Wide Composite Vector Resonances at the LHC

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New Frontiers in Theoretical Physics
XXXV Convegno Nazionale di Fisica Teorica
Galileo Galilei Institute, Firenze

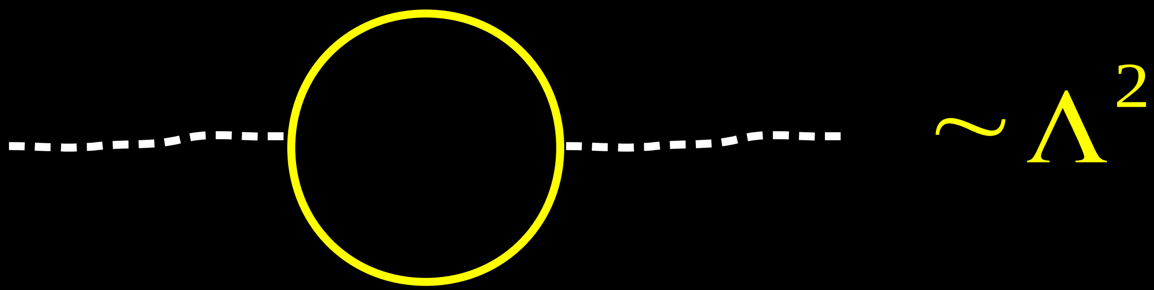
19^{th} May 2016

Barducci and Delaunay JHEP 1602 (2016) 055

Outline

- Naturalness and the Composite Higgs paradigm
- Composite Higgs at the LHC
- Bounding elusive partners: status and prospects
- Conclusions

Naturalness and Composite Higgs



- Naturalness is the main guidance for the search for TeV scale NP
- In the SM no symmetries are protecting the 125 GeV scalar from quadrative divergent radiative corrections
- NP contributions are required to stabilise the EW scale
- A moderate level of fine tuning requires NP to lie at the TeV scale
- The Goldstone symmetry guarantees lightness of scalars

Naturalness and Composite Higgs

- SUSY addresses Naturalness keeping the idea of an elementary Higgs
- What about the possibility of the Higgs being a composite state?

A composite Higgs would ”solve” the SM Hierarchy problem

All the scalar seen in Nature are (QCD) bound states

- Composite Higgs assumes the Higgs boson to be a bound state of a new strongly interacting sector [Terazawa et al ’77. Dimopoulos et al ’79, ’t Hooft ’80]

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$\mathcal{Q}$ How to get a light Higgs from a strongly interacting sector which should lie at a scale greater than the EW scale?

$\mathcal{A}$ Assume the Higgs boson to be a (pseudo) Goldstone boson
Similar to pions in QCD [Georgi and Kaplan ’84]

Naturalness and Composite Higgs

- Strong sector at a scale f>> v invariant under a global symmetry G

$$G \rightarrow H \qquad n = dim(G) - dim(H) \;\; GBs$$

H must be explicitly, but weakly, broken. A potential for the Higgs is generated [Coleman and Weinberg '73]

G/H must contain GBs with the SM Higgs doublet quantum numbers

- Bound states of the strong sector stabilise the Higgs mass

- Linear mixing between SM and heavy fermions can generate Yukawas
  Partial compositeness mechanism [Kaplan '91]

Naturalness and Composite Higgs

- A minimal coset for a Composite Higgs

$$SO(5) \to SO(4) \qquad n = 10 - 6 = 4 \;\; GBs$$

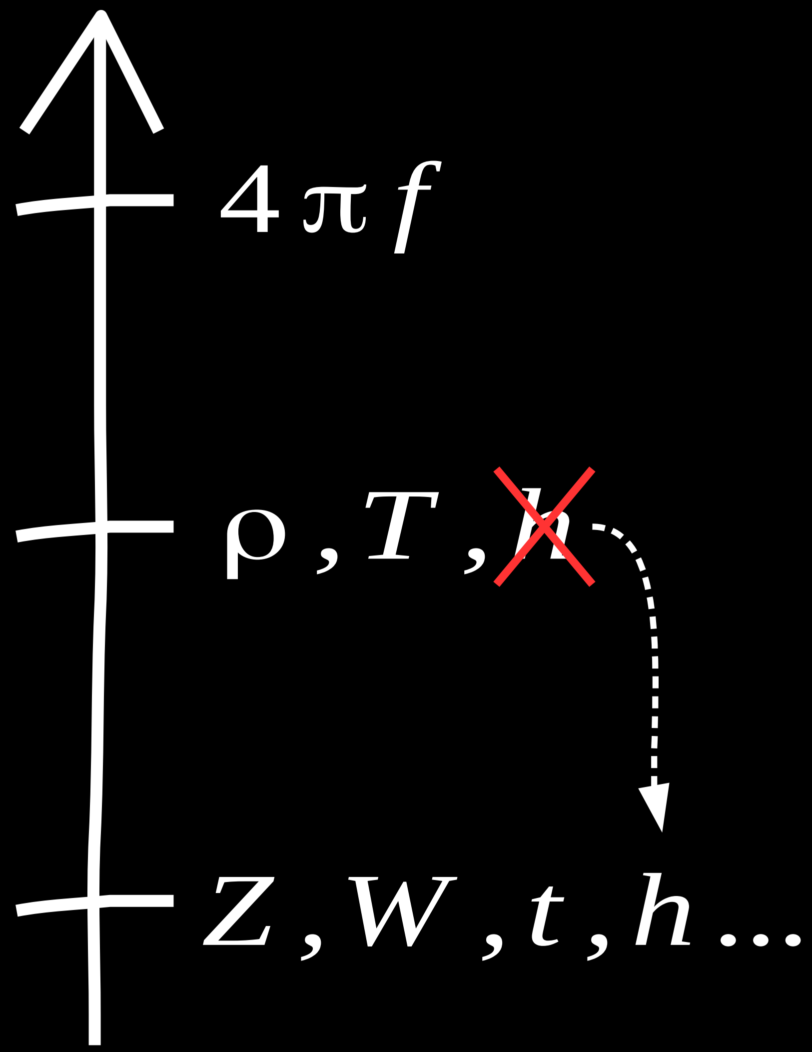
[Agashe et al. '05]

Custodial symmetry for protection of the T parameter

Minimum number to be identified With the Higgs doublet

- Radiative generation of the Higgs potential
- Introduction of new degrees of freedom (bound states)
  - Necessary for generating a correct Higgs potential
  - Necessary for generating Yukawa terms
- Non minimal cosets can provide extra scalars (750 GeV?) and DM

Naturalness and Composite Higgs



A minimal Lagrangian for a Composite Higgs

[For a comprehensive review see Panico and Wulzer '15]

$$L_{pion} = \frac{f^2}{4} d_\mu^2 \xrightarrow{\text{CCWZ for SO(5)/SO(4)}} L_{pion} = \frac{f^2}{4} \partial_\mu \Phi \partial^\mu \Phi$$

$$\Phi = \exp(i\pi/f)\varphi_0$$

- A bidoublet of VLQs in the fundamental of $SO(4) : (T, B)_{1/6} \ (X, T)_{7/6}$

$$L_\Psi = \bar{\Psi}(i\hat{D} - M_\Psi)\Psi + i c_i \bar{\Psi}_R \hat{d} t_R + y_L f \bar{Q}_L U \Psi_R + y_L c_2 f Q_L U t_R$$

Mass term allowed, vectors under the SM gauge group

Mixing between SM quarks and top partners → top yukawa

- Two triplet of EW vectors in the $Adj[SO(4)] \sim SU(2)_L \times SU(2)_R$: $\rho^0_{L,R}, \rho^\pm_{L,R}$

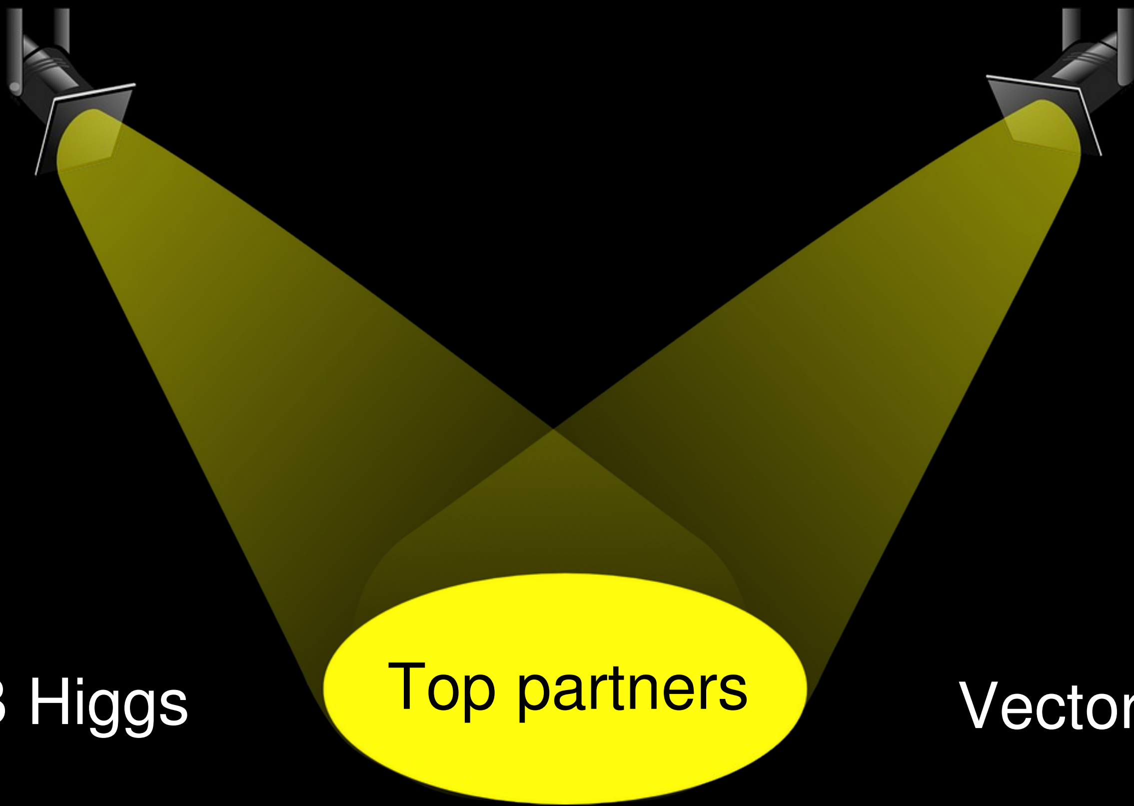
$$L_\rho = -\frac{1}{4}\rho_{\mu\nu}\rho^{\mu\nu} + \frac{m_\rho^2}{2 g_\rho^2}(g_\rho \rho_\mu - e_\mu)^2 + c_3 \bar{\Psi}\gamma^\mu(g_\rho \rho_\mu - e_\mu) T \Psi$$

Interaction between composite resonances. Important for collider searches!

A minimal Lagrangian for a Composite Higgs

This minimal Lagrangian provides a rich phenomenology

A composite GB Higgs

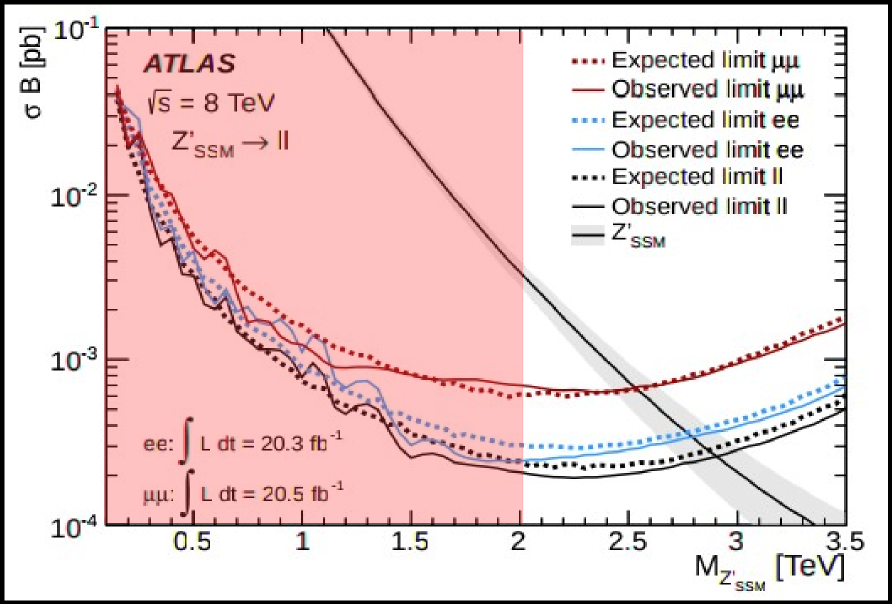


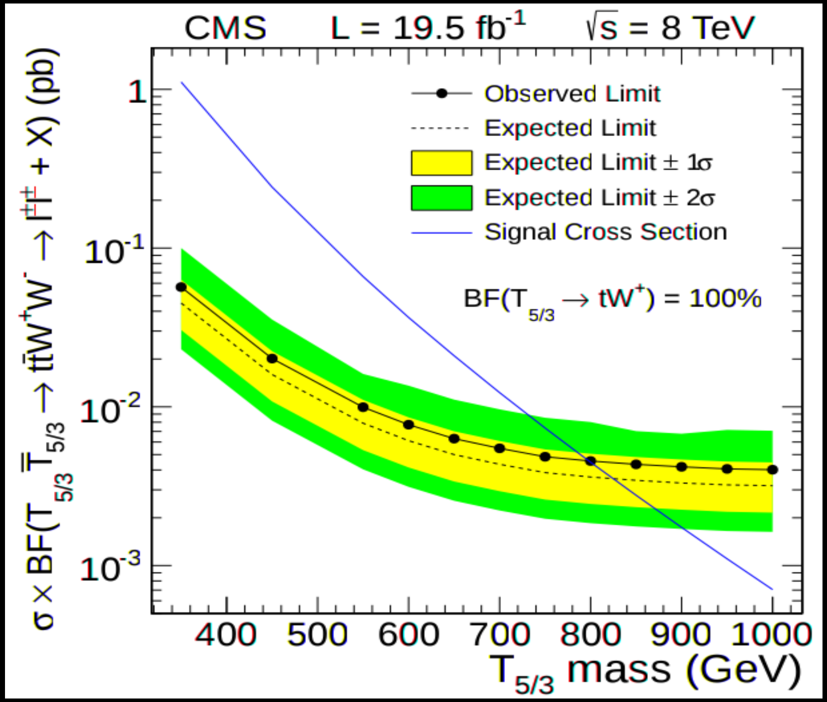
Vector resonances

Different signatures to be looked for at the LHC

Composite Higgs at the LHC

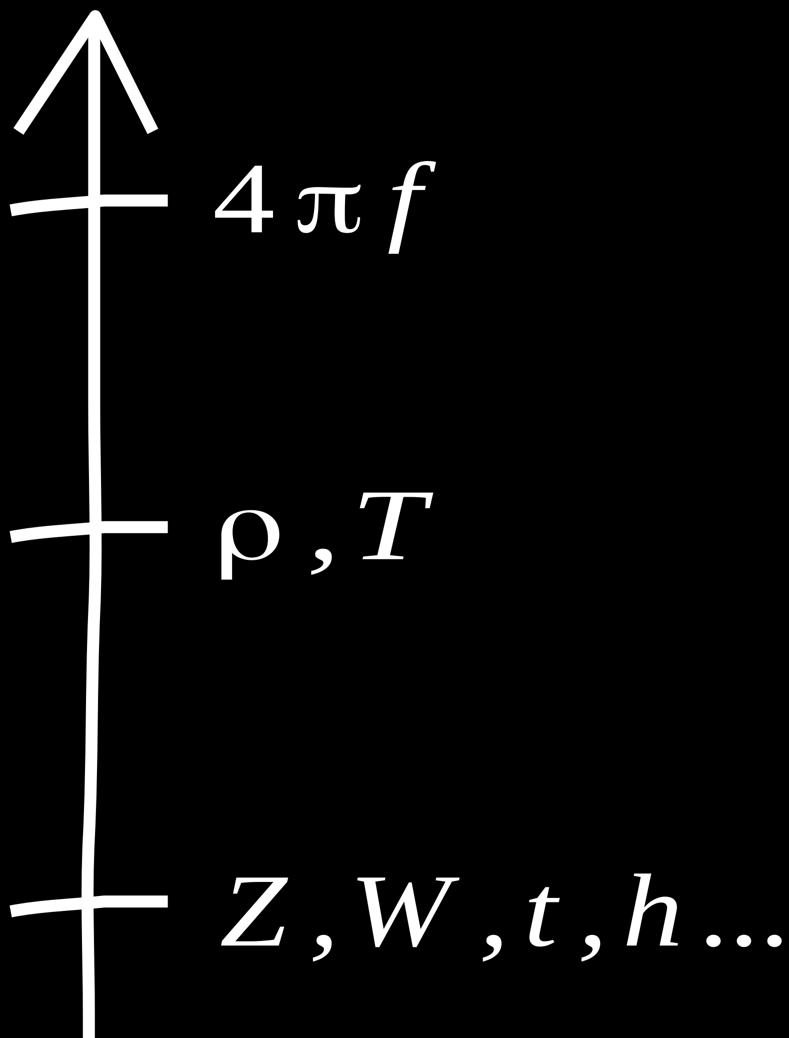
- Modifications of the Higgs signal rates, controlled by $\xi \equiv v^2/f^2$
- DY and diboson production of ρ resonances: (semi)leptonic final states
- Pair and single production of VLQs



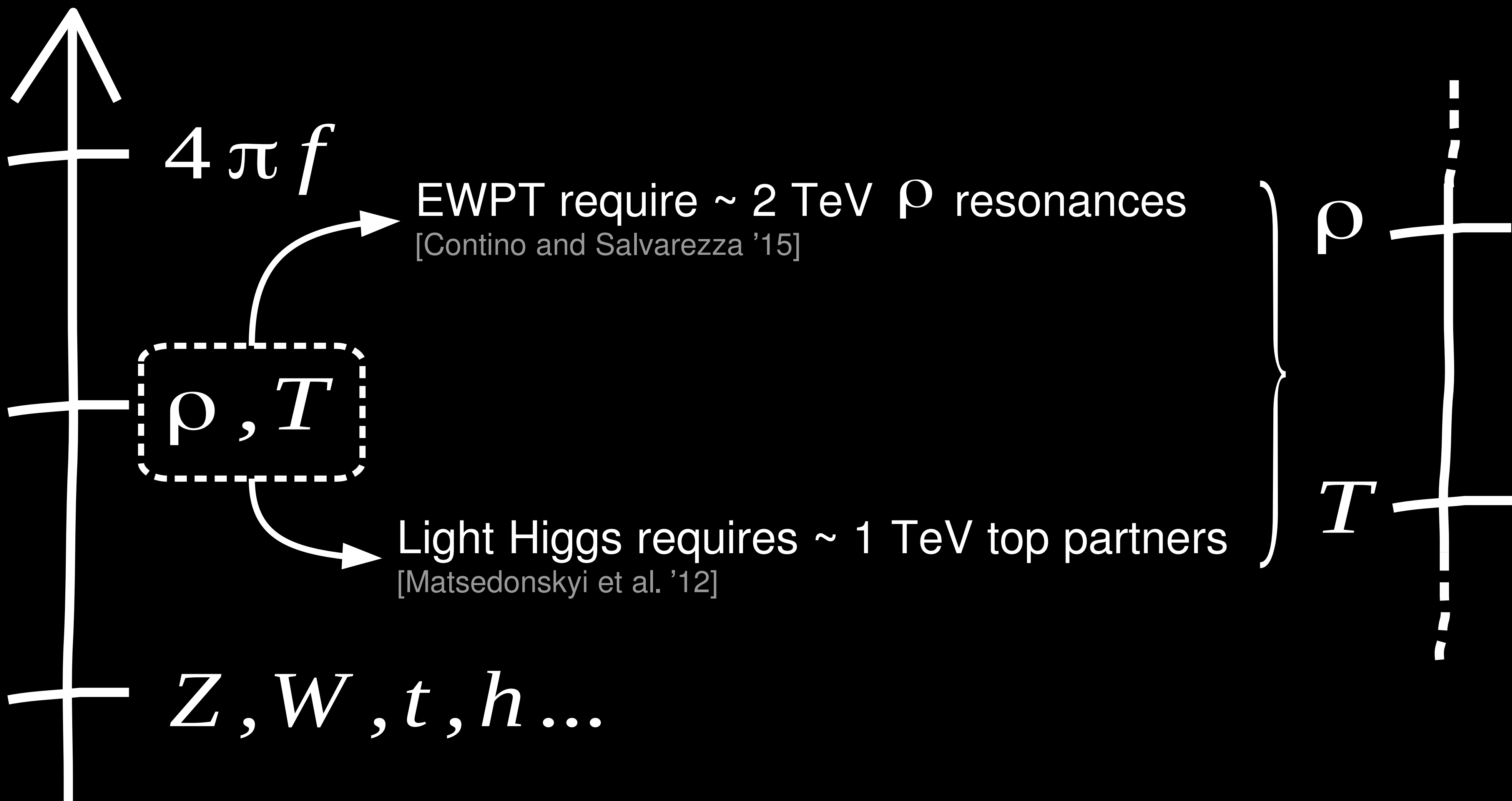


- Limits on ρ resonances ~ 2 TeV, essentially from dilepton
  Preliminary 13 TeV results in the same ballpark
- Limits on VLQs ~ 800 GeV, essentially from pair production
  Preliminary 13 TeV results set a bound ~ 900 GeV

Naturalness and Composite Higgs

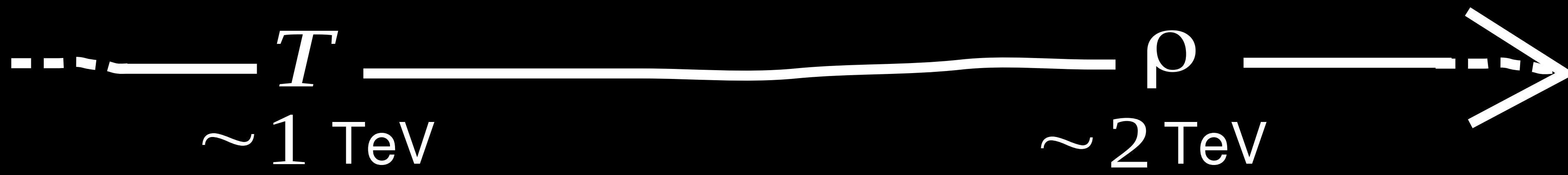


Naturalness and Composite Higgs

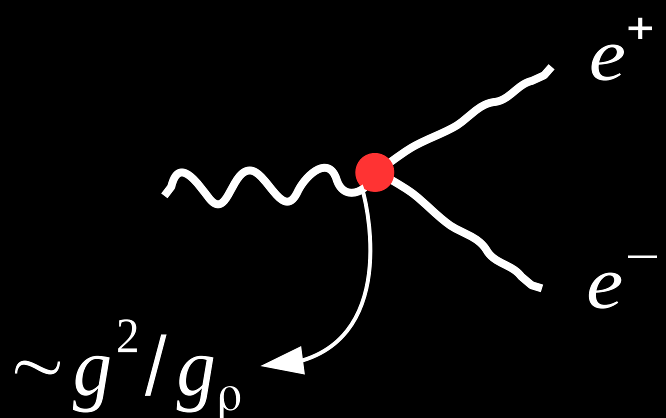


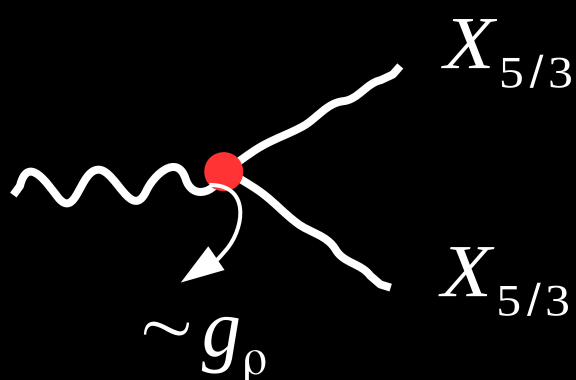
Wide ρ at the LHC

- Naturalness, a light Higgs and the LEP/LHC data point to a particular spectrum configuration



- This opens up a new final state for the Rho decays





$$BR(\rho \to e^+ e^-) \ll BR(\rho \to X_{5/3} X_{5/3})$$

Wide ρ at the LHC

Two consequences of this kinematic configurations

1. $\sigma(pp \to l^+ l^-) \sim \sigma(pp \to \rho) Br(\rho \to l^+ l^-)$ strongly reduced

This relaxes LHC limits on ρ masses

Stronger limit set by the S-parameter [DB et al. '12, Greco and Liu '15]

Vector resonances invisible at the LHC with standard searches

2. It allows a non negligible different pair production mode for VLQs

$$\sigma(pp \to T\bar{T}) = \sigma(pp \to \rho) Br(\rho \to T\bar{T}) + \sigma(pp \to T\bar{T})_{QCD}$$

$Br(\rho \to T\bar{T})$: $O(1)$

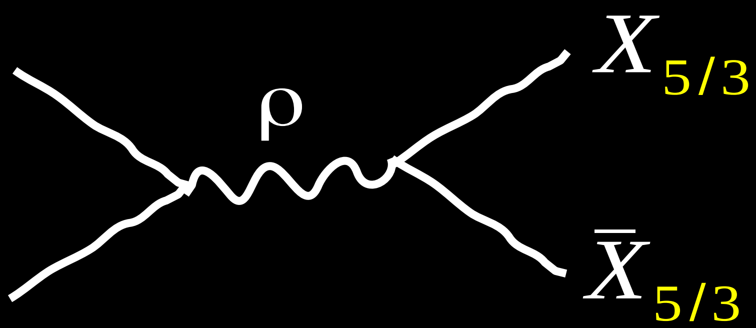
$\sigma(pp \to T\bar{T})_{QCD}$: $\sim 20\, fb \quad m_T = 800\, GeV$; $\sim 3\, fb \quad m_T = 1000\, GeV$

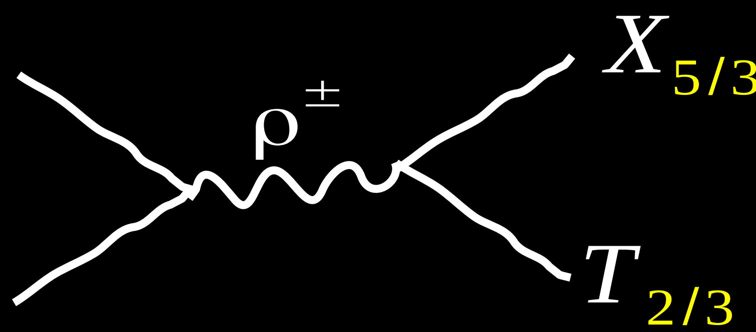
$\sigma(pp \to \rho)$: For a ~ 2 TeV resonance DY σ can be in the ~ 5 fb range

Question Can this be used to bound this otherwise elusive resonances?

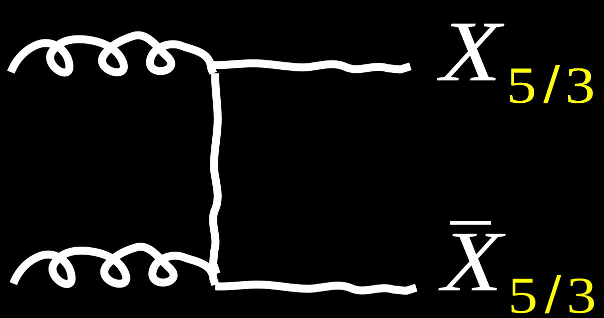
Wide ρ at the LHC

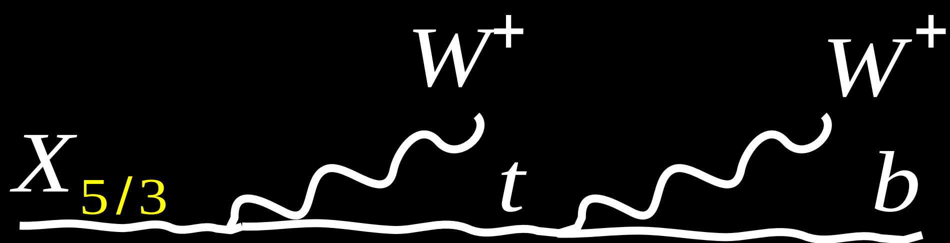
- Typically, ρ mainly decay in the $(X, T)_{7/6}$ doublet





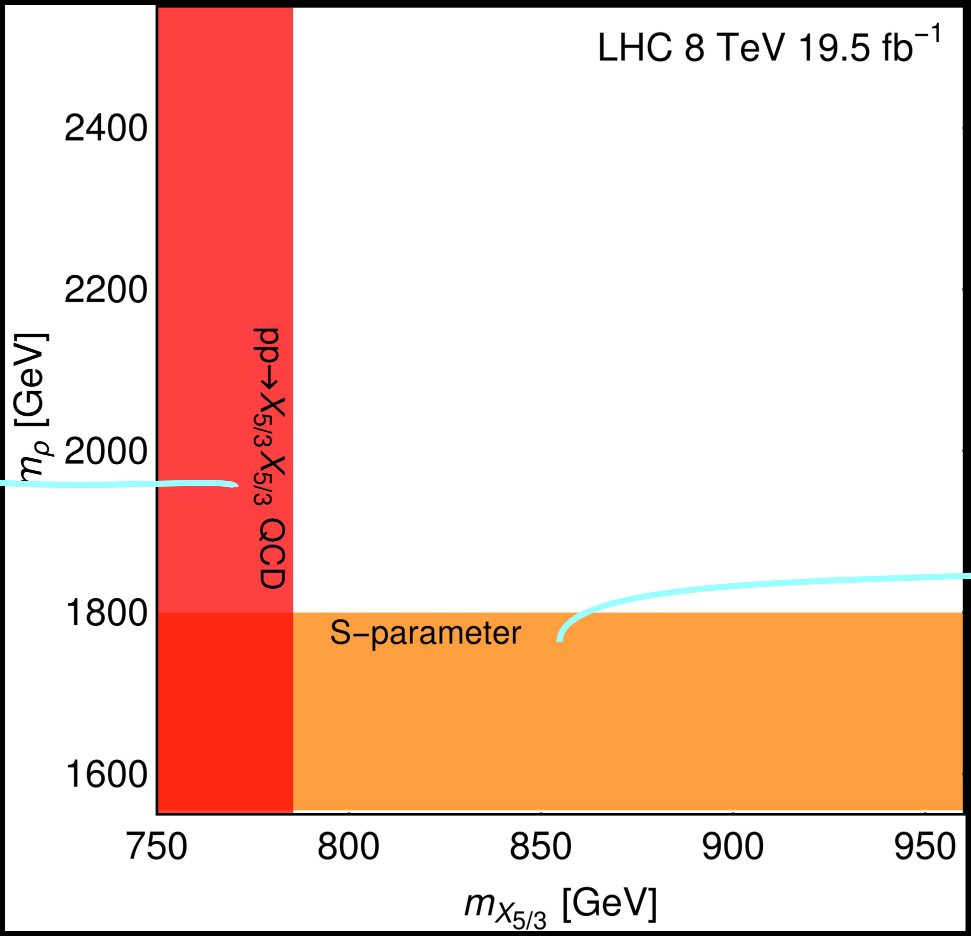
- $X_{5/3}$ decays through charged current and give rise to a SS2L final stat
- The SS2L search use to bound $X_{5/3}$ can be exploited to constrain ρ





Wide ρ at the LHC

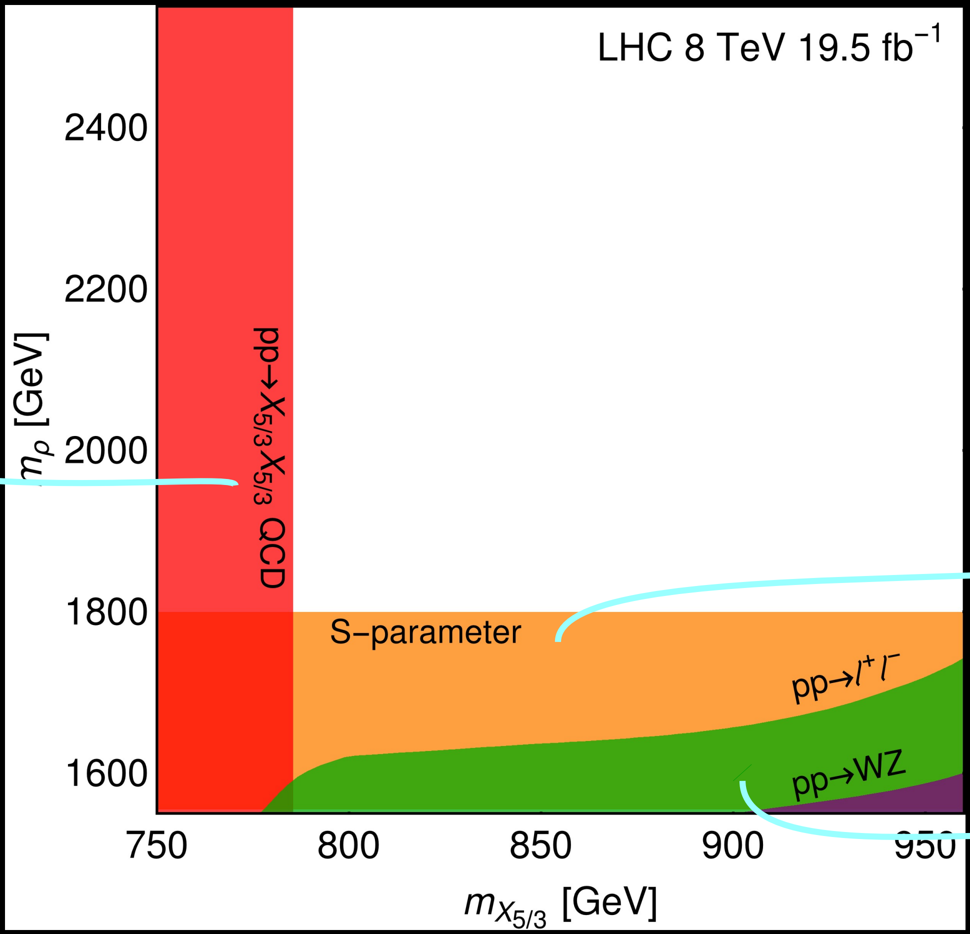
QCD pair production limit



S-parameter limit

Wide ρ at the LHC

QCD pair production limit

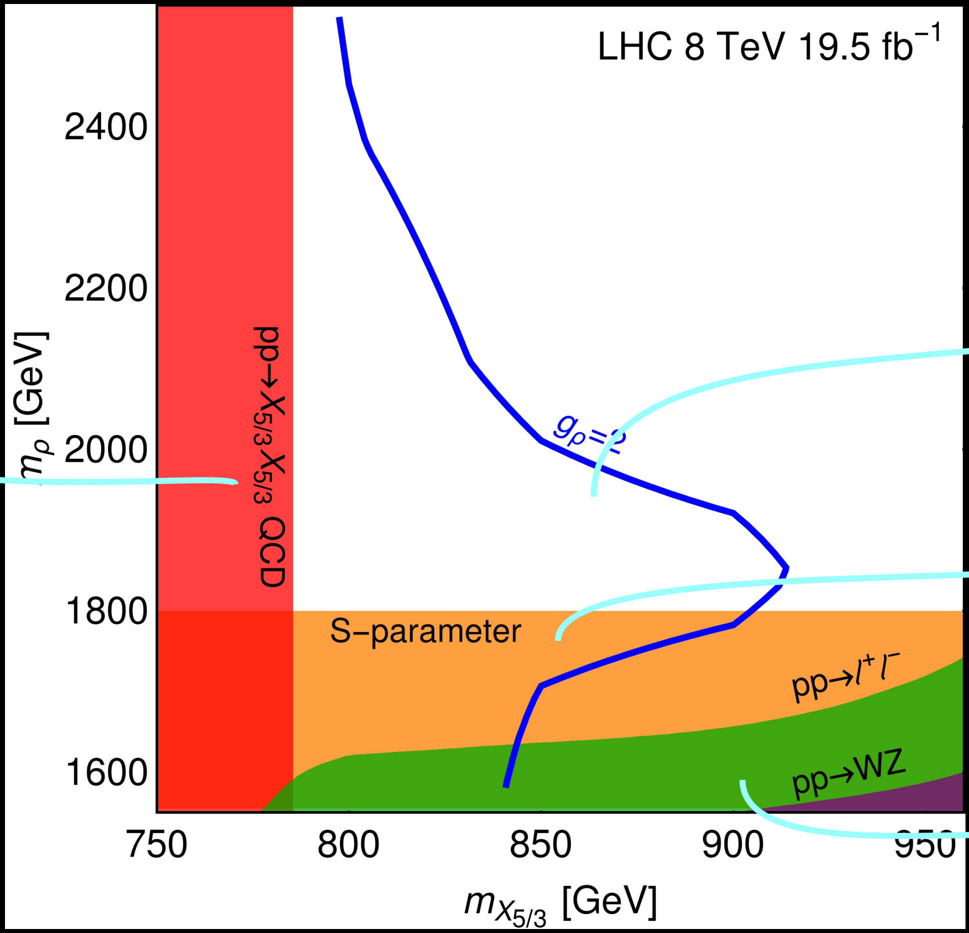


S-parameter limit

Direct search not effective if $m_\rho < 2m_{X_{5/3}}$

Wide ρ at the LHC

QCD pair production limit



LHC8 already constrain this naturalness favoured regime

S-parameter limit

Direct search not effective if $m_\rho < 2 m_{X_{5/3}}$

Wide ρ at the LHC

QCD pair production limit

Different g_ρ values give different exclusions

LHC8 already constrain this naturalness favoured regime

S-parameter limit

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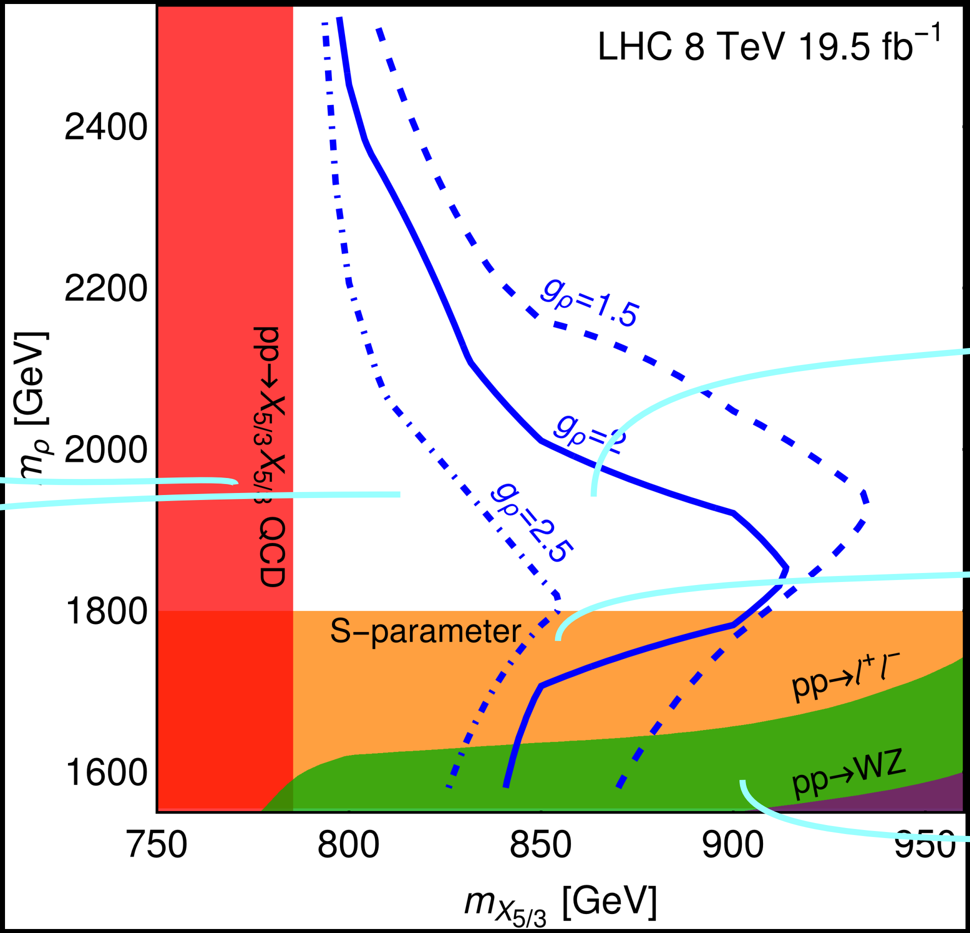
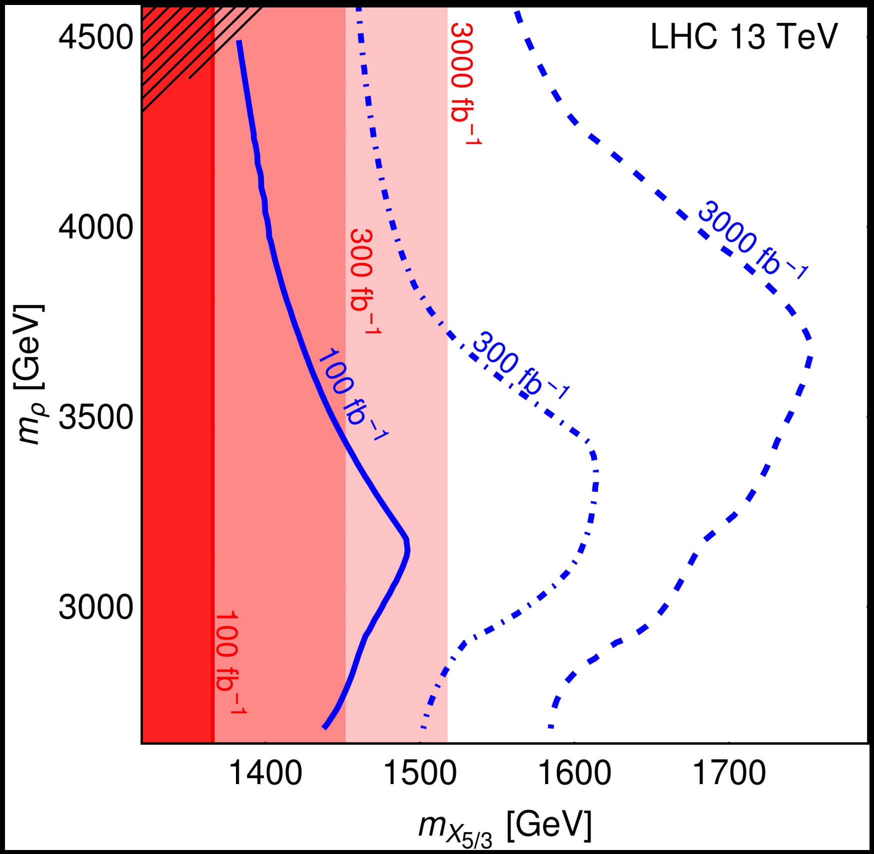


Wide ρ at the LHC



- Sensitivity with 100/fb comparable with 3000/fb and just QCD production
- Up to 3500 GeV ρ with 1700 GeV can be excluded
- CMS already released SS2L analysis with ~3/fb at 13 TeV. Results already competitive with 8 TeV

Question If a SS2L signal will be detected, will we be able to disentangle its origin, i.e. QCD production vs ρ decay?

Answer Distributions differences get partially washed washed out
Need to reconstruct the VLQ system → high lumi required

Conclusions

- Composite Higgs models are a compelling alternative to SUSY theories
- Naturalness, a light Higgs and present collider data point to a scenario where ρ can decay into a pair of light top partners
- These wide ρ excape the limits from direct searches, due to their reduced rates into SM final states
- Providing an alternative mode for pair producing top partners they can be bounded using VLQs designed analyses already with 8 TeV data
- LHC13 will greatly improve on this naturalness favoured scenario
- Reconstruction of (possible) SS2L excess will shed light on the underlying physics structure

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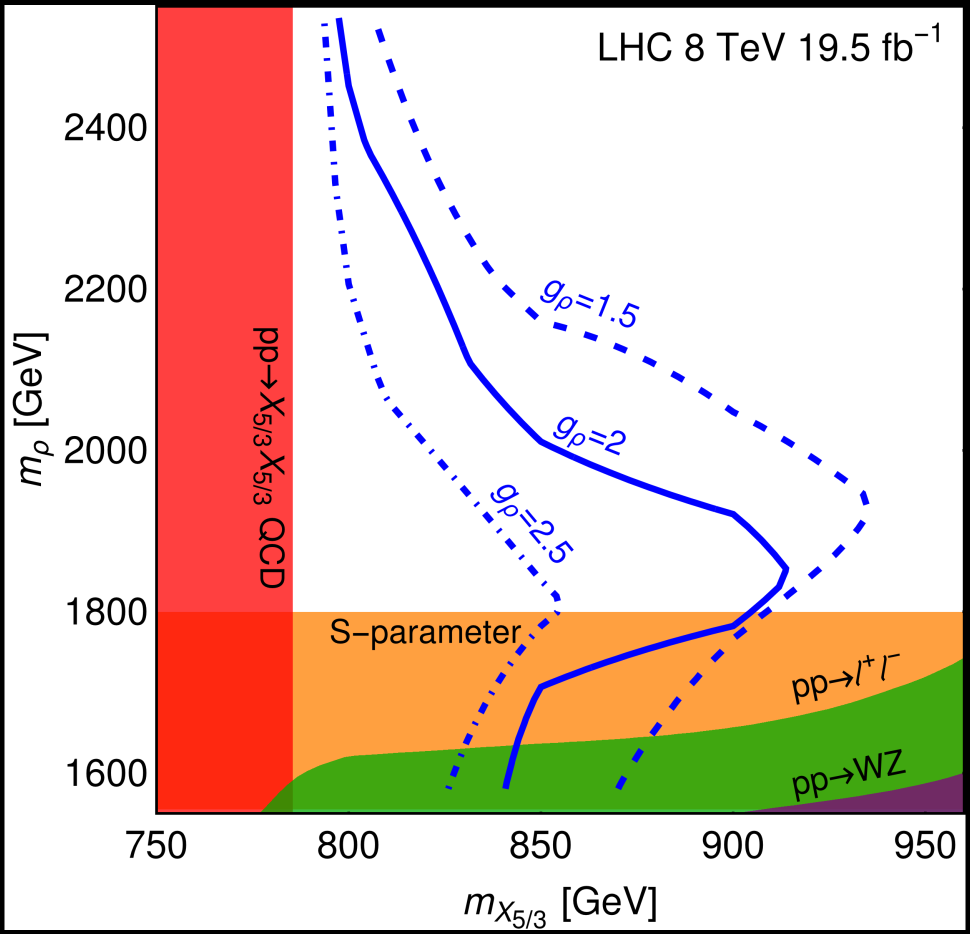
Thank you!

Backup – Interference effects



$m_{X_{5/3}}$	m_ρ	Γ_ρ/m_ρ	QCD	EW-ρ	EW-full	CL-ρ	CL-full
1.7	3.25	6%	2.9	5.0	4.7	1.5σ	1.4σ
1.6	3.25	11%	3.9	6.6	5.9	2.0σ	1.8σ
1.5	3.5	15%	6.6	5.0	6.8	2.1σ	2.4σ
1.5	4.25	20%	6.6	1.7	2.5	1.6σ	1.7σ

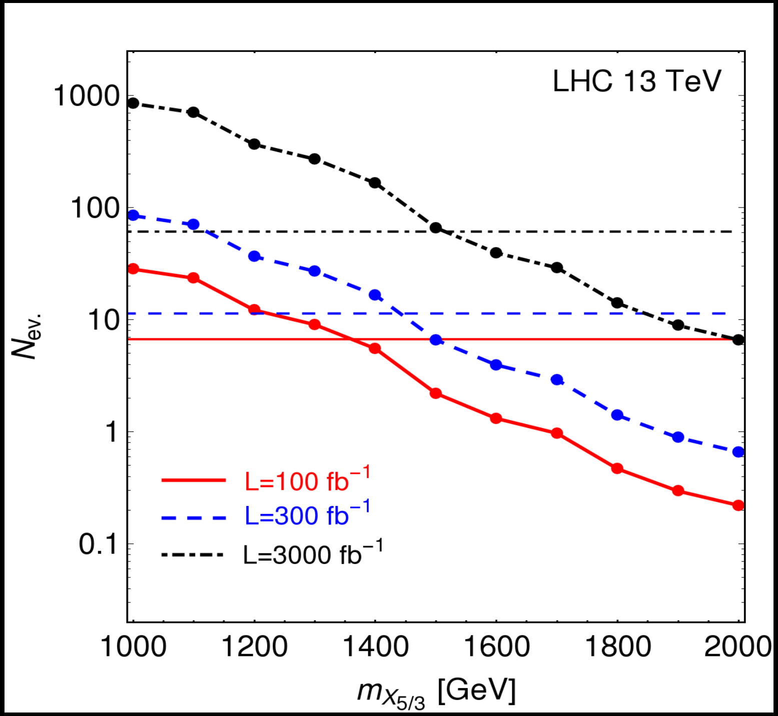
- Negligible in first approximation

Wide ρ at the LHC

- LHC 8 has a good coverage. What about LHC 13?
- We first check what the reach will be for a possible SS2L selection

1. At least two same sign lepton with pT>30 GeV
2. Dilepton Z boson veto |Mee-Mz|>15 GeV
3. pTj1>150 GeV, pTj2>80 GeV
4. MET>100 GeV, HT>1500 GeV, ST>2000 GeV

Main SM backgrounds – ttZ, ttW, WW, WZ, WWW



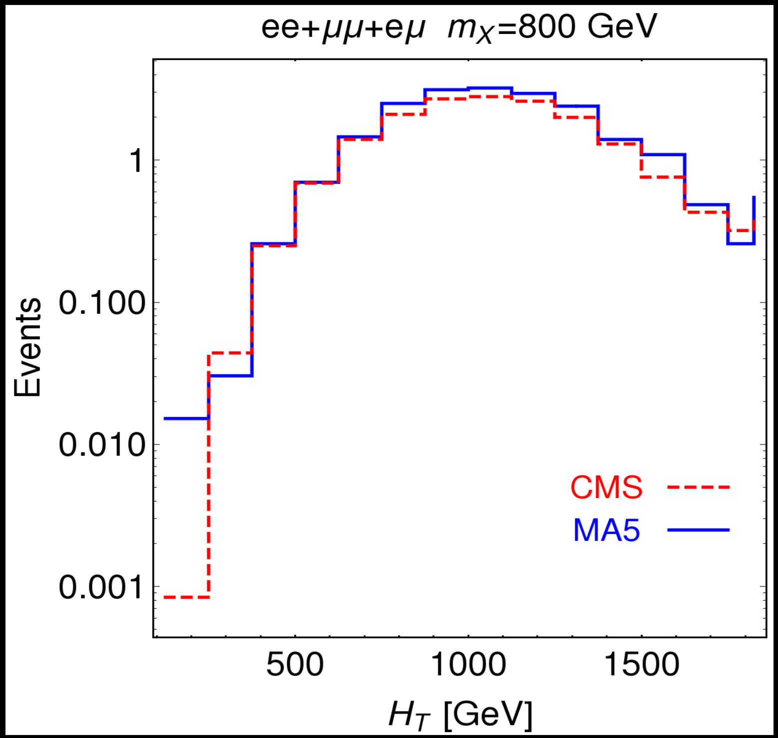
Expected limit using CLs technique

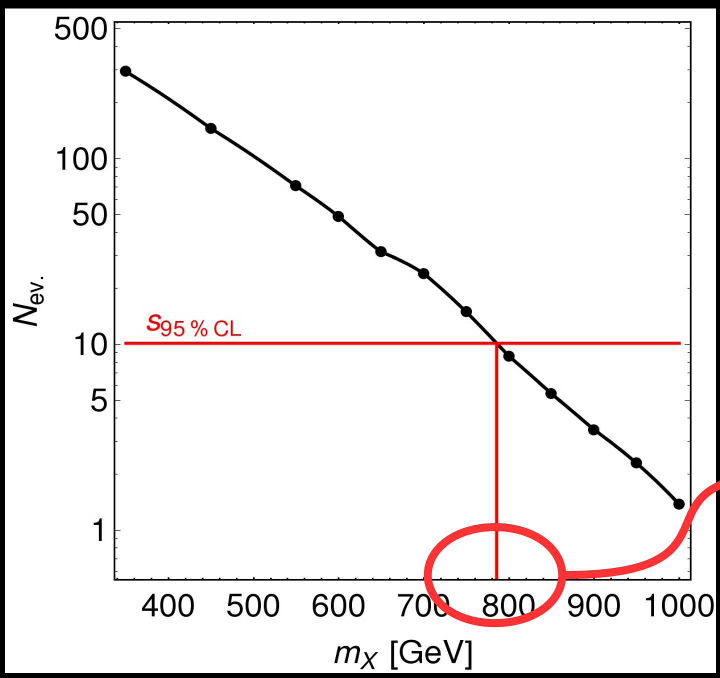
$CLs(B, \Delta B, DATA = B)$

$$m_{X_{5/3}} \begin{cases} 1360\,GeV & L = 100\,fb^{-1} \\ 1450\,GeV & L = 300\,fb^{-1} \\ 1520\,GeV & L = 3000\,fb^{-1} \end{cases}$$

Wide ρ at the LHC - Recast the CMS search

Signal Region	CMS official results	MA5 results
ee	2.1	2.3
$\mu\mu$	2.8	2.1
$e\mu$	4.7	4.2





$m_{X_{5/3}} > 790\, GeV$

CMS results is 800 GeV

Validated

Why can safely apply this search to our Composite Higgs scenario