# New Ideas of Electroweak Symmetry Breaking
# LHC phenomenology

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DESY Theory Group, Hamburg

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# Outline

Hierarchy Problem

The Little Higgs mechanism

Cancellations of divergencies

Generic properties

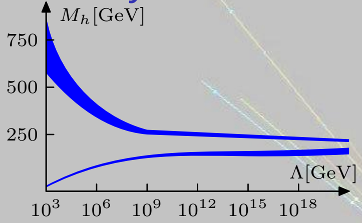
Examples of Models

LHC phenomenology

- Heavy Quark States
- Heavy Vectors
- Heavy Scalars
- Pseudo Axions in LHM
- $T$ parity and Dark Matter

Open Points/Discussion

# Hierarchy Problem




**Motivation: Hierarchy Problem**

- Effective theories below a scale $\Lambda \quad \Rightarrow$
- Loop integration cut off at order $\sim \Lambda$:

$\sim \Lambda^2$

**Problem:** Naturally, $m_h \sim \mathcal{O}(\Lambda^2)$:

$$m_h^2 = m_0^2 + \Lambda^2 \times \text{(loop factors)}$$

◊ *Light* Higgs favoured by EW precision observables ($m_h < 0.5$ TeV)

- $m_h \ll \Lambda \quad \Leftrightarrow \quad$ Fine-Tuning !?
- **Solutions:** Large number of ideas since 1970s

# Overview of Solutions

## (1) **Light Scalar as Pseudo-Goldstone Boson**

a) Higgs as massless Goldstone Boson, Higgs mass connected to explicit symmetry breaking

b) No fundamental scalars in Nature: Technicolor (Repetition of QCD); EW Precision Data problematic

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a) Supersymmetry: **Spin-Statistics** $\Longrightarrow$ Loops of bosons and fermions cancel $\Rightarrow$ W. Kilian's talk

(b) Little Higgs mechanism: **Global symmetries** $\Rightarrow$ Loops of particles of like statistics cancel Incorporates the ideas of (1a) and (1b)

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## (3) Removal of Hierarchy:

a) Large Extra Dimensions: Gravity looks only weak; no fundamental scalars, but components of (higher-dem.) gauge fields
b) Warped Extra Dimensions (Randall-Sundrum): Gravity only weak in our world

## (4) Numbers chosen by Providence

- Anthropic principle: Values are because we can observe them

# Little Higgs paradigm

Old Idea: Georgi/Pais, 1974; Georgi/Dimopoulos/Kaplan, 1984

*Light Higgs* as Pseudo-Goldstone boson $\Leftrightarrow$ spontaneously broken (approximate) *global* symmetry; non-linear sigma model

- w/o Fine-Tuning: $v \sim \Lambda/4\pi$

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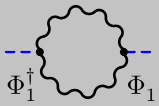
New Ingredience: Arkani-Hamed/Cohen/Georgi/. . . , 2001

**Collective Symmetry Breaking:** no quadratic div. @ 1-loop

$$\Phi_1 = \exp[i\cos\beta\, h/f] f, \qquad \Phi_2 = \exp[i\sin\beta\, h/f] f$$

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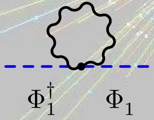


$$= \frac{g^2}{16\pi^2}\Lambda^2 \left(|\Phi_1|^2 + |\Phi_2|^2\right) \sim \frac{g^2}{16\pi^2} f^2$$

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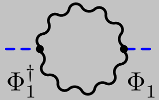


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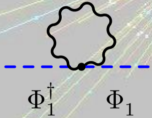


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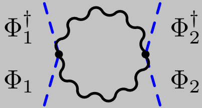
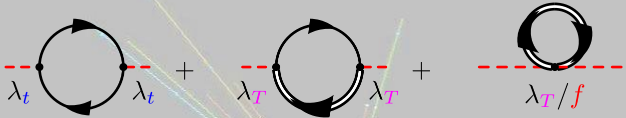



$$= \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) |\Phi_1^\dagger \Phi_2|^2 \Rightarrow \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) f^2 (h^\dagger h)$$

# Cancellations of Divergencies in Yukawa sector




$$\propto \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2(k^2 - m_T^2)} \left\{ \lambda_t^2 (k^2 - m_T^2) + k^2 \lambda_T^2 - \frac{m_T}{F} \lambda_T k^2 \right\}$$

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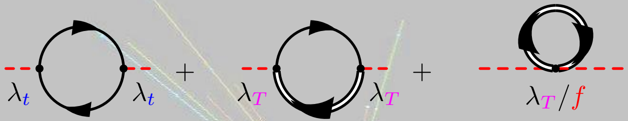


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**Little Higgs global symmetry** imposes relation

$$\boxed{\frac{m_T}{F} = \frac{\lambda_t^2 + \lambda_T^2}{\lambda_T}} \qquad \Longrightarrow \qquad \textbf{Quadratic divergence cancels}$$

- Proof these relations experimentally!

Han et al., 03/05; Kilian/JR, 05

# Generic properties — Scales and Masses

- Extended scalar (Higgs-) sector **Extended global symmetry**
- **Specific form of scalar potential**
- **Extended Gauge Sector:** $B', Z', W'^{\pm}$
- **Extended top sector:** new heavy quarks, $t, t'$ loops $\Rightarrow \quad M_h^2 < 0$
  $\Rightarrow$ EWSB

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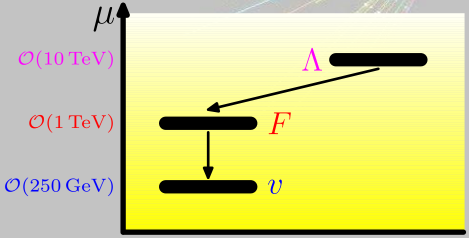


- Scale $\Lambda$: global SB, new dynamics, UV embedding
- Scale $F$: Pseudo-Goldstone bosons, new vector bosons and fermions
- Scale $v$: Higgs, $W^{\pm}$, $Z$, $\ell^{\pm}$, ...

# Little Higgs Models

Plethora of "Little Higgs Models" in 3 categories:

- **Moose Models**
  - Orig. Moose (Arkani-Hamed/Cohen/Georgi, 0105239)
  - Simple Moose (Arkani-Hamed/Cohen/Katz/Nelson/Gregoire/Wacker, 0206020)
  - Linear Moose (Casalbuoni/De Curtis/Dominici, 0405188)
- **Product (Gauge) Group Models** $SU(2)_1 \times SU(2)_2 \to SU(2)_L$
  - Littlest Higgs (Arkani-Hamed/Cohen/Katz/Nelson, 0206021)
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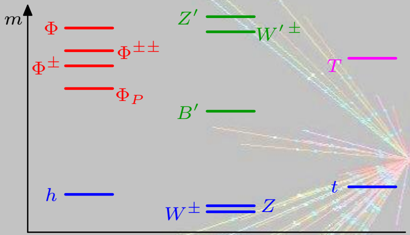
# Varieties of Particle spectra

- $$\mathcal{H} = \frac{SU(5)}{SO(5)}, \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)}$$

  Arkani-Hamed/Cohen/Katz/Nelson, 2002



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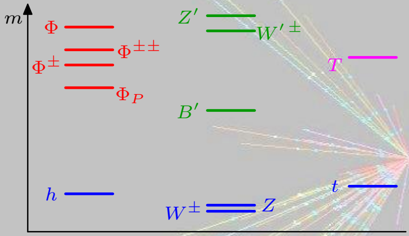


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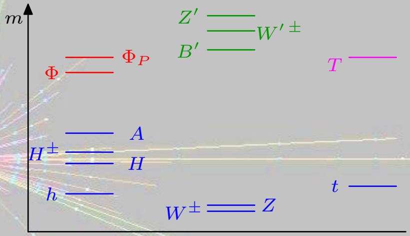

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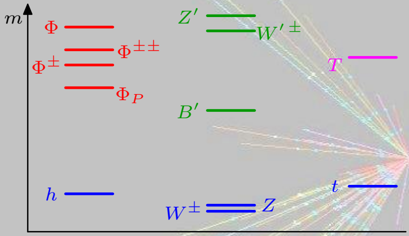


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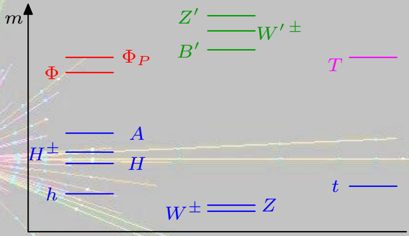
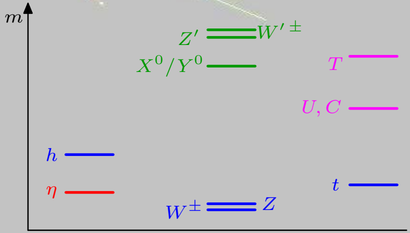



- $\mathcal{H} = \frac{[SU(3)]^2}{[SU(2)]^2}, \mathcal{G} = \frac{SU(3) \times U(1)}{SU(2) \times U(1)}$ $\Longrightarrow$

  Schmaltz, 2004

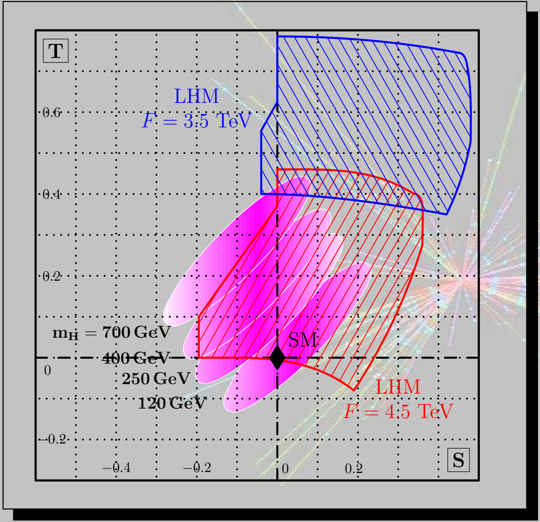



- $[SU(4)]^4 \rightarrow [SU(3)]^4$

  Kaplan/Schmaltz, 2003

  2HDM, $h_{1/2}$, $\Phi'_{1,2,3}$, $\Phi'_{P\,1,2,3}$, $Z'_{1,\ldots,8}$, $W'^{\pm}_{1,2}$, $q'$, $\ell'$

# EW Precision Observables




Higgs mass *variable* (Coleman-Weinberg, UV completion)

$$\Delta S = \frac{1}{12\pi} \ln \frac{m_H^2}{m_0^2}$$

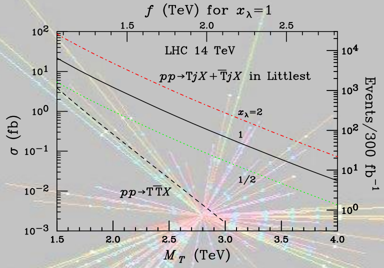
$$\Delta T = -\frac{3}{16\pi c_w^2} \ln \frac{m_H^2}{m_0^2}$$

Csaki et al.; Hewett et al.; Kilian/JR, 2003

*Making the Higgs heavier reduces amount of fine-tuning*

# Heavy Quark States

- EW single dominates QCD pair production: Perelstein/Peskin/Pierce, '03



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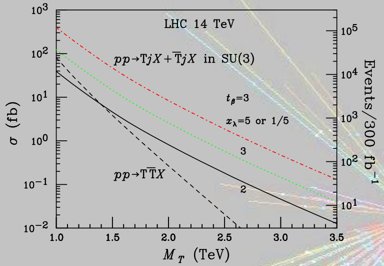
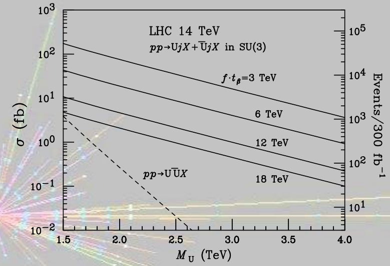



- Characteristic branching ratios :

$$\Gamma(T \to th) \approx \Gamma(T \to tZ) \approx \frac{1}{2}\Gamma(T \to bW^+) \approx \frac{M_T \lambda_T^2}{64\pi}, \qquad \Gamma_T \sim 10\text{--}50\,\text{GeV}$$

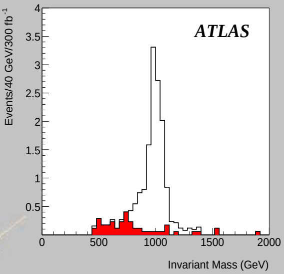
- Proof of $T$ as EW singlet; but: $T \to Z'T, W'b, t\eta$ !

AIM: *Determination of* $M_T, \lambda_T, \lambda_{T'}$

$\lambda_{T'}$ indirect ($T\bar{T}h$ impossible)

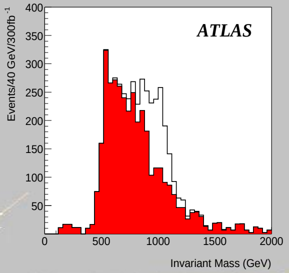
$T \to Zt \to \ell^+ \ell^- \ell \nu b$ SN-ATLAS-2004-038

- $\not{E}_T > 100$ GeV, $\ell\ell\ell, p_T > 100/30$ GeV, $b, p_T > 30$ GeV
- Bkgd.: $WZ, ZZ, btZ$
- Observation for $M_T \lesssim 1.4$ TeV



$T \to Wb \to \ell\nu b$ SN-ATLAS-2004-038

- $\not{E}_T > 100$ GeV, $\ell, p_T > 100$ GeV, $b, p_T > 200$ GeV, max. $jj, p_T > 30$ GeV
- Bkgd.: $t\bar{t}, Wb\bar{b}$, single $t$
- Observation for $M_T \lesssim 2.5$ TeV



$T \to th \to \ell\nu bbb$ SN-ATLAS-2004-038

- $\ell, p_T > 100$ GeV, $jjj, p_T > 130$ GeV, at least 1 $b$-tag
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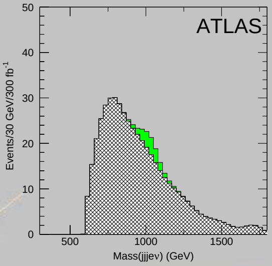

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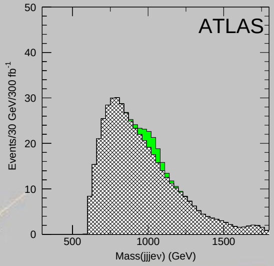
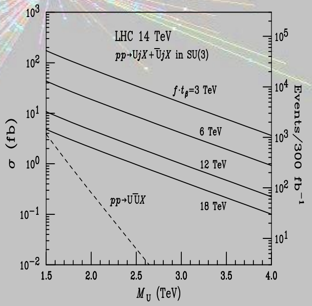



Additional heavy quarks (Simple Group Models): $U, C$ or $D, S$ Han et al., 05

- Large cross section: $u$ or $d$ PDF
- Huge final state $\ell$ charge asymmetry
- Good mass reconstruction



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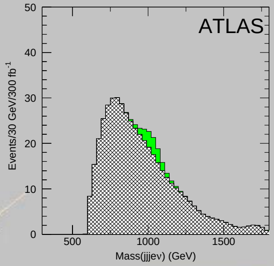


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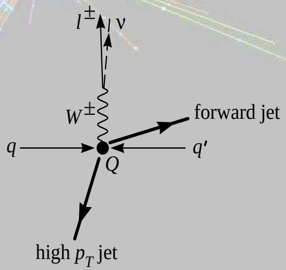

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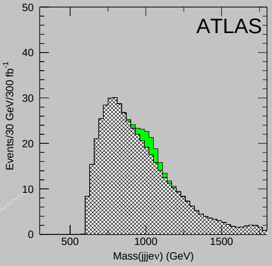


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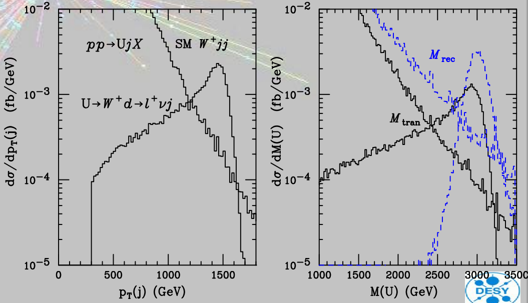

# Heavy Vectors

**Drell-Yan Production:** Tevatron Limits $\sim 500 - 600$ GeV

- Dominant decays:
  Product group: $Z' \to Zh, WW$,
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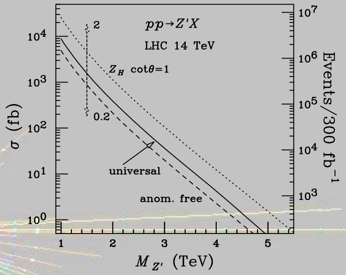
  Simple group: $Z' \to qq$, $X \to fF$



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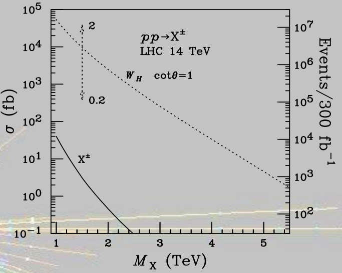

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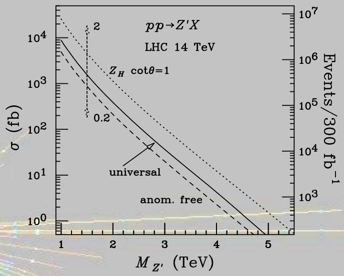
- $\Gamma_{Z'} \sim 10 - 50\,$GeV, $\Gamma_X \sim 0.1 - 10\,$GeV



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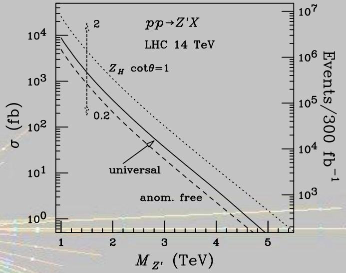
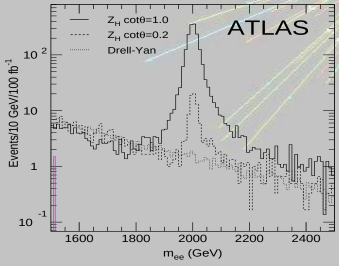
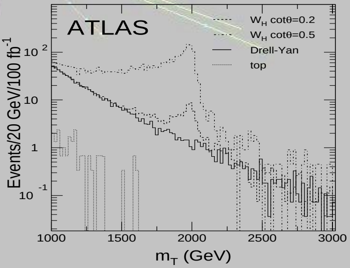
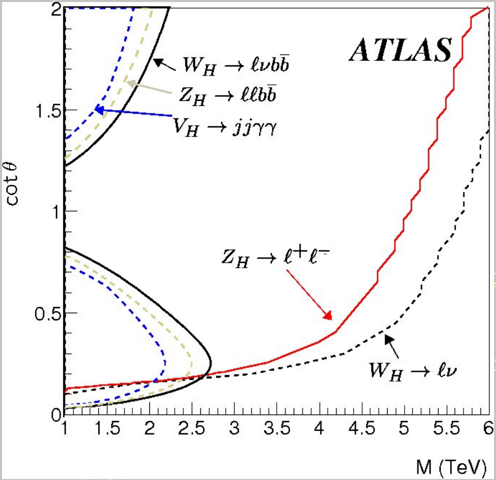
- $\Gamma_{Z'} \sim 10 - 50$ GeV, $\Gamma_X \sim 0.1 - 10$ GeV






**Proof:** Sum rule for cancellation of divergences: $g_{HHVV} + g_{HHV'V'} = 0$, associated production $pp \to V'h$

# Heavy Scalars

Generally: **Large model dependence**

no states complex singlet complex triplet

- Littlest Higgs, complex triplet:
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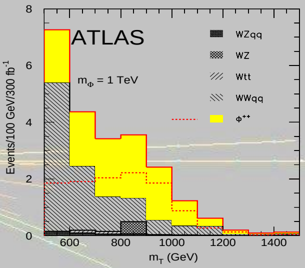

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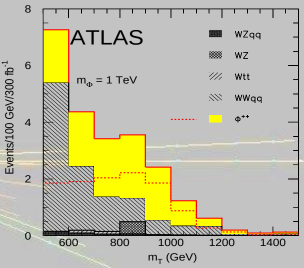


## Unstudied channels:

◇ $q\bar{q} \to \Phi_P h \to Zhh$ $q\bar{q} \to \Phi^+W^- \to WWZ$
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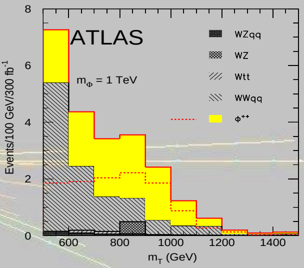


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Alternative: Model-Independent search in $WW$ fusion:

ATLAS-note, Kilian/JR/(Schumacher)$^2$

# Pseudo Axions in LHM

Kilian/Rainwater/JR, 2004

- broken diagonal generator: $\eta$ in QCD; *pseudoscalar*
- analogous particles: techni-axion, topcolor-axion, (N)MSSM-axion
- $m_\eta \lesssim v \sim 250\,$GeV
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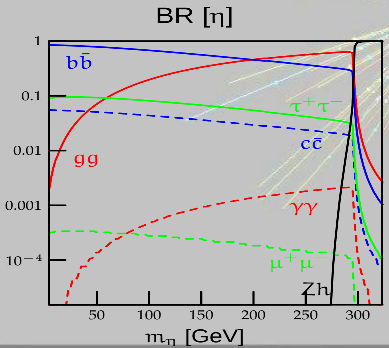


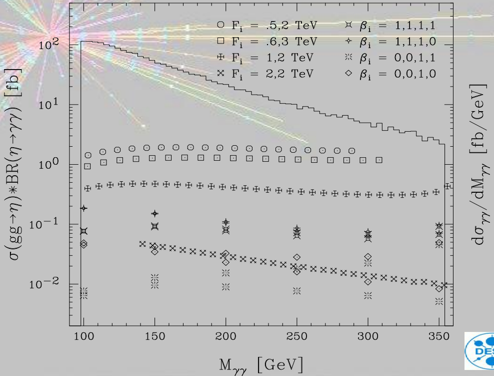

# $T$ parity and Dark Matter

Cheng/Low, 2003; Hubisz/Meade, 2005

- $T$ parity: $T^a \to T^a, \quad X^a \to -X^a$
- analogous to $R$ parity in SUSY, KK parity in extra dimensions
- Bounds on $f$ MUCH relaxed,
- *but:* Pair production!, typical cascade decays
- $T$: $T$-even $\Rightarrow$ phenomenology unchanged, $Z'$ can also be even
- Lightest heavy quark $T'$ is $T$-odd, similar to Simple Group Models
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Littlest Higgs: $A'$ LTP

$W', Z'$ $\sim$ 650 GeV
$\Phi$ $\sim$ 1 TeV
$T, T'$ $\sim$ 0.7-1 TeV

Annihilation:
$A'A' \to h \to WW, ZZ, hh$

- Other LTP candidates: Pseudo-Axion $\eta$ LTP, heavy neutral leptons

# Open Points/Discussion

- Generics: new heavy gauge bosons, scalars, quarks
- Pseudoaxions: Gluon fusion, $T \to t\eta$, $ZH\eta$
- Simple Group Models: $U$, $D$ production, discrimination from other states
- Extensions of $SU(2)_L$ e.g. in Simple Group Models: Pheno of Heavy Vectors, e.g. $X^0 \leftrightarrow Y^0$
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