Distinguishing Z' physics with early LHC data

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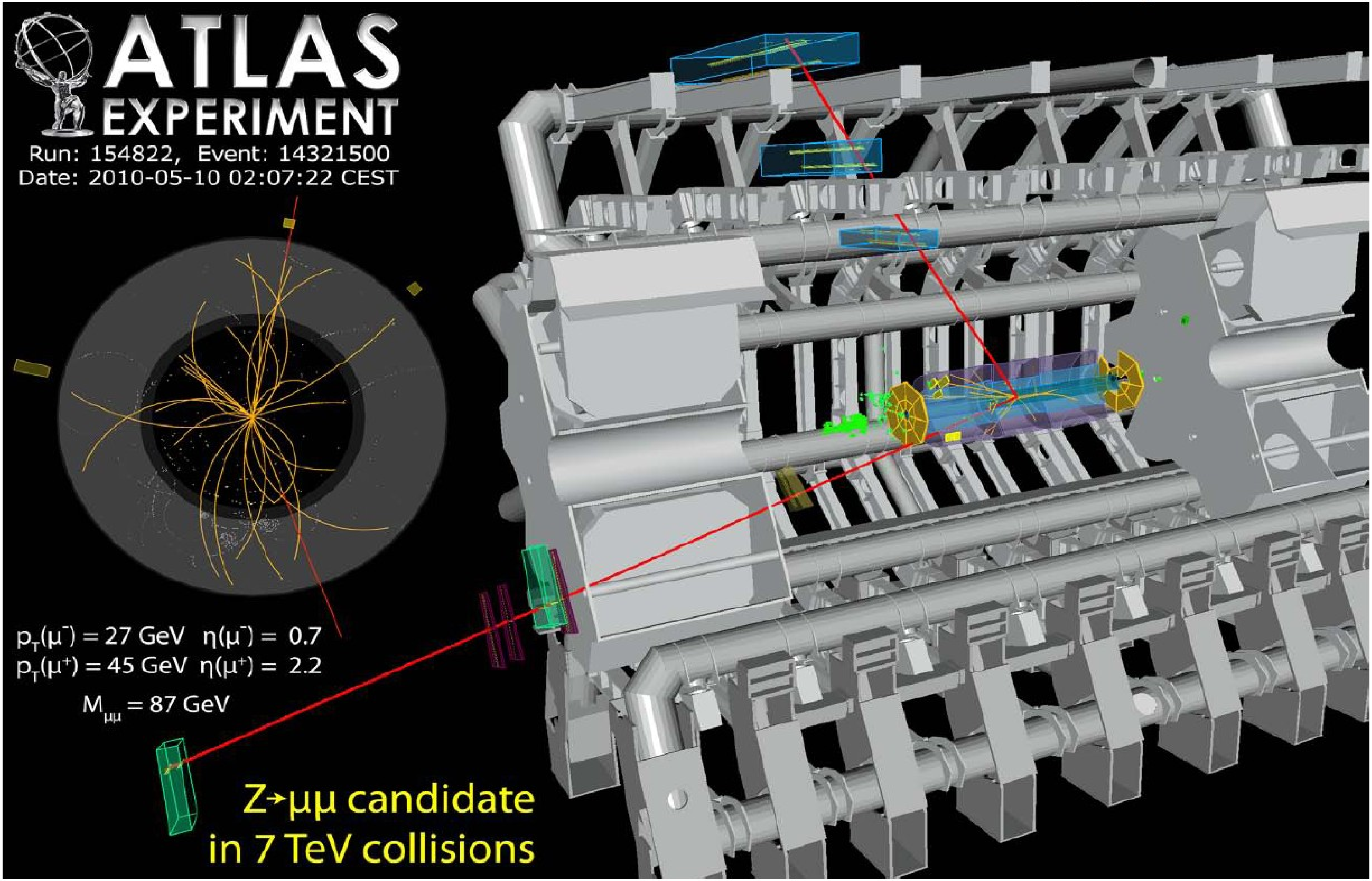
http://arxiv.org/pdf/1010.6058

work in progress

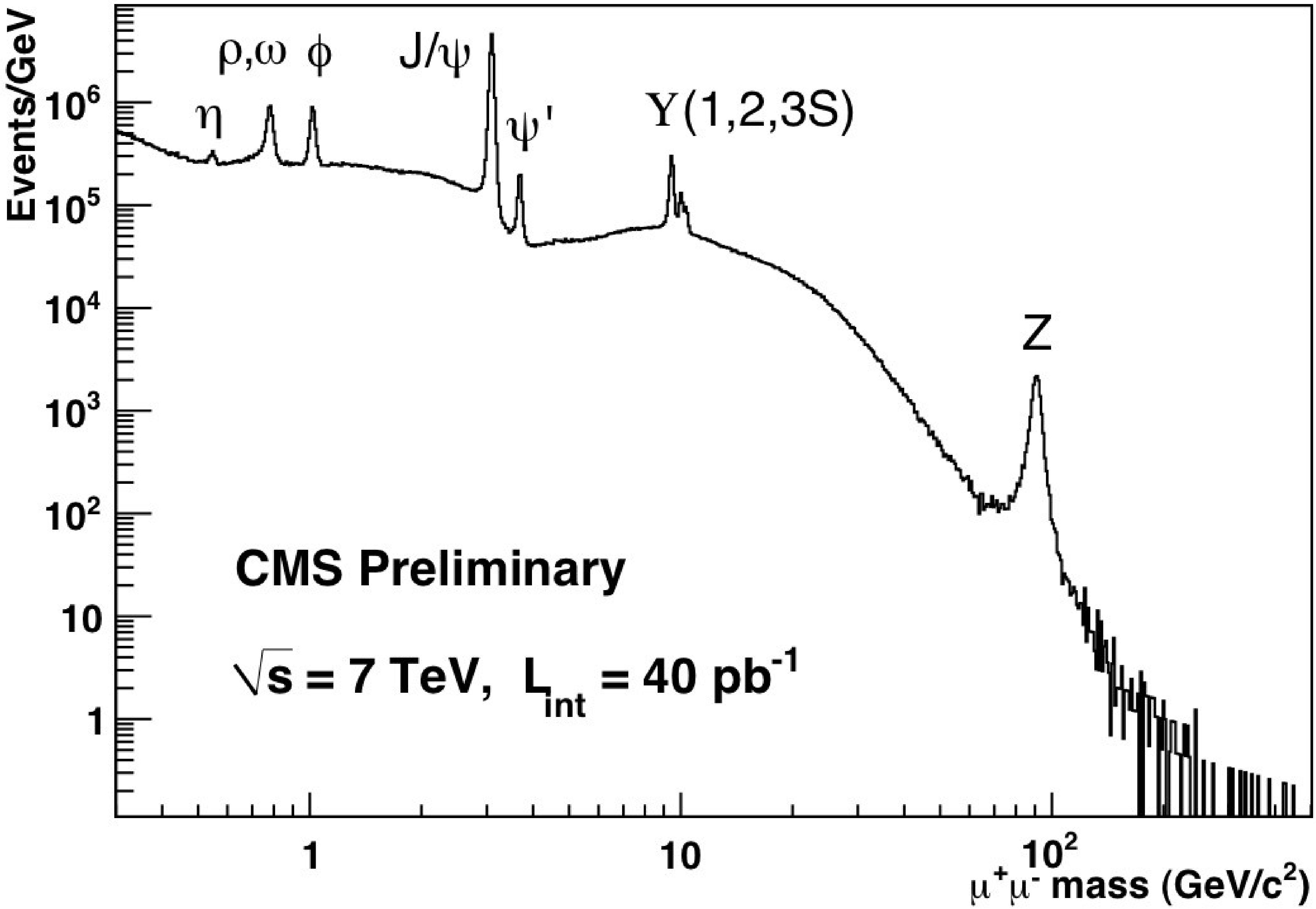
The meaning(s) of Z'

- **Experimentalist:**
  - ***a resonance "bump"more massive than the Z which can be observed in $pp \to e^+e^- + X$ or $pp \to \mu^+\mu^- + X$***

LHC in action: Z –> μ μ candidate



LHC in action: invariant $M_{\mu\mu}$ distribution



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  - ***a new massive electrically neutral, colourless boson which couples to quarks and leptons***

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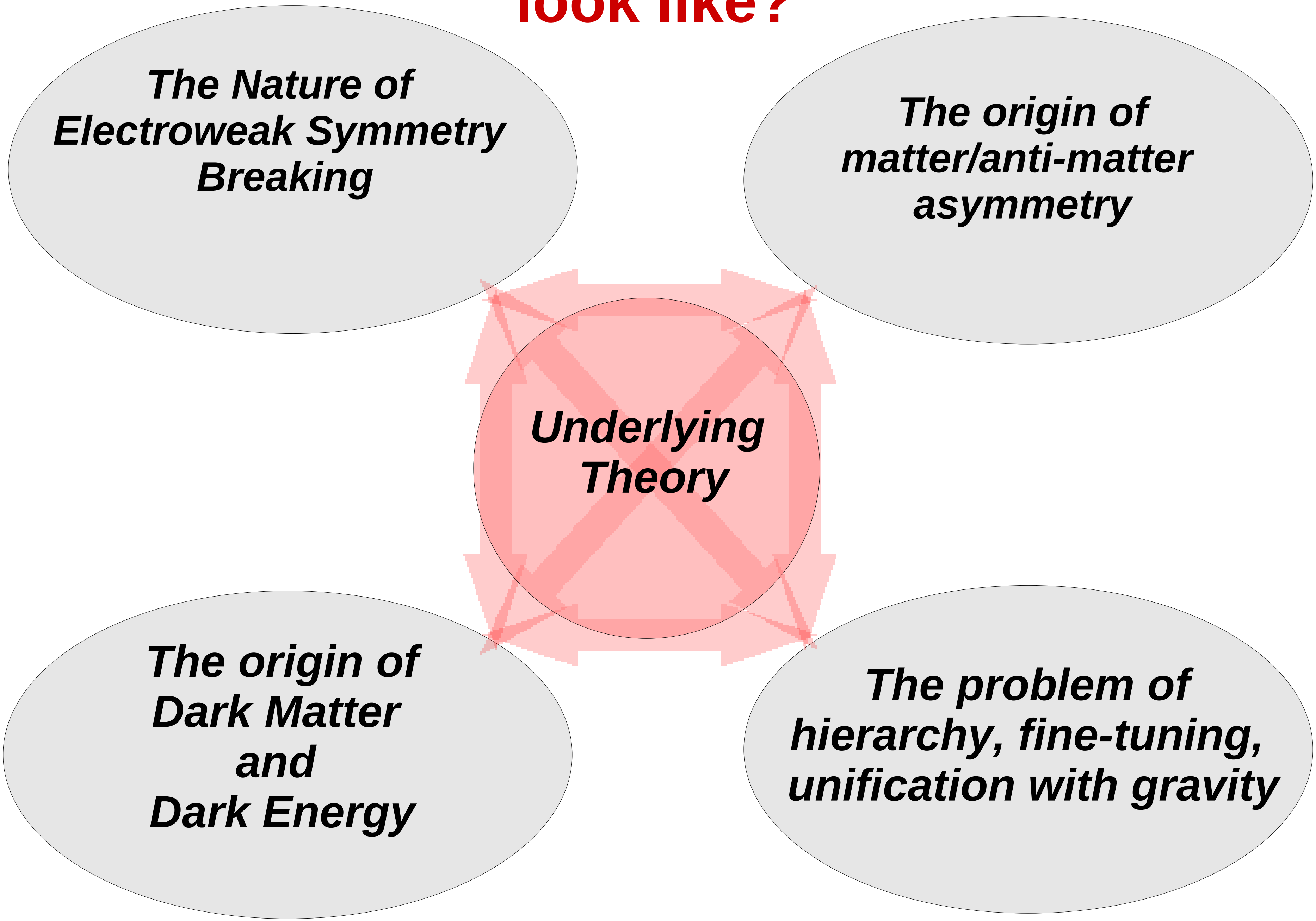
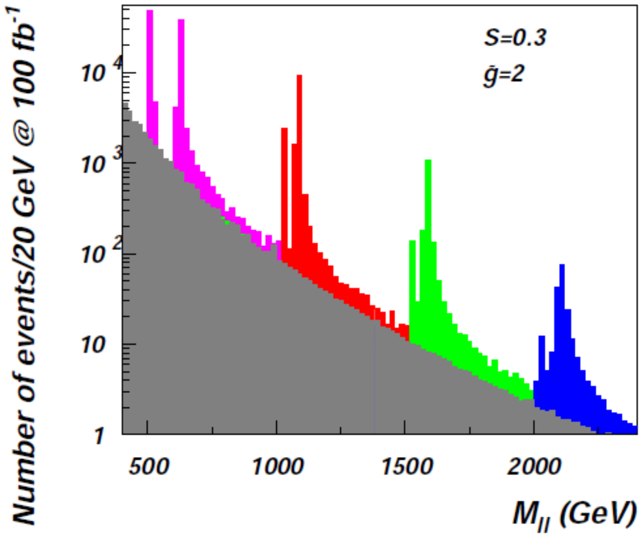
- **Phenomenologist:**
  - ***a new massive electrically neutral, colourless boson which couples to quarks and leptons***
- **Theorist:**
  actually it could be many things….
  - ***Spin-0 : e.g. sneutrino in R-parity violating SUSY***
  - ***Spin-2 : e.g. KK excited graviton as in Randall-Sundrum model***
  - ***Spin-1 :***
    - a new U(1)'gauge boson from E6, L-R models, SUSY E6SSM...
    - KK excited Z bosons or photons
    - Techni-rho bound states (e.g. from Walking TC models)
    - Heavy gauge bosons from Higgsless models (n-site models)

How the Underlying Theory of Nature could look like?



Some promising theory-candidates...

- **Supersymmetry:**
  - **MSSM, NMSSM, USSM, E_6SSM, ...**
    - *In NMSSM we add S3 to break U(1) PQ to Z3 – but this results in cosmological domain walls*
    - *In USSM we gauge the U(1) PQ symmetry to 'eat' the axion resulting in a massive* **Z' gauge boson**
    - *but not anomaly free -> E_6SSM*



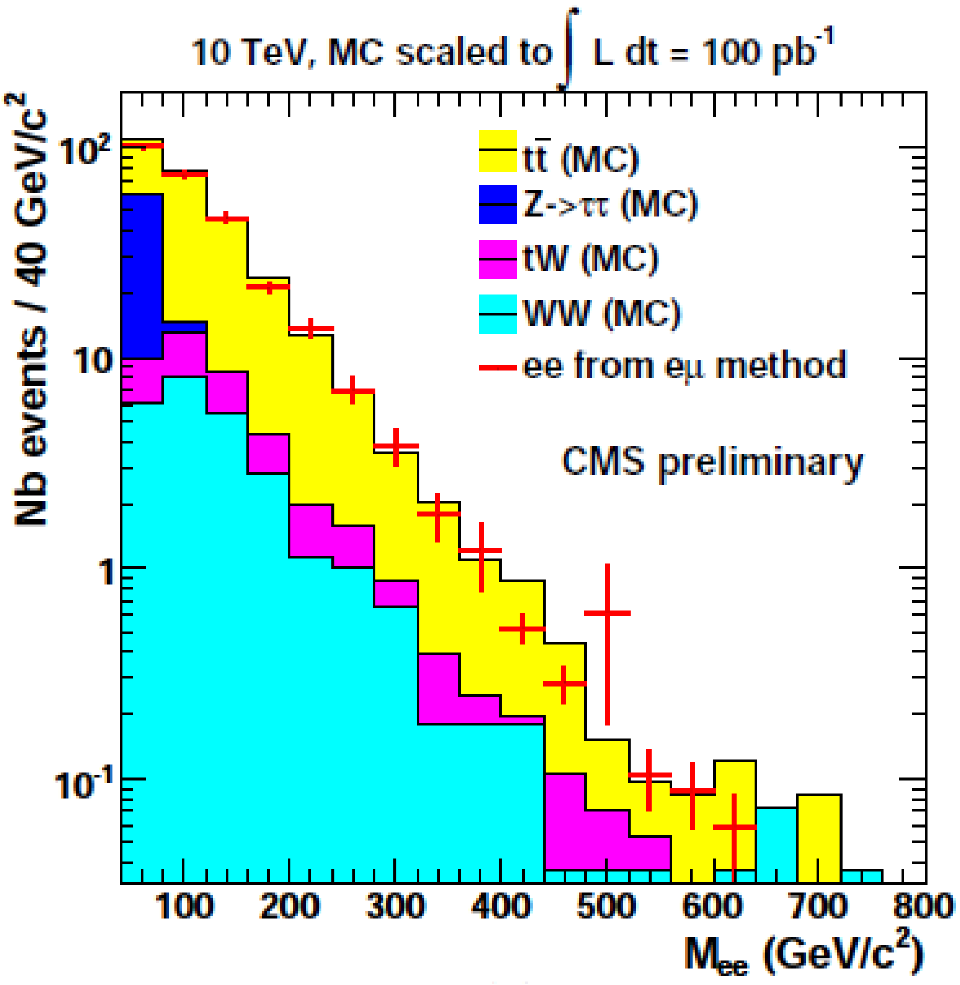
- **Walking Technicolor**
  - **Next to Minimal WalkingTechnicolor**

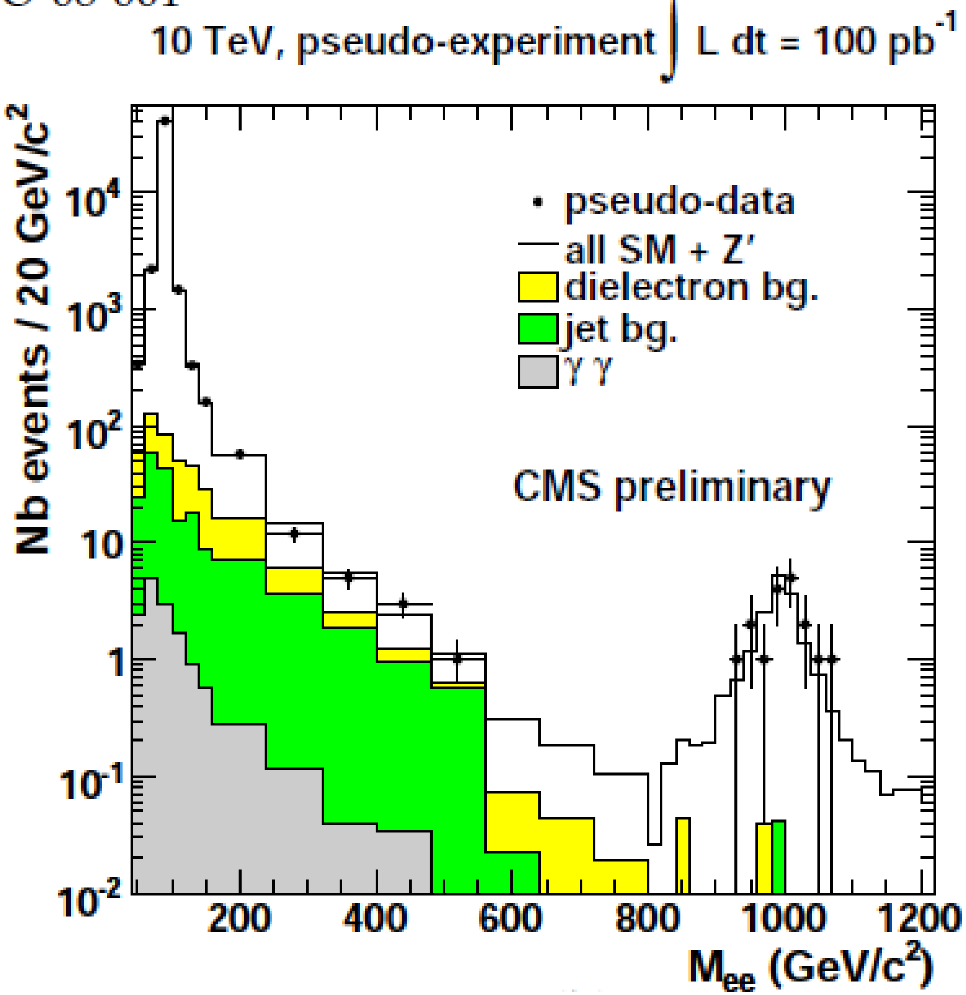
    $SU(2)_L \times SU(2)_R \to SU(2)_V$

    two triplets of heavy mesons
- **Extradimensional Models:**
  - **Universal Extra dimensions: Z'_2 resonances**
  - **Warp extra dimensions: RS graviton resonances**

Back to LHC: what we could expect from coming data?

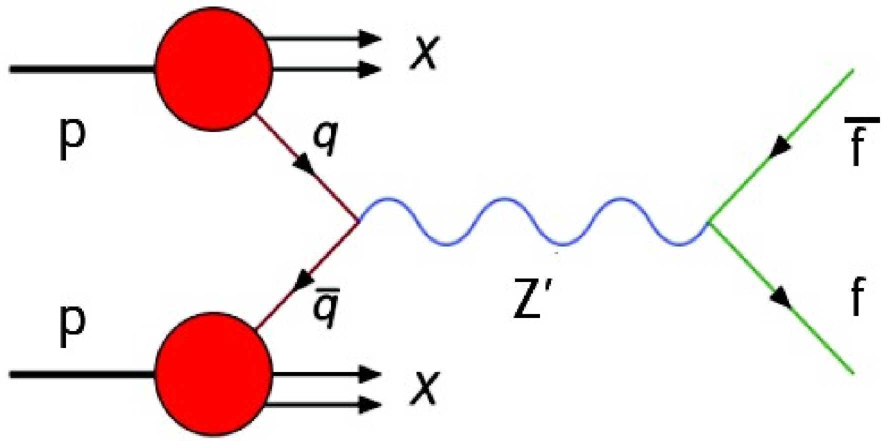
CMS PAS EXO-08-001





The crucial point is to interpret an observed peak in di-lepton invariant mass distribution and connect it to the underlying theory. The Experiment – Theory language should be developed !

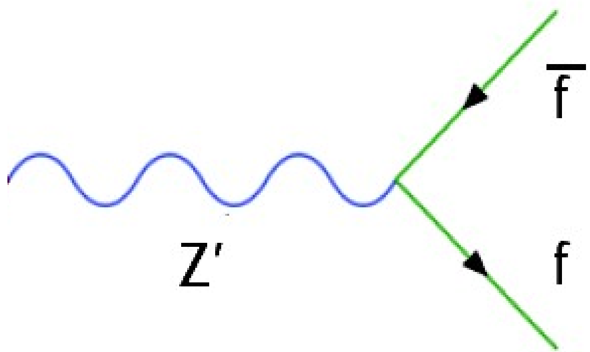
Z' Production and Decay
In the narrow width approximation



$$\sigma_{f\bar{f}} \approx \int_{(M'_Z-\Delta)^2}^{(M'_Z+\Delta)^2} \frac{d\sigma}{dM^2}(pp \to f\bar{f})dM^2$$

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

Case of Spin=1



generic interactions of Z' from SM augmented by an additional U(1)' gauge group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U'(1)$$

Z' interactions with fermions are described by

$$\mathcal{L}_{NC} = \frac{g'}{2} Z'_\mu \bar{f} \gamma^\mu (g_V^f - g_A^f \gamma^5) f \quad = g' Z'_\mu \bar{f} \gamma^\mu (\epsilon_L^f P_L + \epsilon_R^f P_R) f$$

where $P_{L,R} = (1 \pm \gamma_5)/2$ and $g_{V,A}^f = \epsilon_L^f \pm \epsilon_R^f$

Cu-Cd language for Z' production

parton-level cross section takes a form

$$\hat{\sigma}(q\bar{q} \to Z') = \frac{\pi}{12} g_1^2 [(g_V^q)^2 + (g_A^q)^2]$$

while the hadron-level production and decay process is described by

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

[Carena, Daleo, Dobrescu, Tait '04]

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[Carena, Daleo, Dobrescu, Tait '04]

$$c_u = \frac{g'^2}{2} ({g_V^u}^2 + {g_A^u}^2) Br(\ell^+\ell^-)$$

$$c_d = \frac{g'^2}{2} ({g_V^d}^2 + {g_A^d}^2) Br(\ell^+\ell^-)$$

$w_u(s, M_{Z'}^2)$ and $w_d(s, M_{Z'}^2)$

are defined by

$\left(\frac{dL_{u\bar{u}}}{dM_{Z'}^2} \right)$ and $\left(\frac{dL_{d\bar{d}}}{dM_{Z'}^2} \right)$

specific model is entirely encoded in Cu and Cd

w_u and w_d are defined by collider energy and $M_{Z'}$

Z' from motivated GUTs

- **E_6 models**

$E_6 \to SO(10) \times U(1)_\psi$
$\to SU(5) \times U(1)_\chi \times U(1)_\psi$
$\to SM \times U(1)'$

$$\boxed{U(1)' = \cos\theta\, U(1)_\chi + \sin\theta\, U(1)_\psi}$$

$$g^f_{V,A}(\theta) = \cos\theta\; g^f_{V,A}(\chi) + \sin\theta\; g^f_{V,A}(\psi)$$

[was actually suggested ~ 20 years ago in G. Ross papers]

- **L-R models**

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

$$\boxed{U(1)' = \cos\phi\, U(1)_R + \sin\phi\, U(1)_{B-L}}$$

$$g^f_{V,A}(\phi) = \cos\phi\; g^f_{V,A}(R) + \sin\theta\; g^f_{V,A}(B-L)$$

left-right symmetry implies $\phi = -23^o$

- **Sequential models (GSM)**

$$\boxed{U(1)' = \cos\alpha\, U(1)_L + \sin\alpha\, U(1)_Q}$$

$$Q_Z = T_{3L} - s^2_W Q$$
$$Q_{GSM} = \cos\alpha\; T_{3L} + \sin\alpha\; Q$$
$$g^f_{V,A}(\alpha) = \cos\alpha\; g^f_{V,A}(L) + \sin\alpha\; g^f_{V,A}(Q)$$

$\alpha = -13^o$ in SM

gv,ga couplings define C_u,C_d parameters

Couplings of Z' in generalized models

universality amongst three families is assumed

$U(1)'$	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

Cu,Cd, Br and constraints for Z'

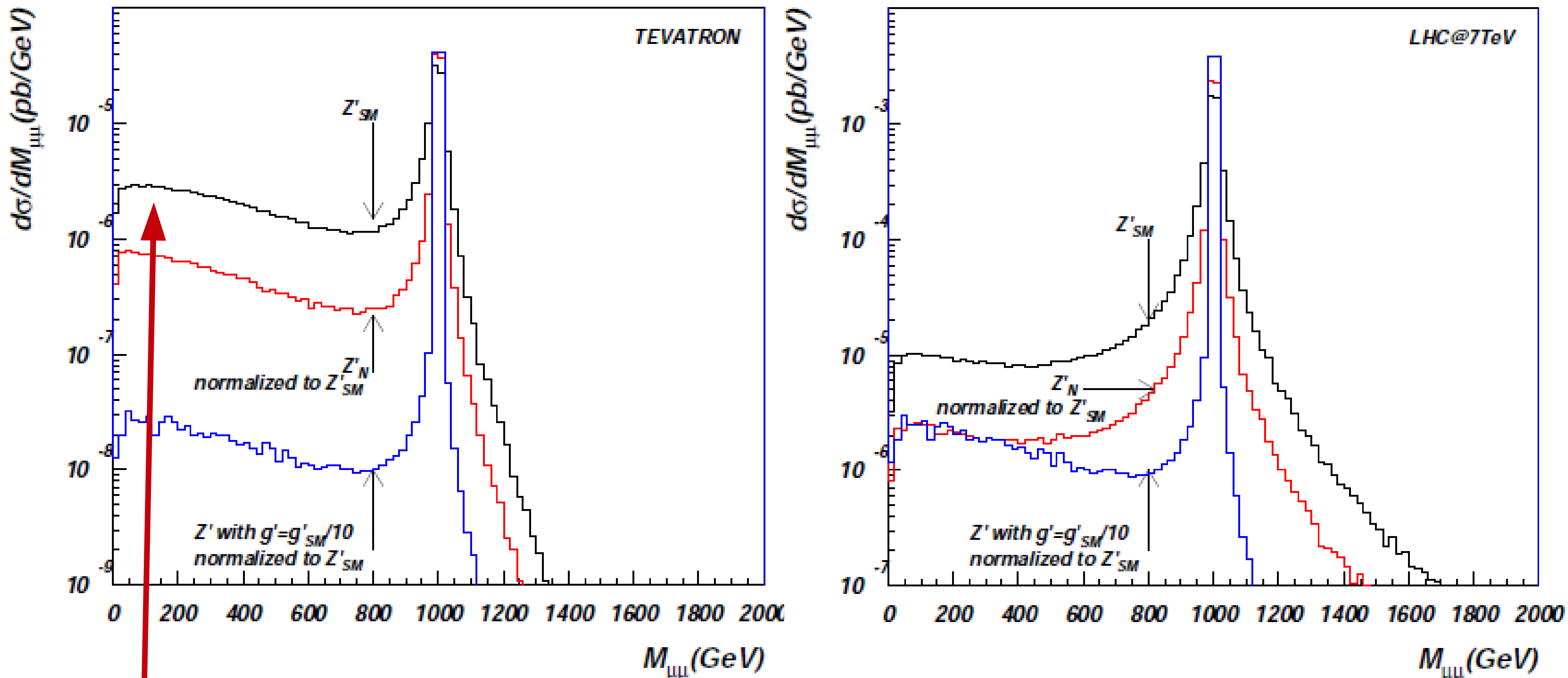
Z-Z' mixing vanishes at tree-level

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

$U(1)'$	$Br(e^+e^-)$	c_u	c_d	c_u/c_d	$\Gamma_{Z'}/M_{Z'}$	$M_{Z'}^{\mathrm{D}}(GeV)$	$M_{Z'}^{\mathrm{I}}(GeV)$
E_6 $(g' = 0.462)$							
$U(1)_\chi$	0.0606	6.46×10^{-4}	3.23×10^{-3}	0.2	0.0117	915	1141^e
$U(1)_\psi$	0.0444	7.90×10^{-4}	7.90×10^{-4}	1	0.0053	915	481^c
$U(1)_\eta$	0.0371	1.05×10^{-3}	6.59×10^{-4}	1.6	0.00636	940	434^c
$U(1)_S$	0.0656	1.18×10^{-4}	3.79×10^{-3}	0.31	0.0117	847	1257^e
$U(1)_I$	0.0667	0	3.55×10^{-3}	0	0.0106	795	1204^e
$U(1)_N$	0.0555	5.94×10^{-4}	1.48×10^{-3}	0.40	0.00635	892	623^e
GLR $(g' = 0.595)$							
$U(1)_R$	0.0476	4.21×10^{-3}	4.21×10^{-3}	1	0.0247	1065	442^e
$U(1)_{B-L}$	0.154	3.02×10^{-3}	3.02×10^{-3}	1	0.015	1035	-
$U(1)_{LR}$	0.0246	1.39×10^{-3}	2.44×10^{-3}	0.57	0.0207	970	998^e
$U(1)_Y$	0.125	1.04×10^{-2}	3.07×10^{-3}	3.4	0.0235	1135	-
SM $(g' = 0.760)$							
$U(1)_{SM}$	0.0308	2.43×10^{-3}	3.13×10^{-3}	0.776	0.0297	1020	1787^c
$U(1)_{T3L}$	0.0417	6.02×10^{-3}	6.02×10^{-3}	1.00	0.045	1095	-
$U(1)_Q$	0.125	6.42×10^{-2}	1.60×10^{-2}	4.01	0.1225	1275	-

The meaning of Z' production cross section

lets take a look at di-lepton mass for pp->Z' ->ℓℓ

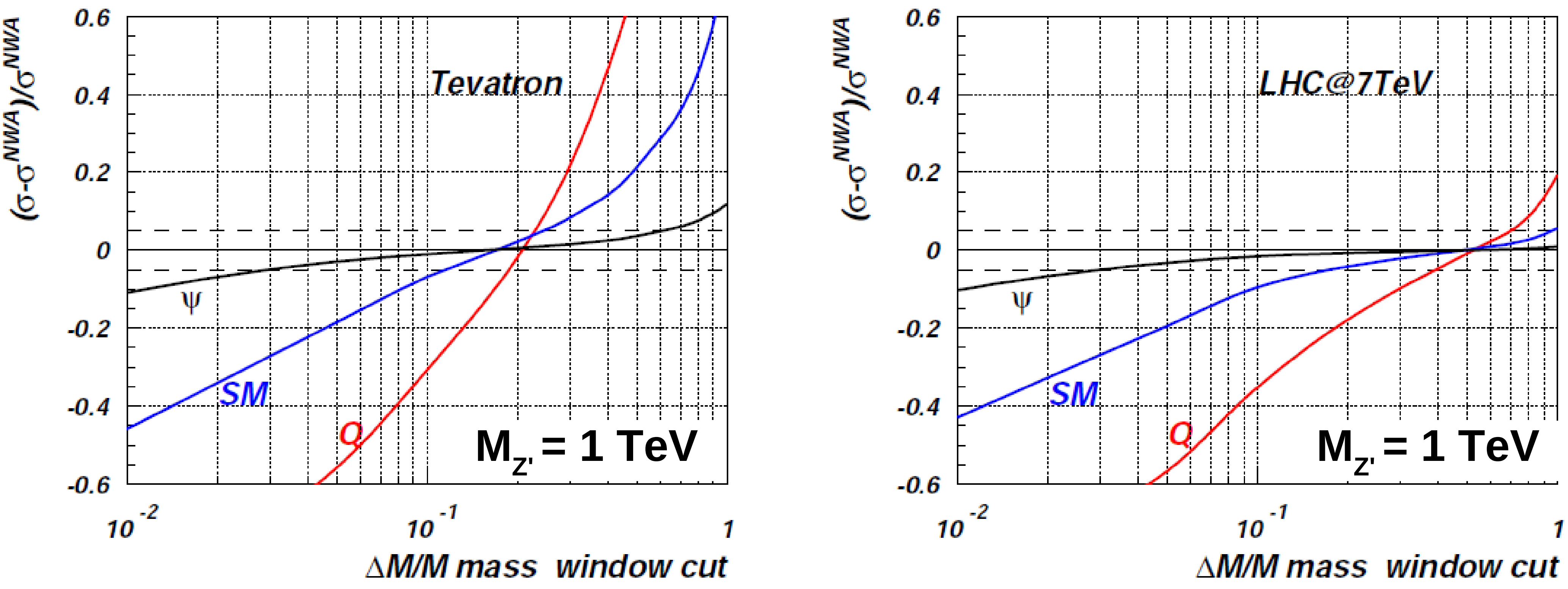


- **The total integral under the curve is twice as large as Z' production cross section at the Tevatron in a narrow-width (NW) approximation**
- **The integral for the invariant mass window within 10-25% around Z' mass agrees with NW approximation at the % level, so theoretical cross section (if calculated for the finite width) should be quoted for this mass window cut**

Full cross-section with a suitable cut reproduces the narrow width approx

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

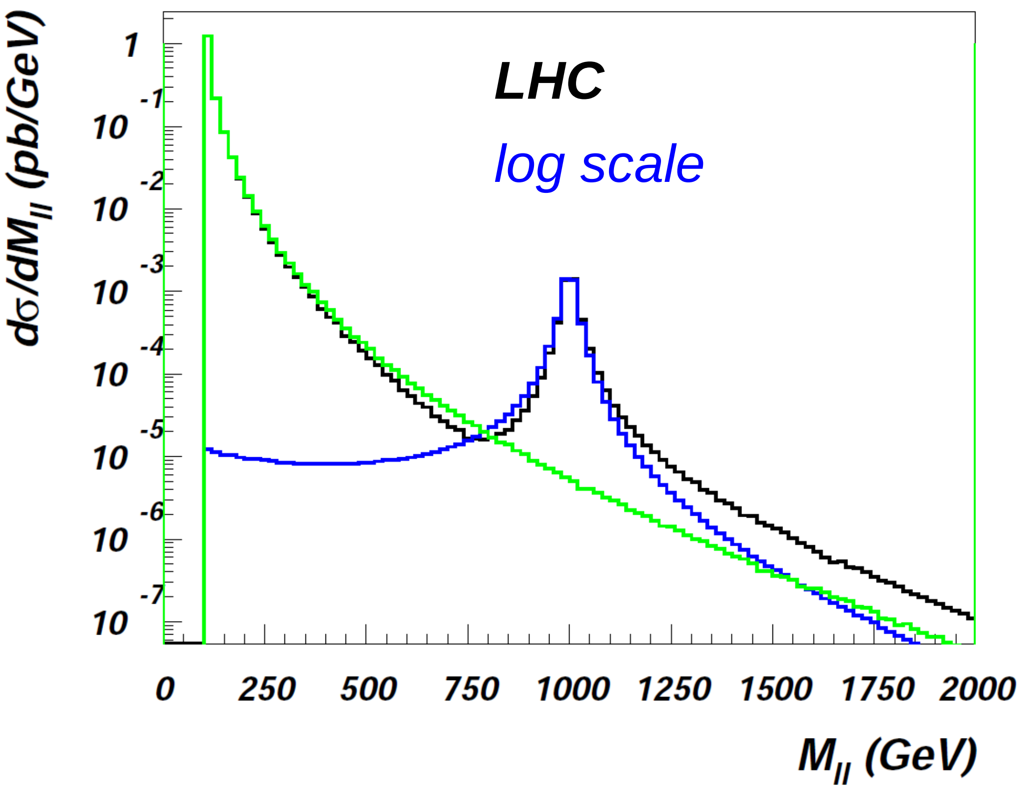
$$\Delta M_{ll}/M_{Z'} = |M_{ll} - M_{Z'}|/M_{Z'}$$

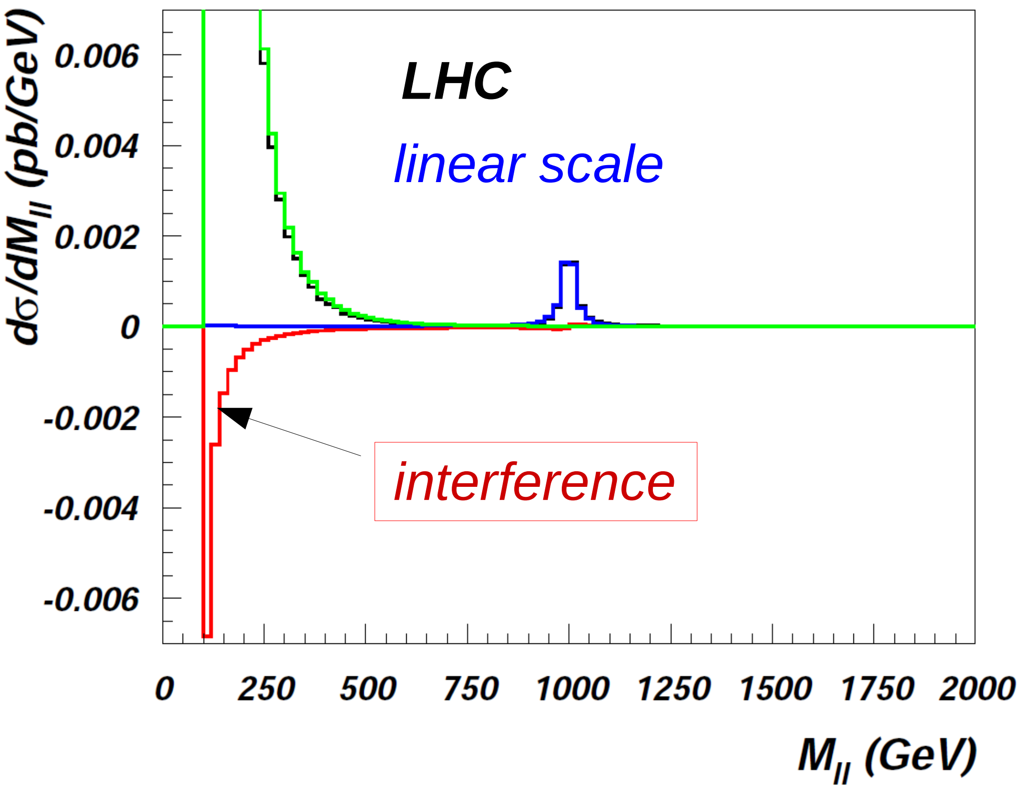


The role of the Signal-Background interference

- ***It depends very strongly on di-lepton invariant mass***
  - $M_{ll}>100$ **GeV cut:** ***interf = -1900% at the Tevatron and -300% at the LHC***
  - $\Delta M_{ll}/M_{Z'} = |M_{ll} - M_{Z'}|/M_{Z'} < 15\%$ **Cut :**

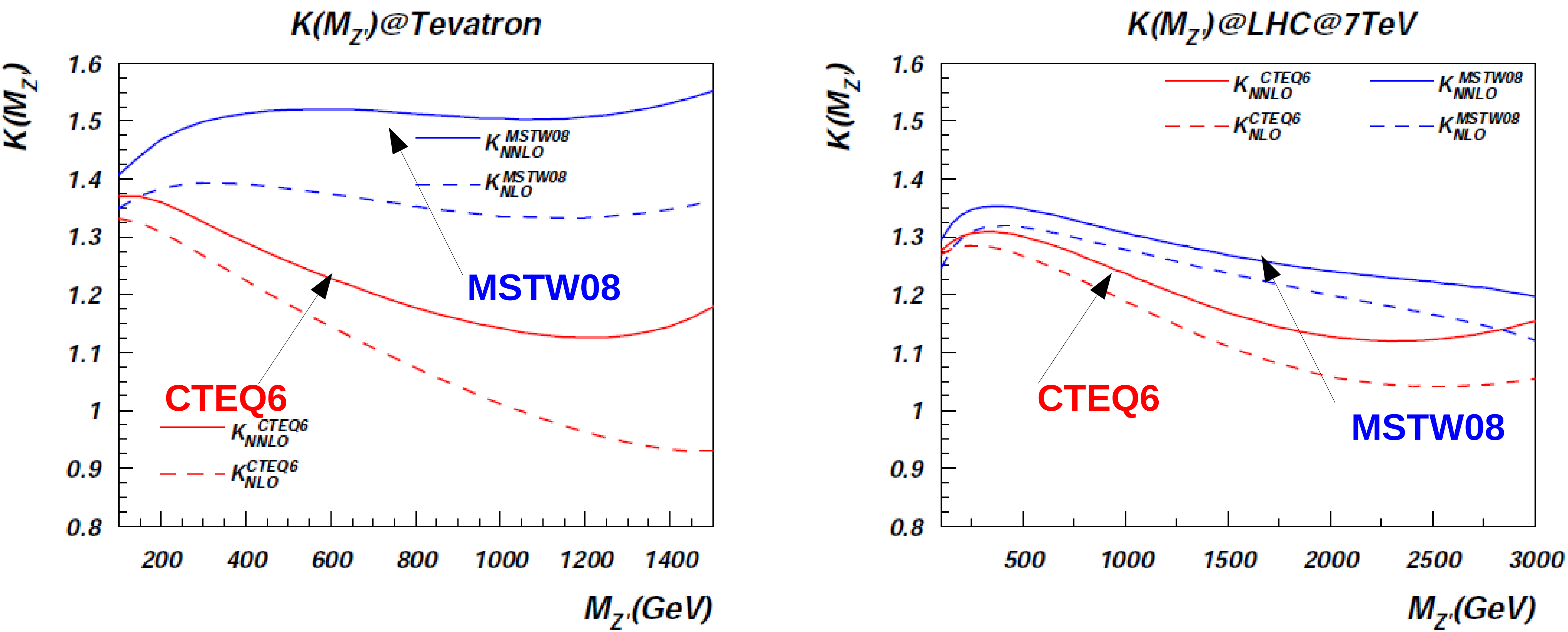
    Interf= -6% at the Tevatron and -2% at the LHC
- ***di-lepton invariant mass cut dramatically reduces model-dependent interference effects!***





The meaning and value of NNLO K-factor

$$\sigma^{NNLO}_{l+l-} = \frac{\pi}{48s}\left[c_u^{NNLO} w_u(s, M^2_{Z'})^{NNLO} + c_d^{NNLO} w_d(s, M^2_{Z'})^{N} = K^{PDF}_{NNLO} K^{BR}_{NNLO} \sigma^{LO}_{l+l-}\right.$$



NNLO K-factor strongly depends on your choice of PDF set!

E.g. for $M_{Z'}$=1 TeV K_{NNLO}~ 1.1 (1.5) for CTEQ(MSTW) at the Tevatron and ~ 1.2 (1.3) at the LHC

This difference is related to PDF fitting procedure

NNLO K-factors are evaluated with ZWPROD package *[van Neerven]* adopted for Z' and new PDFs. Available upon request!

The meaning and value of NNLO K-factor

MSTW08

$M_{Z'}$ (GeV)	Tevatron			LHC@7TeV		
	σ_{LO} (pb)	σ_{NNLO} (pb)	K_{NNLO}	σ_{LO} (pb)	σ_{NNLO} (pb)	K_{NNLO}
100	3.96×10^3	5.57×10^3	1.41	1.63×10^4	2.12×10^4	1.29
150	1.08×10^3	1.56×10^3	1.44	4.45×10^3	5.87×10^3	1.32
200	4.15×10^2	6.09×10^2	1.47	1.70×10^3	2.28×10^3	1.34
250	1.90×10^2	2.83×10^2	1.49	7.89×10^2	1.06×10^3	1.35
300	9.67×10	1.45×10^2	1.50	4.14×10^2	5.60×10^2	1.35
350	5.25×10	7.91×10	1.51	2.37×10^2	3.20×10^2	1.35
400	2.96×10	4.49×10	1.51	1.44×10^2	1.95×10^2	1.35
450	1.72×10	2.61×10	1.52	9.20×10	1.24×10^2	1.35
500	1.02×10	1.54×10	1.52	6.10×10	8.22×10	1.35
550	6.05	9.20	1.52	4.16×10	5.60×10	1.34
600	3.62	5.51	1.52	2.92×10	3.91×10	1.34
650	2.17	3.30	1.52	2.08×10	2.79×10	1.34
700	1.29	1.97	1.52	1.52×10	2.02×10	1.33
750	7.68×10^{-1}	1.16	1.52	1.12×10	1.49×10	1.33
800	4.52×10^{-1}	6.83×10^{-1}	1.51	8.35	1.11×10	1.32
850	2.63×10^{-1}	3.97×10^{-1}	1.51	6.30	8.32	1.32
900	1.51×10^{-1}	2.28×10^{-1}	1.51	4.80	6.32	1.32
950	8.52×10^{-2}	1.28×10^{-1}	1.50	3.69	4.84	1.31
1000	4.72×10^{-2}	7.11×10^{-2}	$\boxed{1.51}$	2.86	3.73	$\boxed{1.31}$

The meaning and value of NNLO K-factor

CTEQ6.6

$M_{Z'}$ (GeV)	Tevatron			LHC@7TeV		
	σ_{LO} (pb)	σ_{NNLO} (pb)	K_{NNLO}	σ_{LO} (pb)	σ_{NNLO} (pb)	K_{NNLO}
100	3.94×10^3	5.40×10^3	1.37	1.52×10^4	1.95×10^4	1.28
150	1.12×10^3	1.54×10^3	1.37	4.23×10^3	5.46×10^3	1.29
200	4.47×10^2	6.08×10^2	1.36	1.64×10^3	2.13×10^3	1.30
250	2.12×10^2	2.85×10^2	1.34	7.66×10^2	1.00×10^3	1.31
300	1.11×10	1.47×10^2	1.32	4.04×10^2	5.29×10^2	1.31
350	6.14×10	8.03×10	1.31	2.32×10^2	3.04×10^2	1.31
400	3.54×10	4.57×10	1.29	1.42×10^2	1.85×10^2	1.31
450	2.10×10	2.67×10	1.27	9.08×10	1.18×10^2	1.30
500	1.26×10	1.58×10	1.26	6.04×10	7.85×10	1.30
550	7.61	9.46	1.24	4.13×10	5.35×10	1.29
600	4.63	5.68	1.23	2.90×10	3.74×10	1.29
650	2.81	3.42	1.21	2.08×10	2.67×10	1.28
700	1.70	2.05	1.20	1.51×10	1.94×10	1.28
750	1.03×10^{-1}	1.22	1.19	1.12×10	1.42×10	1.27
800	6.12×10^{-1}	7.21×10^{-1}	1.18	8.38	1.06×10	1.26
850	3.61×10^{-1}	4.22×10^{-1}	1.17	6.35	7.98	1.26
900	2.11×10^{-1}	2.44×10^{-1}	1.16	4.85	6.06	1.25
950	1.21×10^{-2}	1.39×10^{-1}	1.15	3.74	4.64	1.24
1000	6.80×10^{-2}	7.77×10^{-2}	$\boxed{1.14}$	2.90	3.59	$\boxed{1.24}$

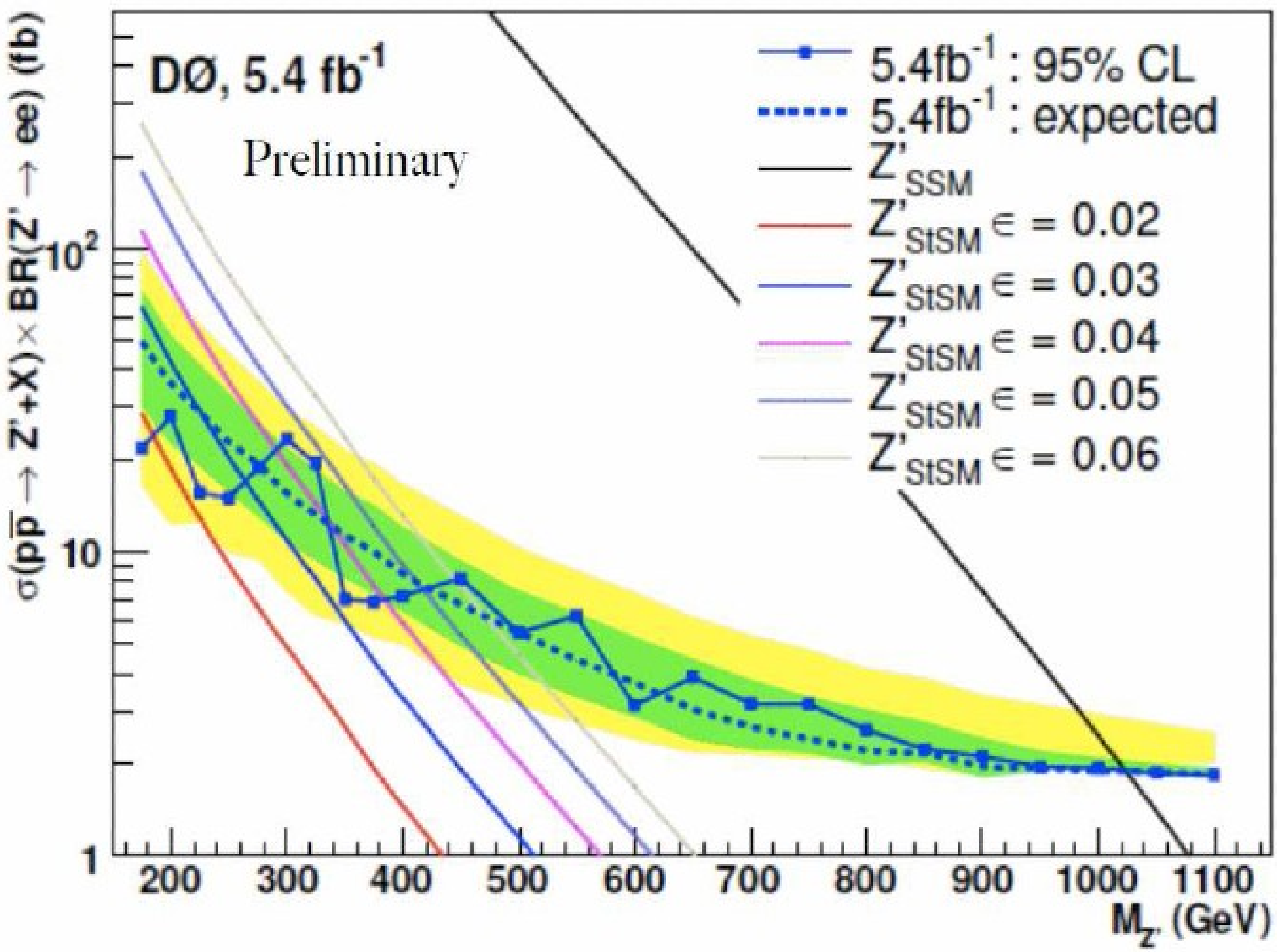
Tevatron limits from ICHEP 2010

Tevatron (D0) limit for 5.4 fb^{-1} @1.96TeV is translated into Cu-Cd plane

Parametrized E6/GLR/GSM models are presented by continuous contours in the Cu-Cd plane

Thus one can visualise and establish limits for the whole continuous class of models!

Limits are established For theory prediction at NNLO



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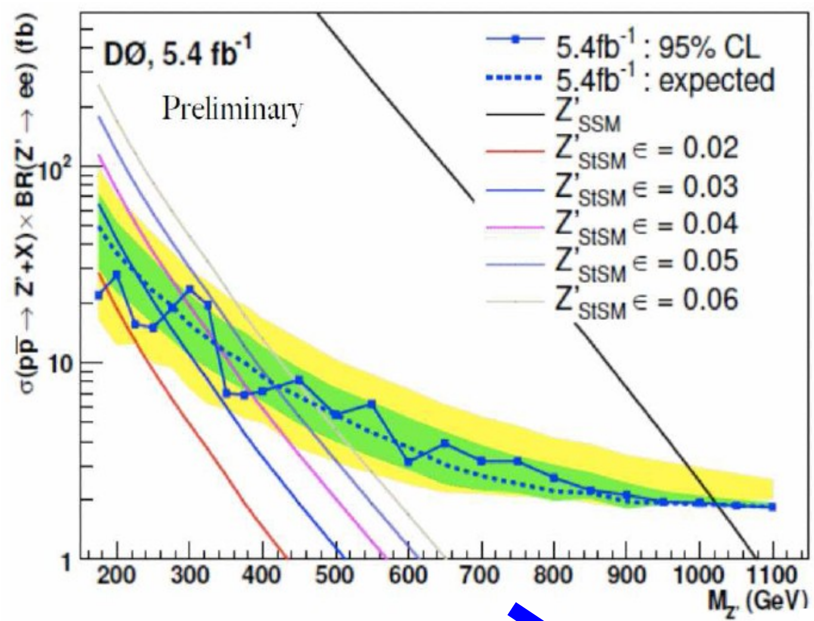

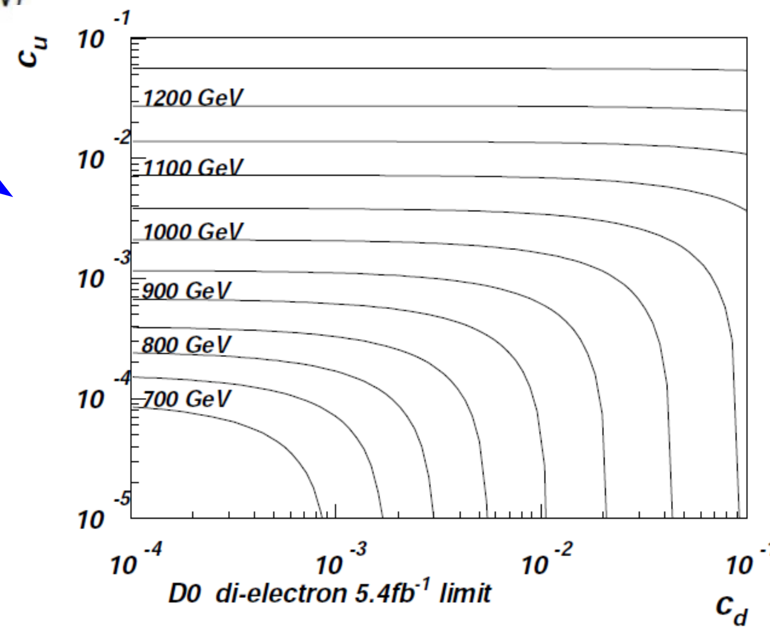

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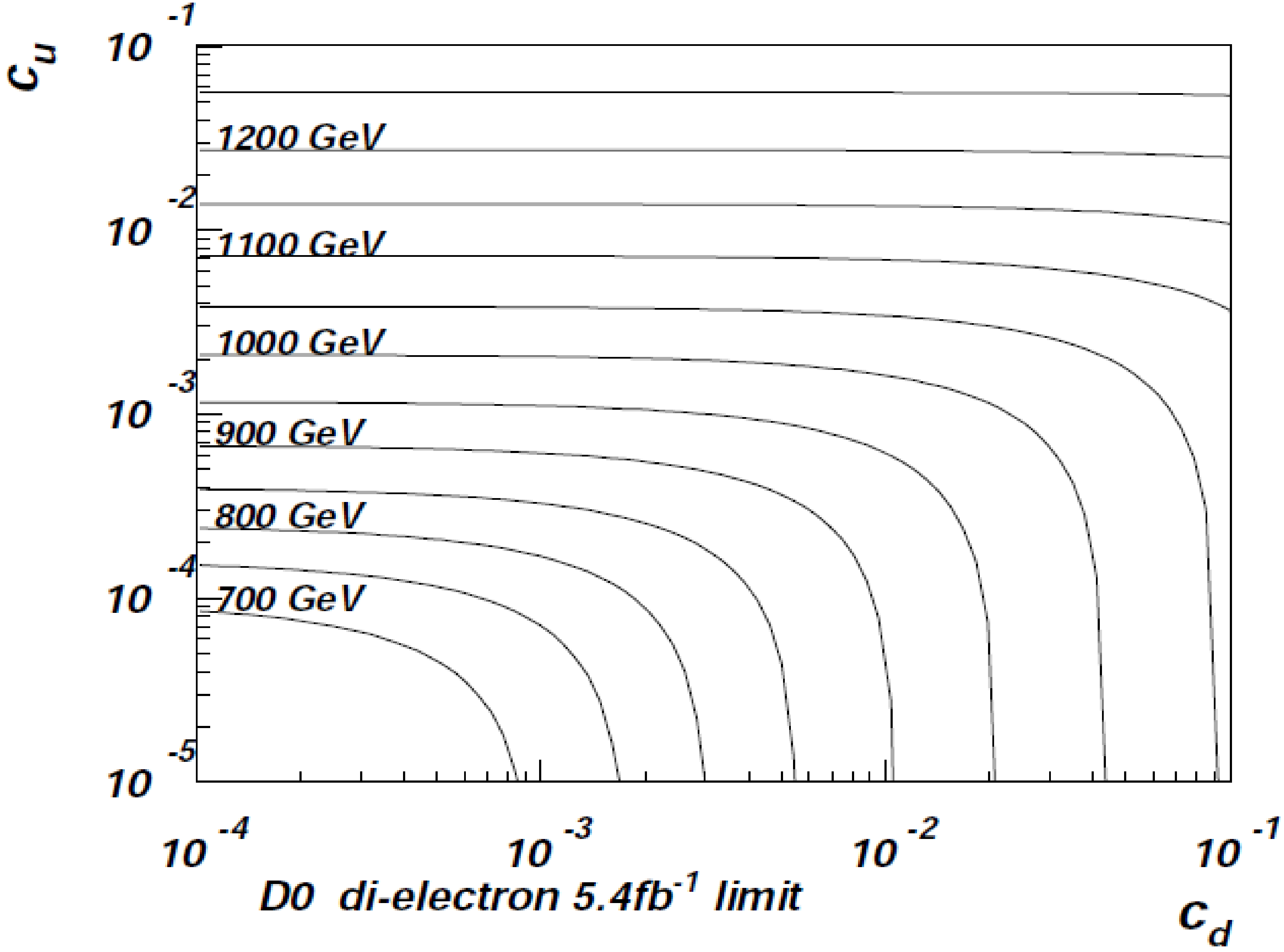


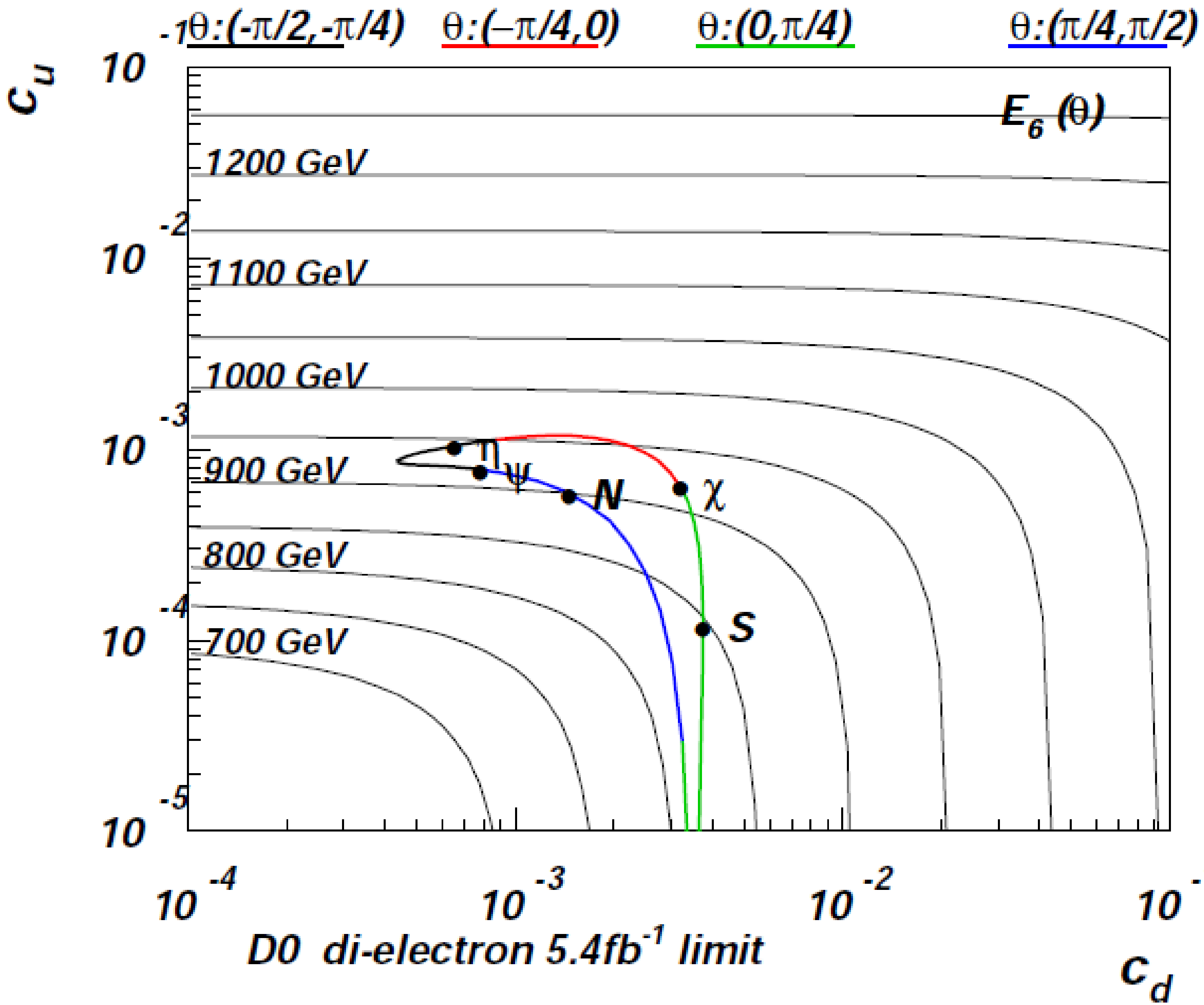
Tevatron limits for E6

Tevatron (D0) limit for 5.4 fb^{-1} @1.96TeV is translated into Cu-Cd plane

Parametrized E6/GLR/GSM models are presented by continuous contours in the Cu-Cd plane

Thus one can visualise and establish limits for the whole continuous class of models!

Limits are established For theory prediction at NNLO



Tevatron limits for GLR

Tevatron (D0) limit for 5.4 fb^{-1} @1.96TeV is translated into Cu-Cd plane

Parametrized E6/GLR/GSM models are presented by continuous contours in the Cu-Cd plane

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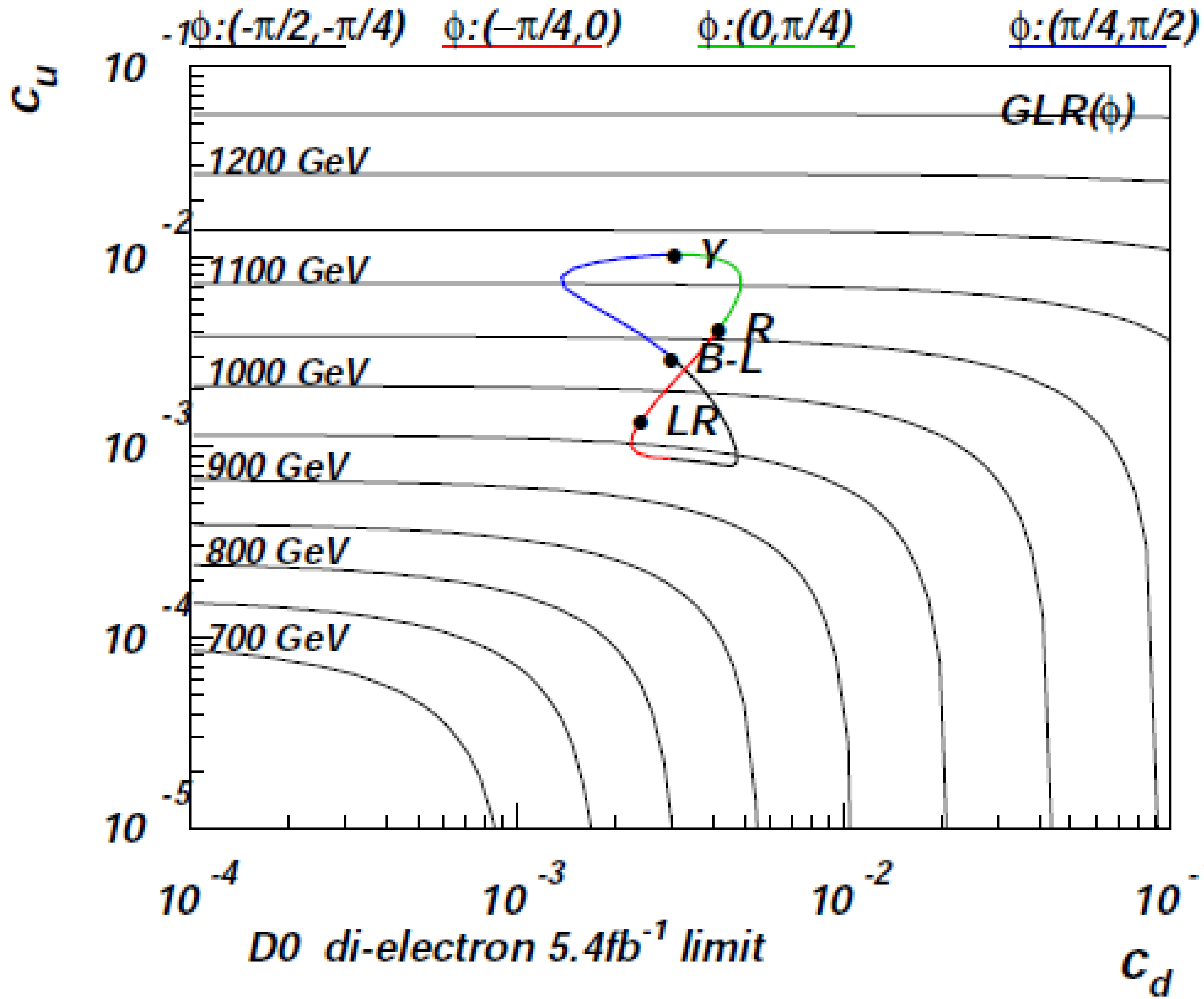
Limits are established for theory prediction at NNLO



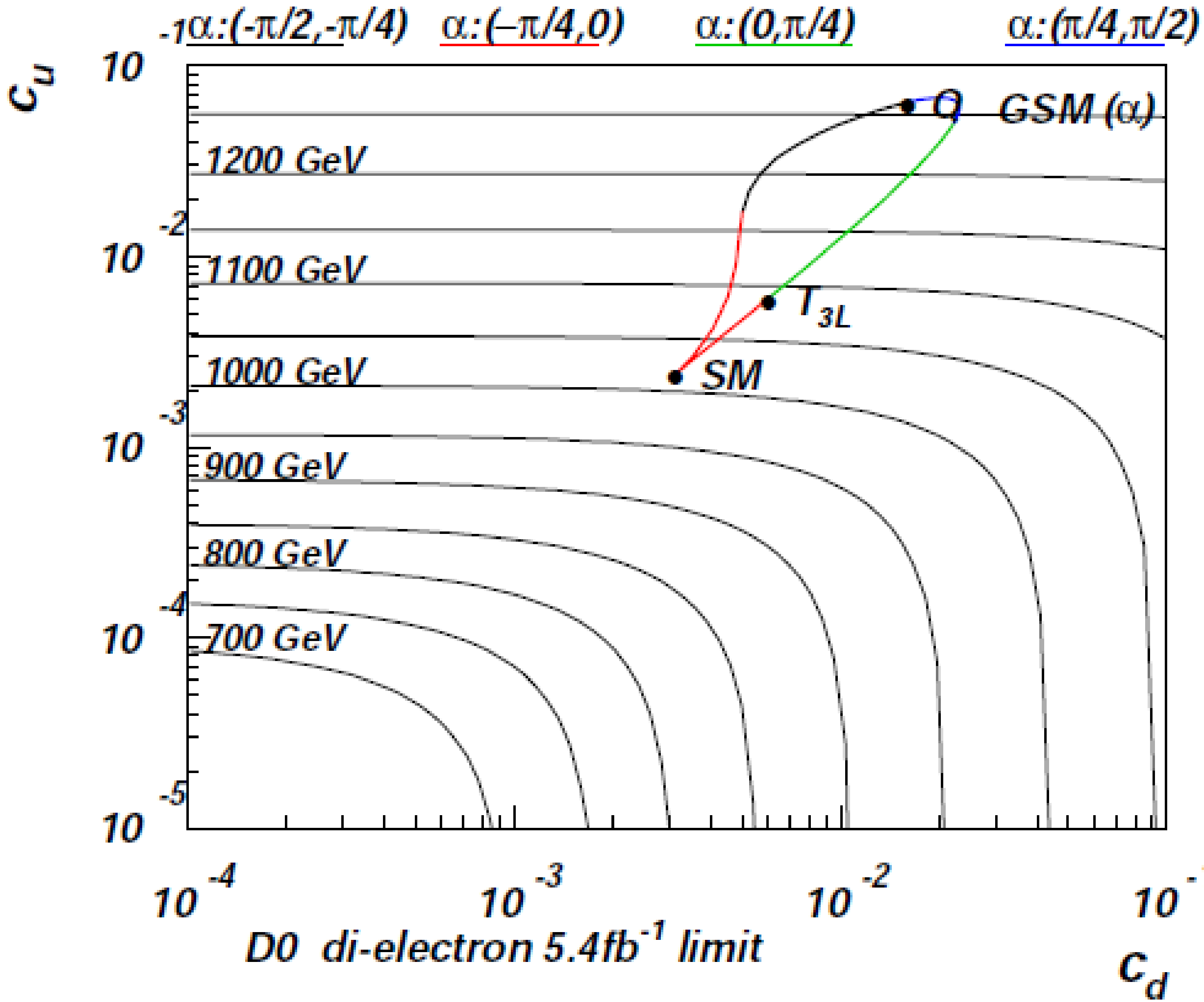
Tevatron limits for GSM

Tevatron (D0) limit for 5.4 fb^{-1} @1.96TeV is translated into Cu-Cd plane

Parametrized E6/GLR/GSM models are presented by continuous contours in the Cu-Cd plane

Thus one can visualise and establish limits for the whole continuous class of models!

Limits are established for theory prediction at NNLO



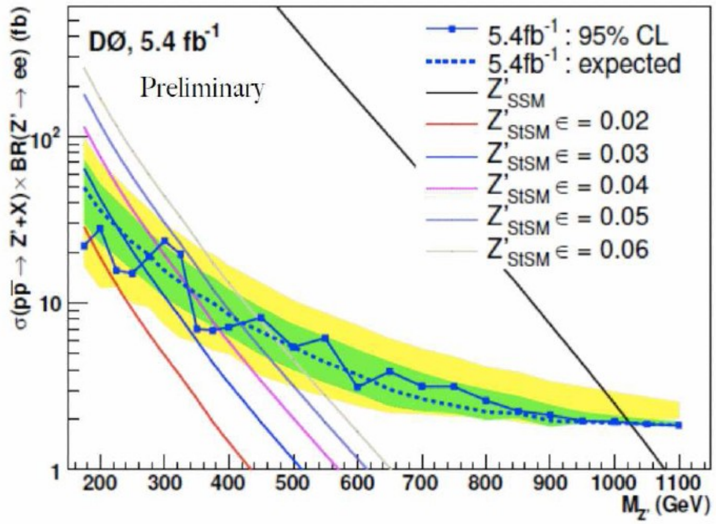
Tevatron limits for for E6/GLR/GSM

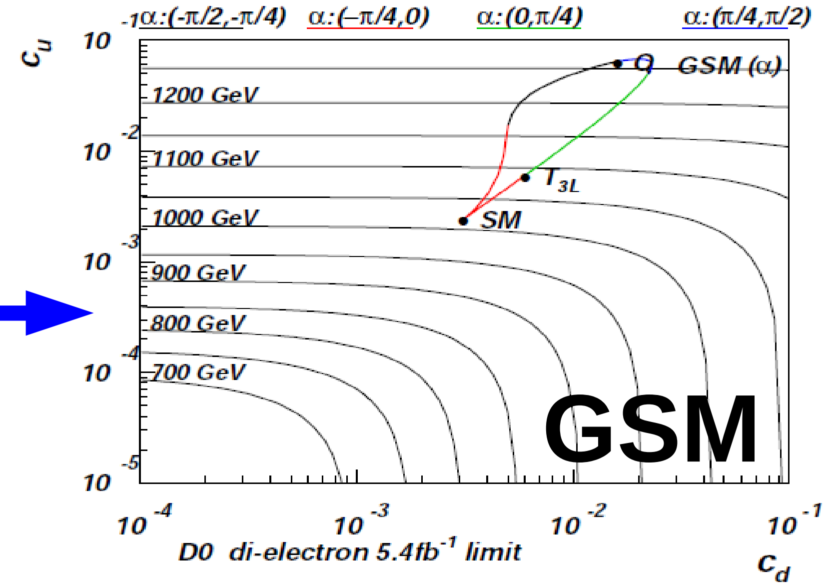
Tevatron (D0) limit for 5.4 fb^{-1} @1.96TeV is translated into Cu-Cd plane

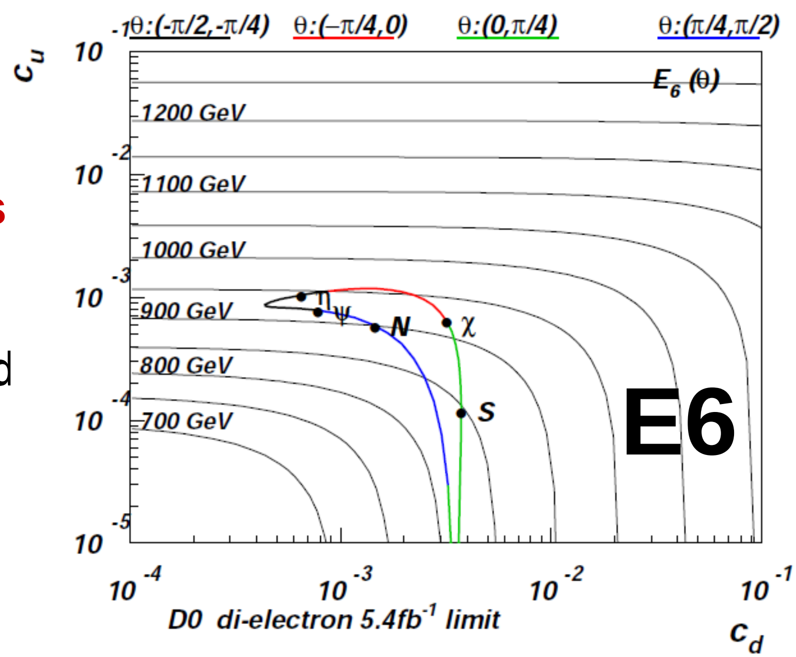
Parametrized E6/GLR/GSM models are presented by continuous contours in the Cu-Cd plane

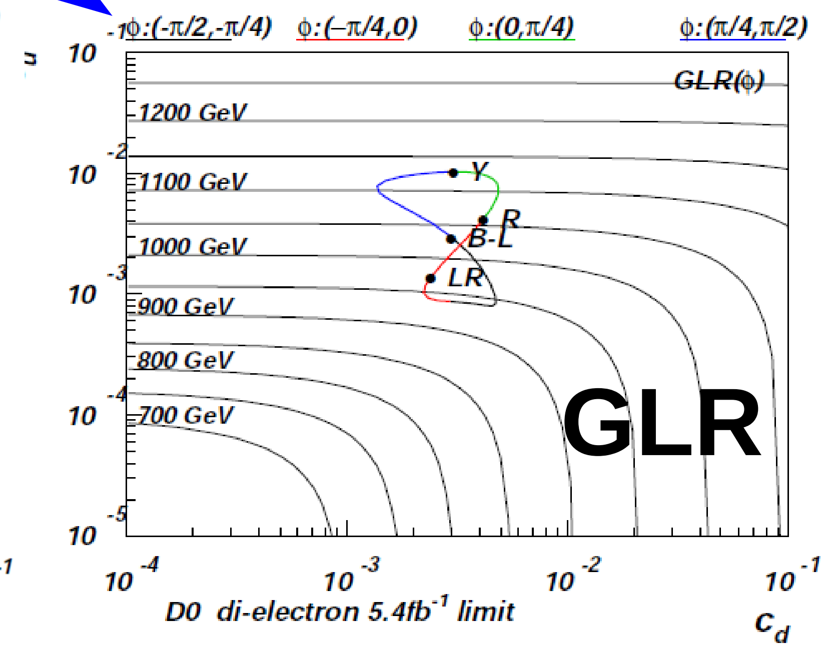
Thus one can visualise and establish limits for the whole continuous class of models!

Limits are established for theory prediction at NNLO

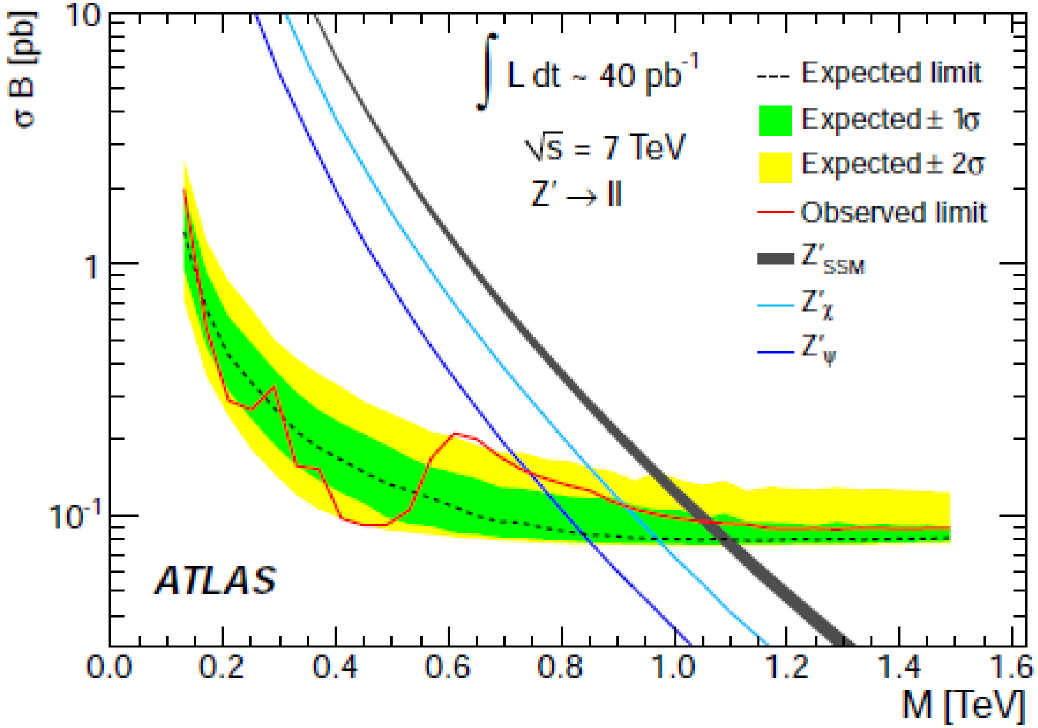








Present LHC limits: ATLAS

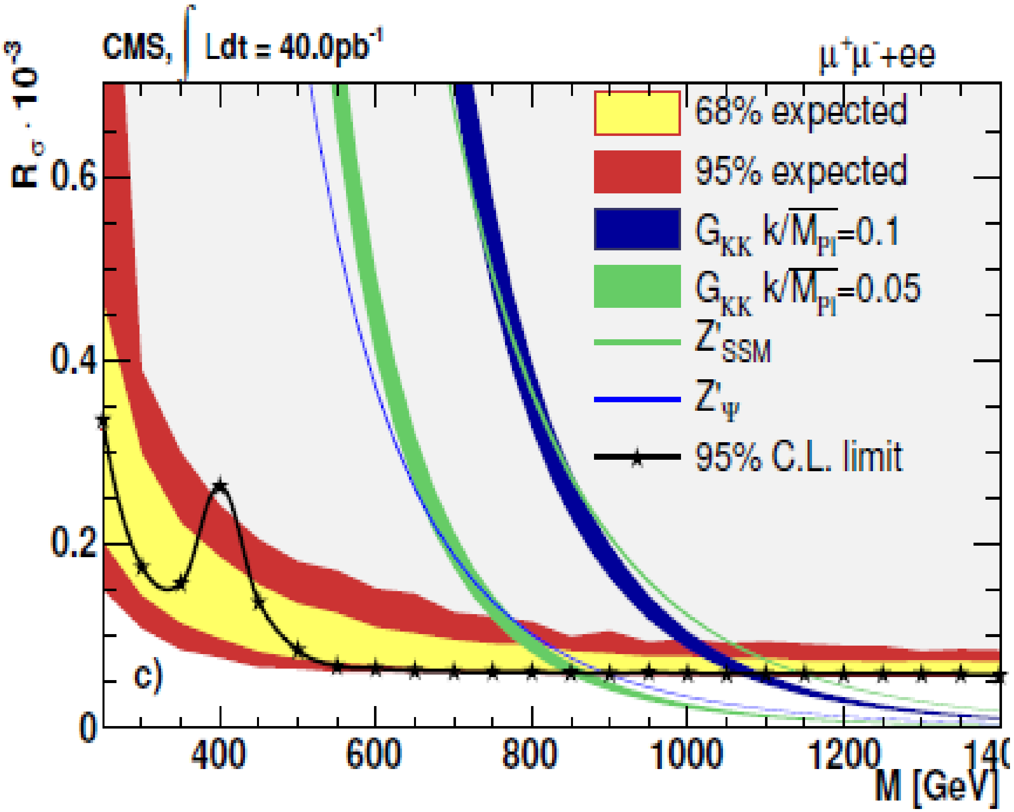


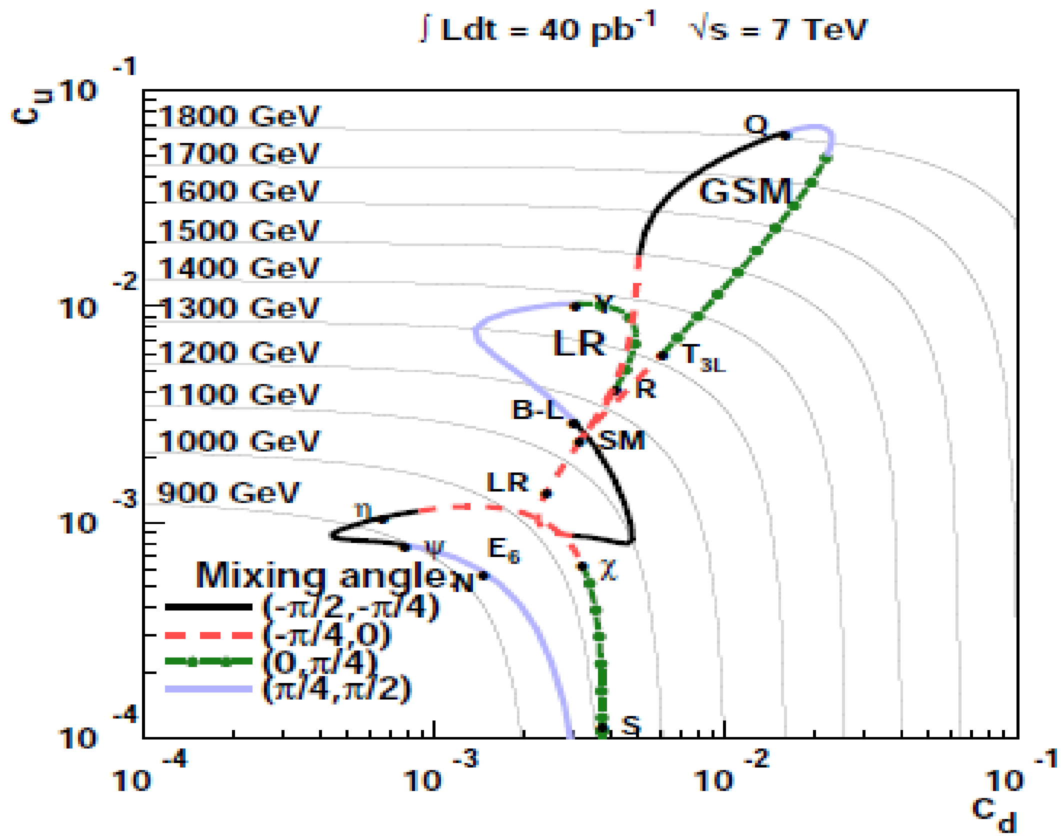
	Observed limit		Expected limit	
	mass [TeV]	σB [pb]	mass [TeV]	σB [pb]
$Z'_{\rm SSM} \to e^+e^-$	0.957	0.155	0.967	0.145
$Z'_{\rm SSM} \to \mu^+\mu^-$	0.834	0.297	0.900	0.201
$Z'_{\rm SSM} \to \ell^+\ell^-$	1.048	0.094	1.088	0.081

Model	Z'_ψ	$Z'_{\rm N}$	Z'_η	Z'_I	$Z'_{\rm S}$	Z'_χ
Mass limit [TeV]	0.738	0.763	0.771	0.842	0.871	0.900

arXiv:1103.6218

Present LHC limits: CMS

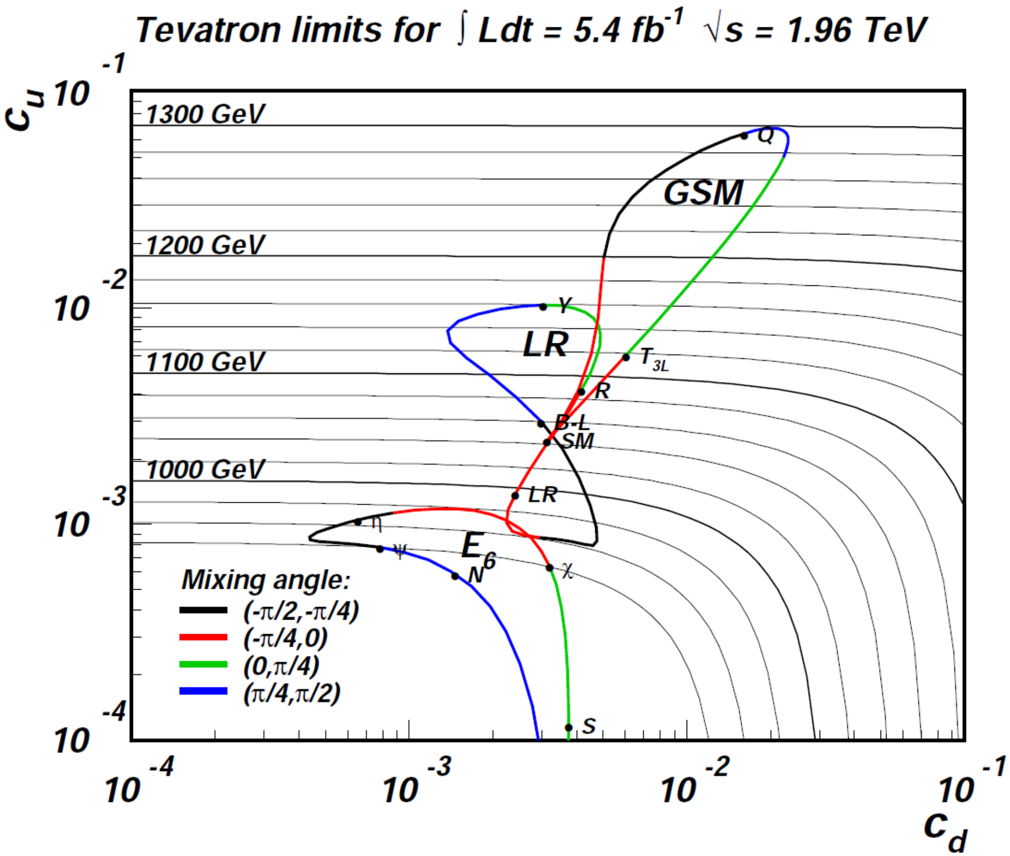


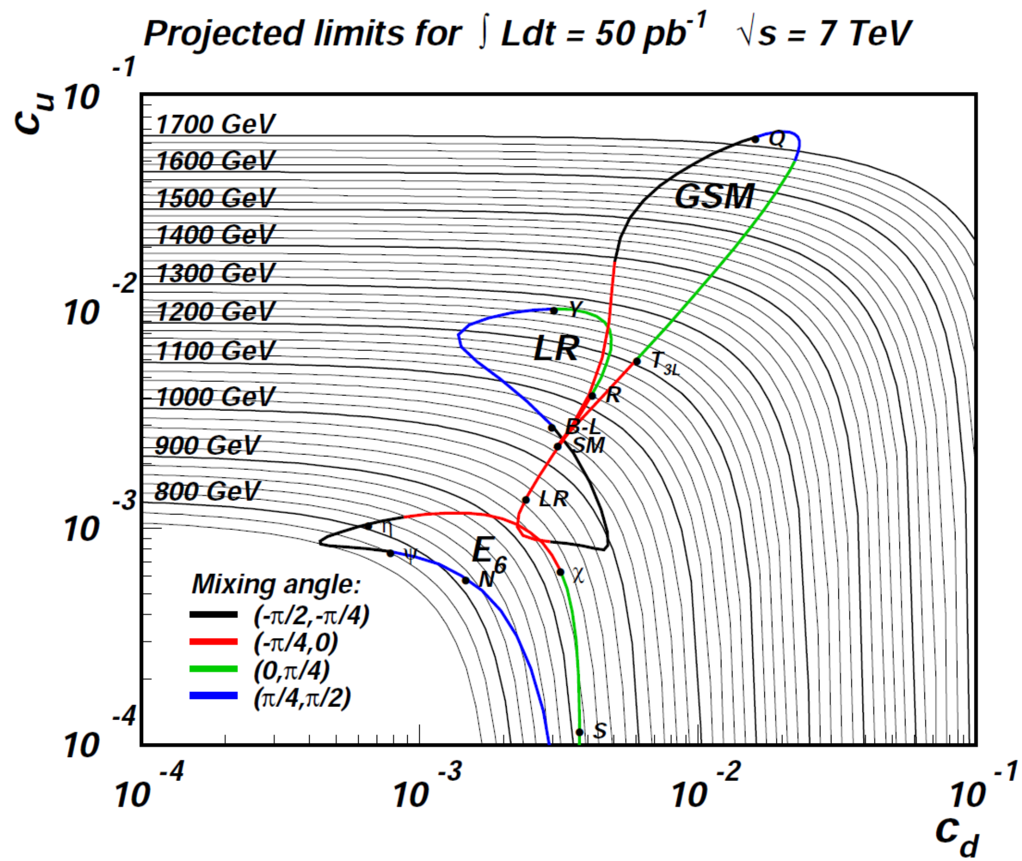


arXiv:1103.0981

For the first time CMS collaboration has established limits on Z' mass for the whole continuous class of models! These are world's best limits!

LHC limits scaled down to 50 pb^{-1} (current) vs current Tevatron limits

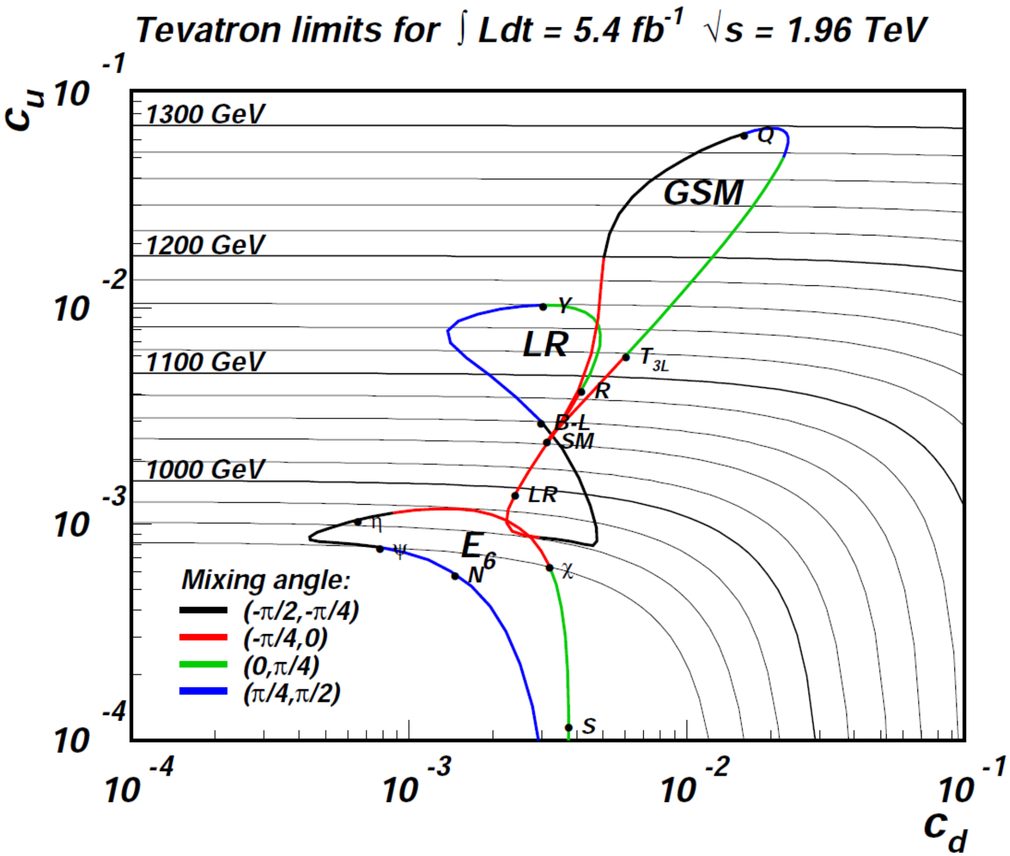


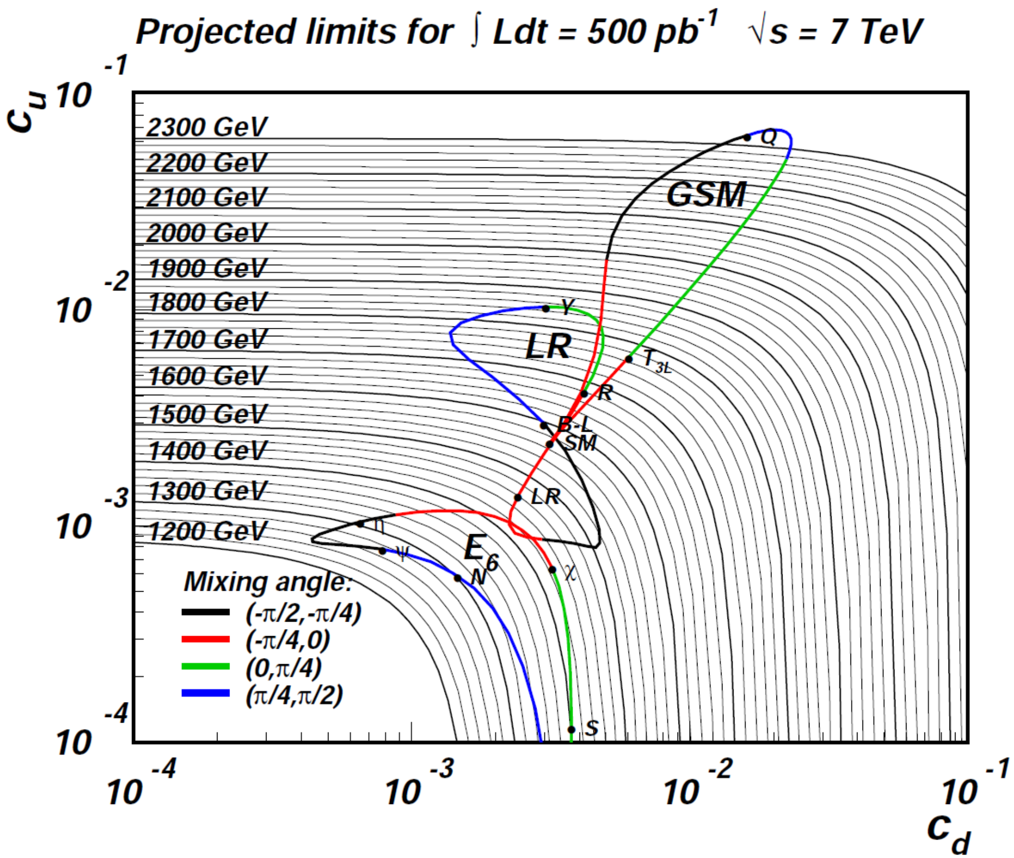


LHC is eventually more sensitive to larger Z' masses – wins on parton luminosity

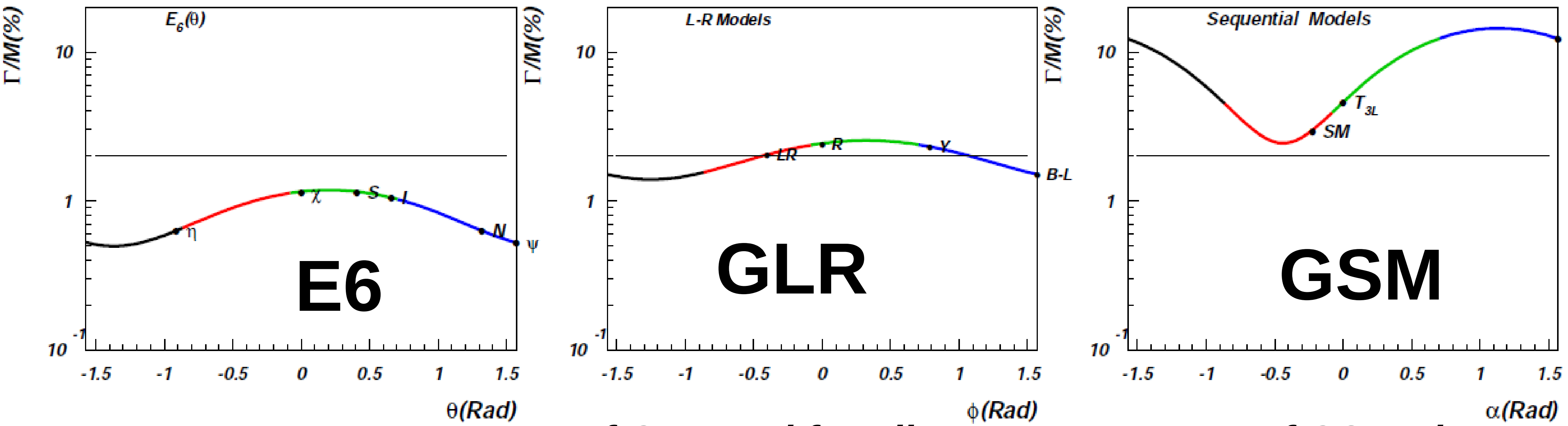
But presently is slightly less sensitive to weakly coupled Z' models – losses in statistics

LHC limits projected to 500 pb^{-1} vs current Tevatron limits



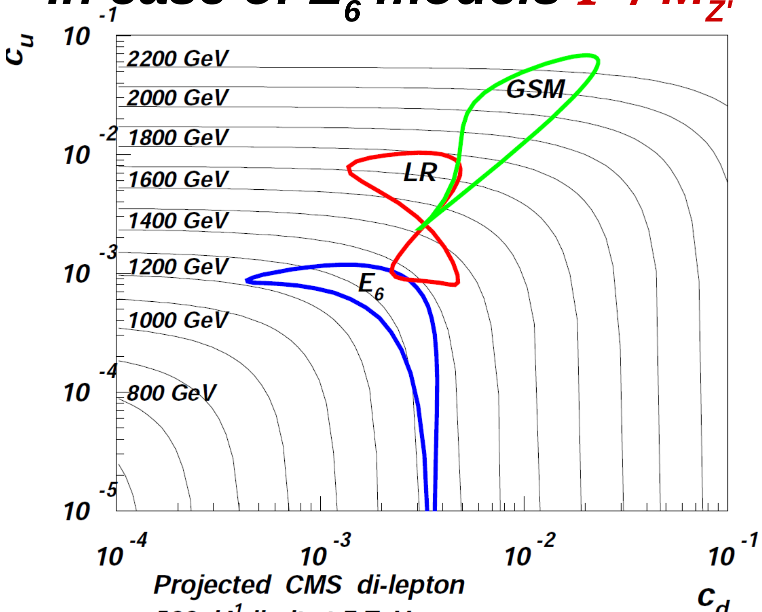


The Z' width for E6/GLR/GSM



For some parameter space of GLR and for all parameter space of GSM the $\Gamma / M_{Z'} > 2\%$ and can be measure in e^+e^- or/and in $\mu^+\mu^-$ channels

In case of E_6 models $\Gamma / M_{Z'} < 1\%$ and will be not accessible



Projected CMS di-lepton $500pb^{-1}$ limit at 7 TeV

Combining the width and cs information

- Essentially there is no overlap between E6/GLR/GSM contours in Cu-Cd plane
- However, the measured cross section defines the mass contour which can cross several model classes
- Interestingly, there is no overlap in the widths of GLR and GSM models!
- **So, E6/GLR/GSM are potentially distinguishable using the cross section and the width information!**

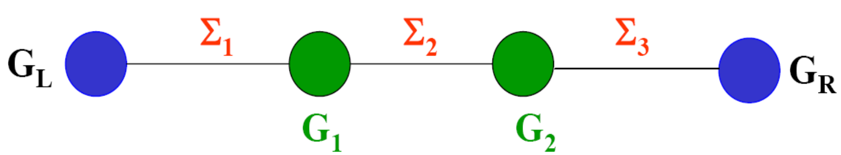
Generic nature of “Cu-Cd” approach: application to four-site model and Technicolour

equivalent description on the languages of Deconstructon and Technicolor

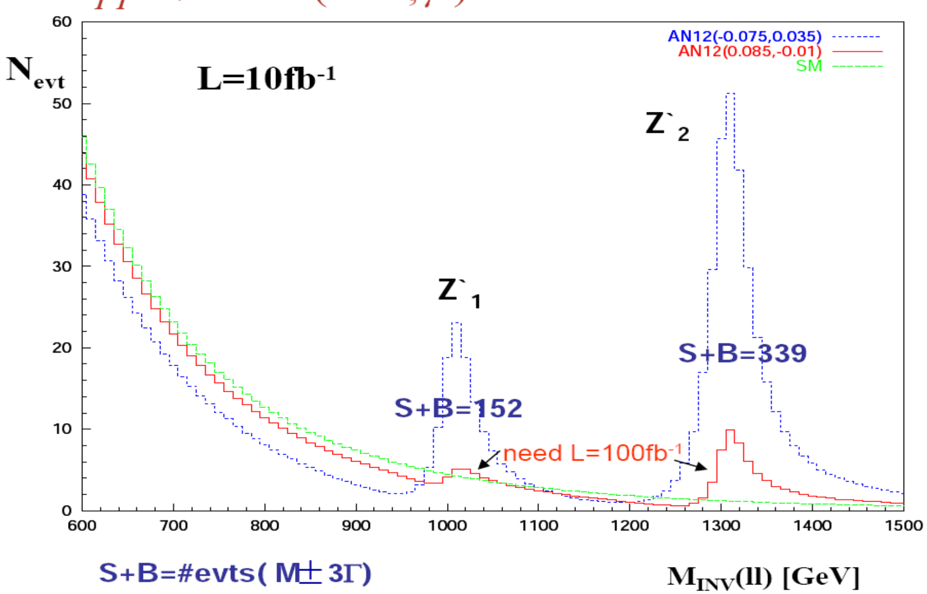
The Higgsless 4-site Linear Moose model

[Accomando, De Curtis, Dominici,Fedeli '08]

equivalent to



$pp \to l^+l^- \quad (l = e, \mu)$



Next to Minimal Walking Technicolor (NMWT)

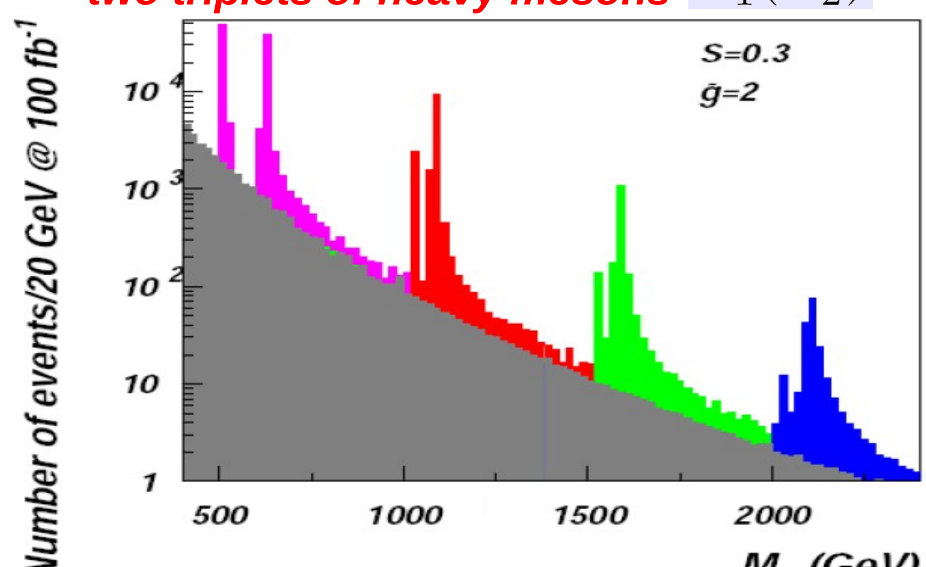
N_c = 3, N_f = 2

in the two-index symmetric

$SU(2)_L$ X $SU(2)_R$ –> $SU(2)_V$

two triplets of heavy mesons

$R_1^\pm(R_2^\pm)$ **and** $R_1^0(R_2^0)$

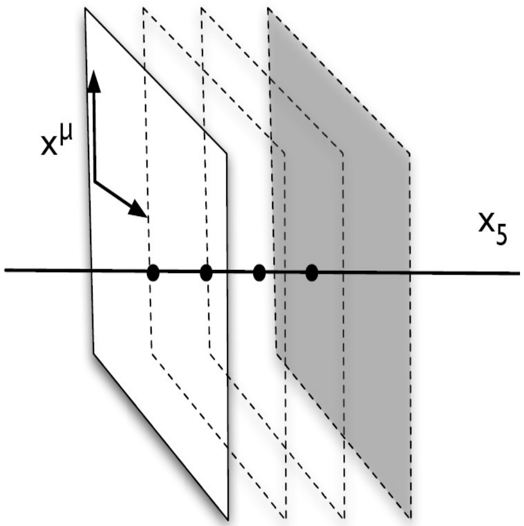


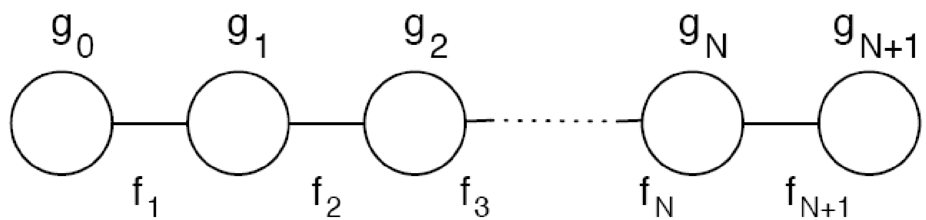
AB, Foadi, Frandsen, Järvinen, Pukhov, Sannino '08

Z' is not necessarily fermiophobic! **Complementarity of DY di-lepton and di-boson channels**

DECONSTRUCTION

moose diagram can be interpreted as the discretization of a continuum gauge theory in 5D along a fifth dimension



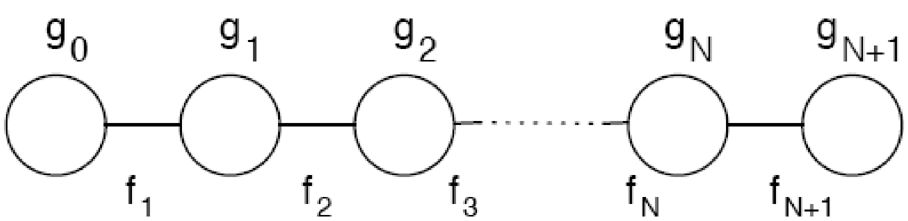


- Discretize fifth dimension
- 4D gauge group at each site
- Nonlinear sigma model link fields
- To include warping: vary f_j
- For spatially dependent coupling: vary g_k
- Continuum Limit: take $N \rightarrow$ infinity
- Finite N, a 4D theory w/o 5D constraints

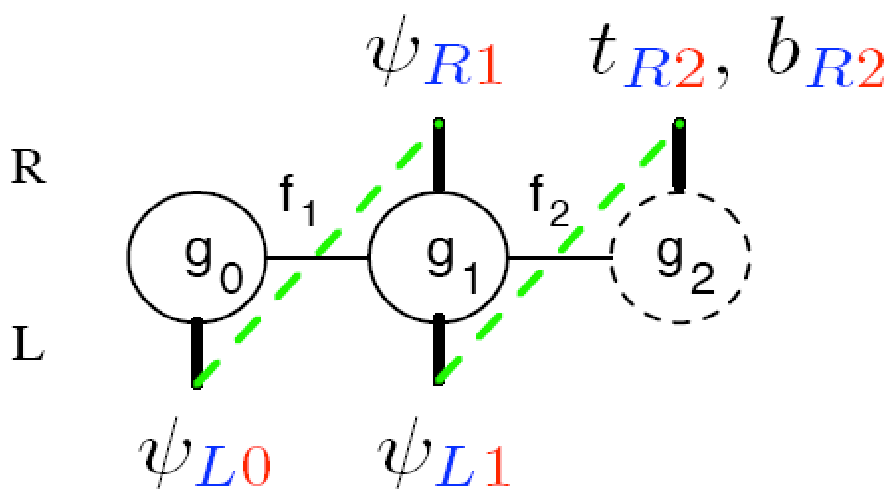
Arkani-Hamed, Georgi, Cohen & Hill, Pokorski, Wang

Three site model (TSM)

simplest, realistic, highly deconstructed,higgsless



Discretized 5th dimension written in the language of 'theory space'
[Arkani-Hammed, Georgi, Cohen; Hill, Pokorski, Wang]



$$SU(2)\times SU(2)\times U(1)$$

[Chivukula, Coleppa, Di Chiara,Simmons '06]

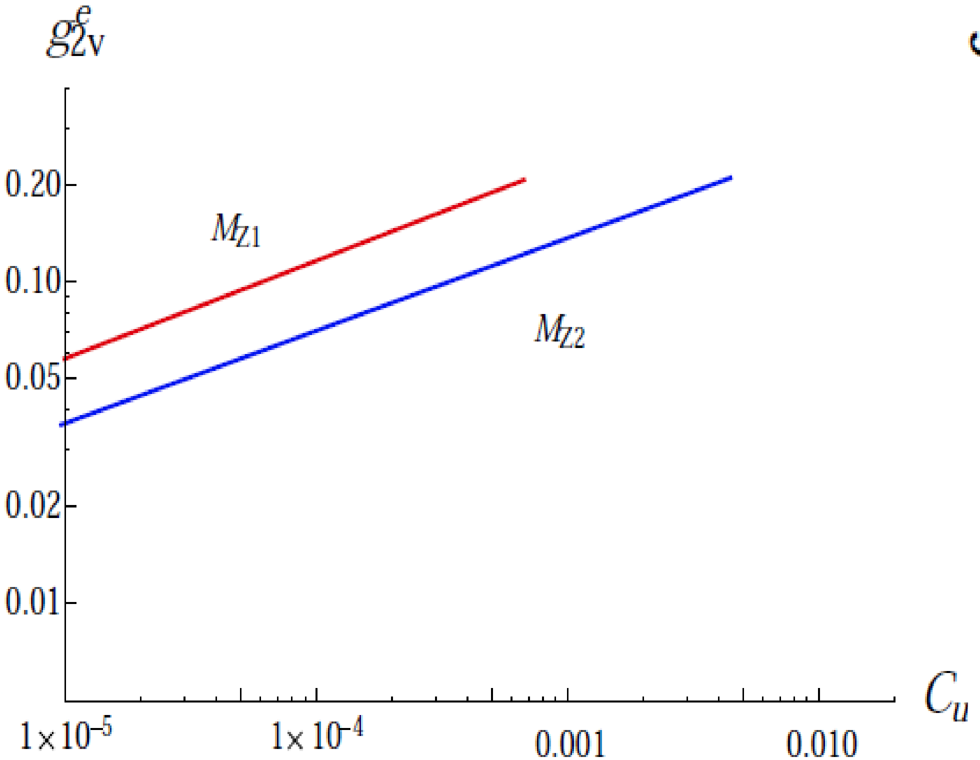
gauge bosons: photon,Z,W, Z',W'

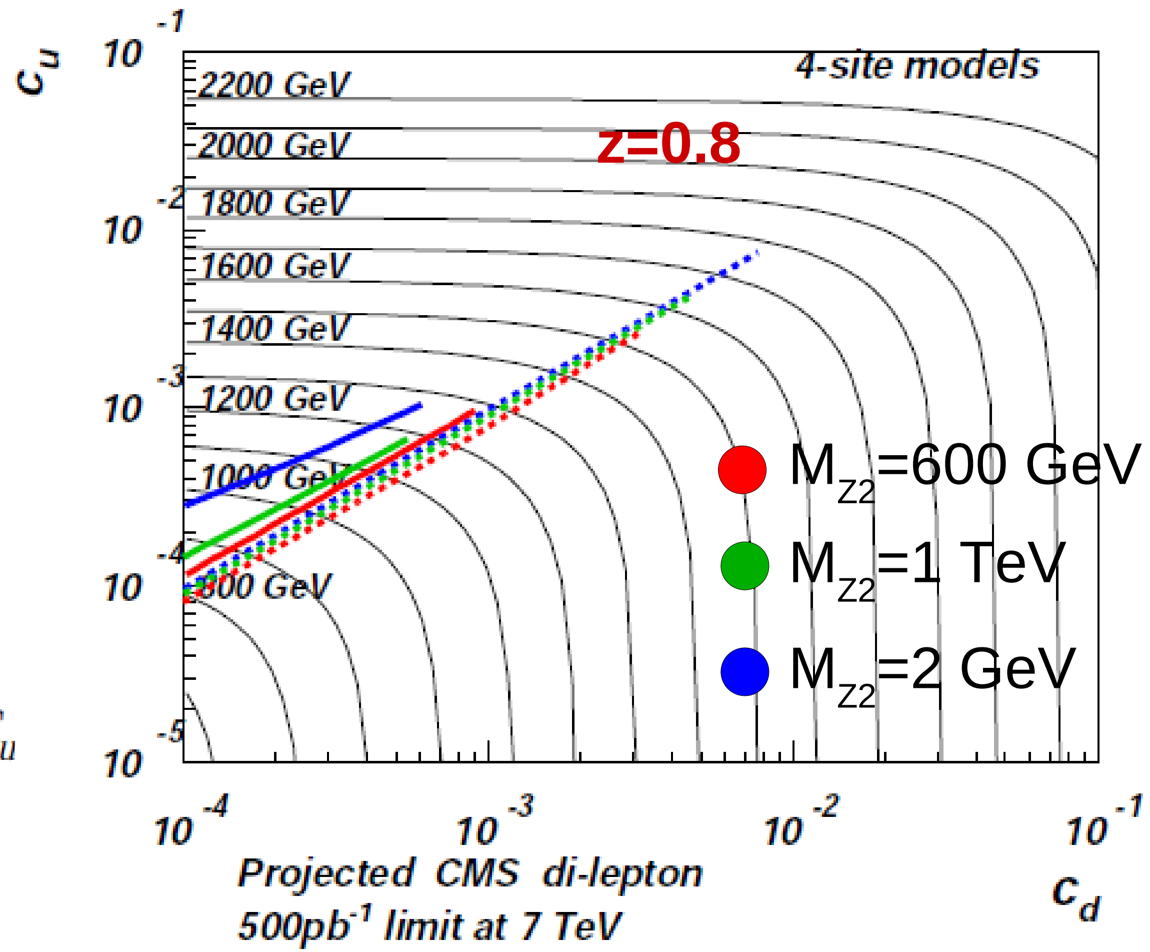
gauge sector is the BESS model
[Casalbuoni, De Curtis, Dominici,Gatto '85]

fermions: u, d, c, s, t, b
U, D, C, S, T, B
plus leptons

Limits for four-site model

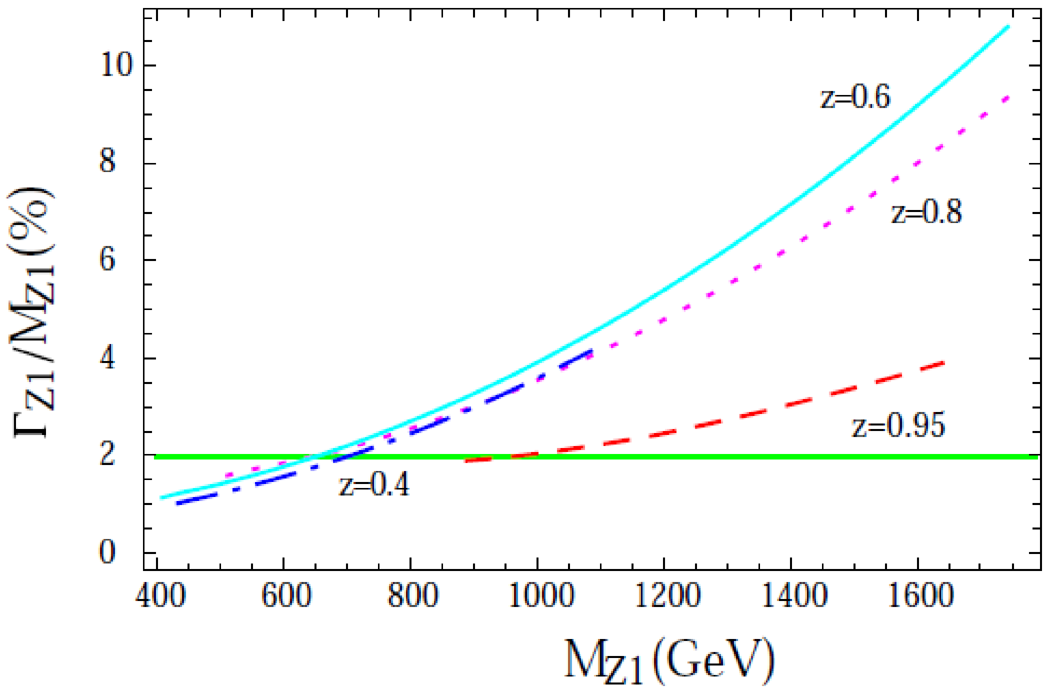
$$SU(2)_L \times SU(2)_1 \times SU(2)_2 \times U(1)_Y$$

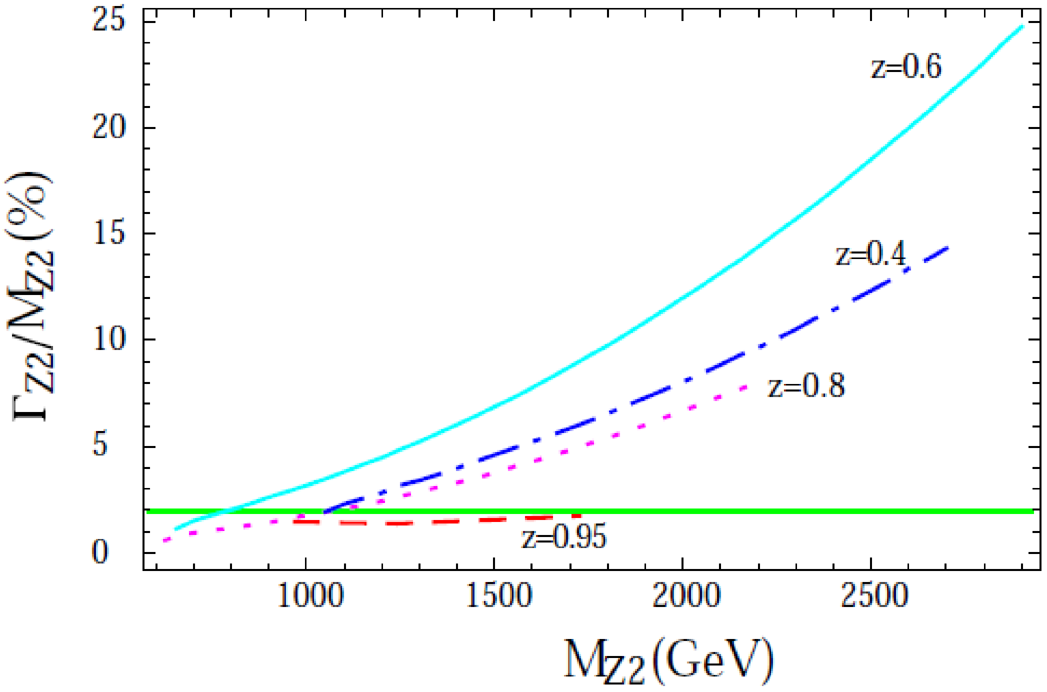




- **Model parameters:** M_{Z2}, $z = M_{Z1}/M_{Z2}$, g_{2v}
- $Z'_{1,2}$ primarily decay to vector bosons

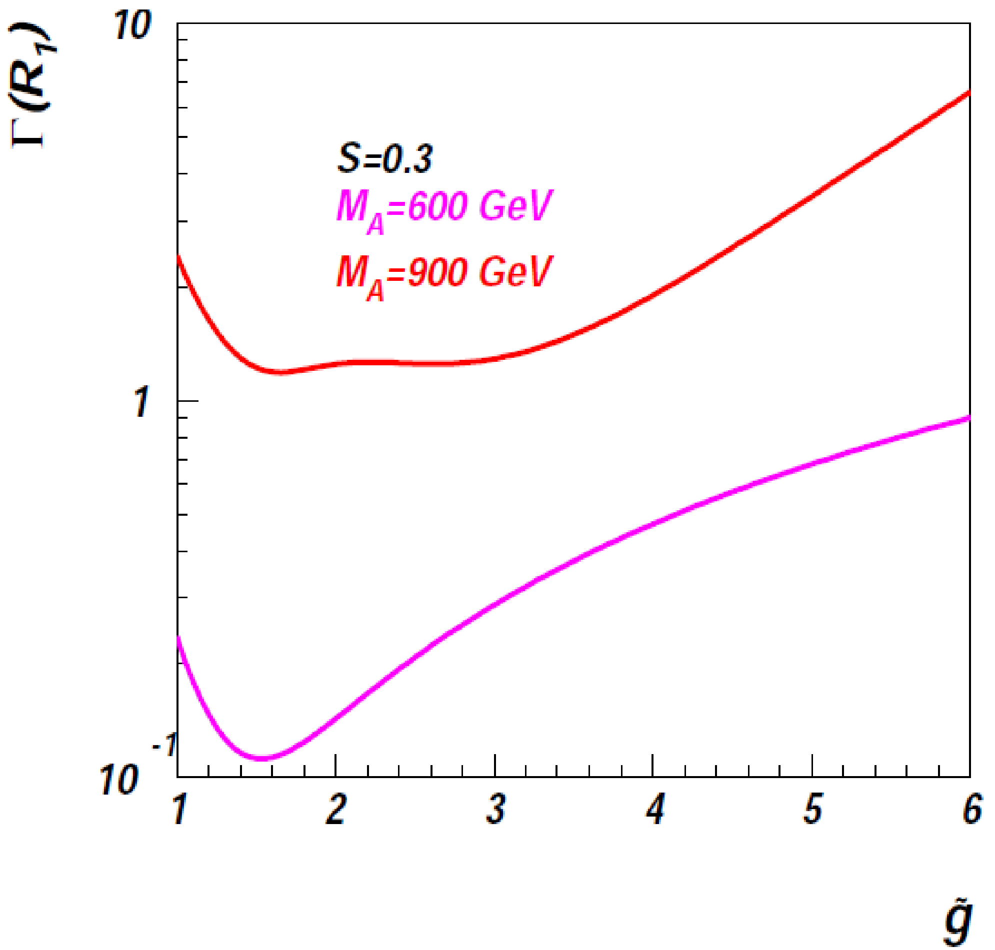
Z' width in four-site model

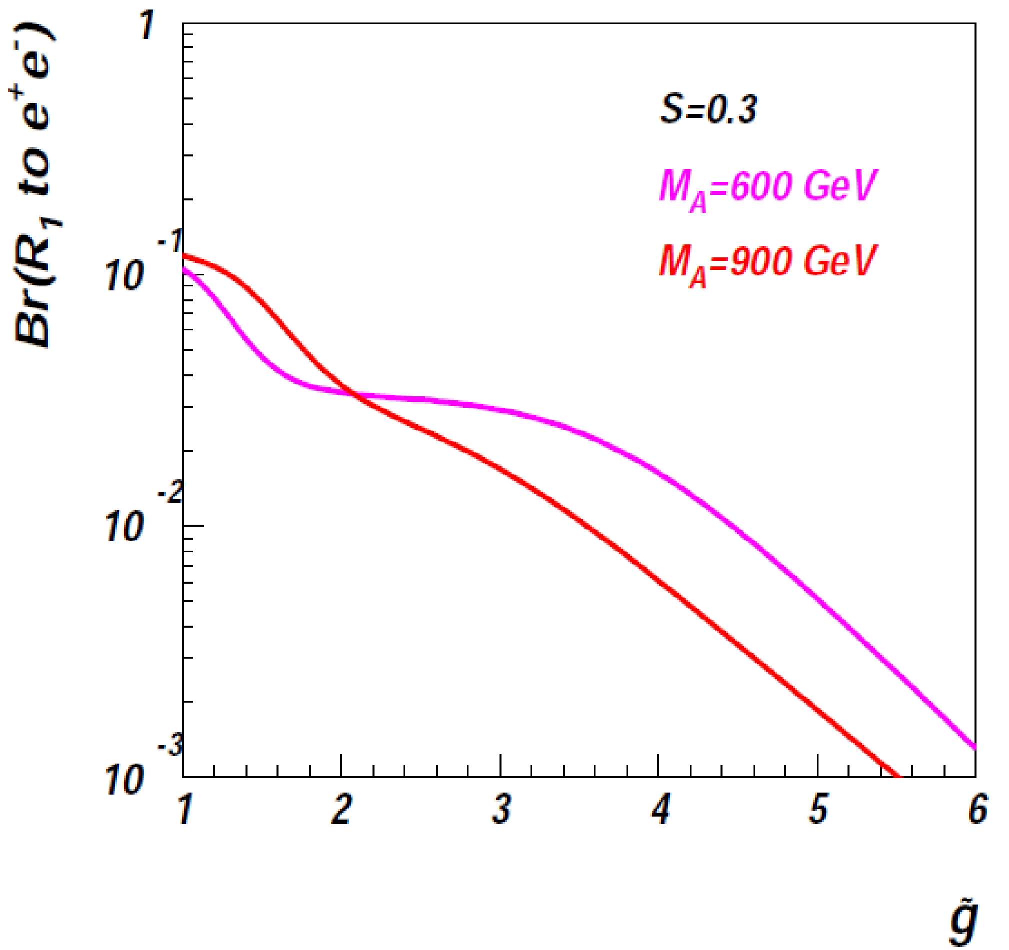




Preliminary results for MWTC model(1)

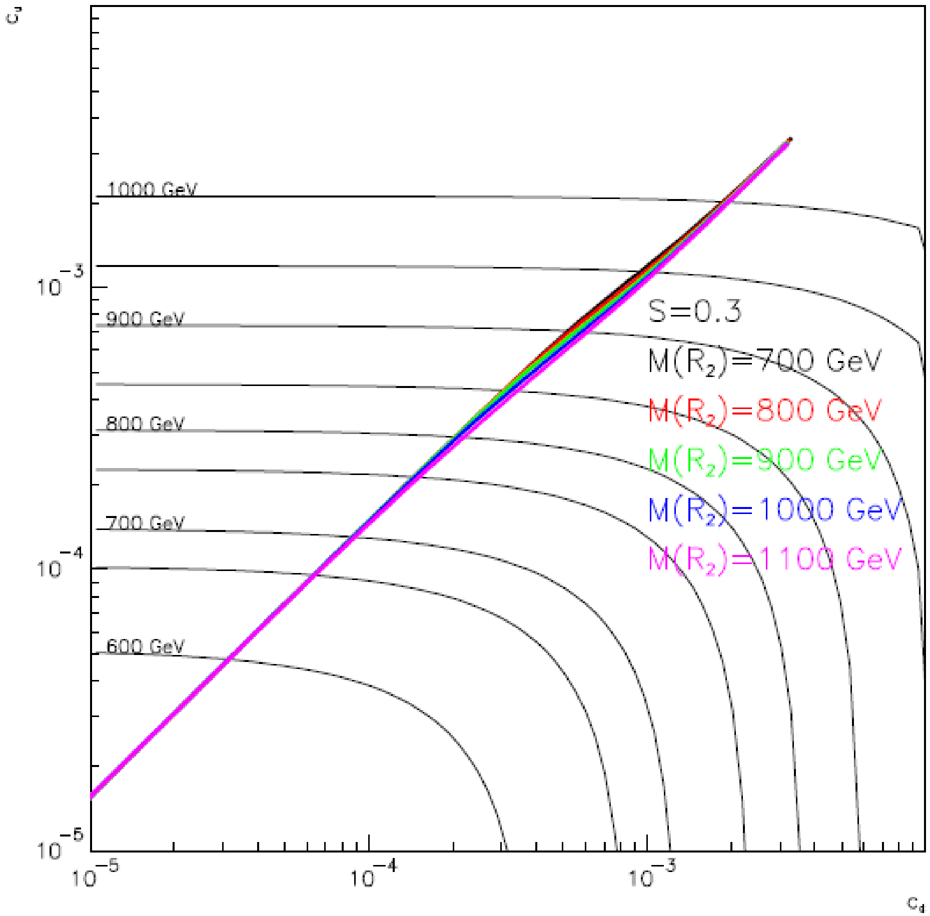
[collaboration with M. Frandsen, M. Jarvinen]

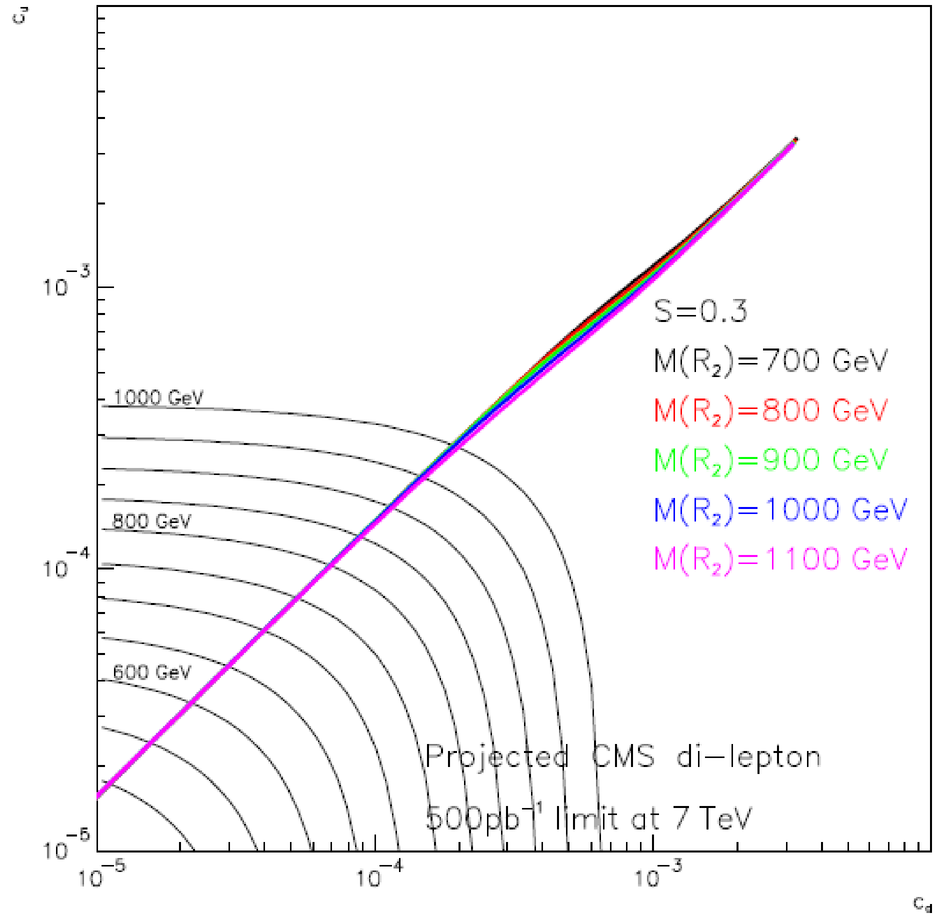




Preliminary results for MWTC model(2)

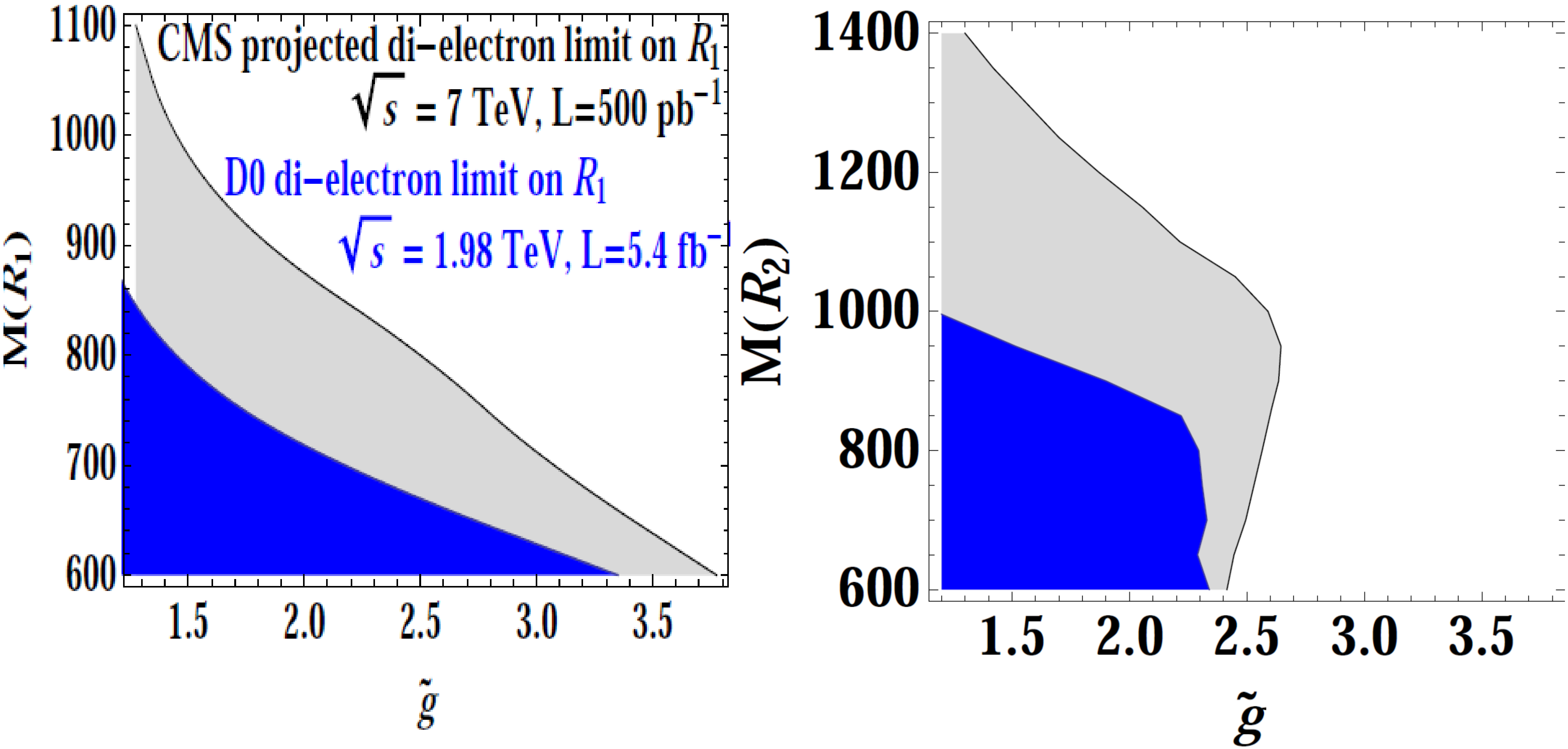
[collaboration with M. Frandsen, M. Jarvinen]



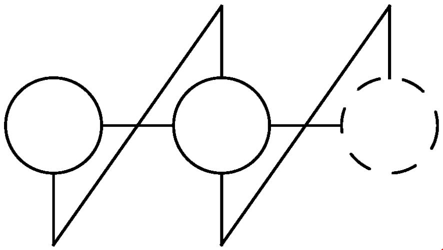


Preliminary results for MWTC model(3)

[collaboration with M. Frandsen, M. Jarvinen]



Tools



CalcHEP

[Alexander Pukhov, AB, Neil Christensen]

- **Automatic calculations of tree-level processes within user-defined model**
- **User friendly graphical interface**
- **Easy implementation of new models**
  - Especially using LanHEP
- **Feynman gauge and unitary gauge**
  - Important cross check.

- **New features of CalcHEP**
  - **batch interface** [Neil Christensen]
  - **Improved CalcHEP-MC interface** [AB, Pukhov]

LanHEP [Andrei Semenov]

- **Automatic generation of Feynman rules from the Lagrangian**
- **Has checks for**
  - *Hermiticity*
  - *BRST invariance*
  - *EM charge conservation*
  - *Particle mixings, mass terms, and mass matrices*

Example of model Implementation using LanHEP

LanHEP

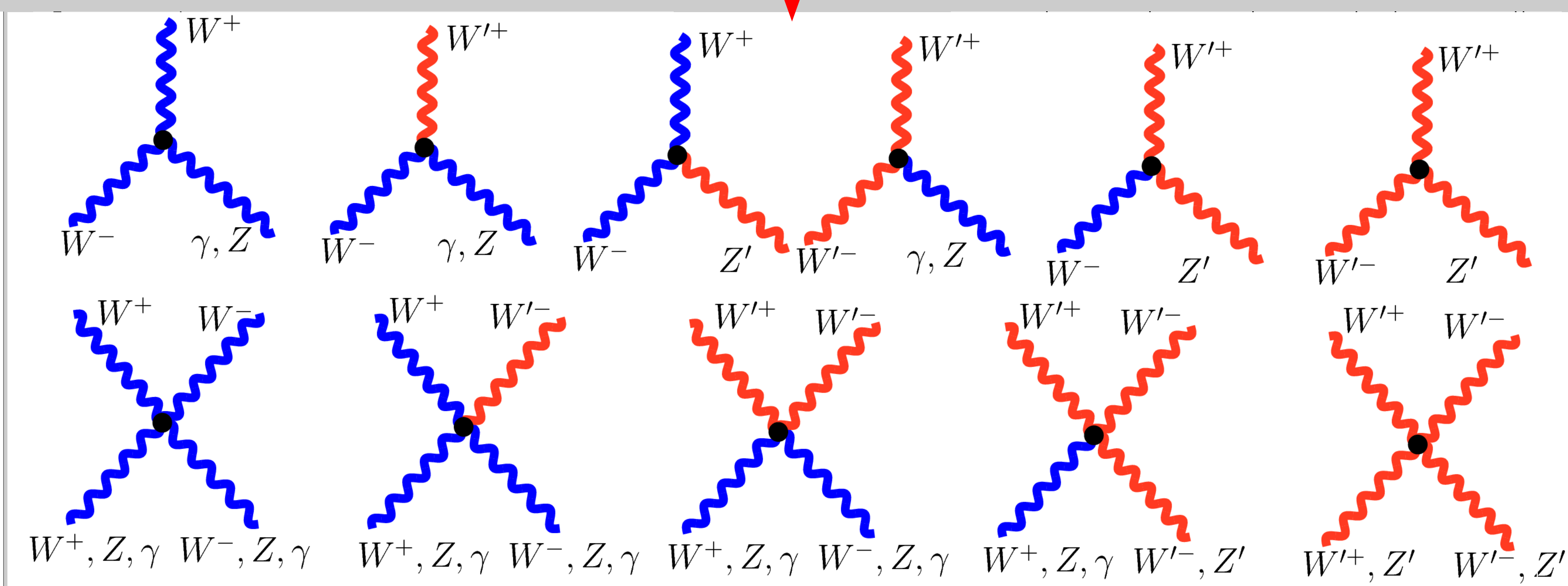
$$\mathcal{L}_{F^2} = -\frac{1}{2}\mathrm{Tr}\left(F_0^2 + F_1^2 + F_2^2\right)$$ **where** $$F_j^{\mu\nu} = \partial^\mu W_j^\mu - \partial^\nu W_j^\mu + i g_j \left[W_j^\mu, W_j^\nu\right]$$

```
%%%%%%%%%%  Kinetic and self interaction Lagrangian terms.
lterm  -F**2/4  where  F=deriv^mu*W23^nu-deriv^nu*W23^mu.
lterm  -F**2/4  where  F=deriv^mu*W0^nu^a-deriv^nu*W0^mu^a-g*eps^a^b^c*W0^mu^b*W0^nu^c.
lterm  -F**2/4  where  F=deriv^mu*W1^nu^a-deriv^nu*W1^mu^a-g/x*eps^a^b^c*W1^mu^b*W1^nu^c.
```

(gauge kinetic term as an example)

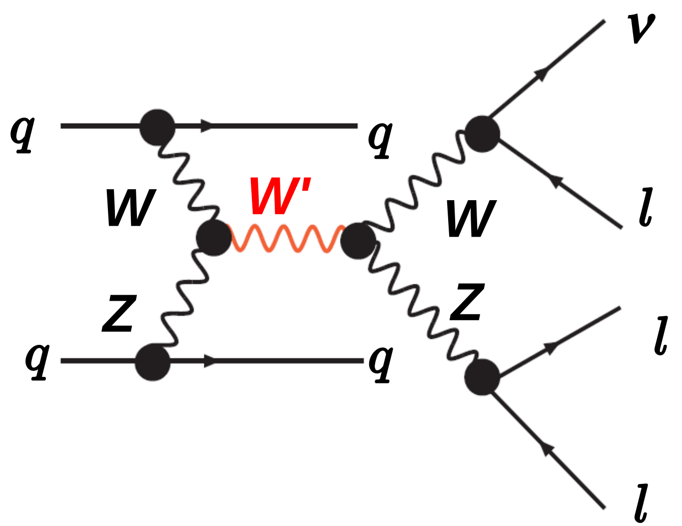
lhep model.mdl

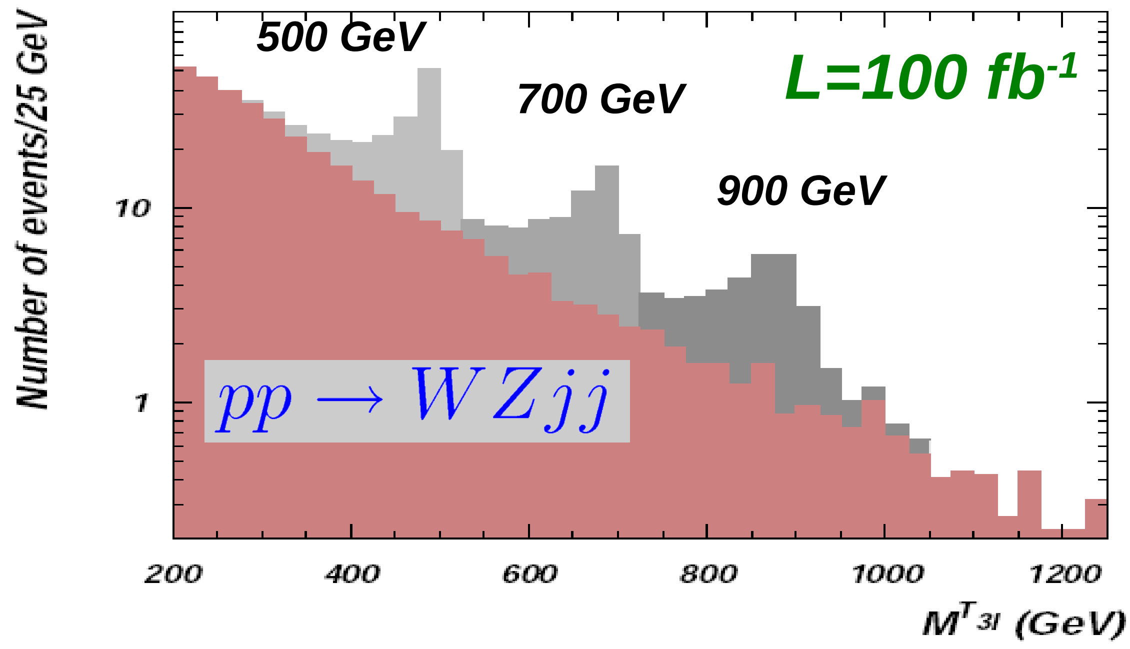
CalcHEP



LHC reach for WZ->W' process

[AB, Chivukula, Christensen, He, Kuang, Pukhov, Qi, Simmons, Zhang '07]





the complete WZjj BG is factor 4 bigger then PYTHIA effective V-boson approximation!

$$E_j > 300 \text{ GeV}$$
$$p_{Tj} > 30 \text{ GeV}$$
$$|\eta_j| < 4.5$$
$$|\Delta\eta(jj)| > 4$$
$$p_{T\ell} > 15 \text{ GeV}$$
$$|\eta_\ell| < 2.5$$
$$0.85 M_{W'} < M_T < 1.05 M_{W'}$$

To be compared with Birkedal, Matchev, Perelstein '05

Recent applications:
phenomenology of WalkingTechnicolor models

arXiv:0809.0793

AB, Foadi, Frandsen, Järvinen, Pukhov, Sannino

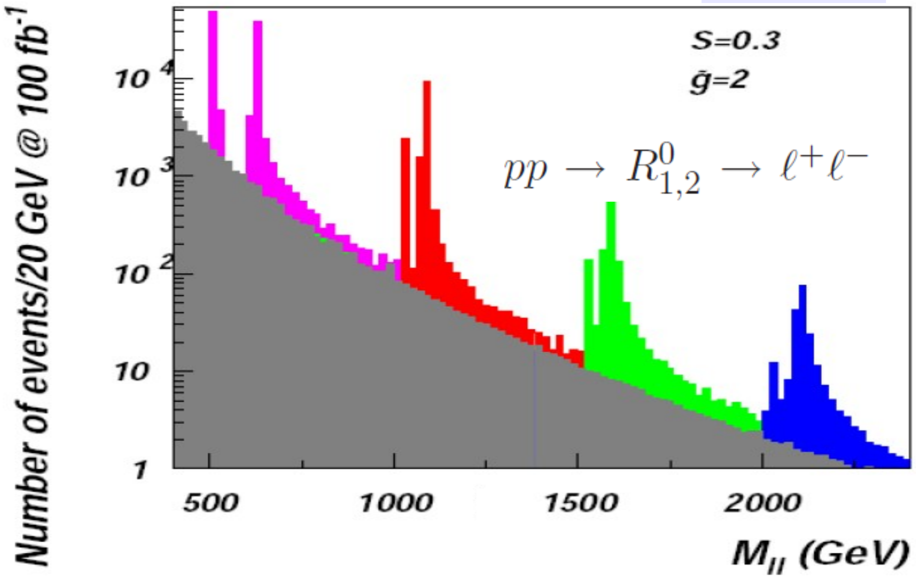
N_c = 3, N_f = 2
in the two-index symmetric
SU(2)$_L$ X SU(2)$_R$ –> SU(2)$_V$
two triplets of heavy mesons

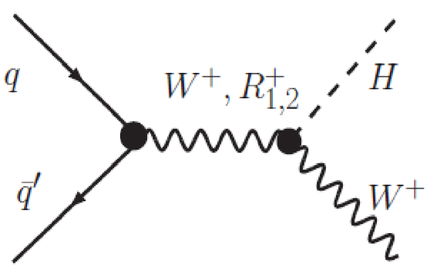
LHC

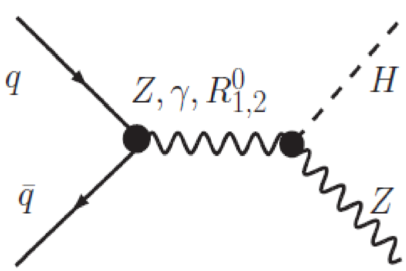
$R_1^\pm(R_2^\pm)$

and

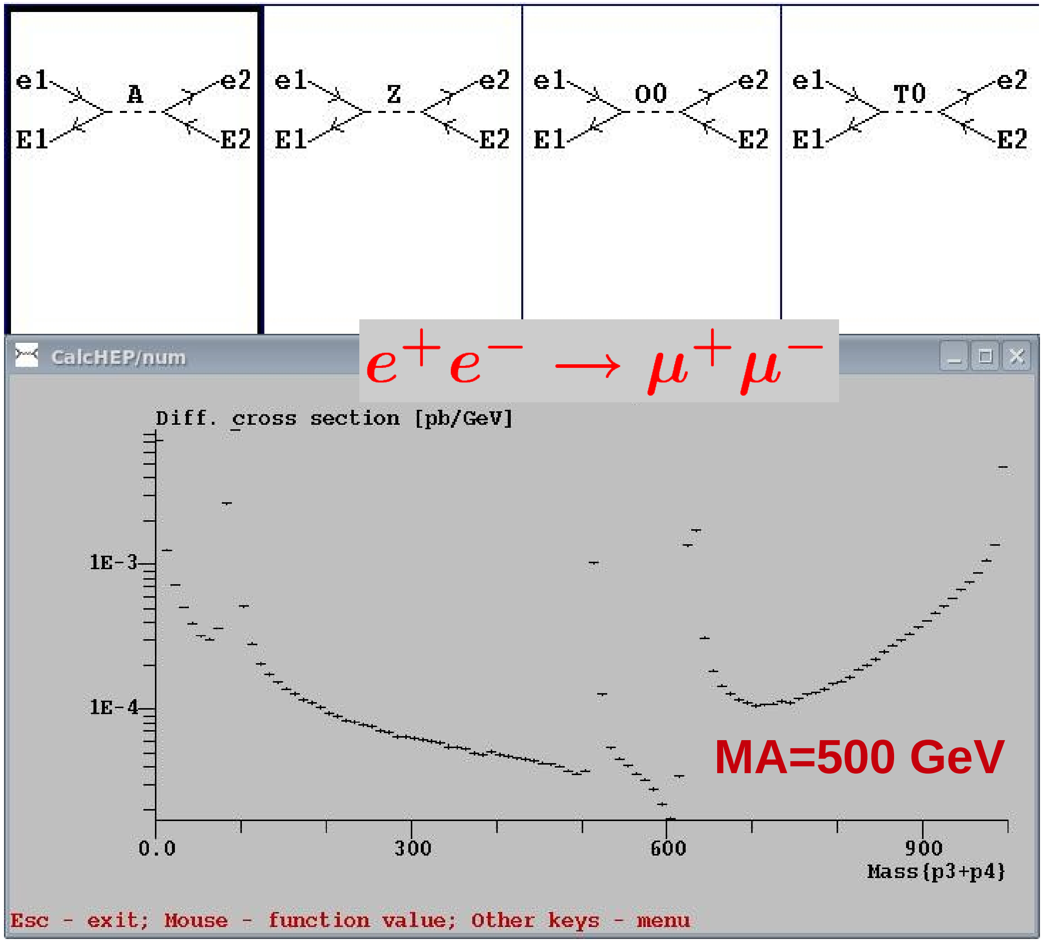
$R_1^0(R_2^0)$





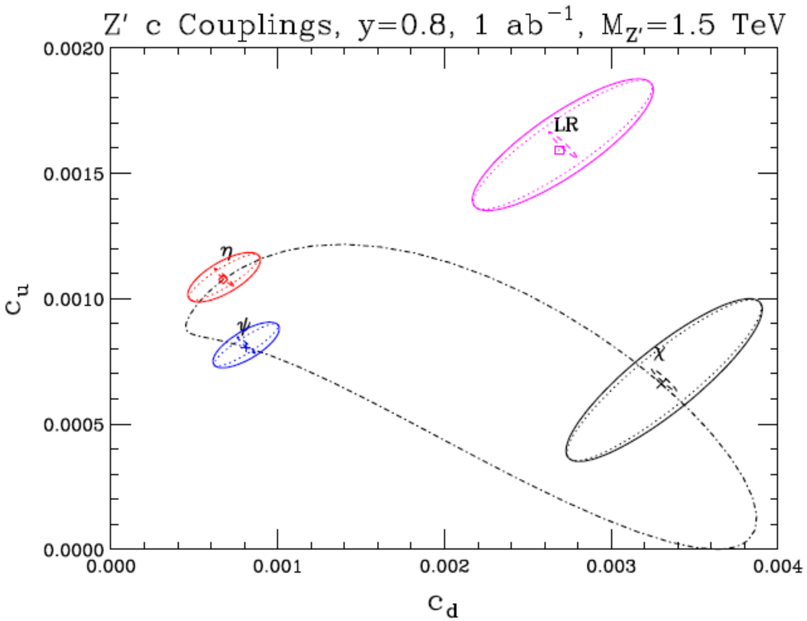


ILC@1TeV
(work in progress)

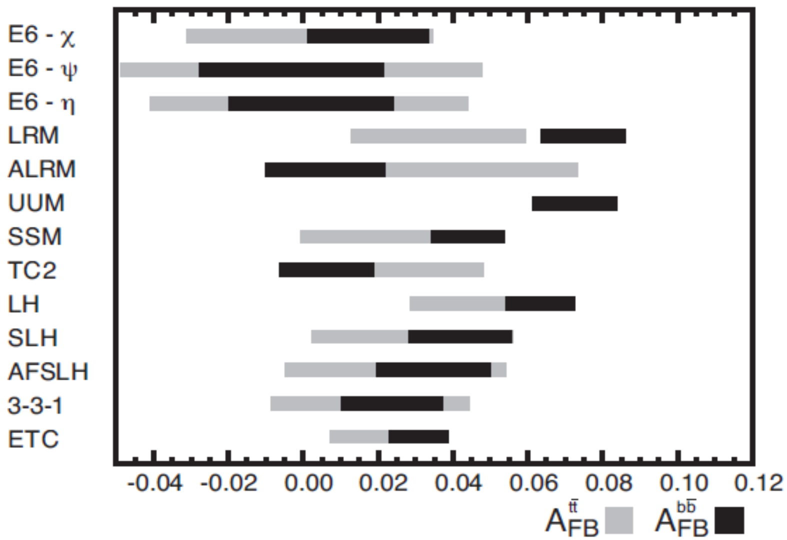


Next step: A_{bf}

$$A_{FB}^{y_1} = \frac{\left[\int_{y_1}^{y_{max}} - \int_{-y_{max}}^{-y_1}\right][F(y) - B(y)]dy}{\left[\int_{y_1}^{y_{max}} + \int_{-y_{max}}^{-y_1}\right][F(y) + B(y)]dy}$$



Petriello,Quackenbush
arXiv:0801.4389



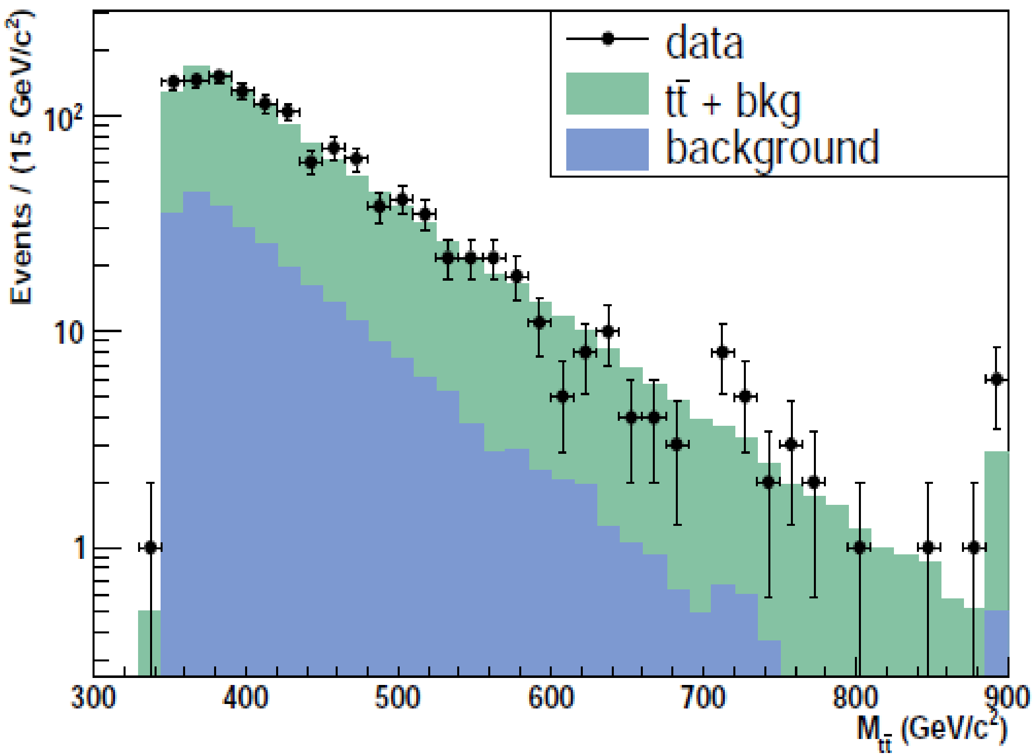
We need more observables to test g_A and g_V (6 couplings!) in model-independent way:

e.g. Z->tt, Z'->ττ, Z' ->bb

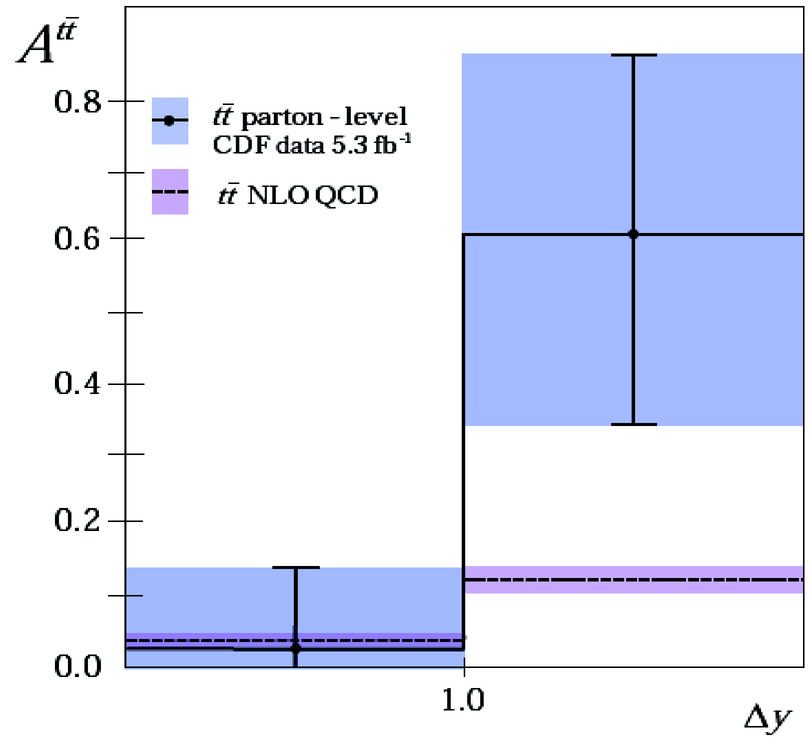
Diener,Godfrey,Martin
arXiv:1006.2845

And we should be ready for new physics!

- **tt-bar forward-backward asymmetry from CDF**



arXiv:1103.0981



$$A^{t\bar{t}} = 0.475 \pm 0.114$$

$$0.088 \pm 0.013$$

Conclusions

- **Cu-Cd parameter space language allows easily to visualize and establish the limit for generic model classes**
- **E6/GLR/GSM/4S/WTC models has been parametrized, projected LHC limits are presented**
- **NNLO K-factors are evaluated, must be used with a specific PDF!**
- **Z' production cross section should be quoted for di-lepton invariant mass window around Z' mass**
- **Signal-Background interference is crucial if no di-lepton mass window cut applied**
- **Just cross section and the width information allows to distinguish some model classes**
- **To experimentalists:**
  lets use Cu-Cd language to establish PRESENT Z' limits!