Narrow Resonances at the LHC: Discovery Potential, Signature Spaces and Model Discrimination

PN

Santa Fe Workshop on LHC

with Boris Kors, Daniel Feldman, and Zuowei Liu

Northeastern University

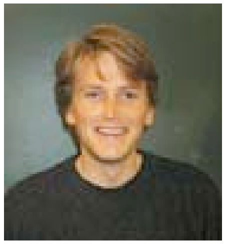
LHC

- pp collider : $\sqrt{s} = 14$ TeV
- Design luminosity $10^{34} cm^{-2} s^{-1}$
- Detectors : ATLAS, CMS, LHCb, ALICE
- Test run : 2007

Narrow resonances

- Z' in Stueckelberg extensions SM
- Massive graviton in warped geometry
- KK modes in some extra dimension models

Outline of the Talk



- The Stueckelberg Mechanism
- St Extension of the Standard Model (StSM)
- Electroweak Constraints
- StSM Z' vs Classic Z' of E6 etc
- CDF, D0 Constraints on StSM Z'
- Reach of LHC for Discovering St Z'
- StSM Z' vs RS Graviton
- Further work (StMSSM)/Conclusions

Mass growth without Higgs mechanism

Abelian 2d Schwinger model
3d Chern-Simon theory
4d: Stueckelberg mechanism

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(mA_\mu + \partial_\mu\sigma)^2 + gA_\mu J^\mu$$

The Lagrangian in invariant under

$$\delta A_\mu \to \partial_\mu \epsilon, \quad \delta\sigma \to -m\epsilon$$

E.C.G. Stueckelberg, *Helv. Phys. Acta* 11, 225(1938).

Stueckelberg in String Theory

In N=1 sugra kinetic energy for the 2-tensor **B_IJ**

$$\partial_{[I}B_{JK]} + A_{[I}F_{JK]}\partial_{[I}B_{JK]} + A_{[I}F_{JK]} + \frac{2}{3}A_{[I}A_{J}A_{K]}$$

Dimensional reduction gives

$$\partial_\mu B_{ij} + A_\mu F_{ij} \simeq \partial_\mu \sigma + m A_\mu$$

$$B_{ij} \simeq \sigma \text{ and } < F_{ij} > \simeq m$$

Stueckelberg in compactificaion of extra dimensions

Compactification of a 5D theory on half circle

$$L_5 = -\frac{1}{4} F_{ab}(z) F^{ab}(z), \ a = 0, 1, 2, 3, 5$$

$$L_4 = -\frac{1}{4} \sum_{n=0}^{\infty} F_{\mu\nu}(x)^{(n)} F^{\mu\nu(n)}(x)$$

$$- \sum_n \frac{1}{2} M_n^2 (A_\mu^{(n)}(x) + \frac{1}{M_n} \partial_\mu \phi^{(n)}(x))^2$$

The mass growth in 4D is via Stueckelberg mechanism

St coupling and Green-Schwarz anomaly cancellation

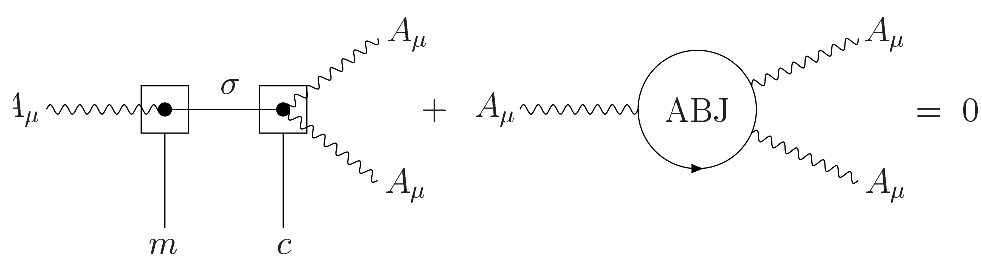
An anomalous U(1) gives at one loop

$$\delta L_{1loop} = \lambda c Tr(G \wedge G), \quad \delta A_\mu = \partial_\mu \lambda$$

$$L_0 = \cdot\cdot + m A^\mu \partial_\mu \sigma + \frac{c\sigma}{m} Tr(G \wedge G)$$

$$\delta L_0 = -\lambda c Tr(G \wedge G), \quad \delta\sigma = -\lambda m$$

$$\delta L_{1loop} + \delta L_0 = 0$$



Anomalous U(1) Case : $c \neq 0$, $m \neq 0$: $\rightarrow$ massive vector

The St coupling $\partial_\mu \sigma A_\mu$ plays a role in Green – Schwarz anomaly cancellation

Non – anomalous U(1) Case : $c = 0$, $m \neq 0$: $\rightarrow$ massive vector

U(1) factors appear quite generically in D brane models which start with a number of unitary group factors. U(n)'s are broken to the special unitary form by St couplings.

$$U(3) \times U(2) \times U(1)^2 \rightarrow SU(3) \times SU(2) \times U(1)$$

Label	Multiplicity	Gauge Group	Name
stack a	$N_a = 3$	$\mathrm{SU}(3) \times \mathrm{U}(1)_a$	Baryonic brane
stack b	$N_b = 2$	$\mathrm{SU}(2) \times \mathrm{U}(1)_b$	Left brane
stack c	$N_c = 1$	$\mathrm{U}(1)_c$	Right brane
stack d	$N_d = 1$	$\mathrm{U}(1)_d$	Leptonic brane

Table 1: Brane content yielding the SM spectrum.

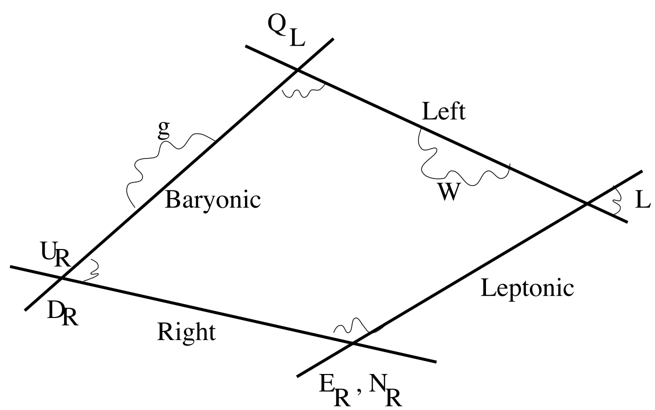


Figure 1: Schematic view of an intersecting D-brane standard model construction. There are four stacks of branes: *Baryonic, Left, Right* and *Leptonic*, giving rise to a gauge group $\mathrm{U}(3)_{Baryonic} \times \mathrm{U}(2)_{Left} \times \mathrm{U}(1)_{Right} \times \mathrm{U}(1)_{Leptonic}$. Open strings starting and ending on the same stack of branes give rise to the SM gauge bosons. Quarks and leptons appear at the intersections of two different stacks of branes.

Stueckelberg vs Higgs Mechanism

Consider a $U(1)$ gauge invariant Lagrangian with $U(1)$ gauge vector A_μ and one complex scalar field ϕ.

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - (D_\mu\phi)^\dagger D_\mu\phi + V(\phi)$$

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

Spontaneous breaking

$$\phi = \frac{1}{\sqrt{2}}(\rho + v)e^{ia/v}, \quad v = \sqrt{-\mu^2/\lambda}$$

Add a gauge fixing term

$$L_{gf} = -\frac{1}{2\xi}(\partial_\mu A^\mu + M\xi a)^2, \quad M = ev$$

$$\begin{aligned} L + L_{gf} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\partial_\mu\rho\partial^\mu\rho + \frac{1}{2}M^2(\frac{\rho}{v}+1)^2(A_\mu - \frac{1}{M}\partial_\mu a)^2 \\ +\frac{1}{4}\lambda(\rho^2 + 2\rho v)^2 - \frac{1}{2\xi}(\partial_\mu A^\mu + M\xi a)^2 \end{aligned} \tag{1}$$

Stueckelberg mechanism can arise as a limit of the Higgs mechanism

In the limit $(-\mu^2, \lambda) \to \infty$ while M remains fixed, ρ becomes infinitely massive and decouples and the residual Lagrangian is

$$(L + L_{gf})_{residual} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}M^2(A_\mu - \frac{1}{M}\partial_\mu a)^2 - \frac{1}{2\xi}(\partial_\mu A^\mu + M\xi a)^2 \quad (2)$$

TJ Allen, MJ Bowick, A. Lahiri, Mod. Phys. Lett. A 6, 559 (1991)

Non-abelian gauge theories

A non-abelian extension of the Stueckelberg Lagrangian leads to a violation of unitarity already at the tree-level, because the longitudinal components of the vector fields cannot be decoupled from the physical Hilbert space. The renormalizability of the theory is then spoiled as well.

M. Veltman, Nucl. Phys. B7 (1968) 637
L. Faddeev and A. A. Slavnov, Theor. Math. Phys. 3 (1970) 312

Early attempts at model building with Stueckelberg

There were early attempts to include the St mass term for the U(1) gauge field in the SU(2)_L x U(1)_Y model

$$\mathcal{L}_B = -\frac{m^2}{2}(B_\mu + \frac{1}{m}\partial_\mu \sigma)^2$$

Here the photon develops a mass of size O(m).

V.A. Kuzmin and D.G.C McKeon, Mod. Phys.Lett. A, Vol. 16, Nov. 11 (2001) 747-753.

Stueckelberg $U(1)_X$ extension of Standard Model

$$\mathcal{L}_{\rm St} = -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} + g_X C_\mu J^\mu_X - \frac{1}{2}(\partial_\mu\sigma + M_1 C_\mu + M_2 B_\mu)^2$$

invariant under

$$\delta_Y B_\mu = \partial_\mu \lambda_Y \ , \quad \delta_Y \sigma = -M_2 \lambda_Y \ , \qquad U(1)_Y$$

$$\delta_X C_\mu = \partial_\mu \lambda_X \ , \quad \delta_X \sigma = -M_1 \lambda_X \ . \qquad U(1)_X$$

The total Lagrangian $\qquad \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{St}$

B. Kors and PN, PLB 586, 2004.

In String models

- **In string models conditions are typically imposed to keep the hypercharge massless**
- **In the analysis here we allow for axionic -hypercharge couplings. These mixings are what makes the Stueckelberg sector affect electroweak physics**
- **More recent string constructions have successfully generated the axionic -hypercharge couplings present in the Stueckelberg models.**
  P. Anastasopoulos, Dijstra, Kiritsis, Schellekens,hep-th/0605226

StSM Vector Boson Mass Squared Matrix

$$\begin{pmatrix} M_1^2 & M_1 M_2 & 0 \\ M_1 M_2 & M_2^2 + \frac{1}{4}v^2 g_Y^2 & -\frac{1}{4}v^2 g_2 g_Y \\ 0 & -\frac{1}{4}v^2 g_2 g_Y & \frac{1}{4}v^2 g_2^2 \end{pmatrix},$$

Eigen modes $\gamma,\ Z,\ Z'$

$$\frac{1}{e^2} = \frac{1}{g_2^2} + \frac{1}{g_Y^2}(1+\epsilon^2)$$

Photon couples with the hidden sector with an irrational unit of e

Electroweak Constaints on StSM

$$M_W^2 \to \frac{\pi\alpha}{\sqrt{2}G_F s_W^2(1-\Delta r)}$$ In the on-shell scheme

$$\delta M_Z = M_Z \sqrt{\left(\frac{1-2\sin^2\theta_W}{\cos^3\theta_W}\frac{\delta M_W}{M_Z}\right)^2 + \frac{\tan^4\theta_W(\delta\Delta r)^2}{4(1-\Delta r)^2}}.$$

$\Delta r = 0.0363 \pm 0.0019$ radiative corrections

$M_W = 80.425 \pm 0.034$ GeV

$M_Z = 91.1876 \pm 0.0021$ GeV

$|\epsilon| \lesssim .061\sqrt{1-(M_Z/M_1)^2}$ Upper limit on ϵ

D. Feldman, Z. Liu, PN: PRL, 97, 021801, 2006.

Electroweak parameters

$$R_l = \frac{\Gamma(had)}{\Gamma(l^+l^-)}$$

$$R_q = \frac{\Gamma(q\bar{q})}{\Gamma(had)}$$

$$\sigma_{had} = \frac{12\pi\Gamma(e^+e^-)\Gamma(had)}{M_Z^2\Gamma_Z^2}$$

$$A_f = \frac{2v_f a_f}{v_f^2 + a_f^2}$$

$$A_{FB}^{(0,f)} = \frac{3}{4}A_e A_f.$$

StSM Fit to Precision Electoweak Data

Quantity	Value (Exp.)	StSM	ΔPull
Γ_Z [GeV]	2.4952 ± 0.0023	(2.4952-2.4942)	(0.2, 0.6)
σ_{had} [nb]	41.541 ± 0.037	(41.547-41.568)	(-0.3, -0.9)
R_e	20.804 ± 0.050	(20.753-20.761)	(-0.1, -0.2)
R_μ	20.785 ± 0.033	(20.800-20.761)	(-0.1, -0.4)
R_τ	20.764 ± 0.045	(20.791-20.807)	(-0.1, -0.3)
R_b	0.21643 ± 0.00072	(0.21575-0.21573)	(0.0, 0.0)
R_c	0.1686 ± 0.0047	(0.1711-0.1712)	(0.0, 0.0)
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	(0.0168-0.0175)	(-0.2, -0.5)
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013	(0.0168-0.0175)	(-0.3, -0.9)
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017	(0.0168-0.0175)	(-0.2, -0.7)
$A_{FB}^{(0,b)}$	0.0991 ± 0.0016	(0.1045-0.1070)	(-0.8, -2.3)
$A_{FB}^{(0,c)}$	0.0708 ± 0.0035	(0.0748-0.0766)	(-0.3, -0.8)
$A_{FB}^{(0,s)}$	0.098 ± 0.011	0.105-0.107)	(-0.1, -0.3)
A_e	0.1515 ± 0.0019	(0.1491-0.1524)	(-1.0, -2.8)
A_μ	0.142 ± 0.015	(0.149-0.152)	(-0.1, -0.4)
A_τ	0.143 ± 0.004	(0.149-0.152)	(-0.5, -1.3)
A_b	0.923 ± 0.020	(0.935-0.935)	(0.0, 0.0)
A_c	0.671 ± 0.027	(0.669-0.670)	(0.0, 0.1)
A_s	0.895 ± 0.091	(0.936-0.936)	(0.0, 0.0)

Table 1: Results of the StSM fit to a standard set of electroweak observables at the Z pole for ϵ in the range $(.035 - .059)$ for $M_1 = 350$ GeV. $\Delta\text{Pull} = (\text{SM} - \text{StSM})/\delta\text{Exp}$ and Pull(StSM)=Pull(SM)+ ΔPull.

D. Feldman, Z. Liu, PN: PRL, 97, 021801, 2006.

StLR Model

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_X$$

$$\begin{pmatrix} M_1^2 & M_1 M_2 & 0 & 0 \\ M_1 M_2 & \frac{1}{4}\left(v_L^2 + v_R^2\right) g'^2 + M_2^2 & -\frac{1}{4} g g' v_L^2 & -\frac{1}{4} g g' v_R^2 \\ 0 & -\frac{1}{4} g g' v_L^2 & \frac{1}{4} g^2 \left(v_L^2 + \kappa^2 + \kappa'^2\right) & -\frac{1}{4} g^2 \left(\kappa^2 + \kappa'^2\right) \\ 0 & -\frac{1}{4} g g' v_R^2 & -\frac{1}{4} g^2 \left(\kappa^2 + \kappa'^2\right) & \frac{1}{4} g^2 \left(v_R^2 + \kappa^2 + \kappa'^2\right) \end{pmatrix}$$

Eigen modes $\gamma,\ Z,\ Z',\ Z''$

$$\frac{1}{e^2} = \frac{1}{g^2}(1-\epsilon^2) + \frac{1}{g_Y^2}(1+\epsilon^2)$$

The Z prime of StLR model is very similar to the Z prime of StSM

Classic U(1) extensions

$$A_\gamma^\mu = W^{3\mu}\sin\theta_W + B^\mu\cos\theta_W$$

Stueckelberg U(1) Extension

$$A_\mu^\gamma = -c_\theta s_\phi C_\mu + c_\theta c_\phi B_\mu + s_\theta A_\mu^3$$

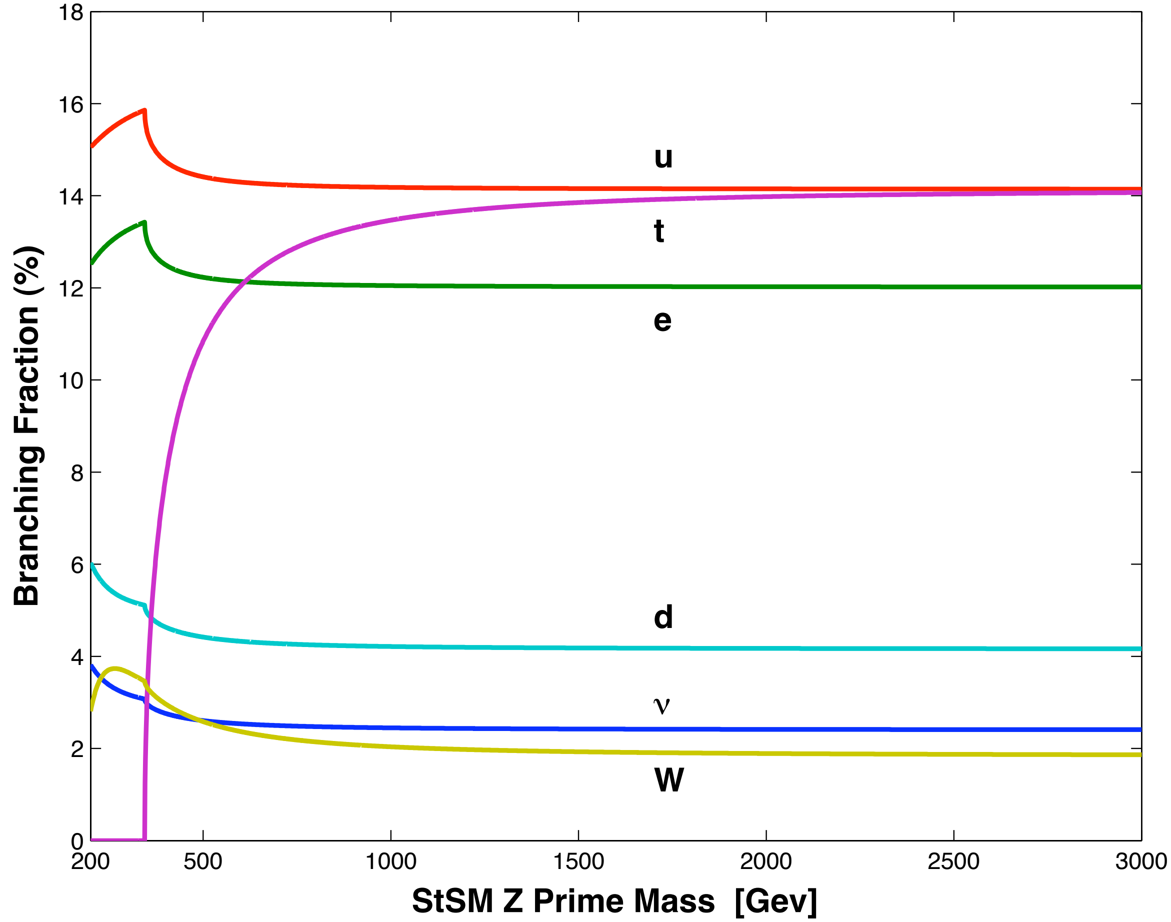
$$\tilde{B}_Y^\mu = B^\mu\cos\phi - C^\mu\sin\phi$$ Dressed up hypercharge

$$C^\mu = B^\mu\sin\phi + C^\mu\cos\phi$$

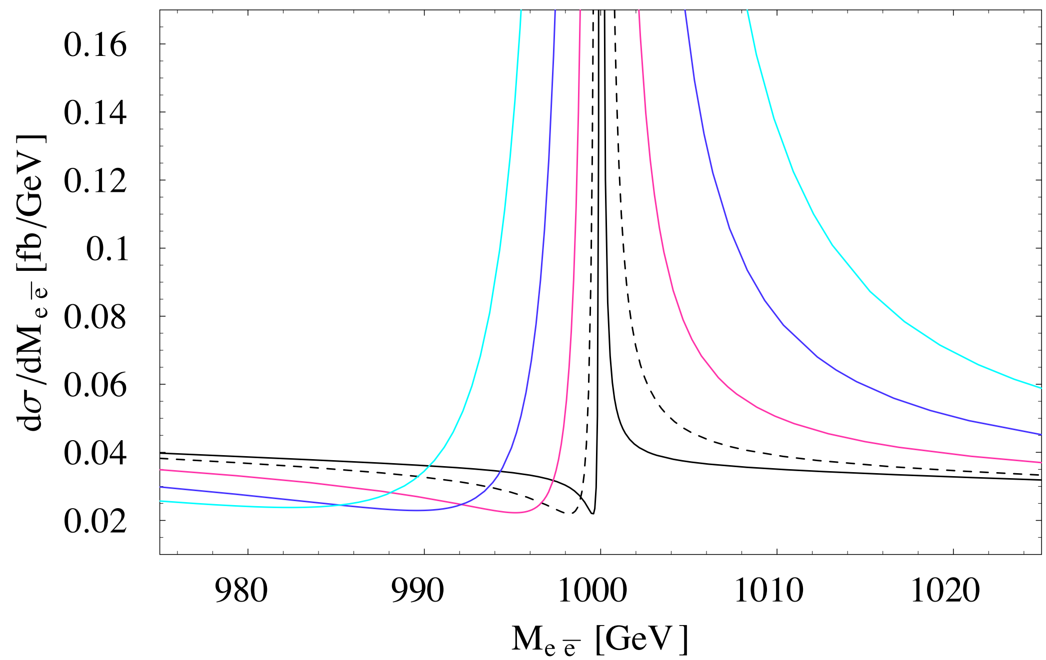
$$A_\gamma^\mu = W^{3\mu}\sin\theta_W + \tilde{B}^\mu\cos\theta_W$$

StSM and the usual U(1) extensions are inequivalent

Leptonic branching ratios are large since Z' couples mainly to hypercharge



Z’ is narrow



$$\Gamma(Z' \to \sum_i f_i \bar{f}_i) \simeq M_{Z'} g_Y^2 \sin^2(\phi) \times \begin{cases} \frac{103}{288\pi} & \text{for } M_{Z'} < 2m_t \\ \frac{5}{12\pi} & \text{for } M_{Z'} > 2m_t \end{cases}$$

Z prime decay width is about 50 MeV for Z Prime Mass of 1 TeV

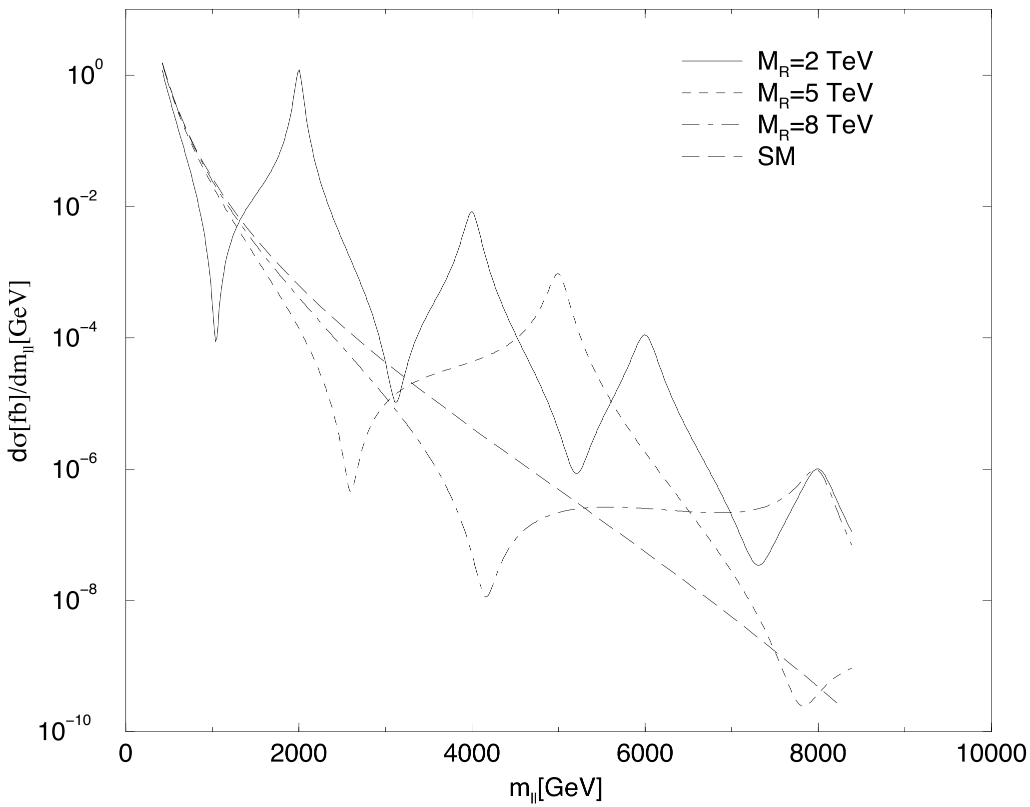
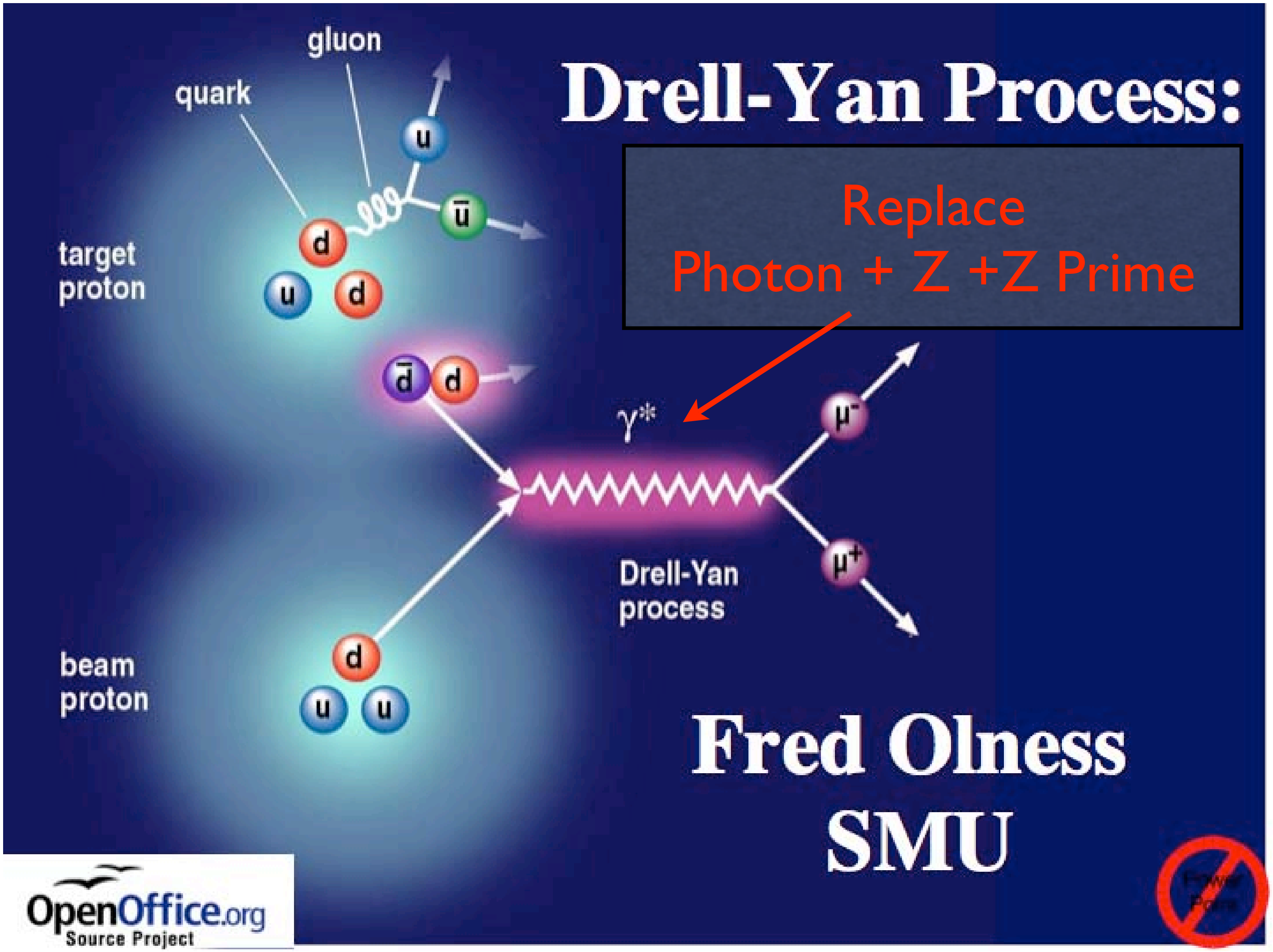


Fig. 2. Differential cross section $d\sigma/dm_{ll}$ as a function of the invariant mass m_{ll} of the charged lepton pair for three different values of the compactified dimension M_R. For comparison the analysis for the SM case is also shown. PN. Y. Yamada, M.Yamaguchi I. Antoniadis, K. Binakli, M. Quiros

The Narrow Z’ and the DY Process

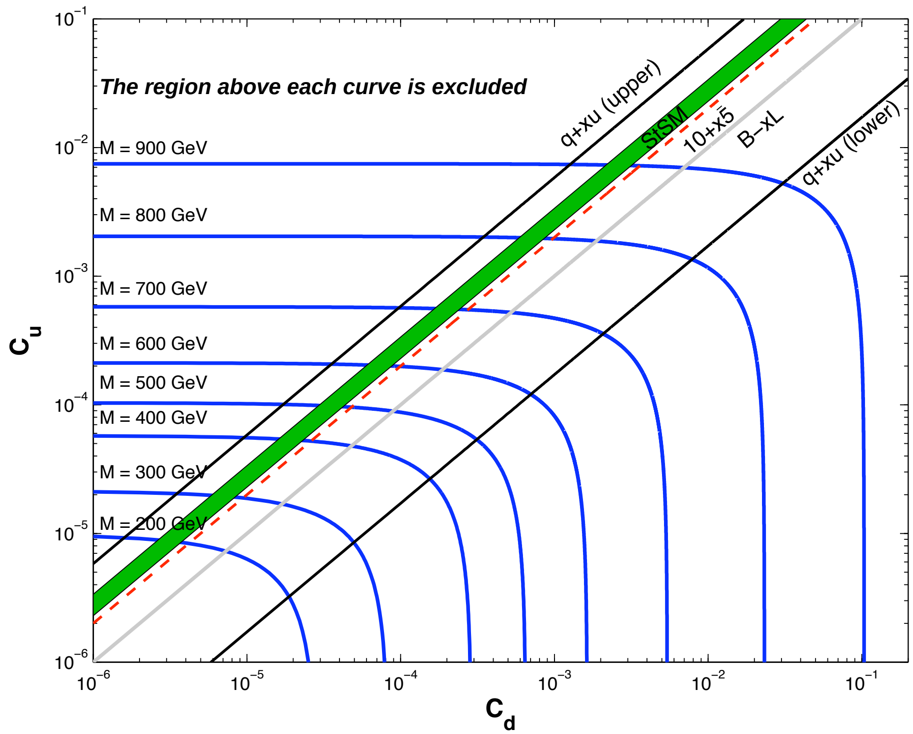


Discovering the StSM Z' via the DY Process

$$\sigma_{AB} \cdot Br(Z' \to l^+ l^-) = K \frac{\pi}{6s} \sum_q C_q \mathcal{W}_{\{AB(q\bar{q})\}}(s, M^2_{Z'})$$

$$C_q = 2g_M^2 Br(Z' \to l^+ l^-)(a'^2_q + v'^2_q), \qquad q = u, d$$

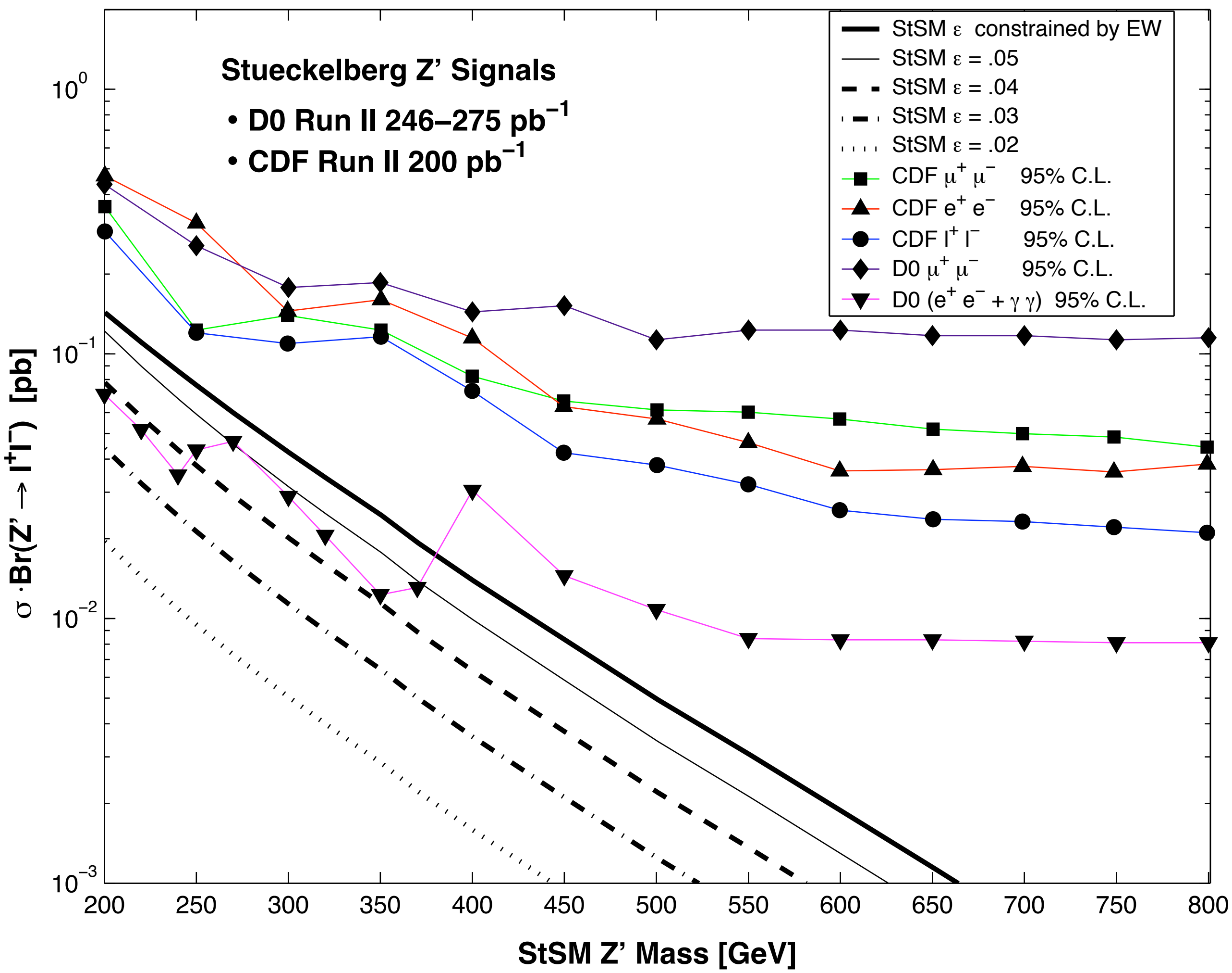
$$\frac{C_u}{C_d} = \frac{(v'^2_u + a'^2_u)}{(v'^2_d + a'^2_d)} \sim \frac{\mathrm{Br}(Z' \to u\bar{u})}{\mathrm{Br}(Z' \to d\bar{d})}.$$



D. Feldman, Z. Liu, PN: hep-ph/0606294

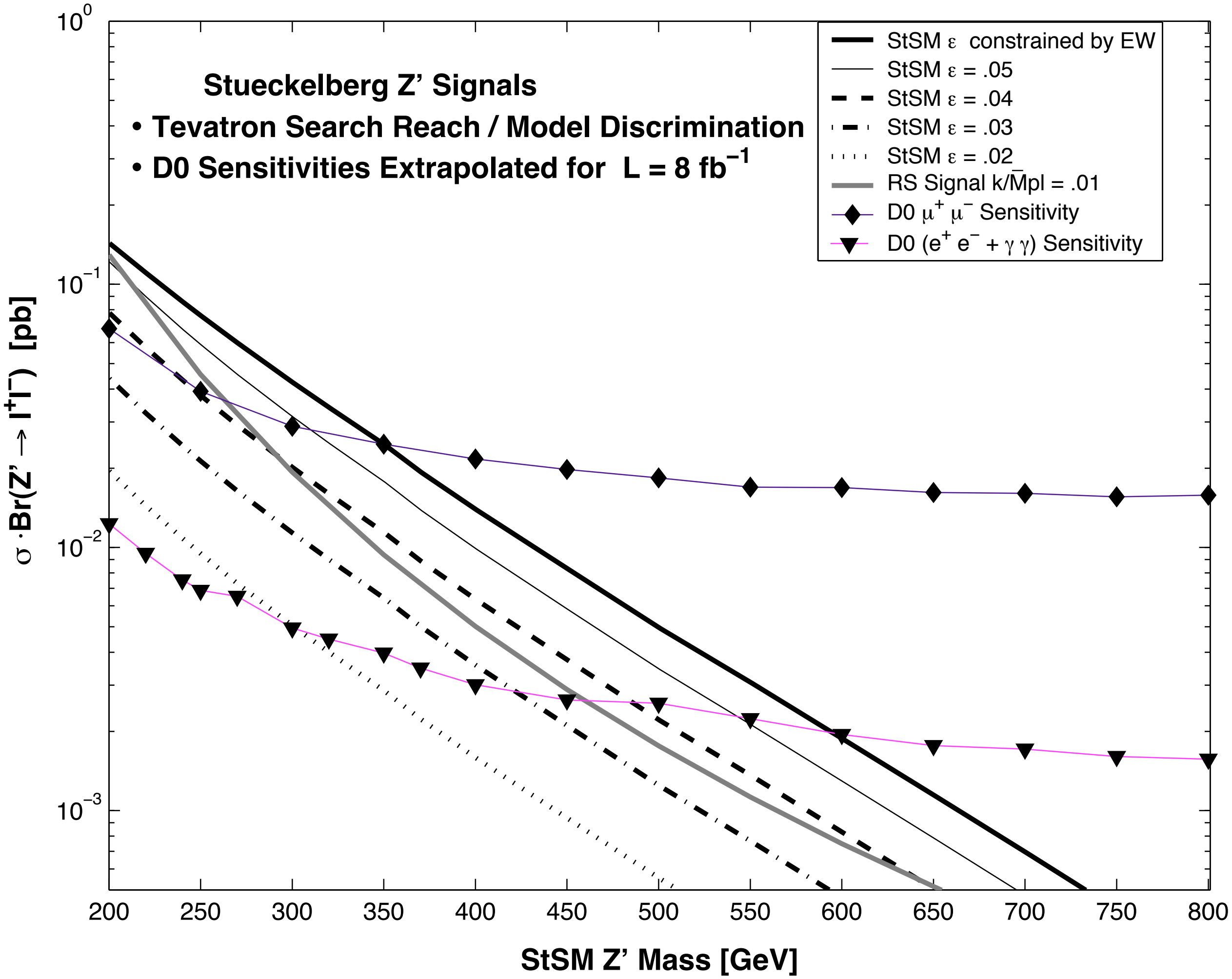
M. Carena, et.al. PRD, 70, 093009, 2004

Limits and the DY Process at the Tevatron



D. Feldman, Z. Liu, PN: PRL, 97, 021801, 2006.

Search for StSM in D0 data



$M_{Z'}$ Lower Mass limits (GeV/c^2)

Model	ee	μμ	ll (Run I)
Z'_{SM}	770	740	825 (690)
Z'_{ψ}	645	585	675
Z'_{χ}	630	605	690
Z'_{η}	675	640	720
Z'_{I}	570	540	615

PRL **95**, 252001 (2005)

$200\, pb^{-1}$

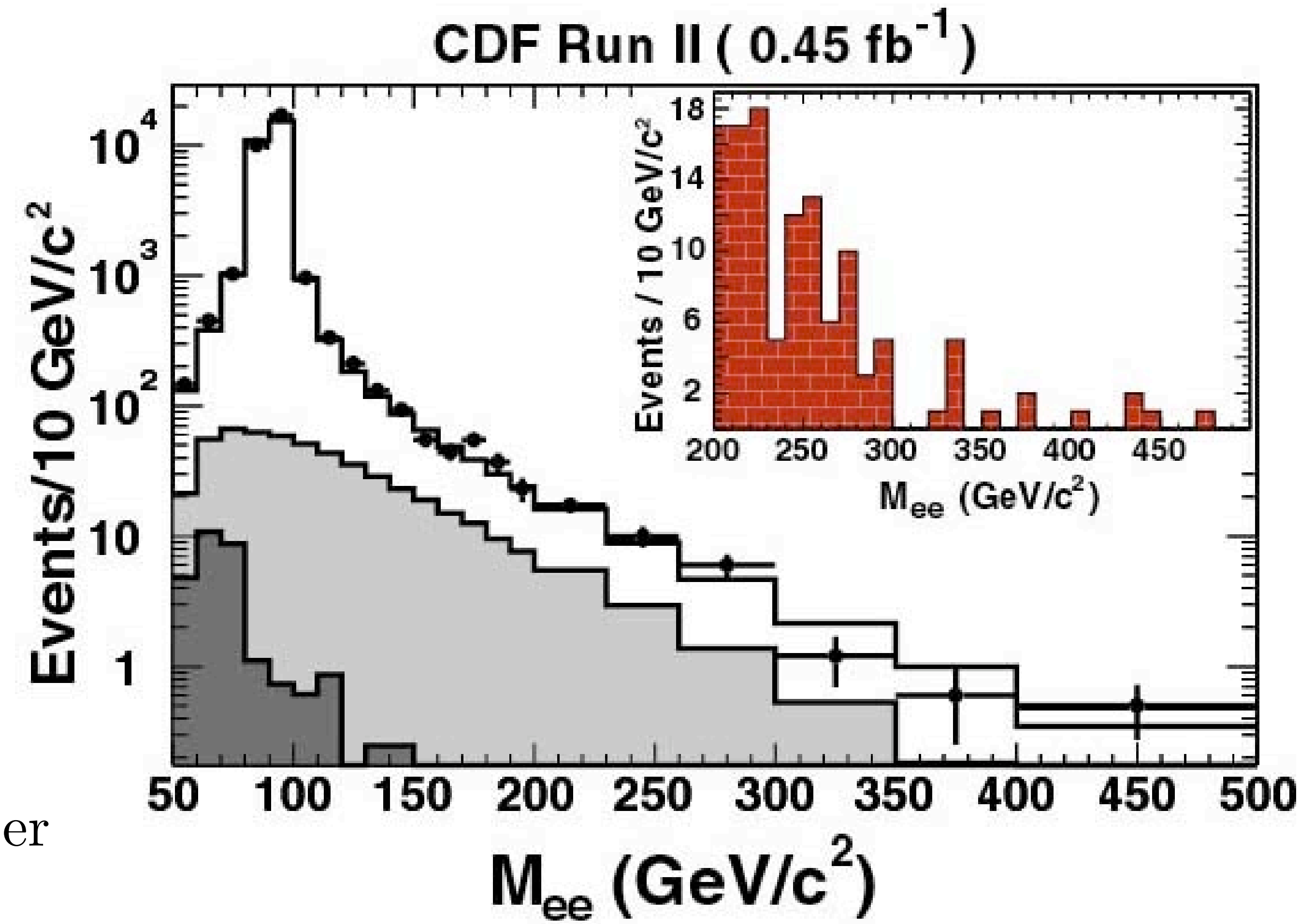
Z'_{St}

350 GeV at 200 pb^{-1} $\epsilon \approx .06$

175 GeV at 200 pb^{-1} $\epsilon \approx .04$

[A. Abulencia et al (CDF collaboration)]

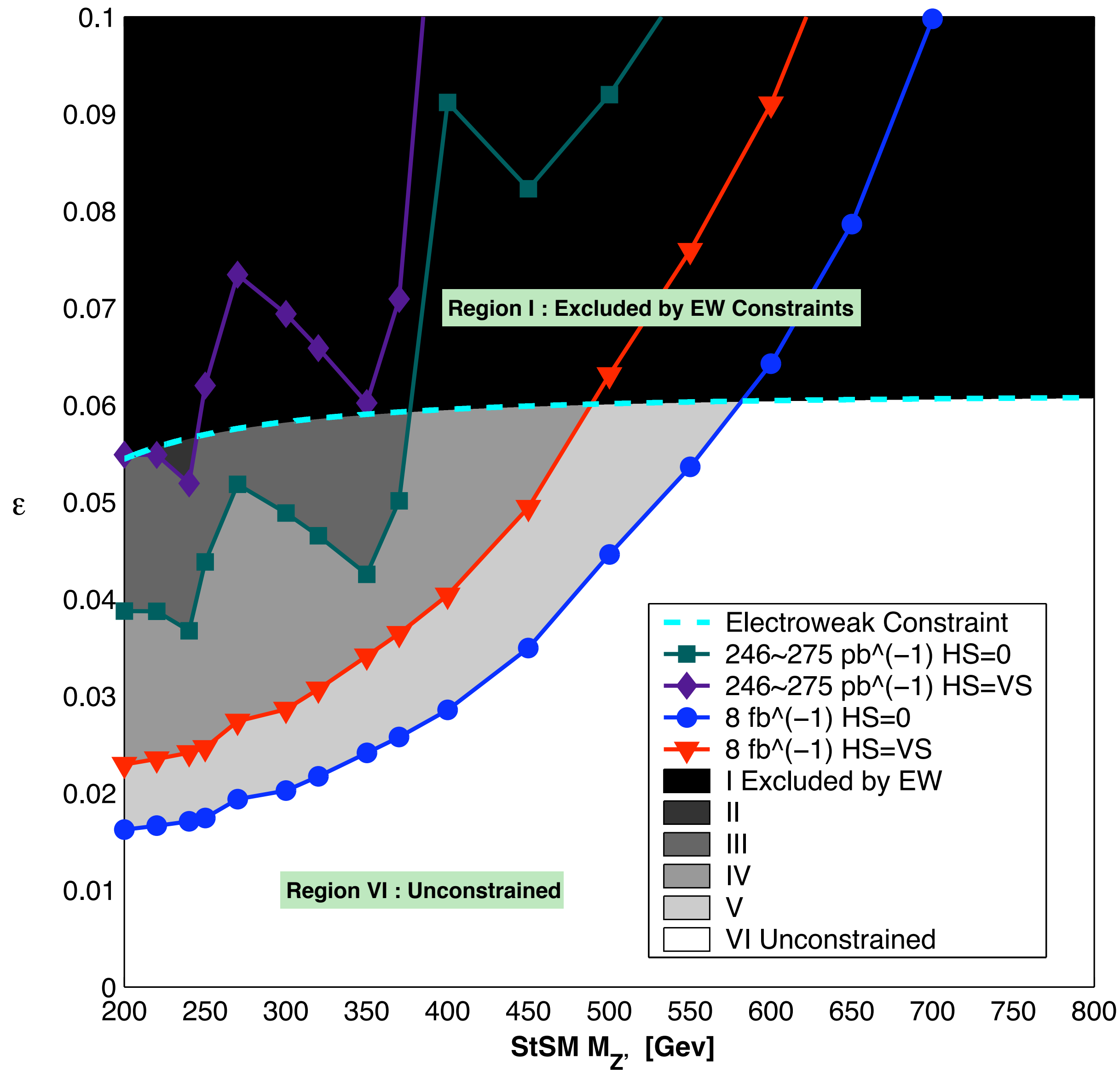
http://www.phys.ufl.edu/~hlee/hunter/



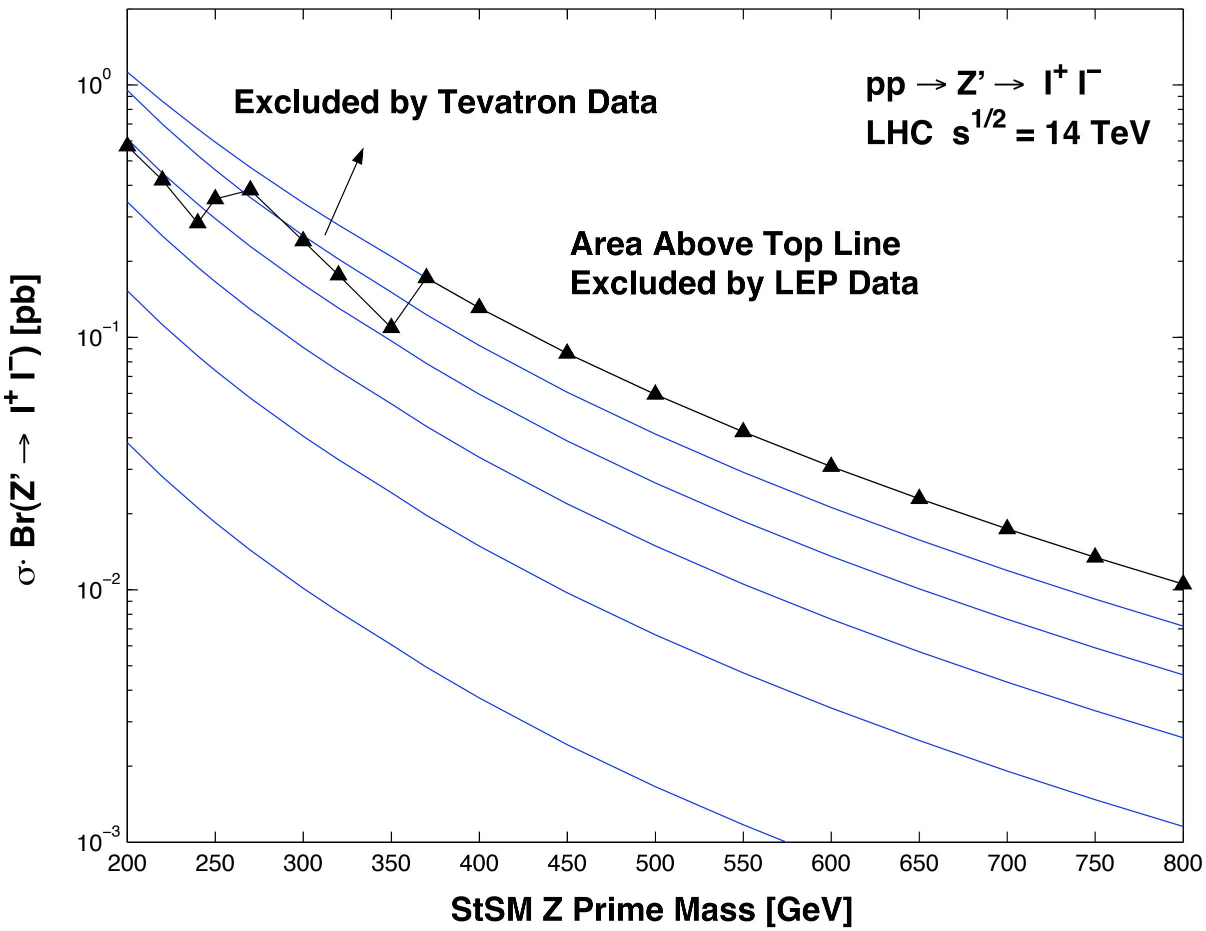
Z' Hunter

[CDF found the Z'! Or not...] The most recent CDF Run2 dielectron plot shows a bump around 175 GeV, which might be the signal of the Z'. The analysis shows no evidence of the signal at 95% CL, but it may lead to a very interesting hint on New Physics. (For example, see the recent narrow Z' model with a Stueckelberg mechanism that can have resonance of this mass without violating direct or precision test.)

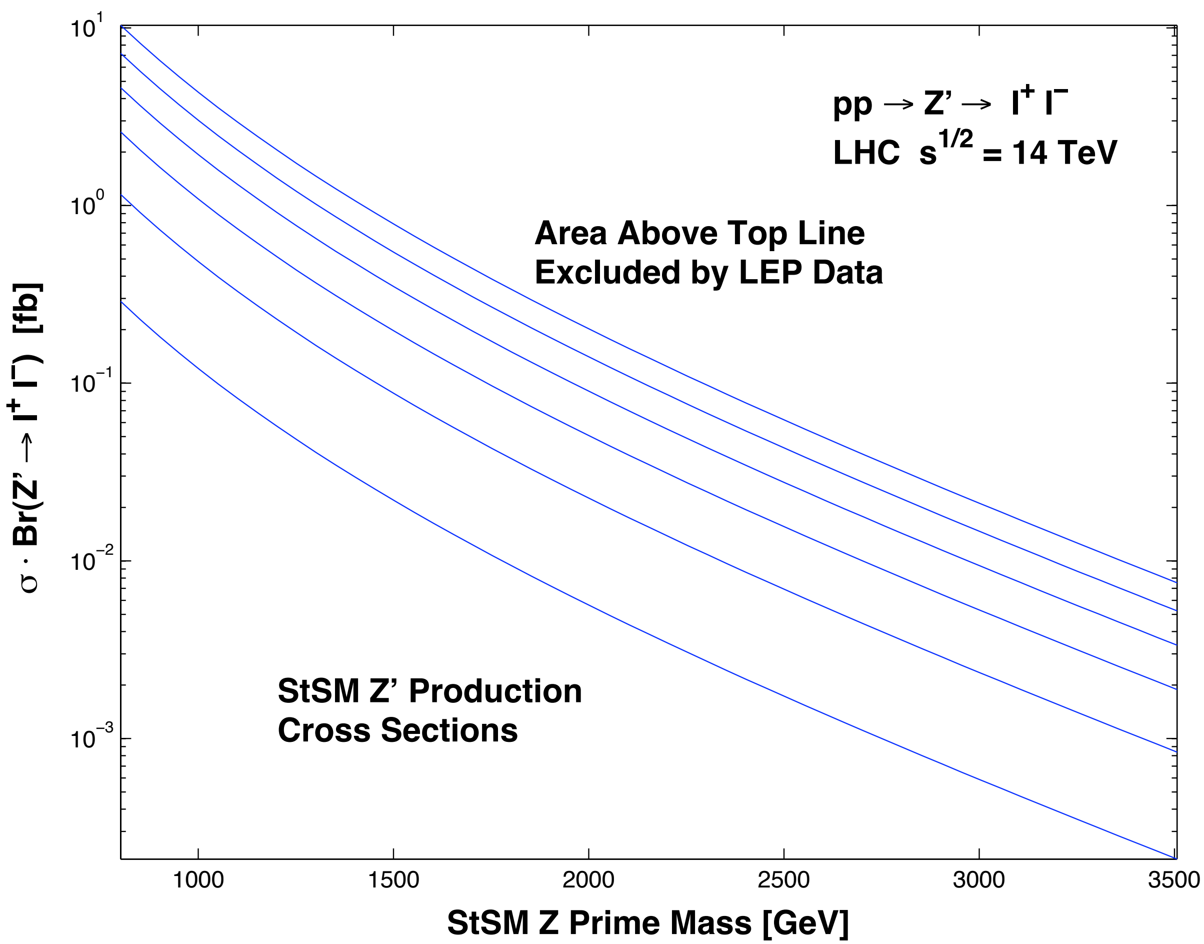
Exclusion plot in epsilon-M_Z' plane with LEP, CDF, D0 data



D. Feldman, Z. Liu, PN: PRL, 97, 021801, 2006.

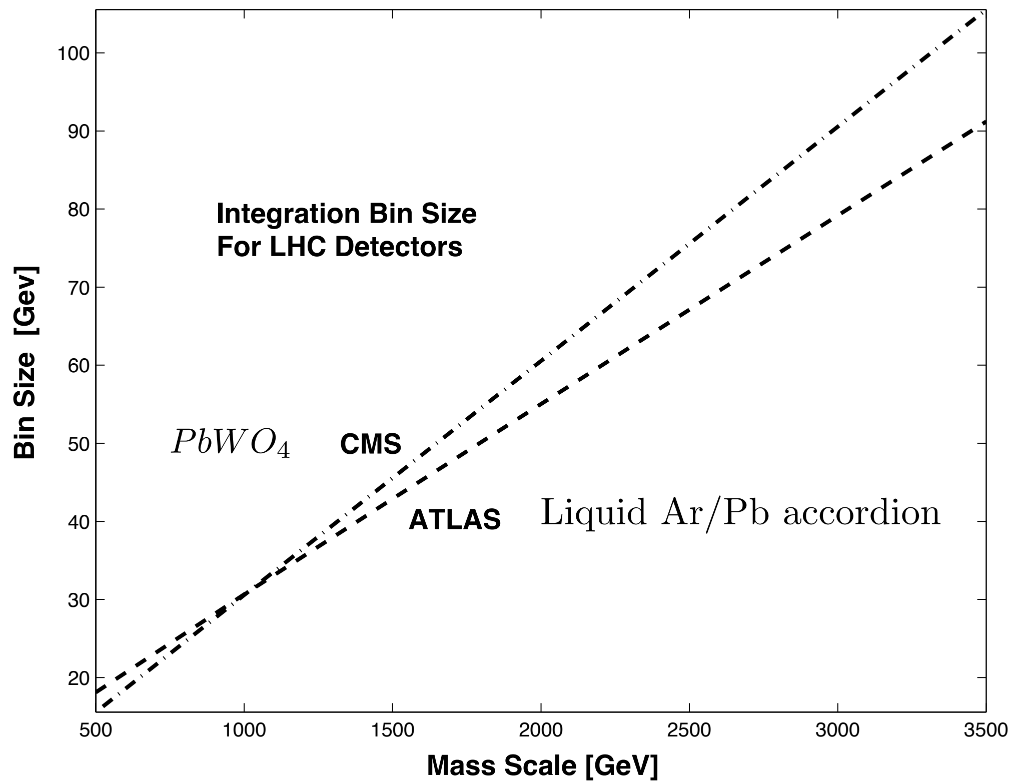


Excluded by Tevatron Data
pp → Z' → l+ l−
LHC s^1/2 = 14 TeV
Area Above Top Line
Excluded by LEP Data
σ· Br(Z' → l+ l−) [pb]
StSM Z Prime Mass [GeV]
10^0
10^−1
10^−2
10^−3
200
250
300
350
400
450
500
550
600
650
700
750
800



pp → Z' → l+ l−
LHC s1/2 = 14 TeV
Area Above Top Line
Excluded by LEP Data
StSM Z' Production
Cross Sections
σ · Br(Z' → l+ l−) [fb]
StSM Z Prime Mass [GeV]
10^1
10^0
10^−1
10^−2
10^−3
1000
1500
2000
2500
3000
3500

Bin Size

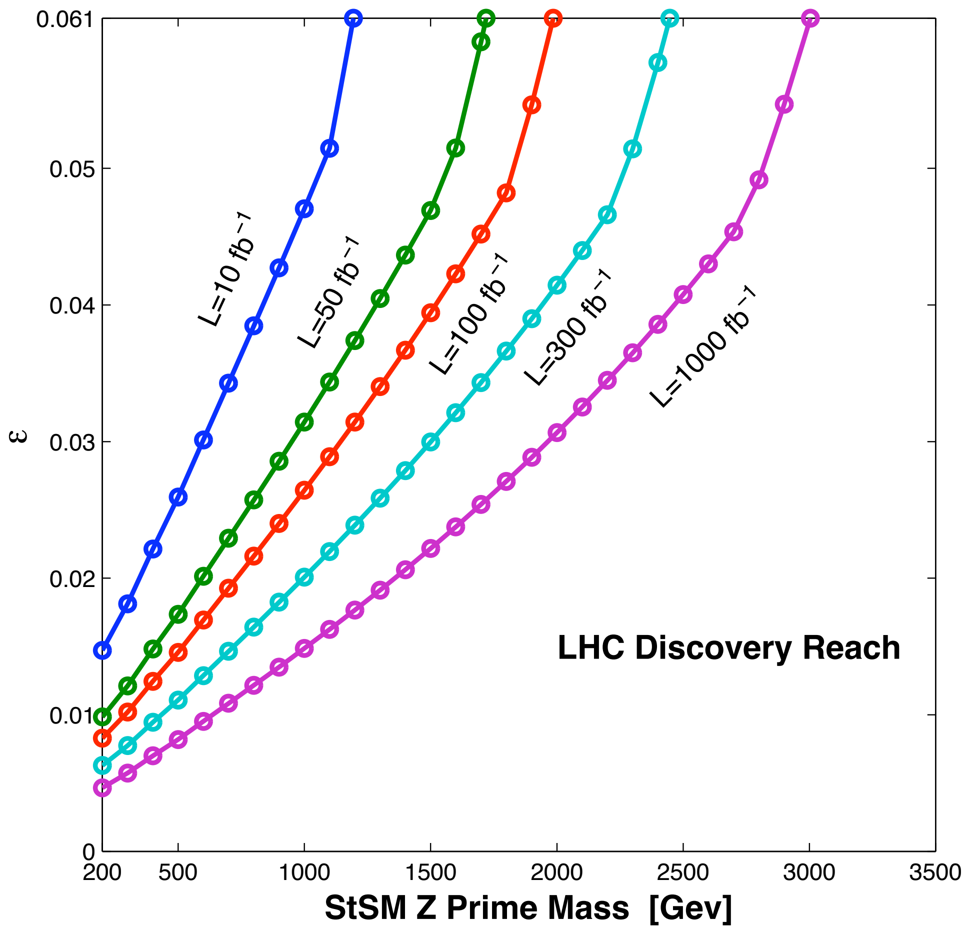


$$\sigma_E/E = a/\sqrt{E} \oplus b \oplus c/E \qquad a - Stochastic:\ b - Calibration:\ c - Noise$$

$$\mathrm{Bin}_{\mathrm{ATLAS}} = 24(.625M + M^2 + .0056)^{1/2}\mathrm{GeV}$$

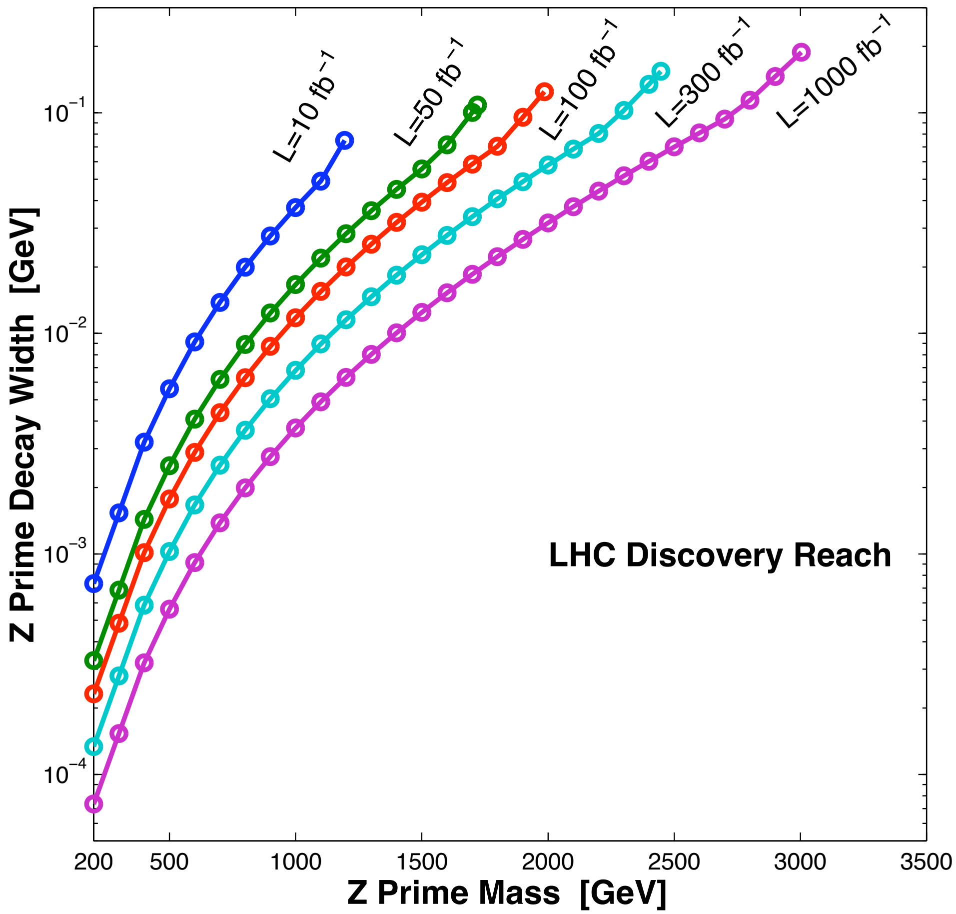
$$\mathrm{Bin}_{\mathrm{CMS}} = 30(.036M + M^2 + .0016)^{1/2}\mathrm{GeV}.$$

Probe of epsilon as a function of LHC luminosity

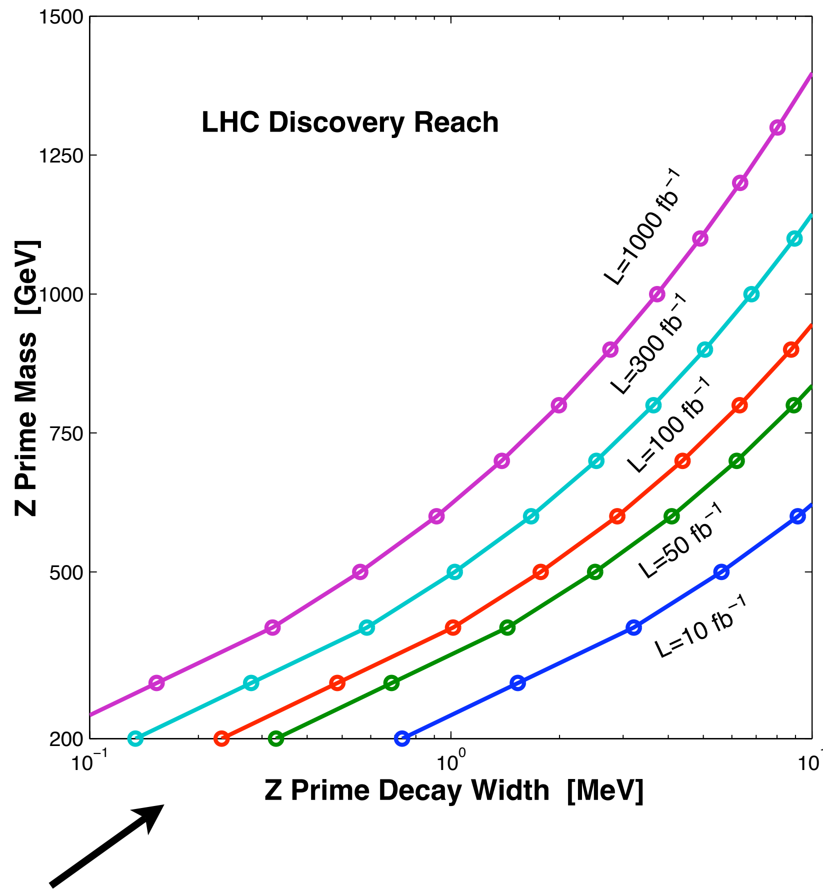


D. Feldman, Z. Liu, PN: hep-ph/0606294

Probe of StSM Z' decay width as a function of LHC luminosity



LHC can probe MeV and sub-MeV size decay widths



D. Feldman, Z. Liu, PN: hep-ph/0606294

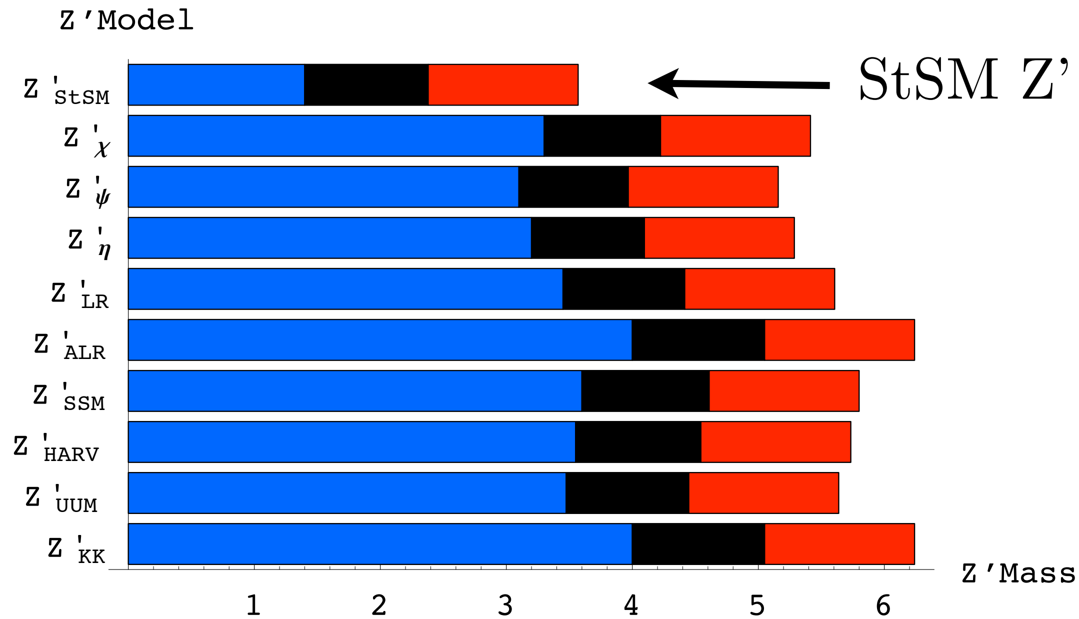
Z prime Discovery Bars

Luminosity

Blue : $10 fb^{-1}$

Black : $100 fb^{-1}$

Red : $1000 fb^{-1}$



D. Feldman, Z. Liu, PN: hep-ph/0606294

M. Cvetic and S. Godfrey, hep-ph/9504216

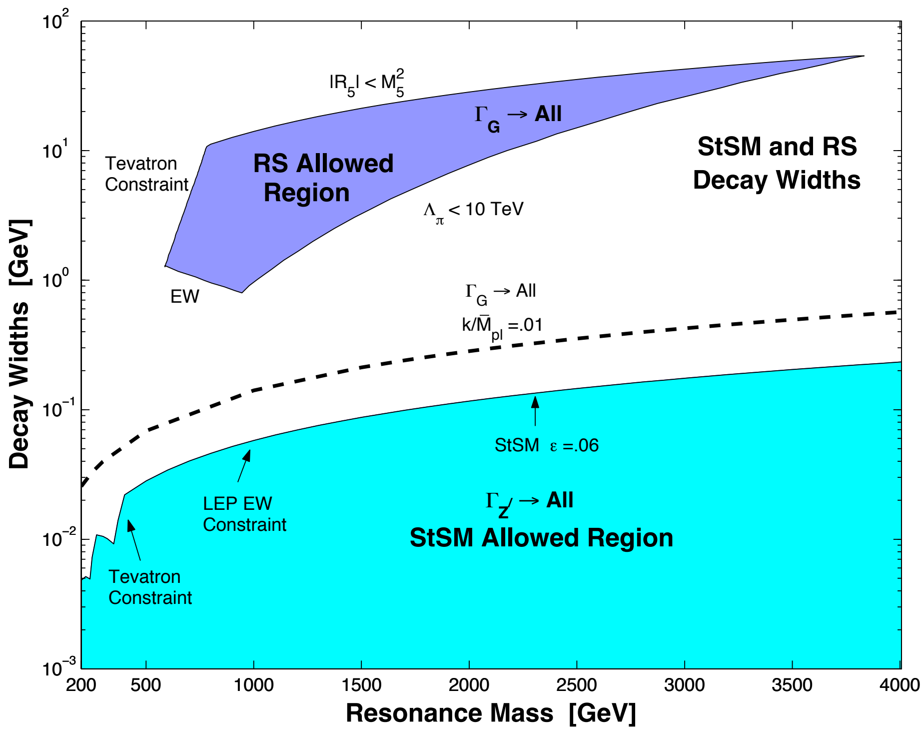
StSM Z' vs graviton of warped geometry

Effective scale in RS $\Lambda_\pi = \bar{M}_{Pl} e^{-\pi k r}$

$$\Lambda_\pi < 10\ TeV, \quad k/\bar{M}_{Pl} = 10^{-5} - .1$$

However, $k/\bar{M}_{Pl} < .01$ appears to be eliminated by EW constraints

Comparison of decay widths of StSM Z' vs RS graviton

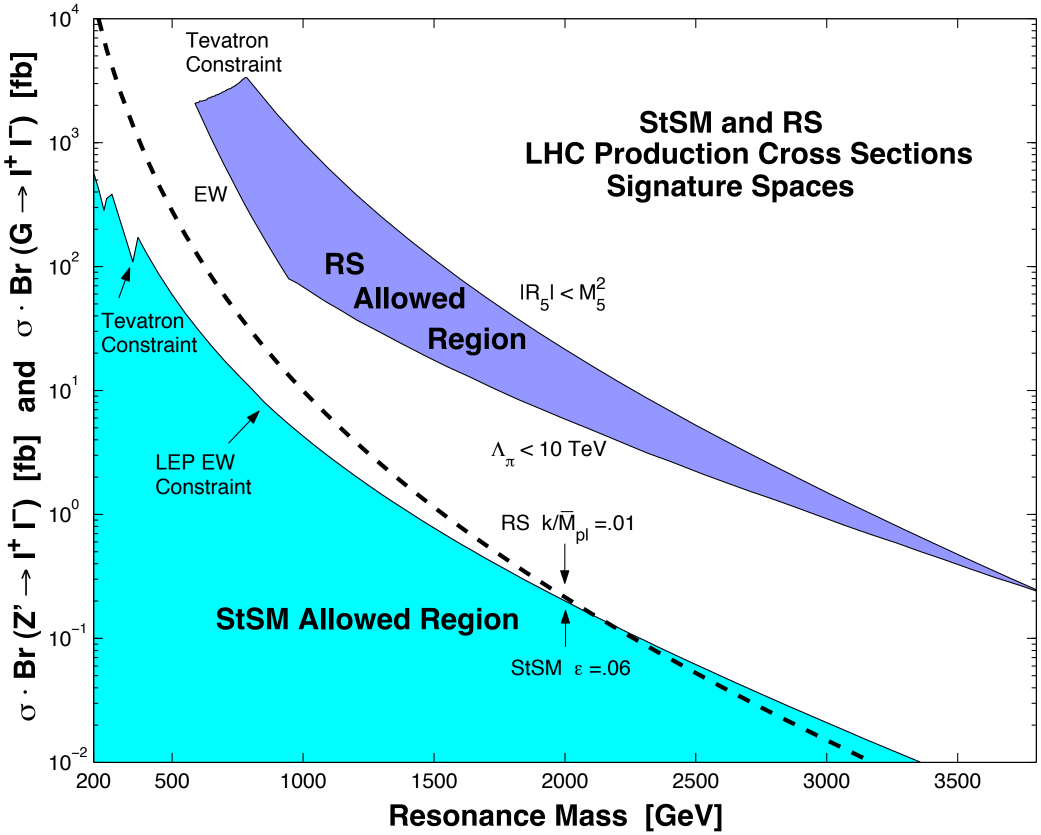


D. Feldman, Z. Liu, PN: hep-ph/0606294

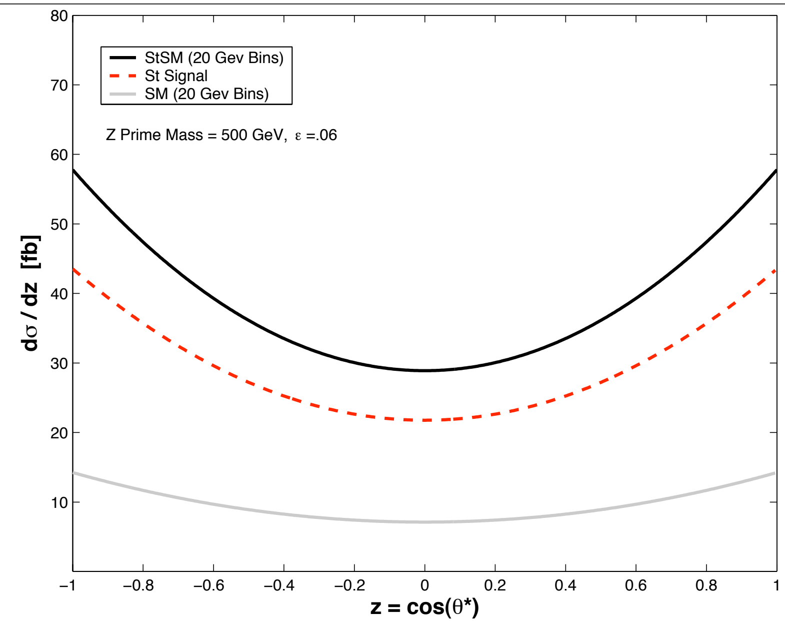
Drell-Yan at the LHC

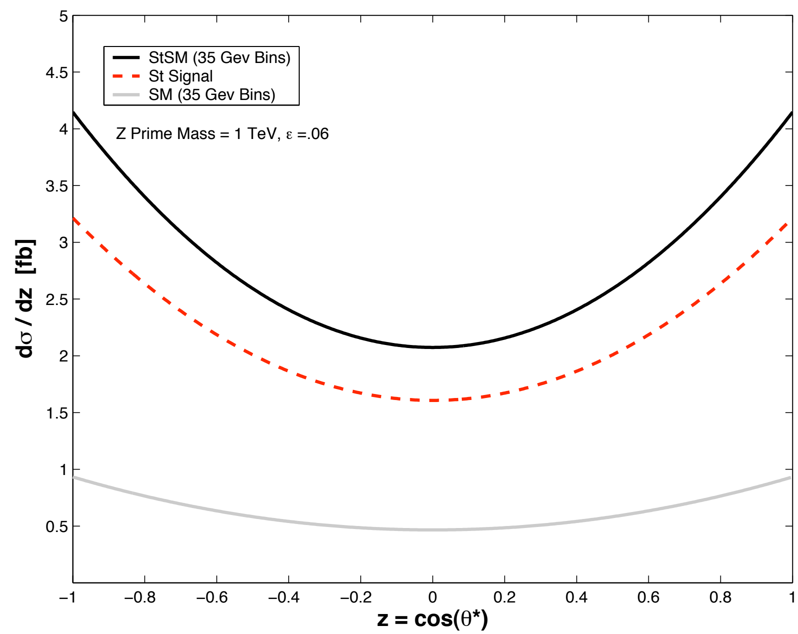
$$pp \to Z' \to l^+ l^-$$

$$pp \to G \to l^+ l^-$$

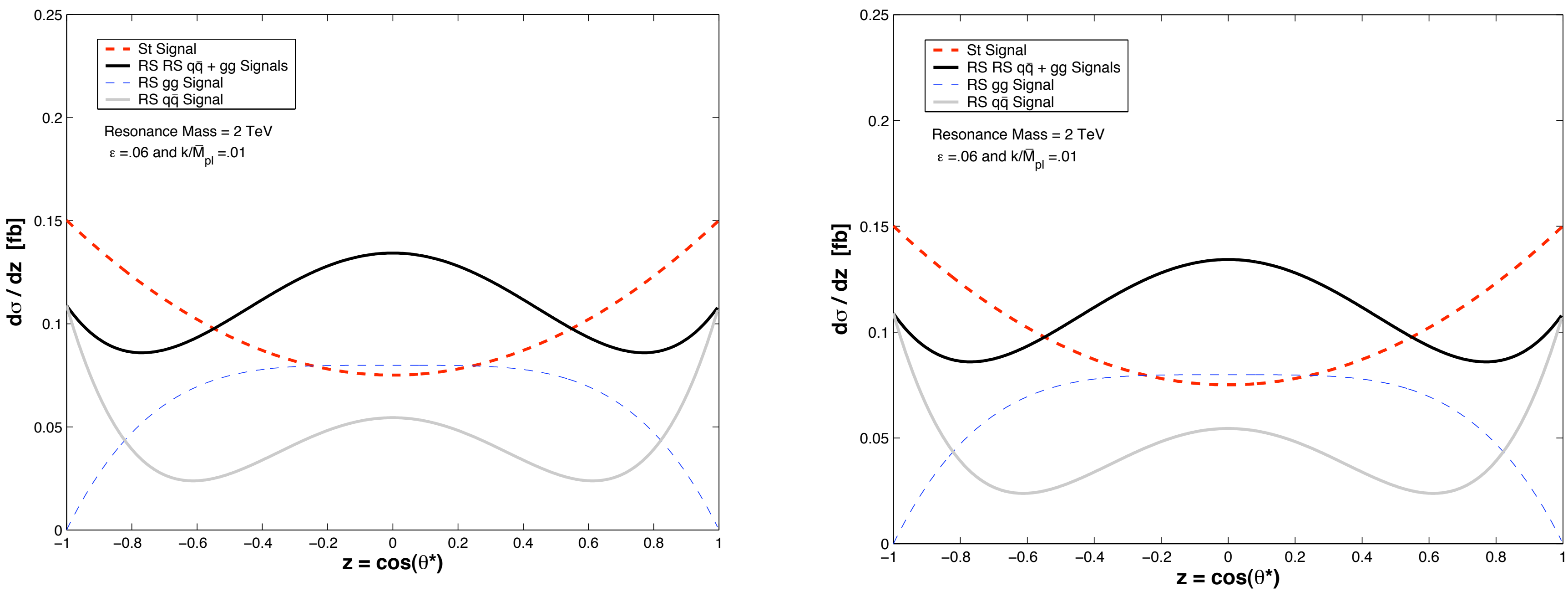


D. Feldman, Z. Liu, PN: hep-ph/0606294


StSM (20 Gev Bins)
St Signal
SM (20 Gev Bins)
Z Prime Mass = 500 GeV, ε =.06
dσ / dz [fb]
z = cos(θ*)
80
70
60
50
40
30
20
10
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1


StSM (35 Gev Bins)
St Signal
SM (35 Gev Bins)
Z Prime Mass = 1 TeV, ε =.06
dσ / dz [fb]
z = cos(θ*)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1

Angular distributions for StSM Z'and RS Graviton in Drell-Yan



D. Feldman, Z. Liu, PN: hep-ph/0606294

The StMSSM Extension

We focus on the extended abelian gauge group $U(1)_Y \times U(1)_X$.

$$\mathcal{L}_{\rm St} = \left[M_1 C + M_2 B + S + \bar{S}\right]^2_{\theta\theta} \ , \tag{1}$$

Invariance under $U(1)_Y$ and $U(1)_X$ transformations

$$\begin{aligned} \delta_Y B = \Lambda_Y + \bar{\Lambda}_Y \ , &\quad \delta_Y S = -M_2 \Lambda_Y \ , \\ \delta_X C = \Lambda_X + \bar{\Lambda}_X \ , &\quad \delta_X S = -M_1 \Lambda_X \ . \end{aligned} \tag{2}$$

The total Lagrangian

$$\mathcal{L}_{\rm StMSSM} = \mathcal{L}_{\rm MSSM} + \Delta\mathcal{L}_{\rm St} + \Delta\mathcal{L}_{\rm hidden}$$

where

$$\begin{aligned} \Delta\mathcal{L}_{\rm St} \ = \ & -\frac{1}{2}(M_1 C_\mu + M_2 B_\mu + \partial_\mu a)^2 - \frac{1}{2}(\partial_\mu \rho)^2 \\ & -\frac{1}{2}(M_1^2 + M_2^2)\rho^2 - \frac{i}{2}\bar{\psi}_S \gamma^\mu \partial_\mu \psi_S - \frac{1}{4} C_{\mu\nu} C^{\mu\nu} \\ & -\frac{i}{2}\bar{\lambda}_X \gamma^\mu \partial_\mu \lambda_X + M_1 \bar{\psi}_S \lambda_X + M_2 \bar{\psi}_S \lambda_Y \\ & -\rho g_Y M_2 \sum_i \bar{z}_i Y z_i + \ \cdots \ , \end{aligned} \tag{3}$$

New degrees of freedom

$$C : C_\mu, \ \lambda_X; \qquad S : \rho + ia, \ \psi_S$$

B, Kors and PN, JHEP 0412, 005 (200); JHEP, 0507, 069 (2003).

SUSY U(1) Higgs → SUSY stueckelberg

The scalar potential suppressing the V_F part

$$V = \frac{g_X^2}{2}(Q_X|\phi^+|^2 - Q_X|\phi^-|^2 + \xi_X)^2$$

Minimization conditions

$$< \phi^+ >= 0, \quad < \phi^- >= \sqrt{\frac{\xi_X}{Q_X}}$$

It is convenient to introduce new variables

$$\phi^- =< \phi^- > + \frac{1}{\sqrt{2}}(\rho + ia)$$

- In the limit

  $$g_X \to 0, \quad < \phi^- >\to \infty$$

  $$\sqrt{2}g_X < |\phi^-| >\to M$$

  the SUSY Abelian Higgs reduces to the SUSY St formulation.

- In addition the chiral superfield ϕ^+ decouples.

- The Fayet-Iliopoulos D term $\xi_X D_C$ plays a central role in the connection.

The Neutral Scalar Sector

The StMSSM does not affect the mass of the CP-odd neutral scalar A^0 in the MSSM

The three CP-even neutral scalars

$$(h_1^0, h_2^0, \rho)$$

$$\left[\begin{array}{cc|c} M_0^2 c_\beta^2 + m_A^2 s_\beta^2 & -(M_0^2 + m_A^2) s_\beta c_\beta & -t_\theta c_\beta M_{\rm W} M_2 \\ -(M_0^2 + m_A^2) s_\beta c_\beta & M_0^2 s_\beta^2 + m_A^2 c_\beta^2 & t_\theta s_\beta M_{\rm W} M_2 \\ \hline -t_\theta c_\beta M_{\rm W} M_2 & t_\theta s_\beta M_{\rm W} M_2 & m_\rho^2 \end{array}\right]$$

$$s_\beta, c_\beta = \sin(\beta), \cos(\beta), t_\theta = \tan(\theta_W)$$

$$M_0^2 = (g_2^2 + g_Y^2)(v_1^2 + v_2^2)/4 \simeq M_{\rm Z}^2$$

One can organize the three eigen states as (H_1^0, H_2^0, ρ_S) such that

$$M_2/M_1 \to 0, (H_1^0, H_2^0, \rho_S) \to (H^0, h^0, \rho)$$

H^0 and h^0 are the heavy and the light CP-even neutral Higgs of the MSSM.

The new real scalar ρ_S is dominantly ρ, but it also carries small components of H^0 and h^0.

B, Kors and PN, JHEP 0412, 005 (200); JHEP, 0507, 069 (2003).

The neutralino sector of StMSSM

Instead of four neutralinos in the MSSM one has six in *StMSSM*

$$\psi_S, \lambda_X, \lambda_Y, \lambda_3, \tilde{h}_1, \tilde{h}_2.$$

After spontaneous electro-weak symmetry breaking the 6×6 neutralino mass matrix

$$\left[\begin{array}{cc|cccc} 0 & M_1 & M_2 & 0 & 0 & 0 \\ M_1 & \tilde{m}_X & 0 & 0 & 0 & 0 \\ \hline M_2 & 0 & \tilde{m}_1 & 0 & -c_1 M_0 & c_2 M_0 \\ 0 & 0 & 0 & \tilde{m}_2 & c_3 M_0 & -c_4 M_0 \\ 0 & 0 & -c_1 M_0 & c_3 M_0 & 0 & -\mu \\ 0 & 0 & c_2 M_0 & -c_4 M_0 & -\mu & 0 \end{array}\right] . \tag{1}$$

the extra states in the limit $M_2/M_1 \to 0$

$$m_{\tilde{\chi}_5^0},\ m_{\tilde{\chi}_6^0} \ = \ \sqrt{M_1^2 + \frac{1}{4}\tilde{m}_X^2} \pm \frac{1}{2}\tilde{m}_X \ , \quad m_{\tilde{\chi}_5^0} \geq m_{\tilde{\chi}_6^0} \ .$$

- As long as $m_{\tilde{\chi}_6^0} > m_{\tilde{\chi}_1^0}$, the lightest neutralino of the MSSM, $\tilde{\chi}_1^0$, will still function as the LSP of StMSSM.
- However, when $m_{\tilde{\chi}_6^0} < m_{\tilde{\chi}_1^0}$, $\tilde{\chi}_{\rm St}^0 = \tilde{\chi}_6^0$ becomes the LSP and (with R-parity conservation) a dark matter candidate.

Relic density of extra weak WIMPS

Although the eWIMPS are extra weakly interacting one could still get a desired relic density via co-annihilation of eWIMPS (ξ^0) and WIMPS (χ^0) via the following set of processes

$$\xi^0 + \xi^0 \to X$$
$$\xi^0 + \chi^0 \to X'$$
$$\chi^0 + \chi^0 \to X"$$

The effective cross -section in this case is

$$\sigma_{eff} = \sigma_{\chi^0\chi^0} \frac{1}{(1+Q)^2}(Q + \frac{\sigma_{\xi^0\chi^0}}{\sigma_{\chi^0\chi^0}})^2$$
$$When Q = \frac{g_{\chi^0}}{g_{\xi^0}}(1+\Delta)^{\frac{3}{2}} e^{-x_f\Delta}$$

g is the degeneracy for the corresponding particle.

$$\Delta = (m_{\chi^0} - m_{\xi^0})/m_{\xi^0}$$

$Q >> \frac{\sigma_{\xi^0\chi^0}}{\sigma_{\chi^0\chi^0}}$ one has σ_{eff} in the form

$$\sigma_{eff} \simeq \sigma_{\chi^0\chi^0}(\frac{Q}{1+Q})^2$$

Since $Q \sim O(1)$ the eWIMP relic density is just a modification of SUGRA WIMIP relic density.

Conclusions/Prospects

The StSM extension predicts a sharp Z' resonance with a width in the MeV-GeV range.

The StSM Z' appears in a region where the RS graviton is already eliminated by precision electroweak data.

Analysis indicates that the dilepton channel via the Drell-Yan can allow one to probe StSM Z' up to about 3.5 TeV at the LHC.

The model also predicts a new unit of elecric charge with which the photon couples with the hidden sector.

The Stueckelberg extension of MSSM has additional features: two more neutralinos and a possible new candidate for dark matter.

Models of this type could arise from type IIB strings and some work has recently appeared along this line.