$H \to \gamma\gamma$ search at low mass with CMS & Electroweak precision test of BSM theories for future colliders

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IP2I Lyon France

Outline

1. Physics analysis and calibration in CMS

- Search for a low mass resonance in the diphoton channel
- Extraction of the photon energy scale calibration

2. Electroweak precision test of BSM theories

- SU(5) aGUT
- PVpy package

Physics analysis and calibration in CMS

Motivation for a $H \to \gamma\gamma$ search at low mass

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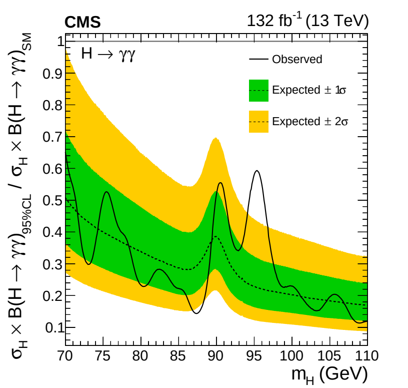

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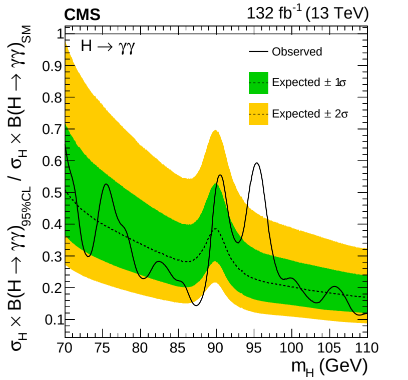
$\rightarrow$ **Pursue the analysis with 2022 + 2023 data**



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Analysis strategy: workflow

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Background modelling (data-driven)
Signal modelling (MC)

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Remove the maximum of background

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Several other type of events have
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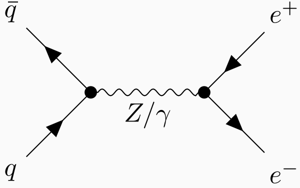

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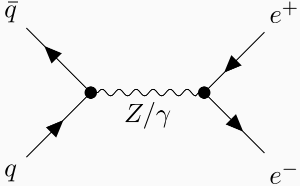

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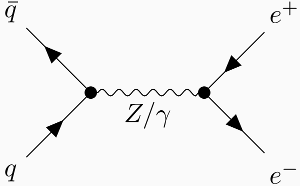

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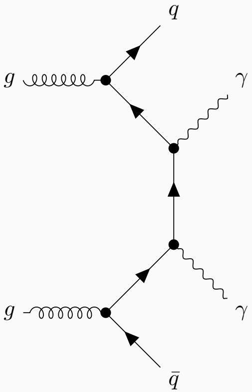

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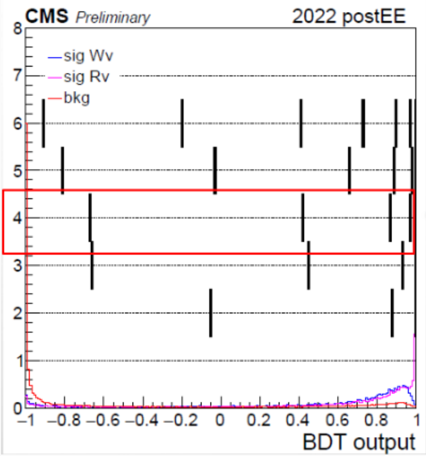

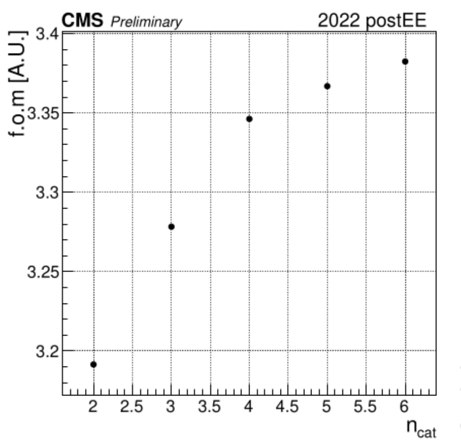

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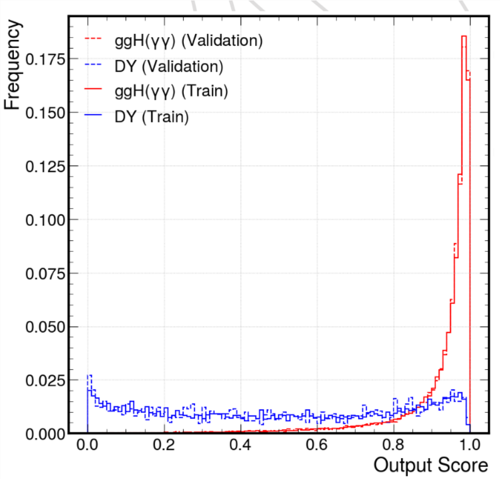

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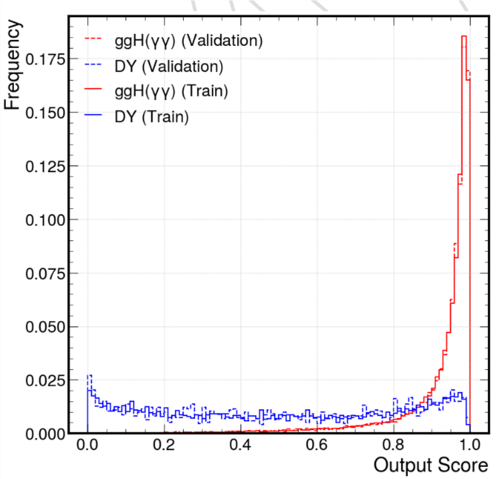

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→ Keep events with a score > 0.7

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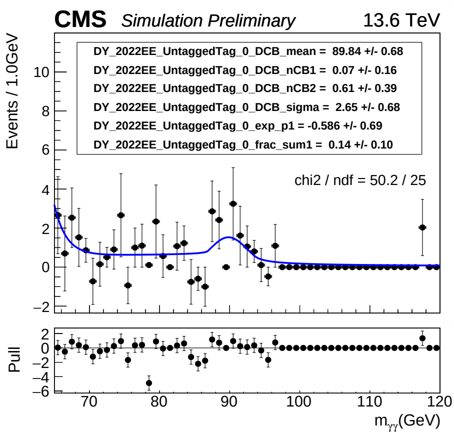

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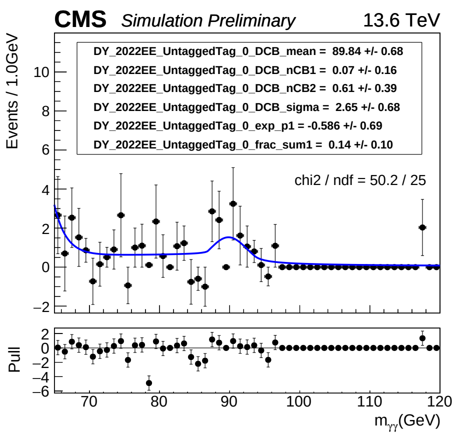
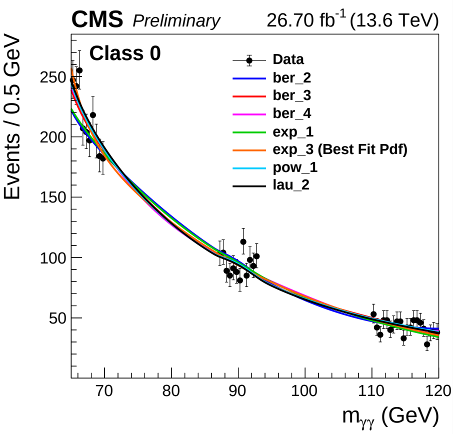
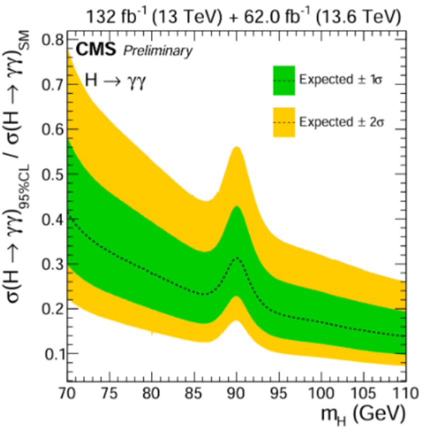


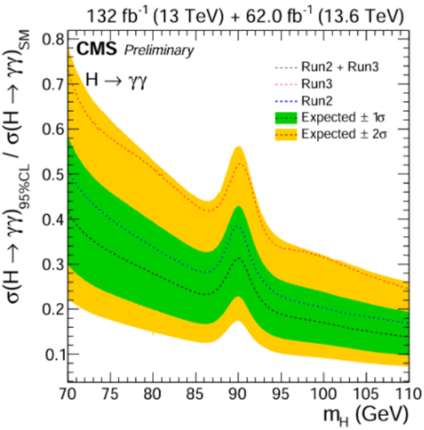


Analysis strategy: limits plots

- Combining Run 2 with 2022–2023 data and improved event selection results in reduced background and better expected limits



Run2 + Run3 (2022 + 2023)



Comparisons

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→ **Currently working on run 2 and run 3 data**

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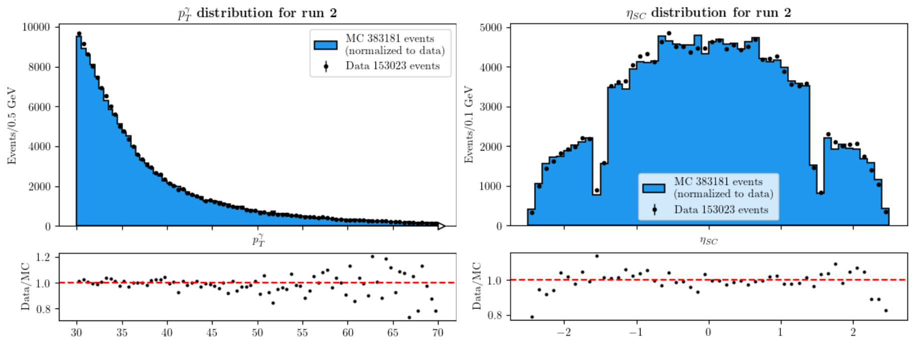
Photon energy response depends on:

- **Detector region** η_{SC}
- **Shower containment** $R9$
- **Energy dependence** p_T



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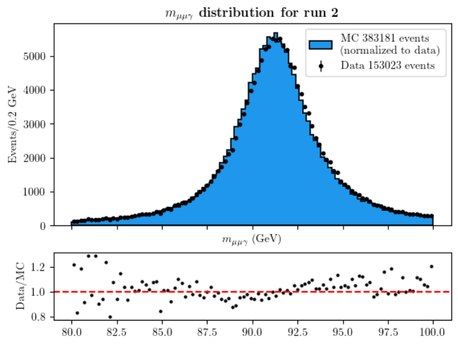

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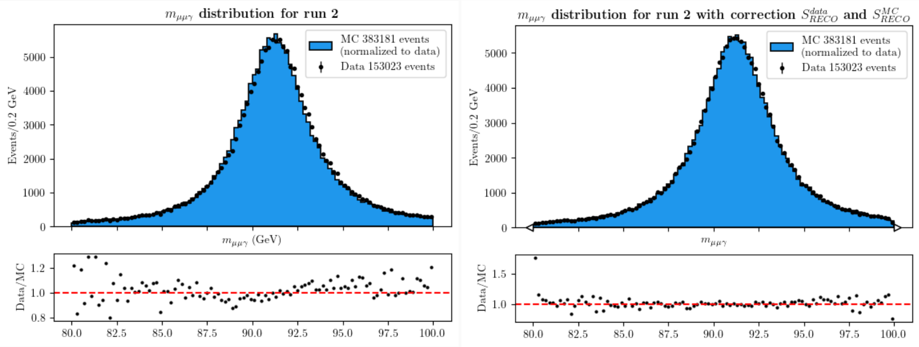

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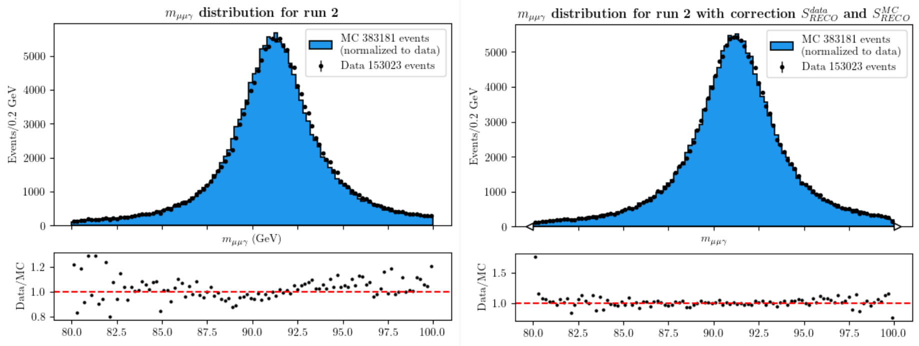
→ Currently comparing results with colleagues using an alternative method (IJaz)



Electroweak precision test of BSM theories

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At future colliders, improvement in precision will make EW precision tests a central tool to probe BSM physics

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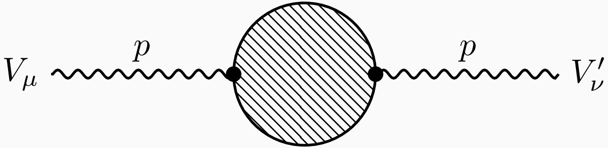

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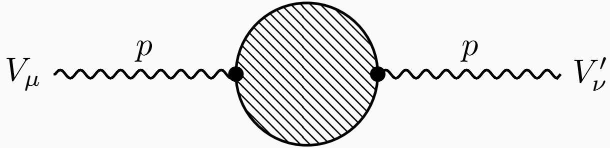

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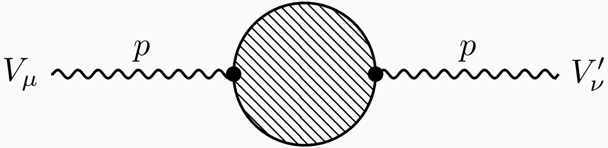

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+ a copy of SM fermions with left singlets and right doublets (only 3rd generation)

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$$\mathbf{A}_\mu = \begin{pmatrix} \mathbf{G} - \frac{1}{3}\mathbf{B} & \mathbf{X} \;\; \mathbf{Y} \\ \overline{\mathbf{X}} & \mathbf{W} + \frac{1}{2}\mathbf{B} \\ \overline{\mathbf{Y}} & \end{pmatrix}_\mu \qquad \phi_5 = \begin{pmatrix} \mathbf{H} \\ \phi_h \end{pmatrix}$$

+ a copy of SM fermions with left singlets and right doublets (only 3rd generation)

Odd and even Kaluza-Klein tower:

Electroweak precision test of SU(5) aGUT

- A BSM theory where couplings g_1, g_2, g_3 are asymptotically unifying in the UV regime

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Odd and even Kaluza-Klein tower:

$$\phi(x,y) = \begin{cases} \sum_n \phi_n(x)\,(\sin,\cos)\left(\frac{ny}{R}\right) & \text{with} \quad n \text{ even} \\ \sum_m \phi_m(x)\,(\sin,\cos)\left(\frac{my}{R}\right) & \text{with} \quad m \text{ odd} \end{cases}$$

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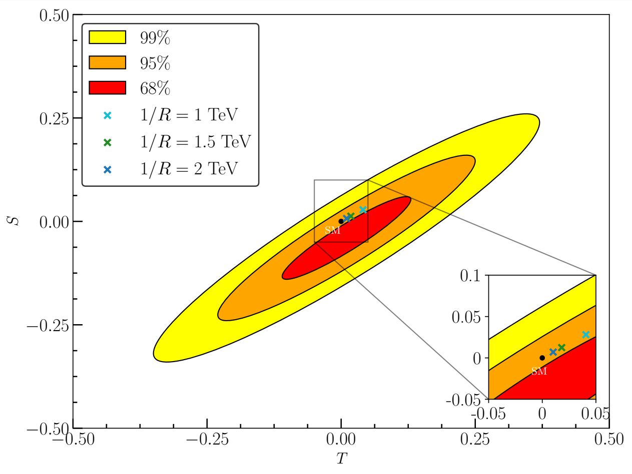

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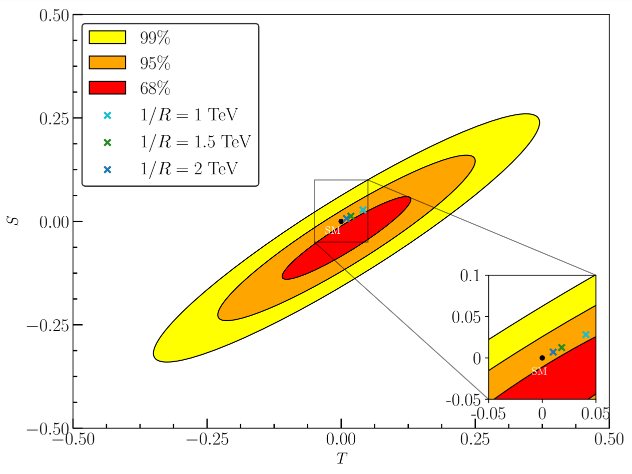
→ No constraints on R with current precision



Electroweak precision test of SU(5) aGUT

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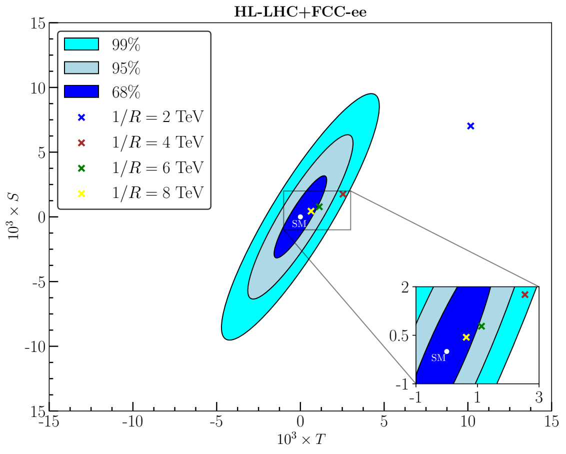

Electroweak precision test of SU(5) aGUT

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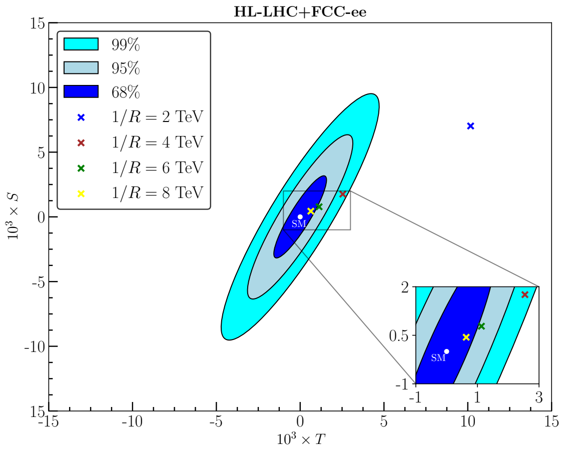
→ **Bounds beyond actual LHC reach**



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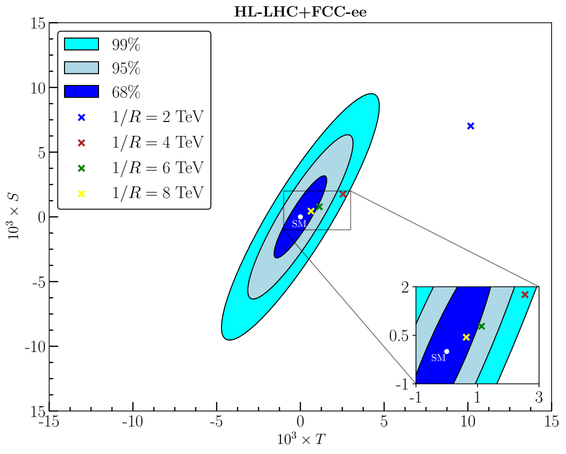
More details on https://arxiv.org/abs/2601.02161



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$$\int \mathrm{d}^d k \, \frac{T_{\mu\nu}(p,k,m_1,m_2)}{\left[(p-k)^2 - m_1^2\right]\left[k^2 - m_2^2\right]}$$

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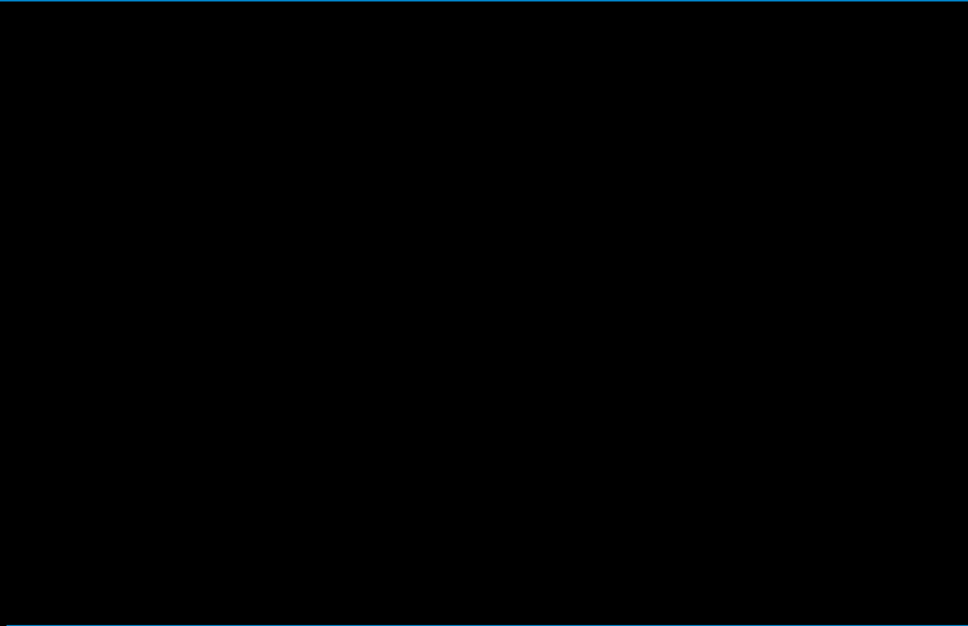
$$\int \mathrm{d}^d k \, \frac{T_{\mu\nu}(p,k,m_1,m_2)}{\left[(p-k)^2 - m_1^2\right]\left[k^2 - m_2^2\right]} = \Pi(p^2)\eta_{\mu\nu} + \Delta(p^2)p_\mu p_\nu$$

Tensorial decomposition

→ Express $\Pi(p^2), \Delta(p^2)$ in terms of Passarino-Veltman (PV) scalar functions A_0, B_0, B_{00} and handle non-trivial singularity structures

PVpy package



PVpy package

```
from pvpy.functions.scalar import A0, B0, B00, dB00_dp2, dB0_dp2
from pvpy.symbols import p2, m1, m2, m
from pvpy.numeric import compile
from IPython.display import display
import sympy as sp
import numpy as np
```

✓ 0.0s

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```
✓ 0.0s

```
expr = (m**2 + p2) * A0(m) + B0(p2, m1, m2) + B00(p2, m1, m2)
display(expr)
expr_diff = sp.diff(expr, p2)
display(expr_diff)
expr_p2_0 = dB00_dp2(0,m1,m2) + B0(0,m,m)
display(expr_p2_0)
```
✓ 0.0s

$$\left(m^2 + p^2\right) A_0\left(m\right) + B_0\left(p^2, m_1, m_2\right) + B_{00}\left(p^2, m_1, m_2\right)$$

$$A_0\left(m\right) + \frac{\partial B_{00}}{\partial p^2}\left(p^2, m_1, m_2\right) + \frac{\partial B_0}{\partial p^2}\left(p^2, m_1, m_2\right)$$

$$B_0\left(0, m, m\right) + \frac{\partial B_{00}}{\partial p^2}\left(0, m_1, m_2\right)$$

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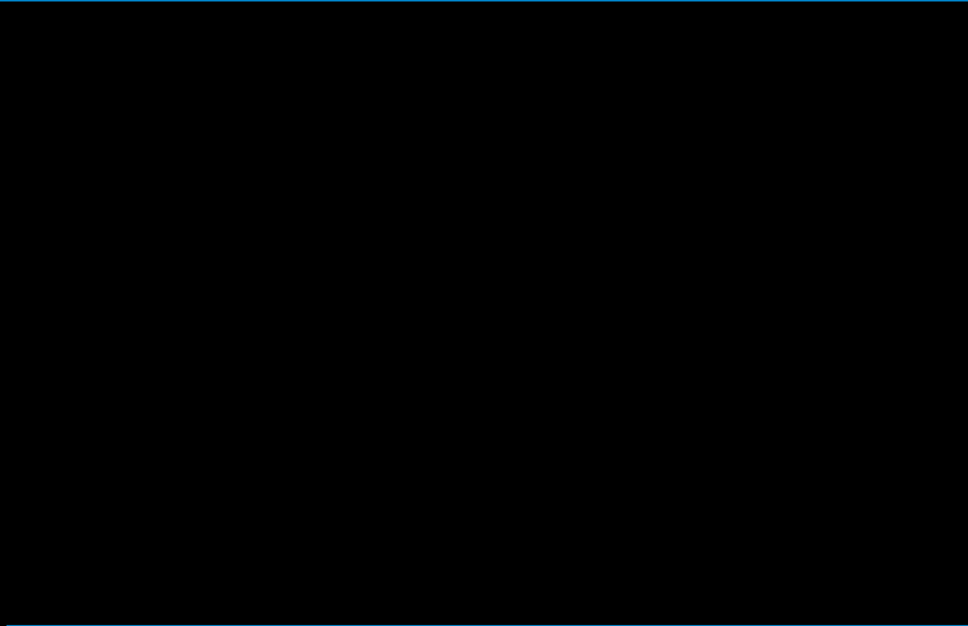
$$(m^2 + p^2)\, A_0(m) + B_0(p^2, m_1, m_2) + B_{00}(p^2, m_1, m_2)$$

$$A_0(m) + \frac{\partial B_{00}}{\partial p^2}(p^2, m_1, m_2) + \frac{\partial B_0}{\partial p^2}(p^2, m_1, m_2)$$

$$B_0(0, m, m) + \frac{\partial B_{00}}{\partial p^2}(0, m_1, m_2)$$

→ Define PV objects that behave like sympy object

PVpy package



PVpy package

```
expr_p2_0.doit(part = "full")
```

✓ 0.0s

$$-\log\left(\frac{m^2}{\mu^2}\right)+\frac{\log\left(\frac{m_1 m_2}{\mu^2}\right)}{12}-\frac{5m_1^4-22m_1^2m_2^2+5m_2^4}{72\left(m_1^2-m_2^2\right)^2}-\frac{\left(-3m_1^6+9m_1^4m_2^2+9m_1^2m_2^4-3m_2^6\right)\log\left(\frac{m_1^2}{m_2^2}\right)}{72\left(m_1^2-m_2^2\right)^3}+\frac{11}{12\epsilon}$$

```
expr_p2_0.doit(part = "pole") # part = "finite"
```

✓ 0.0s

$$\frac{11}{12}$$

→ Get symbolic expressions depending on the kinematic conditions for both the divergent and finite part

PVpy package

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expr_p2_0.doit(part = "full")
```

✓ 0.0s

$$-\log\left(\frac{m^2}{\mu^2}\right) + \frac{\log\left(\frac{m_1 m_2}{\mu^2}\right)}{12} - \frac{5m_1^4 - 22m_1^2m_2^2 + 5m_2^4}{72\left(m_1^2 - m_2^2\right)^2} - \frac{\left(-3m_1^6 + 9m_1^4m_2^2 + 9m_1^2m_2^4 - 3m_2^6\right)\log\left(\frac{m_1^2}{m_2^2}\right)}{72\left(m_1^2 - m_2^2\right)^3} + \frac{11}{12\epsilon}$$

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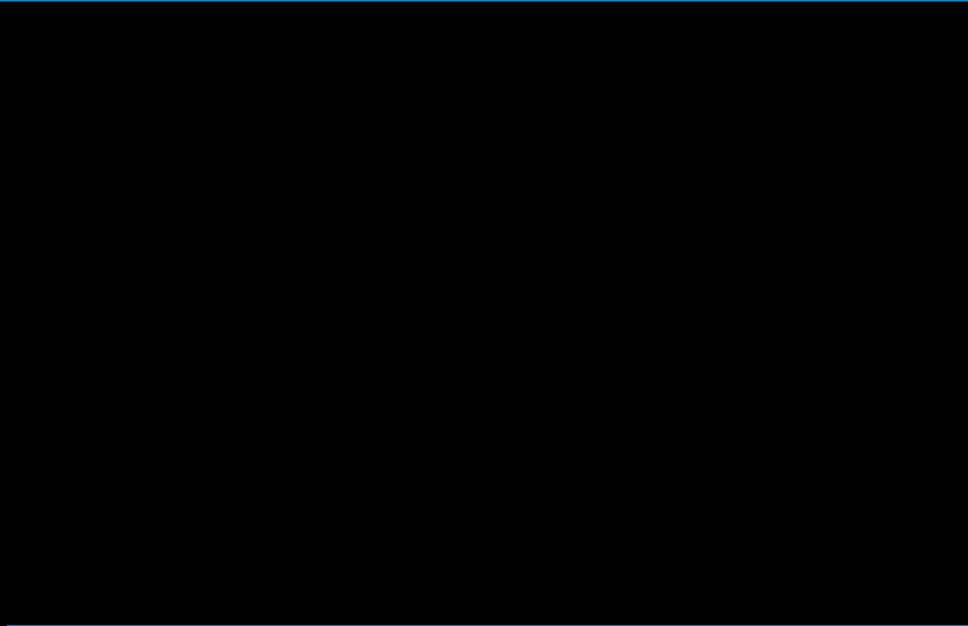
```
expr_p2_0.doit(part = "full").series(m2, n=2)
```

✓ 0.0s

$$\frac{11}{12\epsilon}-\frac{5}{72}-\log\left(\frac{m^2}{\mu^2}\right)-\frac{\log(\mu)}{6}+\frac{\log(m_1)}{6}+O\left(m_2^2\log(m_2)\right)$$

PVpy package



PVpy package

```
mu = 91
# Transform symbolic expressions into numpy numerical functions
a0 = compile( A0(m), mu_default = mu, part = "finite" )
b0 = compile( B0(p2, m1, m2), mu_default = mu, part = "finite" )
b00 = compile( B00(p2, m1, m2), mu_default = mu, part = "finite" )

G_symb =  ( A0(m1) + A0(m2) - 4 * B00(p2,m1,m2) + (m1**2 + m2**2 - p2) * B0(p2, m1, m2) )
G_finite = compile( G_symb, mu_default = mu, part = "finite" )
```

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→ Create numpy callable functions that behave well in the limit of degenerate masses and low momentum

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G_finite = compile( G_symb, mu_default = mu, part = "finite" )
```
✓ 0.0s

→ Create numpy callable functions that behave well in the limit of degenerate masses and low momentum

```python
print( a0(150) , b0(np.zeros(2), np.array([100,200]), np.array([100,150])),
       G_finite(np.zeros(2), np.array([100,200]), np.array([100,150])) )
```
✓ 0.0s

```
10.089558926742736 [-0.18862136 -1.31466962] [ -3772.42717885 -83826.69526718]
```

Conclusion and perspectives

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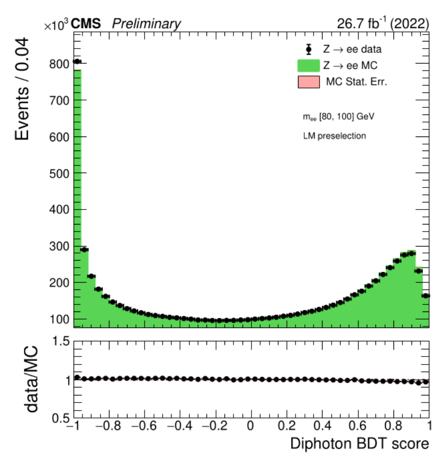
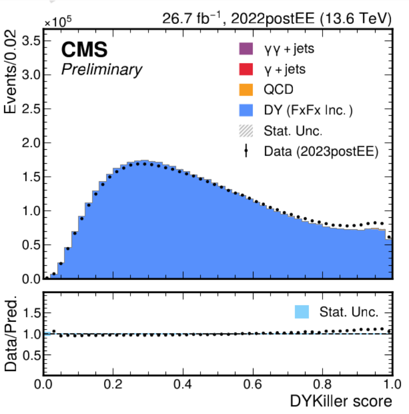
- Developped a package to summarize, need to add tensorial decomposition and 3-points functions for induced couplings
- Other projects using my previous experience: VLQ + Composite Higgs

Thank you for your attention!

BDT and DY killer validation





Electroweak precision test of the SM with additional VLQ

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$$-\sum_{i,j}\int \frac{\mathrm{d}^4k}{(2\pi)^4}\mathrm{Tr}\left[i\gamma_\mu\left(v-a\gamma_5\right)_{ij}\frac{i\left(k_\sigma\gamma^\sigma+m_{1,i}\right)}{k^2-m_{1,i}^2}i\gamma_\nu\left(v'-a'\gamma_5\right)_{ij}\frac{i\left((k-p)_\sigma\gamma^\sigma+m_{2,j}\right)}{(k-p)^2-m_{2,j}^2}\right]$$

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→ need to be done numerically to scan the parameter space
→ PVpy

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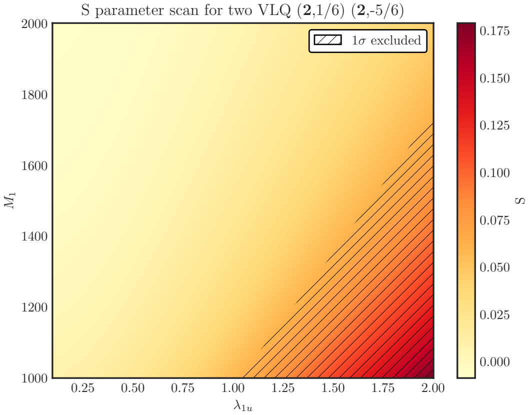

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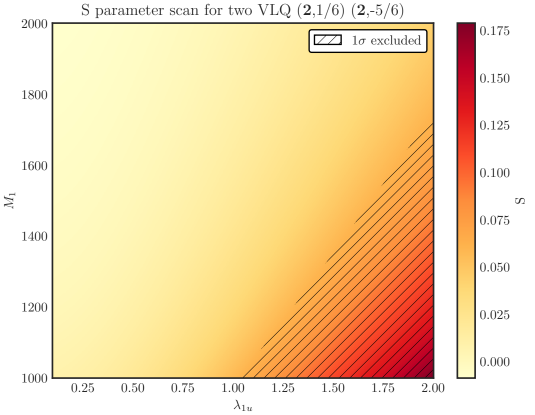
Oblique parameters are extremely sensible
→ need to be stable and accurate (PVpy)



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- Large parameters space + mixing of fermion generations

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Project ongoing, different combinations of multiplets are considered