Search for new Phenomena in Events with a Photon and Missing Transverse Momentum in pp Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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for Group 4

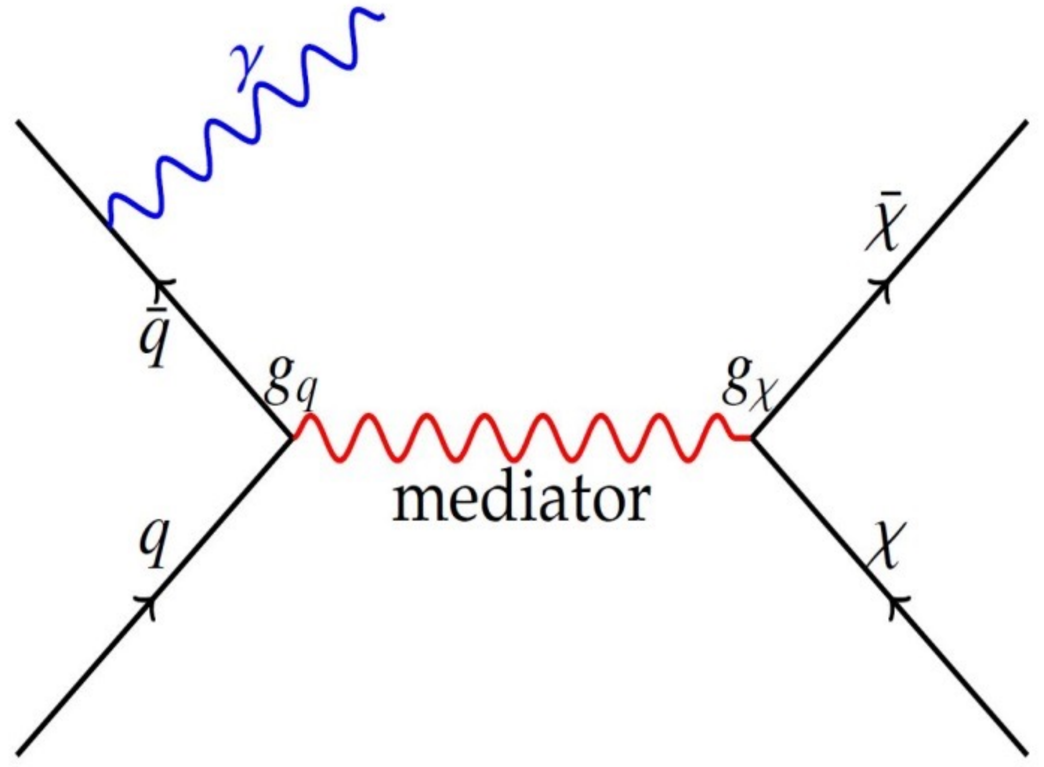
Motivation

- Extensions of the Standard Model (BSM) must exist
  - explain the existence of dark matter
  - deal with hierarchy problem
  - etc.
- BSM physics can be probed in many different ways:
  - this paper probes BSM physics using a single photon and large missing transverse momentum
- This signature targets three different BSM models, such as Simplified models, EFT and Extra dimensions
- The results presented are from the paper arXiv: 1604.01306v2 submitted to JHEP on 16 June 2016, using 3.2 fb^{-1} of ATLAS data collected in 2015 at 13 TeV

Simplified model

One of the models that can be probed with the monophoton signature predicts Dirac fermion DM candidates produced via an s-channel mediator with axial-vector interactions:

$$\mathcal{L}_{axial-vector} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$$



Production of pairs of dark matter particles via an explicit s-channel mediator.

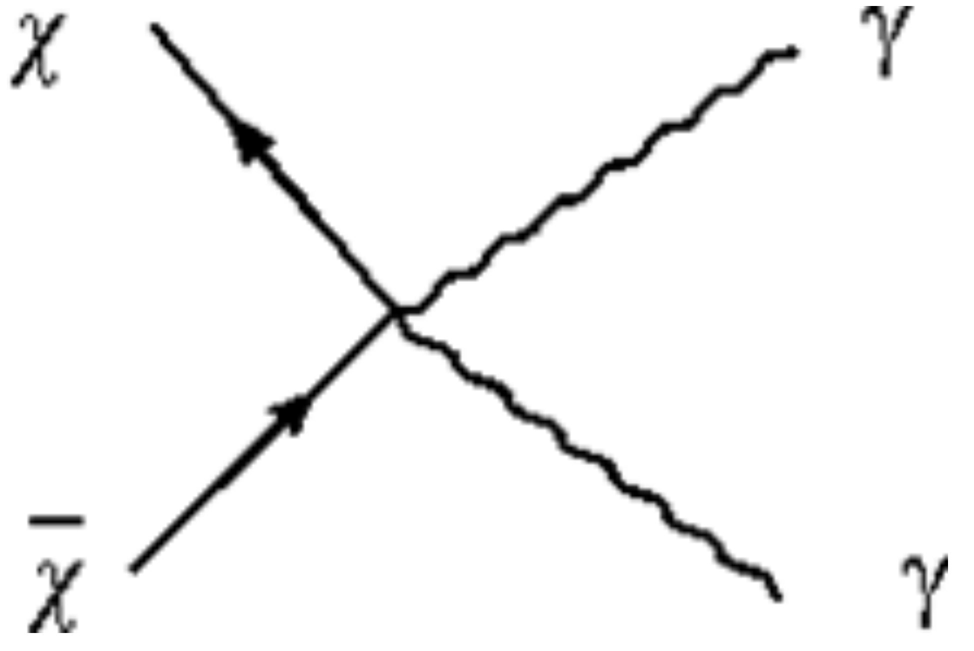
General features:

- initial state radiation provides the single photon signature
- interaction strength with SM particles is near the level of the weak interaction
- the interaction depends on only five parameters:
  - m_χ, m_{med}, Γ_{med}, g_q and g_χ

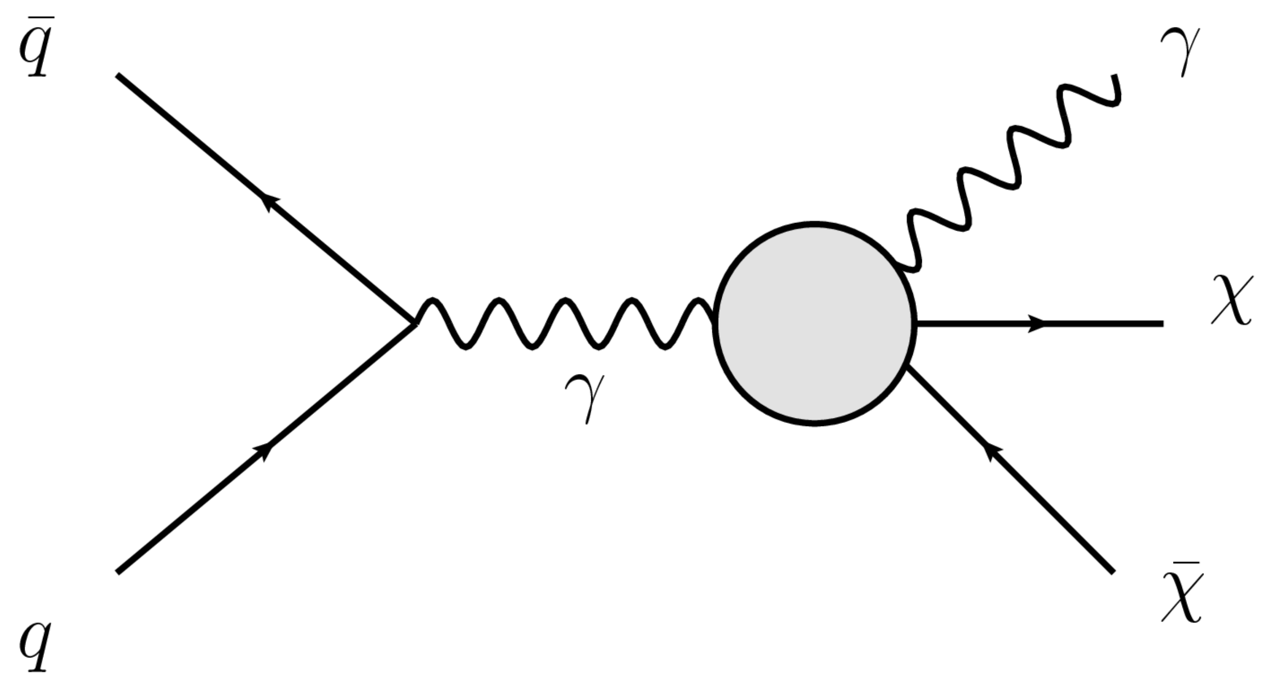
EFT Scenario

- no initial state photon
- interaction is effectively described by four free parameters
- k_1 and k_2 are the couplings to the U(1) and SU(2) parts of the SM gauge bosons respectively

Thus we can have a vertex



and the corresponding process



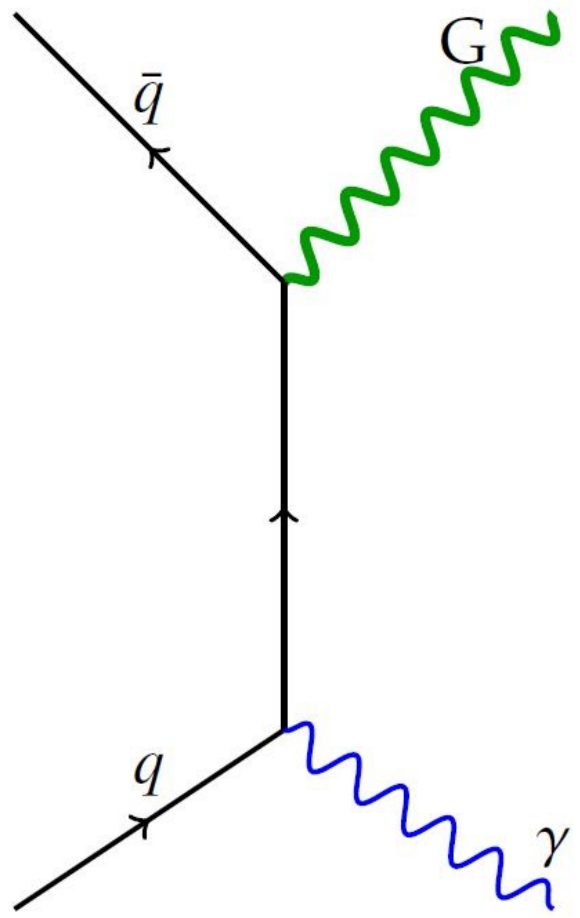
$$\frac{4i}{\Lambda^3}(k_1 + k_2)(p_1^{\mu_2} p_2^{\mu_1} - g^{\mu_1\mu_2} p_1 \cdot p_2)$$

1507.00966 Dark Matter Benchmark Models for Early LHC -2 Searches: Report of the ATLAS/CMS Dark Matter Forum

ADD model ((4 + n) - dimensional model)

1. Interaction of Kaluza-Klein(KK) gravitons

$$-\frac{1}{\bar{M}_{pl}} T^{\mu\nu}(x) \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}(x) \qquad \bar{M}_{pl} = \frac{M_{pl}}{\sqrt{8\pi}}$$



$\boxed{\text{Couplings of all massive KK gravitons are } \bar{M}_{pl}}$

2. Model parameters

   M_D ~ TeV and δ

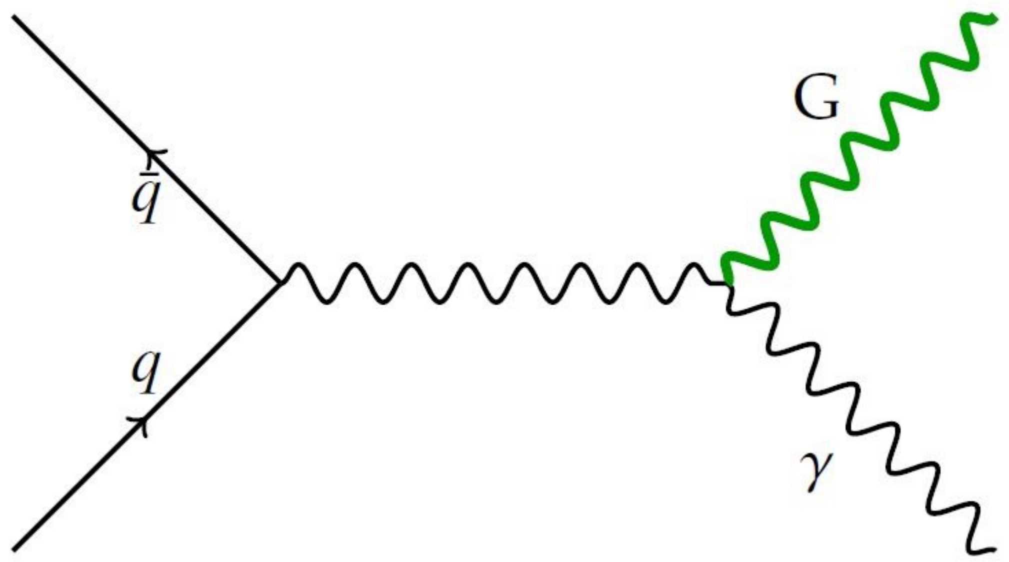
   fundamental scale of the (4 + δ) dimension

$$\bar{M}_{pl}^2 \sim M_D^{2+\delta} R^\delta$$

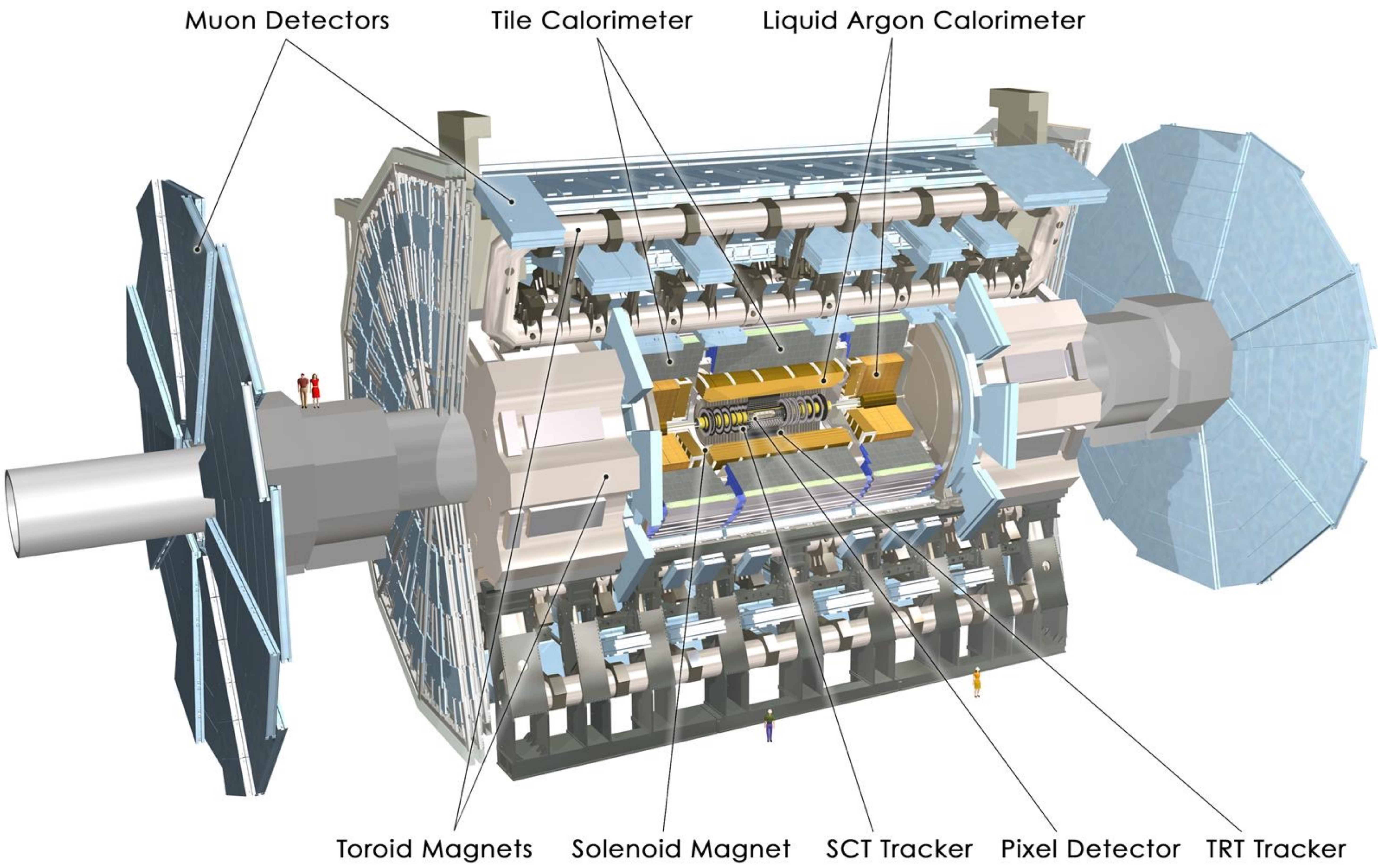
where R is the radius of the extra dimensions

$$m_i \sim \frac{i}{R} (i = 1, 2, \cdots)$$

mass of the KK graviton



The ATLAS detector



- Inner Tracker $|\eta| < 2.5$
- EM Calorimeter $|\eta| < 3.2$
- Hadron Calorimeter $|\eta| < 3.2$
- Muon Spectrometer $|\eta| < 2.7$

Event Reconstruction

Photons reconstructed from

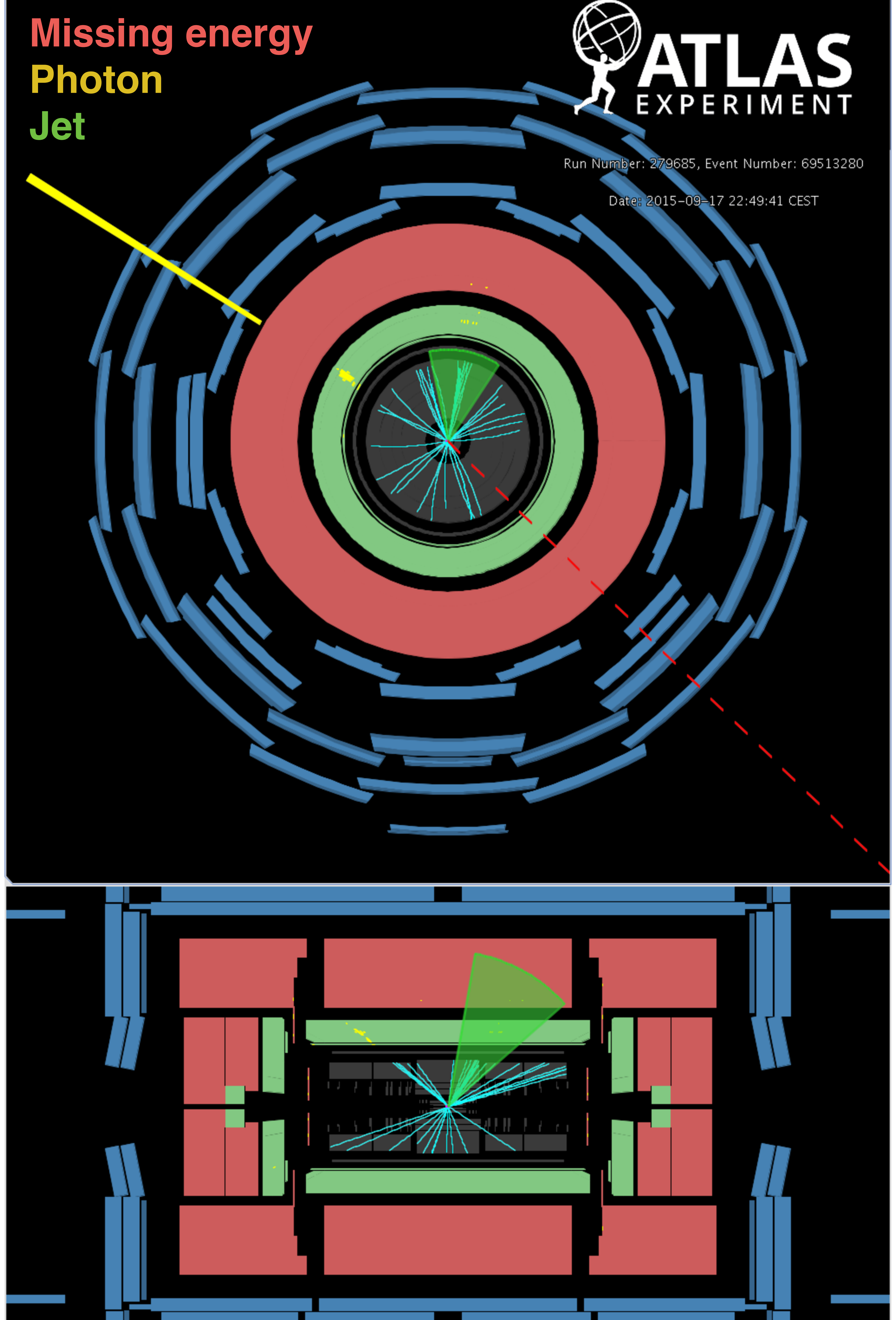
- energy depositions in EM calo
- unconverted photon:
  - clusters in EM calorimeter without matching tracks
- converted photon: (gamma→e+e-)
  - matching to a pair of tracks in TRT and form a vertex in ID
- $p_T > 10$ GeV, $|\eta| < 2.37$

Missing energy calculation

- photons ($p_T > 10$ GeV, $|\eta| < 2.37$)
- electrons ($p_T > 7$ GeV, $|\eta| < 2.47$)
- muons ($p_T > 6$ GeV, $|\eta| < 2.7$)
- jets ($p_T > 20$ GeV, $|\eta| < 2.4$)

$$\vec{E}_T^{miss} = -\sum_i \vec{E}_T^i$$

i = e, μ, gamma, hadron, jet



Event Selection

Data sample

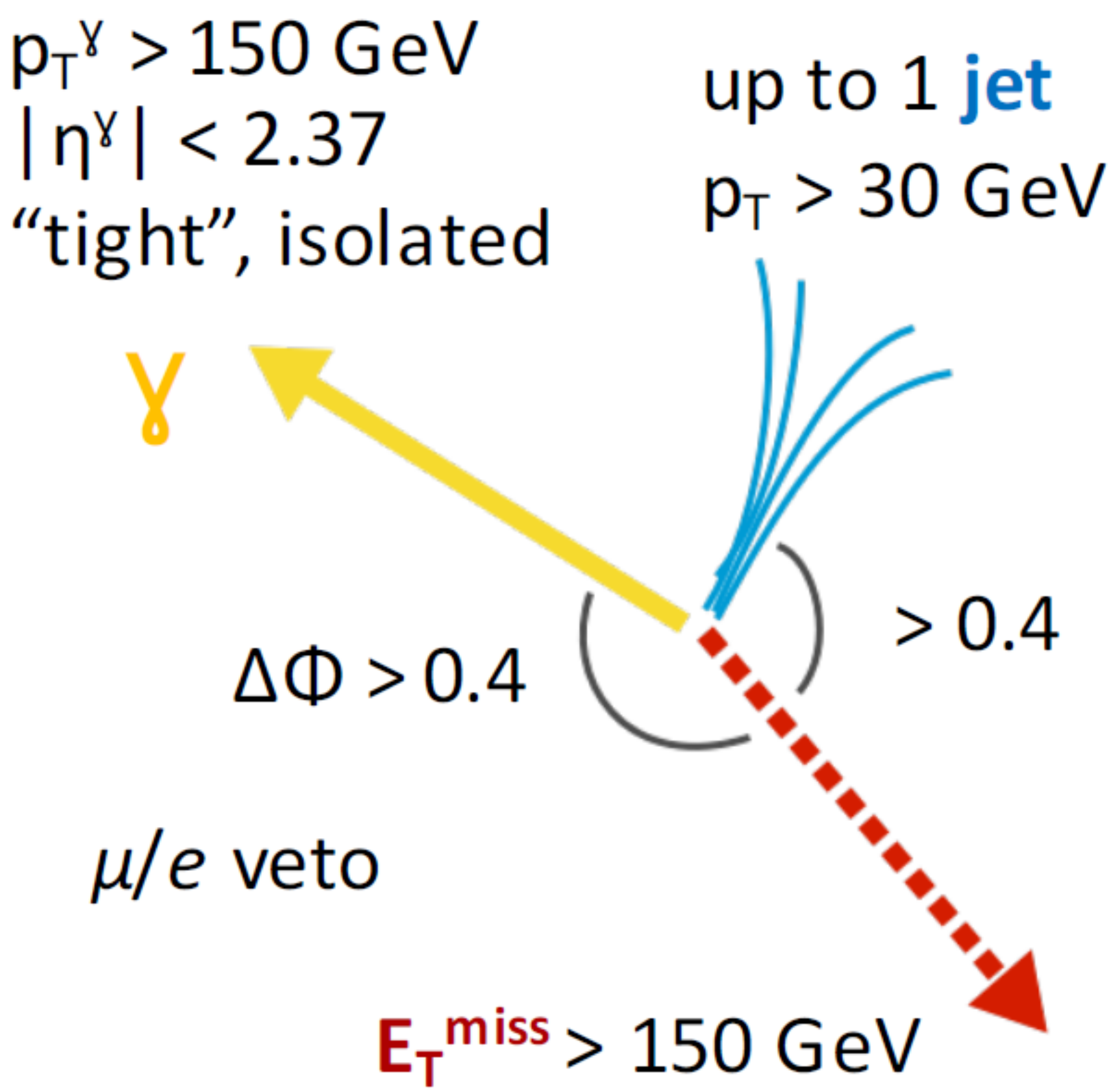
- 3.2 fb^{-1} of *pp* at $\sqrt{s}$ = 13 TeV (2015)
- triggered photons with $p_T > 120$ GeV

Signal region:

- isolated photon $p_T > 150$ GeV, $|\eta| < 2.37$
- $E_T^{miss} > 150$ GeV
- Events w/ more than 1 jets, or events w/ exactly 1 jet are rejected if the $\Delta\phi$(jet, E_T^{miss}) < 0.4
- lepton veto

Total 264 events selected

- 80 with converted photon
- 170 with no jets
- 94 with one jet



Signal Generation

Simplified DM models:

- Free parameter values set from benchmark Run 2 models: g_c=0.25, g_χ=1, Γ_{med} = minimum allowed
- Grid points in m_χ, m_{med} plane generated
- Matrix elements calculated using NNPDF2.3 with A14 tune in Pythia
- Require photon with p_T > 130 GeV required

Dimension-7 EFT DM models:

- Free parameters: $k_1 = k_2 = 1.0$, $\Lambda = 3$ TeV
- Scan over range of m_χ values (up to 1 TeV)
- Same generation procedure

ADD models:

- Same generation procedure
- Require photon $p_{T\,min}$ > 100 GeV in LO calculations
- Simulated for 2 values of M_D (2.0 and 3.0 TeV) and n = 2 - 6

Standard Model Background Estimation

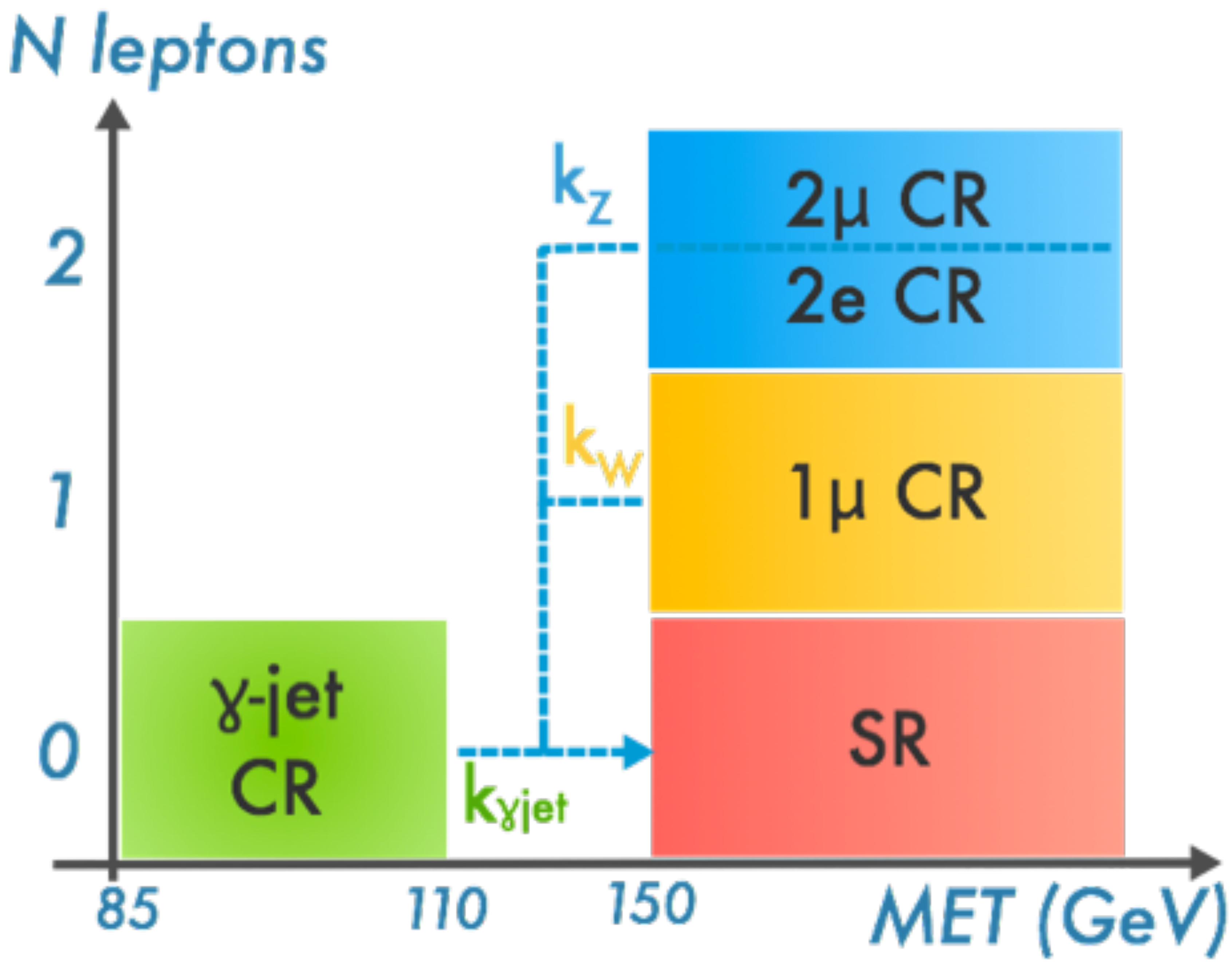
Main backgrounds:

$Z \rightarrow \nu\nu$ (~60%):
- ISR photon

$W/Z\gamma$ (~20%):
- ISR photon with unidentified lepton or hadronically decaying taus
- estimated in CRs with lepton veto inverted (2μ, 2e, 1μ)

W/Z with fake photon (~15%):
- jets or electrons faking a photon
- estimated using data driven technique

γ+jets (~5%):
- instrumental E_T^{miss}: estimated in a CR enriched in γ+jets

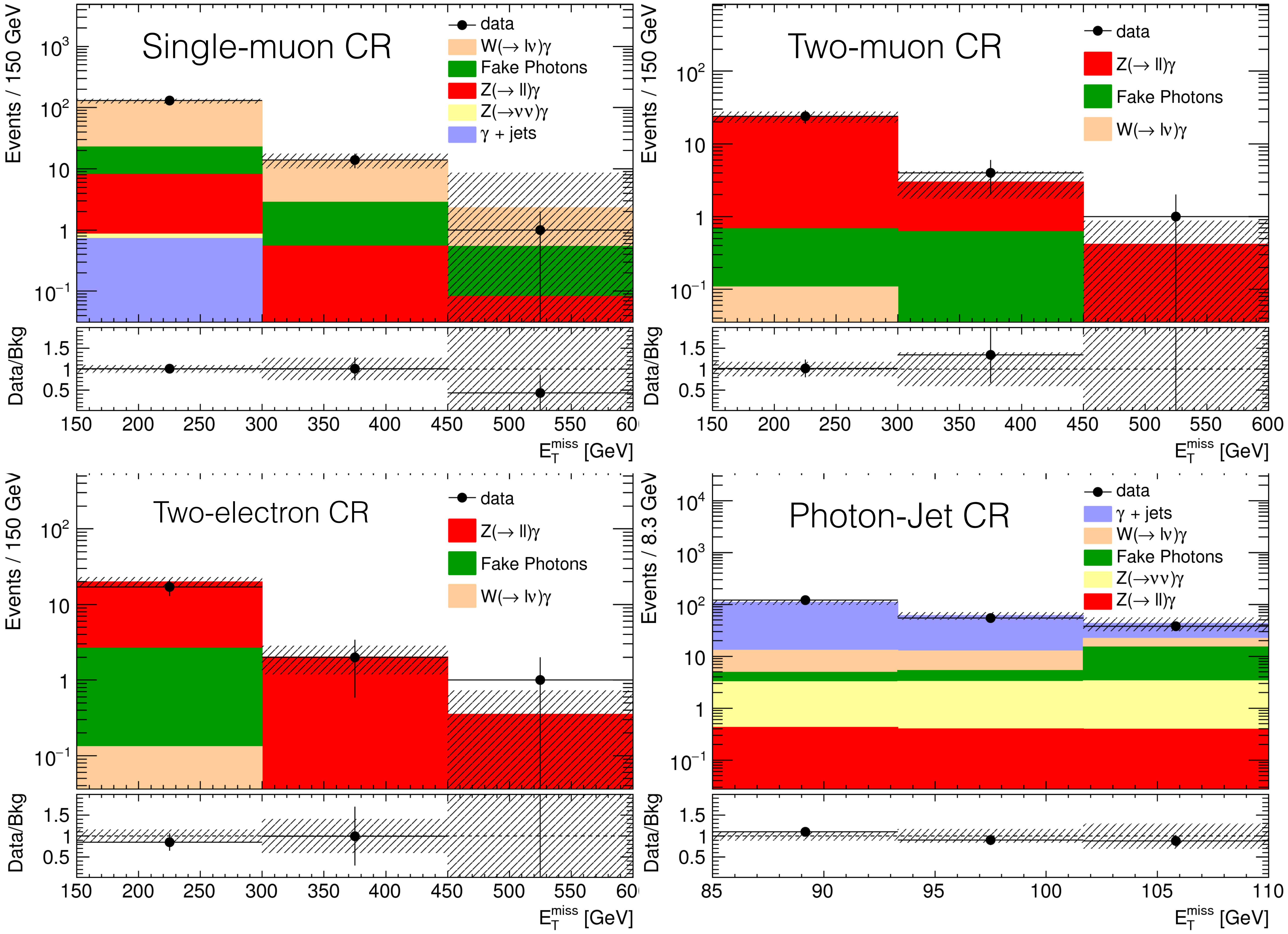


$$BG_{Total} = \boxed{\begin{matrix} Z\rightarrow\nu\nu \\ Z\rightarrow ll \end{matrix}} \times k_Z + \boxed{W\rightarrow\nu l} \times k_W + \boxed{\gamma\text{+jet}} \times k_{\gamma jet} + \boxed{\text{Fake } \gamma}$$

W/Zγ & γ+jets BG: (data/MC method)
- Number of events from MC simulation
- Normalisations with free parameters

Fake photon: (data driven method)

Final background estimation



Background estimates in the SR → simultaneous likelihood fit to the 4 single-bin control region.

Results

A simultaneous fit to the single bin control regions

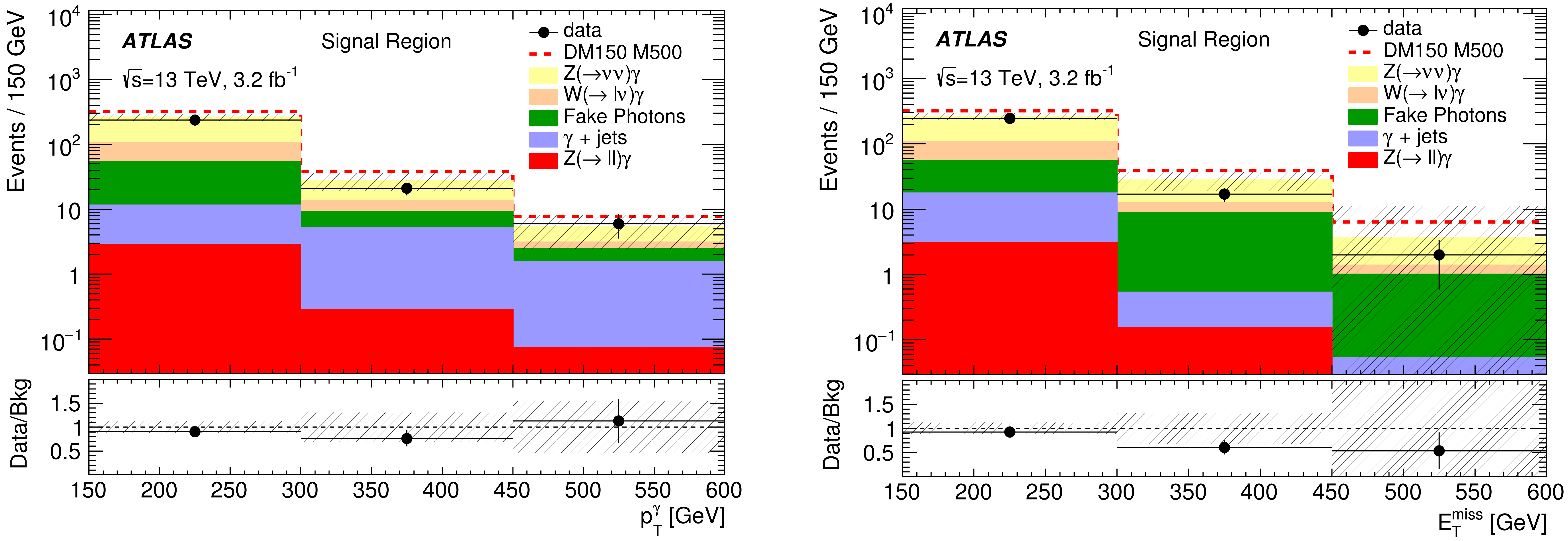
	SR	1muCR	2muCR	2eleCR	PhJetCR
Observed events	264	145	29	20	214
Fitted Background	295±34	145±12	27±4	23±3	214±15
$Z(\to \nu\nu)\gamma$	171±29	0.15±0.03	0.00±0.00	0.00±0.00	8.6±1.4
$W(\to \ell\nu)\gamma$	58±9	119±17	0.14±0.04	0.11±0.03	22±4
$Z(\to \ell\ell)\gamma$	3.3±0.6	7.9±1.3	26±4	20±3	1.2±0.2
γ + jets	15±4	0.7±0.5	0.00±0.00	0.03±0.03	166±17
Fake photons from electrons	22±18	1.7±1.5	0.05±0.05	0.00±0.00	5.8±5.1
Fake photons from jets	26±12	16±11	1.1±0.8	2.5±1.3	9.9±3.1
Pre-fit background	249±29	105±14	23±2	19±2	209±50

The percentages represent the purity of the control regions used to constrain the background cross sections

~82% ~87%

~96% ~78%

Results



- Post fit plots in signal region
- Data agrees with background model within errors

Systematic Uncertainties

Total background	295
Total background uncertainty	11%
Electron fake rate	5.8%
PDF uncertainties	2.8%
Jet fake rate	2.4%
Muons reconstruction/isolation efficiency	1.5%
Electrons reconstruction/identification/isolation efficiency	1.3%
Jet energy resolution [62]	1.2%
Photon energy scale	0.6%
$\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale and resolution	0.4%
Photon energy resolution	0.2%
Jet energy scale [50]	0.1%

Dominant region affected

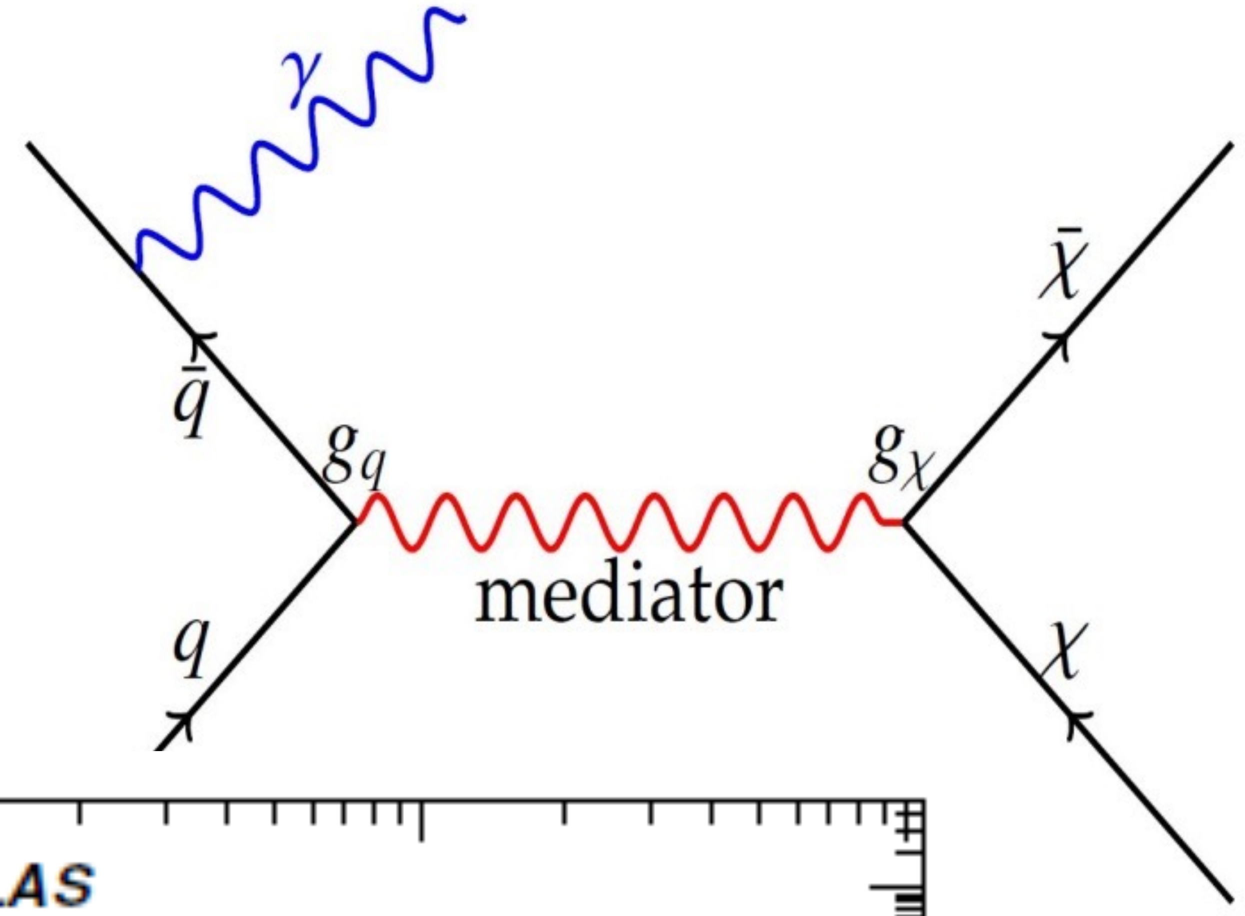
$Z(\rightarrow \nu\nu)\gamma$

$Z(\rightarrow ll)\gamma$

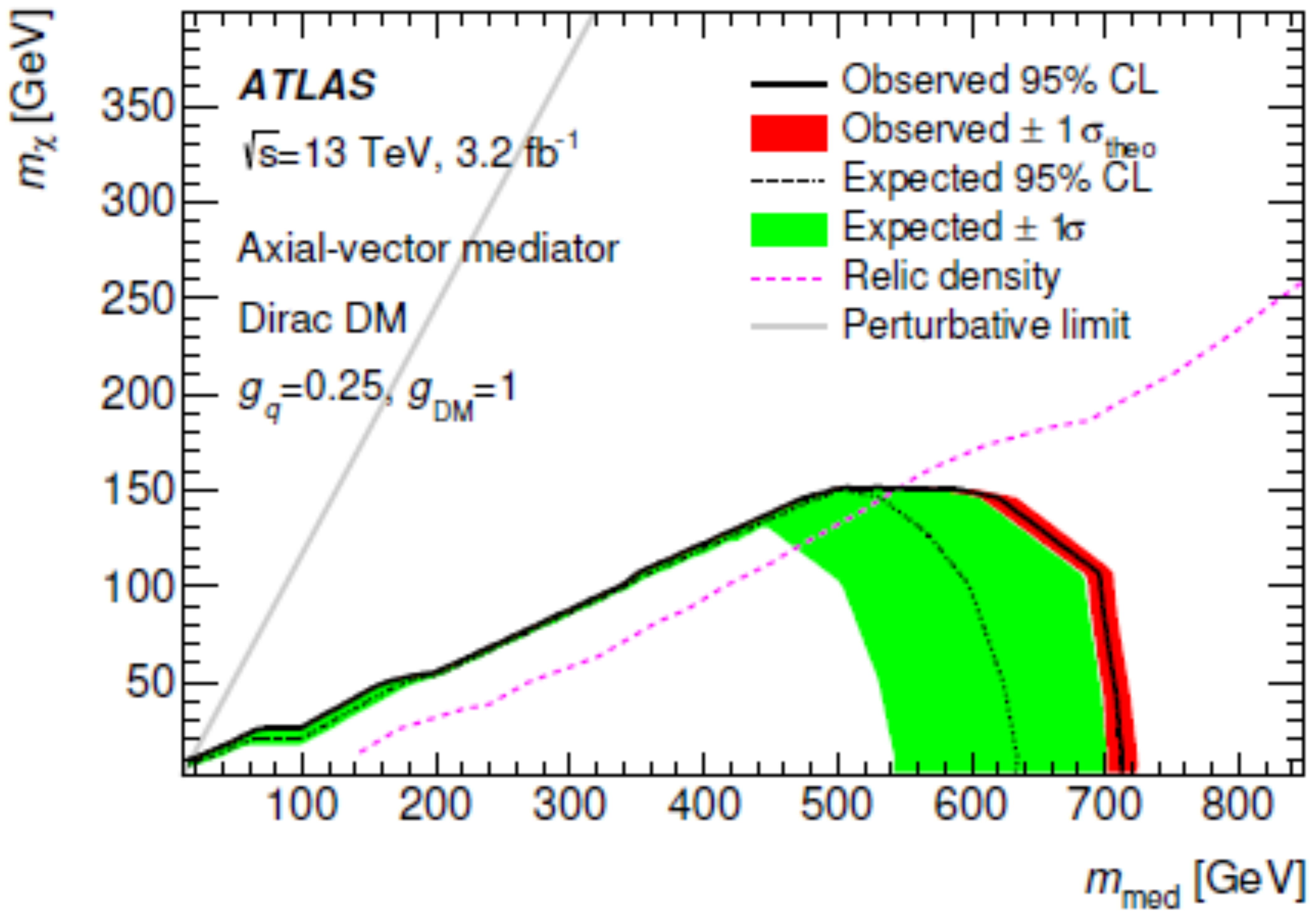
γ+Jets

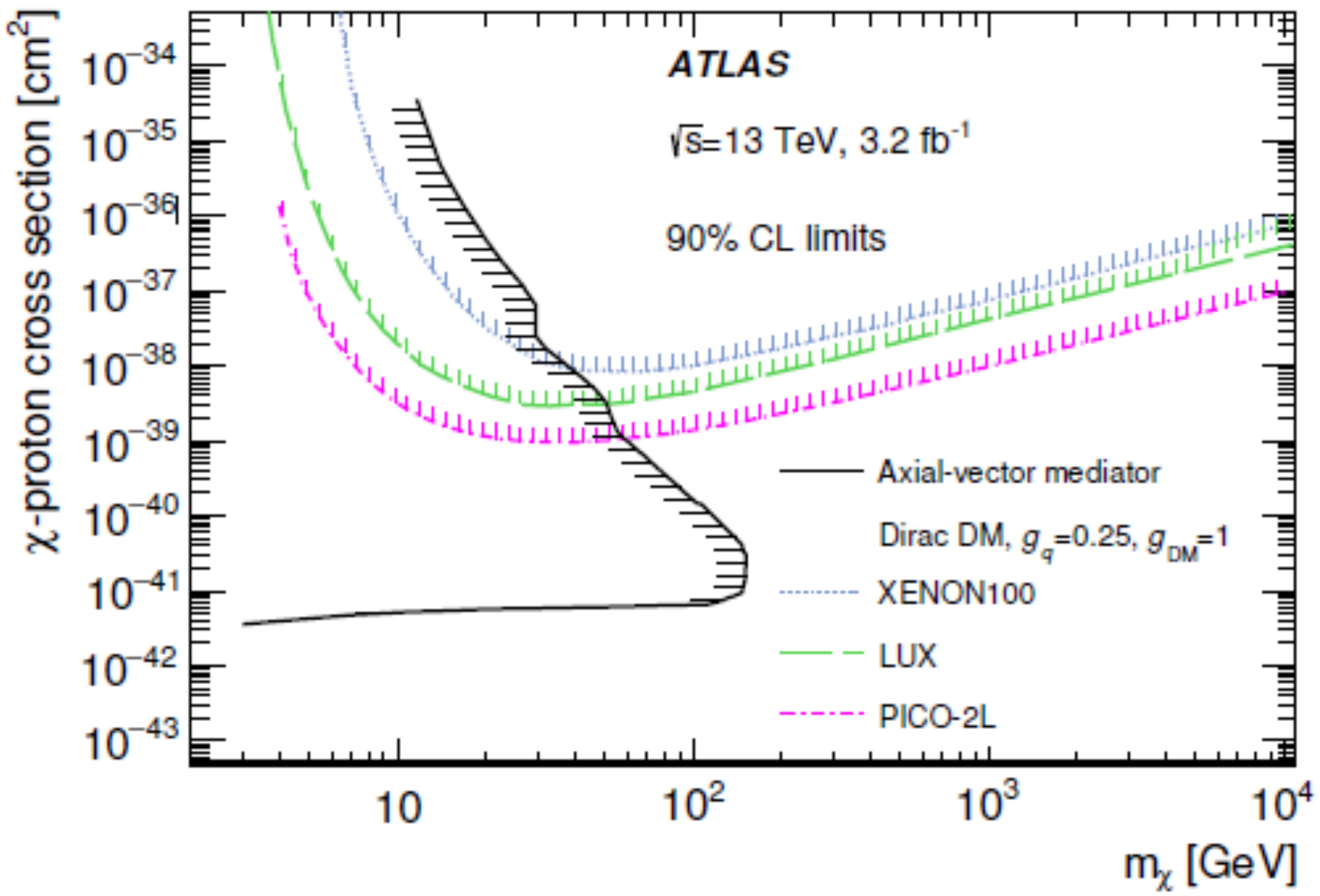
- 9% of total uncertainty due to statistical fluctuations in control regions

Interpretation



Exclusion limit for the axial-vector model (95%CL)



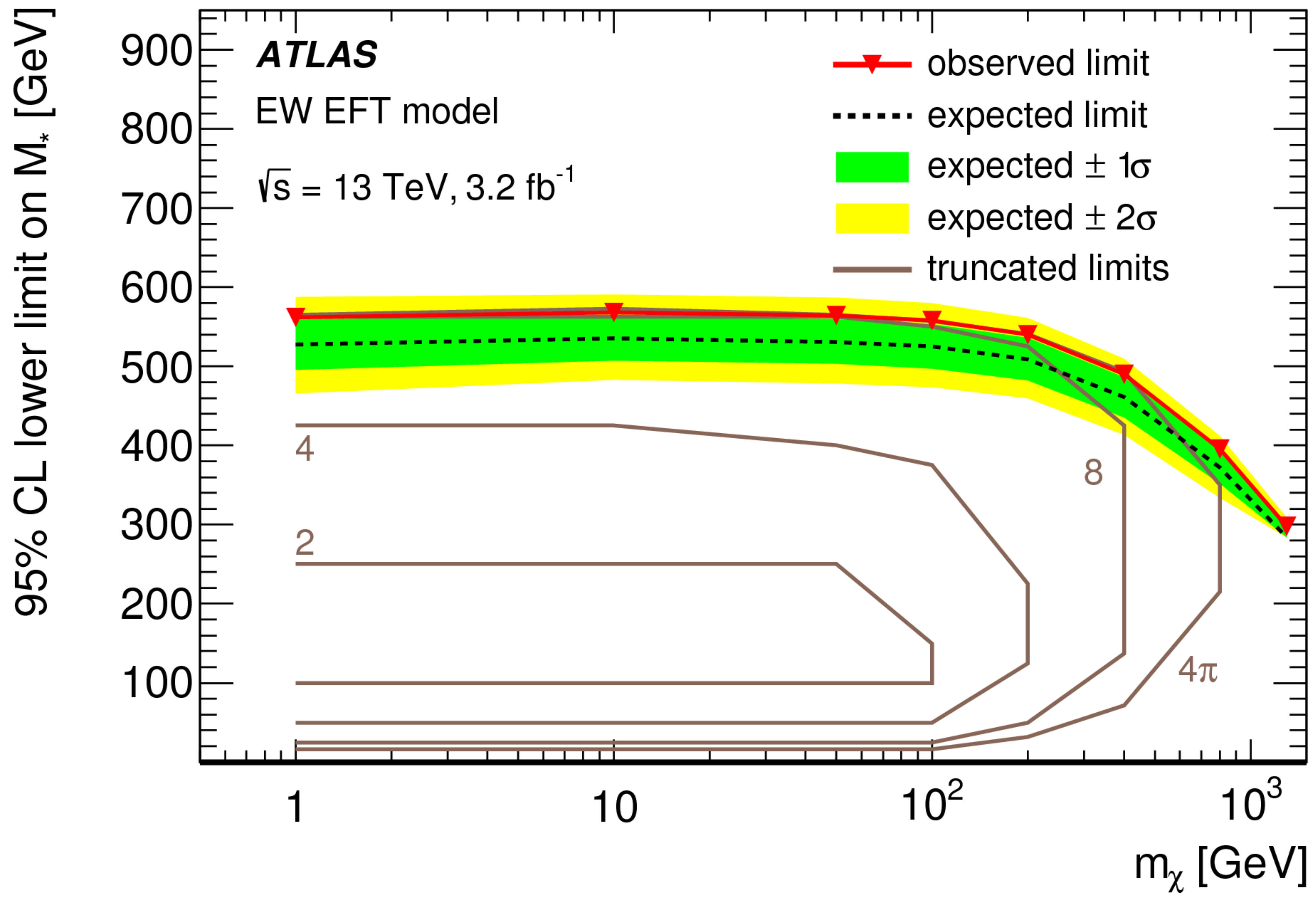


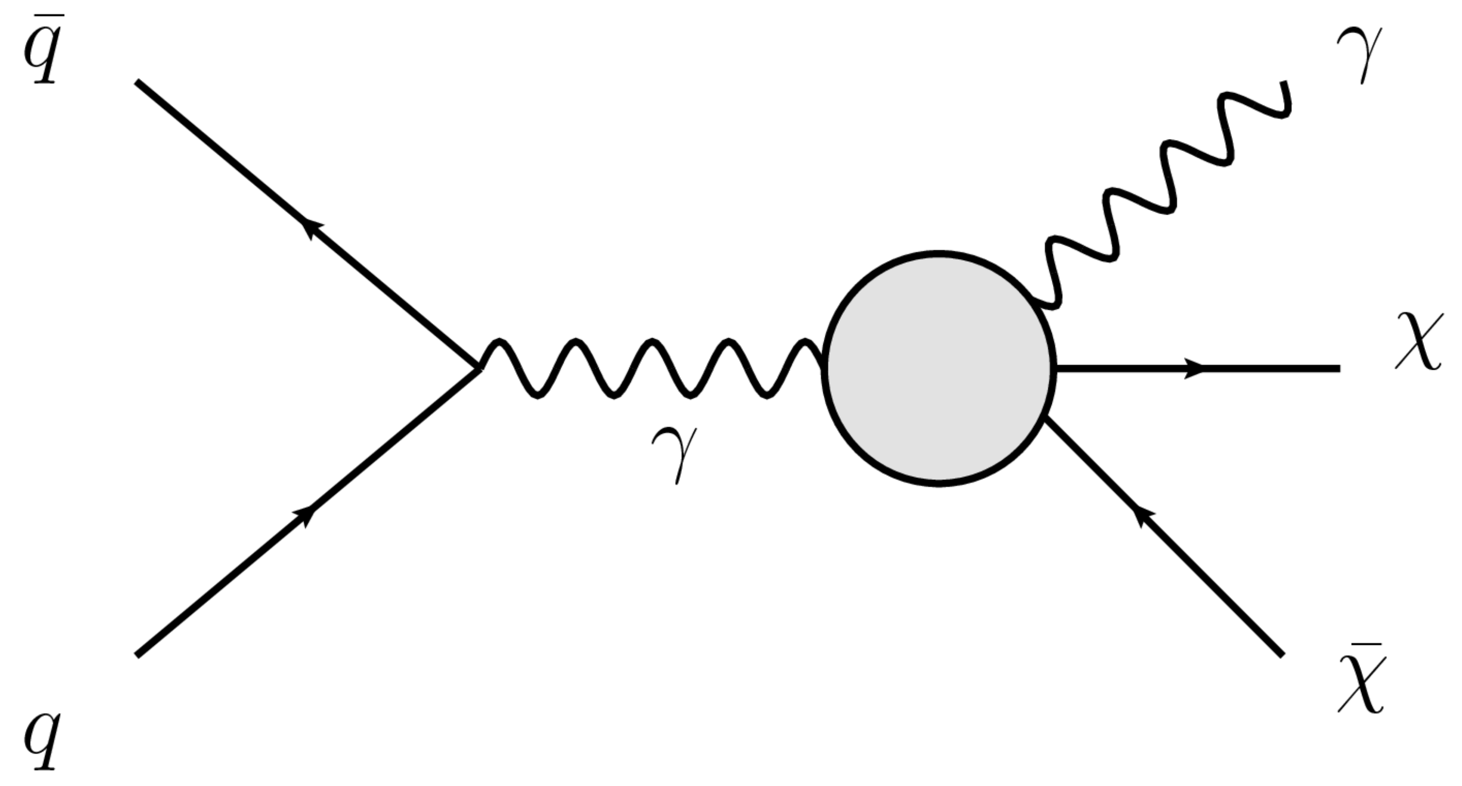
g_q=0.25 and g_χ=1.

The plane under the limit curves is excluded. The region on the left is excluded by the perturbative limit.

Interpretation

Limits on new DM energy scale



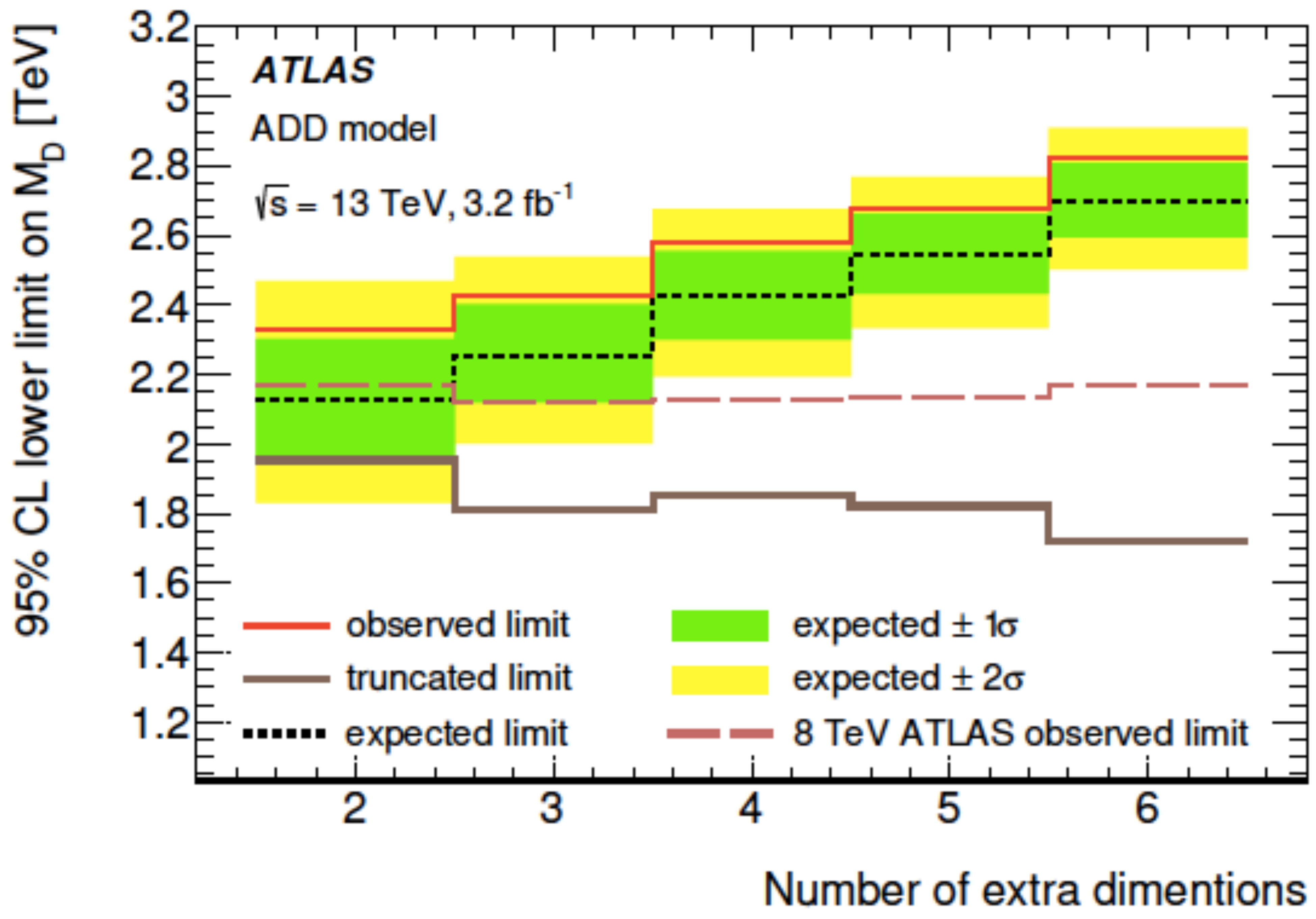


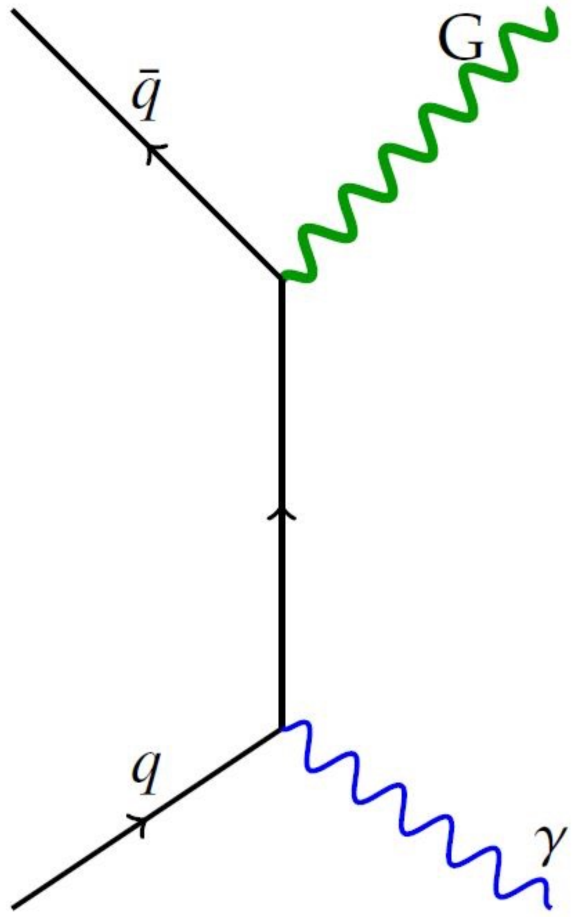
With various representative value $g^*(2, 4, 8, 4\pi)$

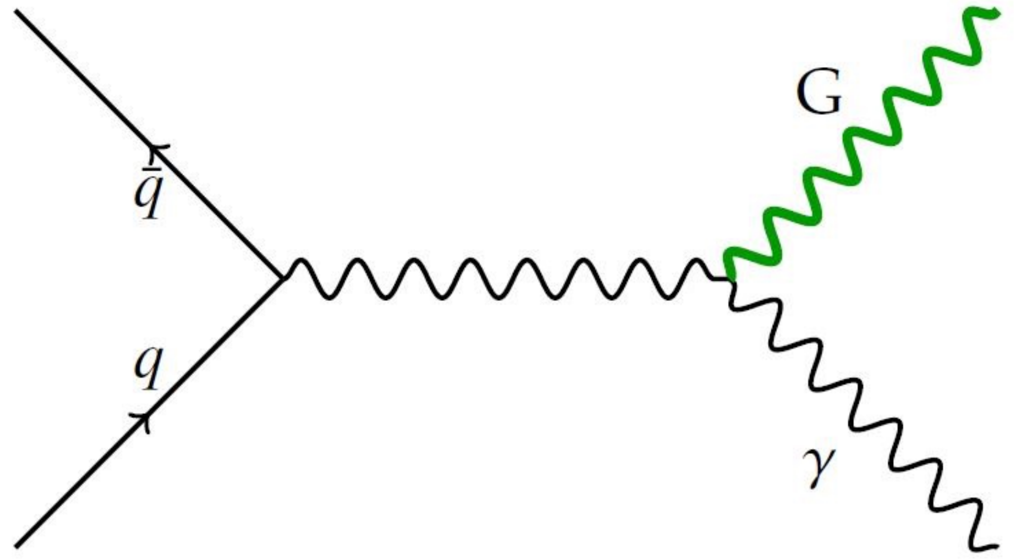
Truncation: $M_{cut} = g^* M_*$

Interpretation

Limits on the mass scale of extra dimensions







Excluding M_D up to about 2.3 TeV

Conclusion

- Result is consistent with the Standard Model
- Observed (expected) 95% upper confidence limit on fiducIary cross section is **17.8 (25.5) fb**

Model Parameter	Excluded below
Dark Matter mediator mass	150 GeV
EFT model M_*	570 GeV
ADD Model M_D (n=2)	2.3 TeV
ADD Model M_D (n=6)	2.8 TeV

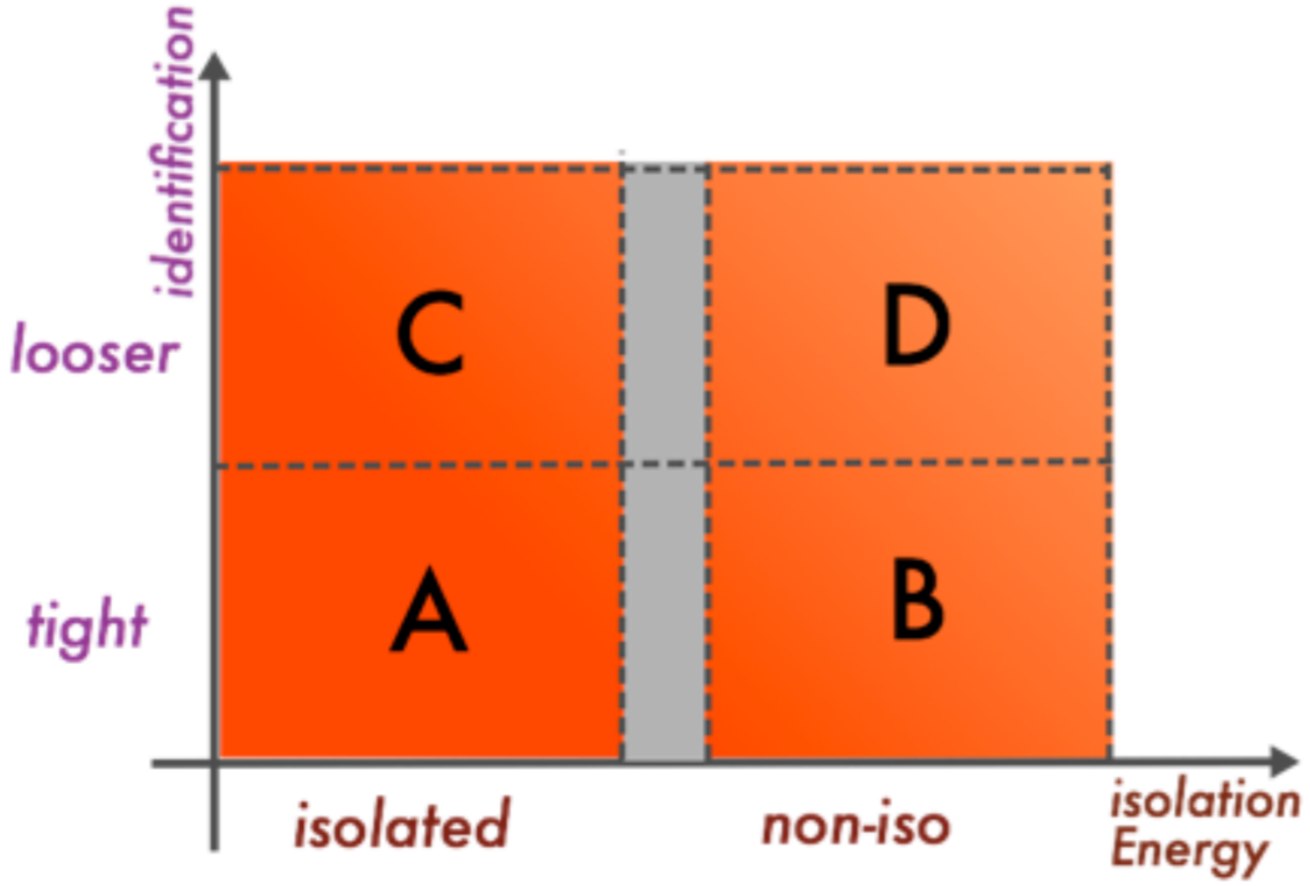
Backup

Fake Photon Background Estimation

The background that due to fake photons are estimated using data-driven techniques.

Fake photons form jets

- count photon candidates in 4 different regions (A signal and B,C,D background) of a two dimensional space of jet id and isolation criteria
- Signal contamination is small and isolation profile in non-tight region is the same as that of the tight region
- The number of background candidate in signal is then calculated by $N_A^{bkg} = N_B \, N_C \, / \, N_D$

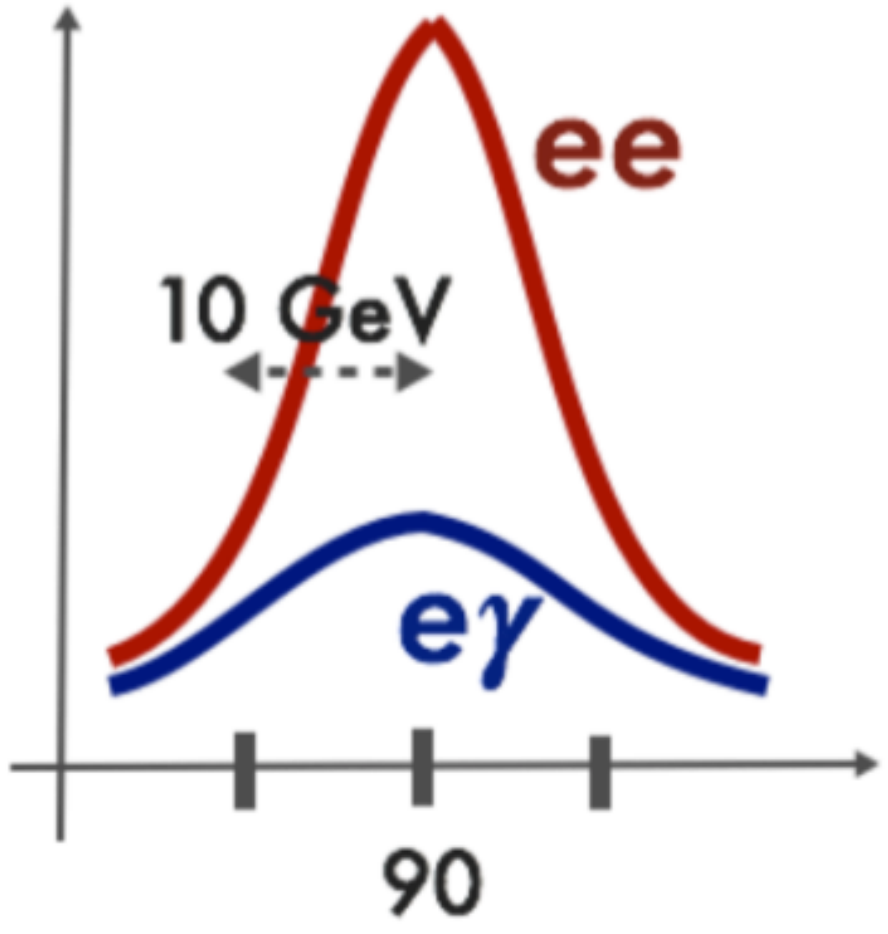


Fake photons from electrons

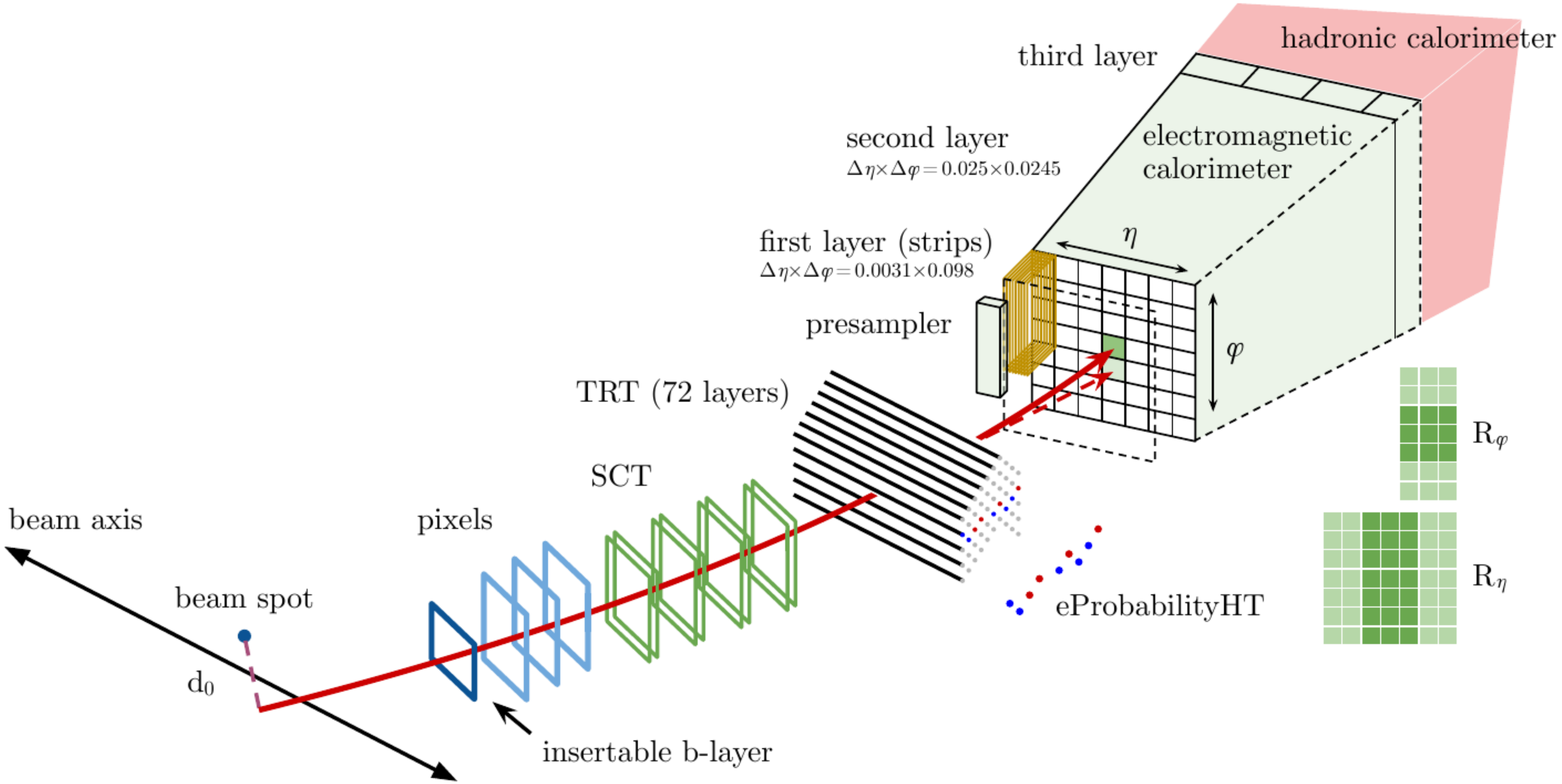
- Misidentification factor $P(e \rightarrow \gamma)$ is measured with mutually exclusive samples of ee and eY in the Z mass window

  $P(e \rightarrow \gamma) = N(e\gamma) / N(ee)$
- The number of background candidates can be found by:

  $N_{bkg} \rightarrow P(e \rightarrow \gamma) \times N(e + E_T^{miss})$

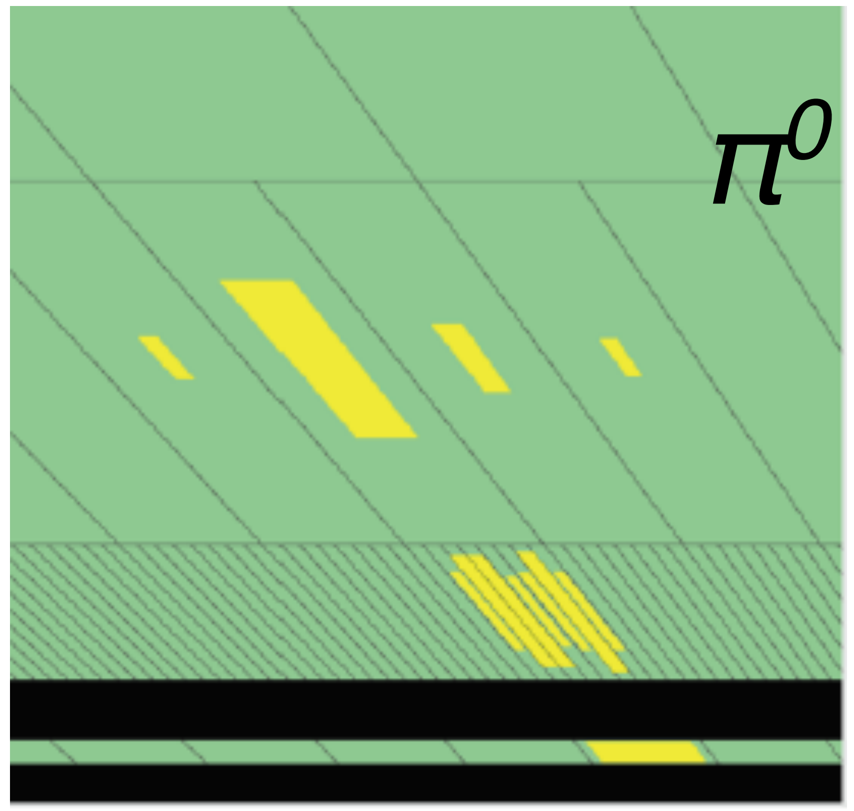


Event reconstruction

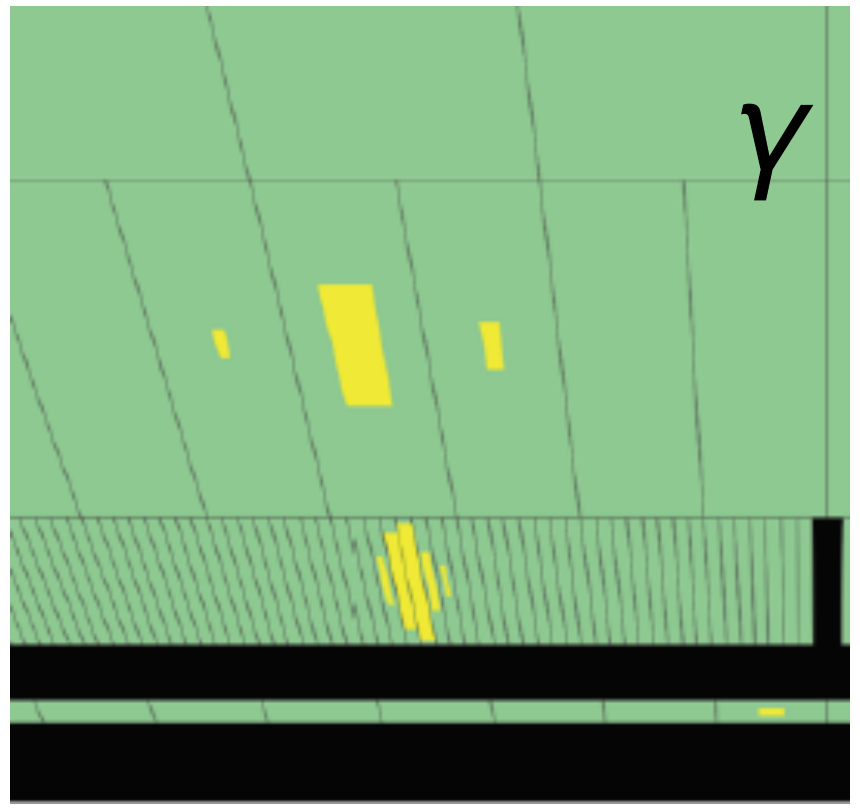


Identification requirements

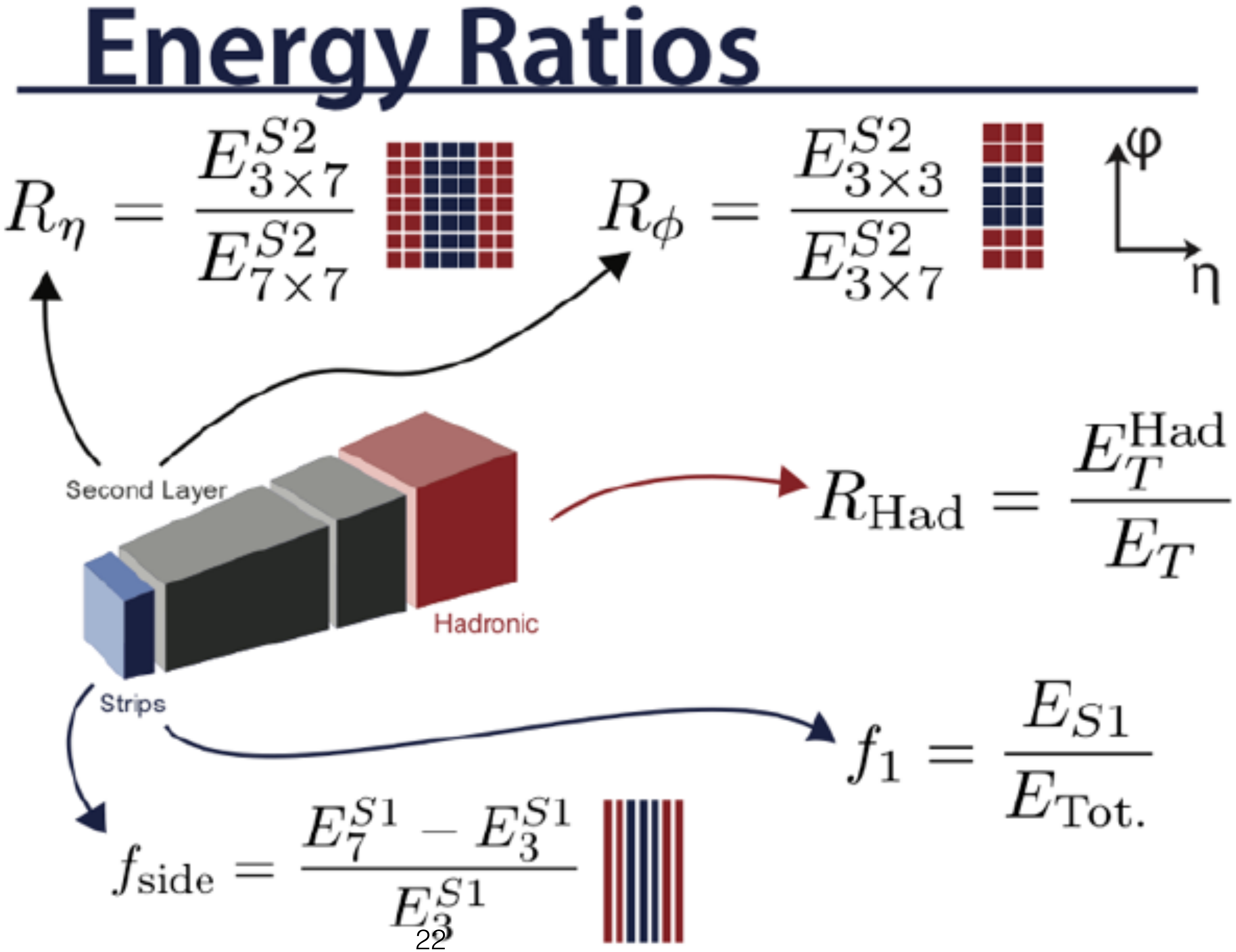
- Based on shower shapes variables in calorimeter clusters



had's->Ys
"Soft term"



single photon



Normalization factor

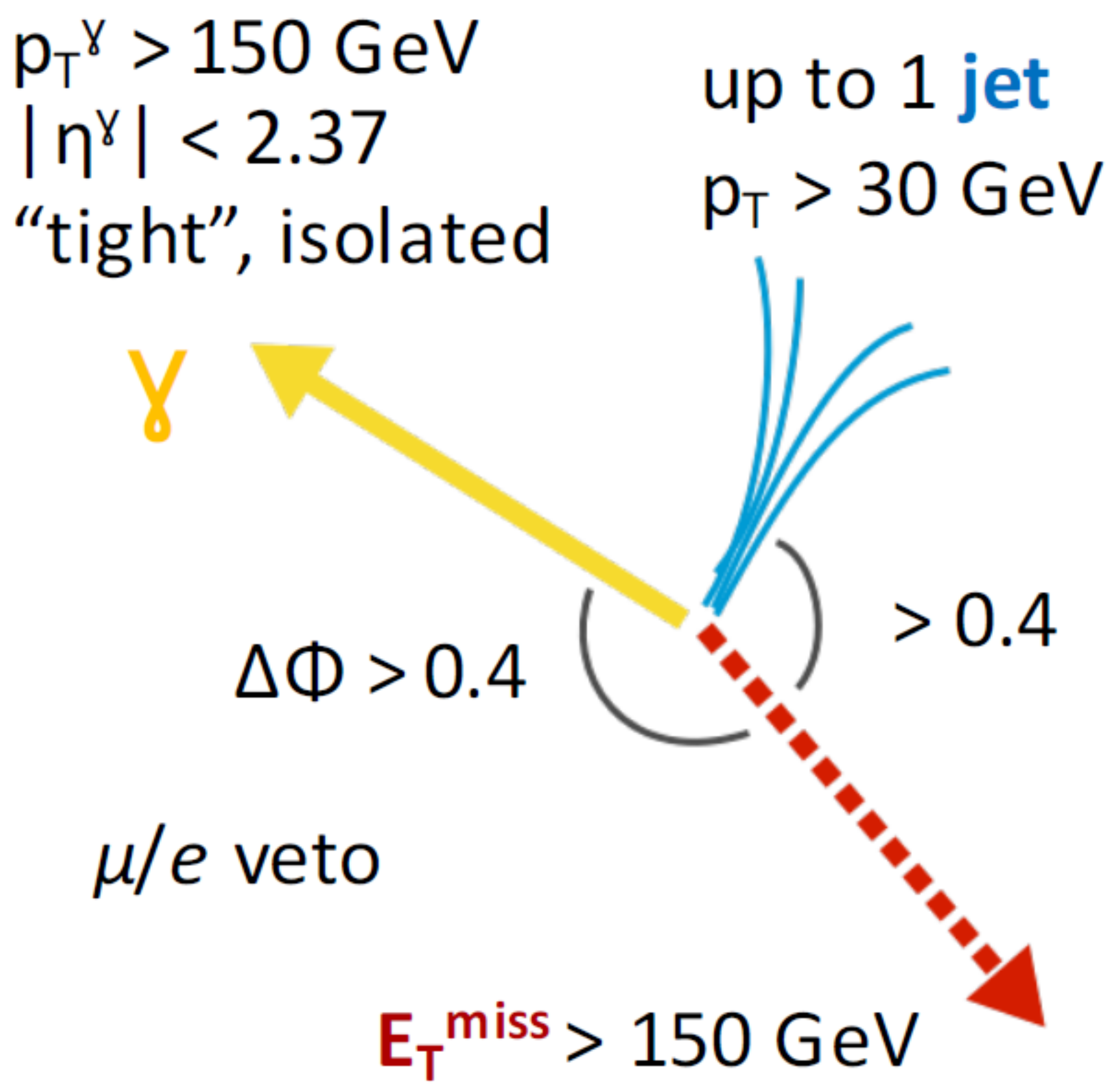
$W\gamma \rightarrow k_{W\gamma} = 1.50 \pm 0.26$

$Z\gamma \rightarrow k_{Z\gamma} = 1.19 \pm 0.21$

Photon + Jet

$\rightarrow k_{\gamma+\mathrm{jets}} = 0.98 \pm 0.28$

Event Se



Signal region (SR)
Trigger: online $p_T > 120$ GeV
Luminosity: 3.2 fb^{-1} pass quality requirement like instrumental problems, too high background, detector noise. Timing cuts to reject cosmic and other non-collision sources

Photon $p_T > 150$ GeV
$|\eta| < 2.37$ excluding barrel/end-cap transition region
Missing $E_T > 150$ GeV reject overlap ΔΦ (jet,E_miss) < 0.4 and ΔΦ (γ,E_miss) > 0.4
==> allow 1 jet No e- and μ Number of events: 264
170 with no jet
94 with 1 jet
80 with converted photon

- pass quality requirement like
  - instrumental problems,
  - too high background,
  - detector noise.
- Timing cuts to reject cosmic and other non-colli

Background Sample Generation

W/Z+ Jets:

- MEM generated upto NLO using SHERPA.
- SHERPA Parton shower using the ME+PS@NLO prescription.
- Normalized to NNLO cross-section

γ+jet

- Generated by some bins of pT(35GeV~4TeV)
- Sherpa parton shower using ME+PS@LO prescription.
- Parton shower tuning using CT10PDF set

Multi-jet process :

- Simulated with pythia generator. A14 tune is used togather with the NNPDF2.3LO PDF Set.

Diboson processes :

- Generated using SHERPA.
- SHERPA Parton shower using the ME+PS@NLO prescription.

tt and top quarks:

- Generated using Powheg generator.
- Pythia parton showering

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.

Systematics - Signal

- PDF uncertainties applied to signal
  - Use alternate internal LHAPDF weights
- QCD scale uncertainties
  - Vary renormalisation and factorisation scales by factors 2 and 0.5
- Vary underlying event tunes in MC