Sensitivity study of a search for a charged scalar particle in 14 TeV proton-proton collisions

WNPPC

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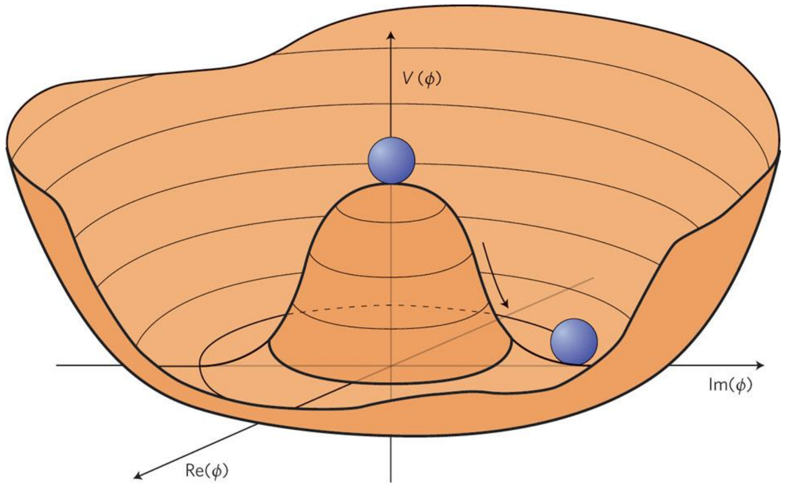
Outline

1. Introduction: Higgs Bosons,
2. Objective of study,
3. Analysis technique,
4. Outlook.

The Higgs boson

- Higgs Boson in the Standard Model (SM) arises from Higgs Mechanism and spontaneous symmetry breaking.



- SM breaks $SU(2) \times U(1)$ symmetry with one complex spin-0 $SU(2)$ doublet $\phi \Rightarrow$ one neutral Higgs boson.

The Higgs boson

- Scenario is not unique; can…
  - ➢break a different (larger) symmetry with same field content,
  - ➢break same symmetry with different field content,
  - ➢break a different symmetry with different field content.

  to obtain SM-like Higgs.
- e.g. Georgi-Machacek model, two higgs-doublet model, minimal supersymmetric standard model, …
- Many alternatives to SM predict a charged Higgs boson, H^+.

$H^{\pm}$

- Searched for in many decay channels and mass ranges; not observed to date.
- Some constraints (95% CL):
  - $m_{H^{\pm}} \geq 78.5$ GeV (LEP) in Type-II 2HDM, assuming $BR(H^{+} \rightarrow \tau^{+}\nu) + BR(H^{+} \rightarrow c\bar{s}) = 1$ [arXiv:hep-ex/0107031],
  - $\sigma_{VBF}(H^{\pm}) \times BR(H^{\pm} \rightarrow W^{\pm}Z) \leq 36 - 573$ fb for $m_{H^{\pm}}$ in range $200 - 2000$ GeV (CMS) (model independent) [Phys. Rev. Lett. 119, (2017) 141802],
  - $BR(t \rightarrow H^{+}b) \leq 0.012 - 0.051$ for $m_{H^{\pm}}$ in range $90 - 150$ GeV (ATLAS) in 2HDM assuming $BR(H^{+} \rightarrow c\bar{s}) = 1$ [Eur. Phys. J. C (2013) 73:2465].

Objective

- Study sensitivity of a search for $H^{\pm}$ through the process $\boldsymbol{pp \to H^+H^- \to W^+\gamma W^-\gamma}$.
  - Studying $jjjj\gamma\gamma$ final state (W's decay hadronically),
  - Study sensitivity with amount of data expected after LHC Run-3 ($\sim$ 300 fb^{-1}),
  - Set limits on $\sigma(pp \to H^+H^-) \times BR^2(H \to W\gamma)$.

Tools

FeynRules → **MadGraph** → **Pythia** → **Delphes**

FeynRules

- Takes Lagrangian of model and generates Feynman rules.

MadGraph

- Generates event kinematics and cross-section/decay rate.

Pythia

- Decays and hadronizes final state particles.
- Adds ISR/FSR.

Also: Generates minimum bias events for pileup simulation.

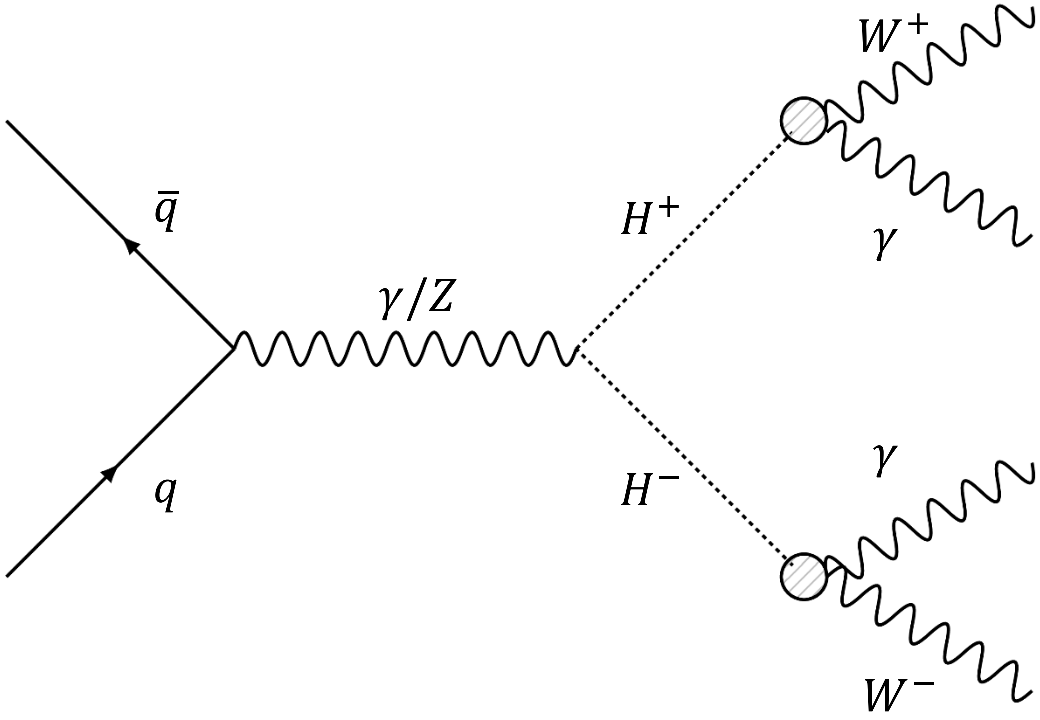
Delphes

- Simulates detector response of a generic cylindrical detector.
  - ➢ Anti-kt jet algorithm, $R = 0.4$.
- Overlays pileup on signal.

- Simulate at center of mass energy $\sqrt{s} = 14$ TeV.
- Average pileup $\langle\mu\rangle = 140$.

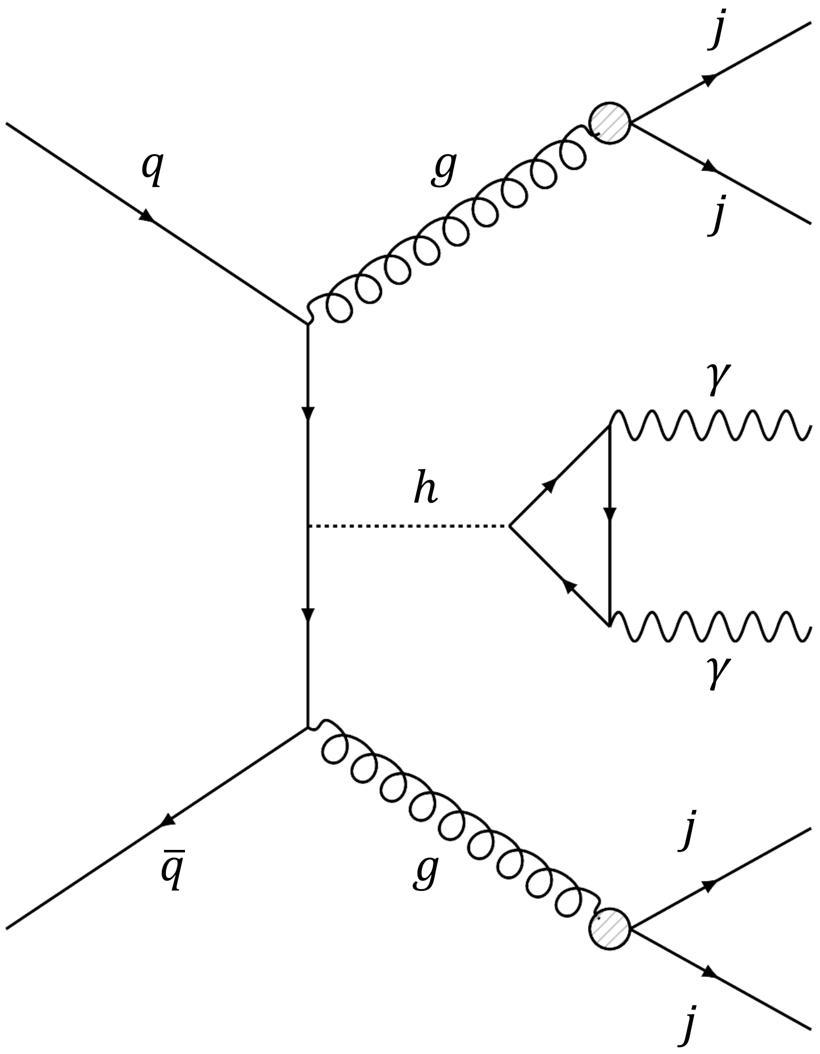
Simulated Events: Signal

- Production: Assume pair produced via s-channel γ/Z boson.
- Decay:
  - Assume generic effective coupling,
    - $\mathcal{L}_{\text{int}} = -W^{+}_{\mu\nu} F^{\mu\nu} H^{+\dagger} + \text{h.c.}$
  - Assume $\Gamma_{\text{tot}}(H^{+}) <$ detector resolution.
- Simulated with $m_{H^{+}} = 100 - 170$ GeV in 10 GeV steps.



Generated Events: Background

- Standard Model processes:
  - Dominant backgrounds:
    - $pp \to ggh \to gg\gamma\gamma$,
    - $pp \to W^+W^-\gamma\gamma \to jjjj\gamma\gamma$.
  - Several other backgrounds considered (e.g. $t\bar{t}h \to t\bar{t}\gamma\gamma, ZZ\gamma\gamma, hh \to b\bar{b}\gamma\gamma$).
- Fake signal background:
  - Objects reconstructed incorrectly as jets or photons,
  - Delphes simulates fakes according to input fake rate;
    - Rate of jet faking photon: 1/1000.
  - Fake rate included in all samples considered.



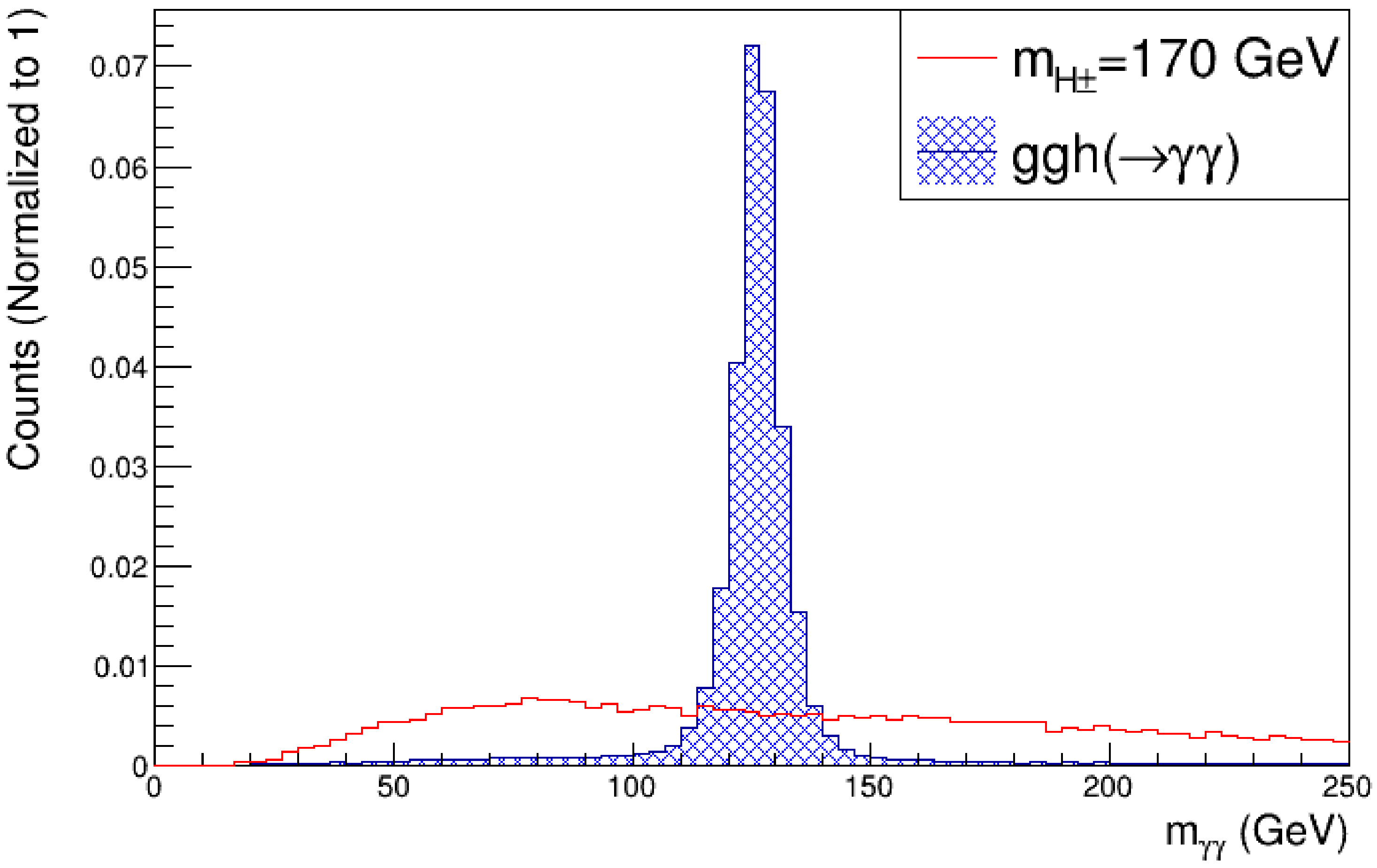
Outline of Analysis

1. Select events compatible with final state.
2. Apply kinematic fit to improve signal resolution.
3. Fit signal $m_{jj\gamma}$ distribution to quantify mass resolution.
4. Calculate expected upper limits on $\sigma(pp \to H^+H^-) \times BR^2(H \to W\gamma)$.

Event Selection

	Absolute Signal Efficiency $m_{H^\pm} =$ 170 GeV	Absolute Background Efficiency
Kinematic & Detector Acceptance Cut ➢ $p_{T,j/\gamma} \geq 20$ GeV, $\lvert\eta_j\rvert < 4.9$, $\lvert\eta_\gamma\rvert < 2.5$	93%	90%
Signal Event Selection ➢ $N_\gamma \geq 2,\ N_j \geq 4$	64%	53%
Background Discrimination Cut ➢ $m_{\gamma\gamma} \geq 150$ GeV or $m_{\gamma\gamma} \leq 100$ GeV	44%	5%

*statistical uncertainty $< 0.2\%$



Kinematic Fit

- Use decay topology to discriminate against background.
- Kinematic fit method;
  - ➢Constrain $m_{jj} = m_W$ for both jet pairs,
  - ➢Constrain $m_{j_1 j_2 \gamma_1} = m_{j_3 j_4 \gamma_2}$.
- Try fitting with all possible combinations of four jets and two photons;
  - ➢Events rejected if no combinations produce convergent fit,
  - ➢If more than one combination converges, choose combination with largest p-value.

Kinematic Fit, continued

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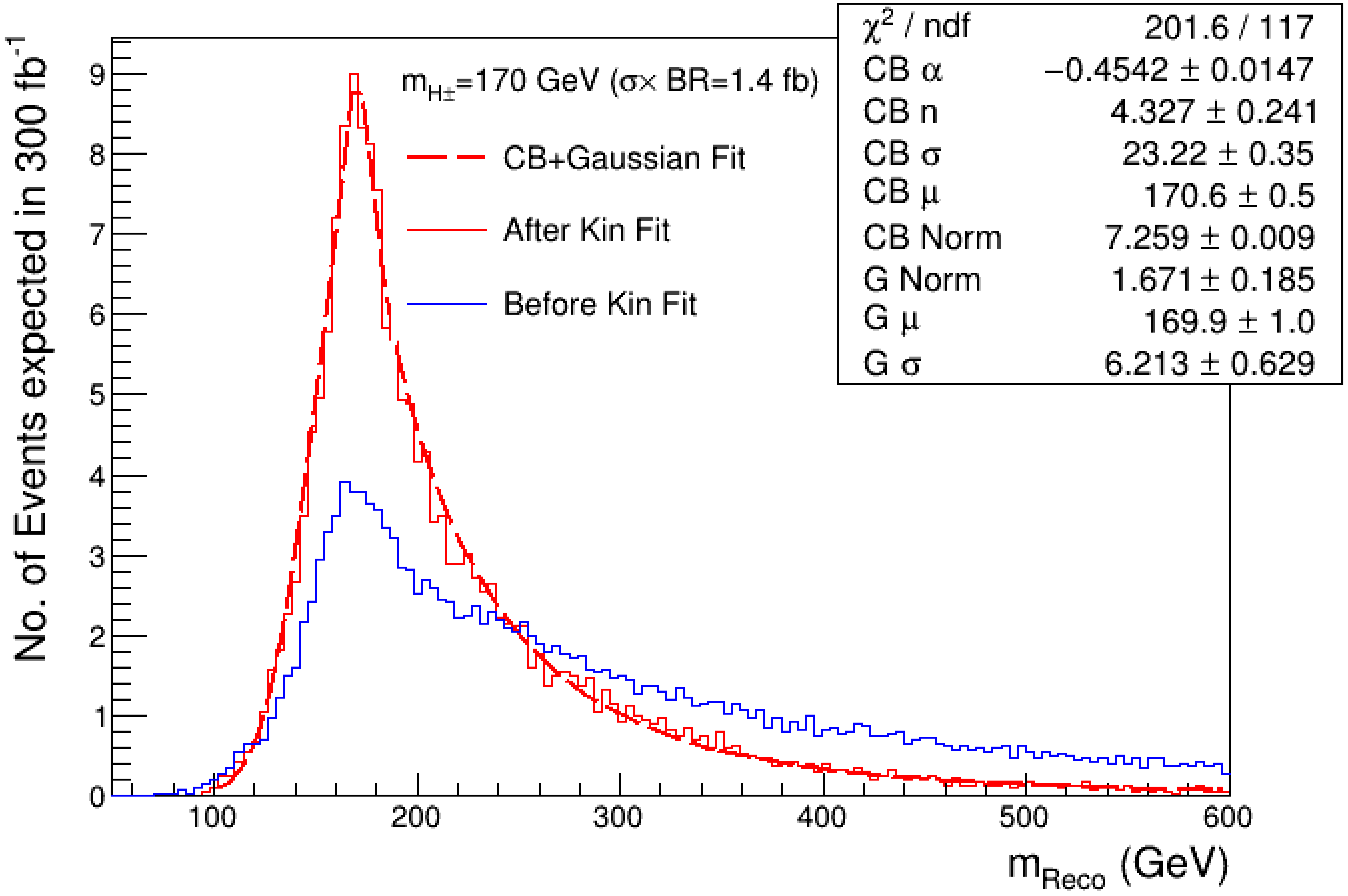
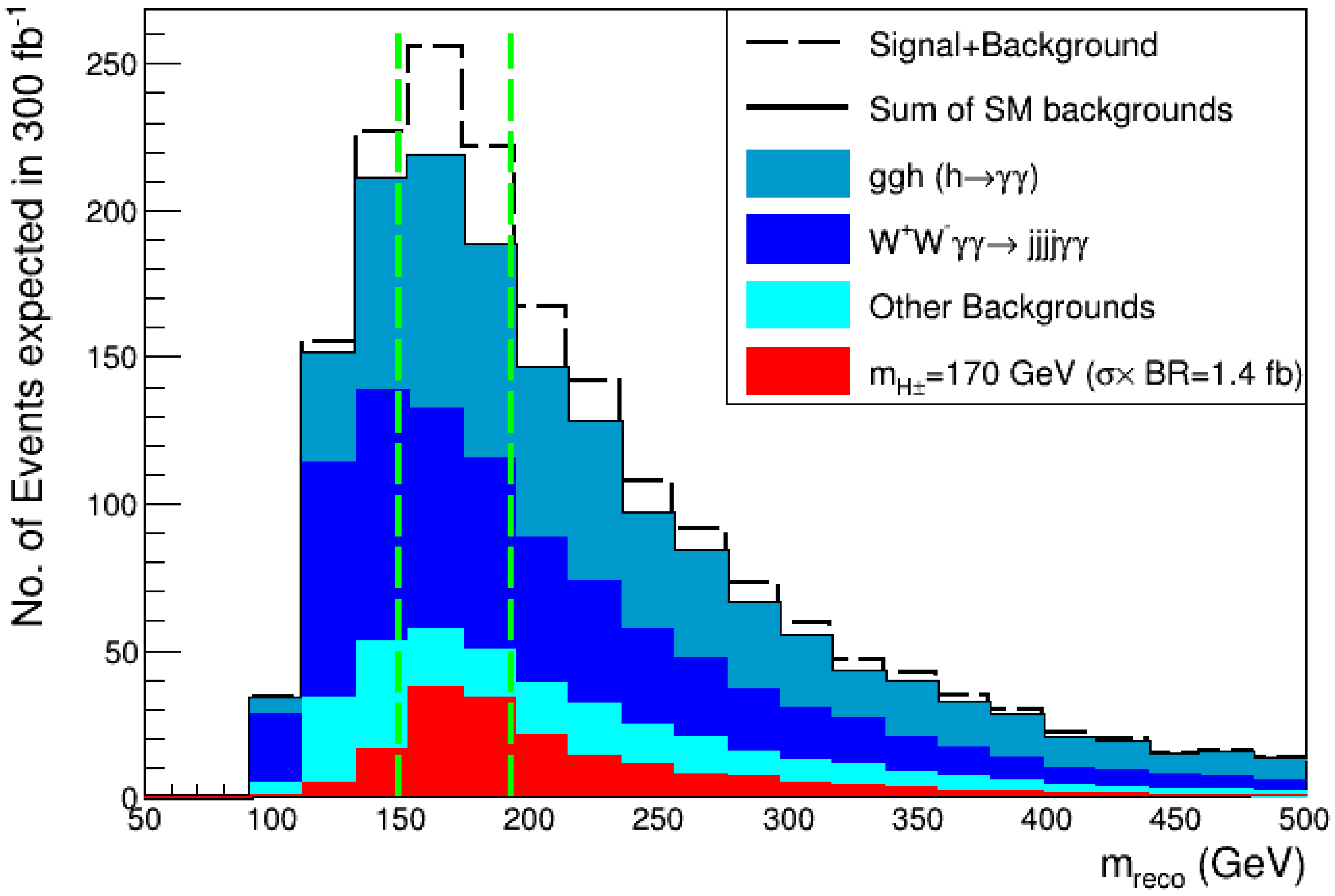


Reconstructed Invariant Mass



- Dominant SM backgrounds: $pp \to ggh \to gg\gamma\gamma$ and $pp \to W^+W^-\gamma\gamma \to jjjj\gamma\gamma$.
- Number of background events and signal efficiency used in limit calculation are taken within a sliding window of size $\pm$ the reconstructed invariant mass resolution.

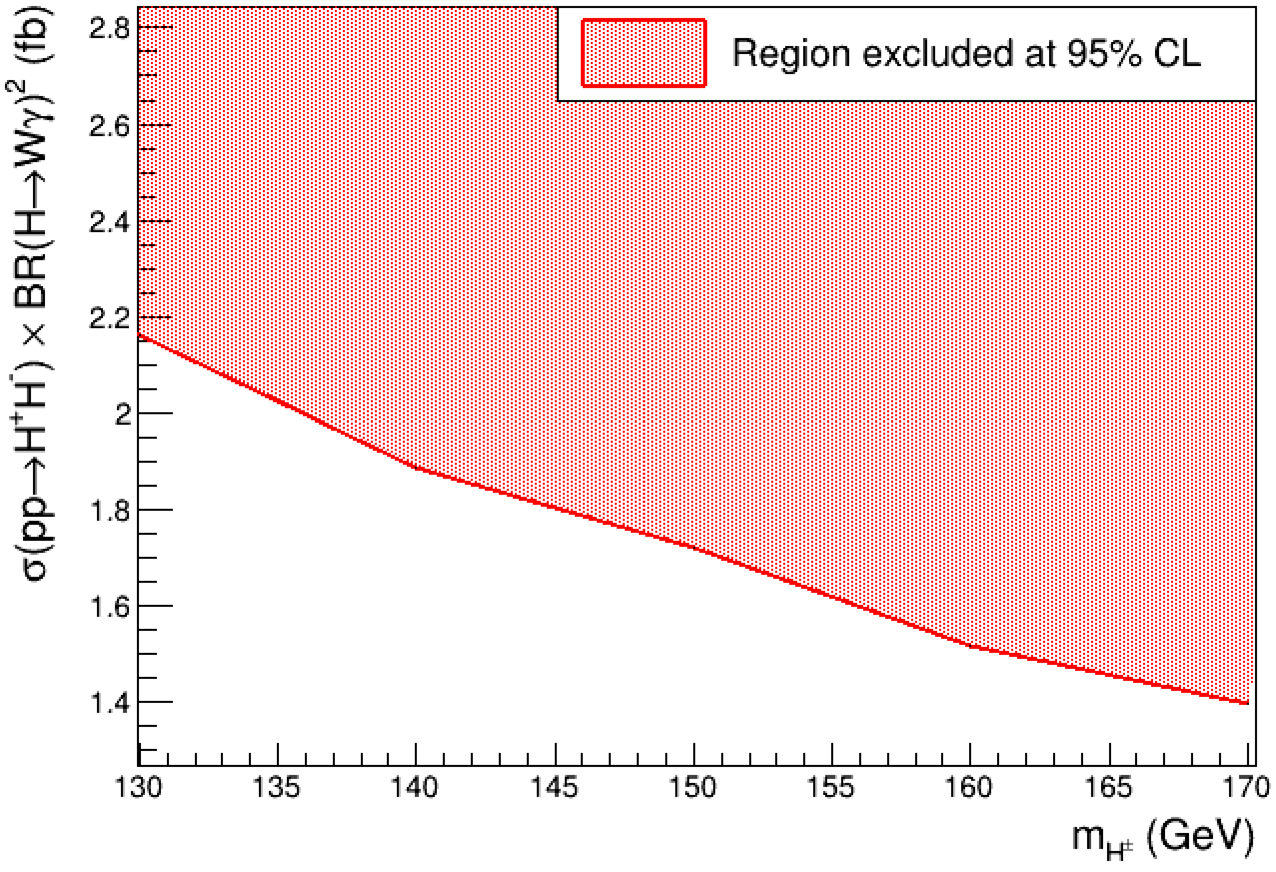
Limit on Production Cross Section

- Assume no signal events observed.
- Set 95% CL on $\sigma(pp \rightarrow H^+H^-) \times BR^2(H \rightarrow W\gamma)$ using Bayesian method:

$$\int_0^{\sigma_{0.95}} P\left(\sigma_{\text{sig}} \middle| n, \epsilon, b\right) d\sigma_{\text{sig}} = 0.95$$

  - $n = L\sigma_{\text{sig}}\epsilon + b$,
  - ϵ: signal efficiency,
  - b: expected number of background.
- Systematic and statistical uncertainties not included in limit calculations.

Preliminary Results



- m_{reco} distributions for $m_{H^\pm} < 130$ GeV are biased by kinematic and detector acceptance cuts.
- Signal mass points for $m_{H^+} > 170$ GeV not yet generated.

- To put results in context:
  - $\sigma(pp \to t\bar{t}h) \sim 600$ fb predicted [arXiv:1610.07922],
  - $\sigma(pp \to H^\pm W^\mp b\bar{b}) \sim 0.1 - 10$ pb predicted in 2HDM with $m_{H^\pm} = 170$ GeV [arXiv:1701.07635].

Future Work

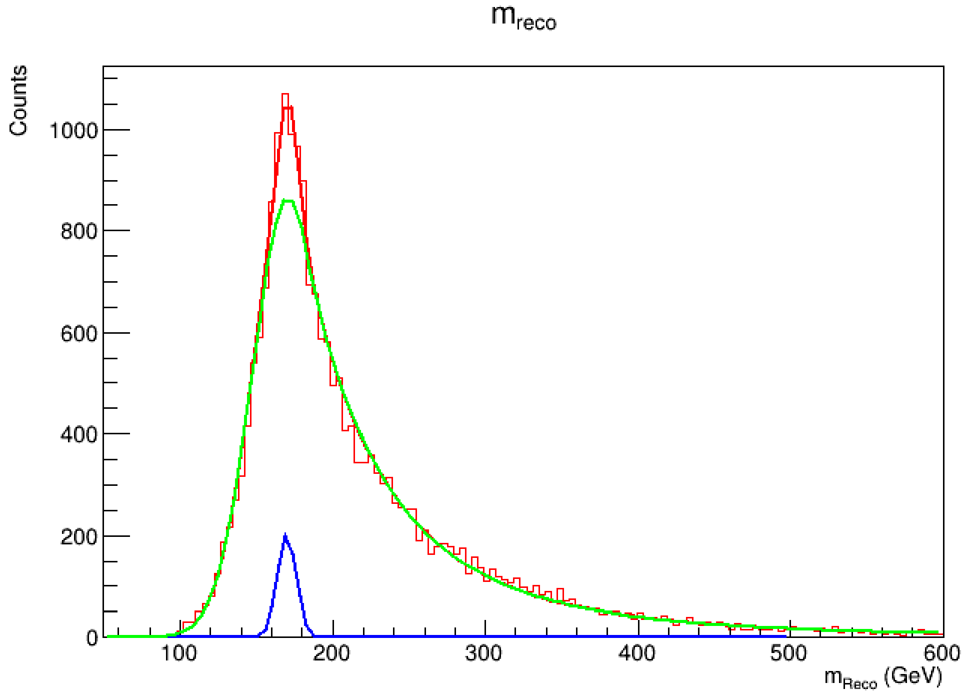
- Complete background estimation.
- Estimate systematic uncertainties on upper limit.
- Extend study to higher charged scalar masses.

References

1. Search for Charged Higgs bosons: Preliminary Combined Results Using LEP data Collected at Energies up to 209 GeV. The LEP Higgs Working Group, arXiv:hep-ex/0107031
2. Search for charged Higgs bosons produced in vector boson fusion processes and decaying into a pair of W and Z bosons using proton-proton collisions at $\sqrt{s} = 13$ TeV. The CMS Collaboration, Phys. Rev. Lett. 119, (2017) 141802
3. Search for a light charged Higgs bosons in the decay channel $H^+ \rightarrow c\bar{s}$ in $t\bar{t}$ events using pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. The ATLAS Collaboration, Eur. Phys. J. C (2013) 73:2465
4. Handbook of LHC cross sections: 4. Deciphering the nature of the Higgs sector. The LHC Higgs Cross Section Working Group, arXiv:1610.07922
5. Precise predictions for charged Higgs boson production. Ubiali, M., arXiv:1701.07635

Backup: Signal and Background Efficiency

- Signal m_{reco} distribution fitted with crystal ball+Gaussian function to define mass window $(m_{H^\pm}-\sigma_{\text{fit}}, m_{H^\pm}+\sigma_{\text{fit}})$
  - ➢(Crystal ball has Gaussian core with exponential decay on one side)



$$\epsilon_{s/b} = \frac{\text{signal/background events in mass window}}{\#\text{ events generated}}$$

$$\sigma_{\text{fit}} = \frac{A_{\text{CB}}\sigma_{\text{CB}} + A_{\text{G}}\sigma_{\text{G}}}{A_{\text{CB}} + A_{\text{G}}}$$

Backup: How to calculate upper limit

- 95% confidence cross-section upper limit
- Assume Poisson process:

$$\mathcal{L}(n|\sigma_{\text{sig}}, \epsilon, b) = \frac{n^b e^{-n}}{b!}, \qquad n = L\sigma_{\text{sig}}\epsilon + b$$

$$P(\sigma_{\text{sig}}|n, \epsilon, b) = \frac{\mathcal{L}(n|\sigma_{\text{sig}}, \epsilon, b)P(\sigma_{\text{sig}})}{\int_0^\infty \mathcal{L}(n|\sigma_{\text{sig}}, \epsilon, b)P(\sigma_{\text{sig}})d\sigma_{\text{sig}}}$$

$$\int_0^{\sigma_{0.95}} P(\sigma_{\text{sig}}|n, \epsilon, b)d\sigma_{\text{sig}} = 0.95$$

Backup: Kinematic Fit

- Kinematic Fitting: changes measured quantities by imposing physical constraints to improve measurement
- Minimize χ^2

$$\chi^2 = \sum_i \left[\frac{\left(p_{T,i} - p_T\right)^2}{\sigma_{p_{T,i}}^2} + \frac{(\eta_i - \eta)^2}{\sigma_{\eta,i}^2} + \frac{(\phi_i - \phi)^2}{\sigma_{\phi,i}^2} \right]$$

subject to constraints

$$\sqrt{(j_1 + j_2)^2} - m_W = 0, \qquad \sqrt{(j_3 + j_4)^2} - m_W = 0$$

$$\sqrt{(j_1 + j_2 + \gamma_1)^2} - \sqrt{(j_3 + j_4 + \gamma_2)^2} = 0$$

using Lagrange multipliers