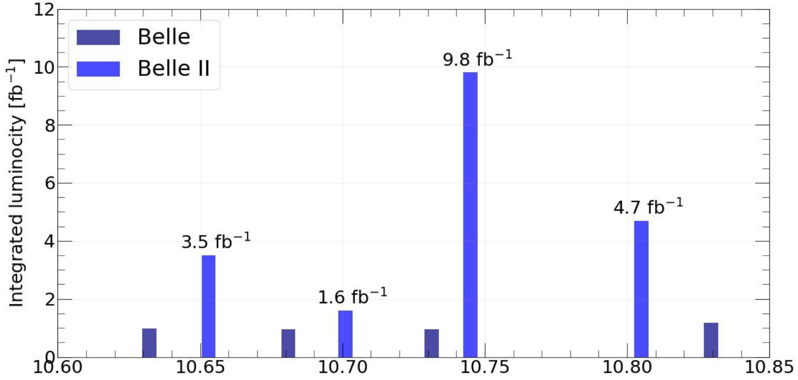
Search for $e^+e^- \to \eta_b(1S)\omega$ at $\sqrt{s}$ = 10.745 GeV

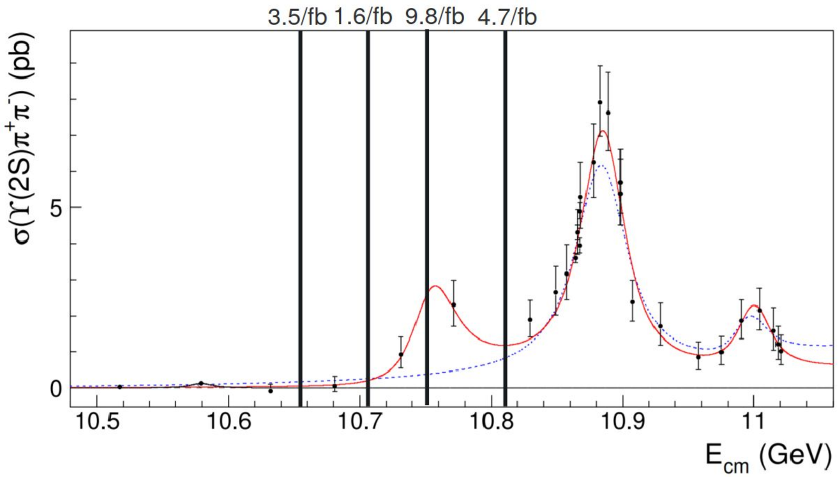
Pavel Oskin, Roman Mizuk, Karim Trabelsi
(IJCLab) (HSE) (IJCLab)

Motivation

JHEP 10 (2019) 220

Recently Belle observed a new structure Υ(10753) in the e+ e- →Υ(nS) π+ π- (n = 1,2,3) cross section energy dependence.





There is tetraquark interpretation (Chin Phys. C 43 123102 (2019)) of Υ(10753) state, which predicts enhancement of the Υ(10753) → η_b(1S)ω transition:

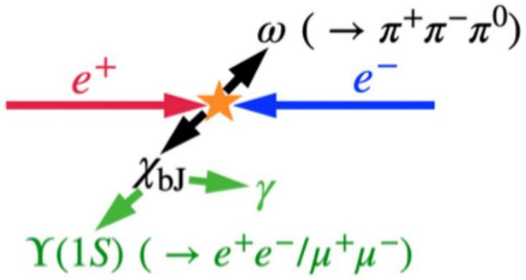
$$\frac{\Gamma(\eta_b\ \omega)}{\Gamma(\Upsilon\ \pi^+\pi^-)} \sim 30$$

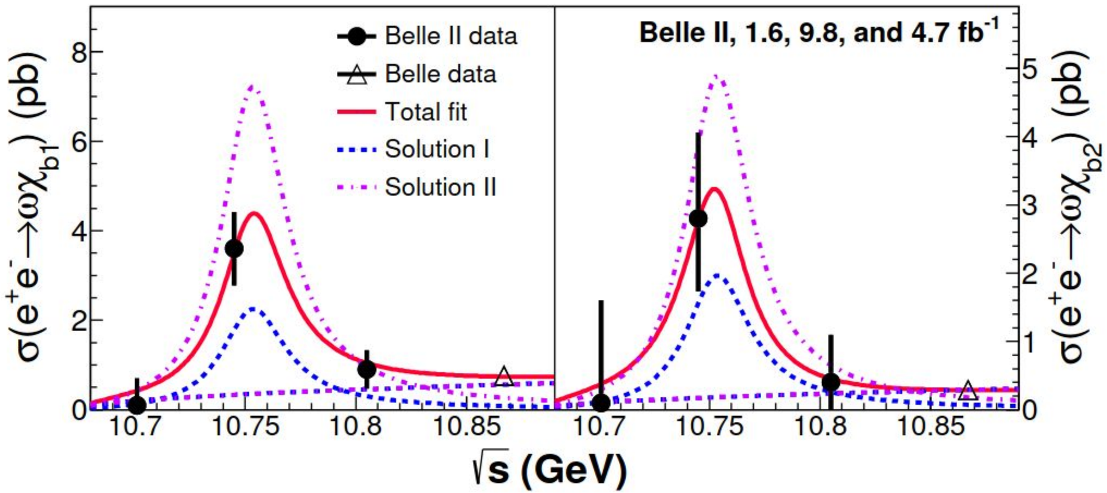
Observation of e+e→ $\omega\chi_{bJ}$(1P) at √s = 10.745 GeV

Strongly enhanced at 10.745 GeV.

arXiv:2208.13189

$$\sigma(e^+e^- \to \omega\chi_{b1}) = 3.6 \pm 0.7 \pm 0.5 \text{ pb}$$
$$\sigma(e^+e^- \to \omega\chi_{b2}) = 2.8^{+1.2}_{-1.0} \pm 0.4 \text{ pb}$$





We search for e+e− → $\omega\chi_{bJ}$(1P) (J = 0), which is not measured due to low BF[χ_{b0}(1P) →Y(1S)] = 1.94%

Search for e+e- $\rightarrow\eta_b(1S)\omega$ at $\sqrt{s}$ = 10.745 GeV

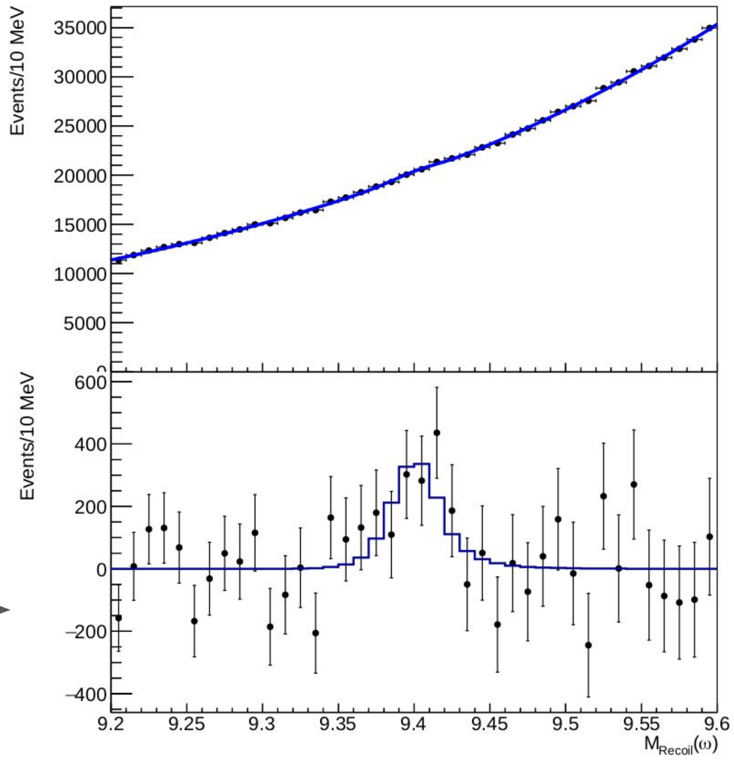
$\eta_b(1S)$ decays to gluons and does not have reconstructable modes.

We reconstruct only $\omega \rightarrow \pi^+\pi^-\pi^0$ and use the recoil mass to identify signal.

$$M_{\mathrm{recoil}}(\omega) = \sqrt{(\sqrt{s} - E^*_\omega)^2 - (p^*_\omega)^2}$$

Assuming the cross section of this transition is the same as $\omega\chi_{b1}(1P)$, we expect to have enough sensitivity to see the signal.

Belle II MC study



Baseline selection criteria

- dr <0.3 cm, |dz|<0.5 cm,
- $L_\pi / (L_\pi + L_K) > 0.1$,
- $L_\pi / (L_\pi + L_p) > 0.1$,
- $L_e / (L_\pi + L_e) < 0.9$,
- 'gamma:tight' selection criteria:
  - $E_{lab}(\gamma_1)$, $E_{lab}(\gamma_2)$>50 MeV for the barrel and forward ECL,
  - $E_{lab}(\gamma_1)$, $E_{lab}(\gamma_2)$>75 MeV for the backward ECL,
- cluster E9/E21 > 0.8,
- minC2TDist > 15 cm,
- cluster Timing < 50 ns,

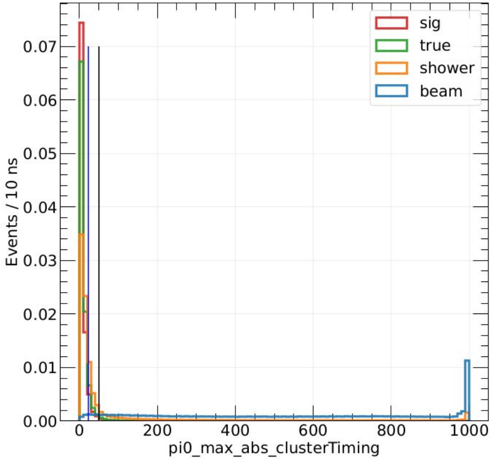
After applying the preselections we iteratively optimize this selections by maximizing

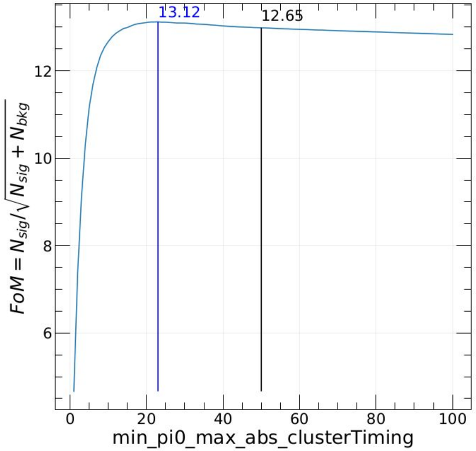
$$\text{FoM} = \frac{\text{signal}}{\sqrt{\text{signal+background}}}.$$

$e^+e^- \to$	
$\eta_b(1S)\omega$	$\chi_{bJ}(1P)\omega$
$p^*(\pi^0)$ >260 MeV	$p^*(\pi^0)$ >150 MeV
$\lvert M(\gamma\gamma) - M(\pi^0)\rvert$ <12 MeV	$\lvert M(\gamma\gamma) - M(\pi^0)\rvert$ <11 MeV
$\lvert M(\pi^+\pi^-\pi^0) - M(\omega)\rvert$ <14 MeV	$\lvert M(\pi^+\pi^-\pi^0) - M(\omega)\rvert$ <14 MeV
R2 <0.23	R2 <0.31
r <0.83	r <0.82
eff = 10.5 %	eff = 8.8 %

Cut based approach to fake photons suppression

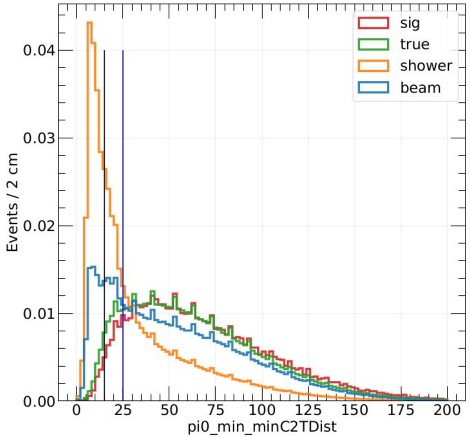
Beam background suppression:

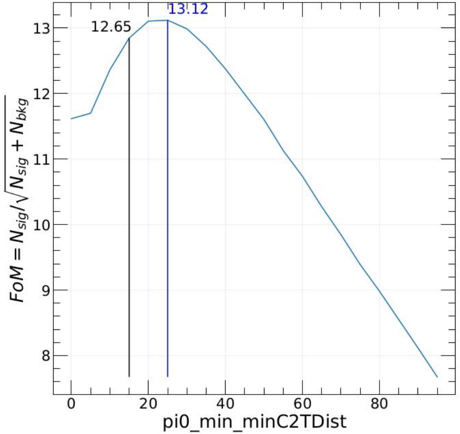




cuts mentioned previously are loose but near to optimal

Fake photons suppression:

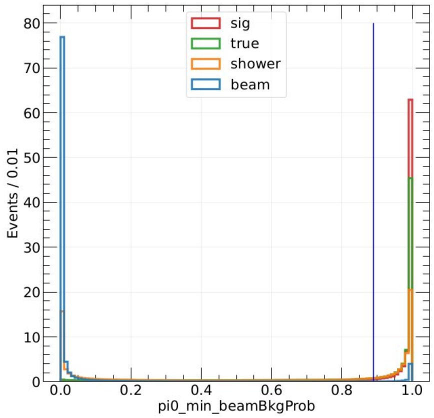


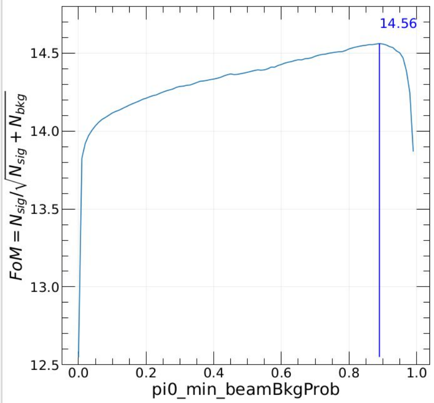


MVA based approach to fake photons suppression

Beam background suppression
beamBackgroundSuppression

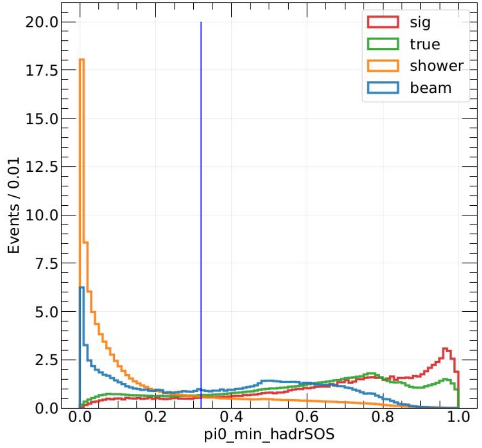
- `clusterTiming`
- `clusterPulseShapeDiscriminationMVA`
- `clusterE`
- `clusterTheta`
- `clusterZernikeMVA`
- `clusterE1E9`
- `clusterLAT`
- `clusterSecondMoment`

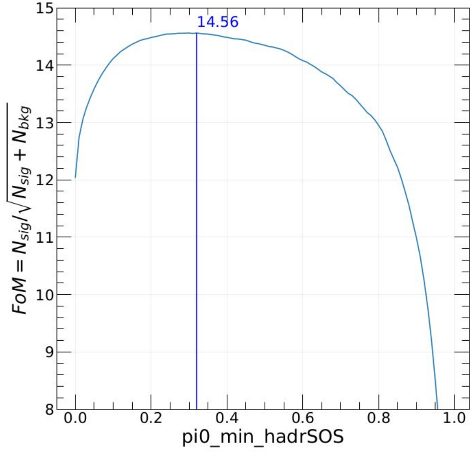




Fake photons suppression
hadronicSplitOffSuppression

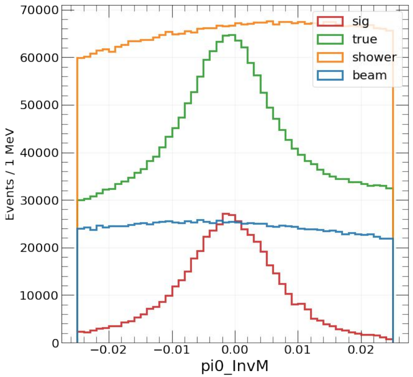
- `clusterPulseShapeDiscriminationMVA`
- `minC2TDist`
- `clusterZernikeMVA`
- `clusterE`
- `clusterLAT`
- `clusterE1E9`
- `clusterSecondMoment`



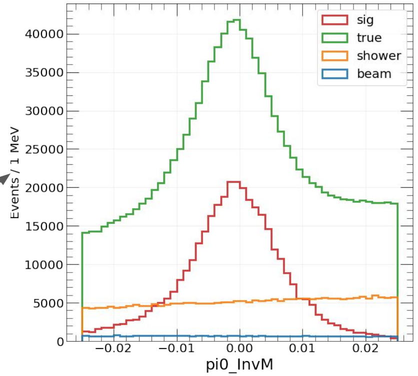


π^0 invariant mass and momenta

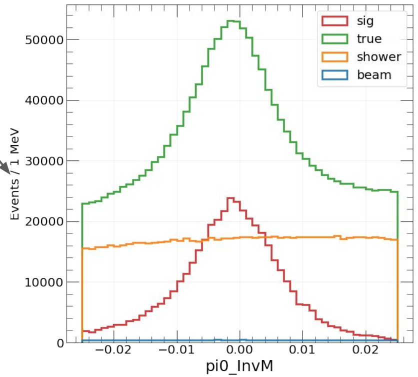
but what is actually happening???

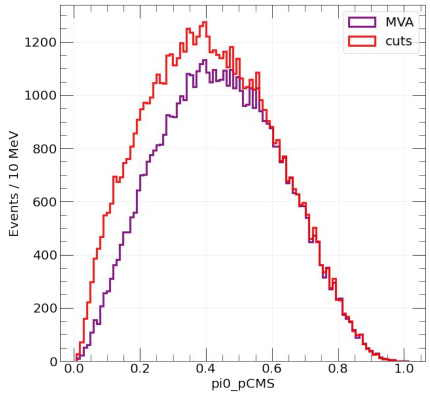


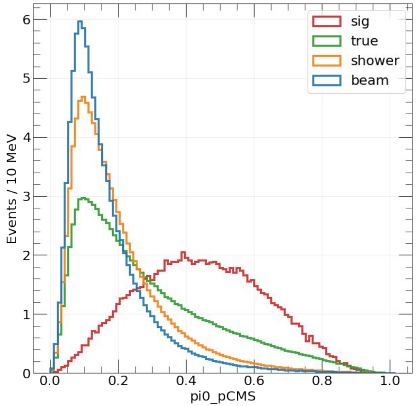
MVA



cuts

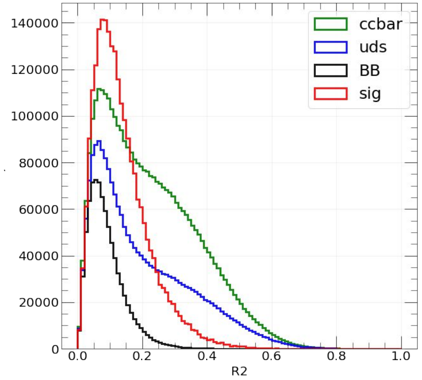


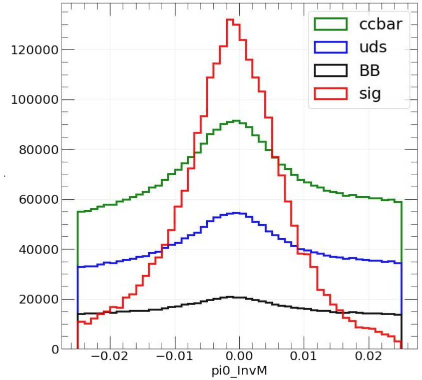




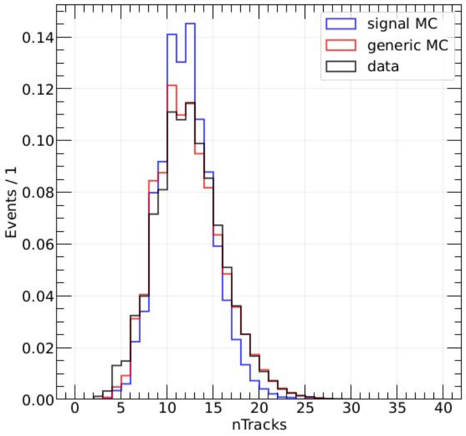
The rest of the background is coming from the real π^0

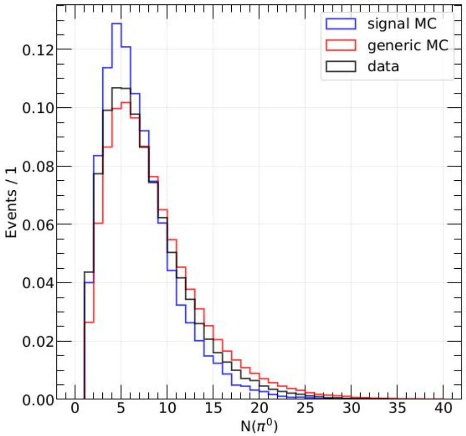
Sources of the true π^0 background





How we can suppress BB background?





Multiplicity does not work.

Conclusion

- The baseline strategy for inclusive search for bottomonium transitions with ω meson emission was developed.
- Optimal fake π^0 suppression selections were found (?).

- Do we have not gamma-related, but π^0 related variables to suppress combinatorial π^0 ($p^*(\pi^0)$ and $InvM(\pi^0)$ are used now)?
- We search for a way to suppress the background events with the real π^0 mostly from BB.
- Does all the fake ω background connected with huge combinatorics due to π^0 or there are other significant sources?

- In case of $\chi_{bJ}(1P)$ the situation is even worse…

Thank you for attention!

Search for $e^+e^- \to \eta_b(1S)/\chi_{bJ}(1P)\omega$ at $\sqrt{s} = 10.751$ GeV

Pavel Oskin, Roman Mizuk, Karim Trabelsi
27.10.2022

HSE (Moscow), IJCLab (Orsay)

Motivation

Recently Belle observed a new structure near $\sqrt{s}$=10.753 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ (n = 1,2,3) cross section energy dependence. JHEP **10**, 220 (2019)

There is tetraquark (diquark-antidiquark) interpretation of this state, which predicts enhancement of $\Upsilon(10753) \to \eta_b(1S)\omega$ transition.

$$\frac{\Gamma(\eta_b\ \omega)}{\Gamma(\Upsilon\ \pi^+\pi^-)} \sim 30 \qquad (1)$$

Z. G. Wang, Chin. Phys. C **43**, no.12, 123102 (2019)

Also we search for $e^+e^- \to \omega\chi_{bJ}(1P)$ (J = 0,1,2) which are found to be enhanced at the scan energies.

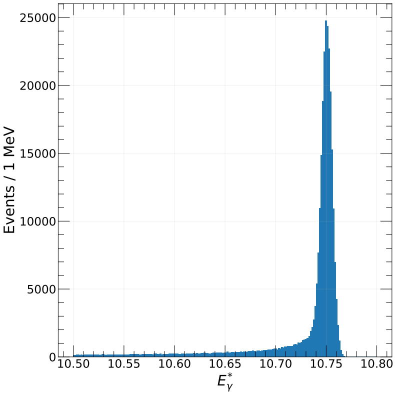
Signal MC generation

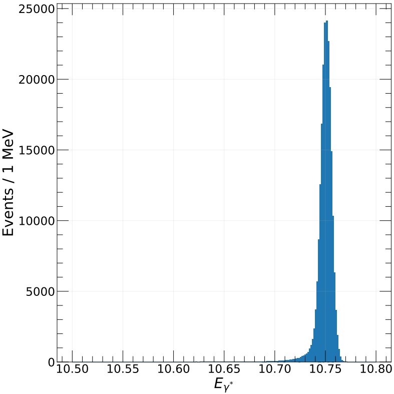
We use `phokhara_evtgen_combination` generator to simulate ISR and decay sequence. The CM energy is 10.751 GeV.
For detector simulation, we use GEANT4 based package available in `release-06-00-03` and beam background samples provided by data production group

```
Decay vpho
1.0   omega   eta_b   PHSP;
Enddecay

Decay eta_b
1.0   g   g   PHOTOS PYTHIA 91;
Enddecay

Decay omega
1.0   pi+   pi- pi0 OMEGA_DALITZ;
Enddecay

Decay pi0
1.0   gamma gamma   PHSP;
Enddecay

End
```

```
Decay vpho
1.0   omega   chi_b1   PHSP;
Enddecay

Decay chi_b1
0.349     gamma   Upsilon          HELAMP 1. 0. 1. 0. -1. 0. -1. 0.;
0.651     g         g        PYTHIA 91;
Enddecay

Decay omega
1.0   pi+   pi- pi0 OMEGA_DALITZ;
Enddecay

Decay pi0
1.0   gamma gamma   PHSP;
Enddecay

End
```

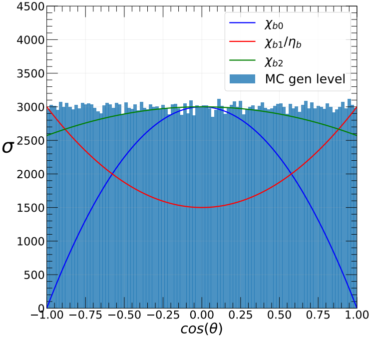
In the `phokhara_evtgen_combination` $\sigma \sim 1/s$. We introduce weights for the events so $\sigma \sim$ line shape of the $\Upsilon(10753)$ resonance with the parameters from JHEP **10**, 220 (2019).





Reweighting of the signal MC

θ is the angle between the normal to the ω decay plane and the difference of the beam momenta measured in the ω rest frame. Initial distributions in $cos(\theta)$ are uniform at generator level.



Process	Expectation
$e^+e^- \to \eta_b(1S)\omega$	$1 + \cos^2\theta$
$e^+e^- \to \chi_{b0}(1P)\omega$	$1 - \cos^2\theta$
$e^+e^- \to \chi_{b1}(1P)\omega$	$1 + \cos^2\theta$
$e^+e^- \to \chi_{b2}(1P)\omega$	$1 - \frac{1}{7}\cos^2\theta$

Selection criteria

We reconstruct only $\omega \to \pi^+\pi^-\pi^0$ and use the recoil mass $M_{\rm recoil}(\omega) = \sqrt{(\sqrt{s} - E^*_\omega)^2 - (p^*_\omega)^2}$ to identify signal.

- $dr < 0.3$ cm, $|dz| < 0.5$ cm
- $L_\pi/(L_\pi + L_K) > 0.1$
- $L_\pi/(L_\pi + L_p) > 0.1$
- $L_e/(L_\pi + L_e) < 0.9$
- `'gamma:tight'` selection criteria:
    - $E_{lab}(\gamma_1), E_{lab}(\gamma_2) > 50$ MeV for the barrel and forward ECL,
    - $E_{lab}(\gamma_1), E_{lab}(\gamma_2) > 75$ MeV for the backward ECL
- cluster E9/E21 > 0.8,
- cluster Timing < 50,
- minC2TDist > 15,
- $9.2 < M_{\rm recoil}(\omega) < 9.6$ GeV

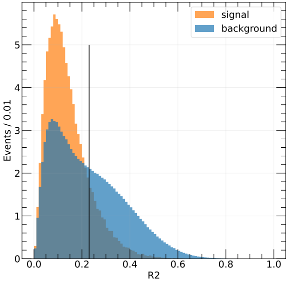
Selection criteria

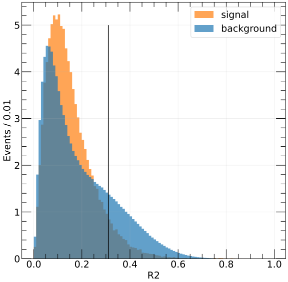
After applying the preselections we iteratively optimize the selections listed below by maximizing the figure of merit FoM $= \frac{\text{signal}}{\sqrt{\text{signal+background}}}$.

$e^+e^- \to$	
$\eta_b(1S)\omega$	$\chi_{bJ}(1P)\omega$
$p^*(\pi^0) >$260 MeV	$p^*(\pi^0) >$150 MeV
$\lvert M(\gamma\gamma) - M(\pi^0)\rvert <$12 MeV	$\lvert M(\gamma\gamma) - M(\pi^0)\rvert <$11 MeV
$\lvert M(\pi^+\pi^-\pi^0) - M(\omega)\rvert <$14 MeV	$\lvert M(\pi^+\pi^-\pi^0) - M(\omega)\rvert <$14 MeV
R2 $<$0.23	R2 $<$0.31
$r <$0.83	$r <$0.82
eff = 10.5 %	eff = 8.8 %

Selection criteria

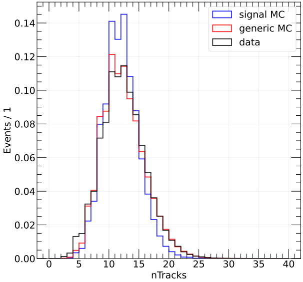
$|\cos(\theta_{thrust})|$ no cut $\rightarrow R2 < 0.31$ increases FoM by 5 % for the $\chi_{b0}(1P)$ channel.
$|\cos(\theta_{thrust})| < 0.76 \rightarrow R2 < 0.23$ increases FoM by 7 % for the $\eta_b(1S)$ channel.

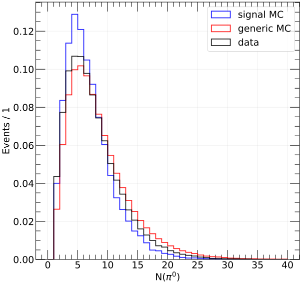




Selection criteria

Also the number of tracks and neutral pions was checked for the signal MC, generic MC and $M_{\mathrm{recoil}}(\omega)$ sidebands in data. No significant difference was found.

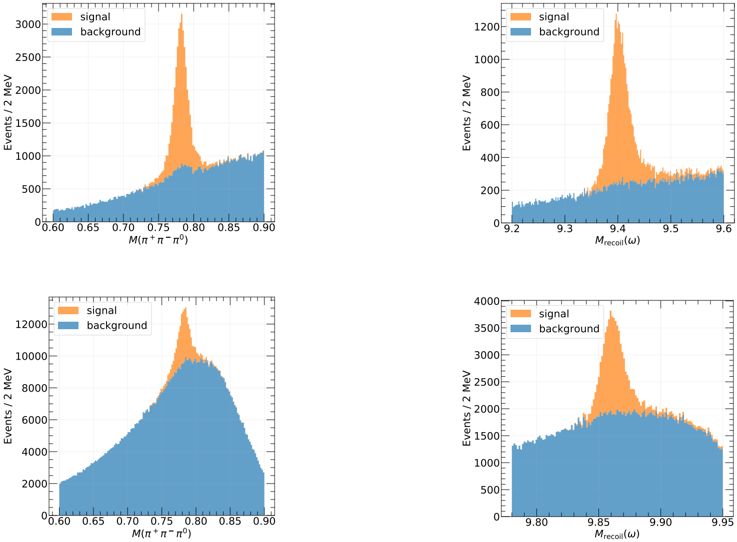




Combinatorial ω background in signal MC

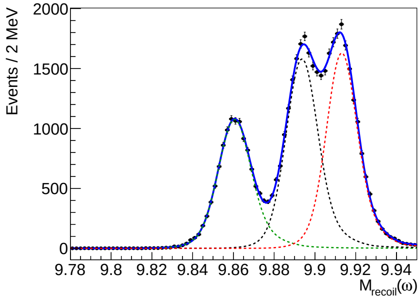
$$|M_{\mathrm{recoil}}(\omega) - M(\eta_b/\chi_{bJ})| < 50\ \mathrm{MeV},$$

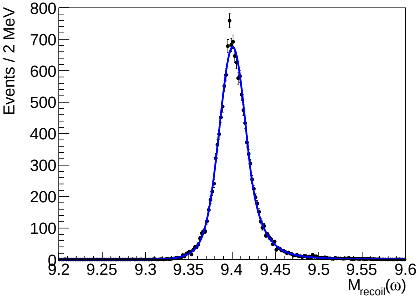
$$\downarrow$$



Fit to signal MC

We use a sum of a Gaussian and a right-sided Crystal Ball function.
χ_{b1} / χ_{b2} yields ratio is fixed according to exclusive measurements.





Parameter	$\eta_b(1S)$	$\chi_{b0}(1P)$
μ	9401.0 $\pm$ 0.4 MeV	9864.6 $\pm$ 1.4 MeV
σ	14.9 $\pm$ 0.7 MeV	14.9 $\pm$ 0.9 MeV
α	1.30 $\pm$ 0.17	1.94 $\pm$ 0.21
n	3.5 $\pm$ 1.3	1.9 $\pm$ 1.0
Δ_G	-5.0 $\pm$ 9.0 MeV	-4.2 $\pm$ 1.4 MeV
σ_G	26.4 $\pm$ 0.9 MeV	7.6 $\pm$ 0.3 MeV
R	0.89 $\pm$ 0.07	0.15 $\pm$ 0.04

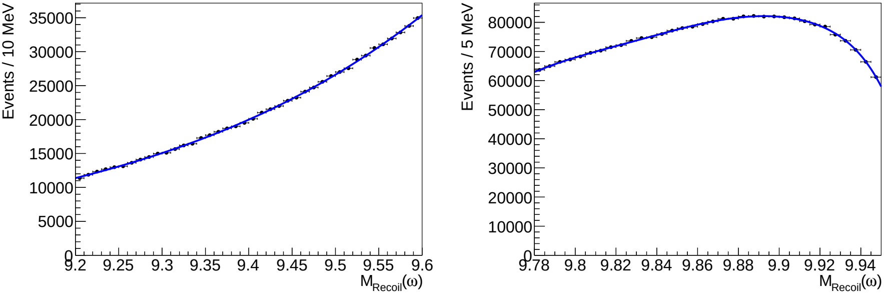
Process	Efficiency
$e^+e^- \to \eta_b(1S)\omega$	10.5%
$e^+e^- \to \chi_{b0}(1P)\omega$	8.8%
$e^+e^- \to \chi_{b1}(1P)\omega$	10.1%
$e^+e^- \to \chi_{b2}(1P)\omega$	9.6%

Parameterization of the background

We use 20% (10 fb^{-1}) of the generic MC sample generated at $\sqrt{s} = 10.751$ GeV

Polynomial order	χ^2	p-value
2	390	0.61
3	362	0.90
4	361	0.90
5	361	0.89
6	361	0.88

Polynomial order	χ^2	p-value
5	178.6	0.22
6	167.3	0.41
7	165.7	0.43
8	165.6	0.41
9	164	0.42

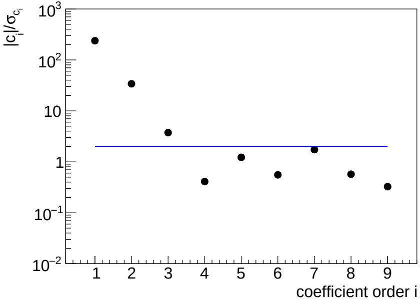


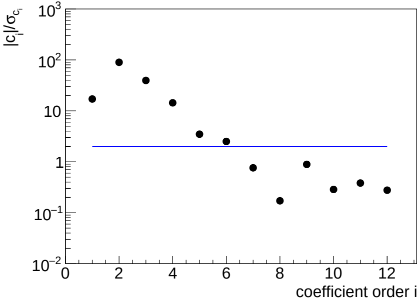
Parameterization of the background

The results are consistent with the ones obtained with the method Umberto proposed.

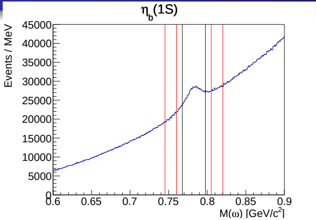
Polynomial order	χ^2	p-value
2	390	0.61
3	362	0.90
4	361	0.90
5	361	0.89
6	361	0.88

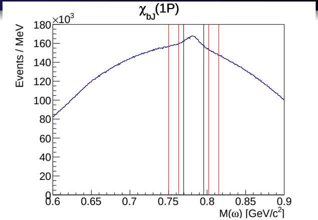
Polynomial order	χ^2	p-value
5	178.6	0.22
6	167.3	0.41
7	165.7	0.43
8	165.6	0.41
9	164	0.42

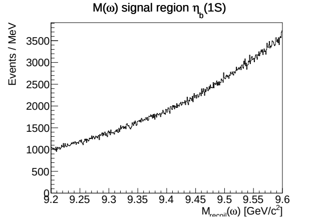


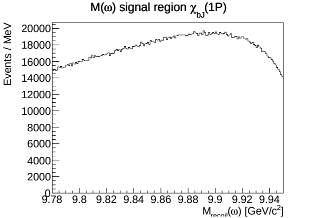


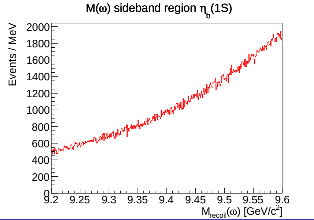
Parameterization of the background

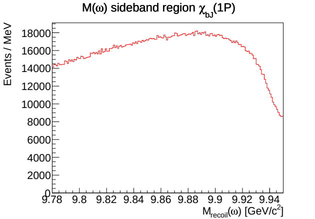












Sensitivity and cross checks

Assuning the $e^+e^- \to \chi_{b0}(1P)\omega$ and $e^+e^- \to \eta_b(1S)\omega$ cross sections are the same as the $e^+e^- \to \chi_{b1}(1P)\omega$ cross section, we calculate expected yield for inclusive reconstruction as:

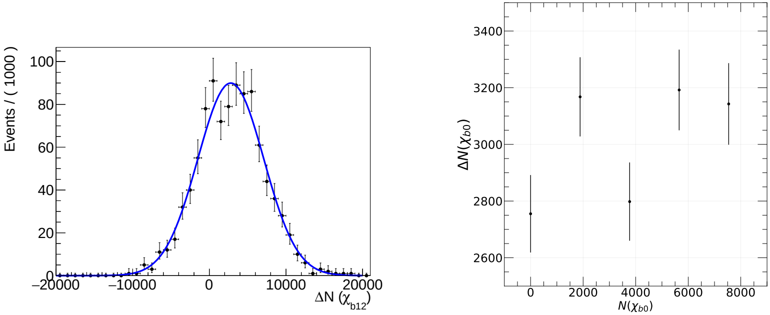
$$N_{\text{incl}} = \frac{\sigma^B \times \times \varepsilon_{\text{partial}} \times [\omega \to \pi^+\pi^-\pi^0] \times [\pi^0 \to \gamma\gamma] \times (1+\delta_{\text{ISR}})}{|1-\Pi|^2}, \quad (2)$$

Process	Expected yield
$e^+e^- \to \eta_b(1S)\omega$	$(2.25 \pm 0.47)\cdot 10^3$
$e^+e^- \to \chi_{b0}(1P)\omega$	$(1.89 \pm 0.39)\cdot 10^3$
$e^+e^- \to \chi_{b1}(1P)\omega$	$(2.17 \pm 0.45)\cdot 10^3$
$e^+e^- \to \chi_{b2}(1P)\omega$	$(1.60 \pm 0.64)\cdot 10^3$

Toy MC studies

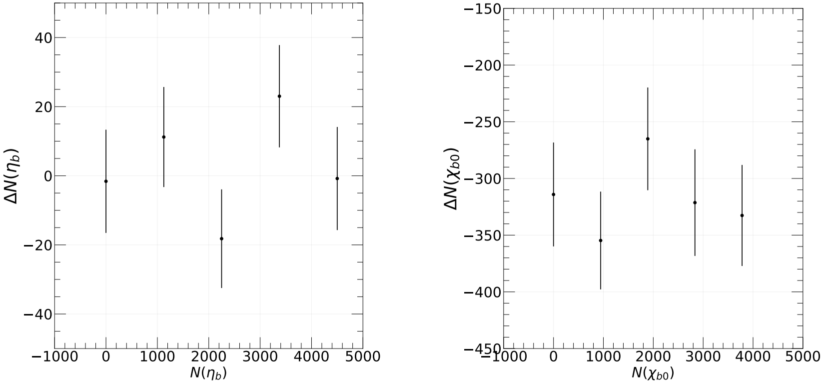
χ_{b12} expected yield: $(3.77 \pm 1.09) \cdot 10^3$
We find a bias of $(2.70 \pm 0.14) \cdot 10^3$
and RMS (expected statistical uncertainty) of $(4.30 \pm 0.10) \cdot 10^3$.

We fix the χ_{b12} yield to the expectations to give the best possible sensitivity for the χ_{b0}, which is not yet measured.



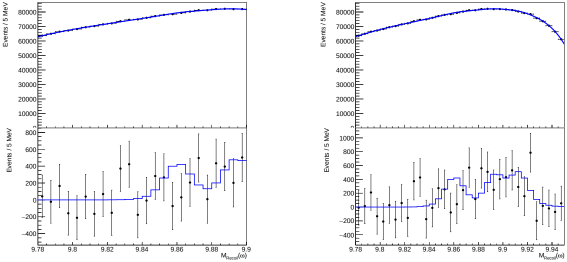
Toy MC studies

Process	Input yield	Fit bias	RMS
$e^+e^- \to \eta_b(1S)\omega$	$2.25 \cdot 10^3$	$(-0.018 \pm 0.014) \cdot 10^3$	$(0.45 \pm 0.01) \cdot 10^3$
$e^+e^- \to \chi_{b0}(1P)\omega$	$1.89 \cdot 10^3$	$(-0.30 \pm 0.04) \cdot 10^3$	$(1.39 \pm 0.03) \cdot 10^3$



Toy MC studies

Background shape becomes complicated only close to the upper boundary. To check the dependence of the bias on the fit range, we vary upper boundary of the fit range.

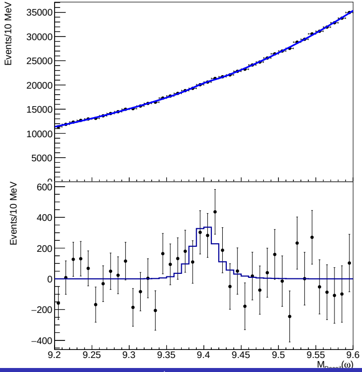


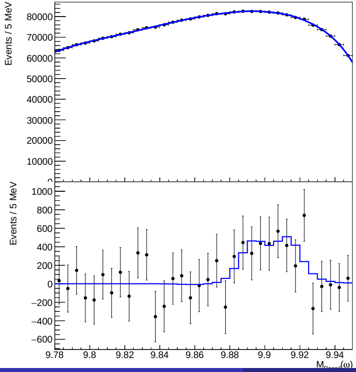
Fit range	Polynomial order	Fit bias, 10^3	RMS, 10^3
[9.78; 9.90]	4	-0.25 ± 0.04	0.98 ± 0.03
[9.78; 9.91]	4	-0.13 ± 0.04	0.86 ± 0.03
[9.78; 9.92]	4	0.15 ± 0.04	1.22 ± 0.03
[9.78; 9.93]	4	0.34 ± 0.04	1.20 ± 0.03
[9.78; 9.94]	6	-0.44 ± 0.05	1.44 ± 0.03
[9.78; 9.95]	7	-0.38 ± 0.05	1.43 ± 0.03

Gsim input-output test

We mix signal and generic MC to obtain the check the input-output consistency.

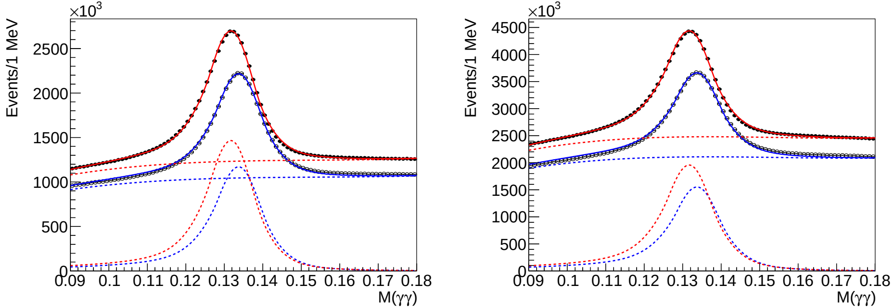
Process	Input yield	Output yield	Deviation
$e^+e^- \to \eta_b(1S)\omega$	$2.25 \cdot 10^3$	$(1.52 \pm 0.46) \cdot 10^3$	$1.6\ \sigma$
$e^+e^- \to \chi_{b0}(1P)\omega$	$1.89 \cdot 10^3$	$(-0.04 \pm 1.46) \cdot 10^3$	$1\ \sigma$





The difference between π^0 masses in generic MC and data is -1.8 MeV for both channels. So we shift the π^0 mass cut in data by this value.

$\eta_b(1S)$ $\chi_{b0}(1P)$



π^0 reconstruction efficiency uncertainty

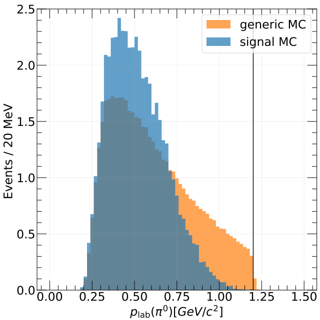
$$R_{\mathrm{MC}}^{\mathrm{Data}} = \frac{\varepsilon_{\mathrm{Data}}(\pi^0)}{\varepsilon_{\mathrm{MC}}(\pi^0)} = \sqrt{\frac{N_{\mathrm{Data}}(\eta\to\pi^0\pi^0\pi^0)/N_{\mathrm{MC}}(\eta\to\pi^0\pi^0\pi^0)}{N_{\mathrm{Data}}(\eta\to\pi^+\pi^-\pi^0)/N_{\mathrm{MC}}(\eta\to\pi^+\pi^-\pi^0)} \cdot R^2(\pi^\pm)}, \quad (3)$$

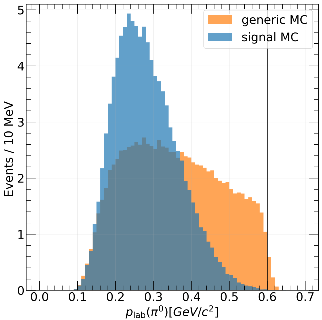
where $R(\pi^\pm)$ is the Data-MC ratio of the track reconstruction efficiency.

$$R_{\mathrm{MC}}^{\mathrm{Data}} = \frac{\varepsilon_{\mathrm{Data}}(\pi^0)}{\varepsilon_{\mathrm{MC}}(\pi^0)} = \sqrt{\frac{\varepsilon_{\mathrm{Data}}(2\pi^0)}{\varepsilon_{\mathrm{MC}}(2\pi^0)}} = \sqrt{\frac{N_{\mathrm{Data}}(\eta\to\pi^0\pi^0\pi^0)/N_{\mathrm{MC}}(\eta\to\pi^0\pi^0\pi^0)}{N_{\mathrm{Data}}(\eta\to\gamma\gamma)/N_{\mathrm{MC}}(\eta\to\gamma\gamma)}} \quad (4)$$

π^0 reconstruction efficiency uncertainty

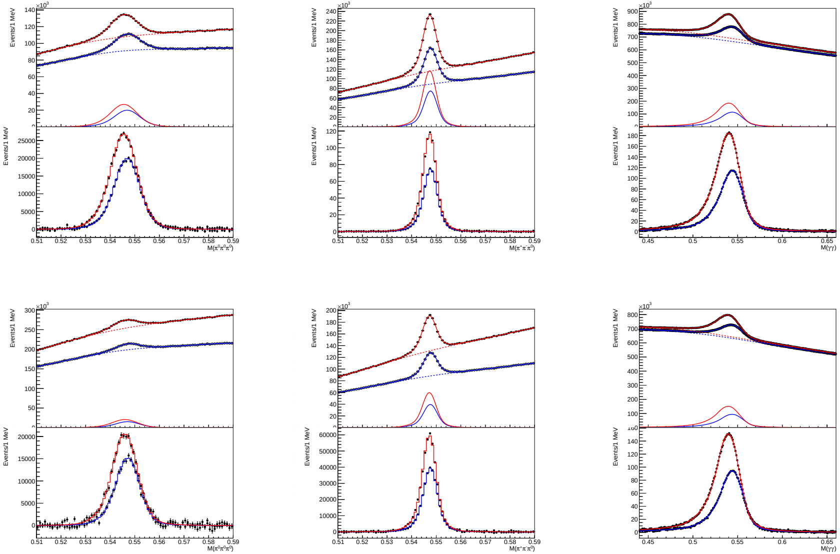
For two $\pi^0/\pi^\pm$, we require momentum in the laboratory frame to be $p_{\rm lab}(\pi)$ <1.2 GeV / 0.6 GeV to reproduce cut-offs in the $\eta_b(1S)$ / $\chi_{bJ}(1P)$ signal MC.





Then the requirement on the η-momentum in the laboratory frame $p_{\rm lab}(\eta)$ <2.5 GeV is applied to reproduce the $p_{\rm lab}(\pi^0\pi^0\pi^0)$ spectrum in the $\chi_{bJ}(1P)$ channel.

π^0 reconstruction efficiency uncertainty



π^0 reconstruction efficiency uncertainty

With $\eta \to \pi^0\pi^0\pi^0$ and $\eta \to \pi^+\pi^-\pi^0$ channels:

$$R^{\rm Data}_{\rm MC} = \frac{\varepsilon_{\rm Data}(\pi^0)}{\varepsilon_{\rm MC}(\pi^0)} = 0.947 \pm 0.022 \pm 0.026 \quad \text{for } \eta_b(1S), (5)$$

$$R^{\rm Data}_{\rm MC} = \frac{\varepsilon_{\rm Data}(\pi^0)}{\varepsilon_{\rm MC}(\pi^0)} = 0.951 \pm 0.038 \pm 0.061 \quad \text{for } \chi_{bJ}(1P), (6)$$

where the first uncertainty is statistical, and the second is systematic. The systematic uncertainties of the π^0 reconstruction are 3.6% and 7.5% for $\eta_b(1S)$ and $\chi_{bJ}(1P)$ selections, respectively.

With $\eta \to \pi^0\pi^0\pi^0$ and $\eta \to \gamma\gamma$ channels:

$$R^{\rm Data}_{\rm MC} = \frac{\varepsilon_{\rm Data}(\pi^0)}{\varepsilon_{\rm MC}(\pi^0)} = 0.924 \pm 0.021 \pm 0.027 \quad \text{for } \eta_b(1S), (7)$$

$$R^{\rm Data}_{\rm MC} = \frac{\varepsilon_{\rm Data}(\pi^0)}{\varepsilon_{\rm MC}(\pi^0)} = 0.937 \pm 0.036 \pm 0.058 \quad \text{for } \chi_{bJ}(1P), (8)$$

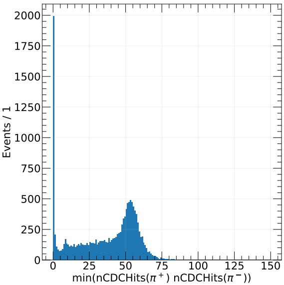
where the first uncertainty is statistical, and the second is systematic. The systematic uncertainties of the π^0 reconstruction are 3.7% and 7.3% for $\eta_b(1S)$ and $\chi_{bJ}(1P)$ selections, respectively.

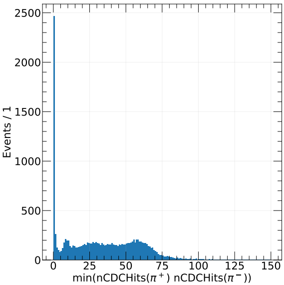
Other sources of the systematic uncertainty

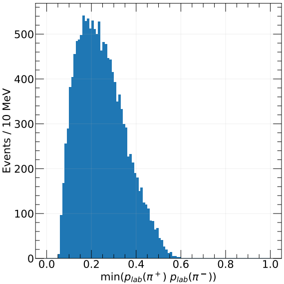
Reconstruction efficiency uncertainty

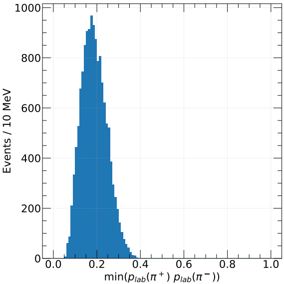
- Charged track reconstruction uncertainty. For the low momentum pions, we use the values obtained in B2N-PH-2022-034 with slow pions from $\bar{B}^0 \to [D^{*+} \to D^0\pi^+_{slow}]\pi^-$ process. For the mid to high momentum pions, we use the values obtained in Ref. B2N-PH-2020-006 with $e^+e^- \to \tau^+\tau^-$ processes. Systematic uncertainties are 1.6% and 1.9% per track for the $\eta_b(1S)$ and $\chi_{bJ}(1P)$ channels, respectively.
- Particle identification uncertainty. To estimate $\pi^\pm$ identification uncertainty, we use π^+ from inclusive $D^{*+} \to [D \to K^-\pi^+\pi^0]\pi^+$ data sample. The obtained Data-MC ratios of $\pi^\pm$ reconstruction efficiency are 0.971 and 0.968 for $\eta_b(1S)$ and $\chi_{bJ}(1P)$ channels, respectively. Systematic uncertainties corresponding to charged pion identification are 2.3% and 2.6% per pion for the $\eta_b(1S)$ and $\chi_{bJ}(1P)$ channels, respectively.

Why tracking and PID uncertainties are so high?









Other sources of the systematic uncertainty

Signal parametrization uncertainty

- Mass and width. To estimate systematic uncertainties due to the mass and width errors, we vary $\eta_b(1S)$ and $\chi_{b0}(1P)$ masses and widths within one standard deviation.
- ISR tail. The shape of the ISR tail depends on the $\eta_b/\chi_{b0}\omega$ production mechanism. Instead of a resonant production via $\Upsilon(10753)$, we consider the energy independent $e^+e^- \to \eta_b/\chi_{b0}\omega$ cross sections to estimate the uncertainty due to the ISR tail parameterization.

Background parameterization uncertainty

- Fit range. We vary upper and lower limit of the fit range by 100 MeV for the $\eta_b(1S)$ channel and 50 MeV for the $\chi_{b0}(1P)$ channel to estimate the uncertainty due to the fit range.
- Polynomial order. We increase or decrease the polynomial order by one to estimate the uncertainty due to the polynomial order.

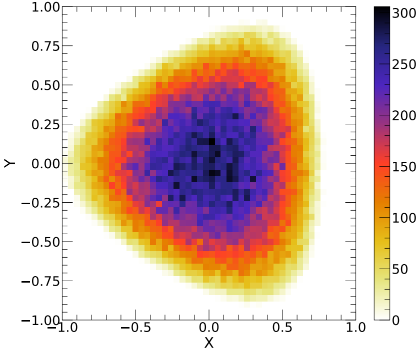
Summary

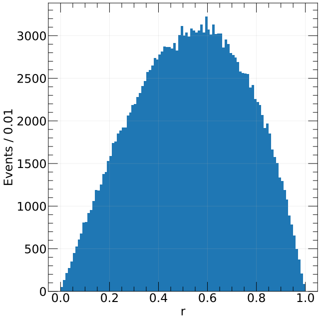
- The reconstruction method was developed.
- The Data-MC discrepancies and systematic uncertainties were studied. We expect background parameterization to be the main source of systematic uncertainty.
- The toy MC studies and input-output studies provided us with an understanding of the fit procedure.
- We expect the 1-2 σ signal for the $e^+e^- \to \chi_{bJ}\omega$ (J = 1,2) channels. But it is not clear for χ_{b0} channel, which was not found exclusively due to low BF[$\chi_{b0} \to \Upsilon(1S)\gamma$]$\sim$2%. We could see the signal only if J = 0 is enhanced compared to J = 1,2.
- For $\eta_b(1S)$, we expect $>$3 σ signal even if the enhancement on the same level as for $\chi_{bJ}(1P)$ (tetraquark model predicts even larger enhancement).

BACKUP

What is r?

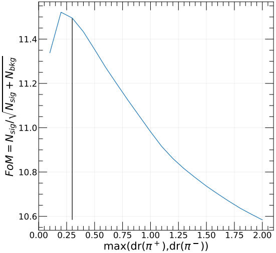
r is a normalized distance to the Dalitz plot (DP) center; r varies from 0 to 1, the points at the DP boundary have r = 1. Signal events are mostly concentrated in the centre of DP.

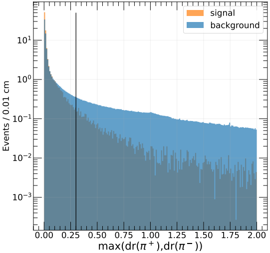


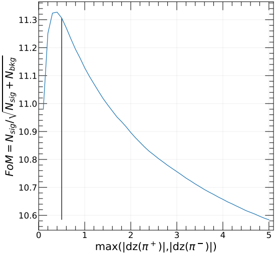


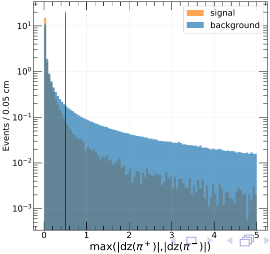
Optimization of impact parameters requirements $\eta_b(1S)$

Left: FoM Right: signal (yellow), background (blue).

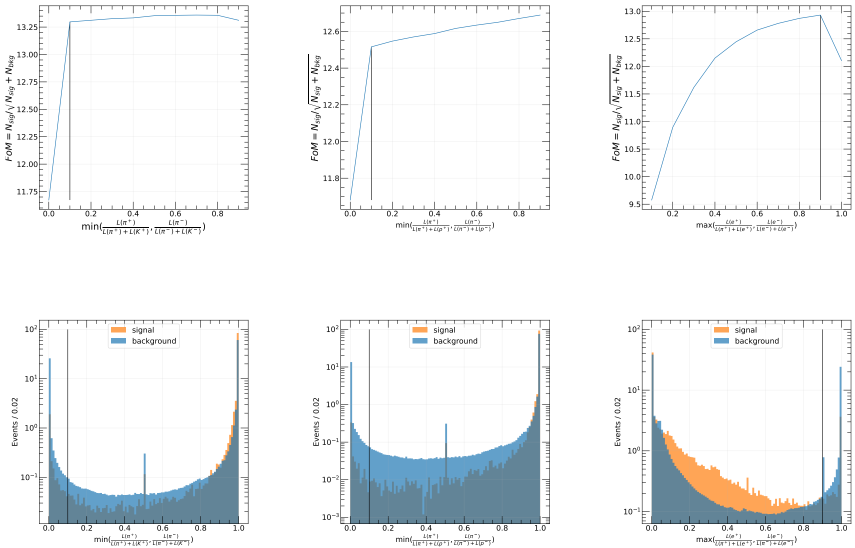




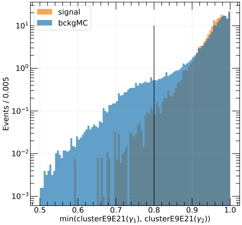


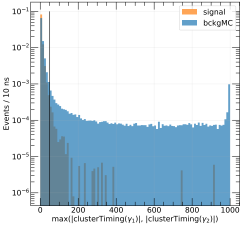


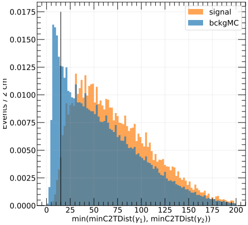
Optimization of PID requirements $\eta_b(1S)$



Optimization of cluster parameters requirements $\eta_b(1S)$

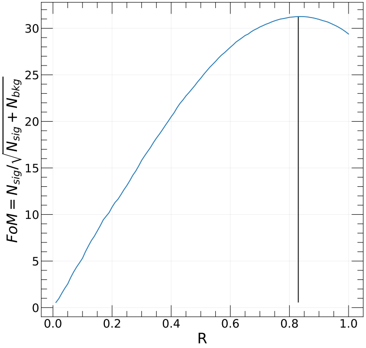


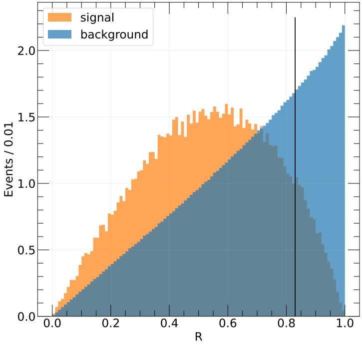




Optimization of r requirement $\eta_b(1S)$

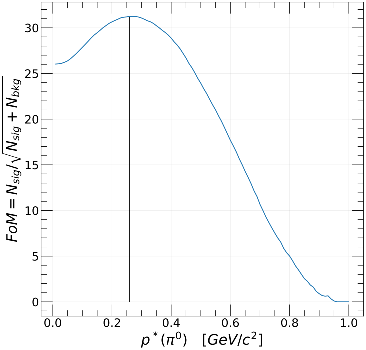
Left: FoM   Right: signal (yellow), background (blue).

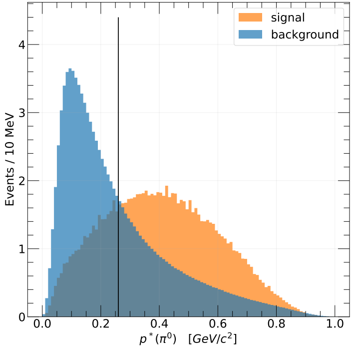




Optimization of $p^*(\pi^0)$ requirement $\eta_b(1S)$

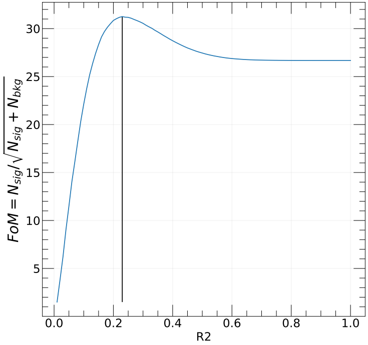
Left: FoM Right: signal (yellow), background (blue).

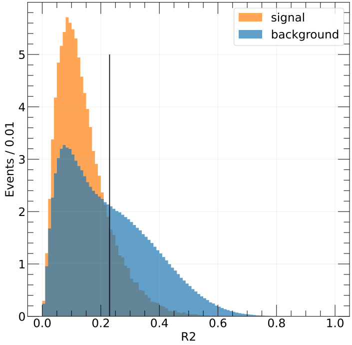




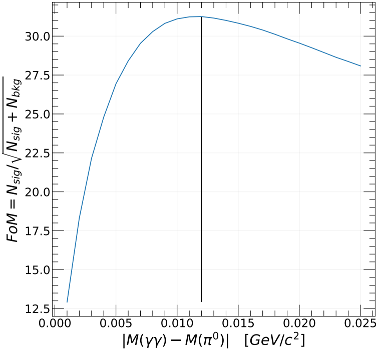
Optimization of R2 requirement $\eta_b(1S)$

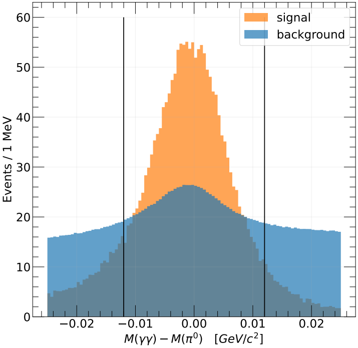
Left: FoM Right: signal (yellow), background (blue).





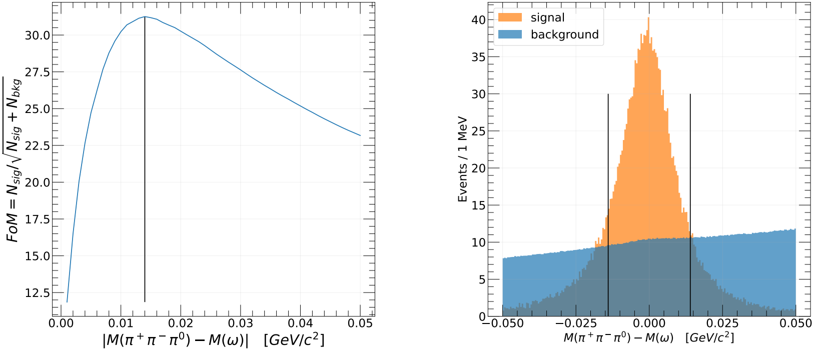
Left: FoM Right: signal (yellow), background (blue).



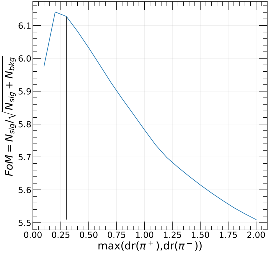


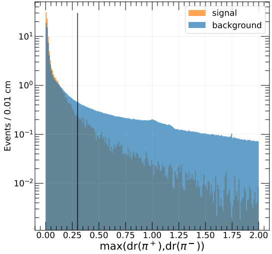
Optimization of $|M(\pi^+\pi^-\pi^0) - M(\omega)|$ requirement $\eta_b(1S)$

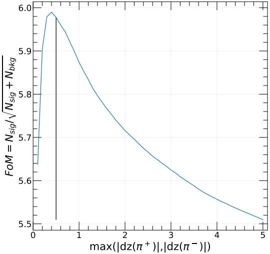
Left: FoM   Right: signal (yellow), background (blue).

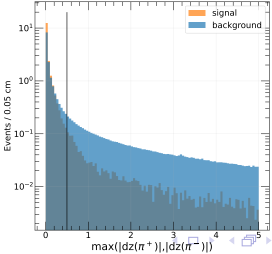


Left: FoM Right: signal (yellow), background (blue).

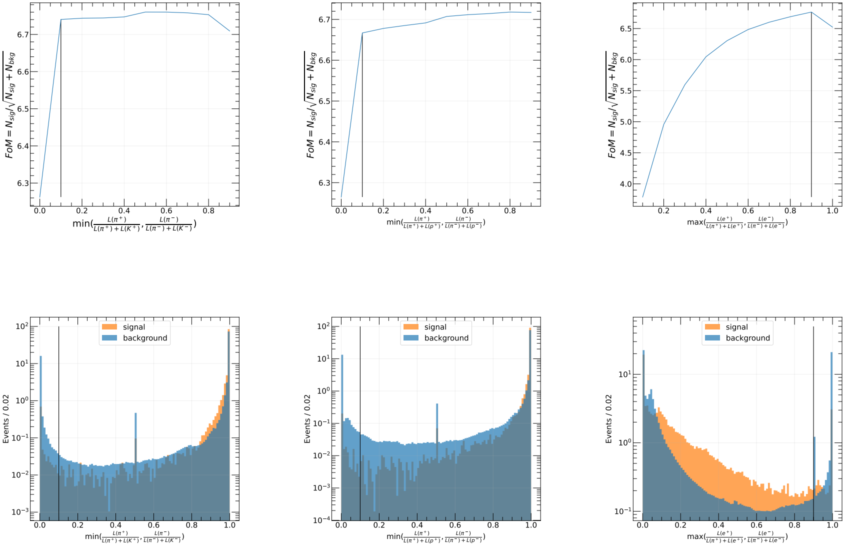




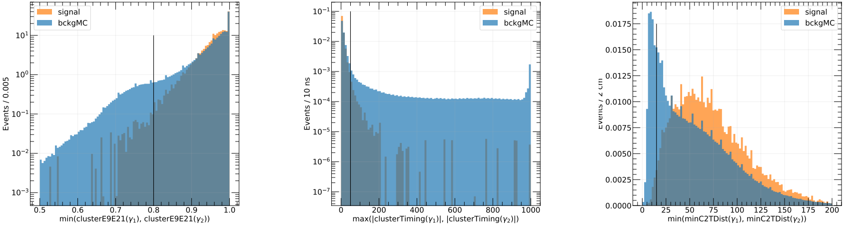




Optimization of PID requirements $\chi_{b0}(1P)$

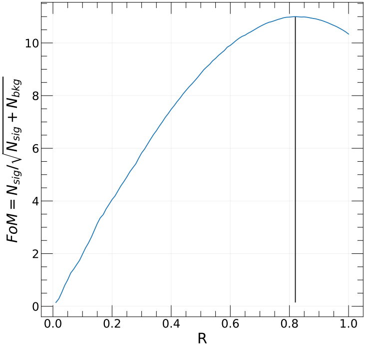


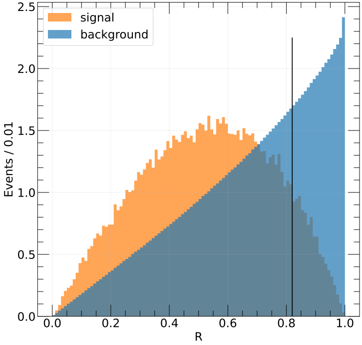
Optimization of cluster parameters requirements $\chi_{b0}(1P)$



Optimization of r requirement $\chi_{b0}(1P)$

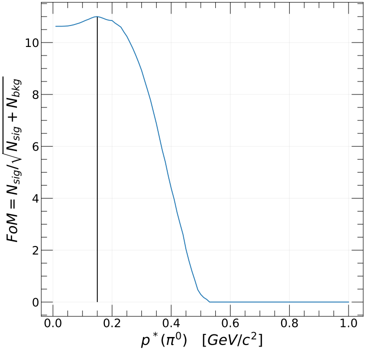
Left: FoM Right: signal (yellow), background (blue).

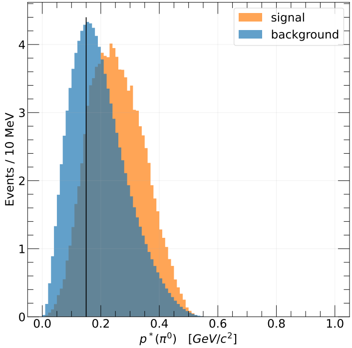




Optimization of $p^*(\pi^0)$ requirement $\chi_{b0}(1P)$

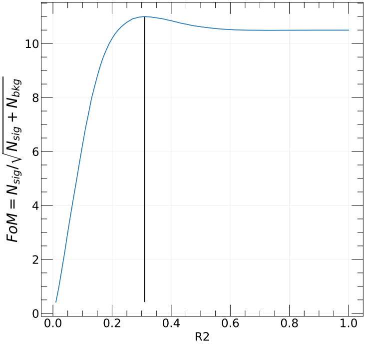
Left: FoM Right: signal (yellow), background (blue).

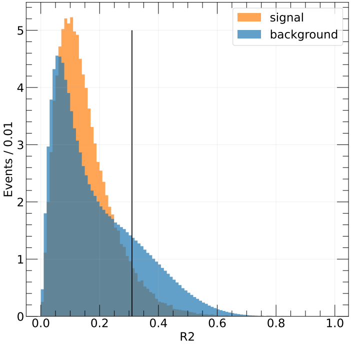




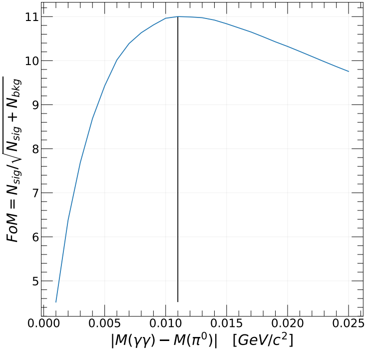
Optimization of R2 requirement $\chi_{b0}(1P)$

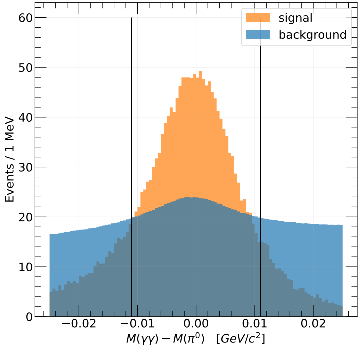
Left: FoM Right: signal (yellow), background (blue).





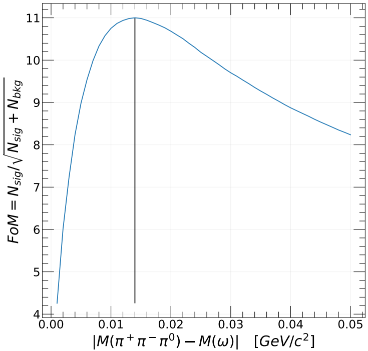
Left: FoM Right: signal (yellow), background (blue).

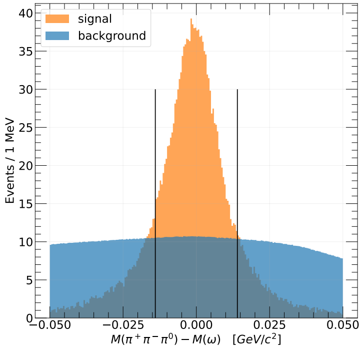




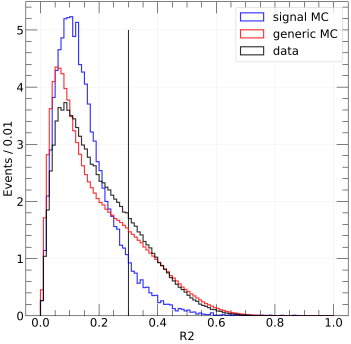
Optimization of $|M(\pi^+\pi^-\pi^0) - M(\omega)|$ requirement $\chi_{b0}(1P)$

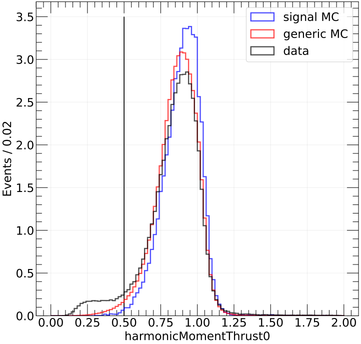
Left: FoM Right: signal (yellow), background (blue).





Data-MC discrepancy in the event shape variables





Signal MC generation

We think that the correct decay of χ_{b1} will be to two gluons with one of them off mass shell; this is not forbidden by the Landau theorem.

Since now we use the event shape variables (R2) in the selection the difference in efficiency compared to the default table is 31.5%. We will include this value in the systematic uncertainty.

```
Decay chi_b0
0.0192    gamma  Upsilon         HELAMP 1. 0. 1. 0.;  #best values from BBR 2014,
using B(Y2S->gamma chib)
0.9808    g      g               PYTHIA 91;
Enddecay

Decay chi_b1
0.349     gamma  Upsilon        HELAMP 1. 0. 1. 0. -1. 0. -1. 0.;   #best values fr
om BBR 2014, using B(Y2S->gamma chib)
0.16275         d       anti-d  PYTHIA 91;
0.16275         u       anti-u  PYTHIA 91;
0.16275         s       anti-s  PYTHIA 91;
0.16275         c       anti-c  PYTHIA 91;
Enddecay

Decay chi_b2
0.187     gamma  Upsilon       HELAMP 1. 0. 1.7320508 0. 2.4494897 0.          2.449
4897 0. 1.7320508 0. 1. 0.;  #best values from BBR 2014, using B(Y2S->gamma chib)
0.813          g       g       PYTHIA 91;
Enddecay
```