Interference Effect on Resonance Studies & the Diboson Excess

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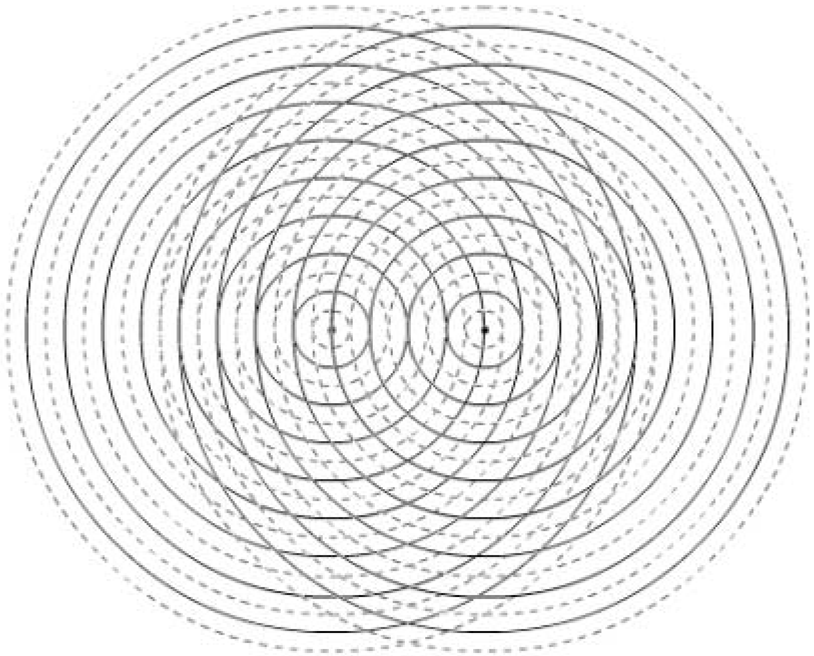
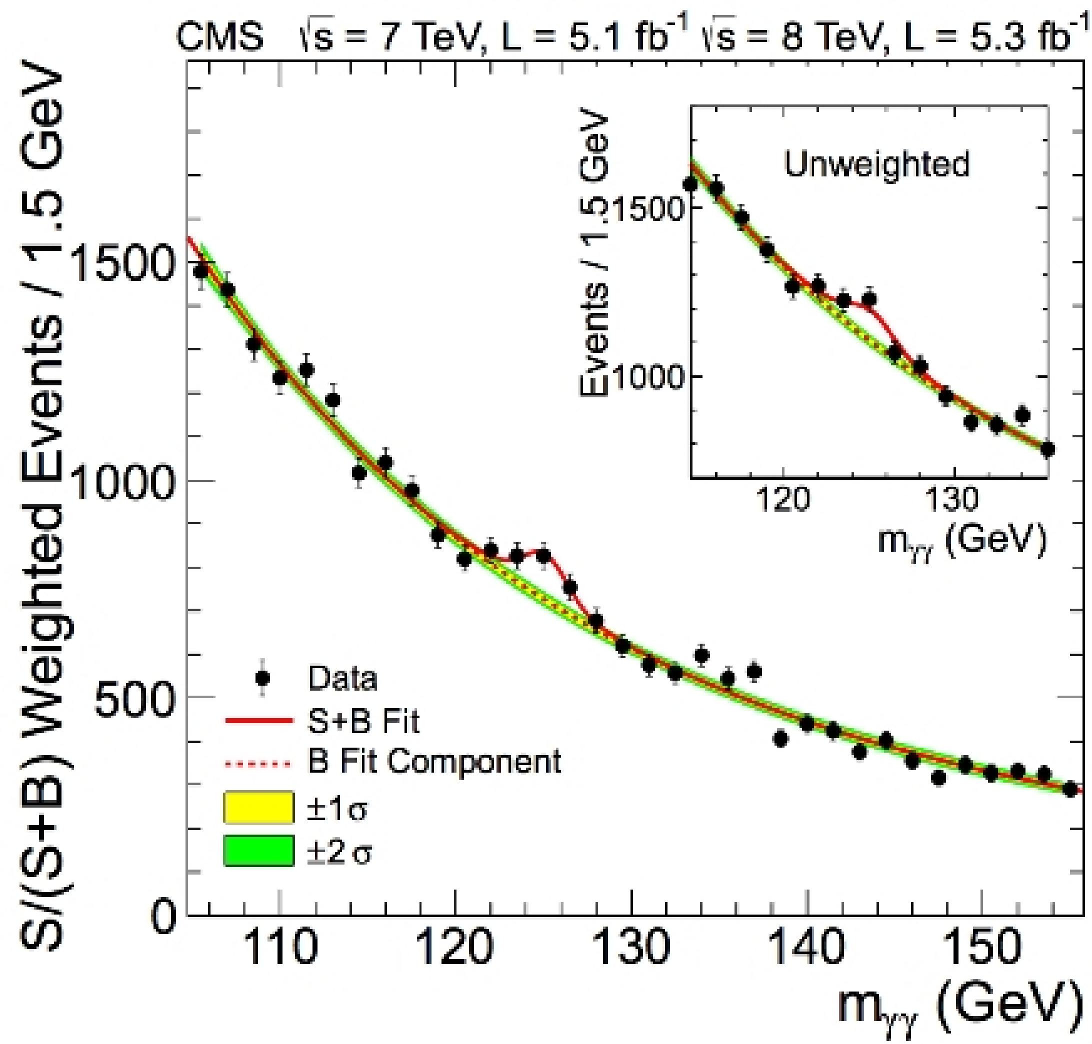
Outline

- Resonance signal and interfering with bkg
- Formalism
- Interference for 2 TeV diboson excess?
- Resonance & interference @ (HL-)LHC14
- Conclusion



Starting point: the 125GeV Higgs



Two lessons

1) The SM Higgs observed in a quantum-interfering manner.

2) Is SM (+ 3 massive neutrinos) complete below the TeV scale? What can we find beyond SM?

Three categories of interference

- “Self”-interfering
  Interference between different helicity states

- “Signal-background” interfering

- “signal-signal” interfering

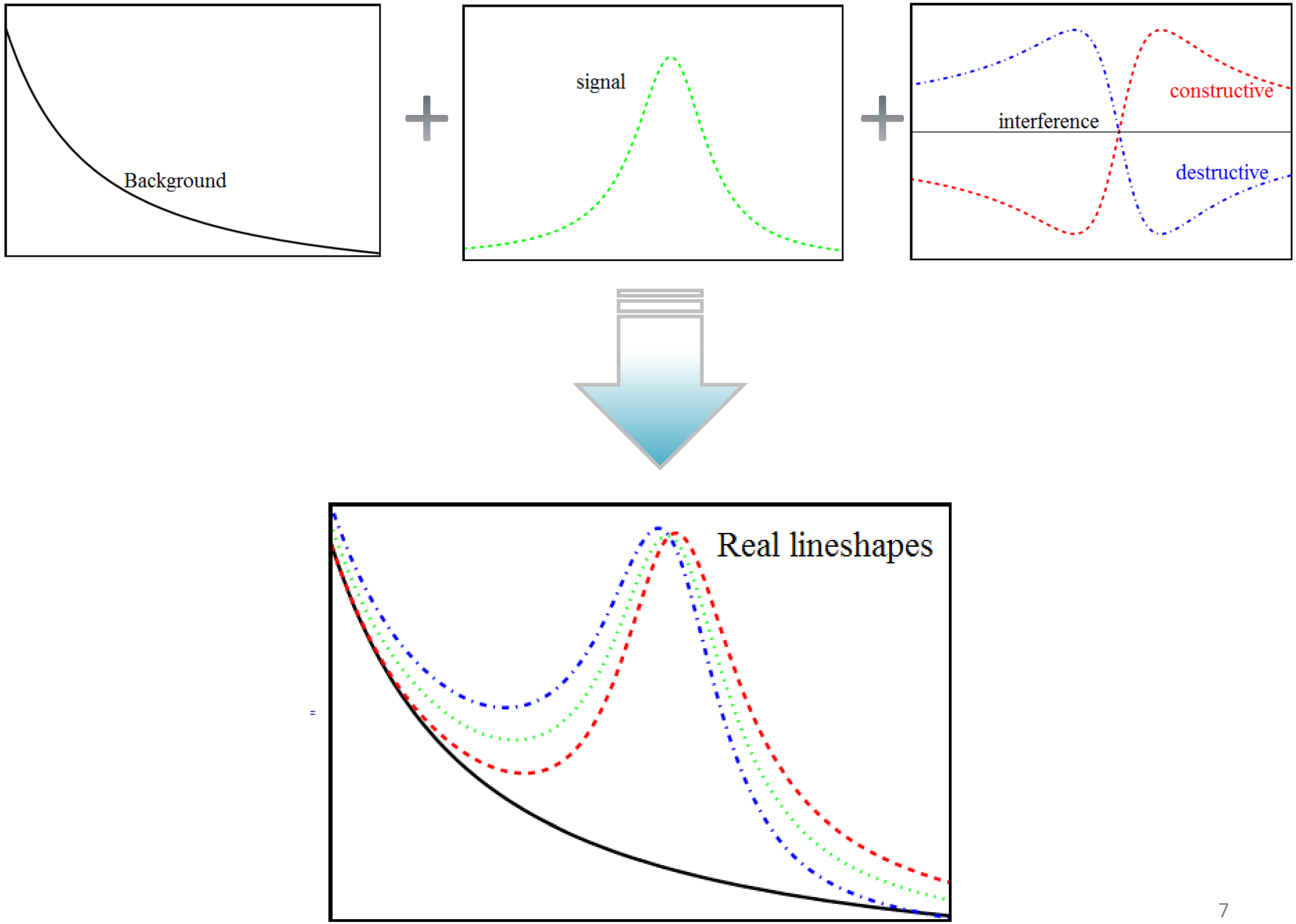
Signal-background interfering

$$
\begin{aligned}
\sigma_{\text{total}} &\sim |\text{bkg} \pm \text{signal}|^2 \\
&\sim |\text{bkg}|^2 + |\text{signal}|^2 \pm (\text{bkg signal}^* + \text{bkg}^* \text{ signal}) \\
&\sim \sigma_{\text{bkg}} + \sigma_{\text{resonance}} \pm \sigma_{\text{interfering}}
\end{aligned}
$$

one positive/negative sign has been split from the signal amplitude:

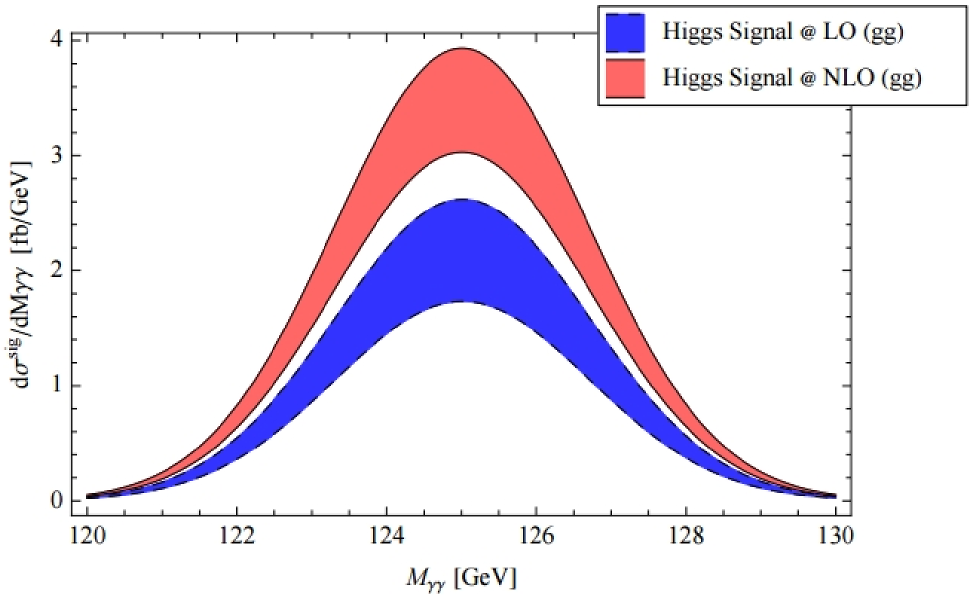
+: constructive interference

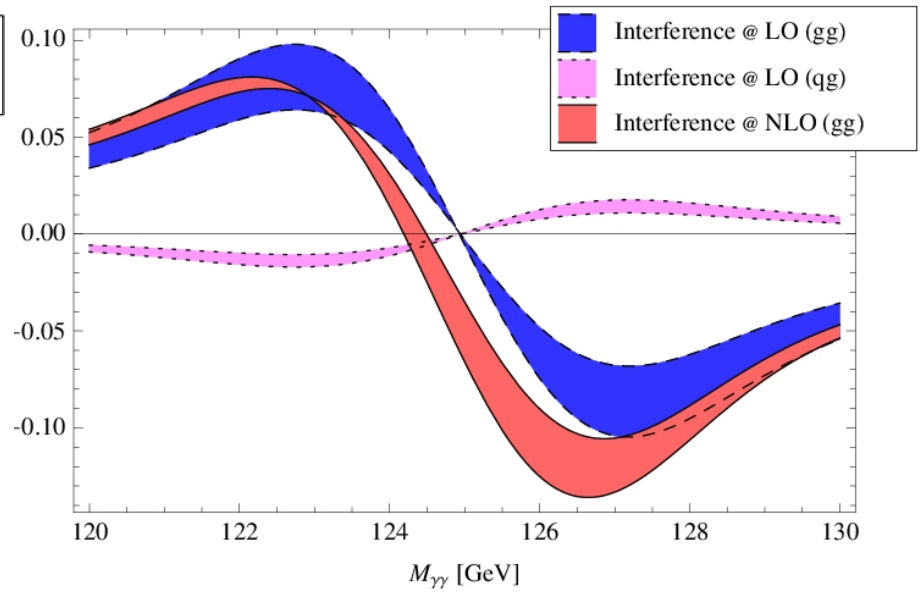
- : destructive interference


Background
signal
interference
constructive
destructive
Real lineshapes

Example: pp -> Higgs -> γγ

Dixon & Li ’13 PRL





Interfering btw different helicity states

- When more than one helicity states are produced and decay, with h = helicity, ϕ = azimuthal angle,

Buckley, Murayama, Klemm & Rentala ‘08
Buckley, Heinemann, Klemm & Murayama ‘08
Keung, Low & Shu '08
Cao, Jackson, Keung, Low & Shu '10
Murayama, Rentala & Shu '14

$$\sigma_{\text{total}} \quad \sim \quad \left| \sum_h \mathcal{M}_{\text{prod}}(h) e^{ih\phi} \mathcal{M}_{\text{decay}}(h, \phi = 0) \right|^2$$

- Explicit example: the Spin Density Matrix (SDM) for e^+e^- -> W^+W^- : non-diagonal elements for the interfering effects.

Bilenky, Kneur, Renard & Schildknecht ‘93

$$\rho_{\tau_- \tau'_- \tau_+ \tau'_+}(\cos\theta) \equiv \frac{\sum_\lambda F^{(\lambda)}_{\tau_- \tau_+} F^{(\lambda)*}_{\tau'_- \tau'_+}}{\sum_{\lambda \tau_- \tau_+} \left| F^{(\lambda)}_{\tau_- \tau_+} \right|^2}$$

$$\rho^{W^-}_{\tau_- \tau'_-}(\cos\theta) = \sum_{\tau_+} \rho_{\tau_- \tau'_- \tau_+ \tau_+}$$

$$\rho^{W^+}_{\tau_+ \tau'_+}(\cos\theta) = \sum_{\tau_-} \rho_{\tau_- \tau_- \tau_+ \tau'_+}$$

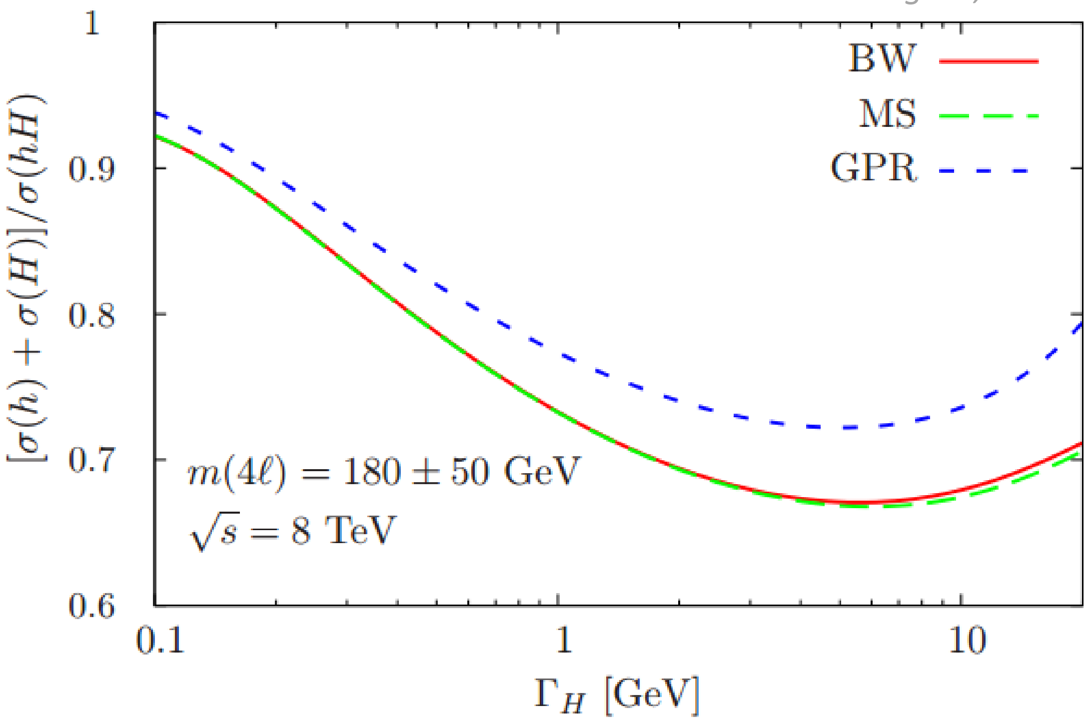
“signal-signal” interfering

- In presence of two resonance states,

$$\begin{aligned}\sigma_{\rm total} &\sim |{\rm bkg} + {\rm signal} + {\rm signal}|^2 \\ &\rightarrow ({\rm signal}\,{\rm signal}^* + {\rm signal}^*\,{\rm signal})\end{aligned}$$

- For example, if there exists heavy scalar beyond the SM one…

Englert, Low & Spannowsky '15



Continuum bkg & resonance signal

- For the resonance X at hadron colliders:
  A & B being particles that could be (partially) reconstructed at colliders

$$pp \to X \to AB$$

- The continuum background:
  assuming no "bkg resonance" in vicinity of the resonance X

$$\mathcal{M}^{\rm bkg}_{X(AB)} = \mathcal{M}_{\rm bkg}(M_{AB})$$

- The resonance signal:

$$\mathcal{M}^{\rm signal}_{X(AB)} = -\frac{\mathcal{M}^{\rm prod}_{X}\mathcal{M}_{X\to AB}}{M^2_{AB} - M^2_X + iM_X\Gamma_X}$$

prescriptions of the resonance propagator

- The Breit-Wigner propagator can not be motivated from first-principle QFT, needs to be modified especially for broad resonances. *Englert, Low & Spannowsky '15*
- Other options:
  1) Running width propagator;
  reflecting all relevant contributions in the high energy limit
  2) complex pole propagator;
  allowing a theoretically robust matching of pseudo-observables between theory and experiment

  Seymour '95
  Goria, Passarino & Rosco '12
  Passarino '14
- When the width is not so large (for the 2 TeV excess), the discrepancies in these different schemes are expected to be small.

Differential cross sections

- The signal resonance

$$\frac{\mathrm{d}\sigma^{\mathrm{signal}}}{\mathrm{d}M_{AB}} \sim \frac{1}{(M_{AB}^2 - M_X^2)^2 + M_X^2\Gamma_X^2}$$

- The interfering lineshape

$$\frac{\mathrm{d}\sigma^{\mathrm{itf}}}{\mathrm{d}M_{AB}} \sim \frac{(M_{AB}^2 - M_X^2)\Re + M_X\Gamma_X\Im}{(M_{AB}^2 - M_X^2)^2 + M_X^2\Gamma_X^2}$$

with the real and imaginary parts

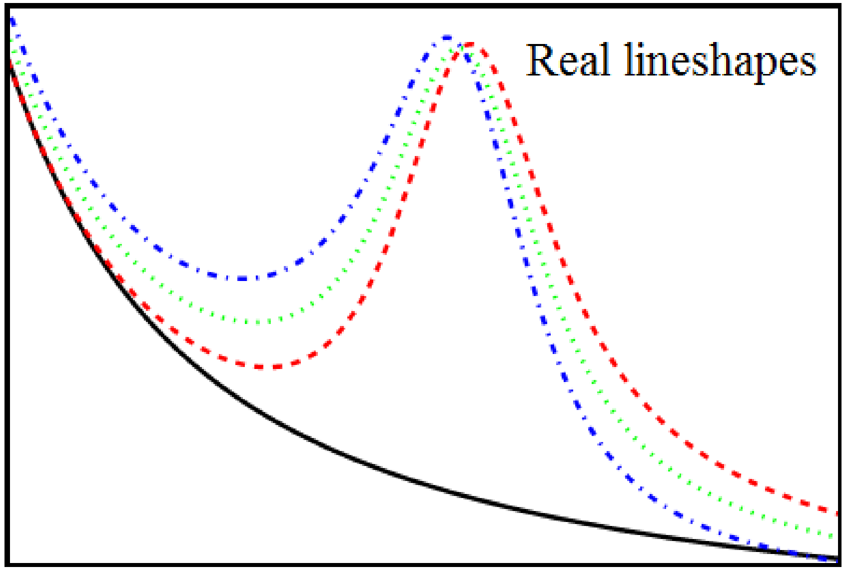
$$\begin{aligned} \Re &\equiv \mathrm{Re}(\mathcal{M}_X^{\mathrm{prod}}\mathcal{M}_{X\to AB}\mathcal{M}_{\mathrm{bkg}}^*)\,, \\ \Im &\equiv \mathrm{Im}(\mathcal{M}_X^{\mathrm{prod}}\mathcal{M}_{X\to AB}\mathcal{M}_{\mathrm{bkg}}^*) \end{aligned}$$

with the imaginary part only “active” in the on-shell region

Constructive vs. destructive interference

- Depending on the signs of resonance couplings (g_{XAB} and/or g_{Xjj}), the interfering terms can be either positive or negative.
- The interference could distort the resonance lineshape:

destructive:
larger cross section on LEFT handed side of resonance, peak shift to the LEFT



constructive:
larger cross section on RIGHT handed side of resonance, peak shift to the RIGHT

Asymmetry parameter

- The asymmetry parameter is defined to measure the interference effect *Lillie, Shu & Tait '07*

$$A_i = \frac{\int \mathrm{d}M_{AB} \left(\frac{\mathrm{d}\sigma}{\mathrm{d}M_{AB}} - \left(\frac{\mathrm{d}\sigma}{\mathrm{d}M_{AB}} \right)_{\mathrm{bkg}} \right) * \Theta(M_{AB} - M_X)}{\int \mathrm{d}M_{AB} \left| \frac{\mathrm{d}\sigma}{\mathrm{d}M_{AB}} - \left(\frac{\mathrm{d}\sigma}{\mathrm{d}M_{AB}} \right)_{\mathrm{bkg}} \right|},$$

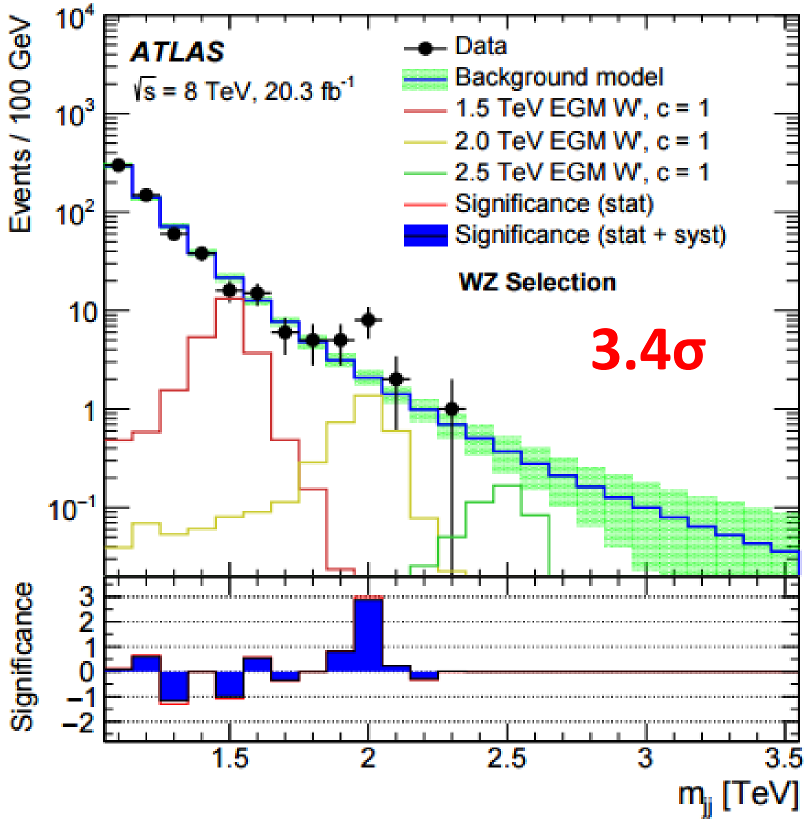
$$\text{with } \Theta(x) = \begin{cases} -1, & x < 0 \\ 1, & x > 0 \end{cases}$$

- The bkg is subtracted to concentrate on the interfering effect
- The sign of Ai:

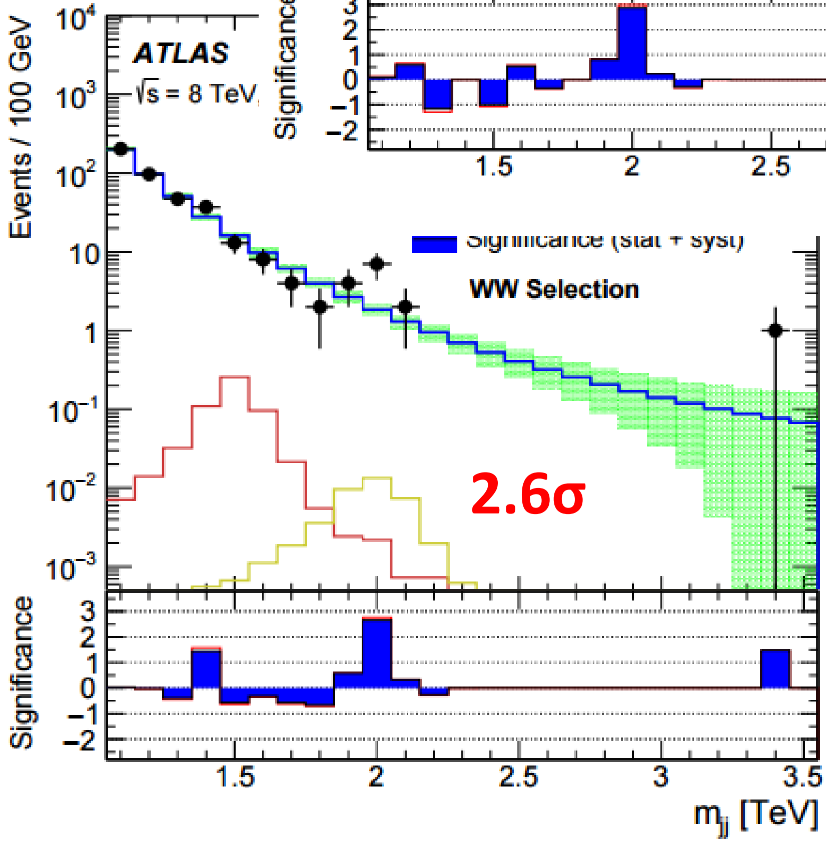
$$A_i \begin{cases} > 0, & \text{constructive interference} \\ = 0, & \text{background} \\ < 0, & \text{destructive interference} \end{cases}$$

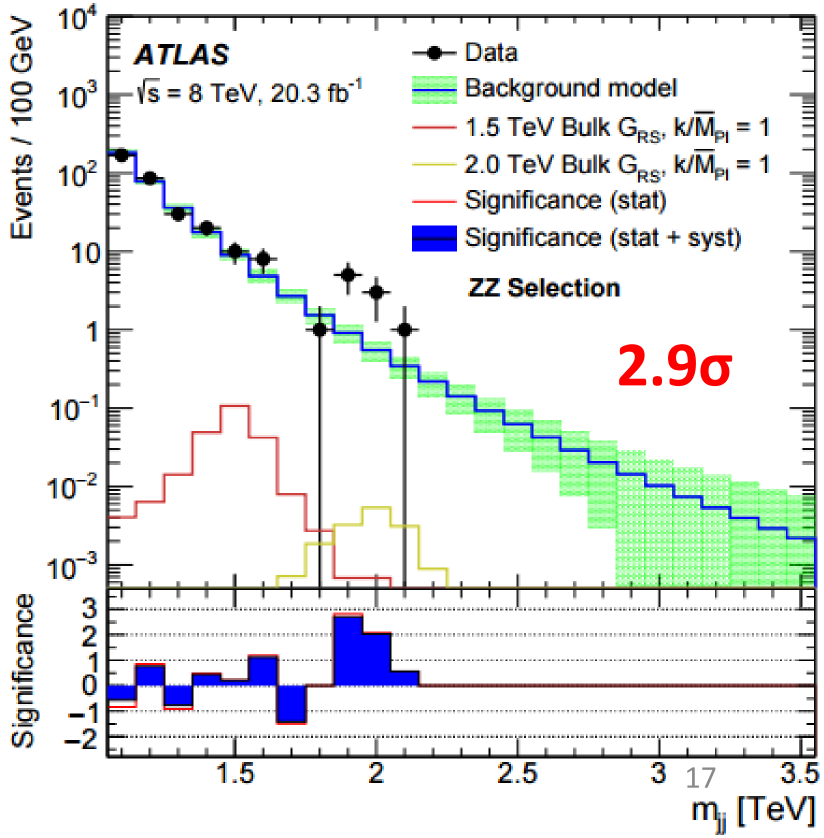
Some comments

- Under this convention, Ai has the same sign as that btw the bkg and signal amplitudes
- We can also use an alternative convention by multiplying an overall minus sign to the definition of Ai, in which Ai>0 for the destructive interference case
- The sign of Ai is independent of the binning for the data around the resonance
- The Ai parameter can be applied to both the theoretical models (with different resonance coupling signs) and experimental data, which is useful to compare theories with experiments to test or constrain the interpreting models.



- Real resonances beyond SM?
- How to interpret these events?
- Constraints from other high mass channels, EWPO, …
- Subtleties of these excesses?
- Tests at LHC Run II?



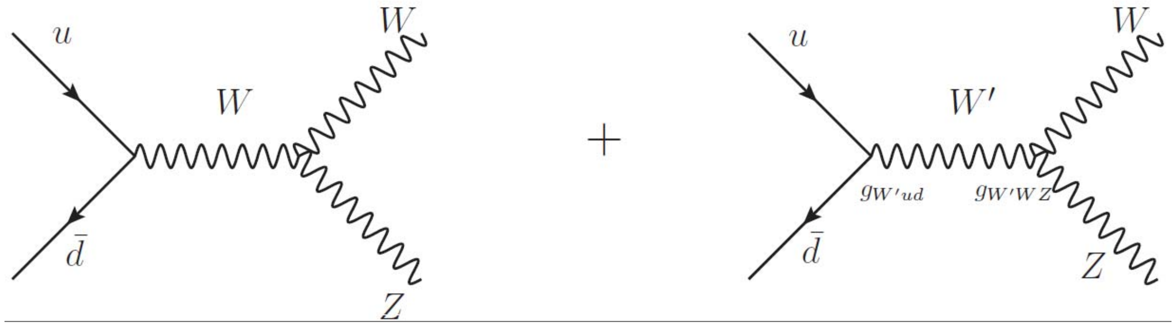


Toy W’ model

- couplings to the SM quarks and the WZ bosons

$$\mathcal{L} \sim g_{W'ud} W'_\mu \bar{u}_L \gamma^\mu d_L$$
$$\mathcal{L}(W'WZ) \sim g_{W'WZ} \mathcal{L}^{\mathrm{SM}}(WWZ \to W'WZ)$$

- For the diboson events, , the toy W’ model can in some sense mimic the extra charged gauge boson in LR models or even the ρ boson in composite Higgs models
- Signal-background interfering



ρ boson in composite Higgs models

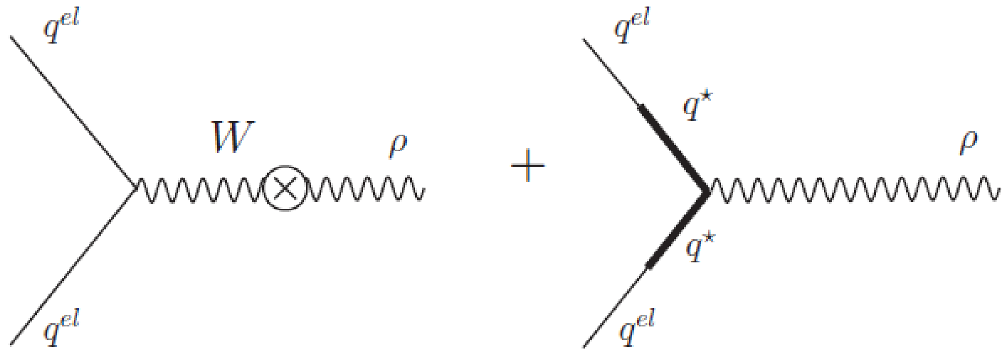


FIG. 1: Two sources of the couplings between ρ and the valence quarks in the partial compositeness scenario. Left: from the mixing of ρ with W, B gauge bosons $(-g^2/g_\rho)$. Right: from the mixing of the quarks with their composite partners (positive and their size depends on the valence quark compositeness). By choosing different valence quark compositeness, one can tune the sign of the total couplings, hence generating the constructive or destructive interference effects.

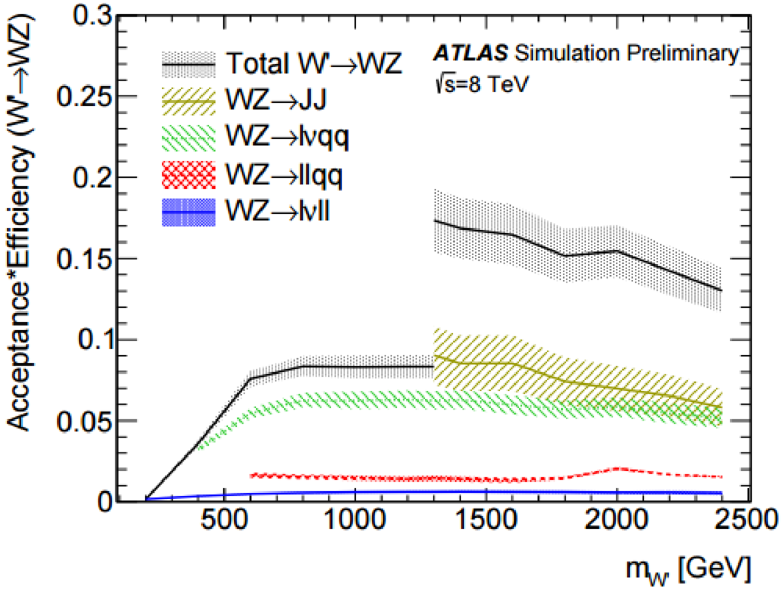
Fitting the ATLAS WZ data

- Simple cuts on the WZ signal events, with acceptance times efficiency factor ≈ 0.07 *ATLAS-CONF-2015-045*

$$p_T > 540\,\mathrm{GeV}\,,\, |\eta| < 2$$

- The dominate JJ bkg model taken from the ATLAS data
- Smearing effect following the ATLAS paper:

  multiplying a Gaussian-distributed factor to the momentum of W and Z jets, setting the width parameter σ to have a Gaussian distribution with a mean of zero and finite width equal to $0.05\mathrm{x}(1.2^2\text{-}1^2)^{1/2}$.



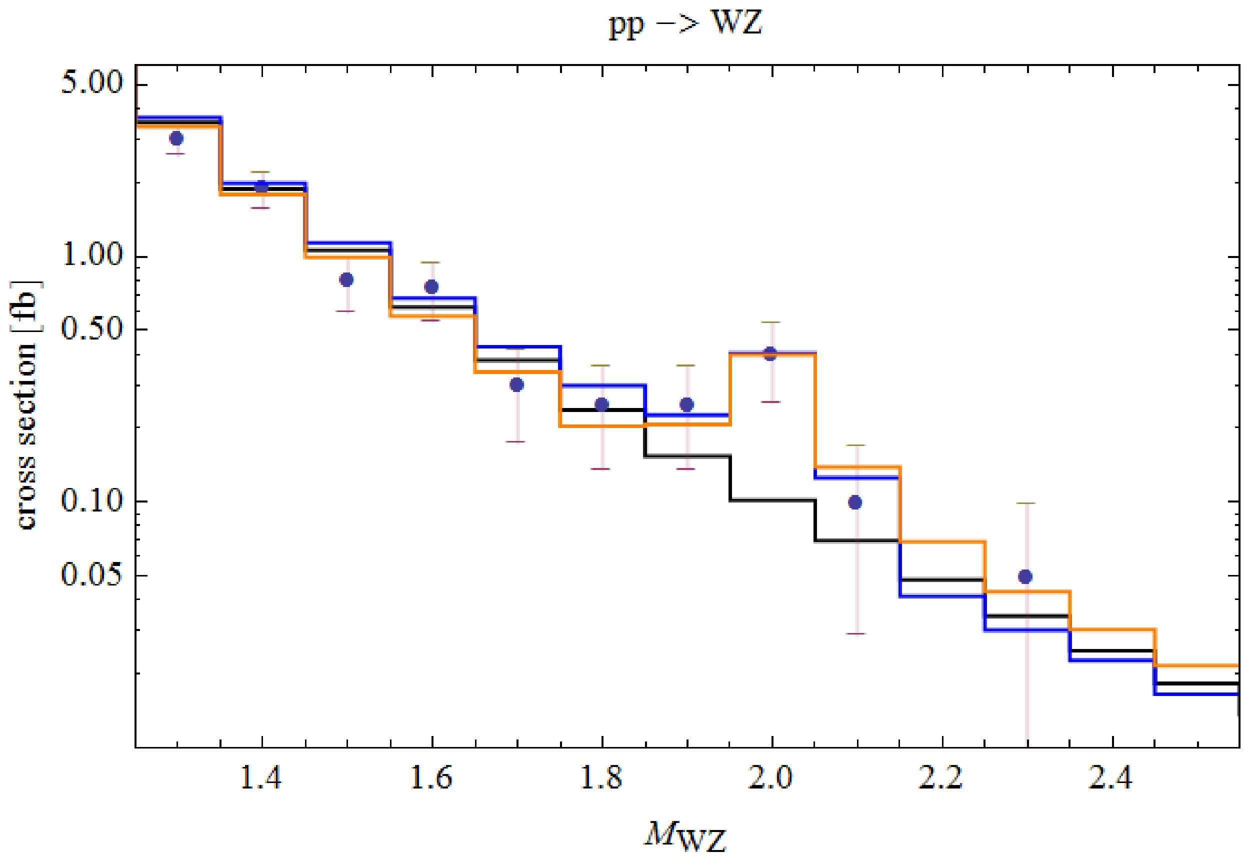
Constructive or destructive?

TABLE I: Input parameters for the constructive and de tive W' interference schemes.

interference	Mass	$\Gamma_{W'}$	$g_{W'WZ}$	$g_{W'ud}$
constructive	2 TeV	70 GeV	0.005	+0.15
destructive	2 TeV	70 GeV	0.005	−0.15

TABLE II: Local A_i for the constructive/destructive interference schemes with input parameters given in Table I and the ATLAS WZ data.

	constructive	destructive	data
A_i	0.11	−0.11	−0.52



2 TeV resonance @ LHC14

channel	backgrounds	S	B	significance
$\ell\ell\ell'\nu$	WZ	6.6	1.9	3.2
$\ell\ell q\bar{q}$	Z+jets	13.1	0.26	8.6
$\ell\nu q\bar{q}$	W/Z+jets	39.4	14.7	7.8
$q\bar{q}q'\bar{q}''$	jj	46.0	8.8	10.4

- Assuming c.m. energy of 14 TeV and an integrated luminosity of 20 fb^{-1}.
- Only events in the range [1.95, 2.05] TeV are counted.
- Numbers of signals from rescaling the current 8 TeV data.
  Using the input parameters in table I to rescale the signals
  Assuming the efficiencies are the same at 8 & 14 TeV [cf. the efficiency fig.]
- Numbers of bkgs from rescaling the 8 TeV bkgs
  ATLAS 1406.4456, 1409.6190, 1503.04677, 1506.00962

Bkg-Signal Interference @ HL-LHC14

Why we need HL to observe the interference effect?

- Generally a HL is needed to fix the line-shape precisely and reduce the background.
- The largest interfering effect occurs not at the top of resonance, but at some place on the "hillside", depending on the couplings and width.
- To maximize the interference effect, we have to collect a broad range of data around the resonance, implying that a HL is required, with the events closest to the resonance mass not contributing too much to the interference effect.

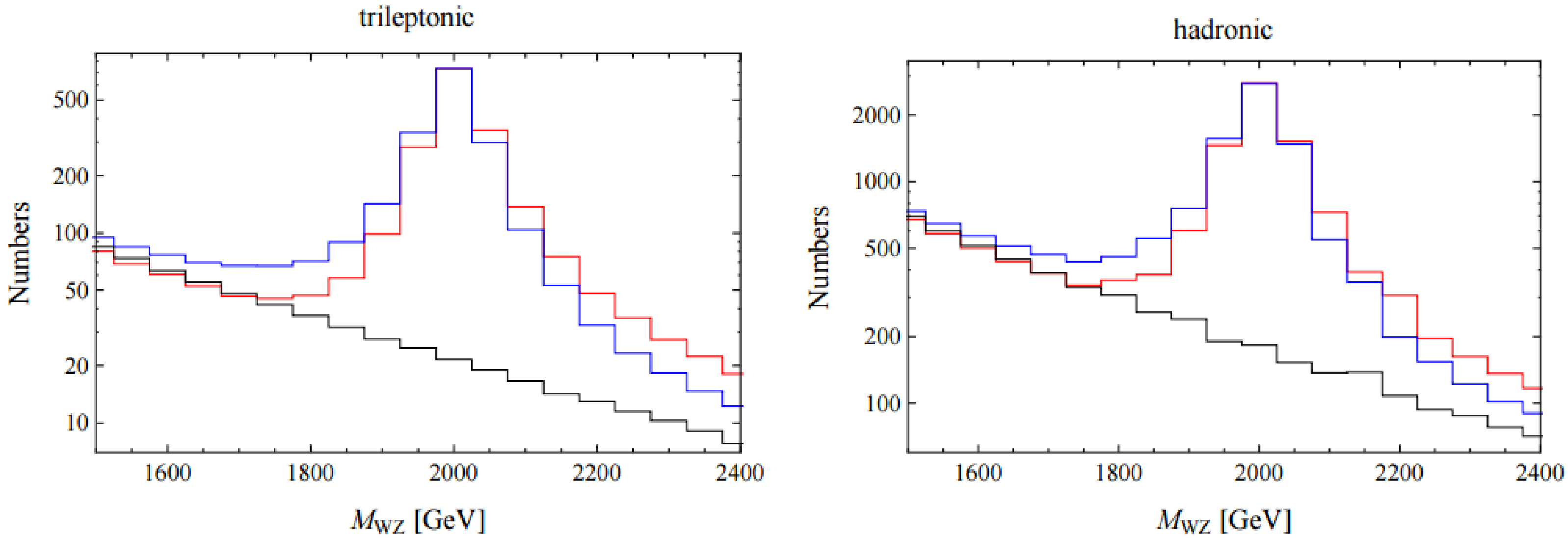


FIG. 2: Invariant mass distribution of M_{WZ} at 14 TeV LHC: the dark, orange and blue lines indicate respectively the simulated background and resonances with destructive and constructive interference. In the plots we assume a total luminosity of 3000 fb^{-1}.

Bkg-Signal Interference @ HL-LHC14

- Assuming c.m. energy of 14 TeV and an integrated luminosity of 3000 fb^{-1}.
- Numbers of signals estimated from direct simulation[not from rescaling] and implementing simple basic cuts
- The reducible JJ bkg in the hadronic channel from effectively reducing the 8 TeV data by a factor of two, which contribute largely to the statistical error, especially for the "optimal" scenario.
- Lepton momentum smearing: $\Delta E/E \simeq 1\%$
  which turn out to be not important. *ATLAS, 0901.0512*

Bkg-Signal Interference @ HL-LHC14

A_i	scenario	constructive	destructive	uncertainty
trileptonic	standard	0.25	−0.13	0.09
	optimal	0.77	−0.37	0.18
hadronic	standard	0.20	−0.10	0.12
	optimal	0.79	−0.33	0.54

- "Standard" scenario: 50 GeV/bin x 17 bins
  "optimal" scenario: 50 GeV/bin x (5+X+5) bins
- For the "optimal" scenario, only the bins with large interference effect are taken into account.
  On the other hand, the number of events largely reduced and the statistical errors increase.
- It is promising to differentiate the two interference schemes at a high CL @ HL-LHC14

Comments

- Robust conclusion from simple cuts?
- Systematic errors?
- More advanced study of the data, e.g. BDT method

- Anyway it is likely that the constructive and destructively interference can be differentiated clearly given the HL-LHC data, if the 2 TeV resonance are confirmed undoubtedly.
- The sign of beyond SM couplings and new physics scenarios are expected to be severely constrained.

If the 2 TeV resonances are falsified…

- We are not unhappy…

- The logic and arguments in this work hold true, for future studies of beyond SM resonances, e.g. particles from SUSY, UED and other popular models.

- The signal-background interference and resonance line-shape can be used to constrain the couplings and their signs beyond the SM.

More comments

If A & B decay further into lighter particles (a_i & b_i), the azimuthal angle between the two decaying planes can help

- To distinguish the resonance from bkg and improve the signal sensitivity, even when we consider only the shape of distributions but not the magnitudes.
- To discriminate the resonance states with different spins.

AB	$a_1a_2b_1b_2$ $[0,\ 2\pi]$	$a_1a_2b_1b_1$ $[0,\ \pi]$	$a_1a_1b_1b_2$ $[0,\ \pi]$	$a_1a_1b_1b_1$ $[0,\ \pi]$
AA	$a_1a_2a_1a_2$ $[0,\ \pi]$	- -	- -	$a_1a_1a_1a_1$ $[0,\ \frac{\pi}{2}]$

Conclusion

- The current WZ diboson data are so rare that they can not distinguish the constructive interference from the destructive one (in the toy W' model), altough the destructive one is slightly prefered.
- We can confirm/falsify the 2 TeV excesses soon @ LHC13. It is promising to differentiate the two interference schemes @ HL-LHC14 at a large confidence level, even up to 5σ.

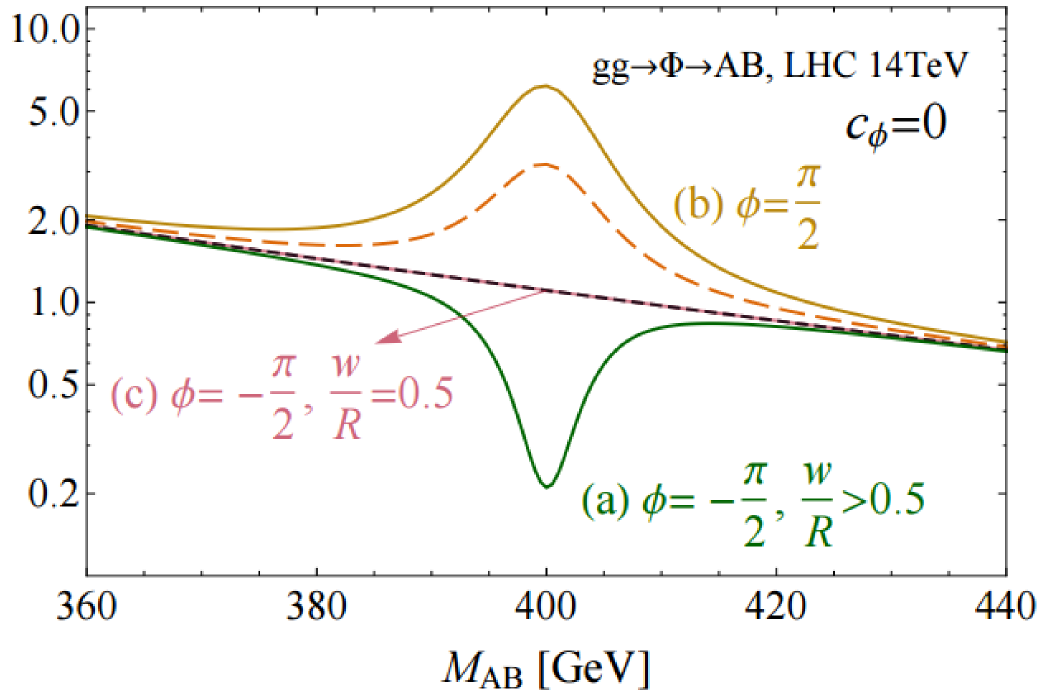
Thank you very much

$\mathbf{Generalization} : \pm \rightarrow \mathbf{e}^{\mathbf{i}\phi}$
"flat" or "Dip"-shape resonance

- If there are non-trivial phase difference between the bkg and signal amplitudes *Jung, Song & Yoon '15*

$$\sigma_{\text{total}} \quad \sim \quad \left|\text{bkg} + \text{signal}\, e^{i\phi}\right|^2$$

- Under certain conditions, it is not impossible that the resonance seems to be "flat" or even dip-like…



In order to compute the significance, we first calculate the p-value using the Poisson distribution under the background-only hypothesis:

$$p = P(n \geq n_{obs}; b, s = 0)\,, \tag{A.1}$$

with

$$P(n; s, b) \equiv \frac{(s+b)^n}{n!} e^{-(s+b)}\,, \tag{A.2}$$

where we have set $n_{obs} = s + b$. The significance Z is then defined as the number of standard deviations that a Gaussian variable would fluctuate in one direction to give the same p-value.

$$p = \int_Z^\infty \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \mathrm{d}x\,. \tag{A.3}$$

According to this definition, the usual 5σ discovery significance corresponds to a p-value $= 2.85 \times 10^{-7}$.