Analysis Summary

Useful stuff:

12.9 fb-1 PAS

35.9 fb-1 CADI

ATLAS (36.1 fb-1) Paper

HppHmmLep GitLab repository

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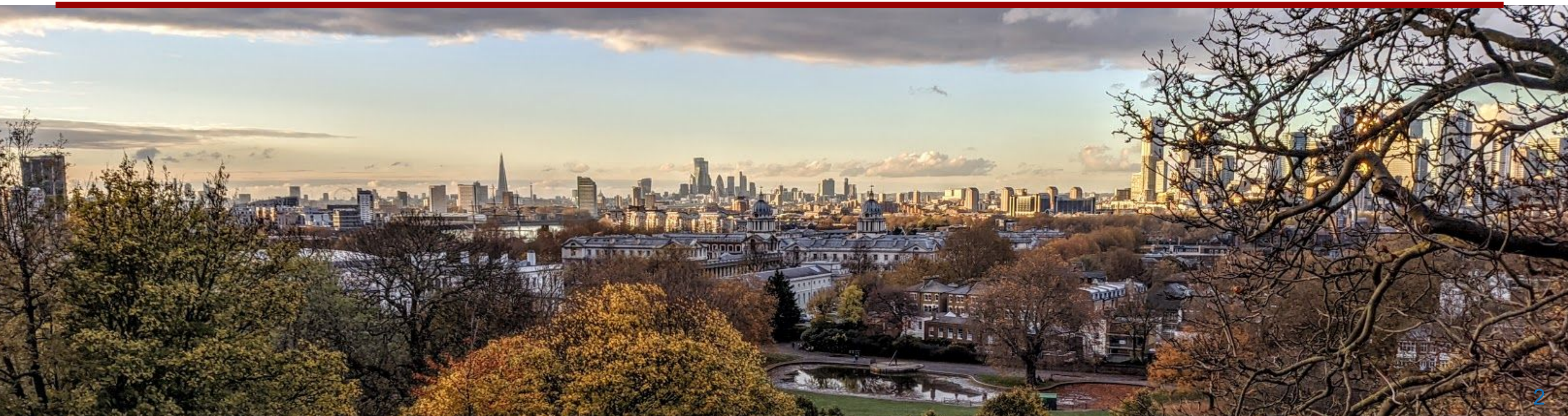
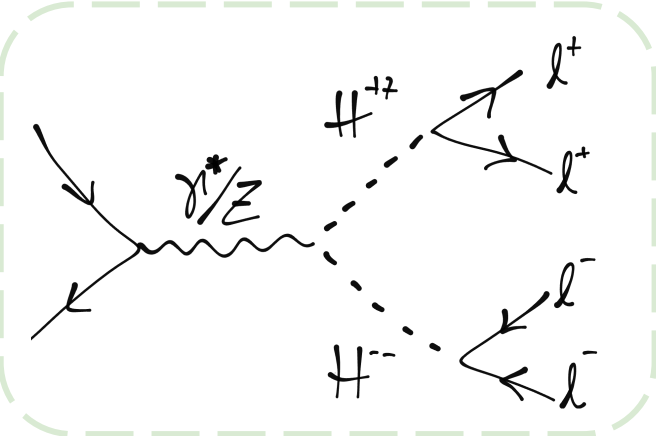
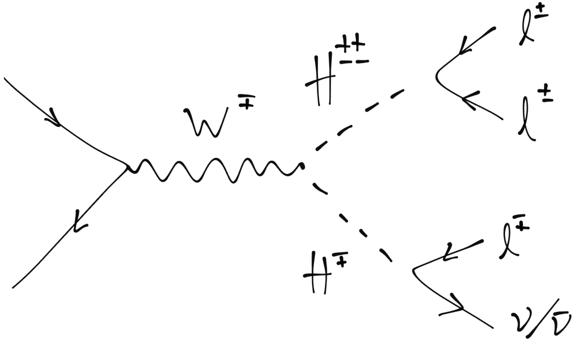
Analysis Summary



Intro & General Idea

- **Search** for **doubly charged Higgs** bosons
  - ↪ Motivated by **extended Higgs** sector models, $\boldsymbol{\nu}$ **mass** models, others
- **Initially** focus on **4 lep** channel
  - ↪ $\mathbf{e/\mu}$ channels





Datasets

Data 2016 part-1 (eras B to F, B ver2 only)

/**MuonEG**/Run2016*-HIPM-**UL**2016_MiniAODv2_NanoAODv9-v2
/**SingleElectron**/Run2016*-HIPM-**UL**2016_MiniAODv2_NanoAODv9-v2
/**SingleMuon**/Run2016*-HIPM-**UL**2016_MiniAODv2_NanoAODv9-v2
/**DoubleEG**/Run2016*-HIPM-**UL**2016_MiniAODv2_NanoAODv9-v2
/**DoubleMuon**/Run2016*-HIPM-**UL**2016_MiniAODv2_NanoAODv9-v2

Data 2016 part-2 (eras F to H)

/**MuonEG**/Run2016*-**UL**2016_MiniAODv2_NanoAODv9-v2
/**SingleElectron**/Run2016*-**UL**2016_MiniAODv2_NanoAODv9-v2
/**SingleMuon**/Run2016*-**UL**2016_MiniAODv2_NanoAODv9-v2
/**DoubleEG**/Run2017*-**UL**2016_MiniAODv1_NanoAODv9-v1
/**DoubleMuon**/Run2016*-**UL**2016_MiniAODv2_NanoAODv9-v2

Data 2017 (eras B to F)

/**MuonEG**/Run2017*-**UL**2017_MiniAODv2_NanoAODv9-v1
/**SingleElectron**/Run2017*-**UL**2017_MiniAODv2_NanoAODv9-v1
/**SingleMuon**/Run2017*-**UL**2017_MiniAODv2_NanoAODv9-v1
/**DoubleEG**/Run2017*-**UL**2017_MiniAODv2_NanoAODv9-v1
/**DoubleMuon**/Run2017*-**UL**2017_MiniAODv2_NanoAODv9-v1

Data 2018 (eras A to D, NanoAODv9-v1/2/3)

/**MuonEG**/Run2018*-**UL**2018_MiniAODv2_NanoAODv9-v*
/**EGamma**/Run2018*-**UL**2018_MiniAODv2_NanoAODv9-v*
/**SingleMuon**/Run2018*-**UL**2018_MiniAODv2_NanoAODv9-v*
/**DoubleMuon**/Run2018*-**UL**2018_MiniAODv2_NanoAODv9-v*

Datasets

Backgrounds --> +NANOAODSIM

/**ZZTo4L**_TuneCP5_13TeV_powheg_pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9-v2
/GluGluToContinTo**ZZTo2mu2tau**_TuneCP5_13TeV-mcfm701-pythia8/**RunIISummer20UL18NanoAODv9**-106X_upgrade2018_realistic_v16_L1v1-v2
/GluGluToContinTo**ZZTo2e2mu**_TuneCP5_13TeV-mcfm701-pythia8/**RunIISummer20UL18NanoAODv9**-106X_upgrade2018_realistic_v16_L1v1-v2
/GluGluToContinTo**ZZTo2e2tau**_TuneCP5_13TeV-mcfm701-pythia8/**RunIISummer20UL18NanoAODv9**-106X_upgrade2018_realistic_v16_L1v1-v2
/GluGluToContinTo**ZZTo4mu**_TuneCP5_13TeV-mcfm701-pythia8/**RunIISummer20UL18NanoAODv9**-106X_upgrade2018_realistic_v16_L1v1-v2
/GluGluToContinTo**ZZTo4tau**_TuneCP5_13TeV-mcfm701-pythia8/**RunIISummer20UL18NanoAODv9**-106X_upgrade2018_realistic_v16_L1v1-v2
/GluGluToContinTo**ZZTo4e**_TuneCP5_13TeV-mcfm701-pythia8/**RunIISummer20UL18NanoAODv9**-106X_upgrade2018_realistic_v16_L1v1-v2
/**WWTo2L2Nu**_TuneCP5_13TeV-powheg-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9-v2
/**WZTo3LNu**_TuneCP5_13TeV-amcatnloFXFX-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9-v2
~~/**WZTo3LNu_mllmin01**_NNPDF31_TuneCP5_13TeV_powheg_pythia8/**RunIISummer20UL17NanoAODv2**-106X_mc2017_realistic_v8-v1~~
/**WWW**_4F_TuneCP5_13TeV-amcatnlo-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9_ext1-v2
/**WWZ**JetsTo4L2Nu_4F_TuneCP5_13TeV-amcatnlo-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9-v2
/**WZZ**_TuneCP5_13TeV-amcatnlo-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9_ext1-v2
/**ZZZ**_TuneCP5_13TeV-amcatnlo-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9_ext1-v2
/**TTW**JetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9_ext1-v2
/**TTZ**ToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9_ext1-v2
/**TTTo2L2Nu**_TuneCP5_13TeV-powheg-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9-v1
/**DY**JetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/**RunIISummer20UL17NanoAODv2**-106X_mc2017_realistic_v8-v1

Exact files per year can be found in nanoaod_location.py

Datasets

Signal → Custom NanoAOD

/HPlusPlusHMinusMinusHTo4L_**M-***_TuneCP5_13TeV_pythia8/lathomas-NANOAOD*/USER
/HPlusPlusHMinusMinusHRTo4L_**M-***_TuneCP5_13TeV_pythia8/lathomas-NANOAOD*/USER

Mass: 200 GeV - 1.5 TeV
Parameters detailed in AN2017_100

Triggers

DATASET   TRIGGER CONDITION   2016

```
1. "MuonEG":"(HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL||HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL)"
2. "DoubleMuon":"(HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL||HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ)"
3. "DoubleEG":"(HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ)"
4. "SingleElectron":"(HLT_Ele27_WPTight_Gsf)"
5. "SingleMuon":"(HLT_IsoMu24||HLT_IsoTkMu24)"
```

- MC ⇒ **OR** of all paths
- Data ⇒ **Per-dataset pass** condition + **fail all previous** datasets' conditions to avoid double counting
  ⇢ Example of **actual trigger cut** for dataset 2 (DoubleMuon):

```
((HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL||HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ))&&(!((HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL||HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL))
```

Triggers

2016

1. "MuonEG":"(HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL||HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL)"
2. "DoubleMuon":"(HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL||HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ)"
3. "DoubleEG":"(HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ)"
4. "SingleElectron":"(HLT_Ele27_WPTight_Gsf)"
5. "SingleMuon":"(HLT_IsoMu24||HLT_IsoTkMu24)"

- MC ⇒ **OR** of all paths
- Data ⇒ **Per-dataset pass** condition + **fail all previous** datasets' conditions to avoid double counting

  ⇢ Example of **actual trigger cut** for dataset 2 (DoubleMuon):

```
((HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL||HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ))&&(!((HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL||HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL))
```

Triggers

2017

1. “SingleMuon":"(HLT_IsoMu27||HLT_IsoMu24)",
2. "SingleElectron":"(HLT_Ele35_WPTight_Gsf)",
3. "DoubleEG":"(HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL)",
4. "DoubleMuon":"(HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ||HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8)",
5. "MuonEG":"(HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ||HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ)"

2018

1. "SingleMuon":"(HLT_IsoMu24)",
2. "EGamma":"(HLT_Ele32_WPTight_Gsf||HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL)",
3. "DoubleMuon":"(HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8)",
4. "MuonEG":"(HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ||HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ)"

Lepton Selection

Electrons

- p_T > 30 GeV
- $|\eta|$ < 2.5
- **Iso**: cutBasedHEEP
  pfRel**Iso**03_all < 0.4
- |d**xy**| < 0.05
- |d**z**| < 0.1

Muons

- p_T > 30 GeV
- $|\eta|$ < 2.4
- **ID**: mediumID
- |d**xy**| < 0.2
- |d**z**| < 0.5
- tkRelIso < 0.4

Event Selection

- Discriminating variable: $\bar{M}$

Pre-Selection

- Trigger + >= 2 lep
- exclusively **4 e/μ**
  - eeee
  - mmmm
  - eeem
  - mmme
  - eemm
  - mmee
- Charge **sum == 0**

Same-sign e/mu pair inv. mass → take **average** $\bar{M}$

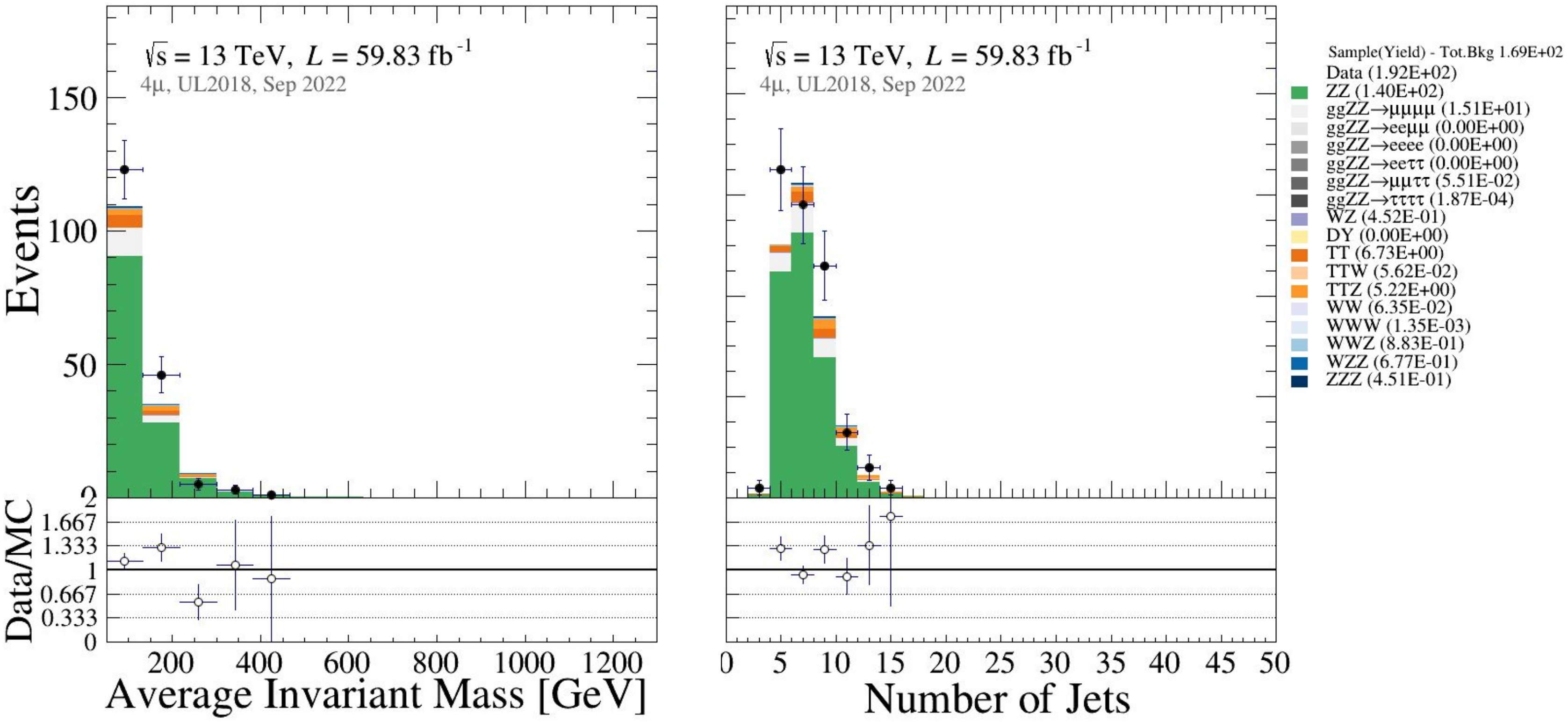
Control Region: 60 GeV < $\bar{M}$ < 150 GeV

Validation Region: 150 GeV < $\bar{M}$ < 200 GeV

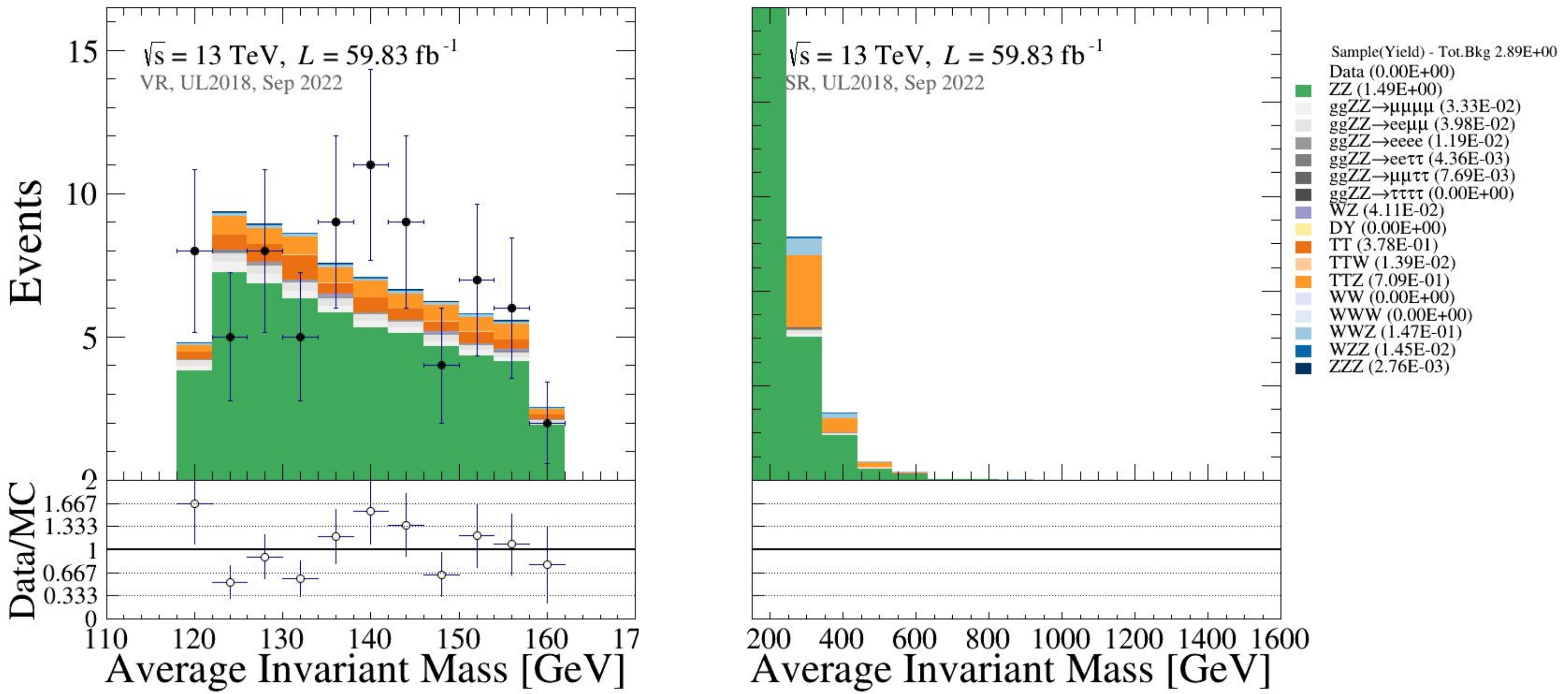
Signal Region:
200 GeV < $\bar{M}$
Veto Z peak
Mass diff. cut (10%)

Status

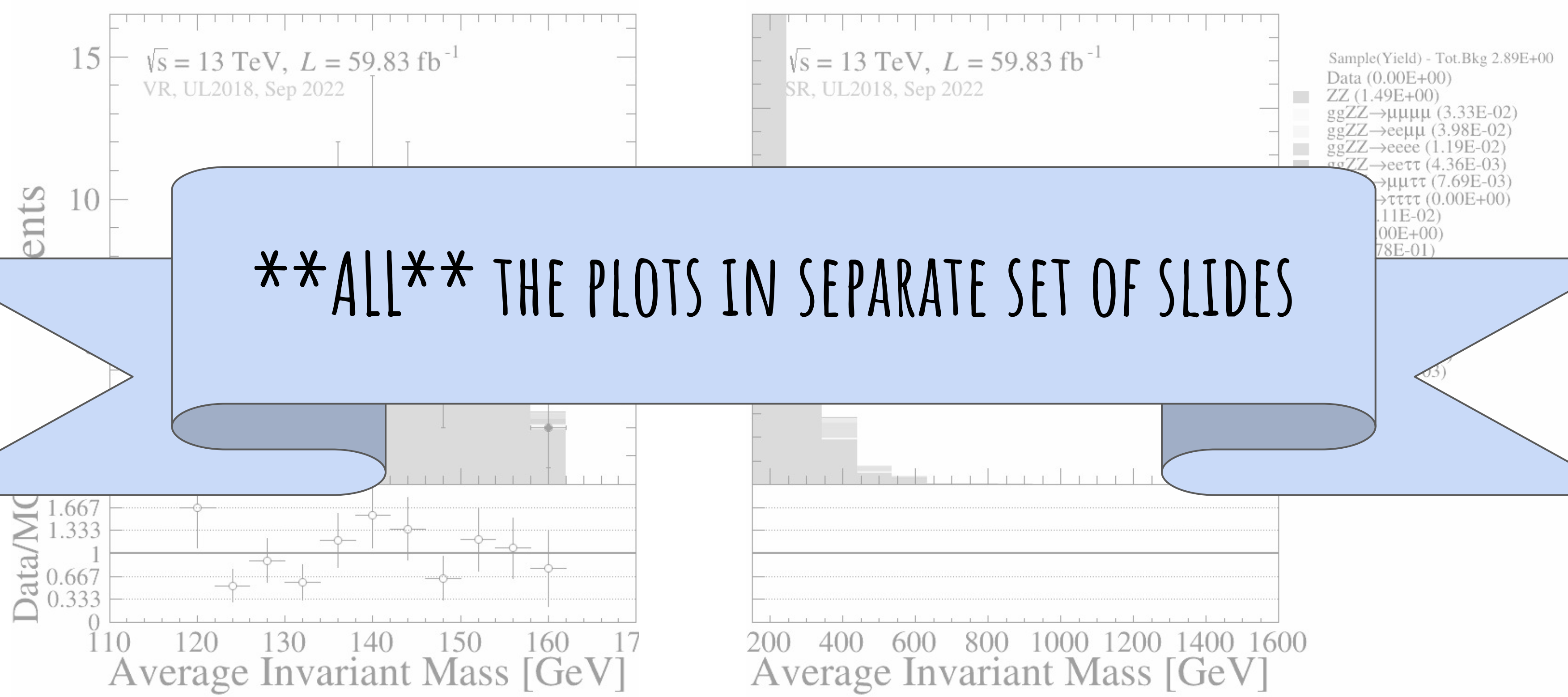
Updated triggers, new variables plotted



New CR/VR/SR definitions

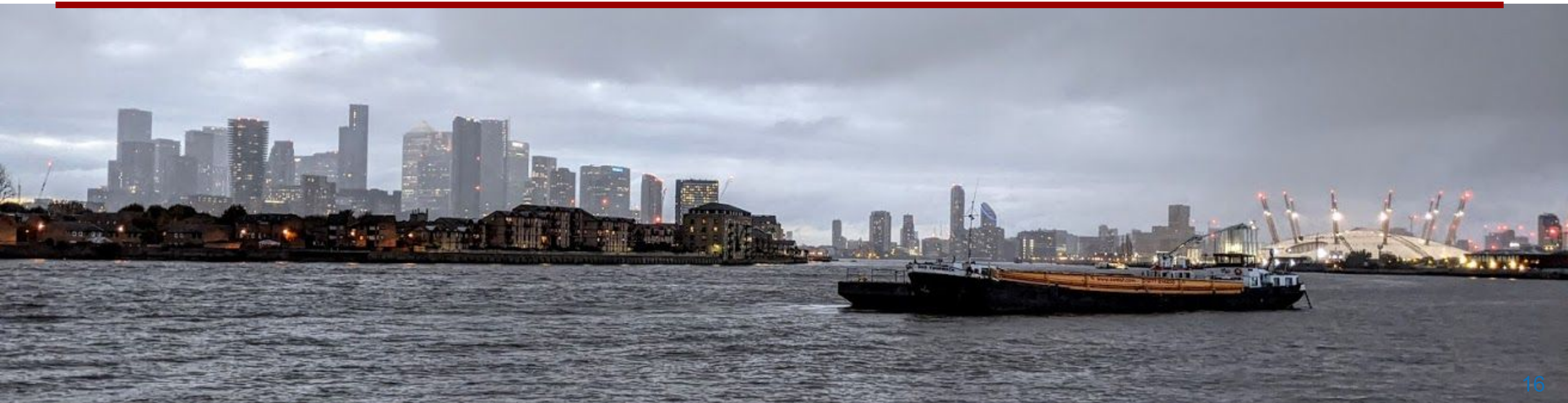


New CR/VR/SR definitions



ALL THE PLOTS IN SEPARATE SET OF SLIDES

Next Steps

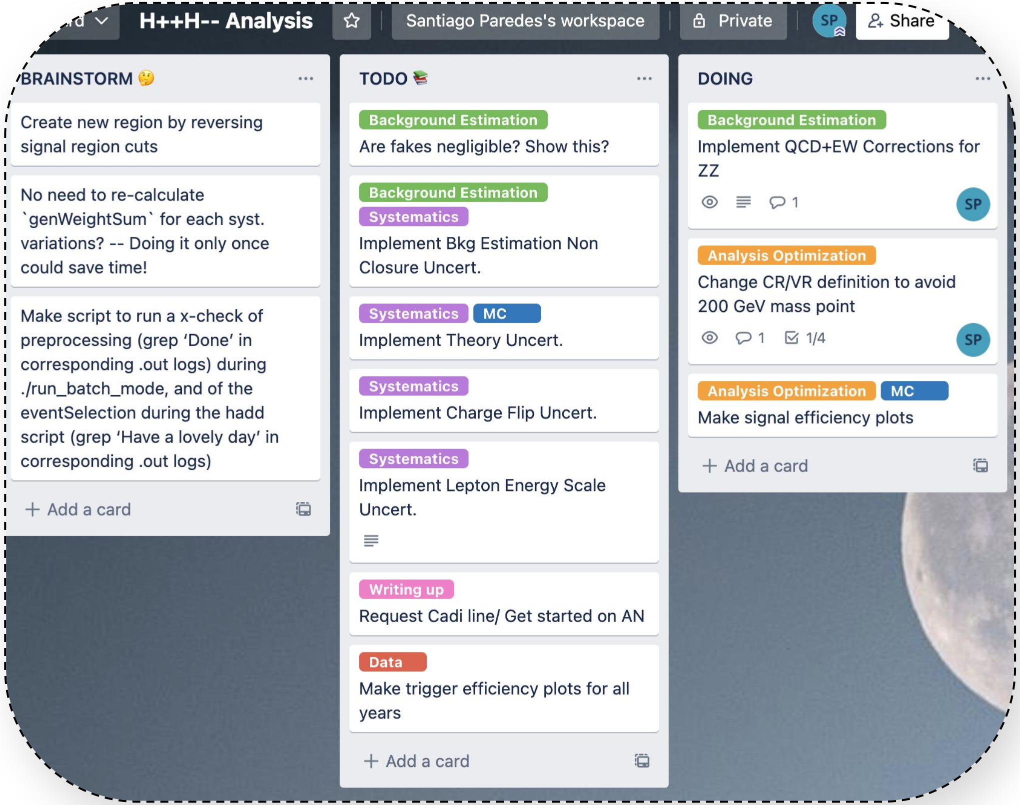


Next steps

- Add e charge misID scale factors
- Add missing systematic uncertainties
  - Background estimate non-closure
  - Charge flip
  - MC cross section
  - Lepton energy scale
- Start on Analysis Note
  - CADI line?

Tracking Objectives + Progress

- Trello board to keep track of tasks and people responsible https://trello.com/b/TunxYh1k/hh-analysis



Backup

Useful stuff:

12.9 fb-1 PAS

35.9 fb-1 CADI

ATLAS (36.1 fb-1) Paper

HppHmmLep GitLab repository

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September 2022

BRUXELLES BRUSSEL

Added 'how to run' section to wiki

GitLab Menu Search GitLab

How to Run

Here are some examples on how to run the code:

Running event selection

This step runs the event selection and outputs histograms that can be used for the statistical analysis in `Combine`, or plotted with the jupyter notebooks in the `tools/plotting/` directory.

The following steps run several scripts that manage the bookkeeping, submission and `hadd`-ing of outputs, but ultimately the script where analysis cuts, quantities, etc are defined is `eventSelection.py`

Example lines for running FW:

```
python tools/htc_scripts/make_htc_sub_file_MC.py -s all -d zz_v2 --year 160G
python tools/htc_scripts/make_htc_sub_file_MC.py -s all -d zz_v2 --year 16
python tools/htc_scripts/make_htc_sub_file_MC.py -s all -d zz_v2 --year 17
python tools/htc_scripts/make_htc_sub_file_MC.py -s all -d zz_v2 --year 18
```

which will generate the following scripts

```
analysis2016OG/sub_MC_zz_v2_syst_all.sh
analysis2016OG/hadd_MC_zz_v2_syst_all.sh
```

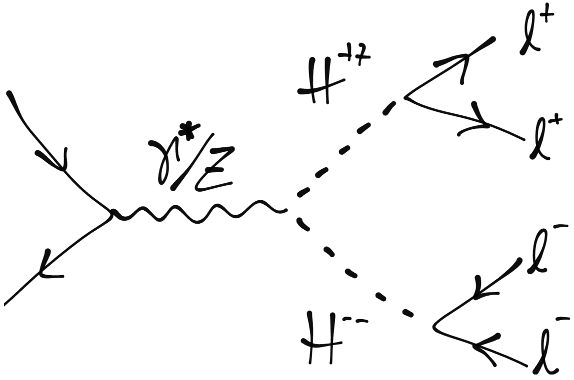
First run the HTC submission script `sub_MC_zz_v2_syst_all.sh`

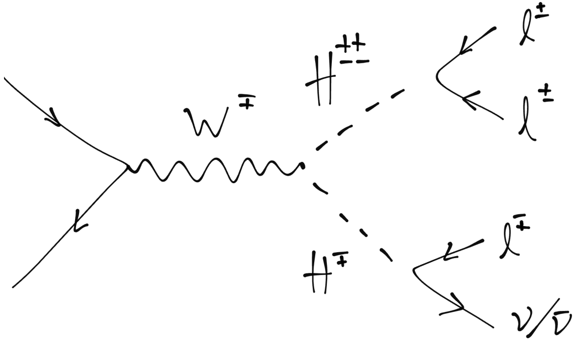
```
source analysis2016OG/sub_MC_zz_v2_syst_all.sh (same for all years)
```

Next hadd the outputs using the other generated script:

Current Results

- CMS-PAS-HIG-16-036 (12.9 fb^{-1})
  - ➢ **Draft** of update: CMS-AN-17-100 (35.9 fb^{-1})
    - ↳ **Archived** since 2018
  - ➢ By **Devin N. Taylor** (UC Davis)
- ATLAS Run 2 conf note
  - ➢ Only targets pair-production





Datasets

Backgrounds → NANOAODSIM

/**ZZTo4L**_TuneCP5_13TeV_powheg_pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9-v2
/**WZTo3LNu_mllmin01**_NNPDF31_TuneCP5_13TeV_powheg_pythia8/**RunIISummer20UL17NanoAODv2**-106X_mc2017_realistic_v8-v1
/**TTTo2L2Nu**_TuneCP5_13TeV-powheg-pythia8/**RunIISummer20UL17NanoAODv9**-106X_mc2017_realistic_v9-v1
/**DYJetsToLL_M-50**_TuneCP5_13TeV-madgraphMLM-pythia8/**RunIISummer20UL17NanoAODv2**-106X_mc2017_realistic_v8-v1

Signal → Custom NanoAOD

/HPlusPlusHMinusMinusHTo4L_**M-***_TuneCP5_13TeV_pythia8/lathomas-NANOAOD*/USER
/HPlusPlusHMinusMinusHRTo4L_**M-***_TuneCP5_13TeV_pythia8/lathomas-NANOAOD*/USER

Mass: 200 GeV - 1.5 TeV
Parameters detailed in AN2017_100

Also (in backup)

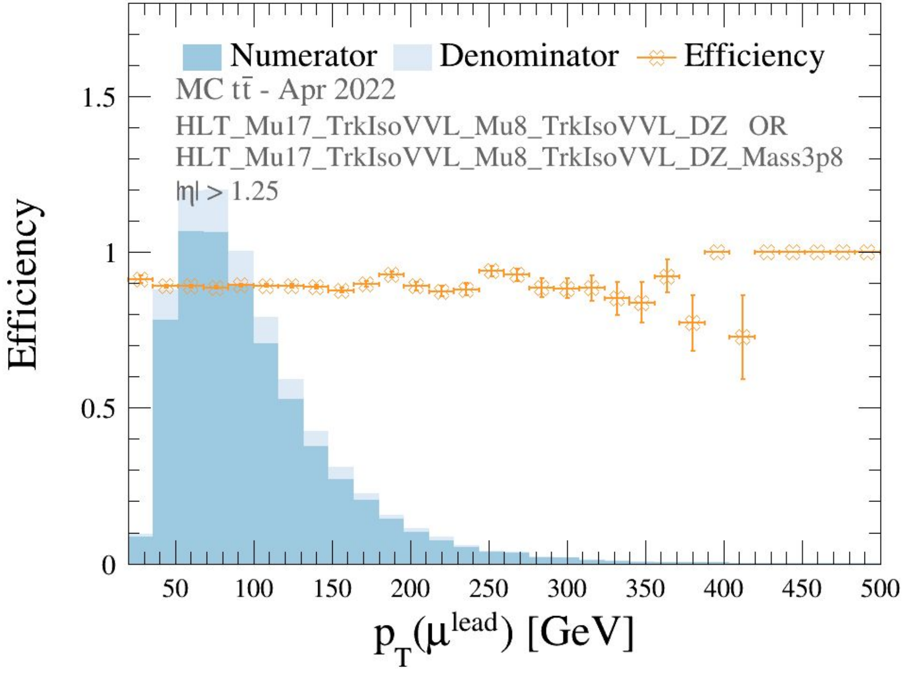
VV
VVV
gg->ZZ
...

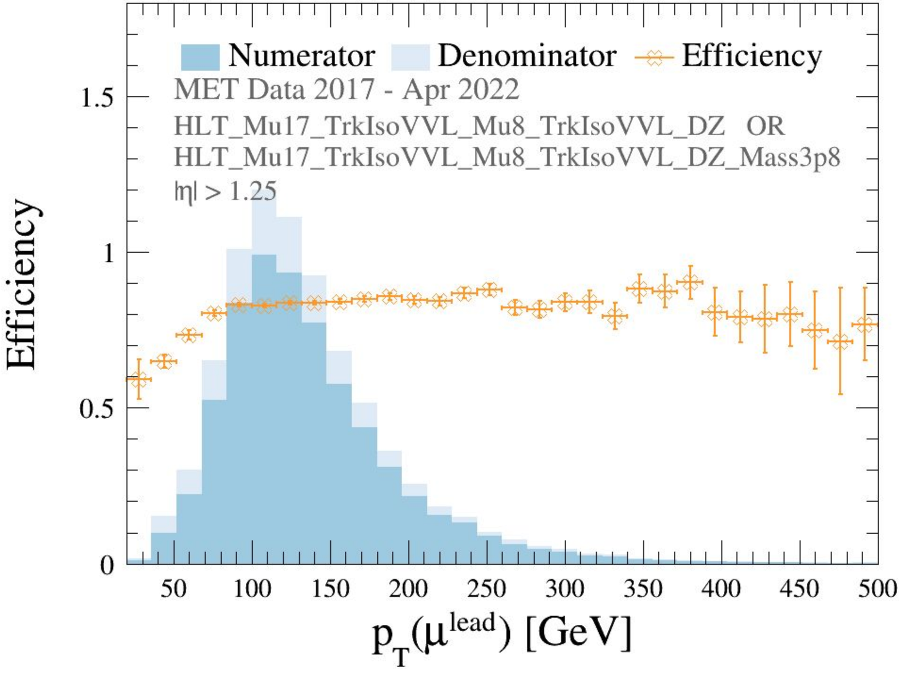
Data → NanoAOD

/**DoubleMuon**/Run2017*-**UL**2017_MiniAODv1_NanoAODv9-v1
/**DoubleEG**/Run2017*-**UL**2017_MiniAODv1_NanoAODv9-v1
/**MuonEG**/Run2017*-**UL**2017_MiniAODv1_NanoAODv9-v1
/**SingleMuon**/Run2017*-**UL**2017_MiniAODv1_NanoAODv9-v1
/**SingleElectron**/Run2017*-**UL**2017_MiniAODv1_NanoAODv9-v1

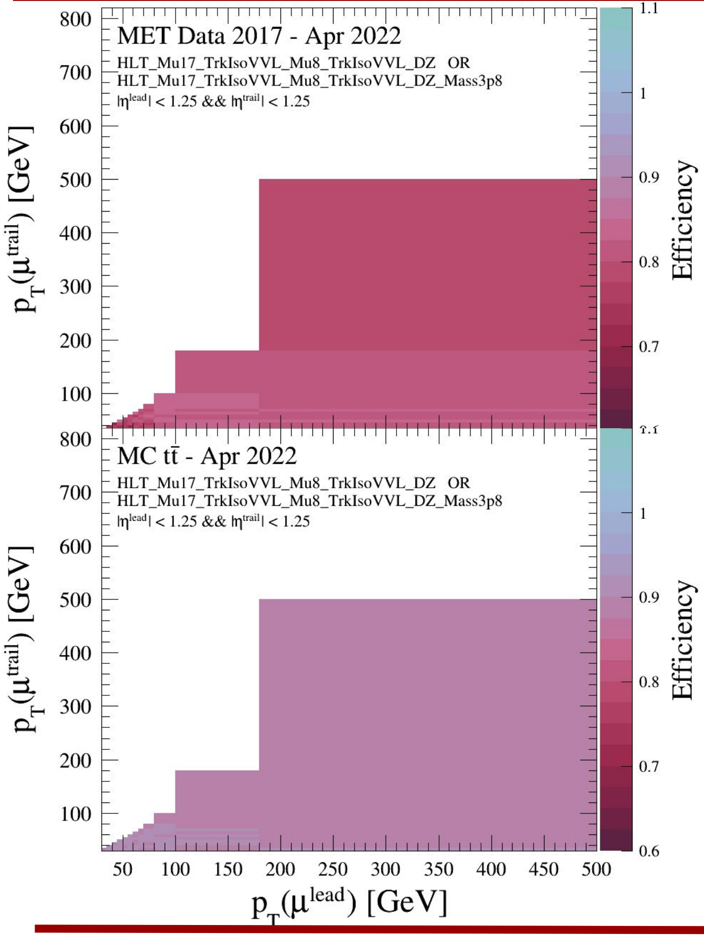
Trigger Efficiency

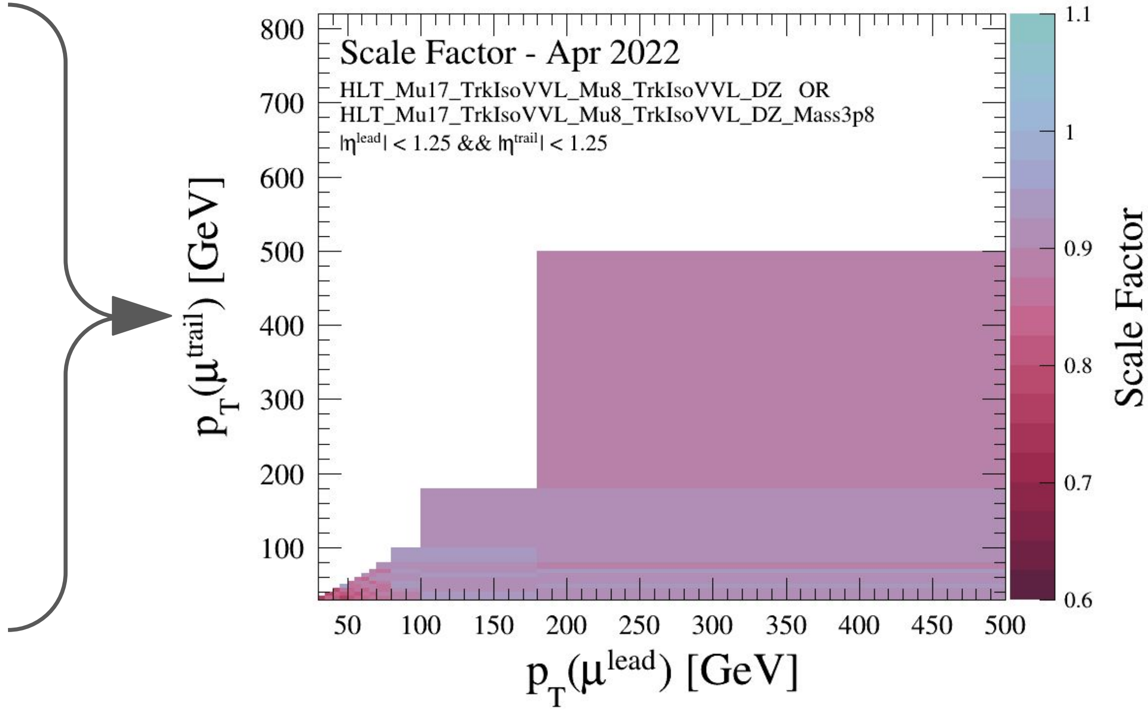
- **Efficiency** vs p_T ⇢ MC/Data differences @ low p_T



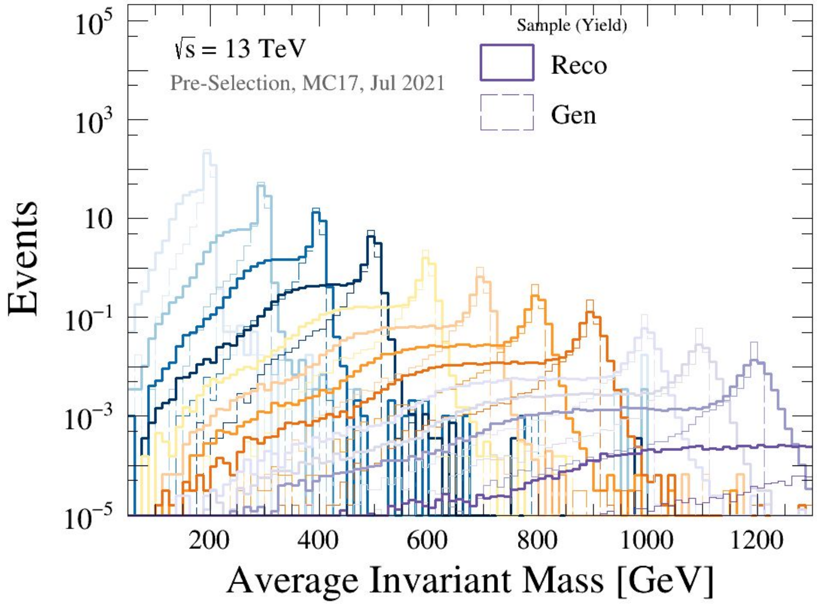


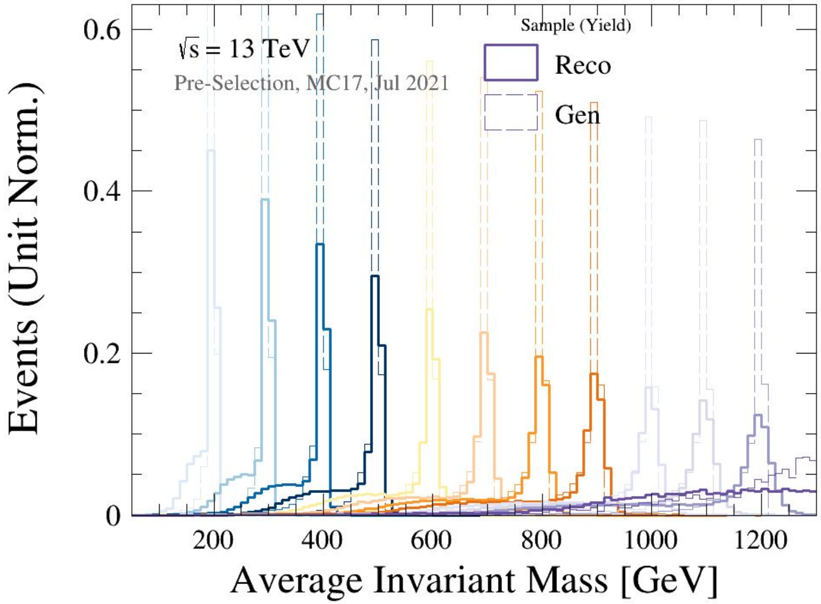
Trigger Scale Factors



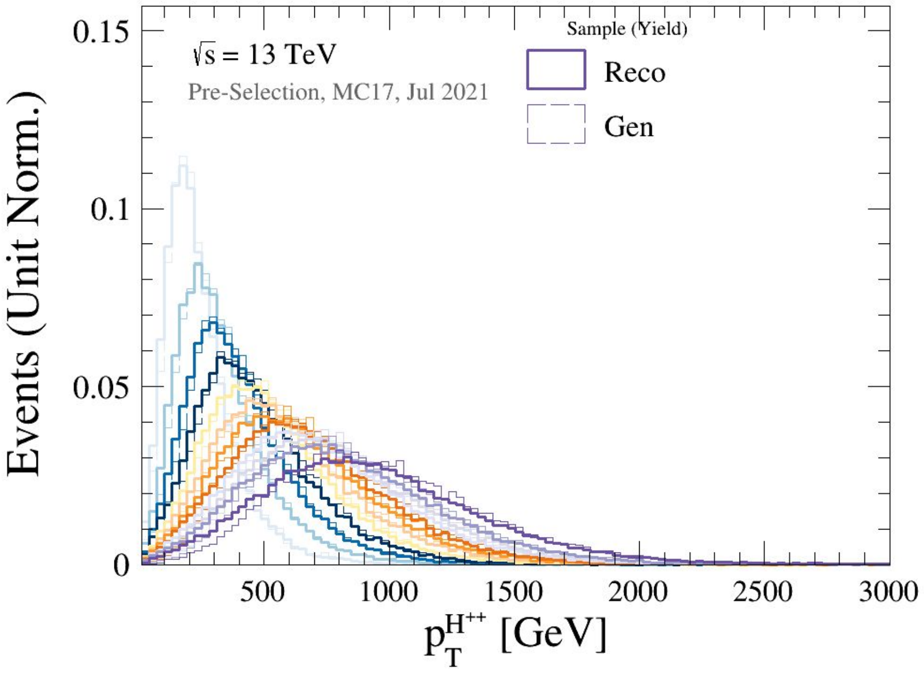


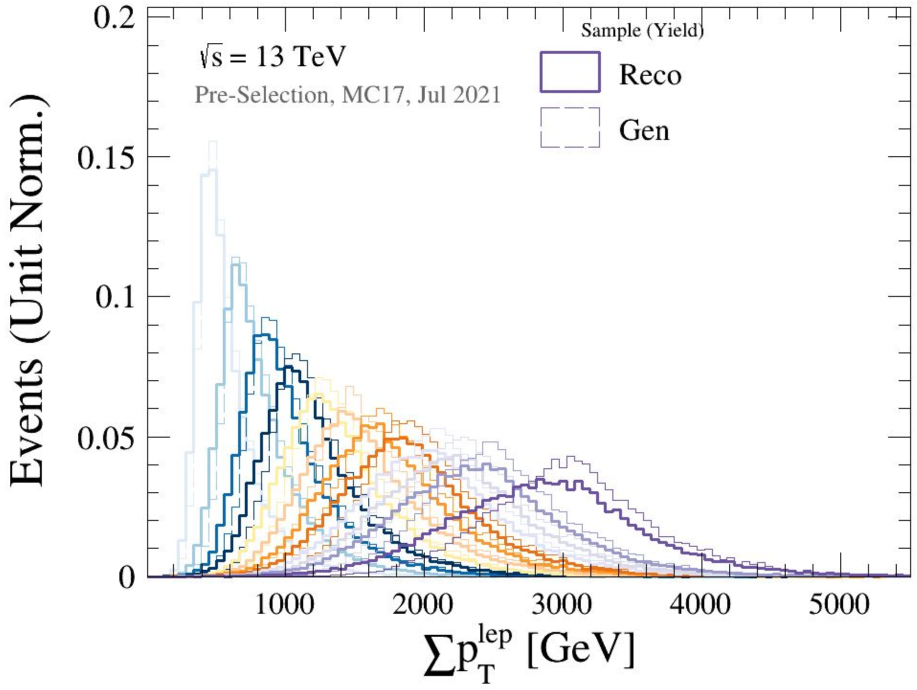
New signal samples





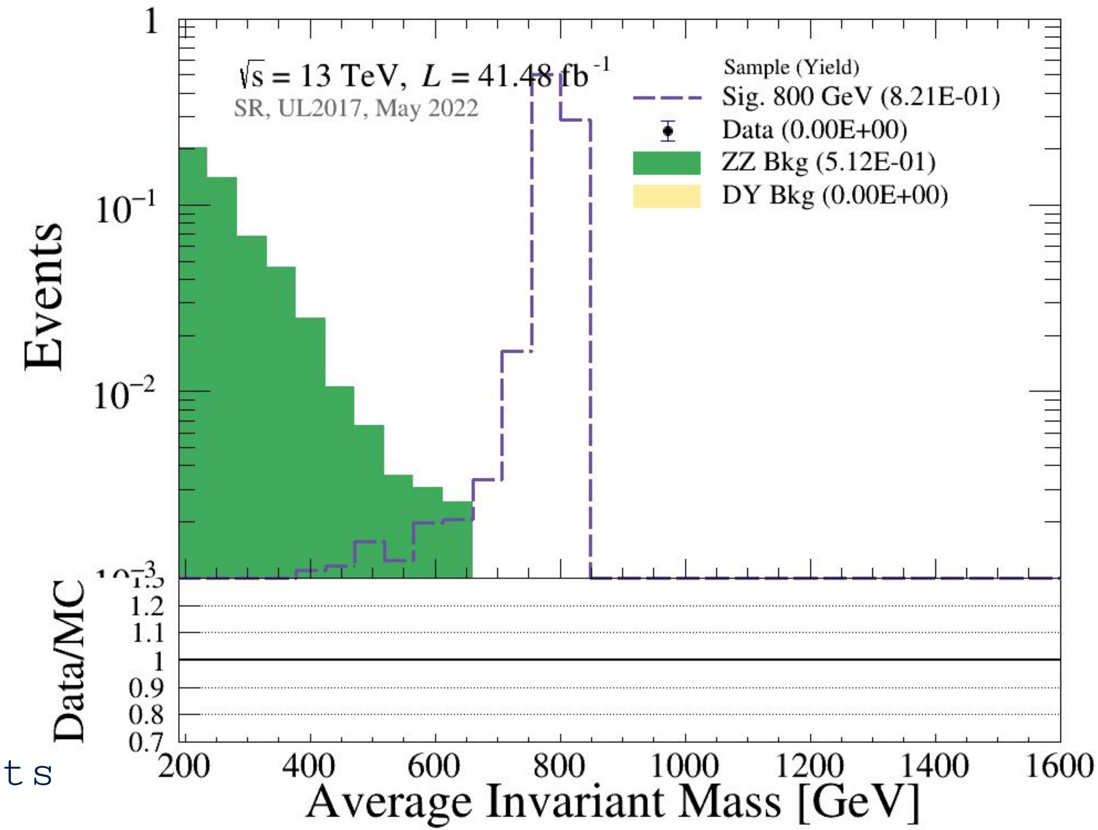
New signal samples





Limits - first pass

- **First pass** combine statistical analysis
  - ↪ **Mass average** used
  - ↪ **No** experimental **data**
  - ↪ **ZZ** bkg only
  - ↪ Lep. ID+ISO **shape uncertainty**
  - ↪ **Lumi** uncertainty
- **Plan** to use `HybridNew`
  - ↪ WIP : `AsymptoticLimits`



Limits - first pass

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  - ↪ Lep. ID+ISO **shape uncertainty**
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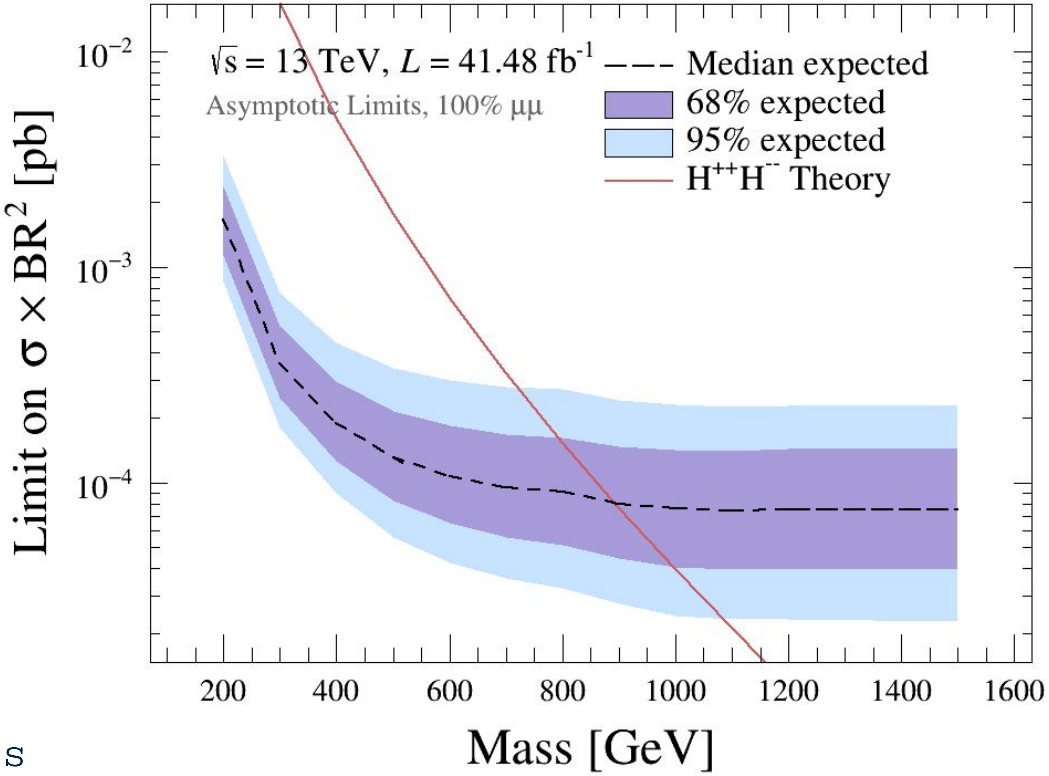
- **Plan** to use `HybridNew`
  - ↪ WIP : `AsymptoticLimits`



Limits - first pass

- **First pass** combine statistical analysis
  - ↪ **Mass average** used
  - ↪ **ZZ** bkg only
  - ↪ **No** experimental **data**
  - ↪ Lep. ID+ISO **shape uncertainty**
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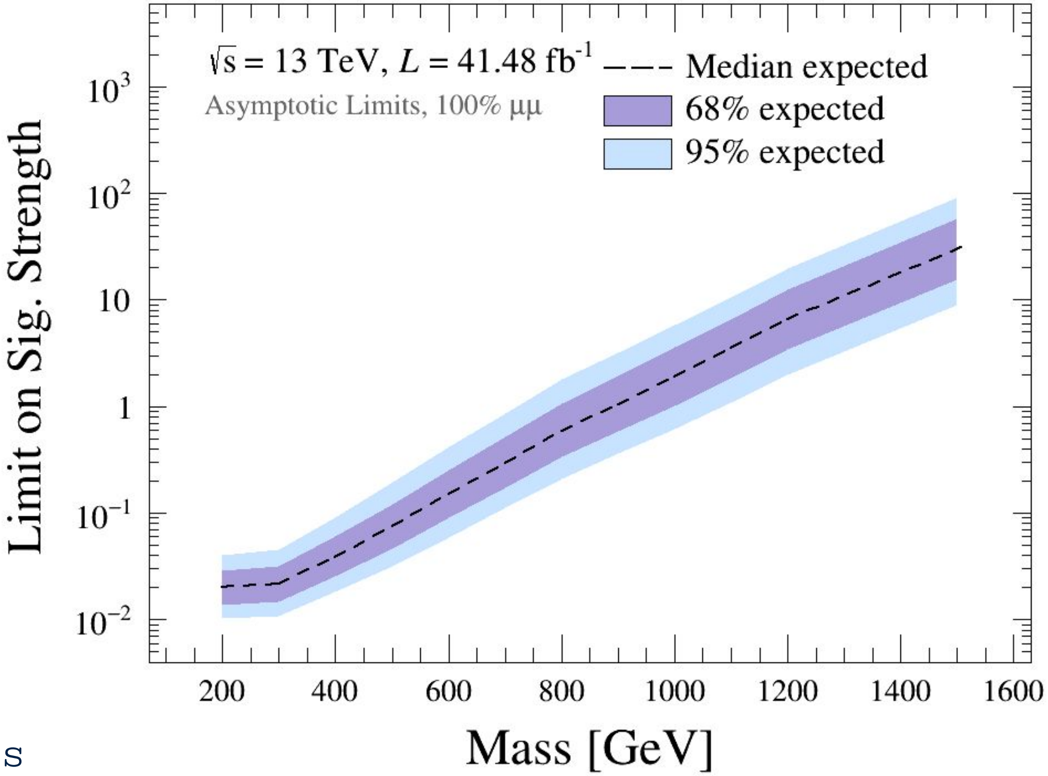
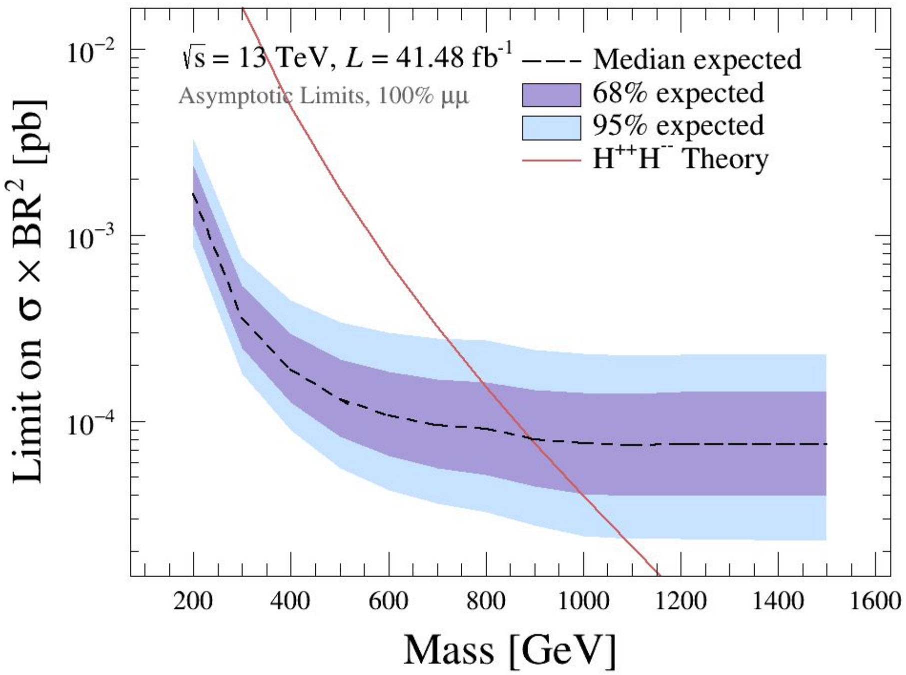
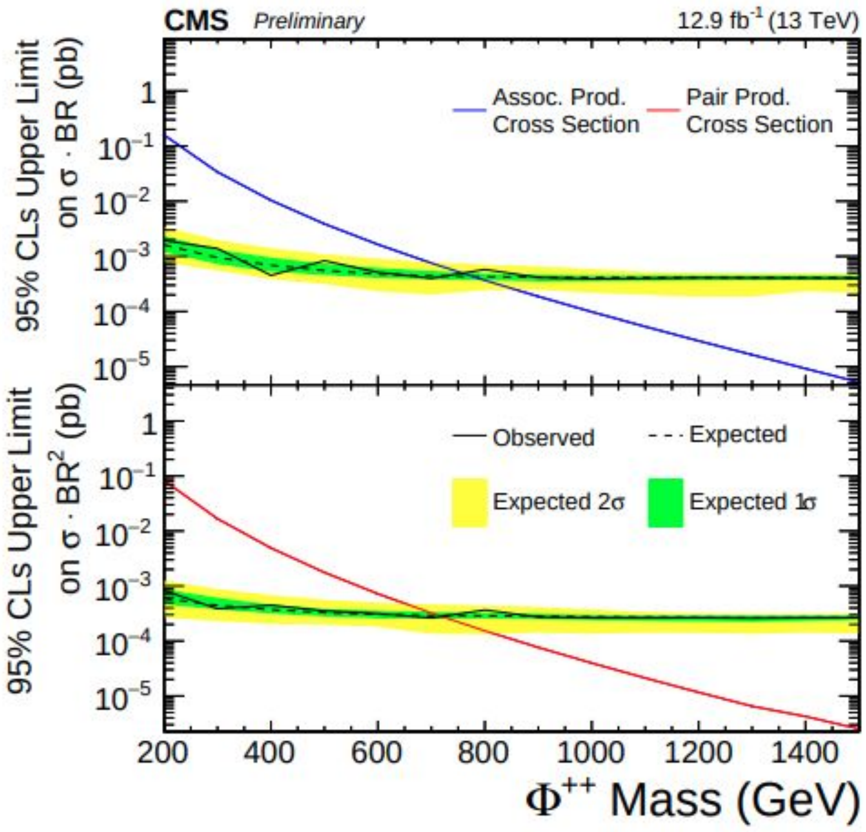
- **Plan** to use `HybridNew`
  - ↪ WIP : `AsymptoticLimits`



Limits vs past analysis

HIG-16-036-pas



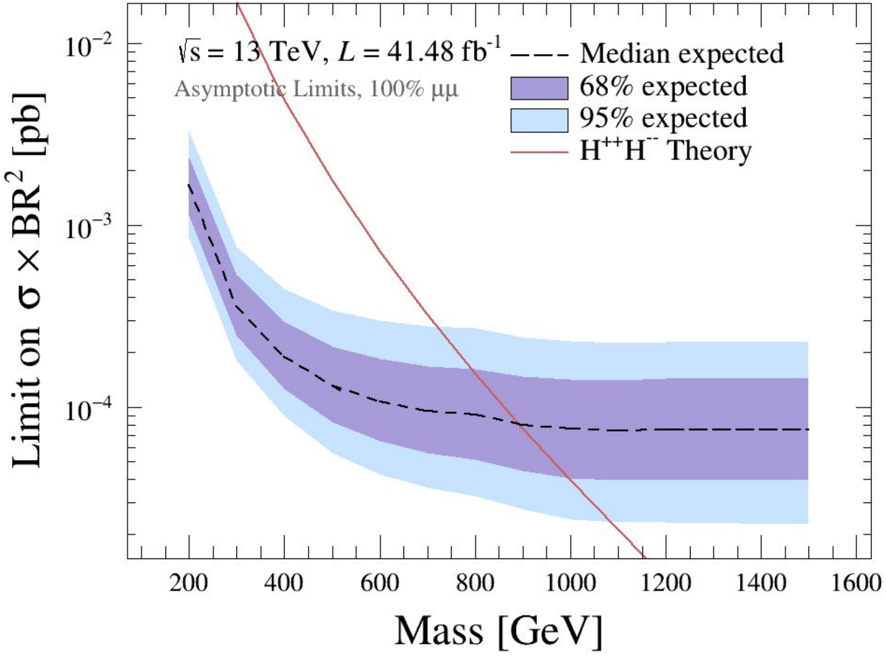


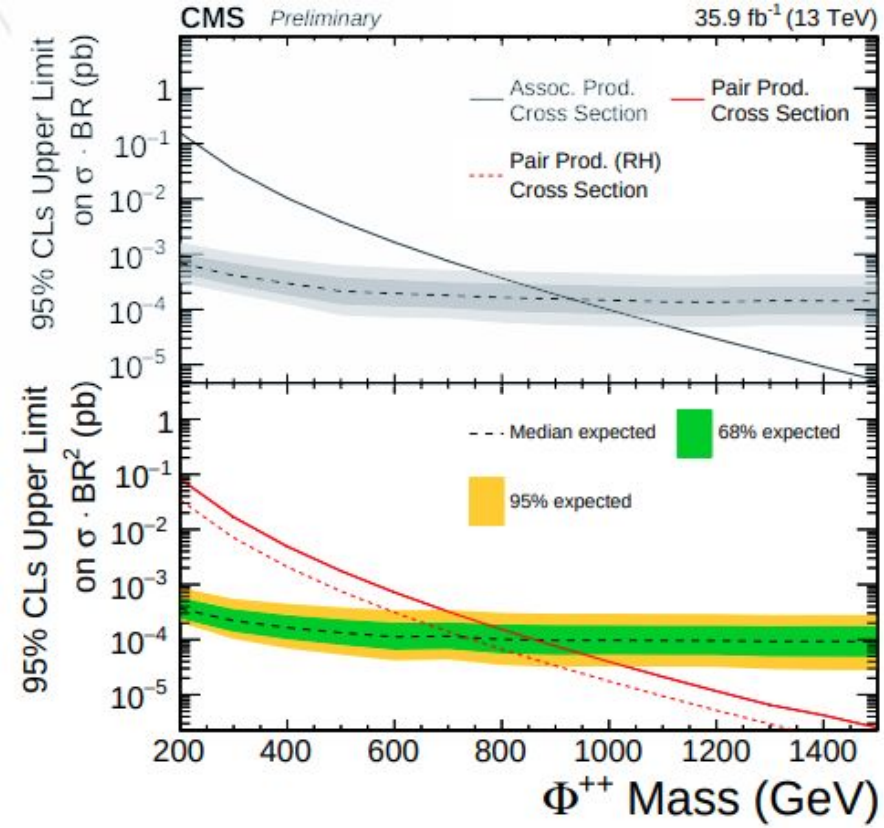
(a) 100% $\mu\mu$

Limits vs past analysis

AN2017_100

- **Similar results** to 35.9 fb $^{-1}$ limits from analysis note draft

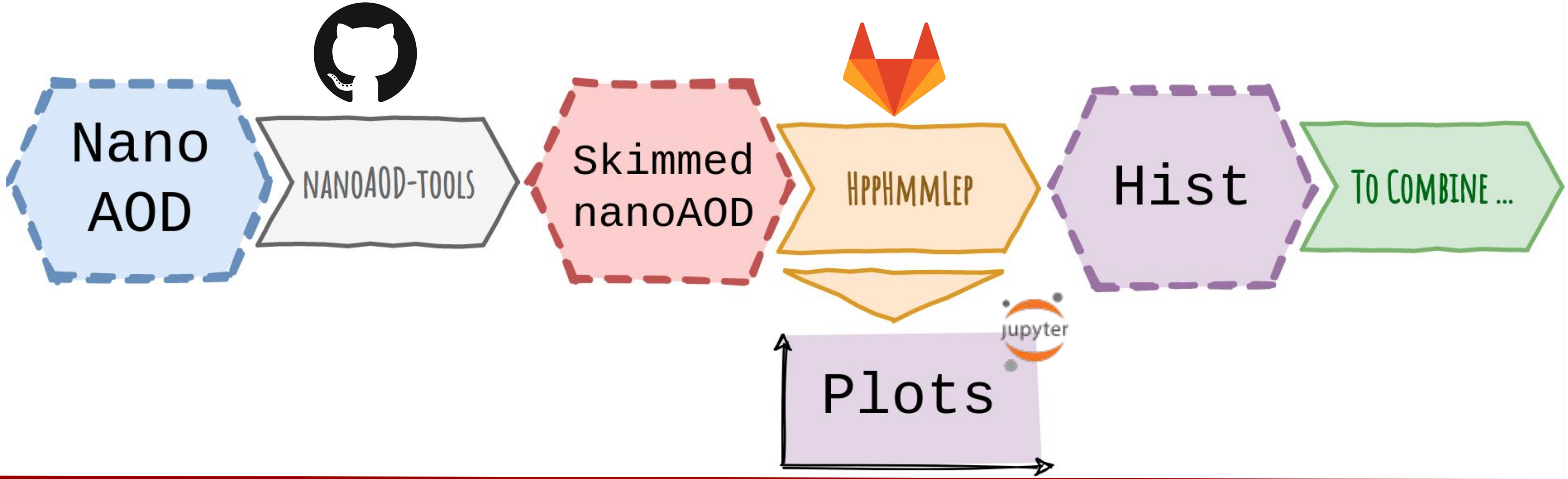




(e) 100% $\mu\mu$

Analysis framework

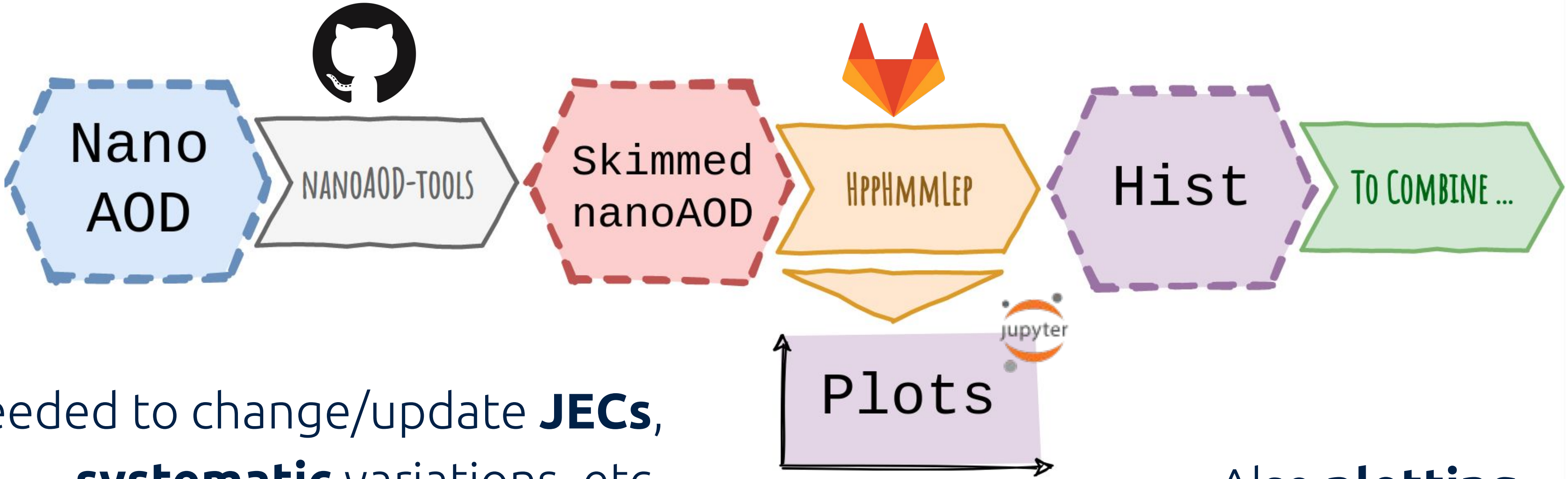
- Requirements: **Git**Lab/Hub , access to `/cvmfs`
- Mainly **pyroot** + ROOT::**RDataFrame**
  - ➳ + python/ bash scripts for automatization



Status - software

- **Software framework**

Object & Event **Selection**, weighting, etc.



Needed to change/update **JECs**, **systematic** variations, etc.
+ some **initial cuts**

Also **plotting**

HppHmmLep Package

HppHmmLep

- eventSelection.py
  - ↳ **Main** analysis **script** written in **python**
  - ↳ `ROOT::RDataFrame` and `ROOT::VecOps::RVec` for event and object selection
    - → Efficient, readable code
    - → Multi-thread friendly(`ROOT.EnableImplicitMT(1)`)
  - ↳ Easy **configuration** and **pipeline integration**

Next Steps - checklist

- **Next** steps:
  - ➳ Run on more **MC bkg** (DY, WZ) samples ✓
  - ➳ **Produce** more **signal** mass points ✓
  - ➳ **Synchronize** SW Frameworks with τ analysis ✓
  - ➳ Finalize **MC background** estimate (UL2017)
  - ➳ **First pass of** statistical setup in **Combine** ✓
  - ➳ **Explore** new **variables**, **cuts** on MC
  - ➳ Full **Run II**, **3-lep** channel, optimization …

Other Steps - checklist

- **Other** steps:
  - ↳ Finalize **trigger** strategy + check **efficiency** ☐
  - ↳ Finalize **selection** and **optimization** ☐
  - ↳ Apply all **scale factors** ☐
  - ↳ **Final background** estimation **CR+VR** and plots ☐
  - ↳ **Unblind** small %tage of **SR** ☐
  - ↳ **Run** analysis on **2016** and **2018** ☐
  - ↳ **Finalize statistical** analysis + **Combine** setup ☐