Search for Dark Photon and E_T^{miss} performance studies in ATLAS

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Summary of activities

- Research activity:
  - Dark Matter searches in final states involving photons and high E_T^{miss}
  - Implementation and performance studies for a “Global Particle Flow” E_T^{miss} towards Run-3

- Cosupervisor of bachelor theses:
  - Matthias Vigl: “*A new combined method to estimate the background from jets and electrons in a photon sample, and its application to the Mono-Photon analysis for Dark Matter search with the ATLAS detector*”
  - Dario Pullia: “*Background study in the search for dark photons from Higgs boson decays in final states with a photon and missing transverse momentum with the ATLAS detector*”
  - Andrea Mitta: *“Study of the reducible background, induced by electrons, in the search for Higgs boson decays to a dark photon and a photon, with the ATLAS detector”*

- Summer schools & conferences:
  - Les Houches Summer School 2021: Dark Matter (26/07/21 - 20/08/21)
  - CERN-Fermilab Summer School (23/08/21 - 4/08/21)
  - Presentation of the Mono-photon analysis at Corfu Summer Institute 2021: Workshop on SM and Beyond (29/08 - 8/09)

Dark Matter searches

Dark Matter searches

Signal: an excess of events with high E_T^{miss} with respect to Standard Model expectations

Mono-photon (Exotics)

- 1 photon + high E_T^{miss}
- Two models of DM production:
  - **WIMPs** (Weakly Interacting Massive Particles)
  - **ALPs** (Axion-Like-Particles)
- Updated results. published on JHEP: JHEP02(2021)226

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- 2 leptons from Z decay + 1 photon and E_T^{miss} from Higgs decay
- Interpretation: **dark-photon** production via $H \rightarrow \gamma\gamma_D$
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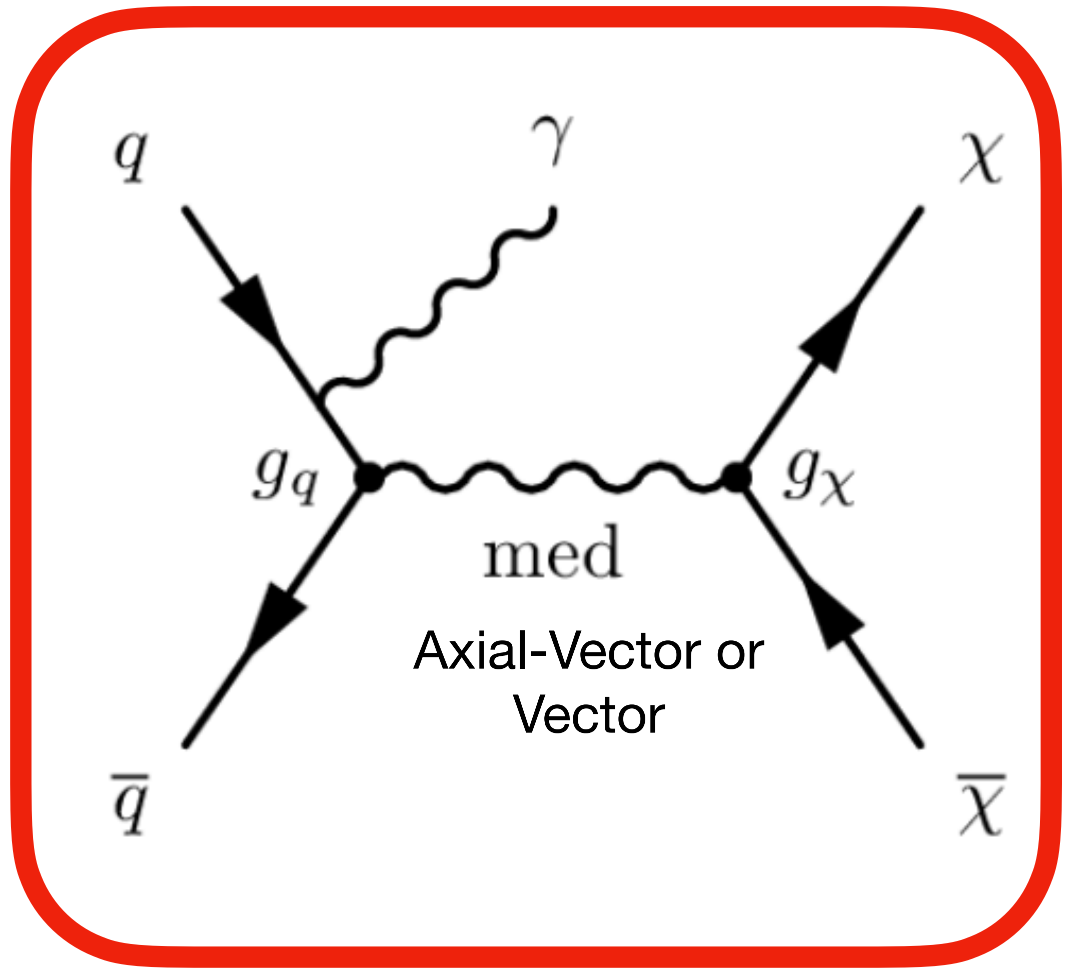

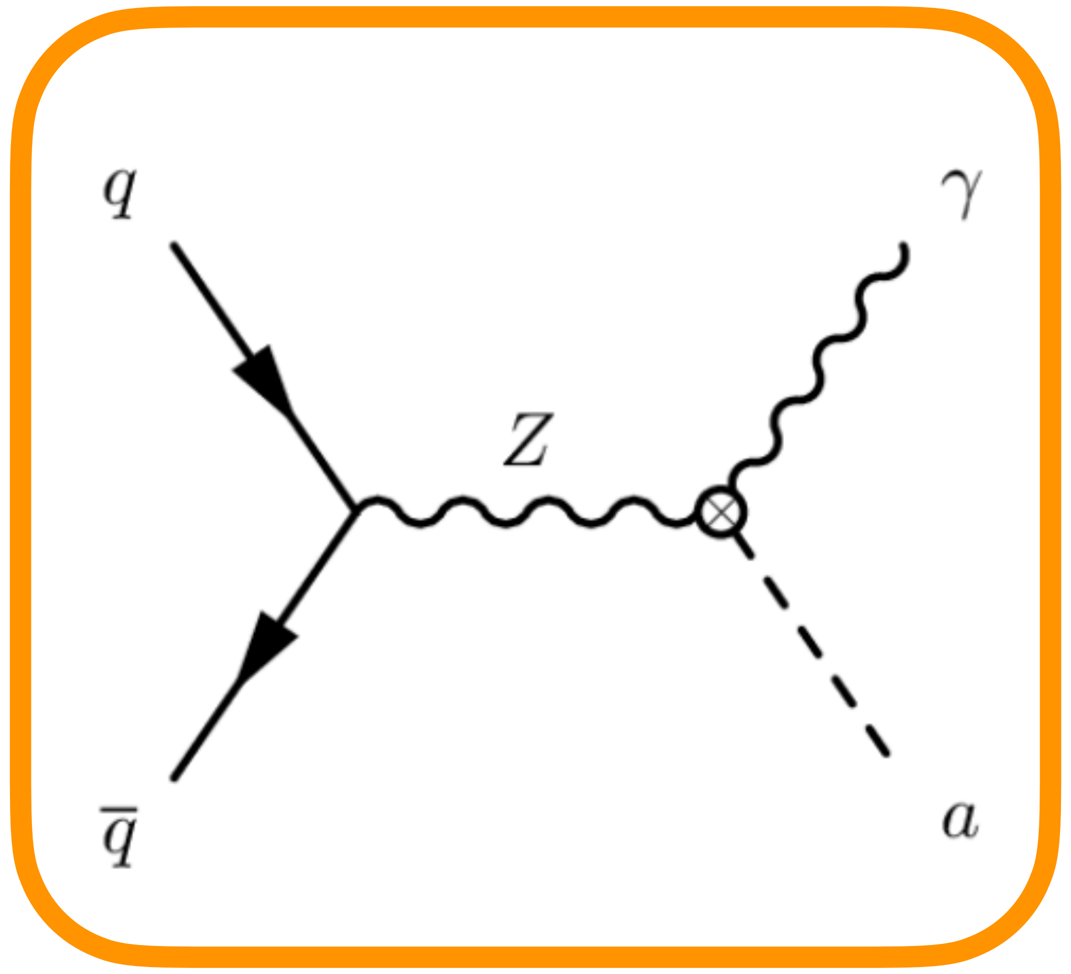

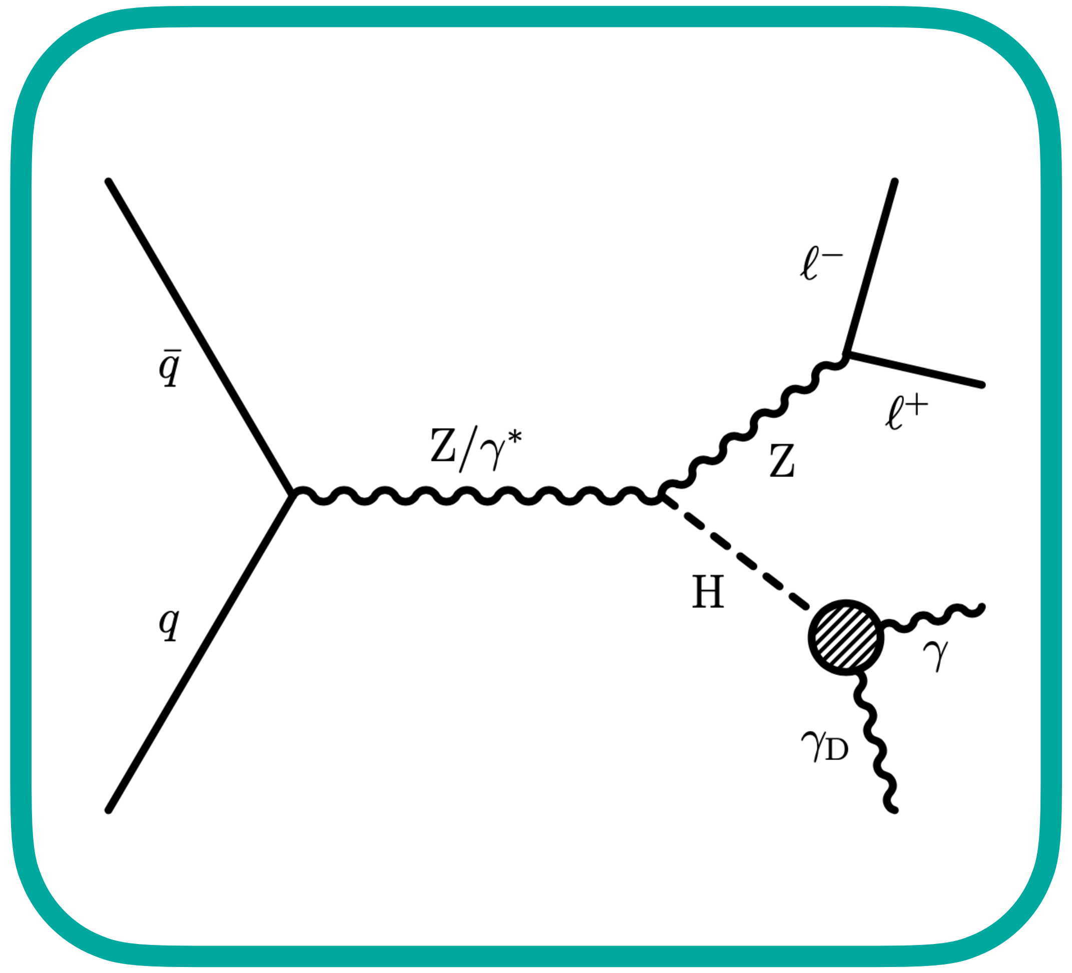

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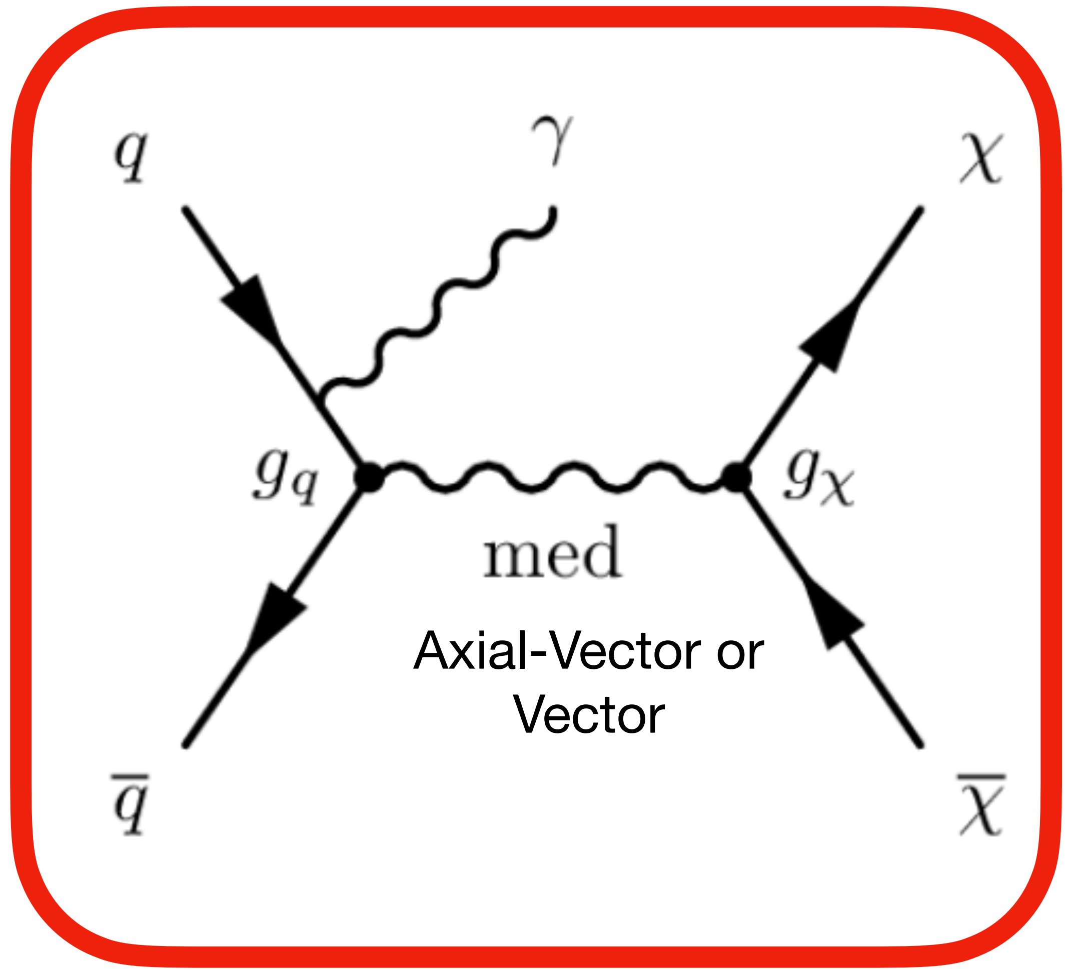
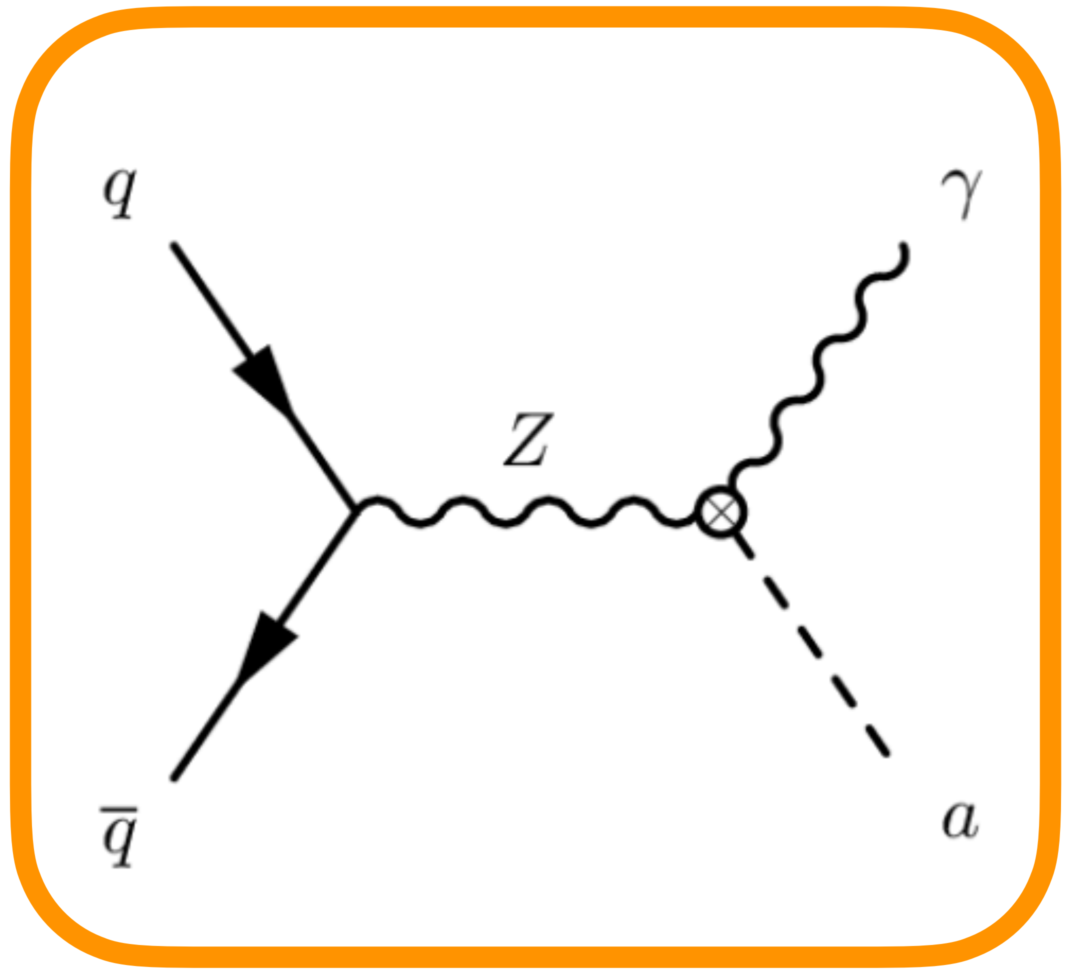
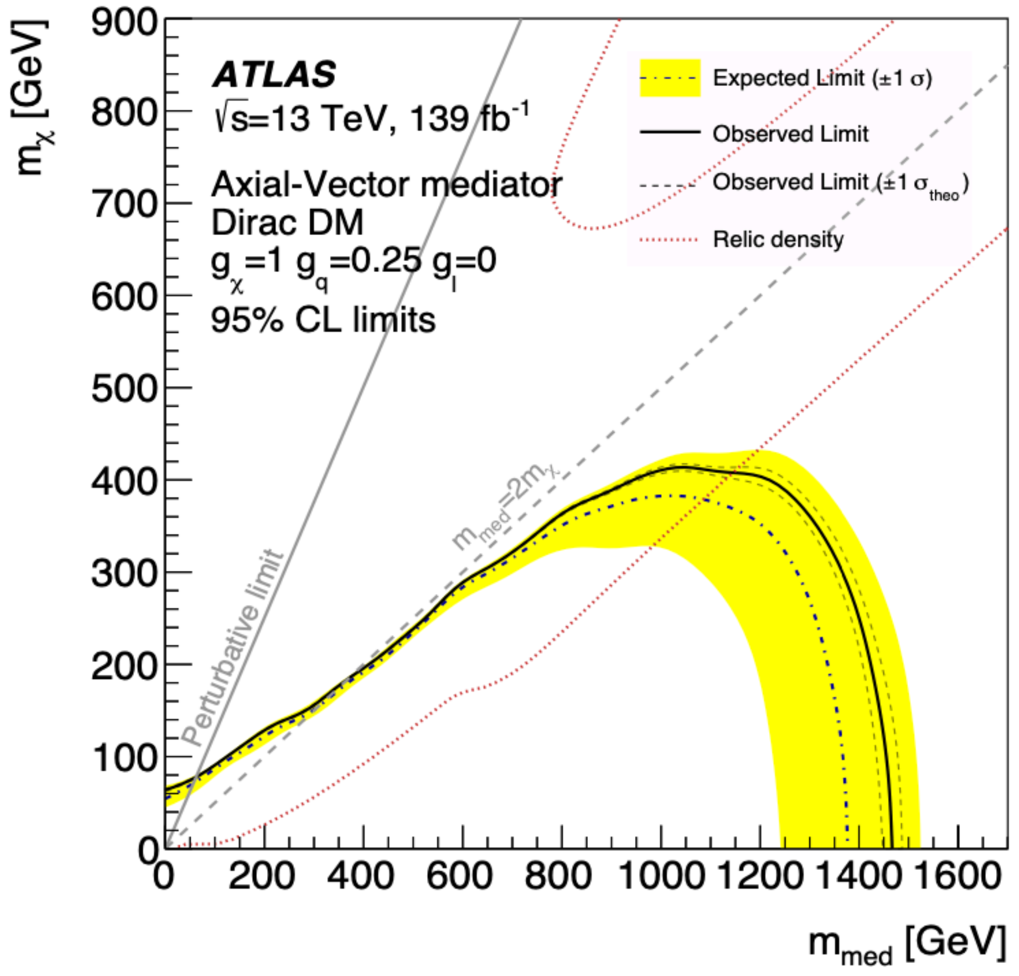
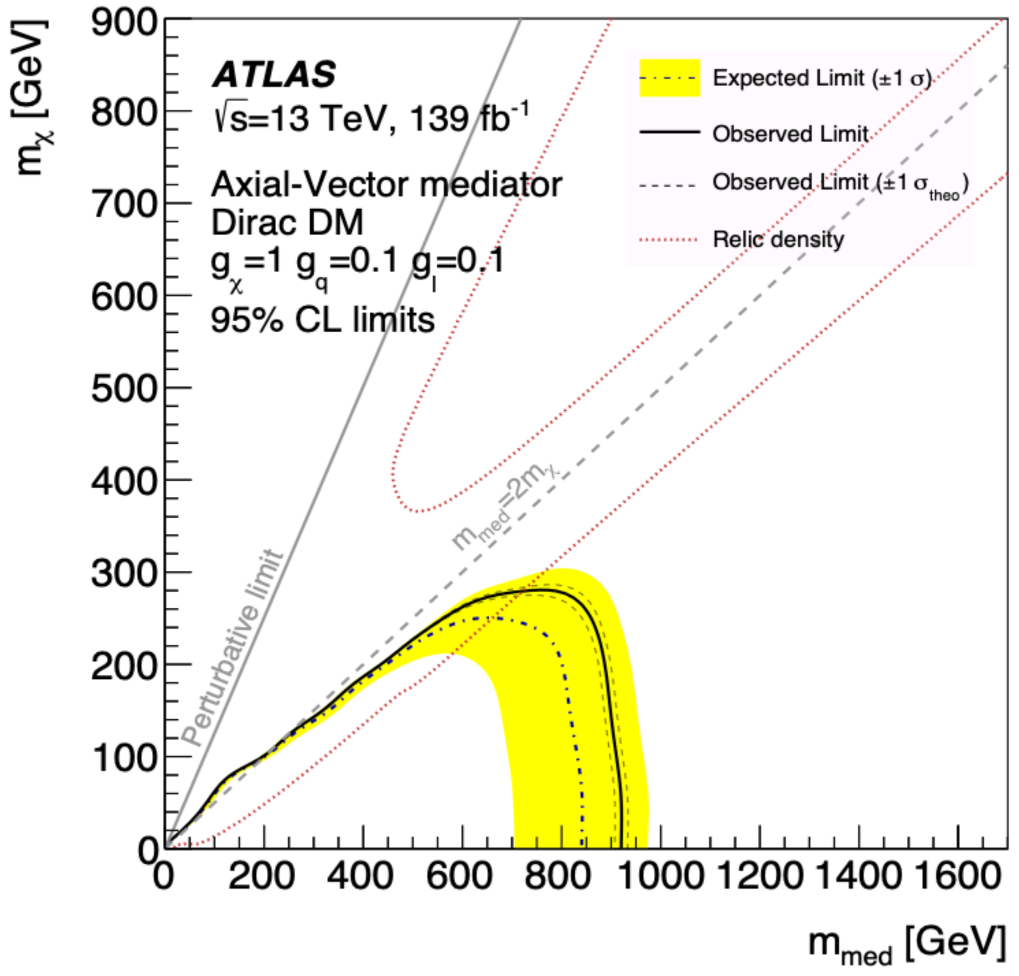


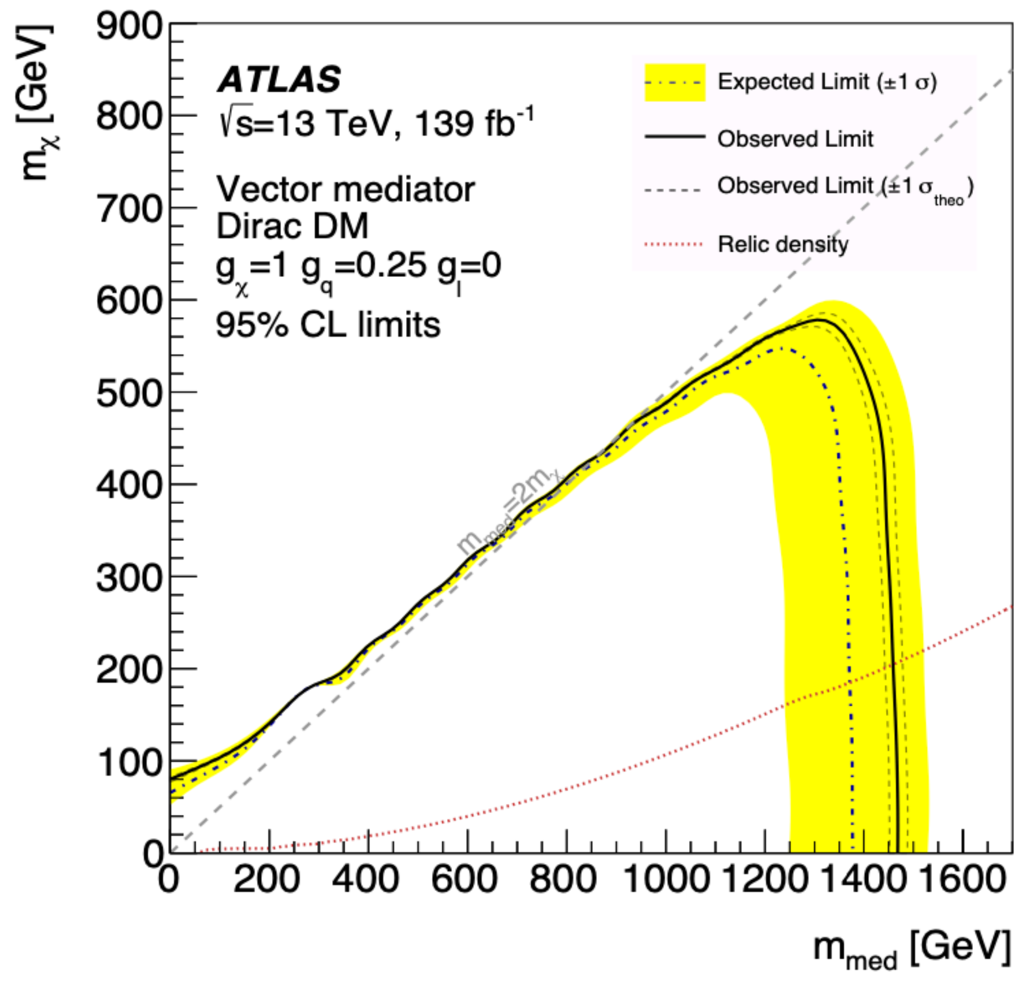


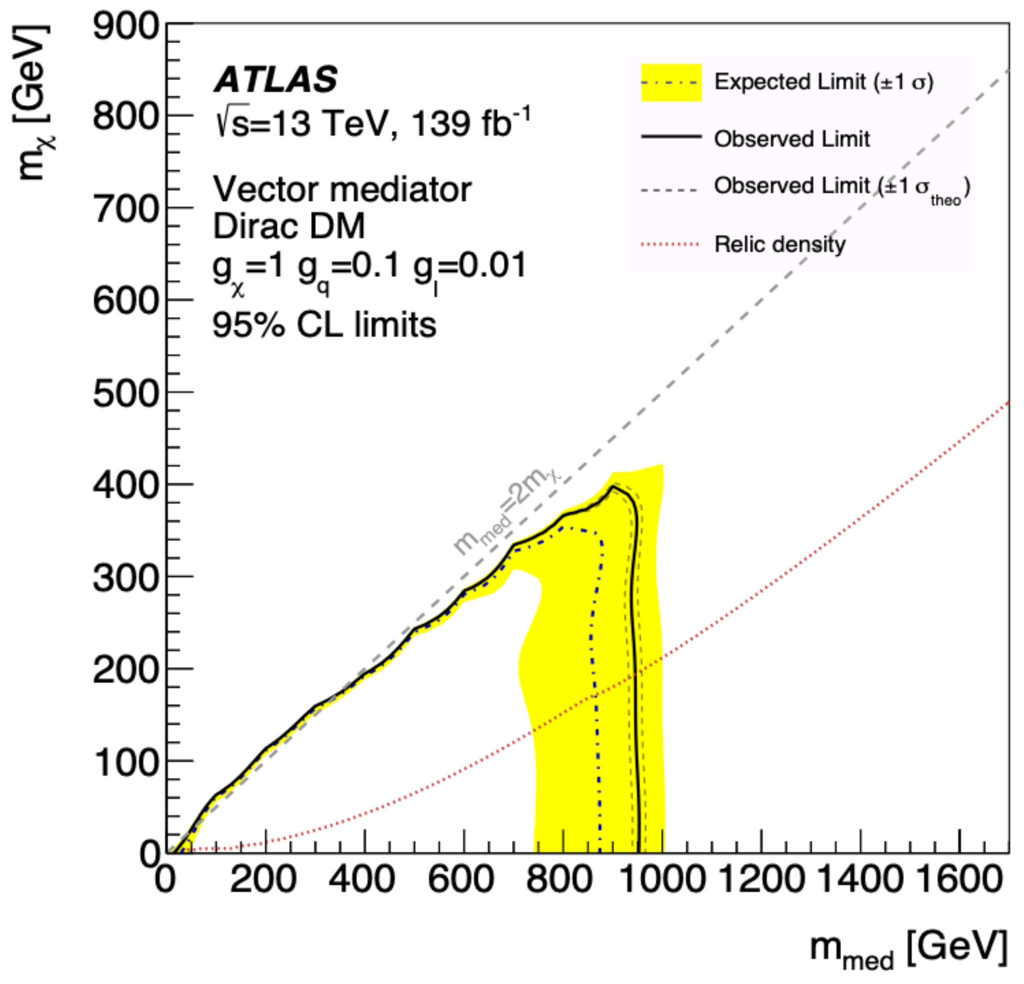
Exclusion limits
WIMPs production

Area below the curves is excluded at 95% CL.

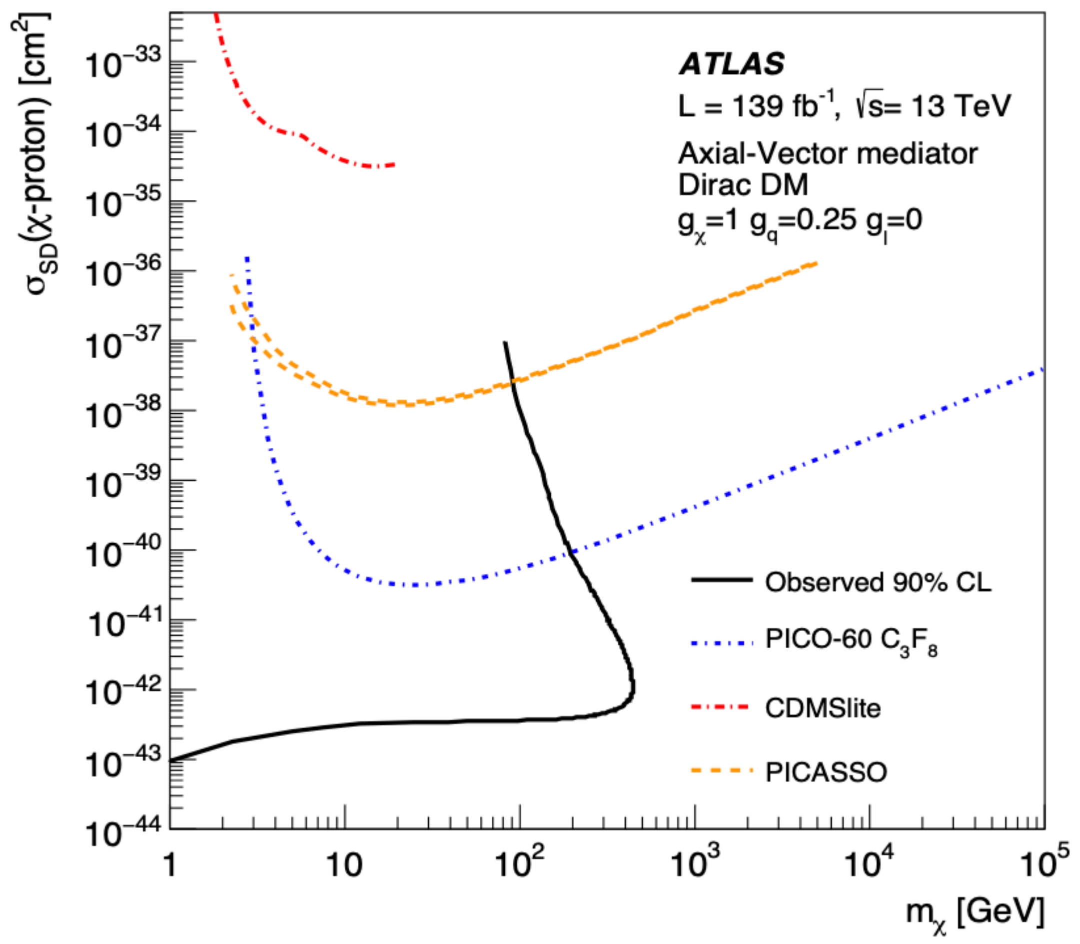


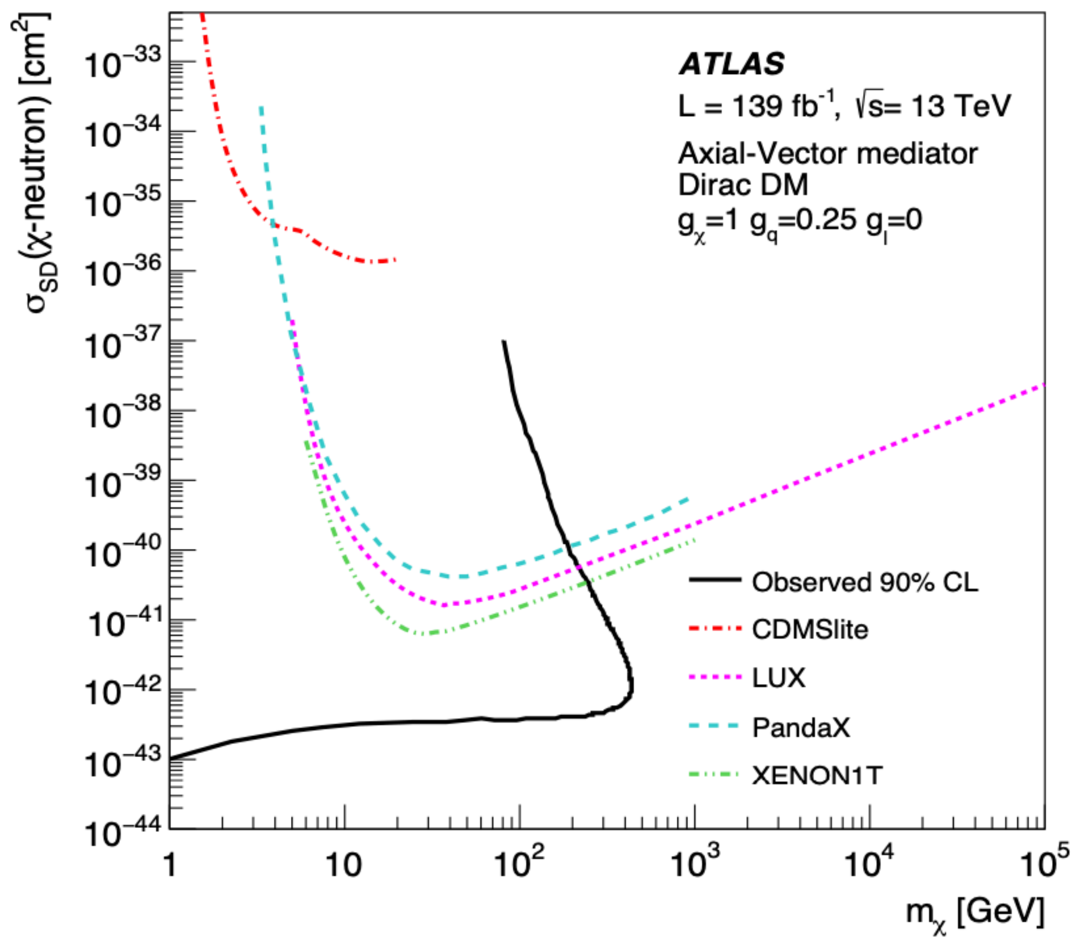


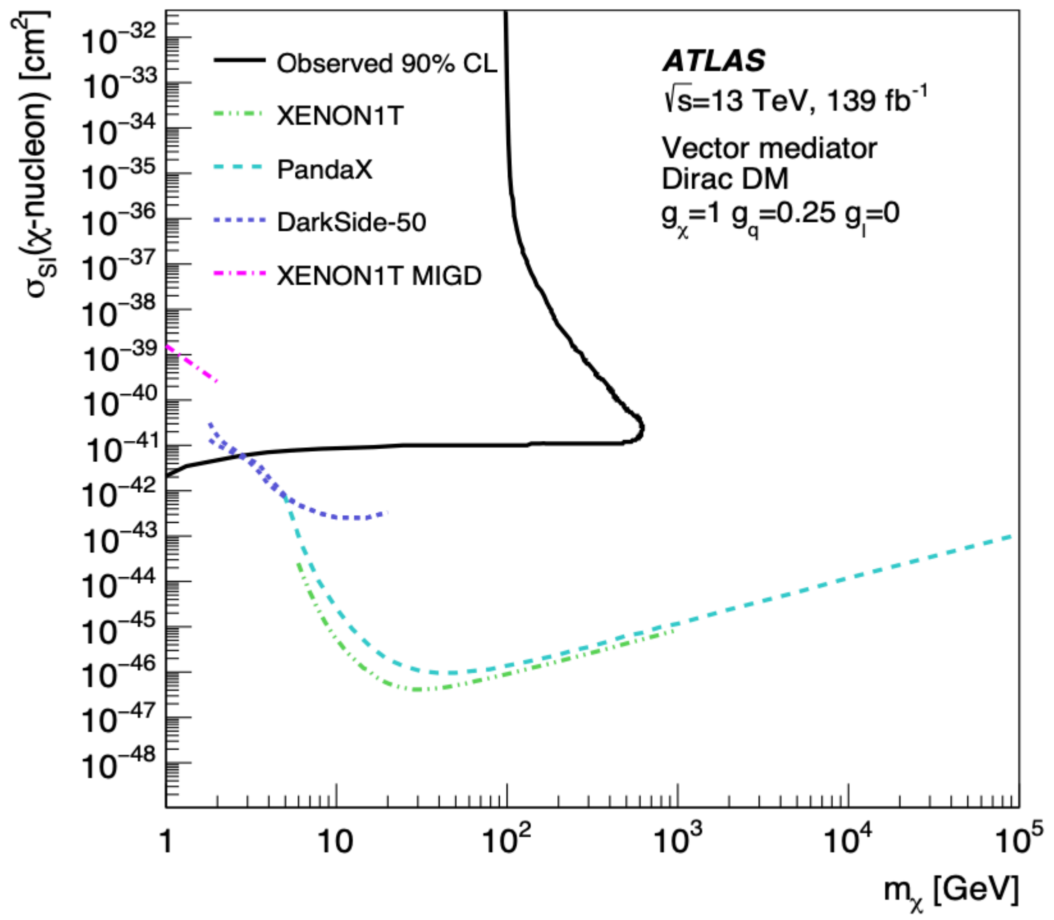




Interpretations in terms of WIMP production can be translated to the m_{DM}-$\sigma_{SD/SI}(\chi$-nucleon) plan, to compare with results obtained by Direct Detection Spin-dependent (SD) or Spin-independent (SI) experiments



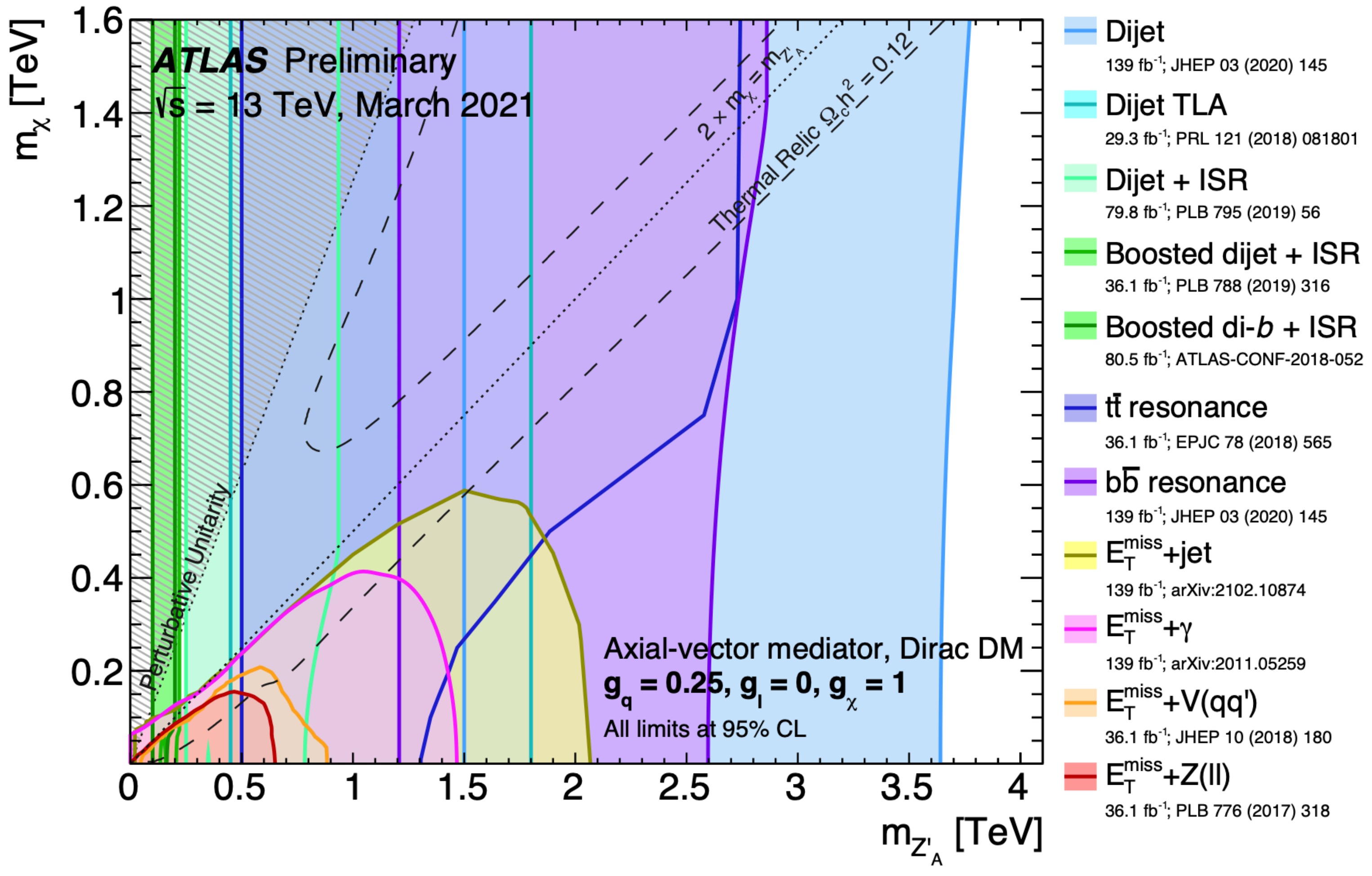


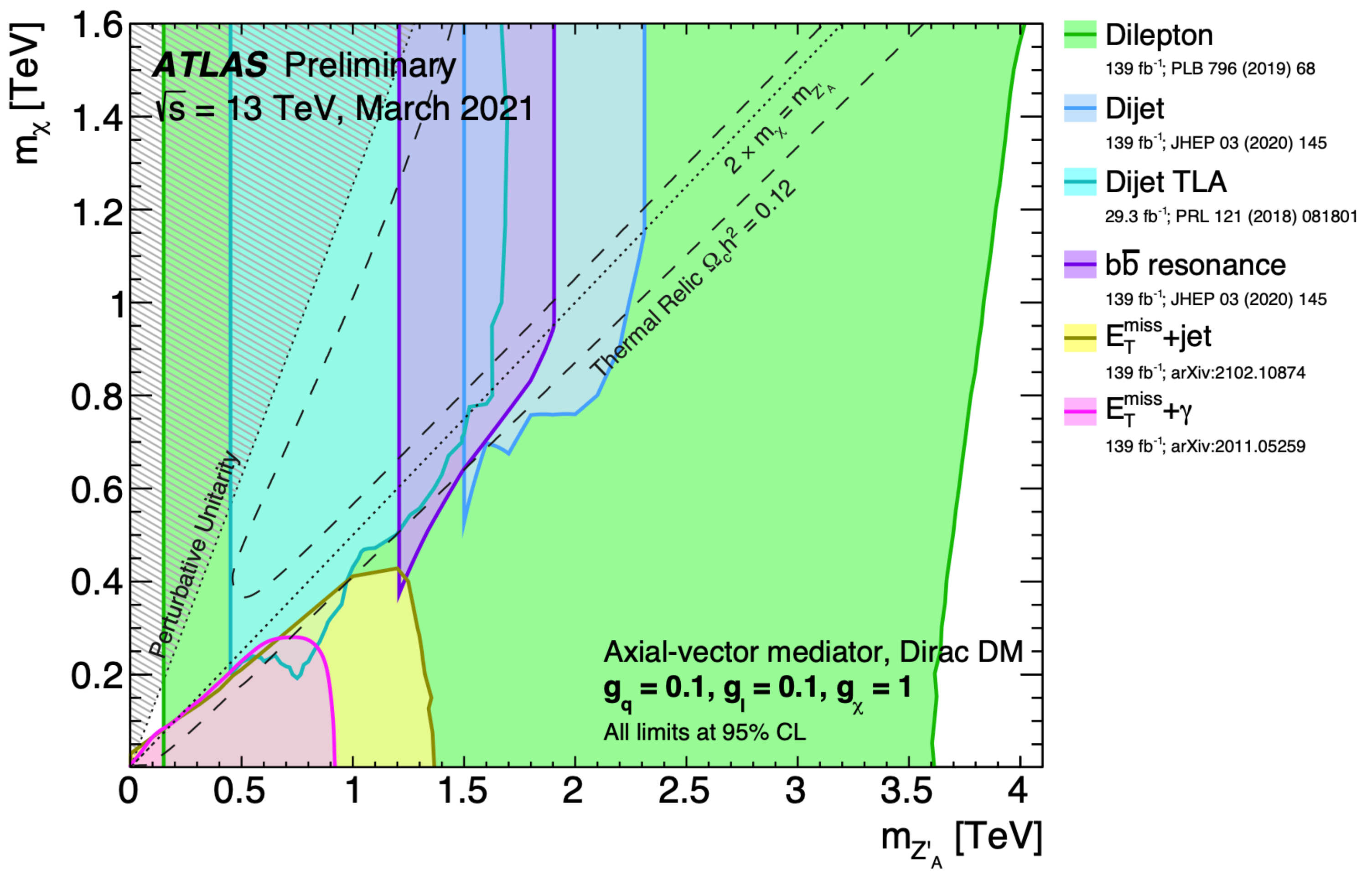


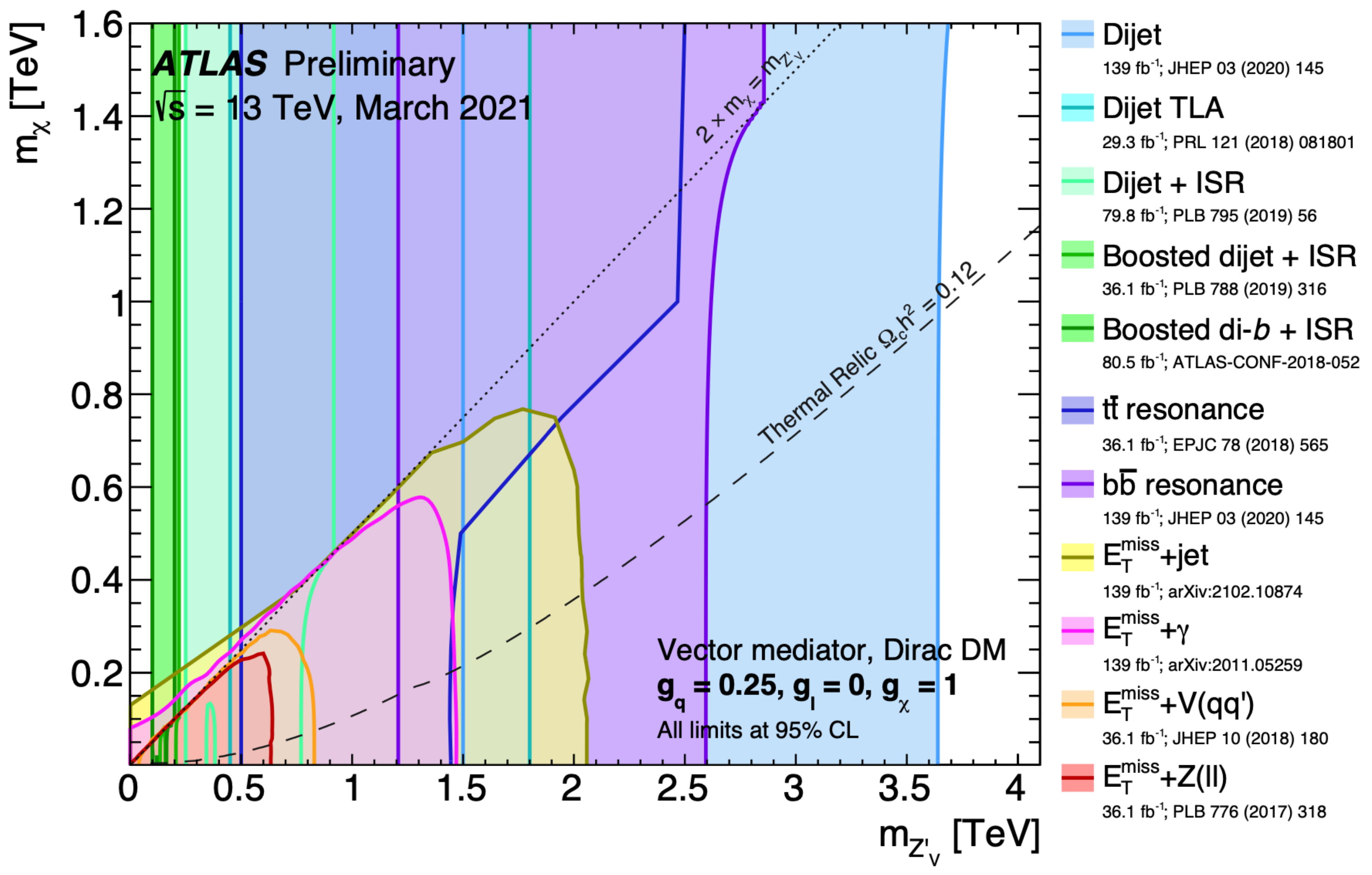
Exclusion limits

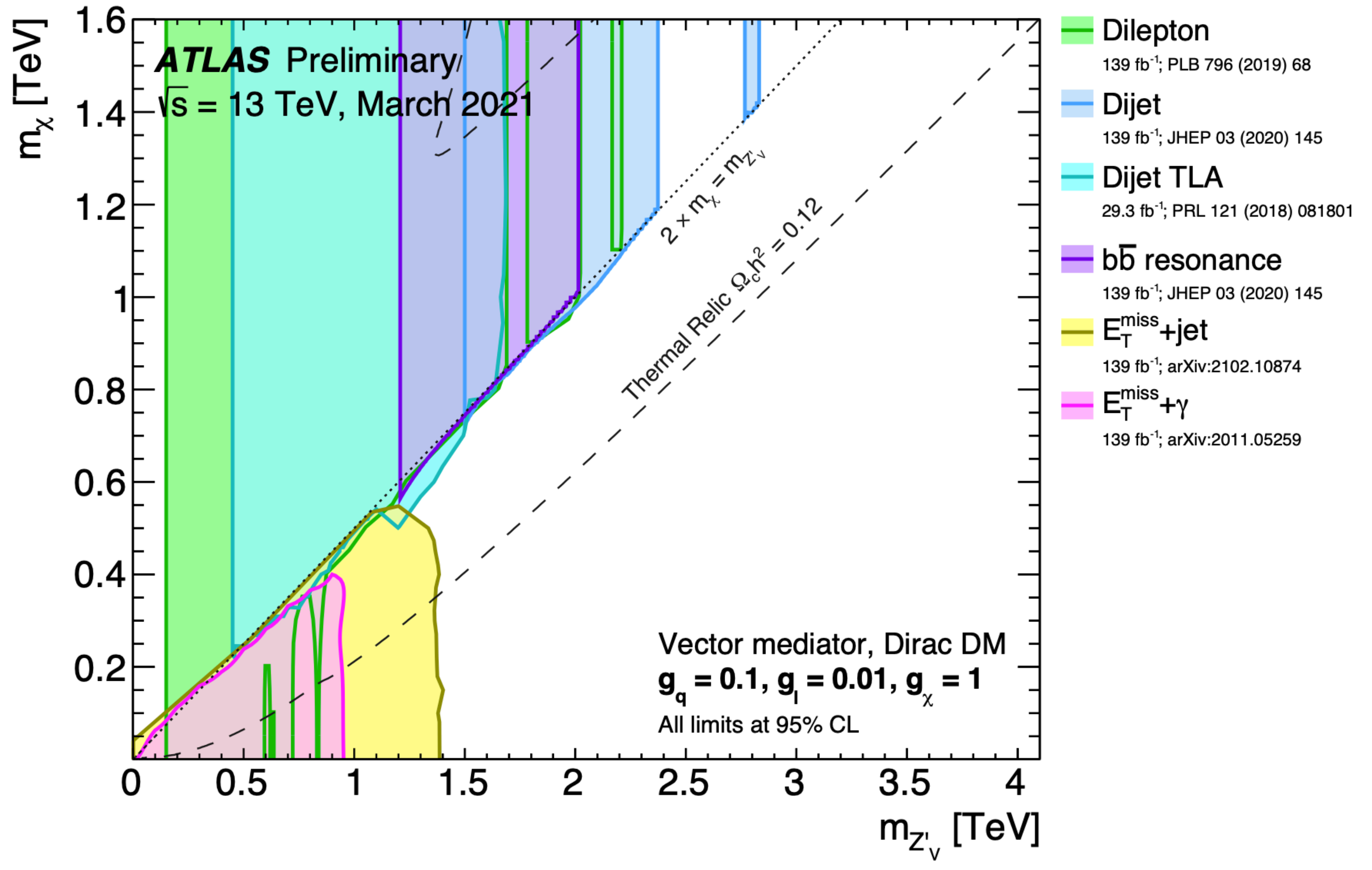
ATL-PHYS-PUB-2021-006

Summary of ATLAS limits for s-channel simplified DM models









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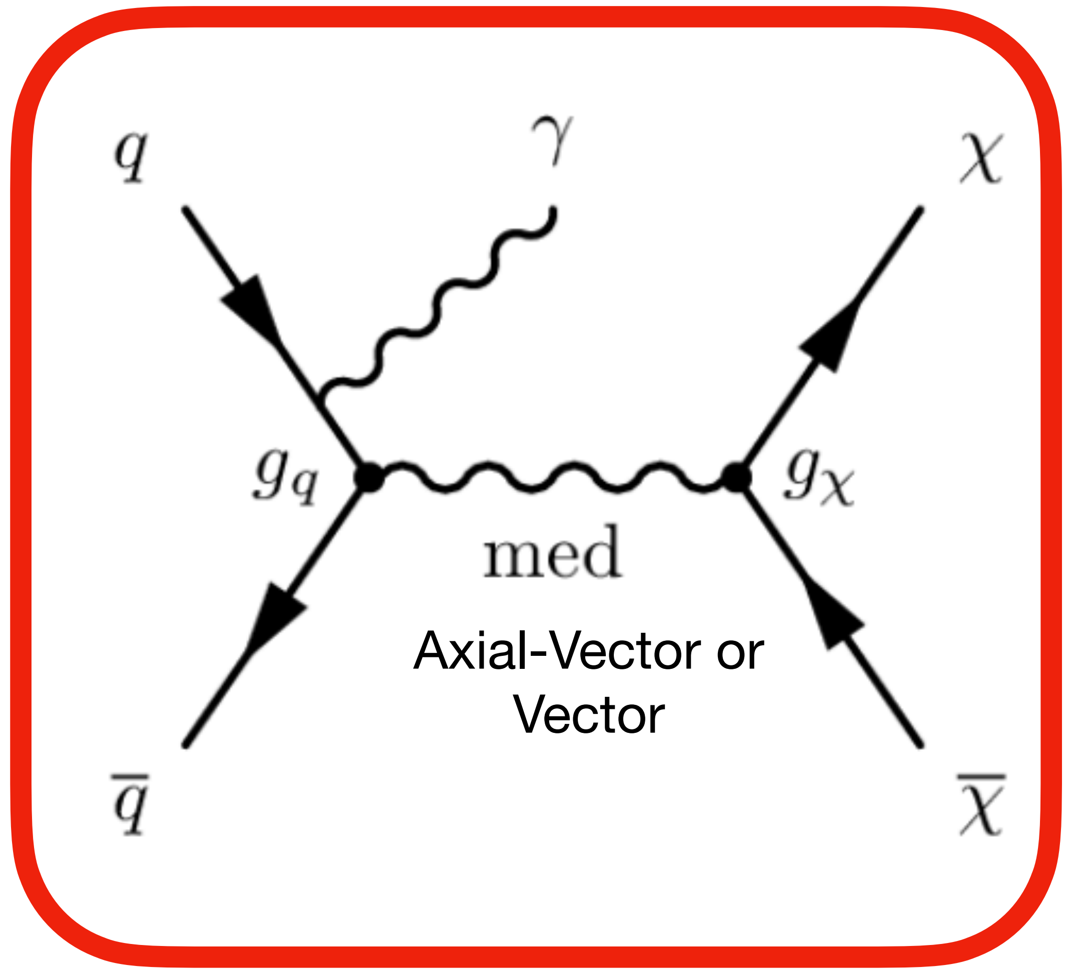

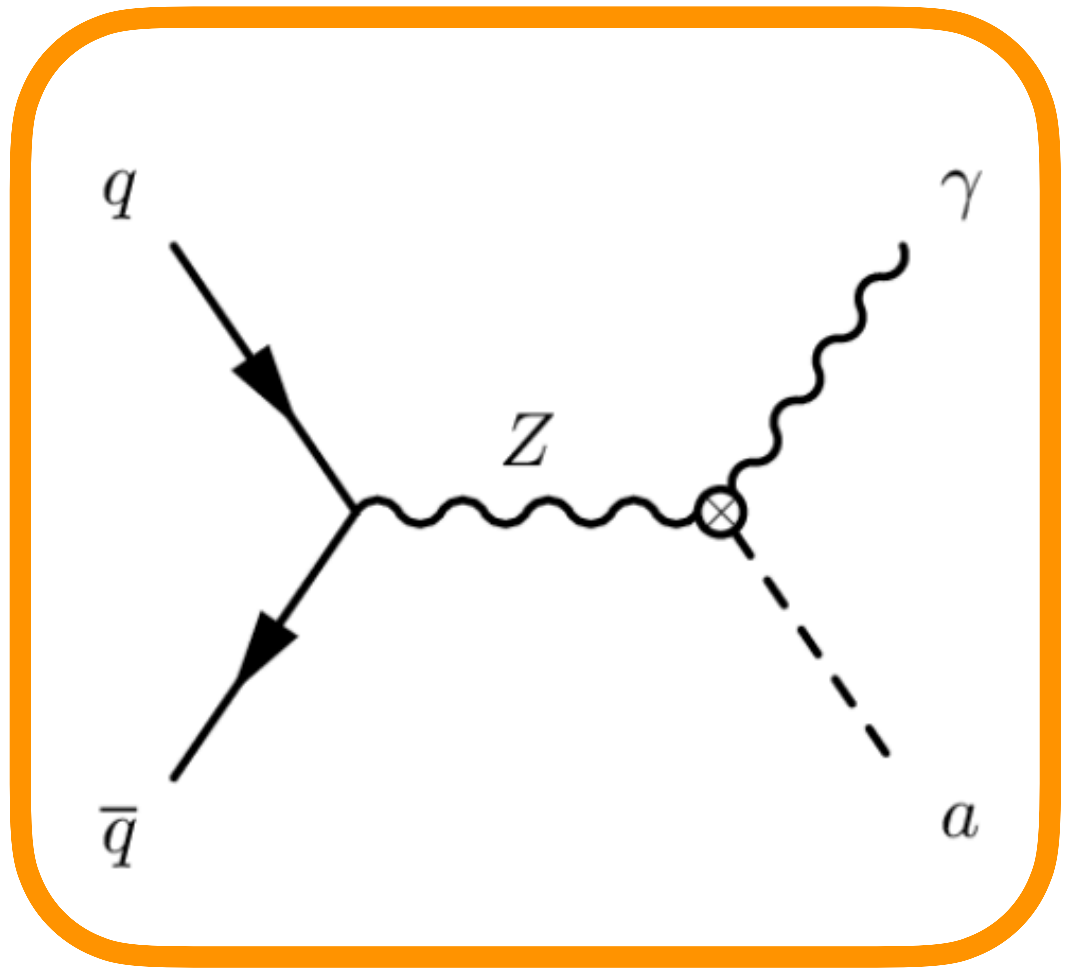

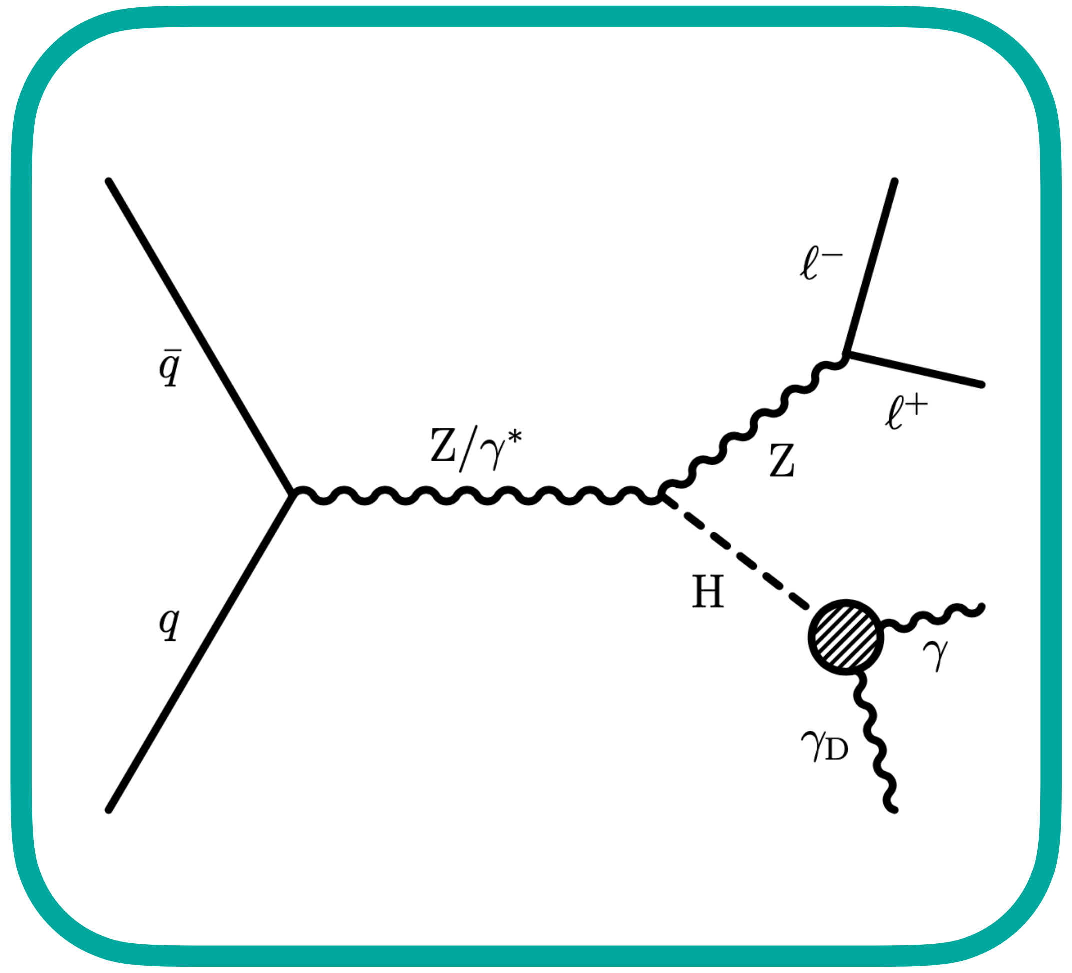

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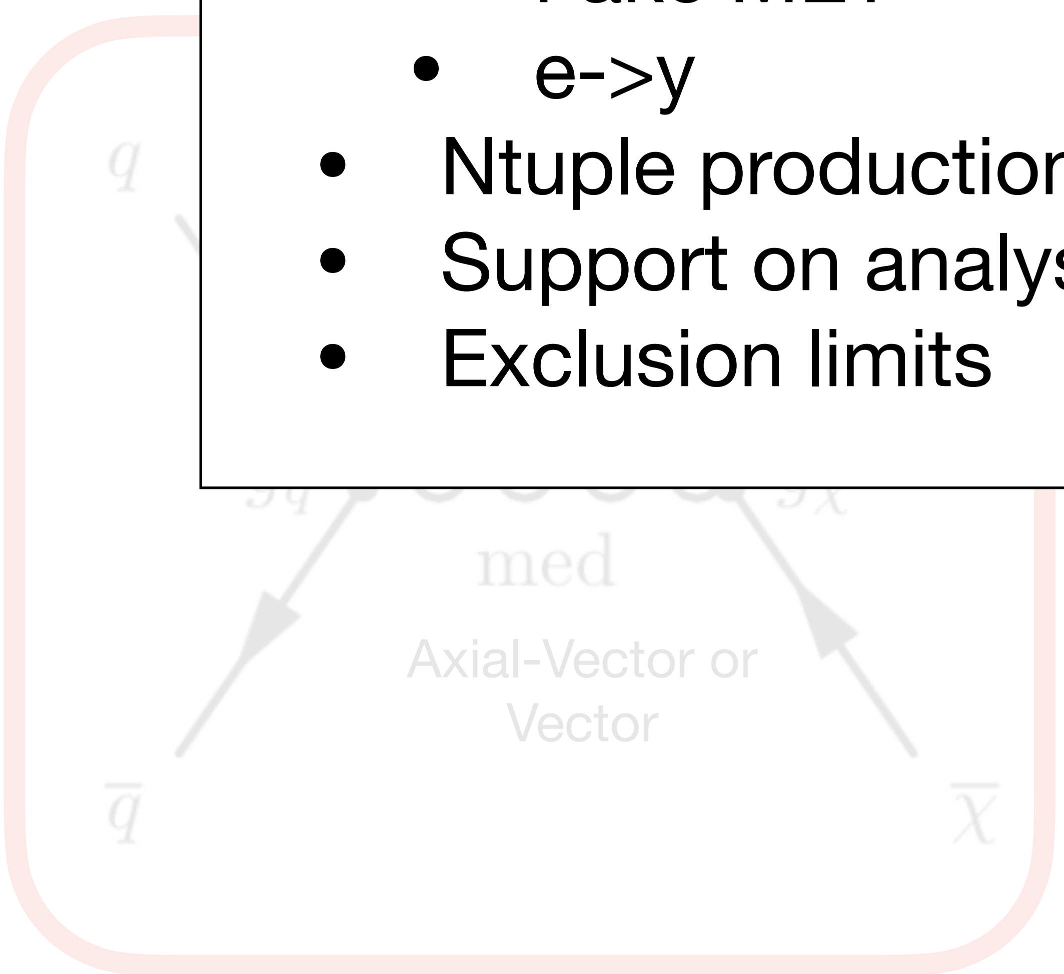
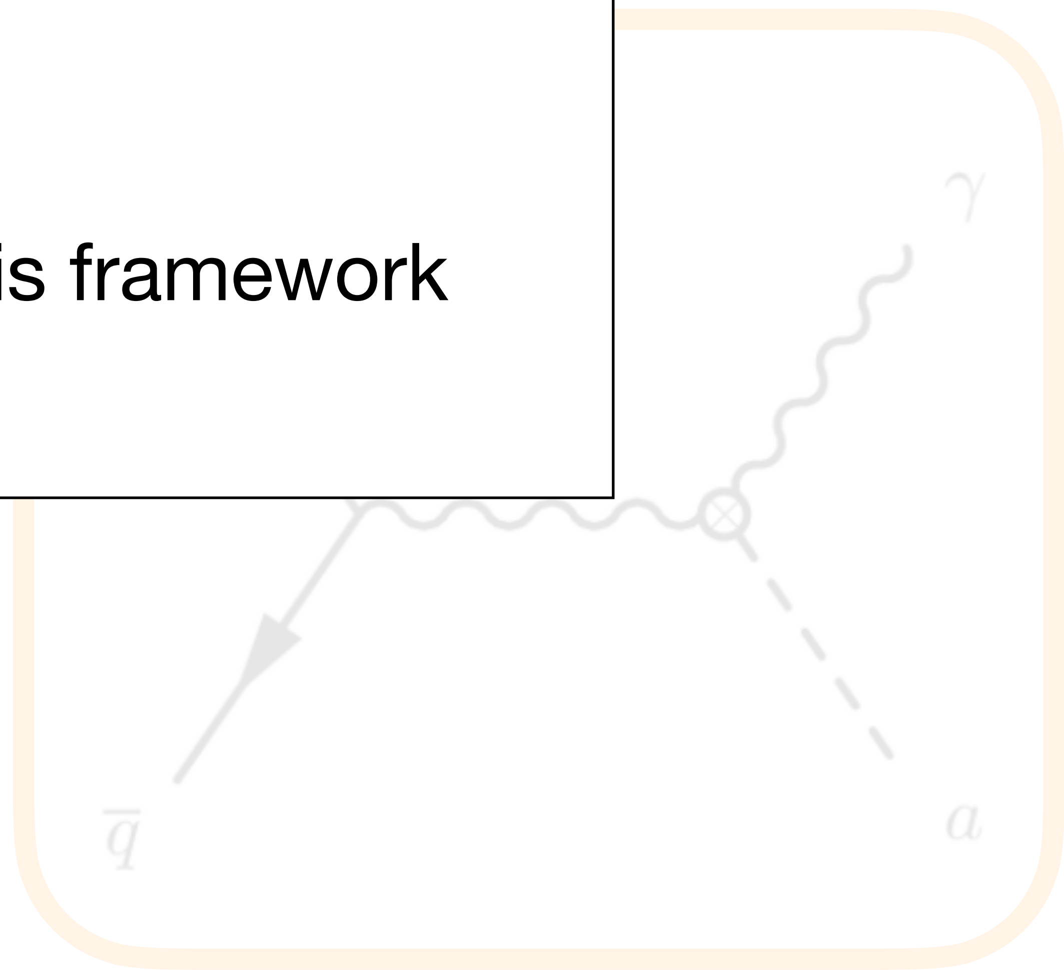
- Two models of DM production:
  - W…
  - Al…
- Upc… 2(2021)226

Contributions:

- Background estimation
  - Fake MET
  - e->y
- Ntuple production
- Support on analysis framework
- Exclusion limits





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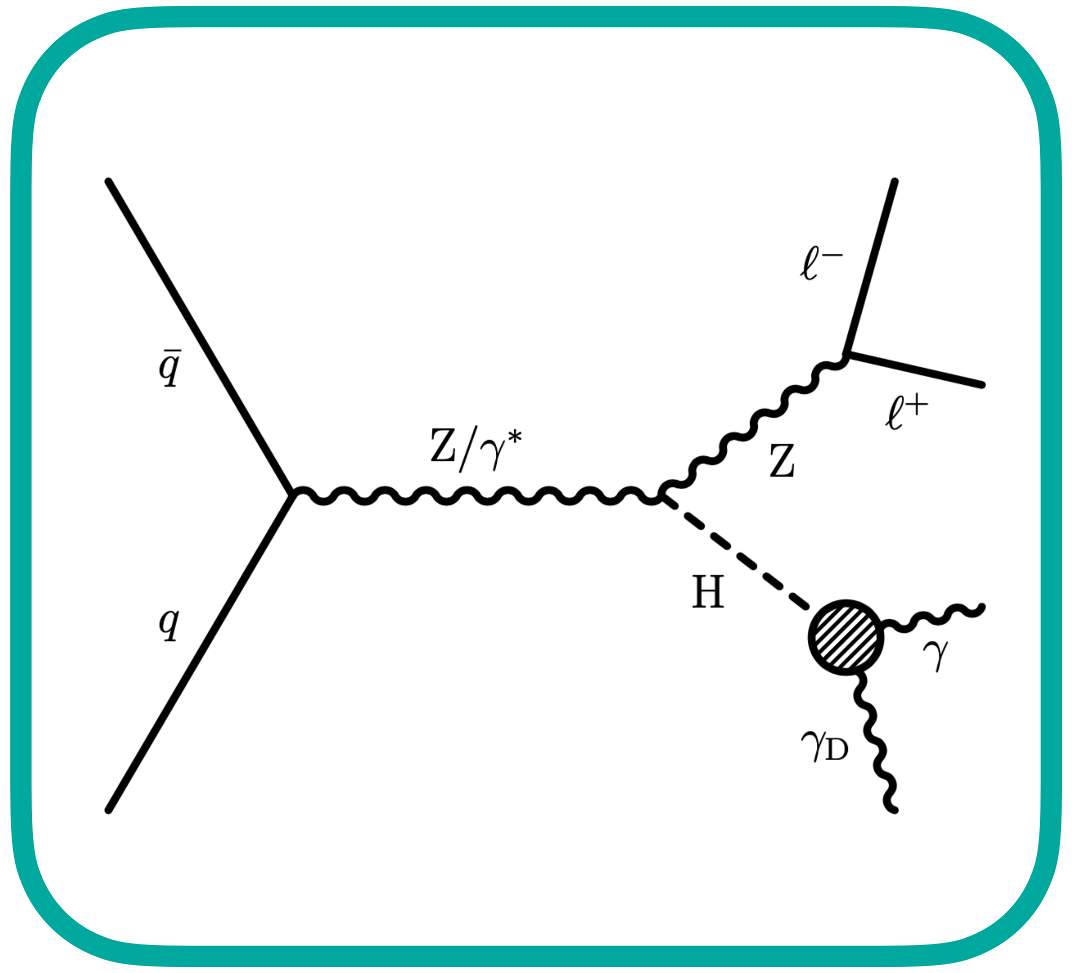
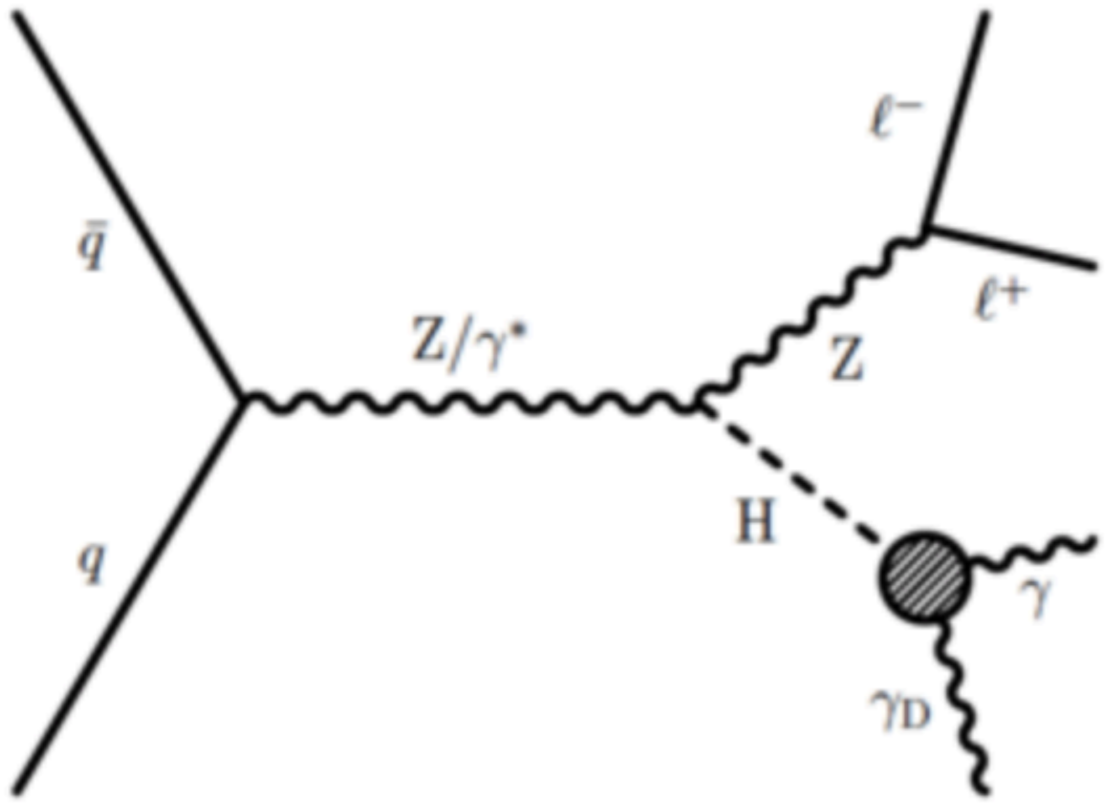


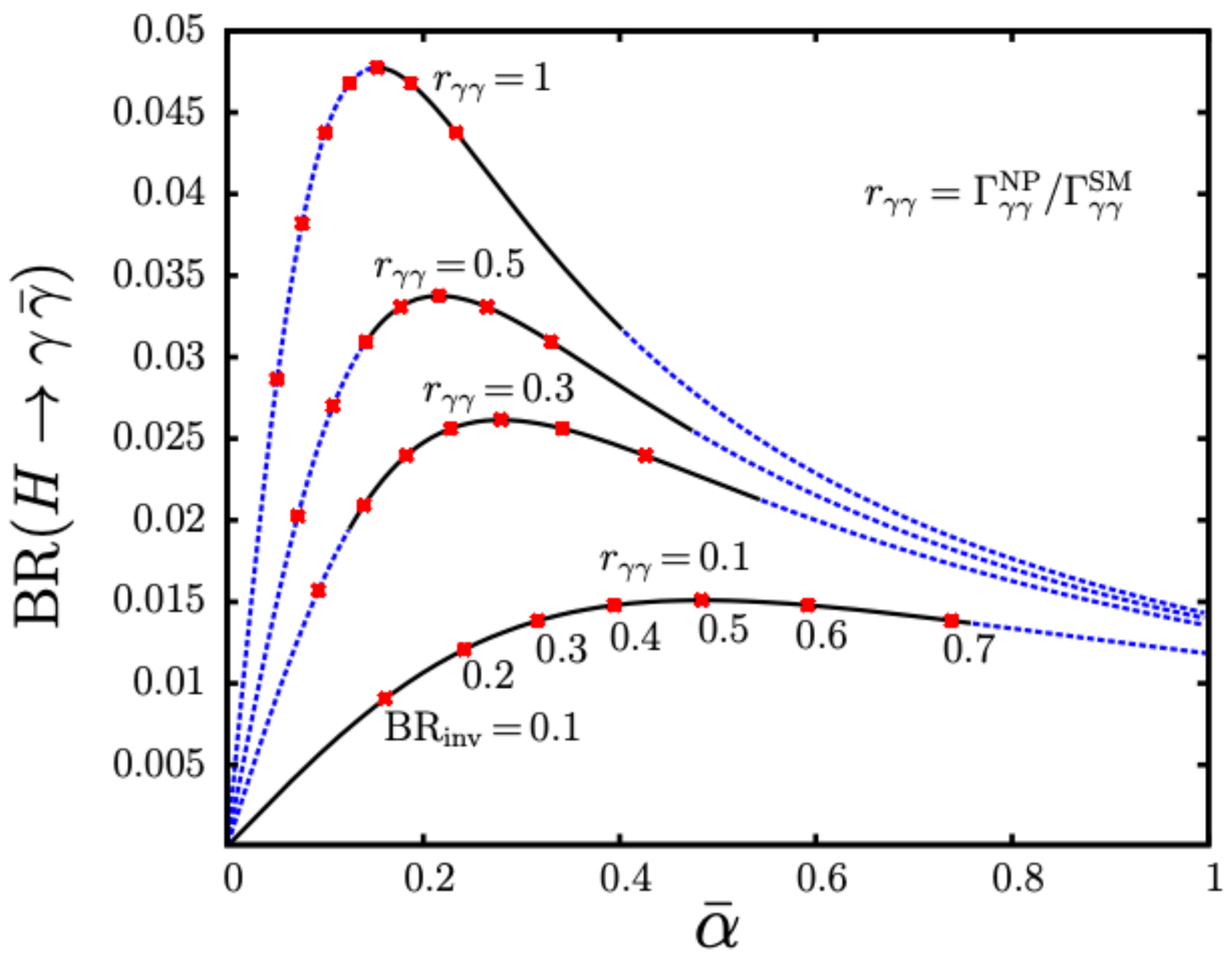
Motivation and phenomenology

- Alternative to WIMP => existence of a Dark Sector with its own gauge interactions, with a “portal” to the SM sector (e.g. “Higgs portal”)

- **Dark-photon** as gauge boson of a new unbroken U(1) group
  We consider a massless (or light) dark-photon
  - No mixing with photons => Decoupled from SM sector at tree level (avoid existing constraints)
  - Coupling with SM sector through higher-dimensional interactions via messenger field
  - Can help explaining small-scale structure formation, light-DM annihilation in asymmetric DM scenarios, Flavor hierarchy problem

- **The analysis:**
  - Dark-photon from Higgs decay, in ZH production mode
  - BSM BR up to 5% allowed by present constraints (Biswas, Gabrielli, Heikinheimo, Mele (2016))
  - Results in this final state already published by CMS





Kinematic selections

Preselections

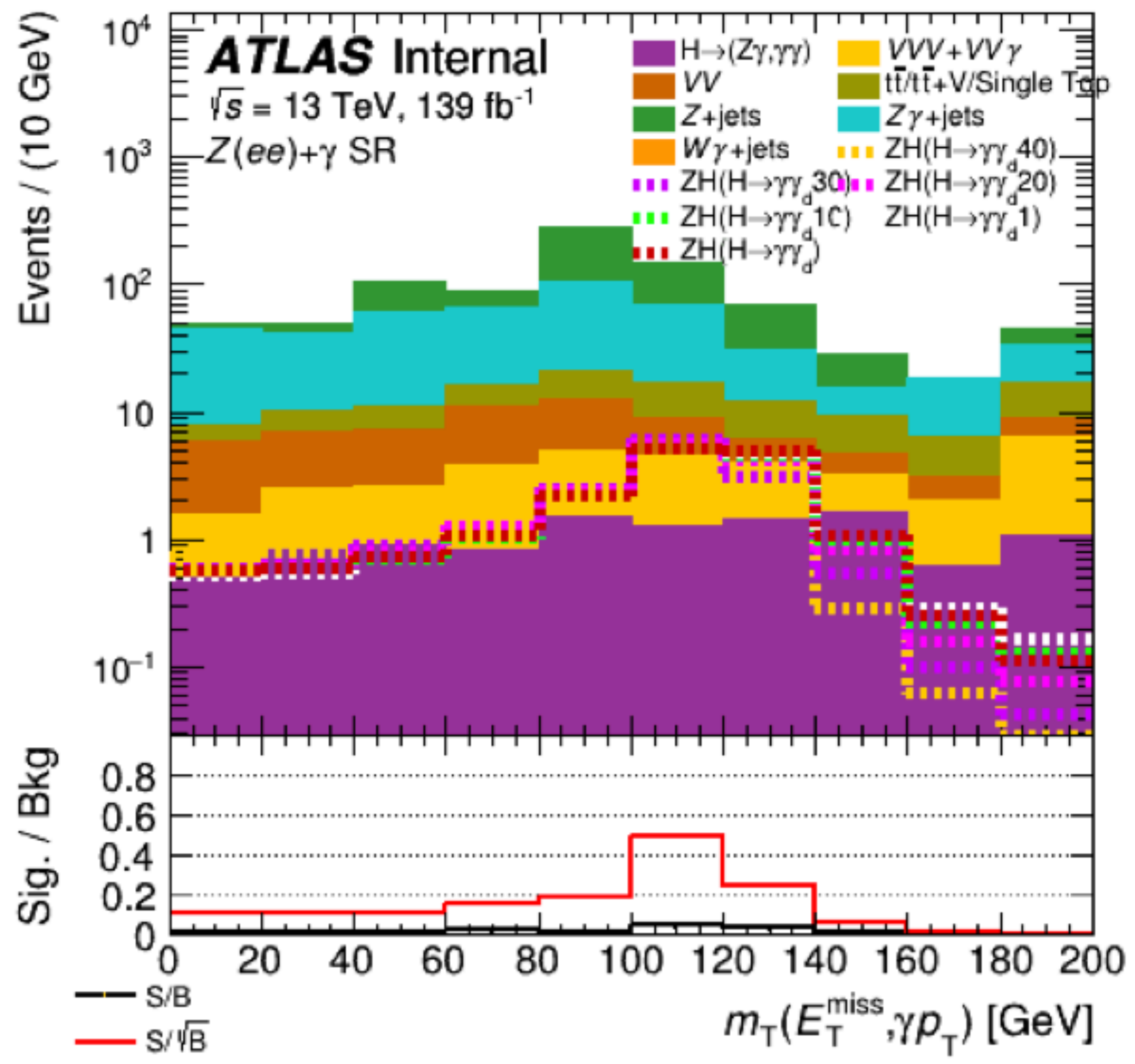
- GRL, Detector event cleaning, PV selection, Loose Jet Cleaning (MiniNtuple skim)
- At least one baseline electron or muon
- Overlap removal between Vy and Vjets MC
- Trigger (single/double lepton)

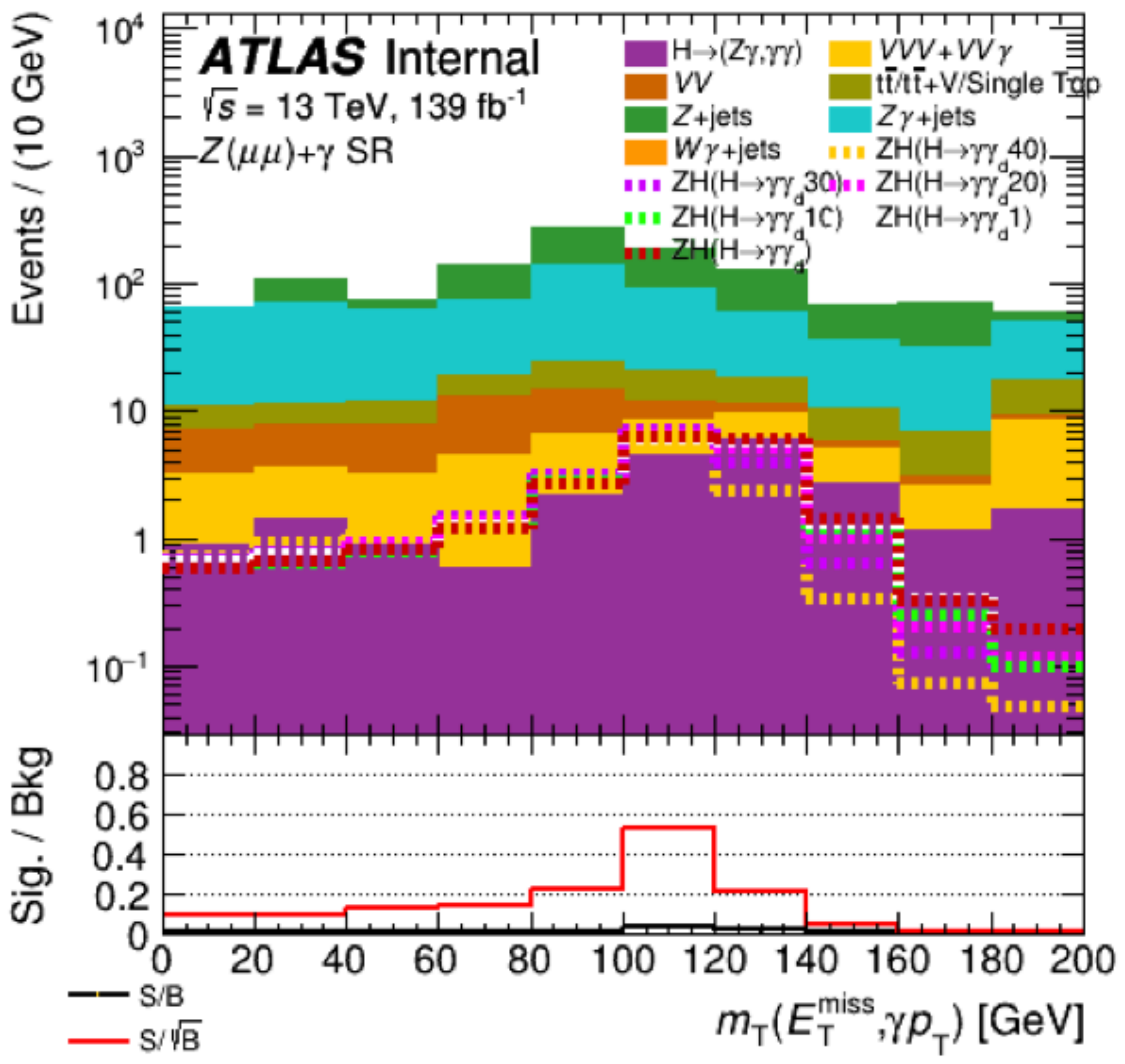
SR selections

- 2 opposite sign muons/electrons with $p_T^{lep1} > 27$ GeV and $p_T^{lep2} > 20$ GeV
- 1 photon with $p_T^{\gamma} > 25$ GeV
- Njet<=2 and Nbjet=0
- $76 < m_{ll} < 116$ GeV
- $m_{ll\gamma} > 100$ GeV
- $E_T^{miss} > 60$ GeV
- $\Delta\phi(\overrightarrow{E}_T^{miss}, \overrightarrow{p}_T^{ll\gamma}) > 2.4$

Background processes

- **Zgam**: Zy+jets
- **Zqcd**: Z+jets
- **Top**: single Top + Vty + ttbar + Vtll + ttV + ttbarVV
- **VV**: ggVV, VV ewk
- **VVV** irreducible background (subdominant)
- **HZy**: ttHZy + VHZy + VBFZy + ggHZy (low contribution)

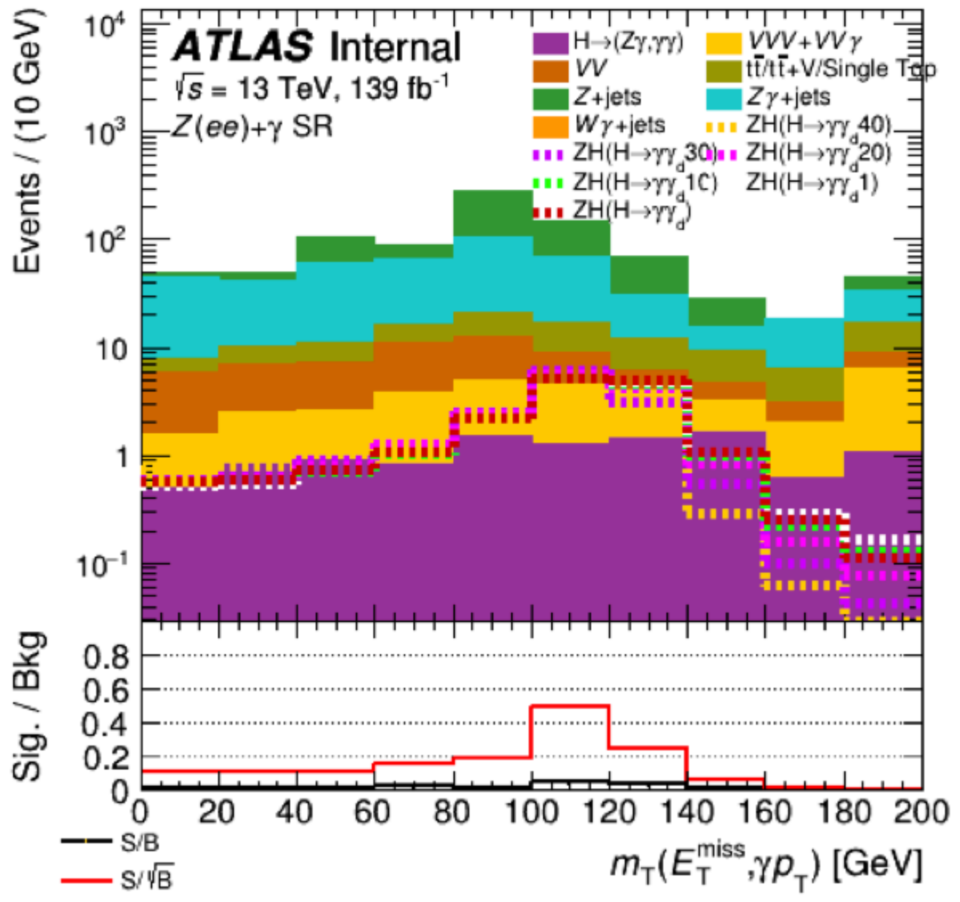


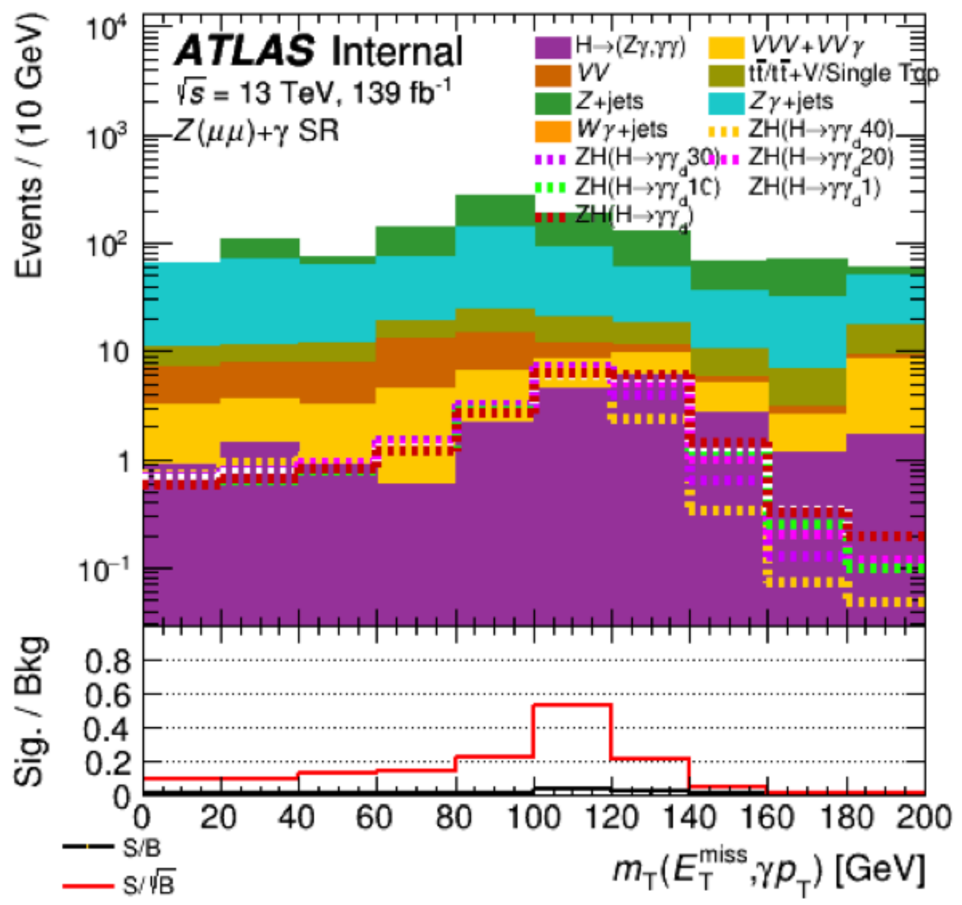


Background estimation

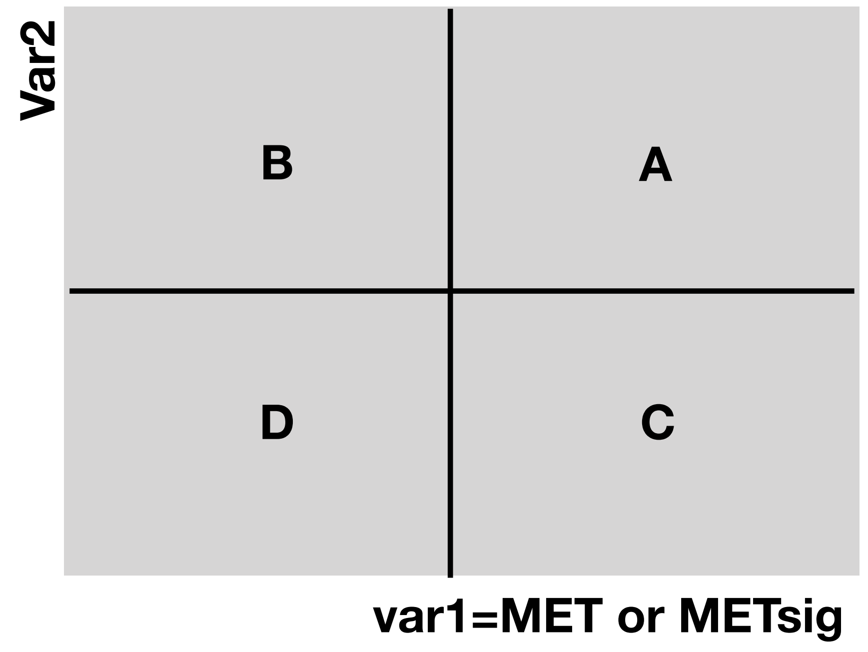
	ee channel	uu channel
hyGr	14.74+/-0.20	17.83+/-0.23
Z_strong	274.22+/-54.97	381.00+/-63.35
Z_ewk	0.10+/-0.07	0.00+/-0.00
Zg_strong	152.18+/-14.83	278.76+/-18.93
Zg_ewk	3.30+/-0.12	4.37+/-0.14
Wg_strong	3.11+/-1.57	1.40+/-1.11
Wty	4.40+/-0.29	4.89+/-0.29
top1	0.04+/-0.04	0.00+/-0.00
ttbarVV	0.03+/-0.01	0.01+/-0.01
ttV	24.21+/-0.97	24.43+/-0.96
ttbar	1.61+/-0.25	1.81+/-0.27
Vtll	2.38+/-0.39	3.13+/-0.45
VV	26.66+/-1.02	23.43+/-1.02
VV_ewk	0.22+/-0.01	0.21+/-0.02
ggVV	0.01+/-0.00	0.01+/-0.00
VVV	0.17+/-0.02	0.14+/-0.02
VVy	10.41+/-0.52	11.49+/-0.51
Vyy	3.16+/-0.63	6.20+/-0.74
ggH125Zy	0.18+/-0.01	0.23+/-0.01
ttH125Zy	0.01+/-0.00	0.01+/-0.00
VBFH125Zy	0.05+/-0.00	0.06+/-0.00
VH125Zy	0.09+/-0.00	0.11+/-0.00
totalMC	506.52+/-56.99	741.71+/-66.15

- e->y => data-driven
  - yields of the probe-e CRs rescaled by fake rate (inherited from the monophoton analysis)
  - VV, VVV, top processes with fake photon
  - subtraction of jet->e in probe-e CRs based on MC and truth info
- **Fake MET** => data-driven
  - ABCD method
  - Zy, Zy+jets, Vyy, Higgs related bkgs
  - Subtraction of e->y contamination in B, C, D regions based on data-driven
  - The other backgrounds temporarily (?) subtracted from MC
- tty, single top, ttbar, Wty, VVy, Wy => MC





Fake E_T^{miss} ABCD optimization



$$N_A^{fakeMET} = R \times \frac{N_B N_C}{N_D}$$

$$R = \frac{N_A^{MC} N_D^{MC}}{N_C^{MC} N_B^{MC}}$$

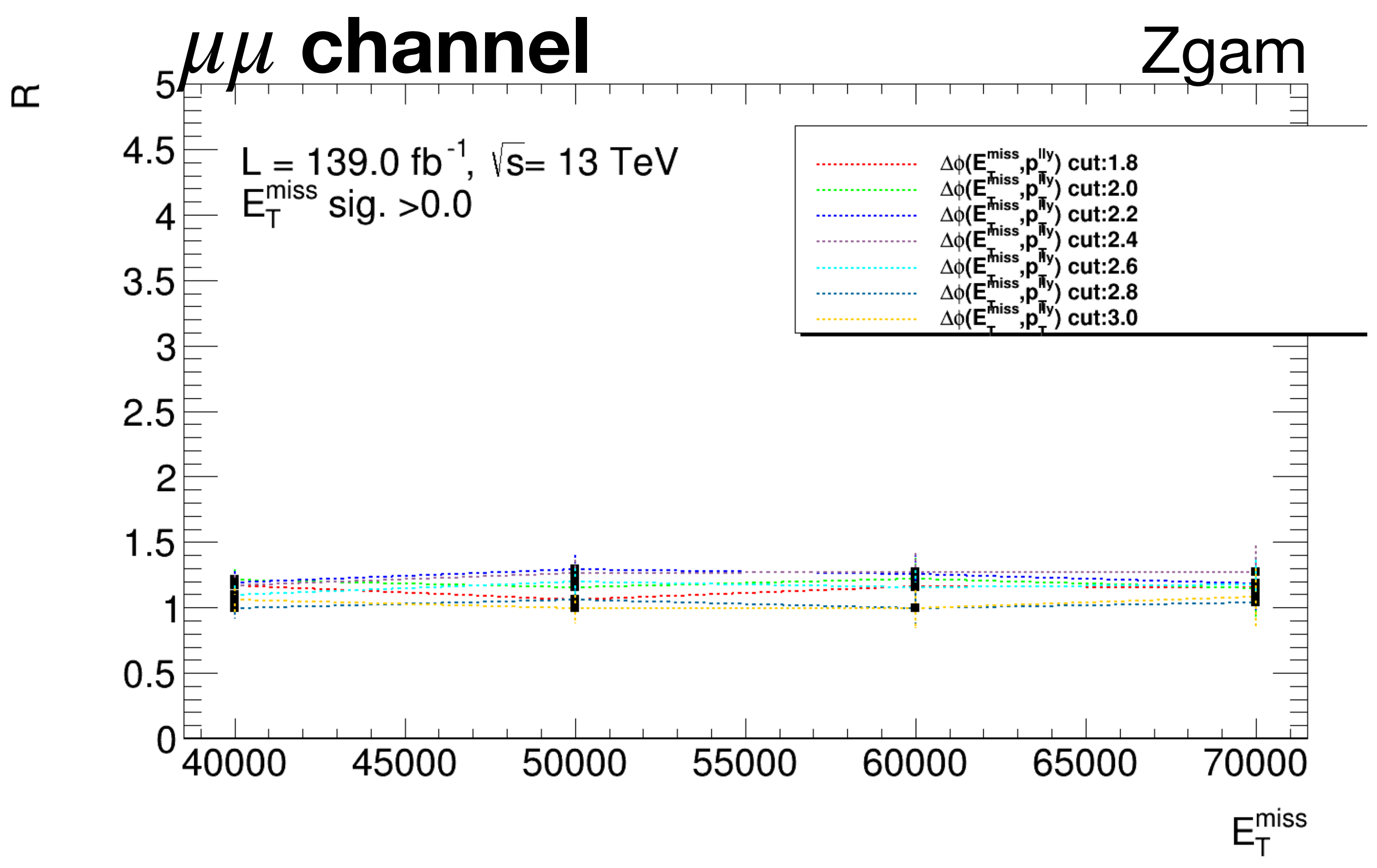
- Defining an ABCD method
  - Different pair of variables and cut values tested
  - Both MET significance and MET considered as a first variable

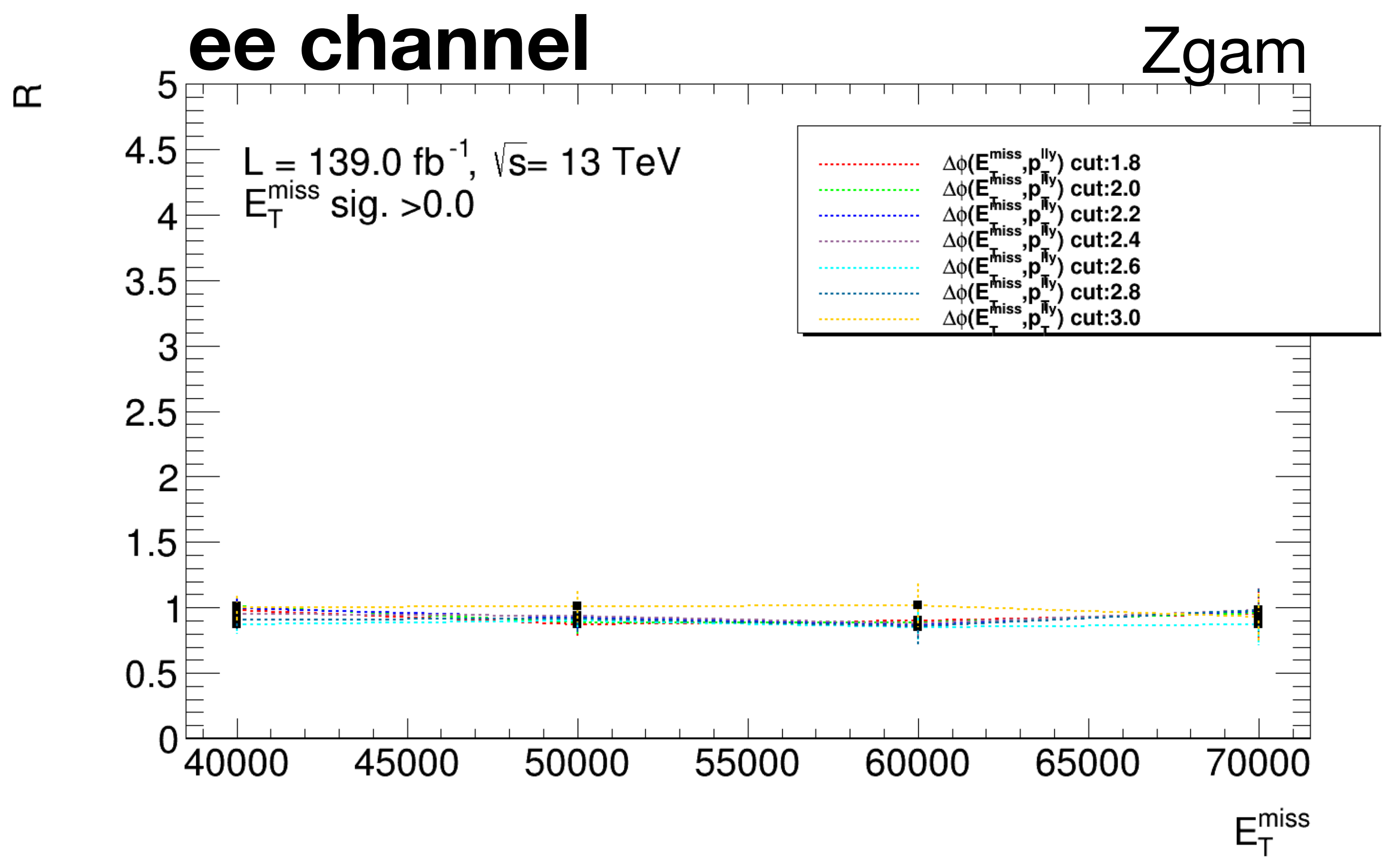
- Several second variables considered. Most promising from preliminary studies:

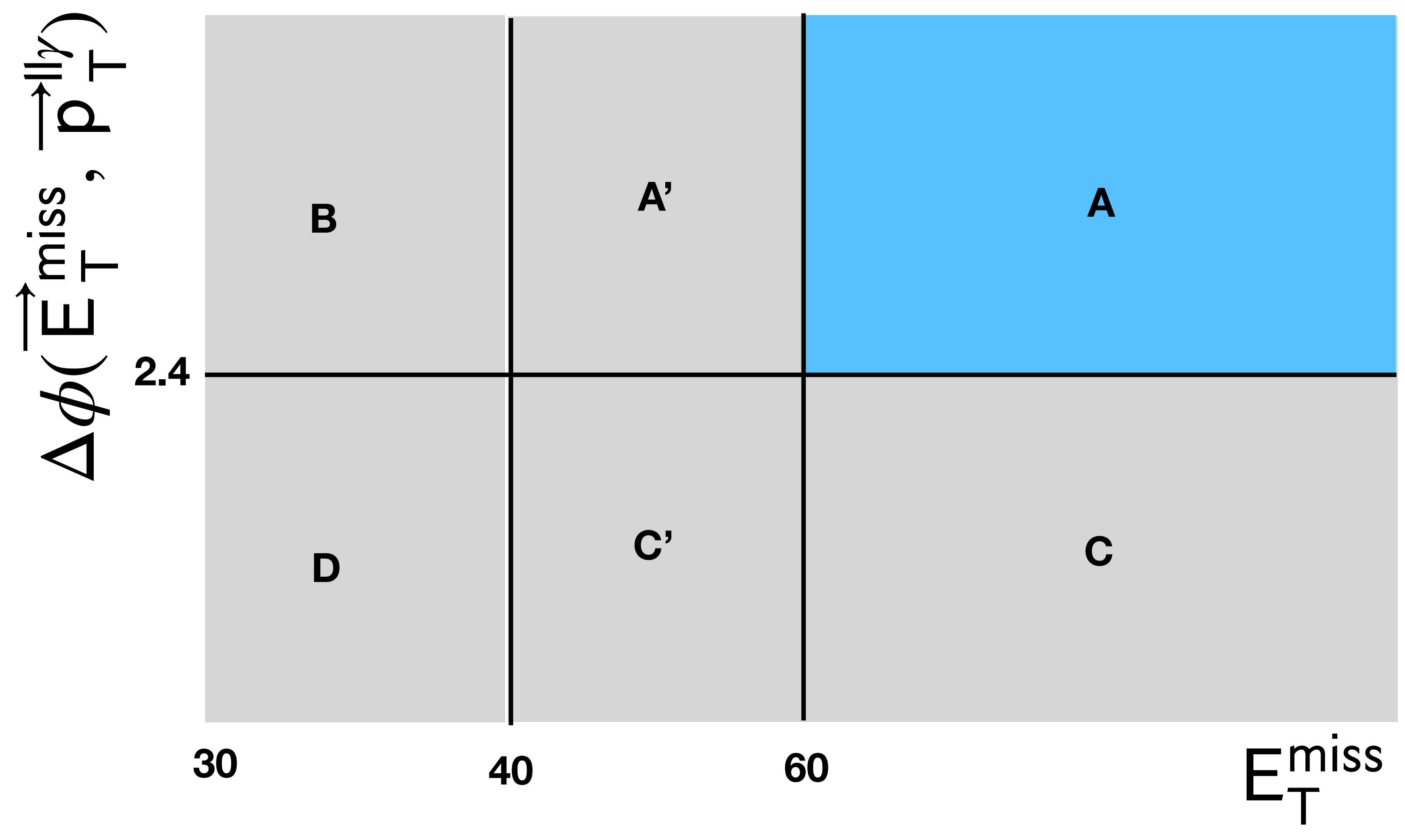
$\Delta\phi(\mathbf{E}_T^{miss}, \mathbf{p}_T^{ll\gamma})$ $\quad$ $\Delta\phi(|\mathbf{E}_T^{miss}+\mathbf{p}_T^{ll\gamma}|, \text{nearest}(\mathbf{E}_T^{miss},\mathbf{p}_T^{ll\gamma}))$ $\quad$ $|\mathbf{E}_T^{miss}/\mathbf{p}_T^{ll\gamma}|$

$\Delta\phi(\mathbf{E}_T^{miss} + \mathbf{p}_T^{\gamma}, \mathbf{p}_T^{ll})$ $\quad$ $\Delta\phi(\mathbf{E}_T^{miss}, \text{nearest obj.})$ $\quad$ $|\mathbf{E}_T^{miss}+\mathbf{p}_T^{ll\gamma}|/E_T^{miss}$

- Optimization criteria:
  - R stability: weak dependence of R coefficient on the choice of cut values
  - R close to 1 (uncorrelated variables)
  - High signal efficiency in SR and low real MET contamination in the CRs
  - Good statistics in CRs



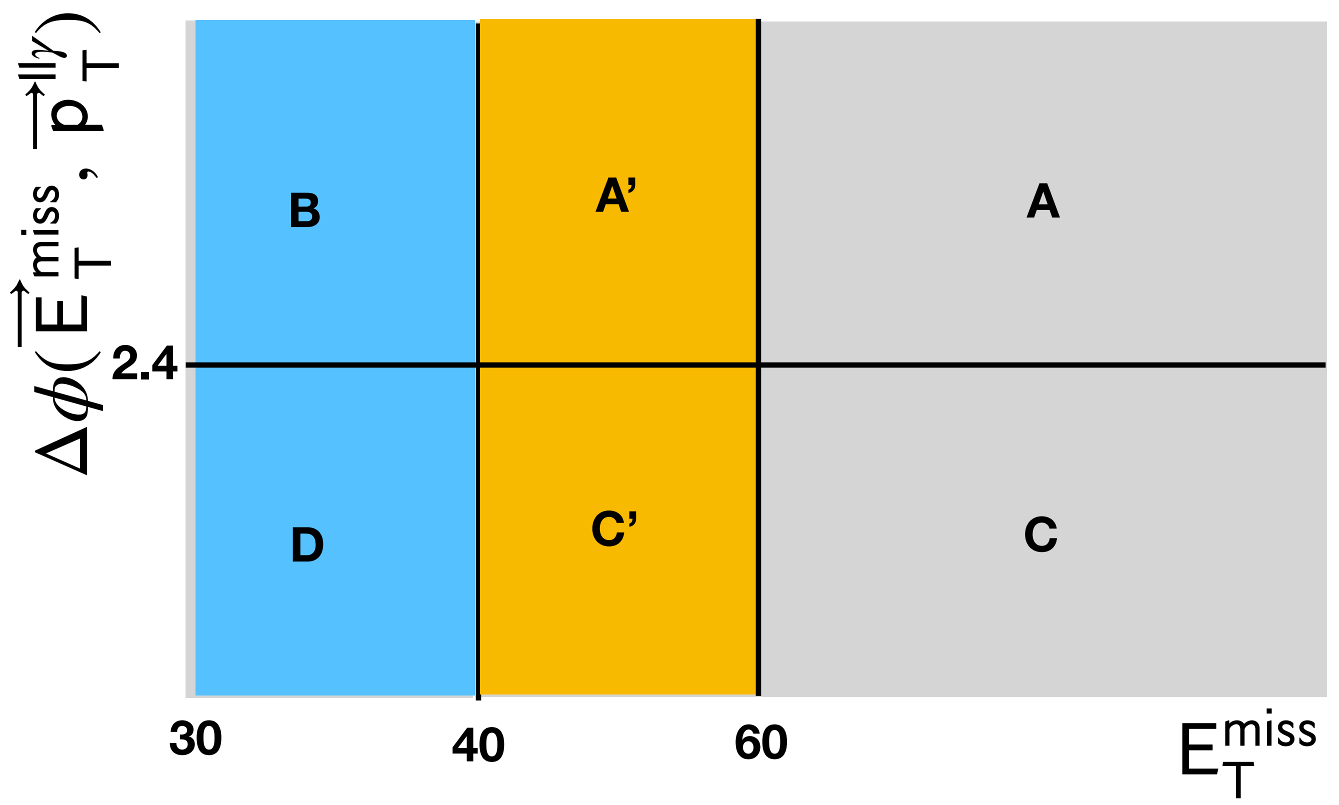


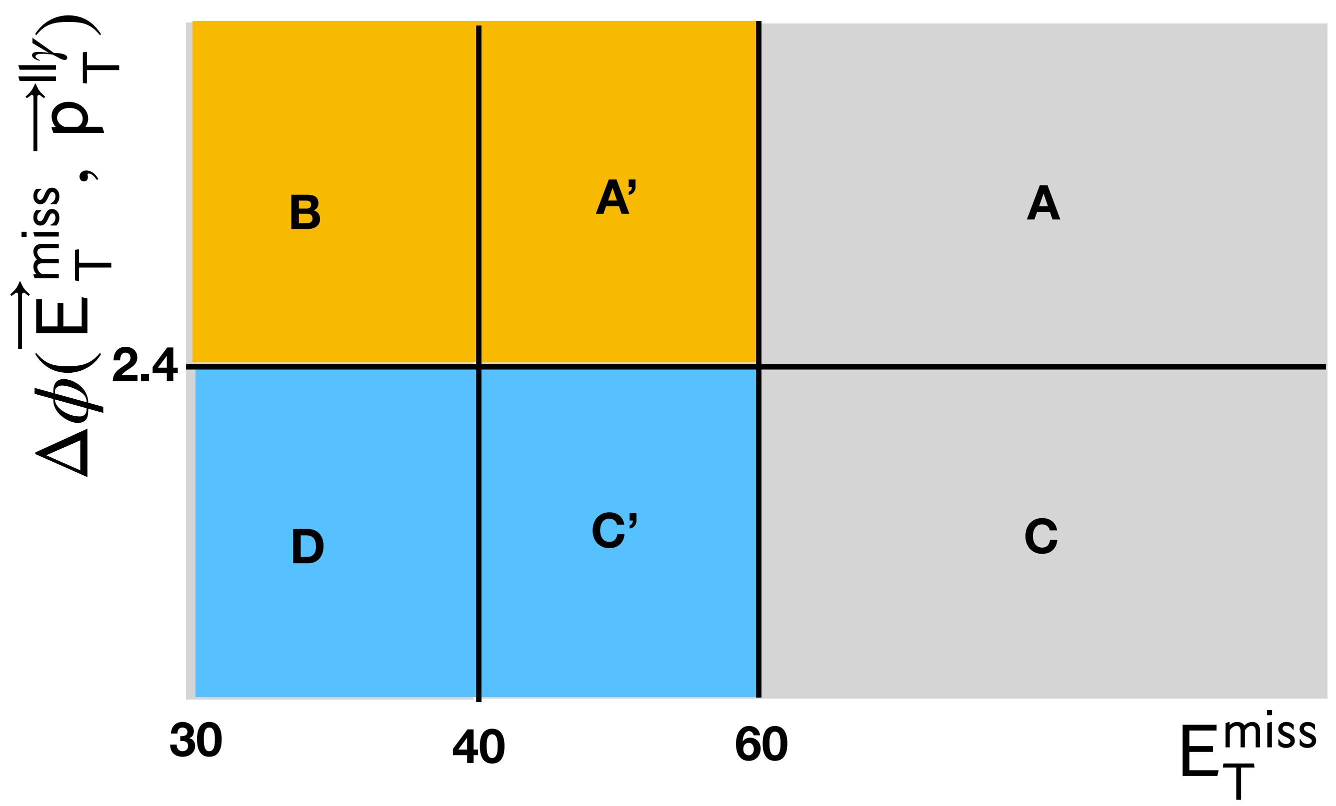


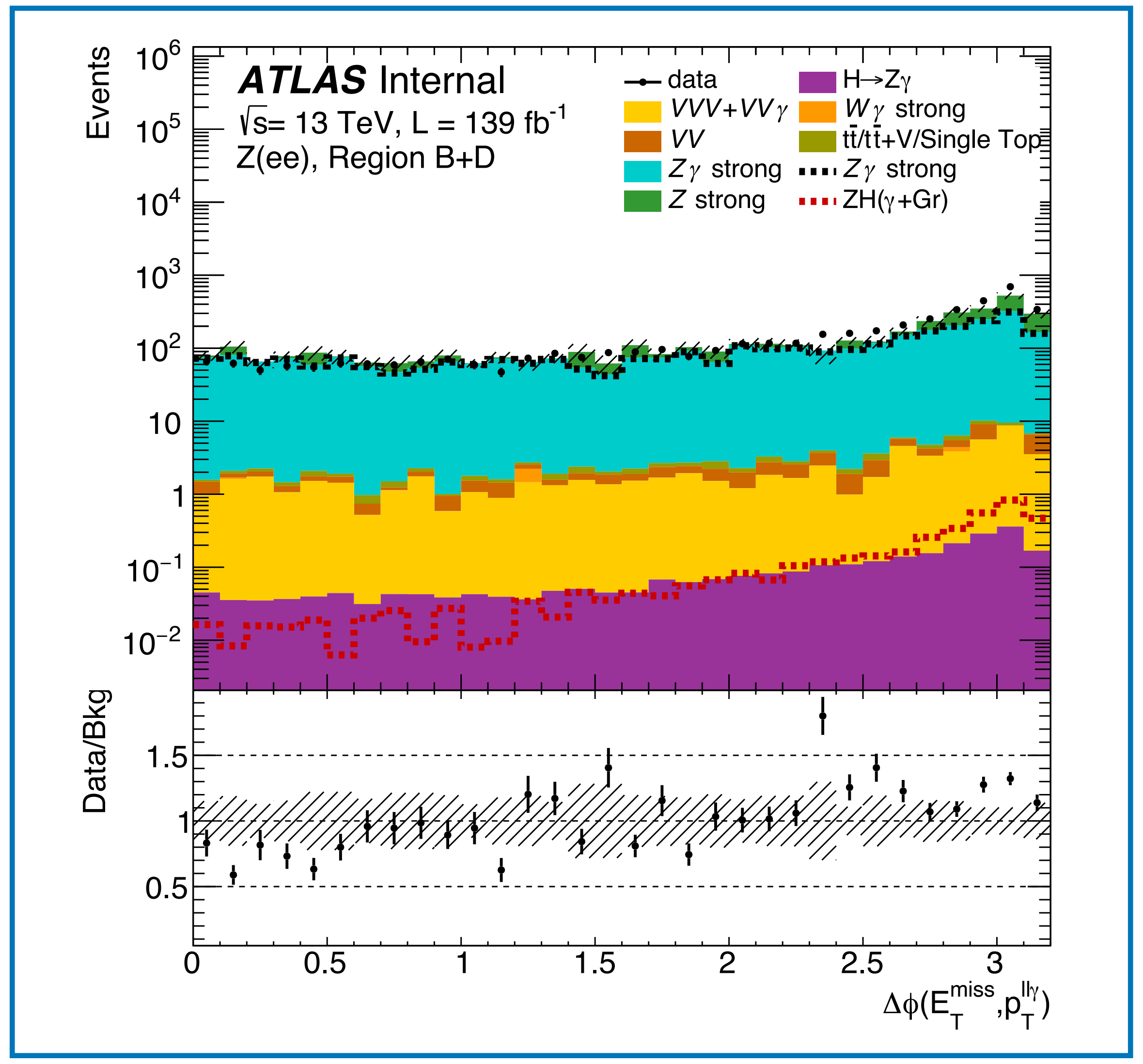
Data/MC agreement

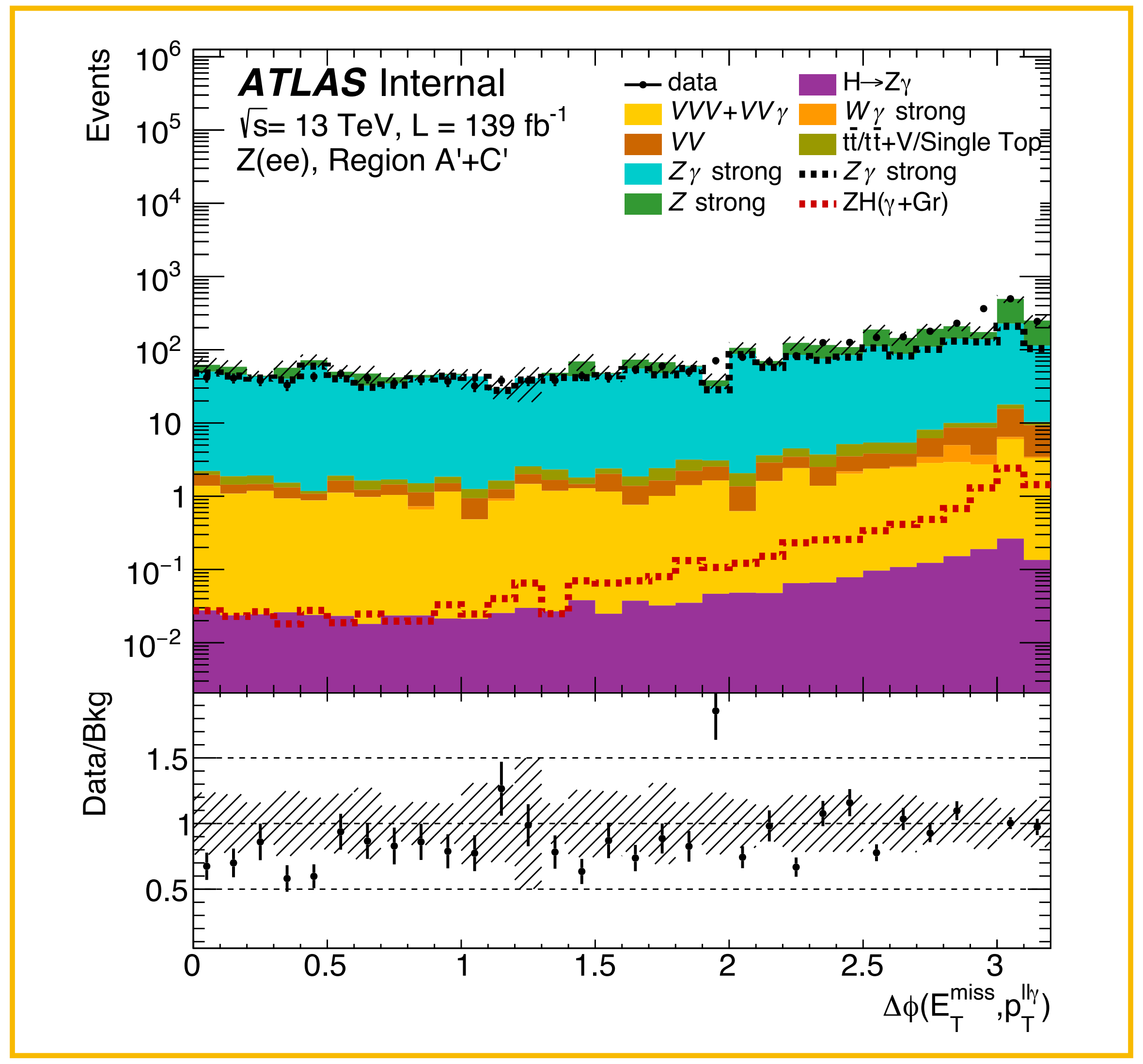
Channel	R'_{MC}	R'_{data}
ee	1.093 ± 0.122	1.163 ± 0.057
uu	1.151 ± 0.111	1.186 ± 0.052

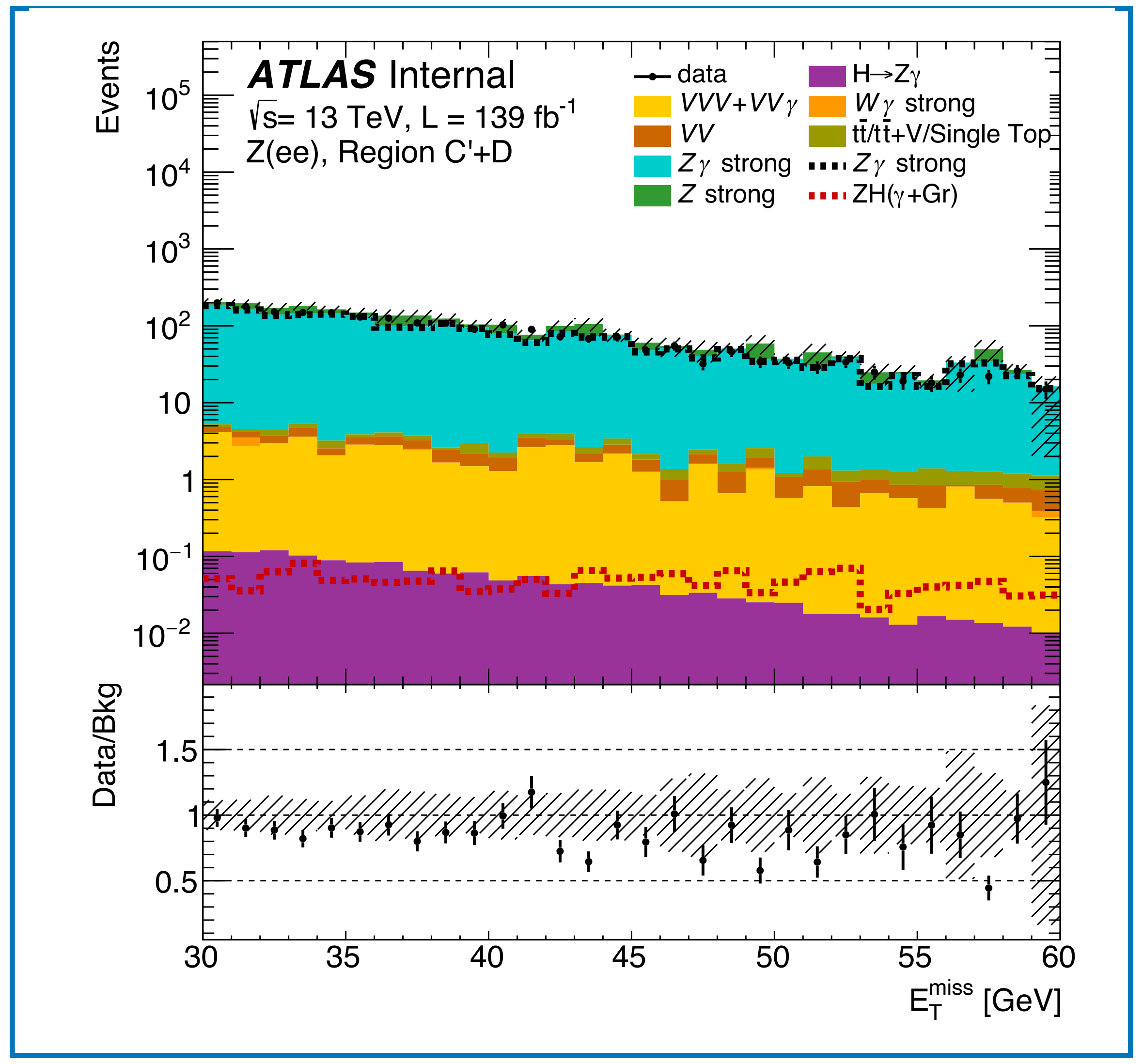
$$R' = \frac{N'_A N_D}{N'_C N_B}$$

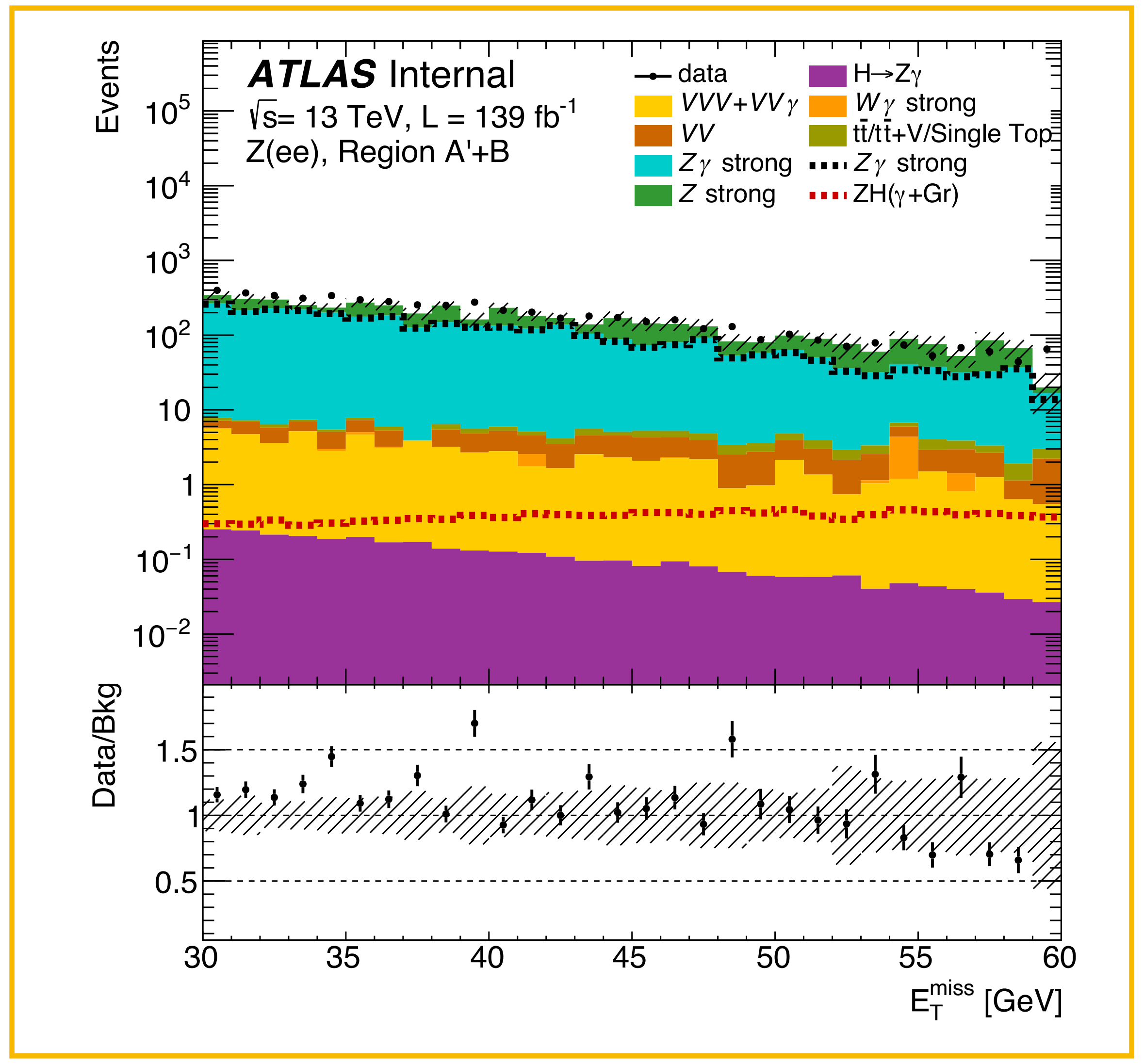








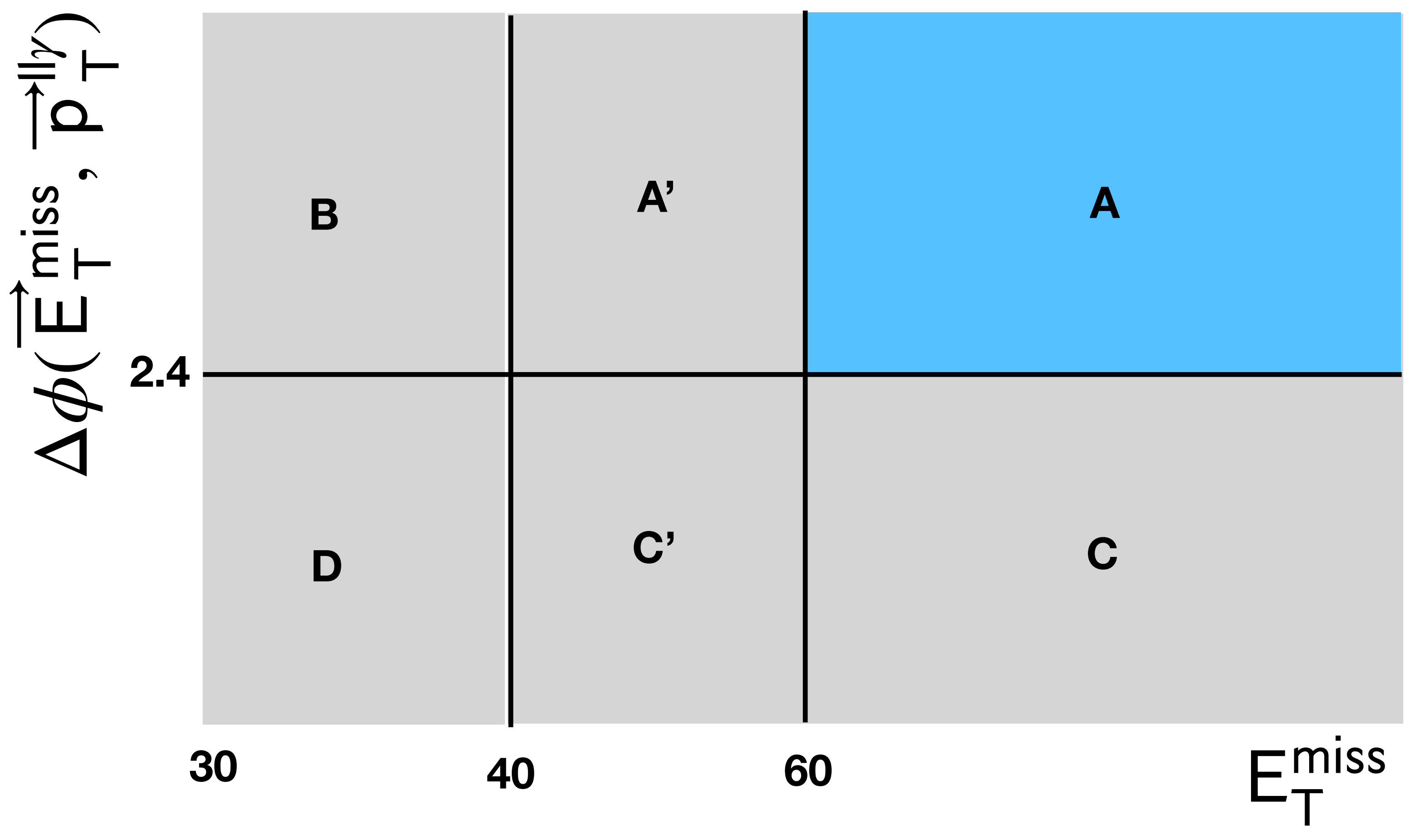


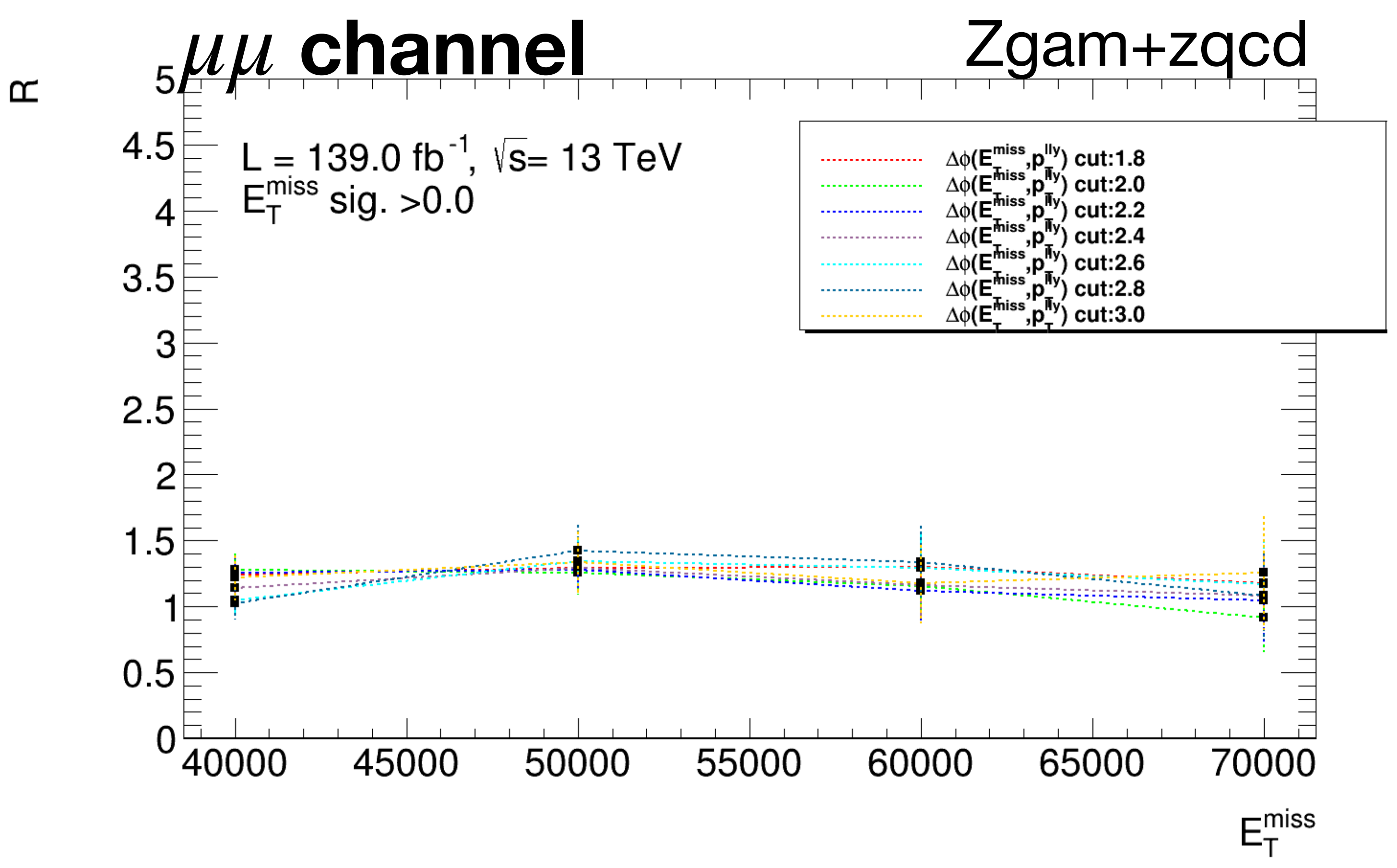


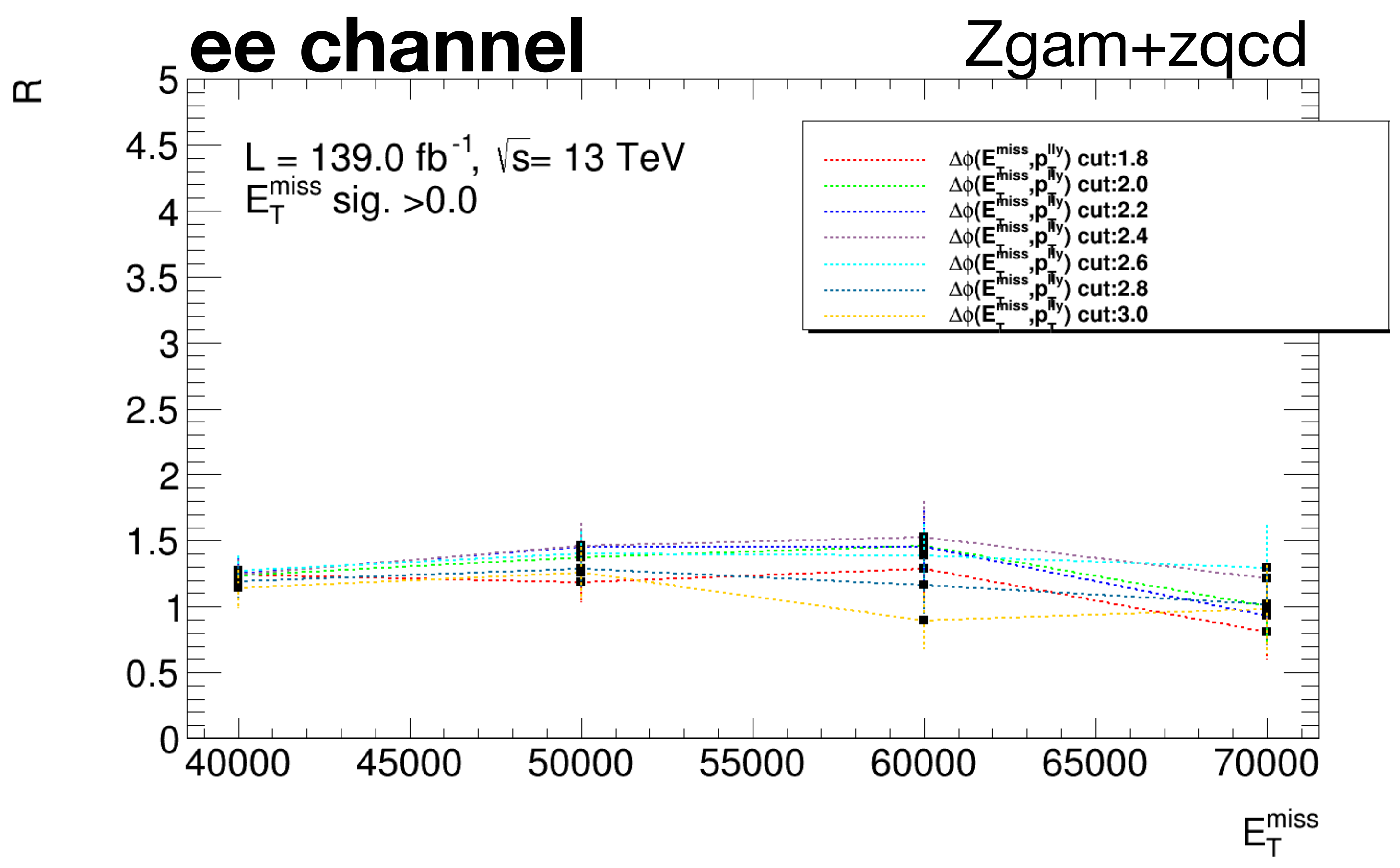
R estimation and uncertainty

- In the final estimates, R from zgam+zqcd+vyy+hzy
- R is stable with ETmiss
  => estimate R from (A+A')B(C+C')D

Channel	R	Rincl
ee	1.201 ± 0.236	1.115 ± 0.109
uu	1.627 ± 0.297	1.244 ± 0.113

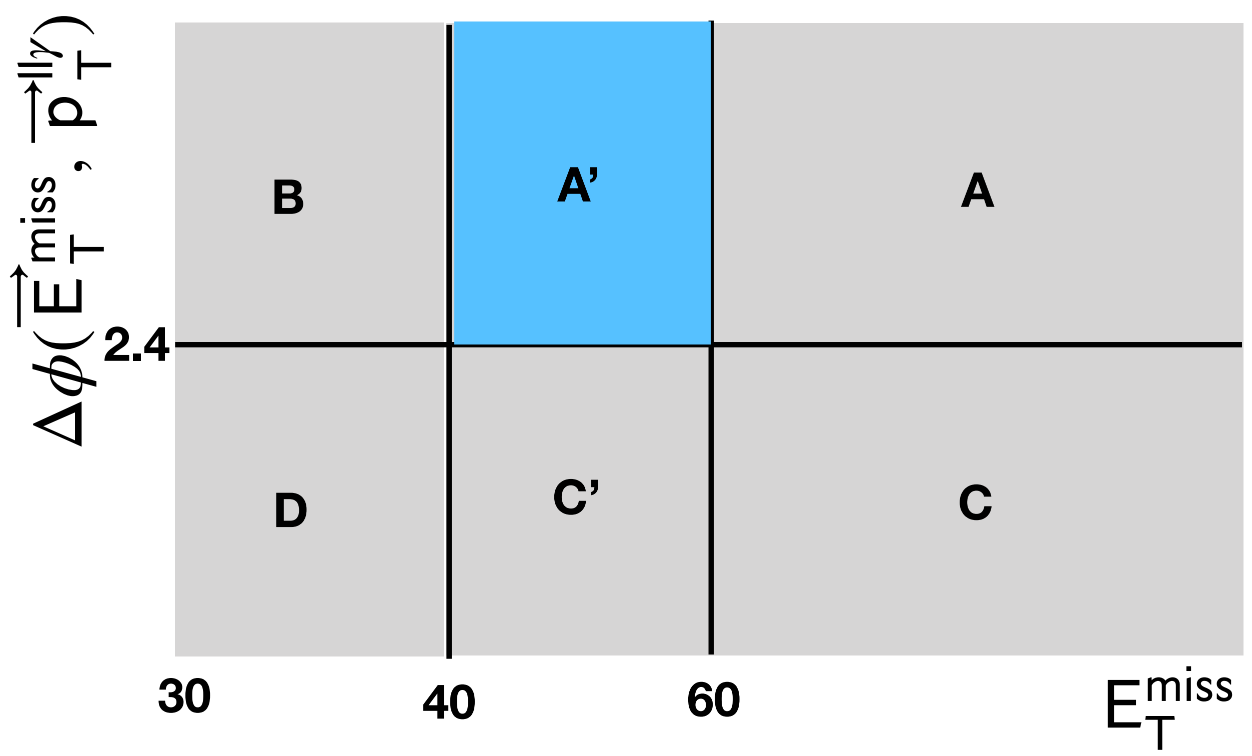






Background estimation in VR

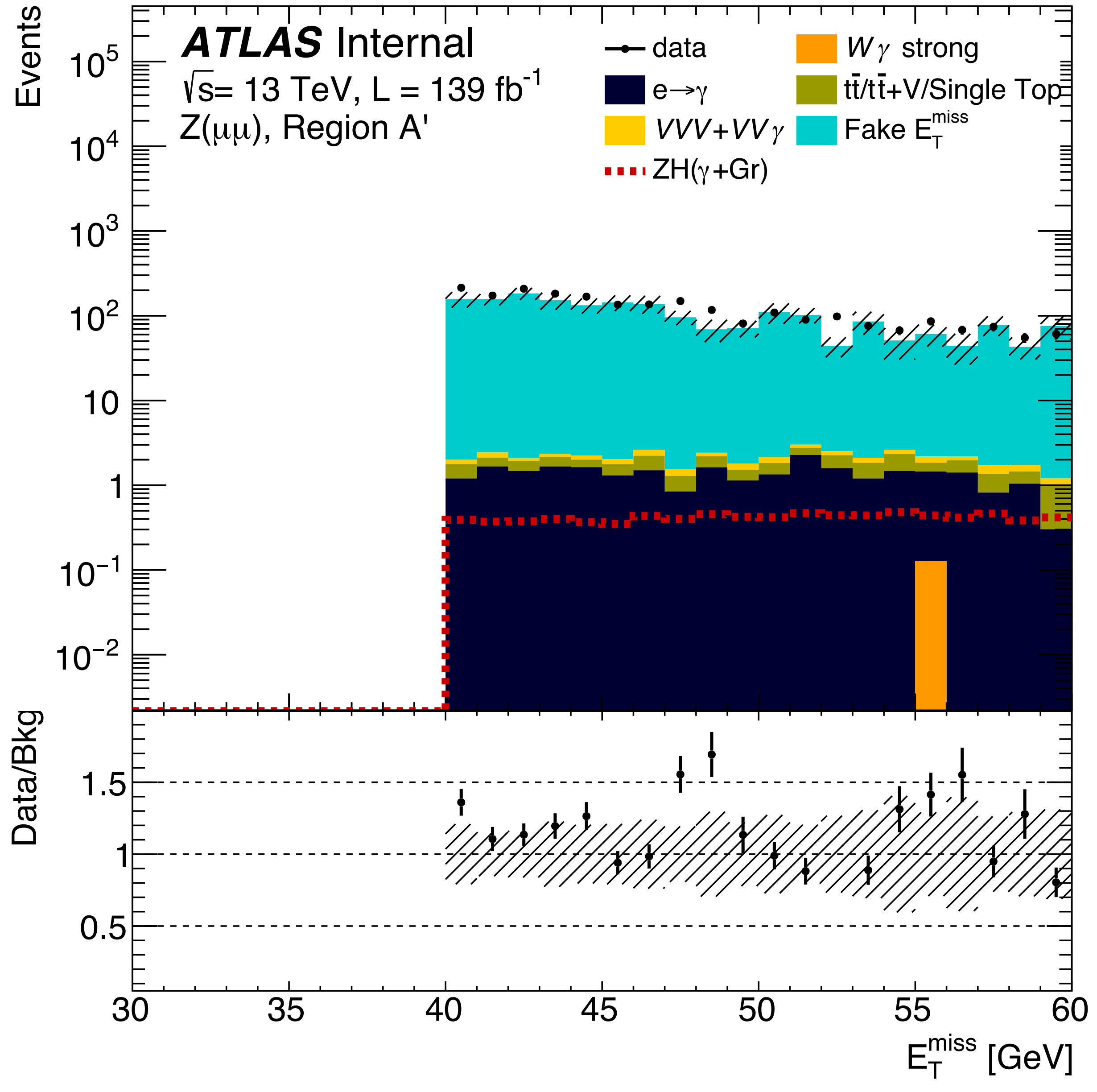
Channel	Fake MET MC	Fake MET ABCD	e->y MC	e->y Data-driven
ee	1531.971 ± 93.777	1782.236 ± 212.506	29.57 ± 1.11	31.96 ± 5.07
uu	1951.629 ± 108.805	2239.634 ± 233.106	27.12 ± 1.61	33.68 ± 3.88



Combining e->y and fake MET estimates (+ MC for other bkg)

Channel	$data$	MC	$Data - driven$
ee	1936 ± 44	1580 ± 93.5	1833 ± 121
uu	2347 ± 48.4	1995 ± 109	2289 ± 137

Pure MC



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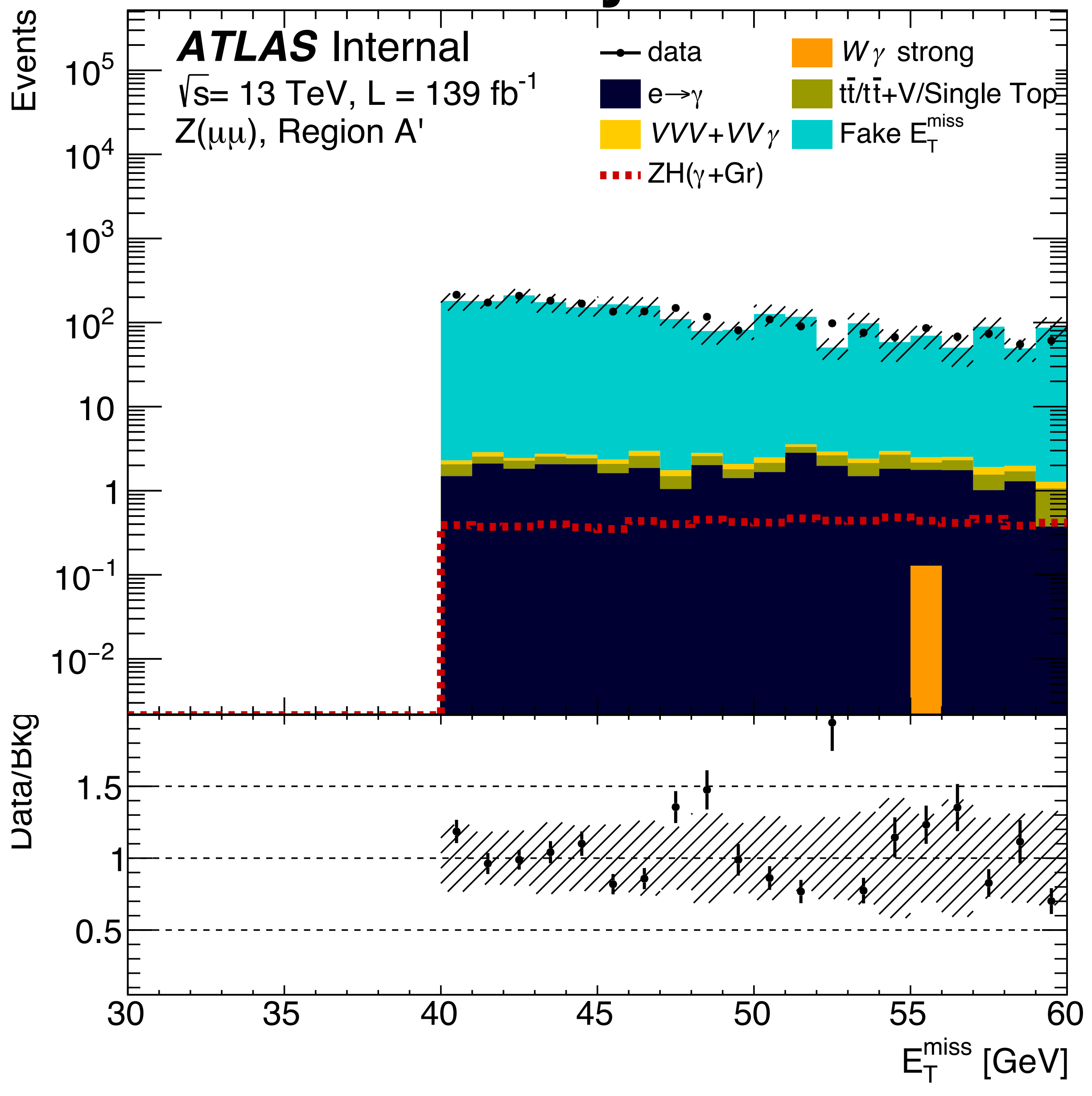

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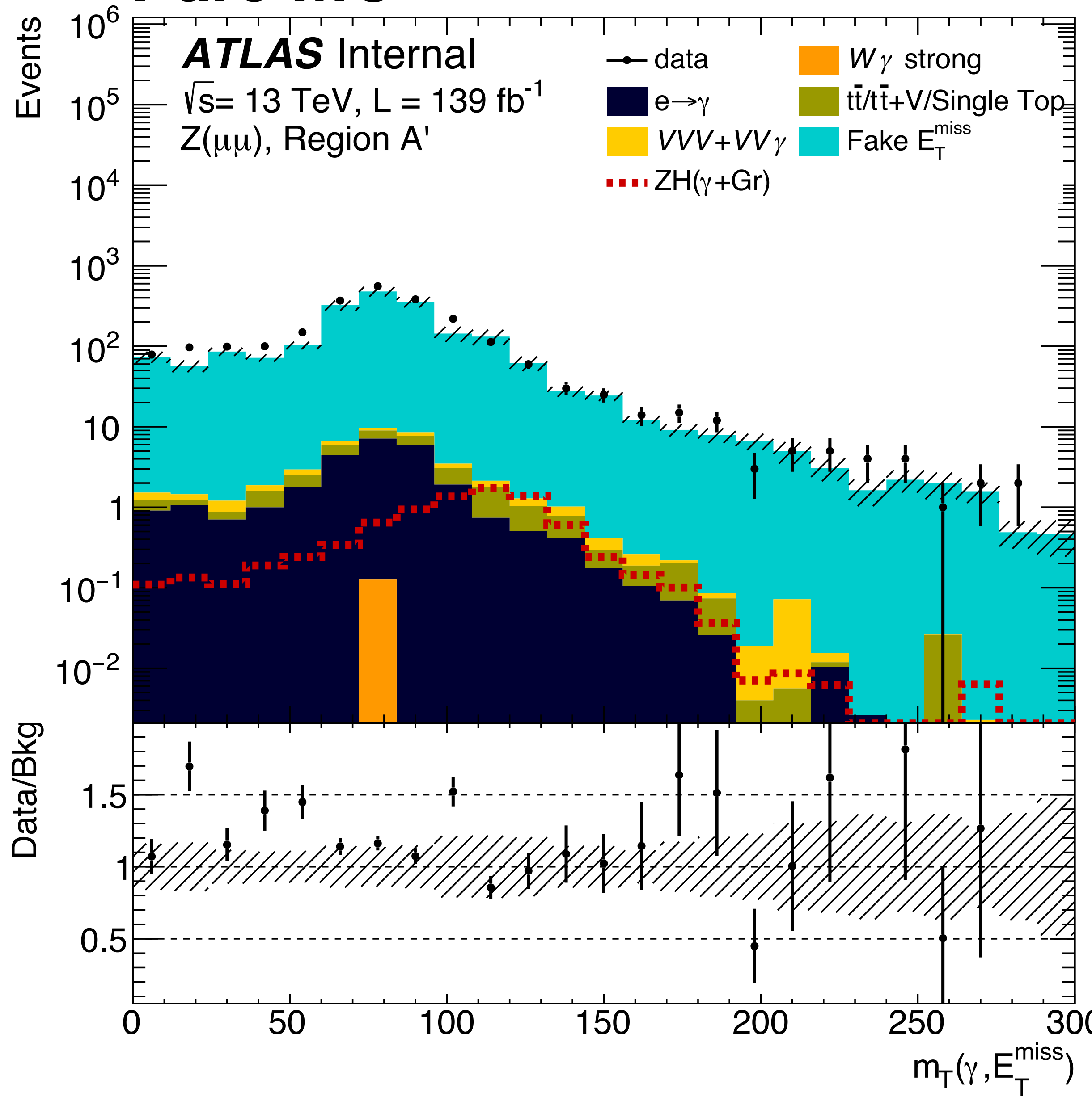

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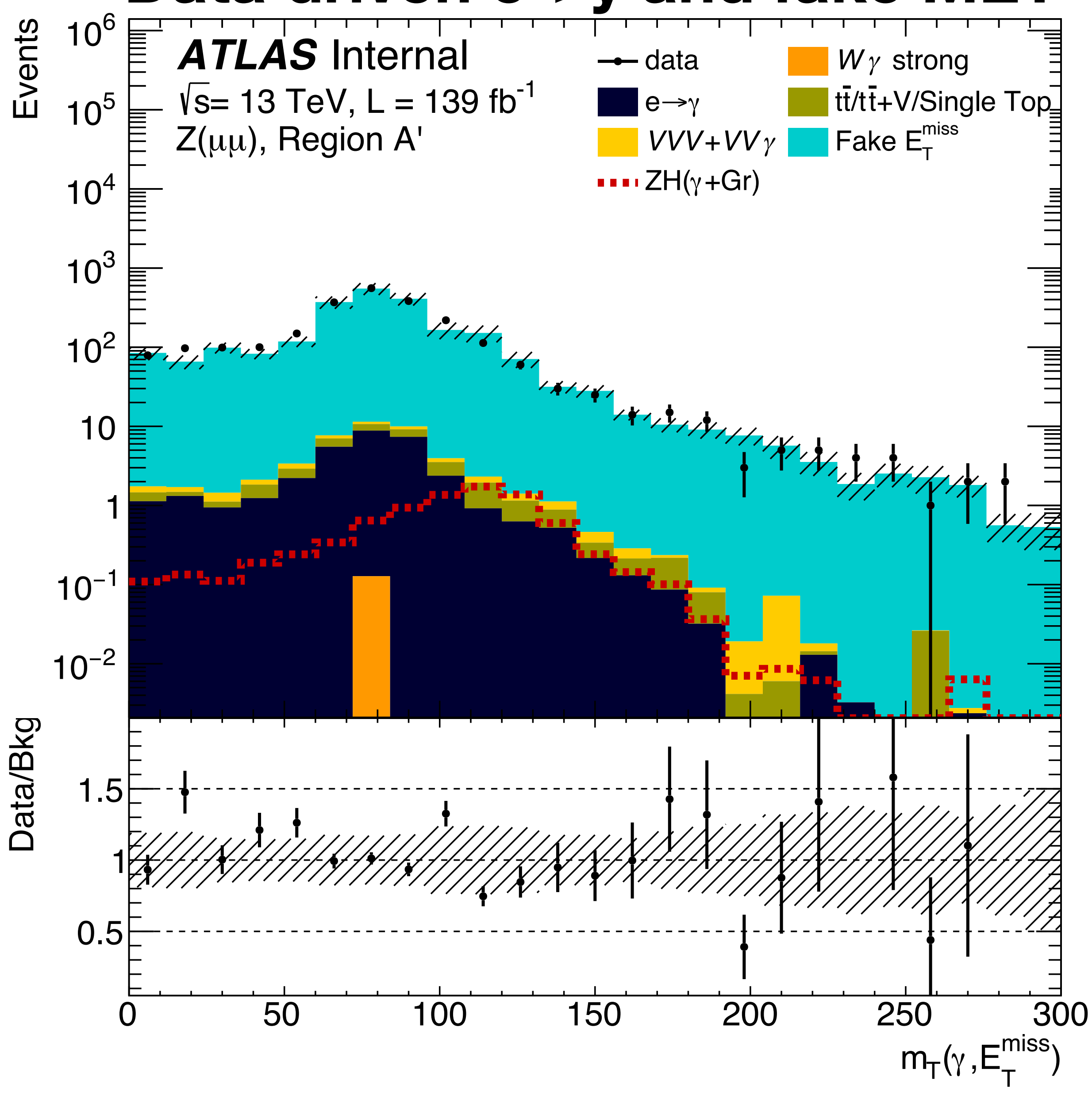

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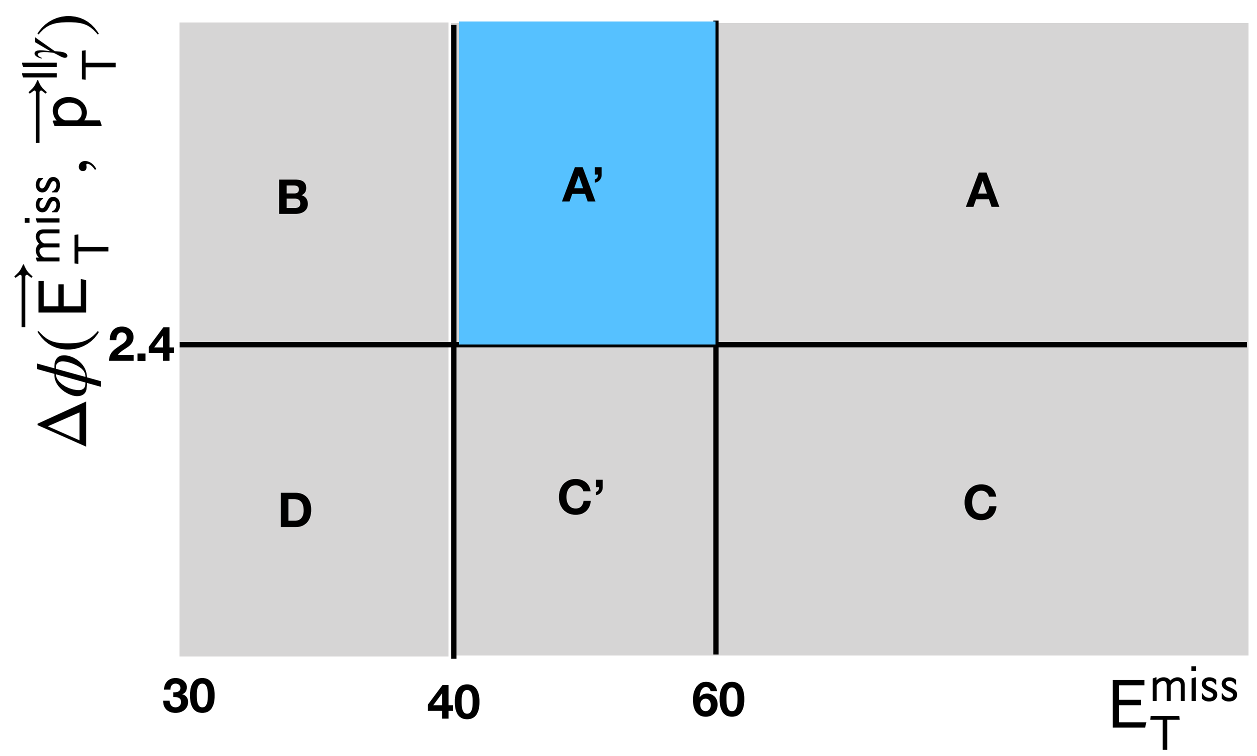

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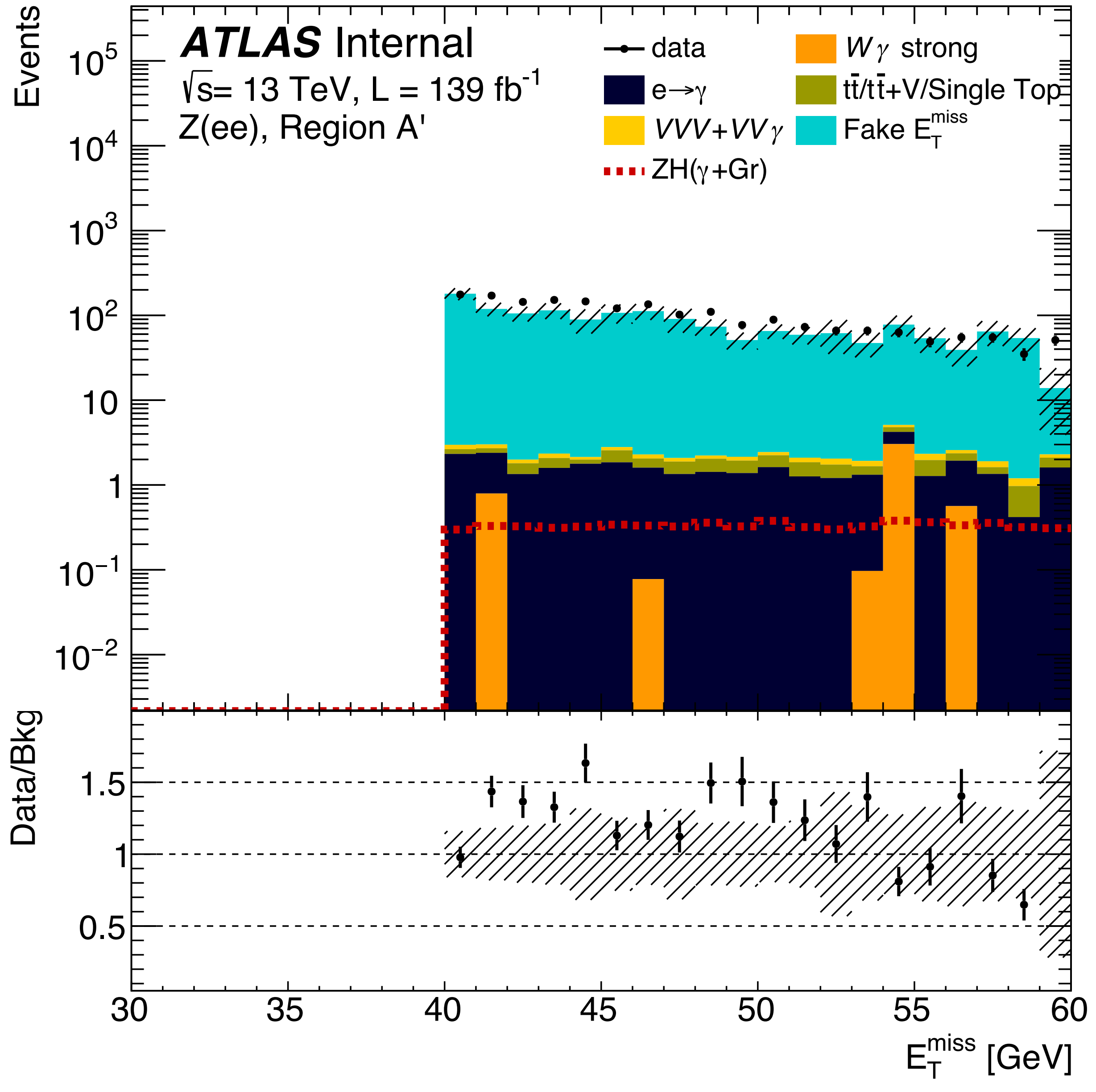
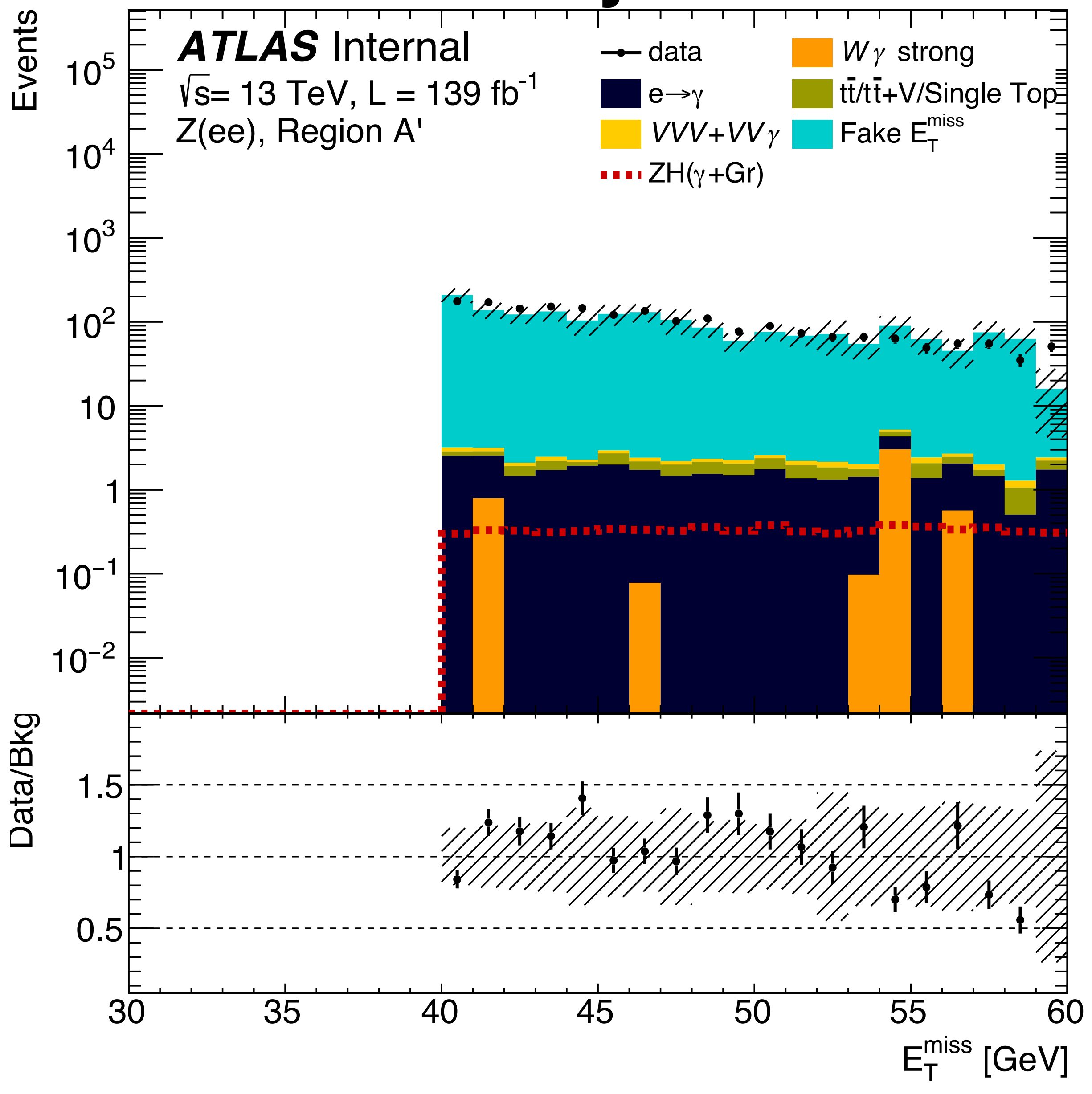
uu	2347 ± 48.4	1995 ± 109	2289 ± 137

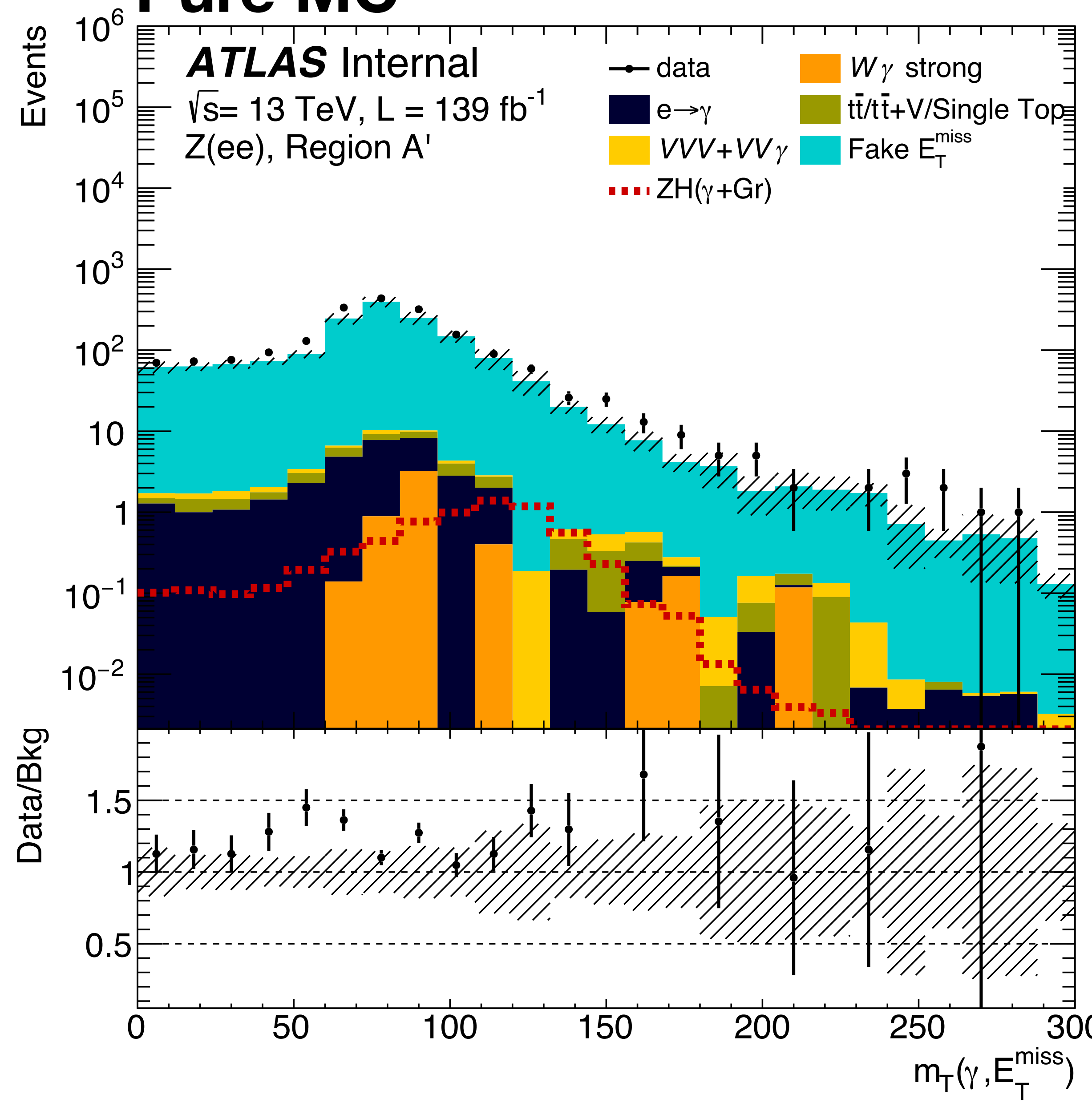
Pure MC



Data driven e->y and fake MET



Pure MC



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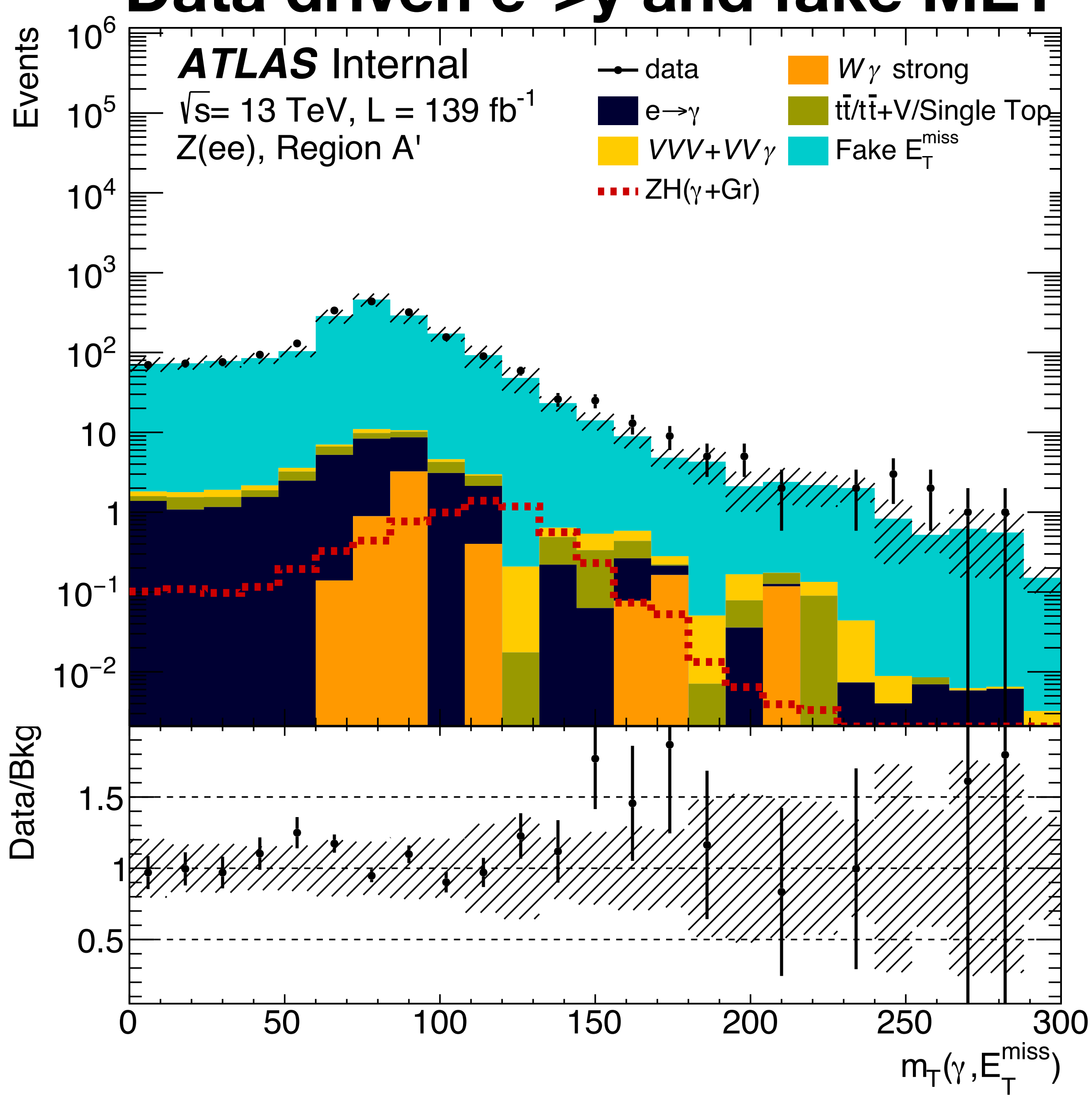


Results in SR and fit strategy

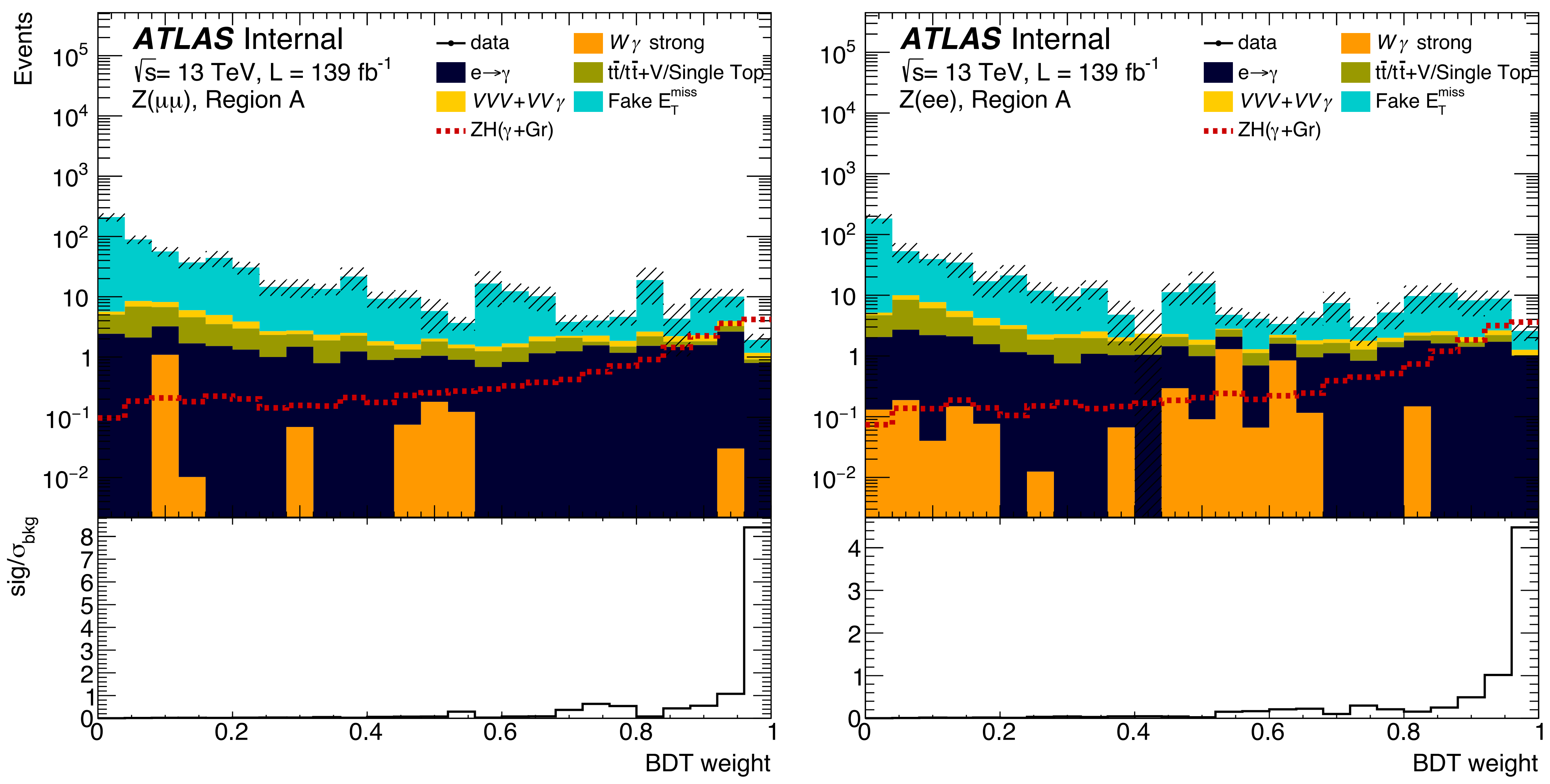
Data-driven estimates in SR

	Fake MET		e->y	
Channel	MC	Data-driven	MC	Data-driven
ee	433.29 ± 56.94	413.8 ± 54.9	31.11 ± 1.12	26.74 ± 3.74
uu	670.75 ± 66.13	578.0 ± 64.5	28.74 ± 1.15	25.97 ± 3.12

Fit strategy

- BDT weights as discriminant variable
- Preliminary binning optimization based on s/σ_b
  - Starting from last bin, merge with previous bins until $(s/\sigma_{b+s})_{step-i} > (s/\sigma_{b+s})_{step-(i-1)}$
  - Iterate until first bin

▶ 0.20 - 0.40 - 0.60 - 0.85 - 0.92 - 0.96 - 1
  - First bins could help constraining bkg
  - BDT < 0.6 => very low sensitivity
  - We can probably use tighter binning for BDT > 0.9 to take advantage of particularly higher sensitivity in this region
  - Lowest bins may help constraining background



- **MC rescaled by data-driven estimates**
- Only stat + syst from data-driven

Input variables:

m_T

$\frac{|\vec{E}_T^{miss} + \vec{p}_T^{\gamma}| - p_T^{ll}}{p_T^{ll}}$

photon p_T

$m_{ll\gamma}$

m_{ll}

MET sig

Expected exclusion limits (Preliminary)

- Using **HistFitter**:
  - BDT shape from MC
  - BDT templates: e->y, fake MET, top, Wgam, VVy
  - Free parameter: signal strength mu_SIG
  - e->y and fake MET bkg: MC rescaled by data-driven estimate, yields constrained by syst uncertainties (included in the likelihood as nuisance parameters, correlated among different bins)
  - top+y, Wgam, VVy backgrounds: temporarily MC. Only stat uncertainty considered
- Exclusion limits provided on signal strength for BR=5%. Can be translated into limits on $\sigma_{ZH} \times \mathrm{BR}(H \to \mathrm{inv} + \gamma)$
- CMS results: BR > 3% excluded at 95% CL

uu channel

```
expected limit (median) 0.759121
expected limit (-1 sig) 0.509608
expected limit (+1 sig) 1.1514
expected limit (-2 sig) 0.360168
expected limit (+2 sig) 1.68947
```

ee channel

```
expected limit (median) 0.95122
expected limit (-1 sig) 0.647391
expected limit (+1 sig) 1.42339
expected limit (-2 sig) 0.463979
expected limit (+2 sig) 2.06529
```

Combined

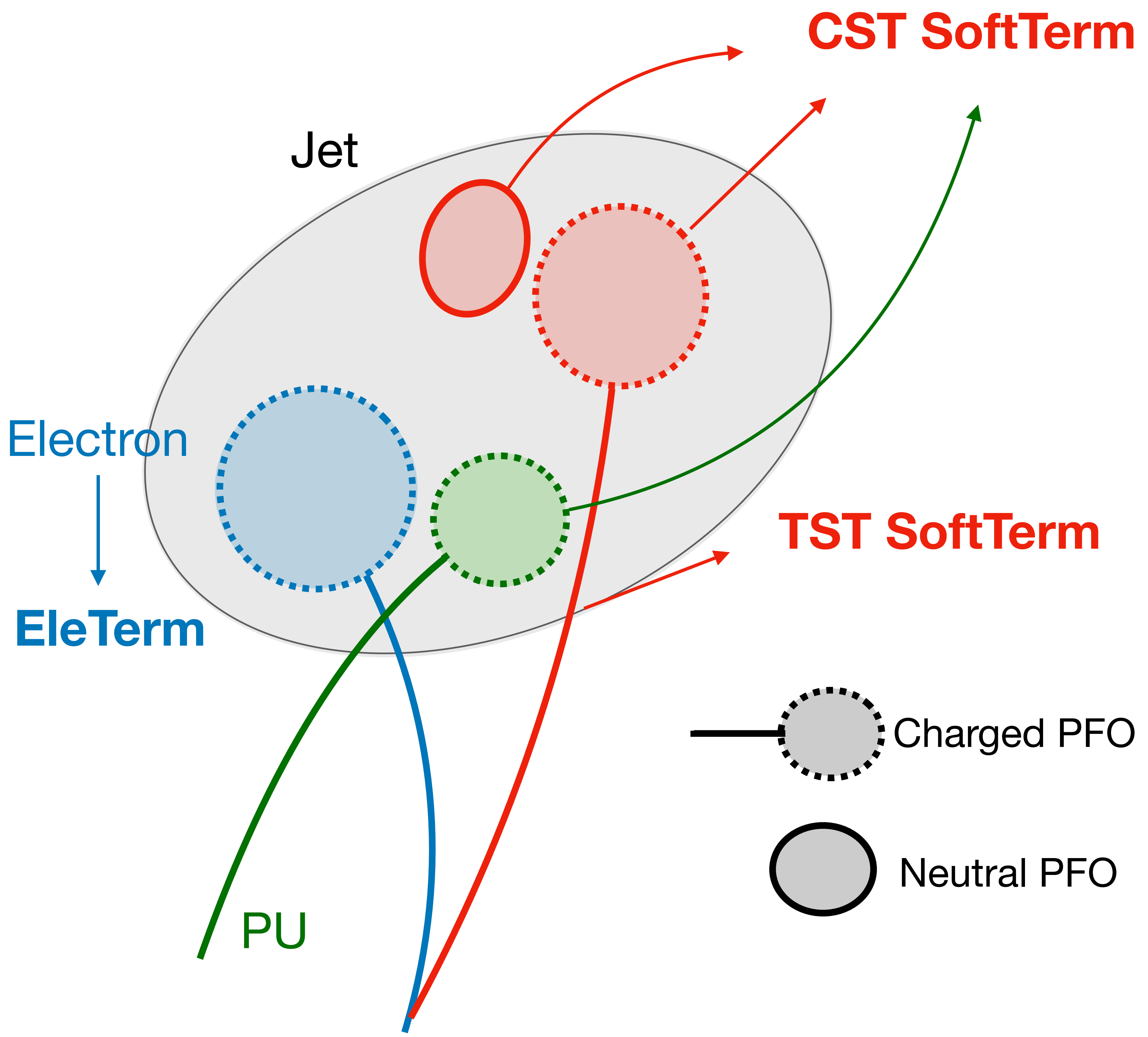
```
expected limit (median) 0.414193
expected limit (-1 sig) 0.280167
expected limit (+1 sig) 0.621804
expected limit (-2 sig) 0.199814
expected limit (+2 sig) 0.905257
```

Global Particle Flow E_T^{miss} (QT)

Introduction

MET reconstruction

- $\vec{E}_T^{miss} = -\sum \vec{p}_T^{\mu} - \sum \vec{p}_T^{e} - \sum \vec{p}_T^{\gamma} - \sum \vec{p}_T^{\tau} - \sum \vec{p}_T^{jets} - \sum \vec{p}_T^{soft}$
  - Hard term: fully reconstructed and calibrated objects
  - Soft term: signals not associated to reconstructed objects
    - CST: Cluster Soft Term
    - TST: Track Soft Term
- Signal ambiguity resolution based on association between signals and reconstructed physics objects in MET Association Map



Global Particle Flow (Rel. 22):

- Aim to combine measurements from the tracker and the calorimeter to build the constituents (Particle Flow Objects, PFOs) for each reconstructed physics object exploiting at best all detector information
- PFOs (or FlowElement) associated to each reconstructed particle with direct links
- Signals in MET reconstruction: tracks/clusters => neutral/charged PFOs (FE)

PFO association with links in MET

Standard PFlow MET

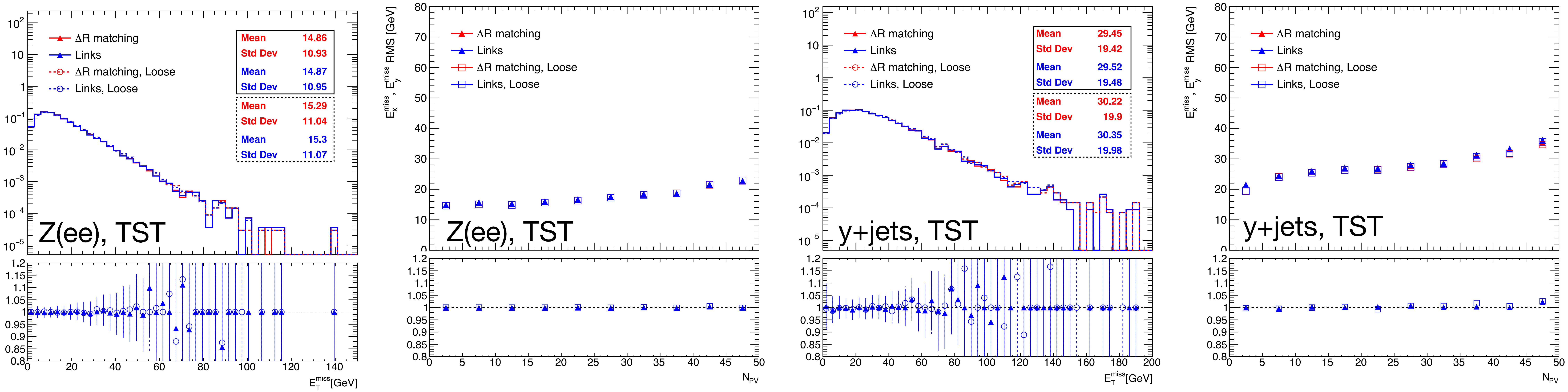
PFO association to leptons and photons through ΔR or clusters/tracks matching

GPF MET

PFO association to leptons and photons using direct links

- Links between leptons/photons and PFOs integrated into the MET Association Map
- Preliminary validation of direct links between e/γ objects and PFOs:
  - Z(ee), W(ev), y+jets topologies
  - both TST and CST
  - Looser and tighter object selections

Good agreement in MET performances between standard and GPF MET reconstruction



JetTerm from “Overlap Removed” Jet collection

Standard PFlow MET

JetTerm from AntiKt4EMPFlowJet + overlap removal with other physics objects within MET

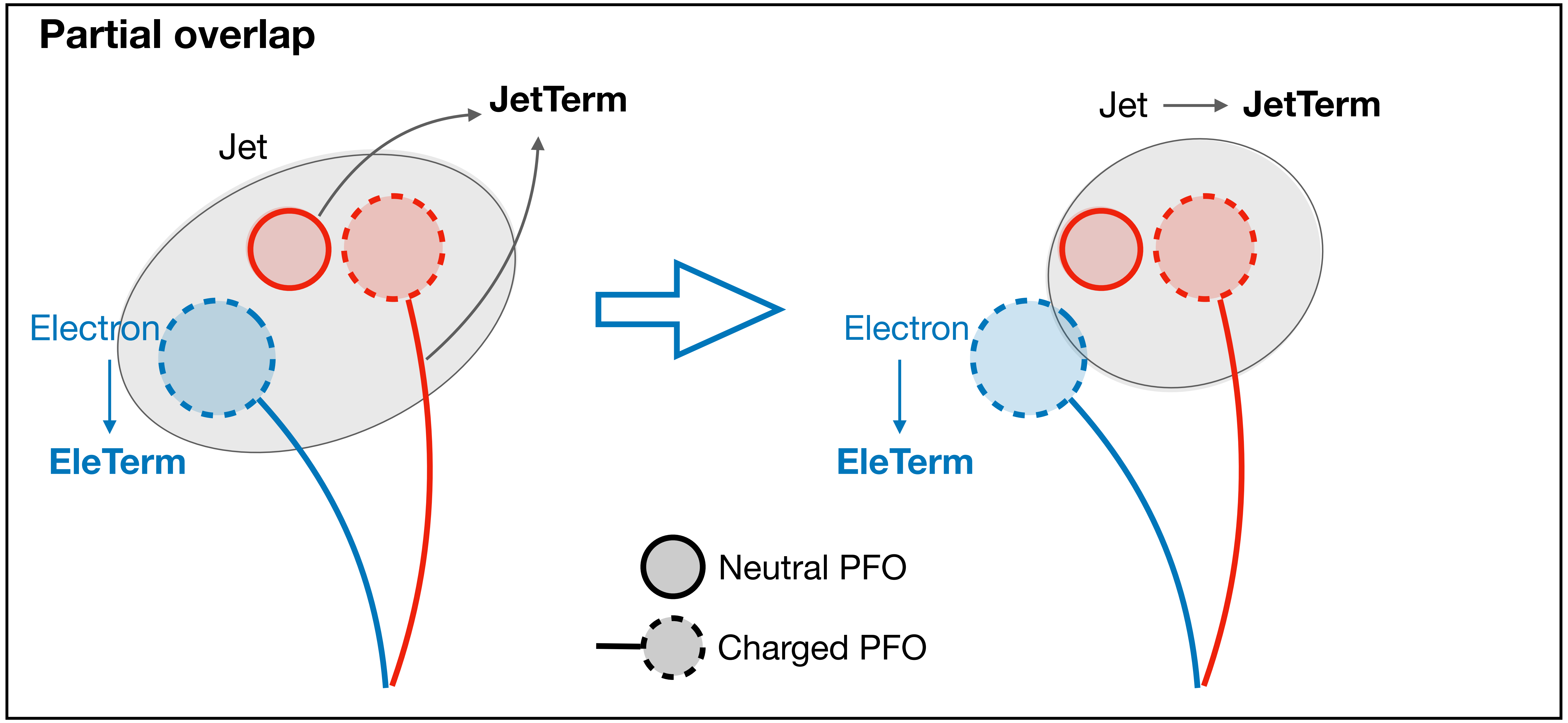
Energy of overlapping object subtracted from jet at constituent level

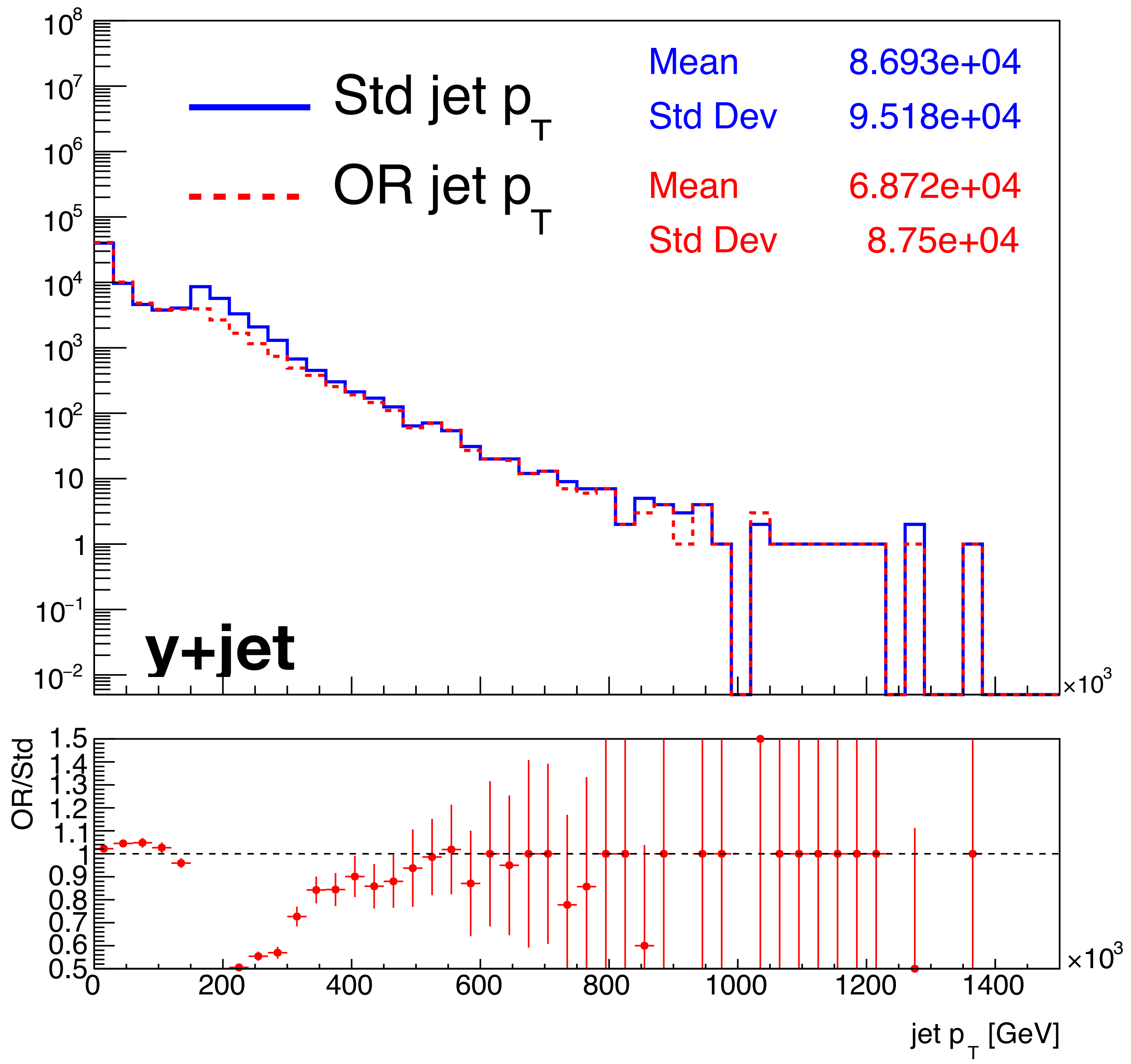
- **residual energy of the jet > 20 GeV => rescaled to recover calibration and added to the JetTerm (partial overlap)**
- residual energy of the jet < 20 GeV => jet added to the SoftTerm at constituent scale (exact overlap)

GPF MET

JetTerm from new “Overlap Removed (OR)” jet collection, i.e. jets reconstructed only from constituents not already associated to other selected physics objects in MET

- Constituents associated to selected physics objects not given as input to jet reconstruction.
- Soft constituents enter the SoftTerm





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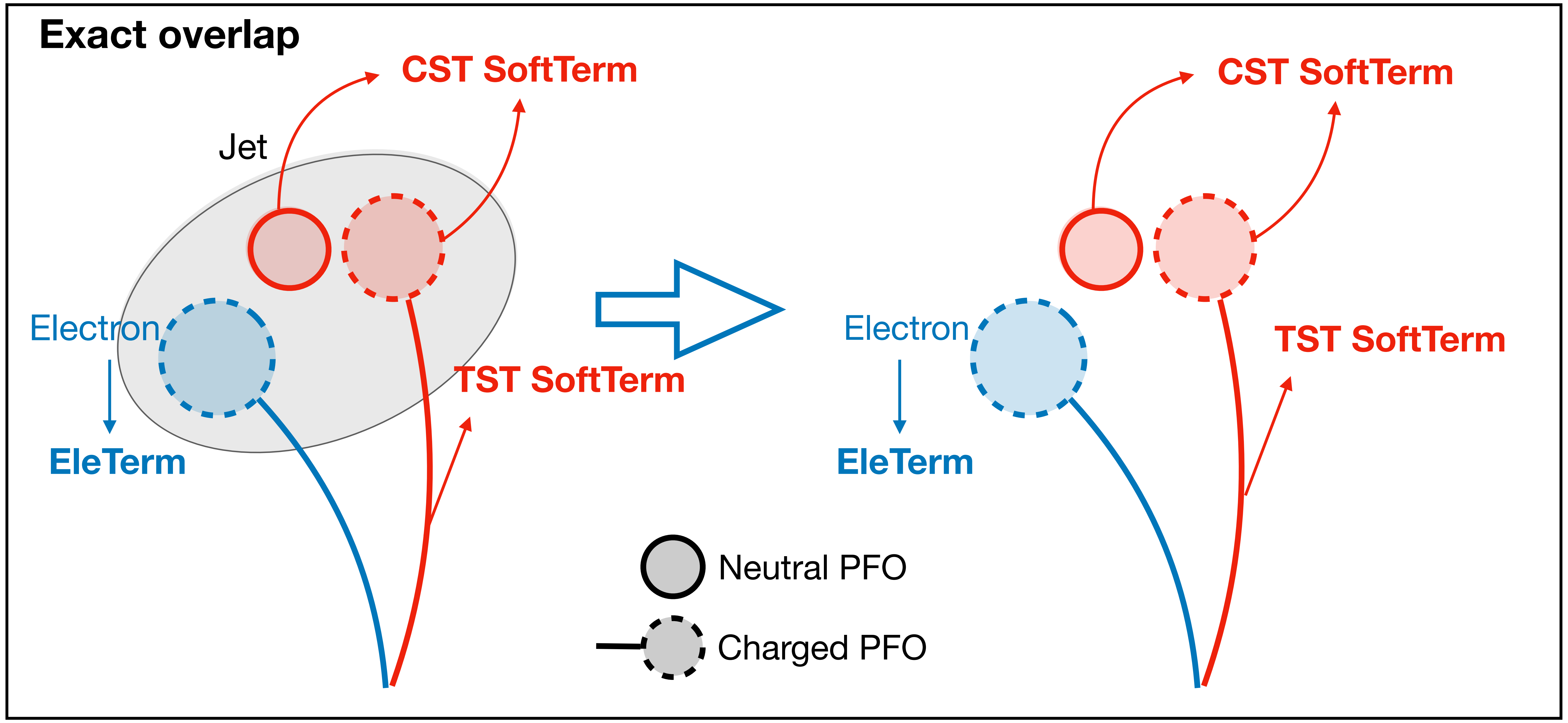
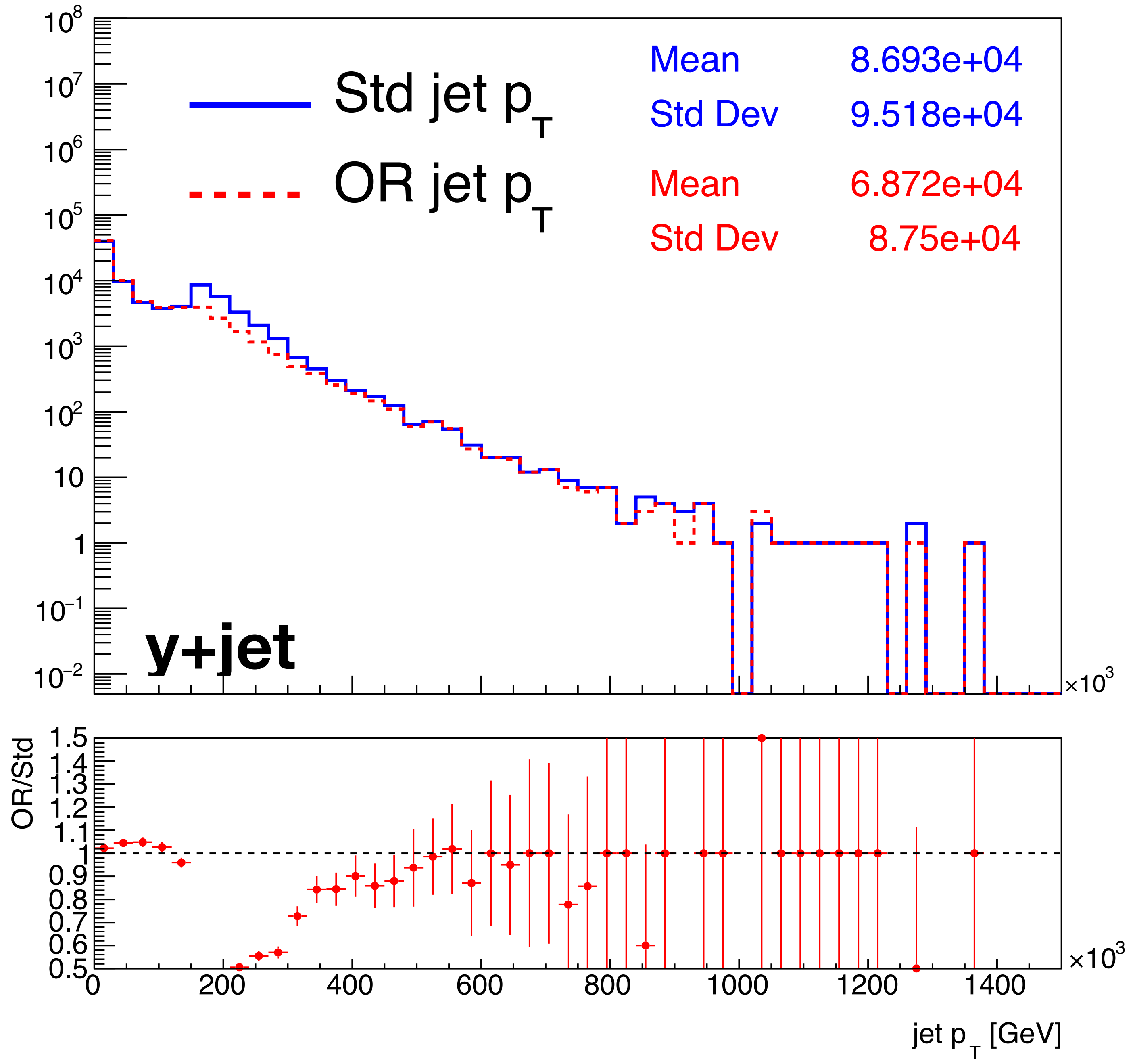
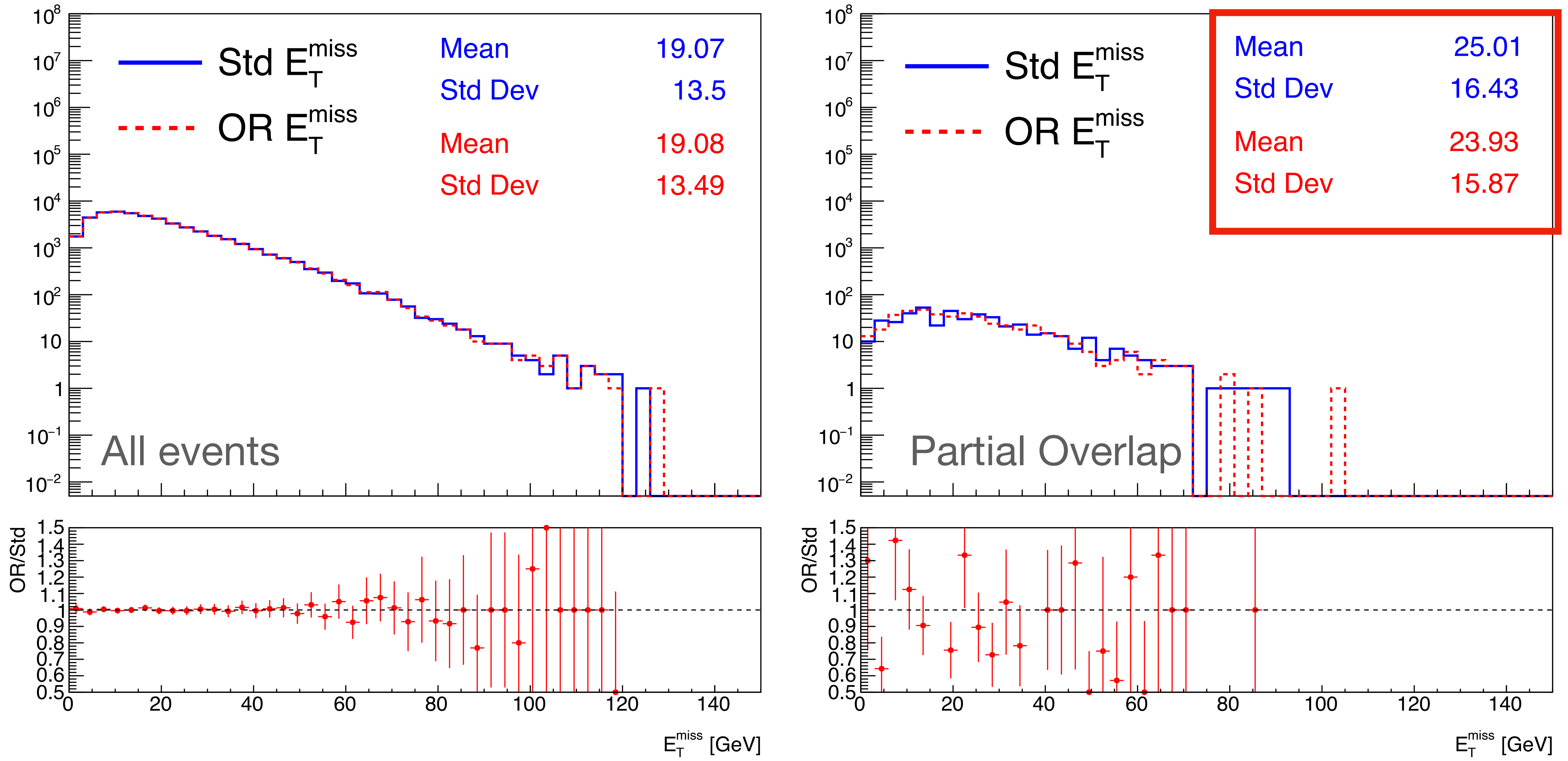




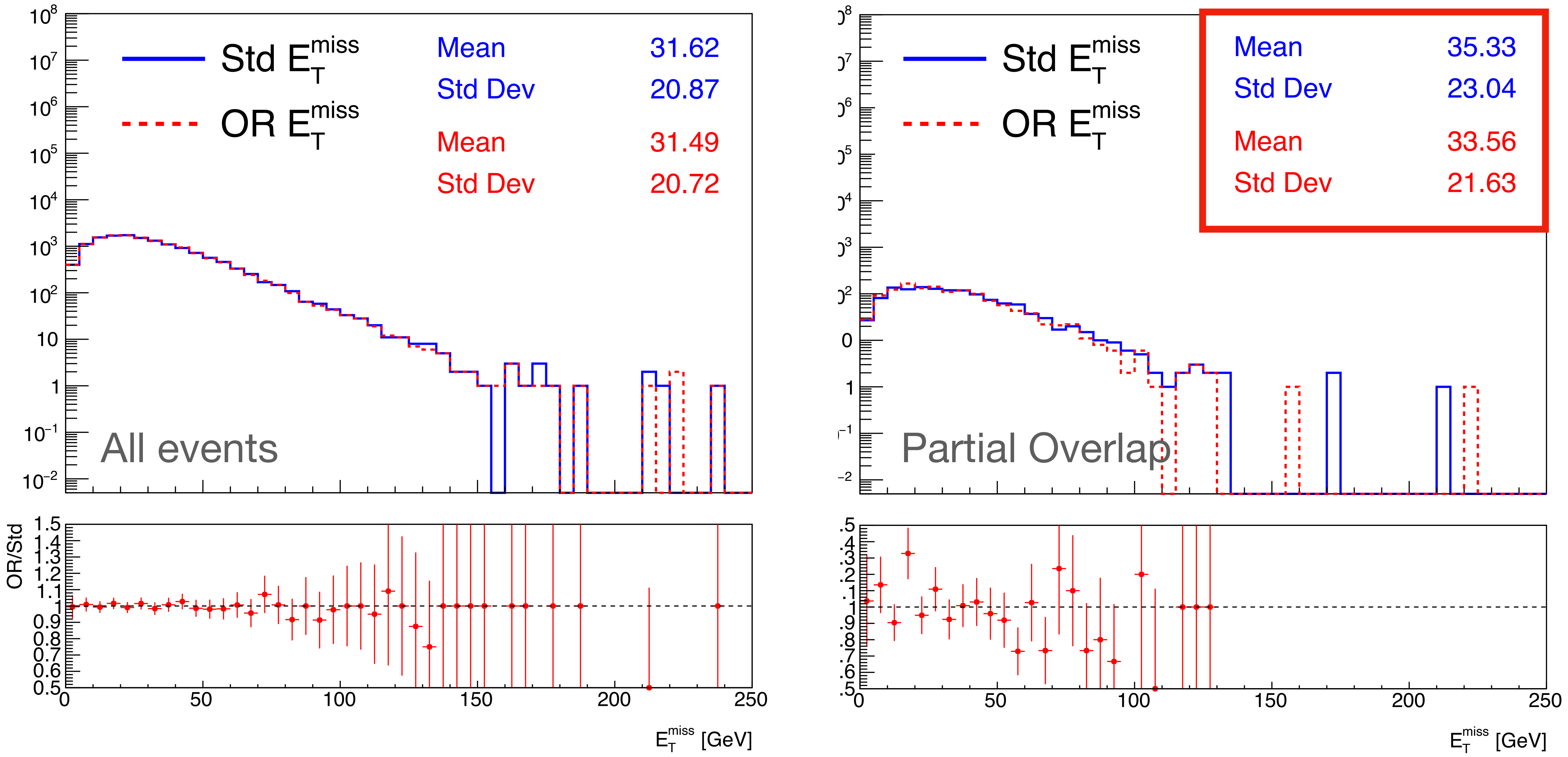
JetTerm from “Overlap Removed” Jet collection

- Different topologies (Zee, y+jets, ttbar) tested with both TST and CST
- Comparable performances between “standard” Jet Term and “Overlap Removed” one
- Some hints of improvement using “Overlap Removed” MET, especially in events with partial overlap between jets and other physics objects (jet partially retained in Jet Term) and y+jets topology

Z(ee), TST



y+jets, TST



Future plans

- Dark-photon analysis: ready for EB request (21 September)
- Performance studies: finalize OR MET implementation in rel22 (muon-jet overlap) and performance studies with Jet/MET validation samples with high statistics
- Hardware: future involvement in LAr HV (Moving to CERN in October)