Strange quark tagging with ILD to search for new physics in the Higgs sector

Higgs 2021 – October 18-22, 2021
YSF Plenary Track – October 21, 2021 – Indico

Presented by **Matthew Basso** (University of Toronto),
on behalf of everyone on the **Snowmass 2021 LoI**
and the **ILD Collaboration**

Overview

- Submitted a Letter of Interest as part of Snowmass 2021
  - Basic goal: assess sensitivity of Higgs to strange couplings with ILD@ILC and set constraints on detector design
    - In line with ILC Snowmass 2021 study questions (2007.03650)
    - Interplay with the instrumentation: strange tagging capabilities strongly depend on the detector (e.g., PID)

Strange quark as a probe for new physics in the Higgs Sector

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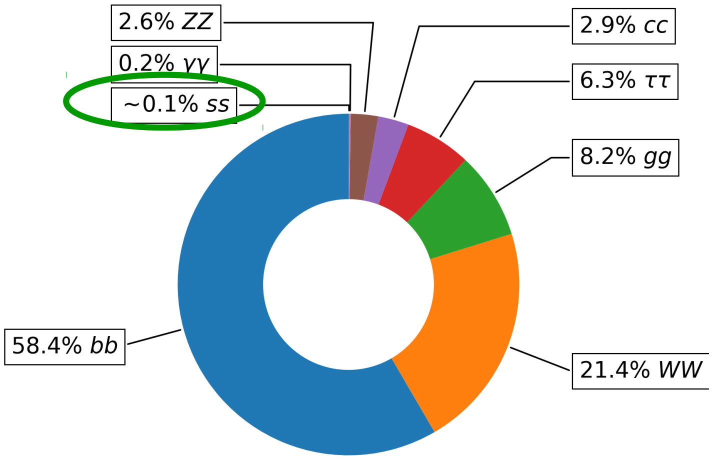
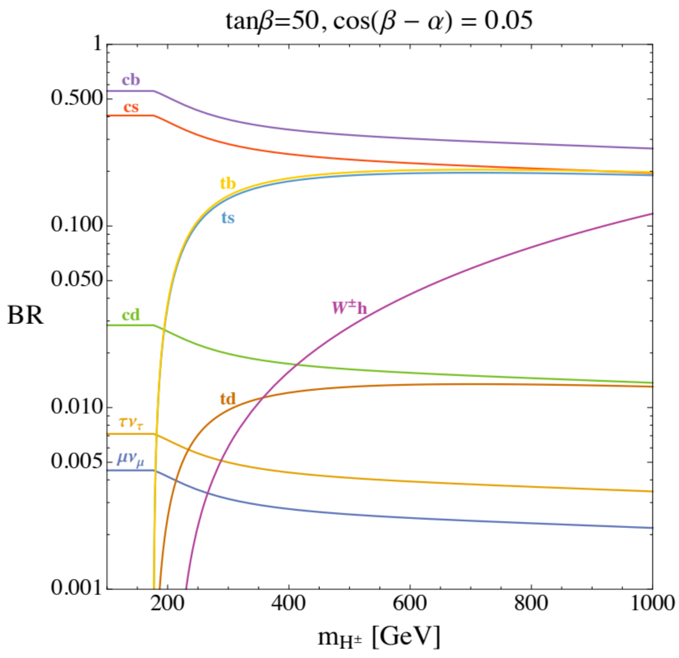


$\sqrt{s}$ = 13 TeV, m_H = 125 GeV

$H \to ss$ and $H \to cs$

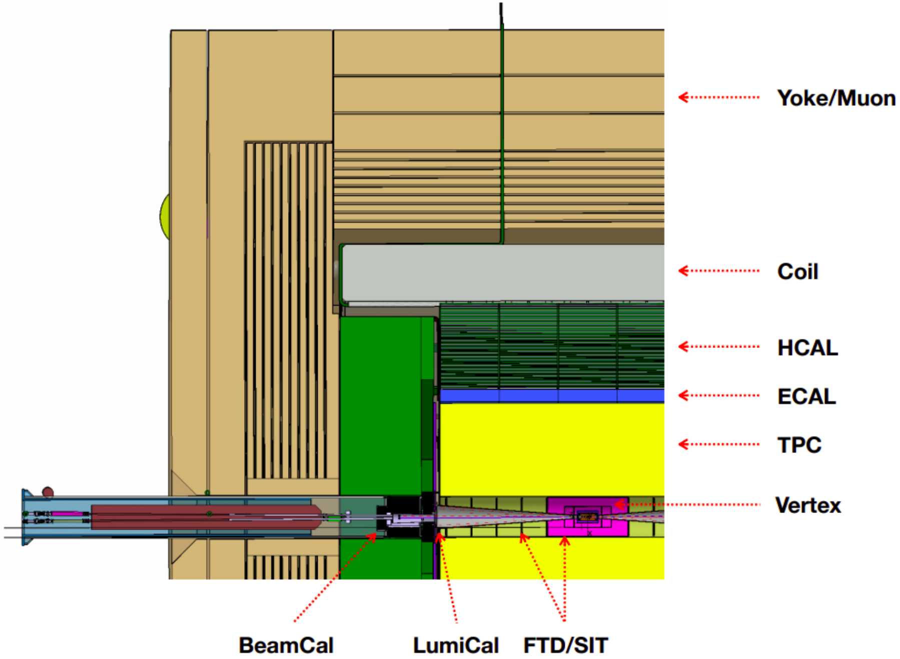
- $H \to ss$: extremely challenging unless enhanced relative to SM expectations
- $H \to cs$: some BSM models allow for the 1st and 2nd generation fermion masses to be an additional source of EW symmetry breaking
  - Result in "SM" and "heavy" Higgs doublets
  - Predicts an ***enhancement*** to Higgs cross section
  - Charged heavy Higgs can undergo flavour violating decays (e.g., *cs*) – *s*/*c*-tagging can help



Charged heavy Higgs branching ratios. Taken from Fig. 6 of 1610.02398.

The International Large Detector

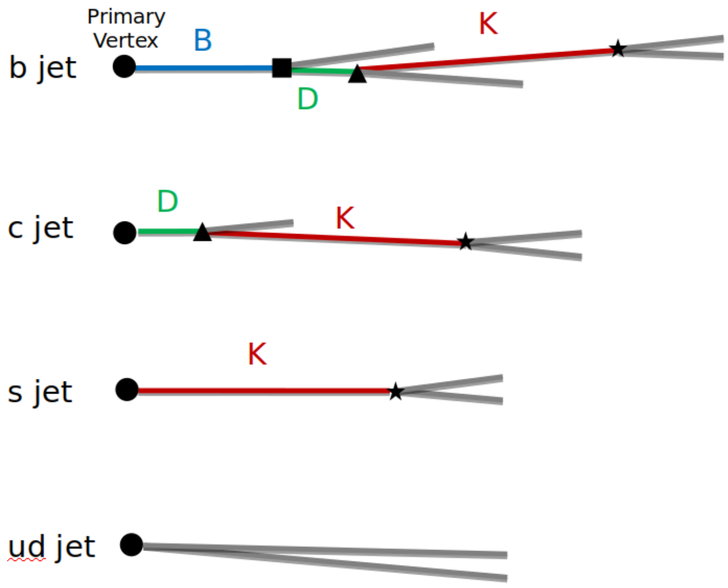
- ILC: $\sqrt{s}$ = 250 GeV, 2000 fb^{-1} (1809.09504)
- The ILD detector
  - 3 double-layer pixel detectors for vertexing
  - Time projection chamber (TPC) for tracking with inner/outer Si layers
    - Low material assists in low-p tracking
  - High granularity sampling calorimeters for particle flow reconstruction
    - Challenge is reconstructing neutral hadrons
    - Precise EM/hadronic design still under study
  - Tracking/calorimetry contained in 3.5 T field



ILD detector quadrant. Taken from Fig. 1 of 1912.04601.

Jet flavour tagging classification

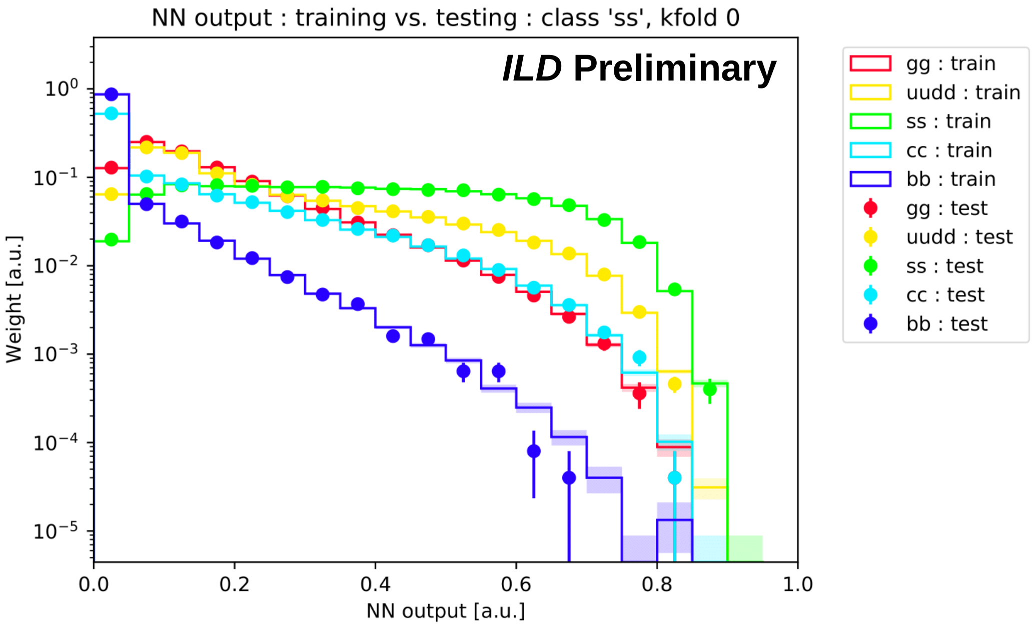
- Use a *neural network*-based tagger (architecture in Backup) for classifying jets by flavour
- Train on ILD-reconstructed ($Z \rightarrow$inv)($H \rightarrow qq/gg$) samples (100% polarized)
- Use per-jet level inputs as well as variables on the 10 leading particles in each jet:
  - Jets: momentum p, pseudorapidity η, polar angle ϕ, mass m, *b*/*c*/*o*-tagger scores, category, $N_{\text{particles}}$
  - Particles: p, η, ϕ, m, charge, **truth** electron/muon/pion/kaon/proton likelihoods (0 or 1, using PDG ID – "kaons" include K_S^0, $K^{+/-}$, and Λ)



Different jet types. Picture borrowed from T. Tanabe's slides, see Backup.

Tagger performance

- Shown is the strange score output – **good** train-test agreement
- Good discrimination of *s* jets from *u*/*d* jets – likely comes from using truth likelihoods
  - Also good discrimination of *s* jets from *g* jets – here, $N_{\text{particles}}$ is powerful



Train-test agreement for all output nodes in Backup (ROC curves too).

$H \rightarrow ss$ analysis

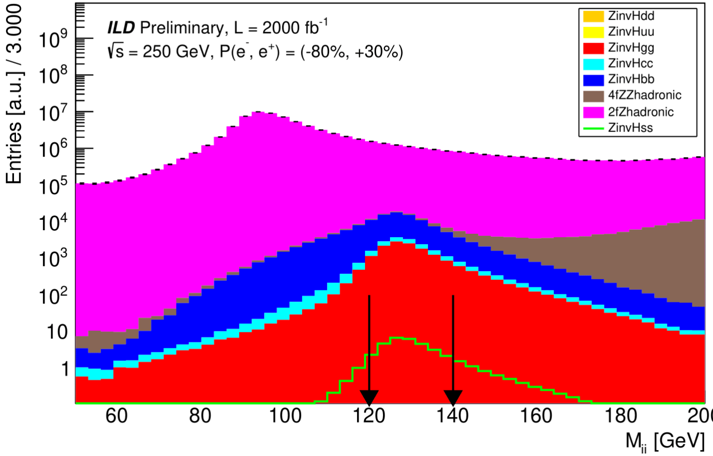
- Performed on same $H \rightarrow qq/gg$ samples (500K events per flavour) as well as $Z \rightarrow qq$ and $ZZ \rightarrow qqqq$ samples (~1M events each)
  - Scale BR[$H \rightarrow cc$] by ratio of *s*/*c* quark mass ratio squared: BR[$H \rightarrow ss$] ~ 2E-4
- Kinematic selection:
  - Jet quantities: leading/subleading jet momenta, p_j; dijet mass, M_{jj}; dijet energy, E_{jj}
  - Missing 4-vector quantities: mass, M_{miss}; angular separation, $\Delta R_{jj,\mathrm{miss}} = \sqrt{(\Delta\phi_{jj,\mathrm{miss}}{}^2 + \Delta\eta_{jj,\mathrm{miss}}{}^2)}$
  - Leading/subleading *b*/*c*/*o*-tagger (1506.08371) scores and jet category
  - Number of Particle Flow Objects (PFOs): per event, N_{PFOs}/event; per jet, N_{PFOs}/jet

Cutflow

ILD Preliminary, $\mathcal{L} = 2000\ \text{fb}^{-1}$, $\sqrt{s} = 250$ GeV, $P(e^-, e^+) = (-80\%, +30\%)$

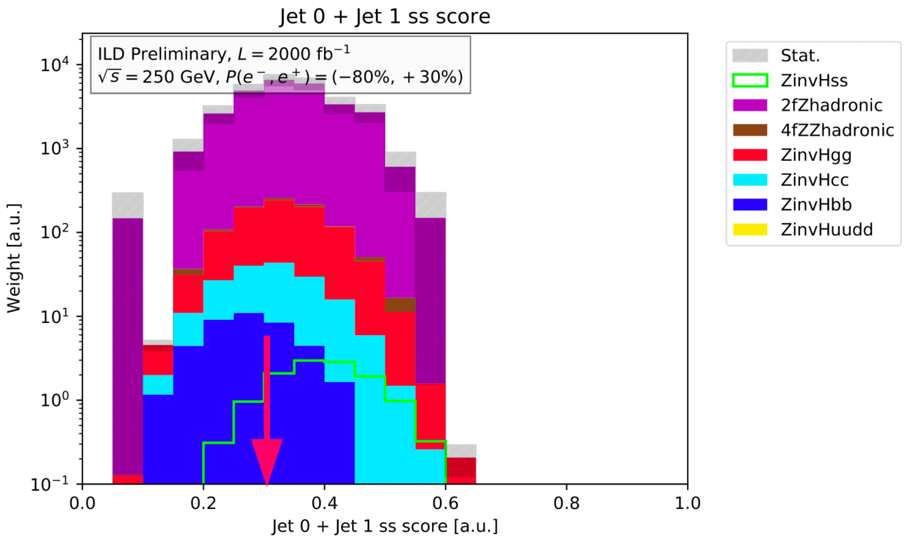
	$(H \to s\bar{s})(Z \to \nu\nu)$	$(H \to gg)(Z \to \nu\nu)$	$(H \to u\bar{u}/d\bar{d})(Z \to \nu\nu)$	$(H \to c\bar{c})(Z \to \nu\nu)$	$(H \to b\bar{b})(Z \to \nu\nu)$	$Z \to q\bar{q}$	$ZZ \to q\bar{q}q\bar{q}$	Sig. eff.	Bkg. eff.
No cut	42.65 ± 0.06	17254.17 ± 24.41	0.59 ± 0.0	5858.77 ± 8.29	116168.67 ± 164.29	$176876516.6 \pm 161411.64$	1342206.08 ± 1338.33	1.00e+00	1.00e+00
No leptons	42.55 ± 0.06	17225.89 ± 24.39	0.59 ± 0.0	5846.08 ± 8.28	115535.31 ± 163.84	$175328405.19 \pm 160703.71$	1335436.33 ± 1334.95	9.98e-01	9.91e-01
≥ 2 jets	42.55 ± 0.06	17225.89 ± 24.39	0.59 ± 0.0	5846.08 ± 8.28	115535.31 ± 163.84	$175328405.19 \pm 160703.71$	1335436.33 ± 1334.95	9.98e-01	9.91e-01
$p_{j0}, p_{j1} > 30$ GeV	39.46 ± 0.06	16424.08 ± 23.81	0.55 ± 0.0	5619.05 ± 8.12	109492.68 ± 159.5	$131310044.43 \pm 139074.89$	1331247.44 ± 1332.86	9.25e-01	7.44e-01
$M_{jj} \in [120, 140]$ GeV	29.75 ± 0.05	12459.56 ± 20.74	0.42 ± 0.0	3883.41 ± 6.75	63849.78 ± 121.8	7424895.55 ± 33070.82	8041.49 ± 103.59	6.97e-01	4.21e-02
$E_{jj} \in [125, 160]$ GeV	29.62 ± 0.05	12401.25 ± 20.69	0.42 ± 0.0	3862.38 ± 6.73	63407.65 ± 121.38	4027593.77 ± 24356.93	6111.86 ± 90.31	6.94e-01	2.31e-02
$M_{\text{miss}} \in [75, 120]$ GeV	27.56 ± 0.05	11614.11 ± 20.02	0.39 ± 0.0	3612.75 ± 6.51	59551.31 ± 117.63	867590.51 ± 11304.65	2105.79 ± 53.01	6.46e-01	5.30e-03
$\Delta R_{jj,\text{miss}} < 4$	23.82 ± 0.05	10039.07 ± 18.62	0.34 ± 0.0	3124.94 ± 6.05	51512.9 ± 109.4	151865.16 ± 4729.65	1537.31 ± 45.29	5.58e-01	1.22e-03
$\text{score}^b/\text{jet} < 0.2$	22.2 ± 0.04	8593.49 ± 17.22	0.32 ± 0.0	1917.39 ± 4.74	551.1 ± 11.32	88968.53 ± 3620.08	689.92 ± 30.34	5.20e-01	5.65e-04
$\text{score}^c/\text{jet} < 0.35$	20.72 ± 0.04	7745.04 ± 16.35	0.3 ± 0.0	302.77 ± 1.88	179.83 ± 6.46	73060.25 ± 3280.5	548.47 ± 27.05	4.86e-01	4.59e-04
$N_{\text{PFOs}}/\text{event} \in [30, 60]$	13.93 ± 0.03	854.7 ± 5.43	0.2 ± 0.0	146.28 ± 1.31	44.14 ± 3.2	33584.15 ± 2224.16	64.05 ± 9.25	3.27e-01	1.95e-04
$N_{\text{PFOs}}/\text{jet} \in [10, 40]$	12.53 ± 0.03	778.96 ± 5.19	0.18 ± 0.0	136.34 ± 1.26	39.96 ± 3.05	26955.7 ± 1992.62	56.05 ± 8.65	2.94e-01	1.57e-04

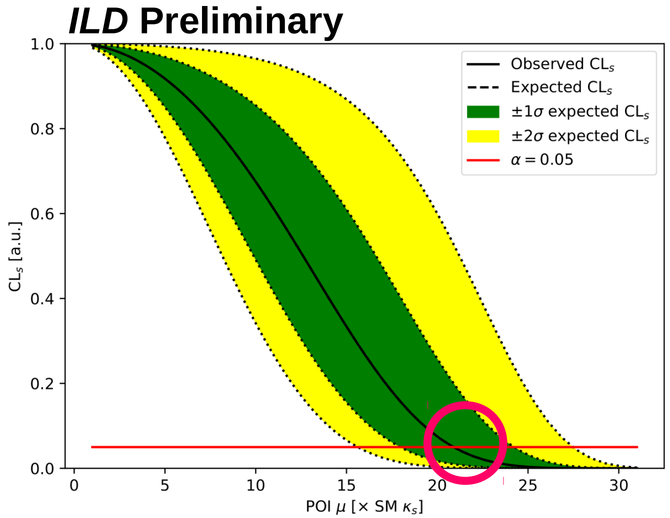
- Largest **decrease** in signal efficiency at M_{jj} cut
  - Provides one of the strongest handles on reducing $Z \to qq$
  - $H \to bb$ s/b = 0.00065 @ No cut – comparable to analysis from T. Ogawa's thesis (Section 6.2)
- **29% signal, 0.016% background efficiency**
  - All histograms in Backup



Limits on coupling strength modifier

- Cut on (0.5x) sum of strange scores for leading and subleading jets >0.3, generated limits for modifier to SM BR
  - Asymptotic significance ~ 0.1σ (see Backup)
- 95% upper confidence bounds at **~21 x SM κ_s** (in the kappa framework, κ_s^2 is the modifier to BR[$H\rightarrow ss$])
  - N.B.: observed is *identical* (by design) to expected in the plot
  - Sigma bands around expected decrease with smaller cut values (better $Z\rightarrow qq$ MC stats)





Generated with pyhf v0.5.4.

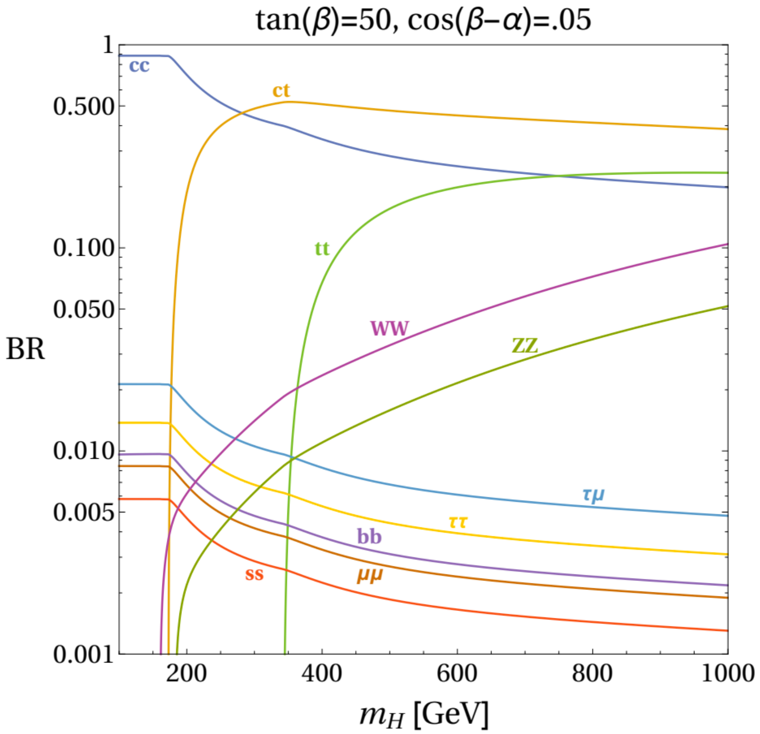
Discussion and outlook

- Discovery measurement seems ***unlikely*** – looking at best case tagger
  - For 30% signal efficiency, need **10,000x** better background rejection
  - Set limits on coupling strength modifier κ_s at **O(20) x SM prediction** using 2000 fb^{-1} of data at $\sqrt{s}$ = 250 GeV (combined limits for ILC and other future colliders in Backup)
- Gains would come from **reducing** the $Z \to qq$ background
  - As a suggestion from the ILD community, quantities like $\Delta\phi_{jj}$ or p_T^j should help
  - More statistics are available for the $Z \to qq$ and $ZZ \to qqqq$ backgrounds
- May try and provide prospects for BSM 2HDM $H \to cs$ or $H(125) \to bs$ decays
- Work will be documented in a paper as part of Snowmass 2021

Questions?

Backup

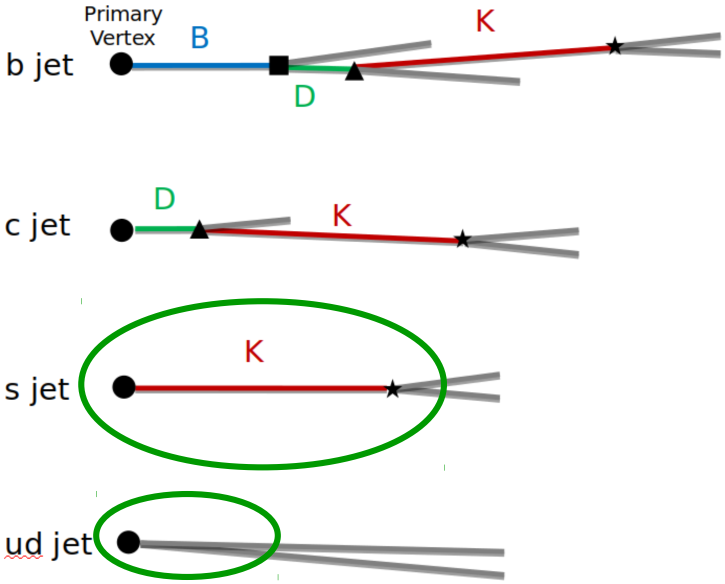
Neutral heavy Higgs BRs



Neutral heavy Higgs branching ratios. Taken from Fig. 3 of 1610.02398.

Different jet types, pictorially

Discriminants



Charged Kaon track

- Zero track impact parameter w.r.t. primary vertex
- Momentum fraction relative to the jet momentum carried by the leading Kaon
  - (Longitudinal vs transverse components?)

V^0 (K_S^0,Λ^0)

- Vertex momentum & displacement must point in the same direction
- Mean vertex distance smaller compared to b/c

+ the usual b/c discriminants (vertex mass, impact parameter for all tracks, etc.)

Remember to normalize the discriminants to make them boost invariant (as much as possible)

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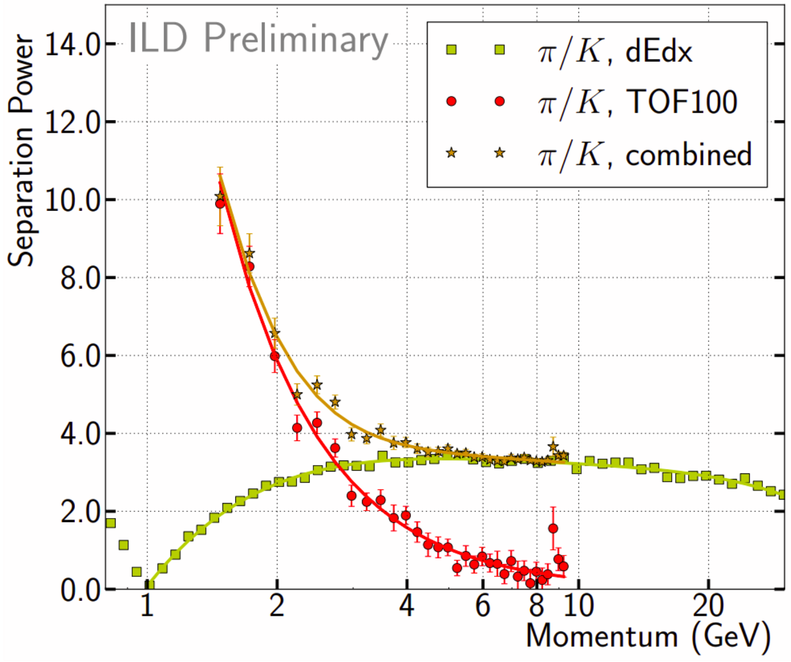
Taken from Slide 5 of Tomohiko Tanabe's 2020/11/24 presentation.

Flavour tagging requirements

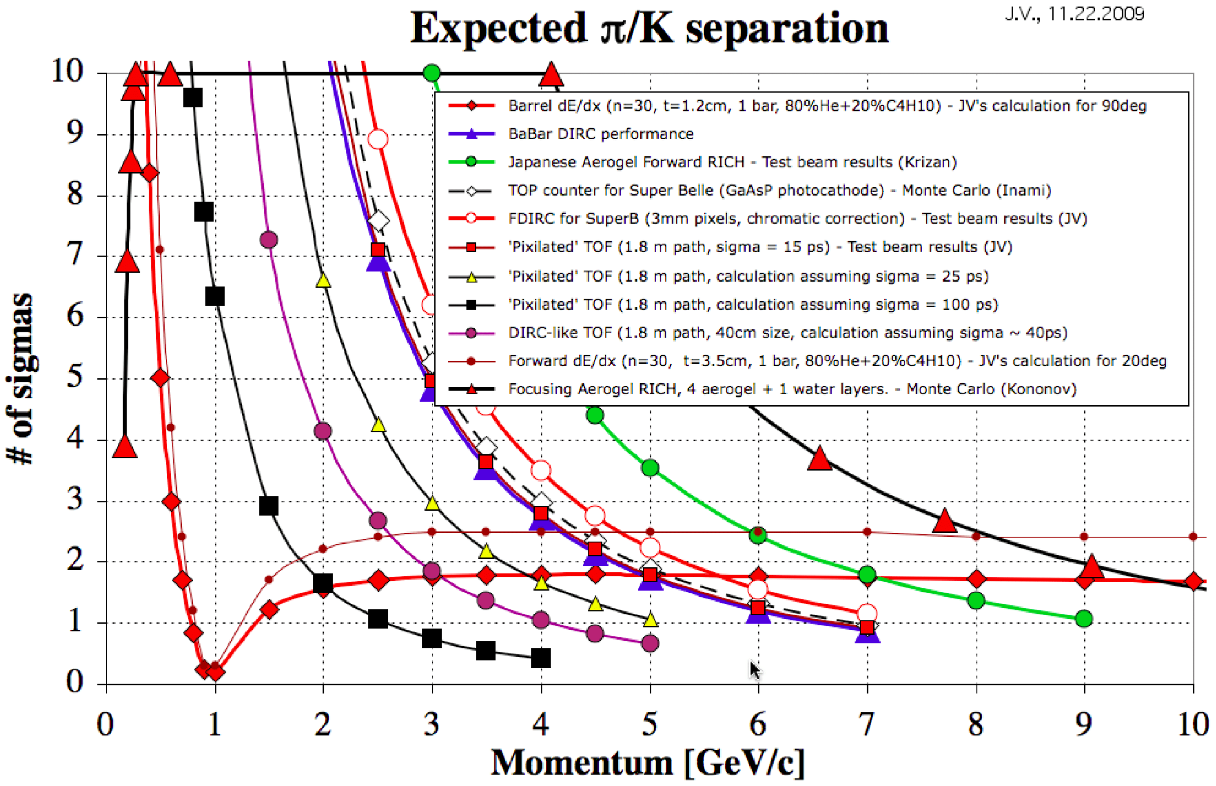
- Good impact parameter resolution, secondary vertexing – pertinent to *b*/*c*-tagging
- For strange versus up/down ("light") quark tagging, there's a need for **kaon tagging**
  - TPC provides *dE*/*dx*, Si detectors on either side of TPC provide time-of-flight (TOF) measurement
  - TOF works best at low *p* (< 10 GeV), expect *dE*/*dx* to work better for kaon tagging (where *p* > 10 GeV)
- ILD already provides BDT scores for *b*/*c*-taggers and an other ("*o*") tagger per jet



ILD separation power for pions and kaons using dE/dx and TOF (100 ps resolution). Taken from Fig. 3 of 1912.04601.

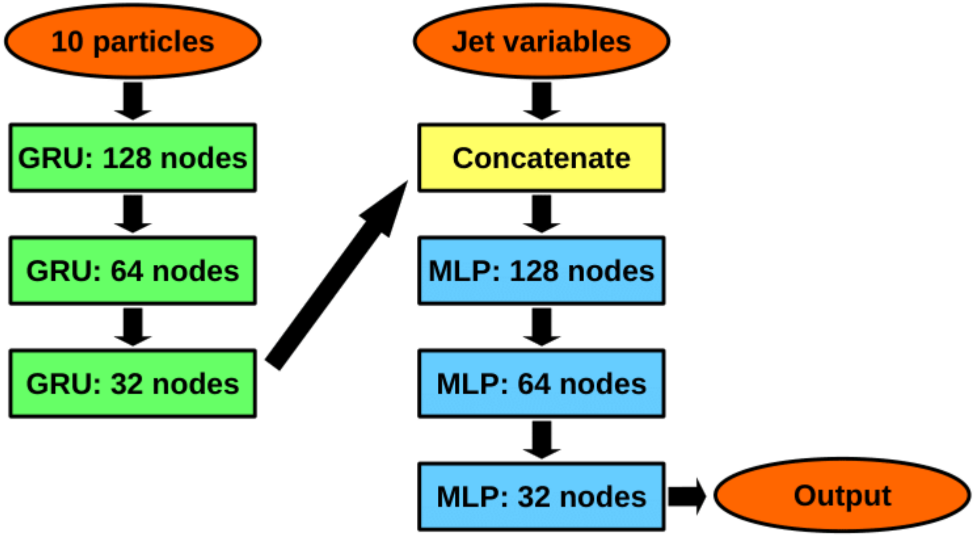
π/K separation for different detectors

Plot from Jerry Va'vra (SLAC).



Tagger architecture: pictorially

- Neural network architecture:
  - *Multiclassifer* (5 output classes: gluon, light, strange, charm, or bottom)
  - 3 layer recurrent neural network (using Gated Recurrent Units or GRUs) for particle-level inputs
  - Concatenated with jet-level inputs and fed into a 3 layer MultiLayer Perceptron (MLP)
  - Applied to strange tagging performance at **hadron** colliders
    - “Maximum performance of strange-jet tagging at hadron colliders” (2011.10736)



e^+e^- cross sections

Table 2, taken from page 62 of Tomohisa Ogawa's thesis.

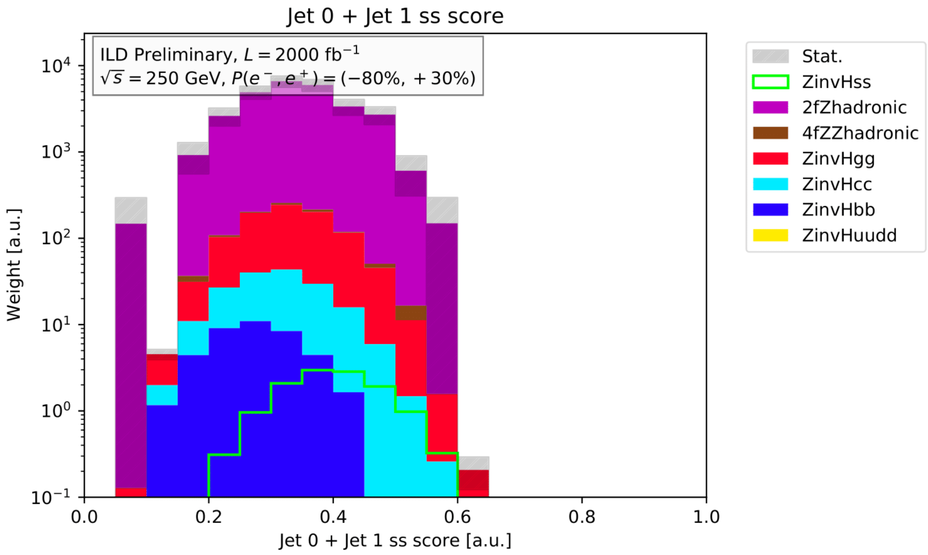
Table 2: Cross-sections and number of generated MC samples on the Higgs production processes and the major SM background processes for both $\sqrt{s} = 250$ and 500 GeV. The cross-sections given in the table are set to be each operation beam polarization states: $P(e^-, e^+) = (-80\%, +30\%)$ and $P(e^-, e^+) = (+80\%, -30\%)$, whereas the number of MC samples are given with fully beam polarization states: $P(e^-, e^+) = P^L_{e^-} P^R_{e^+} = (-100\%, +100\%)$. The eeH(s) and eeH(t) denote the s-channel ZH process and the t-channel ZZ-fusion processes. $2f\_l$ and $2f\_h$ in the table indicate that the final state has a lepton pair such as charged leptons or neutrinos, and a quark pair like $u\bar{u}$, $d\bar{d}$ except $t\bar{t}$. $4f\_l$ and $4f\_h$ are the same indication with $2f\_l$ or $2f\_h$, that means a final state has two lepton pairs or two quark pairs. $4f\_sl$ shows that a final state has a lepton pair and a quark pair. At $\sqrt{s} = 500$ GeV $6f$ is included in the SM backgrounds, where possible diagrams of 6 fermions in a final state are considered such as $t\bar{t}$ and a fermion pair with two W bosons and two fermion pairs with the Z boson.

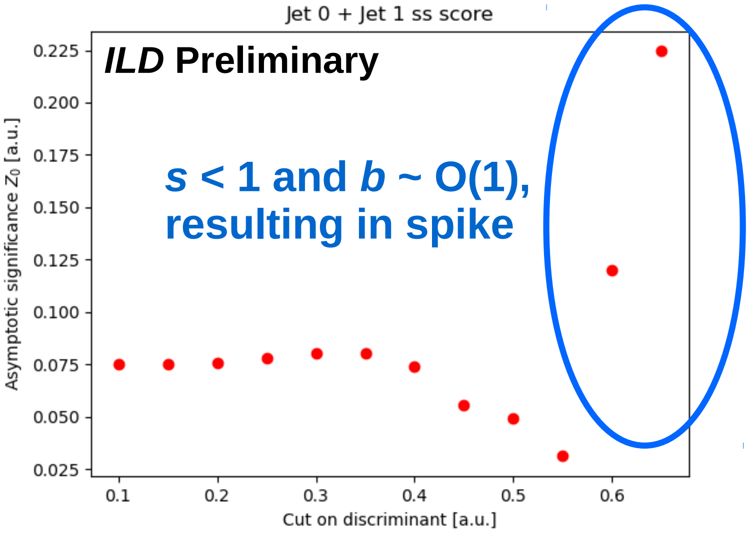
$\sqrt{s}$=250 GeV operation polarization			fully polarization			
	Cross-section (fb)		MC sample			
$P(e^-, e^+)$	$(-80\%, +30\%)$	$(+80\%, -30\%)$	$P^L_{e^-} P^R_{e^+}$	$P^R_{e^-} P^L_{e^+}$	$P^L_{e^-} P^L_{e^+}$	$P^R_{e^-} P^R_{e^+}$
eeH(s)	10.7	7.14	$4.00 \cdot 10^4$	$1.00 \cdot 10^4$	0	0
eeH(t)	0.71	0.52	$1.00 \cdot 10^4$	$1.00 \cdot 10^4$	3992	3992
$\mu\mu H$	10.4	7.03	$4.00 \cdot 10^4$	$1.00 \cdot 10^4$	0	0
qqH	210.2	141.9	$5.45 \cdot 10^5$	$2.94 \cdot 10^5$	0	0
$\nu\nu H$ (s)	61.6	41.6	$12.8 \cdot 10^4$	$6.50 \cdot 10^4$	0	0
$\nu\nu H$ (t)	15.4	0.93	$12.8 \cdot 10^4$	$6.50 \cdot 10^4$	0	0
$2f\_l$	$3.82 \cdot 10^4$	$3.49 \cdot 10^4$	$2.63 \cdot 10^6$	$2.13 \cdot 10^6$	$5.03 \cdot 10^5$	$5.03 \cdot 10^5$
$2f\_h$	$7.80 \cdot 10^4$	$4.62 \cdot 10^4$	$1.75 \cdot 10^6$	$1.43 \cdot 10^6$	0	0
$4f\_l$	$6.03 \cdot 10^3$	$1.47 \cdot 10^3$	$2.25 \cdot 10^6$	$9.80 \cdot 10^4$	$2.73 \cdot 10^5$	$2.73 \cdot 10^5$
$4f\_sl$	$1.84 \cdot 10^4$	$2.06 \cdot 10^3$	$4.04 \cdot 10^6$	$3.56 \cdot 10^5$	$9.78 \cdot 10^4$	$9.78 \cdot 10^4$
$4f\_h$	$1.68 \cdot 10^4$	$1.57 \cdot 10^3$	$2.38 \cdot 10^6$	$2.42 \cdot 10^5$	0	0

Signal discriminant

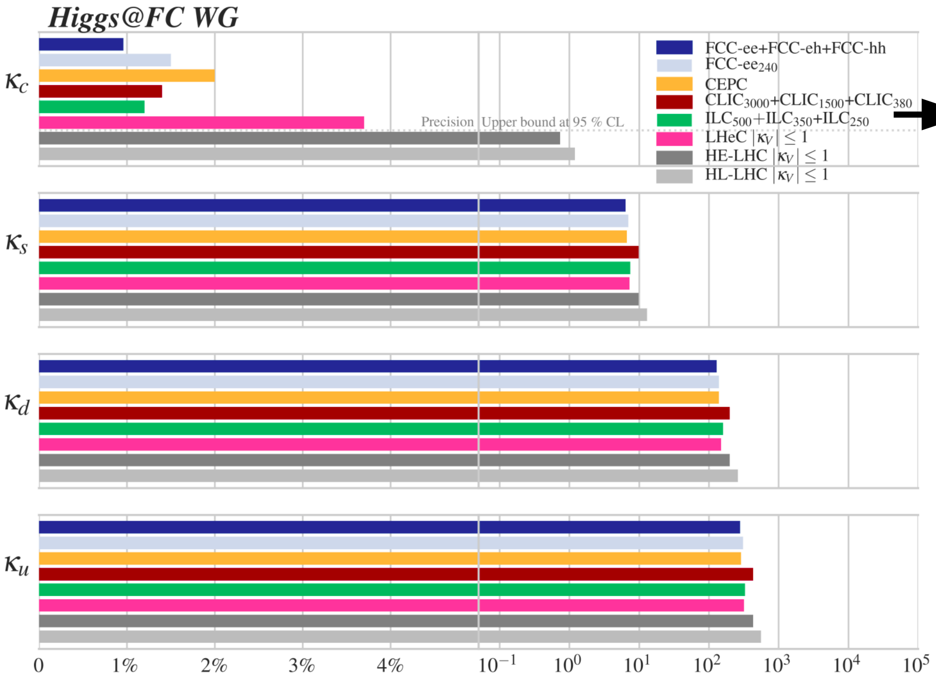
- Use (0.5x) sum of strange jet scores for the leading and subleading jets as the discriminant
  - Tested different cuts, calculating the asymptotic significance (neglecting MC stats) as:

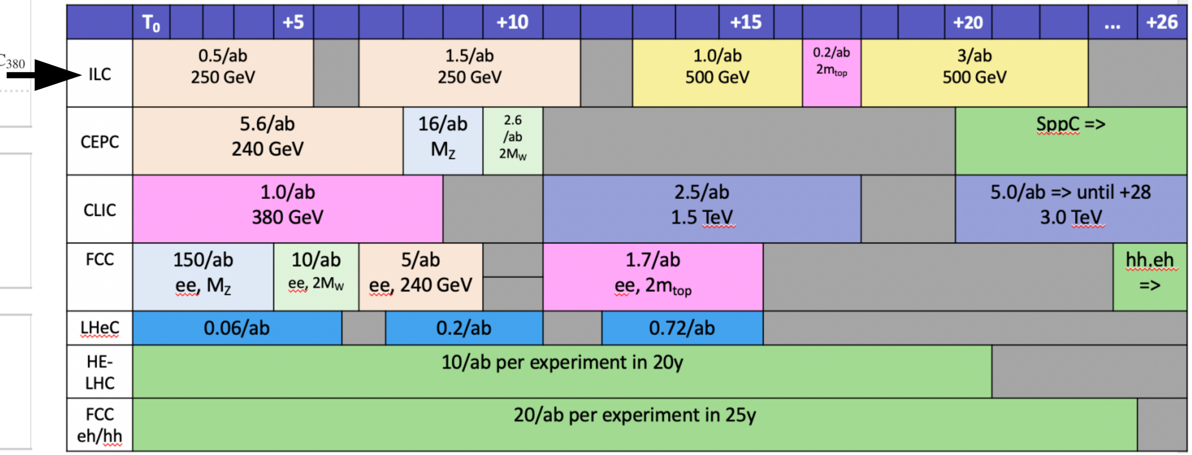
    $Z_0 = \sqrt{(2 * ((s + b) * \ln(1 + s / b) - s))}$
- Best cut seems to be around **>0.3**
  - Corresponds to $\boldsymbol{Z_0 \sim 0.1\sigma}$





Expected limits from future colliders

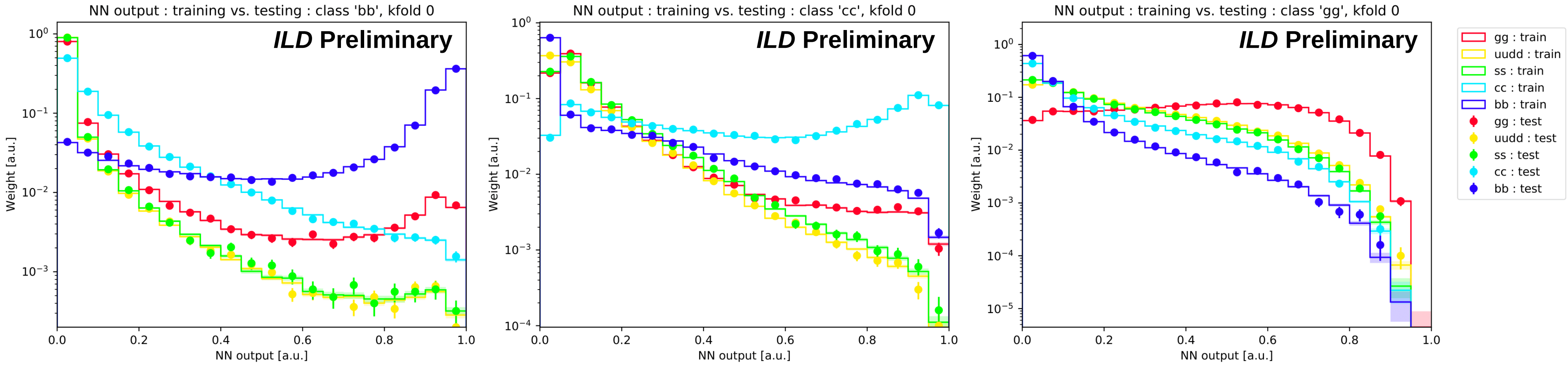




Limits on couplings of Higgs to charm, strange, and light quarks and timeline for different future collider running scenarios. Taken from Figs. 1 and 12 of 1905.03764.

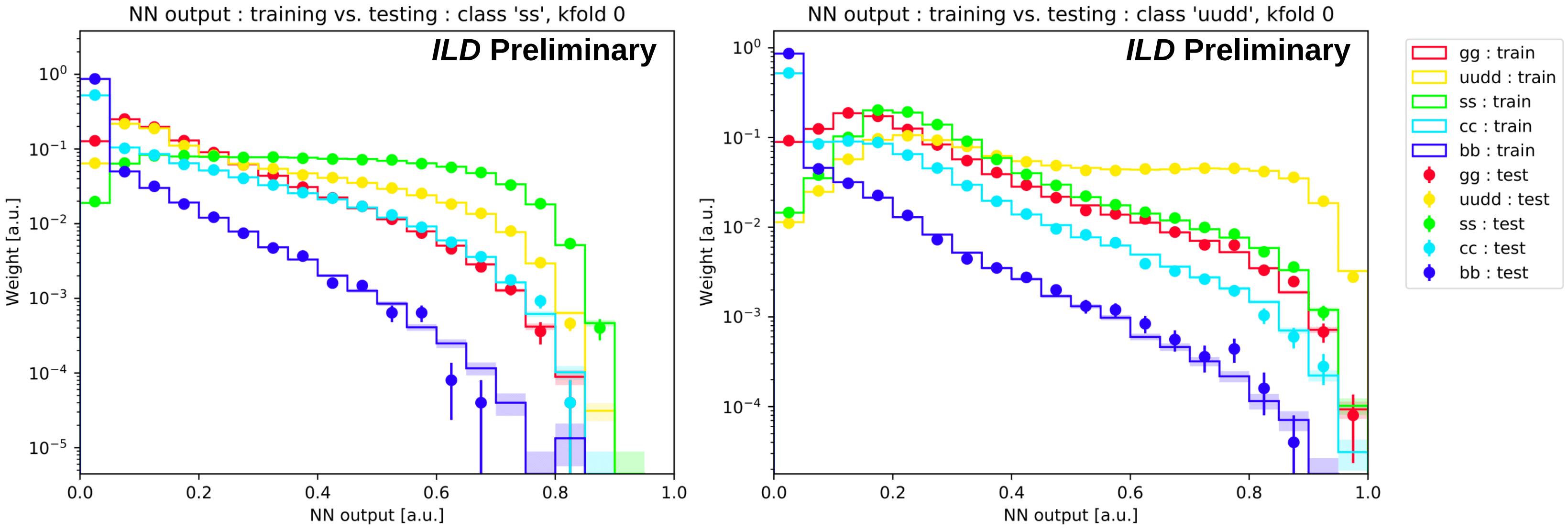
Train-test agreement in neural network output nodes

Performance: *b*, *c*, and *g* jets



- Network likely returning *b*/*c*-tagger scores – should do just as well or better than input BDT scores
- Good discrimination of gluon jets

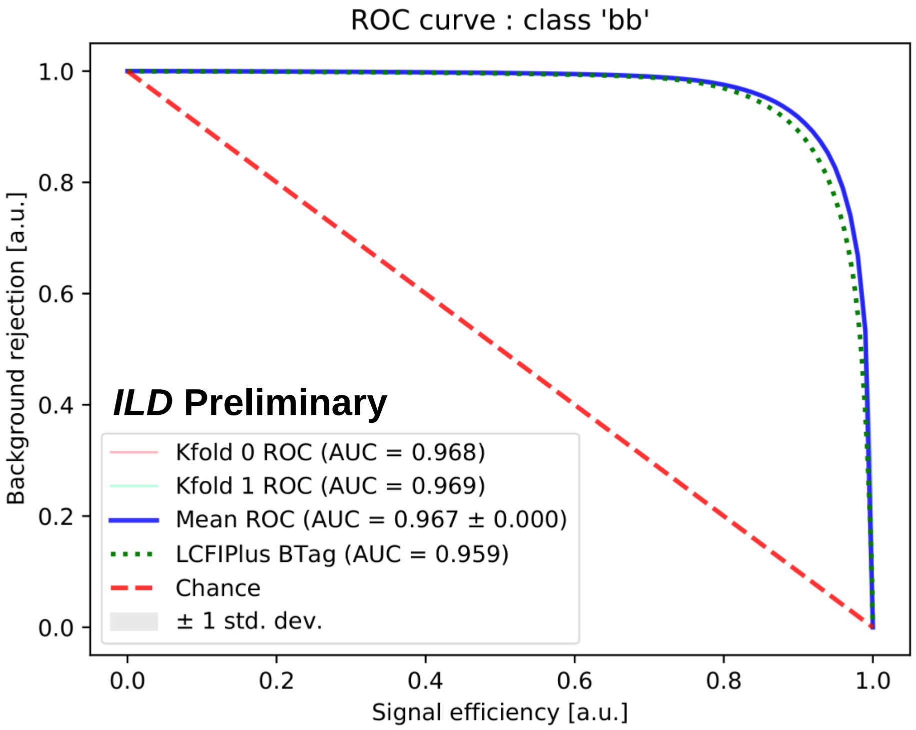
Performance: *s* and *u*/*d* jets

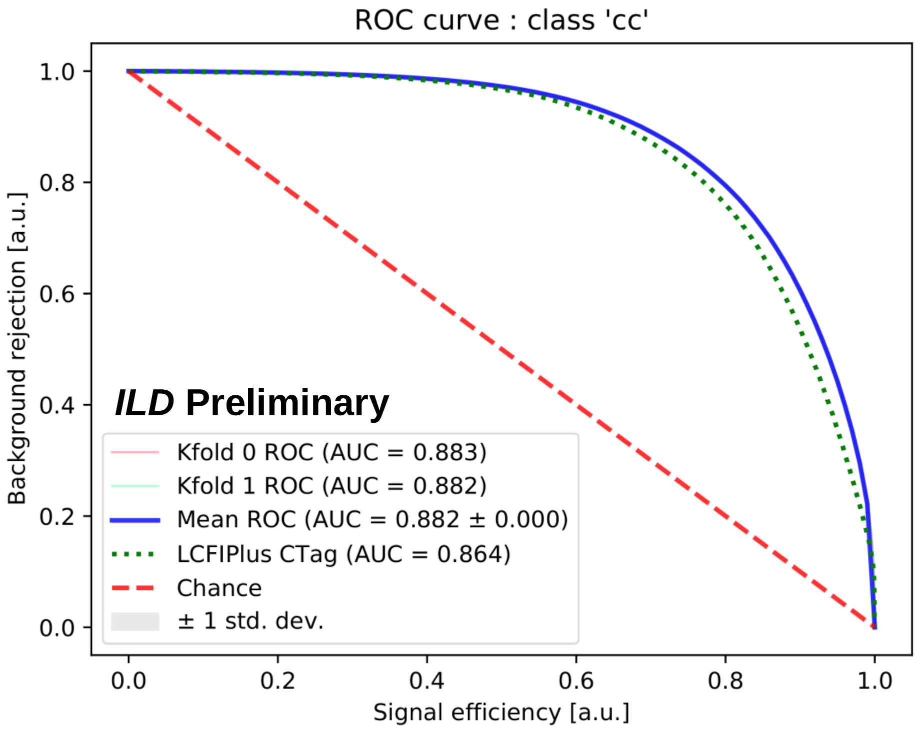


- Separation of *s* and *u*/*d* is **possible** with using truth likelihoods
- At 50% strange tagging efficiency, we have **90%** background rejection over **70%** for LCFIPlus Otag (see ROC curves)

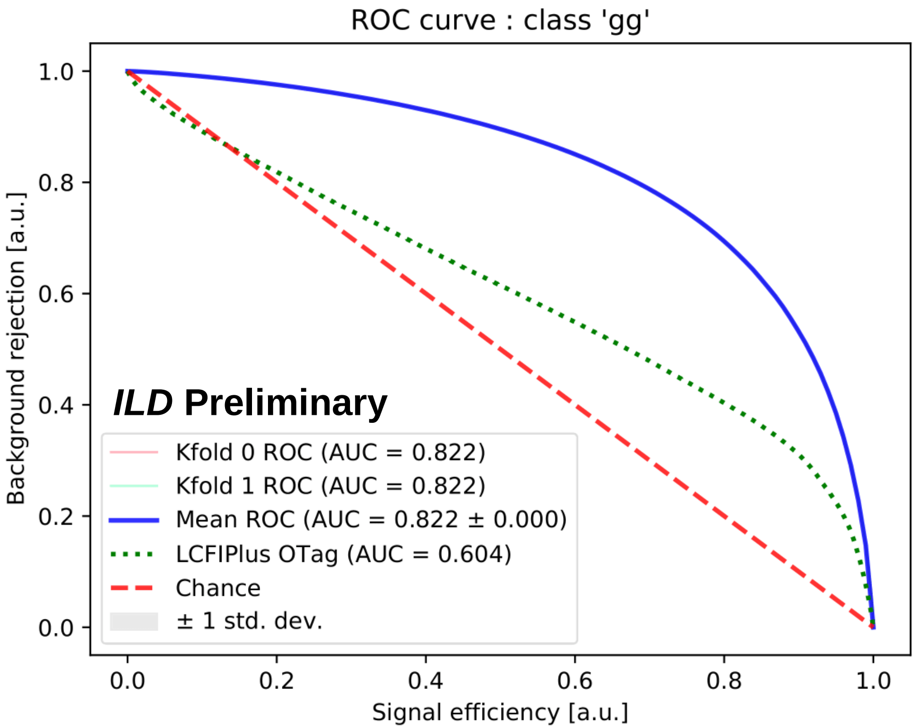
ROC curves for neural network output nodes

ROC curves: *b* and *c* jets

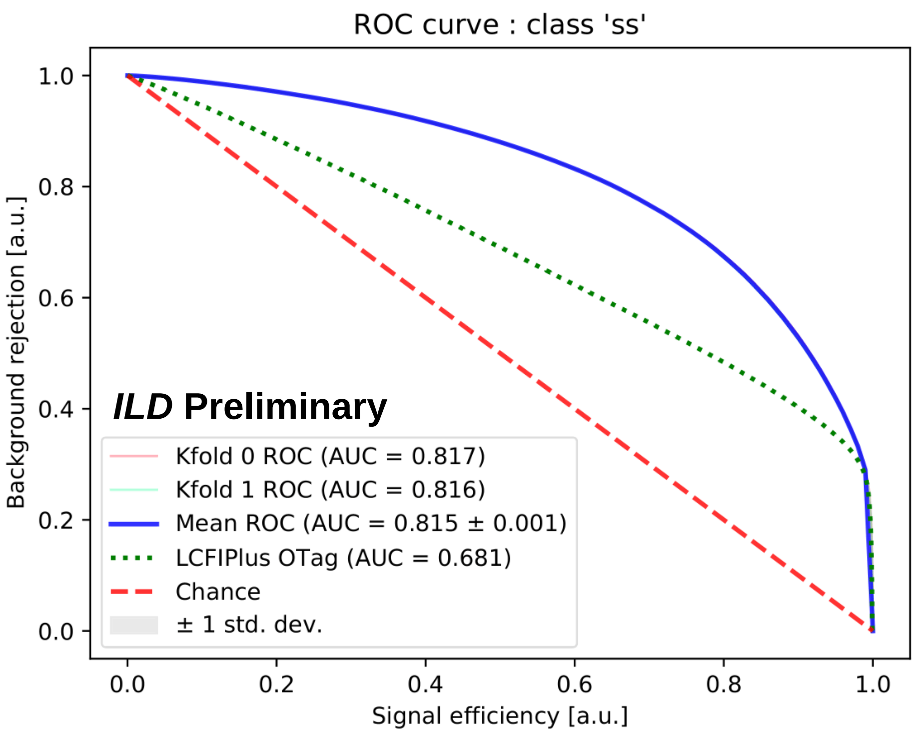


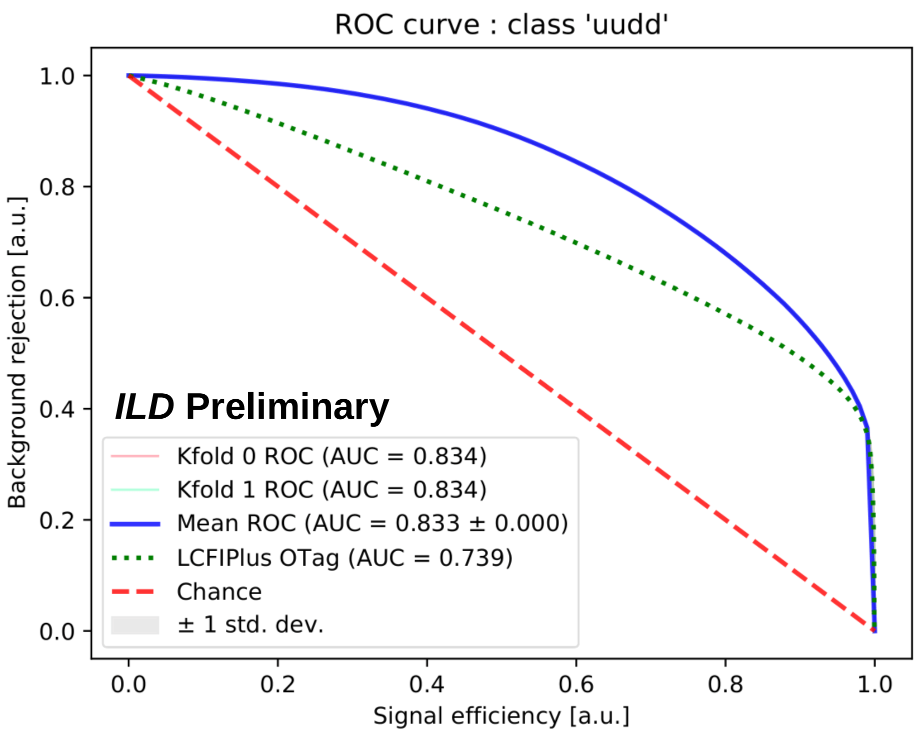


ROC curves: *g* jets



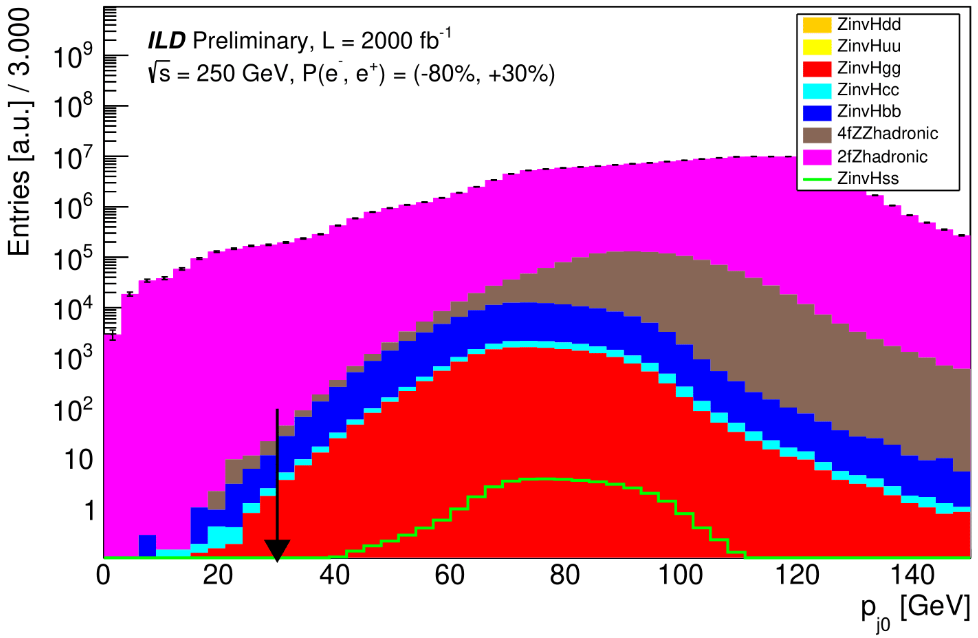
ROC curves: s and *u/d* jets

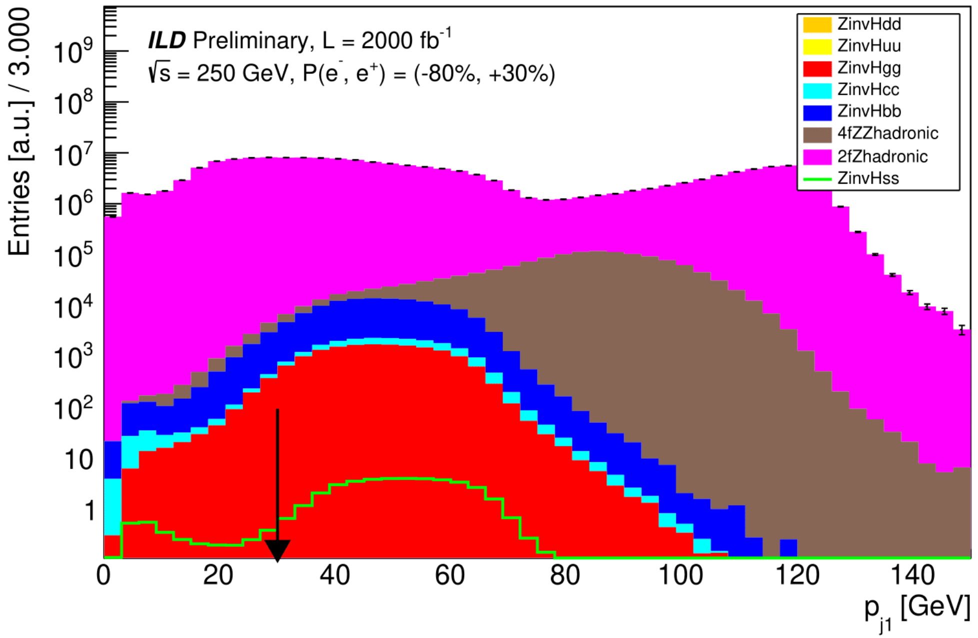




Histograms at each cut in $H \rightarrow ss$ analysis

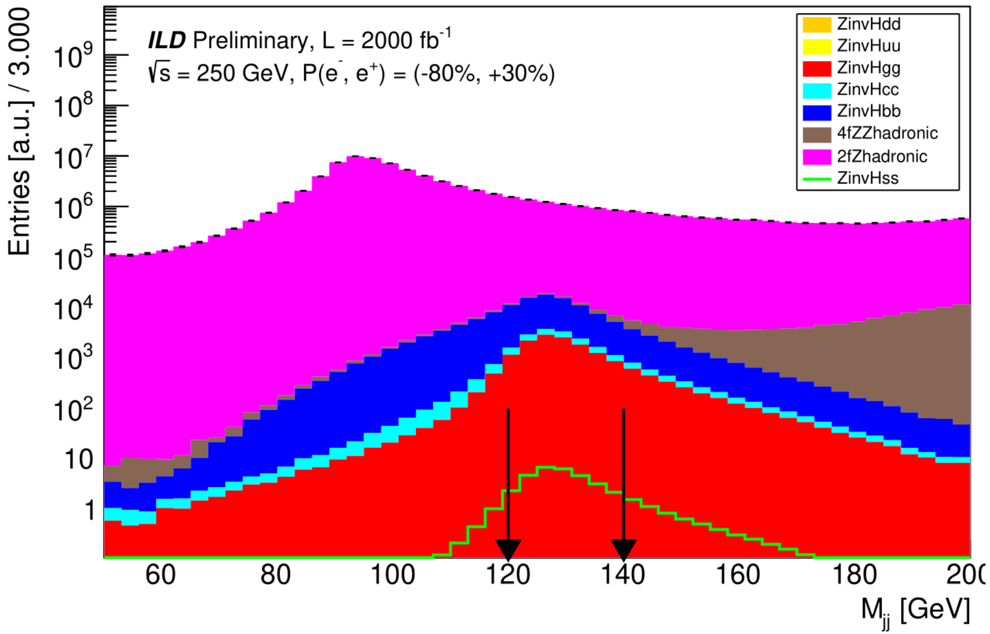
Histograms: p_{j0} and p_{j1}

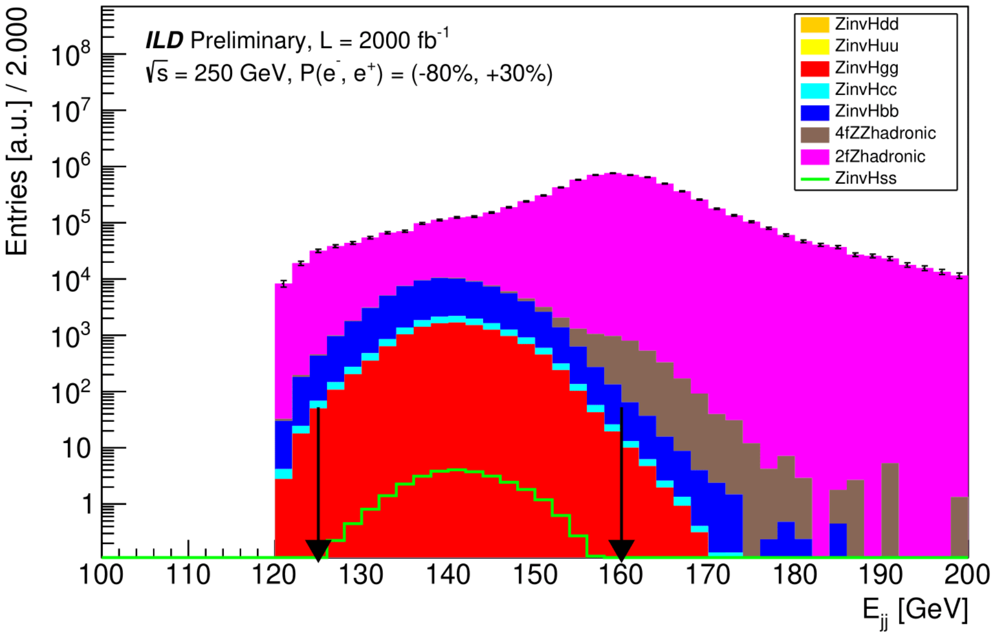




****Unstacked green line is signal****

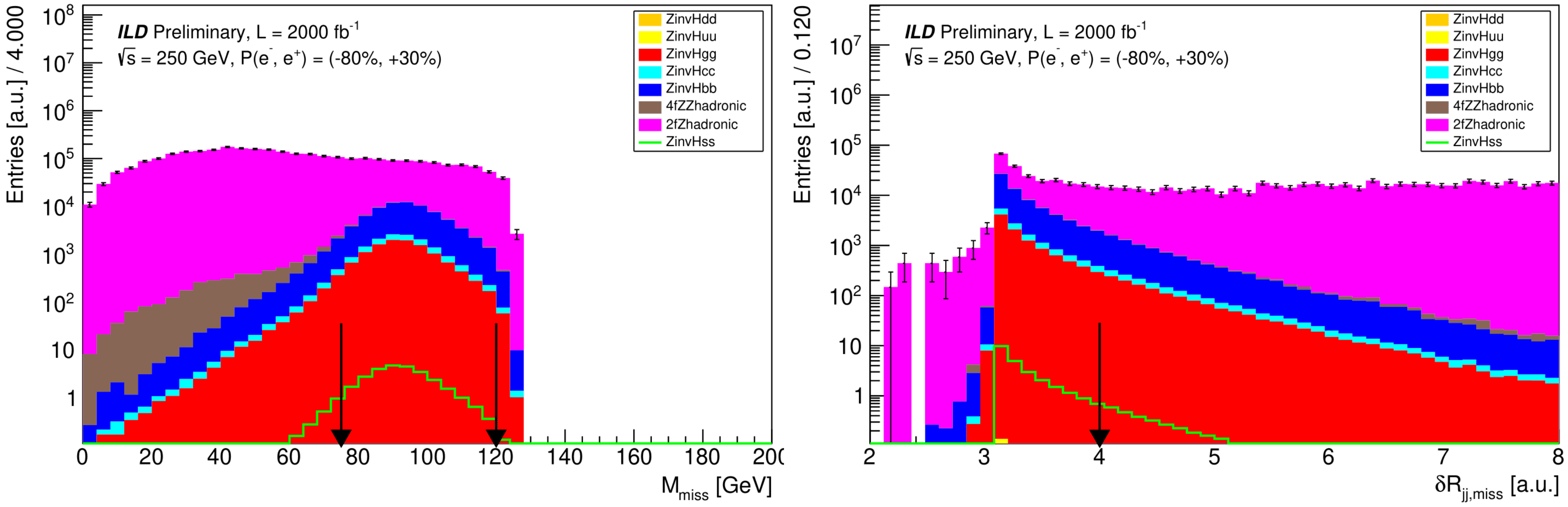
Histograms: M_{jj} and E_{jj}





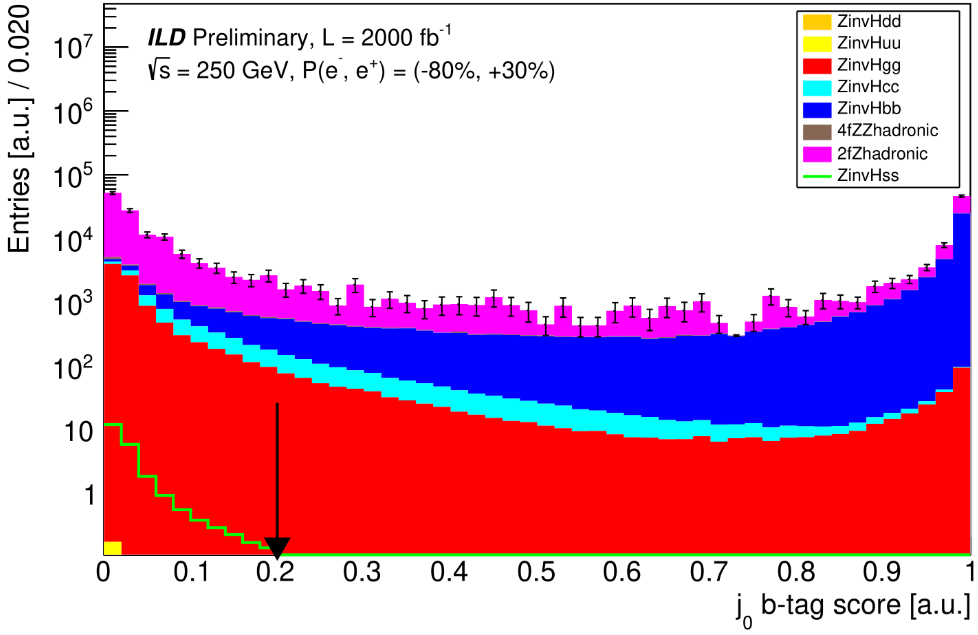
****Unstacked green line is signal****

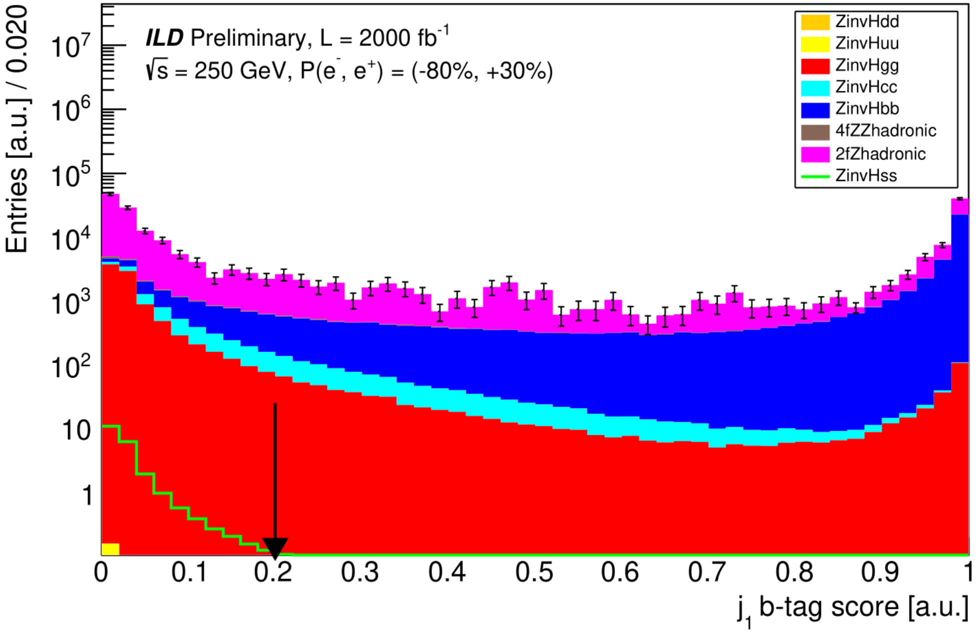
Histograms: M_{miss} and $\Delta R_{jj,\text{miss}}$



Unstacked green line is signal

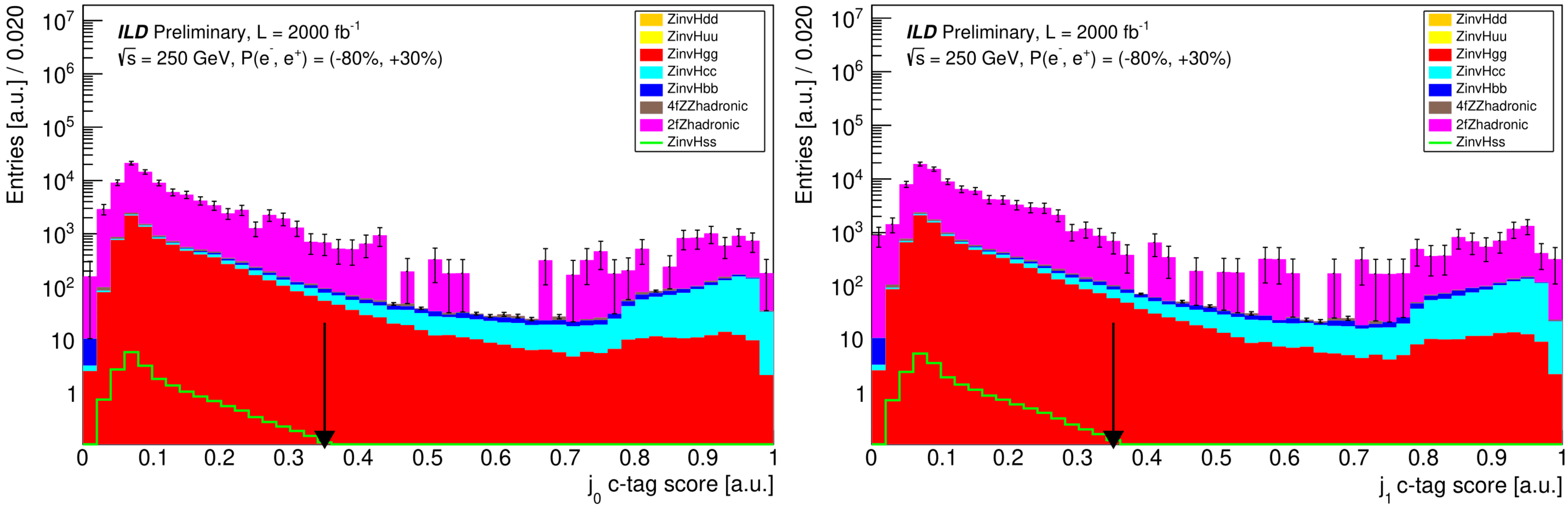
Histograms: *b*-tagger scores





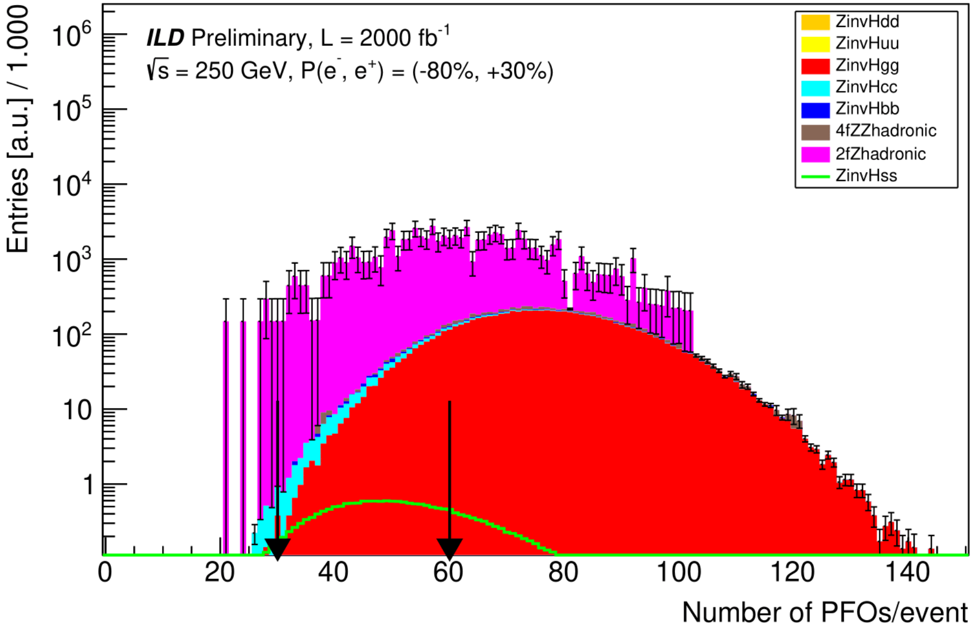
****Unstacked green line is signal****

Histograms: *c*-tagger scores



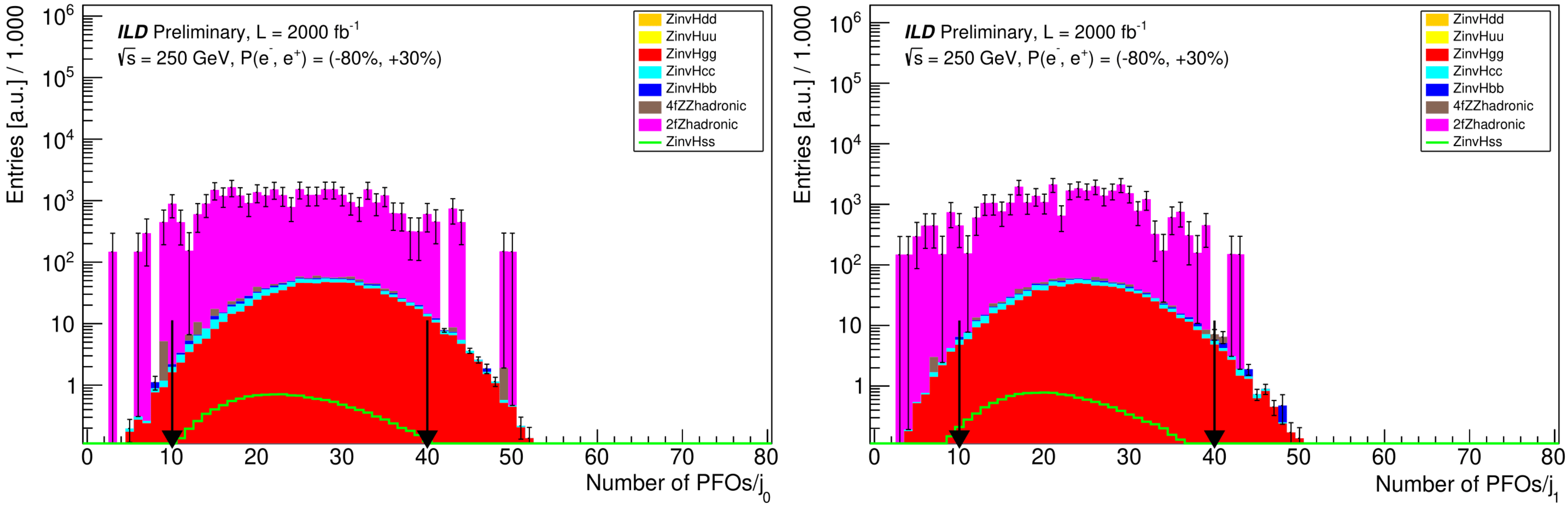
****Unstacked green line is signal****

Histograms: N_{PFOs}/event



****Unstacked green line is signal****

Histograms: N_{PFOs}/jet



****Unstacked green line is signal****