Higgs Prospect at CEPC and Physics at 360 GeV run

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on behalf of CEPC Physics Working Group

The 7th China LHC Physics Workshop (CLHCP2021)
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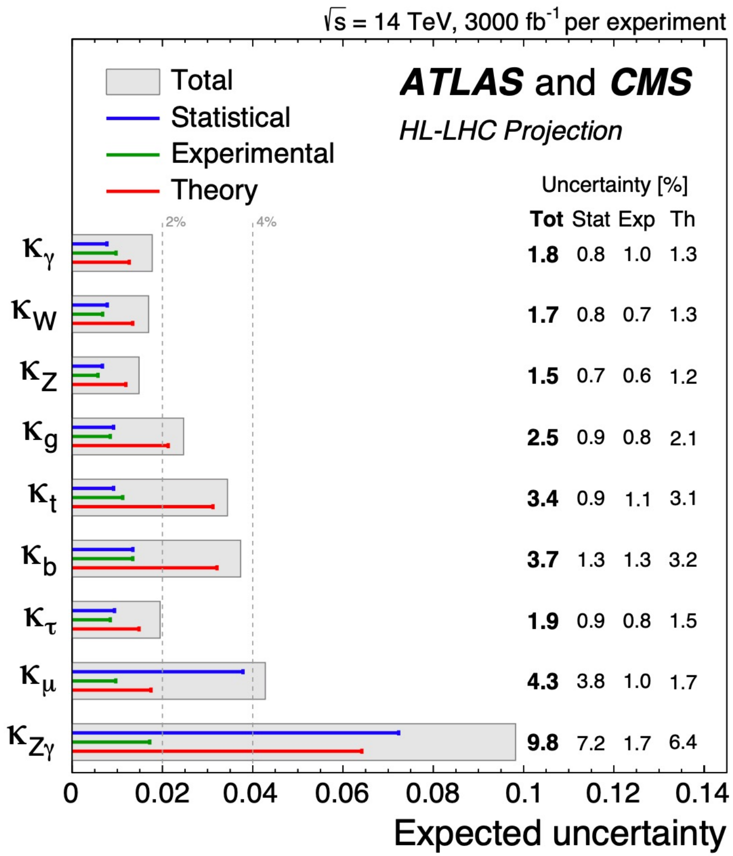
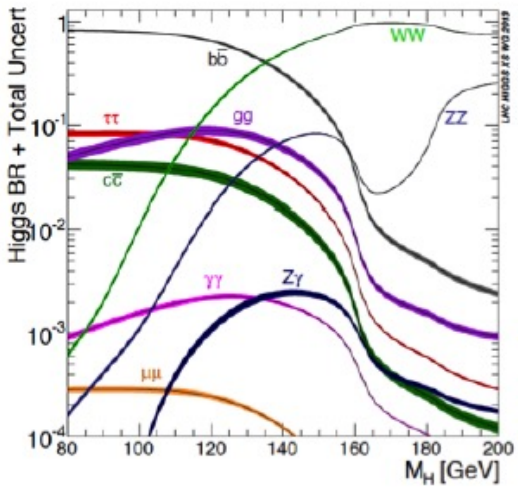
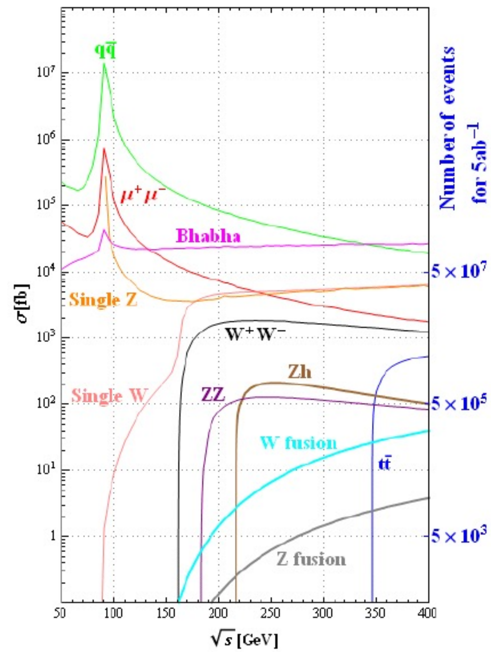
Why do we need e+e- collider?



- For HL-LHC (3000 fb-1), the precisions of measurements of Higgs coupling parameters are not better than a few percent.
  - Theoretical uncertainties start to be the dominant one.
- If the new physics is at the sub-percent level, HL-LHC is not sensitive.
- Need e^+e^- machine to precisely measure Higgs property as well as explore new physics.

SM Higgs decay branching ratio, Bkg process

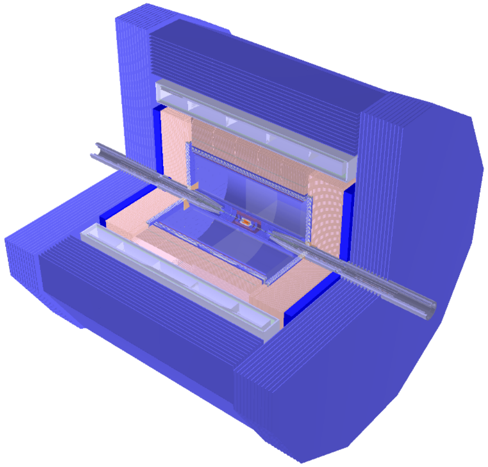


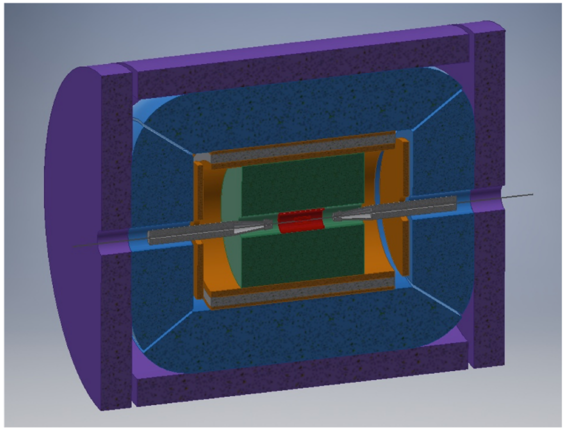


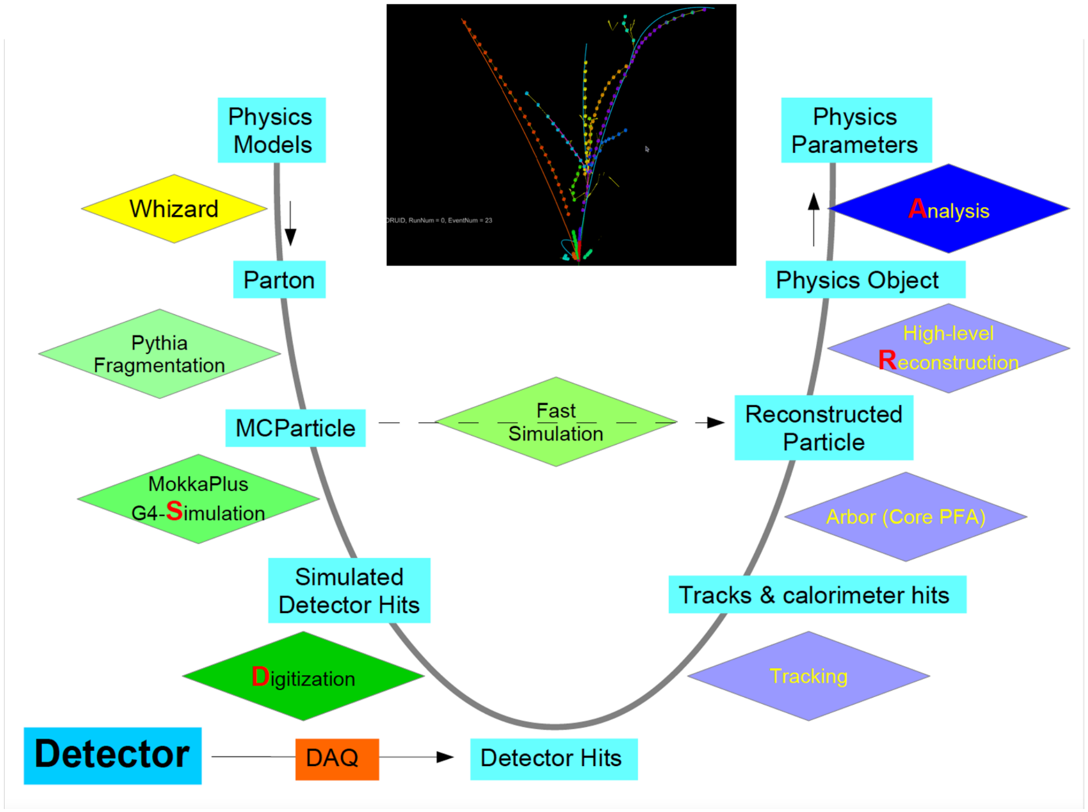
✓ e^+e^- collider provides a good opportunity to measure the jj, invisible decay of Higgs.

✓ For 5.6 ab^{-1} data with CEPC, 1M Higgs, 10M Z, 100M W are produced.

Detector & Software

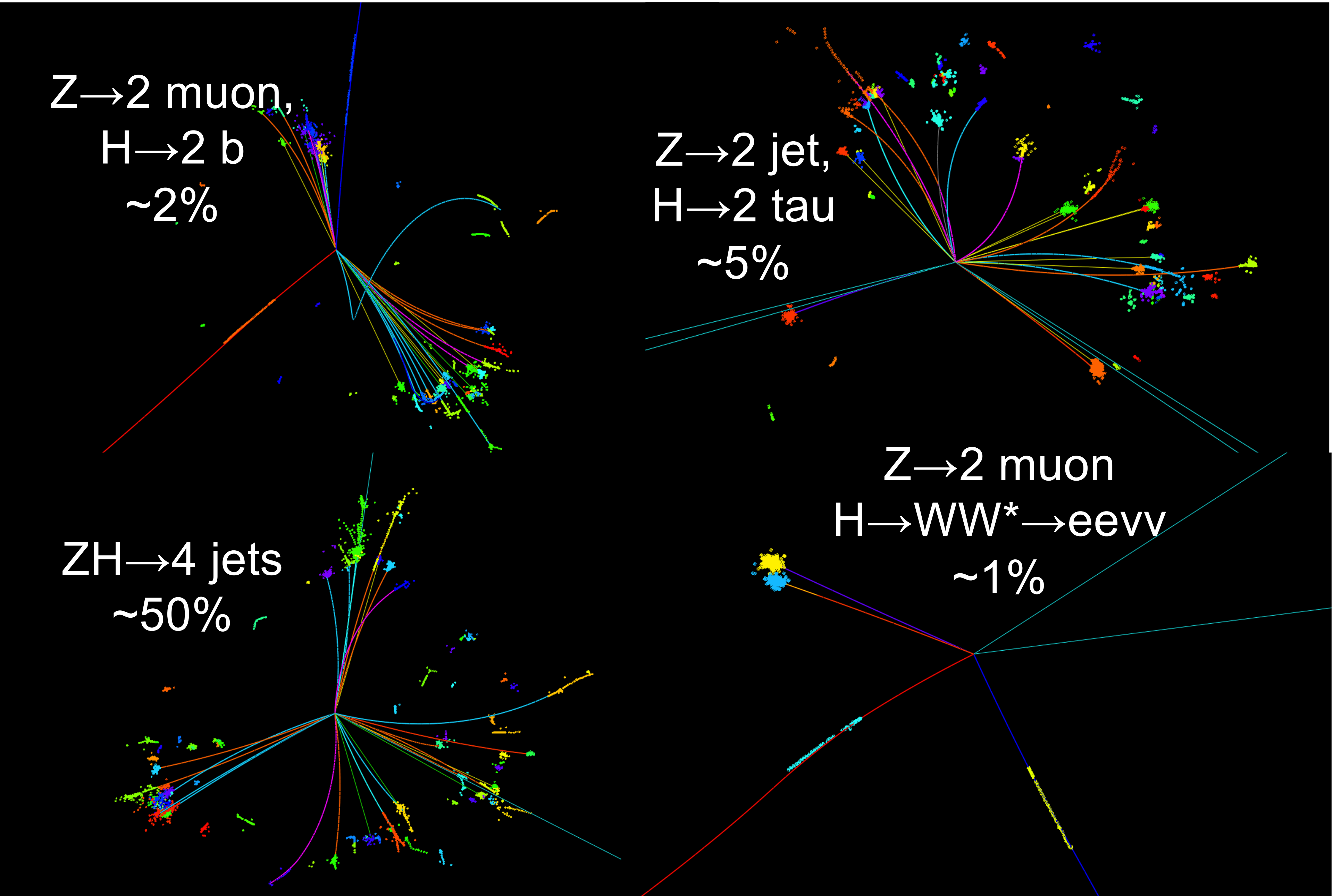




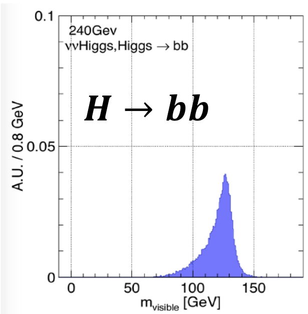


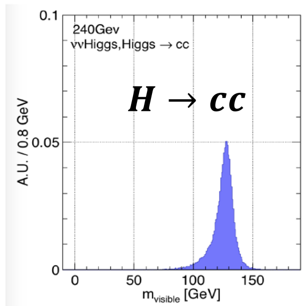
Full simulation reconstruction Chain functional, iterating/validation with hardware studies

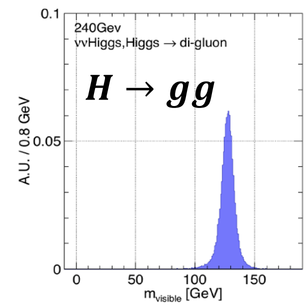
Events Display for Higgs

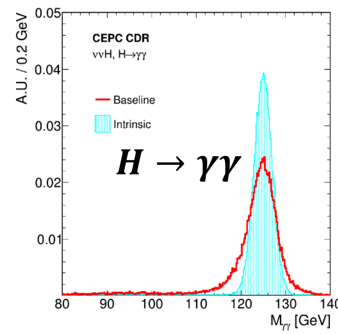


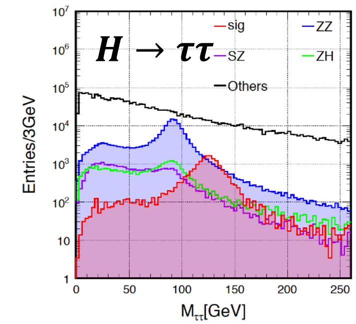
Reminder: Recon. Higgs Signatures& Detector Performance@CDR

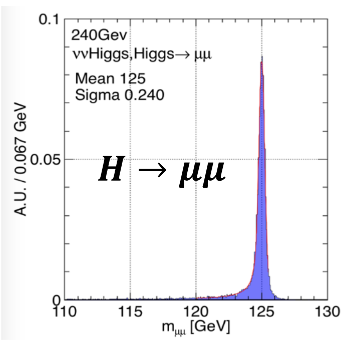


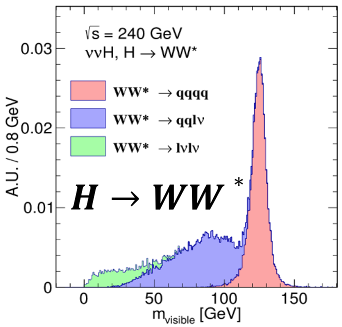


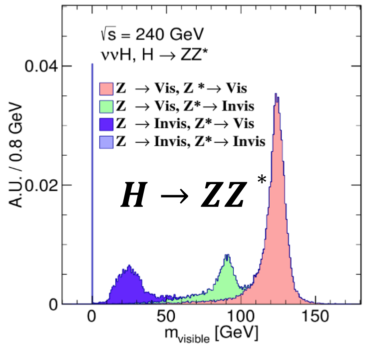






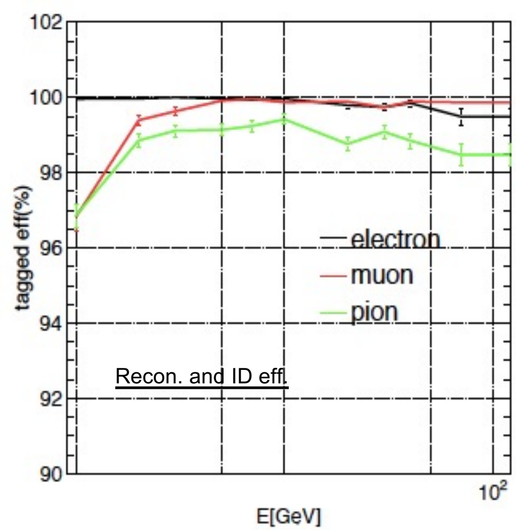


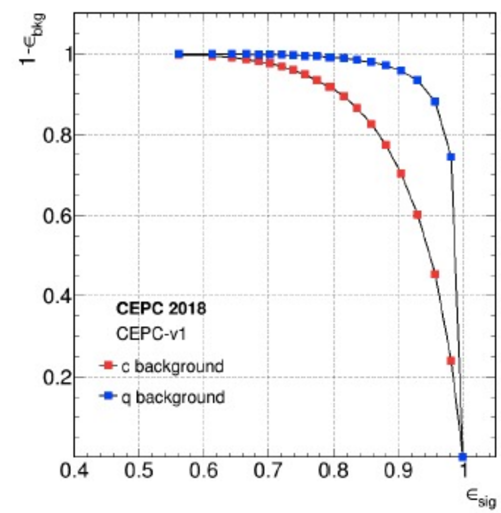




- ✓ Clear Higgs Signature in all SM decay modes
- ✓ Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level
- ✓ *Di-tau mass distribution at qqH events using collinear approximation*

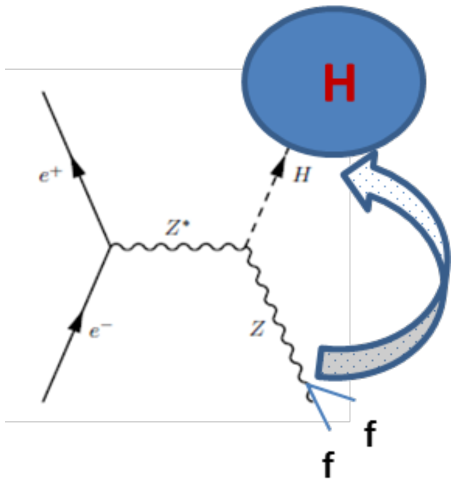
- ✓ Acceptance: |cos(θ)| < 0.99
- ✓ Tracks: Pt threshold, ~ 100 MeV
  - ✓ δp/p ~ o(0.1%)
- ✓ Photons:
  - ✓ Energy threshold, ~ 100 MeV
  - ✓ δE/E: 3 – 15%/sqrt(E)
- ✓ BMR: 3.7%
- ✓ b-tagging: eff*purity @ Z→qq: 70%
- ✓ c-tagging: eff*purity @ Z→qq: 40%





Direct measurement of Higgs cross-section

$$M^2_{\rm recoil} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$



- ✓ **For this model independent analysis, we reconstruct the recoil mass of Z without touching the other particles in a event.**
- ✓ **The M_{recoil} should exhibit a resonance peak at m_H for signal; Bkg is expected to smooth.**
- ✓ **The best resolution can be achieved from Z(→e^+e^-, $\mu^+\mu^-$).**

Measurement of Higgs width

- **Method 1: Higgs width can be determined directly from the measurement of σ(ZH) and Br. of (H->ZZ*)**

$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

Precision : 5.1%

  - **But the uncertainty of Br(H->ZZ*) is relatively high due to low statistics.**

- **Method 2: It can also be measured through:**

$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{BR(H \to bb)} \qquad \sigma(\nu\bar{\nu}H \to \nu\bar{\nu}b\bar{b}) \propto \Gamma(H \to WW^*) \cdot \mathrm{BR}(H \to bb) = \Gamma(H \to bb) \cdot \mathrm{BR}(H \to WW^*)$$

3.0%

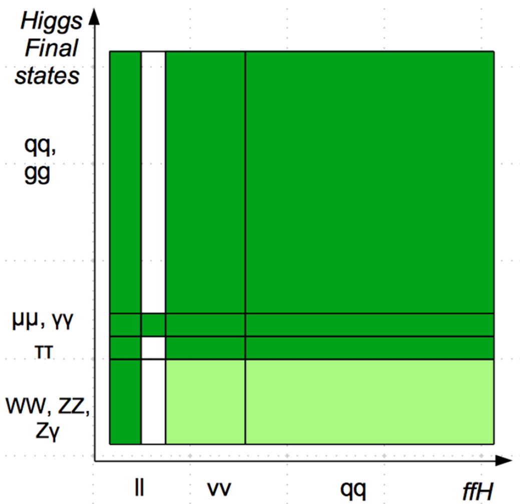
$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\bar{\nu}H \to \nu\bar{\nu}b\bar{b})}{\mathrm{BR}(H \to b\bar{b}) \cdot \mathrm{BR}(H \to WW^*)}$$

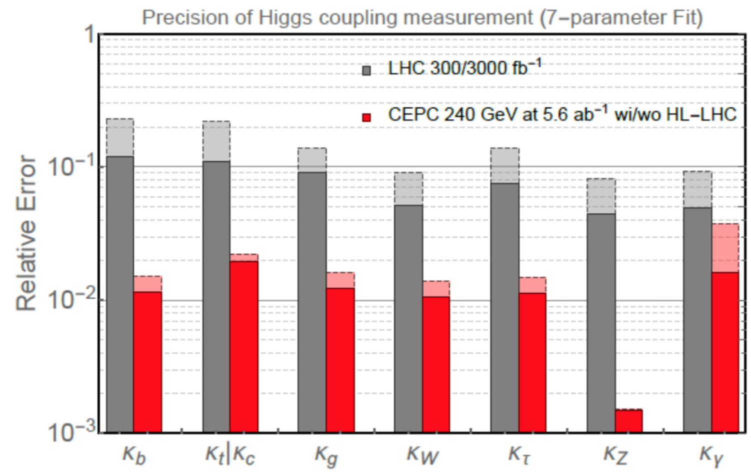
Precision : 3.5%

- **These two orthogonal methods can be combined to reach the best precision.**

Combined Precision : 2.9%

Physics Potential@ CDR





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Precision Higgs Physics at the CEPC*

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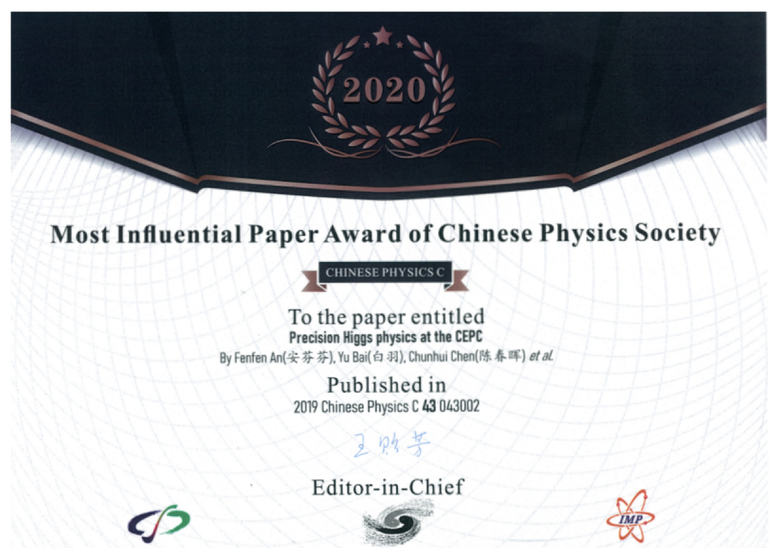
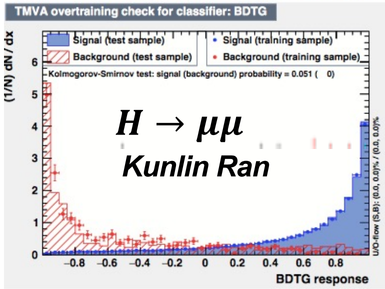
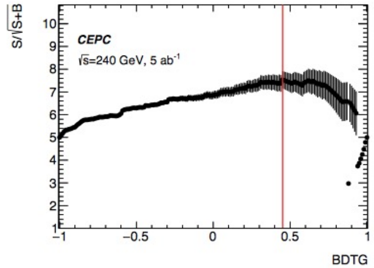


MVA methods widely used Higgs analyses

- After training with 6 variables: $cos\theta_{ee}$, $cos\theta_{\mu\mu}$, $\Delta_{\mu\mu}$, M_{qq}, E_{ee}, $E_{qq\mu\mu}$, get the BDTG response

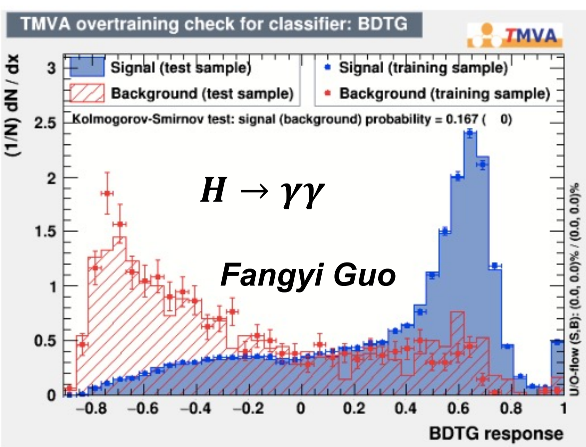




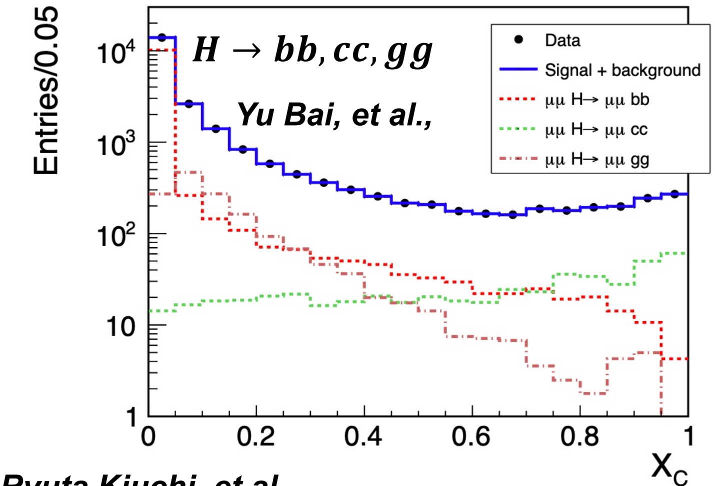
- There is a overtraining in the background due to poor statistics: ~1600
- Scan the total sensitivity ($S/\sqrt{S+B}$) vs BDTG to find the optimal BDTG point
- The sensitivity is estimated in the 90% signal coverage region

	Sig yield	Bkg yield	Sensitivity	Mass range (GeV)
BDTG > 0.45	86.20 +/- 0.51	198.20 +/- 19.82	7.46 +/- 0.27	[120.78 - 125.33]
BDTG < 0.45	29.77 +/- 0.30	1402.95 +/- 52.73	1.08 +/- 0.03	[114.08 - 125.28]
Total	115.97 +/- 0.59	1601.15 +/- 56.33	7.54 +/- 0.38	

- For H->$\mu\mu$, the improvement is ~35% w.r.t cut based one for the signal significance (improvement on precision 17%-12%).
- The overall precision has been improved from 6.8% to 5.7% with MVA as well as full simulated samples used for H->$\gamma\gamma$.



CPC Vol. 44, No.1 (2020)013001



Ryuta Kiuchi, et al.,

$H \to ZZ$ ArXiv: 2103.09633

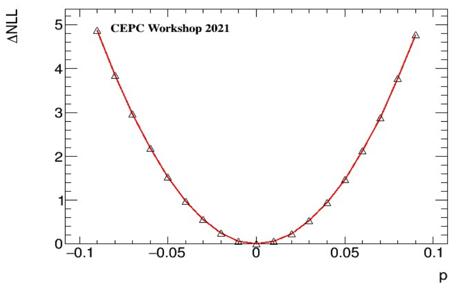
Category	$\frac{\Delta(\sigma \cdot BR)}{(\sigma \cdot BR)}$ [%] cut-based	BDT
$\mu\mu H\nu\nu qq^{cut/mva}$	15.5	13.6
$\mu\mu H qq\nu\nu^{cut/mva}$	48.0	42.1
$\nu\nu H\mu\mu qq^{cut/mva}$	11.9	12.5
$\nu\nu H qq\mu\mu^{cut/mva}$	23.5	20.5
$qqH\nu\nu\mu\mu^{cut/mva}$	45.3	37.0
$qqH\mu\mu\nu\nu^{cut/mva}$	52.4	44.4
Combined	8.34	7.89

Other activities in Higgs group

Higgs CP Study

Study channel: *Qiyu Sha*

$ee \to ZH \to \mu\mu H(\to b\bar{b}/c\bar{c}/gg)$

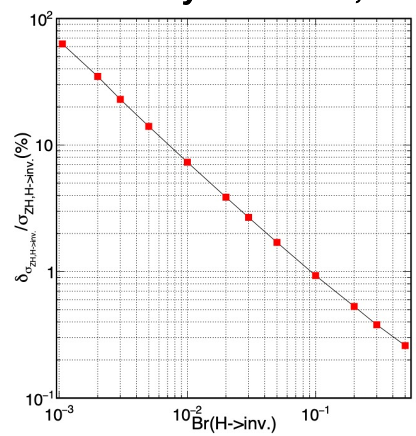


68% CL: $[-2.9\times10^{-2}, 2.9\times10^{-2}]$
95% CL: $[-5.7\times10^{-2}, 5.7\times10^{-2}]$

Higgs invisible decays

ArXiv:2103.09633

Ryuta Kiuchi, et al.



Global analysis

$$\Sigma^N = N_t^e \begin{pmatrix} B_1(1-B_1) & -B_1B_2 & \dots & -B_1B_m \\ -B_2B_1 & B_2(1-B_2) & \dots & -B_2B_m \\ \vdots & \vdots & \ddots & \vdots \\ -B_mB_1 & -B_mB_2 & \dots & B_m(1-B_m) \end{pmatrix},$$

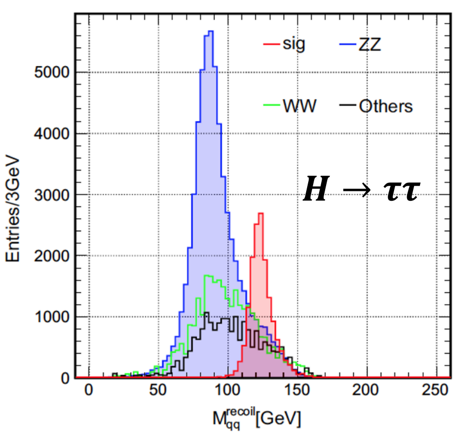
Gang Li

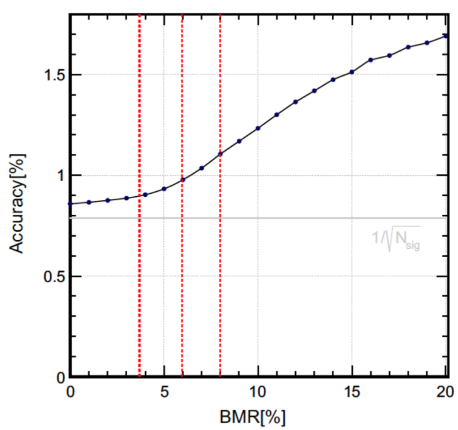
ArXiv:2105.14997

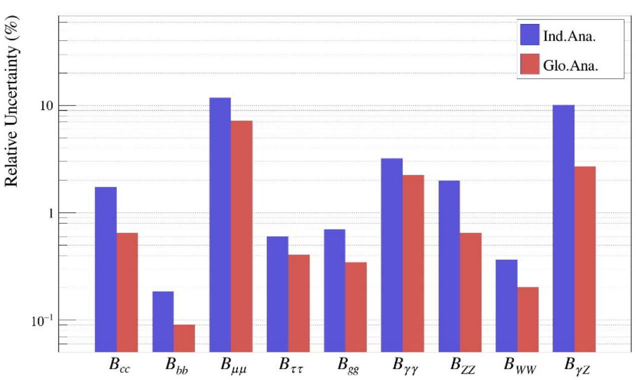
- ✓ Calculate the efficiency matrix
- ✓ Particle level information as the input.
- ✓ Proof-of-Principle study shows precision improved by a factor of ~2.
- ✓ Full simulation study is ongoing.

Higgs decays to $\tau\tau$

Euro. Phys. J. C(2020) 80:7 **Dan Yu**







Physics @ 360 GeV Run

CDR/Latest Runs at CEPC

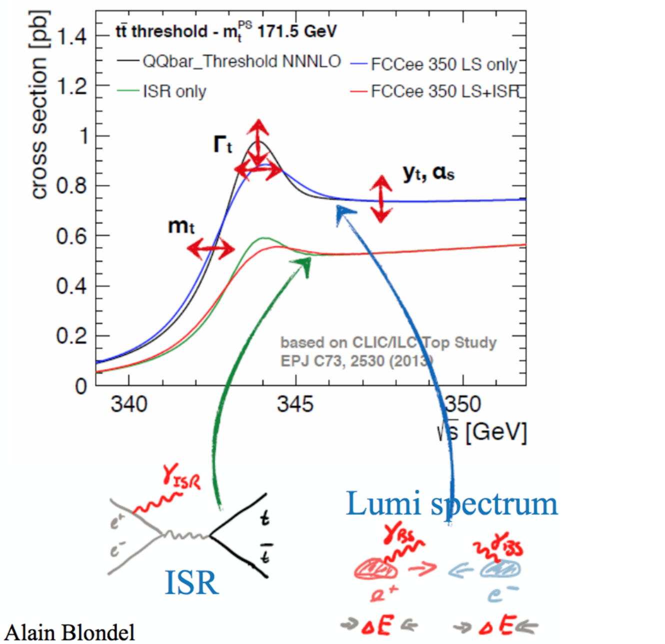
Operation mode		ZH	Z	W^+W^-	ttbar (new)
$\sqrt{s}$ [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	7.7
CDR	L / IP [$\times 10^{34}$ $cm^{-2}s^{-1}$]	3	32	10	
	$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	
Latest	L / IP [$\times 10^{34}$ $cm^{-2}s^{-1}$]	5.0	115	15.4	0.5
	$\int L\,dt$ [ab^{-1}, 2 IPs]	9.3	57.5	4.0	1.0
	Event yields [2 IPs]	1.7×10^6	2.5×10^{12}	3×10^7	3×10^5

✓Studies are mostly based on CDR Setup.
✓The impacts of the latest plans will be briefly addressed in some studies.

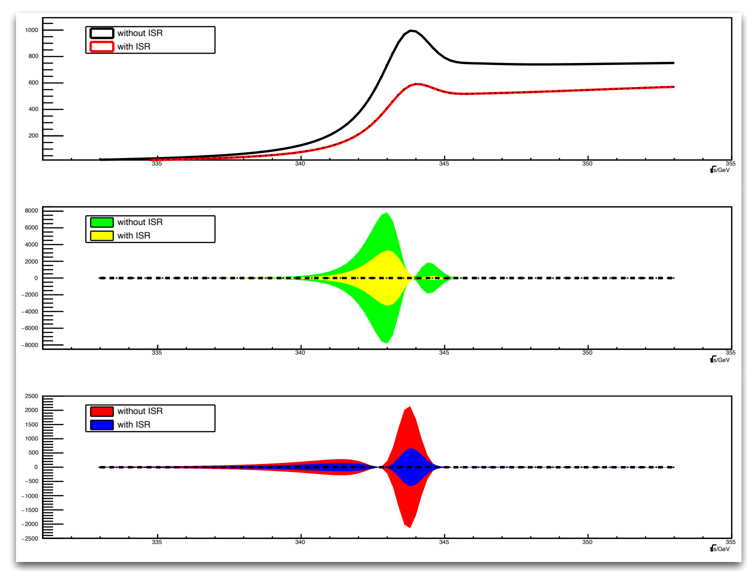
Top property measurement

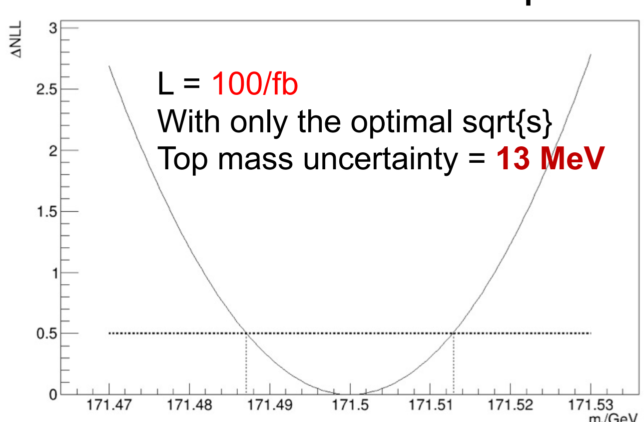
Zhan Li

- 360 GeV runs open a door to measure top properties in high precision that hadron colliders cannot reach
- Currently we study the top mass and width measurements using the tt threshold method at ~360 GeV
  - One order of magnitude better precision than the hadron collider is expected
  - A single run at the energy where the tt xsection varies most largely in a given top mass range is found to provide the best performance : from 18 MeV to 13 MeV
  - A quick energy scan with low luminosity to find the optimal energy point before data taking with the full luminosity is proposed
  - More studies are ongoing for the simultaneous measurements of the top mass, width and α_s



The peak indicates the optimal sqrt{s} for the top mass



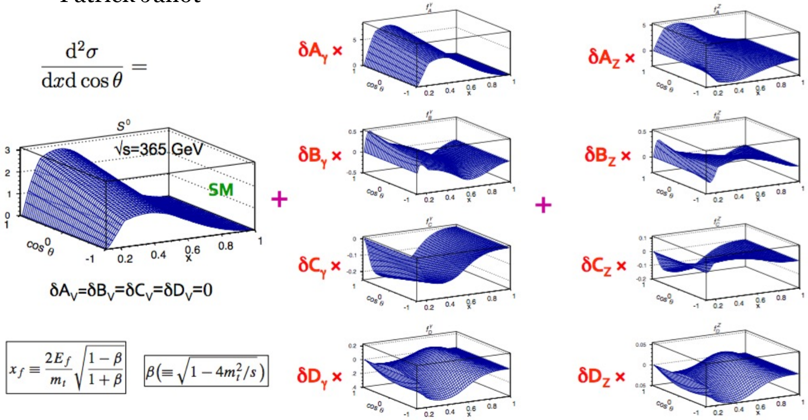


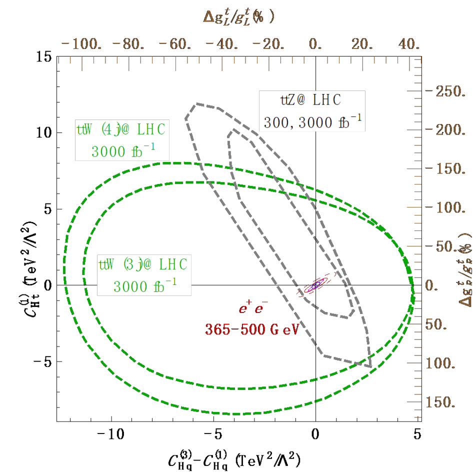
Top quark and Higgs EFT $O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Ht}$

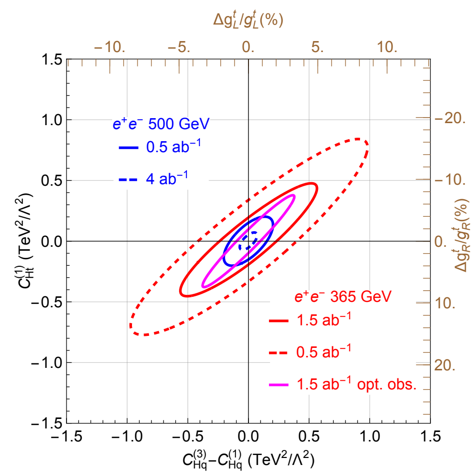
Zhen Liu

At or above $t\bar{t}$ threshold at lepton colliders, one immediately again great sensitivities to the top gauge couplings.

Patrick Janot





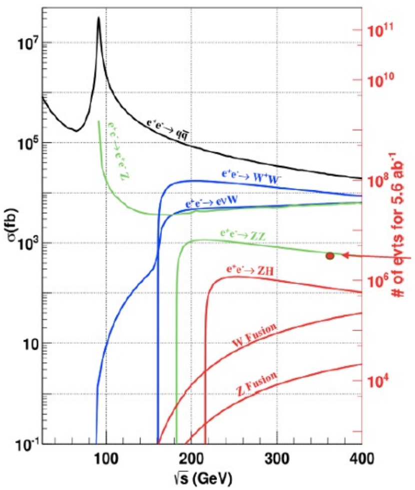


- ✓ Note that the opt. obs. Analysis is a rescaling of the study from Janot, we are working on CEPC simulation and analysis
- ✓ Expect to be consistent with FCC-ee.

Additional sensitivity to Higgs measurements

Kaili Zhang, Jiayin Gu

- 2 ab^{-1}@360 GeV
- 30% more Higgs events
- Improvement on Higgs width : 2 times better (2.9% → 1.4%)
- Constraint on HH measurement.



	240GeV, 5.6ab^{-1}	360GeV, 2ab^{-1}	
	ZH	ZH	ννH
any	**0.50%**	**1%**	****
H → bb	**0.27%**	**0.63%**	**0.76%**
H → cc	**3.3%**	**6.2%**	**11%**
H → gg	**1.3%**	**2.4%**	**3.2%**
H → WW	**1.0%**	**2.0%**	**3.1%**
H → ZZ	**5.1%**	**12%**	**13%**
$H \to \tau\tau$	**0.8%**	**1.5%**	**3%**
$H \to \gamma\gamma$	**5.7%**	**8%**	**11%**
$H \to \mu\mu$	**12%**	**29%**	**40%**
$\mathrm{Br_{upper}}(H \to \mathrm{inv.})$	**0.2%**	****	****
$\sigma(ZH) * \mathrm{Br}(H \to Z\gamma)$	**16%**	**25%**	****
Width	**2.9%**		
Combined Width 240/360	**1.4%**		

$t\bar{t}$: here

Fcc-ee 240 GeV/365 GeV:
CERN-ACC-2018-0057

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

combined width: 1.3%

For Higgs physics results, there are no significant different for the colliding energy with 360 GeV or 365 GeV.

Impact of the updated running plans on Higgs physics

With the Lum@ 240 GeV：5.6 ab^{-1} → 9.3 ab^{-1} & the Lum@360 GeV Run：2 ab^{-1} → 1 ab^{-1}:

the precision for Higgs width： 1.43% → 1.36% (very stable ☺)

	240GeV, 5.6ab^{-1}	360GeV, 2ab^{-1}	
	ZH	ZH	vvH
any	**0.50%**	**1%**	****
$H \to bb$	**0.27%**	**0.63%**	**0.76%**
$H \to cc$	**3.3%**	**6.2%**	**11%**
$H \to gg$	**1.3%**	**2.4%**	**3.2%**
$H \to WW$	**1.0%**	**2.0%**	**3.1%**
$H \to ZZ$	**5.1%**	**12%**	**13%**
$H \to \tau\tau$	**0.8%**	**1.5%**	**3%**
$H \to \gamma\gamma$	**5.7%**	**8%**	**11%**
$H \to \mu\mu$	**12%**	**29%**	**40%**
$Br_{upper}(H \to inv.)$	**0.2%**	****	****
$\sigma(ZH) * Br(H \to Z\gamma)$	**16%**	**25%**	****
Width	**2.9%**		
Combined Width 240/360	**1.43%**		

	240GeV, 9.3ab^{-1}	360GeV, 1ab^{-1}		
	ZH	ZH	vvH	eeH
any	0.4%	1.4%	\\	\\
$H \to bb$	0.2%	1%	1%	5%
$H \to cc$	2.6%	9%	16%	41%
$H \to gg$	1.0%	3%	5%	22%
$H \to WW$	0.8%	3%	4%	9%
$H \to ZZ$	6.1%	20%	21%	
$H \to \tau\tau$	0.6%	2%	4%	10%
$H \to \gamma\gamma$	4.4%	11%	16%	
$H \to \mu\mu$	9.3%	41%	57%	
Br_upper ($H \to inv.$)	0.2%			
$\sigma(ZH) * Br(H \to Z\gamma)$	12.4%	35%		
Width	**2.34%**			
Combined width 240/360	**1.36%**			

Conclusion

- After the Higgs white paper and CDR are done, analyses from individual channels have been documented. Several publications of them are available now.
- Improved analyses on CEPC Higgs are on going
- We also have a generic study on Higgs physics at 360 GeV (360 GeV/2 ab^{-1} as a benchmark)
  - Can bring some improvements in Higgs precision measurement in addition to top coupling measurements.
    - Significant improvement on Higgs width measurement.
  - The impacts of 360GeV/1 ab^{-1} on Higgs are studied.

backup Slides

Workshops for white papers

White paper activities:

- 2019.3 Higgs White Paper delivered
- 2019.7 WS @ PKU: EW, Flavor, QCD working group formed
- 2020.1 WS @ HKIAS: Review progress & iterate. EW Draft Ready
- 2021.4 WS @ Yangzhou: BSM working group formed

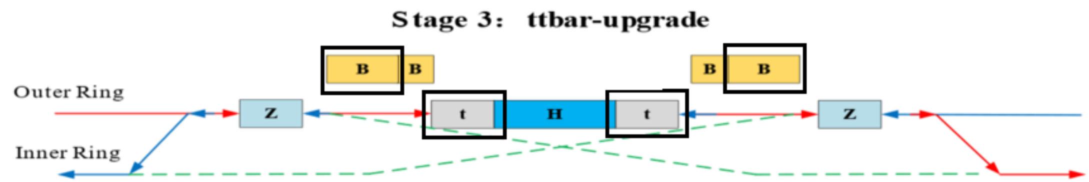
https://indico.ihep.ac.cn/event/13888/

- CEPC Physics/Detector WS, **April 2021 @ Yangzhou**
  - ~ 45 Physics reports
  - ~ 10 Performance/Optimization study
  - Significant Fresh
- *Higgs: Impact of 360 GeV Runs*
- *Top physics at 360 GeV*
- *EW: Draft ready*
- *QCD: intensive discussions...*
- *Flavor + BSM:*
  - *Many Performance & Benchmark analyses*

Accelerator at ttbar

Yiwei Wang

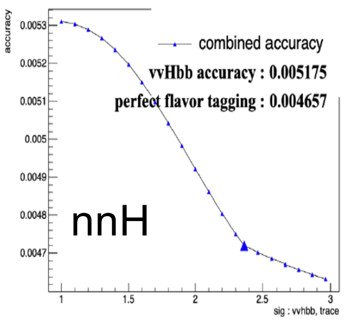
- Extra Hardware:
  - ttbar cavities (international sharing): Collider + 7 GV 650 MHz 5-cell cavity, Booster + 6 GV 1.3 GHz 9-cell cavity
  - some septum magnets for beam separation in the RF regions
  - several quadrupole magnets for final focusing
- Accelerator physics design:
  - With SR power limit of 30MW, currer design achieved a luminosity of 0.5E34/cm^2/s/IP
  - corresponding to 1ab^{-1} for 7.7 years with 1.3 Snowmass units running/year
- To achieve 2 ab^{-1} for 7.7 years
  - reducing the βy*, coupling factor anc increasing the synchrotron radiation power limit.

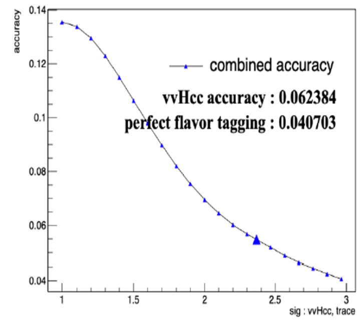


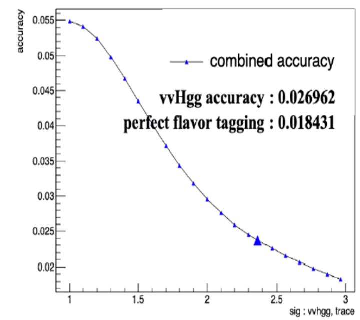
Extra RF cavities for ttbar in collider ring and booster ring

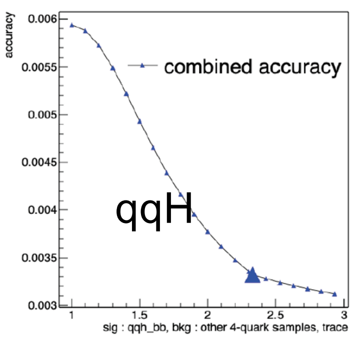
	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	0.27/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	0.10/0.17	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3/2.6	1.7/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071/0.1	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Longitudinal tune Qs	0.078	0.049	0.062	0.035
Beam lifetime (bhabha/beamstrahlung)[min]	81/23	39/40	60/700	80/18000
Beam lifetime total [min]	18	20	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

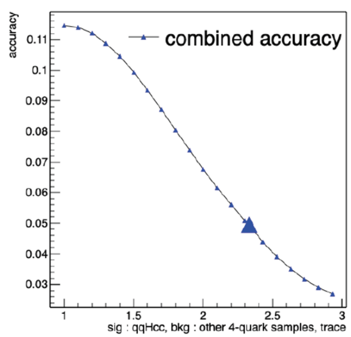
H→bb, cc, gg: BMR, Color Singlet id (CSI) & Flavor tagging (Preliminary)

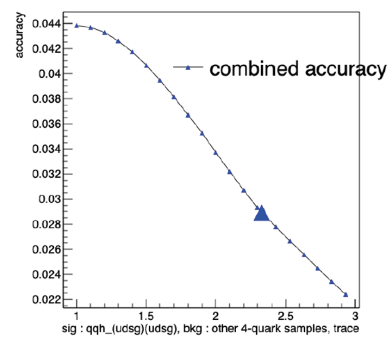


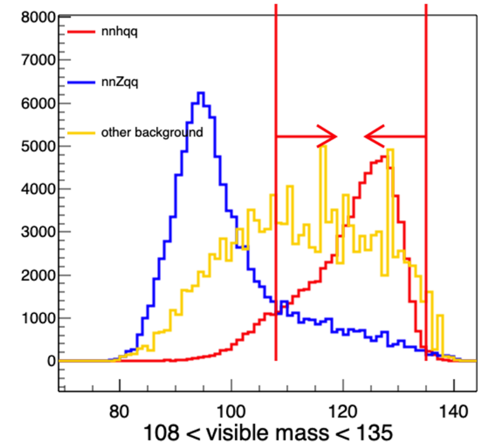


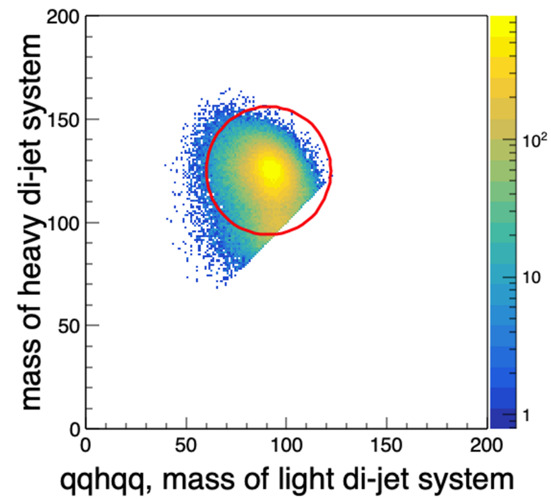












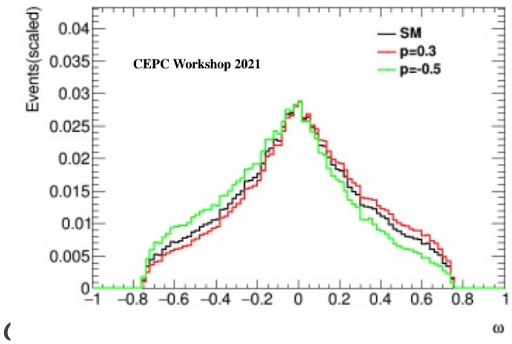
- BMR is good enough... Huge penitential compared to Baseline FT + Naive CSI (ee-kt jet clustering & matching)
- Ideal CSI improves the accuracies by up to 2 times...
- Ideal Flavor tagging improves the accuracy of of Hcc by 2 times @ qqH, & 50% @ nnH

How to develop Jet Charge?

Jet Charge Algorithm:

- *Use Jet Clustering to divide final leading particles into two jets*
- *Find the relationship between observables(charge, energy) of final leading particles and jet charge:*
  - *For $Z \to b\bar{b}$ samples:*
    - $e^-, \mu^-, K^-, \pi^-, p^+$ *are closer to* b *jet*
    - $e^+, \mu^+, K^+, \pi^+, p^-$ *are closer to* $\bar{b}$ *jet*
  - *For $Z \to c\bar{c}$ samples:*
    - $e^+, \mu^+, K^-, \pi^+, p^+$ *are closer to* c *jet*
    - $e^-, \mu^-, K^+, \pi^-, p^+$ *are closer to* $\bar{c}$ *jet*
- *Combine the information of final leading particles of two jets*
- *Use those observables(charge, energy) of final leading particles to measure jet charge*
- *Use Misjudgment rate ω and effective tagging power to describe Jet Charge*

Higgs CP study at CEPC



<u>Study channel:</u> $ee \to ZH \to \mu\mu H(\to b\bar{b}/c\bar{c}/gg)$

Differential cross section could be represent as:

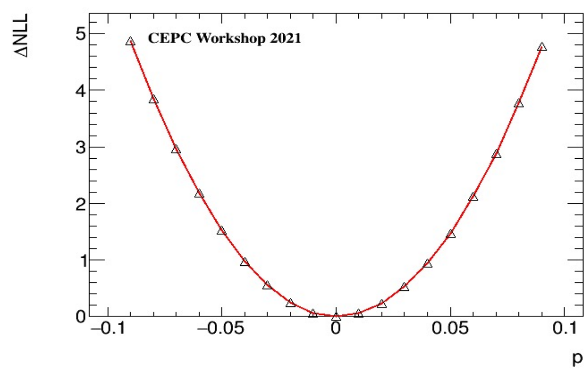
$$\frac{d\sigma}{dcos\theta_1 dcos\theta_2 d\phi} = N \times (J_{CP-even}(\theta_1, \theta_2, \phi) + p \times J_{CP-odd}(\theta_1, \theta_2, \phi)).$$

<u>An</u> Optimal Variable ω which combines the information from $\{\theta_1,\ \theta_2,$

$\omega = \frac{J_{CP-odd}(\theta_1,\theta_2,\phi)}{J_{CP-even}(\theta_1,\theta_2,\phi)}$ to measure p

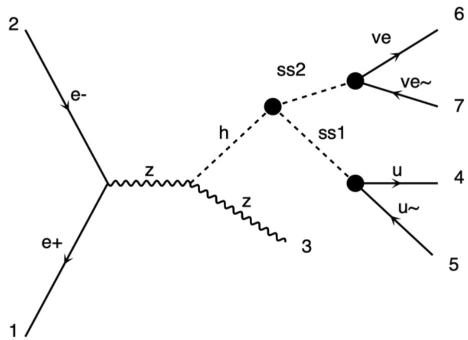
<u>Used ML-fit in ω distribution to extract p.</u>

Result:

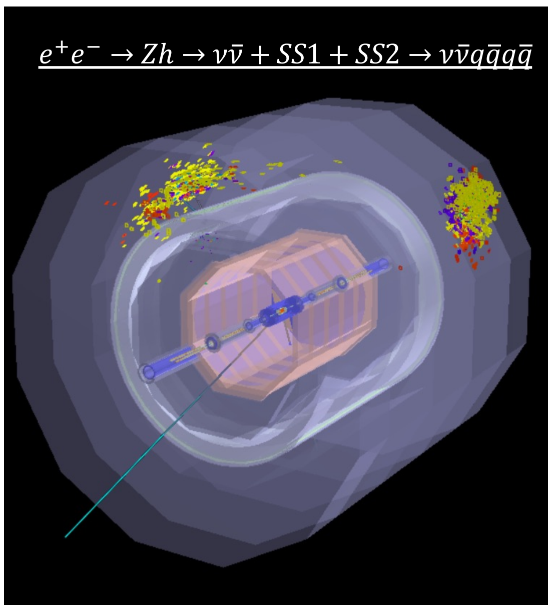


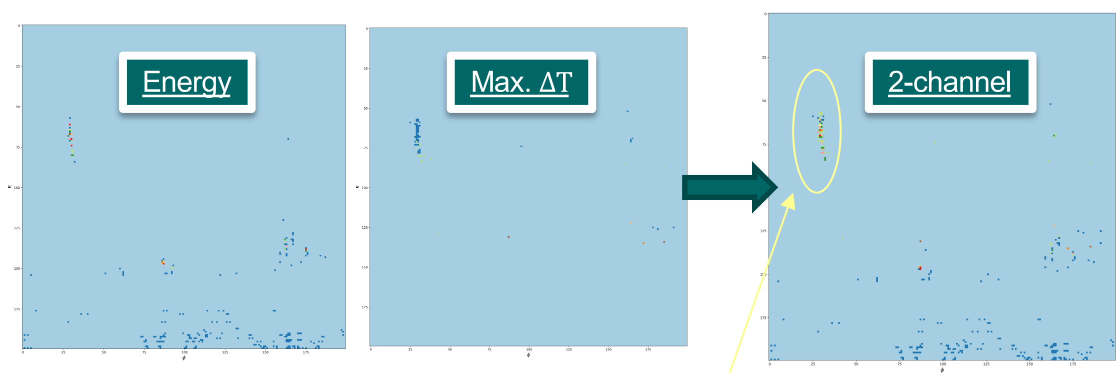
<u>For p:</u>
<u>68% CL: $[-2.9\times10^{-2}, 2.9\times10^{-2}]$</u>
<u>95% CL: $[-5.7\times10^{-2}, 5.7\times10^{-2}]$</u>

Image Recognition Techniques to Identify Long-Lived Particles(h->LLPs)



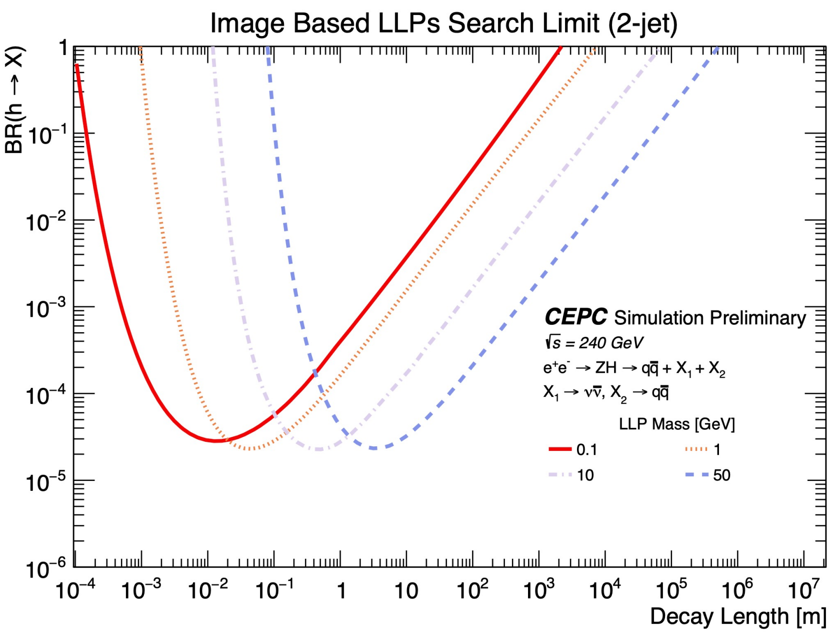
- Mapping the raw detector information to a 2D image
- Input information: image with resolution of $(\mathrm{R}, \phi) = 200 \times 200$ and 1 to 2 channel(s)
  - R starts from 0 to 8 m, ϕ starts from $-\pi$ to π
  - Energy is the sum of Calorimeter hits.
  - Time is the maximum ΔT $(E > 0.1\ GeV)$ within (R, ϕ) pixel
- Model: ResNet18 (Classification), ResNet50 (Vertex Finding)
- **Binary Cross Entropy Loss:** $loss(x_i, y_i) = -\omega_i[y_i \log(x_i) + (1 - y_i)\log(1 - x_i)]$





A LLP Event

Expected Search Sensitivity



Signal Efficiency of ML-based and Cut-based analysis for

Selections	Signal: $Z \to \nu\bar{\nu}$	$ee \to q\bar{q}$	$ee \to ZH$
-		2.5×10^8	
-	1.0×10^6	0.99×10^7	
$\not{E} > 190\text{GeV}$, $N_{PFOs} > 8$	88,077	290	3,361
ML score > 0.95	87,050	0	0
Efficiency (ML-based)	98.83%		
$E_{2j} \geq 30\text{GeV}$	67,244	0	0
Efficiency (cut-based)	75.19%		

- Best branching ratio exclusion limit at decay length around a few meters: $BR(h \to XX) > \sim 10^{-5}$ for most LLP masses
- Good sensitivity for low LLP mass (as low as 1 GeV)

Global analysis for CEPC Higgs

Efficiency modulate N → n

$$\mathbf{n} = \mathbf{E}\mathbf{N} \ .$$

Similar for their covariances

$$\mathbf{\Sigma}^n \equiv \left(c_{ij}^n\right) = \mathbf{E}\mathbf{\Sigma}^N\mathbf{E}^T \ ,$$

We know the covariance of N

~ multinomial

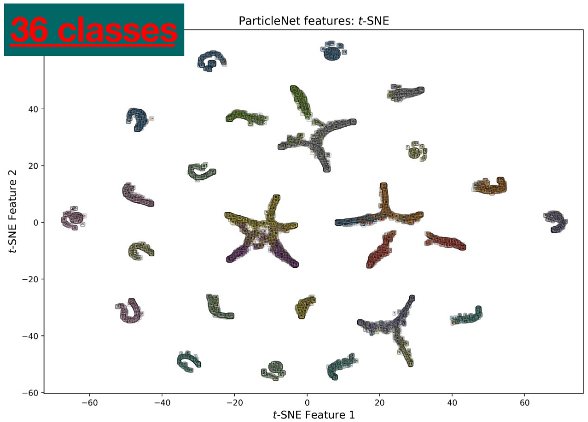
so Σ^n is easy

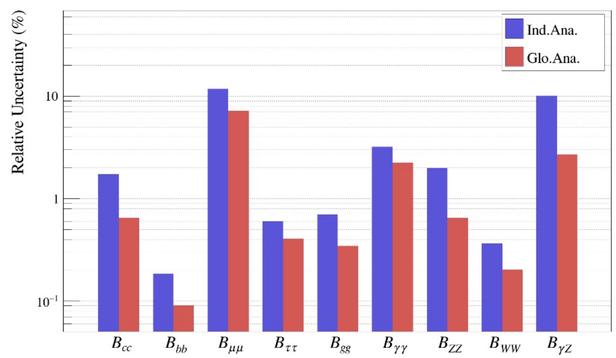
$$\mathbf{\Sigma}^N = N_t^e \begin{pmatrix} B_1(1-B_1) & -B_1B_2 & \ldots & -B_1B_m \\ -B_2B_1 & B_2(1-B_2) & \ldots & -B_2B_m \\ \vdots & \vdots & \ddots & \vdots \\ -B_mB_1 & -B_mB_2 & \ldots & B_m(1-B_m) \end{pmatrix} ,$$

Solve all Ni by minimizing

$$\chi^2_{ee} = \sum_i \frac{(\sum_k \epsilon_{ik} N_k - n_i)^2}{c_{ii}} + \frac{(\sum_k N_k - N_t^e)^2}{\sigma^2_{N_t}},$$

Global analysis : Enhance Higgs coupling precision





ArXiv:2105.14997

calculate the efficiency matrix

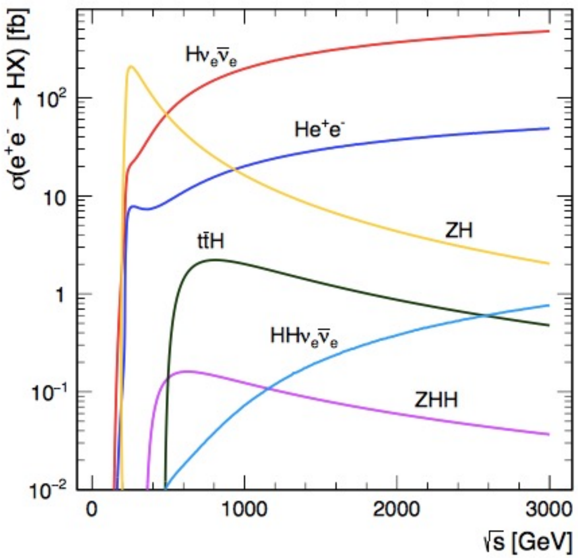
Particle level information as input, no dependence on jet-clustering, …

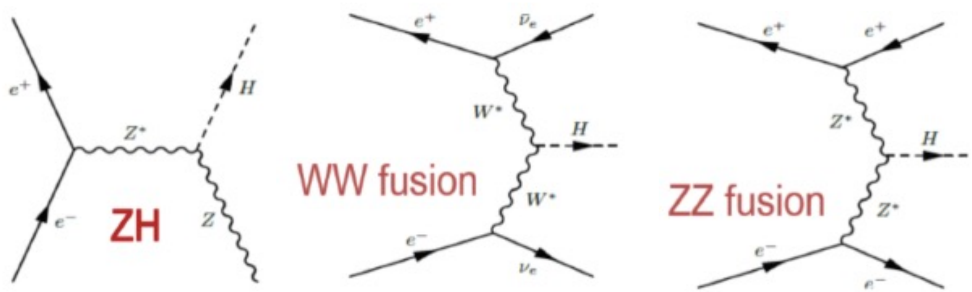
Proof-of-principle study shows precision improved by a factor of ~2

Full simulation study is ongoing …

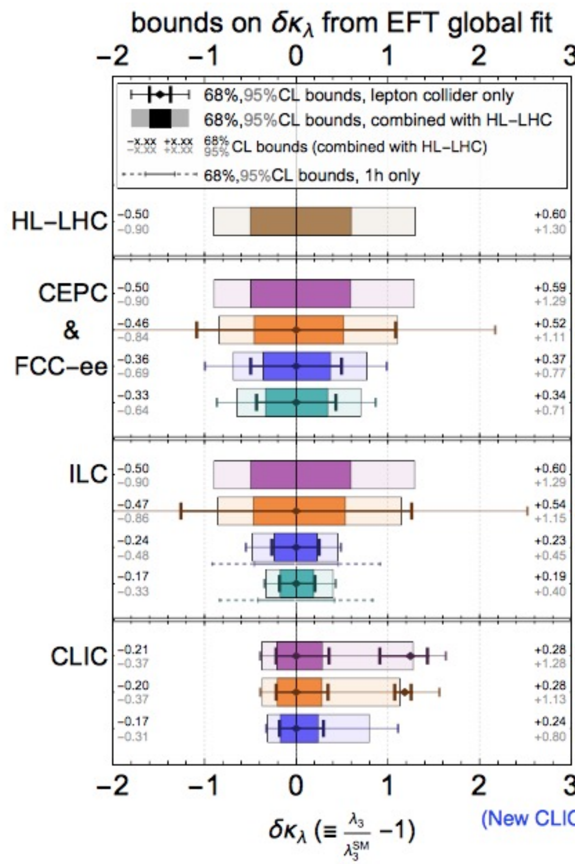
Decay Mode	Ind.Ana.	Glo.Ana.	IP	CEPC CDR
$H \to c\bar{c}$	1.8%	0.65%	2.7	3.3%
$H \to b\bar{b}$	0.19%	0.09%	2.1	0.56%
$H \to \mu^+\mu^-$	12%	7.2%	1.7	17%
$H \to \tau^+\tau^-$	0.61%	0.41%	1.4	1.0%
$H \to gg$	0.7%	0.35%	2.0	1.4%
$H \to \gamma\gamma$	3.3%	2.3%	1.4	6.9%
$H \to ZZ$	2.0%	0.65%	3.0	5.1%
$H \to W^+W^-$	0.37%	0.21%	1.7	1.1%
$H \to \gamma Z$	11%	2.8%	3.9	15%

Higgs related physics at e^+e^- collider





Impact on Higgs self-coupling



(New CLIC projected precision is $\sim$ 10%, see [arXiv

S and T in EW

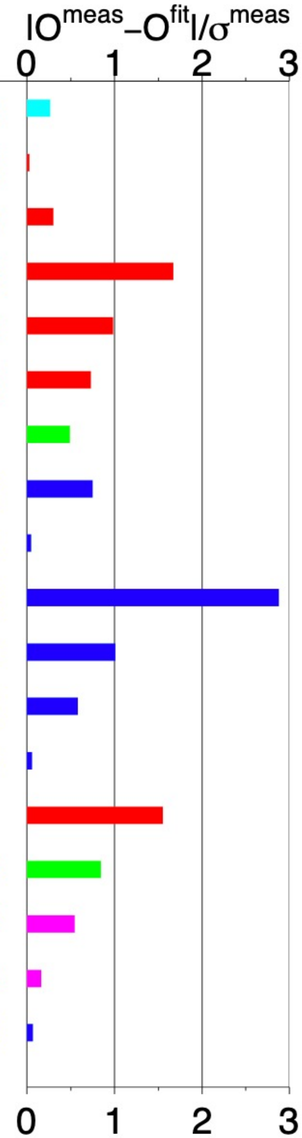
If the new physics enters at the TeV scale, the effect of the theory will be well-described by expansion to linear order in q^2, requiring only the three parameters (S, T, and U) originally defined by Peskin and Takeuchi [4]:

$$S = \left(\frac{4s_w^2c_w^2}{\alpha}\right)\left(\left[\frac{\delta\Pi_{ZZ}(m_Z^2)-\delta\Pi_{ZZ}(0)}{m_Z^2}\right]-\frac{(c_w^2-s_w^2)}{s_wc_w}\delta\Pi'_{Z\gamma}(0)-\delta\Pi'_{\gamma\gamma}(0)\right), \tag{2.2}$$

$$T = \left(\frac{1}{\alpha}\right)\left[\frac{\delta\Pi_{WW}(0)}{m_W^2}-\frac{\delta\Pi_{ZZ}(0)}{m_Z^2}\right], \tag{2.3}$$

$$\begin{aligned} U = \left(\frac{4s_w^2c_w^2}{\alpha}\right)\Bigg(&\left[\frac{\delta\Pi_{WW}(m_W^2)-\delta\Pi_{WW}(0)}{m_W^2}\right]-c_w^2\left[\frac{\delta\Pi_{ZZ}(m_Z^2)-\delta\Pi_{ZZ}(0)}{m_Z^2}\right] \\ &-2c_ws_w\delta\Pi'_{Z\gamma}(0)-s_w^2\delta\Pi'_{\gamma\gamma}(0)\Bigg), \end{aligned} \tag{2.4}$$

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

Measurement of Higgs width

- **Method 1: Higgs width can be determined directly from the measurement of σ(ZH) and Br. of (H->ZZ*)**

$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

  - **But the uncertainty of Br(H->ZZ*) is relatively high due to low statistics.**

- **Method 2: It can also be measured through:**

$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{BR(H \to bb)} \qquad \sigma(\nu\bar{\nu}H \to \nu\bar{\nu}b\bar{b}) \propto \Gamma(H \to WW^*) \cdot \mathrm{BR}(H \to bb) = \Gamma(H \to bb) \cdot \mathrm{BR}(H \to WW^*)$$

$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\bar{\nu}H \to \nu\bar{\nu}b\bar{b})}{\mathrm{BR}(H \to b\bar{b}) \cdot \mathrm{BR}(H \to WW^*)}$$

- **These two orthogonal methods can be combined to reach the best precision.**

Lepton Flavor Universality (Violation)

Lepton flavor universality (LFU) demands that charged leptons have (almost) identical interactions, only differ by their Yukawa couplings and hence their masses.

However, in both flavor changing neutral current (FCNC) and flavor changing **charged current** (FCCC) processes

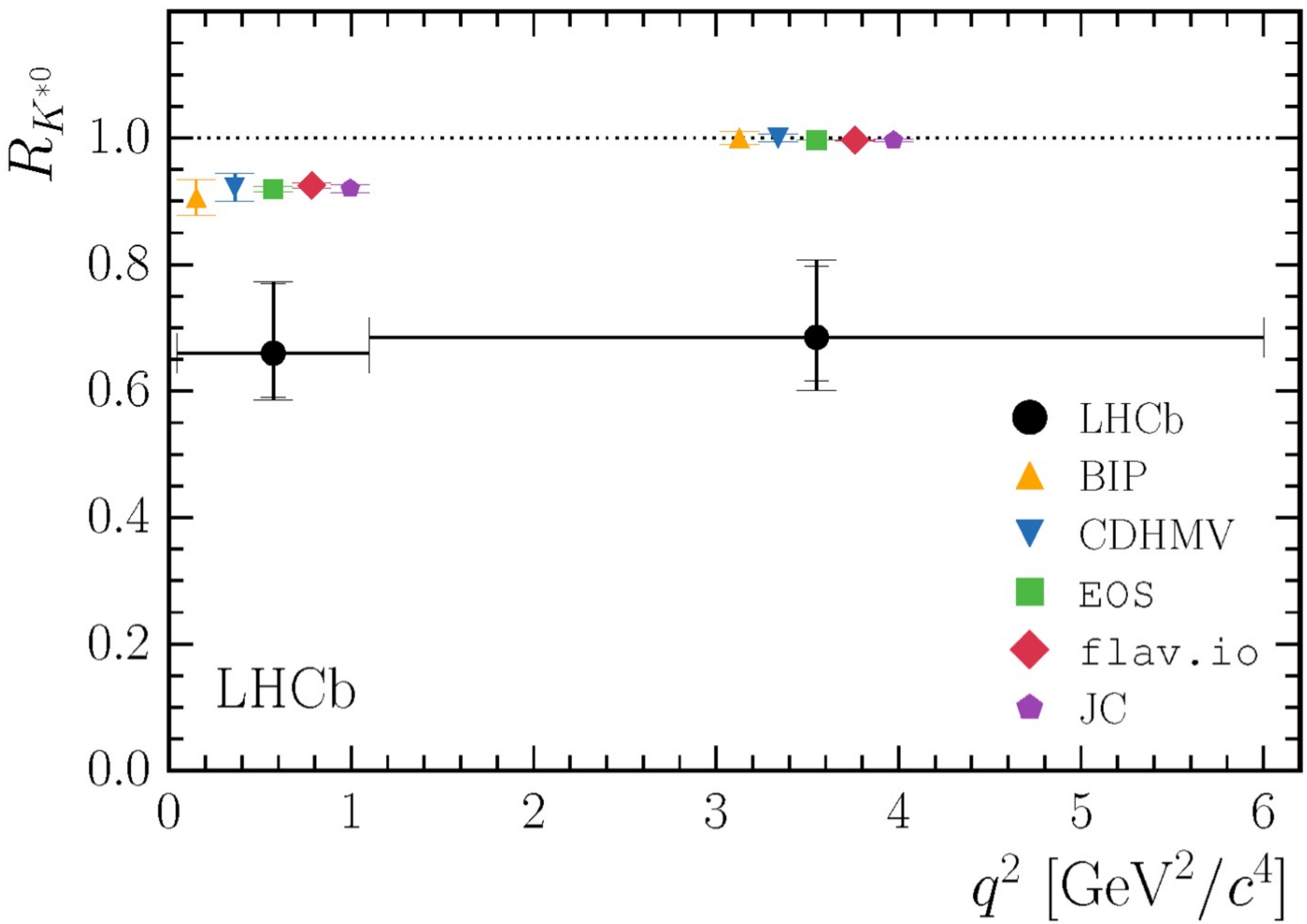
$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} , \tag{1}$$

$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} , \tag{2}$$

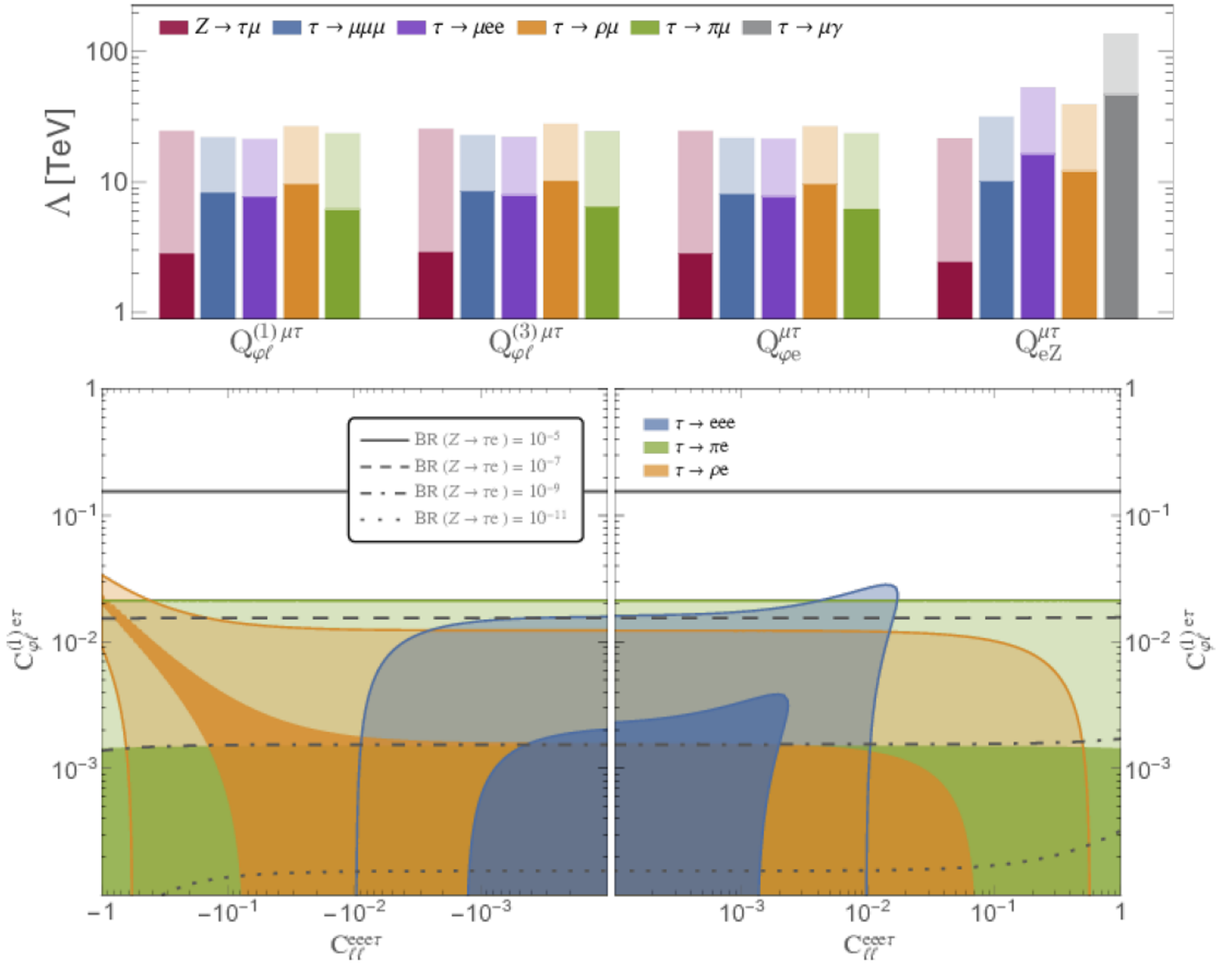
$$R_{J/\psi} \equiv \frac{\mathrm{BR}(B_c \to J/\psi\tau\nu)}{\mathrm{BR}(B_c \to J/\psi\ell\nu)} , \tag{3}$$

LFU is challenged.

LHCb LFUV results



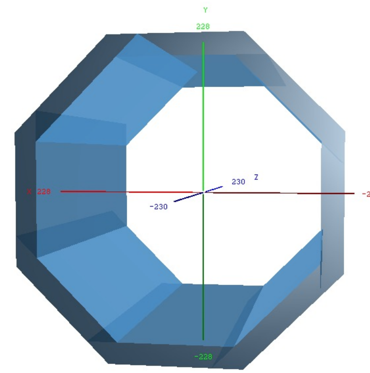
Lepton Flavor Violation (II)

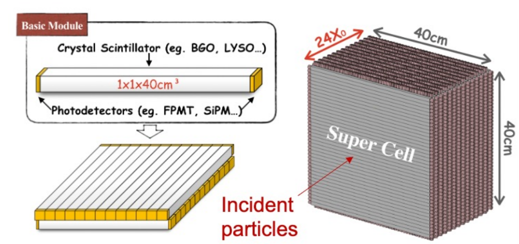


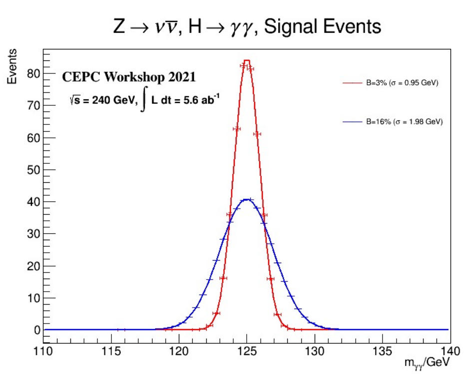
[Calibbi et al., 2021]

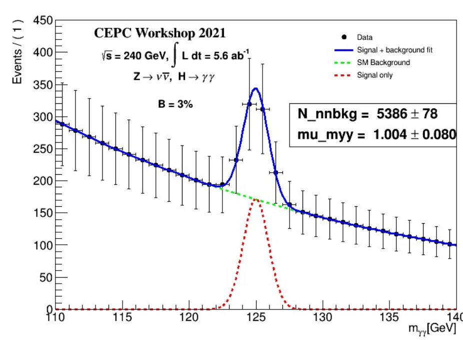
$H \rightarrow \gamma\gamma$ precision @ CEPC conceptual detector

- BGO crystal ECAL in CEPC conceptual detector:
  - full BGO crystal, 24 X_0, expected energy resolution $\frac{\sigma_E}{E} \sim \frac{3\%}{\sqrt{E}} \oplus \sim 1\%$.
  - Simulate the detector response by smearing truth MC.
- $\sigma(ZH) \times Br(H \rightarrow \gamma\gamma)$ precision @ CEPC:
  - Only consider the σ_E influence in $m_{\gamma\gamma}$ shape in $\nu\nu H \rightarrow \gamma\gamma$ and $\mu\mu H \rightarrow \gamma\gamma$ channels, with cut-based analysis.
  - Combined statistical only precision: $\delta Br(H \rightarrow \gamma\gamma) = 8.0\%$ (11% @ SiW ECAL scheme, 27% improvement.)





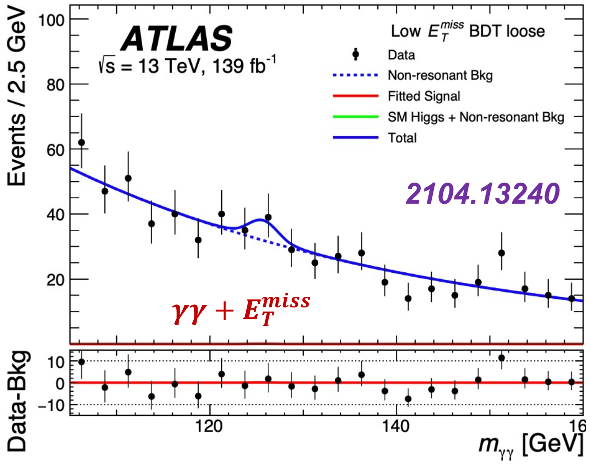


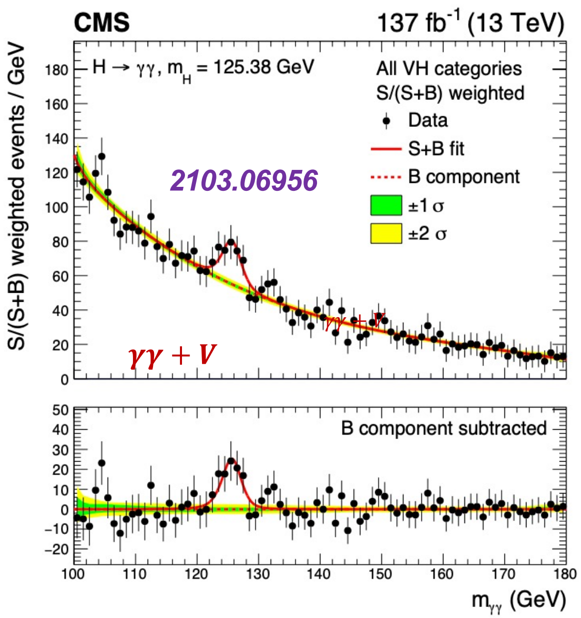


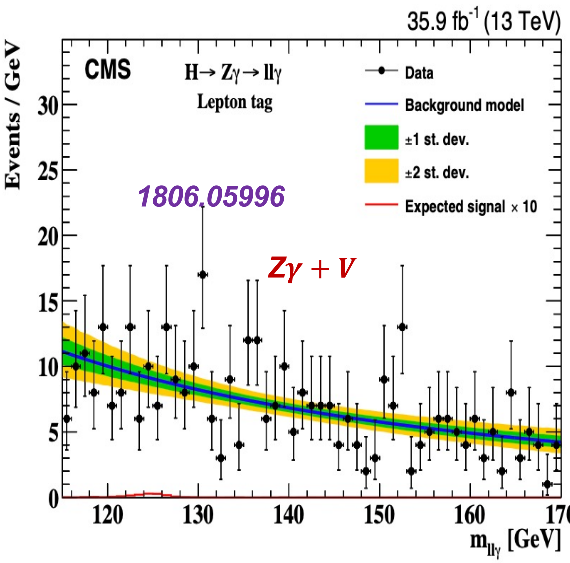
New Concept

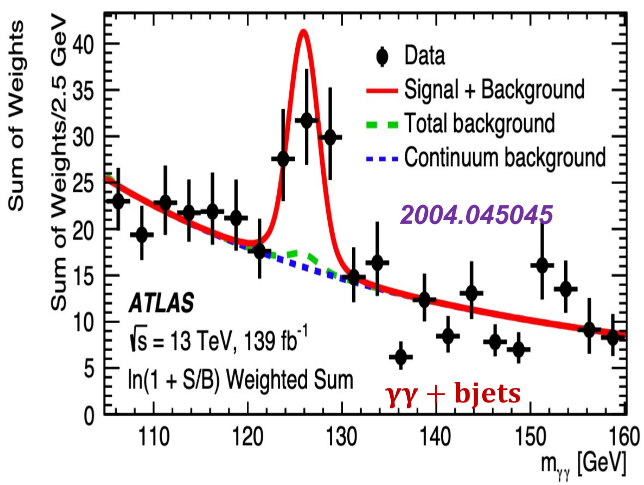
EM Resolution	$\delta(\sigma \times Br)$
$3\%/\sqrt{E} \oplus 1\%$	8.0%
$16\%/\sqrt{E} \oplus 1\%$	11%

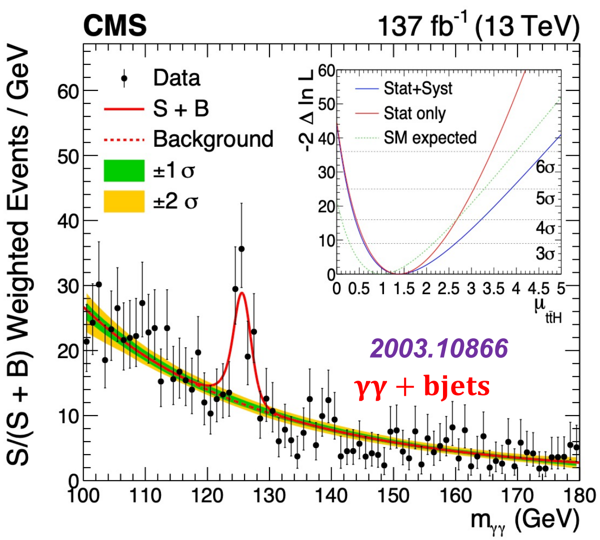
Excesses for di-photon, zγ final states associated with leptons, missing energy, b-jets

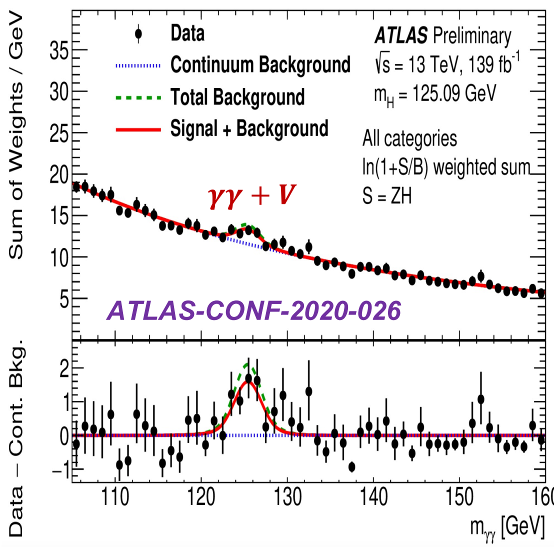




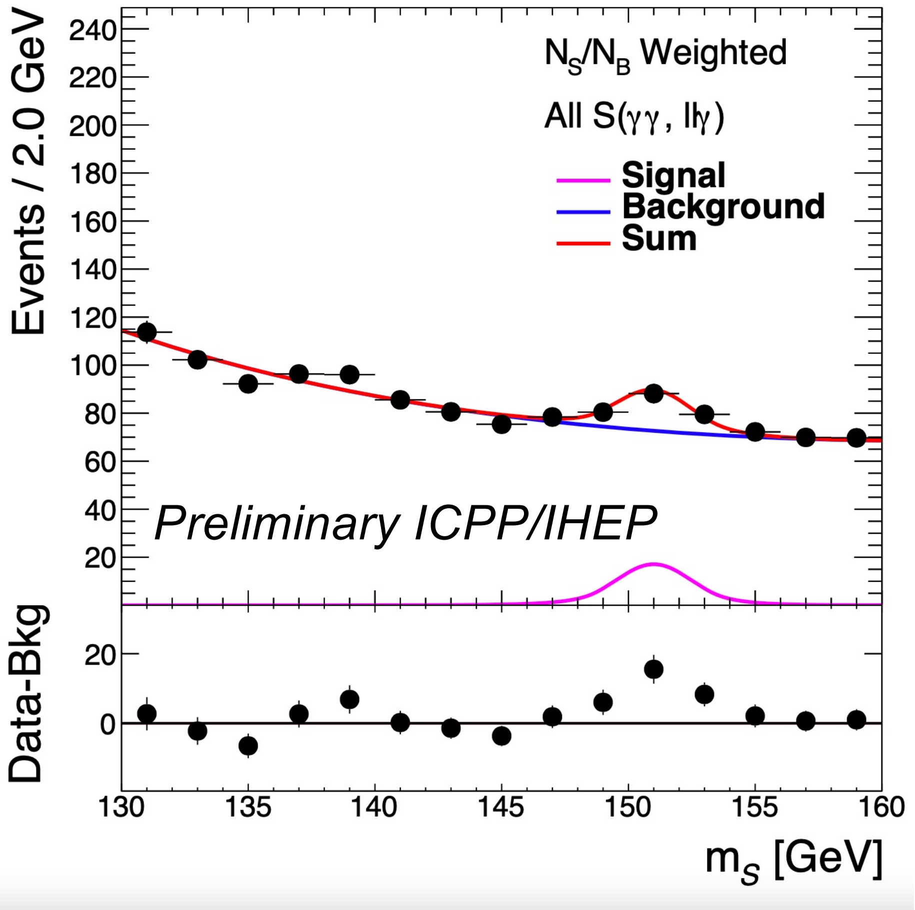








Excess for ATLAS/CMS di-photon/Zγ related results



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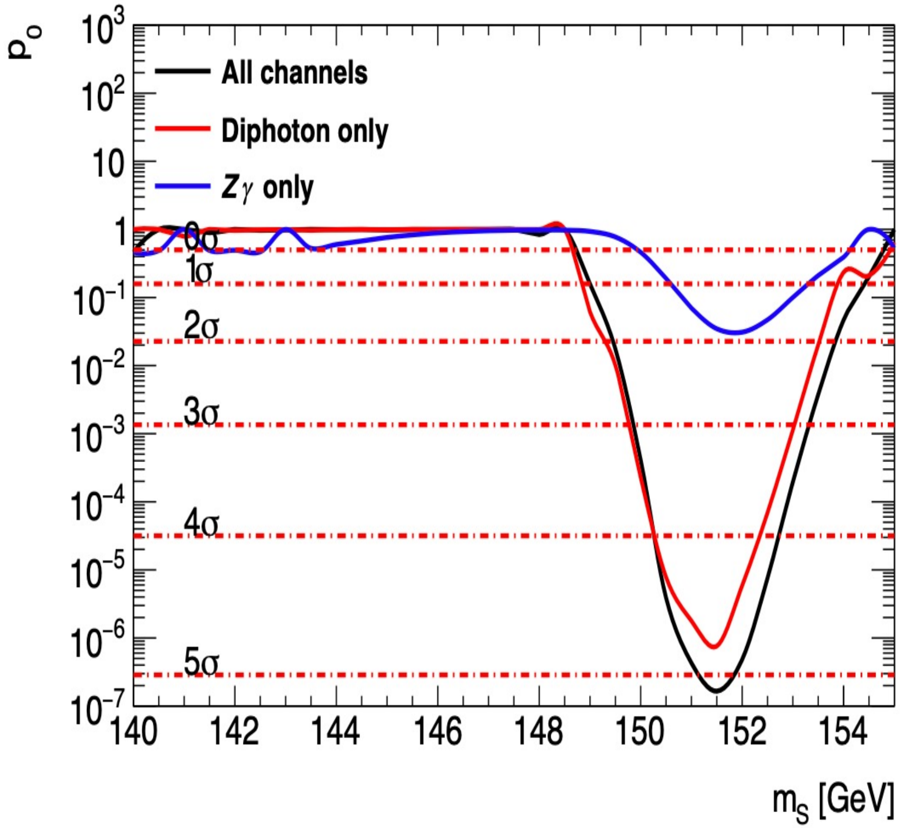

- Using public ATLAS/CMS results with di-photon and Zγ results, we can extract the excess around 151 GeV with 5.1σ and 4.8σ considering Look-Else-Where effect.
  - ✓ Most contribution from di-photon.
- Consistent with H →SS* hypothesis with m_H=270 GeV