Minimal Walking Technicolor

Dark Matter and Collider Signatures

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TOOLS2010, Southampton, June 30$^{\mathrm{th}}$ 2010

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Outline

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In collaboration with:

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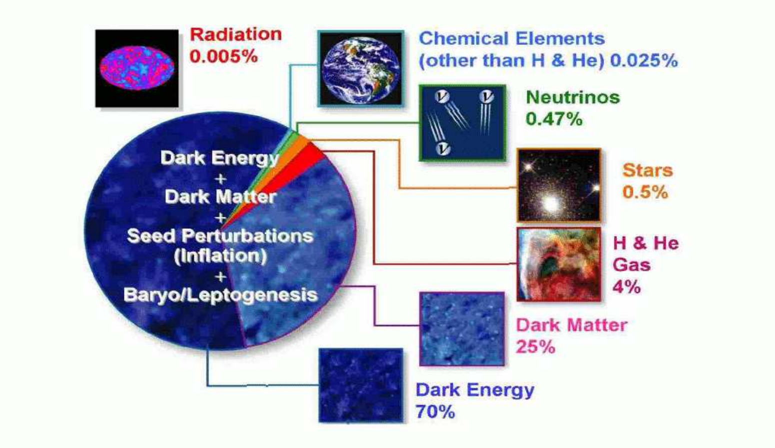
Matti Jaȑvinen (CP3-Origins),
Alexander Pukhov (Moscow State U.),
Francesco Sannino (CP3-Origins),
Subir Sarkar (Oxford U.)
Alexander Sherstnev (Oxford U.).

A. Belyaev, M.T.F and A. Sherstnev In progress

The origin of bright and dark mass



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- Flavor sector simply parametrized

Technicolor

EWSB from Technicolor: (Weinberg 78, Susskind 78)

1. In the SM without a Higgs, QCD breaks the EW symmetry:

$$\langle \bar{u}_L u_R + \bar{d}_L d_R \rangle \neq 0 \quad \rightarrow \quad M_W = \frac{g f_\pi}{2} \ .$$

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Example: Scaled-up QCD !

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Minimal chiral symmetries: 3 GB's + Custodial + DM.

$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \rightarrow SU_V(2) \times U_{TB}(1) \ .$$

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Lightest Technibaryon as Asymmetric Dark Matter

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$$\Omega_{TB}/\Omega_B \sim m_{TB}/m_B \times (m_{TB}/T_{sphaleron})^{3/2} e^{-m_{TB}/T_{sphaleron}}$$

$$T_{sphaleron} \sim v_{EW} \; ,$$

(Chivukula and Walker 90; Bahr, Chivukula and Farhi 90; Harvey and Turner 90; Ellis et al 95; Sarkar 95; Gudnason, Kouvaris and Sannino 05)

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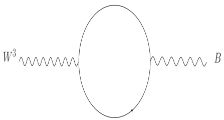
- Or 'Dark Baryon' with $m_{DB} \sim 5 - 10 GeV$?

(D.B.Kaplan 92; An, Chen, Mohapatra and Zhang 09; D.E.Kaplan, Luty and Zurek 09; Fitzpatrick, Zurek and Hooper 10; M.T.F and Sarkar 10)

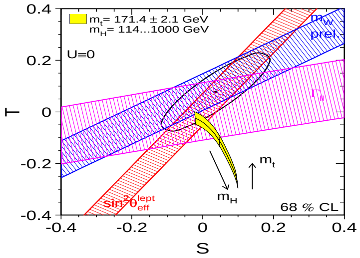
Constraints from LEP

1. A minimal matter content in the TC sector is favored:

$$S \equiv -16\pi\Pi'_{W^3B}(0)\ ,\ \ T \equiv \frac{4\pi}{s_W^2 c_W^2 M_Z^2}(\Pi_{W^1W^1}(0) - \Pi_{W^3W^3}(0))$$



$$S_{\rm naive} = N_D \frac{d(R_{\rm TC})}{6\pi}$$



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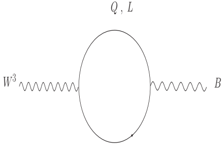

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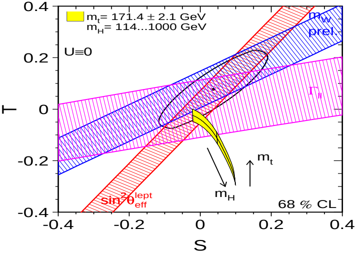

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2. $S \sim S_{\text{naive}}$ in Walking (near-conformal) Technicolor (?)
(Sundrum and Hsu 92; Appelquist and Sannino 98; Harada, Kurachi and Yamawaki 03; Kurachi and Shrock 06; Sannino 10)

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

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(M.T.F and F.Sannino 09)

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(Other candidates in MWT: Gudnason, Kouvaris and Sannino 05; Kainulainen, Virkajärvi and Tuominen 06, 09, 10; Kouvaris 07; Khlopov and Kouvaris 08)

Minimal Models of Walking Technicolor

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MWT model: (Sannino and Tuominen 04)

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- $\mathcal{R} = F, Adj$
- TIMP, $\phi \sim \lambda\lambda$

(Ryttov and Sannino 08)

- Other TC Models (non-minimal/including ETC):
  Farhi and Susskind 79; Eichten and Lane 89; Appelquist and Terning 94; Appelquist, Christensen, Pia and Shrock 04; Lane and Martin 06; Ryttov and Shrock 10

EFT for strong dynamics @ LHC

common sector:

$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \to SU_V(2) \times U_{TB}(1) \ .$$

- New states: Lightest (axial)-vector triplets and scalar

$$R_1^{\pm,0}, \ R_2^{\pm,0}, \ H. \quad \text{TIMPs}$$

- Input parameters and constraints:

$$e, \ G_F, \ M_Z; \ S, \ \text{Sum Rules.}$$

- Main free parameters:

$$M_A, \ \tilde{g}, \ M_H.$$

(Appelquist, Da Silva and Sannino 99; Foadi, M.T.F, Ryttov and Sannino

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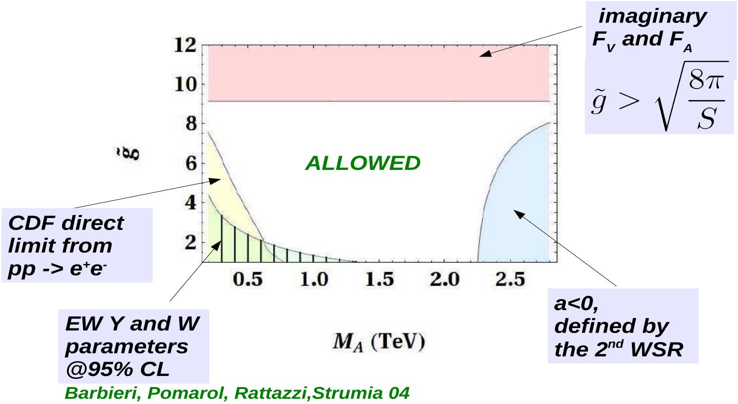
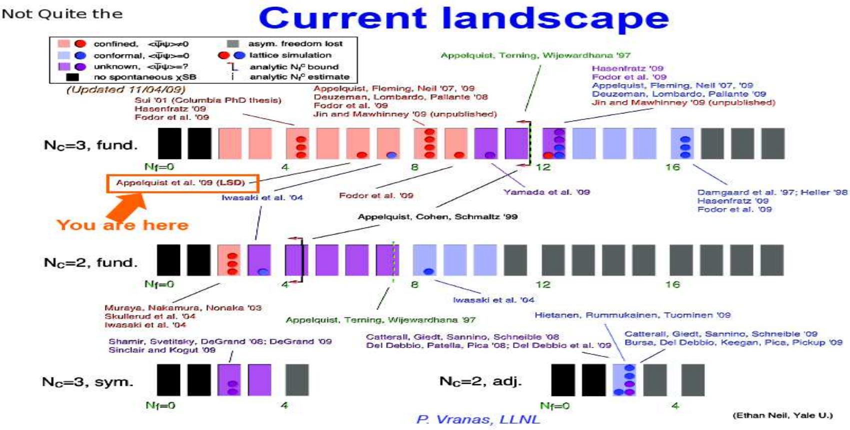
- EFTs for 'BESS' models, '3-site/4-site' models and LSTC (Casalbuoni, Deandrea, De Curtis, Dominici, Gatto, Grazzini 95; He et al 08; Lane and Martin 09)

Parameter space



(Foadi, M.T.F and Sannino 07 ; Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

Lattice simulations



(Dedicated collaborations: Lattice Strong Dynamics (US) ; Strong BSM (EU))

Mass spectrum, imposing S and WSR1

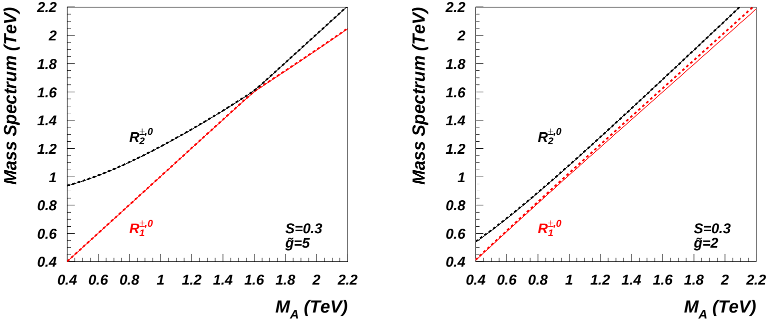
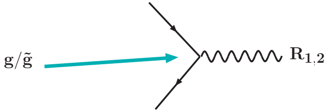


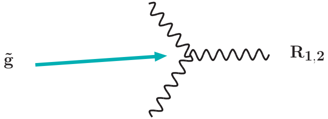
Figure: $R_{1,2}$ spectrum.

(Foadi, M.T.F, Ryttov and Sannion 08)

LHC Phenomenology

- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.





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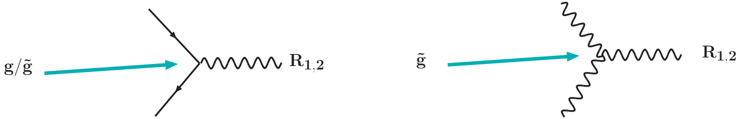

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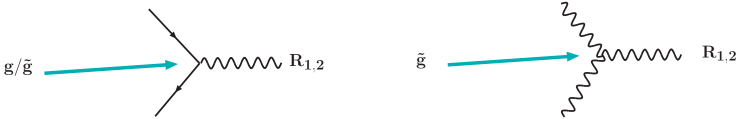

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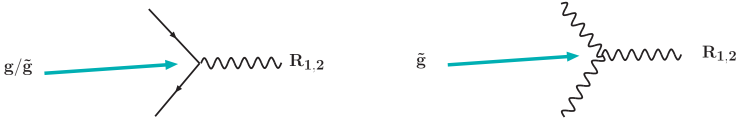

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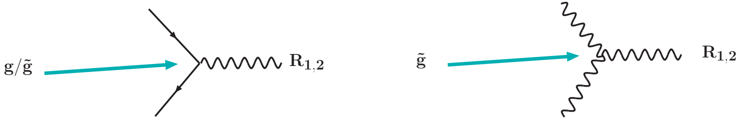

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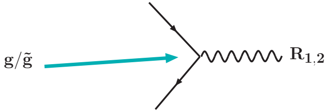

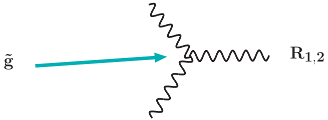

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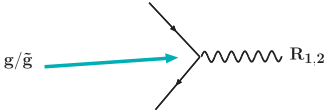

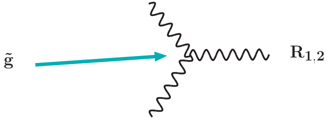

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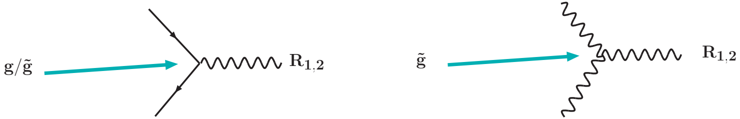

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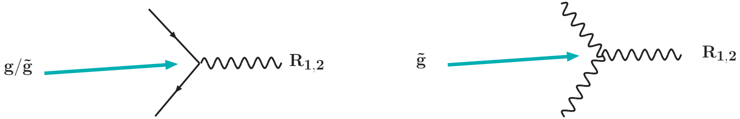

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  - MWT/OMT, NMWT, UMT etc...

Model Implementation

- (N)MWT, UMT and OMT models in:
  - `LanHEP` (A.Semenov) `FeynRules` (C.Duhr et al)
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- Used ThePEG/HERWIG++ for showering/hadronization (Lönnblad/Bahr et al)
- Used DELPHES for Fast Detector Simulation (Ovyn and Rouby)

Vector BRs

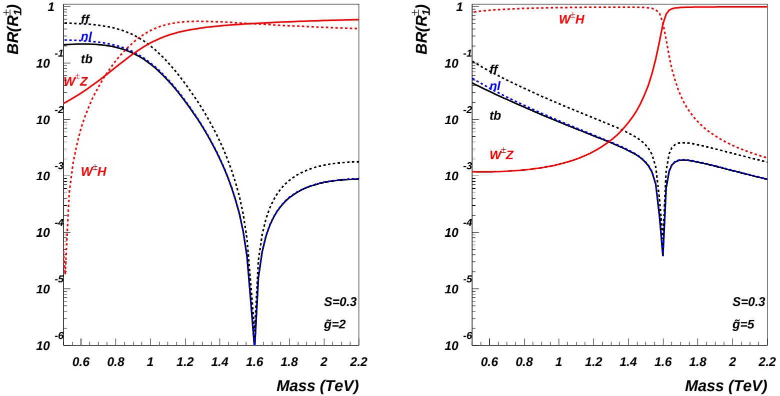

Figure: BR's of R_1.

Vector Production

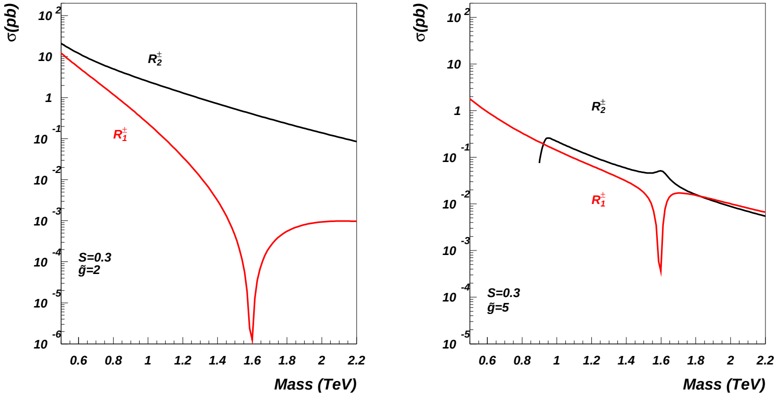

Figure: DY production of $R_{1,2}$.

$\ell^+\ell^-$ signature @ LHC using CalcHEP

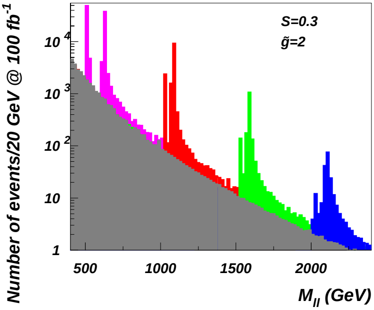

Figure: Dilepton invariant mass distribution $M_{\ell\ell}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$

(Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

$\ell^+\ell^-$ signature @ LHC using HERWIG/DELPHES

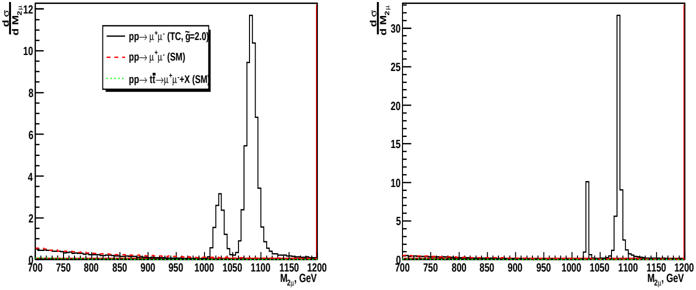

Figure: Dilepton invariant mass distribution $M_{\mu\mu}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$. $M_A = 1$ TeV, $\tilde{g} = 2$, $S = 0.3$.

Additional Cuts: $M_{\mu\mu} > 500 GeV$ and $R_j = 1$.

(A. Belyaev, M.T.F and A.Sherstnev in preparation)

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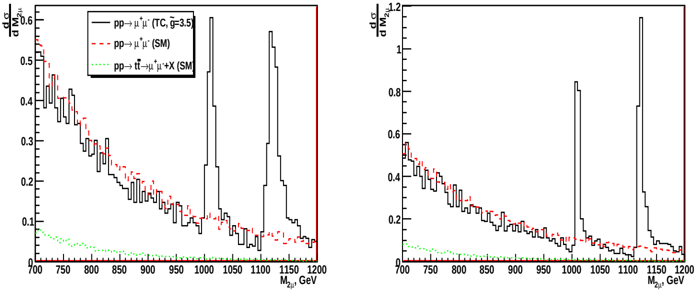
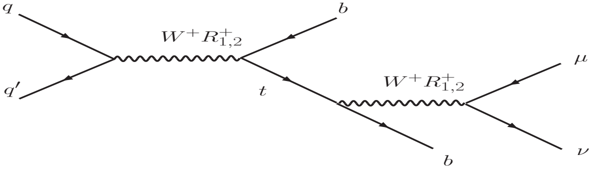


Figure: Dilepton invariant mass distribution $M_{\mu\mu}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$. $M_A = 1$ TeV, $\tilde{g} = 3.5$, $S = 0.3$.

Additional Cuts: $M_{\mu\mu} > 500 GeV$ and $R_j = 1$.

(A. Belyaev, M.T.F and A.Sherstnev in preparation)

Parton level *tb* signature @ LHC using CompHEP



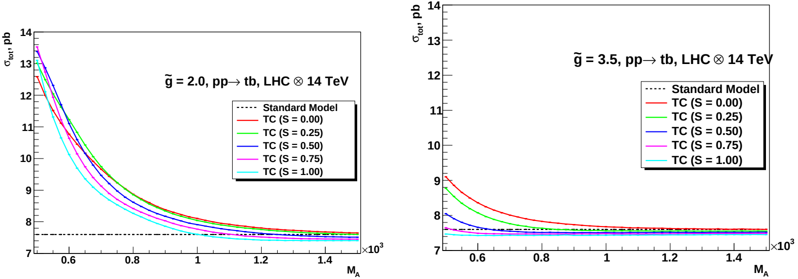


Figure: tb cross-section

Results for *tb*

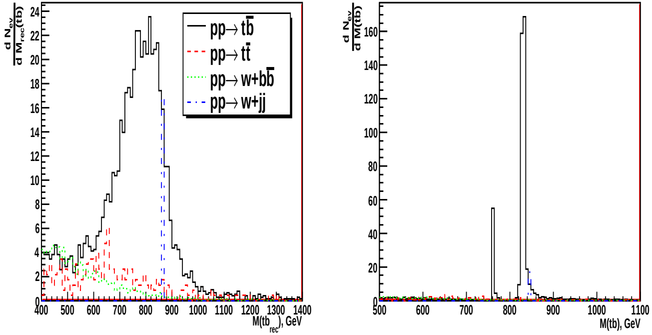
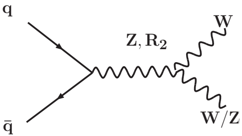
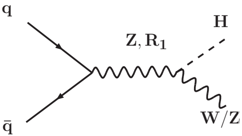
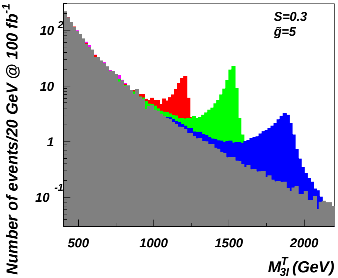


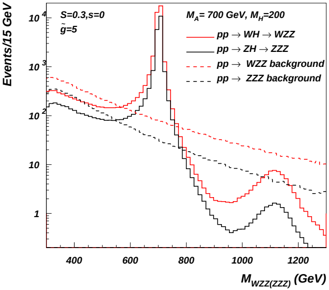
Figure: Reconstructed (left plot) and partonic (right plot) invariant mass of top and b-quarks after final cuts. Distributions normalized to 30 fb^{-1}.

Di-boson vs Higgs-strahlung









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Higgs Strahlung in the SM and TC

1. Enhanced HZ/HW cross-section from a resonance

Higgs Strahlung in the SM and TC

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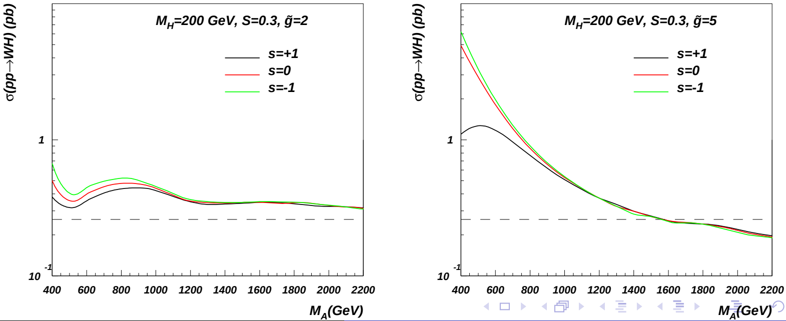
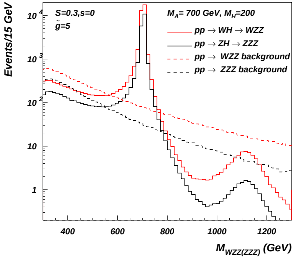
2. $U(1)$ techni-omega, $U(1)$ Z', axial techni-vector (R_1) resonance

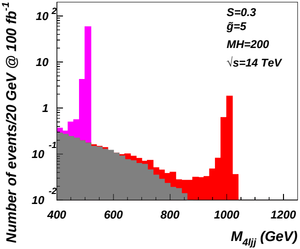
   (Zerwekh 05; Barger, Langacker and Lee 05; Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)



Higgs Strahlung in the SM and TC

1. Resonance peaks from axial-vector R_1





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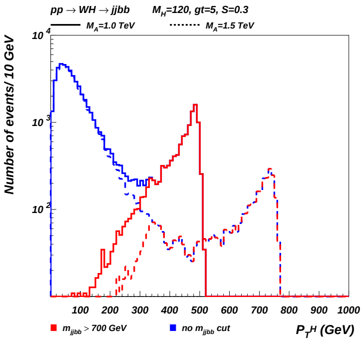
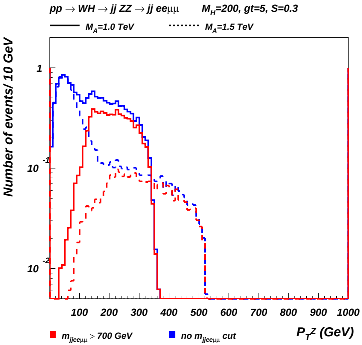
Boosted WH final states: Preliminary analysis





- Large Higgs transverse momenta peaked at $p_T(H) \sim M_{R_1}/2$ (Belyaev, M.T.F and Sherstnev in progress)

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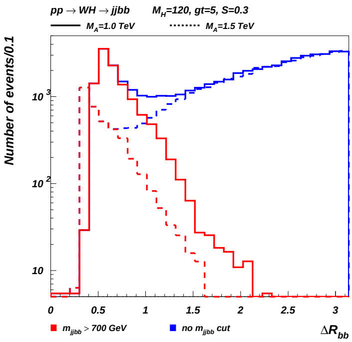

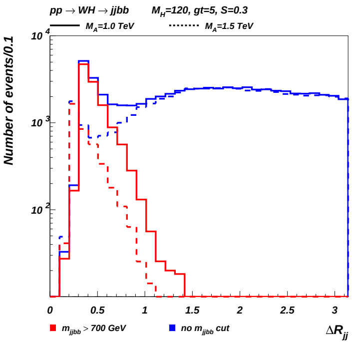

- ΔR_{bb} and ΔR_{jj} accordingly small in the $b\bar{b}$ channel: Peaked at $\Delta R_{bb} \sim 4M_H/M_{R_1}$, $\Delta R_{jj} \sim 4M_Z/M_{R_1}$ (Belyaev, M.T.F and Sherstnev in progress)

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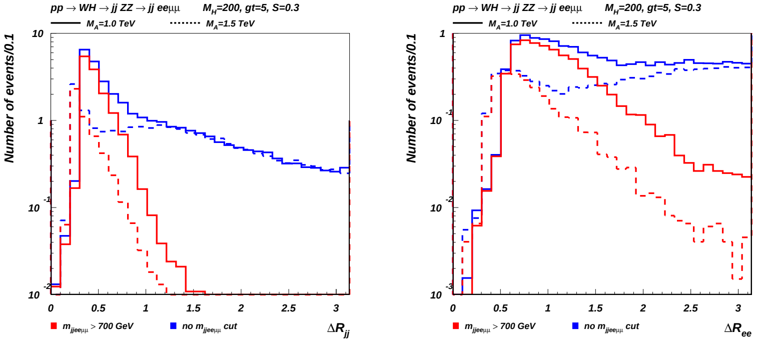
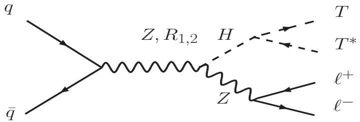
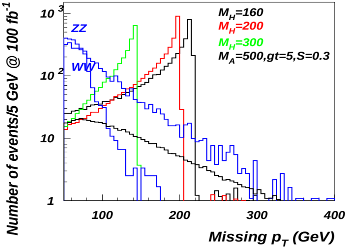


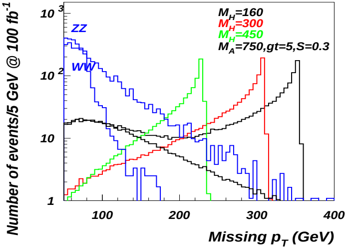
- Boost analysis also relevant when $M_H > 2M_W$ for the W associated with H and for the $Z's$

  (Belyaev, M.T.F and Sherstnev in progress)

(i)TIMP missing energy signals (Invisible Higgs)







(Foadi, M.T.F and Sannino 08; Shrock and Suzuki 88; Godbole, Guchait, Mazumdar, Moretti and Roy 03).

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