Z' gauge bosons at the LHC start-up

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What is a Z' ?

to a theorist it could be many things...

It is useful to classify the Z' according to its spin
(even though measuring the spin will require high statistics):

Spin-0 (e.g. sneutrino in R-parity violating SUSY)
Spin-2 (e.g. KK excited graviton as in Randall-Sundrum)
Spin-1 (the only cases considered here, e.g.

a) a new U(1) gauge boson from E_6 or L-R models

b) KK excited Z bosons from ED and/or Higgsless models

c) Techni-rho bound states from Walking TC models)

Z' from an extra U(1) gauge group

3 most popular classes of models

- **SSM** or SM-like: not realistic but used as benchmark

- **E_6 models** :
- E_6 -> SO(10) x U(1) -> SU(5) x U(1) x U(1) -> SM x U(1)
- $U(1) = \cos\theta\, U(1)_\chi + \sin\theta\, U(1)_\psi$

- **LR models:**
- $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(2)_L \times U(1)_Y \times U(1)$
- $U(1) = \cos\varphi\, U(1)_R + \sin\varphi\, U(1)_{B-L}$
- N.B. left-right symmetry implies $\varphi = -23^o$
- other values are a pheno generalization

Z' from an extra U(1) gauge group

3 most popular classes of models

D0 Note 5923-CONF

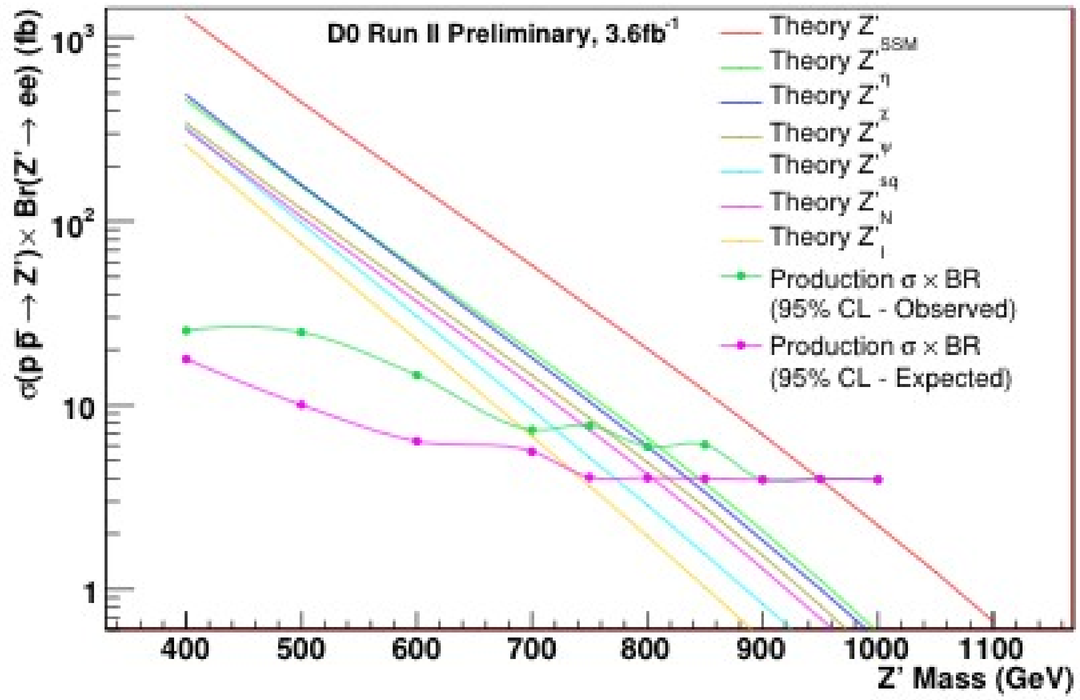


FIG. 5: The upper limit on the observed and expected cross section at 95% CL with superimposed the SSM Z', and E6 Z' models.

Z' from an extra U(1) gauge group

3 most popular classes of models

D0 Note 5923-CONF

TABLE IV: Expected and observed lower mass limits for the SSM Z', E6 Z' models, and RS gravitons.

Model	Nominal		Conservative	
	Expected Lower Mass Limit (GeV/c^2)	Observed Lower Mass Limit (GeV/c^2)	Expected Lower Mass Limit (GeV/c^2)	Observed Lower Mass Limit (GeV/c^2)
Z'_{SSM}	949	950	942	944
Z'_{η}	844	810	837	800
Z'_{χ}	834	800	827	787
Z'_{ψ}	817	763	809	751
Z'_{sq}	774	719	767	713
Z'_{N}	803	744	796	736
Z'_{I}	732	692	716	683
RS ($k/M_{Pl} = 0.1$)	826	786	819	767
RS ($k/M_{Pl} = 0.07$)	767	708	758	700

D0 3.6 fb^{-1}: Mass limit ~ 700-800 GeV

Warped Extra Dimensions

a special class of models

With $SU(2)_L$ x $SU(2)_R$ x U(1) in the bulk we can break the electroweak gauge symmetry by boundary conditions
"Higgsless models"

or the Higgs may be located close to TeV brane
"Walking TechniColor models"

They both predict spin-1 KK excited versions of W and Z-gauge bosons

Strong motivation for extra U(1)'s: delaying the violation of perturbative unitarity

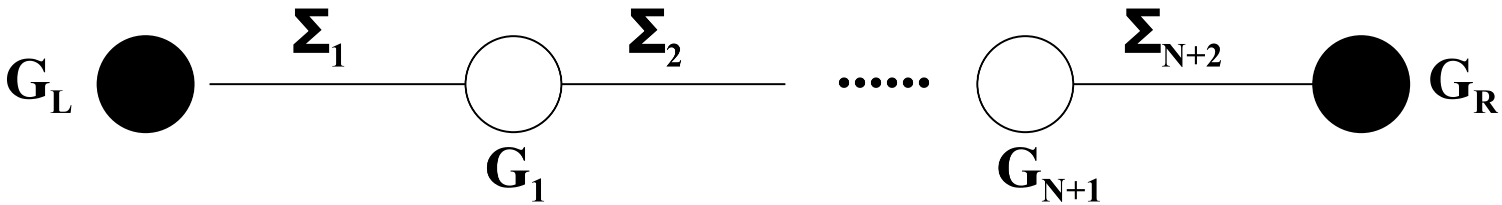
Higgsless Models and New gauge bosons

... a bit of history

•**BESS `85** **[Casalbuoni, De Curtis, Dominici, Gatto]**	**1 extra vector boson**
•**Extra dimension `90** **[Antoniadis, Arkani-Hamed, Dimopoulos, Dvali, ...]**	**A tower of extra bosons**
•**Deconstructed models `00** **[Arkani-Hamed, Cohen, Georgi, Hill, Pokorsky, Wang, ...]**	**1 and more extra bosons**
•**Linear Moose model** **[Foadi et al., Casalbuoni et al., Chivukula et al., ...]**	**1 and more extra bosons**

The Higgsless Linear Moose model

or the most general framework



● The '85 BESS model can be recast in a 3-site model (N=0), and its extension (N=1) in a

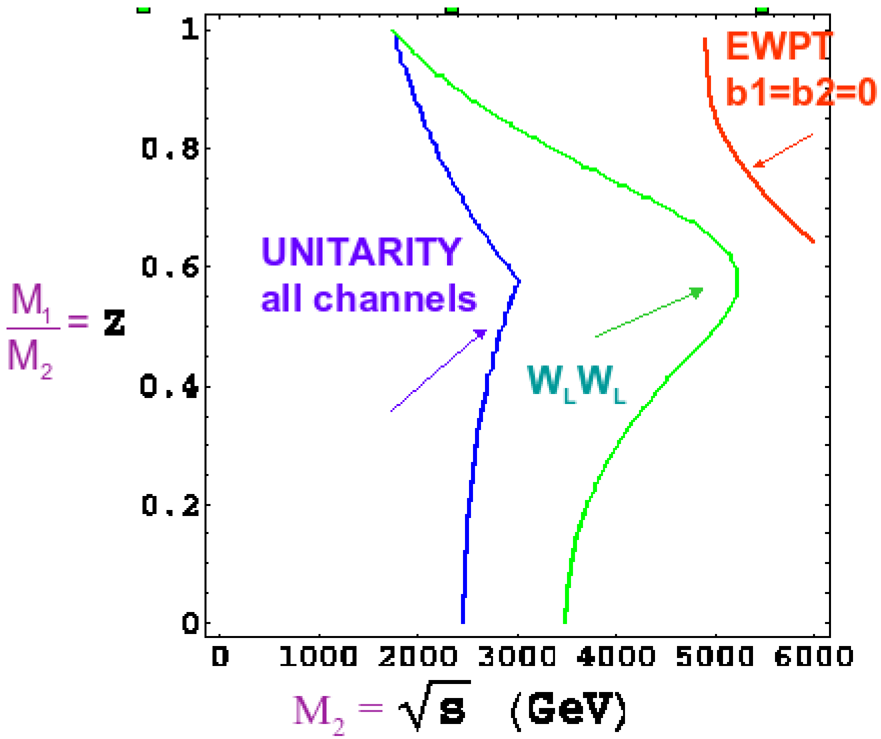
4-site Linear Moose model (N=1)

(Casalbuoni, De Curtis, Dominici, Gatto, Feruglio, '89, see also E.A., '08, Foadi, Frandsen, Ryttov, Sannino, '07)

- Gauge groups G_i=SU(2) with symmetry $SU(2)_L \ast SU(2)_R$
- 6 extra gauge bosons $W`_{1,2}$ and $Z`_{1,2}$
- 4 new parameters $\{M_1, M_2, b_1, b_2, g_1\}$ related to their 2 masses and couplings to bosons and fermions.

The Higgsless 4-site Linear Moose model

Unitarity versus EW precision tests



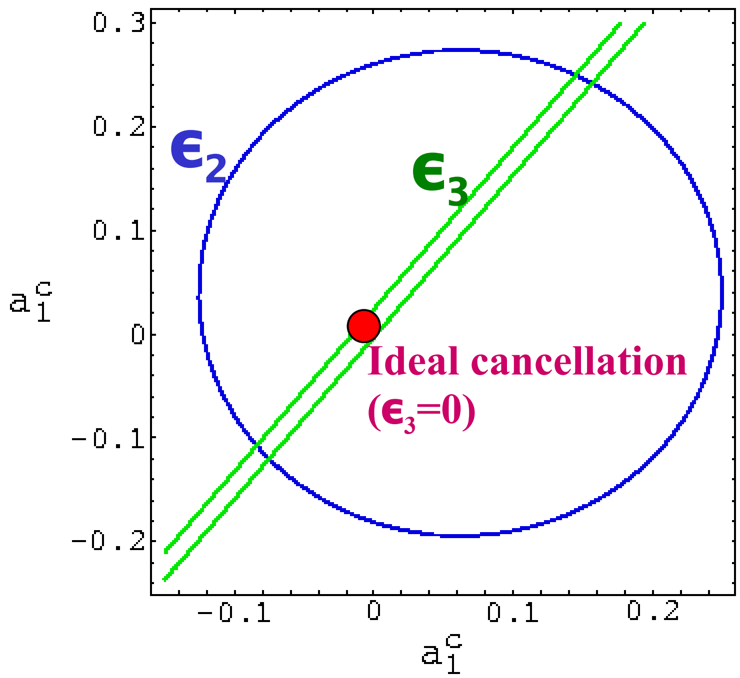
Generally, in Higgsless theories, Unitarity and EWPT are hardly compatible!

A direct coupling between new gauge bosons and ordinary SM matter must be included: $b_{1,2} \neq 0$

The Higgsless 4-site Linear Moose model

and the EW precision tests

De Curtis, Dominici, Fedeli



Bounds on charged couplings (and masses) from low energy precision measurements ϵ_i

$-0.1 < a^c_{1,2}(W`_{1,2}\ ff) < 0.25$

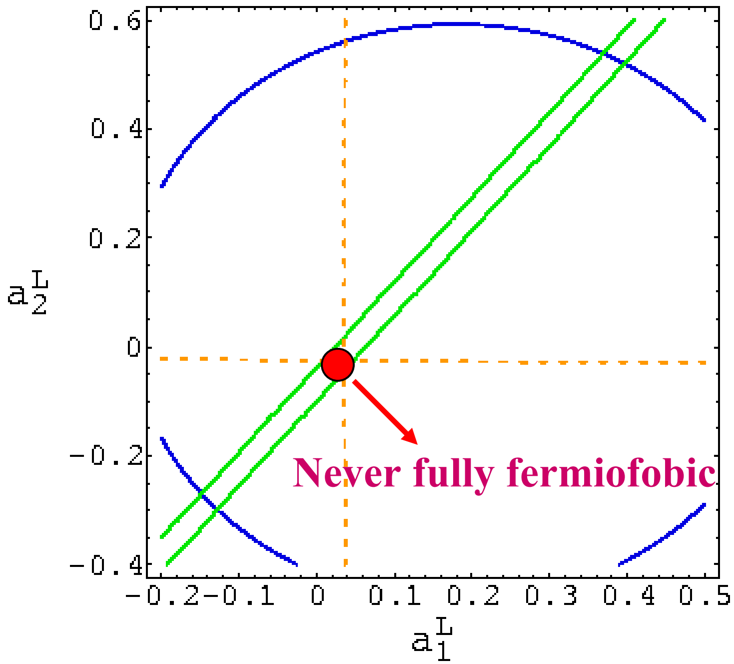
M_1=1000 GeV and M_2=1250 GeV

couplings are SM-size

The Higgsless 4-site Linear Moose model

and the EW precision tests

De Curtis, Dominici, Fedeli



Bounds on <u>neutral couplings</u> (and masses) from low energy precision measurements ϵ_i

$-0.3 < a^L_{1,2}(Z`_{1,2}\ ff) < 0.5$

M_1=1000 GeV and M_2=1250 GeV

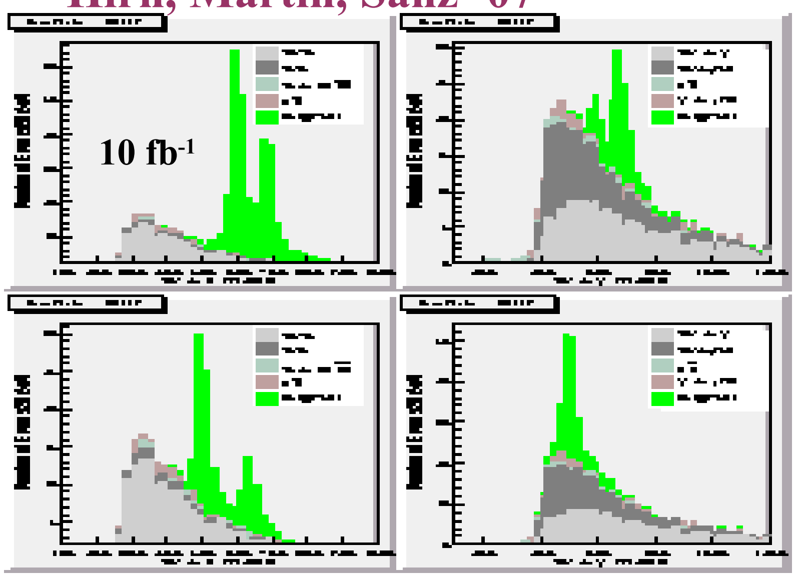
couplings are SM-size

Higgsless Models and new $Z_{1,2}$ and $W_{1,2}$ at the LHC

Owing to the usual tension between unitarity and EW precision tests, the extra gauge-boson couplings to SM matter must be small!

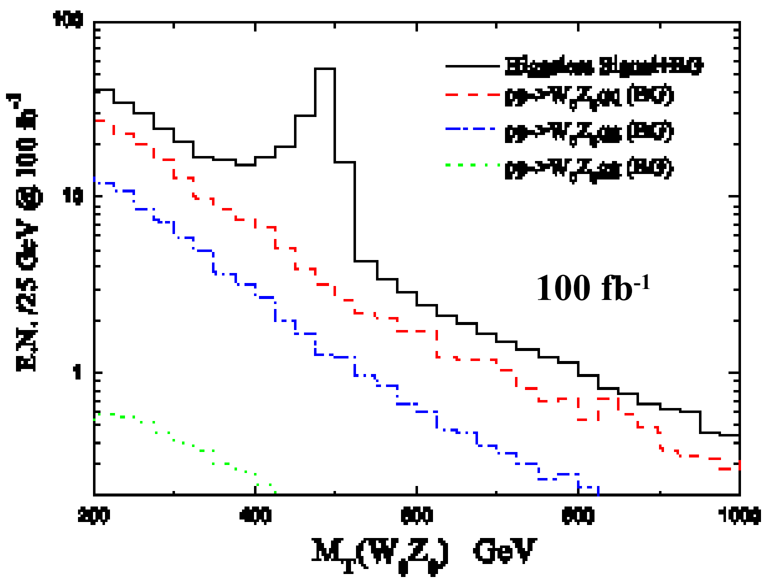
In literature main focus was on complex processes

Hirn, Martin, Sanz `07



di-boson production

Belyaev, Chivukula et al. `08



Vector boson scattering

Higgsless Models and new $Z_{1,2}$ and $W_{1,2}$ at the LHC

Drell-Yan processes can be as well

a good EWSB discovery channel

Let`s start from the simple!

Belyaev et al. Phys. Rev. '09
E.A., De Curtis, Dominici, Fedeli, Phys. Rev. '08

Event Generator FAST_2f

(E.A.)

FAST_2f is an upgrade of PHASE [E.A., Ballestrero, Maina], a MCEG for multi-particle processes at the LHC. It is dedicated to Drell-Yan processes at the Leading-Order and it is interfaced with PYTHIA

Processes

We consider charged and neutral Drell-Yan leptonic channels

- **pp -> *ll* with *l*=e,μ**
- **pp -> $l\nu$ with *l*=e,μ and $l\nu = l^-\nu + l^+\nu$**

Kinematical cuts

Acceptance cuts:

$\eta(l)<2.5$, $P_t(l)>20$ GeV, $P_t^{miss}>20$ GeV

Selection cuts:

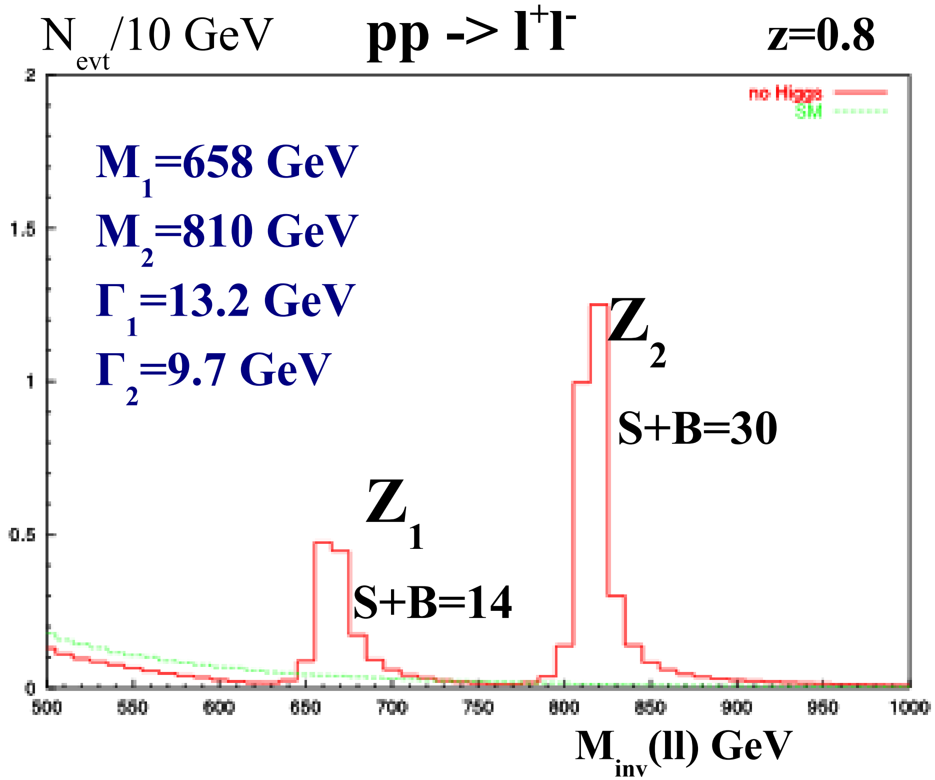
$M_{inv}(ll) > 250$ GeV for pp -> *ll*

$P_t(l)>150$ GeV for pp -> $l\nu$

no realistic detector simulation is included!

$Z_{1,2}$ Drell-Yan production at the LHC 1 fb^{-1}

E.A., De Curtis, Dominici, Fedeli



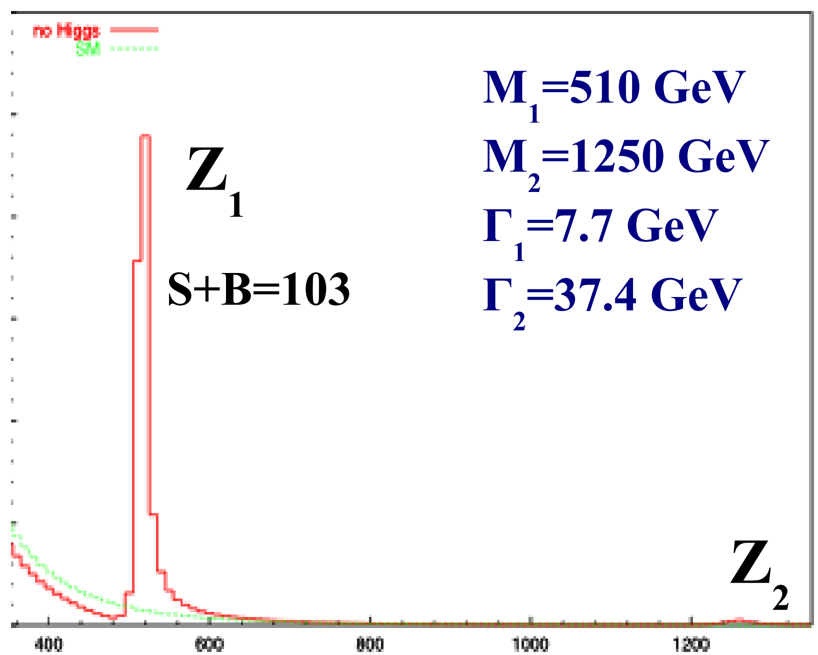
signal acceptance = 0.75

Two observable resonances -> distinctive signature

$Z_{1,2}$ Drell-Yan production at the LHC 1 fb^{-1}

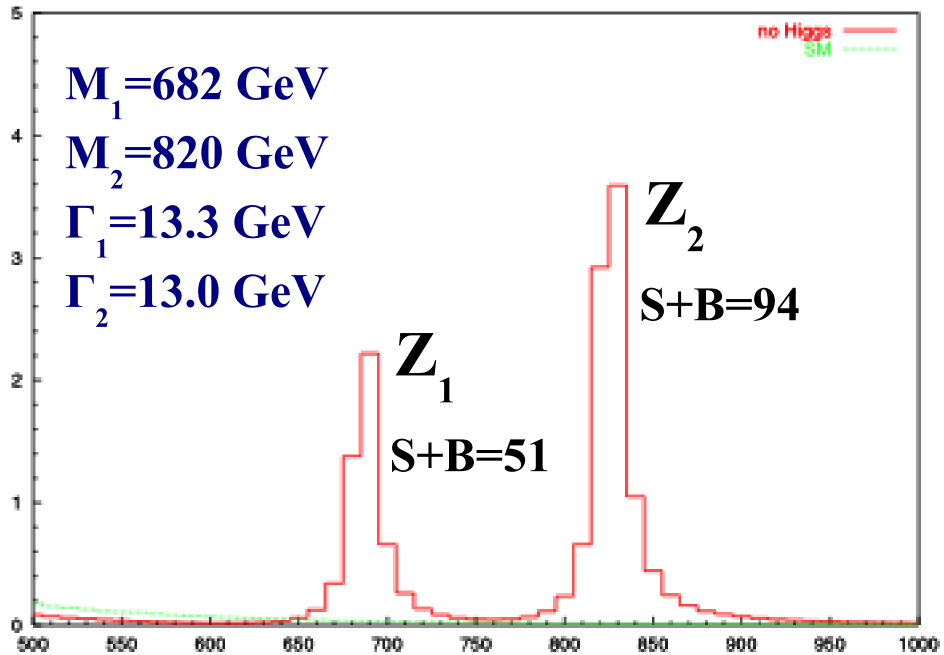
E.A., De Curtis, Dominici, Fedeli

N_{evt}/10 GeV **pp -> l^+l^-** **z=0.4**



M_{inv}(ll) GeV

N_{evt}/10 GeV **pp -> l^+l^-** **z=0.95**



M_{inv}(ll) GeV

Only one observable resonance -> degeneracy with single Z' models

Exclusion at the Tevatron: D0 3.6 fb^{-1}

D0 Note 5923-CONF

TABLE II: Numbers of expected and observed events in different mass windows, and signal acceptance.

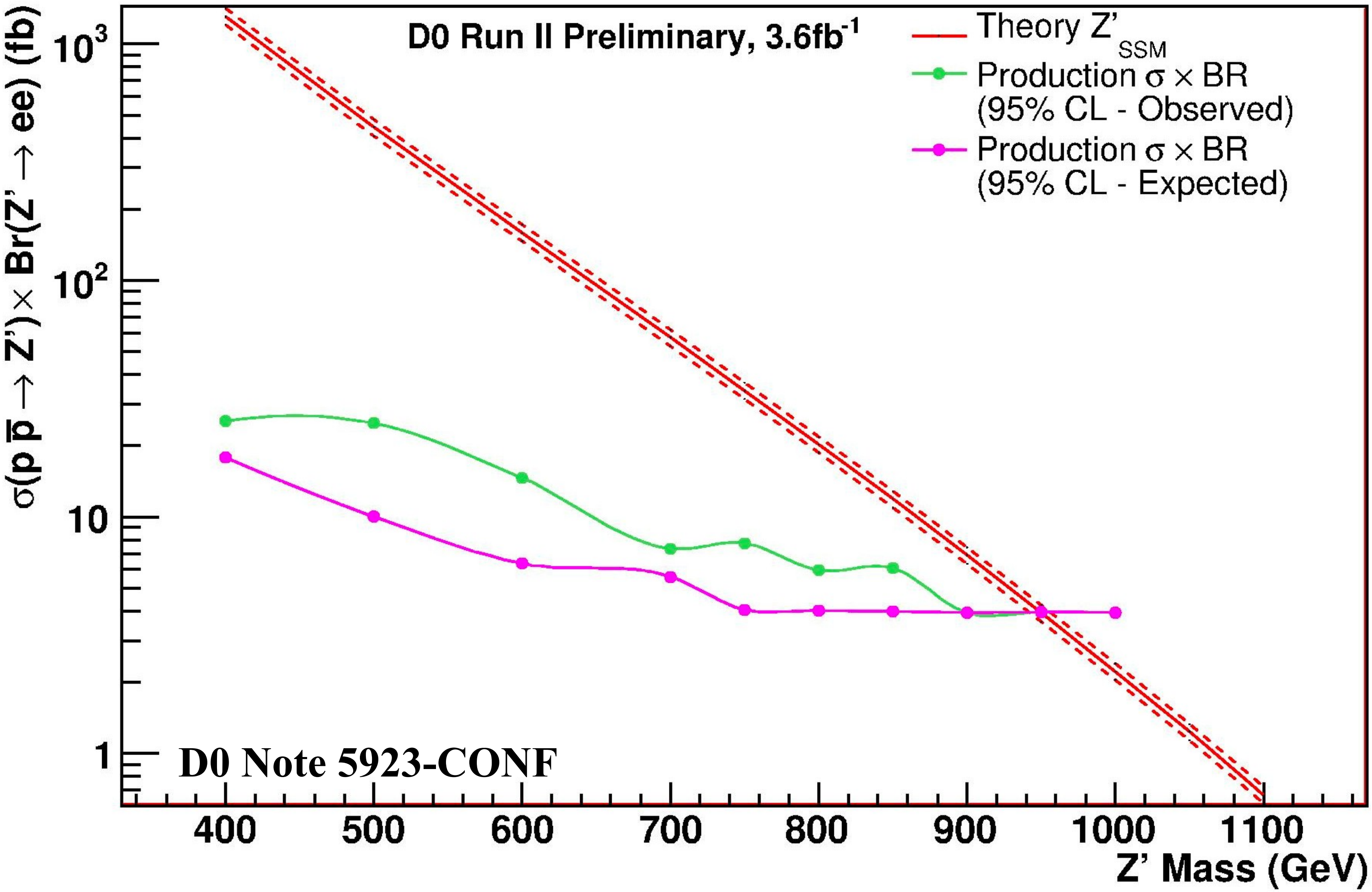
$M_{Z'}$ (GeV/c^2)	Mass Window Lower limit (GeV/c^2)	Data Events	Expected Background Events	Signal Acceptance
400	354	27	22.4 ± 0.7	0.172 ± 0.014
500	445	16	7.92 ± 0.22	0.188 ± 0.015
600	536	7	2.93 ± 0.07	0.199 ± 0.016
700	626	2	1.052 ± 0.025	0.207 ± 0.017
750	673	2	0.631 ± 0.016	0.209 ± 0.017
800	718	1	0.384 ± 0.010	0.211 ± 0.018
850	762	1	0.222 ± 0.006	0.212 ± 0.018
900	810	0	0.134 ± 0.004	0.216 ± 0.019
950	858	0	0.0701 ± 0.0023	0.214 ± 0.019
1000	902	0	0.0410 ± 0.0015	0.216 ± 0.021

Counting strategy:

Asymmetric mass window: $M_{Z'} > M_{Z'}-3R$

R=mass resolution=3-4% $M_{Z'}$

Exclusion at the Tevatron: D0 3.6 fb^{-1}



Exclusion at the Tevatron: D0 3.6 fb^{-1}

D0 Note 5923-CONF

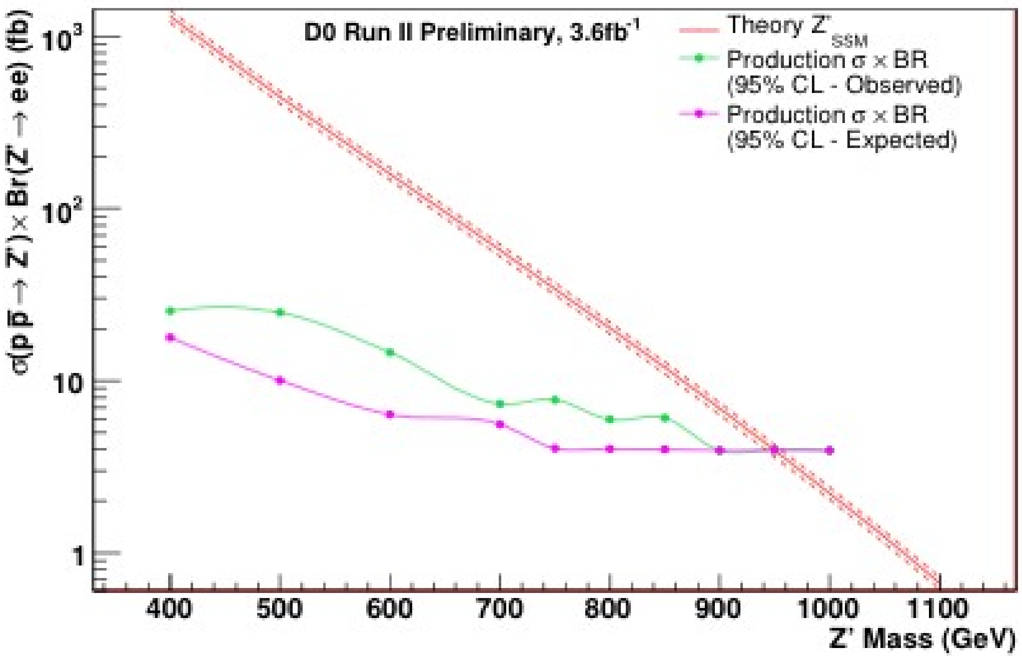


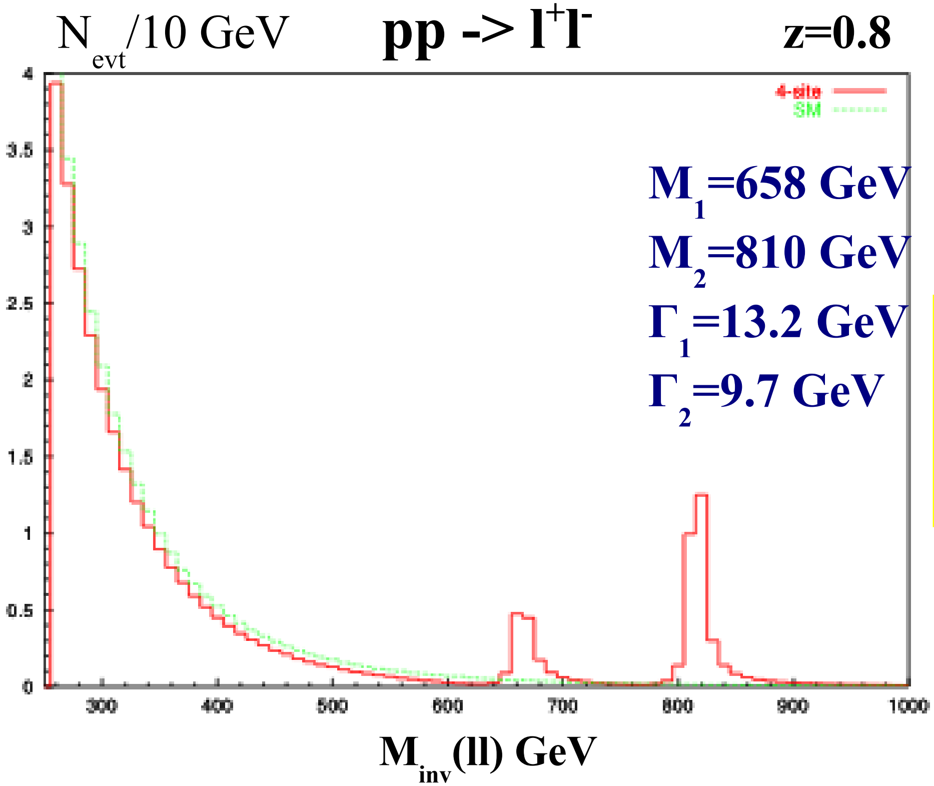
FIG. 4: 95% CL limit on $\sigma \times BR(X \rightarrow e^+e^-)$, where X is a high-mass neutral narrow resonance. The theoretical cross-section of the SSM Z' with its uncertainty is included for comparison

TABLE III: Expected and observed 95% confidence level upper limits on production $\sigma \times BR$.

Mass (GeV/c^2)	Expected Limit on Production ($\sigma \times BR$)(fb)	Observed Limit on Production ($\sigma \times BR$)(fb)
400	17.89	25.36
500	10.02	24.89
600	6.36	14.65
700	5.59	7.35
750	4.05	7.74
800	4.02	5.95
850	3.99	6.07
900	3.94	3.94
950	3.96	3.96
1000	3.94	3.94

Exclusion at the Tevatron: D0 3.6 fb^{-1}

and Narrow width approximation, i.e. σ(pp->Z') x Br(Z'->ll)



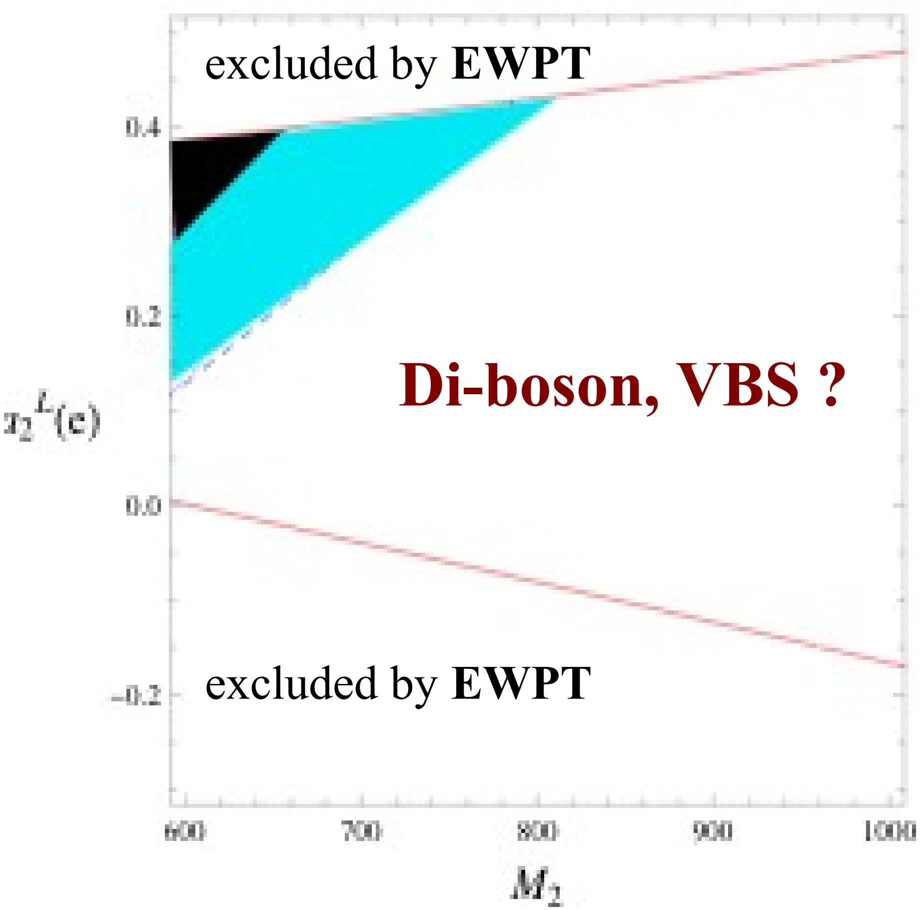
Strong negative interference between $Z_{1,2}$, Z*, γ*

σ Br	σ Br, full interference
45 (fb)	**13 (fb)**

a warning on NWA and counting strategy

Exclusion at the Tevatron: D0 3.6 fb^{-1}

Higgsless model: DY-processes with Z_1 and Z_2-boson exchange



Theory $Z_{1,2}$ versus

----- 95% CL Observed

----- 95% CL Expected

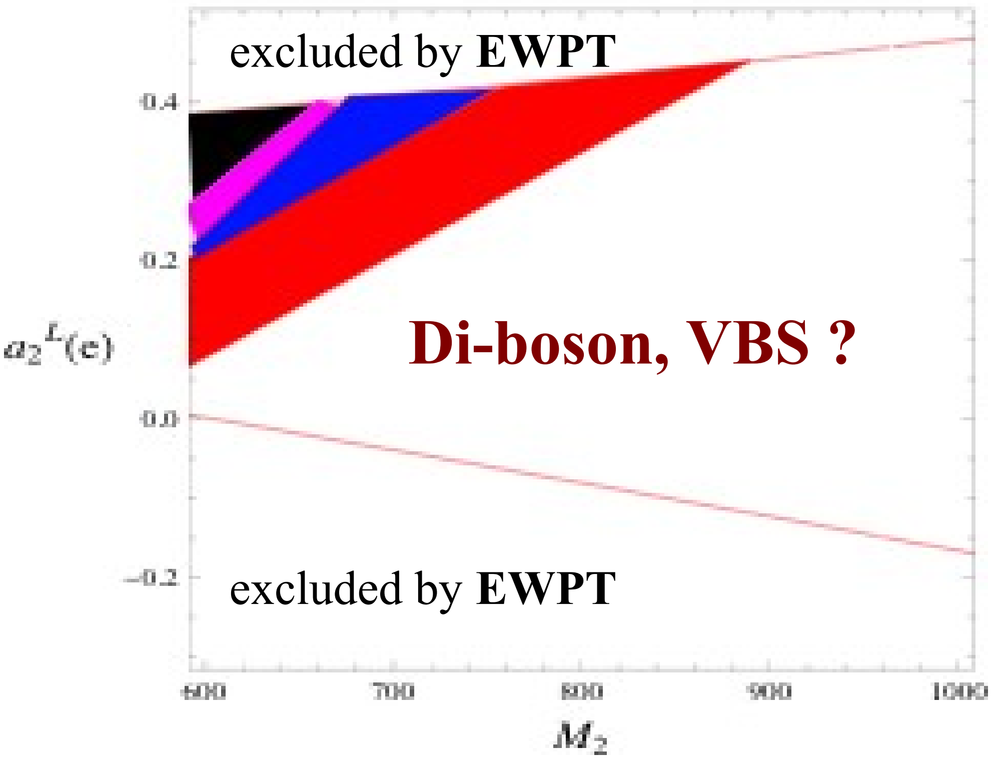
(Poisson significance estimator in perfect agreement!)

in the following: $Z_{1,2}$ mass limit from D0 observed data

D0 3.6 fb^{-1}: Mass limit ~ 650 GeV

Discovery at the Tevatron: D0 10 fb^{-1}

Neutral channel: DY-processes with Z_1 and Z_2-boson exchange



Di-boson, VBS ?

---- 95% CL D0 3.6 fb^{-1} excl.

---- $Z_{1,2}$ discovery

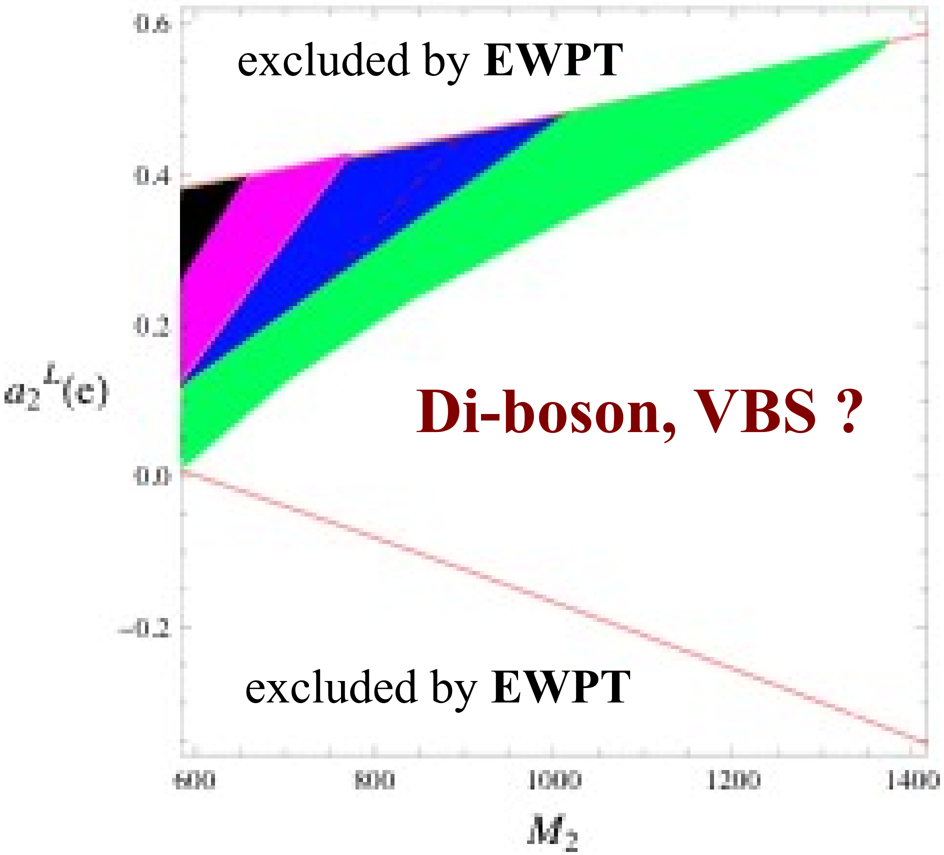
---- Z_2 discovery

---- 95% CL exclusion

D0 @ 10 fb^{-1} can exclude M < 900 GeV

Discovery at the LHC: CMS 1 fb^{-1}

Neutral channel: DY-processes with Z_1 and Z_2-boson exchange



---- 95% CL D0 3.6 fb^{-1} excl.

---- $Z_{1,2}$ discovery

---- Z_2 discovery

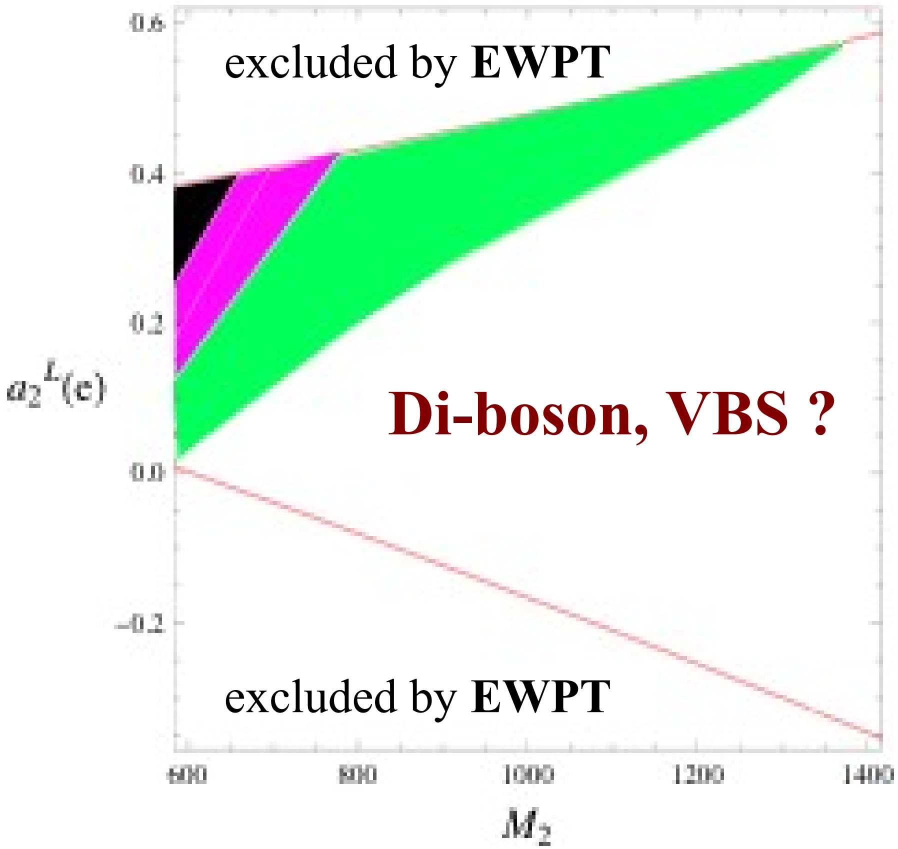
---- 95% CL exclusion

LHC @ 50 pb^{-1} improves bounds from D0 3.6 fb^{-1}

LHC @ 1 fb^{-1} can exclude M < 1400 GeV

Z_1 Discovery: LHC 1 fb^{-1} vs D0 10 fb-1

Neutral channel: DY-processes with Z_1 and Z_2-boson exchange



---- 95% CL D0 3.6 fb^{-1} excl.

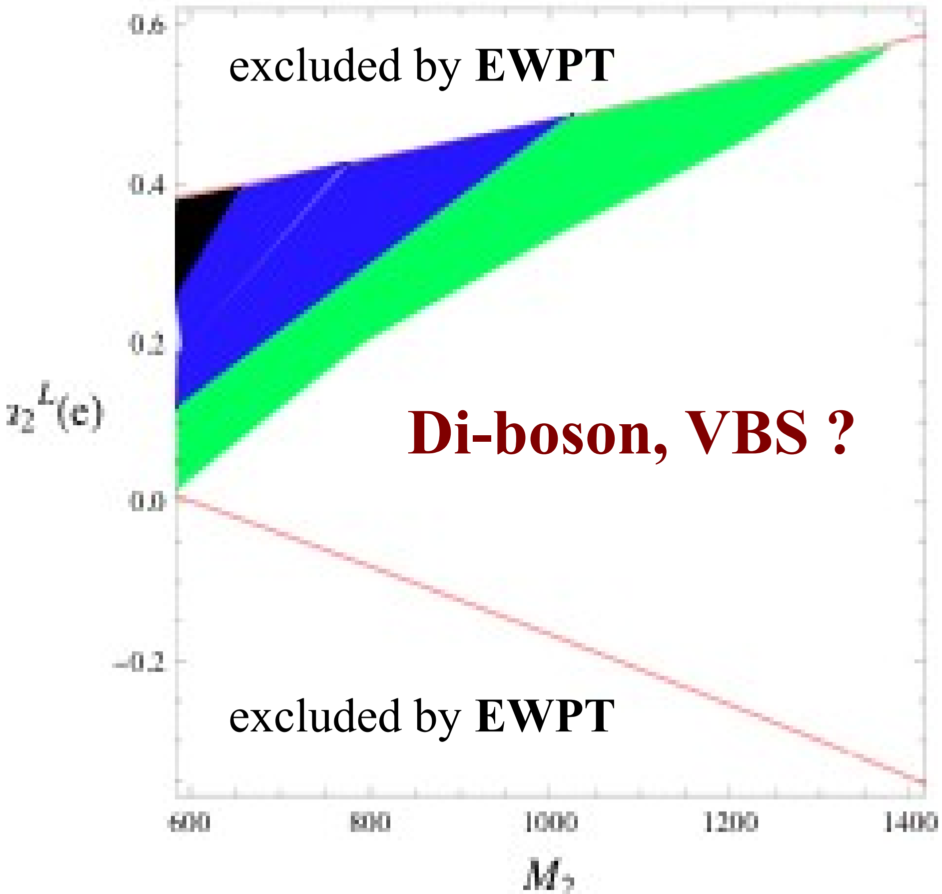
---- Z_1 discovery

---- 95% CL exclusion

LHC @ 1 fb^{-1} extends Z_1-mass bound: M_1=700 -> 800 GeV

Z_2 Discovery: LHC 1 fb^{-1} vs D0 10 fb-1

Neutral channel: DY-processes with Z_1 and Z_2-boson exchange



---- 95% CL D0 3.6 fb^{-1} excl.

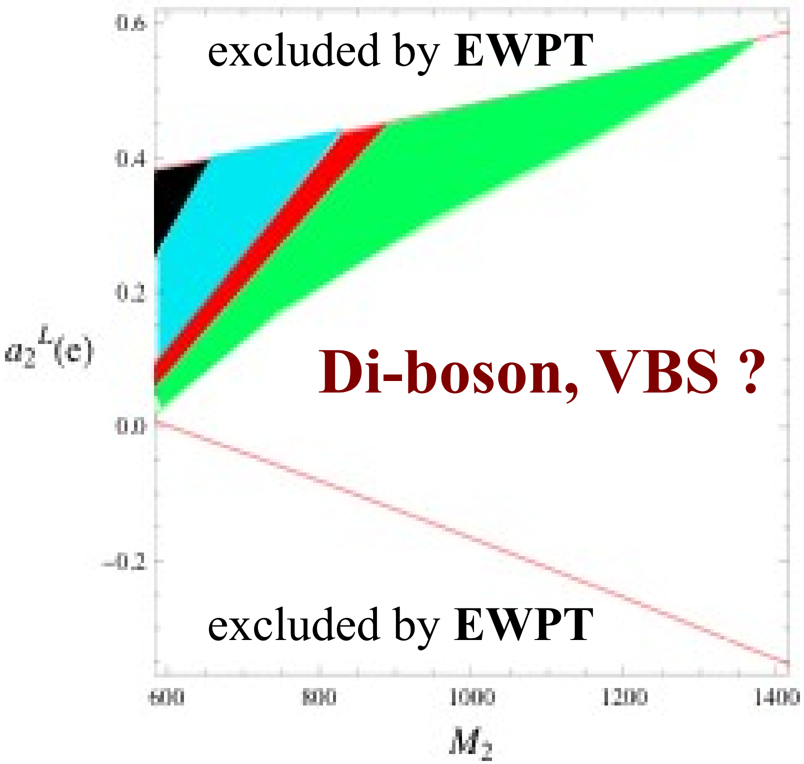
---- Z_2 discovery

---- 95% CL exclusion

LHC @ 1 fb^{-1} extends Z_2-mass bound: M_2=800 -> 1000 GeV

$Z_{1,2}$ exclusion: LHC 1 fb^{-1} vs D0 10 fb^{-1}

Neutral channel: DY-processes with Z_1 and Z_2-boson exchange



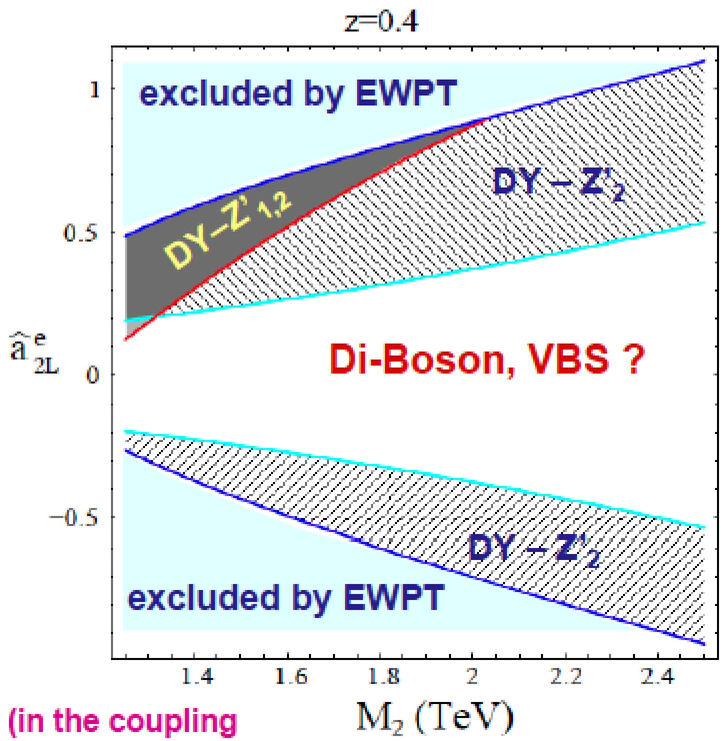
---- 95% CL **D0 3.6 fb^{-1}** observed
---- 95% CL **D0 3.6 fb^{-1}** expected
---- 95% CL **D0 10 fb^{-1}** exclusion
---- 95% CL **LHC 1 fb^{-1}** exclusion

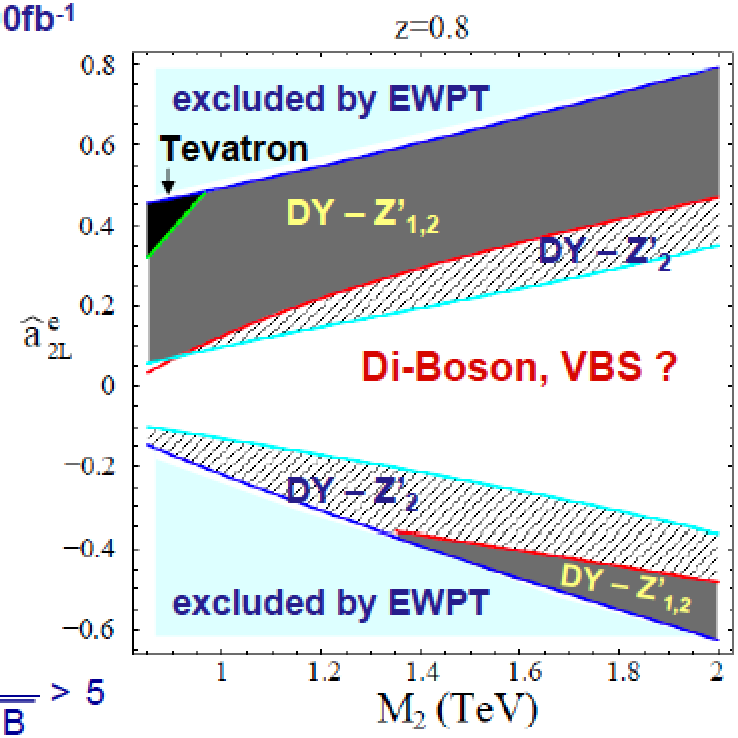
LHC @ 1 fb^{-1} extends $Z_{1,2}$-boson exclusion: M=1000 -> 1400 GeV

Discovery @ the LHC <u>14 TeV, 100 fb^{-1}</u>

DY-processes in the neutral channel, $Z`_1$, $Z`_2$ exchanges

L=100fb^{-1}





(in the coupling the electric charge –e is factorized)

$$\frac{S}{\sqrt{S+B}} > 5$$

within $|M_{inv}(l^+l^-)-M_i| < \Gamma_i$ (i=1,2)

acceptance cuts: $\eta(l)<2.5$, $Pt(l)>20$ GeV

Tevatron: direct limit from neutral DY leptonic channels for L=4fb^{-1} in $p\bar{p} \to l^+l^- \quad (l = e, \mu)$

Bounds from LEP2 not effective

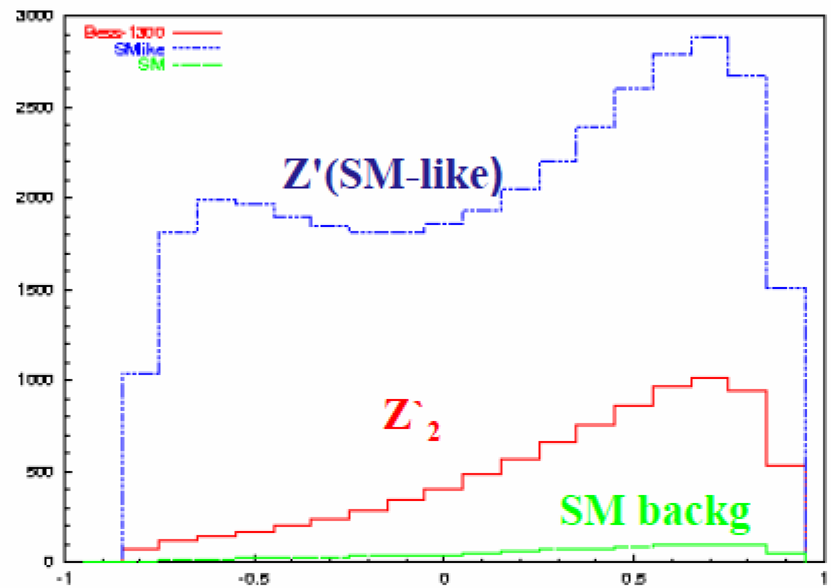
More needed: LHC at 14 TeV and 100 fb^{-1}

How to distinguish the various models? Forward-backward charge asymmetry A_{FB} in pp $\rightarrow l^+ l^-$

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{3}{8}(1+\cos^2\theta^*) + A^{\ell}_{FB}\cos\theta^*$$

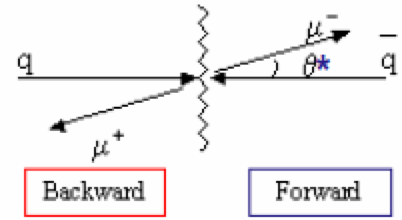
L=100 fb^{-1}

dσ L/dcosθ*(l^-) (l=e,μ)



cosθ*(l^-)

evts for Z`$_2$ ~ 1000



θ* is the angle of the l^- with the incoming quark in the dilepton frame (Collins-Soper)

Approximate the direction of the incoming quark with the boost direction of the leptonic system with respect to the beam axis (Dittmar, 1997)

$M_{Z`2}=M_{Z'(SM\text{-}like)}$=1.3 TeV

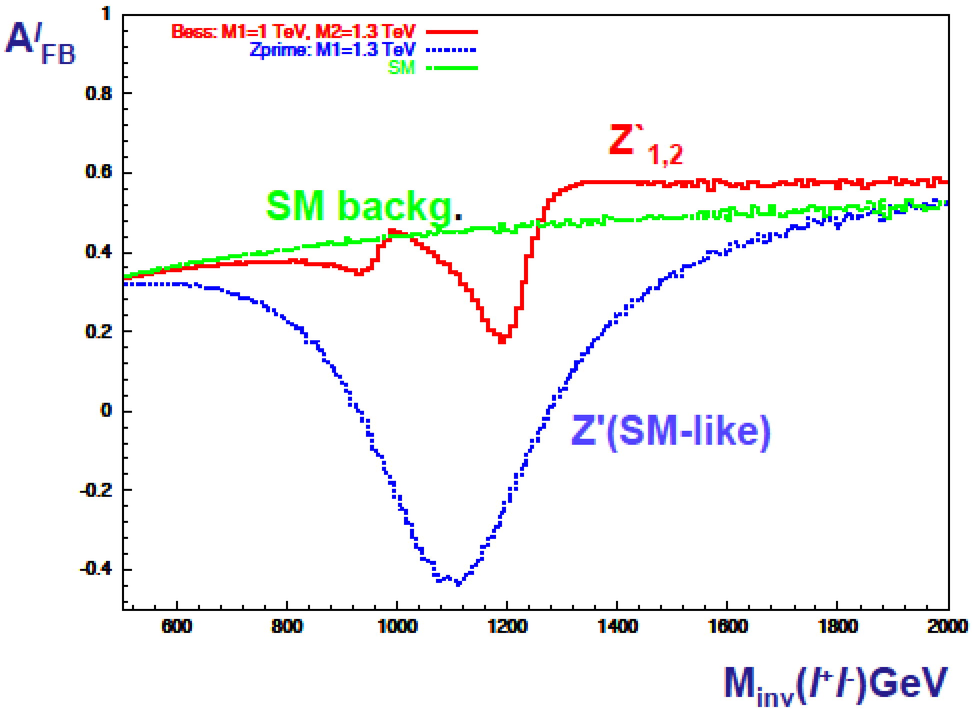
we select the events within
$|M_{inv}(l^+l^-)-M_{Z'}| < 3\Gamma_{Z'}$

Rapidity cut: $|y(l^+l^-)|>1$

More needed: LHC at 14 TeV and 100 fb^{-1}

Forward-backward asymmetry A_{FB} in $pp \rightarrow l^+ l^-$

(Dittmar,Nicollerat,Djouadi 03; Petriello,Quackenbush 08)

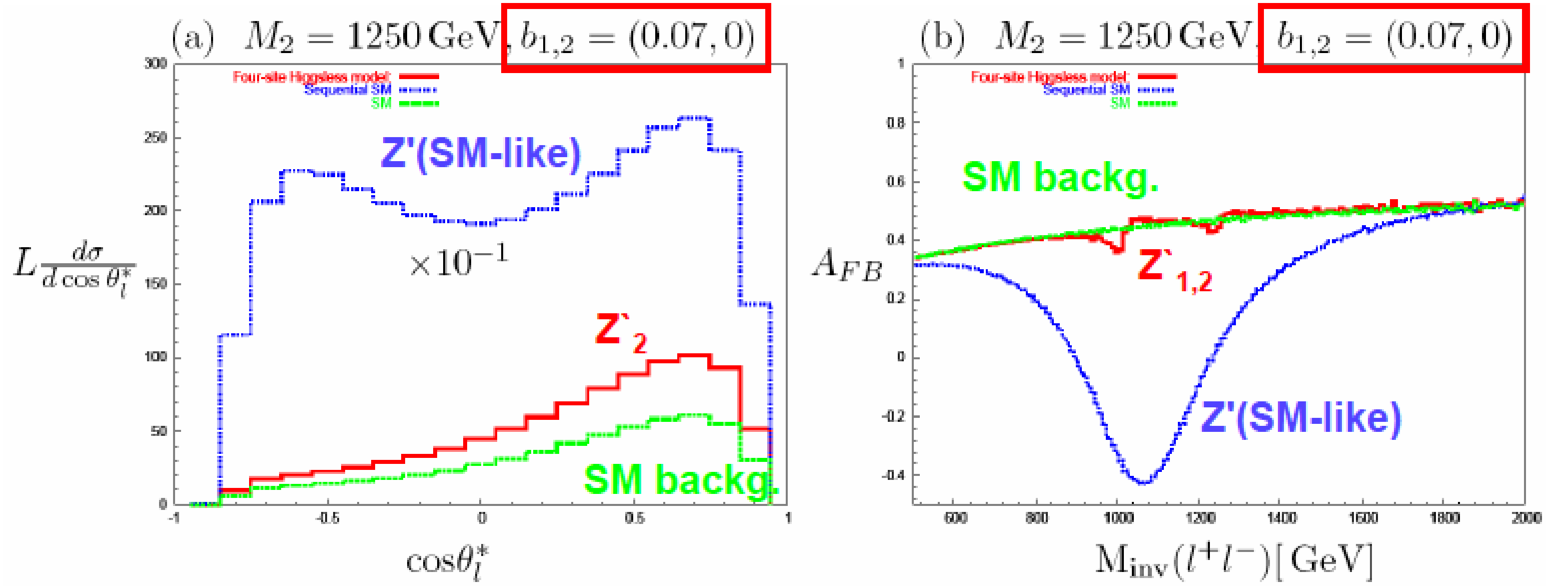


$M_{Z`1}$ =1.0TeV
$M_{Z`2}$ =1.3TeV
$M_{Z`(SM\text{-}like)}$ =1.3TeV

$$A_{FB} = \left[\frac{d\sigma^F}{dM_{\rm inv}} - \frac{d\sigma^B}{dM_{\rm inv}}\right] / \left[\frac{d\sigma^F}{dM_{\rm inv}} + \frac{d\sigma^B}{dM_{\rm inv}}\right]$$

More needed: LHC at 14 TeV and 100 fb^{-1}

On- and off-resonance A_{FB} for a single resonance scenario



- The on-resonance A_{FB} is more pronounced in the 4-site model due to the difference between the left and the right-handed fermion-boson couplings
- The off-resonance A_{FB} could reveal the double-resonant structure not appreciable in the dilepton invariant mass distribution

Conclusions

- Higher dimensional gauge theories naturally suggest the possibility of Higgsless theories
- Linear moose models provide an effective description of Higgsless theories. They are calculable, not excluded by the EW precision measurements and describe new spin-1 gauge bosons which delay the unitarity violation scale
- **DY processes are the favoured channel to discover the new $Z'_{1,2}$ and $W'_{1,2}$ even during the early stage LHC data taking!**
- A_{FB} for distinguishing among various models with Z`

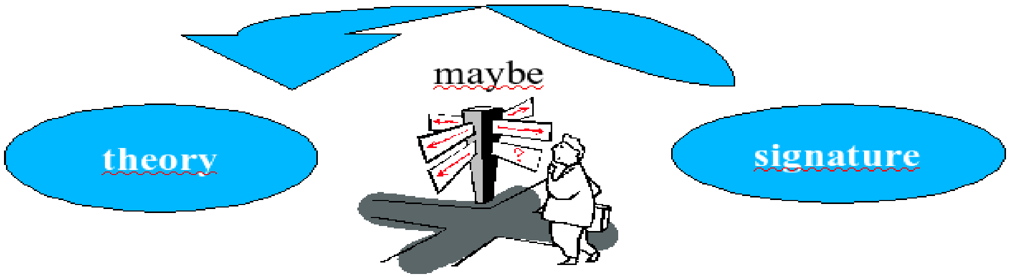
This analysis is part of a wider project developed within NExT

NexT project

E. A., A. Belyaev, L. Fedeli, S. King, C. Shepherd-Themistocleous

or solving the LHC inverse problem:

Which model is it?



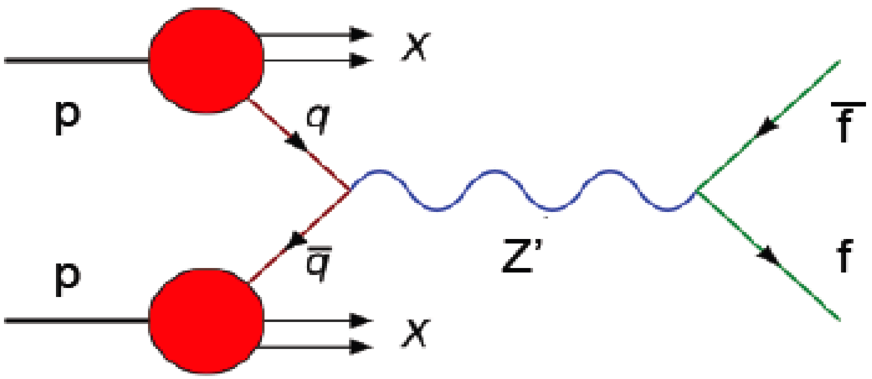
Degeneracies !

By exploring the most promising BSM theories , i.e. SUSY, DEWSB, and LEXD, the basic idea is to create a strategy capable to deconvolute the LHC signals using a comprehensive set of kinematical variables, and to identify the underlying theory.

theory and experiment for the same goal!

NexT project

Drell-Yan production cross-section



$$\sigma_{f\bar{f}} \equiv \sigma(pp \to Z'X \to f\bar{f}X)$$

Narrow width approximation

$$\sigma_{f\bar{f}} \approx \int_{(M'_Z-\Delta)^2}^{(M'_Z+\Delta)^2} \frac{d\sigma}{dM^2}(pp \to f\bar{f})dM^2 \approx \left(\frac{1}{3}\sum_{q=u,d}\left(\frac{dL_{q\bar{q}}}{dM^2_{Z'}}\right)\hat{\sigma}(q\bar{q} \to Z')\right) \times Br(Z' \to f\bar{f})$$

Simple structure

$$\sigma_{l^+l^-} \approx \frac{\pi}{48s}\left[c_u w_u(s, M^2_{Z'}) + c_d w_d(s, M^2_{Z'})\right]$$

Carena, Daleo, Dobrescu, Tait

Model dependent

$$\begin{cases} c_u \propto \hat{\sigma}(u\bar{u} \to Z') \times Br(Z' \to l^+l^-) \\ c_d \propto \hat{\sigma}(d\bar{d} \to Z') \times Br(Z' \to l^+l^-) \end{cases}$$

depend on g' and $g_{V,A}^f$

Model independent

$$w_u \propto \frac{dL_{u\bar{u}}}{dM^2_{Z'}} \qquad w_d \propto \frac{dL_{d\bar{d}}}{dM^2_{Z'}}$$

depend on s and $M_{Z'}$

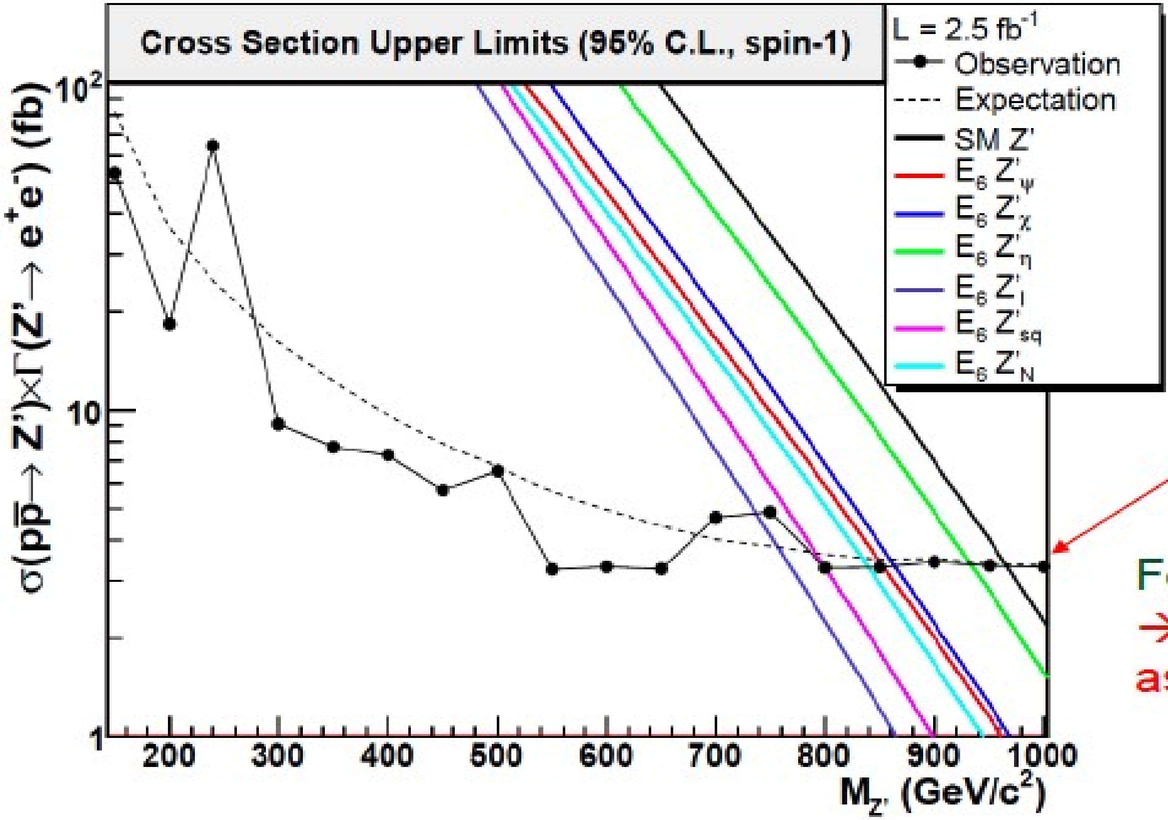
All Z' models in one picture

$$\sigma_{l^+l^-} \approx \frac{\pi}{48s}\left[c_u w_u(s, M_{Z'}^2) + c_d w_d(s, M_{Z'}^2)\right]$$

						Direct limit	Indirect limit	Z-Z' mixing limit
$U(1)'$	$Br(l^+l^-)$	c_u	c_d	c_u/c_d	$\Gamma_{Z'}/M_{Z'}$	$M_{Z'}^{\mathrm{D}}$	$M_{Z'}^{\mathrm{I}}$	$\lvert\theta_{ZZ'}\rvert$
E_6 $(g' = 0.462)$								
$U(1)_\chi$	0.0606	$6.46.10^{-4}$	$3.23.10^{-3}$	0.2	0.0117	892	1141^e	$1.6.10^{-3}$
$U(1)_\psi$	0.0444	$7.90.10^{-4}$	$7.90.10^{-4}$	1	0.0053	878	481^c	$1.8.10^{-3}$
$U(1)_\eta$	0.0371	$1.05.10^{-3}$	$6.59.10^{-4}$	1.6	0.00636	982	434^c	$4.7.10^{-3}$
$U(1)_S$	0.0656	$1.18.10^{-4}$	$3.79.10^{-3}$	0.31	0.0117	821	1257^e	$1.3.10^{-3}$
$U(1)_I$	0.0667	0	$3.55.10^{-3}$	0	0.0106	789	1204^e	$1.2.10^{-3}$
$U(1)_N$	0.0555	$5.94.10^{-4}$	$1.48.10^{-3}$	0.40	0.00635	861	623^e	$1.5.10^{-3}$
GLR $(g' = 0.595)$								
$U(1)_R$	0.0476	$4.21.10^{-3}$	$4.21.10^{-3}$	1	0.0247	-	442^e	-
$U(1)_{B-L}$	0.154	$3.02.10^{-3}$	$3.02.10^{-3}$	1	0.015			
$U(1)_{LR}$	0.0246	$1.39.10^{-3}$	$2.44.10^{-3}$	0.57	0.0207	630	998^e	$1.3.10^{-3}$
$U(1)_Y$	0.125	$1.04.10^{-2}$	$3.07.10^{-3}$	3.4	0.0235	-	-	-
SM $(g' = 0.74)$								
$U(1)_{SM}$	0.0308	$2.42.10^{-3}$	$3.12.10^{-3}$	0.775	0.0297	1030	1787^c	9.10^{-4}

All Z' models in one picture

CDF Run II Preliminary



$$\sigma_{l^+l^-} \approx \frac{\pi}{48s}\left[c_u w_u(s, M_{Z'}^2) + c_d w_d(s, M_{Z'}^2)\right]$$

$$c_u = a - b c_d$$

$$a = \frac{48s}{\pi}\frac{\sigma_{l^+l^-}}{w_u}$$

$$b = \frac{w_d}{w_u}$$

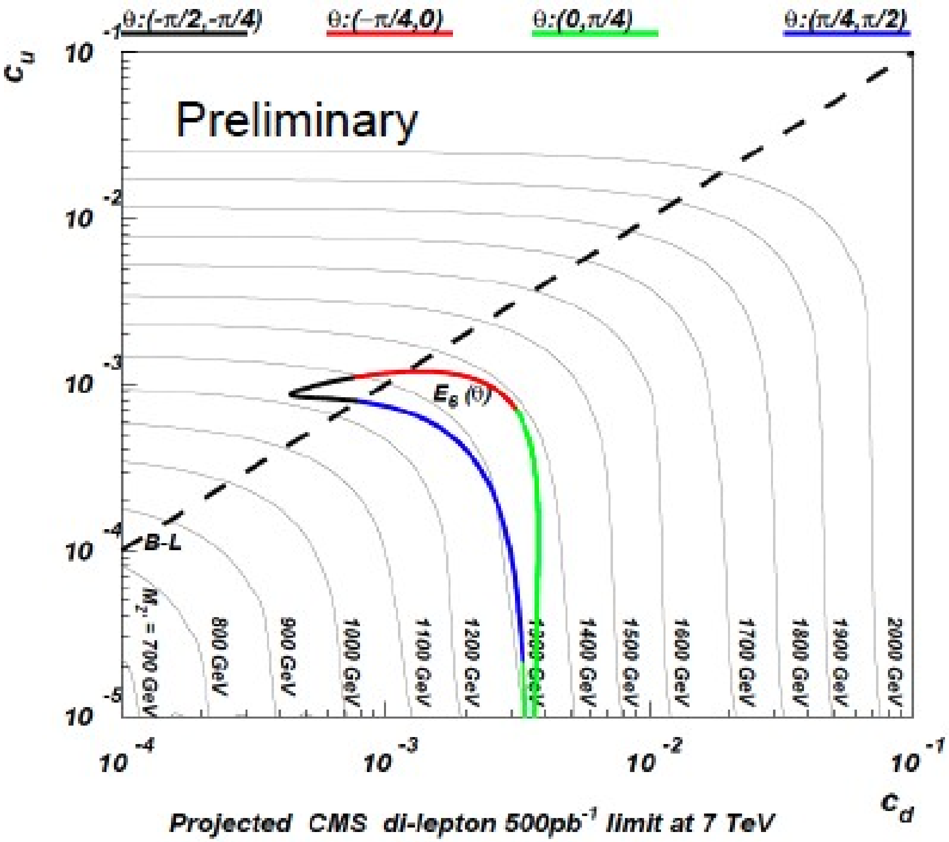
For fixed s, $M_{Z'}$ a,b are known

→ can plot cross-section limit as contours in c_u-c_d plane

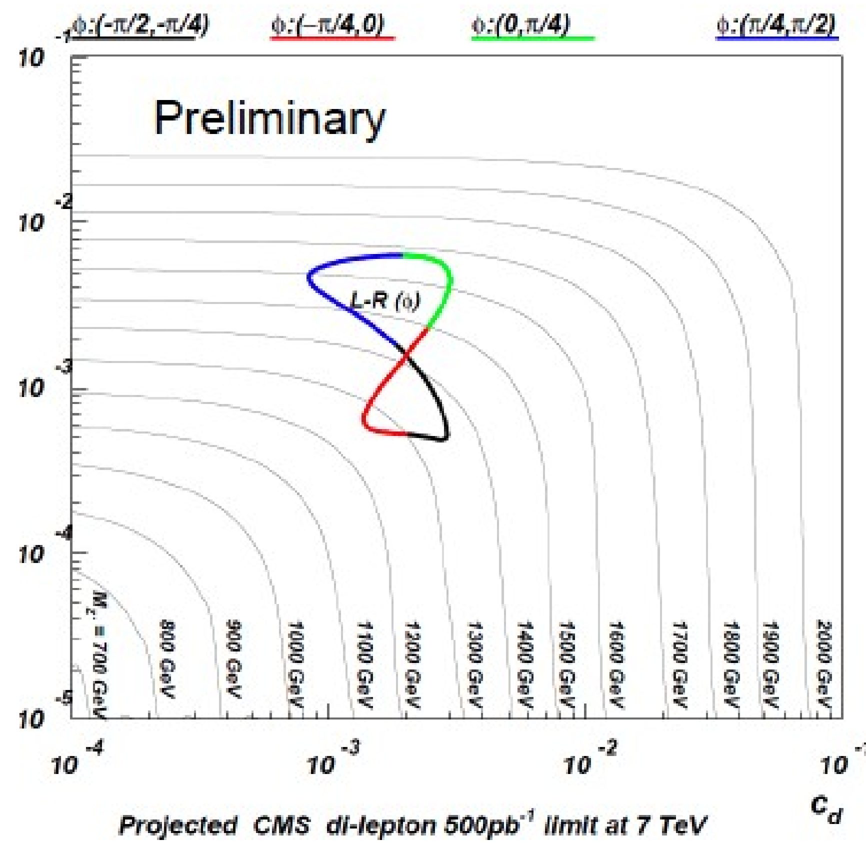
Z' mass limit contours in the c_d-c_u plane

LHC 500 pb^{-1}

E_6 models



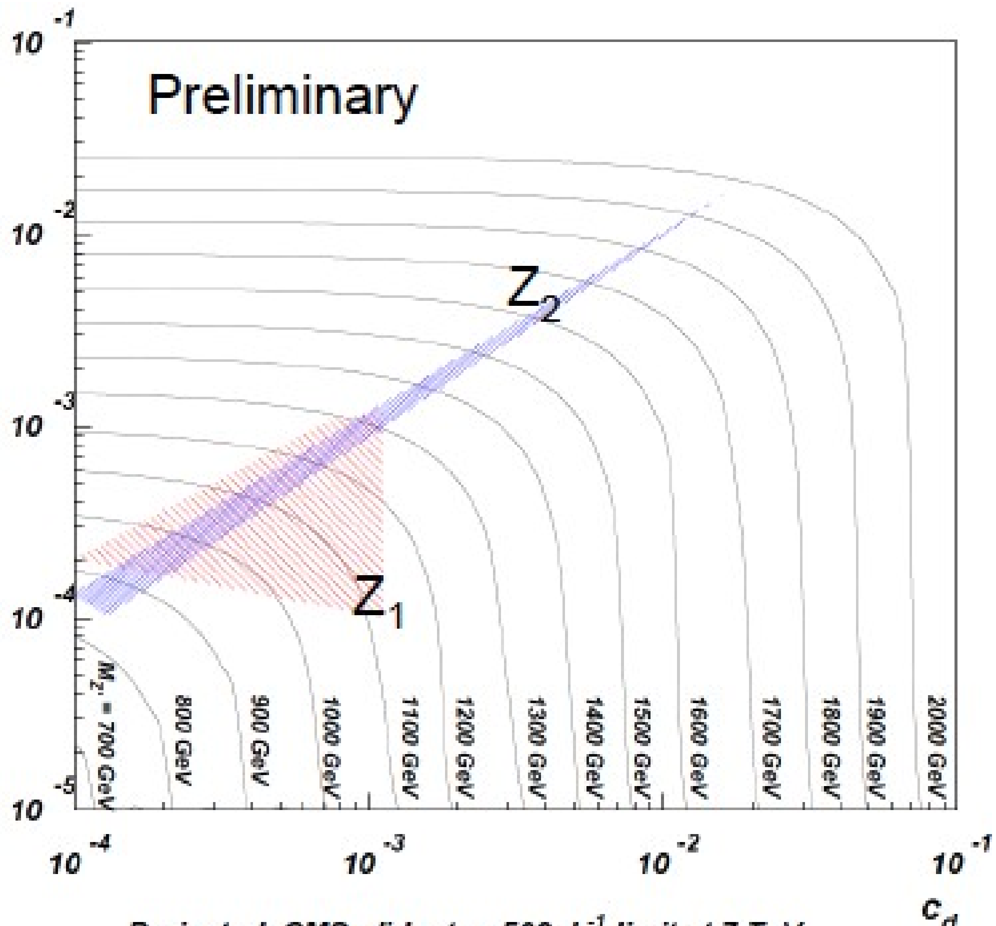
Generalized LR models



Z' mass limit contours in the c_d-c_u plane

LHC 500 pb^{-1}

Higgsless model



non trivial $M_{1,2}$ dependence from branchings/couplings

not possible to nail down the 4-site model, but one can give constraints on the parameter space M_1, M_2, b_1, b_2

Work in progress

E. A., A. Belyaev, L. Fedeli, S. King, C. Shepherd-Themistocleous

or from LHC to the Lagrangian parameters

Z' is very easy to discover in the first LHC run @ 7 TeV and 1 fb^{-1}

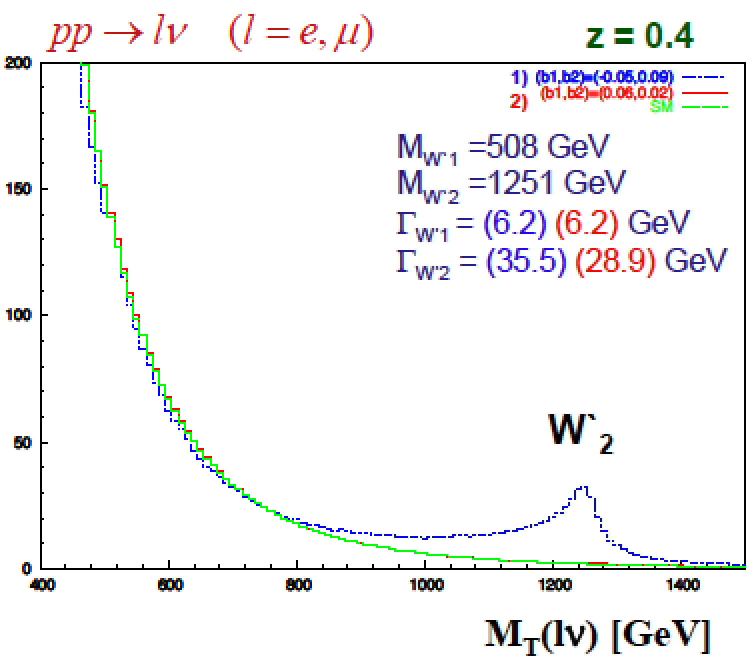
Z' is also predicted by 100s of models

A fully comprehensive and synthetic way of presenting/intrepreting experimental results is needed

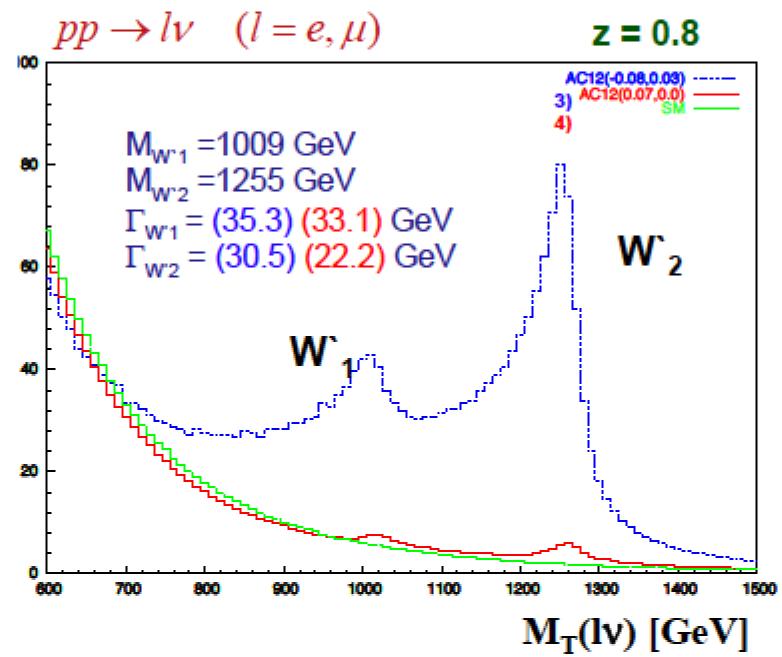
theory and experiment for the same goal!

$W'_{1,2}$ Drell-Yan production at the LHC

E.A., De Curtis, Dominici, Fedeli



$M_2 = M_1/z$



al # of evts in a 10GeV-bin versus $M_T(l\nu)$ for $L=10fb^{-1}$. Sum over e,μ

$W'_{1,2}$ Drell-Yan production at the LHC

	$M_{1,2}$(GeV)	$b_{1,2}$	M_t^{cut}(GeV)	$N_{evt}^{sig}(W_1)$	$N_{evt}^{tot}(W_1)$	$\sigma(W_1)$	$N_{evt}^{sig}(W_2)$	$N_{evt}^{tot}(W_2)$	$\sigma(W_2)$
1)	500,1250	-0.05,0.09	400	36	2435	0.7	776	2214	16.5
2)	500,1250	0.06,0.02	400	0	2609	0	1	1807	0
3)	1000,1250	-0.08,0.03	700	808	1230	23.0	1112	1189	32.3
4)	1000,1250	0.07,0.0	700	12	443	0.6	17	88	1.8

# of evts for the $W'_{1,2}$ DY-production for $M_t(l\nu_l) > M_t^{cut}$

$\sigma = N_{evt}^{sig}/\sqrt{N_{evt}^{tot}}$ for an integrated luminosity L=10 fb^{-1}

The statistical significance for the W`s production can be a factor 2 bigger than for the Z`s but it is less clean.

Neutral and charged channel are complementary

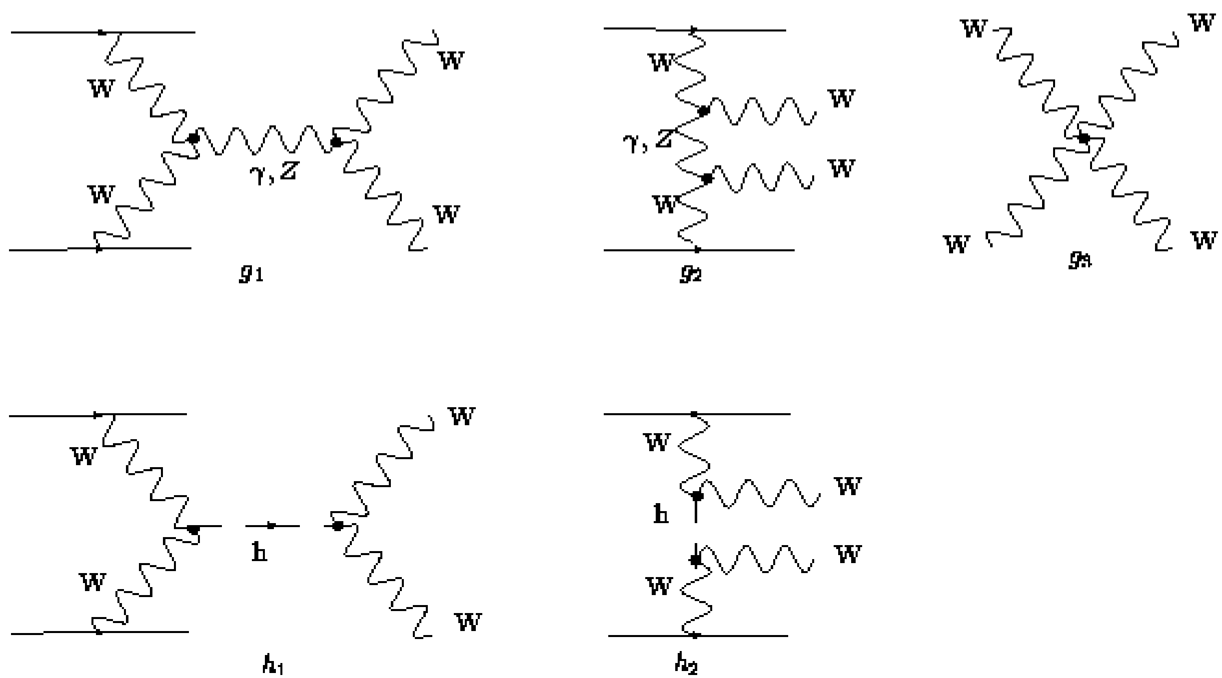
All six extra gauge bosons could be investigated at the LHC start-up with L ~ 1-2 fb^{-1} for $M_{1,2}$ < 1TeV

Four-site model: $Z_{1,2}$-boson properties

E.A., De Curtis, Dominici, Fedeli

w/wo Higgs models and unitarity

e.g. WW scattering:



for ON-SHELL incoming W's

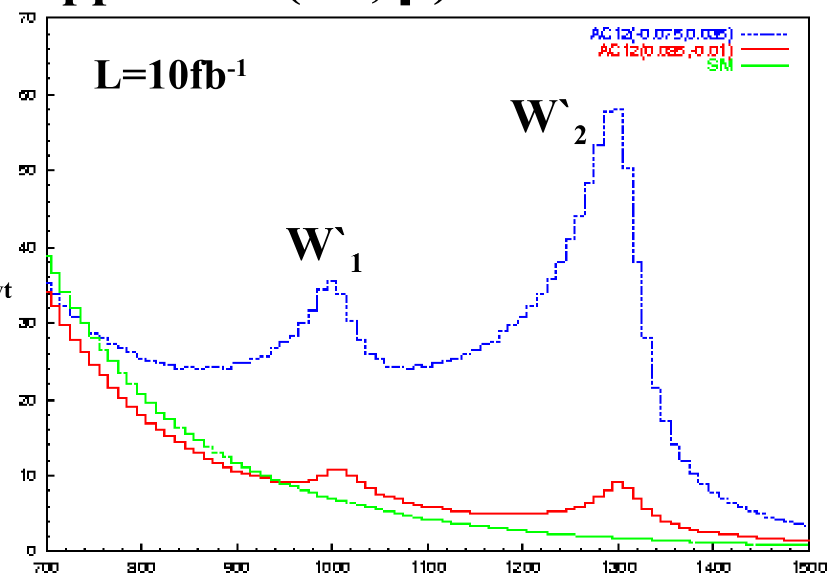
$g_i \propto s^2$ $\boxed{\Sigma\, g_i \propto s = M^2_{WW}}$ $\Sigma(g_i + h_i) \rightarrow Const.$

The Higgsless Linear Moose model in Drell-Yan processes at the LHC

E.A., De Curtis, Dominici, Fedeli

pp -> l ν (l=e, μ)

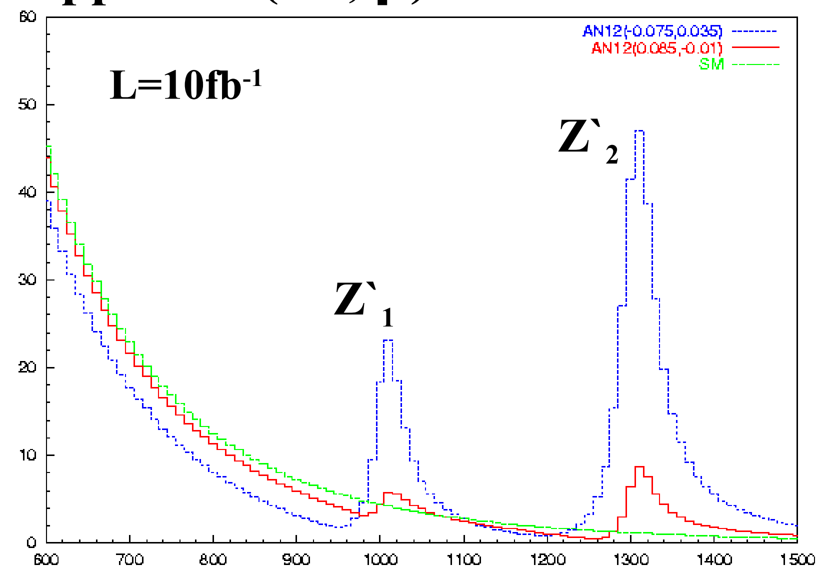
N_{evt}



$M_T(l\nu)$ [GeV]

pp -> l l (l=e, μ)

N_{evt}



$M_{INV}(ll)$ [GeV]