Cornering charming Higgs decays

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New York University
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- Processes considered
- Data collection
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Why H -> cc

Can we pin down the yukawa coupling for light fermions?

$$\kappa_c = \frac{y}{y_{SM}}$$

Current upper bound from CMS [1]

$$\frac{\sigma(VH)Br(H \to c\bar{c})}{\sigma_{SM}(VH)Br_{SM}(H \to c\bar{c})} = \kappa_c^2 < 70(37^{+16}_{-10})$$

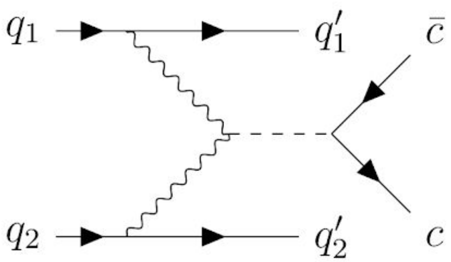
Charming higgs decays dominated by huge backgrounds

[1] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update 6th December, 2019

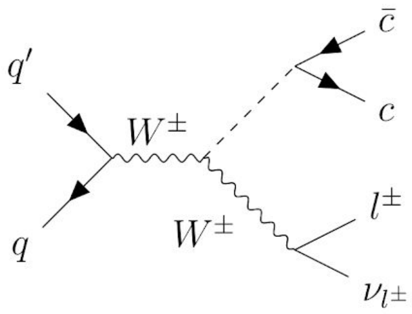
Signals

We consider three signal processes

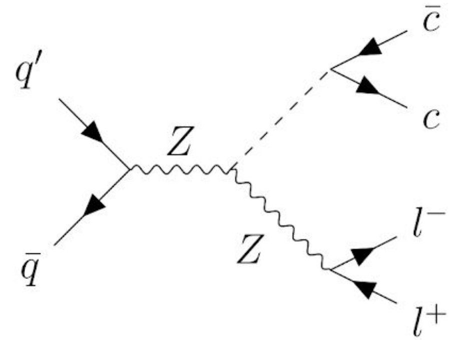
Vector Boson Fusion



W Higgs-Strahlung



Z Higgs-Strahlung



This gives us 3 channels;

0 Isolated Leptons

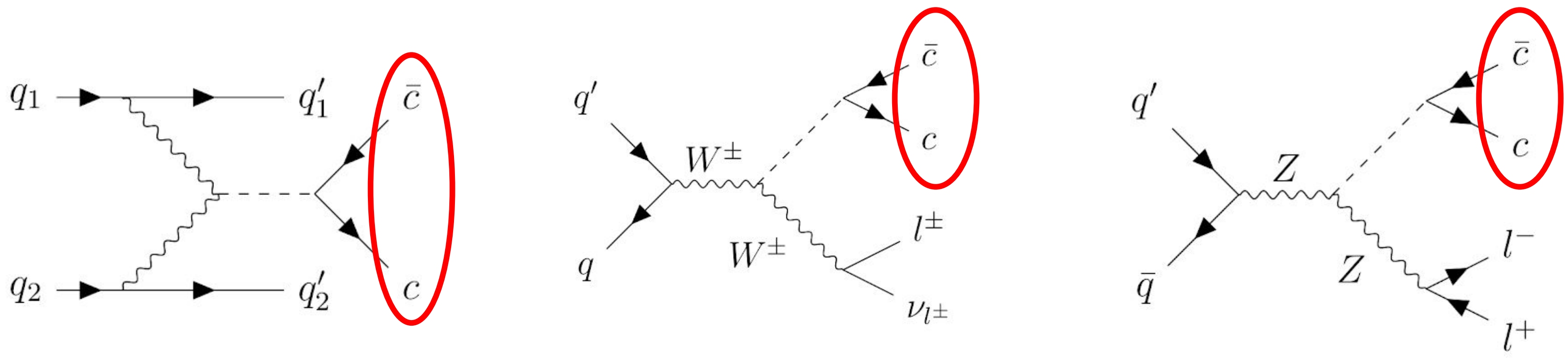
1 Isolated Leptons

2 Isolated Leptons

Signals

We consider three signal processes

Vector Boson Fusion | W Higgs-Strahlung | Z Higgs-Strahlung



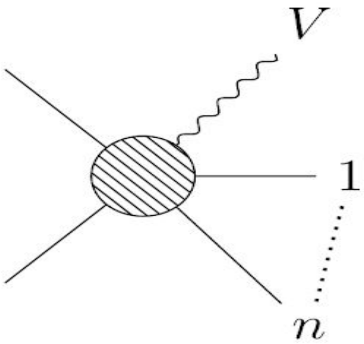
This gives us 3 channels;

0 Isolated Leptons | 1 Isolated Leptons | 2 Isolated Leptons

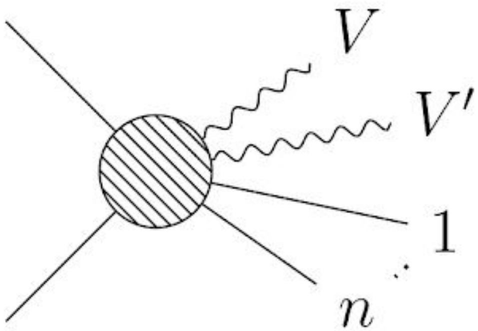
Using fat jets as a gateway to background elimination

Backgrounds

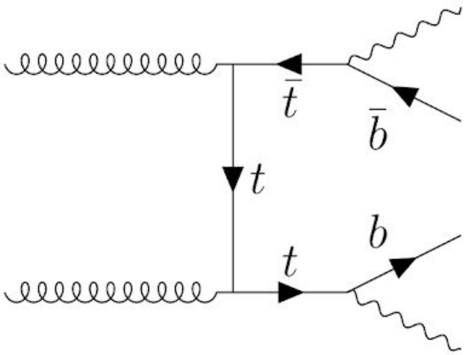
Single Vector Boson production + jets



Diboson production + jets



$t\bar{t} \rightarrow b\bar{b}W^+W^-$



In total 19 background runcards are used;

- Higgs couplings turned off
- MEPS(2)
- Decay of one vector boson is enforced in the hard matrix element

Data

Data is generated using Sherpa 2.7.7 at MEPS(2) for a selection of Backgrounds. Analysis performed by Rivet 2.7.0 and Fastjets 3.3.2

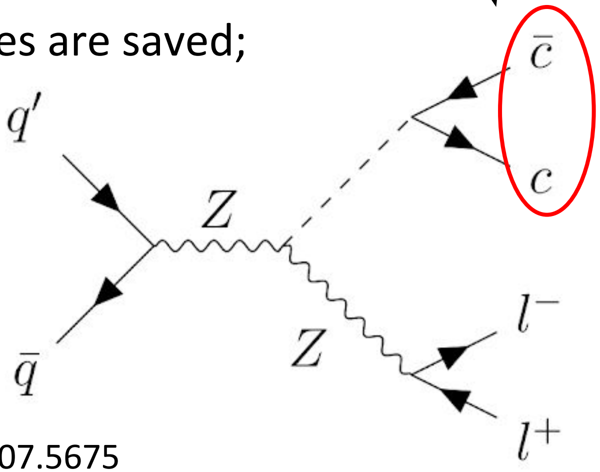
Many Runcards are used to boost the efficiency of backgrounds being generated.

We find fatjets with R=1 with the Anti-Kt algorithm with pT > 250 GeV

We apply a set of simple cuts to identify candidate fatjets

All surviving events are analysed and three data structures are saved;

1. Observables [2]
2. Jet Images [3]
3. Particle Flows [4]



[2] arXiv:1712.03634 & arXiv:1106.3076 [3] arXiv:1612.01551 & arXiv:1407.5675
[4] arXiv:1810.05165v2

Cutflows

We have 3 cut flows / 3 channels.

0. Eta and pT cuts on event

1. A Missing Transverse Energy condition
   0: < 10 GeV
   1: > 80 GeV
   2: < 10 GeV

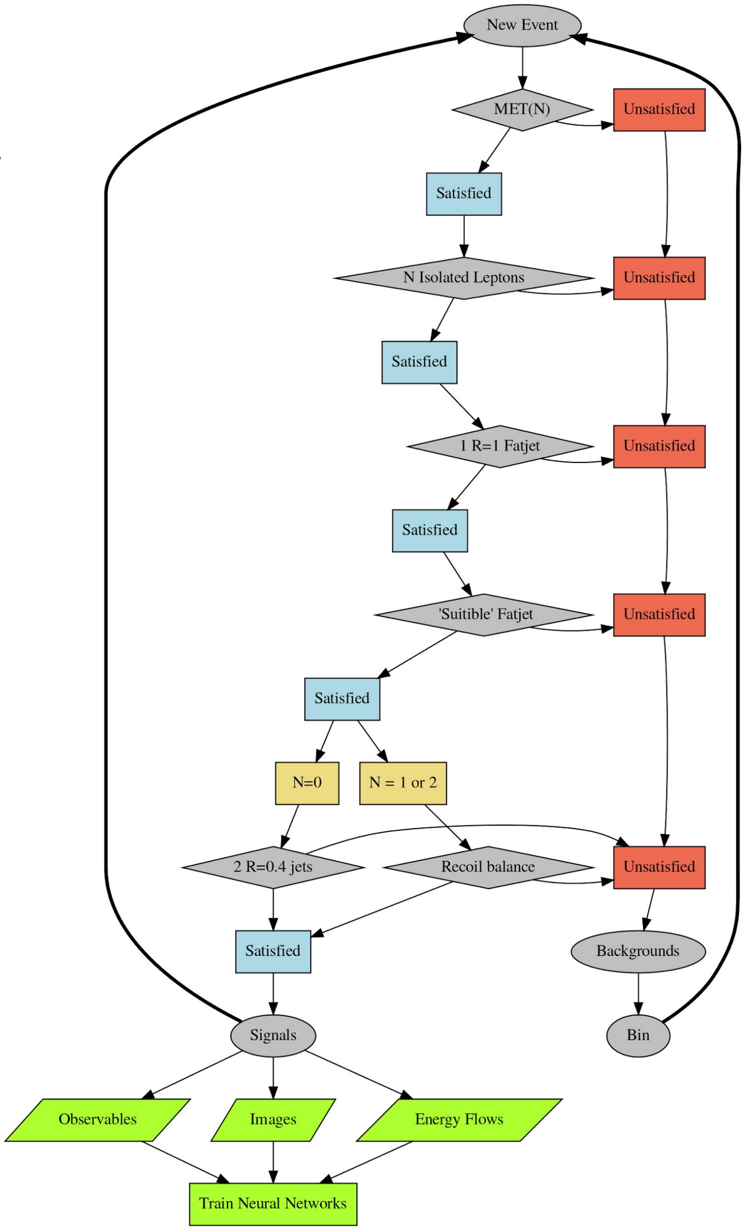
2. Demand N isolated leptons

3. Demand at least 1 R = 1.0 fatjet, pT > 250 GeV

4. Pick fatjet with suitable properties
   a. C tagged
   b. |JetMass - 125 GeV| < 30 GeV

5. Demand 2 R = 0.4 jets **OR**
   Demand Isolated leptons and cadidate jet back-to-back.

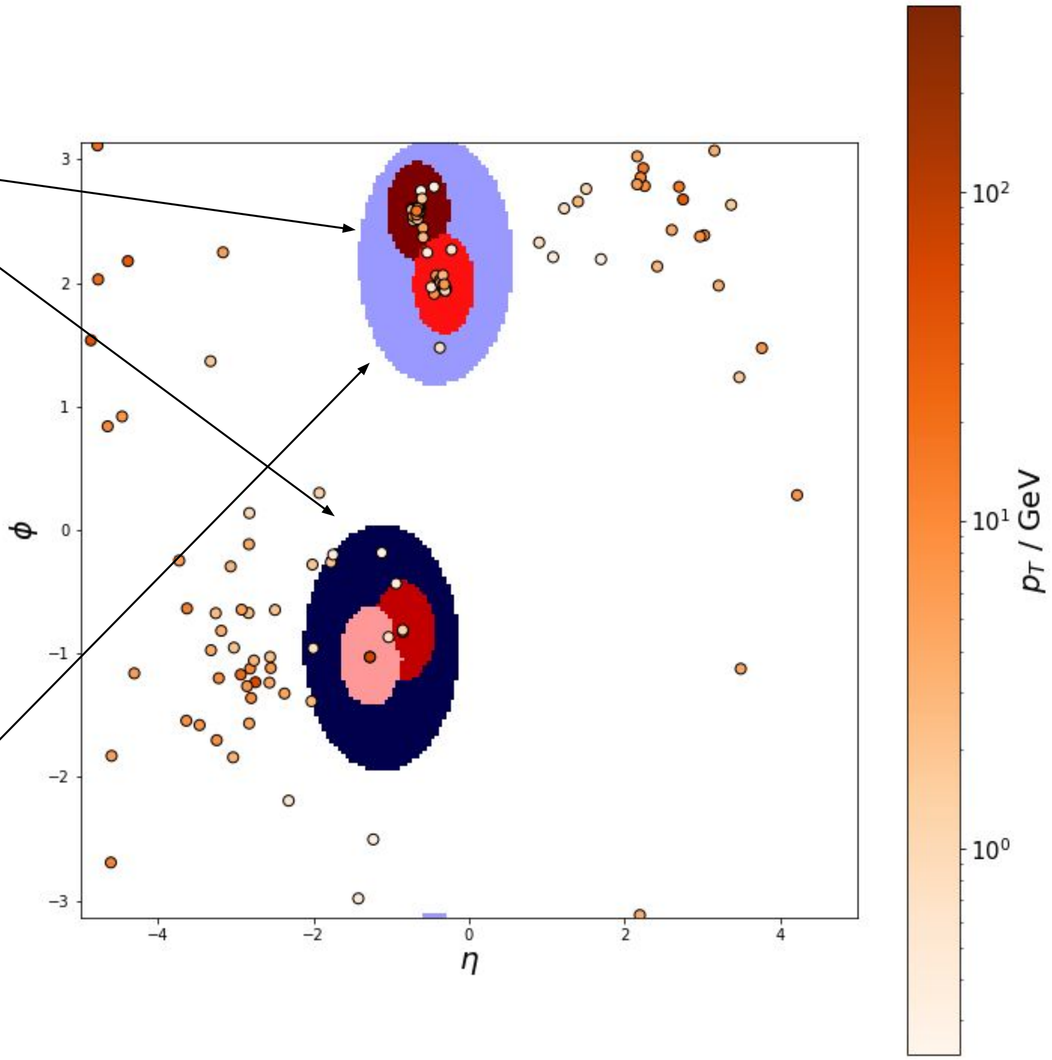
Cuts based on **arXiv:1912.01662**



Example accepted event

Two fat jets observed

Cuts Identify best candidate



[5] pyjets

Chosen Processes

We collect data from any process with an expectation of surviving events for $\int \mathcal{L}dt = 3000fb^{-1}$

0 Isolated Leptons

1. VBF (11%)
2. WZ[qq] (0.90%)
3. WW[qq] (0.14%)
4. t[bw]t[bw] (0.017%)
5. WZ[ll] (0.012%)
6. W[qq] (0.0034%)
7. Z[ll] (0.0002%)
8. Z[qq] (0.0001%)

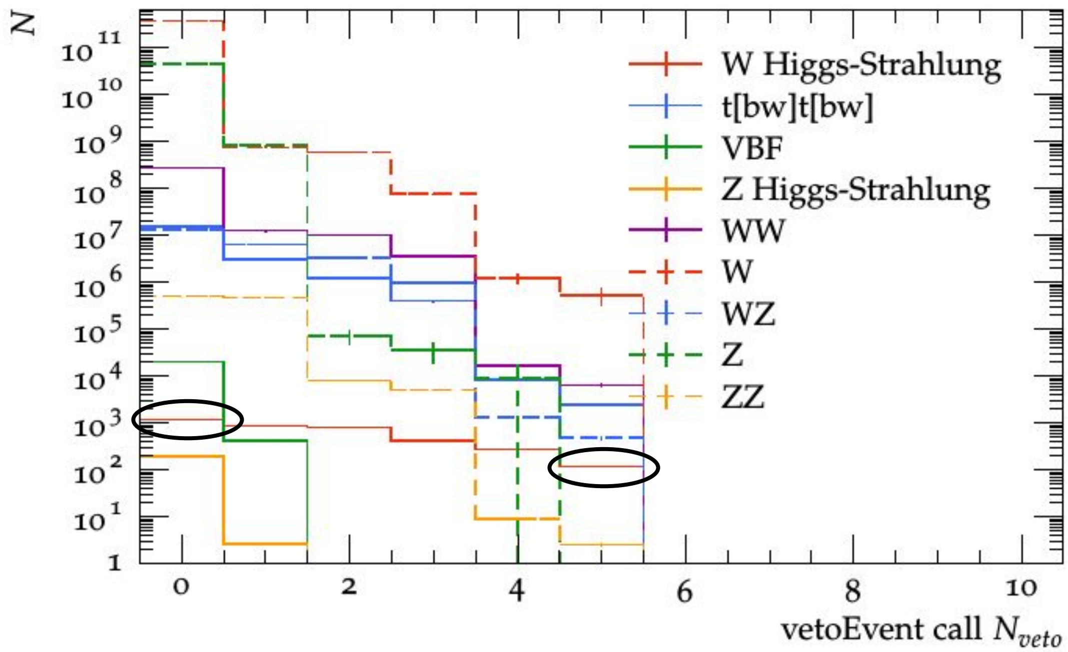
1 Isolated Leptons

1. W Higgs-Strahlung (10%)
2. t[bw]t[bw] (0.016%)
3. WW[lv] (0.0098%)
4. W[lv]Z (0.0057%)
5. W[lv] (0.0006%)

2 Isolated Leptons

1. Z Higgs-Strahlung (17%)
2. WZ[ll] (0.16%)
3. Z[ll] (0.0020%)
4. Z[qq] (0.0020%)

These runcards are boosted to generate balanced classes



Chosen Processes - Cross sections

We collect data from any process with an expectation of surviving events for $\int \mathcal{L}dt = 3000\, fb^{-1}$

0 Isolated Leptons

1. VBF 0.19(4) pb
2. WZ[qq] 20(1) pb
3. WW[qq] 0.12(2) nb
4. t[bw]t[bw] 5.4(7) pb
5. WZ[ll] 1.8(1) pb
6. W[qq] 90(5) nb
7. Z[ll] 3.3(1) nb
8. Z[qq] 27(2) nb

$$\frac{S}{B} \simeq 10^{-6}$$

1 Isolated Leptons

1. W Higgs-Strahlung 0.008(2) pb
2. t[bw]t[bw] 5.4(7) pb
3. WW[lv] 31(4) pb
4. W[lv]Z 2.9(3) pb
5. W[lv] 29(2) nb

$$\frac{S}{B} \simeq 10^{-7}$$

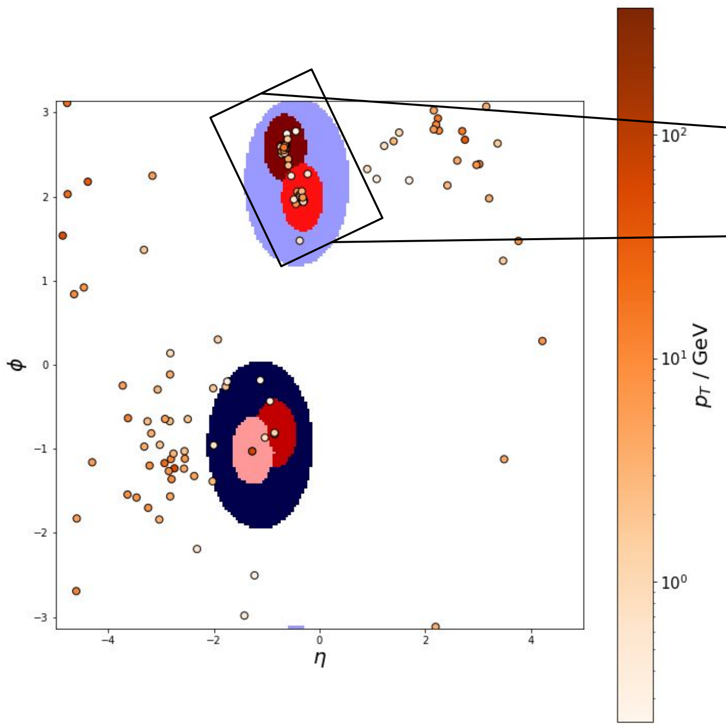
2 Isolated Leptons

1. Z Higgs-Strahlung 0.00123(4) pb
2. WZ[ll] 1.8(1) pb
3. Z[ll] 3.3(1) nb
4. Z[qq] 27(2) nb

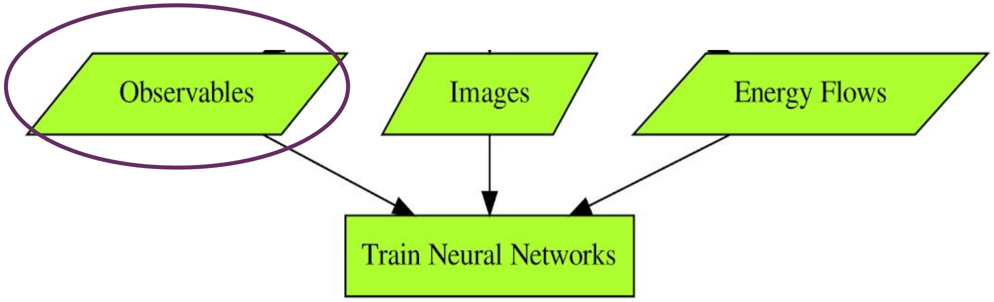
$$\frac{S}{B} \simeq 10^{-7}$$

LO Cross sections!

Example accepted event



	Cparticles	CE	JMass	JetpT	angularities	planar_flow	tau12	zy	D21_10	D32_21	Etmiss
0	27.0	423.055	125.777	124.506	0.067474	0.090827	0.139254	0.943321	0.345896	0.067589	2.86338

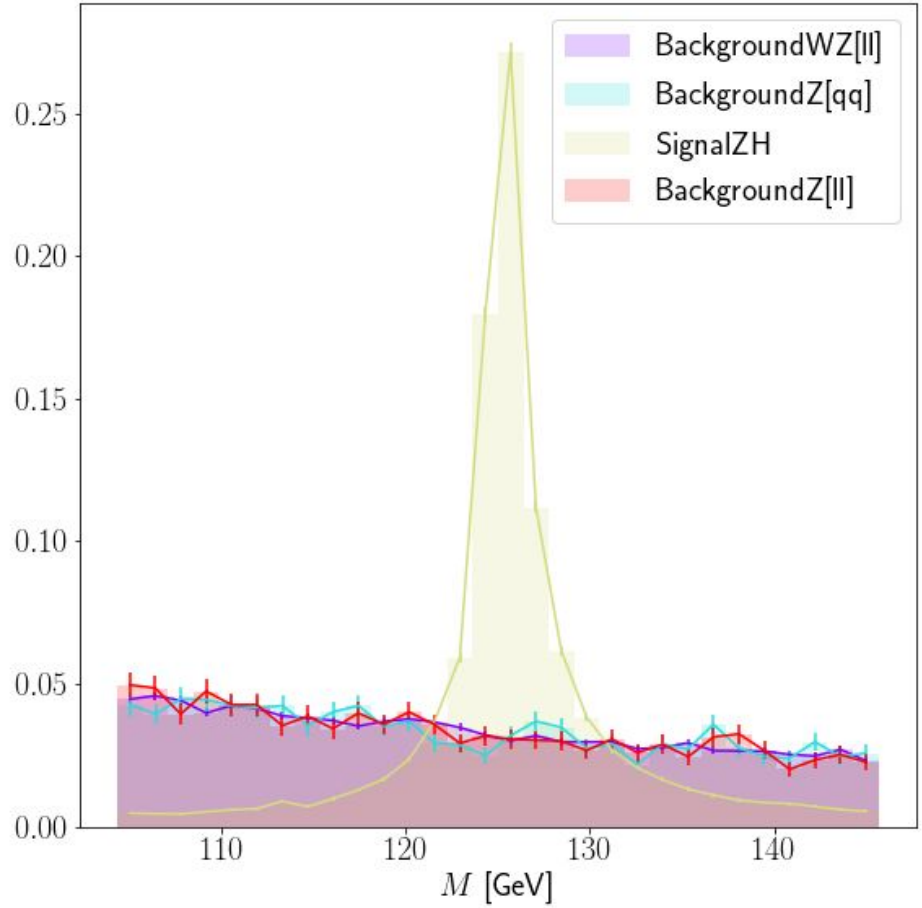


Example accepted event

11 Chosen observables

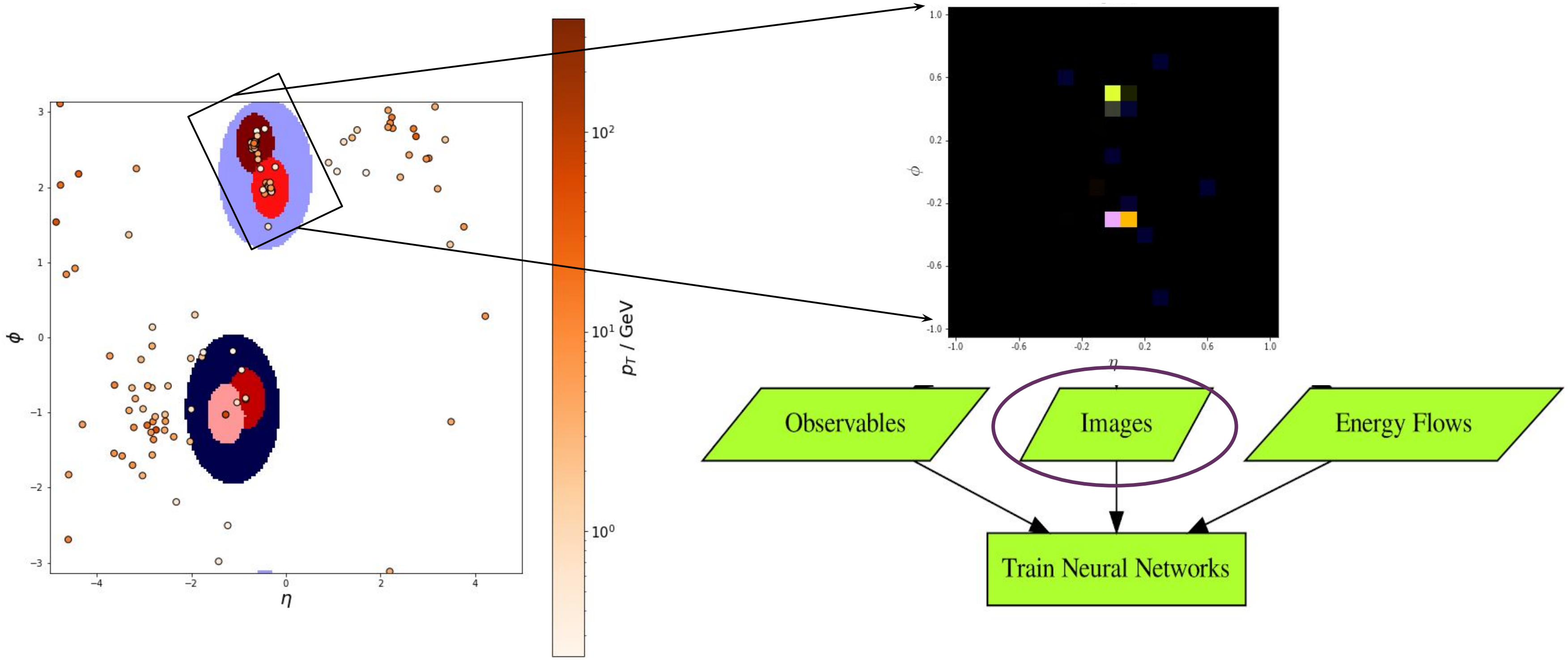
1. Number of charged particles
2. Energy in Charged Particles
3. Jet mass
4. Momentum perpendicular to jet axis
5. Angularities (a = -2)
6. Planar Flow
7. Ratio of 1 and 2 subjettiness
8. Subjet energy balance
9. D(2->1) / PT
10. D(3->2)/D(2->1)
11. Missing Transverse momentum

Selected based on individual classifying power.

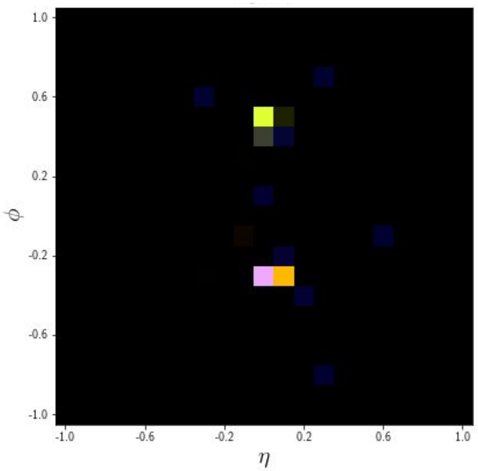


~500 Trainable Parameters

Example accepted event



Example accepted event



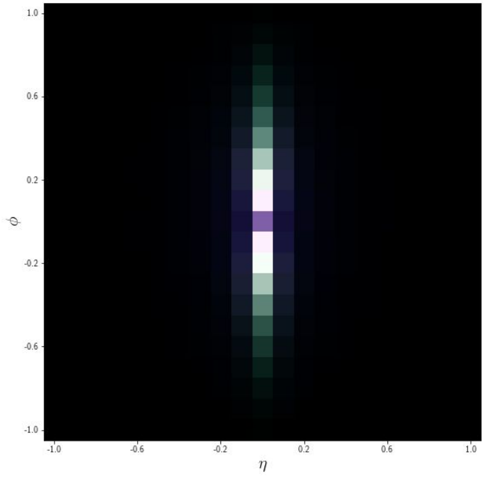
Create RGB images

red ~ Energy
green ~ Perpendicular momentum to jet momentum
blue ~ Charge particle multiplicity

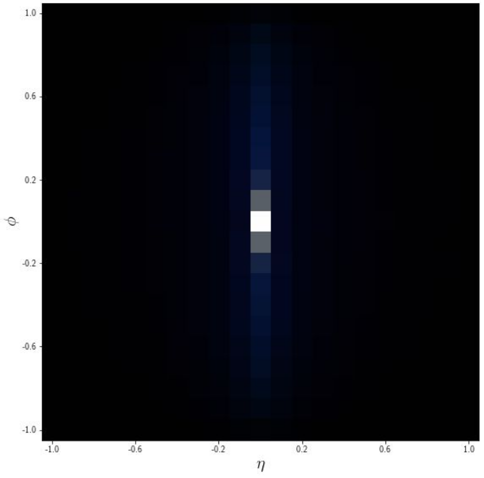
Jet axis lined up with (0,0) pixel
Sum up variables in each bin then rescale

~15k Trainable Parameters

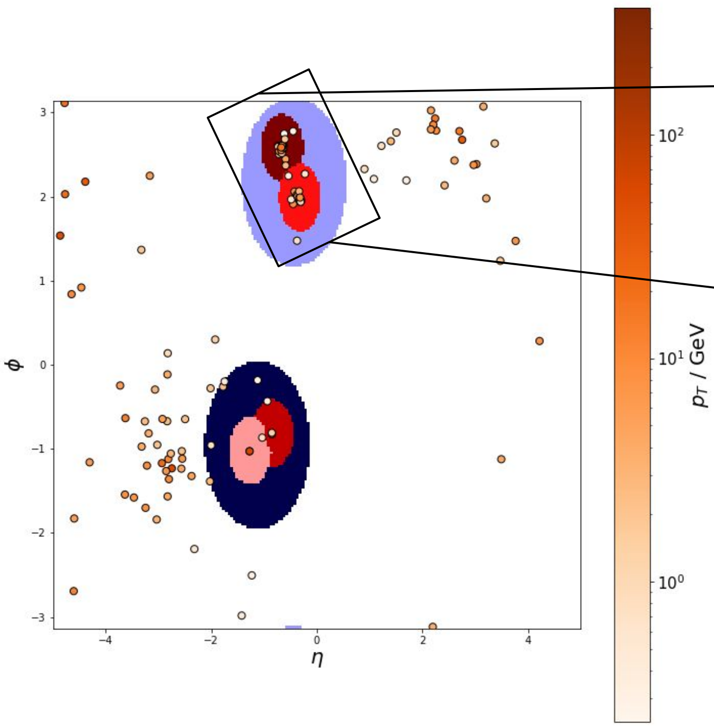
A mean ‘signal image’



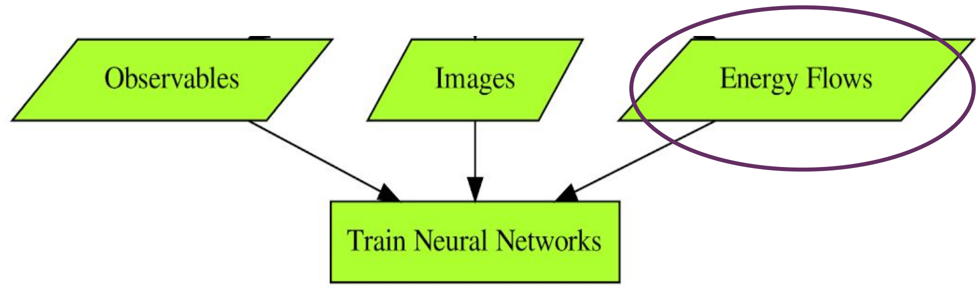
A mean ‘background image’



Example accepted event



	DEta	DPhi	log(pt)	log(E)	log(pt/jetpt)	log(E/jetE)	DR
0	0.012631	-0.054196	5.04692	5.57067	-0.590013	-0.570963	0.055648
1	0.334012	-0.252075	2.35535	3.09847	-3.281580	-3.043170	0.418456
2	0.231418	0.024186	2.67646	2.97307	-2.960470	-3.168560	0.232679
3	0.208372	0.038378	2.50181	2.81440	-3.135130	-3.327240	0.211877
4	0.349394	-0.149882	2.02044	2.77714	-3.616490	-3.364500	0.380186
5	0.224771	0.326364	2.24209	2.54319	-3.394850	-3.598450	0.396277
6	0.117750	-0.088291	1.88444	2.44333	-3.752490	-3.698310	0.147175



Example accepted event

Particles in jet ordered in decreasing energy

Form a sequence of 10 particles to be fed into a particle flow network.

1. $\Delta\eta$
2. $\Delta\phi$
3. $log(p_T)$
4. $log(E)$
5. $log(p_T/p_{T jet})$
6. $log(E/E_{jet})$
7. ΔR
8. PID

	DEta	DPhi	log(pt)	log(E)	log(pt/jetpt)	log(E/jetE)	DR
0	0.012631	-0.054196	5.04692	5.57067	-0.590013	-0.570963	0.055648
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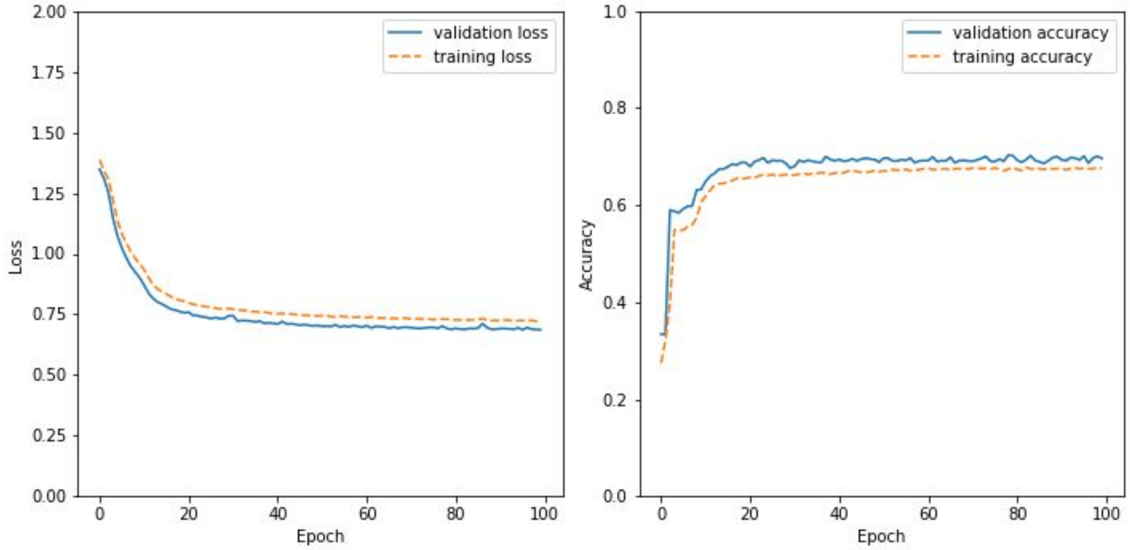
6	0.117750	-0.088291	1.88444	2.44333	-3.752490	-3.698310	0.147175

~1.6k Trainable Parameters

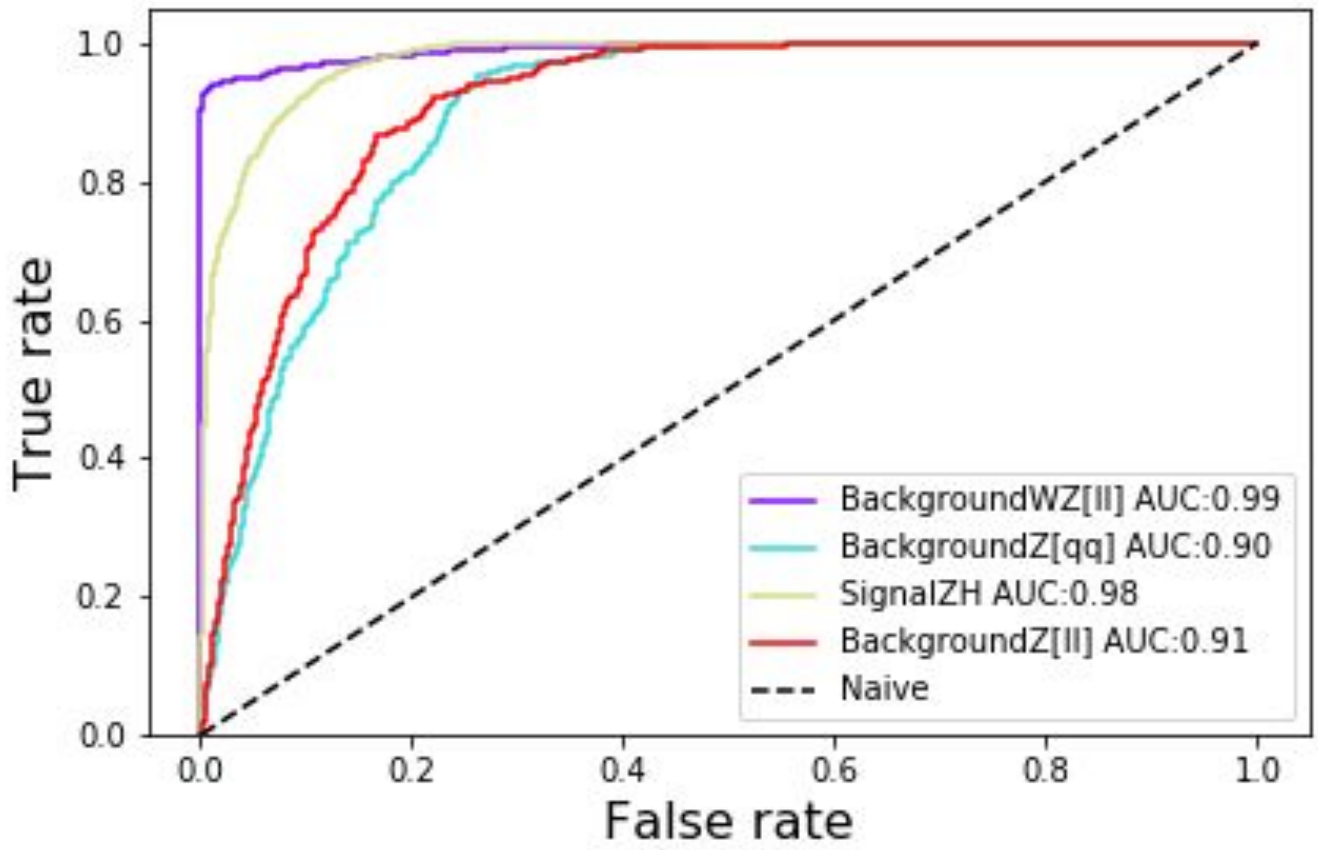
The pipeline

1. Determine appropriate backgrounds for each channel
2. Boost events to give balanced classes ~10k samples
3. Normalise and rescale data
4. Learn in tensorflow



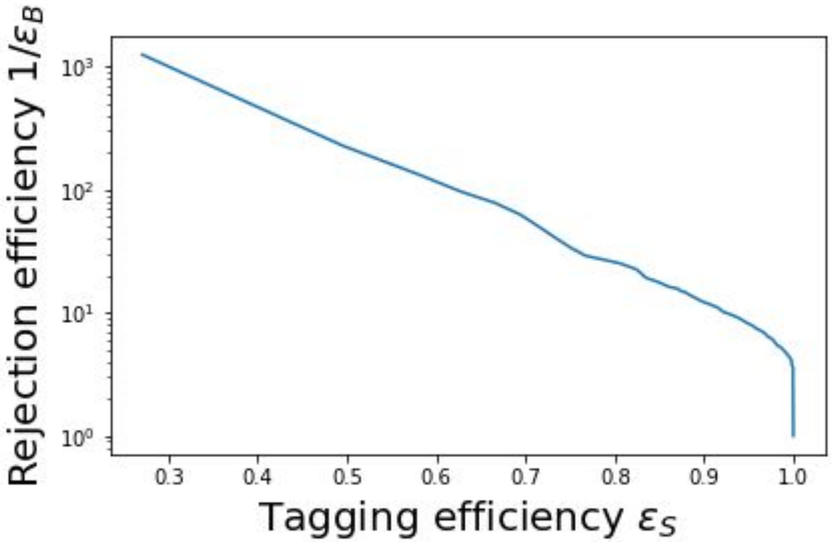
Time to learn - 2 Lepton Channel

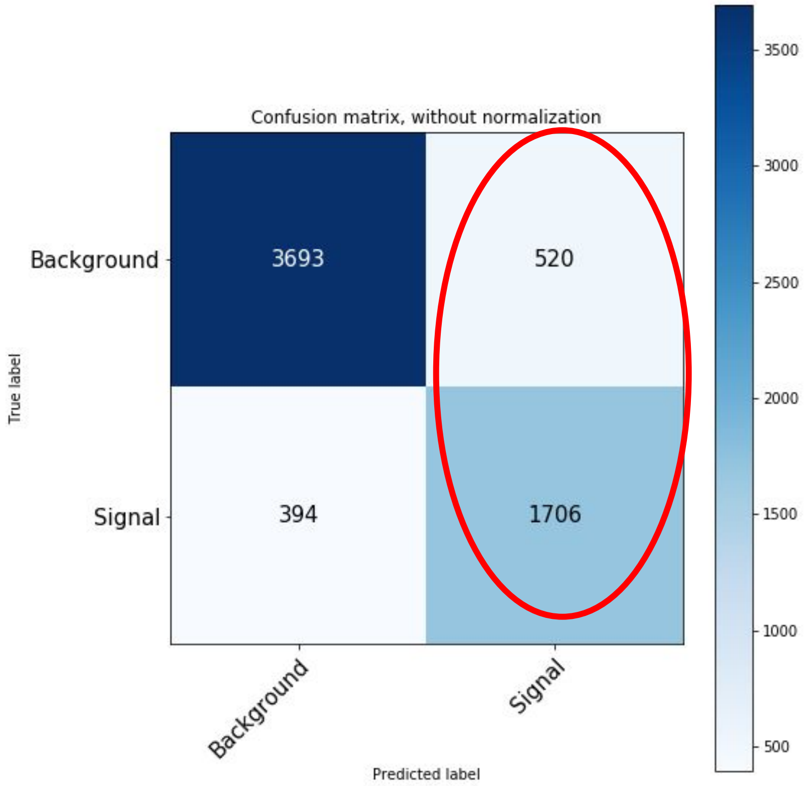
Observables



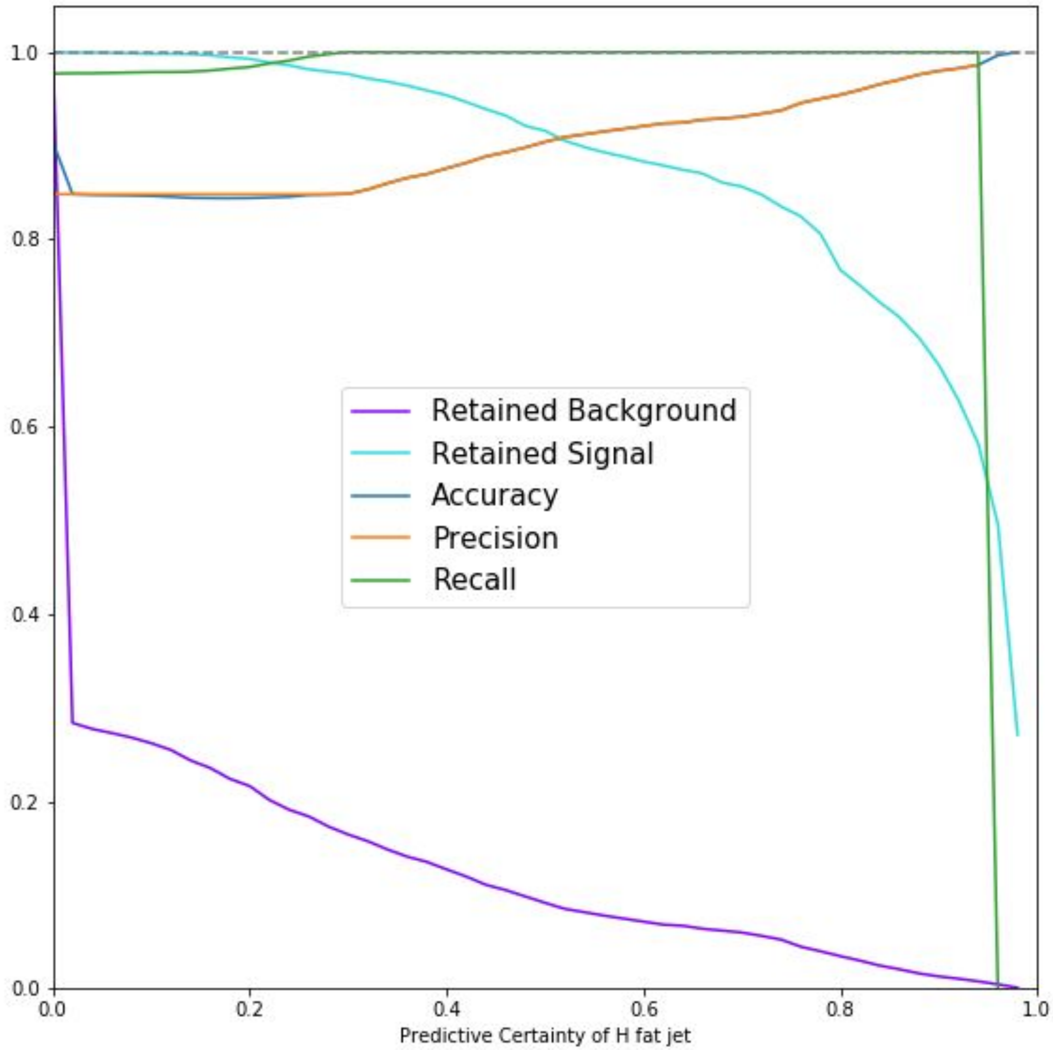
Time to learn - 2 Lepton Channel

Observables



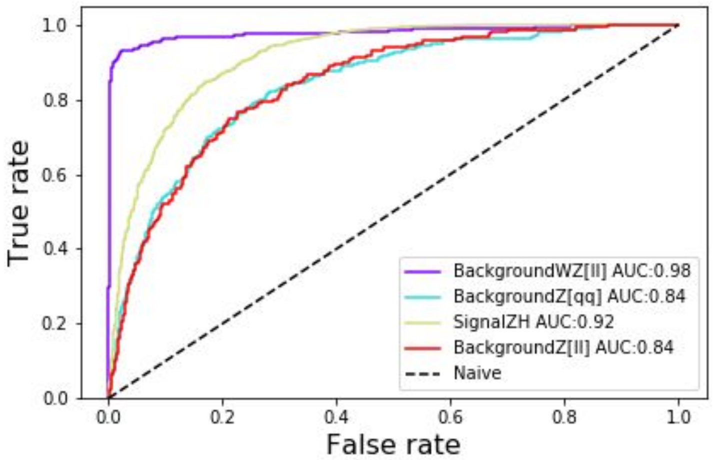


Time to learn - 2 Lepton Channel

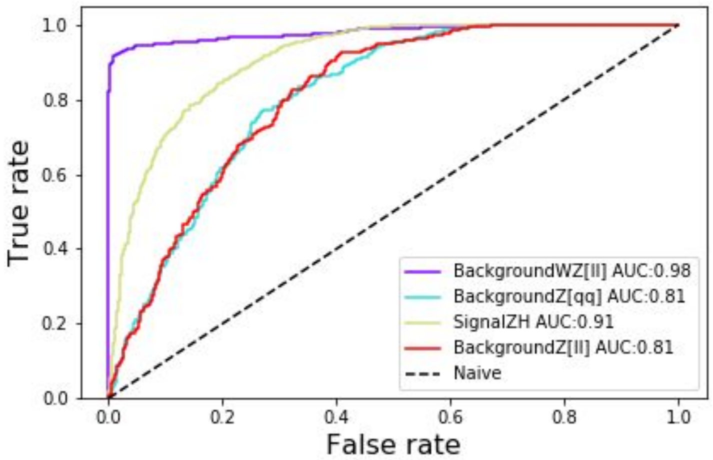


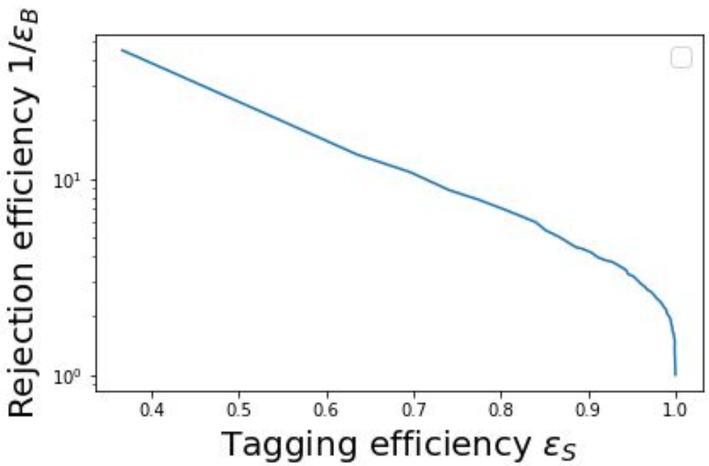
Time to learn - 2 Lepton Channel

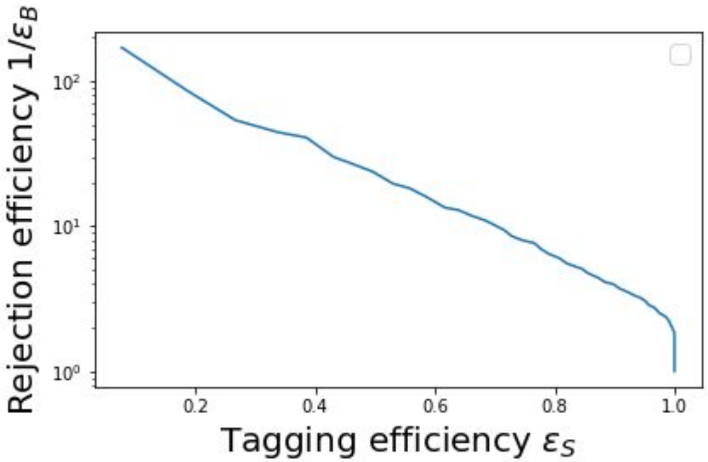
Images



Flow







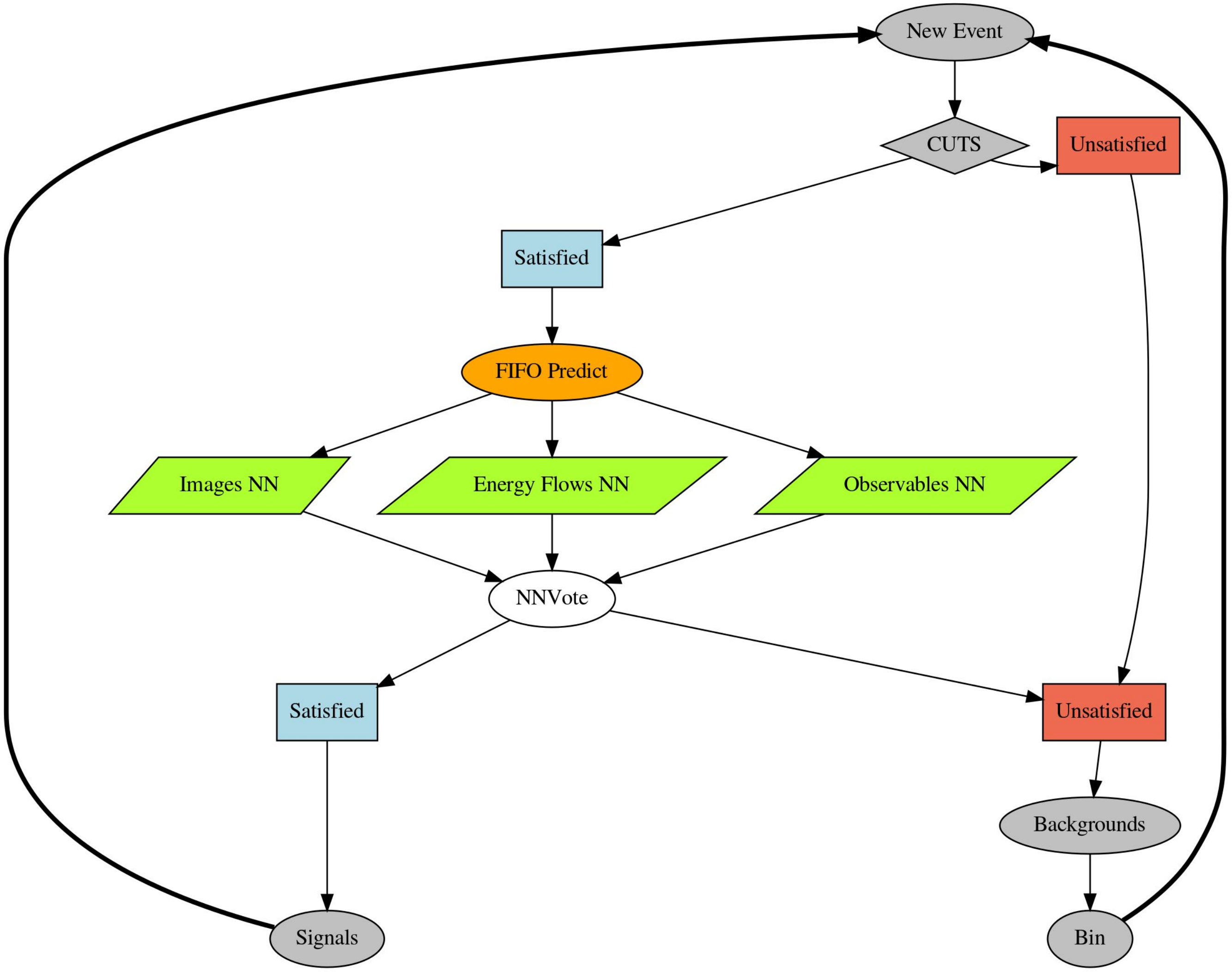
FIFO

Sherpa -> Rivet Analysis <--> Python

```
  reduce max for 2_2__j__j__W-[Q__Q] to 0.715086 ( eps = 0.001 )
Read in channels from directory : Results/Comix/MC_2_3__j__j__W-[Q__Q]__j
Process_Group::CalculateTotalXSec(): Calculate xs for '2_3__j__j__W-[Q__Q]__j' (Comix)
2_3__j__j__W-[Q__Q]__j : 4244.64 pb +- ( 10.0767 pb = 0.237399 % )  exp. eff: 0.58381
%
  reduce max for 2_3__j__j__W-[Q__Q]__j to 0.593677 ( eps = 0.001 )
----------------------------------------------------------
-- SHERPA generates events with the following structure --
----------------------------------------------------------
Perturbative       : Signal_Processes
Perturbative       : Hard_Decays
Perturbative       : Jet_Evolution:CSS
Perturbative       : Lepton_FS_QED_Corrections:Photons
Perturbative       : Multiple_Interactions:None
Perturbative       : Minimum_Bias:Off
Hadronization      : Beam_Remnants
Hadronization      : Hadronization:Ahadic
Hadronization      : Hadron_Decays
Unknown            :
Analysis           : Rivet
---------------------------------------------------------
Rivet.Analysis.Handler: WARN  Analysis 'FatJets0Lep' is unvalidated: be careful, it ma
y be broken!
Rivet.Analysis.Handler: WARN  Analysis 'FatJets1Lep' is unvalidated: be careful, it ma
y be broken!
Rivet.Analysis.Handler: WARN  Analysis 'FatJets2Lep' is unvalidated: be careful, it ma
y be broken!
#--------------------------------------------------------------------------
#                         FastJet release 3.3.1
#                 M. Cacciari, G.P. Salam and G. Soyez
#     A software package for jet finding and analysis at colliders
#                           http://fastjet.fr
#
# Please cite EPJC72(2012)1896 [arXiv:1111.6097] if you use this package
# for scientific work and optionally PLB641(2006)57 [hep-ph/0512210].
#
# FastJet is provided without warranty under the terms of the GNU GPLv2.
# It uses T. Chan's closest pair algorithm, S. Fortune's Voronoi code
# and 3rd party plugin jet algorithms. See COPYING file for details.
#--------------------------------------------------------------------------
  Event 200 ( 1s elapsed / 5s left ) -> ETA: Sun Jan 05 15:26
  XS = 107484 pb +- ( 10097 pb = 9.39 % )
```

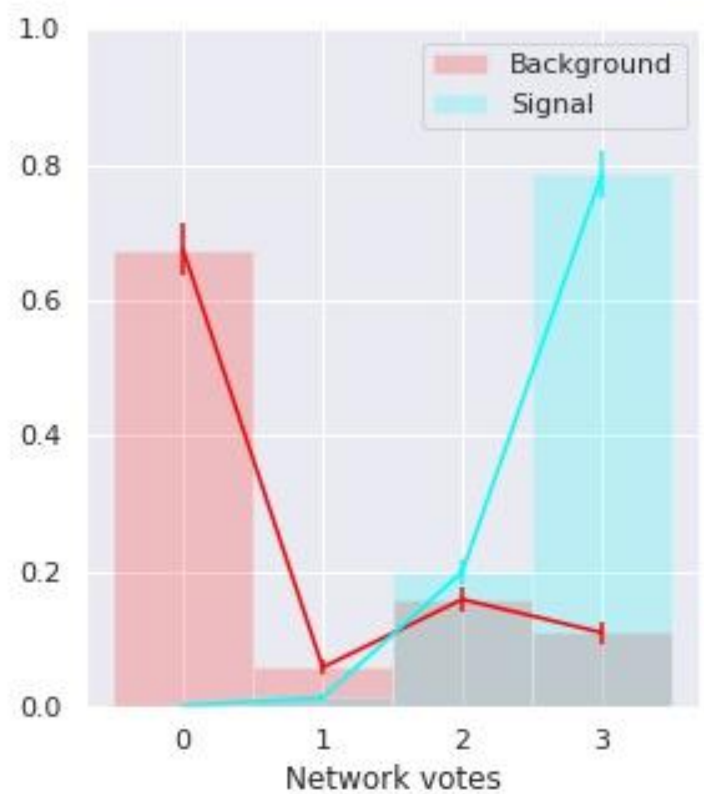
```
Ims [0.97180384, 1]
Flow [0.9024279, 1]
Obs [0.81896096, 1]
Ims [0.96480846, 1]
Flow [0.91917694, 1]
Obs [0.99326575, 1]
Ims [0.9584786, 1]
Flow [0.89479154, 1]
Obs [0.9947601, 1]
Ims [0.9261591, 1]
Flow [0.8904244, 1]
Obs [0.9974905, 1]
Ims [0.9860474, 1]
Flow [0.8871511, 1]
Obs [0.7706096, 1]
Ims [0.9582879, 1]
Flow [0.9047799, 1]
Obs [0.9870056, 1]
Ims [0.88494724, 1]
Flow [0.49075803, 0]
Obs [0.99569356, 1]
Ims [0.939048, 1]
Flow [0.8998179, 1]
Obs [0.99020326, 1]
Ims [0.94132274, 1]
Flow [0.91626483, 1]
Obs [0.9833592, 1]
Ims [0.949657, 1]
Flow [0.9092387, 1]
Obs [0.99601537, 1]
Ims [0.9835242, 1]
Flow [0.9188933, 1]
Obs [0.42806774, 0]
Ims [0.20386374, 0]
Flow [0.8513089, 1]
Obs [0.9964684, 1]
Ims [0.97812784, 1]
Flow [0.9187265, 1]
Obs [0.9929892, 1]
Ims [0.9795156, 1]
Flow [0.90042114, 1]
```

FIFO


New Event
CUTS
Unsatisfied
Satisfied
FIFO Predict
Images NN
Energy Flows NN
Observables NN
NNVote
Satisfied
Unsatisfied
Backgrounds
Signals
Bin

Voting

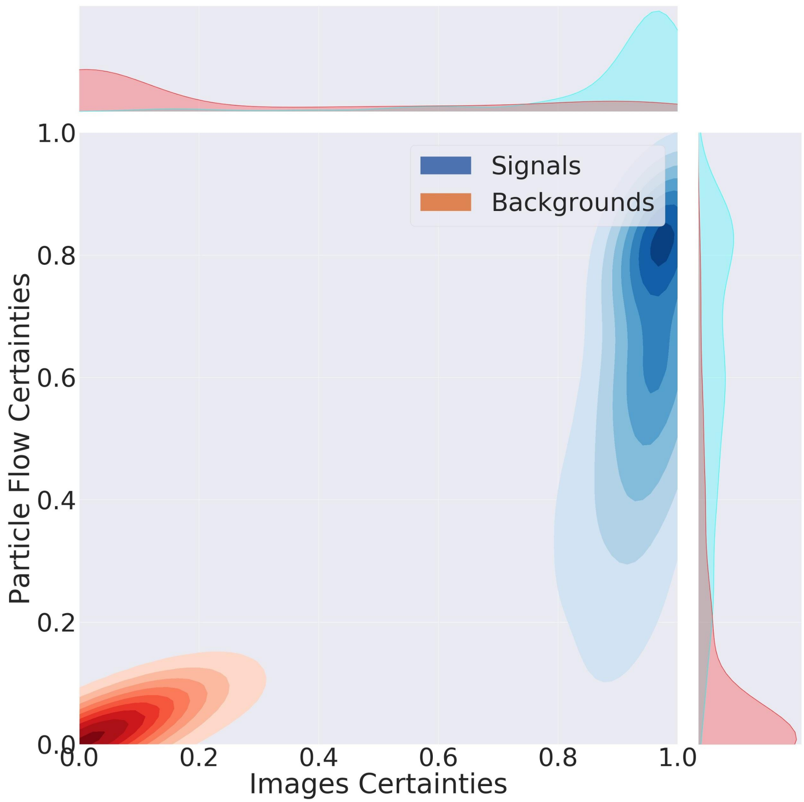
Each network returns a probability for each class.

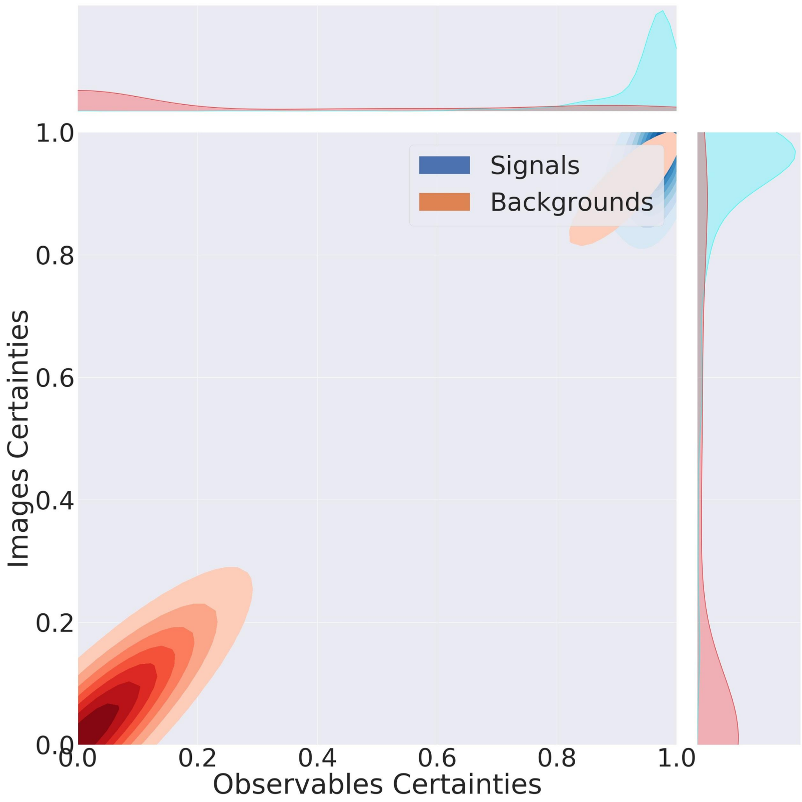


We have a naive voting system, but can we do better?

Voting

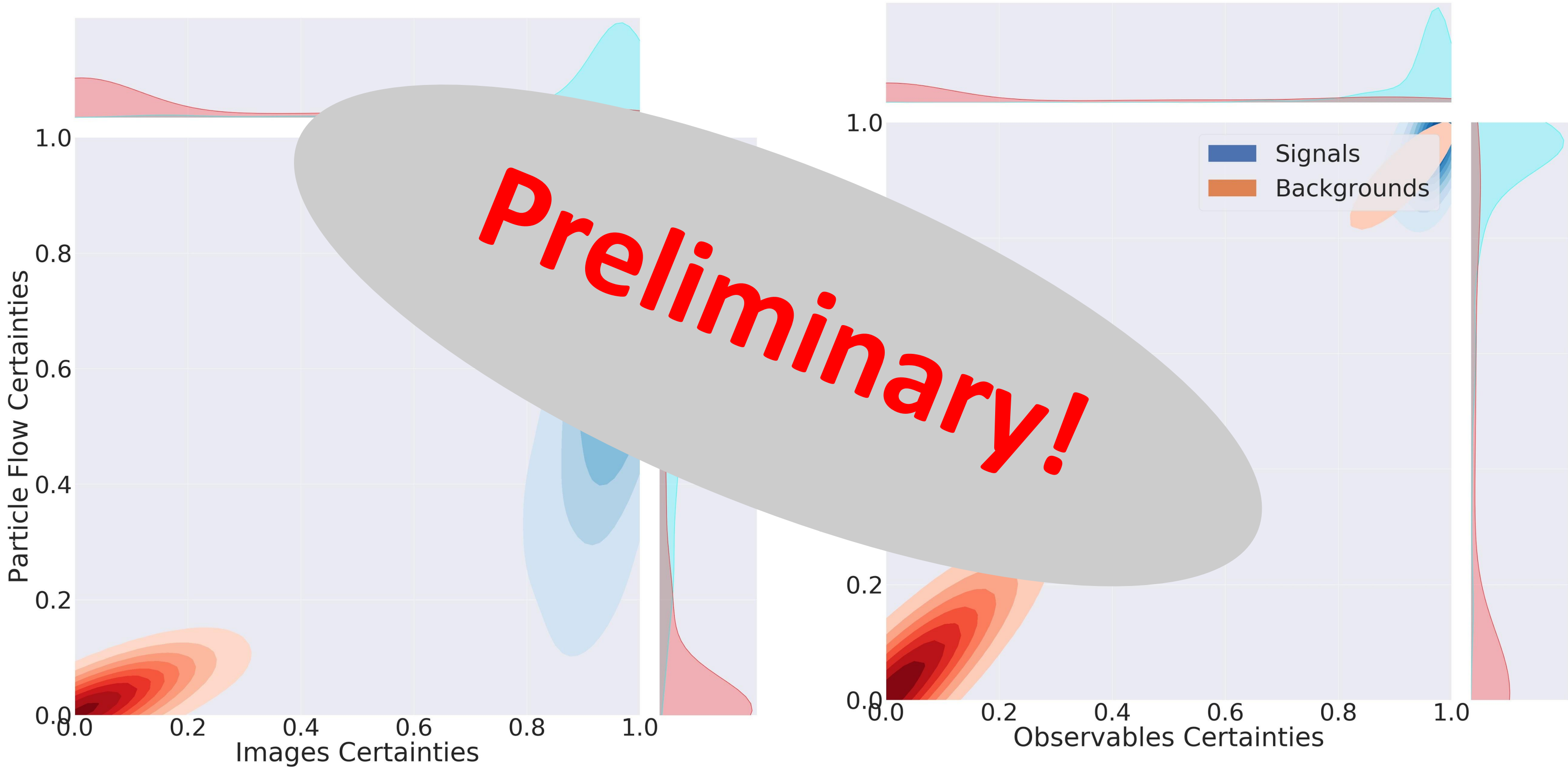
The networks are providing complementary information! More classifying power!





Voting

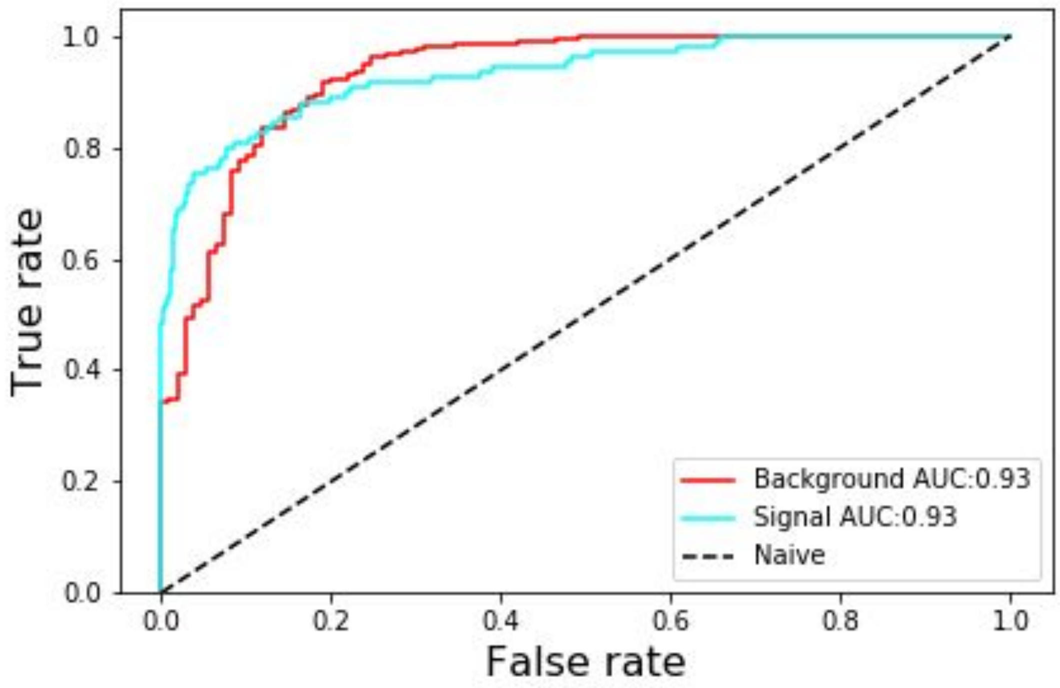
The networks are providing complementary information! More classifying power!



Only a few 1K data points (for now!)

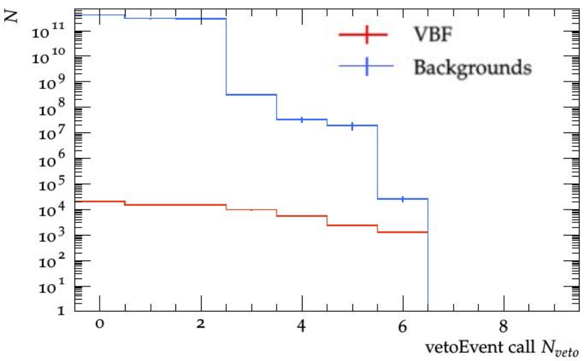
Time to learn

Learn how to vote!

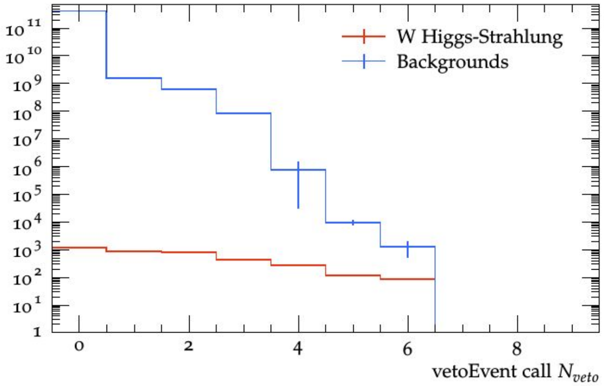


Results and Conclusions

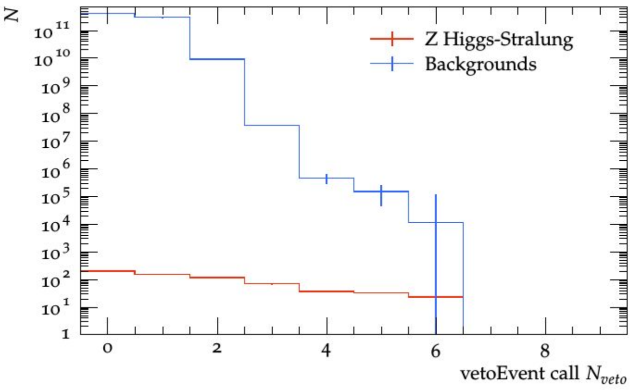
Combined networks give superior killing power than individual networks!



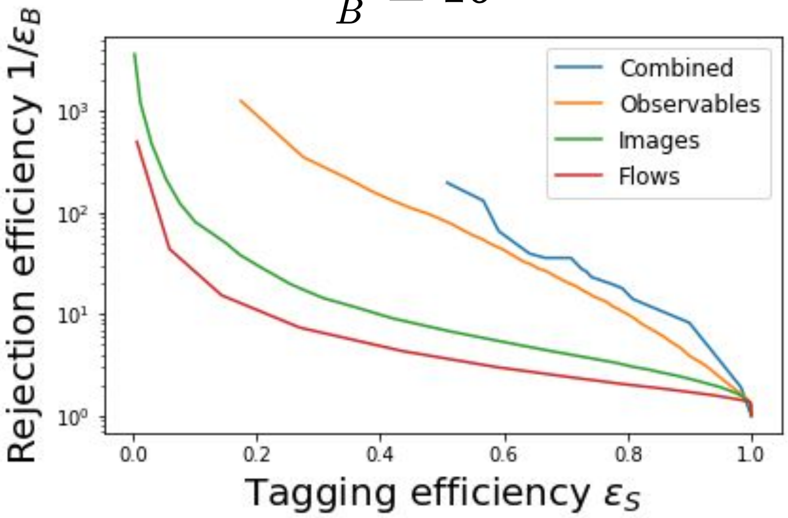
$$\frac{S}{B} \simeq 10^{-2}$$



$$\frac{S}{B} \simeq 10^{-2}$$



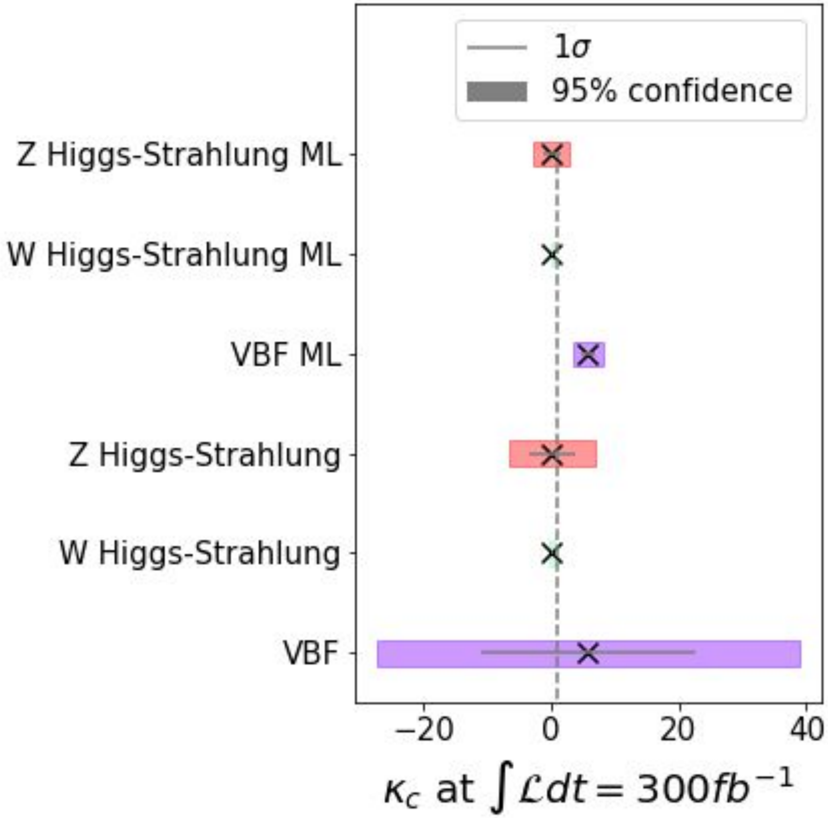
$$\frac{S}{B} \simeq 10^{-3}$$



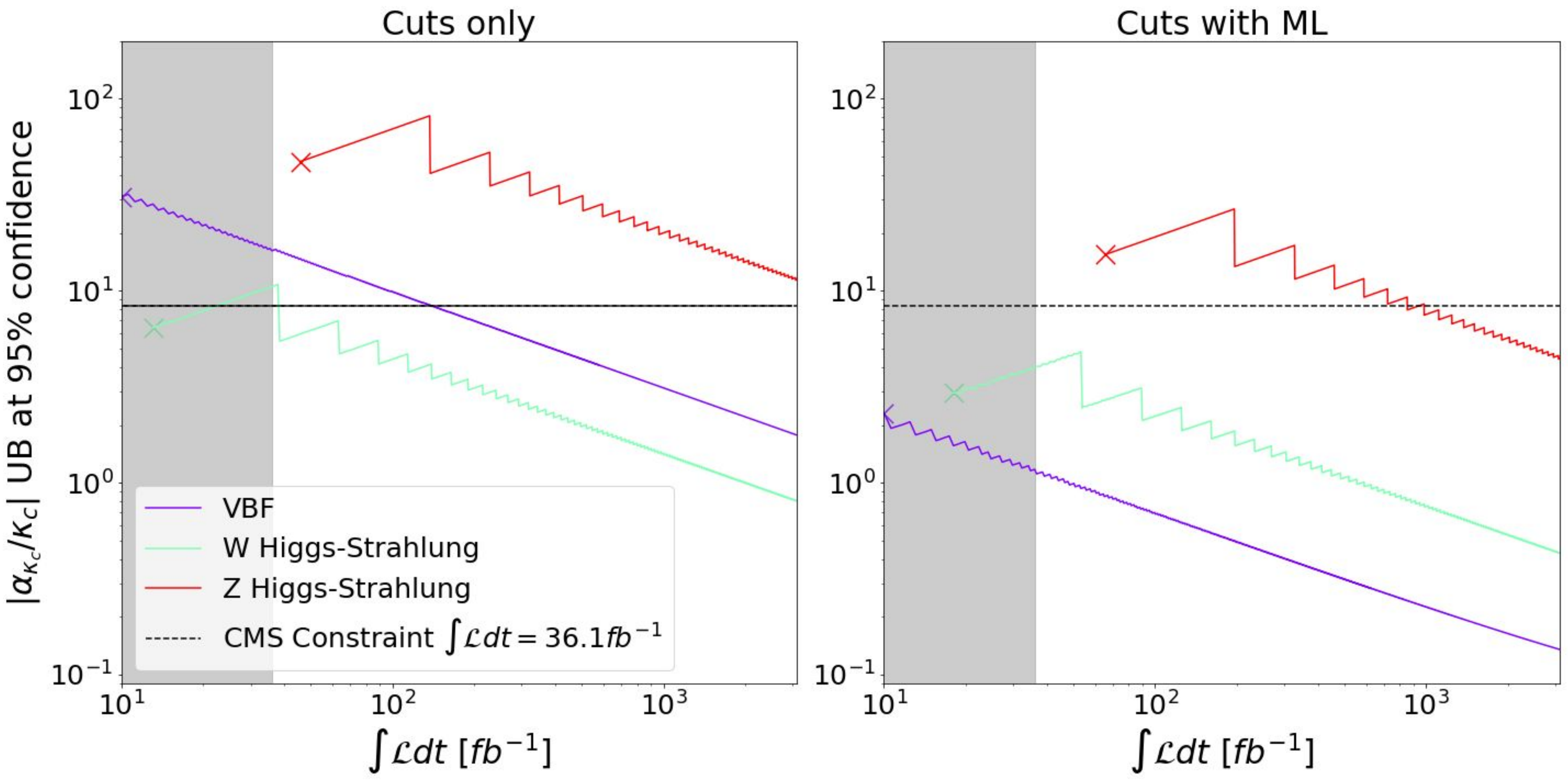
Results and Conclusions

$$\frac{\sigma(VH)Br(H\to c\bar{c})}{\sigma_{SM}(VH)Br_{SM}(H\to c\bar{c})} = \kappa_c^2$$

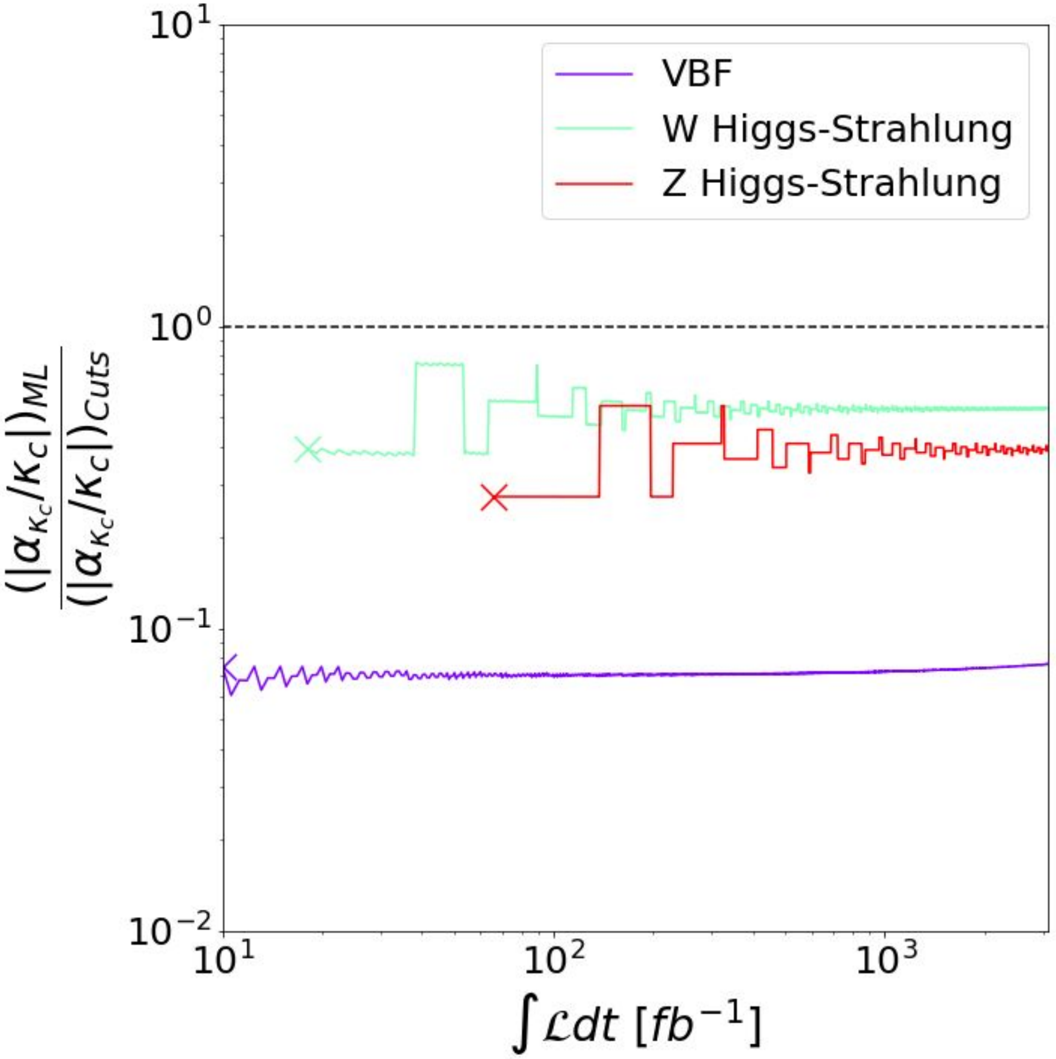
$$Br_{SM}(H \to c\bar{c}) = 2.89 \times 10^{-2} \, {}^{+5.5\%}_{-2.0\%}$$



Results and Conclusions



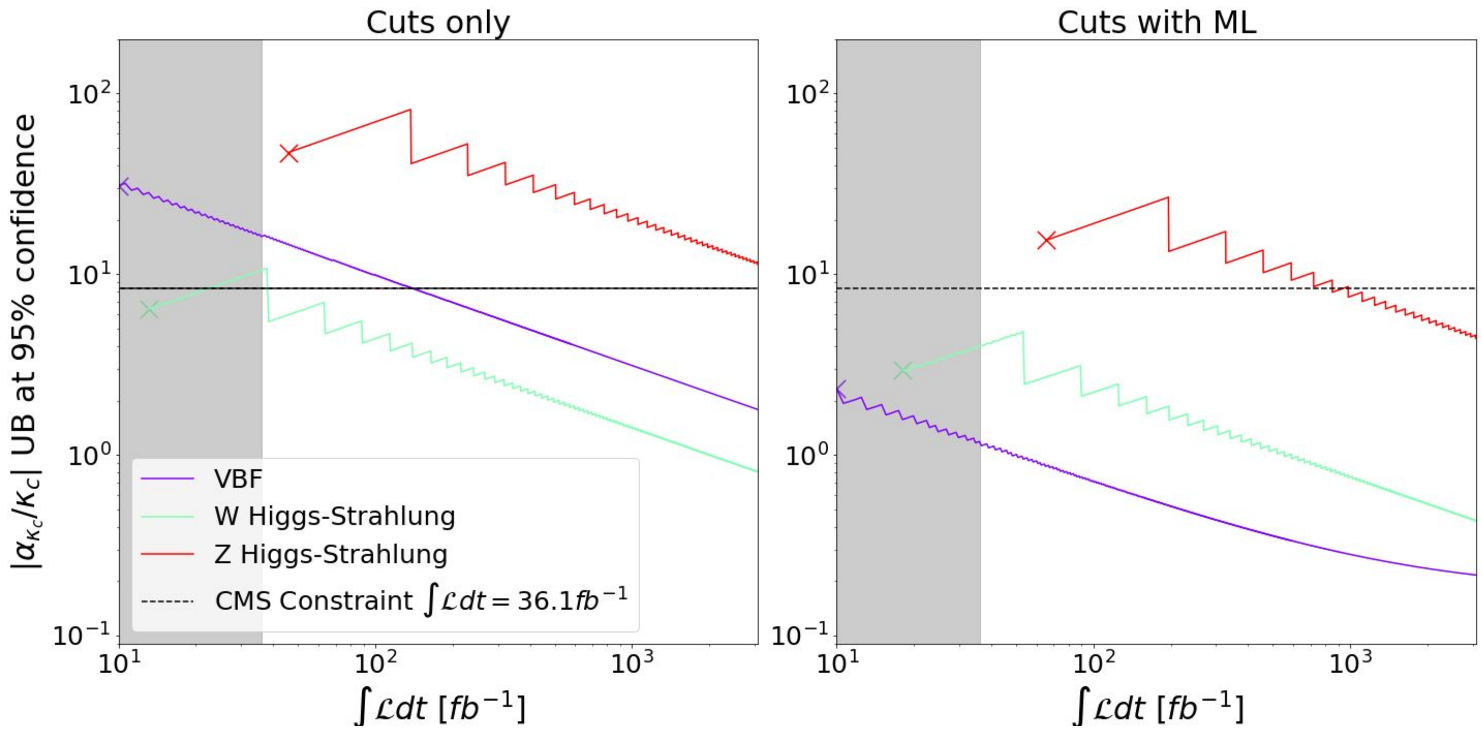
Results and Conclusions



Results and Conclusions

Key points
1. A proof of concept
2. Promising results
3. Pipeline ready to go!

Considerations
1. This was only a LO study
2. Possibility to consider more backgrounds
3. Detector simulation
4. More data!

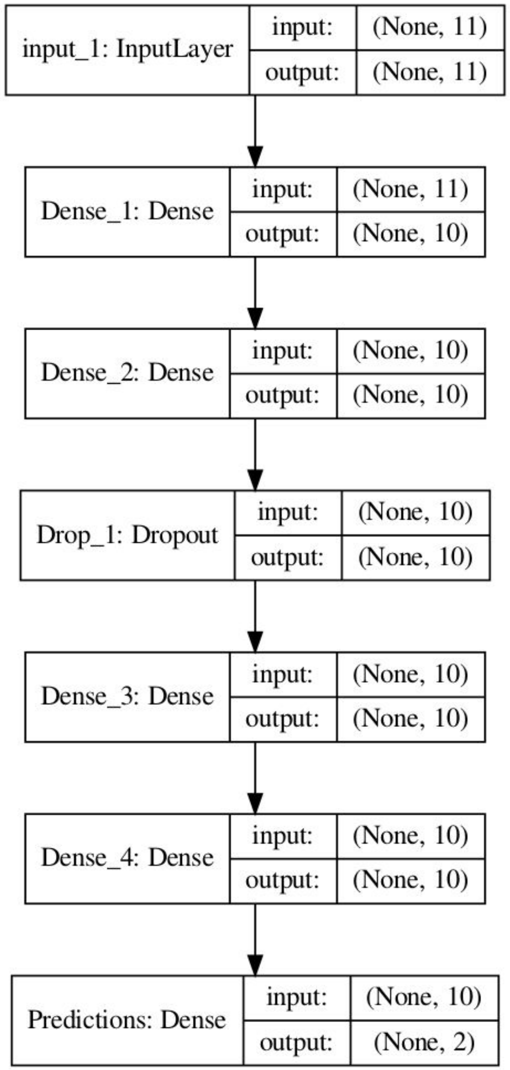


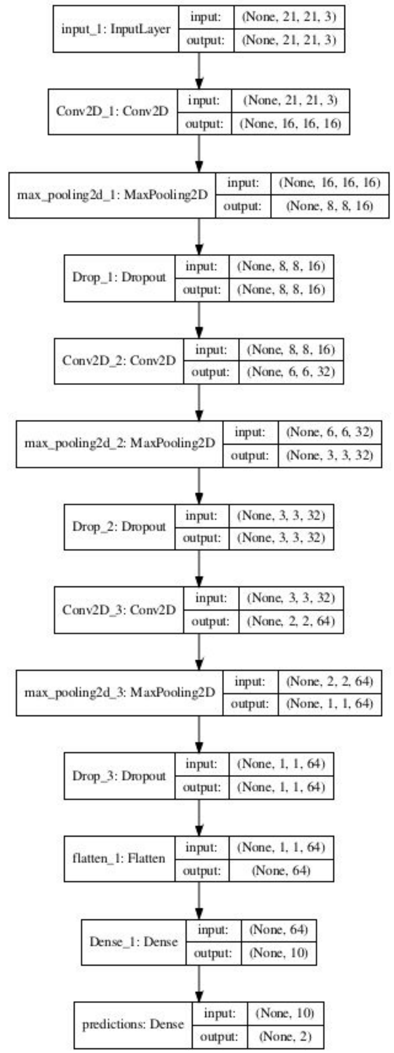
Backups

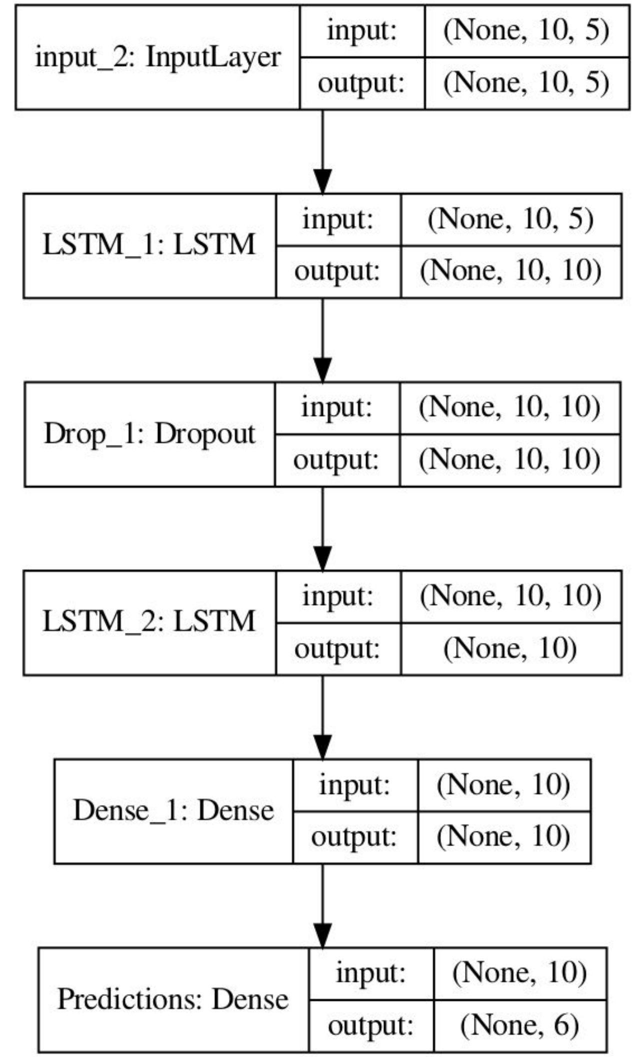
BACKUP SLIDES

1. Network Architectures
2. Chosen Observables
3. Distributions

Architectures

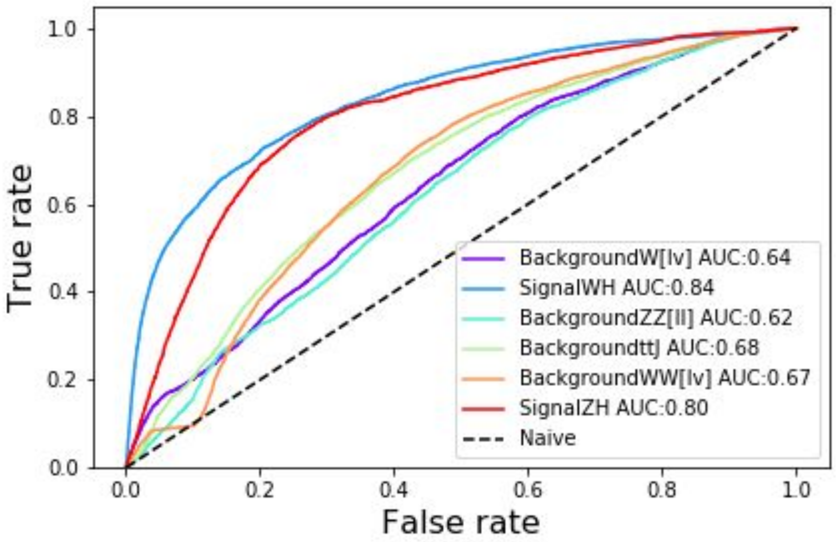




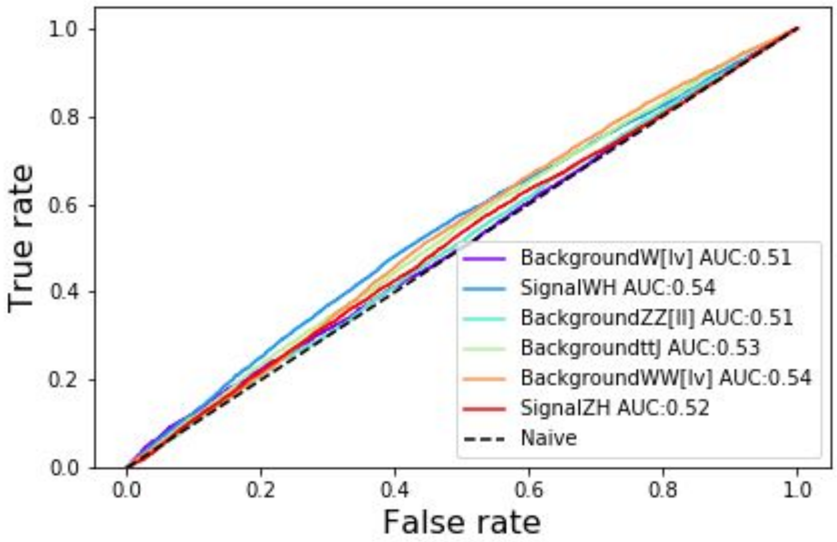


Chosen Observables

A good observable: Jet Mass

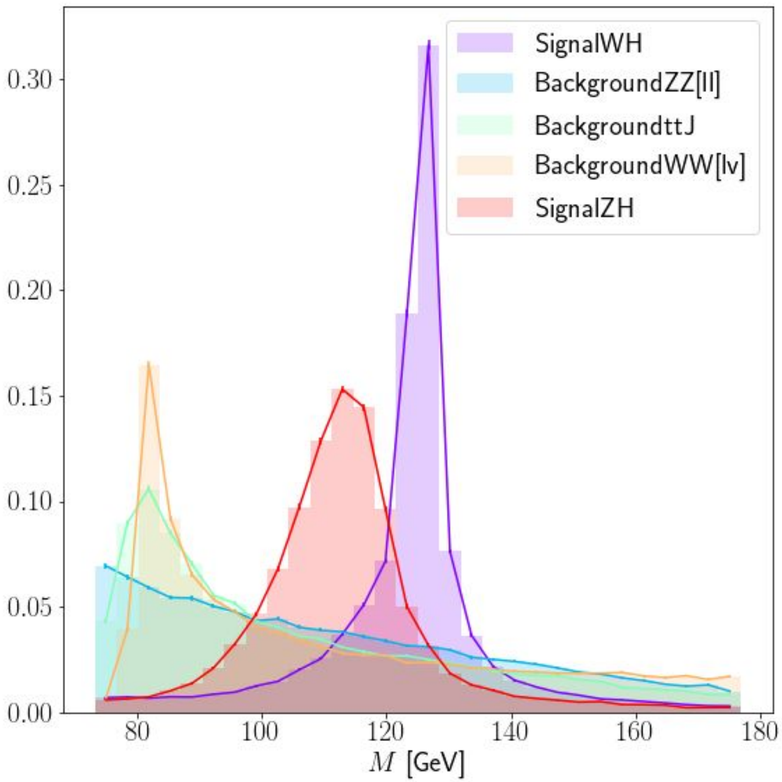


A bad observable: Jet Rapidity

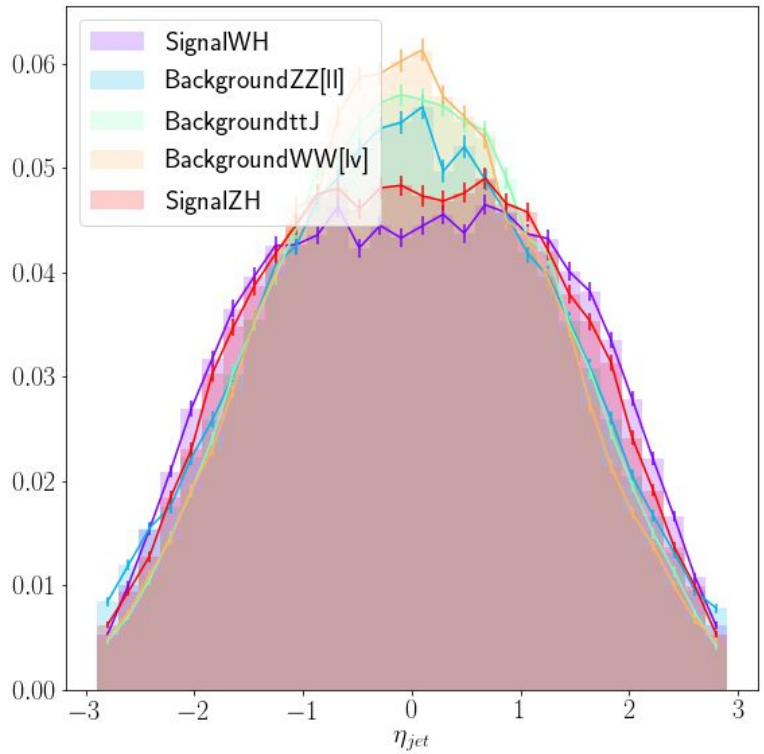


Chosen Observables

A good observable: Jet Mass



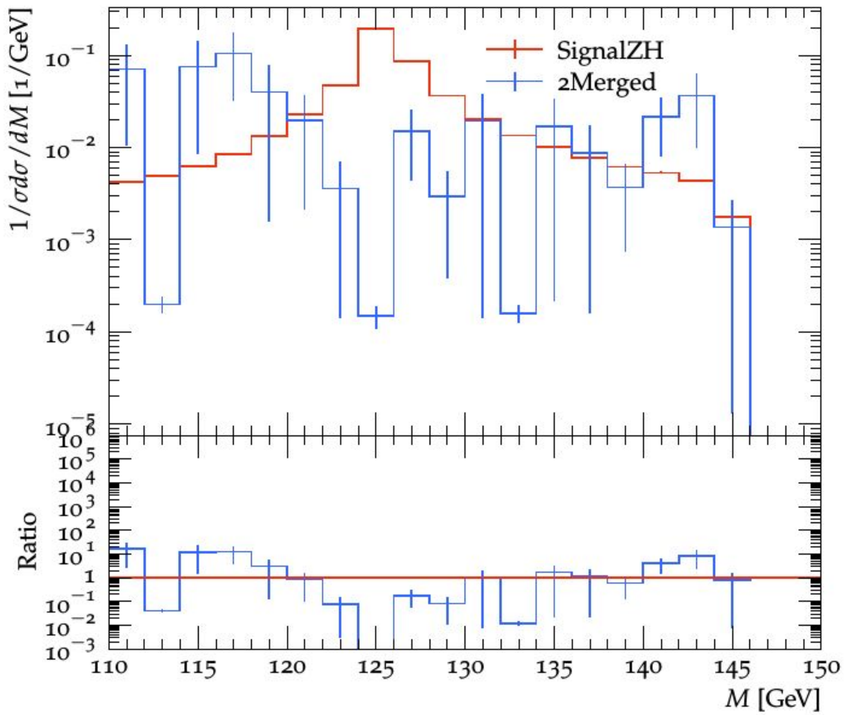
A bad observable: Jet Rapidity



Distributions

Sanity checks - 2 Isolated lepton channel

Candidate fatjet distributions



Leptons invariant mass