Vector Boson Fusion and CMS Upgrades

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Introduction

The CMS experiment is very actively searching for signs of a Higgs boson at low masses, less than around 600 GeV. If a low mass signal is seen then it is important to establish that the object found is in fact a Higgs boson. In particular, the Higgs must make the W+W (or more generally V+V) scattering cross section obey the unitary limit. These vector boson scattering processes can most readily be isolated and measured using the process of vector boson fusion (VBF) where incoming quarks emit virtual gauge bosons which then scatter. CMS must be prepared to make an incisive study of the VBF process in order to explore how the gauge boson scattering processes are made unitary.

Higgs and WW Scattering

The Standard Model (SM) has an S wave amplitude for W+W scattering which diverges at high W+W mass. Perturbative S wave unitarity then sets the mass scale (Higgs mass) at or below which the process should be constrained.

$$\begin{aligned} &\sigma_o = 16\pi \,|\, a_o \,|^2 \,/ s < 4\pi / s \\ &a_o < 1/2 \\ &a_o = \hat{s} / 8\pi v^2 \\ &M_H < v\sqrt{4\pi} = 872 GeV \end{aligned} \qquad (1)$$

The Feynman diagrams for W+W scattering are shown in Fig.1. Beside s and t channel gamma and Z diagrams, there are also two Higgs diagrams which control the high energy behavior of the cross section. Finally, there is the quartic coupling which is characteristic of non-Abelian theories.

A low energy Higgs would limit the S wave scattering amplitude to small values. At the other extreme, as shown in Eq.1, at mass scales ~ 1 TeV, the W+W scattering becomes strong and the process is unitarized in some other fashion, for example, resonance production. The extreme alternatives are shown in Fig.2.

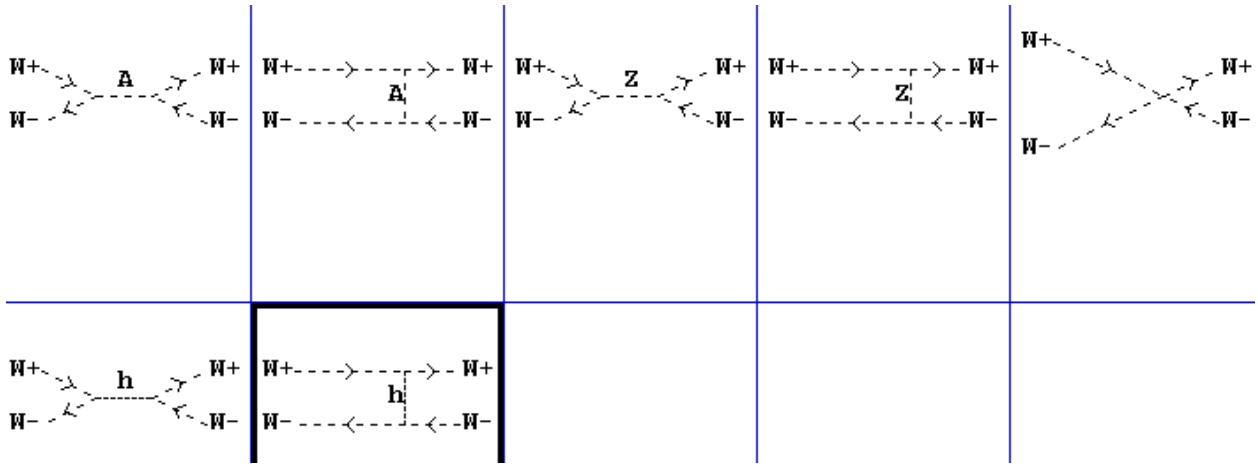

Figure 1: Feynman diagrams for W+W scattering.

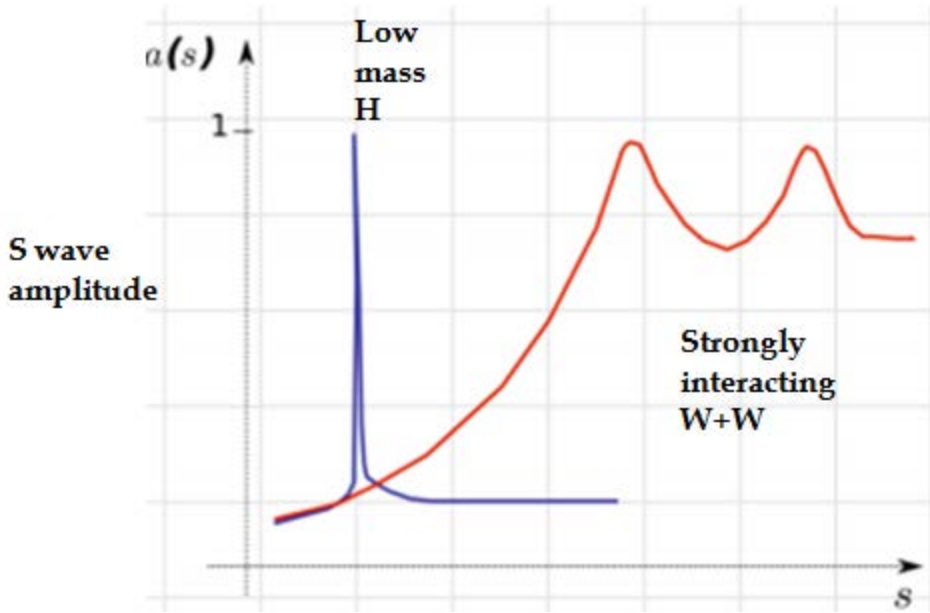

Figure 2: W+W scattering amplitude in 2 extreme limits; low mass H and strongly interacting vector bosons.

As seen in Eq. 1, without a low mass Higgs the fraction of wide angle scatters (S wave) increases quadratically with the W+W mass. This is illustrated in Fig. 3 where the W+W scattering angle distribution for a 125 GeV H is compared to the level attained for a 1 TeV Higgs boson. The differences are very large, and the 1 TeV Higgs boson has a distribution which approaches the unitary limit.

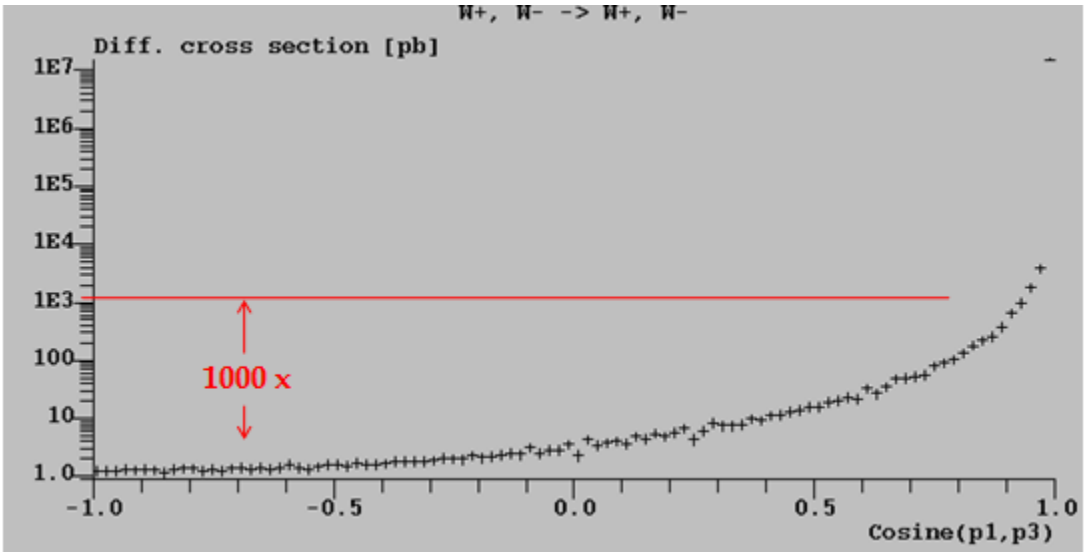

Figure 3: Angular distribution in W+W scattering at 2 TeV for the case of a 125 GeV Higgs, crosses, and a 1 TeV Higgs, shown as the red line. The difference in rate at wide angles is very large.

VBF Characteristics

Clearly, it is useful to measure the W+W scattering angular distribution in order to explore how the process is made unitary. Indeed, the extreme cases are very distinguishable. The mechanism of choice to isolate the process is VBF. The cross section is shown in Fig. 4 and is, for a 1 TeV H, ~ 100 fb. Fully leptonic decays of the W+W then have a cross section ~ 3 fb. Clearly, at 14 TeV at least 1000 /fb will be needed to look at W+W scattering at high masses because of trigger, reconstruction and selection efficiencies.

The basic characteristic of the VBF process is the existence of 2 'tag" jets in the final state. Because they recoil against the virtual emission of a W, they have a transverse momentum ~ half the W mass. Because the W are low mass the "tag" jets continue in the forward/backward direction, leading to small angle jets with a large dijet mass and a large rapidity difference.

The "tag" jet rapidity and rapidity difference is plotted in Fig. 5. Note that a typical tag jet rapidity is, y ~ 3.

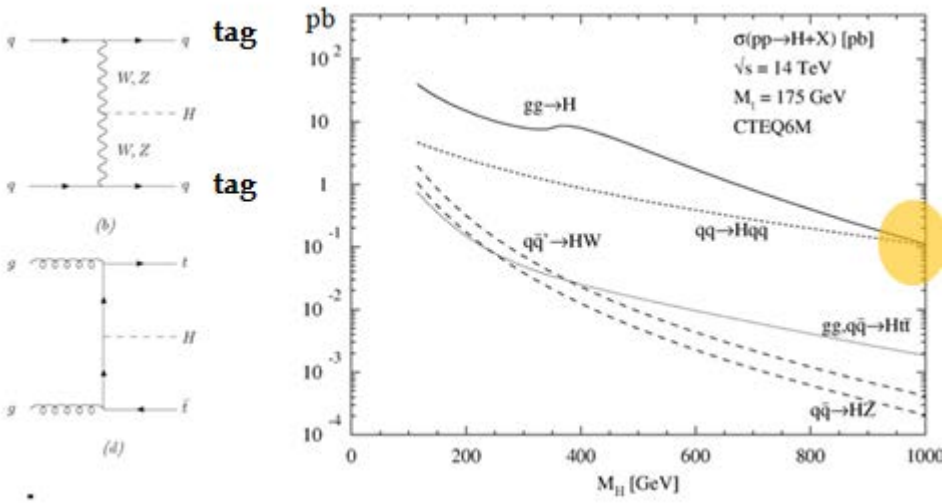

Figure 4: Feynman diagrams for VBF scattering showing the existence of the 2 "tag" jets. The cross section for Higgs production via VBF is large at high H masses, becoming comparable to the normal gluon fusion production cross section.

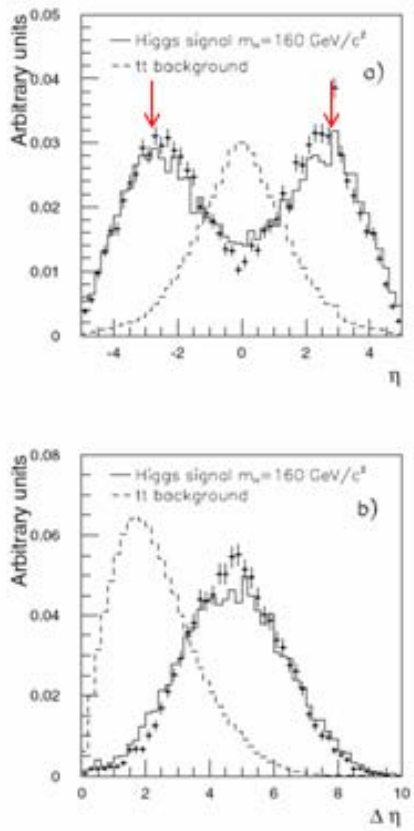

Figure 5: Plot of the VBF tag jet rapidity and the dijet rapidity difference for H production and for the top pair production background, which also has W+W in the final state and a much larger cross section.

VBF Like Events in 2011 Data

The 2011 CMS data is at too low an energy and with too little luminosity to establish the VBF process at high W+W mass. However, a first look can be taken to see if the VBF-like topology is evident. Figure 6 shows the contours of Dijet mass and rapidity difference for the 'tag" jets in W+j+j+J+J events at CMS.

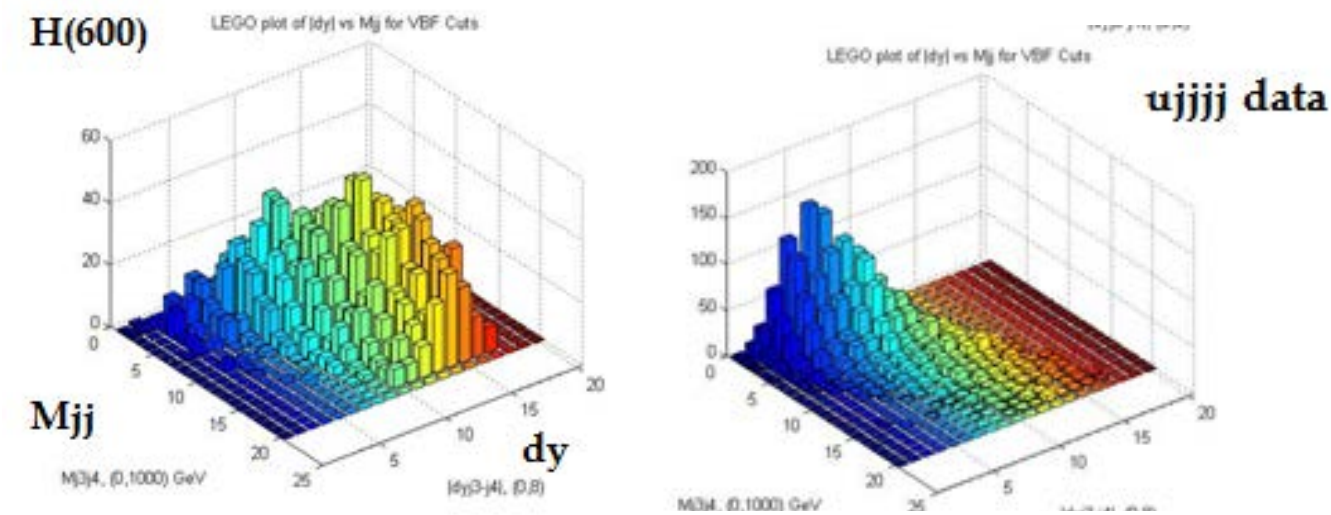

Figure 6: Monte Carlo contour of dijet mass and rapidity difference for a H of 600 GeV and for 2011 muon data for events with a muon, MET and 4 jets in the final state.

Fake Tag Jets

Since the VBF cross section is small, even at full LHC energy, the study of W+W scattering requires high luminosity. The "tag' jets allow VBF to be isolated from the much larger SM backgrounds, such as top pair production and W plus jet production.

However, particle flow (PF) cannot be used at full effectiveness because there is presently no tracking in the region where the top jets exist (see Fig. 5). In the absence of tracking, the tag jets will be swamped by pileup jets because the jet transverse momentum is quite low. Some effort has been made to use the distribution of the fraction of jet energy carried by the tag jet elements. The rejection of pileup and fake jets in the case where tracking exists and where it does not shows the problem graphically in Fig. 7. Clearly, efficient tag jet detection will not be possible for high luminosity operation with sufficient pileup jet rejection.

One strategy to improve the signal to background ratio would be to look at like sign W+W scattering by using double leptonic decays of the W. The final state branching ratio is reduced but there is no direct SM background.

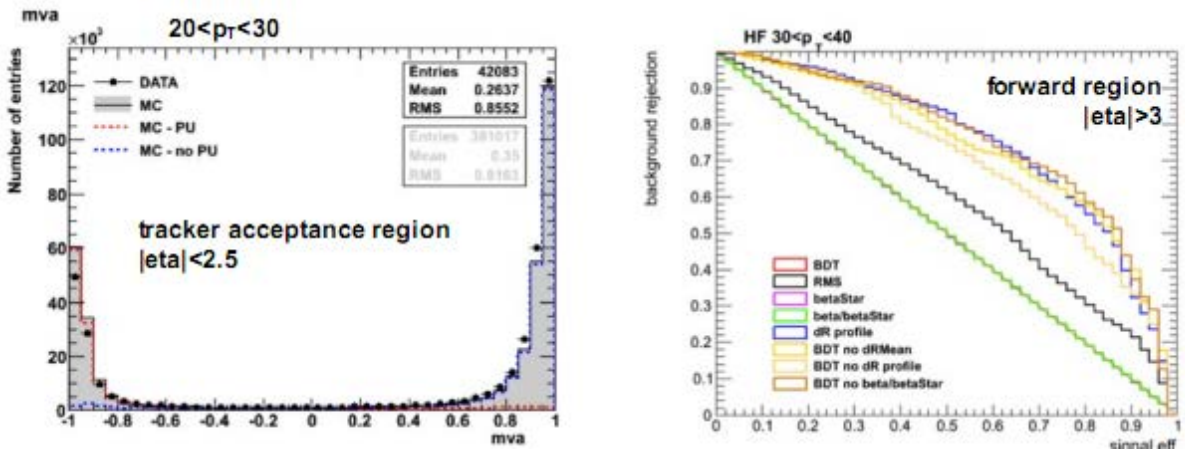

Figure 7: The MVA variable for PF jets in |y| < 2.4 and the rejection/efficiency boundary in HF, 3<|y|<5.

Forward Calorimetry

- **The physics role of HF is to provide better MET coverage (jets to y~4.5) and VBF tagging.**
- **Tag jets have Pt~Mw/2 or E of ~ 400 GeV at y~3. The energy resolution will be dominated by the "constant term". The issue for HF is not resolution.**
- **VBF jets peak at y ~ 3, right at the HE/HF interface where jets are badly measured.**
- **A separate HF can be serviced as it becomes radioactive – garage. However, a smaller HE "plug" might well turn out to be easier to service or replace.**
- **A separate HF was chosen by CMS long ago to keep the tracker from "cooking" in a "neutron bottle". Is this choice confirmed by early operating experience? ATLAS?**
- **These choices should be revisited and thought through for the high luminosity data taking driven by the desire to explore W+W scattering via the VBF mechanism.**

It is important to recall that there is not good heavy crane coverage in SX5. Thus it seems likely that for HE the 300 T + 300 T absorber structure will be retained in any upgraded CMS detector. In fact, the removable "pizza pans" can be easily be removed and outfitted with more radiation hard active elements than the present scintillator fairly easily.

The present HE/HF boundary is discontinuous. Let us assume that an HF plug "insert' can be installed which will make the region near the peak of the tag jet population in |y| quite seamless. The radiation dose scales as ~ 1/z^2, which will require some R&D to accommodate the enhanced radiation dose.

The EE will become heavily darkened and in a non-uniform fashion in depth. This non-uniform medium will then have an unacceptable constant term for energy measurements. Assume, rather, a compact twenty radiation length Pb sampling calorimeter, readout

unspecified for now. The layout so conceived is shown in Fig.8. Note that the existing EE "dees" can be removed quite easily when and if that becomes required.

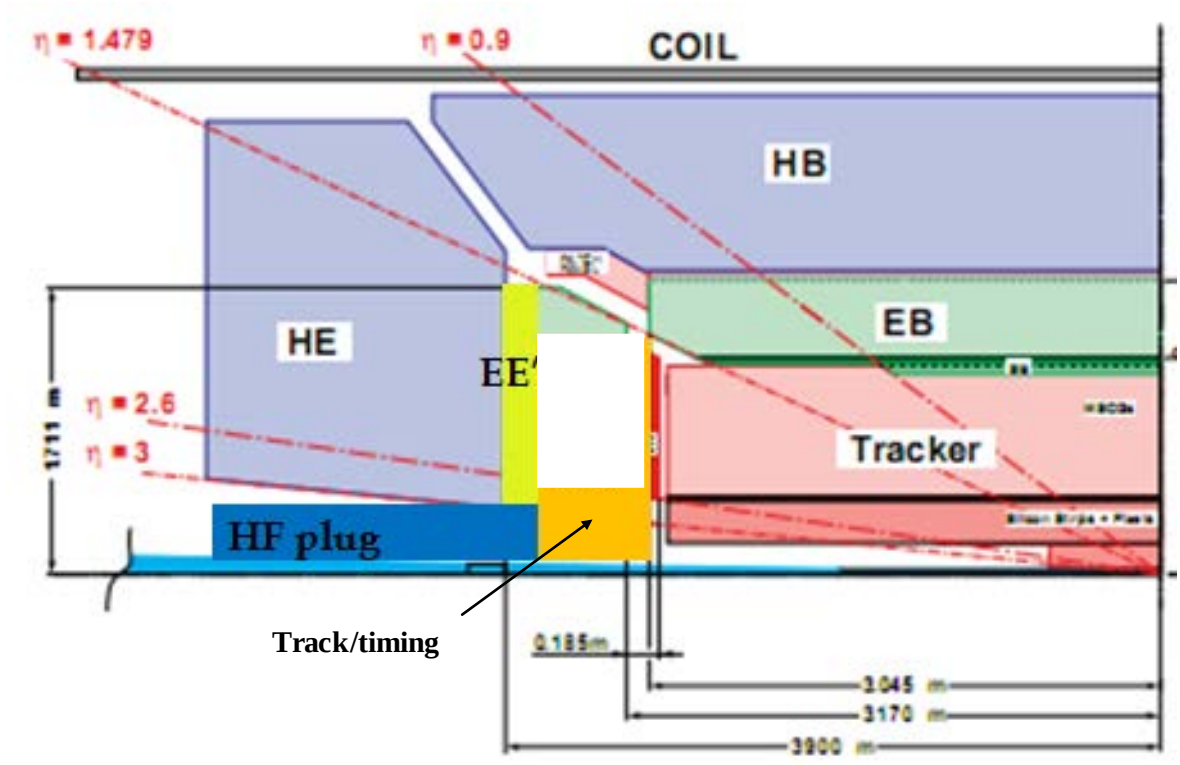

Figure 8: Rough sketch of a possible HF plug, a compact sampling EE' and a station of tracking/timing which covers the y range populated by VBF tag jets.

The relevant angles and radius at z = 3.5 m are displayed in Table 1.

Table 1: Angular Coverage of the Present HF

y	Θ(rad)	r(z = 3.5 m) - cm
3	0.1	35
4	0.037	13
5	0.0135	4.7

Forward Tracking/Timing

The need to reject pileup jets which fake tag jets will require either tracking or timing or, preferable, both. The space freed up with a compact EE' is dedicated to those measurements.

First, consider tracking. The devices are in the CMS magnetic field, so that the momentum and hence the multiple scattering weight of the track will be known which is important in correct determination of the vertex. The primary vertex (PV) resolution for the tracking is determined by the distance D from the vertex, the angle of the track, the length of the tracking region and the measurement error.

$$dz_V \sim [D\sqrt{2} / \theta\ell]dx \qquad (2)$$

Assume there are 100 primary vertices uniformly populating a beam spot of 10 cm which requires a 0.1 cm vertex resolution. With a 50 cm tracking region and extrapolating by 3.5 m, a y = 4 track requires a 4 micron resolution. That would require pixels with analogue readout – diamond? An intermediate station at z ~ 1.5 m would halve the needed resolution as indicated in Fig. 9. Note, however, that at 1.5 m a |y| = 5 track would be at a radius ~ 2 cm, so that the beam pipe must have a small radius at that z location.

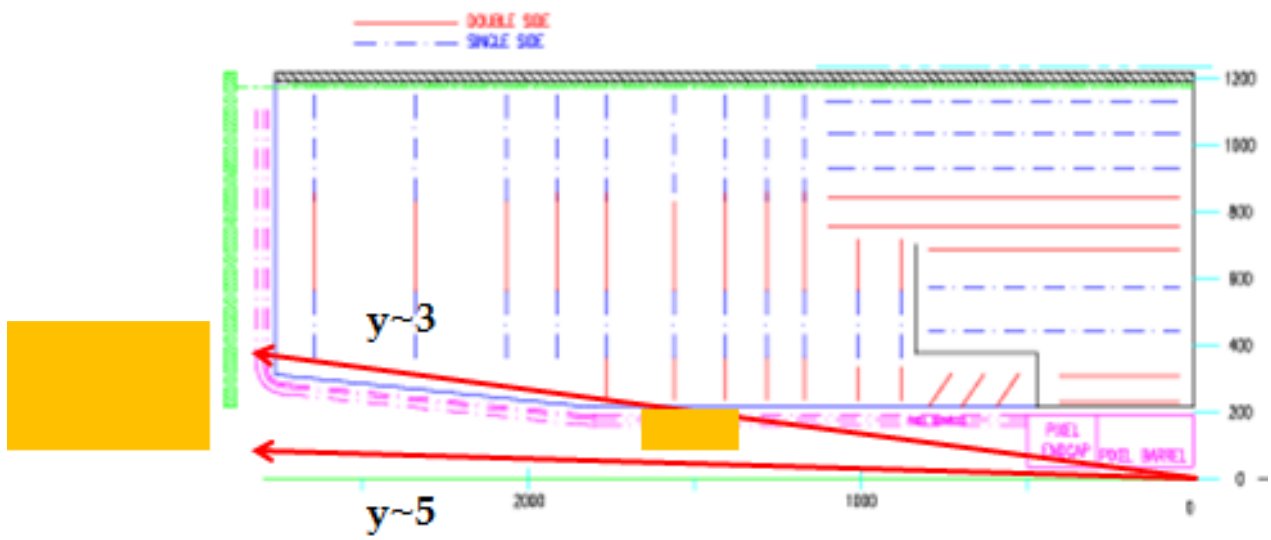

Figure 9: Tracking/timing station locations at z = 3.5 m and 1.5 m. At 1.5 m the station covers radii from 2 to 15 cm. At z = 3.5 m the radii are 4.7 and 35 cm.

For timing, sorting on the 100 PV requires a timing for a hit of ~ 3 ps. Note that a 1 nsec rise time device needs ~ 10,000 "photoelectrons" to have a 10 ps resolution. Much R&D will be needed to provide such a small time resolution over a large area. Could both timing and tracking be provided by a single detector element?

Summary

- **The primary goal of the LHC is to understand EWSB.**

- **Independent of the existence of a light SM H, the unitarization of W+W scattering must be explored and understood.**
- **The preferred mechanism to study V+V scattering is by using VBF.**
- **VBF requires high luminosity, high energy, and a rethought forward region in CMS.**
- **Pileup must be reduced to use VBF with clean tag jets. Timing and tracking need to be made available to provide the clean samples.**