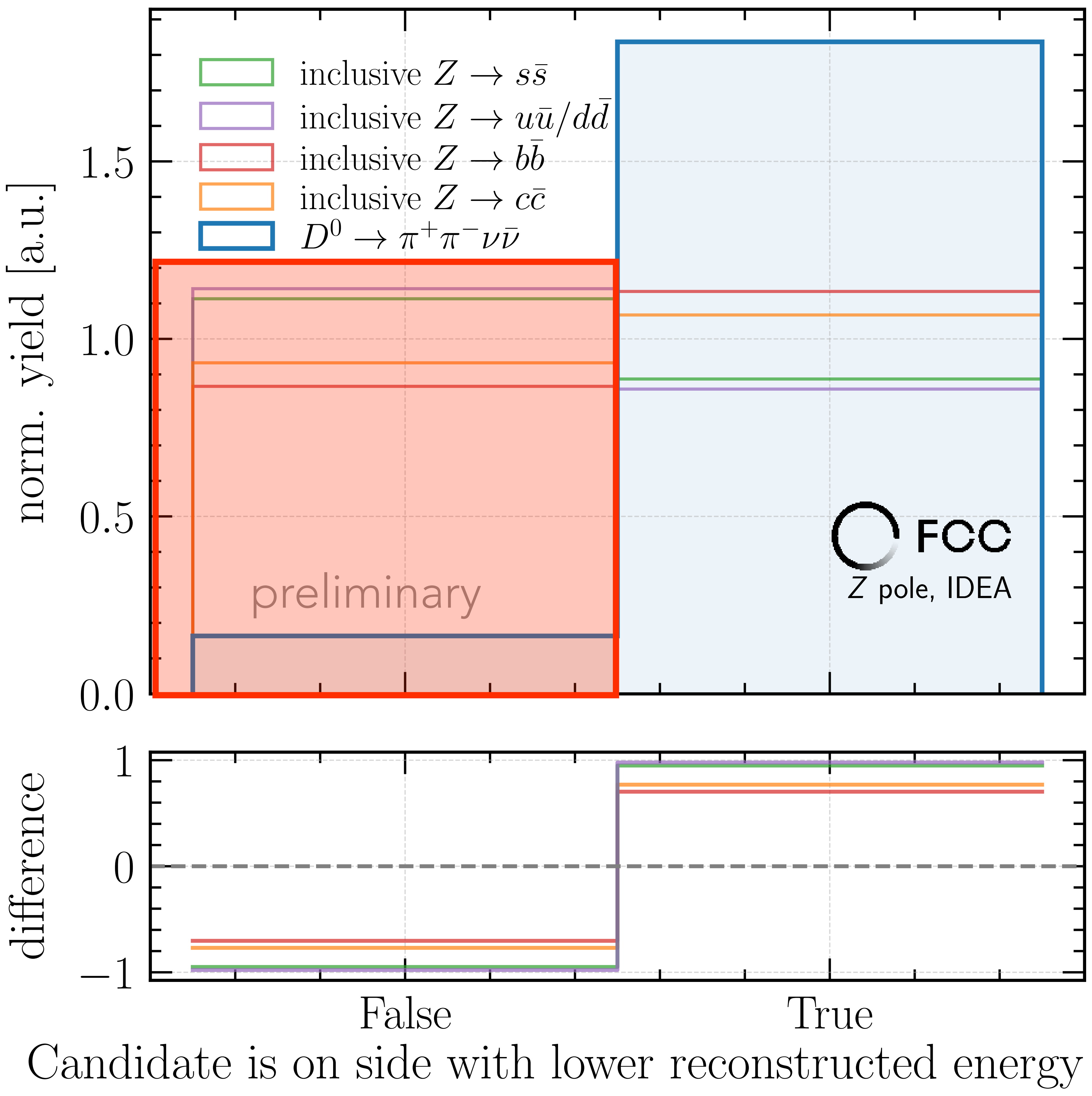
- Invariant mass of all tracks assigned to LR



tabea.hacheney@tu-dortmund.de

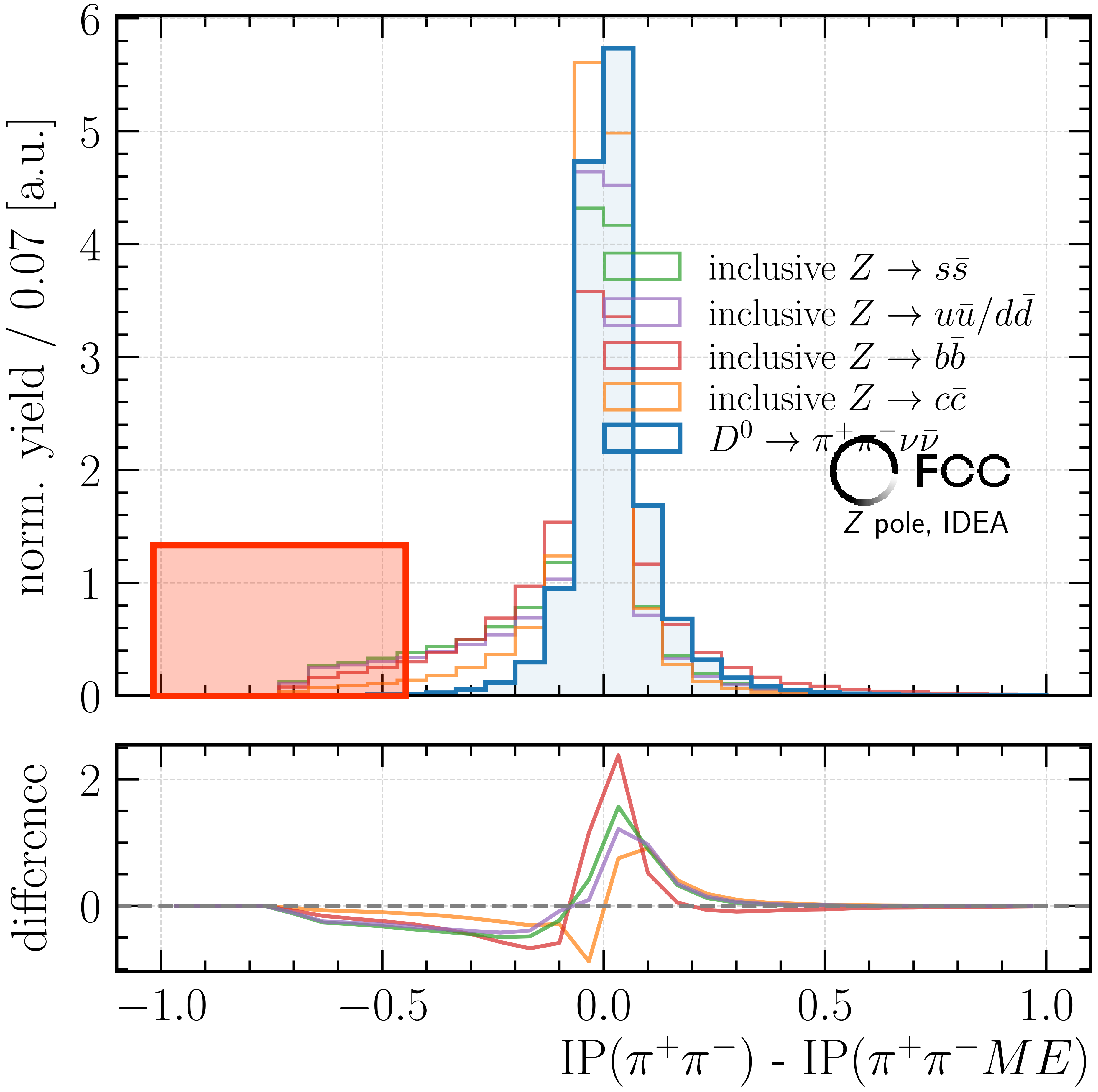
ON SIDE WITH LOWER ENERGY

- Boolean, whether the signal candidate is on hemisphere with lower reconstructed energy
  - Preselection: True



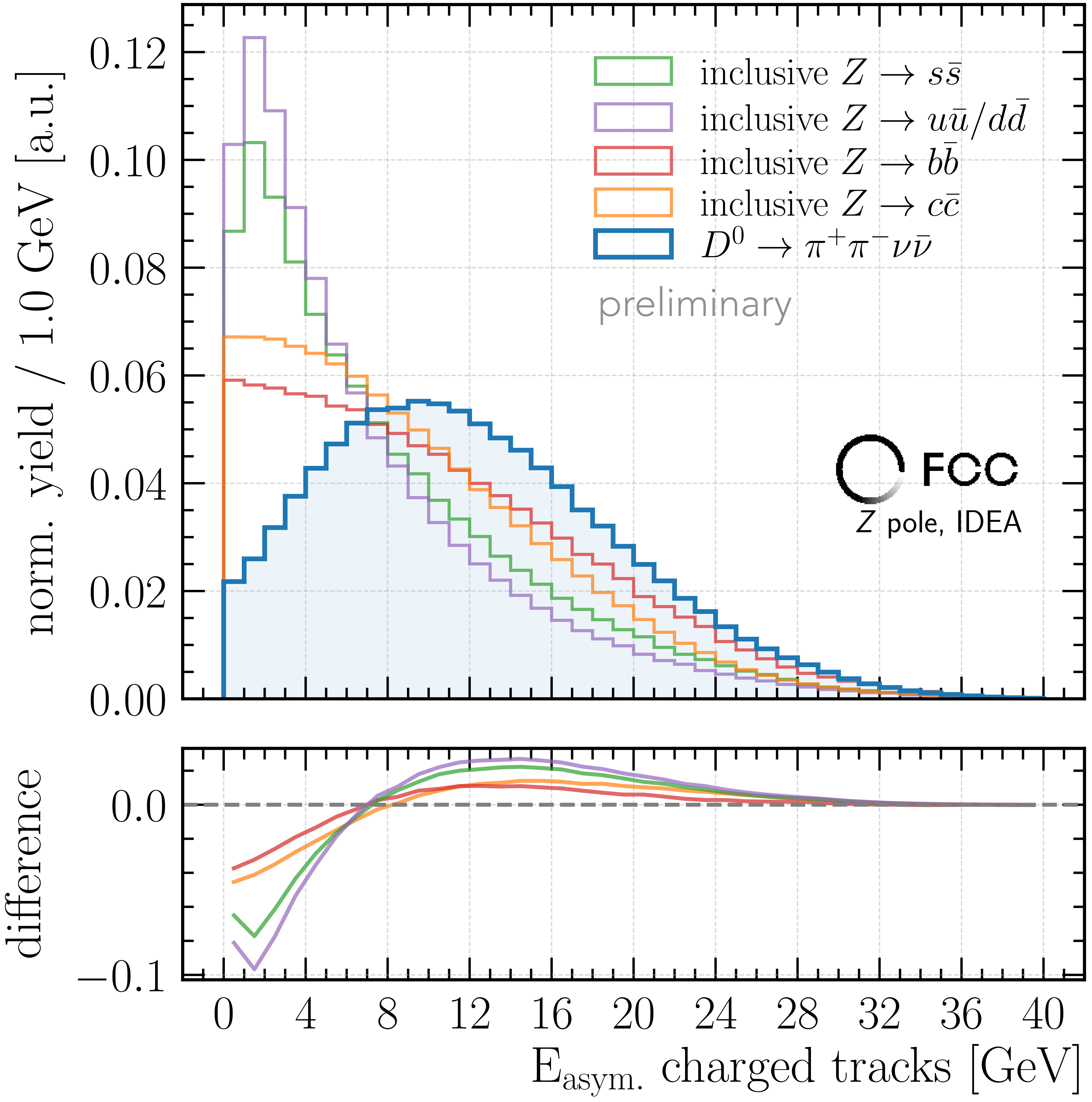
IMPACT PARAMETER W ME

- Difference of the IP of signal candidates using only the two pions vs. using the pions together with the missing energy (ME)
  - IP should on average slightly improve with additional ME for signal
  - Worsen for the background ✅
  - Preselection: $\mathrm{IP}(\pi^+\pi^-) - \mathrm{IP}(\pi^+\pi^-\mathrm{ME}) > -0.7$



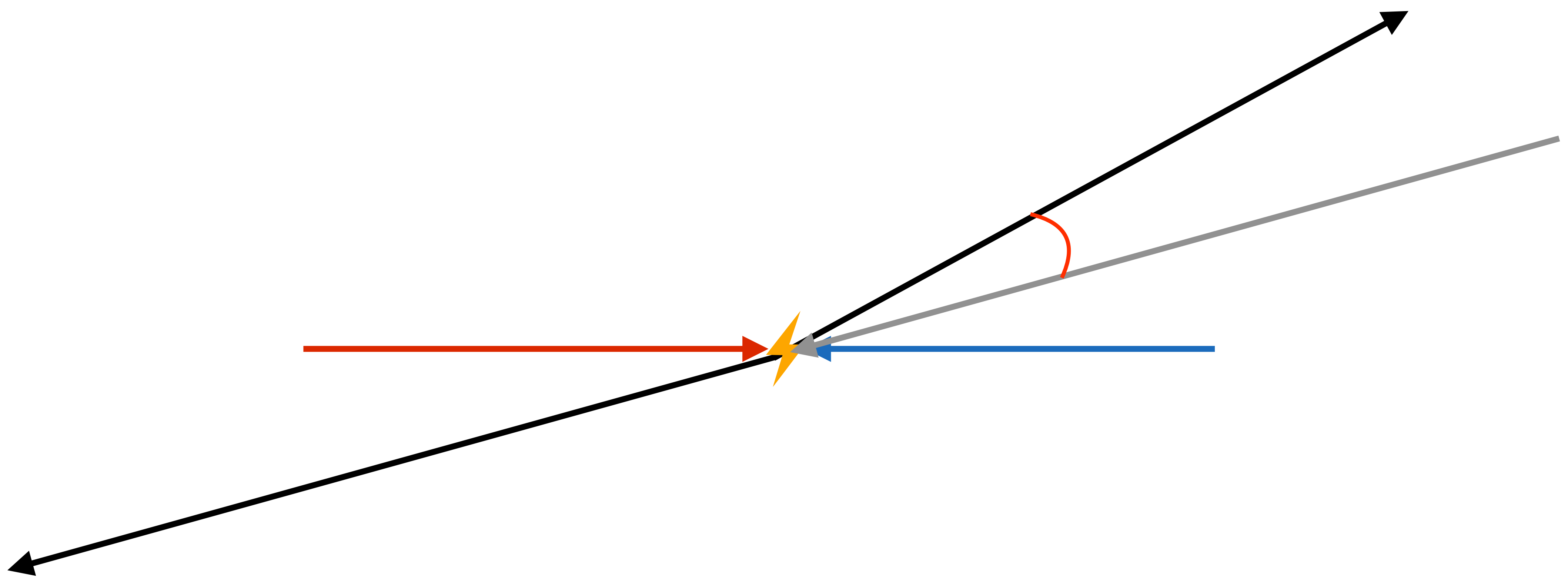
E ASYM. TRACKS

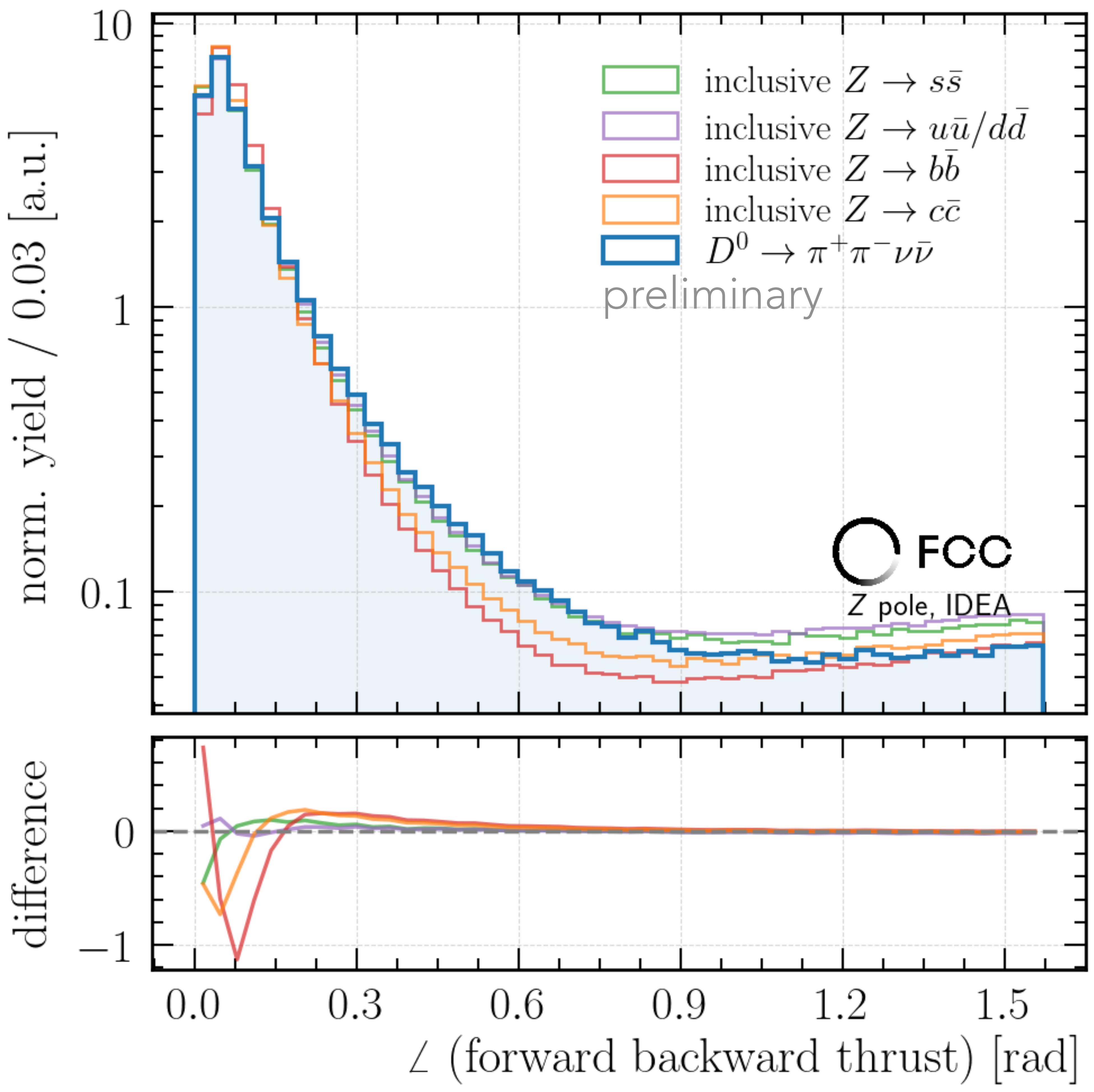
- Total asymmetry of the reconstructed energy of both hemispheres



ANGLE BETWEEN HEMIS. THRUSTS

- Angle between the thrust axes of hemispheres
  - Recalculate thrusts of either hemisphere with particles assigned to it





tabea.hacheney@tu-dortmund.de