Vector Boson Scattering at Hadron Colliders

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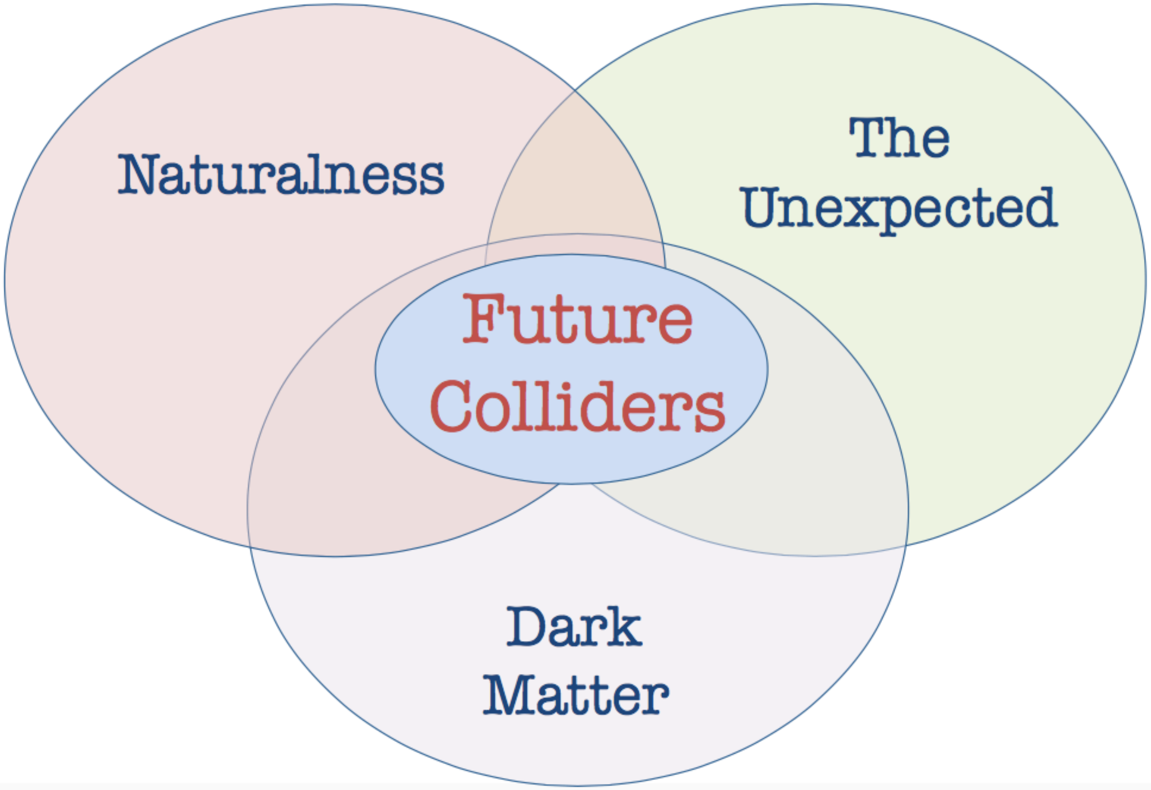


VBS @ Snowmass
January 29, 2021

Old and New Questions

- How to think of the vacuum as an “electroweak condensed state” ?
- How are the mysteries associated with a single, fundamental scalar field solved?
- What is the origin and nature of Dark Matter?
- What is the origin of the Baryon Asymmetry in the Universe?
- Why is Dark Energy so small but non-zero?

Fundamental *vs* Parametric Physics

- Fundamental principles lead to
  - Chiral fermions from irreducible representations of Lorentz group
    - fermions as spin ½ representations of Lorentz group
    - Fermi-Dirac statistics → Pauli Exclusion Principle
    - why matter occupies volume
  - Massless force mediators (gauge bosons) from gauge invariance
  - Massive gauge bosons and fermions from spontaneous breaking of gauge symmetry

- In comparison, the breaking of gauge symmetry by the Higgs VeV is parametrically induced
  - No dynamic or underlying principle behind it in the Standard Model

Why is Higgs Puzzling

Gauge sector $$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$$

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

h: a new kind of
elementary particle

Higgs sector

$$L = \left(h_{ij}\bar{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda_{CC}^4$$

Why is Higgs Puzzling

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

Ad-hoc potential, similar to and motivated by Landau-Ginzburg theory of superconductivity

Higgs potential in SM can be extrapolated to Planck scale without additional parameters; but no a-priori reason for a parameterization to respect this condition

Higgs boson puzzles

- First fundamental (?) scalar field to be discovered
- Spontaneous symmetry breaking by development of a VeV
  - But VeV is induced parametrically by ad-hoc Higgs potential, no dynamics
- Parameters of Higgs potential are not stable under radiative corrections
  - First time that the radiative correction to a particle mass is additive and quadratically divergent
  - Gauge boson masses are protected by gauge invariance
  - Fermion masses are protected by chiral symmetry of massless fermions
- Single scalar Higgs field is a strange beast, compared to fermions and gauge bosons
- Additional symmetries and/or dynamics strongly motivated by Higgs discovery

Why is the Higgs Boson So Light?

- Old idea: Higgs doublet (4 fields) is a Goldstone mode generated from the spontaneous breaking of a larger global symmetry
  - Higgs boson and W_L, Z_L are all Goldstone bosons from, eg. Spontaneously breaking global SO(5) → SO(4)
  - Small, loop effects cause some additional, explicit breaking of SO(5) symmetry, causing Higgs to be not exact (massless) Goldstone but Pseudo-Goldstone (light)
  - Examples: Holographic Higgs, Little Higgs models...
  - Electroweak vev "*v*" is small compared to SO(5) breaking scale "*f*"

- Vector boson scattering topology
  - Quarks emit longitudinal vector bosons which interact with new (presumably strong) dynamics
  - Quarks scatter by small angle in the forward direction

Motivation for Resonances in VBS

- Assumption is that there is a strong dynamics at the energy scale "f" which causes a condensate to form and break the SO(5) symmetry
- Resonances will be associated with this strong dynamics
- Lightest resonance will decay to the "pseudo-Goldstones" which are much lighter, ie longitudinal gauge bosons and Higgs bosons
  - Similar to QCD $\rho \to \pi\pi$
- Simplified model: arXiv:1109.1570 (Contino *et al.*) "On the effect of resonances in composite Higgs phenomenology"
  - Scalar resonance: $\eta \to hh, V_L V_L$

Motivation

- Lagrangian from Contino *et al.* for a scalar resonance η coupling to the Goldstones

$$\mathcal{L}^{(\eta)} = \frac{1}{2}\left(\partial_\mu \eta\right)^2 - \frac{1}{2} m_\eta^2 \eta^2 + \frac{f^2}{4}\left(2a_\eta \frac{\eta}{f} + b_\eta \frac{\eta^2}{f^2}\right) \mathrm{Tr}\left[d_\mu d^\mu\right]$$

- Width of the resonance:

$$(D_\mu \Phi)^T (D^\mu \Phi)$$

$$\Gamma_\eta = \frac{a_\eta^2 m_\eta^3}{8\pi f^2}$$

Unitary is fully preserved by setting $a_\eta = 1$, no need for ad-hoc unitarization

Eliminates the complications of unitarization for anomalous couplings and higher-dimensional operators

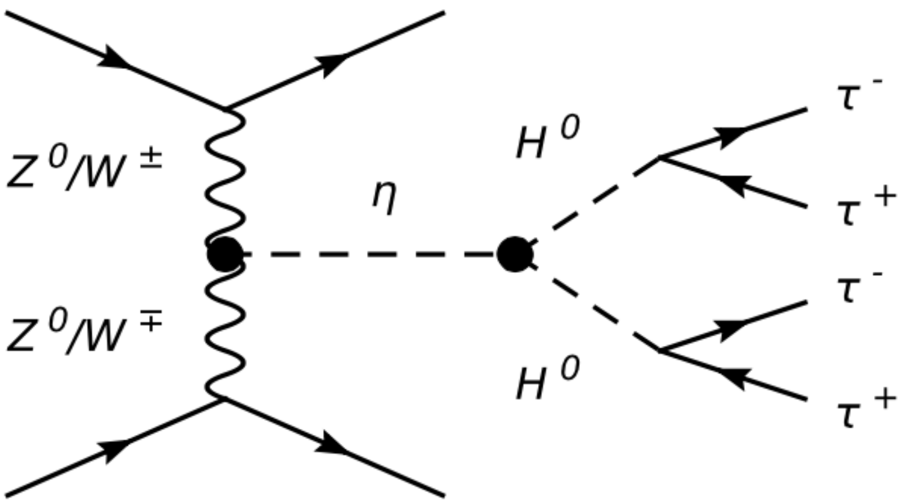
Two free parameters: mass and width of the resonance

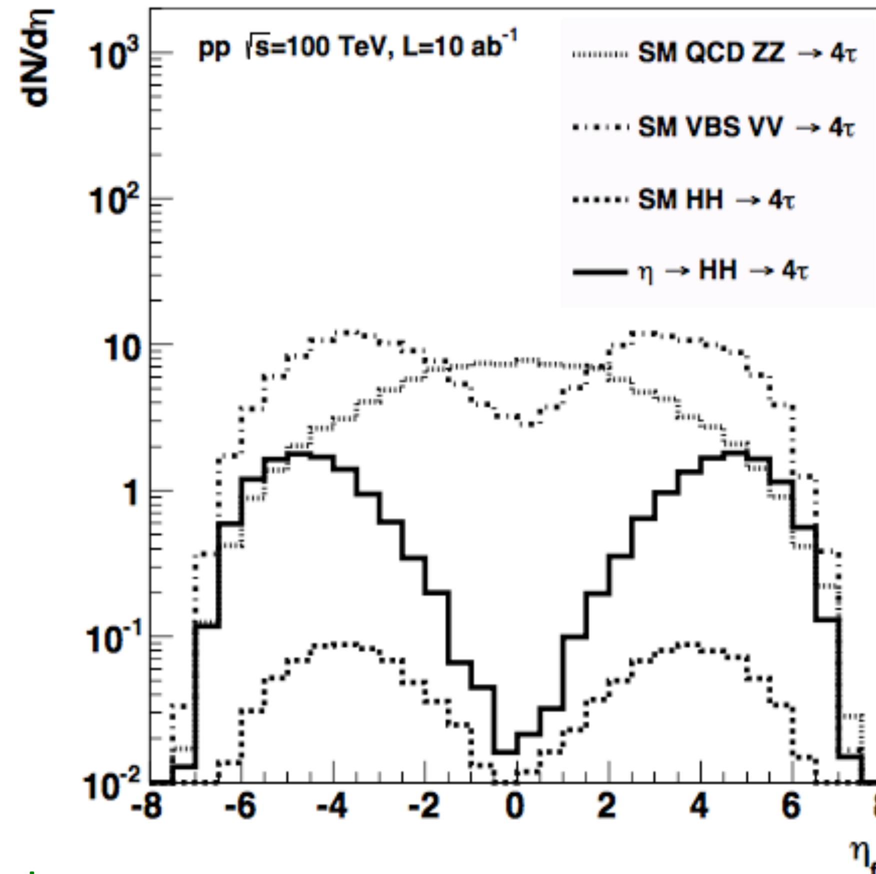
Longitudinal Vector Boson Scattering

Double Higgs Boson Production in the 4τ Channel from Resonances in Longitudinal Vector Boson Scattering at a 100 TeV Collider

AVK, S. Chekanov, M. Low

Phys.Rev. D91 (2015) 114018





(a)The pseudo-rapidity distributions of the forward jets.

60% efficiency for τ identification assumed

Forward Jet Coverage for Longitudinal VBS

$V_L V_L \rightarrow \eta \rightarrow HH$

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TABLE II. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a pp collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10$ ab^{-1}, for various cuts values on minimum p_T of the forward jets. The fractional width of the η resonance is set to $\Gamma/M = 20\%$.

$p_T^{\rm min}$ (GeV)	30	50	70	90	110
m_η (TeV)	3.53	2.90	2.35	1.92	1.56

- Lower p_T threshold on forward tagging jets is preferred
  - Reject pileup jets with good tracking in forward direction
  - Resolve overlapping pileup jets with higher granularity / spatial resolution (*a la* CMS high-granularity endcap calorimeter for HL-LHC)

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TABLE III. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a pp collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10$ ab^{-1}, for various cuts values on the maximum rapidity (y) of the forward jets. The fractional width of the η resonance is set to $\Gamma/M = 20\%$.

y^{max}	8	7	6	5	4
m_η (TeV)	2.9	2.9	2.81	2.42	1.75

Want jet rapidity coverage up to 6

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Sensitivity grows rapidly with luminosity

Gains with collider energy not as impressive

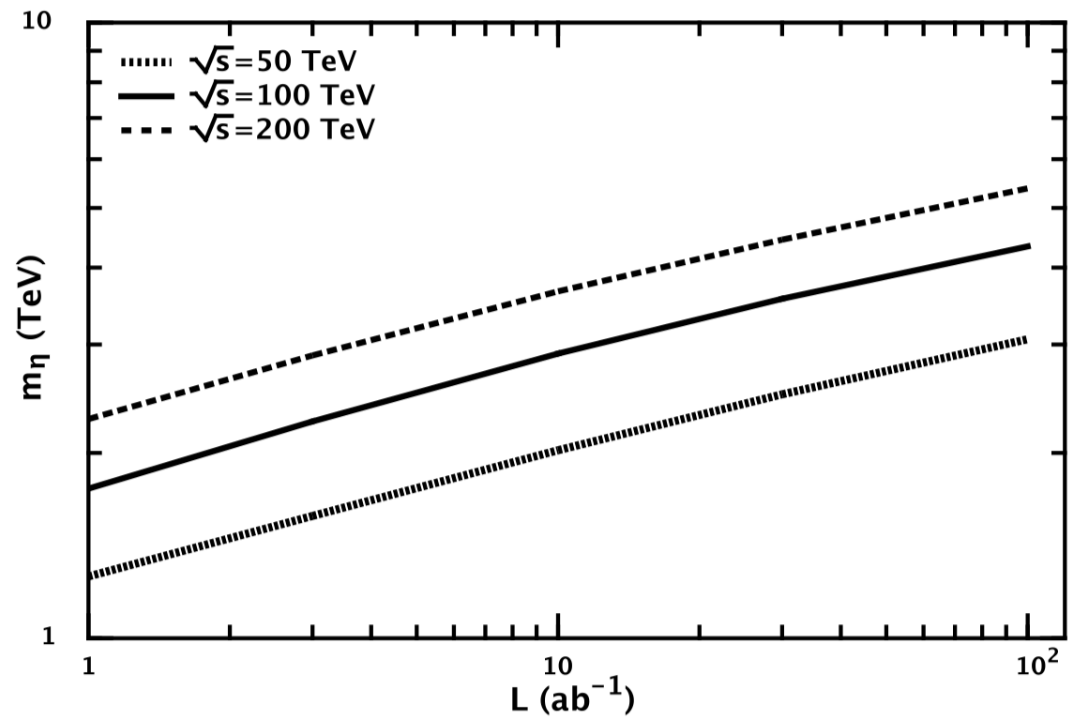

FIG. 13. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, as a function of the integrated luminosity and $\sqrt{s}$ of a pp collider. The fractional resonance width Γ_η/m_η is fixed at 20%.

Vector Boson Scattering

[Double Higgs Boson Production in the 4τChannel from Resonances in Longitudinal Vector Boson Scattering at a 100 TeV Collider]

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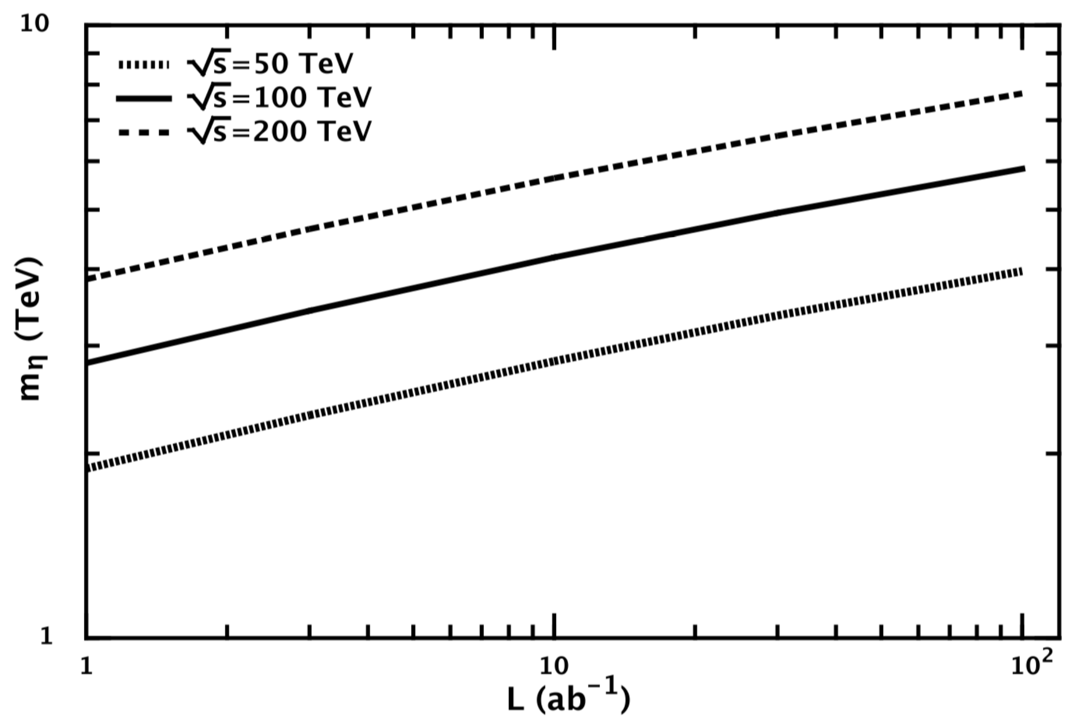
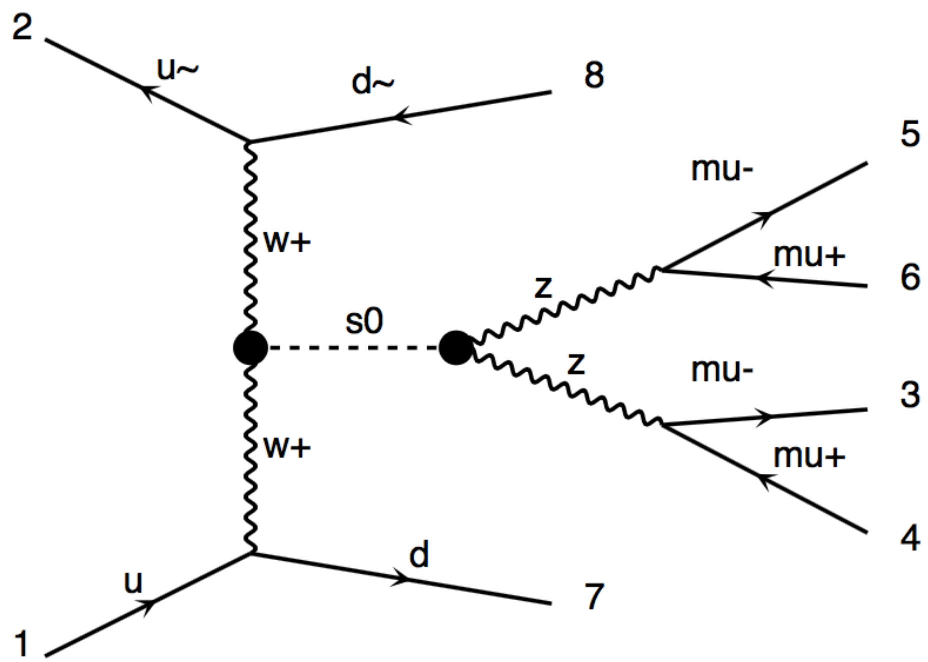


FIG. 14. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, as a function of the integrated luminosity and $\sqrt{s}$ of a pp collider. The fractional resonance width Γ_η/m_η is fixed at 70%.

ZZ final state

- Branching ratio to hh, $W_L W_L$ and $Z_L Z_L$ in the 1:2:1 ratio is a definitive prediction



Resonance decaying to two Z_L bosons is a distinctive signature of the Goldstone nature of the Higgs boson

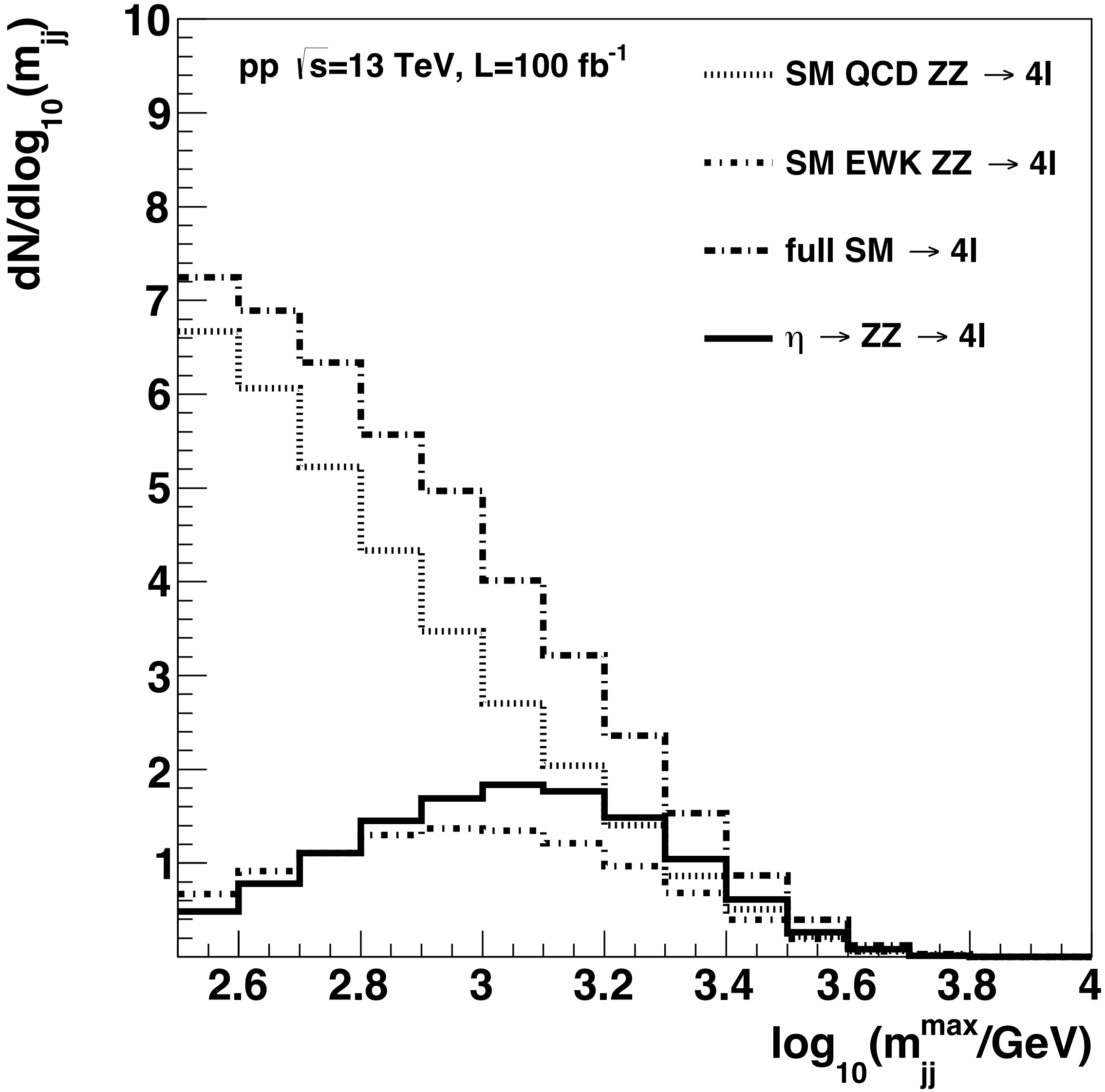
VBS ZZ Resonance at LHC

- Study *ZZ* -> 4 leptons channel
- Plots shown next use the following generator-level cuts
  - η (jet) < 4.9
  - η (lepton) < 2.5
  - p_T (lepton) > 7 GeV

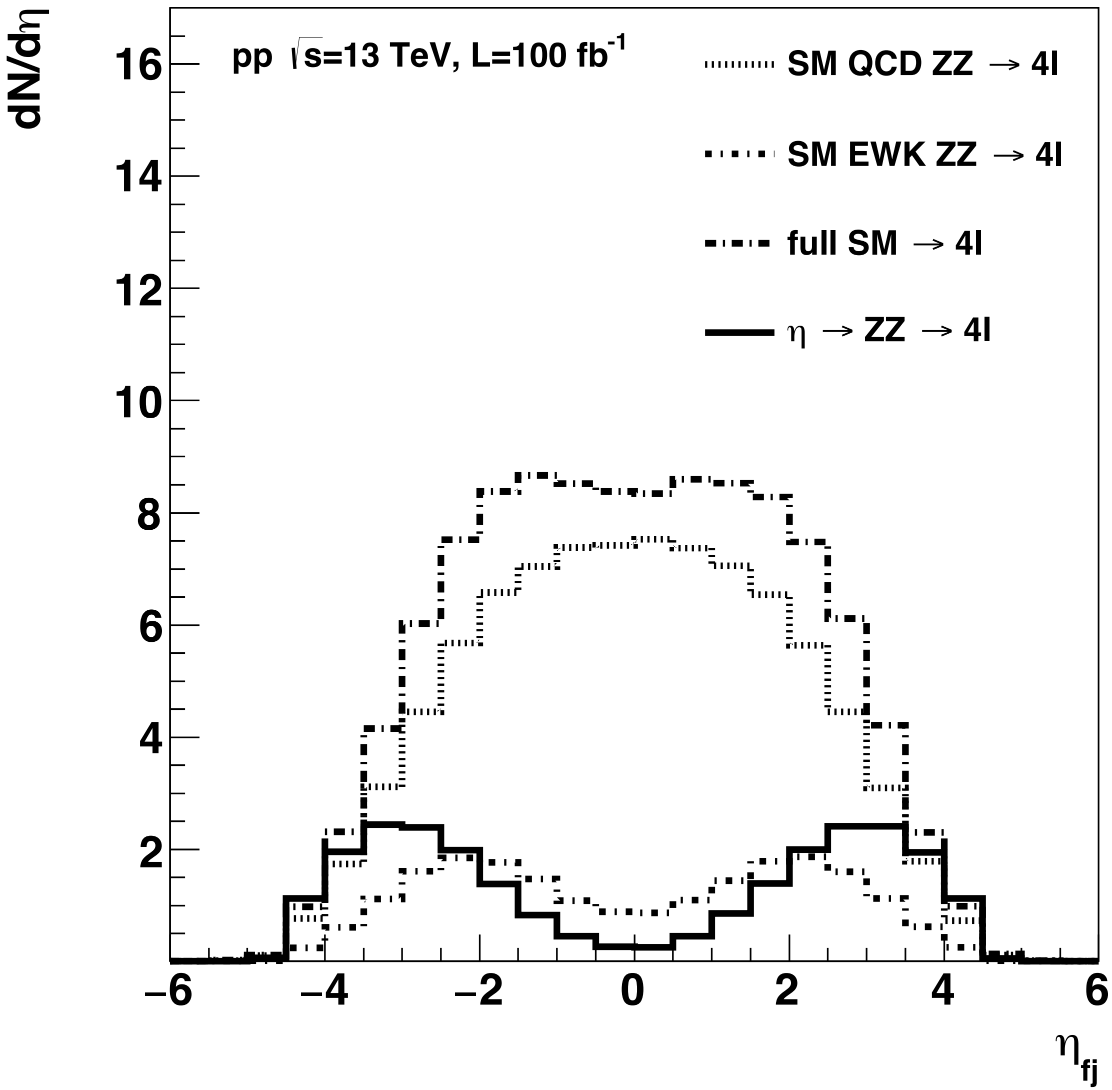
- PYTHIA used for showering and hadronization

- Detector model
  - Each lepton efficiency = 80%
  - Particles are clustered into jets using FastJet with anti-kt algorithm and R = 0.4

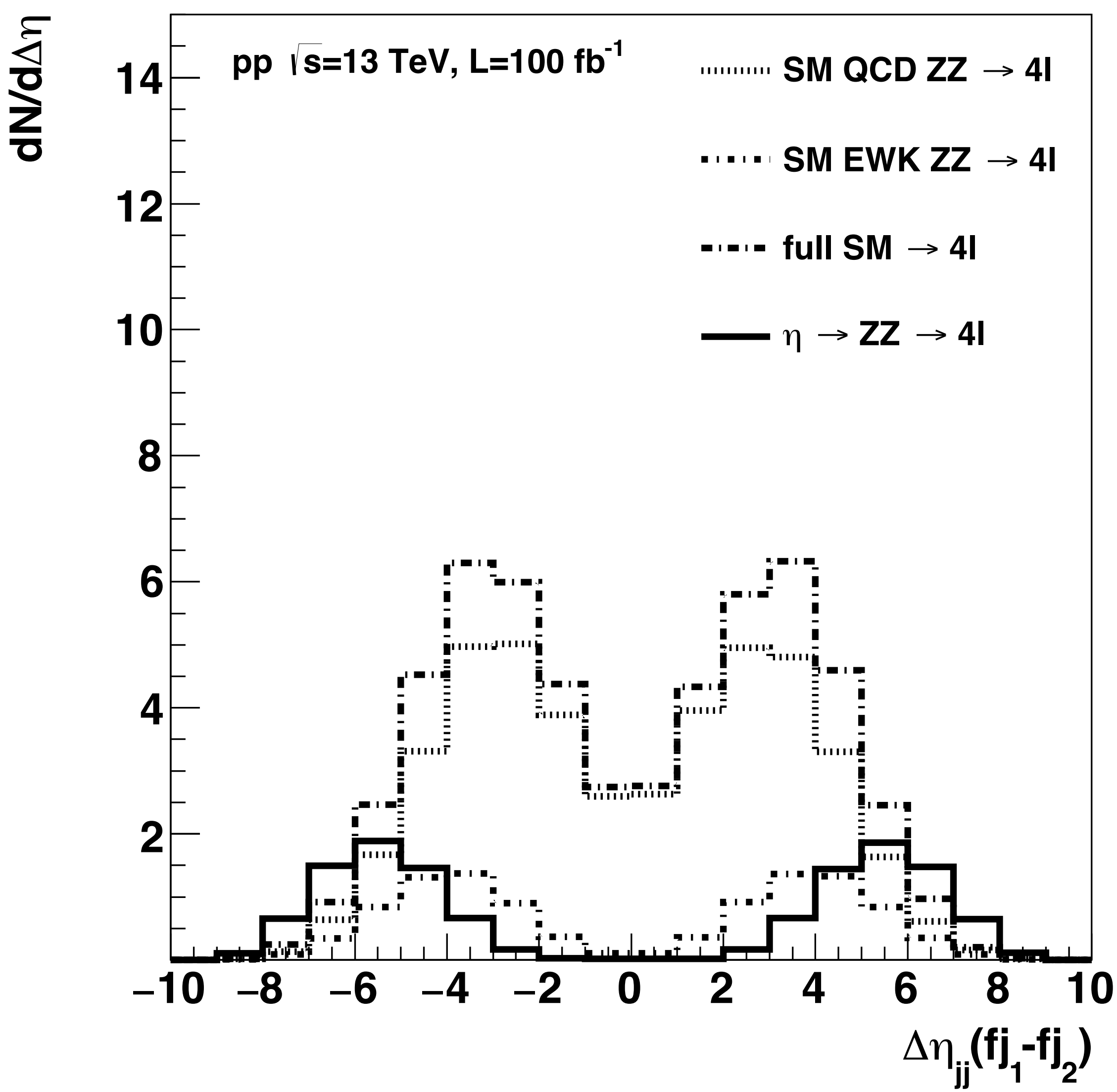
Invariant Mass of forward Jets



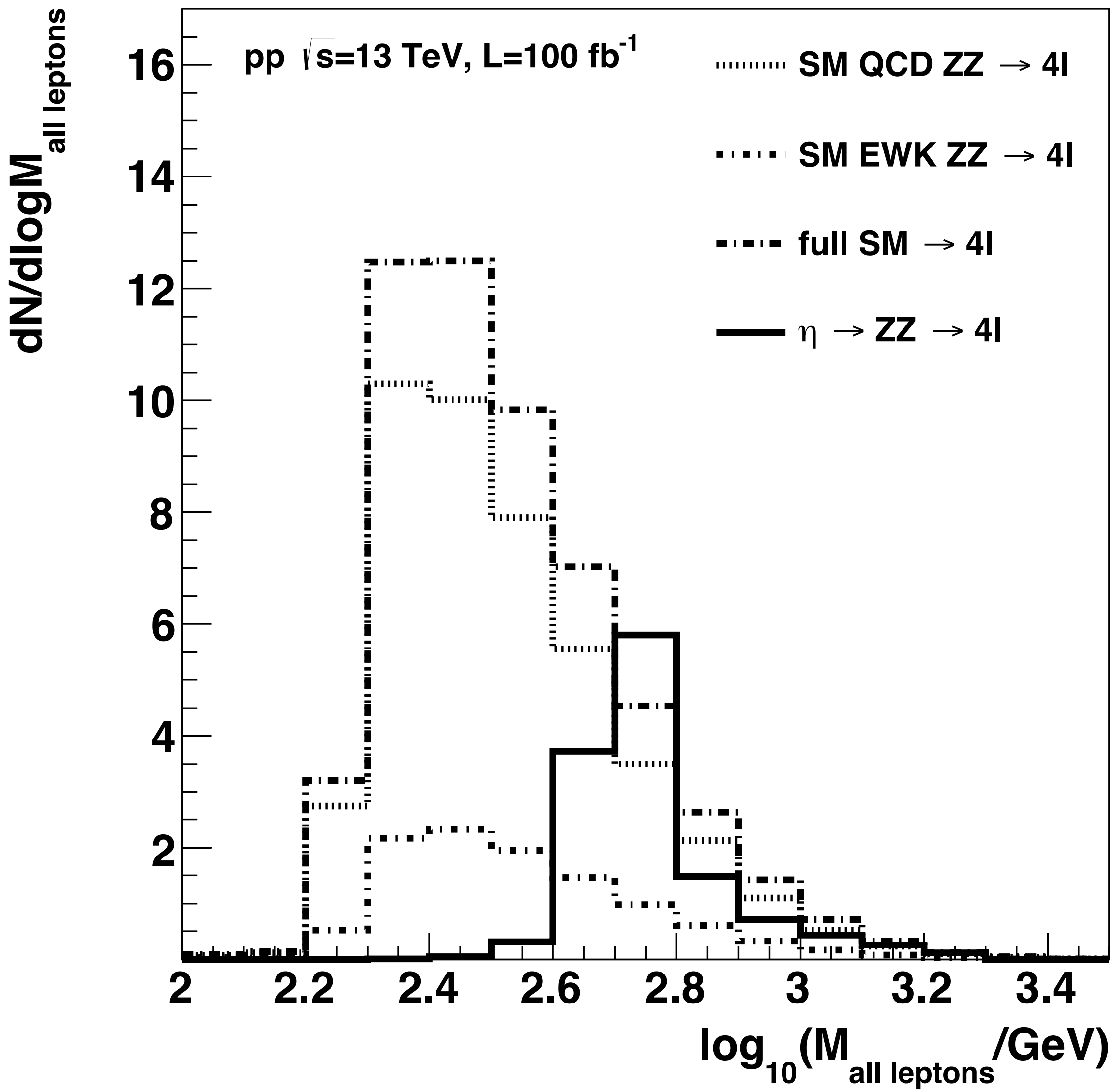
η of forward Jets



Δη of forward Jets

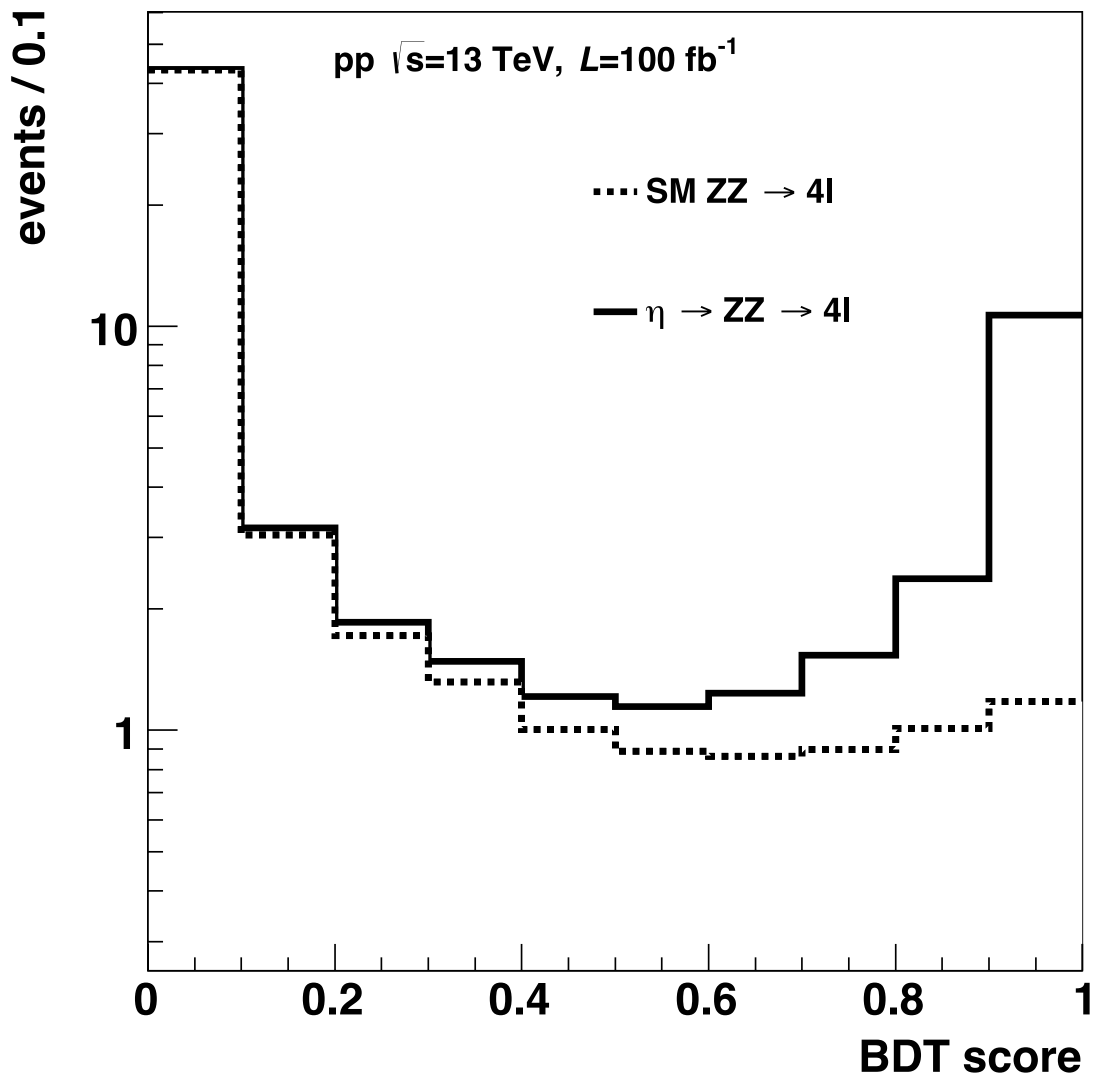


Invariant Mass of all four leptons



BDT Multivariate Discriminant

Signal is
η -> ZZ resonance
with mass = 500 GeV
And width = 20%



Frequentist
Significance
= 5.4σ in
4-lepton channel
alone

Conclusions

- It is conceivable that new strong dynamics in the Higgs sector may only be accessible via collisions of longitudinal vector boson scattering
  - A sort of "longitudinal vector boson portal"
- Can use resonance signatures mediating VV->η-> hh, ZZ production at high resonance mass
- No signal in Drell-Yan or gluon fusion production modes because no coupling to light fermions and gluons
- Resonance mass > 500 GeV can be discovered at LHC
- Resonance mass > 3 TeV can be discovered at 100 TeV *pp* collider
  - Requires tagging forward jets ~ 40 GeV and pseudorapidity ~ 6
  - VBS resonance mass reach grows nicely with integrated luminosity (better than collider energy)
- Distinctive signature, comparison between HH and VV channels can prove Composite Goldstone nature of Higgs doublet