DY production of multi-*Z'*s at the LHC

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Overview

- **Introduction: the state of art of DY production of neutral resonances**

- **Finite width and interference effects: single *Z'* scenario**

- **Phenomenology of multi-Z' models: the NUED and the 4DCHM**
  - Search strategies and current limits
  - Finite width and interference effects: multi-*Z'* scenarios
  - Exclusion and discovery limits for LHC Run-II

- **Conclusions**

Current status

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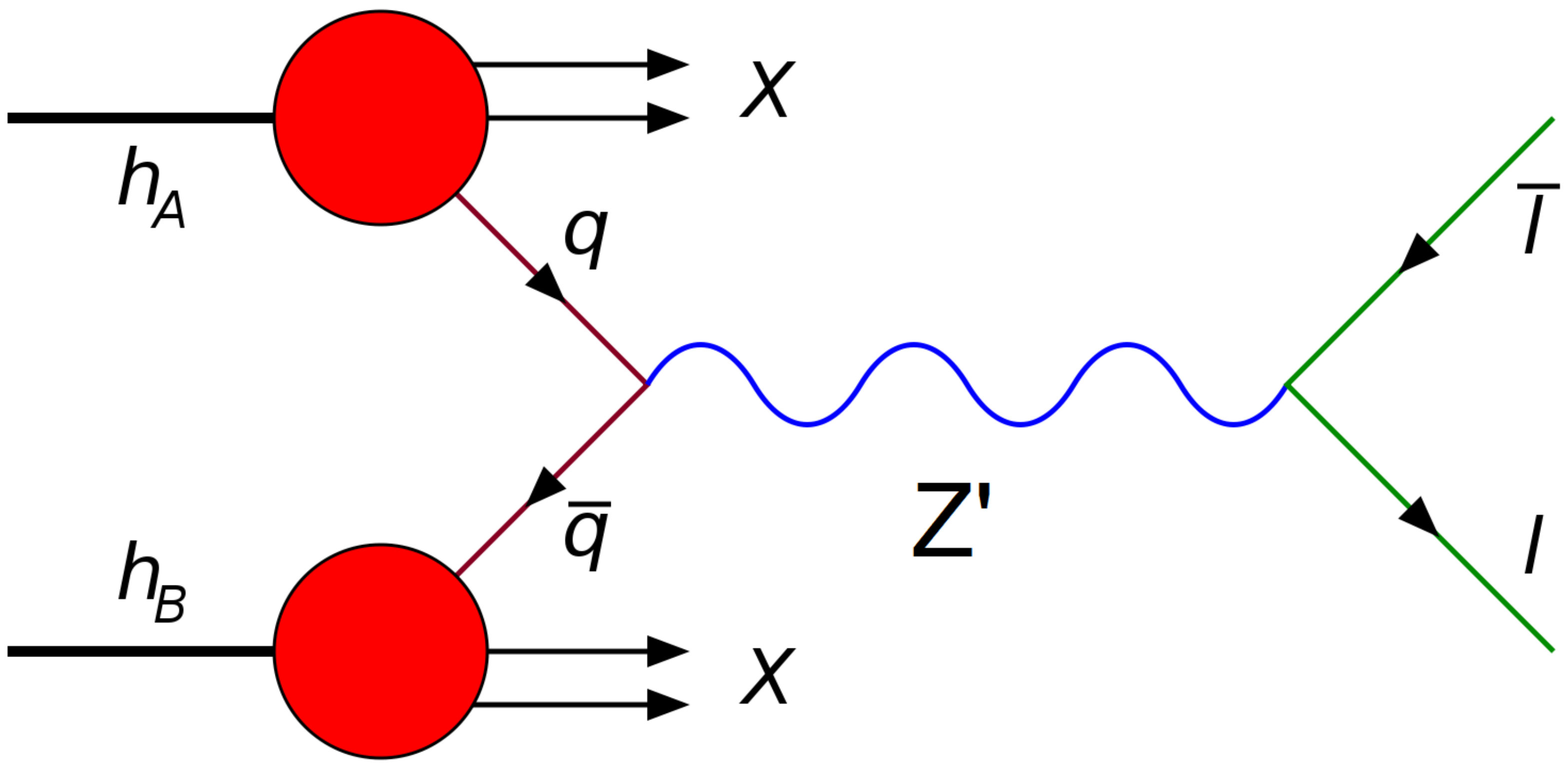
DY production of neutral resonance



Motivations:

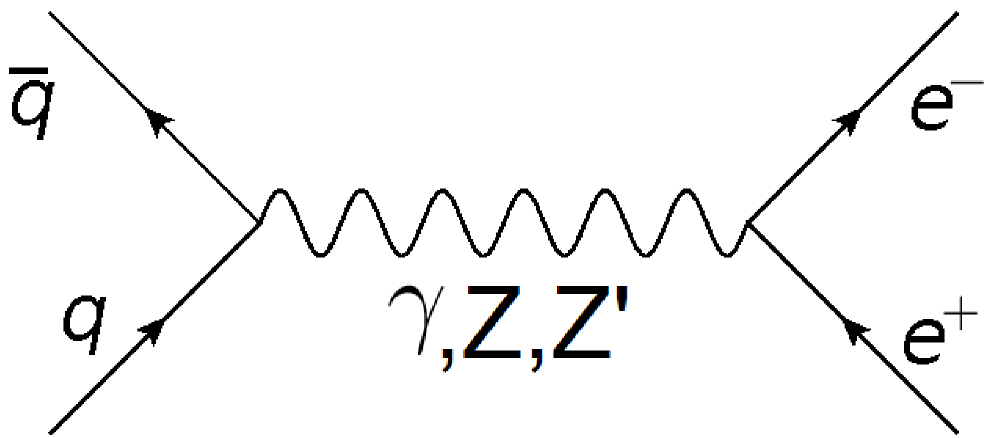
Leptons in the final state are:

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

- Easy to detect
- Precise to measure
- Almost background-free

CTEQ6L1 PDFs were used

The DY search



Experimentally unobserved signal

↓

Bump search / Counting strategy

↓

Excluded cross section

↓

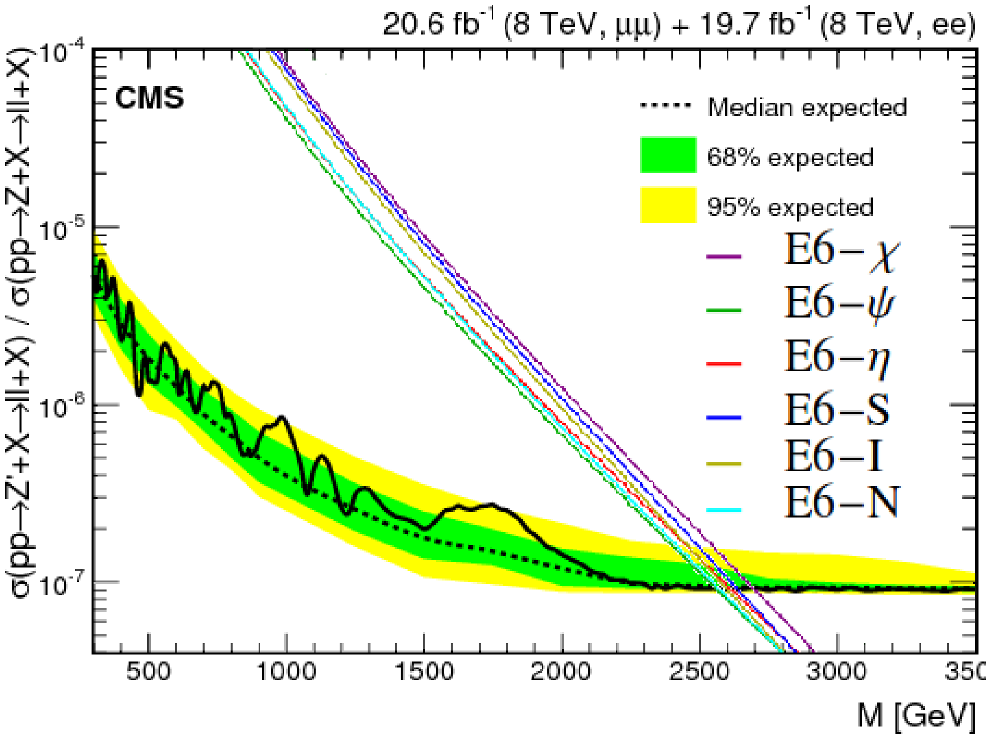
Narrow Width Approximation (NWA) → Finite width and interference effects are neglected

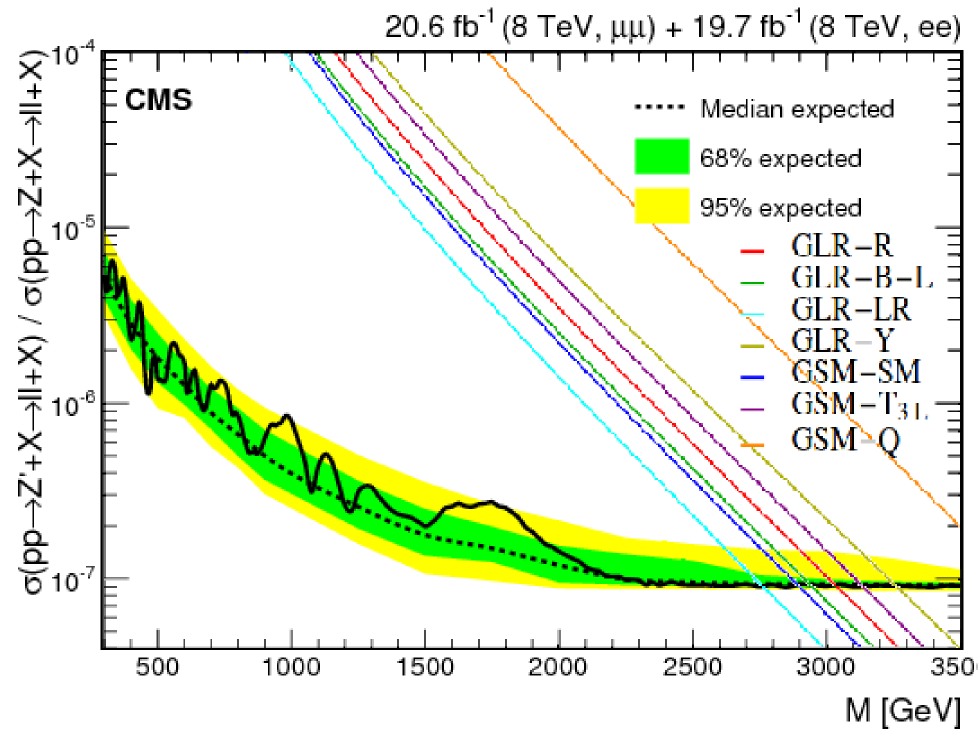
↓

***Z'* mass bounds**

Single Z' bounds after Run-I

pp → γ, Z, Z' → ee, μμ with |M(ll)-M$_{Z'}$| < 5% E$_{coll}$





Class	E_6						GLR				GSM		
$U'(1)$ Models	χ	ψ	η	S	I	N	R	$B-L$	LR	Y	SM	T_{3L}	Q
$M_{Z'}$ [GeV]	2700	2560	2620	2640	2600	2570	3040	2950	2765	3260	2900	3135	3720

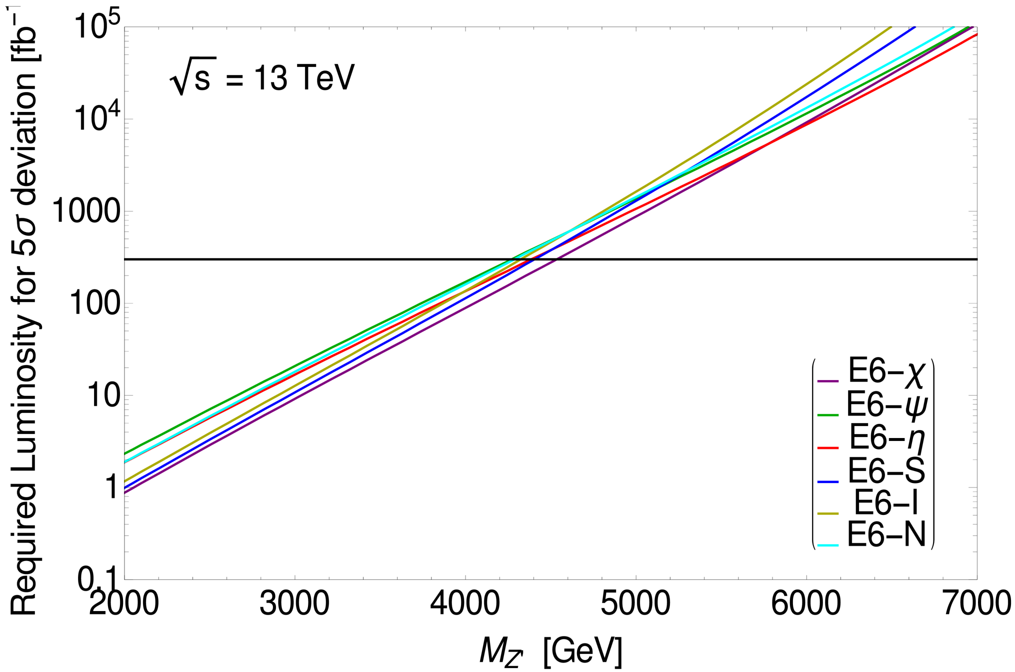
exclusion →

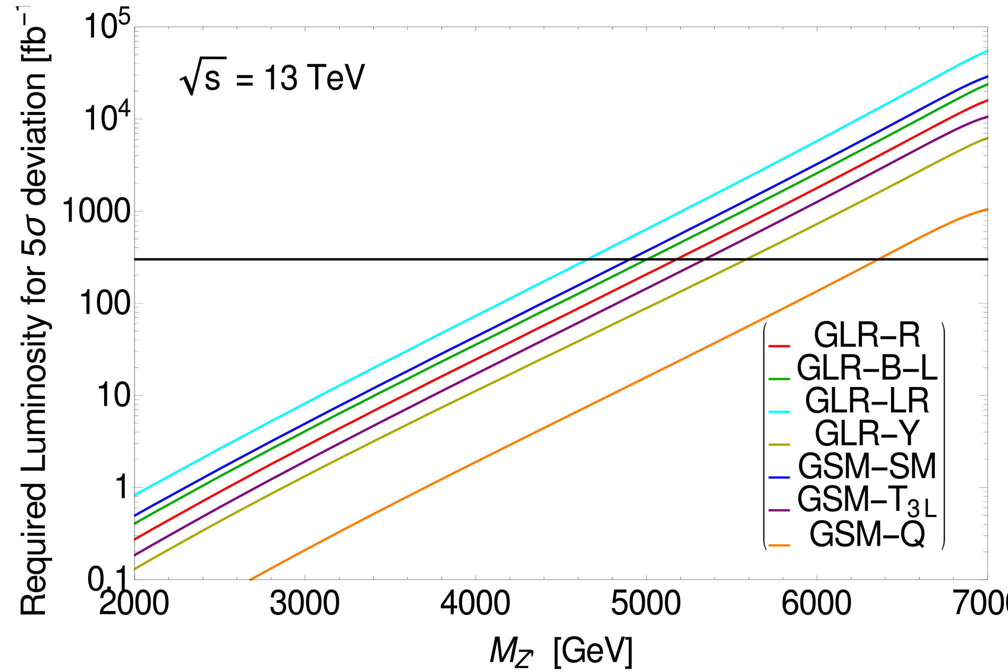
Begin of the search window for Run II

Accomando, Belyaev, JF, Mimasu, Moretti, Shepherd-Themistocleous arXiv:1503.02672

Projected Z' limits for Run-II

pp → γ, Z, Z' → ee, μμ with |M(ll)-M$_{Z'}$| < 5% E$_{coll}$





	Class	E_6						GLR				GSM		
	$U'(1)$ Models	χ	ψ	η	S	I	N	R	$B-L$	LR	Y	SM	T_{3L}	Q
discovery	$M_{Z'}$ [GeV]	4535	4270	4385	4405	4325	4290	5175	5005	4655	5585	4905	5340	6360
exclusion	$M_{Z'}$ [GeV]	5330	5150	5275	5150	5055	5125	6020	5855	5495	6435	5750	6180	8835

Search window in the Run II : 2.5 TeV < Mz' < 6.5 TeV

Accomando, Belyaev, JF, Mimasu, Moretti, Shepherd-Themistocleous arXiv:1503.02672

Finite width and interference

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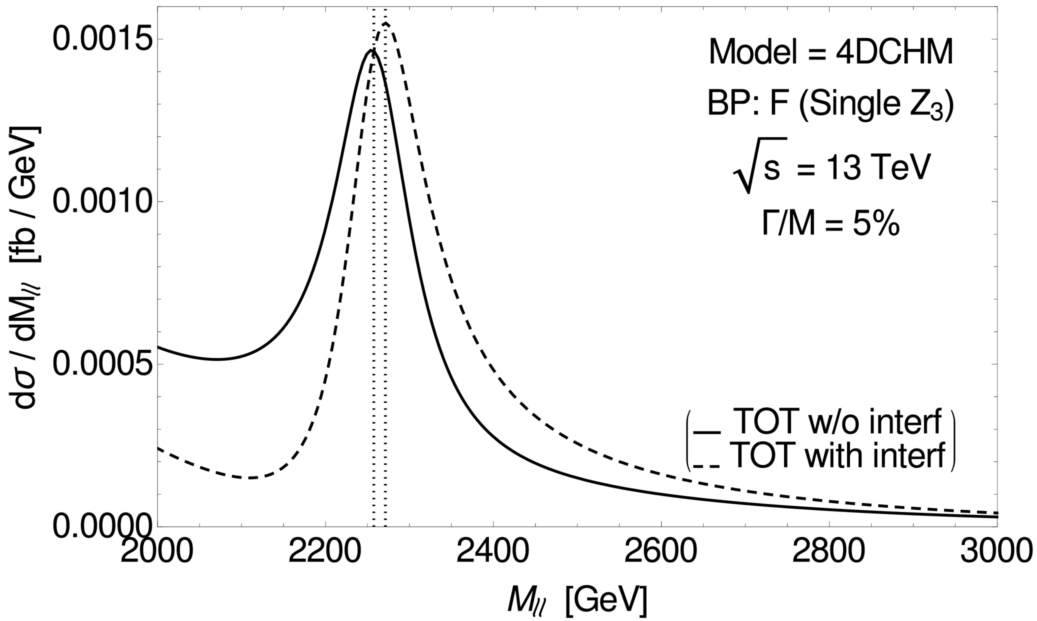
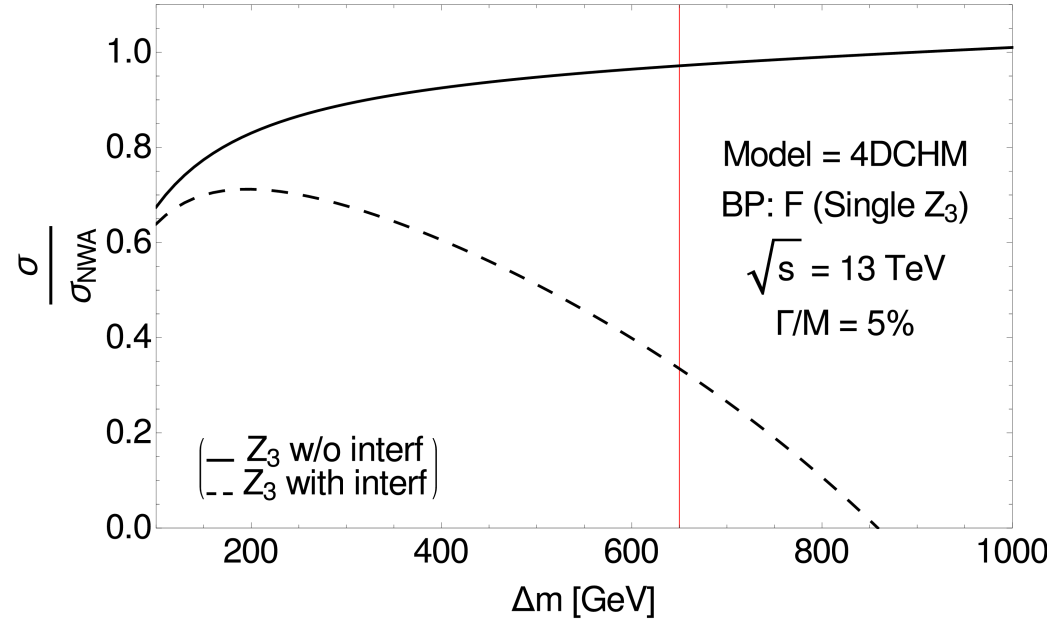
Finite width and interference





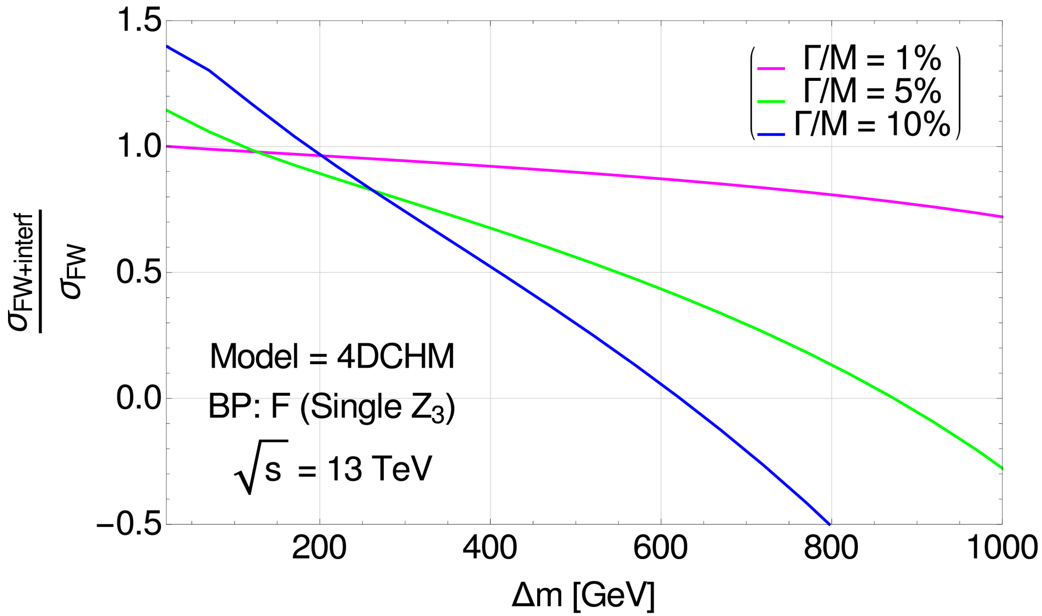
Interference effects <u>shift</u> the peak

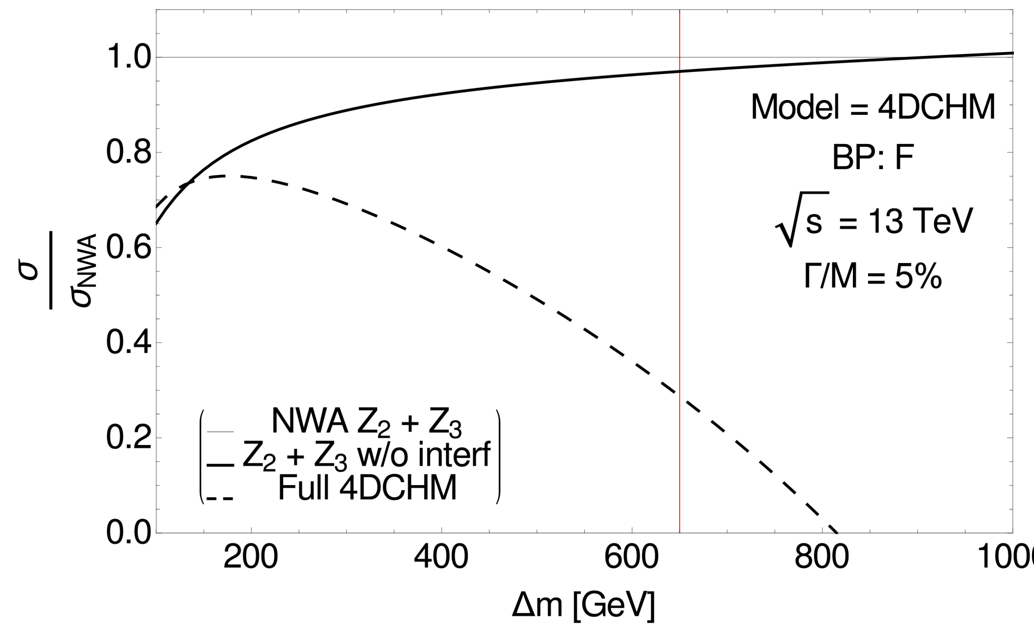
The position of the peak is not at the <u>resonance pole</u>

The choice of the <u>integration region</u> strongly affects the resulting cross section prediction

The exclusion / discovery limits can be mis-estimated

Finite width and interference





The FW approximation works if the integration interval do not include the <u>negative interference contribution</u>

The distance between the dip and the peak is <u>strongly dependent</u> by the model parameters

In the realistic <u>complete model</u> with a multi-Z' peaked structure, <u>deviations from NWA</u> are large

Again FW approach could be used for setting mass limits, choosing an <u>appropriate</u> integration interval.

Still it would fail in the analysis of the signal shape for profiling the new resonances in case of discovery.

The multi-*Z'* scenario

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The NUED

- **Minimal version of the large Extra Dimensions class of models.**
  - Only the EW SM gauge bosons are allowed to propagate in the EDs.
- **Two energy scales determine the phenomenology:**
  - $M_s = l_s^{-1}$ → string length related (very high energy ~ M_{plank}).
  - R^{-1} → related to the length of the extra dimensions compactified on a D-dimensional torus.
- **We can decompose the higher-dimensional space as $3 + d_{\parallel} + d_{\perp}$**
  - $3 + d_{\parallel}$ longitudinal dimension of the big brane that contains the 3D brane where the SM lives.
  - $d_{\perp}$ indicates the EDs which are felt by the gravity and are transverse to the big brane.
- **The particle content of the model is:**
  - Gravitons: closed strings propagating in the whole space.
  - SM fermions: <u>localized on the 3D brane.</u>
  - SM gauge bosons: open strings propagating in the $(3 + d_{\parallel})$ brane.

Antoniadis, Benakli, Phys.Lett.B 326:69-78 1994, arXiv:9310151 [hep-th]

The NUED

- **We consider the case of a *5D* NUED model:**
  - D = $d_{\parallel}$ = 1 and periodic boundary conditions on the compact direction.
  - The states propagating in the (4+D)-dimensional space are seen from the 4D point of view as a <u>tower of resonances</u> with masses

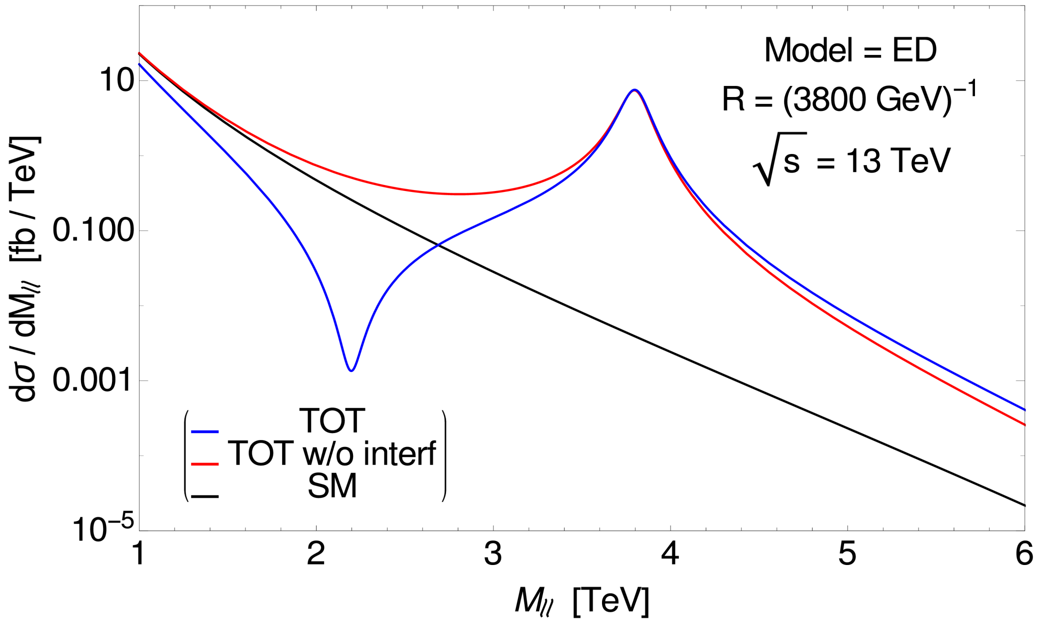
$$M_{KK}^2 = m_0^2 + \frac{n^2}{R^2}$$

Antoniadis, Benakli, Quiros, Phys.Lett. B331:313-320, 1994, arXiv:9403290 [hep-ph]

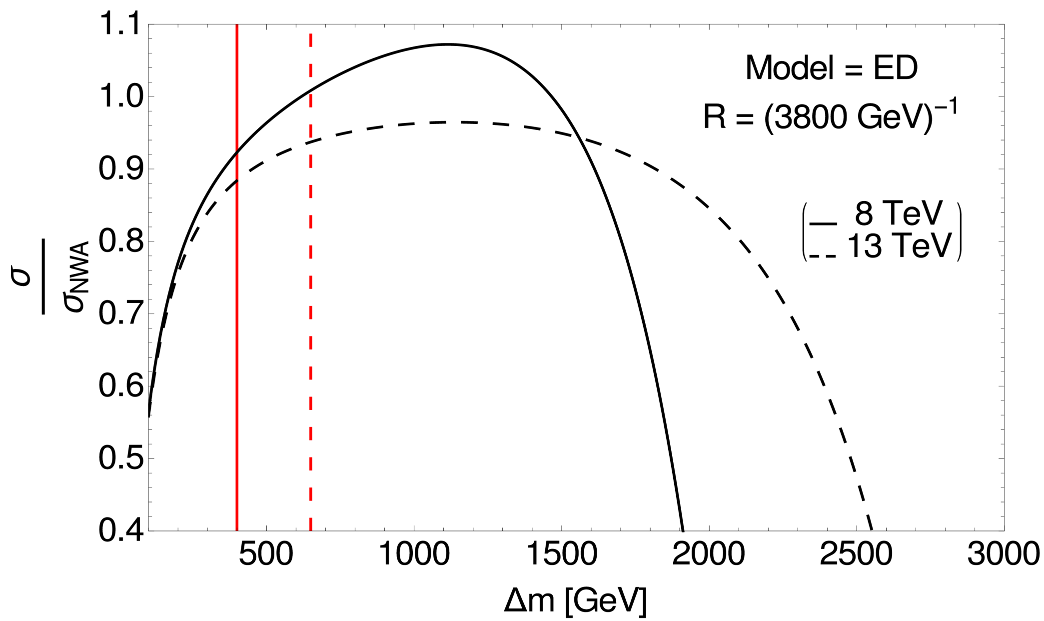
- **The localization of the fermions allows the direct production of KK resonances through $f\bar{f}' \to V^{(n)}_{KK}$ while $VV \to V^{(n)}_{KK}$ is forbidden.**
  - In the <u>NUED</u> all the SM gauge group can propagate in the 5D bulk space and therefore have KK excitations.
  - In the <u>NUED(EW)</u> only the *SU(2)⊗U(1)* EW gauge group can propagate in the compactified extra dimension and acquire KK excitations.
  - <u>The two scenarios do not differ</u> in the purpose of our analysis.

Bella, Etzion, Hod, Oz, Silver, et al. JHEP, 1009, 025 (2010), arXiv:1004.2432 [hep-ex]

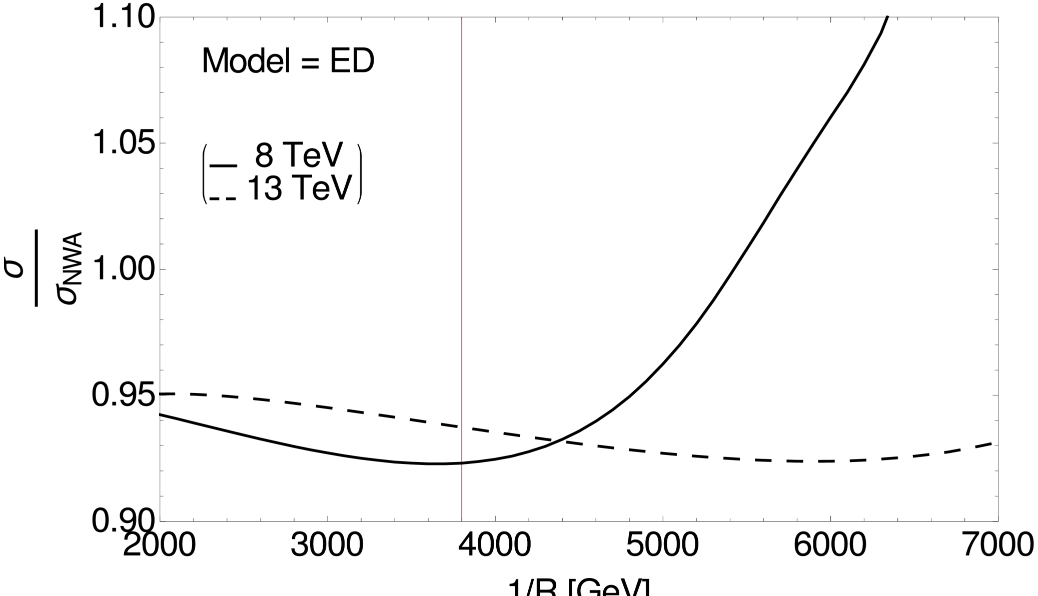
Phenomenology of NUED model



Typical profile of the ED model

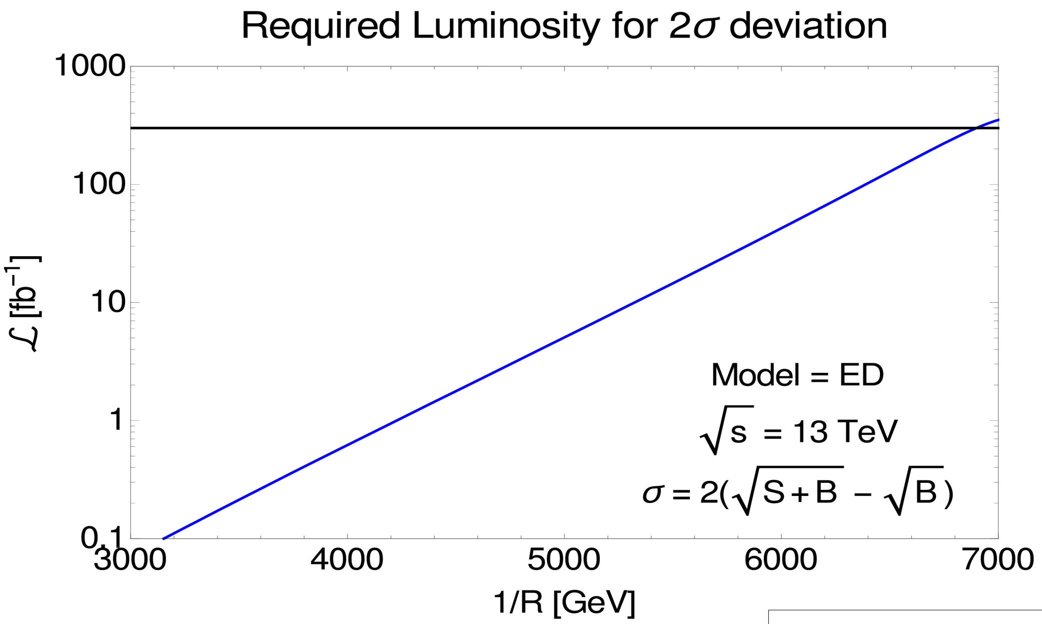


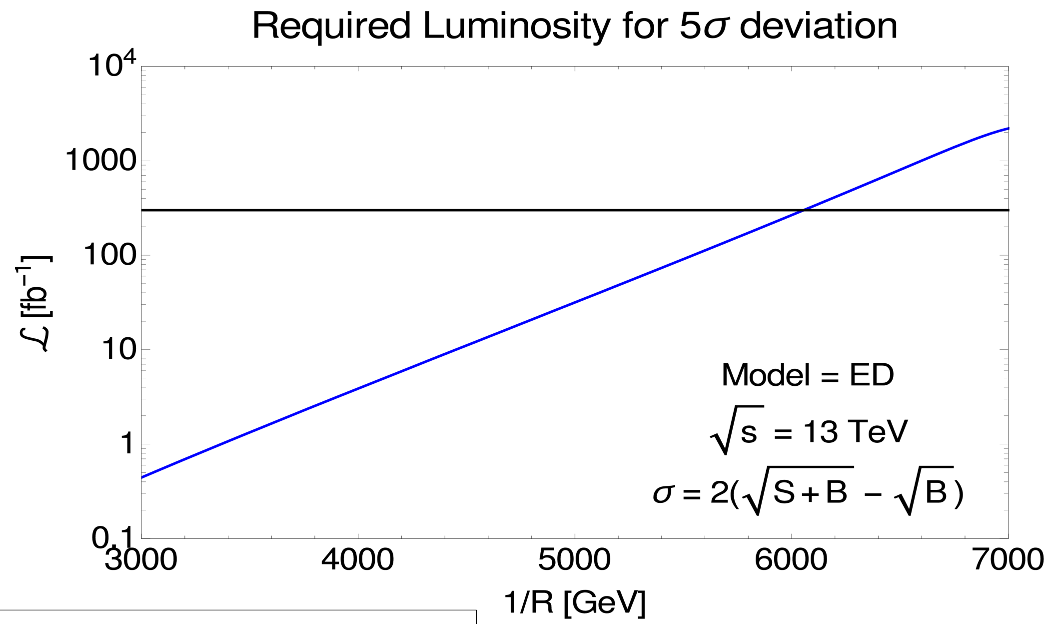
In the ED model NWA works well because the dip is very far from the peak



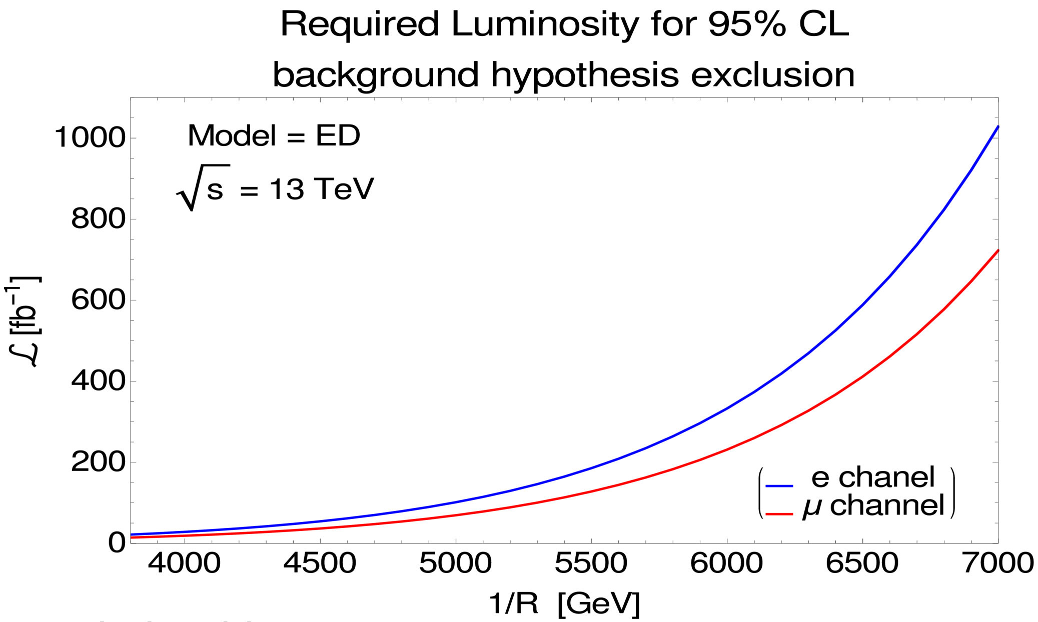
This conclusion is valid up to very high energy (R^{-1})

Phenomenology of NUED model





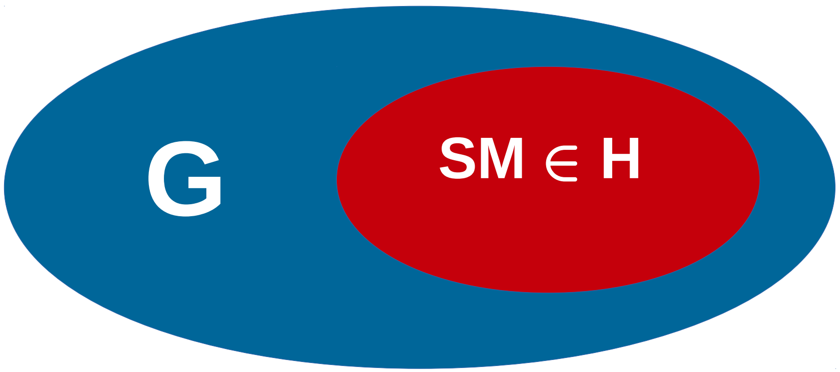
Exclusion / Discovery limits



In the High Luminosity regime the presence of a pronounced dip can be used to characterize the model

The 4DCHM

- **The Higgs boson is a bound state arising from a strong dynamics.**
  - The Higgs boson is a pseudo Nambu-Goldstone Boson.



- **Higgs from a spontaneous breaking of G → H**
  - The most studied in the literature is *SO(5) / SO(4)*

Agashe, Contino, Pomarol, Nucl. Phys. B719, 2005, 183

- **The *SO(5) / SO(4)* coset:**
  - 4 Goldstone bosons to be identified with the SM ones.
  - Contains the SO(4) custodial symmetry to protect the parameter ρ.
  - *SO(5)* → *SO(4)* at the TeV scale.
  - Minimum number of degrees of freedom that give a correct Higgs potential.

- **The gauge sector of the 4DCHM is described by two non linear σ-models.**
  - The introduction of the covariant derivative makes the two models interact:

$$SO(5)_L \otimes SO(5)_R \rightarrow SO(5)_{L+R} \rightarrow SO(4)$$

  - In addition there is an extra *U(1)* which crosses the *SO(5)*.

Son and Stephanov, Phys. Rev. D69, 2004, 065020

The 4DCHM

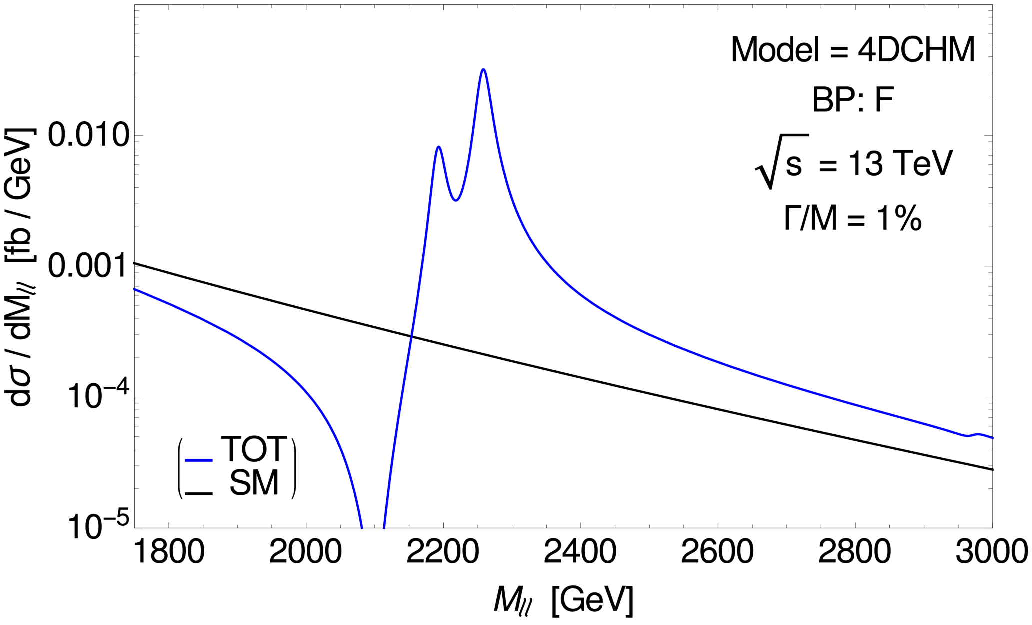
- **We can define an unitary gauge. The degrees of freedom are:**
  - 10+1+4 scalars provided by the two σ-models.
  - 10+1 give mass to the 5 neutral and 6 charged spin 1 physical states.
  - The 4 left are identified with the SM Higgs sector d.o.f..
- **We need to introduce a new fermionic sector to misalign the vacuum. The particle content of the model is:**
  - 5 Z'
  - 3 W'
  - 2 T and 2 B quarks (with exotic charges)

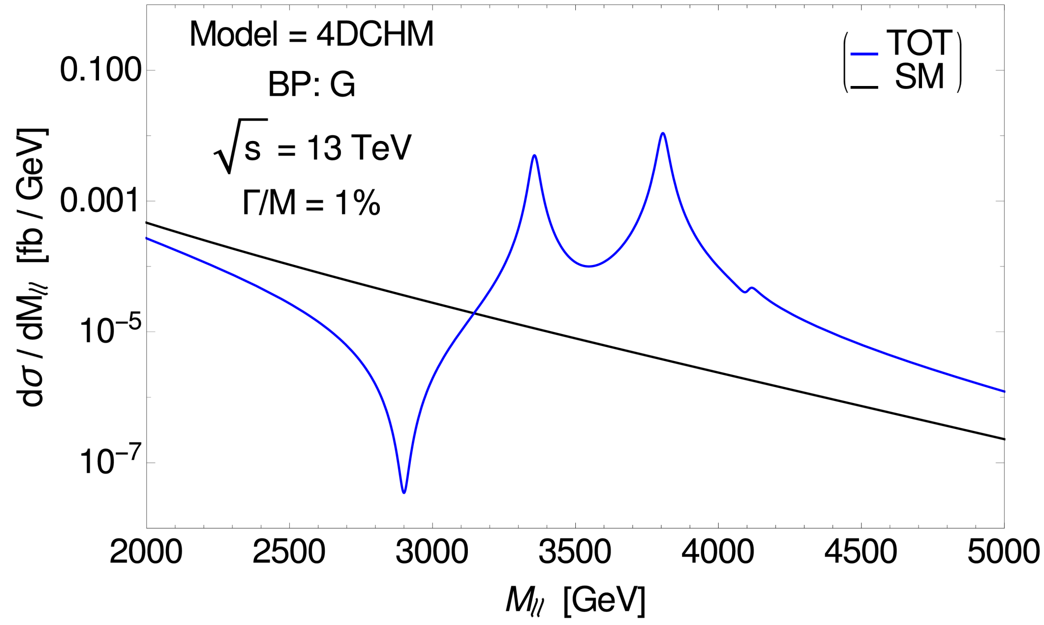
Agashe et al., Nucl. Phys. B719, 2005, 165

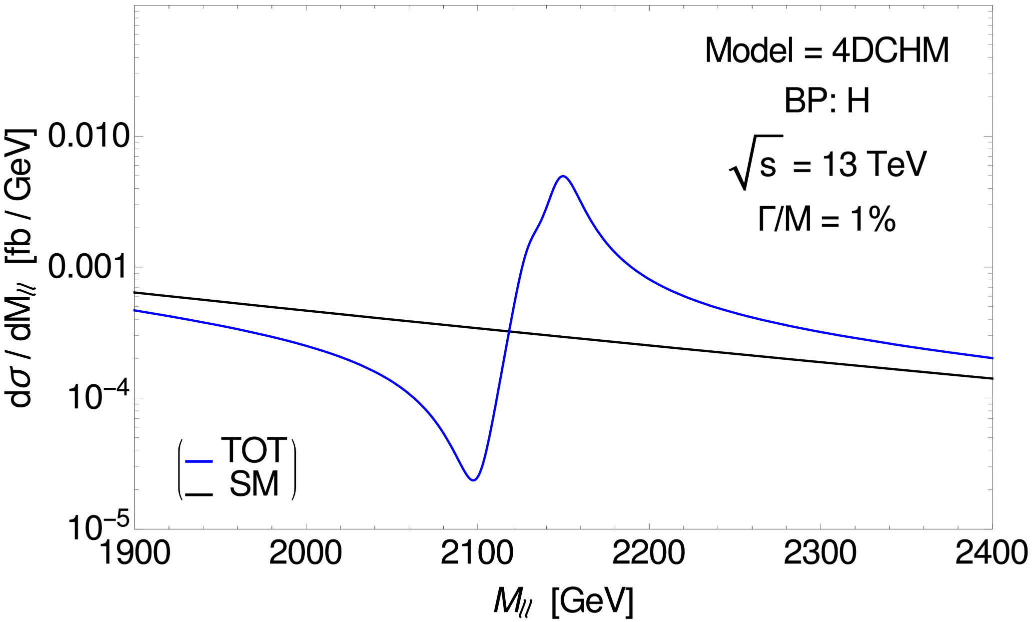
- **We will be interested in the phenomenology of the *Z'*s. Brief recall of their properties:**
  - Only three of the five *Z'*s interact with the SM fermions, thus they will be the only one producible at the LHC (Z_2, Z_3 and Z_5).
  - First approximation two of them have mass equal to $m_\rho = f\, g_\rho$, while the other has mass equal to $\sqrt{2} m_\rho$.
  - After the symmetries breaking, fine corrections to those masses arise proportional to $\xi = v^2 / f^2$ (degree of compositness).

Barducci, Belyaev, Brown, De Curtis, Moretti, Pruna, JHEP 1309 (2013) 047, arXiv:1302.2371 [hep-ph]

Phenomenology of 4DCHM

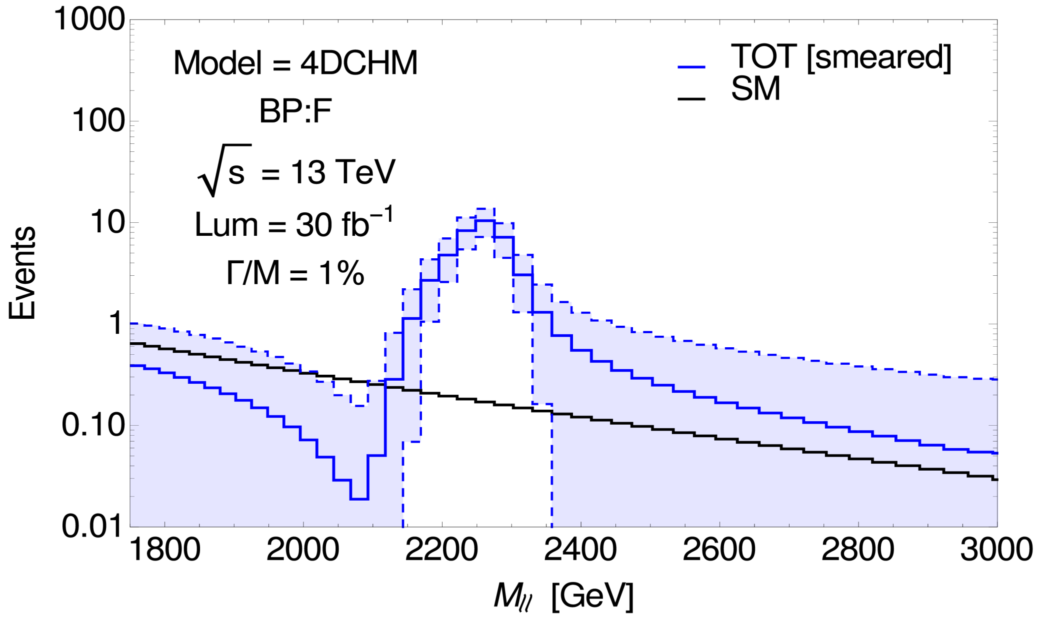


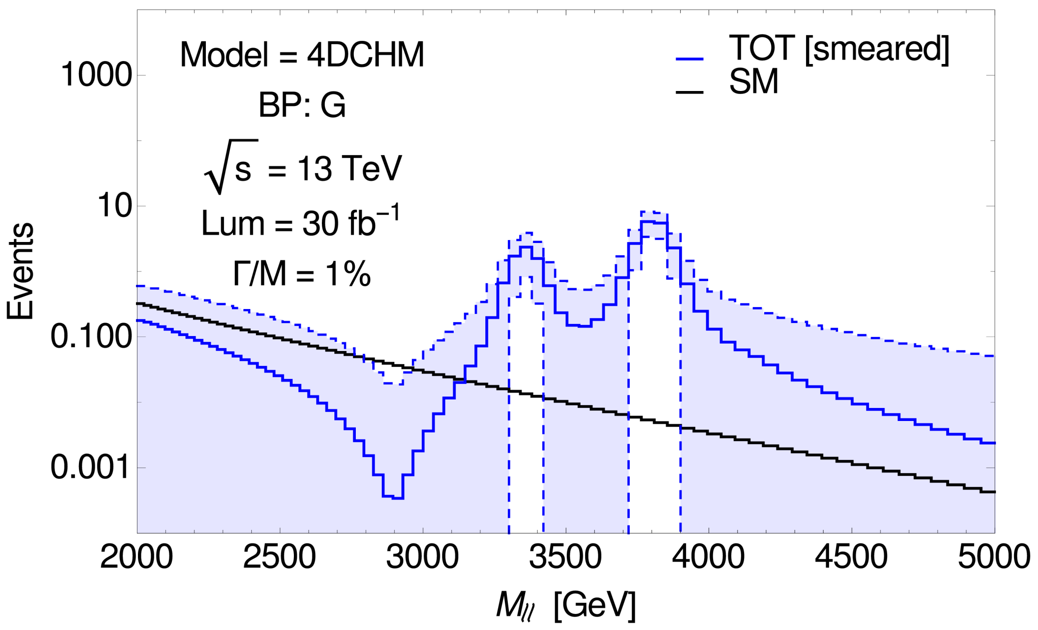


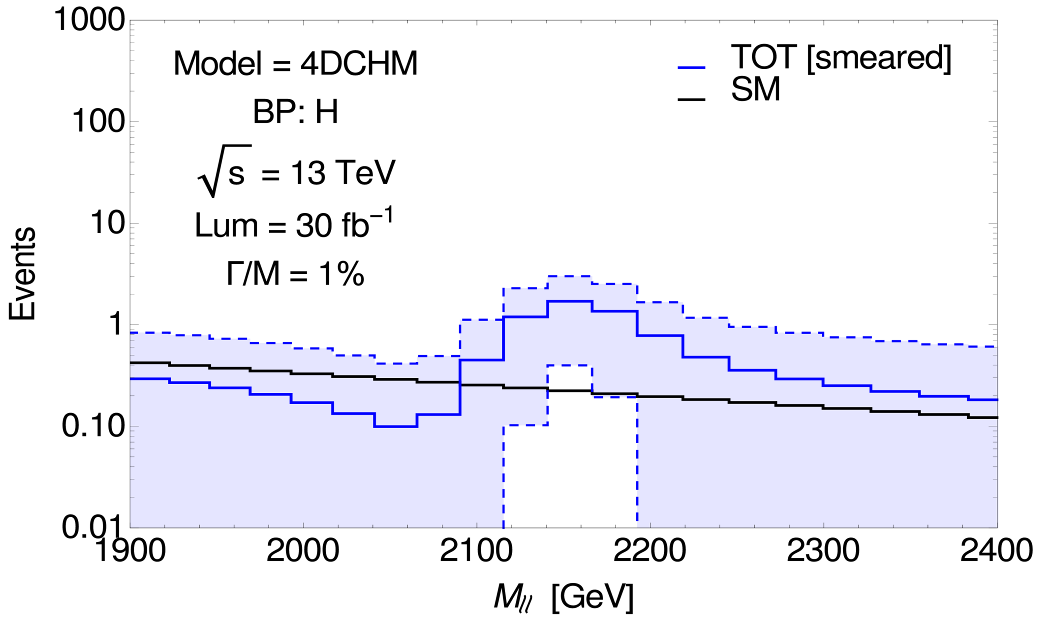


Typical invariant mass distribution profile of the 4DCHM in different points of the parameter space

Phenomenology of 4DCHM

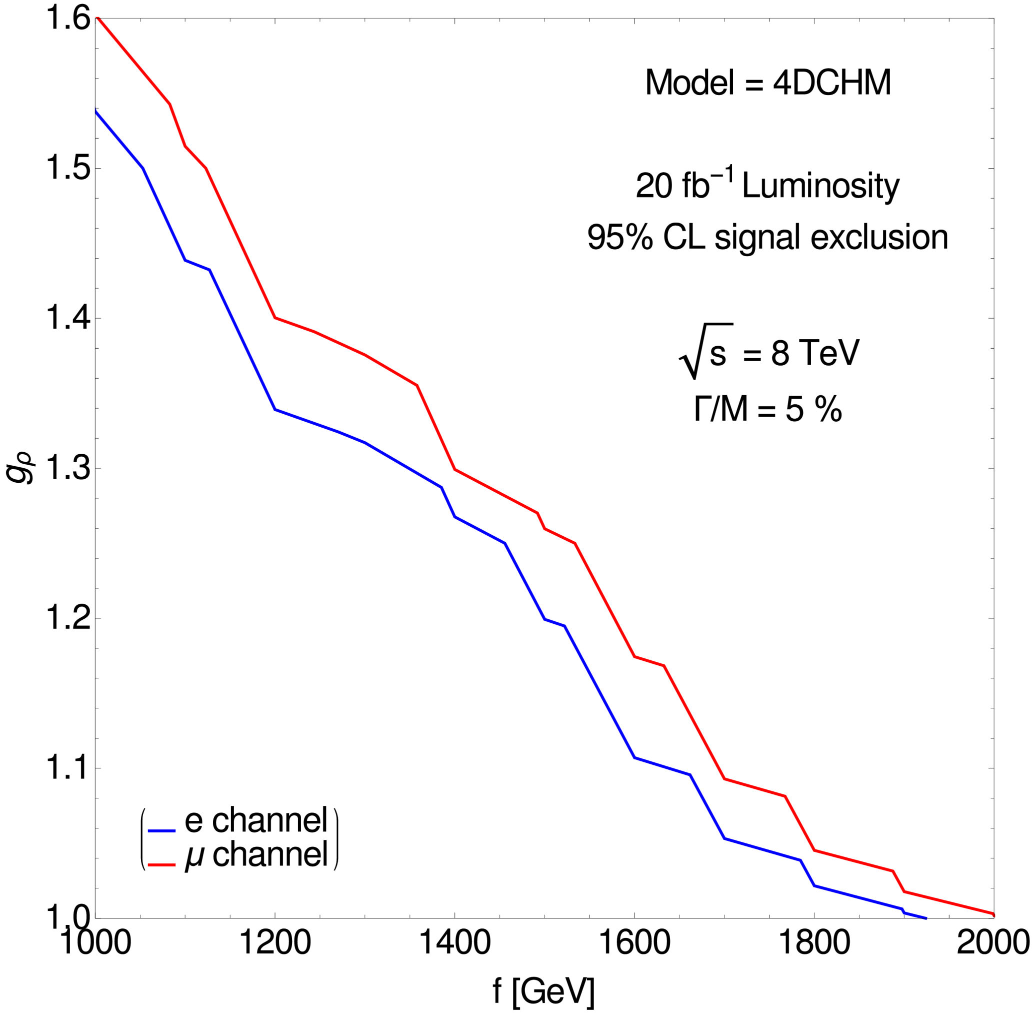




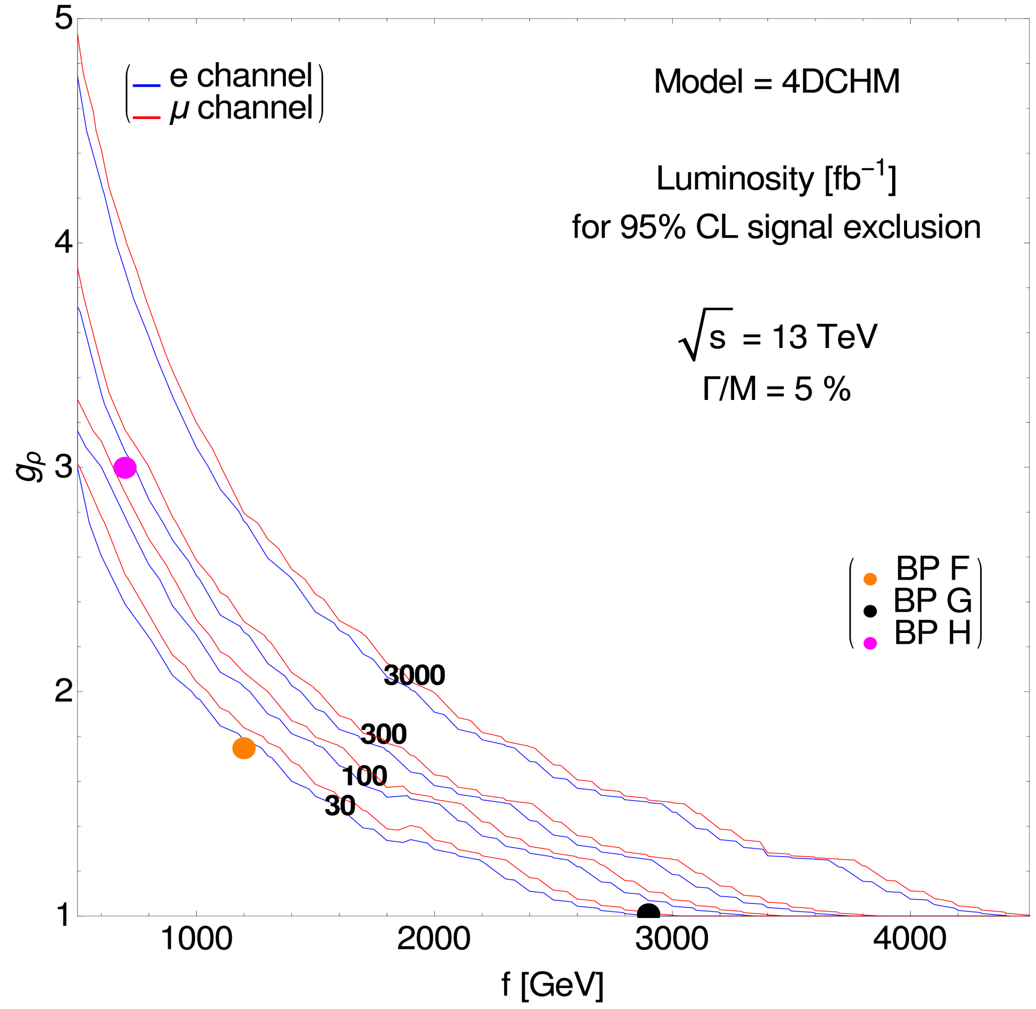


Considering the smearing due to the finite detector resolution (electron channel), we may lose the double peaked structure

Phenomenology of 4DCHM

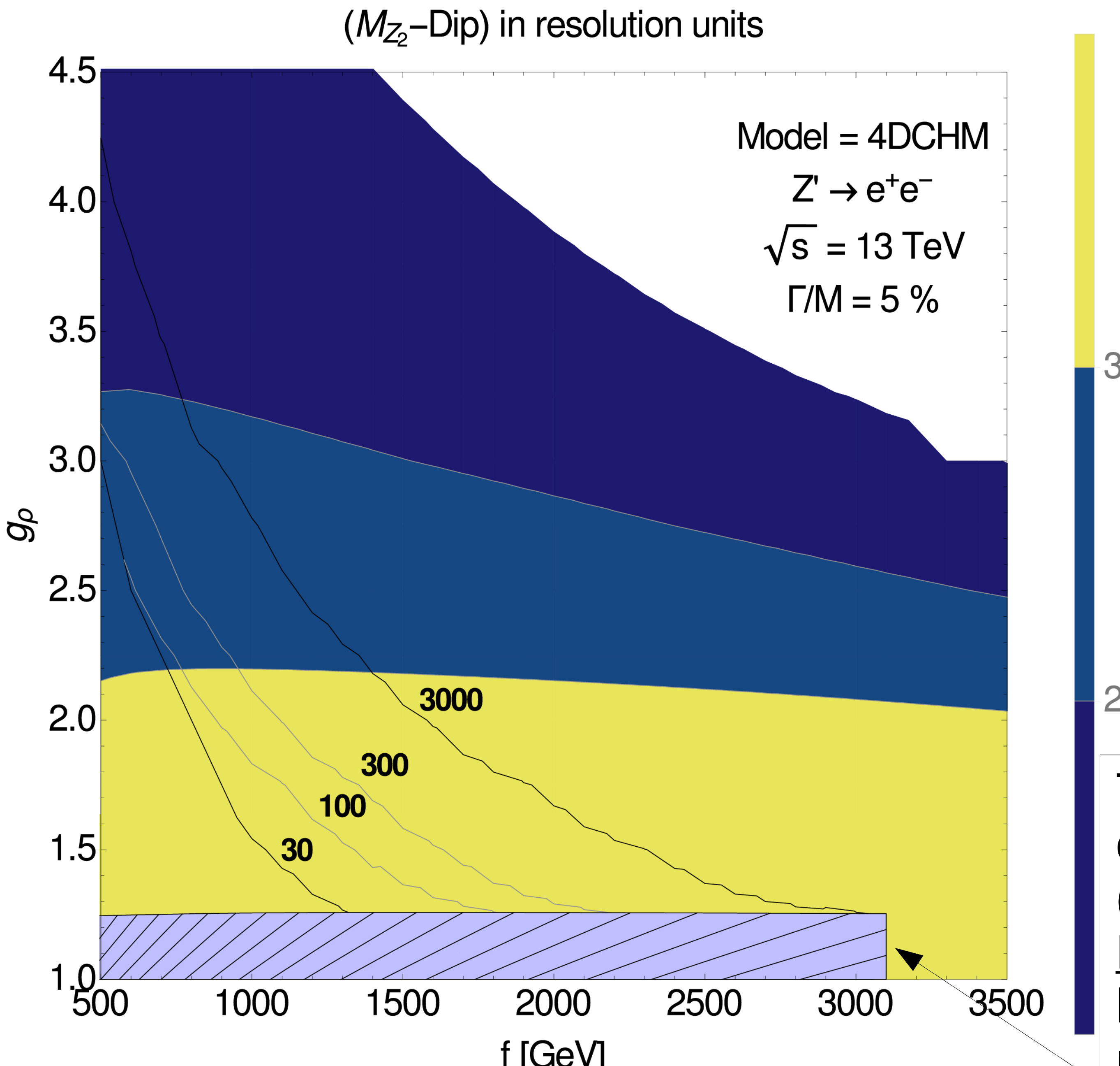


Exclusion Limits after Run-I



Exclusion Limits after Run-II

Phenomenology of 4DCHM



Parameter space region where we are able to <u>disentangle the peak from the dip</u> in the electron channel (<u>good resolution</u>)

The muon channel does contribute to the statistic (<u>good Acceptance x Efficiency</u>), but do not help the diagnostic (<u>bad resolution</u>)

Conclusions

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- **Our goal is to study the phenomenology of models with multiple vector neutral resonances.**

- **We have chosen to explore the ED and the 4DCHM models, as they provide a well motivated (from EWSB) framework for our purpose.**

- The **ED model** provides a benchmark to study the case of very degenerate neutral resonances, where also the interference effects are maximal, due to the choice of the chiral couplings to the resonances.
  - The degeneracy of the peaks lead to a wide single peak.
  - The peak is preceded by a pronounced dip, due to the interplay of interference effects.
    - In the invariant mass distribution, the dip is far enough from the peak that is possible to disentangle the two contributions.
    - NWA can be used to interpret experimentally excluded cross sections and therefore to set limits on the size of the compactified extra-dimension.

- We have exploited those features to compute the exclusion limits after Run-I and we have found a perfect agreement with the current bounds.

- Following this path we have been able to project exclusion and discovery limits for the LHC Run-II.

Conclusions

- **In the 4DCHM we have more freedom in the choice of the model parameters. This lead to a very rich and variegated phenomenology.**

- We have at first considered the case of a single *Z′* (single Z_3 boson), in order to check if the theoretical tools frequently used in the literature were appropriate in this framework:
  - We have found that Finite Width effects are sizeable even for relatively narrow resonances ($\Gamma/M > 5\%$).
  - Interference effects also are sizeable and they can also shift the position of the peak.
    - The interpretation of excluded cross sections and the procedure of setting bounds on the *Z′* mass in general cannot be performed though the simple NWA approach.

- In the **complete model** (i.e. in the **multiple *Z′* scenario**) the invariant mass distribution profile appear strongly dependent on the choice of the parameters of the model:
  - We can have a double peaked structure or a single degenerate peak.

- We have studied the effect of the detector smearing due to its finite resolution:
  - In the **electron channel** we have a good resolution (~ 1% M_{inv}), thus in large part of the parameter space of the model we still would be able to disentangle the two peaks.
    - In a post discovery stage, this channel will allow a diagnostic analysis of the signal (dip analysis).
  - In the **muon channel** we have a quite bad resolution (~ 9% M_{inv}) that forbids the detection of a multi peaked structure.
    - Still the good Acceptance x Efficiency factor makes this channel very important in the discovery stage to accumulate statistic.

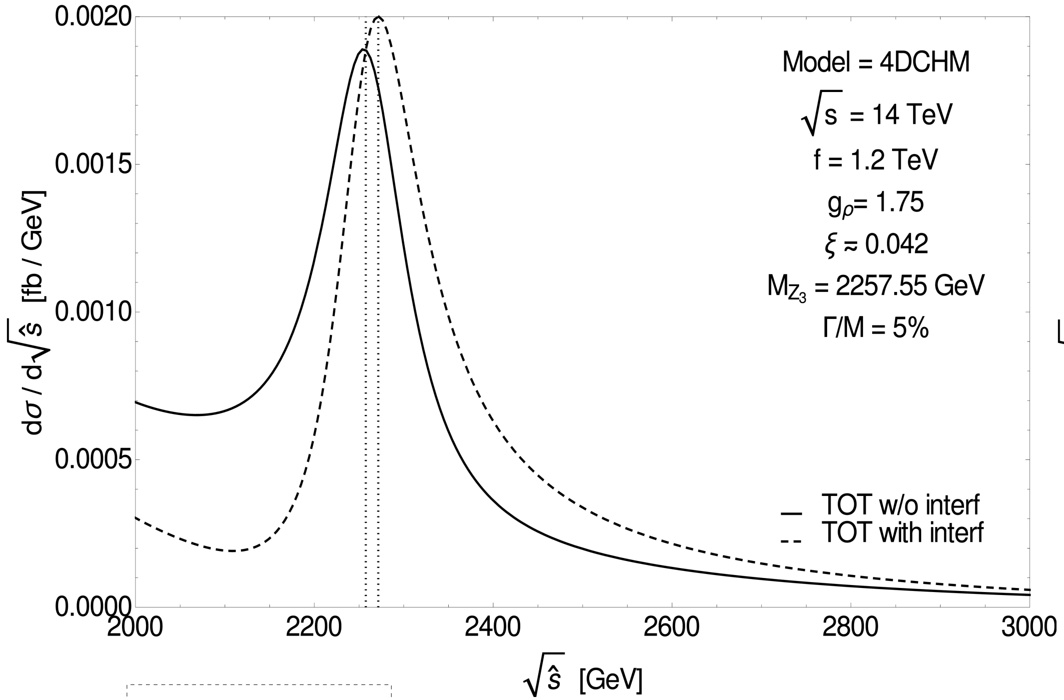
Conclusions

- The interpretation of a signal of this kind cannot be performed though a simple NWA approach, neither simply including FW effects.
- The bounds we set in the parameter space of the model has been evaluated though an optimized procedure.
  - The integration interval has been chosen to maximise the contribution of the BSM signal, in order to reproduce as closely as possible the experimental analysis.
- In our future work we will focus on finding some simple functional forms that would allow the fitting of the negative interference contribution, in order to maximize our sensitivity in a context where a pronounced dip appear.

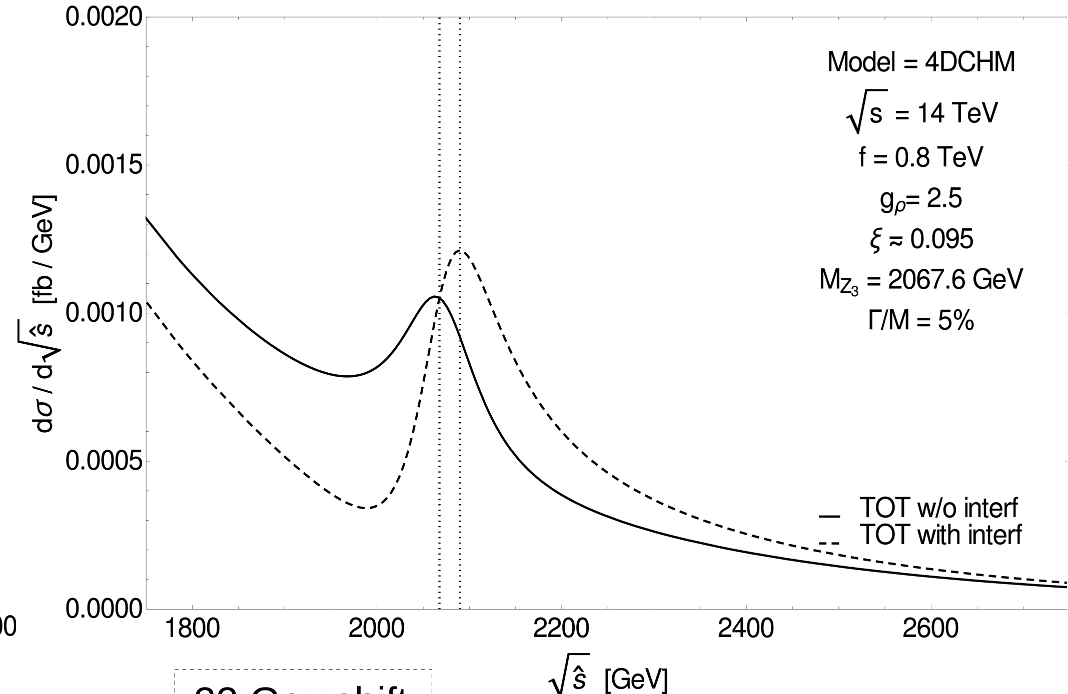
Thank you!

Single Z'

Peak in the invariant mass distribution for the Z_3-boson



14 Gev shift



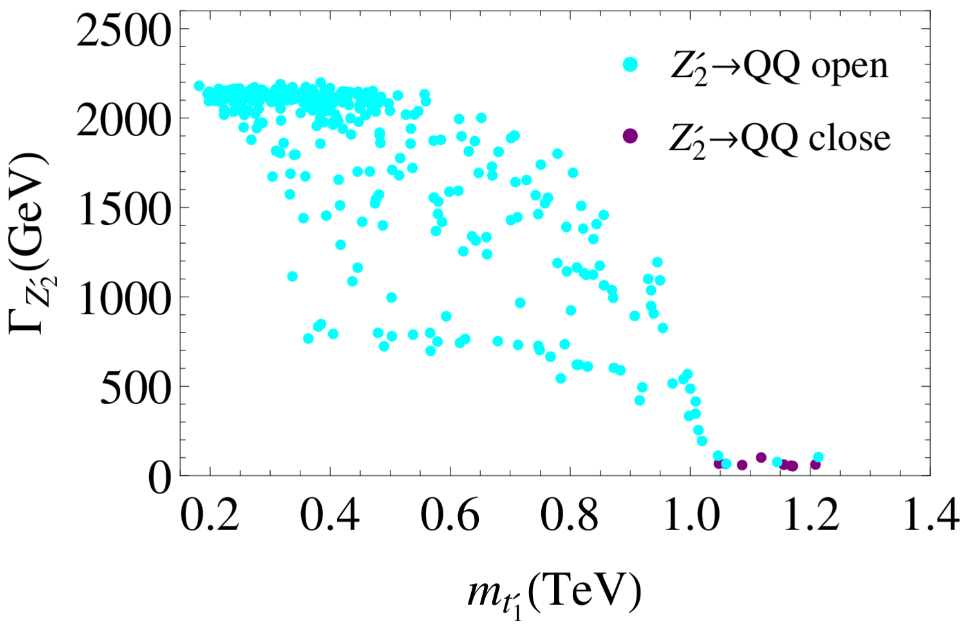
22 Gev shift

We are here considering only the Z_3 boson which has the largest couplings to the light fermions

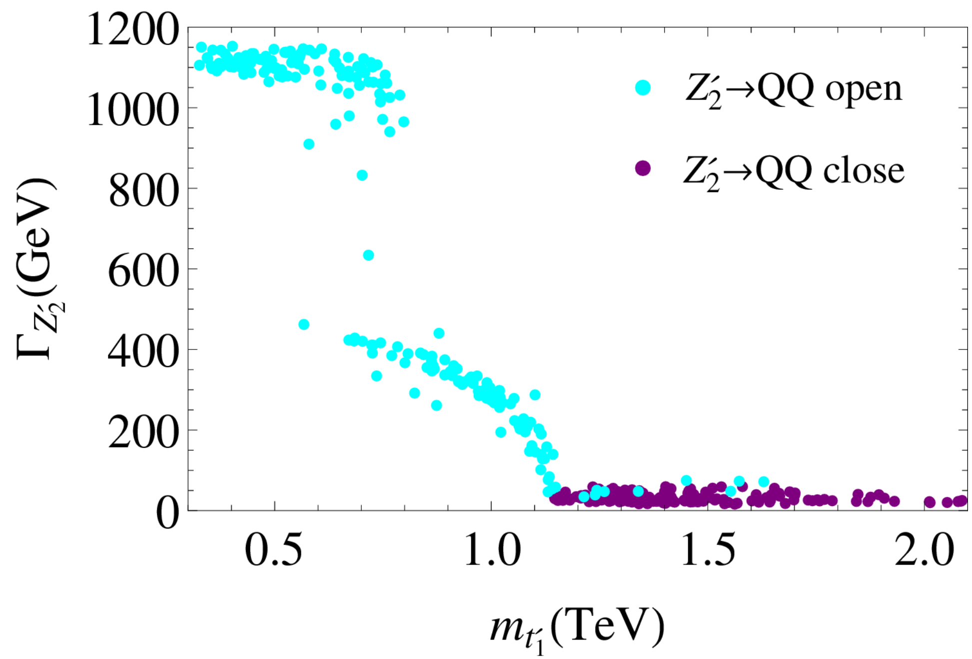
Interference effects <u>shift</u> the peak → The position of the peak is not at the <u>resonance pole</u>

Single Z'

Width of the Z_2 boson

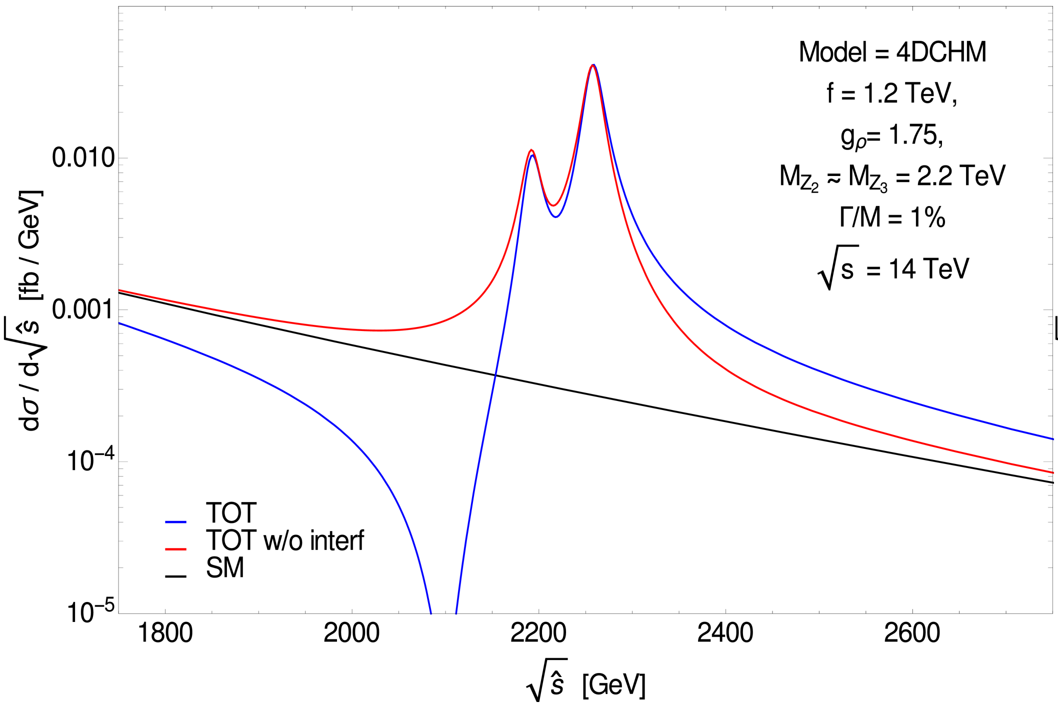


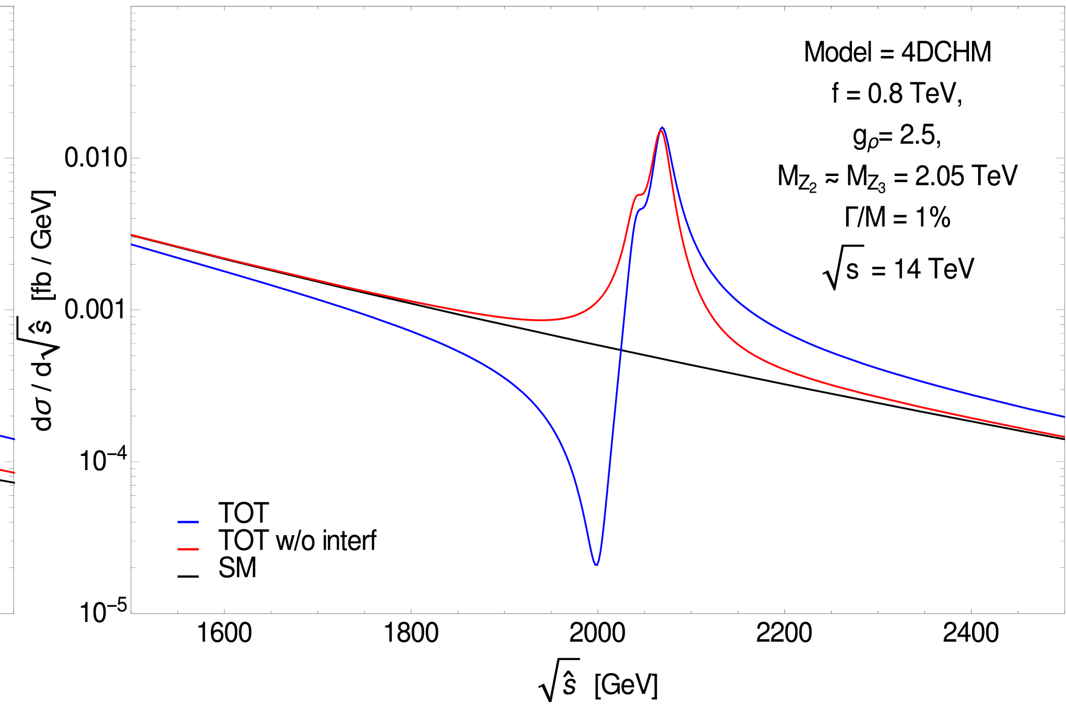
Opening the decay channel of the gauge boson into heavy fermions lead to <u>broad resonances</u>



Multiple Z'

Cross section distribution in the multiple Z' scenario





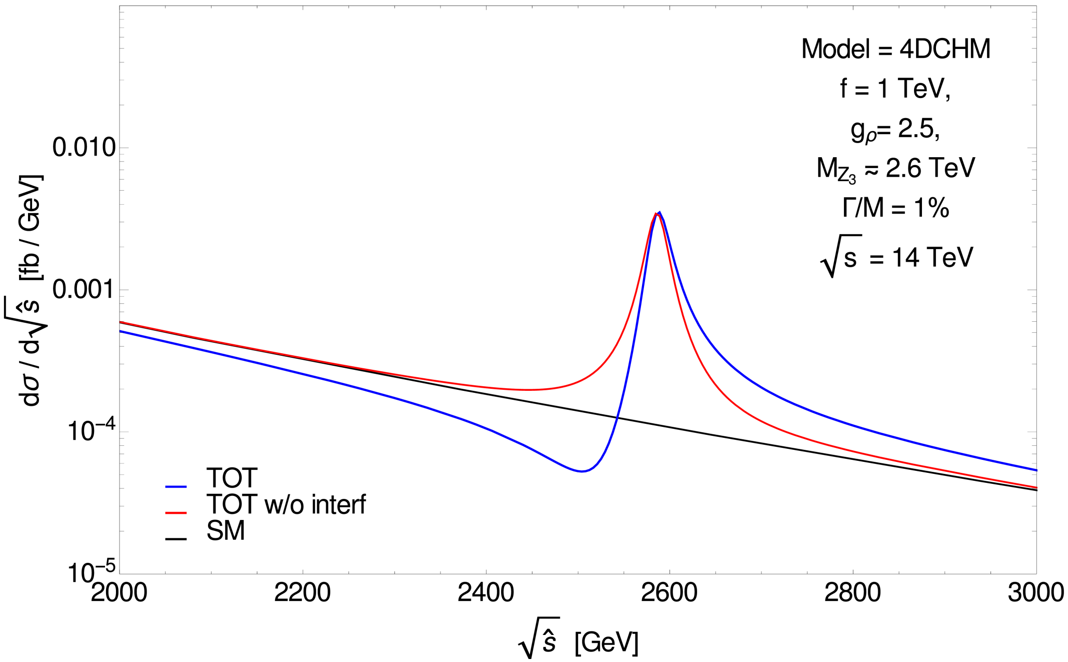
Here we have included the Z2-boson which is slightly lighter and less coupled to the fermions than the Z3

Sometimes is possible to disentangle two almost degenerate resonances

Sometimes this is not possible

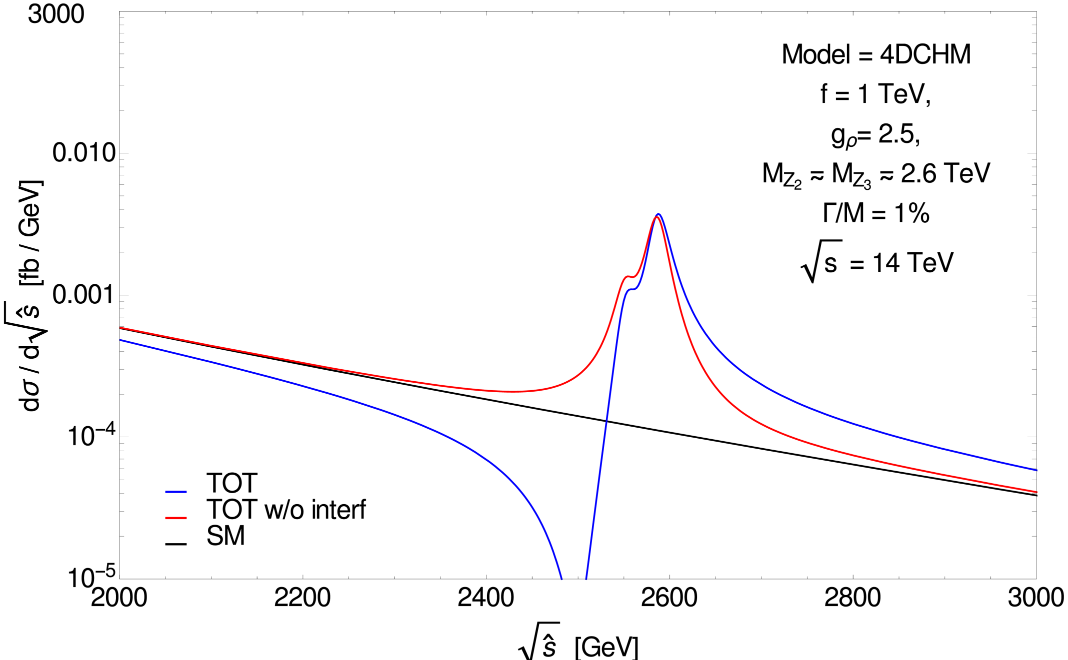
Multiple Z'

Cross section predictions



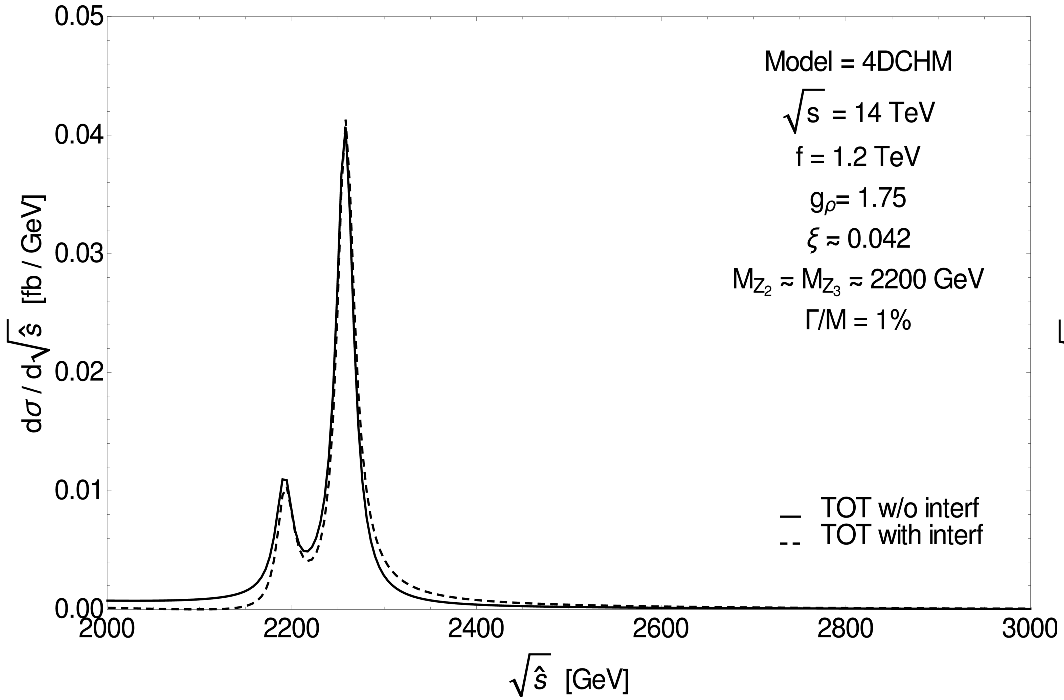
	σ [fb]
NWA	0.14
Single Z_3	0.09
Multiple Z'	0.11

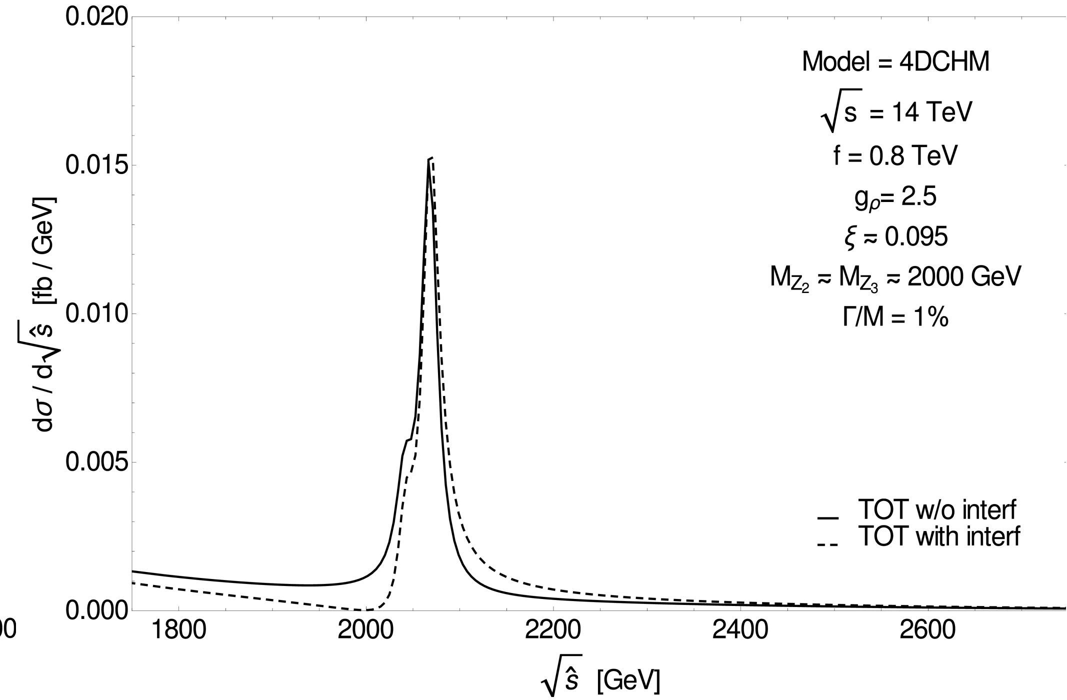
Multiple resonances <u>strongly affect</u> the cross section distribution



Multiple Z'

Cross section distribution in the multiple Z' scenario





Sometimes is possible to disentangle two close resonances

Sometimes it is not