Prospects for new physics searches at the LHC in the forward proton mode

Sylvain Fichet
ICTP/SAIFR, Sao Paulo

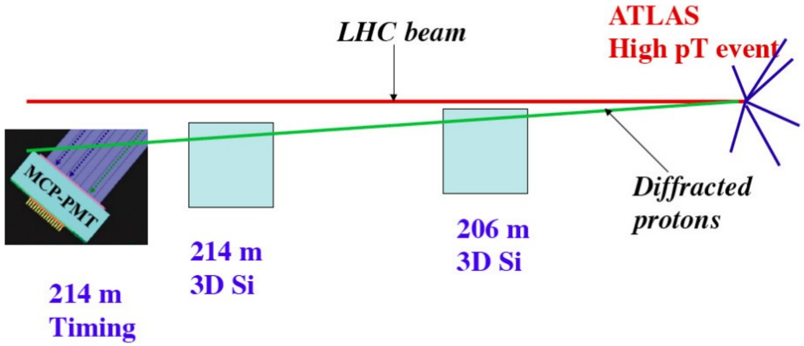
02/07/15

Based on 1311.6815 (JHEP), 1312.5153 (PRD), 1411.6629 (JHEP)
+ upcoming works

With: G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert

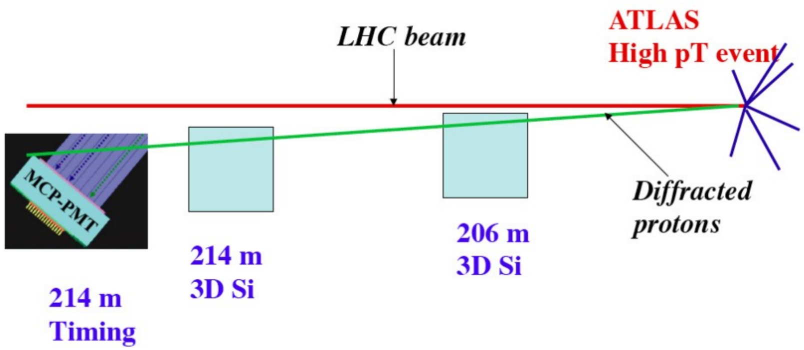
Forward proton detectors

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

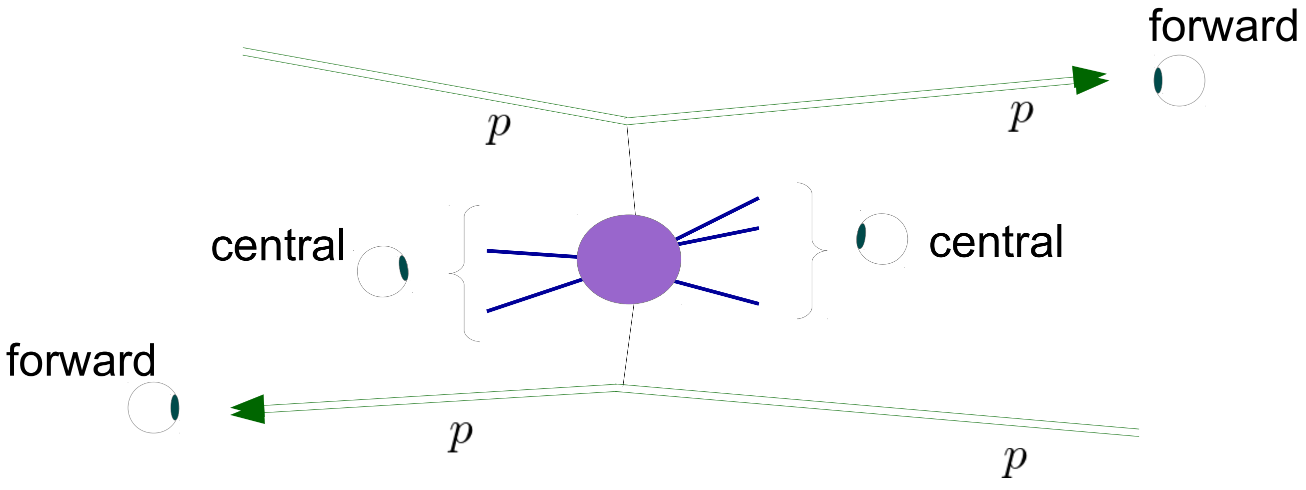


Forward proton detectors

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



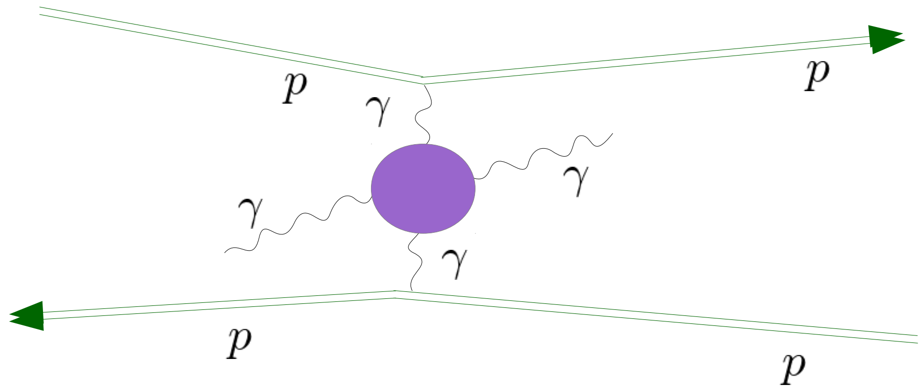
- Open possibility to measure central exclusive processes



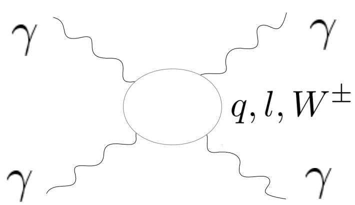
Light-by-light scattering

Light-by-light scattering

- Let's focus on four-photon interactions



- The SM amplitudes

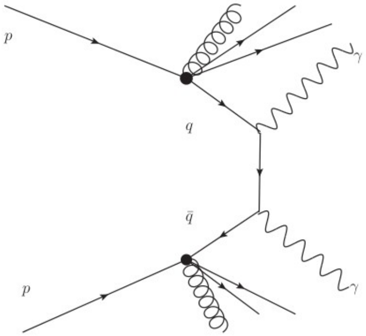


are $\propto \alpha_{em}^2$

- Thus potentially a good place to search for physics beyond the Standard Model

Backgrounds and cuts

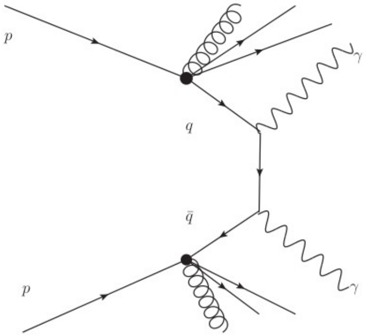
- Main background: inclusive diphoton
  + intact protons from pile-up
- Others : central exclusive QCD, DPE



+ pile-up

Backgrounds and cuts

- Main background: inclusive diphoton
  + intact protons from pile-up
- Others : central exclusive QCD, DPE



+ pile-up

Acceptance+ basic cuts (no forward dector needed)

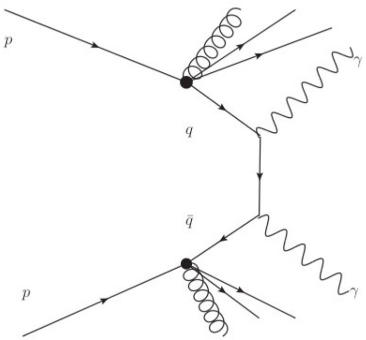
Full kinematics (provided by forward detectors)

Cut / Process	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100)$ GeV]	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	0.20	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	0.19	0	0	80.2
$\sqrt{\xi_1 \xi_2 s} = m_{\gamma\gamma} \pm 3\%$	0.18	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	0.18	0	0	0

Backgrounds and cuts

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

- Others : central exclusive QCD, DPE



+ pile-up

Acceptance+ basic cuts
(no forward dector needed)

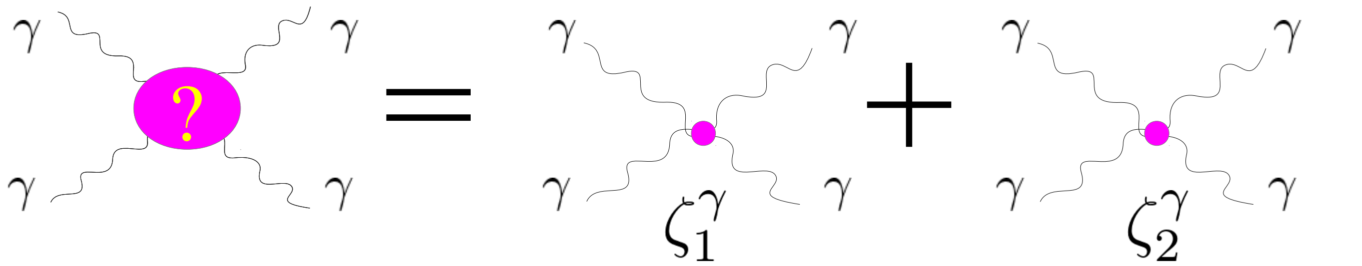
Full kinematics
(provided by forward detectors)

Cut / Process	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100)$ GeV$]$	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	0.20	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	0.19	0	0	80.2
$\sqrt{\xi_1 \xi_2 s} = m_{\gamma\gamma} \pm 3\%$	0.18	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	0.18	0	0	0

- The SM is hardly reachable (~ too small and too soft), at least with standard beam configuration. What about new physics signals ?

Discovery potential for heavy new physics

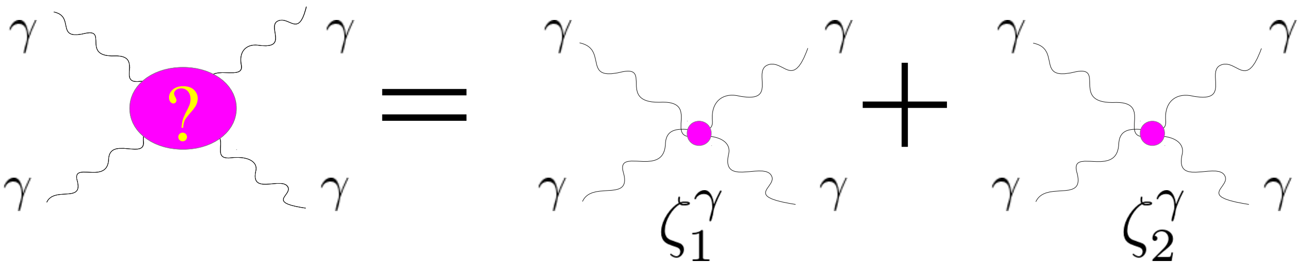
- When $m_{NP} > E$, low-energy NP effects can be described by local operators



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

Discovery potential for heavy new physics

- When $m_{NP} > E$, low-energy NP effects can be described by local operators

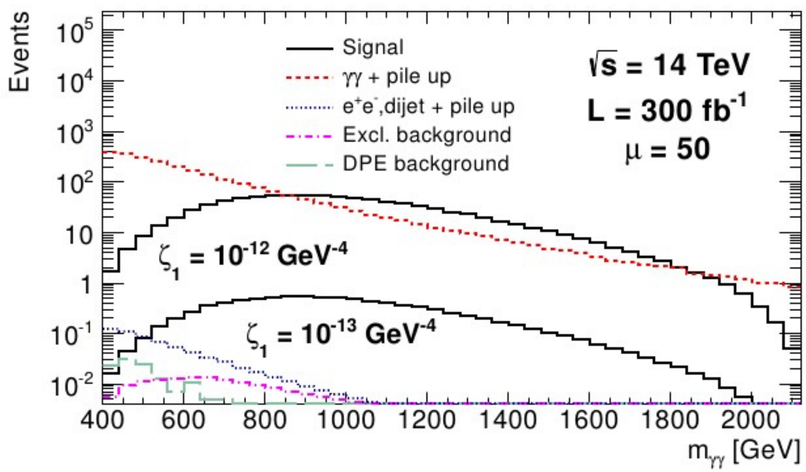


$$\mathcal{L}_{4\gamma} = \zeta_1^\gamma F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2^\gamma F_{\mu\nu}F^{\nu\rho}F_{\rho\sigma}F^{\sigma\mu}$$

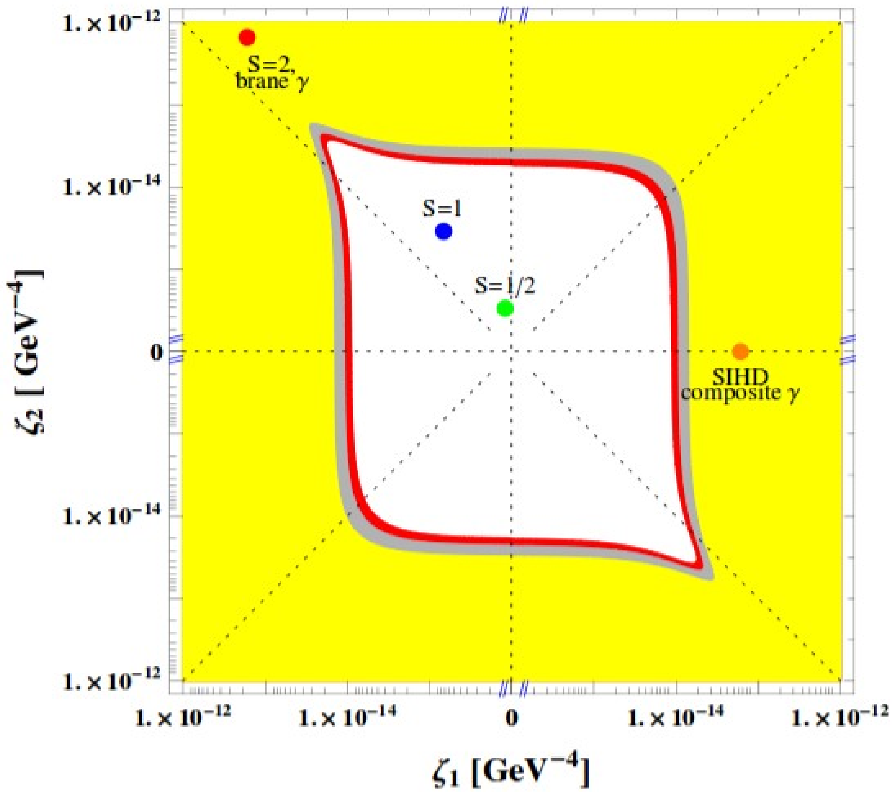
- EFT 5σ bounds for $300\,\mathrm{fb}^{-1}, \quad \mu = 50$

$$\zeta_1^\gamma < 9 \cdot 10^{-15}\ \mathrm{GeV}^{-4}$$

$$\zeta_2^\gamma < 2 \cdot 10^{-14}\ \mathrm{GeV}^{-4}$$



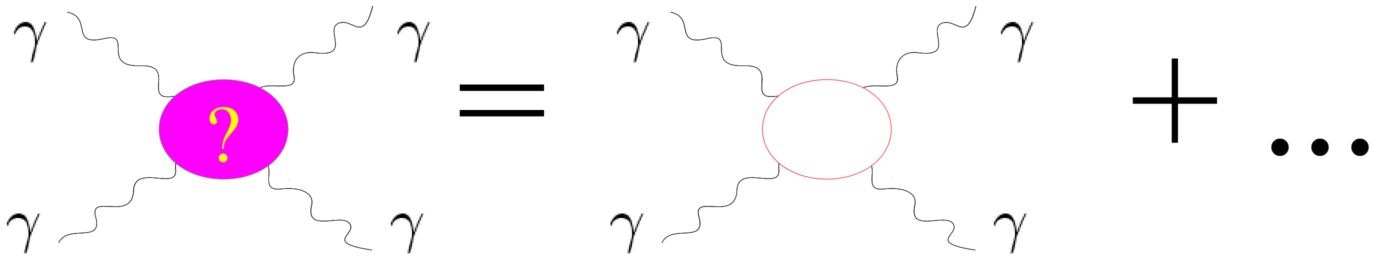
Discovery potential for heavy new physics



- KK graviton (IR brane photon): $m_{\rm KK} < 5670\,{\rm GeV}\,(5\,\sigma)$
  Strongly-interacting heavy dilaton: $m_{\varphi} < 4260\,{\rm GeV}\,(5\,\sigma)$ [SF/Gersdorff '13]

→ Actual models can be discovered

Charged particles



Discovery potential for new charged particles

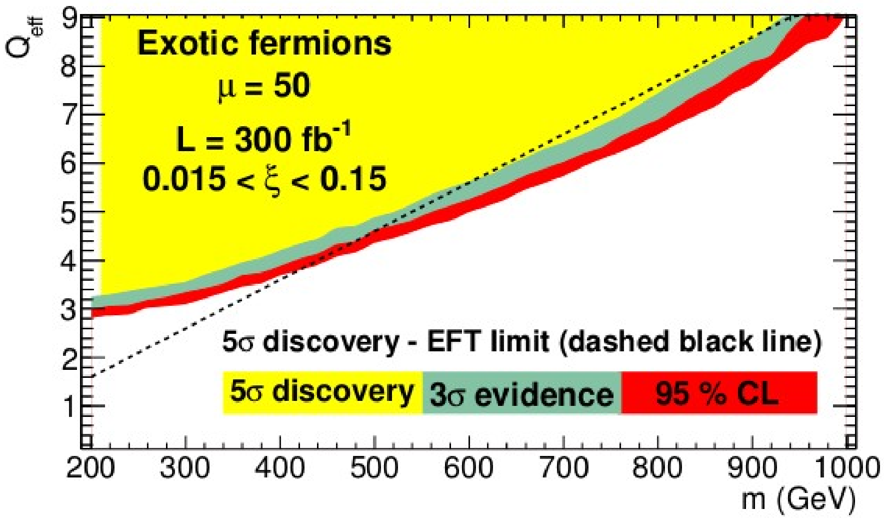
- Consider generic new electrically charged particles. Because of gauge symmetry, their effects in the four-photon interactions are controled by only mass, spin, charge and multiplicity. One can use the parameters

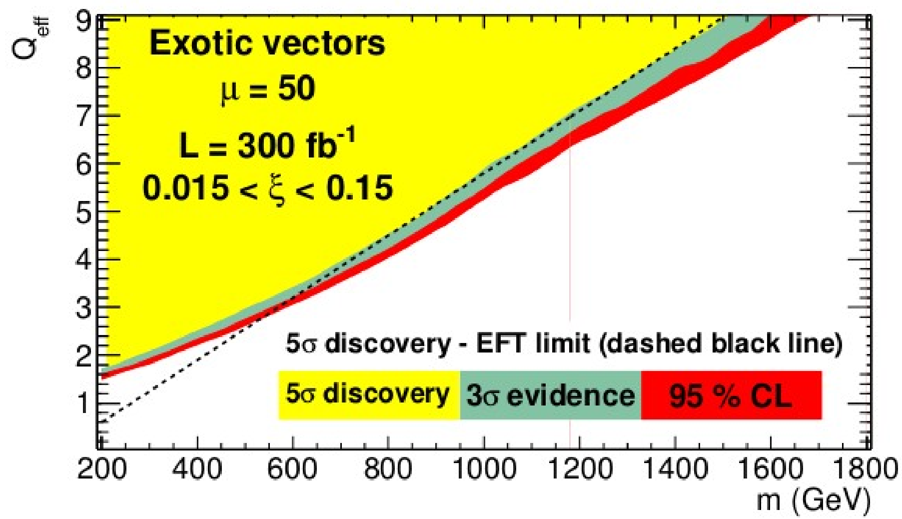
$$m,\, S,\; Q_{eff} \equiv N^{1/4} Q$$

Discovery potential for new charged particles

- Consider generic new electrically charged particles. Because of gauge symmetry, their effects in the four-photon interactions are controled by only mass, spin, charge and multiplicity. One can use the parameters

$$m, S,\ Q_{eff} \equiv N^{1/4} Q$$

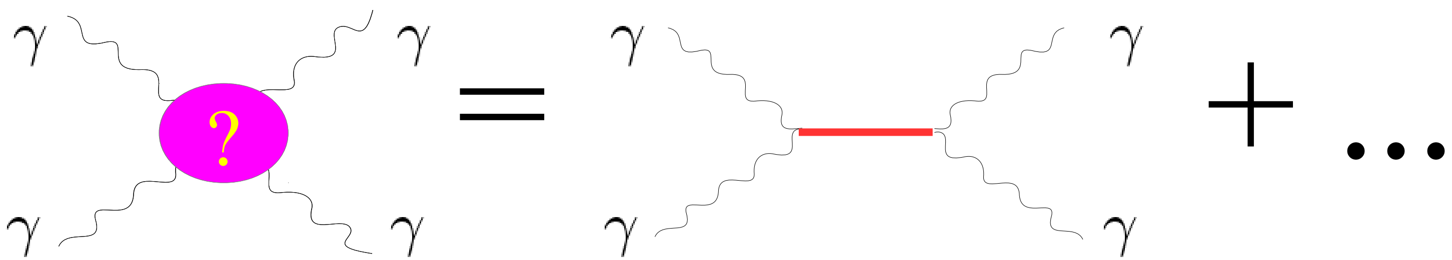




- Provides model-independent bounds on any charged particles. This is complementary with respect to direct searches, that are typically very model-dependent.

- Example : vector-like leptons, vector-like quarks...

Neutral particles



Discovery potential for new neutral particles

- The effects of generic neutral particles can also be classified using simplified models. Only S=0 (CP even or odd) and S=2 are possible at tree-level. The generic Lagrangian is therefore

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

  Unlike charged particles, neutral particles can be strongly-coupled.

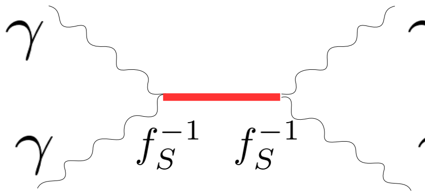
Discovery potential for new neutral particles

- The effects of generic neutral particles can also be classified using simplified models. Only S=0 (CP even or odd) and S=2 are possible at tree-level. The generic Lagrangian is therefore

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

  Unlike charged particles, neutral particles can be strongly-coupled.

- There are only 2 parameters (coupling and mass). However this is a tree-level parametrisation. Not sufficient because neutral particles can resonate, and because these tree-level diagrams violate unitarity.



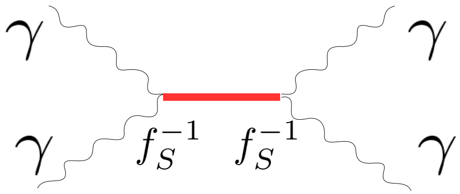
Discovery potential for new neutral particles

- The effects of generic neutral particles can also be classified using simplified models. Only S=0 (CP even or odd) and S=2 are possible at tree-level. The generic Lagrangian is therefore

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

  Unlike charged particles, neutral particles can be strongly-coupled.

- There are only 2 parameters (coupling and mass). However this is a tree-level parametrisation. Not sufficient because neutral particles can resonate, and because these tree-level diagrams violate unitarity.



- Both issues are solved at one-loop.
  The exact generic propagator (with no NWA) reads

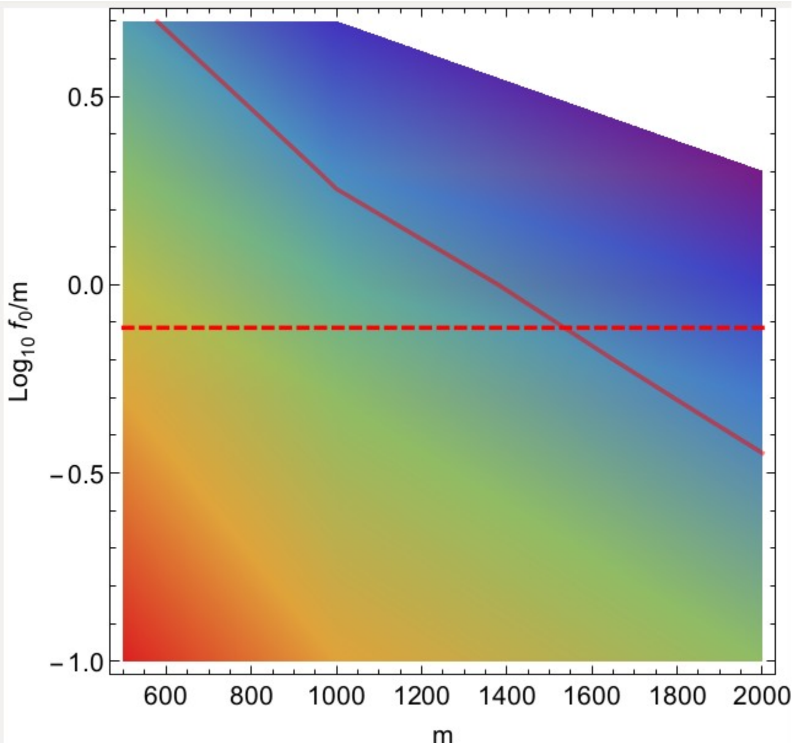
$$\frac{i}{s - m^2 + i(a_2 s^2/(4\pi f_0^2) + m\Gamma_{\text{const}})}$$

  with $a_2 \geq 1$ because the scalar always decays into photons by assumption.
- Only consistency constraint is $E/4\pi f_0 \ll 1$

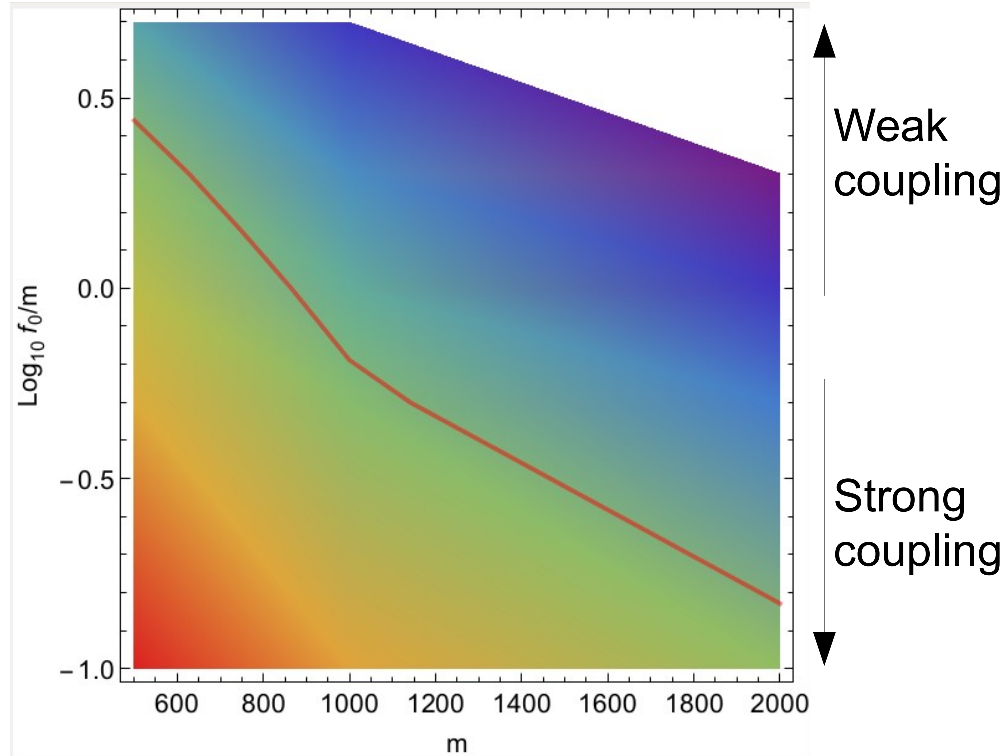
Discovery potential for new neutral particles

- Preliminary results ($\Gamma_{\mathrm{const}} = 0$)

$a_2 = 1$



$a_2 = 10$



- Below red line: enough sensitivity for discovery using CEP with 300 fb-1.
- Above dashed line: NWA region, where bump searches in inclusive channels are ~possible. ⇨ Searches using CEP probe strong coupling and are complementary with bump searches

Conclusion

- We estimated the new physics discovery potential from the observation of light-by-light scattering at the LHC, relying on forward proton tagging.
- The main detector effects have been modeled into FPMC.
- All the background can be cut because forward detectors give access to the full kinematics of the process.
- Model-independent bounds on massive charged particles with S=0,1/2,1
- Model-independent bounds on massive neutral particles with S=0,2
- Complementarity with inclusive searches.
- Warped KK gravitons and the SIHD can be detected in the multi-TeV range.

Thank you !

More

Discovery potential for new charged particles

- Earlier we also computed directly the EFT coefficients from charged particles using the background field method [SF/Gersdorff '13]

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

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

Scalar loops are smaller !

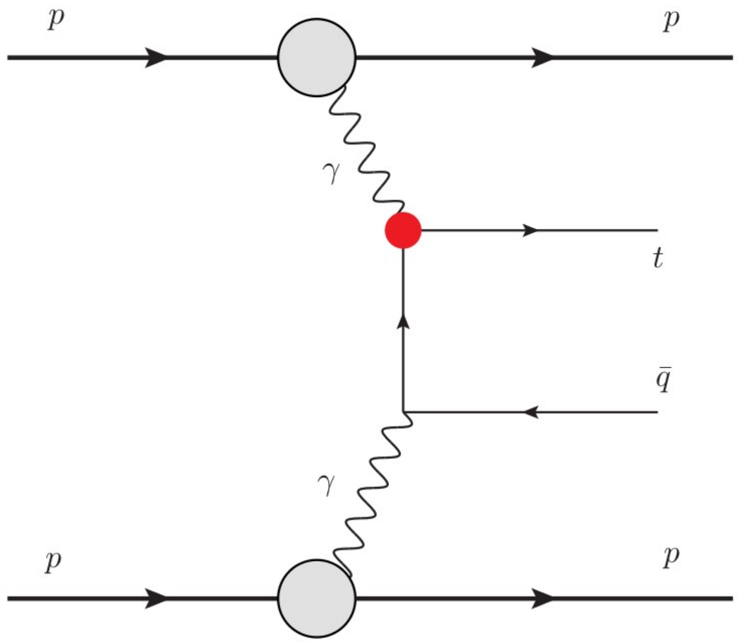
- What happens to the four-photon interaction for higher-spin particles ? (such like higher-spin resonances of a strong sector)

- A part of the above computation can be generalised, showing a S^5 dependence. But higher-spin theories are not so simple, much more developments are needed. (Work in progress with G. Gersdorff)

Beyond four-photon studies

Some interesting directions: dipole operators

- Dipole operators $\frac{\alpha_{ij}}{\Lambda^2}\bar{f}_i\sigma_{\mu\nu}f_j^{(\prime)}HV^{\mu\nu}$ are predicted in many new physics scenarios. For example,

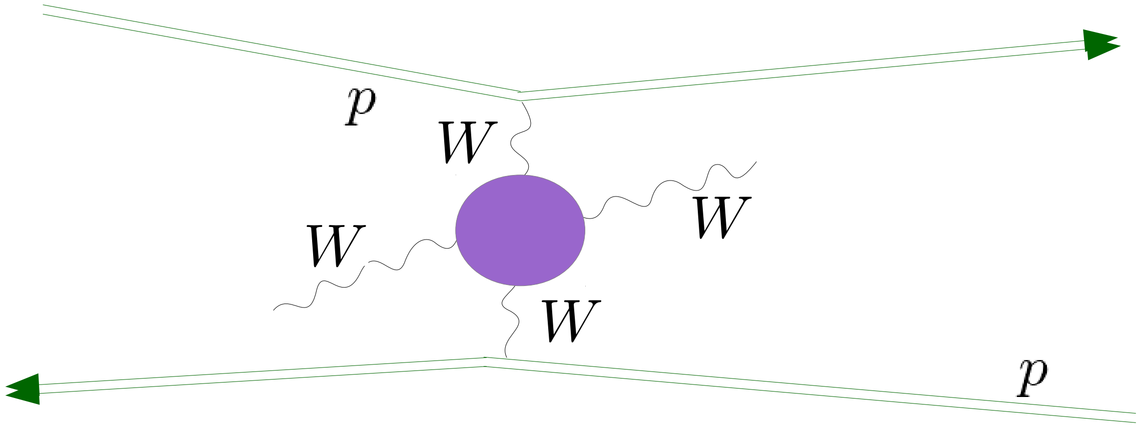


- New possibilities to search for dipole operators

- If a BSM flavour violating dipole is discovered, directly provides a way of testing the hypothesis of SU(5) unification. The relation to test is $\alpha_{ij} = \alpha_{ji}$. Can be tested using top polarimetry. [SF, Herrmann, Stoll 15']

Some interesting directions: W,Z fluxes

- Having the W,Z fluxes from intact protons would open many many possibilities, including precision tests of $W_L W_L$ scattering.



- The equivalent W, Z approximation does not apply, because the intermediate W, Z cannot be on-shell.

⇒ Work in progress (any discussion is welcome !)

Some interesting directions: W,Z fluxes

- What about heavy ions ? For UPCs, electric charges radiate coherently. Should be the same for EW charges.

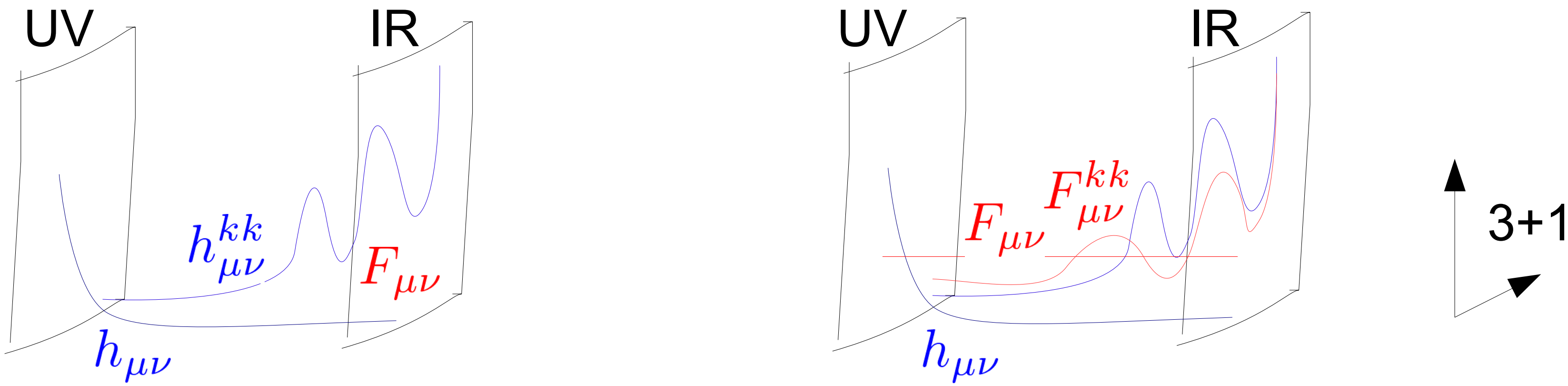
- Assume EW charges add-up coherently:

fluxes	proton	ion
f_γ	$\propto e^2 \sim 0.1$	$\propto Z^2 e^2$
f_{W^+}	$\propto 2g^2 \sim 0.9$	$\propto \frac{g^2 (Z+A)^2}{2}$
f_{W^-}	$\propto g^2/2 \sim 0.2$	$\propto \frac{g^2 (2A-Z)^2}{2}$
f_Z	$\propto g^2/c_w^2 (1/4 - s_w^2 + 2 s_w^4) \sim 0.07$	$\propto \frac{g^2}{c_w^2} \left[\frac{(2Z-A)^2}{4} - Z(2Z-A) s_w^2 + 2Z^2 s_w^4 \right]$

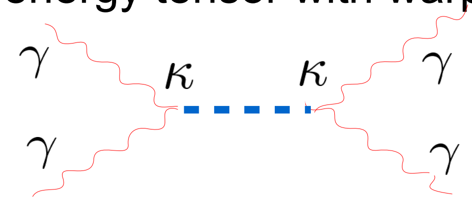
Collision	$\gamma - \gamma$	$W^+ - W^-$	$Z - Z$
Pb–Pb / p-p	$\sim 4.5 \cdot 10^7$	$\sim 9.4 \cdot 10^9$	$\sim 4.1 \cdot 10^6$

- Enhancement for $W^+ - W^-$ collisions is 200 larger than for $\gamma - \gamma$ collisions

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 $O(1)$



- 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

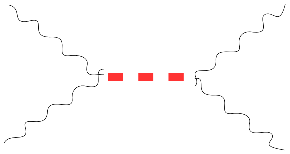
Strongly-interacting heavy dilaton

- 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)

- 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,

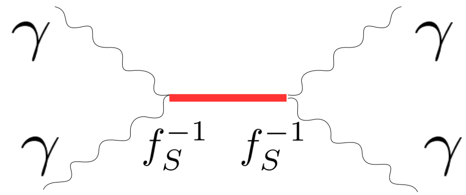
$$\zeta_1^{\gamma} \sim \frac{\pi^2}{2\,m_\phi^4} \longrightarrow m_\phi = 4.8\,\mathrm{TeV}$$

Simplified models

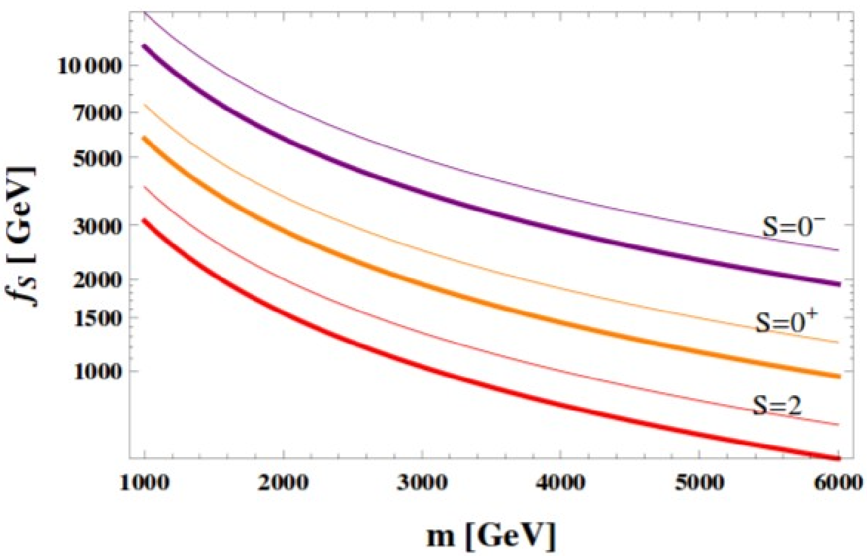
- Assume that the photon interacts with generic neutral particles. Couplings to CP-even scalar, CP-odd scalar, and CP-even spin-2 are possible,

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

- Tree-level exchange :



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



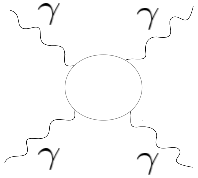
Low-energy effect of higher-spin objects

- 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.

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

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

- 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)