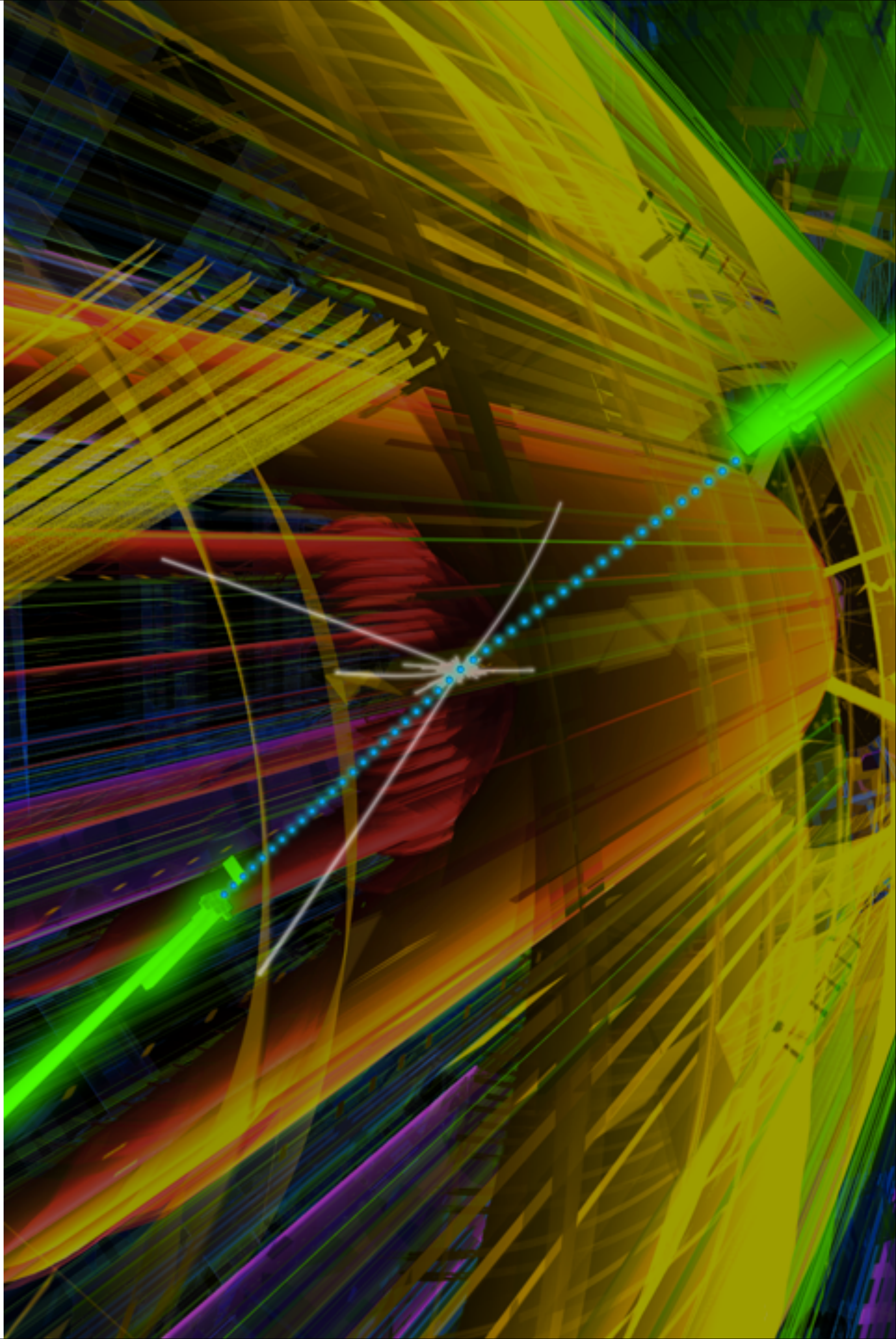
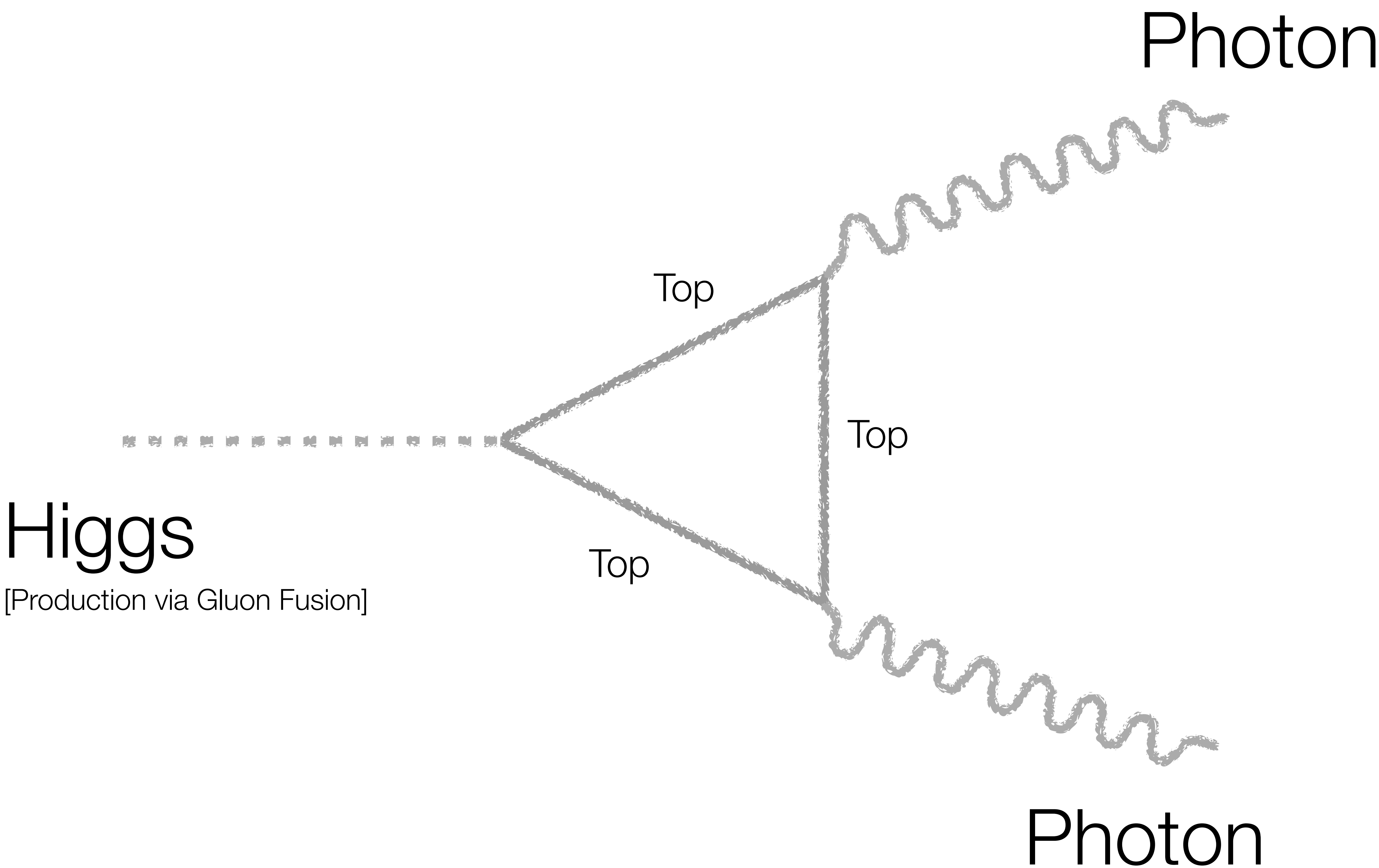
Lecture 3

Observation of a New Particle

in Search for the SM Higgs



The Discovery Channel



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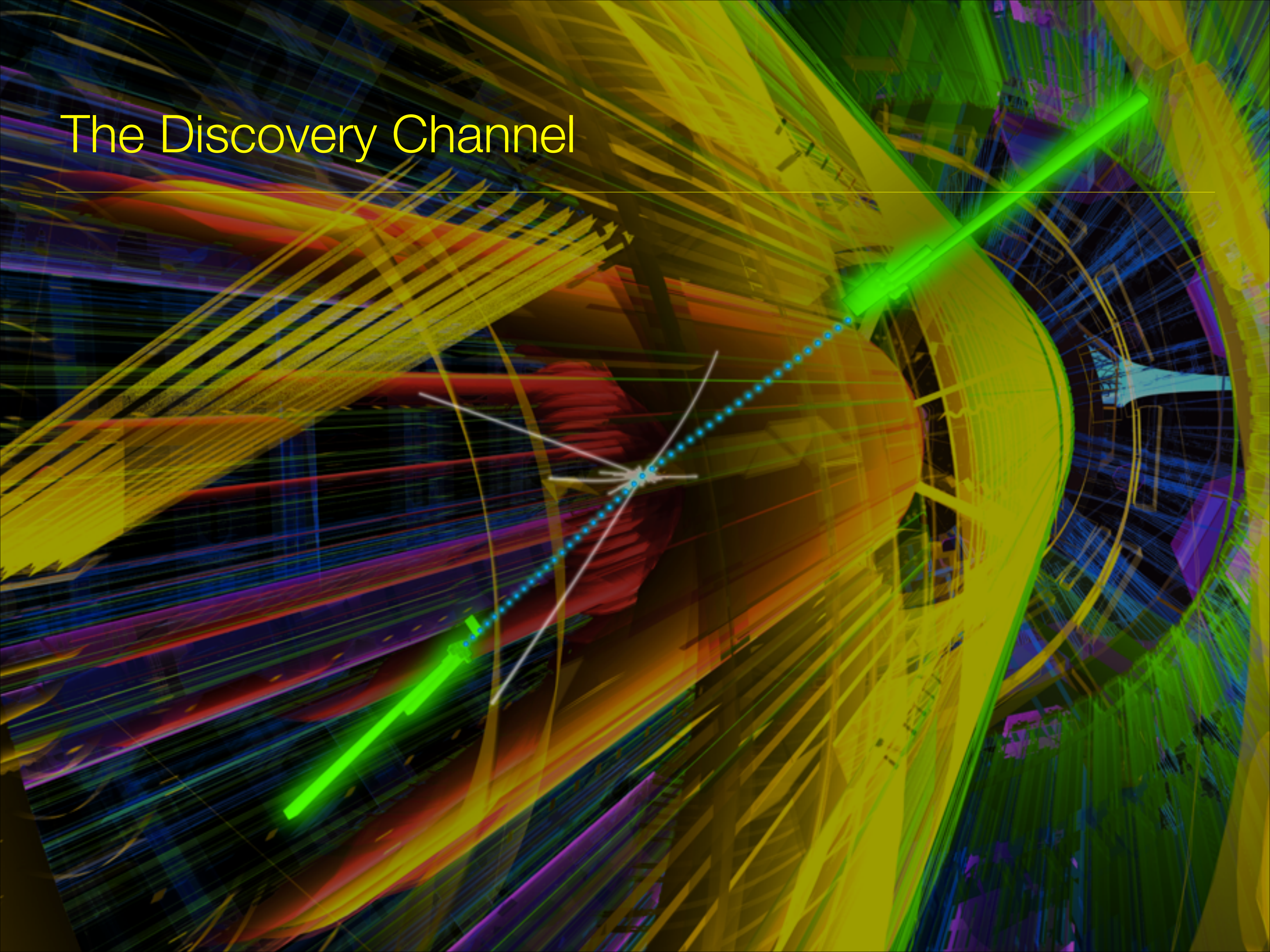
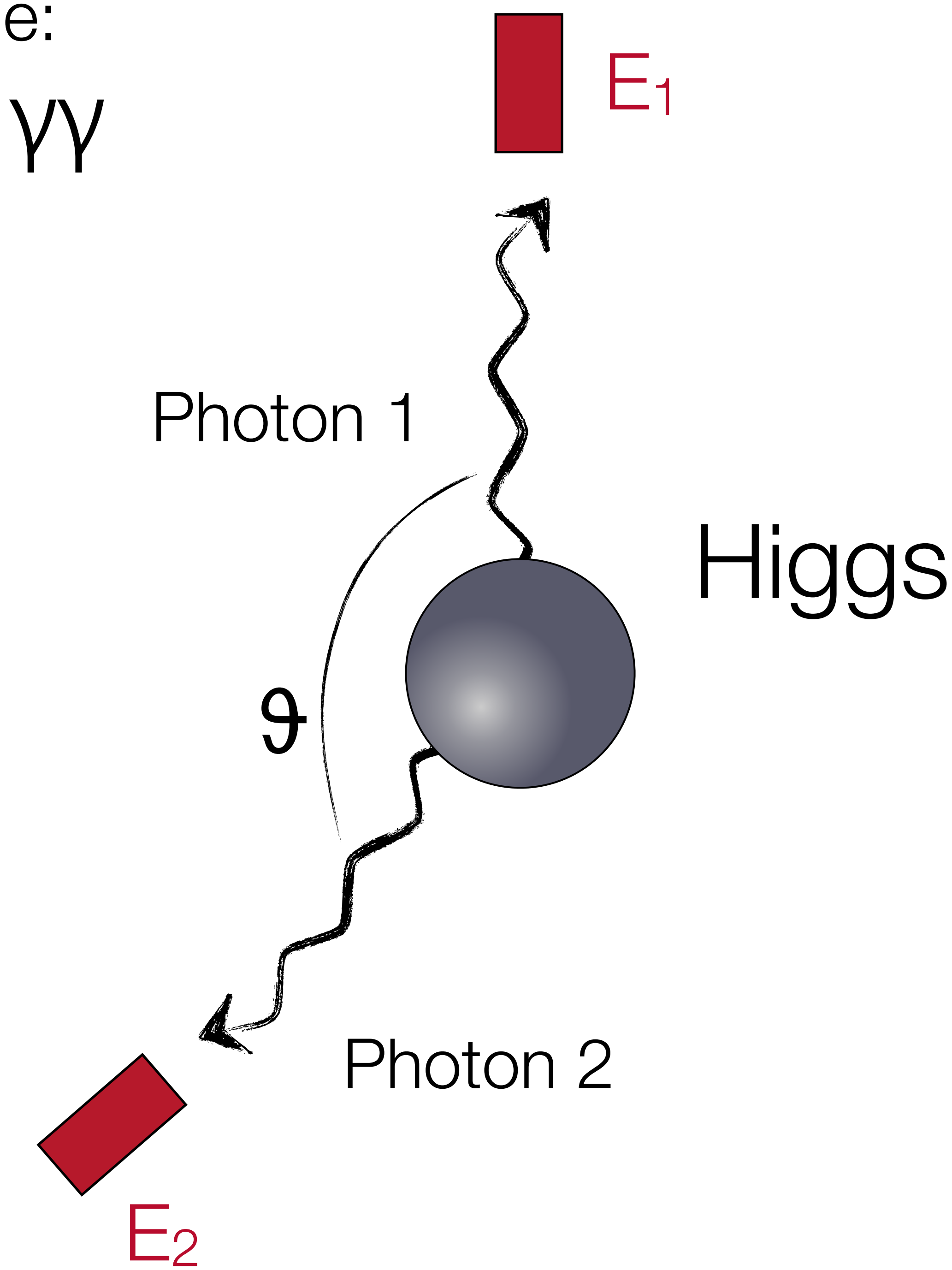
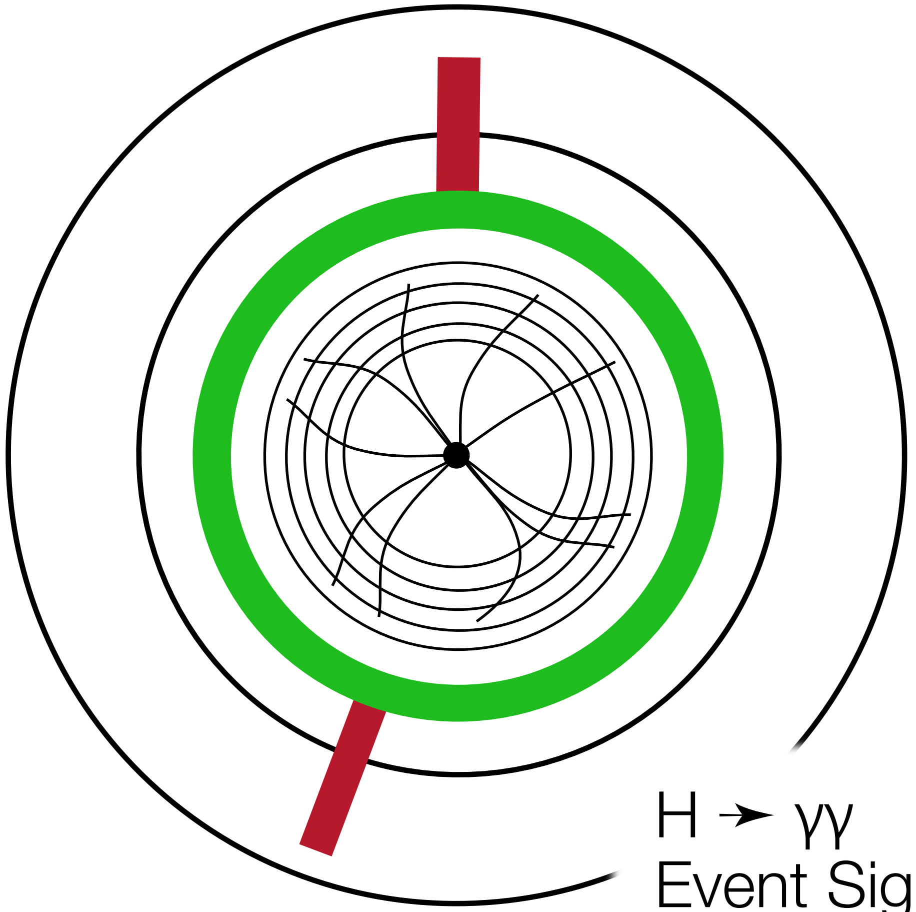


Basic Analysis Principle

Example:

$H \rightarrow \gamma\gamma$



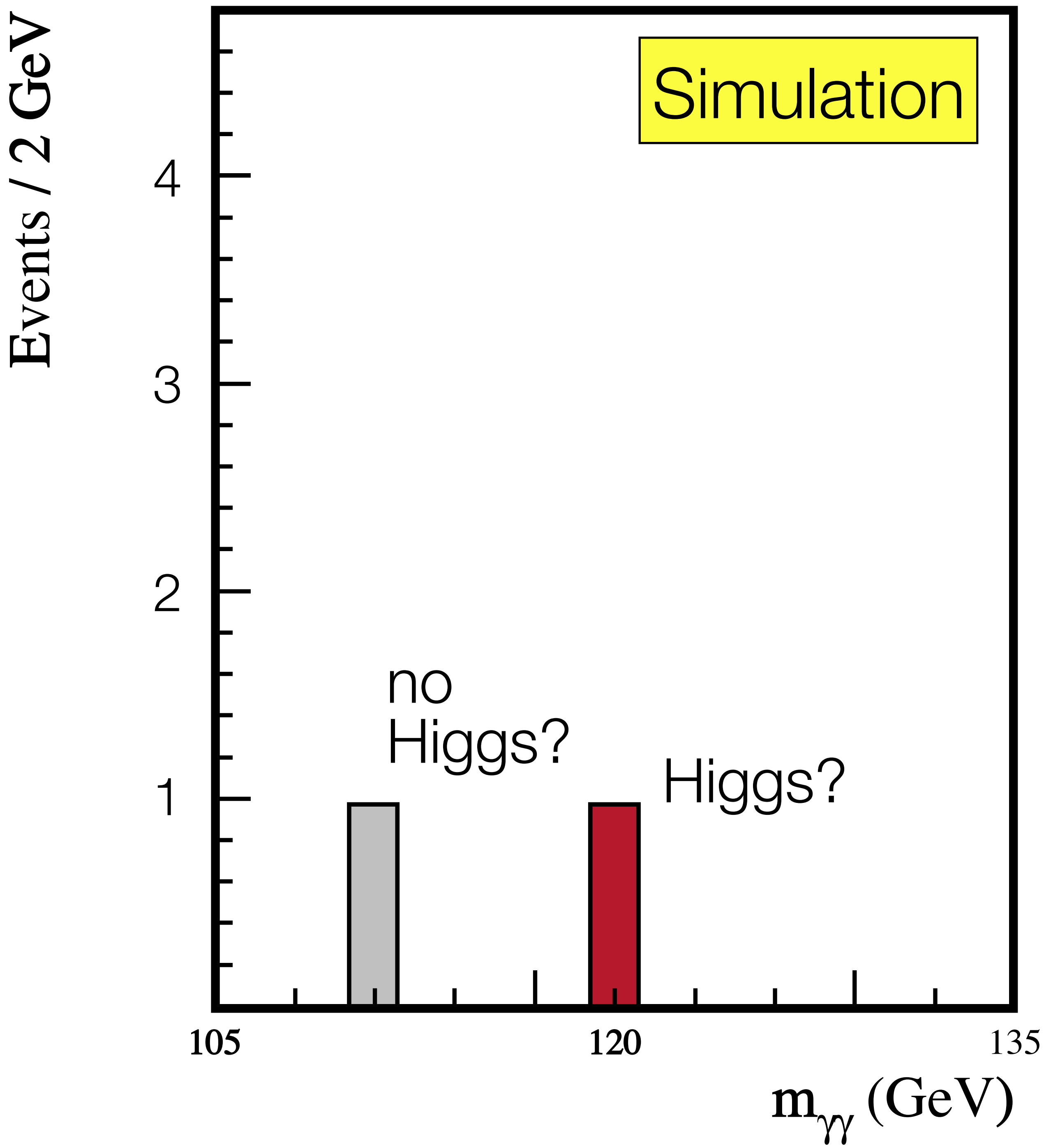


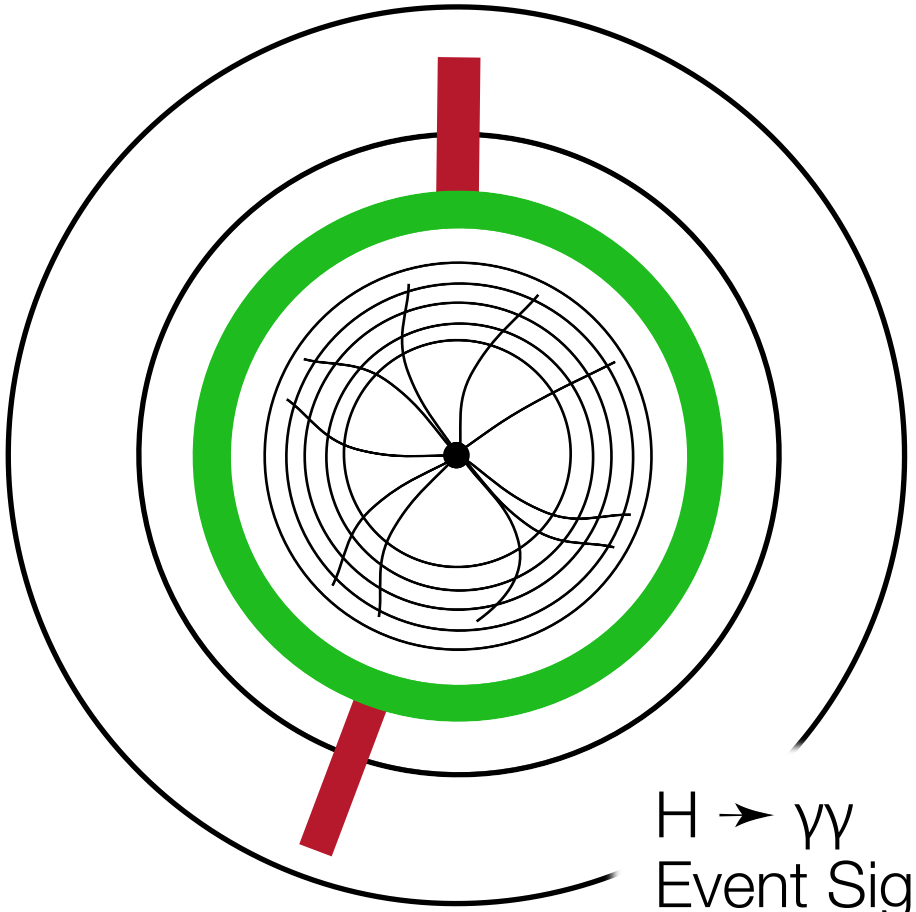
$H \rightarrow \gamma\gamma$
Event Signature
[Schematic]

Invariant Mass:

$$m_{\gamma\gamma}^2 = 2\,E_1 E_2\,(1-\cos\vartheta)$$

Basic Analysis Principle





H ➛ γγ
Event Signature
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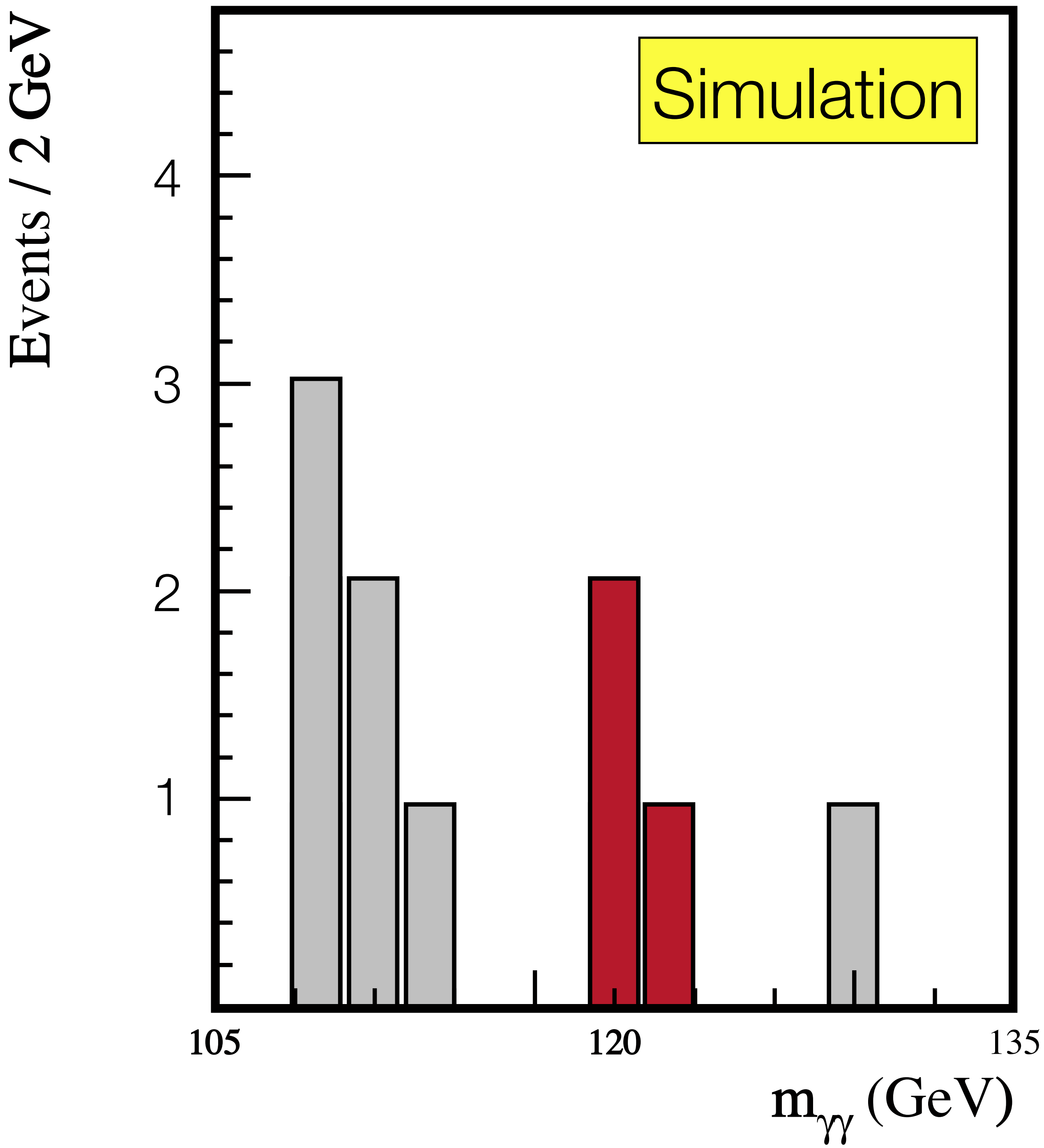

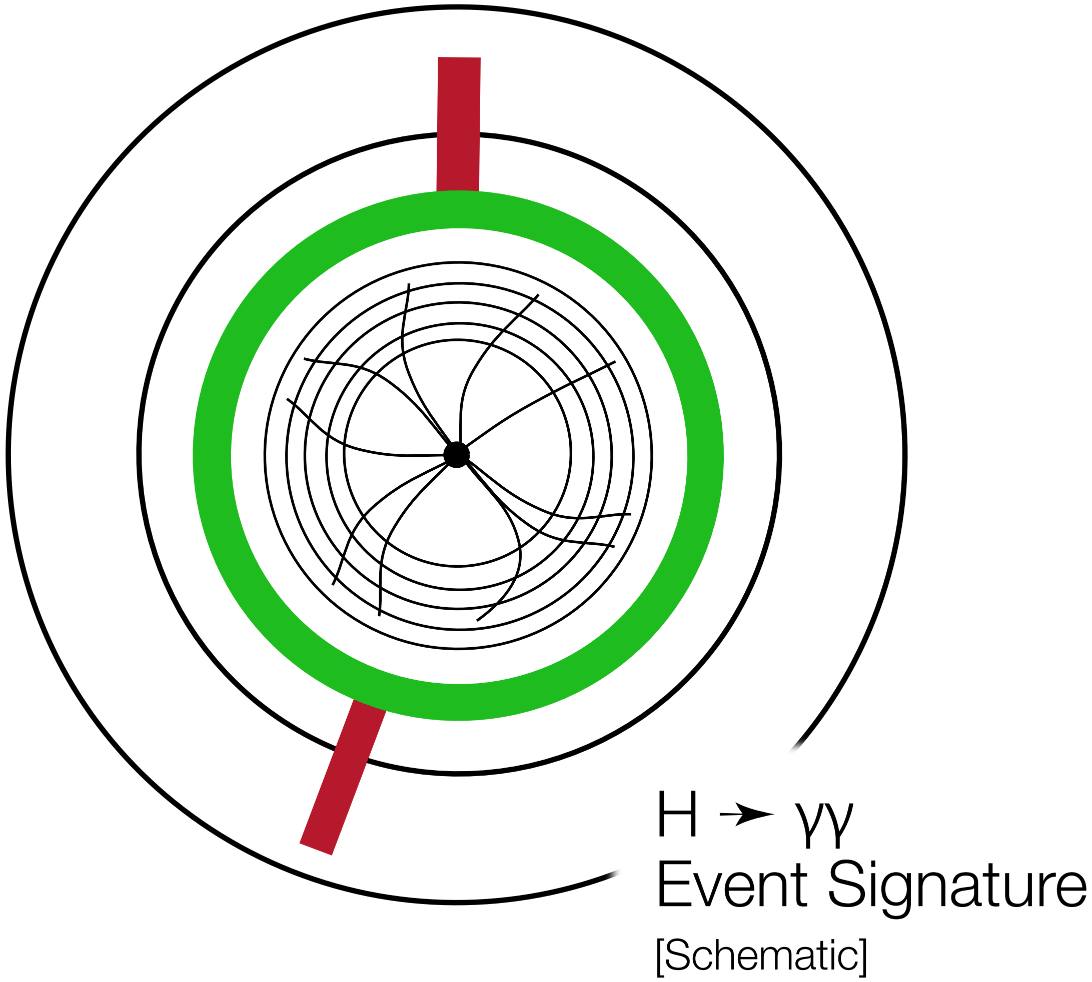

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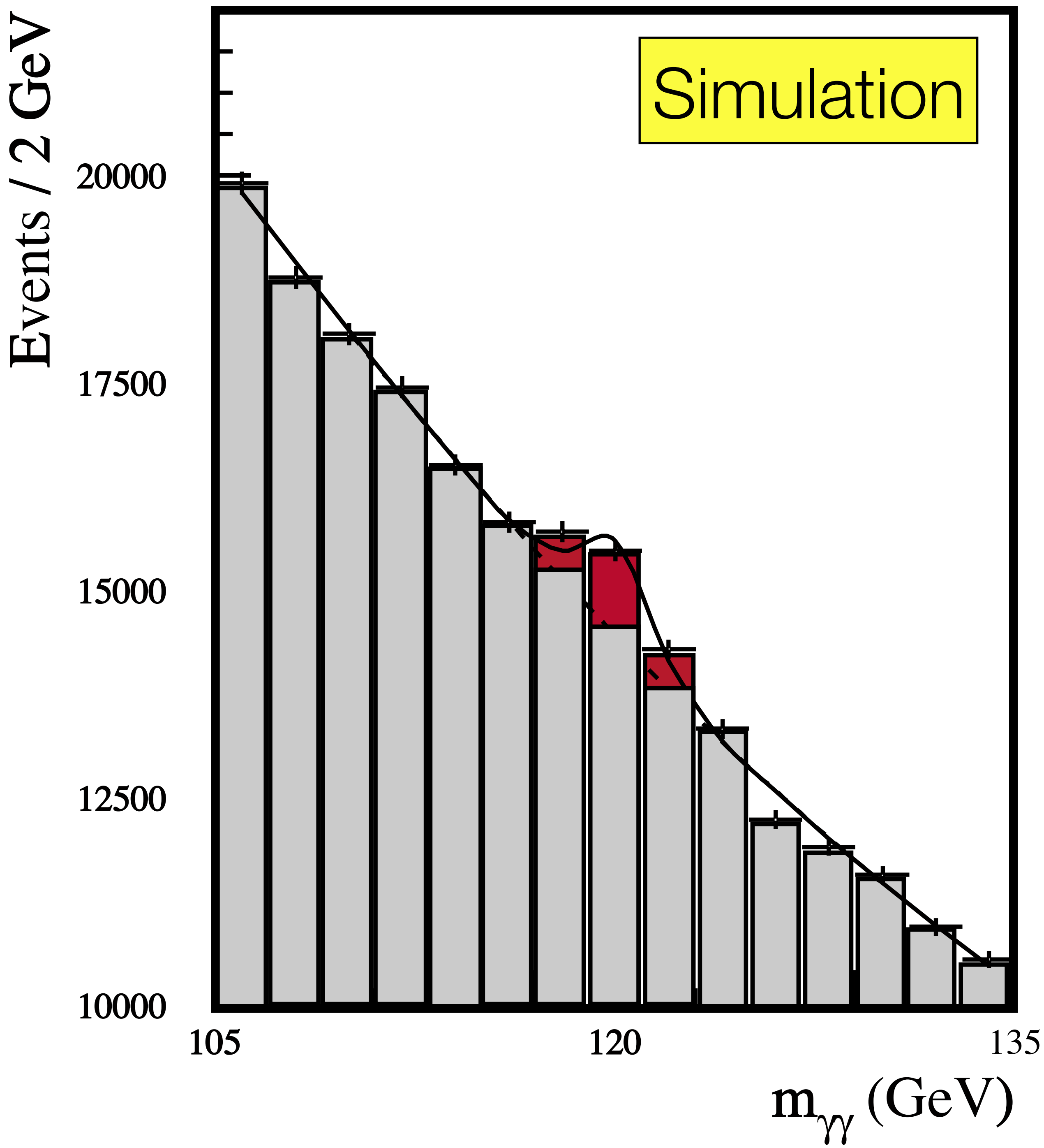
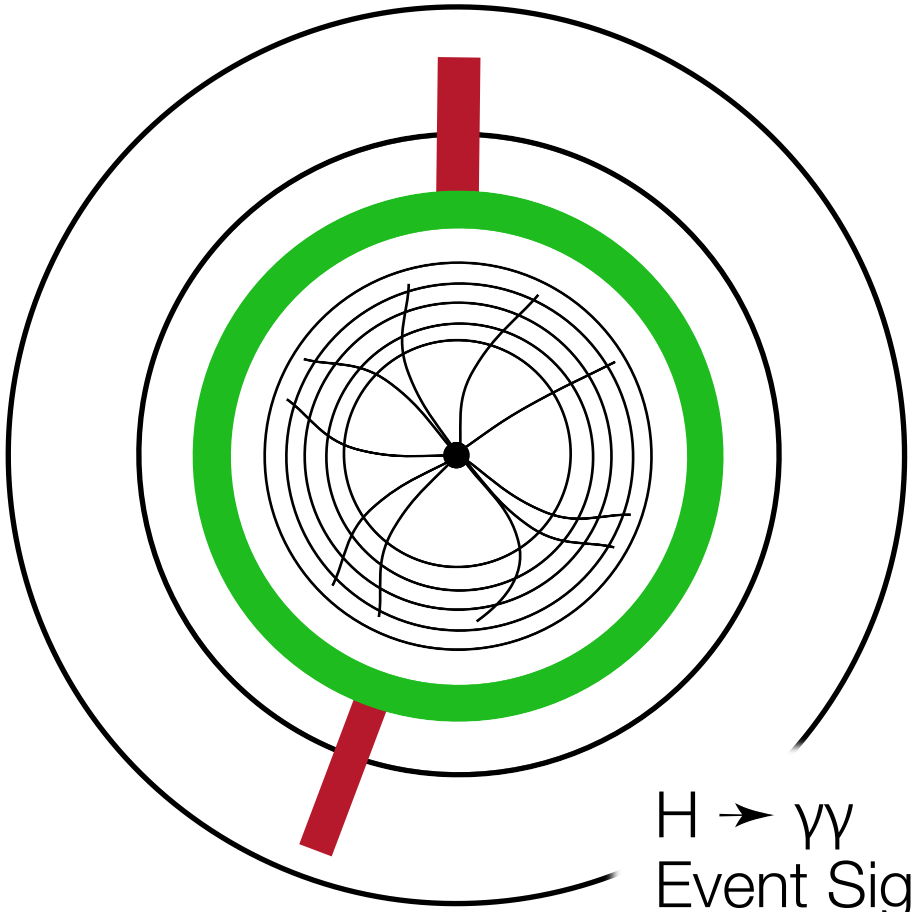


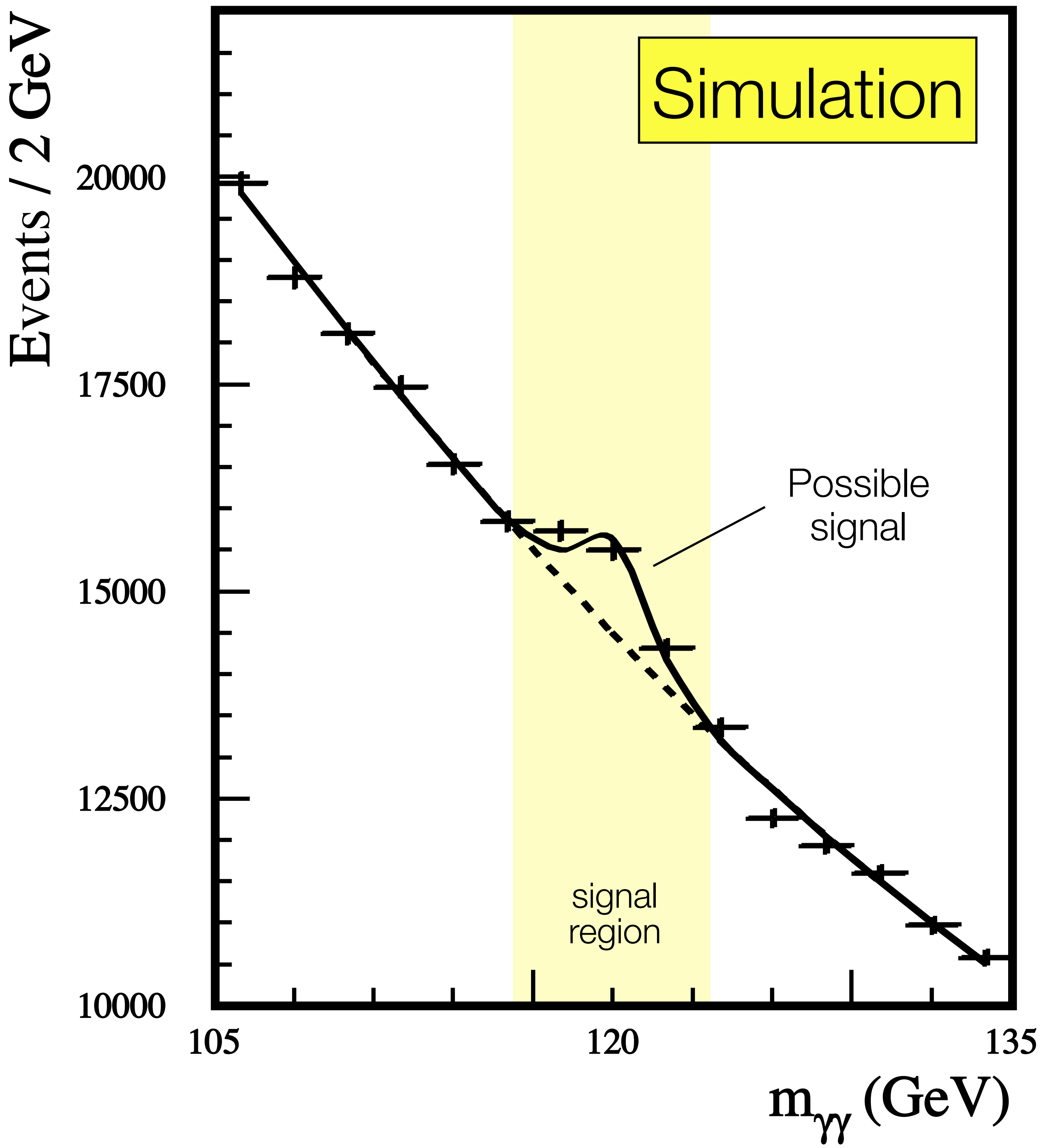


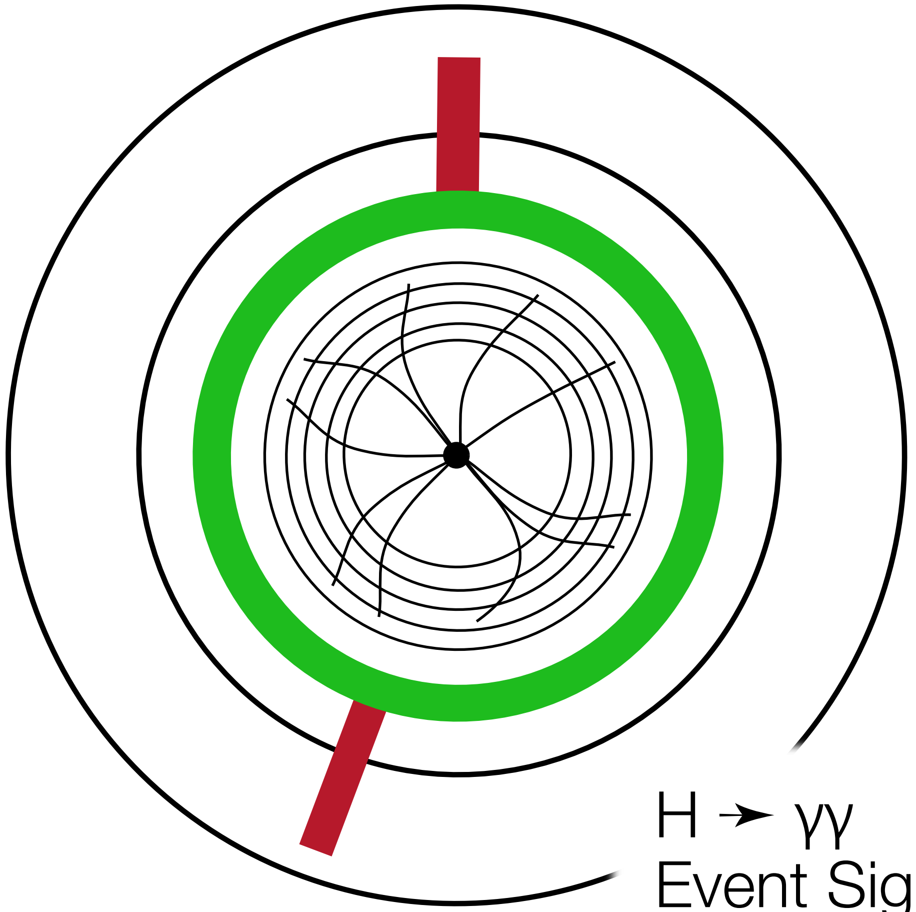
H ➛ γγ
Event Signature
[Schematic]

Invariant Mass:

$$m^2_{\gamma\gamma} = 2E_1E_2\,(1-\cos\vartheta)$$

Basic Analysis Principle





$H \rightarrow \gamma\gamma$
Event Signature
[Schematic]

Invariant Mass:

$$m_{\gamma\gamma}^2 = 2 E_1 E_2 (1 - \cos\vartheta)$$

The Discovery Channel

10^9 Events/sec

[1 Mbyte/Event]

10^{10}

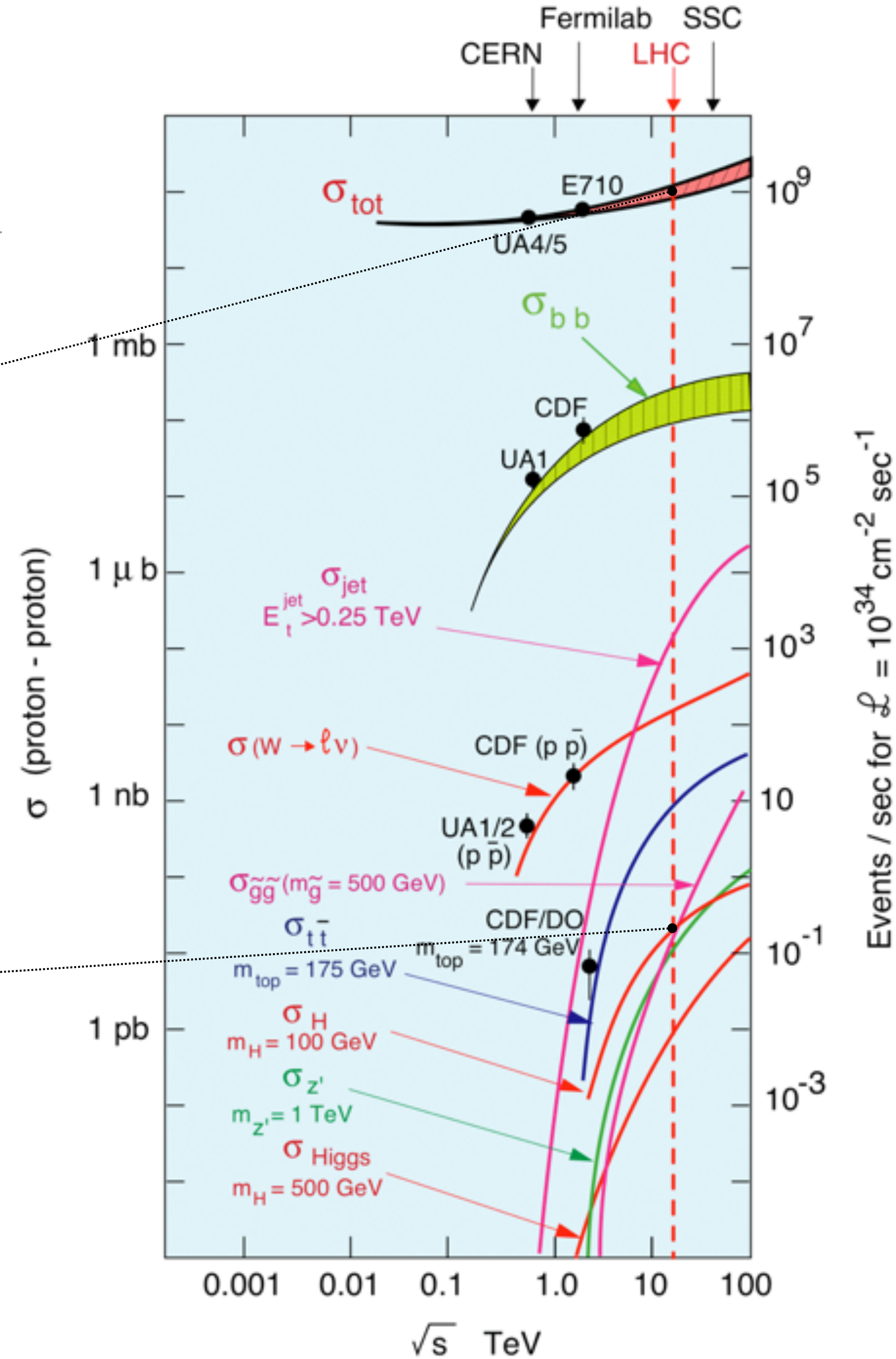
Efficient
rate reduction needed

[Storage rate: 100 Hz]

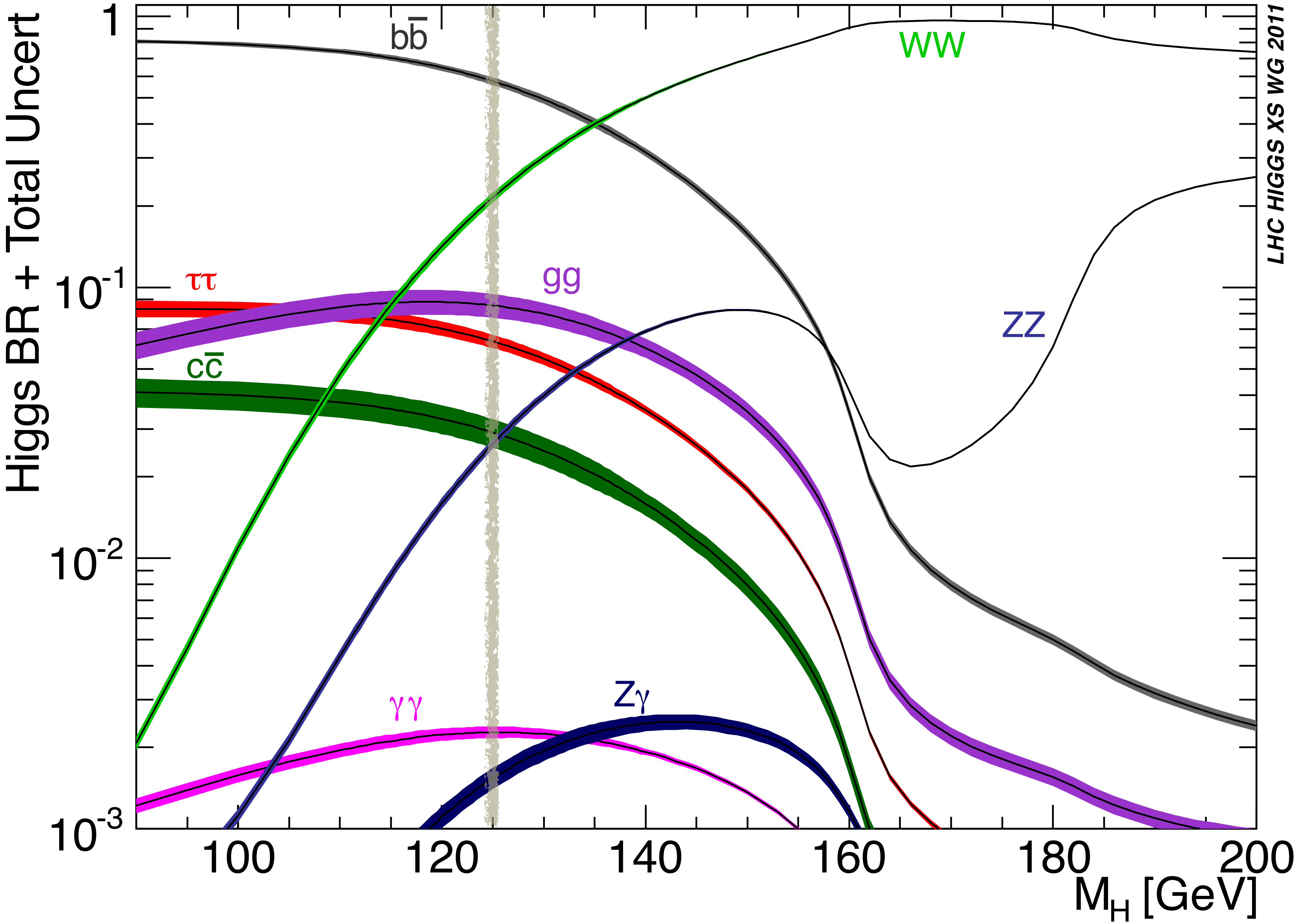
10 Events/min

[$m_H \approx 100$ GeV]

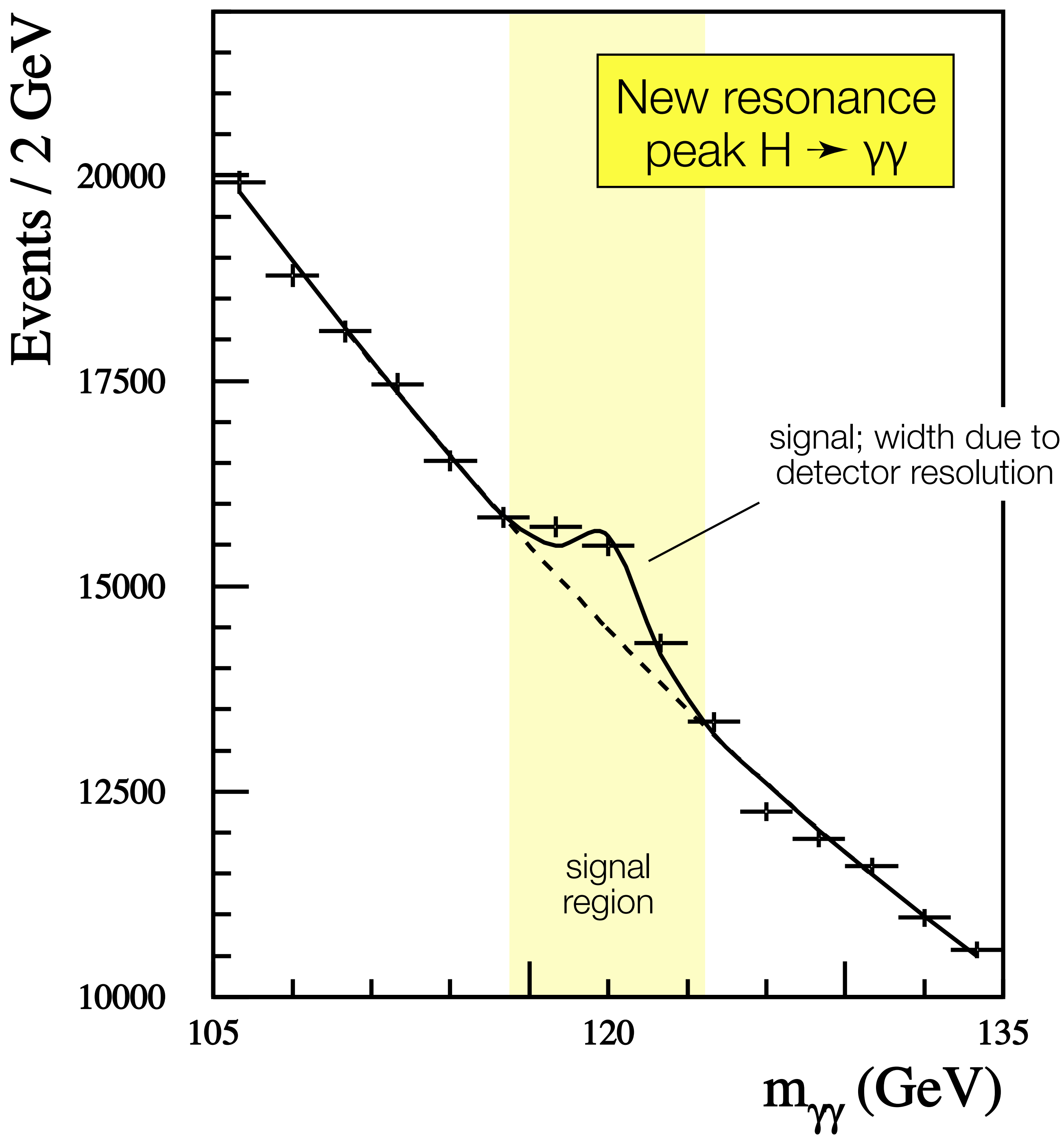
with 0.2% $H \to \gamma\gamma$
1.5% $H \to ZZ$



Reminder: Higgs Branching Ratios …



How to Make a Discovery



Signal significance:

$$S = \frac{N_S}{\sqrt{N_B + N_S}}$$

N_S: # signal events
N_B: # background events

... in peak region

S > 5:

Signal $N_S = N_{tot} - N_B$ is 5 times larger than statistical uncertainty on $N_B + N_S$ ...

Gaussian probability that upward fluctuation by more than 5σ is observed ...

$$P_{5\sigma} = 10^{-7}.$$

Discovery!

Maximizing the Significance S

1. Choose channels with low SM background

not possible: $H \to bb$ ... without associated production ...

possible: $H \to \gamma\gamma$ ... despite of small branching ratio ...

$H \to ZZ$ ... with at least one Z decaying leptonically ...

$tt\ H \to ttbb$ ... via additional top selection ...

2. Optimize detector resolution

Example: mass resolution σ_m increases by a factor of 2;

thus: peak region has to be increased by a factor 2 and number N_B of background events increases by factor of 2

$S \approx N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$ ➜

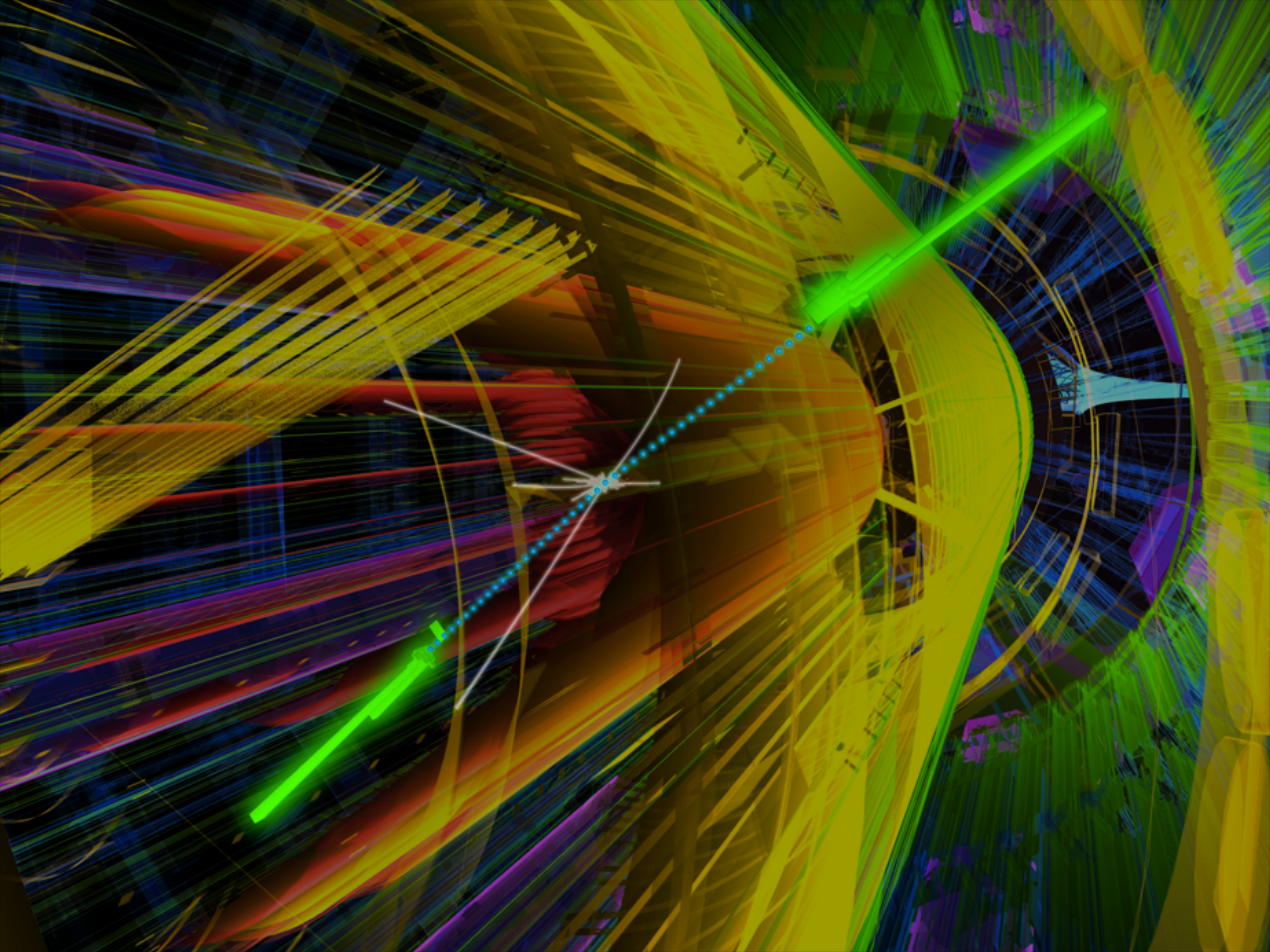
$$S \sim \frac{1}{\sqrt{\sigma_m}}$$

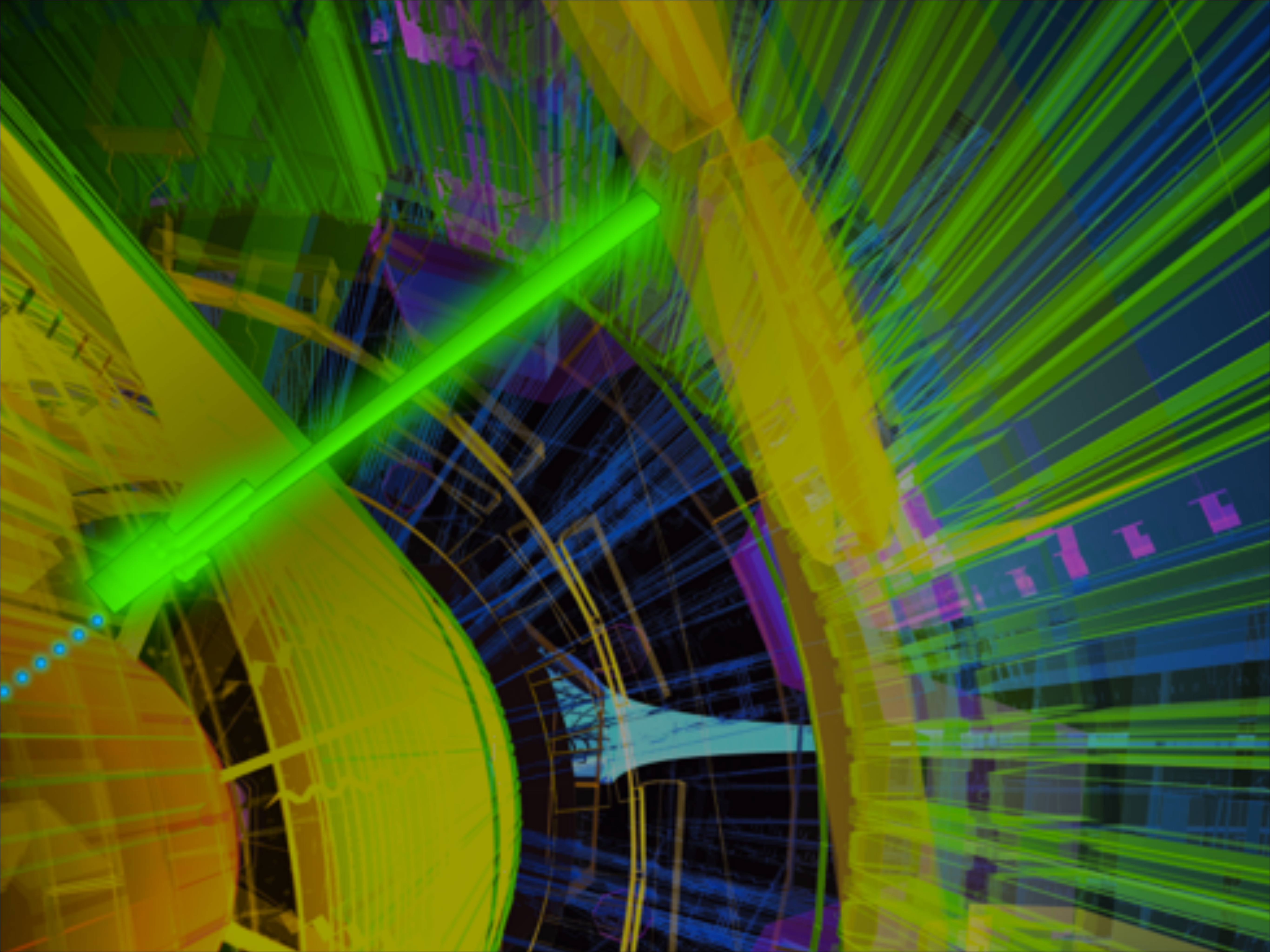
3. Maximize luminosity L

Signal: $N_S \sim L$

Background: $N_B \sim L$

➜ $$S \sim \sqrt{L}$$



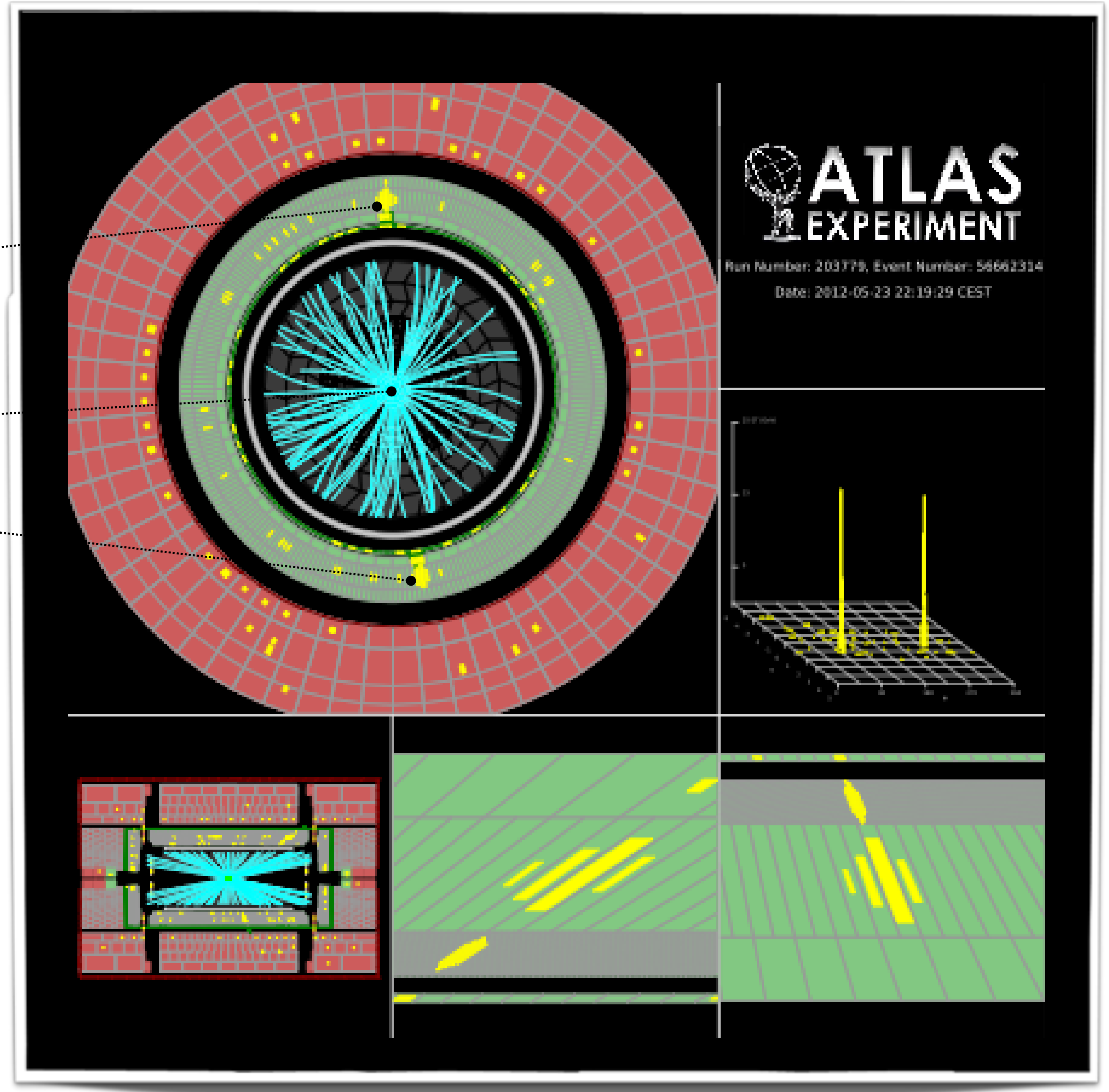


Analysis Necessities & Steps …

Photon reconstruction
Photon identification
Photon isolation
Primary vertex
Energy calibration
Background modeling

Event categories

Limits & signal strength



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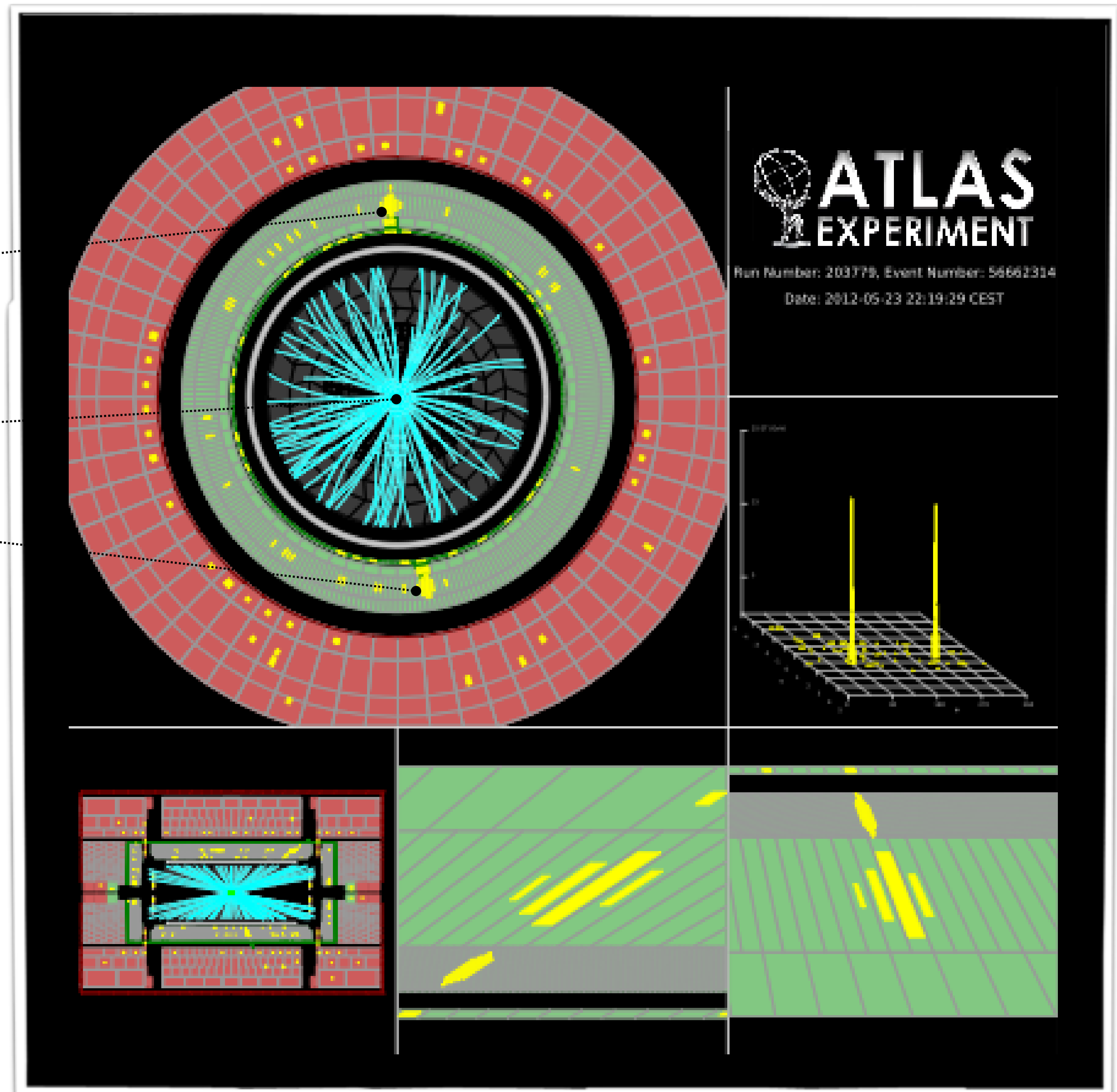

Photon & Object Reconstruction

Photons

isolated EM clusters, identified using shower shape variables
[use rack or calorimeter isolation cone $\Delta R < 0.2$ or 0.4]

converted (two matched tracks, or single with no inner layer hit) and un-converted photon categories utilized

Jets

reconstructed with $R = 0.4$ anti-k_T algorithm
[inputs noise-suppressed topological clusters …]

$p_T > 25$ (30) GeV in central (forward, $2.4 \leq |\eta| \leq 4.5$) region, jet vertex fraction (JVF) to suppress pileup jets

pile-up correction based on NPV, energy density, jet area

b-tagging using NN-based combination of impact parameter and secondary vertex information

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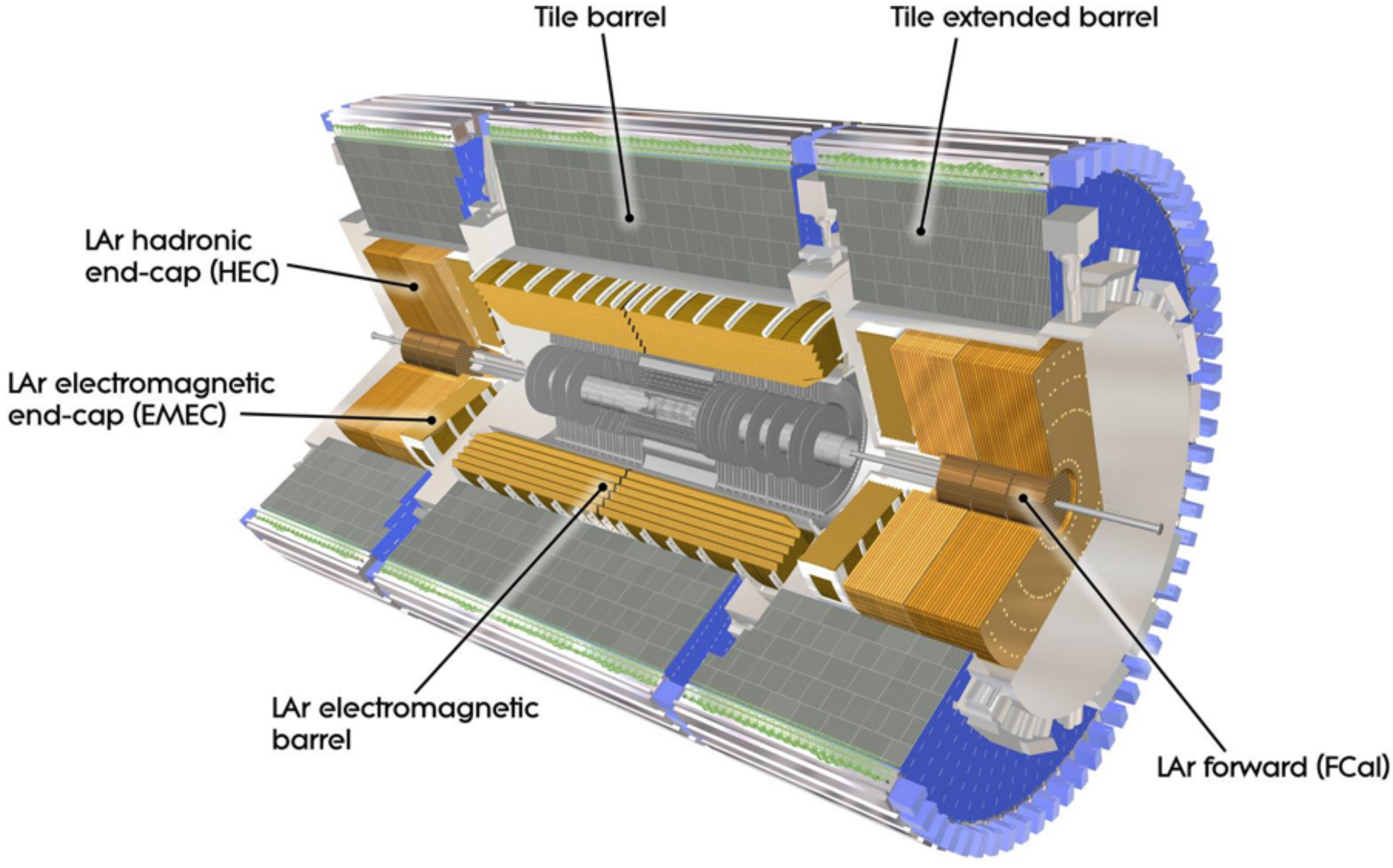
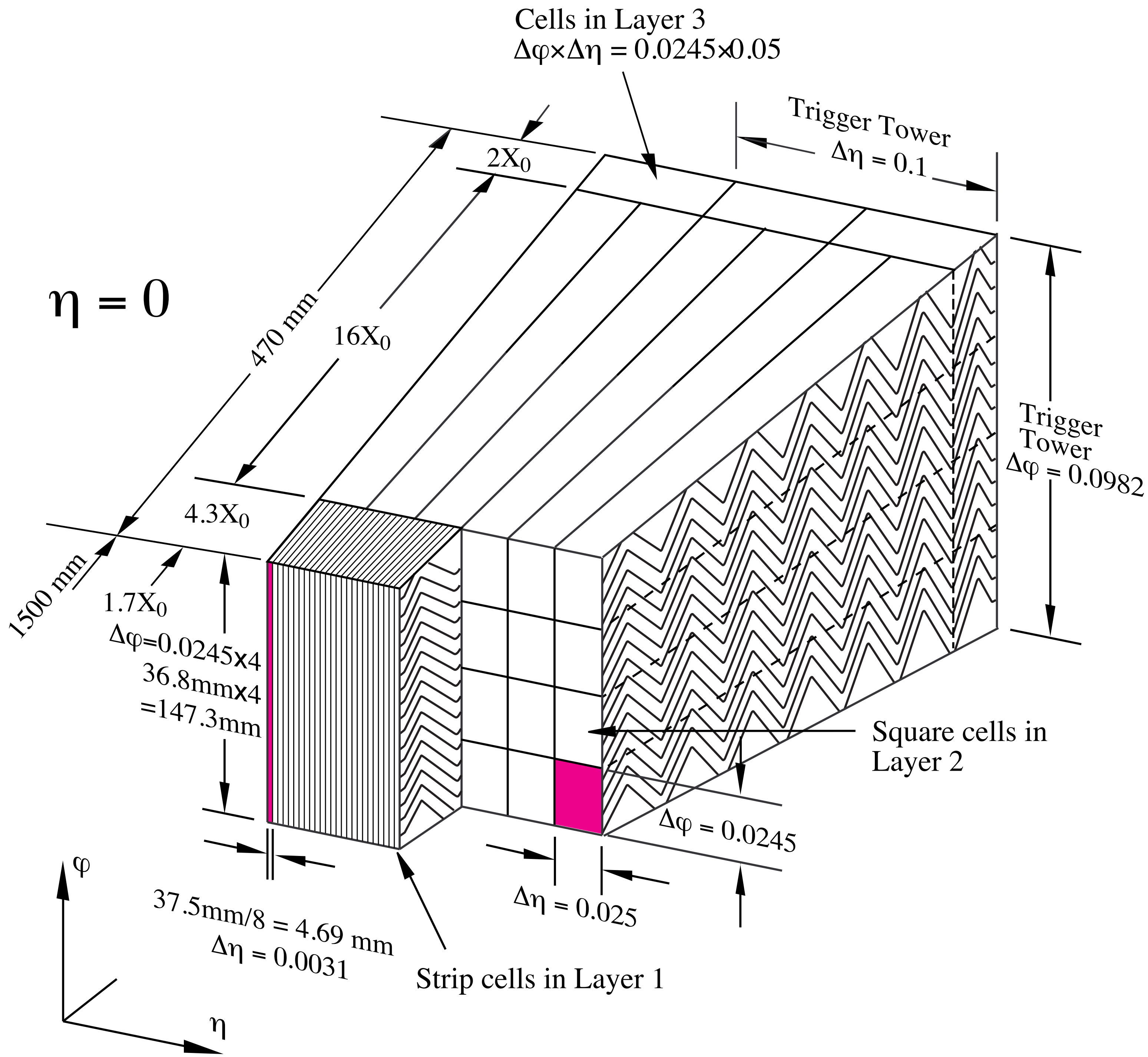
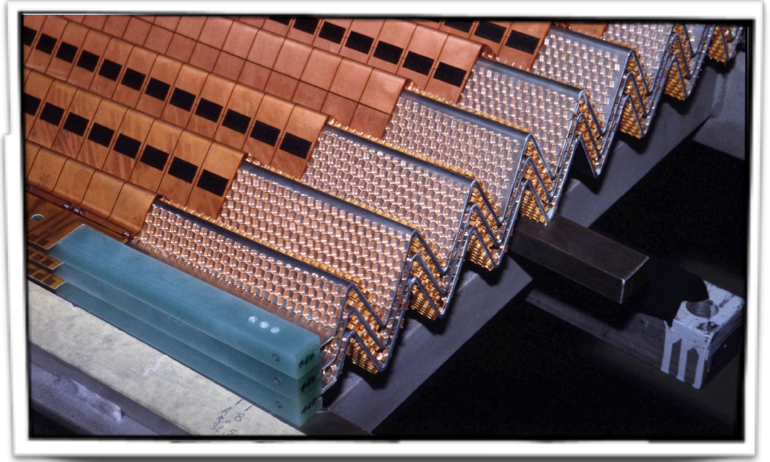
The ATLAS Calorimeter

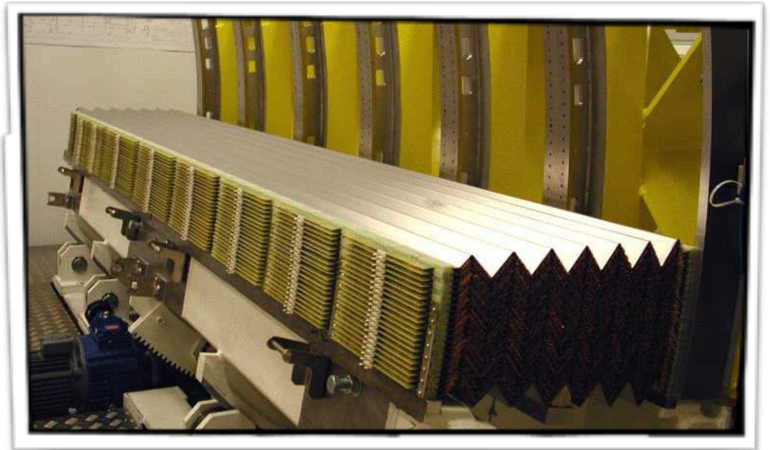
ECAL: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$
HCAL: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$

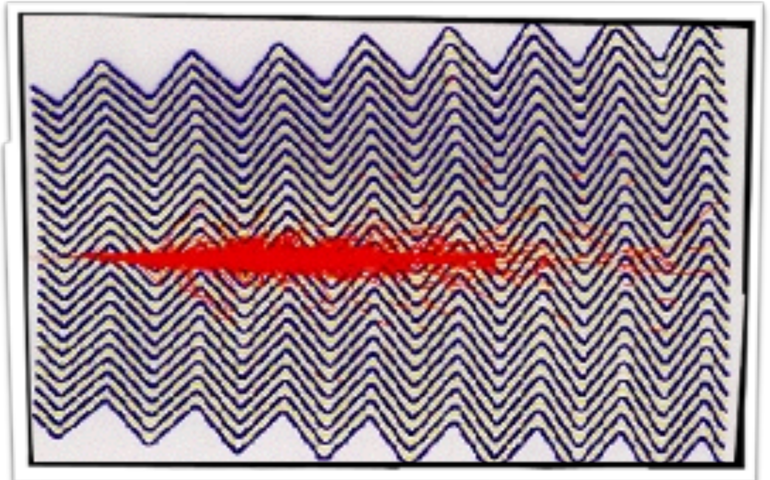


Sketch of ECAL Barrel Module









Shower Comparison …

Electromagnetic shower

consists of visible electromagnetic energy only

is very compact ($X_0 \approx 2$ cm)

can be simulated with high precision since mostly electromagnetic processes need to be calculated

allows high accuracy calibration

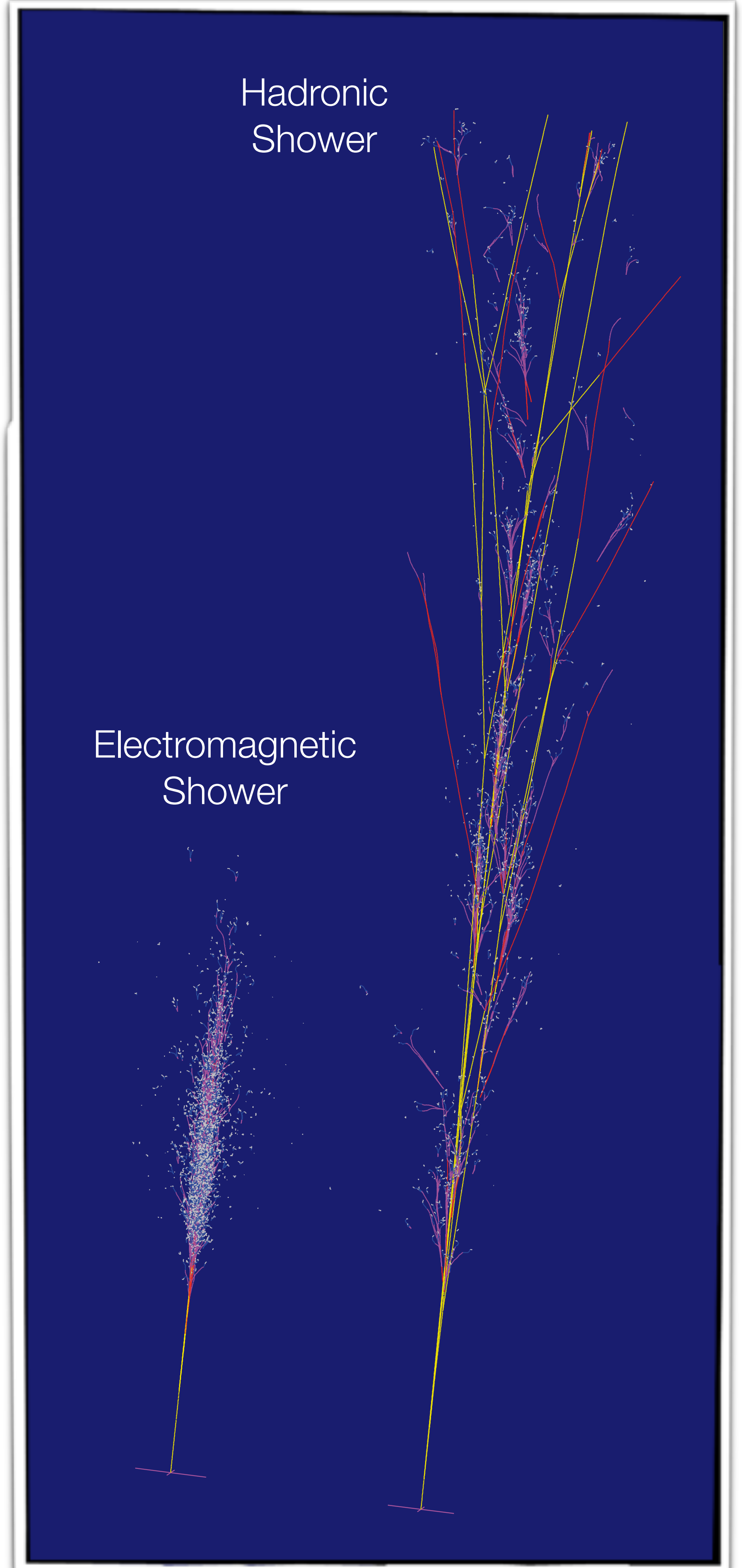
Hadronic shower

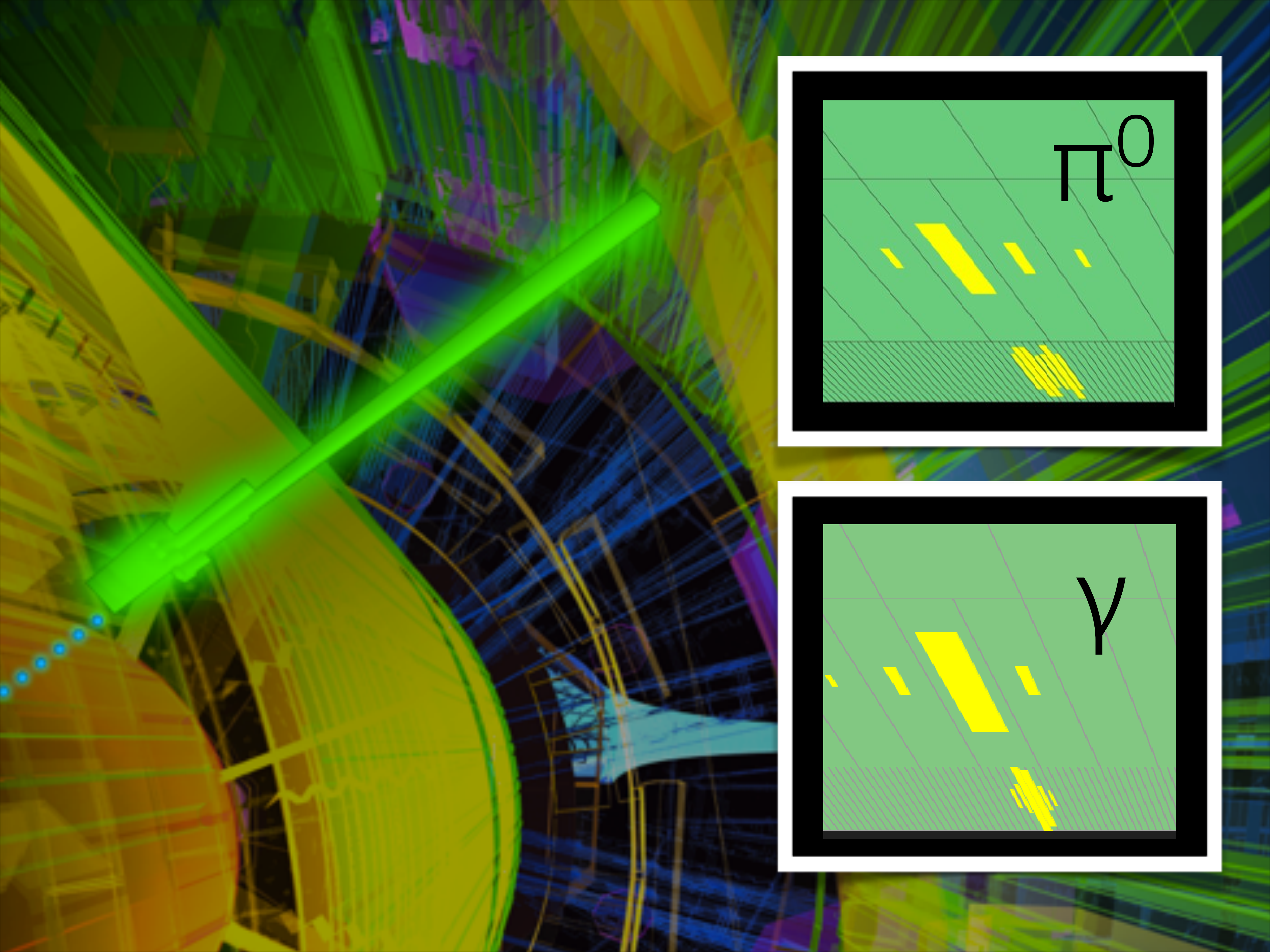
consists of EM and hadronic energy (some invisible)
is very large ($\lambda_0 \approx 20$ cm)

is difficult to simulate since it involves QCD

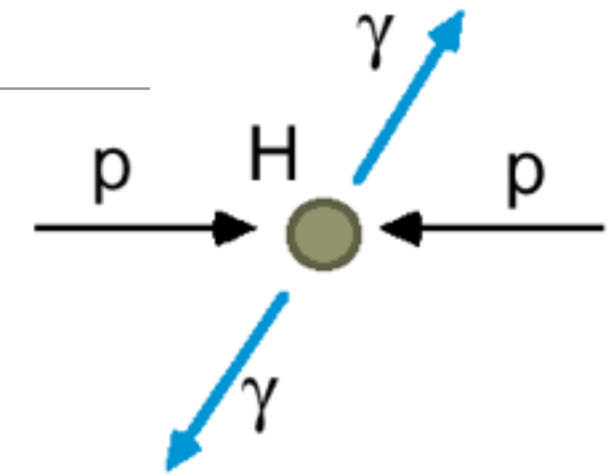
limits the accuracy for calibration
(mostly due to large fluctuations)

Examples show 50 GeV showers
of an electron and a pion in iron …




π^0
γ

2γ-Channel – Signal and Background

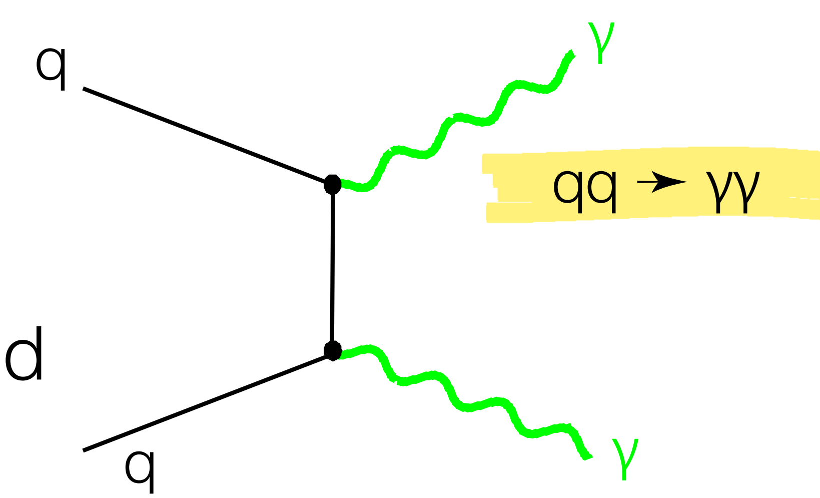


Signal: $\sigma \cdot BR = 50$ fb [$m_H = 100$ GeV]

very demanding channel due to huge irreducible background ...

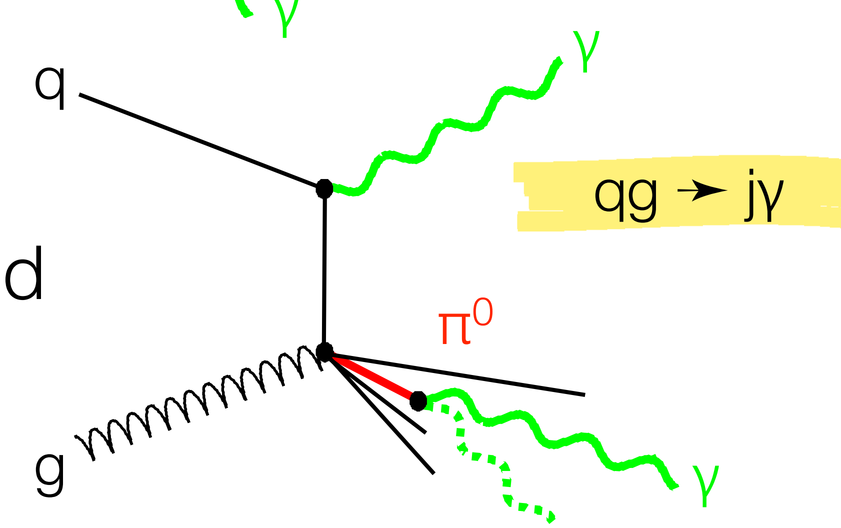
very harsh requirements on calorimeter performance
[acceptance, E and θ-resolution, separation of γ from jets and π^0]

Two main background sources:



2γ-production: irreducible background

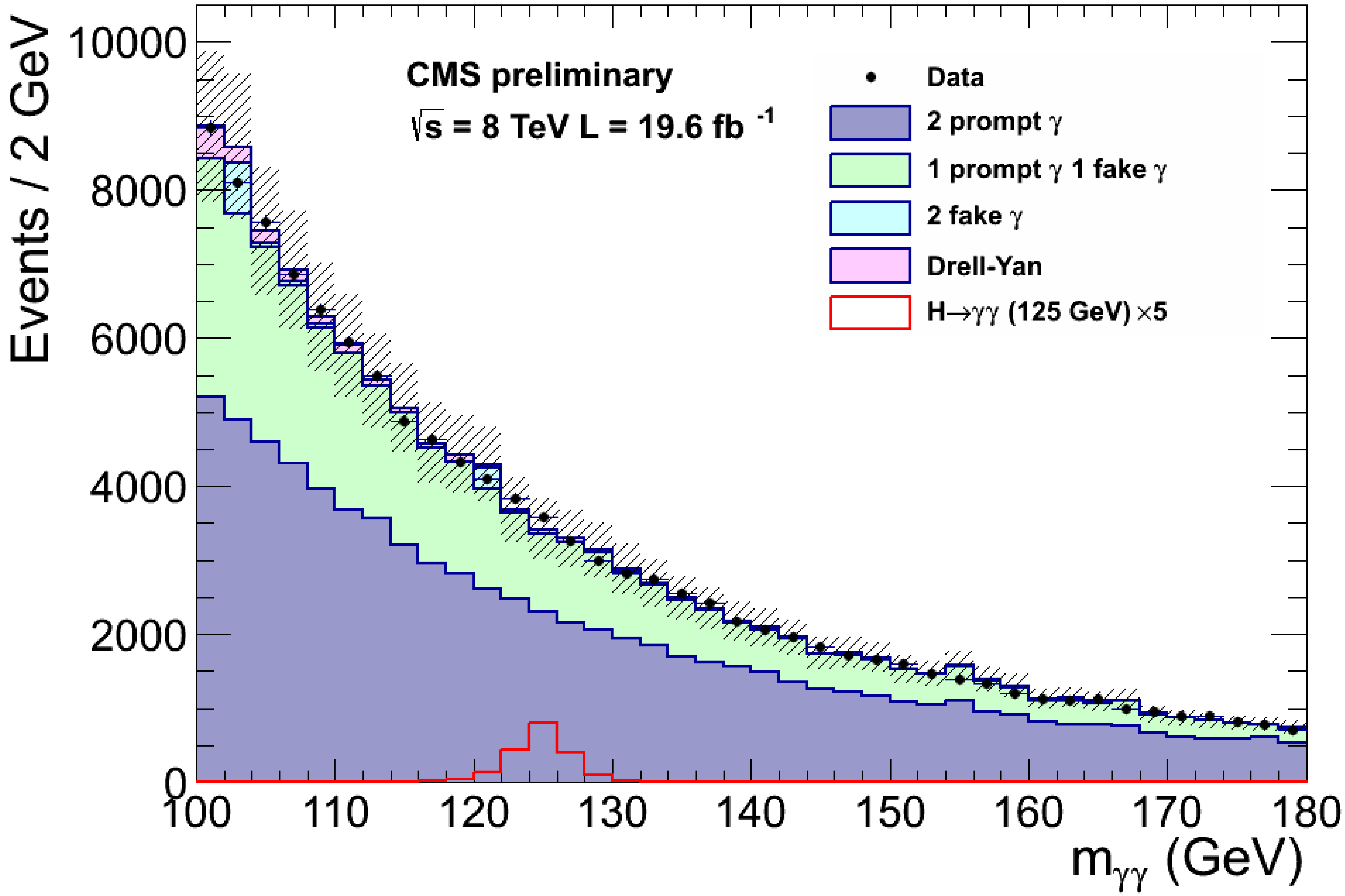
$\sigma_{\gamma\gamma} \sim 2$ pb/GeV and $\Gamma_H \sim$ MeV
implies $\sigma(m_{\gamma\gamma})/m_{\gamma\gamma} \sim 1\%$



γ-jet and di-jet production: reducible background

$\sigma_{\gamma j+jj} \sim 10^6\ \sigma_{\gamma\gamma}$; jet rejection of > 10^3 needed

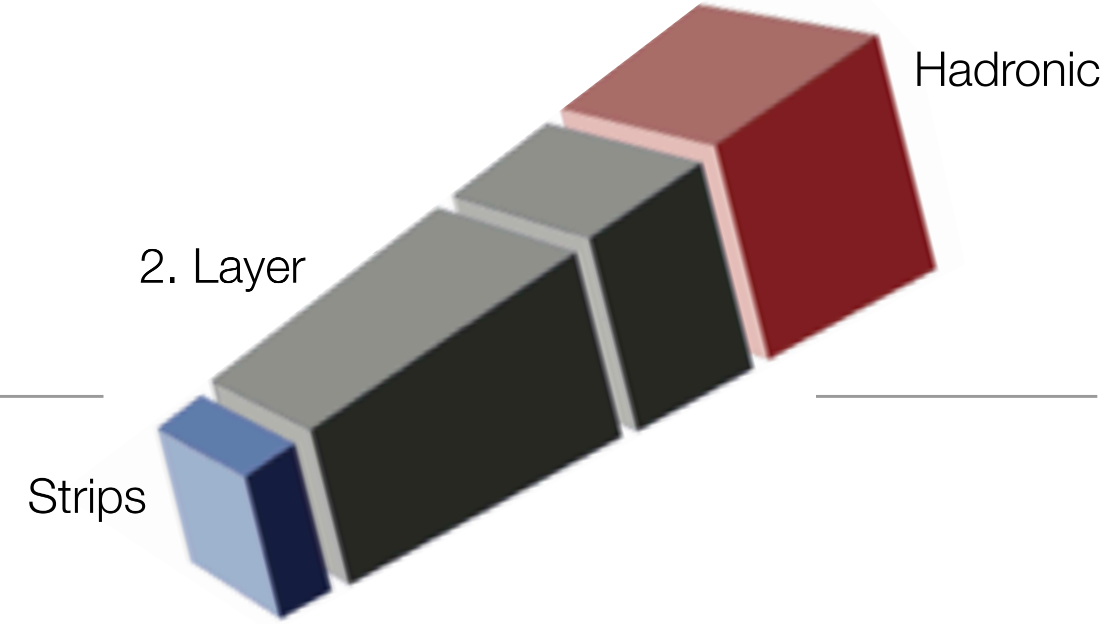
Di-Photon Invariant Mass Distribution



Photon Reconstruction

Category	Description	Name	Loose	Tight
Acceptance	$\|\eta\| < 2.37$, $1.37 < \|\eta\| < 1.52$ excluded	–		✓
Hadronic leakage	Ratio of E_T in the first sampling of the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| < 0.8$ and $\|\eta\| > 1.37$)	R_{had_1}	✓	✓
	Ratio of E_T in all the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$)	R_{had}	✓	✓
EM Middle layer	Ratio in η of cell energies in 3×7 versus 7×7 cells	R_η	✓	✓
	Lateral width of the shower	w_2	✓	✓
	Ratio in ϕ of cell energies in 3×3 and 3×7 cells	R_ϕ		✓
EM Strip layer	Shower width for three strips around maximum strip	$w_{s\,3}$		✓
	Total lateral shower width	$w_{s\,\mathrm{tot}}$		✓
	Fraction of energy outside core of three central strips but within seven strips	F_{side}		✓
	Difference between the energy associated with the second maximum in the strip layer, and the energy reconstructed in the strip with the minimal value found between the first and second maxima	ΔE		✓
	Ratio of the energy difference associated with the largest and second largest energy deposits over the sum of these energies	E_{ratio}		✓

Photon Reconstruction



Variables & Positions

	Strips	2nd	Had.
Ratios	f_1, f_{side}	$R_\eta{}^*$, R_ϕ	$R_{\text{Had.}}{}^*$
Widths	$w_{s,3}$, $w_{s,tot}$	$w_{\eta,2}{}^*$	-
Shapes	ΔE, E_{ratio}		

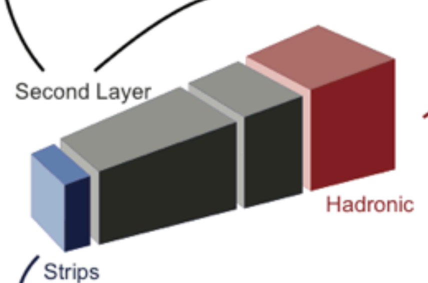
* Used in PhotonLoose.

Energy & Ratios

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

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

φ η



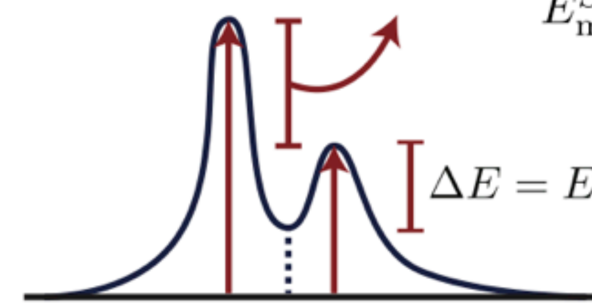
$$R_{\text{Had}} = \frac{E_T^{\text{Had}}}{E_T}$$

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

$$f_{\text{side}} = \frac{E_7^{S1} - E_3^{S1}}{E_3^{S1}}$$

Shower Shapes & Width

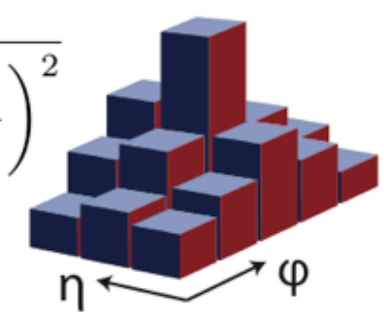
$$E_{\text{ratio}} = \frac{E^{S1}_{\text{max},1} - E^{S1}_{\text{max},2}}{E^{S1}_{\text{max},1} + E^{S1}_{\text{max},2}}$$

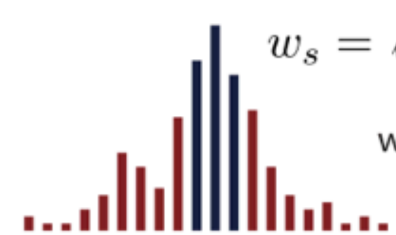


$$\Delta E = E^{S1}_{\text{max},2} - E^{S1}_{\text{min}}$$

$$w_{\eta,2} = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i}\right)^2}$$

Width in a 3×5 (Δη×Δφ) region of cells in the second layer.

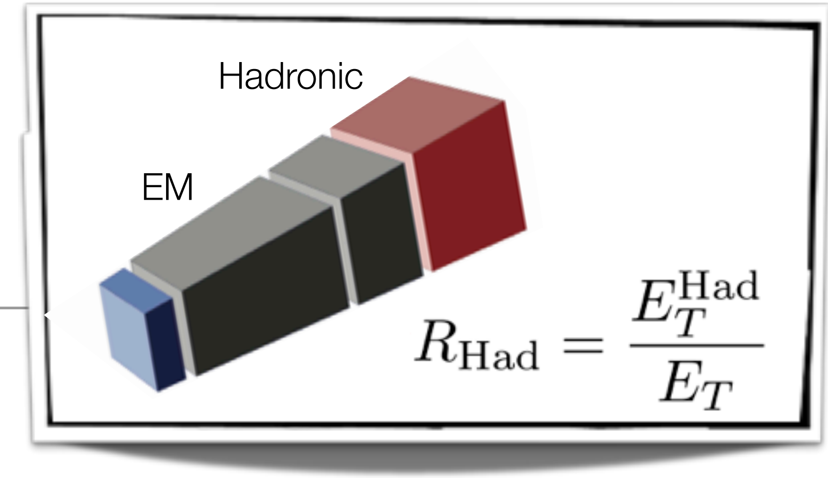


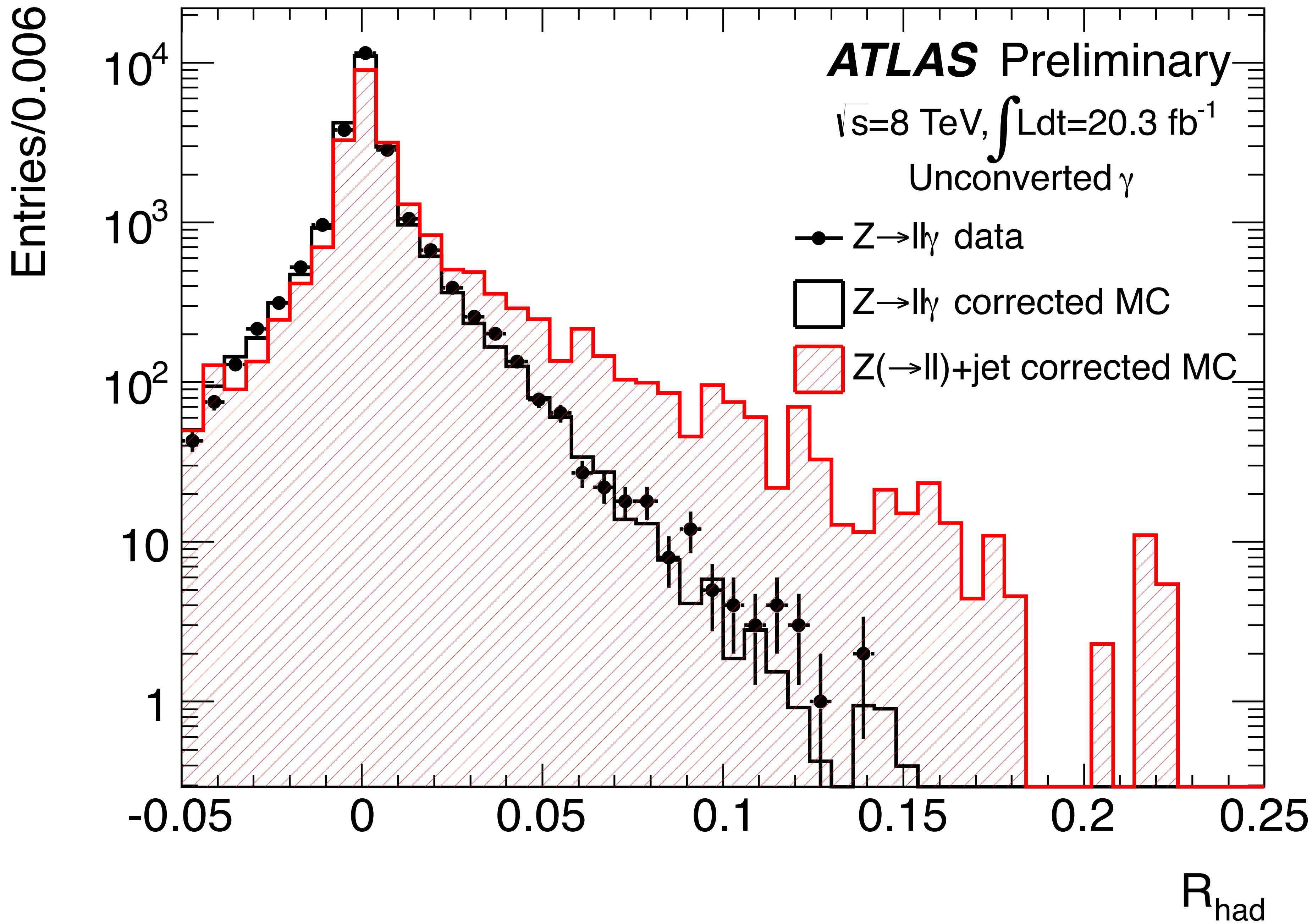


$$w_s = \sqrt{\frac{\sum E_i (i - i_{\text{max}})^2}{\sum E_i}}$$

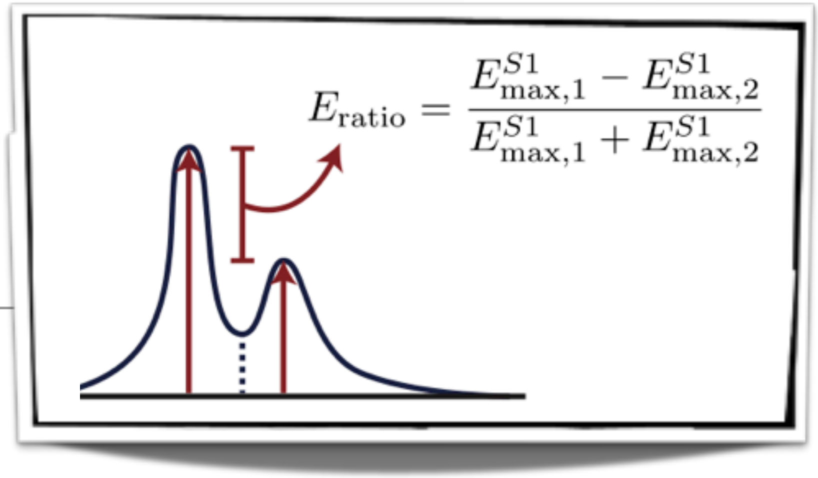
ws3 = w_1 uses 3 strips in η; wstot is defined similarly, but uses 20 strips.

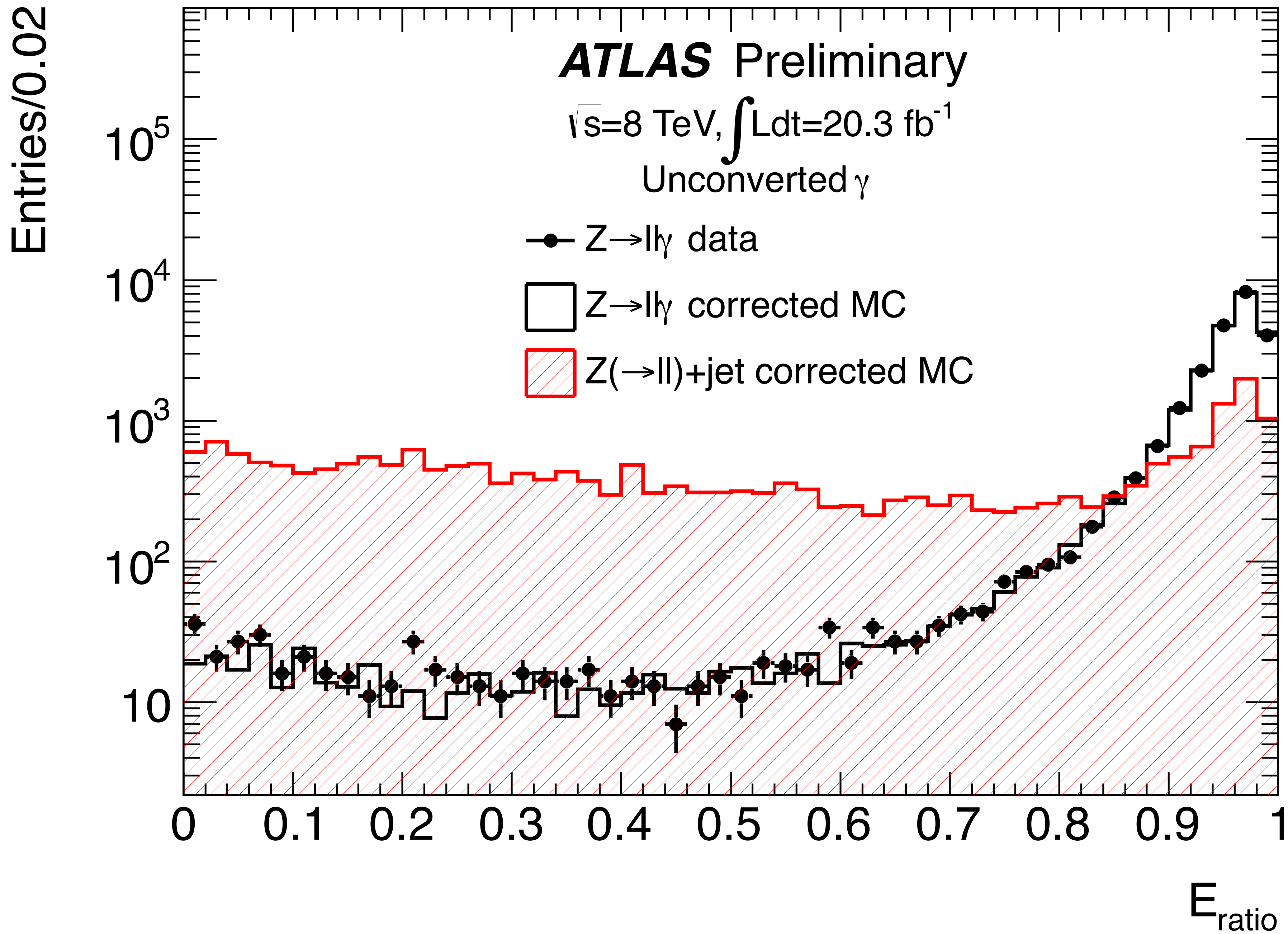
Hadronic Leakage





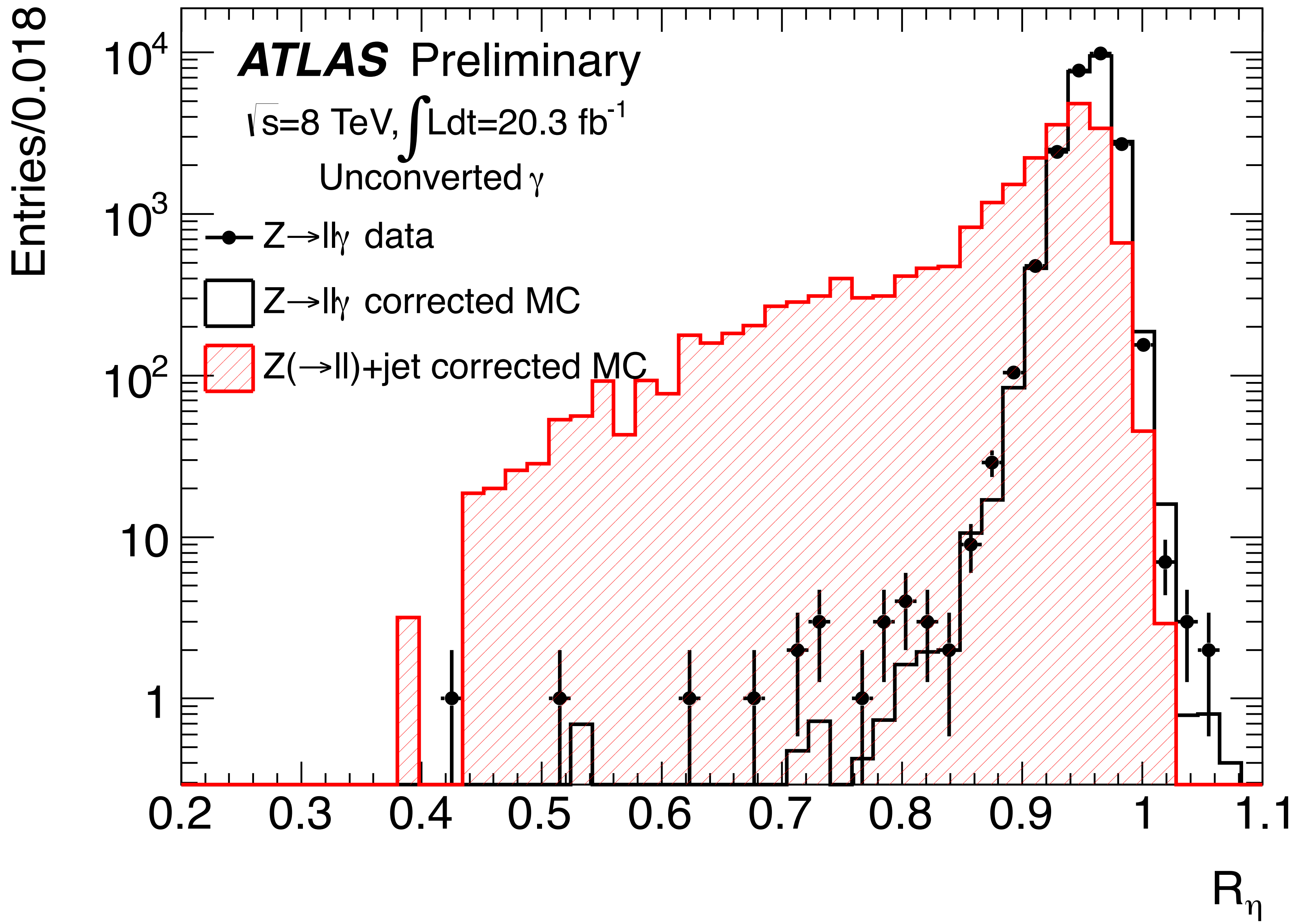
Energy Ratio in EM Strip Layer



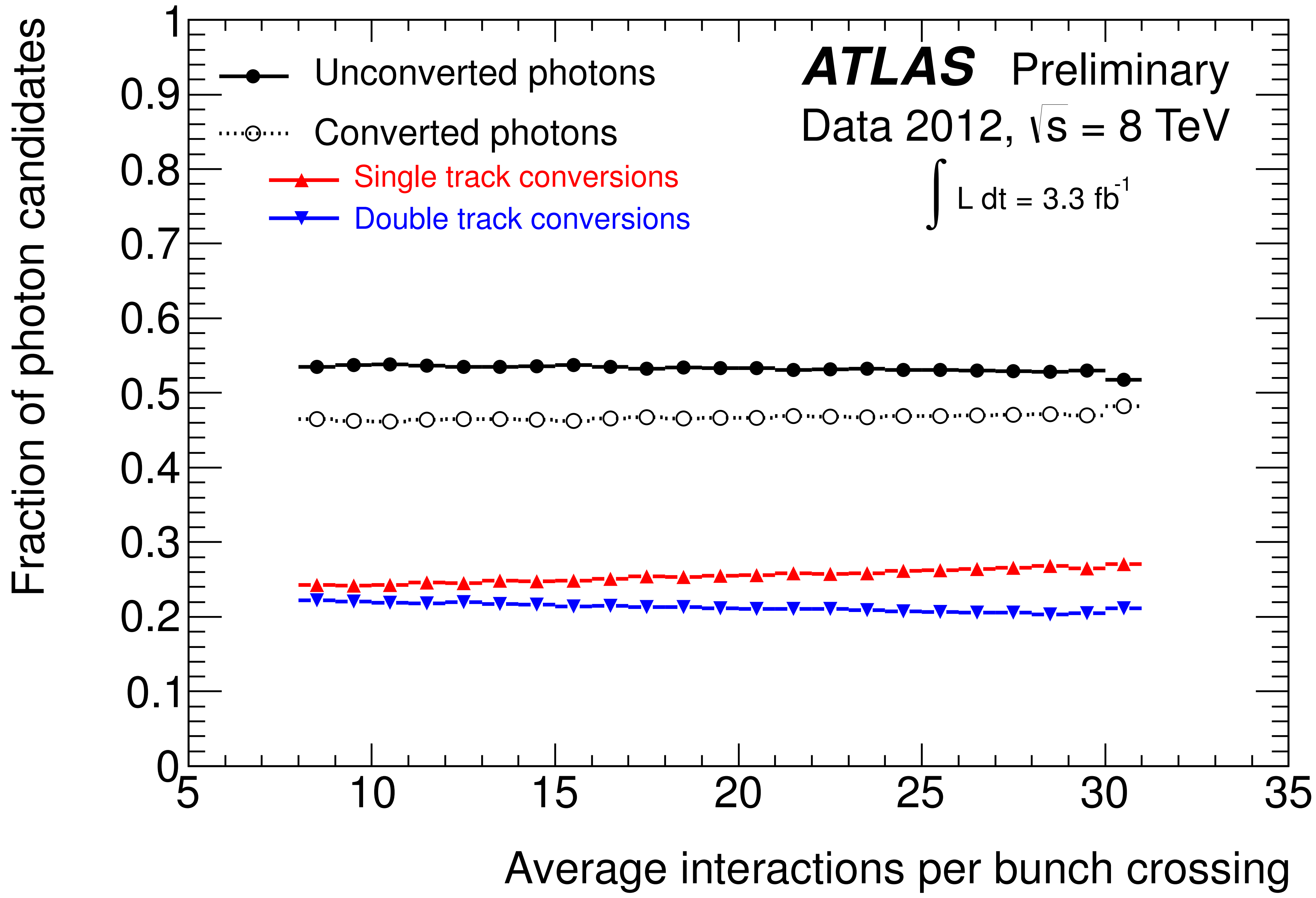


Middle Layer Cell Energy η-Ratio

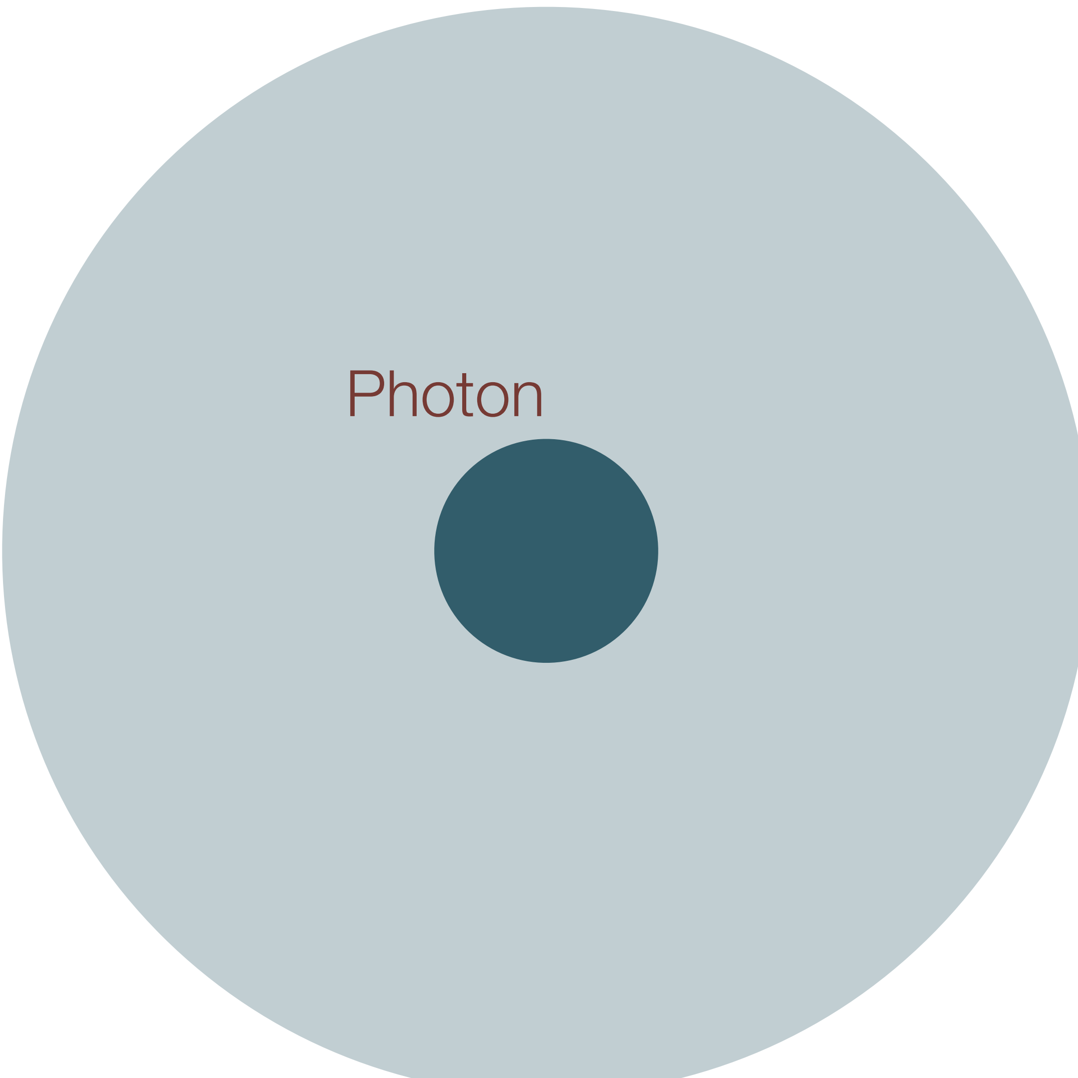
$$R_\eta = \frac{E^{S2}_{3\times7}}{E^{S2}_{7\times7}}$$



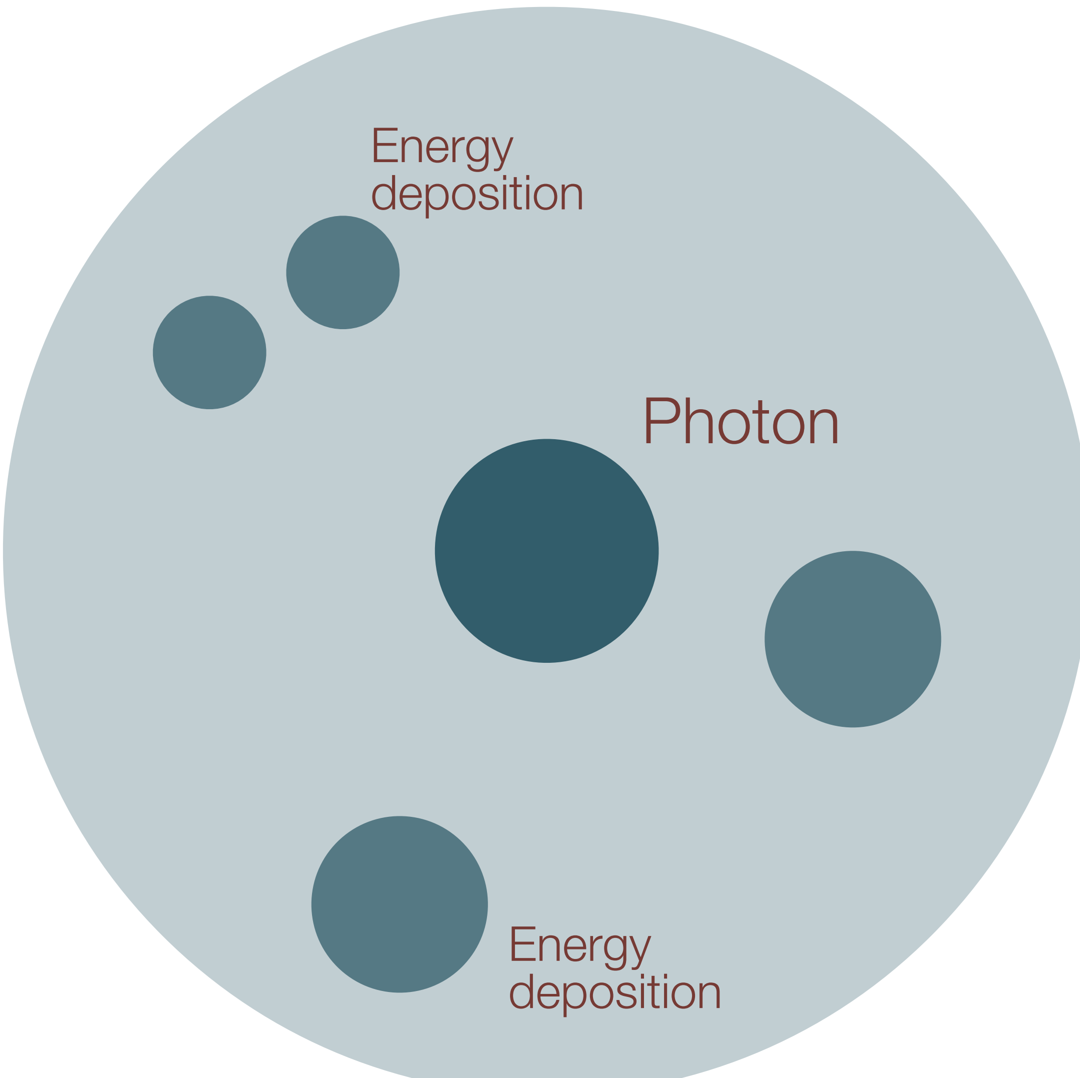
Pile-Up Robustness



Finding Isolated Photons …



Isolated



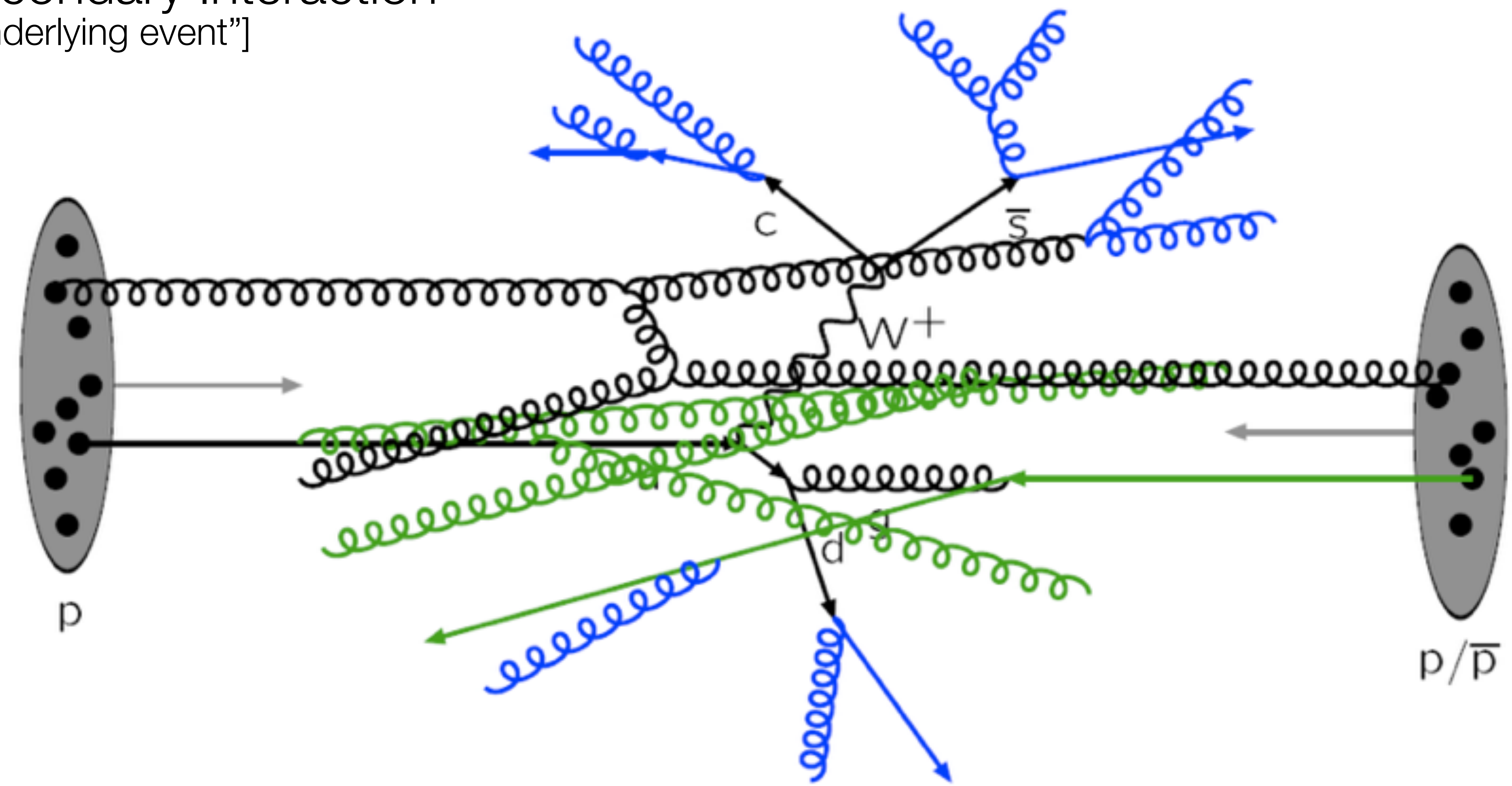
Non-isolated

Proton-Proton Scattering at LHC

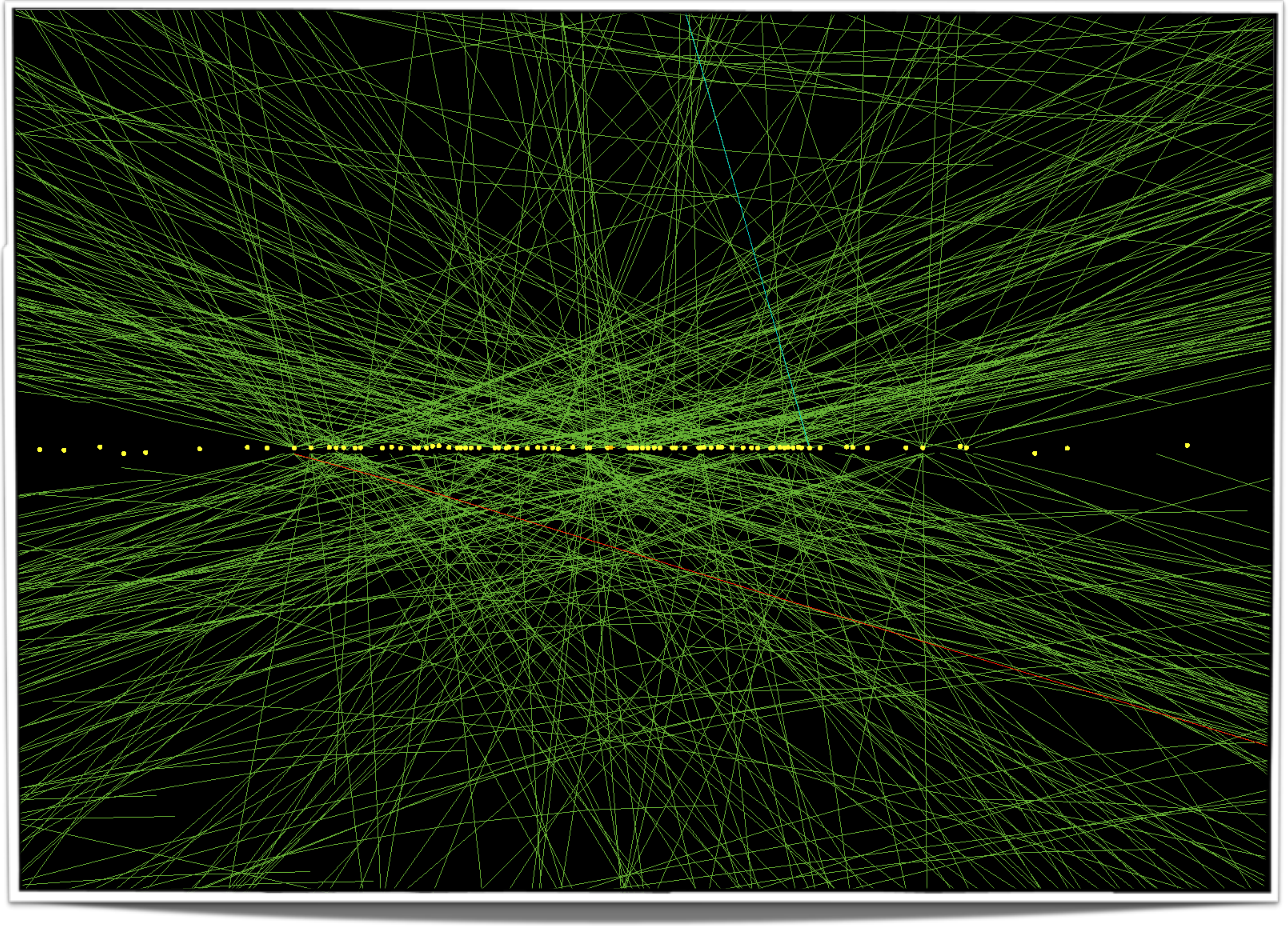
Hard interaction: qq, gg, qg fusion

Initial State Radiation (ISR)

Secondary Interaction
["underlying event"]

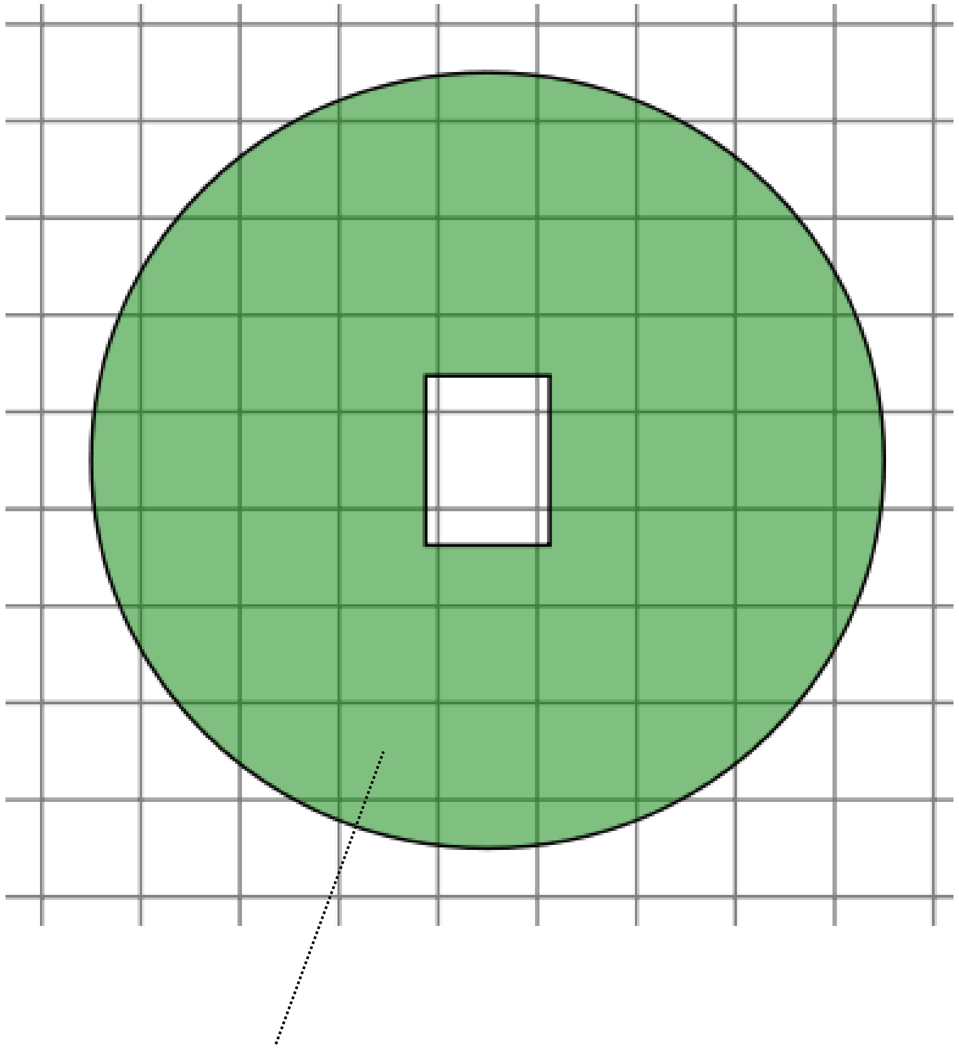


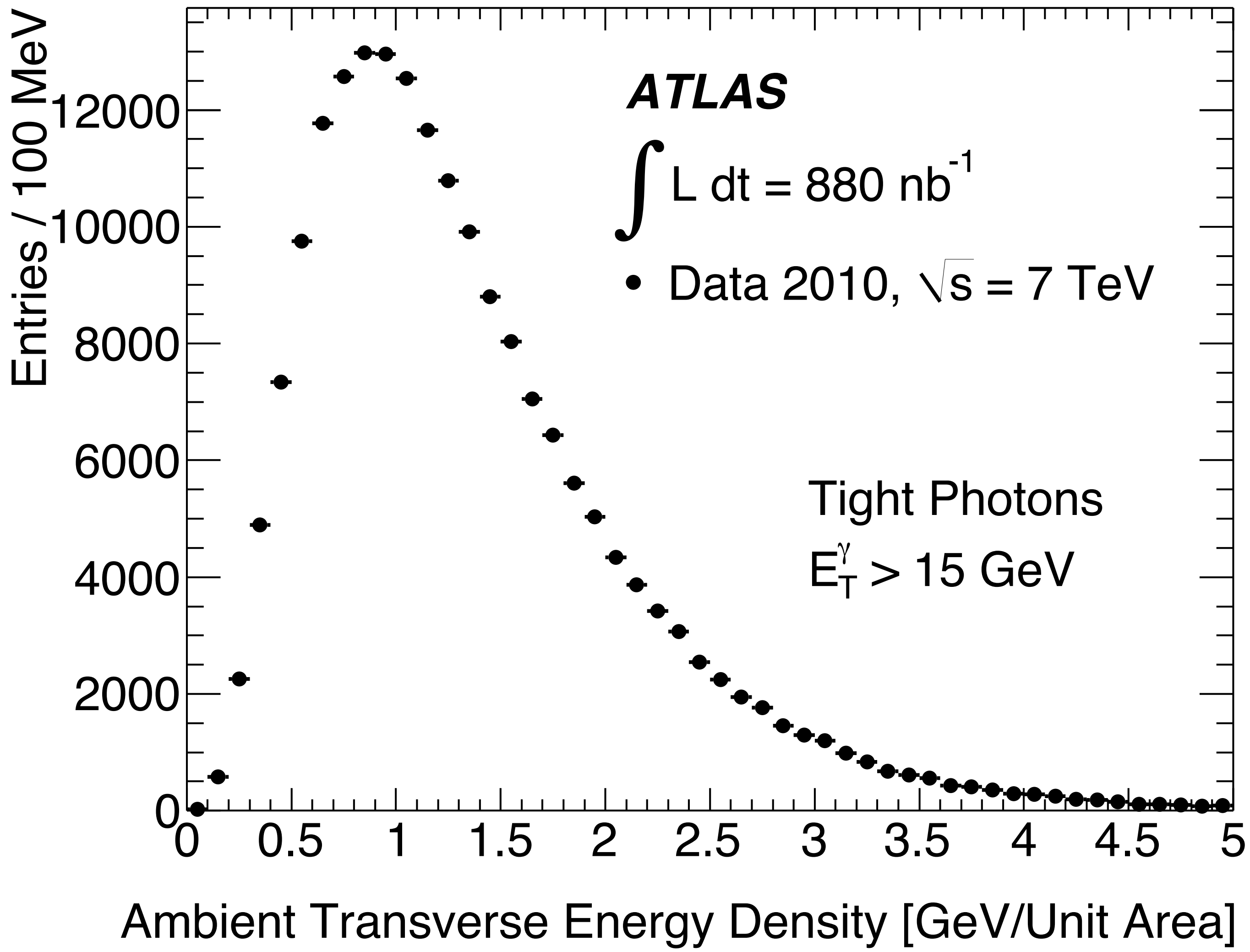
Extreme Pile-up Event



CMS

Cell Based Calorimeter Isolation





Transverse isolation energy
within R =0.4 from cell energies …
energy in core excluded …

Pile-up and underlying event correction
using ambient transverse energy density …

Event-by-event estimate of ambient transverse
energy density using topological clusters …

To avoid correlations with E_T of photon use
median of jet transverse energy density in each event …

Topological Cluster Finding

Goal:

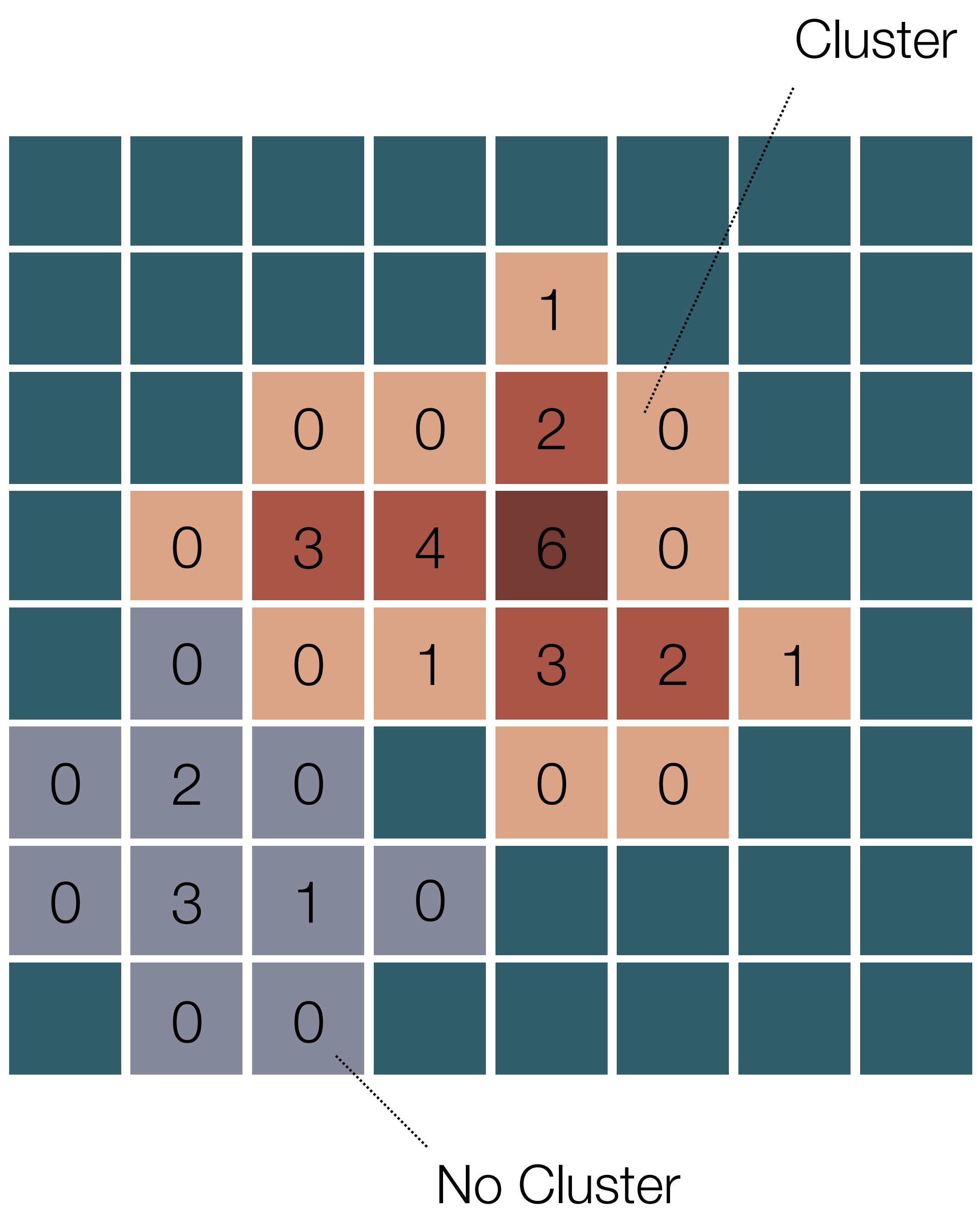
Reconstruct group of calorimeter cells topologically interconnected …

Algorithm:

Select by energy significance …

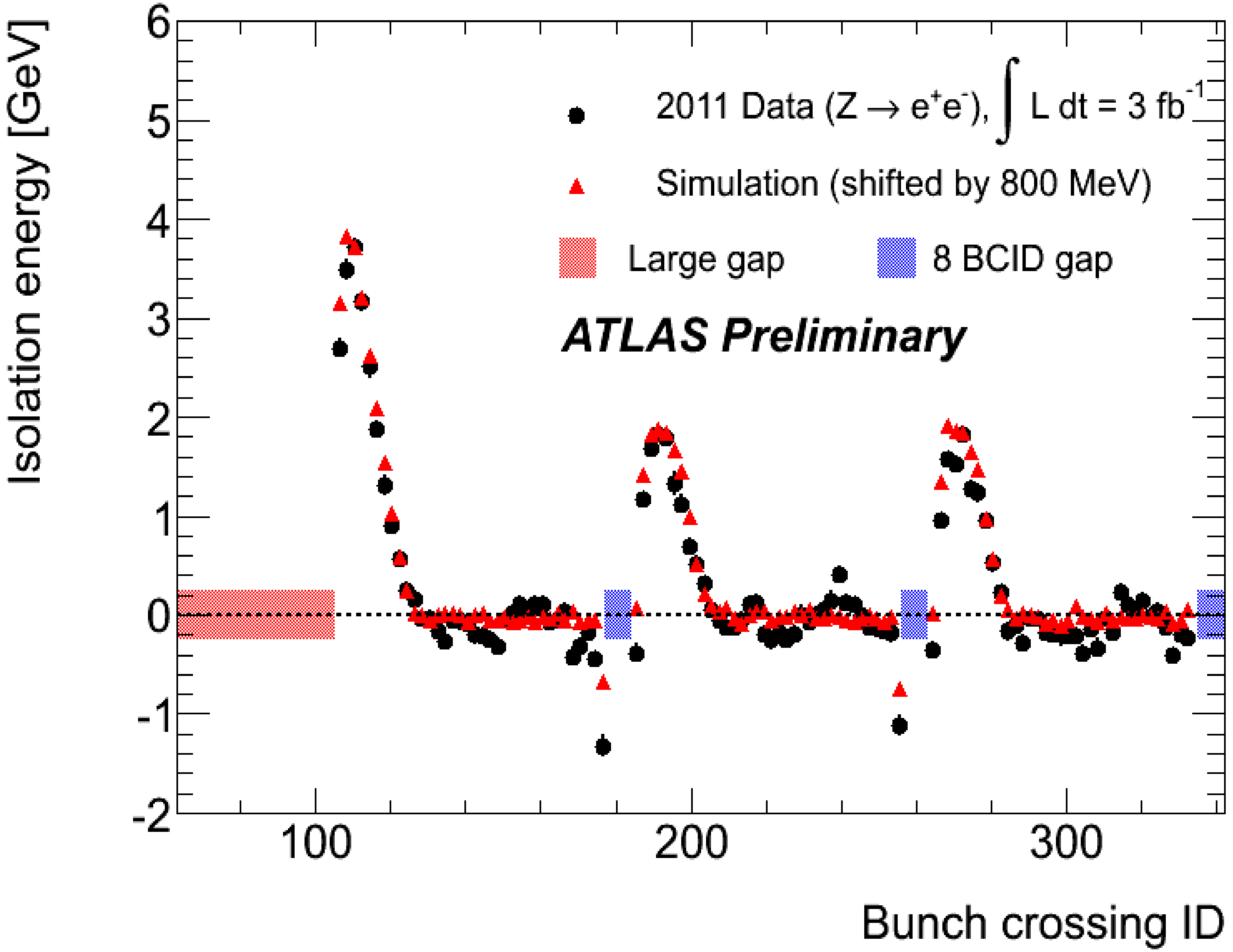
Seed cell: $|E_{cell}| > 4\sigma$ noise
Neighboring cells: $|E_{cell}| > 2\sigma$ noise

Add All cells surrounding the cluster

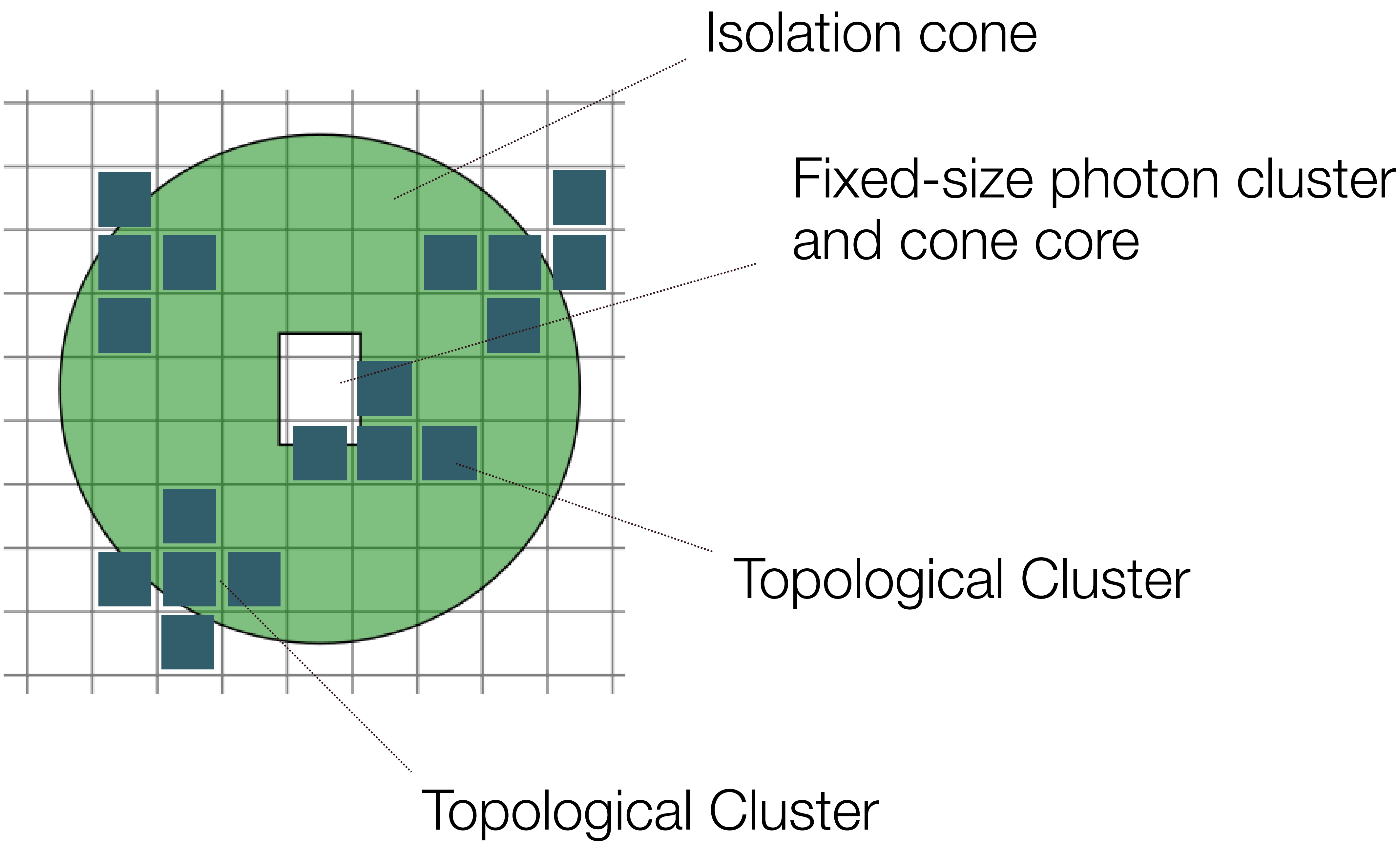


Algorithm tries to match the shape of an EM shower …

Out-of-Time Pile-up

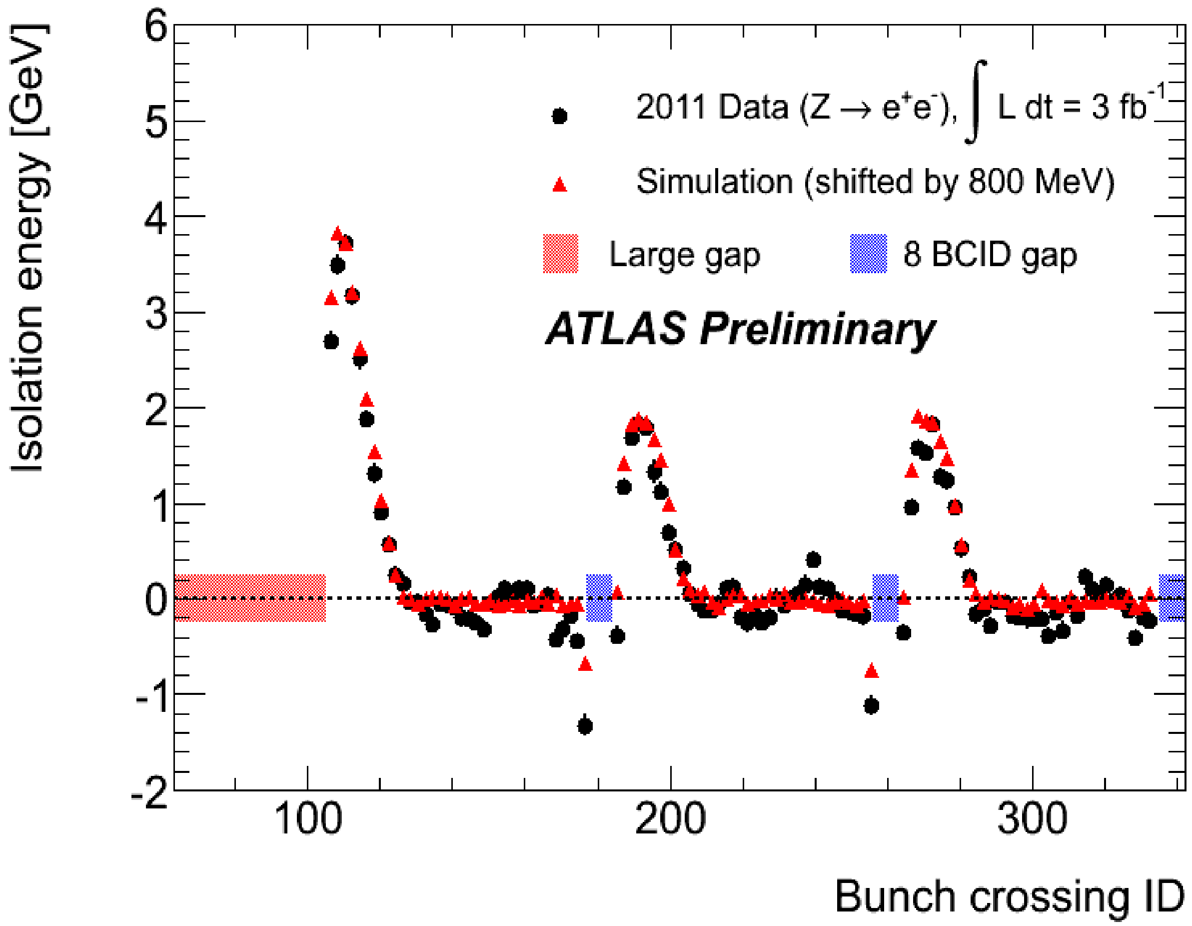


Isolation Based on Topological Clusters



Consistent approach …

Cell Based Calorimeter Isolation Dependence on Pileup



Topo-Cluster Based Calorimeter Isolation Dependence on Pileup