Low scale SUSY breaking and signatures at LHC from Higgs decay

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DFT/IFT - UAM/CSIC

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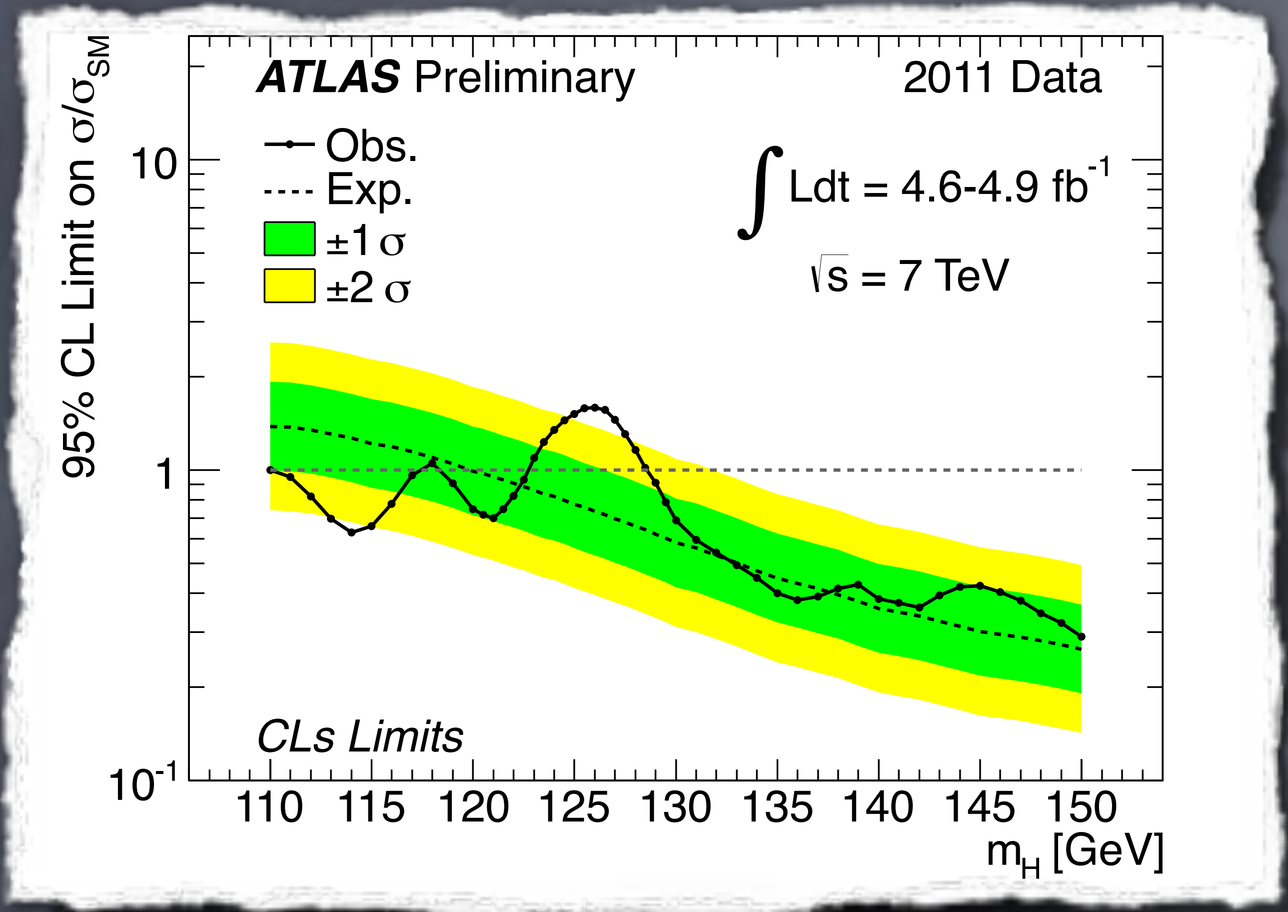
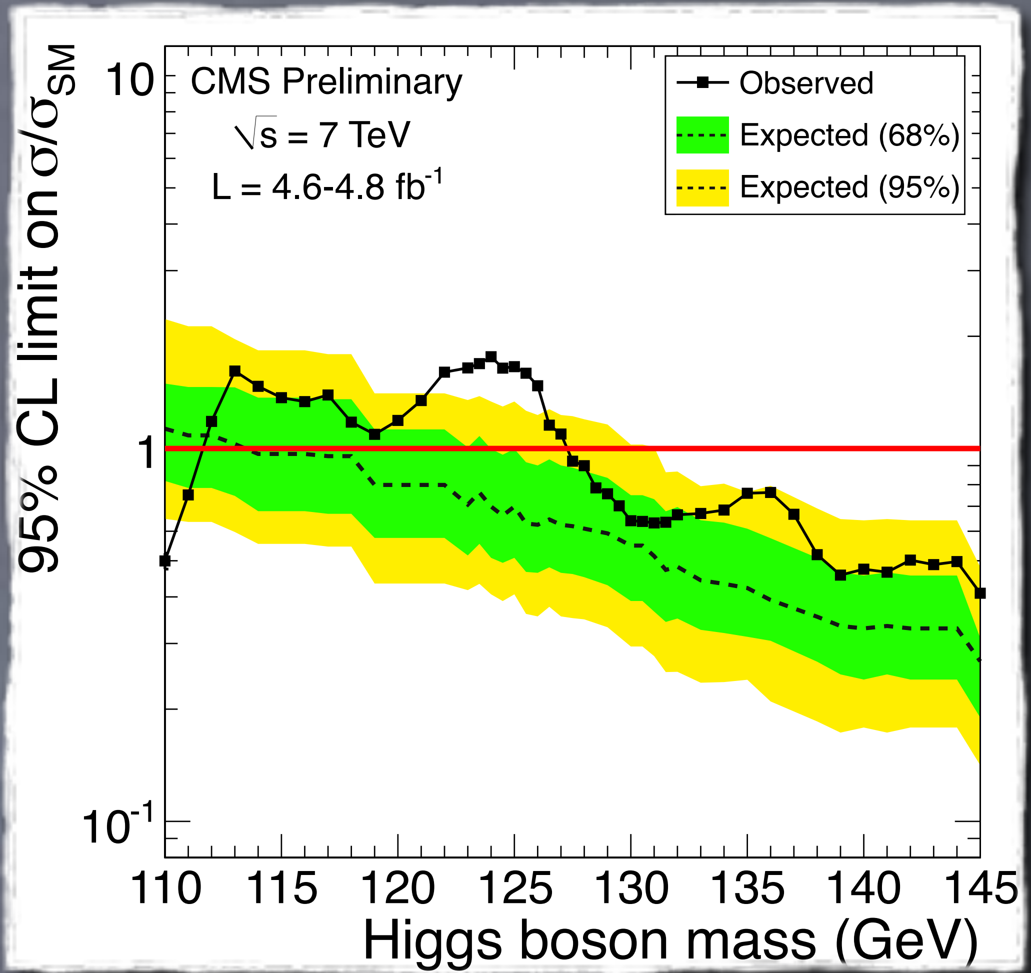
C. Petersson, A. R., JHEP 1202 142, arXiv:1111.3368 [hep-ph]
C. Petersson, A. R. and Riccardo Torre, arXiv:1203.4563 [hep-ph]

First hints of Brout-Englert-Higgs?





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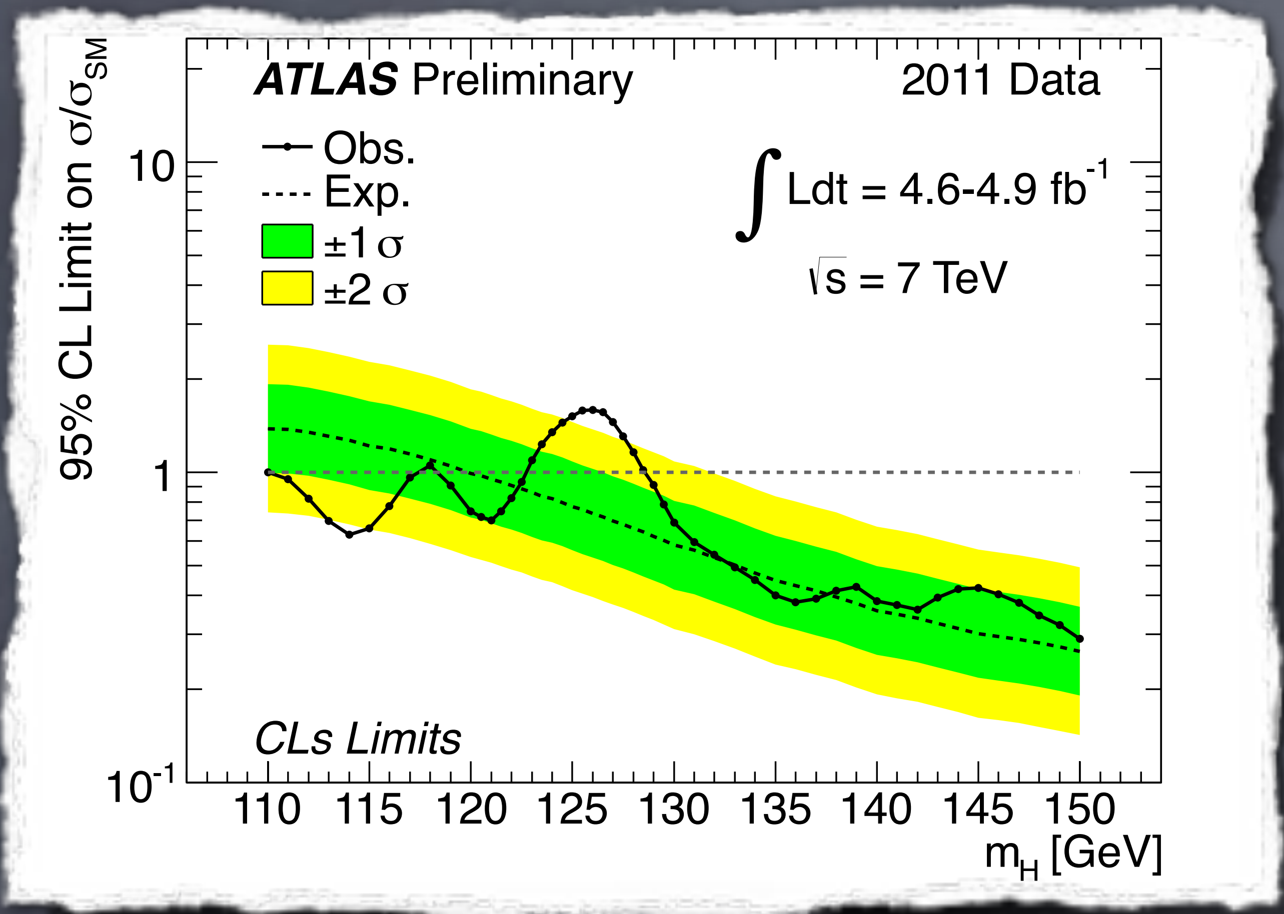
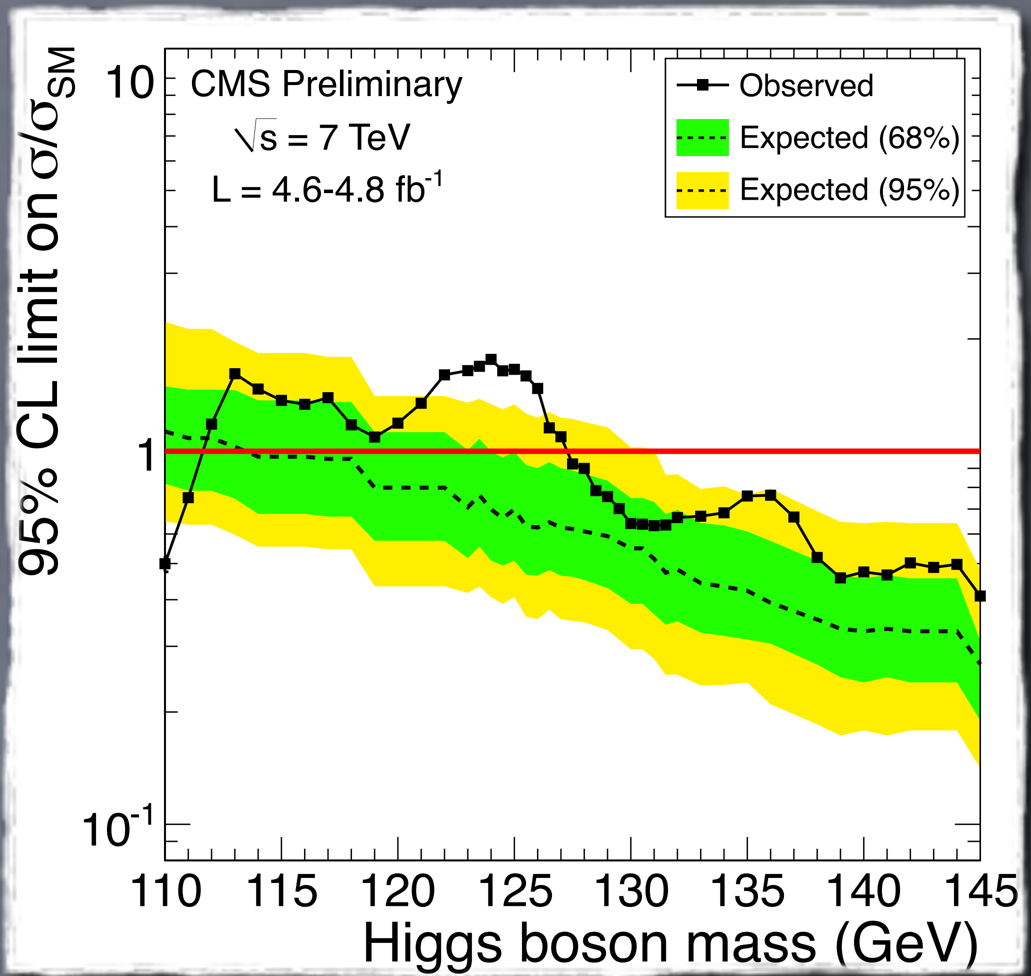


ATLAS Collaboration



CMS Collaboration

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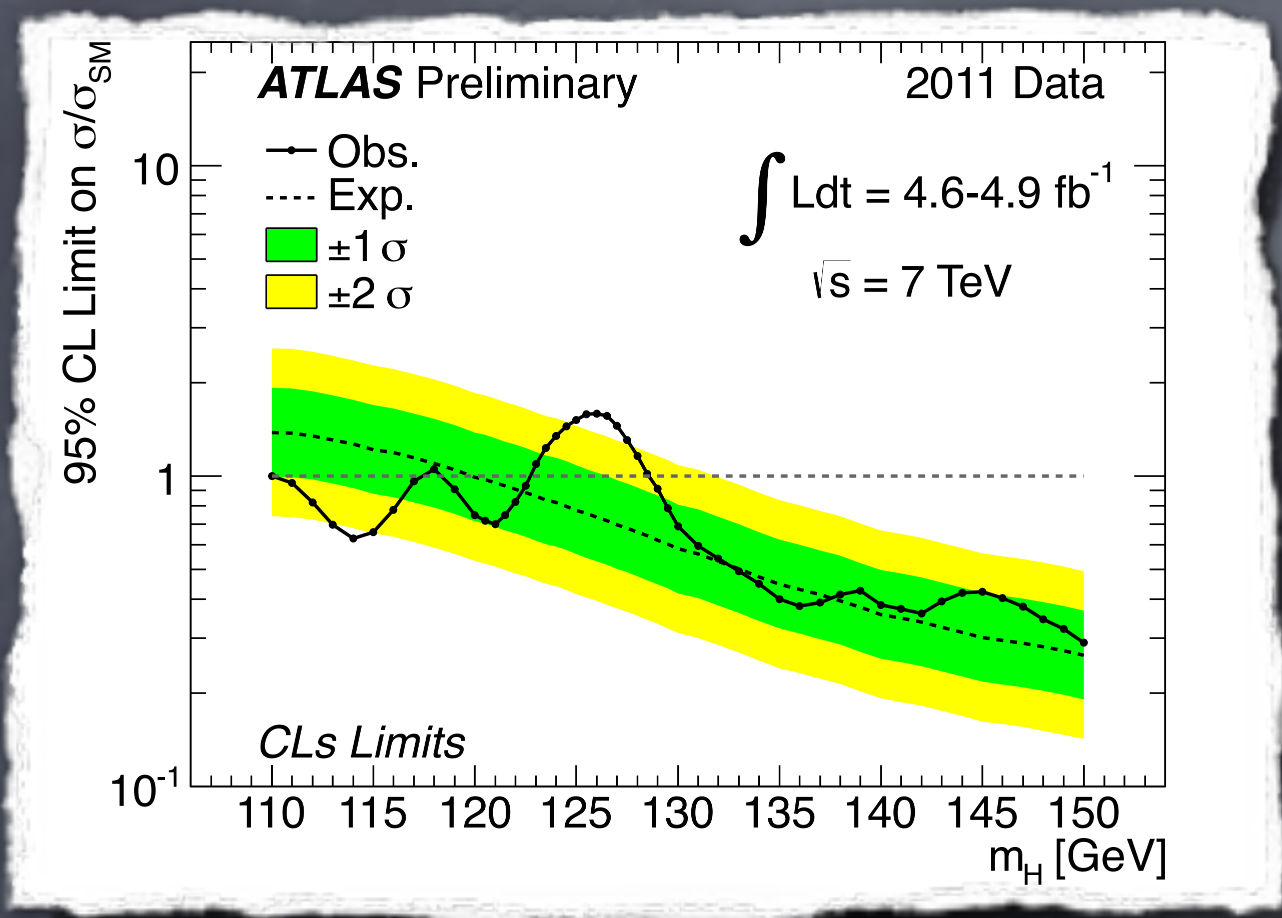

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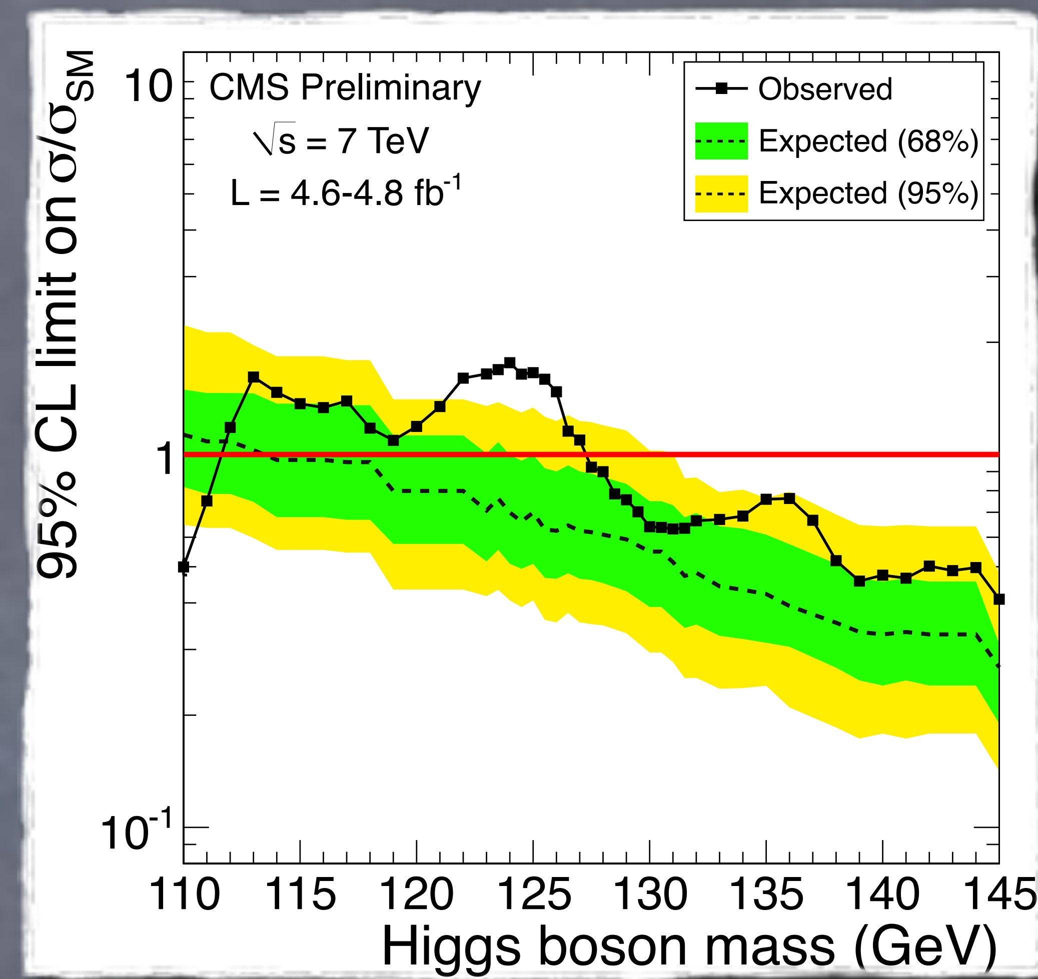
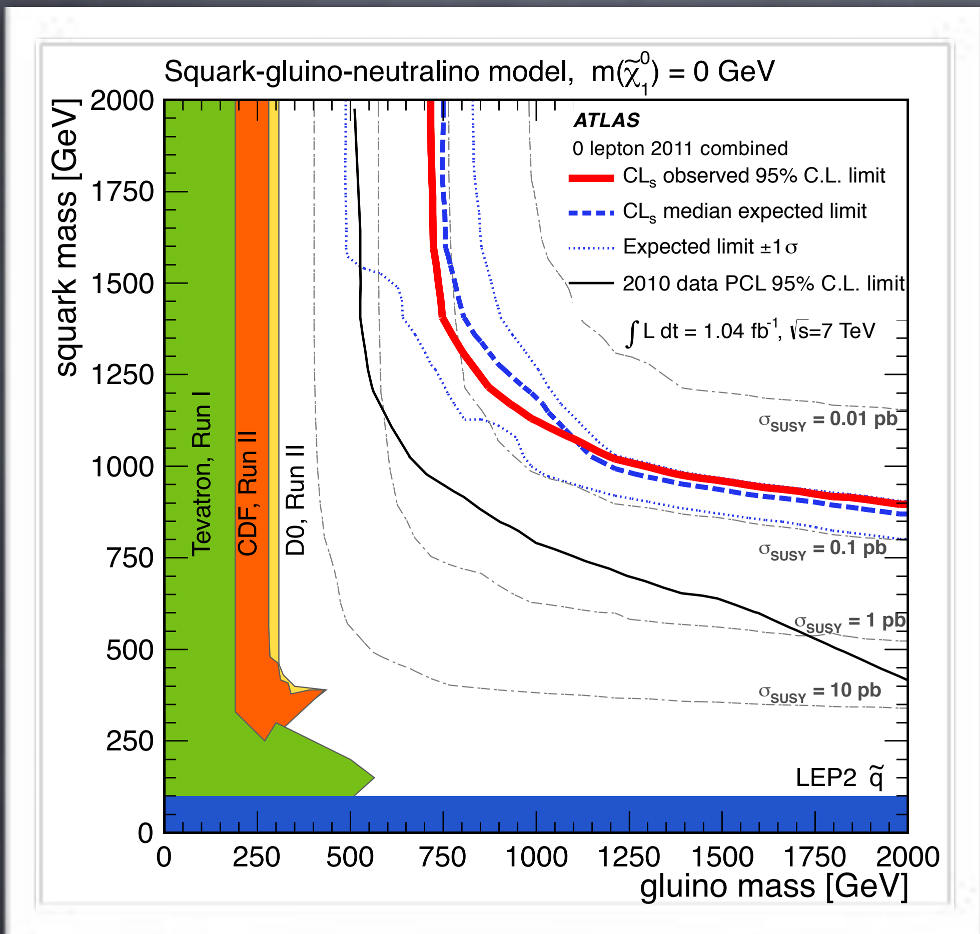


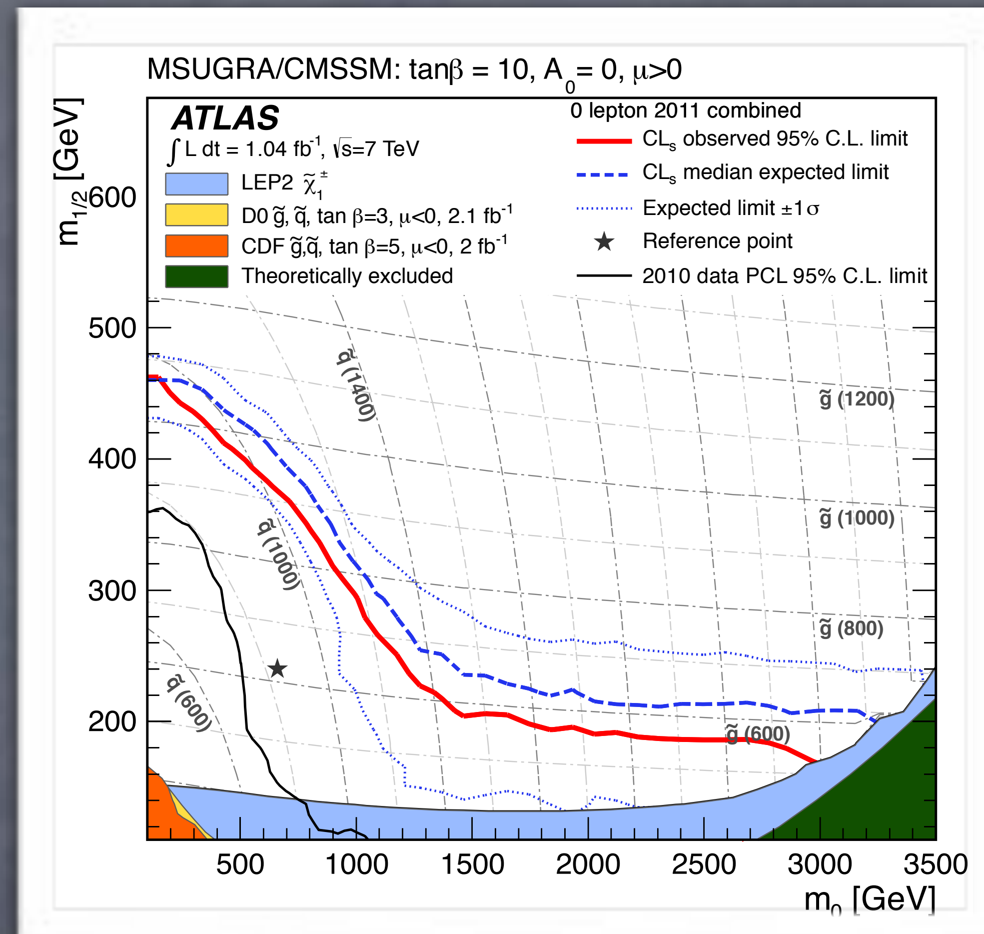
CMS Collaboration

- Hint of physics beyond the SM?
- A 125 GeV Higgs is in good agreement with SUSY.
- However ...

… well, but where's SUSY?

- Despite of the huge theoretical relevance of SUSY, it has never been observed experimentally, either directly or indirectly





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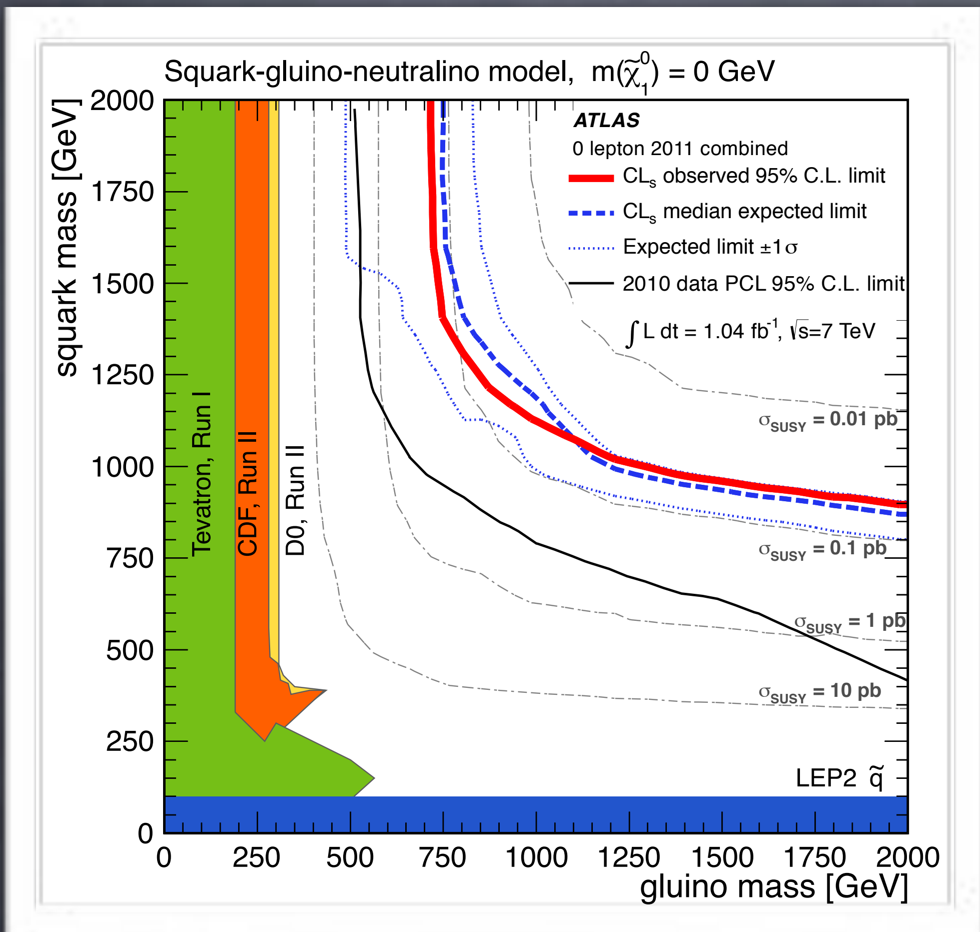

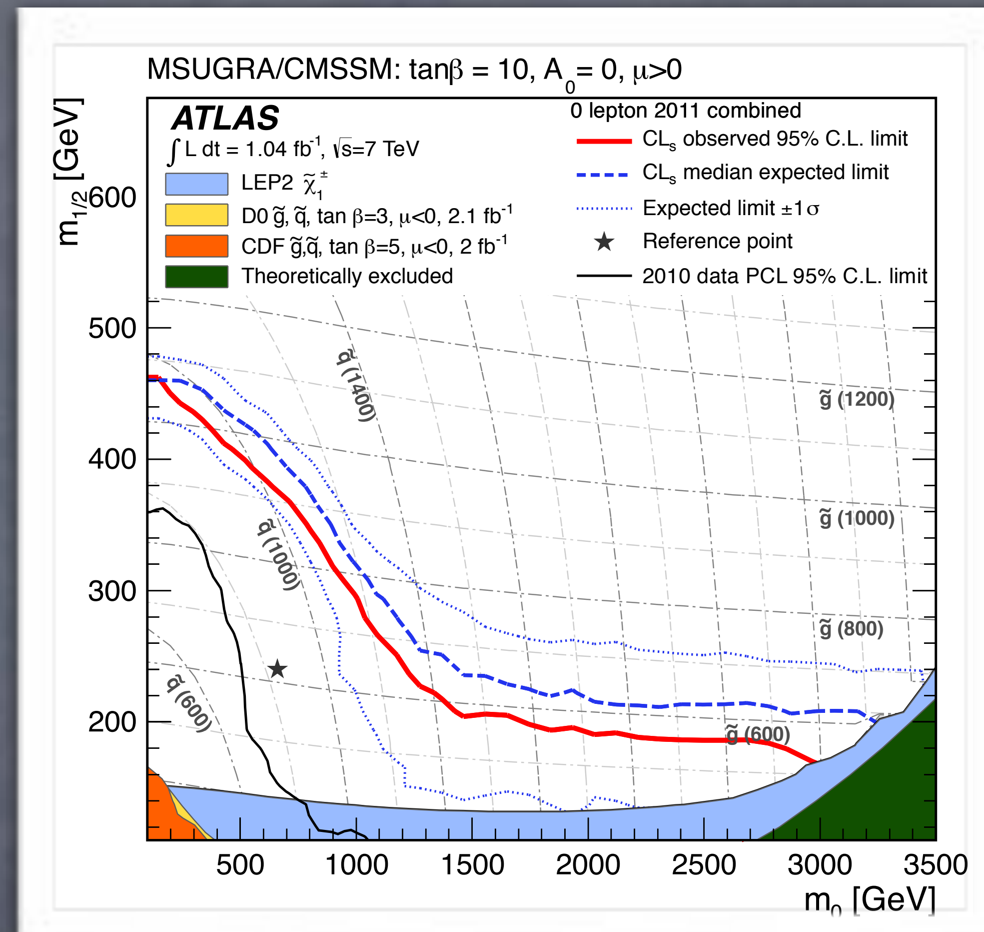

ATLAS Collaboration, 1109.6572 [hep-ex]

- s-particles discovery is also a primary task of the LHC
- However, the SUSY signatures strongly depend on the different models (spectrum, SUSY breaking, LSP, etc.)

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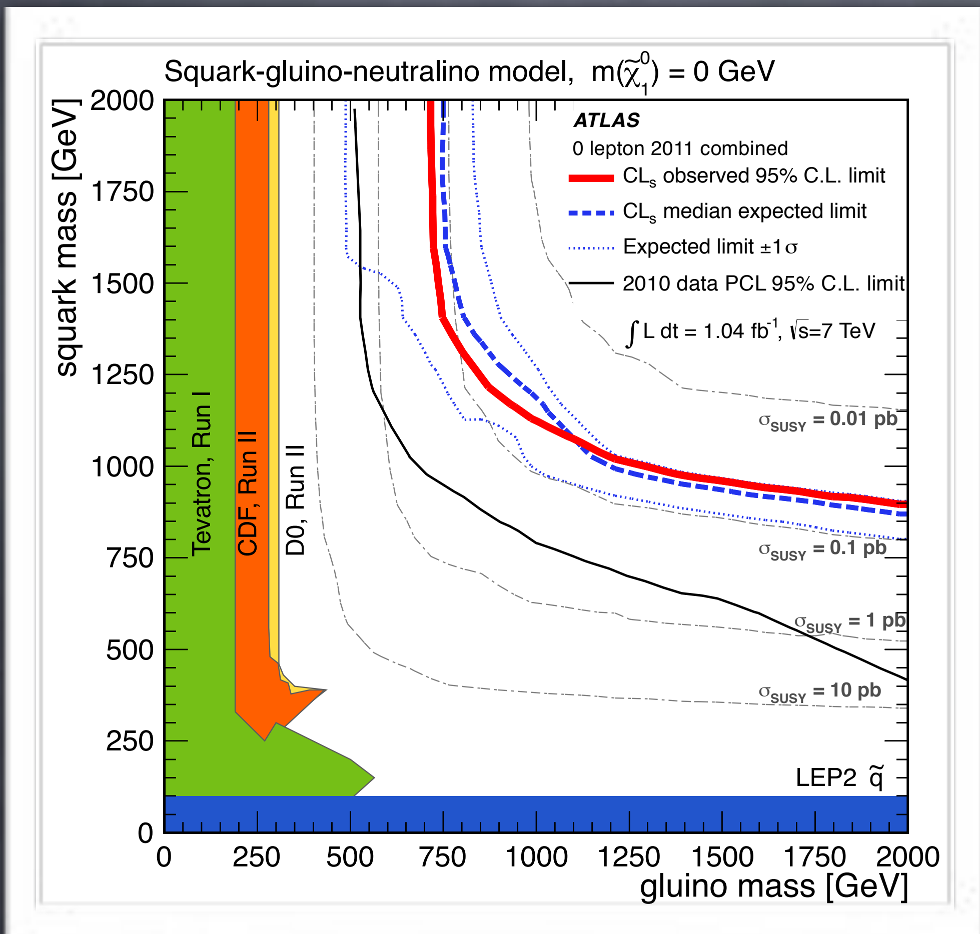
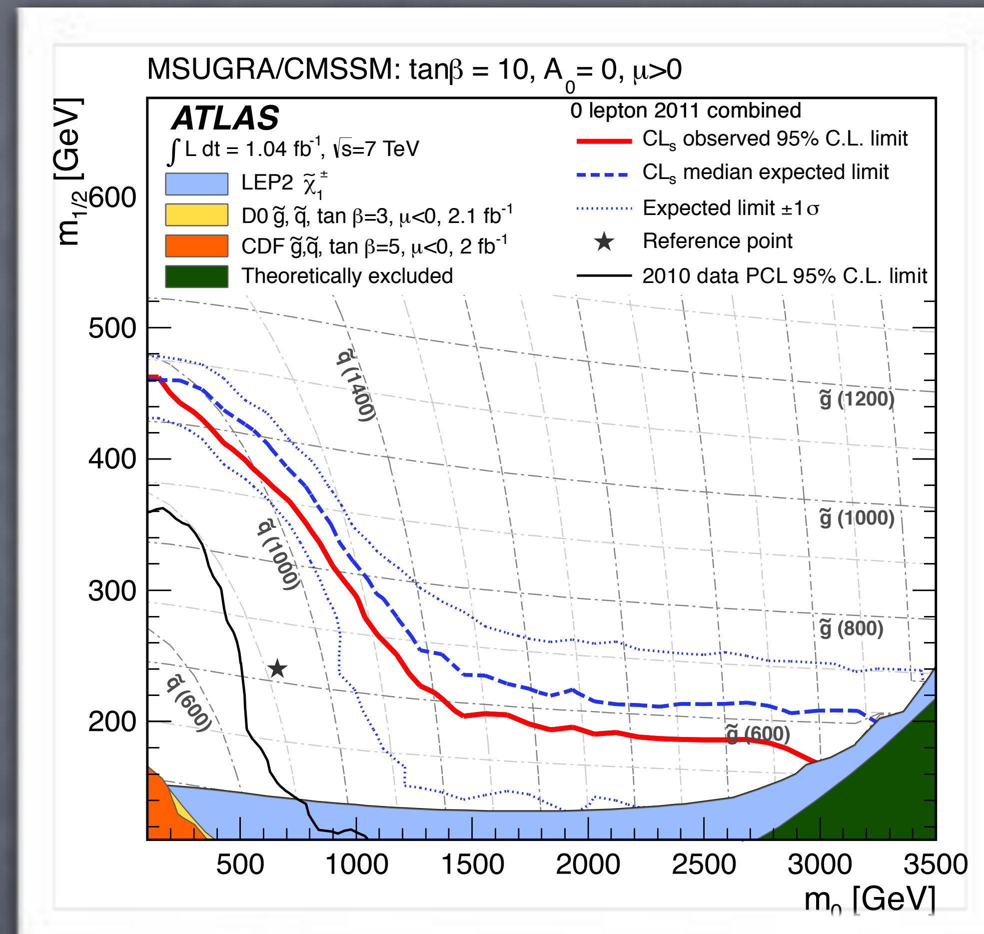




ATLAS Collaboration, 1109.6572 [hep-ex]

Are we looking for SUSY in the wrong place?

This talk:

SUSY broken spontaneously at around the TeV scale

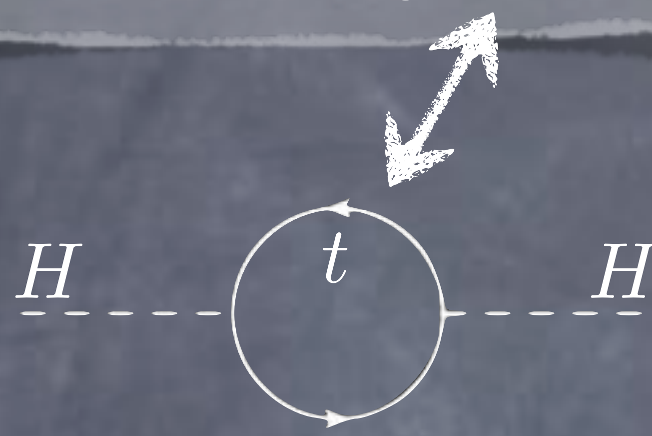
Could be discovered through a non-standard decay of a SM-like Higgs

Outline

- Introduction and motivations
- Dynamical goldstino supermultiplet
- Promoting the MSSM soft terms to SUSY operators
  - The Higgs mass spectrum
  - Characteristic signatures
- Simplified model for photon + MET signal
  - Signal vs Background
  - LHC@8 predictions
  - Conclusions and future directions

- An elementary Higgs is problematic

$$m_H^2 \approx m_{H,\text{tree}}^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 + \cdots$$



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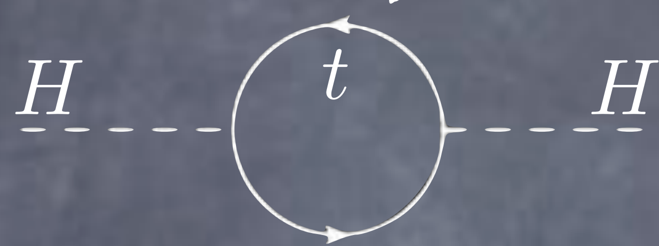

Hierarchy Problem

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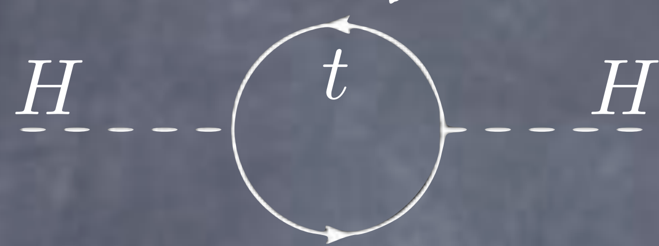

Hierarchy Problem

- One potential solution: SUSY $t \leftrightarrow \tilde{t}$

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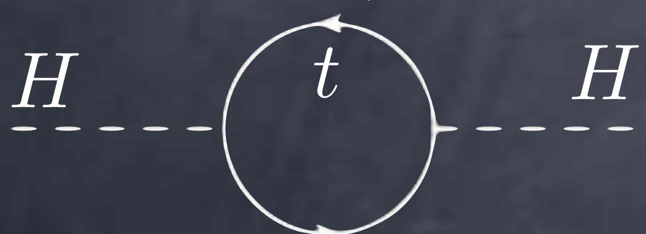

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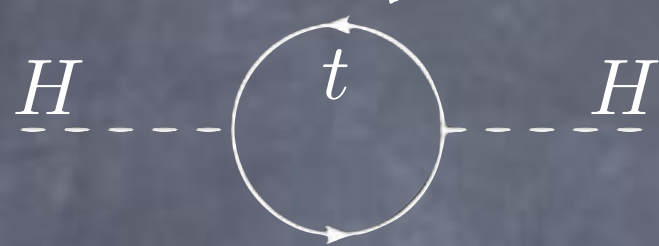

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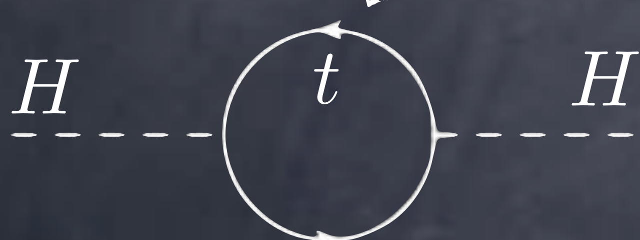

The Higgs mass in the MSSM

$$m_h^2 \approx m_Z^2 \cos^2 2\beta$$

Tree level

The Higgs mass in the MSSM

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) .$$

Tree level 1-loop

$m_h^2 >> m_Z^2$ requires heavy stops

The Higgs mass in the MSSM

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$$X_t = A_t - \mu/\tan\beta$$

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...or a large stop A-term

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Little Hierarchy Problem

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Little Hierarchy Problem

Hints toward non-minimal SUSY extensions?

Beyond the MSSM

- Singlet extensions
  - NMSSM: Adds a gauge singlet scalar superfield $\mu H_d H_u \to \lambda S H_d H_u$
  - $\mu\nu$SSM: Adds 3 scalars superfield and breaks R-parity to take into account "μ"-problem and TeV neutrino seesaw
  - SMSSM: A version of the NMSSM focusing on improving the little-hierarchy problem (forgetting the μ).
  - λ-SUSY: As NMSSM, improving the little-hierarchy problem, but loosing perturbativity around 10 TeV
- Gauge group extensions
- Higher-dimensional operators (E.g. $W \supset (H_d H_u)^2/M$)
- Spontaneous ~~SUSY~~ at low scales

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- Spontaneous ~~SUSY~~ at low scales ← This talk

Spontaneous SUSY breaking

- Spontaneous breaking of (global) SUSY implies the existence of a massless spin 1/2 Goldstone particle, the goldstino.
- In the presence of gravity, the goldstino is eaten by the spin 3/2 gravitino and the gravitino acquires a mass:

$$m_{3/2} = \frac{f}{\sqrt{3}M_{\rm P}}$$

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Exp. Bound	Gauge Mediation	Gravity Mediation
$m_{3/2} \approx 10^{-5}$ eV	$m_{3/2} \approx 1$ eV	$m_{3/2} \approx 1$ TeV
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Exp. Bound

Focus of this talk :
$m_{3/2} \approx 10^{-3}$ eV
$\sqrt{f} \approx$ few TeV

Gauge Mediation

Gravity Mediation

Goldstino Superfield

$\sqrt{f}$: SUSY breaking scale

- MSSM soft terms

$$m^2_{soft} h^\dagger_u h_u = \frac{m^2_{soft}}{f^2} \int d^4\theta X^\dagger_{\rm soft} X_{\rm soft} H^\dagger_u H_u$$

$$X_{\rm soft} = \theta^2 f$$

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- Non-linear SUSY

Komargodski, Seiberg; 0907.2441 [hep-th]

Antoniadis et al.; 1006.1662 [hep-ph]

$$X_{\rm nl} = \frac{\psi_X \psi_X}{2F_X} + \sqrt{2}\theta\psi_X + \theta^2 F_X$$

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- Dynamical

Brignole et al.; hep-ph/9709111

Casas et al.; hep-ph/0301121

C.Petersson, A.R.; 1111.3368 [hep-ph]

$$X = x + \sqrt{2}\theta\psi_X + \theta^2 F_X$$

$$X_{\rm nl} \to X$$

Goldstino Superfield

$\sqrt{f}$: SUSY breaking scale

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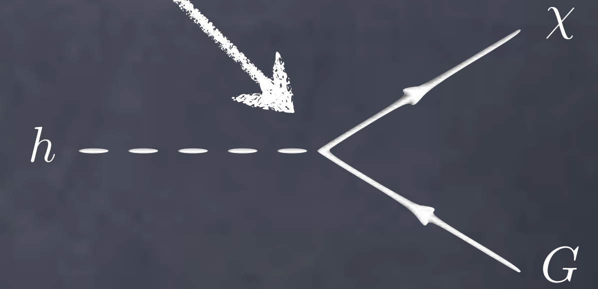

The Model

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$$\mathcal{L}_X = \int d^4\theta \left(1 - \frac{m_x^2}{4f^2} X^\dagger X\right) X^\dagger X + \left\{ \int d^2\theta f X + \text{h.c.} \right\}$$

The Higgs mass

The Higgs mass

- Additional quartic interactions in the Higgs potential

$$V_{\text{tree}}^{(h^4)} = \frac{g_2^2 + g_1^2}{8}\left(|h_d|^2 - |h_u|^2\right)^2 + \frac{g_2^2}{2}|h_d^\dagger h_u|^2 + \left|\frac{m_d^2}{f}|h_d|^2 + \frac{m_u^2}{f}|h_u|^2 - \frac{B_\mu}{f} h_d \cdot h_u\right|^2$$

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- The mass of the lightest CP-even Higgs particle

$$m^2_{h,\rm tree}=\left[\frac{(g_1^2+g_2^2)}{2}\cos^2 2\beta+\left(\frac{2\mu^2}{f}-\frac{B_\mu}{f}\sin 2\beta\right)^2\right]v^2$$

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$$V_{\rm tree}^{(h^4)} = \underbrace{\frac{g_2^2+g_1^2}{8}\left(|h_d|^2-|h_u|^2\right)^2 + \frac{g_2^2}{2}|h_d^\dagger h_u|^2}_{\rm MSSM} + \underbrace{\left|\frac{m_d^2}{f}|h_d|^2 + \frac{m_u^2}{f}|h_u|^2 - \frac{B_\mu}{f} h_d\cdot h_u\right|^2}_{\rm Extra}$$

- The mass of the lightest CP-even Higgs particle

$$m_{h,\rm tree}^2 = \left[\underbrace{\frac{(g_1^2+g_2^2)}{2}}_{\rm MSSM}\cos^2 2\beta + \underbrace{\left(\frac{2\mu^2}{f} - \frac{B_\mu}{f}\sin 2\beta\right)^2}_{\rm Extra}\right] v^2$$

The Higgs mass

- Additional quartic interactions in the Higgs potential

$$V_{\rm tree}^{(h^4)} = \underbrace{\frac{g_2^2+g_1^2}{8}\left(|h_d|^2-|h_u|^2\right)^2 + \frac{g_2^2}{2}|h_d^\dagger h_u|^2}_{\text{MSSM}} + \underbrace{\left|\frac{m_d^2}{f}|h_d|^2 + \frac{m_u^2}{f}|h_u|^2 - \frac{B_\mu}{f} h_d\cdot h_u\right|^2}_{\text{Extra}}$$

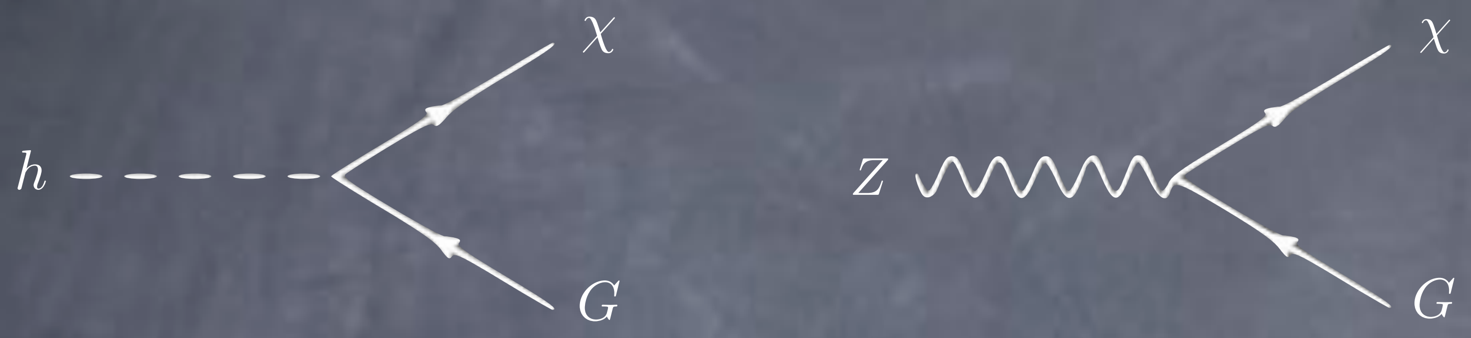
- The mass of the lightest CP-even Higgs particle

$$m_{h,\rm tree}^2 = \left[\frac{(g_1^2+g_2^2)}{2}\cos^2 2\beta + \left(\frac{2\mu^2}{f} - \frac{B_\mu}{f}\sin 2\beta\right)^2\right] v^2$$

$$= m_Z^2\cos^2 2\beta + \left(\frac{B_\mu}{f}\right)^2 v^2 \sin^2 2\beta + \cdots$$

We will focus on the case where the lightest neutralino:

- is the NLSP
- is lighter than the Higgs particle



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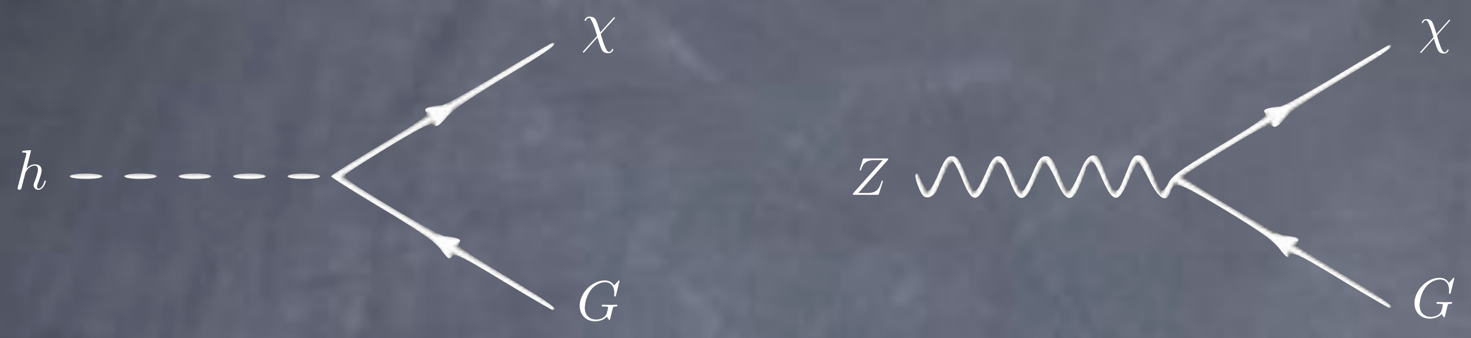
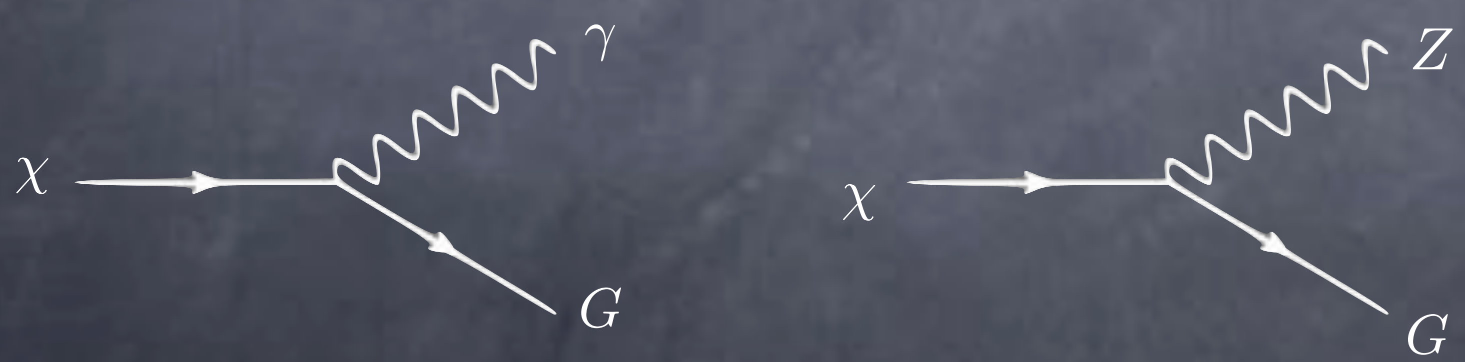


In this case, the neutralino decays only into a goldstino and a photon (or a Z)



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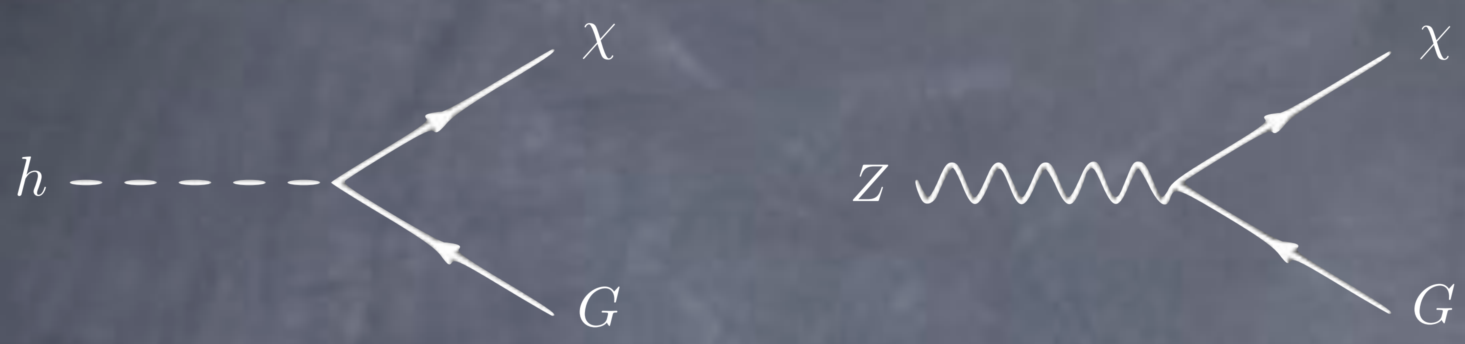

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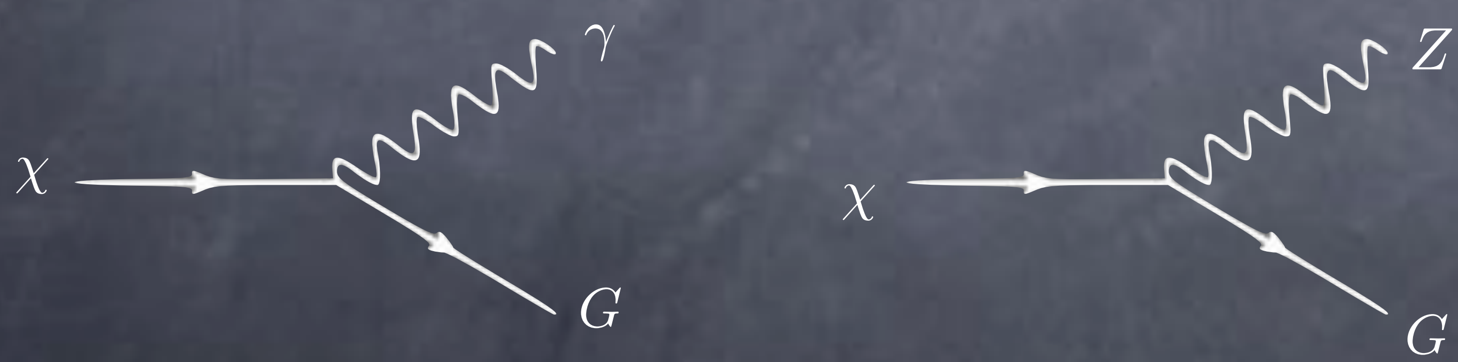

→ Final state: Mono-photon + MET

The signal: γ+MET

The model gives rise to this signal through the following diagrams:

C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

The signal: γ+MET

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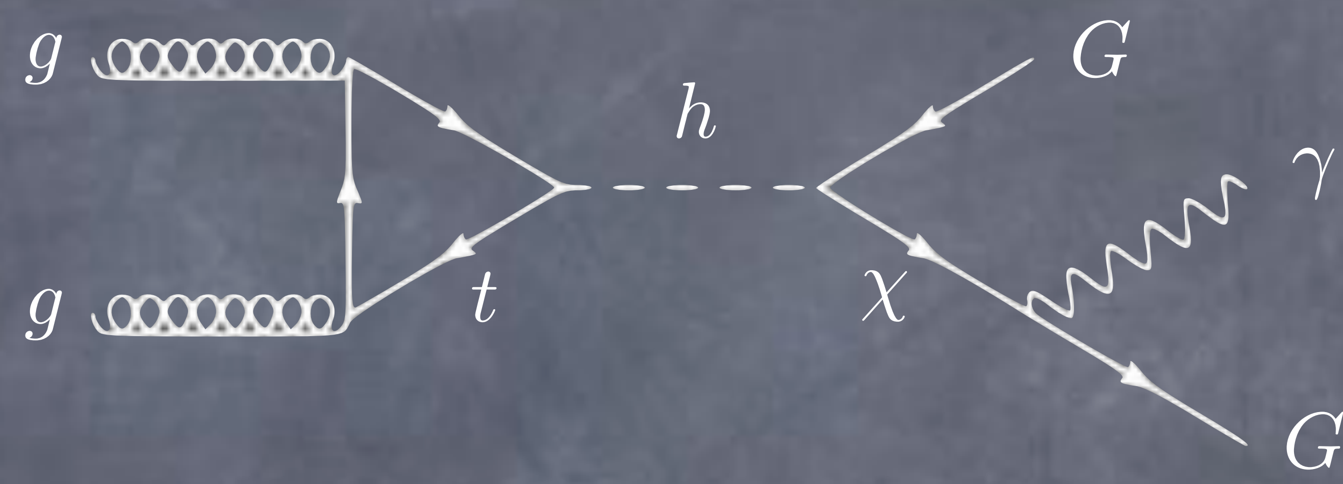

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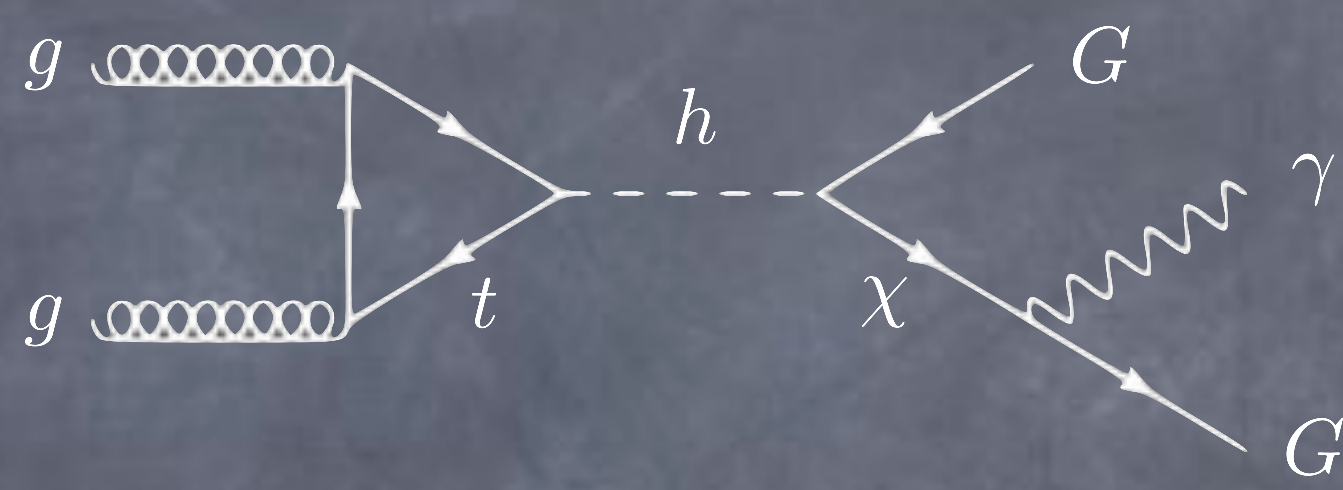

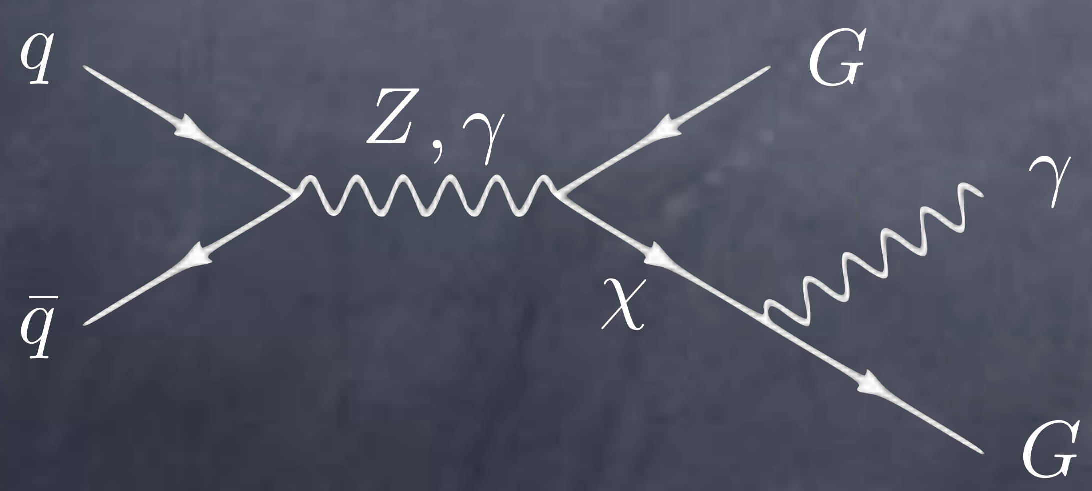

C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

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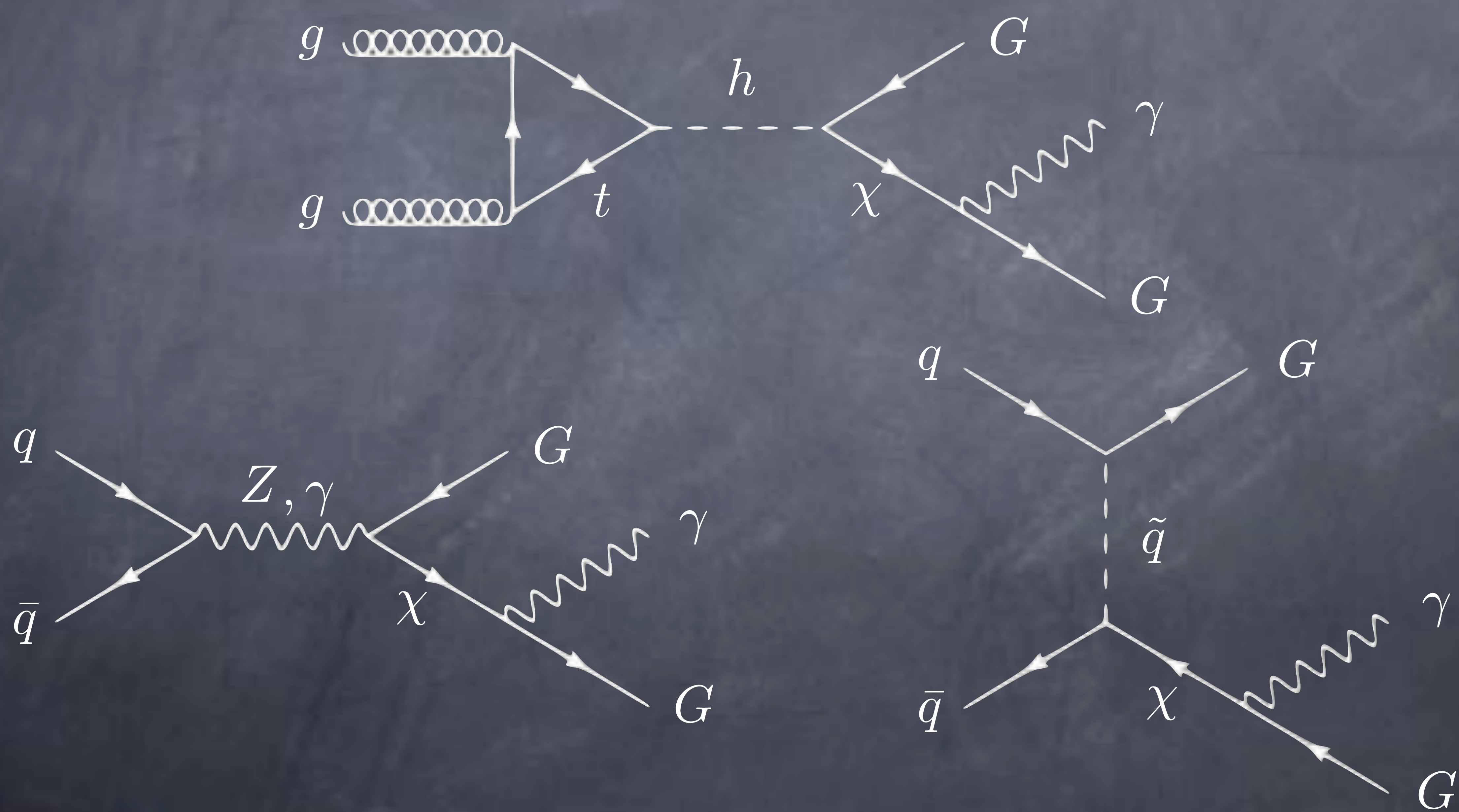
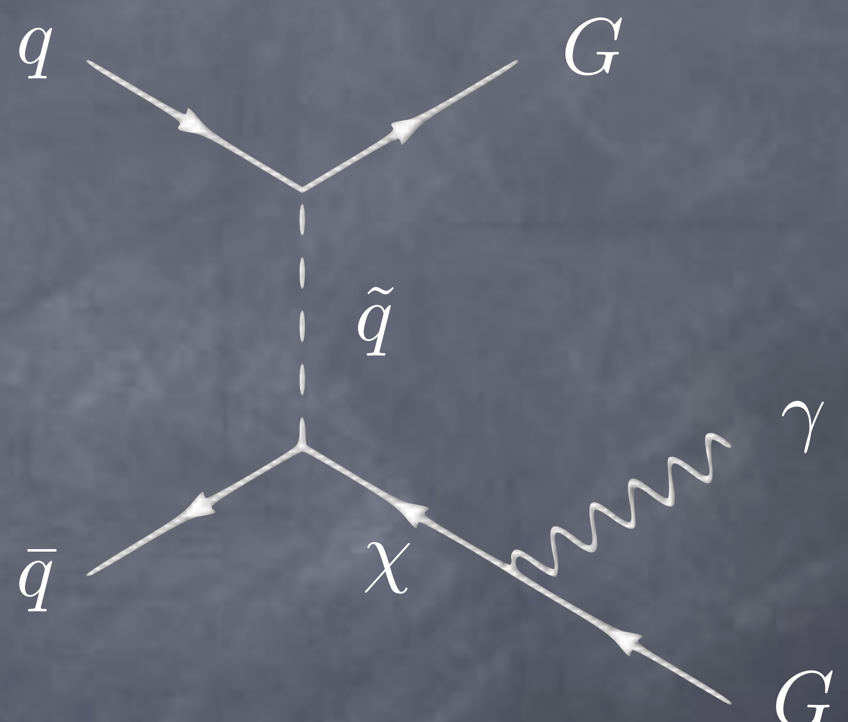


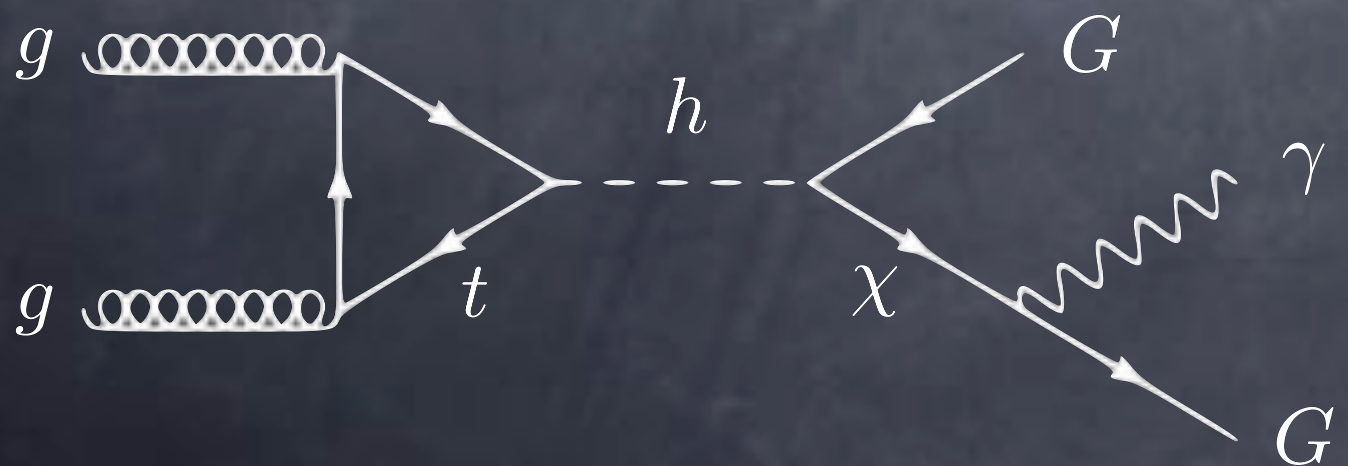
C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

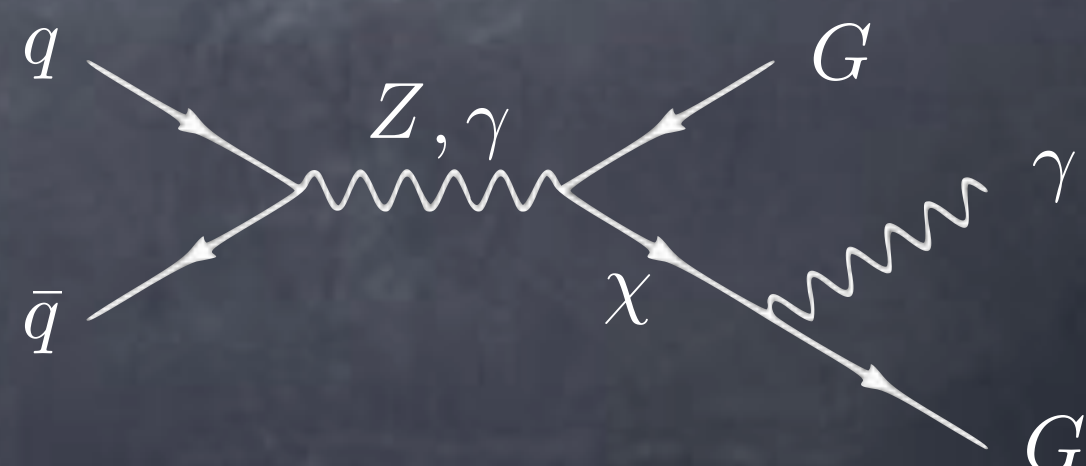
The signal: γ+MET

The model gives rise to this signal through the following diagrams:

- The non-resonant production was studied in the literature with an effective approach based on integrating out everything but the Goldstino
  Brignole et al.; hep-ph/9711516 and hep-ph/9801329
- It gives a subleading contribution in the low p_T^γ region while it is relevant for high p_T^γ studies





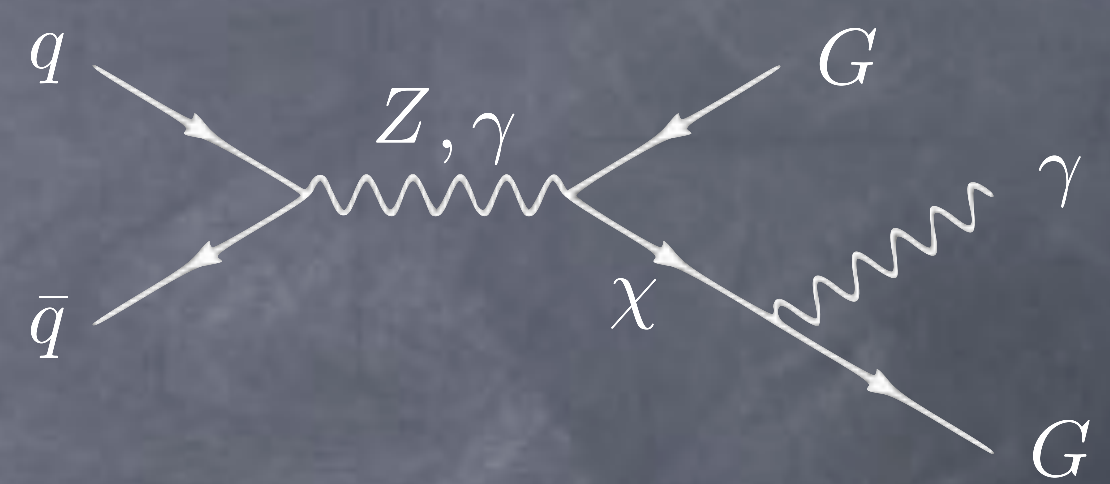


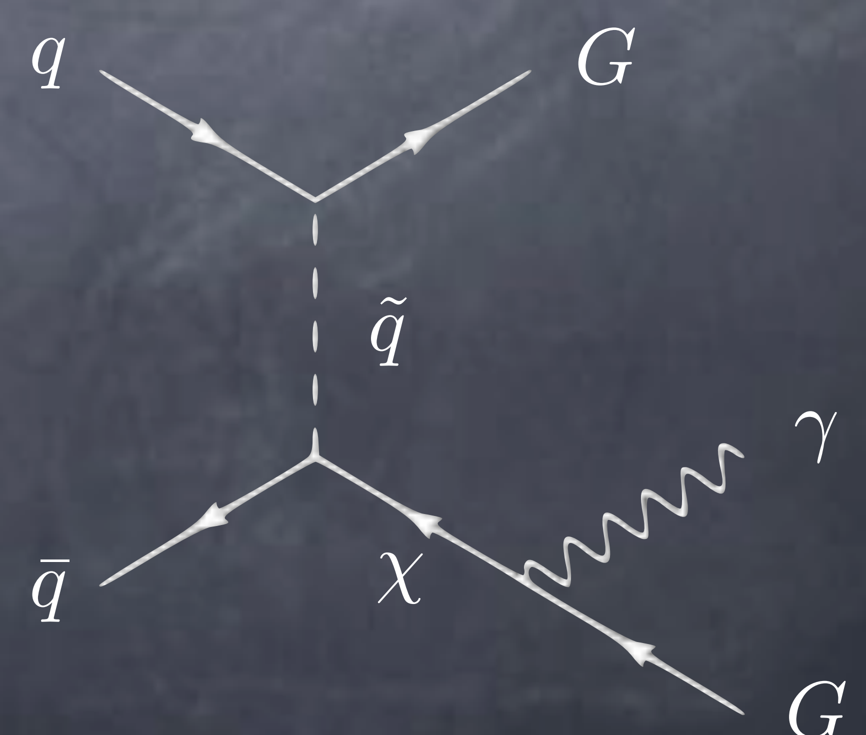
C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

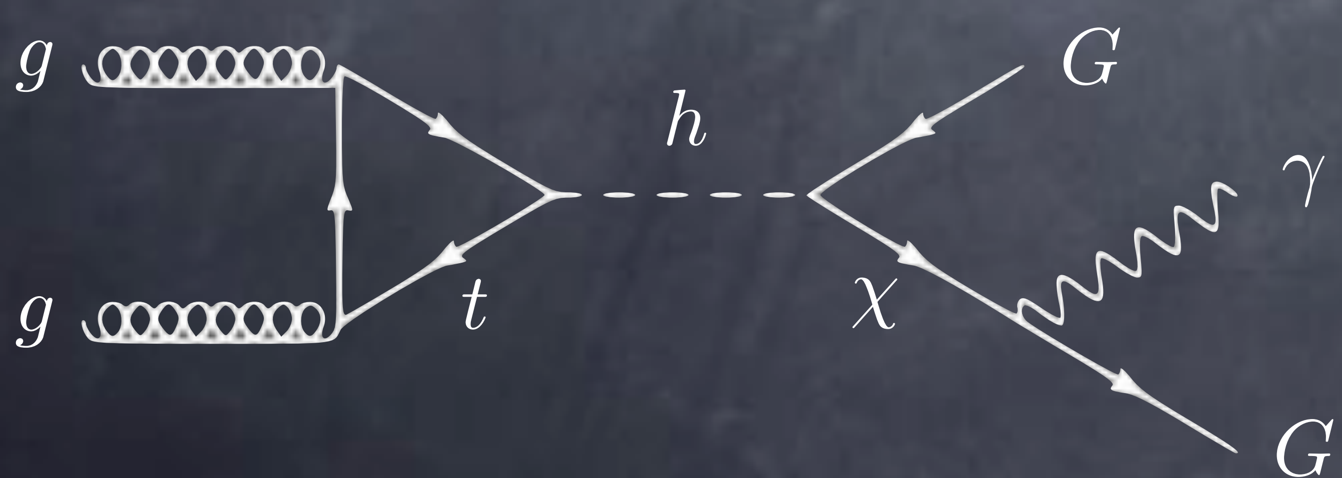
The signal: γ+MET

The model gives rise to this signal through the following diagrams:

- The photon s-channel contribution is completely negligible while the Z one is relevant only for $m_\chi \lesssim m_Z$
- It contributes only in the $p_T^\gamma \lesssim m_Z/2$ region



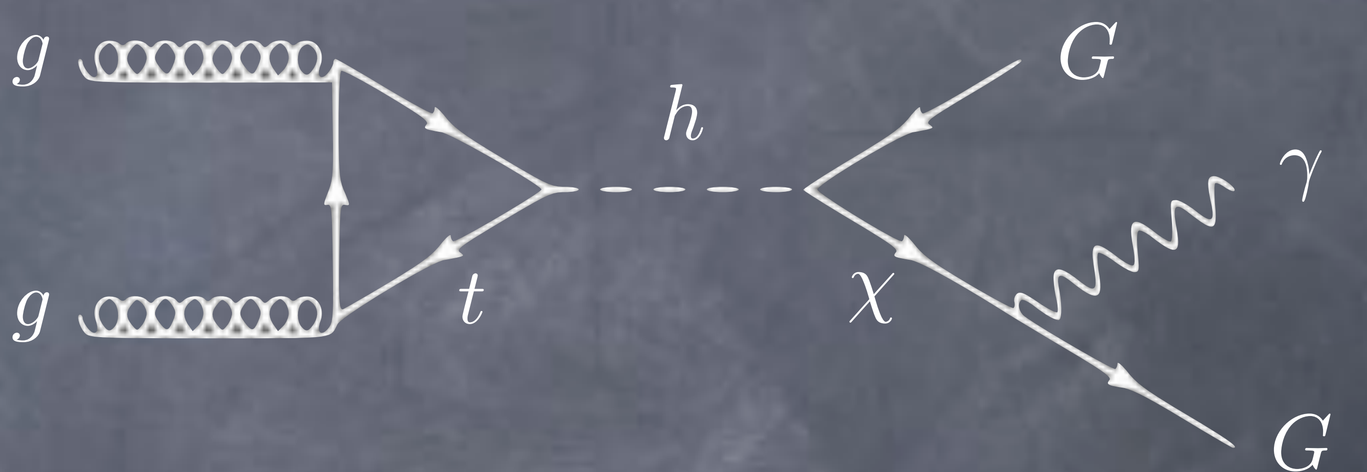


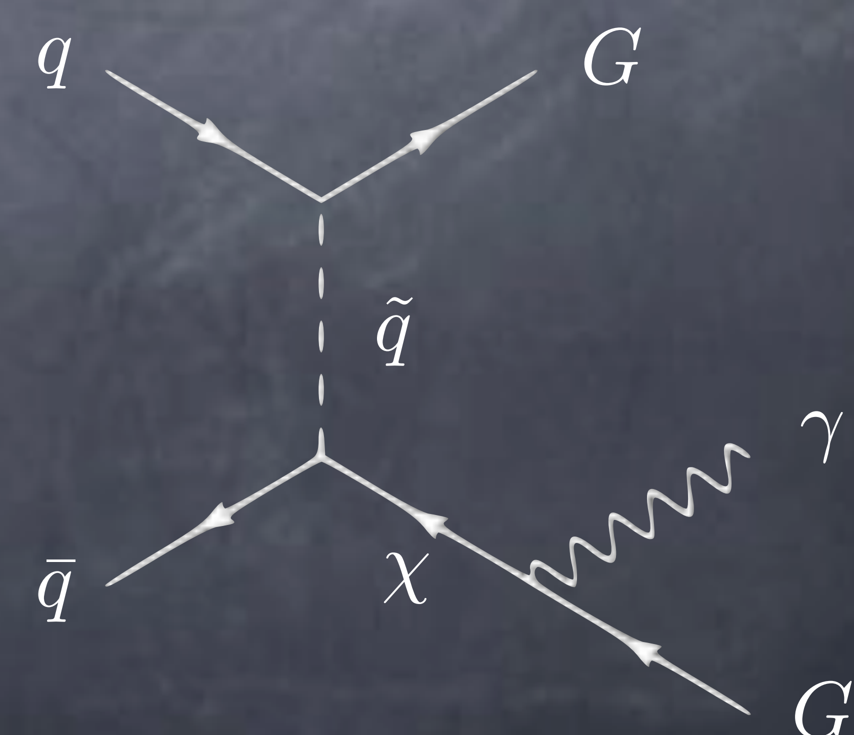


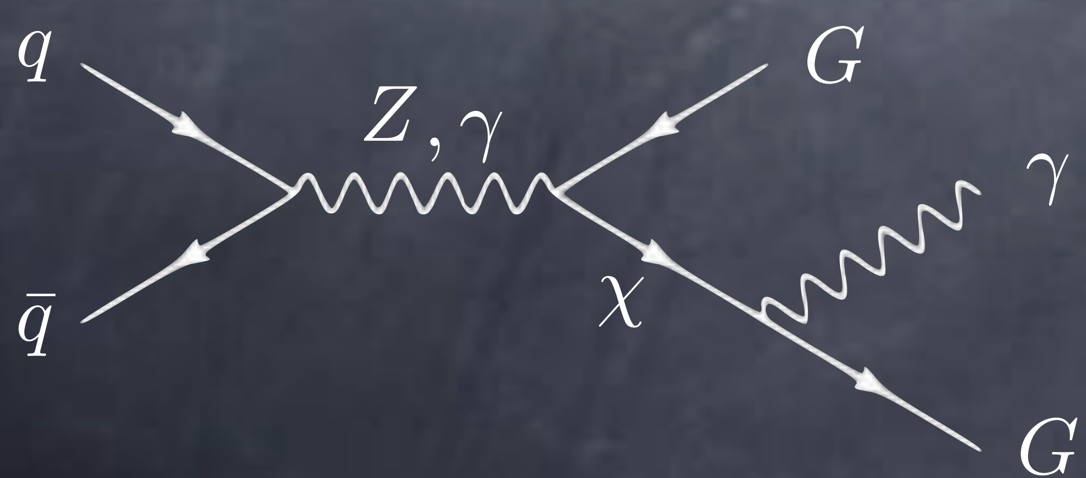
The signal: γ+MET

The model gives rise to this signal through the following diagrams:

- Contributes in the region $p_T^\gamma \lesssim m_h/2$







C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

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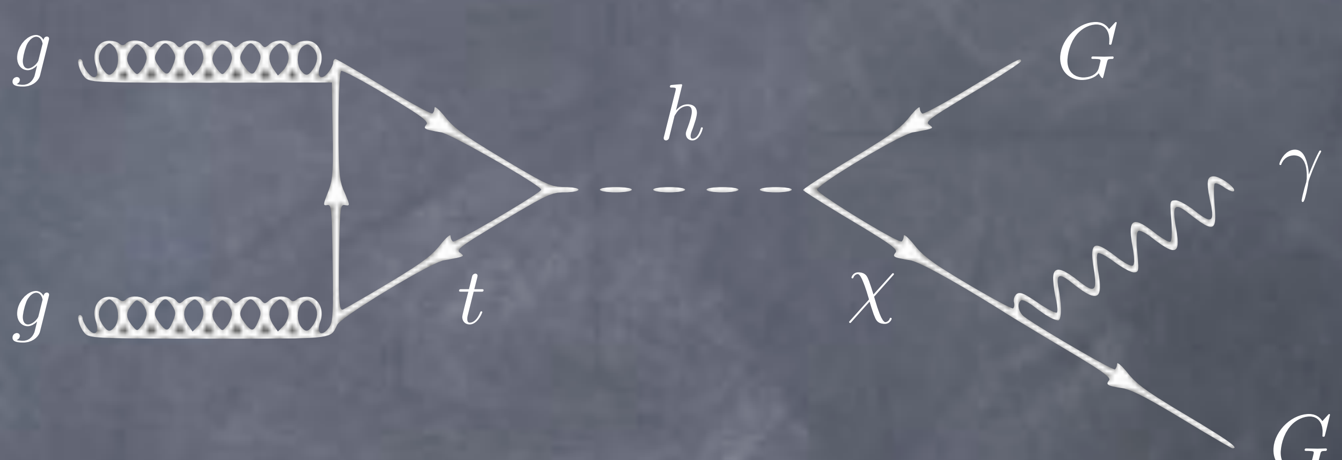
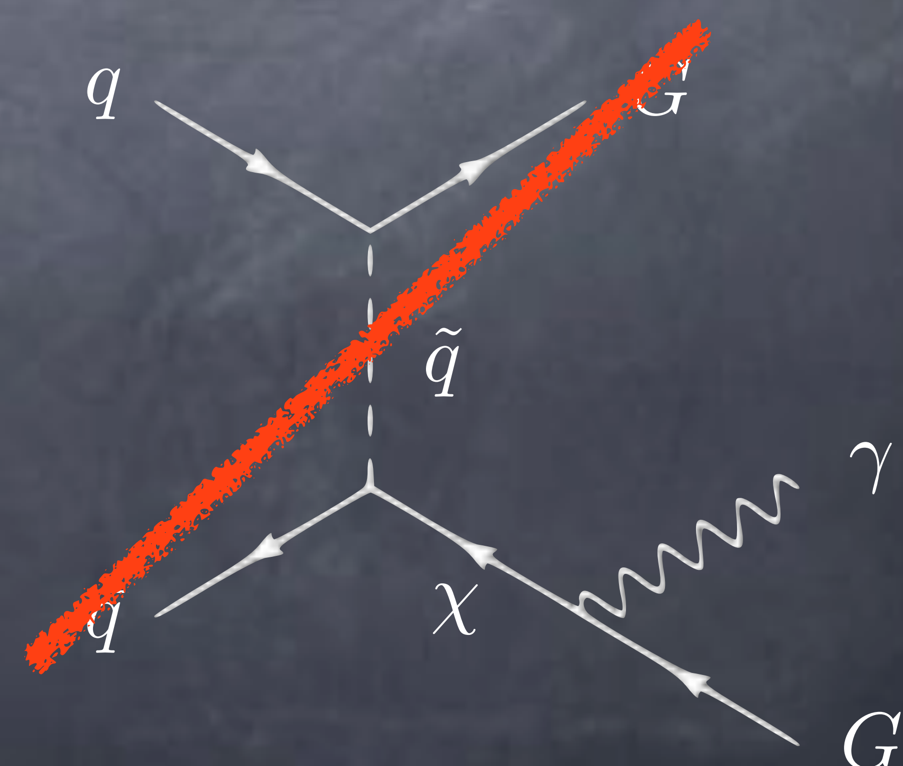
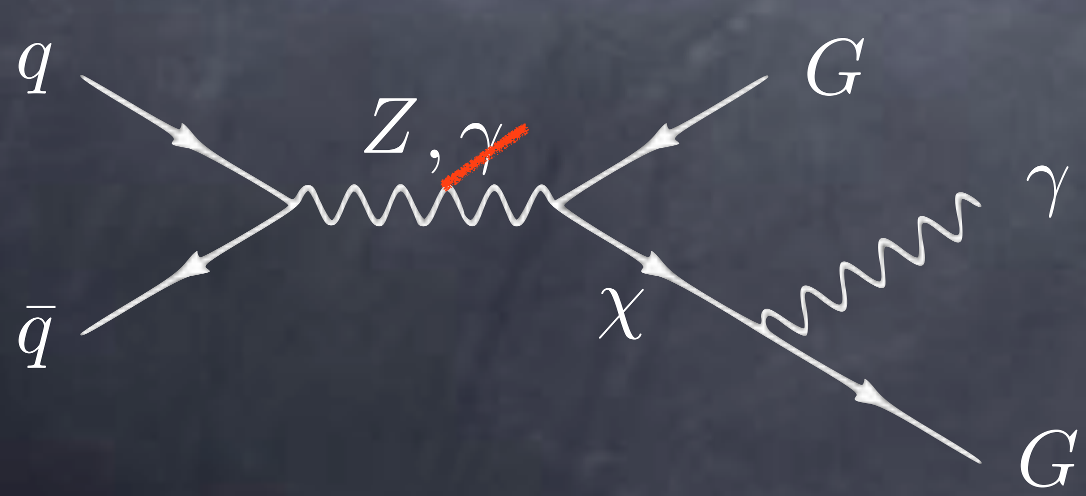
The model gives rise to this signal through the following diagrams:

- Contributes in the region $p_T^\gamma \lesssim m_h/2$
- Focus on this region







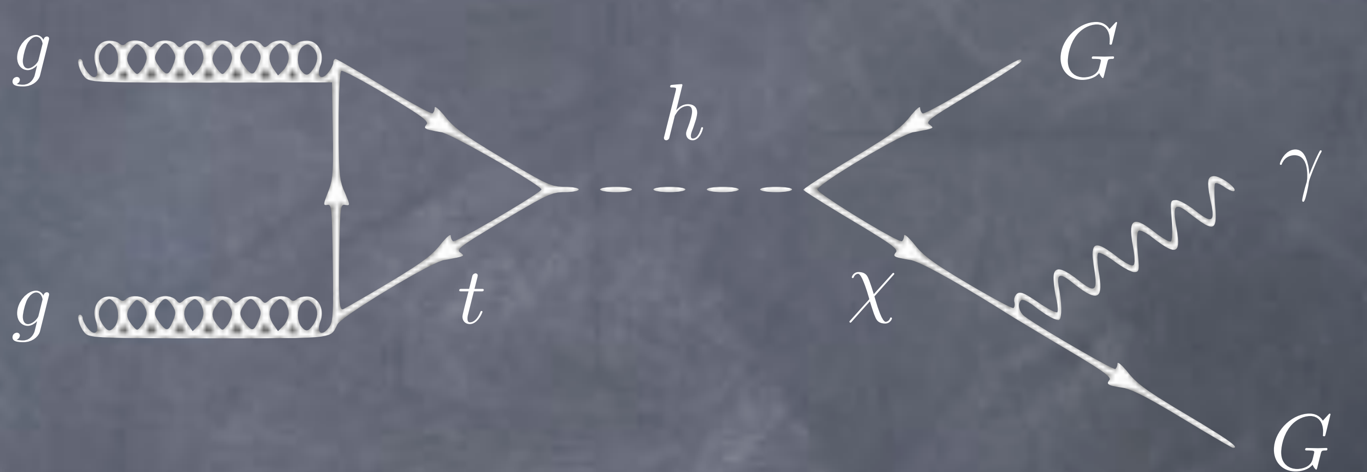
The signal: γ+MET

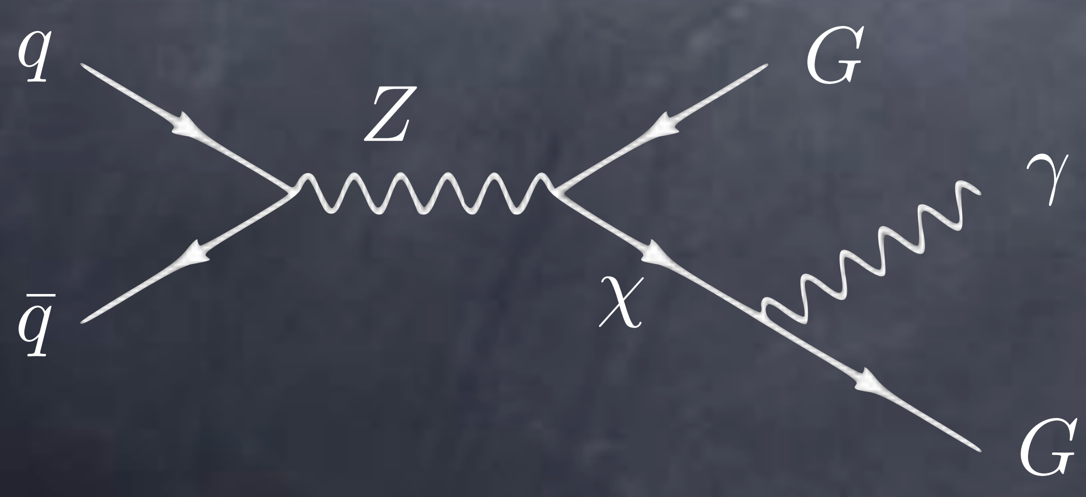
C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

The model gives rise to this signal through the following diagrams:

- Contributes in the region $p_T^\gamma \lesssim m_h/2$
- Focus on this region
- Need only the new vertices:

$$h\chi G,\ \chi\gamma G,\ \chi Z G$$





C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

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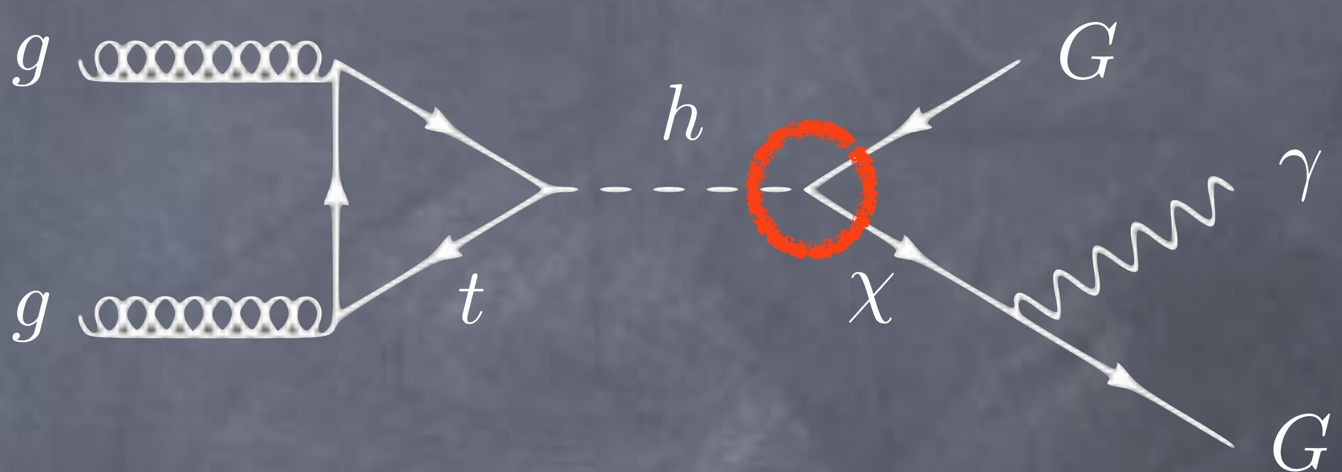

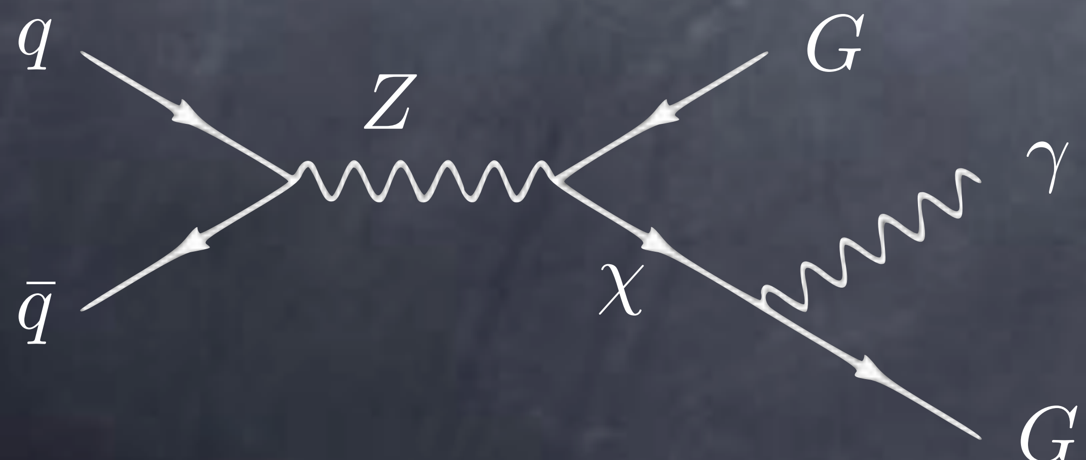

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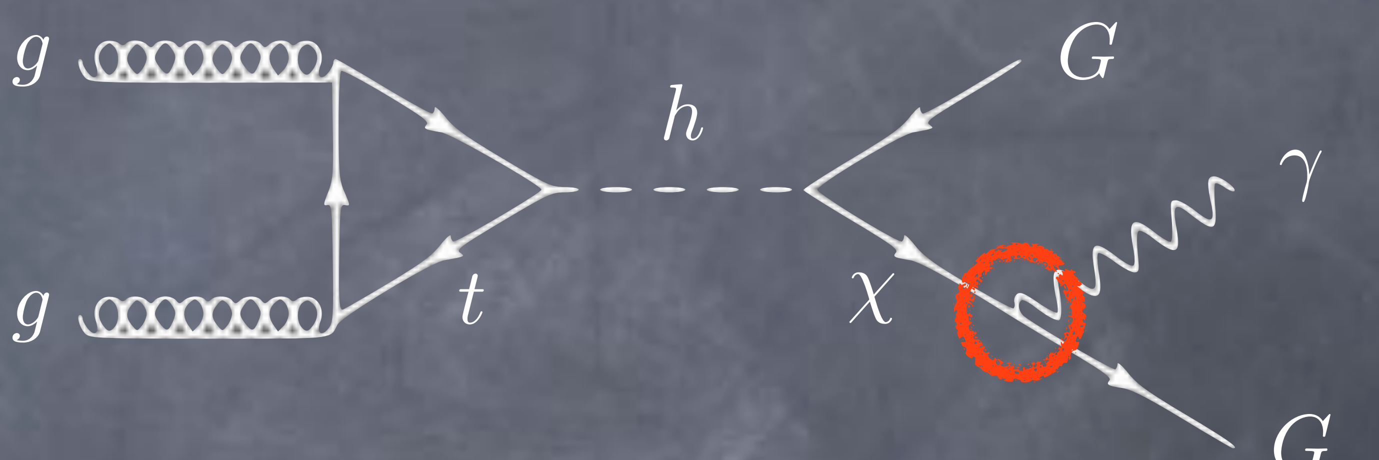

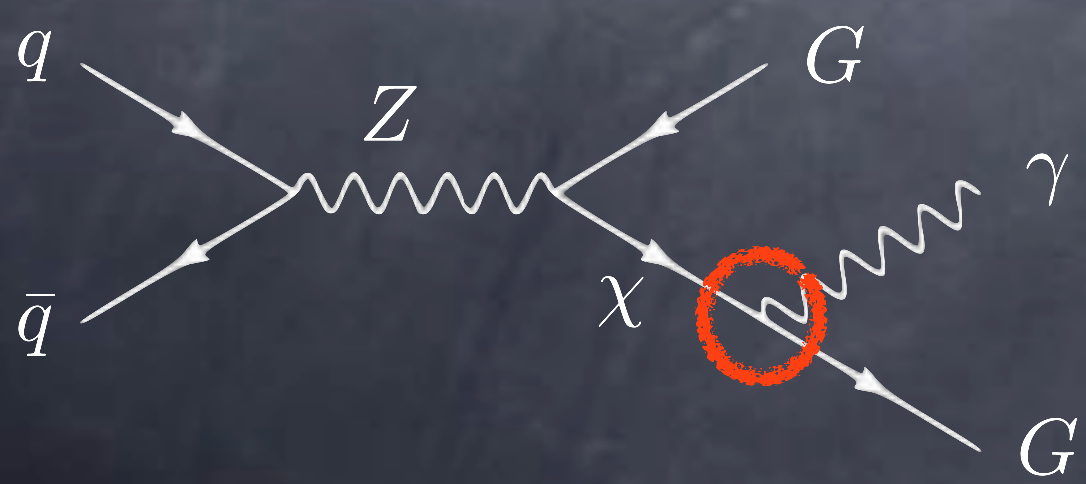

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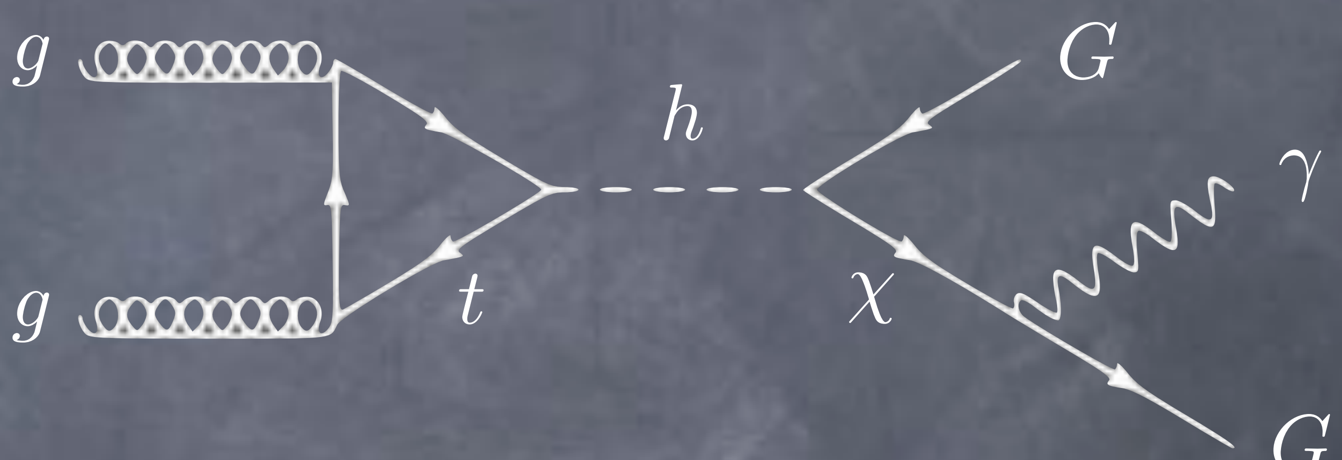
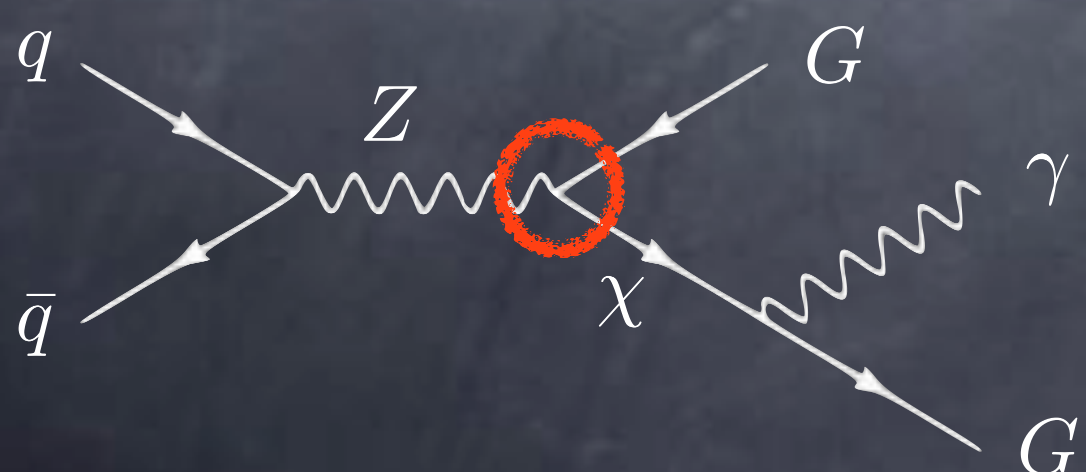




Simplified model for γ+MET

- These new vertices (+ the SM ones) can be described in terms of a simplified model containing only the relevant particles (SM + LSP goldstino + NLSP neutralino)

$$\begin{aligned} \mathcal{L}_{\rm eff} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP} \\ \mathcal{L}_{\rm NP} &= \frac{m^2}{\sqrt{2}f}\Big[g_{h\chi} h \chi_1^0 G + \frac{g_{\chi\gamma}}{m} G\sigma^{\mu\nu} F_{\mu\nu}\chi_1^0 \\ &\quad + \frac{g_{\chi Z\,1}}{m} G\sigma^{\mu\nu} Z_{\mu\nu}\chi_1^0 + g_{\chi Z\,2}\bar{G}\bar{\sigma}^{\mu} Z_{\mu}\chi_1^0 + \text{h.c.}\Big] \end{aligned}$$

$$m_h/2 < m_\chi < m_h, \ \text{where } m_h = 125 \text{ GeV}$$

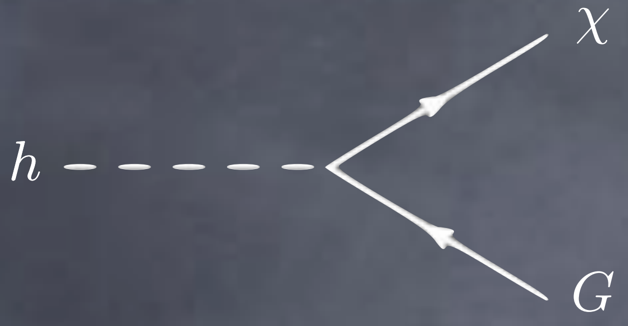
- The neutralino decays promptly inside the detector

$$L_\chi = \frac{1}{g_{\chi\gamma}^2}\frac{(100\,\text{GeV})^5}{m_\chi^3 m^2}\left(\frac{\sqrt{f}}{1\,\text{TeV}}\right)^4 \cdot 10^{-10}\,\text{cm}\,.$$

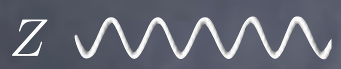
New decay channels

C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

New decay channels

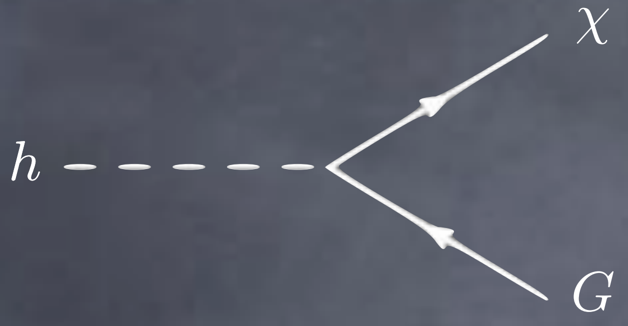


$$\Gamma(h \to \chi_1^0 G) = \frac{m_h}{16\pi} \frac{g_{h\chi}^2 m^4}{f^2} \left(1 - \frac{m_\chi^2}{m_h^2}\right)^2$$



C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

New decay channels



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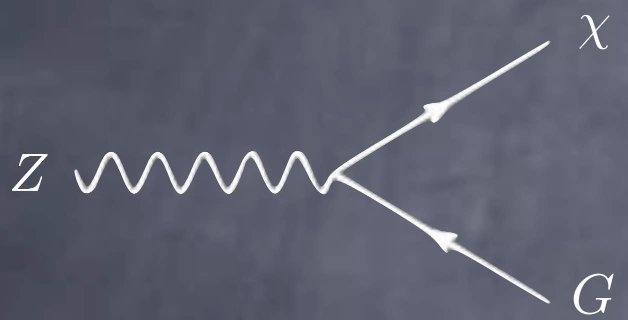
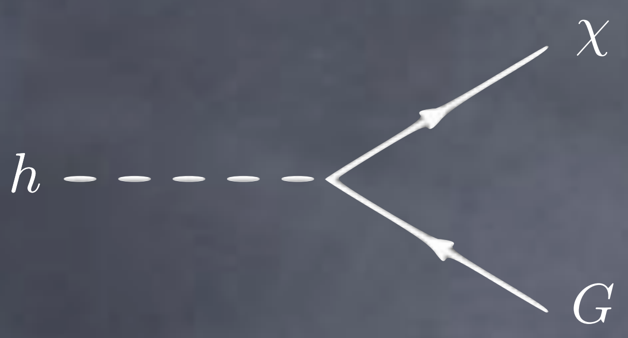


$$\Gamma(Z \to \chi_1^0 G) = \frac{1}{48\pi m_Z} \left(1 - \frac{m_\chi^2}{m_Z^2}\right) \frac{m^4}{f^2} \left[g_{\chi Z\,2}^2 (2m_Z^2 - m_\chi^2 - \frac{m_\chi^4}{m_Z^2}) + 6 \frac{g_{\chi Z\,1} g_{\chi Z\,2}}{m} m_\chi (m_Z^2 - m_\chi^2) + \frac{g_{\chi Z\,1}^2}{m^2} (m_Z^4 + m_\chi^2 m_Z^2 - 2m_\chi^4) \right]$$

C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

New decay channels



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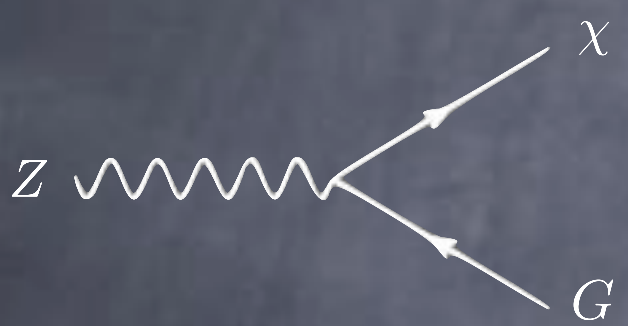

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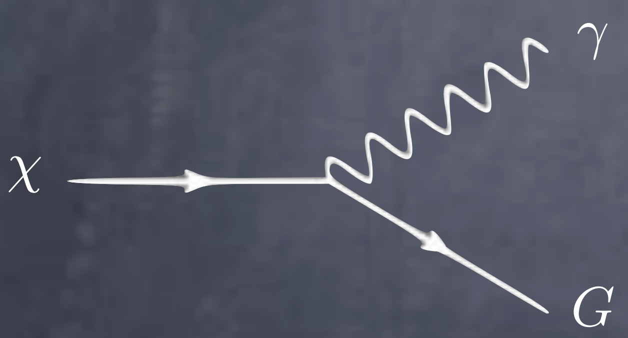
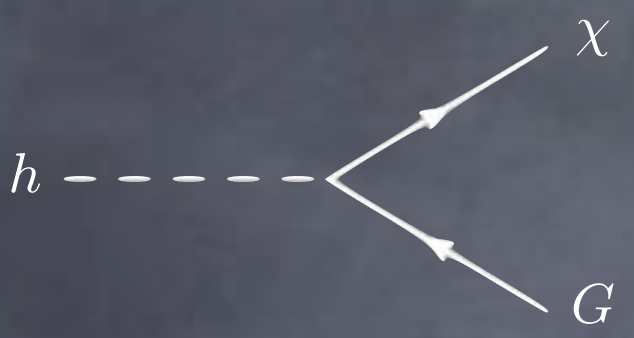


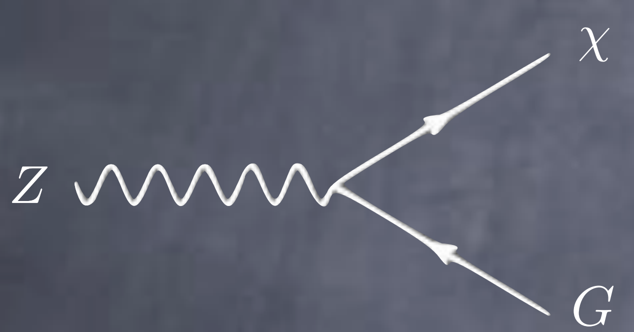
$$\Gamma(\chi_1^0 \to \gamma G) = \frac{m_\chi^3}{16\pi} \frac{g_{\chi\gamma}^2 m^2}{f^2}$$

C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

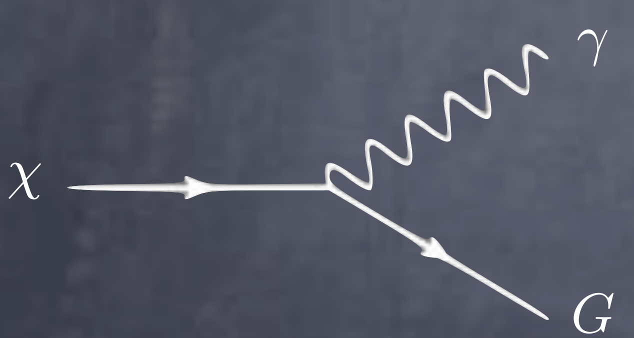
New decay channels



$$\Gamma(h \to \chi_1^0 G) = \frac{m_h}{16\pi}\frac{g_{h\chi}^2 m^4}{f^2}\left(1 - \frac{m_\chi^2}{m_h^2}\right)^2$$



$$\begin{aligned}\Gamma(Z \to \chi_1^0 G) \quad = \quad & \frac{1}{48\pi m_Z}\left(1 - \frac{m_\chi^2}{m_Z^2}\right)\frac{m^4}{f^2}\left[g_{\chi Z\,2}^2\left(2m_Z^2 - m_\chi^2 - \frac{m_\chi^4}{m_Z^2}\right)\right. \\ & \left. +6\frac{g_{\chi Z\,1}g_{\chi Z\,2}}{m}m_\chi(m_Z^2 - m_\chi^2) + \frac{g_{\chi Z\,1}^2}{m^2}(m_Z^4 + m_\chi^2 m_Z^2 - 2m_\chi^4)\right]\end{aligned}$$

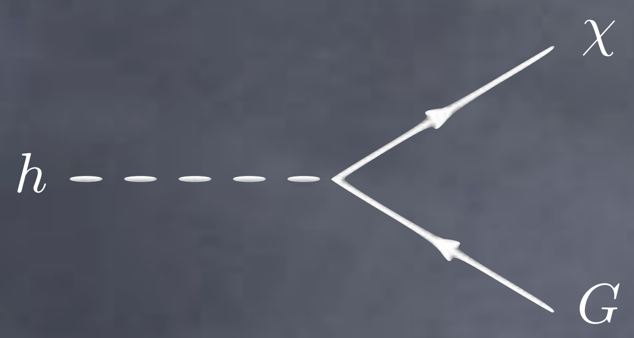


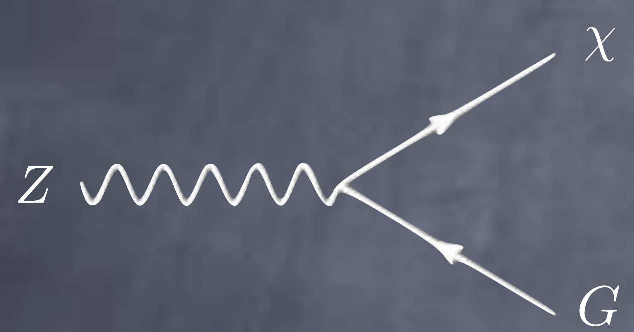
$$\Gamma(\chi_1^0 \to \gamma G) = \frac{m_\chi^3}{16\pi}\frac{g_{\chi\gamma}^2 m^2}{f^2}$$

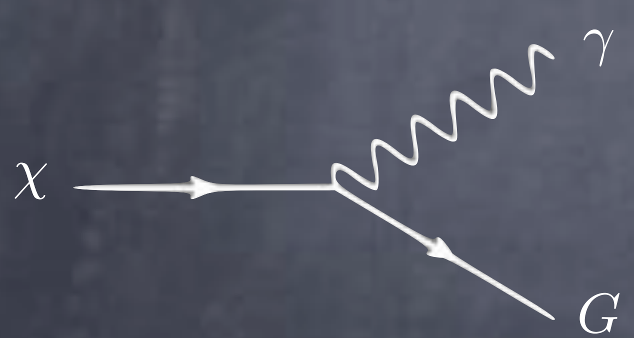
$$\begin{aligned}\Gamma(\chi_1^0 \to Z G) \quad = \quad & \frac{1}{32\pi m_\chi}\left(1 - \frac{m_Z^2}{m_\chi^2}\right)\frac{m^4}{f^2}\left[g_{\chi Z\,2}^2\left(m_\chi^2 + \frac{m_\chi^4}{m_Z^2} - 2m_Z^2\right)\right. \\ & \left. +6\frac{g_{\chi Z\,1}g_{\chi Z\,2}}{m}m_\chi(m_\chi^2 - m_Z^2) + \frac{g_{\chi Z\,1}}{m^2}(2m_\chi^4 - m_Z^4 - m_\chi^2 m_Z^2)\right]\end{aligned}$$

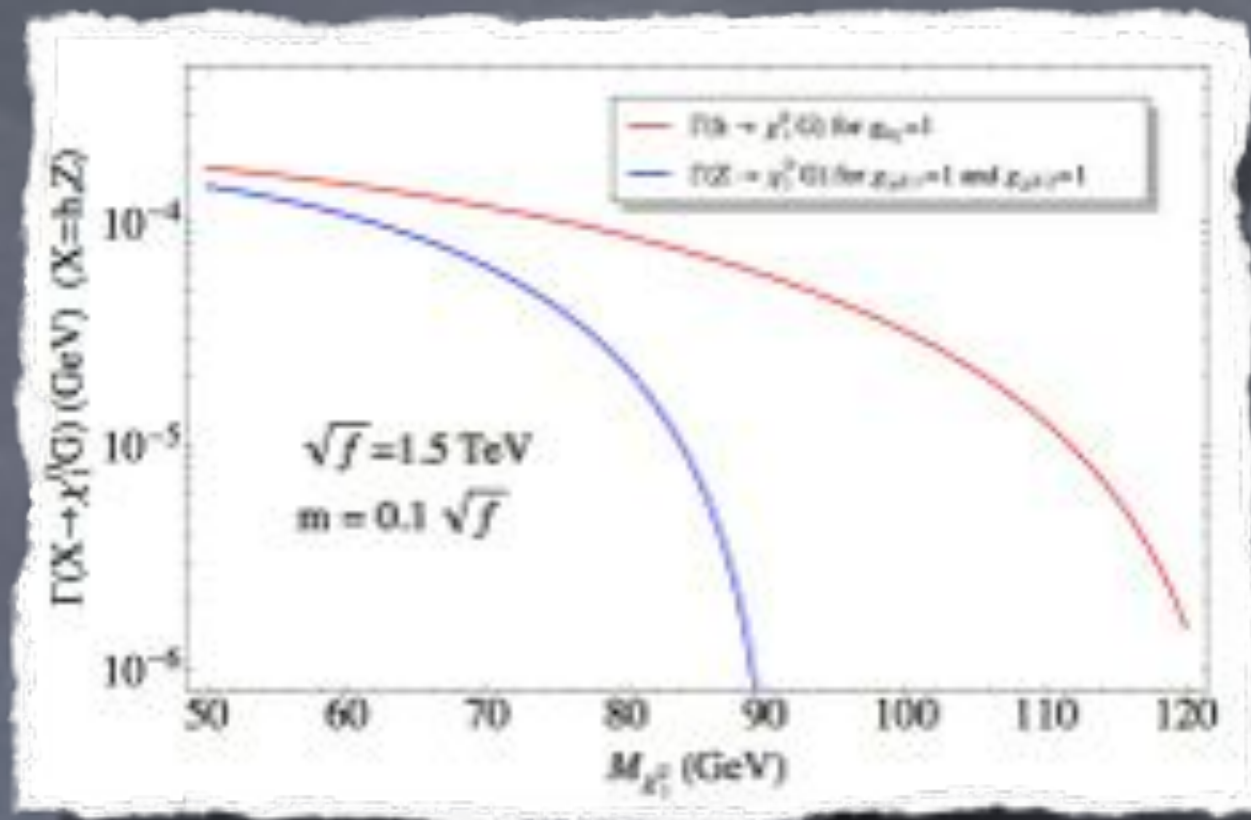
C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

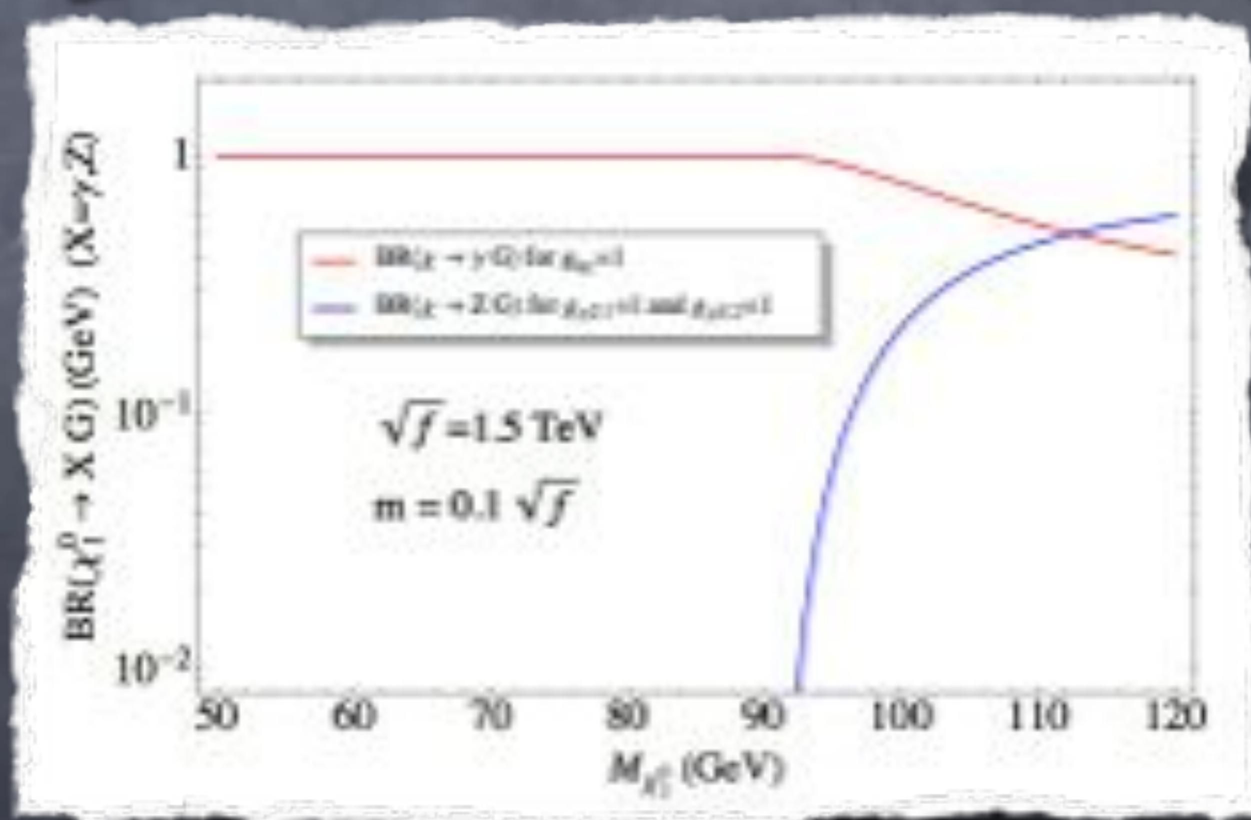
New decay channels





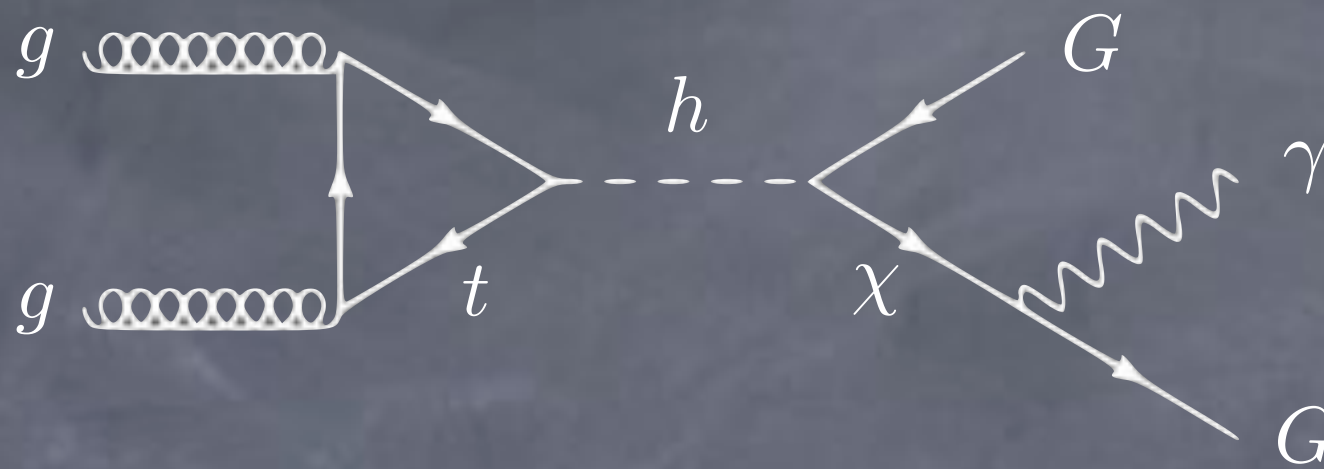




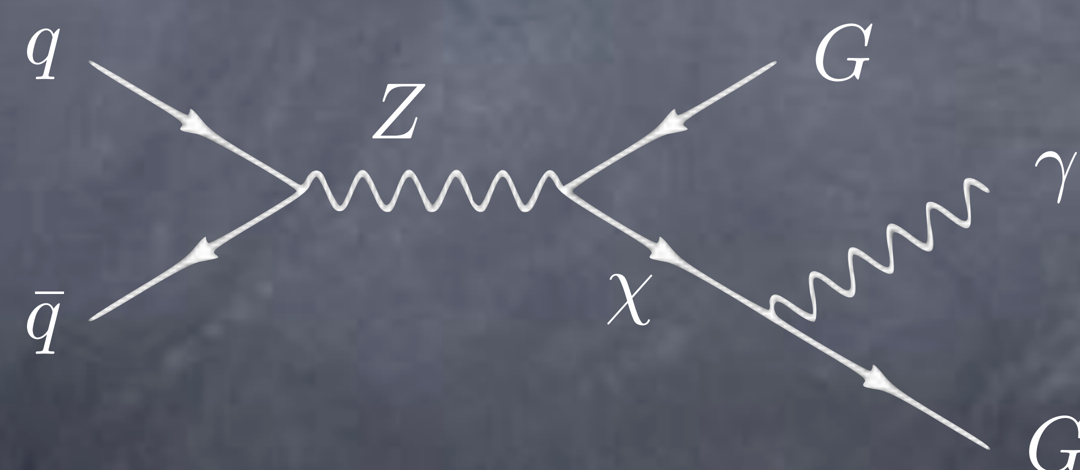


C.Petersson, A.R., Torre; 1203.4563 [hep-ph]

The signal: γ+MET



$$N_{\rm sig}^{h} = \sigma_h^{\rm SM} \times {\rm BR}\left(h \to \chi_1^0 G\right) \times {\rm BR}\left(\chi_1^0 \to \gamma G\right) \times \mathcal{A}_{\rm sig}^{h} \times \epsilon_\gamma \times L$$



$$N_{\rm sig}^{Z} = \sigma_Z^{\rm SM} \times {\rm BR}(Z \to \chi_1^0 G) \times {\rm BR}(\chi_1^0 \to \gamma G) \times \mathcal{A}_{\rm sign}^{Z} \times \epsilon_\gamma \times L$$

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The SM background: γ+MET

Name	Process	Source
bg1	$pp \to Z\gamma \to \gamma 2\nu$	Irreducible background
bg2	$pp \to Zj \to j2\nu$	Jet fakes a photon
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- The irreducible $Z\gamma$ background comes from the t-channel di-boson production in the SM
- This is the most relevant BG for high p_T^γ searches (e.g. non resonant production, large ED)

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- The γj SM production contributes when the jet is missed by the detector
- This BG is the most difficult to estimate especially at low p_T^γ due to detector effects on jet identification and reconstruction
- We have estimated it assuming that jets in the very forward region $|\eta| > 4$ are missed (this assumptions agrees with the CMS analysis at high p_T^γ)

Kinematics

- Do kinematic cuts on the signal and the background to maximize the signal significance
- There are only 3 relevant kinematic variables, i.e. the three components of the photon momentum
- We can trade them $(p_x^\gamma, p_y^\gamma, p_z^\gamma)$ for 3 more useful variables $(p_T^\gamma, \eta, \phi,)$

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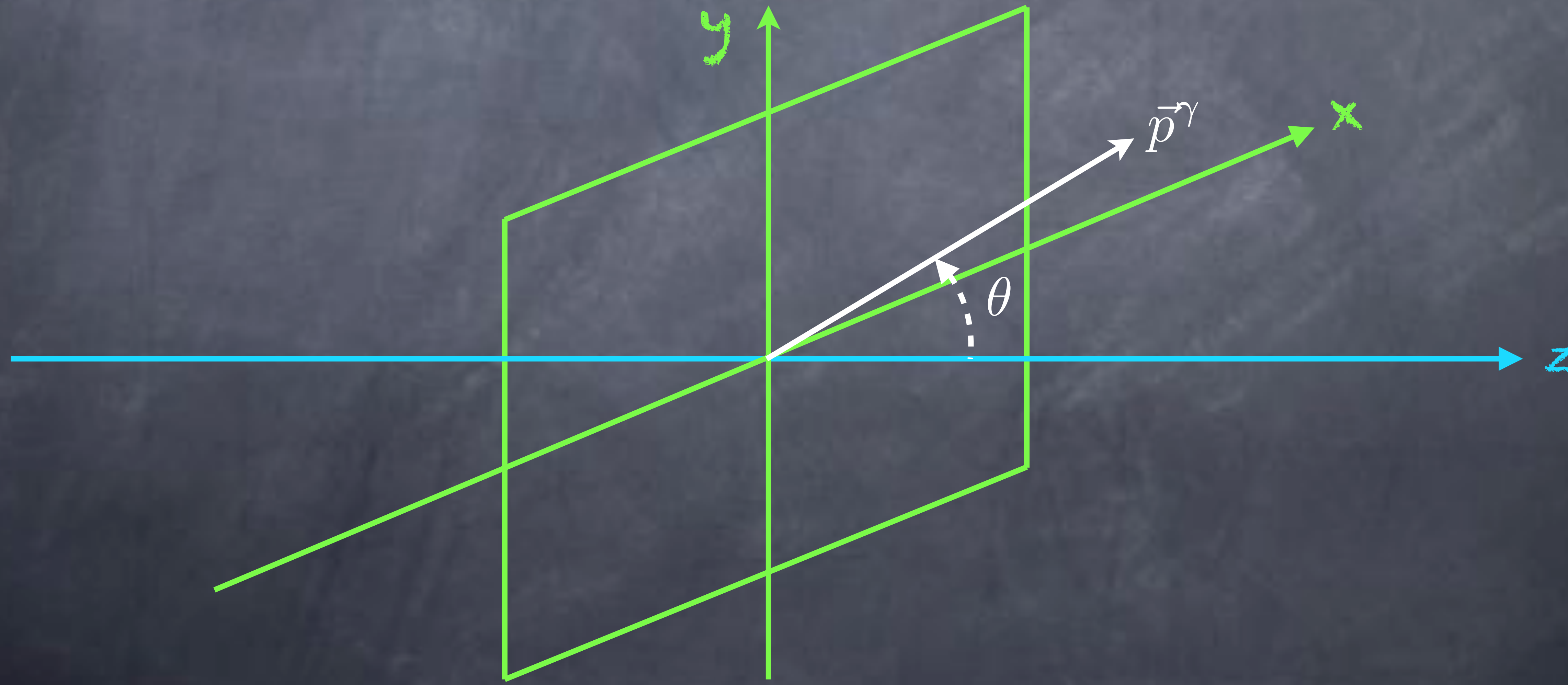

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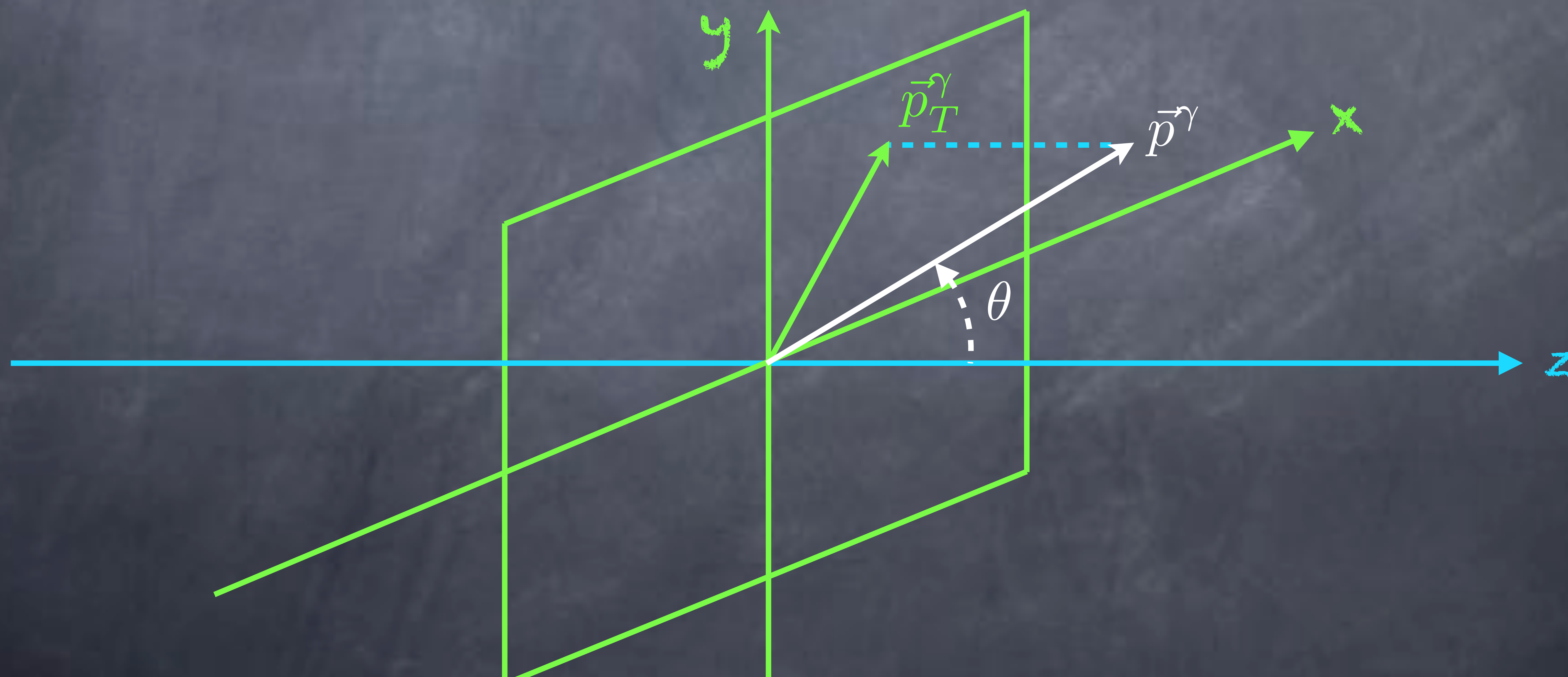

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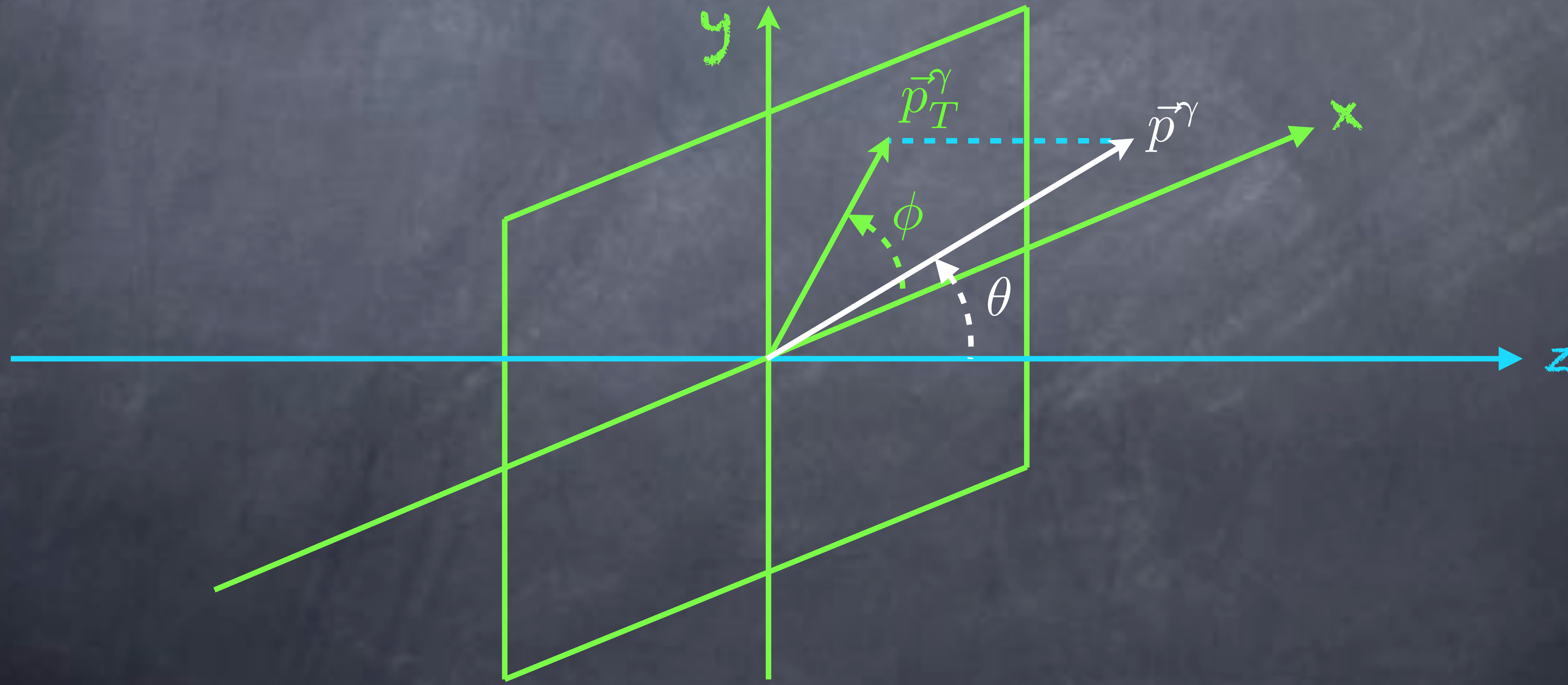

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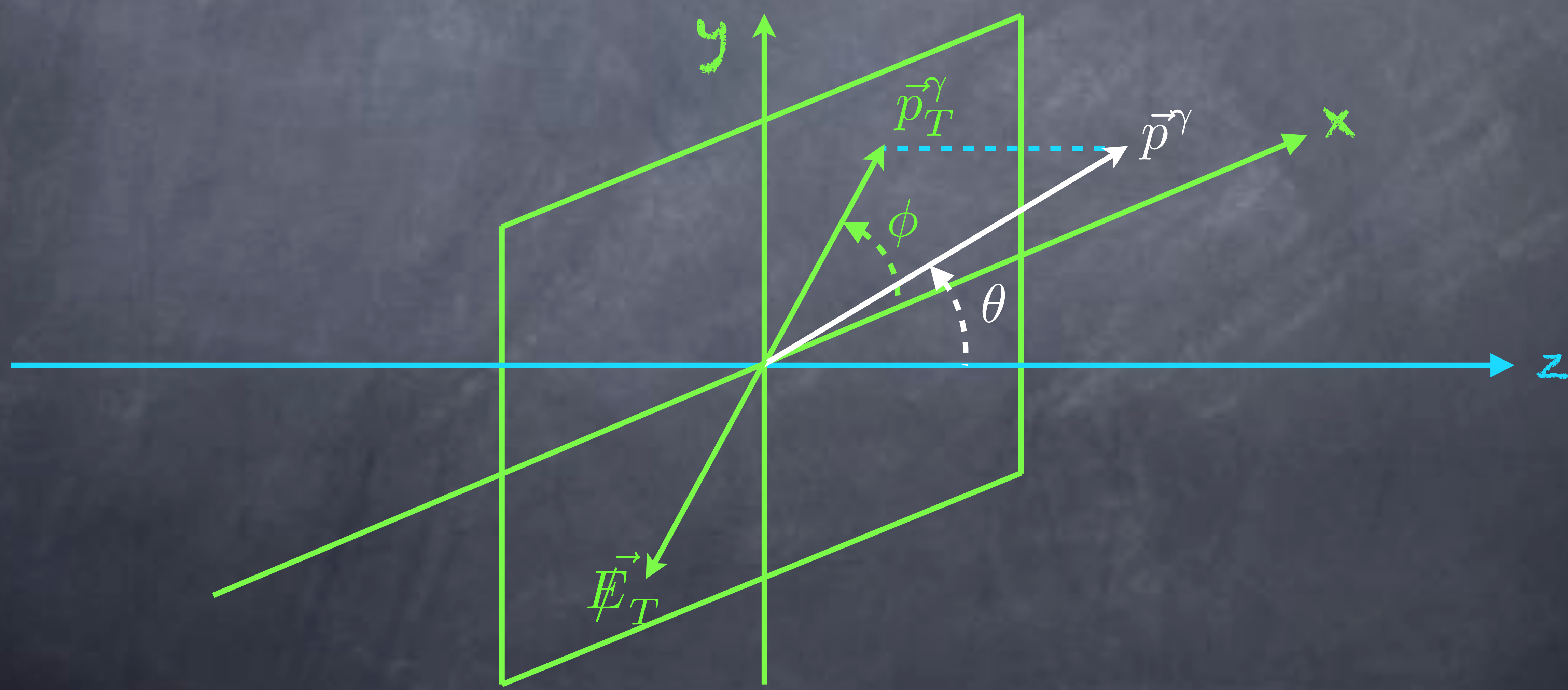

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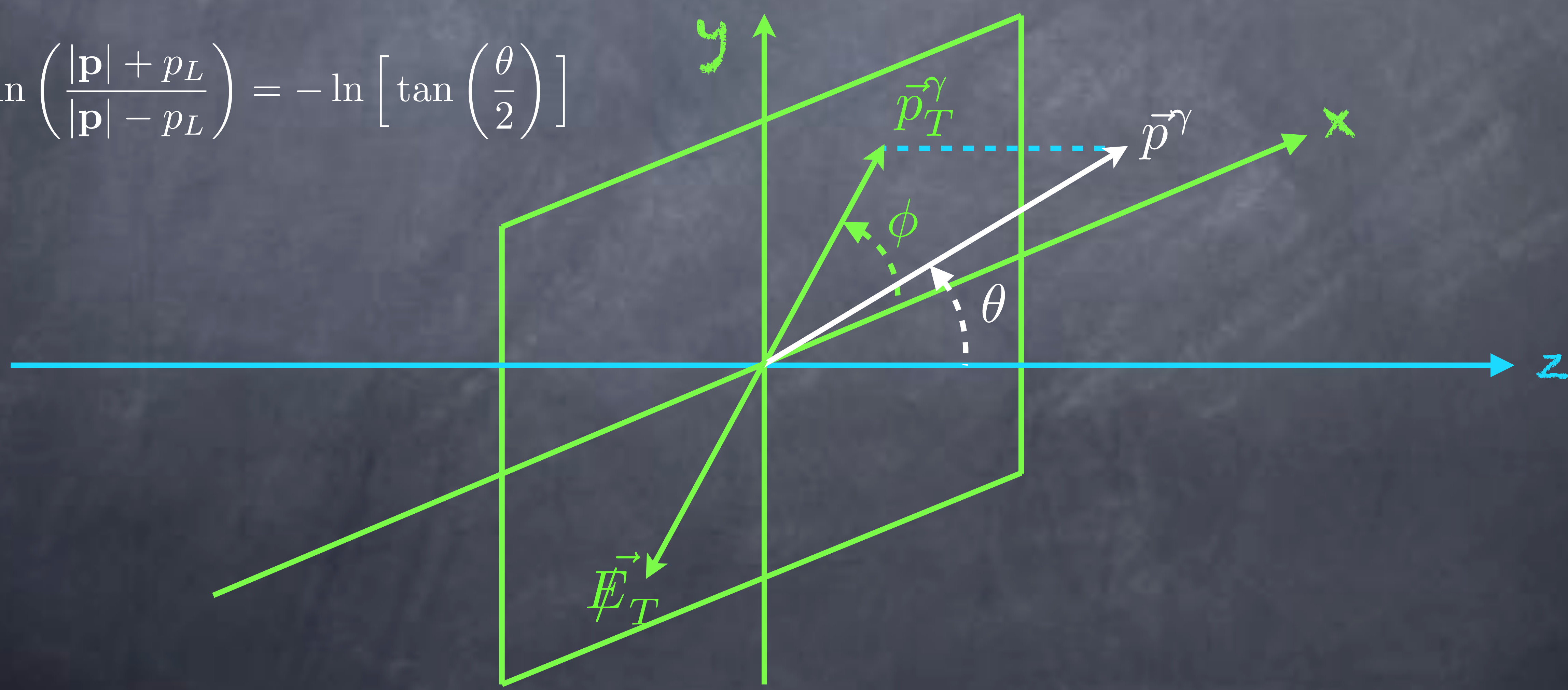
$$\eta = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L} \right) = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]$$



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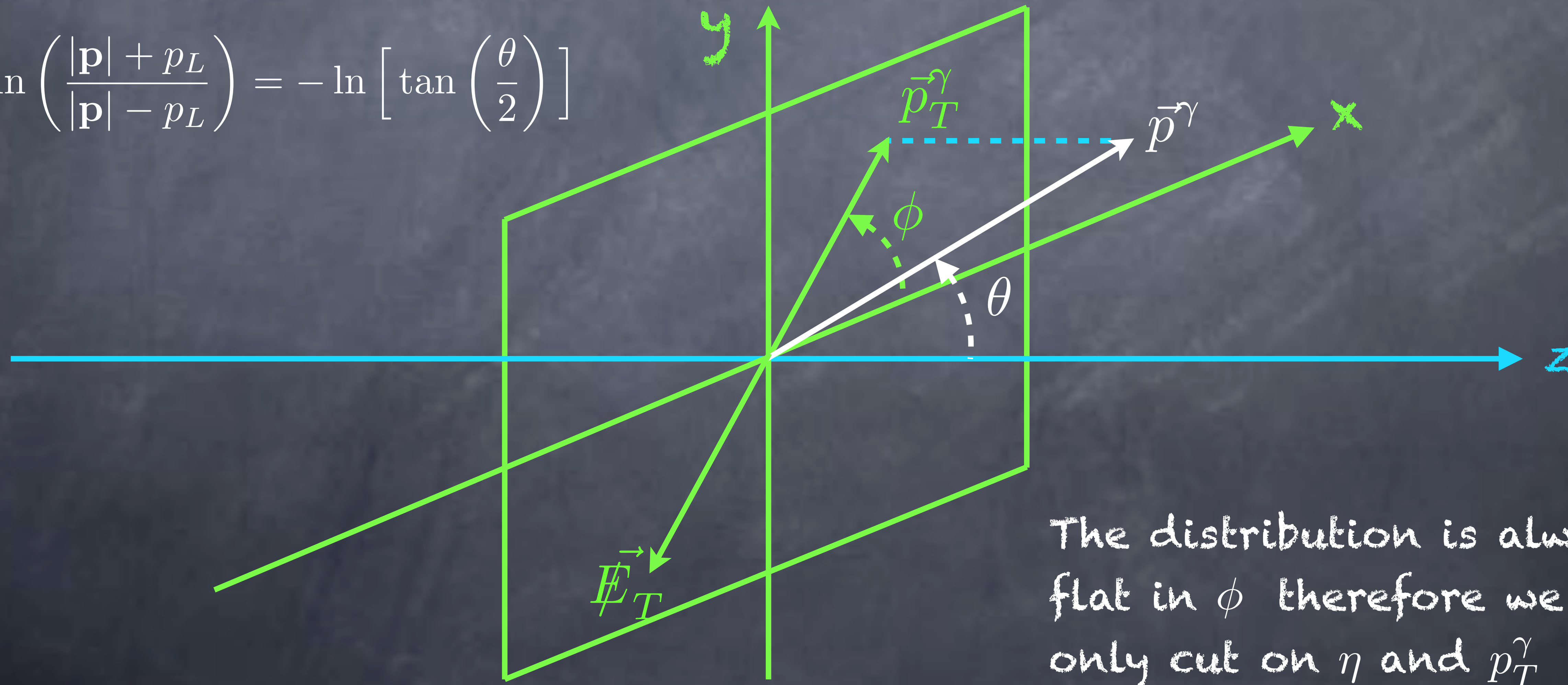

The distribution is always flat in ϕ therefore we can only cut on η and p_T^γ

Kinematic cuts

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- The $|\eta|$ cut is chosen to be $|\eta| < 1.44$ which represents the barrel ECAL fiducial region for the CMS experiment
- The p_T^γ distributions coming from the Higgs and Z boson on shell productions have an end point at $m_h/2$ and $m_Z/2$ respectively
- Therefore we can choose as upper p_T^γ cut $p_T^\gamma < m_h/2$
- To optimize the lower p_T^γ cut we have studied the signal significance as a function of this cut for LHC@8 with 20/fb of integrated luminosity

$p_T^\gamma\vert_{\rm min}$	Total bg	Signal	$N_S/\sqrt{N_B}$
30	$27.4 \cdot 10^3$	138	3.7
35	$15.5 \cdot 10^3$	107	3.8
40	5539	80	4.8
45	1975	55	5.5
50	942	33	4.8

$m_\chi = 80\,\mathrm{GeV}$

$\mathrm{BR}\left(h \to \chi_0^1 G\right) = 2 \cdot 10^{-2}$

- The signal significance is optimized for $p_T^\gamma|_{\rm min} = 45\,\mathrm{GeV}$

Other Technicalities

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- Acceptances:

m_χ	$A^h_{\rm sign}$	m_χ	$A^h_{\rm sign}$
60	0.126	100	0.262
70	0.141	110	0.370
80	0.165	120	0.418
90	0.198		

- The Higgs production cross section at the LHC@8 at NNLO+NNLL with exact top mass dependence up to NLO+NLL: we get $\sigma_h^{\rm NNLO} = 19.49$ pb computed with http://theory.fi.infn.it/cgi-bin/higgsres.pl

- We have assumed photon reconstruction efficiency $\epsilon_\gamma = 0.85$ which is an average value in the range of photon transverse energy considered ATLAS, 1012.4389 [hep-ex]

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Bounds on BRs and coupling

- The minimum value of $\mathrm{BR}\left(h \to \chi_1^0 G\right) \times \mathrm{BR}\left(\chi_1^0 \to \gamma G\right)$ that can be discovered/excluded at LHC@8 is given by

$$\mathrm{BR}(h \to \chi_1^0 G) \times \mathrm{BR}(\chi_1^0 \to \gamma G)\Big|_{\min} = \frac{\mathcal{S}\sqrt{N_B}}{\sigma_h^{\mathrm{NNLO}} \times \mathcal{A}_{\mathrm{sign}}^h \times \epsilon_\gamma \times L}$$

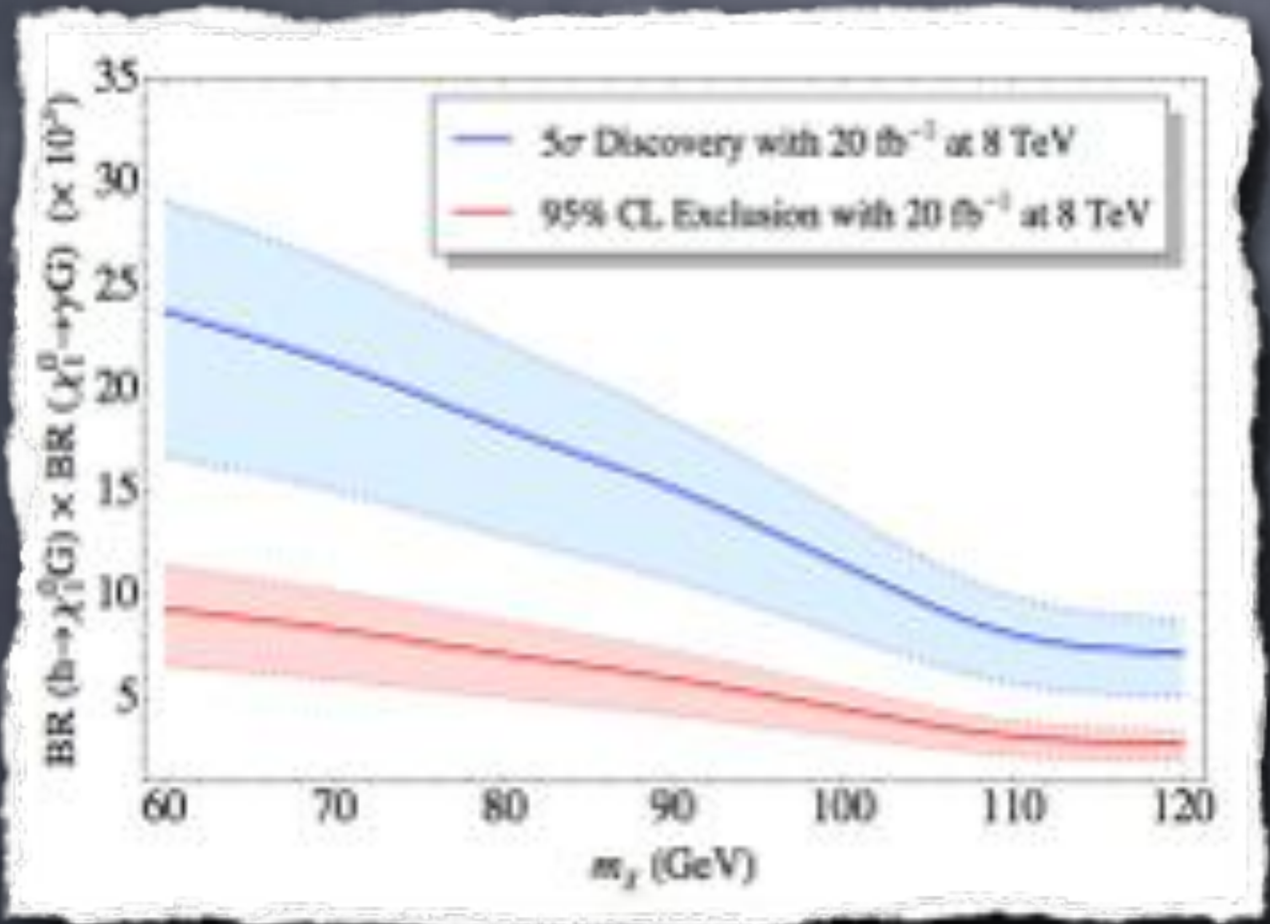
- Notice that $\mathrm{BR}\left(\chi_1^0 \to \gamma G\right) = 1$ for $m_\chi < m_Z$

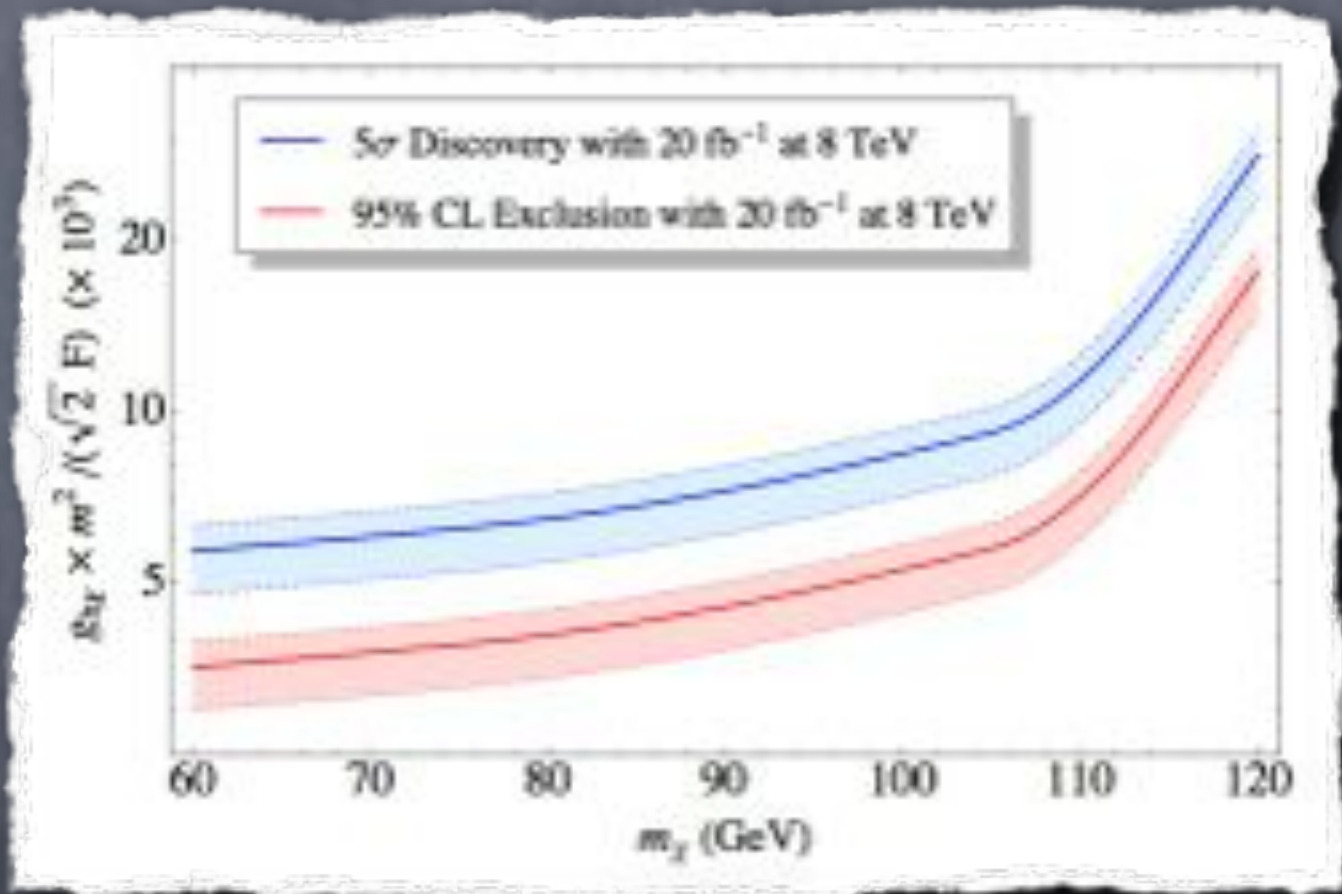
- By using the expression for $\Gamma(h \to \chi_1^0 G)$ it is possible to obtain the corresponding minimal coupling

$$\left[\frac{g_{h\chi} m^2}{\sqrt{2}F}\right]_{\min} = \sqrt{\frac{\left[\mathrm{BR}(h \to \chi_1^0 G) \times \mathrm{BR}(\chi_1^0 \to \gamma G)\right]_{\min}}{\mathrm{BR}(\chi_1^0 \to \gamma G)} \left(1 - \frac{m_\chi^2}{m_h^2}\right)^{-2} \frac{8\pi \Gamma_{\mathrm{tot}}^h}{m_h}}$$

Discovery and exclusion limits

- We have plotted the sensitivity of the LHC@8 with 20/fb of integrated luminosity to $\mathrm{BR}\left(h \to \chi_1^0 G\right) \times \mathrm{BR}\left(\chi_1^0 \to \gamma G\right)$ and to the $h\chi_1^0 G$ coupling both for 5σ discovery and 95% CL exclusion





- Discovery/exclusion require the $h\chi_1^0 G$ coupling to above $10^{-3} - 10^{-2}$
- This sets bounds on the parameters of the model

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The $h\chi G$ coupling is given by

$$\frac{1}{\sqrt{2}f}\Big(R_{(h,u)}(\sqrt{2}B_\mu N_{(1,d)} + g_1 v N_{(1,B)}(m_1 \sin\beta - \mu\cos\beta) \\ +\sqrt{2}N_{(1,u)}\left(-B_\mu\cot\beta + \mu^2\right) + g_2 v N_{(1,W)}(\mu\cos\beta - m_2\sin\beta) \\ +R_{(h,d)}(\sqrt{2}N_{(1,d)}\left(\mu^2 - B_\mu\tan\beta\right) + g_1 v N_{(1,B)}(\mu\sin\beta - m_1\cos\beta) \\ +\sqrt{2}B_\mu N_{(1,u)} + g_2 v N_{(1,W)}(m_2\cos\beta - \mu\sin\beta))\Big)\,.$$

which depend strongly on the ratio B_μ/f

arising from

$$\mathcal{L}_{\mu,X} = -\int d^2\theta\,\frac{B_\mu}{f}XH_d\cdot H_u + \text{h.c.} \supset \frac{B_\mu}{f}\psi_X\psi_{H_d^0}h_u^0 + \cdots$$

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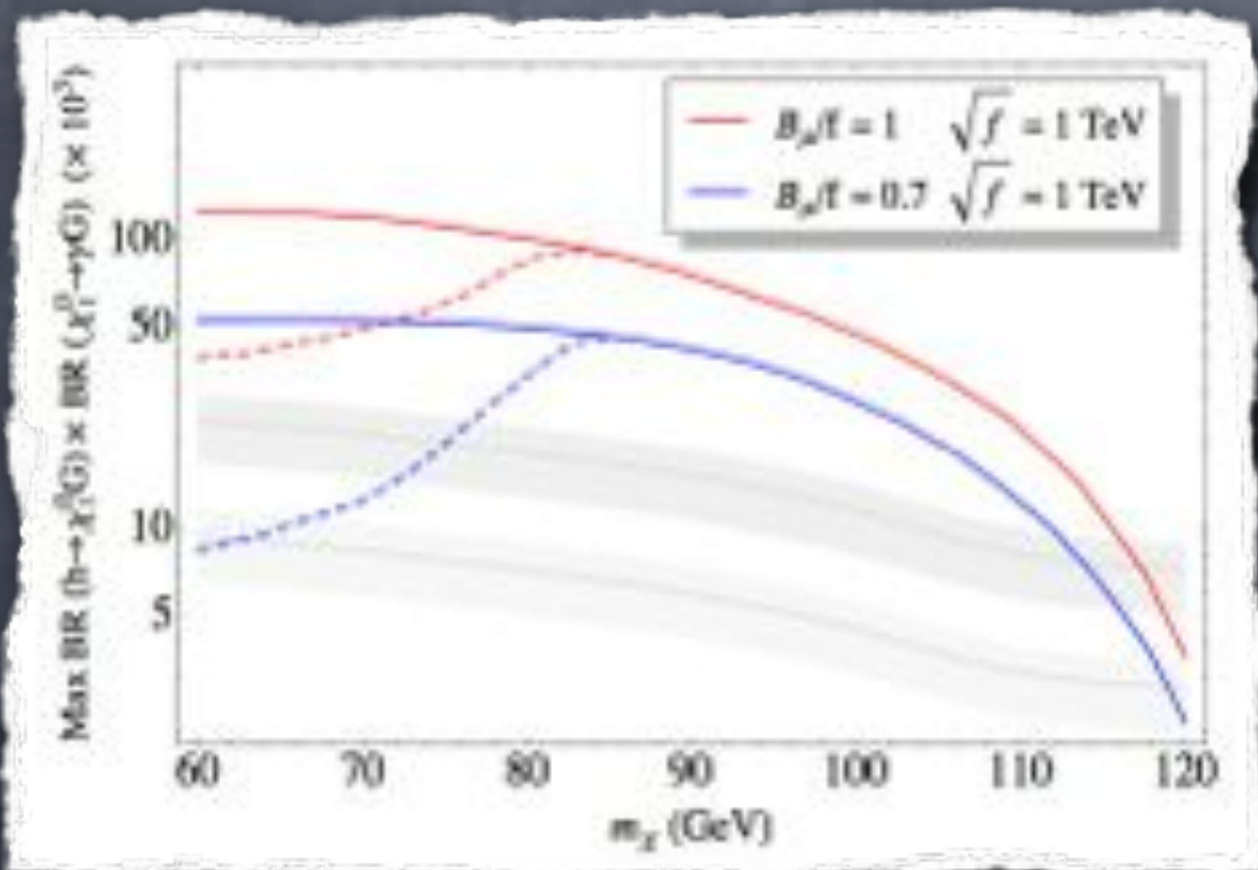
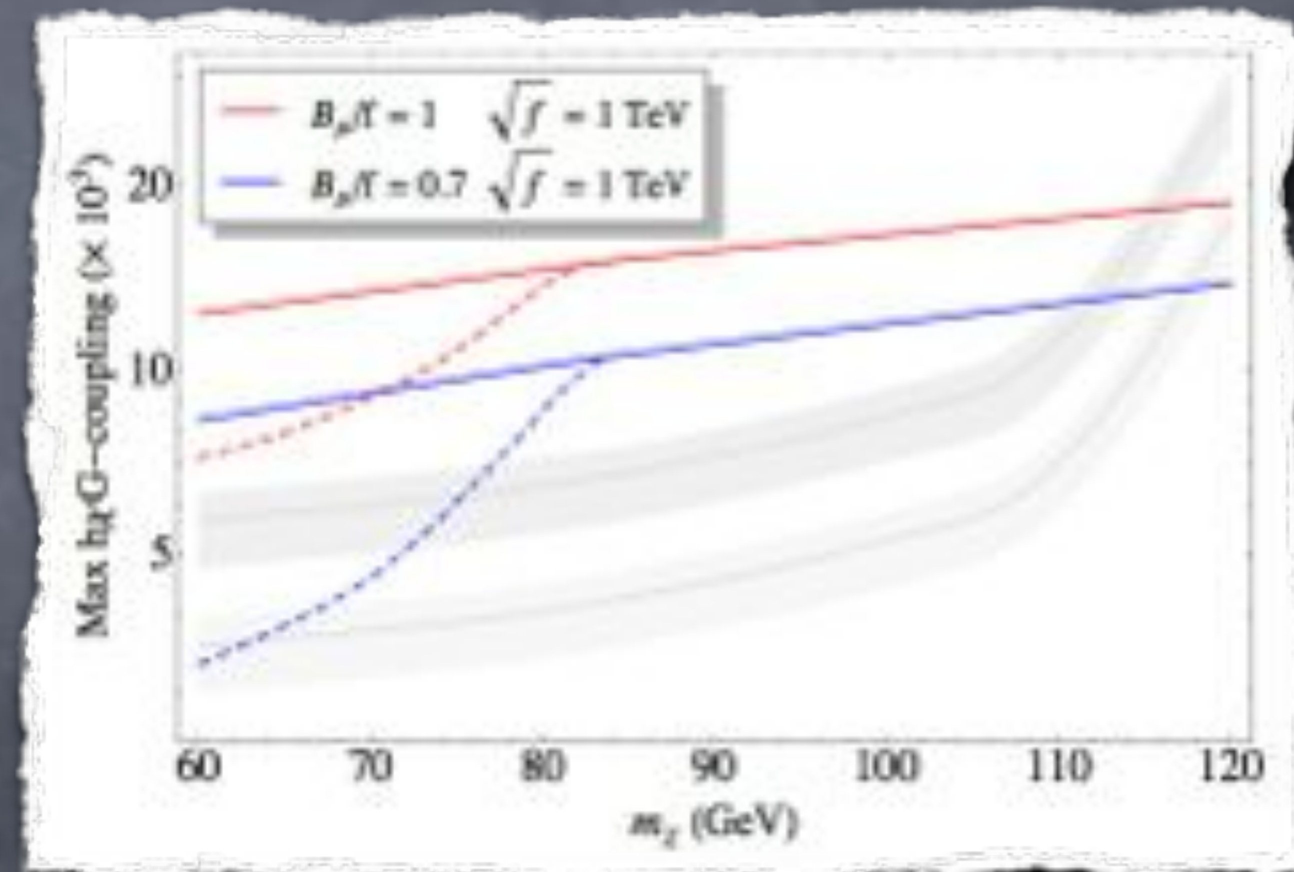
Try for the following two values:

$$\frac{B_\mu}{f} = 0.7$$ (1-loop contribution required to increase m_h to 125 GeV)

$$\frac{B_\mu}{f} = 1$$ (Mixing contribution required to decrease m_h to 125 GeV)





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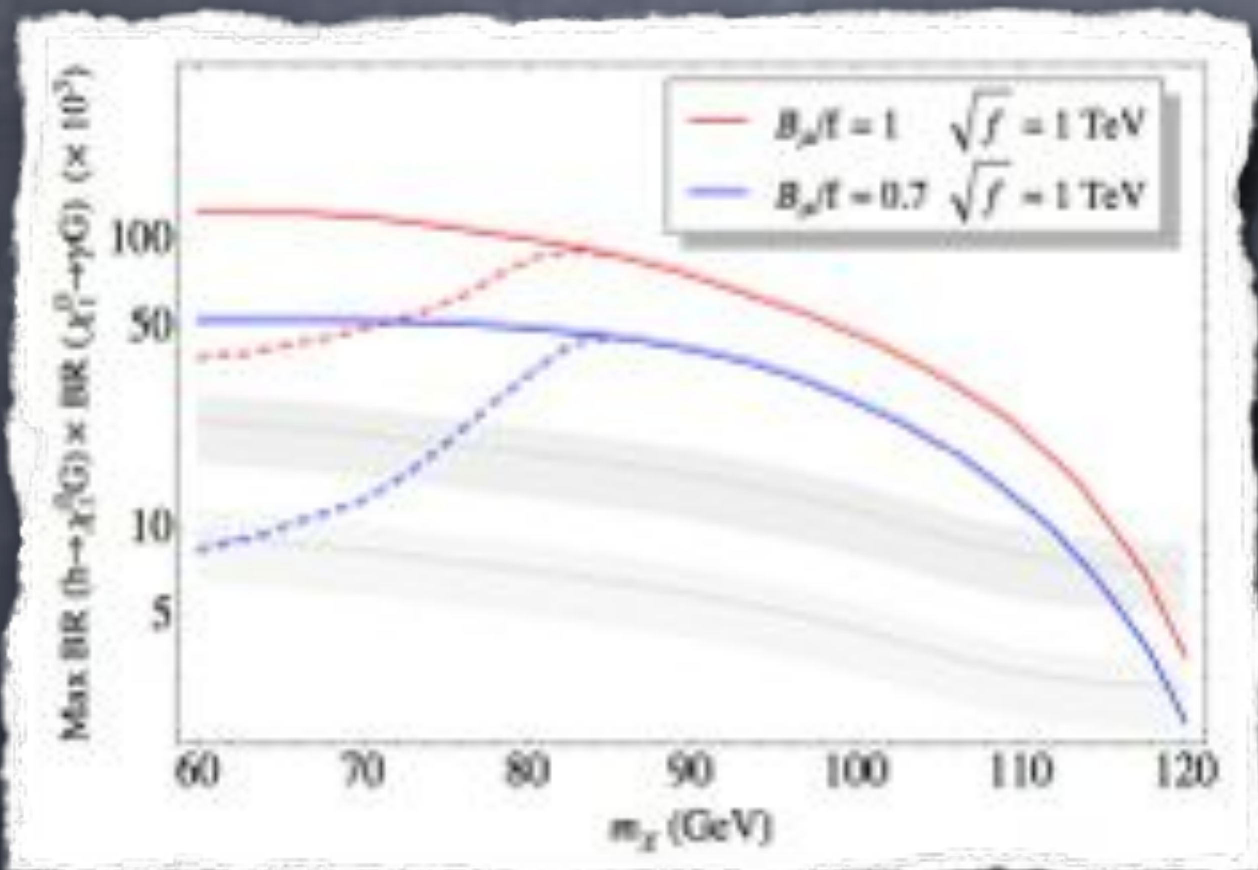

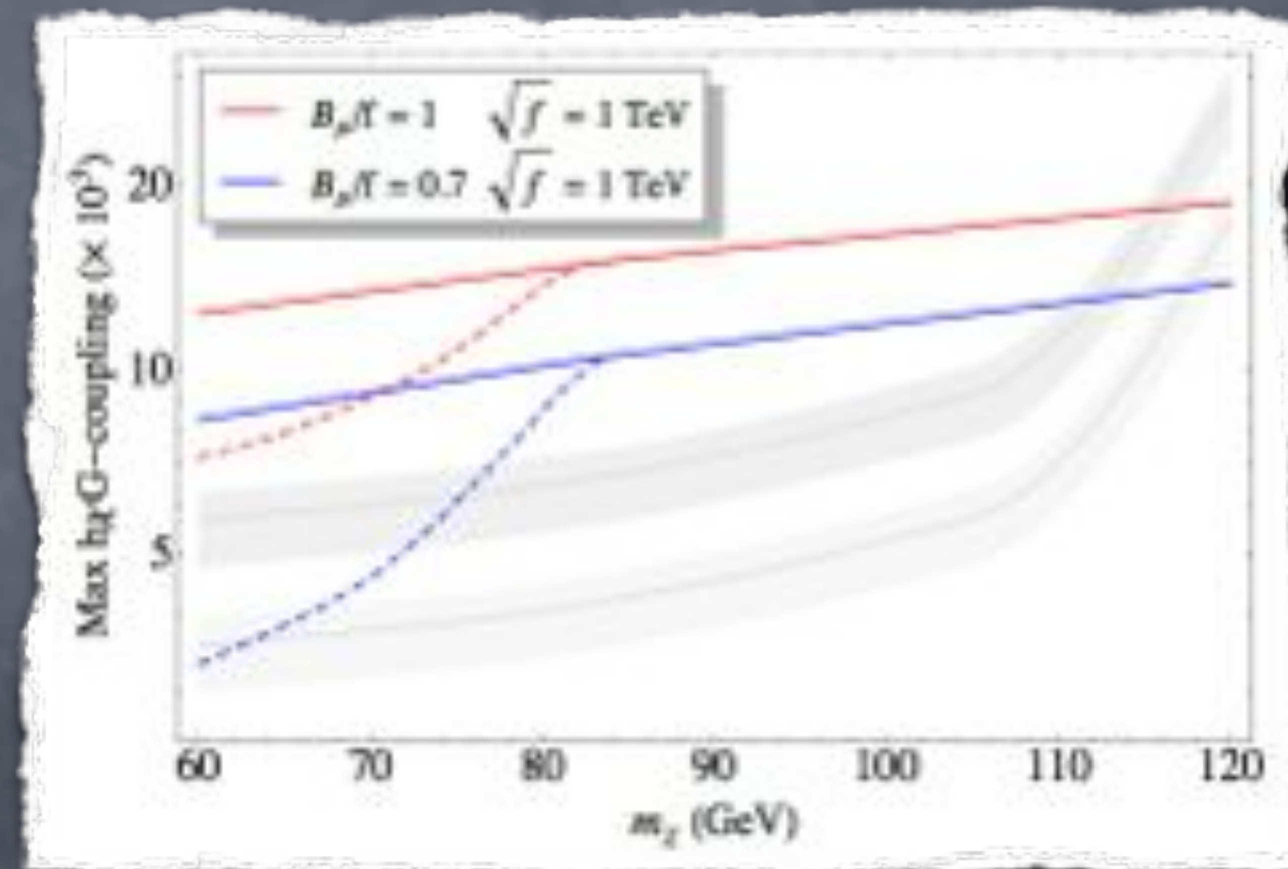

Possible to discover by the 2012 LHC run!

Conclusion

- The lack of superpartner observations and the hint for a Higgs boson with a mass around 125 GeV motivate studies beyond the minimal supersymmetric extension of the SM.
- We discussed the scenario in which SUSY is broken spontaneously at the TeV scale and the MSSM soft terms are promoted to supersymmetric operators.
- This scenario takes into account the dynamics and interactions of the goldstino (and sgoldstino) and modifies the usual MSSM phenomenology.
- For example, a SM-like 125 GeV Higgs can easily be accommodated (without large quantum corrections) and novel Higgs decays can occur.
- A smoking gun signature arises from the decay of a Higgs into a photon and two goldstinos and this could be discovered by the 2012 LHC run.
- We propose a search for a γ + MET signal where $45\,\mathrm{GeV} < p_T^\gamma < m_h/2\,.$

Future directions

- Other characteristic decays involving the goldstino or sgoldstino
- More general set of higher dimensional operators
- UV completion
- Dark matter candidate

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Expect new results and hints from the LHC very soon!

Open Issues: Mediation of SUSY breaking

- Tree-level SUSY breaking mediation is problematic, due to the Str formula. SUSY is expected to be broken in some "hidden" sector, and being communicated to the visible by some mediation mechanism
- Explicit examples are:

$$\mathcal{L} = \mathcal{L}_{\text{MSSM,SUSY}} +$$

Gravity mediation

$$\int d^2\theta \frac{1}{M_{\text{Pl}}} X W^\alpha W_\alpha$$

$$\int d^2\theta d^2\bar{\theta} \frac{1}{M_{\text{Pl}}^2} X^\dagger X Q^\dagger Q$$

- The soft terms are suppressed by the Planck scale and SUSY is broken at a very high scale

$$\frac{f}{M_{\text{Pl}}} \sim \text{TeV} \implies \sqrt{f} \sim 10^{11}\text{GeV}$$

Gauge mediation

$$\int d^2\theta \left(X\Phi\tilde{\Phi} + M\Phi\tilde{\Phi} \right) + \text{c.c.}$$

$$\int d^2\theta d^2\bar{\theta} \left(\Phi^\dagger e^{gV}\Phi + \tilde{\Phi}^\dagger e^{-gV}\tilde{\Phi} + X^\dagger X \right)$$

- The soft terms are generated at loop level

$$M_\phi^2 \geq 0 \implies M^2 \geq f$$

$$\Downarrow$$

$$\frac{g^2}{16\pi^2}\frac{f}{M} \sim \text{TeV} \implies \sqrt{f} \geq 100\,\text{TeV}$$

Open Issues: Mediation of SUSY breaking

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- Remember that here we are asking for

$$\sqrt{f} \sim 1\,\mathrm{TeV}$$

Non-standard" type of mediation

(tree-level GMSB? Messengers at few TeV ?)

Open Issues: Dark Matter

$$\sqrt{f} \sim 1\,\mathrm{TeV}$$

Implies a very light gravitino

$$m_{3/2} \sim 10^{-2} - 10^{-3}\,\mathrm{eV}$$

The LSP cannot be cold dark matter

Again we need another sector (messengers?)

MSSM + Dynamical Goldstino Supermultiplet

$$\mathcal{L} = \mathcal{L}_H + \mathcal{L}_X + \mathcal{L}_{H,X}$$

$$\mathcal{L}_H = \int d^4\theta \sum_{i=1}^{2} H_i^\dagger e^V H_i + \left\{ \int d^2\theta \, \mu H_1 \cdot H_2 + \text{h.c.} \right\}$$

Visible Higgs sector

$$\mathcal{L}_X = \int d^4\theta \, X^\dagger X \left(1 - \frac{c_X}{4M^2} X^\dagger X \right) + \left\{ \int d^2\theta \, f X + \text{h.c.} \right\}$$

Hidden Sector

$$\mathcal{L}_{H,X} = \int d^4\theta \sum_{i=1}^{2} -\frac{c_i}{M^2} X^\dagger X H_i^\dagger e^V H_i - \left\{ \int d^2\theta \, c_B X H_1 \cdot H_2 + \text{h.c.} \right\}$$

Soft terms

Dictionary: $\frac{c_i f^2}{M^2} \to m_i^2$ $\quad c_B f \to B_\mu$

What if the sgoldstino is very heavy?

- The MSSM EW breaking conditions change for terms of order

  f^{-1} and m_X^{-1}

- In this case the vacuum solution for the sgoldstino is

$$v_x = \frac{\mu^3 v^2}{m_x^2 f} \sin 2\beta$$

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$$m_{A^0}^2 = \frac{2c_B f}{\sin 2\beta} + v^2 c_B \left[2c_B - \frac{2\mu^2}{f \sin 2\beta} + \frac{4\mu^2}{m_x^2 \sin 2\beta} \left(\frac{\mu^2}{f} - \frac{c_B}{\sin 2\beta} \right) \right]$$

$$m_{H^0}^2 = m_Z^2 \sin^2 2\beta + m_{A^0}^2 + \frac{4c_B \mu^2}{m_x^2 \sin 2\beta} v^2 \left[\frac{\mu^2}{f} - \frac{c_B}{\sin 2\beta} \right]$$

$$m_{\mathrm{Re}x}^2 \simeq m_{\mathrm{Im}x}^2 \simeq m_X^2$$

Plots for the tree-level Higgs mass ($\sqrt{f} = 2$)

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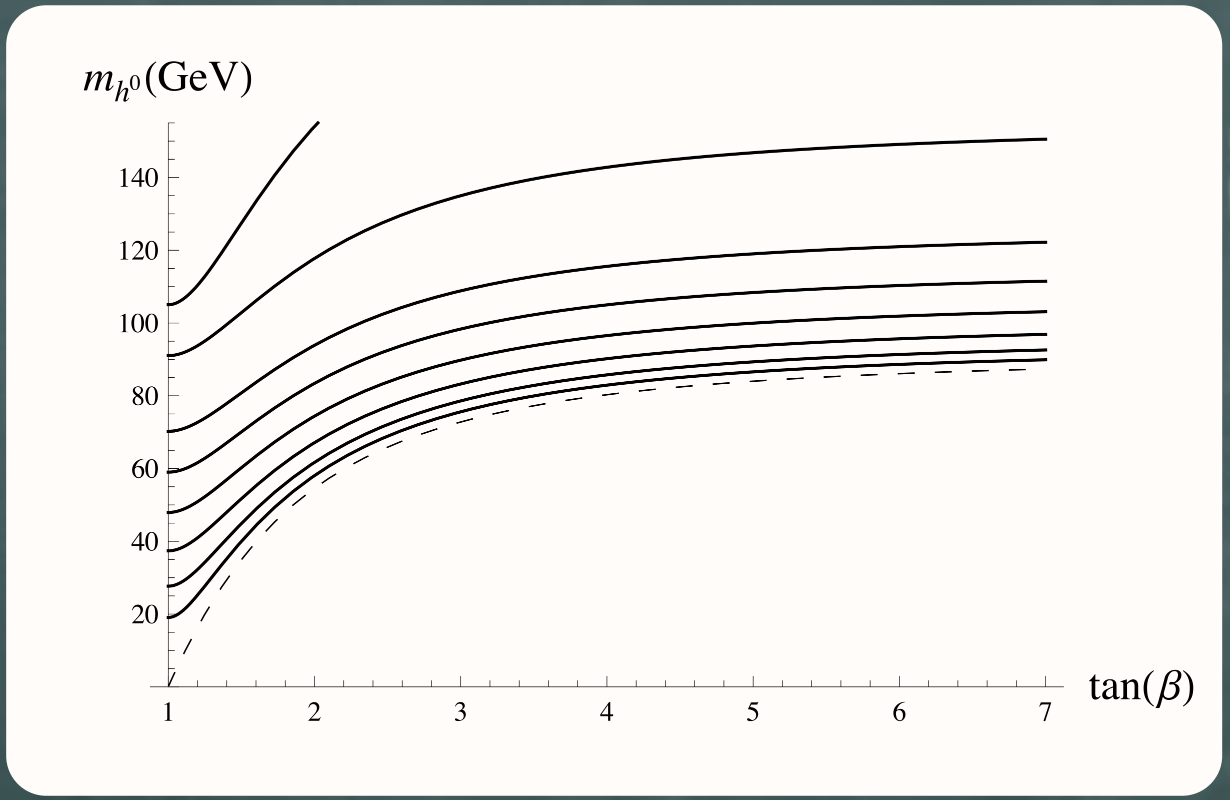
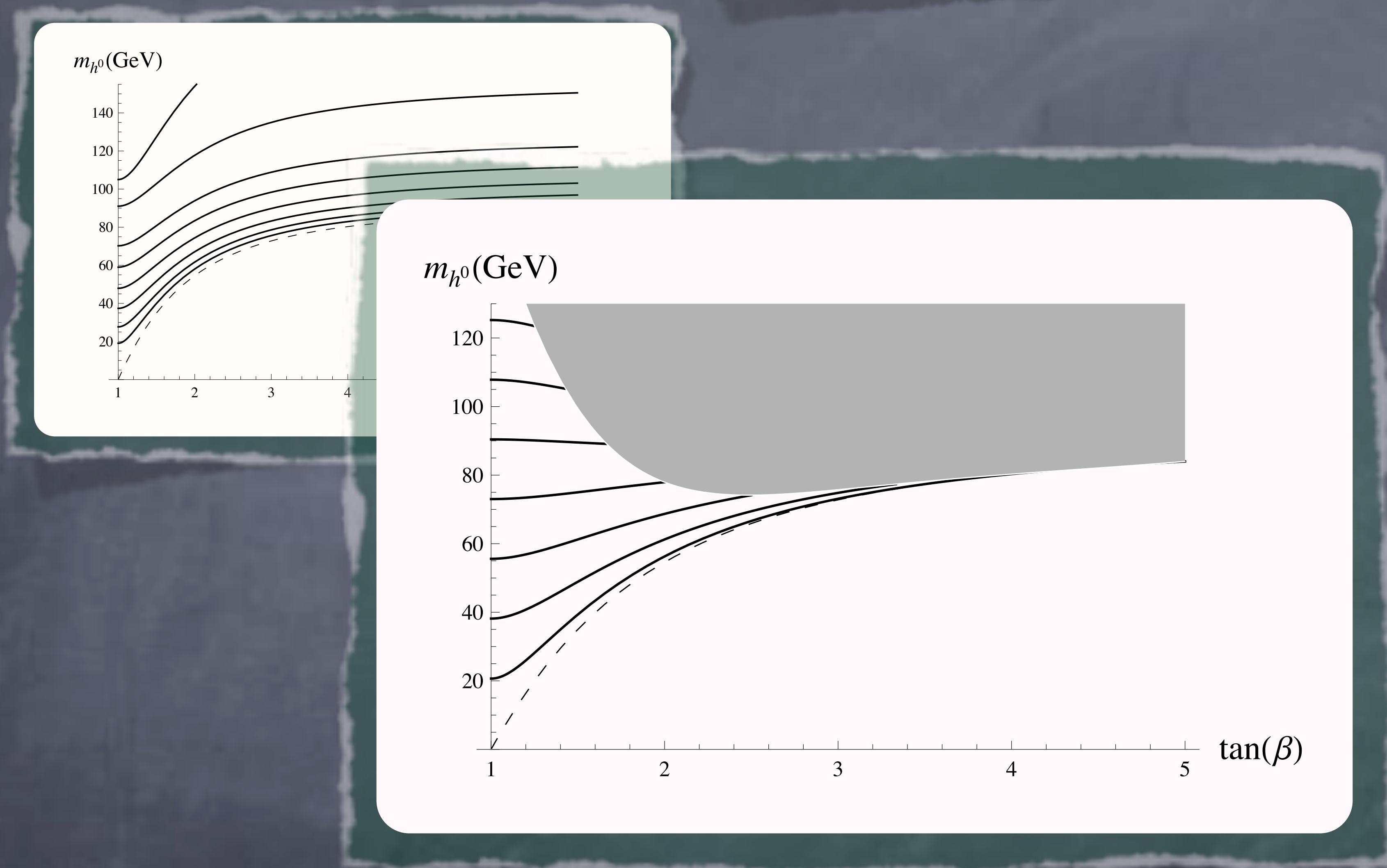
$c_B = 0.01,\ m_X = 1.8\,\mathrm{TeV},\ \mu = [0.5 - 1.5]\mathrm{TeV}$



Plots for the tree-level Higgs mass ($\sqrt{f} = 2$)

$\mu = 400\,\mathrm{GeV},\ m_X = 1.8\,\mathrm{TeV},\ c_B = [0.2 - 0.8]$



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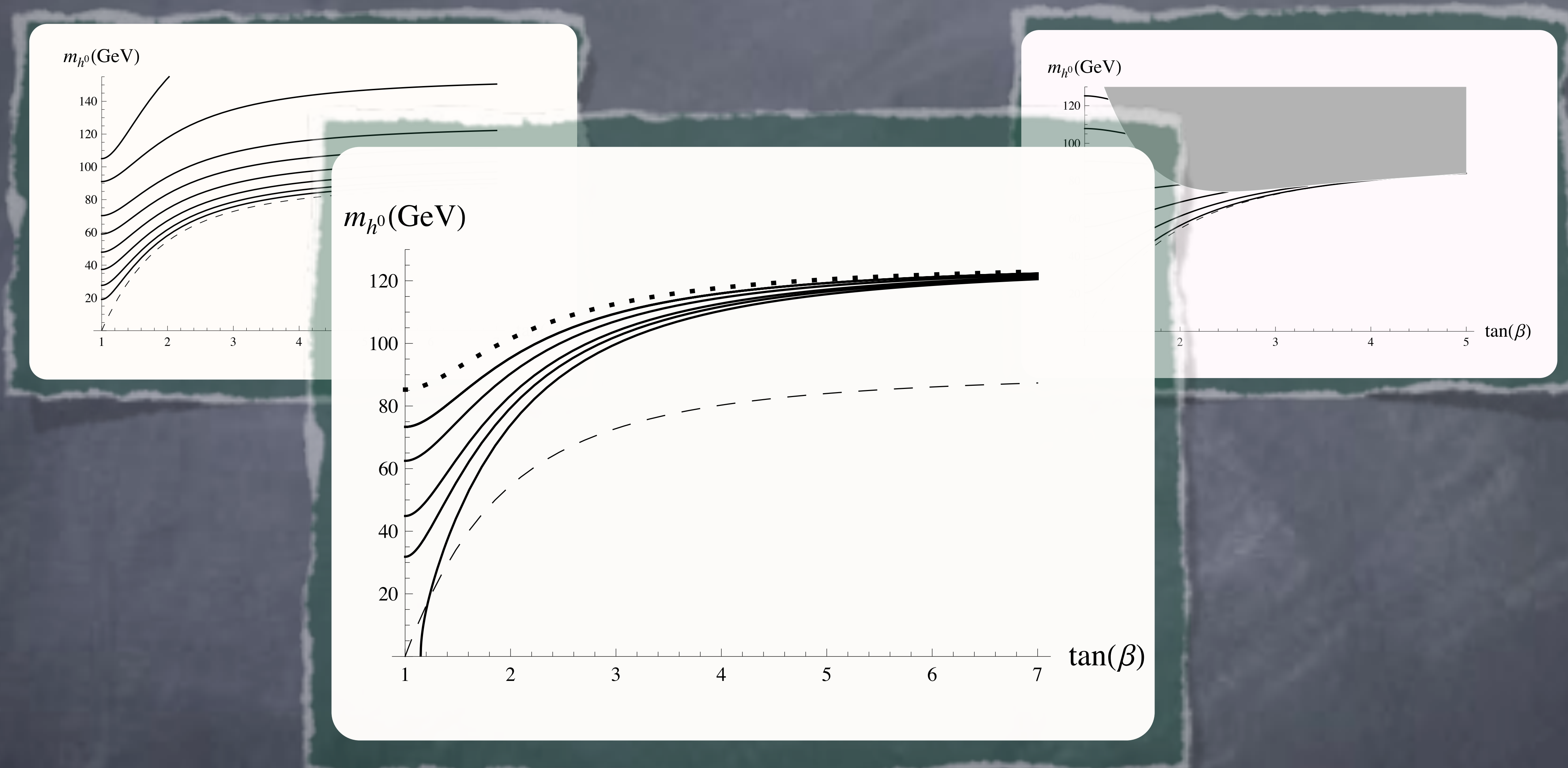
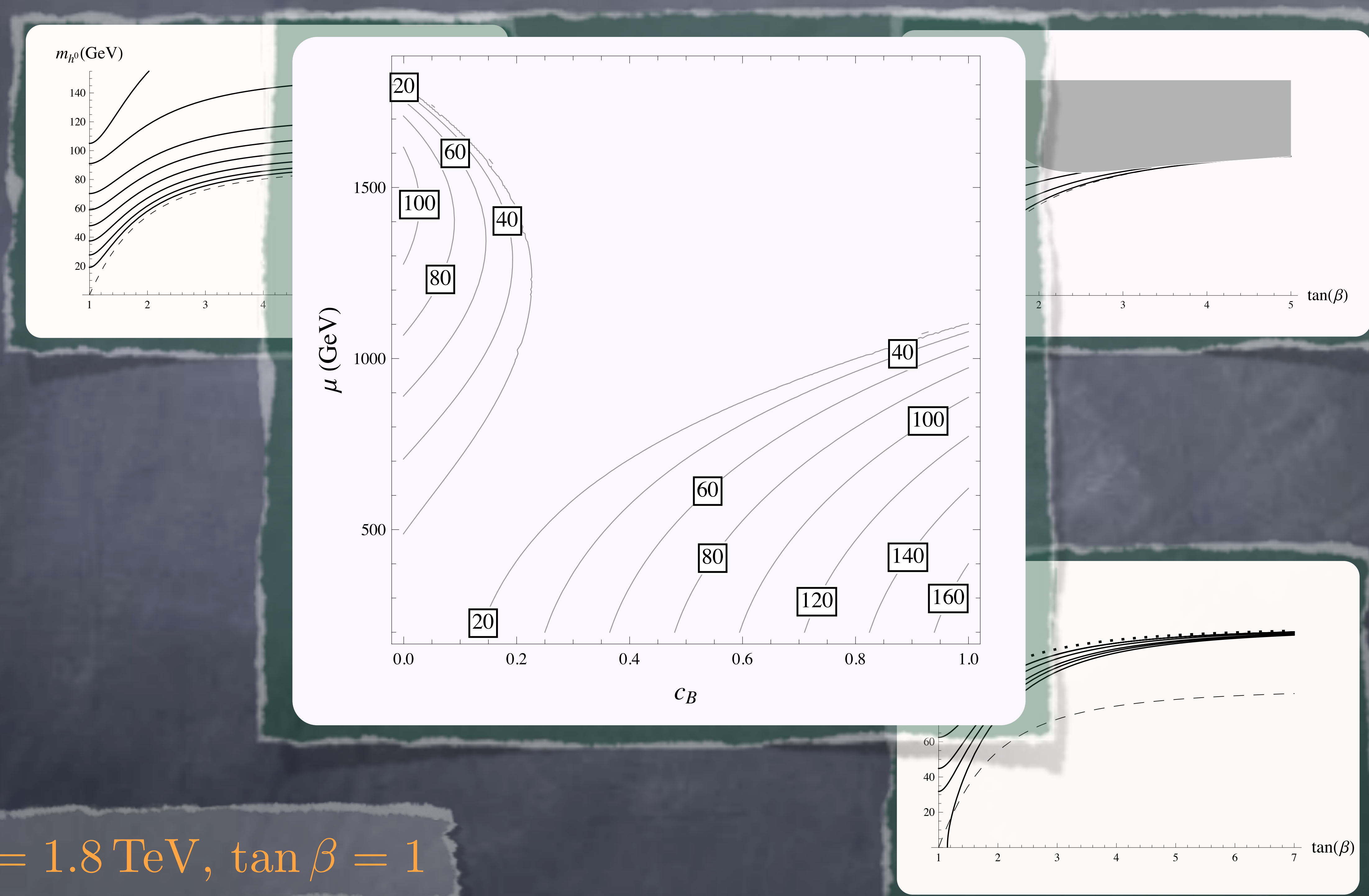


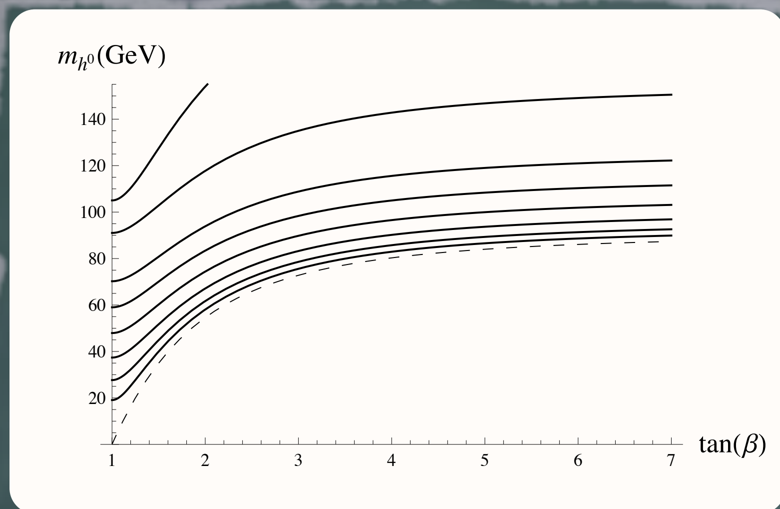
$\mu = 1\text{TeV},\ c_B = 0.01,\ m_X = [1-2]\text{TeV}$

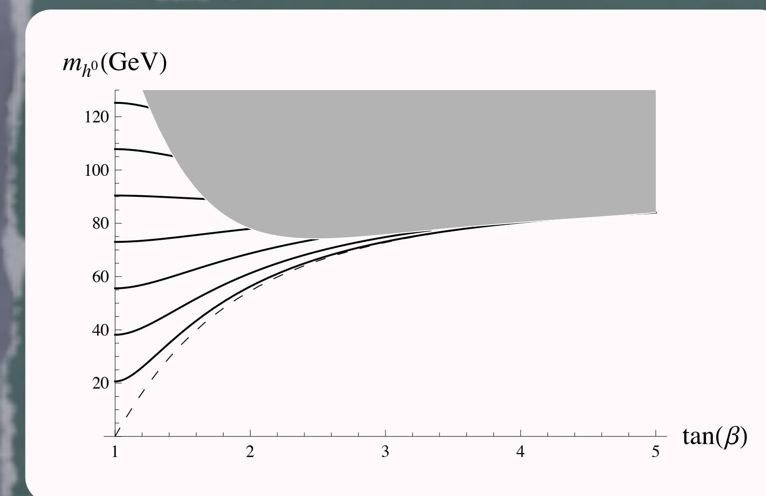
Plots for the tree-level Higgs mass ($\sqrt{f}=2$)

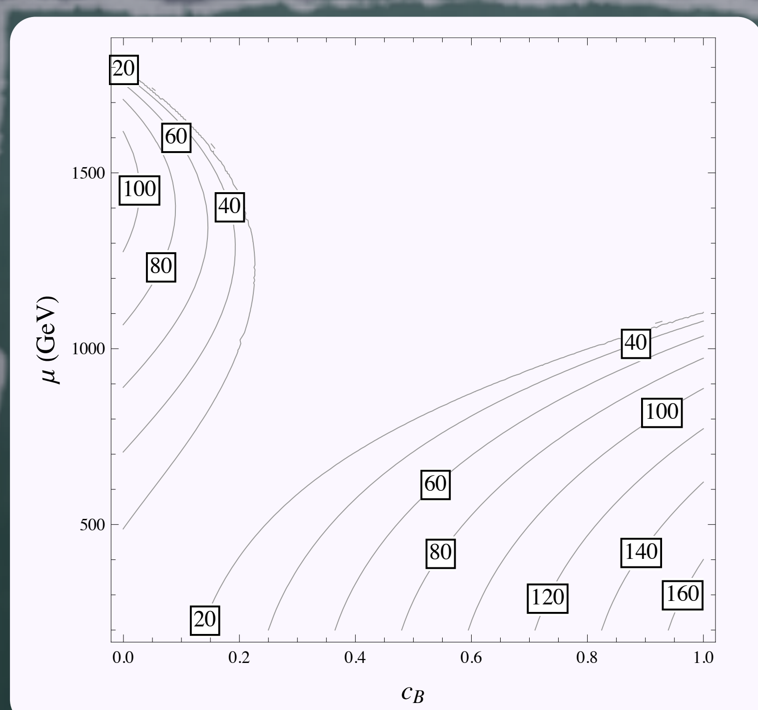


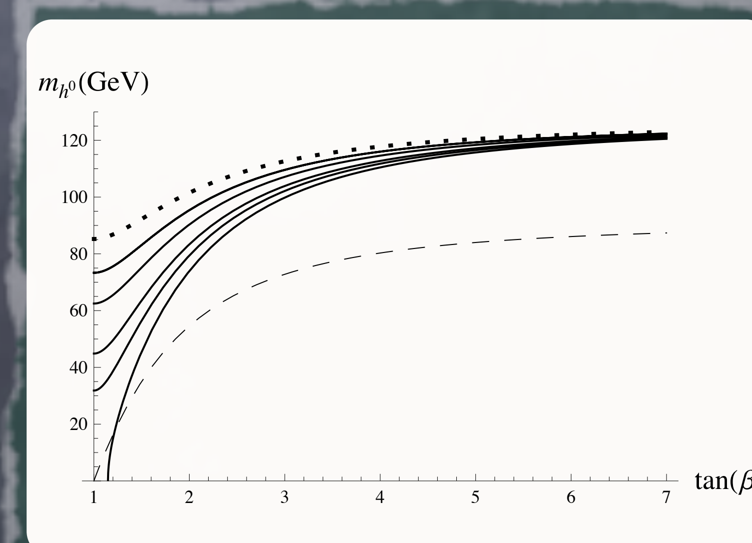
$m_X = 1.8\,\mathrm{TeV},\ \tan\beta = 1$

Plots for the tree-level Higgs mass ($\sqrt{f} = 2$)

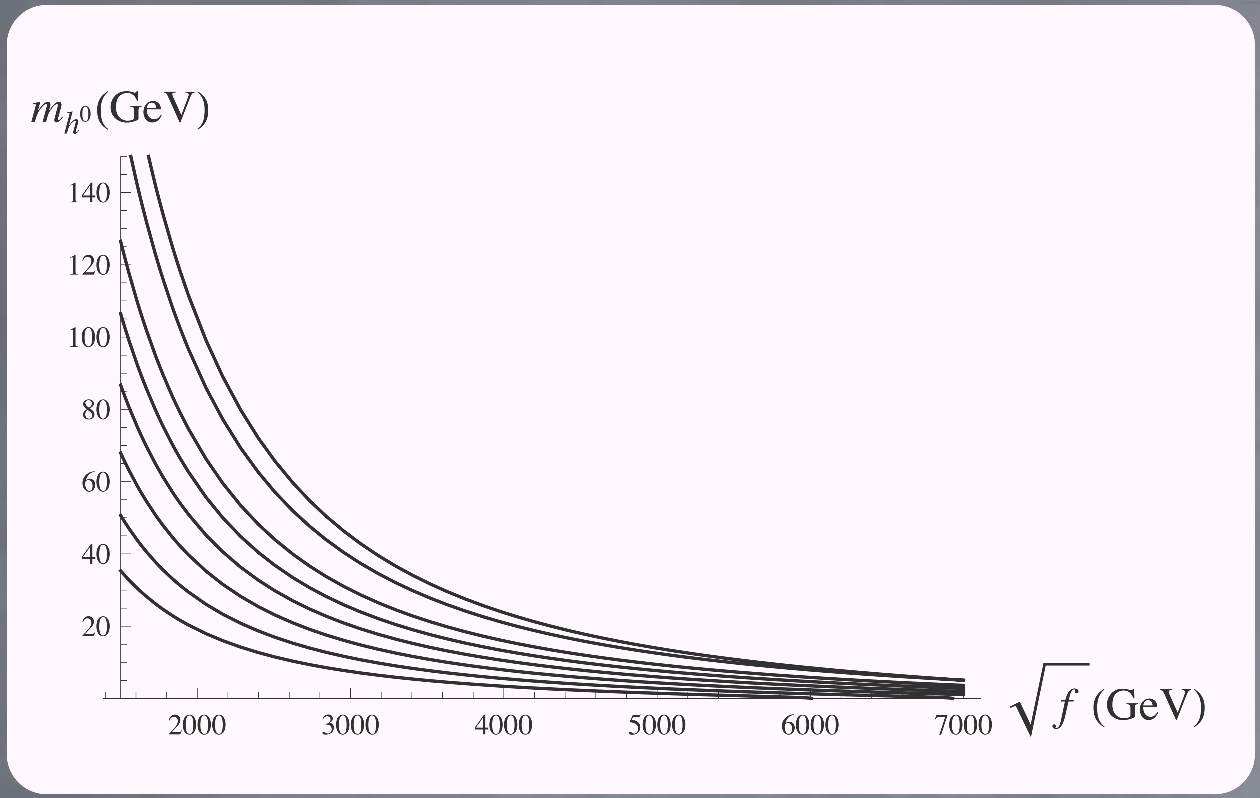






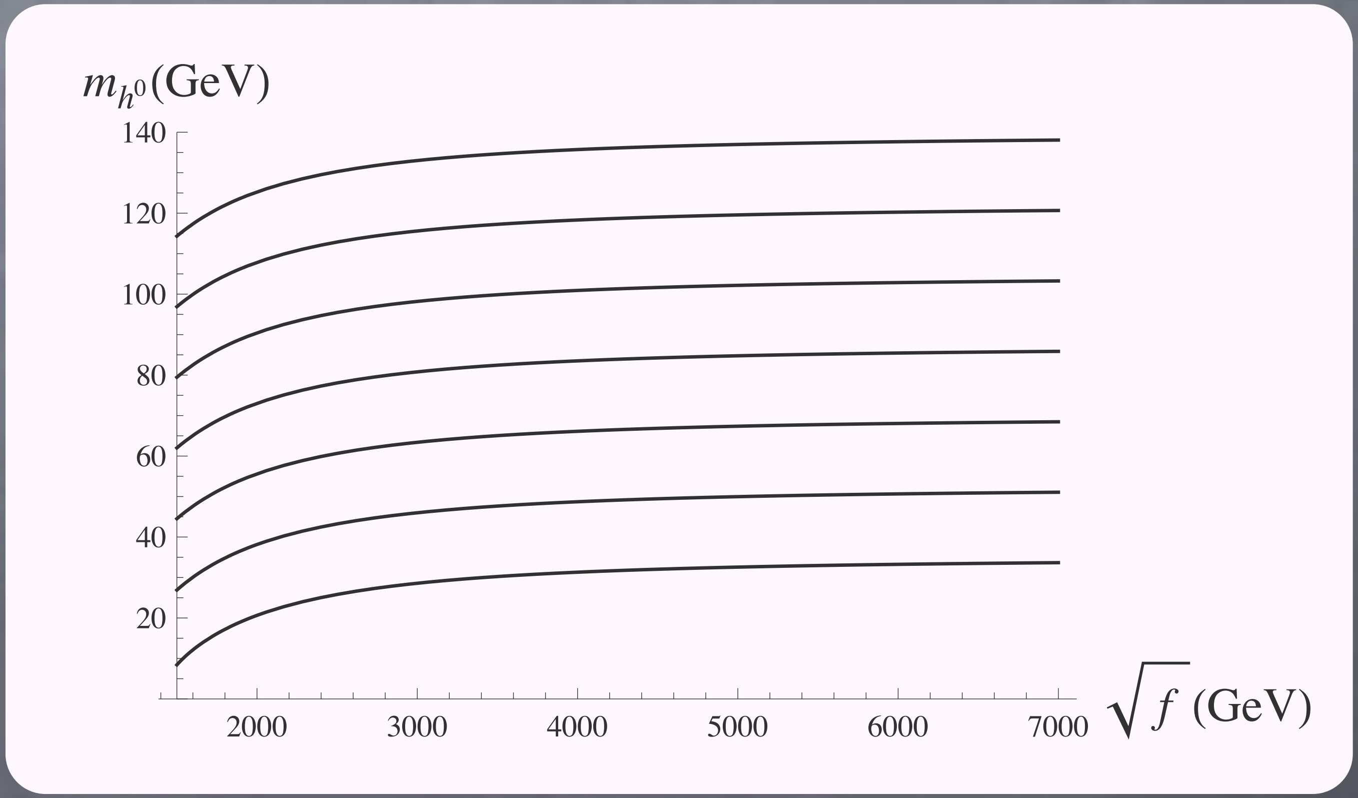


Plots for the tree-level Higgs mass ($\tan\beta = 1$)



$$m_X = 1.8\ \text{TeV}$$
$$c_B = 0.01$$
$$\mu = [0.5 - 1.5]\ \text{TeV}$$

$$m_X = 1.8\ \text{TeV}$$
$$\mu = 400\ \text{GeV}$$
$$c_B = [0.2 - 0.8]$$



What if the sgoldstino is the lighter scalar?

- Let's consider the region where the soft mass $m_X \ll v$

  (Clearly also the region $m_X \sim v$ is phenomenologically viable, but analytically difficult)

- In this case there is a new vacuum solution, for large $\tan\beta$

$$v_X \simeq f\frac{\tan^{-1}\beta}{\mu} + \delta_\gamma \tan^{-1}\beta + \delta_x \frac{m_X^2}{v^2}$$

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- The scalar masses read now:

  (technicality: $c_B \to C_B \tan^{-1}\beta$)

$$m_{h^0}^2 = m_Z^2 + \frac{4v^2\mu^4}{f^2} - \tan^{-2}\beta v^2 \left(16\, C_B\frac{\mu^2}{f} + 3\,\frac{m_Z^2}{v^2} + 12\,\frac{\mu^4}{f^2}\right)$$

$$m_{\mathrm{Re}x}^2 = m_{\mathrm{Im}x}^2 = \frac{4C_B v^2\mu^4}{C_B f^2 + 2f\mu^2} + \delta_{\mathrm{Re}x,C_X}\,\frac{m_x^2}{v^2} + \delta_{\mathrm{Re}x,\gamma}\,\tan^{-2}\beta$$

$$m_{A^0}^2 \simeq m_{H^0}^2 = \frac{C_B f}{2}\left(1 + \frac{m_Z^2}{2\mu^2}\right) + \mu^2 + v^2\left(C_B^2 - \frac{m_Z^2}{2v^2} + \frac{\mu^4}{f^2} - \frac{C_B^3 f}{C_B f + 2\mu^2} - \frac{2C_B\mu^2}{f}\right)$$
$$+\delta_{H^0,C_X}\,\frac{m_x^2}{v^2} + \delta_{H^0,\gamma}\,\tan^{-2}\beta$$

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- Let's consider the region where the

  (Clearly also the region $m_X \sim v$
  viable, but analytically difficult)

- In this case there is a new vacuum solu

Solutions also for $m_X \to 0$

$$v_X \simeq f \frac{\tan^{-1}\beta}{\mu} + \delta_\gamma \tan^{-1}\beta + \delta_x \frac{m_X^2}{v^2}$$

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Plots for the tree-level scalar mass ($\sqrt{f} = 2$)

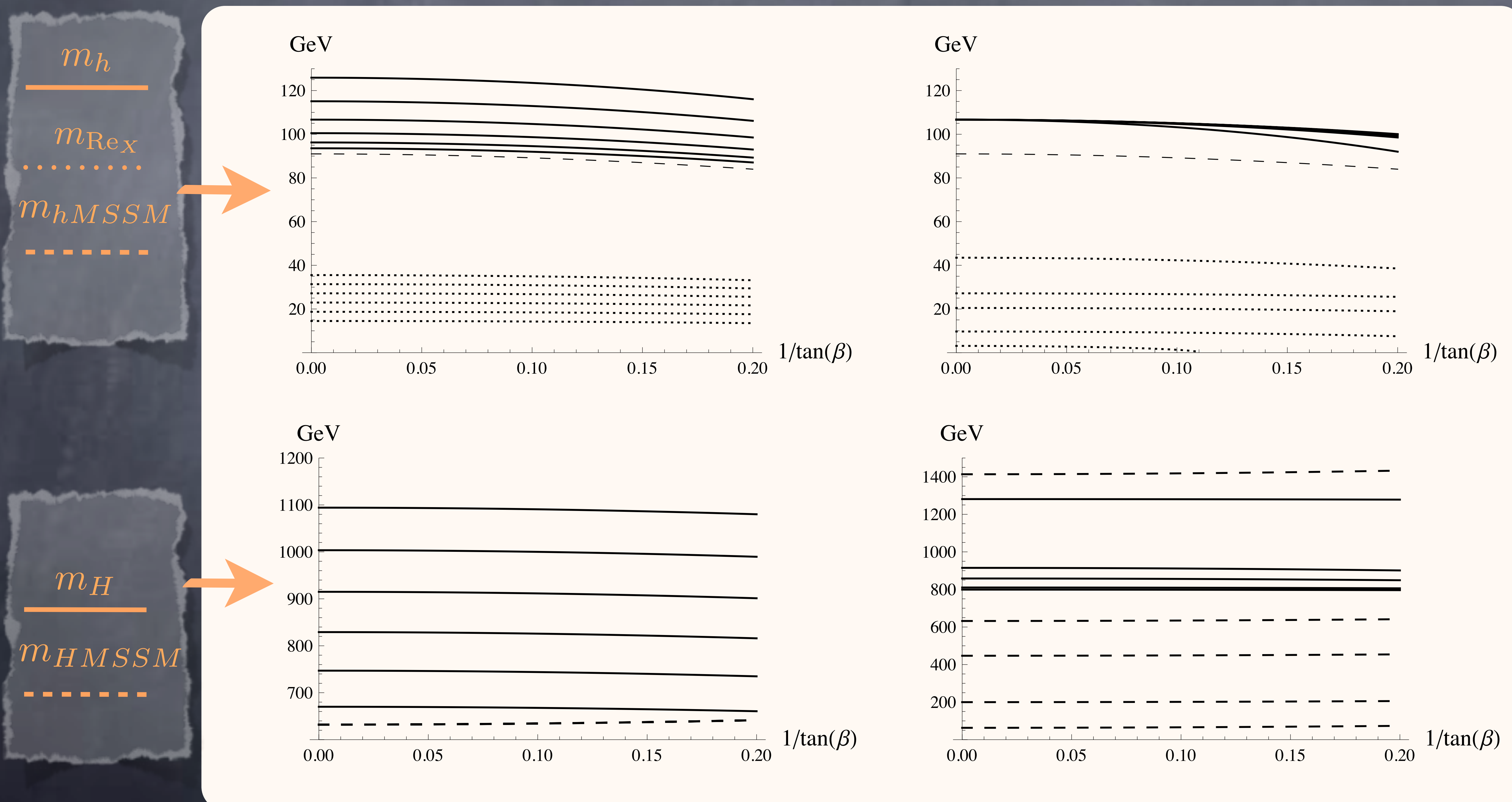
(CP-even, $m_X = 0$)

Plots for the tree-level scalar mass ($\sqrt{f} = 2$)

(CP-even, $m_X = 0$)

$C_B = 0.1,\ \mu = [0.5 - 1]\text{TeV}$

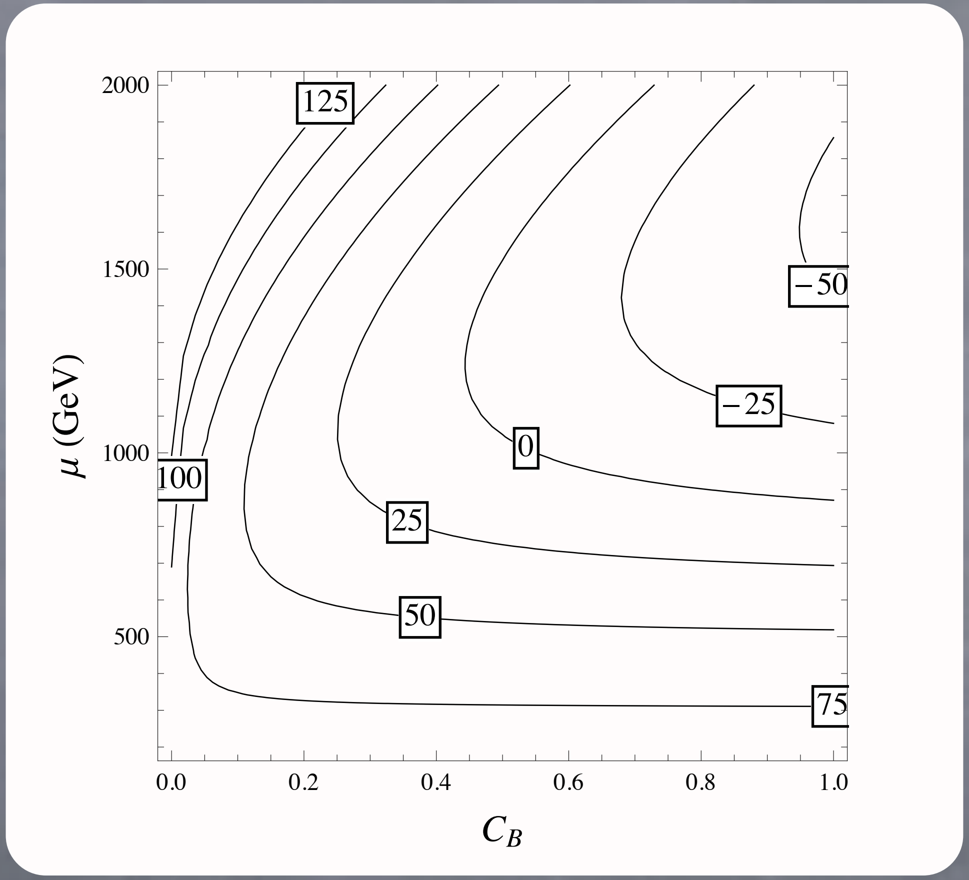
$\mu = 0.8\text{TeV},\ C_B = [0.001, 0.01, 0.05, 0.1, 0.5]$



Plots for the tree-level scalar mass ($\sqrt{f} = 2$)

(CP-even, $m_X = 0$, $\tan\beta \to \infty$)

$m_h - 2m_{\mathrm{Re}\,X}$



Room for new phenomenology

(even with $m_X = 0$)

Plots for the tree-level scalar mass ($\sqrt{f} = 2$)

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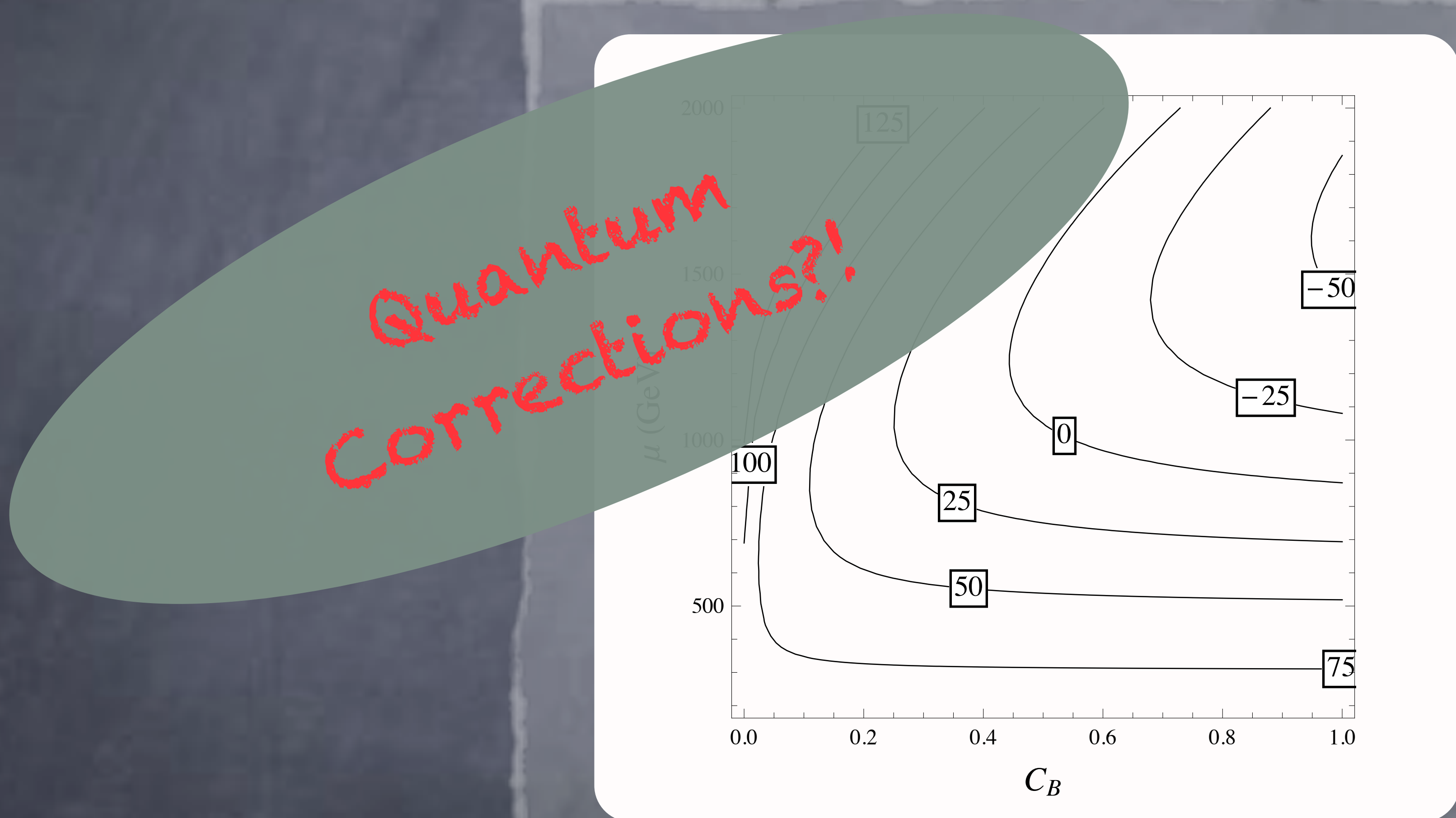

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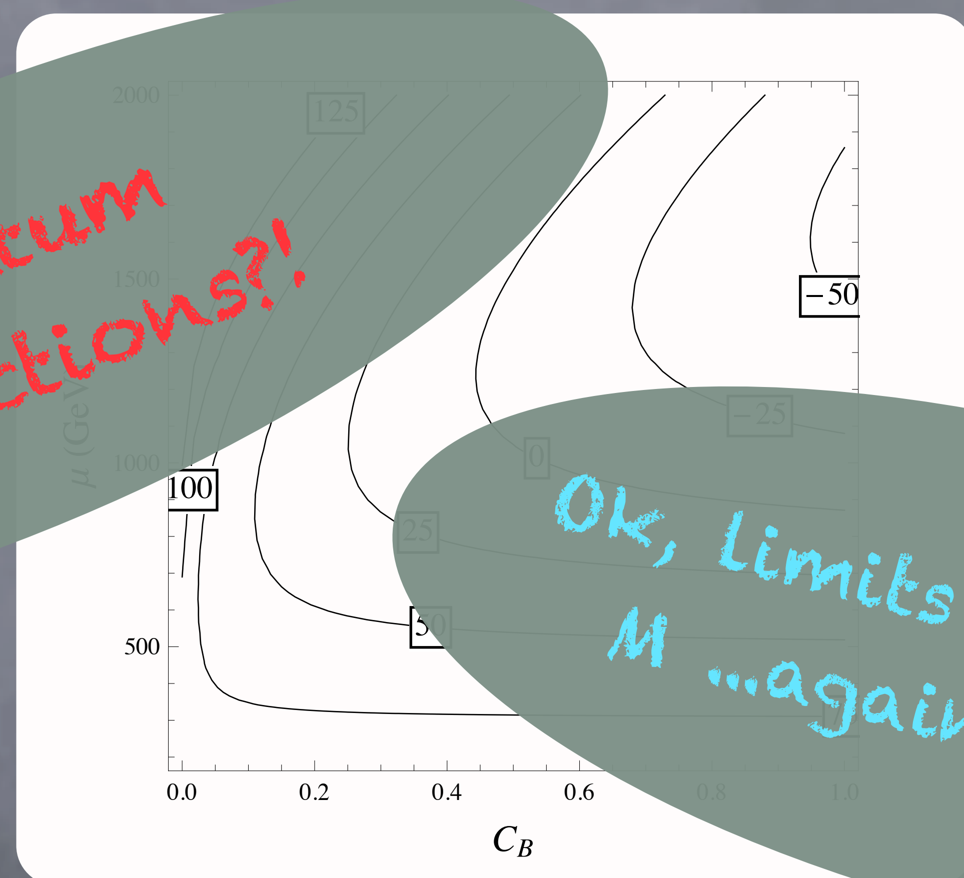


Quantum Corrections?!

Ok, limits on the cut-off M ...again of few TeV

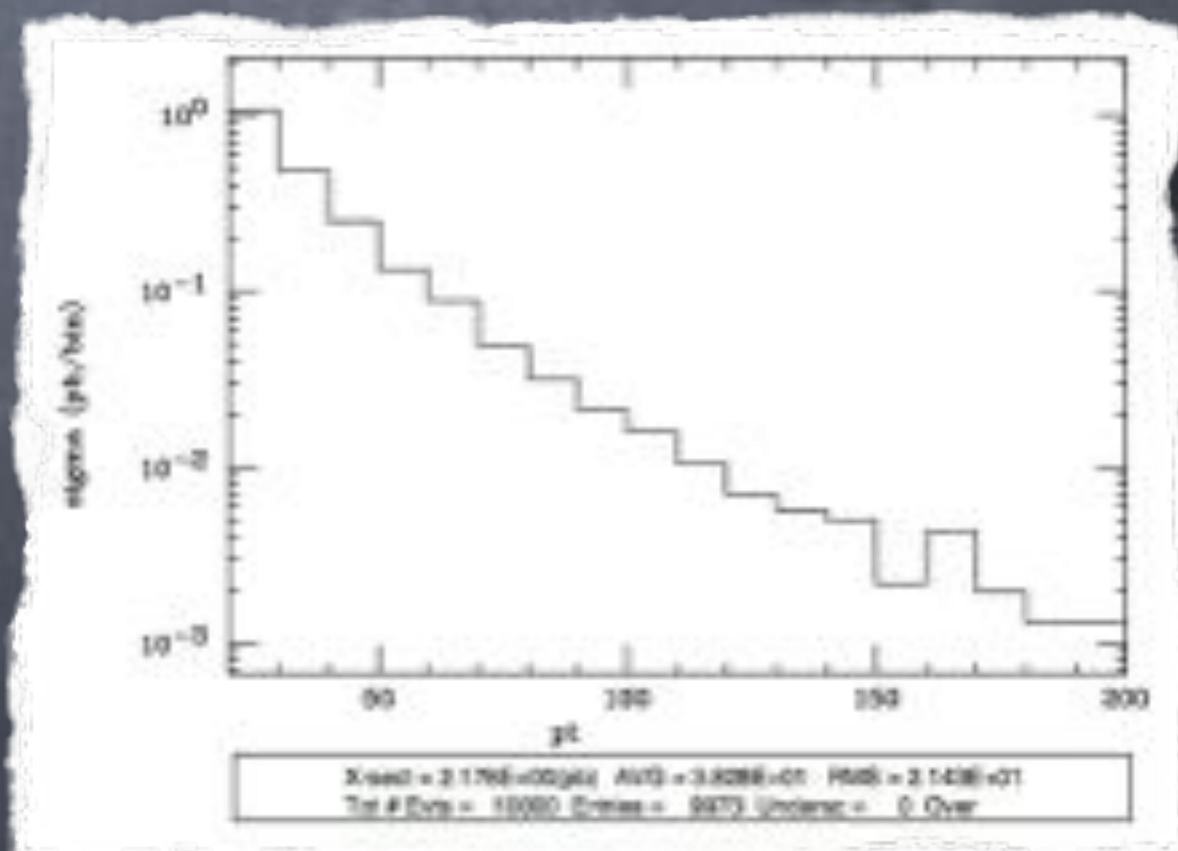
Room for new phenomenology

(even with $m_X = 0$)

The SM background: γ+MET

Name	Process	Source
bg1	$pp \to Z\gamma \to \gamma 2\nu$	Irreducible background
bg2	$pp \to Zj \to j 2\nu$	Jet fakes a photon
bg3	$pp \to W \to e\nu$	Electron fakes a photon
bg4	$pp \to \gamma j$	Missing jet
bg5	$pp \to W\gamma \to \gamma l\nu$	Missing lepton
bg6	$pp \to \gamma\gamma$	Missing photon

- The irreducible $Z\gamma$ background comes from the t-channel di-boson production in the SM
- This is the most relevant BG for high p_T^γ searches (e.g. non resonant production, large ED)



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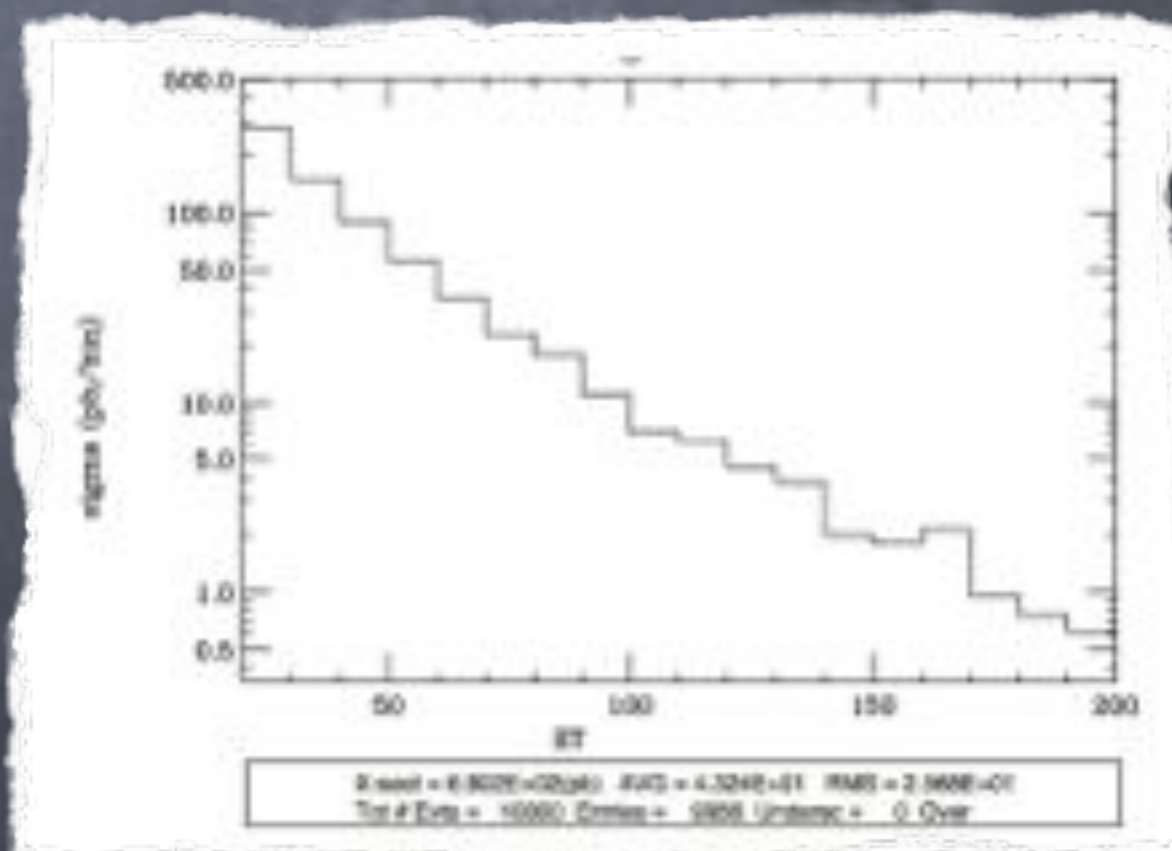
bg5	$pp \to W\gamma \to \gamma l\nu$	Missing lepton
bg6	$pp \to \gamma\gamma$	Missing photon

- The Zj t-channel production contributes when the jet is misidentified as a photon
- The rejection factor for the misidentification is a function of p_T^γ
- We take $r_{\gamma-j} = 10^3$ for $p_T^\gamma > 25$ GeV which is always conservative with a photon reconstruction efficiency $\epsilon_\gamma > 0.95$



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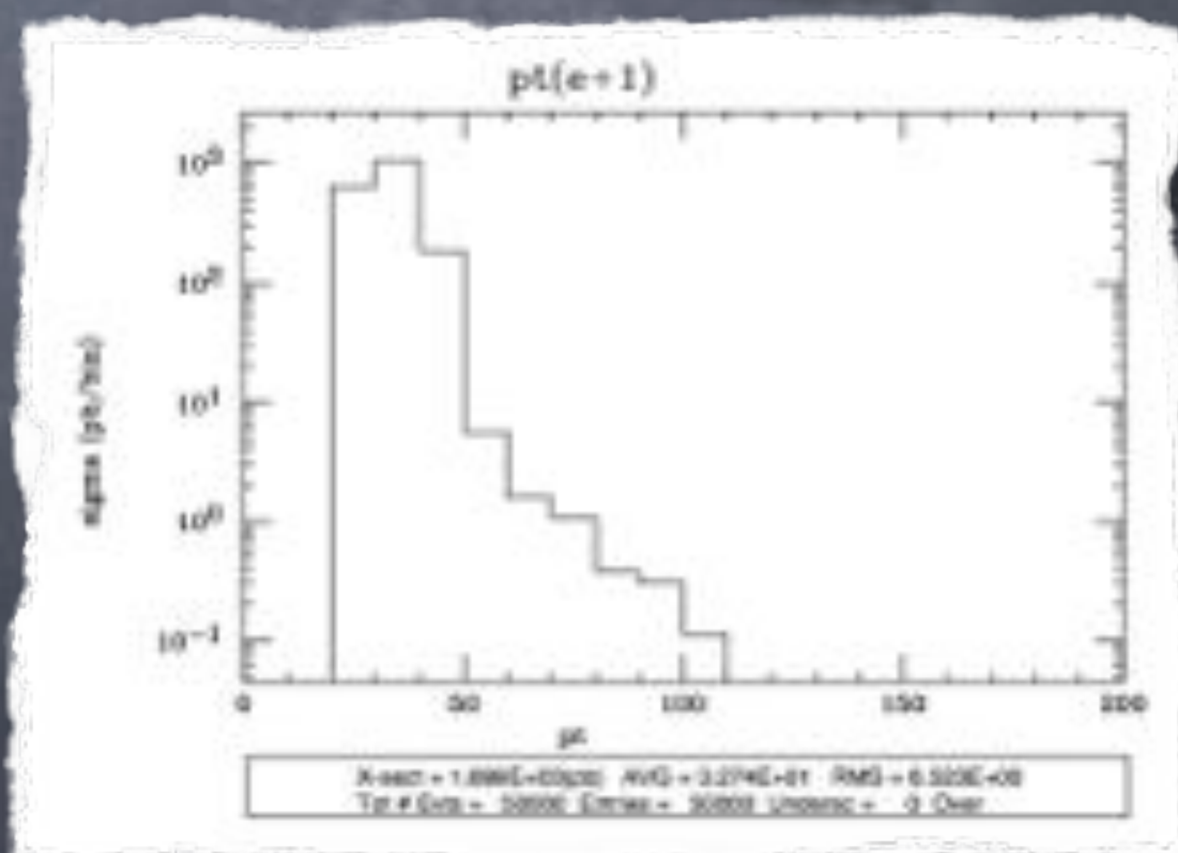
bg5	$pp \to W\gamma \to \gamma l\nu$	Missing lepton
bg6	$pp \to \gamma\gamma$	Missing photon

- The W boson production contributes when the lepton is misidentified as a photon
- The rejection factor for the misidentification is a function of p_T^γ
- We take $r_{e-j} = 200$ estimating it from the CMS analysis of this final state at high p_T^γ (CMS PAS EXO-11-058) but we expect slightly better performances at lower p_T^γ



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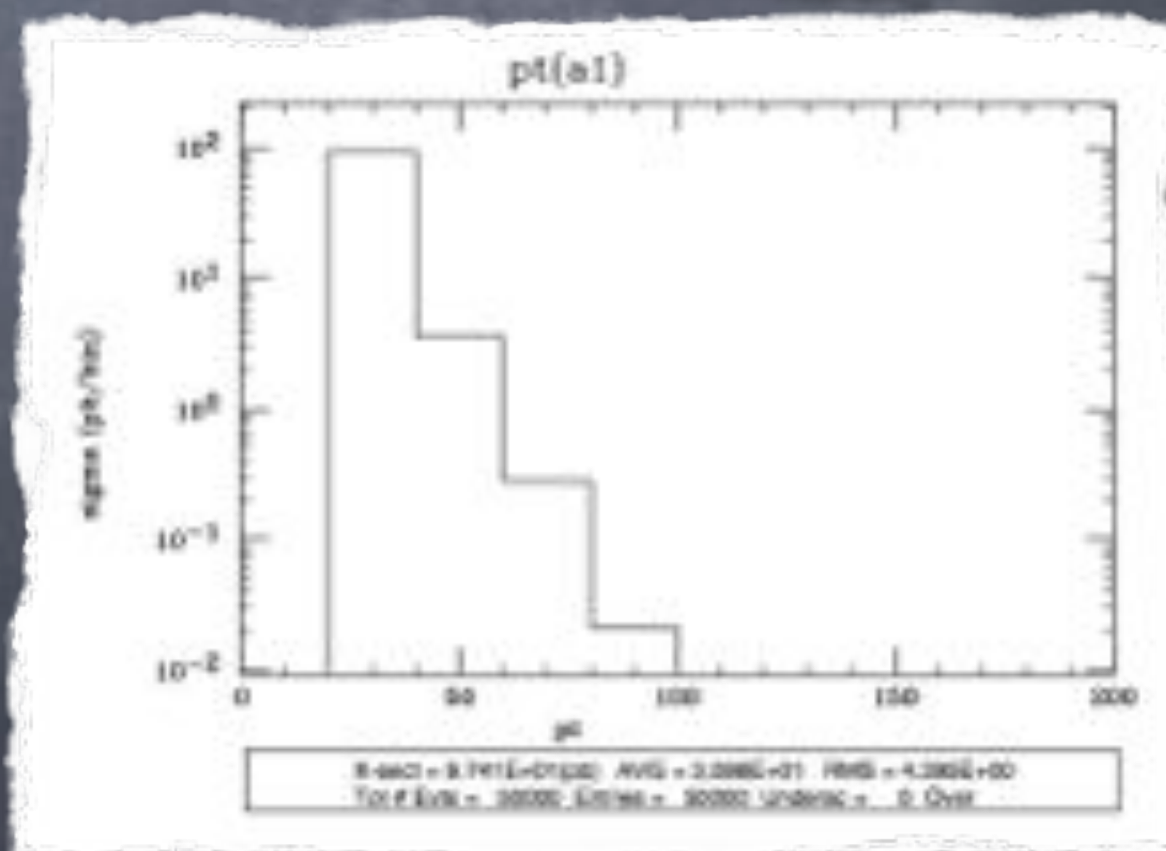
bg4	$pp \to \gamma j$	Missing jet
bg5	$pp \to W\gamma \to \gamma l\nu$	Missing lepton
bg6	$pp \to \gamma\gamma$	Missing photon

- The γj SM production contributes when the jet is missed by the detector
- This BG is the most difficult to estimate especially at low p_T^γ due to detector effects on jet identification and reconstruction
- We have estimated it assuming that jets in the very forward region $|\eta| > 4$ are missed (this assumptions agrees with the CMS analysis at high p_T^γ)



The SM background: γ+MET

Name	Process	Source
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bg6	$pp \to \gamma\gamma$	Missing photon

- The two backgrounds involving di-bosons productions where a lepton or a photon is missed are subleading with respect to the others
- We will neglect these backgrounds in our analysis

Thanks for your attention!