Search for a low mass ($m_{\gamma\gamma}$<110 GeV) Higgs boson in the di-photon decay channel at $\sqrt{s}$ = 13 TeV in pp collisions at CMS

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IPNL

Journées de Rencontre des Jeunes Chercheurs

October 2018

Outline

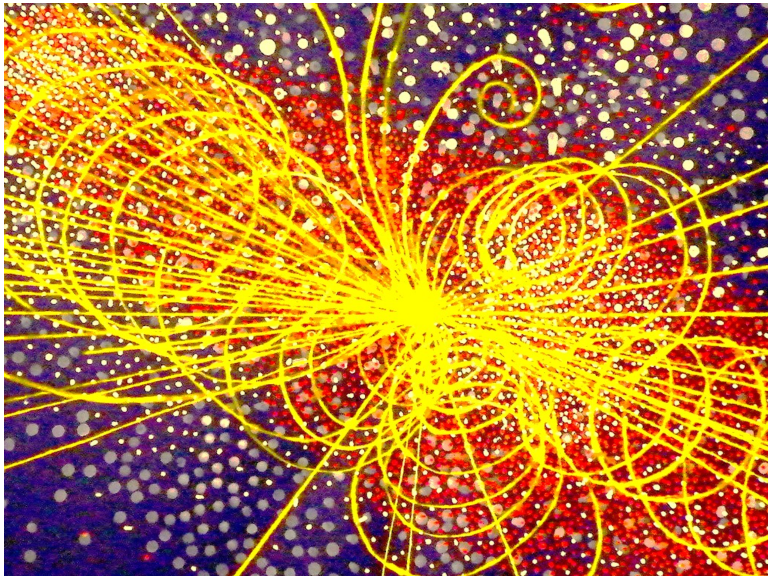
Theoretical context
- The Higgs boson in the standard model (SM)
- Why Higgs bosons beyond the SM
- Two Higgs doublet models (2HDM)

Search for a light Higgs boson in the diphoton channel : motivations

The CMS (Compact Muon Solenoid) detector

Analysis Strategy
- Background
- Boosted Decision Trees (BDT)
- Analysis Steps and results

Conclusion

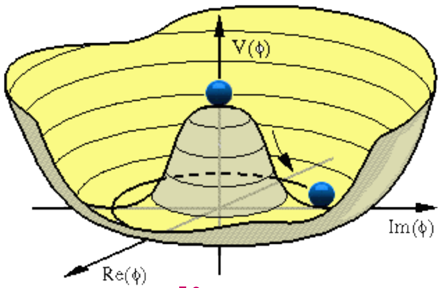


The Higgs boson in the standard model (SM)

Problem: How to give a mass to the Z and W boson without breaking the SM gauge invariance ?

1964 : Higgs, **Englert** & **Brout**, **Hagen Guralnik** and **Kibble** imagine a new solution :

→ Introducing a new **complex scalar field** in the SM in a **« mexican hat »** shaped **potential**



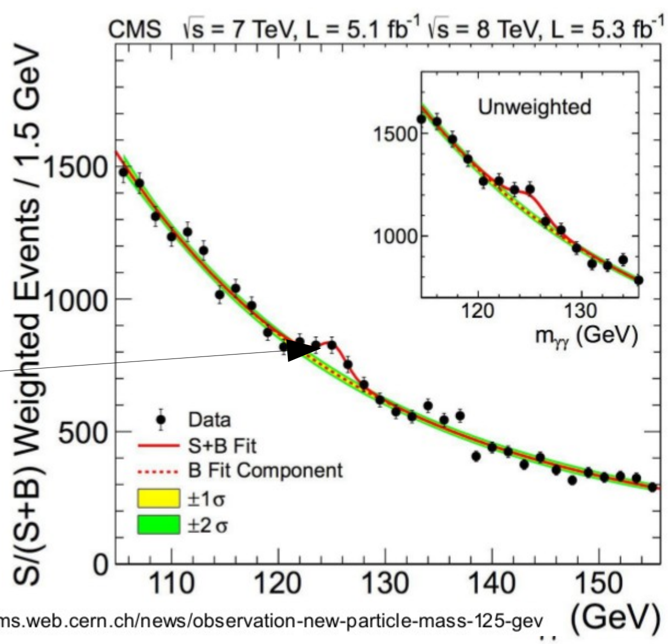
→ **Infinite** number of **minima** => **spontaneous symmetry breaking**

→ Generating **mass** term for Z and W **bosons,** for **fermions** via **Yukawa couplings**

→ Prediction of a new particle **:** The **Higgs Boson**

2012: discovery of a new boson at 125 GeV

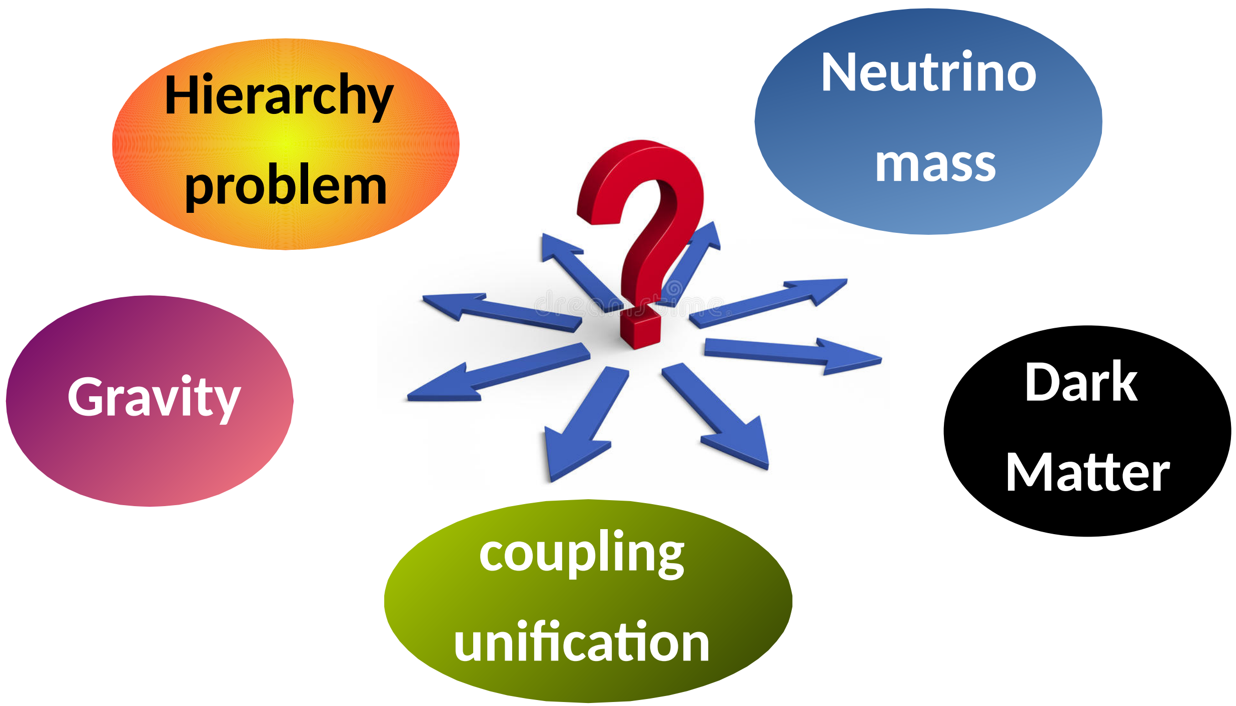
consistent with the SM Higgs boson in **H→γγ,** **H→ZZ, H→WW** decay channels at **8 TeV** at **LHC.**



http://cms.web.cern.ch/news/observation-new-particle-mass-125-gev

Why Higgs bosons beyond the SM

PROBLEM: THE SM IS NEVERTHELESS INCOMPLETE AND CANNOT ADRESS SEVERAL ISSUES !



Many indications that the SM is only a **low-energy approximation** of a more global theory => **Beyond SM** theories

Additional higgs bosons…

Two Higgs-doublet models (2HDM)

Two Higgs-doublet models are simple extension of the SM with an enriched **scalar sector**

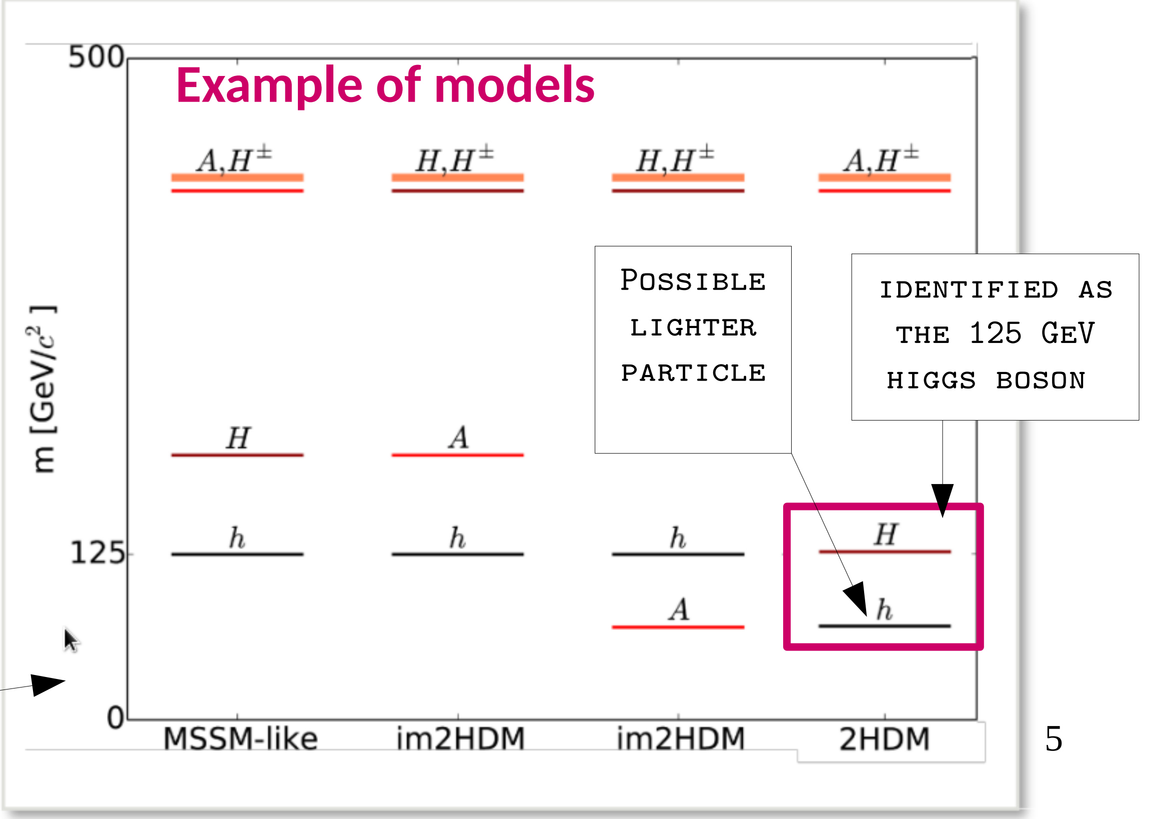
→ Introduction of an **additional scalar field** => 2 doublet scalar fields Φ_1 **and** Φ_2 in the SM lagrangian (8 degrees of freedom).

→ After symmetry breaking => Prediction of physical 5 states/**Higgs Boson :**

- Two CP-even bosons **h** and **H**
- One CP-odd boson **A**
- Two **charged** bosons H^+ and H^-

→ **4 ways of couplings** to quark and leptons => 4 **types of models**

→ Different **mass hierarchy**



Search for a light Higgs boson in the diphoton channel

LEP 2003: historical motivation

→ **LEP combined** results

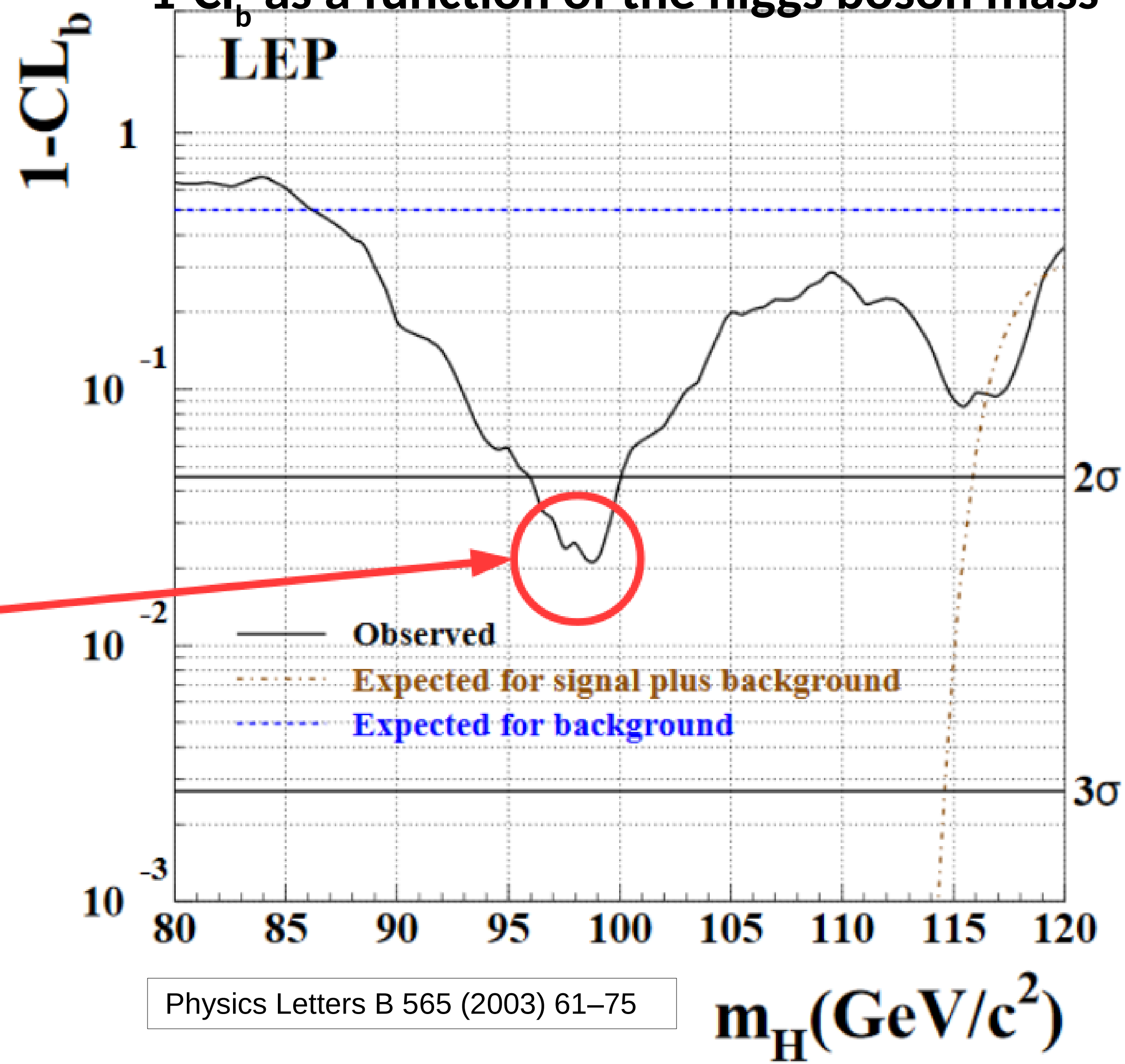
(ALEPH DELPHI L3 OPAL)

Decay channel

- H→ bb
- H→ ττ

Excess of events above 2 σ at ~ 98 GeV

1-Cl$_b$ as a function of the higgs boson mass

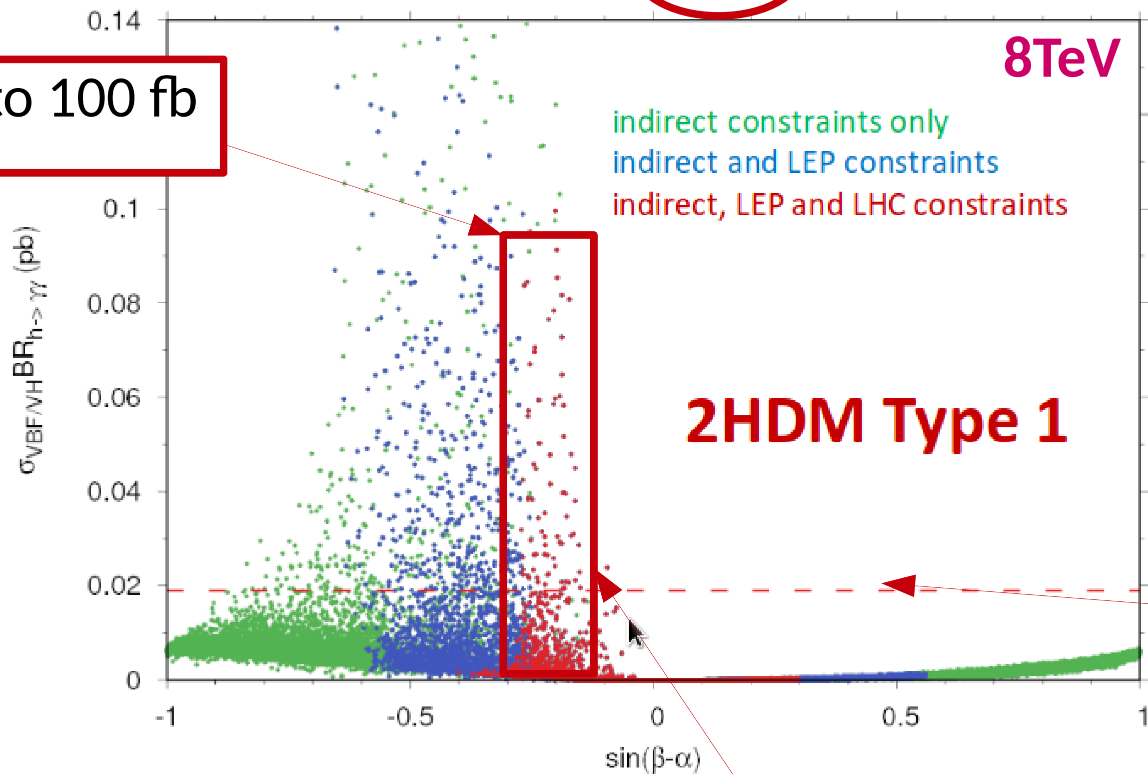


Physics Letters B 565 (2003) 61–75

Search for a light Higgs boson in the diphoton channel

Signal strength

Cross section x branching ratio h→γγ vs sin(β-α) for type I model



G. Cacciapagia et al., JHEP 1612 (2016) 068

Up to 100 fb

One of the 8 2HDM parameters
β rotates doublets in a basis where only one of them acquires a vacuum expectation value, α mixes CP-even scalar states to give mass-eigenstates.

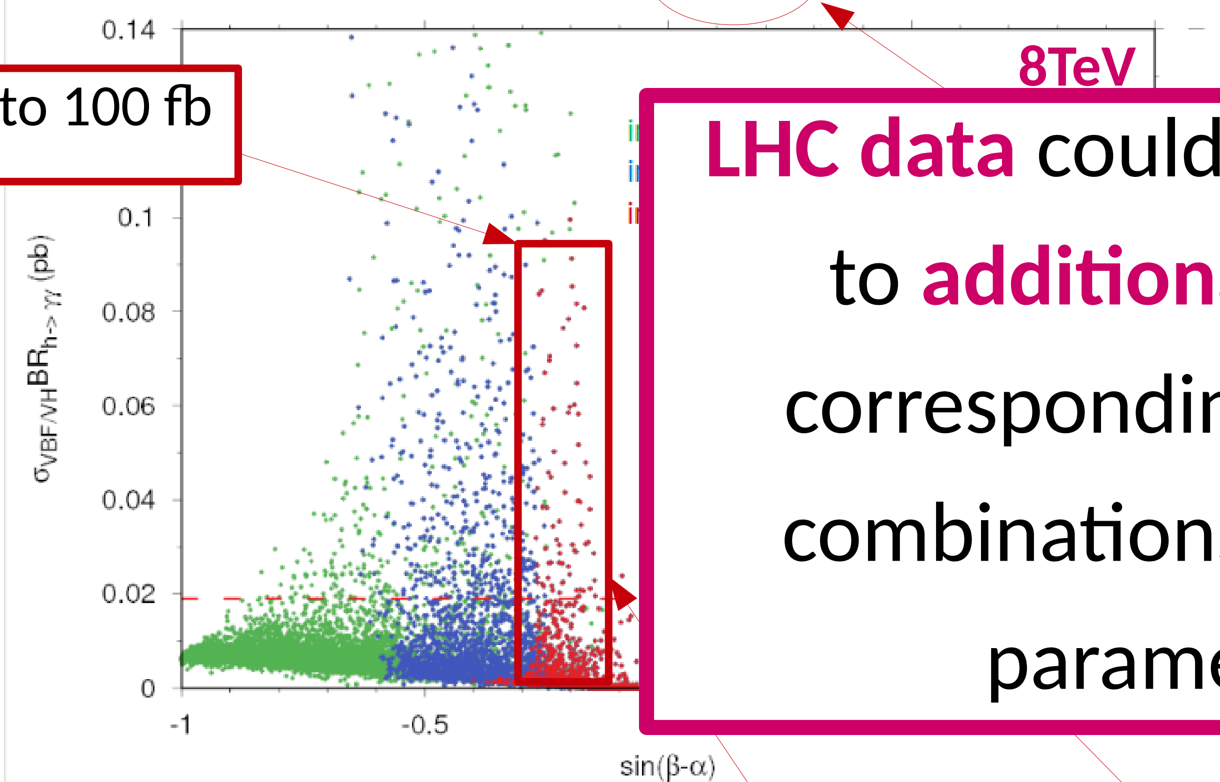
Typical LHC sensitivity

Model predictions surviving all the theoretical and experimental constrains

Search for a light Higgs boson in the diphoton channel

Signal strength

Cross section x branching ratio $h \to \gamma\gamma$ vs $\sin(\beta-\alpha)$ for type I model



G. Cacciapagia et al., JHEP 1612 (2016) 068

Up to 100 fb

LHC data could be **sensitive** to **additional scalars** corresponding to some combinations of **2HDM** parameters

Model predictions surviving all the theoretical and experimental constrains

Typical LHC sensitivity

Search for a light Higgs boson in the diphoton channel

LHC Run 1 (8 TeV)

→ **IPNL** responsible for the **low mass** (m<110 GeV) search in the **diphoton** channel

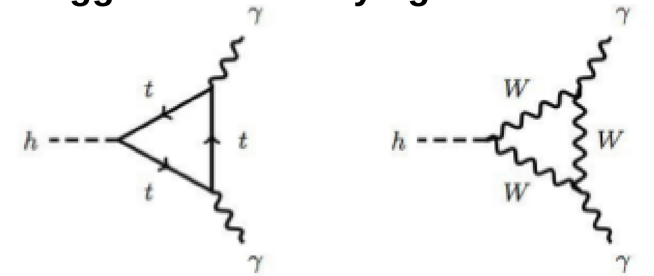
In **CMS**

Why the diphoton channel ?

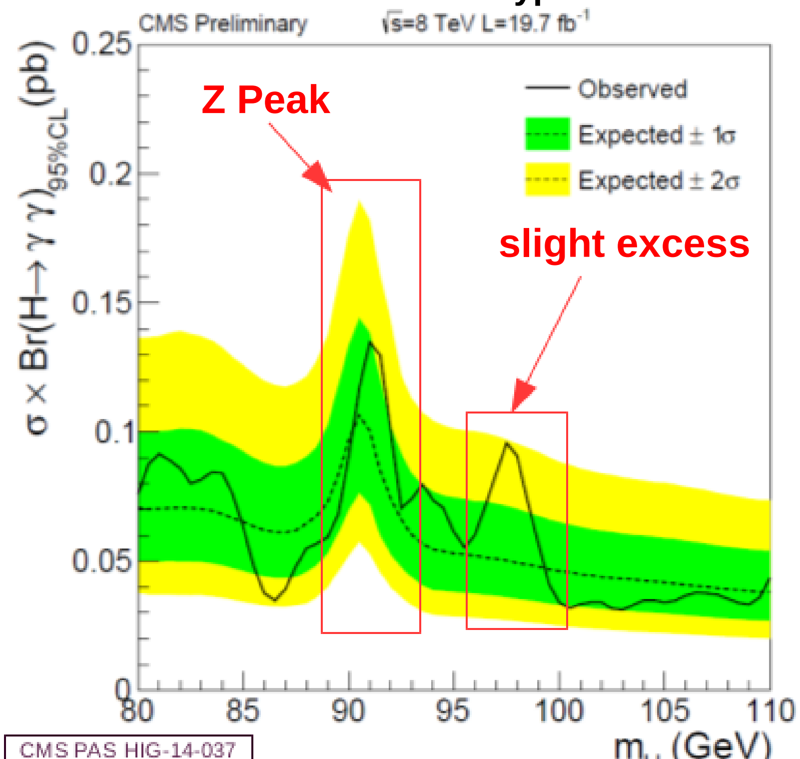
- Clear signature with two **isolated** and **highly energetic** photons
- Excellent invariant mass **resolution**

→ **2015 (8 TeV): 2σ** excess at **97.5 GeV** (γγ channel)

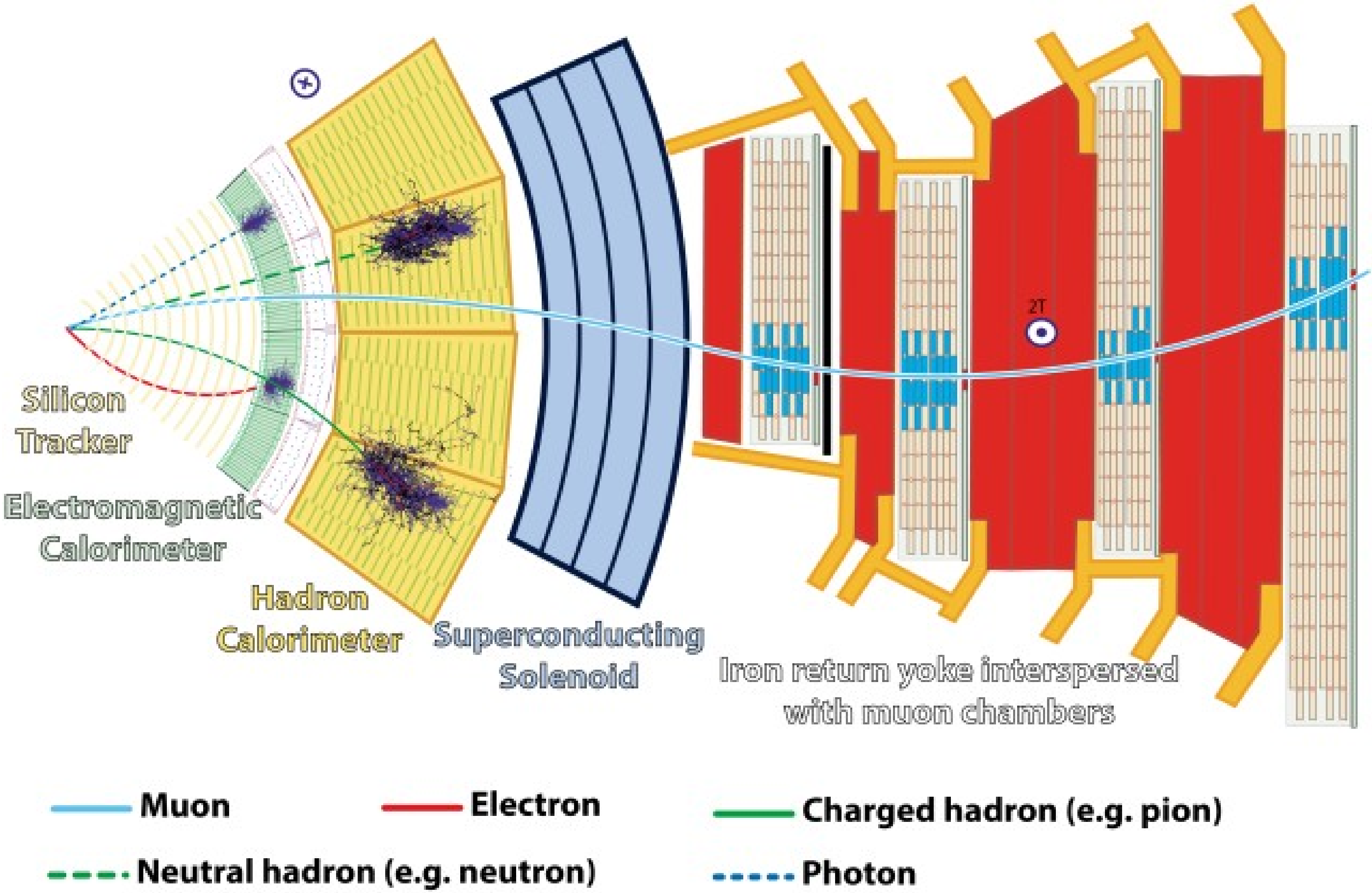
SM Higgs boson decaying into 2 Photons



Exclusion limit on higgs boson cross section for different mass hypothesis

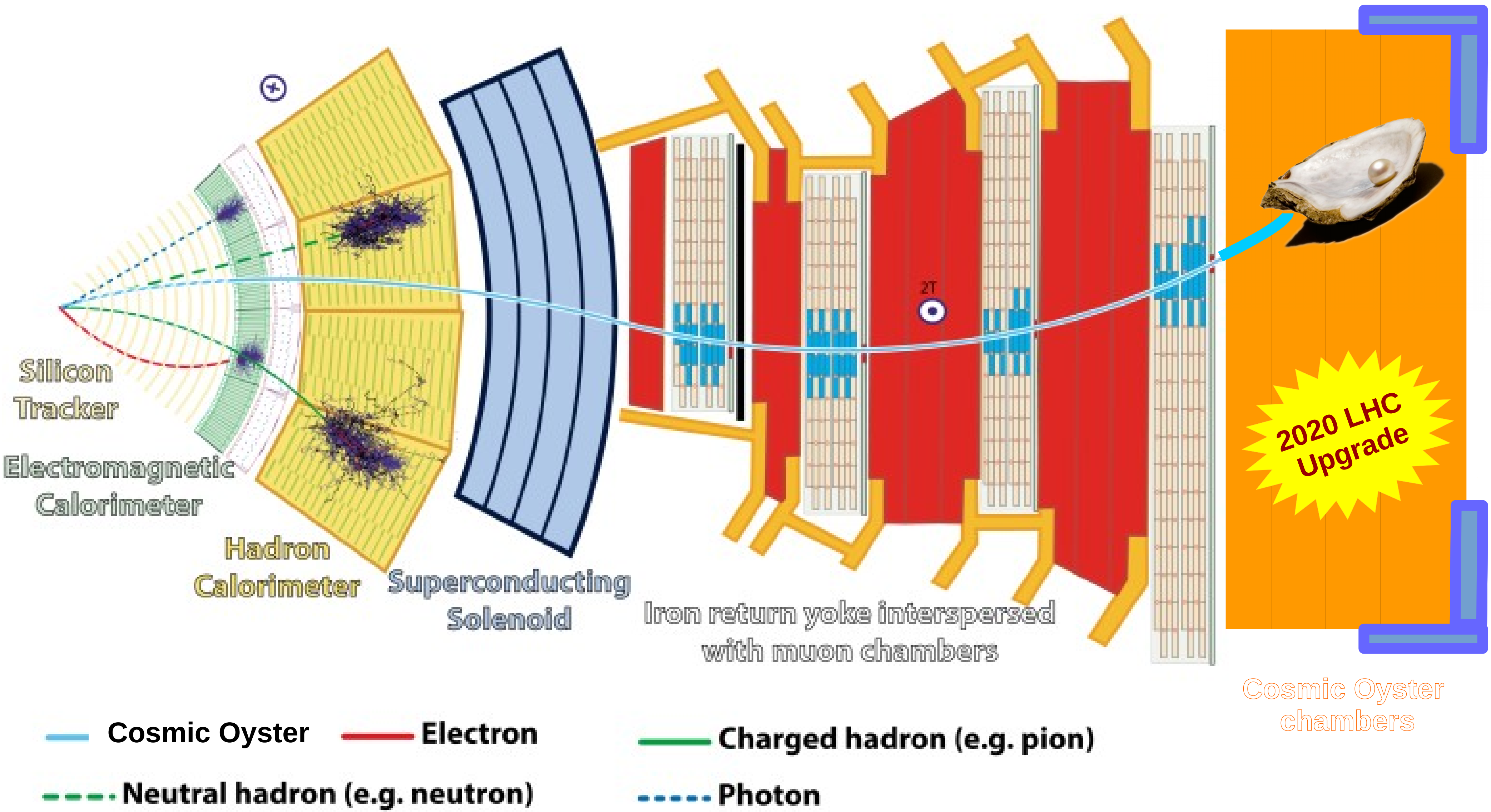


CMS experiment and particle reconstruction



http://www.particlecentral.com/images/cms_slice.jpg

CMS experiment and particle reconstruction

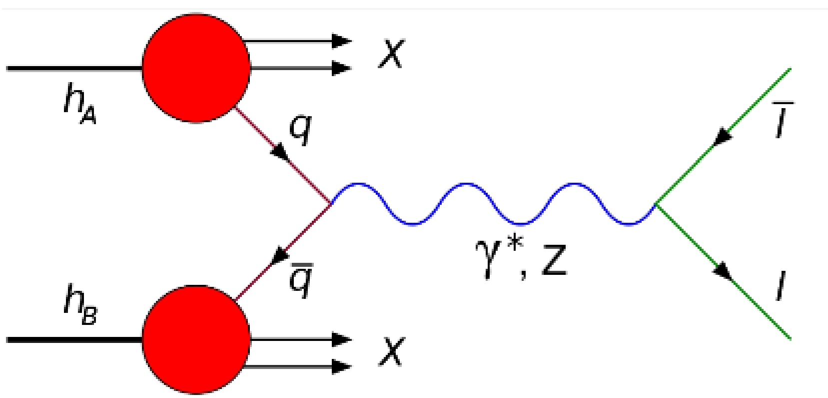


http://www.particlecentral.com/images/cms_slice.jpg

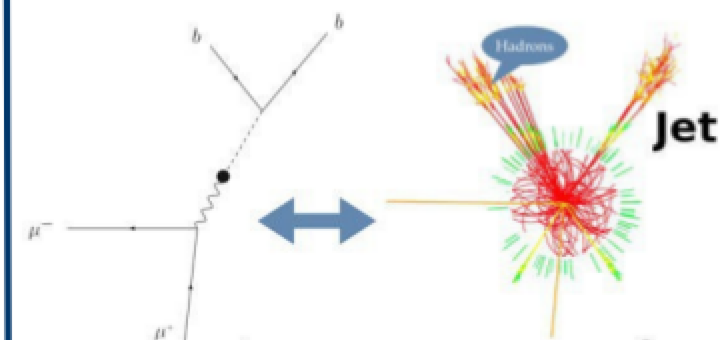
Analysis Strategy

Backgrounds

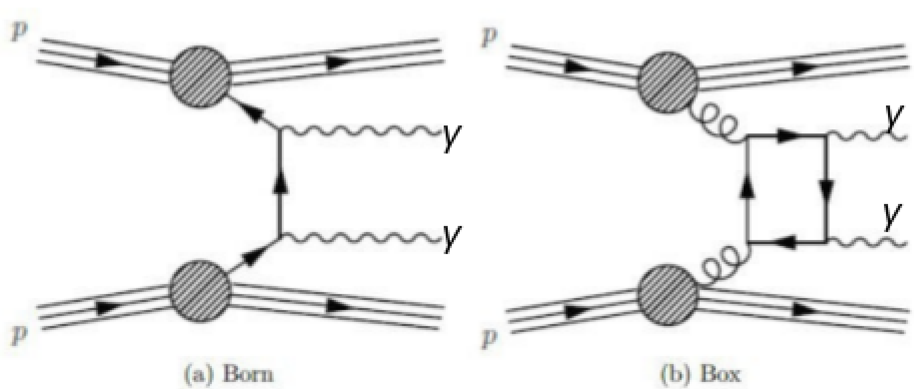
Composante Drell-Yan



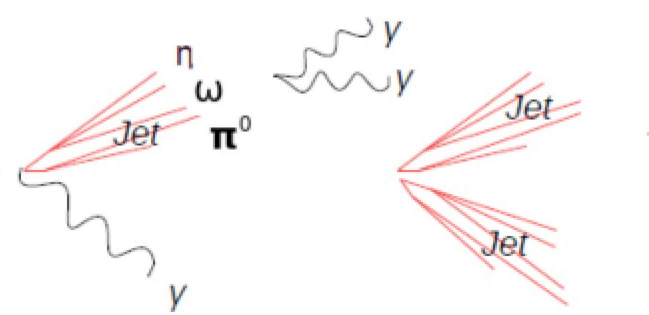
Quarks → hadronisation → Jet



Composante irréductible



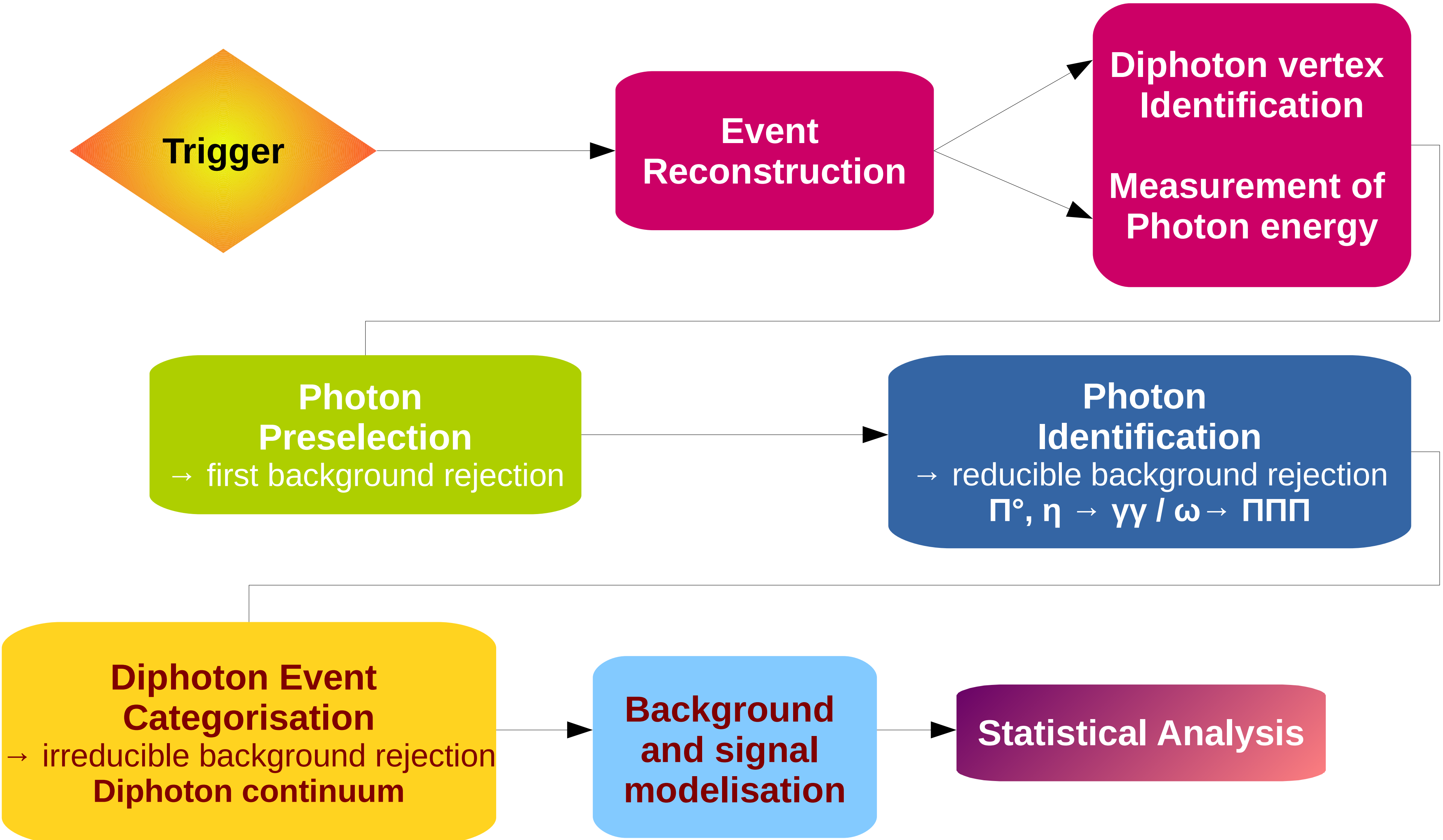
Composante réductible



Gamma-Jet *Di-Jet*

Analysis Strategy

Analysis Steps overview



Analysis Strategy

Boosted decison trees (BDT)

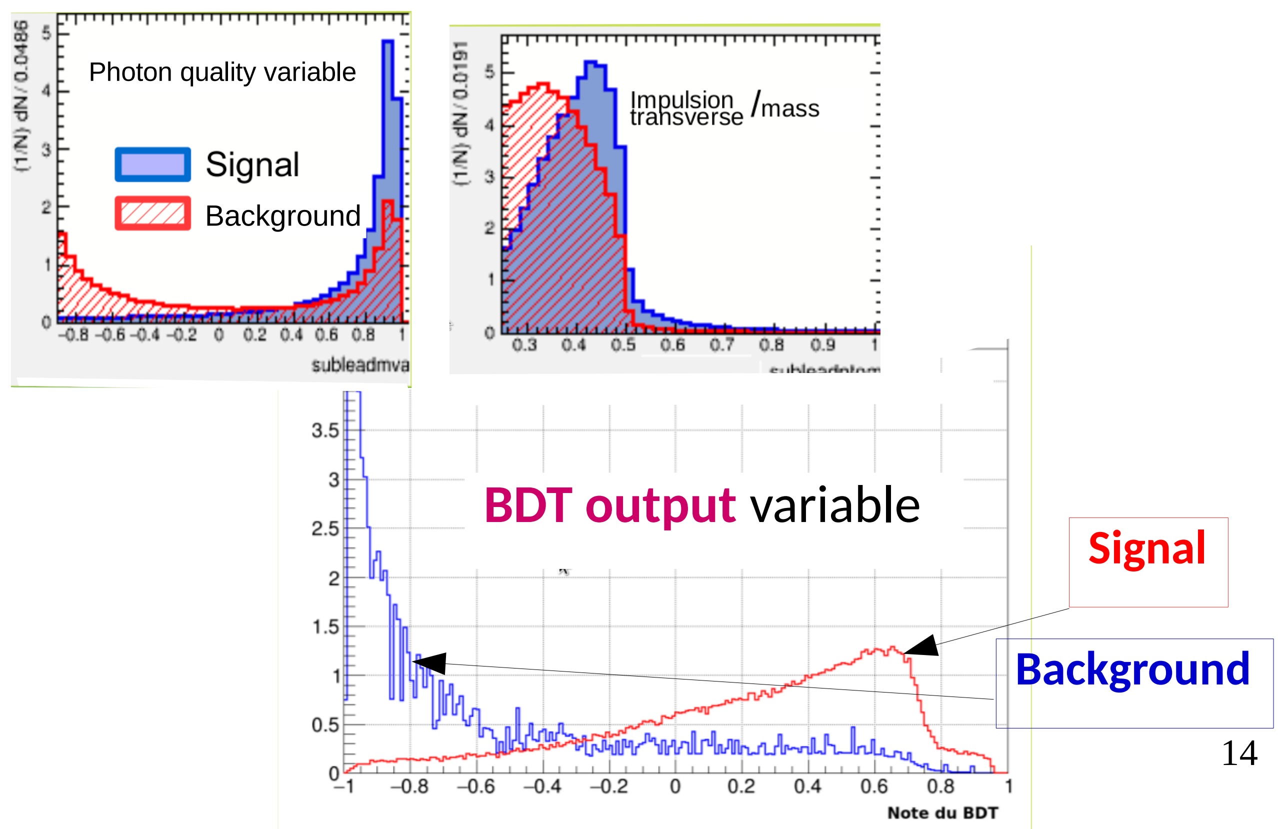
→ Analysis performed using many **BDT : tools** allowing to **ordinate** events in more or less **signal-like** categories.

How ?

Converting a bunch of **discriminating** variables into a **single** one

Example

discriminating variables



Analysis Strategy

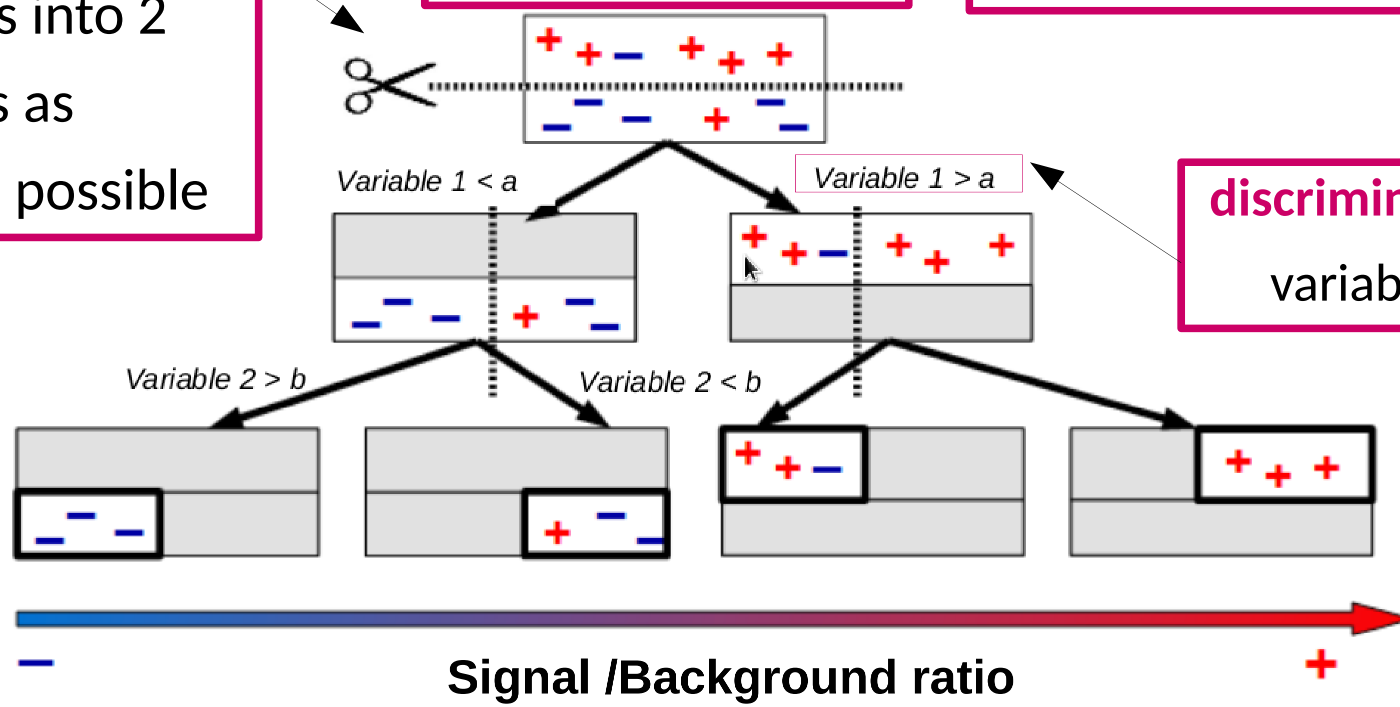
Boosted decison trees (BDT)

How does it work ?

Separate events into 2 subsamples as homogeneous as possible

Simulated Samples

Boosted = successive trainings of trees to improve the classification

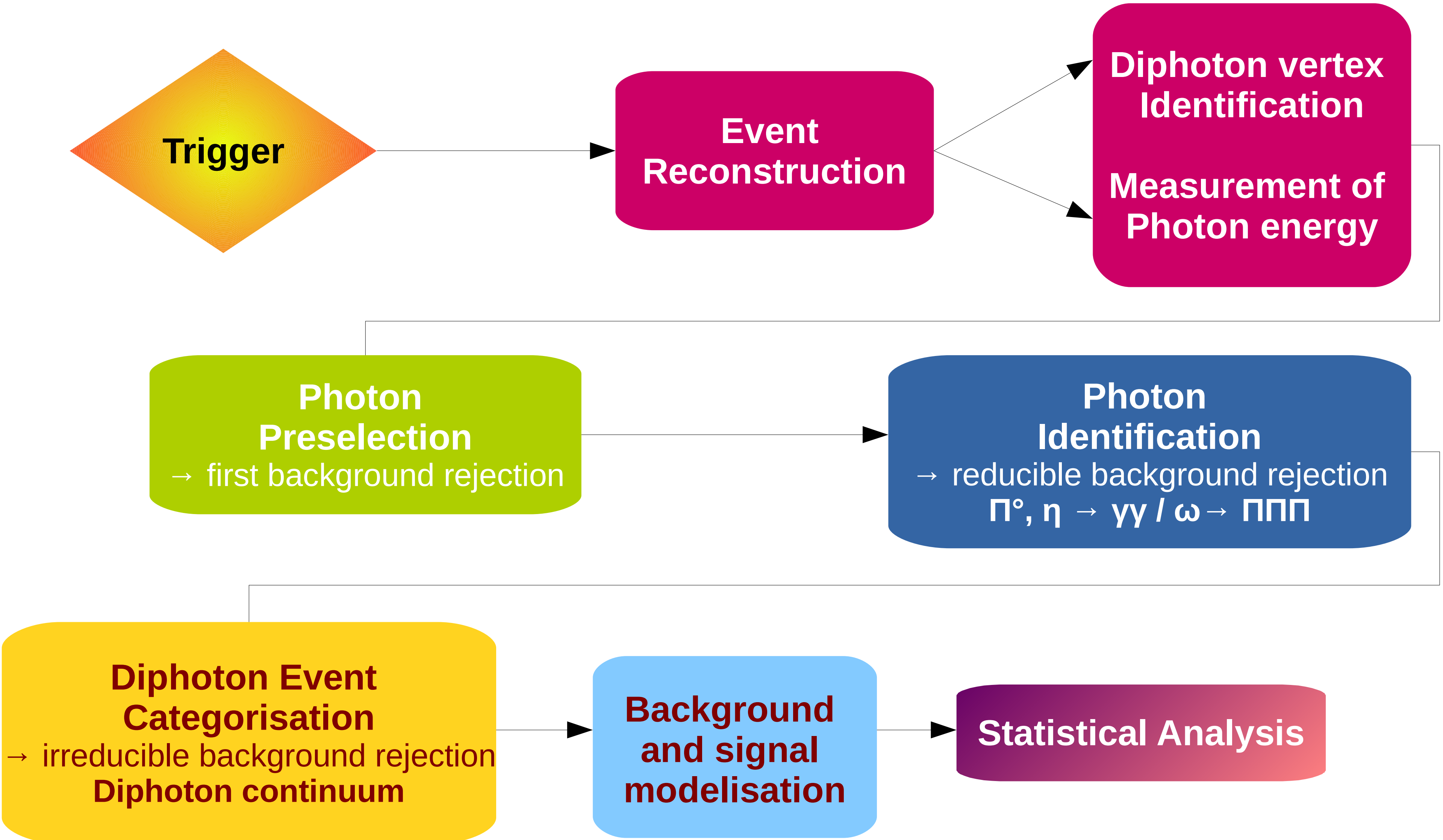


discriminating variables

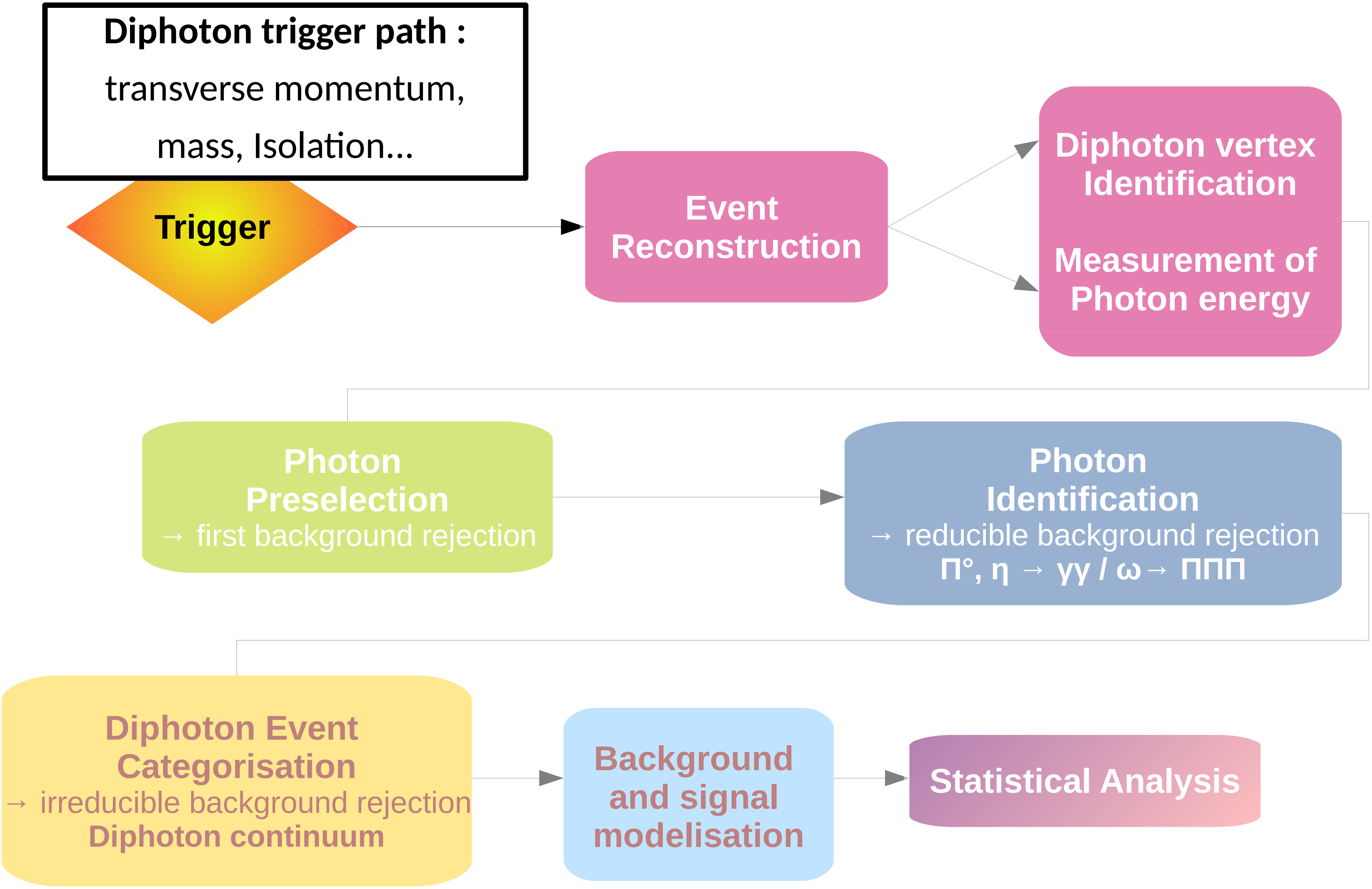
- BDT **trained** on **simulated** samples so it knows which event are **signal** or **background**
- Then applied to **real data**

Analysis Strategy

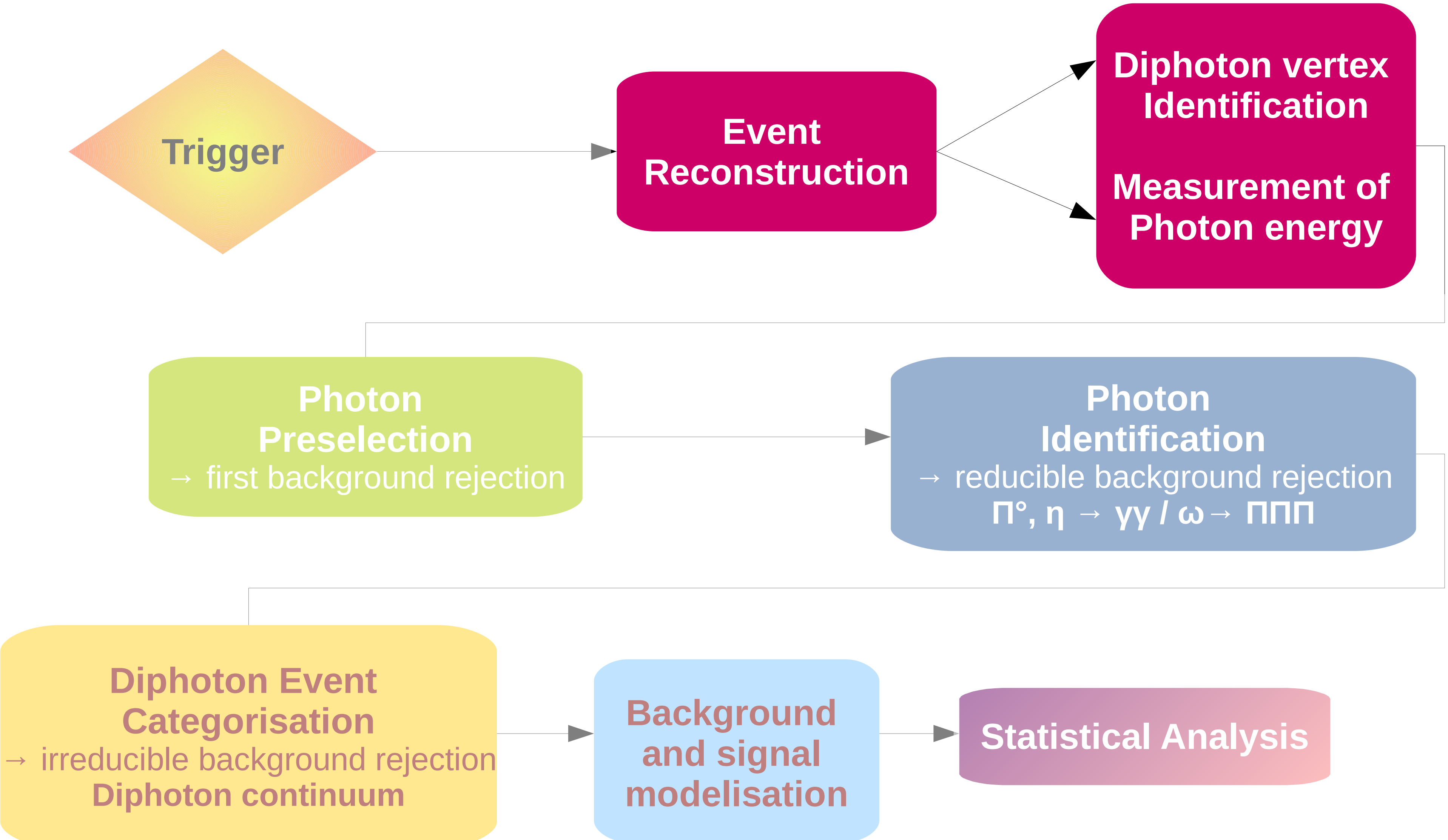
Analysis Steps overview



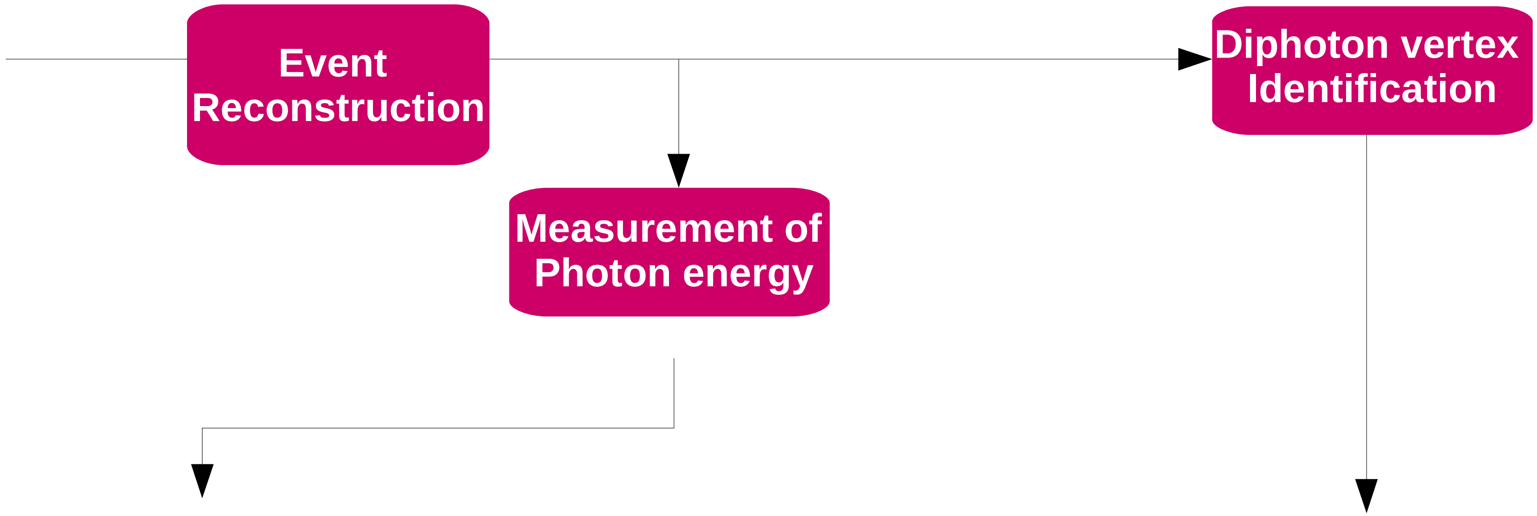
Analysis Strategy



Analysis Strategy



Analysis Strategy : event reconstruction



Photon energy

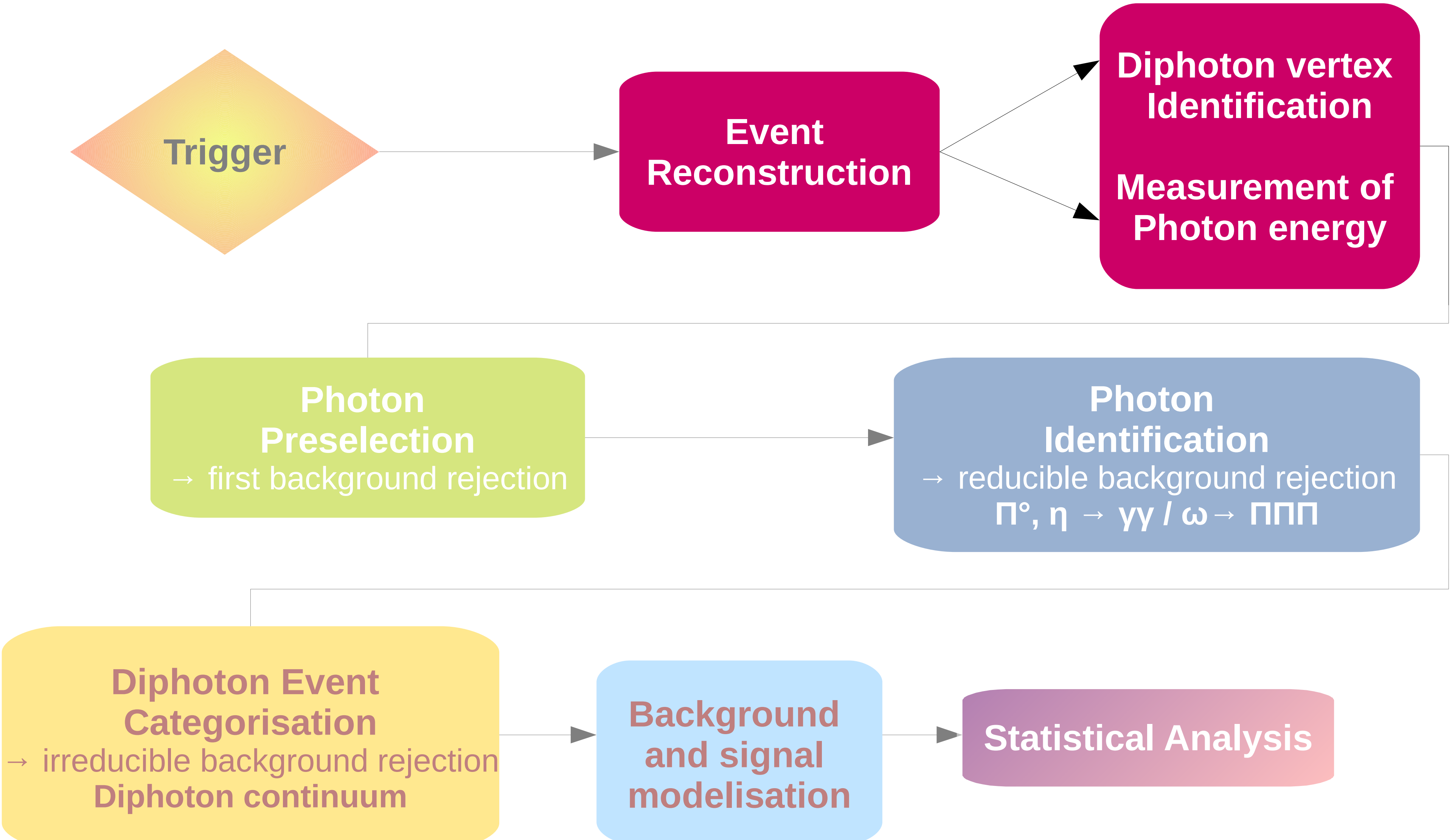
- **Clustering** the **energy hits** in the crystals of the **electromagnetic** calorimeter (ECAL)
- Energy corrected by **Boosted Regression Tree** *(same method as BDT but predicting the value of a variable instead of classifying events)*

Vertex ID

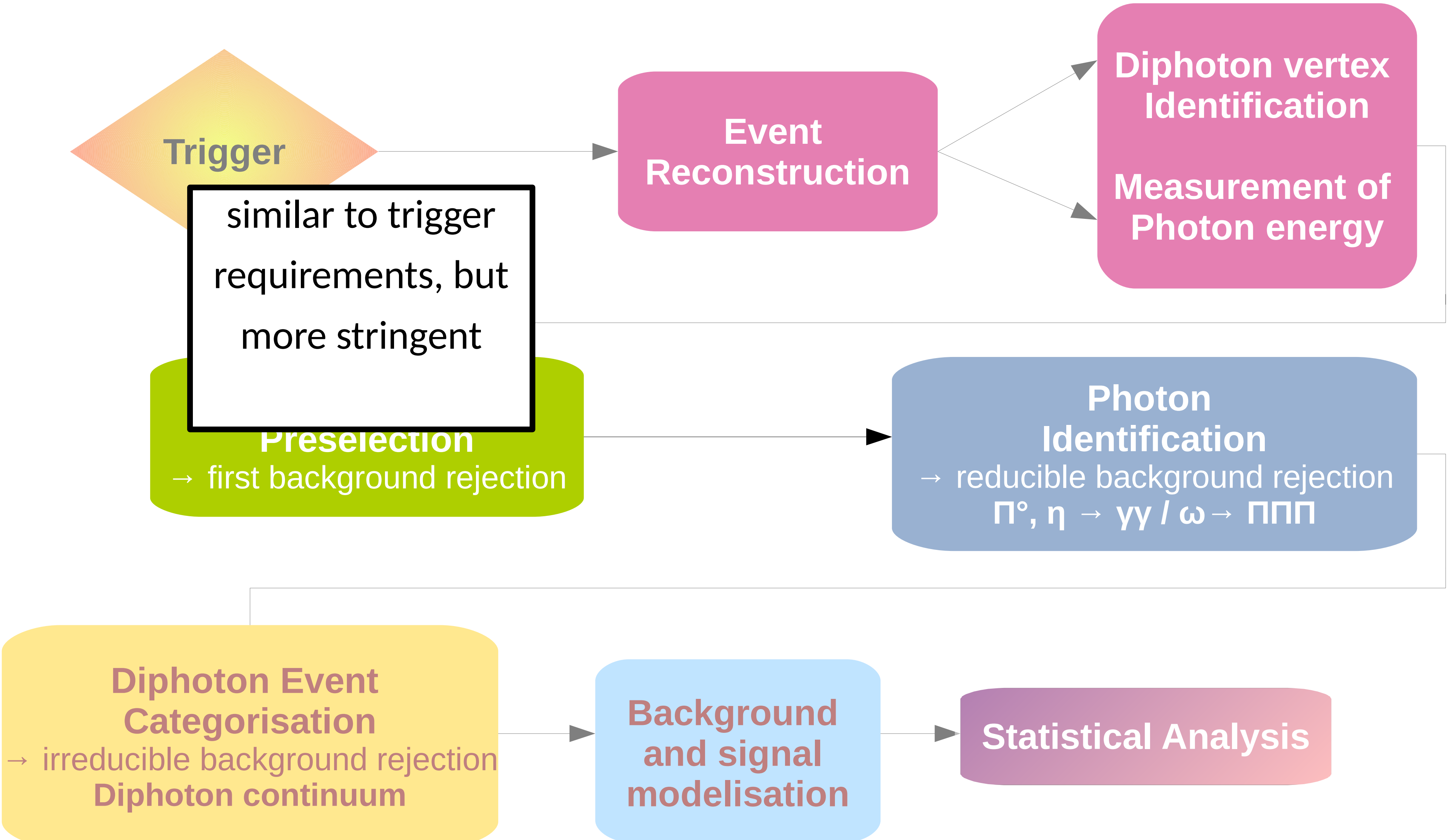
- if the vertex assigned to the event stands within 1cm to the real diphoton interaction point **= Correct vertex assignement**
- **Second BDT** to estimate the **probability** for the vertex assignment to be **correct** (within 1 cm)

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$$

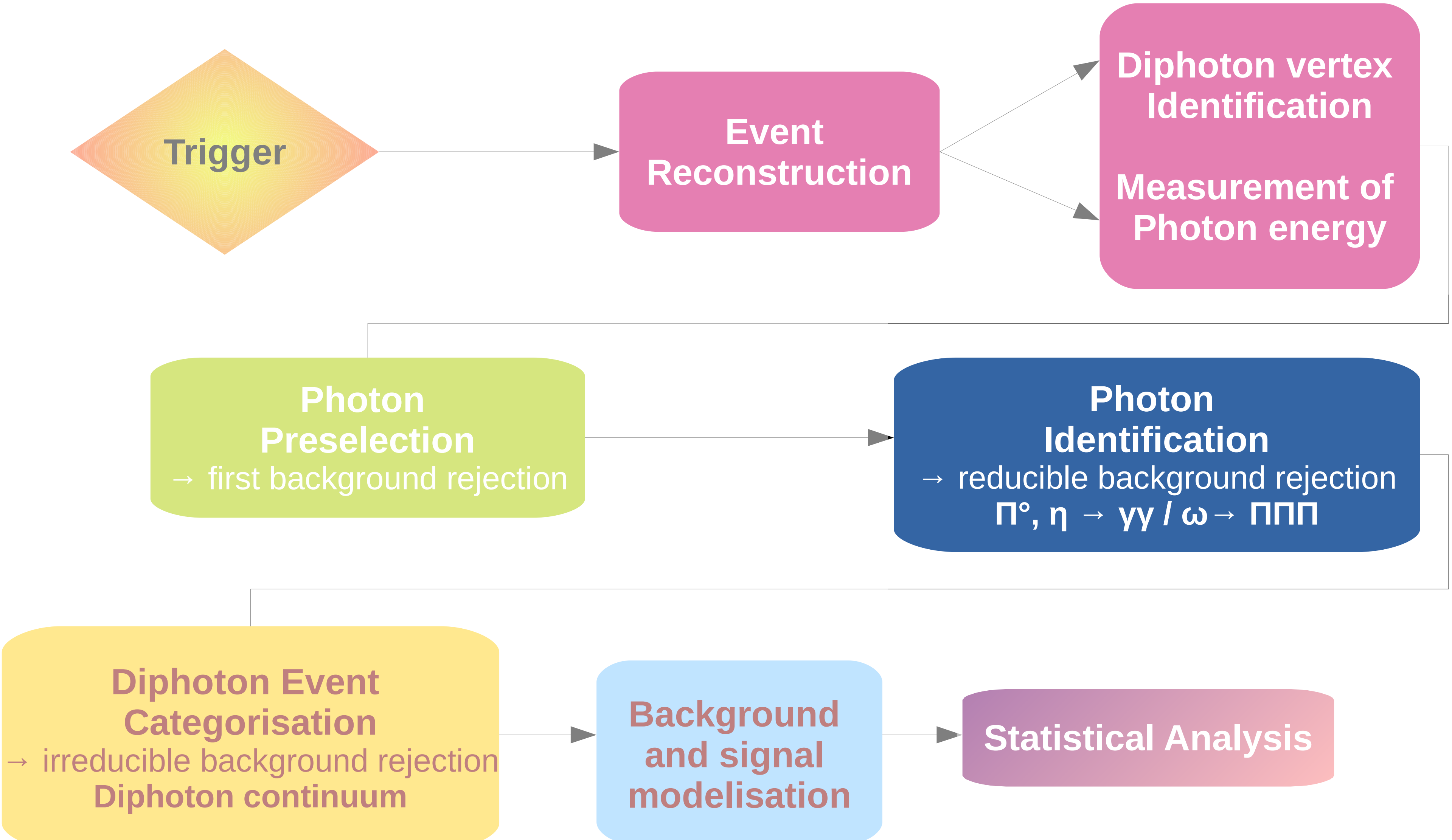
Analysis Strategy



Analysis Strategy



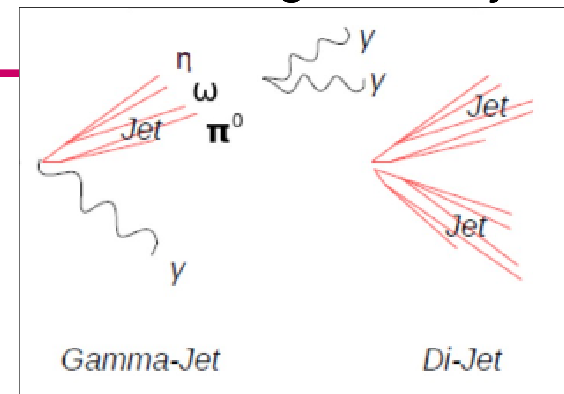
Analysis Strategy



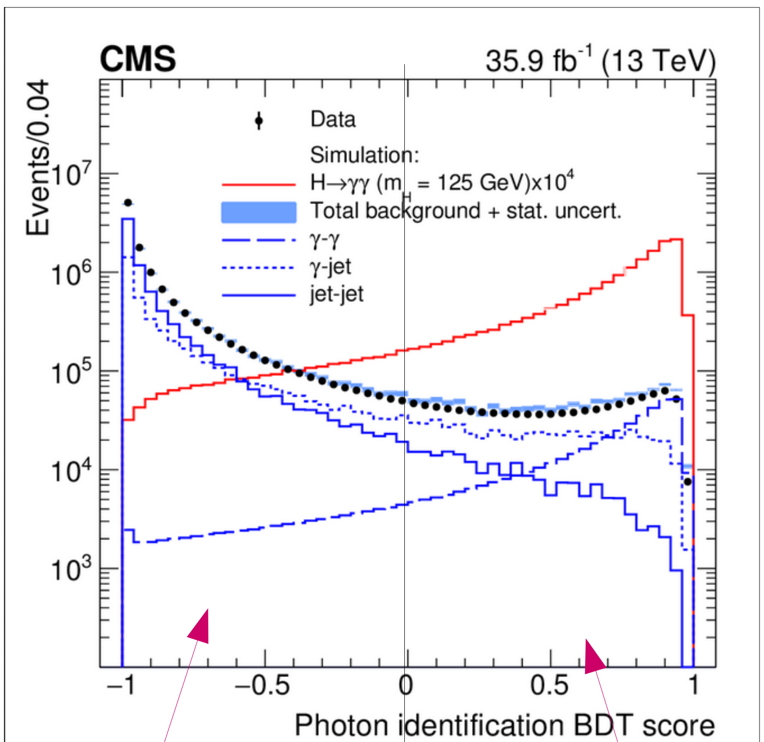
Analysis Strategy : Photon Identification

Photon Identification

reducible background rejection



Photon ID Output variable



HIG-16-040

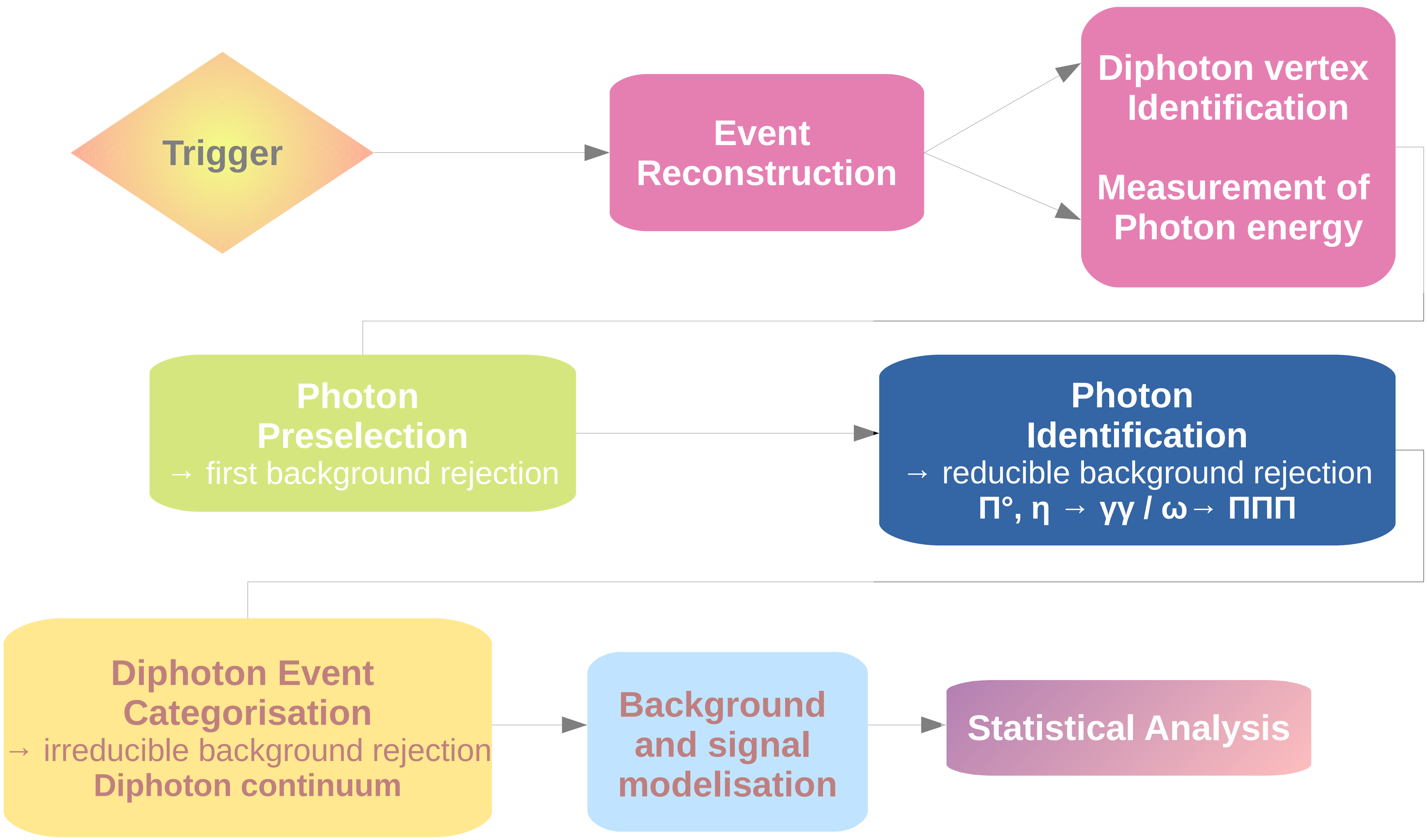
BACKGROUND-LIKE PHOTONS

SIGNAL-LIKE PHOTONS

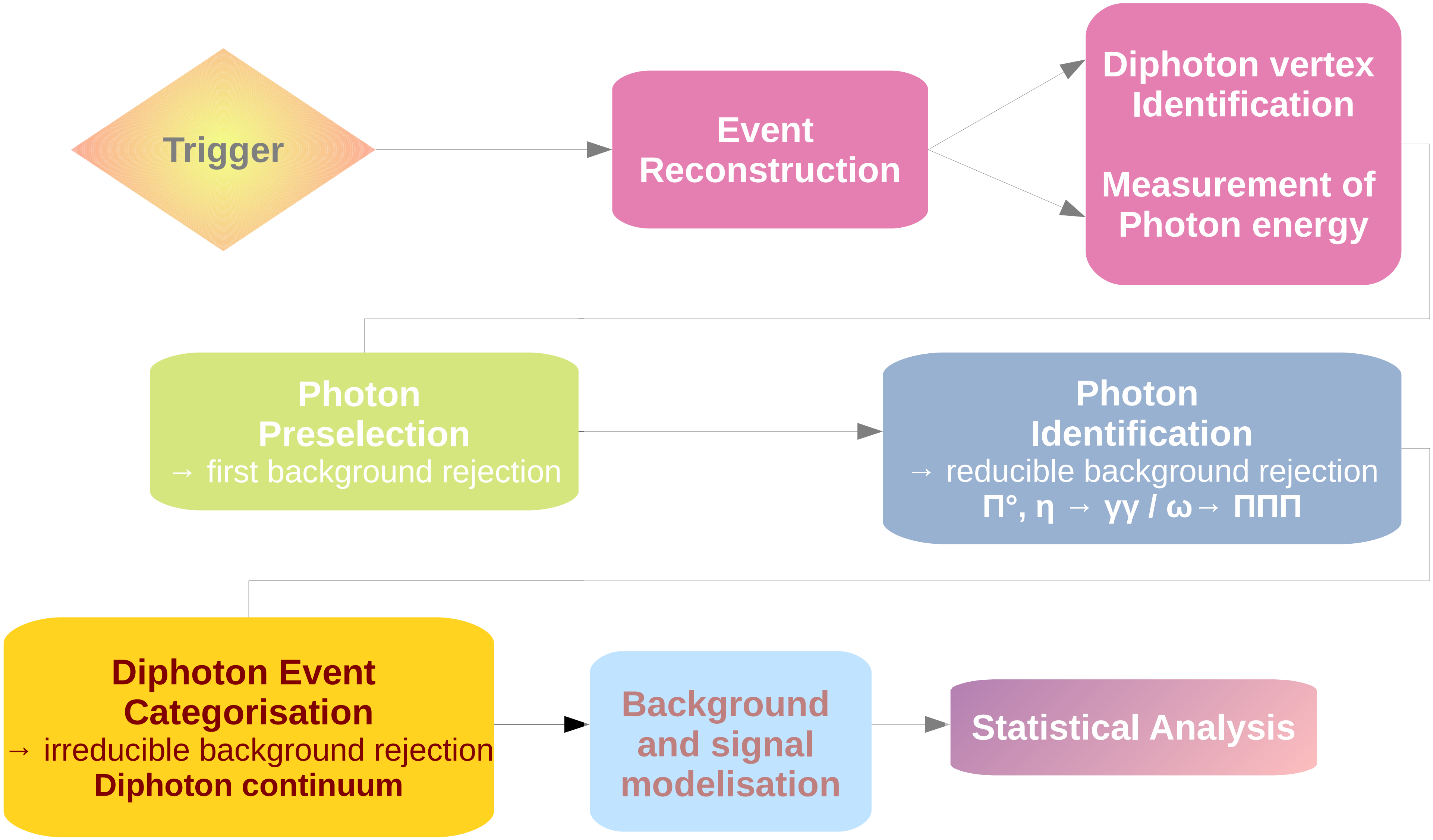
Photon ID

- Reject **fake photon candidates** coming from mesons produced in jets
- Discriminating variables **: isolation, shower shape, kinematics variables…**
- **BDT Output variable** = estimate the **photon « quality »**

Analysis Strategy



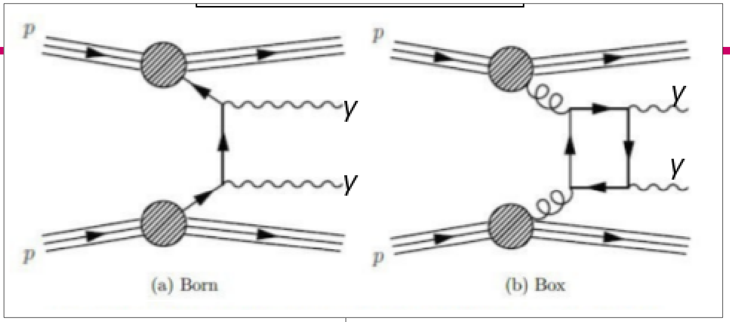
Analysis Strategy



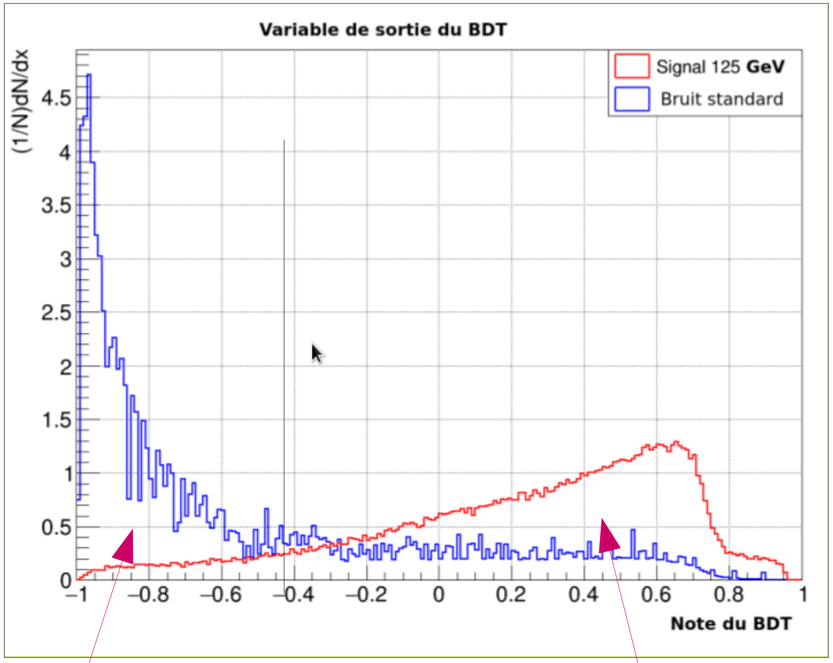
Analysis Strategy : Diphoton event Selection

Diphoton Event Selection

irreducible background rejection



Diphoton BDT Output variable



BACKGROUND-LIKE EVENTS

SIGNAL-LIKE EVENTS

Diphoton BDT

- Reject **diphoton candidates** from physical processes with 2 photons in the final state
- Discriminating variables **: PhotonID, invariant mass resolution, kinematic** variables
- **BDT Output variable** = estimate the **diphoton event « quality »**

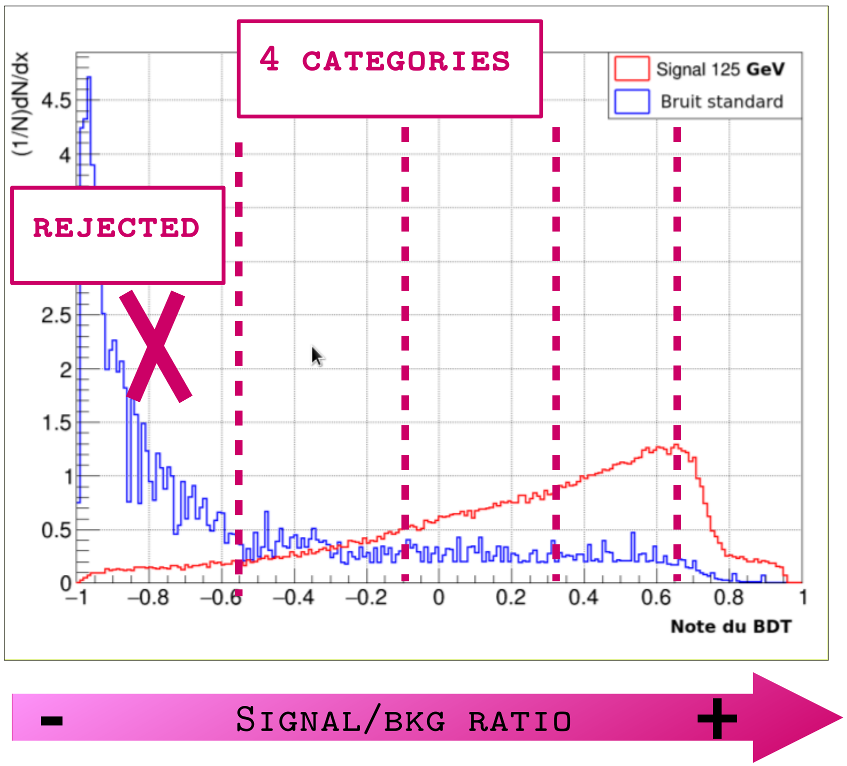
Analysis Strategy : Diphoton event categorisation

Diphoton Event Categorisation

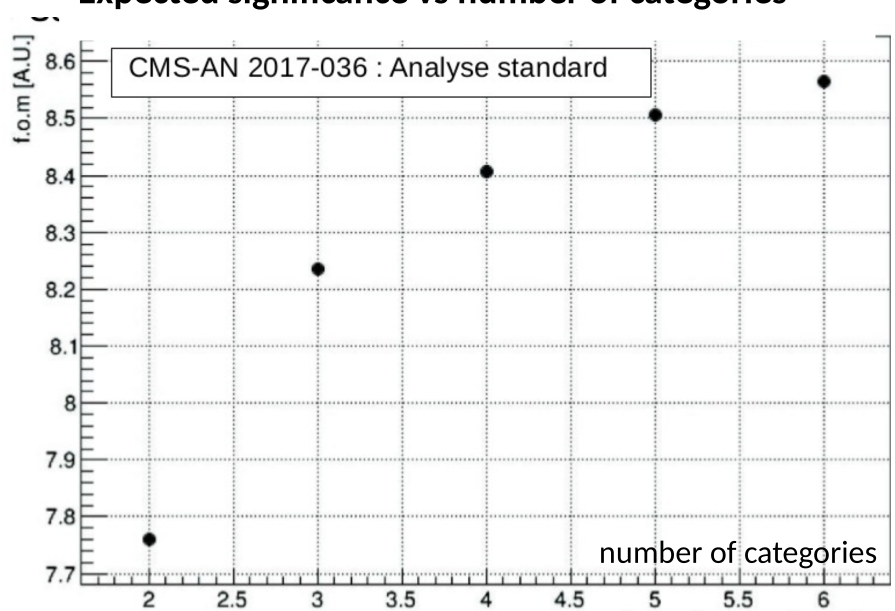
Optimize the significance

- Set **boundaries** on the output variable distribution to form **categories** with different **signal /background ratio**
- **number** of categories and boundarie optimized to **maximize** the **expected significance**

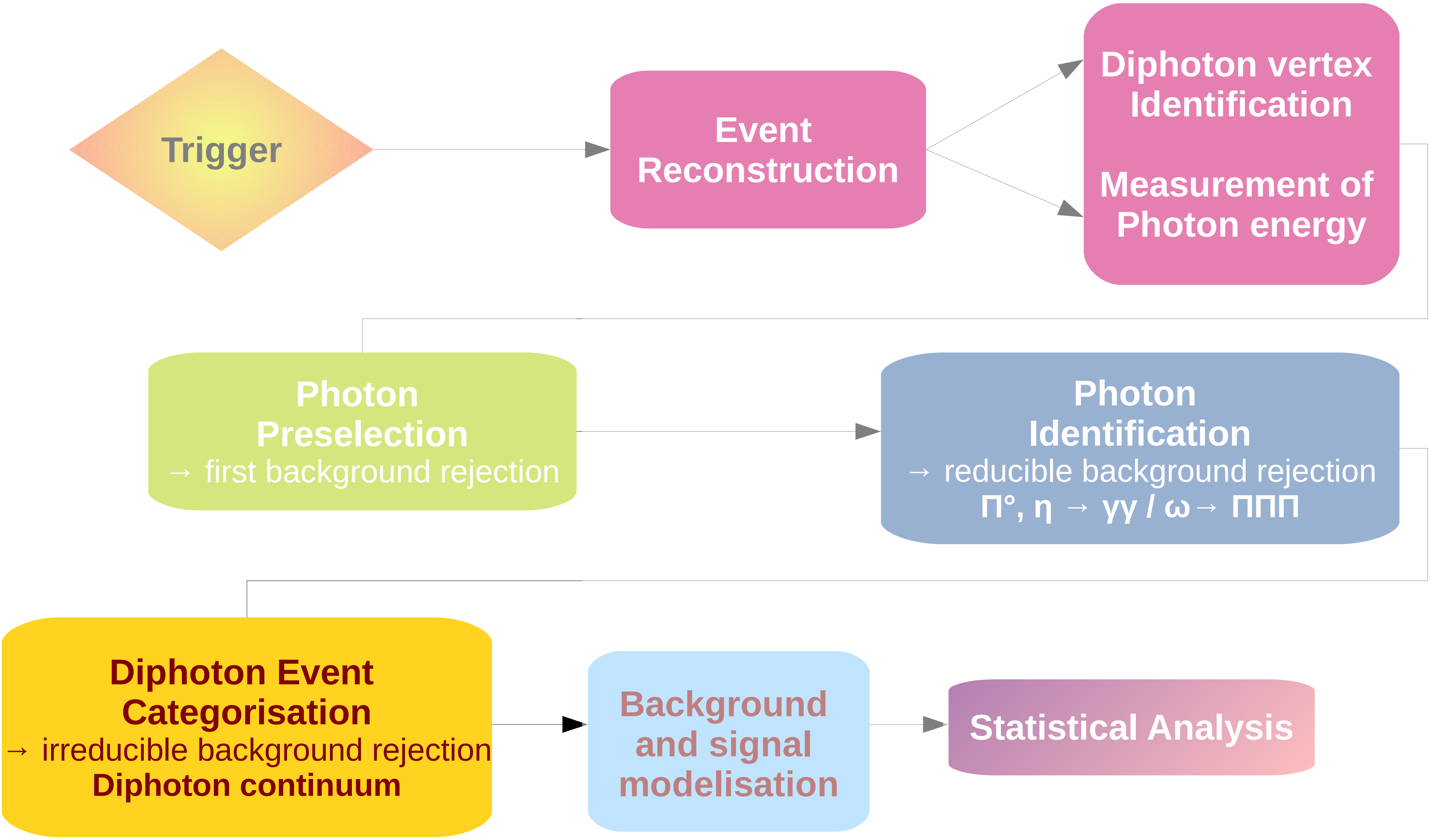
Diphoton BDT Output variable



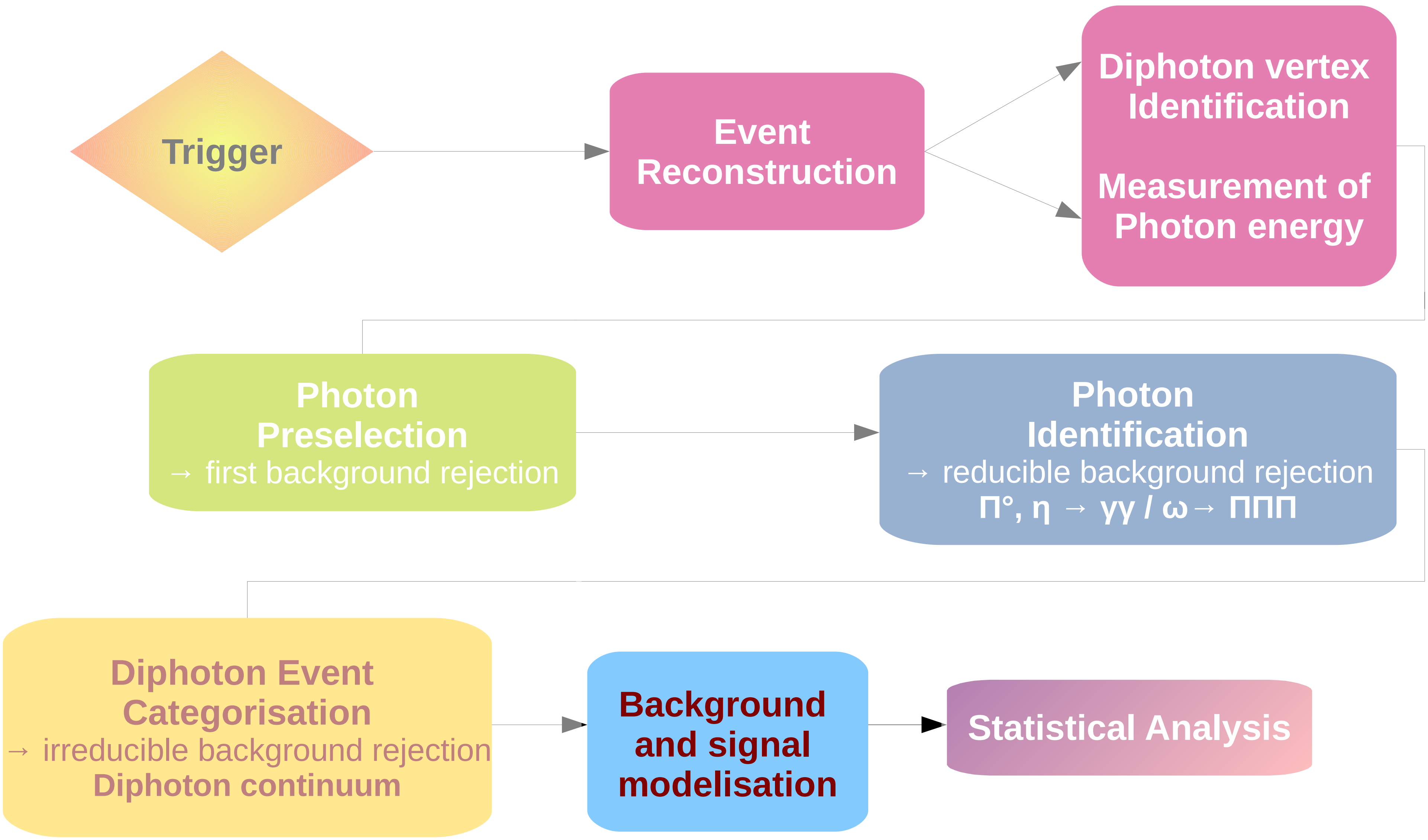
Expected significance vs number of categories



Analysis Strategy



Analysis Strategy

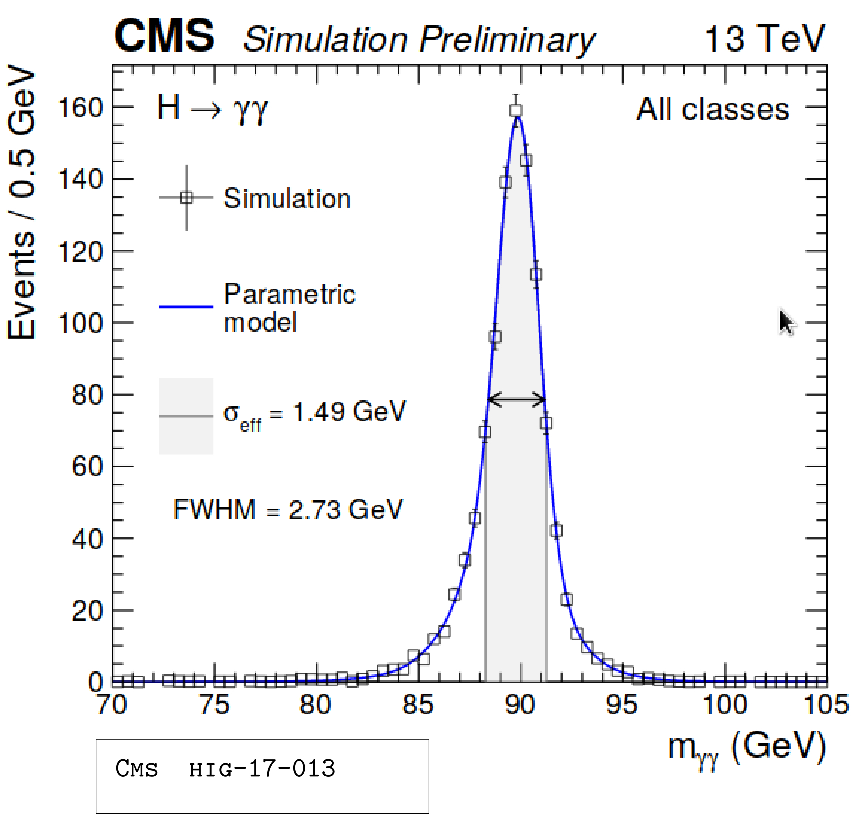


Analysis Strategy : background and signal modelisation

Background and signal modelisation

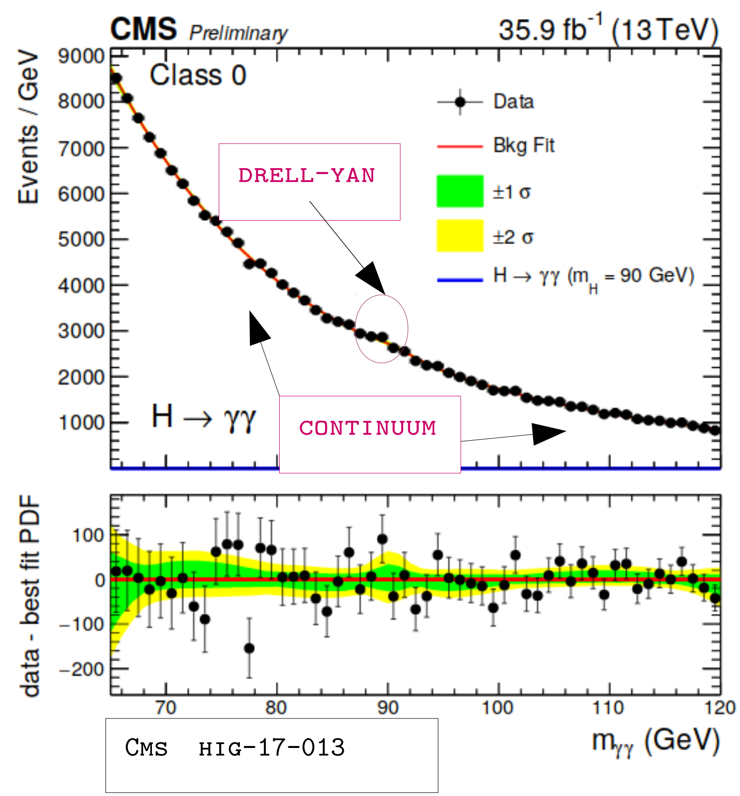
Signal

- Parametric model extracted from **simulation : H→ γγ standard** samples for different higgs masses.

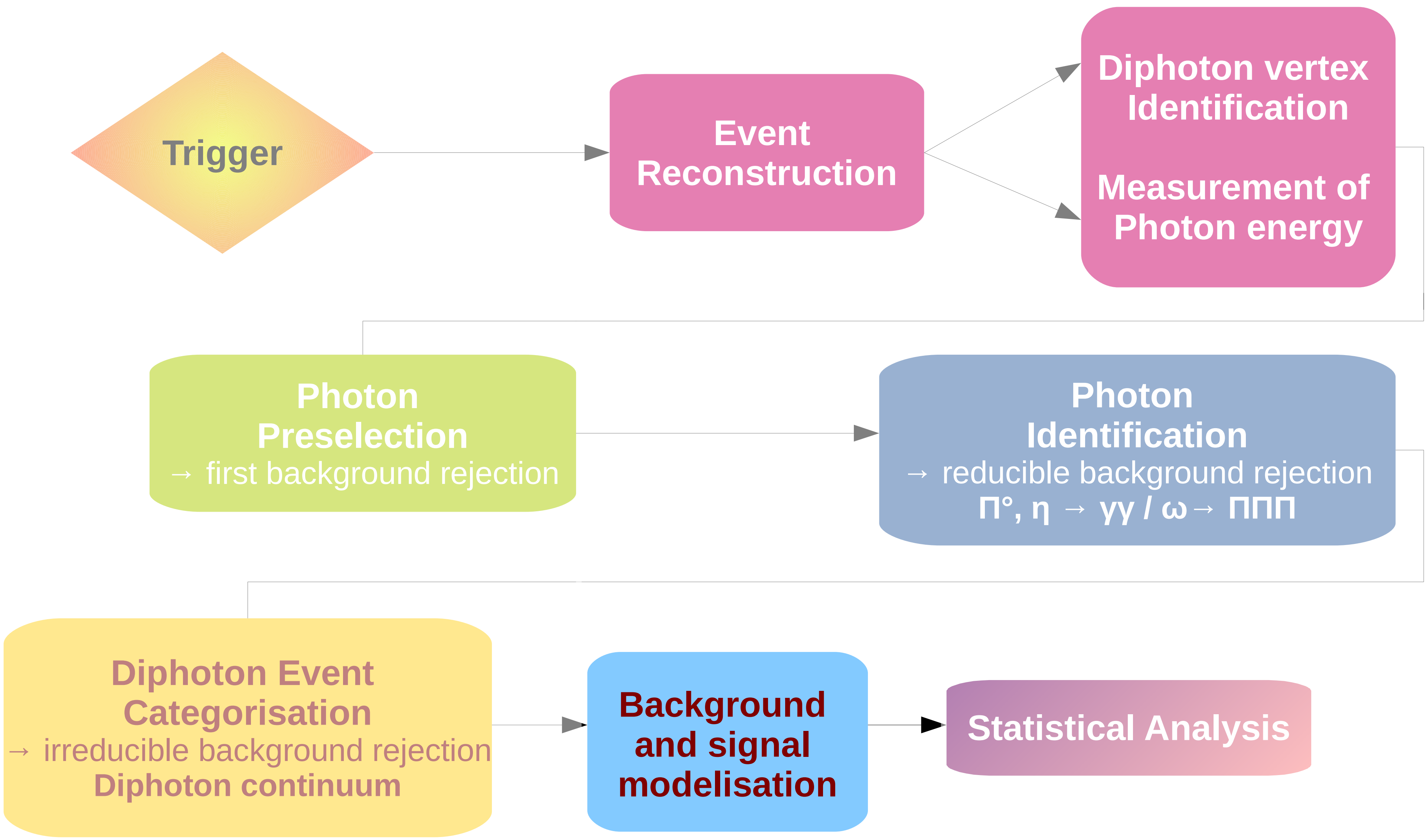


Background

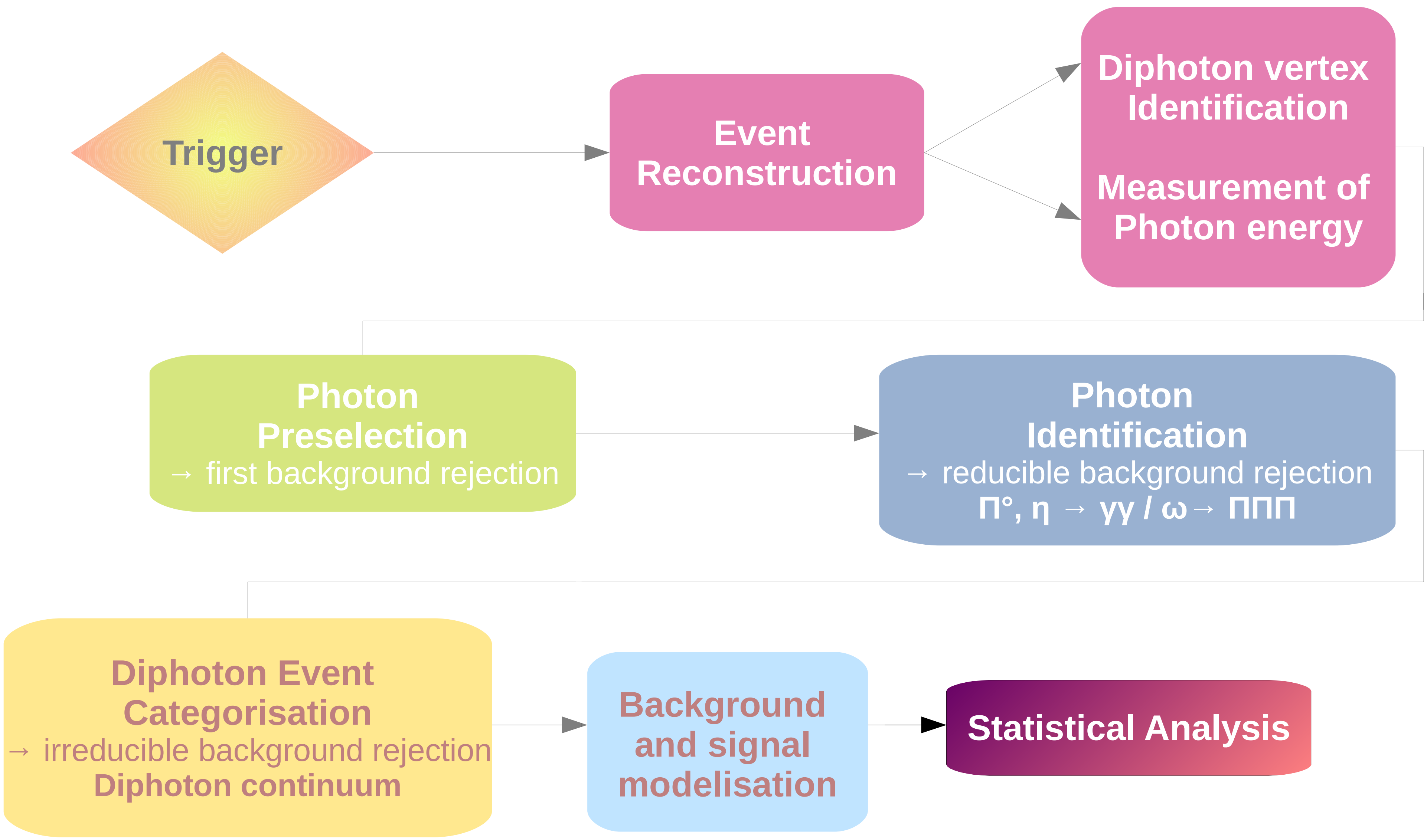
- **Drell-Yan** Parametric model extracted from **simulation : Z→e⁺e⁻**
- **Continuum background** extracted from **data**



Analysis Strategy



Analysis Strategy



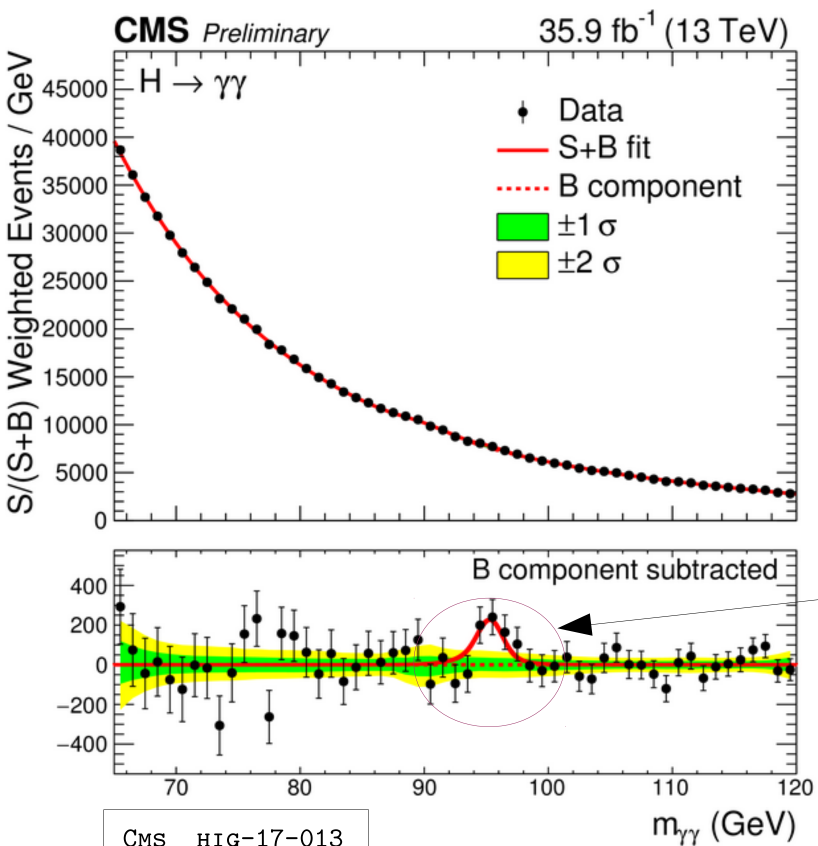
Analysis Strategy : Statistical Analysis

Statistical analysis

Signal extracted from background by **fitting** the **observed di-photon Mass** distributions in each category

- Fitting LHC data with **Signal+background model**
- Substracting **background component** to data

di-photon Mass distributions weighted by categories



CMS HIG-17-013

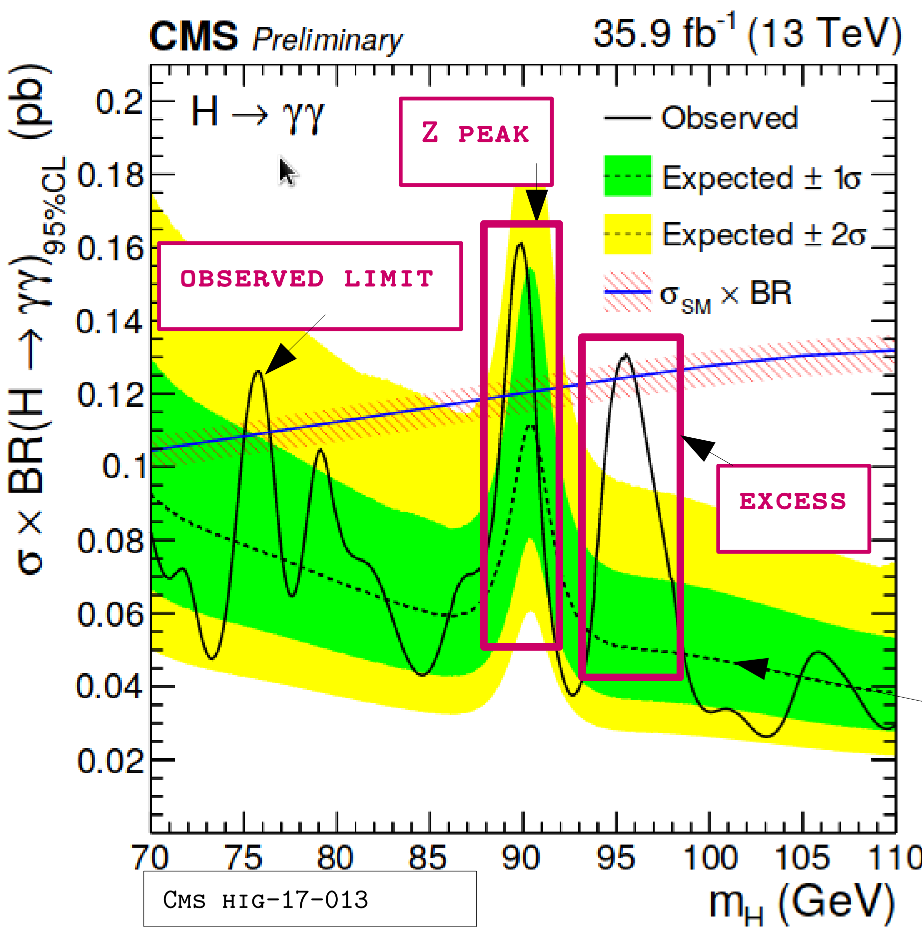
slight excess at **95.3 GeV**

Analysis Strategy : Statistical Analysis

Statistical analysis

Signal extracted from background by **fitting** the **observed di-photon Mass** distributions in each category

Exclusion limit on higgs boson cross section for different mass hypoyhesis



EXPECTED LIMIT FOR BACKGROUND ONLY HYPOTHESIS

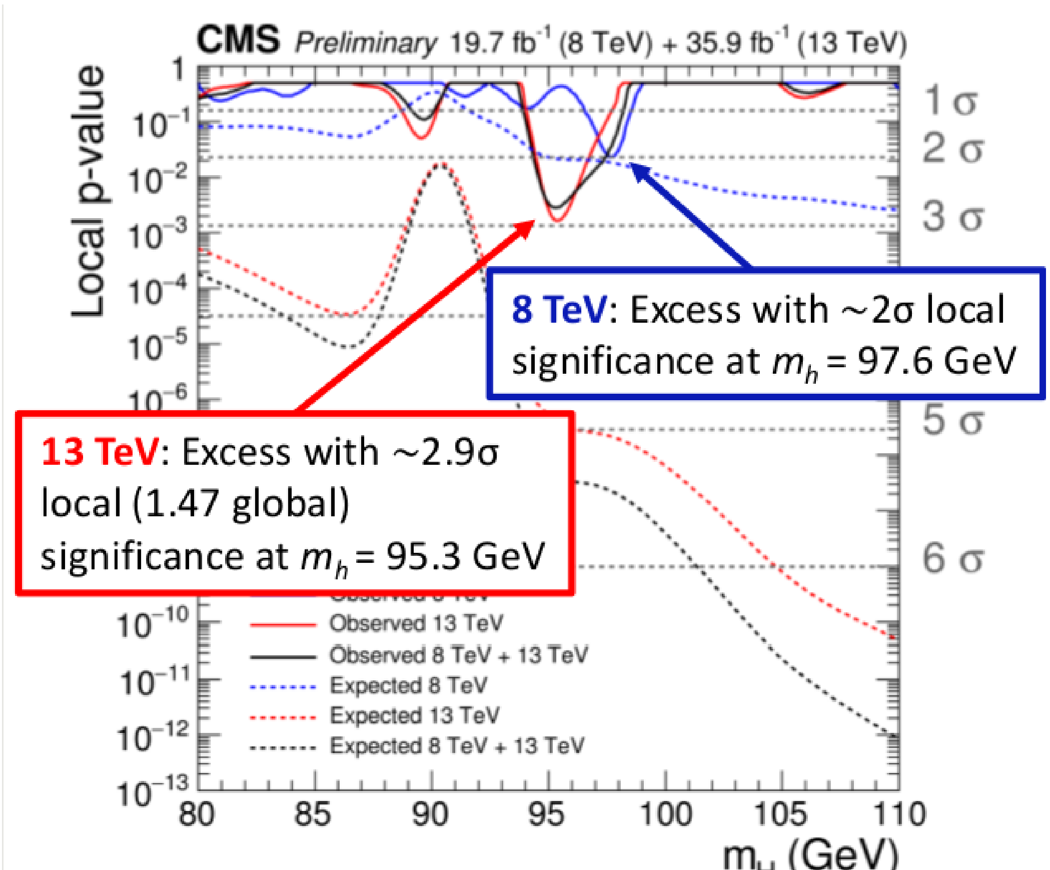
Exclusion limit

- For each mass hypothesis → set limits on **H→ γγ** cross section with 95 % confident level
- Compare limits: **observed** limit consistent with the **expected** one
- => **2.9 σ** slight excess at **95.3 GeV**

Analysis Strategy : Statistical Analysis

Statistical analysis → **Signal extracted** from background by **fitting** the **observed di-photon Mass** distributions in each category

Local p-value section for different mass hypoyhesis



CMS HIG-17-013

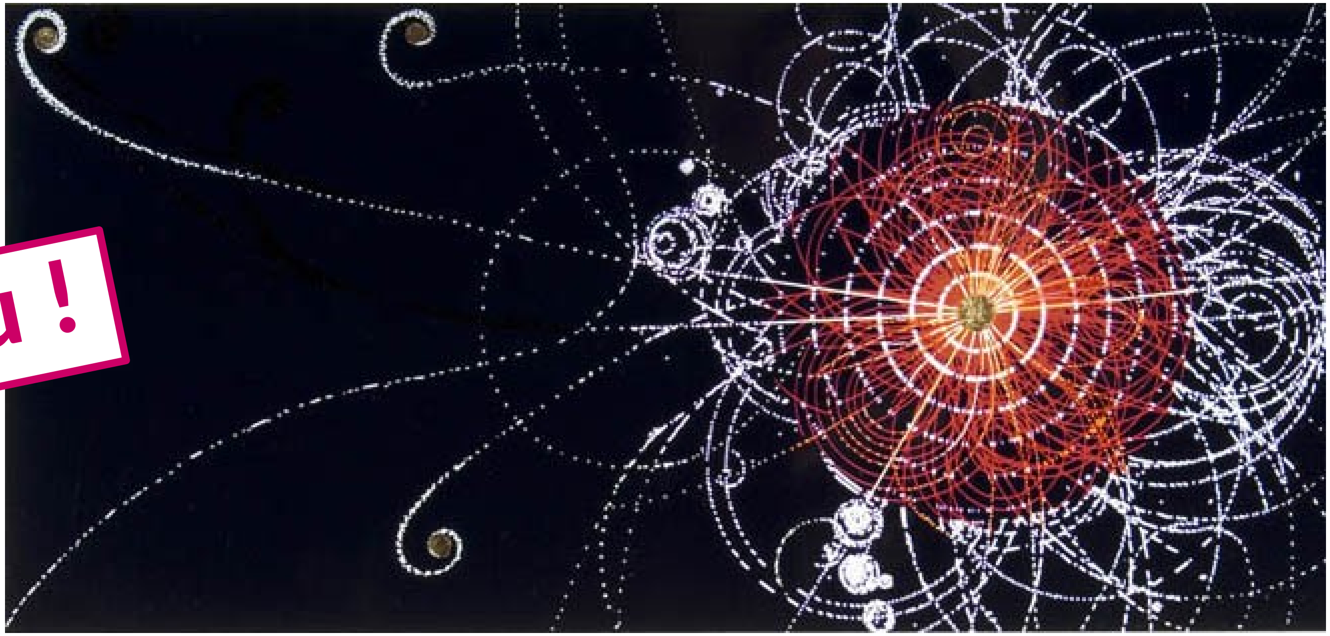
Exclusion limit

- For each mass hypothesis → set limits on **H→ γγ** cross section with 95 % confident level
- Compare limits: **observed** limit consistent with the **expected** one
- => **2.9 σ** slight excess at **95.3 GeV**

Conclusion

- LHC data are **sensitive** to some theoretical models (2HDM, NMSSM…)
- Results of the **CMS H → γγ** analysis have been reported, using **35.9 fb -1** of collision data collected in **2016 at 13 TeV**
- **New data** collected in **2017** → more **statistics** and better **sensitivity** to constrain models and to confirm or not the 2016 excess.

Thank you !



Back Up

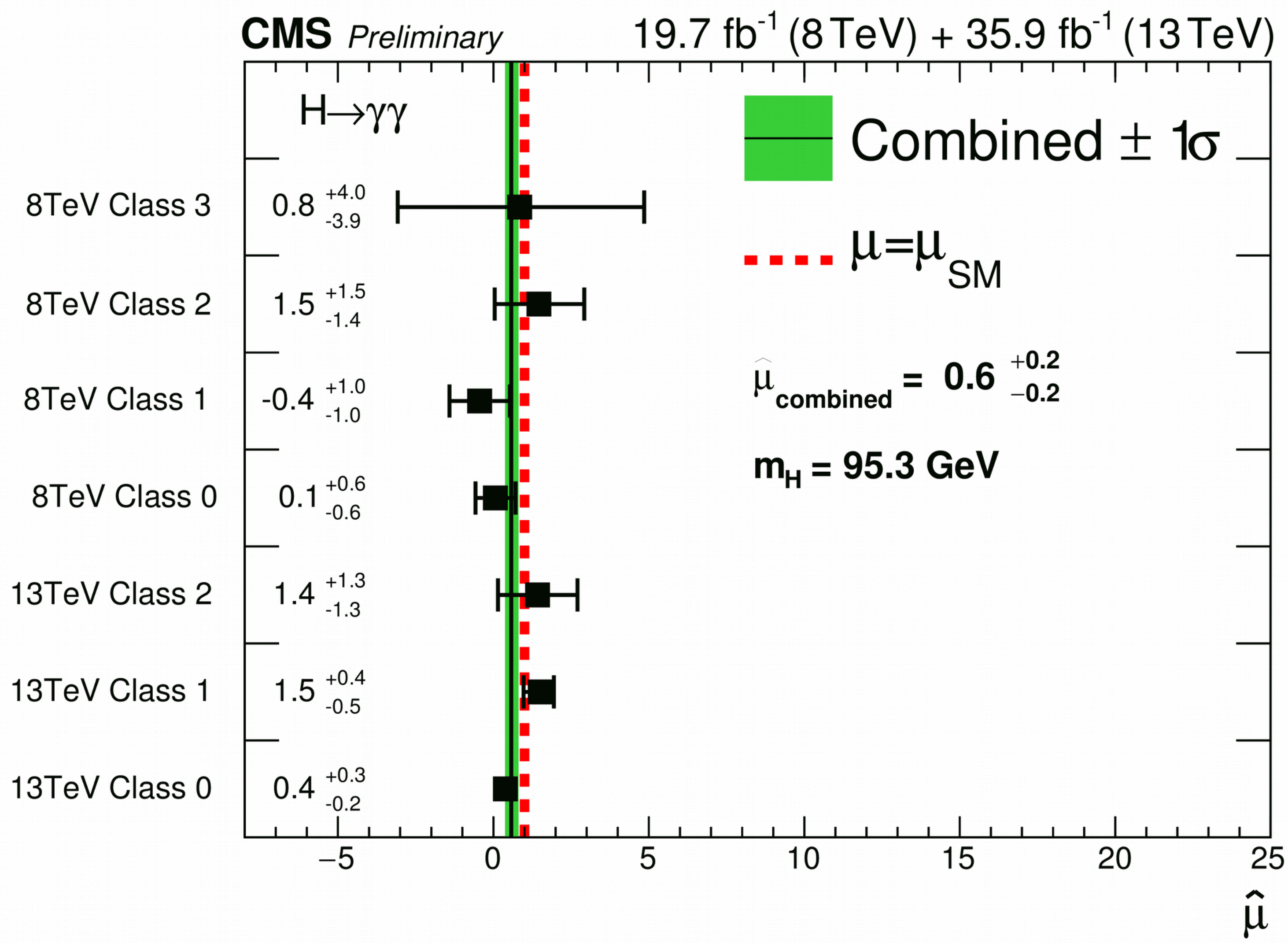
2HDM types

The different possible **couplings** between the **SM fermions** and the two **scalar doublets** in 2HDMs.

	Type I	Type II	Flipped (Type Y)	Lepton Specific (Type X)
Up-type quark	ϕ_2	ϕ_2	ϕ_2	ϕ_2
Down-type quark	ϕ_2	ϕ_1	ϕ_1	ϕ_2
Leptons	ϕ_2	ϕ_1	ϕ_2	ϕ_1

All fermions of a given electric charge couple to at most one Higgs doublet. These couplings can occur in different ways

Signal Strength



PhotonID : photon identification

GOAL : REJECT REDUCIBLE BACKGROUND

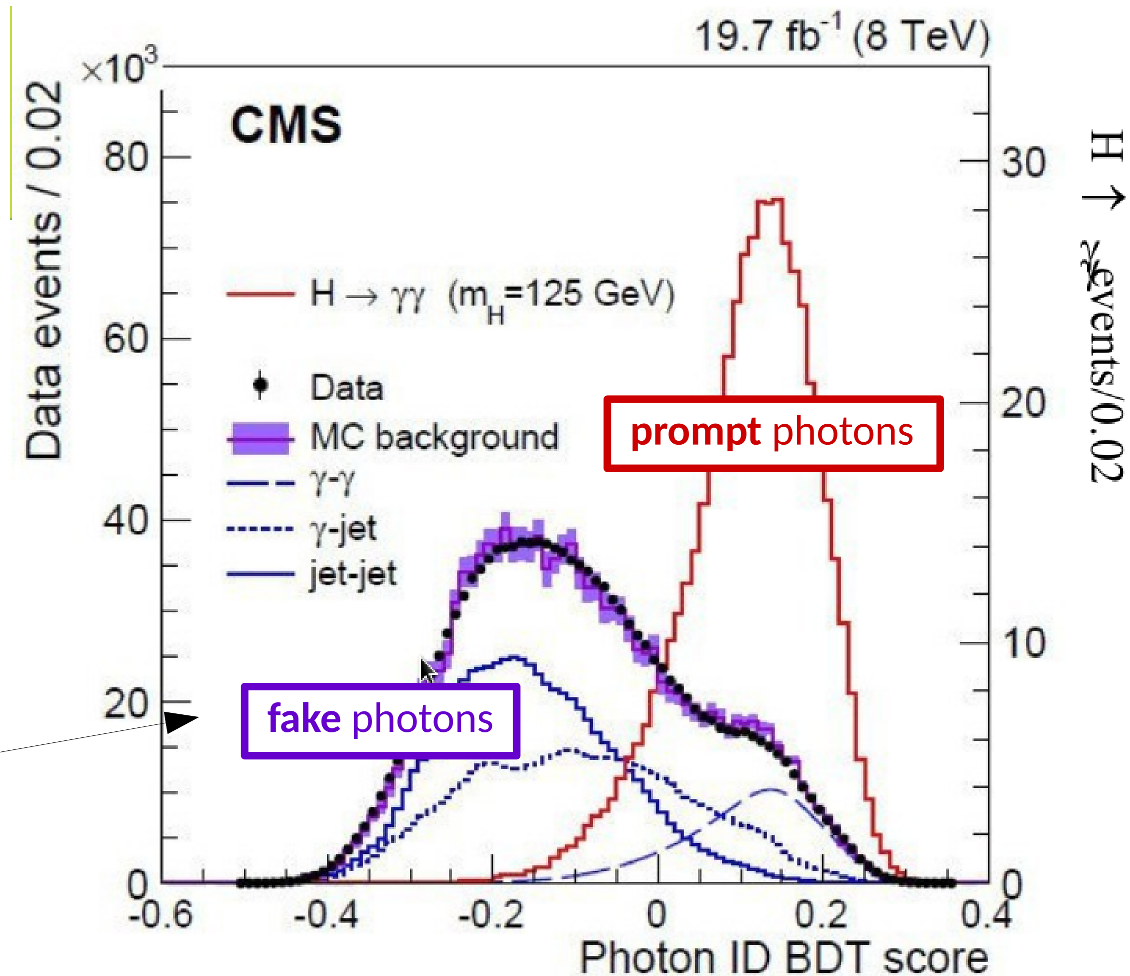
Discriminating variables :

- **Shower shape** variables
- **Isolation** variables

=> a fake photon is not isolated since it is in a jet

- **Median Energy density**

BDT ouput = score obtained by **fake** photons and **prompts** photons for data and simulation



VertexID: vertex identification

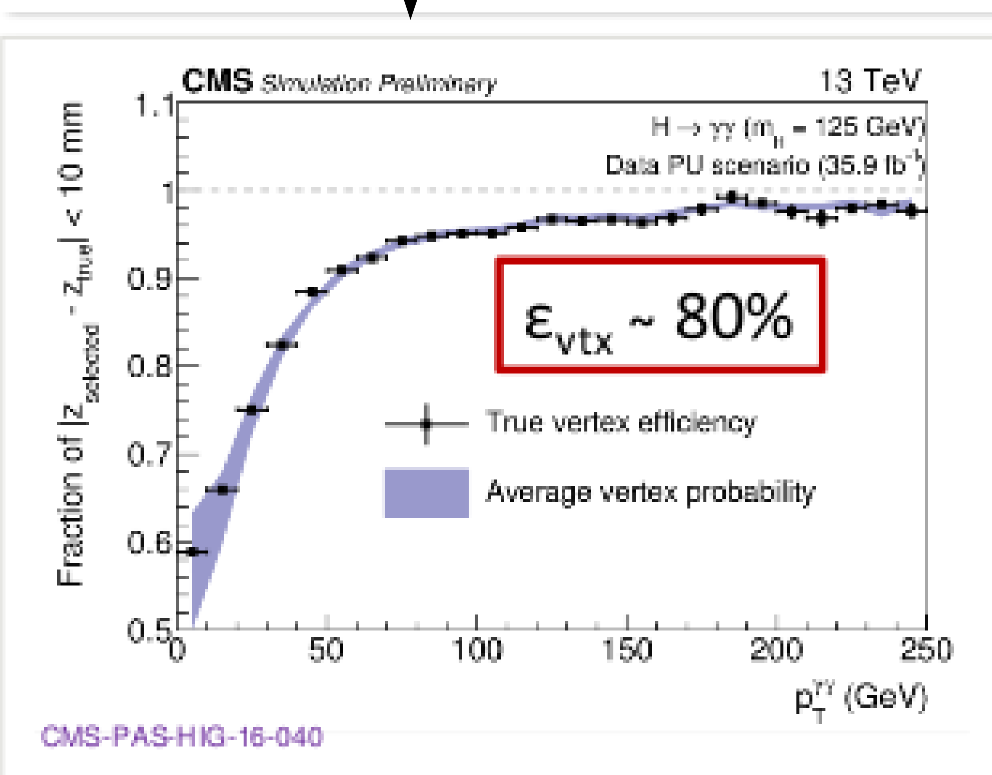
GOAL : IDENTIFY DIPHOTON VERTEX INTERACTION

Discriminating variables :

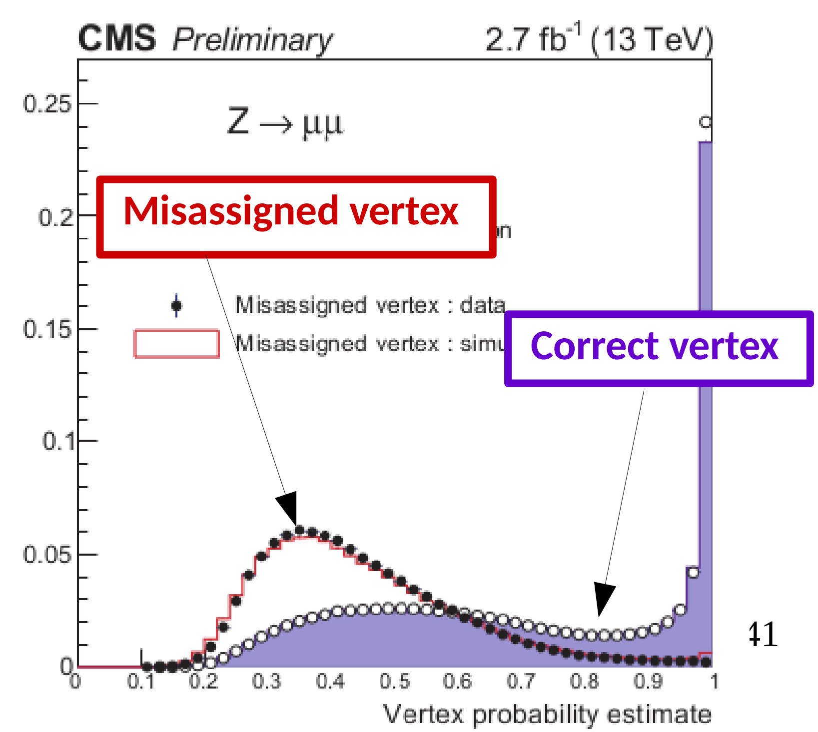
- Observables related to **tracks recoiling against the diphoton system**
- **direction** of conversion tracks

Second BDT = to estimate the **probability** for the vertex assignment to be within 1 cm

1cm →(**negligible** impact on **mass resolution**)



Method validated on **Z → μμ** events, by refitting **vertices ignoring the muon tracks**



Variables discriminantes du BDT diphoton : cas standard

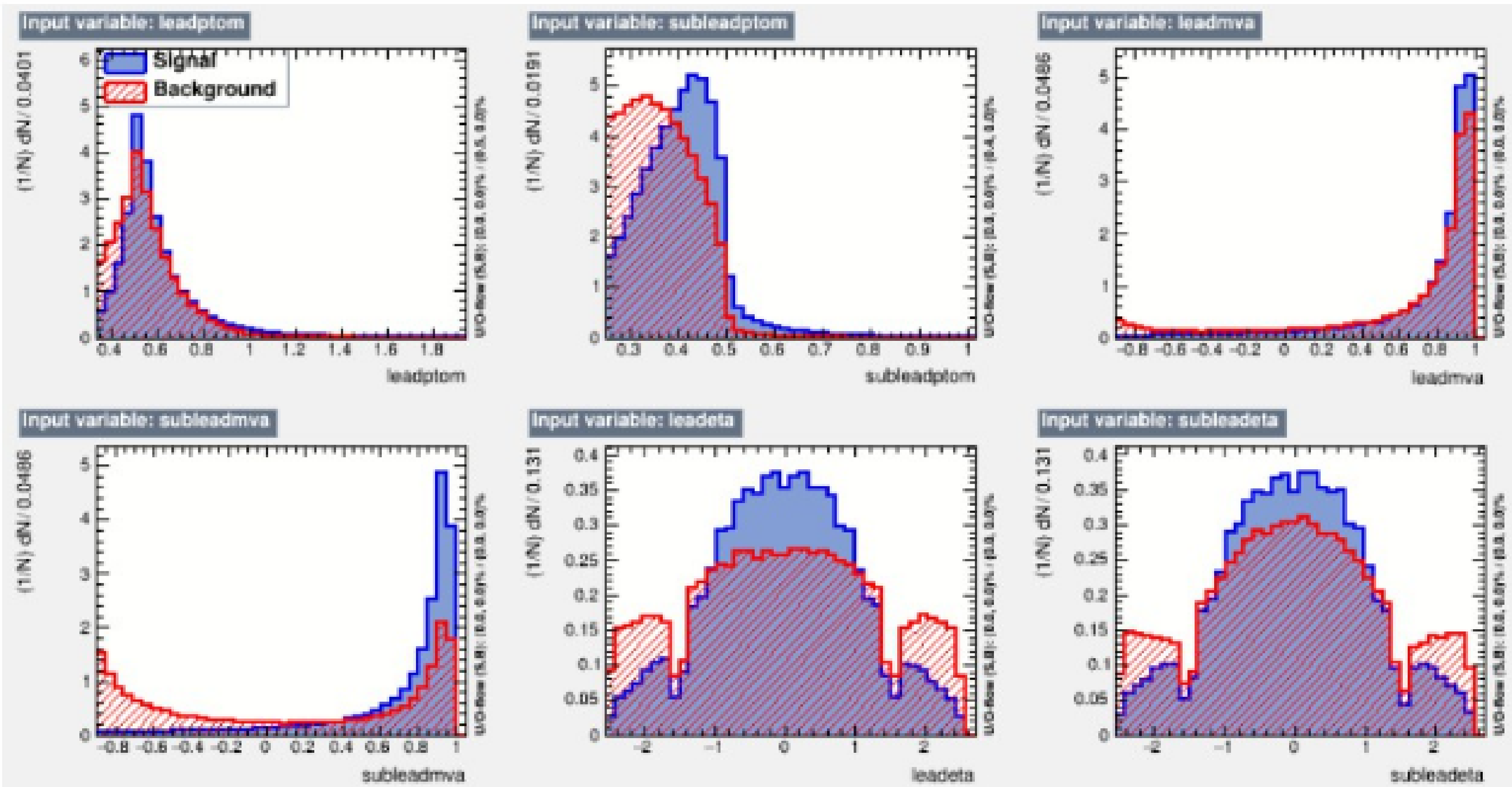


FIGURE 26 – distribution des événements pour le signal (en bleu) et le bruit de fond (en rouge) pour l'ensemble des variables discriminantes du BDT diphoton : cas standard.

Variables discriminantes du BDT diphoton : cas standard

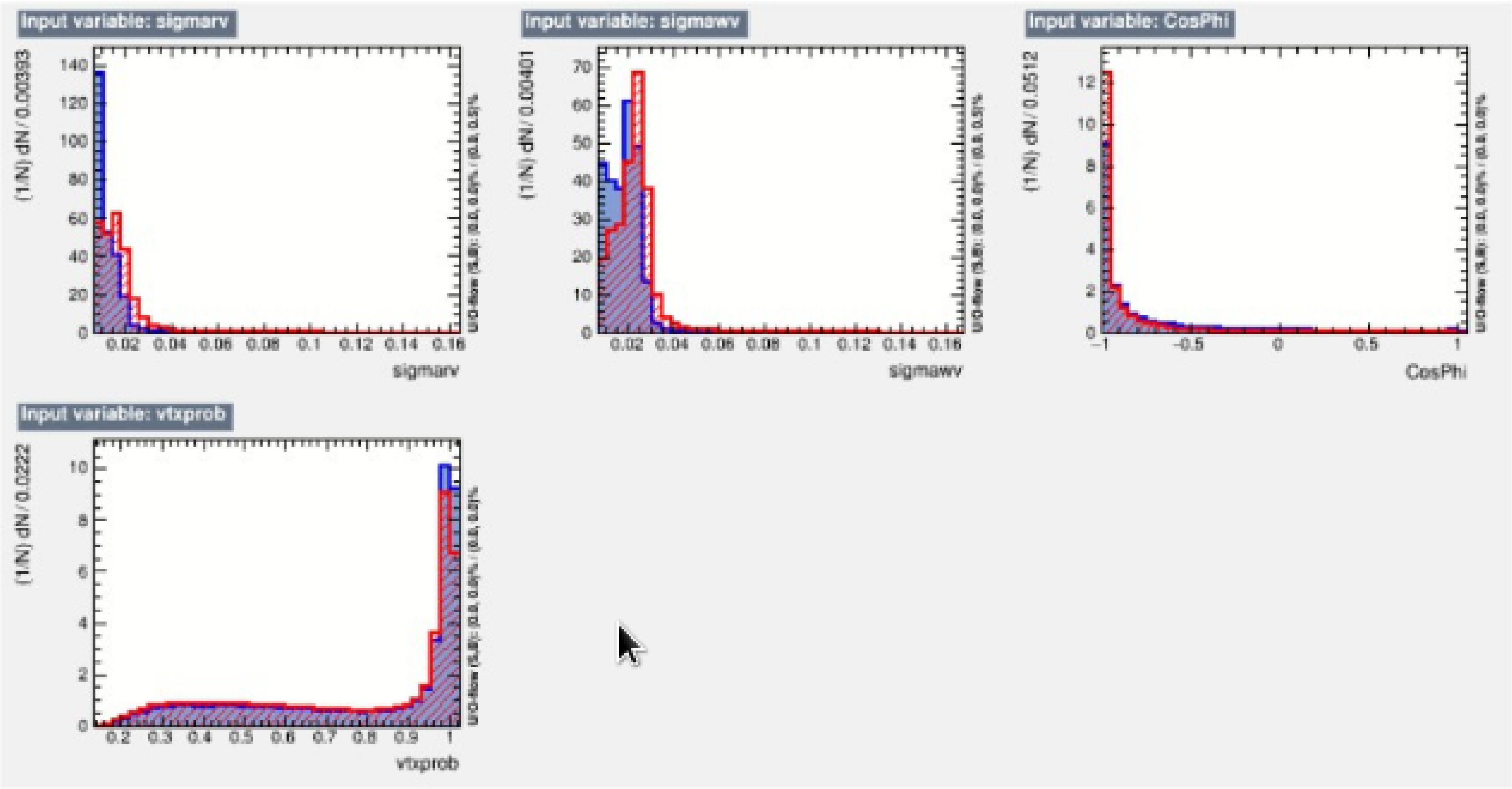


FIGURE 27 – distribution des événements pour le signal (en bleu) et le bruit de fond (en rouge) pour l'ensemble des variables discriminantes du BDT diphoton : cas standard.

Présélection standard

Présélection des photons

	R_9	H/E	$\sigma_{\eta\eta}$	$\mathcal{I}_{\text{ph}}$	$\mathcal{I}_{\text{tk}}$
Barrel	$[0.5, 0.85]$	< 0.08	< 0.015	< 4.0	< 6.0
	> 0.85	< 0.08	–	–	–
Endcaps	$[0.8, 0.90]$	< 0.08	< 0.035	< 4.0	< 6.0
	> 0.90	< 0.08	–	–	–

Chemins de déclenchement

Trigger selection for HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90.

	H/E	$\sigma_{i\eta i\eta}$ (5x5)	R_9 (5x5)	ECAL PF cluster iso.	Track iso.
EB; $R_9 > 0.85$	< 0.12	–	> 0.5	–	–
EB; $R_9 \leq 0.85$	< 0.12	< 0.015	> 0.5	$< (6.0 + 0.012E_T)$	$< (6.0 + 0.002E_T)$
EE; $R_9 > 0.90$	< 0.1	–	> 0.8	–	–
EE; $R_9 \leq 0.90$	< 0.1	< 0.035	> 0.8	$< (6.0 + 0.012E_T)$	$< (6.0 + 0.002E_T)$
Other trigger requirements					
HLT seeded $E_T > 30$ GeV		HLT unseeded $E_T > 18$ GeV		$m_{\gamma\gamma} > 90$ GeV	

Présélection basse masse

Table 6: Preselection cuts.

		R9 (5x5)	HoE	$\sigma_{i\eta i\eta}$ (5x5)	pfPhoIso	TrackerIso
Both photons in barrel	Barrel	> 0.5	< 0.07	< 0.0105	< 4 GeV	< 6 GeV
At least one in endcap	Barrel	> 0.85	< 0.07	< 0.0105	< 4 GeV	< 6 GeV
At least one in endcap	Endcap	> 0.9	< 0.035	< 0.0275	< 4 GeV	< 6 GeV

HLT_Diphoton30PV_18PV_R9Id_AND_IsoCaloId_AND_HE_R9Id_DoublePixelVeto_Mass55_v7

	E_T	Low $R_9 >$	$H/E <$	high $R_9 >$	$\sigma_{i\eta i\eta} <$	ECAL PF cluster iso $<$	Track iso$<$
Seeded leg							
Photons in EB	30 GeV	0.5	0.1	0.85	0.015	$6.0 + 0.12E_T$	-
Photons in EE	30 GeV	0.8	0.1	0.9	0.035	$6.0 + 0.12E_T$	-
Unseeded leg							
Photons in EB	18 GeV	0.5	0.1	0.85	0.015	$6.0 + 0.12E_T$	$6+0.002E_T$
Photons in EE	18 GeV	0.8	0.1	0.9	0.035	$6.0 + 0.12E_T$	$6+0.002E_T$
Other trigger requirements							
Pixel veto				$m_{\gamma\gamma} > 55$ GeV			

HLT_Diphoton30EB_18EB_R9Id_OR_IsoCaloId_AND_HE_R9Id_DoublePixelVeto_Mass55_v7

	E_T	Low $R_9 >$	$H/E <$	high $R_9 >$	$\sigma_{i\eta i\eta} <$	ECAL PF cluster iso $<$	Track iso $<$
Seeded leg	30 GeV	0.5	0.1	0.85	0.015	$6.0 + 0.12E_T$	-
Unseeded leg	18 GeV	0.5	0.1	0.85	0.015	$6.0 + 0.12E_T$	$6+0.002E_T$
Other trigger requirements							
Pixel veto				$m_{\gamma\gamma} > 55$ GeV			