T-odd quarks

in the Littlest Higgs model

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arXiv:0911:4630,
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The model

- Stabilisation of the EW scale: Higgs as a Pseudo-Goldstone boson
- Global symmetry $\mathcal{G}$ broken to subgroup $\mathcal{H}$ at a scale f ($\Lambda = 4\pi f$)
- Higgs part of the coset $\mathcal{G}/\mathcal{H}$
- Gauged subgroup contains SM gauge groups
- Quadratic divergences cancelled at one loop by same spin particles!

The model: Littlest Higgs

- $\mathcal{G}$ = SU(5) broken to $\mathcal{H}$ = SO(5)
- Gauged 2X [SU(2) x U(1)] → SU(1)$_L$ xU(1)$_Y$
- 24-10=14 Nambu-Goldstone bosons: Heavy gauge bosons (4) + H (4) + heavy triplet φ (6)

$$\Pi = \begin{pmatrix} 0 & \frac{H}{\sqrt{2}} & \Phi \\ \frac{H^\dagger}{\sqrt{2}} & 0 & \frac{H^T}{\sqrt{2}} \\ \Phi^\dagger & \frac{H^*}{\sqrt{2}} & 0 \end{pmatrix}$$

- Many new states: A_H , W_H , Z_H , φ; mass O(f)
- Tree level corrections to EWPTs: f > few TeV! The naturalness problem is reintroduced!

The model: Littlest Higgs with T-parity

- To avoid EWP bounds, I.Low proposed a discrete parity (T-parity) that exchanges the two SU(2)xU(1) gauged groups
- $W = W_1 + W_2$ even; $W_H = W_1 - W_2$ odd!
- Requires T-odd partner for all fermions: Q_H and L_H!
- bound (loops) softened to $f > 500$ GeV!
- A_H plays the role of dark matter candidate.

The model: Littlest Higgs with T-parity

- Vector masses:

$$M_{A_H} \simeq \frac{g' f}{\sqrt{5}}, \quad M_{V_H} \simeq g f,$$

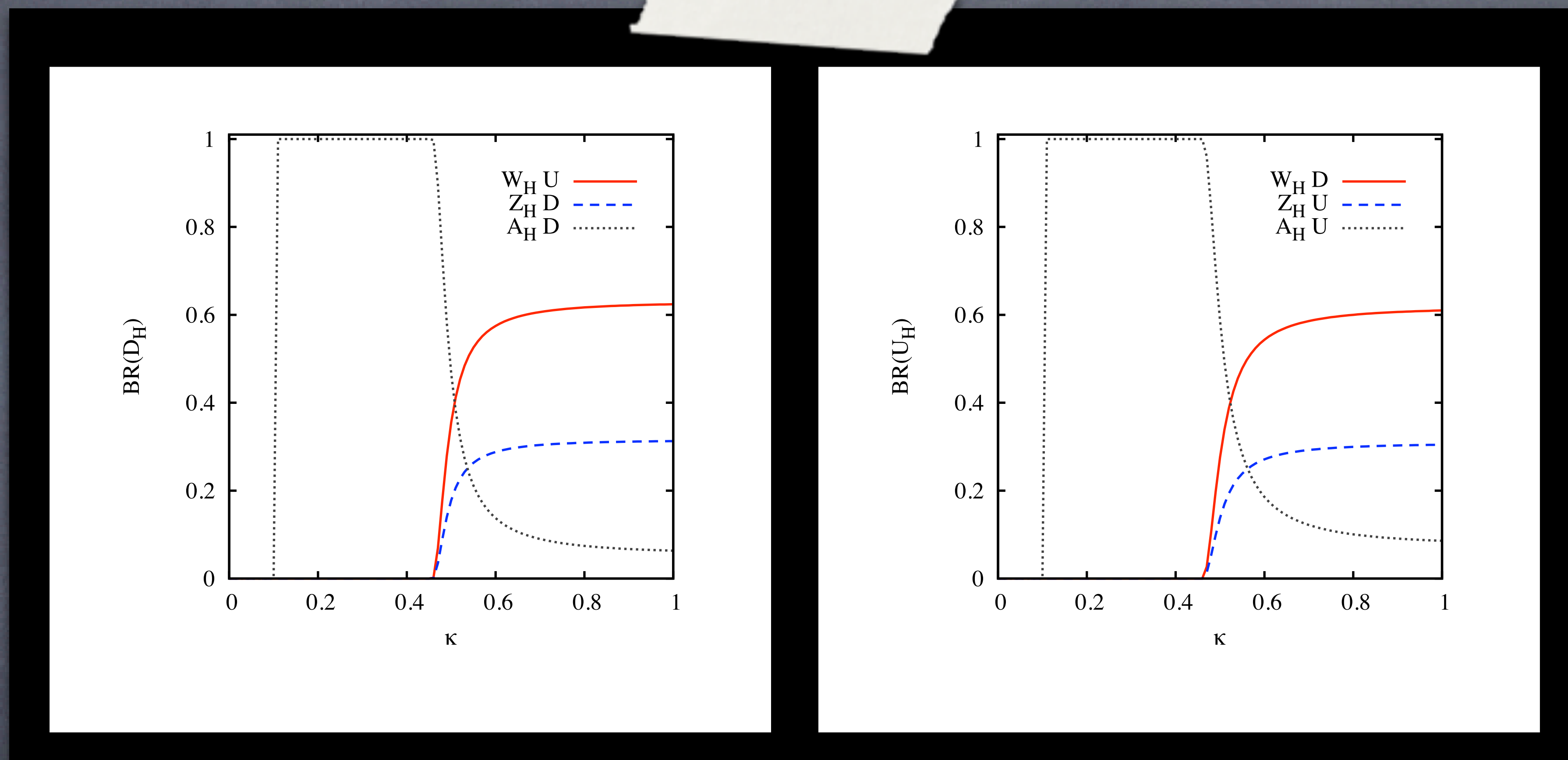
- Fermion masses (κ = Yukawa coupling, κ < 3.5 f/TeV, flavour blind and universal):

$$M_{D_{H,i}} \simeq \sqrt{2}\,\kappa_i\, f\ , \qquad M_{U_{H_i}} \simeq \sqrt{2}\,\kappa_i\, f\,\left(1 - \frac{v_{\rm SM}^2}{8\,f^2}\right)$$

- Numerically:

$$m_{A_H} \simeq \frac{g' f}{\sqrt{5}} \simeq 0.156 f\ , \quad m_{V_H} \simeq g f \simeq 0.653 f\ , \quad m_{Q_H} \simeq \sqrt{2}\kappa f \simeq 1.414 \kappa f\ ,$$

Branching ratios



60% 100% 21%

For $\kappa \geq 0.46$, $Q_H \to W_H q \to A_H W q \to A_H l \nu q \to$ l jet MET

Chain branching ratio: 12%

Production cross sections

In previous work, i.e. Freitas/Wyler and Choudhuri/Gosh:

- Only strong production from gluons and quark annihilation
- Dominated by s-channel diagrams (fall-off rapidly with s)
- Only opposite sign dilepton signatures

Production cross sections

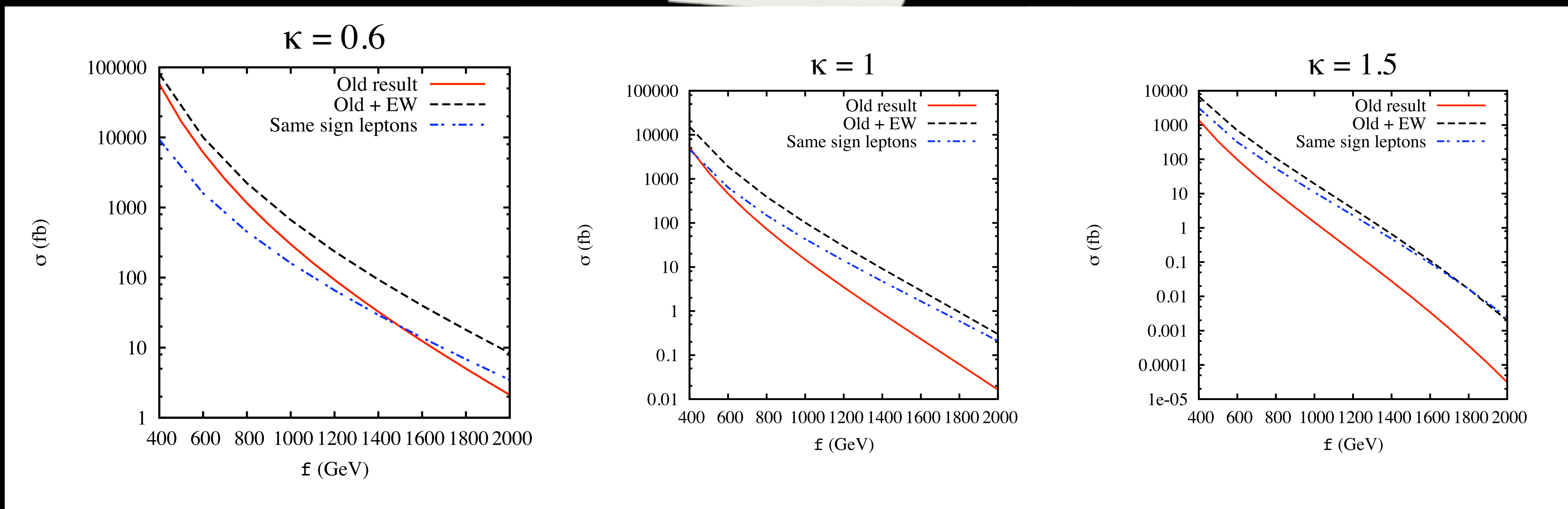
In our work:

- We consider both strong and weak processes
- Weak t-channel (heavy gauge bosons) give a large contribution in the forward region (exp. at large κ) Belyaev, Chen, Tobe, Yuan
- We included $\frac{v^2}{f^2}$ corrections to the vertices
- We included NLO k-factors for both signal and background

Opposite sign dilepton $\Rightarrow$ $pp \rightarrow Q_H \bar{Q}_H$ (QCD+EW)
$pp \rightarrow U_H D_H$ (EW)

Same sign dilepton $\Rightarrow$ $pp \rightarrow \bar{U}_H D_H + U_H \bar{D}_H$ (EW)

Production cross sections @ 14TeV



RED: only QCD (Choudhuri et al)
BLACK: QCD+EW oposite-sign processes
BLUE: EW same-sign processes

Note: EW more imp for large κ

Our simulation:
3 benchmark points

Model parameters → Particle masses (in GeV) ↓	$f = 1000$ GeV $\kappa = 0.6$	$f = 1000$ GeV $\kappa = 1$	$f = 700$ GeV $\kappa = 1.5$
M_{A_H}	150	150	100
M_{V_H}	648	648	450
M_{U_H}	842	1403	1462
M_{D_H}	848	1414	1484

Signal generated with CalcHEP 2.5.4 + PYTHIA 6.4.21
CalcHEP model files can be found in
http://deandrea.home.cern.ch/deandrea/LHTmodl.tgz

Opposite sign leptons: backgrounds

PYTHIA 6.4.21

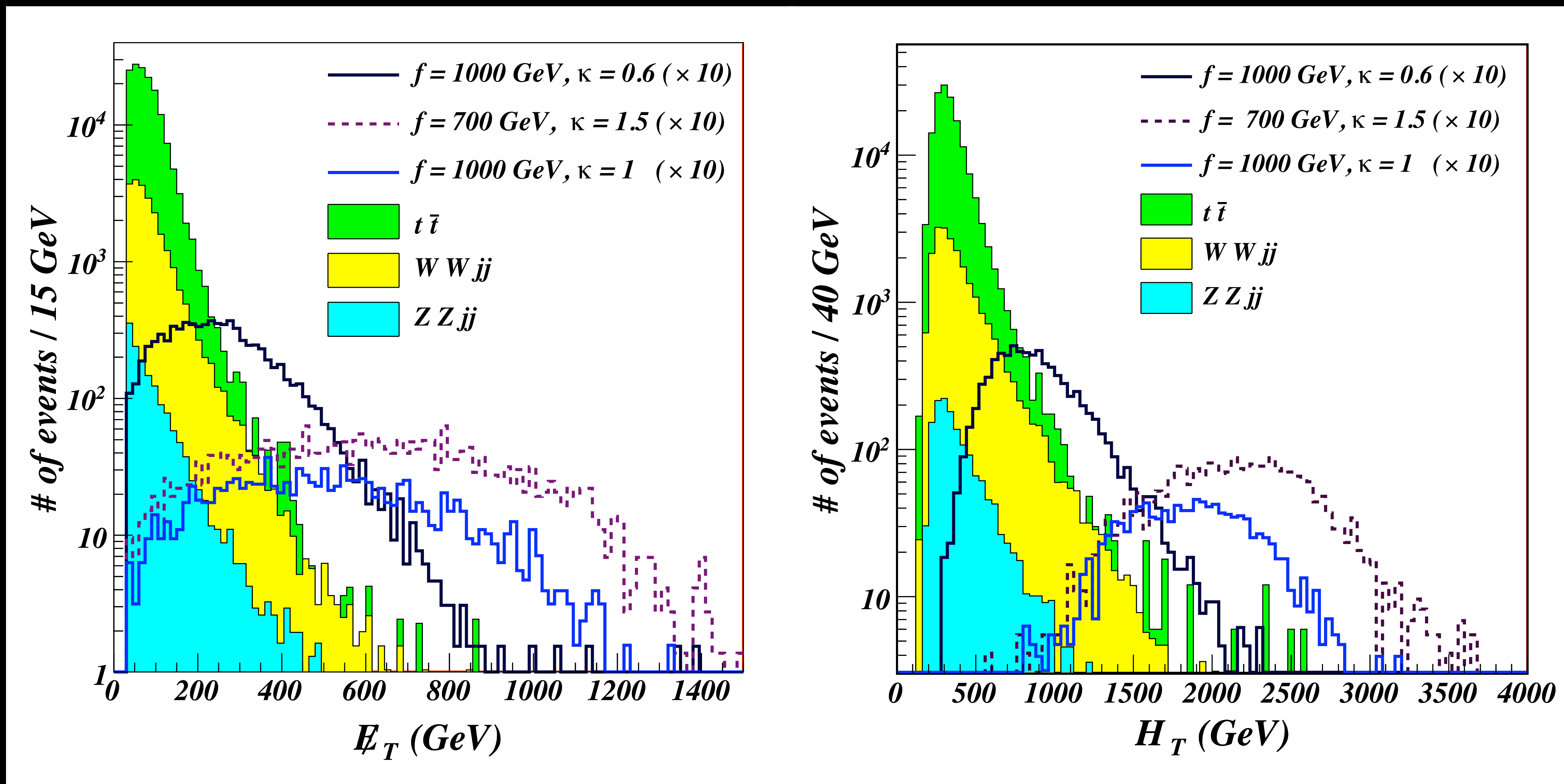
- t tbar, with both tops decaying leptonically and bottoms misidentified for light jets
- WWjj, with both W decaying leptonically
- ZZjj, with one Z decaying leptonically and the other invisible

and cuts:

- two leptons with pt > 15 GeV and $\eta < 2.5$
- b-jet veto, with a b-tagging accuracy of 60% ⇐ suppress t tbar
- two light jets with pt > 30 GeV and $\eta < 2.5$
- MET > 30 GeV
- dilepton invariant mass > 15 GeV ⇐ suppress photons

Same-sign leptons

Naveen Gaur



Luminosity 100 fb-1

$$H_T = \sum_{j,\ \ell,\ \not{E}_T} |\vec{p}_T|.$$

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Same-sign leptons

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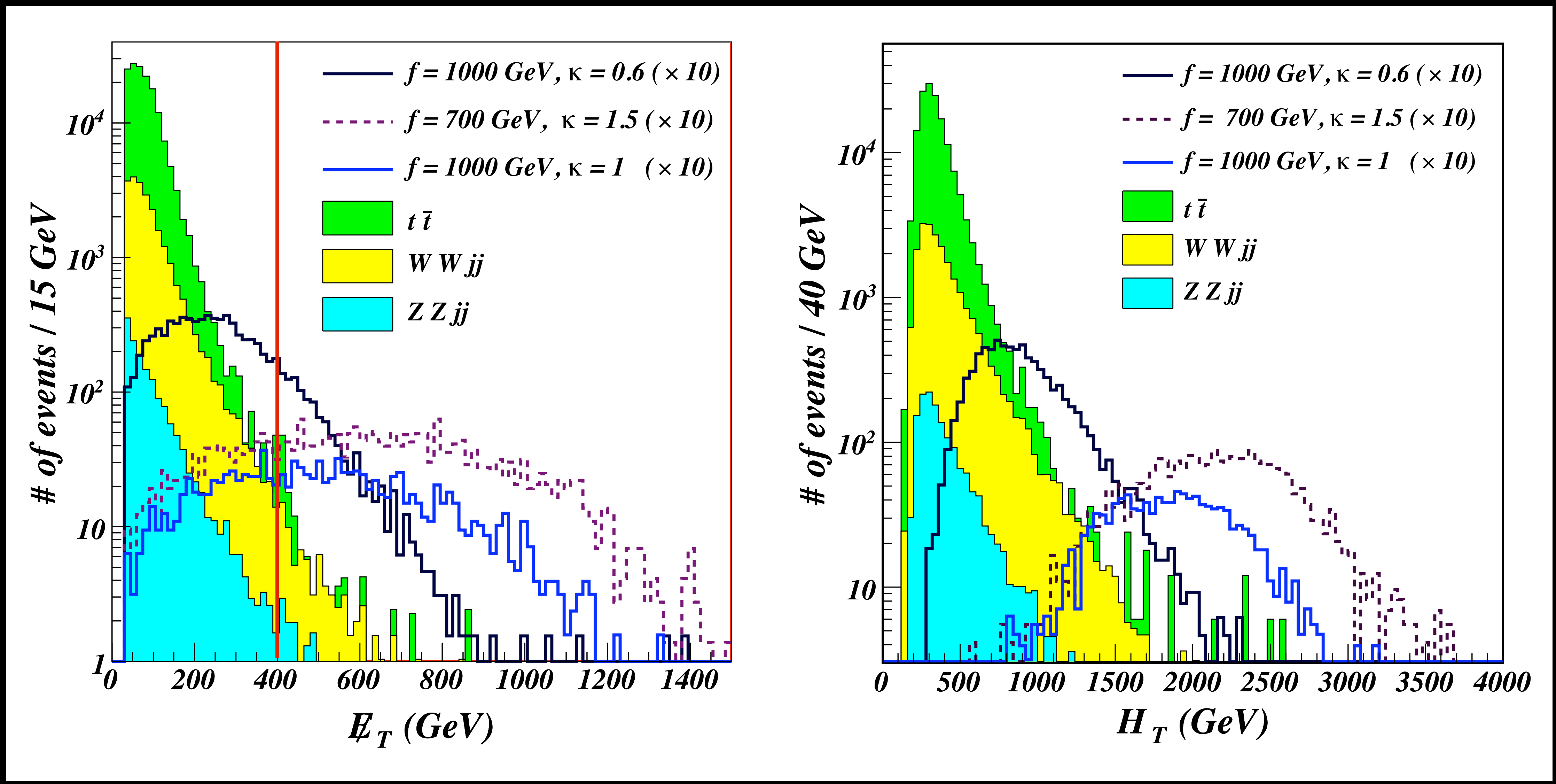

Luminosity 100 fb-1

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Numerical results

Parameter set ⇒ Cuts ⇓	$f = 1000$ $\kappa = 0.6$	$f = 1000$ $\kappa = 1$	$f = 700$ $\kappa = 1.5$	SM $t\bar{t}$	SM W^+W^-jj	SM $ZZjj$
Production σ (fb)	1039.1 (298)	157.4 (14.8)	412.3 (31.4)			
Preselection cuts	795.7	120.7	262.6	1.54×10^5	2.29×10^4	1520.6
$m_{jj} \notin [65, 105]$	755	120.1	261.7	1.26×10^5	1.88×10^4	1227.5
$m_{\ell\ell} \notin [75, 105]$	696.8	111.9	239.4	9.94×10^4	1.5×10^4	64.5
$\not{E}_T > 100$	623.8	108.8	234.5	2.5×10^4	4946.4	19.9
$\not{E}_T > 200$	441.2	100.5	220.3	2136.4	899.5	3.9
$\not{E}_T > 300$	237.3	87.5	200.1	396.1	239	1.3
$\not{E}_T > 400$	107.1	71.9	174.6	114.1	69.5	0.7
$\mathcal{S}$	7.2	4.9	11.2			

- MET cut very effective to reduce backgrounds!
- Discovery for O(100 fb-1)

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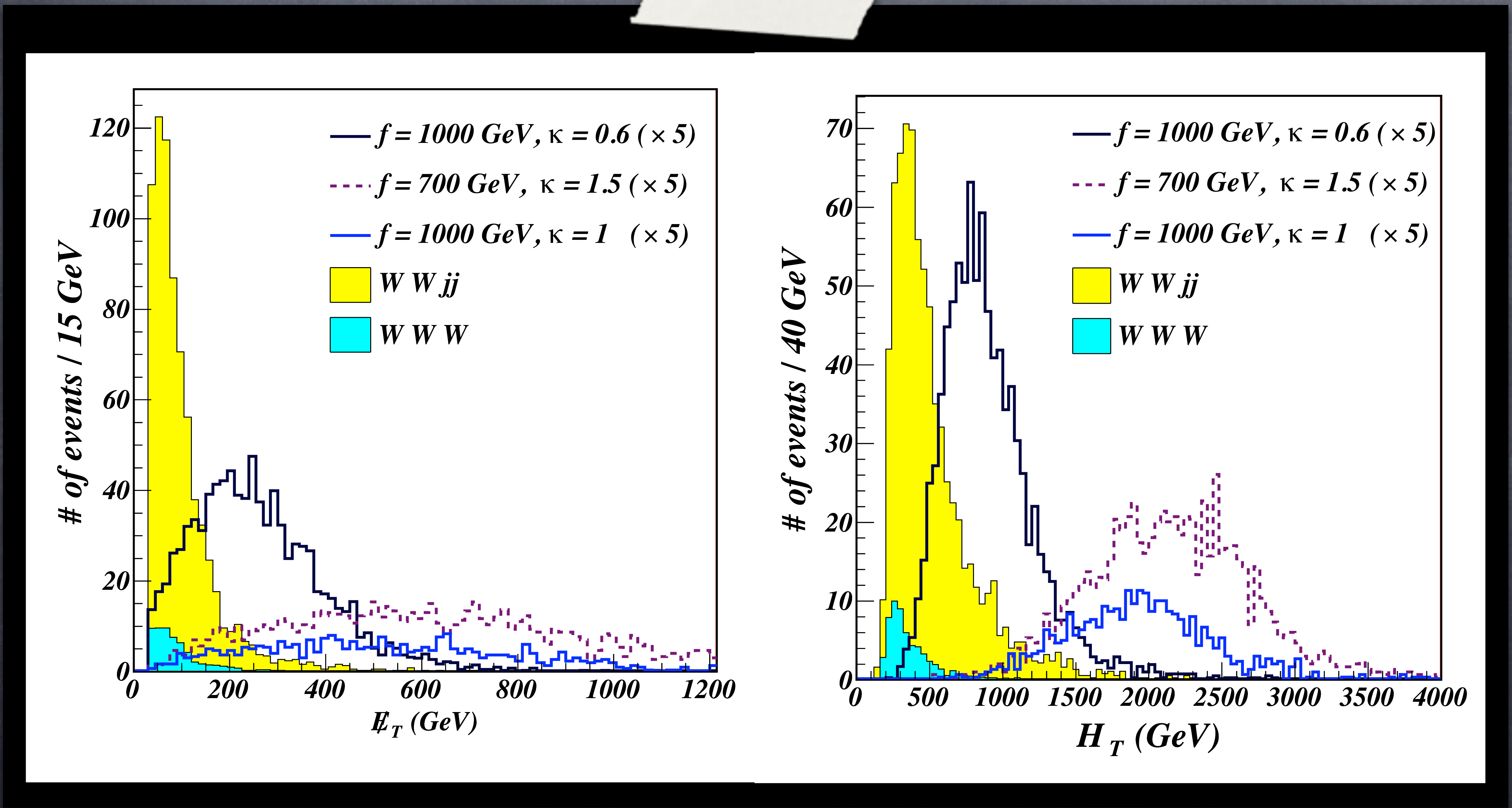
Opposite-sign leptons

Naveen Gaur



Luminosity 100 fb-1

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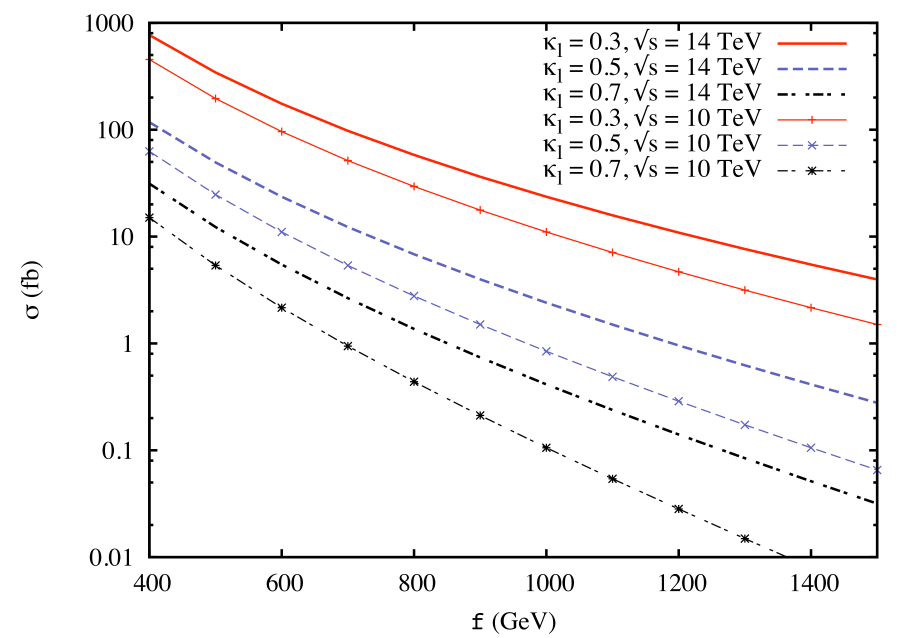
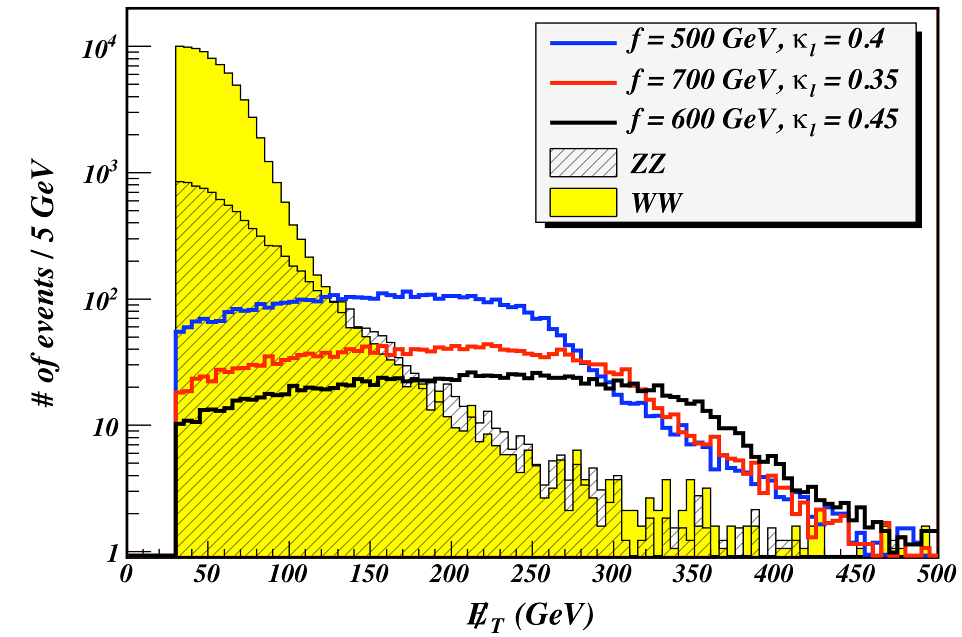
Numerical results

Parameter set ⇒ Cuts ⇓	$f = 1000$ $\kappa = 0.6$	$f = 700$ $\kappa = 1.5$	$f = 1000$ $\kappa = 1$	SM $W^{\pm}W^{\pm}jj$	SM $W^{\pm}W^{\pm}W^{\mp}$
Production σ (fb)	235.1	240.7	80.1		
Pre-selection	180.5	140.9	58.5	747.2	59.1
$\|m_{jj} - M_W\| > 20$ GeV	173.9	140.6	58.5	651.2	20.3
$\not{E}_T > 100$	155.7	138.5	56.6	236.1	5.8
$\mathcal{S}$	9.1	8.2	3.5		
$\not{E}_T > 200$	108.4	129.4	51.6	57.8	0.9
$\not{E}_T > 300$	57.7	117.4	45.1	22.2	0.3
$\not{E}_T > 400$	24.9	103	37.5	9.6	0.1
$\mathcal{S}$	6.2	18.6	8.6		

T-odd Leptons: 2 lepton signal





pp -> $l_H l_H$

l_H -> A_H l @ 100%

Model parameters ⇒ Cuts ⇓	SM WW	SM ZZ	$f = 500$ $\kappa_\ell = 0.4$	$f = 600$ $\kappa_\ell = 0.35$	$f = 700$ $\kappa_\ell = 0.3$	$f = 600$ $\kappa_\ell = 0.45$	$f = 700$ $\kappa_\ell = 0.35$
σ (fb)			117.6	97.5	97.58	36.27	53.48
Pre-selection cuts	7.67×10^4	9316.8	4738	3918.9	3993.4	1449.5	2142.8
$\not{E}_T > 100$ GeV	1994.1	1672.8	3669	3071.7	3065.5	1247.6	1767.3
$\lvert m_{\ell\bar{\ell}} - m_Z \rvert > 10$ GeV	1814.1	233.7	3496.7	2942.1	2869.3	1216.2	1710.7
$m_T^{2\ell} > 200$ GeV	1419.2	210.4	3433.6	2890.8	2869.3	1202.9	1687.8
$S/\sqrt{B}(1\ \text{fb}^{-1})$			8.5	7.1	7.1	3	4.2
$S/\sqrt{B}(3\ \text{fb}^{-1})$			14.9	12.4	12.4	5.2	7.3
$S/\sqrt{B}(10\ \text{fb}^{-1})$			26.9	22.6	22.5	9.4	13.2

T-odd Leptons: 1 lepton signal

Parameters ⇒ Cuts ⇓	SM on shell	SM off shell	$f = 700$ $\kappa_\ell = 0.4$	$f = 600$ $\kappa_\ell = 0.4$	$f = 500$ $\kappa_\ell = 0.4$	$f = 600$ $\kappa_\ell = 0.45$	$f = 700$ $\kappa_\ell = 0.35$
σ (fb)			114.8	212.8	433	133.55	195.16
Presel. cuts	1.7×10^9	6.1×10^4	5823.1	11067.9	22882.8	6800.5	10072.7
$p_T^\ell > 100$ GeV	4.9×10^5	2137.4	4916.4	8656.8	15652.2	5687.9	7852.9
$m_T > 200$	3.16×10^5	1818	4849.8	8481.5	15212.2	5604.8	7689
$m_T > 300$	8.17×10^4	451	3623.8	5722.9	8887.6	4138.4	5157.2
$m_T > 400$	2.72×10^4	147	2343.7	3335	4593	2664.7	3001.2
$p_T^\ell > 200$ GeV	2.82×10^4	147.9	2350.1	3351.6	4607.1	2673.1	3011.3
$m_T > 300$	2.82×10^4	146.8	2349.2	3350.3	4604.5	2672.2	3009.2
$m_T > 400$	2.72×10^4	139.4	2278.7	3238.2	4422	2592	2904.7
$p_T^\ell > 300$ GeV	3026.7	26.8	866.2	1074.2	1284.3	966.5	949.6
$m_T > 400$	30.3	0.26	8.7	10.7	12.8	9.7	9.5
$S/\sqrt{B}$ (10 fb^{-1})	-	-	5	6.2	7.3	5.5	5.4
$S/\sqrt{B}$ (100 fb^{-1})	-	-	15.6	19.5	23.2	17.5	17.2

pp -> ν_H l_H

ν_H/l_H -> A_H ν/l @ 100%

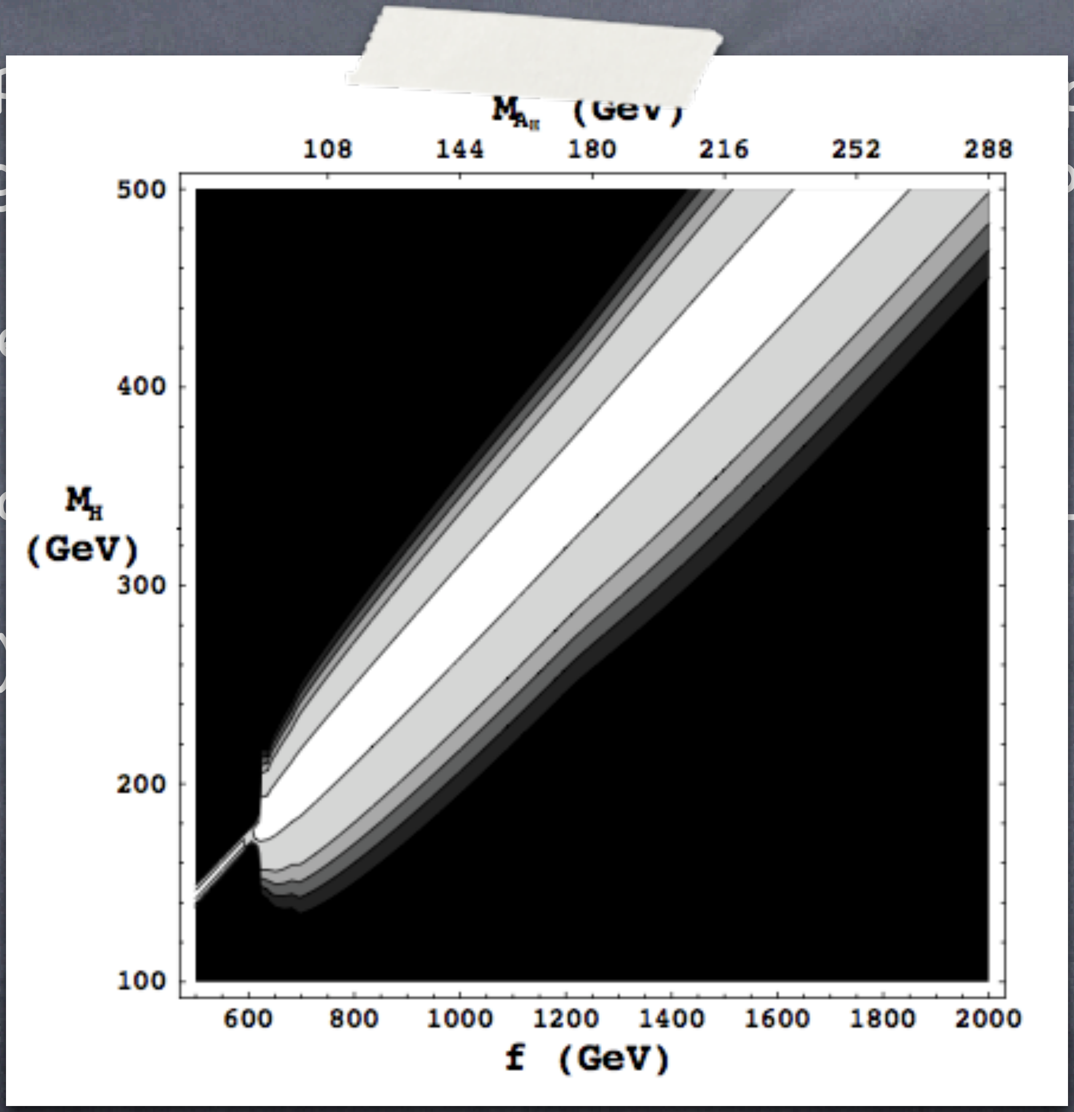
Conclusion

- Light quark (and lepton) partner are a necessary ingredient in Little Higgs models with T-parity
- We show that the EW interactions give an important (previously ignored) contribution to the production cross section
- Opposite-sign and same-sign dilepton signatures offer a good discovery channel for quarks at large luminosities (L = 100 fb-1)
- single lepton and dilepton are discovery channels at low luminosity for leptons

Bonus track

The model: Littlest Higgs with T-parity

- To avoid EWP … parity (T-parity) that exchang … s
- W = W1+W2 …
- Requires T-o… LH!
- bound (loops) …
- AH plays the …



from Hubitz and Meade

Same sign leptons: backgrounds and cuts

- WWW, with same sign Ws decaying leptonically and the other in jets
- WWjj, with same sign Ws decaying leptonically

Cuts:

- two same sign leptons with pt > 15 GeV and $\eta < 2.5$
- two light jets with pt > 30 GeV and $\eta < 2.5$
- MET > 30 GeV

One lepton: backgrounds and cuts

- on-shell W, decaying leptonically
- WZ, with W decaying leptonically and Z invisibly (neutrinos)

Cuts:

- one isolated lepton with $p_t > 10$ GeV and $\eta < 3$
- jet veto, with $p_t > 30$ GeV and $\eta < 3$

Two leptons: backgrounds and cuts

- WW, both decaying leptonically
- ZZ, with one Z decaying leptonically and the other invisibly (neutrinos)

Cuts:

- two isolated lepton with pt > 10 GeV and η < 3
- jet veto, with pt > 30 GeV and η < 3
- MET threshold 30 GeV