top quark CKM and EWK couplings

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FCC project

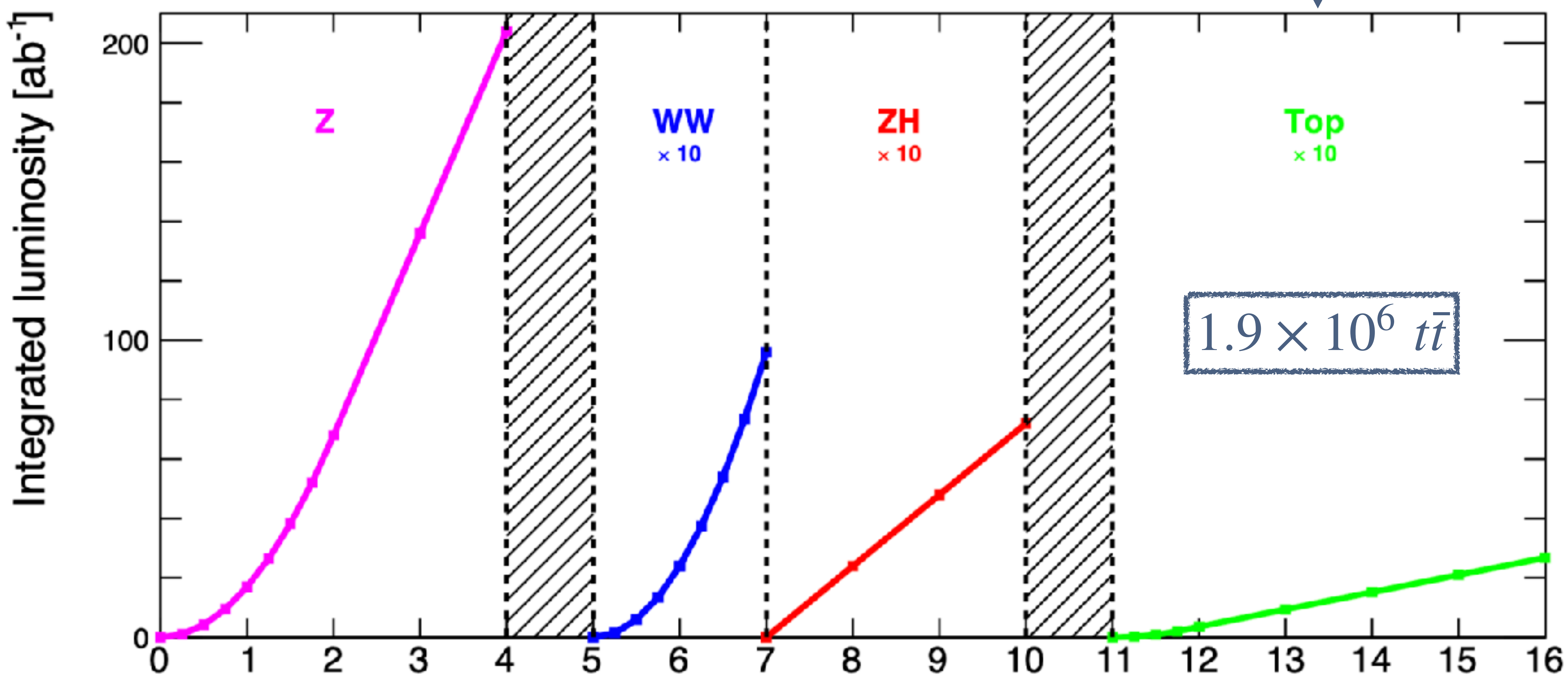
New infrastructure

- 90.7 km tunnel
- 8 surface points
- 4 experimental sites
- Deepest shaft 400 m, average 240 m

Two stages

- FCC-ee (~15 years)
- FCC-hh (>20 years)

FCC-ee dataset



Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	$1.9 \times 10^{6}\ t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

$|V_{ts}|$ measurement

$|V_{ts}|$ introduction

Current measurements on $|V_{ts}|$

- PDG value: $|V_{ts}| = (41.5 \pm 0.9) \times 10^{-3}$
  - From $B_s^0 - \bar{B}_s^0$ mixing, mediated via t-W box diagrams
  - Assume no NP in the loop
  - Dominated by theory uncertainty from lattice QCD
- Also keep $|V_{cb}|$ in mind
  - Inclusive $(42.2 \pm 0.5) \times 10^{-3}$ vs exclusive $(39.8 \pm 0.6) \times 10^{-3}$ (6% tension)

Potential at e^+e^- colliders

- Model-independent direct measurement
- FCC-ee expects $1.9 \times 10^6 \times 2 \times |V_{ts}|^2 \sim$ 6400 cases of $t \to Ws$
  - s-tagging is the core
  - Limited by statistical uncertainty

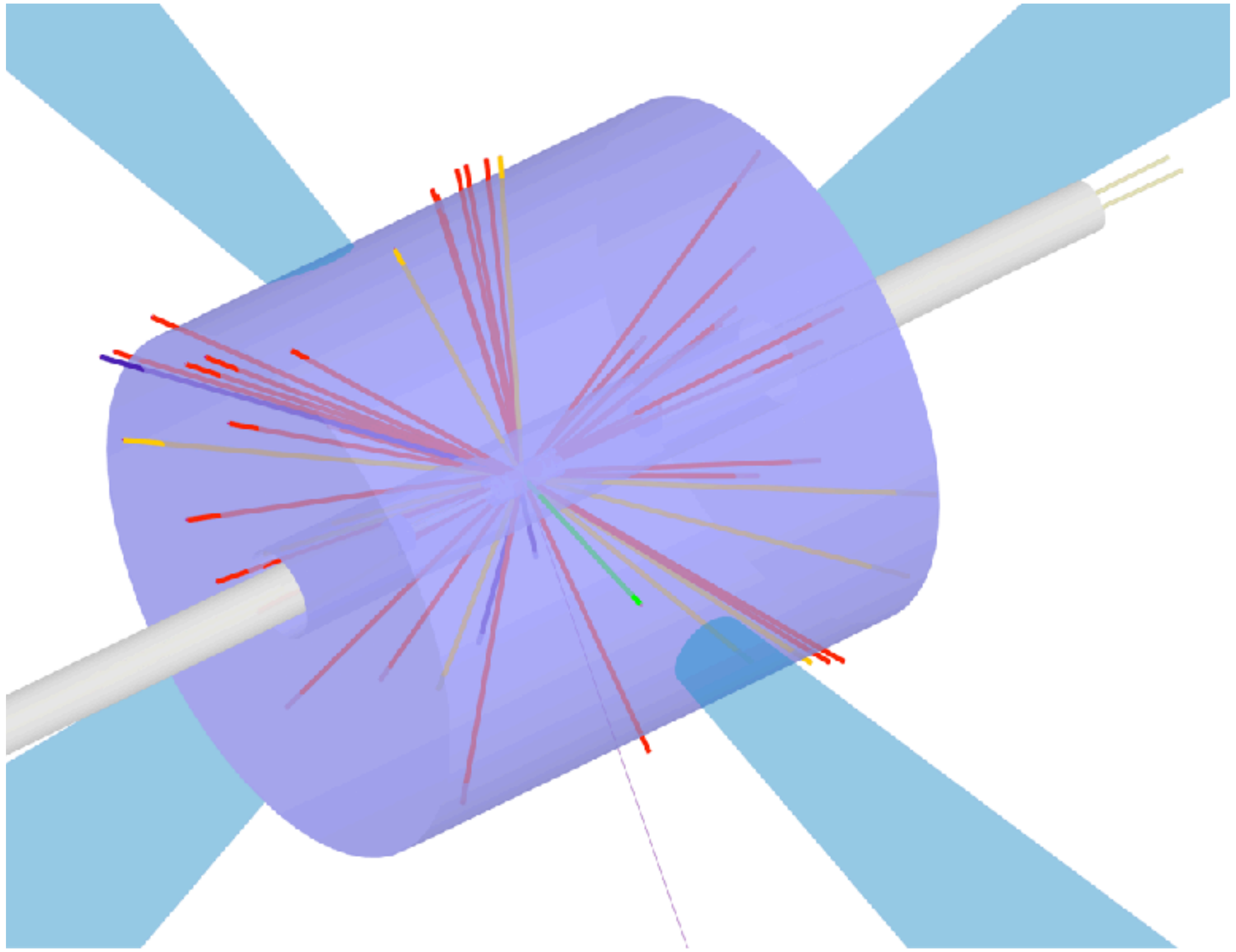
jet clustering

Crucial ingredient of this analysis

- Correctly categorize dileptonic, semi-leptonic, fully hadronic $t\bar{t}$ decays
- Well-defined jets for flavor tagging

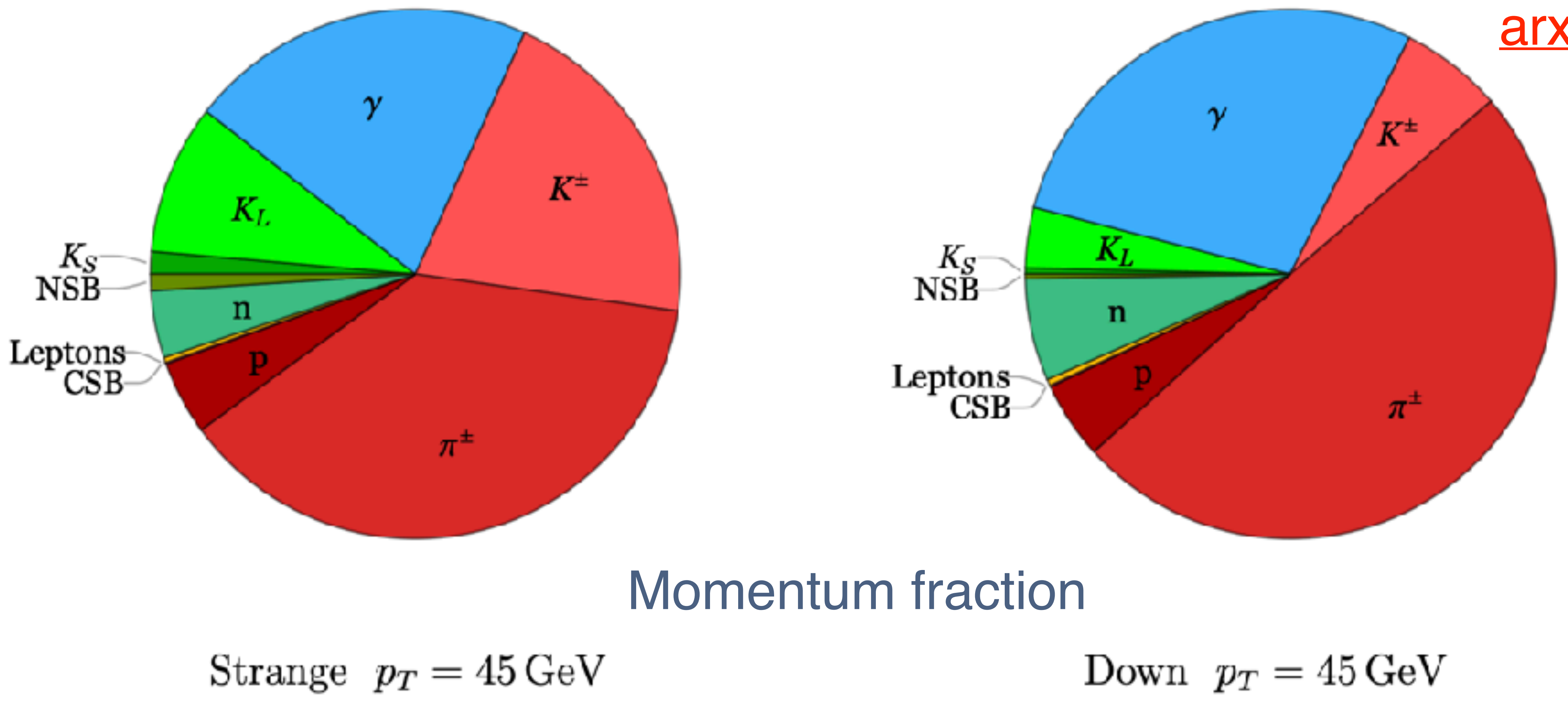
Two types considered

- Exclusive clustering (fixed number of jets in events)
  - subjet distance $d_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})$
- Inclusive clustering (roughly fixed cone size)
  - subjet distance $d_{ij} = \min(E_i^{2p}, E_j^{2p})\frac{1-\cos\theta_{ij}}{1-\cos R}$
  - merge i, j until $\forall\ d_{ij} > E_i^{2p}$



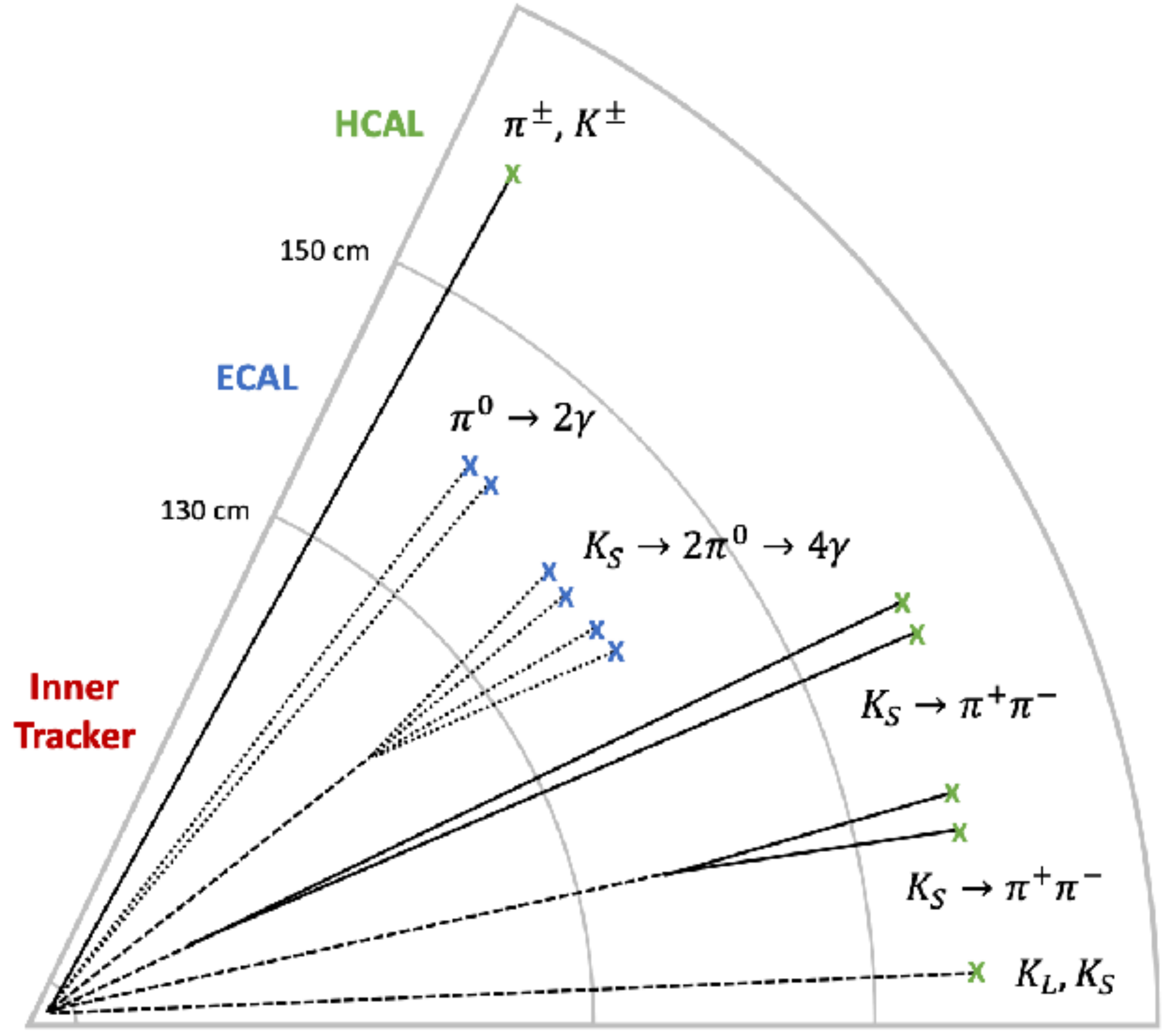
Inclusive jet with R=0.5 as nominal choice in this work

Strange jet tagging



arxiv:2003.09517

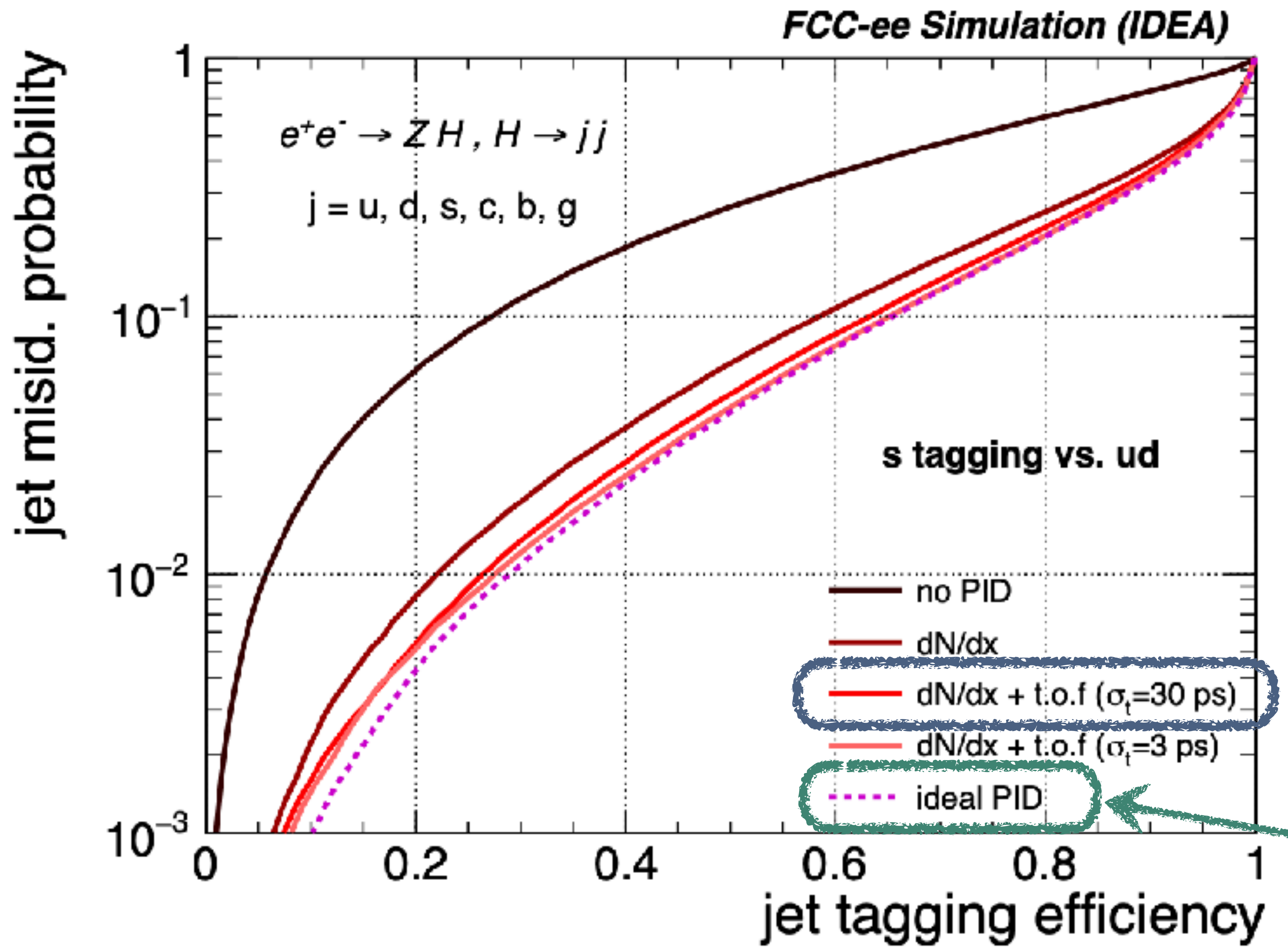
Not to scale



s-baryons Λ, Σ, Ξ have $c\tau \approx 1 - 10$ cm

- Higher fraction of momentum carried by **kaons**
  - K^+/π^+ separation is the key
- Neutral kaons and s-baryons are long-lived
  - $c\tau(b/c) \approx 0.5$ mm, $c\tau(s) \approx 50$ mm
  - Depends on reco efficiency of highly displaced vertices

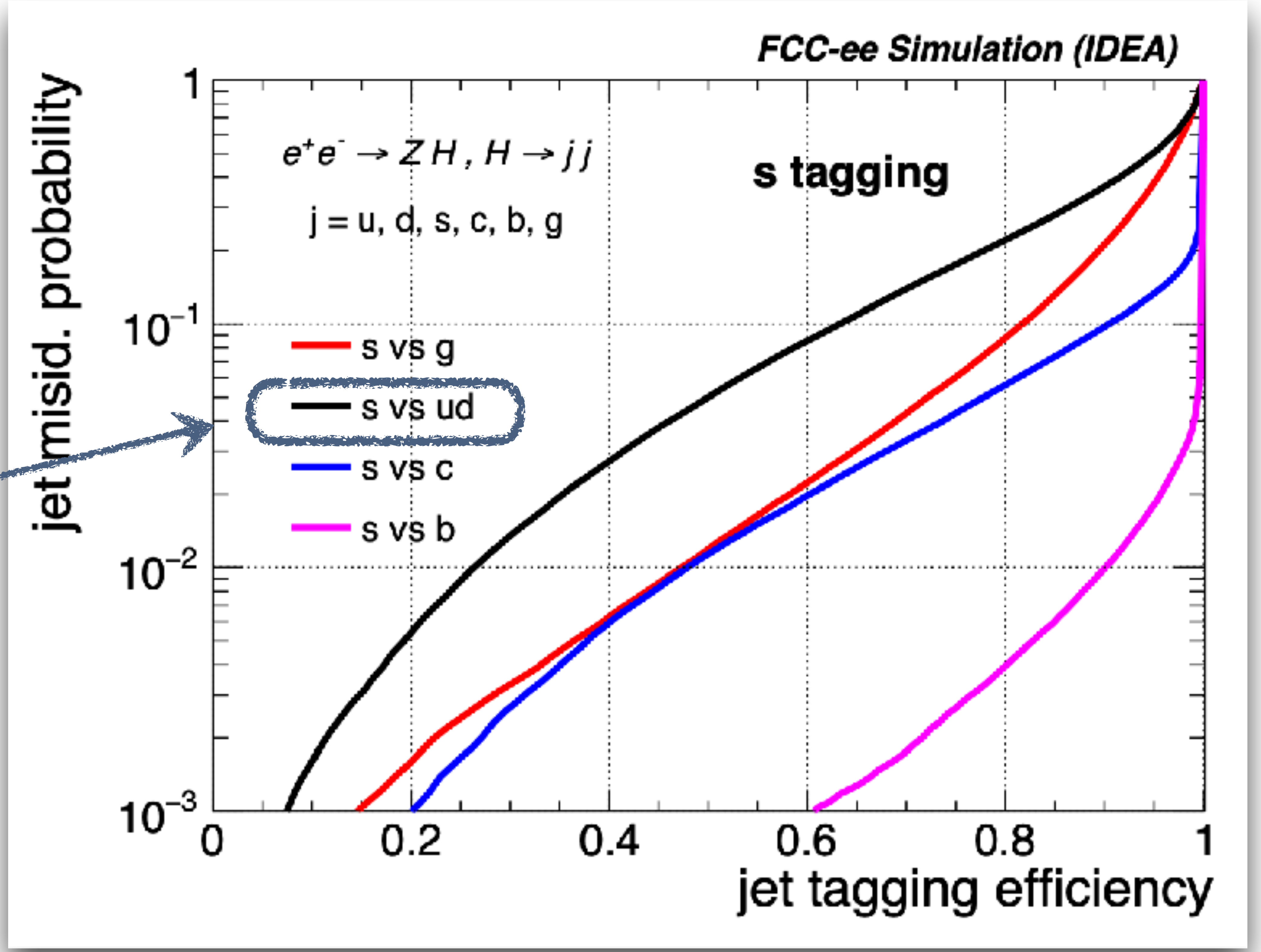
Strange tagging at FCC-ee



Nominal performance

gen PID info

[EPJC 82, 646 (2022)]



- Most improvement from dN/dx
- With nominal design (dN/dx, $\sigma(\text{TOF}) = 30$ ps), already close to perfect PID
- Limited natural separation between s and ud

	Eff (**s**)	Mistag (**g**)	Mistag (**ud**)	Mistag (**c**)	Mistag (**b**)
Loose	90%	20%	40%	10%	1%
Medium	80%	9%	20%	6%	0.4%

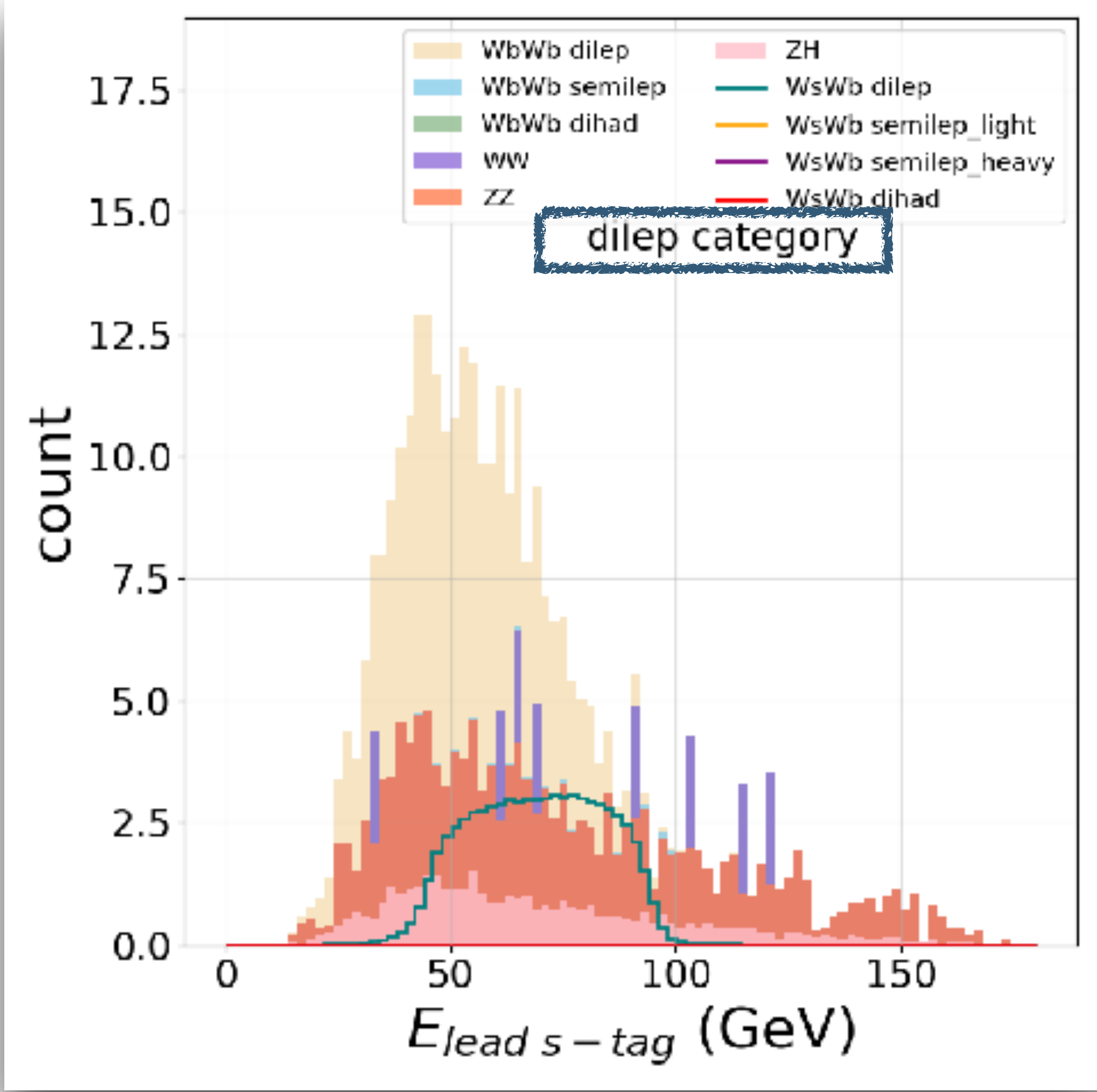
Basic category selection

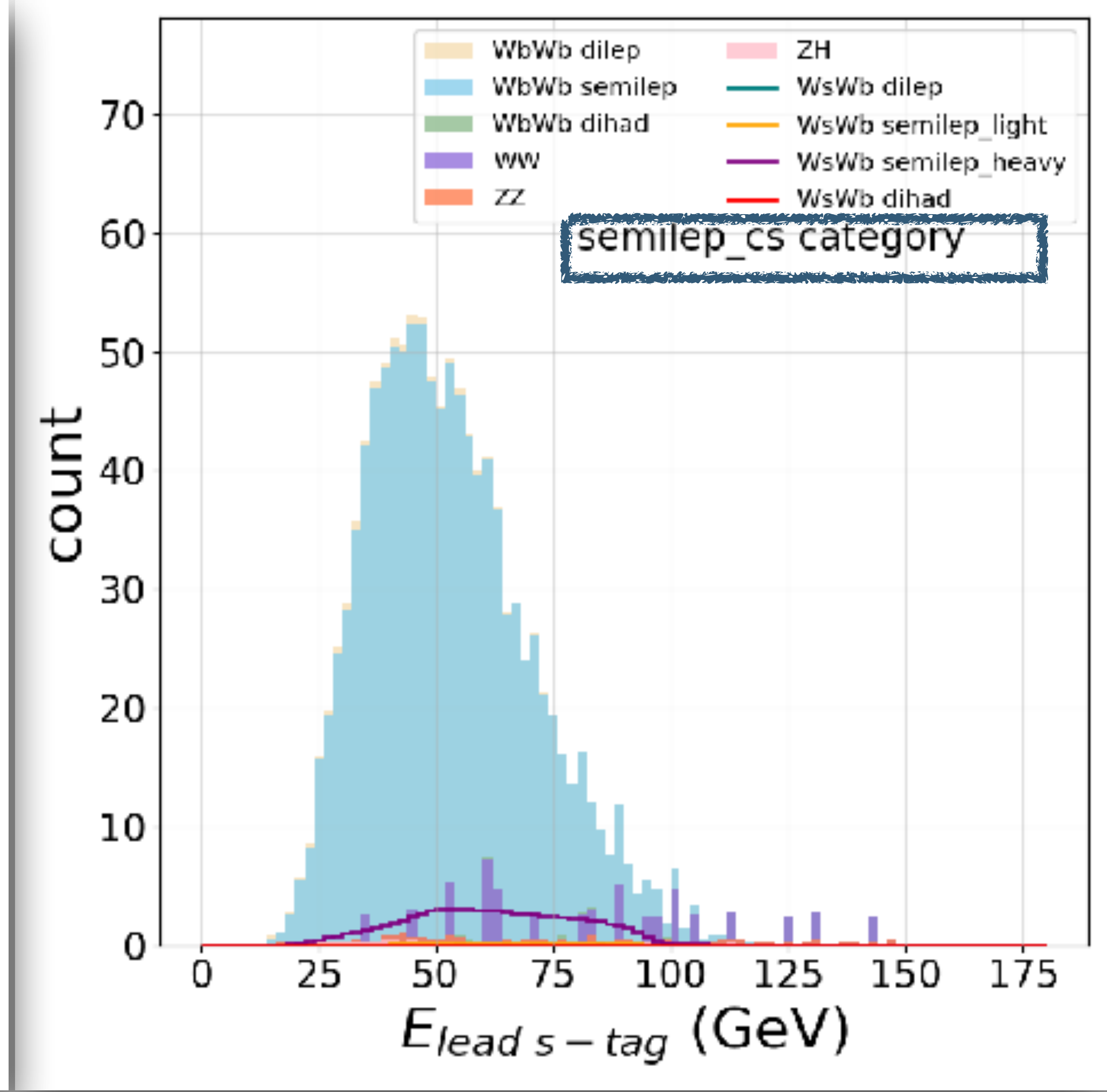
Common pre-selection for $t\bar{t} \rightarrow WsWb$

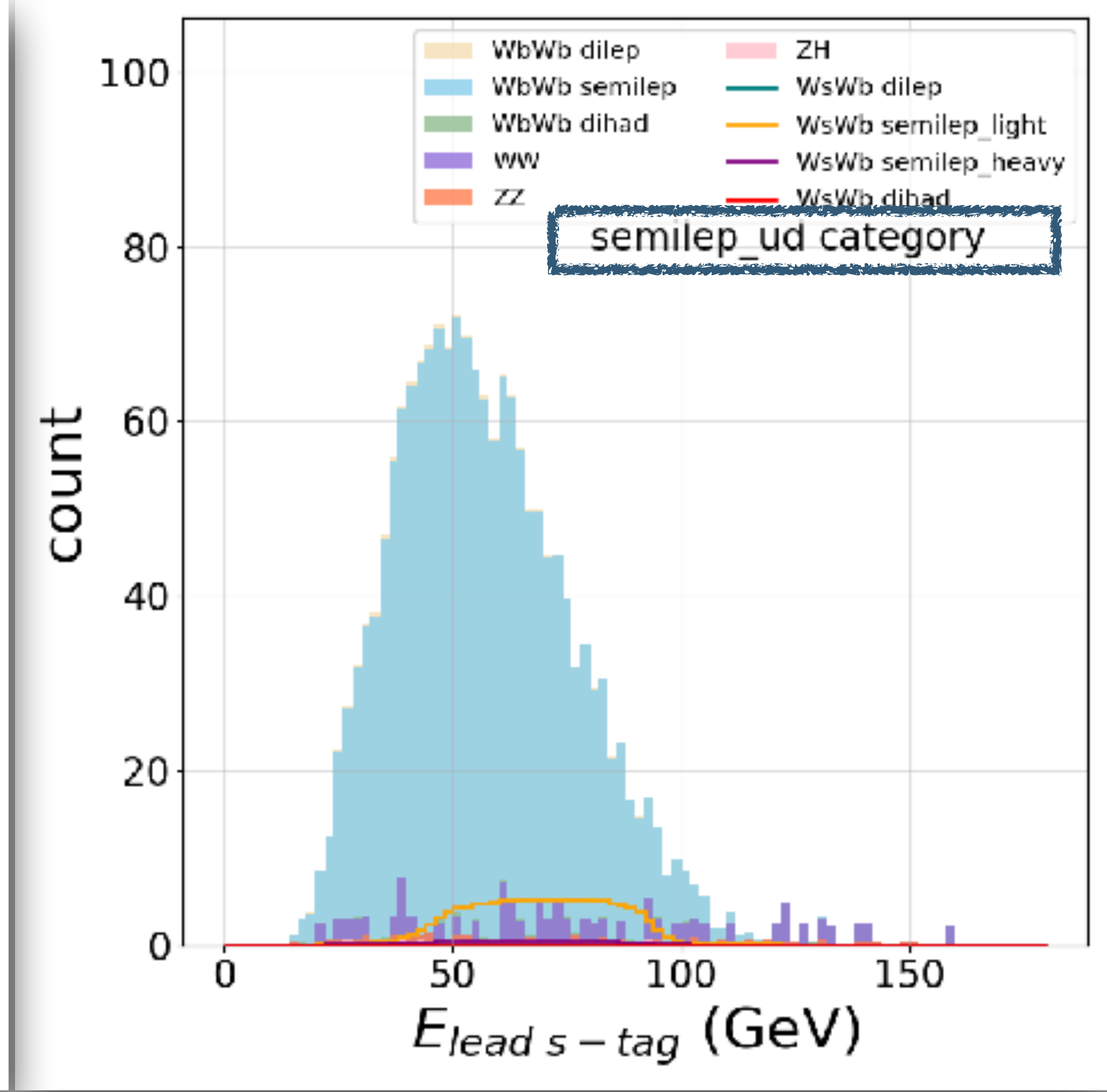
- Exactly 1 “tightly” b-tagged jet (b-score > 0.8),
- Veto additional “loosely” b-tagged (b-score > 0.5)
- At least 1 “tightly” s-tagged jet (s-score > 0.7)
- Always 1 more s-jet than c-jet (s/c-score > 0.5)

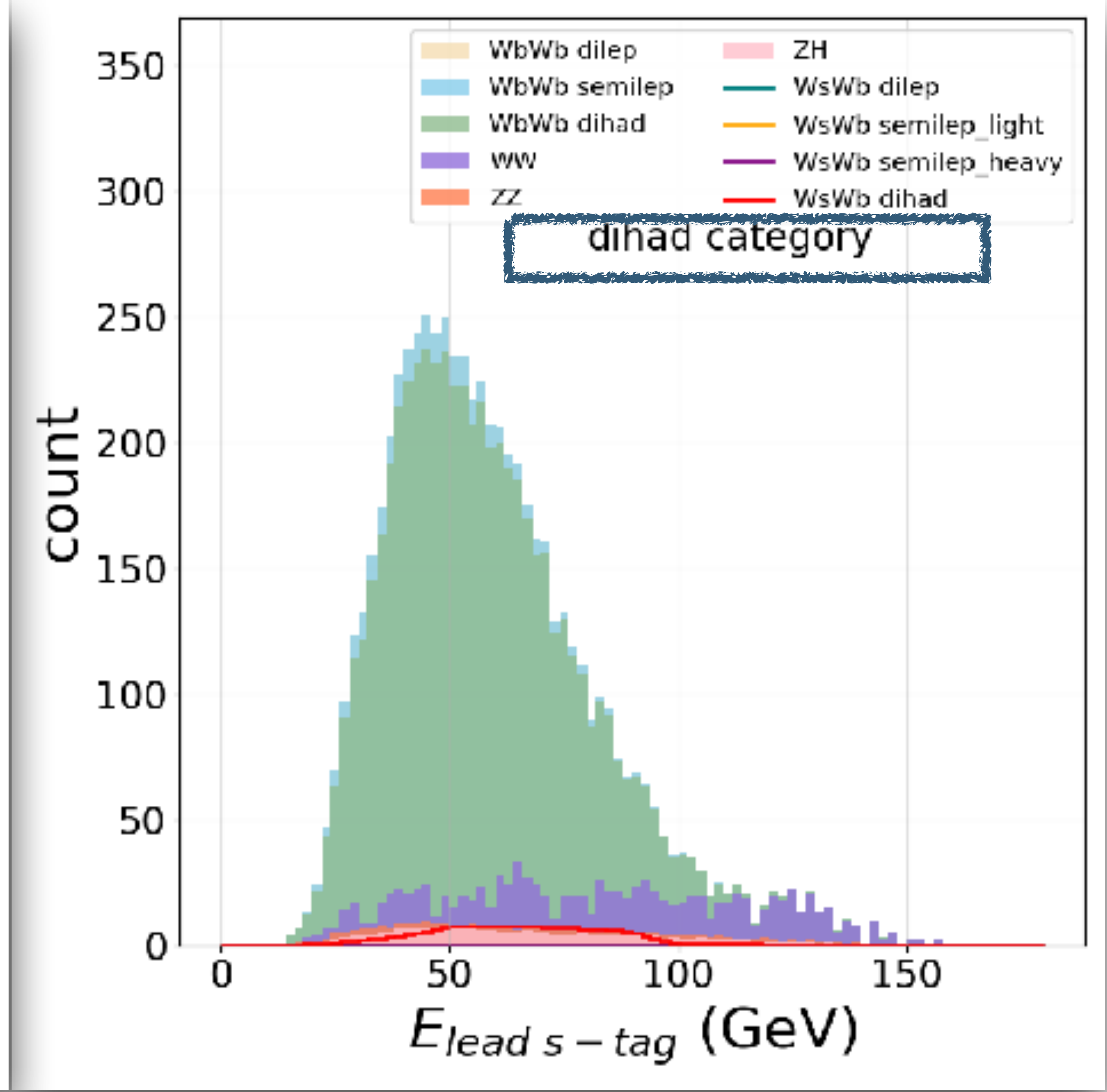
Event categories

- **dilep**: exactly 2 leptons, 2 jets
- **semilep_ud**: exactly 1 leptons, 4 jets (sb+ud)
- **semilep_cs**: exactly 1 leptons, 4 jets (sb+cs)
- **dihad:** exactly 0 lepton, 6 jets









Final selections

dilep cat

- missing energy > 80 GeV
- s-jet candidate energy > 45 GeV
- b-jet candidate energy > 25 GeV
- b-jet b-score > 0.9

semilep_cs cat

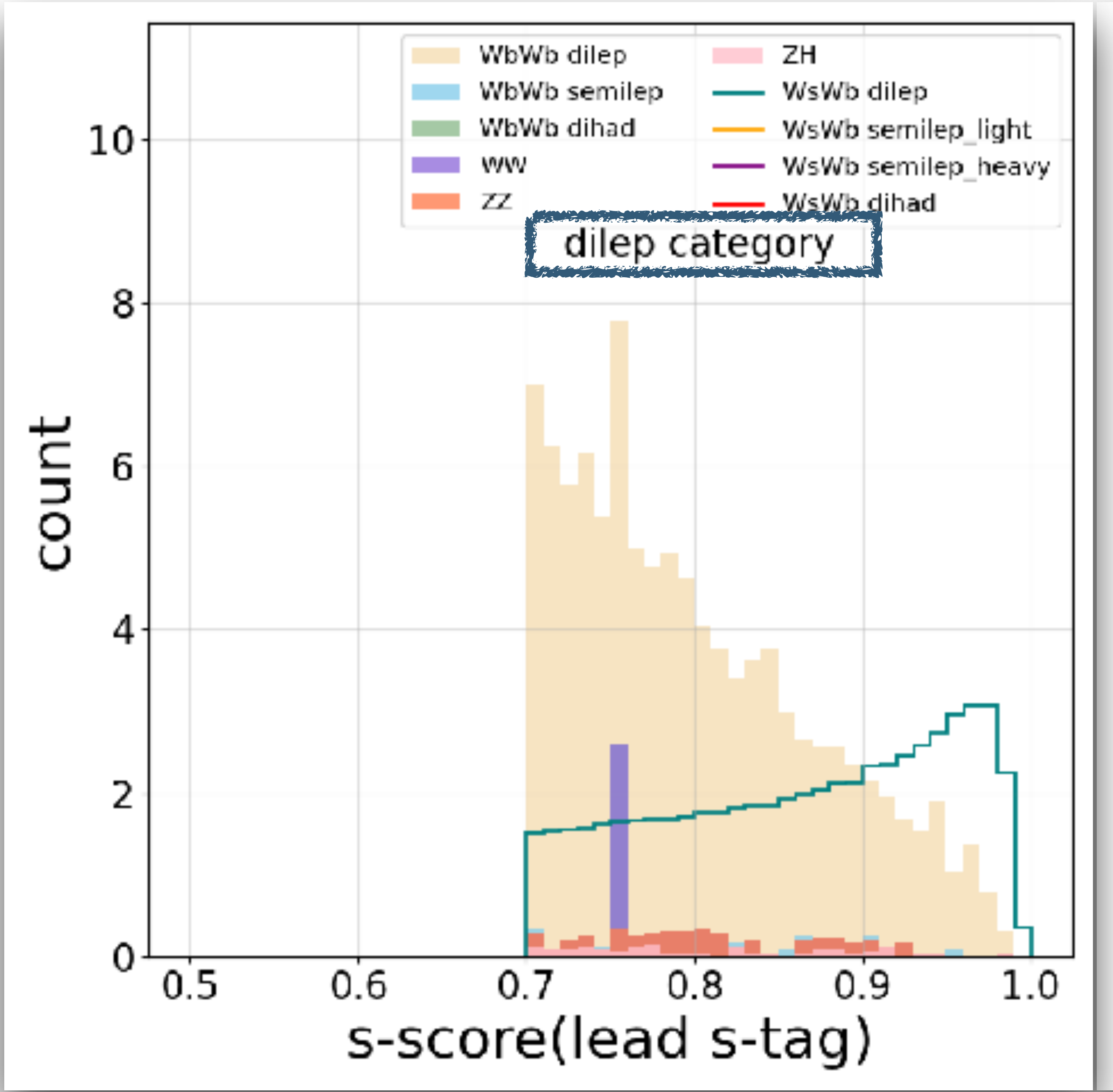
- missing energy > 30 GeV
- Can reconstruct 1 $t \to W(cs)b$ or $t \to W(cs)s$ decay
  - c-score and s-score > 0.5
  - $60 < m_W^{cs} < 80$ GeV
  - $140 < m_{top}^{bcs/scs} < 175$ GeV

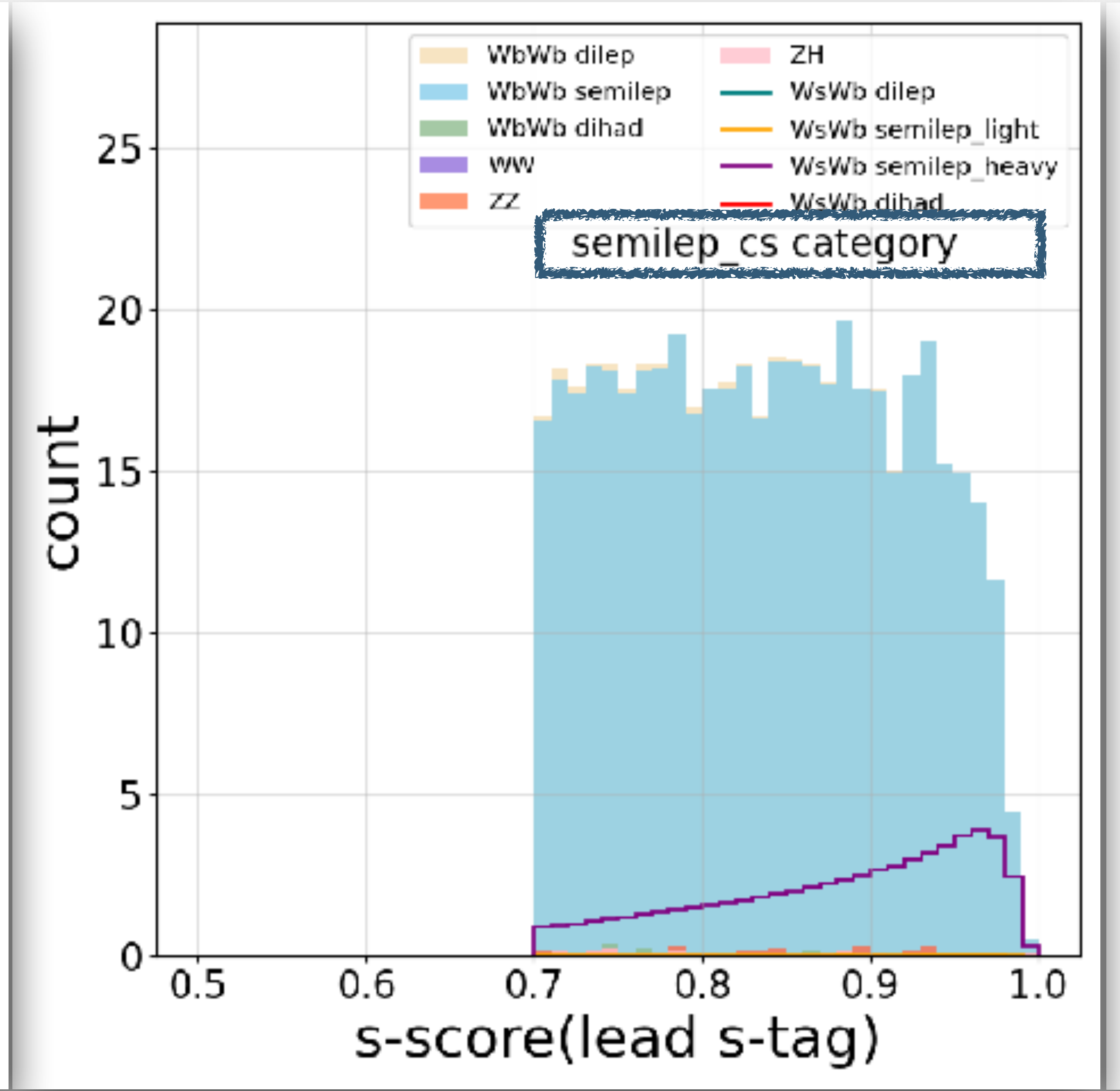
semilep_ud cat

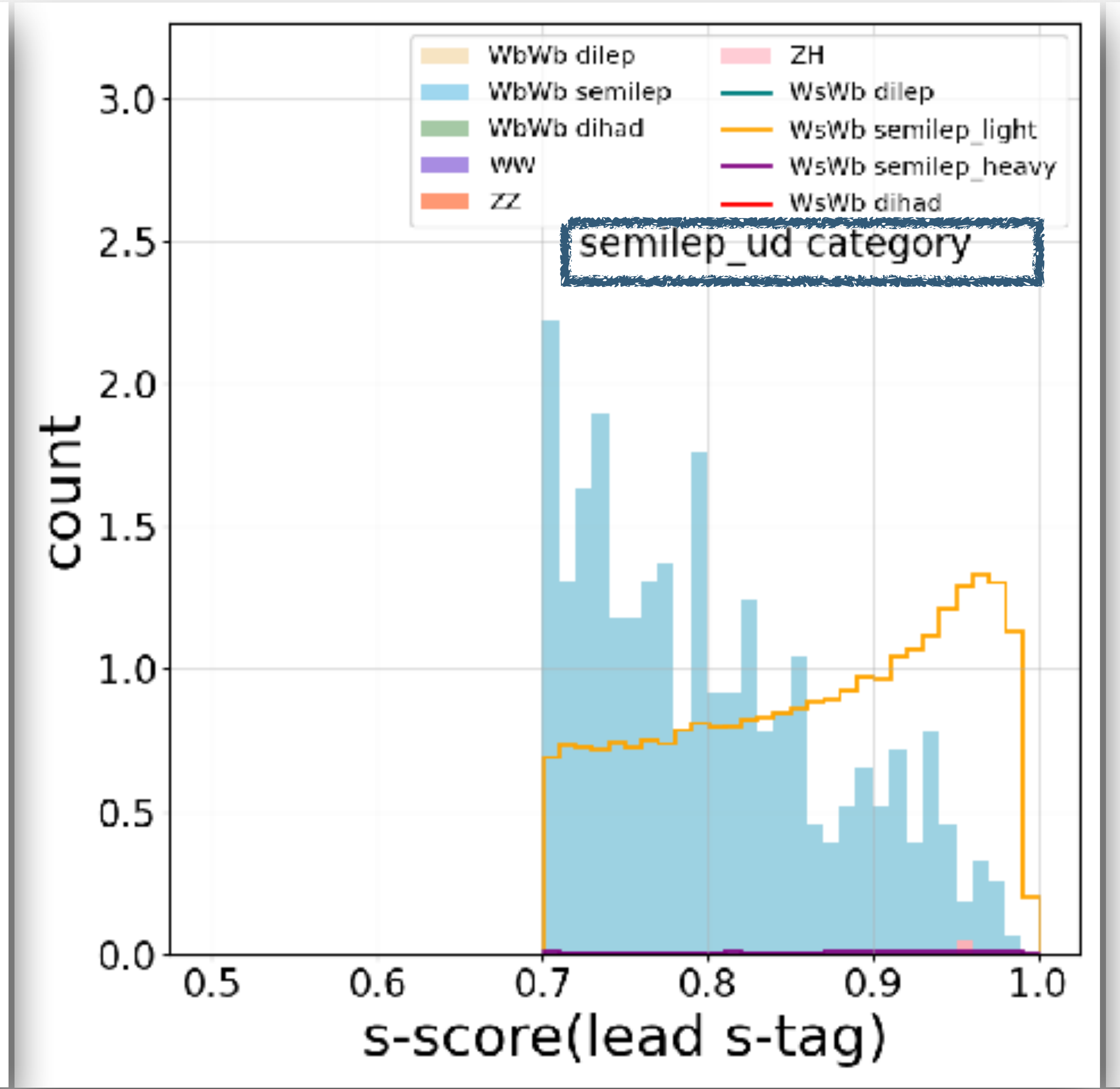
- missing energy > 30 GeV
- Can reconstruct 1 $t \to W(ud)b$ or $t \to W(ud)s$ decay
- s-jet candidate energy > 60 GeV
- s-jet candidate energy > 45 GeV
- b-jet b-score > 0.9

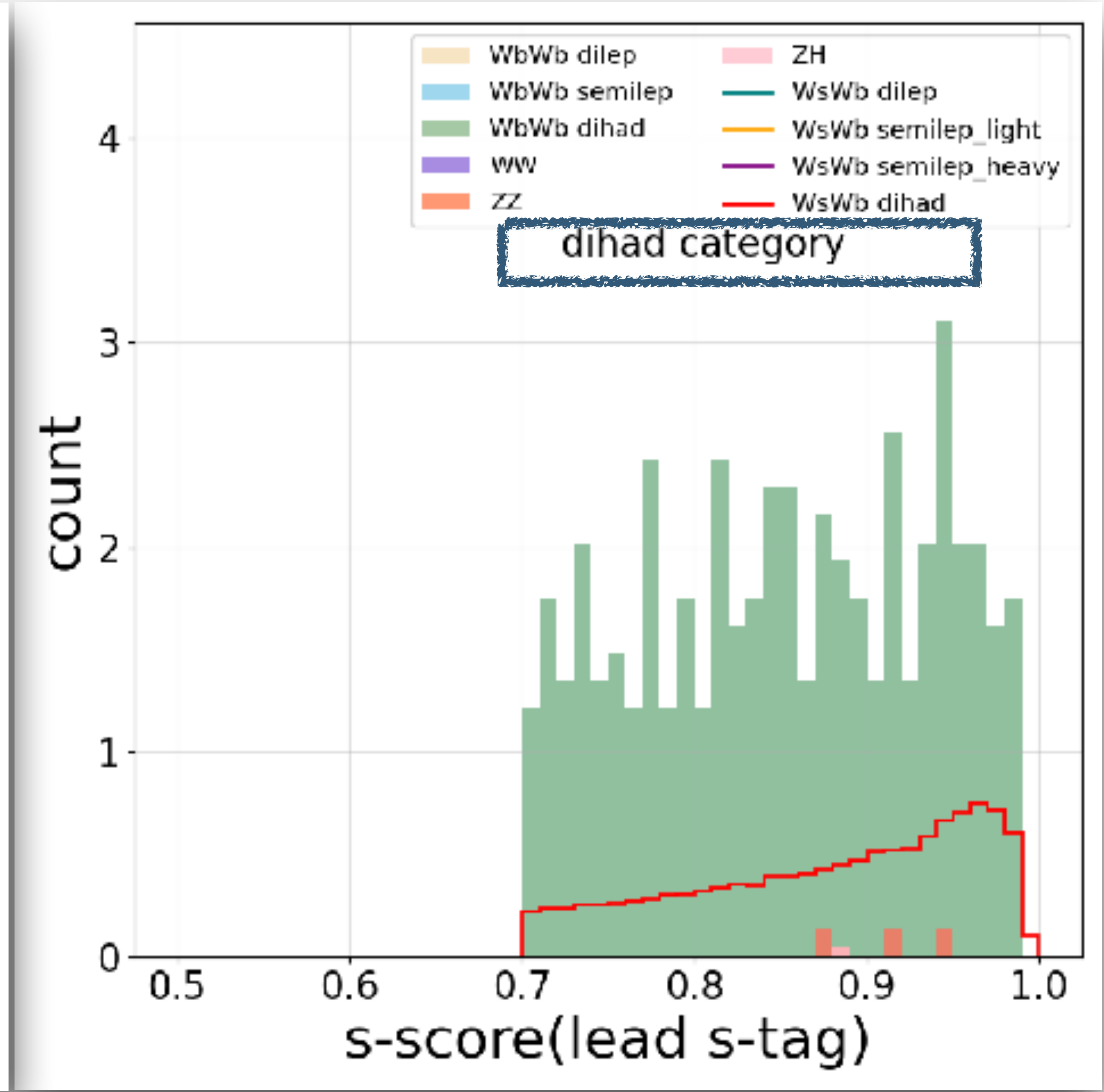
dihad cat

- missing energy < 20 GeV
- s-jet candidate energy > 60 GeV
- b-jet candidate energy > 40 GeV
- b-jet b-score > 0.9
- Can reconstruct 2 top candidates









Expected precision

- Extracted with binned maximum-likelihood fit

category	dilep	semilep_cs	semilep_ud	dihad	combined
significance	5.83	1.13	4.78	1.49	7.77
precision	+29%/-25%	+97%/-88%	+42%/-33%	+177%/-99%	+22%/-20%

- As $\mathscr{B}(t \to Ws) \propto |V_{ts}|^2$, expect $\sigma(|V_{ts}|) \sim 10\%$

More work to be done on pheno impacts

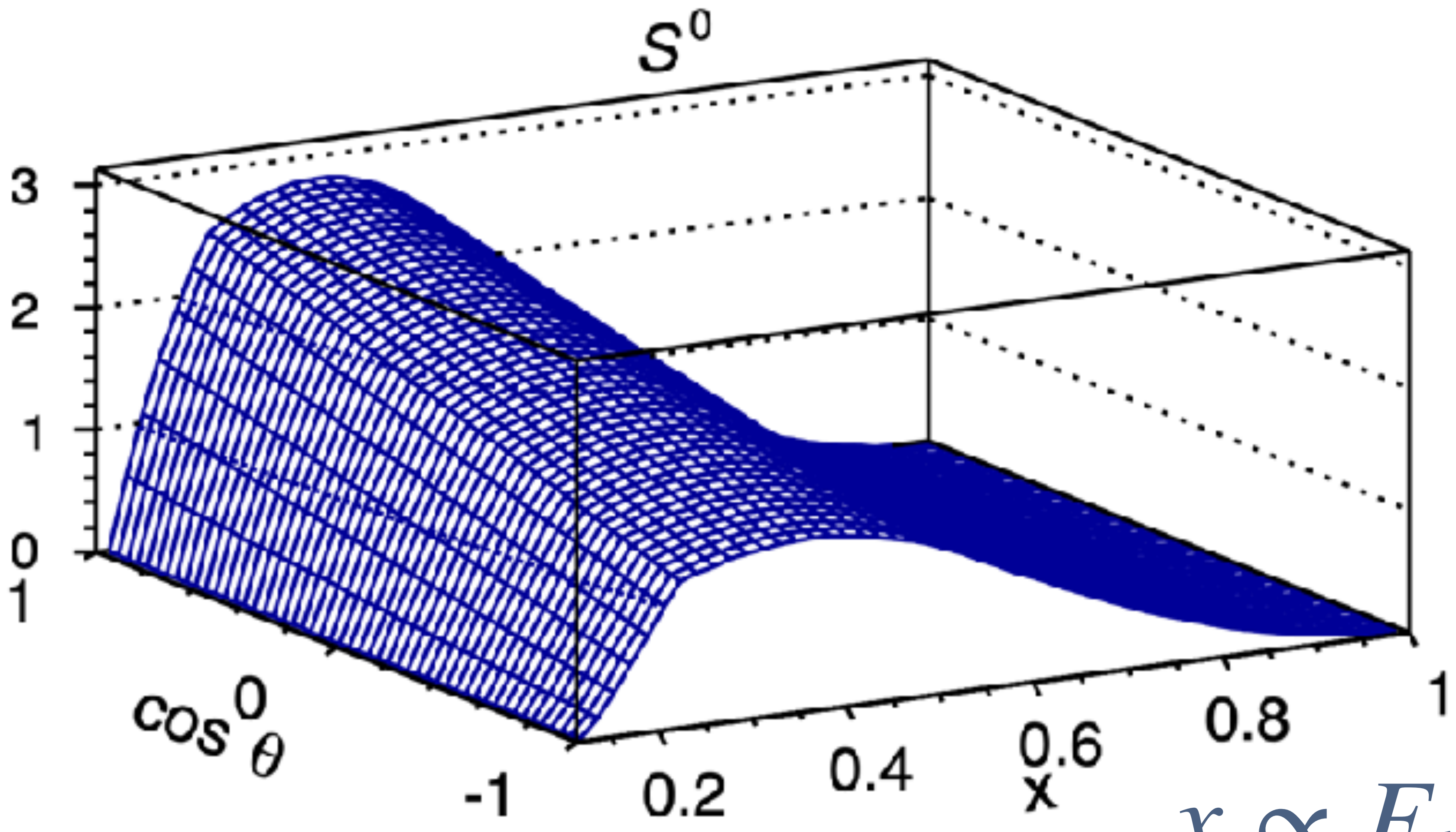
ttZ and $tt\gamma$ couplings

This work is conducted by Simon Keilbach for his bachelor thesis

Top EWK couplings parameters

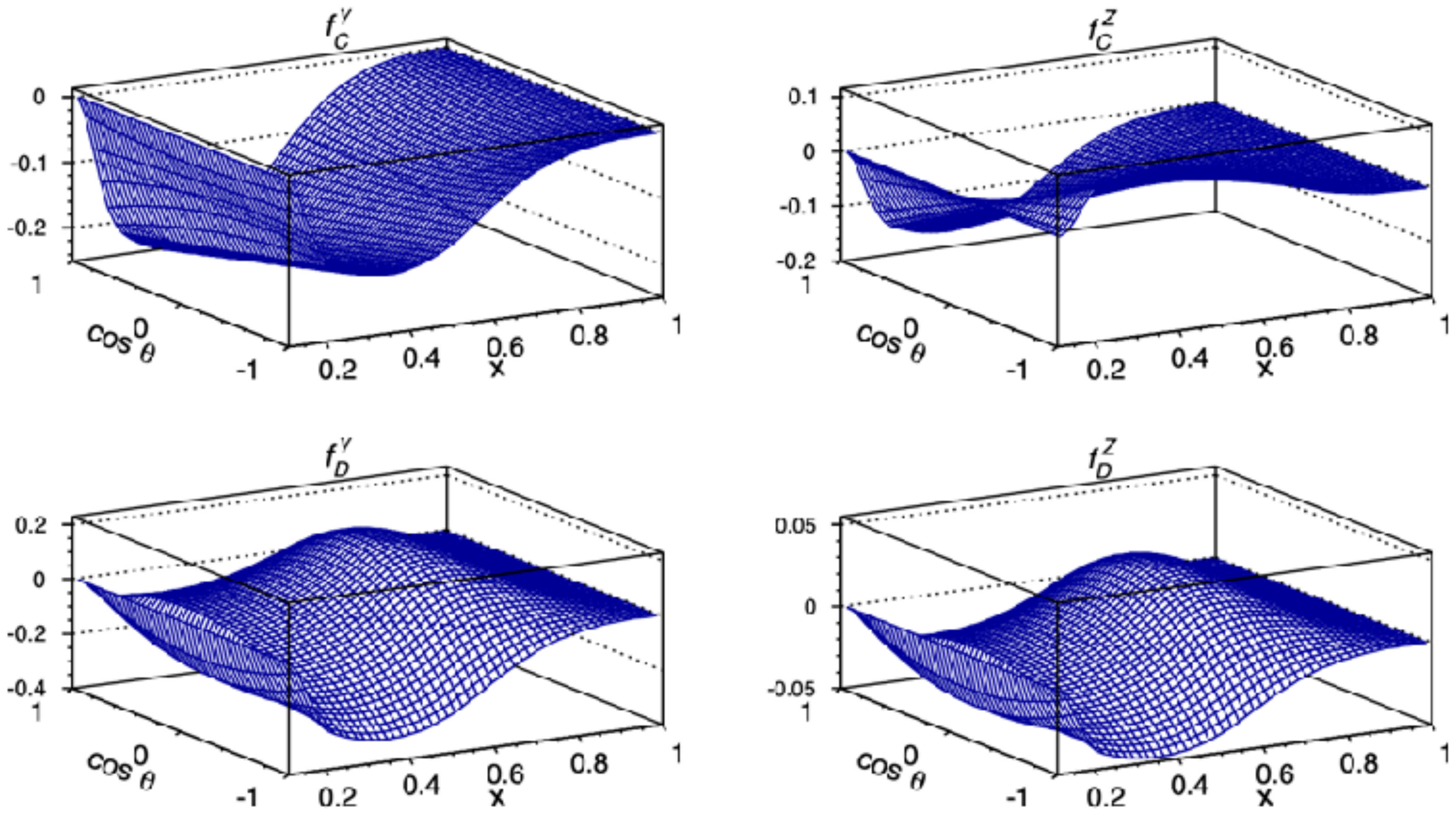
- Direct measurement of ttZ and ttγ couplings
  - Some BSM models can lead to significant deviations from SM
  - Traditionally more discussed in polarized e+e- collisions. For example at ILC (arXiv 1306.6352)
  - Study from FCC (10.1007/JHEP04(2015)182) also expects sensitivity without beam polarization.

SM case



$x \propto E_l$

examples of BSM contributions



Frameworks for modified couplings

10.1007/JHEP04(2015)182

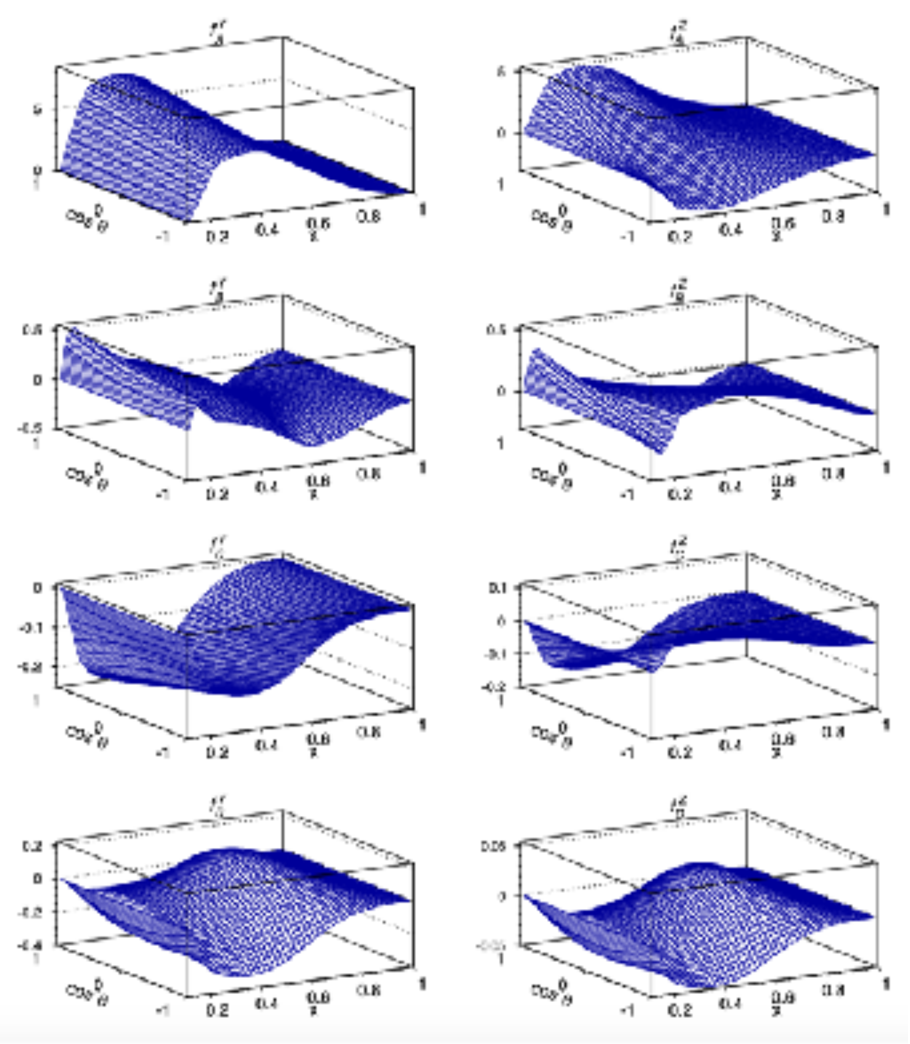
- coupling constants expressed in form factors

$$\Gamma_\mu^{ttX} = -ie\left\{\gamma_\mu\left(F_{1V}^X + \gamma_5 F_{1A}^X\right) + \frac{\sigma_{\mu\nu}}{2m_t}(p_t + p_{\bar{t}})^\nu\left(iF_{2V}^X + \gamma_5 F_{2A}^X\right)\right\},$$

- optimal observable parametrization

$$A_v + \delta A_v = -2i\sin\theta_W\left(F_{1V}^X + F_{2V}^X\right), \qquad B_v + \delta B_v = -2i\sin\theta_W F_{1A}^X,$$
$$\delta C_v = -2i\sin\theta_W F_{2V}^X, \qquad \delta D_v = -2\sin\theta_W F_{2A}^X.$$

- 8 independent modifications



Whizard setup (F. Bach thesis)

- Lagrangians

$$\mathcal{L}_{ttZ} = -\frac{g}{2c_w}\bar{t}\gamma^\mu\left(X_{tt}^L P_L + X_{tt}^R P_R - 2s_w^2 Q_t\right)t\,Z_\mu - \frac{g}{2c_w}\bar{t}\frac{\mathrm{i}\sigma^{\mu\nu}q_\nu}{m_Z}\left(d_V^Z + \mathrm{i}d_A^Z\gamma_5\right)t\,Z_\mu,$$

$$\Delta\mathcal{L}_{tt\gamma} = -eQ_t\bar{t}\gamma^\mu t\,A_\mu - e\bar{t}\frac{\mathrm{i}\sigma^{\mu\nu}q_\nu}{m_t}\left(d_V^\gamma + \mathrm{i}d_A^\gamma\gamma_5\right)t\,A_\mu$$

- Parameterization in Whizard SM_top_anom model

$X_{tt}^L = \texttt{vl\_ttZ}$ $\qquad X_{tt}^R = \texttt{vr\_ttZ}$

$d_V^Z = \texttt{tv\_ttZ}$ $\qquad d_A^Z = \texttt{ta\_ttZ}$

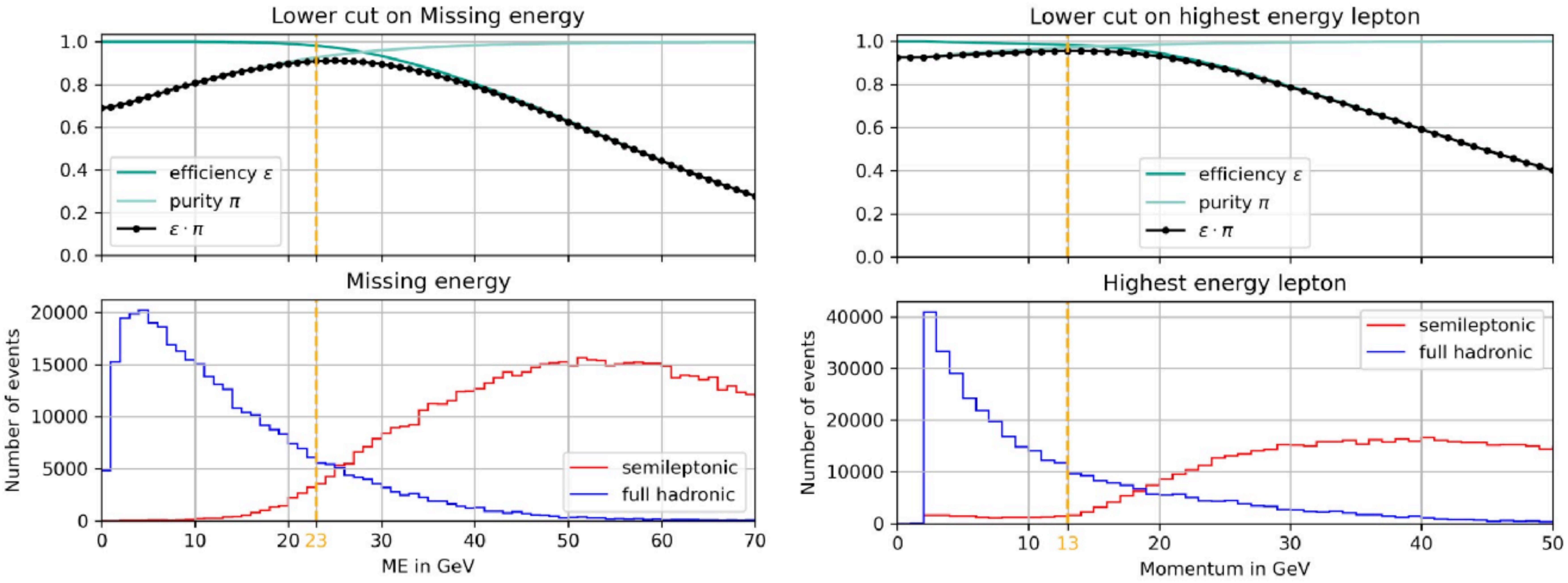
$d_V^\gamma = \texttt{tv\_ttA}$ $\qquad d_A^\gamma = \texttt{ta\_ttA}$

- Independent modifications
  - 6 parameters related to ttZ and ttγ couplings, 3 are constrained by gauge invariance
  - tv_ttZ fixed by tv_ttA, ta_ttZ fixed by ta_ttA, vl_ttZ fixed by vl_tbW
  - **In this work, use 3 independent modifications: tv_ttA, ta_ttA, vr_ttZ**

Event selection

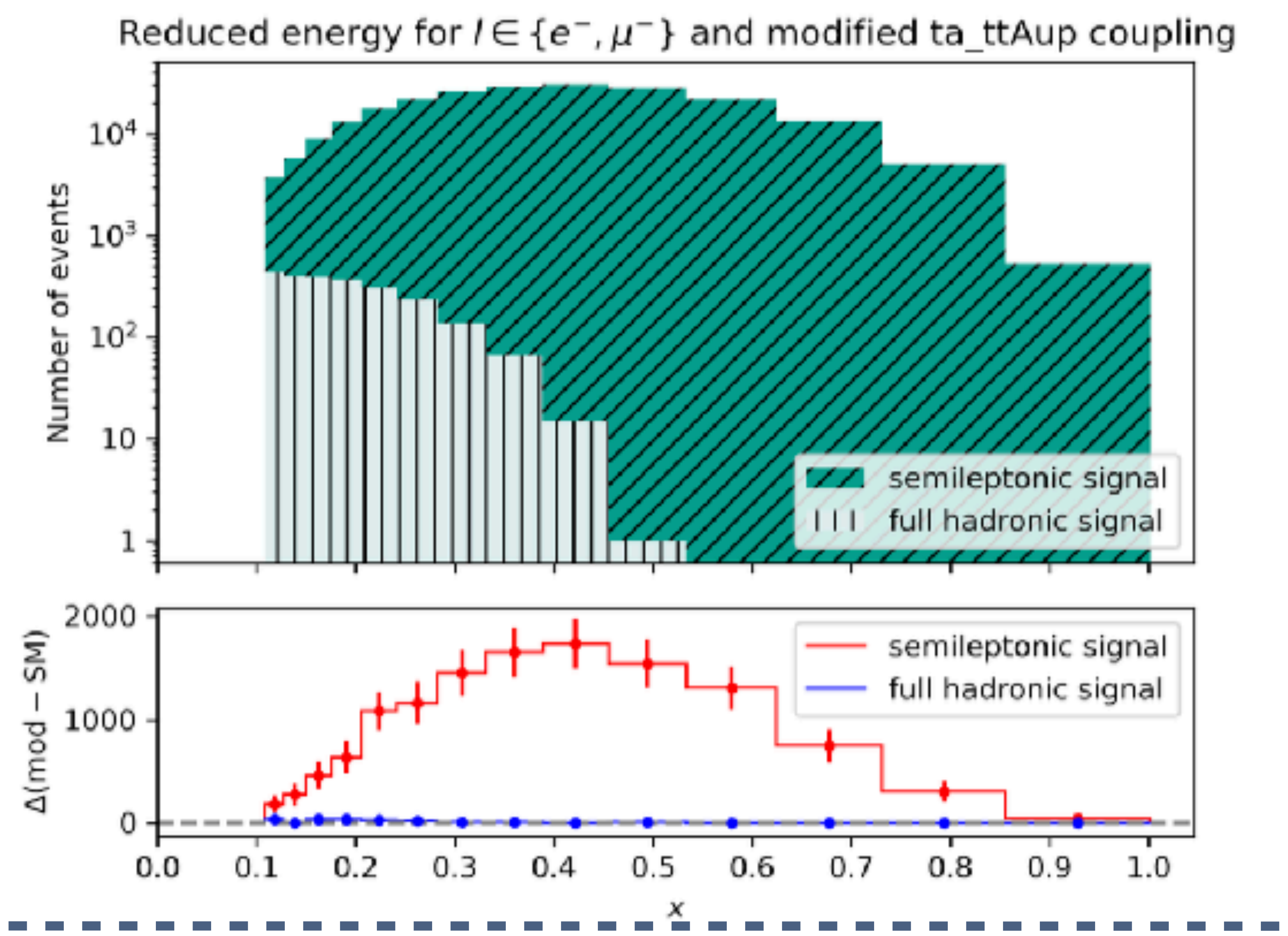
This analysis targets semileptonic $t\bar{t}$ decay:

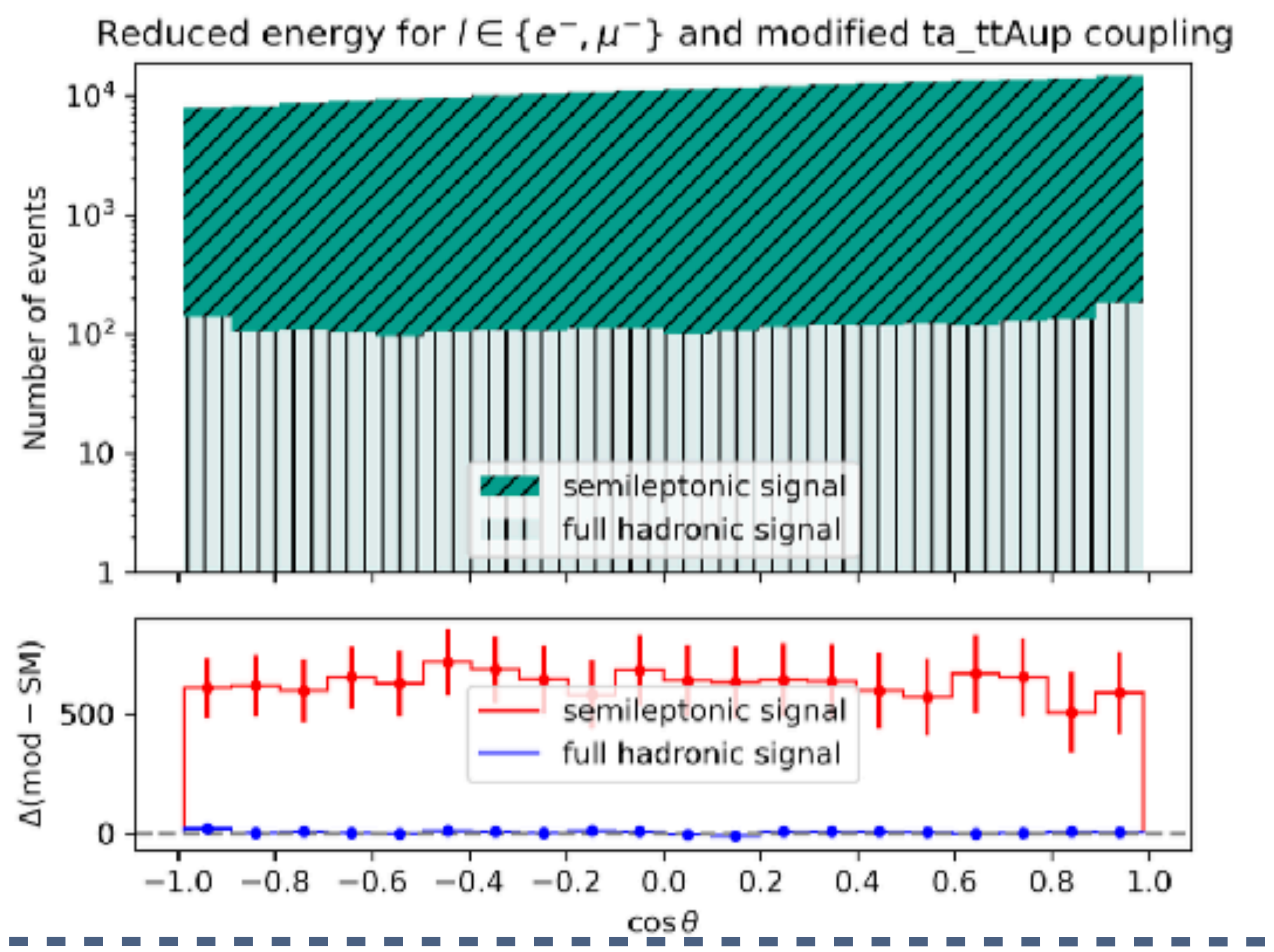
- $n_{\mu,e} > 0$ for leptons with $\Delta R(\ell, J) > 0.4$ or $E_\ell / E_J > 0.5$
- missing energy $\not{E} > 23$ GeV
- lepton momentum $p_{\text{lead}} > 13$ GeV
- PV compatibility $d_0 < 0.05\ \text{mm}, \frac{\text{d}_0}{\sigma(\text{d}_0)} < 50$



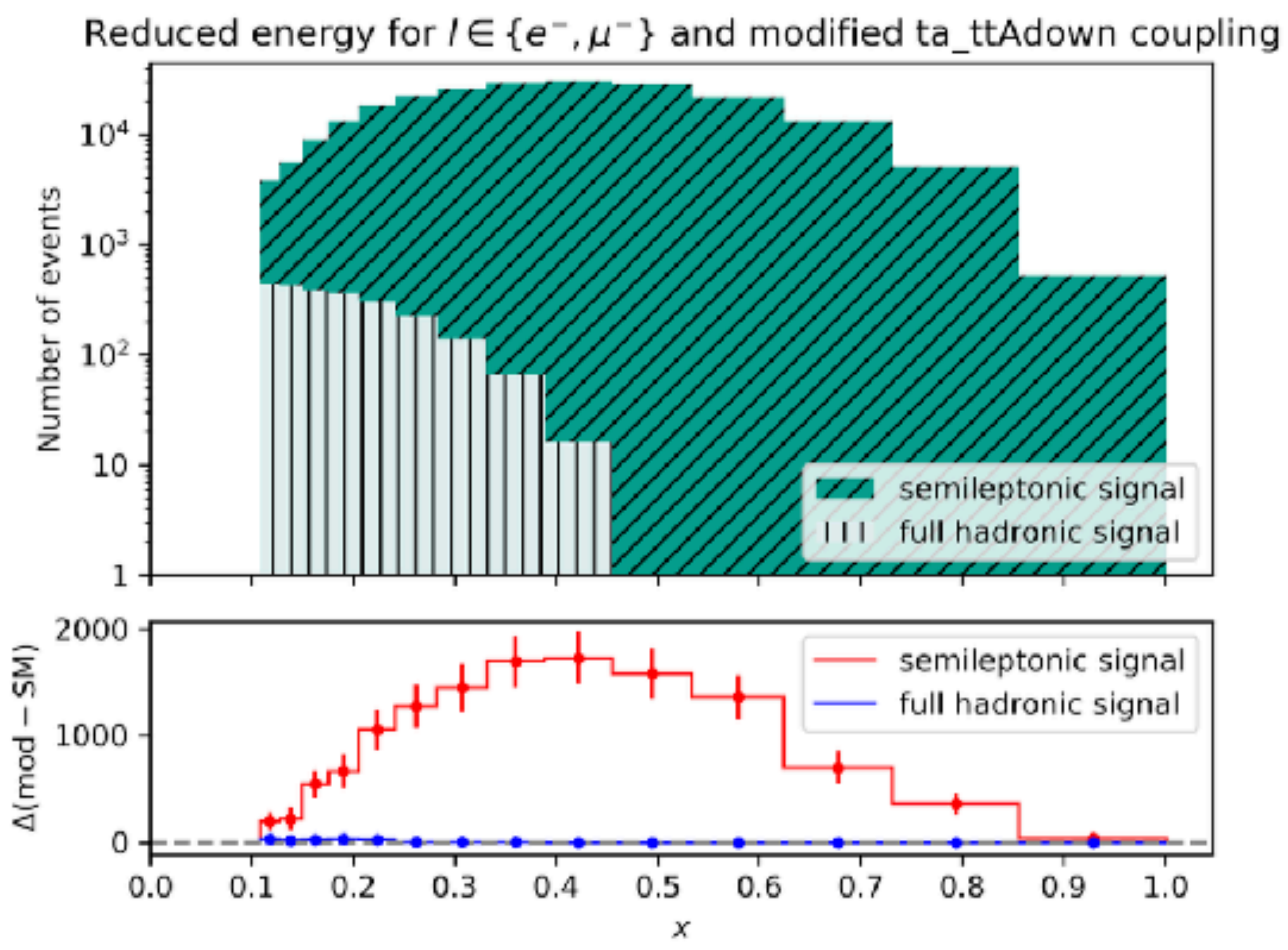
ta_ttA variation

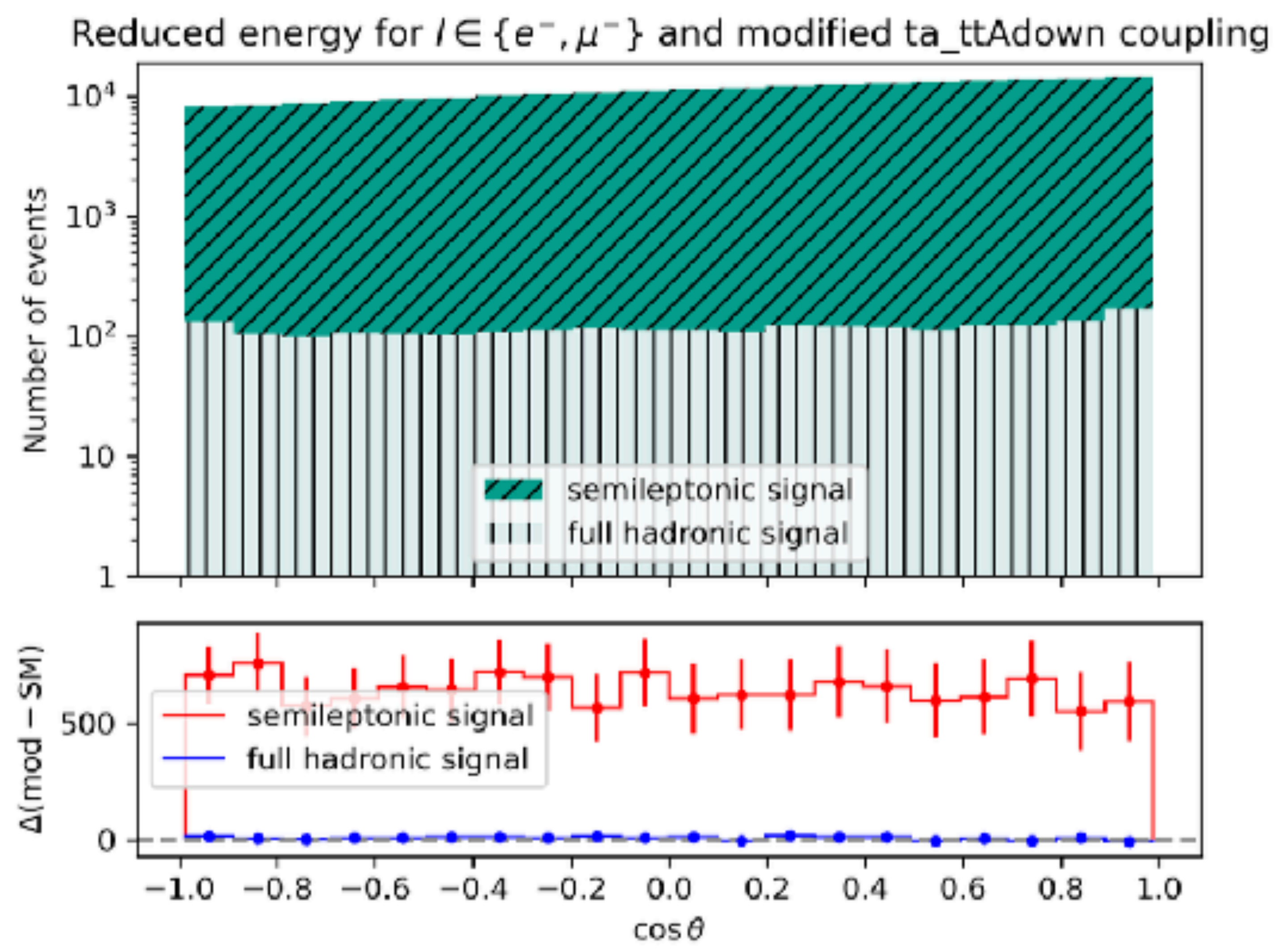
ta_ttA up variation





ta_ttA down variation

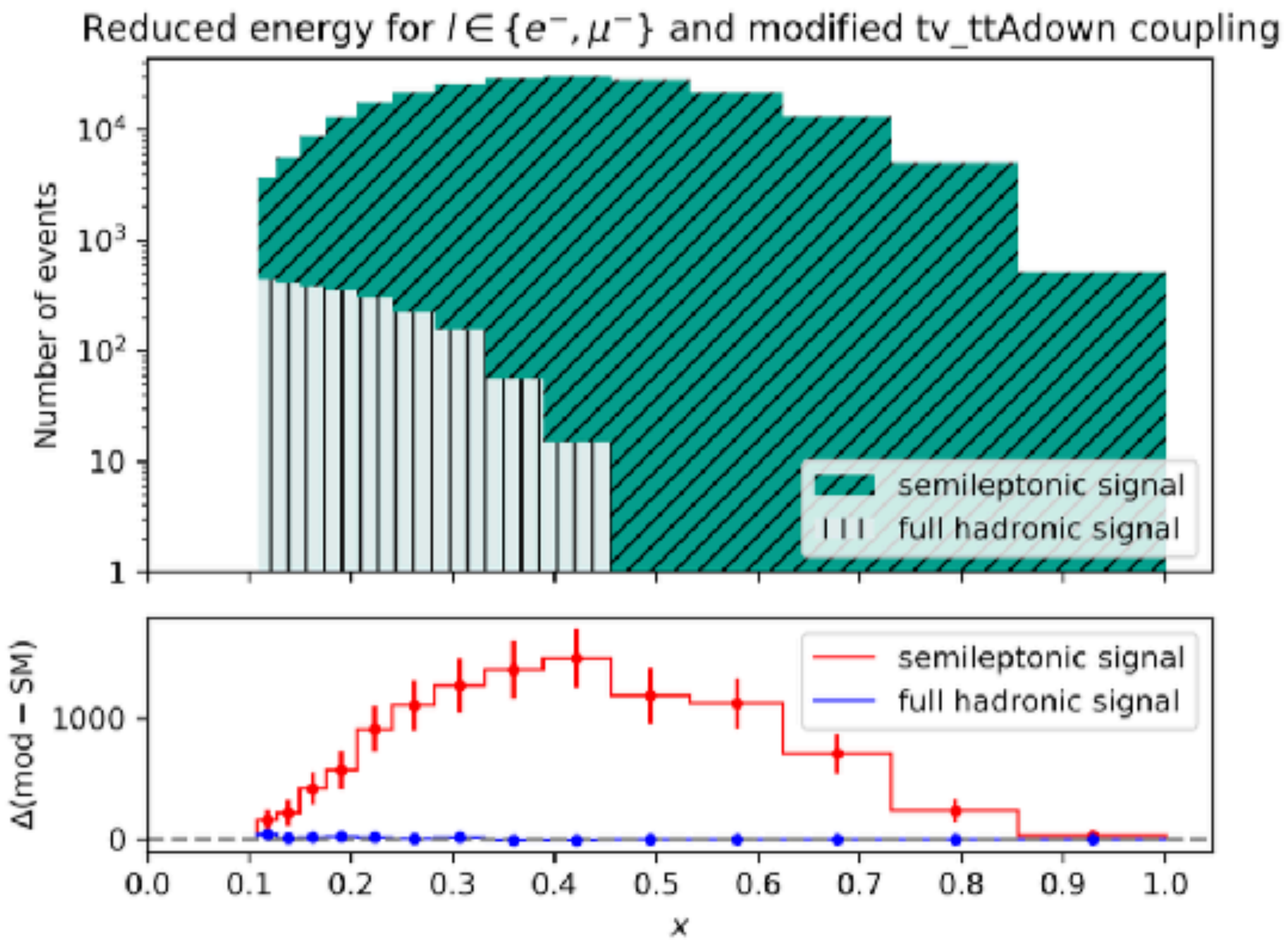


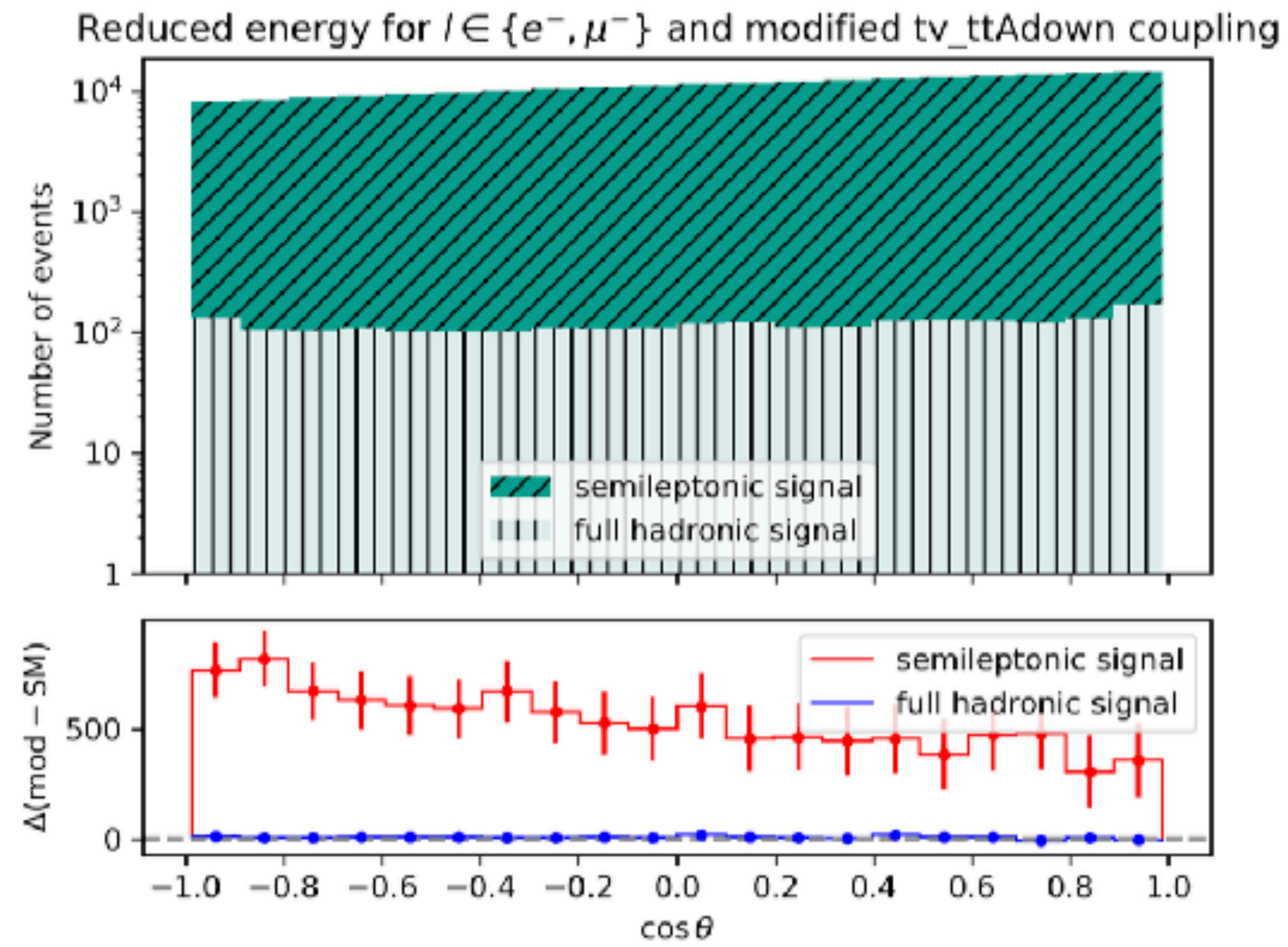


$x \propto E_l$ $\cos\theta_\ell$

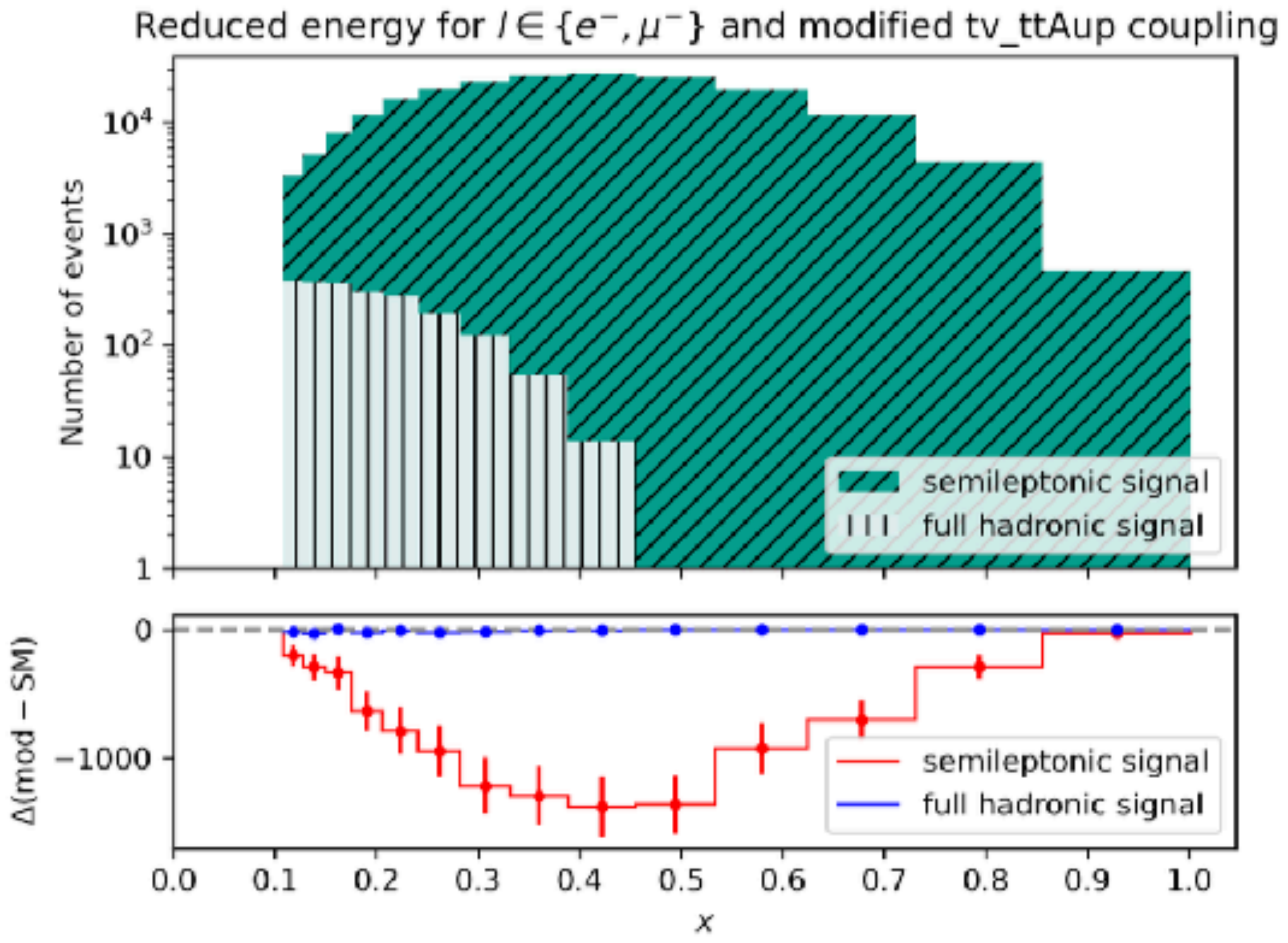
tv_ttA variation

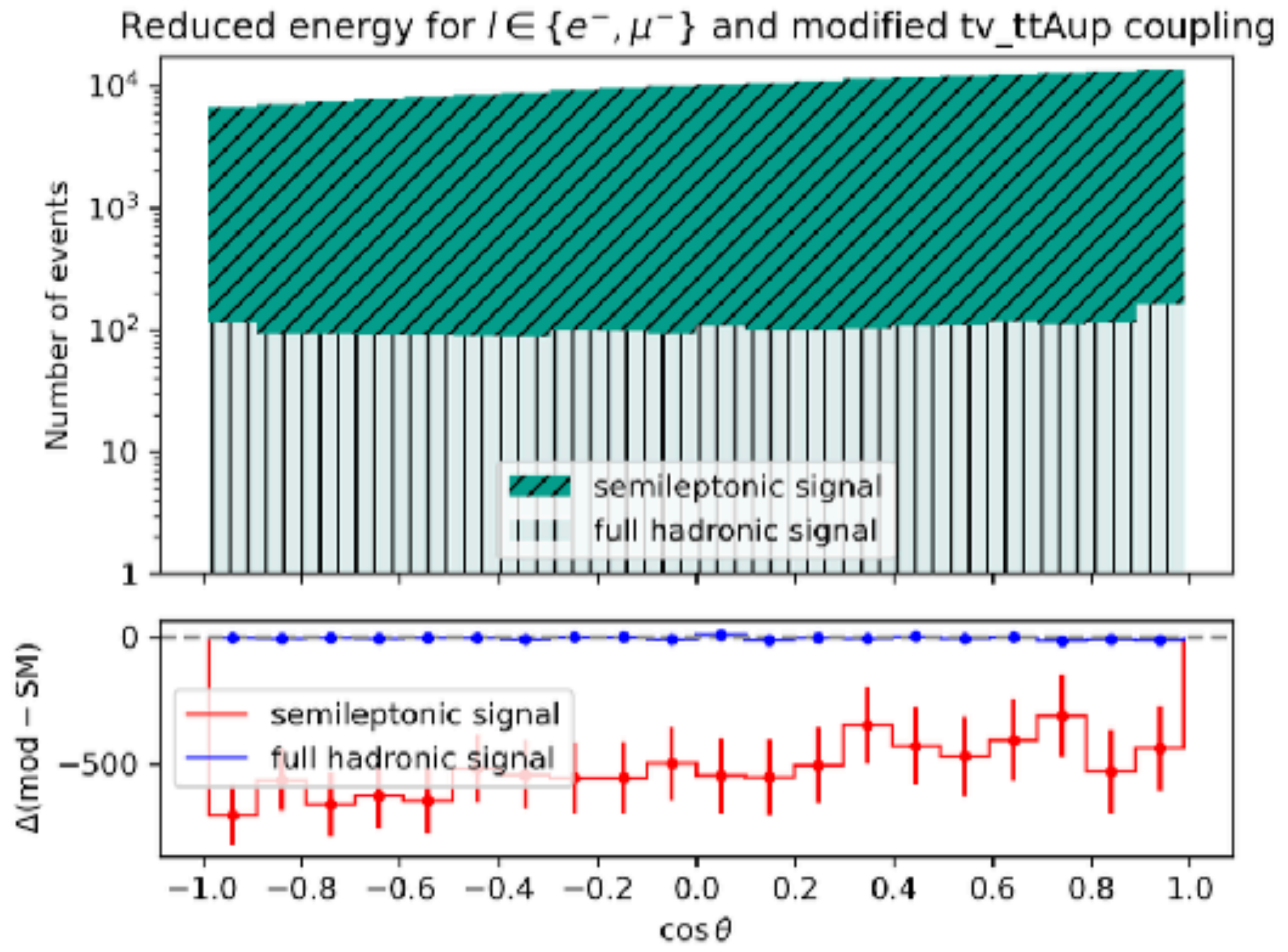
tv_ttA up variation





tv_ttA down variation

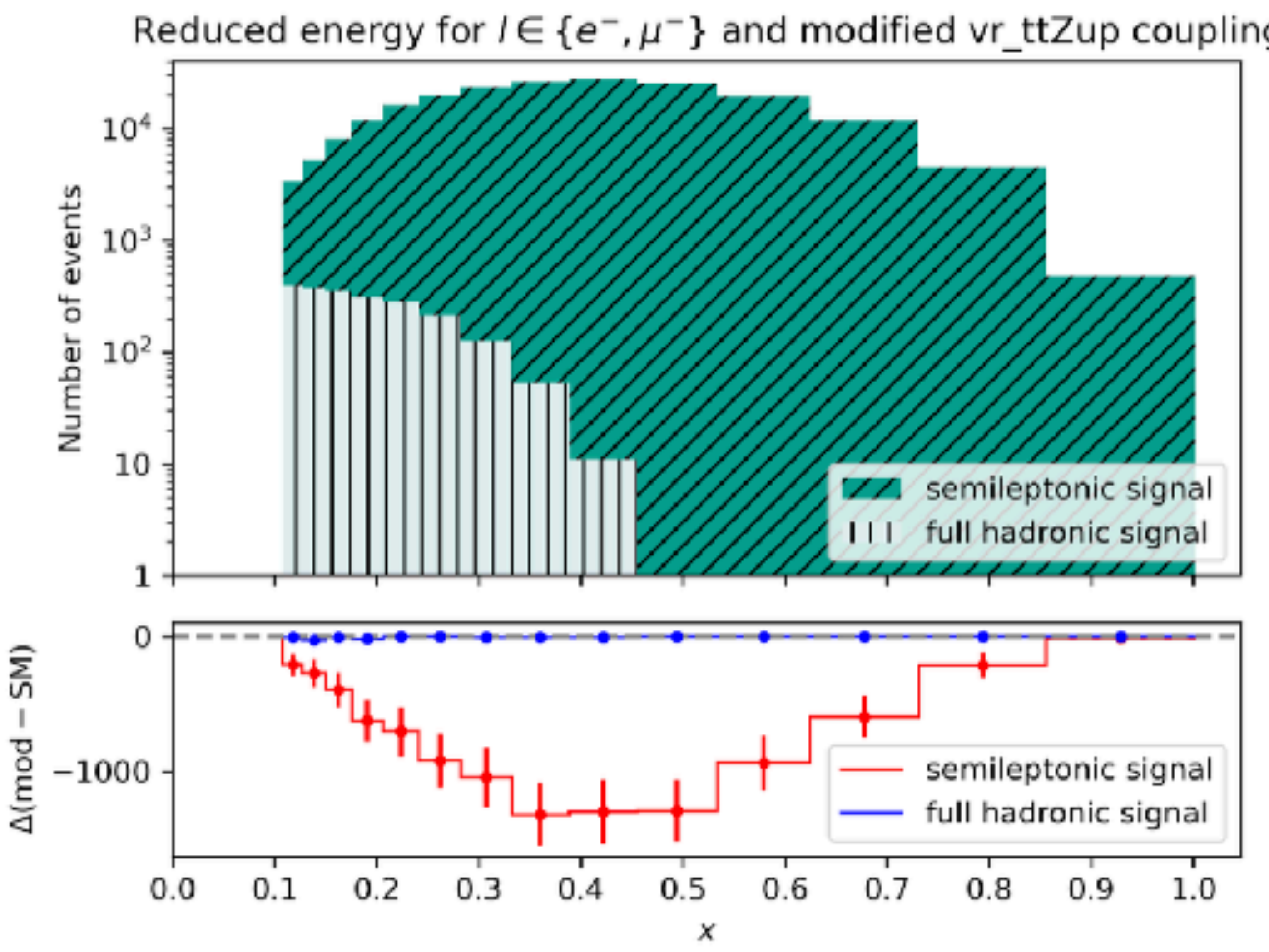


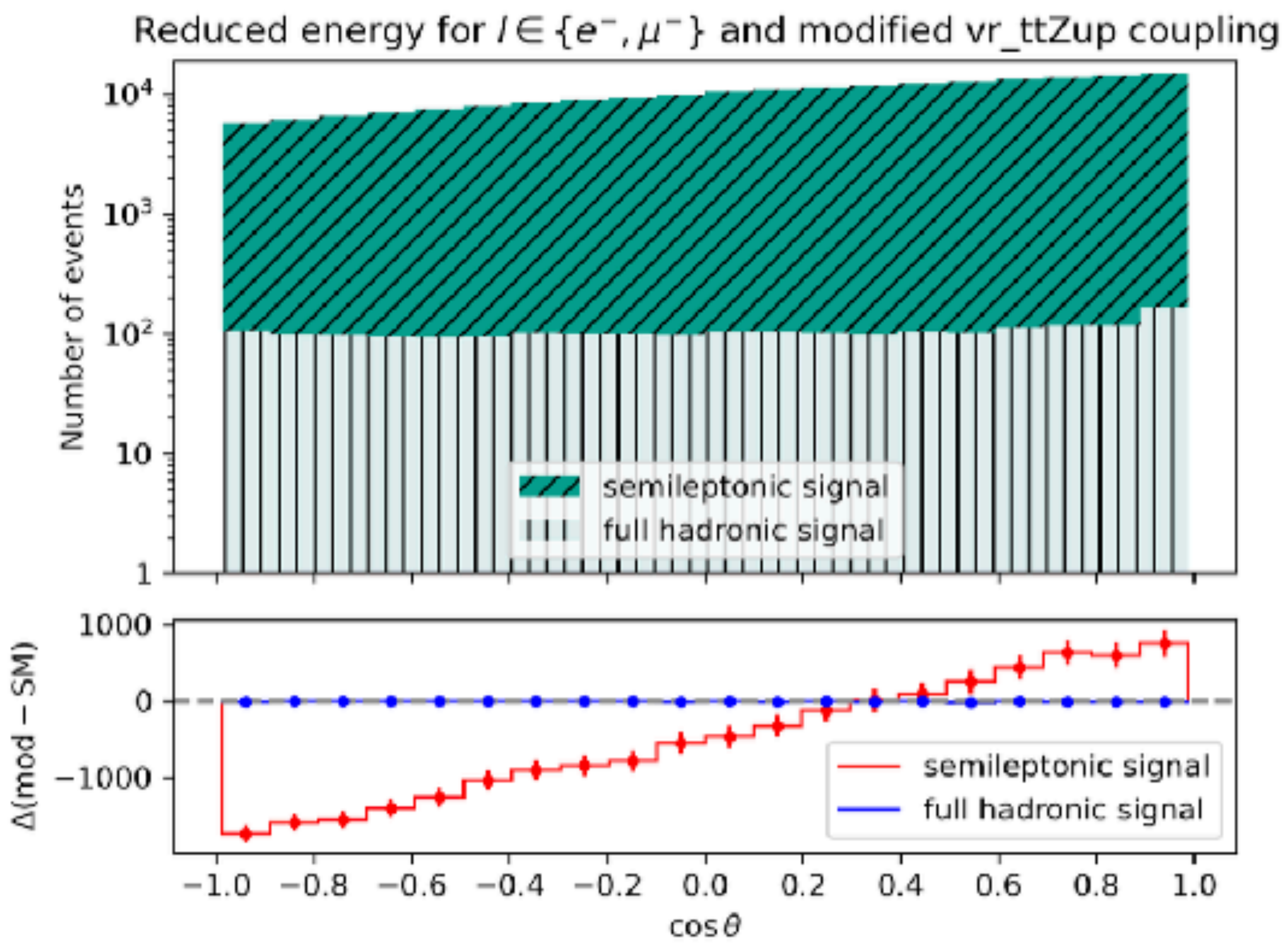


$x \propto E_l$ $\cos\theta_\ell$

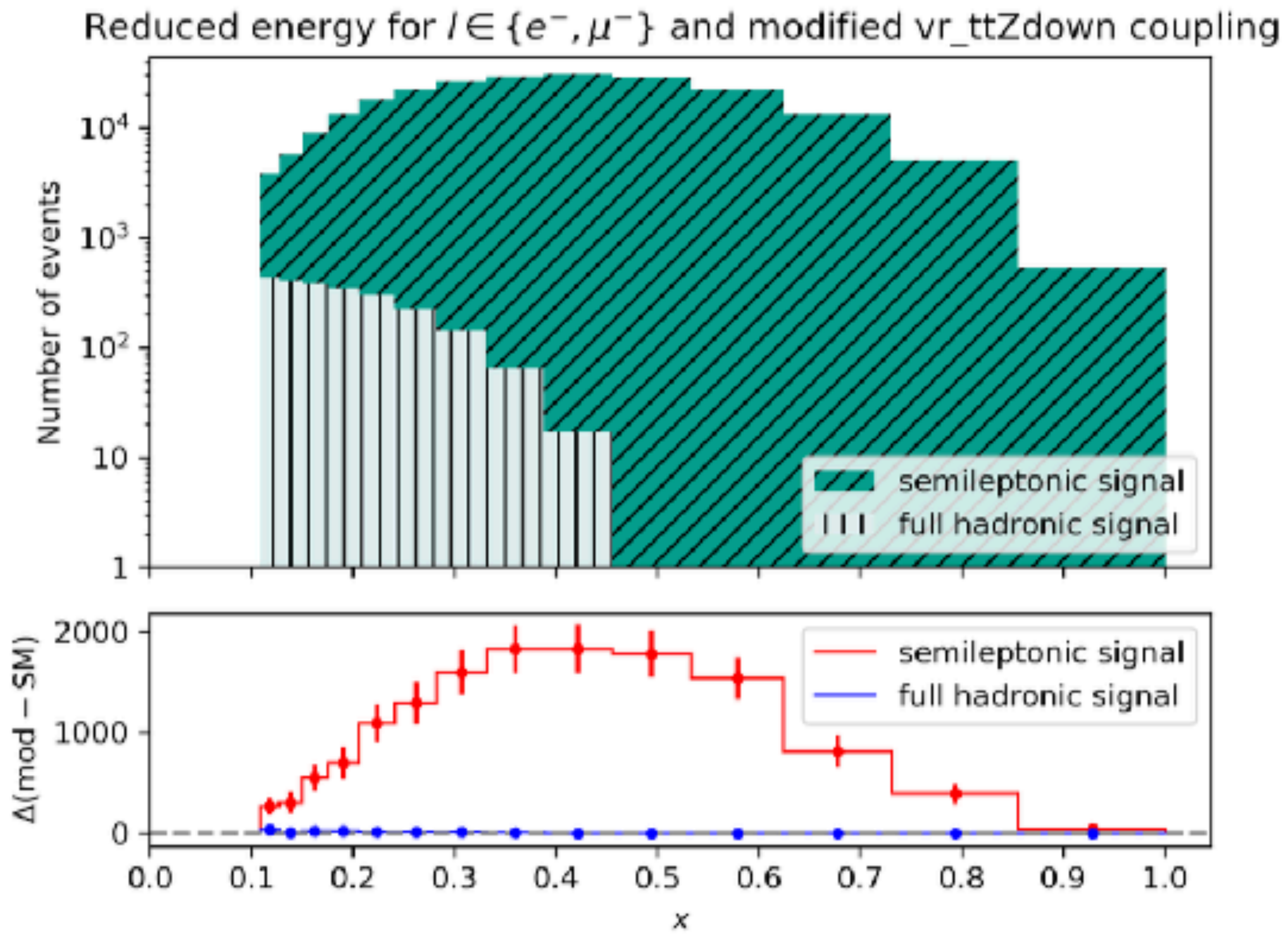
vr_ttZ variation

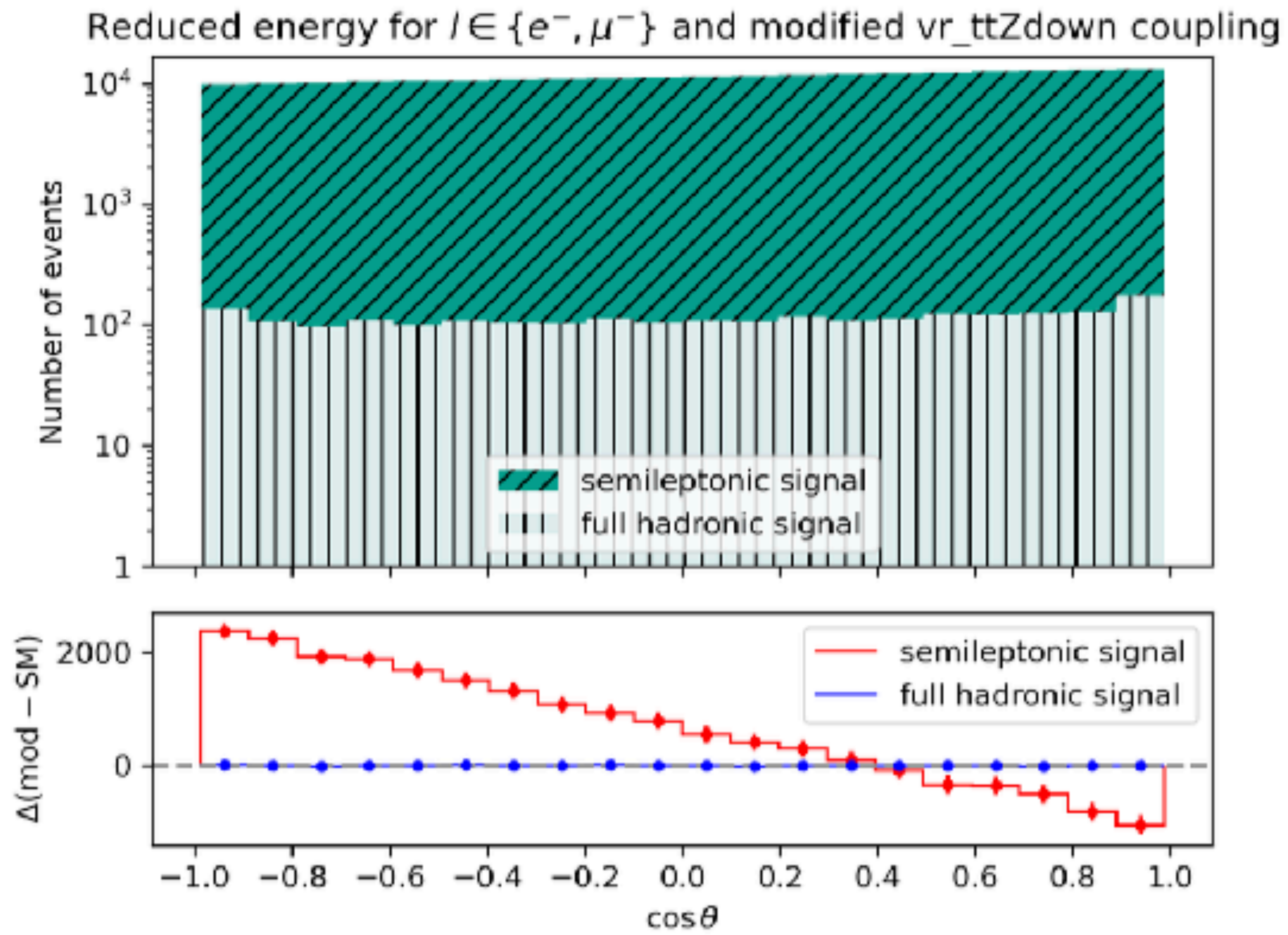
ta_ttA up variation





ta_ttA down variation





$x \propto E_l$

$\cos\theta_\ell$

Signal sensitivity

Extracted with binned χ^2 fit, assuming SM Asimov toy data

- ta_ttA = $0.00^{+1.46\times10^{-2}}_{-1.40\times10^{-2}}$
- tv_ttA = $0.00^{+4.20\times10^{-4}}_{-3.92\times10^{-4}}$
- vr_ttZ = $0.00^{+3.86\times10^{-3}}_{-2.89\times10^{-3}}$

More work ongoing

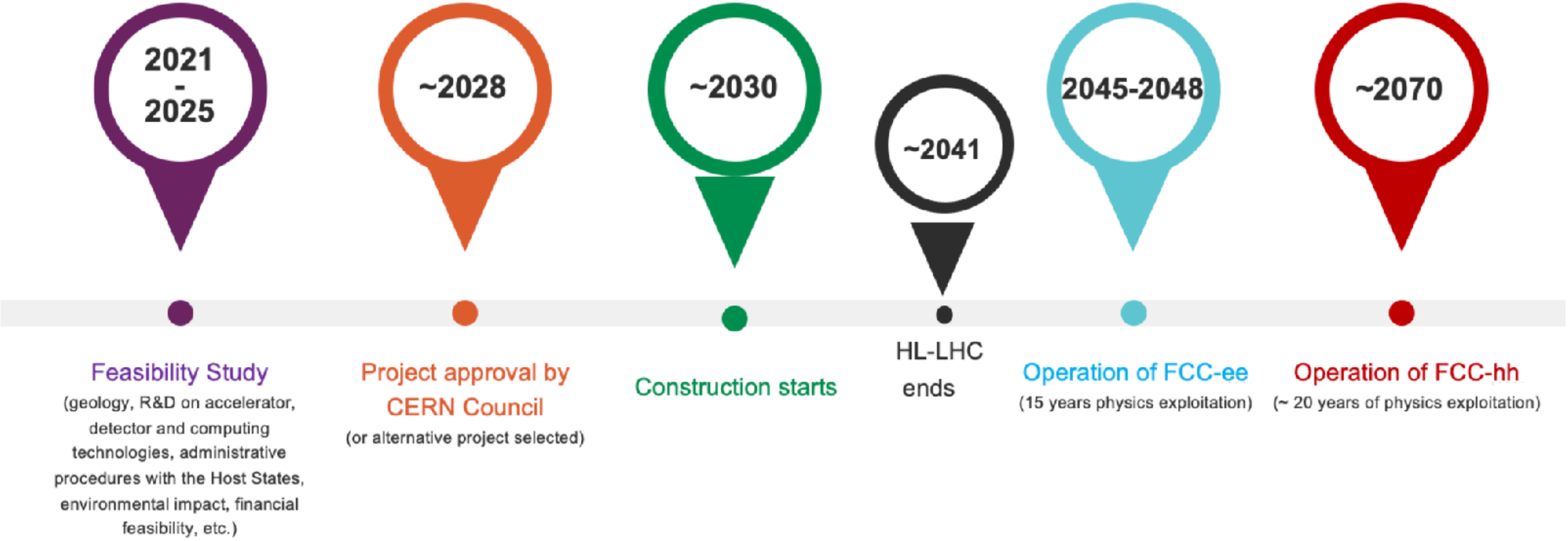
- Compare these results to the form factor parametrization in ref (10.1007/JHEP04(2015)182)
- Consider coupling modifications in EFT framework

Summary

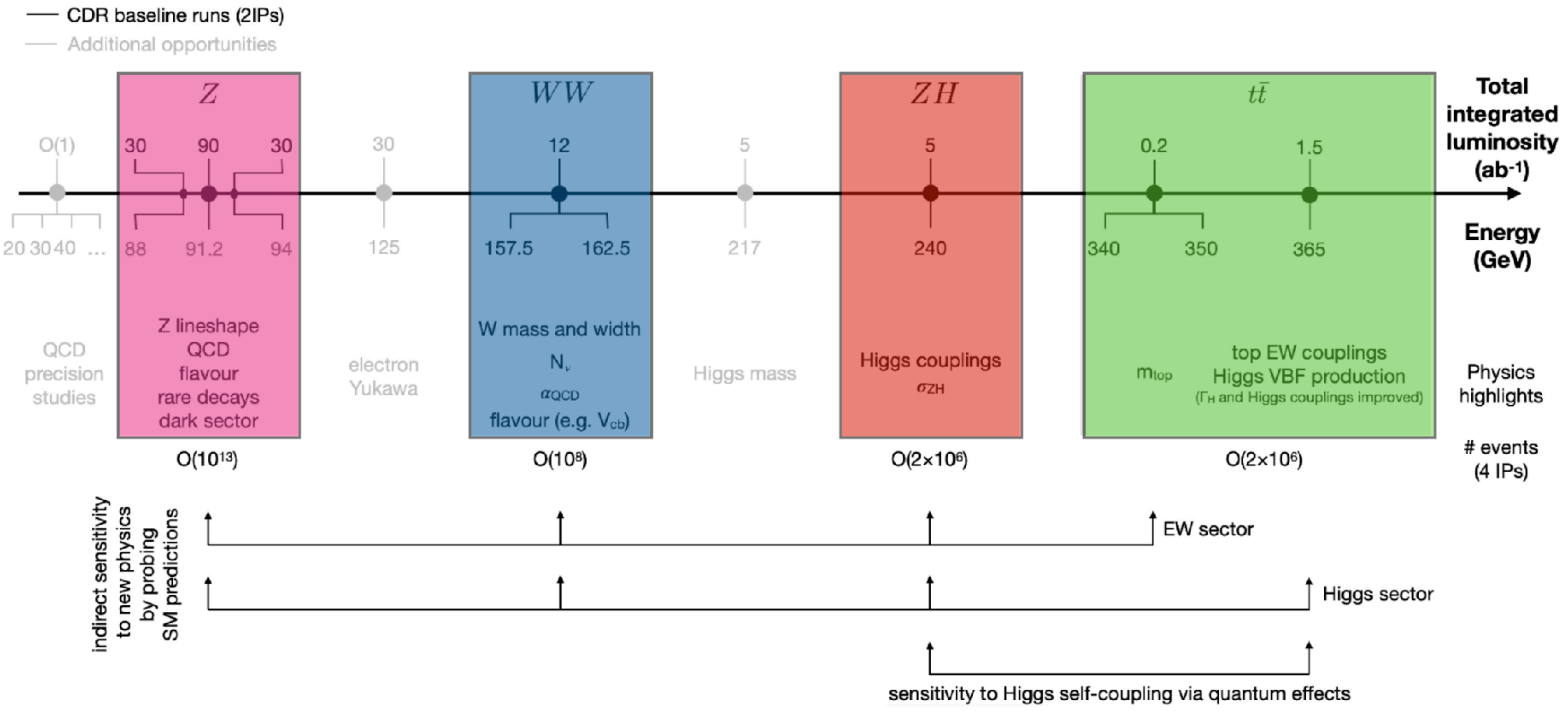
- Clean $t\bar{t}$ dataset at FCC-ee, offering unique opportunities
- Two examples presented
  - $|V_{ts}|$ from $t \to Ws$ decay
    - Model-independent direct measurement
    - (Preliminary) $\sigma(|V_{ts}|) \sim 10\%$
  - ttZ and $tt\gamma$ couplings from differential cross section
    - Sensitivity from energy and angular distribution of decay products, not relying on beam polarization
- Promising results from both studies, more work on the way

Backup

schedule


2021 - 2025
Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)
~2028
Project approval by CERN Council
(or alternative project selected)
~2030
Construction starts
~2041
HL-LHC ends
2045-2048
Operation of FCC-ee
(15 years physics exploitation)
~2070
Operation of FCC-hh
(~ 20 years of physics exploitation)

FCC-ee program



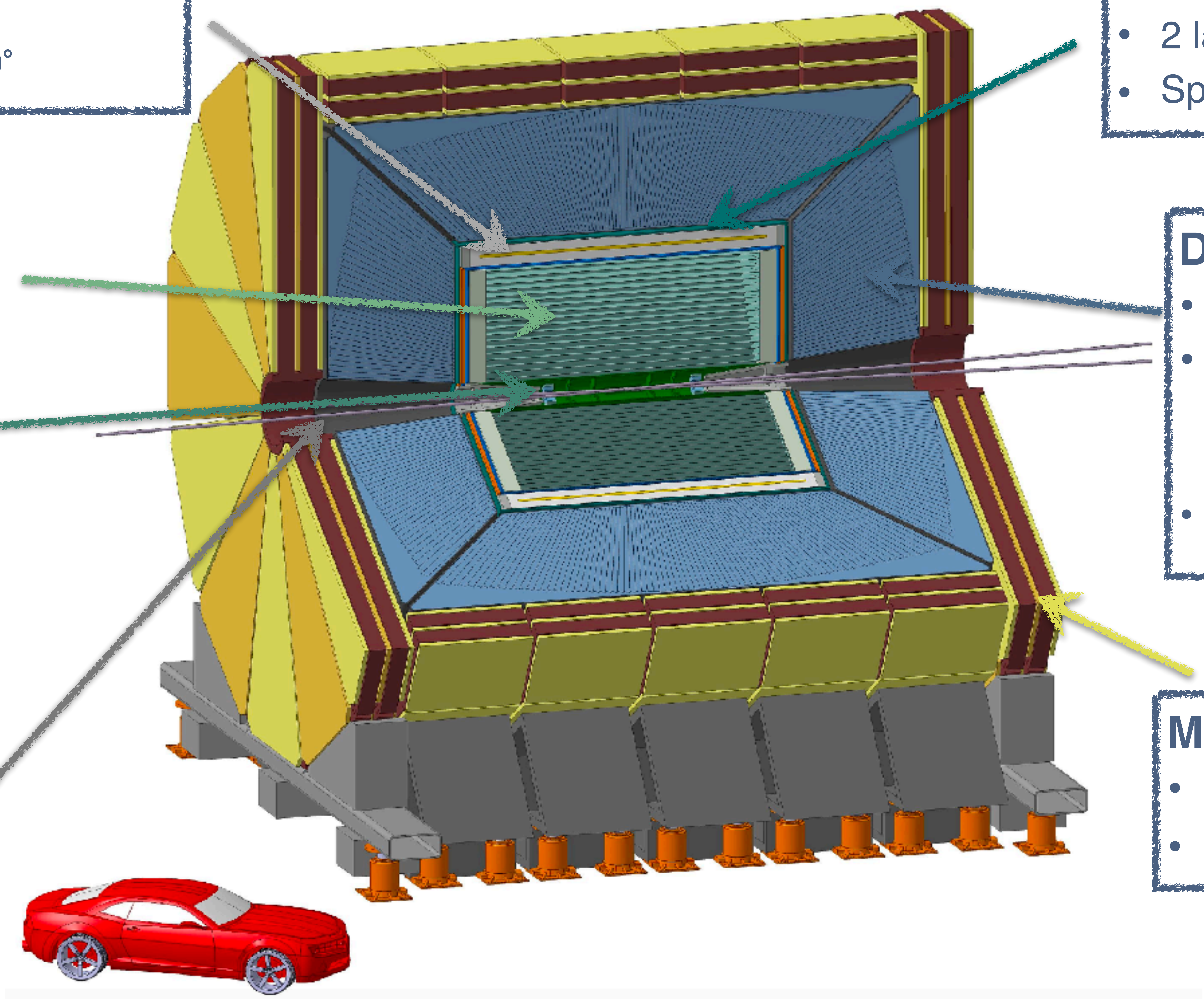
IDEA detector

Superconducting solenoid
- 2 T, R = 2.0 - 2.4 m
- $0.74\ X_0,\ 0.16\ \lambda\ @90^\circ$

Wire drift chamber
- 112 layers, R = 35 - 200 cm
- 0.016 $X_0 @90^\circ$

Silicon vertex detector
- 5 layers, R = 1.7 - 34 cm
- Pixel $20 \times 20\ \mu m^2$

Beam pipe
- R ~ 1.5 cm



Preshower
- 2 layers, gas detector
- Spatial reso < 100 μm

Dual-readout calorimeter
- 2 m capillaries
- Alternate Cherenkov and scintillation fibers
- $\sigma_{EM} \approx \frac{10\,\%}{\sqrt{E}}$, $\sigma_{had} \approx \frac{30\,\%}{\sqrt{E}}$

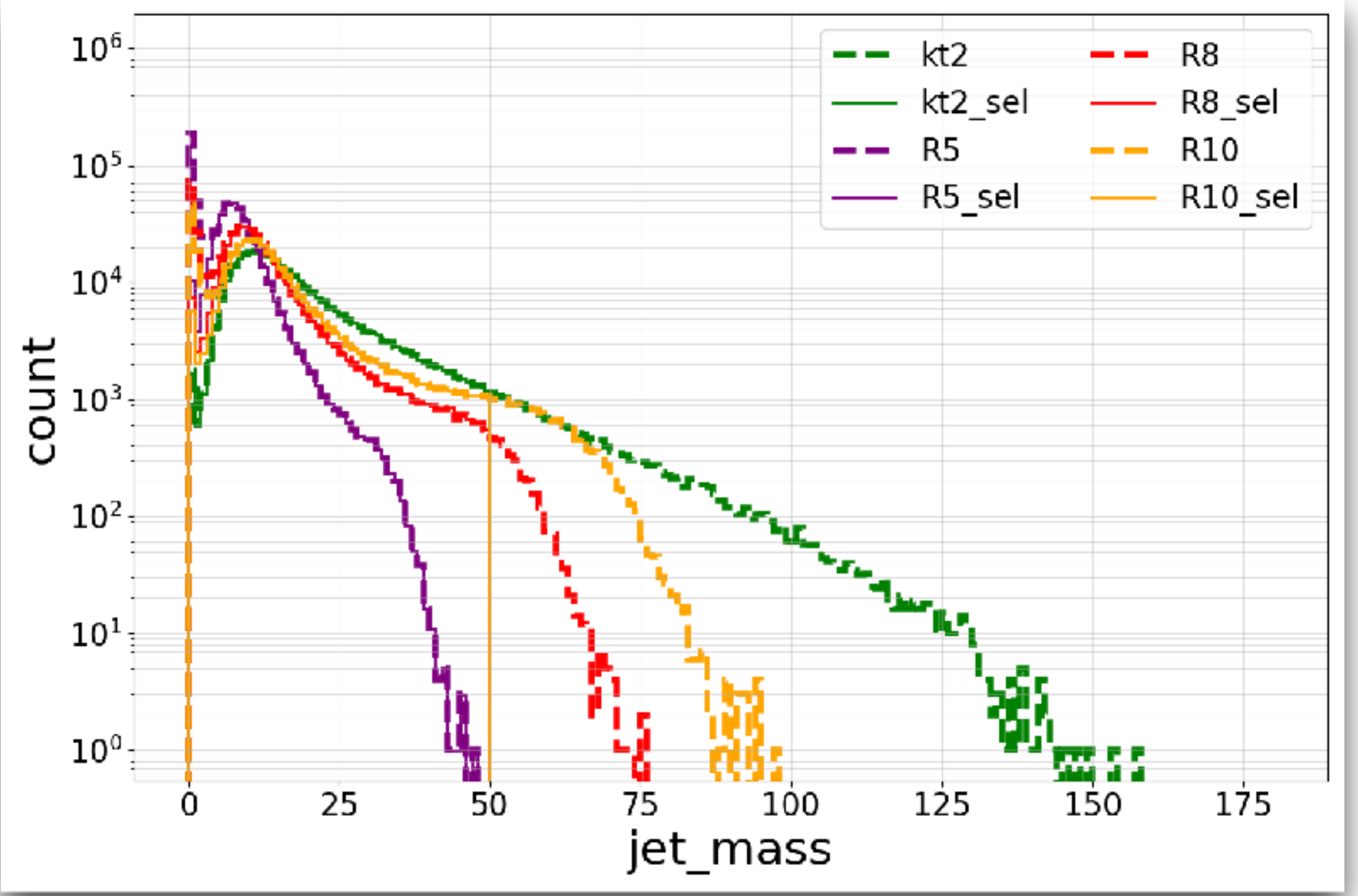
Muon chambers
- 3 layers, gas detector
- Spatial reso < 400 μm

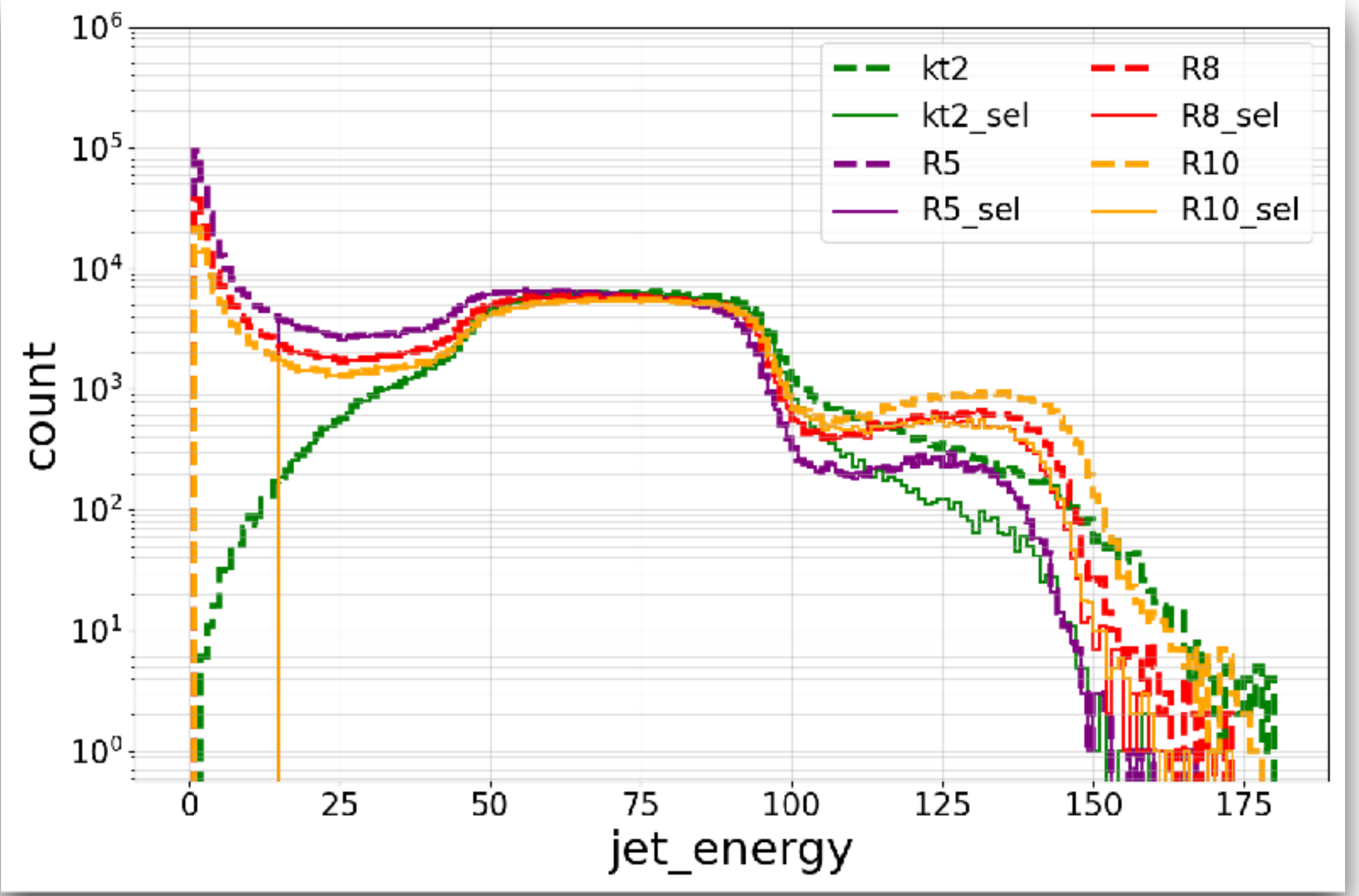
Jet definition

- In **dileptonic** events, the kt2 is the most correct
- A lot of low energy jets in the inclusive jet collections
- After jet selection, profiles of the inclusive jets look similar to the kt2 jets

jet sel:

$m(j) < 50$ GeV and $E(j) > 15$ GeV



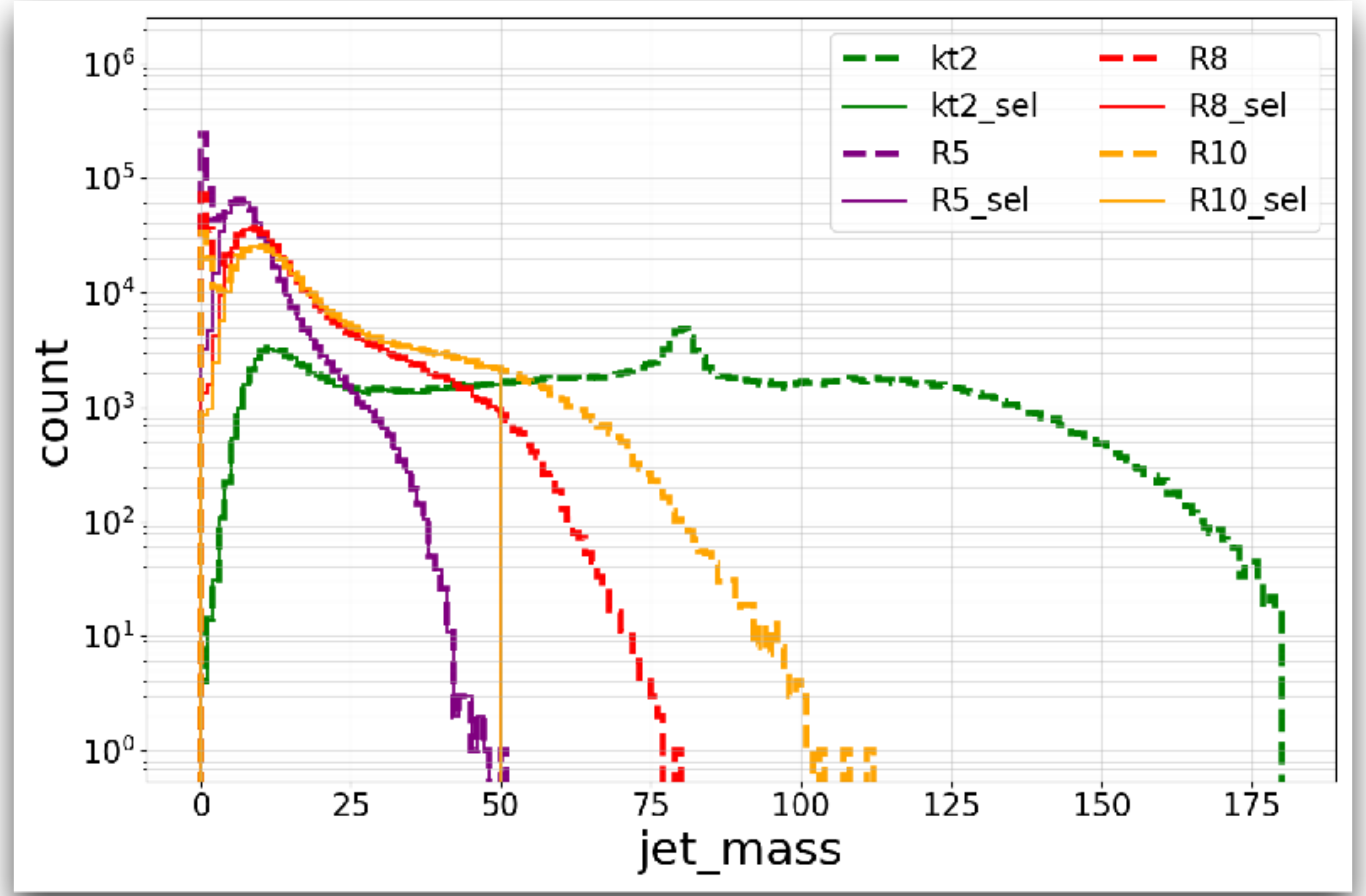


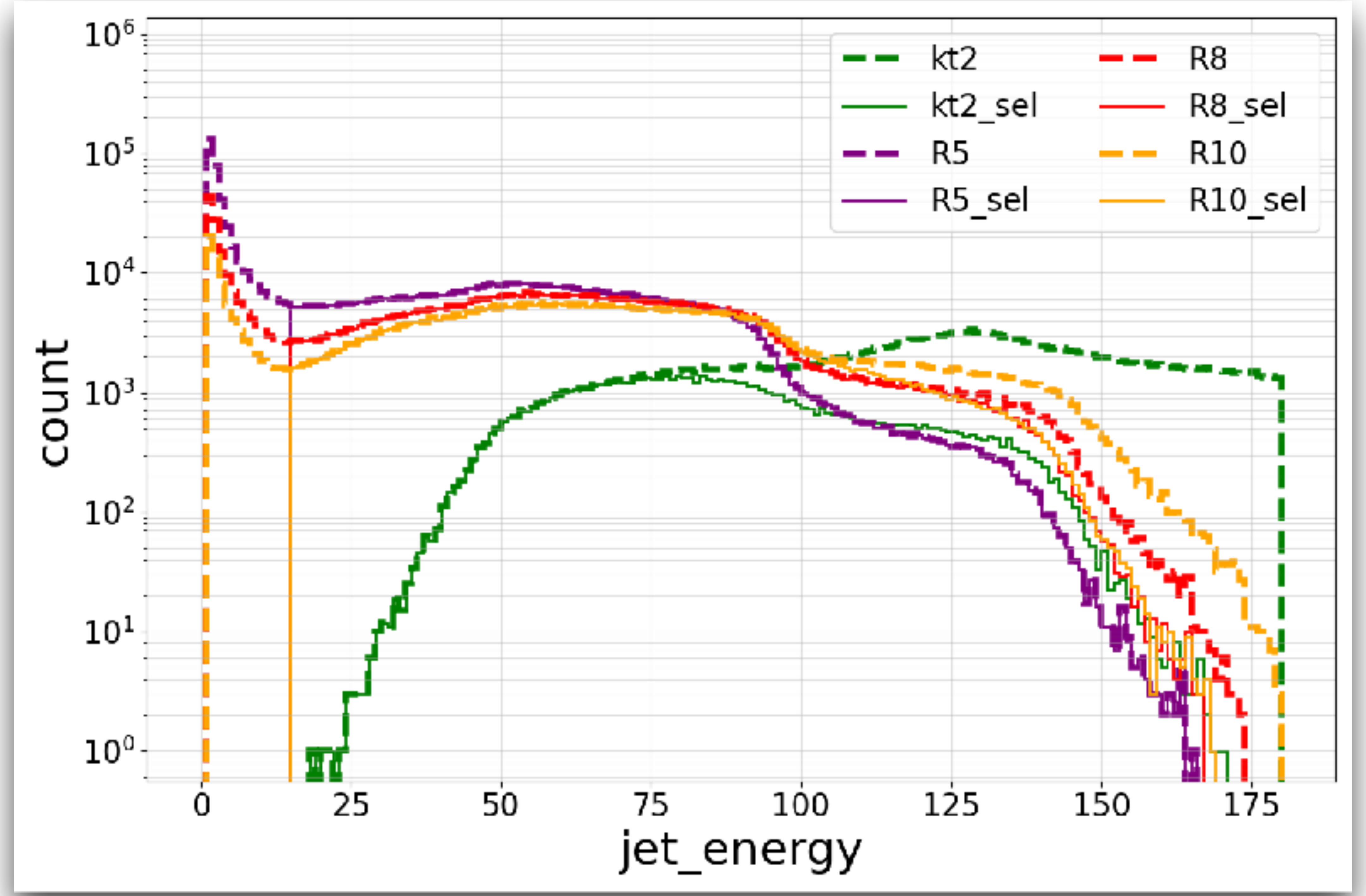
Jet definition

- In **semileptonic Wcs** events, the kt2 biased
- Inclusive clustering gives stable performance
- Kinematic profiles with different jet radius definitions are somewhat consistent

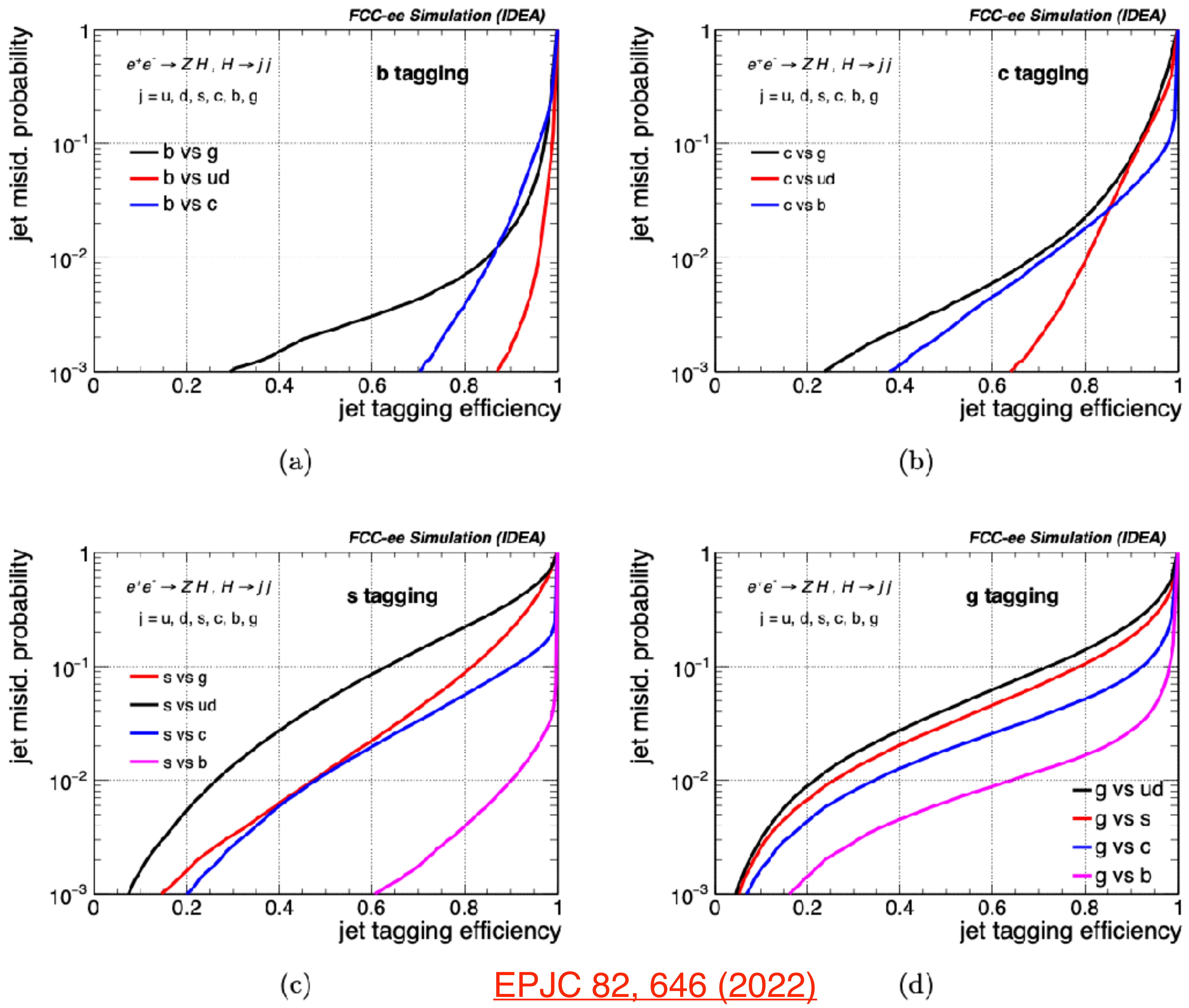
jet sel:

$m(j) < 50$ GeV and
$E(j) > 15$ GeV





flavor tagging



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semileptonic events

- Comparing inclusive clustering algo with different jet radii
- Performance with inclusive jets is in general better than those with exclusive jets
- Performance seems to be better with small R jets
  - Large jets may have multiple heavy-flavor constituents

semileptonic events

- Compare exclusive clustering algo with different numbers of jets
- s-tagging performance is better if the jet reconstruction is more appropriate
- But not matching the performance from the training

correct jet assignment