Invisible Higgs Decays

Tilman Plehn

Universität Heidelberg

University of Pittsburgh, August 2016

Motivating invisible Higgs searches 1

Higgs portal to dark matter scalar [Silveira & Zee; Burgess, Pospelov, 'ter Velthuis]

– renormalizable Higgs sector

$$V_{\text{SM}} = \mu_H^2 \, \phi^\dagger \phi + \lambda_H (\phi^\dagger \phi)^2 \supset -\frac{m_H^2}{2} H^2 + \frac{m_H^2}{2 v_H} H^3 + \frac{m_H^2}{8 v_H^2} H^4$$

with observed mass scale

$$v_H = \sqrt{\frac{-\mu_H^2}{\lambda_H}} = 246 \quad \text{GeV}$$

$$m_H = \sqrt{2 \lambda_H} \, v_H = 2 \sqrt{-\mu_H^2} = 125 \quad \text{GeV} \approx \frac{v_H}{2}$$

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– renormalizable (portal) extension by real scalar [dark $\mathbb{Z}_2$ parity, Higgs mediator]

$$V \supset -\frac{m_H^2}{2} H^2 + \frac{m_H^2}{2 v_H} H^3 + \frac{m_H^2}{8 v_H^2} H^4 - \mu_S^2 \, S^2 + \lambda_S \, S^4 + \frac{\lambda_3}{2} (H + v_H)^2 S^2$$

new mass scale: $m_S^2 = 2\mu_S^2 - \lambda_3 v_H^2$

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1. relic density: light scalar $m_S = 10 \; ... \; 50$ GeV

$$\langle \sigma v \rangle \Big|_{SS \to b\bar{b}} = \frac{N_c \lambda_3^2 m_b^2}{\pi m_H^4} \stackrel{!}{=} \frac{4 \cdot 10^{-9}}{\text{GeV}^2} \qquad \Leftrightarrow \qquad \lambda_3 = 0.35$$

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2. relic density: resonance annihilation $m_S = m_H/2$

$$\langle \sigma v \rangle \Big|_{SS \to b\bar{b}} = \frac{N_c \lambda_3^2 m_b^2}{\pi m_H^2 \Gamma_H^2} \stackrel{!}{=} \frac{4 \cdot 10^{-9} \, \text{BR}_{H \to b\bar{b}}}{\text{GeV}^2} \qquad \Leftrightarrow \qquad \lambda_3 \approx 10^{-5}$$

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3. relic density: heavy scalar $m_S \gtrsim 200$ GeV

$$\langle \sigma v \rangle \Big|_{SS \to HH} = \frac{\lambda_3^2}{8 \pi m_S^2} \stackrel{!}{=} \frac{4 \cdot 10^{-9}}{\text{GeV}^2} \qquad \Leftrightarrow \qquad \lambda_3 \gtrsim 0.06$$

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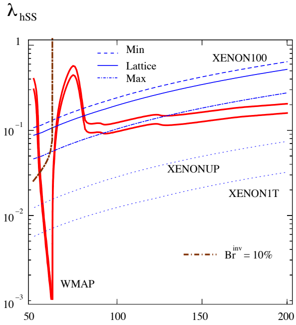
$\Rightarrow$ invisible Higgs decays possible...

[Djouadi, Lebedev, Mambrini, Quevillon]



Motivating invisible Higgs searches 2

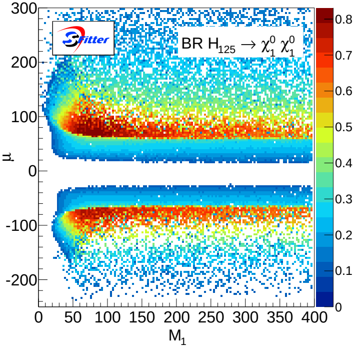
MSSM Higgs boson [SFitter: Butter,...]

- take LHC hints and decouple squarks and gluinos
- decouple sleptons and their co-annihilation channels
- mass parameters: M_1, M_2, μ

  SM-like Higgs coupling requiring higgsino fraction

$$g_{H\tilde{\chi}\tilde{\chi}}\Big|_{\text{MSSM}} = (g_1 N_{11} - g_2 N_{12})\;(\sin\alpha N_{13} + \cos\alpha N_{14})$$

1. require $m_h = 125$ GeV in M_1 vs μ [tan $\beta = 40$]



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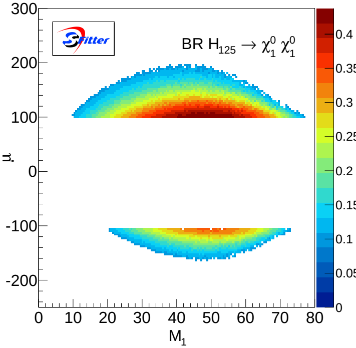

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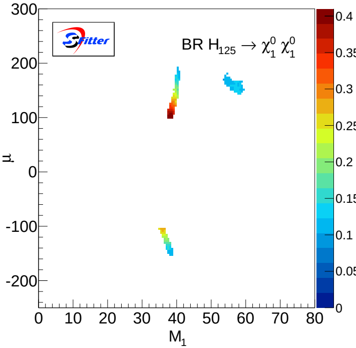

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1. require $m_h = 125$ GeV in M_1 vs μ [tan $\beta = 40$]
2. add LEP chargino mass limit
3. add relic density
4. add direct detection

$$\text{BR}(H_{125} \to \tilde{\chi}\tilde{\chi}) \lesssim 50\% \qquad \text{for} \quad \mu = 100\ \text{GeV}, \quad M_1 = 45\ \text{GeV}\ ,$$

$\Rightarrow$ not generic, but possible...

Weak boson fusion

Classic paper

- prime application of WBF strategy
- weak backgrounds $\sigma_{Vjj} \propto \alpha_s^2 \alpha, \alpha^3$

  missing transverse momentum
  tagging jet cuts [including ϕ_{jj}]
  central jet veto
- analysis focus on background extrapolation
  $\phi_{jj} > 1$ and $Z \to \ell^+ \ell^-$
- trigger issue central

University of Wisconsin - Madison

MADPH-00-1191
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Observing an invisible Higgs boson

O. J. P. Éboli[1] and D. Zeppenfeld[2]
[1]*Instituto de Física Teórica – UNESP*
R. Pamplona 145, 01405-900 São Paulo, Brazil
[2]*Department of Physics, University of Wisconsin, Madison, WI 53706, USA*

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$$p_T^j > 40 \text{ GeV} \quad , \quad |\eta_j| < 5.0$$
$$|\eta_{j1} - \eta_{j2}| > 4.4 \quad , \quad \eta_{j1} \cdot \eta_{j2} < 0 \, ,$$
$$\not{p}_T > 100 \text{ GeV} \, .$$

the backgrounds, with good signal efficiency, is
M_{jj}, of the two tagging jets,

$$M_{jj} > 1200 \text{ GeV} \, ,$$

where the azimuthal angle between the tagging
nall,

$$\phi_{jj} < 1 \, ,$$

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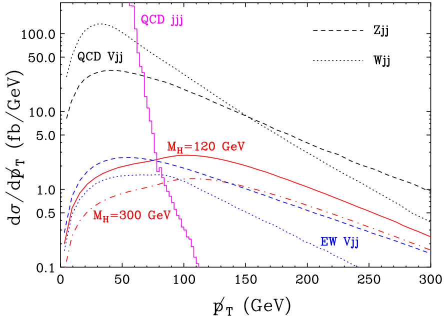

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	QCD Zjj	QCD Wjj	EW Zjj	EW Wjj	total
σ	1254	1284	151	101	2790
$P_{surv}\ \sigma$	351	360	124	83	918
$P_{surv}\ \sigma(\phi_{jj} < 1)$	71.8	70.2	14.8	9.9	167

TABLE II. Total cross sections (in fb) for the backgrounds after applying the cuts (1-3) (first two lines) and (4). In the last two lines we also include the central jet veto survival probabilities of Table I.

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$\Rightarrow$ room for improvement, time for an update?

Update

Analysis update [Bernaciak, TP, Schichtel, Tattersall]

- impact of 3rd jet kinematics? [rapidity-ordered, beyond veto]
- two multivariate analyses

$$\{p_{T,j_1},\ \eta_{j_1},\ p_{T,j_2},\ \eta_{j_2},\ \Delta\phi_{j_1,j_2},\ \not{p}_T\} \qquad \text{(2-jet)}$$
$$\{p_{T,j_1},\ \eta_{j_1},\ p_{T,j_2},\ \eta_{j_2},\ \Delta\phi_{j_1,j_2},\ \not{p}_T,\ p_{T,j_3},\ \eta_{j_3},\ \Delta\phi_{j_1,j_3}\} \qquad \text{(3-jet)}$$

- fast detector simulation Delphes/CheckMate
- fixed signal efficiency [$p_{T,j} > 20$ GeV for central jets]

	2-jets	3-jets	4-jets
S/B after WBF cuts	1/240	1/360	1/475
ϵ_S	0.01	0.01	0.01
ϵ_B	1.7×10^{-6}	1.3×10^{-5}	2.7×10^{-5}
σ_S (fb)	80.0	80.0	80.0
S/B	1/2.6	1/21	1/42

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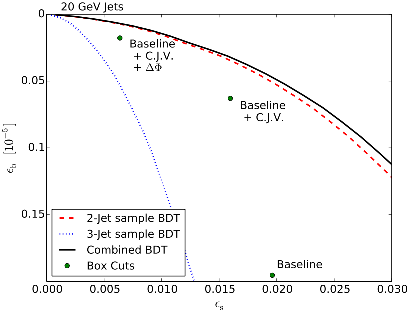
– fast detector simulation Delphes/CheckMate

– full ROC curve

⇒ 3rd jet not all that useful?



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$\Rightarrow$ 3rd jet not all that useful?

Using central jets rather than killing them

– central (micro-) jets to 10 GeV

	$p_{T,j} > 20$ GeV			$p_{T,j} > 10$ GeV		
	2-jets	3-jets	4-jets	2-jets	3-jets	4-jets
S/B after WBF cuts	1/240	1/360	1/475	1/213	1/303	1/429
ϵ_S	0.01	0.01	0.01	0.01	0.01	0.01
S/B	1/2.6	1/21	1/42	1/1.2	1/5	1/38

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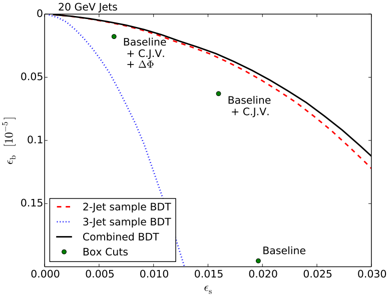

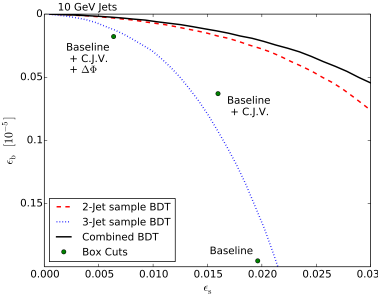

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Using central jets rather than killing them

– central (micro-) jets to 10 GeV

– reach for invisible branching ratio [95% CL]

	$p_{T,j} > 20$ GeV				$p_{T,j} > 10$ GeV	
$\mathcal{L}$[fb^{-1}]	WBF cuts	+ jet veto	+ $\Delta\phi_{jj}$	BDT 2-jets	BDT 2-jets	+ BDT 3-jets
10	1.02	0.49	0.47	0.28	0.18	0.16
100	0.49	0.20	0.18	0.10	0.07	0.061
3000	0.25	0.094	0.069	0.035	0.025	0.021

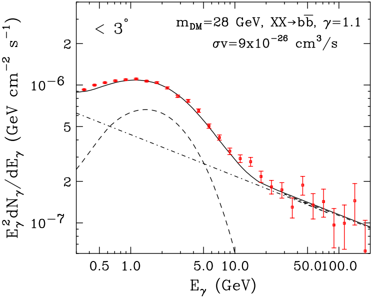
⇒ QCD and analysis challenge, really...

Hooperon — fun with dark matter

Galactic center excess in FERMI data, by theorists

[Goodenough & Hooper (unpublished? 2009)]

- look at gamma ray spectrum in galaxy
- remove all foregrounds
- check radial distributions
- explain by DM annihilation with photons
- $m_\chi \sim 30$ GeV from spectrum



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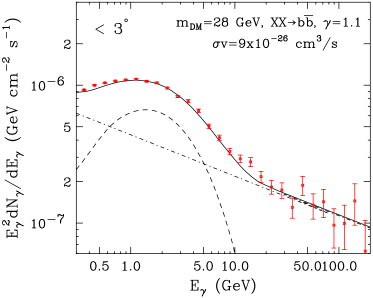

In conclusion, we have studied the angular distribution and energy spectrum of gamma rays measured by the Fermi Gamma Ray Space Telescope in the region surrounding the Galactic Center, and find that this data is well described by a scenario in which a 25-30 GeV dark matter particle, distributed with a halo profile slightly steeper than NFW ($\gamma = 1.1$), is annihilating with a cross section within a factor of a few of the value predicted for a thermal relic.

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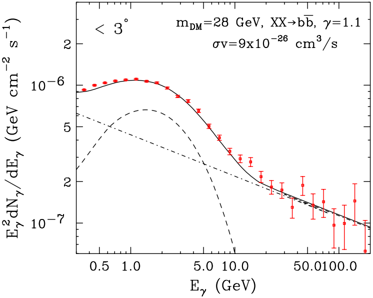
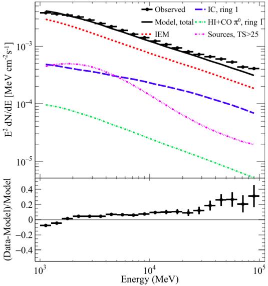


Kind of confirmed by FERMI [Murgia etal (2015)]

- analysis with all uncertainties
- fit without dark matter not good



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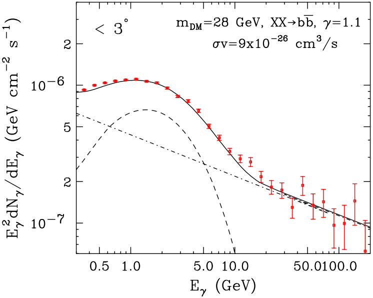

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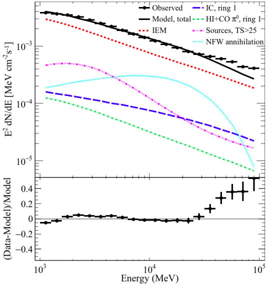
– improved with NFW contribution



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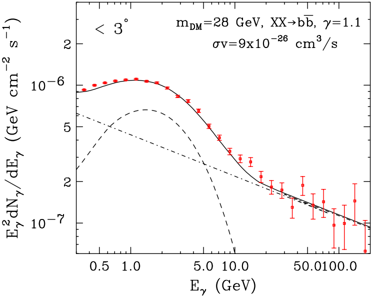

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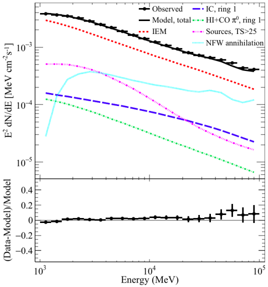
- analysis with all uncertainties
- fit without dark matter not good
- improved with NFW contribution
- even better with modified NFW contribution

of the analysis that has previously not been employed. After subtraction of interstellar emission and point sources, an extended residual is present. It can be fit with a centrally peaked profile with a specified spectral model, but not all of the positive residual is accounted for by such a model. Because of the uncertain nature of the properties of the positive residual due to the IEM and point source determination, a precise physical interpretation of its origin is premature.



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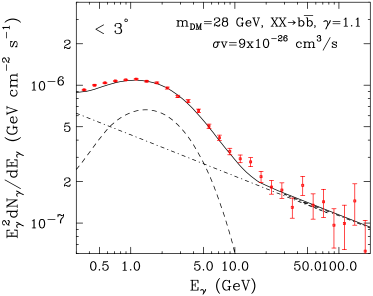
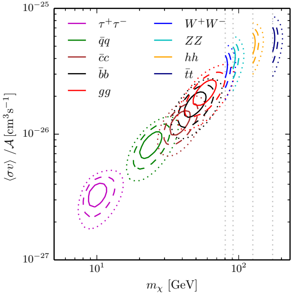


Kind of confirmed by FERMI [Murgia etal (2015)]

– analysis with all uncertainties
– fit without dark matter not good
– improved with NFW contribution
– even better with modified NFW contribution
– different DM candidates [Calore etal; ask Asher]

$\Rightarrow$ DM model playground, but probably astrophysics



NMSSM Hooperons

Hooperon in the NMSSM [Berlin, Hooper, McDermott; Butter etal]

- scalars largely decoupled from h_{125} [through A_λ]
- higgsino mass parameter μ
  singlino mass parameter $2\kappa\mu$
  singlino-higgsino mixing parameter λ

$$M_{\tilde{\chi}} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w & 0 \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w & 0 \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu & -m_Z s_\beta \frac{\lambda}{g} \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 & -m_Z c_\beta \frac{\lambda}{g} \\ 0 & 0 & -m_Z s_\beta \frac{\lambda}{g} & -m_Z c_\beta \frac{\lambda}{g} & 2\tilde{\kappa}\mu \end{pmatrix}$$

- *s*-channel mediators

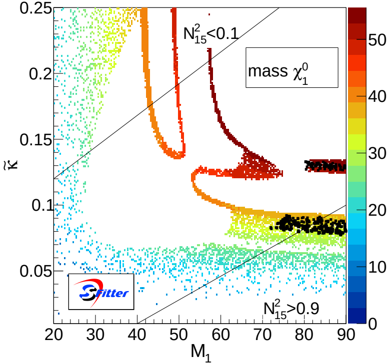
  Standard Model: Z, h_{125}
  new: heavy/singlet pseudoscalars
- Fermi: light pseudo-scalar mediator
  higgsino-admixed singlino DM

$\Rightarrow$ LHC signatures? [Cao, Zurek,...]

Higgs decays to Hooperons

LHC signatures [SFitter: Butter...]

– squarks, gluinos, sleptons decoupled
  $\tan\beta = 10$, Higgs mass correct,...
– singlino vs bino mass parameter space [slice $\mu = 220$ GeV]
– funnel off-pole annihilation: Z and h_{125}
  strips with $m_{\tilde{\chi}} = 40, 48, 55$ GeV
– Hooperon at $M_1 \gtrsim 70$ GeV



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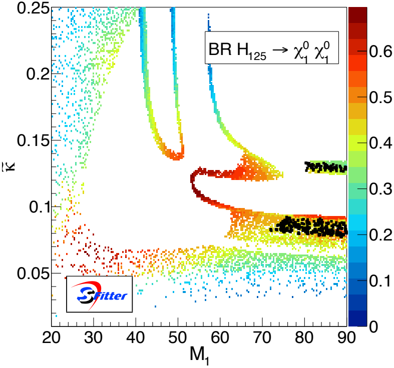
$\Rightarrow$ strong correlation with $h_{125} \to$ invisible



Pep talk

Invisible Higgs searches...

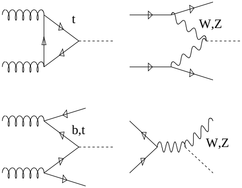
...are well motivated in many models

...are an example of one person changing something

...are a challenge to QCD and jet reconstruction

...can be linked to astrophysical anomalies

Higgs couplings



Test SM-like Higgs sector [SFitter]

– or: all couplings proportional to masses?

– assume: narrow CP-even scalar
Standard Model operators

– total production/decay rates only

– Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
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– electroweak renormalizability through some UV completion

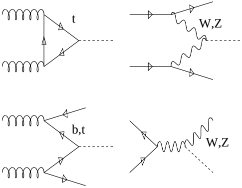
– QCD renormalizability not an issue

$gg \to H$
$qq \to qqH$
$gg \to t\bar{t}H$
$qq' \to VH$

$\longleftrightarrow$ $g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)$ $\longleftrightarrow$

$H \to ZZ$
$H \to WW$
$H \to b\bar{b}$
$H \to \tau^+\tau^-$
$H \to \gamma\gamma$

Higgs couplings



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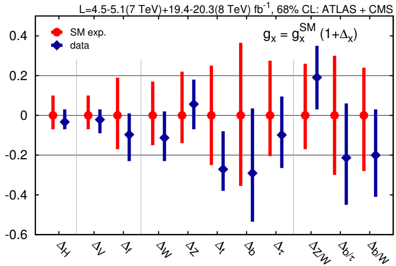
Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, Lopez-Val, TP, Rauch]

- assume SM-like [secondary solutions possible]
- SFitter: correct theory uncertainties



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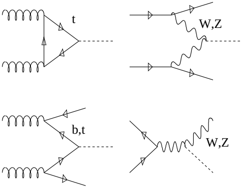

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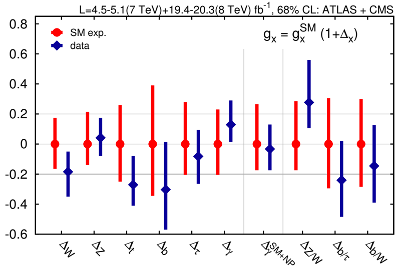
– g_γ with new loops



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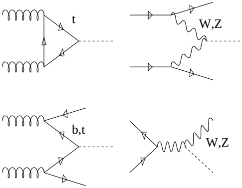

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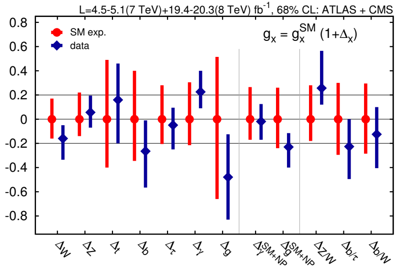

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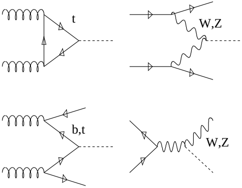

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$\Rightarrow$ including invisible decays