Higgs invisible width measurement at FCC-ee and detector constraints

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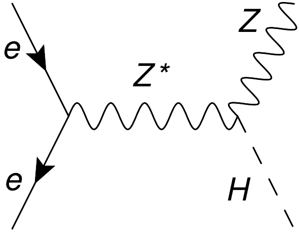
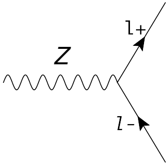
Higgs factory at FCC-ee

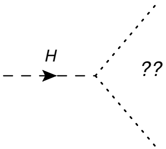
FCC-ee 3rd run:

- $\sqrt{s} = 240$ GeV
- $\mathcal{L} = 3.5$ ab^{-1}/yr
- $7.0 \cdot 10^5$ HZ events/yr



$\sigma_{HZ} = 201.2$ fb (PYTHIA8)





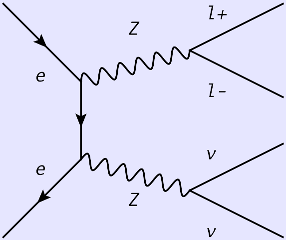
$BR_{Z \to e^+e^-/\mu^+\mu^-} \simeq 3.3\%$

$BR_{H \to invisible} < 25\%$ (LHC[1])

[1] arXiv:1509.00672 [hep-ex] by ATLAS.

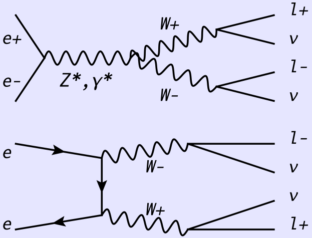
Background

$ZZ \to l^+l^-\nu\bar{\nu}$



$\sigma_{ZZ} = 1.36\ \text{pb}$ (PYTHIA8)

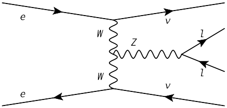
$W^+W^- \to l^+l^-\nu\bar{\nu}$



$\sigma_{WW} = 16.4\ \text{pb}$ (PYTHIA8)

$e^+e^- \to Z\nu\bar{\nu}$

Negligible ($\sigma < 50\ \text{fb}$)



$BR(H \to ZZ \to inv)$
$1.06 \times 10^{-3} \pm 4\%$ (PDG)

Data generation

- *PYTHIA8* (standalone) inclusive generation:
  - 2M events for WW, ZZ and HZ process
  - W and Z forced to leptonic decay
  - $H \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, $Br = 100\%$ ($M_{\chi_1^0} = 5$ GeV)
  - ISR, FSR and beam energy spread (BES)
- *Delphes 3.2.0* (standalone) simulation :
  - `delphes_card_CMS.tcl`, in use
  - ILD card, in use
- Vetoes and event selection:
  - No jets with $P_T > 20 GeV$ detected
  - 2μ XOR $2e$ with opposite charge and $P_T > 10$ GeV
  - 1γ max reconstructed[2]with $P_T > 10$ GeV. If present, it is assumed to be FSR.

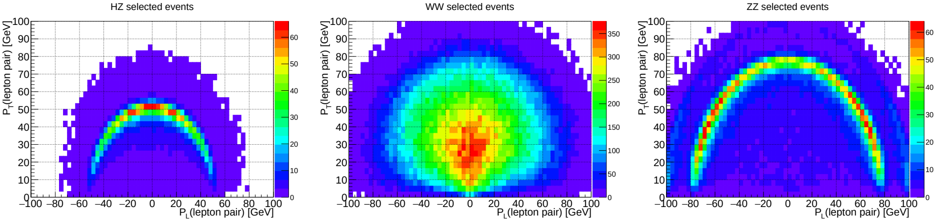
Unless specified differently CMS @$\mathcal{L} = 500$ fb^{-1}, as presented in arXiv:1208.1662v2 [hep-ex] 17 Oct 2012 for LEP3

[2]Softer γ are clustered or discarded by Delphes.

Analysis: Cuts 1/2

Variables: $\Delta\theta_{ll}$, θ_{aco}, $\phi_{helicity}$, PLvsPT, M_{miss} and M_{ll}

Not indipendet one each other



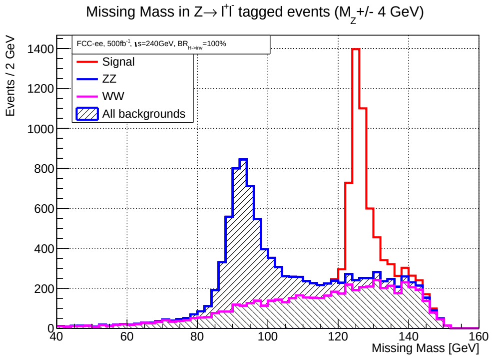
Cuts[3]:

Reduce ZZ background: $\bullet \Delta\theta_{ll} > 100$ deg $\bullet\ P_L^{ll} < 50$ GeV

Avoid Radiative return: $\bullet \theta_{aco} > 10$ deg $\bullet\ P_T^{ll} > 10$ GeV

[3] Similar to LEP3 study.

Analysis: Cuts 2/2



Z tag:

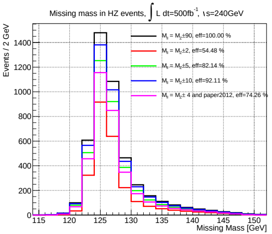
M_{ll} in $M_Z \pm 4\text{GeV}$

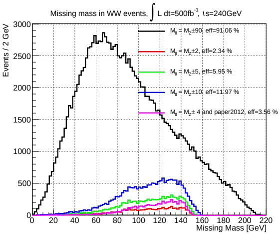
Final efficiency

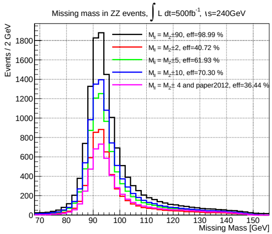
HZ events: 74%

WW events: 3.5%

ZZ events: 36%







Analysis: Fit strategy

Analytic pdf:

$\times$ Too many parameters $\Rightarrow$ unstable fit

- Crystal Ball (5 param.), Polynomial, ARGUS (3 param.)

Template pdf:

✓ ZZ events: MC (here), real data from $ZZ \to 4l$ (@FCC-ee)

✓ WW events: MC(here), real data from $WW \to e\mu\nu_e\nu_\mu$ (@FCC-ee)

✓ HZ events: MC simulation (PYTHIA8)

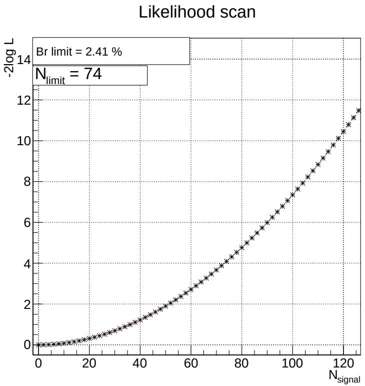
Discovery significance:

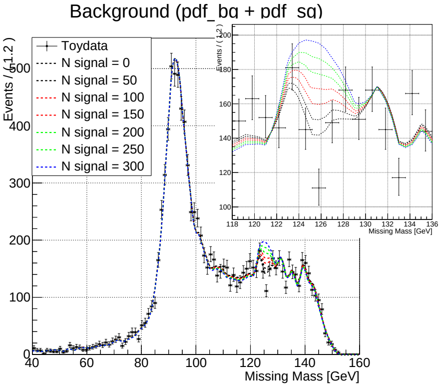
- s+b dataset, s from fixed BR
- $\sigma = \sqrt{-2 \log \frac{\mathcal{L}_b}{\mathcal{L}_{s+b}}}$

Limit on BR(95% cl):

- b only dataset
- $0.95 \equiv \int_0^{N_S^*} \mathcal{L}(s+b|N_S)dN_S$

Result 1/2 : Limit on BR @ $500 fb^{-1}$





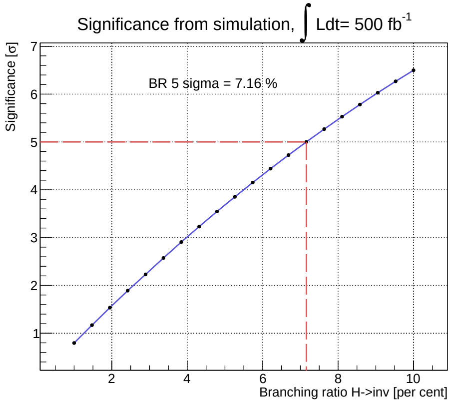
Actual cuts:

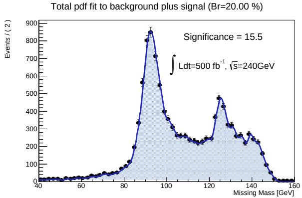
$\bullet \Delta\theta_{ll} > 110 deg$ $\bullet \theta_{aco} > 10 deg$ $\bullet P_T^{ll} > 10 GeV$

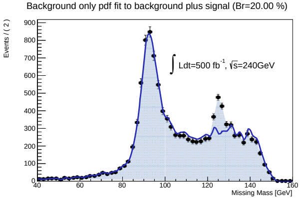
$\bullet P_L^{ll} < 50 GeV$ $\bullet 87.2 GeV < M_{ll} < 95.2 GeV$

$BR_{lim95\%}@CMS = 2.6 \pm (0.8)_{stat}\%$, 68% CL

Result 2/2 : Minimum Br for discovery @ $500 fb^{-1}$





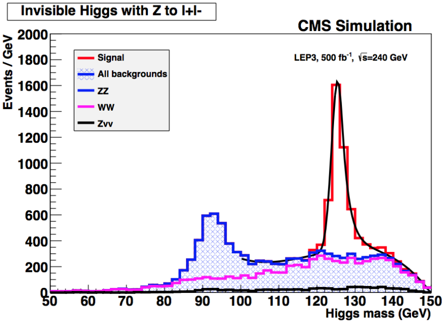


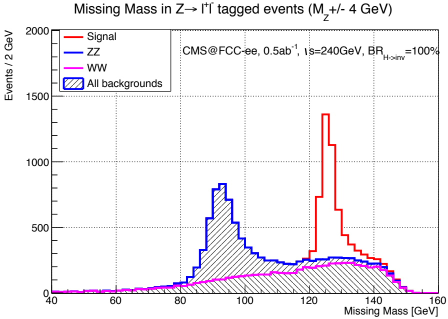
Actual cuts:

•$\Delta\theta_{ll} > 110deg$ •$\theta_{aco} > 10deg$ •$P_T^{ll} > 10GeV$
•$P_L^{ll} < 50GeV$ •$87.2GeV < M_{ll} < 95.2GeV$

$BR_{5\sigma}@CMS = 7.4 \pm (0.4)_{stat}\%$, 68% CL

Comparison with 2012 LEP3 paper





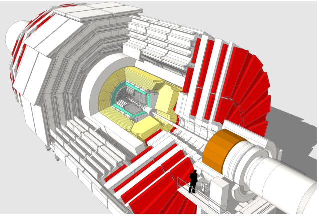
$$BR_{limit} = 1.7\%^2$$
$$BR_{5\sigma} = 4\%^2$$

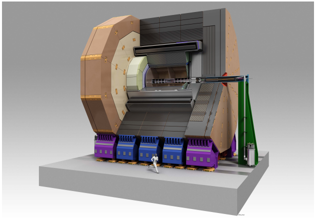
$$BR_{limit} = 2.6\%$$
$$BR_{5\sigma} = 7.4\%$$

- Results for $\int L = 3.5$ ab^{-1} scale with the factor ~ 3 given by the larger sample size.

[2] $Z \to l\bar{l}$ and $Z \to b\bar{b}$ combined analysis

A new detector: ILD[4]





CMS

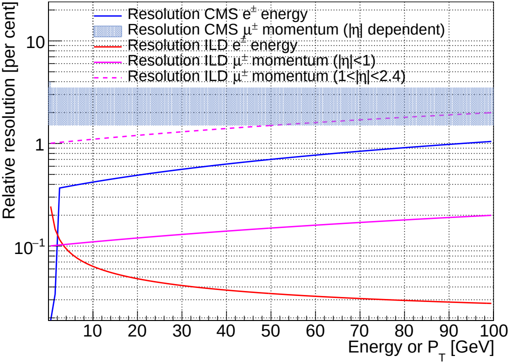
- $B_Z = 3.8$T
- $R_B = 1.29$m, $L_B = 3.0$m
- Acceptance up to $\theta = 85.3$ deg
- Tracker: silicon pixels and strips
- LHC optimized parameters

ILD

- $B_Z = 3.5$T
- $R_B = 1.8$m, $L_B = 2.4$m
- Acceptance up to $\theta = 84.8$ deg
- Tracker: TPC and silicon
- Optimized for e^+e^- collision

[4] T.Behnke et al. ILC Collaboration The International Linear Collider Technical Design Report - Volume 4: Detectors [arXiv:1306.6329 [hep-ex]].

Simulated resolution and efficiency



ILD resolution ~ 10 times better than CMS resolution

CMS

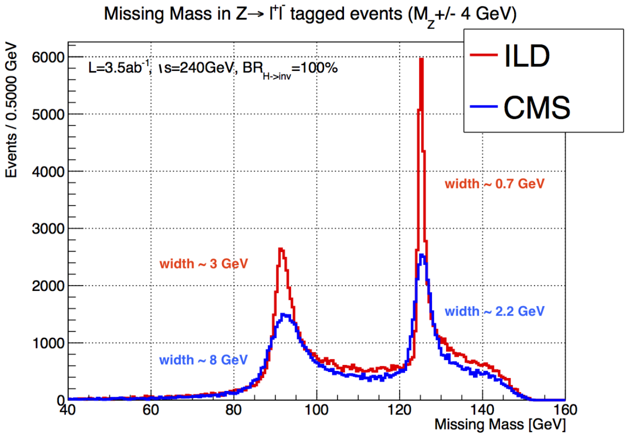
- Tracking eff. : 95% for $P_T > 100\text{MeV}$ and $|\eta| < 2.5$
- Reconstruction eff. : $85 - 95\%$ (e,μ and γ) for $P_T > 10\text{GeV}$

ILD

- Tracking eff. : 99% for $P_T > 100\text{MeV}$ and $|\eta| < 2.4$
- Reconstruction eff. : 99% (e,μ and γ) for $P_T > 10\text{GeV}$

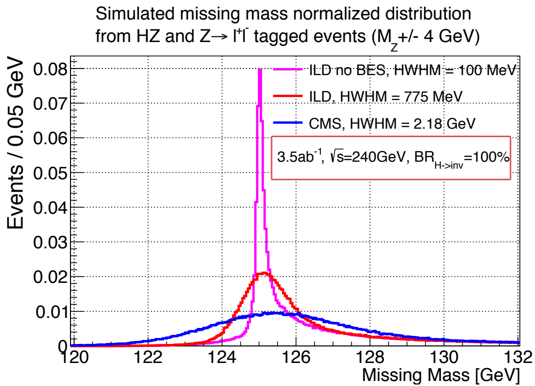
ILD vs CMS

In spite of 10 times better momentum/energy resolution, M_{miss} resolution improves by only a factor ~ 3



- Better resolution: due to advanced ILD tracker design
  $\Rightarrow$ reduced width of Z and H peaks
- Larger efficiency: artifact of parameterizing the CMS reconstruction performances on the results derived at the LHC

Beam energy spread effect (BES)



Missing mass depends on collision energy knowledge:

$\Delta\sqrt{s} \sim$ Beam Energy Spread (0.2% @FCCee)

$$\frac{\Delta M}{M} \sim \frac{\Delta\sqrt{s}}{\sqrt{s}} \oplus \frac{\Delta P}{P}$$

- ILD: Collision energy knowledge is a limiting factor
- CMS: $\frac{\Delta\sqrt{s}}{\sqrt{s}}$ negligible w.t.r. to $\frac{\Delta P}{P}$

ILD results shows an improvement of a factor ~ 2 on BR limits if compared with the CMS ones.

Summary

- A coupling of the Higgs boson to new invisible particles is predicted in many extensions of the SM
- H invisible width can be measured during FCC-ee 3^{rd} run (Higgs factory) with unprecedented precision.

State of art:

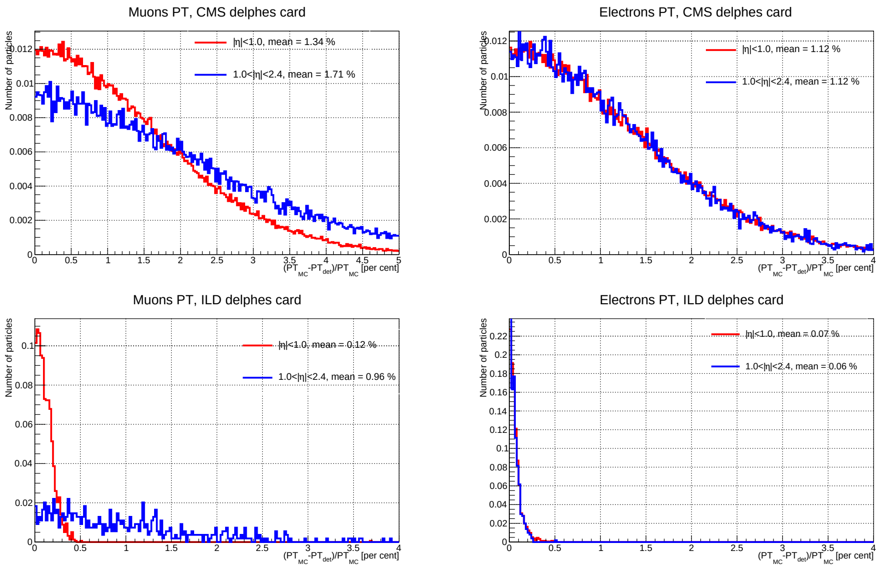
- 500 fb^{-1} results in agreement with previous analysis (LEP3)
- In 1 year data acquisition with CMS@FCC-ee $\sim 1\%$ precision can be reached:
  $\Rightarrow$ Main limiting factor is momentum/energy resolution
- In the same time ILD@FCC-ee can not do more than a factor 2 better:
  $\Rightarrow$ Main limiting factor is Beam Energy Spread
- Improvement in DM cross section limits for Higgs-portal models[4].

[4] See talk by Michele De Gruttola.

Thank you for your attention

Questions?

Energy/momentum resolution Comparison



Missing Mass resolution

Given P_1 and P_2, the leptons 4-vector, and θ, the angle among them, the visible mass is:

$$M_{ll} = \sqrt{P_1^2 + P_2^2 + 2P_1P_2} \simeq 2P_1P_2(1 - \cos\theta)$$

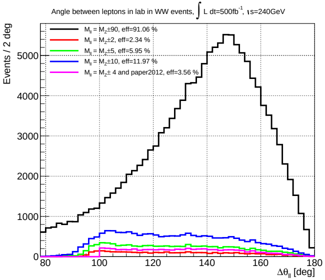
While, given the center of mass energy $\sqrt{s}$, the missing mass is:

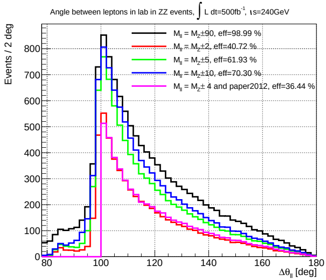
$$M_{miss}^2 = \left[\begin{pmatrix} \sqrt{s} \\ \vec{0} \end{pmatrix} - P_1 - P_2 \right]^2$$

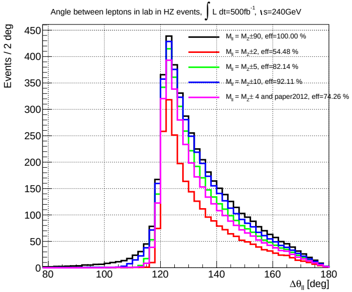
And using $\theta \sim 120\text{deg}$ (most probable value for HZ decays) and $|\vec{P_1}| \simeq |\vec{P_2}| = P$ we can obtain:

$$\Delta M_{miss} \simeq \begin{cases} \frac{\sqrt{s}-2P}{M_{miss}} \Delta\sqrt{s} & \text{if } \Delta\sqrt{s} \text{ is dominant} \\ \\ \frac{2\sqrt{s}-3P}{\sqrt{2}M_{miss}} \Delta P & \text{if } \Delta P \text{ is dominant} \end{cases}$$

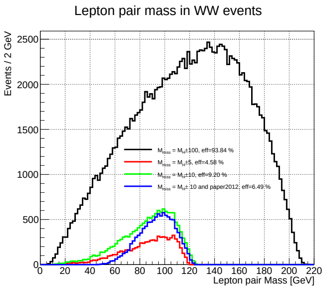
$\Delta\theta_{ll}^{LAB}$ distribution @CMS

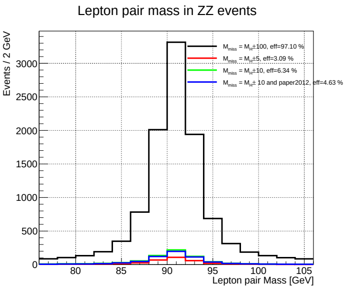


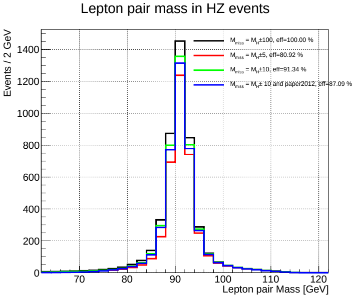




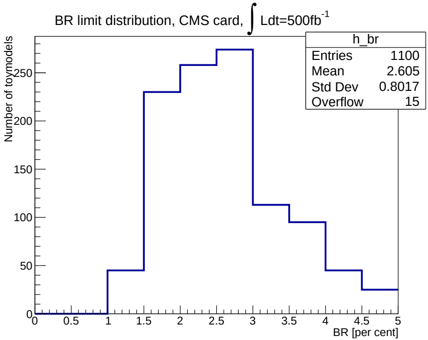
M_{ll} distribution @CMS

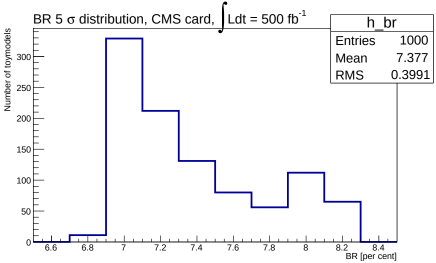






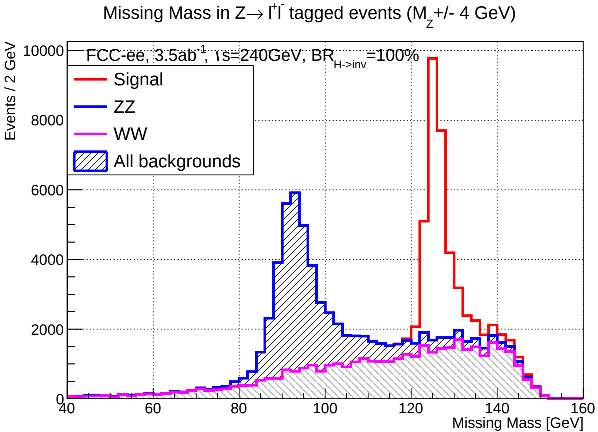
Toy experiment results distribution





Distributions obtained repeating the experiment several times with different toy data set.

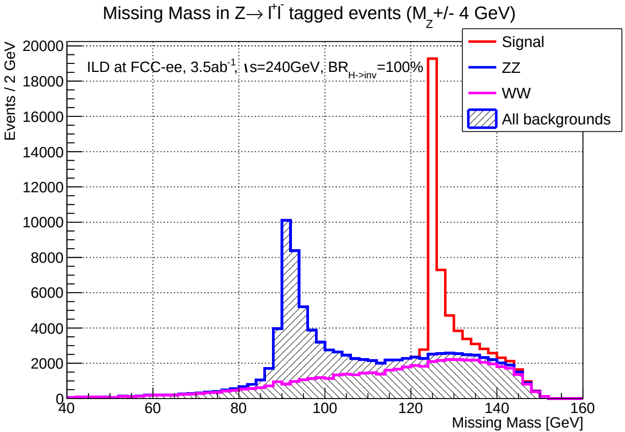
CMS @ FCC-ee results, $\mathcal{L} = 3.5ab^{-1}$



$BR_{lim95\%} = 0.92 \pm (0.30)_{stat} \pm (0.02)_{sys}\%$, 68% CL

$BR_{5\sigma} = 2.5 \pm (0.2)_{stat} \pm (0.1)_{sys}\%$, 68% CL

ILD @ FCC-ee results, $\mathcal{L} = 3.5ab^{-1}$



$BR_{lim95\%} = 0.63 \pm (0.20)_{stat} \pm (0.02)_{sys}\%$, $68\%\ CL$

$BR_{5\sigma} = 1.7 \pm (0.1)_{stat} \pm (0.01)_{sys}\%$, $68\%\ CL$