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# Electroweak Phase Transition in Exotic Higgs Decays with CEPC

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# Outline

- Physics Motivation
- Theoretical Prospects
- Sample Production
- Selections and Cutflow
- BDT Approach
- Limit Setting with TRExFitter
- Summary and future plans

# Physics Motivation

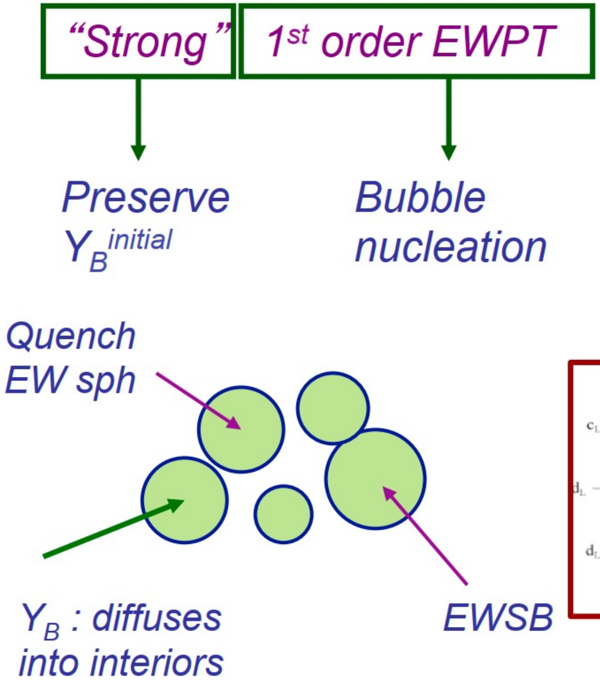
J. Kozaczuk, M. J. Ramsey-Musolf, and J. Shelton *Phys. Rev. D* **101**, 115035 (2020).

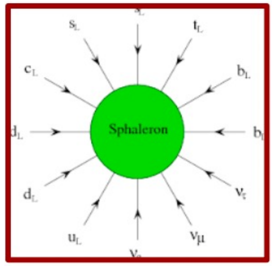


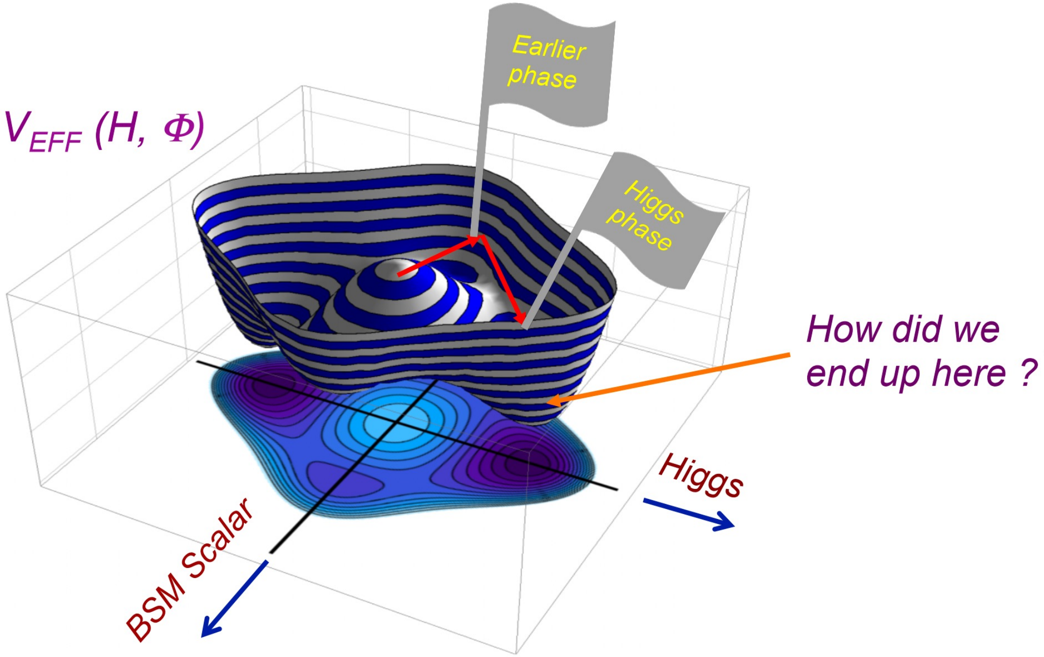
- We are interested in the strong first-order electroweak phase transition in the "SM Higgs + Light Real Singlet Scalar" model:

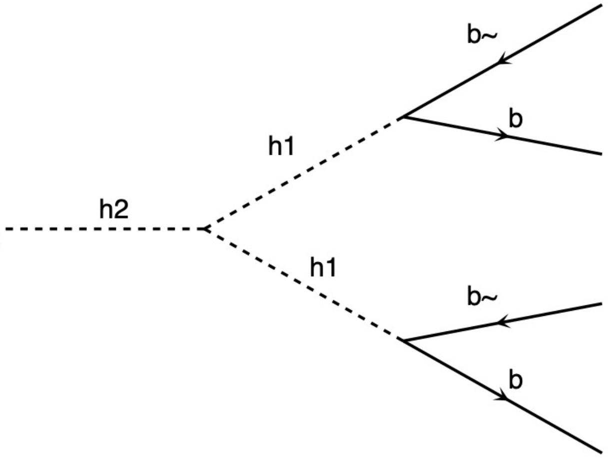
$$V = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}a_1|H|^2S + \frac{1}{2}a_2|H|^2S^2 + b_1S + \frac{1}{2}b_2S^2 + \frac{1}{3}b_3S^3 + \frac{1}{4}b_4S^4$$

- Mass eigenstates: $h_1 = h\cos\theta + s\sin\theta$ ( $h_1$ : singlet-like )
  $h_2 = -h\sin\theta + s\cos\theta$ ( $h_2$ : SM-like Higgs )



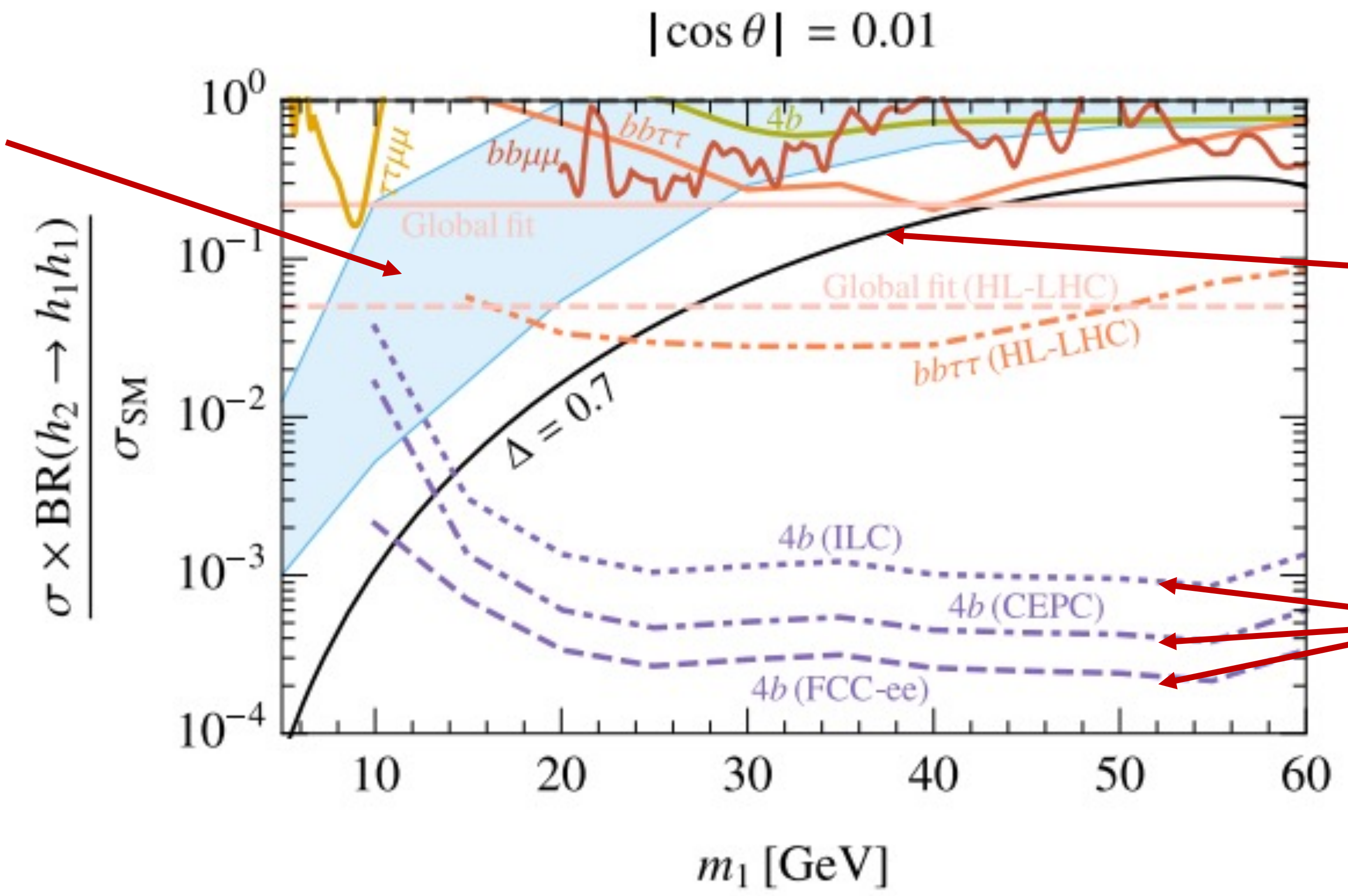




Extrema can evolve differently as T evolves
→ Rich possibilities for symmetry breaking

# Theoretical Prospects

$h_2 \to h_1 h_1 \to 4b$

EWPT viable: numerical




EWPT viable: semi analytic

Future $e^+e^-$

J. Kozaczuk, M. J. Ramsey-Musolf, and J. Shelton *Phys. Rev. D* **101**, 115035 (2020).
Z. Liu *et al., Chinese Phys. C* **41**, 063102 (2017).

# Sample Production

- **Signal:** The samples are generated at 240 GeV. 50000 events per mass point from 5 to 60 GeV for electron and muon channel separately
- **Generator:** Madgraph5 and Pythia8
- **Simulation and reconstruction:** cepcsoft 0.1.1 , CEPC_v4

| $m_1[GeV]$ | $a_2$ | $b_3$ | $b_4$ | $D\_width$ | $BR$ |
|---|---|---|---|---|---|
| 5 | 0.00379269019 | 0.00087284094 | 3.16227766017e-05 | 7.3774e-05 | 0.01780479 |
| | 0.00033598183 | 0.00693322201 | 8.91250938133e-07 | 1.0348e-06 | 0.00025421 |
| 10 | 0.02511886432 | 0.01954047457 | 0.00125892541179 | 0.0030277 | 0.42627589 |
| | 0.00199526231 | 0.04908345294 | 1.58489319246e-05 | 2.1351e-05 | 0.00521904 |
| 15 | 0.05011872336 | 0.00389883725 | 0.00446683592151 | 0.011795 | 0.73632455 |
| | 0.00375837404 | 0.19540474574 | 7.94328234724e-05 | 5.9206e-05 | 0.01422012 |
| 20 | 0.00630957344 | 0.49083452948 | 0.00025118864315 | 0.0001866 | 0.04347394 |
| 25 | 0.01 | 0.97934363956 | 0.00063095734448 | 0.00044524 | 0.09859974 |
| 30 | 0.01678804018 | 1.55215506742 | 0.00125892541179 | 0.0011898 | 0.22613126 |
| 35 | 0.02511886432 | 2.46 | 0.00251188643151 | 0.0025006 | 0.38033656 |
| 40 | 0.02660725059 | 3.89883725345 | 0.00398107170553 | 0.0025799 | 0.38771480 |
| 45 | 0.04216965034 | 4.90834529482 | 0.00630957344480 | 0.0058611 | 0.58957125 |
| 50 | 0.04216965034 | 7.77920304401 | 0.01 | 0.0050107 | 0.55126677 |
| 55 | 0.06309573445 | 9.79343639562 | 0.01584893192461 | 0.0089054 | 0.68549957 |
| 60 | 0.05956621435 | 15.5215506742 | 0.02511886431509 | 0.0045989 | 0.53001523 |

**Table.** Parameters and related BRs that satisfy a strong 1-st order electroweak phase transition. The orange shading represent parameter when BR is at its upper bound, and blue shading represent the lower bound.

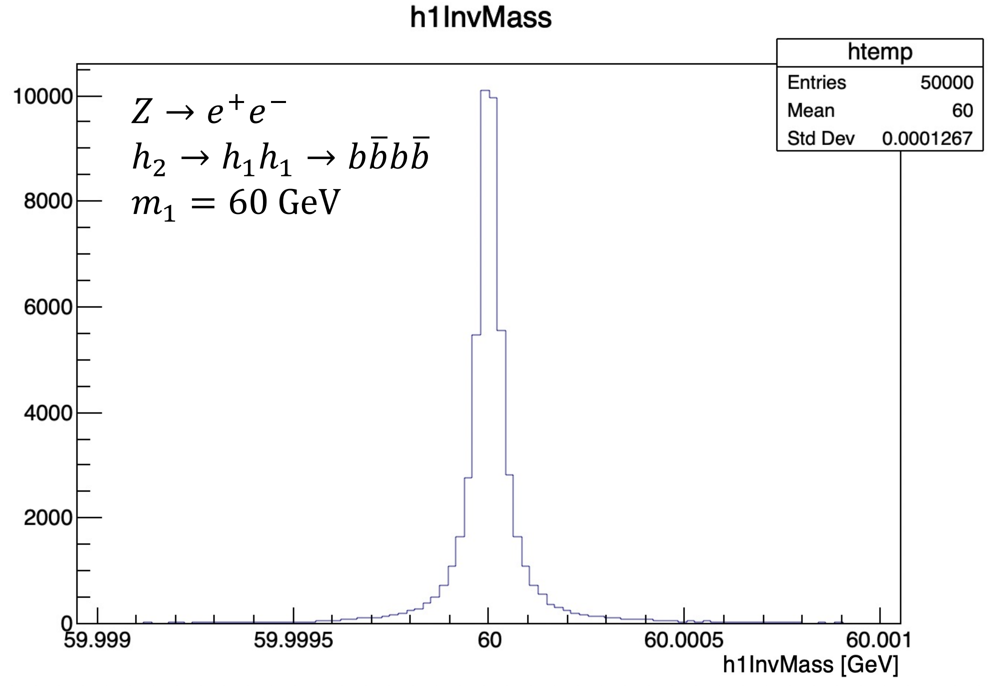



**Fig.** Mass distribution of $h_1$ when $m_1 = 60\text{GeV}$

# Sample Production

- Background : 2-Fermion, 4-Fermion, eeH, mumuH as our background. Expect luminosity : $5.6\ \mathrm{ab}^{-1}$ .

| Process | $\int L$ | Final states | X-sections (fb) | Comments |
|---|---|---|---|---|
| Higgs signal | 5 $\mathrm{ab}^{-1}$ | $ffH$ | 203.66 | all signals |
| | 5 $\mathrm{ab}^{-1}$ | $e^+e^-H$ | 7.04 | including ZZ fusion |
| | 5 $\mathrm{ab}^{-1}$ | $\mu^+\mu^-H$ | 6.77 | |
| | 5 $\mathrm{ab}^{-1}$ | $\tau^+\tau^-H$ | 6.75 | |
| | 5 $\mathrm{ab}^{-1}$ | $\nu\bar{\nu}H$ | 46.29 | all neutrinos (ZH+WW fusion) |
| | 5 $\mathrm{ab}^{-1}$ | $q\bar{q}H$ | 136.81 | all quark pairs (Z$\rightarrow q\bar{q}$) |

## 2 fermion backgounds

| Process | $\int L$ | Final states | X-sections (fb) | Comments |
|---|---|---|---|---|
| $e^+e^- \rightarrow e^+e^-$ | 5 $\mathrm{ab}^{-1}$ | $e^+e^-$ | 24770.90 | |

http://cepcsoft.ihep.ac.cn/guides/Generation/docs/ExistingSamples/#240-gev

lxslc7 : /cefs/data/DstData/CEPC240/CEPC_v4_update

# Sample Production

- Higgs decay mode

| decay mode | branching ratio | relative uncertainty |
|---|---|---|
| $H \to b\bar{b}$ | 57.7% | +3.2%, −3.3% |
| $H \to c\bar{c}$ | 2.91% | +12%, −12% |
| $H \to \tau^+\tau^-$ | 6.32% | +5.7%, −5.7% |
| $H \to \mu^+\mu^-$ | $2.19\times10^{-4}$ | +6.0%, −5.9% |
| $H \to WW^*$ | 21.5% | +4.3%, −4.2% |
| $H \to ZZ^*$ | 2.64% | +4.3%, −4.2% |
| $H \to \gamma\gamma$ | $2.28\times10^{-3}$ | +5.0%, −4.9% |
| $H \to Z\gamma$ | $1.53\times10^{-3}$ | +9.0%, −8.8% |
| $H \to gg$ | 8.57% | +10%, −10% |
| $\Gamma_H$ | 4.07 MeV | +4.0%, −4.0% |

https://iopscience.iop.org/article/10.1088/1674-1137/43/4/043002/pdf

# Selections and Cutflow

**Origin :** Original Events from FSClasser

**ll_costheta :** Polar angle of the dilepton system

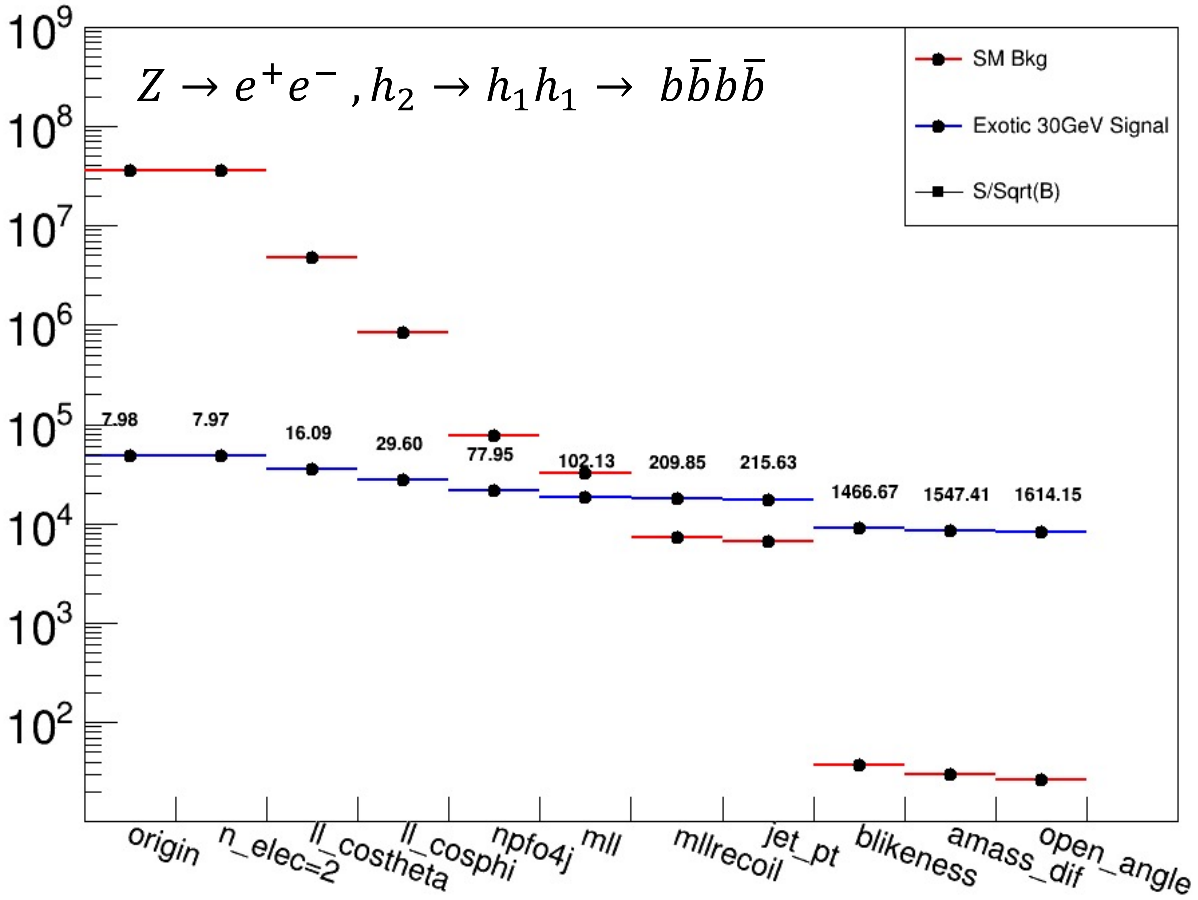
**ll_cosphi :** Separation angle between two Z-leptons

**npfo4j :** Number of particles in the 4 jets each with energy larger than 0.4 GeV

**blikeness :** $\frac{L_{b1}\times L_{b2}\times L_{b3}\times L_{b4}}{L_{b1}\times L_{b2}\times L_{b3}\times L_{b4}+(1-L_{b1})\times(1-L_{b2})\times(1-L_{b3})\times(1-L_{b4})}$

**amass_dif :** Mass difference between the two reconstructed $h_1$ singlet.

**Open_angle :** Opening angle between the two jets from each singlet




Thanks to Yu Bai.
Y. Bai *et al., Chinese Phys. C* **44**, 013001 (2020).

# Selections and Cutflow

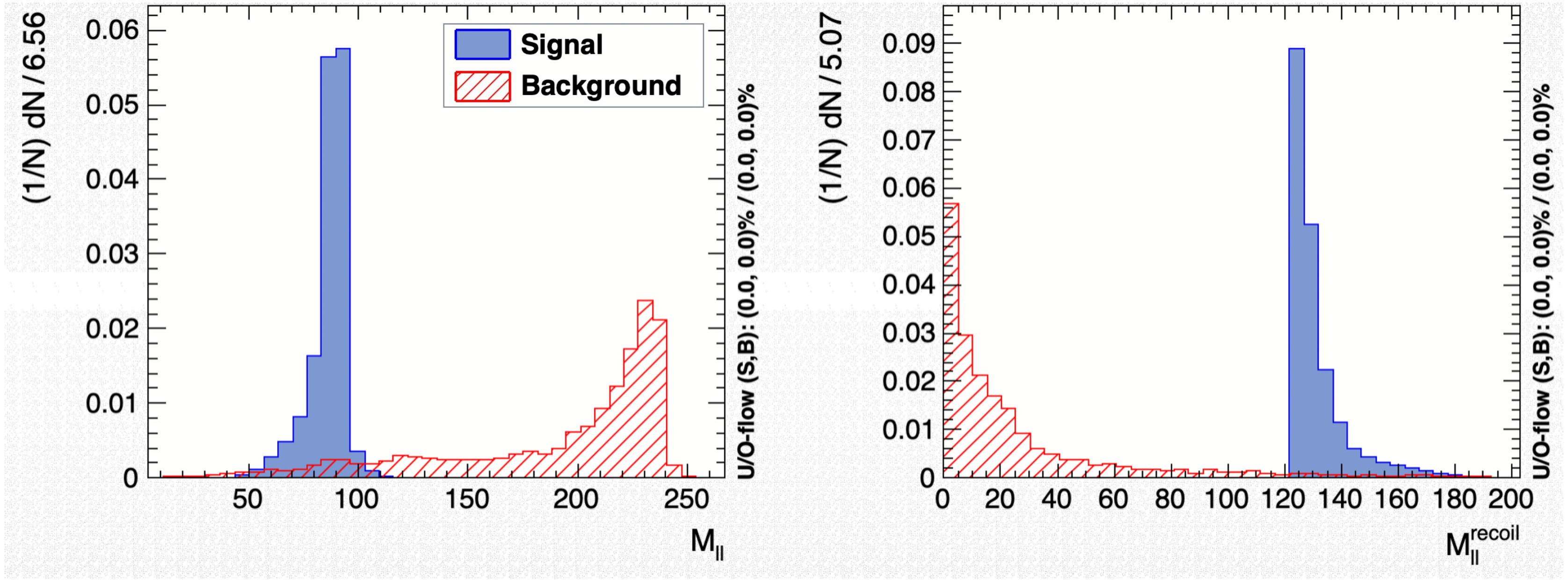
| Cut Set | $\lvert Cos\theta_{ll} \rvert$ | $Cos\psi$ | mll | mll_recoil |
|---|---|---|---|---|
| Cut Baseline | <0.71 | >-0.74 | 77.5~104.5 | 120~140 |

| Cut Set | npfo4j | ljpt | Sljpt | amass_dif | Cos(angle) | blikeness |
|---|---|---|---|---|---|---|
| Cut 1 | >40 | <80 | <50 | <20 | <0.9 | >0.9999 |

- Higgs to bb process is our dominant background
- Background process are strongly suppressed by the blikeness cut.

$$Z \to e^+e^-, h_2 \to h_1 h_1 \to b\bar{b}b\bar{b}$$

- $M_{ll}$ and $M_{ll}^{recoil}$ distribution before the cut



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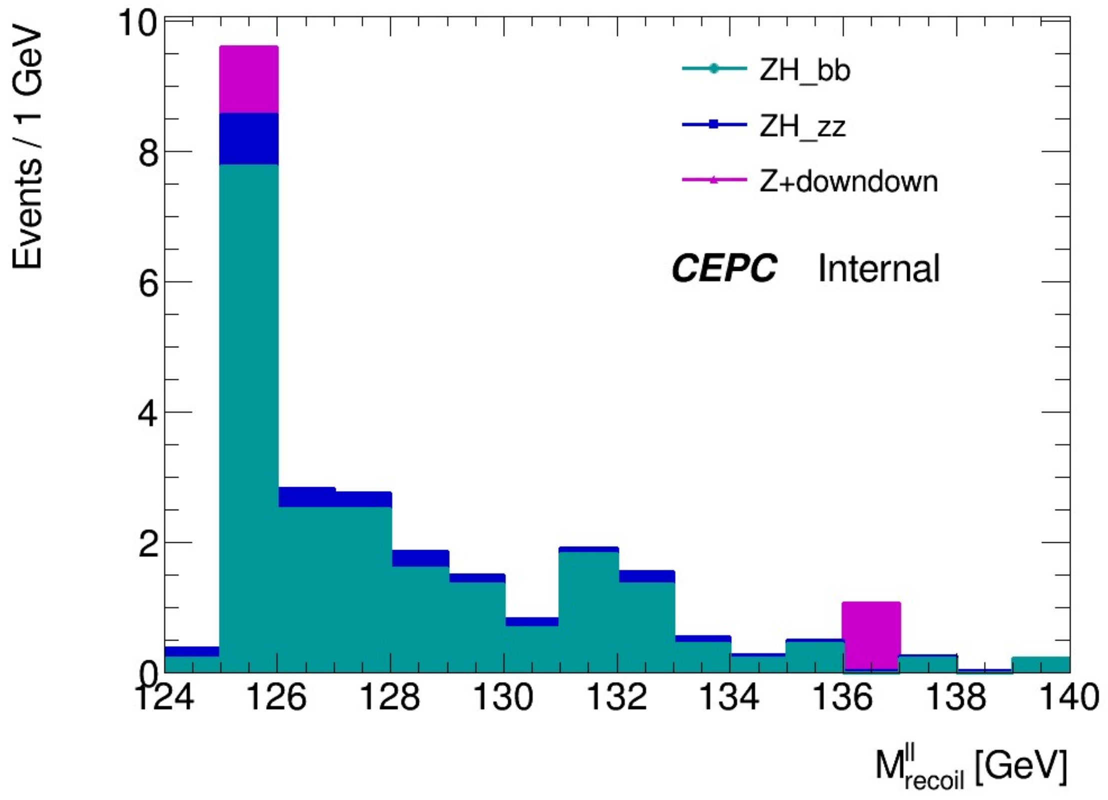
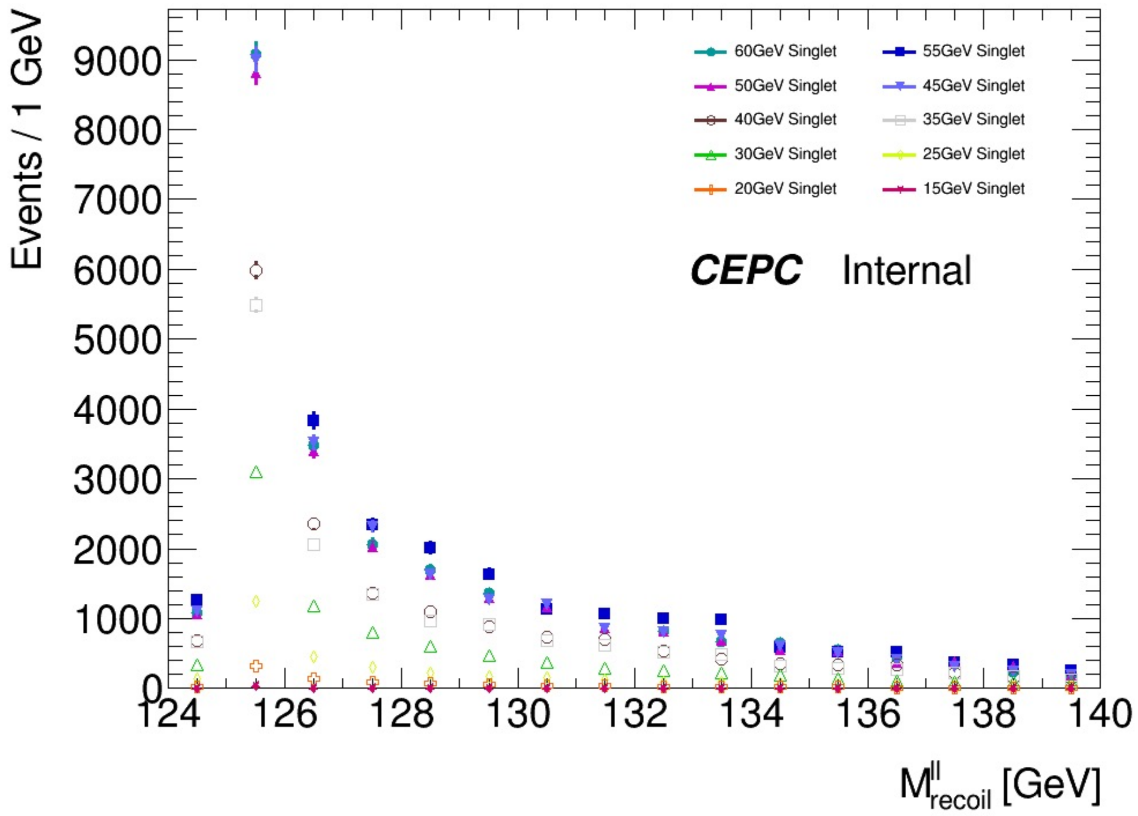


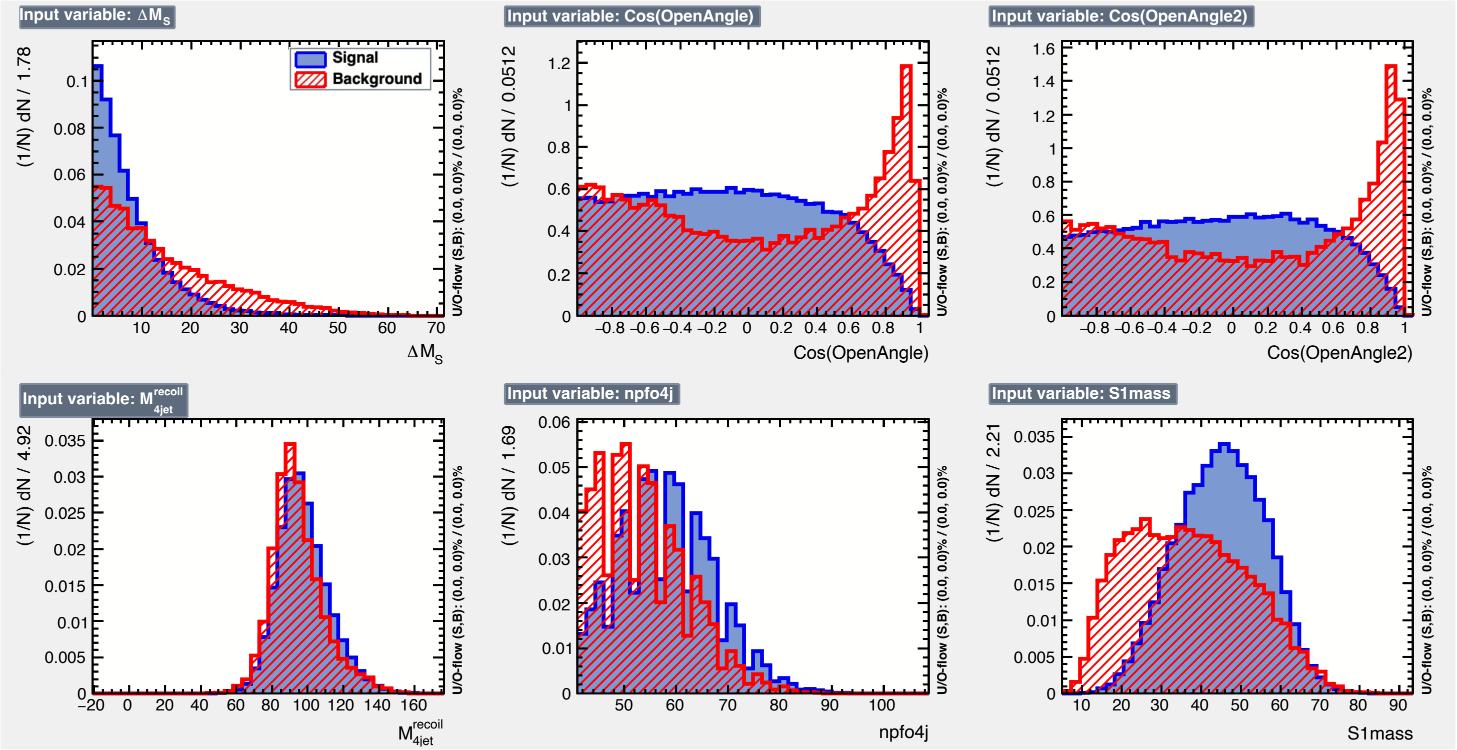



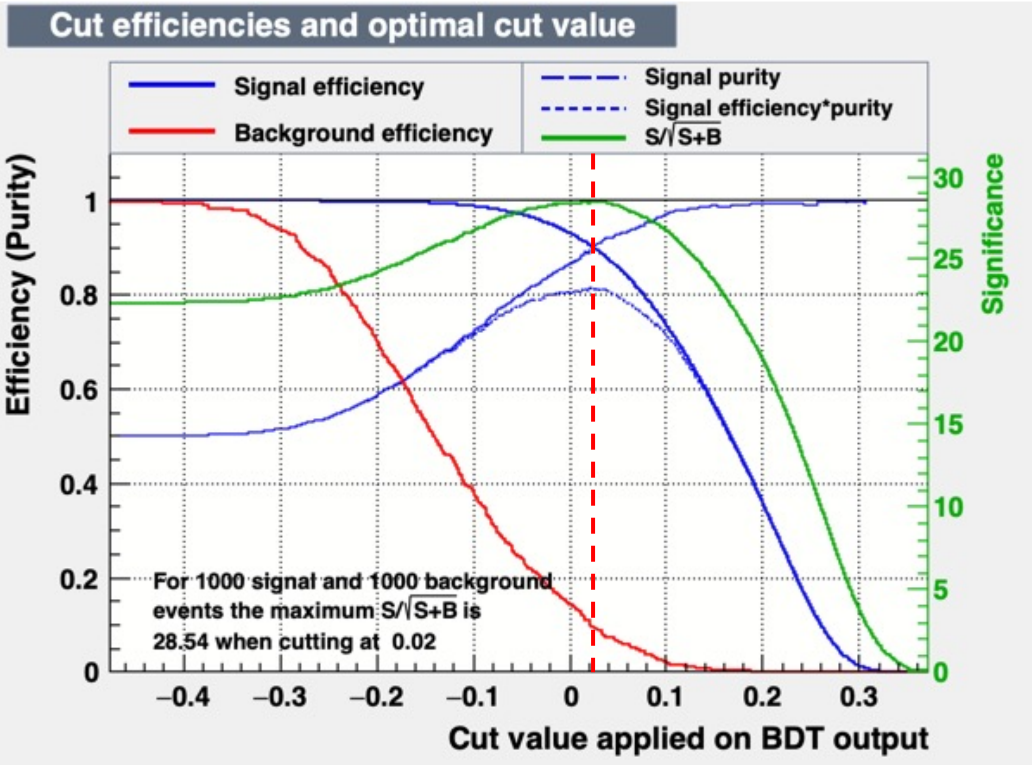
# BDT Approach

- Trained the variables after some loose selections

| Cut Set | npfo4j | blikeness |
|---|---|---|
| Cut bdt | >20 | >0.01 |

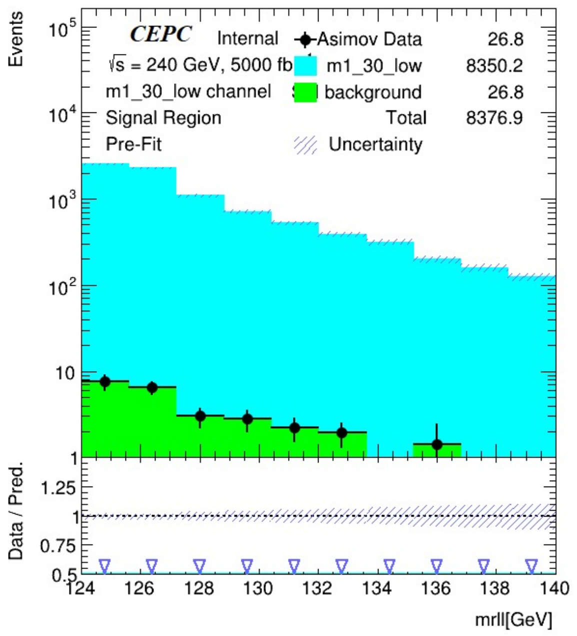
Some example of input variables (S1 refer to the $h_1$ singlet)

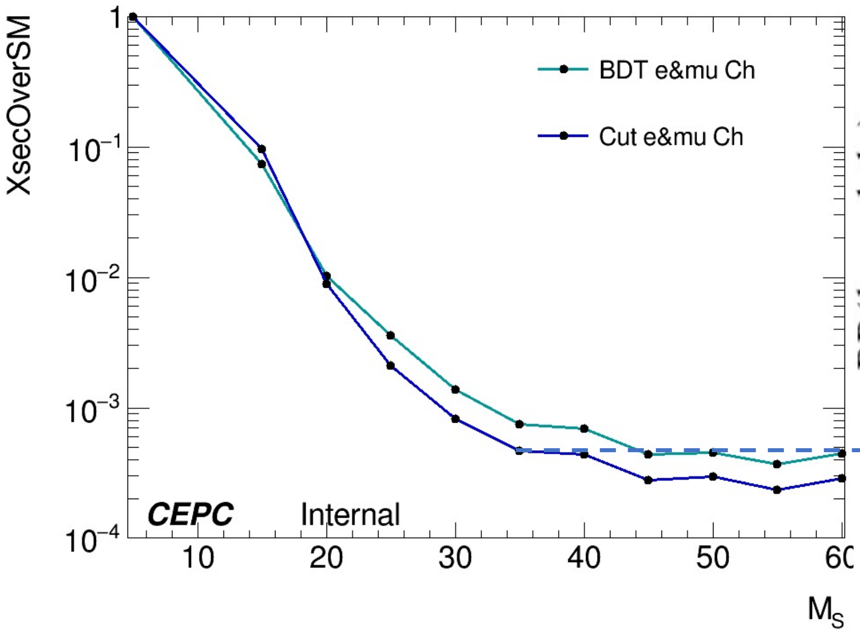


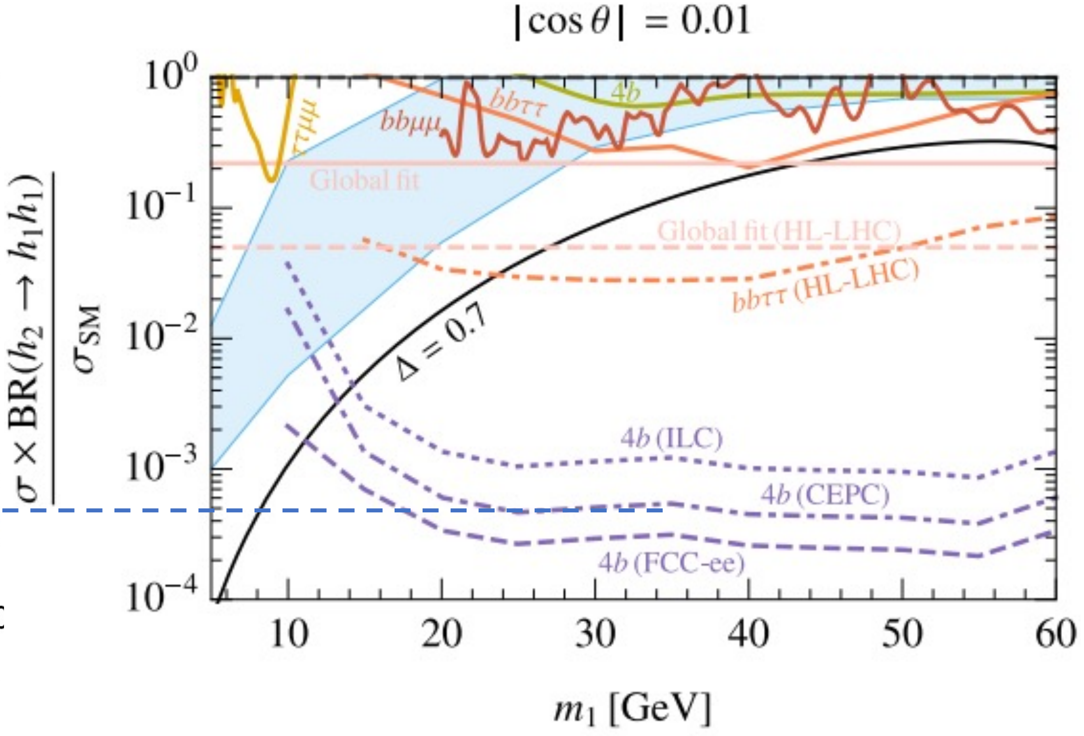



# Limit Setting with TRExFitter

- **Settings :**
  - **Variable :** m_recoil_ll
  - **Signal Sample :** Exotic decay signal at different mass point after selection
  - **Bkg Sample :** All the background event after selection
  - **Data :** Asimov data with all bkg samples
- **Sensitivity by cut based is better than BDT**



# Summary

- Prepared $Z \to e^+e^-/\mu^+\mu^-, h_2 \to h_1h_1 \to b\bar{b}b\bar{b}$ signal samples ( $5\times10^4$ events for each channel and mass point) .
- Reconstructed signal samples. ( Background samples are from /cefs/data )
- Cut set preliminary determined and optimized.
- MVA approach.
- Preliminary limit setting by TRExfitter.

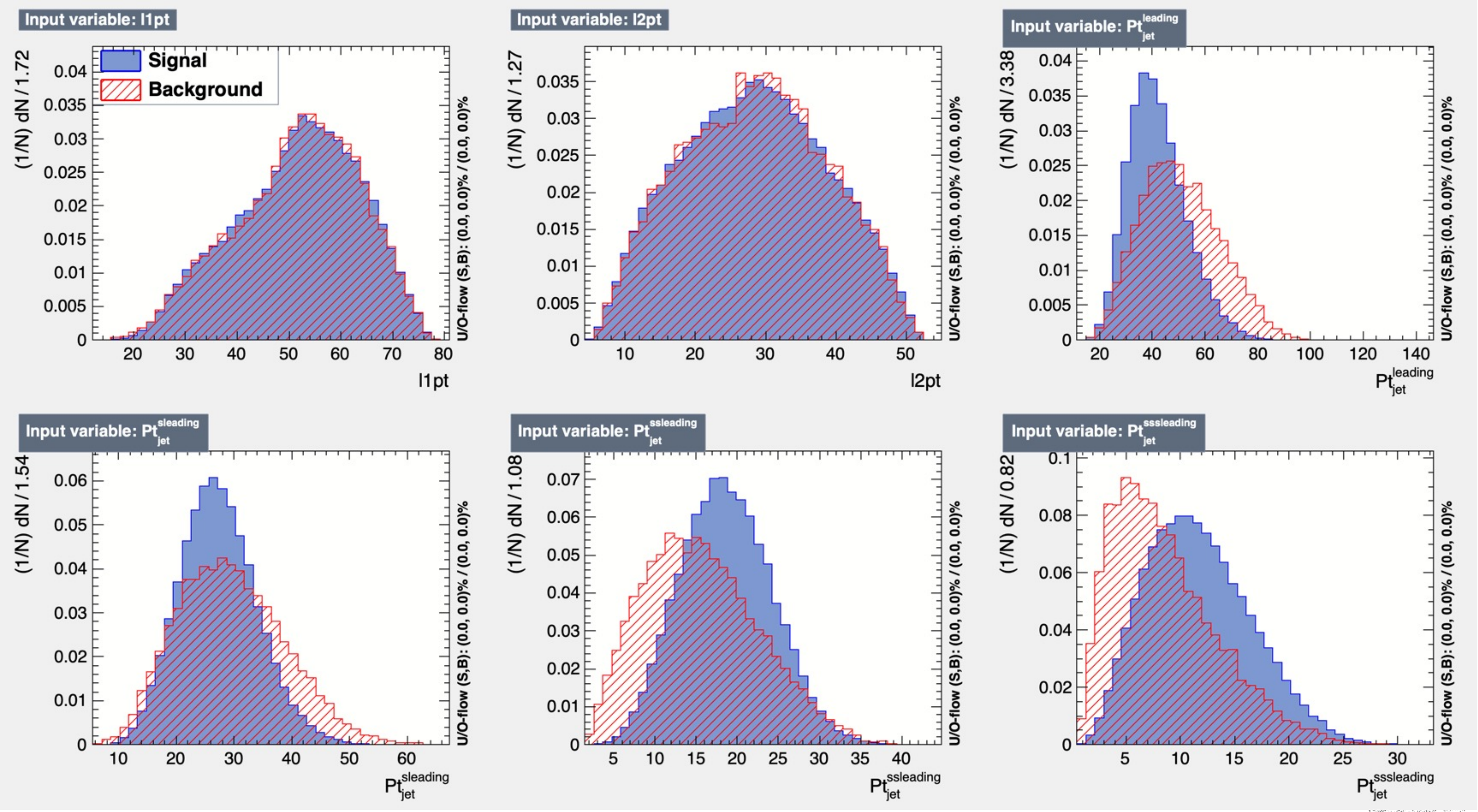
# Future Plans

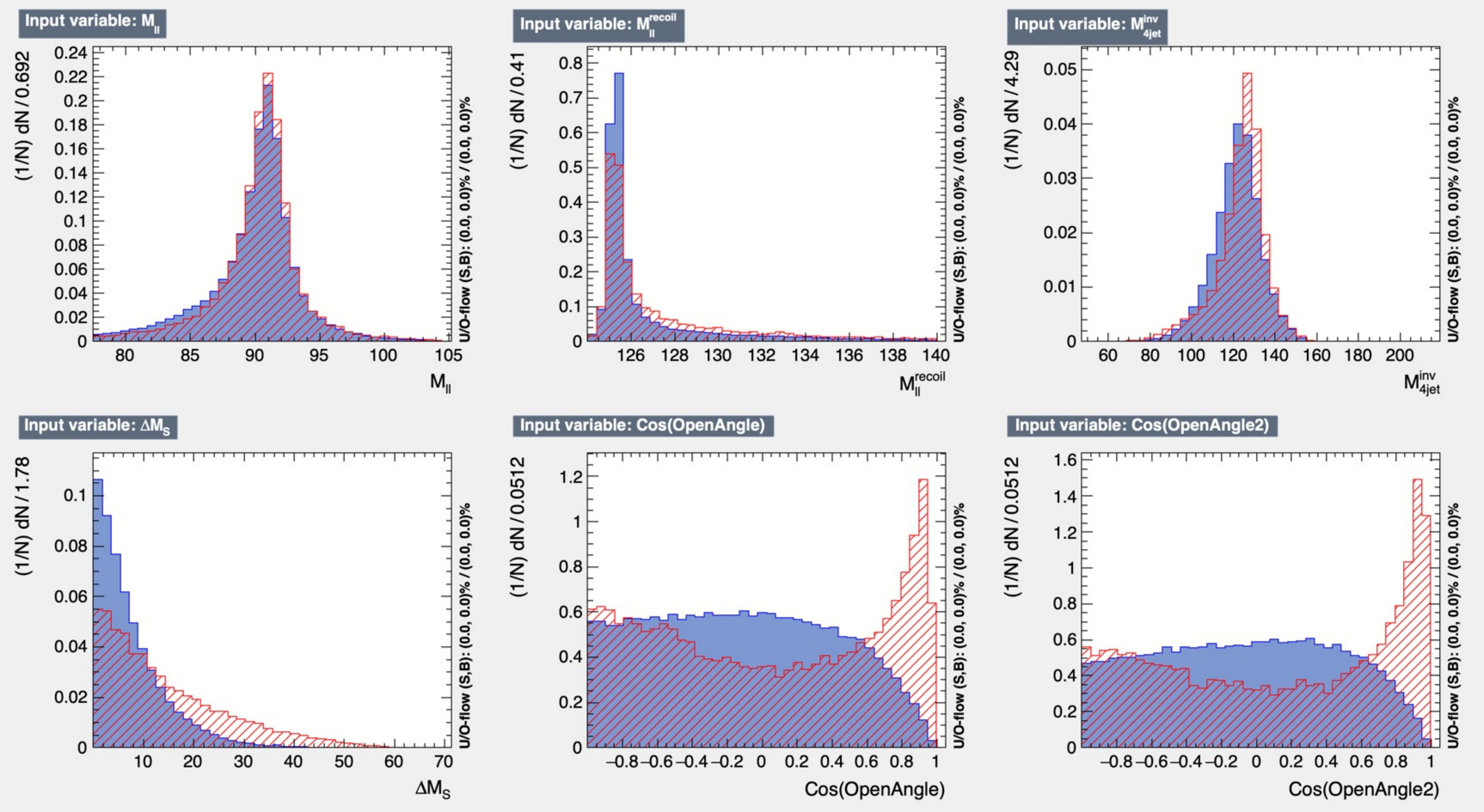
- Optimization of cuts targeting electron and muon channel.

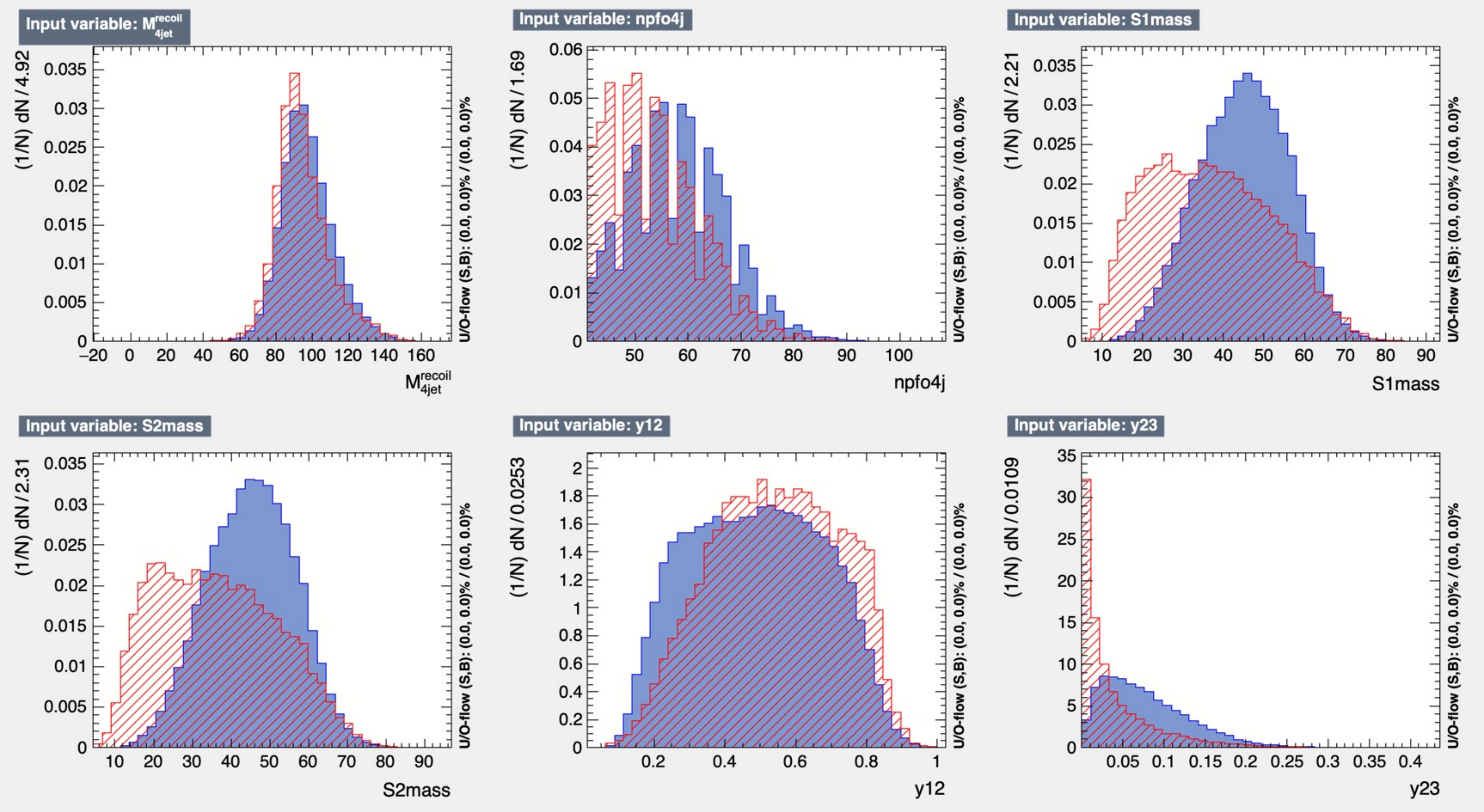
# Thanks!

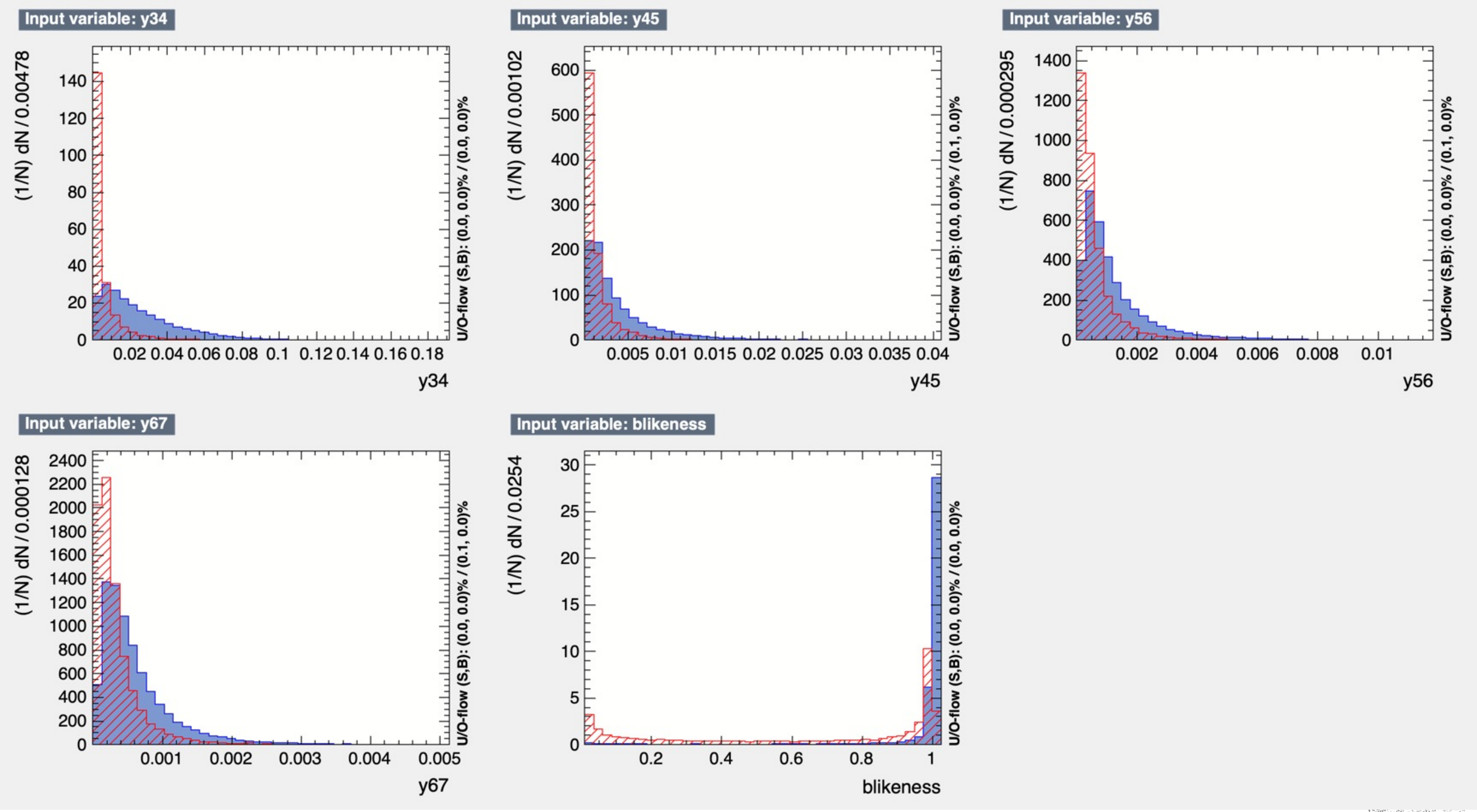
# Backup

- Analysis code git repo : https://gitlab.com/ykrsama/fsclasser.git


Input variable: l1pt
Signal
Background
(1/N) dN / 1.72
l1pt
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%
Input variable: l2pt
(1/N) dN / 1.27
l2pt
Input variable: Pt leading jet
(1/N) dN / 3.38
Pt leading jet
Input variable: Pt sleading jet
(1/N) dN / 1.54
Pt sleading jet
Input variable: Pt ssleading jet
(1/N) dN / 1.08
Pt ssleading jet
Input variable: Pt sssleading jet
(1/N) dN / 0.82
Pt sssleading jet


Input variable: $M_{ll}$
(1/N) dN / 0.692
$M_{ll}$
Input variable: $M_{ll}^{recoil}$
(1/N) dN / 0.41
$M_{ll}^{recoil}$
Input variable: $M_{4jet}^{inv}$
(1/N) dN / 4.29
$M_{4jet}^{inv}$
Input variable: $\Delta M_S$
(1/N) dN / 1.78
$\Delta M_S$
Input variable: Cos(OpenAngle)
(1/N) dN / 0.0512
Cos(OpenAngle)
Input variable: Cos(OpenAngle2)
(1/N) dN / 0.0512
Cos(OpenAngle2)
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%


Input variable: $M^{recoil}_{4jet}$
(1/N) dN / 4.92
$M^{recoil}_{4jet}$
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%
Input variable: npfo4j
(1/N) dN / 1.69
npfo4j
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%
Input variable: S1mass
(1/N) dN / 2.21
S1mass
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%
Input variable: S2mass
(1/N) dN / 2.31
S2mass
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%
Input variable: y12
(1/N) dN / 0.0253
y12
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%
Input variable: y23
(1/N) dN / 0.0109
y23
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%


Input variable: y34
(1/N) dN / 0.00478
y34
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%
Input variable: y45
(1/N) dN / 0.00102
y45
U/O-flow (S,B): (0.0, 0.0)% / (0.1, 0.0)%
Input variable: y56
(1/N) dN / 0.000295
y56
U/O-flow (S,B): (0.0, 0.0)% / (0.1, 0.0)%
Input variable: y67
(1/N) dN / 0.000128
y67
U/O-flow (S,B): (0.0, 0.0)% / (0.1, 0.0)%
Input variable: blikeness
(1/N) dN / 0.0254
blikeness
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%