W' and Z' searches at the LHC

Elena Accomando
Southampton University and RAL

- New heavy vector resonances: Drell-Yan processes @ the 7 & 8 TeV LHC
- Common used approximations: Neglecting Interference and FW effects
- Extra W'-bosons: benchmark model and interpretation of exp. results
- Extra Z'-bosons: benchmark model and presentation of exp. results

based on papers by:

E. A., Becciolini, Belyaev, King, Moretti, Shepherd-Themistocleous (NExT)

& De Curtis, Dominici, Fedeli (Florence Uni. and INFN)

DIS2013

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Extra Heavy gauge bosons

From theory, the simplest origin is the following:

- **An extra heavy neutral vector boson, Z', can come from at least an additional U(1) gauge group**
  [E_6, Left-Right, SM-like models, …]

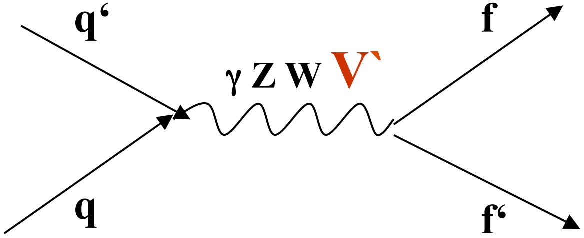
- **An extra heavy charged vector boson, W', can come from an additional SU(2) gauge group**
  [Left-Right, SSM, …]

More complicated scenarios predict multi-resonances:

- **A tower of extra heavy vector bosons, Z'_n and W'_n, can come from extended gauge groups, and relate EWSB and unitarity**
  [Composite Higgs, Technicolor, Extra Dimensions, …]

W' and Z' bosons at the LHC

The Drell-Yan channel is the favoured process for ALL models



- **In models with an extra U(1) or SU(2) and at least a light elementary Higgs [E_6, Left-Right, SSM, Non-Universal Extra Dimensions, ...] the extra V’(s) couple preferebly to fermions**

- **Models with a light composite Higgs [Strongly Interacting Light Higgs, (N)MWT, ...] are believed to be NOT fermiophobic since ‘08**

We focus on the SSM taken as the reference model by CMS and ATLAS [Altarelli, Mele, Ruiz-Altaba 1989]

W' and Z' searches at the LHC in DY: tools and methods

At NLO, mass scale dependent K-factors are often considered:
NLO QCD via MC@NLO [Frixione et al.] or POWEG [Alioli et al.]
NLO EW via HORACE [Carloni Calame et al. '05]

At LO, two main approximations are commonly adopted in theoretical studies and experimental analyses:

- neglecting interference effects between New Physics and SM because model-dependent and CPU consuming
- neglecting finite width effects i.e. adopting NWA
  to represents experimental results and extract mass bounds on Z'-bosons in the cu-cd plane
  [Carena et al. arXiv:hep-ph/0408098, E.A. et al arXiv:1010.6058]

Focus on LO: where do we stand?

W' and Z' searches at the LHC in DY

Latest analyses in the Drell-Yan channel

ATLAS:

- Z' search in the dilepton invariant mass distribution, arXiv:1209.2535
  interference included only for Kaluza-Klein Z's in ED theories as suggested by [Bella et al, arXiv:1004.2432]

- W' search in the dilepton transverse mass distribution, arXiv:1209.4446
  no intereference included

CMS:

- Z' search in the dilepton invariant mass distribution, arXiv:1212.7165
  no intereference included

- W' search in the dilepton transverse mass distribution, arXiv:1204.4764
  interference included as suggested by [E.A. et al, arXiv:1110.0713]
  see talk by Philipp Millet

$M_{Z'} > 2.22$ TeV and $M_{W'} > 3.10 – 3.35$ TeV

W' and Z' searches at the LHC: approximate vs complete result

[E. A., Becciolini, Belyaev, King, Moretti, Shepherd-Themistocleous (NExT) & De Curtis, Dominici, Fedeli (Florence University and INFN: arXiv:1110.0713 on W' and arXiv:1304.6700 on Z'].

A Southampton – RAL collaboration
in the spirit of the NExT Institute

Our point: the impact of Interference and Finite Width effects on presentation of exp. results, data interpretation and mass bound extraction can be sizeable for both W' and Z' searches

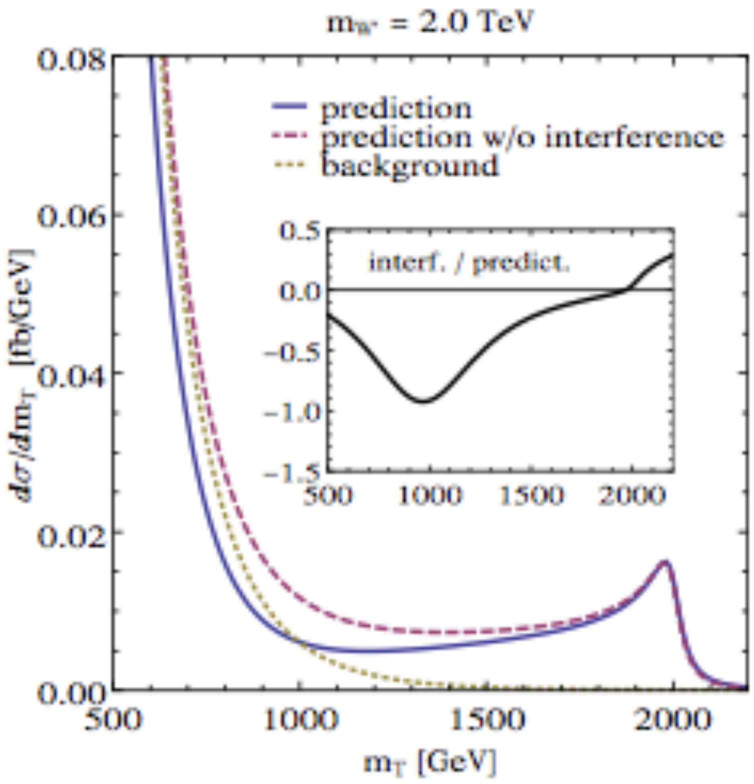
We consider the SSM, where the extra W' and Z' are heavy replica of the SM W and Z-boson, in the leptonic DY channels at the 7 & 8 TeV LHC:

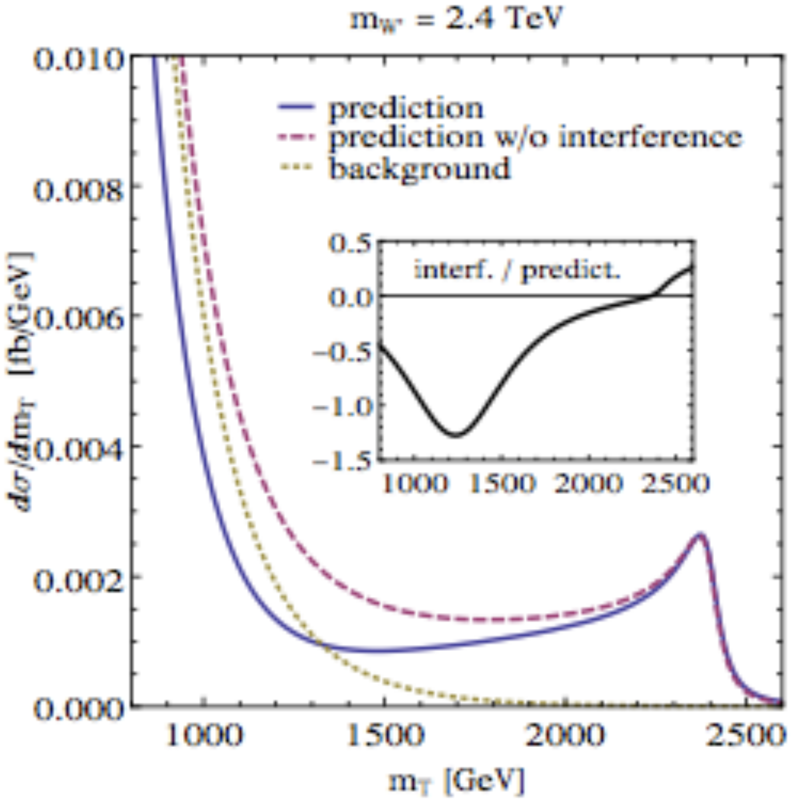
pp → W, W' → lepton + neutrino
pp → γ, Z, Z' → lepton pair

SSM W' Drell-Yan production @ the LHC

Non-interferred model à la Pythia vs complete SSM

[E.A., Becciolini, De Curtis, Dominici, Fedeli, Shepherd-Themistocleous: '11]



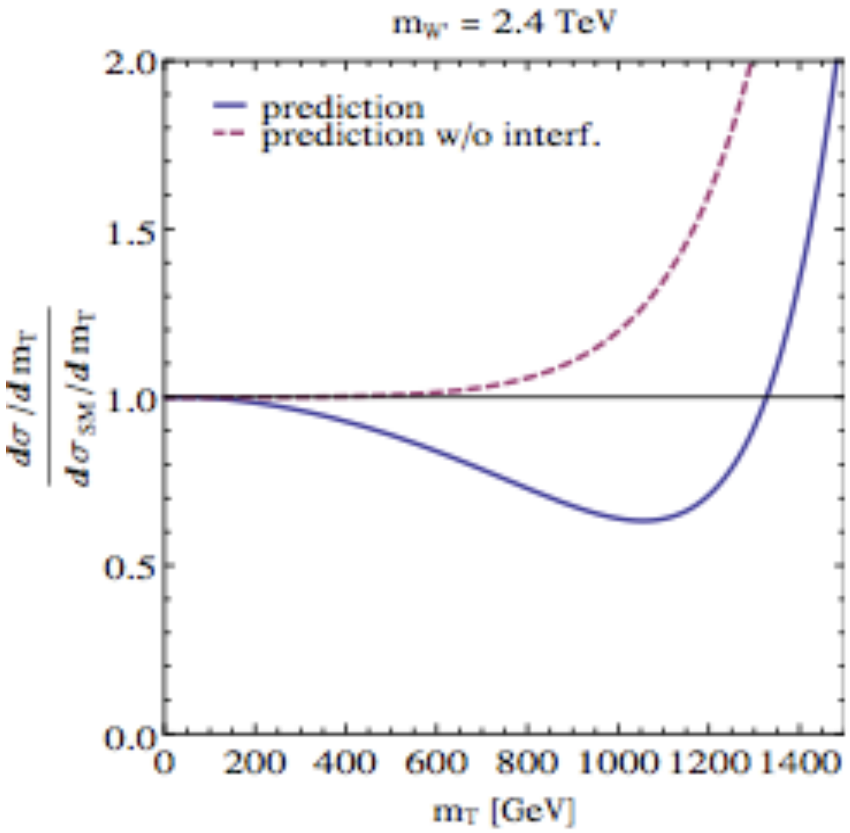


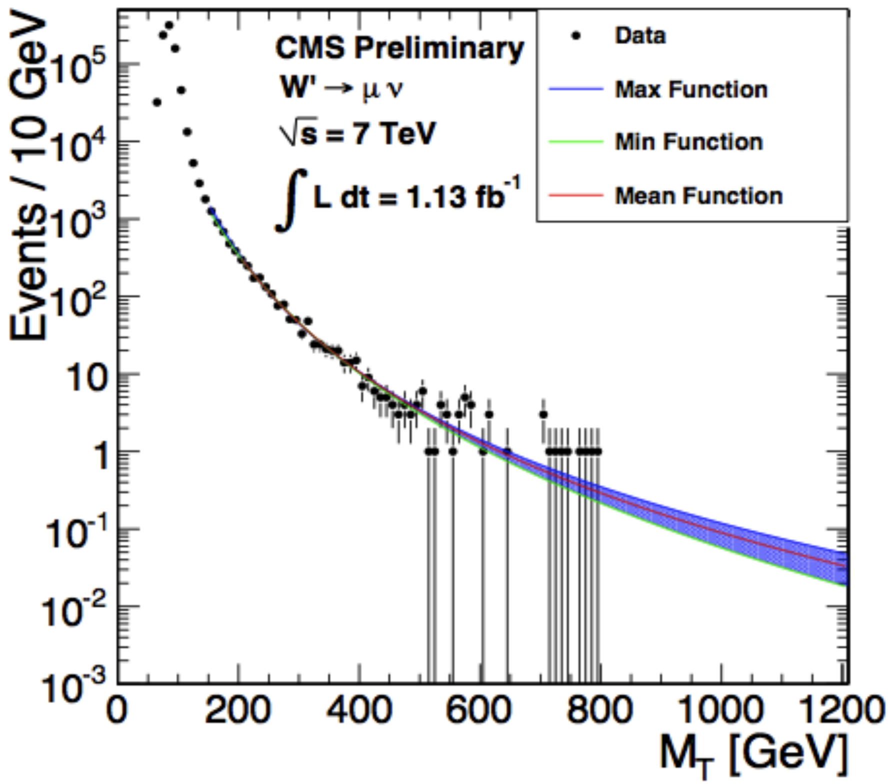
Interference effects are sizeable and model-dependent:

up to O(140%) in the SSM

SSM W' search: Theory vs Exp.
on the SM background shaping

[E.A., Becciolini, De Curtis, Dominici, Fedeli, Shepherd-Themistocleous: '11]

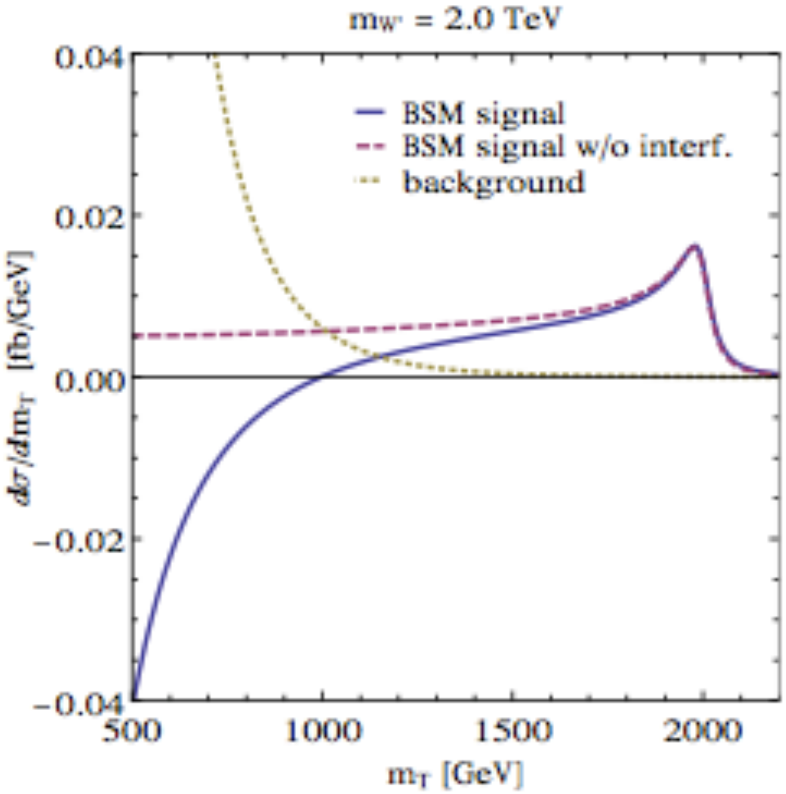


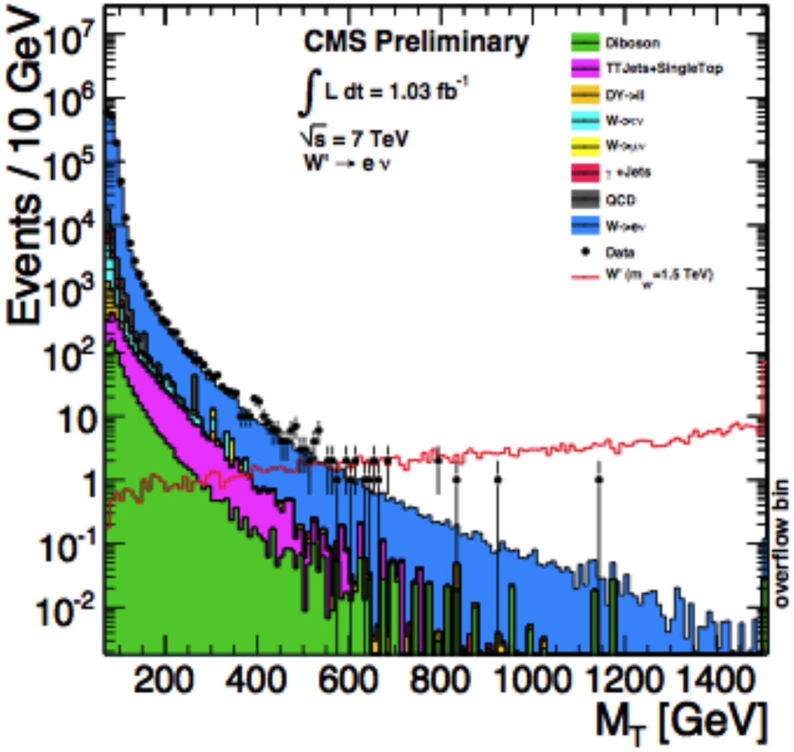


The control region (NP free) shrinks considerably

SSM W' search: Theory vs Exp. on the W' signal definition

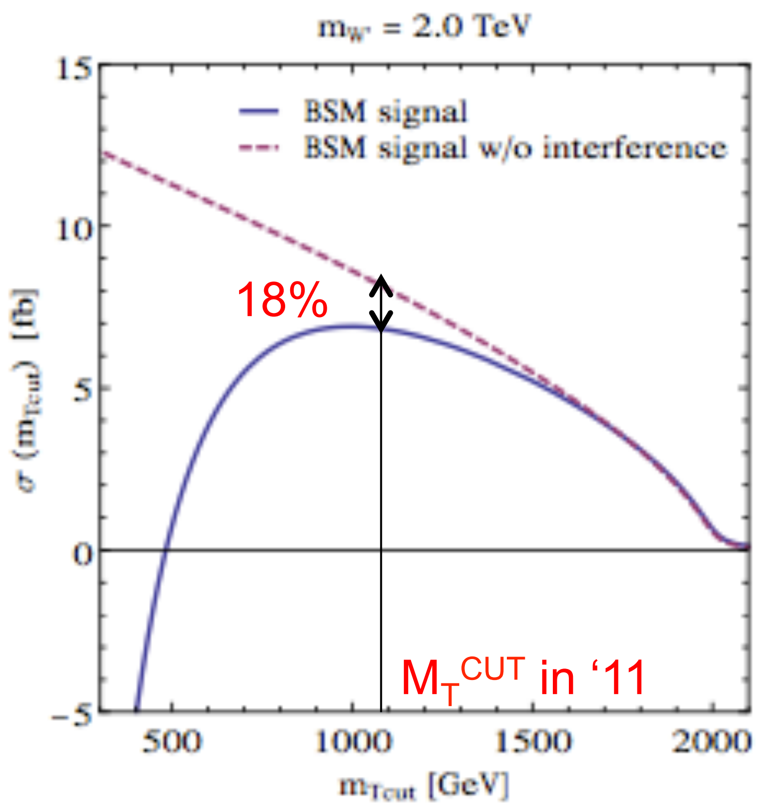
[E.A., Becciolini, De Curtis, Dominici, Fedeli, Shepherd-Themistocleous: '11]

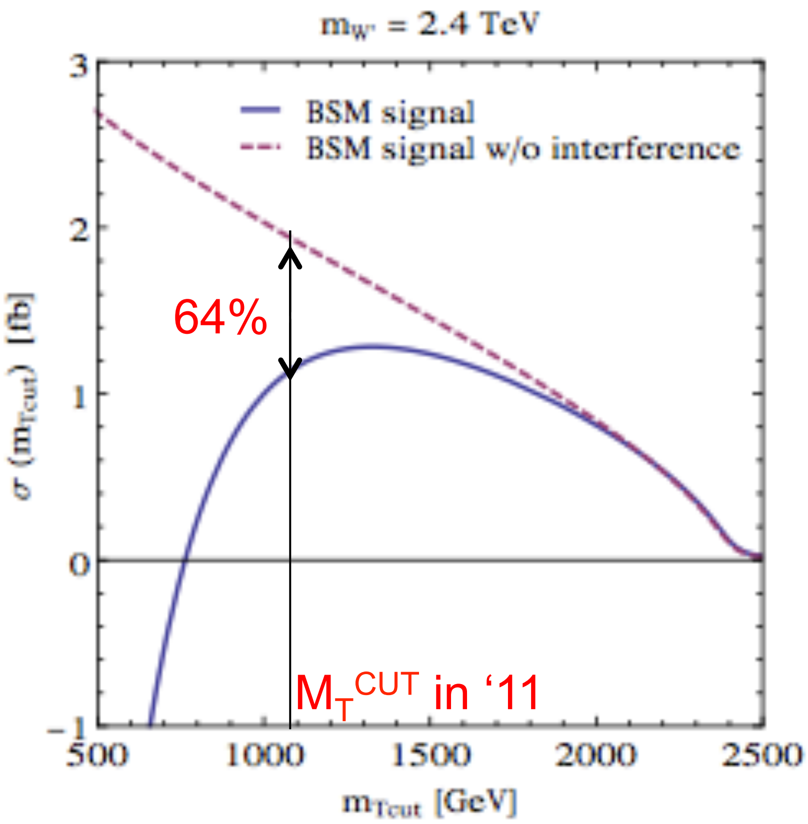




The complete BSM signal might not be positive definite over the full transerve mass range and its shape is model-dependent

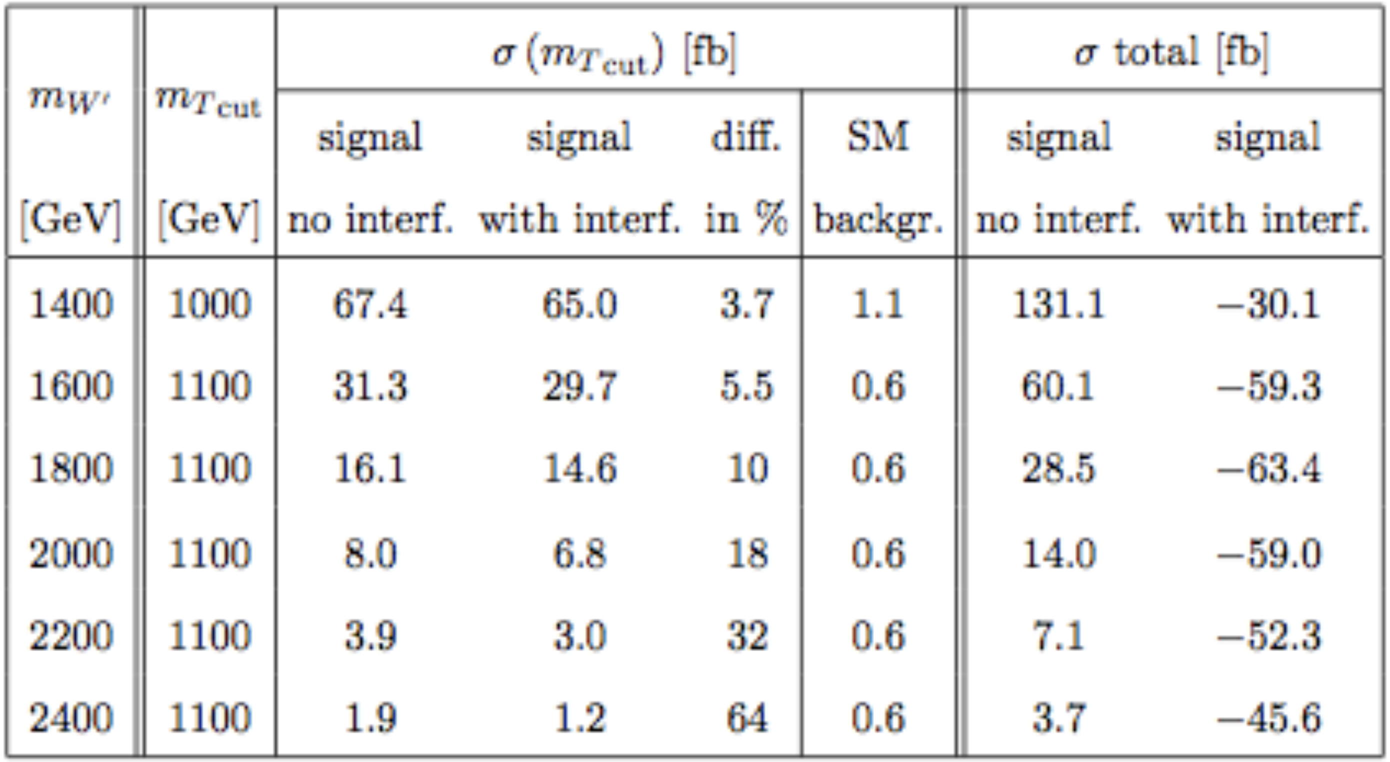
SSM W' exclusion bounds: Theory vs Exp. on the signal definition





The cumulative BSM signal might be not positive definite: strong dependence on the M_T cut

SSM W' exclusion bounds: Theory vs Exp. on the signal definition



$m_{W'}$ [GeV]	$m_{T\text{cut}}$ [GeV]	$\sigma\,(m_{T\text{cut}})$ [fb] signal no interf.	signal with interf.	diff. in %	SM backgr.	σ total [fb] signal no interf.	signal with interf.
1400	1000	67.4	65.0	3.7	1.1	131.1	−30.1
1600	1100	31.3	29.7	5.5	0.6	60.1	−59.3
1800	1100	16.1	14.6	10	0.6	28.5	−63.4
2000	1100	8.0	6.8	18	0.6	14.0	−59.0
2200	1100	3.9	3.0	32	0.6	7.1	−52.3
2400	1100	1.9	1.2	64	0.6	3.7	−45.6

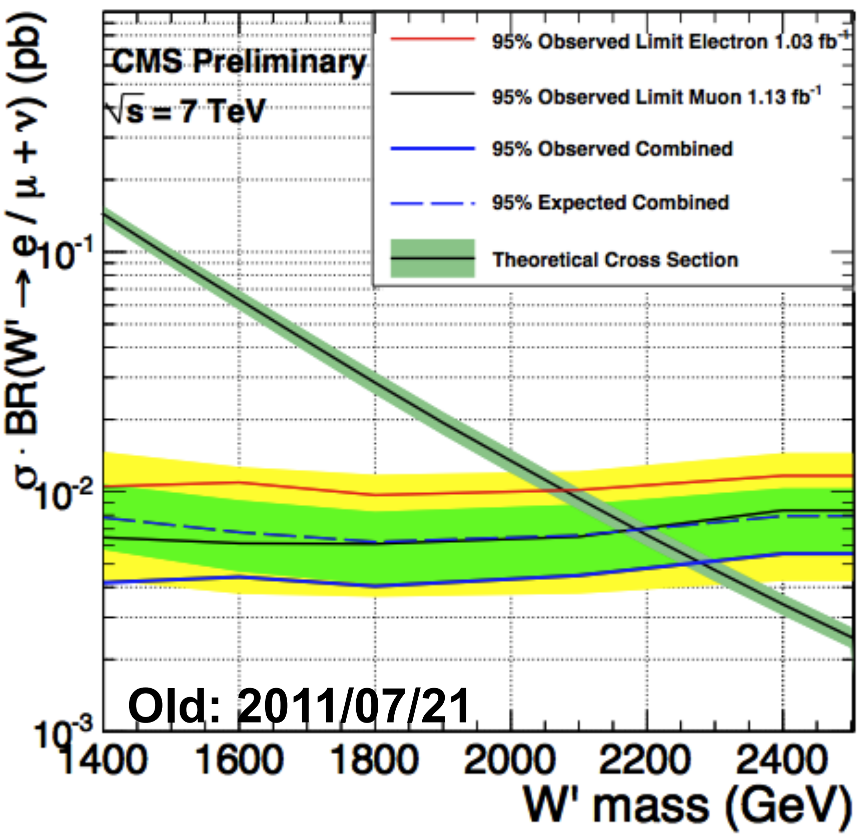
Exclusion limits with no interference are likely to be overestimated

$M_{W'}$ > 3.35 TeV (noI SSM) vs $M_{W'}$ > 3.1 TeV (SSM)

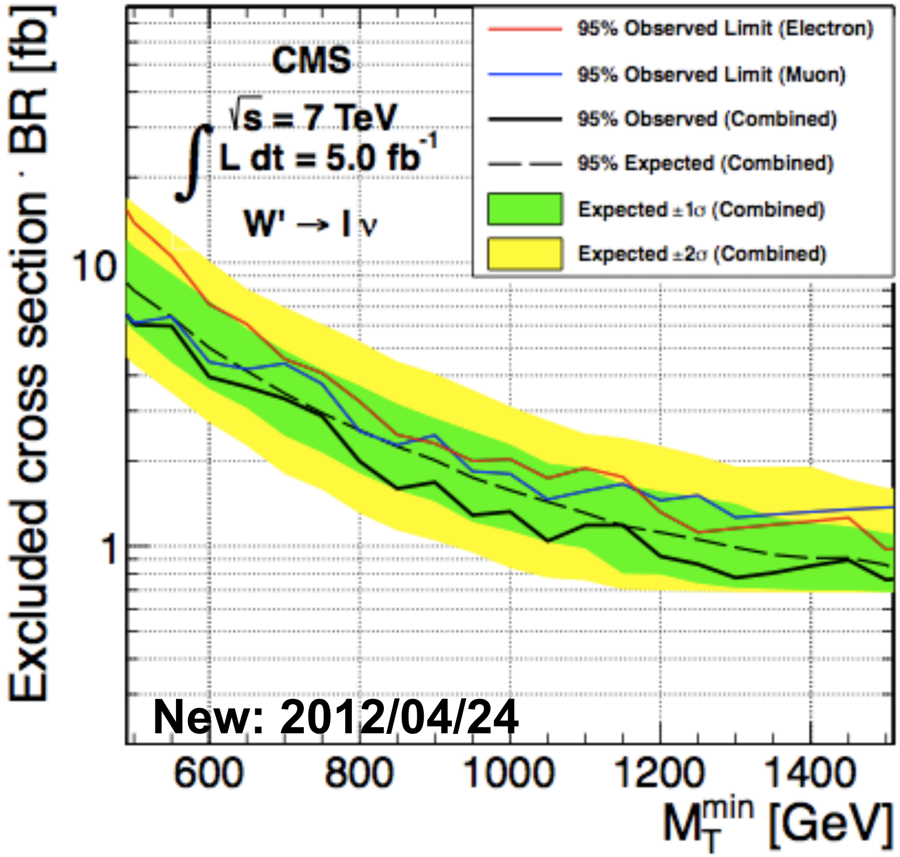
& the total BSM σ is not an appropriate observable

W' exclusion bounds: Exp. vs Theory

Old vs New 95% C.L. upper limit on the W' cross section



Old: 2011/07/21



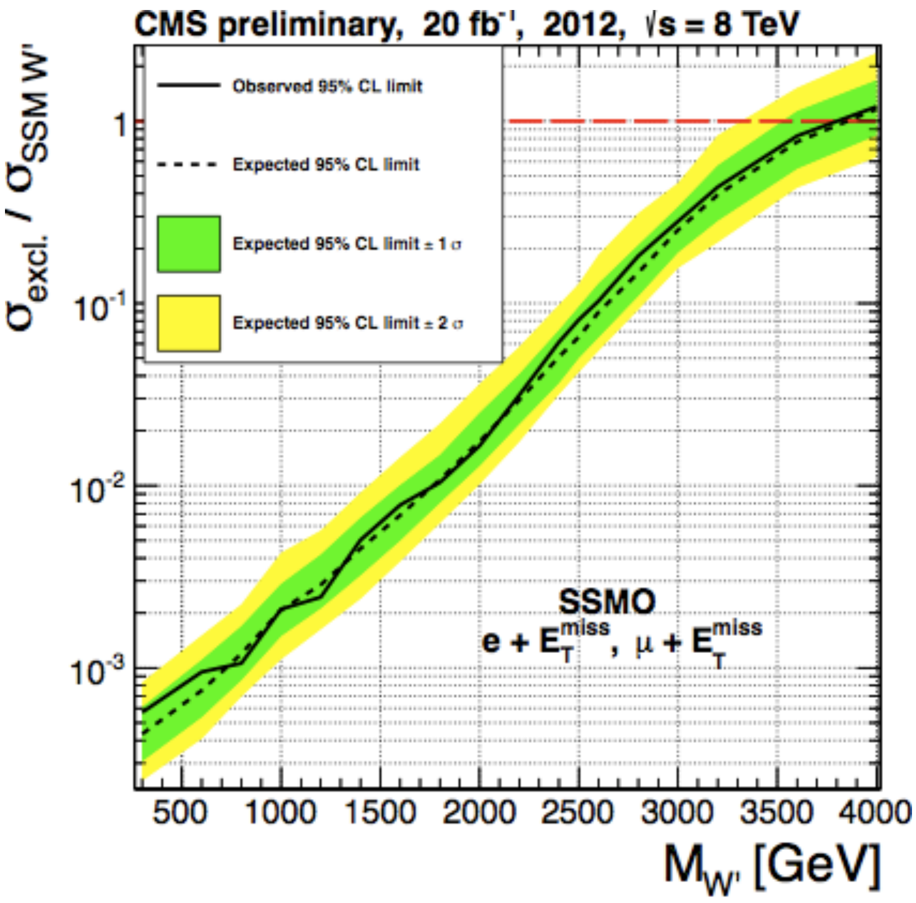
New: 2012/04/24

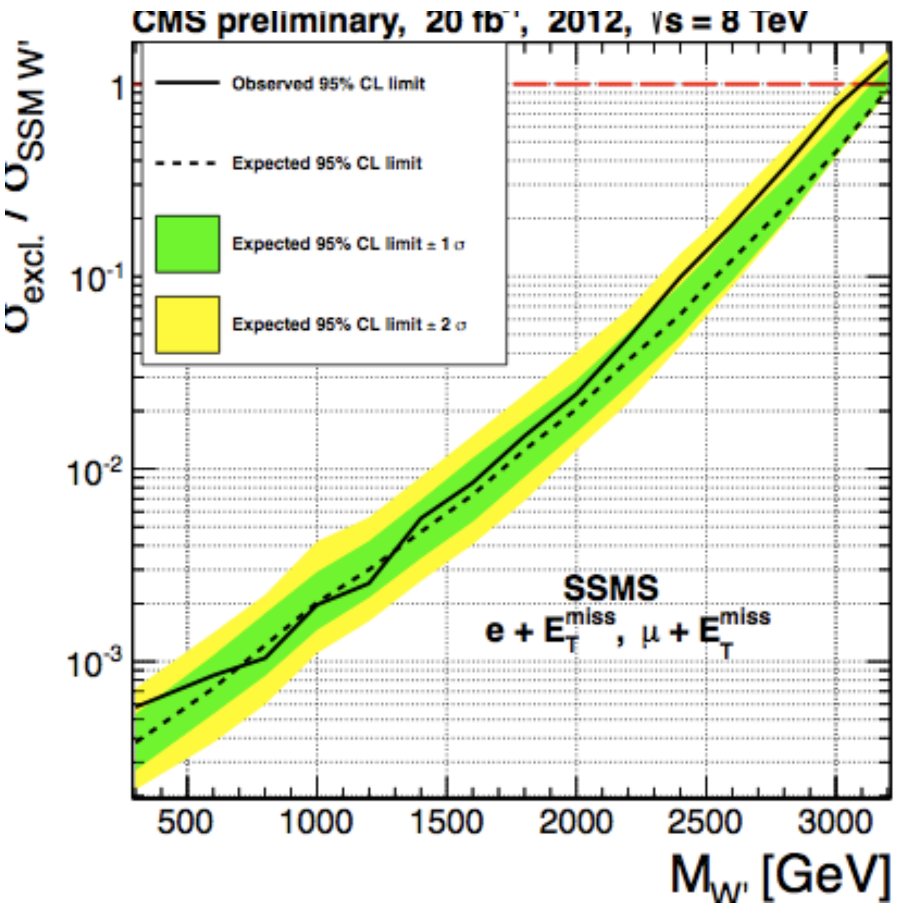
Based on fully integrated W' cross section, i.e. no interference & no M_T^{cut} :
holds for non-interferred models & Not fully informative for theorists

It includes the interference, and keeps the M_T cut as suggested in **[E.A. et al, arXiv:1110.0713]: Model-independent & Informative**

W' exclusion bounds: Exp. Vs Theory

New 95% C.L. upper bound on the W' cross section

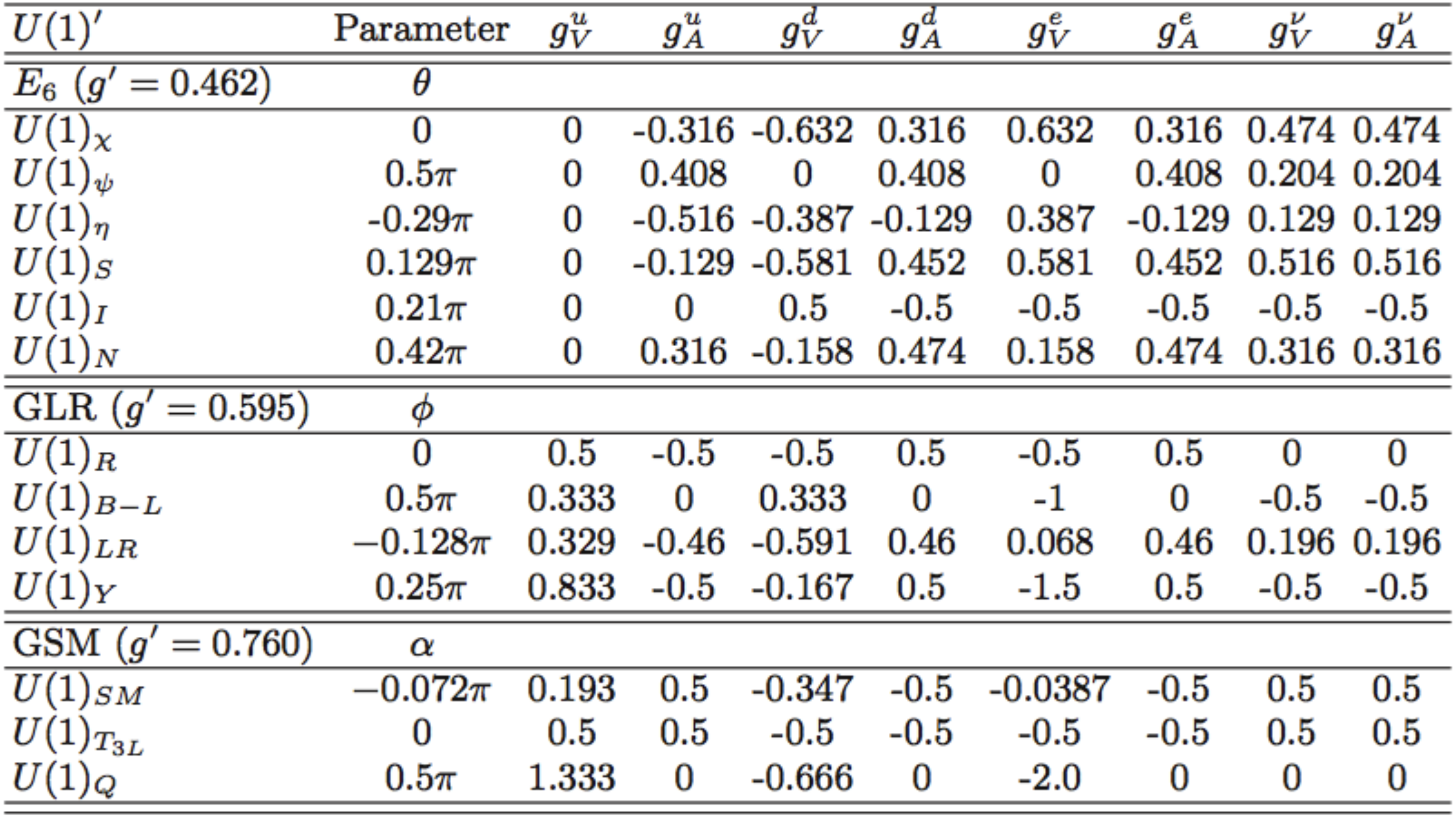




Constructive (SSMO) vs destructive (SSMS) interference:
Δ (mass bound) = 700 GeV

Z'-boson at the LHC in DY
Benchmark models

[E.A., Belyaev, King, Fedeli, Shepherd-Themistocleous, 2011]

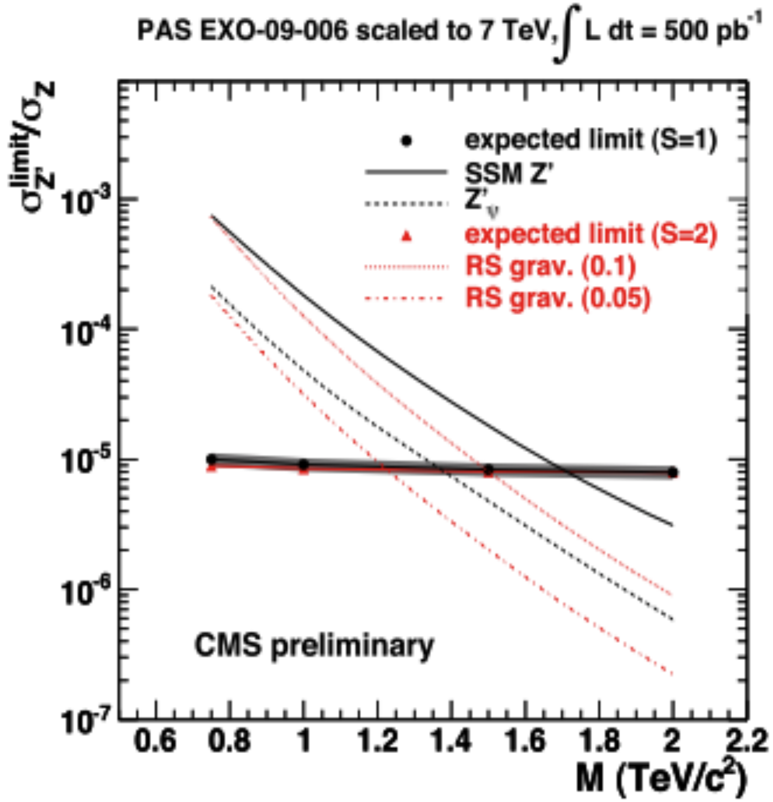


$U(1)'$	Parameter	g_V^u	g_A^u	g_V^d	g_A^d	g_V^e	g_A^e	g_V^ν	g_A^ν
E_6 $(g' = 0.462)$	θ								
$U(1)_\chi$	0	0	-0.316	-0.632	0.316	0.632	0.316	0.474	0.474
$U(1)_\psi$	0.5π	0	0.408	0	0.408	0	0.408	0.204	0.204
$U(1)_\eta$	-0.29π	0	-0.516	-0.387	-0.129	0.387	-0.129	0.129	0.129
$U(1)_S$	0.129π	0	-0.129	-0.581	0.452	0.581	0.452	0.516	0.516
$U(1)_I$	0.21π	0	0	0.5	-0.5	-0.5	-0.5	-0.5	-0.5
$U(1)_N$	0.42π	0	0.316	-0.158	0.474	0.158	0.474	0.316	0.316
GLR $(g' = 0.595)$	ϕ								
$U(1)_R$	0	0.5	-0.5	-0.5	0.5	-0.5	0.5	0	0
$U(1)_{B-L}$	0.5π	0.333	0	0.333	0	-1	0	-0.5	-0.5
$U(1)_{LR}$	-0.128π	0.329	-0.46	-0.591	0.46	0.068	0.46	0.196	0.196
$U(1)_Y$	0.25π	0.833	-0.5	-0.167	0.5	-1.5	0.5	-0.5	-0.5
GSM $(g' = 0.760)$	α								
$U(1)_{SM}$	-0.072π	0.193	0.5	-0.347	-0.5	-0.0387	-0.5	0.5	0.5
$U(1)_{T_{3L}}$	0	0.5	0.5	-0.5	-0.5	-0.5	-0.5	0.5	0.5
$U(1)_Q$	0.5π	1.333	0	-0.666	0	-2.0	0	0	0

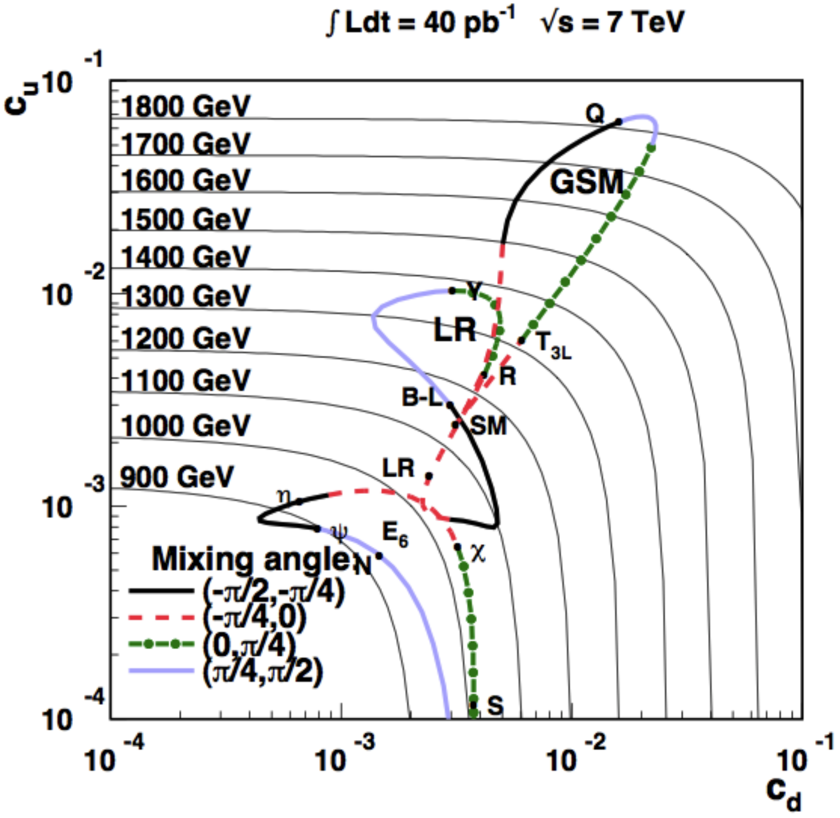
Z' searches @ the LHC in DY
a new parametrization in the cu-cd plane

[Carena et al. '04, E.A. et al. '11, CMS '12]

$$c_u = a - b c_d \quad \text{with:} \quad a = \frac{48s}{\pi}\frac{\sigma^{exp}_{\ell^+\ell^-}}{w_u}, \qquad b = \frac{w_d}{w_u}$$



PAS EXO-09-006 scaled to 7 TeV, $\int L\, dt = 500\ \text{pb}^{-1}$



$\int Ldt = 40\ \text{pb}^{-1}$ $\sqrt{s} = 7$ TeV

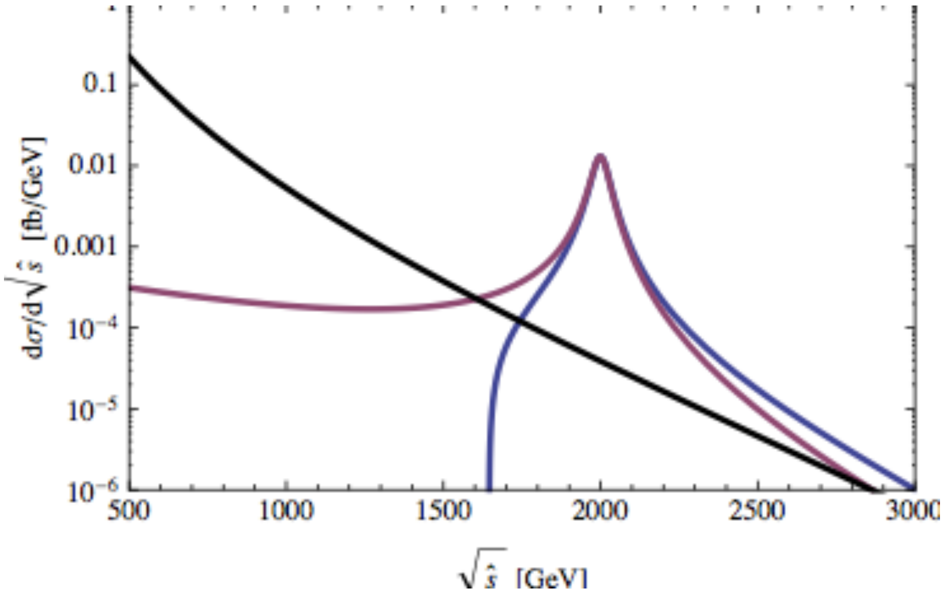
No Interference

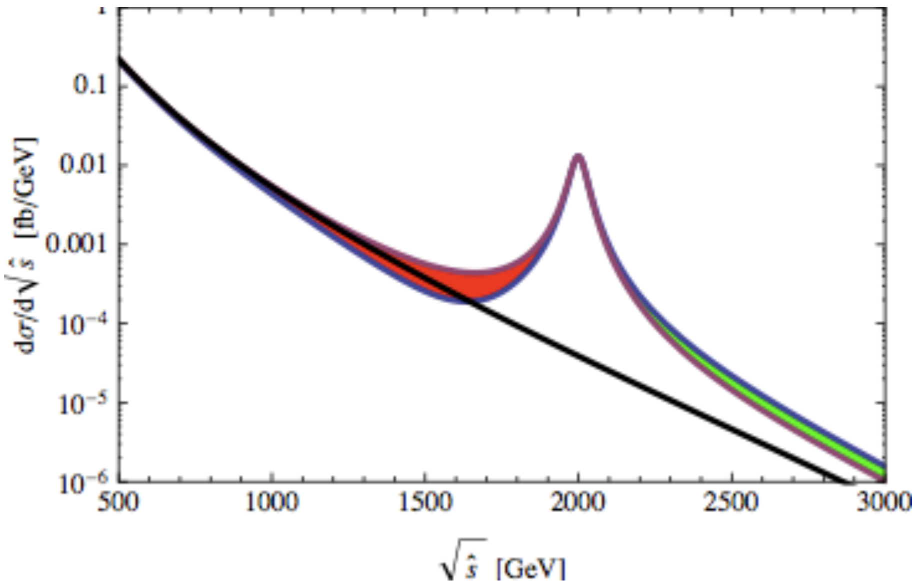
No Interference plus NWA

SSM Z' Drell-Yan production @ the LHC

Non-interferred model vs complete SSM

[E.A., Becciolini, Belyaev, Moretti, Shepherd-Themstocleous, arXiv:1304.6700]



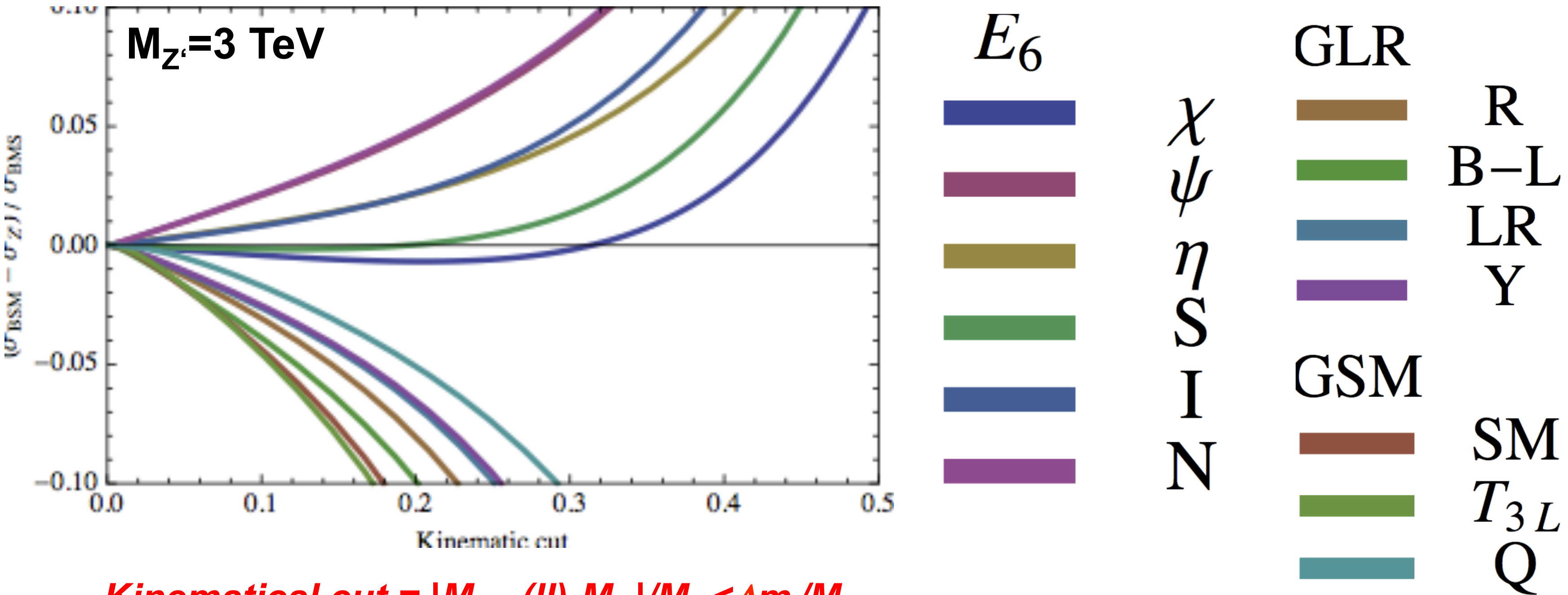


Interference effects are sizeable and model-dependent:

up to O(200%) in the SSM

Z' @ the LHC in all models: size and sign of interference effects

[E.A., Becciolini, Belyaev, Moretti, Shepherd-Themstocleous, arXiv:1304.6700]



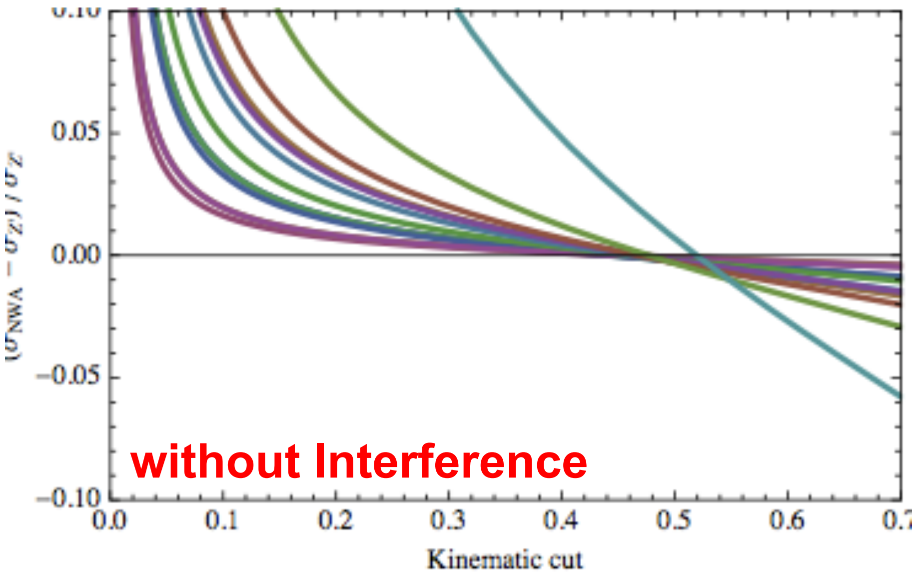
Kinematical cut = $|M_{inv}(ll) - M_{Z'}| / M_{Z'} < \Delta m / M_{Z'}$

Strategy #1: New dedicated analysis to distinguish between Z' models
Strategy #2: interference below theoretical uncertainties via cuts i.e.
quasi-model independent analysis as in the current scheme

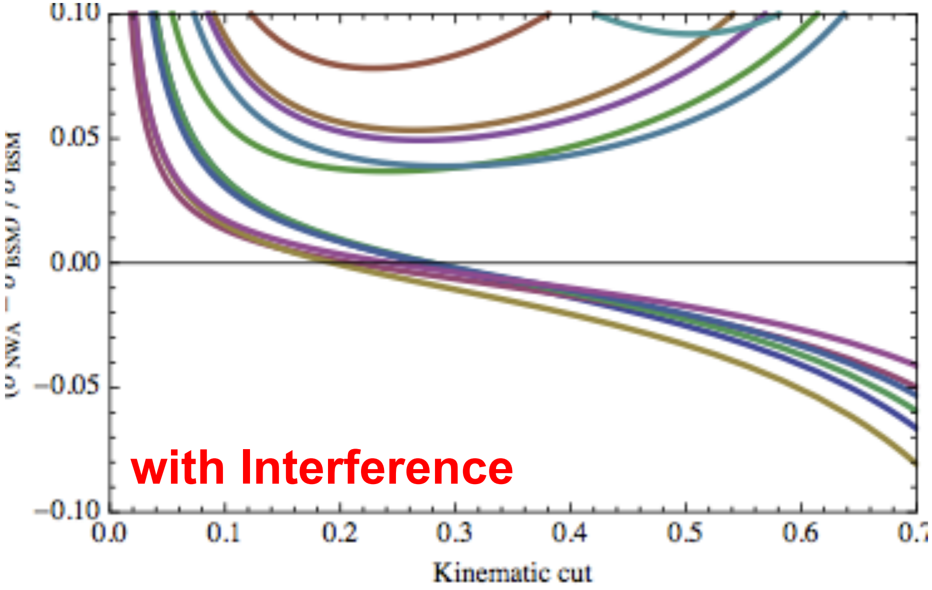
Z' @ the LHC in all models: NWA vs FW

[E.A., Becciolini, Belyaev, Moretti, Shepherd-Themstocleous, arXiv:1304.6700]

$(\sigma_{NWA} - \sigma_{Z'})/\sigma_{Z'}$



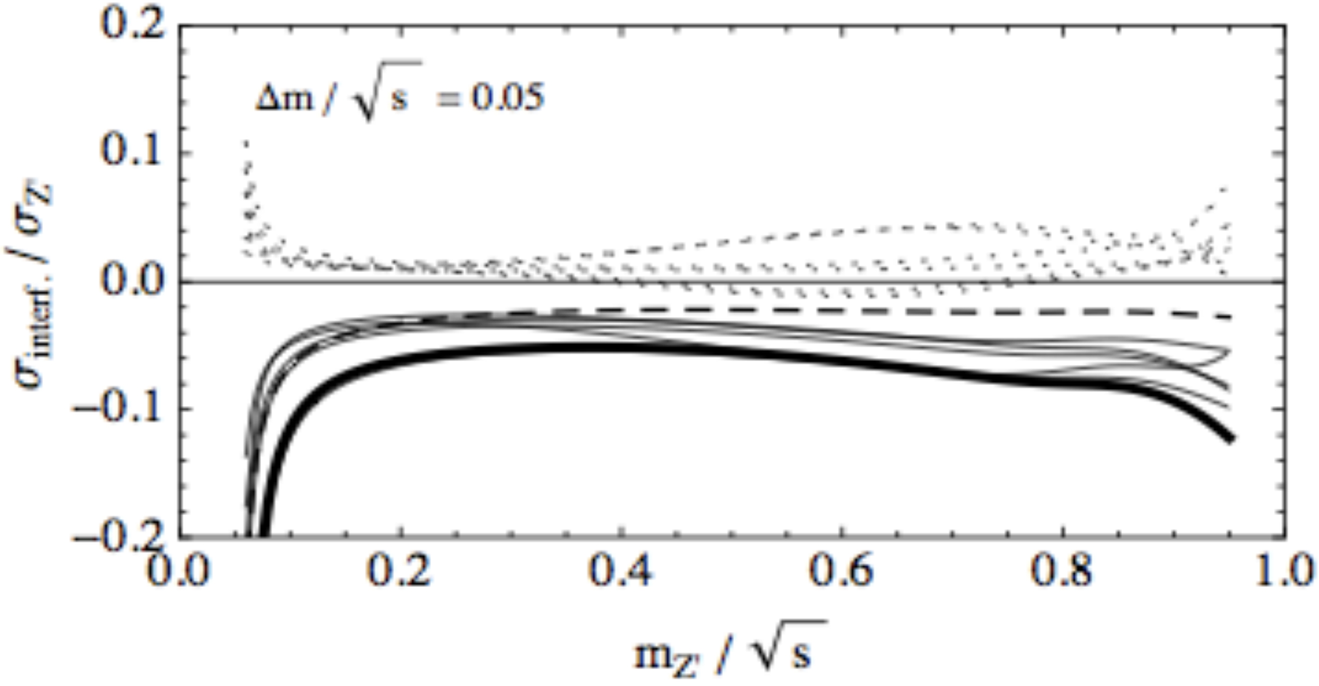
$(\sigma_{NWA} - \sigma_{BSM})/\sigma_{BSM}$



Results in NWA cannot be reproduced exactly when interference is included, or the NWA can only be valid up to some accuracy

Strategy #2 : NWA accuracy below theoretical uncertainties via cuts

Z' @ the LHC in all models: search strategy & theoretical accuracy



Strategy #1: New dedicated analysis to distinguish between Z' models

Strategy #2: reduce the current NWA and non-interferred approach within O(10%) accuracy, comparable with PDF's and NLO EW+QCD uncertainties, via $|M(ll)-M_{Z'}|/E_{coll} < 0.05$.

Conclusions

- We have discussed the importance of interference effects and the reliability of the NWA in searches for extra heavy W' and Z' bosons.
- Interference and Finite Width effects are often being neglected when analysing and interpreting data. To make our point, we have taken as sample case the SSM benchmark model in the leptonic DY channel.
- Our result is that:

(1) neglecting the interference can lead to over/under estimate the 95% C.L. exclusion bound on Z' and W' masses by O(10-20%)

(2) the 95% C.L. upper bound on the fully integrated signal cross-section, via which data are traditionally presented and Z' & W' mass bounds are extracted, is not an appropriate variable.

Novel ways of presenting experimental results just started.

extra slides

Z' exclusion limits @ the LHC

A new parametrization: the c_u-c_d plane [Carena et al. 2004]

$$\sigma_{f\bar{f}} = \int_{(M_{Z'}-\Delta)^2}^{(M_{Z'}+\Delta)^2} \frac{d\sigma}{dM^2}(pp \to Z' \to f\bar{f}X)\,dM^2$$

⇒ Narrow Width Approximation ⇒

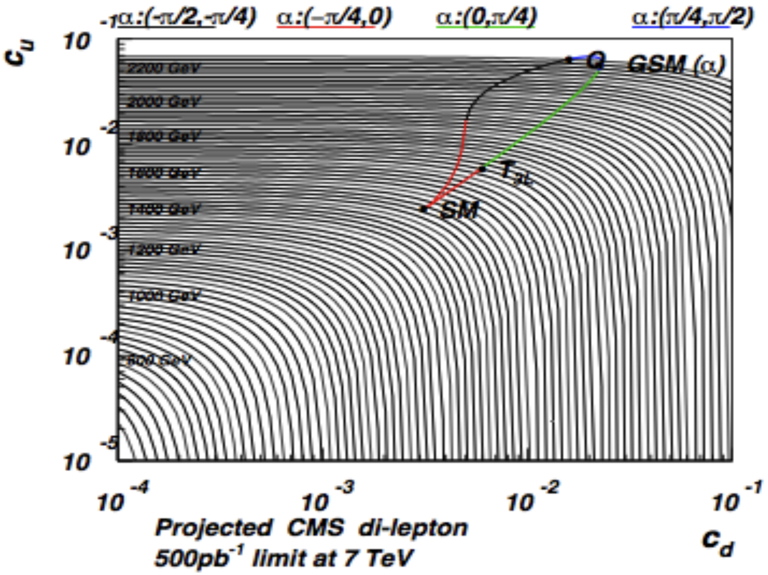
$$\sigma_{f\bar{f}} \approx \left(\frac{1}{3} \sum_{q=u,d} \left(\frac{dL_{q\bar{q}}}{dM_{Z'}^2} \right) \hat{\sigma}(q\bar{q} \to Z') \right) \times Br(Z' \to f\bar{f})$$

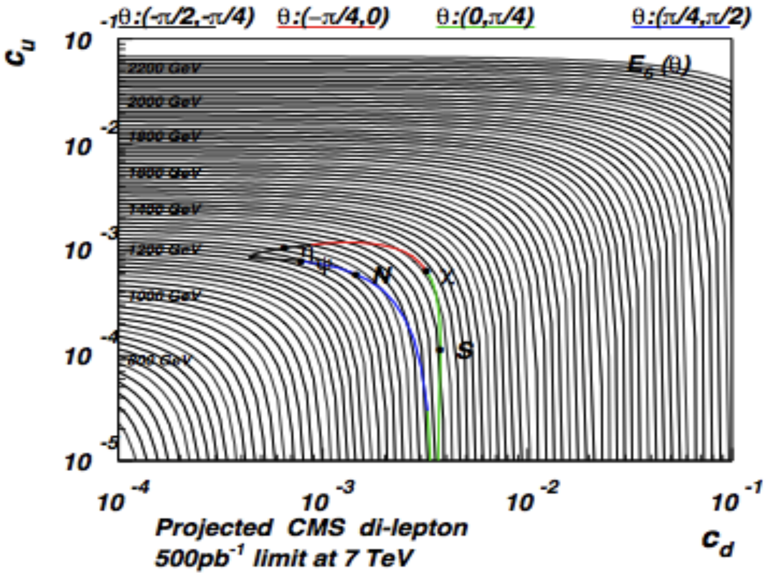
where $\hat{\sigma}(q\bar{q} \to Z') = \frac{\pi}{12} {g'}^2 [(g_V^q)^2 + (g_A^q)^2]$

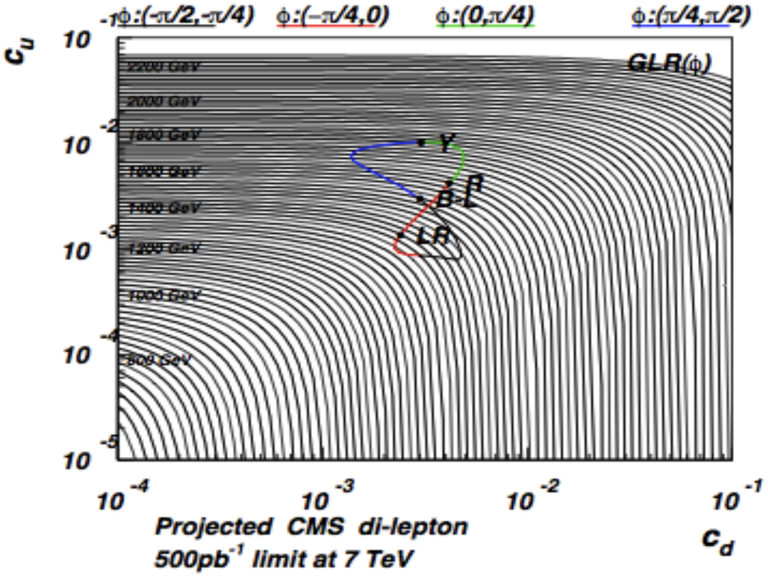
Defining: $c_u = \frac{{g'}^2}{2}({g_V^u}^2 + {g_A^u}^2) Br(\ell^+\ell^-), \quad c_d = \frac{{g'}^2}{2}({g_V^d}^2 + {g_A^d}^2) Br(\ell^+\ell^-),$

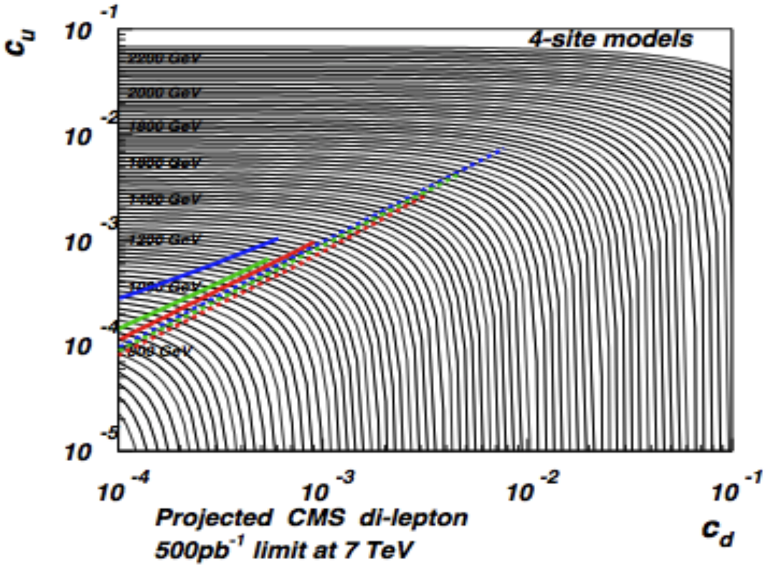
$$\boxed{\sigma_{\ell^+\ell^-}^{LO} = \frac{\pi}{48s}\left[c_u w_u(s, M_{Z'}^2) + c_d w_d(s, M_{Z'}^2)\right]}$$

Heavy Z' in the c_u-c_d plane



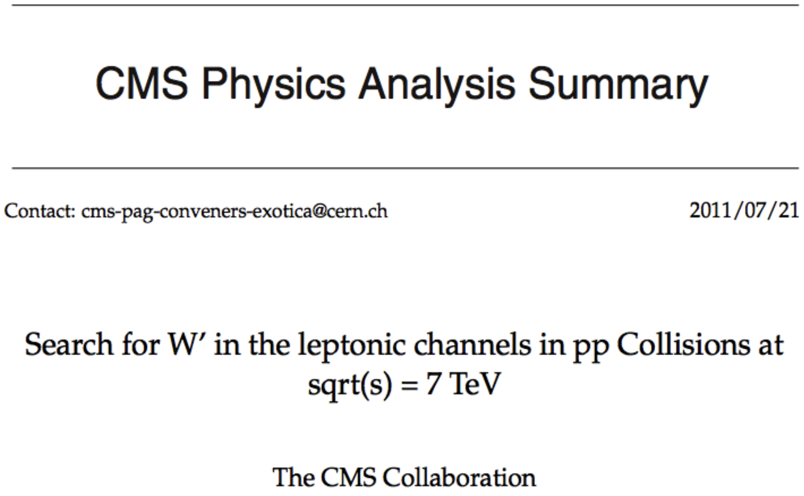






W' exclusion bounds: Exp. vs Theory

Old 95% C.L. upper limit on the W' cross section

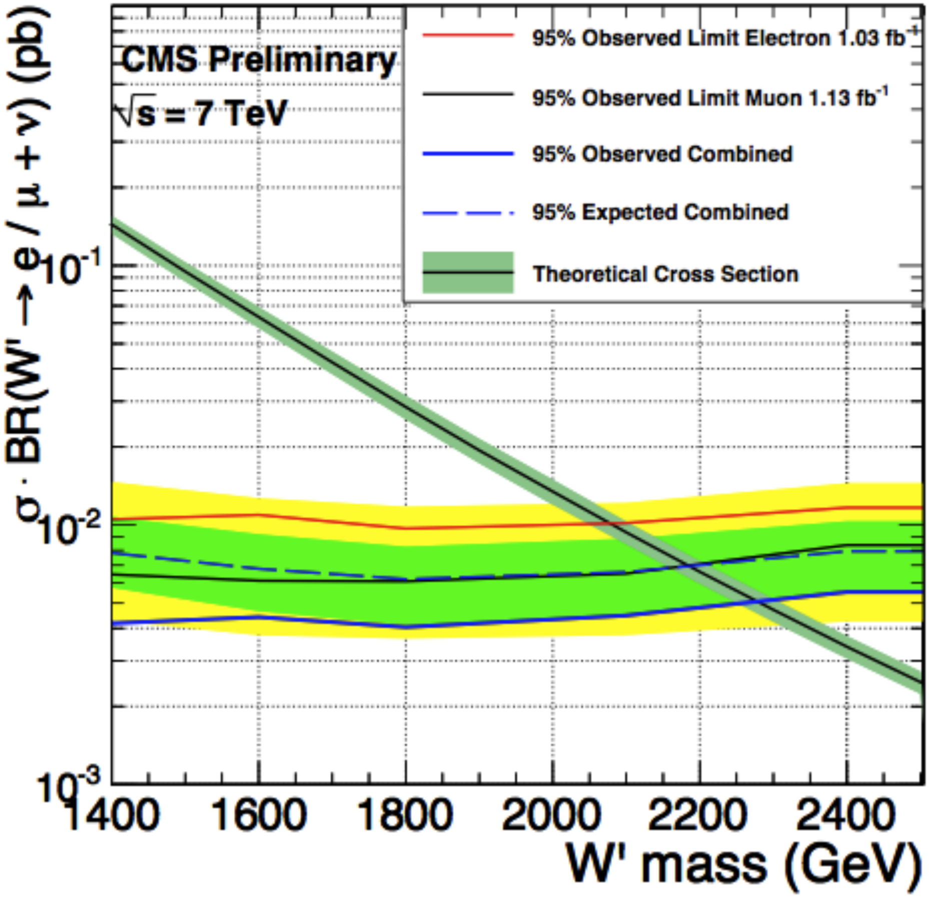


CMS Physics Analysis Summary

Contact: cms-pag-conveners-exotica@cern.ch 2011/07/21

Search for W′ in the leptonic channels in pp Collisions at sqrt(s) = 7 TeV

The CMS Collaboration



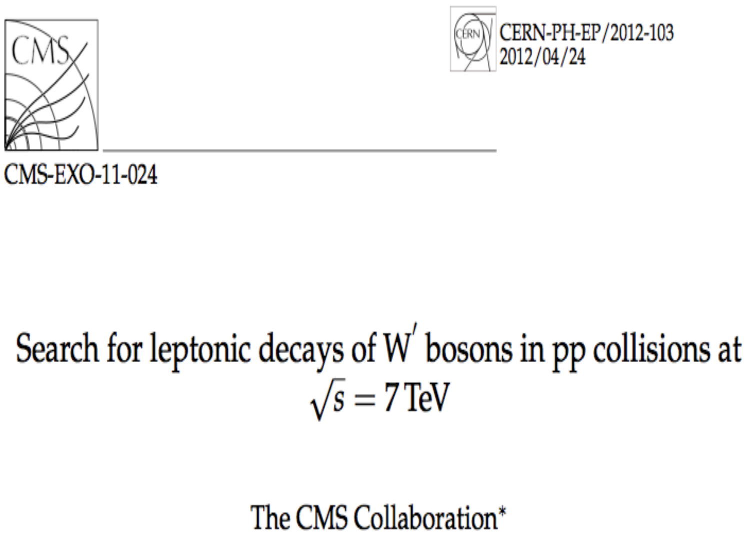
Based on fully integrated cross section for W' production and decay, i.e. no cut & no interference between extra W' and SM W.

Past analysis strictly holds only for non- interferred models

NOT fully informative for theorists and model dependent

W' exclusion bounds: Exp. Vs Theory

New 95% C.L. upper bound on the W' cross section

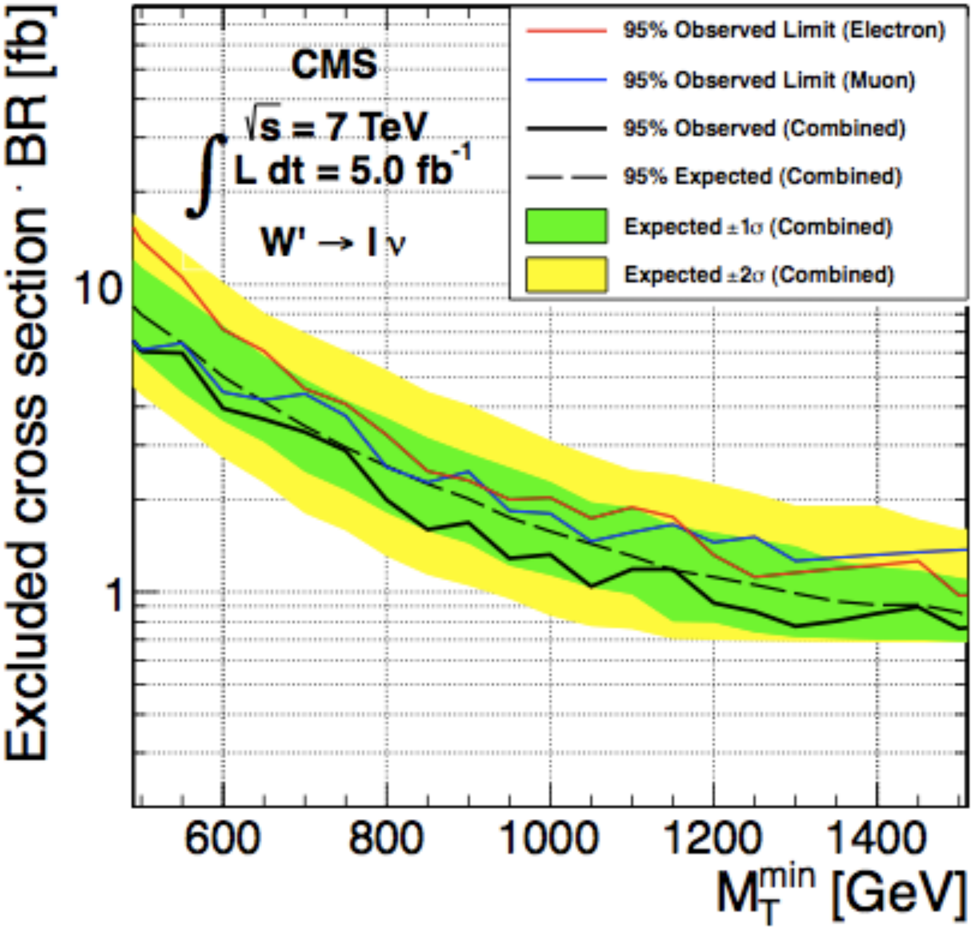


CMS-EXO-11-024

CERN-PH-EP/2012-103
2012/04/24

Search for leptonic decays of W' bosons in pp collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*



It includes for the first time the interference between extra W' and SM W, and keeps the M_T cut in the presentation of experimental results as suggested by **[E.A. et al, arXiv:1110.0713]**

A consistent and useful interpretation of data needs M_T^{cut}.

W' and Z' searches at the LHC: approximate vs complete result

Two main approximations are commonly adopted in theoretical and experimental analyses:

- neglecting interference effects between New Physics and SM:
- neglecting finite width effects i.e. adopting NWA

Our point: their impact on presentation of exp. results, data interpretation and mass bound extraction can be sizeable

We consider the SSM, where the extra W' and Z' are heavy replica of the SM W and Z-boson, in the leptonic DY channels at the 7 & 8 TeV LHC:

pp → W, W' → lepton + neutrino
pp → γ, Z, Z' → lepton pair

SSM W' exclusion bounds: Exp. Vs Theory

95% CL upper limit on the W' cross section from observed data

A consistent and useful interpretation of data needs the inclusion of M_T^{cut}.

arXiv:1110.0713

[E.A., Becciolini, De Curtis, Dominici, Fedeli, Shepherd-Themistocleous]

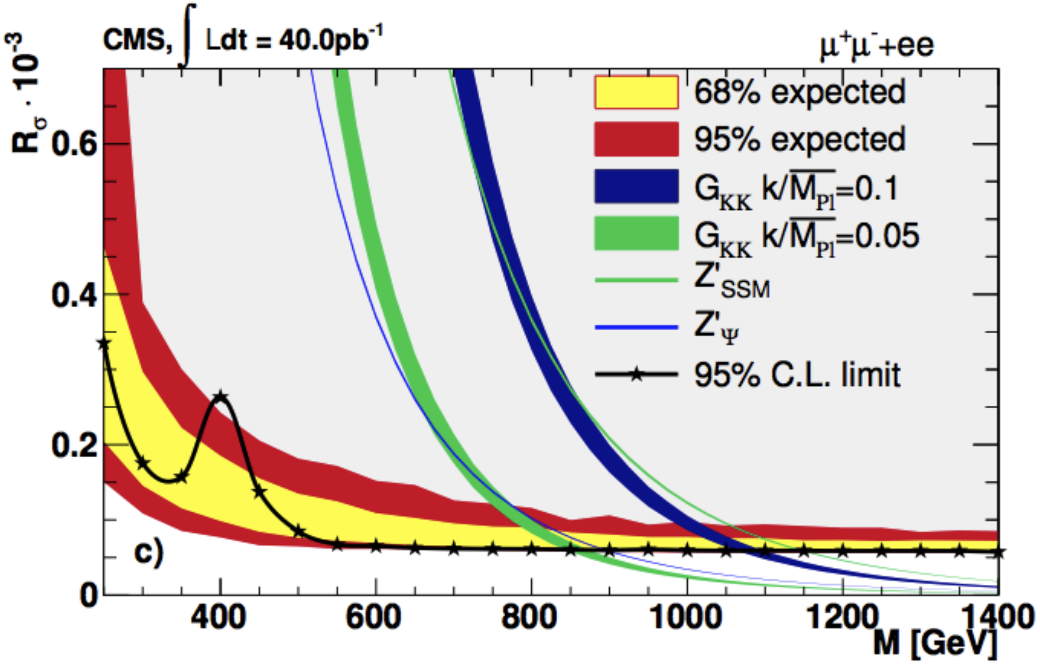
A Soton-RAL collaboration in the spirit of the NExT Institute

Z' exclusion limits @ the LHC as for the W' search…

A consistent and useful interpretation of data needs the inclusion of M_{ll}^{cut}.

Work in progress

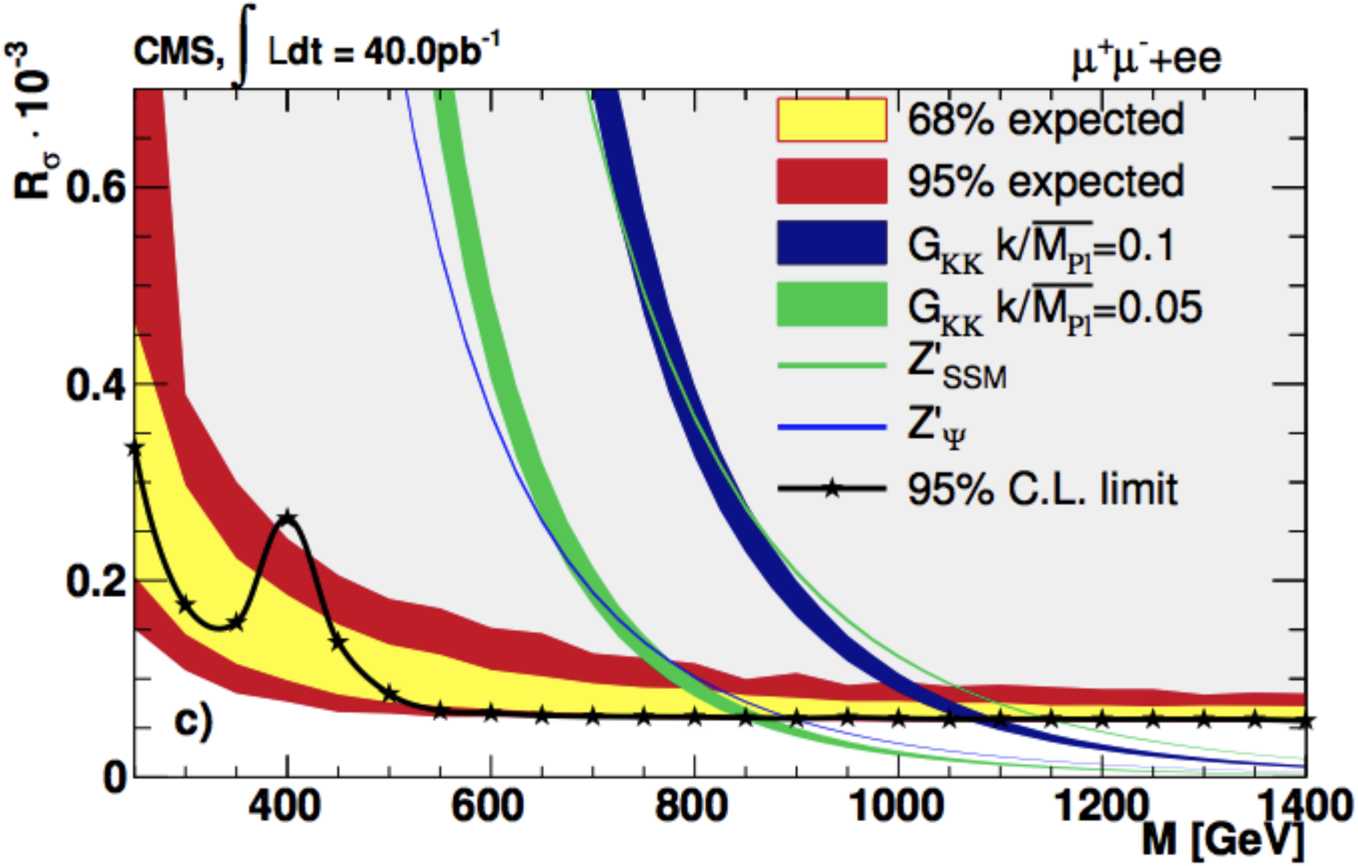
[E.A., Becciolini, Shepherd-Themistocleous]



OR

Z' exclusion limits @ the LHC

… same problem in the interpretation of exp. results for Z' searches i.e. no cut and no interference between extra Z' and SM Z are presently taken into account



W' searches at the LHC

In order to discuss the approximations and their validity range, we consider the popular benchmark scenario:

- SSM: the extra W'-boson is a heavy replica of the SM W-boson, which is the reference model in experimental analyses

in the leptonic charged Drell-Yan channel at the 7 TeV LHC:

$pp \rightarrow l\nu$ with $l = e, \mu$

Monte Carlo Event Generator FAST_2f

[E.A.]

FAST_2f is part of PHASE [E.A., Ballestrero, Maina, '07], **a MCEG for multi-particle processes at the LHC. It is dedicated to Drell-Yan processes at the Leading-Order and interfaced with PYTHIA**

Processes

We consider charged and neutral Drell-Yan leptonic channels

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

CTEQ6L PDF

Kinematical cuts

Acceptance cuts:

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

Selection cuts:

$M_{inv}(ll)>500$ GeV for pp → *ll*

$P_t(l)>250$ GeV for pp → *lν*

no detector simulation is included

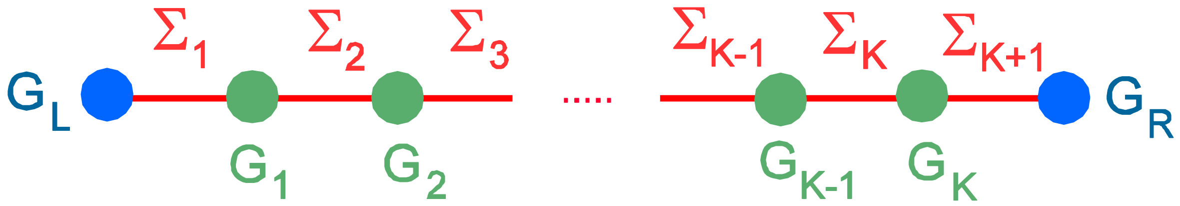
Enlarging the σ model

Enlarge the non-linear σ model by introducing vector resonances. One bonus is that unitarity properties improve (as it is known from QCD). To be consistent with the non-linear realization one uses the tool of hidden gauge symmetries (Bando,Kugo, et al 1985):

- Introduce a non-dynamical gauge symmetry together with a set of new scalar fields.
- The scalar fields can be eliminated by using the local symmetry and the theory is equivalent to the non linear $\sigma-$model.
- Promoting the local symmetry to be dynamical allows to introduce in a simple way vector resonances which are the gauge fields of the new gauge interaction.
- The new vector resonances are massive due to the breaking of the local symmetry implied by the non-linear realization.

Linear Moose Model: Breaking the EW symmetry without Higgs Fields

- Generalize the moose construction: many copies of the gauge group G intertwined by link variables Σ
- Simplest example: $G_i = SU(2)$. Each Σ_i describes 3 scalar fields.



- The model has two global symmetries related to the beginning and to the end of the moose, $G_L = SU(2)_L$ and $G_R = SU(2)_R$ which can be gauged to the standard $SU(2)_L x U(1)_Y$
- Particle content: 3 massive gauge bosons, W and Z, the massless photon and 3K massive vectors. $SU(2)_{diag}$ is a custodial symmetry
- The **BESS model** can be recast in a **3-site model** (K=1), and its V-A generalization (Casalbuoni, DC, Dominici, Gatto, Feruglio, 1989) can be recast in a 4-site model (K=2) (see also Foadi,Frandsen,Ryttov,Sannino, 2007)

The transformation properties of the fields are

$$\begin{aligned}\Sigma_1 &\longrightarrow L\Sigma_1 U_1^\dagger,\\ \Sigma_i &\longrightarrow U_{i-1}\Sigma_i U_i^\dagger\ , \qquad i=2,\cdots,K,\\ \Sigma_{K+1} &\longrightarrow U_K \Sigma_{K+1} R^\dagger,\end{aligned}$$

$$\begin{array}{rlll} U_i \in G_i \equiv SU(2)_i & A^i_\mu = A^{ia}_\mu \tau^a/2, & g_i, & i=1,2,\cdots,K,\\ L \in G_L \equiv SU(2)_L & \tilde{W}_\mu = \tilde{W}^a_\mu \tau^a/2, & \tilde{g}, & \\ R \in G_R \equiv SU(2)_R \supset U(1)_Y & \tilde{Y}_\mu = \tilde{\mathfrak{Y}}_\mu \tau^3/2, & \tilde{g}' & \end{array}$$

$$\boxed{\mathcal{L} = \sum_{i=1}^{K+1} f_i^2 \mathrm{Tr}[D_\mu \Sigma_i^\dagger D^\mu \Sigma_i] - \frac{1}{2}\sum_{i=1}^{K} \mathrm{Tr}[(F^i_{\mu\nu})^2] - \frac{1}{2}\mathrm{Tr}[(F_{\mu\nu}(\tilde{W}))^2] - \frac{1}{2}\mathrm{Tr}[(F_{\mu\nu}(\tilde{Y}))^2]}$$

Covariant derivatives

$$\begin{aligned}D_\mu \Sigma_1 &= \partial_\mu \Sigma_1 - i\tilde{g}\tilde{W}_\mu \Sigma_1 + i\Sigma_1 g_1 A^1_\mu,\\ D_\mu \Sigma_i &= \partial_\mu \Sigma_i - i g_{i-1} A^{i-1}_\mu \Sigma_i + i\Sigma_i g_i A^i_\mu, \qquad\qquad i=2,\cdots,K,\\ D_\mu \Sigma_{K+1} &= \partial_\mu \Sigma_{K+1} - i g_K A^K_\mu \Sigma_{K+1} + i\tilde{g}'\Sigma_{K+1}\tilde{Y}_\mu\end{aligned}$$

The continuum limit

- The moose picture for large values of K can be interpreted as the discretization of a continuum gauge theory in 5D along a fifth dimension. The continuum limit is defined by

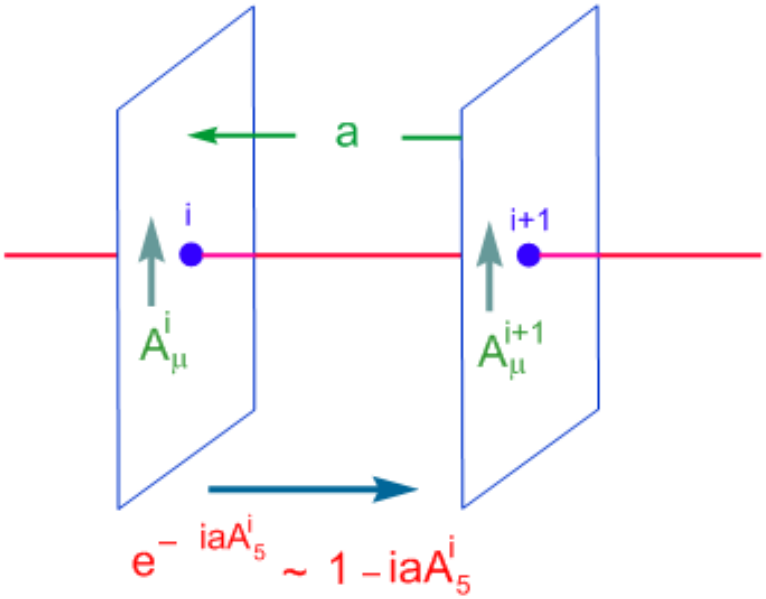
$$K \to \infty, \quad a \to 0, \quad Ka \to \pi R$$

$$\lim_{a \to 0} a g_i^2 = g_5^2, \quad \lim_{a \to 0} a f_i^2 = f^2(z)$$

a = lattice spacing, R= compactification radius, g_5= bulk gauge coupling

- The link couplings f_i and the gauge couplings g_i can be simulated in the continuum by non-flat 5-dim metrics.
- Flat metric corresponds to equal f's and g's
- In the continuum limit, the structure of the moose has an interpretation in terms of a geometrical Higgs mechanism in a pure 5D gauge theory.

- A gauge field is a connection: a way of relating the phases of the fields at nearby points. After discretizing the 5th dim the field A_5 is naturally substituted by a link variable realizing the parallel transport between two lattice sites ($A_\mu{}^i$ = KK modes)



$$\Sigma_i \approx 1 - iaA^i{}_5 \approx e^{-iaA^i{}_5}$$

$$\Sigma\Sigma^\dagger = 1$$

$$D_\mu \Sigma_i \approx iaF^{i}_{\mu 5}$$

$$F^i_{m5} = \partial_m A^i_5 - \partial_5 A^i_m - i[A^i_m, A^i_5]$$

- The action for the deconstructed gauge theory is (**Hill, Pokorski, Wang; Arkani-Hamed, Cohen, Georgi, 2001**)

$$S = \int d^4x \frac{a}{g^2}\left(-\frac{1}{2}\sum_i \mathrm{Tr}\left[F^i_{\mu\nu}F^{\mu\nu i}\right] + \frac{1}{a^2}\mathrm{Tr}\left[(D_\mu\Sigma_i)(D^\mu\Sigma_i)^\dagger\right]\right), \quad A^i_\mu = \text{KK modes}$$

- Sintetically described by a moose diagram (**Georgi, 1986**)

Direct fermionic couplings

(Casalbuoni, DC, Dolce, Dominici; Chivukula, Simmons, He, Kurachi)

- Left- and right-handed fermions, $\psi_{L\,(R)}$ are coupled to the ends of the moose, but they can couple to any site by using a Wilson line

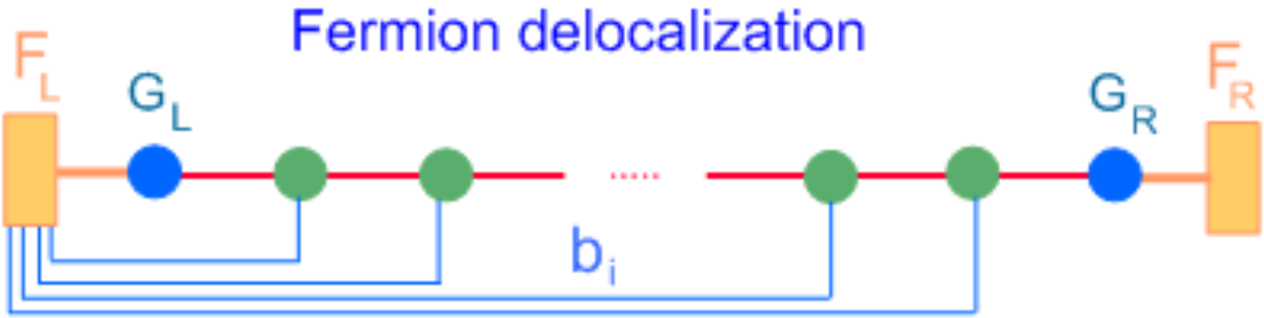
$$\chi_L^i = \Sigma_i^\dagger \Sigma_{i-1}^\dagger \cdots \Sigma_1^\dagger \psi_L, \quad \chi_L^i \to U_i \chi_L^i$$

$$\Downarrow$$

$$b_i \bar{\chi}_L^i \gamma^\mu \left(\partial_\mu + i g_i V_\mu^i + \frac{i}{2} g' (B-L) Y_\mu \right) \chi_L^i$$

no delocalization of the right-handed fermions.

Small terms $O(10^{-3})$ since they could contribute to right-handed currents constrained by non-leptonic K- decays and $b \to s\gamma$ processes



In the unitary gauge ($\Sigma_i \equiv I$) and after a rescaling $\psi_L \rightarrow \frac{1}{\sqrt{1+\sum_i b_i}}\psi_L$:

$$\mathcal{L}^{tot}_{fermions} = \bar{\psi}_R i\gamma^\mu \left[\partial_\mu + i\tilde{g}'\frac{\tau^3}{2}\tilde{\mathcal{Y}}_\mu + \frac{i}{2}\tilde{g}'(B-L)\tilde{\mathcal{Y}}_\mu\right]\psi_R$$

$$+\bar{\psi}_L i\gamma^\mu \left[\partial_\mu + \frac{1}{1+\sum_{i=1}^{K} b_i}\left(i\tilde{g}\tilde{W}_\mu + i\sum_{i=1}^{K} b_i g_i A^i_\mu\right) + \frac{i}{2}\tilde{g}'(B-L)\tilde{\mathcal{Y}}_\mu\right]\psi_L$$

correction to the SM gauge boson couplings

new couplings of the extra gauge bosons ~ b_i g_i

How can we get b_i from a 5D bulk?

(Foadi,Gopalakrishna,Schmidt; Csaki,Hubitsz,Meade; Bechi,Casalbuoni, DC, Dominici)

Consider fermions propagating in the warped 5D bulk with additional brane kinetic terms + BC's: $\psi_R|_0 = 0$, $\psi_L|_{\pi R} = 0$

$$S_{ferm.} = \int d^4x \int_0^{\pi R} dz \Big[e^{-4A(z)} [(\frac{i}{2}\bar{\psi}\Gamma^M D_M \psi + h.c.)] - e^{-A(z)} M \bar{\psi}\psi \Big]$$

$$+ e^{-4A(0)} \frac{\delta(z)}{\hat{t}_L^2} i\bar{\psi}_L \gamma^\mu D_\mu \psi_L + \ e^{-4A(\pi R)} \delta(\pi R - z) i\bar{\psi}_R (\frac{1}{\hat{t}_R^2}) \gamma^\mu D_\mu \psi_R \Big]$$

where $D_M \psi = (\partial_M + iT^a A^a_M(z) + iY_L A^3_M(\pi R))\psi$ and $\hat{t}_{L,R}$ set the weight of the brane kinetic terms with respect to the bulk one.

- **DISCRETIZE** the fifth dimension $\longrightarrow$ the fermions on the j-site with $j = 0, .., K+1$, with a mass term $m_j = (aM_j + 1)/a$, $j = 1, .., K$, "hop" from one site to the near one due to ∂_z.

- Study the effects of ψ_i $(i = 1, .., K)$ in the low-energy limit that is neglect kinetic terms with respect to mass terms. **DECOUPLE** the heavy fermions with the solutions of their e.o.m. (consider only the quadratic interactions among fermions)

$$\alpha_j L_j - m_{j+1} L_{j+1} = 0, \qquad j = 0, .., K-1$$
$$\alpha_j R_{j+1} - m_j R_j = 0, \qquad j = 1, .., K$$

where $L_j = \psi_L^j$ e $R_j = \psi_R^j$ $(j = 1, .., K)$, L_0 and R_{K+1} are, up to mixing corrections, the left and right components of the SM fermions, and $\alpha_0 = \hat{t}_L/\sqrt{a}$, $\alpha_j = 1/a$ $(j = 1, .., K-1)$, $\alpha_K = \hat{t}_R/\sqrt{a}$, are the "hopping" strengths.

- **PLUG** the solutions in the gauge-fermion interaction, get direct SM fermion couplings to A_μ^i + SM fermion mass term (normalized fields):

$$S^b_{ferm} = \int d^4x \sum_{j=1}^{K} \frac{b_j^L}{1+\sum_{i=1}^K b_i^L} i\bar{L}_0 \gamma^\mu (\partial_\mu + i g_j T^a A_\mu^{aj} + i\tilde{g}' Y_L A_\mu^{K+1}) L_0$$
$$+ \sum_{j=1}^{K} \frac{b_j^R}{1+\sum_{i=1}^K b_i^R} \; i\bar{R}_{K+1} \gamma^\mu (\partial_\mu + i g_j T^3 A_\mu^{3j} + i\tilde{g}' Y_L A_\mu^{K+1}) R_{K+1}$$
$$+ \sum_{j=1}^{K} \frac{b_j^R}{1+\sum_{i=1}^K b_i^R} \frac{g_j}{\sqrt{2}} (\bar{R}_{K+1} \gamma^\mu A_\mu^{+j} R_{K+1} + h.c.) - m^f (\bar{L}_0^f R_{K+1}^f + h.c.)$$

with $b_j^L = (\frac{\alpha_0}{m_j} \prod_{i=1}^{j-1} \frac{\alpha_i}{m_i})^2 \geqslant 0$, $\quad b_j^R = (\frac{\alpha_K}{m_K} \prod_{i=j}^{K-1} \frac{\alpha_i}{m_i})^2 \geqslant 0$ $\quad (\alpha_K \ll \alpha_0)$

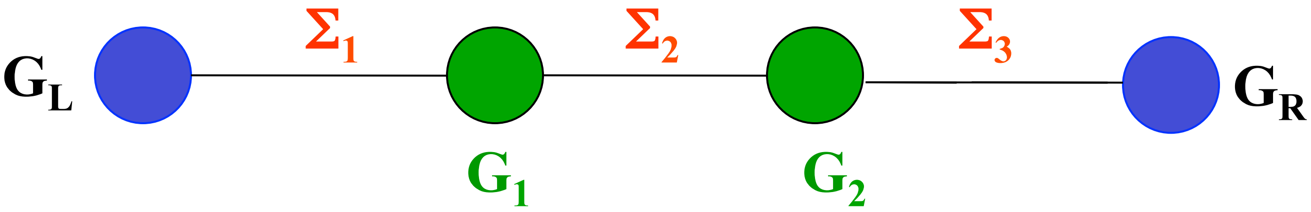
$$m^f = m_j \sqrt{\frac{b_j^L}{(1+\sum_{i=1}^K b_i^L)}} \sqrt{\frac{b_j^R}{(1+\sum_{i=1}^K b_i^R)}} \qquad \forall j = 1, .., K$$

The Higgsless 4-site Linear Moose model

(Accomando, DC, Dominici, Fedeli, 2008)

- 2 gauge groups $G_i = SU(2)$ with global symmetry $SU(2)_L \otimes SU(2)_R$ plus LR symmetry: $g_2 = g_1$, $f_3 = f_1$

- 6 extra gauge bosons $W`_{1,2}$ and $Z`_{1,2}$ (have definite parity when $g = g` = 0$)



(K=2)

- 5 new parameters $\{f_1, f_2, b_1, b_2, g_1\}$ related to their masses and couplings to bosons and fermions (one is fixed to reproduce M_Z)

$$f_1, f_2 \rightarrow M_1, M_2$$

$$M_1 = f_1 g_1$$

$$M_2 = \frac{M_1}{z} > M_1$$

$$z = \frac{f_1}{\sqrt{f_1^2 + 2f_2^2}} < 1$$

charged and neutral gauge bosons almost degenerate

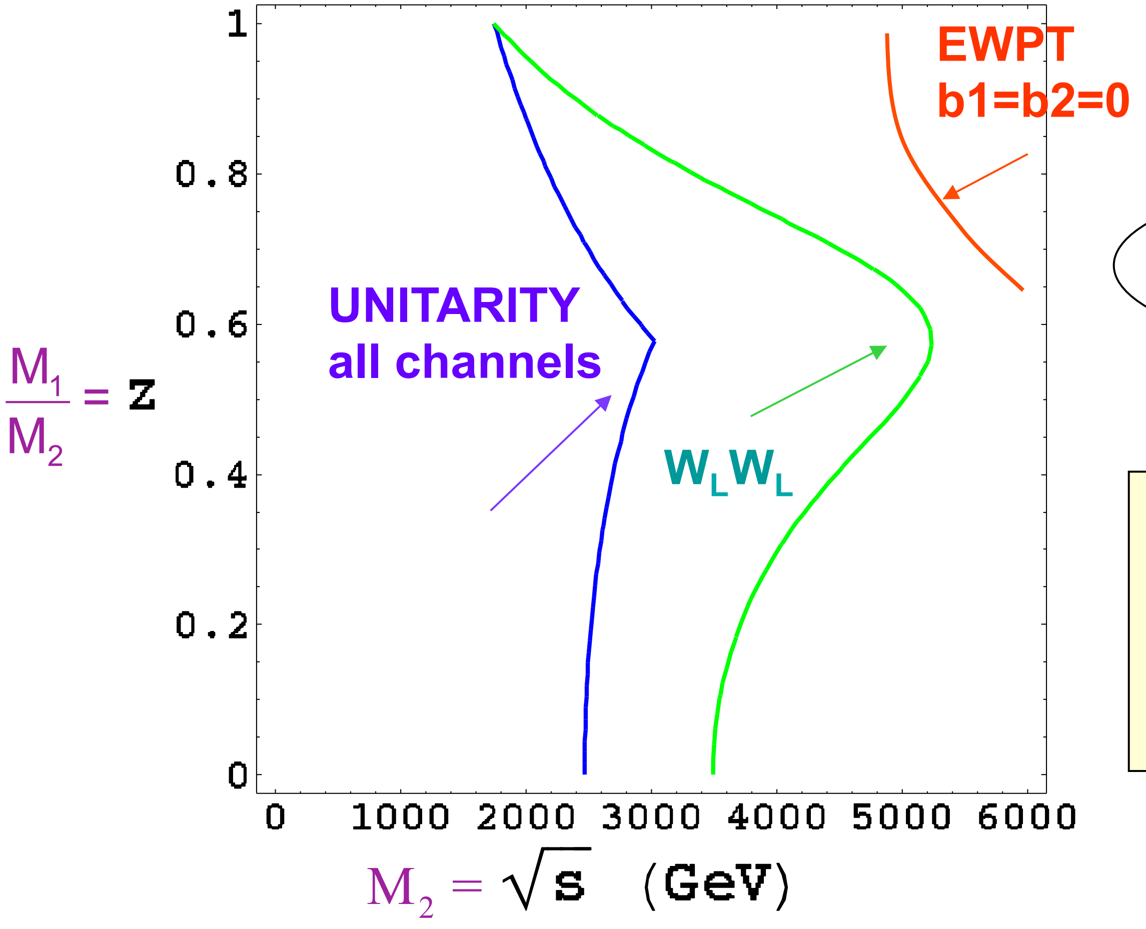
$$M_{1,2}^{c,n} \sim M_{1,2} + O\left(\frac{e^2}{g_1^2}\right)$$

The Higgsless 4-site Linear Moose model

Unitarity and EW precision tests

$$\varepsilon_1 \approx 0 \quad \varepsilon_2 \approx 0, \quad \varepsilon_3 \approx \left(\frac{g^2}{2g_1^2}(1 - z^4) \right)$$

$O(e^2/g_1^2)$, $b_1 = b_2 = 0$



Best unitarity limit for $f_1=f_2$ or z=1/p3

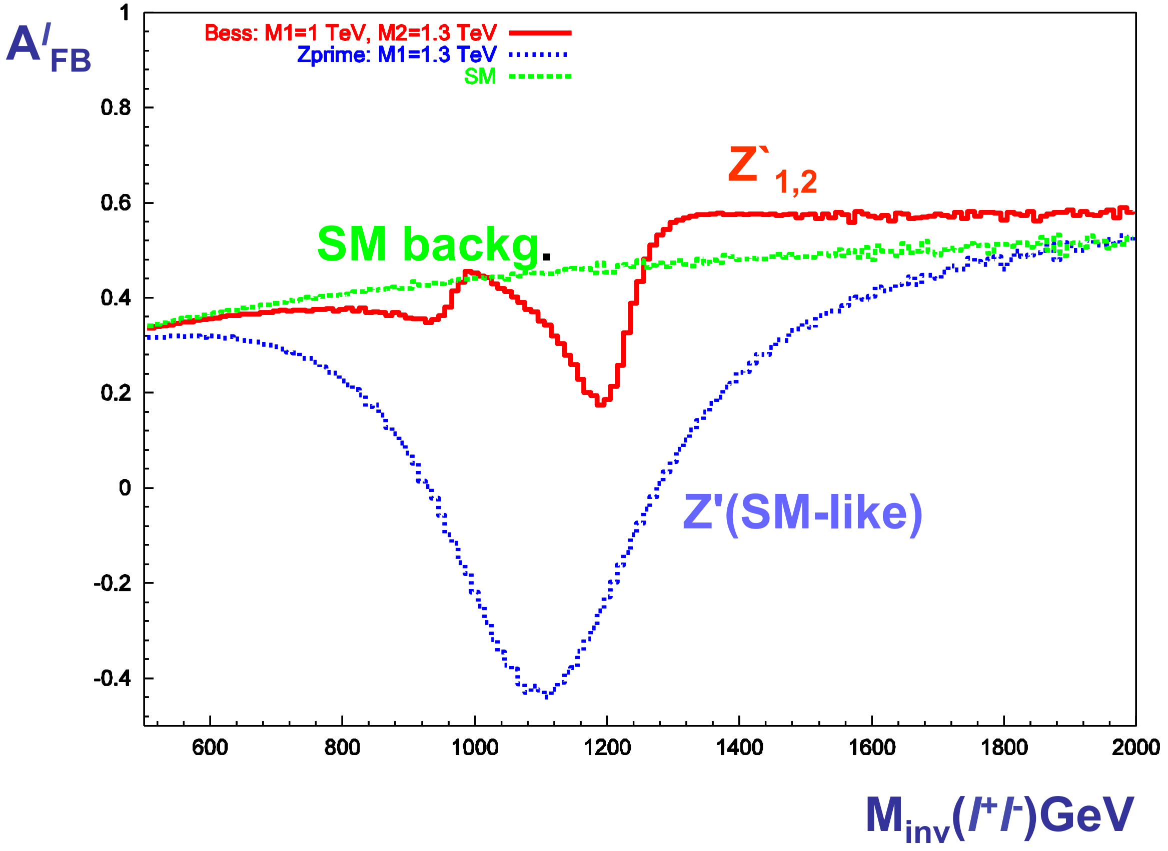
Unitarity and EWPT are hardly compatible !

↓

A direct coupling of the new gauge bosons to ordinary matter must be included: $b_{1,2} \neq 0$

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

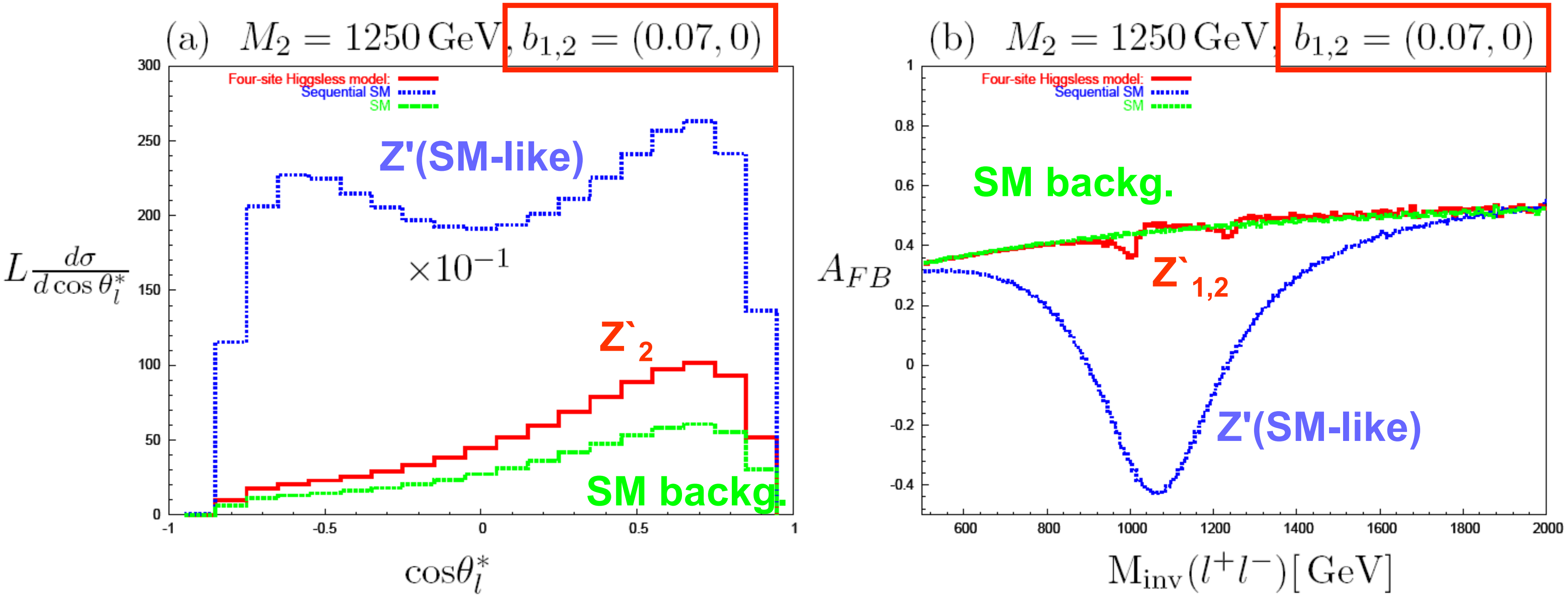
(Dittmar,Nicollerat,Djouadi 03; Petriello,Quackenbush 08)



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

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

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