Measurement of the cross section for inclusive B_s production in e^+e^- collisions at energies around 11 GeV

PhD thesis defence (demo-version)

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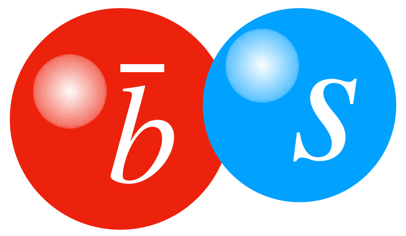
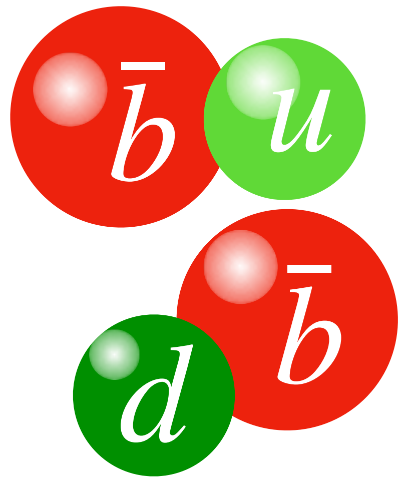
Goal

Goal of this dissertation — $\sigma(e^+e^- \to B_s\bar{B}_sX)$ and $\sigma(e^+e^- \to B\bar{B}X)$ at $E_{\rm cm}$ from 10.63 to 11.02 GeV

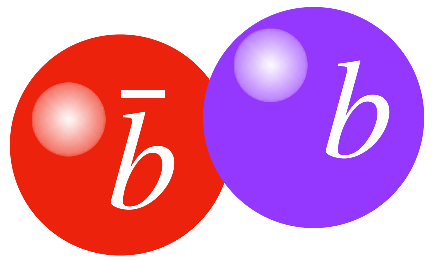


B_s mesons — open-flavor,
$m = (5366.92 \pm 0.10)$ MeV

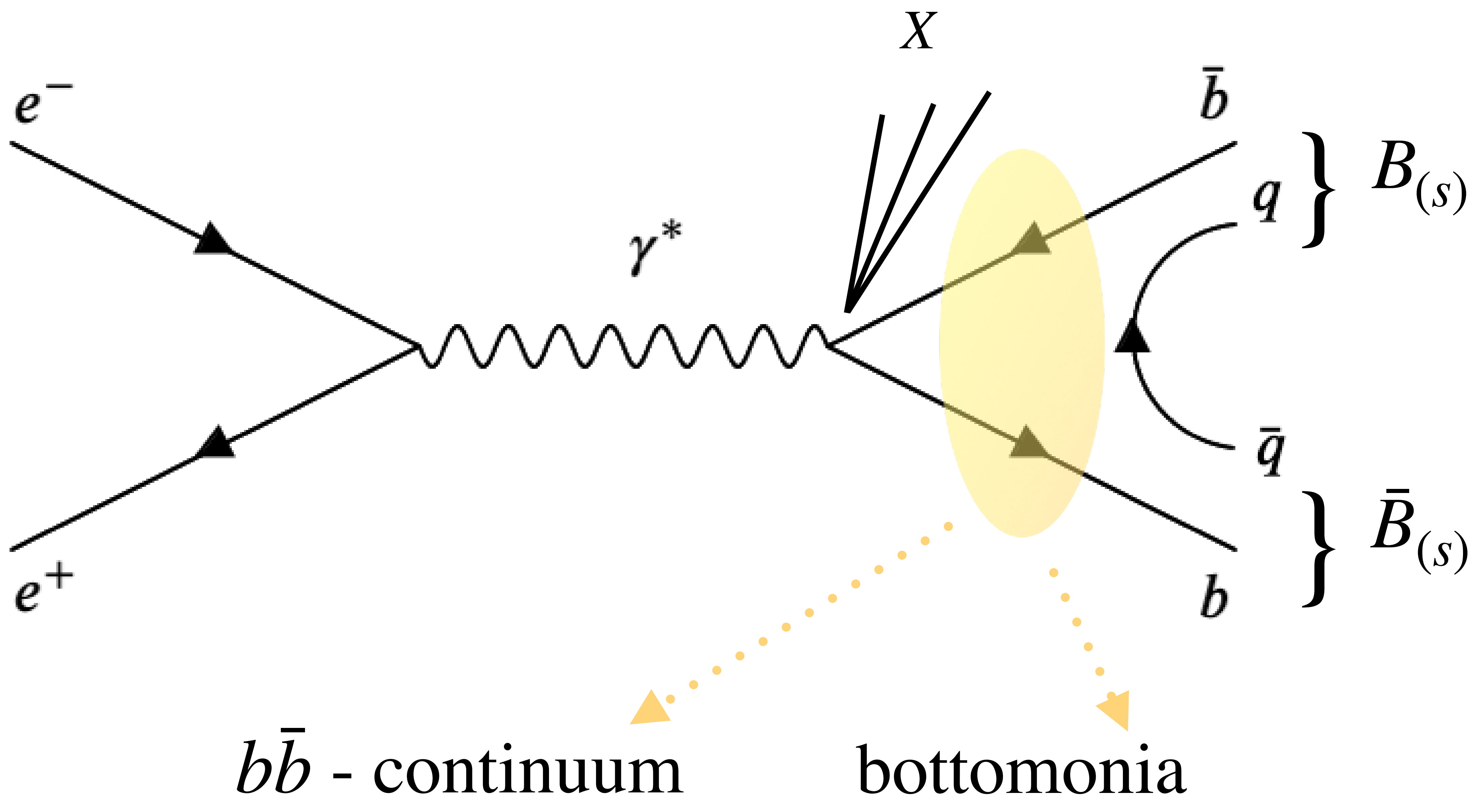


B^0 and B^+ mesons — open-flavor,

$m = (5279.66 \pm 0.12)$ MeV



Bottomonia — hidden-flavor



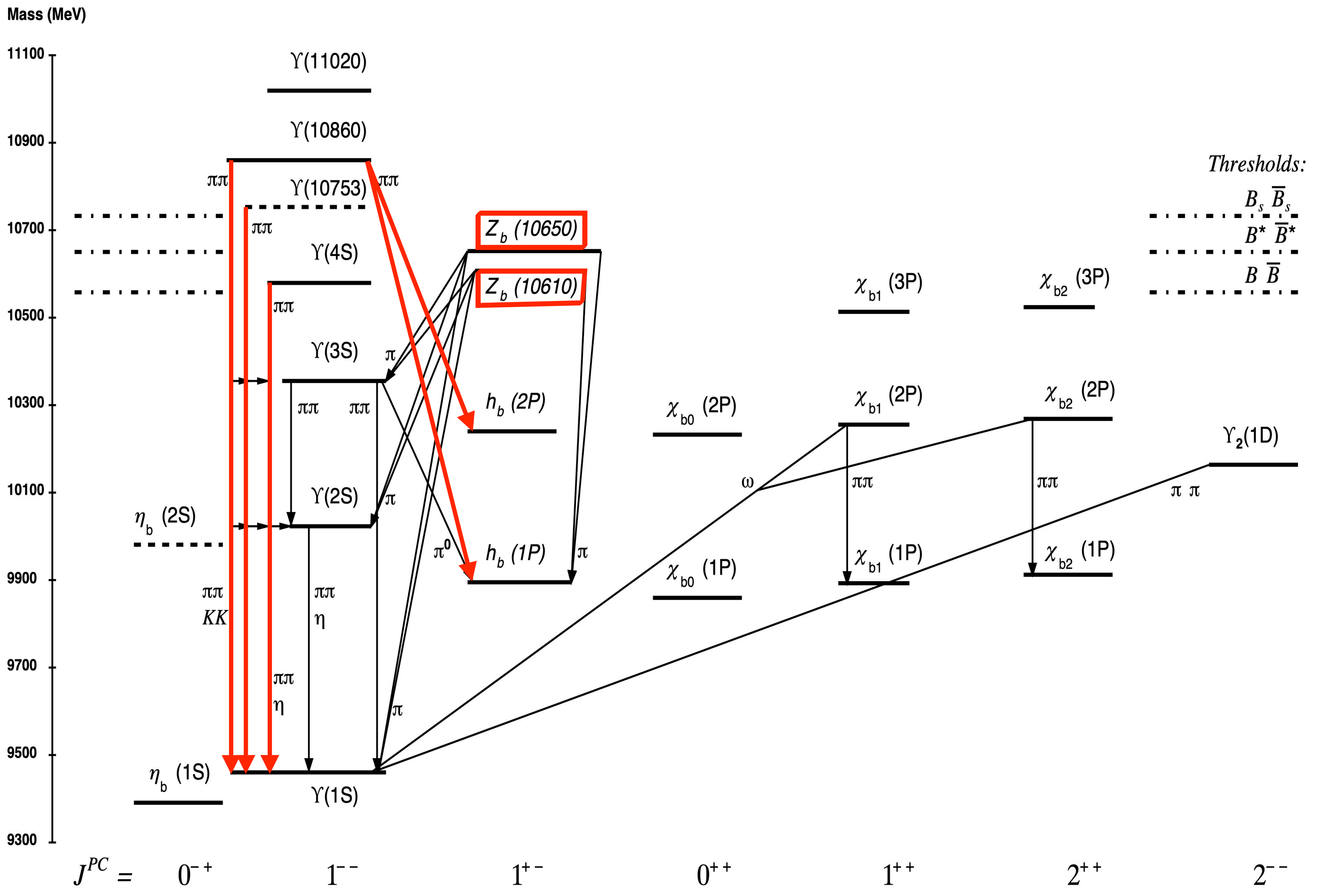
Bottomonium spectroscopy

Heavy quarkonium spectroscopy is an excellent laboratory to study non-perturbative QCD

Bottomonium states below $B\bar{B}$ threshold are well described by quark model

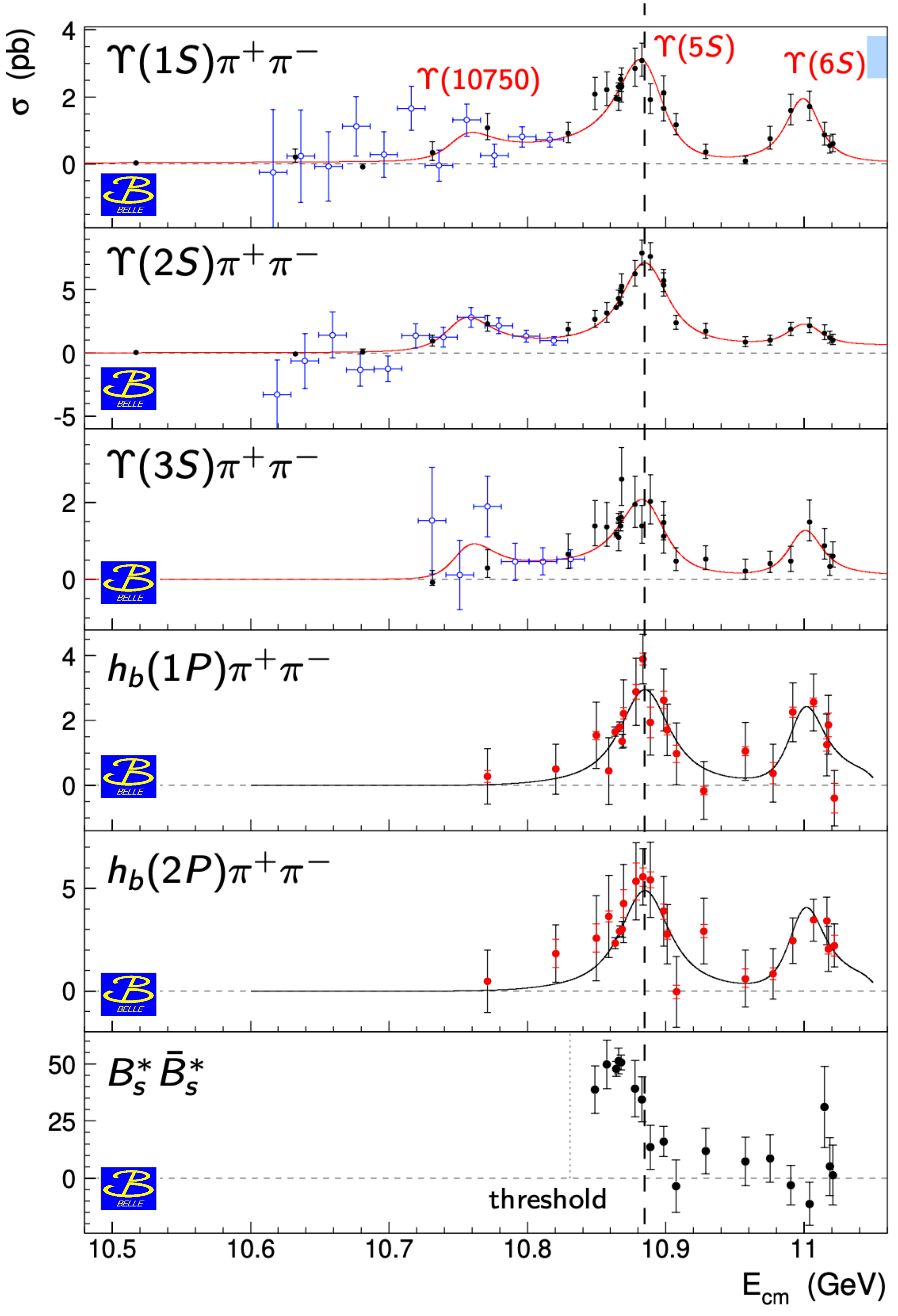
Bottomonium states above $B\bar{B}$ threshold demonstrate unexpected properties

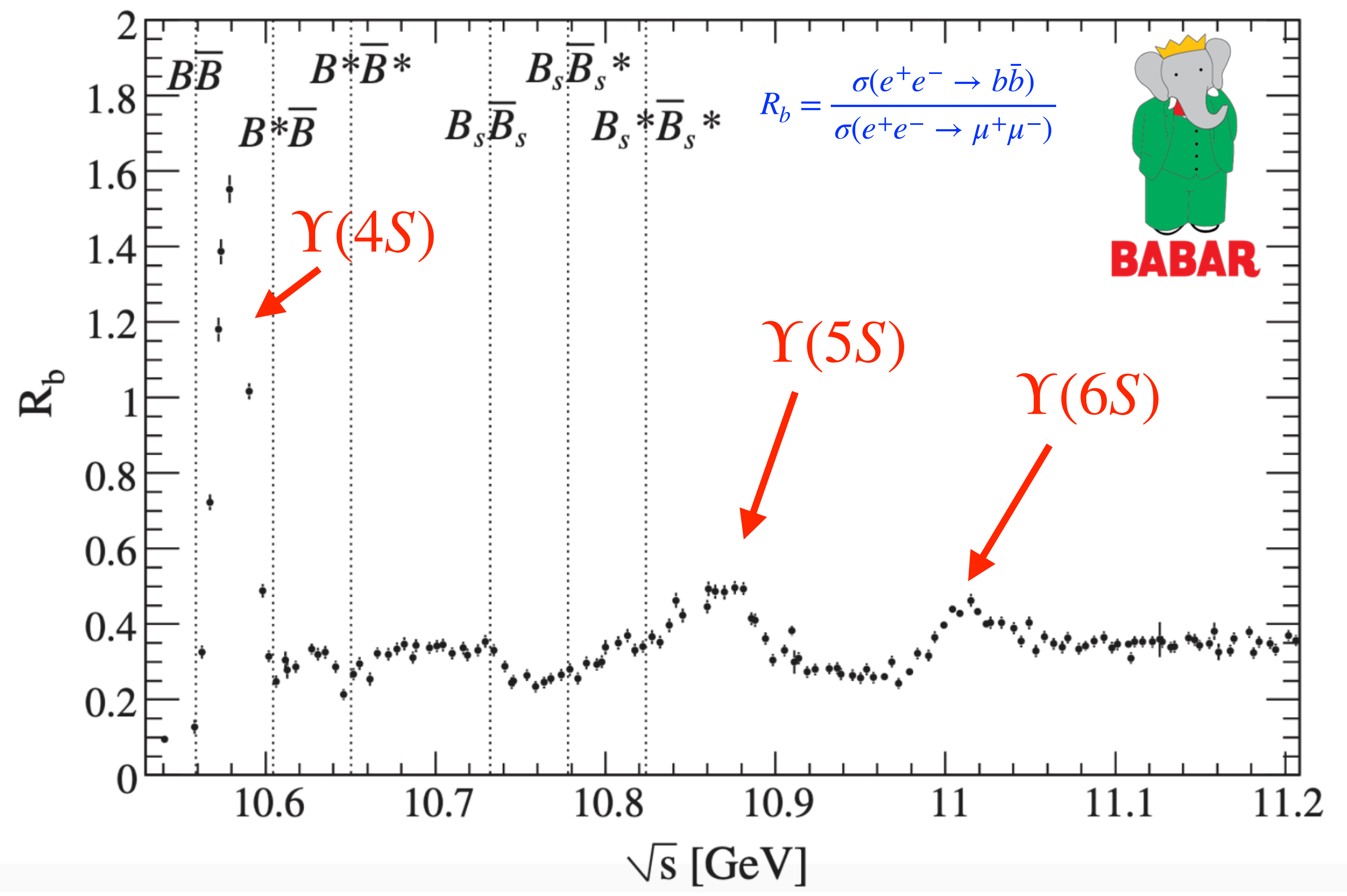
- Z_b and Z_b' are charged (at least 4 quarks)
- Rates of hadronic transition to lower bottomonia are higher then expected for pure $b\bar{b}$ (violate OZI-rules)
- η transitions are not suppressed relative to dipion transitions (violate HQSS)

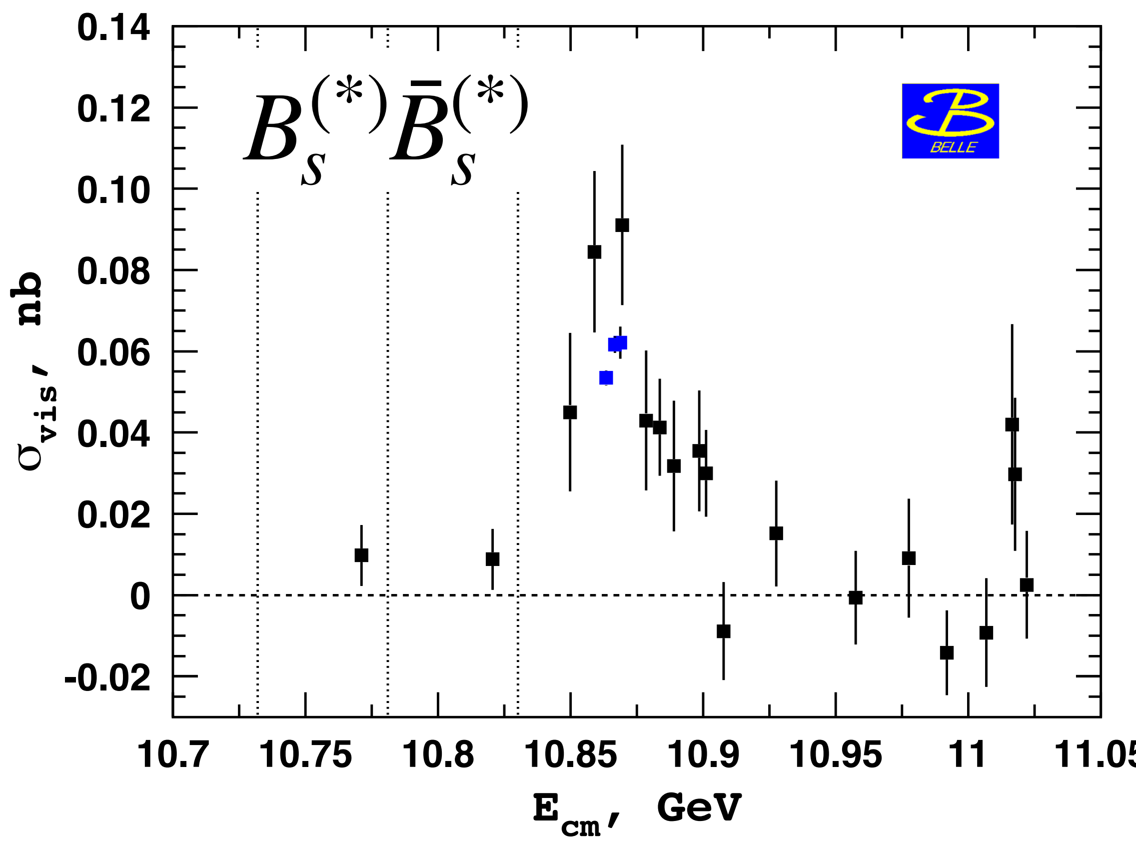


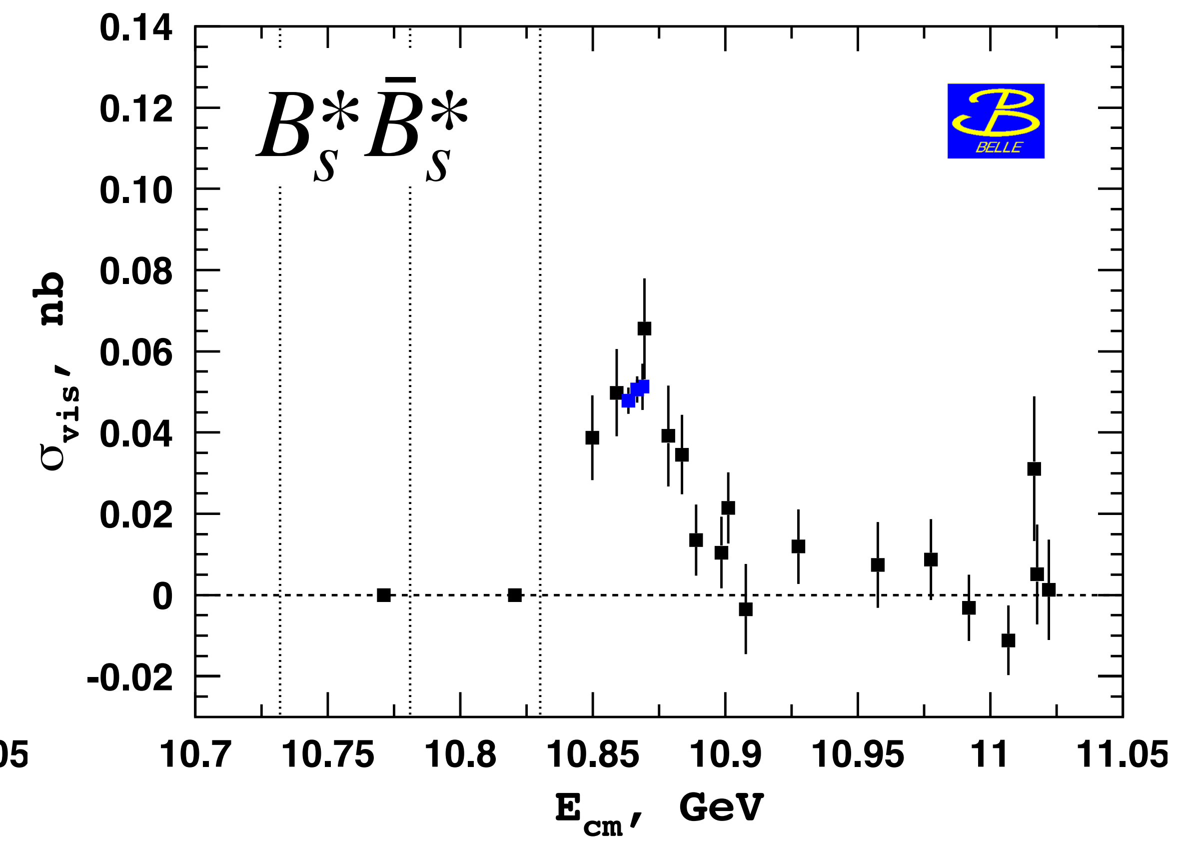
Nature of bottomonia above threshold is not well understood yet!

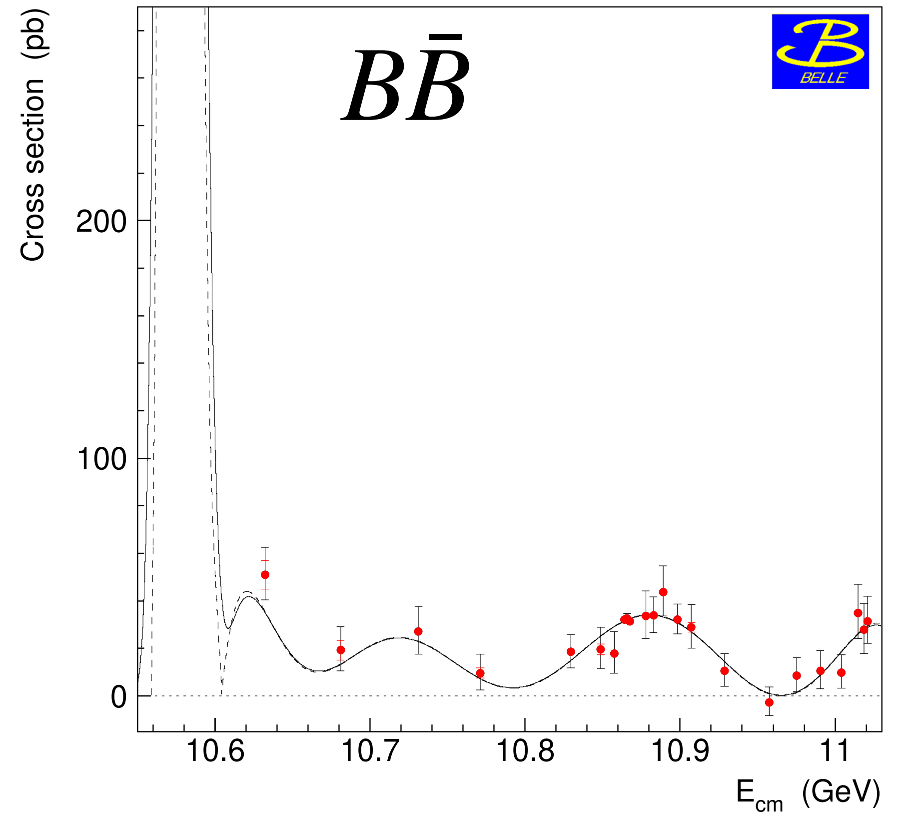
Analysis of the individual cross sections

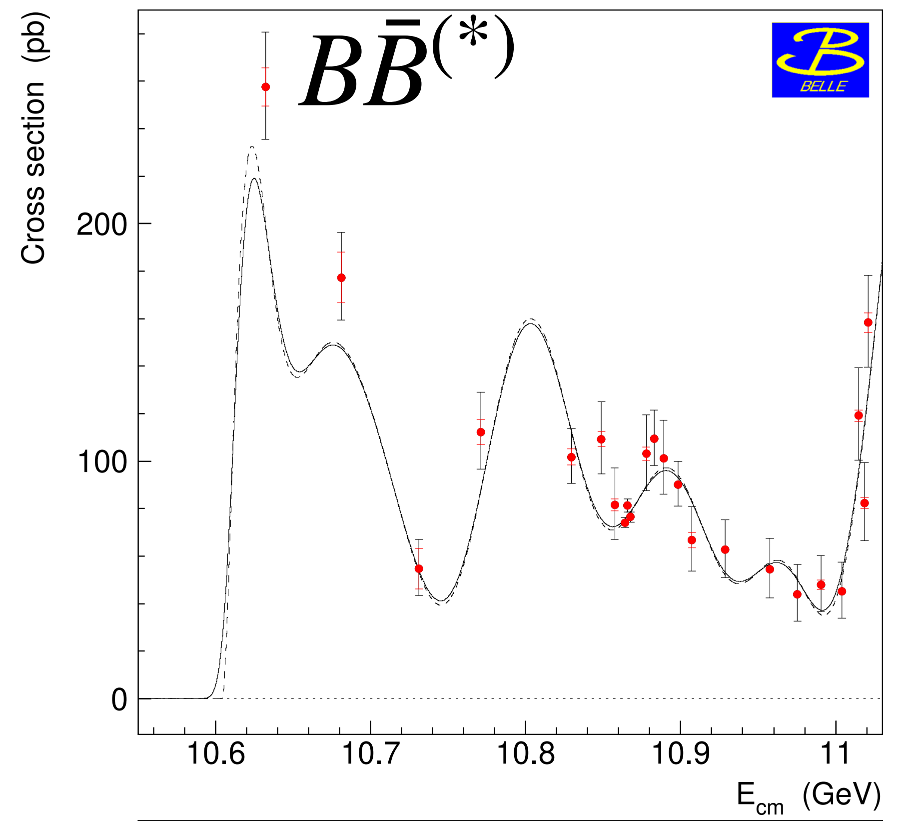


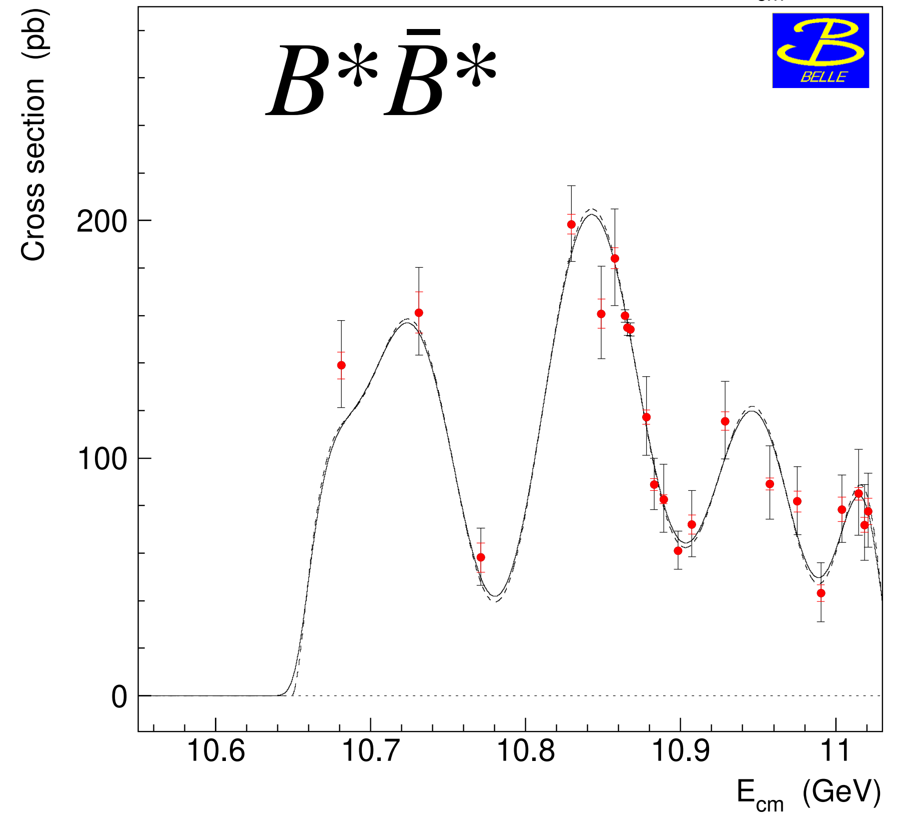




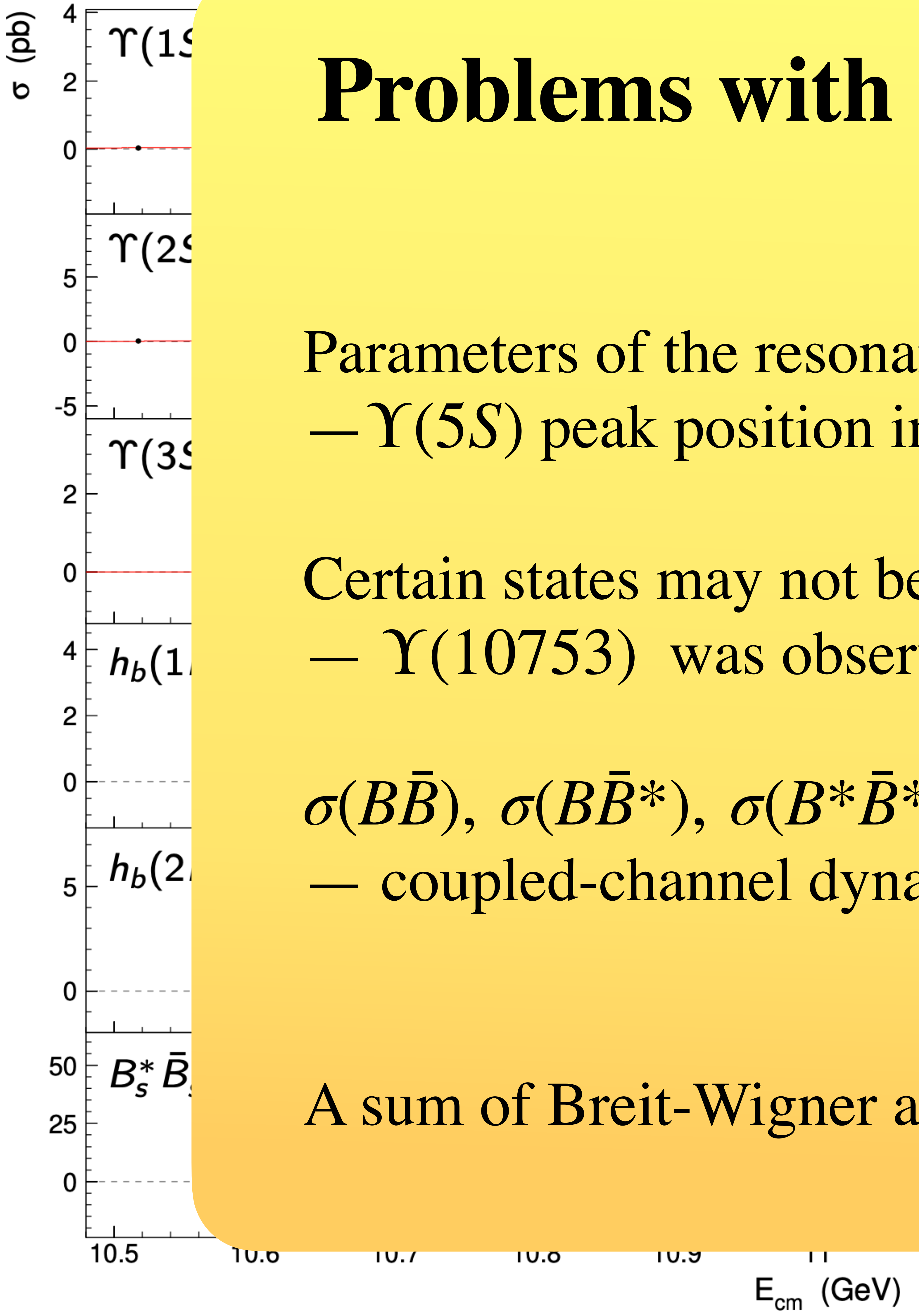


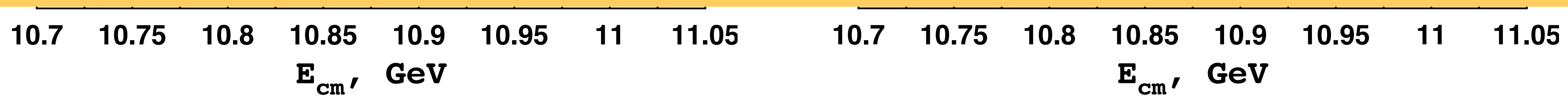


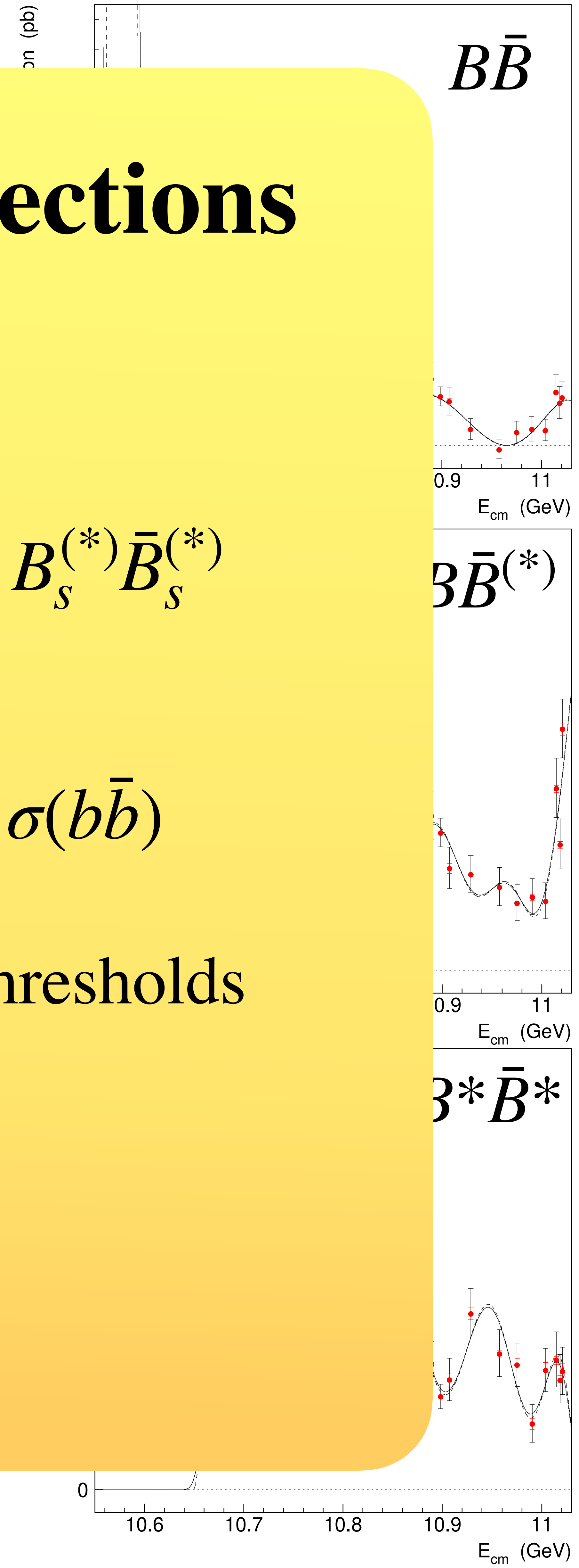




Analysis of the individual cross sections







Problems with the analysis of the individual cross sections

Parameters of the resonances extracted from different channels may differ
— $\Upsilon(5S)$ peak position in $\Upsilon(nS)\pi^+\pi^-$ and $h_b(1{,}2P)\pi^+\pi^-$ are shifted from peak in $B_s^{(*)}\bar{B}_s^{(*)}$

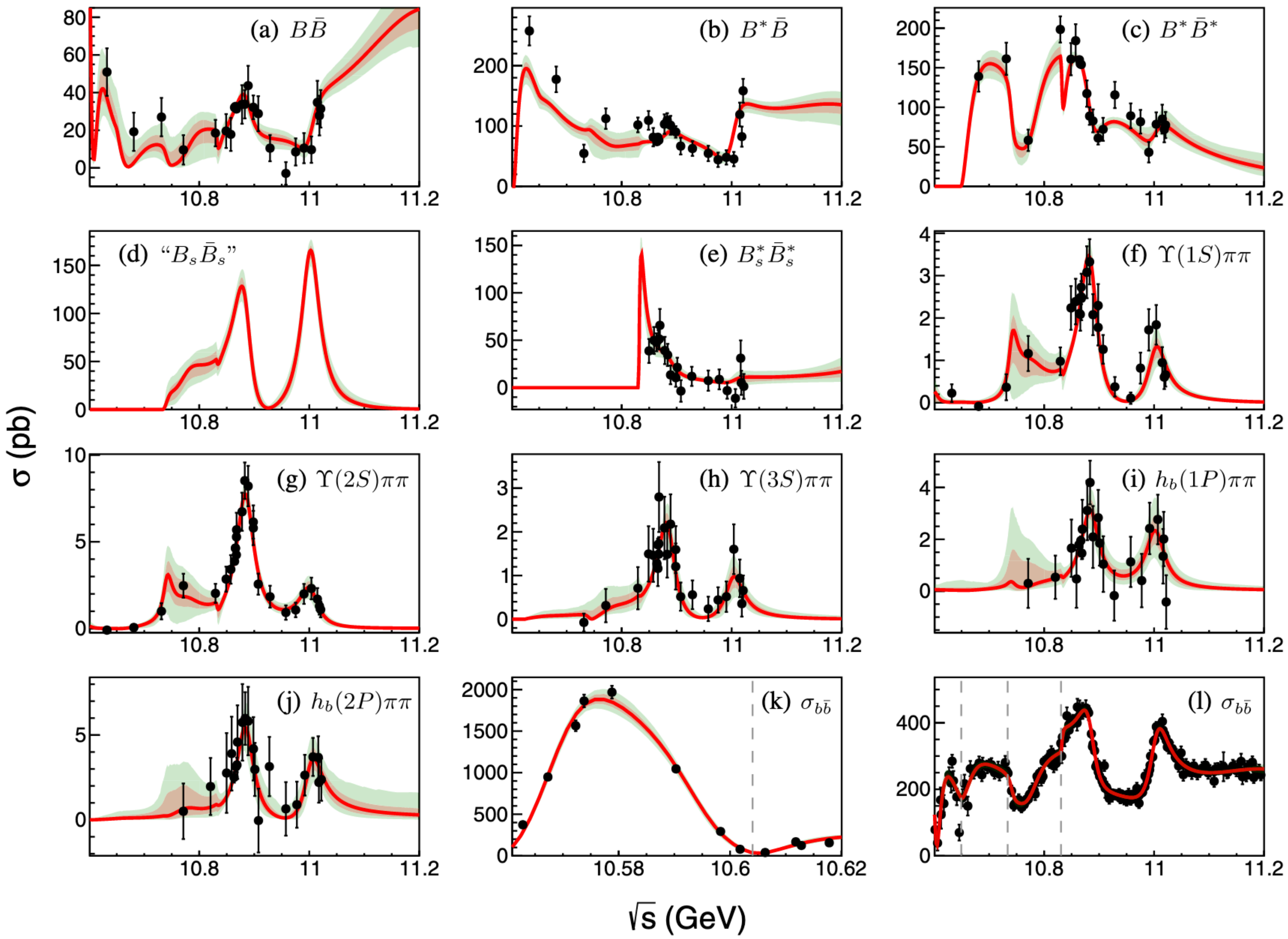
Certain states may not be seen in some channels
— $\Upsilon(10753)$ was observed in $\Upsilon(1{,}2{,}3S)\pi^+\pi^-$ final states and is not seen in total $\sigma(b\bar{b})$

$\sigma(B\bar{B})$, $\sigma(B\bar{B}^*)$, $\sigma(B^*\bar{B}^*)$ have complex shape with peaks and valleys/dips near thresholds
— coupled-channel dynamic should be taken into account

A sum of Breit-Wigner amplitudes violate unitarity — results are unreliable

Global phenomenological analysis

N. HÜSKEN, R. E. MITCHELL, and E. S. SWANSON PRD 106 (2022) 9, 094013



Used data:

$B\bar{B}, B^*\bar{B}, B^*\bar{B}^*, B_s^*\bar{B}_s^*, \Upsilon(1S)\pi^+\pi^-, \Upsilon(2S)\pi^+\pi^-, \Upsilon(3S)\pi^+\pi^-, h_b(1P)\pi^+\pi^-, h_b(2P)\pi^+\pi^-,$ and $\sigma_{b\bar{b}}$

Poles for:

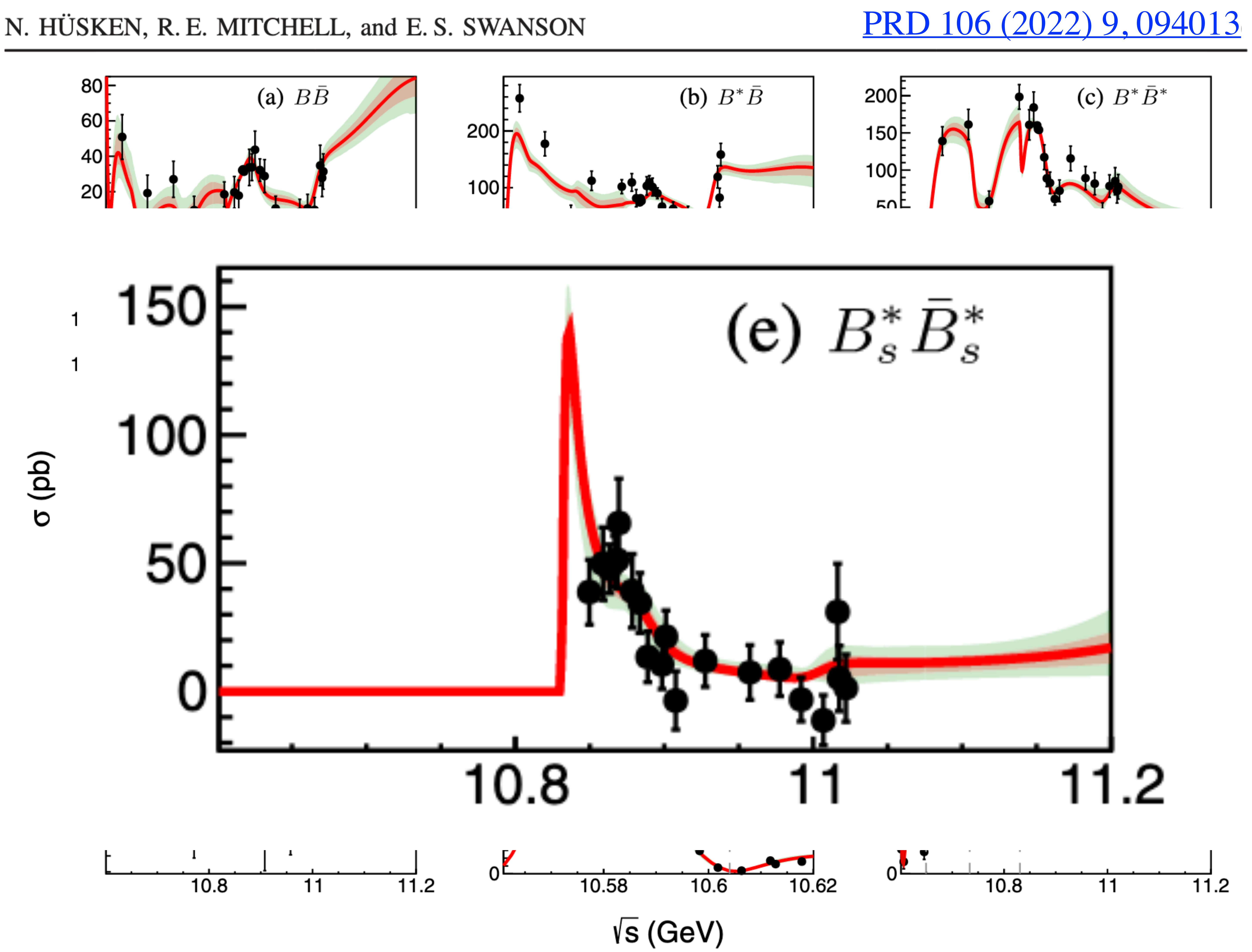
$\Upsilon(4S), \Upsilon(10753), \Upsilon(5S), \Upsilon(6S)$

Various $\mathscr{B}'s$ and electronic widths

The uncertainties are still large

Need more data

Channel $e^+e^- \rightarrow B_s^{(*)}\bar{B}_s^{(*)}$



$B_s^{(*)}\bar{B}_s^{(*)}$ channel — the current data doesn't constrain the fit function well

Need to improve the accuracy in $B_s^{(*)}\bar{B}_s^{(*)}$ channel

Summary of introduction

- Bottomonia above the open-bottom threshold are still puzzling
- Global combined analysis is promising approach to investigate the bottomonia nature
- Every additional channel is very important for the global analysis
- Improving accuracy in particular channels will allow better constrained fitting function

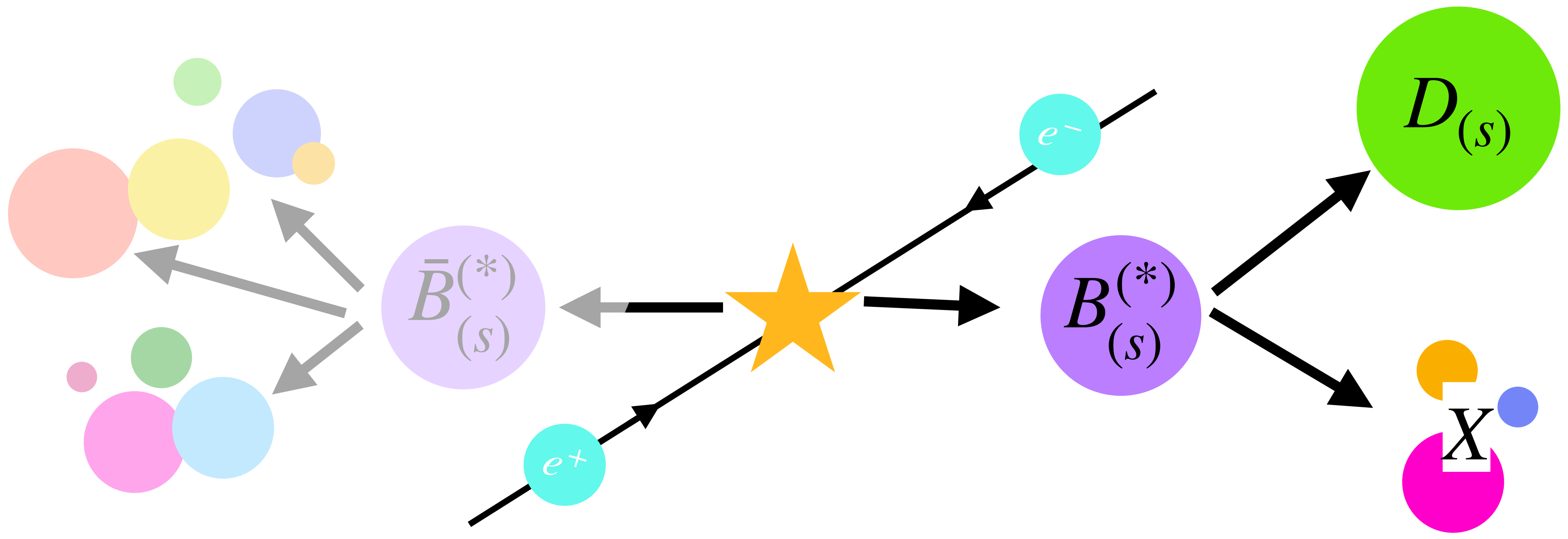
More experimental data and new measurements are welcome!

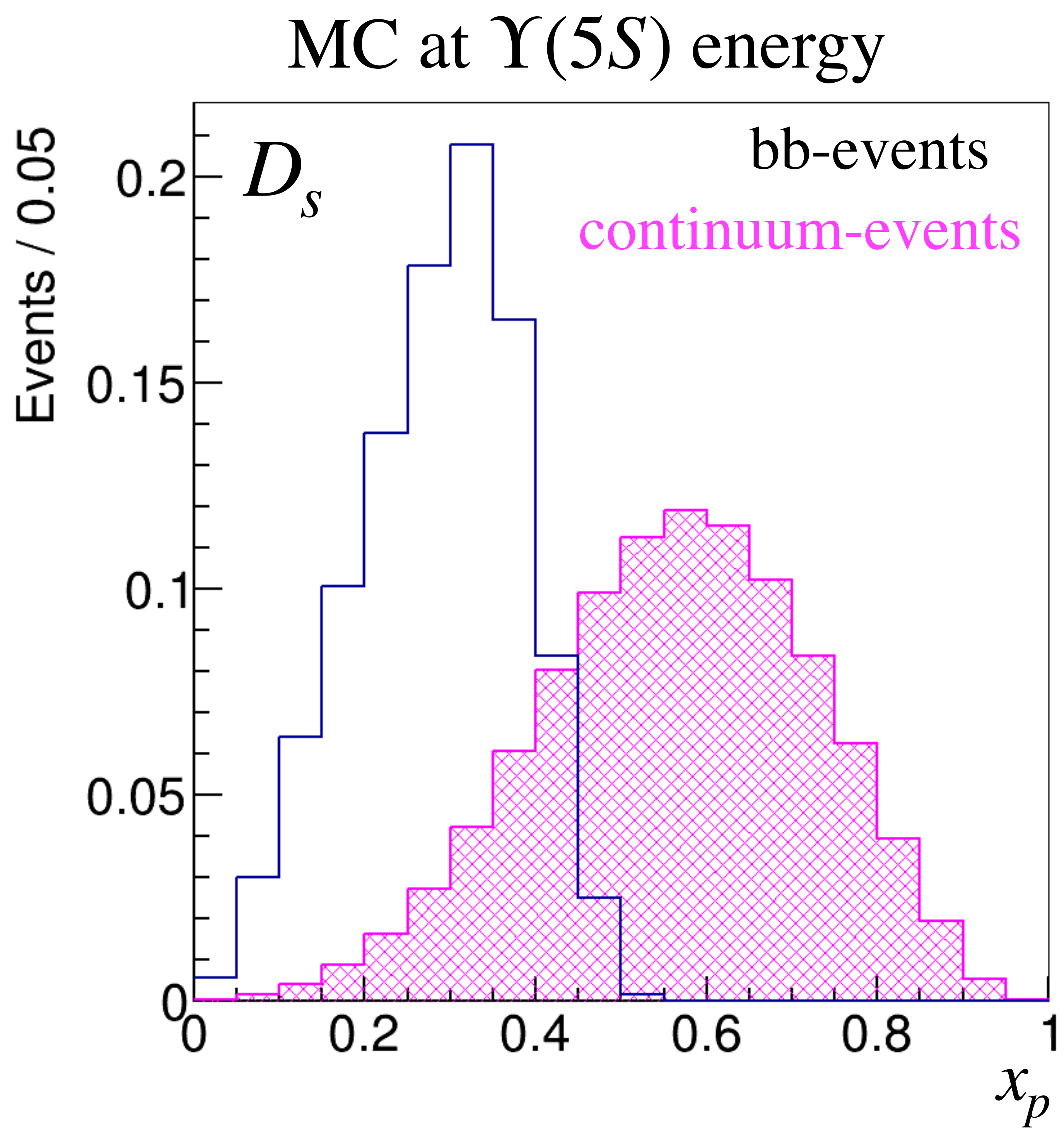
Goal:

Measuring $\sigma(e^+e^- \to B_s\bar{B}_sX)$ and $\sigma(e^+e^- \to B\bar{B}X)$ with high accuracy

Idea

Reconstruct inclusive D_s and D^0 at each energy scan point,





$x_p = \dfrac{p}{p_{max}}$ is used to separate continuum and $b\bar{b}$- events;

$\sigma(D_s X)$ and $\sigma(D^0 X)$

Measured cross sections can be expressed as:

$$\sigma(D_sX)/2 = \underbrace{\mathscr{B}(B_s \to D_sX)}_{(60.2 \pm 6.2)\,\%} \cdot \sigma(B_s\bar{B}_sX) + \underbrace{\mathscr{B}(B \to D_sX)}_{(8.7 \pm 1.2)\,\%} \cdot \sigma(B\bar{B}X)$$

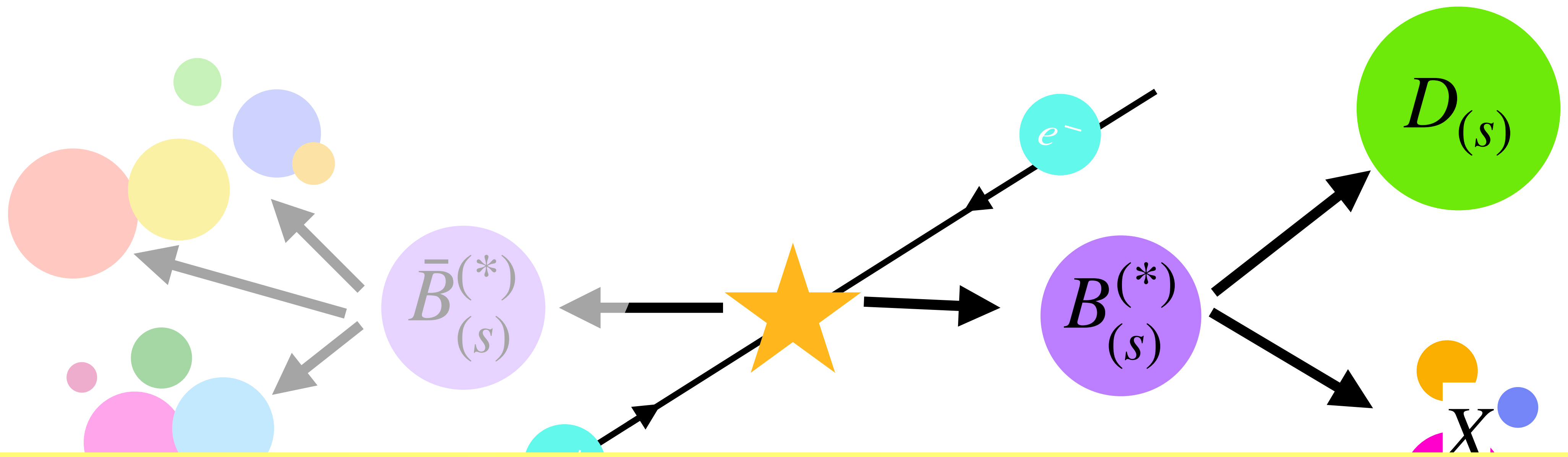
$$\sigma(D^0X)/2 = \underbrace{\mathscr{B}(B_s \to D^0X)}_{\text{model: } (8 \pm 7)\,\%} \cdot \sigma(B_s\bar{B}_sX) + \underbrace{\mathscr{B}(B \to D^0X)}_{(64.0 \pm 3.0)\,\%} \cdot \sigma(B\bar{B}X)$$

Explicite formulas for:

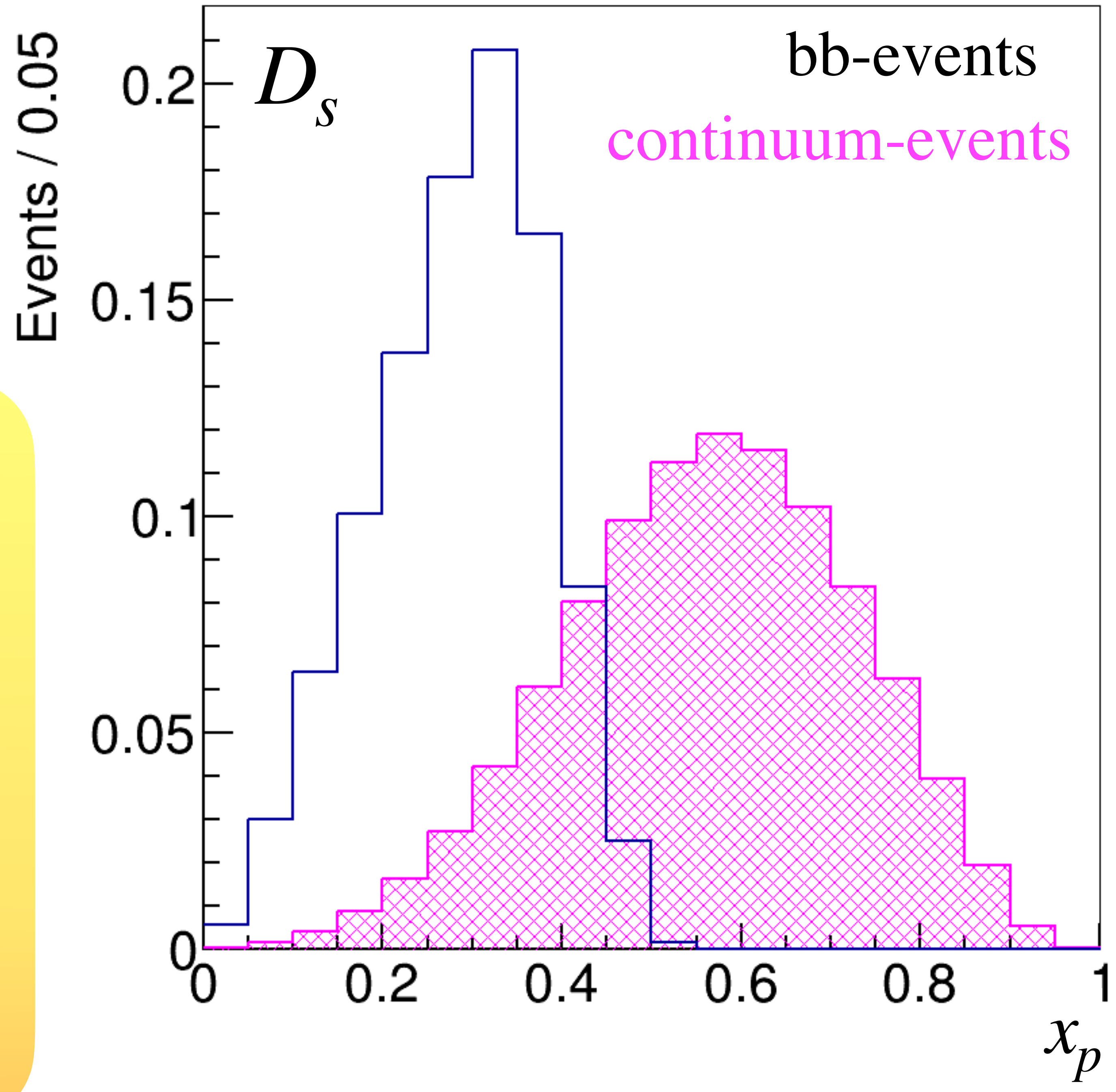
$\sigma\,(B_s\bar{B}_sX)$ and $\sigma\,(B\bar{B}X)$

Idea

Reconstruct inclusive D_s and D^0 at each energy scan point,



MC at $\Upsilon(5S)$ energy



but $\mathscr{B}(B_s \to D_s X)$ has large uncertainty

$\mathscr{B}(B_s \to D^0 X)$ is not measured, only prediction

(60.2 ± 6.2) % (8.7 ± 1.2) %

$$\sigma(D_s X)/2 = \mathscr{B}(B_s \to D_s X) \cdot \sigma(B_s \bar{B}_s X) + \mathscr{B}(B \to D_s X) \cdot \sigma(B\bar{B}X)$$

$$\sigma(D^0 X)/2 = \mathscr{B}(B_s \to D^0 X) \cdot \sigma(B_s \bar{B}_s X) + \mathscr{B}(B \to D^0 X) \cdot \sigma(B\bar{B}X)$$

model: (8 ± 7) % (64.0 ± 3.0) %

Explicite formulas for:

$\sigma(B_s \bar{B}_s X)$ and $\sigma(B\bar{B}X)$

Idea

No B_s at energy point near $\Upsilon(4S)$:

Measure with high accuracy $\mathscr{B}(B \to D_s X)$, $\mathscr{B}(B \to D^0 X)$

At energy point near $\Upsilon(5S)$:

$$\sigma(D_s X)|_{\Upsilon(5S)}/2 = \mathscr{B}(B_s \to D_s X) \cdot \sigma(B_s \bar{B}_s X)|_{\Upsilon(5S)} + \mathscr{B}(B \to D_s X) \cdot \sigma(B\bar{B}X)|_{\Upsilon(5S)}$$

$$\sigma(D^0 X)|_{\Upsilon(5S)}/2 = \mathscr{B}(B_s \to D^0 X) \cdot \sigma(B_s \bar{B}_s X)|_{\Upsilon(5S)} + \mathscr{B}(B \to D^0 X) \cdot \sigma(B\bar{B}X)|_{\Upsilon(5S)}$$

$$C = \frac{\mathscr{B}(B_s \to D^0 X)}{\mathscr{B}(B_s \to D_s X)} = \frac{\sigma(D^0 X)|_{\Upsilon(5S)} - \mathscr{B}(B \to D^0 X) \cdot \sigma(B\bar{B}X)|_{\Upsilon(5S)}}{\sigma(D_s^{\pm} X)|_{\Upsilon(5S)} - \mathscr{B}(B \to D_s X) \cdot \sigma(B\bar{B}X)|_{\Upsilon(5S)}}$$

We can measure using $\Upsilon(5S)$ data

We can measure using $\Upsilon(4S)$ data

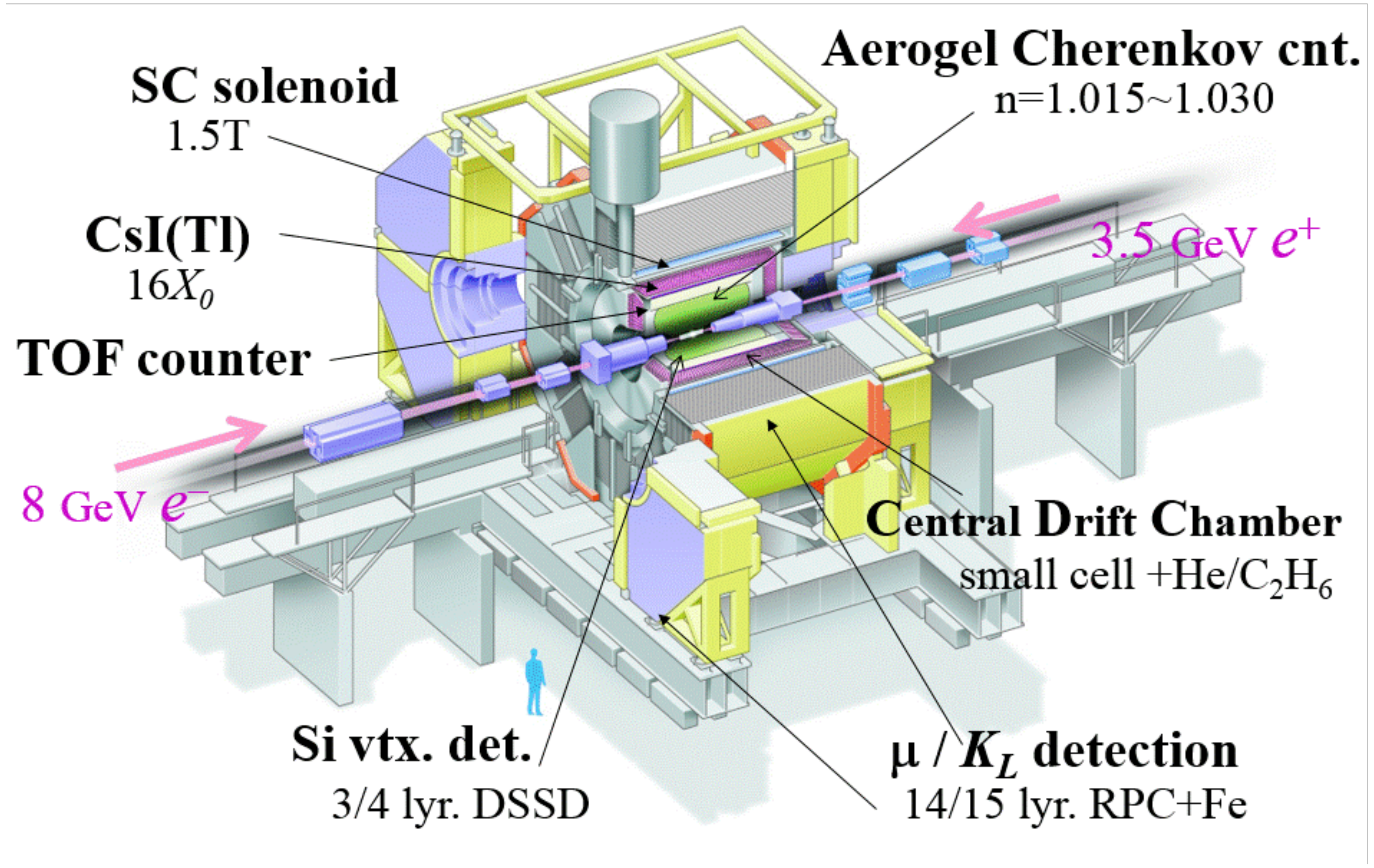
from JHEP 06 (2021) 137

At scan points:

$$\begin{cases} \sigma(D_s X)/2 = \mathscr{B}(B_s \to D_s X) \cdot \sigma(B_s \bar{B}_s X) + \mathscr{B}(B \to D_s X) \cdot \sigma(B\bar{B}X) \\ \sigma(D^0 X)/2 = C \cdot \mathscr{B}(B_s \to D_s X) \cdot \sigma(B_s \bar{B}_s X) + \mathscr{B}(B \to D^0 X) \cdot \sigma(B\bar{B}X) \end{cases}$$

Solving eq's system: → energy dependence of the $\sigma(B_s \bar{B}_s X) \cdot \mathscr{B}(B_s \to D_s X)$ and $\sigma(B\bar{B}X)$

Data samples and selection criteria



Data used in this analysis:

data at $\Upsilon(4S)$ energy: $\mathscr{L}_{4S} = 571\ \text{fb}^{-1}$

data at $\Upsilon(5S)$ energy: $\mathscr{L}_{5S} = 121\ \text{fb}^{-1}$

data at $E_{cm} = 10.52$ GeV: $\mathscr{L}_{cont} = 74\ \text{fb}^{-1}$
(continuum data sample)

22 energy scan points: $\mathscr{L}_i \approx 1\ \text{fb}^{-1}$
E_{cm} from 10.63 GeV to 11.02 GeV

Charged tracks:

$$|dr| < 0.5 \text{ cm and } |dz| < 2.0 \text{ cm}$$
$$\mathscr{L}_{K/\pi} = \mathscr{L}_K/(\mathscr{L}_K + \mathscr{L}_\pi) > 0.6$$
$$\mathscr{L}_{\pi/K} = \mathscr{L}_\pi/(\mathscr{L}_K + \mathscr{L}_\pi) > 0.1$$

$D_s^+ \to \phi\pi^+,\ \phi \to K^+K^-$

$$|M_{inv}(K^-K^+) - m_\phi| < 19 \text{ MeV/c}^2$$
$$|\cos\theta_{hel}| > 0.25$$
$$1.9 < \text{M}(\text{D}_\text{s}) < 2.02 \text{ GeV/c}^2$$

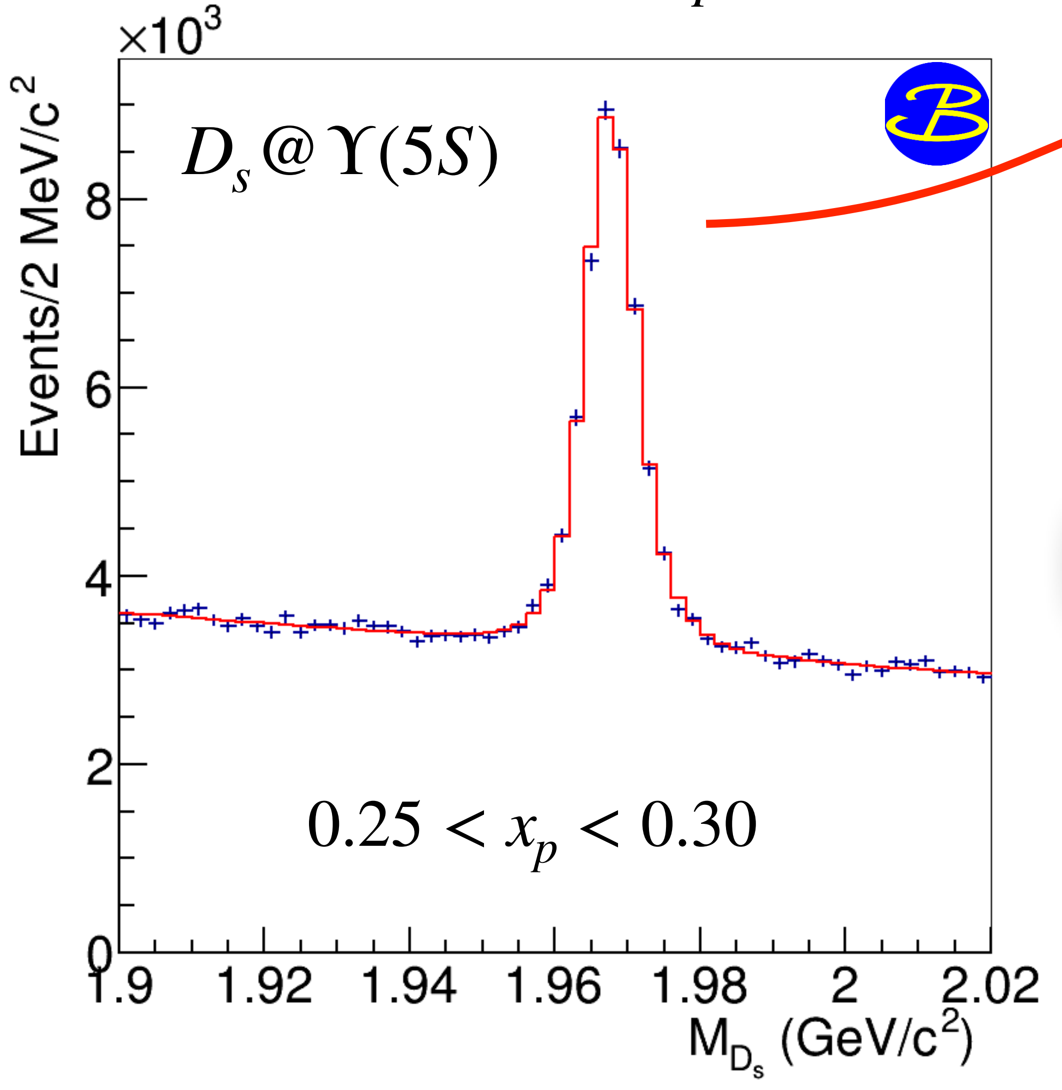
θ_{hel} — the angle between K^+ and D_s^+ in ϕ rest frame

$D^0 \to K^-\pi^+$

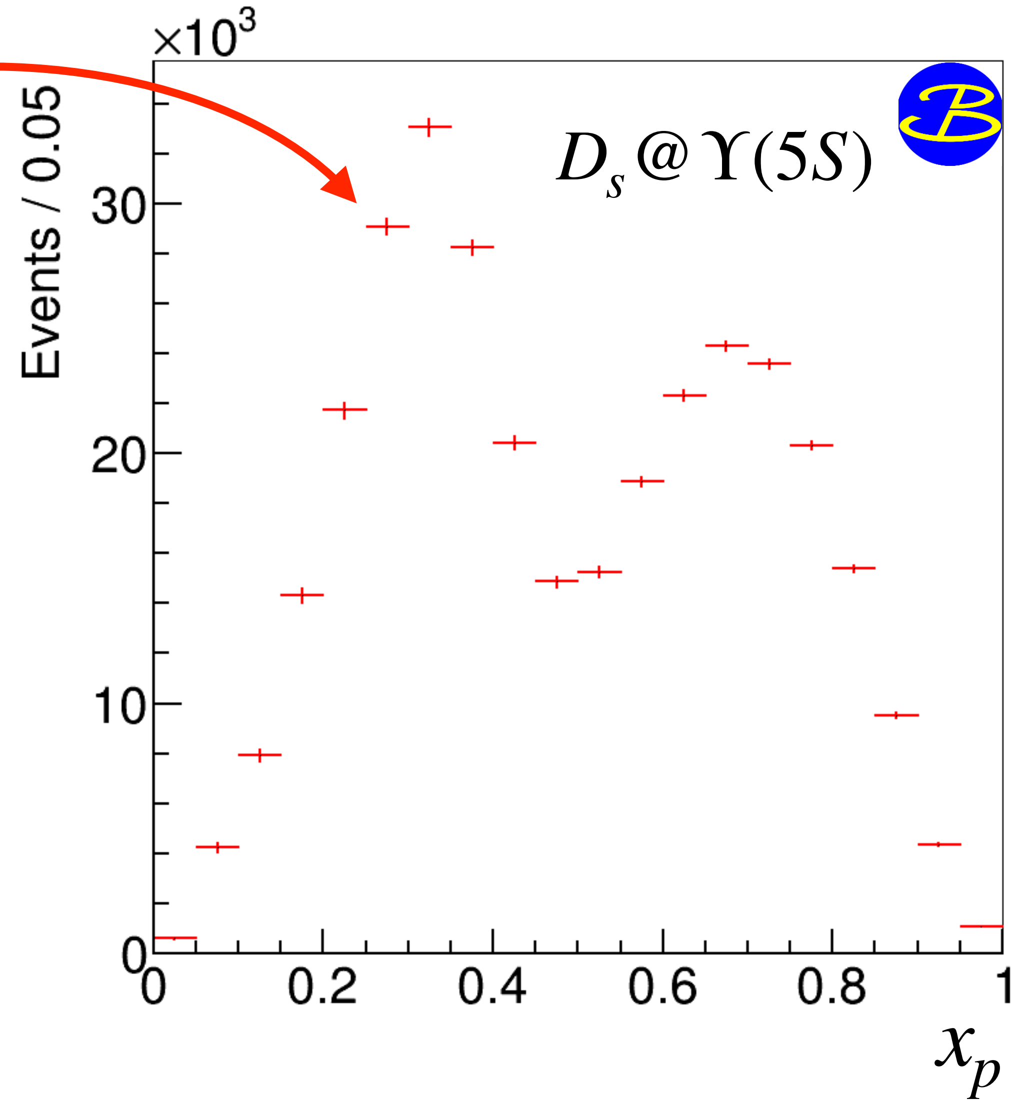
$$1.8 < \text{M}(\text{D}^0) < 1.932 \text{ GeV/c}^2$$

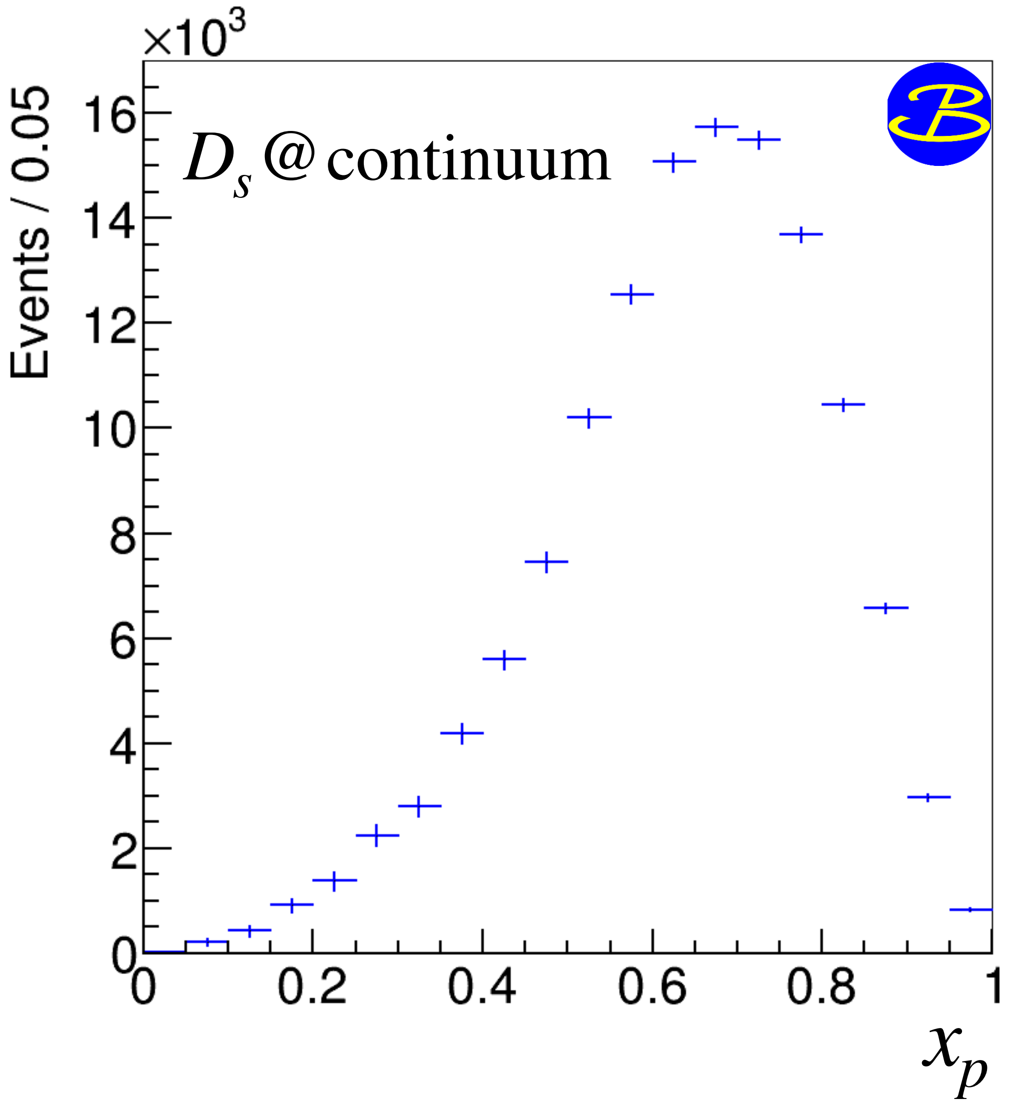
Method

Fit $M(Ds)$ in x_p bins

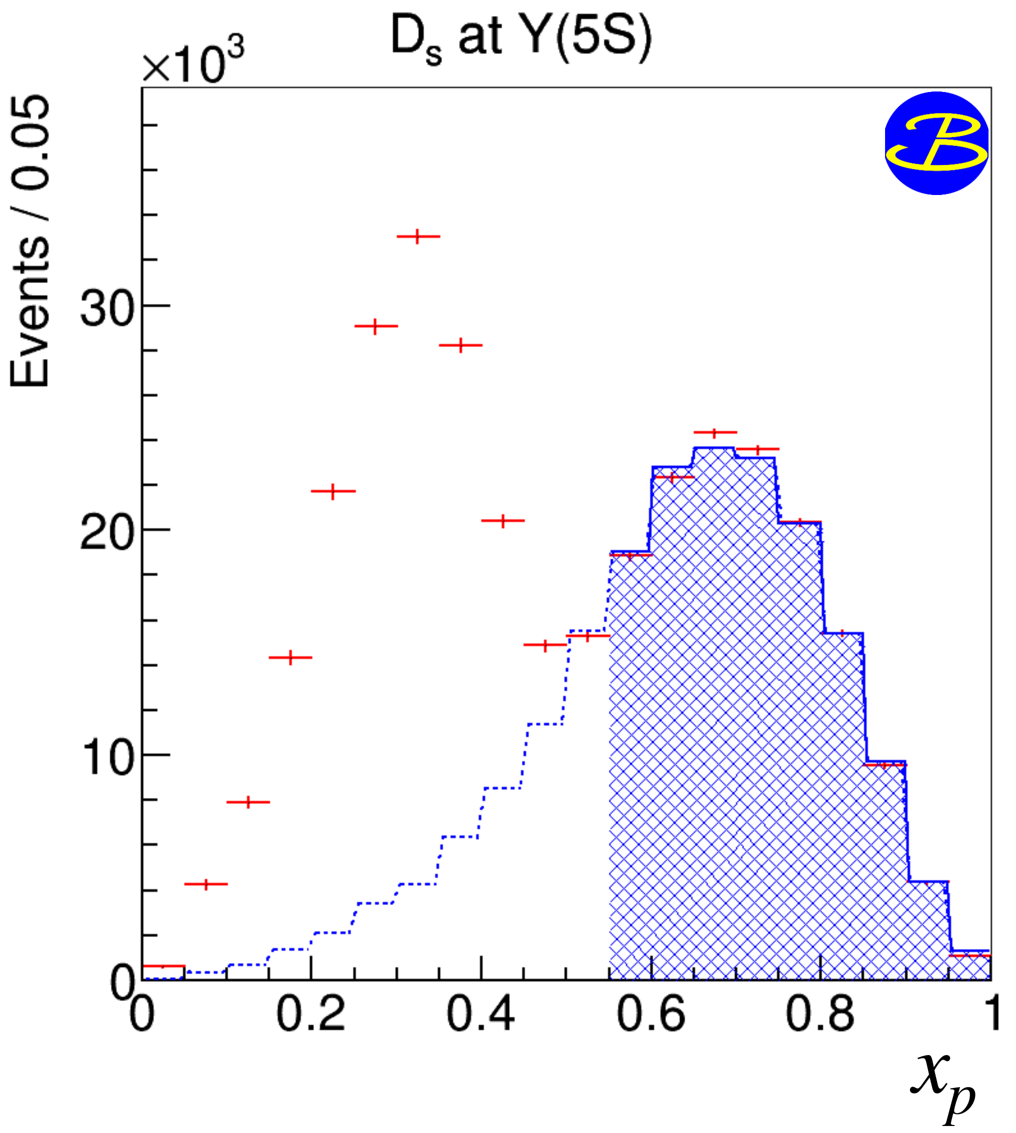


Obtain the x_p spectra

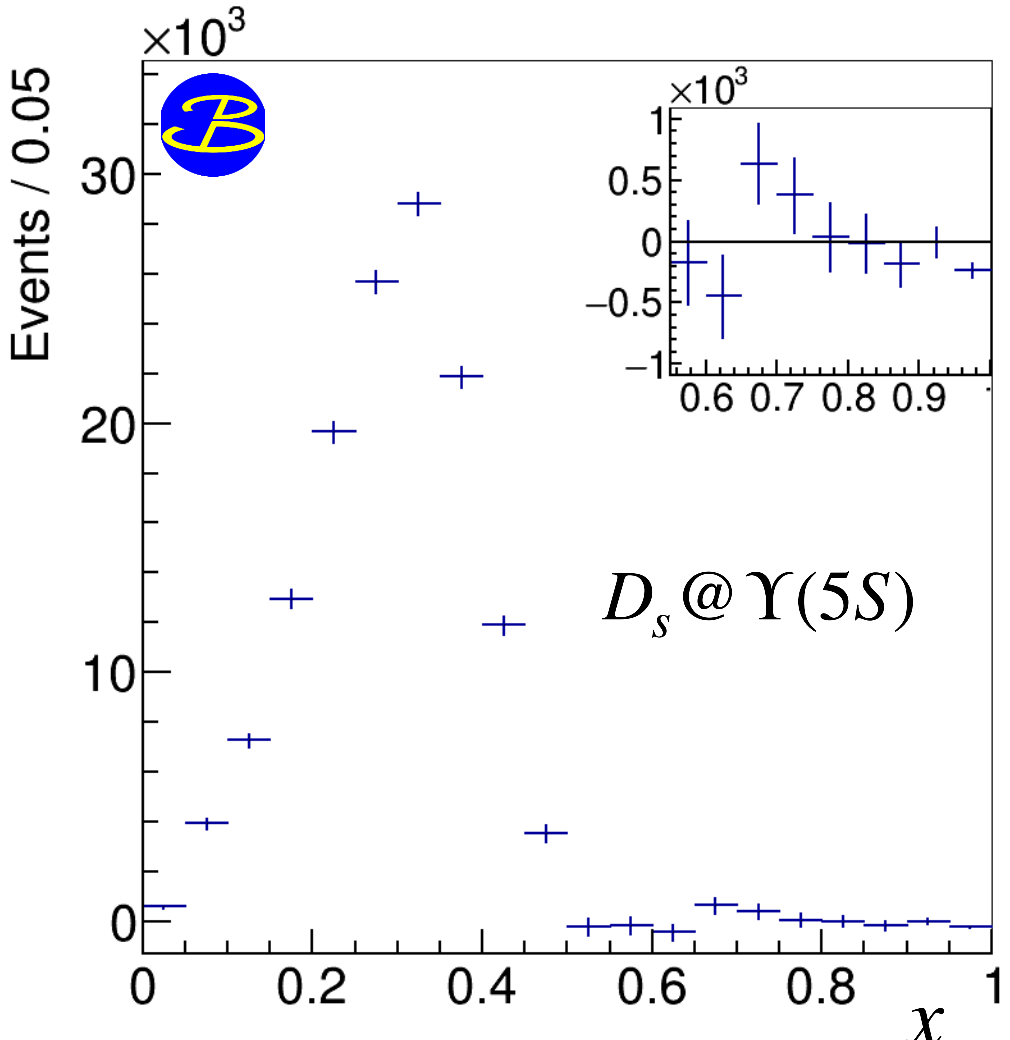




Fit in high x_p to continuum x_p



After continuum subtraction



D cross sections

D cross sections at $\Upsilon(4S)$ and $\Upsilon(5S)$:

$\mathscr{B}(B \to D_s X)$

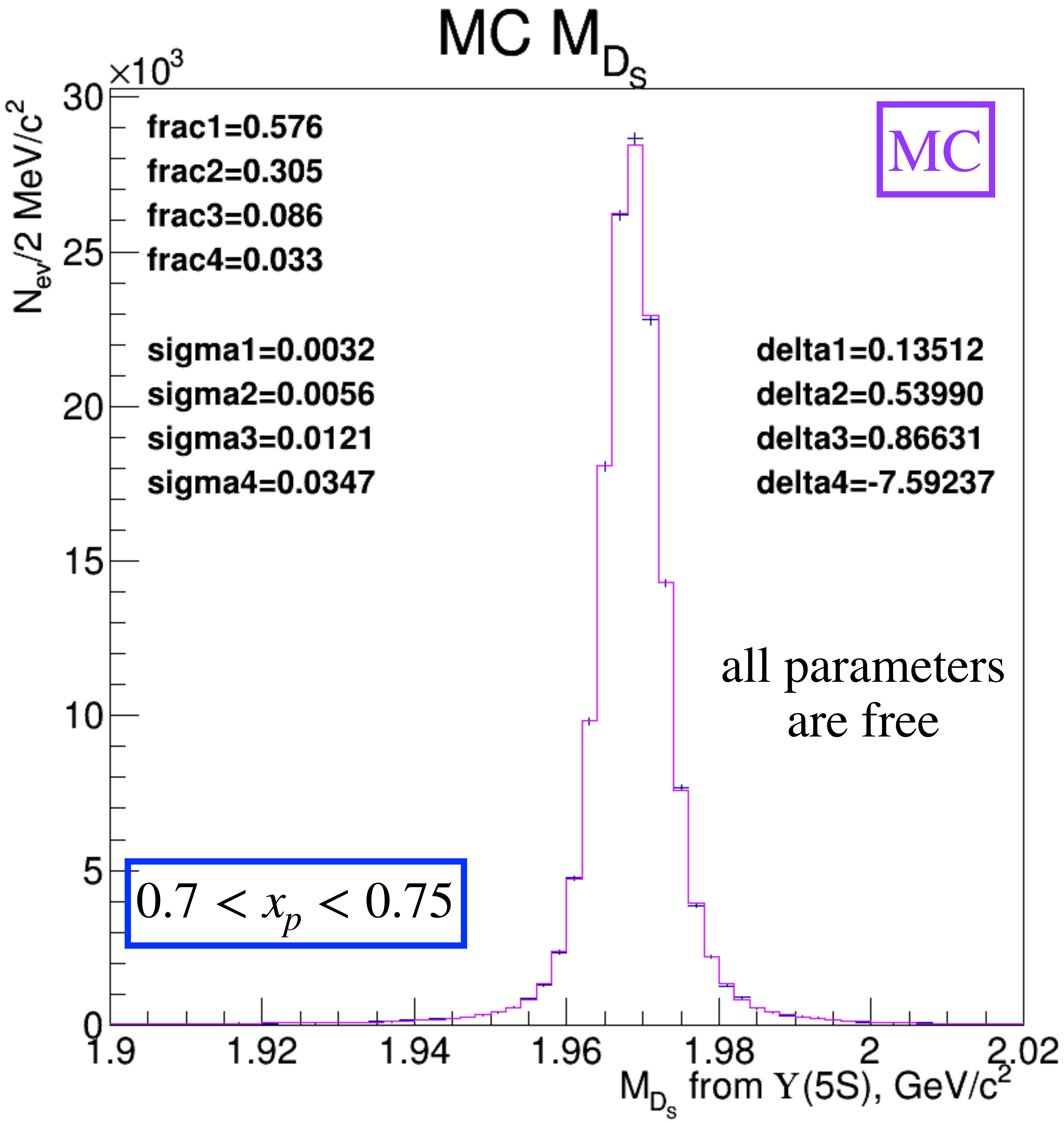
$\mathscr{B}(B \to D^0 X)$

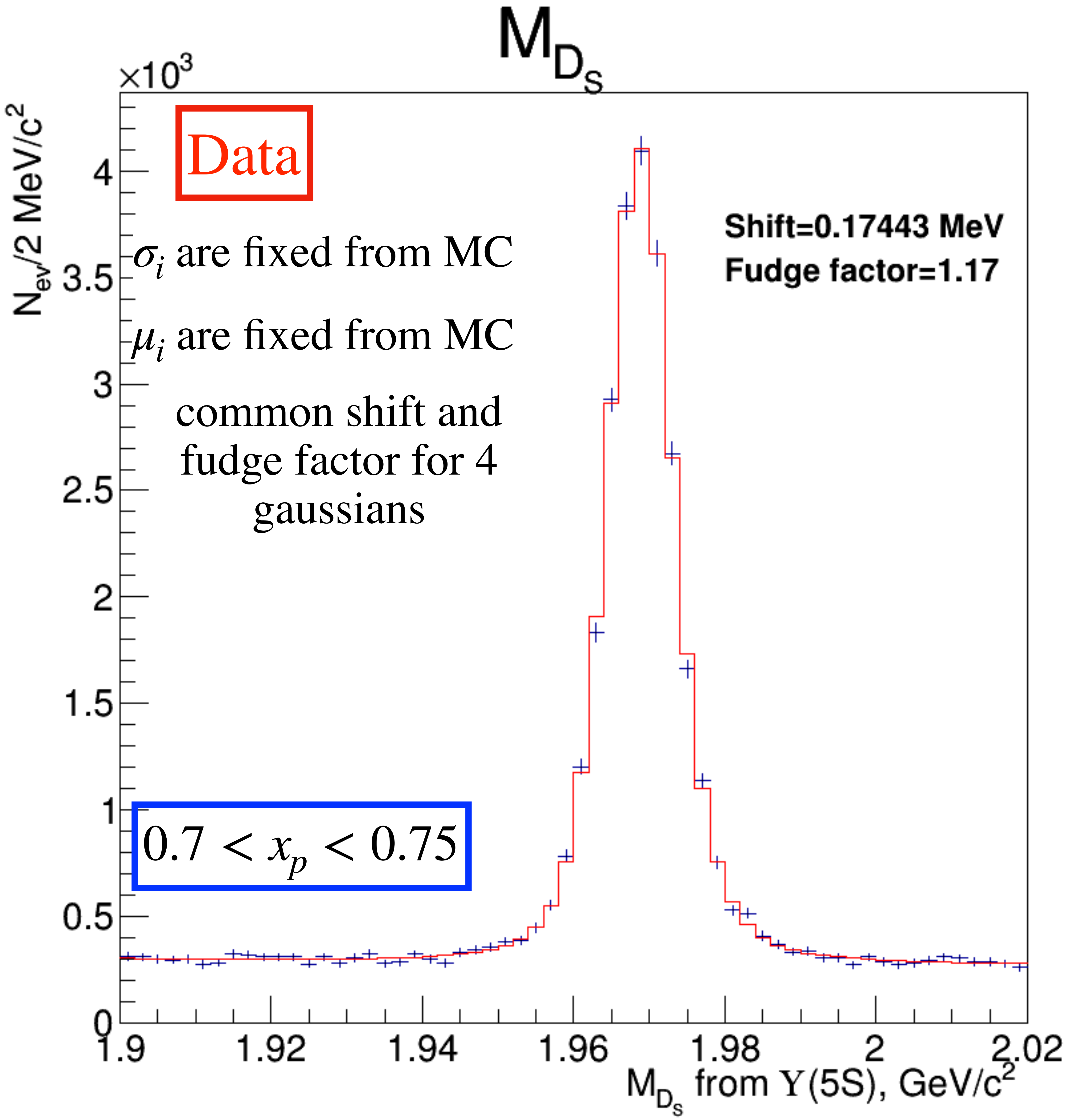
$$\frac{\mathscr{B}(B_s \to D^0 X)}{\mathscr{B}(B_s \to D_s X)}$$

At each scan point:

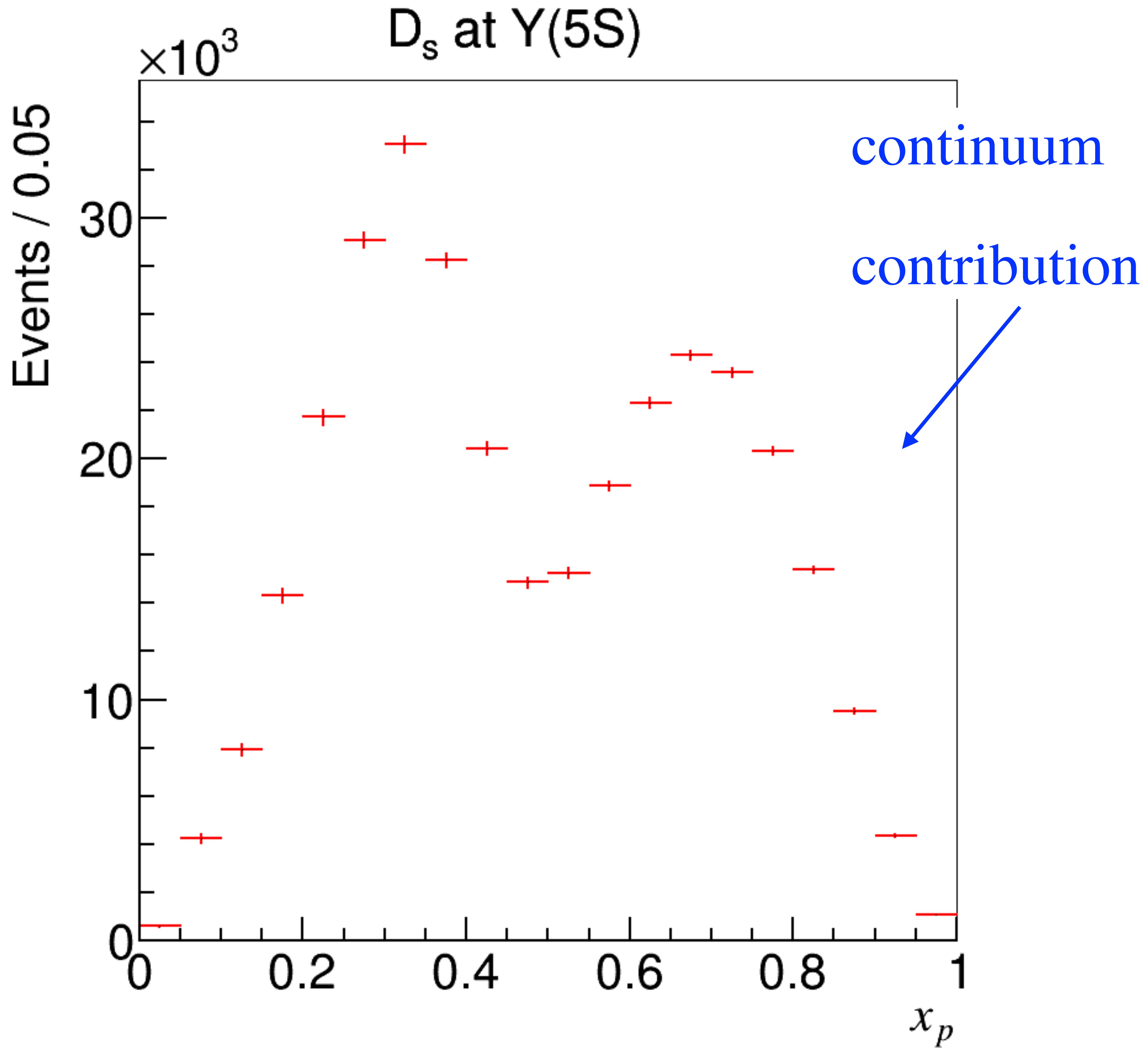
$B_s \bar{B}_s X$ and $B\bar{B}X$ cross sections

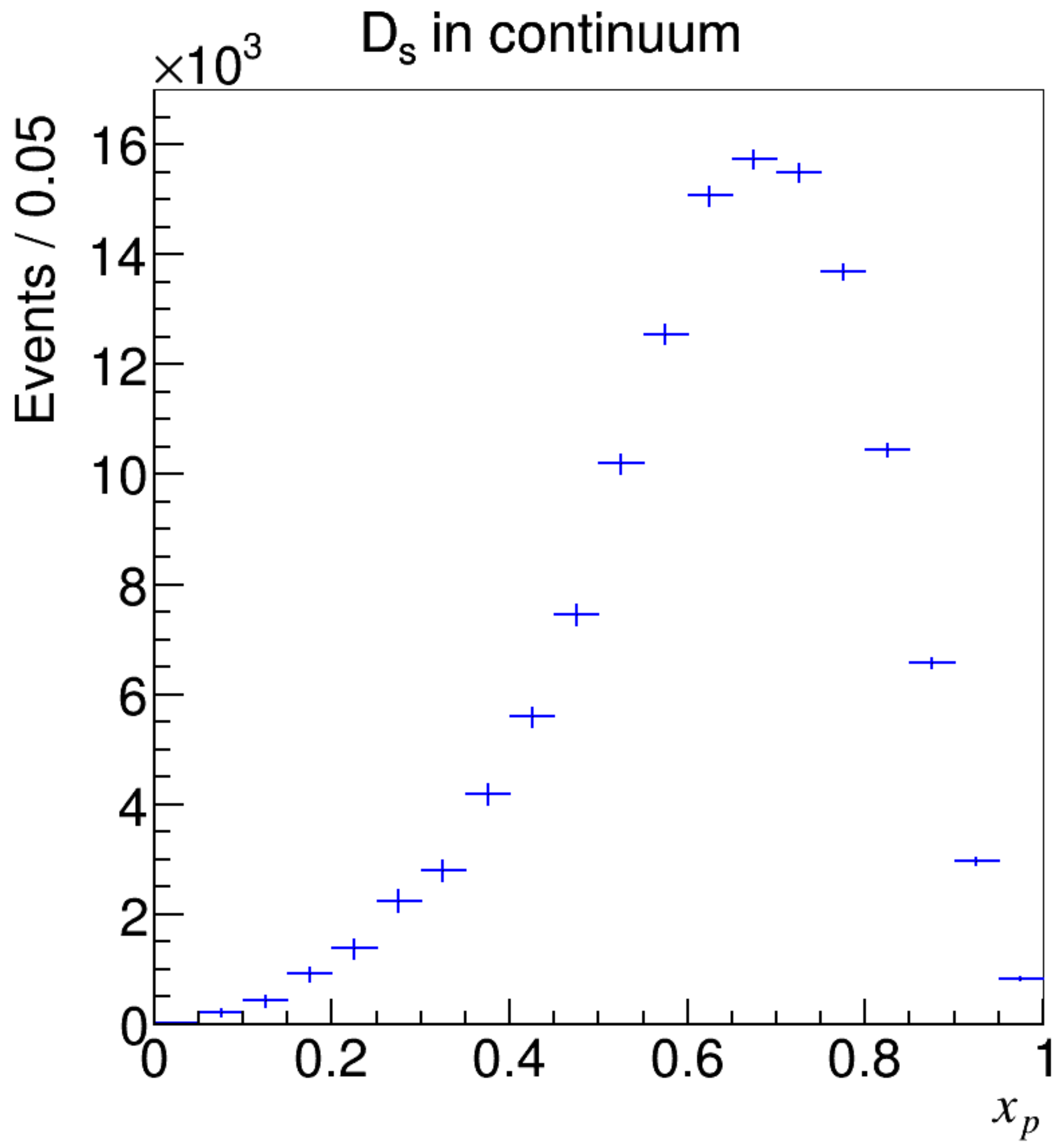
Fit the D_s mass distributions in the different x_p bins at $\Upsilon(5S)$



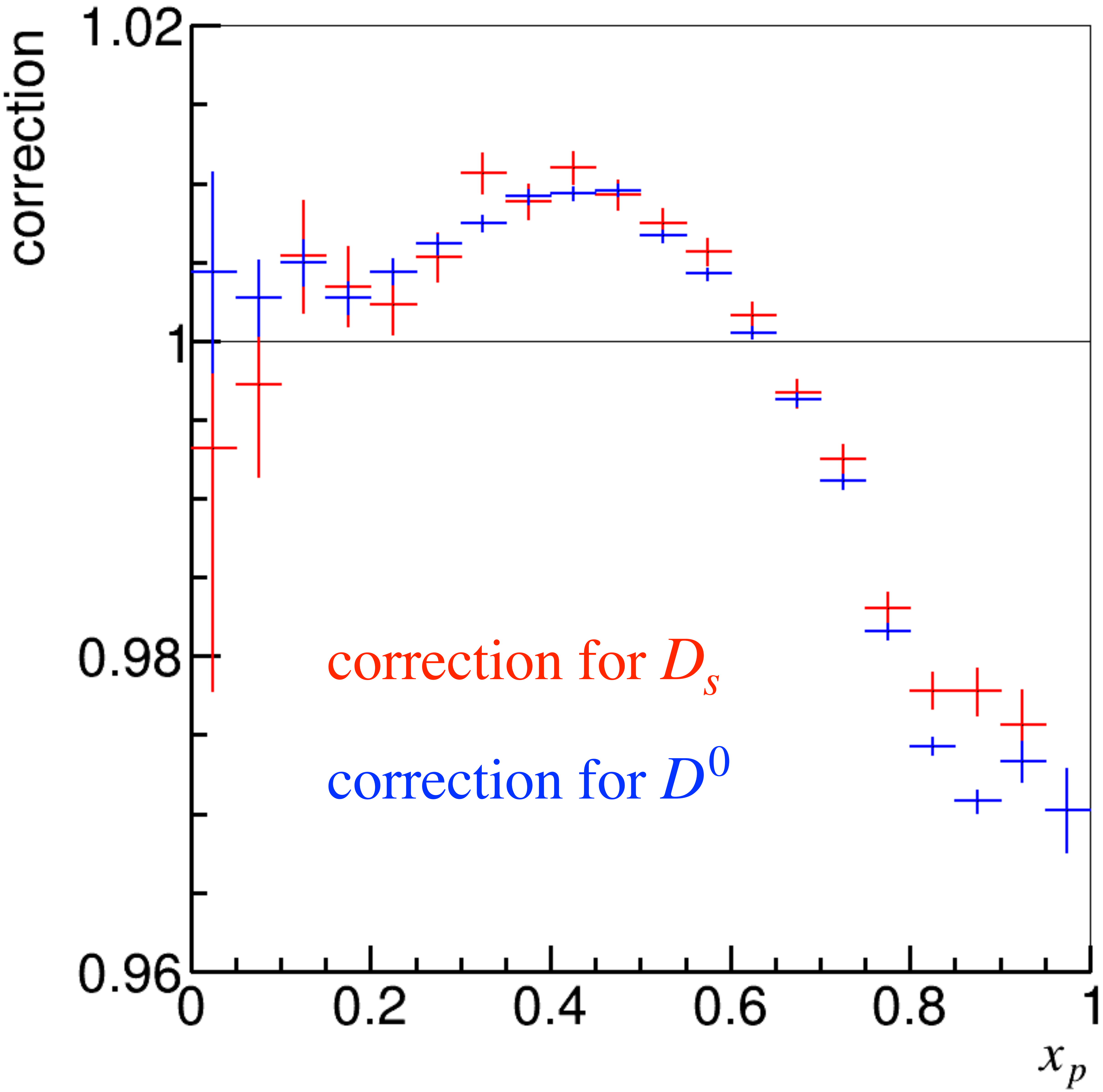


x_p spectra of D_s at $\Upsilon(5S)$ and below $\Upsilon(4S)$





Continuum spectrum correction



Due to the evolution of fragmentation with energy the shape of the continuum spectrum changes noticeably between E_{cm} = 10.52 GeV and the $\Upsilon(5S)$ energy

The continuum x_p spectra should be corrected

Belle II generators:
KKMC — initial state radiation,
Pythia 8.2 — c-quark fragmentation

x_p spectra at $\Upsilon(5S)$ and $\Upsilon(4S)$ data

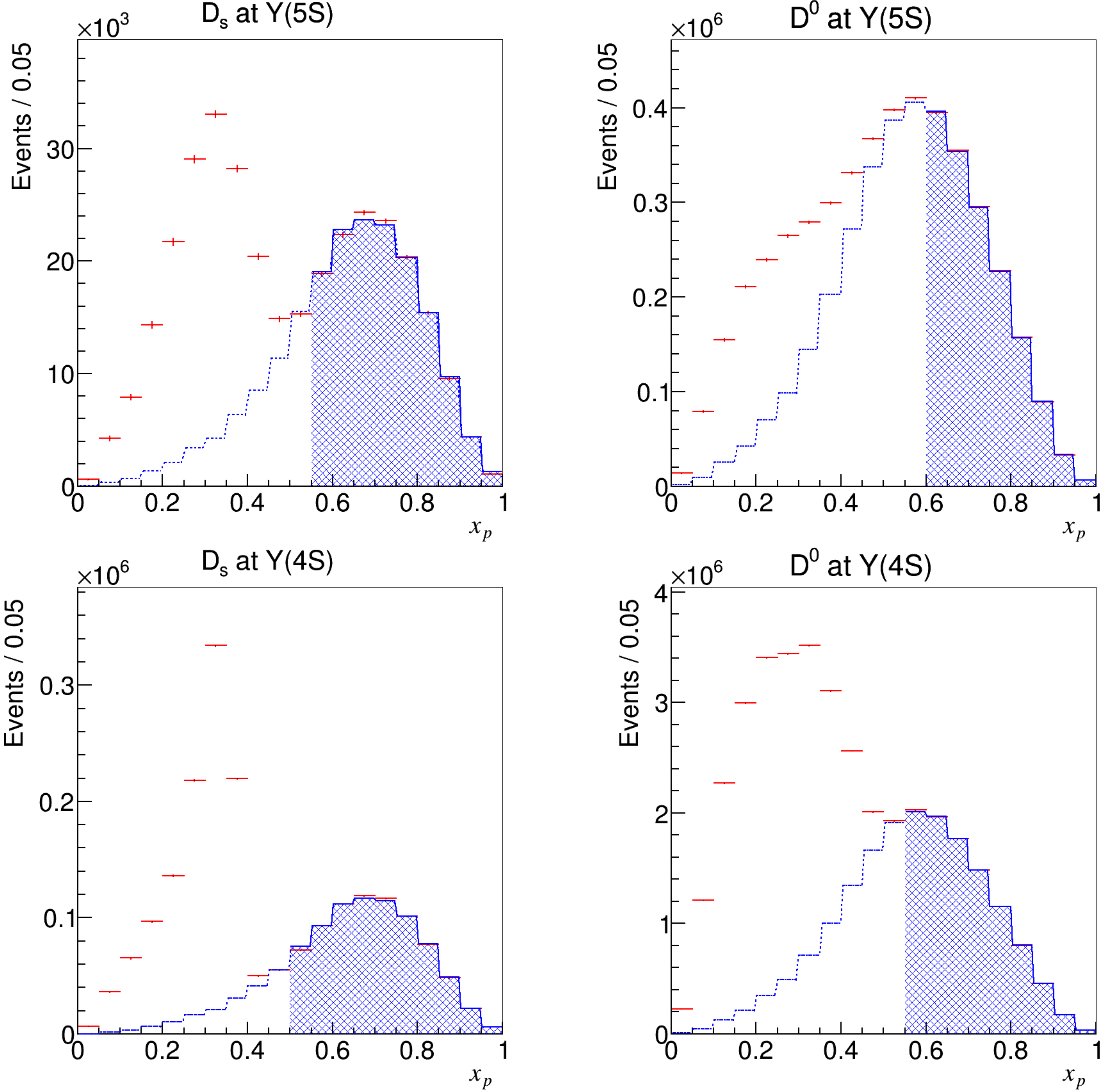
Red points — on-resonance data

We fit the large x_p part of the on-resonance spectra to find the continuum contribution in the $b\bar{b}$ region

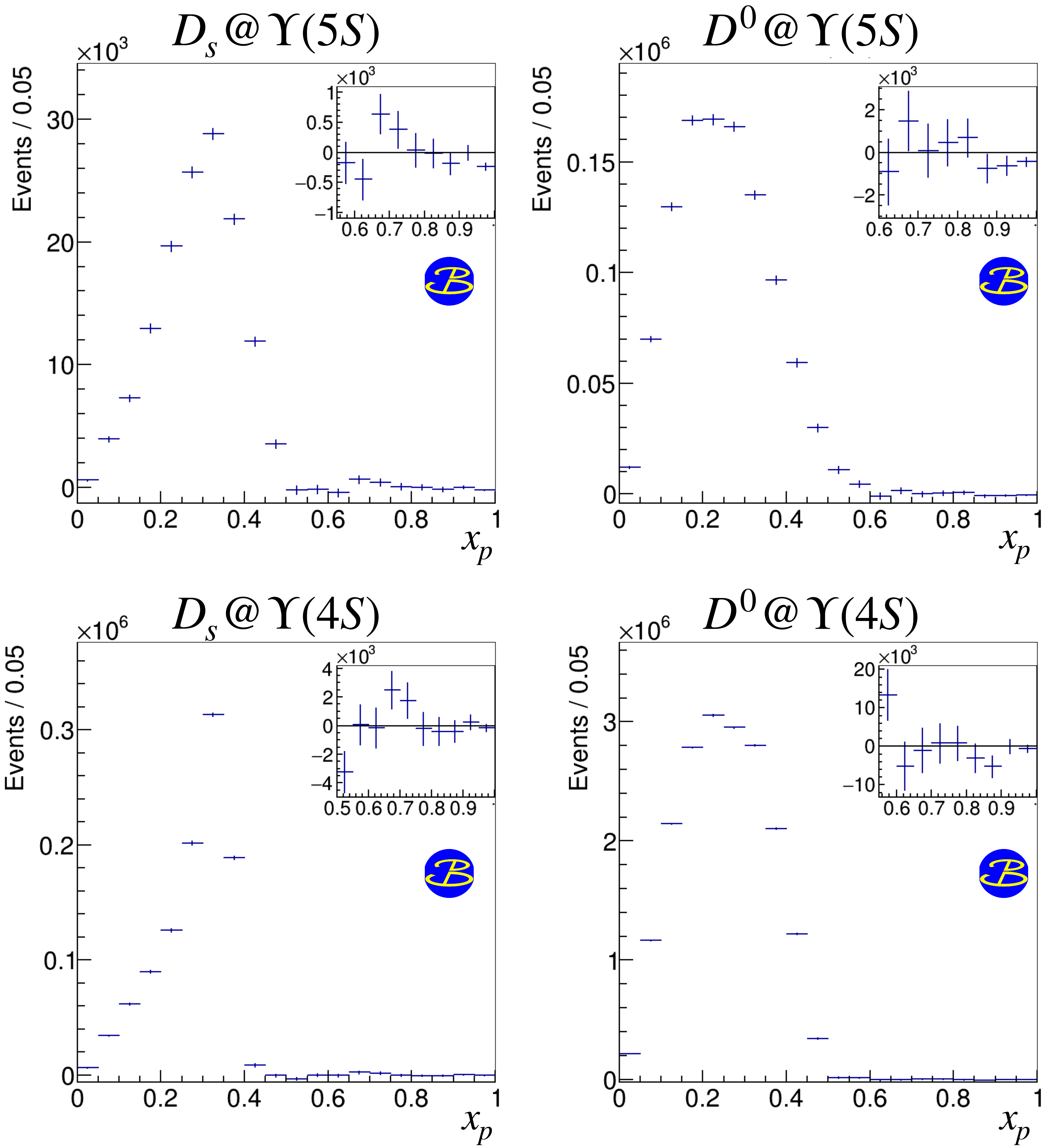
Fitting function — shape of the x_p spectra for the data below the $\Upsilon(4S)$

Blue hatched histograms — fit results
Open dashed histograms — extrapolation of the continuum component

We subtract the continuum component to obtain pure $b\bar{b}$ spectra



Continuum subtraction



Points in the high x_p region are consistent with zero, it means that continuum spectra shapes are correct

Apply efficiency correction to calculate $e^+e^- \to b\bar{b} \to DX$ cross sections

$\sigma(e^+e^- \to DX)$ calculation

$$\sigma(e^+e^- \to b\bar{b} \to D_sX) = \sum_{i=1}^{i_{\max}} \frac{N_i(D_S) - k \cdot n_i(D_S)}{\mathscr{L} \cdot \mathscr{E}_i \cdot \mathscr{B}(D_S \to K^+K^-\pi) \cdot r_{\phi-cut}}$$

$$\sigma(e^+e^- \to b\bar{b} \to D^0X) = \sum_{i=1}^{i_{\max}} \frac{N_i(D^0) - k \cdot n_i(D^0)}{\mathscr{L} \cdot \mathscr{E}_i \cdot \mathscr{B}(D^0 \to K^-\pi^+)}$$

N_i — number of D events from fit in i-bin of the x_p spectrum for on-resonance data

n_i — number of D events from fit in i-bin of the x_p spectrum for continuum

k — scale factor for continuum spectrum normalisation

$r_{\phi-cut} = 0.981 \pm 0.006$

$\sigma(e^+e^- \to b\bar{b} \to D_sX)|_{\Upsilon(5S)} = (151.8 \pm 1.0 \pm 5.5)$ pb

$\sigma(e^+e^- \to b\bar{b} \to D^0X)|_{\Upsilon(5S)} = (379.7 \pm 1.6 \pm 10.0)$ pb

$\sigma(e^+e^- \to b\bar{b} \to D_sX)|_{\Upsilon(4S)} = (248.6 \pm 0.6 \pm 9.2)$ pb

$\sigma(e^+e^- \to b\bar{b} \to D^0X)|_{\Upsilon(4S)} = (1468.5 \pm 0.9 \pm 36.6)$ pb

Results at $\Upsilon(4S)$ and $\Upsilon(5S)$

	This measurement	PDG full recon	PDG same method
$\mathscr{B}(B \to D_s X) = \dfrac{\sigma(D_s X)\|_{\Upsilon(4S)}}{2 \cdot \sigma(e^+e^- \to b\bar{b})\|_{\Upsilon(4S)}}$	$(11.28 \pm 0.03 \pm 0.43)\,\%$	$(10.4^{+1.3}_{-1.8})\,\%$	$(8.3 \pm 0.8)\,\%$
$\mathscr{B}(B \to D^0 X) = \dfrac{\sigma(D^0 X)\|_{\Upsilon(4S)}}{2 \cdot \sigma(e^+e^- \to b\bar{b})\|_{\Upsilon(4S)}}$	$(66.63 \pm 0.04 \pm 1.77)\,\%$	$(71.6 \pm 4.6)\,\%$	$(61.6 \pm 2.9)\,\%$

$\Upsilon(4S)$ data:

$\Upsilon(5S)$ data:

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(255.5 ± 7.9) pb

$$C = \frac{\mathscr{B}(B_s \to D^0 X)}{\mathscr{B}(B_s \to D_s X)} = \frac{\sigma(e^+e^- \to b\bar{b} \to D^0 X)|_{\Upsilon(5S)} - \mathscr{B}(B^0 \to D^0 X) \cdot \sigma(e^+e^- \to B\bar{B}X)|_{\Upsilon(5S)}}{\sigma(e^+e^- \to b\bar{b} \to D_s X)|_{\Upsilon(5S)} - \mathscr{B}(B^0 \to D_s X) \cdot \sigma(e^+e^- \to B\bar{B}X)|_{\Upsilon(5S)}}$$

$$C = 0.416 \pm 0.018 \pm 0.092$$

Results at $\Upsilon(4S)$ and $\Upsilon(5S)$

Fractions of $B_s\bar{B}_sX$ events produced at $\Upsilon(5S)$:

$$f_s = \frac{\sigma(e^+e^- \to B_s\bar{B}_sX)|_{\Upsilon(5S)}}{\sigma(e^+e^- \to b\bar{b}))|_{\Upsilon(5S)}} = (23.0 \pm 0.2 \pm 2.8)\ \%$$

This measurement	Belle 2013 PRD 87 (2013) 3, 031101	Belle 2022 PRD 105 (2022) 012004
$(23.0 \pm 0.2 \pm 2.8)\ \%$	$(17.2 \pm 3.0)\ \%$	$(28.5 \pm 3.2 \pm 3.7)\ \%$

Source	Systematic uncertainty (%)
$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)\|_{\Upsilon(5S)}$	1.4
$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)\|_{\Upsilon(4S)}$	0.7
$\sigma(e^+e^- \to B\bar{B}X)\|_{\Upsilon(5S)}$	1.4
$\mathcal{B}(B_s^0 \to D_s^\pm X)$	10.5
$\sigma(e^+e^- \to b\bar{b})\|_{\Upsilon(5S)}$	4.5
Correlated contributions	
– tracking	1.1
– K/π identification	2.3
– r_ϕ	0.6
– $\mathcal{B}(D_s^+ \to K^+K^-\pi^+)$	1.9
Total	12.0

Belle

PRD 105 (2022) 1, 012004

$\mathcal{B}(B_s \to D_sX) = (60.2 \pm 5.8 \pm 2.3)\ \%$

To improve accuracy we fit

$$f_s = (23.0 \pm 0.2 \pm 2.8)\ \%$$

$$f_{B\bar{B}X} = (75.1 \pm 4.0)\%$$

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$$f_{\not{B}}^{\text{known}} = (4.9 \pm 0.6)\%$$

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with one constraint

$$f_s + f_{B\bar{B}X} + f_{\not{B}} = 1$$

Result from the fit: $f_s = (22.0^{+2.0}_{-2.1})\ \%$

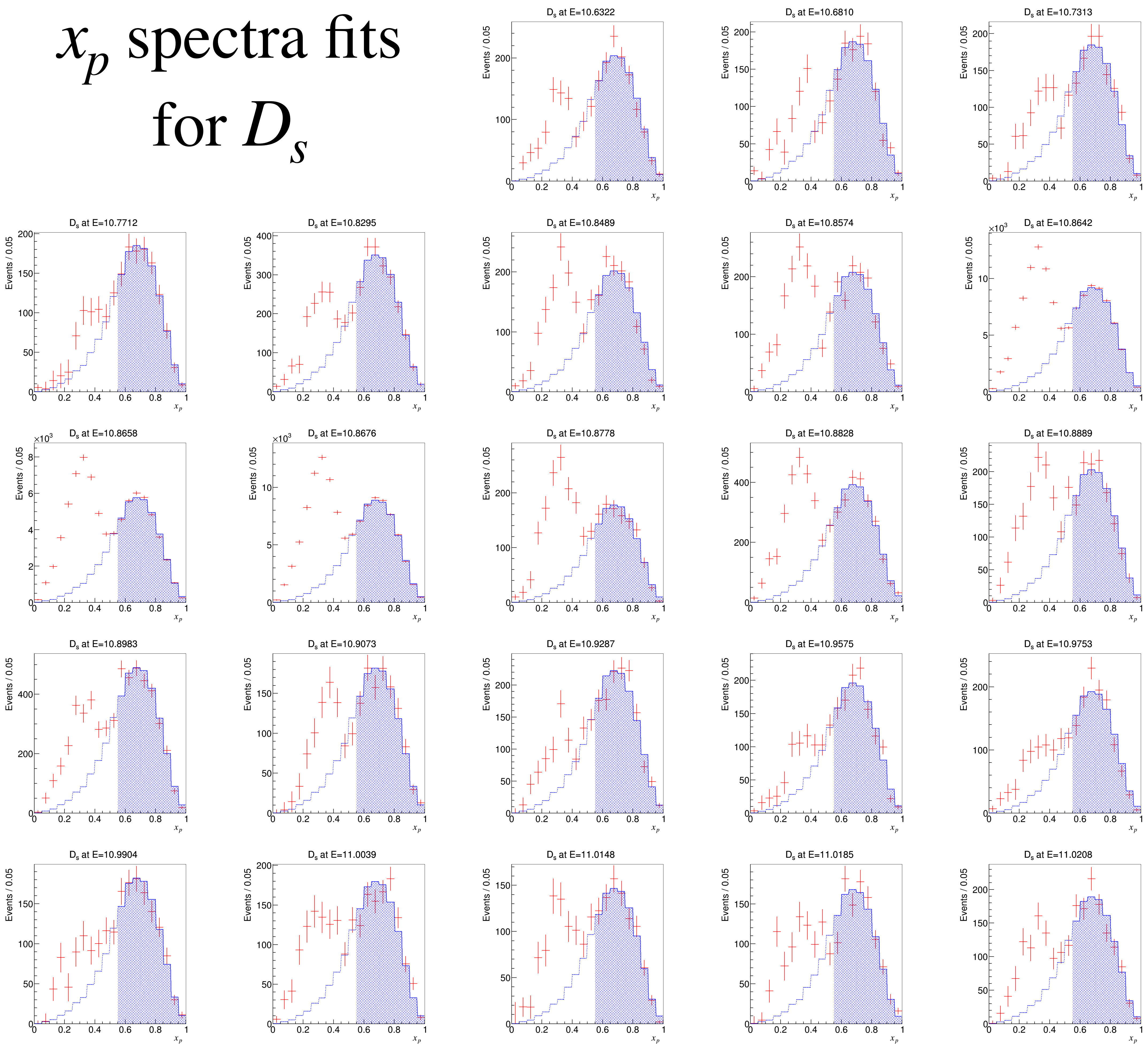
Energy scan points

23 energy points from 10.63 to 11.02 GeV — repeat the procedure at each of them

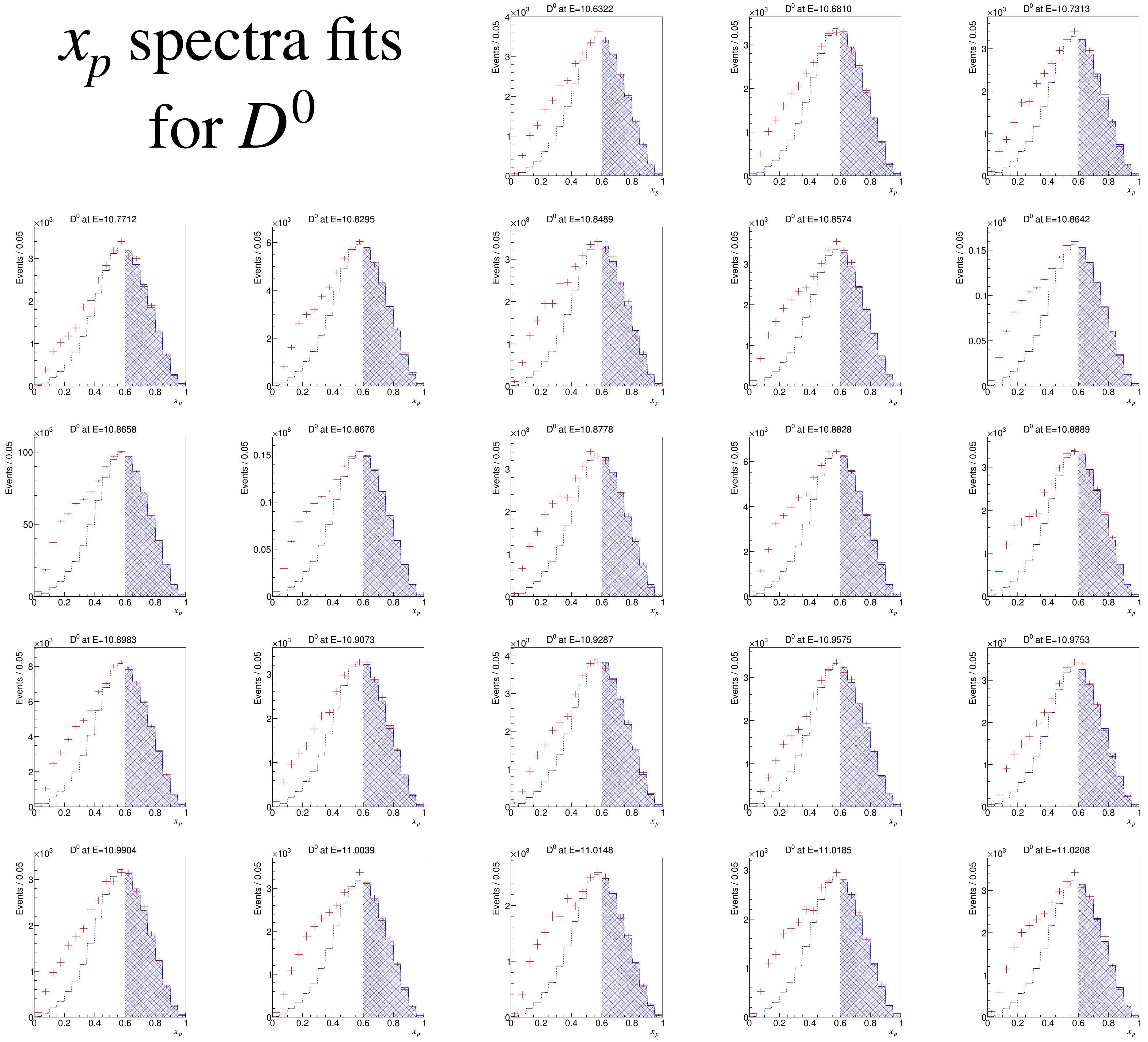
$b\bar{b}$

fit results

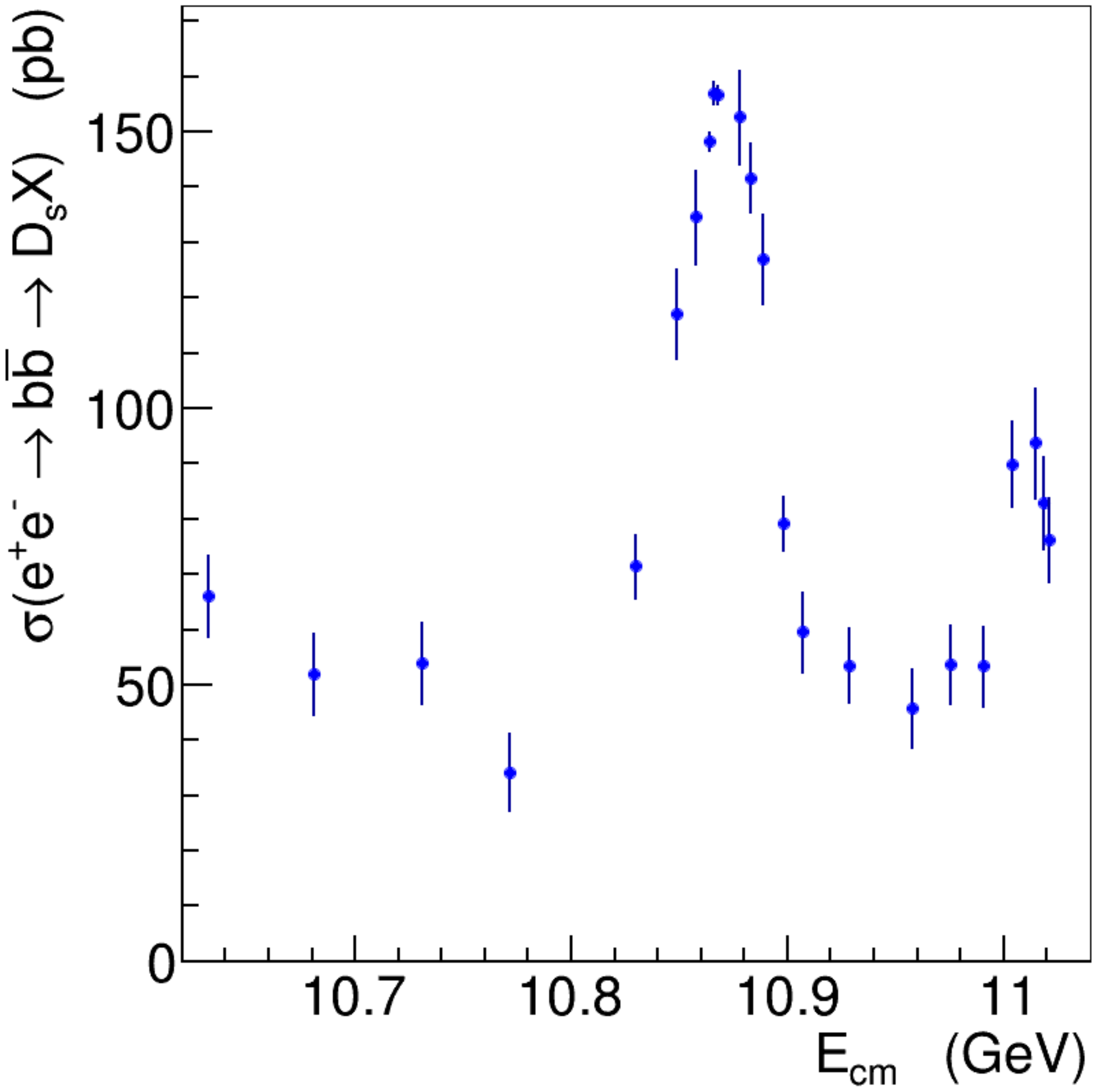
x_p spectra fits for D_s

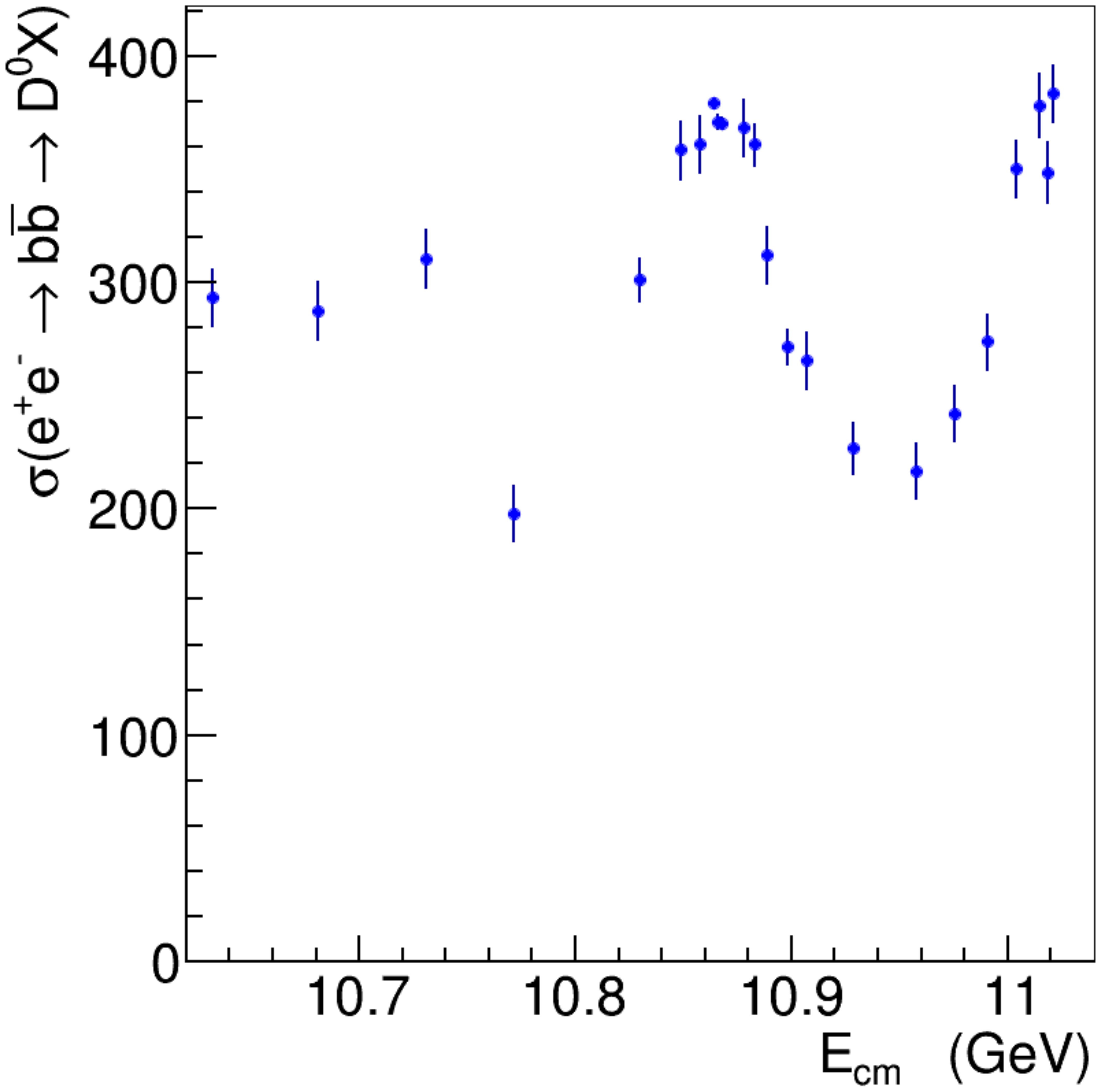


x_p spectra fits for D^0



$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)$ and $\sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0 X)$





From D to B

$$\sigma(e^+e^- \to b\bar{b} \to D_s^+X)/2 = \mathscr{B}(B_s^0 \to D_s^+X)\cdot\sigma(e^+e^- \to B_s\bar{B}_sX) + \mathscr{B}(B \to D_sX)\cdot\sigma(e^+e^- \to B\bar{B}X)$$

$$\sigma(e^+e^- \to b\bar{b} \to D^0X)/2 = C\cdot\mathscr{B}(B_s^0 \to D_s^+X)\cdot\sigma(e^+e^- \to B_s^0\bar{B}_s^0X) + \mathscr{B}(B \to D^0X)\cdot\sigma(e^+e^- \to B\bar{B}X)$$

This work:

$$\mathscr{B}(B \to D^{\pm}X) = (11.28 \pm 0.03 \pm 0.43)\,\%$$

$$\mathscr{B}(B \to D^0/\bar{D}^0X) = (66.63 \pm 0.04 \pm 1.77)\,\%$$

$$C = \frac{\mathscr{B}(B_s \to D^0X)}{\mathscr{B}(B_s \to D_sX)} = 0.416 \pm 0.018 \pm 0.092$$

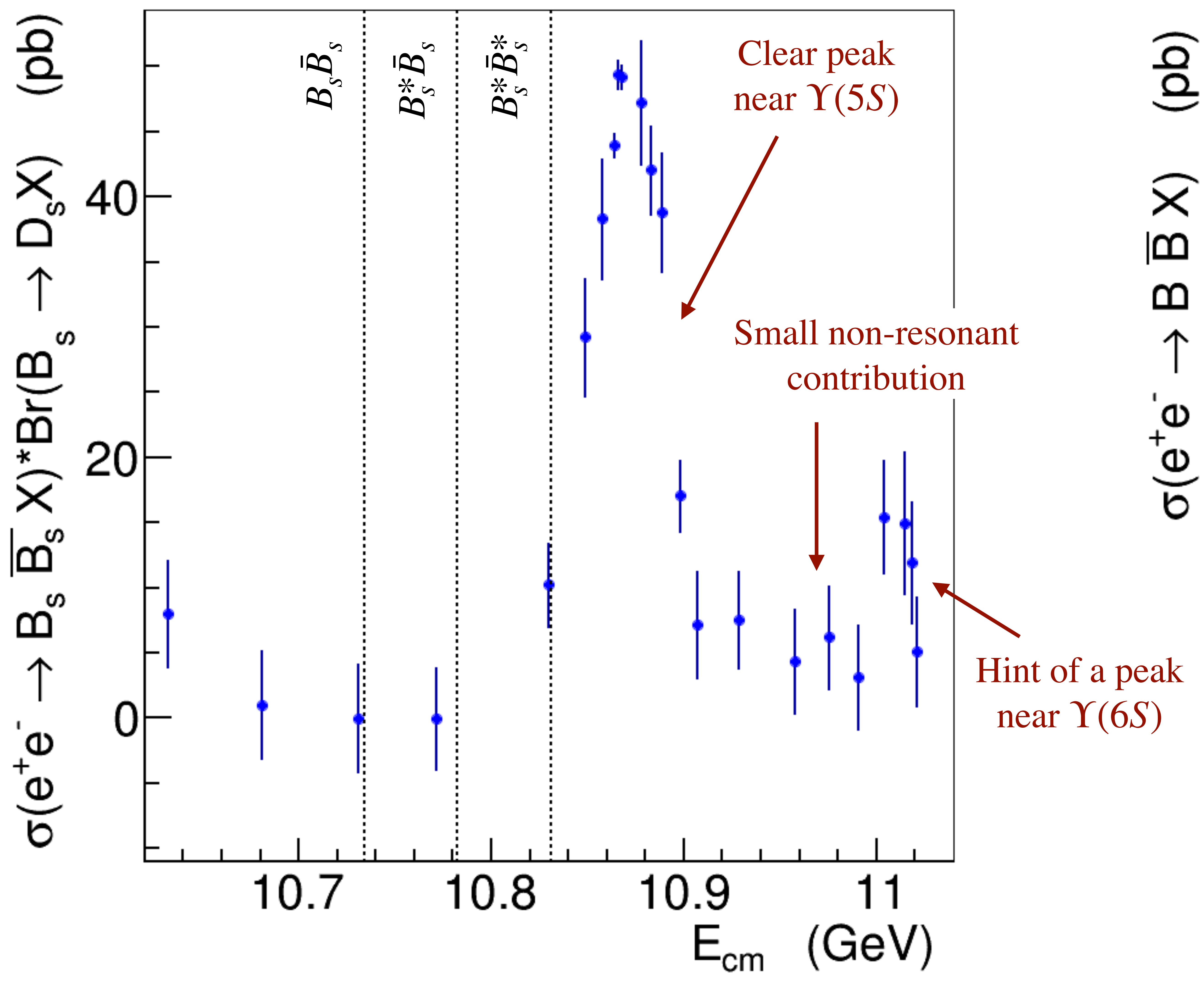
$\sigma(e^+e^- \to B_s\bar{B}_sX) = \sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})$

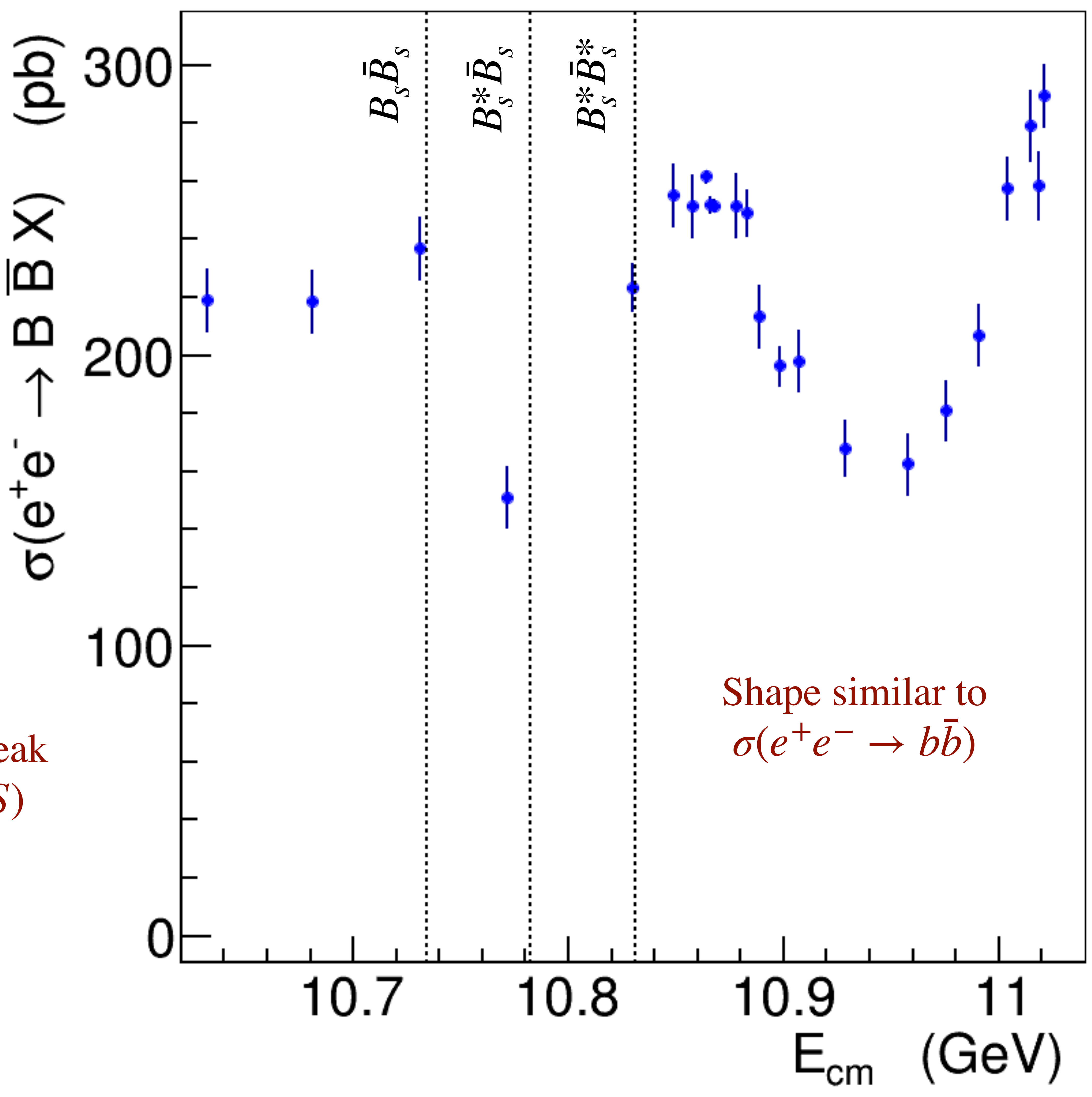
up to $B_s\bar{B}_s\pi^0\pi^0$ threshold (11.004 GeV)

$$\sigma(e^+e^- \to B_s^0\bar{B}_s^0X)\cdot\mathscr{B} = 0.54\cdot\sigma(e^+e^- \to b\bar{b} \to D_s^+X) - 0.09\cdot\sigma(e^+e^- \to b\bar{b} \to D^0X),$$

$$\sigma(e^+e^- \to B\bar{B}X) = -0.34\cdot\sigma(e^+e^- \to b\bar{b} \to D_s^+X) + 0.81\cdot\sigma(e^+e^- \to b\bar{b} \to D^0X)$$

$\sigma(e^+e^- \to B_s\bar{B}_sX)$ and $\sigma(e^+e^- \to B\bar{B}X)$





Summary

- ✓ Cross sections $\sigma(e^+e^- \to b\bar{b} \to D_s^{\pm}X)$ and $\sigma(e^+e^- \to b\bar{b} \to D^0\bar{D}^0X)$ as well as $\sigma(e^+e^- \to B_s\bar{B}_sX)$ and $\sigma(e^+e^- \to B\bar{B}X)$ are measured from 10.63 to 11.02 GeV

- ✓ Inclusive $\mathscr{B}(B \to D^0X)$ and $\mathscr{B}(B \to D_sX)$ are obtained

- ✓ Ratio $\mathscr{B}(B_s \to D^0X)/\mathscr{B}(B_s \to D_sX) = 0.416 \pm 0.018 \pm 0.092$ is determined

- ✓ The fraction of B_s mesons at $\Upsilon(5S)$ is measured to be $f_s = (22.0^{+2.0}_{-2.1})\ \%$

Thank you very much for your attention!

Backup

Cross sections for open flavour channels

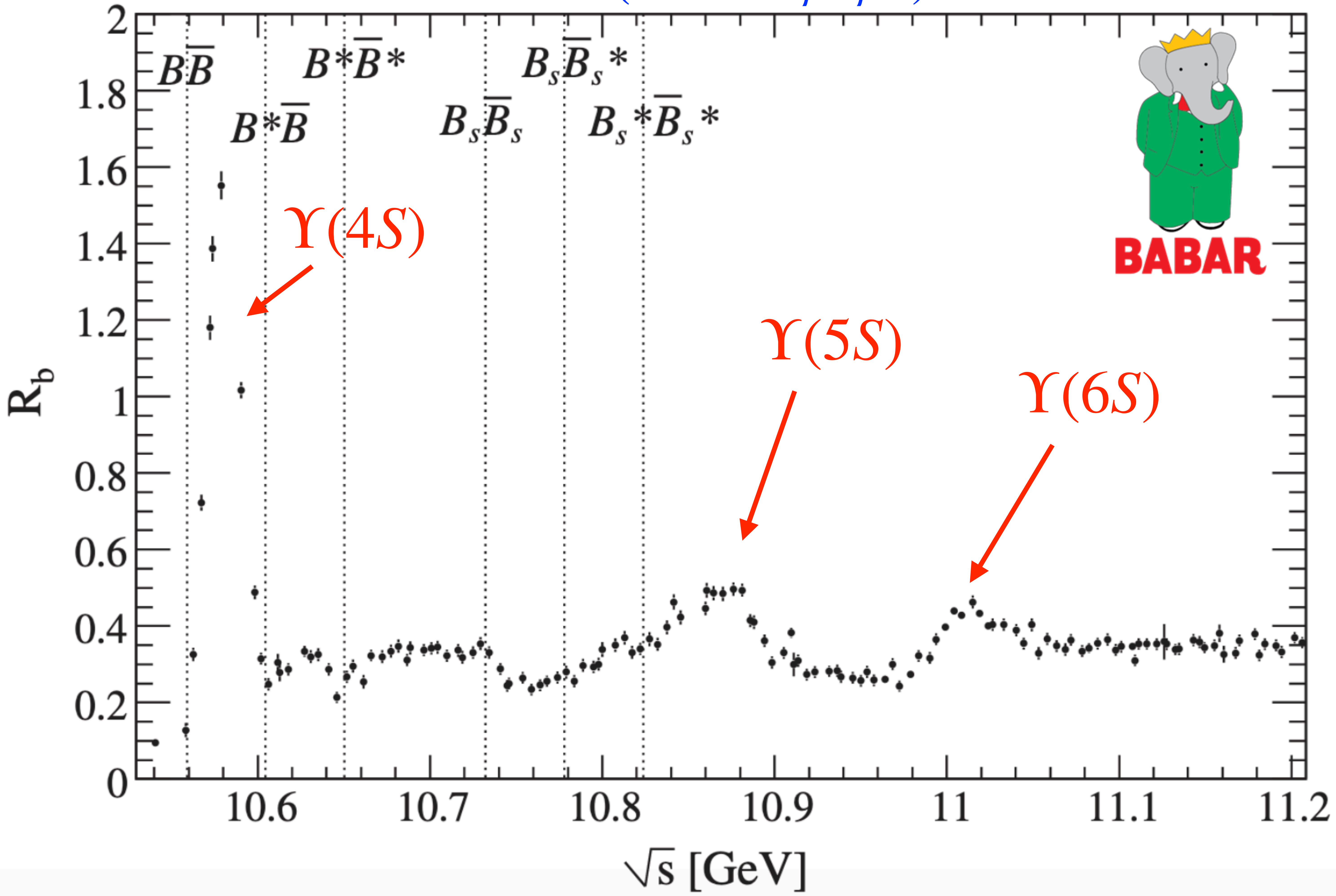
Total hadronic cross section has peaks at the $\Upsilon(4S)$, $\Upsilon(5S)$ and $\Upsilon(6S)$, and dips near the open bottom thresholds

$\Upsilon(5S)$ and $\Upsilon(6S)$ could provide an oscillatory behaviour of the corresponding exclusive cross sections

The individual cross sections contain considerably more information than their sum

$e^+e^- \to \Upsilon(nS)\pi^+\pi^-$, $e^+e^- \to h_b\pi^+\pi^-$ and $e^+e^- \to B^{(*)}\bar{B}^{(*)}(\pi)$ has been already measured

$$R_b = \frac{\sigma(e^+e^- \to b\bar{b})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



Measurements of the exclusive cross sections should shed light on the nature of bottomonium states

Puzzling bottomonium states

Mass splitting is too large

$M(\Upsilon(5S)) - M(\Upsilon(4S)) = 305.8\ \mathrm{MeV/c^2}$

$M(\Upsilon(4S)) - M(\Upsilon(3S)) = 224.2\ \mathrm{MeV/c^2}$

$\Delta = 81.6\ \mathrm{MeV/c^2}$

$\Delta_{b\bar{b}}^{\mathrm{expected}} \approx 40\ \mathrm{MeV/c^2}$

Anomalous production of $\Upsilon(nS)\pi^+\pi^-$

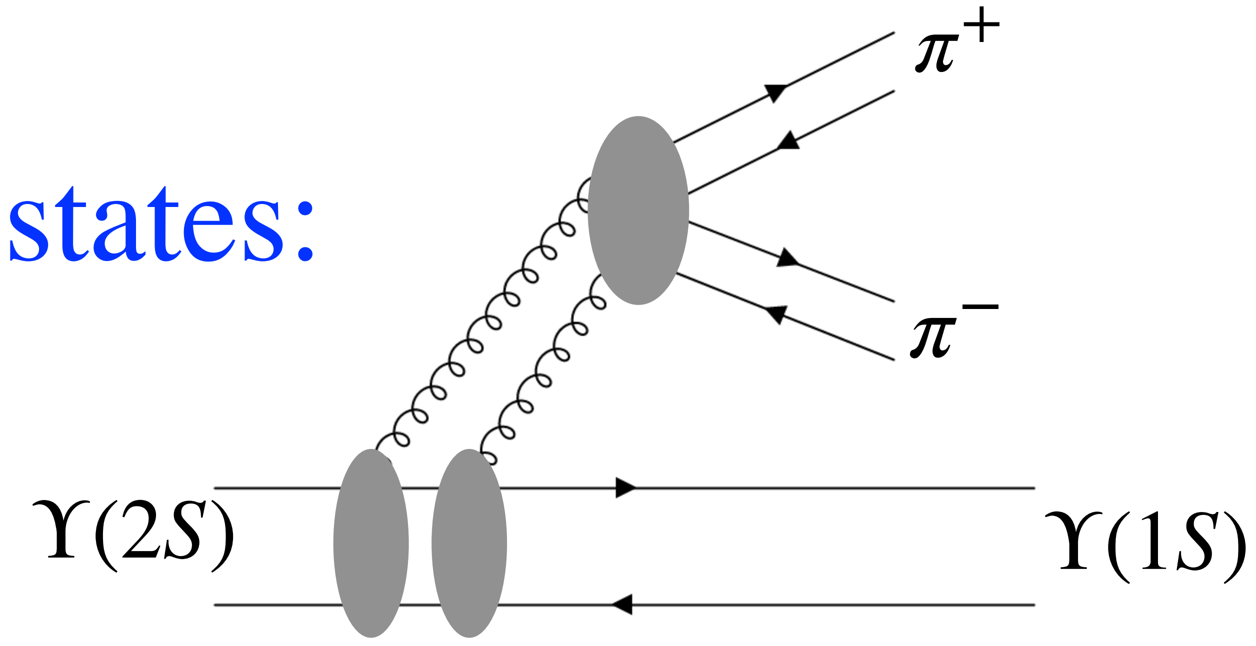
PRL100,112001(2008)	Γ, MeV
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	0.59 +- 0.04 +- 0.09
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	0.85 +- 0.07 +- 0.16
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	0.52+0.20-0.17+-0.013
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2

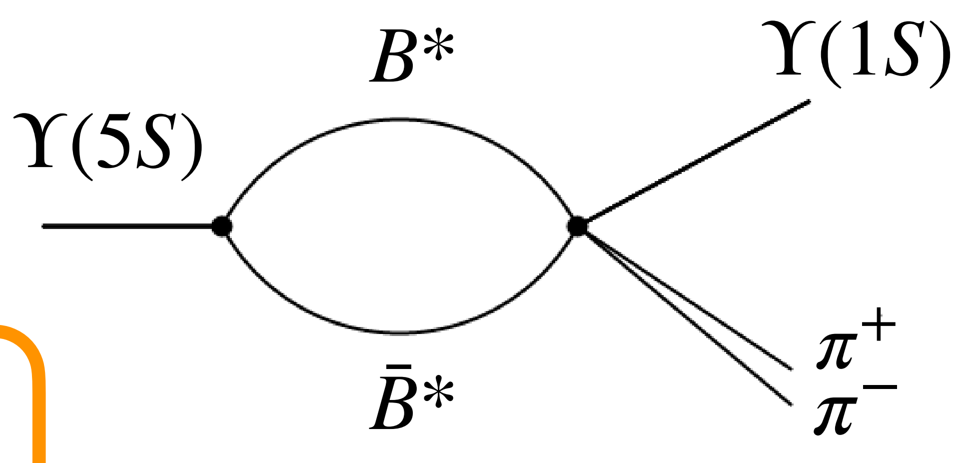
η transitions are not suppressed

Transition	Partial width (keV)
$\Upsilon(2S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	5.7 ± 0.5
$\Upsilon(1S)\,\eta$	$(9.3 \pm 1.5) \times 10^{-3}$
$\Upsilon(3S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	0.89 ± 0.08
$\Upsilon(1S)\,\eta$	$< 2 \times 10^{-3}$
$\Upsilon(2S)\,\pi^+\pi^-$	0.57 ± 0.06
$\Upsilon(4S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\,\eta$	4.0 ± 0.8
$\Upsilon(2S)\,\pi^+\pi^-$	1.8 ± 0.3
$h_b(1P)\,\eta$	45 ± 7
$\Upsilon(5S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	238 ± 41
$\Upsilon(1S)\,\eta$	39 ± 11
$\Upsilon(1S)\,K^+K^-$	33 ± 11
$\Upsilon(2S)\,\pi^+\pi^-$	428 ± 83
$\Upsilon(2S)\,\eta$	204 ± 44

Pure $b\bar{b}$-states:

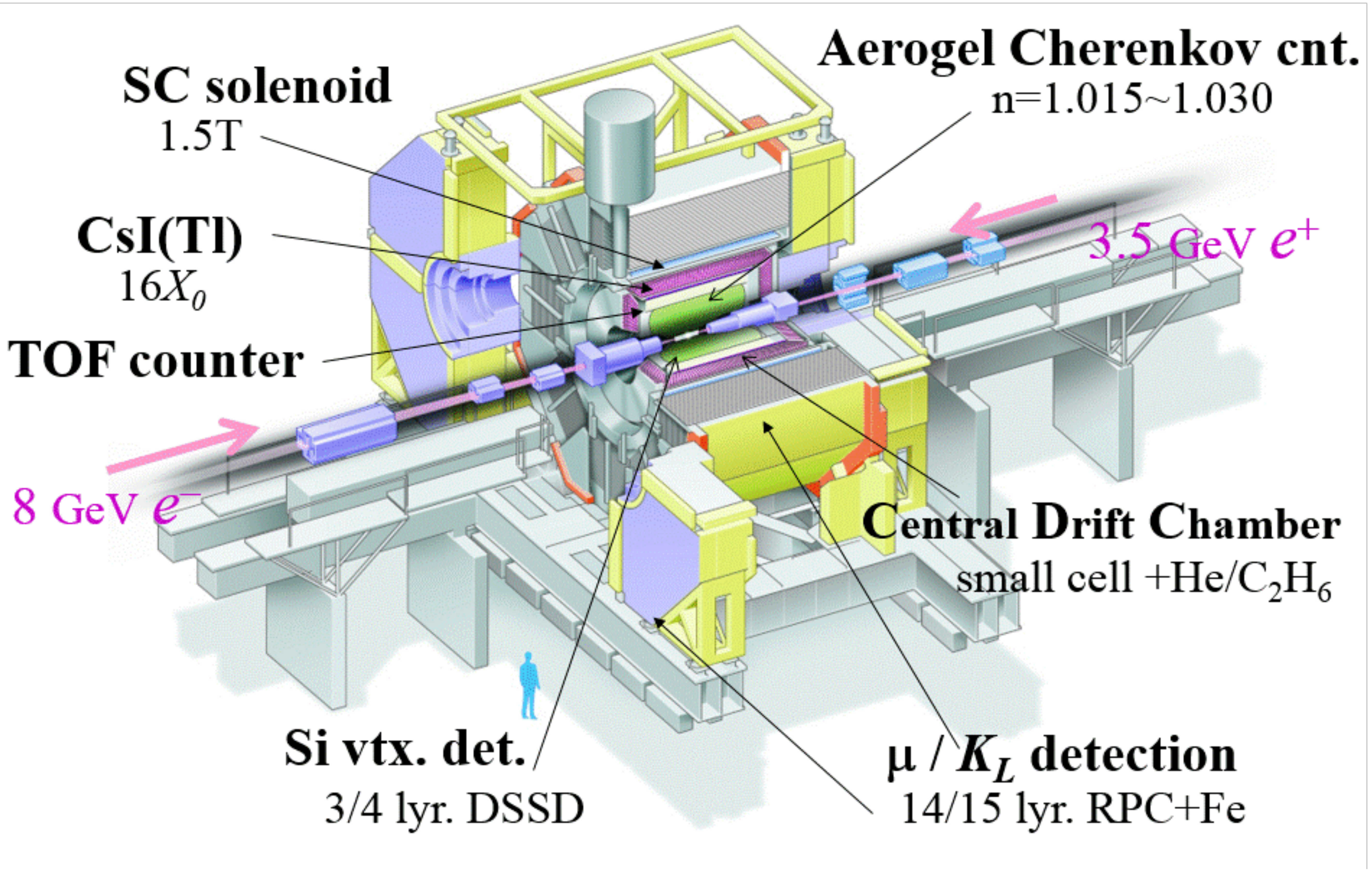


Rescattering $\Upsilon(5S) \to B^{(*)}B^{(*)} \to \Upsilon(nS)\pi\pi$?



Conclusion: states above threshold are not pure $b\bar{b}$

Data samples for the analysis



Data used in this analysis:

data at $\Upsilon(4S)$ energy:

$\mathscr{L}_{4S} = 571\ \mathrm{fb}^{-1}$

data at $\Upsilon(5S)$ energy:

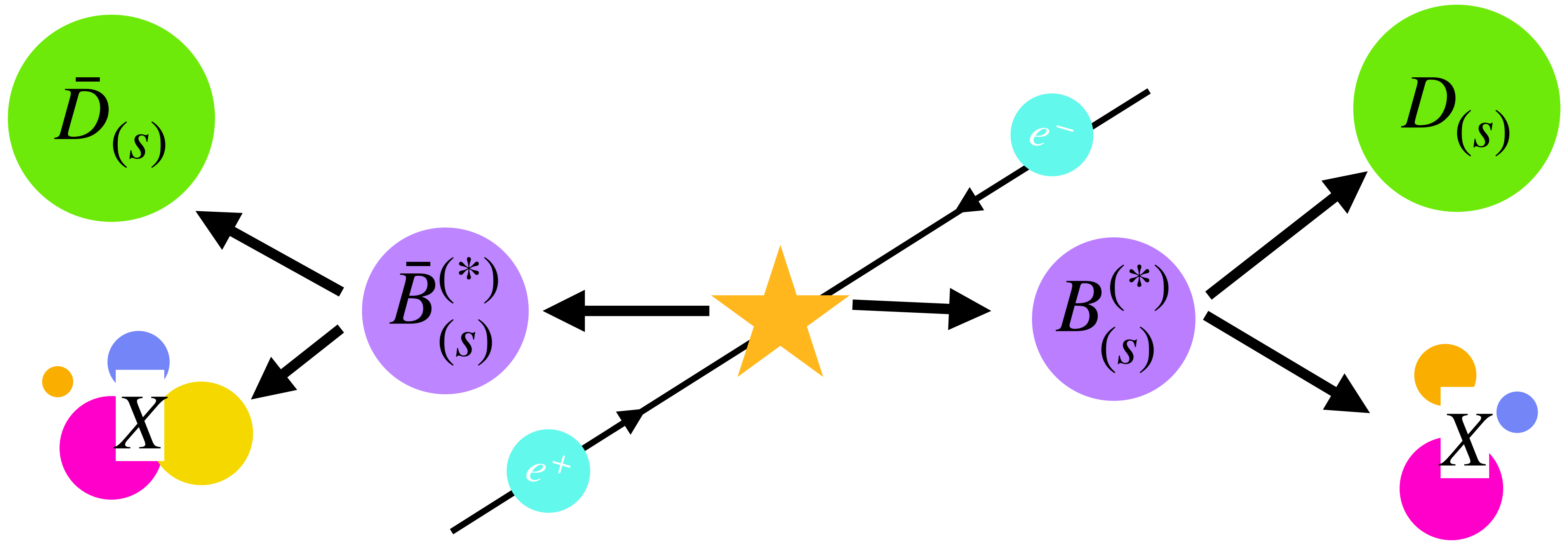
$\mathscr{L}_{5S} = 121\ \mathrm{fb}^{-1}$

data at $E_{cm} = 10.52$ GeV (continuum data sample):

$\mathscr{L}_{cont} = 74\ \mathrm{fb}^{-1}$

22 energy scan points (E_{cm} from 10.63 GeV to 11.02 GeV):

$\mathscr{L}_i \approx 1\ \mathrm{fb}^{-1}$



Belle detector

Charged particles: $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$
Neutral particles: γ, K_L

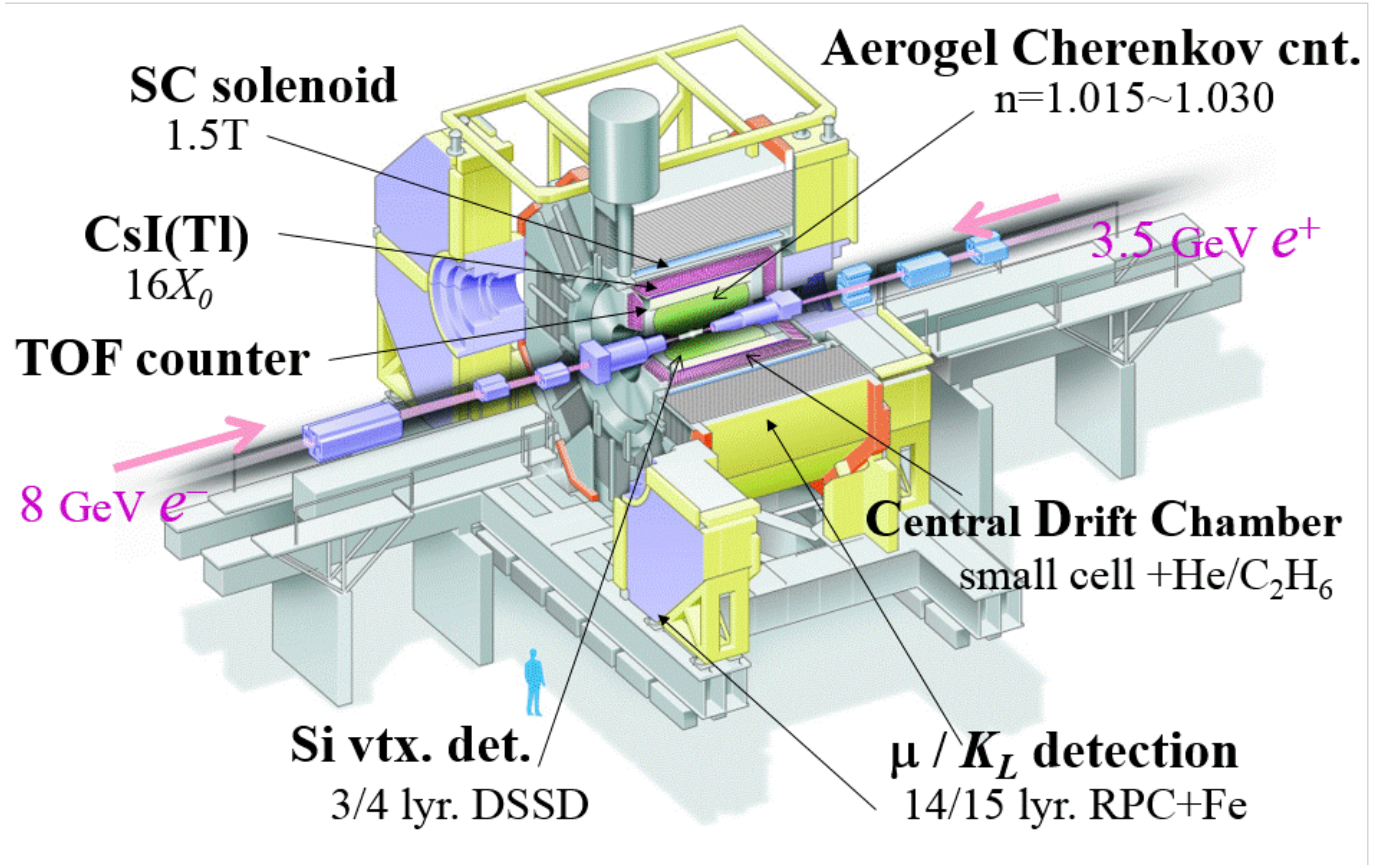
Decay vertices - SVD

Charged particle tracking — CDC

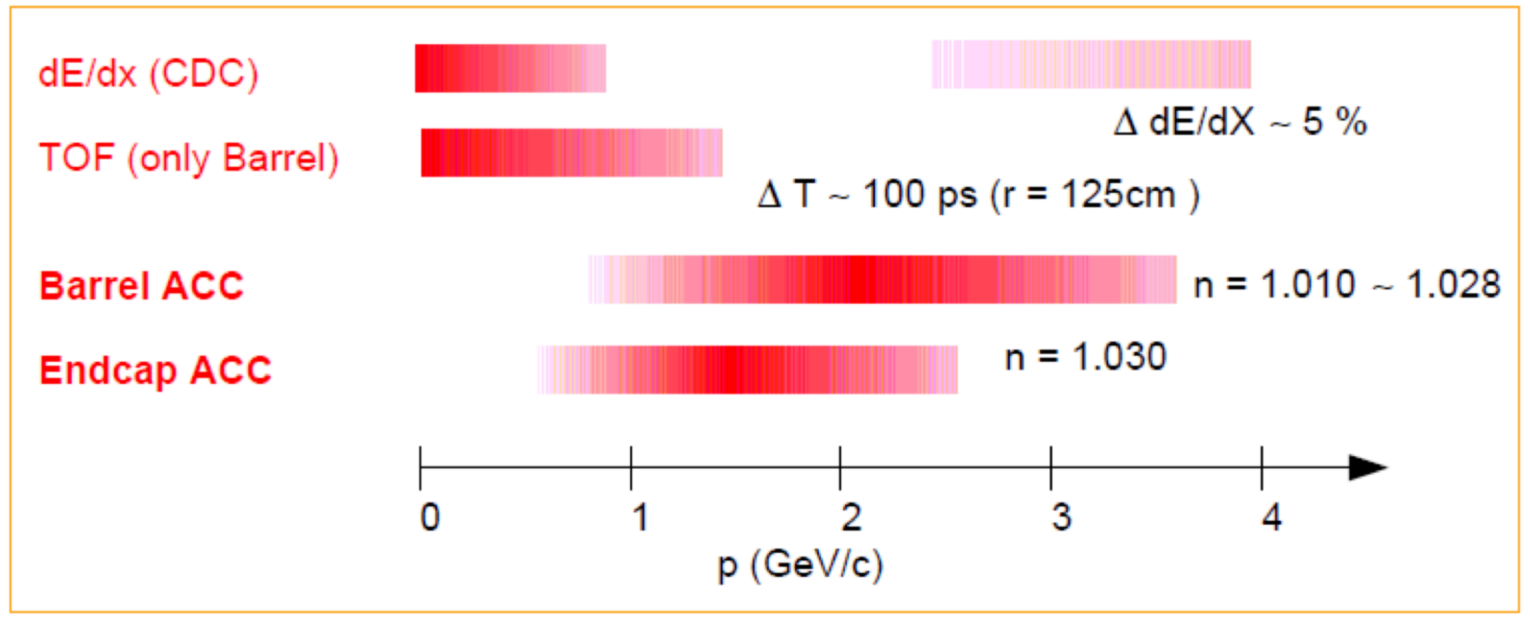
Particle ID — $\frac{dE}{dx}$ in CDC (p<1 GeV),
ACC (1.2 < p < 3.5 GeV), and
TOF (p < 1.2 GeV)

Electromagnetic showers — ECL

μ and K_L — KLM system



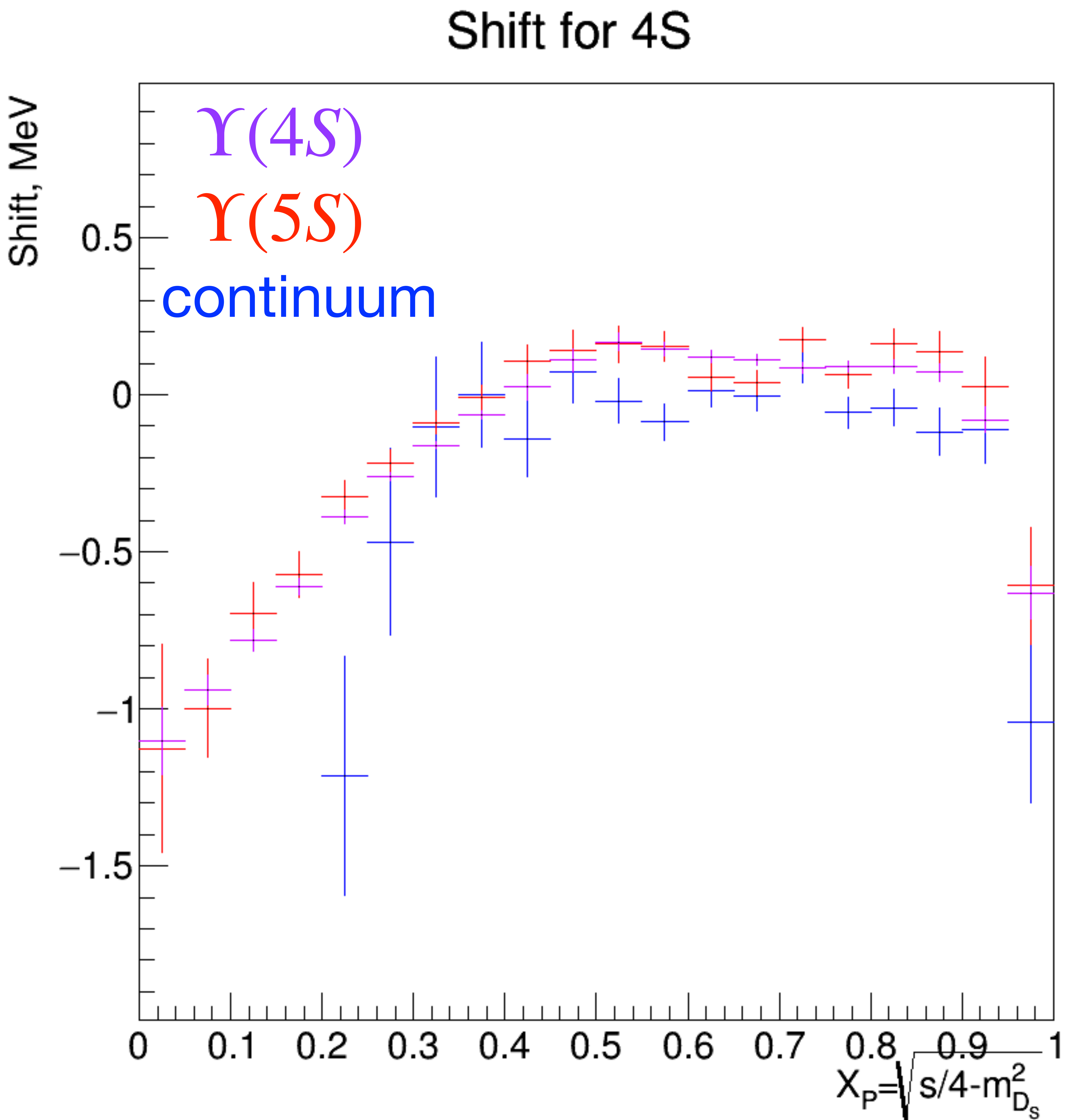
Belle detector

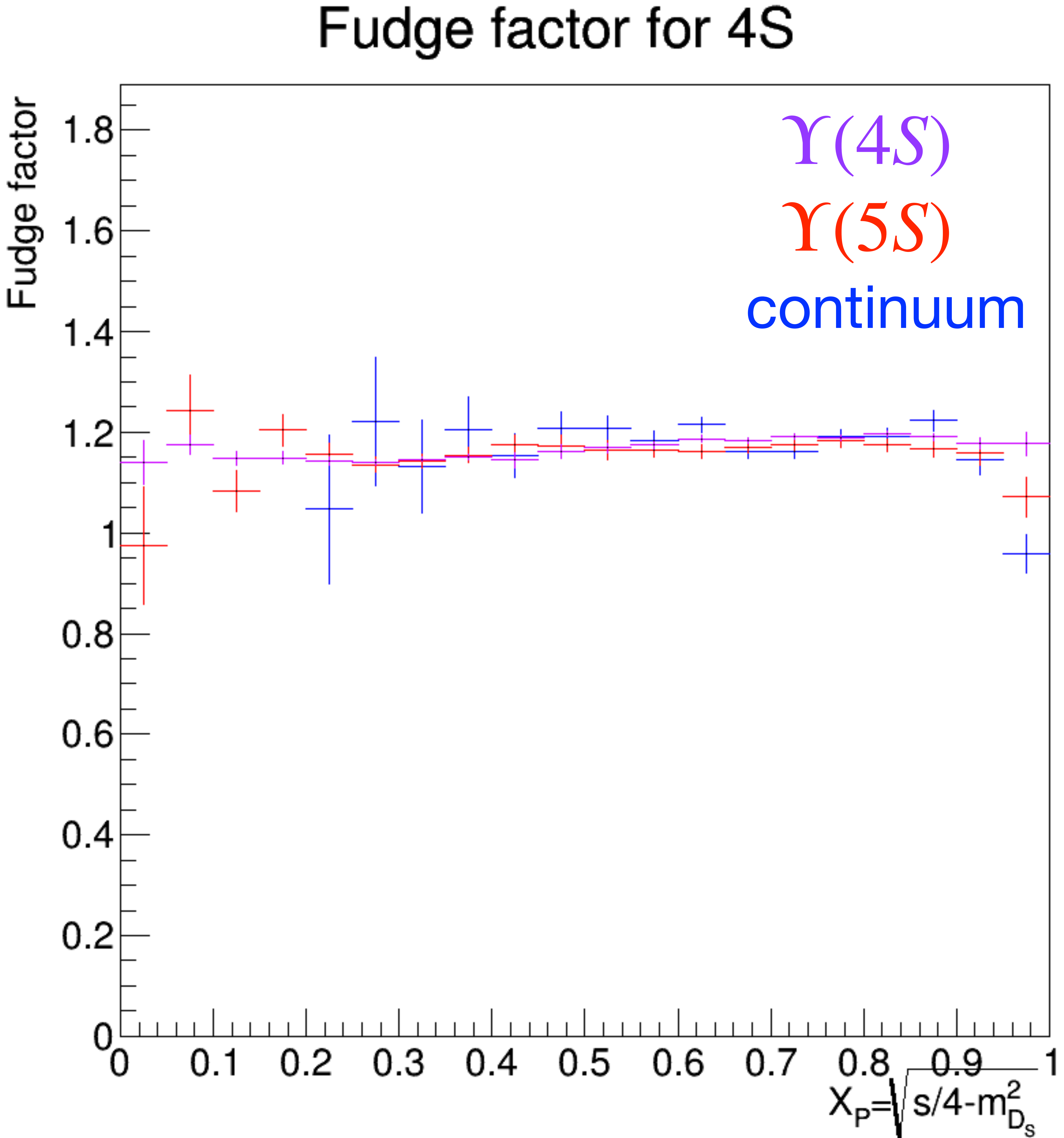


Performance parameters expected (or achieved) for the Belle detector

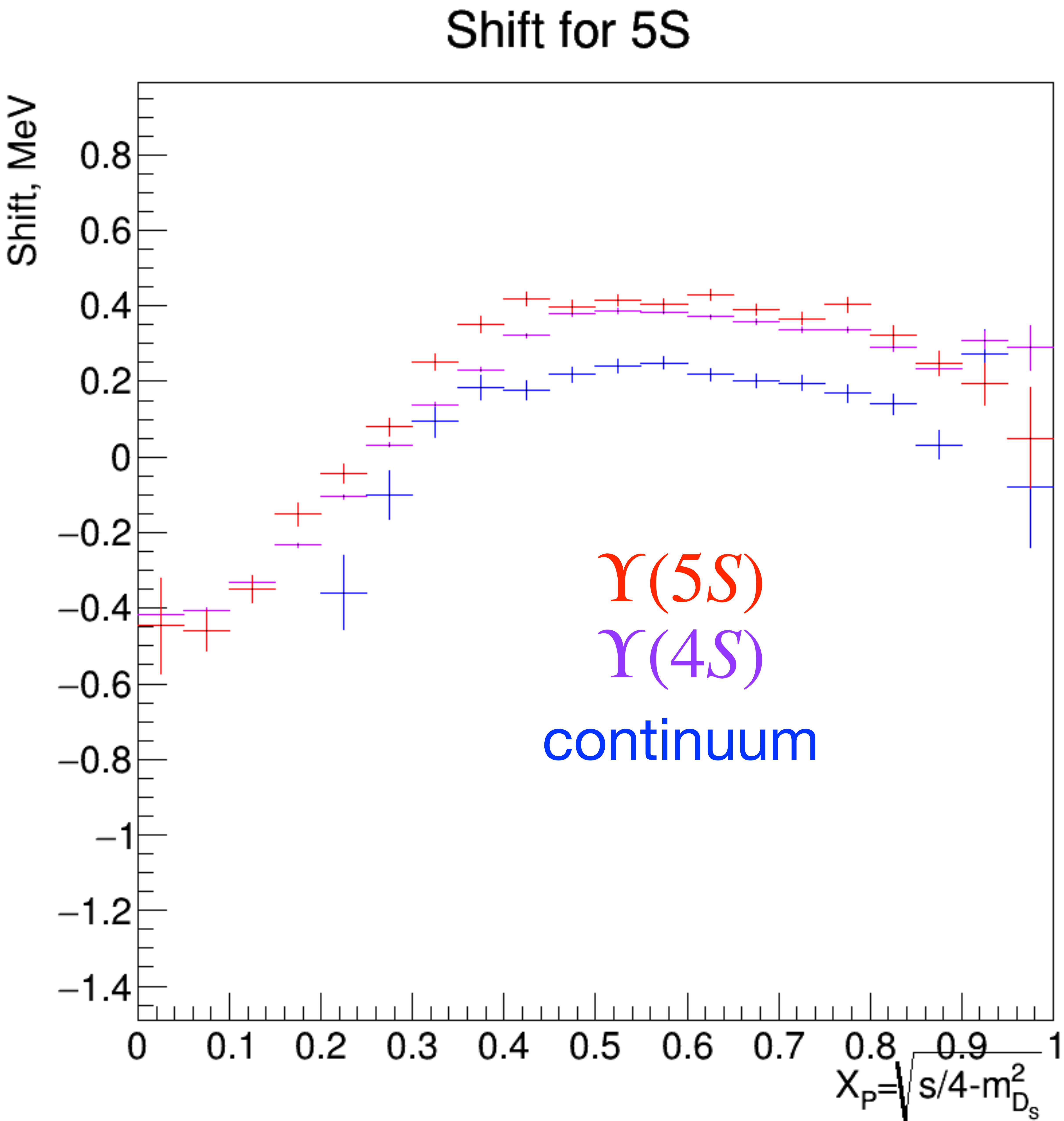
Detector	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double wall	Cylindrical, $r = 20$ mm 0.5/2.5/0.5 (mm) = Be/He/Be		He gas cooled
EFC	$Bi_4Ge_3O_{12}$	Photodiode readout segmentation: 32 in ϕ; 5 in θ	160×2	RMS energy resolution: 7.3 % at 8 GeV 5.8% at 3.5 GeV
SVD	Double-sided Si strip	Chip size: 57.5×33.5 mm^2 Strip pitch: 25 (p)/50 (n) μm 3 layers: 8/10/14 ladders	ϕ: 40.96k z: 40.96k	$\sigma_{\Delta_z} \sim 80$ μm
CDC	Small cell drift chamber	Anode: 50 layers Cathode: 3 layers $r = 8.3$–86.3 cm $-77 \leqslant z \leqslant 160$ cm	A: 8.4k C: 1.8k	$\sigma_{r\phi} = 130$ μm $\sigma_z = 200$–1400 μm $\sigma_{p_t}/p_t = 0.3\%\sqrt{p_t^2 + 1}$ $\sigma_{\mathrm{d}E/\mathrm{d}x} = 6\%$
ACC	Silica aerogel	960 barrel/228 end-cap FM-PMT readout		$N_{\mathrm{p.e.}} \geqslant 6$ K/π separation: $1.2 < p < 3.5$ GeV/c
TOF TSC	Scintillator	128 ϕ segmentation $r = 120$ cm, 3-m long 64 ϕ segmentation	128×2 64	$\sigma_t = 100$ ps K/π separation: up to 1.2 GeV/c
ECL	CsI (towered structure)	Barrel: $r = 125$–162 cm End-cap: $z = -102$ cm and $+196$ cm	6624 1152 (F) 960 (B)	$\sigma_E/E = 1.3\%/\sqrt{E}$ $\sigma_{\mathrm{pos}} = 0.5$ cm$/\sqrt{E}$ (E in GeV)
KLM	Resistive plate counters	14 layers (5 cm Fe + 4 cm gap) 2 RPCs in each gap	θ: 16k ϕ: 16k	$\Delta\phi = \Delta\theta = 30$ mr for K_L $\sim 1\%$ hadron fake
Magnet	Supercon.	Inner radius = 170 cm		$B = 1.5$ T

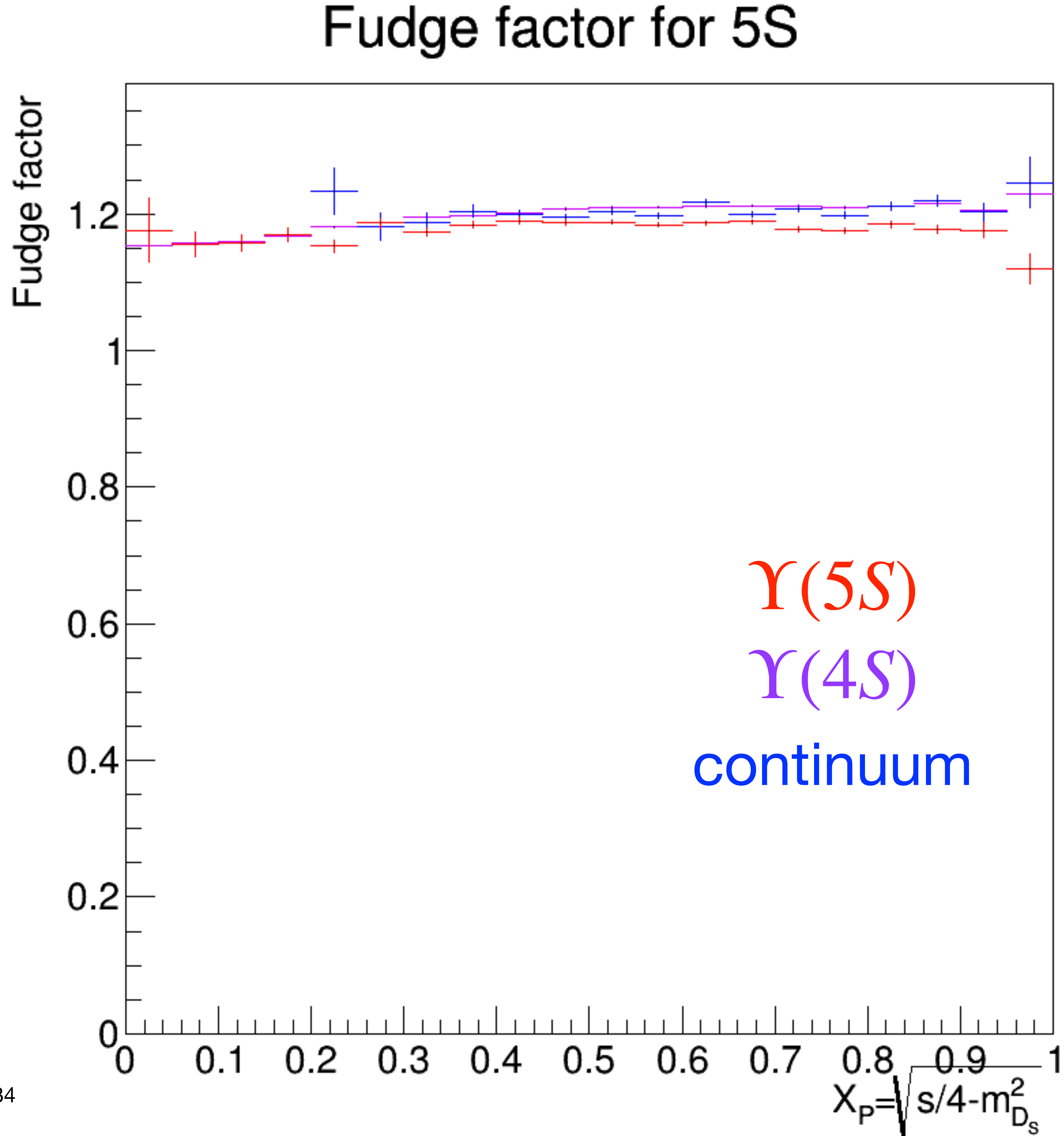
Fit the D_S mass distributions in the different x_p bins at $\Upsilon(4S)$





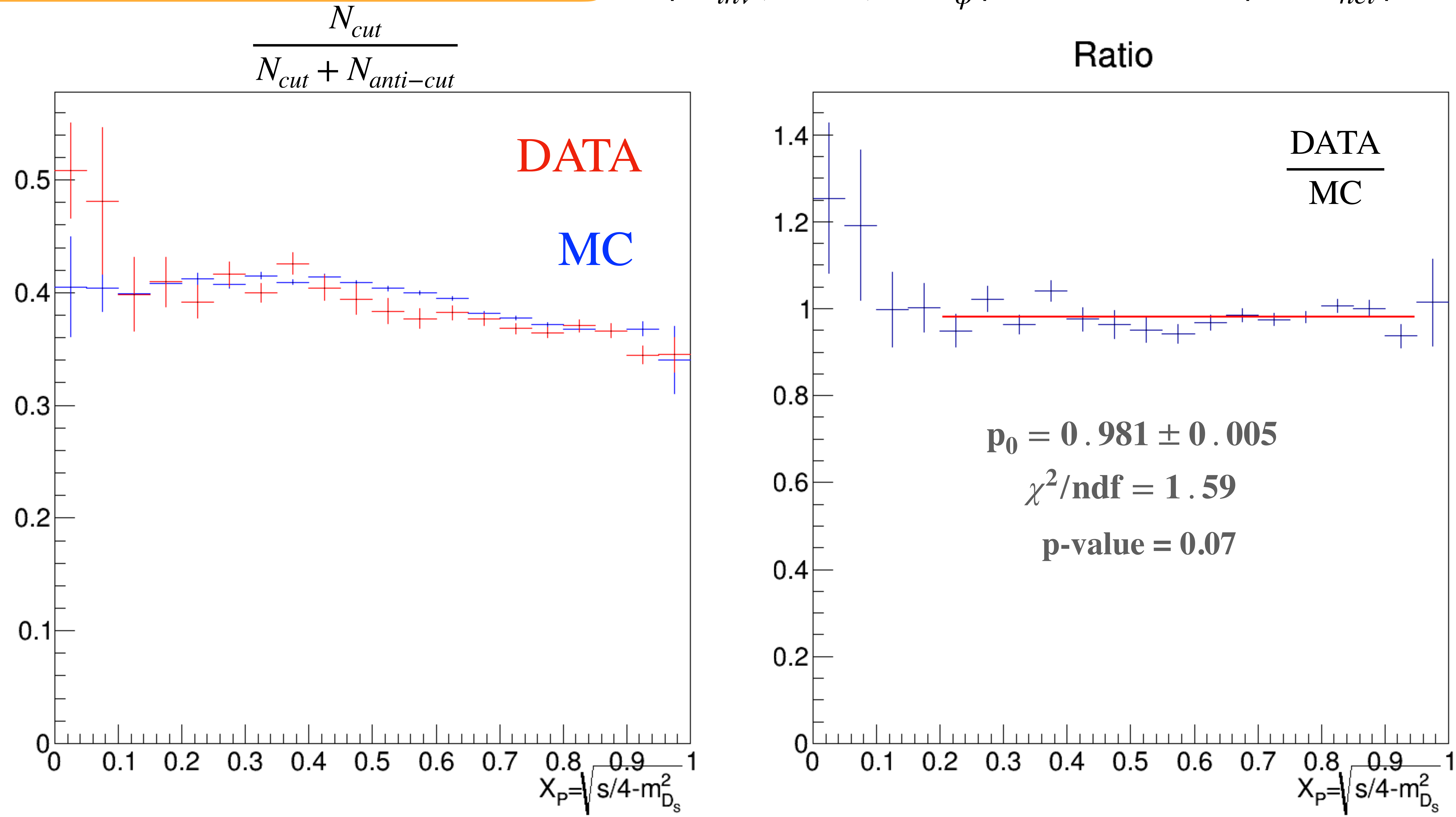
Fit the D^0 mass distributions in the different x_p bins at $\Upsilon(4S)$



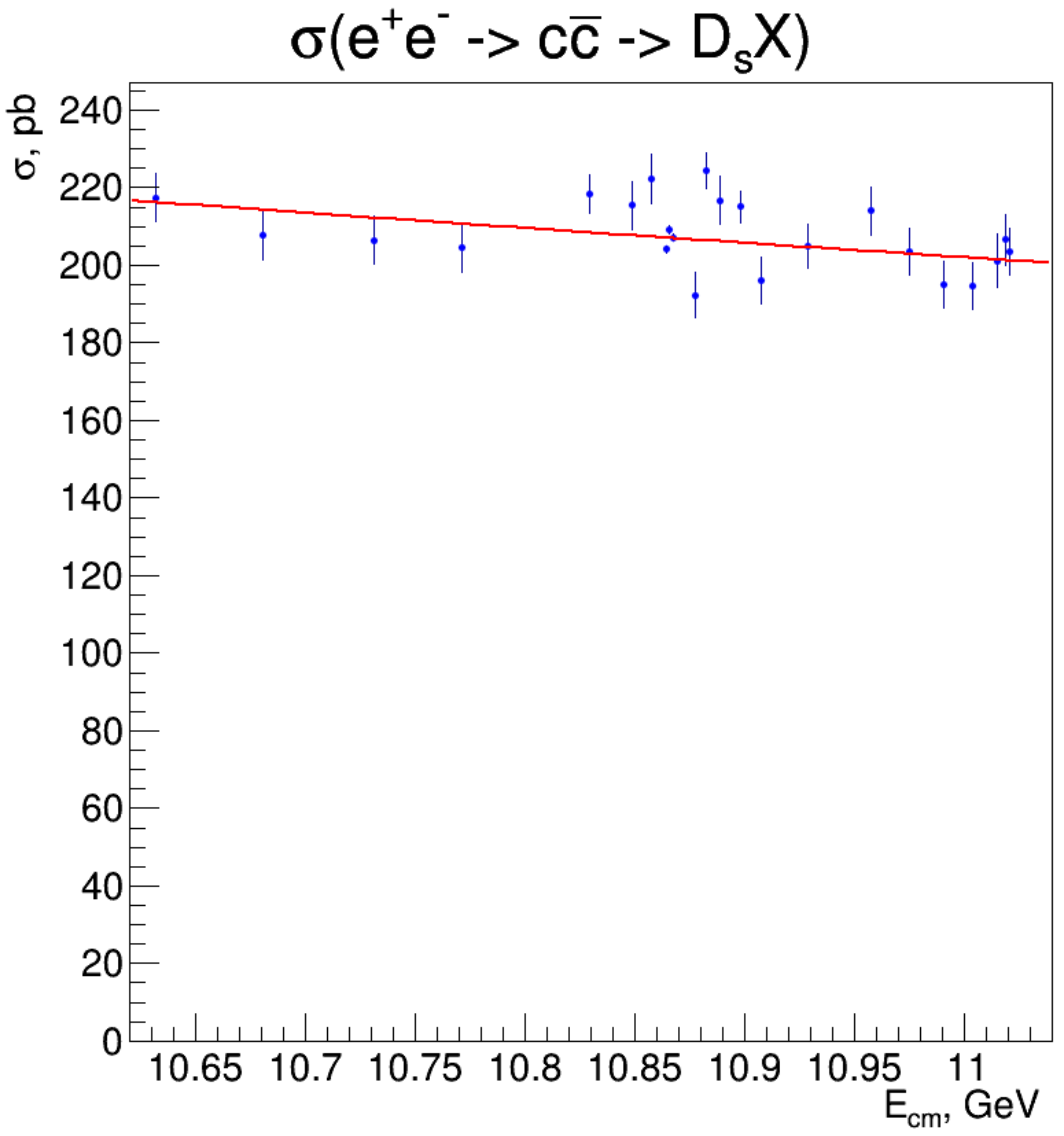


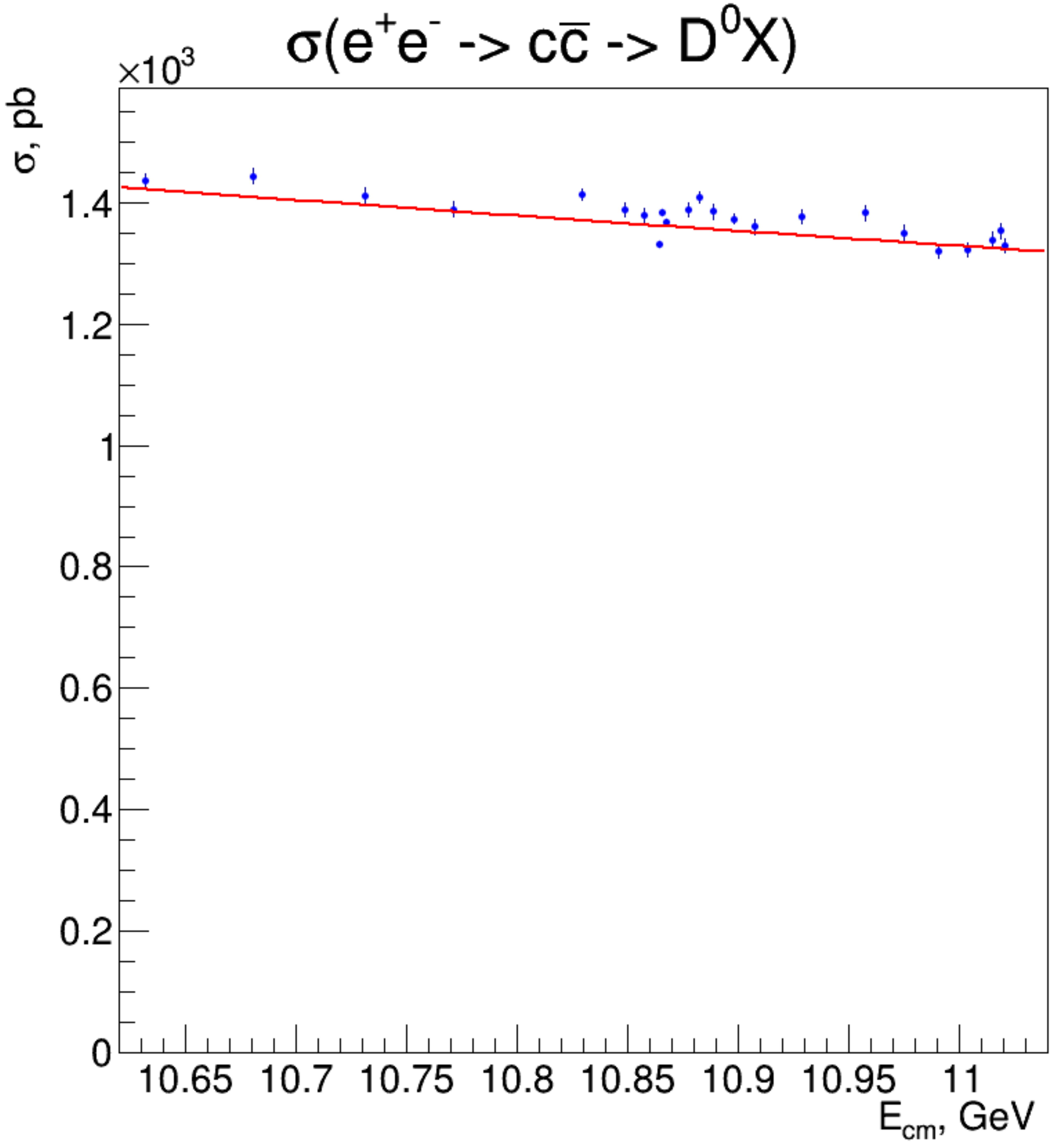
ϕ-cut efficiency correction

$|M_{inv}(K^-K^+) - m_\phi| < 19$ MeV/c^2, $|\cos\theta_{hel}| > 0.25$

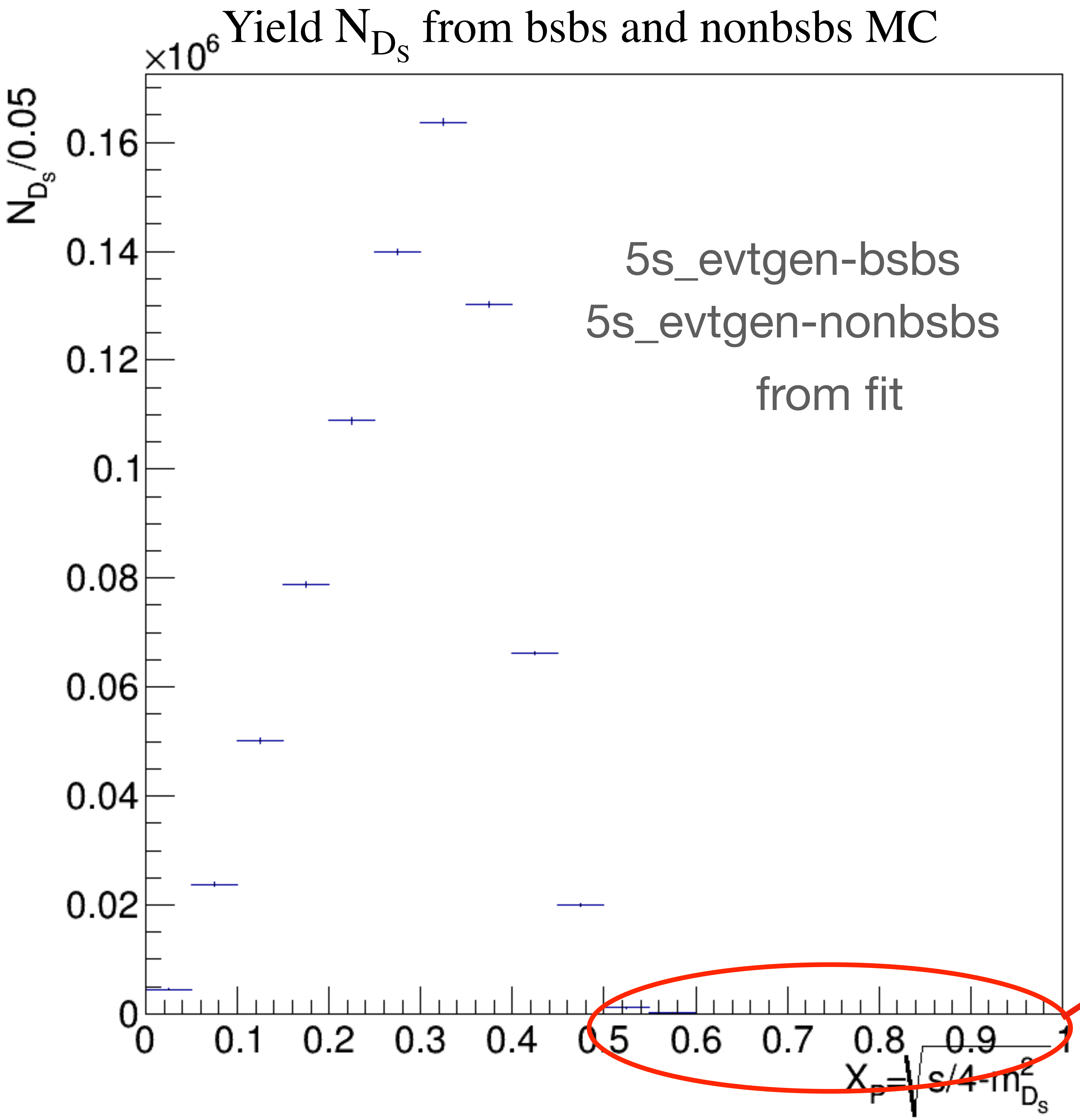


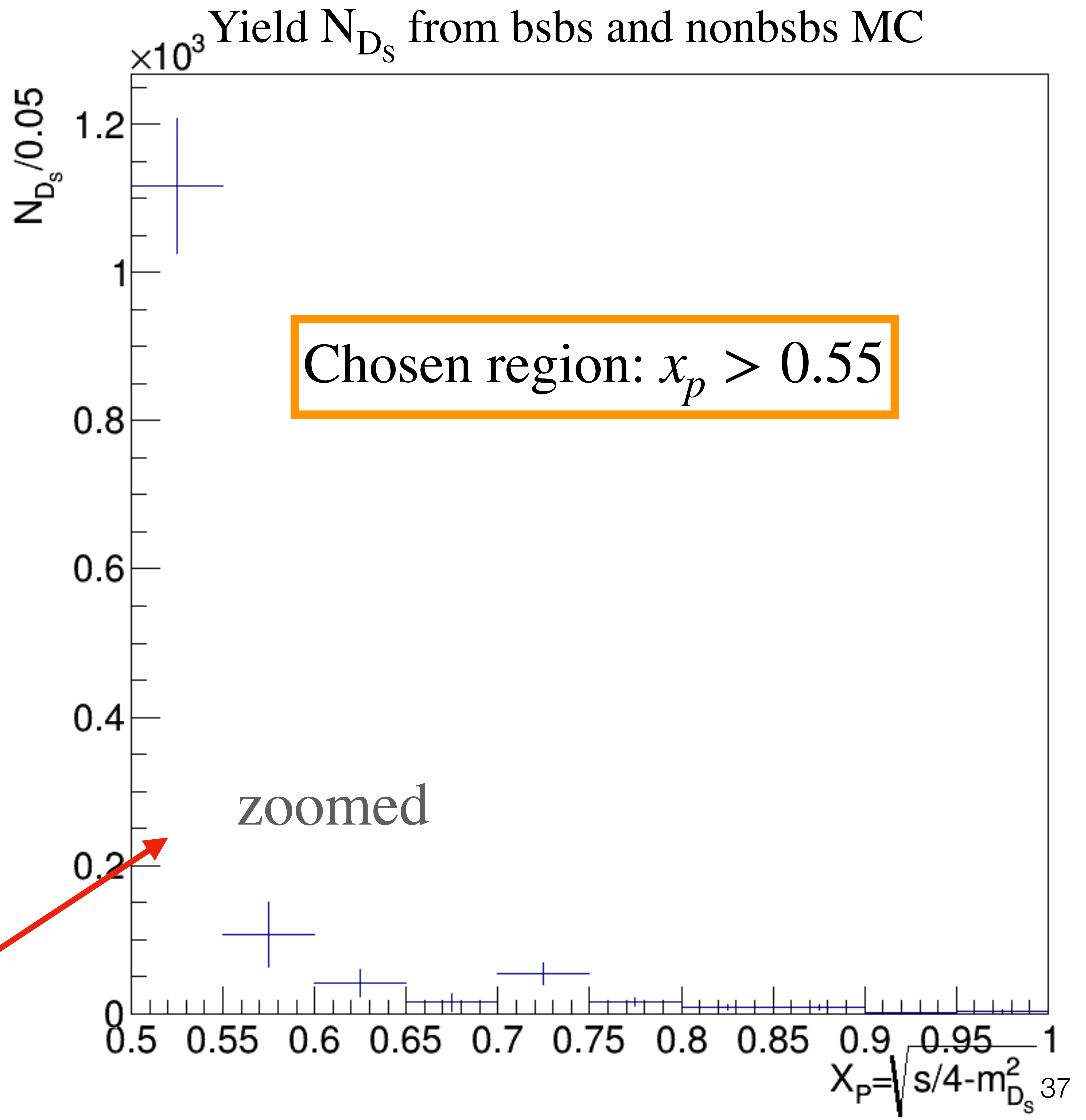
$\sigma(e^+e^- \to c\bar{c} \to D_s X)$ and $\sigma(e^+e^- \to c\bar{c} \to D^0 X)$



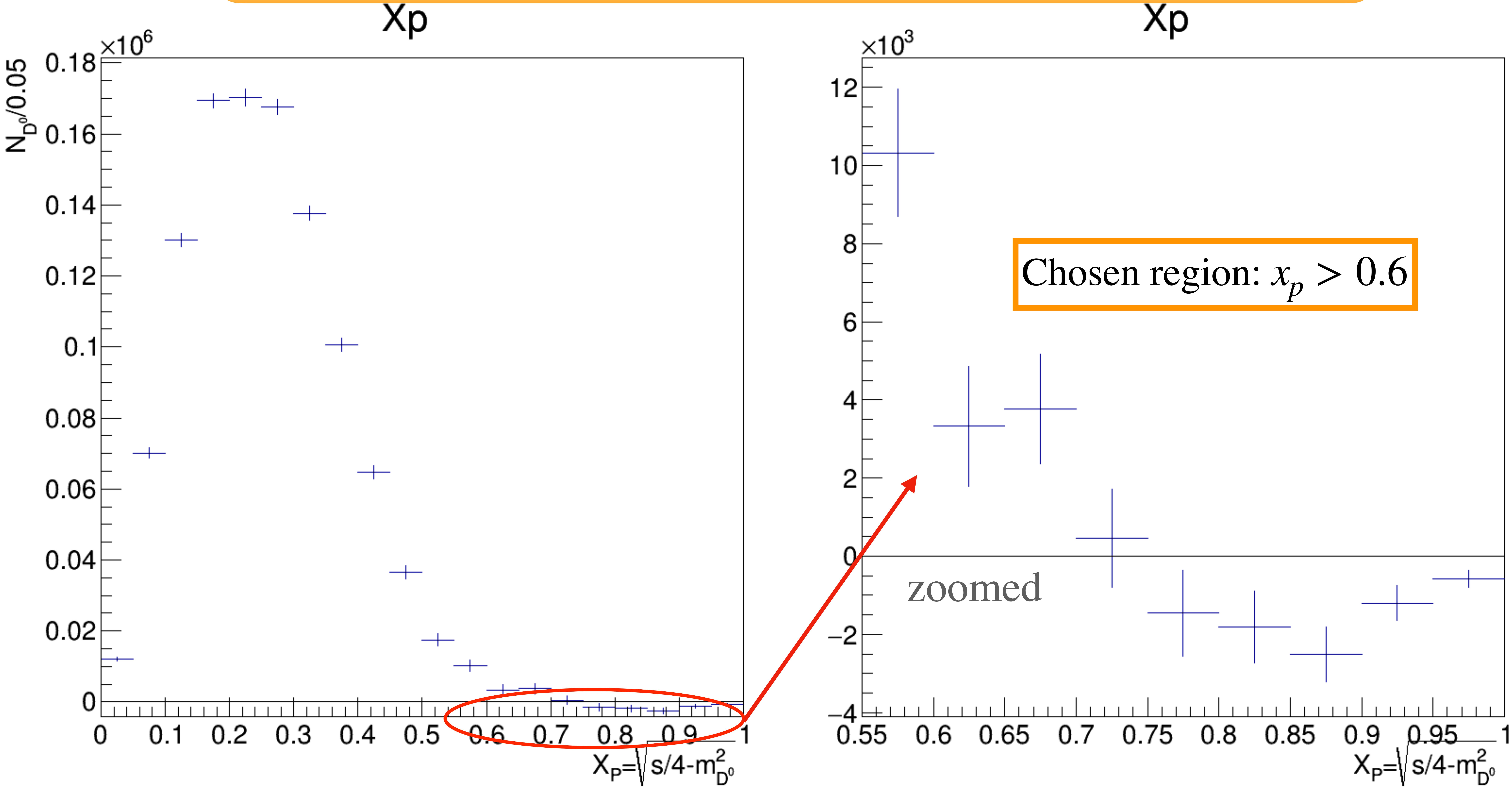


x_p spectra of D_S in bb MC at $\Upsilon(5S)$



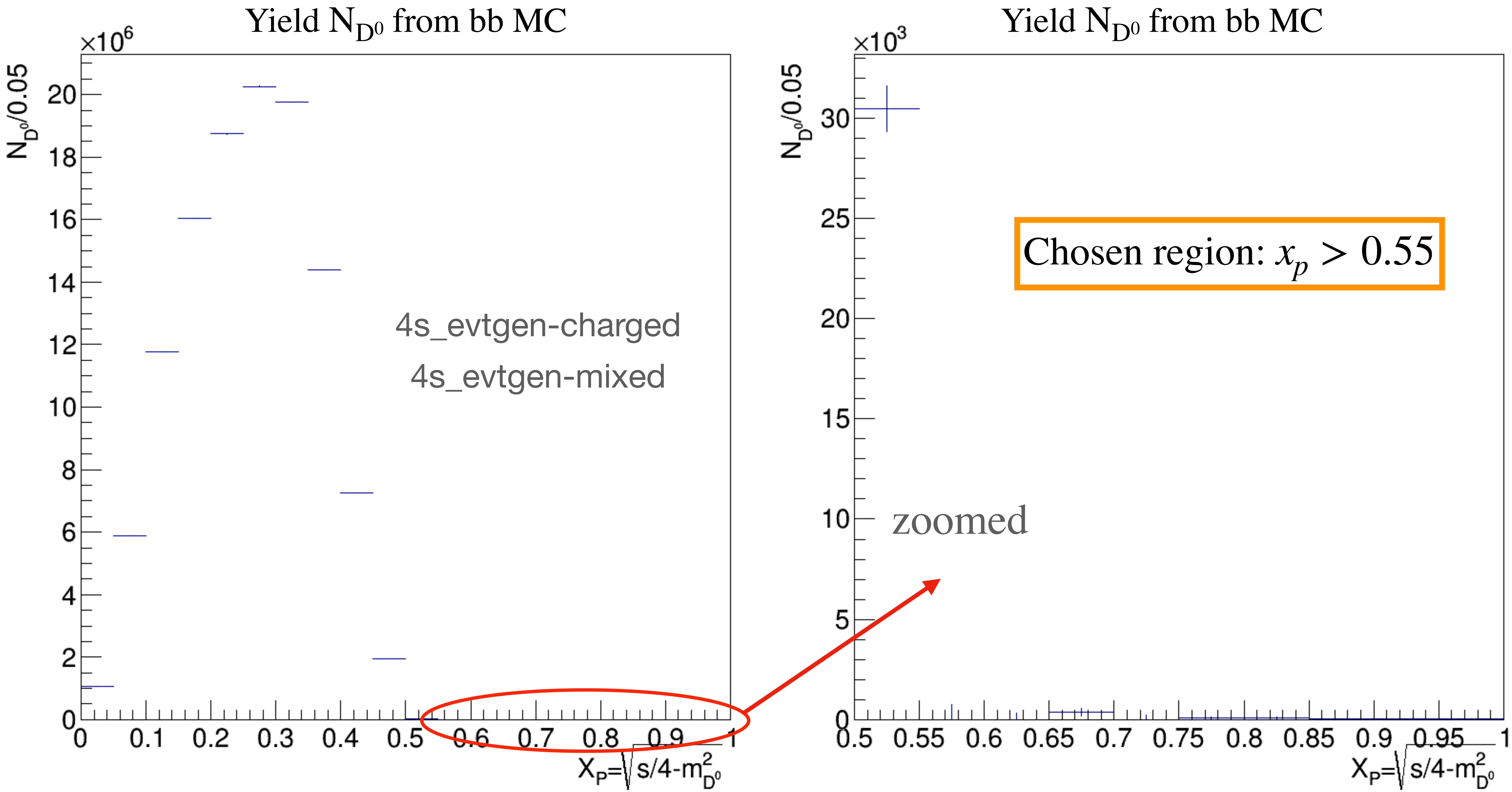


Continuum spectrum subtraction for D^0 at $\Upsilon(5S)$



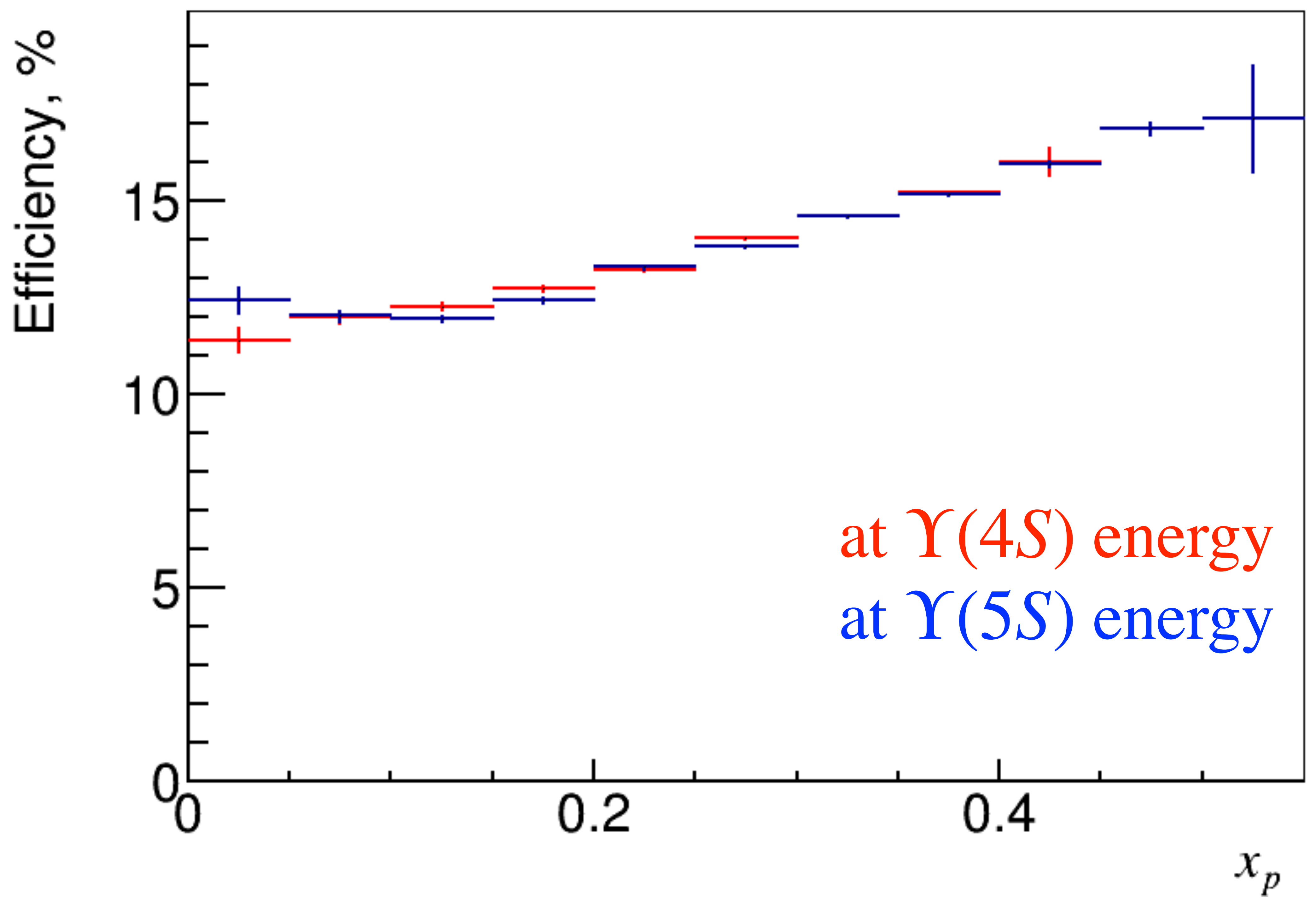
x_p spectra of D_S in bb MC at $\Upsilon(4S)$

x_p spectra of D^0 in bb MC at $\Upsilon(4S)$

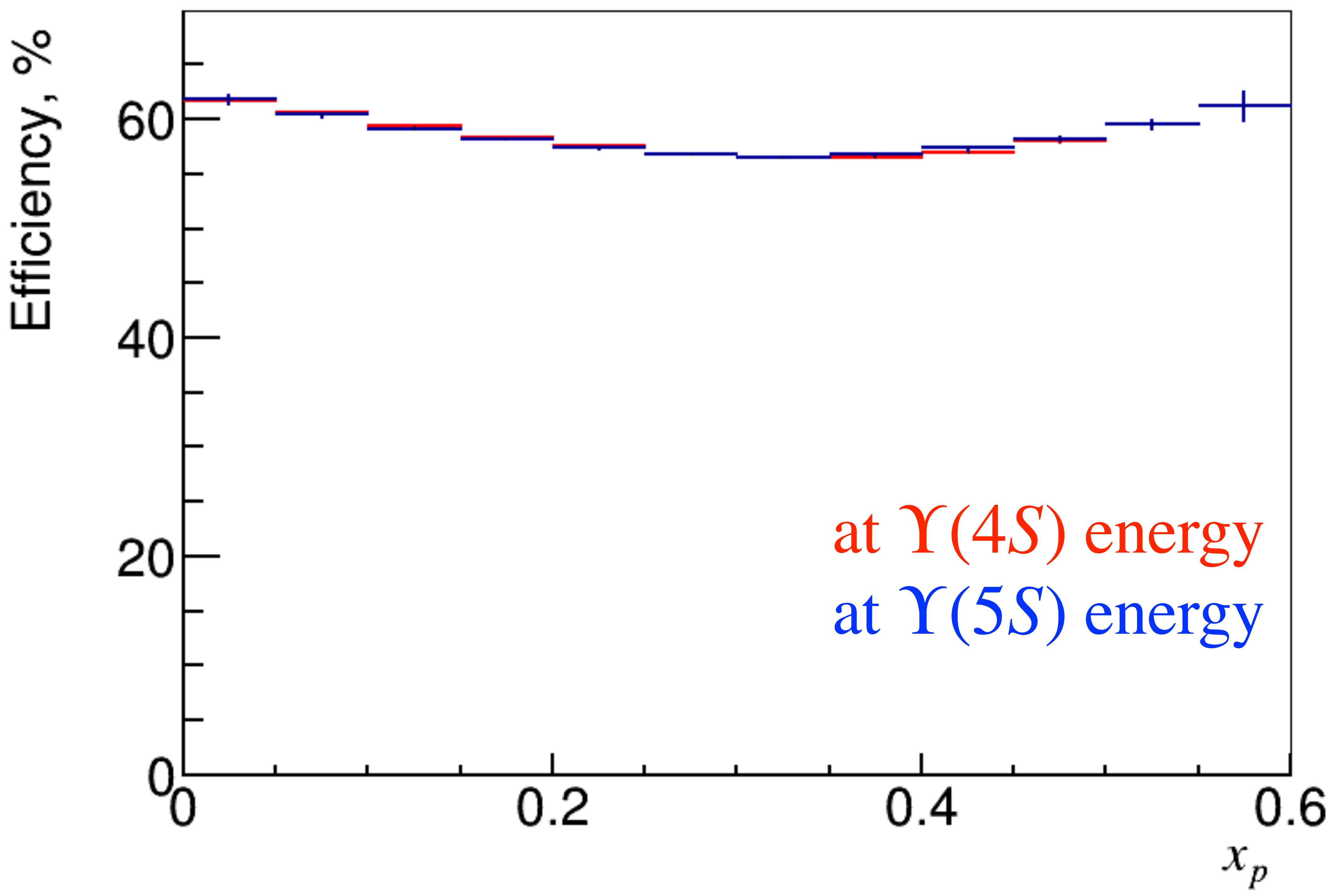


Reconstruction efficiency

D_s efficiency as function x_p



D^0 efficiency as function x_p



Systematic uncertainties in $\sigma(e^+e^- \to D\,X)$

Source	**Ds at Υ(5S)**	**D^0 at Υ(5S)**	**Ds at Υ(4S)**	**D^0 at Υ(4S)**
Fit model	0.6	0.3	1.0	1.1
Continuum xp spectrum statistical error	0.6	0.4	0.4	0.1
Continuum xp spectrum correction	0.3	1.3	-	-
MC statistical error	0.2	0.1	0.1	0.0
rϕ	0.6	-	0.6	-
Tracking	1.1	0.7	1.1	0.7
K/π identification	2.3	1.4	2.3	1.4
Luminosity	1.4	1.4	1.4	1.4
Branching fraction	1.9	0.8	1.9	0.8
Total	**3.6**	**2.6**	**3.7**	**2.5**

Continuum xp spectrum statistical error:

$$\frac{1}{\sigma}\sqrt{\sum_{i=1}^{i_{\max}}\left(\sigma_i\,\frac{\Delta n_i\,k}{N_i - k\,n_i}\right)^2}$$

MC statistical error:

$$\frac{1}{\sigma}\sqrt{\sum_{i=1}^{i_{\max}}\left(\sigma_i\,\frac{\Delta\mathscr{E}_i}{\mathscr{E}_i}\right)^2}$$