Searching for the Higgs by calling all angles

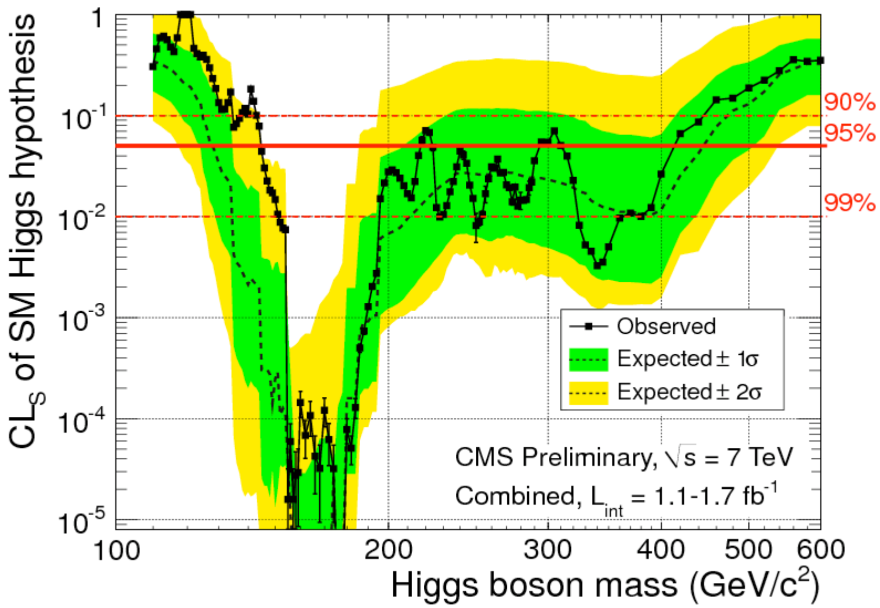
Ian Low @ CERN TH Institute

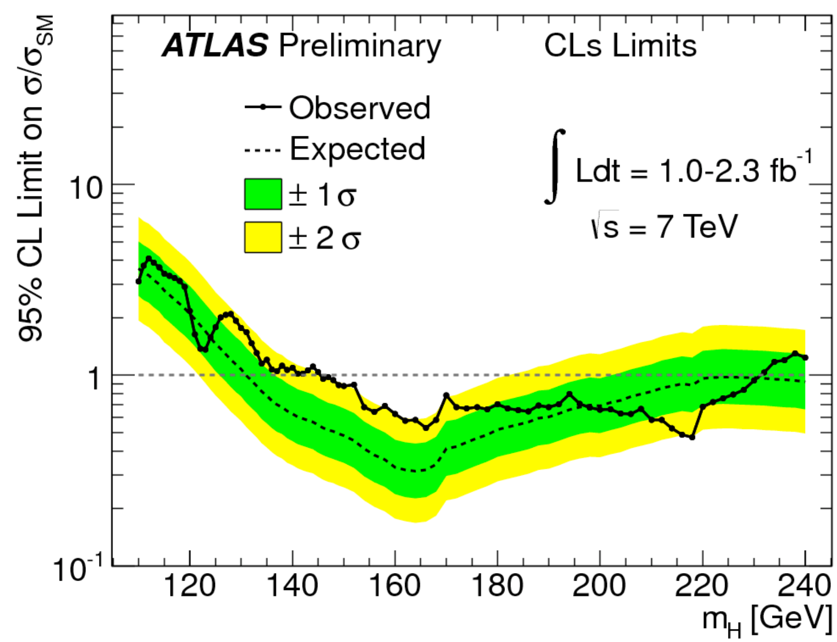
Argonne NATIONAL LABORATORY

NORTHWESTERN UNIVERSITY

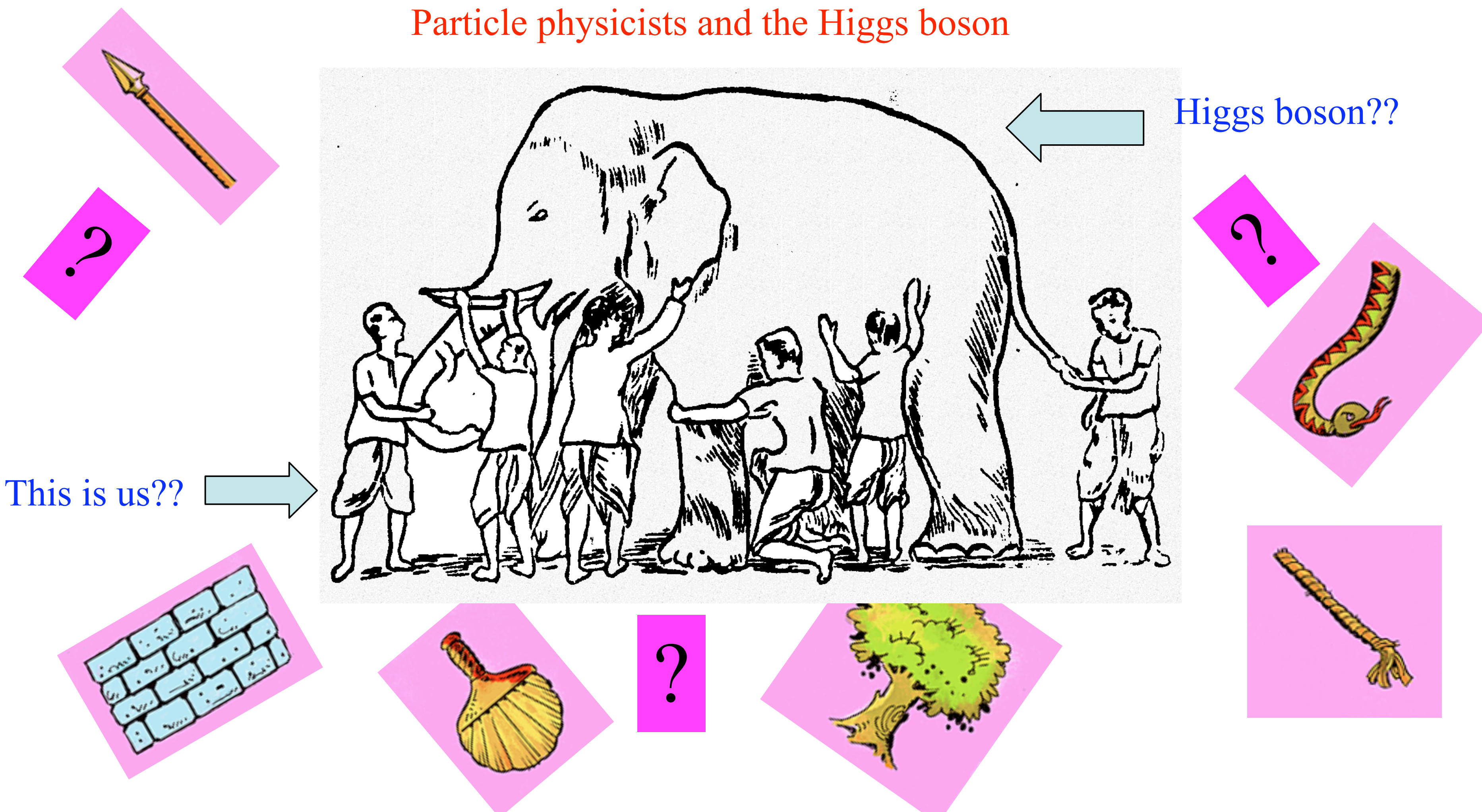
References: Keung, Low, Shu, arXiv:0806.2864.
Cao, Jackson, Keung, Low., Shu, arXiv:0911.3398
Gainer, Kumar, Low,Vega-Morales, arXiv:1108.2274

Higgs searches are among the top priority of the LHC physics program.





the challenge:
if we see a “bump”, what is it?
is it *the* Higgs boson that we all have been waiting for?



- What *is* a Higgs boson?

  we are going after the neutral component of an electroweak doublet scalar whose VEV gives a mass to the W and Z bosons.

  as such, the couplings to pairs of Ws and Zs are fixed by gauge structure:

$$\Rightarrow \quad \left(1+\frac{h}{v}\right)^2 m_V^2 V_\mu V^\mu \qquad g_{hVV} = -2i\frac{m_V^2}{v}g_{\mu\nu}$$

- Our goal should be 1) find the Higgs, and 2) verify the above coupling structure!

Spin and coupling structure of the Higgs (imposters)

- ZZ ->4 leptons final state is unique because full kinematic distributions can be reconstructed.

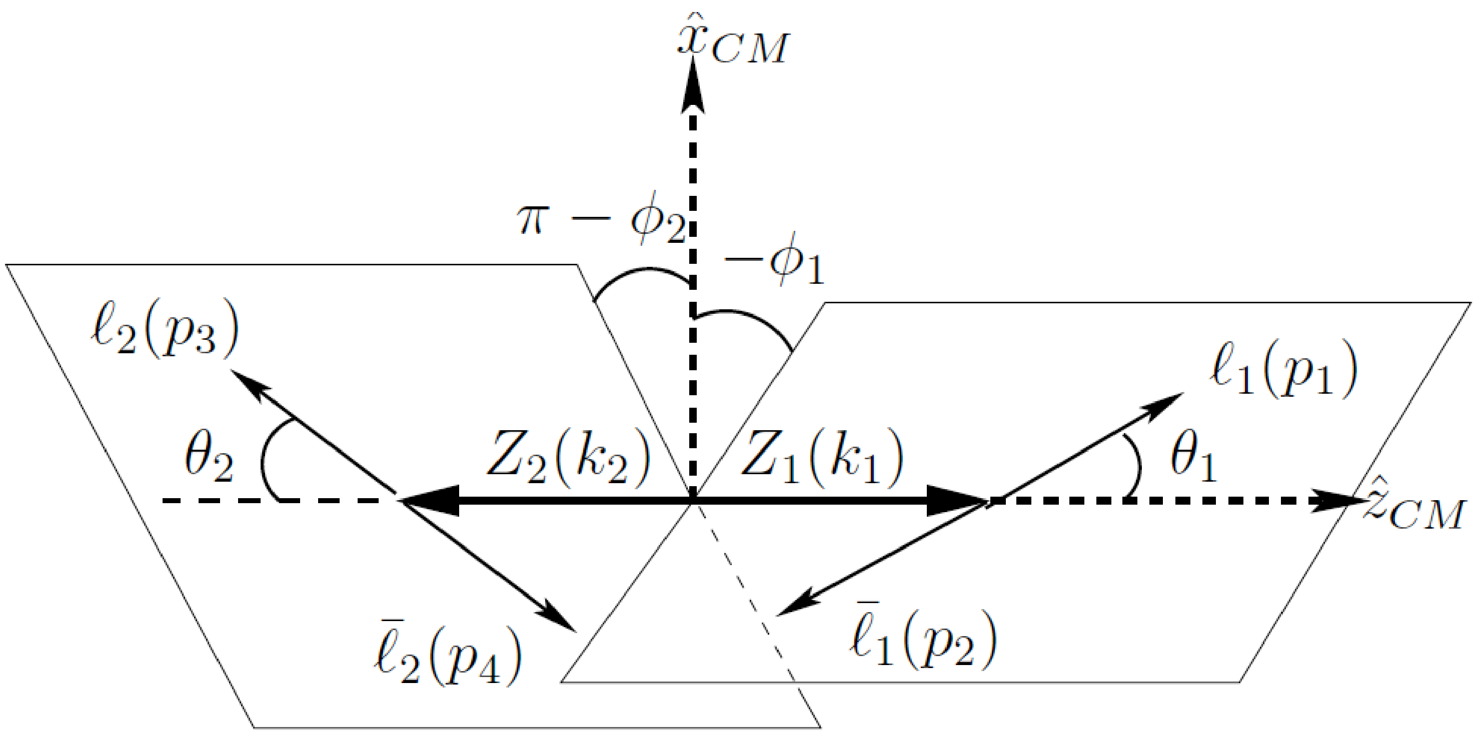
- a general analysis of a scalar decaying into ZZ:

the other two terms are higgs imposters!!

$$\mathcal{L}_{eff} = \frac{1}{2} m_S\, S \left(c_1 Z^\nu Z_\nu + \frac{1}{2}\frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

higgs mechanism predicts only this term!

- Four decay angles can be defined for ZZ -> 4 leptons. (An additional production angle can also be defined in the zero-jet bin.)



- One particular angle is very useful: the azimuthal angle between the decay planes. we computed the azimuthal angular distribution:

Negligible (~0.06) in the SM!

$$\frac{d\Gamma}{\Gamma d\phi} = \frac{1}{N}\left\{\frac{8}{9}\cos(2\phi + 2\delta) + \frac{\pi^2}{2}\frac{M_L}{M_T}\left(\frac{g_R^2 - g_L^2}{g_R^2 + g_L^2}\right)^2 \cos(\phi + \delta) + \frac{16}{9}\left(\frac{M_L^2}{M_T^2} + 2\right)\right\}.$$

$\delta = 0$ for vanishing c_3. (CP-even scalar!)

$\delta = \pi/2$ for vanishing c_1 and c_2. (CP-odd scalar!)

- previous studies (eg, CMS TDR) only focus on c_1 and c_3 without including c_2!

- A spin-1 particle (Z-prime) decaying into ZZ has cos(ϕ) instead of cos(2ϕ) dependence:

$$\frac{8\pi dN}{N d\cos\theta_1 d\cos\theta_2 d\phi} = \frac{9}{8}\Big[1 - \cos^2\theta_1\cos^2\theta_2 - \cos\theta_1\cos\theta_2\sin\theta_2\sin\theta_1\cos(\phi+2\delta) + \frac{(g_L^2 - g_R^2)^2}{(g_L^2 + g_R^2)^2}\sin\theta_1\sin\theta_2\cos(\phi+2\delta)\Big]$$

$$O_{CPV} = f_4 Z'_\mu(\partial_\nu Z^\mu)Z^\nu, O_A = f_5\epsilon^{\mu\nu\rho\sigma}Z'_\mu Z_\nu(\partial_\rho Z_\sigma)$$

$$\delta = \tan^{-1}(-f_4/f_5\beta)$$

- The cos(ϕ) v.s. cos(2ϕ) dependence of spin-1 resonance v.s. spin-0 resonance is easy to understand in terms of a generalization of the Landau-Yang theorem:

TABLE I: Helicity states $\Psi^{\lambda_1\lambda_2}$ of the Z bosons

P \ J	0	1
$+$	$\Psi^{++}+\Psi^{--}, \Psi^{00}$	$\Psi^{+0}-\Psi^{0-}, \Psi^{0+}-\Psi^{-0}$
$-$	$\Psi^{++}-\Psi^{--}$	$\Psi^{+0}+\Psi^{0-}, \Psi^{0+}+\Psi^{-0}$

$$\Psi^{++}+\Psi^{--} \sim |e^{+i\phi}A + e^{-i\phi}B| \sim C + D\cos(2\phi)$$

$$\Psi^{+0}+\Psi^{0-} \sim |e^{+i\phi}A' + B'| \sim C' + D'\cos(\phi)$$

Focus on the spin-0 case for the ϕ distribution:

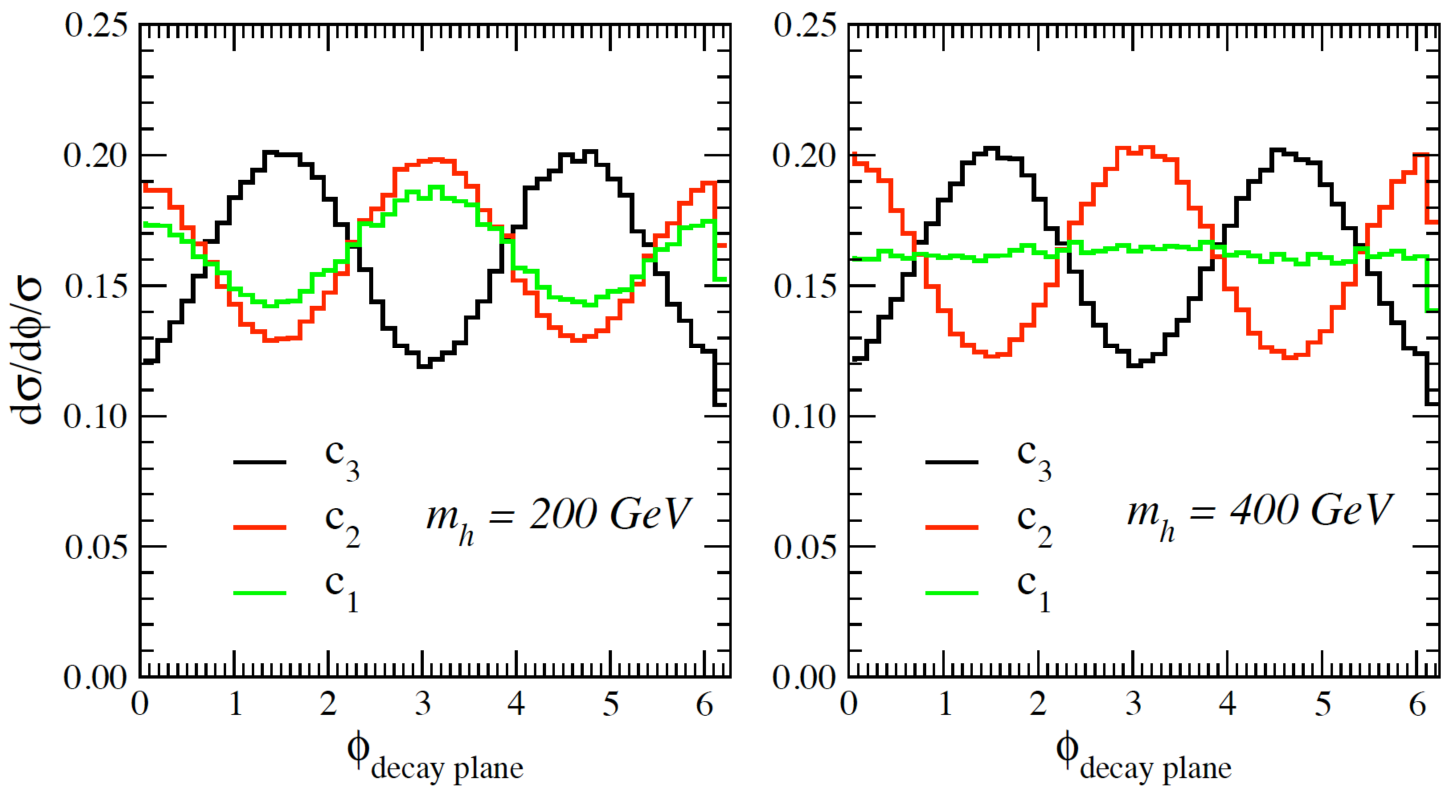


FIG. 4: *The normalized azimuthal angular distributions for 200 and 400 GeV scalar masses, turning on one operator at a time.*

- In fact, one can perform a multivariate analysis (MVA) to include all observable angles and test the different hypotheses for the spin and coupling structure of a putative Higgs signal.

- This was achieved in two (CMS) papers in 1001.3396 and 1001.5300:

Spin determination of single-produced resonances at hadron colliders

Yanyan Gao,[1,2] Andrei V. Gritsan,[1] Zijin Guo,[1] Kirill Melnikov,[1] Markus Schulze,[1] and Nhan V. Tran[1]

Higgs look-alikes at the LHC

A. De Rújula[a,b,c], Joseph Lykken[d], Maurizio Pierini[c], Christopher Rogan[e], and Maria Spiropulu[c,e]

However, these two works focus on the scenario where a signal was already found and went on to testing one hypothesis versus another.

- It’s natural to think about using spin correlations to separate signal from background.

- Traditional search strategies in the ZZ->4 leptons channel only rely on measuring the total invariant mass without incorporating angular information! (Surprisingly, there exists no MVA in this channel!)

- We performed a MVA analysis -- the matrix element method (MEM) -- to improve search sensitivity of the Higgs boson at 7 TeV LHC.

MEM is the use of maximum likelihood method where the probability density function is simply the differential cross section we compute in QFT!

- The goal is to exploit differences in the production and decay matrix elements between signal and the dominant irreducible SM background from

$$q\bar{q} \to ZZ^{(*)} \to 4\ell$$

- We need to compute the fully different cross section of the background, which is best organized using the method of helicity amplitudes.

- When both Z bosons are on-shell, the amplitude for the background has been computed long ago in

> Gunion and Kunszt, PRD 33, 665 (1986)
> Duncan, Kane, and Repko, NPB, 272, 517 (1986)
> Hagiwara, Peccei, Zeppenfeld, and Hikasa, NPB, 282, 253 (1987)

 (although there was no analytic expressions for the full differential distributions.)

- Since we are interested in a higgs mass range below 2mZ, we extended the calculation to the case of off-shell Z bosons.

- Just to show that we did the work:

$$q(k_q,\sigma) + \bar{q}(k_{\bar{q}},\bar{\sigma}) \longrightarrow Z_1(k_1,\lambda_1) + Z_2(k_2,\lambda_2)$$

$$Z_1(k_1,\lambda_1) \longrightarrow \ell_1(p_1,\sigma_1) + \bar{\ell}_1(p_2,\sigma_2)$$

$$Z_2(k_2,\lambda_2) \longrightarrow \ell_2(p_3,\sigma_3) + \bar{\ell}_2(p_4,\sigma_4)$$

$$\boxed{\mathcal{M}^{ZZ}_{\sigma\bar{\sigma};\lambda_1\lambda_2} = 4\sqrt{2}\,\left(g^{Zq\bar{q}}_{\Delta\sigma}\right)^2\,\epsilon\,\delta_{|\Delta\sigma|,\pm 1}\frac{\mathcal{A}^{\Delta\sigma}_{\lambda_1\lambda_2}(\Theta)\;d^{J_0}_{\Delta\sigma,\Delta\lambda}(\Theta)}{4\beta_1\beta_2\sin^2\Theta + (1-\beta_1\beta_2)^2 - x^2(1+\beta_1\beta_2)^2}}$$

$$\Delta\lambda = \pm 2:\;\; \mathcal{A}^{\Delta\sigma}_{\pm\mp} = -\sqrt{2}(1+\beta_1\beta_2)\;,$$

$$\Delta\lambda = \pm 1:\;\; \mathcal{A}^{\Delta\sigma}_{\pm 0} = \frac{1}{\gamma_2(1+x)}\Bigg[(\Delta\sigma\Delta\lambda)\left(1+\frac{\beta_1^2+\beta_2^2}{2}\right) - 2\cos\Theta$$
$$-(\Delta\sigma\Delta\lambda)(\beta_2^2-\beta_1^2)x - 2x\cos\Theta - (\Delta\sigma\Delta\lambda)\left(1-\frac{\beta_1^2+\beta_2^2}{2}\right)x^2\Bigg]$$

$$:\;\; \mathcal{A}^{\Delta\sigma}_{0\pm} = \frac{1}{\gamma_1(1-x)}\Bigg[(\Delta\sigma\Delta\lambda)\left(1+\frac{\beta_1^2+\beta_2^2}{2}\right) - 2\cos\Theta$$
$$-(\Delta\sigma\Delta\lambda)(\beta_2^2-\beta_1^2)x + 2x\cos\Theta - (\Delta\sigma\Delta\lambda)\left(1-\frac{\beta_1^2+\beta_2^2}{2}\right)x^2\Bigg]$$

$$\Delta\lambda = 0:\;\; \mathcal{A}^{\Delta\sigma}_{\pm\pm} = -(1-\beta_1\beta_2)\cos\Theta - \lambda_1\Delta\sigma(1+\beta_1\beta_2)x\;,$$

$$\Delta\lambda = 0:\;\; \mathcal{A}^{\Delta\sigma}_{00} = 2\gamma_1\gamma_2\cos\Theta\left[((1-x)\beta_1 + (1+x)\beta_2)\sqrt{\frac{\beta_1\beta_2}{1-x^2}} - (1+\beta_1^2\beta_2^2)\right]$$

t-channel singularity
In the high eneryg limit.

$$\boxed{\mathcal{M}^{(i)}_{\lambda_i;\sigma_i\bar{\sigma}_i} = \Delta\sigma_i\;(-1)^{\lambda_i}\sqrt{2}\;g^{Z\ell\bar{\ell}}_{\Delta\sigma}\;d(\Delta\sigma_i,\lambda_i,\theta_i)\;m_i\;e^{i\lambda_i\phi_i}}$$

- In the end the analytic expression is quite long, but we have it. it's interesting to plot some singly and doubly angular distributions.

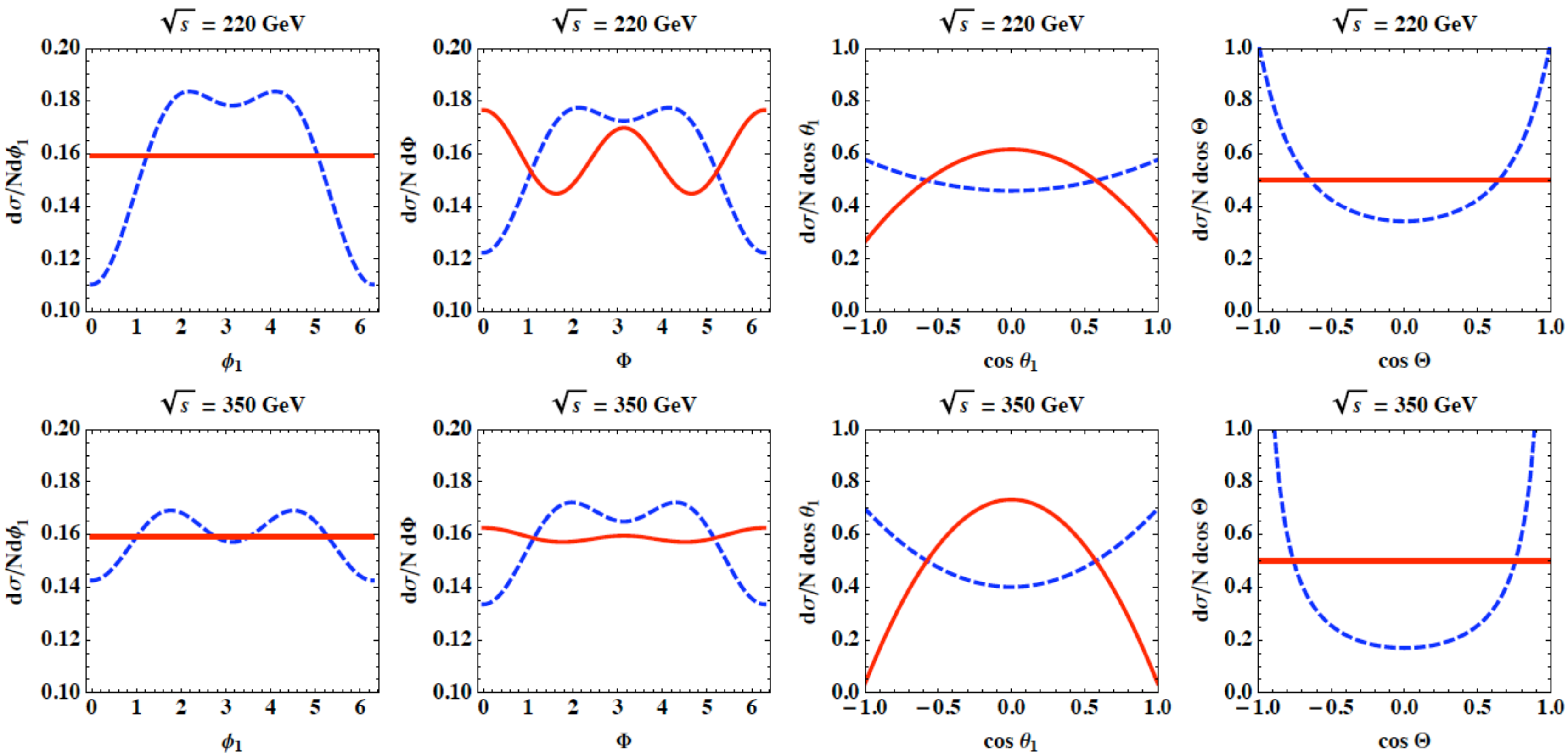
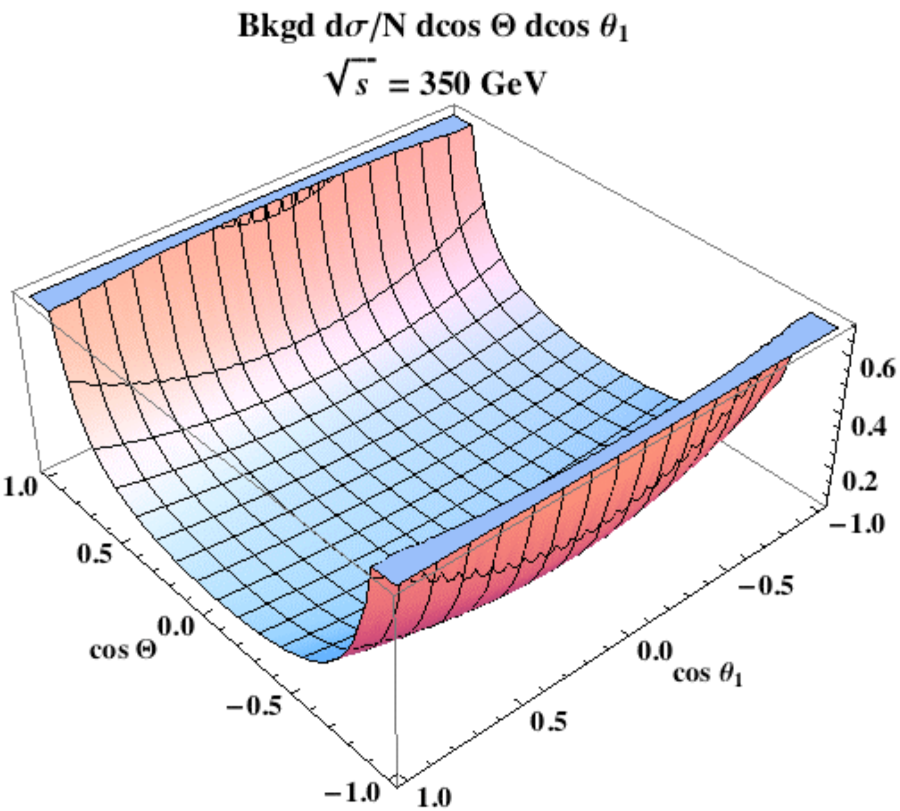
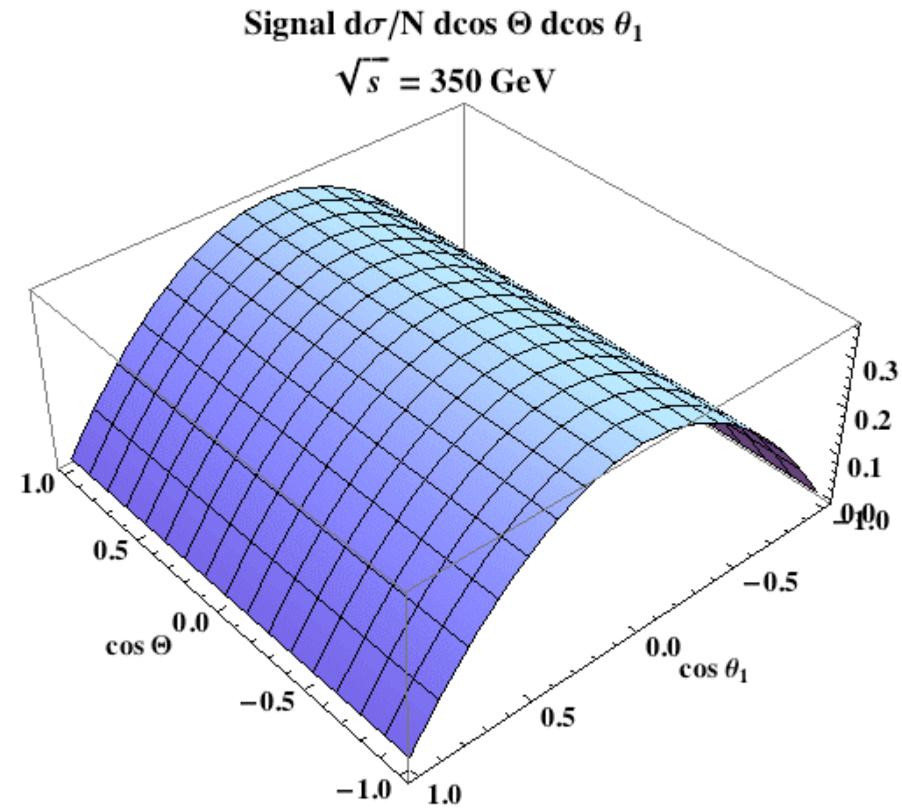


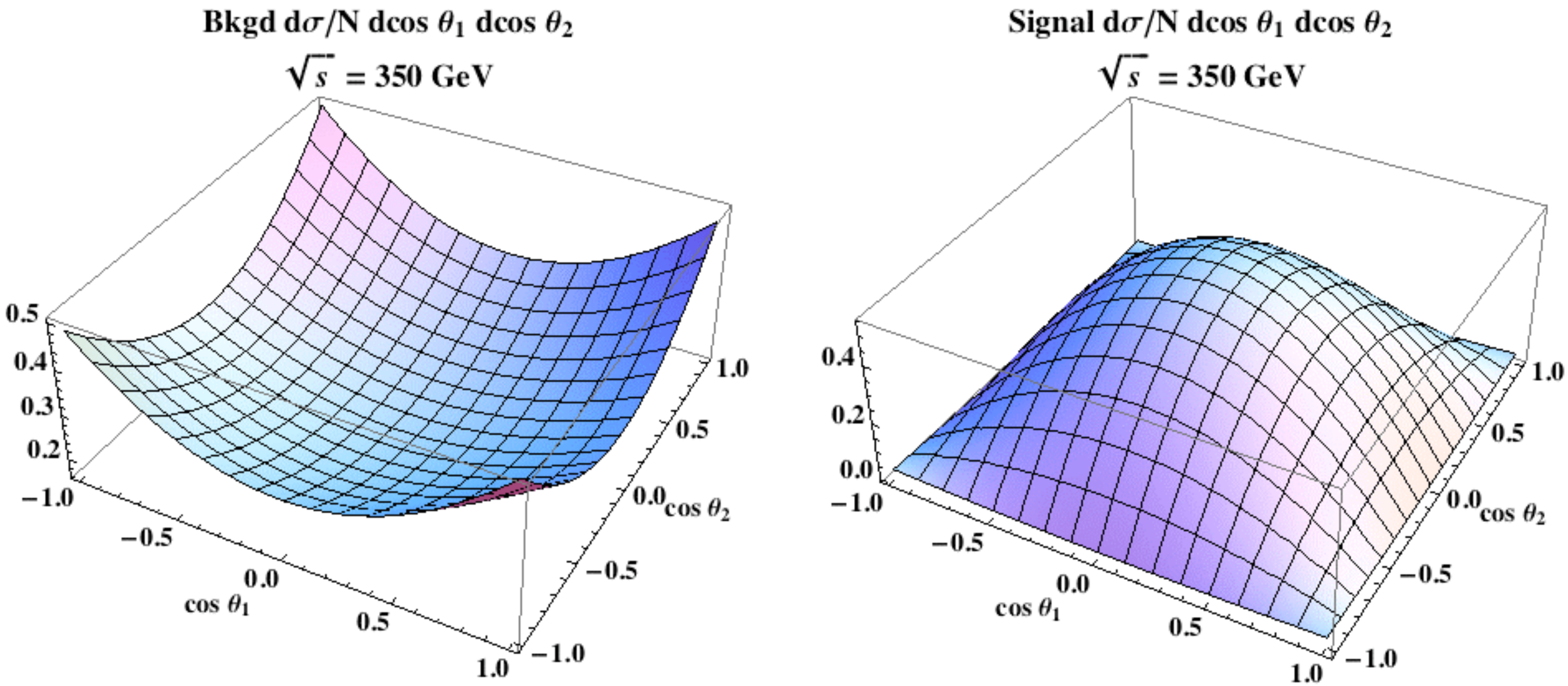
FIG. 3. *Signal and background singly differential distributions at* $m_h = \sqrt{s} = 220$ *and* 350 *GeV. The blue (dashed) lines are background distributions and the red (solid) lines are signal distributions.*



Bkgd dσ/N dcos Θ dcos θ1
√s = 350 GeV
cos Θ
cos θ1
0.6
0.4
0.2
1.0
0.5
0.0
−0.5
−1.0



Signal dσ/N dcos Θ dcos θ1
√s = 350 GeV
cos Θ
cos θ1
0.3
0.2
0.1
1.0
0.5
0.0
−0.5
−1.0


Bkgd $d\sigma/N\,d\cos\theta_1\,d\cos\theta_2$
$\sqrt{s} = 350$ GeV
0.5
0.4
0.3
0.2
−1.0
−0.5
0.0
$\cos\theta_1$
0.5
1.0
−1.0
−0.5
0.0
$\cos\theta_2$
0.5
1.0
Signal $d\sigma/N\,d\cos\theta_1\,d\cos\theta_2$
$\sqrt{s} = 350$ GeV
0.4
0.2
0.0
−1.0
−0.5
0.0
$\cos\theta_1$
0.5
1.0
−1.0
−0.5
0.0
$\cos\theta_2$
0.5
1.0

- To obtain the expected sensitivity, both for discovery significance and exclusion limit, we perform a Monte Carlo study with 10,000 pseudo-experiments.

- We use Gaussian smearings on the electron energy and muon P_T according CMS TDR.

- We introduce the following cuts

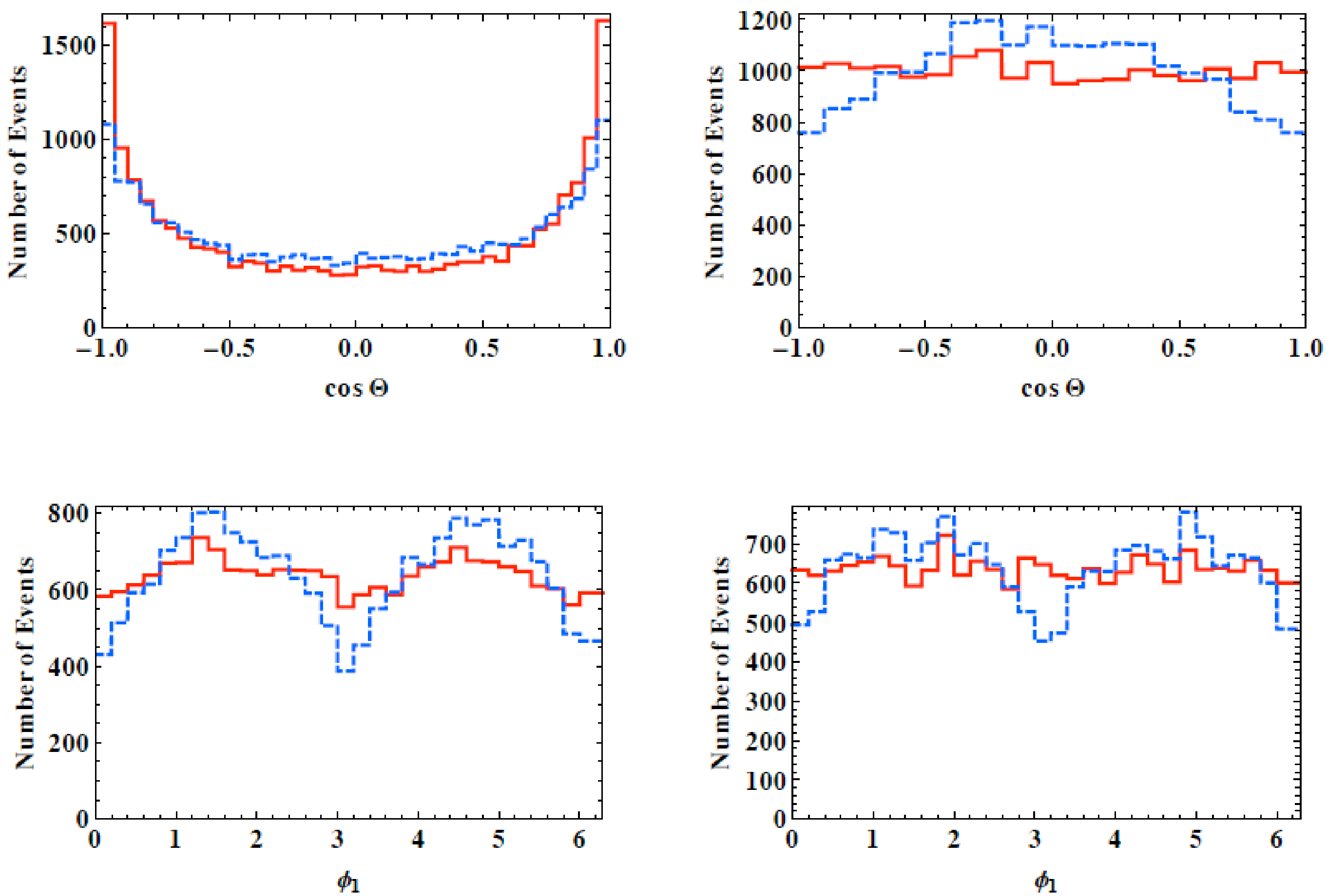
$$|p_T| \geq 10 \quad \mathrm{GeV}$$

$$|\eta| \leq 2.5$$

- We focus on the invariant mass window:

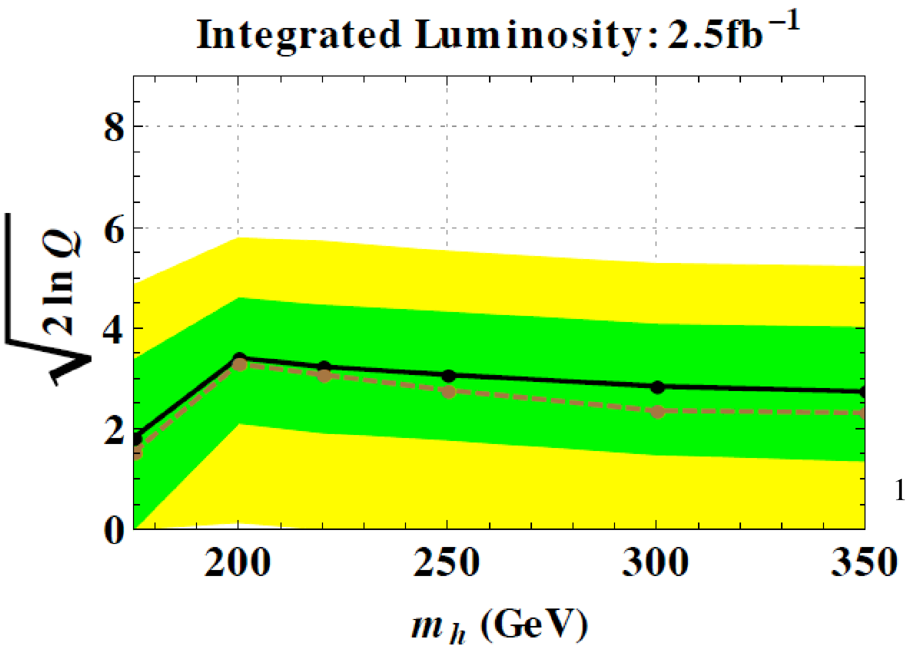
$$150 \quad \mathrm{GeV} \ \leq \ \hat{s} \ \leq \ 450 \quad \mathrm{GeV}$$

- Smearing and detector acceptance modify the angular distributions:

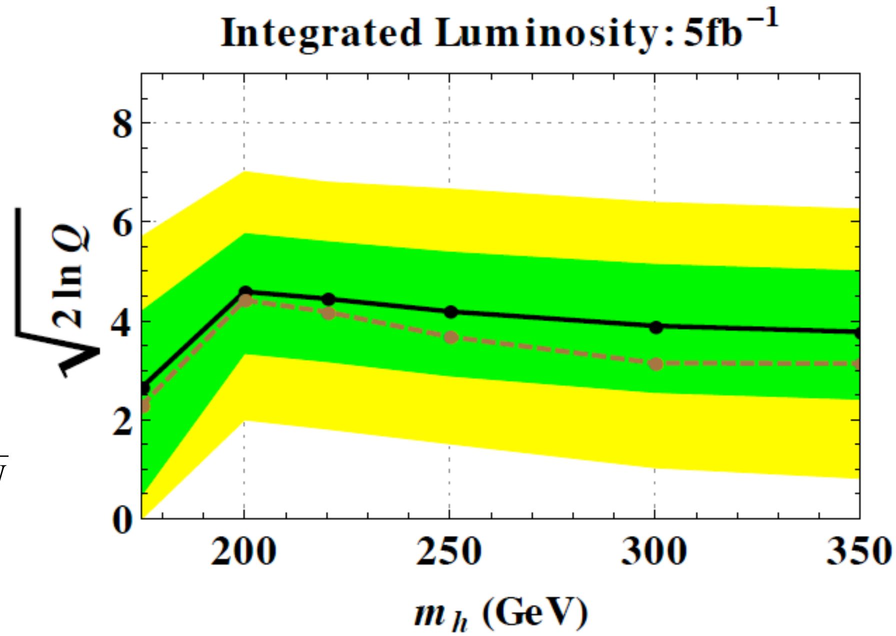


Left column is background and right column is signal.
Red is before and blue after smearing/cuts.

The results for discovery significance:

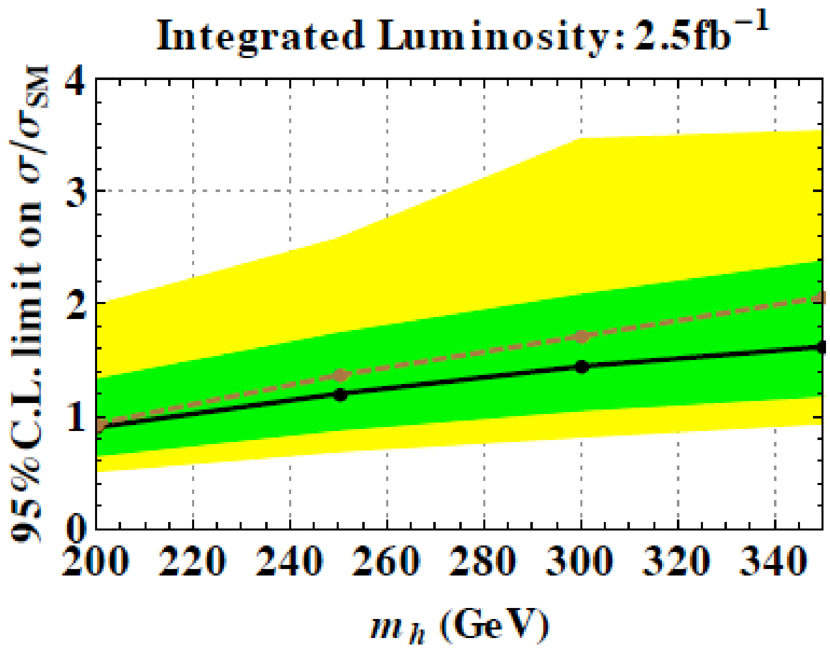


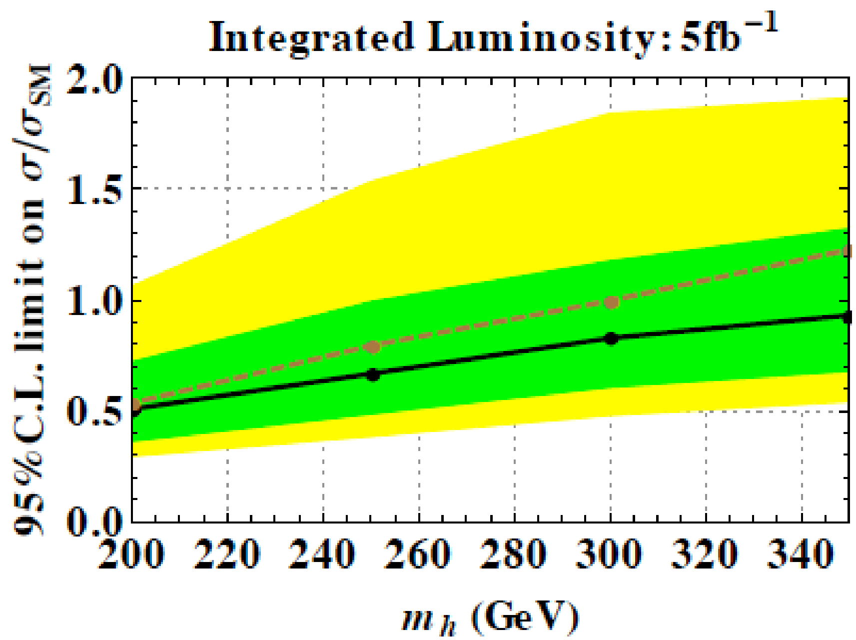
$1/\sqrt{N}$



- Red dotted line is from invariant mass measurement only while solid black line is including all angular variables.
- Improvement is in 10 -- 20 % toward high mass region, in the ballpark of what one would expect from a MVA analysis.
- This is not far from the 40% improvement from doubling the amount of data, which scales like Sqrt{N}.

- Similarly for exclusion limits:





- We are already providing theory support for CMS, which has started implementing the MEM analysis in this channel.
- ATLAS has also shown strong interests.
- Since we allow Zs to be off-shell, our analysis applies to a Higgs mass below 150 GeV!

What's next?

- All eyes on a low mass Higgs now. If we see some exccess in WW channel, would like confirmation (and mass measurement) in the ZZ -> 4l channel.

- However, in this mass range, Z\gamma -> l+l-\gamma is actually more competitive than 4l channel since you pay only one factor of 3% for BF(Z->l+l-), instead of (3%)^2!!

- Furthermore, all final states can also be reconstructed in Z\gamma channel. There is enough information to allow for spin determination!

  Ref: Gainer, Keung, Low, Schwaller, in progress

- One should also directly test the spin hypothesis at the onset of discovery, by comparing spin 0/1/2 v.s. background.