Faculté de physique et ingénierie
Université de Strasbourg

Improvement of the $H \to b\bar{b}$ mass reconstruction with a kinematic fit

Master 2 Subatomic and Astroparticle Physics defence

Under the guidance of Maxime Gouzevitch

22/06/2022

Elise Jourd'huy

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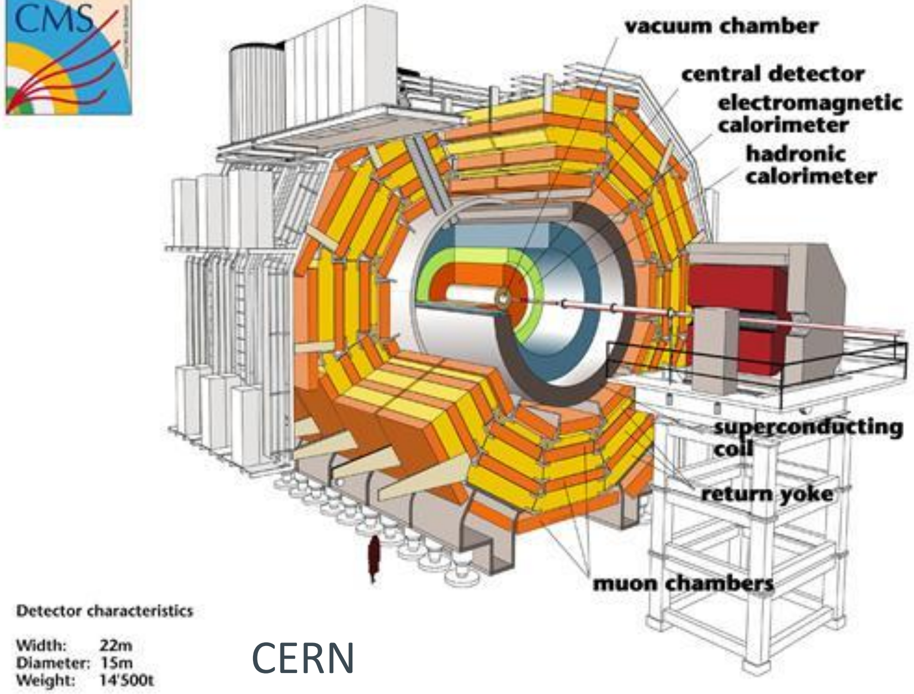
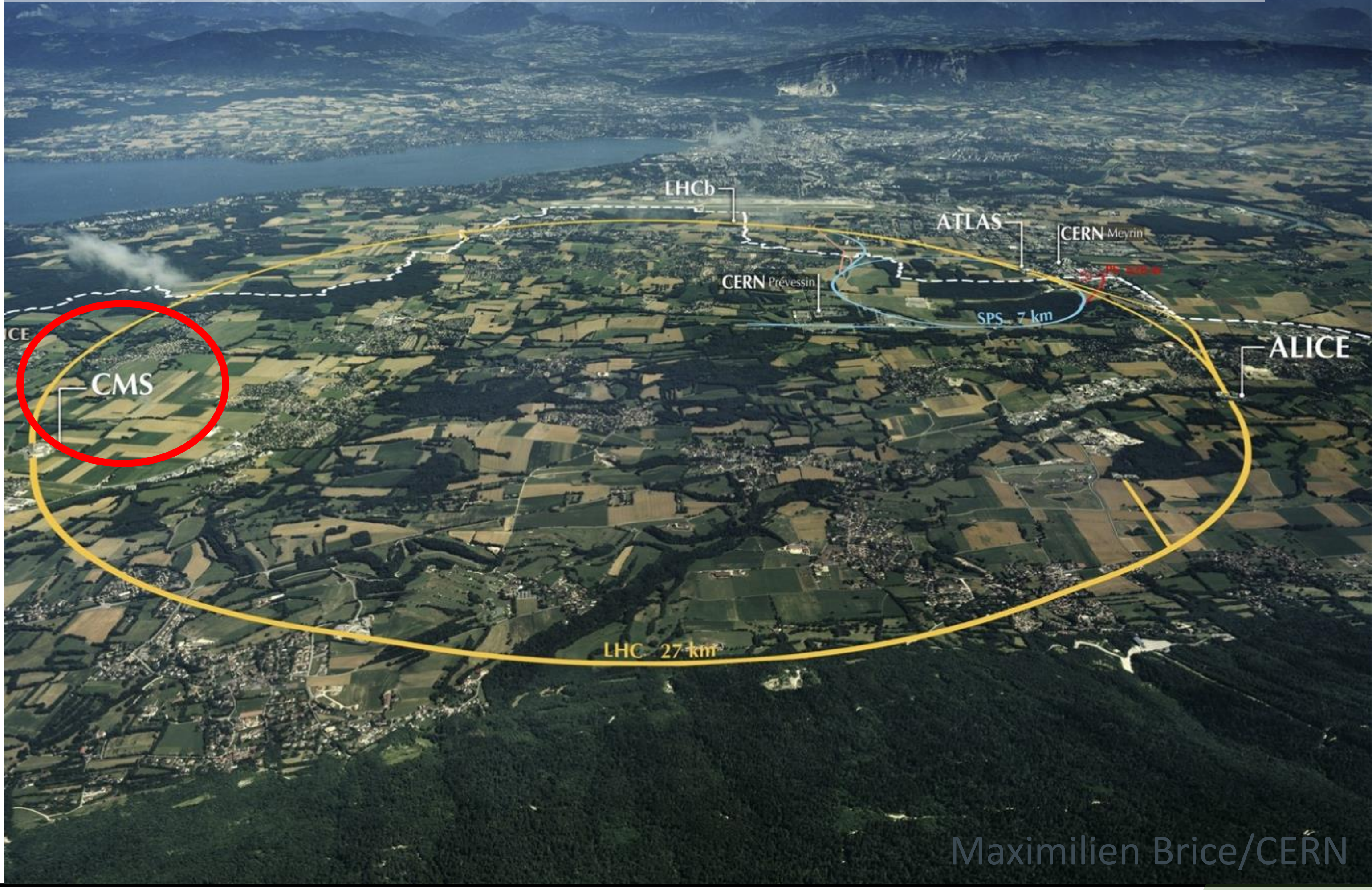
I. The Higgs boson self-coupling constant

CMS

Compact Muon Solenoid is one of the 4 *Large Hadron Collider* (LHC) experiments at CERN. This international collaboration aims to study, among other things, the parameters of the standard model.



CERN



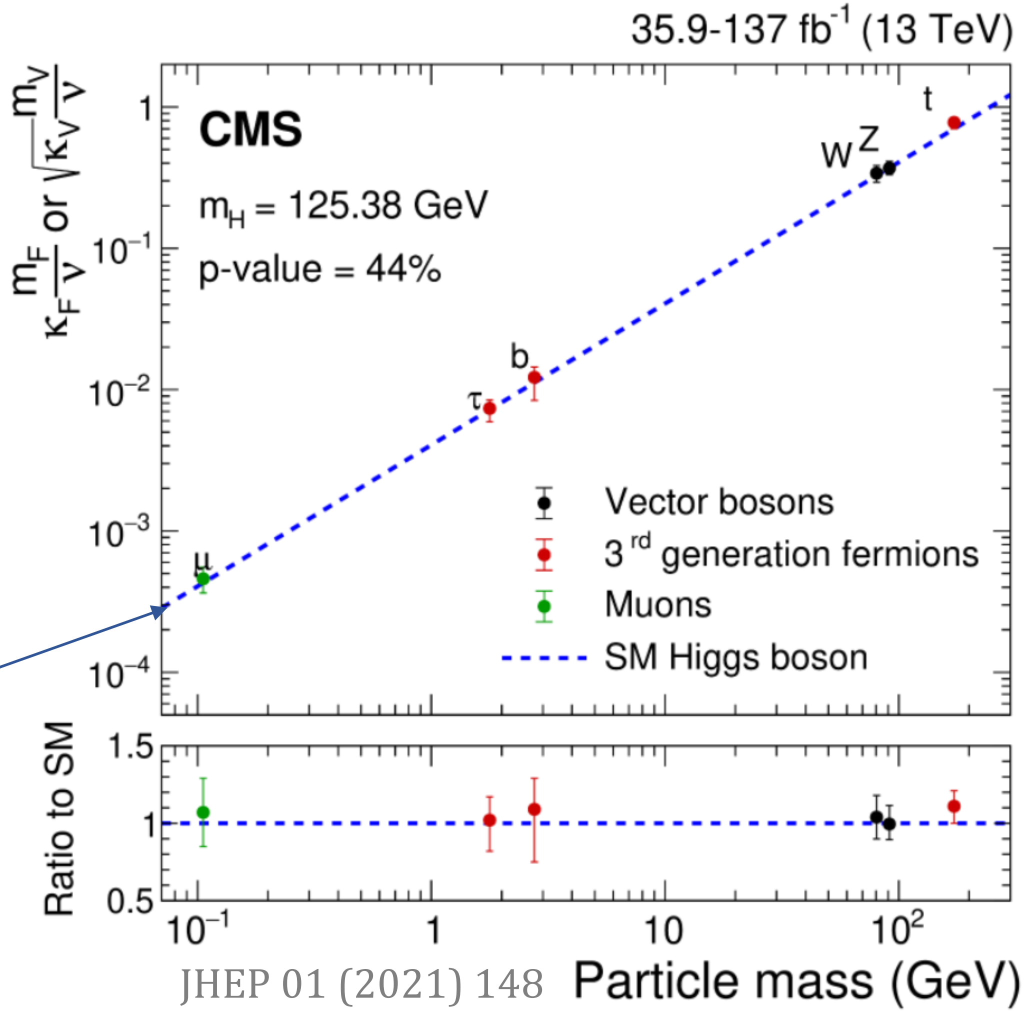
Maximilien Brice/CERN

The Higgs boson

1964 : Higgs, Englert & Brout, Hagen & Guralnik & Kibble predicted a **field** (and its **boson**) **responsible for the masses of elementary particles.**

2012 : Observation of a Higgs boson at CMS and ATLAS.

Mass ∝ Interaction force with the Higgs field × Vacuum expectation value of the Higgs field (v)



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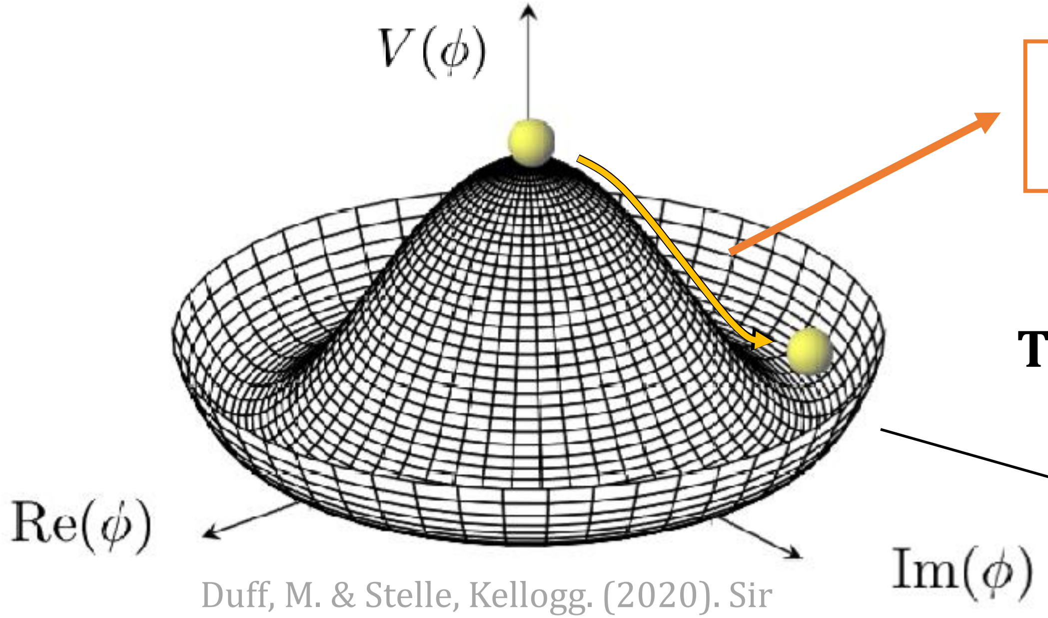
The BEH mechanism



Duff, M. & Stelle, Kellogg. (2020). Sir Thomas Walter Bannerman Kibble CBE.

Spontaneous symmetry breaking ⟹ **Mass gain**

The Standard Model postulates the simplest potential shape :

$$V(\phi) = \lambda(\phi^2 - v^2)^2$$

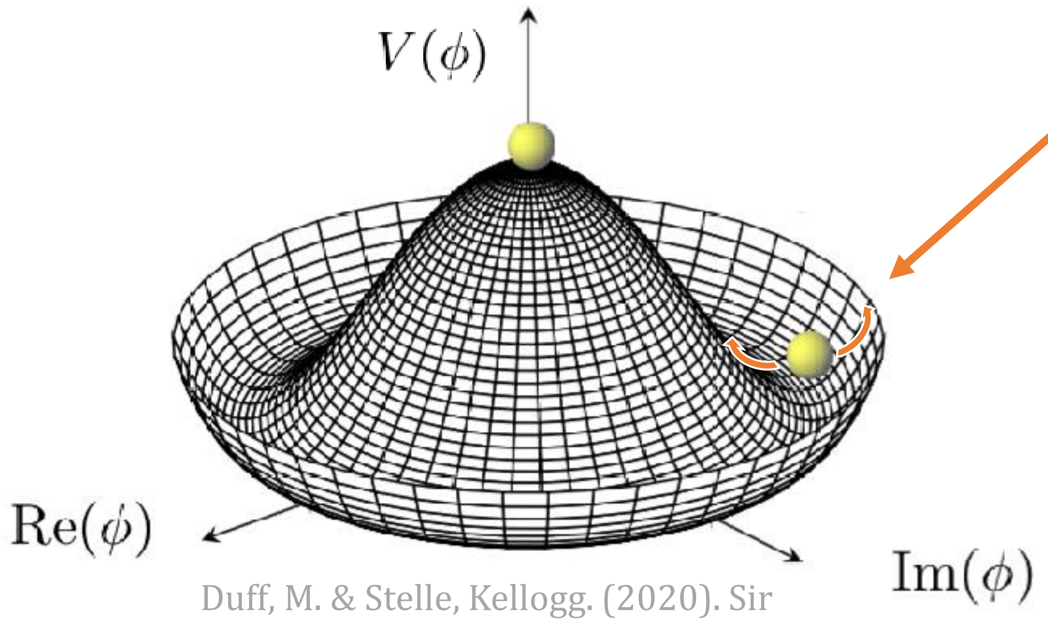
Higgs field

$\boldsymbol{\lambda_{SM} \approx 0,13}$

Vaccum exepectation value **Already measured**

This potential was never experimentally observed!
The only way is to do so is to measure λ

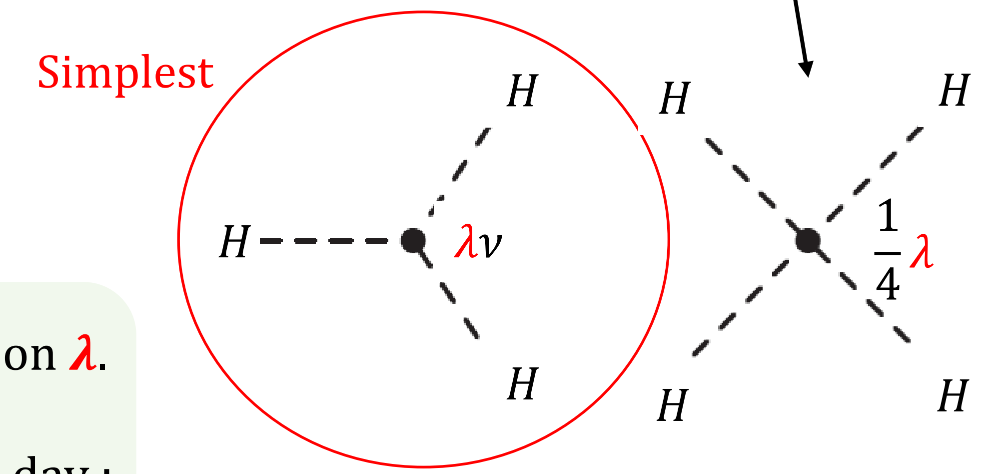
The self-coupling constant λ



Duff, M. & Stelle, Kellogg. (2020). Sir Thomas Walter Bannerman Kibble CBE.

Fluctuations around v : $\boldsymbol{\phi = (H + v)/\sqrt{2}}$

$$V(H) = \frac{1}{4} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$$

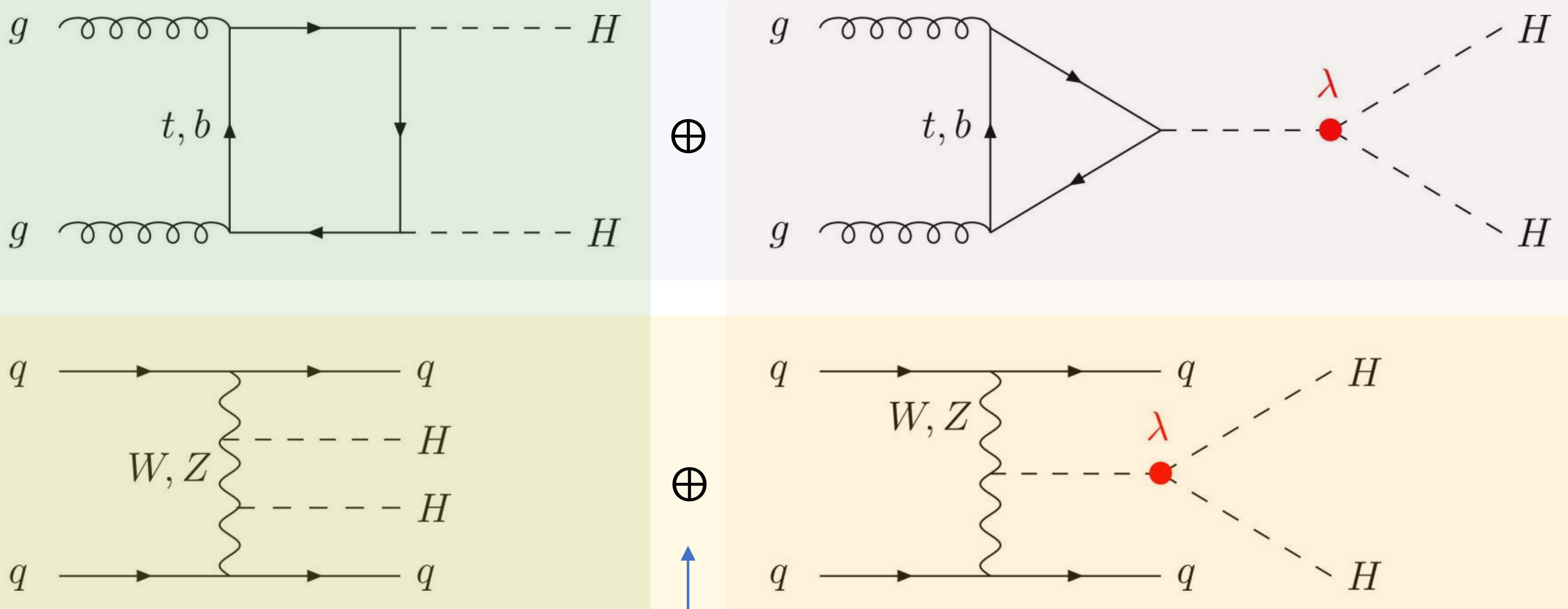


Higgs boson self-interaction

- The number of observed **Higgs boson pairs** events depends on $\boldsymbol{\lambda}$.
- The Higgs boson pair production was **never observed** to this day : $\approx$ **1000** $\times$ **rarer** than a single Higgs production

II. Experimental realities

Higgs bosons pair production at CMS



2× single Higgs boson

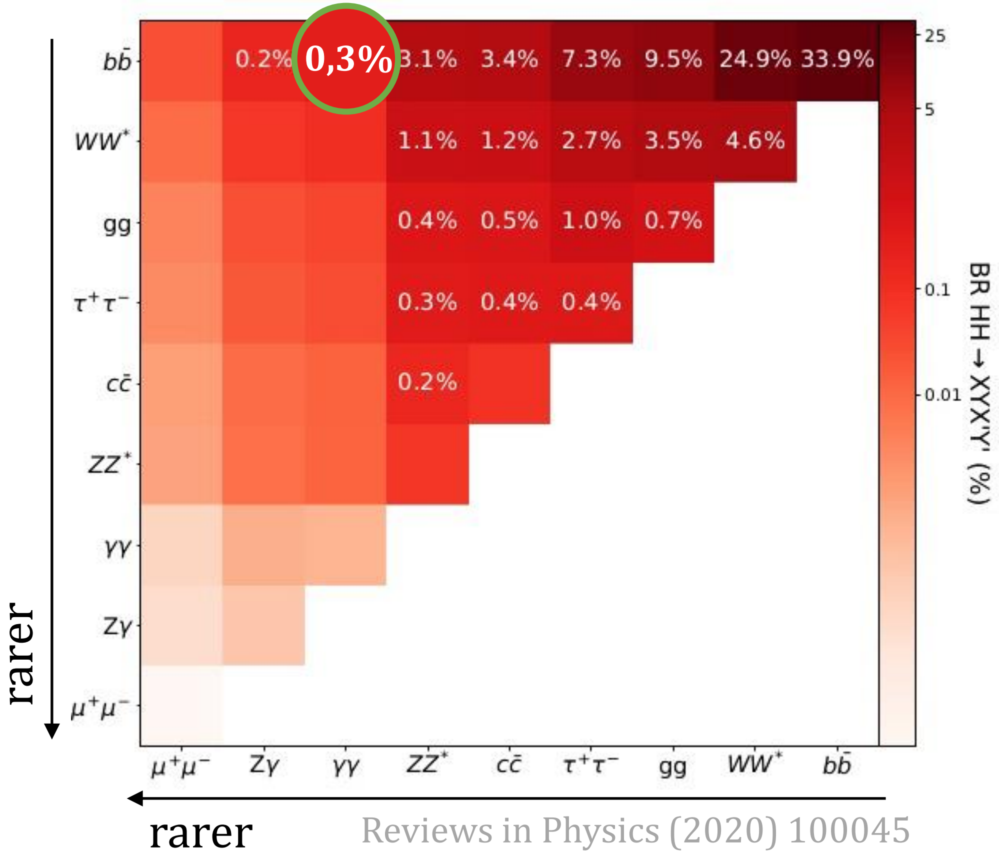
Higgs boson self-coupling

Interferences

Gluon-Gluon fusion (ggF) ≈ **90** %

Vector boson fusion (VBF) ≈ **5** %

$HH \to b\bar{b}\gamma\gamma$



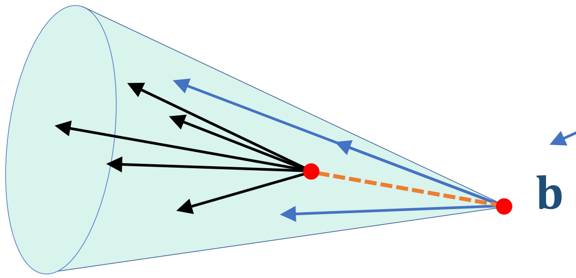
Reviews in Physics (2020) 100045

$HH \to b\bar{b}\gamma\gamma$ is the most sensitive channel

b quarks	Photons
Strong interaction with the Higgs boson	**Good selection** of the event

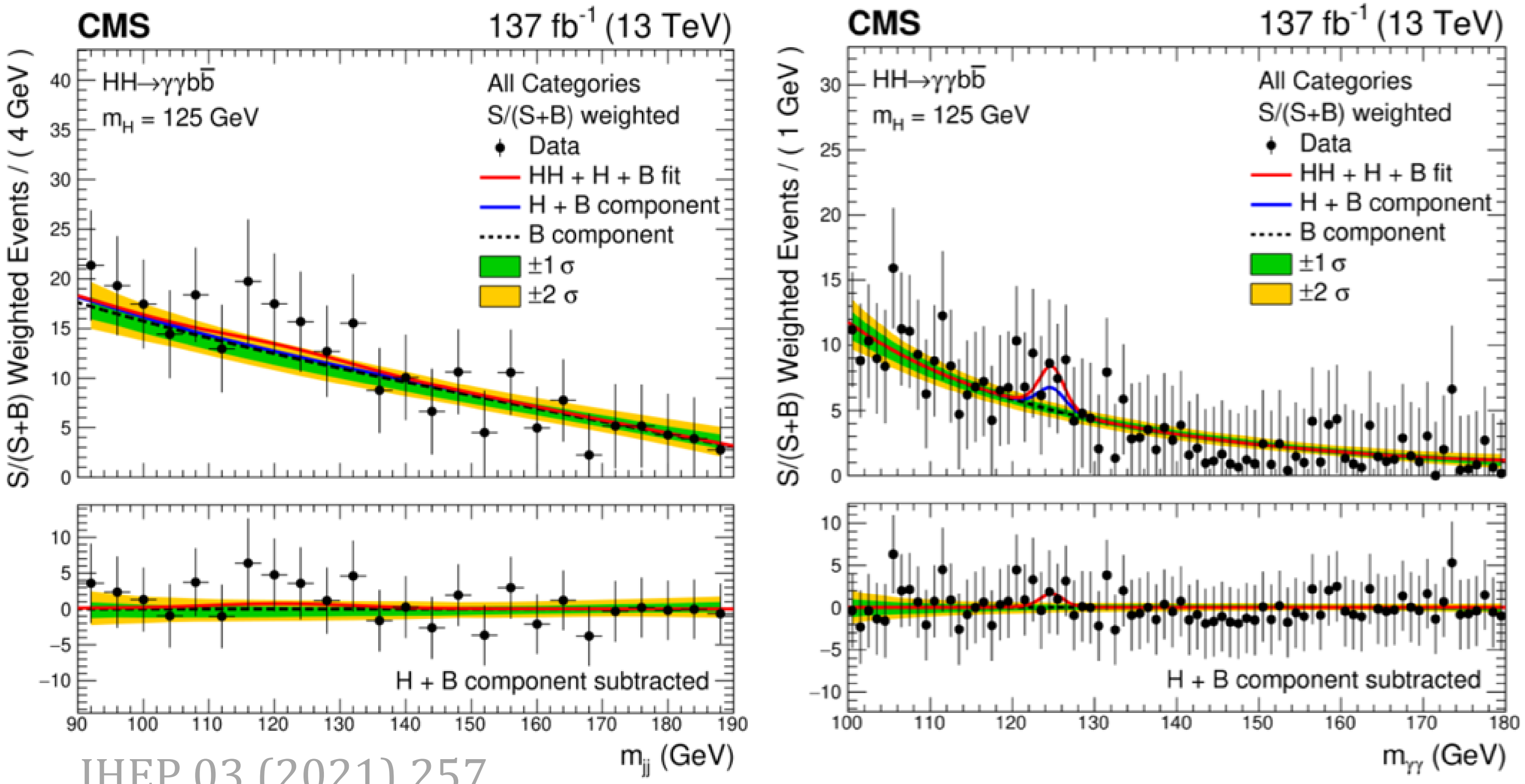
Compromise

Color confinement $\Longrightarrow$ b quarks cannot be isolated. They materialize as **particle jets** in the detector.



➢ **Room for improvement in the reconstruction of b jets**

Aim of the internship



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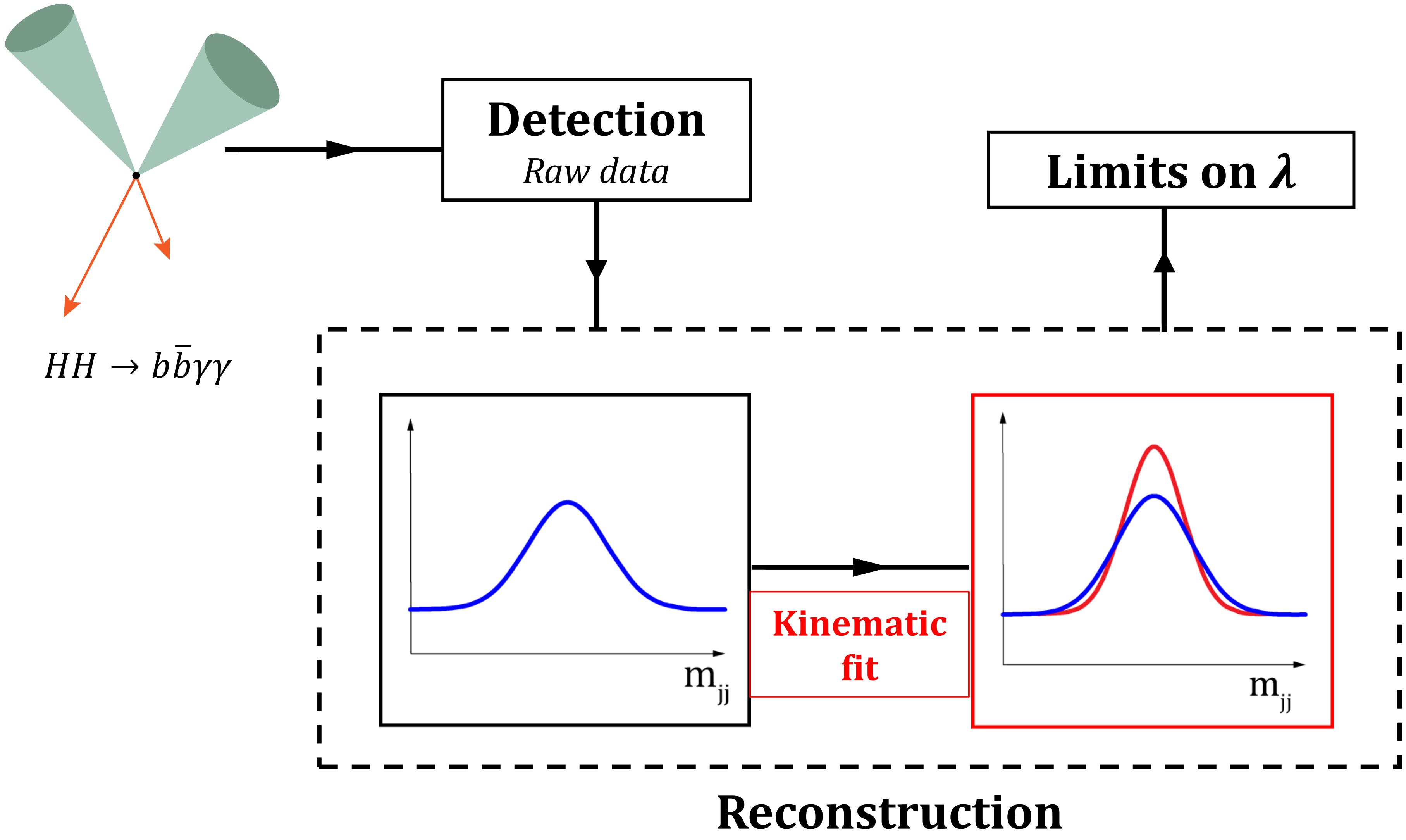
HH never observed to this day
$\Longrightarrow$ limits on $\boldsymbol{\kappa_\lambda} = \frac{\lambda}{\lambda_{SM}} \in [-\mathbf{3.3}\,,\ \mathbf{8.5}]$

- Photons well reconstructed
- Need both photons and b jets to observe a HH signal
- The **b jets reconstruction is a limiting factor**
- Need to **improve the Signal to Noise Ratio** for b jets

Improving the b jets reconstruction with a kinematic fit

III. The kinematic fit

Data processing chain



Kinematic fit : principle

Initially : Missing transverse energy due to **misreconstructions** and **neutrinos**

Modifying measured kinematic variables in their uncertainties to fulfil the **transverse momentum conservation** law

Minimizing with the least square method :

Measured parameters

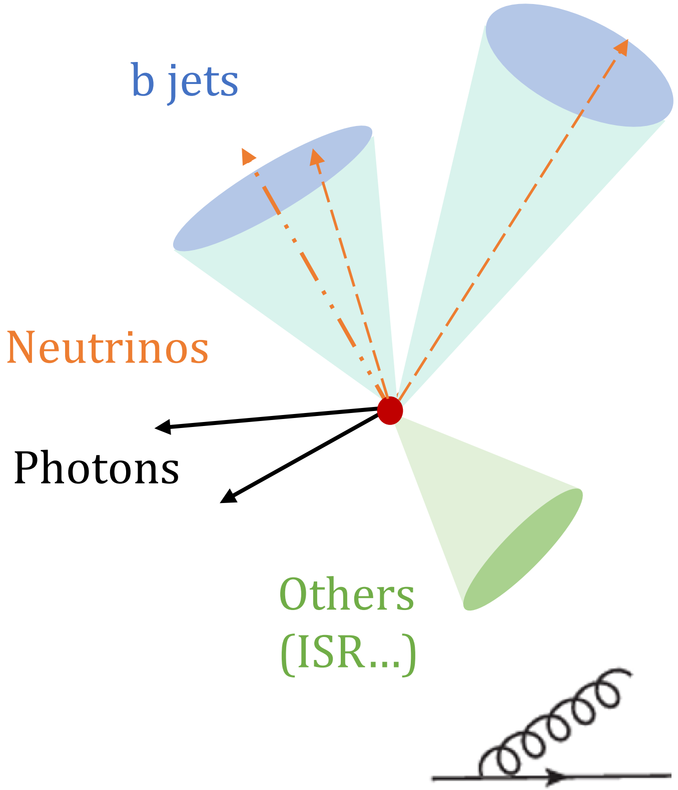
Lagrange multipliers

$$L\left(\vec{y},\vec{\lambda}\right) = S(\vec{y}) + 2\sum_{k=1}^{m} \lambda_k f_k(\vec{y})$$

Constraints

Covariance matrix

$\Leftrightarrow$ **Minimizing** $S(\vec{y}) = \Delta\vec{y}^{T} V^{-1} \Delta\vec{y}$ for $f_k = 0$



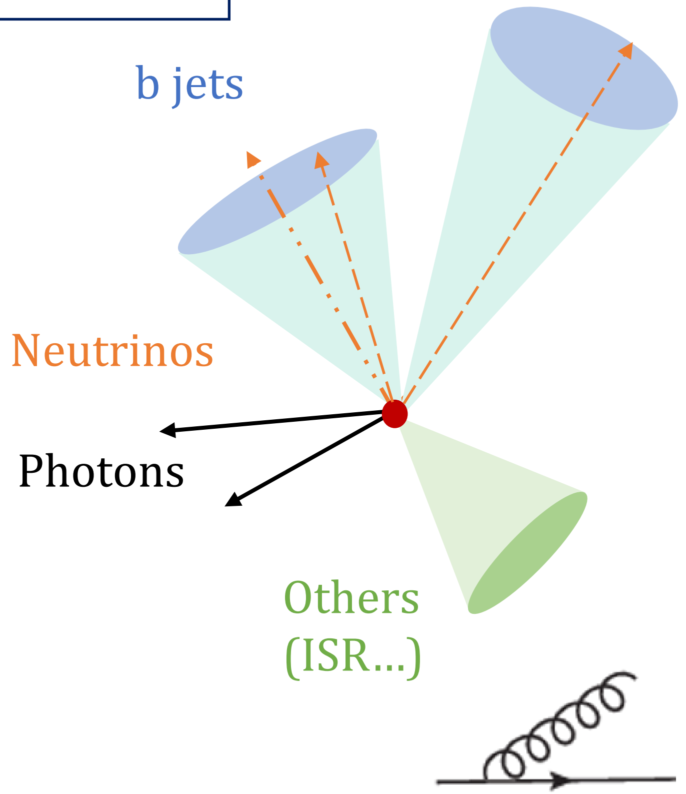
Parametrization of a simulation

$$S(\vec{y}) = \Delta\vec{y}^T V^{-1} \Delta\vec{y}$$

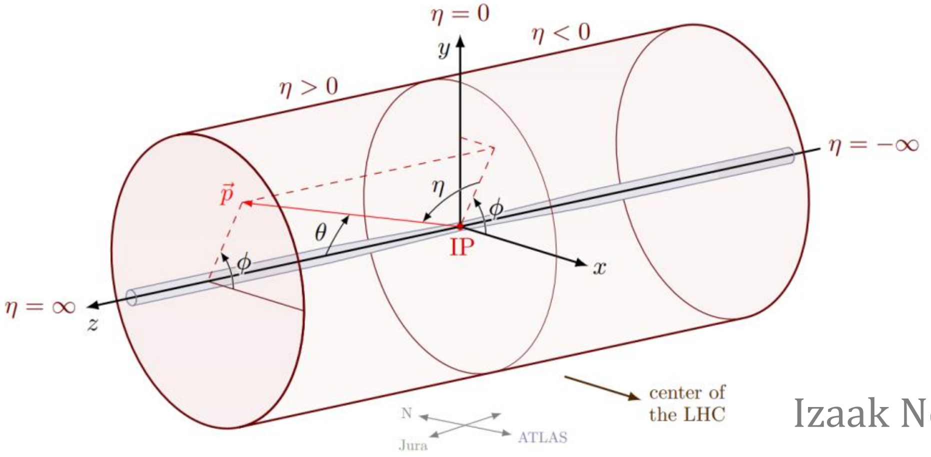
$$p_x^{SumExtra+MET} + p_x^{jets} + p_x^{photons} = 0$$
$$p_y^{SumExtra+MET} + p_y^{jets} + p_y^{photons} = 0$$

$$\vec{p}^{SumExtra+MET} = -\vec{p}^{jets} - \vec{p}^{photons} - \vec{p}^{MET}$$

The transverse momentum conservation is disequilibrated by MET
(*Missing Transverse Energy*)



CMS coordinate system : $(\boldsymbol{p_t}, \boldsymbol{\eta}, \boldsymbol{\phi})$: Independent variables ⇒ Diagonal matrix
⇒ Invertible covariance matrix



Izaak Neutelings, tikz.net

Parametrization of a simulation

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$$p_x^{MET} + p_x^{SumExtra} + p_x^{jets} + p_x^{photons} = 0$$
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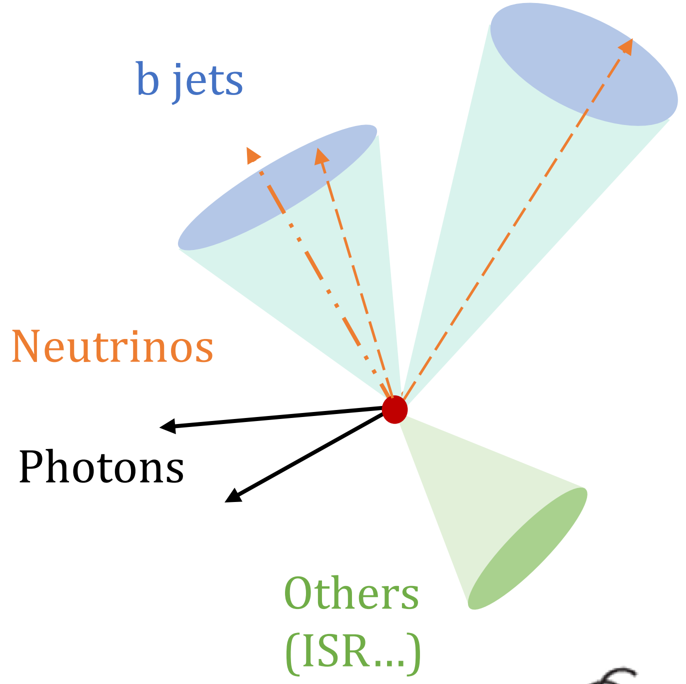
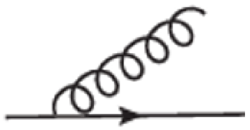




	b jets	photons	SumExtra+MET
$\sigma^2_{E_t}$	Given by the simulation		$a^2 + b^2 E_t + c^2 {E_t}^2$
σ^2_{η}	η should not be modified		
σ^2_{ϕ}	$a/_{E_t^2} + b/_{E_t} + c$		

Use of the KinFitter package

Problem : absurd final variables , divergence of the algorithm

Origin

$$\vec{p} = \begin{pmatrix} p_t \cos\phi \\ p_t \sin\phi \\ p_t \sinh\eta \end{pmatrix}$$

Massive particle

$$\vec{p} = \begin{pmatrix} E_t \cos\phi \\ E_t \sin\phi \\ E_t \sinh\eta \end{pmatrix}$$

Massless particle

Redefinition of the particles' momentum by the algorithm !

$$p_t = \frac{E}{\cosh\eta}$$

Solution

Initially defining the particles as massless

↓ *Fit*

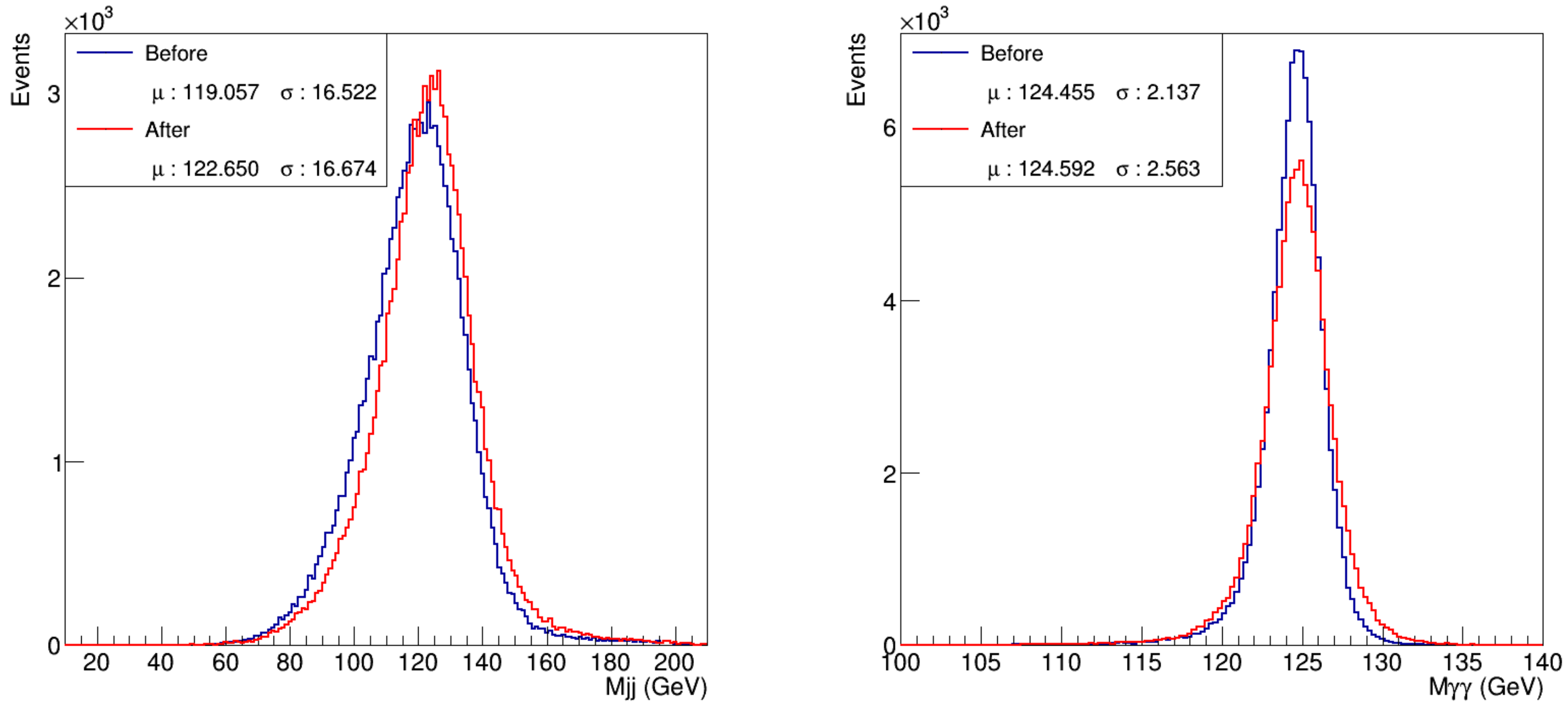
Redefining masses as :

$$m_{fit} = \frac{p_{t,fit}}{p_{t,ini}} m_{ini}$$

IV. Results

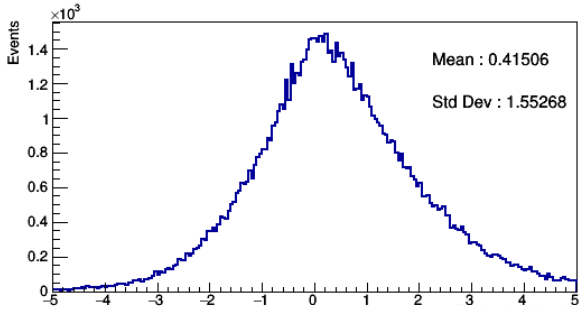
1st Observations (1)

HHbbggMVA >0.5 : "score" obtained by the event representing its chance of not being part of the background
mbbNu>0 : if > 0 the b jets were matched with the generated b jets. Can be considered as "reality".

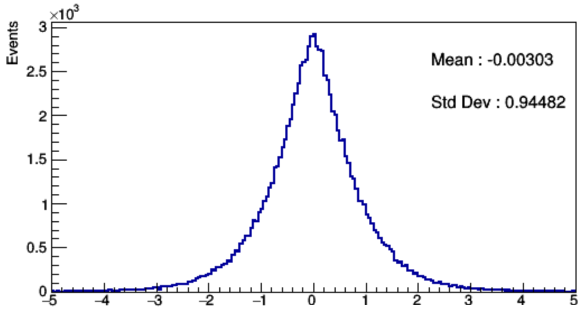


Dijet invariant mass reconstruction seems to improve

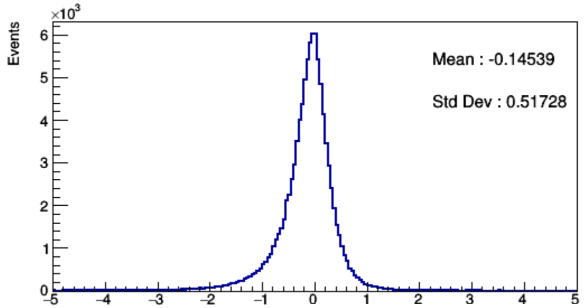
1st Observations (2)



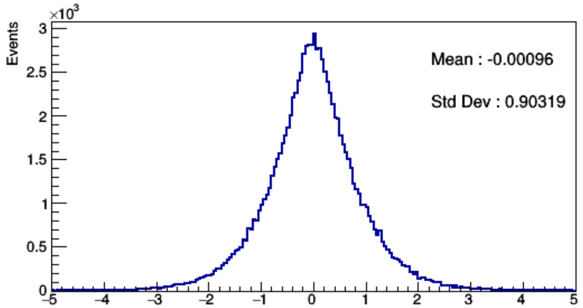
Pulls of p_t, leading jet



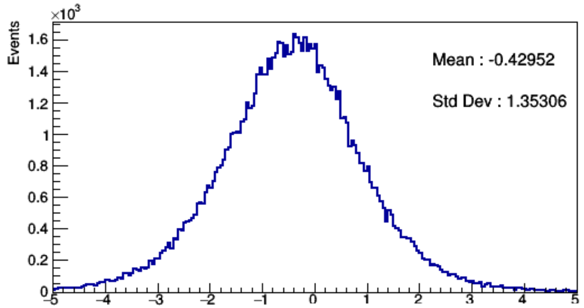
Pulls of ϕ, leading jet



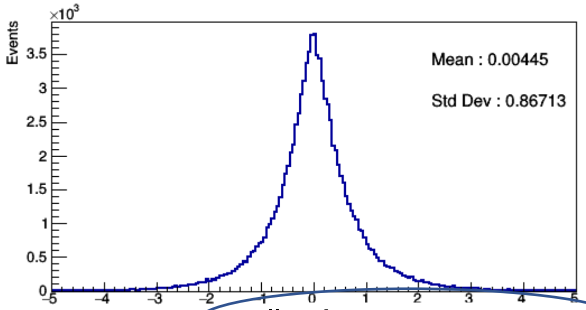
Pulls of p_t, leading photon



Pulls of ϕ, leading photon



Pulls of p_t, SumExtra+MET



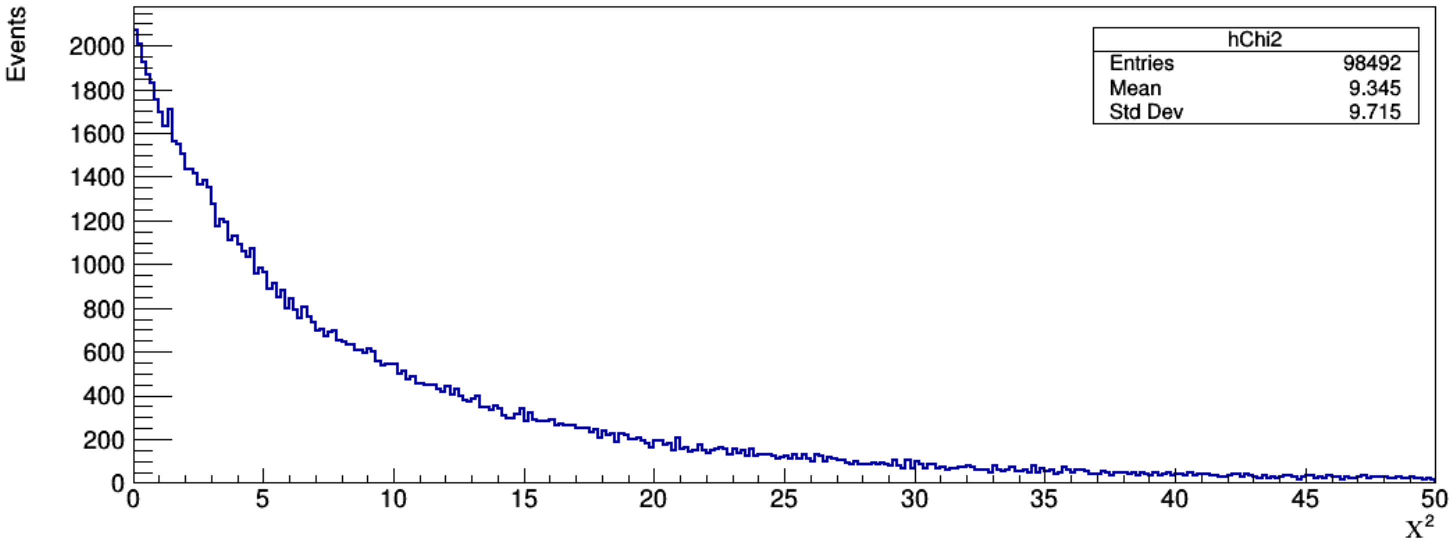
Pulls of ϕ, SumExtra+MET

Std Dev >1 : Uncertainties under-estimated
Std Dev<1 : Uncertainties over-estimated

Uncertainties ill-defined

$$\boldsymbol{pulls = \frac{y_i^{fit} - y_i^{meas}}{\sigma_i}}$$

1^{st} Observations (3)



$$ndf = measured\ parameters - fitted\ parameters + constraints = 2$$

$$Mean = ndf = 2$$
$$Std\ Dev = \sqrt{2 \times ndf} = 2$$

Expectation

Shape corresponds to $ndf = 2 \implies Mean \approx Std\ Dev$

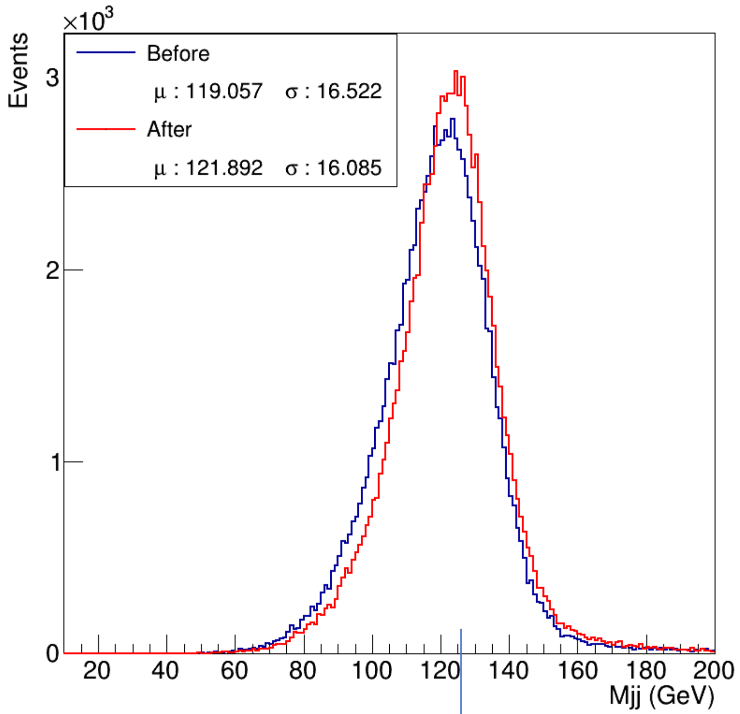
$$Mean \approx Std\ Dev \approx 9{,}5$$

reality

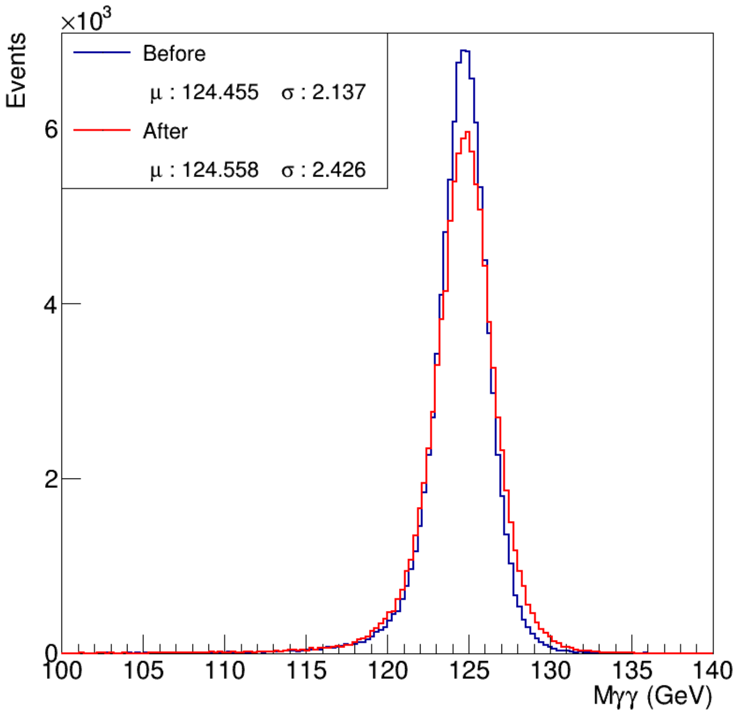
Uncertainties ill-defined

System tuning

SumExtra+MET was entirely modelized by generic functions → Tuning the system by variating their uncertainties



$m_H \approx 125$ GeV

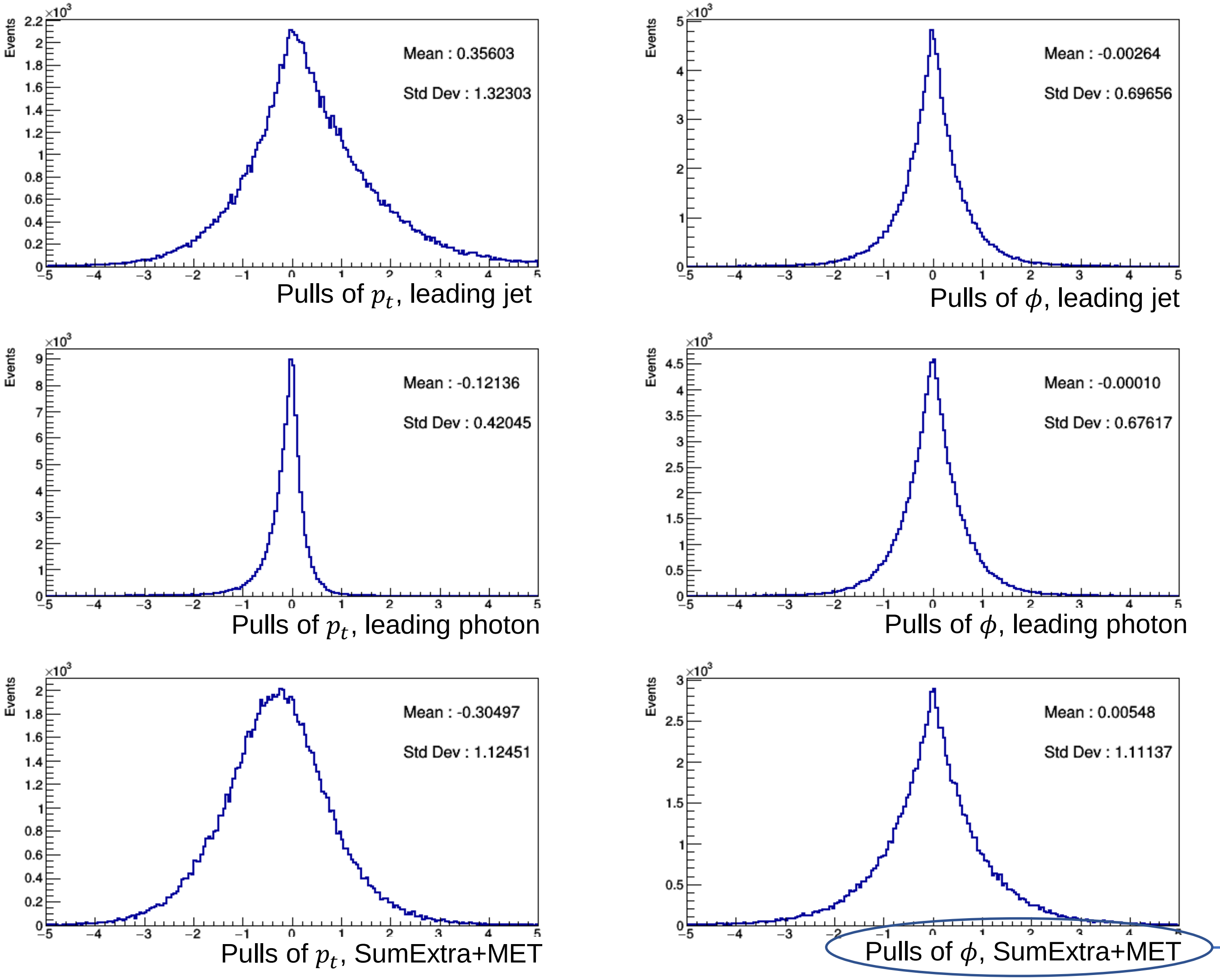


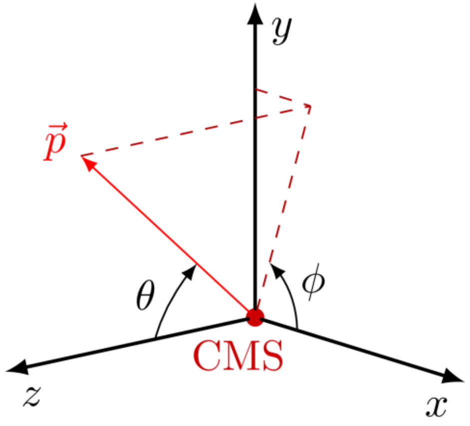
- **Improvement of the b jets** invariant mass distribution
- Photons invariant mass distribution is worsening

We can keep $\boldsymbol{m_{jj}^{fit}}$ and $\boldsymbol{m_{\gamma\gamma}^{ini}}$ if the two distributions are not correlated

Results obtained for $\sigma^{SumExtra} \times 3$

Pulls of the tuned system



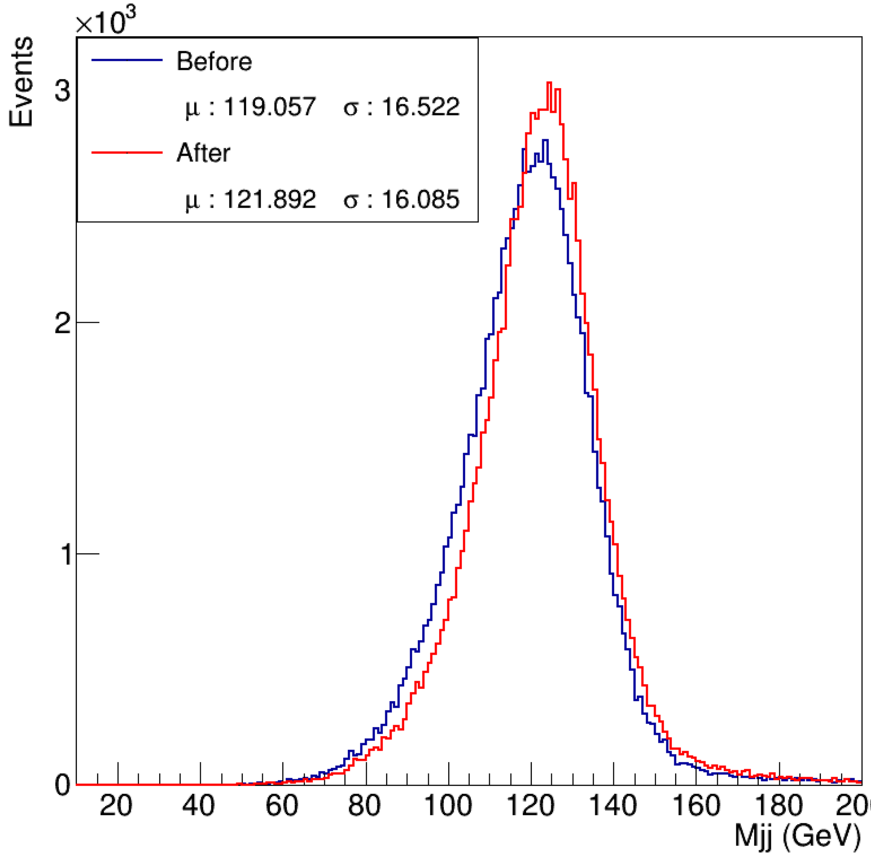


- ☑ $|pulls_\phi| \approx 0$ → p_x or p_y should not be favored
- ☑ $|pulls_{p_t}| \neq 0$ → p_t should increase for particles producing MET

Distributions not ideals but still logic

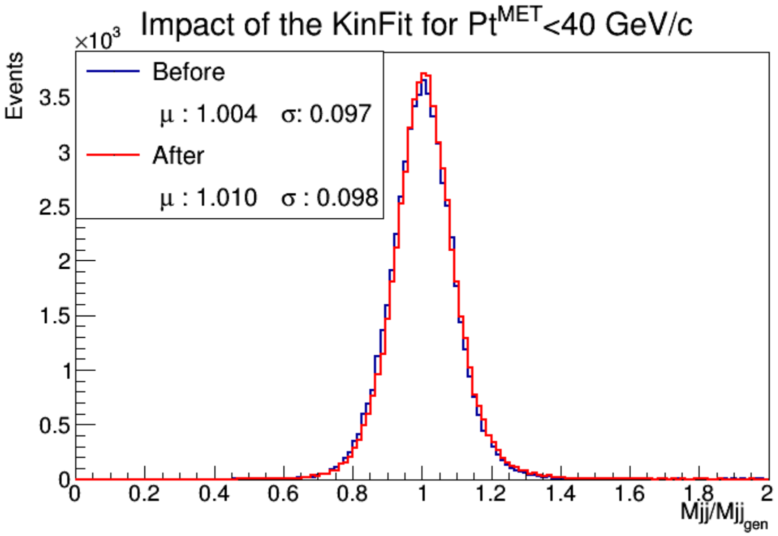
$$pulls = \frac{y_i^{fit} - y_i^{meas}}{\sigma_i}$$

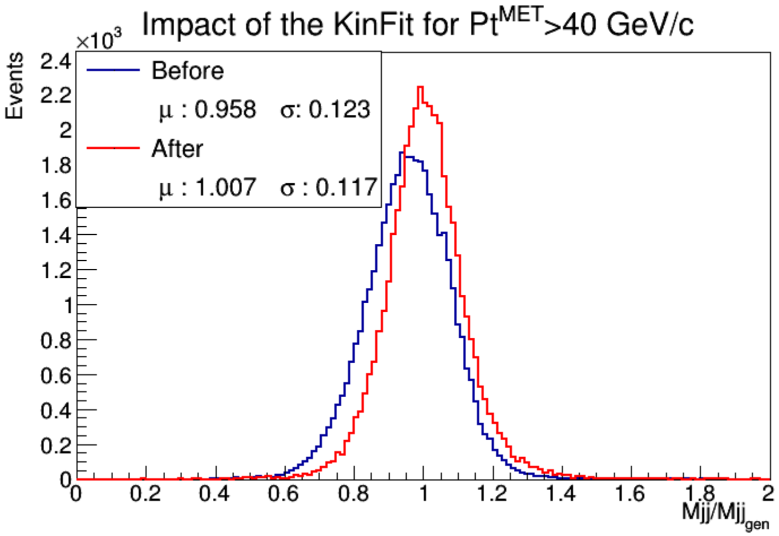
A more “realistic” mass



b jets produce lots of MET (reconstructions uncertainties and neutrinos)
⟹ **Shift toward higher mass values**
⟹ Invariant mass more “realistic”

The more unbalanced the system is, the more the regression will improve the dijet invariant mass reconstruction





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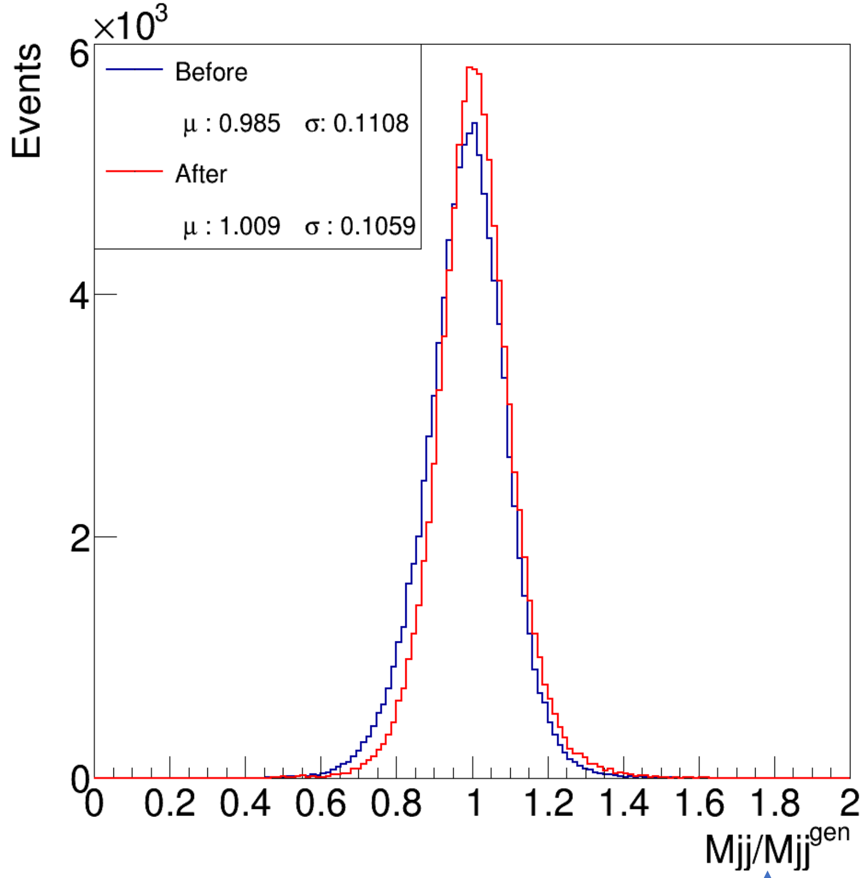

mass initially generated by the simulation (mbbNu)

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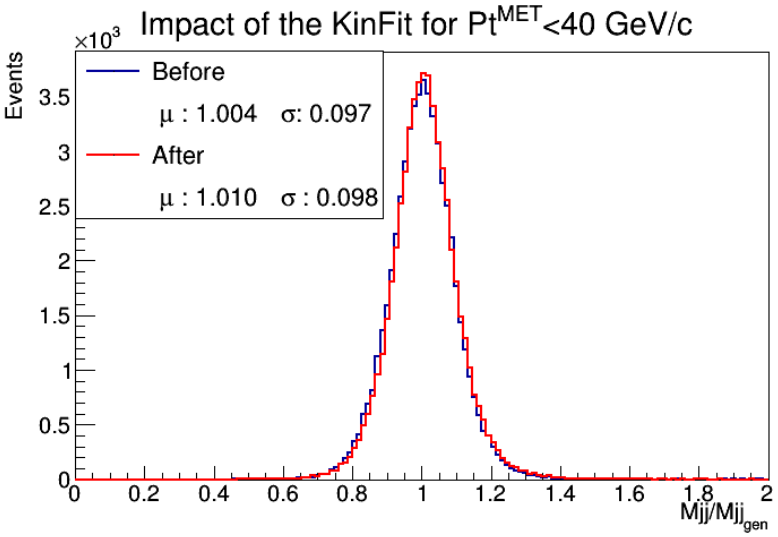

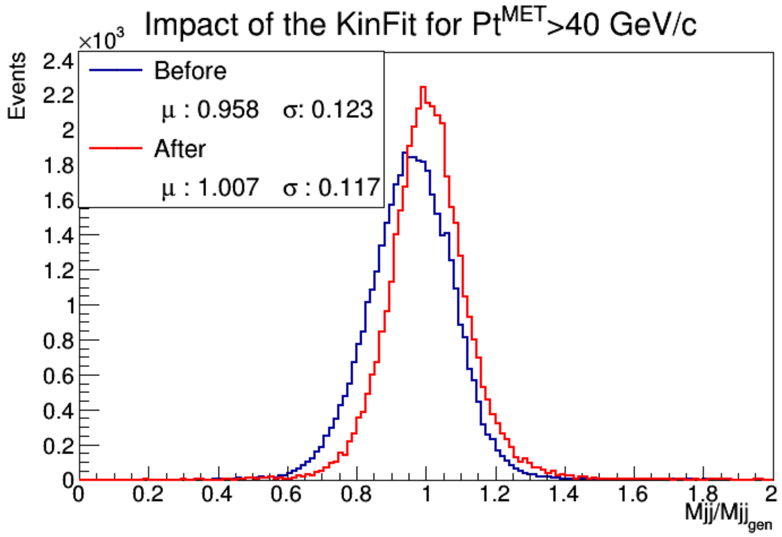

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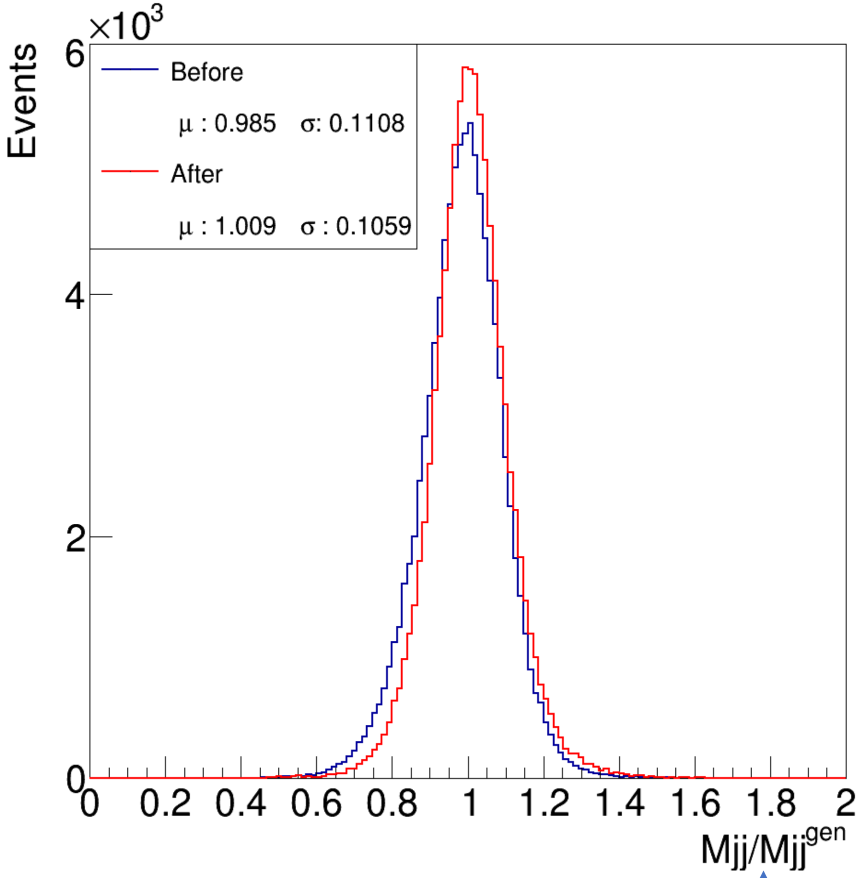

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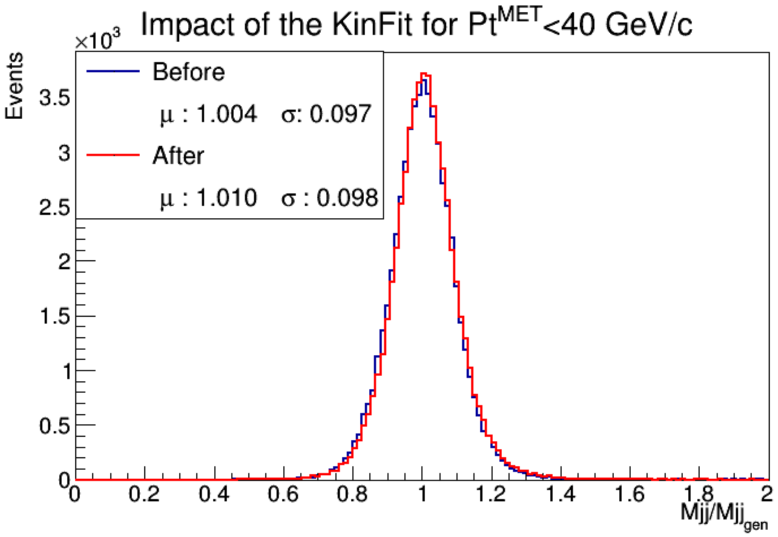
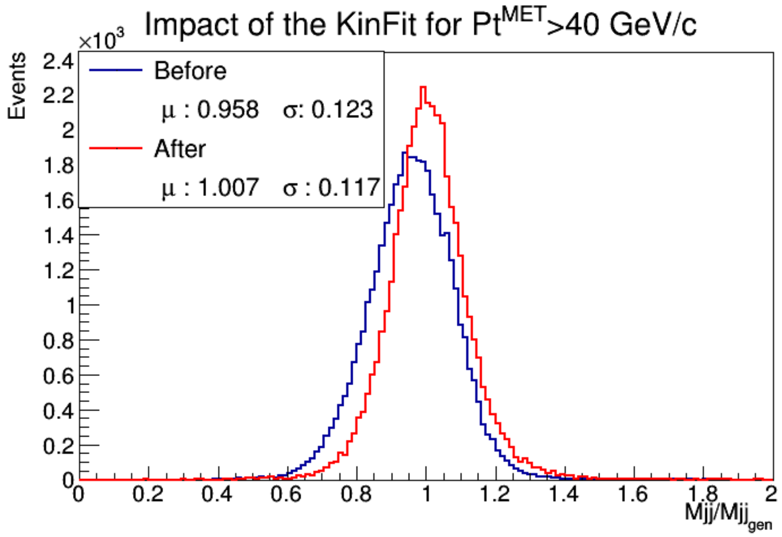




Conclusion

- **The kinematic fit improves the dijet invariant mass reconstruction** but not the photon invariant mass one : We can keep m_{bb}^{fit} and $m_{\gamma\gamma}^{ini}$ if no correlation is found between the two distributions

- **Problem in the definition of the system uncertainties,** but the obtained **results are still logic**

What comes next ?

- Applying the kinematic fit to a simulation with registered hadronic contributions
- Updating the uncertainties
- Checking the m_{bb}^{fit} and $m_{\gamma\gamma}^{ini}$ correlation
- Verifying that no observation bias was introduced
- Applying the kinematic fit on real data (from Run II)

Outlook

Improvement of the dijet reconstruction

⇓

Higher Signal to Noise Ratio of the invariant mass distribution

⇓

Lower limits on the $HH \rightarrow b\bar{b}\gamma\gamma$ production cross-section

⇓

Better constraints on λ

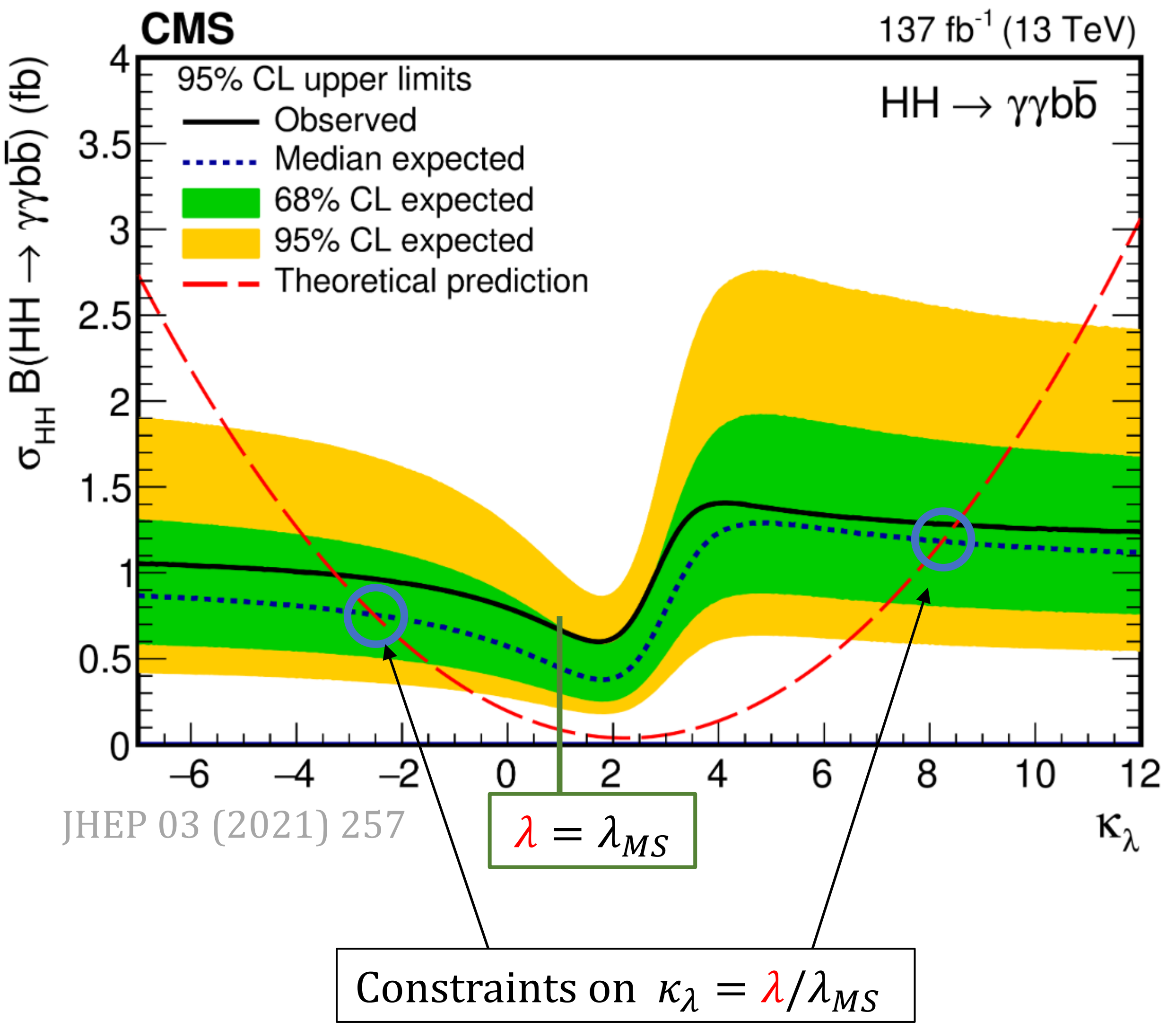
LHC Run III (2022-2025)

More statistics and improvement of the analysis's performances

$\Longrightarrow$ *Thesis*

Thank you for your attention !

State of the research



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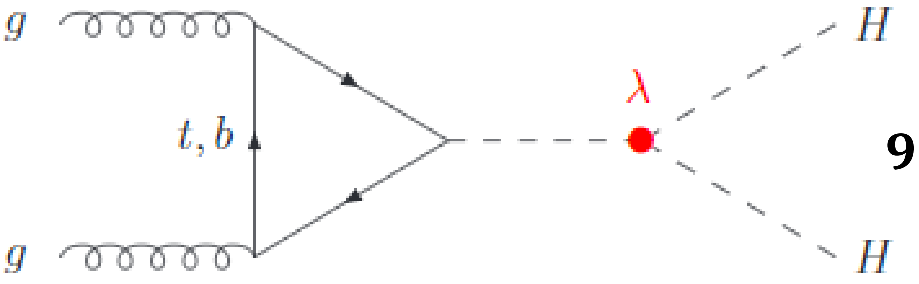
HH never observed to this day

Limits on its production cross-section

Limits on $\boldsymbol{\lambda}$

$\boldsymbol{\kappa_\lambda \in [-3.3\,, 8.5]}$

HH Production at CMS (1)



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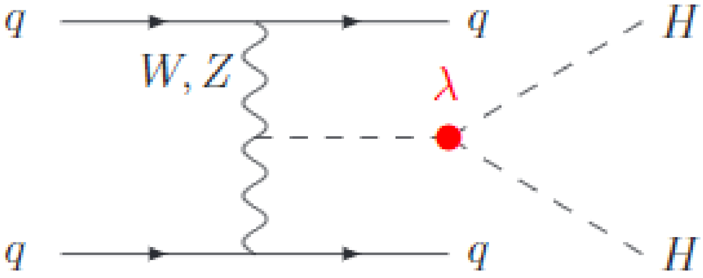

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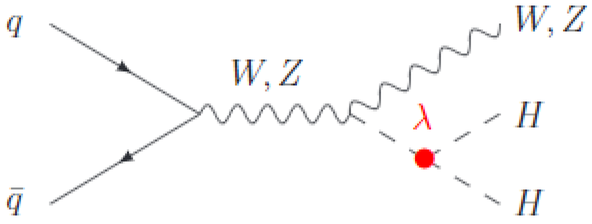

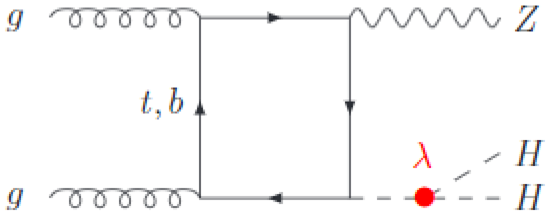

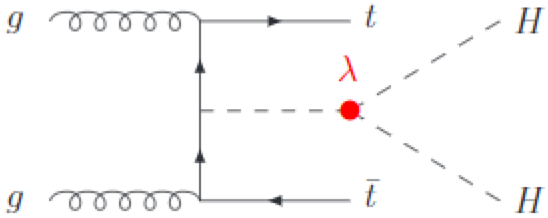

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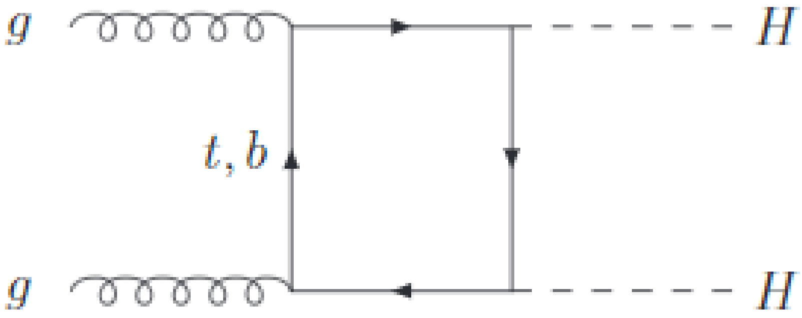
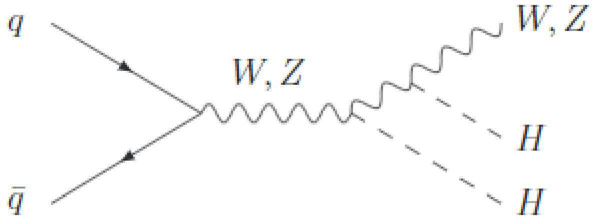
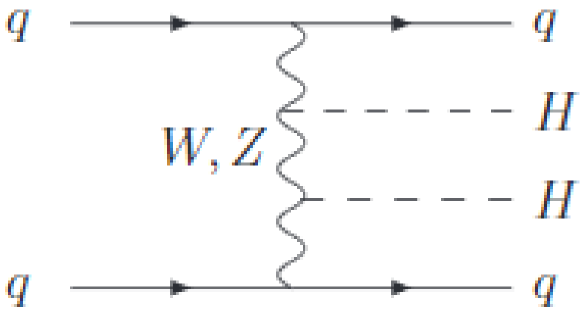
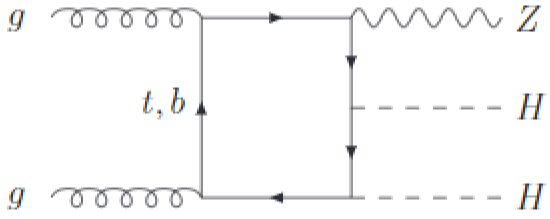
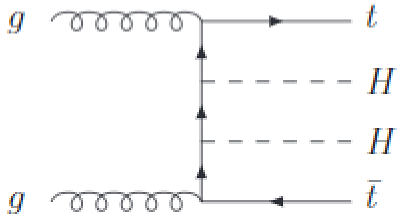
HH Production atCMS (2)









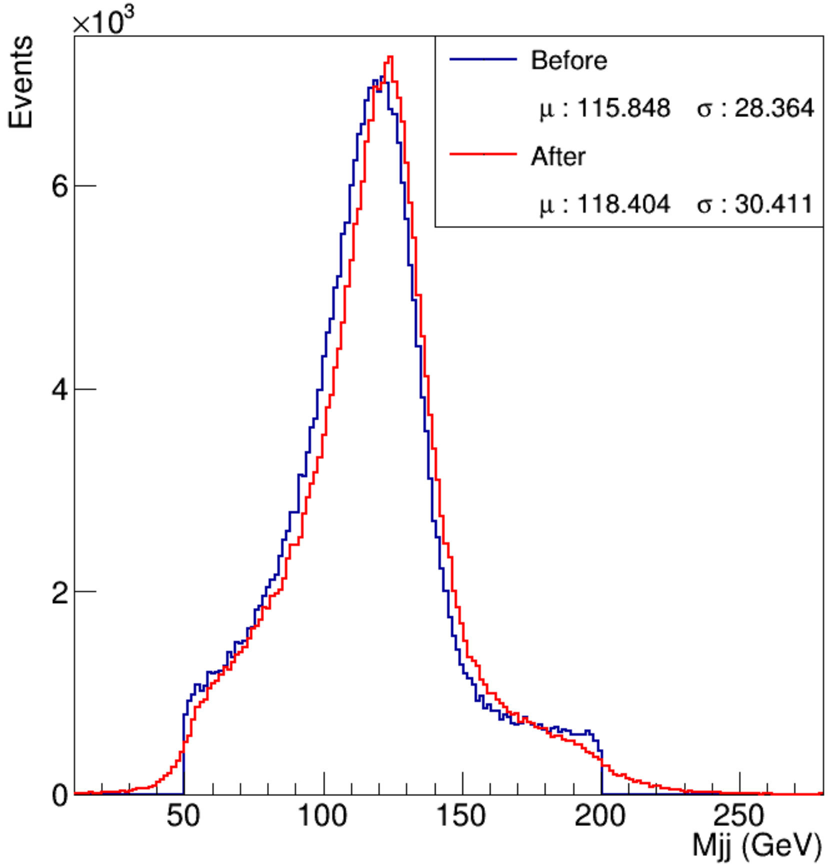


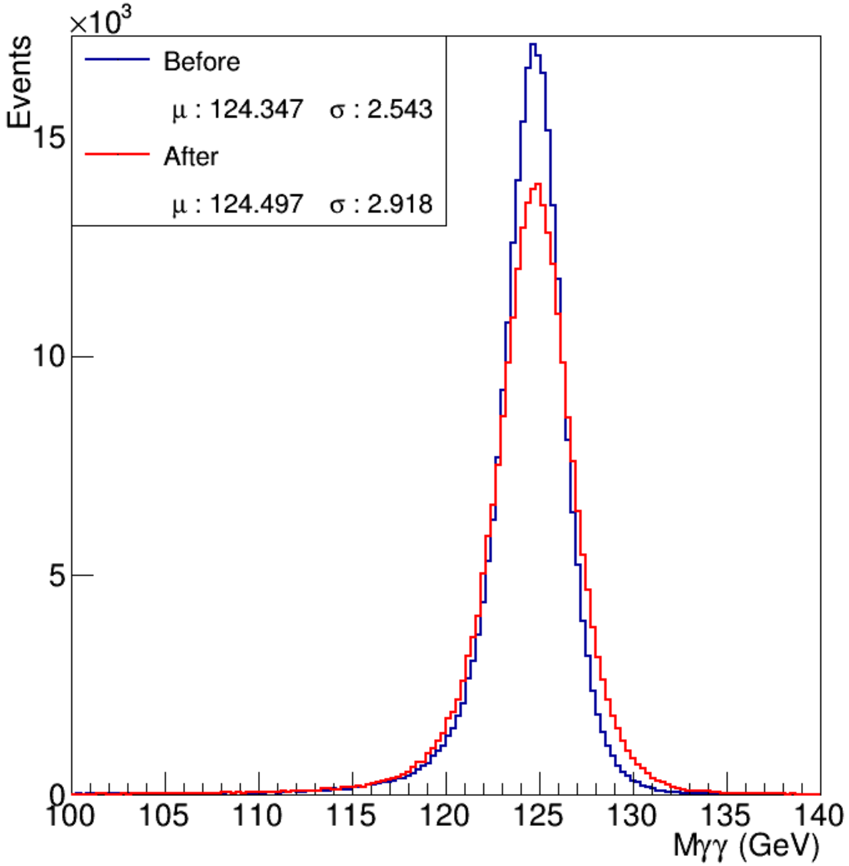
Uncertainties

$$\sigma_{E_t}^2 = a^2 + b^2 E_t + c^2 E_t^2 \quad \text{with} \quad a, b, c = \begin{cases} 5.6, 1.25, 0.033 & \text{if} \quad |\eta| < 1.4 \\ 4.8, 0.89, 0.043 & \text{else} \end{cases}$$

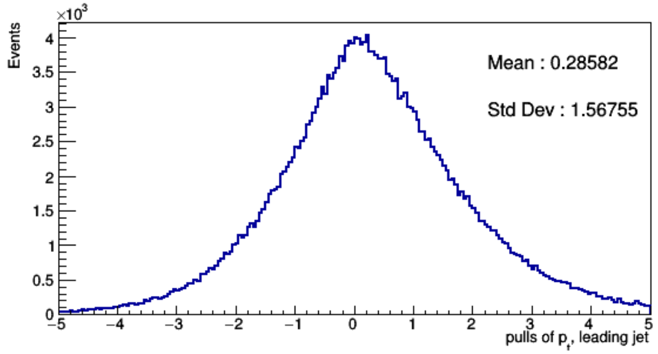
$$\sigma_{\phi}^2 = {}^{a}/_{E_t^2} + {}^{b}/_{E_t} + c \quad \text{with} \quad \mathrm{a, b, c} = \begin{cases} 6.65, 0.04, 8.49 \times 10{-}5 & \text{if} \quad |\eta| < 1.4 \\ 2.908, 0.021, 2.59 \times 10{-}4 & \text{else} \end{cases}$$

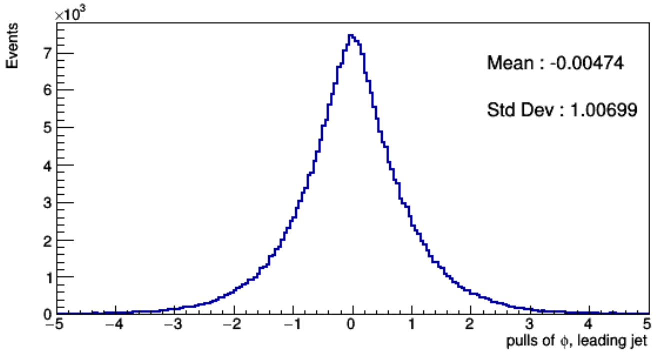
Invariant mass without MVA & matching

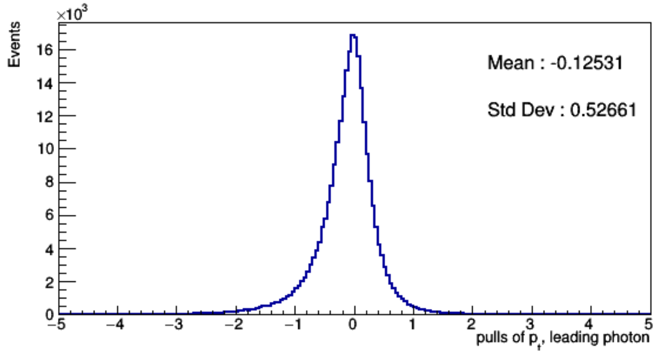


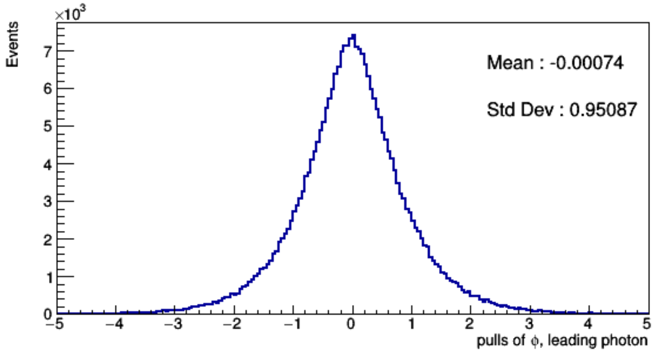


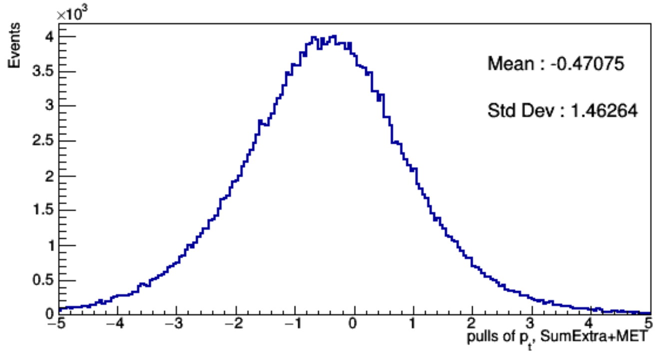
Invariant mass without MVA & matching

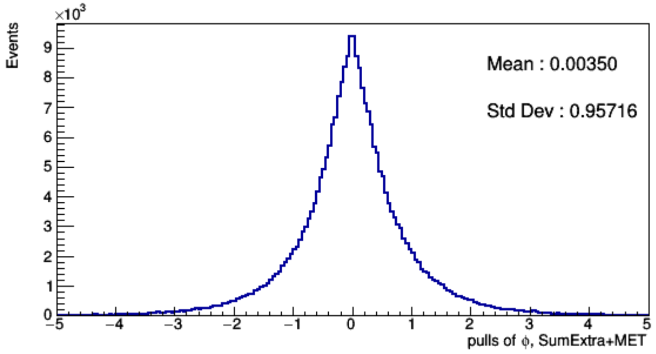




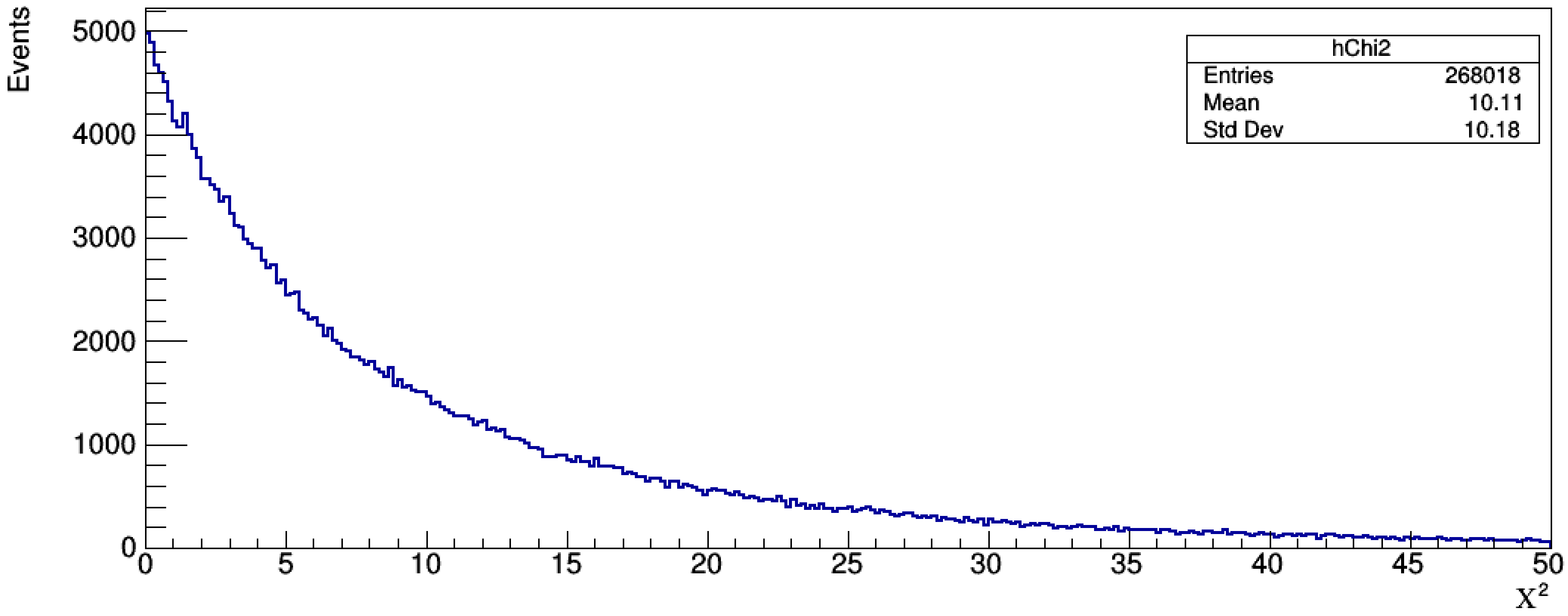




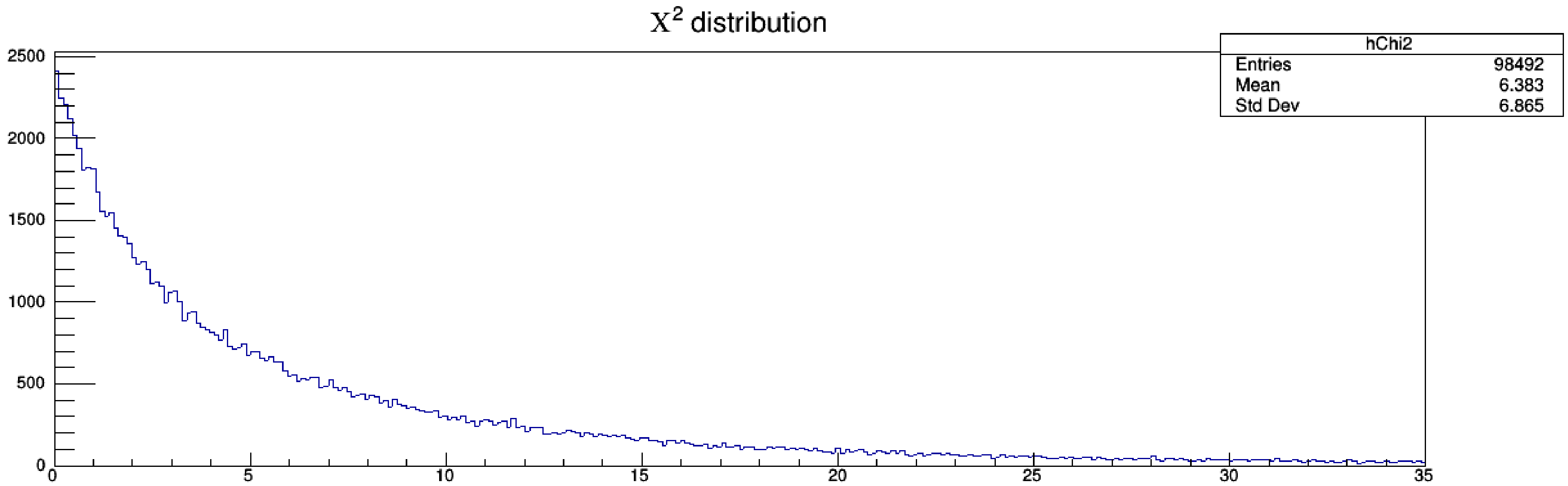




Invariant mass without MVA & matching

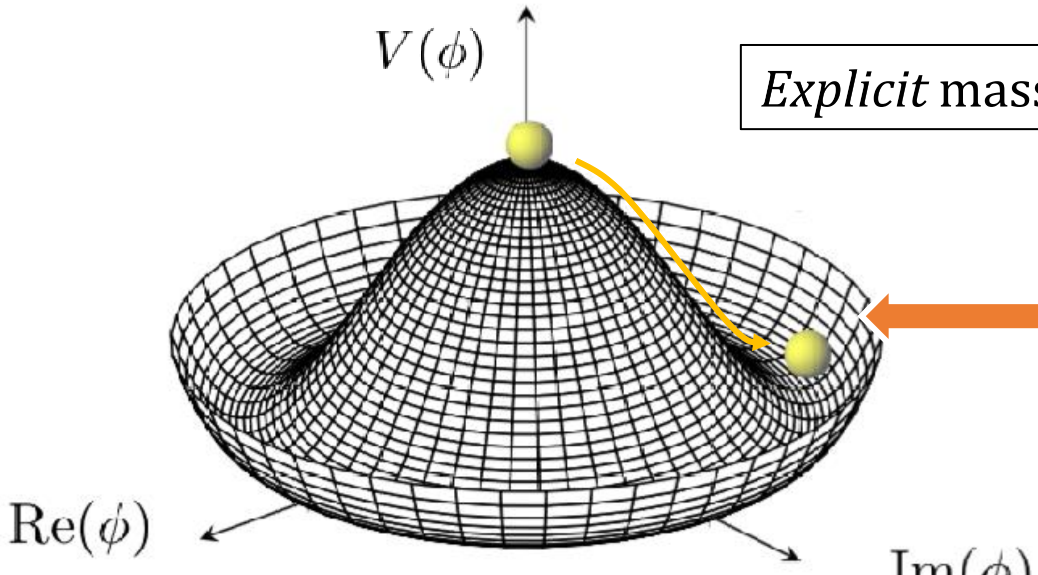


χ^2 of the final system



χ^2

The BEH mechanism



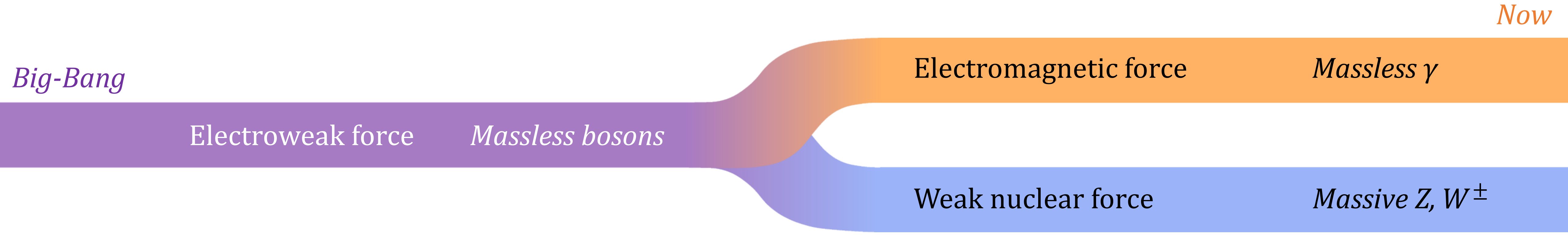
Duff, M. & Stelle, Kellogg. (2020). Sir Thomas Walter Bannerman Kibble CBE.

Explicit mass term in the Lagrangian $\Longrightarrow$ Breaking of the gauge symmetry

***Spontaneous* symmetry breaking**

Induced by the shape of the Higgs potential

Elementary particles gain mass



Higgs mechanism

Yukawa coupling constant

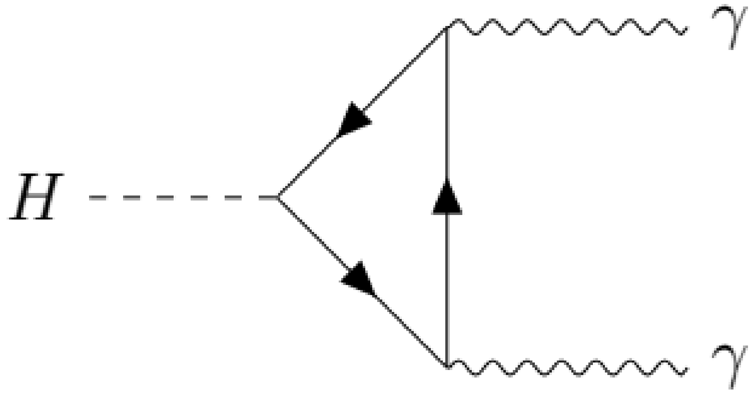
$$m_W^2 = \frac{1}{4} g^2 v^2 \qquad m_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2 \qquad m_f = y_f \frac{v}{\sqrt{2}} \qquad m_H^2 = 2\lambda v^2$$

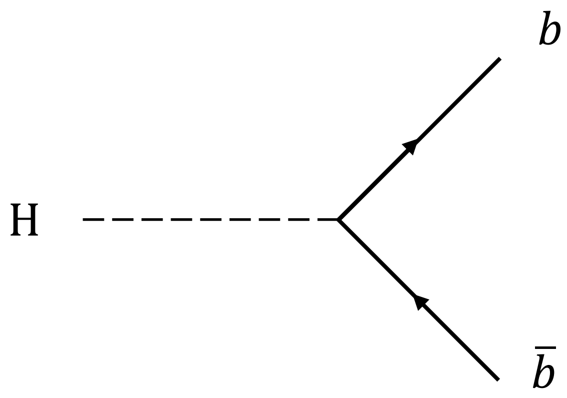
Coupling constant associated to $SU(2)_L$ and $U(1)_Y$ symetries

$HH \rightarrow b\bar{b}\gamma\gamma$

Table 17.1 The predicted branching ratios of the Higgs boson for $m_H = 125$ GeV.	
Decay mode	Branching ratio
$H \rightarrow b\bar{b}$	57.8%
$H \rightarrow WW^*$	21.6%
$H \rightarrow \tau^+\tau^-$	6.4%
$H \rightarrow gg$	8.6%
$H \rightarrow c\bar{c}$	2.9%
$H \rightarrow ZZ^*$	2.7%
$H \rightarrow \gamma\gamma$	0.2%

Thomson, M. (2013).
Modern Particle Physics



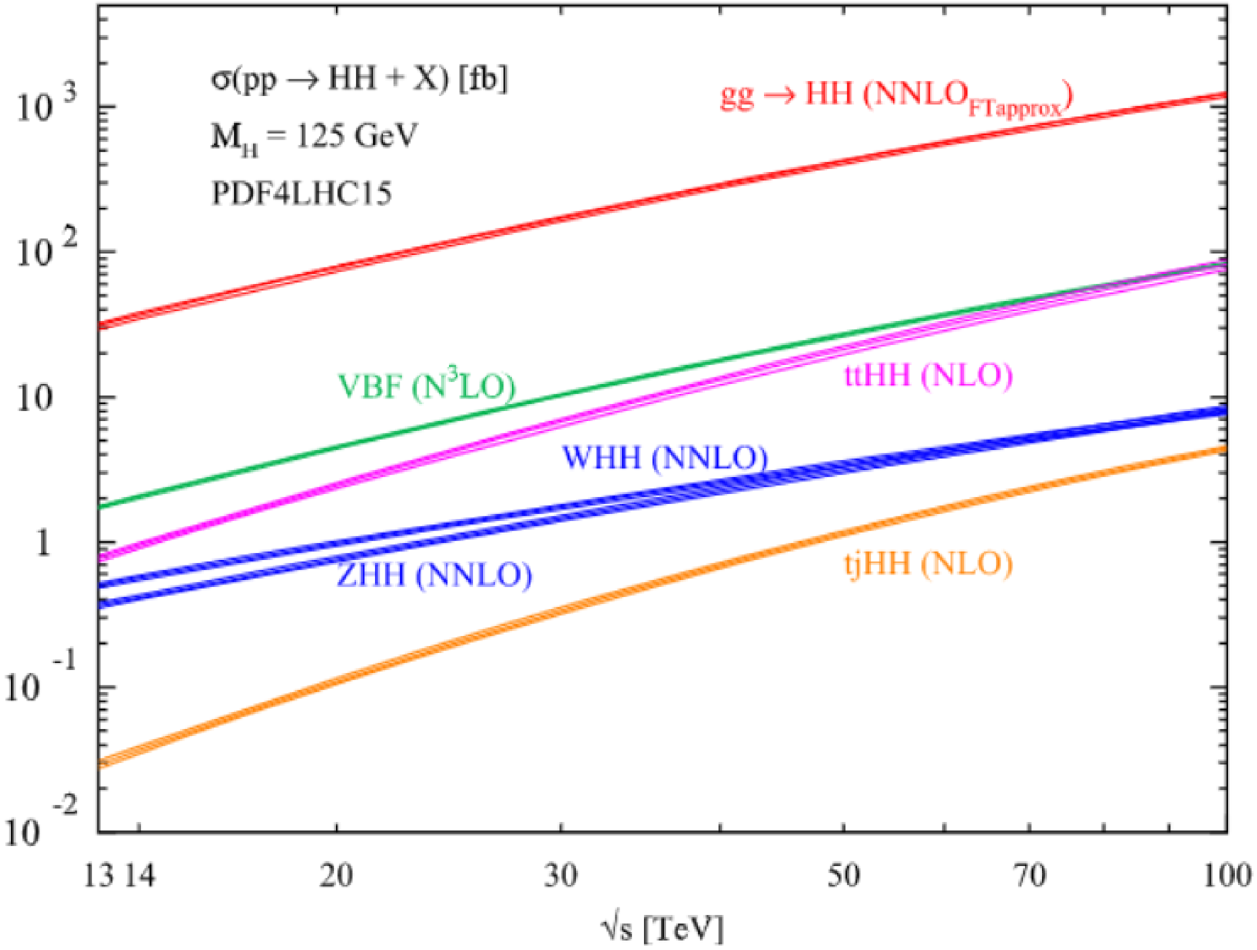


Cross-sections (1)

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
ggF HH	$31.05^{+2.2\%}_{-5.0\%} \pm 3.0\%$	$36.69^{+2.1\%}_{-4.9\%} \pm 3.0\%$	$139.9^{+1.3\%}_{-3.9\%} \pm 2.5\%$	$1224^{+0.9\%}_{-3.2\%} \pm 2.4\%$
VBF HH	$1.73^{+0.03\%}_{-0.04\%} \pm 2.1\%$	$2.05^{+0.03\%}_{-0.04\%} \pm 2.1\%$	$8.40^{+0.11\%}_{-0.04\%} \pm 2.1\%$	$82.8^{+0.13\%}_{-0.04\%} \pm 2.1\%$
ZHH	$0.363^{+3.4\%}_{-2.7\%} \pm 1.9\%$	$0.415^{+3.5\%}_{-2.7\%} \pm 1.8\%$	$1.23^{+4.1\%}_{-3.3\%} \pm 1.5\%$	$8.23^{+5.9\%}_{-4.6\%} \pm 1.7\%$
W^+HH	$0.329^{+0.32\%}_{-0.41\%} \pm 2.2\%$	$0.369^{+0.33\%}_{-0.39\%} \pm 2.1\%$	$0.941^{+0.52\%}_{-0.53\%} \pm 1.8\%$	$4.70^{+0.90\%}_{-0.96\%} \pm 1.8\%$
W^-HH	$0.173^{+1.2\%}_{-1.3\%} \pm 2.8\%$	$0.198^{+1.2\%}_{-1.3\%} \pm 2.7\%$	$0.568^{+1.9\%}_{-2.0\%} \pm 2.1\%$	$3.30^{+3.5\%}_{-4.3\%} \pm 1.9\%$
$t\bar{t}HH$	$0.775^{+1.5\%}_{-4.3\%} \pm 3.2\%$	$0.949^{+1.7\%}_{-4.5\%} \pm 3.1\%$	$5.24^{+2.9\%}_{-6.4\%} \pm 2.5\%$	$82.1^{+7.9\%}_{-7.4\%} \pm 1.6\%$
$tjHH$	$0.0289^{+5.5\%}_{-3.6\%} \pm 4.7\%$	$0.0367^{+4.2\%}_{-1.8\%} \pm 4.6\%$	$0.254^{+3.8\%}_{-2.8\%} \pm 3.6\%$	$4.44^{+2.2\%}_{-2.8\%} \pm 2.4\%$

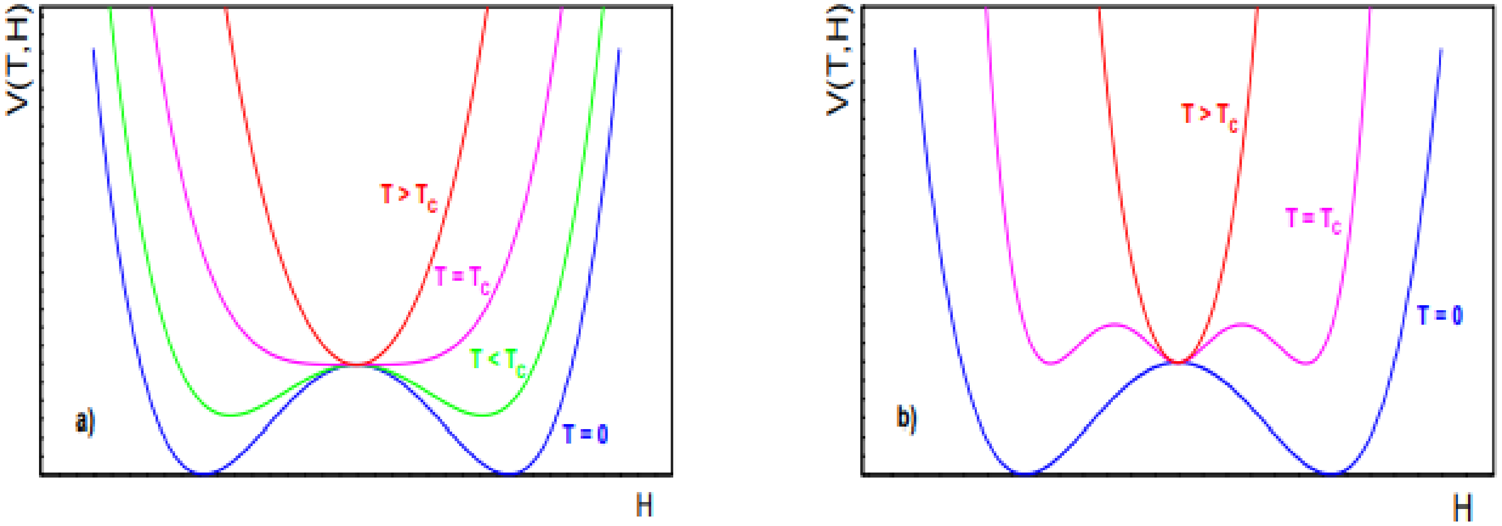
Reviews in Physics (2020) 100045

Cross-sections (2)



Reviews in Physics (2020) 100045

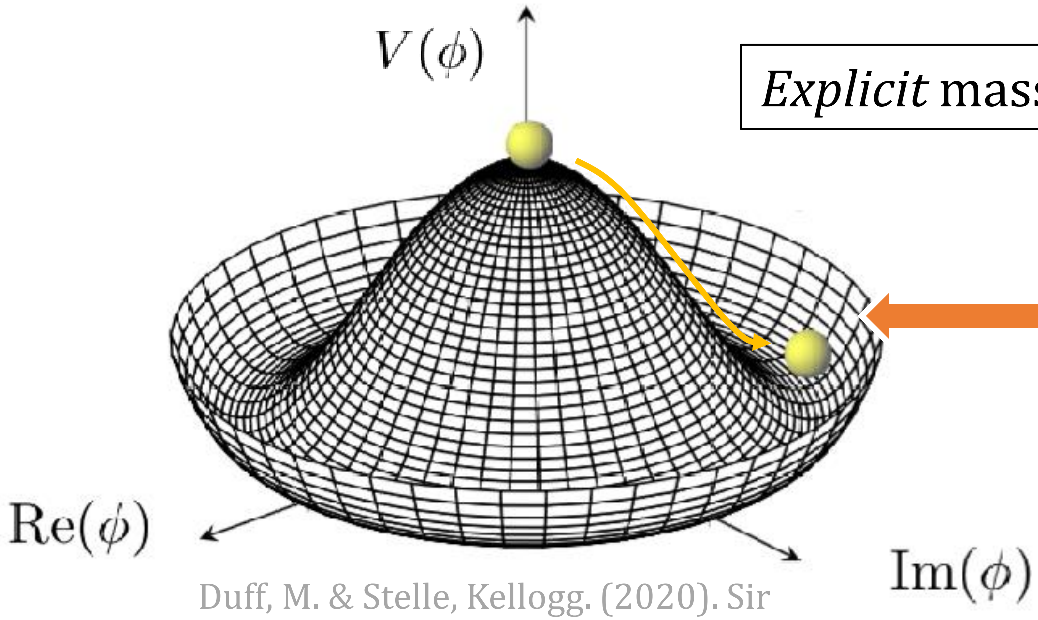
Electroweak phase transition



Modèle standard

•*Eur.J.Phys.* 38 (2017) 6, 065404

The BEH mechanism



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Now

Big-Bang

Electroweak force *Massless bosons*

Electromagnetic force *Massless γ*

Weak nuclear force *Massive $Z, W^{\pm}$*