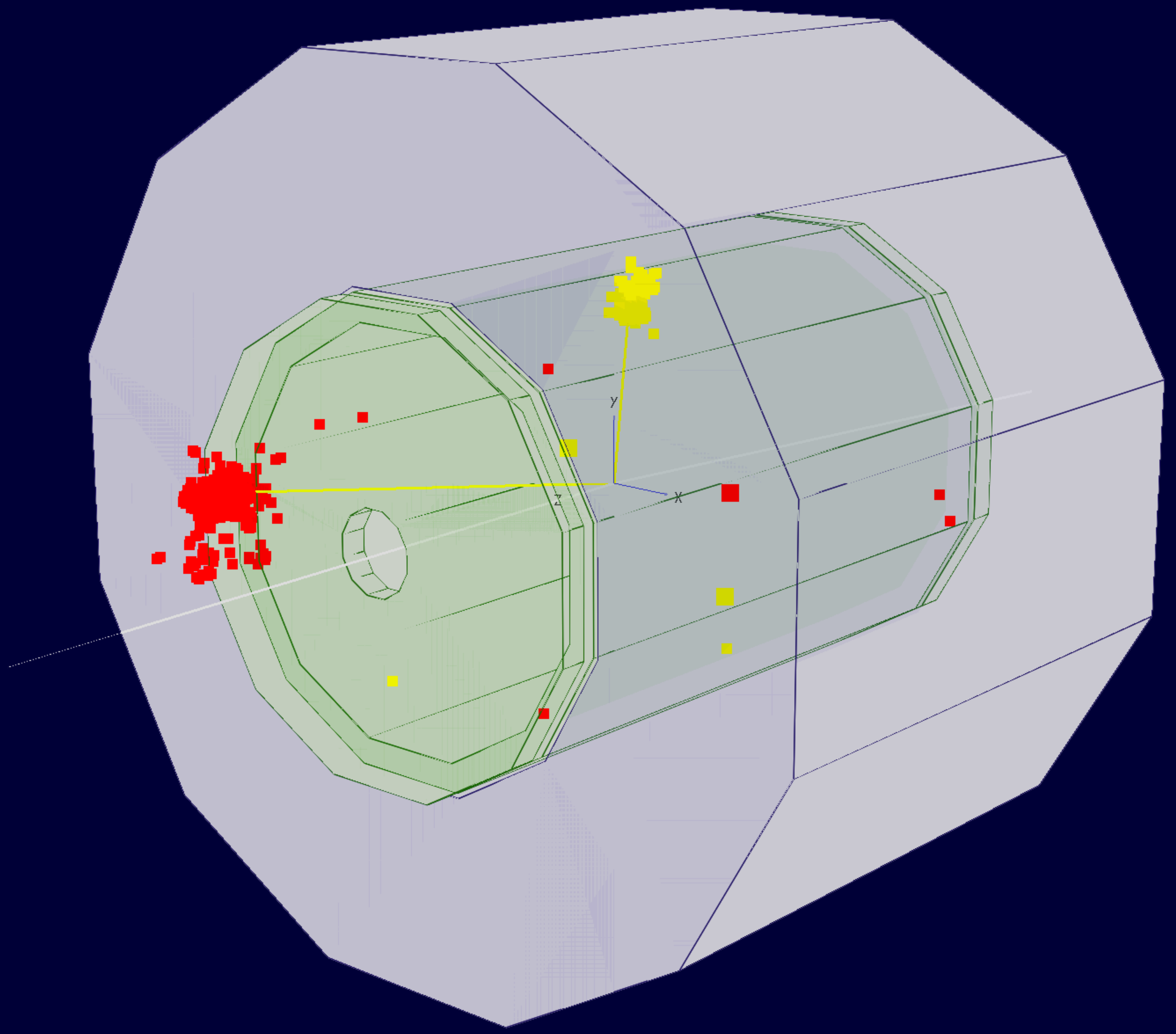
Muon Collider Joint Tracker and Calorimeter Meeting



$H \to \gamma\gamma$ reconstruction

DAVIDE ZULIANI, 13/09/2022

State of the art

- Higgs physics is a hot topic for the muon collider
- So far, a lot of channels have been analysed, with full simulation and BIB contribution ($H \to b\bar{b}/c\bar{c}$, $H \to \mu\mu$, $H \to WW$, $H \to ZZ$, HH)
- To complete the picture, it might be interesting to study the remaining decays:
  - $H \to \gamma\gamma$ **(this talk)**
  - $H \to Z\gamma$ (doable, several channels)
  - $H \to \tau\tau$ and $t\bar{t}H$ (lots of final objects…)

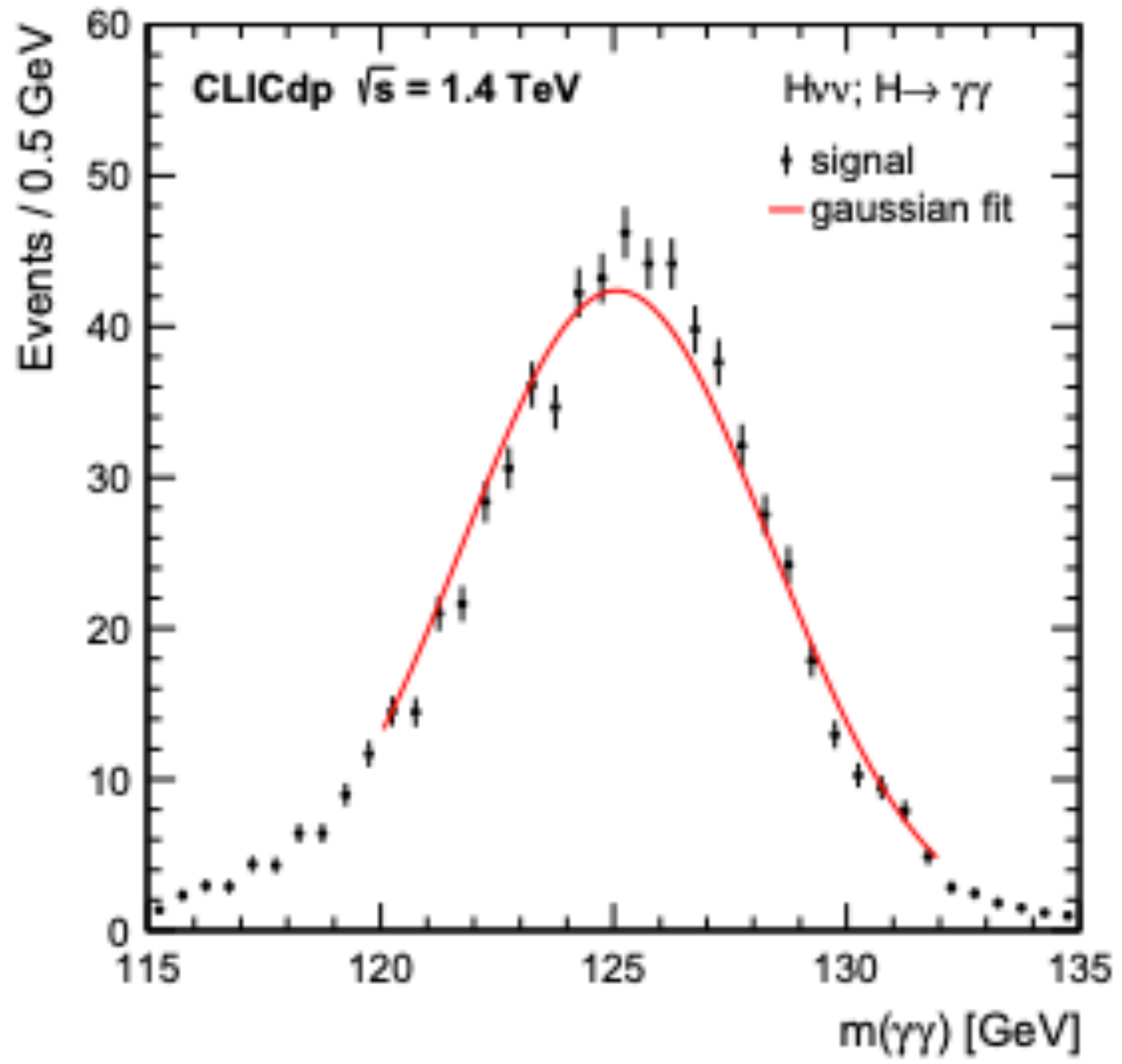
- Disclaimer 1: photon reconstruction is based on studies done by Alessandro and Massimo, so well before what Karol presented today
- Disclaimer 2: results here are preliminary and yet without BIB (work in progress)

State of the art — CLIC strategy

- Starting point for this analysis: CLIC paper on Higgs physics
- The analysis is quite standard:
  - Select **two high p_T photons**
    - $E_\gamma > 15$ GeV and $p_T > 10$ GeV
  - Additional **cuts** on **invariant mass** and **photon isolation**
  - Classify signal and background events with **BDT**
  - Estimation of the statistical uncertainty $\Delta\sigma/\sigma$

$$\frac{\Delta[\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)]}{\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)} = 15\,\%$$

Process	σ/fb	ε_{presel}	ε_{BDT}	N_{BDT}
$e^+e^- \to H\nu_e\bar{\nu}_e; H \to \gamma\gamma$	0.56	85 %	47 %	337
$e^+e^- \to \nu\bar{\nu}\gamma$	29.5	34 %	7.3 %	1110
$e^+e^- \to \nu\bar{\nu}\gamma\gamma$	17.3	31 %	8.6 %	688
$e^+e^- \to \gamma\gamma$	27.2	20 %	0.68 %	55
$e^+e^- \to e^+e^-\gamma$	289	9.2 %	0.66 %	265
$e^+e^- \to e^+e^-\gamma\gamma$	12.6	5.2 %	0.2 %	2
$e^+e^- \to q\bar{q}\gamma$	67.0	0.8 %	0.0 %	0
$e^+e^- \to q\bar{q}\gamma\gamma$	16.6	1.4 %	0.57 %	2



Signal and background preselection

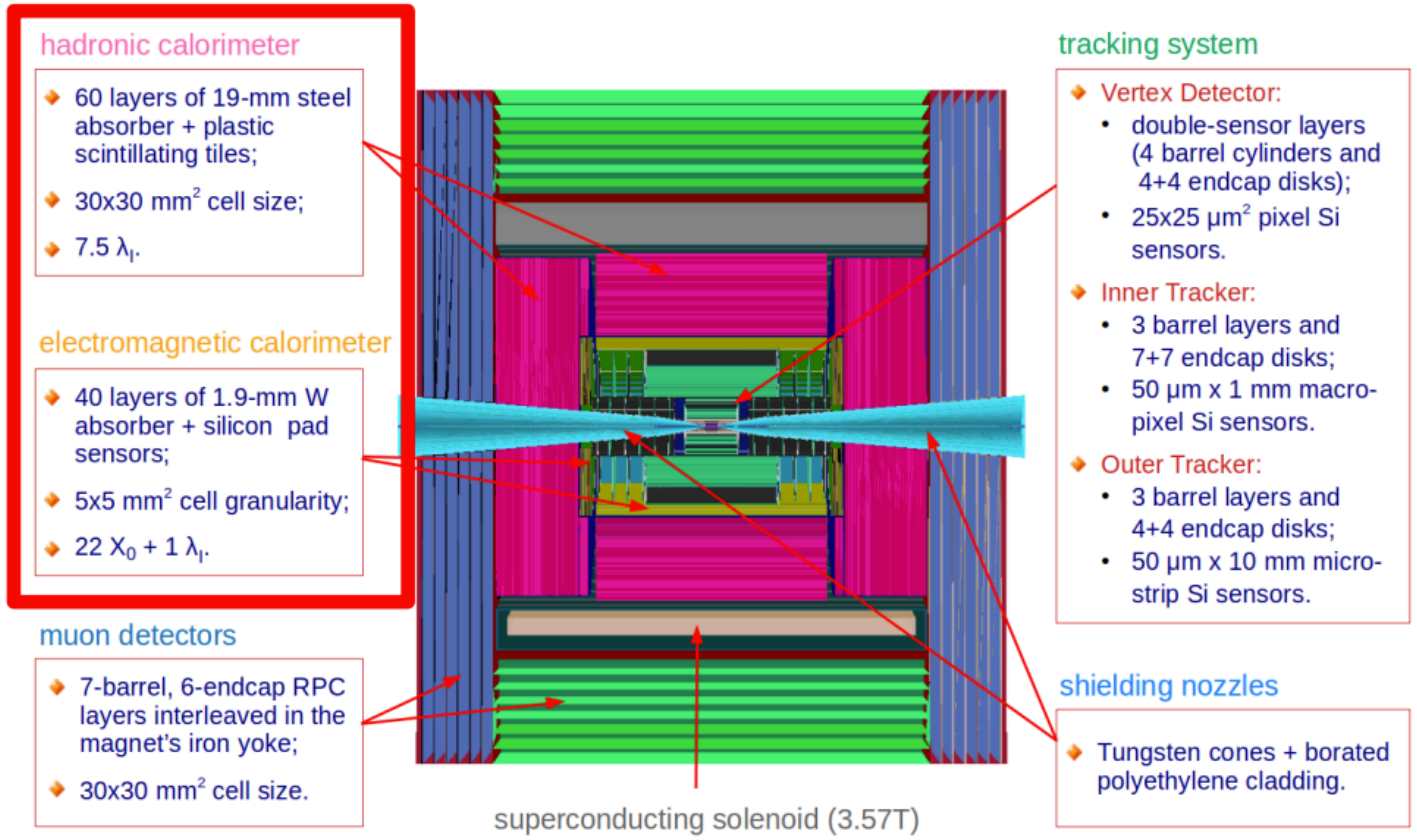
- We expect the same types of backgrounds as CLIC
- Signal and background contribution have been computed with MADGRAPH+PYTHIA
- Events have been generated with the following generation cuts:
  - $p_T(\gamma, l^{\pm}) > 10$ GeV (increase generation eff.), $\eta(\gamma, l^{\pm}) < 2.436$ (avoid interaction with nozzles)

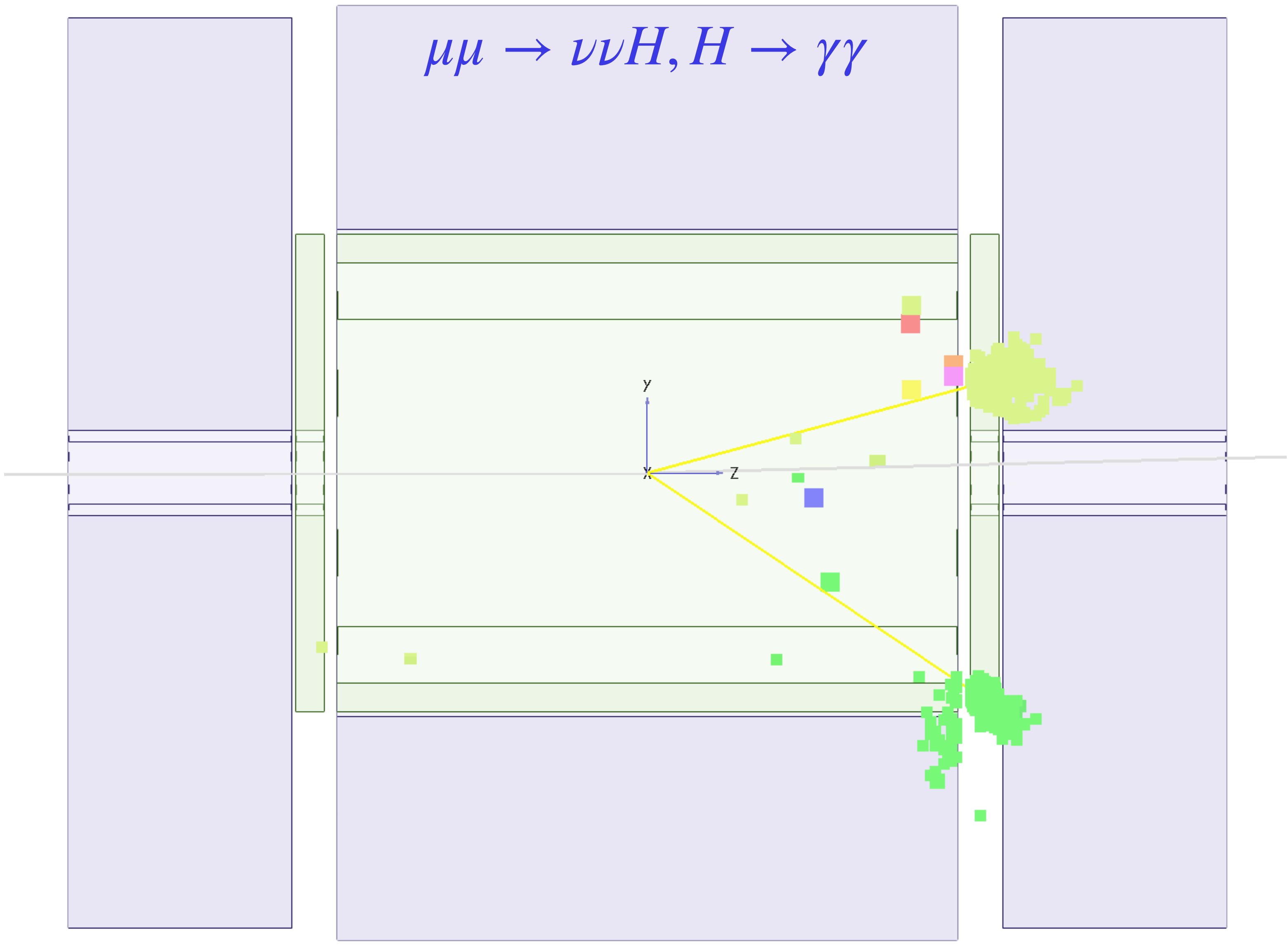
Process	σ (fb)	Expected events	Simulated events
$\mu\mu \to H\nu\nu, H \to \gamma\gamma$	0.5754 ± 0.0017	575	10000
$\mu\mu \to \nu\nu\gamma\gamma$	81.98 ± 0.27	81980	10000
$\mu\mu \to ll\gamma\gamma$	4.419 ± 0.016	4419	10000
$\mu\mu \to ll\gamma$	159.0 ± 0.6	159000	10000
$\mu\mu \to \gamma\gamma$	60.15 ± 0.03	60150	10000

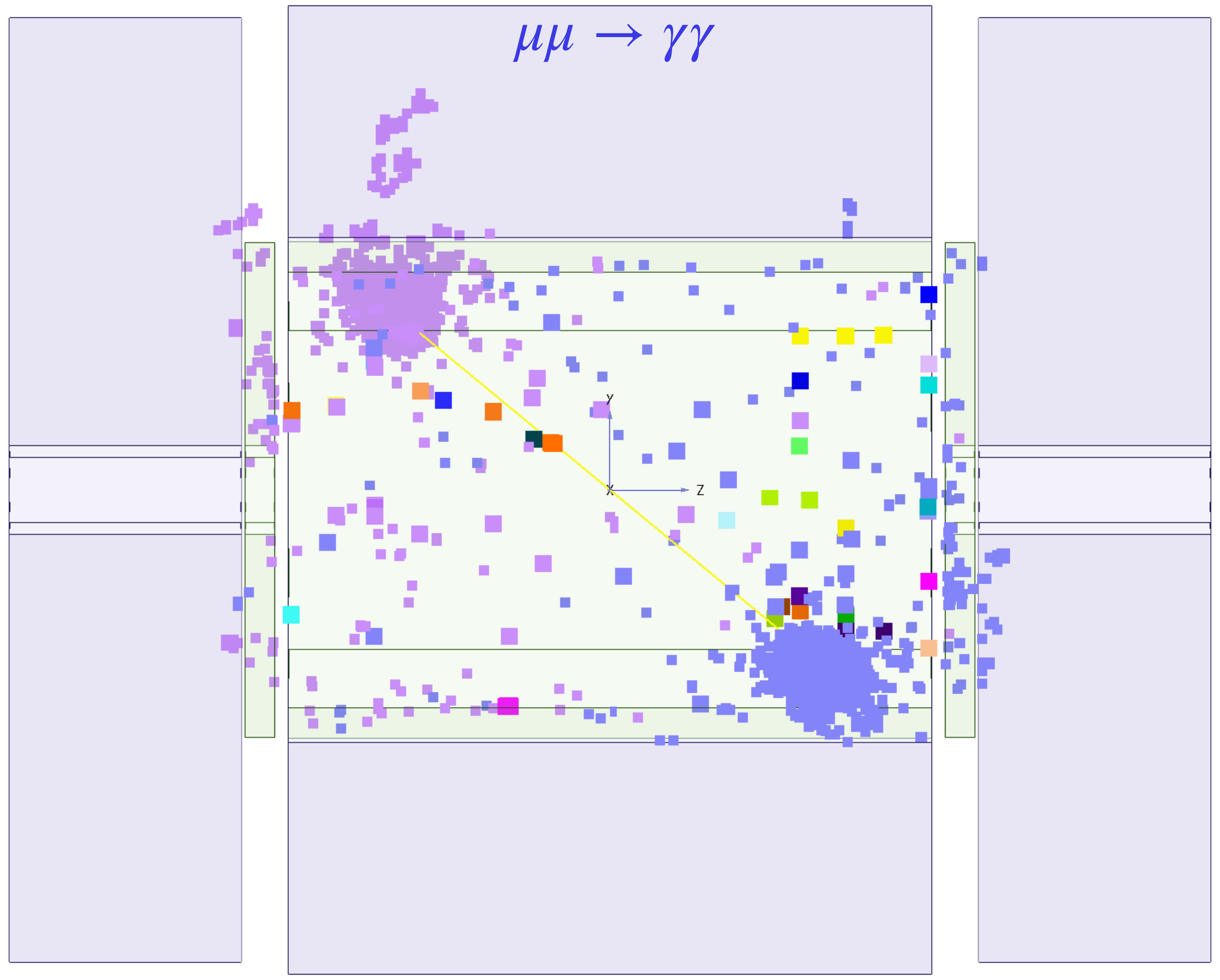
- $\mathscr{L} = 1\ \mathrm{ab}^{-1}$ and $\sqrt{s} = 3\ \mathrm{TeV}$
- $\mu\mu \to \nu\nu\gamma$ not considered (see later)
- $\mu\mu \to q\bar{q}\gamma\gamma$ not simulated (to do, but in principle not relevant)

Detector simulation

- Simulation uses the standard `MuColl_v1` geometry
- Standard parameters used so far in every detector simulation







Event reconstruction

- Track reconstruction:
  - Double-layer filter ON
  - ACTS tracking
- Calorimeter reconstruction:
  - ECAL and HCAL hit threshold $E_{\mathrm{thr}} = 2\ \mathrm{MeV}$
- Photon reconstruction and identification:
  - Default Pandora setting

```xml
<processor name="MyCKFTracking" type="ACTSSeededCKFTrackingProc">
  <!-- Path to material description -->
  <parameter name="MatFile" type="string">
    /opt/ilcsoft/muonc/ACTSTracking/v1.0.0/data/material-maps.json
  </parameter>
  <!-- Path to tracking geometry -->
  <parameter name="TGeoFile" type="string">
    /opt/ilcsoft/muonc/ACTSTracking/v1.0.0/data/MuColl_v1.root
  </parameter>
  <!-- Vol Layer, use -1 for all, ACTS numbers -->
  <parameter name="SeedingLayers" type="string">
    13 2
    13 6
    13 10
    13 14
    14  2
    14  6
    14 10
    14 14
    15  2
    15  6
    15 10
    15 14
  </parameter>
  <parameter name="SeedFinding_RMax" type="float">150</parameter>
  <parameter name="SeedFinding_DeltaRMin" type="float">5</parameter>
  <parameter name="SeedFinding_DeltaRMax" type="float">80</parameter>
  <parameter name="SeedFinding_CollisionRegion" type="float">1</parameter>
  <parameter name="SeedFinding_RadLengthPerSeed" type="float">0.1</parameter>
  <parameter name="SeedFinding_SigmaScattering" type="float">50</parameter>
  <parameter name="SeedFinding_MinPt" type="float">500</parameter>
  <!-- CKF Configuration -->
  <parameter name="CKF_Chi2CutOff" type="float">10</parameter>
  <parameter name="CKF_NumMeasurementsCutOff" type="int">1</parameter>
```

- Parameters used by Massimo with BIB, in principle no problems when applied without BIB

Event reconstruction

- Cuts on photons*:
  - $E_\gamma > 15$ GeV and $p_T > 10$ GeV
- Select two most energetic photons in each event
  - The "first" photon is required to have $p_T > 40$ GeV
- Reconstruct invariant mass and ask $m_{\gamma\gamma} > 40$ GeV

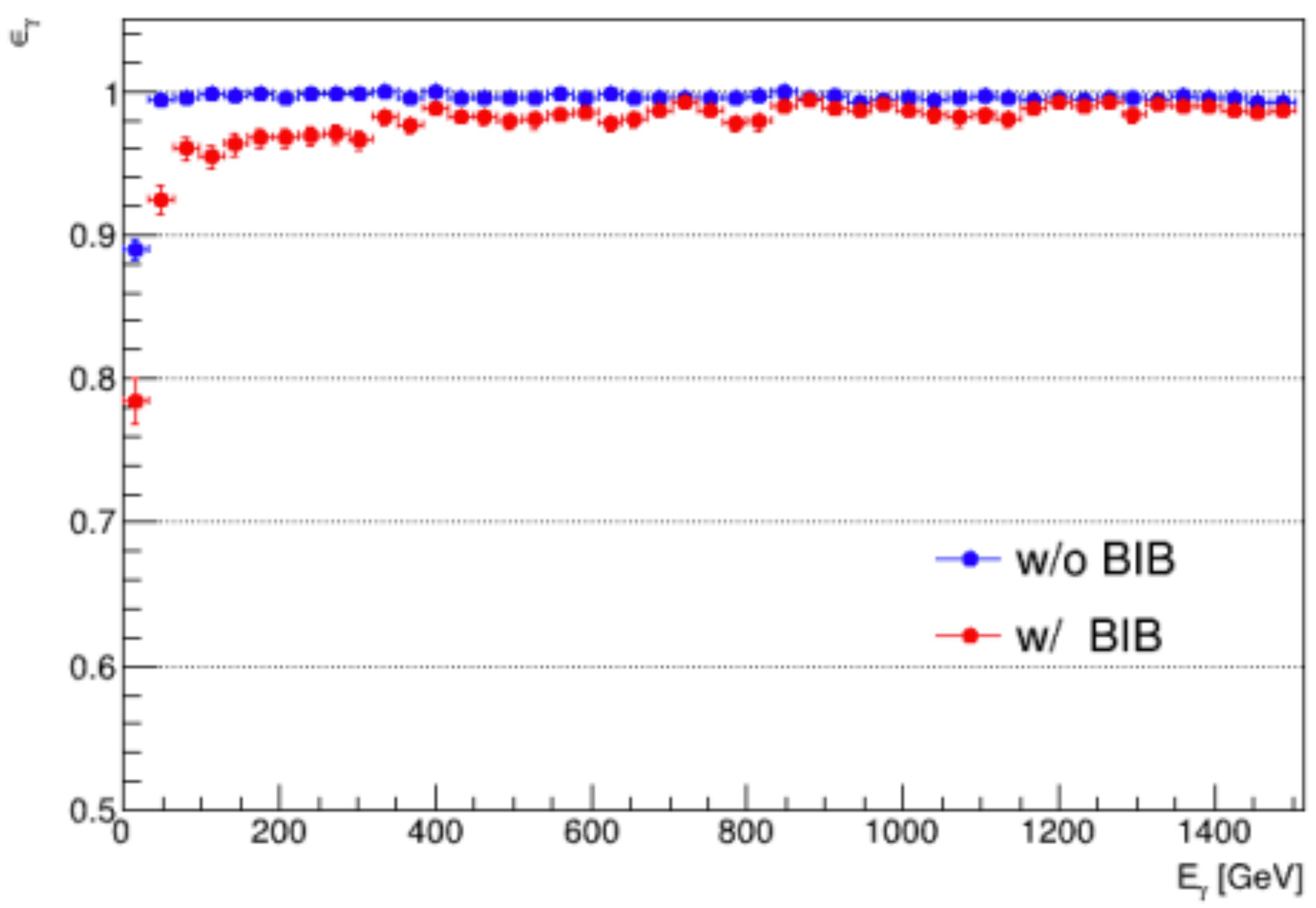
Process	$\varepsilon_{reco} = N_{reco}/N_{gen}$	Events
$\mu\mu \to H\nu\nu, H \to \gamma\gamma$	0,783	450
$\mu\mu \to \nu\nu\gamma\gamma$	0,368	30168
$\mu\mu \to ll\gamma\gamma$	0,609	2678
$\mu\mu \to ll\gamma$	0,029	4738
$\mu\mu \to \gamma\gamma$	0,996	59933

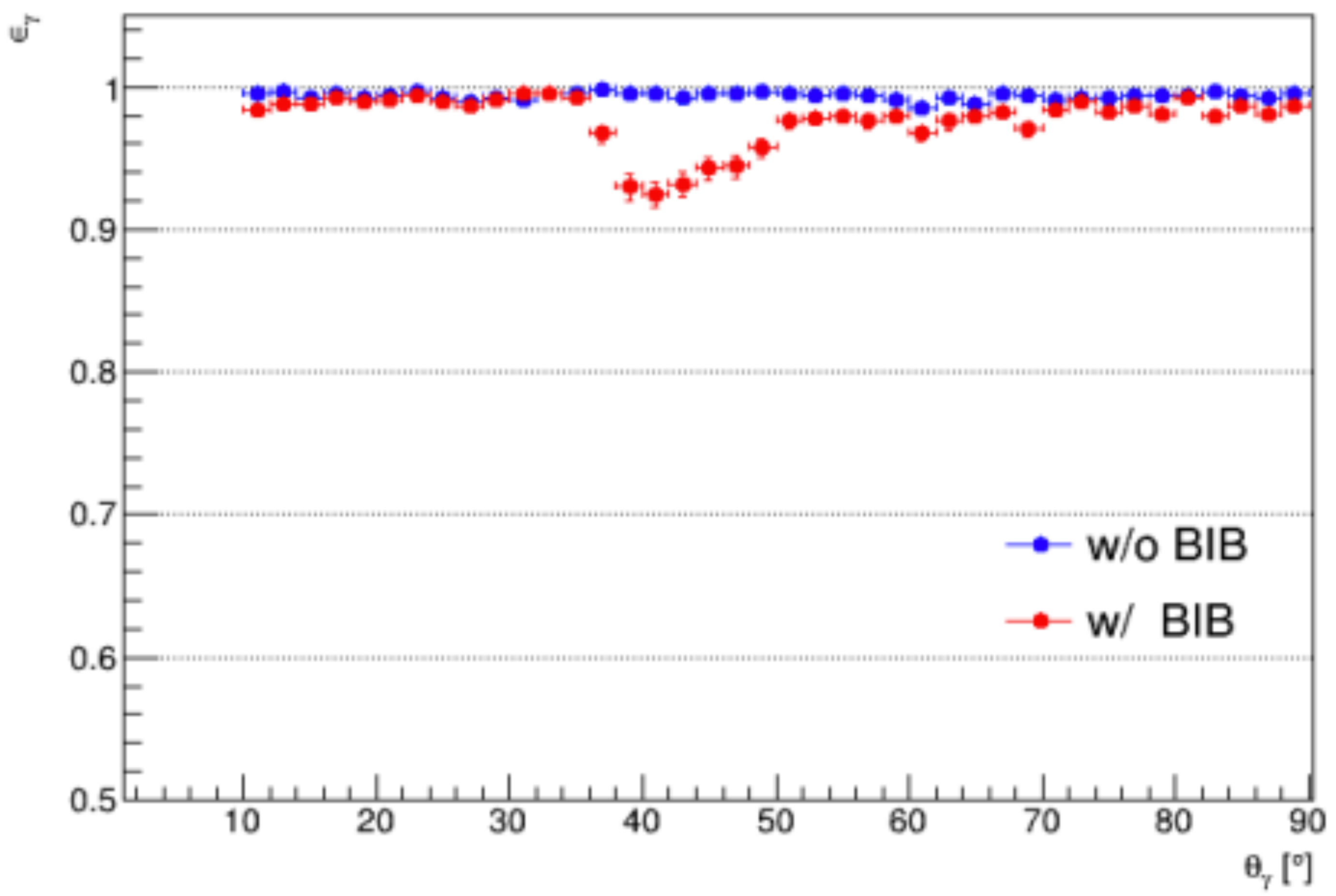
In principle one should find isolated clusters and identify them as photons

- *Disclaimer 1: photons are identified by Pandora feature `rctyp[irec]` (ok if no BIB)
- Disclaimer 2: so far no cuts on E_T^{miss}

Photon reconstruction

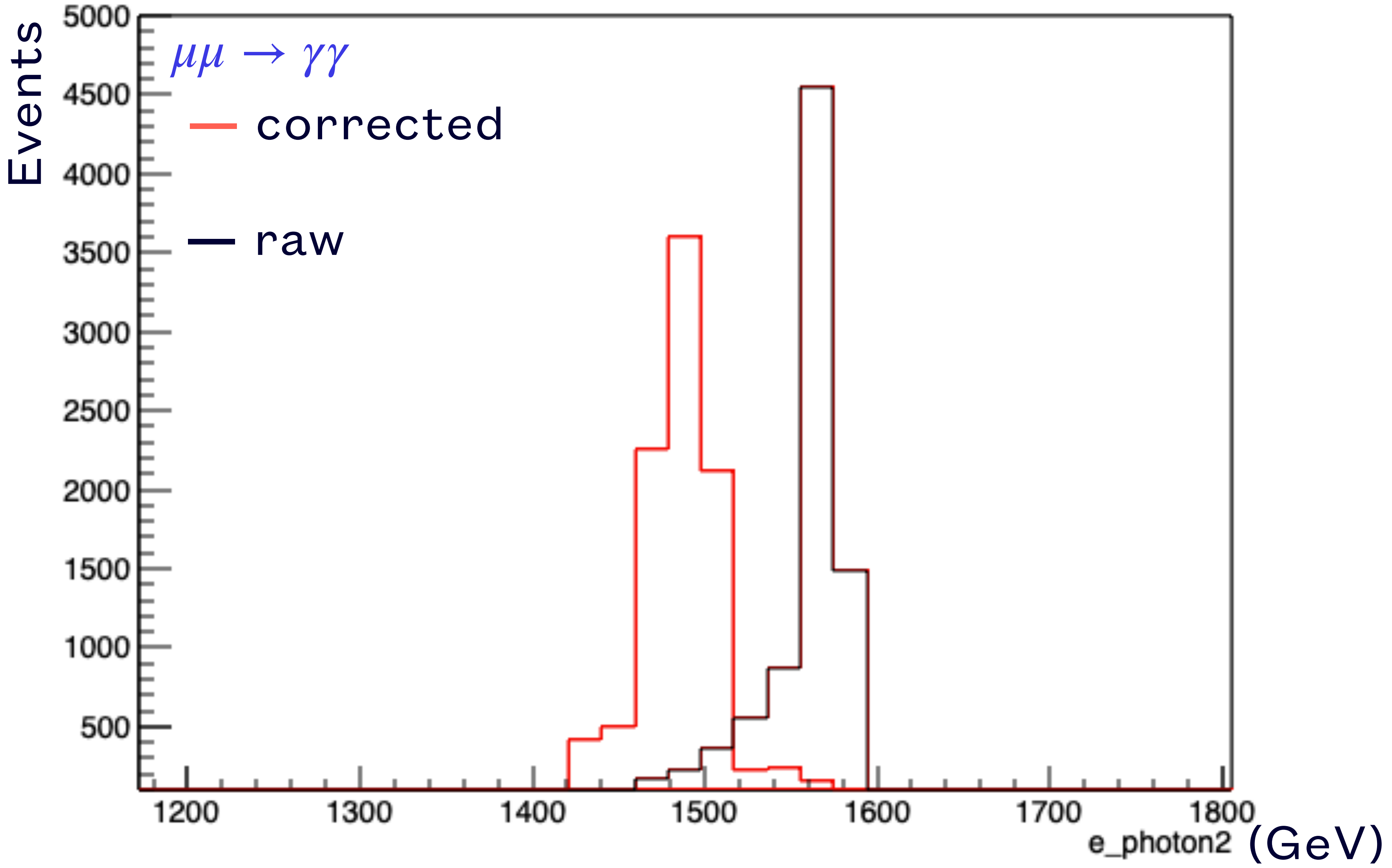
- Photon energy correction from previous studies by Alessandro and Massimo





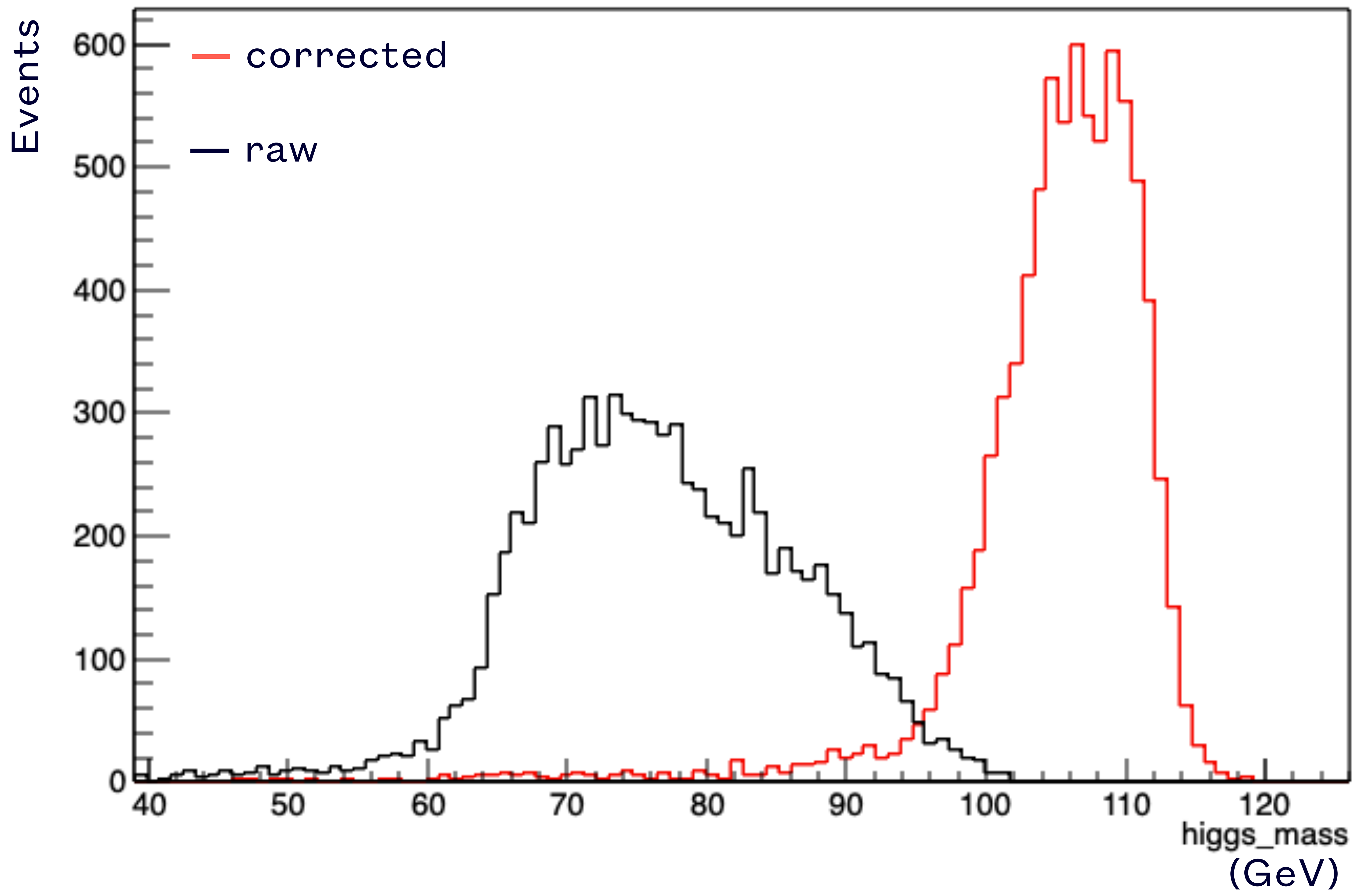
Correction is done as a function of E_γ and θ_γ

- "Tweaked" a bit in order to correct for energies taken into consideration
- Basically, add correction also for energies $E_\gamma > 1500$ GeV
- Definitely it can be improved



Photon reconstruction

- A quick look at $m_{\gamma\gamma}$ for $H \to \gamma\gamma$ shows that energy correction is working quite well



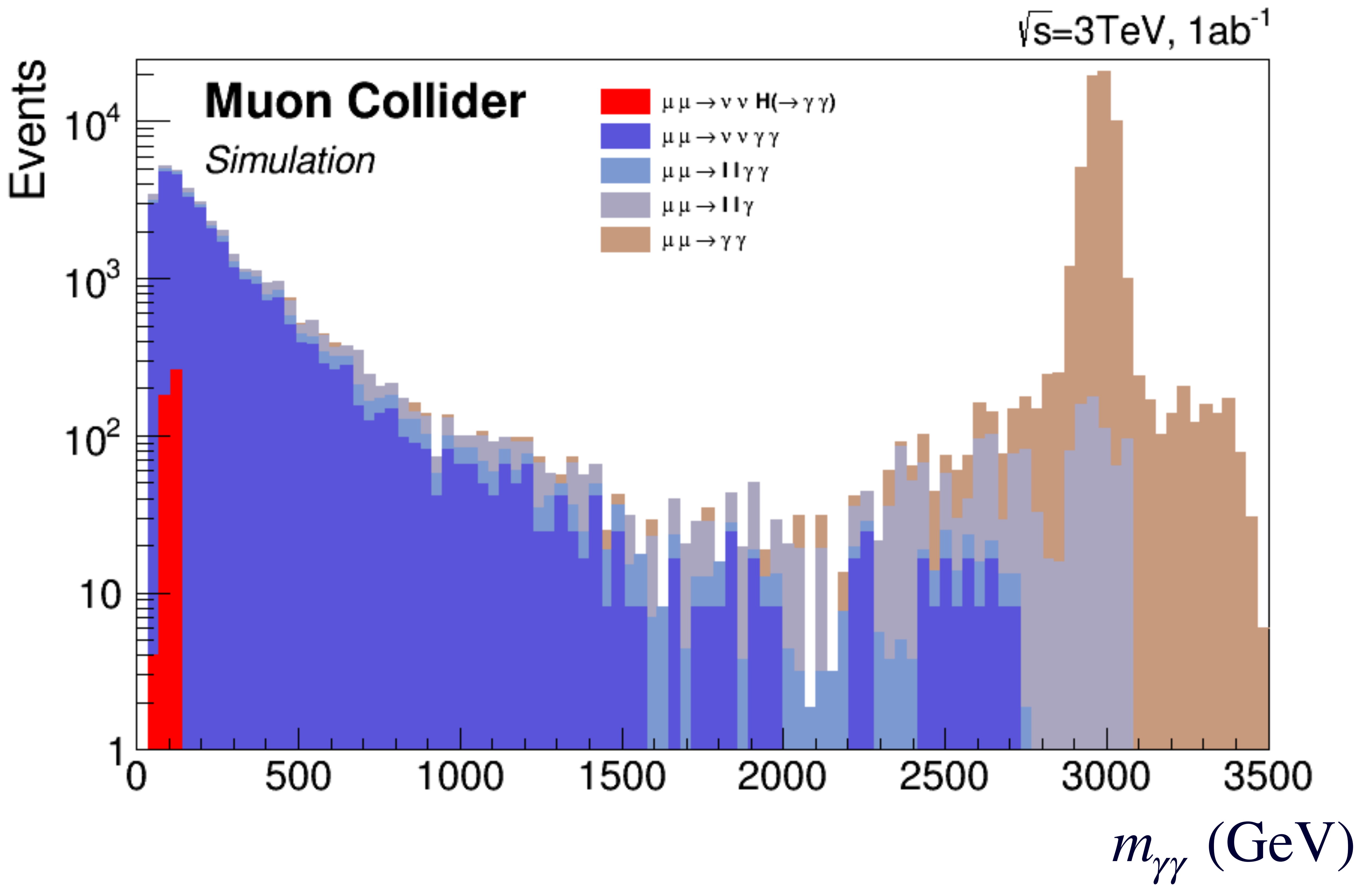
- Fitting the Higgs mass with a gaussian function gives:

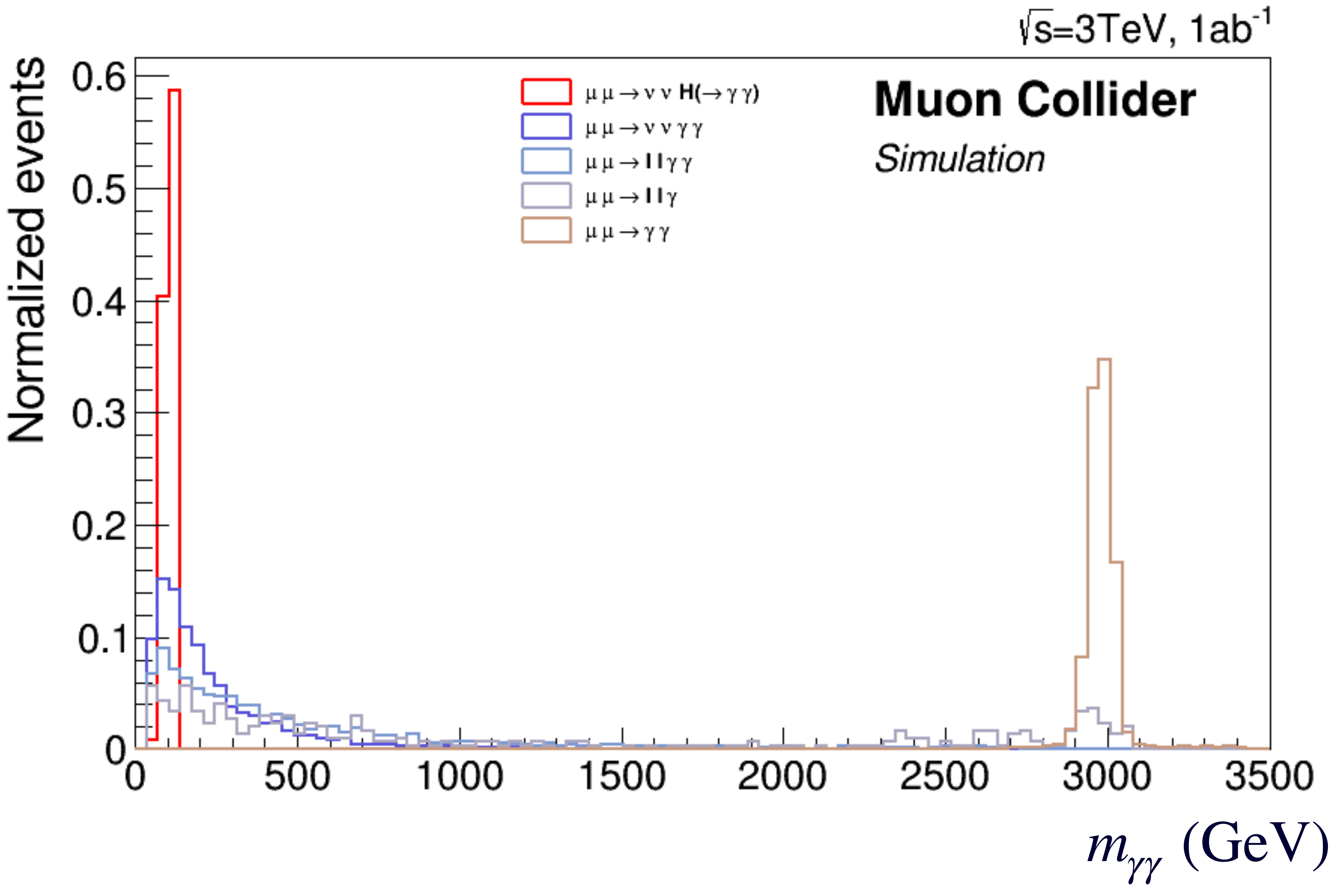
$$m_H = 105.93 \pm 0.06 \text{ GeV}$$

$$\sigma_H = 4.16 \pm 0.04 \text{ GeV}$$

- There is quite a shift in the invariant mass value, energy correction to be cross checked
- CLIC gets a mass resolution $\sigma = 3.3$ GeV

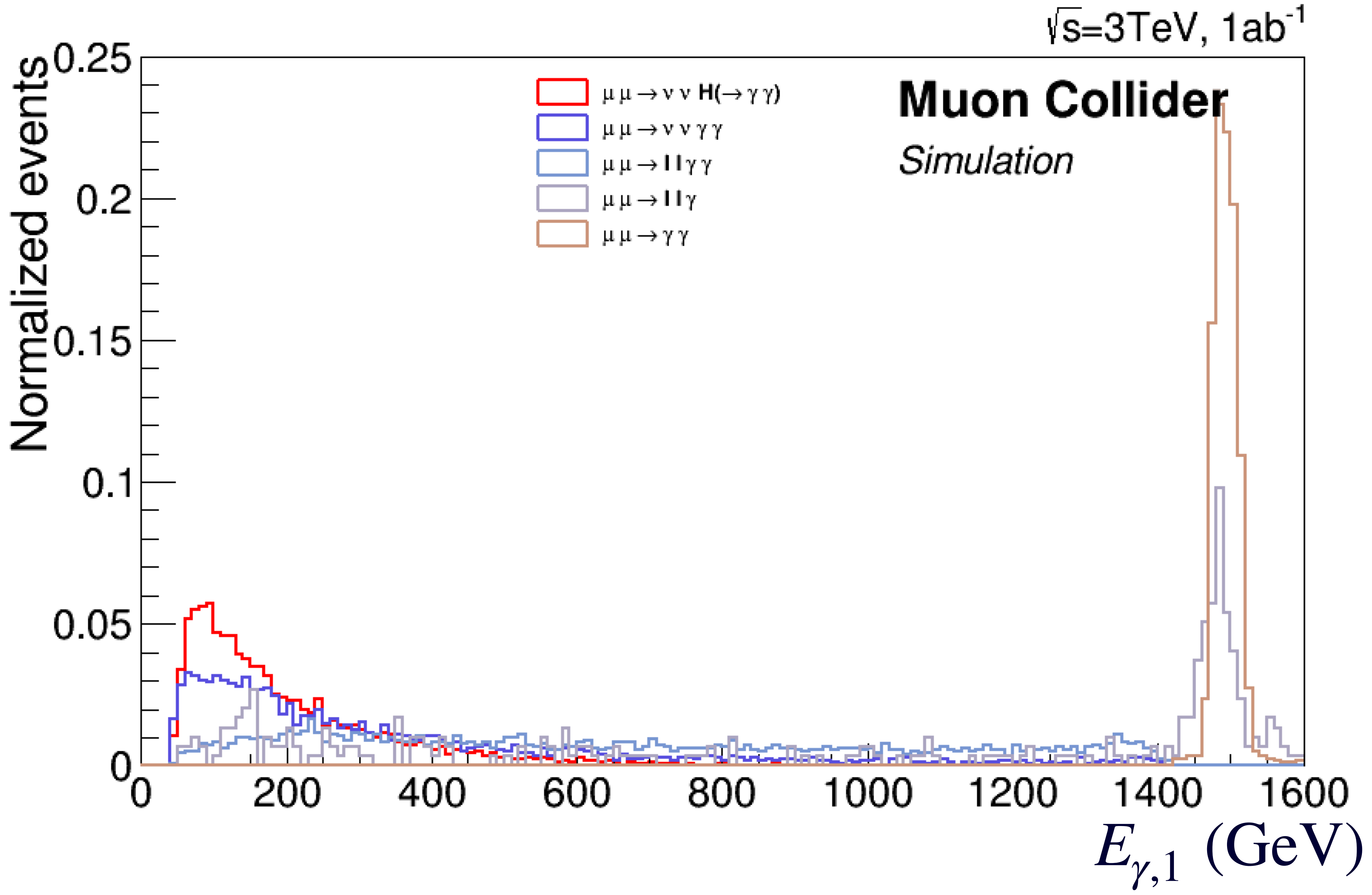
Some plots

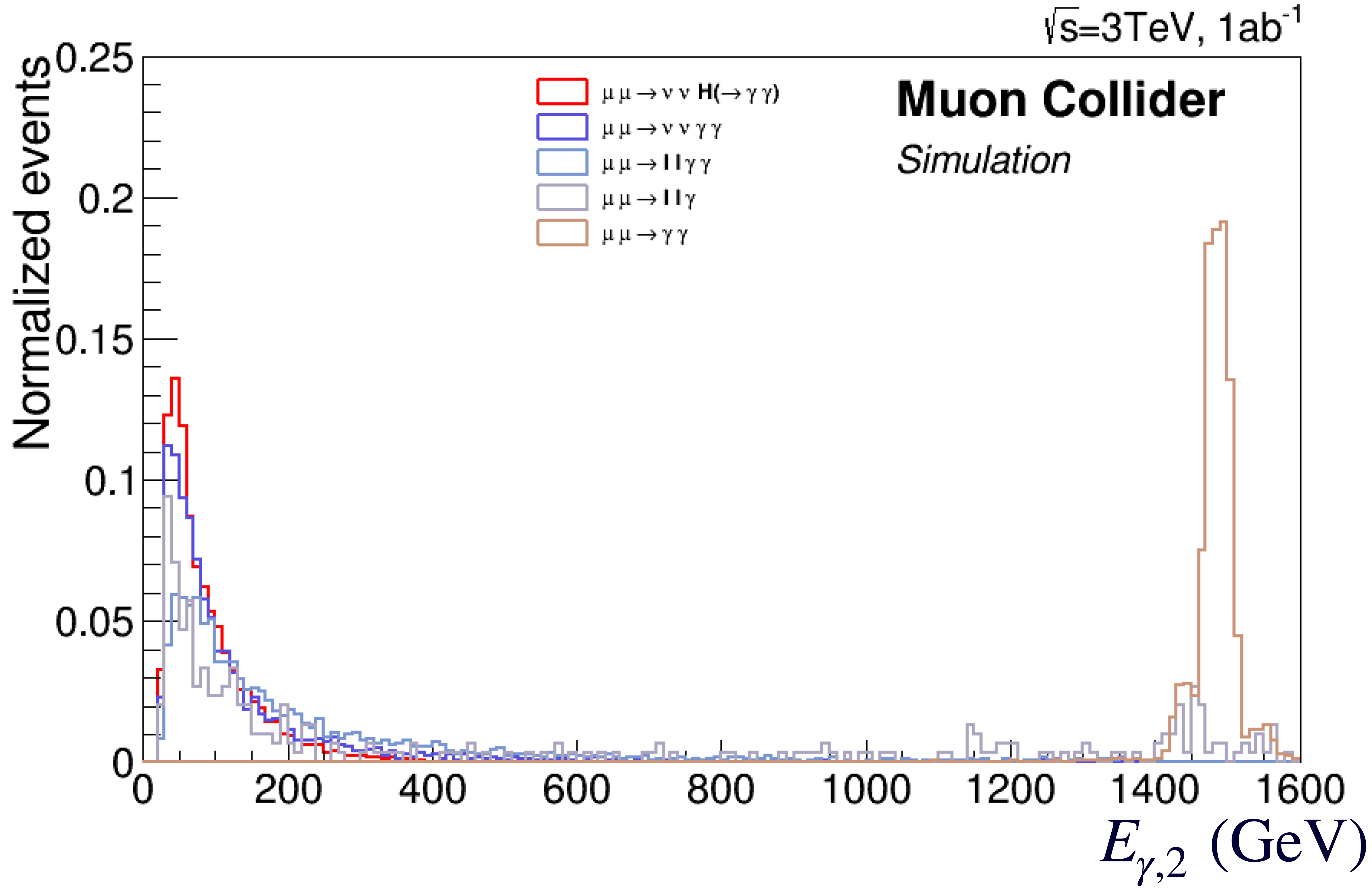




Invariant mass $m_{\gamma\gamma}$ weighted for luminosity (left) and normalised to 1 (right)

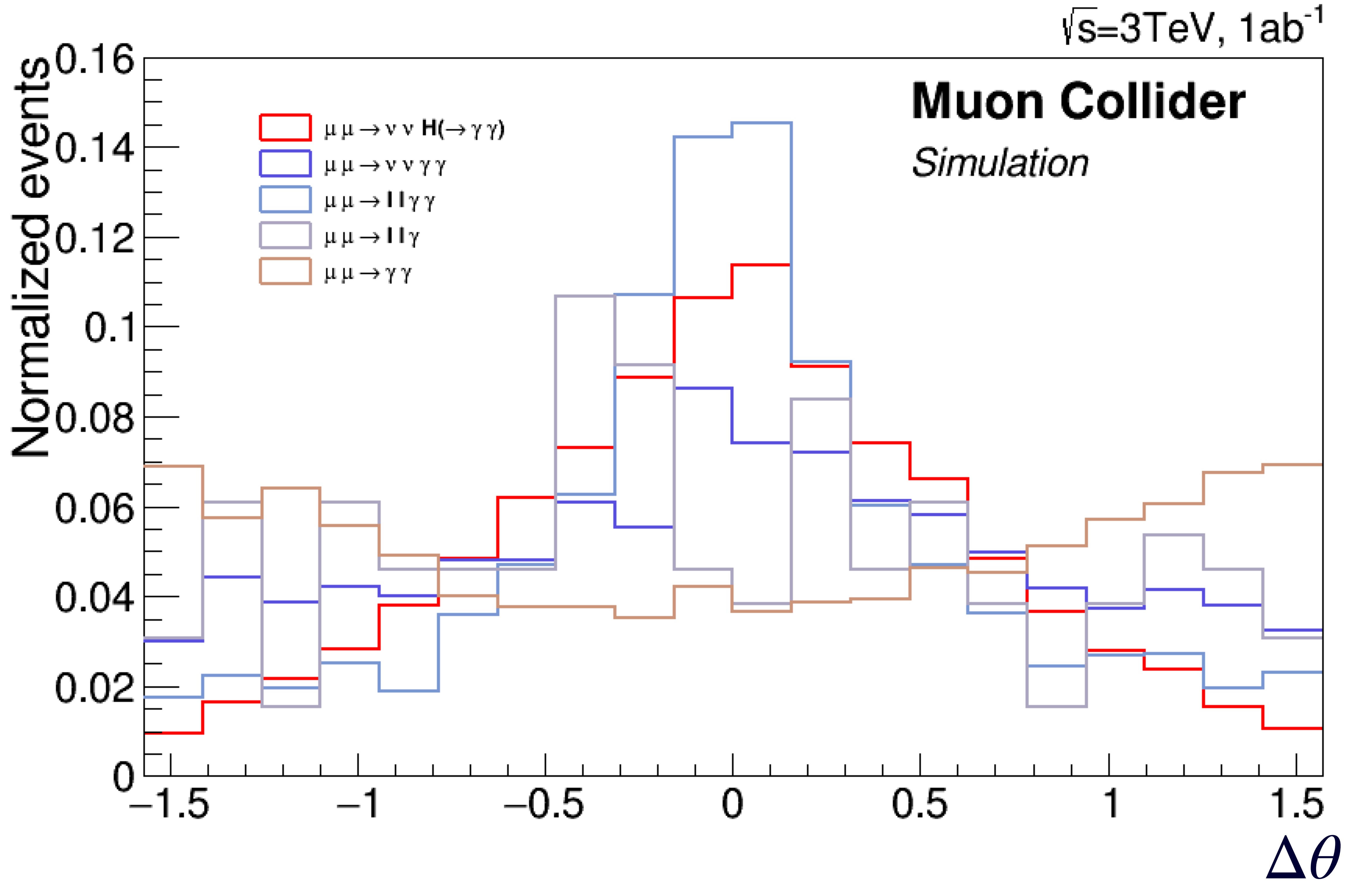
Some plots

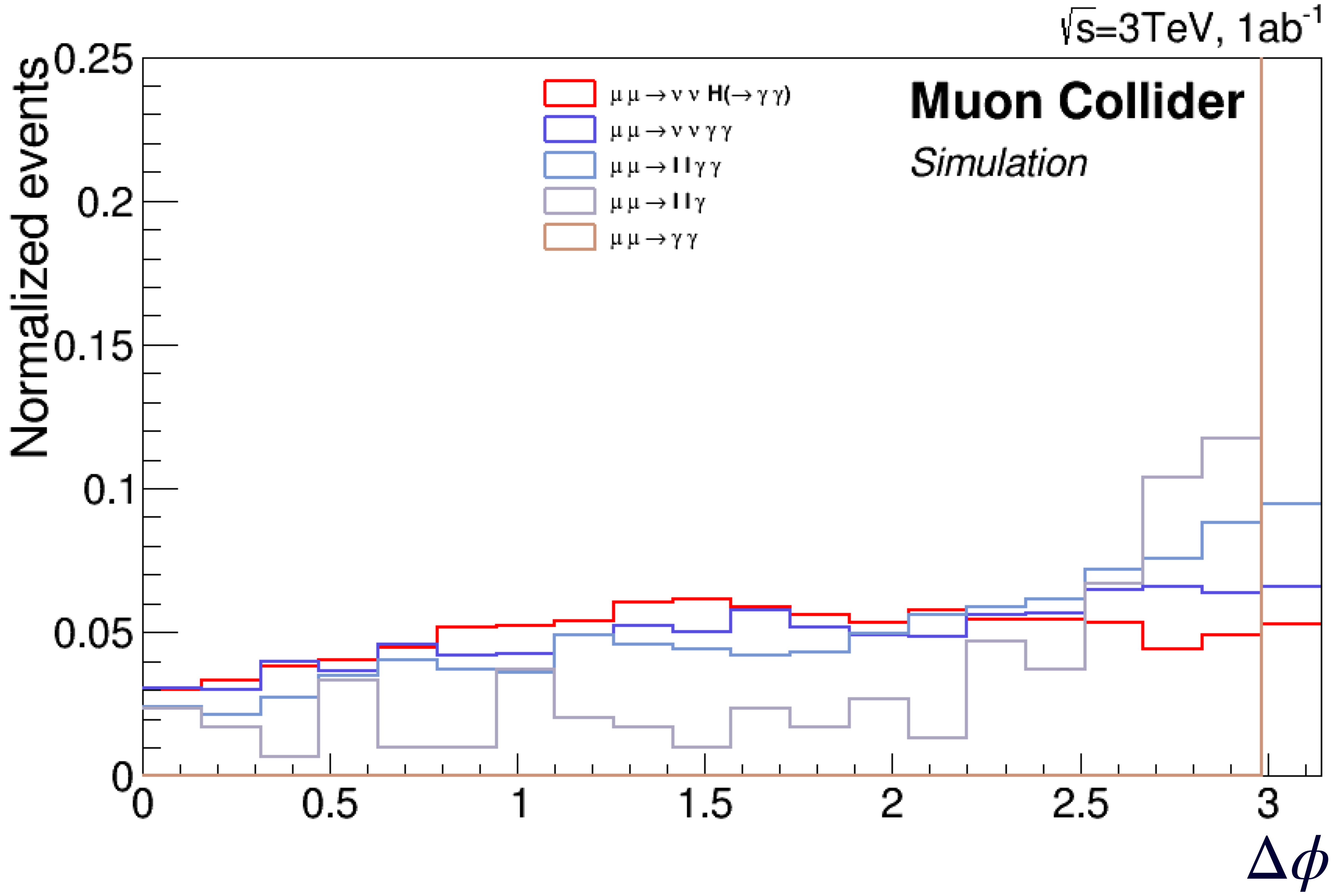




Energy of photon 1 (left) and photon 2 (right)

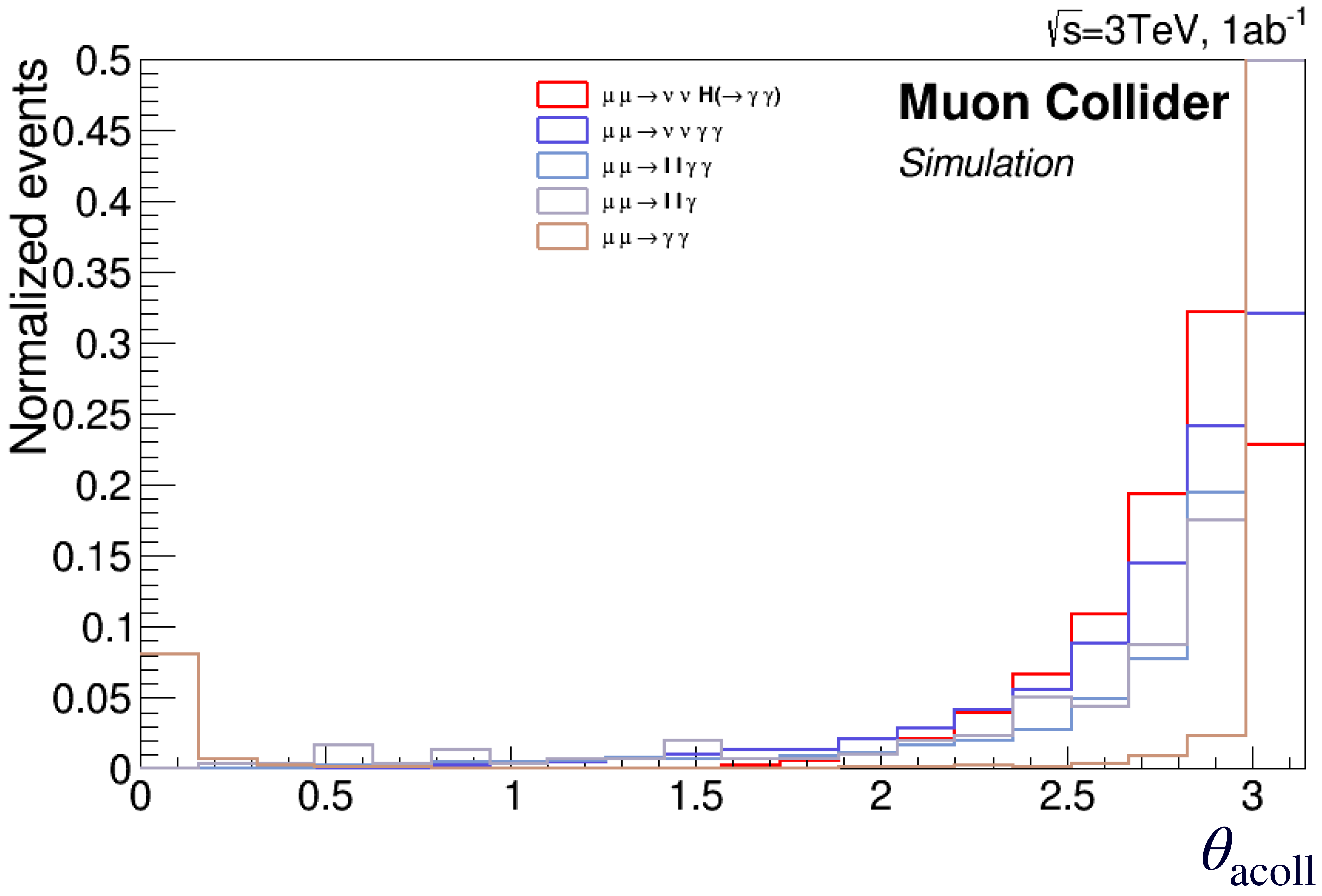
Some plots

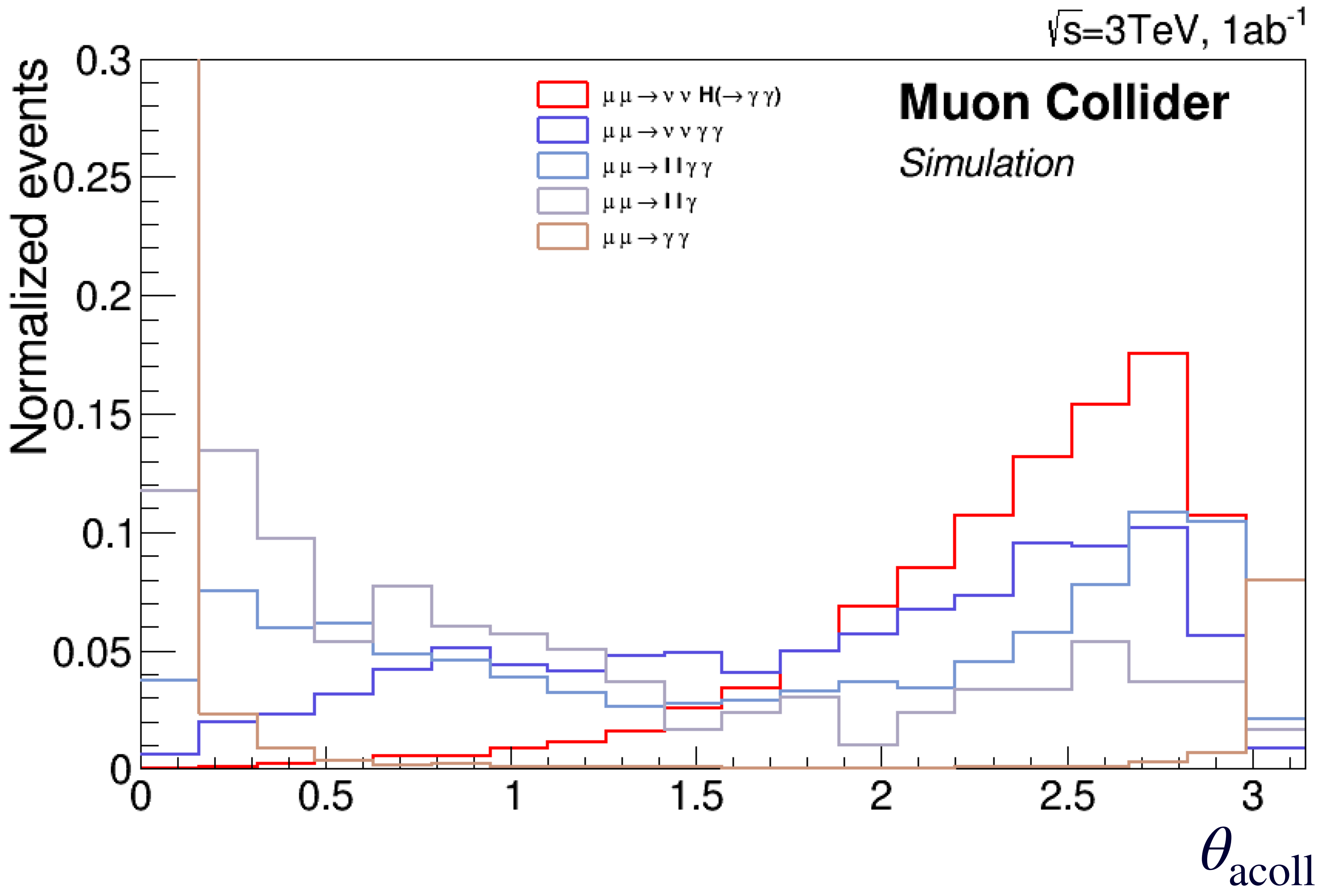




$\Delta\theta$ (left) and $\Delta\phi$ (right) between photons

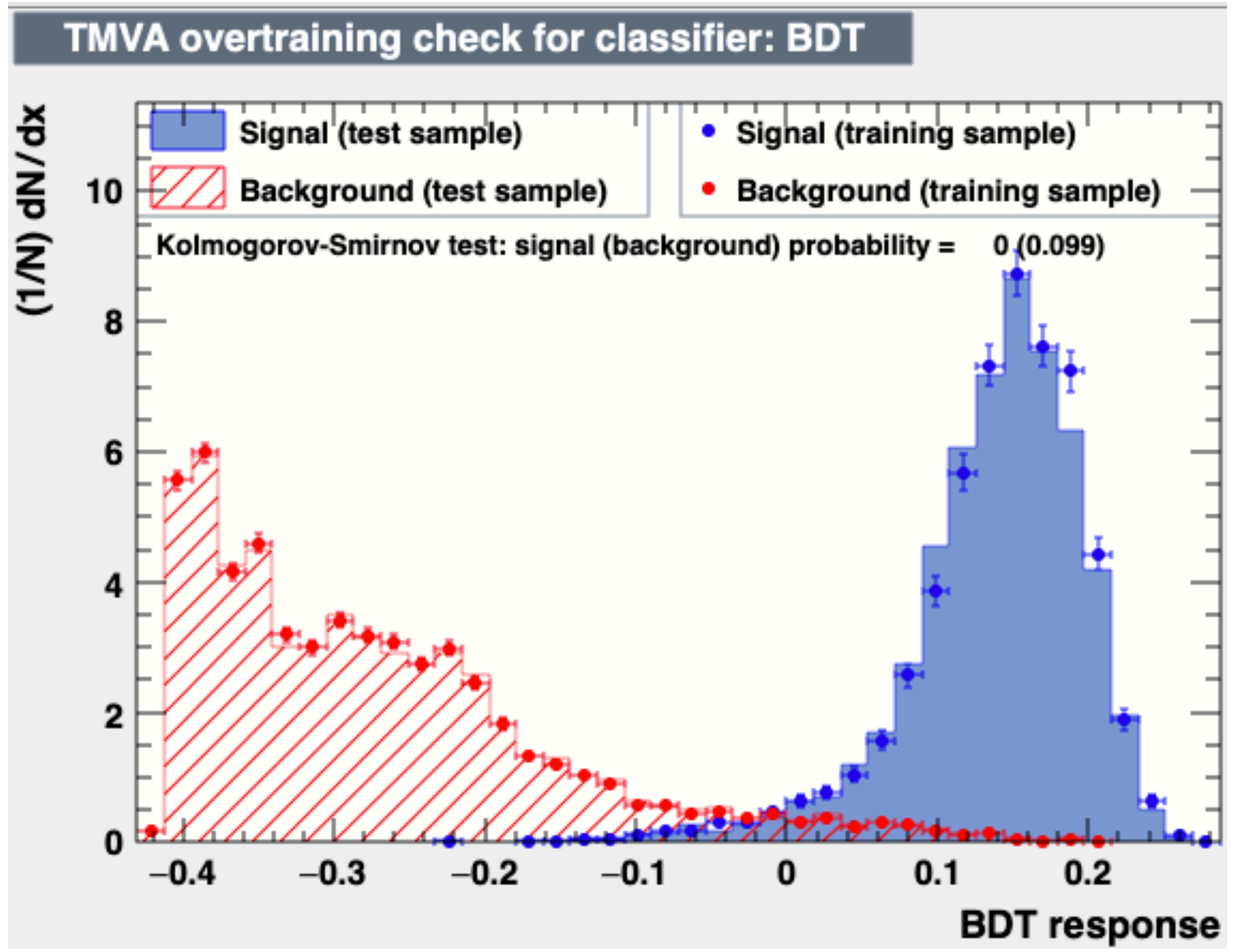
Some plots



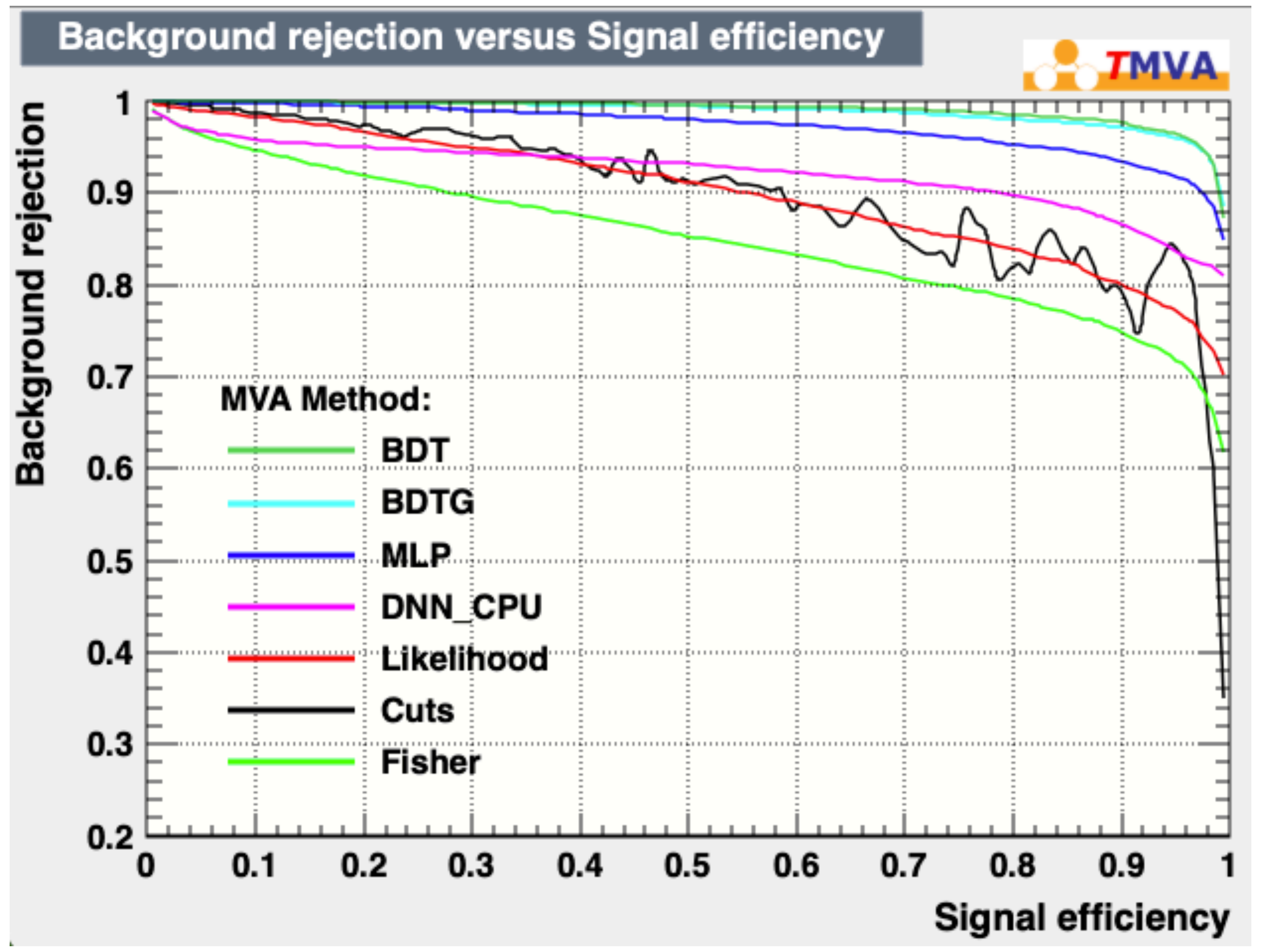


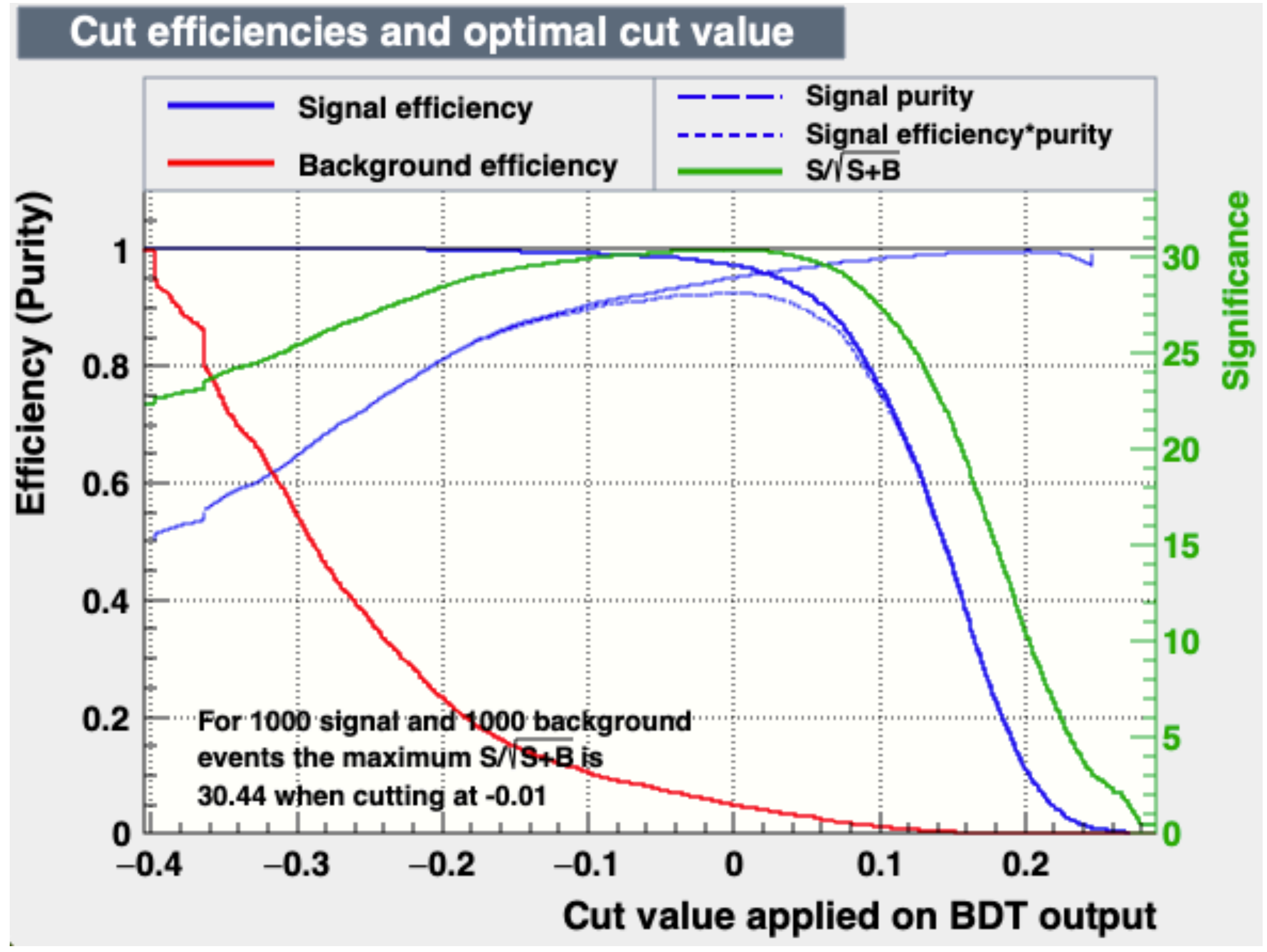
Acollinearity $\theta_{acoll} = \pi - \text{acos}\left(\frac{p_{1,x} \cdot p_{2,x} + p_{1,y} \cdot p_{2,y} + p_{1,z} \cdot p_{2,z}}{p_1 \cdot p_2}\right)$ between "Higgs" and photon 1 (left) and photon 2 (right)

BDT classification



- A BDT is used to perform signal vs. background separation
- The following variables have been used:
  - Invariant mass $m_{\gamma\gamma}$
  - Higgs' p_{T}
  - Photons' p_{T}
  - $\Delta\theta$ and $\Delta\phi$ between photons
  - Acollinearity between photons
  - Acollinearity between photon and Higgs

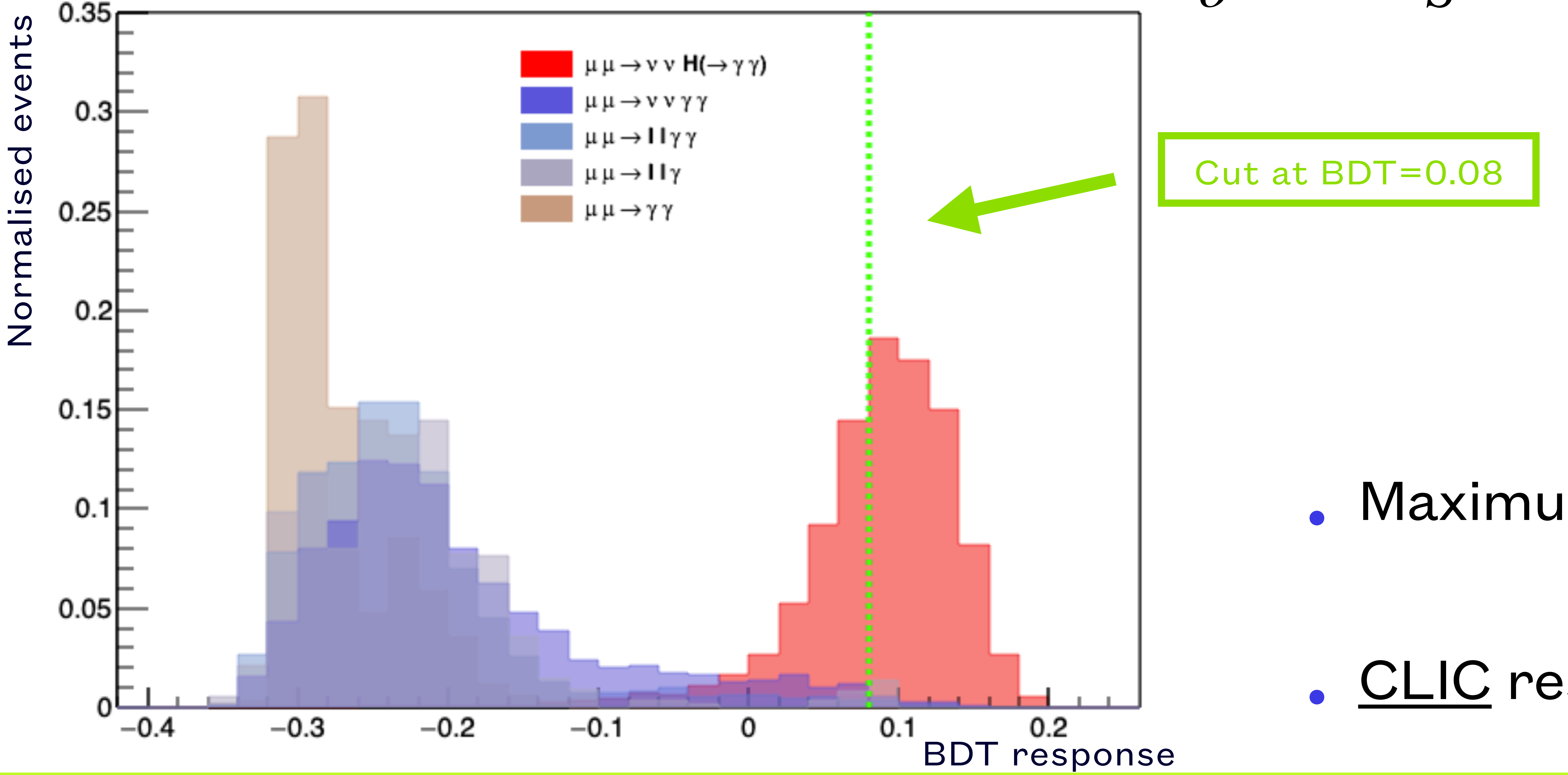




BDT classification

*CLIC results are obtained for $\sqrt{s} = 1.5$ TeV and $\mathscr{L} = 1.4$ ab^{-1}

- Given the good separation between signal and background, a cut approach is used
- A cut on BDT is placed in order to maximise $\dfrac{\Delta\sigma}{\sigma} = \dfrac{\sqrt{S+B}}{S}$



Process	Events	$\varepsilon_{\mathrm{BDT}} = N_{\mathrm{BDT}}/N_{\mathrm{reco}}$
$\mu\mu \to H\nu\nu, H \to \gamma\gamma$	294	0,65
$\mu\mu \to \nu\nu\gamma\gamma$	901	0,03
$\mu\mu \to ll\gamma\gamma$	31	0,01
$\mu\mu \to ll\gamma$	302	0,06
$\mu\mu \to \gamma\gamma$	0	0,00

- Maximum $\dfrac{\Delta\sigma}{\sigma} = \dfrac{\sqrt{S+B}}{S} = 13.3\,\%$
- CLIC results* $\dfrac{\Delta\sigma}{\sigma} = \dfrac{\sqrt{S+B}}{S} = 15\,\%$

Conclusions and future steps

- While being preliminary results, pipeline for $H \rightarrow \gamma\gamma$ is in place (thanks to Massimo & Lorenzo)
- Results ~~might~~ will deteriorate due to BIB contribution, but so far it's competitive with CLIC

- Future steps:
  - **Add the BIB**
    - Perform photon reconstruction using ECAL cluster instead of Pandora `rctyp[irec]`
    - Understand better photon reconstruction
      - Very high energetic photon go into HCAL → "new" processors
    - Maybe better cuts and better BDT classification (more variables)