Measurement of the $e^+e^- \to B_s\bar{B}_sX$ cross section in the energy range from 10.63 to 11.02 GeV at Belle

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on behalf of the Belle collaboration

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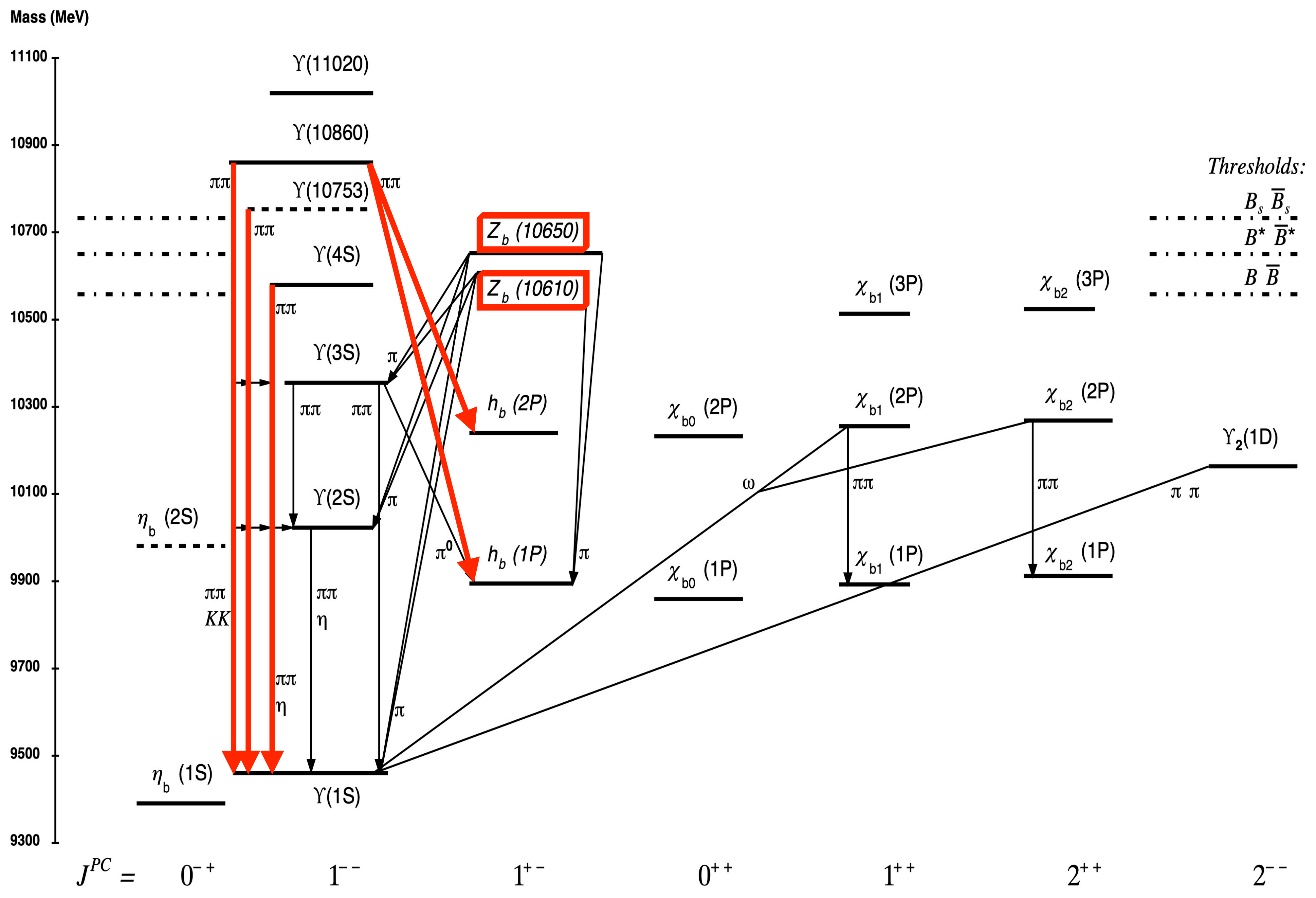
Introduction

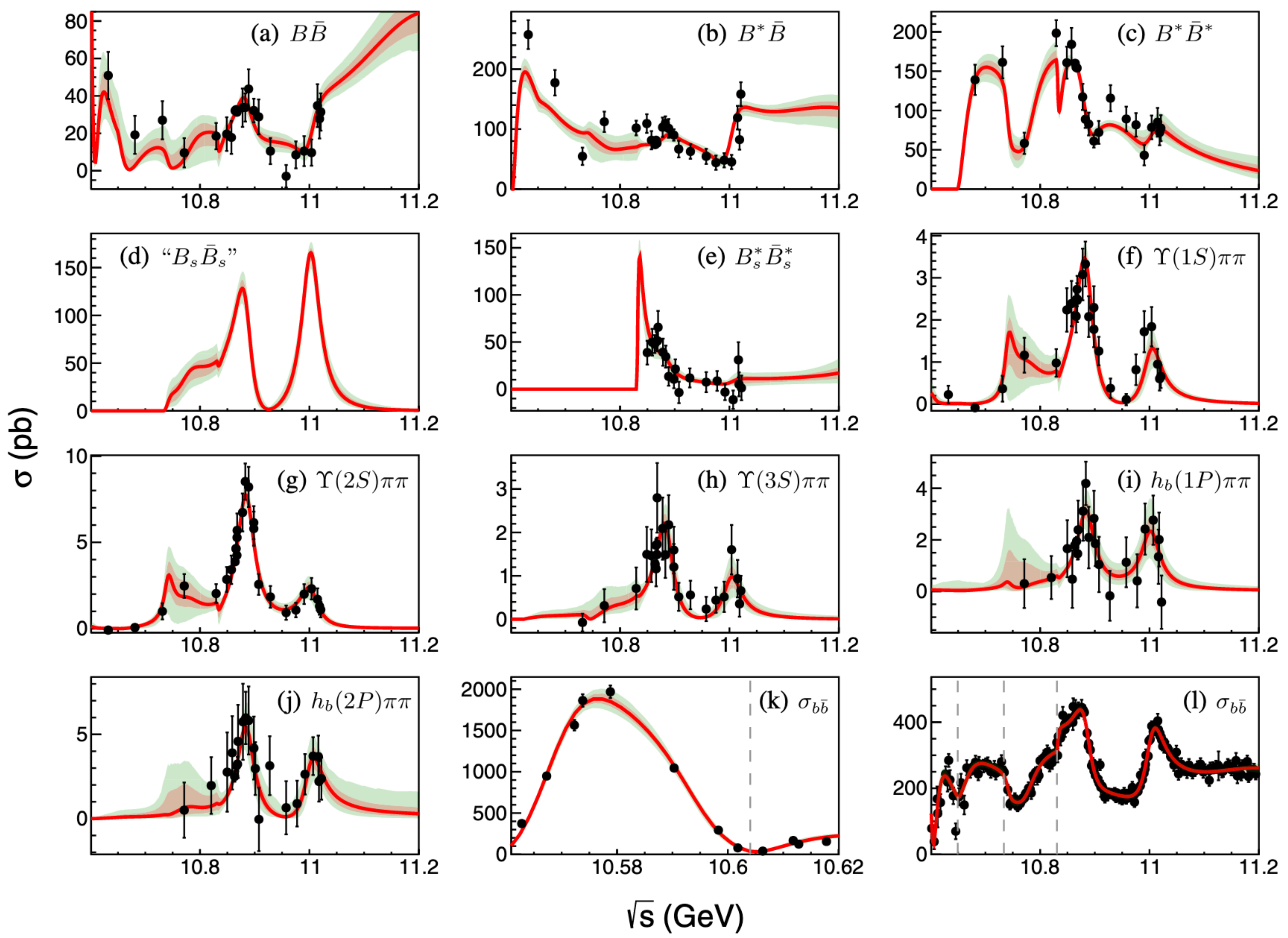


Unexpected properties of the bottomonium above $B\bar{B}$

- 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)
- η transitions are not suppressed relative to dipion transitions (violate HQSS)

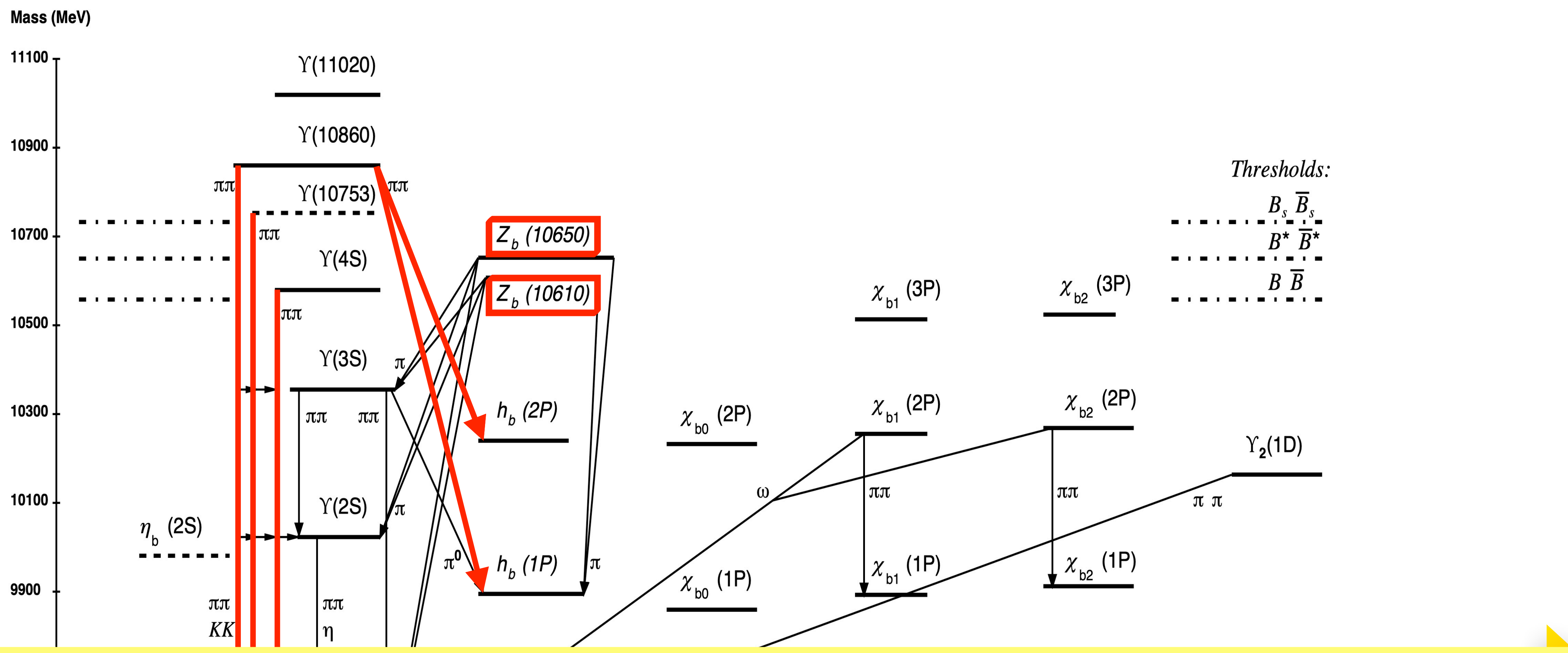
Combined theoretical analysis of all available data

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



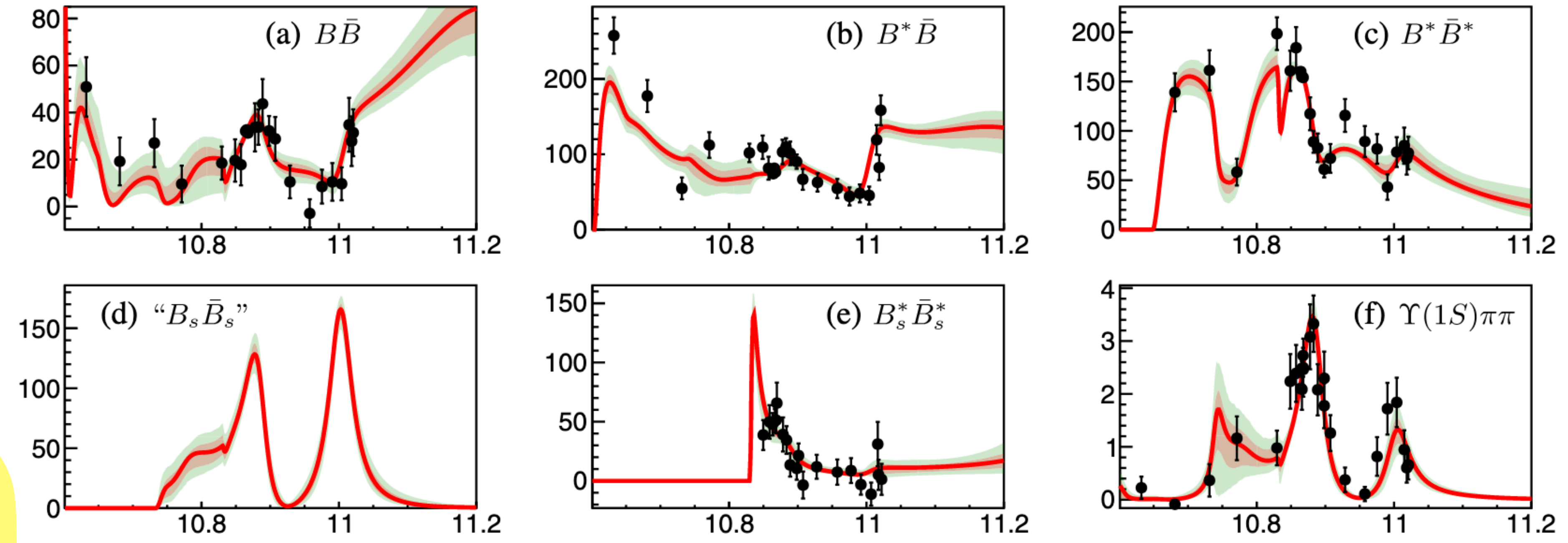
To extract the properties of resonances lying in this energy region

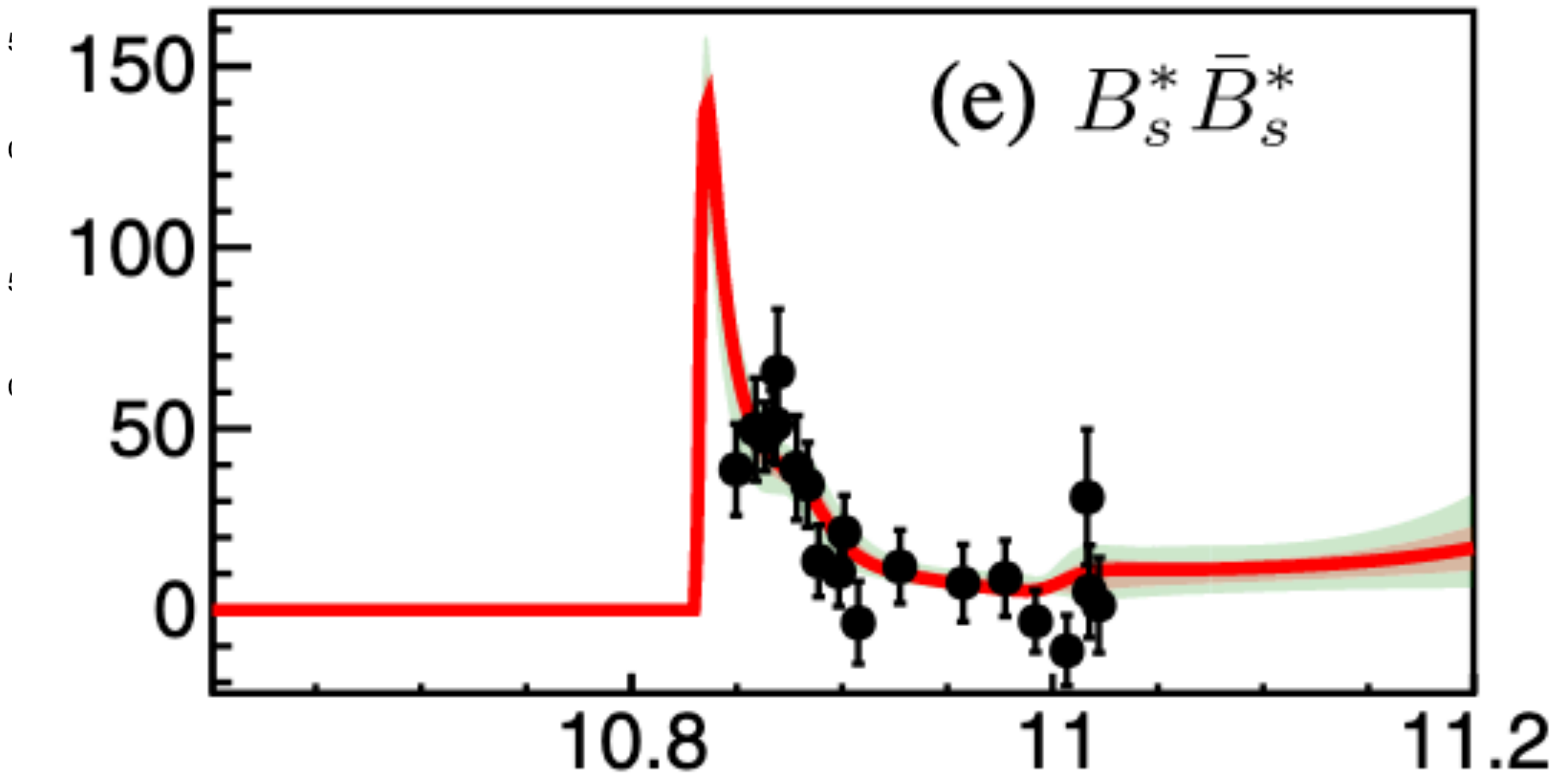
Introduction



Combined theoretical analysis of all available data

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





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

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

To extract the properties of resonances lying in this energy region

dipion transitions (violate HQSS)

Method

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

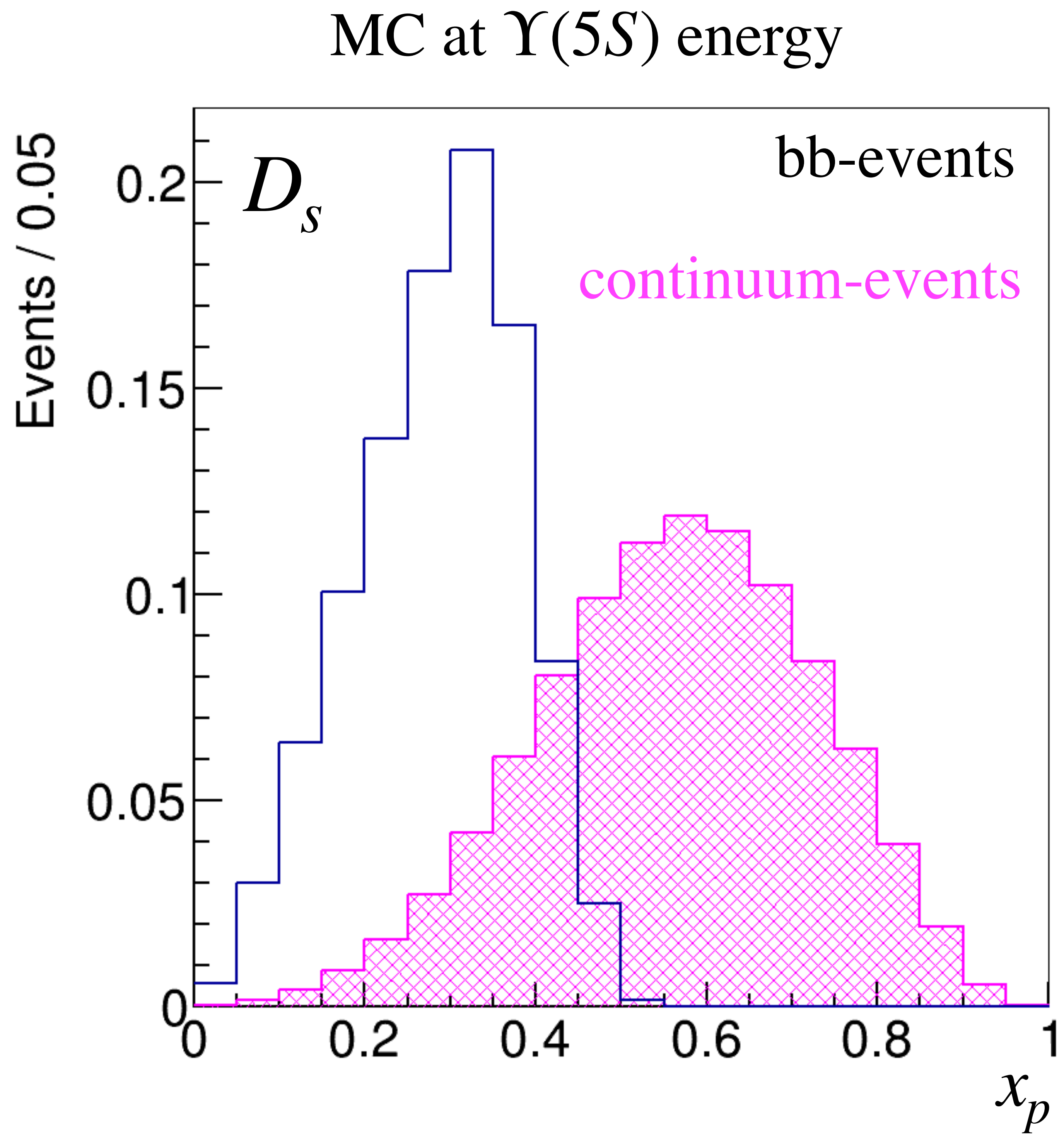
$x_p = \dfrac{p}{p_{max}}$ is used to separate continuum and $b\bar{b}$- events;

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

Measured cross sections can be expressed as:

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

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



Solving eq's system: $\sigma\,(B_s\bar{B}_sX)$ and $\sigma\,(B\bar{B}X)$

$$\boxed{\begin{array}{l}\sigma(e^+e^- \to B_s\bar{B}_sX) = \sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}) \\ \text{up to } B_s\bar{B}_s\pi^0\pi^0 \text{ threshold (11.004 GeV)}\end{array}}$$

$\mathscr{B}(B_s \to D_sX)$ has large uncertainty

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

Method

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

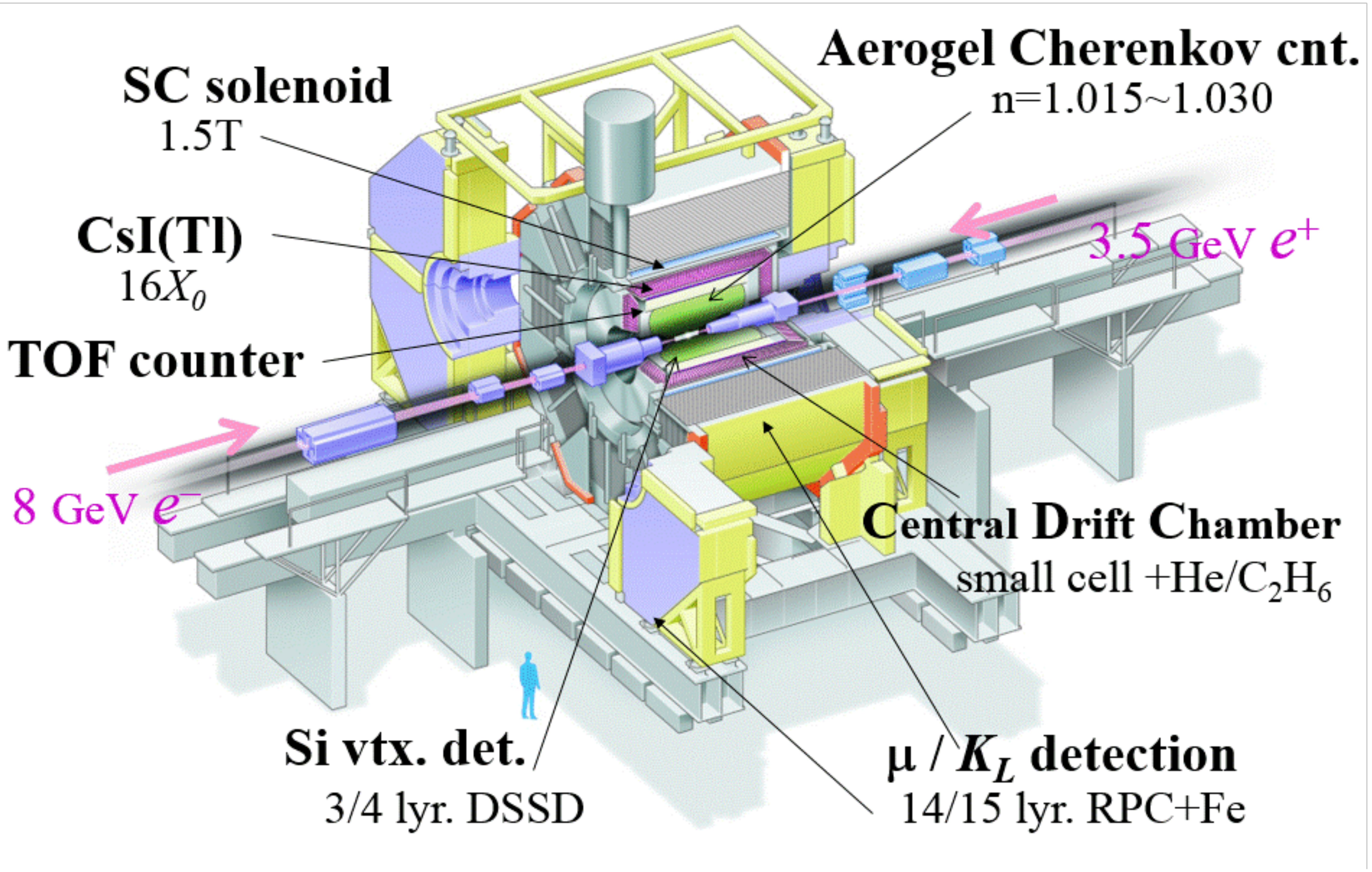
from JHEP 06 (2021) 137

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 for the analysis



Data used in this analysis:

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

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

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

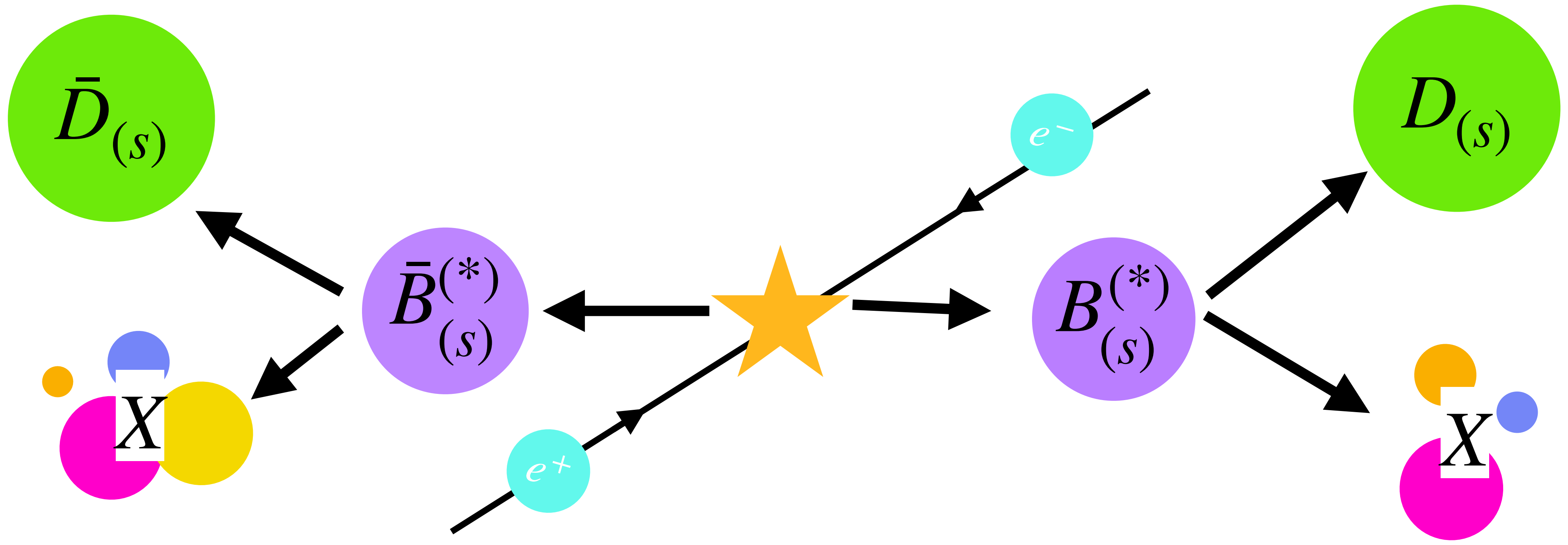
$\mathscr{L}_{5S} = 121\ \text{fb}^{-1}$

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

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

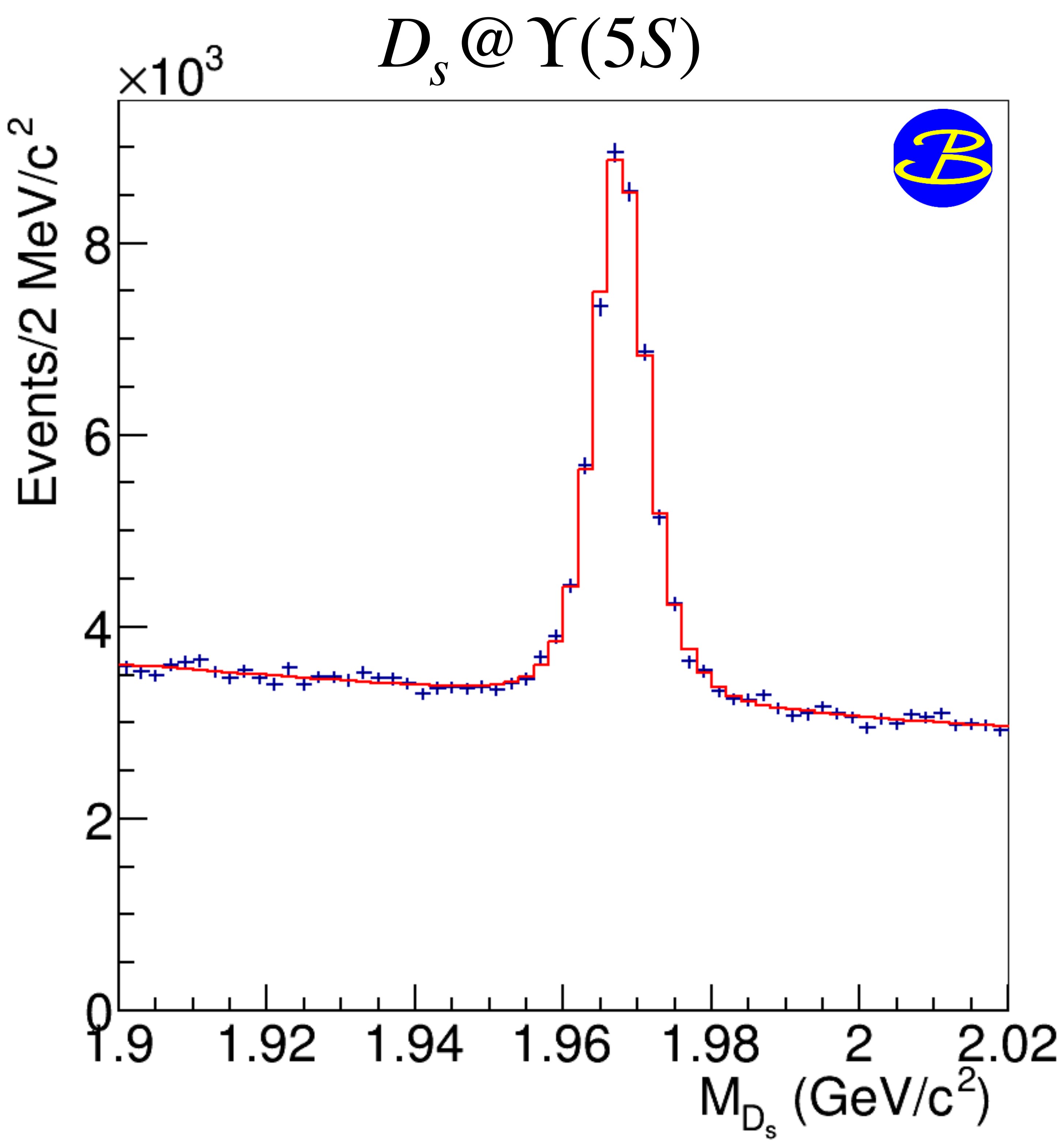
22 energy scan points (E_{cm} from 10.63 GeV to 11.02 GeV):

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



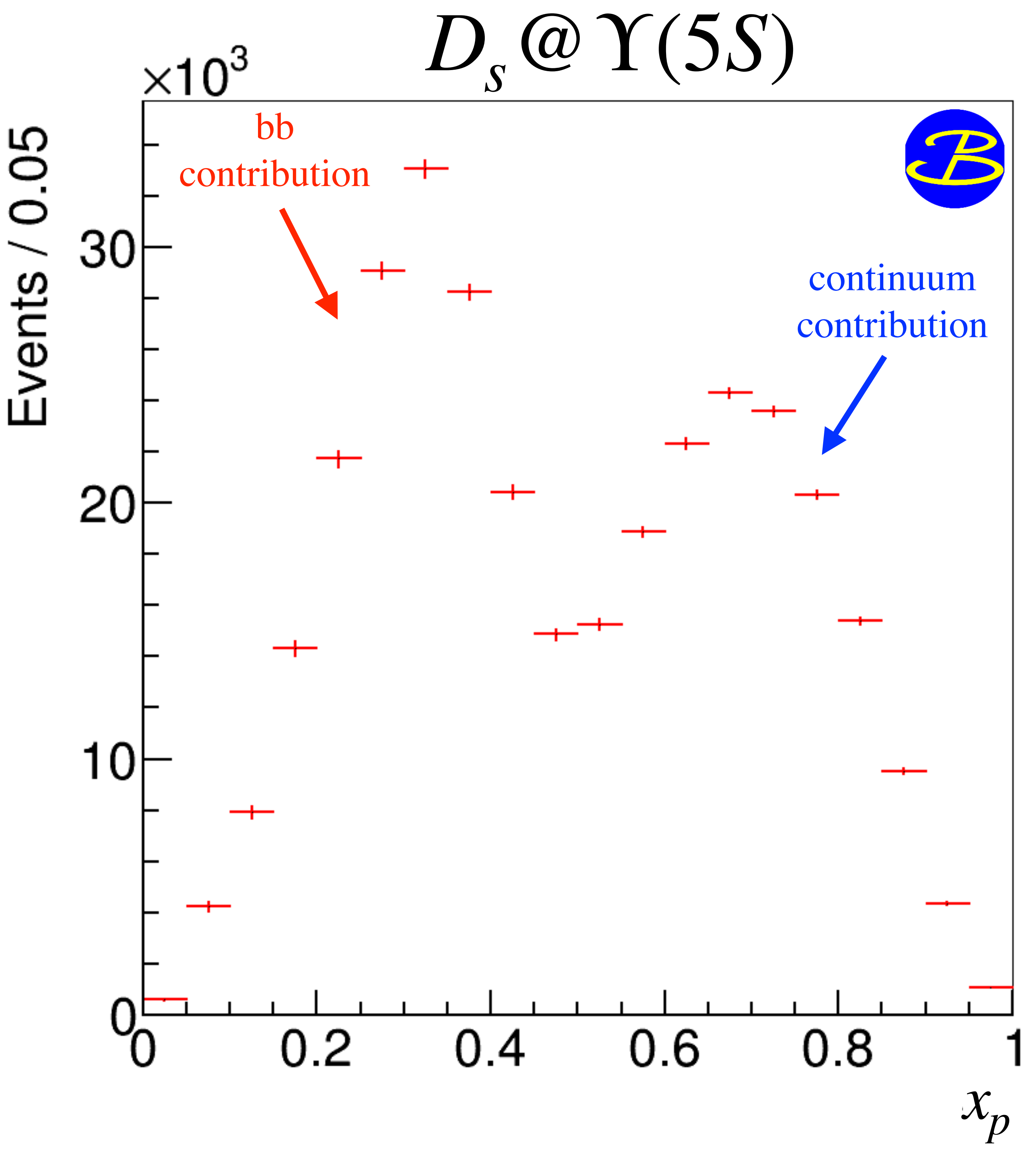
Analysis

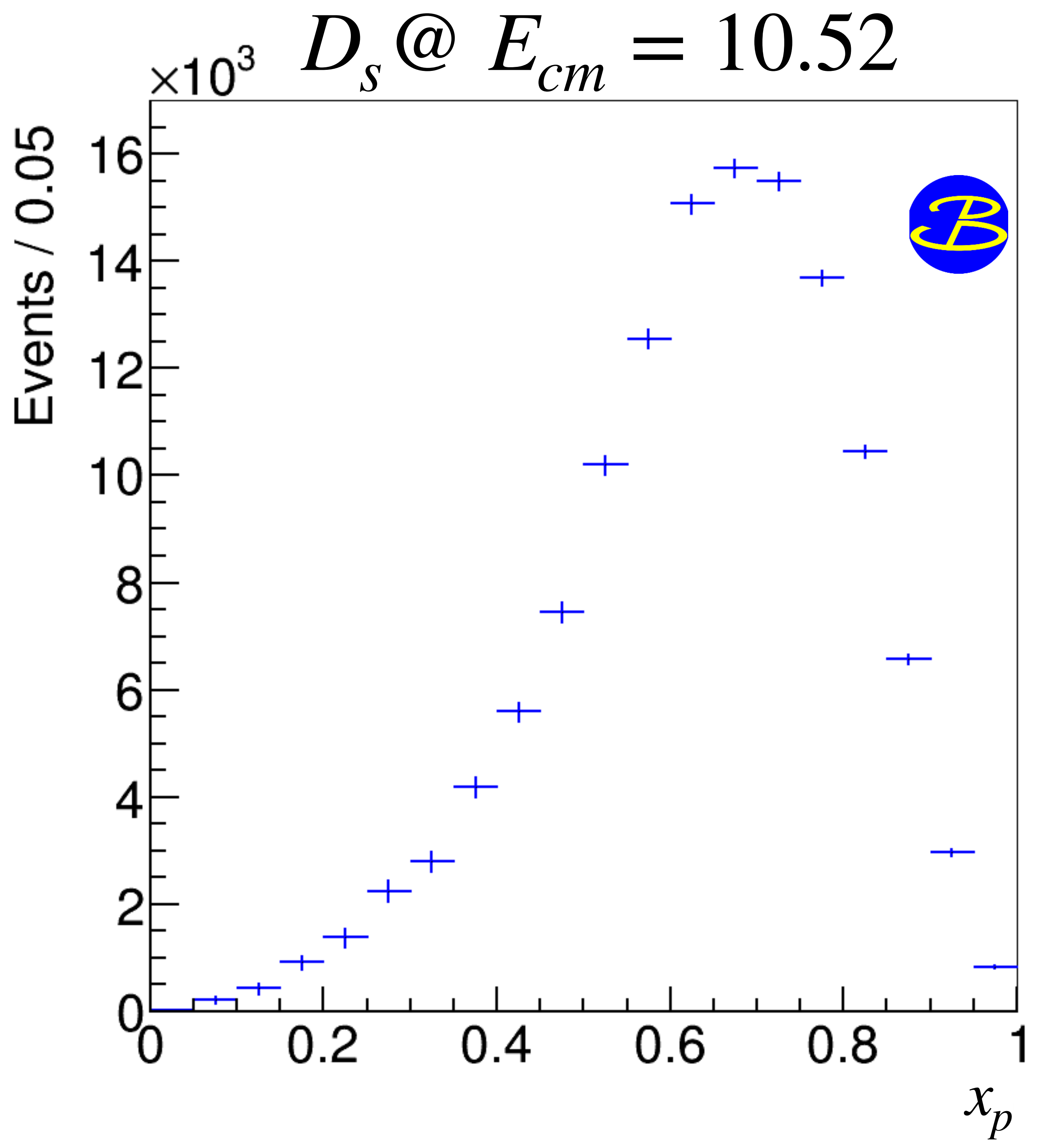
Fit $M(Ds)$ in each x_p bin



$0.25 < x_p < 0.30$

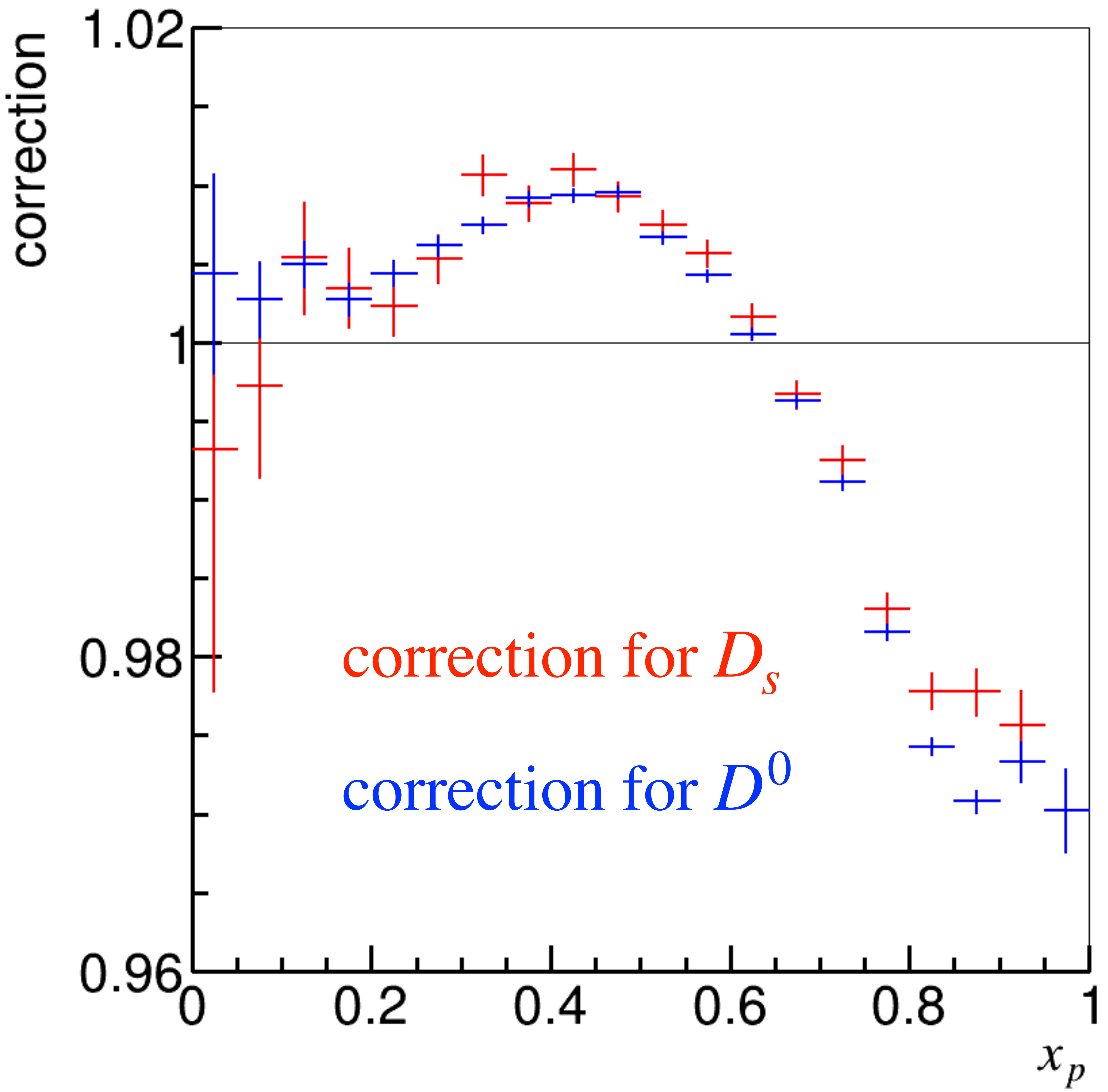
Momentum spectra





Subtraction of the continuum component is needed to obtain pure $b\bar{b}$ spectra

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

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

Continuum normalisation

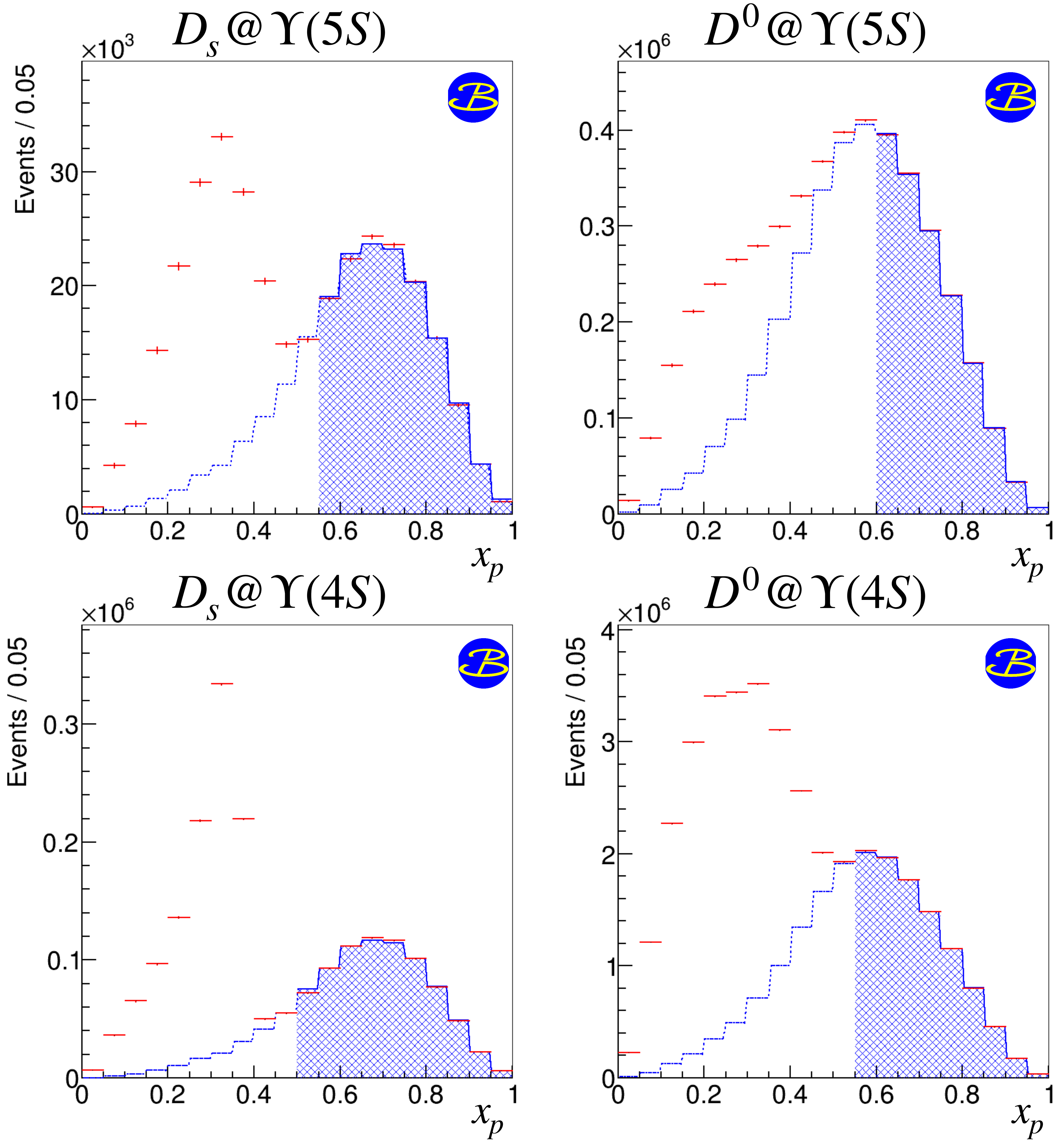
Red points — on-resonance data

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

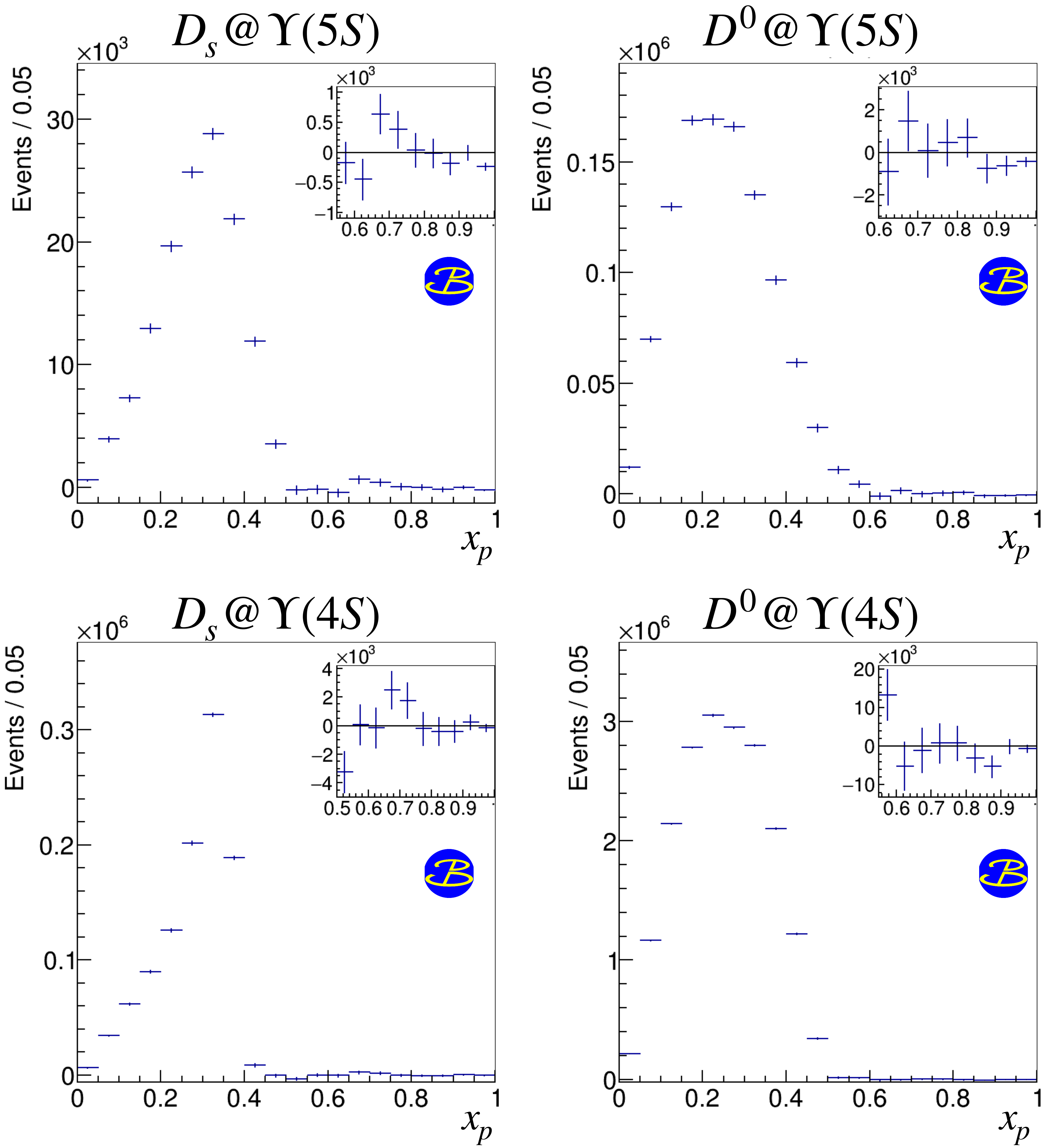
Fitting function — shape of the x_p spectra of the data at $E_{cm} = 10.52$ GeV

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

We obtain the scaling factors for continuum spectrum normalisation



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

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

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

$\Upsilon(5S)$ data:

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

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

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

This measurement

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

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

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: $\boxed{f_s = (22.0^{+2.0}_{-2.1})\,\%}$

Source	Systematic uncertainty (%)
$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)\vert_{\Upsilon(5S)}$	1.4
$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)\vert_{\Upsilon(4S)}$	0.7
$\sigma(e^+e^- \to B\bar{B}X)\vert_{\Upsilon(5S)}$	1.4
$\mathcal{B}(B_s^0 \to D_s^\pm X)$	10.5
$\sigma(e^+e^- \to b\bar{b})\vert_{\Upsilon(5S)}$	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

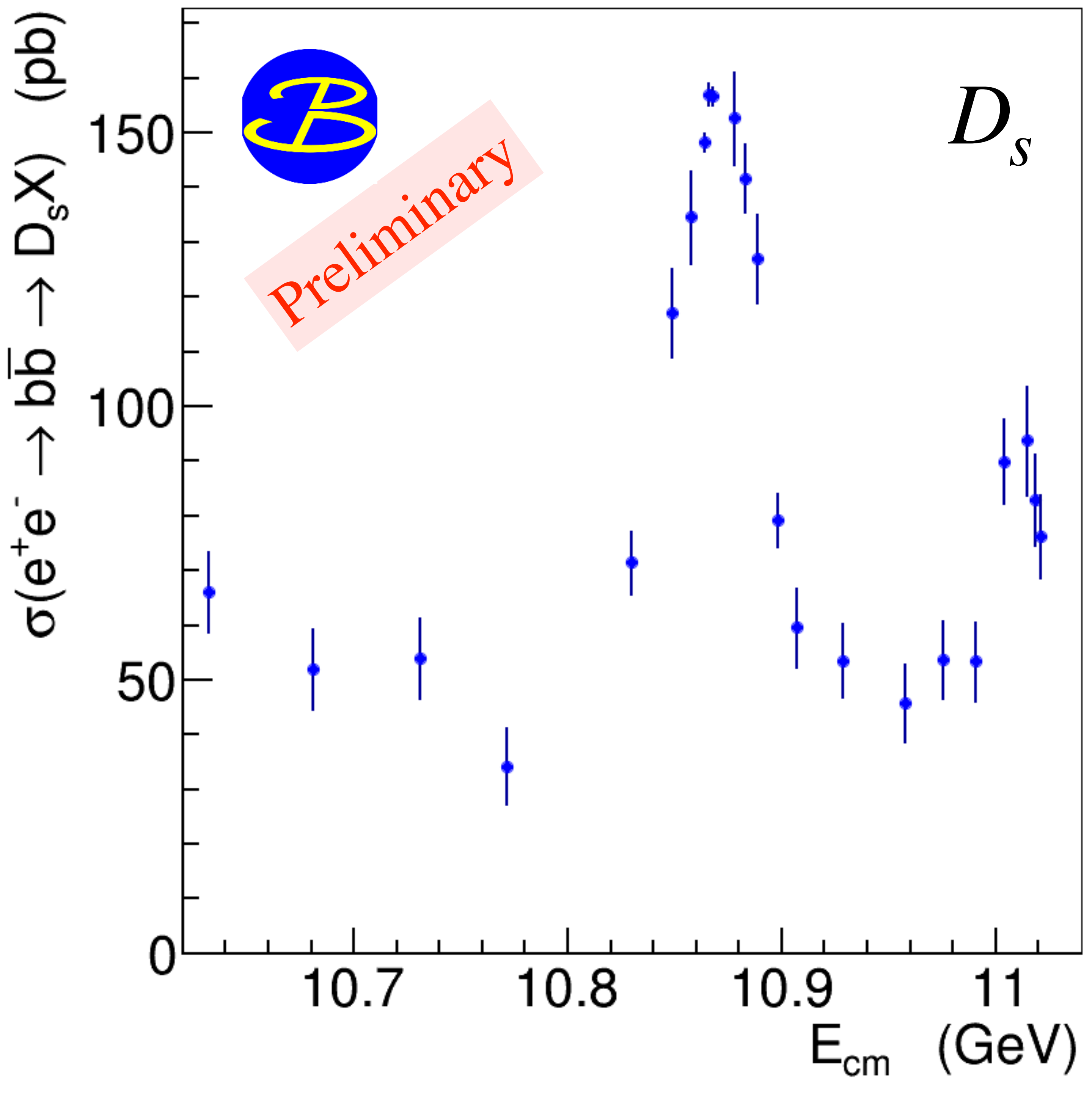
PRD 105 (2022) 1, 012004

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

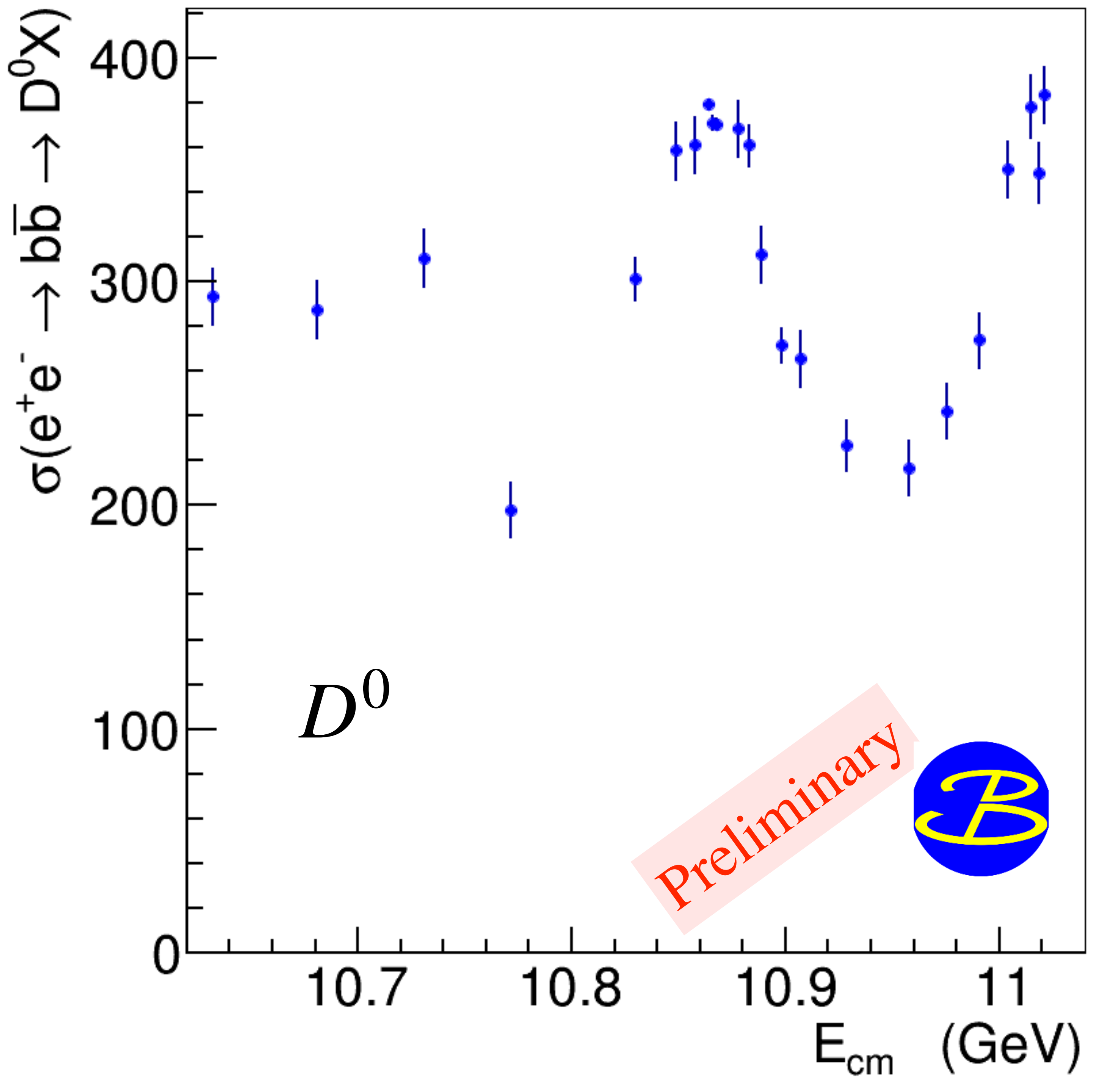
$\sigma(e^+e^- \to b\bar{b} \to D_s X)$ and $\sigma(e^+e^- \to b\bar{b} \to D^0 X)$

Repeat procedure at each energy scan point:

$\sigma(e^+e^- \to b\bar{b} \to D_s X)$



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



+ results at $\Upsilon(4S)$ and at $\Upsilon(5S)$:

$$\mathcal{B}(B \to D_s X) = (11.28 \pm 0.03 \pm 0.43)\,\%$$

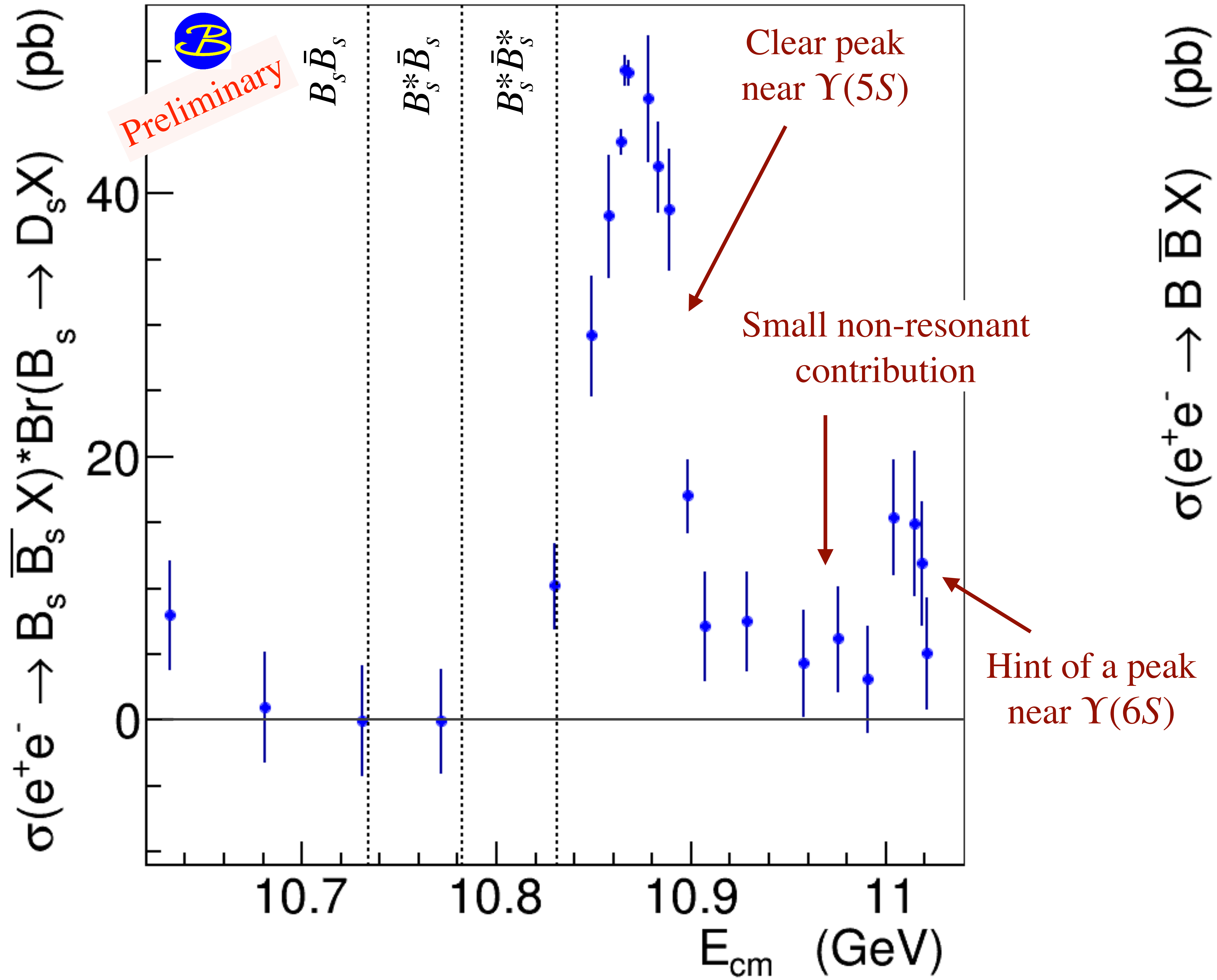
$$\mathcal{B}(B \to D^0 X) = (66.63 \pm 0.04 \pm 1.77)\,\%$$

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

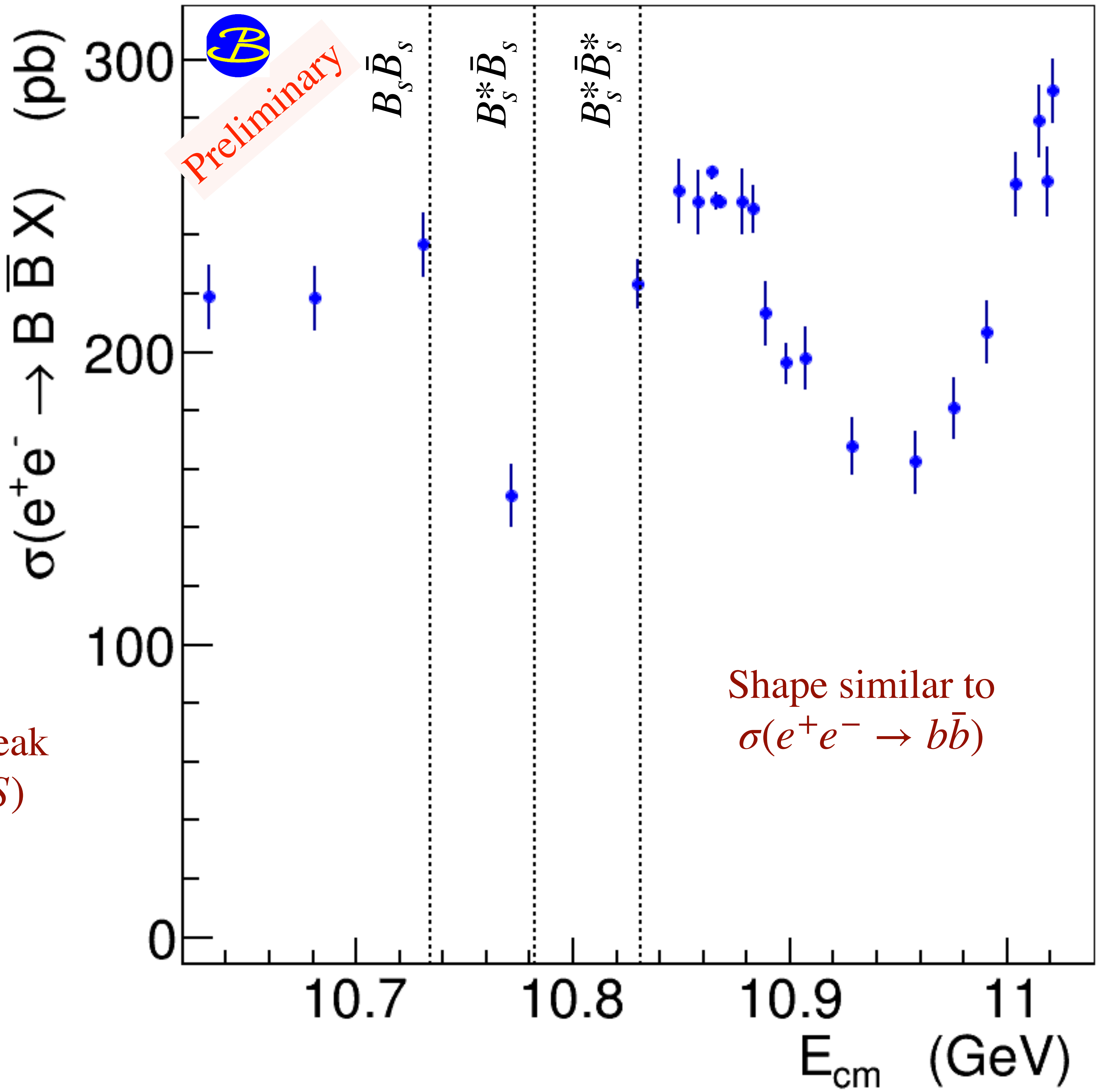
$$\begin{cases} \sigma(B_s\bar{B}_sX) \cdot \mathcal{B}(B_s \to D_s X) = 0.54 \cdot \sigma(D_s X) - 0.09 \cdot \sigma(D^0 X) \\ \sigma(B\bar{B}X) = -0.34 \cdot \sigma(D_s X) + 0.81 \cdot \sigma(D^0 X) \end{cases}$$

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

$\sigma(e^+e^- \to B_s\bar{B}_sX)\cdot\mathscr{B}(B_s \to D_sX)$



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



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

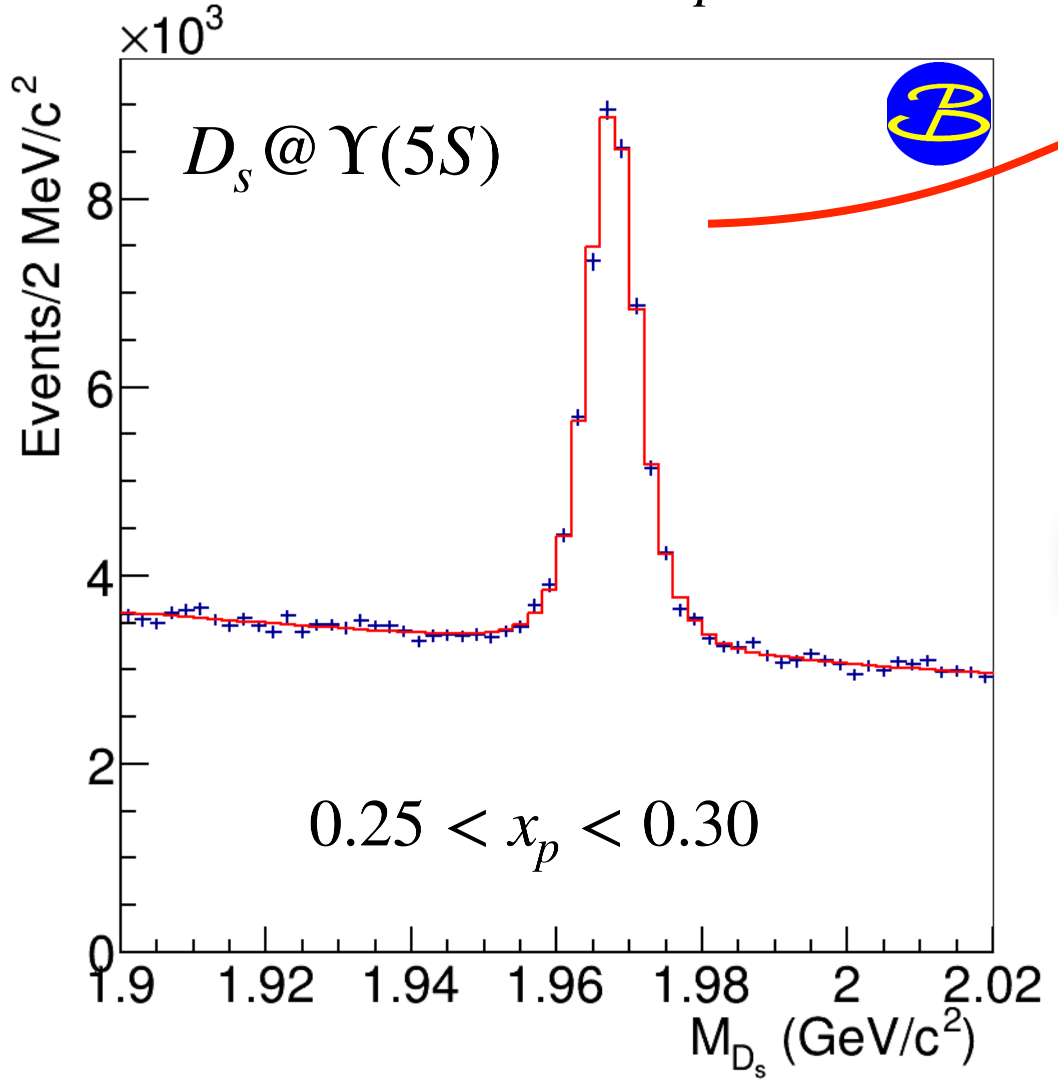
- ✓ The fraction of B_s mesons at $\Upsilon(5S)$ is measured to be $f_s = (22.0^{+2.0}_{-2.1})\ \%$

Thank you very much for your attention!

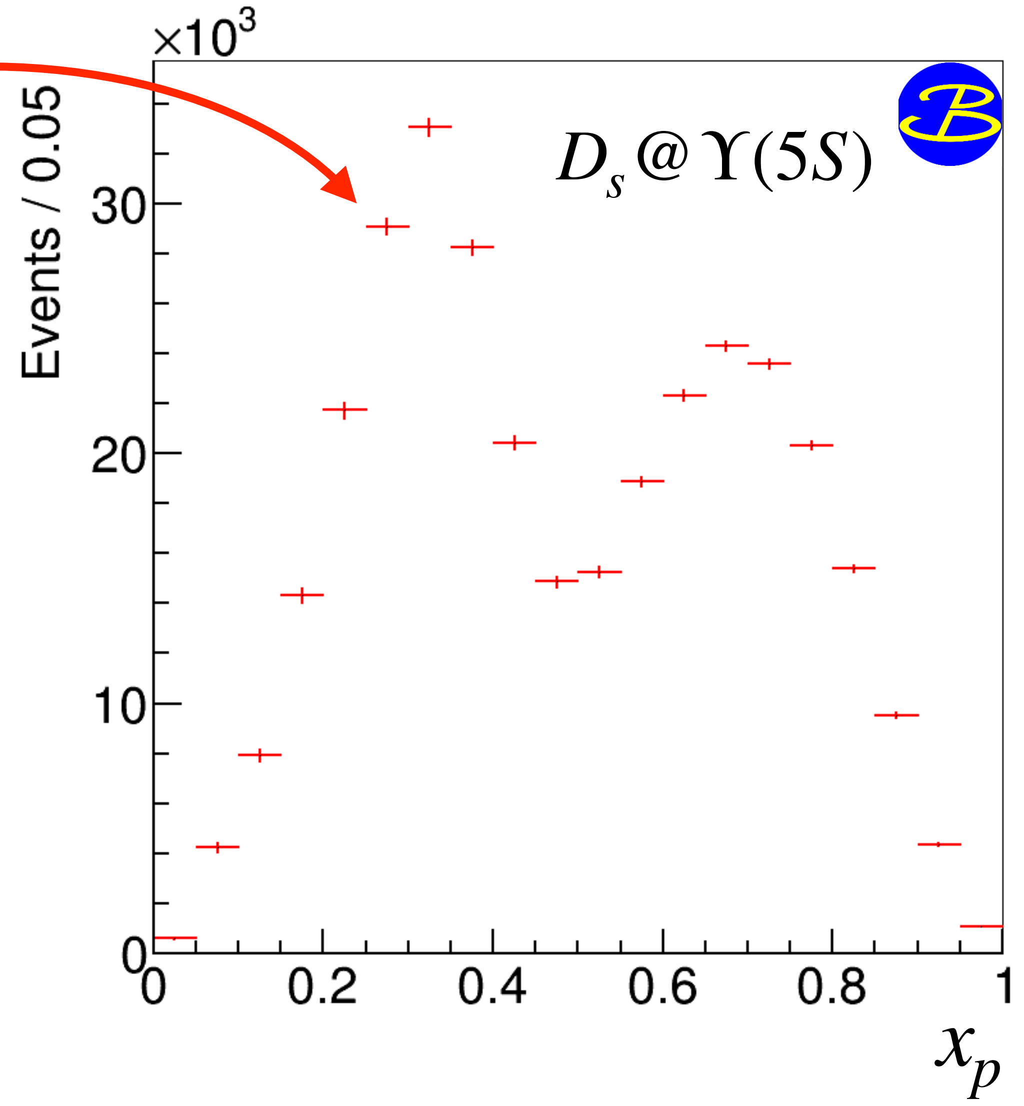
Backup

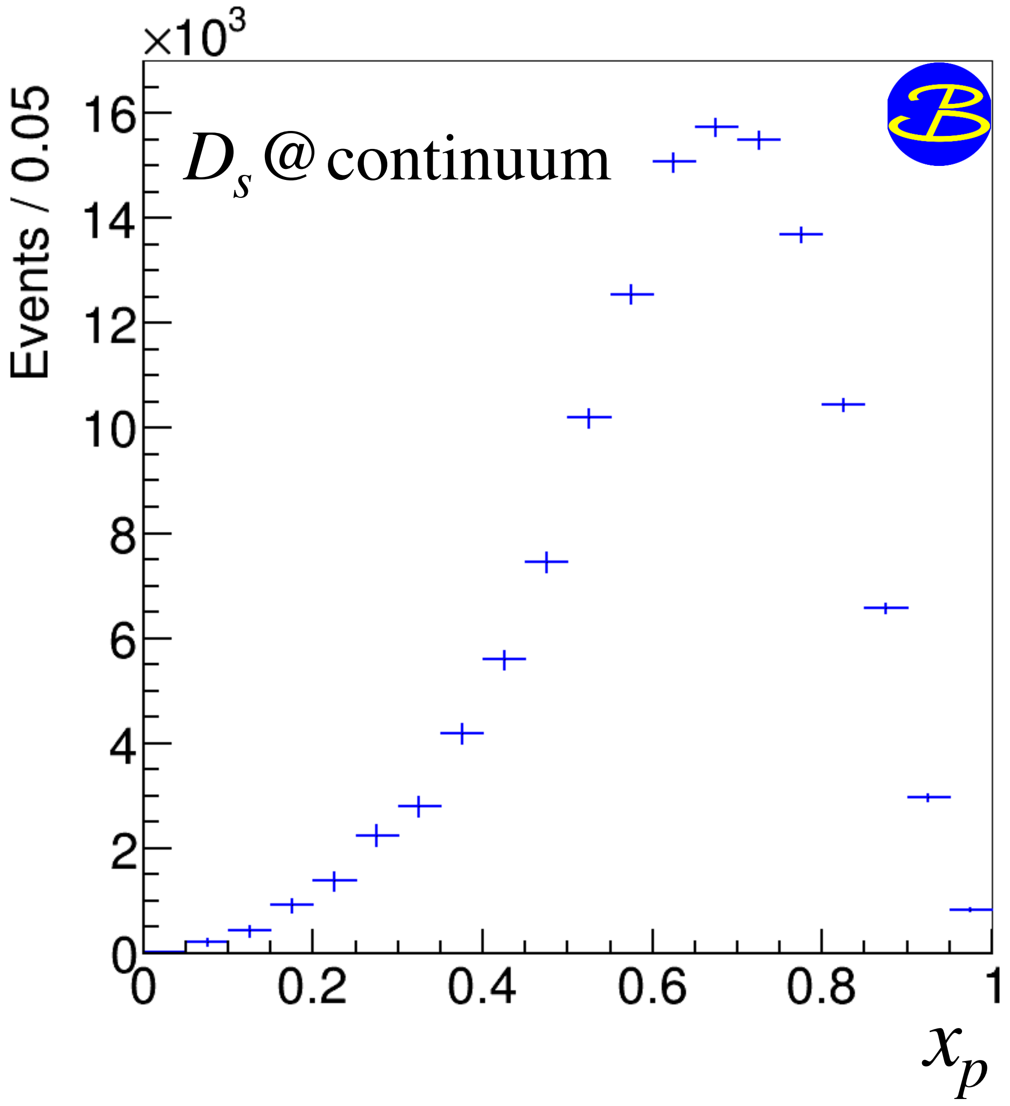
Analysis

Fit $M(Ds)$ in x_p bins

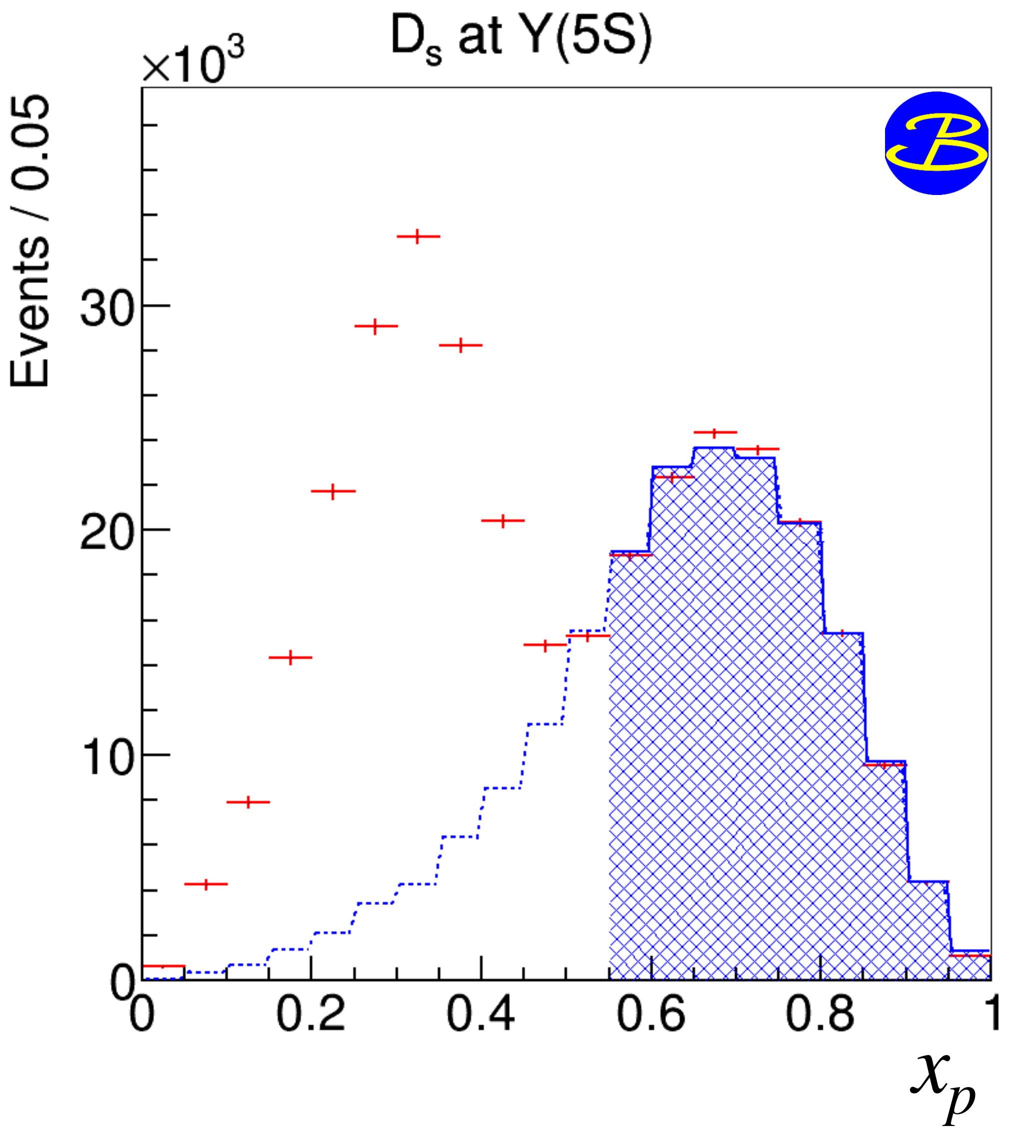


Obtain the x_p spectra

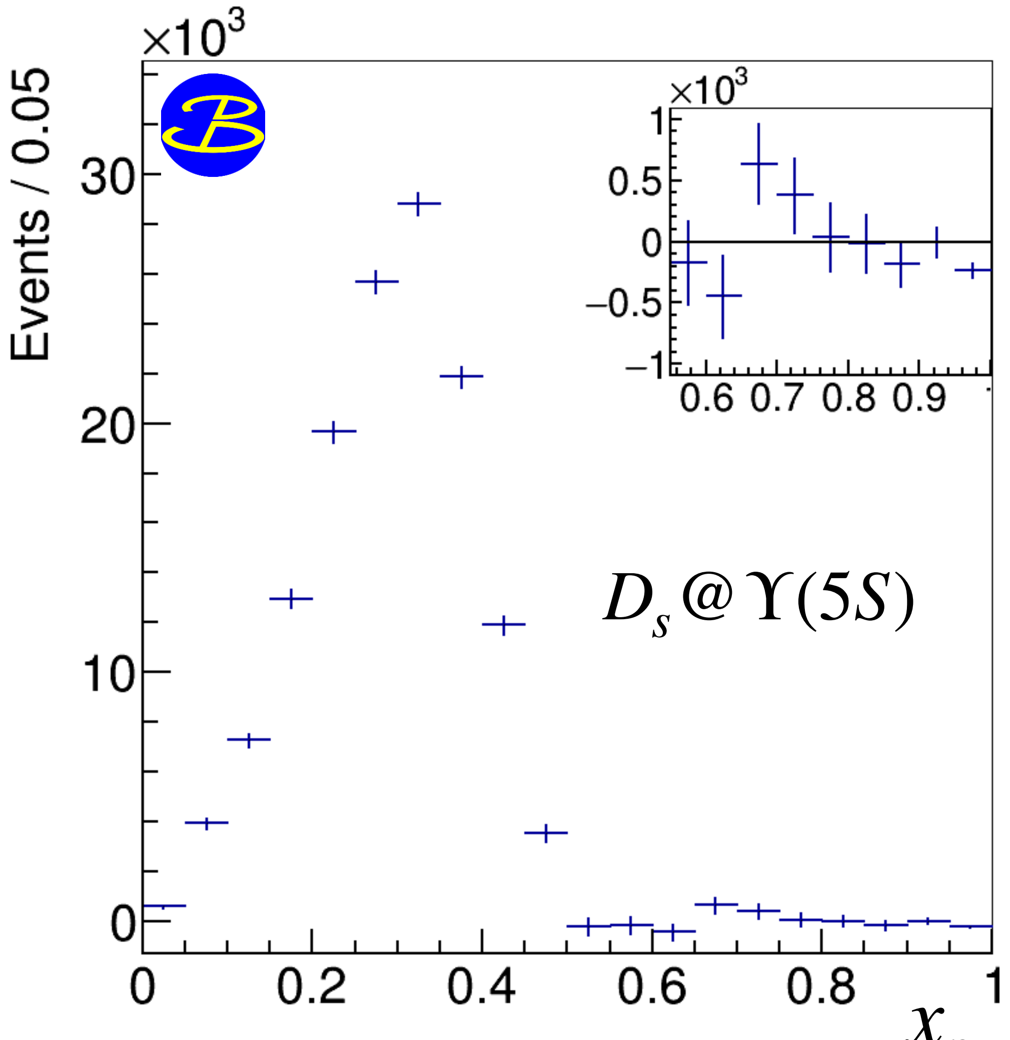




Fit in high x_p to continuum x_p



After continuum subtraction



D cross sections

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

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

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

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

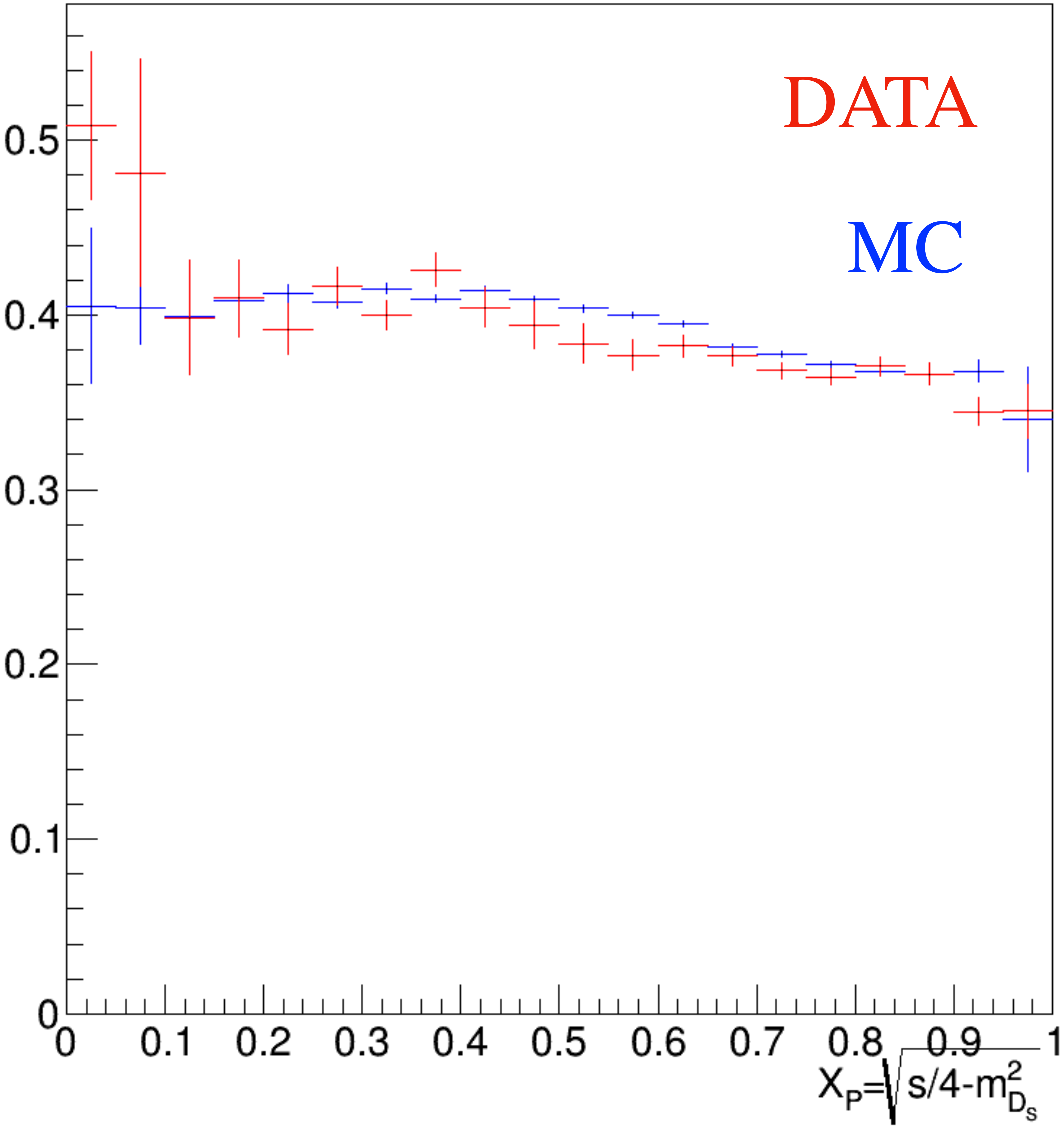
At each scan point:

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

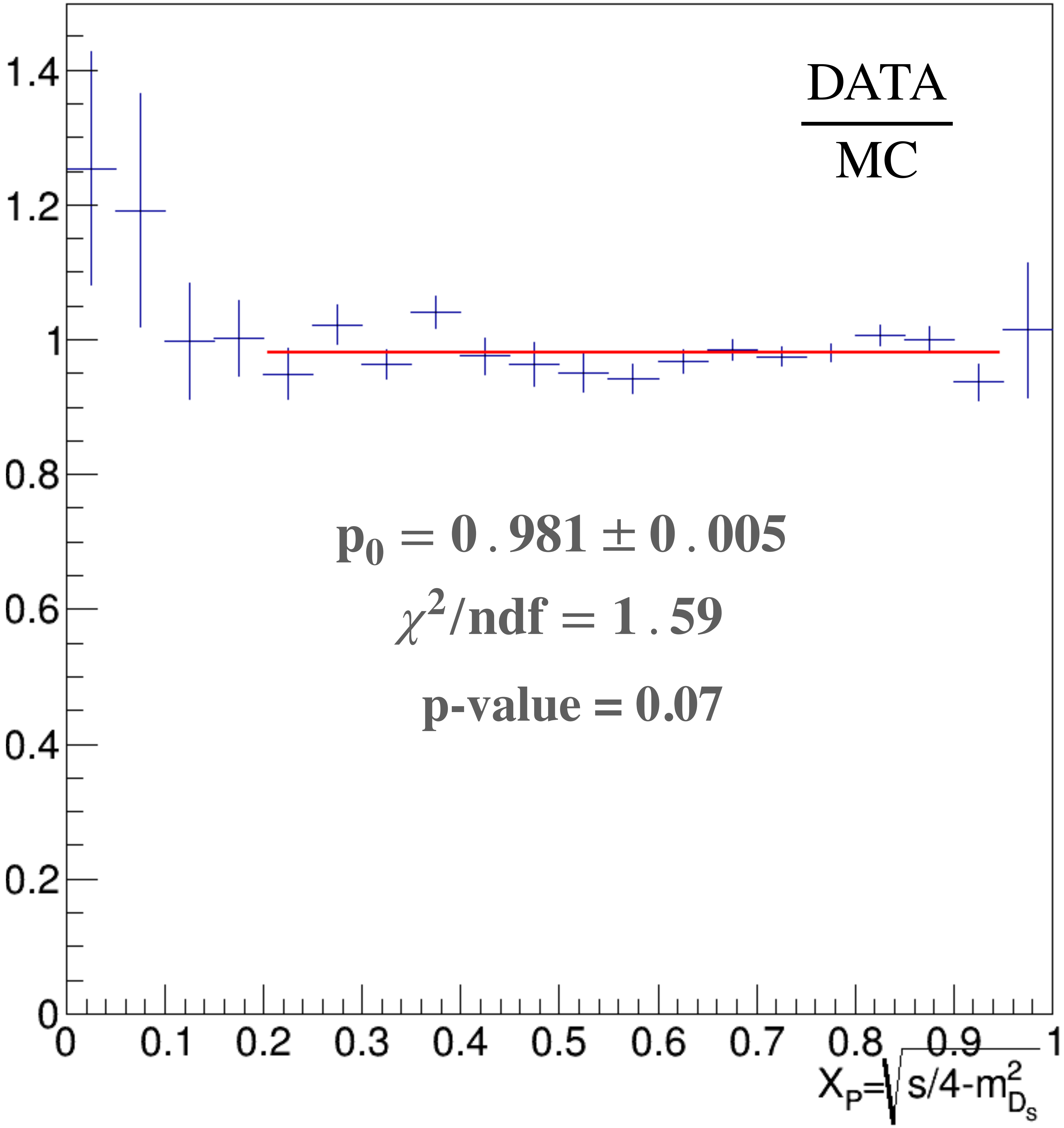
ϕ-cut efficiency correction

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

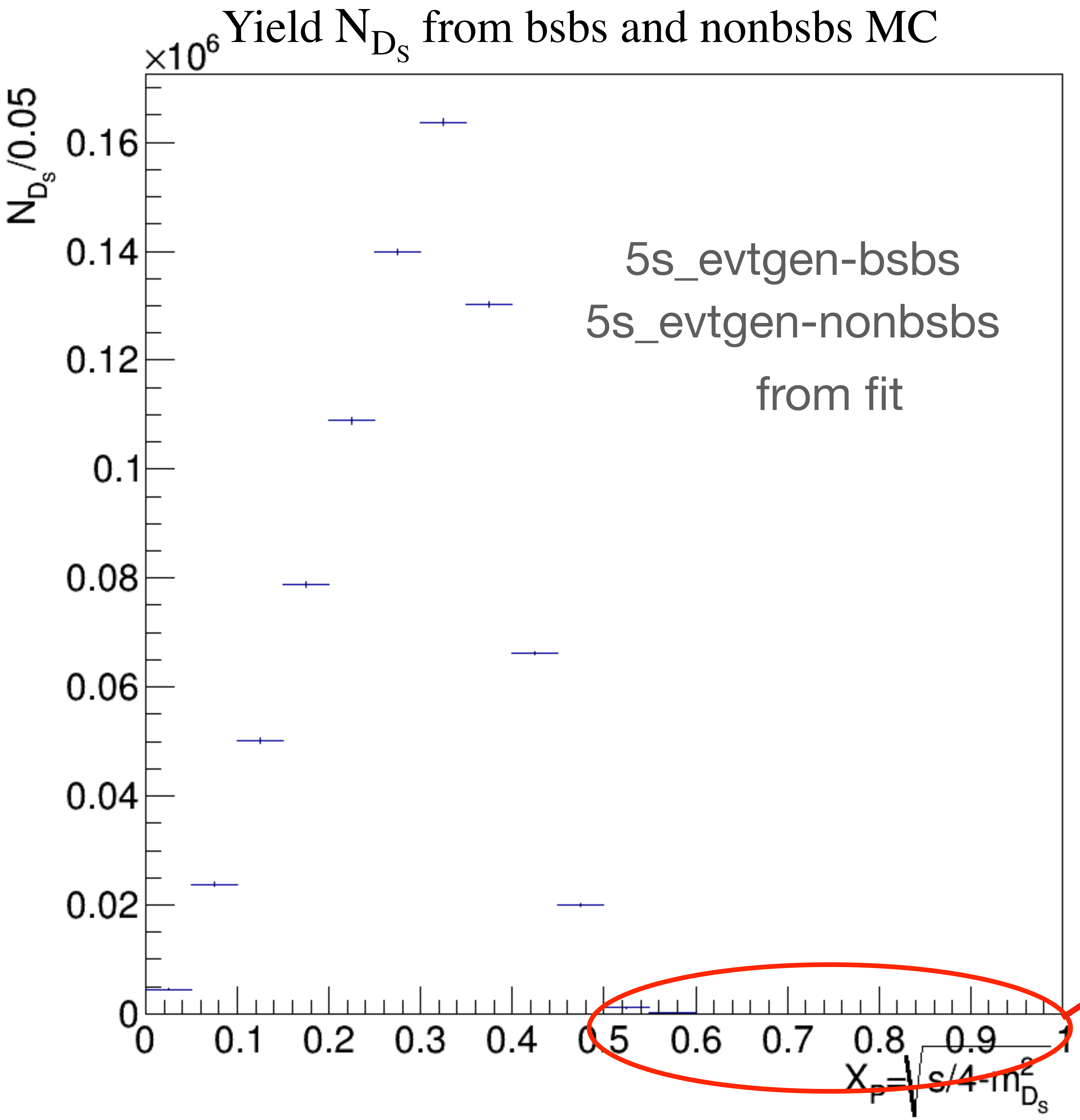
$$\frac{N_{cut}}{N_{cut} + N_{anti-cut}}$$

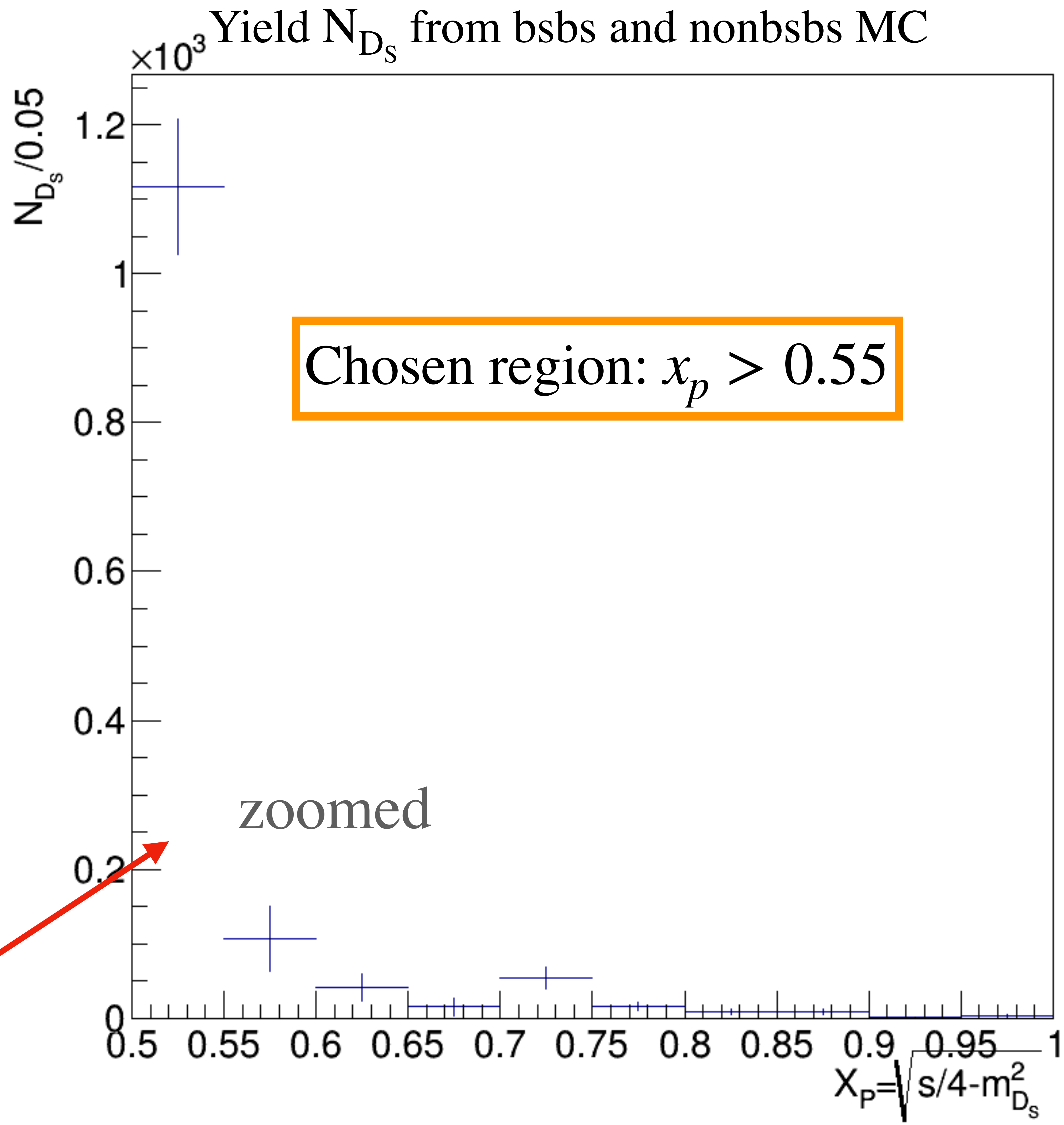


Ratio

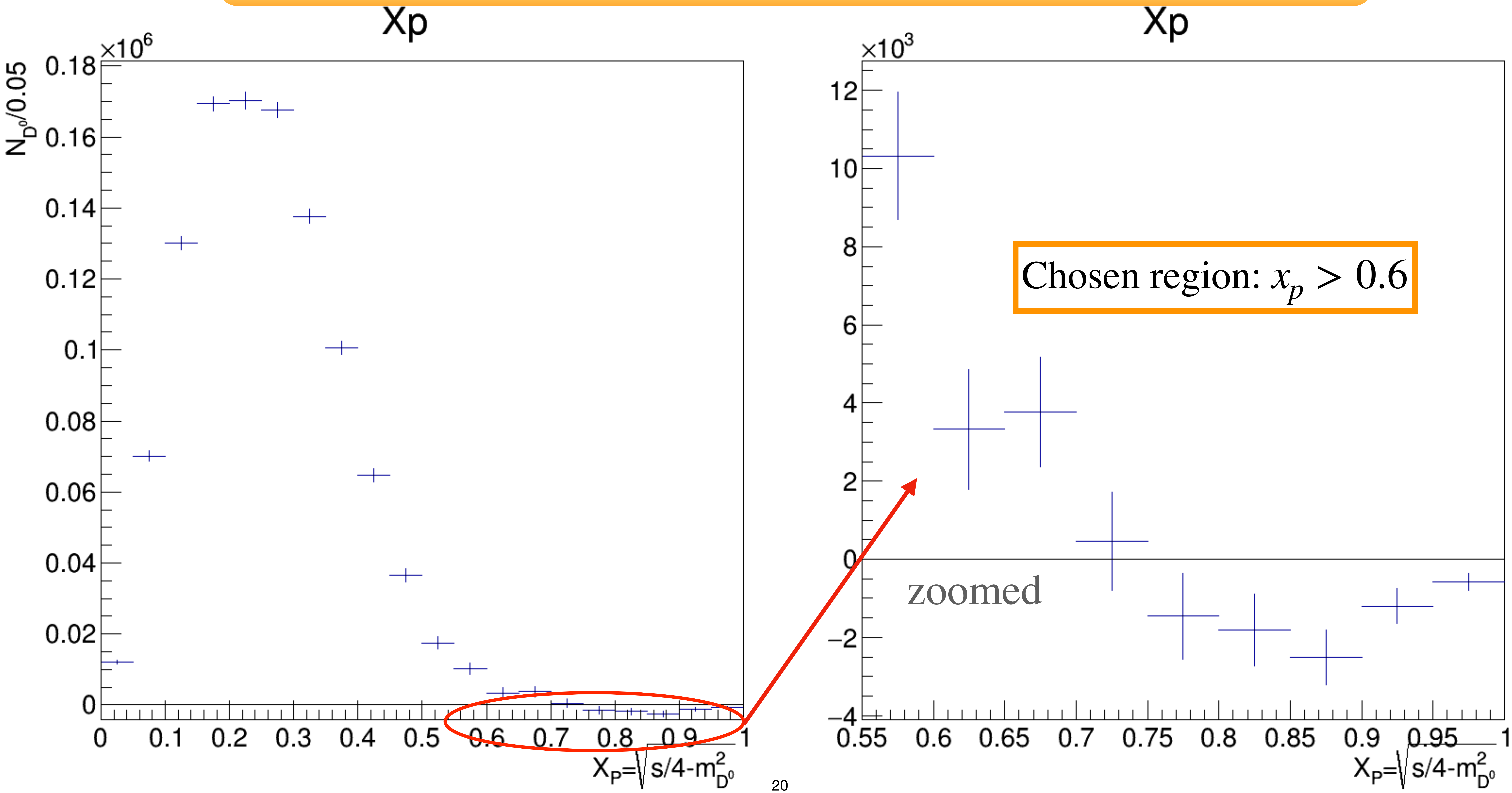


x_p spectra of D_S in bb MC at $\Upsilon(5S)$

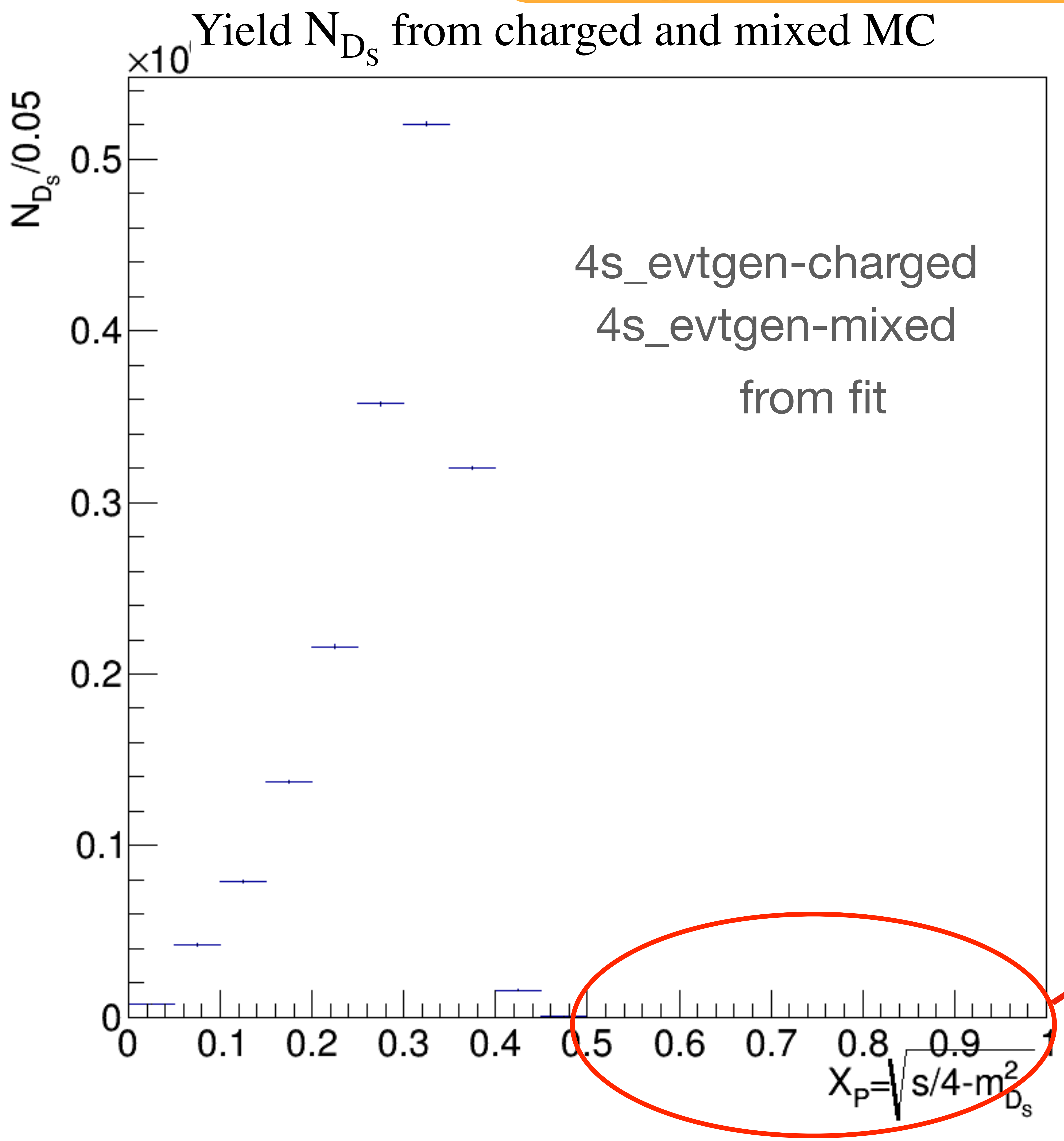


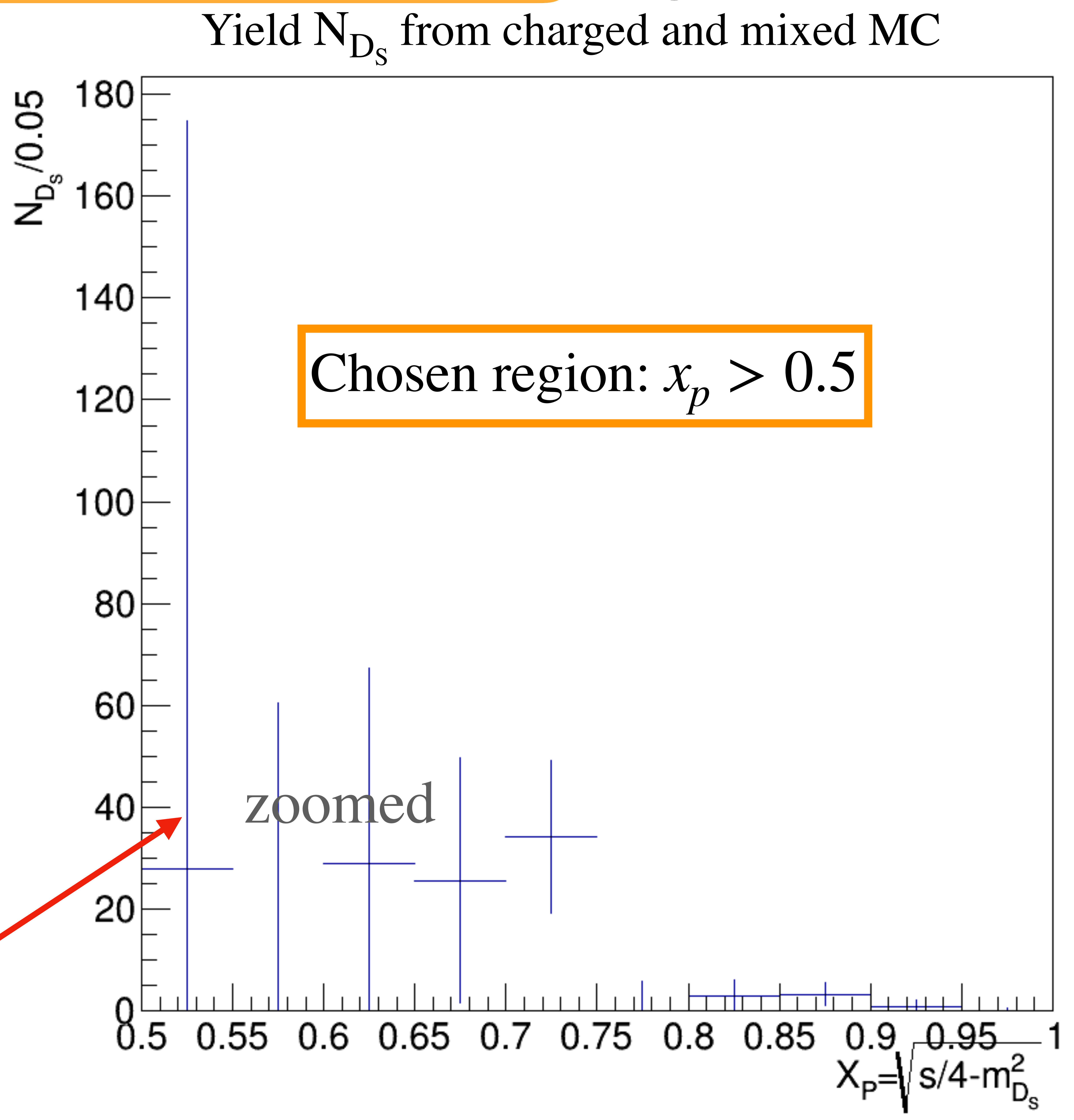


Continuum spectrum subtraction for D^0 at $\Upsilon(5S)$

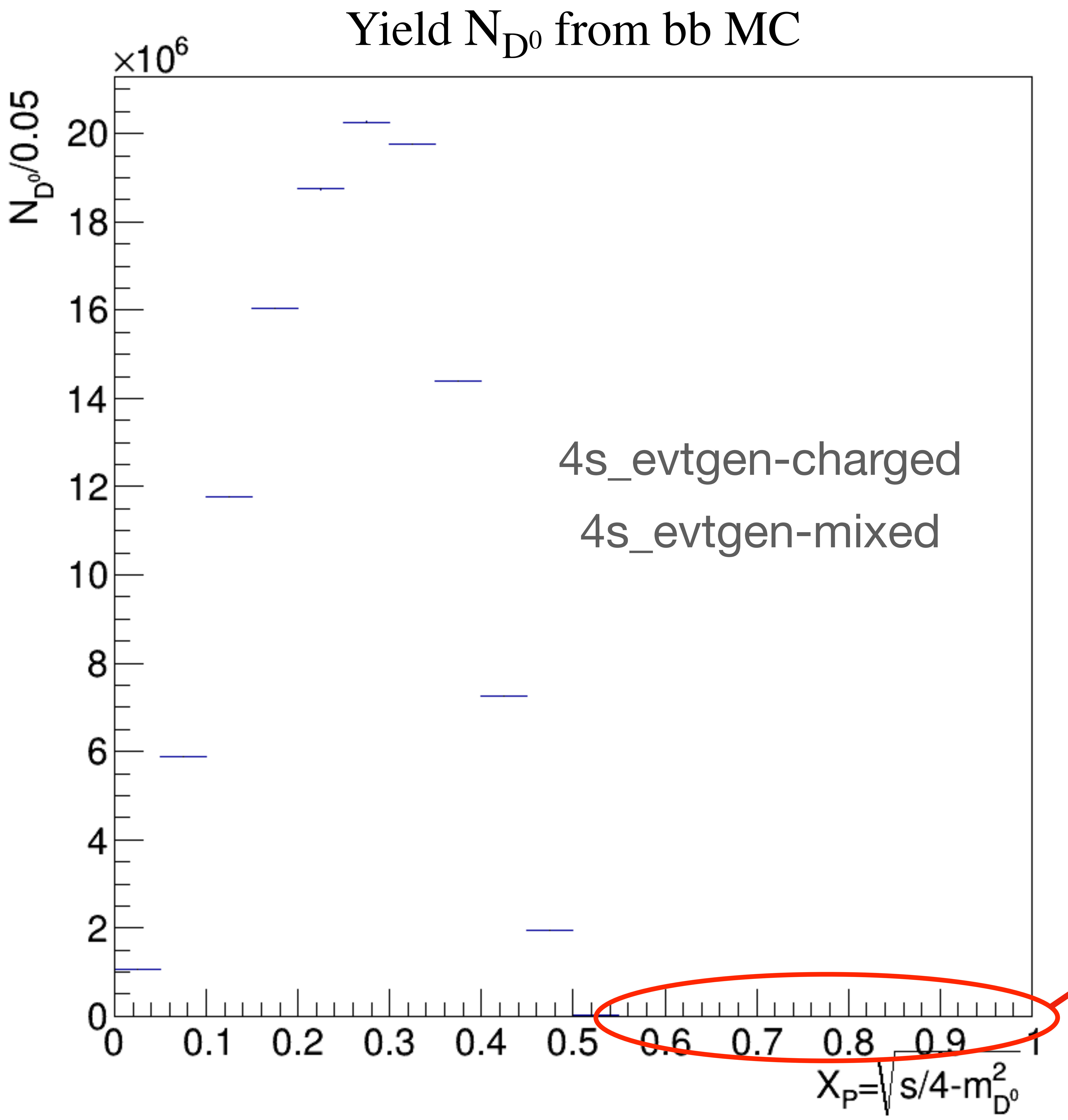


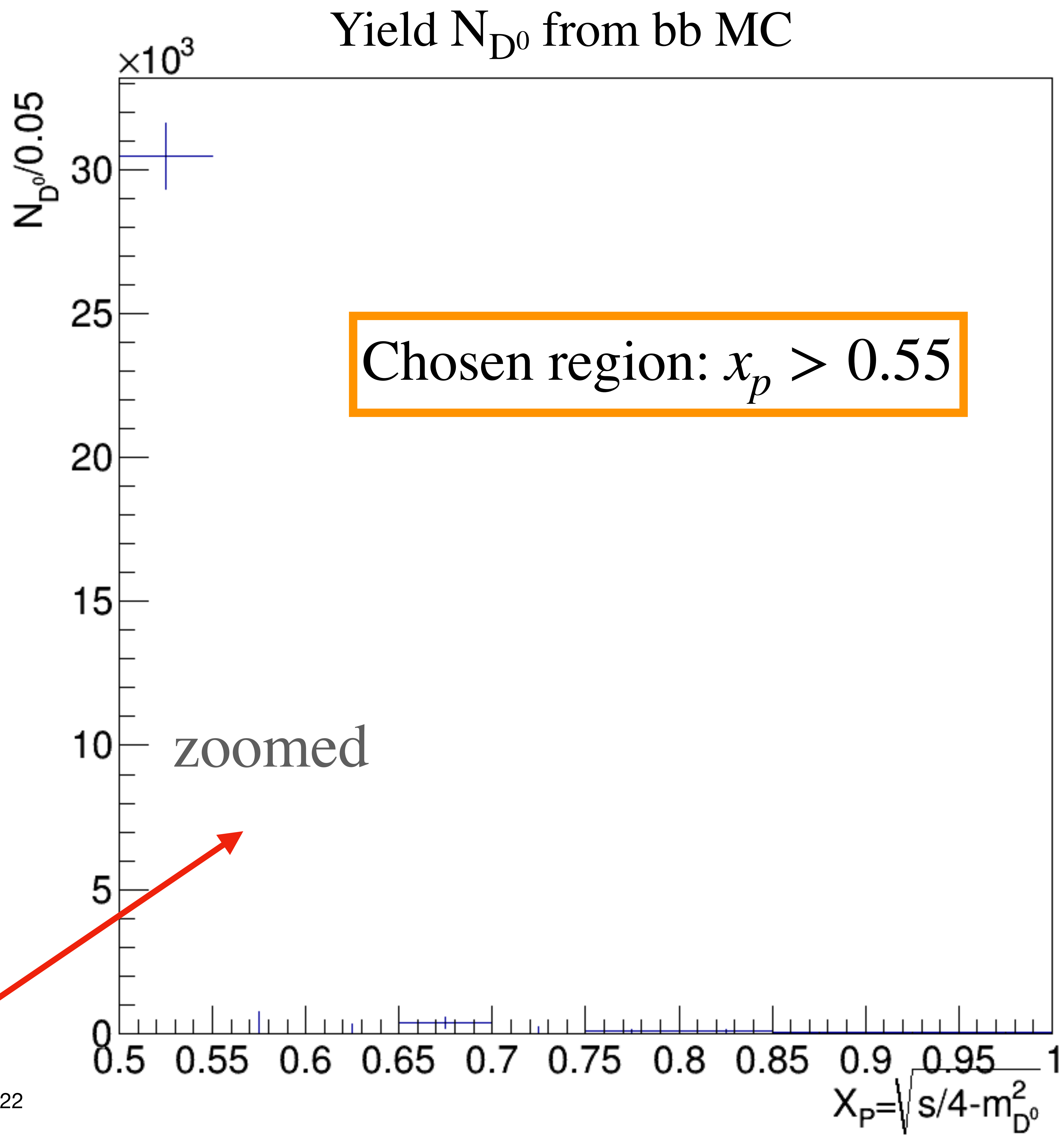
x_p spectra of D_S in bb MC at $\Upsilon(4S)$





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





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

Source	**Ds at Υ(5S)**	**D0 at Υ(5S)**	**Ds at Υ(4S)**	**D0 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**	**2.3**

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:

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

Absolute systematic uncertainties