Very-low mass resonance search in the $\gamma\gamma$ channel with the ATLAS detector

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LPNHE ATLAS

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ATLAS EXPERIMENT

LPNHE PARIS

Theoretical motivation

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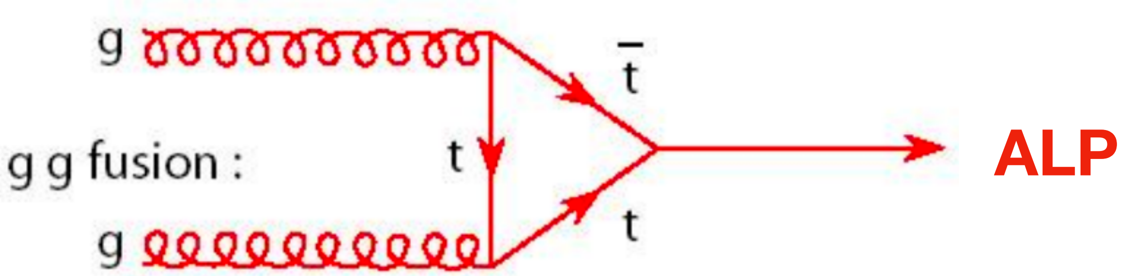
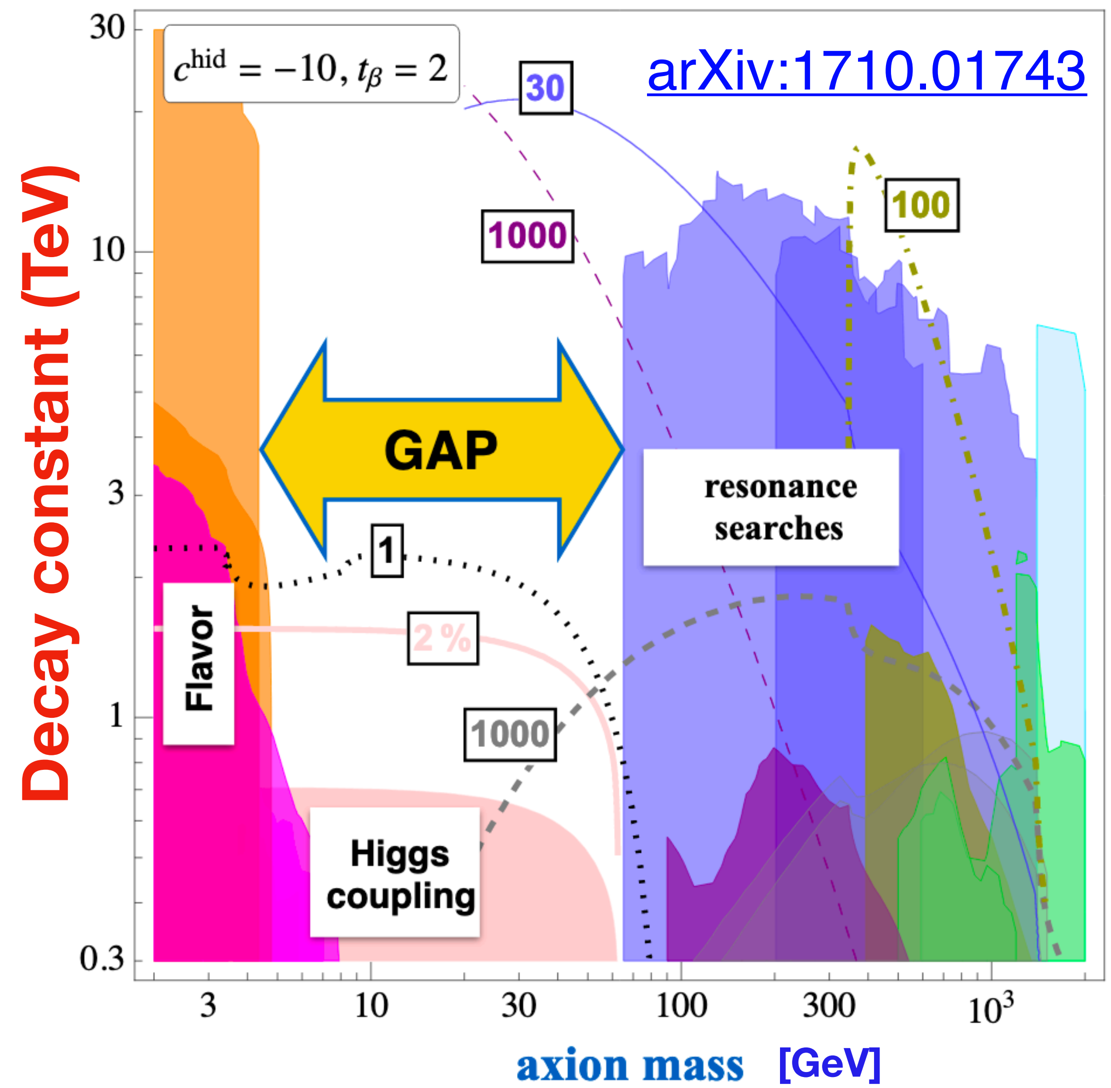
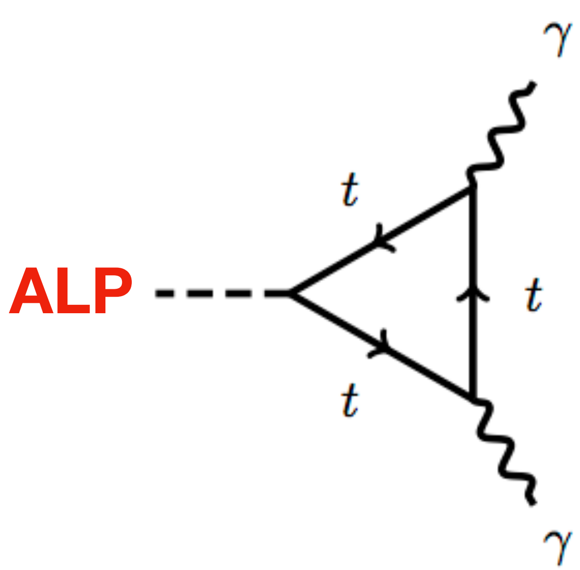
- Pseudo Nambu-Golstone bosons (pNGB) arise from spontaneously broken approximate symmetries.
  - Often called Axion-Like Particles (ALPs)
- Main interest as a possible **Dark Matter** mediator due to its weakly interacting nature.





ALPs couple to both gluons and photons.



Large decay constant implies weak interaction.

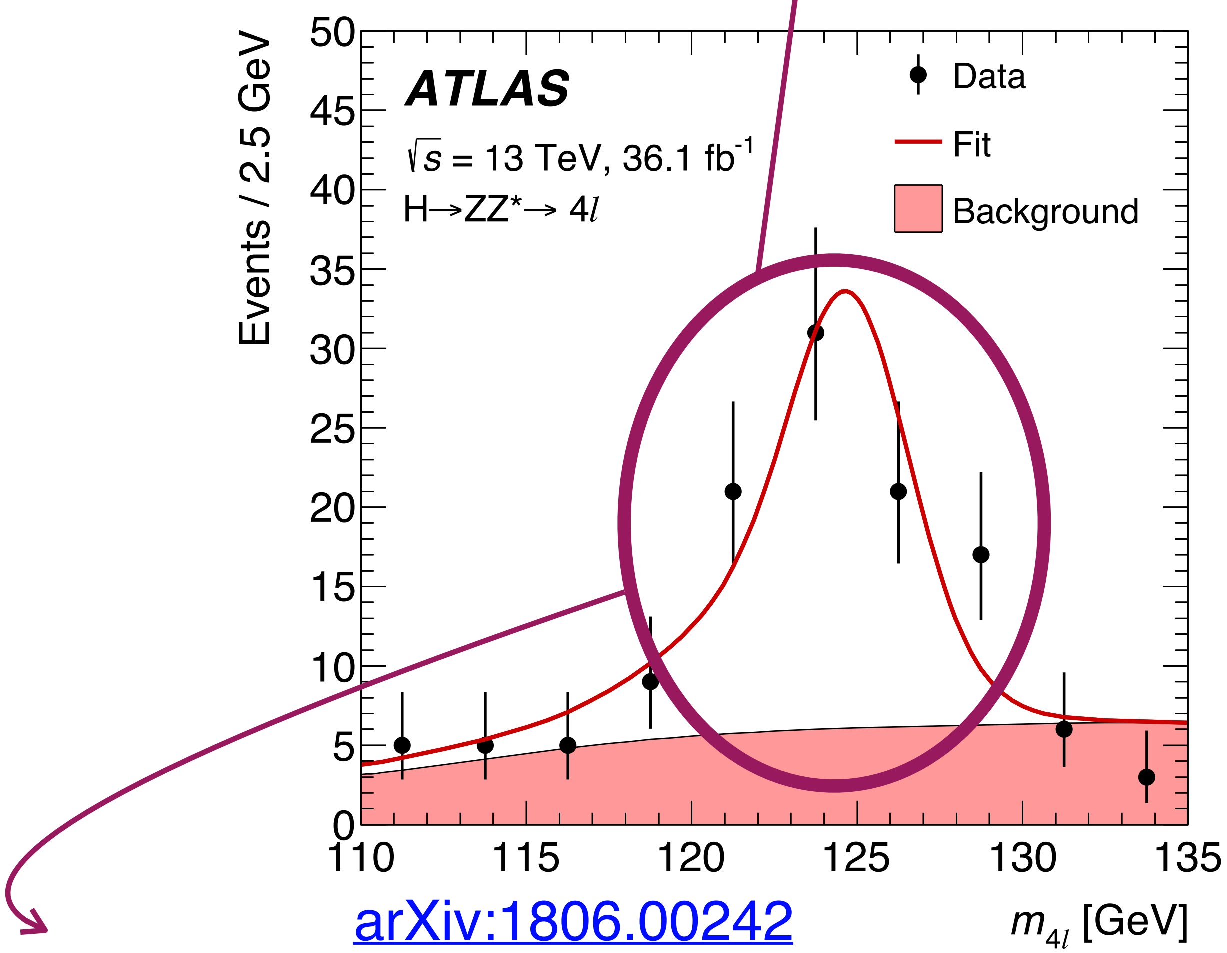
Experimental motivation

New Physics at the LHC

There are many different ways to access **New Physics** (NP) with the ATLAS detector. They can be classified as:

Direct searches

Direct searches for new particles, which would be detected as **resonances**.

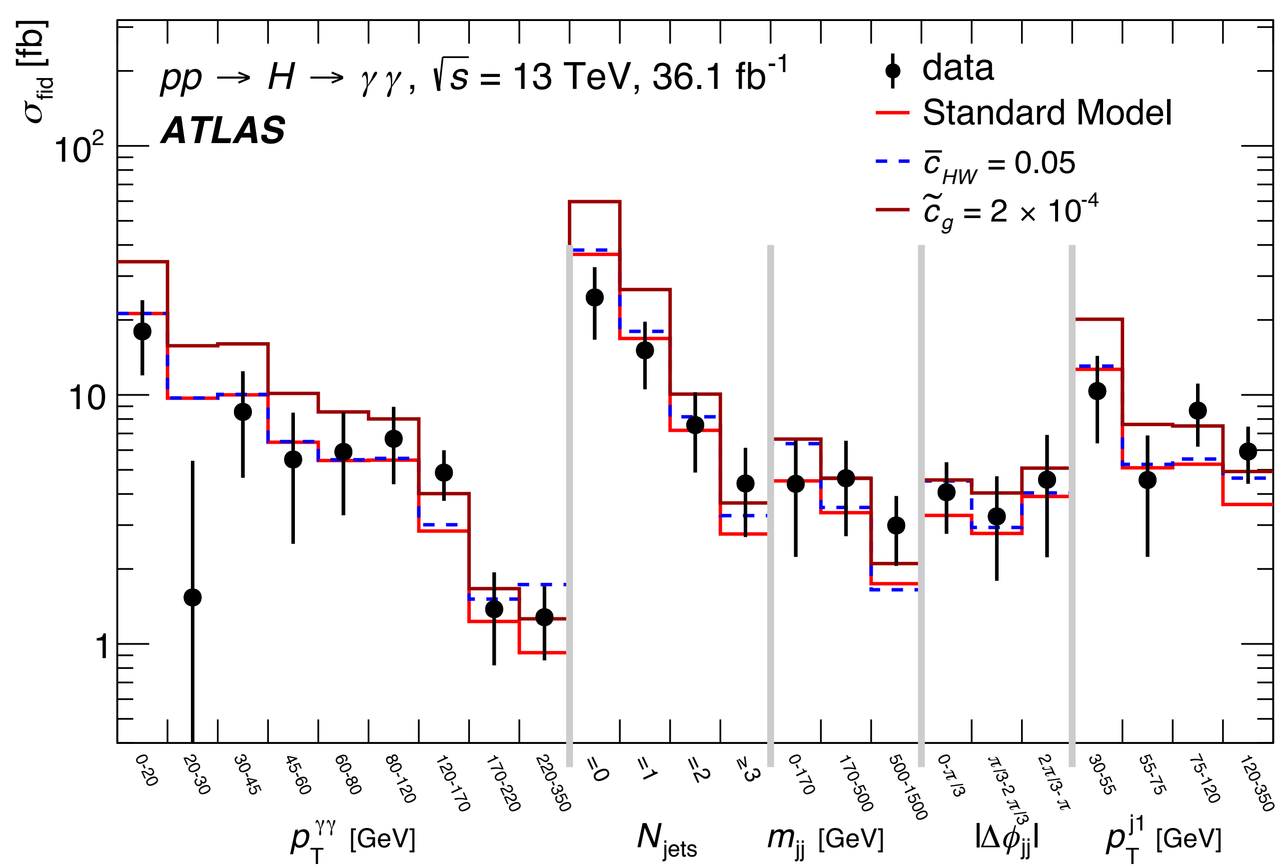


arXiv:1806.00242

Indirect searches

Precision measurements of known processes in search for **small deviations** with respect to the Standard Model (SM)

arXiv:1802.04146



Resonances: peaks in the measured cross-section as a function of the mass of the outgoing particles.

Why very-low mass resonance searches at the LHC?

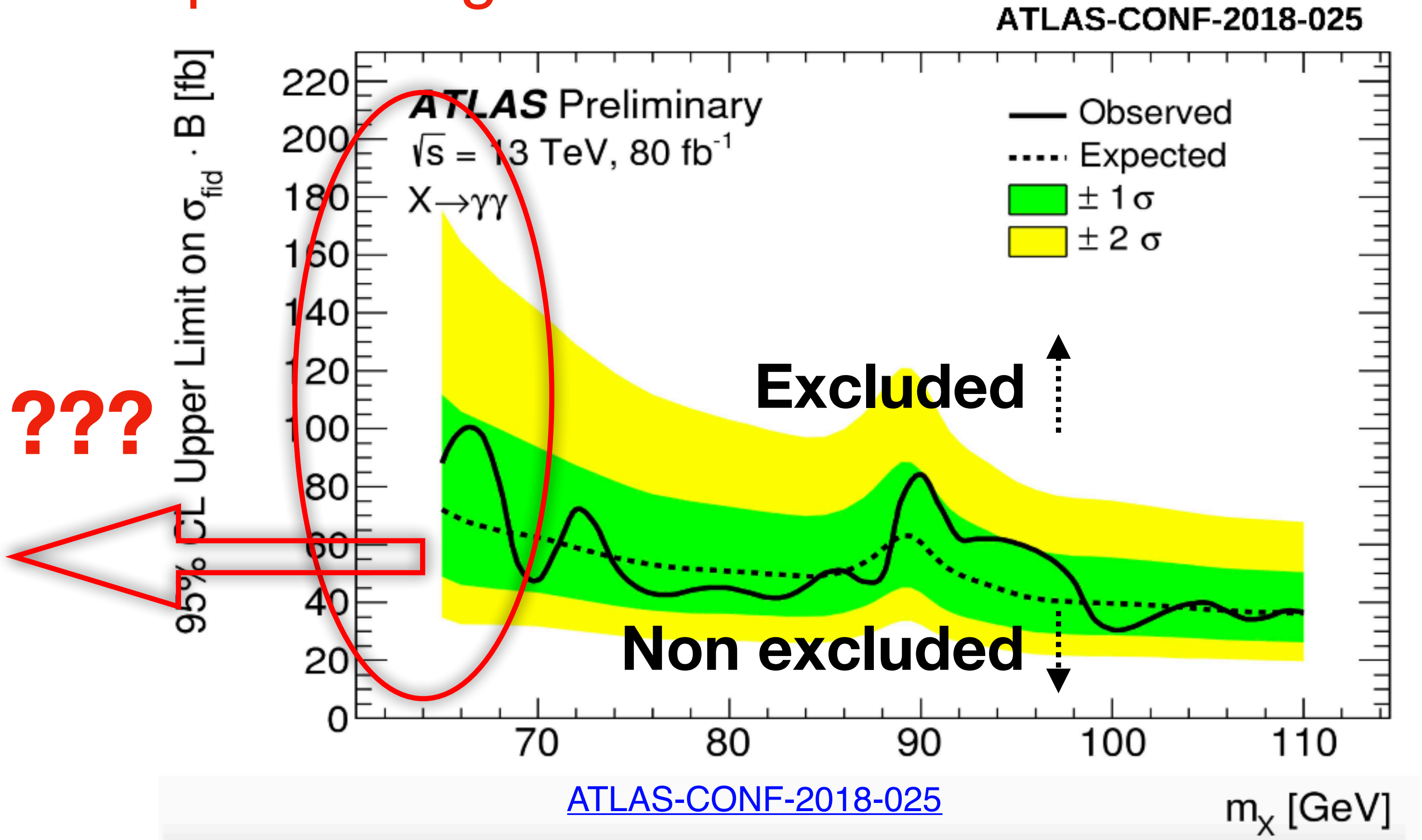
Existing resonance searches performed in the $\gamma\gamma$ channel cover low (from 65 GeV up to 125 GeV) and high (above 125 GeV up to 4.5 TeV) mass regions.

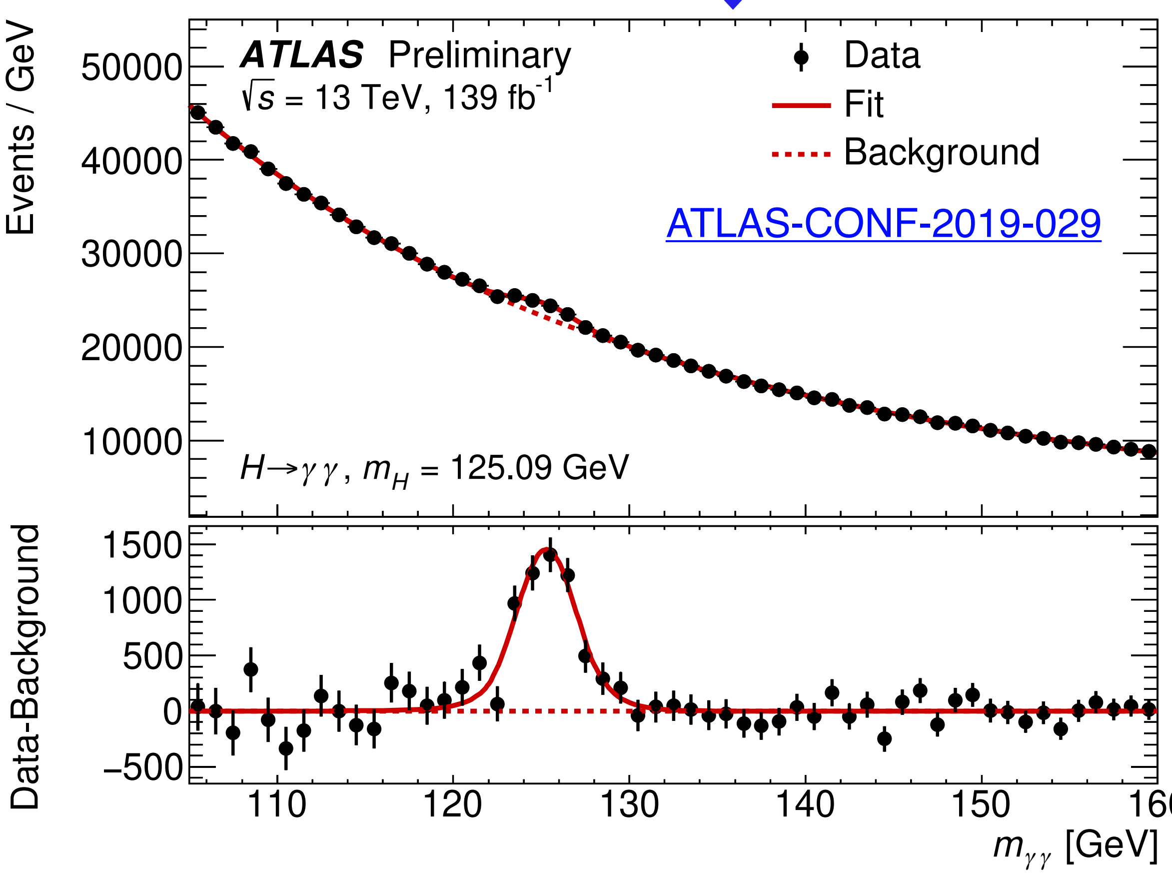
- All searches in agreement with SM predictions.

Why the diphoton channel?

- Clear signature of two isolated and energetic photons
- Very good photon energy resolution

Unexplored region!





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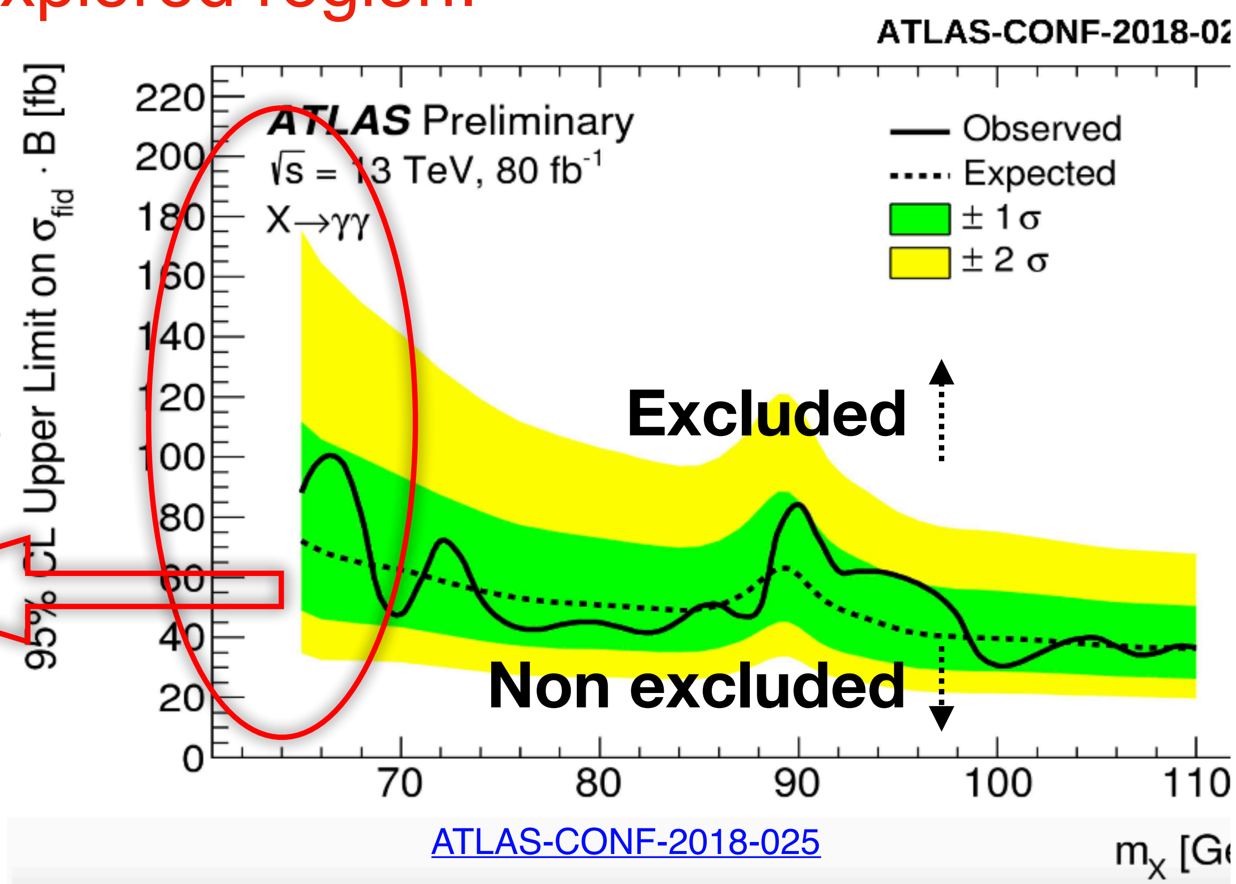
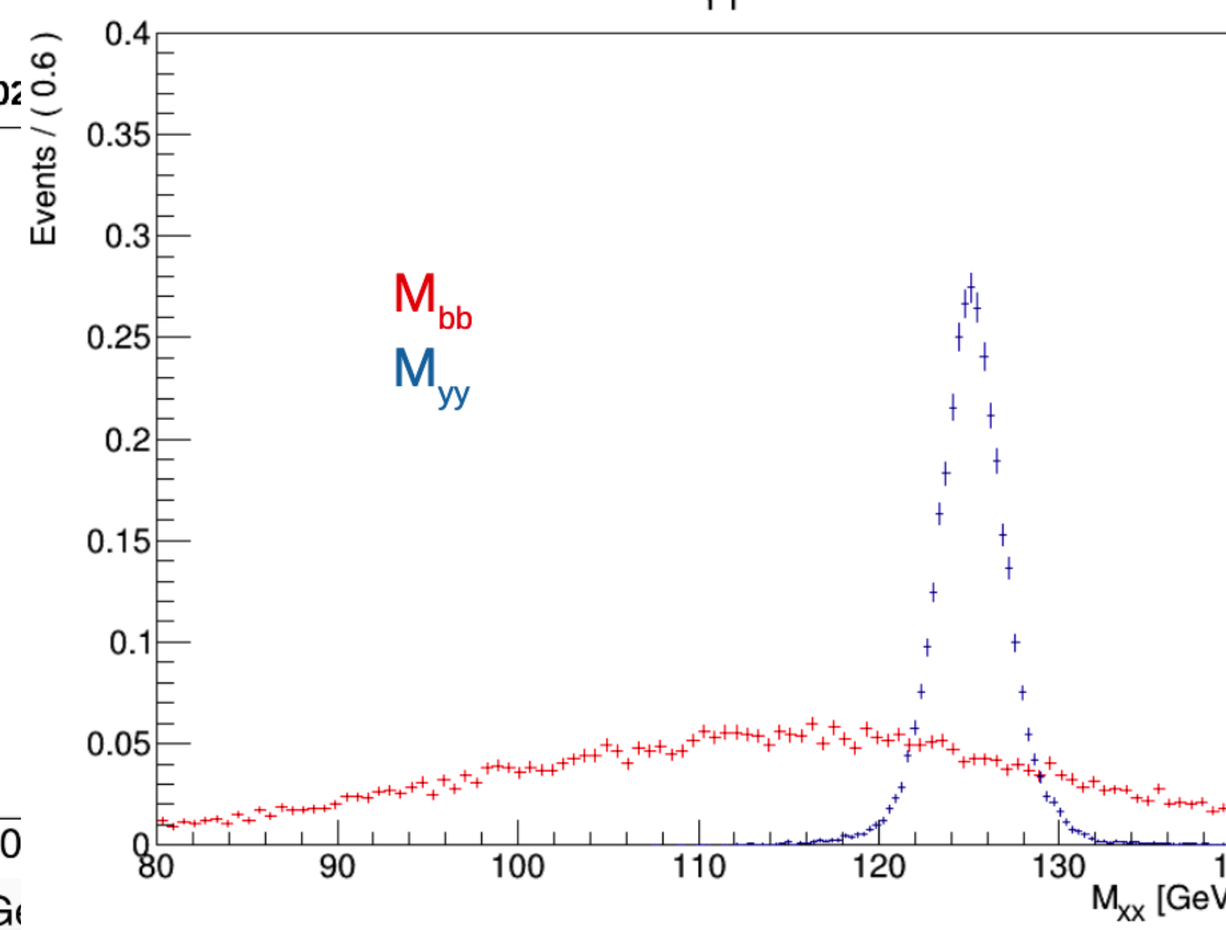


Compare M_{YY} and M_{BB}



ATLAS - CMS comparison

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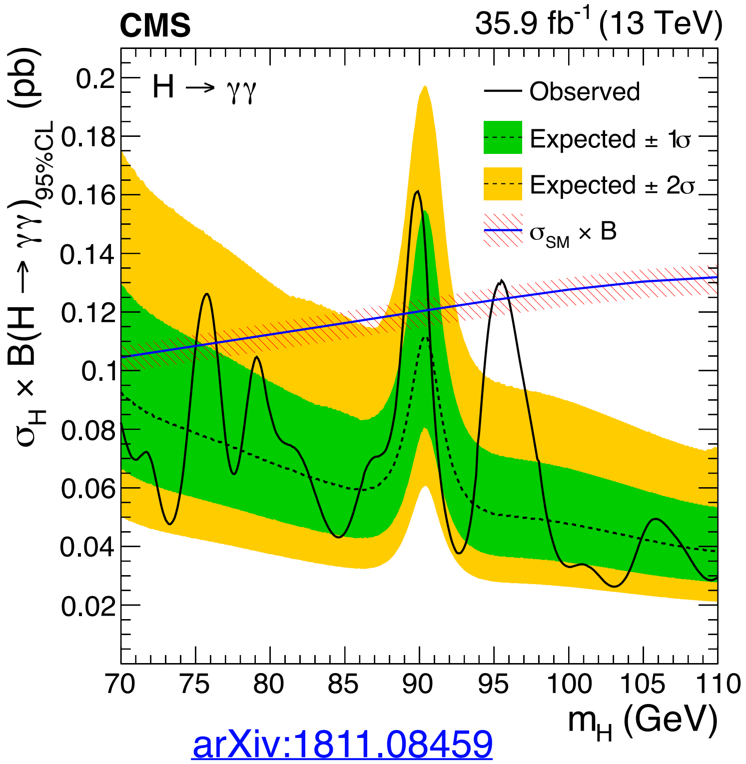
Both experiments have results published for low and high mass ranges.

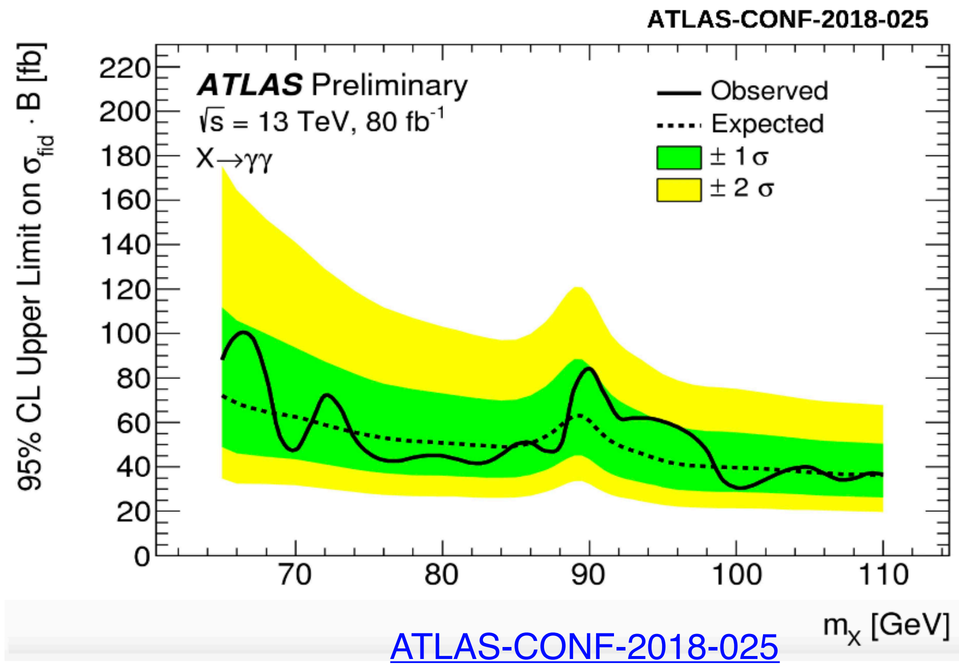
- Slight excess observed by CMS of ~2.9σ at 95 GeV not seen by ATLAS.

Low range

ATLAS $m_{\gamma\gamma}$: [65,110] GeV
CMS $m_{\gamma\gamma}$: [70,110] GeV



arXiv:1811.08459



ATLAS-CONF-2018-025

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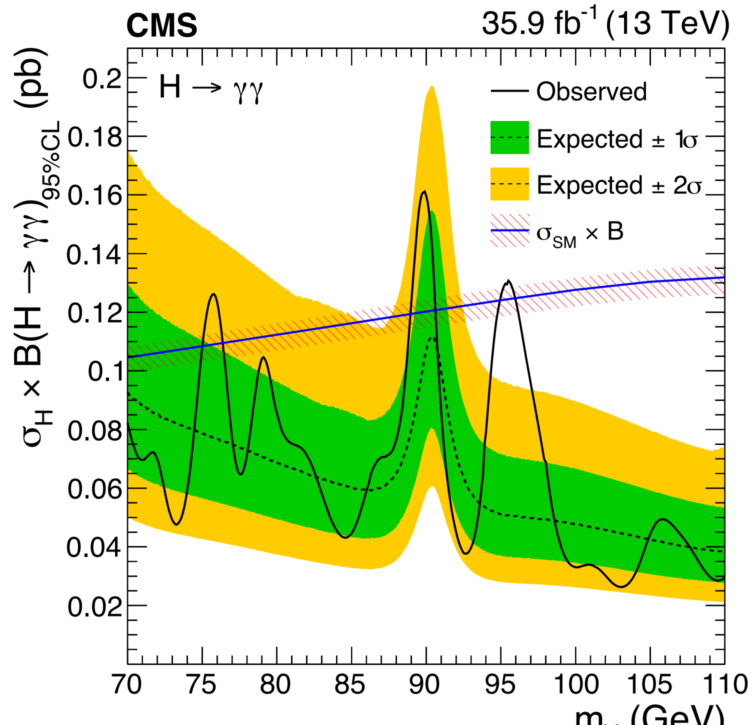

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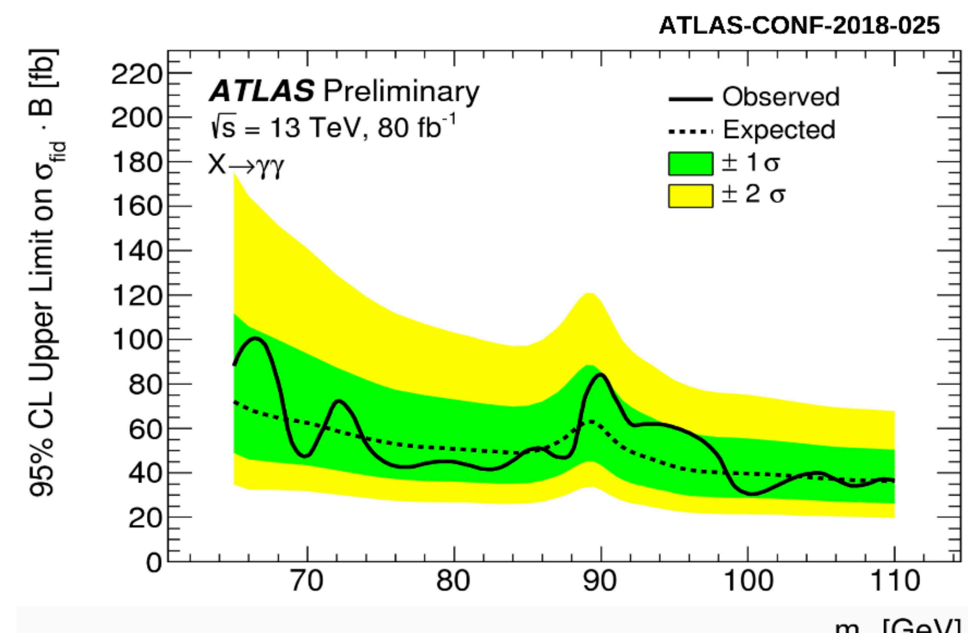

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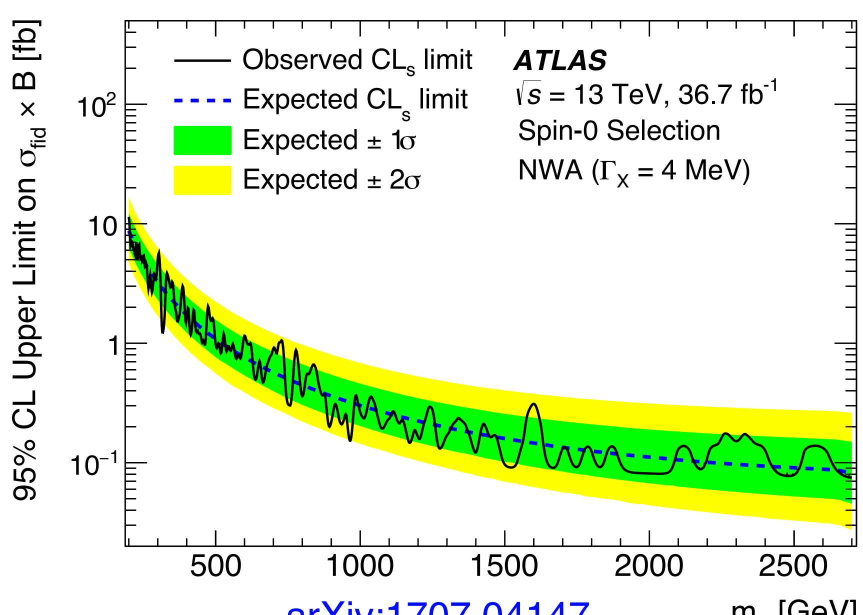
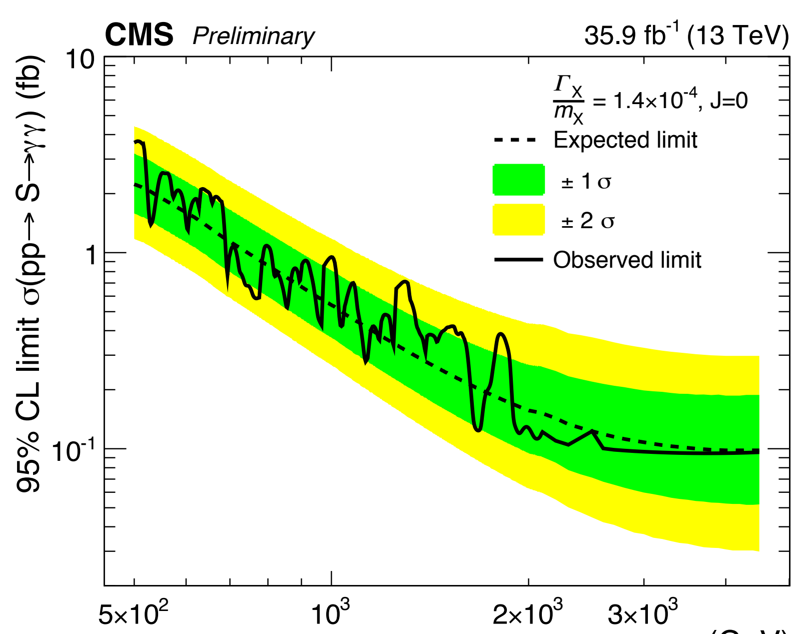
CMS $m_{\gamma\gamma}$: [0.5,4.5] TeV



arXiv:1707.04147



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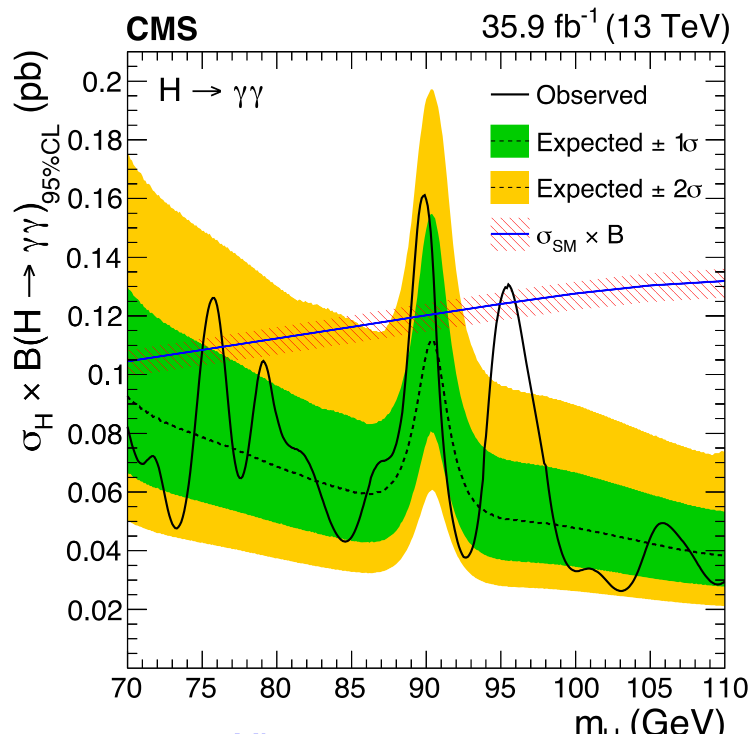

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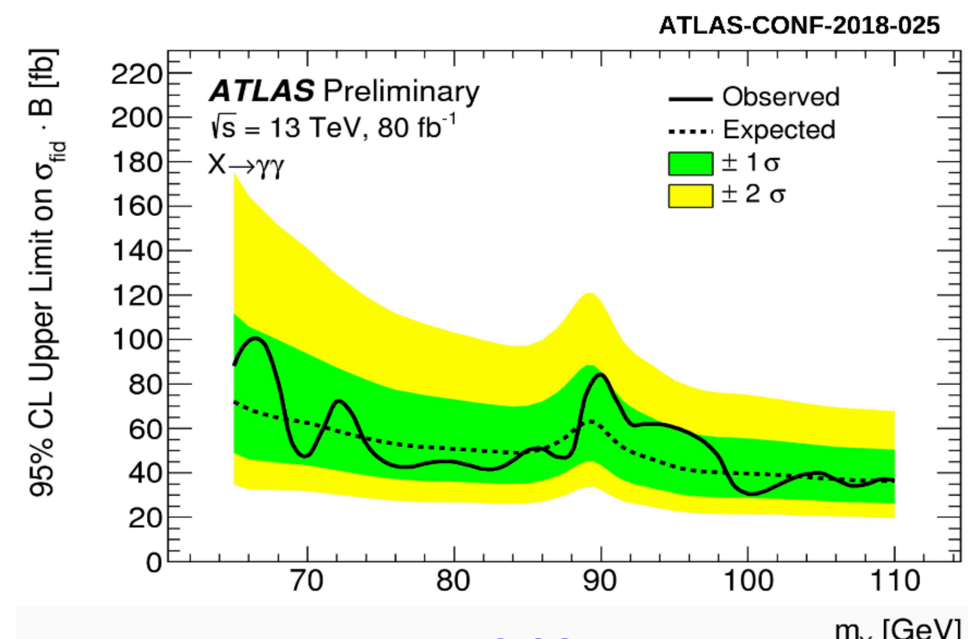

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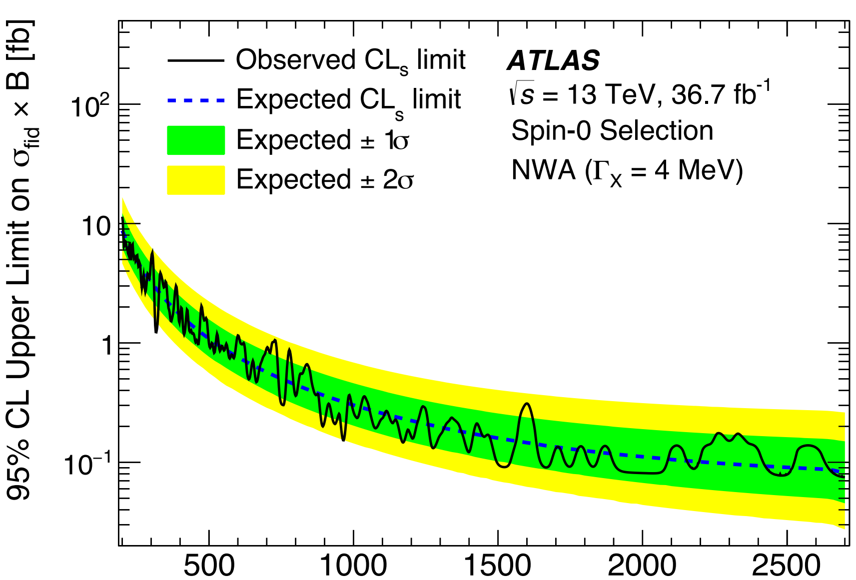

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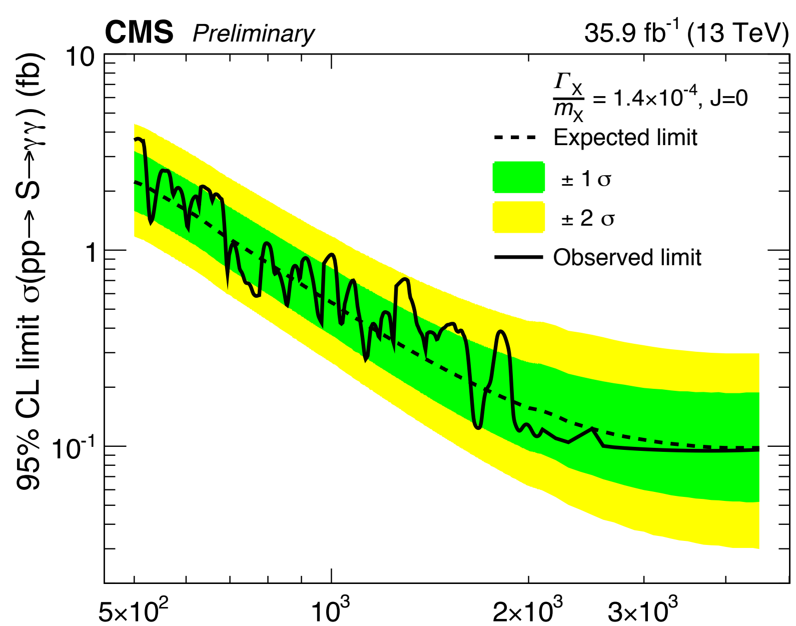

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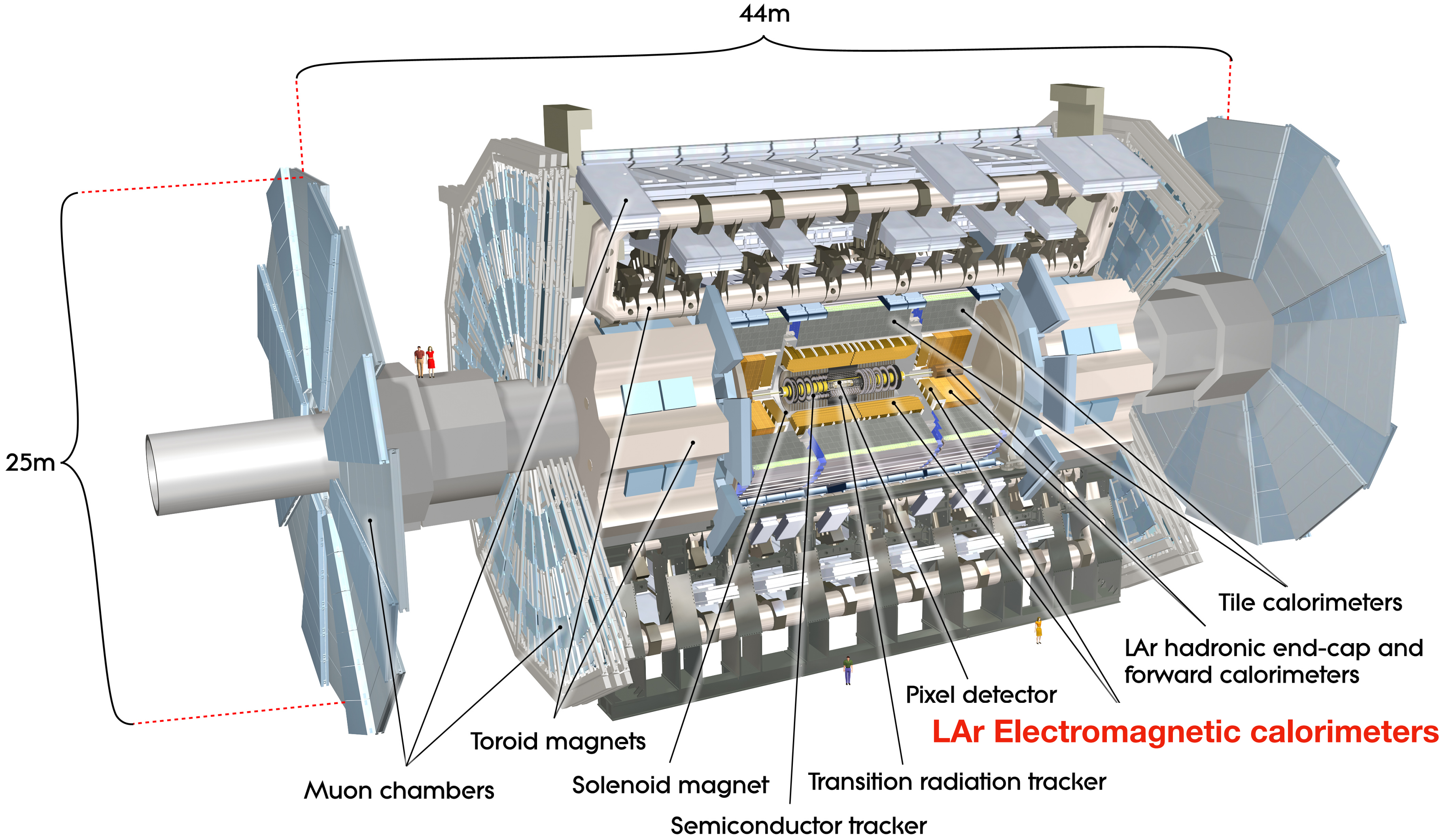
No significant excess is observed with respect to the background-only hypothesis.

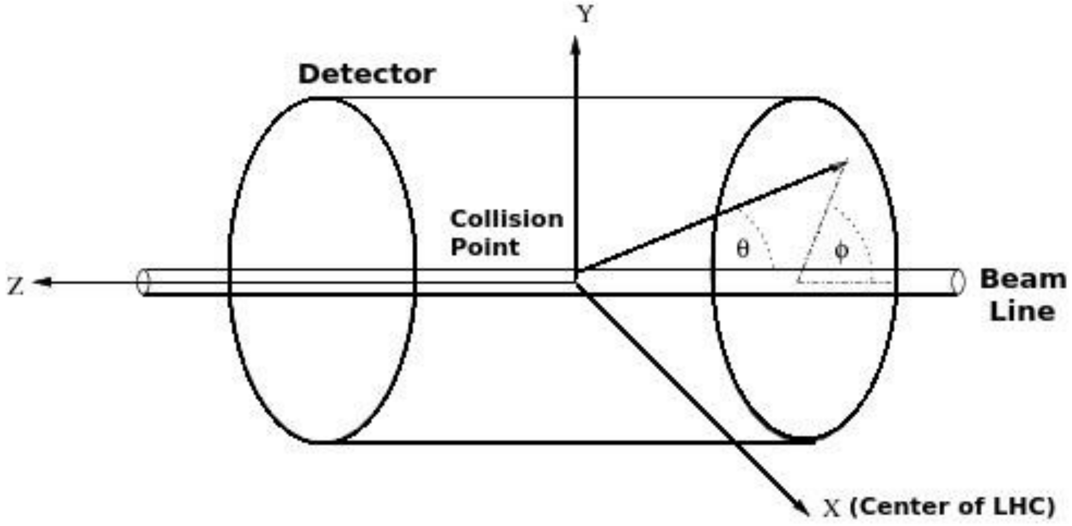
Experimental setup: the ATLAS detector

The ATLAS detector



Multipurpose particle physics detector

Photon reconstruction makes use mainly of the EM calorimeter + additional information from the hadronic and inner detector.



Useful variables

$$\eta = -\log\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Pseudo-rapidity

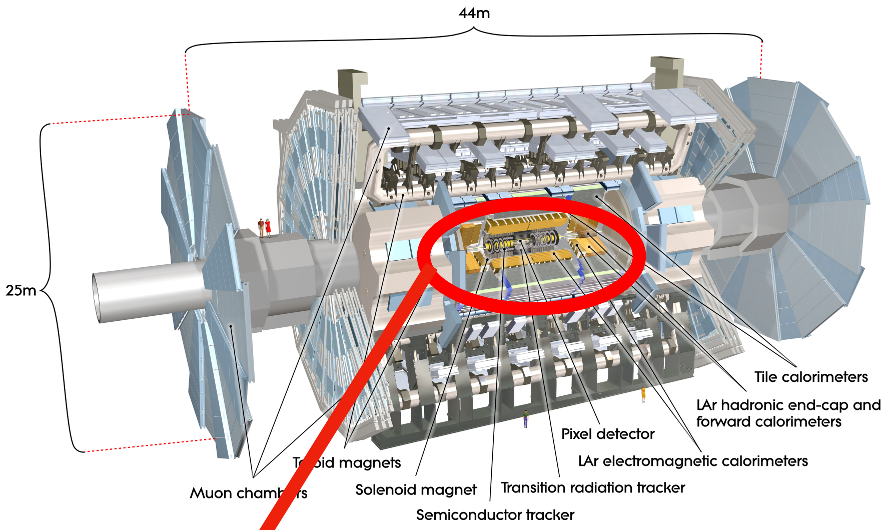
$E_T \equiv$ transverse energy. Commonly used in proton colliders.

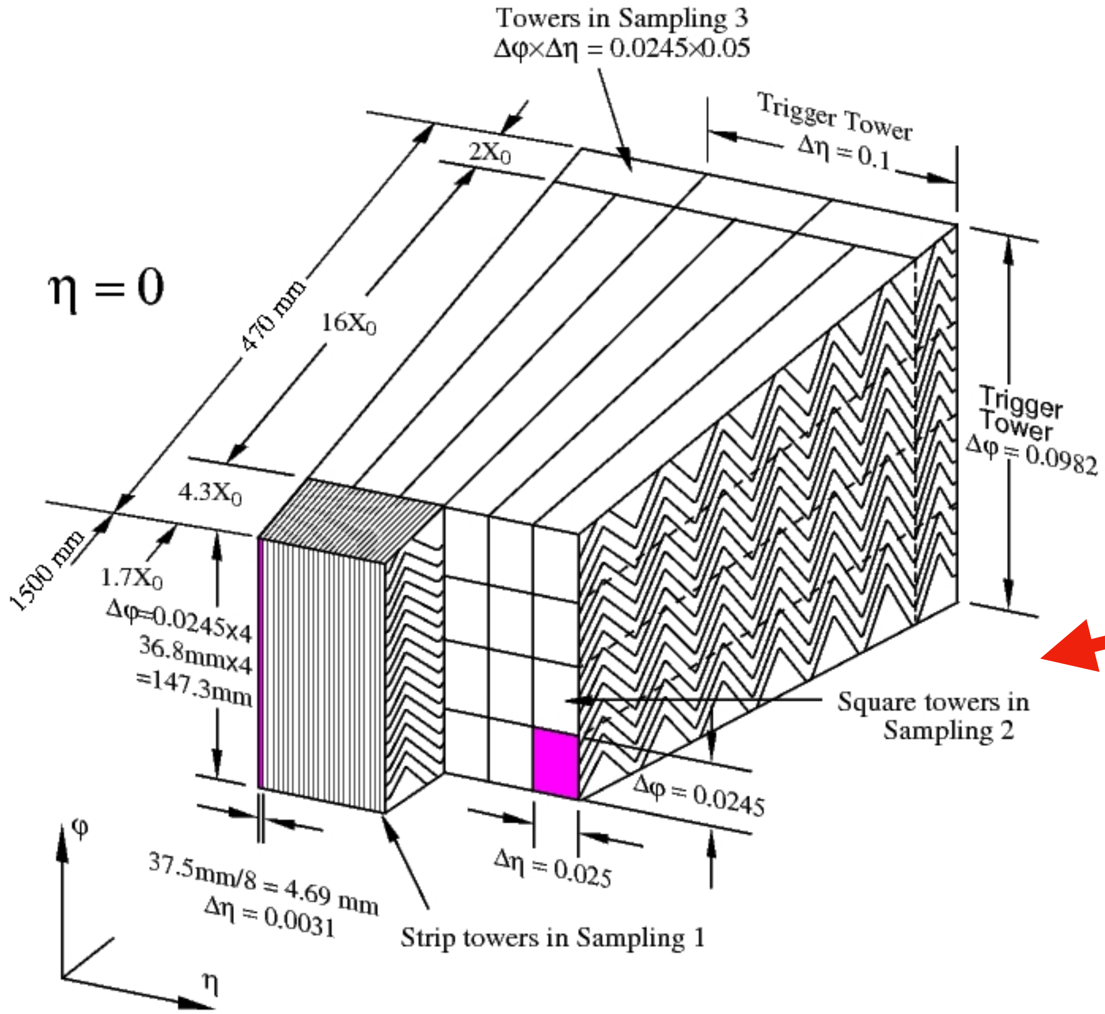
$$E_T = \sqrt{E_x^2 + E_y^2}$$

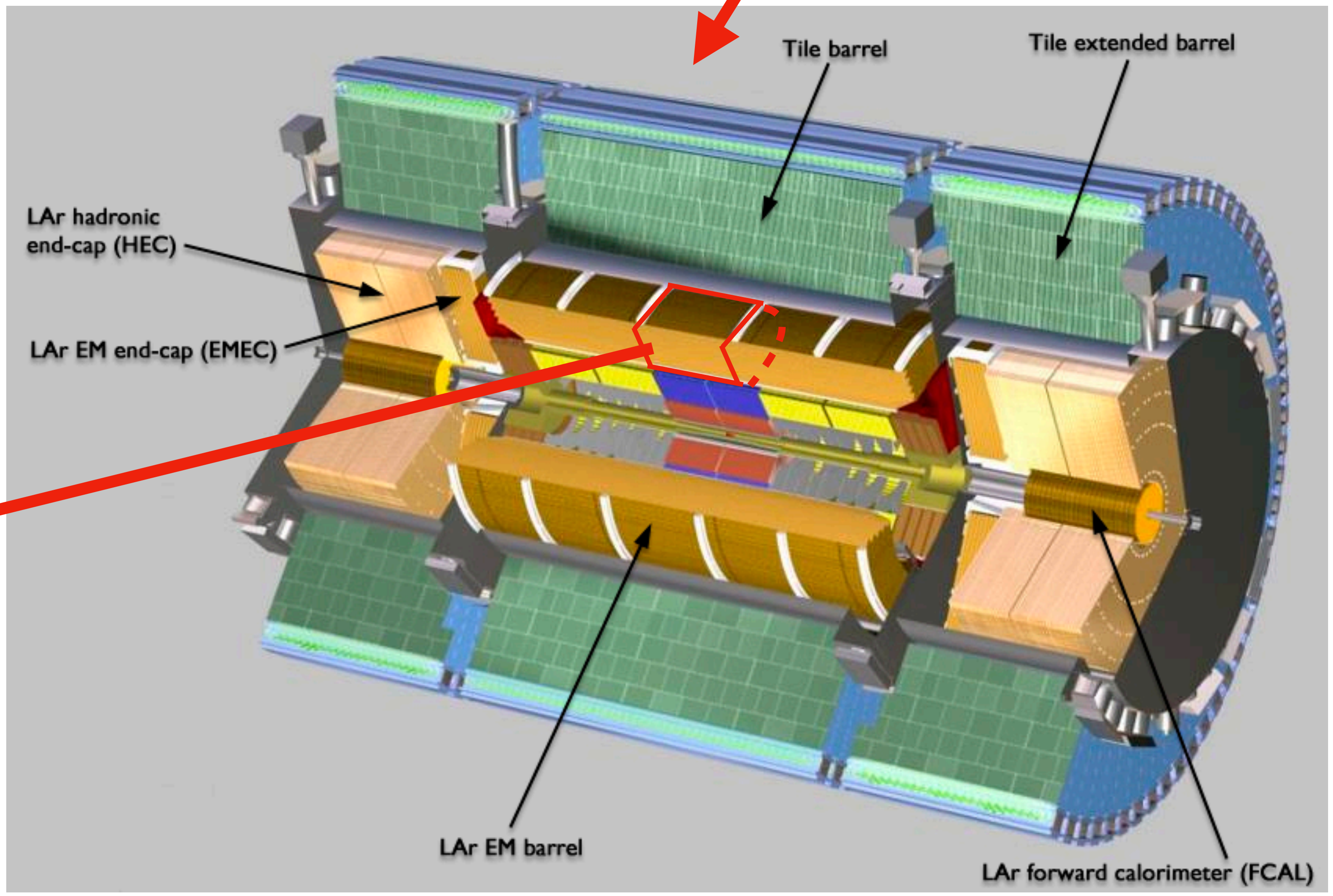
Electromagnetic calorimeter

- Sampling electromagnetic calorimeter measures the energy loss by photons and electrons as they interact with matter.
- Longitudinal three layer segmentation.

$$\frac{\sigma(E)}{E} = \frac{10\,\%\sqrt{GeV}}{\sqrt{E}} \oplus 0.7\,\%$$







Photons in ATLAS

Photon reconstruction and energy calibration

Particles going through the detector deposit energy in the calorimeter cells

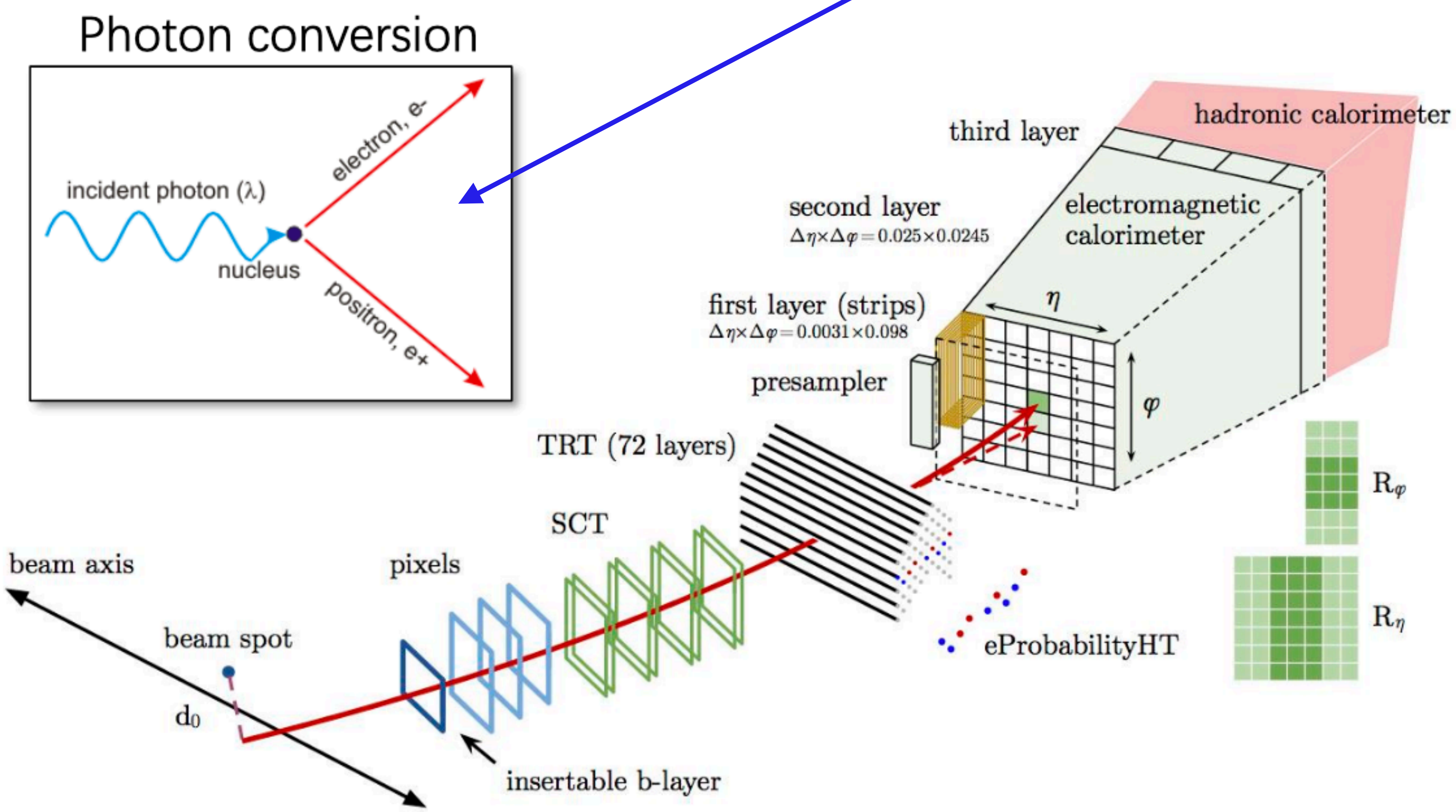
- Collections of cells are **clustered together**.

Match clusters to tracks

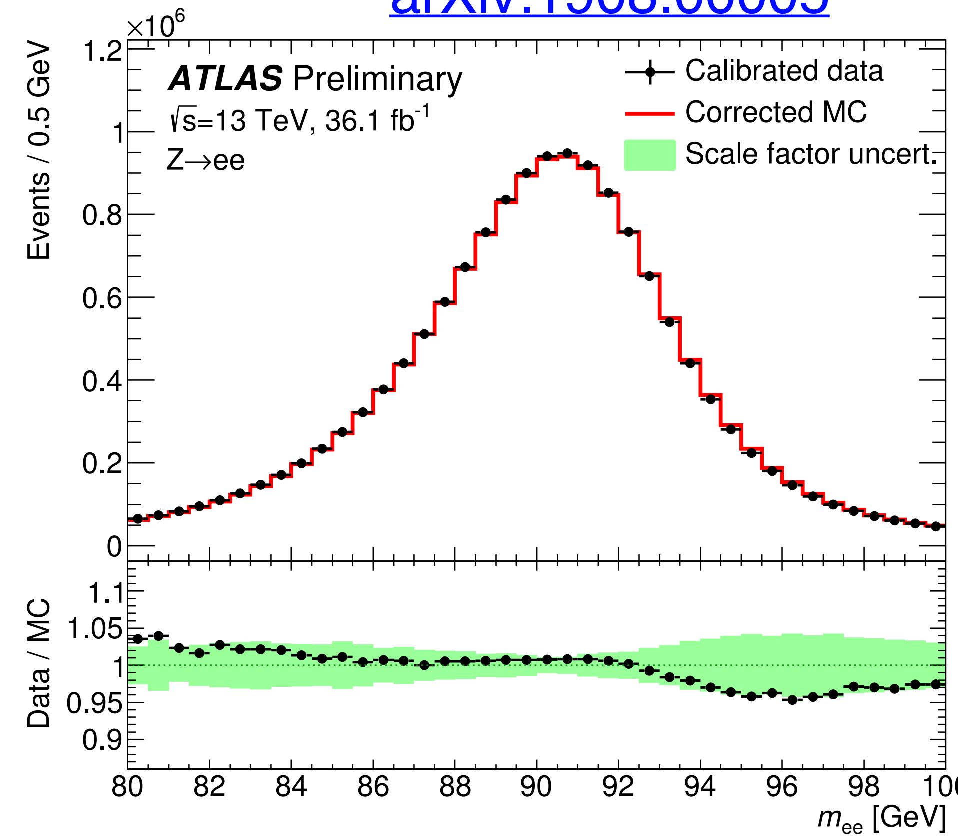
- Distinguish electrons from unconverted photons.

Match track to secondary vertex

- Distinguish electrons from converted photons



arXiv:1908.00005



Energy obtained by summing the energy of the cells in the cluster

- Energy is calibrated to obtain the original energy of the electromagnetic particle

$$E_{data} = E_{MC}(1 + \alpha_i)$$

Photon identification

Electromagnetic shower development **almost identical** for any photon.

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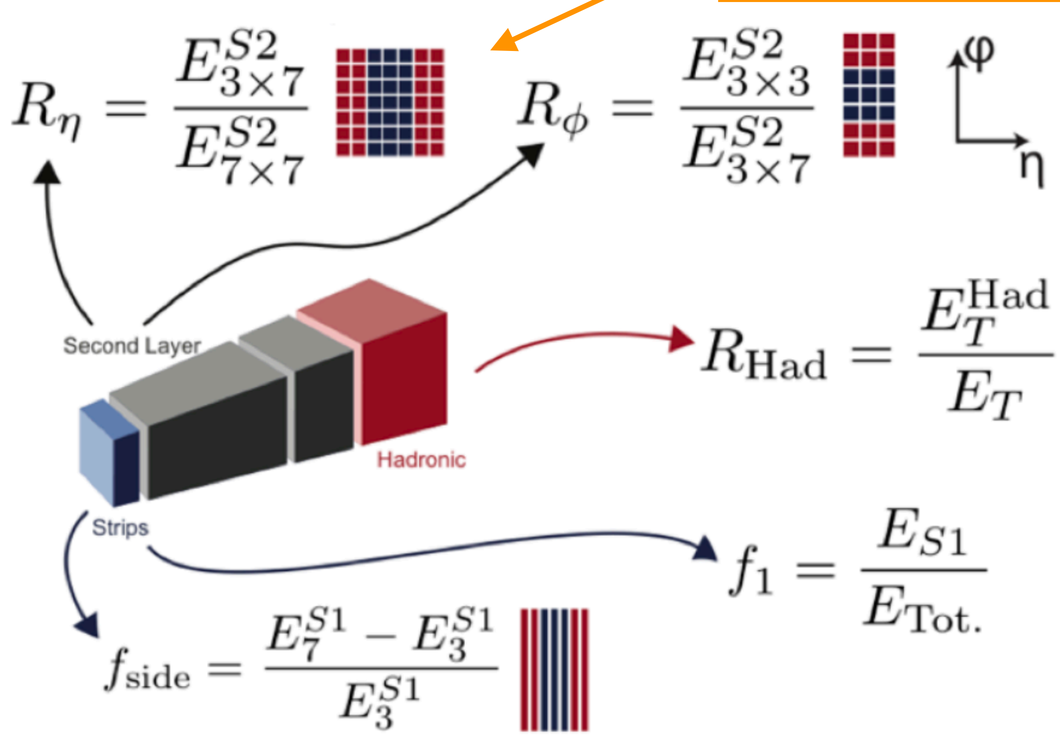
Variables that characterize a photon shower longitudinal and lateral profile.



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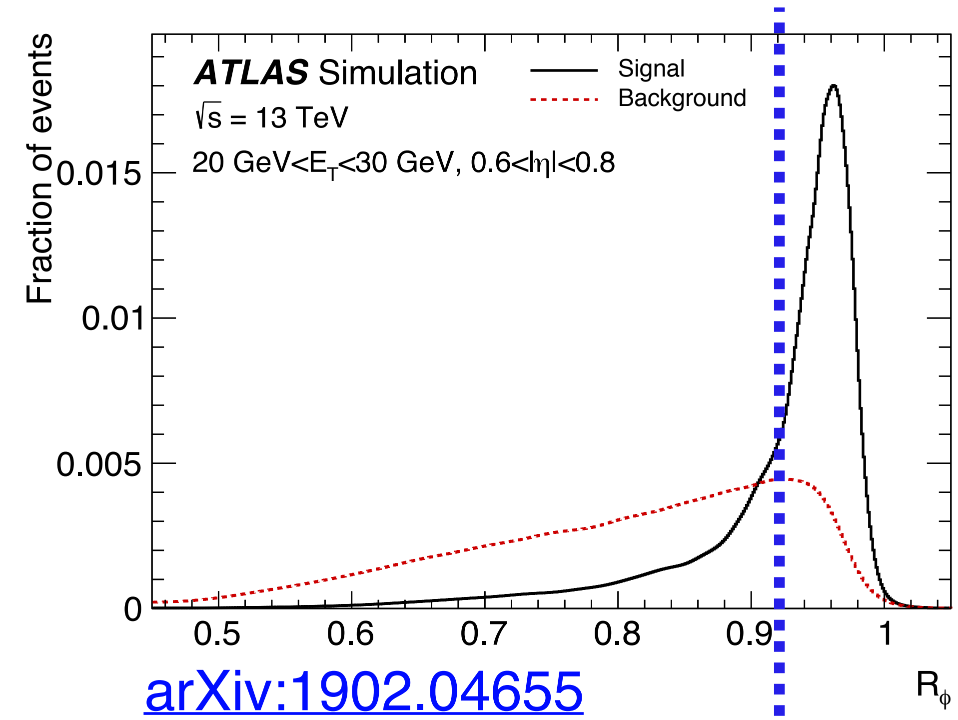
Electromagnetic shower development **almost identical** for any photon.

Different sets of cuts provide good separation between e/γ and QCD background



arXiv:1902.04655

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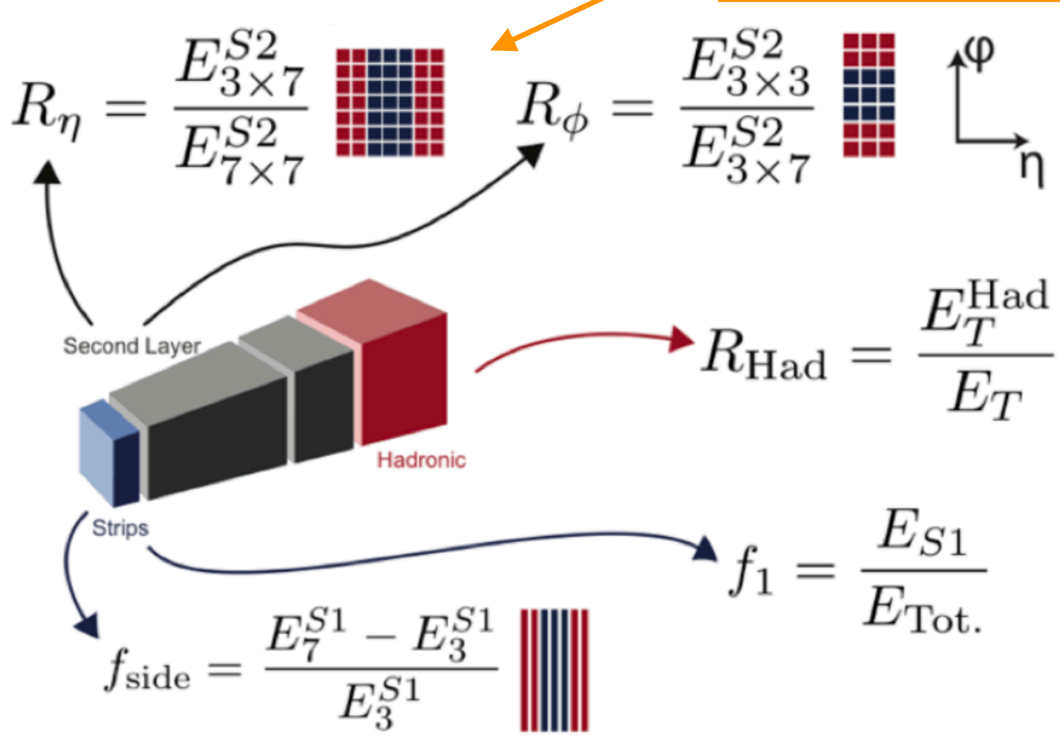

$$R_\eta = \frac{E^{S2}_{3\times7}}{E^{S2}_{7\times7}} \qquad R_\phi = \frac{E^{S2}_{3\times3}}{E^{S2}_{3\times7}}$$

$$R_{\mathrm{Had}} = \frac{E^{\mathrm{Had}}_T}{E_T}$$

$$f_1 = \frac{E_{S1}}{E_{\mathrm{Tot.}}}$$

$$f_{\mathrm{side}} = \frac{E^{S1}_7 - E^{S1}_3}{E^{S1}_3}$$

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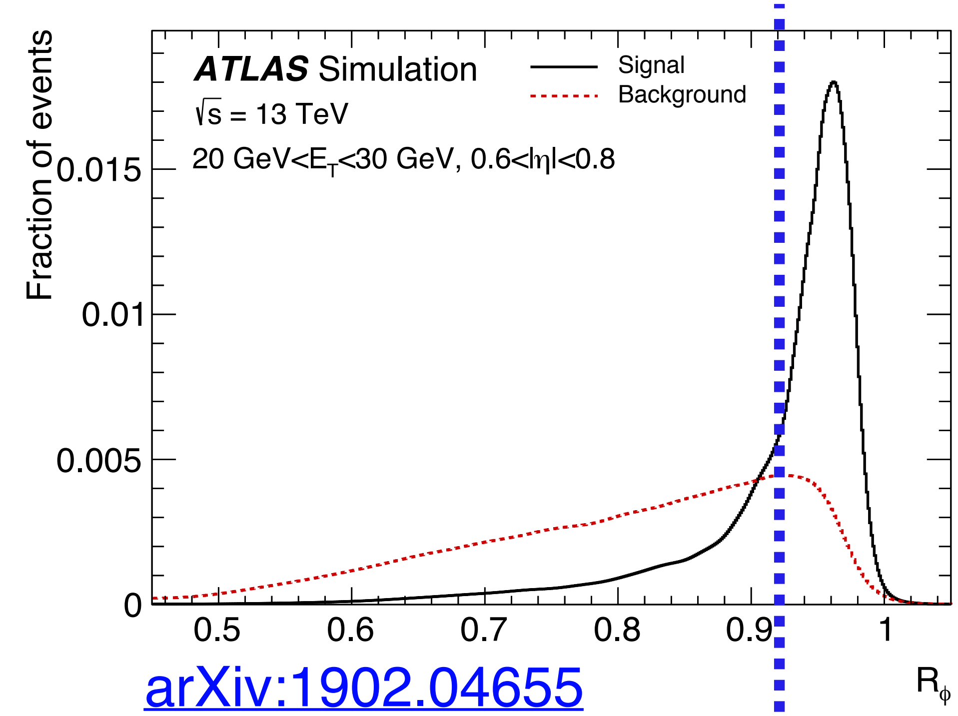

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Example of γ/π^0 discrimination

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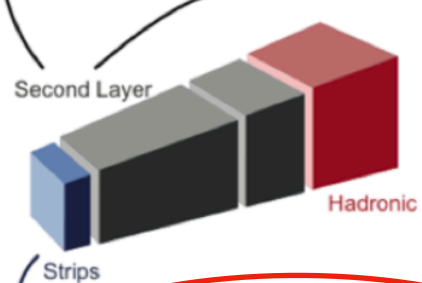
φ η



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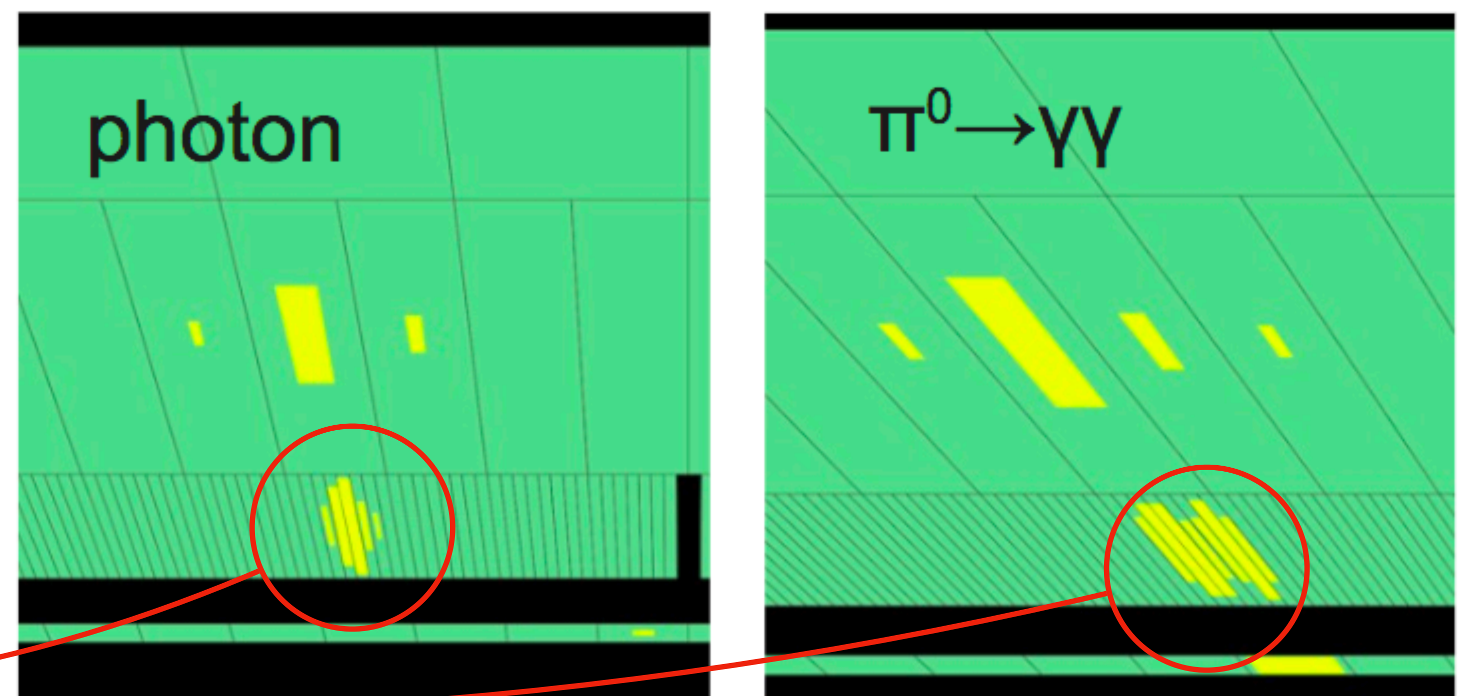


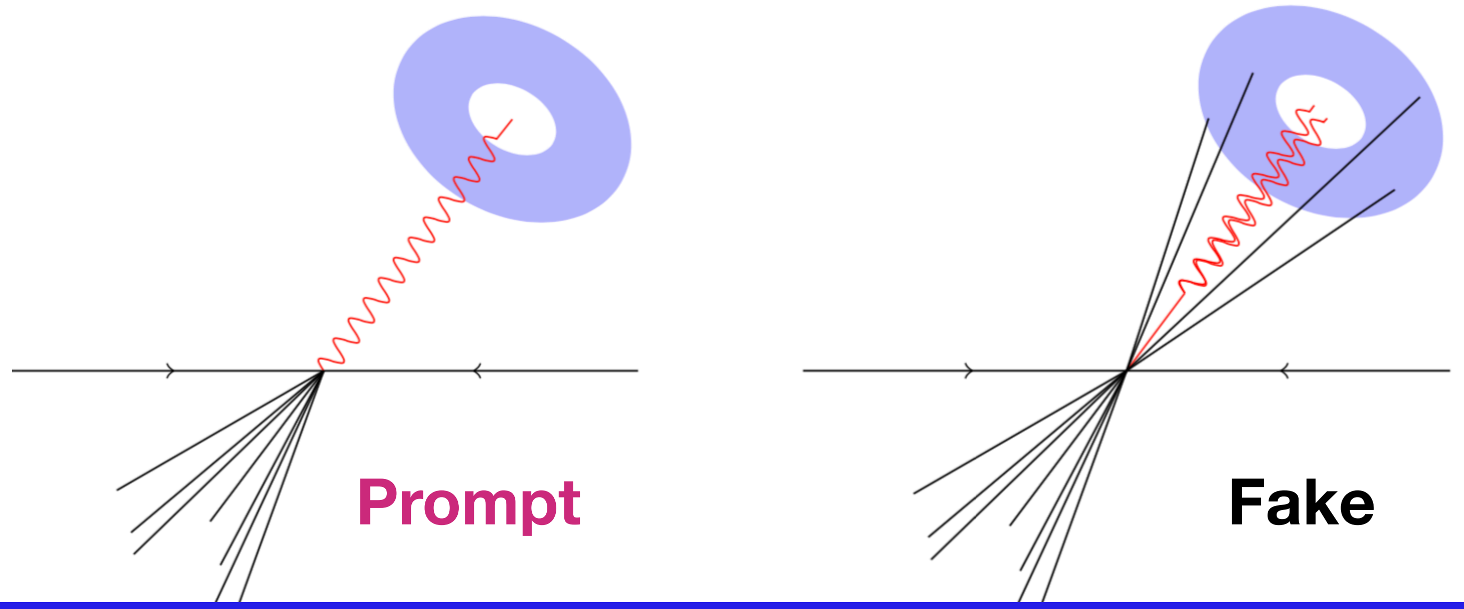
High granularity of the detector plays a crucial role in photon ID.

Photon isolation

Photon isolation is applied on top of photon ID to further suppress backgrounds.

Photon isolation helps to suppress fakes (like $\pi^0 \rightarrow \gamma\gamma$) and bremsstrahlung photons as the **energy flow** around them is **higher** than for prompt photons

Estimated using information from the calorimeters and the tracker.



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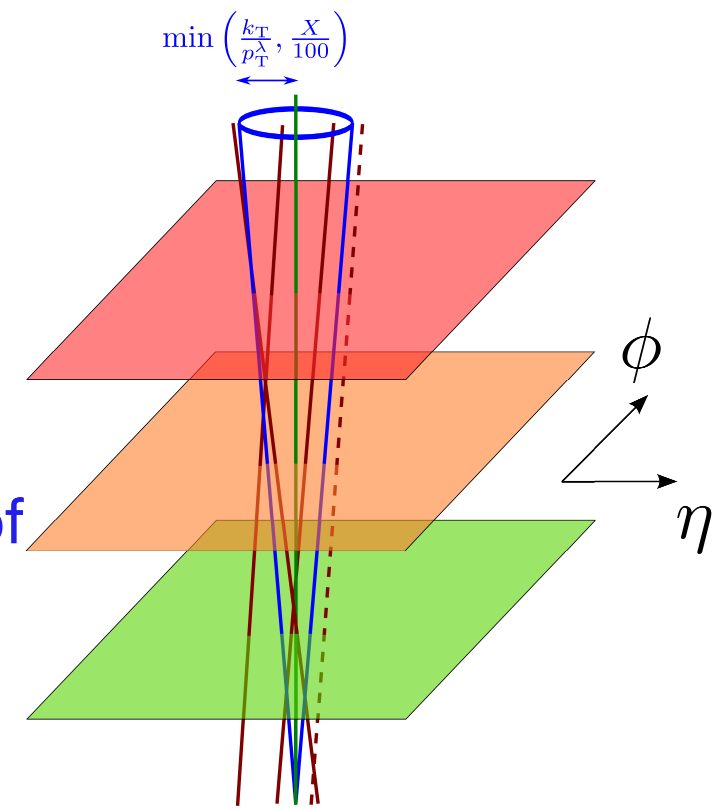
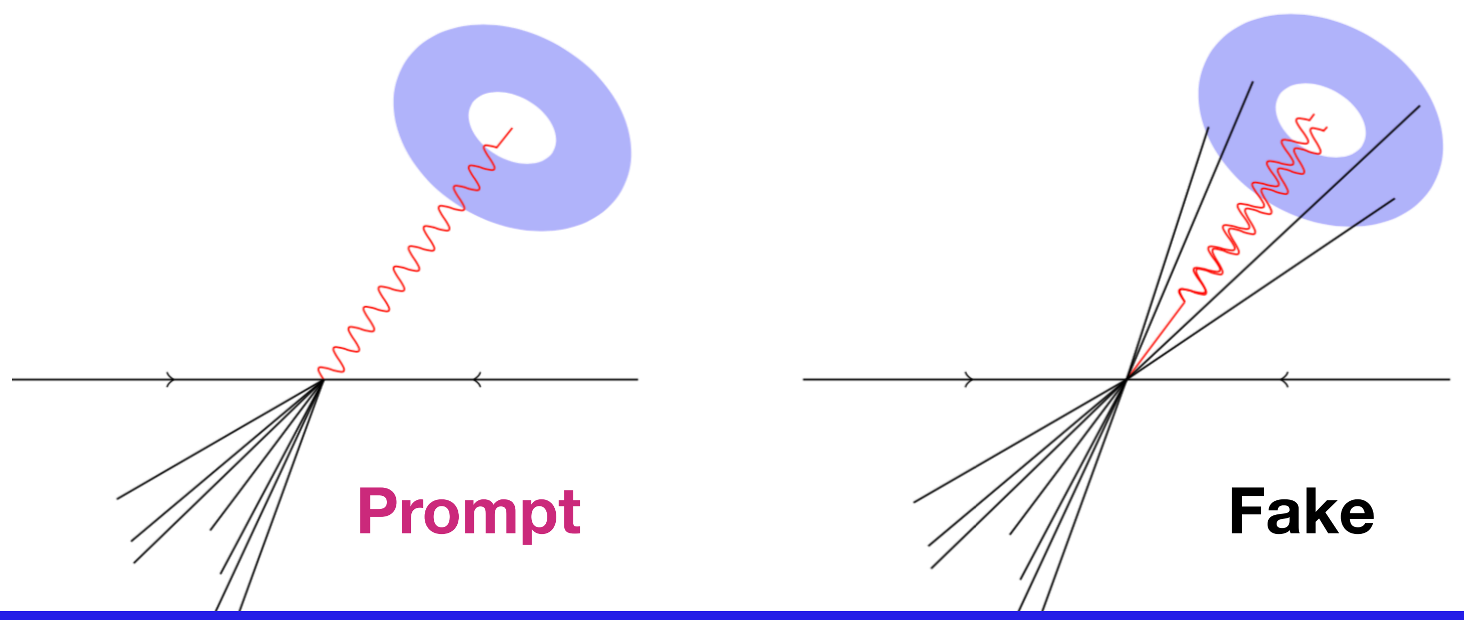
Track isolation energy: sum of the energy of the tracks around the photon





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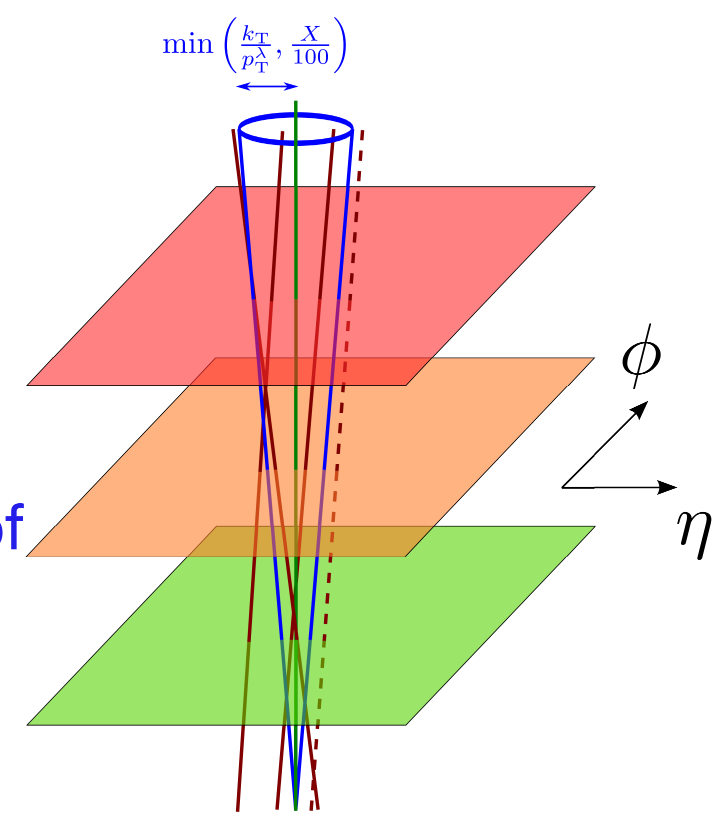
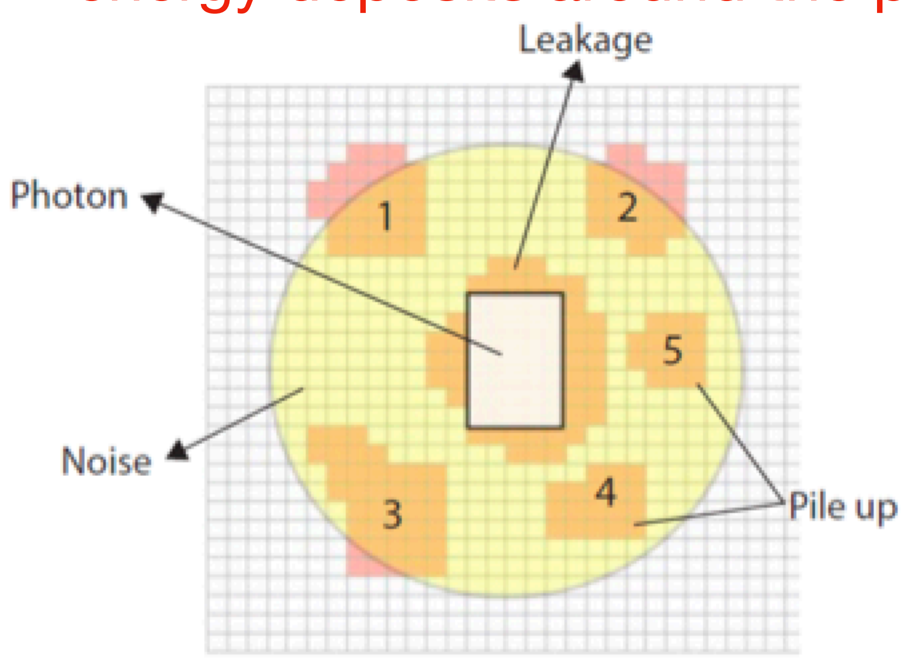
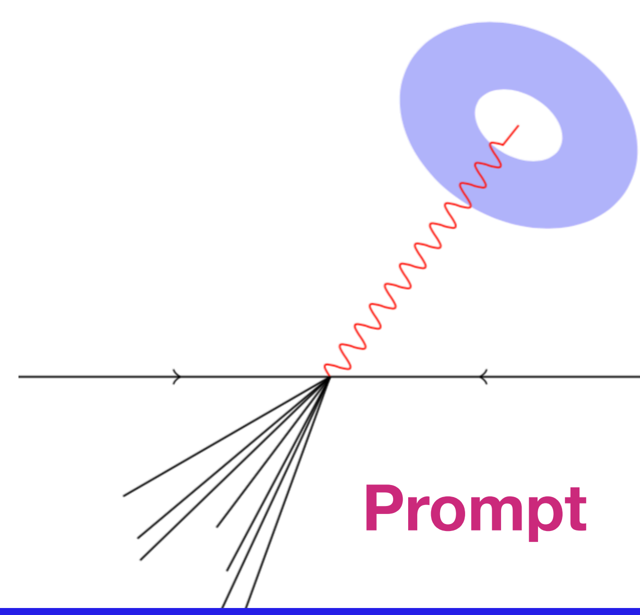
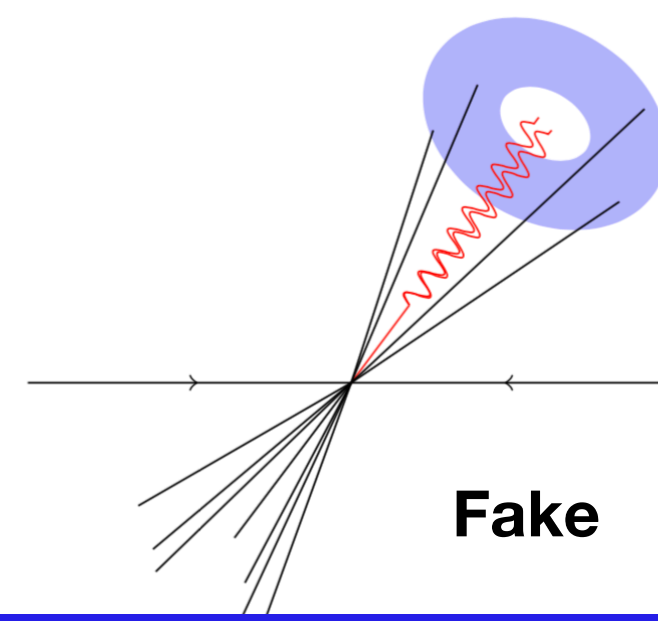


Calorimetric isolation energy: sum of energy deposits around the photon







Analysis strategy

Analysis strategy in a nutshell

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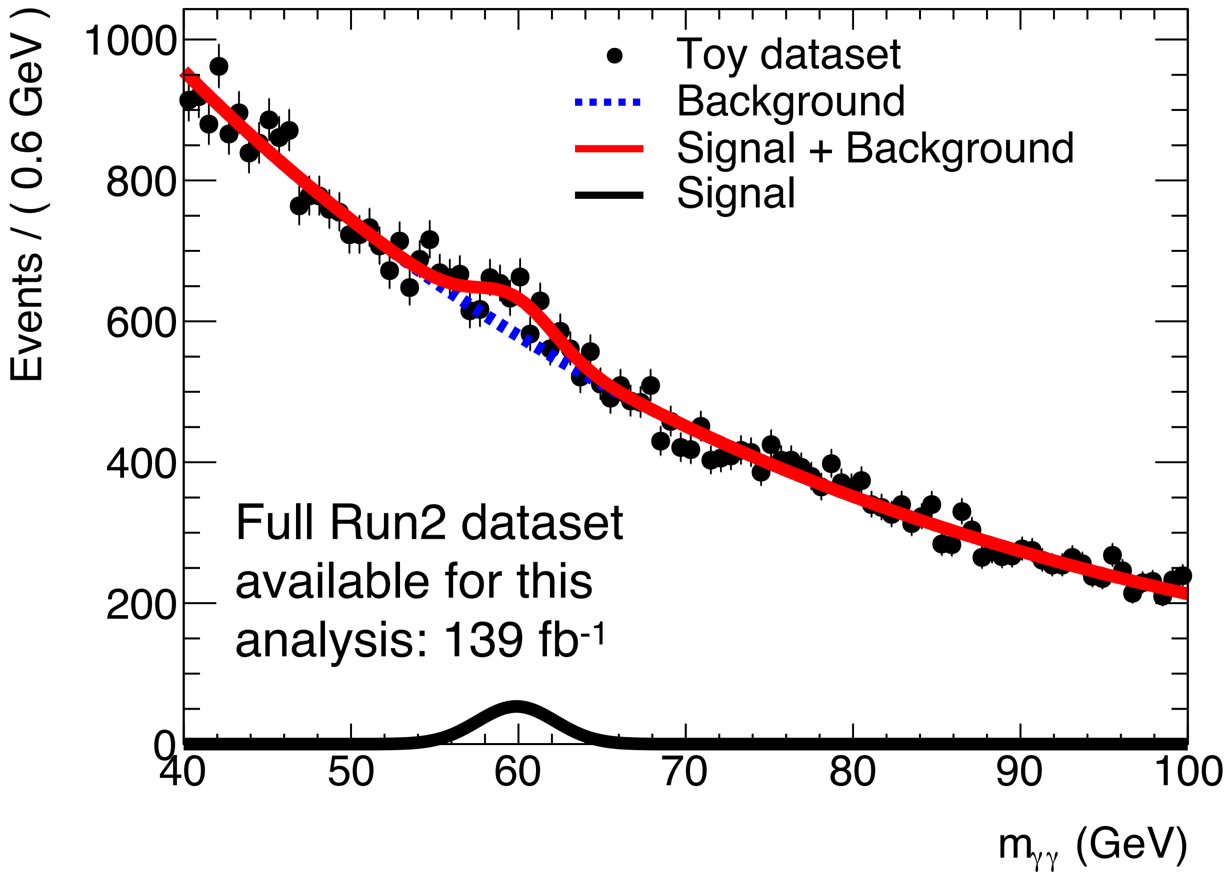
"Bump" search strategy: event excess over a **smoothly falling background** in the $m_{\gamma\gamma}$ distribution.



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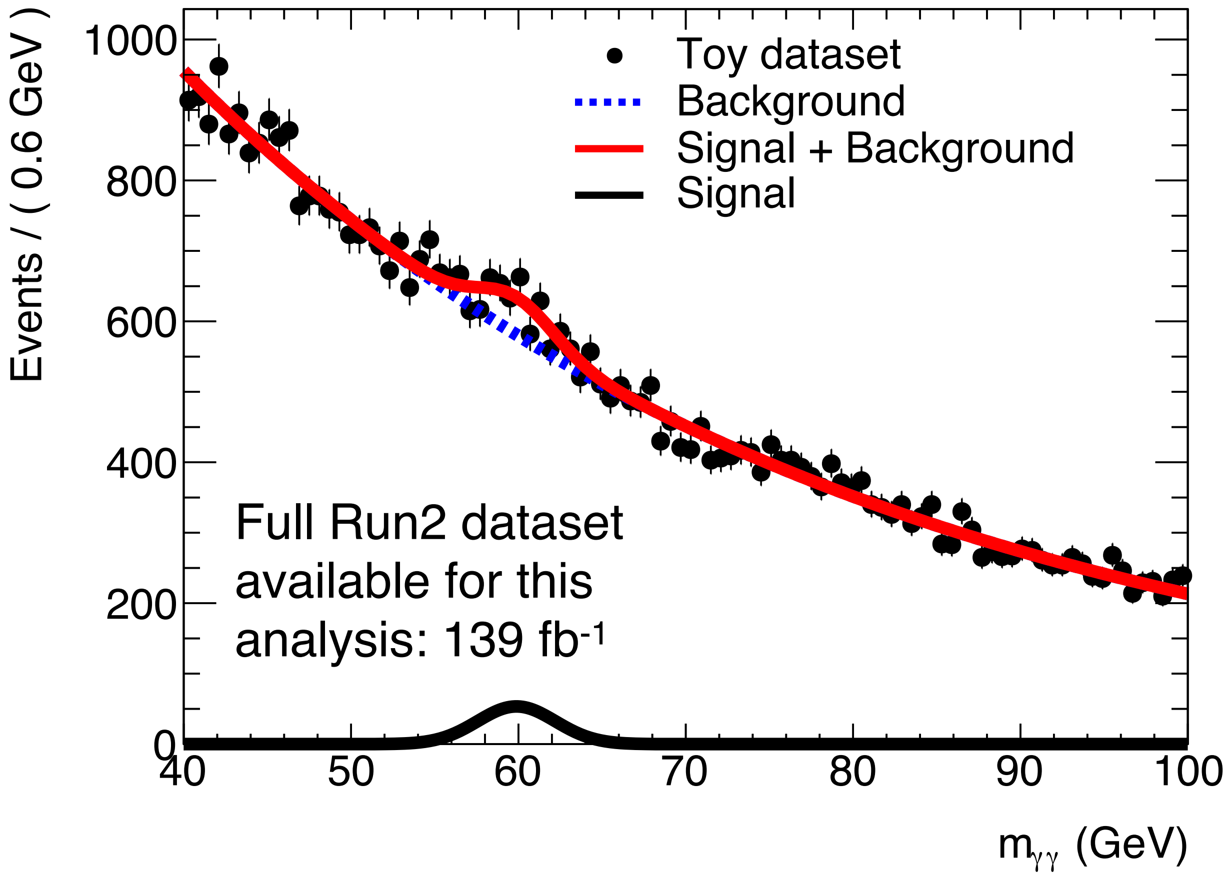

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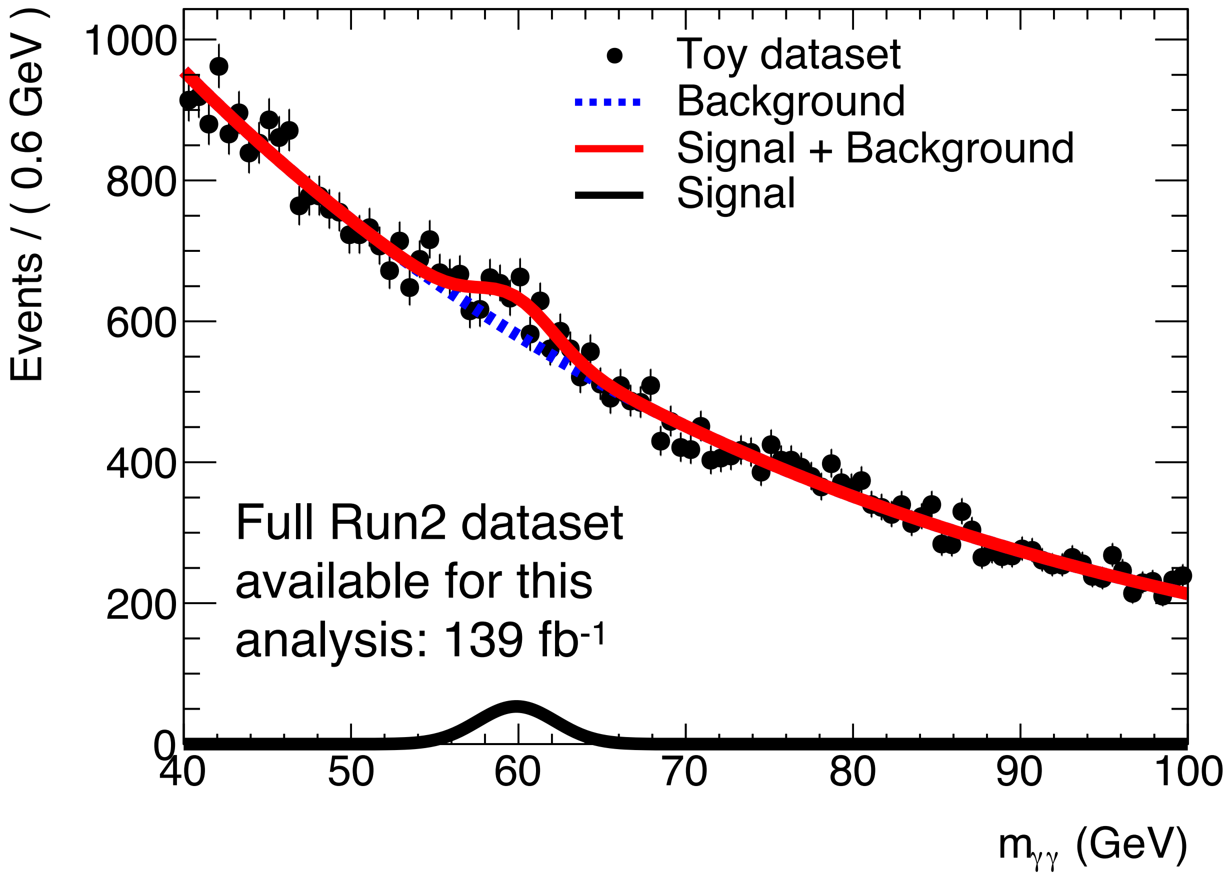

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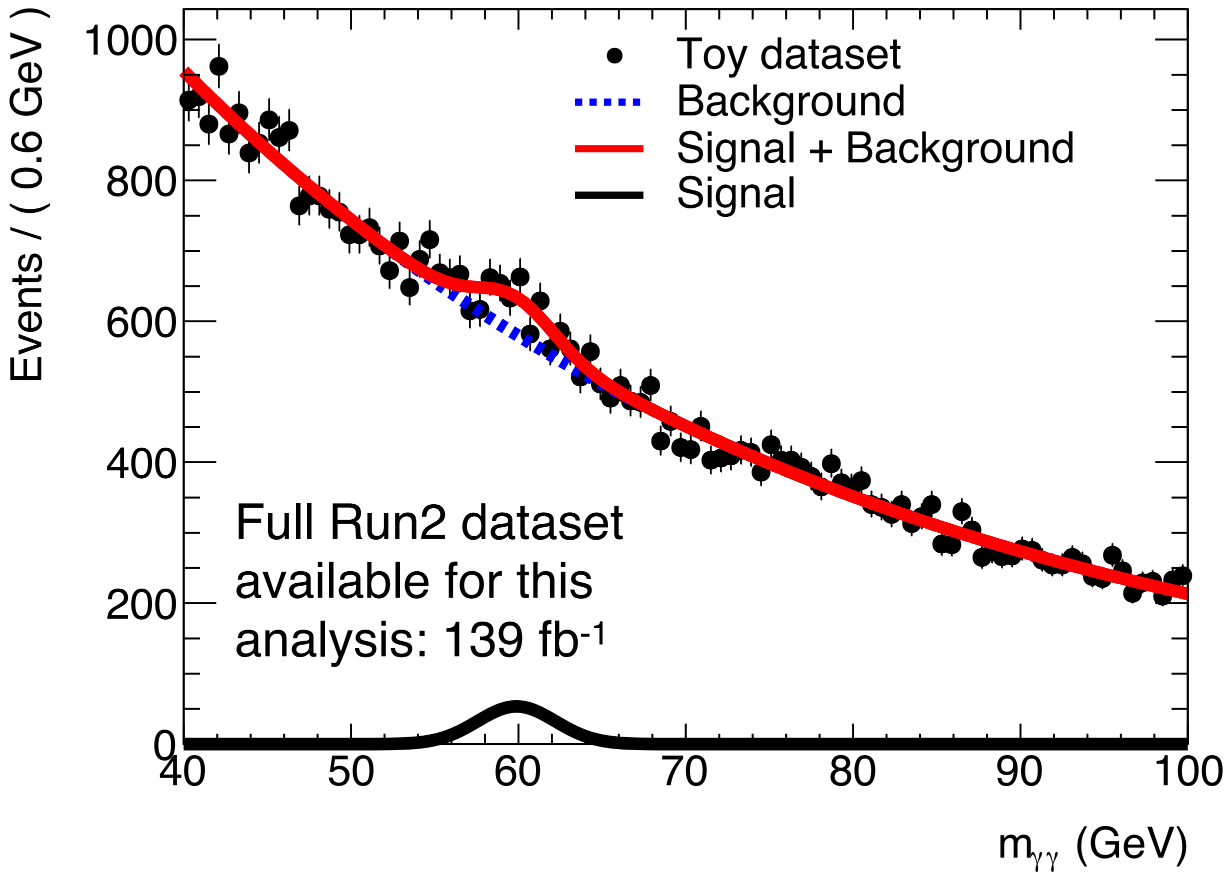

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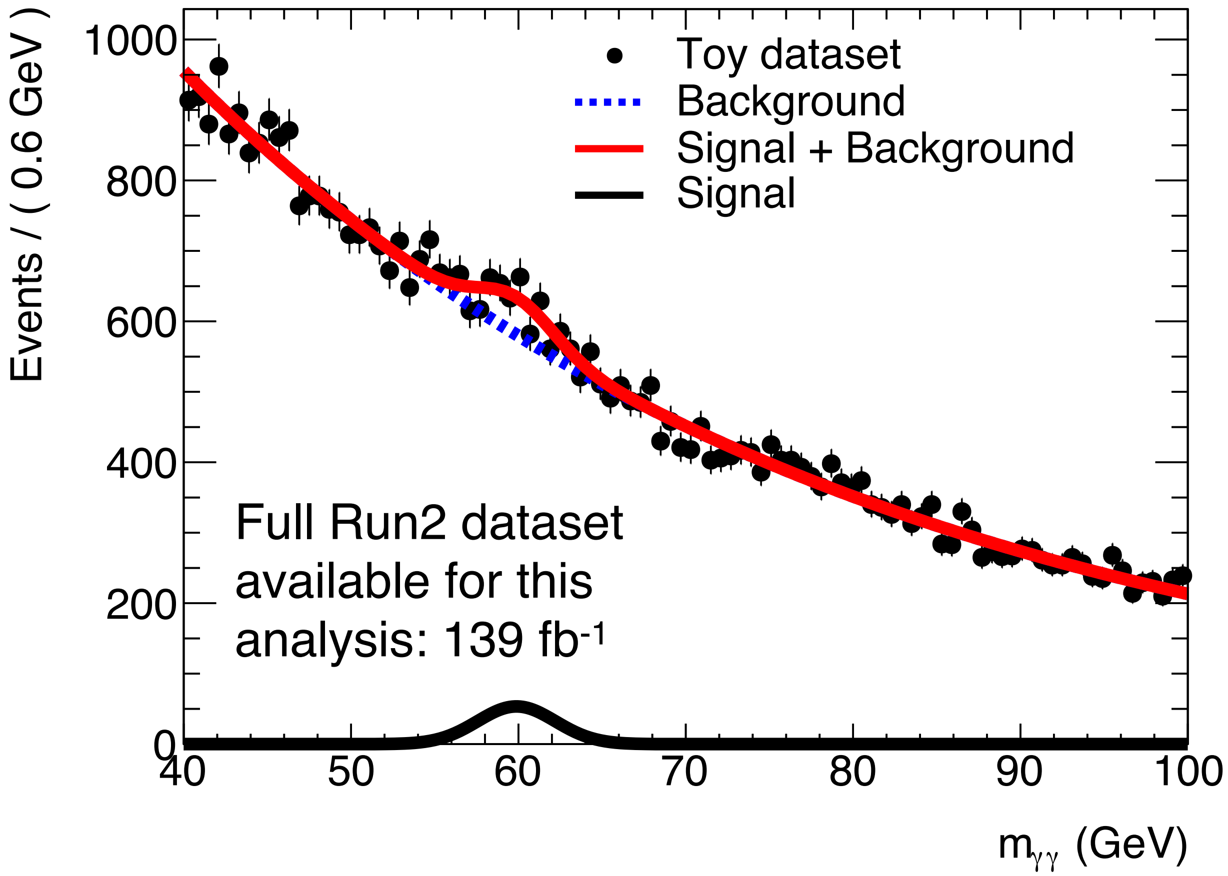

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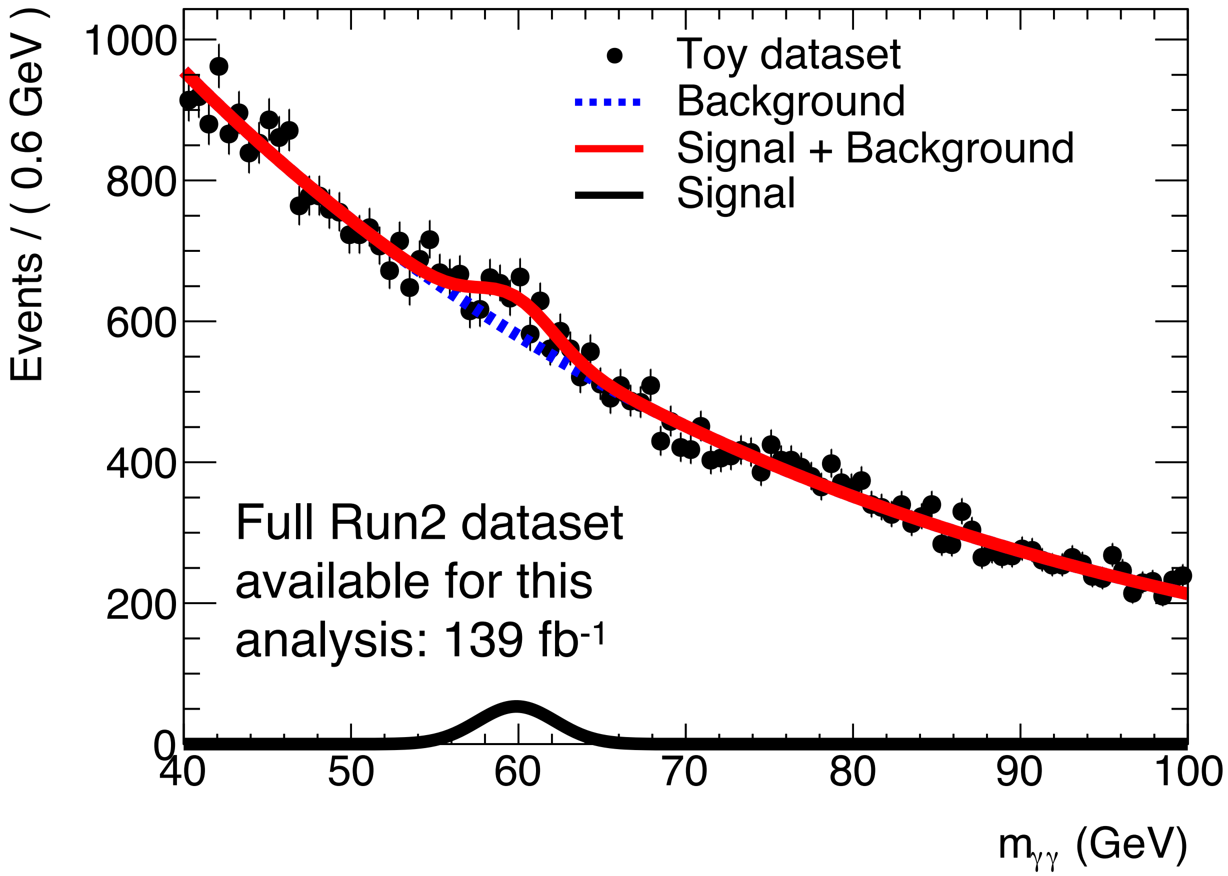

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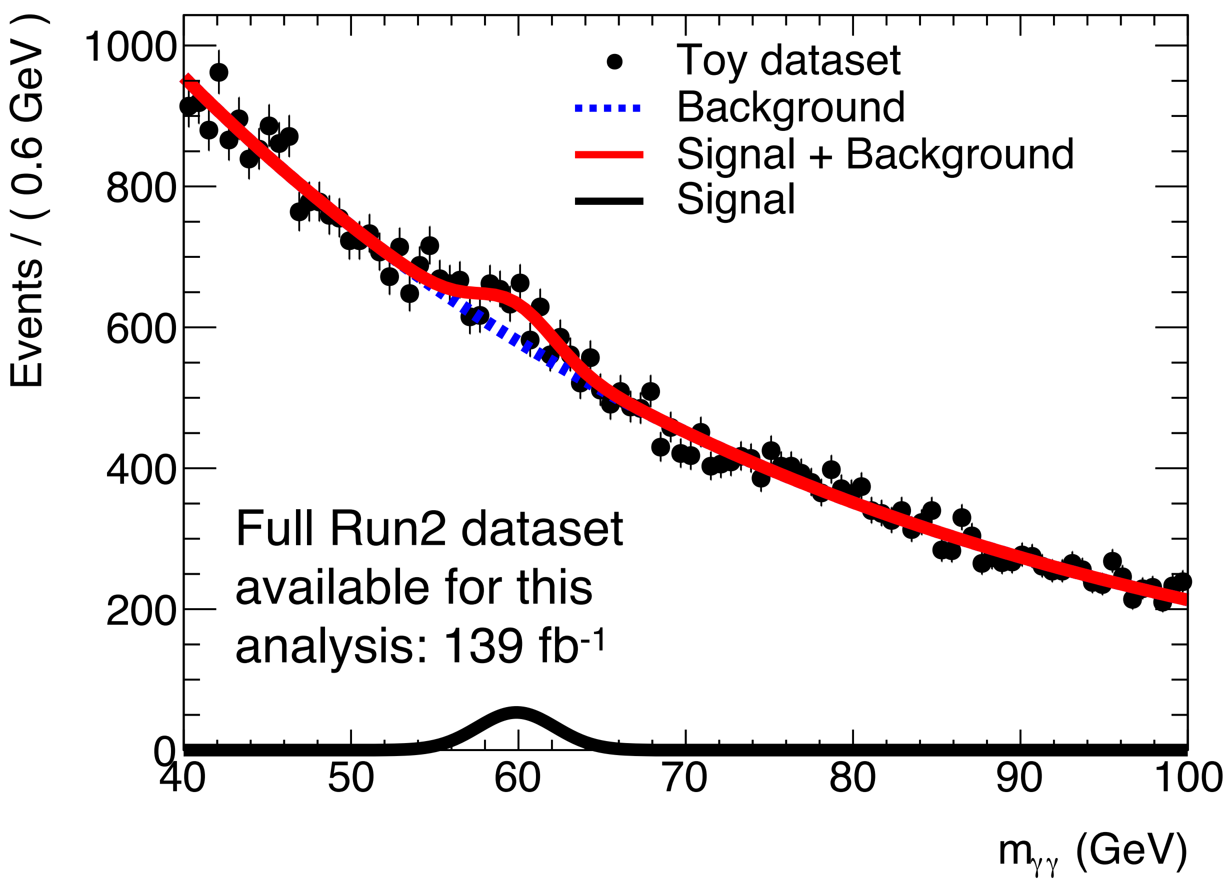
   - Search for excesses and put limits if necessary



Event selection: first step towards low masses

Diphoton event candidates (recorded events passing photon ID) are used to build the **invariant mass distribution** of the diphoton pair.

Preliminary event selection:

- $P_{T,\gamma_1}, P_{T,\gamma_2} > 25GeV$
- Pass diphoton trigger
- Photon identification and isolation

Two key ingredients for reaching low invariant masses kinematically:

- Low energy photons $P_{T,\gamma_1}, P_{T,\gamma_2}$
- Angular distance between photons $\Delta R_{\gamma_1\gamma_2}$

$$m_{\gamma\gamma} = \sqrt{2P_{T,\gamma_1}P_{T,\gamma_2}\left(cosh(\Delta\eta) - cos(\Delta\phi)\right)} \approx \Delta R_{\gamma_1\gamma_2}\sqrt{P_{T,\gamma_1}P_{T,\gamma_2}}$$

Experimental limitations: how low can we go in $m_{\gamma\gamma}$?

Three main aspects set a lower bound in the mass that can be reached.

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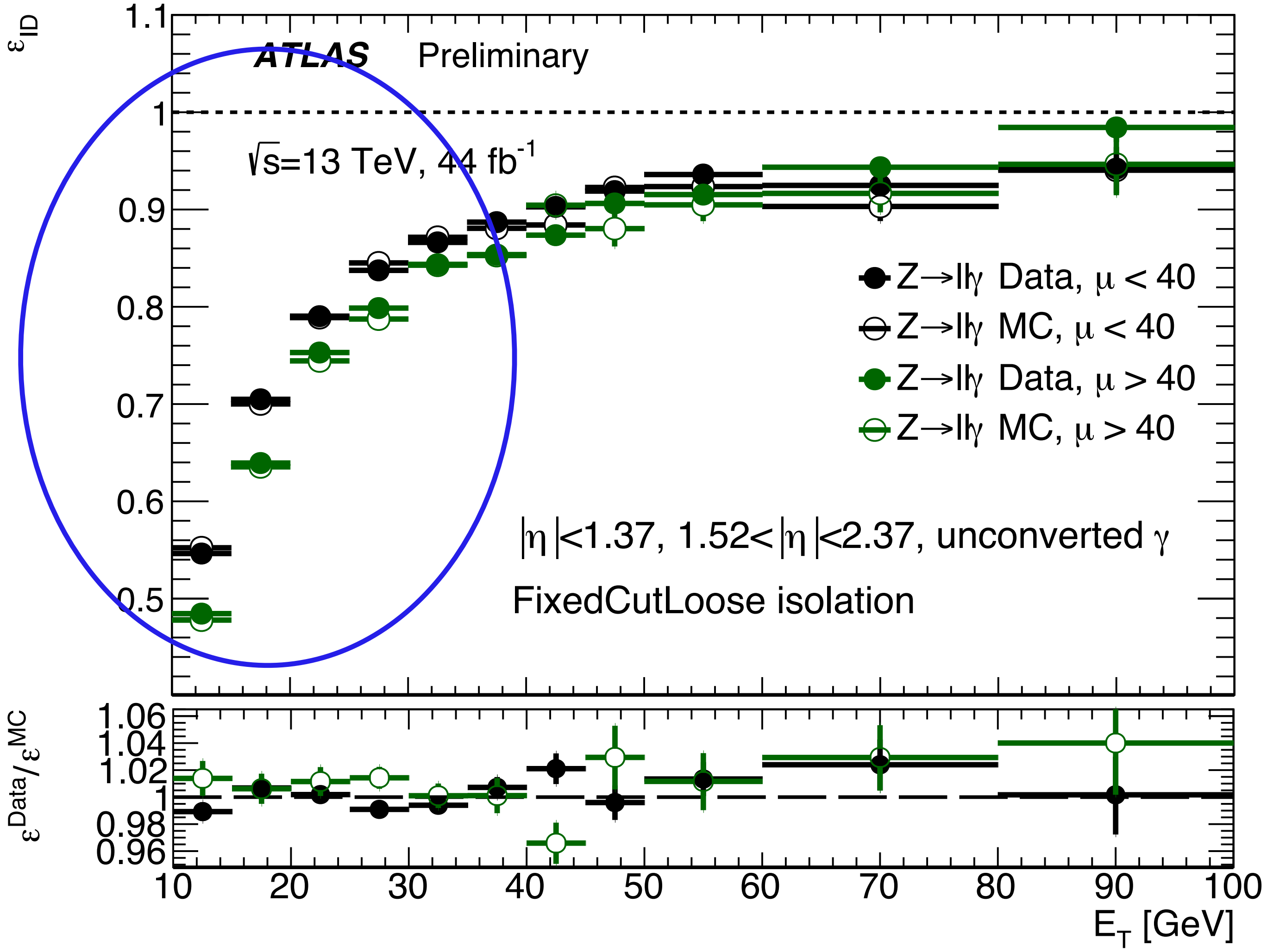
Ref fig01

- Performance efficiencies

Photon ID and isolation efficiencies decrease at lower photon energies



Experimental limitations: how low can we go in $m_{\gamma\gamma}$?

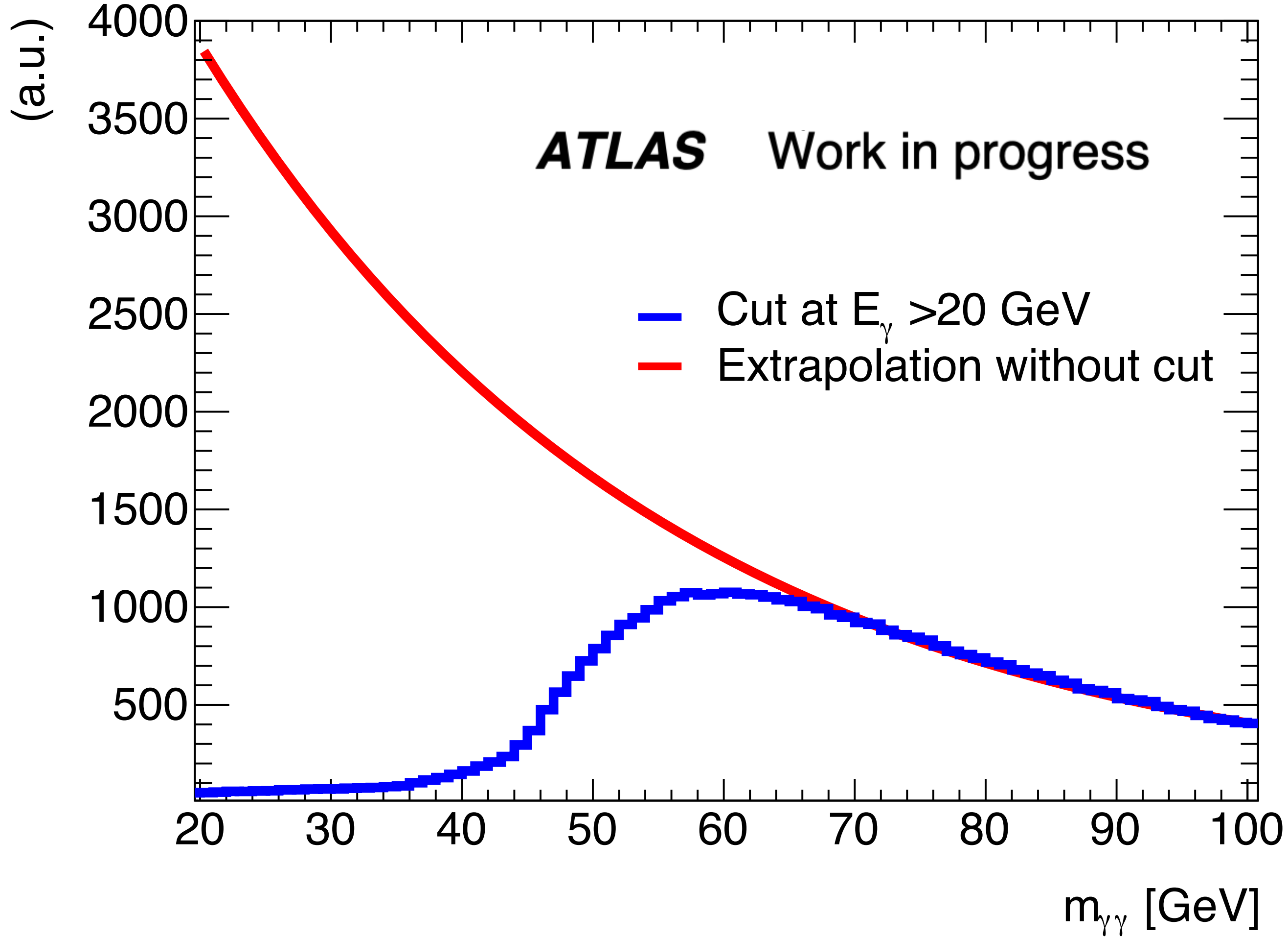
Three main aspects set a lower bound in the mass that can be reached.

- Performance efficiencies
- Trigger

QCD rate of two low energy photons is too large.

- Only photons with energies over certain energy threshold are recorded

This shapes the $m_{\gamma\gamma}$ distribution, making difficult its description

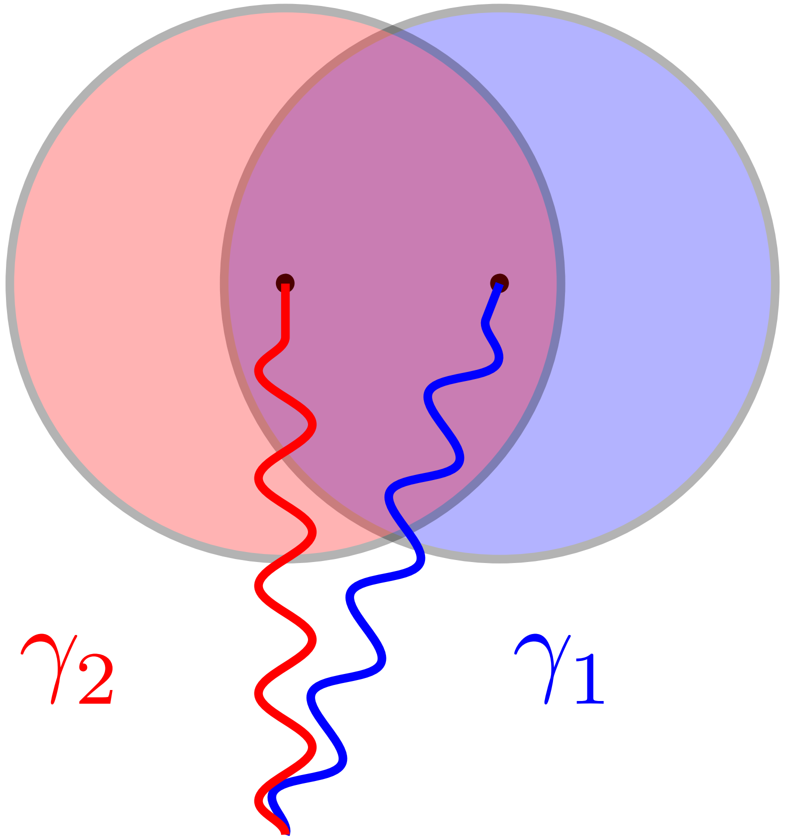


Experimental limitations: how low can we go in $m_{\gamma\gamma}$?

Three main aspects set a lower bound in the mass that can be reached.

- Performance efficiencies
- Trigger
- Isolation

Two close-by photons may “kill” each other if they are within the isolation cone of the other photon.



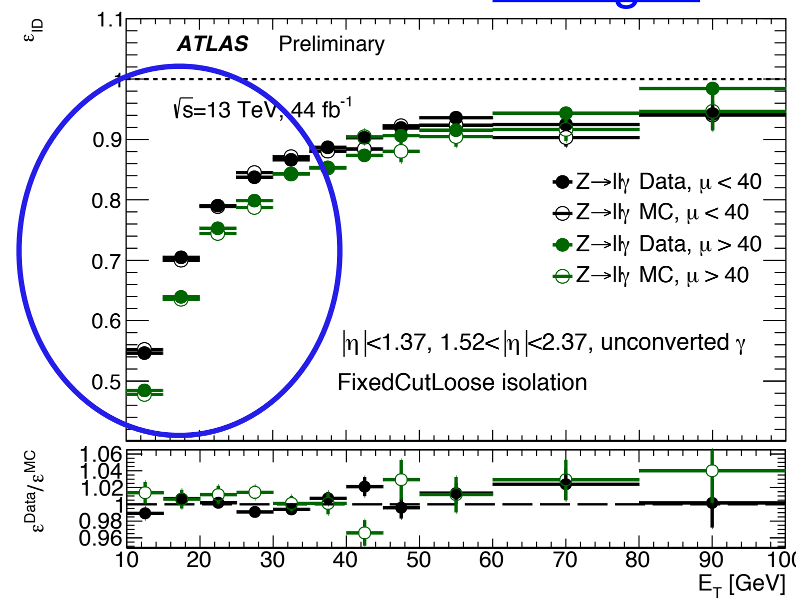
Experimental limitations: how low can we go in $m_{\gamma\gamma}$?

Three main aspects set a lower bound in the mass that can be reached.

[Ref fig01]

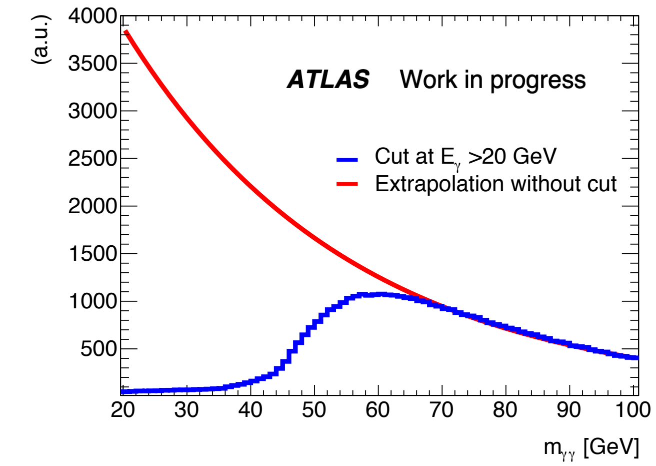
- Performance efficiencies
- Trigger
- Isolation

Photon ID and isolation efficiencies decrease at lower photon energies

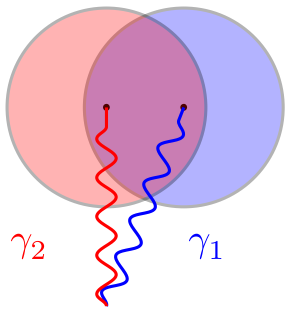


QCD rate of two low energy photons is too large.

- Only photons with energies over certain energy threshold are recorded



Two close-by photons may “kill” each other if they are within the isolation cone of the other photon.



$$m_{\gamma\gamma} \approx \Delta R_{\gamma_1\gamma_2}\sqrt{P_{T,\gamma_1}P_{T,\gamma_2}}$$

Given:

$$\Delta R_{\gamma_1\gamma_2} > 0.4$$

$$P_{T,\gamma_1}, P_{T,\gamma_2} > 25GeV$$

$$m_{\gamma\gamma} \sim 10\ GeV$$

Additional event selection

Recorded low mass diphoton events are collimated in the detector.

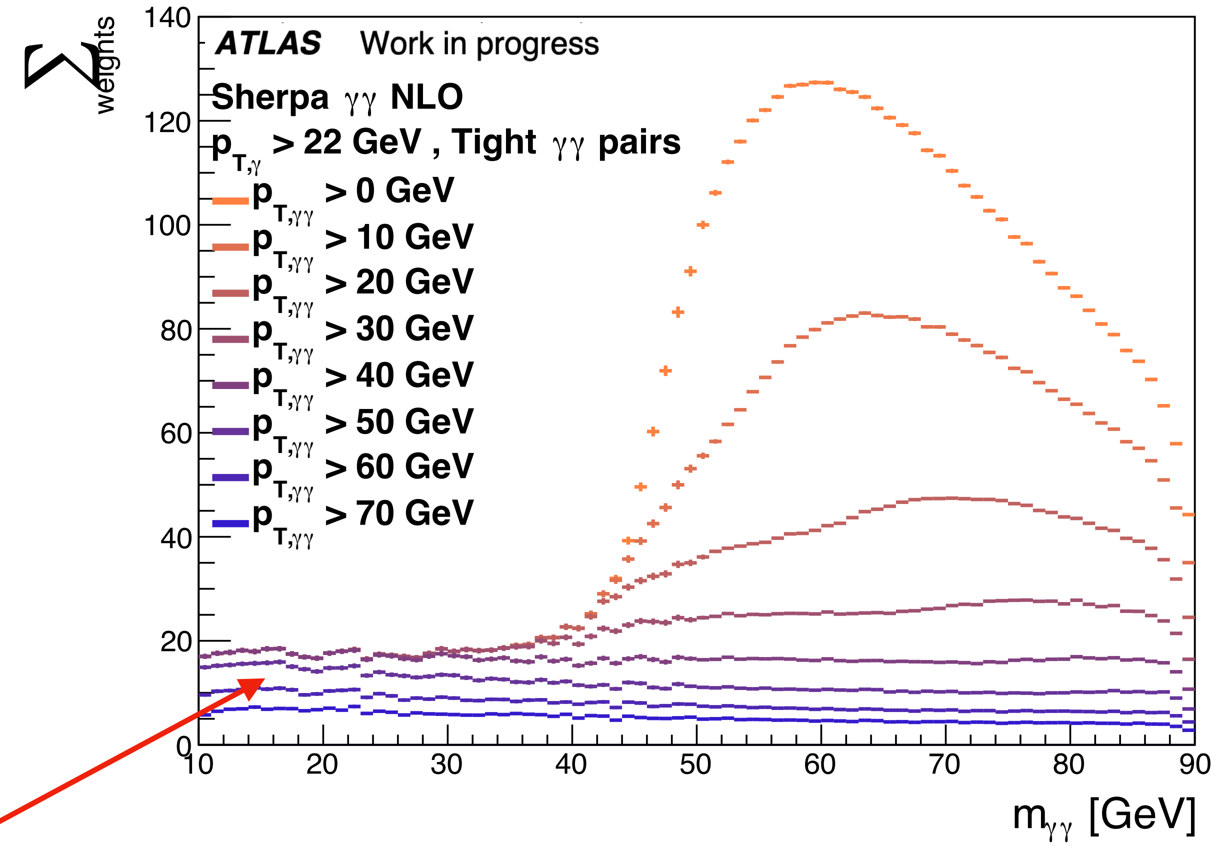
- This topology is denominated **boosted.**

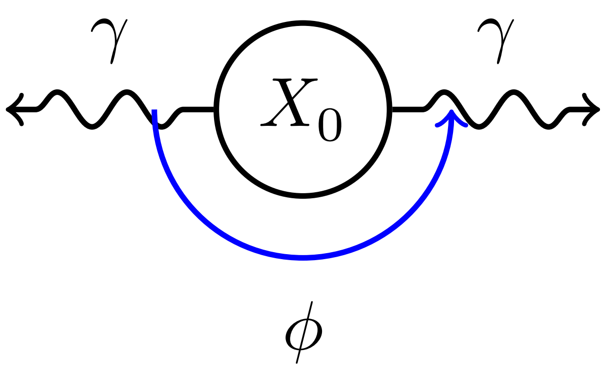
Instead of performing an inclusive search, only **boosted diphoton pairs** are selected.

Finally, $p_{T,\gamma\gamma} > 50 GeV$ pairs are selected

- Flattens the background distribution (easier to describe analytically!)
- Keeps sensible signal-to-noise ratio

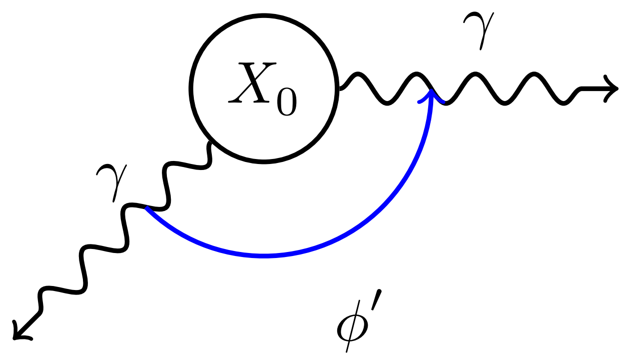
$$p_{T,\gamma\gamma} = \sqrt{P_{T,\gamma_1}^2 + P_{T,\gamma_2}^2 + 2P_{T,\gamma_1}P_{T,\gamma_2}cos\left(\Delta\phi\right)}$$





Non-boosted topology

$p_{T,\gamma\gamma} \sim 0$



Boosted topology

$p_{T,\gamma\gamma} \neq 0$

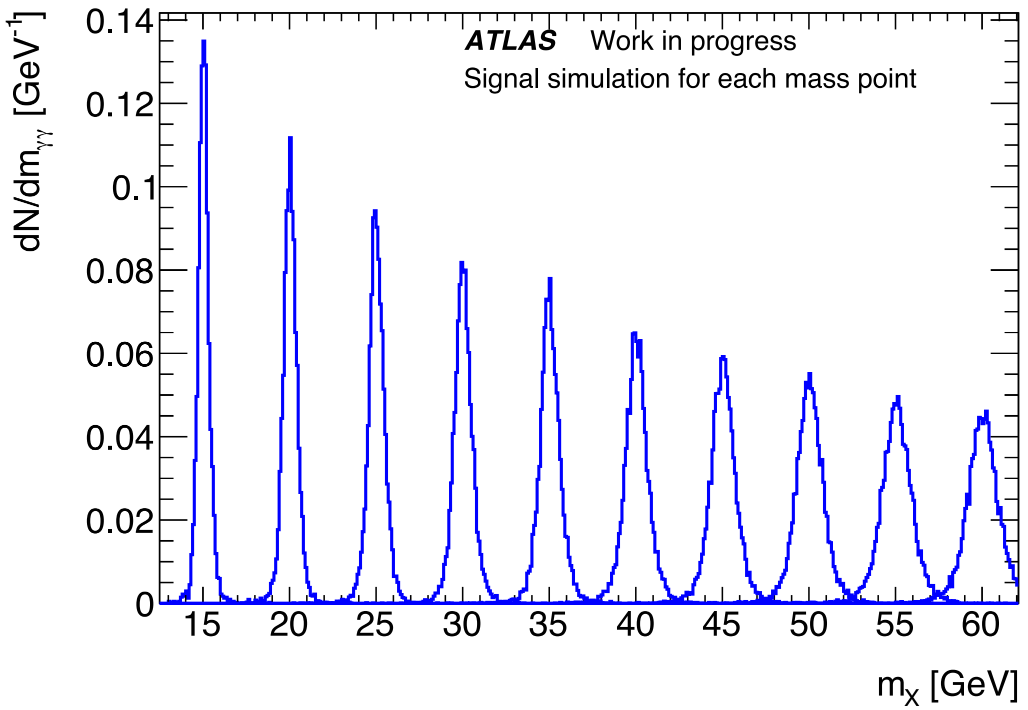
Signal modelling

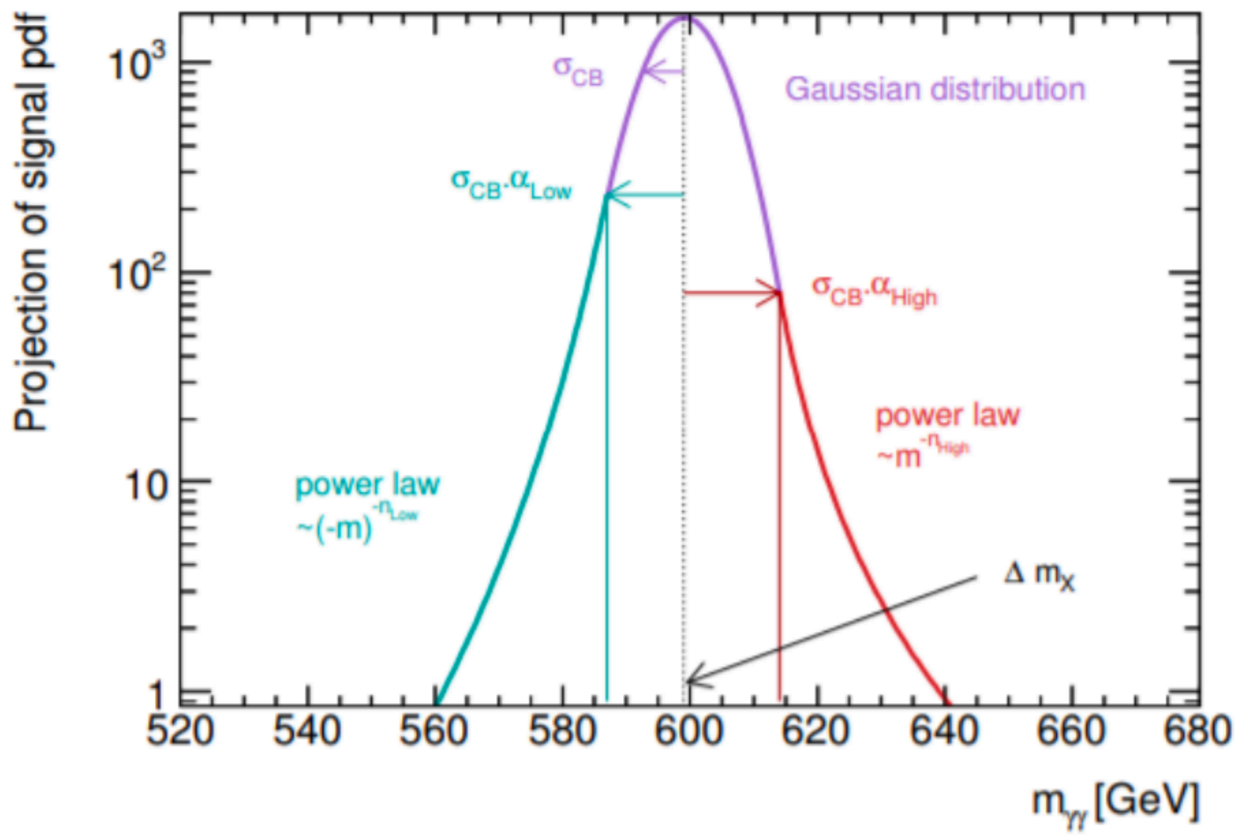
Narrow-width resonance: shape dominated by the detector resolution.

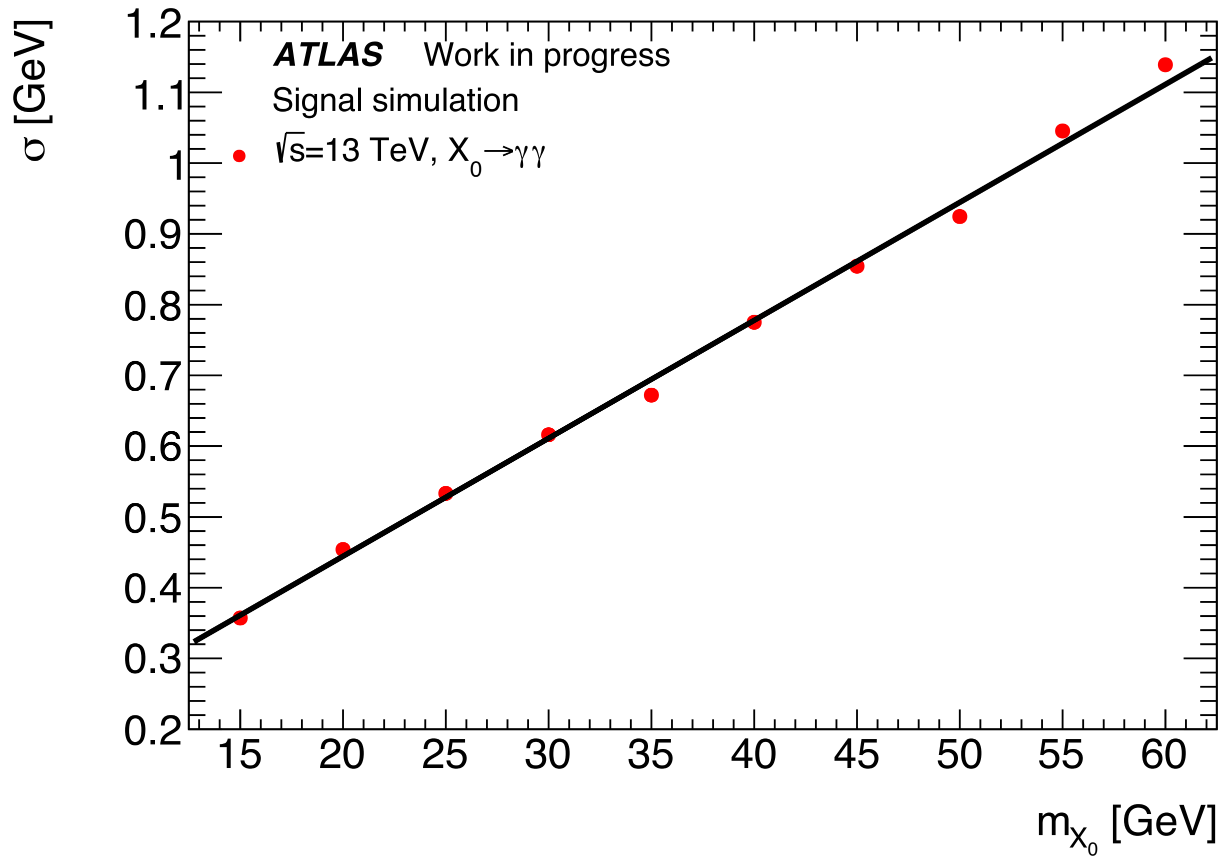
- Width increases almost linearly with $m_{\gamma\gamma}$

Signal shape: parametric model from simulation: $H\rightarrow\gamma\gamma$ standard samples for different masses.

- Double Sided Crystal Ball function.





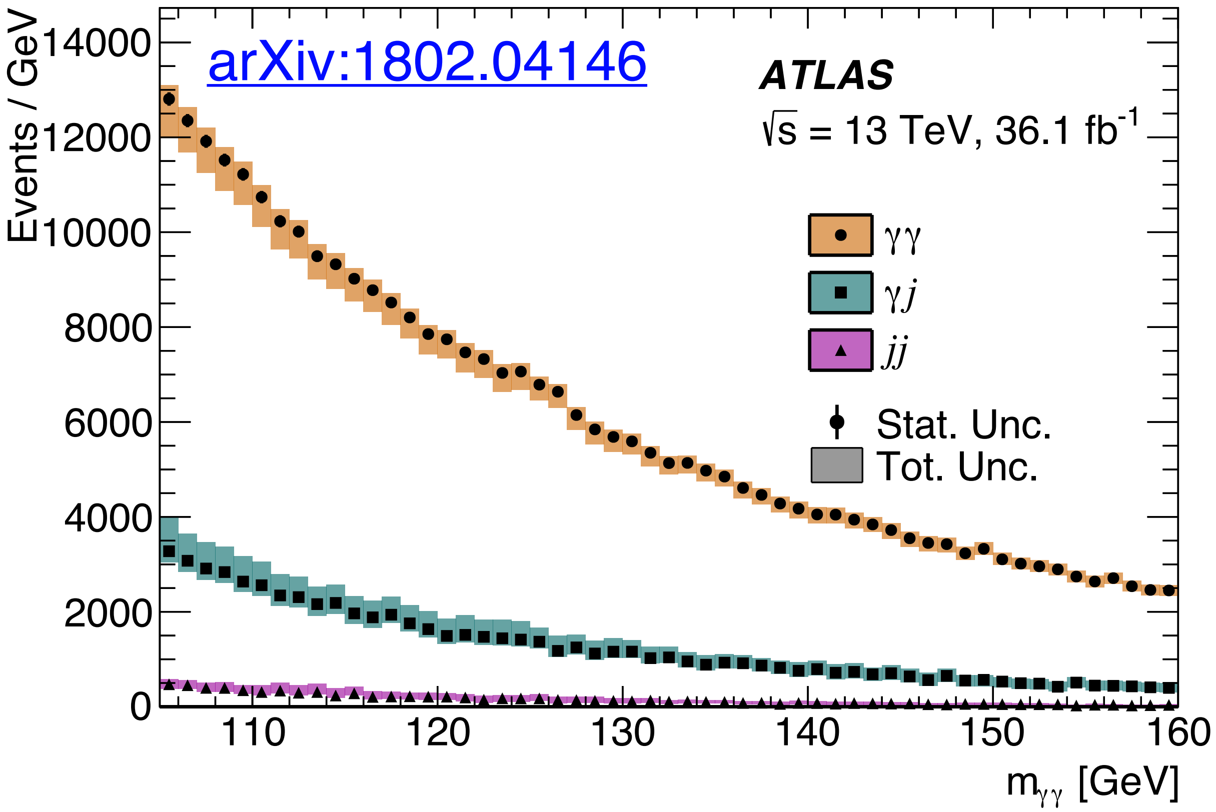


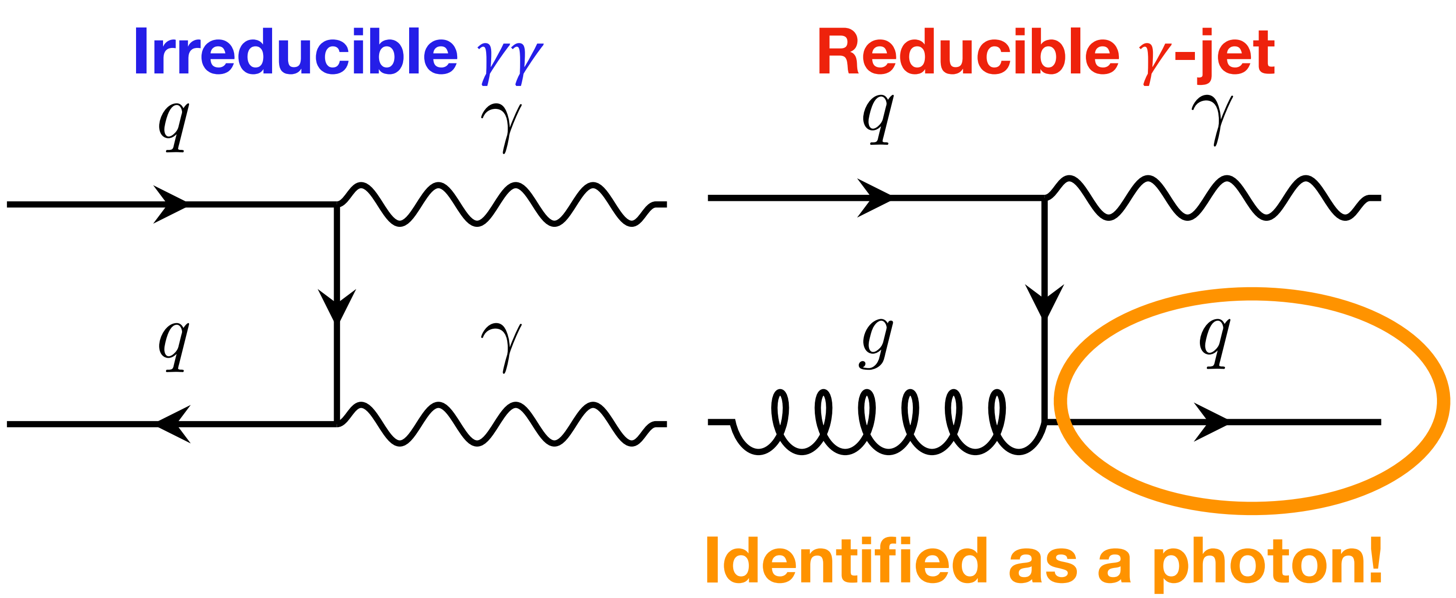
Background modelling

Several backgrounds affect this analysis:

- Irreducible background from non-resonant diphoton production ($\gamma\gamma$ component)
- Reducible background from QCD photons + jet or dijet events in which one or both jets are misidentified as photons (γj, jγ and jj components)

Each background has a different shape.





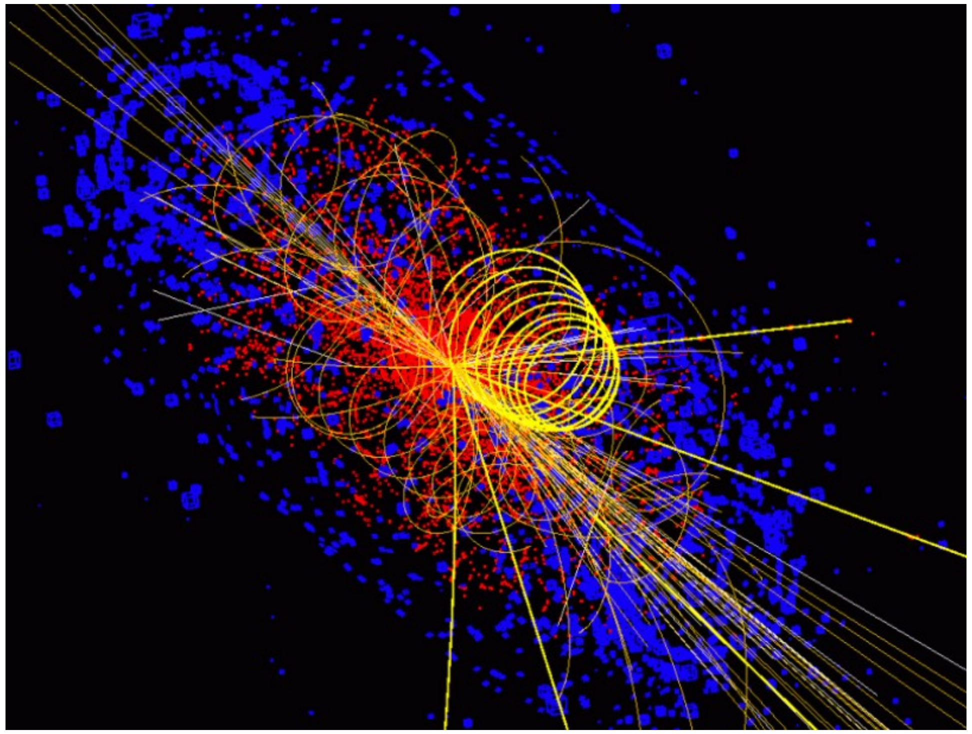
Reducible background contribution increases at lower masses.

CAVEAT: analysis ongoing!

Results presented for other $m_{\gamma\gamma}$ range

Conclusions

- LHC is sensitive to New Physics models
  - Axion-like-particles as plausible Dark Matter candidates
- Novel original analysis, to cover unexplored mass regions
  - Full Run2 dataset available
  - Edge of performances and efficiencies
  - Boosted selection
- Analysis ongoing
  - Limits will be set on the σ_{fid} x Br as a function of the mass of the resonance.
- Future analysis will benefit from new diphoton triggers with lower energy thresholds, pushing forward the lower $m_{\gamma\gamma}$ limit.



Backup

Outline

Theoretical motivation
Experimental motivation
Experimental setup
Photons in ATLAS
Analysis strategy
Conclusions

Photon energy calibration

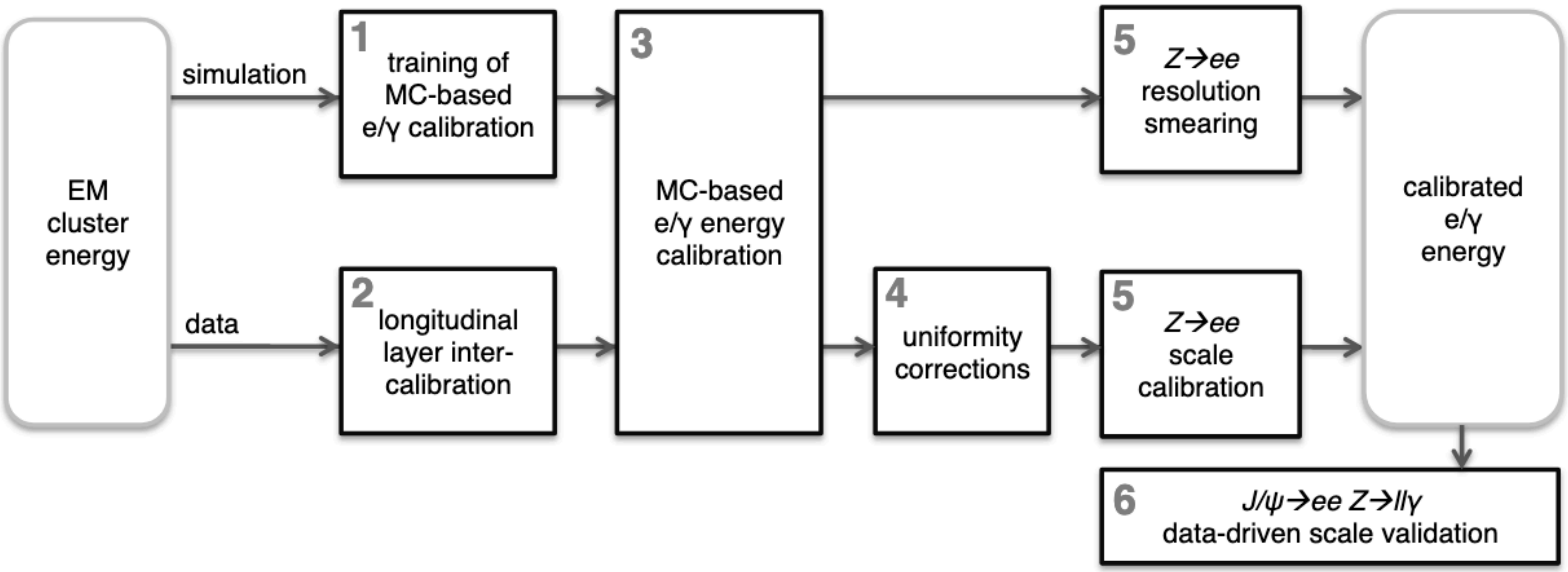
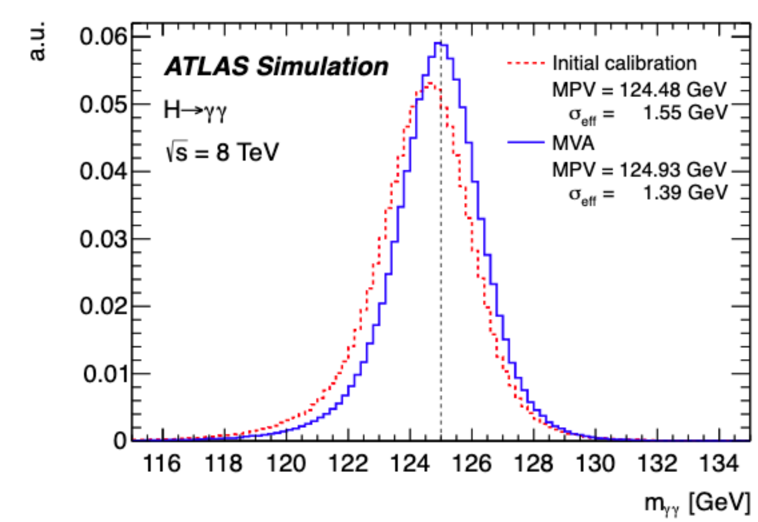


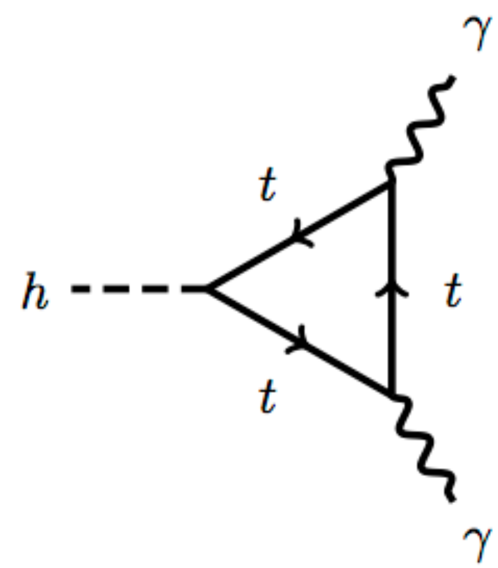
Figure 6.3: Schematic overview of the procedure used to calibrate the energy response of electrons and photons in ATLAS (143).

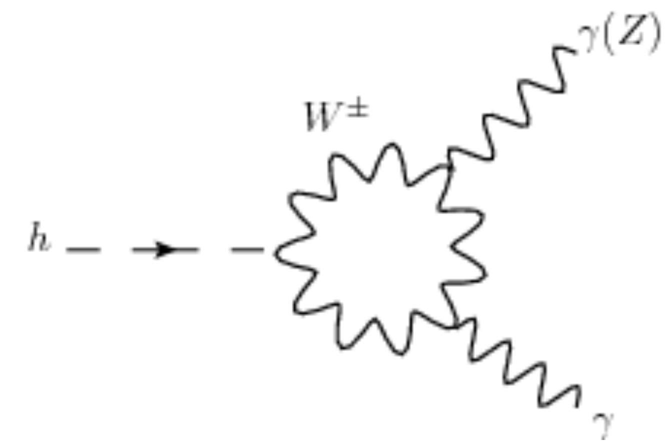


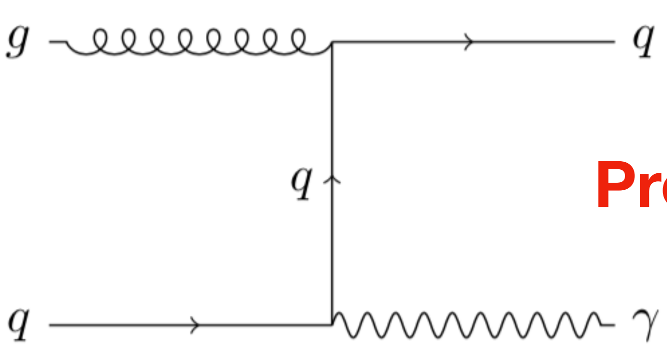
(a) $H \to \gamma\gamma$

Photon production at pp collisions

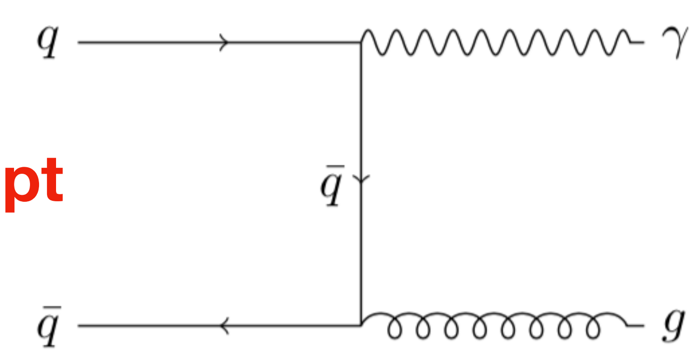
- Physics motivation:
  - Analyses with photons in the final state such as H→γγ and diboson studies (Zγ,Wγ)
  - Diphoton resonances searches
- These analyses are affected by several backgrounds:
  - Irreducible background from QCD photons: prompt or bremsstrahlung photons.
  - Reducible: jets faking photons
- All these are background photons for analyses with photons in the final state.



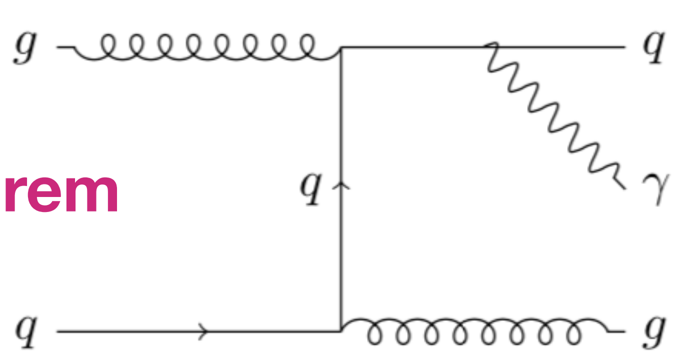




Prompt



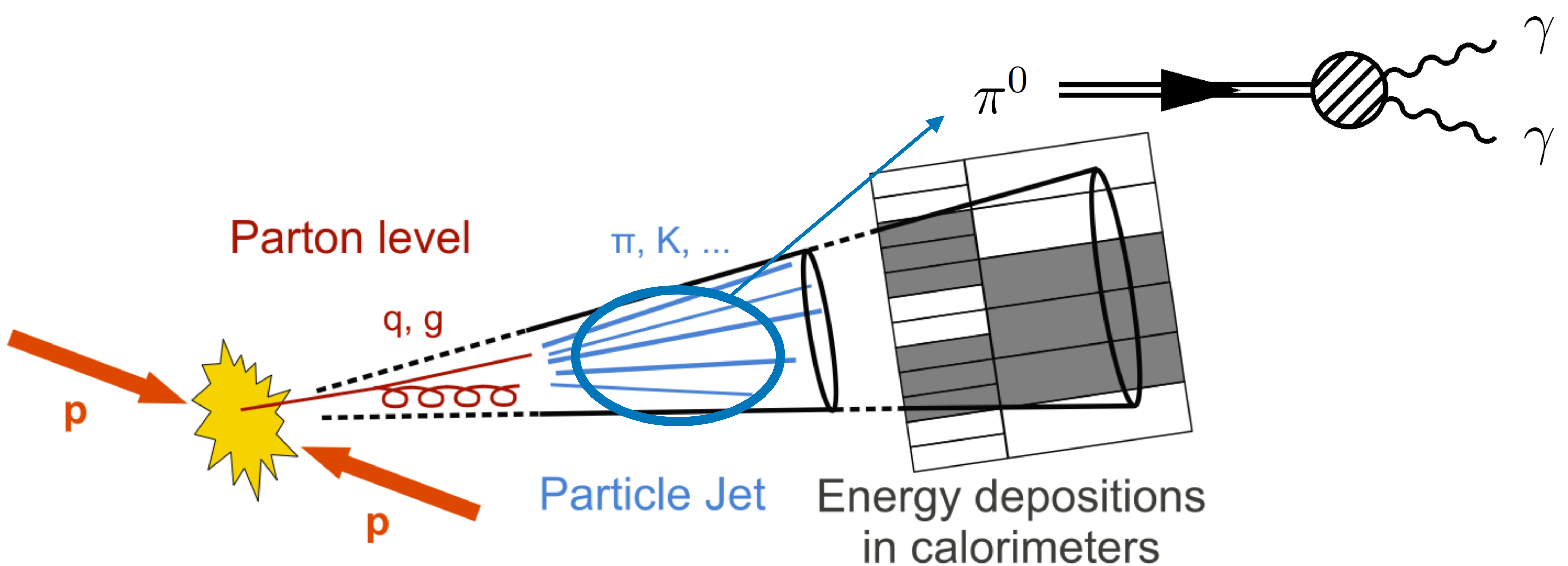
Brem



A large background contribution

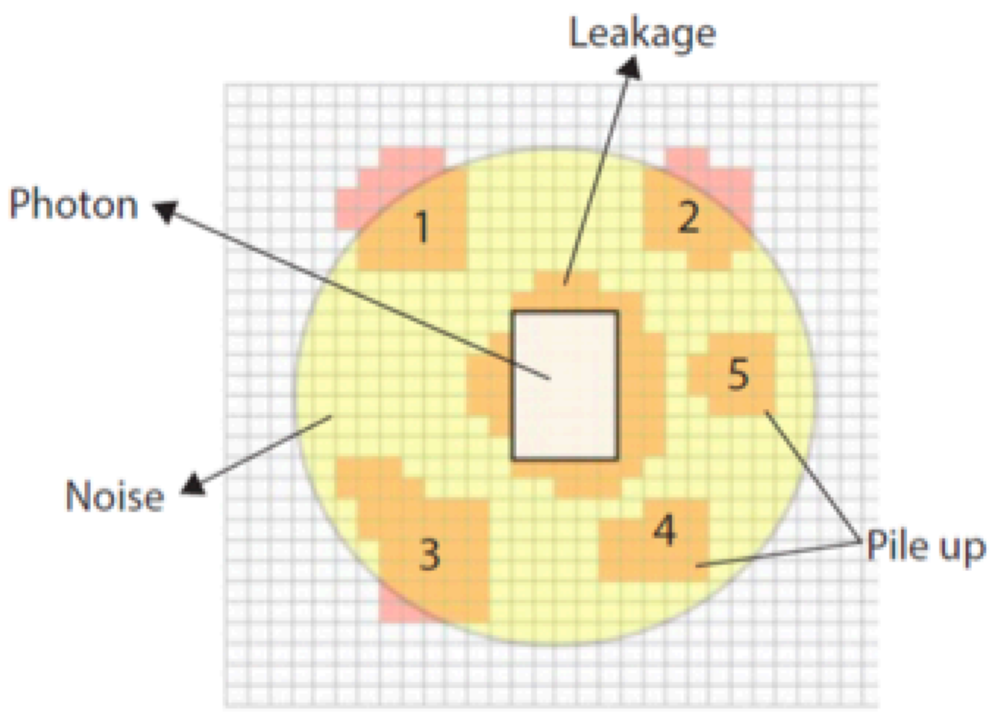
- Fakes are mainly composed by hadrons inside jets (mostly π^0 decaying into pairs of photons).
- Large jet/dijet/QCD γ cross sections:
- Very large fakes rejection is required for analyses with photons in the final state.

$$\sigma(jet) = 10^6 pb$$
$$\sigma(dijet) = 10^5 pb$$
$$\sigma(\gamma) = 5 \cdot 10^4 pb$$
$$\sigma(pp \to H) \times Br(H \to \gamma\gamma) = 6 \cdot 10^{-2} pb$$



Photon isolation: calorimetric isolation

- The calorimetric isolation energy, computed as the sum of the transverse energy in a cone around the photon candidate, is used to discriminate prompt photons from fakes.



- Clusters are sets of adjacent cells in the calorimeters with energy deposits over a certain energy threshold.

$$E^T_{pileup} = \rho_{median} \times (\pi \Delta R^2 - A_{mask})$$

Photon cluster

$$E^T_{iso,corr} = \sum_{i,\Delta R<0.4}^{clusters} E^T_{i,raw} - E^T_{core} - E^T_{leakage}(p_T, \eta) - E^T_{pileup}(\eta)$$

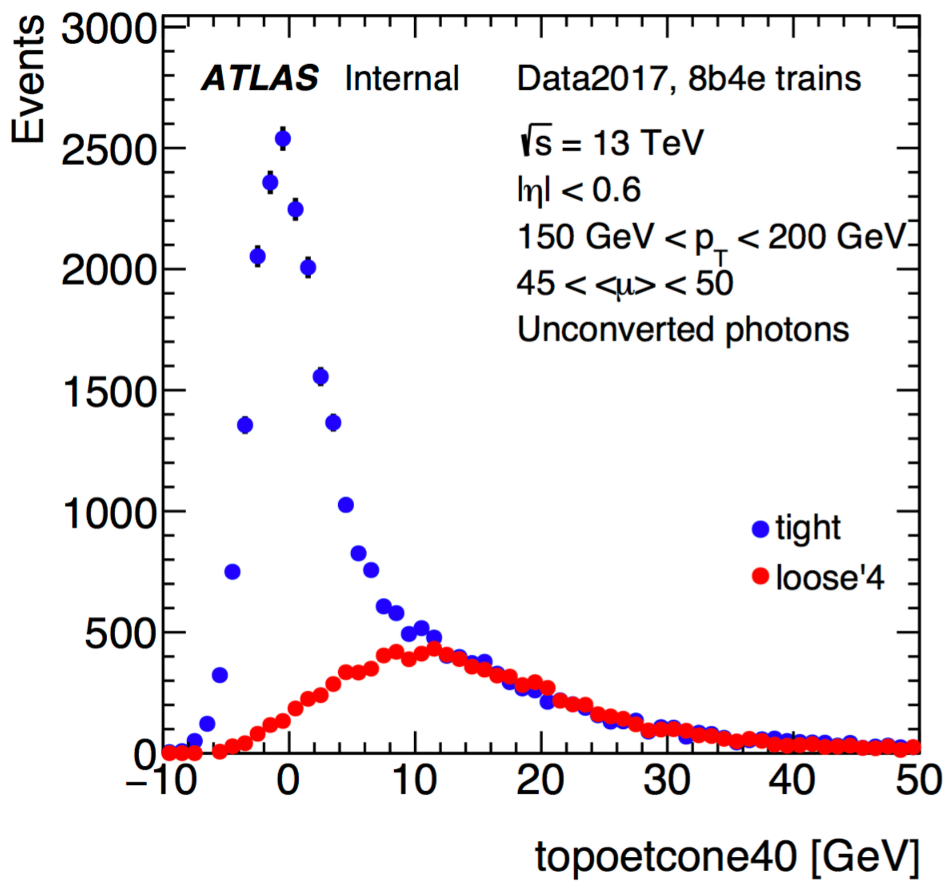
Pileup correction

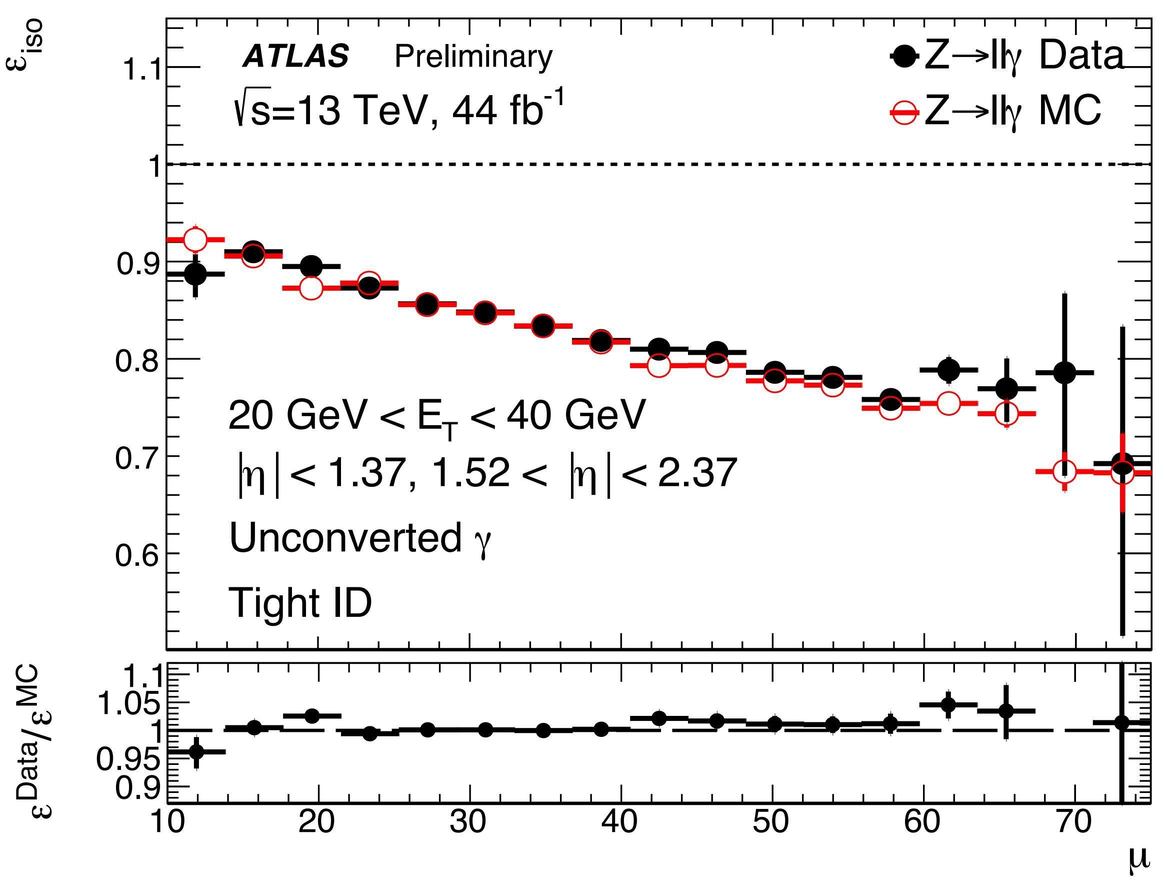
- Pileup correction is computed event by event using the median energy density of all the jets in the acceptance of the detector.

Isolation energy distribution and current performances

- No energy flow around prompt photons → peak around 0
- More energy flow around fake photons → higher $E^{T}_{iso,corr}$
  - Fakes: neutral hadrons in jets decaying into pairs of photons

- Increasing pileup degrades photon performances
  - Pileup increases the width of the isolation energy distribution, worsening the efficiency and purity of the selection.



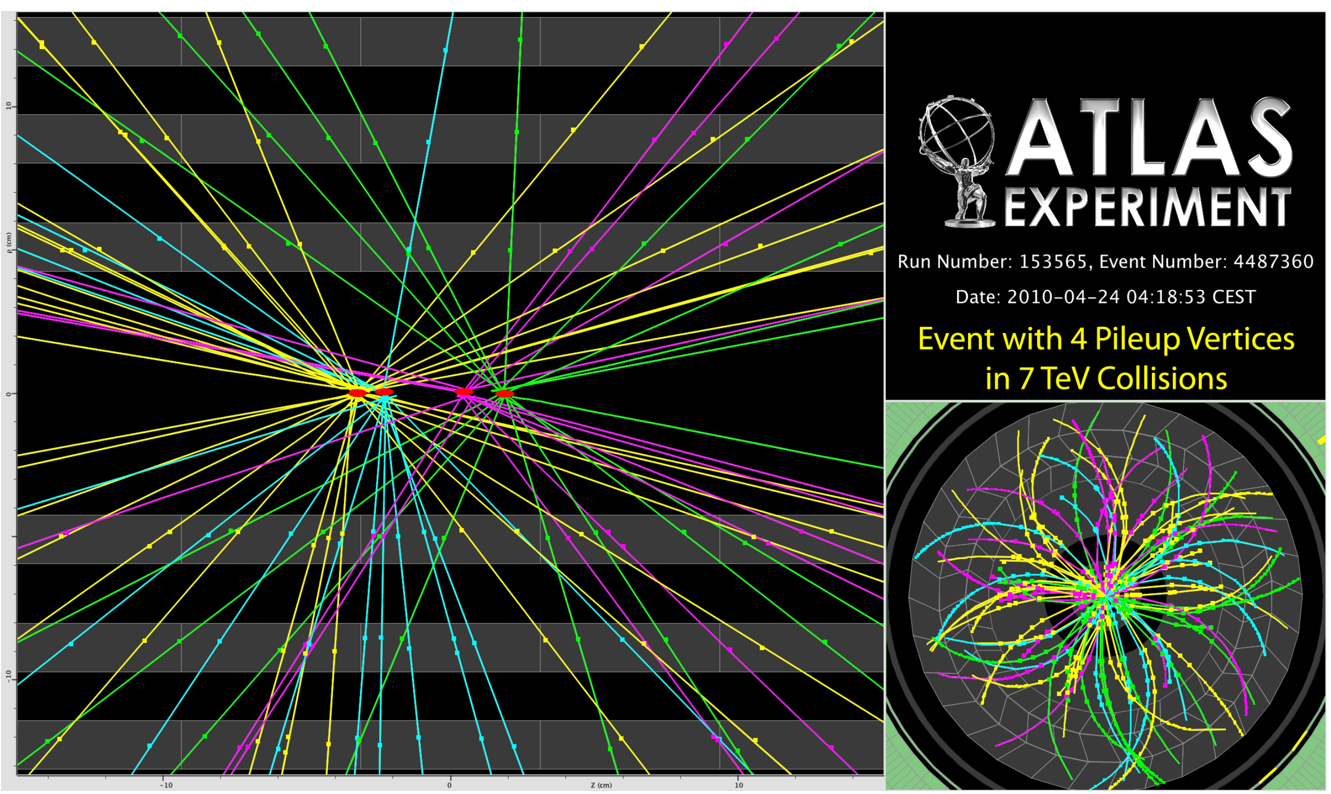


Pileup

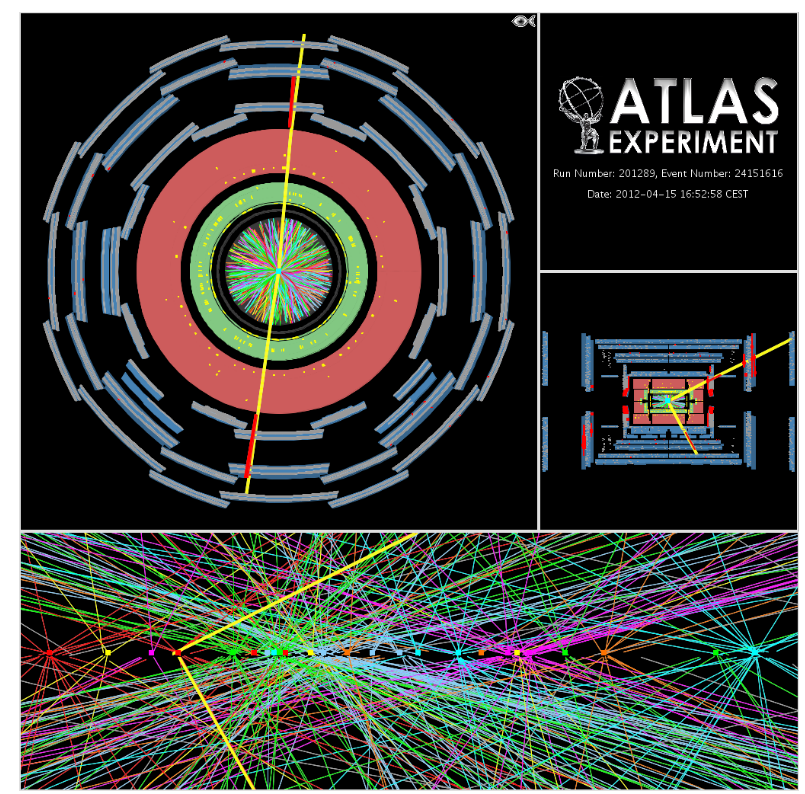
- Pileup: particles from collisions different from the collision under study. It can come from the same bunch crossing or from the previous/next bunch crossing.
- Pileup is the price to pay for increasing instantaneous luminosity.
- Photon performances are affected by this increase in pileup.

$\mu \equiv$ number of interactions per bunch crossing

$\mu = 4$



$\mu = 25$ $Z \rightarrow \mu\mu$ event



And this is the future…

$\mu = 200$