# Higgs at 360GeV Extrapolation @ PKU Workshop

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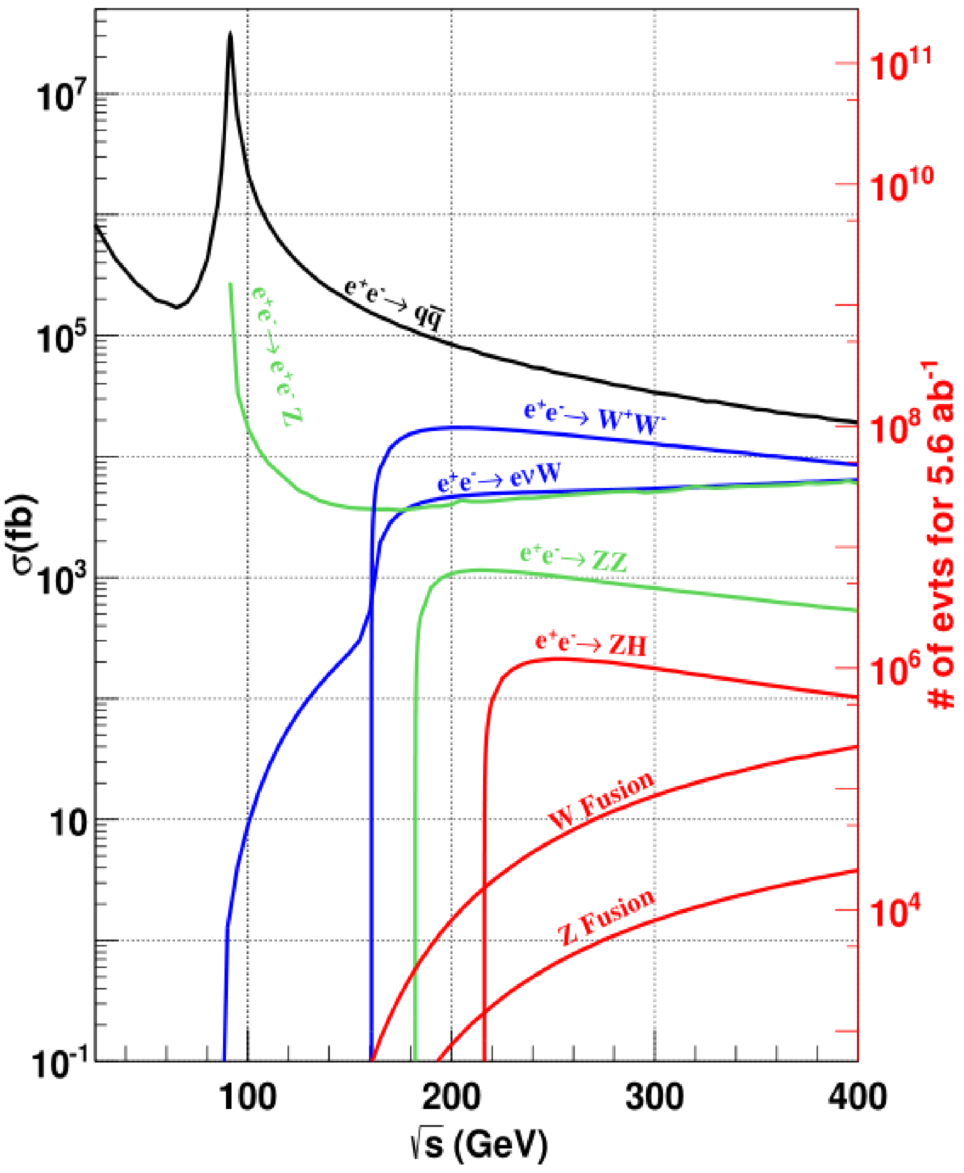
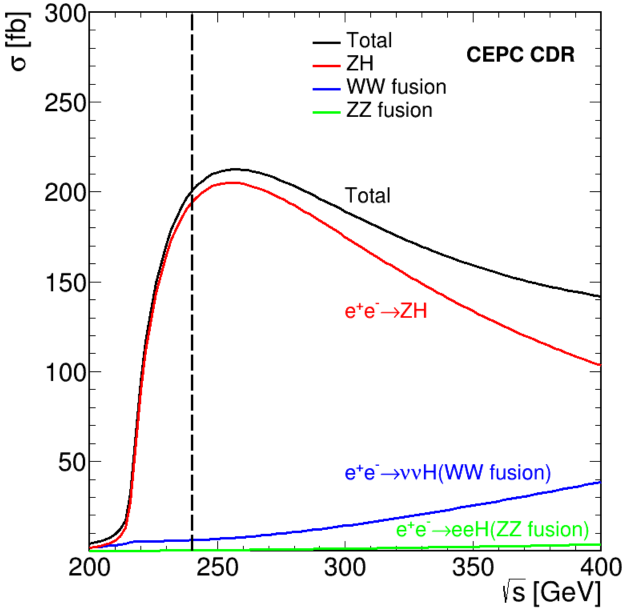
# Higgs Physics @ CEPC

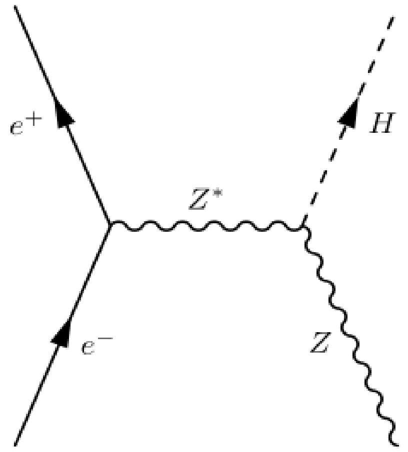



CEPC CDR: arxiv:1811.10545

White Paper: arxiv:1810.09037

Combination Report in Oxford;




**CDR：1M Higgs in 240GeV, 5.6ab$^{-1}$**

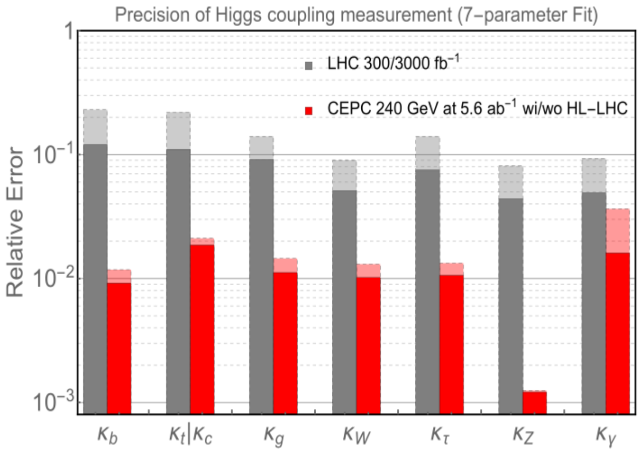
| Process | Cross section | Events in 5.6 ab$^{-1}$ |
|---|---|---|
| Higgs boson production, cross section in fb | | |
| $e^+e^- \to ZH$ | 196.2 | $1.10 \times 10^6$ |
| $e^+e^- \to \nu_e\bar{\nu}_e H$ | 6.19 | $3.47 \times 10^4$ |
| $e^+e^- \to e^+e^- H$ | 0.28 | $1.57 \times 10^3$ |
| Total | 203.7 | $1.14 \times 10^6$ |

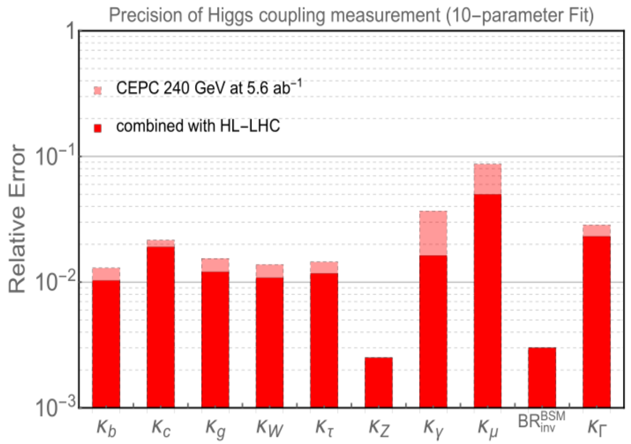
# Existing results:240GeV, 5.6iab

| (240GeV,5.6ab$^{-1}$) | CDR | 2019.07 |
|---|---|---|
| $\sigma(ZH)$ | **0.50%** | |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$ | **0.27%** | |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{cc})$ | **3.3%** | |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{gg})$ | **1.3%** | |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{WW})$ | **1.0%** | |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{ZZ})$ | **5.1%** | |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \tau\tau)$ | **0.8%** | |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \gamma\gamma)$ | **6.8%** | **5.4%** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mu\mu)$ | **17%** | **12%** |
| $\sigma(\nu\nu H) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$ | **3.0%** | |
| $\mathrm{Br}_{\mathrm{upper}}(\mathrm{H} \to \mathrm{inv.})$ | **0.41%** | **0.2%** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to Z\gamma)$ | **16%** | |
| Width | **2.8%** | |

Relative coupling measurement precision and the 95% CL upper limit on $\mathrm{BR}^{\mathrm{BSM}}_{\mathrm{inv}}$

| Quantity | 10-parameter fit CEPC | 10-parameter fit CEPC+HL-LHC | 7-parameter fit CEPC | 7-parameter fit CEPC+HL-LHC |
|---|---|---|---|---|
| $\kappa_b$ | 1.3% | 1.0% | 1.2% | 0.9% |
| $\kappa_c$ | 2.2% | 1.9% | 2.1% | 1.9% |
| $\kappa_g$ | 1.5% | 1.2% | 1.5% | 1.1% |
| $\kappa_W$ | 1.4% | 1.1% | 1.3% | 1.0% |
| $\kappa_\tau$ | 1.5% | 1.2% | 1.3% | 1.1% |
| $\kappa_Z$ | 0.25% | 0.25% | 0.13% | 0.12% |
| $\kappa_\gamma$ | 3.7% | 1.6% | 3.7% | 1.6% |
| $\kappa_\mu$ | 8.7% | 5.0% | – | – |
| $\mathrm{BR}^{\mathrm{BSM}}_{\mathrm{inv}}$ | $<0.30\%$ | $<0.30\%$ | – | – |
| $\Gamma_H$ | 2.8% | 2.3% | – | – |



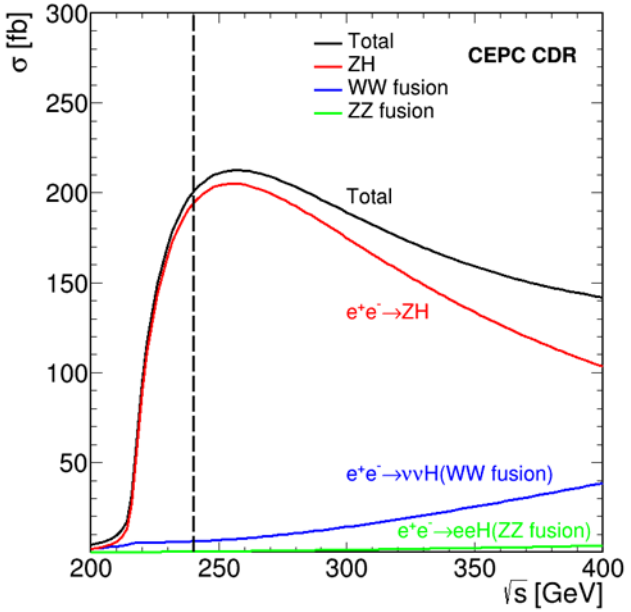
# Higher Energy Run

- 350~365GeV Run: worthwhile
  - Over top threshold, EW/EFT/Theoretical part benefits;
  - Larger vvH cross section; Benefit width measurement
    - All constrained by width(2.8%), in current CEPC 240GeV run, Higgs coupling suffered;
  - Fcc-ee/ILC/CLIC all have similar plan
- Temporary benchmark: 2 iab @ 360GeV
  - 360 saves 10% energy with respect to 365 GeV

The Plan for Fcc-ee (CERN-ACC-2018-0057) :
0.2iab 350GeV + 1.5iab 365GeV

# Signal Cross Sections

- 240GeV:
  - ZH: 196.9; vvH: 6.2; about 318:10; (Z->vv : vvH = 6.4:1)
  - Interference are ignored.
- 350GeV: (vvH ~ 100% Z->vv ), (eeH ~ 60% Z->ee)
- 360GeV: (vvH ~ 117% Z->vv ), (eeH ~ 67% Z->ee)
- 365GeV: (vvH ~ 126% Z->vv ), (eeH ~ 71% Z->ee)

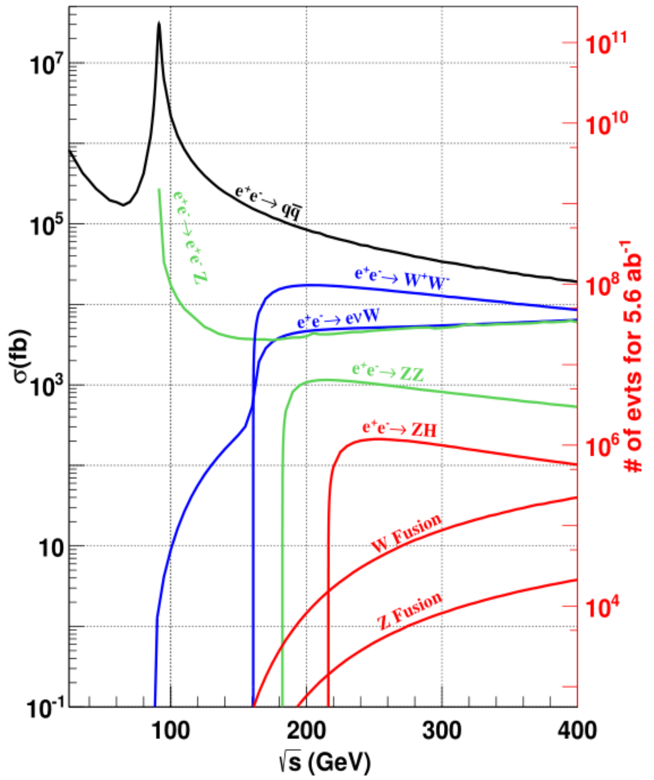



| fb | 240 | 350 | 360 | 365 | 360/240 |
|---|---|---|---|---|---|
| ZH | 196.9 | 133.3 | 126.6 | 123.0 | -36% |
| WW fusion | 6.2 | 26.7 | 29.61 | 31.1 | +377% |
| ZZ fusion | 0.5 | 2.55 | 2.80 | 2.91 | +460% |
| Tot | 203.6 | | 159.0 | | |
| Tot Events | 1.14M | | 0.32M | | |

ZZ fusion (2%) also cannot be ignored.

# Major background cross sections

| pb | 240 | 350 | 360 | 365 | 360/240 |
|---|---|---|---|---|---|
| ee($\gamma$) | 930 | 336 | 325 | 319 | -65% |
| $\mu\mu$($\gamma$) | 5.3 | 2.2 | 2.1 | 2.1 | -60% |
| qq($\gamma$) | 54.1 | 24.7 | 23.2 | 22.8 | -57% |
| WW | 16.7 | 10.4 | 10.0 | 9.81 | -40% |
| ZZ | 1.1 | 0.66 | 0.63 | 0.62 | -42% |
| tt | \ | 0.155 | 0.317 | 0.369 | |
| sZ | 4.54 | 5.72 | 5.78 | 5.83 | +27% |
| sW | 5.09 | 5.89 | 6.00 | 6.04 | +18% |



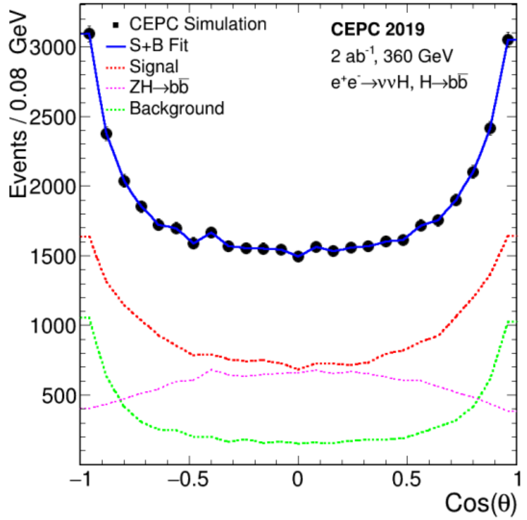

In 240GeV, most channels are 4f bkg dominant, usually ZZ.

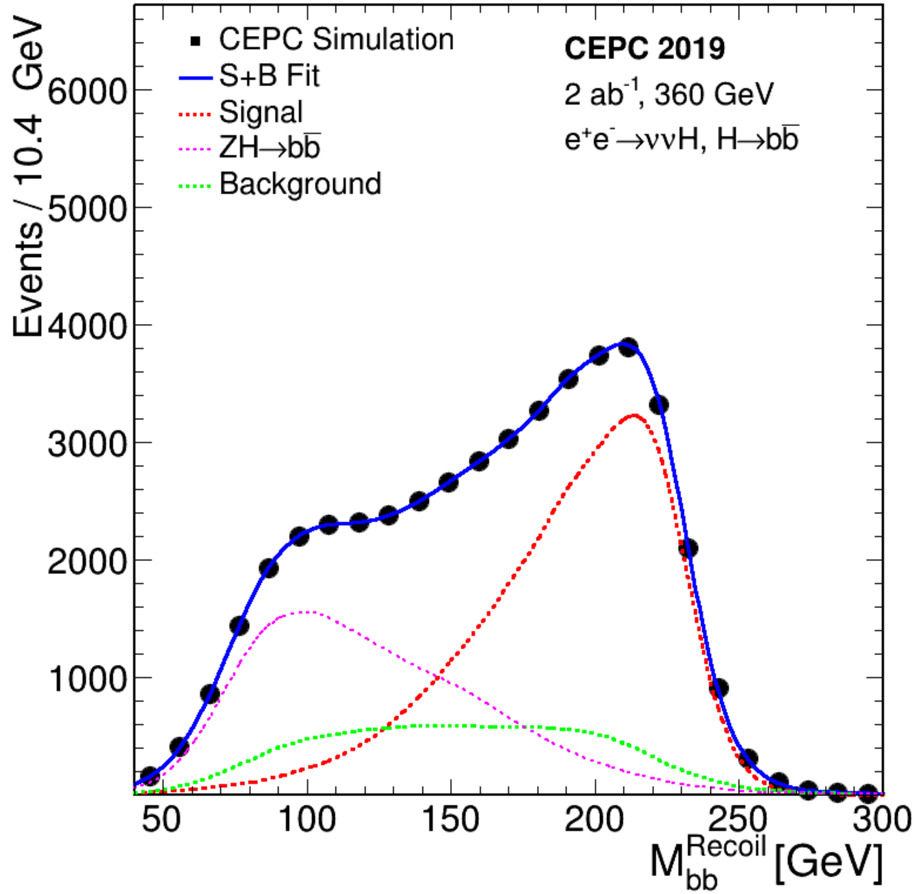
$ee \to t\bar{t} \to WW^*b\bar{b}$ would be 6 jets/ llνν+2jets.
Would challenging for jet clustering.

MC Simulation for $t\bar{t}$ still tuning;

# vvH->bb, Full simulation

- See Hao's slides for further information
  - vvH Eff 60+%;
  - Bkg: 4f bkg full simulation, qq scaled from 240 case
    - tt MC not ready; Consider qq +20%;
  - 2d Recoil qq + Cos $\theta_{qq}$ Fit
  - Considering ZH constrain:
    - $\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$:0.79%
    - 240GeV: 3%; big improvement;
  - ZH->bb (0.63%) share the anti-correlation -45%.



# Results

| | 5.6ab$^{-1}$, 240 | 2ab$^{-1}$, 360 | 1.5ab$^{-1}$, 360 |
|---|---|---|---|
| $\sigma(ZH)$ | **0.50%** | **1%** | |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$ | **0.27%** | **0.63%** | **0.71%** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{cc})$ | **3.3%** | **6.2%** | **7.2%** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{gg})$ | **1.3%** | **2.4%** | **2.7%** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{WW})$ | **1.0%** | **2.0%** | **2.3%** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{ZZ})$ | **5.1%** | **12%** | **14%** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \tau\tau)$ | **0.8%** | **1.5%** | **1.7%** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \gamma\gamma)$ | **5.4%** | **8%** | **9.2%** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mu\mu)$ | **12%** | **29%** | **33%** |
| $\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$ | **3%** | **0.79%** | **0.91%** |
| $\mathrm{Br}_{\mathrm{upper}}(\mathrm{H} \to \mathrm{inv.})$ | **0.2%** | **** | **** |
| $\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to Z\gamma)$ | **16%** | **25%** | **29%** |
| Width | **2.8%** | **~0.8%** | |

*: $\sigma(ZH)$ estimated as 1%. qqH $\sigma(ZH)$ still unreproducible

Fcc:

| $\sqrt{s}$ (GeV) | 240 | | 365 | |
|---|---|---|---|---|
| Luminosity (ab$^{-1}$) | 5 | | 1.5 | |
| $\delta(\sigma\mathrm{BR})/\sigma\mathrm{BR}$ (%) | HZ | $\nu\bar{\nu}$ H | HZ | $\nu\bar{\nu}$ H |
| $\mathrm{H} \to$ any | $\pm 0.5$ | | $\pm 0.9$ | |
| $\mathrm{H} \to \mathrm{b\bar{b}}$ | $\pm 0.3$ | $\pm 3.1$ | $\pm 0.5$ | $\pm 0.9$ |
| $\mathrm{H} \to \mathrm{c\bar{c}}$ | $\pm 2.2$ | | $\pm 6.5$ | $\pm 10$ |
| $\mathrm{H} \to \mathrm{gg}$ | $\pm 1.9$ | | $\pm 3.5$ | $\pm 4.5$ |
| $\mathrm{H} \to \mathrm{W^+W^-}$ | $\pm 1.2$ | | $\pm 2.6$ | $\pm 3.0$ |
| $\mathrm{H} \to \mathrm{ZZ}$ | $\pm 4.4$ | | $\pm 12$ | $\pm 10$ |
| $\mathrm{H} \to \tau\tau$ | $\pm 0.9$ | | $\pm 1.8$ | $\pm 8$ |
| $\mathrm{H} \to \gamma\gamma$ | $\pm 9.0$ | | $\pm 18$ | $\pm 22$ |
| $\mathrm{H} \to \mu^+\mu^-$ | $\pm 19$ | | $\pm 40$ | |
| $\mathrm{H} \to$ invisible | $< 0.3$ | | $< 0.6$ | |

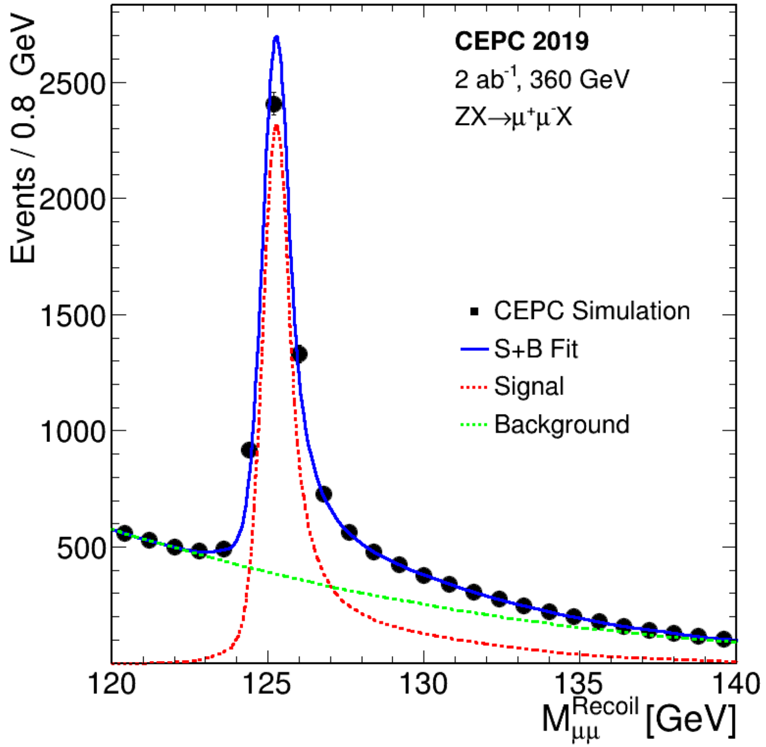
Generally, since the extrapolation is not so accurate, results are comparable.

For $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mu\mu$, resolution changes considered.
Keep diphoton resolution ~(2.5GeV) : 9%
2.5GeV to 2GeV(Better): 8%

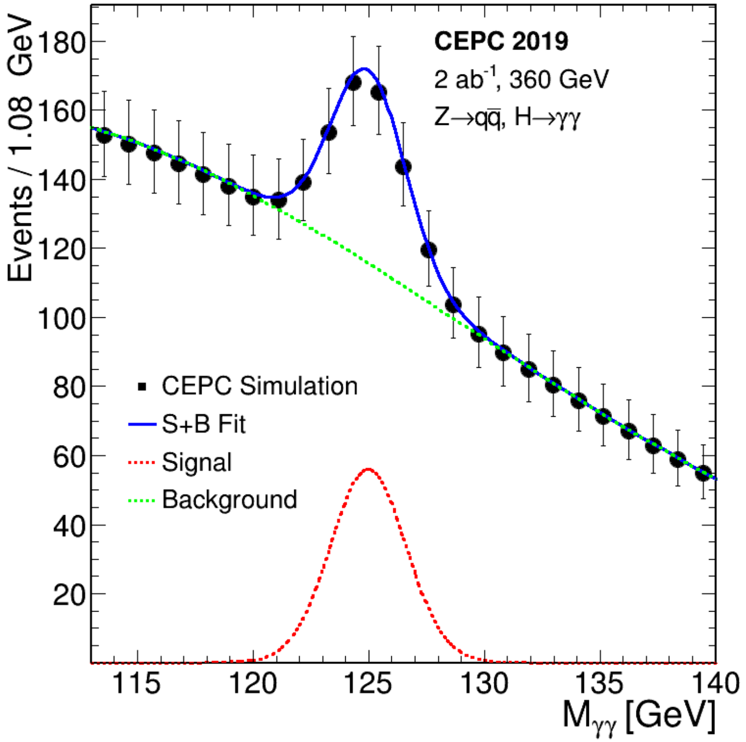
Keep dimuon resolution ~(0.3GeV): 23%
0.3GeV to 1GeV(Worse): 29%

# 360 GeV Plots

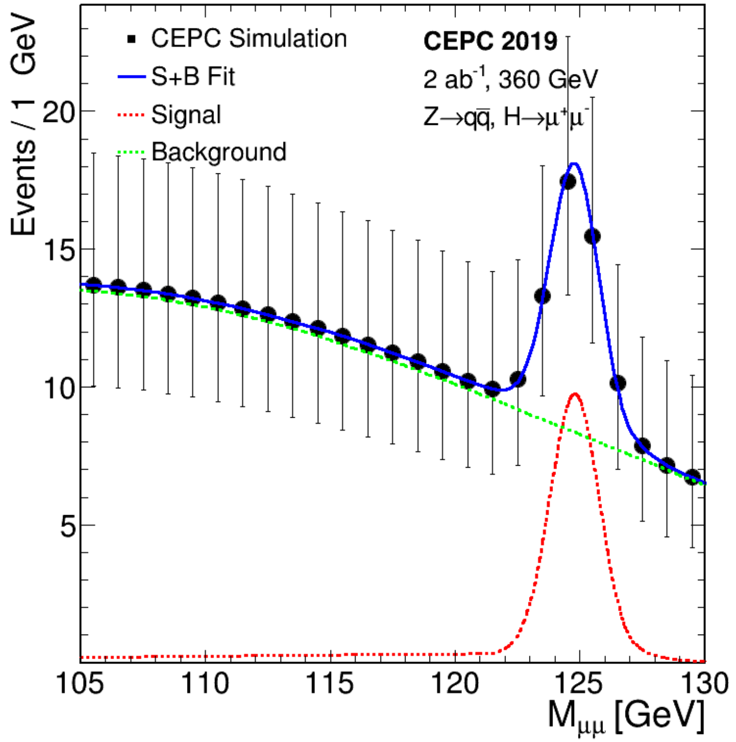
Inclusive: 0.92% -> 1.72%



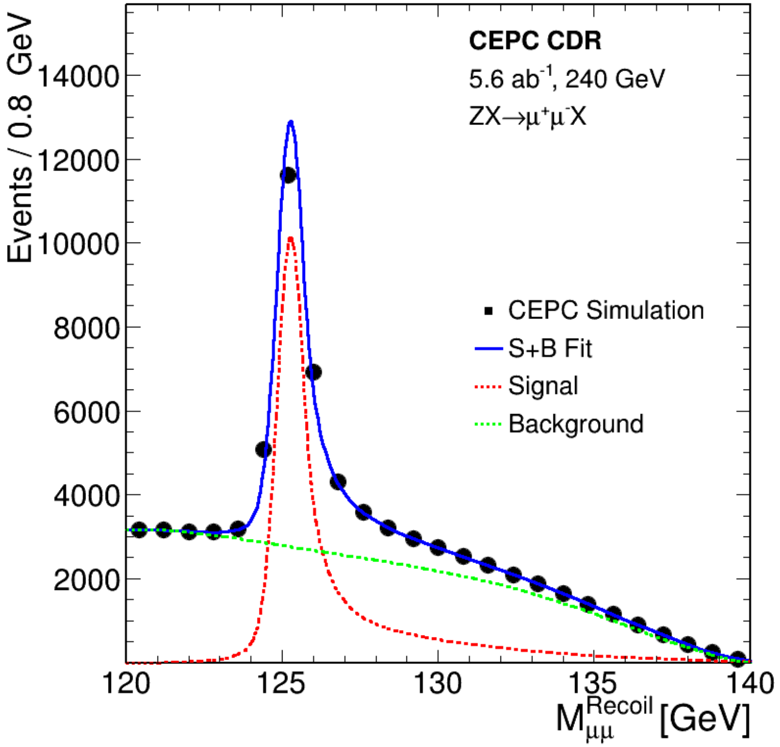

Resolution: 2GeV;

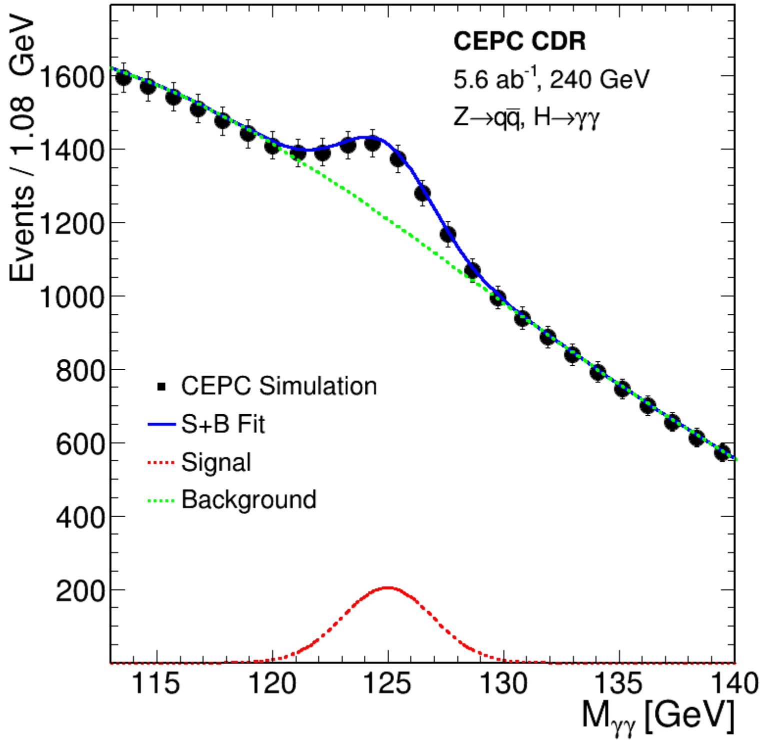


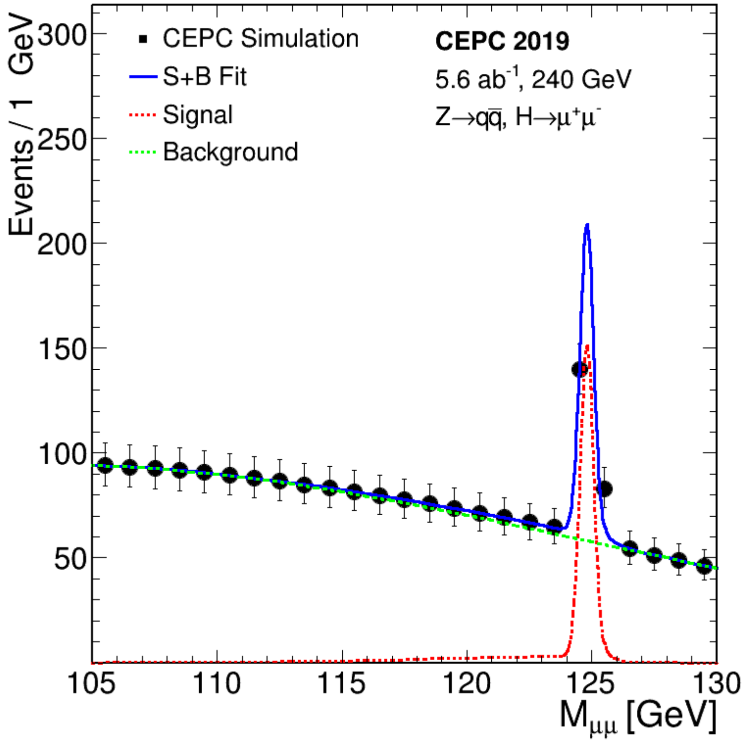

Resolution: 1GeV;



# 240 GeV Plots



# Discussion

- Current extrapolation
  - Mainly scale yields
    - bkg could be even lower if correct analysis strategies are applied.
      - Proved by Hao’s work: 360GeV selection has much better effiencicy.
  - Not reliable in channels like vvH, eeH, inclusive……
    - need further study
- To dos

Also mentioned in Jianming’s summary

  - $\sigma(ZH)$ estimation
  - Other vvH besides bb; eeH;
  - Combined measurement;

# Fit techniques discussion

Discussion raised by Jianming, so I did several validations.

# Recoil Mass calculation

**Severval methods available, which is equivalent to a simple kinematic fit.**

- $m_{recoil}^2 = s - 2\sqrt{s}\mathrm{E_h^{rec}} + (\mathrm{m_h^{rec}})^2$
- $\left(m_{recoil}^{E}\right)^2 = s - 2\sqrt{s}E_h^{rec} + \mathrm{m_h^2}$
- $\left(m_{recoil}^{p}\right)^2 = s - 2\sqrt{s}\sqrt{m_h^2 + \left|p_h^{rec}\right|^2} + \mathrm{m_h^2}$
- $\left(m_{recoil}^{shift}\right)^2 = s - 2\sqrt{s}\cdot\Gamma\cdot E_h^{rec} + \mathrm{m_h^2}$

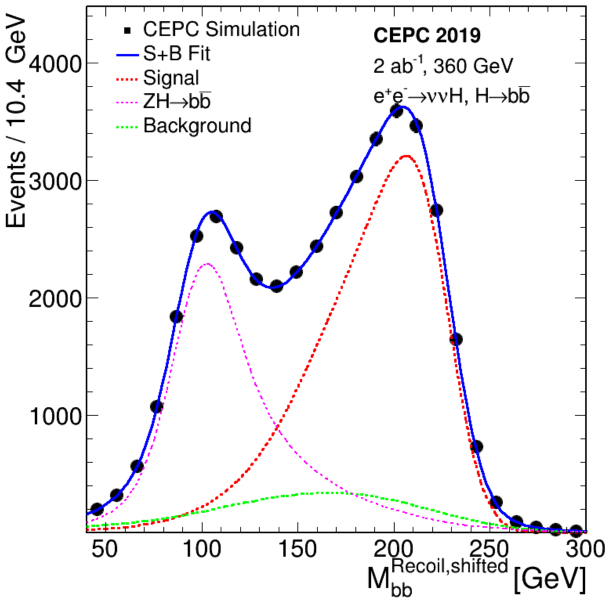
$= s - 2\sqrt{s}\sqrt{m_h^2 + \left|\Gamma\cdot p_h^{rec}\right|^2} + \mathrm{m_h^2}$, where $\Gamma = \frac{m_h}{m_h^{rec}}$;

For sensitivity,

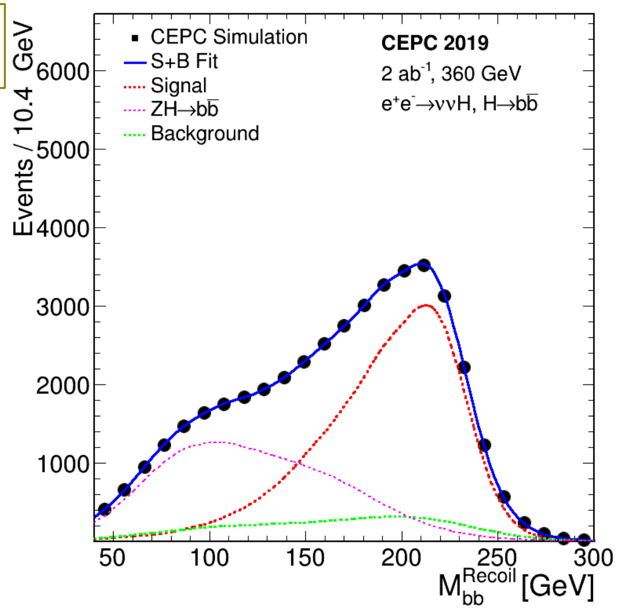
$m_{recoil}^{shift} \approx m_{recoil}^{p} > m_{recoil} > m_{recoil}^{E}$

Also we see better resolution

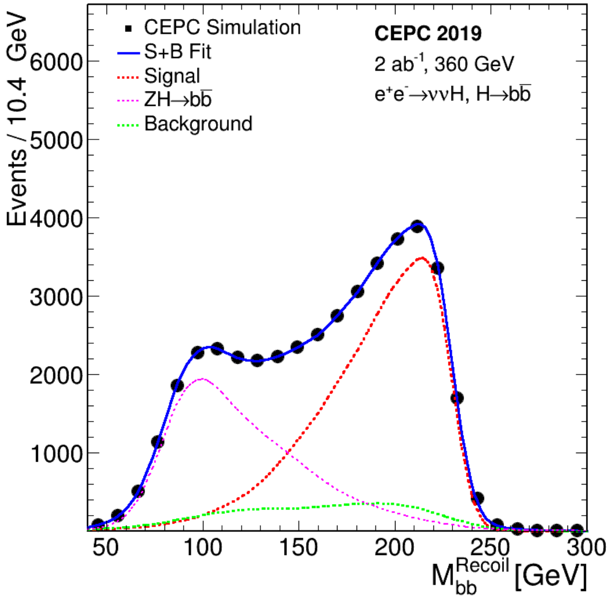
$(m_{recoil}^{shift})$



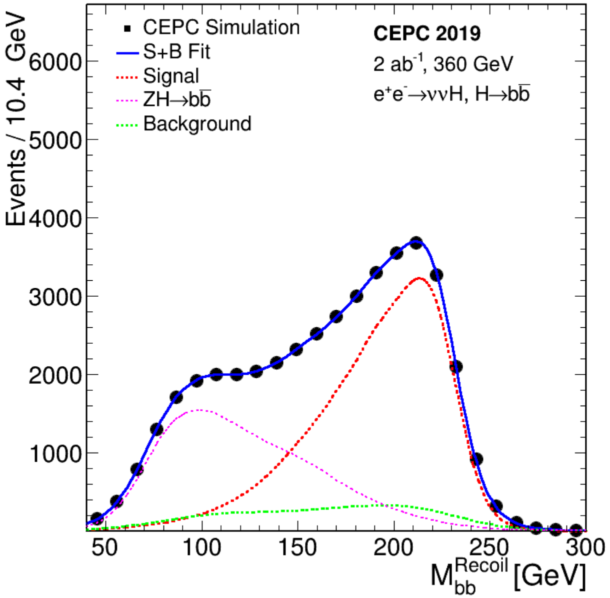

$(m_{recoil}^{E})$




$(m_{recoil}^{p})$




$m_{recoil}$

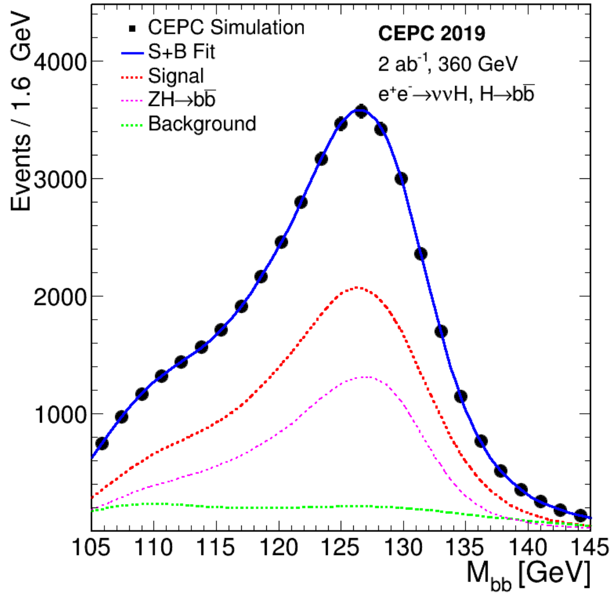


# Fit Shape

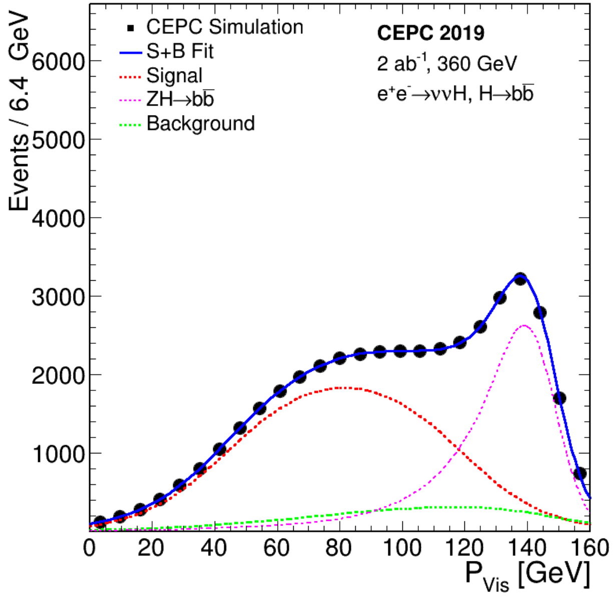
- For the same yields, shape matters.
- vvH->bb case, $\mathrm{M}_{vis}$ has no separation power
  - results would close to simple number counting.
- While $m_{recoil}^{p}$ is only determined by $p_{vis}(p_{vis}^{2})$;

| Tier | Gain | Method | Precision |
|---|---|---|---|
| 3 | Didn't get benefits from shape at all; | $\frac{\sqrt{s+b}}{s}$ | 0.87% |
| | | $M_{vis}$ | 0.86% |
| 2 | Bad; | $m_{recoil}^{E}$ | 0.77% |
| 1 | Good separation. | $m_{recoil}^{p}$ | 0.75% |
| | | $m_{recoil}^{shift}$ | 0.75% |
| | | $m_{recoil}$ | 0.76% |
| | | $p_{vis}$ | 0.76% |
| | | $p_{vis}^{2}$ | 0.76% |

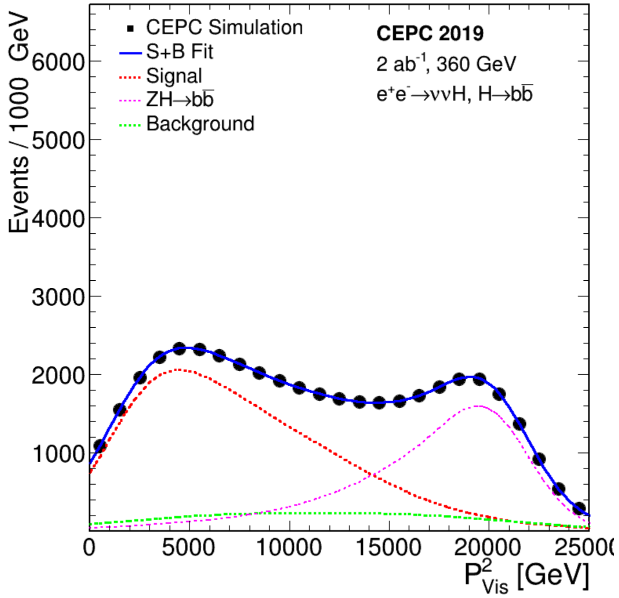
$\mathrm{M}_{vis}$




$p_{vis}$

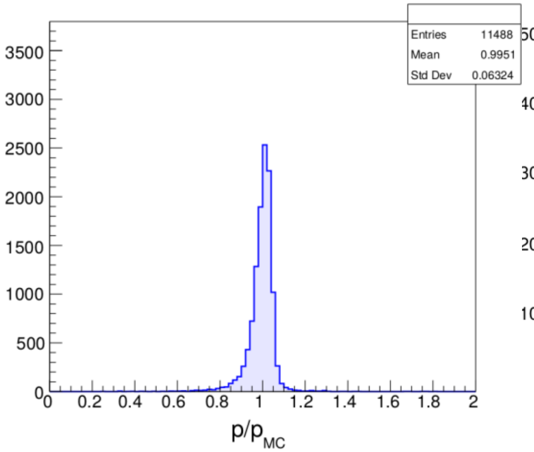



$p_{vis}^{2}$

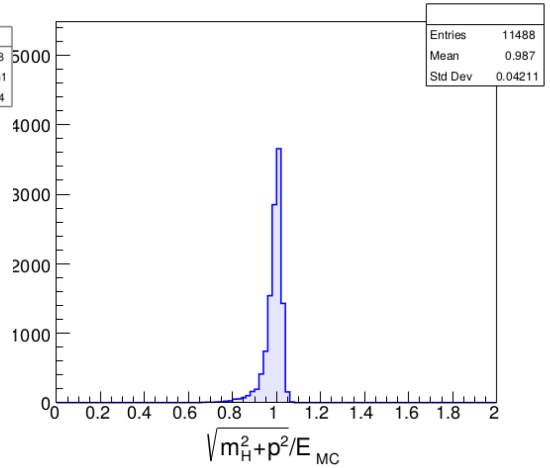


# Truth information From Hao

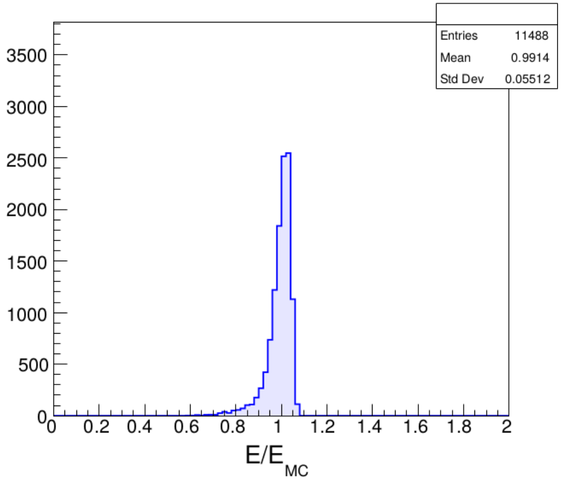
- Reco/Truth resolution, $\sqrt{m_H^2 + p^2}$ is best:  Smaller distortion




6.3%




4.2%




5.5%

Different recoil mass method corresponding to different correction.

I recommend apply $m_{recoil}^{p}$ or $m_{recoil}^{shift}$ to all channels.

$$\left(m_{recoil}^{p}\right)^2 = s - 2\sqrt{s}\sqrt{m_h^2 + \left|p_h^{rec}\right|^2} + \mathrm{m_h^2}$$

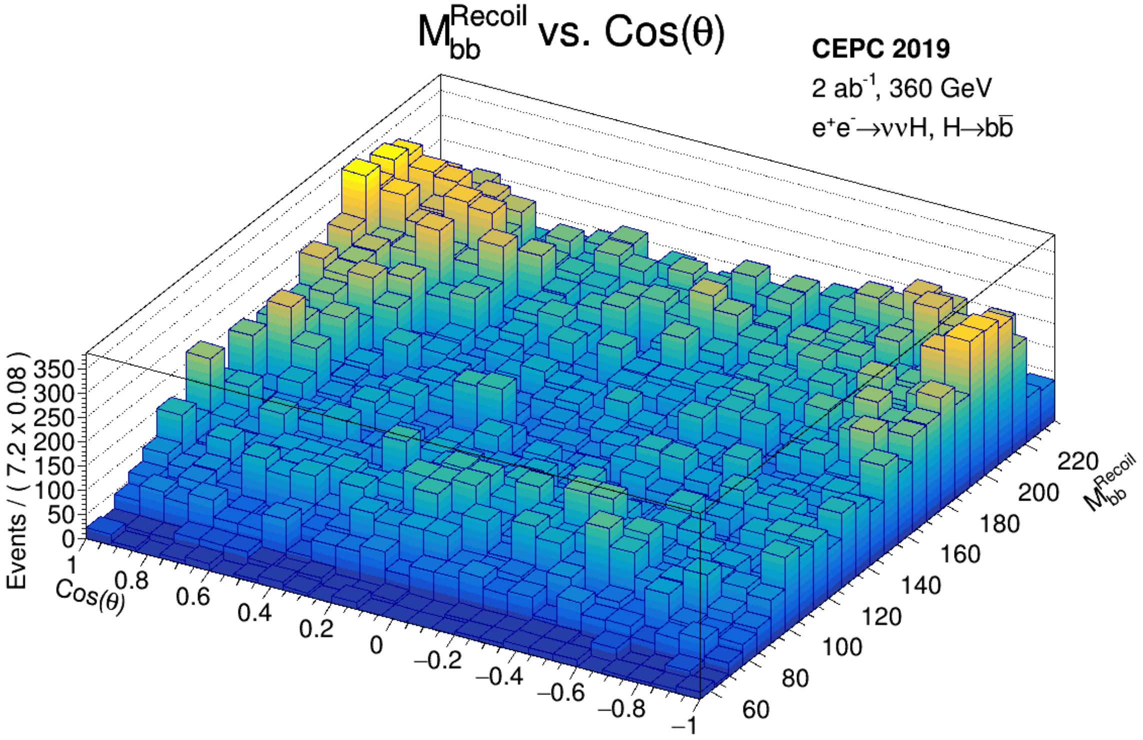
$$\left(m_{recoil}^{shift}\right)^2 = s - 2\sqrt{s}\sqrt{m_h^2 + \left|\frac{m_h}{m_h^{rec}} \cdot p_h^{rec}\right|^2} + \mathrm{m_h^2}$$

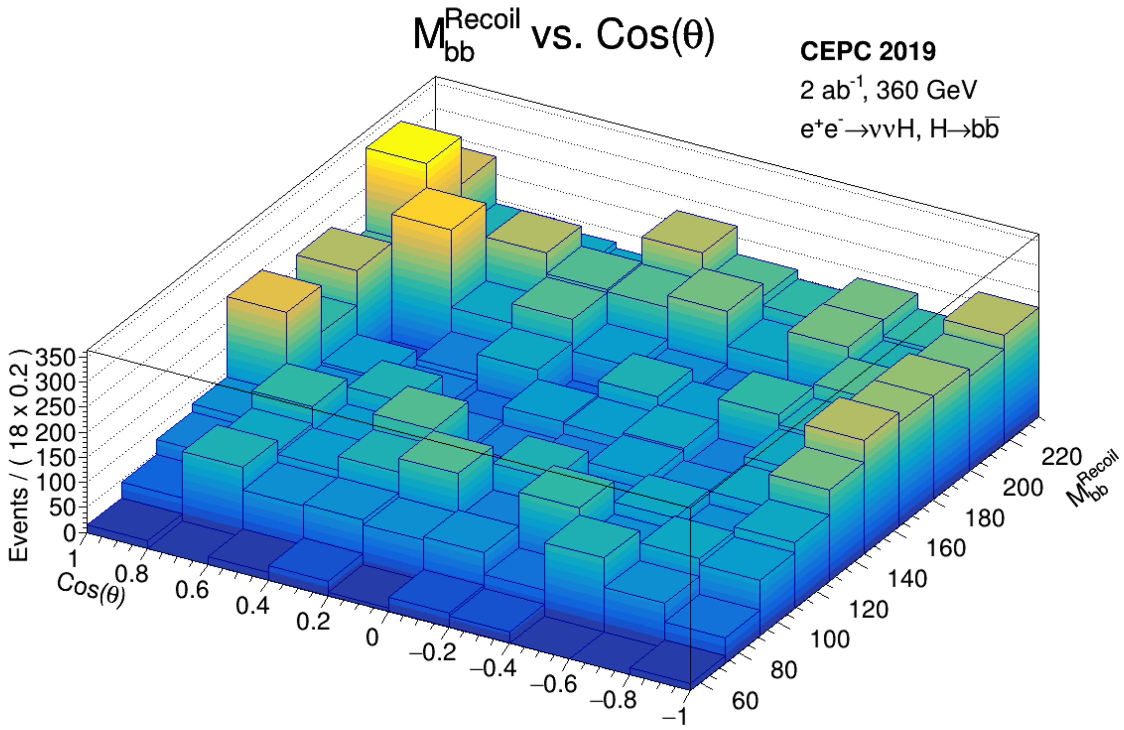
# 2d Recoil qq + Cos $\theta_{qq}$ Fit

- Hard to find 2d pdf to describe and fit
  - RooNDKeysPdf usually crash; RooHistPdf need small bin

Original Shape
Asymmetry but not big bias;
Cannot fit this shape so well;

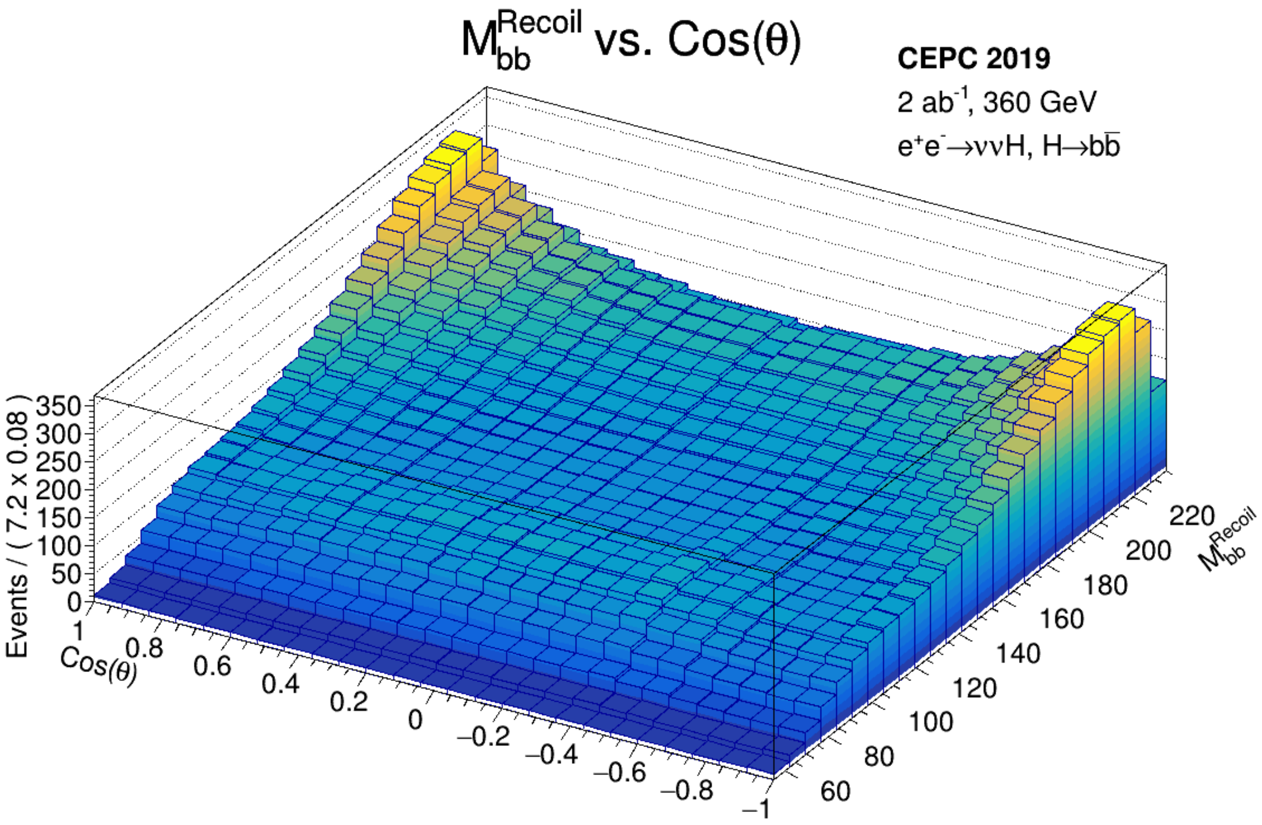
When bins 10*10;
0.75%; results are good;
But hard to avoid the overfitting.



# 2d Recoil qq + Cos $\theta_{qq}$ Fit

- 1d*1d smooth pdf: Easy to describe, clear physics meaning.
- Surely 2d pdf contains more information
  - Overfitting? ->is that we want?




Need to determine to use which method：

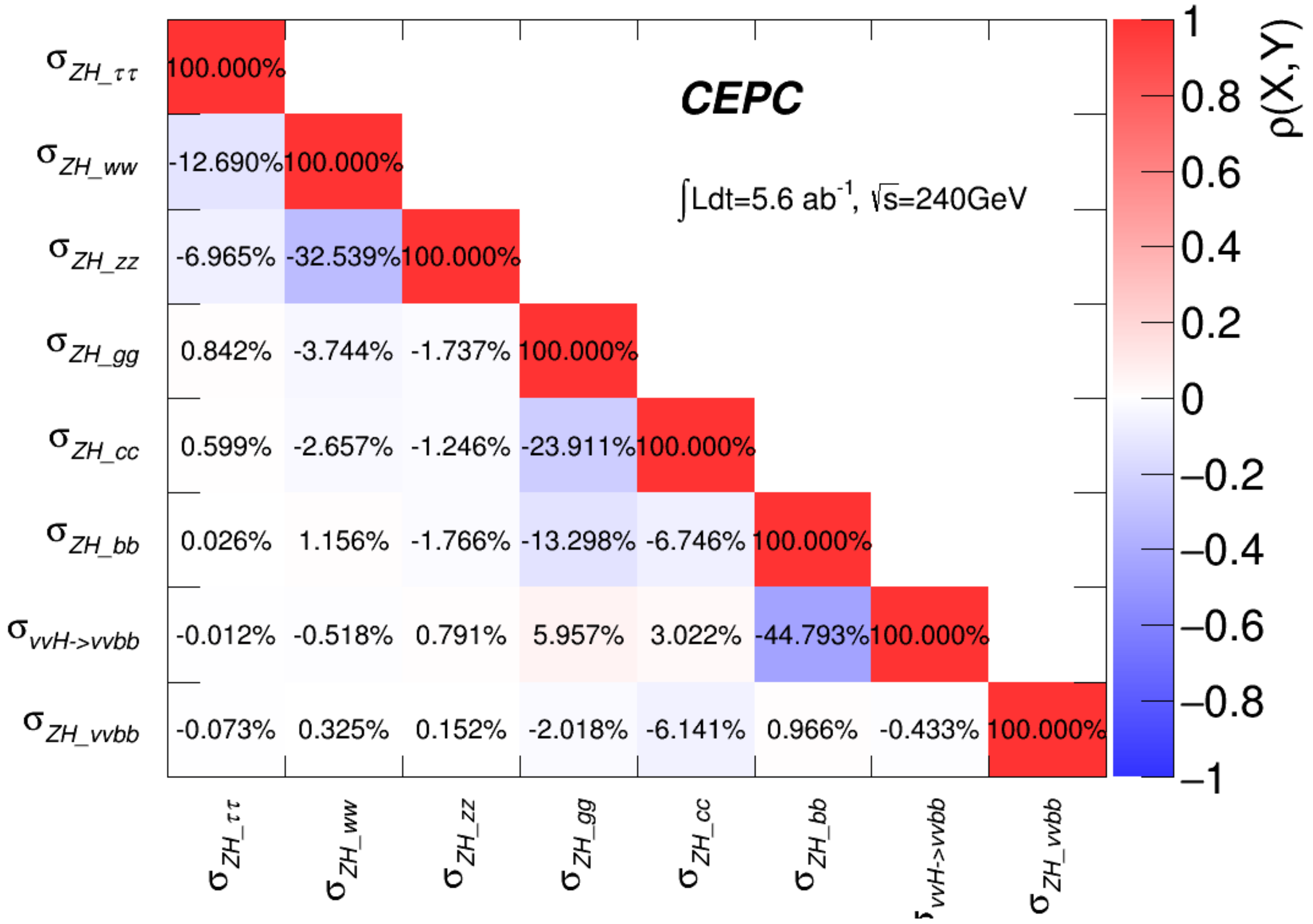
2d RooHistPdf or 1d*1d Smooth shape;

Personally I prefer 1d*1d. Easy to understand.

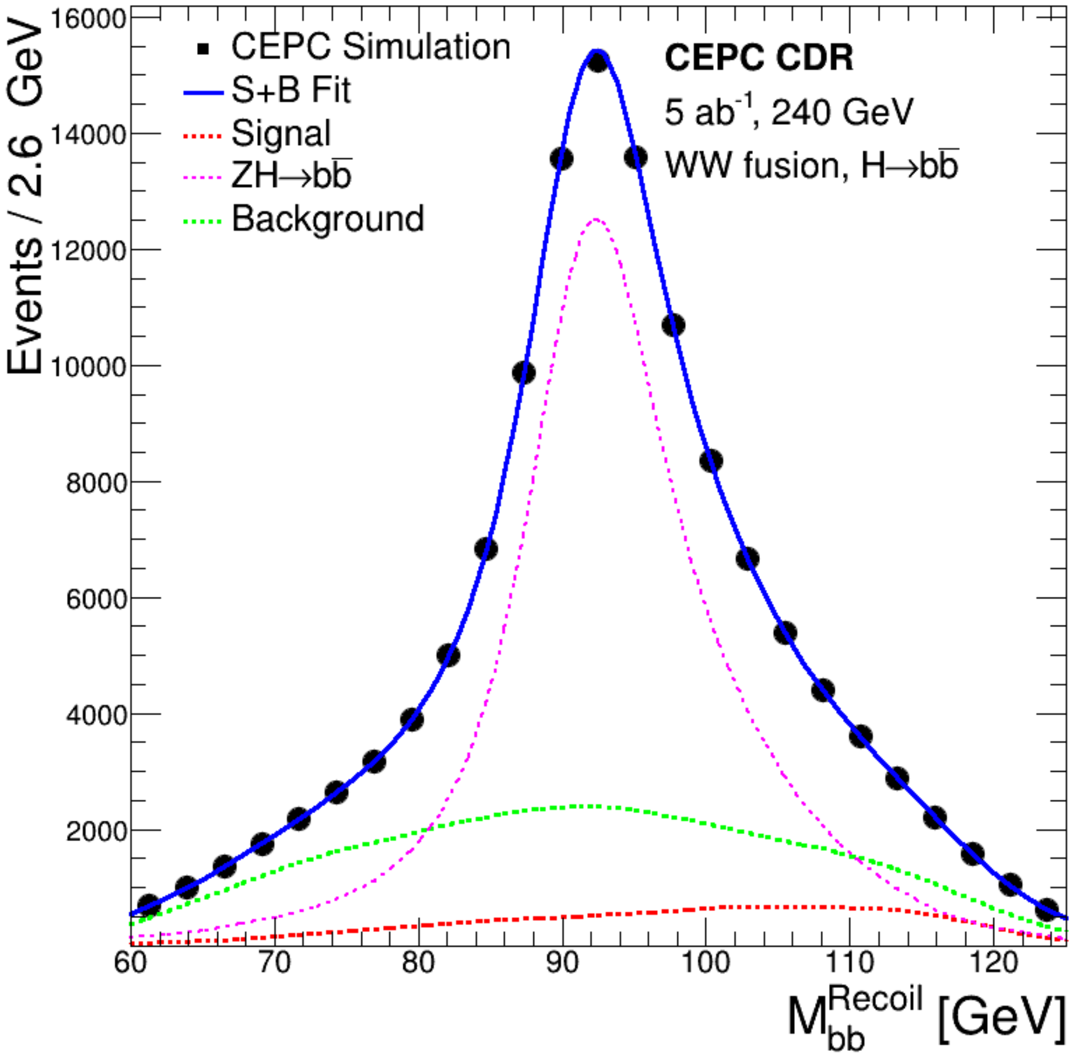
Need to see the 2d distribution first to avoid huge bias case.

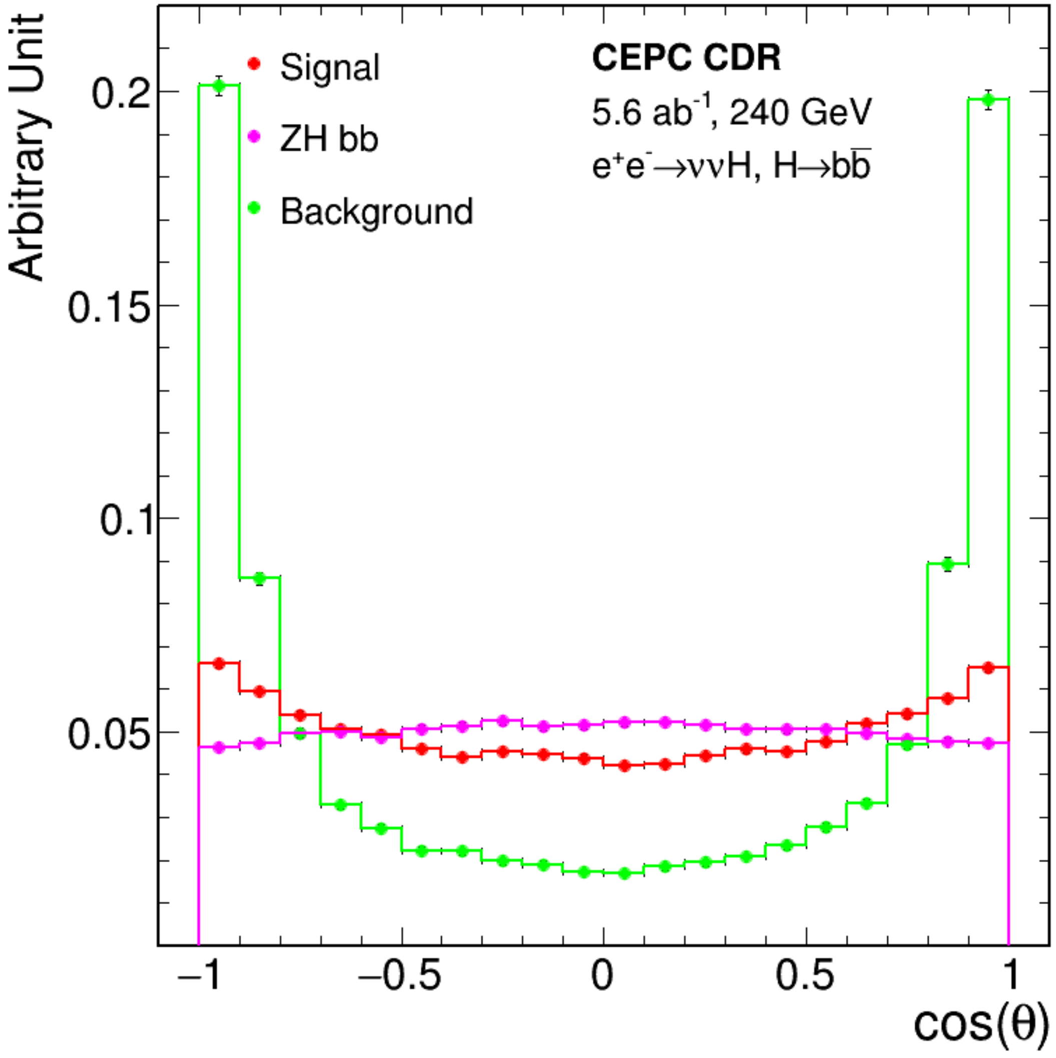
# backup

# Correlation matrix



# vvH->bb 240GeV

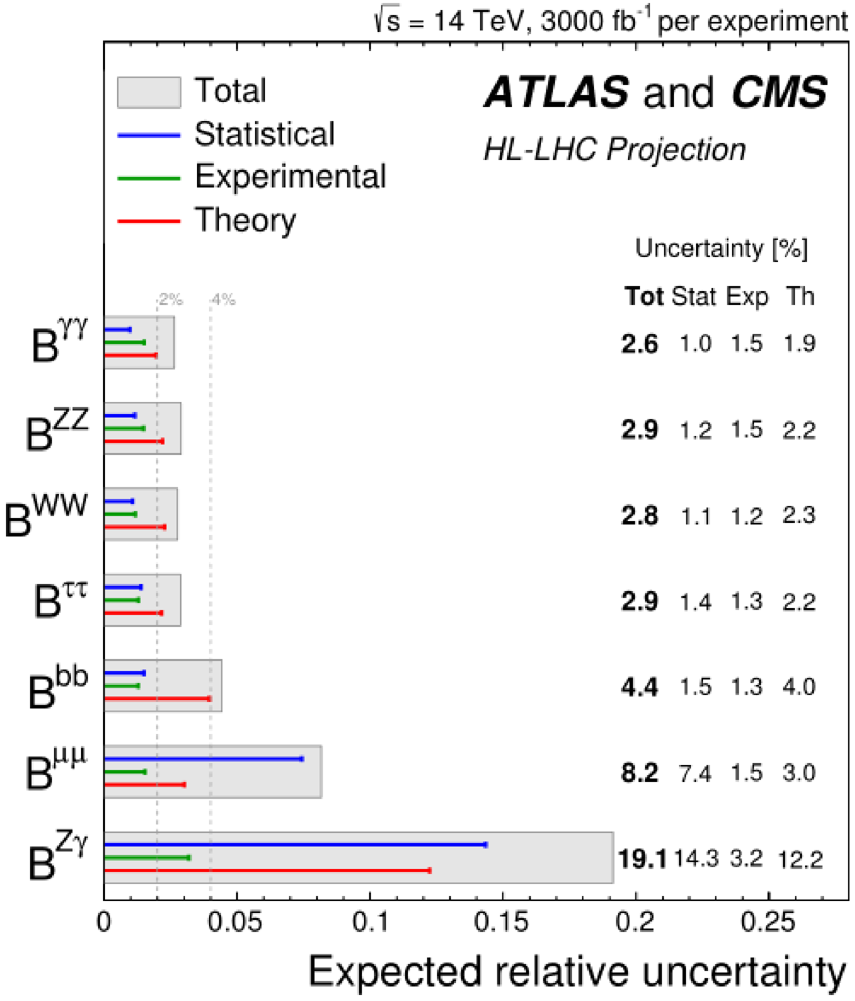


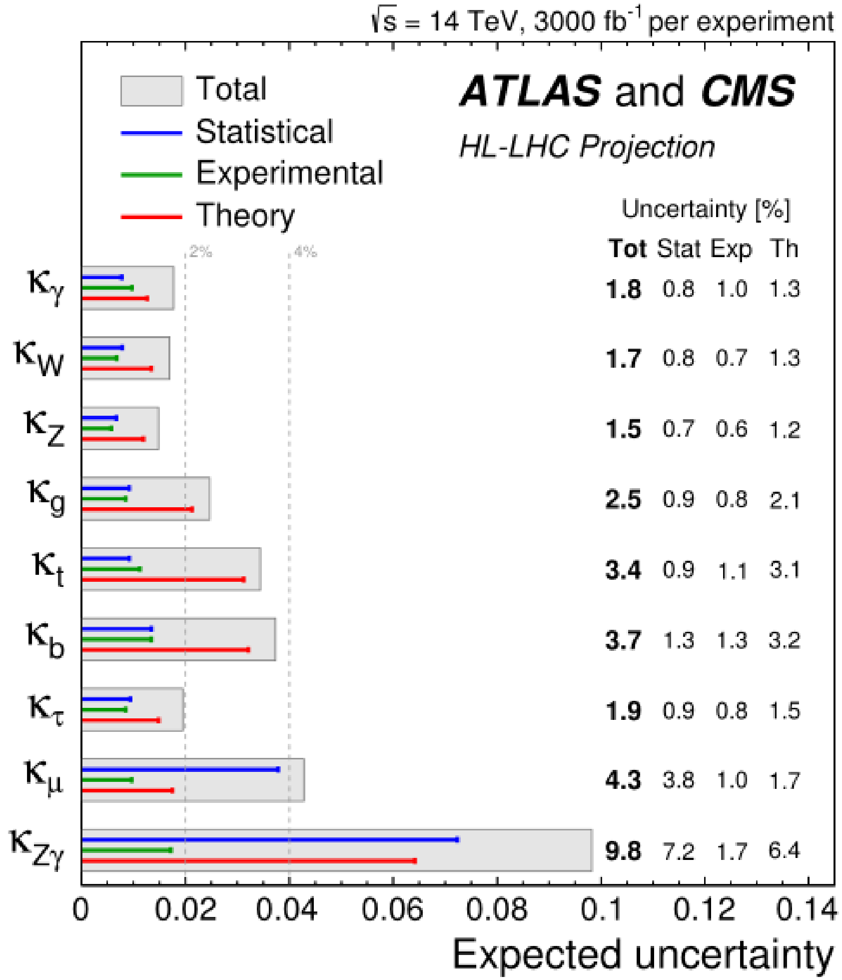



# Synergy of HL-LHC

Arxiv:1902.00134

- HL-LHC S2 estimation; has wonderful prediction on such channels like $\gamma\gamma$.




$B_{\gamma\gamma}: \sigma * Br(H \to \gamma\gamma);$

# Kappa Synergy

| Collider | HL-LHC | $ILC_{250}$ | $CLIC_{380}$ | $LEP3_{240}$ | $CEPC_{250}$ | $FCC\text{-}ee_{240+365}$ | | |
|---|---|---|---|---|---|---|---|---|
| Lumi ($ab^{-1}$) | 3 | 2 | 1 | 3 | 5 | $5_{240}$ | $+1.5_{365}$ | + HL-LHC |
| Years | 25 | 15 | 8 | 6 | 7 | 3 | +4 | |
| $\delta\Gamma_H/\Gamma_H$ (%) | SM | 3.6 | 4.7 | 3.6 | 2.8 | 2.7 | **1.3** | 1.1 |
| $\delta g_{HZZ}/g_{HZZ}$ (%) | 1.5 | 0.3 | 0.60 | 0.32 | 0.25 | 0.2 | **0.17** | 0.16 |
| $\delta g_{HWW}/g_{HWW}$ (%) | 1.7 | 1.7 | 1.0 | 1.7 | 1.4 | 1.3 | **0.43** | 0.40 |
| $\delta g_{Hbb}/g_{Hbb}$ (%) | 3.7 | 1.7 | 2.1 | 1.8 | 1.3 | 1.3 | **0.61** | 0.56 |
| $\delta g_{Hcc}/g_{Hcc}$ (%) | SM | 2.3 | 4.4 | 2.3 | 2.2 | 1.7 | **1.21** | 1.18 |
| $\delta g_{Hgg}/g_{Hgg}$ (%) | 2.5 | 2.2 | 2.6 | 2.1 | 1.5 | 1.6 | **1.01** | 0.90 |
| $\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%) | 1.9 | 1.9 | 3.1 | 1.9 | 1.5 | 1.4 | **0.74** | 0.67 |
| $\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%) | 4.3 | 14.1 | n.a. | 12 | 8.7 | 10.1 | **9.0** | 3.8 |
| $\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%) | 1.8 | 6.4 | n.a. | 6.1 | 3.7 | 4.8 | **3.9** | 1.3 |
| $\delta g_{Htt}/g_{Htt}$ (%) | 3.4 | – | – | – | – | – | – | 3.1 |
| $BR_{EXO}$ (%) | SM | $< 1.7$ | $< 2.1$ | $< 1.6$ | $< 1.2$ | $< 1.2$ | $< \mathbf{1.0}$ | $< \mathbf{1.0}$ |