Light-by-light scattering at the LHC from new physics

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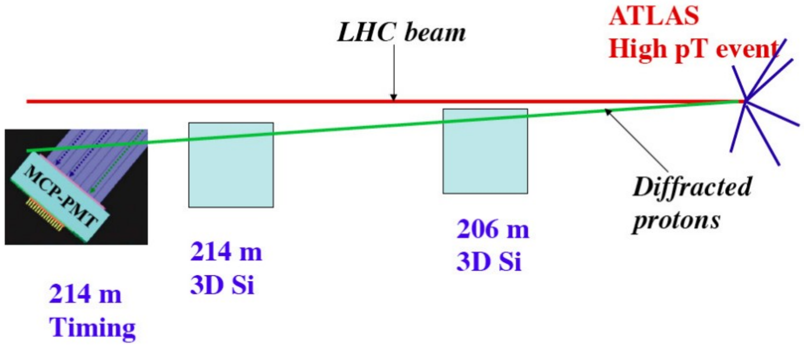
17/01/15

based on 1311.6815 (with G. von Gersdorff)
1312.5153, 1411.6629
(with G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert)

Forward proton detectors

- New detectors scheduled at CMS (CT-PPS) and ATLAS (AFP) to detect intact protons from proton diffraction at small angles



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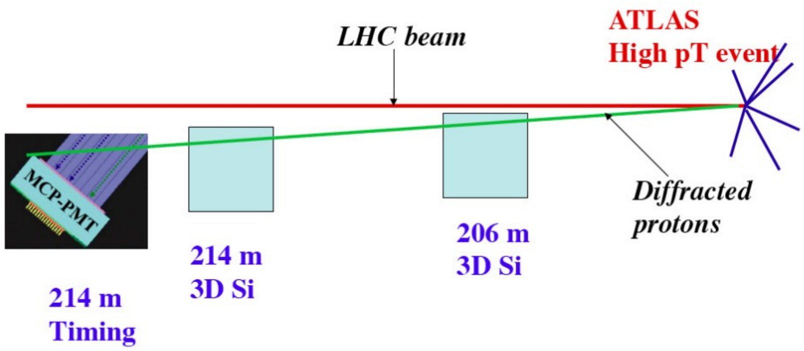
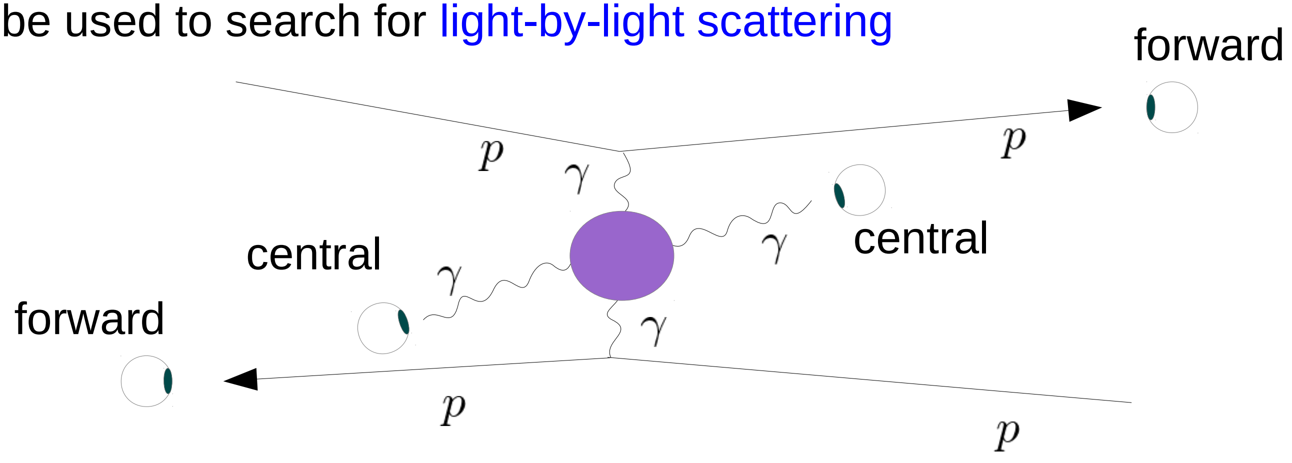


- Can be used to search for light-by-light scattering



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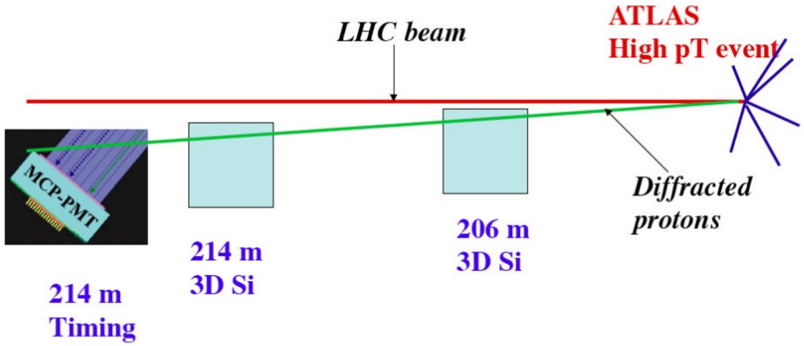

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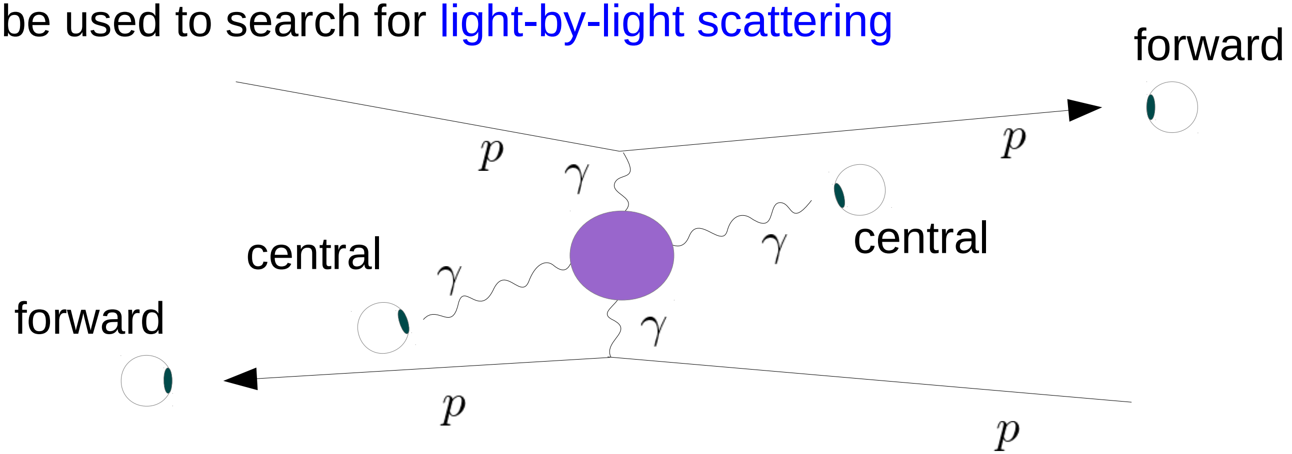
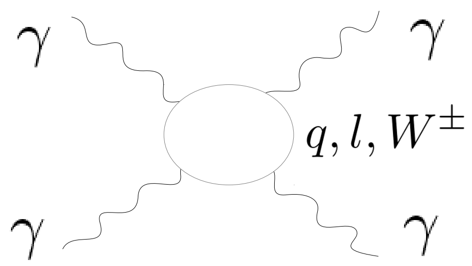


- Our goal : estimating the discovery potential of this measurement

Light-by-light scattering

- Standard Model signal



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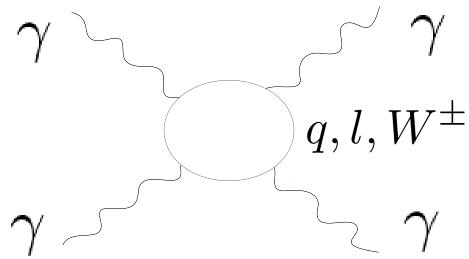
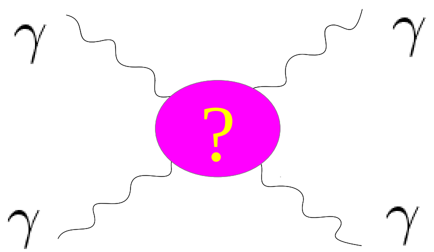
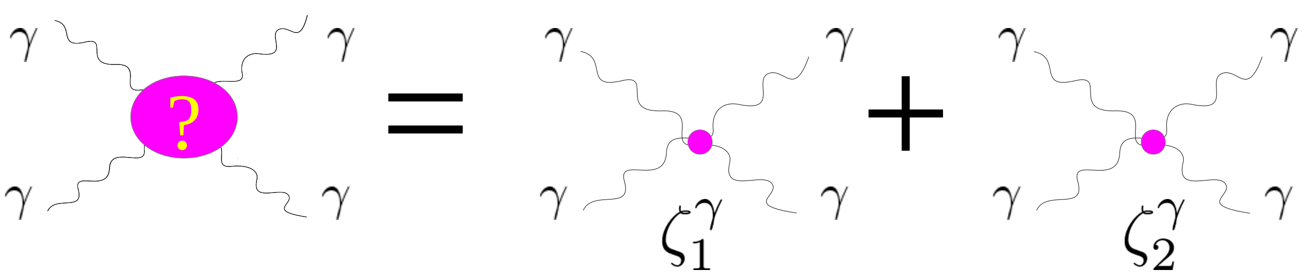


- Beyond SM signal



- In the EFT regime $M_{NP} > E$,

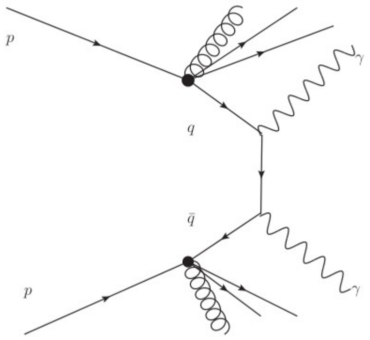
$$\mathcal{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\sigma} F^{\sigma\mu}$$



Backgrounds and simulation

- Main background: inclusive diphoton
  + intact protons from pile-up

- Others : central exclusive QCD, double pomeron exchange



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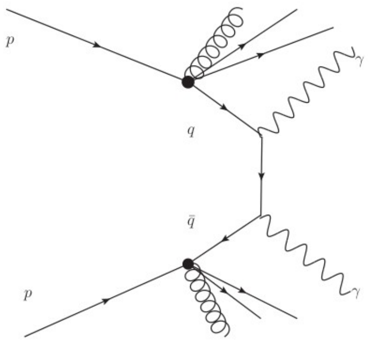

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- For the simulation we use the Forward Proton Monte Carlo generator (FPMC). Main detectors effects are modeled.

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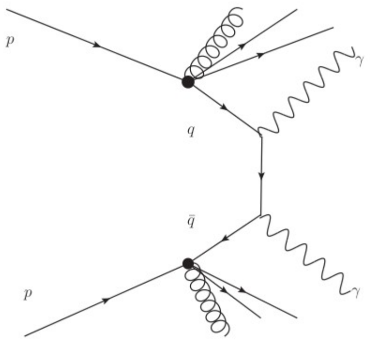
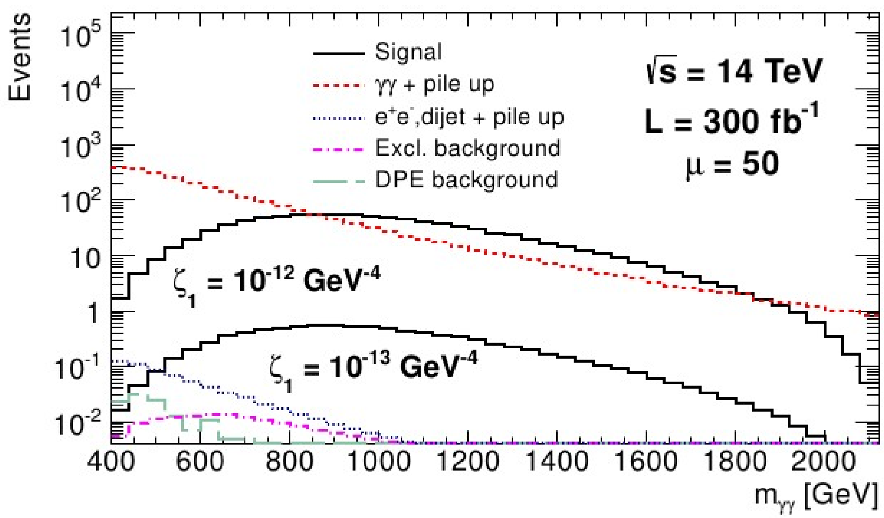


\+ pile-up

- For the simulation we use the Forward Proton Monte Carlo generator (FPMC). Main detectors effects are modeled.

- With or without forward detectors, the SM does not seem reachable. (~ too small and too soft).

- But BSM signals are harder...



Cuts and EFT bounds

Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{\mathrm{T}1,(2)} > 200, (100)$ GeV$]$	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	128.3	34.9 (371.6)	0.20	0	0.2	1023
$[p_{\mathrm{T}2}/p_{\mathrm{T}1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	128.3	34.9 (371.4)	0.19	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	122.0	32.9 (350.2)	0.18	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

Closed kinematics

Cuts and EFT bounds

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Closed kinematics

- EFT 5sigma bounds for $300\,\mathrm{fb}^{-1}$, $\mu = 50$

$$\boxed{\zeta_1^\gamma < 9 \cdot 10^{-15}\ \mathrm{GeV}^{-4} \qquad \zeta_2^\gamma < 2 \cdot 10^{-14}\ \mathrm{GeV}^{-4}}$$

- Bonus: $$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 s}(s^2+t^2+st)^2\left[48(\zeta_1)^2 + 40\zeta_1\zeta_2 + 11(\zeta_2)^2\right]$$

New charged particles

EFT for spin 0,1/2,1 charged particles

- Contributions from new charged particles caracterized only by mass, electric charge and spin. Computation done using the background field method. [SF/Gersdorff '13]

- In case of 4γ vertices : $\mathcal{L}_{4\gamma} = \zeta_1^\gamma F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2^\gamma F_{\mu\nu}F^{\nu\rho}F_{\rho\sigma}F^{\sigma\mu}$

$$\zeta_i^\gamma = \alpha_{\rm em}^2 Q^4\, m^{-4}\, N\, c_{i,s} \quad c_{1,s} = \begin{cases} \frac{1}{288} & s=0 \\ -\frac{1}{36} & s=\frac{1}{2} \\ -\frac{5}{32} & s=1 \end{cases}, \quad c_{2,s} = \begin{cases} \frac{1}{360} & s=0 \\ \frac{7}{90} & s=\frac{1}{2} \\ \frac{27}{40} & s=1 \end{cases}$$

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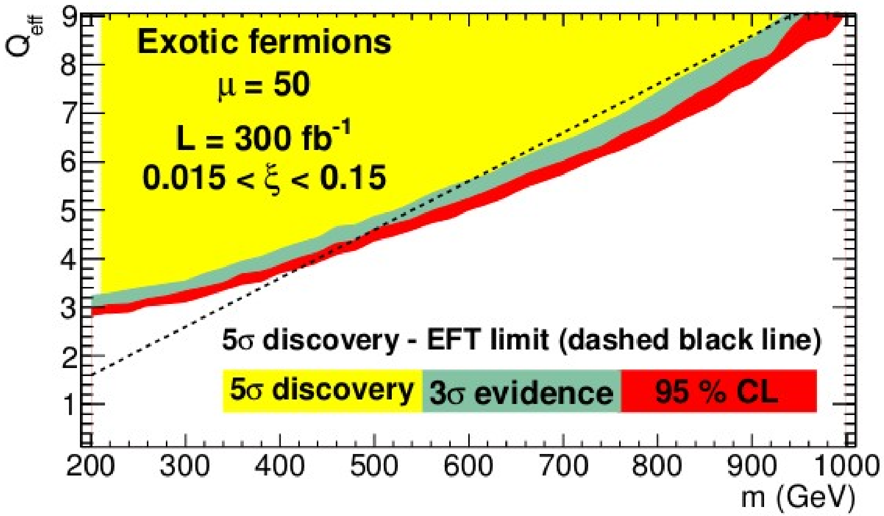
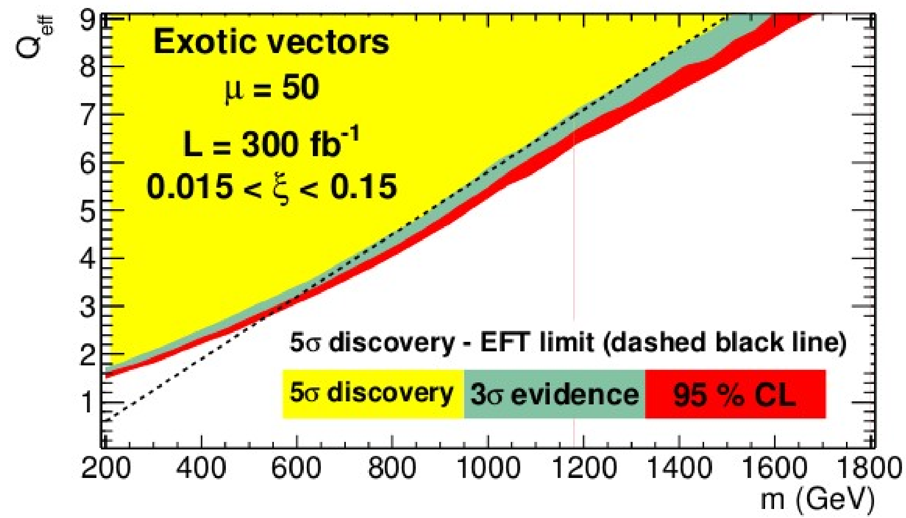
Scalar loops are smaller !

- Model-independent limits, depending only on m, S and $Q_{eff} \equiv N^{1/4} Q$.
  In familiar BSM theories (at least their minimal form), Q_{eff} hardly exceeds 3 or 4.
  For these values, mass bounds are below ~ 1 TeV
  → EFT is not valid anymore !

Spin 1/2,1 charged particles for any mass

- We implemented the full amplitudes in FPMC for S=1/2, 1.
  (looks easy but in practice tricky because of numerical unstability of dilogs)
  They were also used to simulate the SM background.

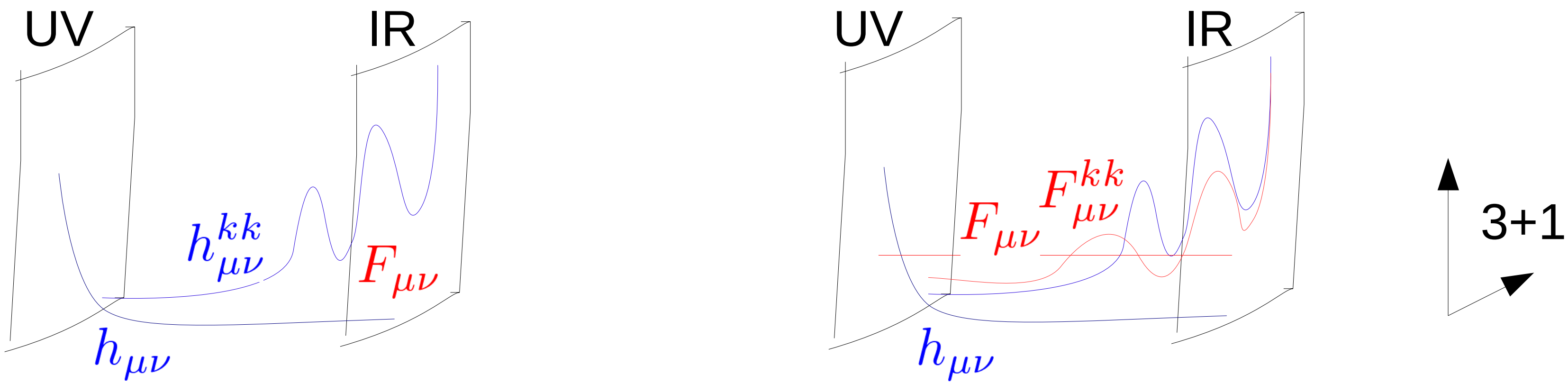




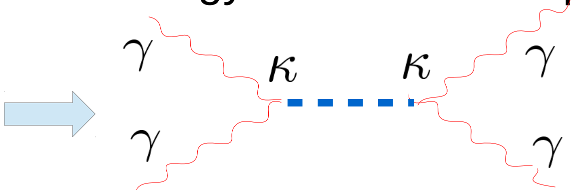
- Results valid for any mass, model-independent, no ad-hoc form factors

Neutral particles

Warped extra dimensions



- KK gravitons near the IR brane. Gauge fields either on the UV brane or in the bulk. KK gravitons couple to the photon through the 5d stress-energy tensor with warped gravity strength $\kappa = \tilde{k}/M_{Pl}$, that can be $O(1)$



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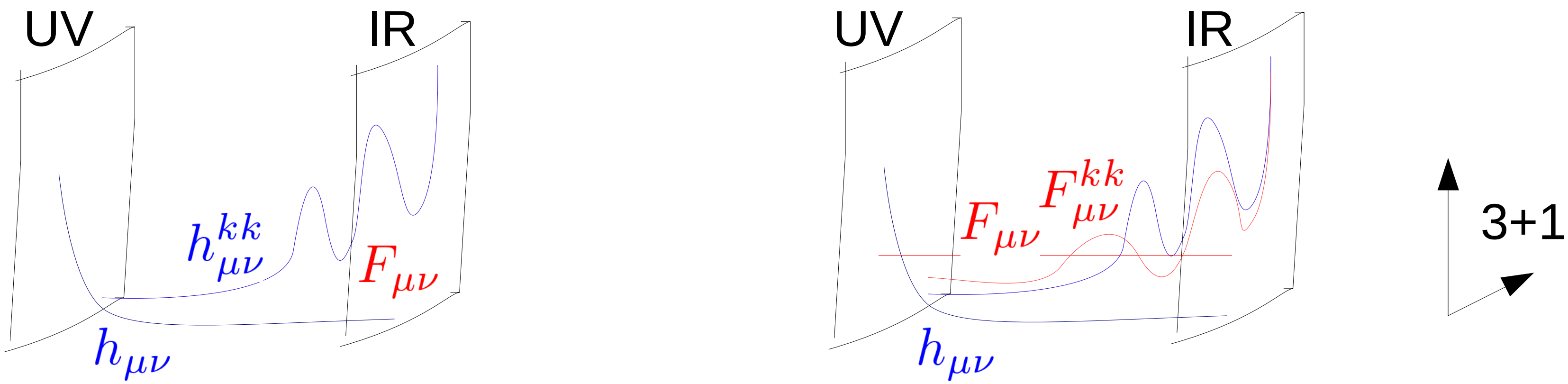

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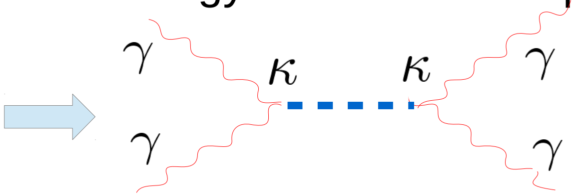

- Brane scenario : KK gravitons reachable up to

$$m_2 = 6.5\,\mathrm{TeV}$$

- Bulk scenario : KK gauge fields contribute to EWPO, Higgs couplings, TGCs. But EW IR brane kinetic terms need to be taken into account. $\mathcal{L}_{IR} \supset \frac{r}{4}(W^a_{\mu\nu})^2 + \frac{r'}{4}(B^a_{\mu\nu})^2$

All constraints can be relaxed and KK gravitons reachable in the multi-TeV range

Strongly-interacting heavy dilaton

- BSM theories often feature a new strongly-coupled sector (e.g CH models). If conformal in the UV, conformality is broken in the IR (at least by EWSB and QCD).
- The spectrum then features a neutral scalar, the dilaton. Unless the theory is fine-tuned, its mass is of order of the conformal breaking scale. In absence of fine-tuning, the dilaton couplings are unsuppressed with respect to this scale. We call this the Strongly-Interacting Heavy Dilaton (SIHD)

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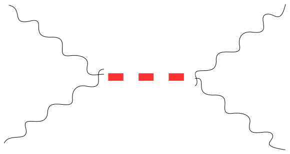
- The SIHD couples to the trace of the SE tensor ϕT^{μ}_{μ} . The SE tensor contains $(F^{\mu\nu})^2,\ (Z^{\mu\nu})^2,\ (W^{\mu\nu})^2$, thus the tree-level dilaton exchange generates $\zeta_1^{\gamma,Z,W}$

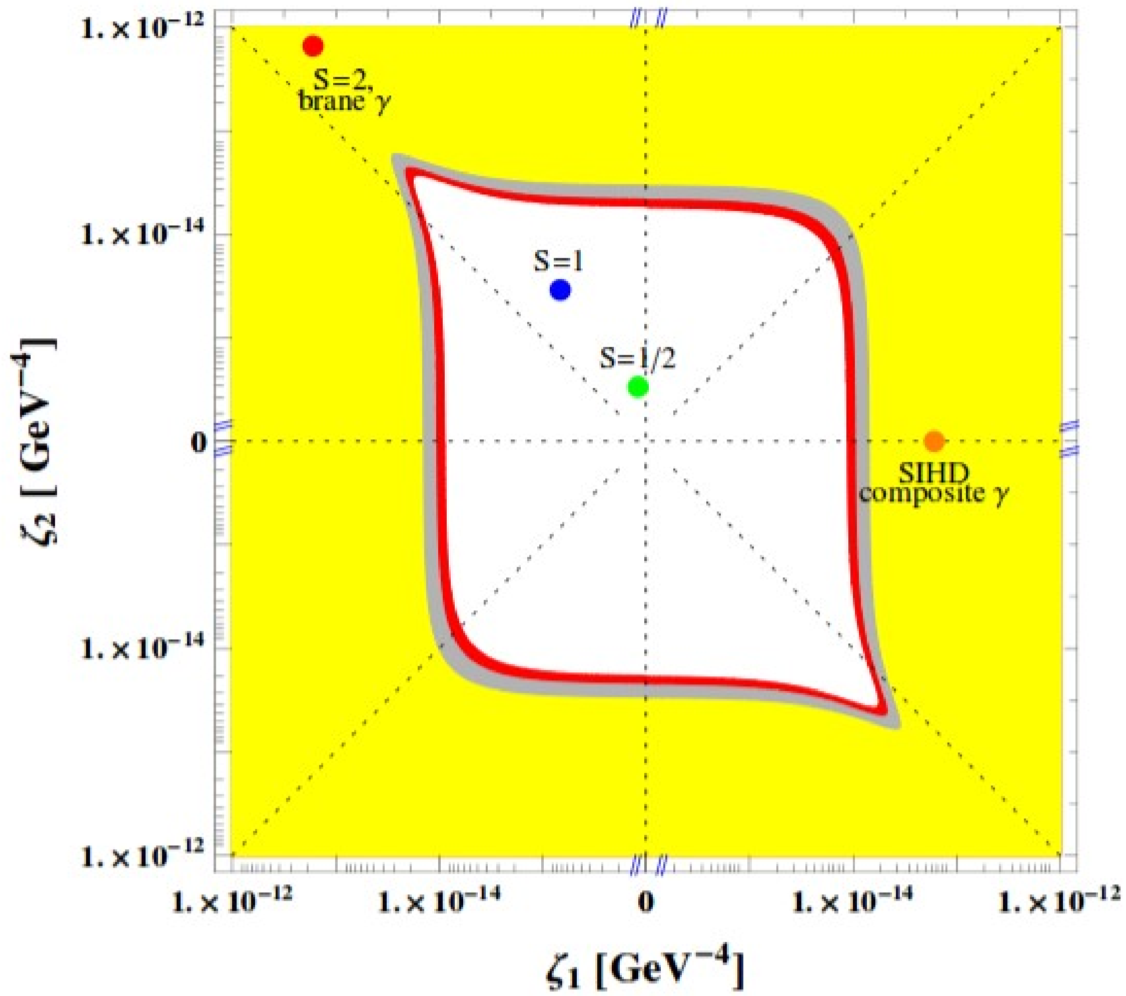
$$\Rightarrow \mathcal{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma}$$



- The contribution is large if one has a partially composite photon. For a pure composite photon,

$$\zeta_1^{\gamma} \sim \frac{\pi^2}{2\, m_\phi^4} \longrightarrow m_\phi = 4.8\,\mathrm{TeV}$$

EFT summary plot



Summary

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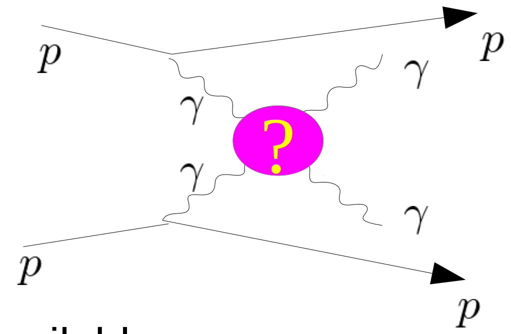

- We estimated the new physics discovery potential from light-by-light scattering at the LHC14, relying on forward proton tagging.
- All the background can be cut because full kinematics is available.
- Model-independent bounds on massive charged particles with S=0,1/2,1
- Model-independent bounds on massive neutral particles with S=0,2
- Warped KK gravitons and the SIHD can be detected in the multi-TeV range

Look at the EFT results for charged particles.

The zeta's grow fast with the spin...

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$$\vdots$$

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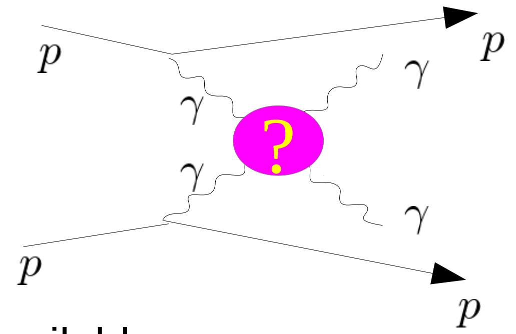

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- Warped KK gravitons and the SIHD can be detected in the multi-TeV range
- OUTLOOK : Charged higher-spin particles might be detected through LbL scattering. But first the appropriate QFT tools need to be set up...

  ⇒ upcoming work, stay tuned for more results !

Thank you !

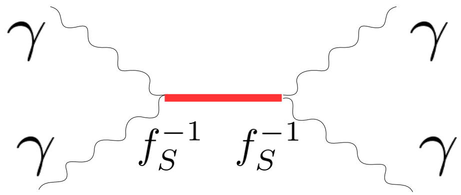
More

Simplified models

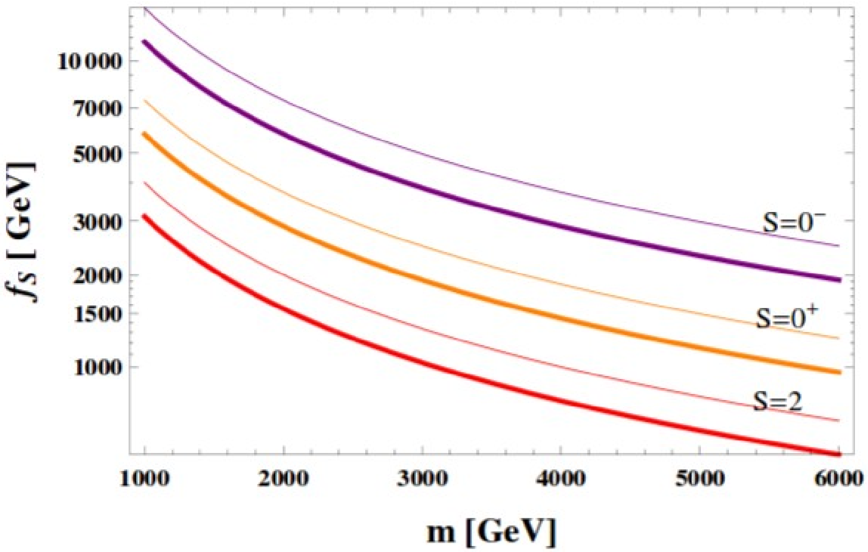
- Assume that the photon interacts with generic neutral particles. Couplings to CP-even scalar, CP-odd scalar, and CP-even spin-2 are possible,

$$\mathcal{L}_{\gamma\gamma} = f_{0^+}^{-1}\,\varphi\,(F_{\mu\nu})^2 + f_{0^-}^{-1}\,\tilde{\varphi}\,F_{\mu\nu}F_{\rho\lambda}\,\epsilon^{\mu\nu\rho\lambda} + f_2^{-1}\,h^{\mu\nu}\,(-F_{\mu\rho}F_\nu^{\ \rho} + \eta_{\mu\nu}(F_{\rho\lambda})^2/4)$$

- Tree-level exchange :



- Using the sensitivities on $\zeta_{1,2}$, one gets model-independent bounds on the couplings



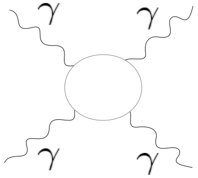
Low-energy effect of higher-spin objects

- Any strongly-interacting extension of the SM potentially features higher-spin composites in its spectrum. In low-energy strings scenarios, strings feature higher-spin excited modes. Assuming the size of the high-spin object is small, it appears to be pointlike at low-energy.

  ⇒ EFT Lagrangian for higher-spin particles

- HS couplings to the SM have to be bilinear, ie $\mathcal{L} \supset \mathcal{O}\phi_{(s)}\phi^{*}_{(s)}$

  ⇒ HS particles could be spotted in loops.

- A naive generalization of the background field computation gives 

$\propto S^5$

  ⇒ Light-by-light scattering might be a good place to look for HS particles

- HS QFT computations: never done and challenging... STAY TUNED !

Open problem: Magnetic monopoles

- [Ginzburg/Panfil 82']: Assume a heavy point-like monopole. Its Lagrangian is unknown, but one can use electromagnetic duality to deduce its coupling to the photon.

$$B \to E \qquad F_{\mu\nu} \to \tilde{F}_{\mu\nu}$$
$$E \to -B \qquad \tilde{F}_{\mu\nu} \to -F_{\mu\nu} \qquad g = \frac{2\pi n}{e} \quad n \in \mathbf{N}$$

$$\zeta_i^{\gamma} = \alpha_{\rm em}^2 Q^4 \, m^{-4} \, N \, c_{i,s} \qquad \zeta_{i,s} \to \frac{g^4}{e^4}\zeta_{i,s} = \left(\frac{n}{2\alpha_e}\right)^4 \zeta_{i,s}$$

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- Very nice reasoning... but what about higher loops ?

  - As far as I understand, in the GP paper higher-loops are assumed to be absorbed by renormalization. In reality this does not happen.

  - The formal computation they provide goes through the background field method. This computation provides only the one-loop result and neglects higher loops.

→ Open problem !
(let me know if you have any idea)

The anomalous Lagrangian in the broken phase

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{CGC}} + \mathcal{L}_{\text{NGC}}$$

$$\mathcal{L}_{\text{NGC}} = \mathcal{L}^{v}_{\text{NGC}} + \mathcal{L}^{\partial}_{\text{NGC}}$$

$$\mathcal{L}_{\text{CGC}} = \mathcal{L}^{\text{SM},v}_{\text{CGC}} + \mathcal{L}^{\partial}_{\text{CGC}}$$

- $$\begin{aligned}\mathcal{L}^{\partial}_{\text{CGC}} =& \lambda^Z \left[i g_Z Z_{\mu\nu} (\hat{W}^-_{\nu\rho} \hat{W}^+_{\rho\mu} - \hat{W}^+_{\nu\rho} \hat{W}^-_{\rho\mu}) \right] + \lambda^\gamma \left[i e F_{\mu\nu} (\hat{W}^-_{\nu\rho} \hat{W}^+_{\rho\mu} - \hat{W}^+_{\nu\rho} \hat{W}^-_{\rho\mu}) \right] \\ &+ \zeta^W_1 F^{\mu\nu} F_{\mu\nu} W^{+\rho\sigma} W^-_{\rho\sigma} + \zeta^W_2 F^{\mu\nu} F_{\nu\rho} W^{+\rho\sigma} W^-_{\sigma\mu} \\ &+ \zeta^W_3 F^{\mu\nu} W^+_{\mu\nu} F^{\rho\sigma} W^-_{\rho\sigma} + \zeta^W_4 F^{\mu\nu} W^+_{\nu\rho} F^{\rho\sigma} W^-_{\sigma\mu} \,.\end{aligned}$$

Keep only $\geq 2\,\gamma$ operators

- $$\begin{aligned}\mathcal{L}^{\partial}_{\text{NGC}} =& \zeta^\gamma_1 F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} F_{\rho\sigma} + \zeta^\gamma_2 F^{\mu\nu} F_{\nu\rho} F^{\rho\sigma} F_{\sigma\mu} \\ &+ \zeta^{\gamma Z}_1 F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} Z_{\rho\sigma} + \zeta^{\gamma Z}_2 F^{\mu\nu} F_{\nu\rho} F^{\rho\sigma} Z_{\sigma\mu} \\ &+ \zeta^Z_1 F^{\mu\nu} F_{\mu\nu} Z^{\rho\sigma} Z_{\rho\sigma} + \zeta^Z_2 F^{\mu\nu} F_{\nu\rho} Z^{\rho\sigma} Z_{\sigma\mu} \\ &+ \zeta^Z_3 F^{\mu\nu} Z_{\mu\nu} F^{\rho\sigma} Z_{\rho\sigma} + \zeta^Z_4 F^{\mu\nu} Z_{\nu\rho} F^{\rho\sigma} Z_{\sigma\mu} \,,\end{aligned}$$

The background field method

- Decompose gauge fields into background and fluctuation $A^\mu \to A^\mu + \mathcal{A}^\mu$. Plug into the generating functional, integrate over fluctuations :

$$S^S_{\rm eff} = +\frac{i}{2}\log\left(-D^2 - m_S^2\right)$$
$$S^f_{\rm eff} = -\frac{i}{2}\log\left(-D^2 - m_f^2 + g\, S^{\mu\nu}\, V^a_{\mu\nu} t^a_f\right)$$
$$S^X_{\rm eff} = \frac{i}{2}\log\left(-[D^2 + m_X^2]\eta_{\mu\nu} + 2ig\, V^a_{\mu\nu} t^a_X\right) + \frac{i}{2}(1-2)\log\left(-D^2 - m_X^2\right)$$

- The one-loop effective action remains covariant in background fields. To obtain the 3 and 4-point functions one expands at 3rd and 4th order. Coefficients (Gilkey-De Witt) of the expansion are computed in [Gilkey '75, Tseytlin et al '83, 88'].

- $\mathcal{L}^{(6)} \supset \dfrac{g^3}{16\pi^2}\left(-\dfrac{1}{144\, m_S^2} + \dfrac{1}{36\, m_f^2} - \dfrac{1}{48\, m_X^2}\right)\dfrac{(d^2-1)d}{24}\mathcal{O}_{W^3}$

- $$\mathcal{L}^{(8)} \supset \frac{1}{16\pi^2 m_S^4}\left\{\frac{1}{576}\mathcal{A}+\frac{1}{720}\mathcal{B}+\frac{1}{420}\mathcal{C}+\frac{2}{35}\mathcal{D}\right\} + \frac{1}{16\pi^2 m_f^4}\left\{-\frac{1}{36}\mathcal{A}+\frac{7}{90}\mathcal{B}-\frac{64}{105}\mathcal{C}+\frac{104}{35}\mathcal{D}\right\} + \frac{1}{16\pi^2 m_X^4}\left\{-\frac{5}{64}\mathcal{A}+\frac{27}{80}\mathcal{B}-\frac{111}{140}\mathcal{C}+\frac{342}{35}\mathcal{D}\right\},$$

- $$\mathcal{A} = g'^4\, d\, Y^4\, \mathcal{O}_8 + g^4\left(\frac{(d^4-1)d}{240}\mathcal{O}_9 + \frac{(d^2-1)(d^2-4)d}{120}\mathcal{O}_{10}\right) + g^2 g'^2\,\frac{(d^2-1)d}{6}Y^2\,(\mathcal{O}_{11}+2\mathcal{O}_{12}),$$

$$\mathcal{B} = g'^4\, d\, Y^4\, \mathcal{O}_{13} + g^4\left(\frac{(d^4-1)d}{120}\mathcal{O}_{14} + \frac{(d^2-9)(d^2-1)d}{240}\mathcal{O}_{15}\right) + g^2 g'^2\,\frac{(d^2-1)d}{6}Y^2\,(2\mathcal{O}_{16}+\mathcal{O}_{17}).$$

$$\mathcal{C} = g^4\,\frac{d(d^2-1)}{1152}(\mathcal{O}_{10}-\mathcal{O}_9), \qquad \mathcal{D} = g^4\,\frac{d(d^2-1)}{1152}(\mathcal{O}_{15}-\mathcal{O}_{14}),$$

Depend only on m, d, Y

Scalar loops are small

The electroweak and Higgs precision observables

small

- $$S = \left(2 s_w c_w \alpha_{WB} + s_w^2(\alpha_D - 2\alpha_{4f}) + c_w^2(\alpha'_D - 2\alpha'_{4f})\right)\frac{v^2}{\Lambda^2}$$
$$T = \left(-\frac{1}{2}\alpha'_{D^2} + \frac{1}{2}\alpha'_D - \frac{1}{2}\alpha'_{4f}\right)\frac{v^2}{\Lambda^2}$$
$$a_{Z,W} = 1 + \left(\frac{1}{2}\alpha_{D^2} - \frac{1}{4}(\alpha_D - \alpha_{4f}) \pm \frac{1}{4}\alpha'_{D^2}\right)\frac{v^2}{\Lambda^2}$$

- S,T with BKTs : $S = 2\pi\, f_2(\nu)\left(1 + (r + r')\,\frac{2+\nu}{3+\nu}\right)\frac{v^2}{\tilde{k}^2}$ exact !

$$T = \frac{\pi\, V}{2\, c_w^2}\, f_1(\nu)\left(1 + \frac{r'}{V}\right)\frac{v^2}{\tilde{k}^2}$$ (non-Custodial), $T = 0$ (Custodial)

- Higgs couplings : $a_Z \approx a_W \approx 1 - \frac{3g^2 + 3g'^2}{16} V f_1(\nu)\frac{v^2}{\tilde{k}^2}$ (Custodial)

$$a_W - a_Z \propto g'^2$$

- With BKTs: $a_W - a_Z$ strongly depends on r'