# Beyond the SM studies with ATLAS

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*(U.C.Irvine & CERN )*
for the ATLAS Collaboration

XIIIth Lomonosov Conference - Moscow
23 - 29 August 2007

# SM ingredients

▸ *Fermions* as matter particles
- Quarks & Leptons

▸ *Gauge group structure*
- gauge bosons as force carriers

▸ *EW Symmetry Breaking*
- mass via Higgs bosons

▸ 3+1 space-time

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▸ *SM can not be the final theory:*
- Hierarchy problem: $\delta H \sim M_H$
- EW and Strong forces not unified
- Arbitrary fermion masses & mixings
- Arbitrary number of families
- Unknown source of baryogenesis

# SM to BSM

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# SM to BSM

▸ *Fermions* as matter particles
  • Quarks & Leptons

  **new quarks**   **new leptons**   **lepto-quarks**   **new constituents**

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**Fourth Family**

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new quarks · new leptons · lepto-quarks · new constituents · **composite models**

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**Gauge G**

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**Technicolor**

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new scalars    new EWSB

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**2HDMs**

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new scalars | new EWSB

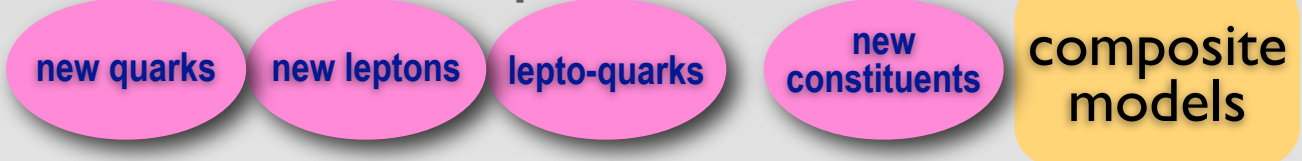**2HDMs**

**Technicolor**

▶ 3+1 space-time

new dimensions

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**RS Model**

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new dimensions

**RS Model**  **ADD Models**

# SM to BSM

**Super Symmetry**
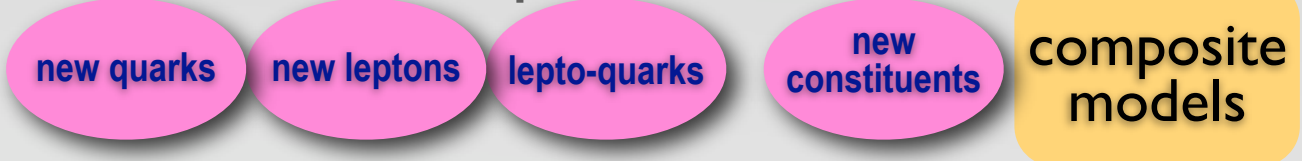
**Fourth Family**

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**Little Higgs**

**2HDMs**

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**Dynamical Symmetry Breaking**

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**Dynamical Symmetry Breaking**

**Technicolor**

▸ 3+1 space-time

*new dimensions*

**RS Model**  **ADD Models**

**disclaimer:**

For the rest of the talk, a search based approach will be followed.

# Gearing up

▸ LHC at $\sqrt{s}=14$ TeV starts in 2008

- aims to reach 100 fb⁻¹/yr *at 2010*

▸ ATLAS detector installation & commissioning ongoing

- Preparations with technical and cosmic runs
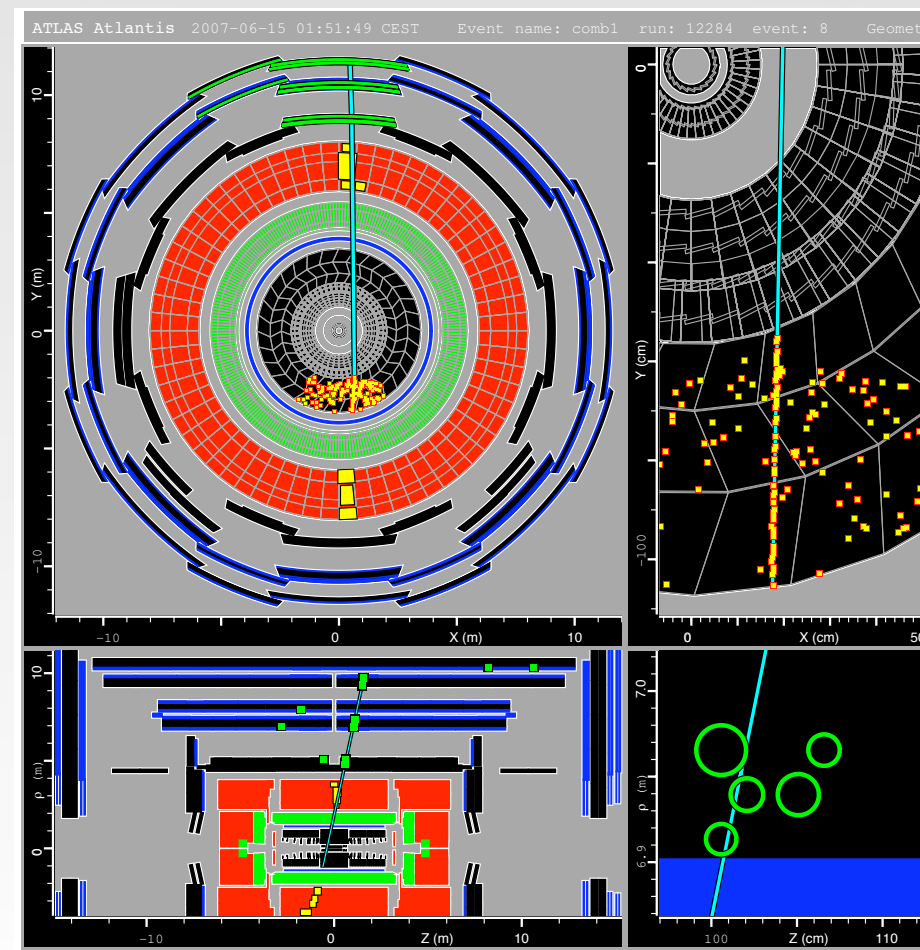


ATLAS experiment will provide unprecedented opportunity to probe the BSM physics

# SM to BSM

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new dimensions

RS Model  ADD Models

# New constituents excited νs*

- **predicted by:** composite (preonic) models
- **produced as:** single ($\nu\nu^*/\nu^*e$) via Z,W,$\gamma$
- **decay via:** boson + lepton: $\nu\gamma, \nu Z, eW$

- Fast MC based study
- scan neutrino mass: [500,..,2500]
- consider 2 coupling possibilities:
  - with and w/o νγ decay (same disc. limit)



$pp \rightarrow e\nu^* \rightarrow eeW \rightarrow ee\mu\nu$

$\Lambda$=Mass

Cuts

$P_T^{elec} > 50$ GeV

$\eta^{elec} < 2.5$

Backgrounds
- ........ WZ
- ........ WWW
- —— Total

with 300fb⁻¹ data

9 TeV @ 300GeV
2.5 TeV @ 2 TeV

$\sigma > 3$

$\sigma > 5$

eW (W→jj  e/μ ν) AND
eZ (Z→jj  μμ) considered
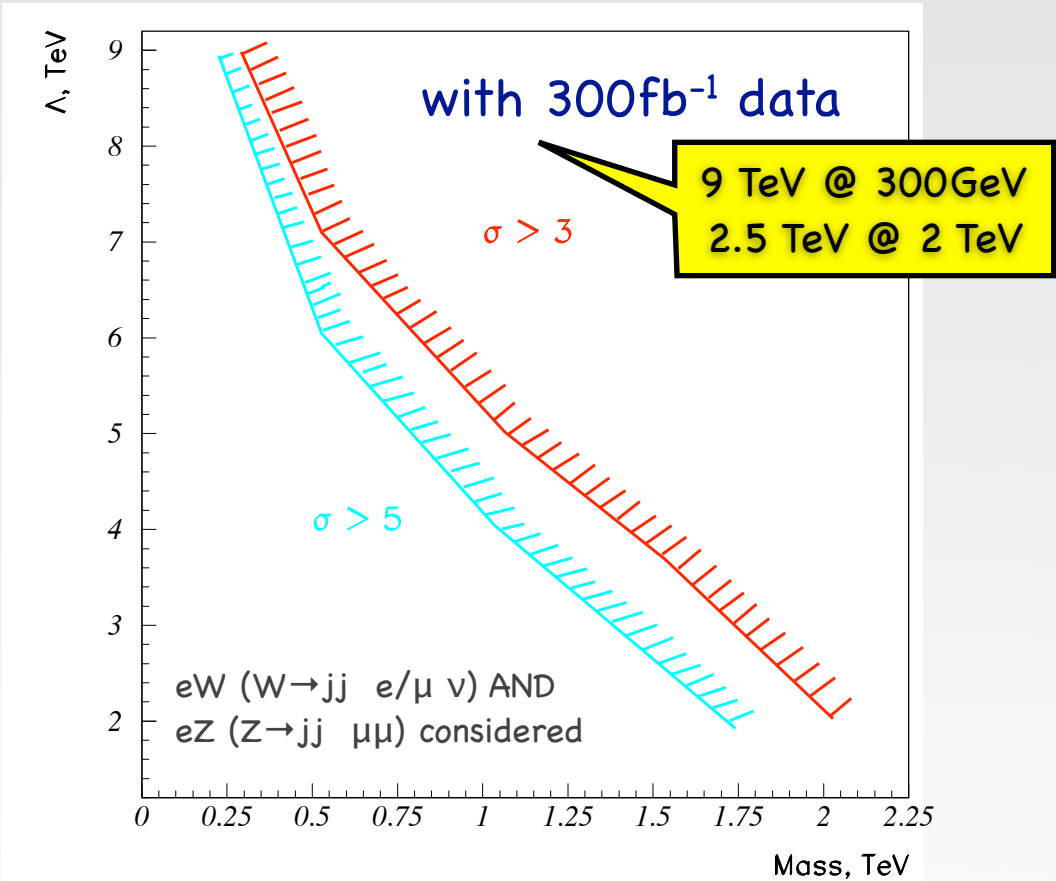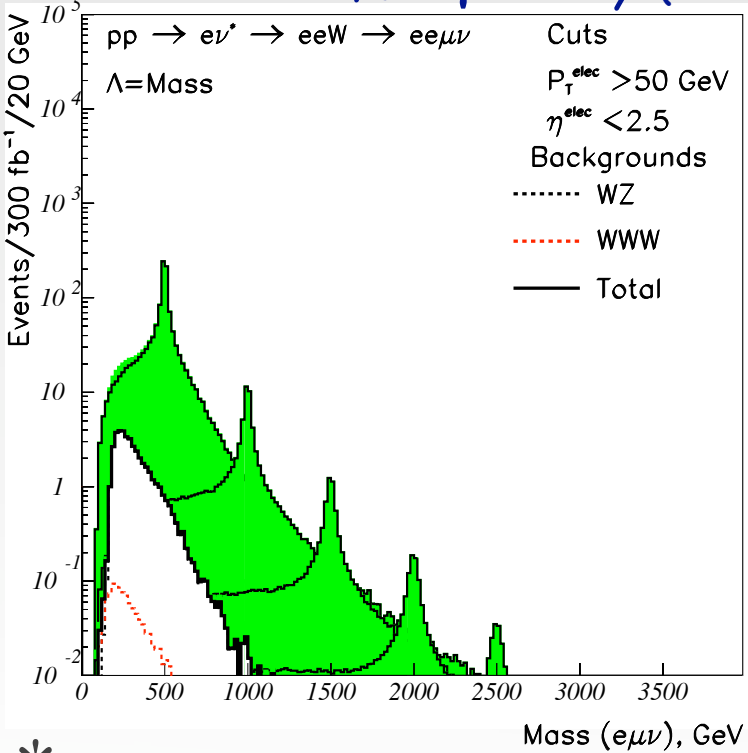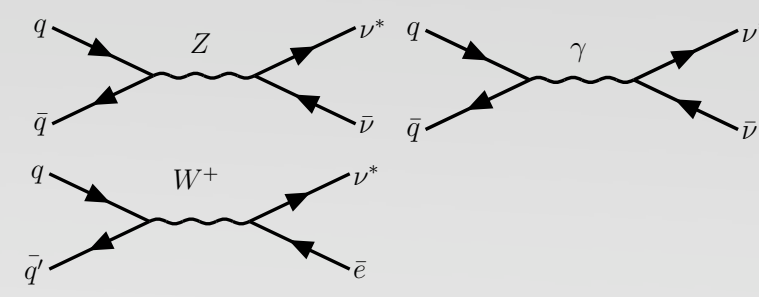
* other excited fermions (e*,q*)  also studied in earlier works but not reported here.

# New quarks q=-1/3 singlets

- **predicted by:** E$_6$ GUT
- **produced as:** pairs from gluon (quark) fusion
- **decay via:** boson + light jet
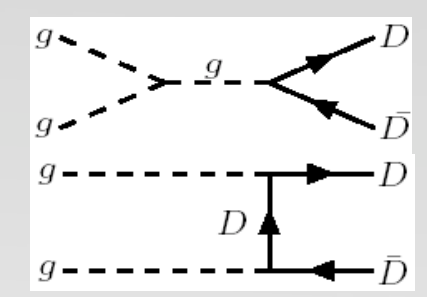
- Fast MC based study
- scan new quark mass
- pair production is mixing independent

$$D\bar{D} \rightarrow ZjZj \rightarrow 4\ell2j$$





@ 100 fb$^{-1}$
900 GeV reach
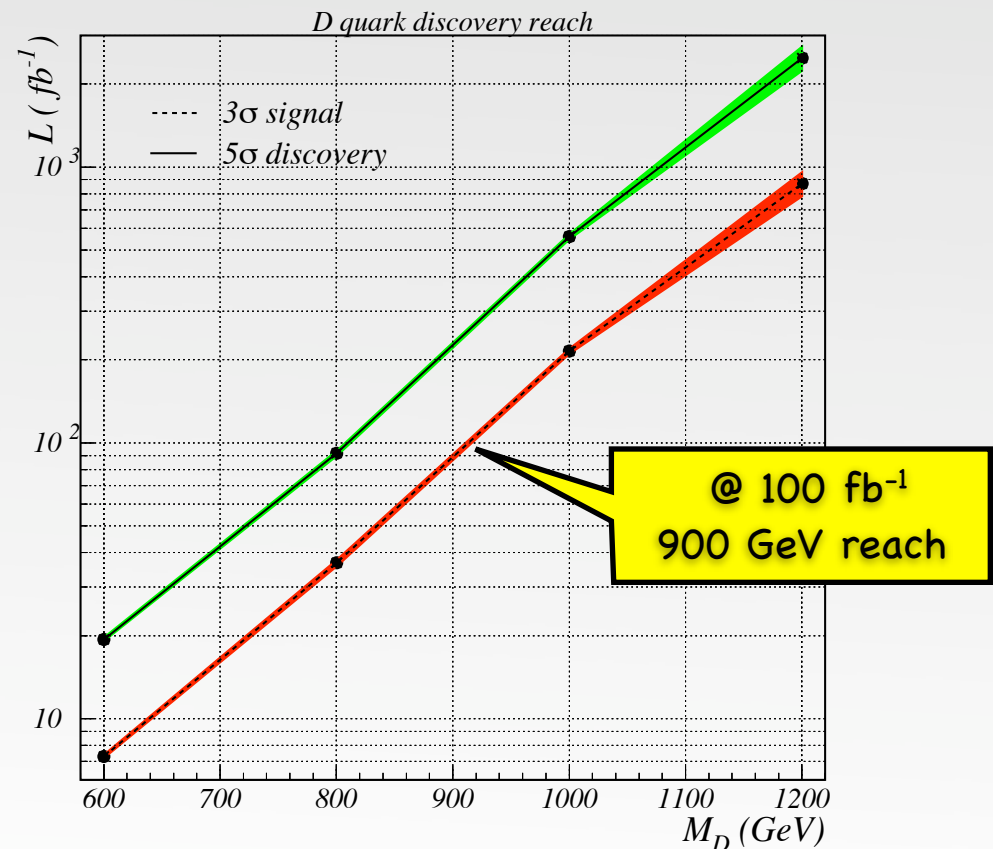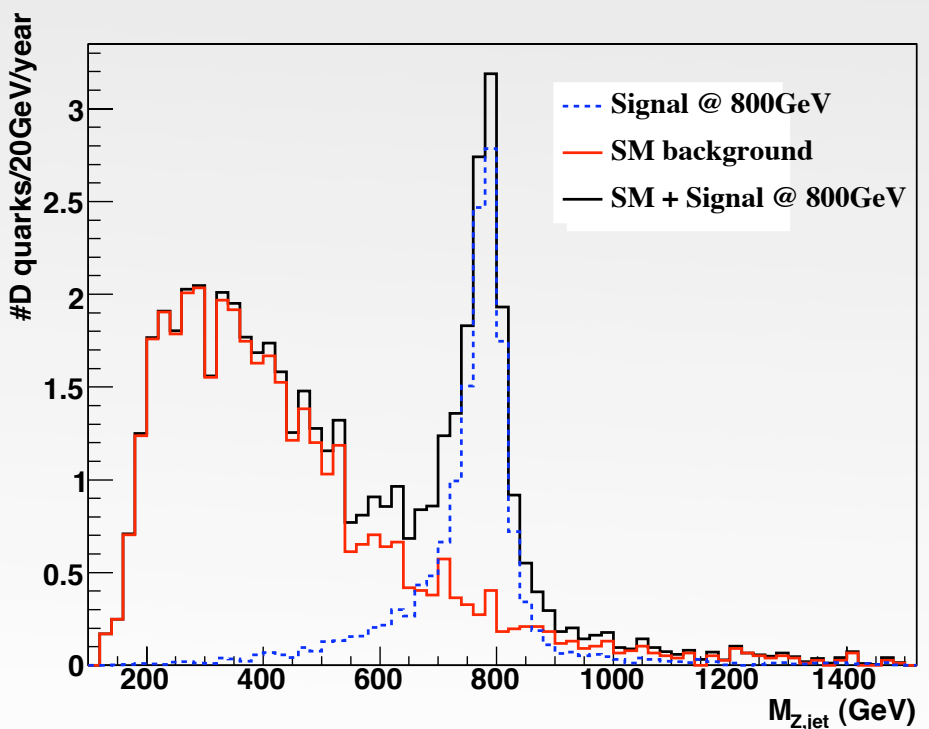
# New quarks q=2/3 singlets

- **predicted by:** Little Higgs
- **produced as:** single from W exchange
- **decay via:** boson + light jet

$$qb \rightarrow q'T \rightarrow q'Wb \ (ht, Zt)$$

- Fast MC based study
- function of T quark mass and t–T mixing
- all 3 decay channels studied.
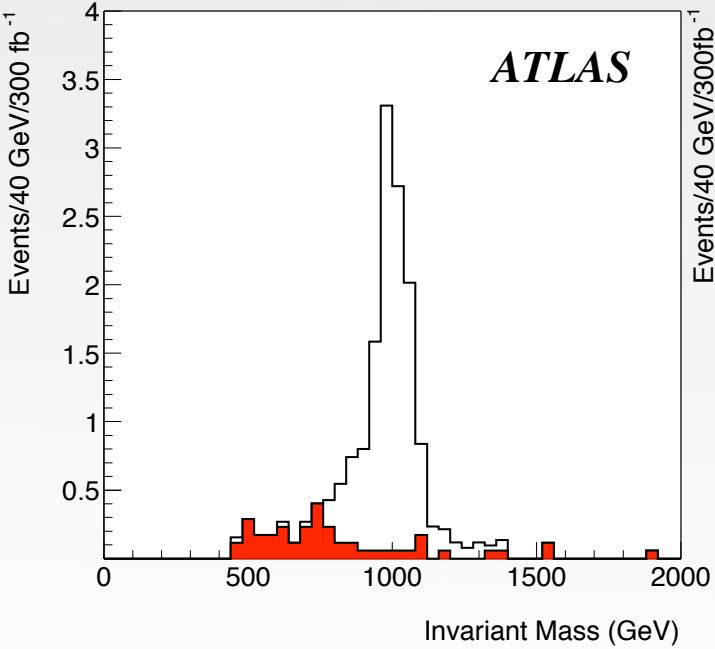
$$Zt \rightarrow \ell\ell\ell\nu j_b \qquad Wb \rightarrow \ell\nu j_b$$
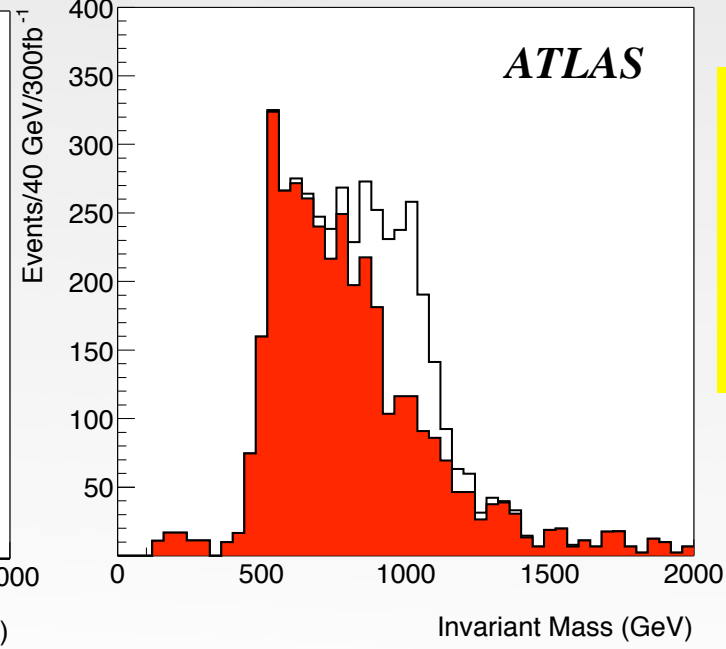


T is observable with 300 fb⁻¹:
- up to ~2.5 TeV via Wb,
- up to ~1.4 TeV via Zt.

at maximum t–T mixing

# New quarks doublets

- predicted by: DMM
- produced as: pairs from gluon (quark) fusion
- decay via: W + jet (no FCNC)

$$pp \rightarrow u_4 \bar{u}_4 \text{ or } d_4 \bar{d}_4$$

- Fast MC based study
- scan new quark mass
- results for 100 fb$^{-1}$ shown

$$u_4 \rightarrow W^+ b$$



Events / 20 GeV

- total background
- $pp \rightarrow t\bar{t}$
- $pp \rightarrow W + \text{jets}$
- $pp \rightarrow u_4 \bar{u}_4$

$m_{jjb}(\text{GeV})$

- **61σ signal from 320 GeV u₄**
- **13σ signal from 640 GeV u₄**

$$d_4 \rightarrow W^- t$$



Events / 30 GeV

- Signal + background
- $pp \rightarrow t\bar{t}$
- $pp \rightarrow d_4 \bar{d}_4$

$m_{4jb}(\text{GeV})$
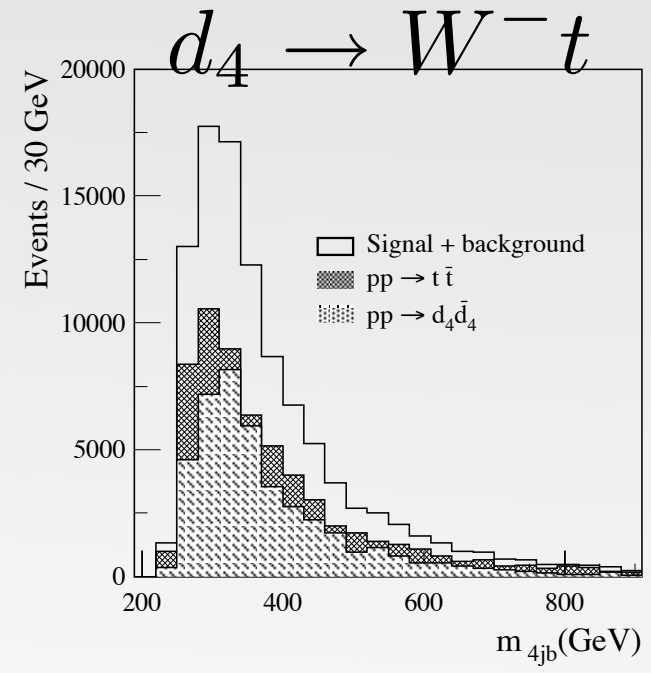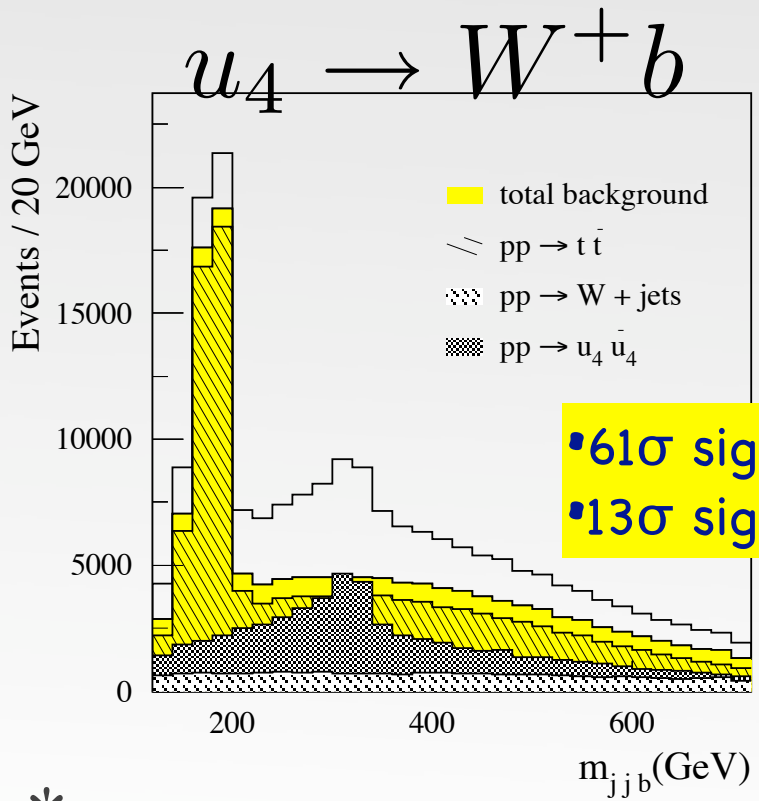
- broad signal at 320 GeV d₄
- Exact knowledge of BG shape needed

*new studies for other CKM mixings done, but not yet made public.

# New Leptons

- **predicted by:** Fourth family, $E_6$ GUT, technicolor..
- **produced as:** pairs from gluon (quark) fusion
- **decay via:** boson + lepton

- Fast MC based study
- function of L, Z′ mass





signal:
$M_L$=0.5 TeV/c²
$M_{Z'}$=0.7 TeV/c²

background

$M(\mu^{\pm}Z^0_{1,2})$ (GeV/c²)

| Constant | 371.0 |
|---|---|
| Mean | 490.1 |
| Sigma | 28.29 |



- High Luminosity
- Low Luminosity

$L \rightarrow \mu Z^0$
$M(Z')=0.7$ TeV

**@ 100 fb⁻¹ 800 GeV reach**

5 σ

$M_L$ (GeV/c²)
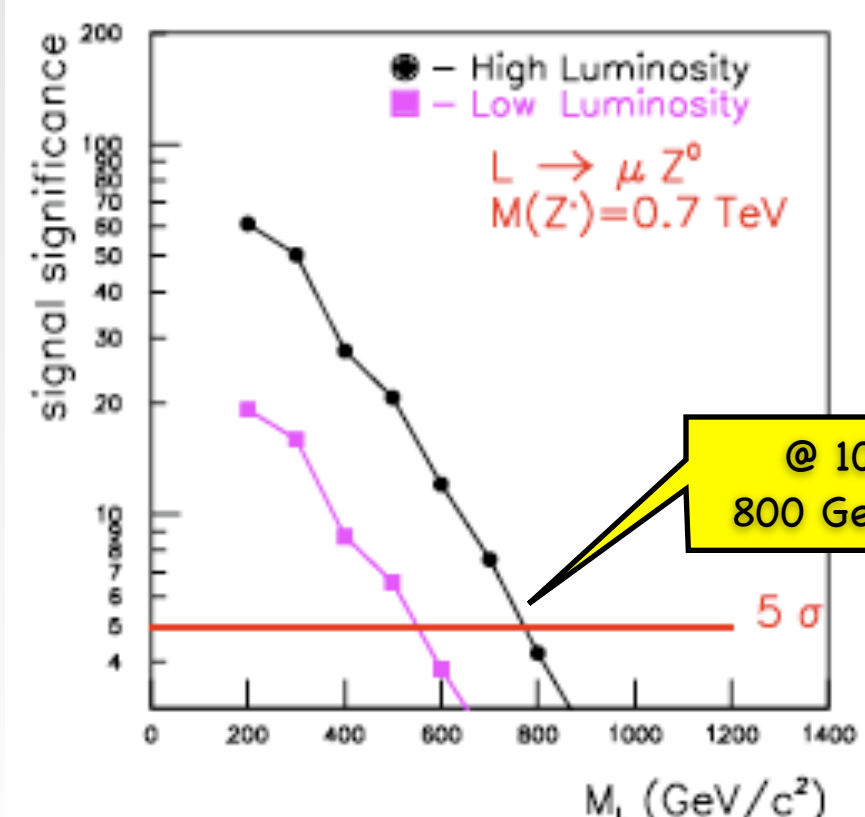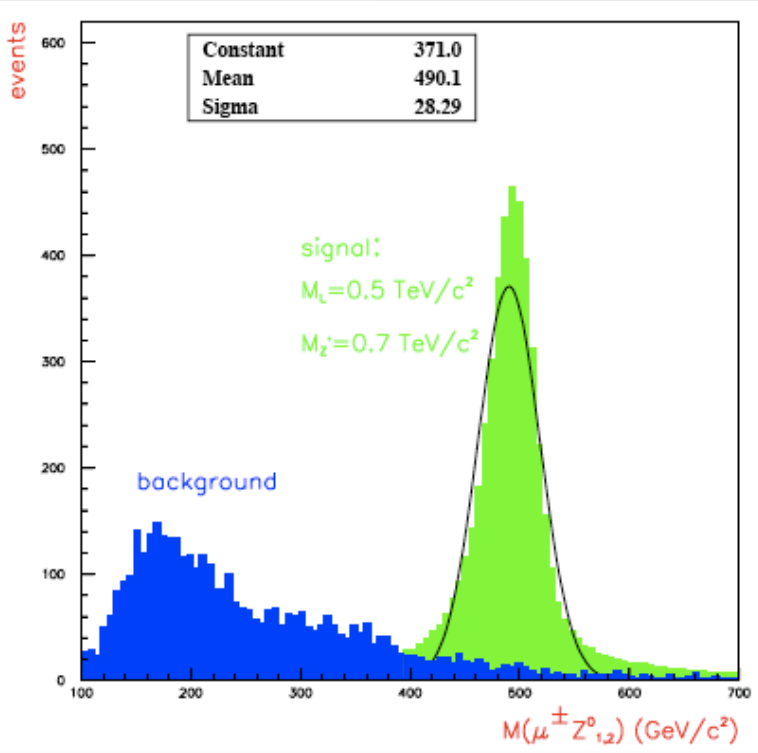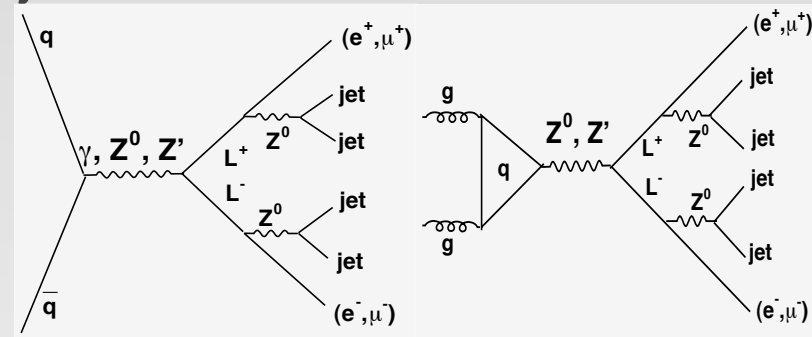
Higher Z′ mass increases the L mass reach: Z′=2TeV, L=1TeV accessible

# Lepto-quarks

- **predicted by:** GUTs & composite models
- **produced as:** pairs + single from g–g (q) fusion
- **decay via:** e(type1) or ν(type2) + light jet

- Fast MC based study for Scalar & Vector LQs
- Coupling κ, λ=e (for V)
- LQ-mass scanned
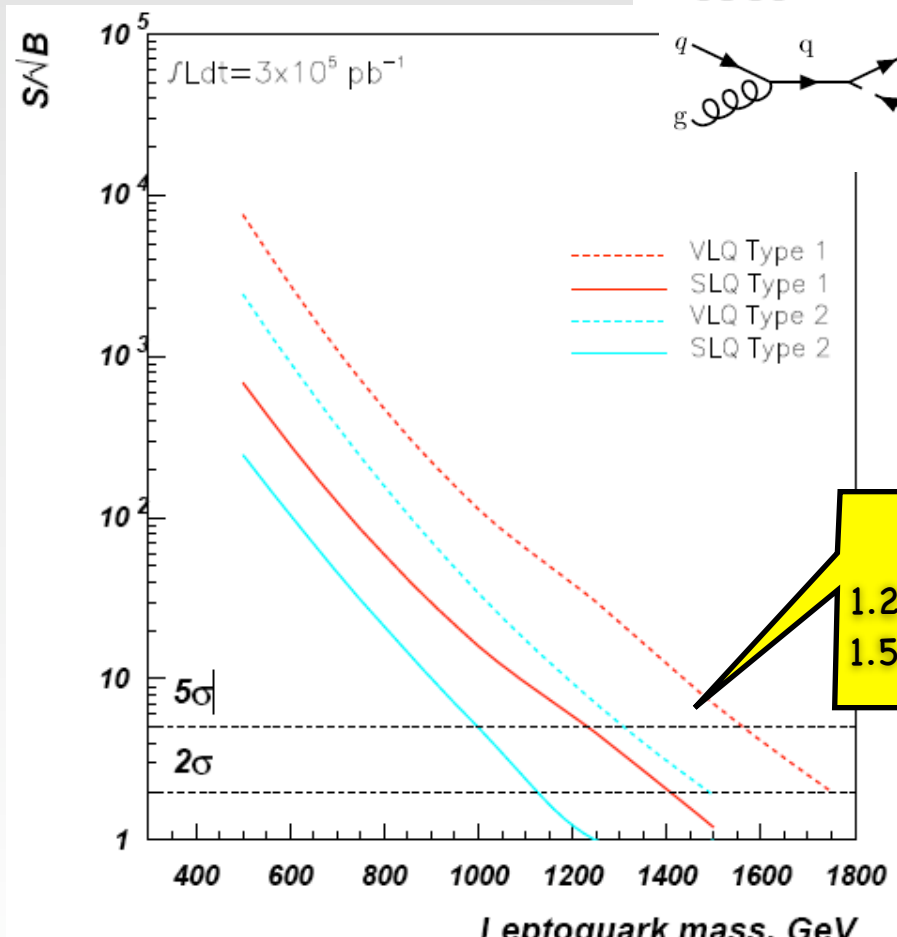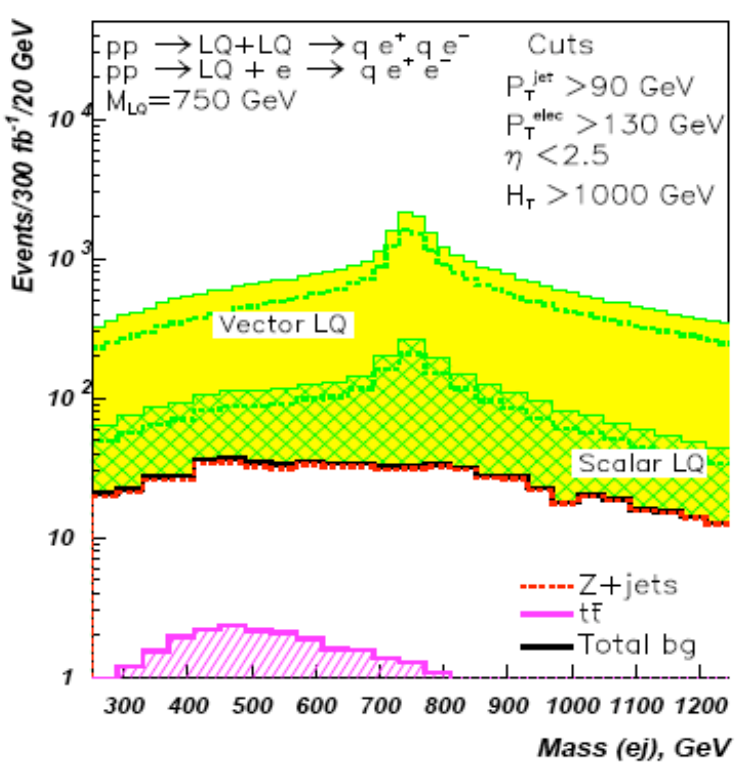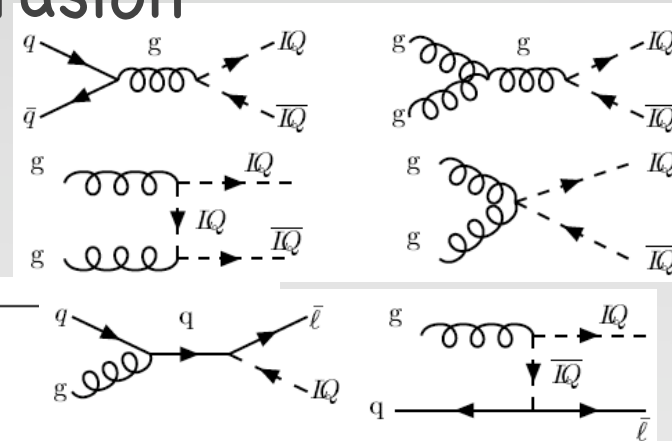


@ 100 fb⁻¹
1.2 TeV reach for S LQs
1.5 TeV reach for V LQs

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**Super Symmetry**

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2HDMs

new scalars new EWSB

Dynamical Symmetry Breaking

Technicolor

▸3+1 space-time

new dimensions

**RS Model**

**ADD Models**

# New bosons Z′

- predicted by: SO(10), $E_6$.. GUTs, Little Higgs, EDs
- produced as: from q-q annihilation
- decay via: fermion pairs

- Full MC based study
- 1.5 & 4 TeV considered
- CDDT parametrization shown
  - g is global coupling strength
  - x is fermion coupling
  - M is Z′ mass

by G. Veramendi at Pheno 2005

| | B-$x$L | q+$x$u | 10+$x\overline{5}$ | d-$x$u |
|---|---|---|---|---|
| $q_L=(u_L,d_L)$ | +1/3 | +1/3 | +1/3 | 0 |
| $u_R$ | +1/3 | +$x$/3 | -1/3 | -$x$/3 |
| $d_R$ | +1/3 | (2-$x$)/3 | -$x$/3 | +1/3 |
| $l_L=(e_L,\nu_L)$ | -$x$ | -1 | +$x$/3 | ($x$-1)/3 |
| $e_R$ | -$x$ | -(2+$x$)/3 | -1/3 | +$x$/3 |
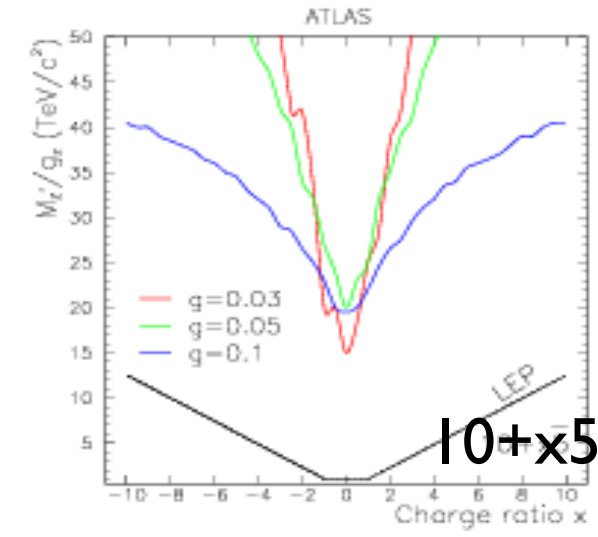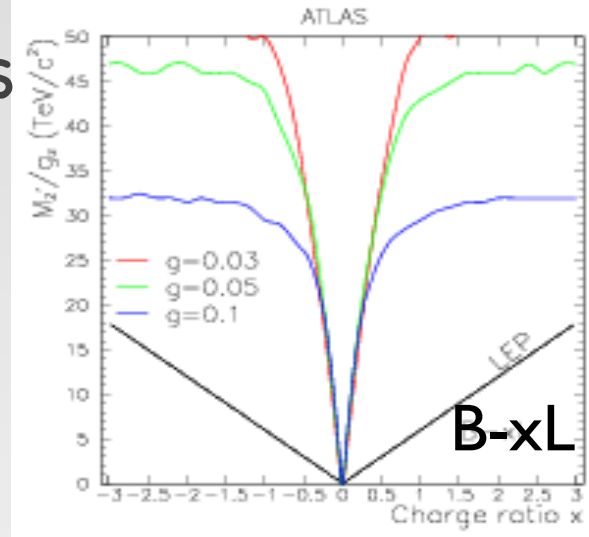
results with 100 fb$^{-1}$ of data shown



B-xL

10+x5

d-xu

q+xu
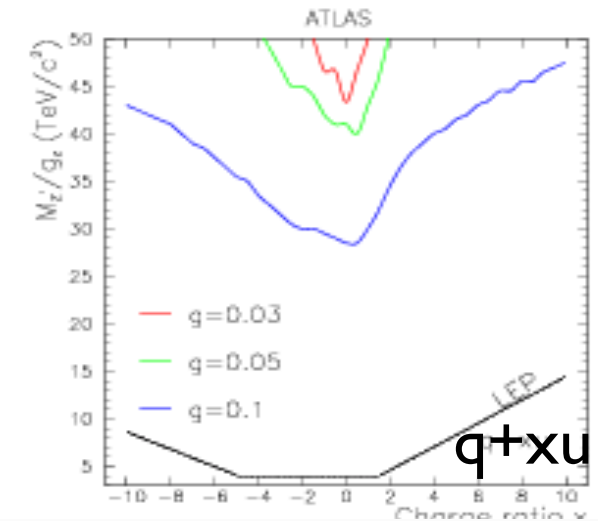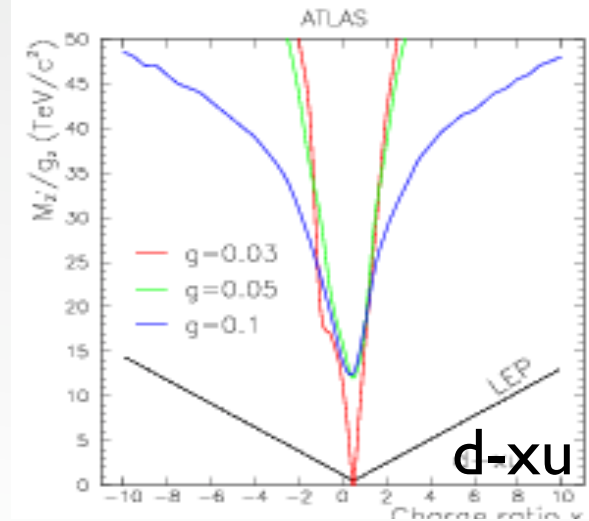
# New bosons $Z^n$

- **predicted by:** RS, ADD models
- **produced as:** from q-q annihilation
- **decay via:** lepton pairs

$$pp \to \gamma^n / Z^n \to \ell^+ \ell^-$$

- FULL simulation based study
- 3 Parameter sets to reproduce the fermion masses & mixings (A, B, C)
- only electrons were reconstructed
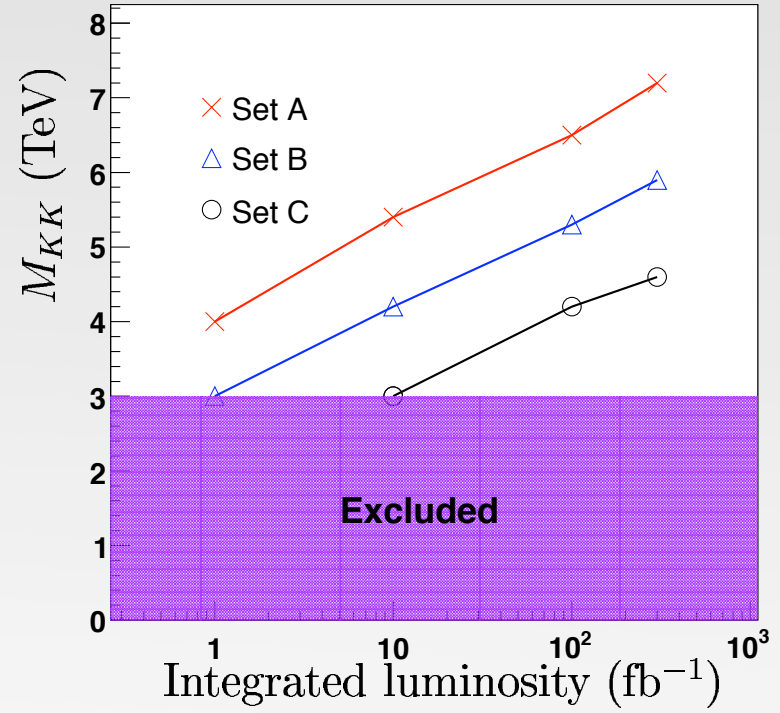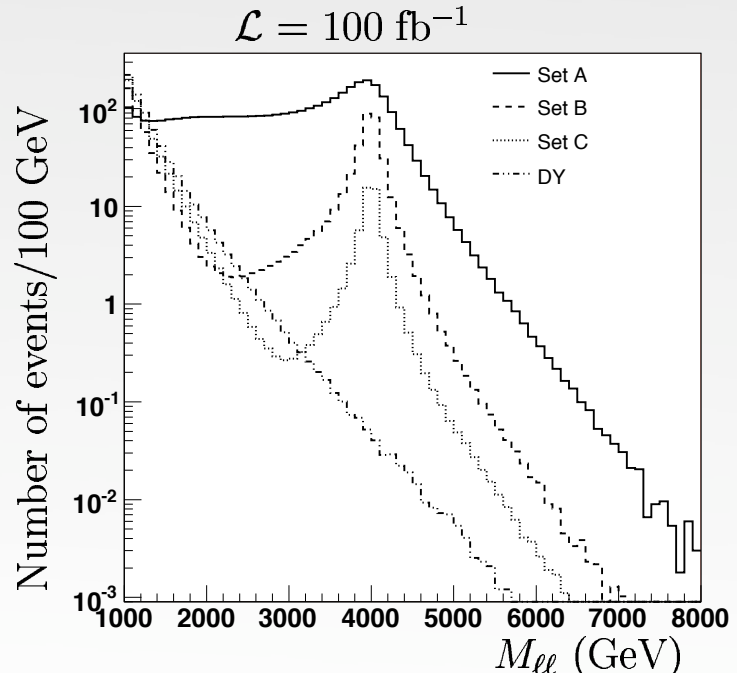


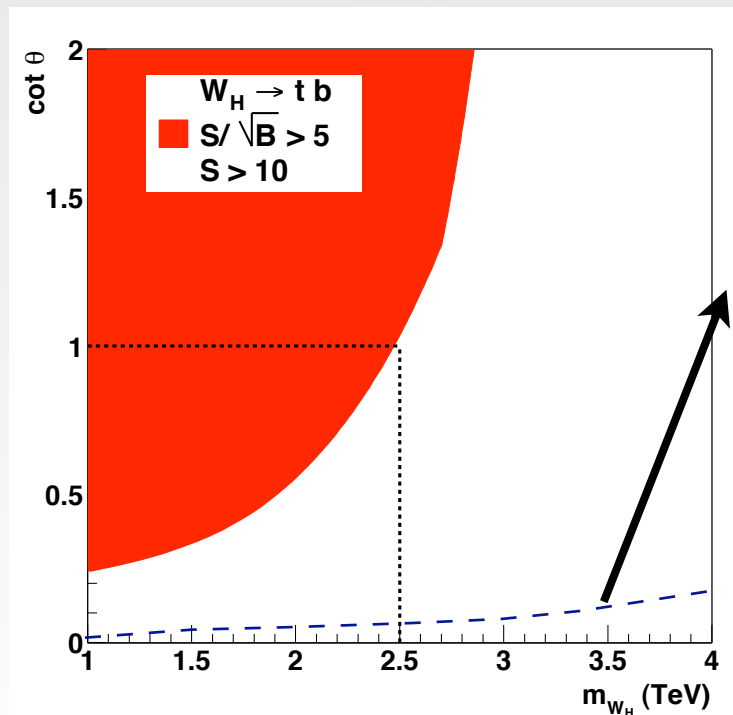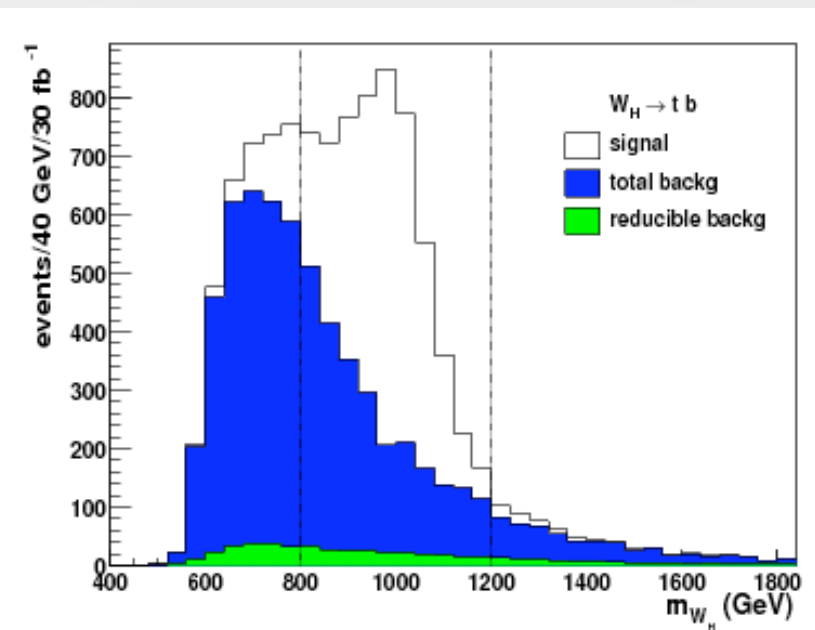Discovery reach is about 6 TeV depending on the model for 100fb⁻¹ data.

# New bosons W`/W$_H$

- predicted by: SO(10), E$_6$.. GUTs, <u>Little Higgs</u>, EDs
- produced as: s channel  from q-q′ annihilation
- decay via: top-b  $q\bar{q}' \rightarrow W' \rightarrow tb \rightarrow \ell\nu bb$

- Fast MC based study
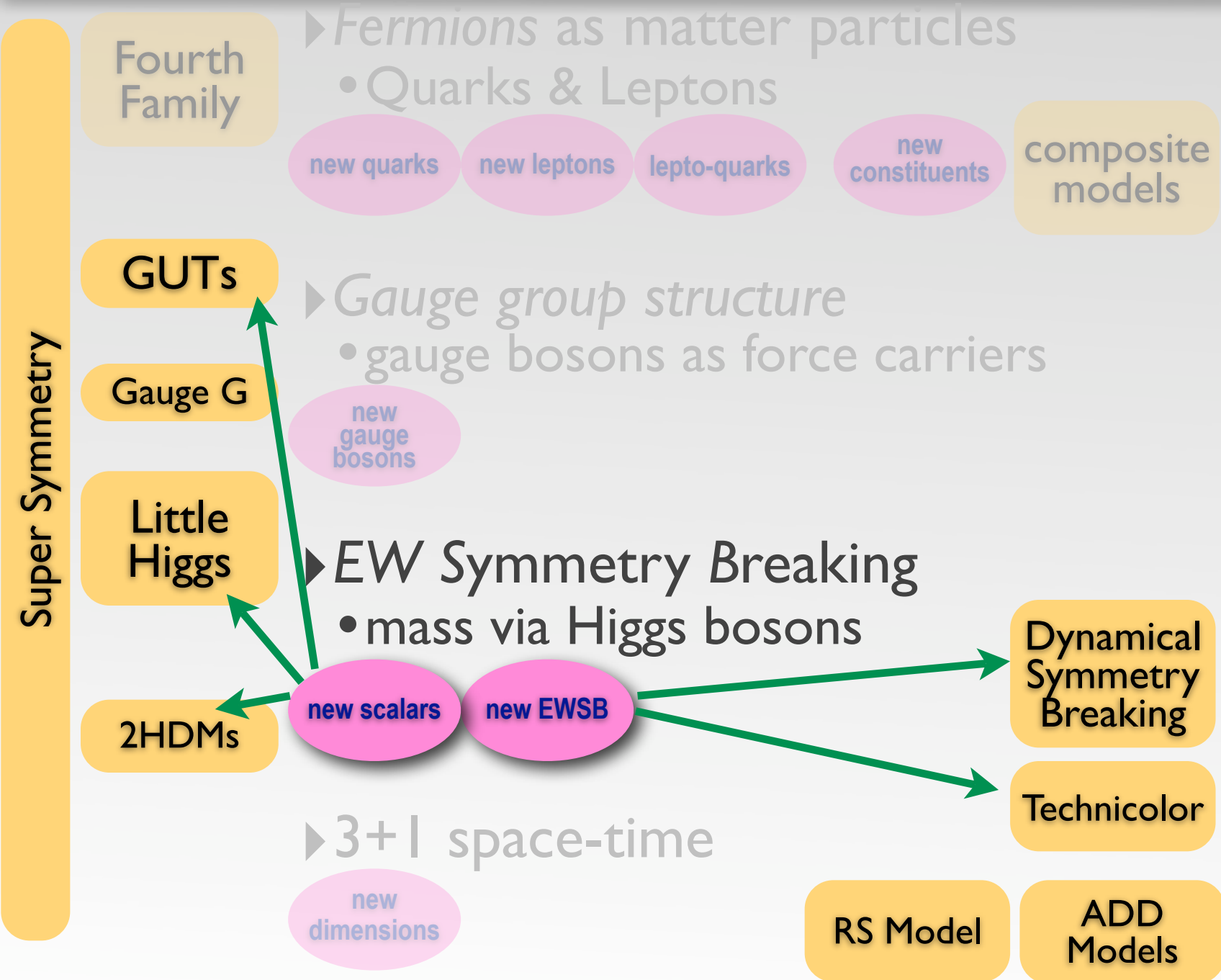- W–W$_H$ coupling via cotθ
- W$_H$ mass 1 & 2 TeV considered

Discovery plane for 300fb$^{-1}$ data



compare to W$_H$ →ev
from  SN-ATLAS-2004-038

Discovery reach is 6.5 TeV depending on the W–W$_H$ mixing.

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▸3+1 space-time

new dimensions

RS Model    ADD Models

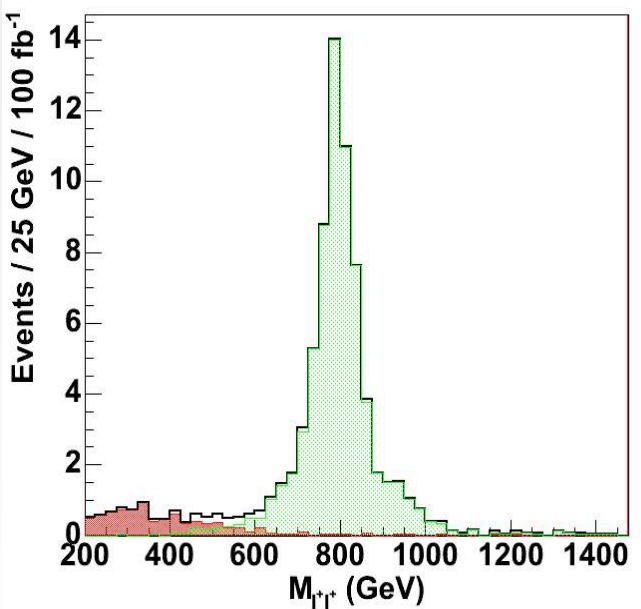# New Scalars q=±2

- predicted by: Little Higgs, <u>LRSM</u>
- produced as: pair via q-q annihilation & single via W fusion
- decay via: lepton pairs
  - Fast MC based study
  - $W^+_R$ & $\Delta^{++}$ mass scanned for min 10evts
  - e,μ & τ channels separately studied
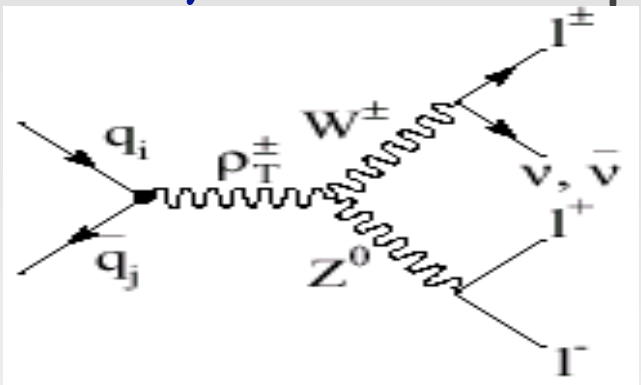  - results for 100(a) & 300(b) fb$^{-1}$ shown
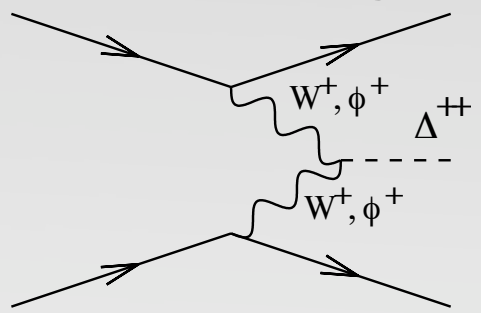
single production reach ~1.8TeV depending on mW$^+$

pair production reach 1.1 TeV depending on mZ$_R$ with 3 and 4 leptons
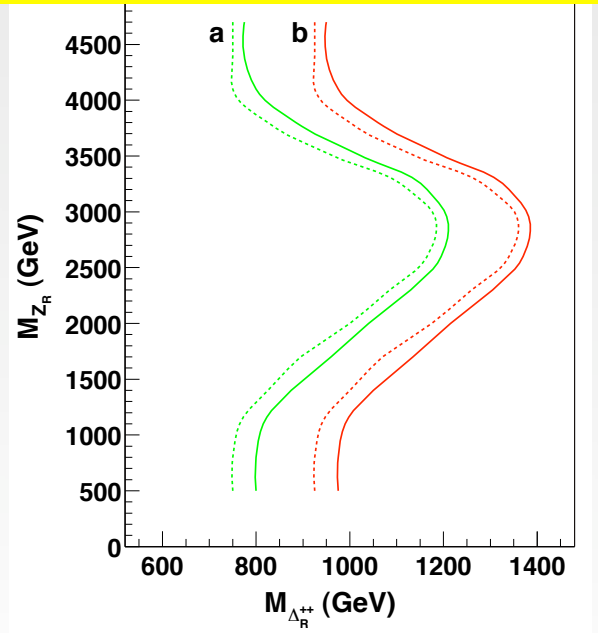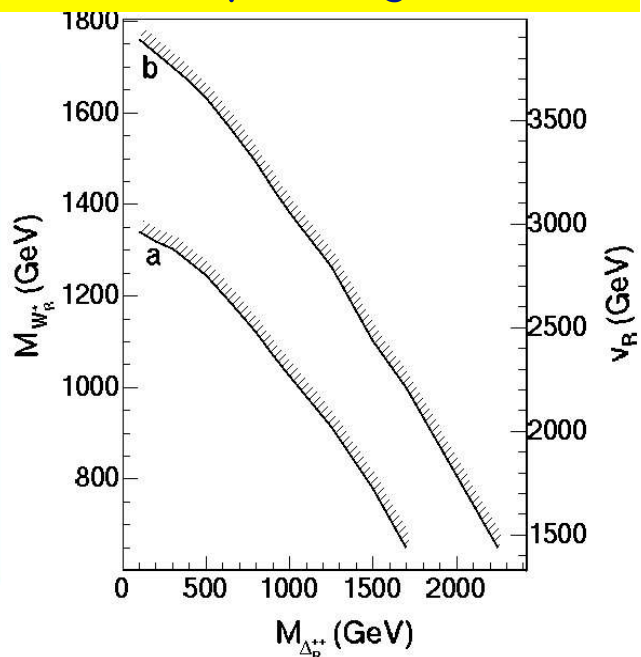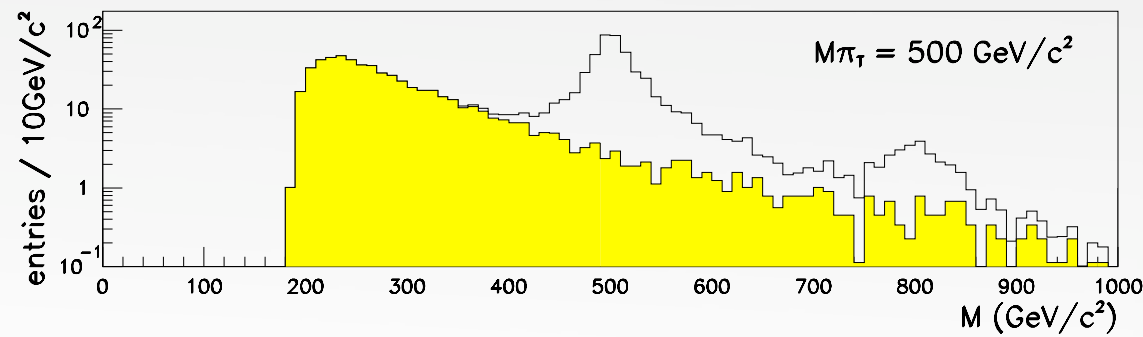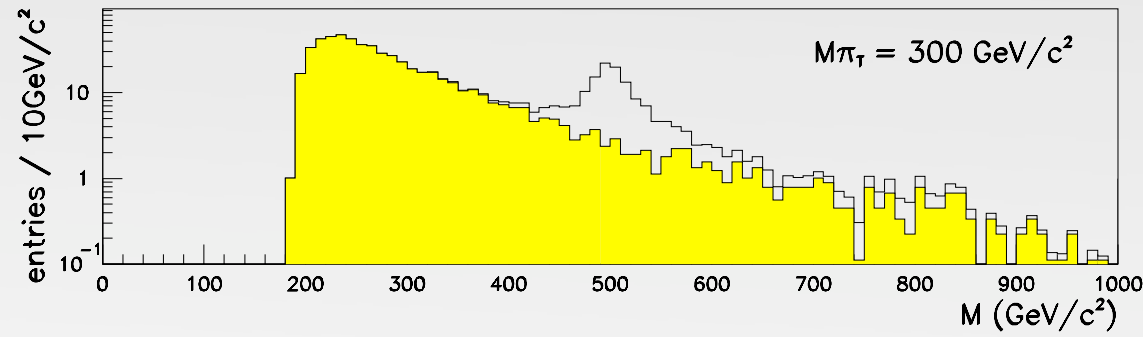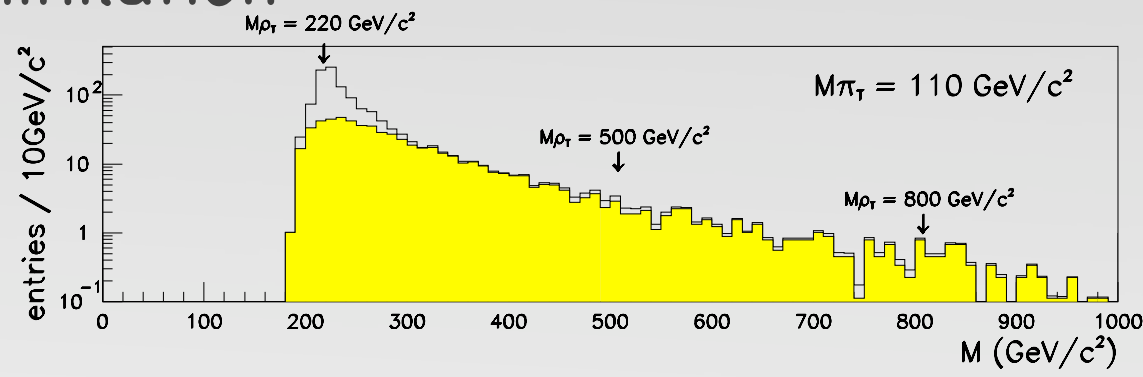
# New EWSB no scalar

- predicted by: Dynamical SB models, <u>technicolor</u>
- produced as: from q-q annihilation
- decay via: boson pairs



- Fast MC based study
- Scan $\rho_T$ mass for different $\pi_T$

**Discovery with 30fb$^{-1}$ data possible depending on model parameters**



$M\rho_T = 220$ GeV/c$^2$

$M\pi_T = 110$ GeV/c$^2$

$M\rho_T = 500$ GeV/c$^2$

$M\rho_T = 800$ GeV/c$^2$

$M\pi_T = 300$ GeV/c$^2$

$M\pi_T = 500$ GeV/c$^2$

\* new studies are available, but not yet public.

# New EWSB SUSY

- Give up the (so far) observed "spin" asymmetry between matter and force carriers: partners for all SM particles
  - solves Fine Tuning, DM.. problems

- SUSY not observed: sparticles heavy: broken symmetry
- Rich phenomenology (even with $R_{parity}$):
  - large # of parameters: >100 in MSSM case[R]
  - many SB options: MSSM, mSUGRA, GMSB, AMSB..

  has 5 parameters

  has 6 parameters

- Common properties:
  - cascade decays of sparticles to high $p_T$ objects ,
  - stable LSP escapes undetected: large $E_T^{miss}$ .

Look for: jets + $E_T^{miss}$ and leptons +jets + $E_T^{miss}$

[R] #parameters=124 given in SN-ATLAS-2006-058

# New EWSB mSUGRA

- mSUGRA's LSP is DM candidate
  - model should be consistent with WMAP data $\tilde{\chi}_1^0$
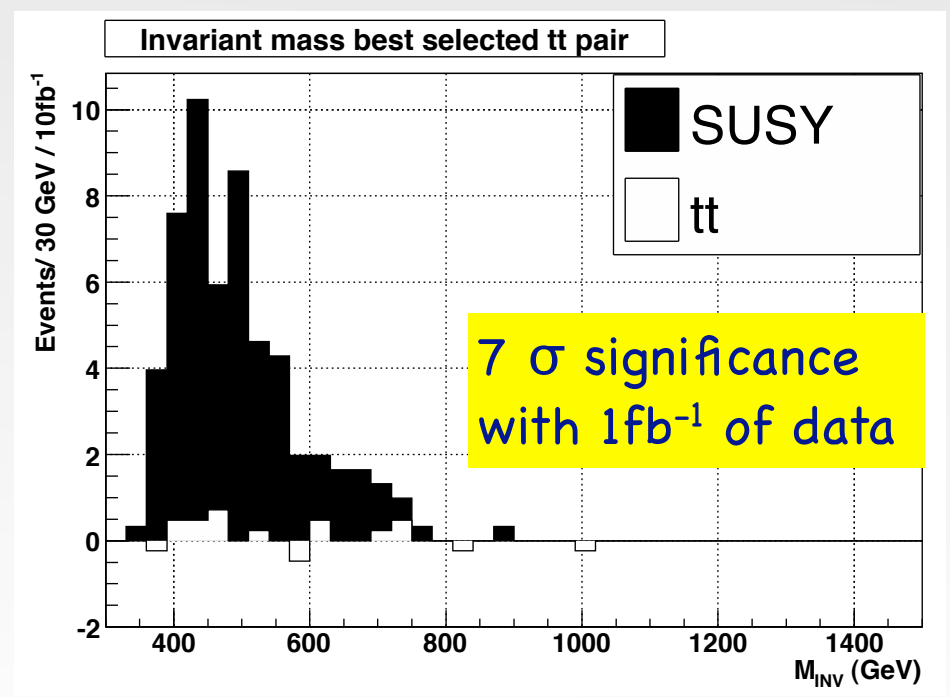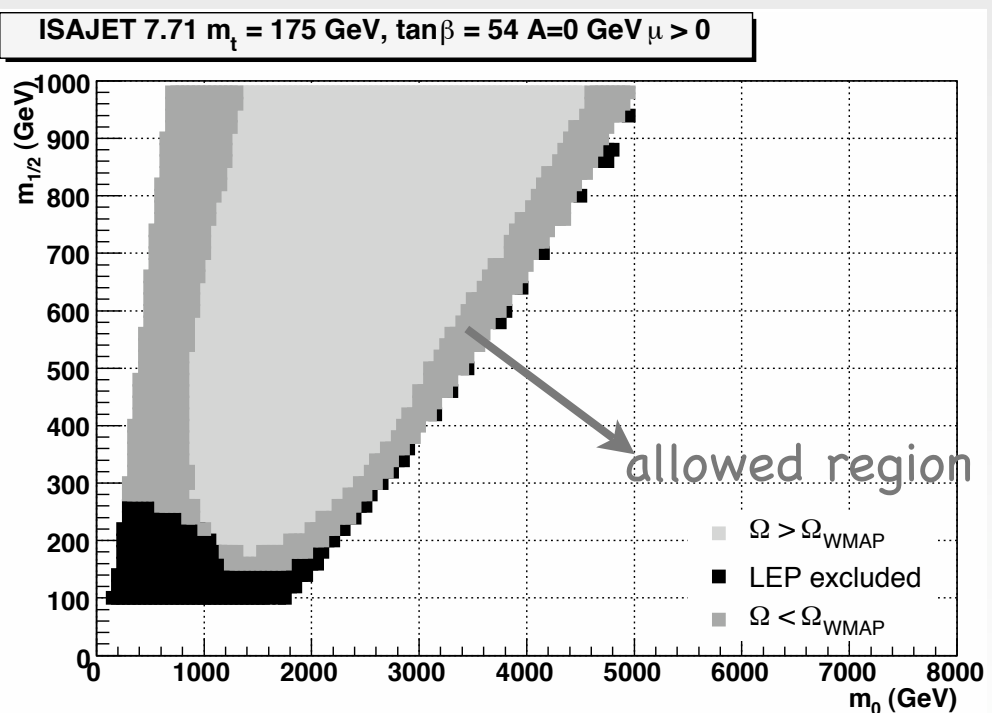- R parity imposes pair production
  - Fast MC based study
  - $m_{1/2}$–$m_0$ parameter space scanned

$$pp \rightarrow \tilde{g}\tilde{g} \qquad \tilde{g} \rightarrow \tilde{\chi}^+ t\bar{b}$$
$$\tilde{g} \rightarrow \tilde{\chi}^- \bar{t}b$$
$$\tilde{g} \rightarrow \tilde{\chi}^0 t\bar{t}$$

jets + $E_T^{miss}$



ISAJET 7.71 $m_t$ = 175 GeV, $\tan\beta$ = 54 A=0 GeV $\mu$ > 0

allowed region

$\Omega > \Omega_{WMAP}$
LEP excluded
$\Omega < \Omega_{WMAP}$



Invariant mass best selected tt pair

SUSY
tt

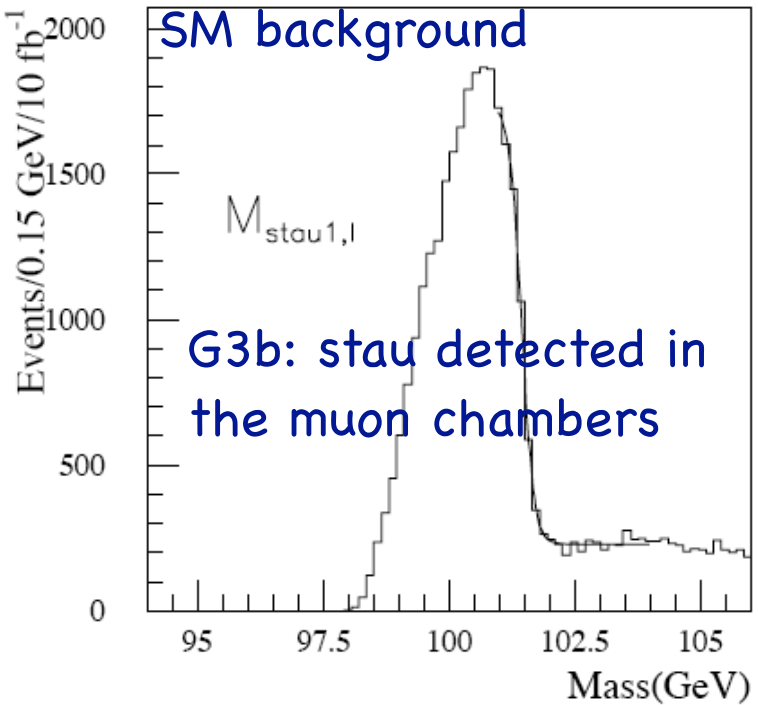7 $\sigma$ significance with 1fb$^{-1}$ of data

# New EWSB GMSB

- Susy breaking scale close to weak scale
  - LSP is gravitino, FCNC is suppressed
- Reference points with different model parameters & NLSP
  - Fast MC based study @ G3 (NSLP is stau)
  - G3b: NLSP is quasi-stable
  - G3a: NLSP immediately decays

$$\tilde{q} \to \tilde{\chi}^0_{1,2} q \to \tilde{\ell}\ell q \to \tilde{\tau}(\tau)\ell\ell q \to \tilde{G}\tau(\tau)\ell\ell q$$

**leptons +jets + $E_T^{miss}$**

Negligibly small
SM background



G3b: stau detected in the muon chambers
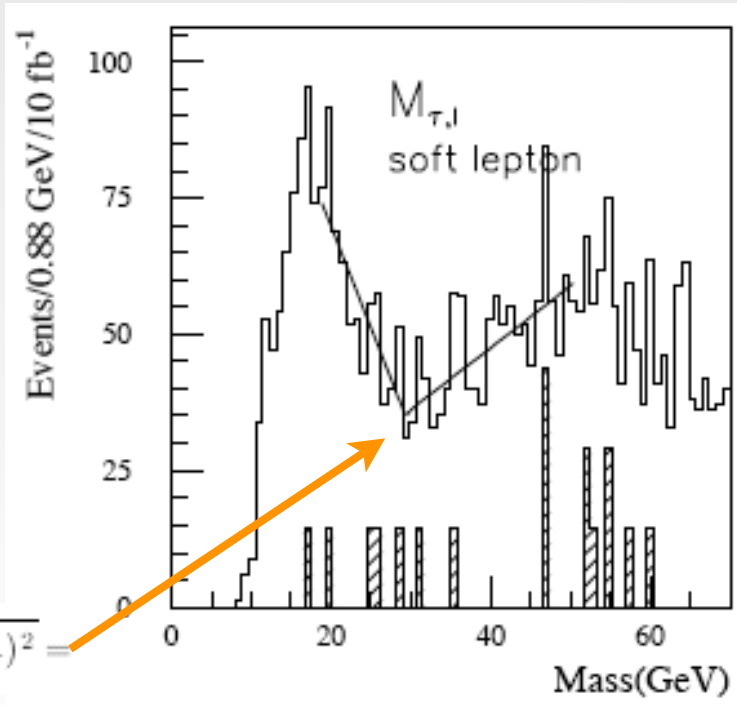
Excellent signal with few fb⁻¹ in both cases

G3a: stau decays before detection but dips can be calculated & fit:

$$M_{\tau l}^{max} = \sqrt{M_{\tilde{l}_R}^2 - (M_{\tilde{\tau}_1} + M_\tau)^2} =$$

# SM to BSM

**Fourth Family**

▸ *Fermions* as matter particles
 • Quarks & Leptons

new quarks   new leptons   lepto-quarks   new constituents   composite models

**GUTs**

▸ *Gauge group structure*
 • gauge bosons as force carriers

**Gauge G**

new gauge bosons

**Little Higgs**

▸ *EW Symmetry Breaking*
 • mass via Higgs bosons

**2HDMs**

new scalars   new EWSB

Super Symmetry

▸ 3+1 space-time

new dimensions
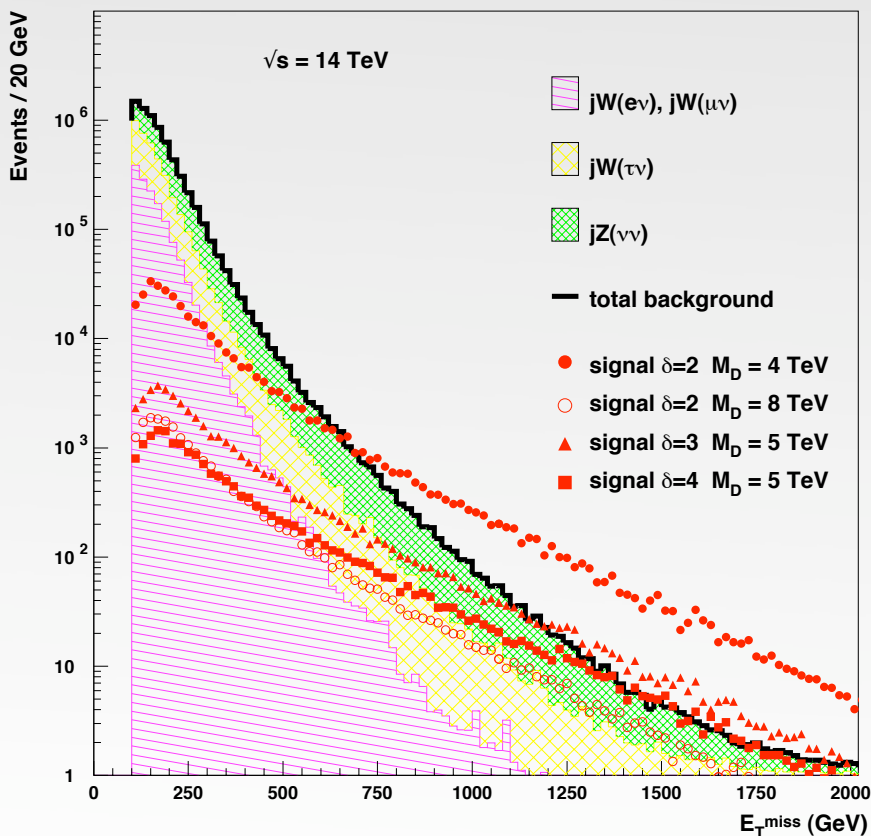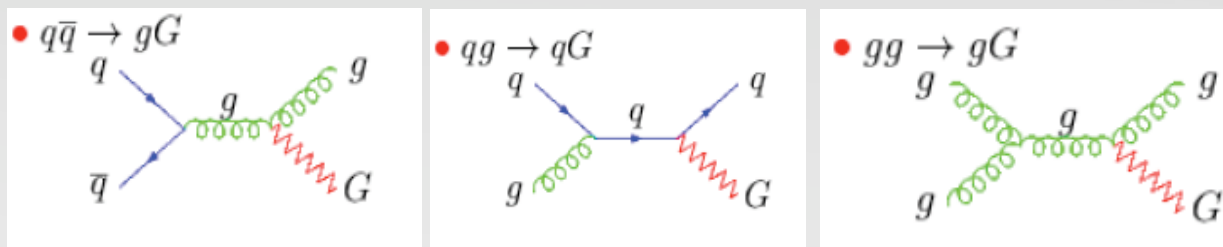
Dynamical Symmetry Breaking

Technicolor

RS Model   ADD Models

# EDs graviton

- predicted by: all ED models
- produced as: from q-q annihilation, q-g/g-g fusion
- decay via: - (stable)

$$gg/gq/q\bar{q} \rightarrow gG$$

- Fast MC based study
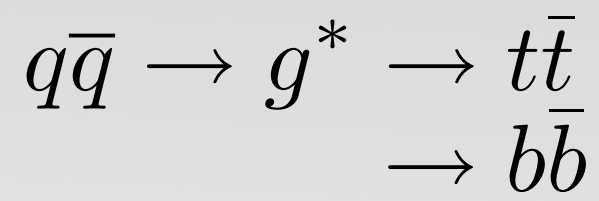- #EDs=2,3,4 & ED scale scanned





| $M_{Pl(4+d)}^{MAX}$(TeV) | $\delta=2$ | $\delta=3$ | $\delta=4$ |
|---|---|---|---|
| 30fb$^{-1}$ | 7.7 | 6.2 | 5.2 |
| 100fb$^{-1}$ | 9.1 | 7.0 | 6.0 |

$$q\bar{q} \rightarrow \gamma G$$

- lower rate,
- lower sensitivity due to Zγ background

# EDs Excited gluons

- predicted by: TEV$^{-1}$ EDs (ADD)
- produced as: from q-q annihilation
- decay via: heavy quark pairs

$$q\bar{q} \rightarrow g^* \rightarrow t\bar{t}$$
$$\rightarrow b\bar{b}$$

- Fast MC based study
- g* mass scanned [1..3] TeV
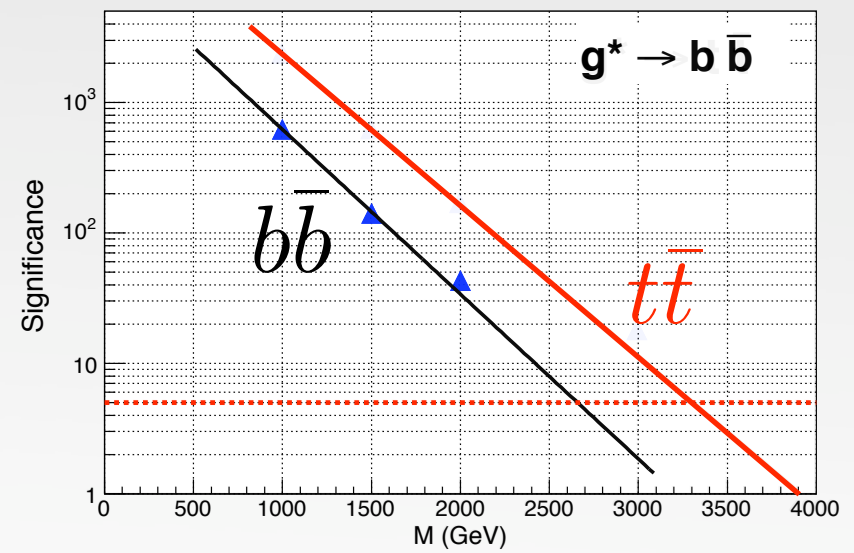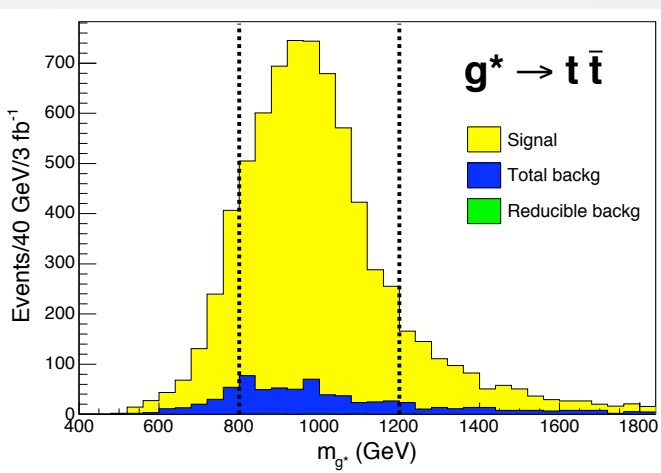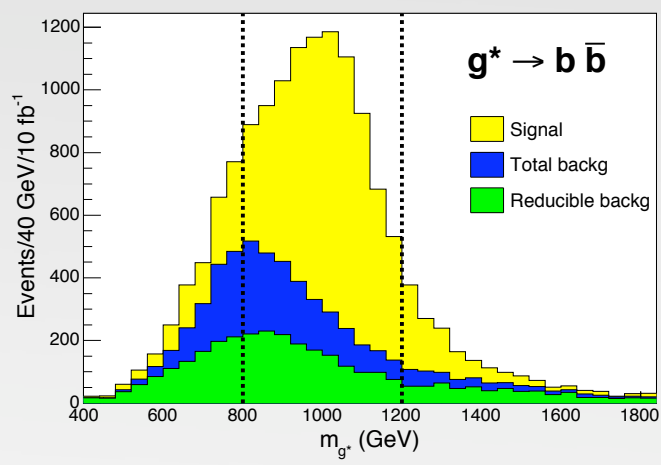






**300 fb$^{-1}$ allows reaching 3.3 TeV with 5σ**

# Summary

ATLAS has very rich discovery potential for BSM physics.
- scientific or pub note results shown, (mostly published)

Concentrated on a selection* of discovery possibilities;
- some models (e.g. micro BHs) not mentioned,
- differentiation between models not shown,
- boost to standard searches from BSM physics not shown.

Some results with Fast MC were shown,
- New analyses with full simulation ongoing for first 1fb$^{-1}$,
- Trigger aware studies immediately applicable to LHC data

Next few years will be very exciting, stay tuned..

*Apologies to all the analyses not mentioned here...

# auxiliary slides
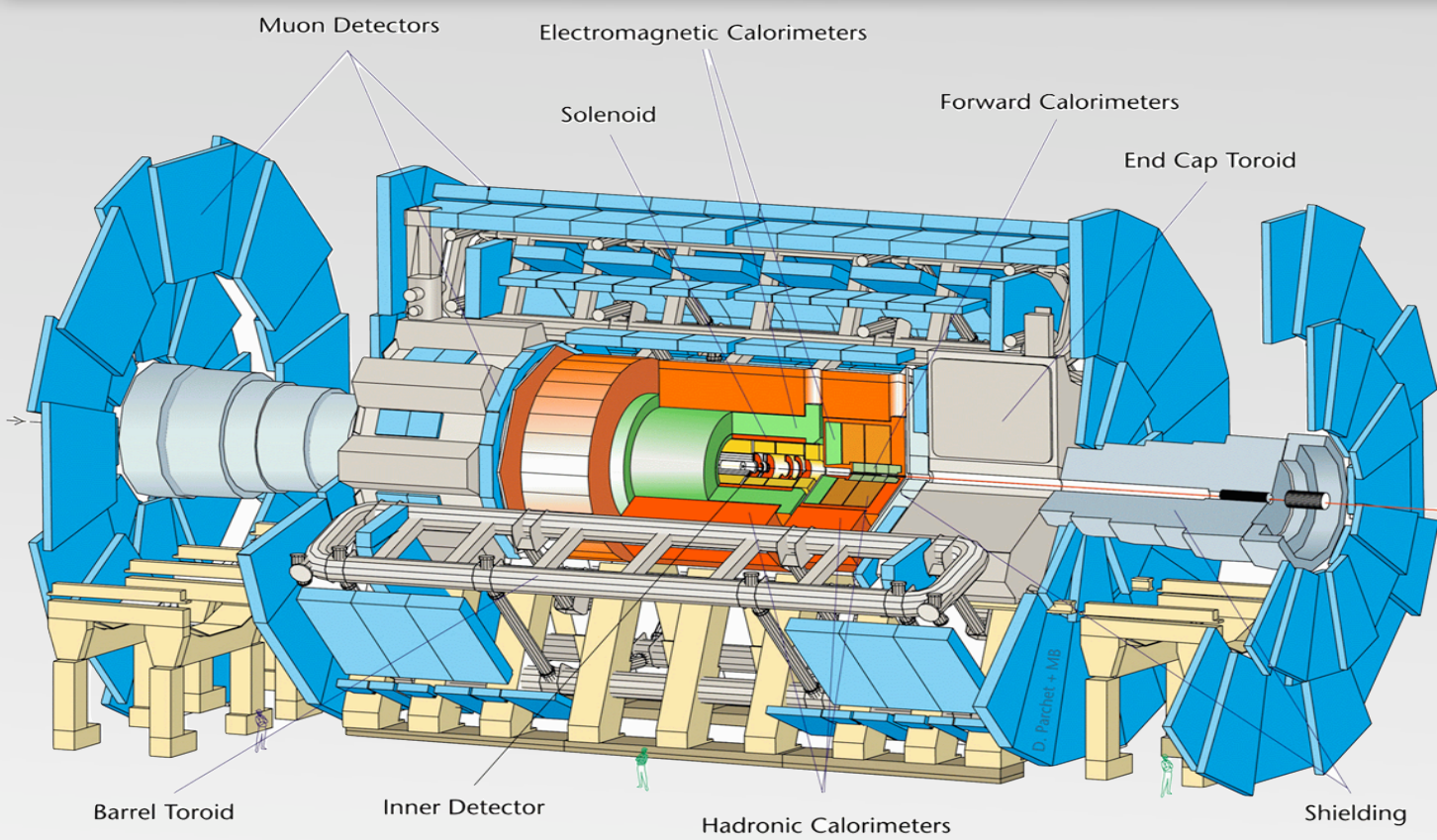


| | ATLAS |
|---|---|
| weight | 7 000 t |
| diameter | 25 m |
| length | 46 m |
| B Field | 2 T |

| year | energy | luminosity | aimed ∫L (fb$^{-1}$) | physics beam time |
|---|---|---|---|---|
| 2008 | 7+7 TeV | $0.5 \times 10^{33}$ | 1-2 | **protons - from July on ➡ $4 \times 10^6$ seconds** <br> **ions - after proton run - 5 days at 50% efficiency ➡ $0.2 \times 10^6$ seconds** |
| 2009 | 7+7 TeV | $1 \times 10^{33}$ | 10 | **protons: 50% better than 2008 ➡ $6 \times 10^6$ seconds** <br> **ions: 20 days at 50% efficiency ➡ $10^6$ seconds** |
| 2010 | 7+7 TeV | $1 \times 10^{34}$ | 100 | **TDR targets:** <br> protons: ➡ $10^7$ seconds <br> ions: ➡ $2 \times 10^6$ seconds |

# BSM models: Exotics

▸A brief summary of popular models:

- Grand Unified Theories:

    - SM gauge group is embedded into a larger one like SO(10), to unify EW and QCD.

    - additional fermions and bosons predicted.

- Little Higgs models:

    - spontaneously broken global symmetry to impose a cut-off ~10 TeV.

    - additional bosons and quarks introduced to cure the hierarchy problem.

- Extra Dimensions:

    - Low Planck scale in d dimensional theory solves the hierarchy problem between EW and Gravitational couplings.

    - Excitations of SM bosons and fermions are predicted.

▸ *These models do **not** exclude supersymmetry.*