The study of D_{sJ} at Belle and Belle II

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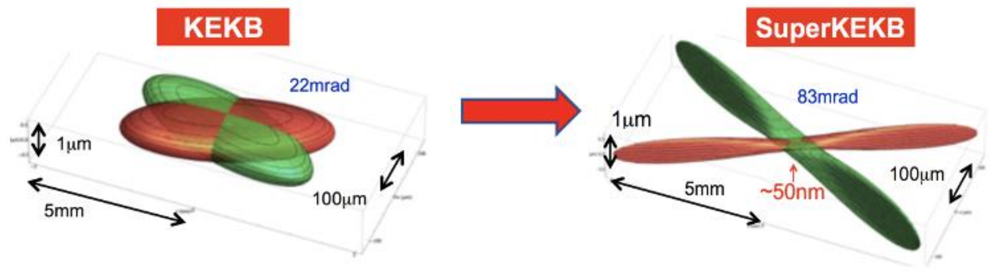
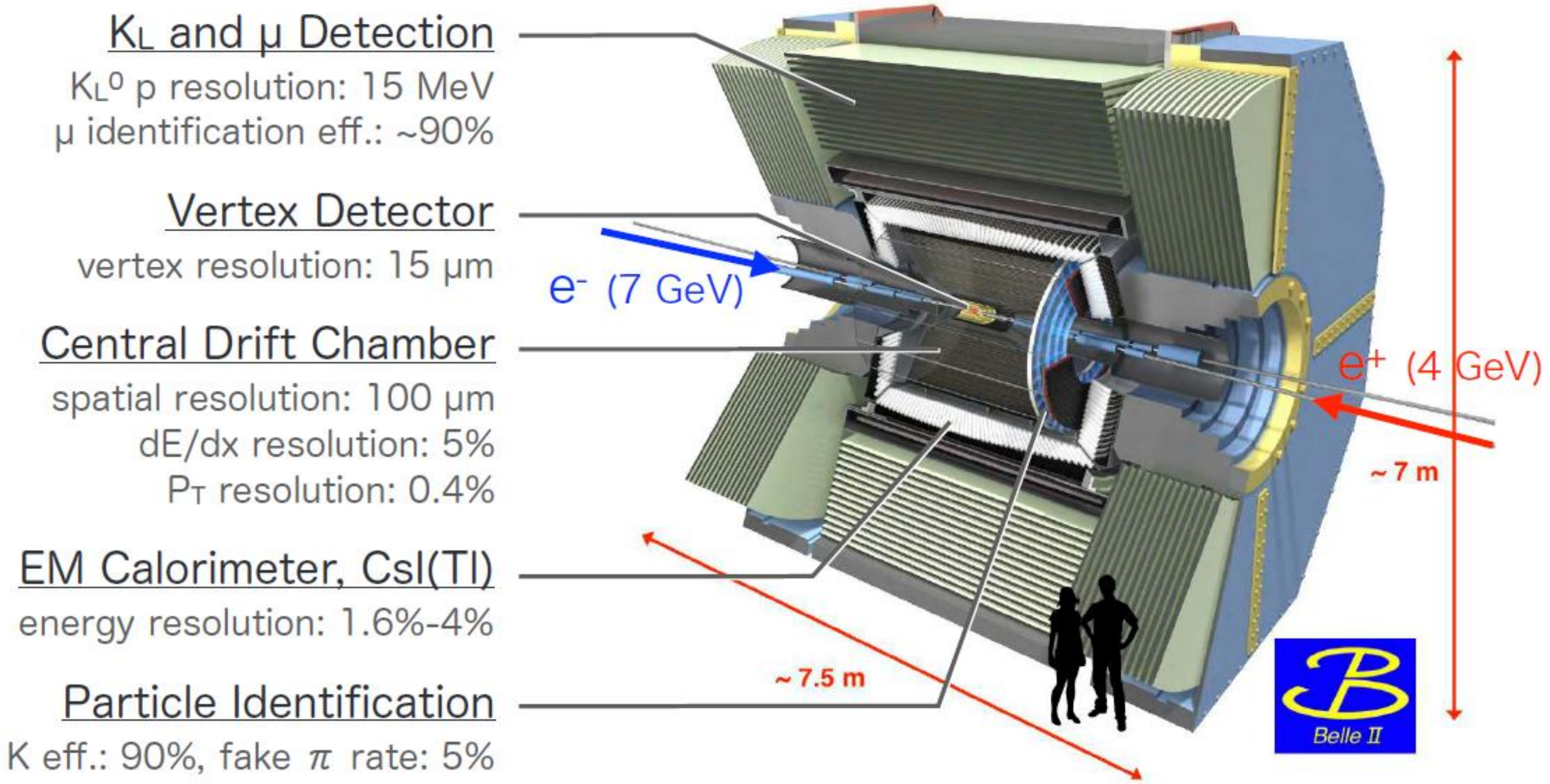
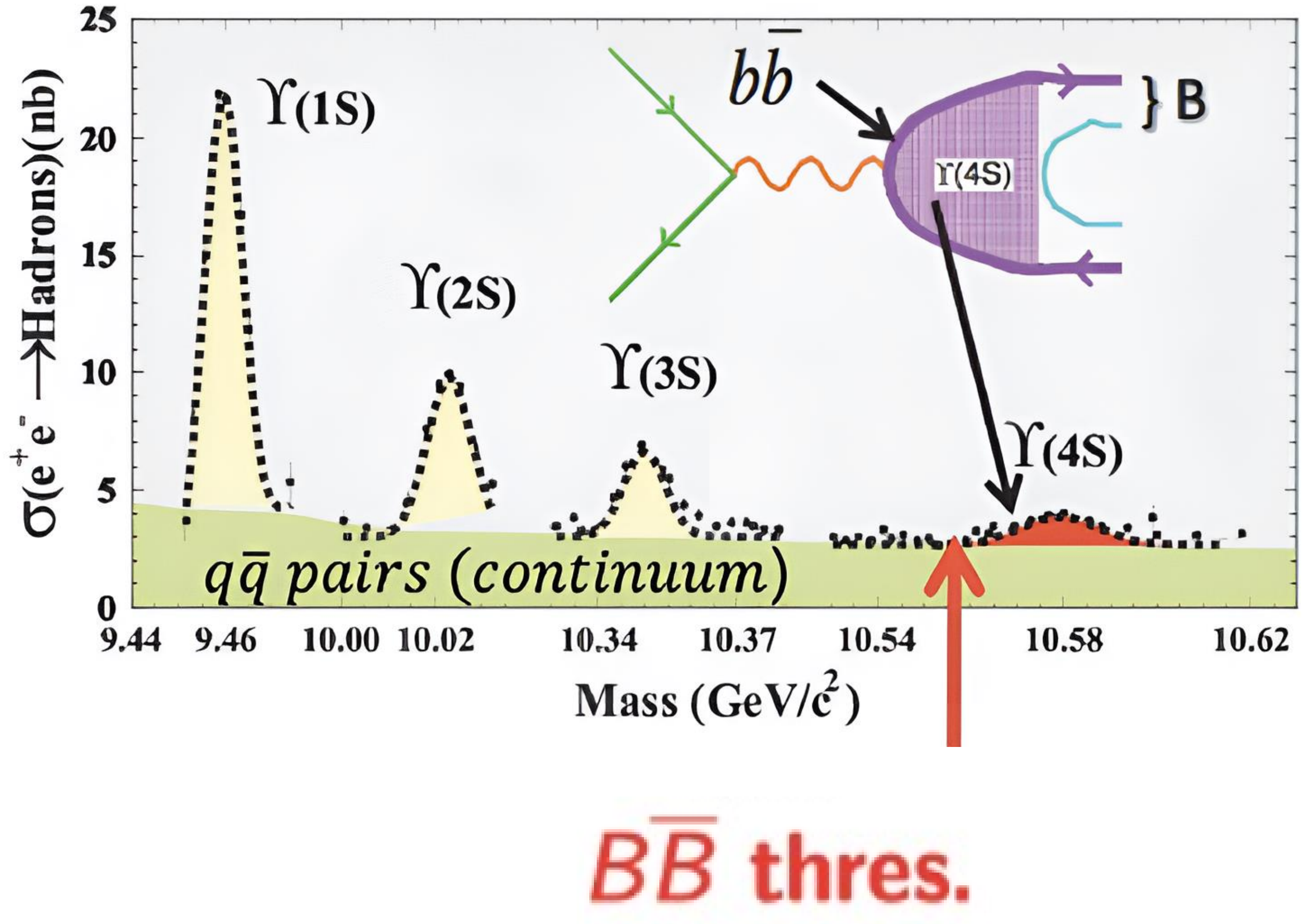
D_{sJ} physics

- Extract $|V_{cs}|$ via (semi)leptonic decay $\rightarrow$ BESI
- Amplitude analyses $\rightarrow$ BESIII
- Spectroscopy $\rightarrow$ Belle and LHCb
- … …



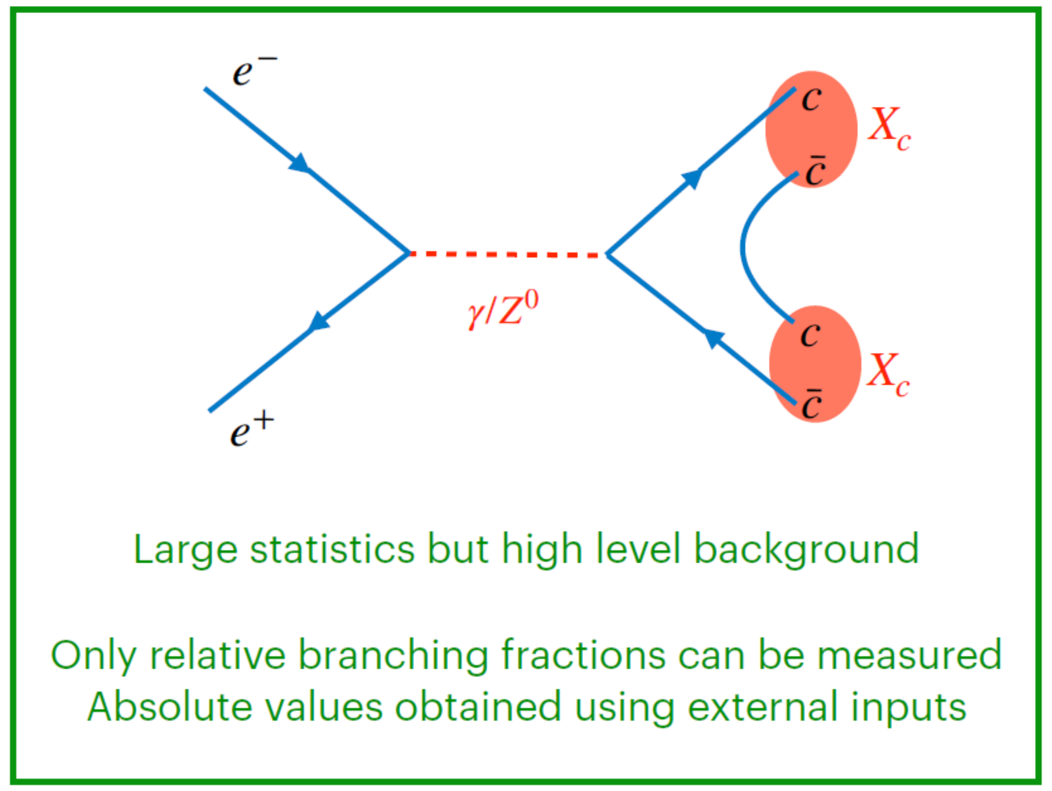


Two processes of D_{sJ} generation at Belle (II) :

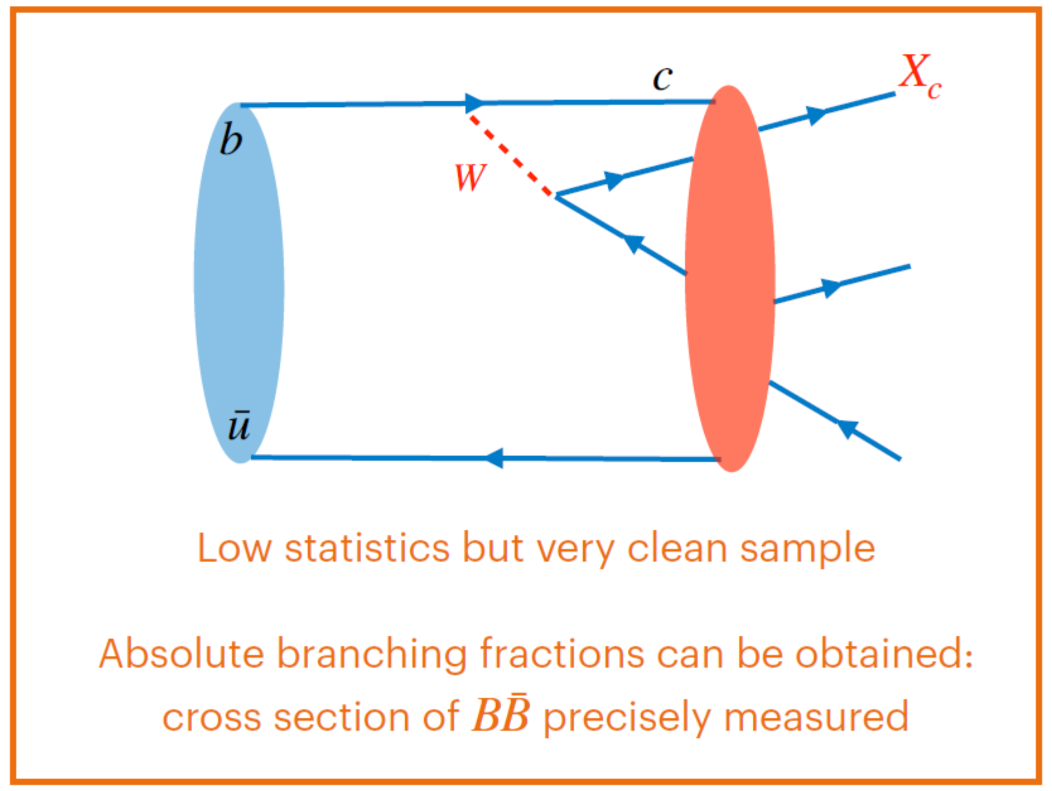


$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3

Two charmed hadrons produced from continuum



One or more charmed hadrons produced in B decays



Spectrum of D_{sJ}

Xian-Hui Zhong 2110.05024

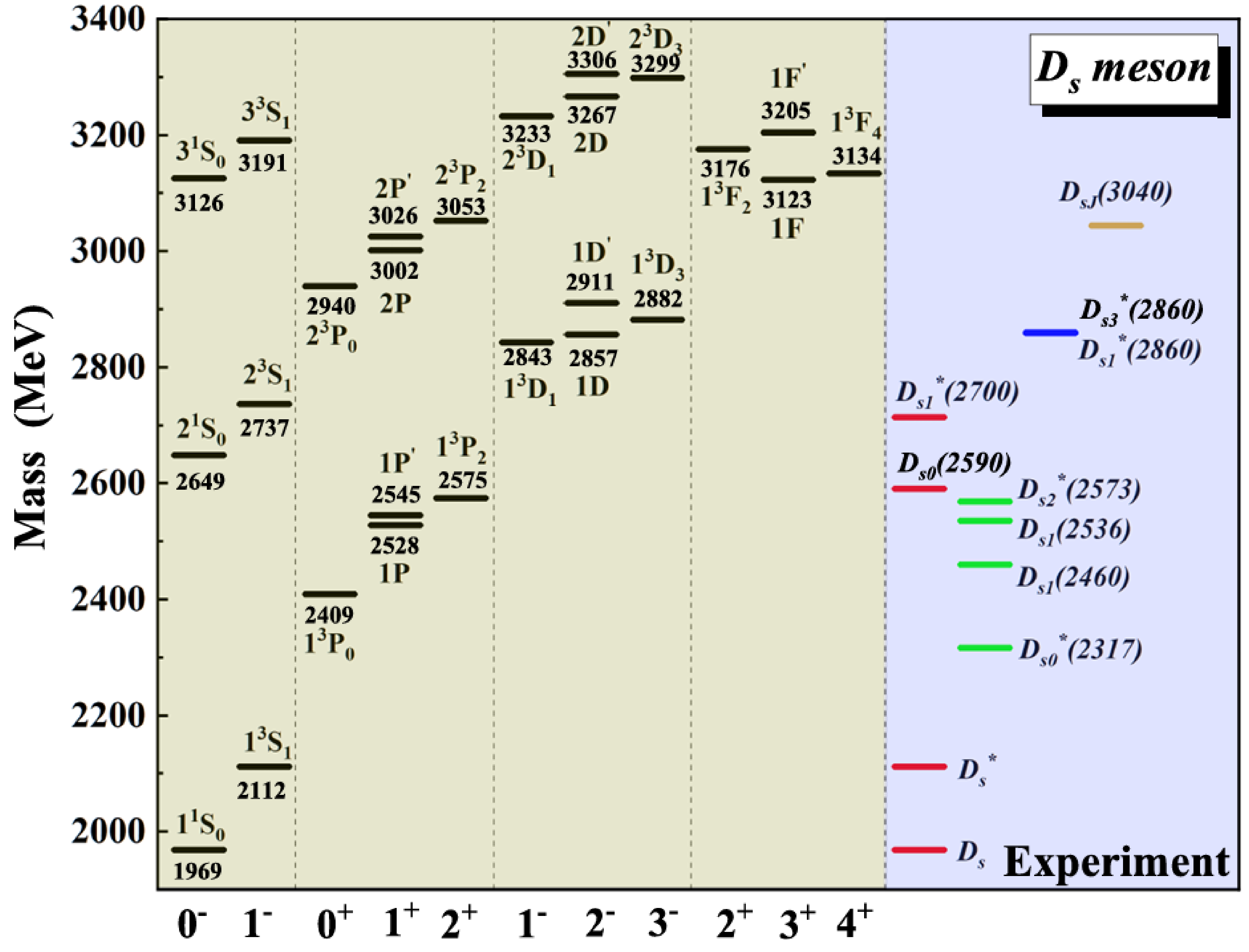


FIG. 2: Predicted charmed-strange meson mass spectrum compared with the observations.

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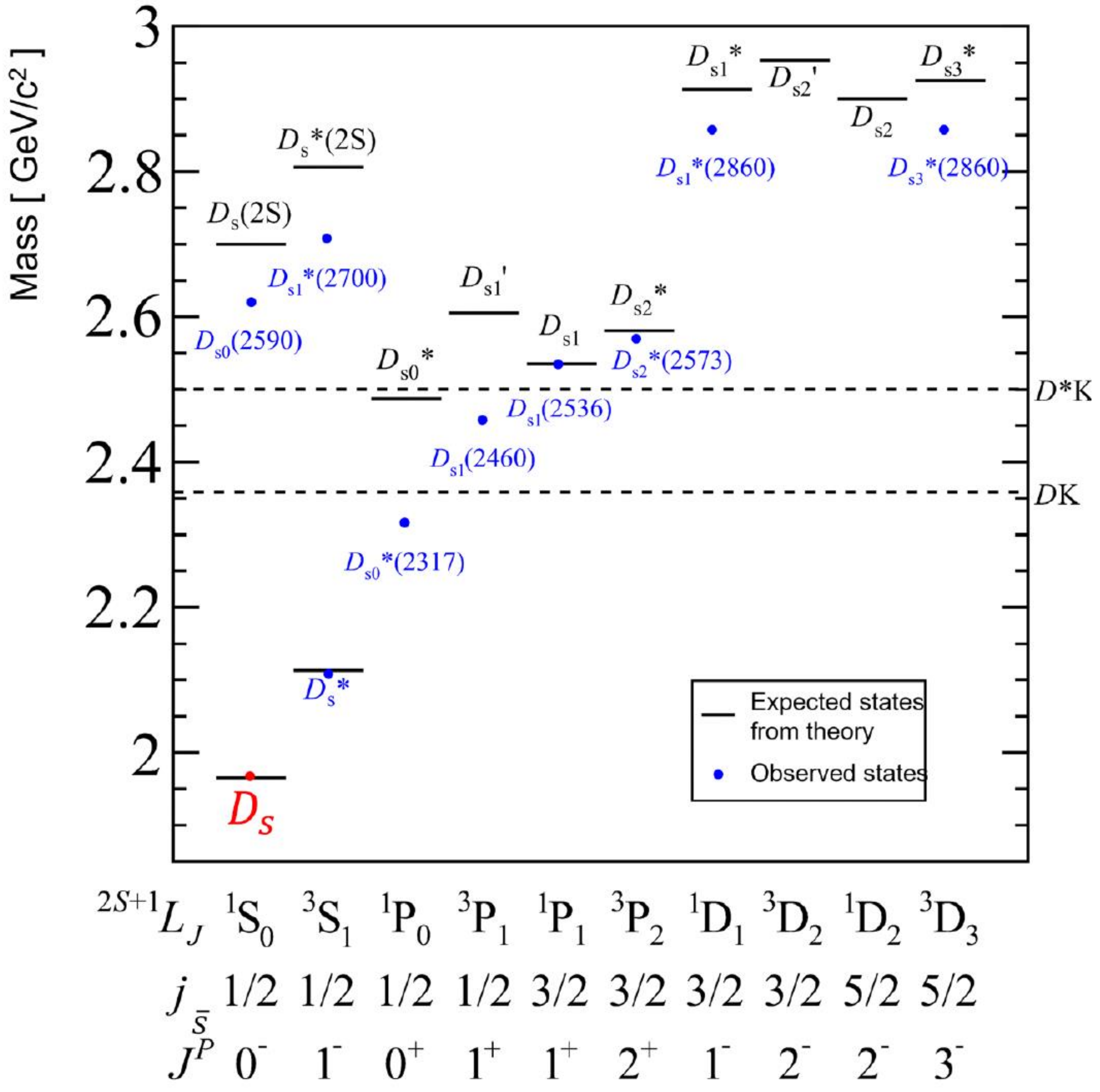
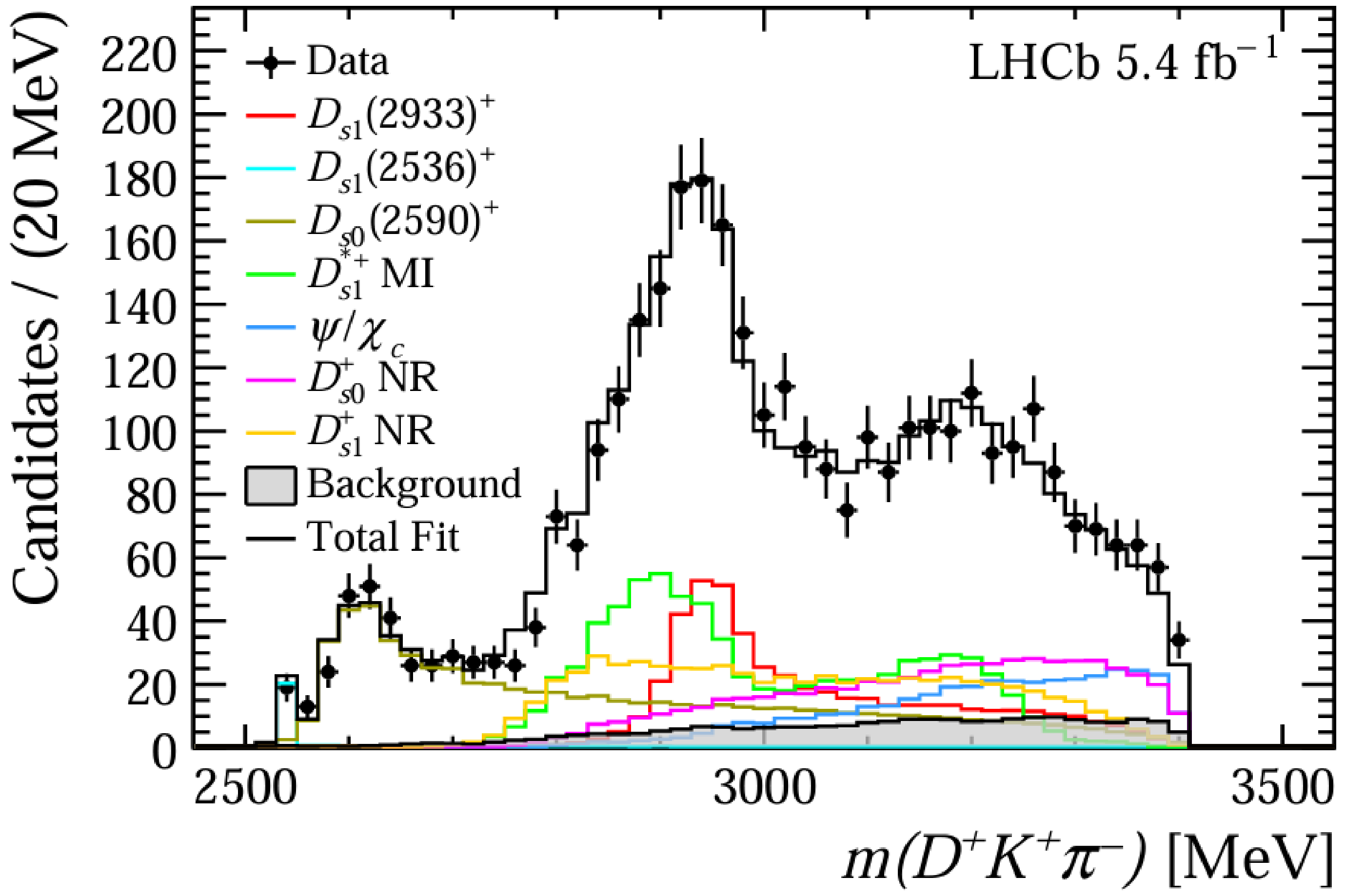
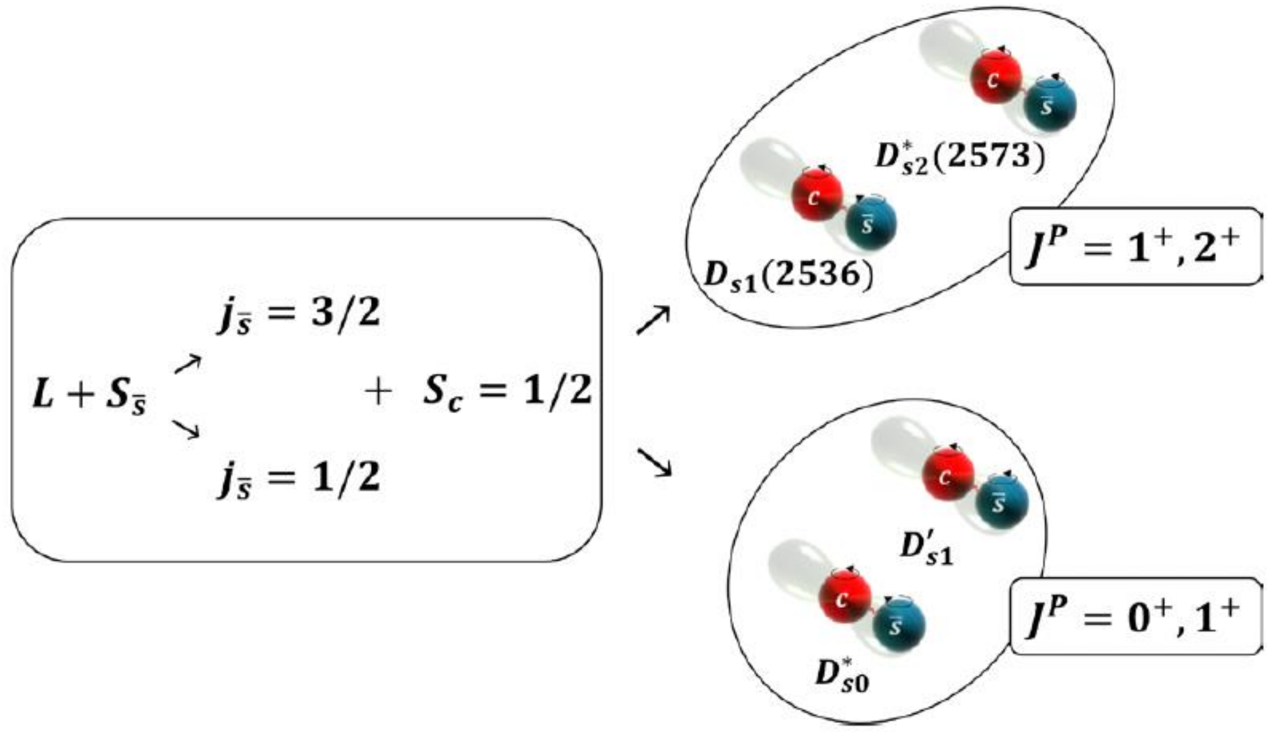


2604.21257 $D_{s1}(2933)^+, J^P = 1^+$



- low-lying status are well known
- High excited states less know: mixing states?
- Possible exotic particle.
- There is still missing D_s



D_{sJ}@Belle (II)

Production:

- $B \to \overline{D} D_{s0}^{*+}(2317)$: Phys.Rev.D 91 (2015) 9, 092011
  - ➢measured the branching fraction
  - ➢Search for the isospin partners of $D_{s0}^{*+}(2317)$

$$\frac{\mathcal{B}(B^+ \to \overline{D}^0 D_{s0}^{*+})}{\mathcal{B}(B^+ \to \overline{D}^0 D_s^+)} = 0.081^{+0.026}_{-0.021}$$

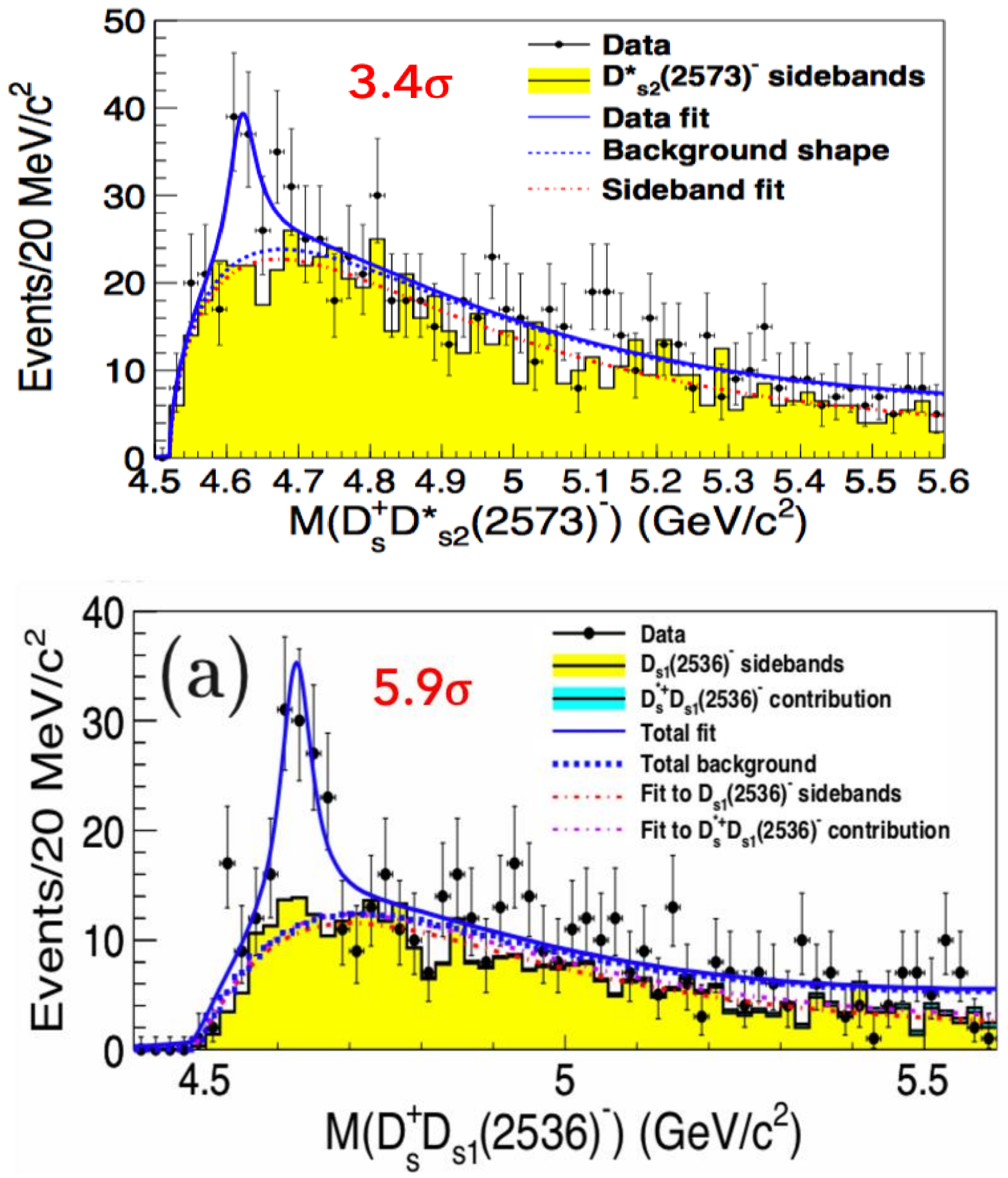
$$\frac{\mathcal{B}(B^0 \to D^- D_{s0}^{*+})}{\mathcal{B}(B^0 \to D^- D_s^+)} = 0.13^{+0.06}_{-0.05}$$

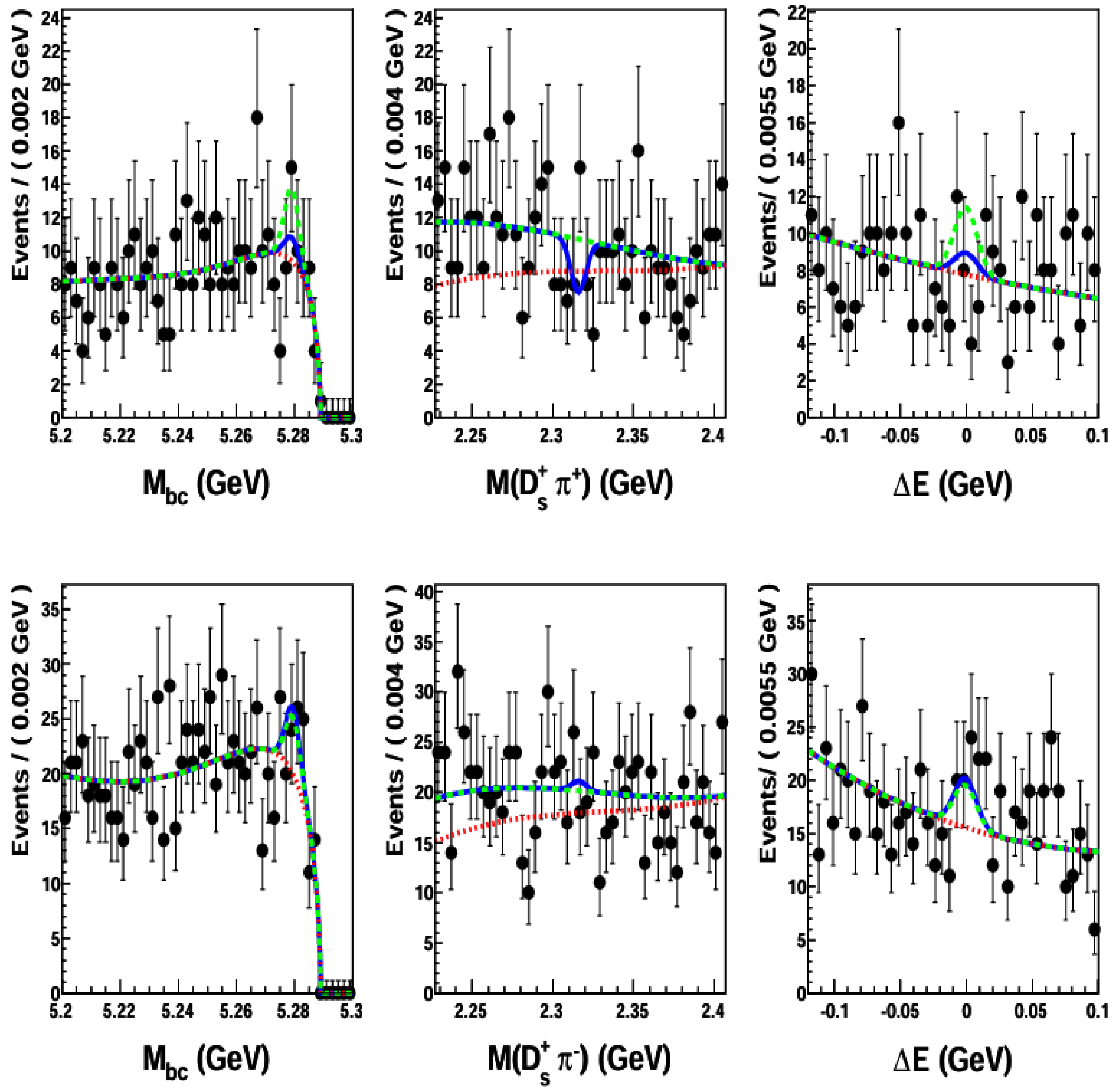
below expectations for a purely $\overline{c}s$ stat

- $e^+e^- \to D_s^+ D_{s1}(2536)^- / D_s^+ D_{s2}^*(2573)^-$:

PRD 101, 091101(R) PRD 100, 111103(R)

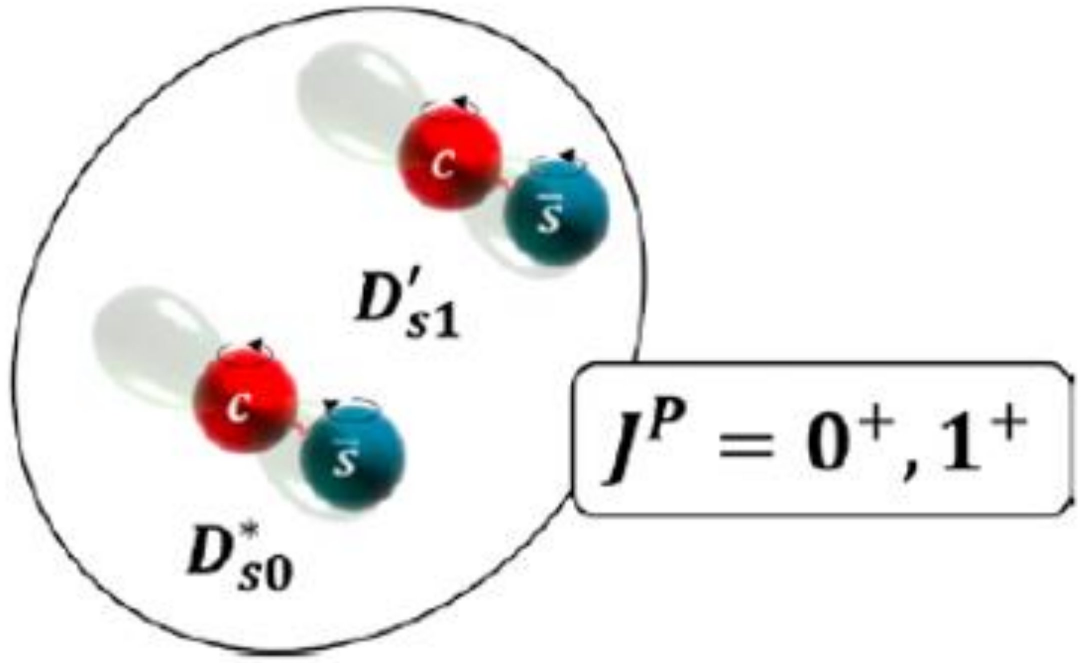
Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda_c^+ \Lambda_c^-$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, $\pi^+\pi^-\psi(2S)$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$
BaBar, $\pi^+\pi^-\psi(2S)$	$4669 \pm 21 \pm 3$	$104 \pm 48 \pm 10$
Belle, $D_s^+ D_{s1}(2536)^-$	$4626^{+7}_{-7} \pm 1$	$49.8^{+14}_{-12} \pm 4$
Belle, $D_s^+ D_{s2}^*(2573)^-$	$4620^{+9}_{-8} \pm 3$	$47.0^{+32}_{-15} \pm 5$





$D_{s0}(2317)^+$ and $D_{s1}(2460)^+$

- Mass of $D_{s0}(2317)^+$ and $D_{s1}(2460)^+$ are much lower than the quark model predictions of the lowest $c\bar{s}$ mesons with the corresponding J^P quantum number
  - modifying the $c\bar{s}$ quark model
  - D^*K hadronic molecule
  - compact tetraquarks
  - chiral partners of the ground state D_s^* meson



- Electromagnetic transitions can be well described by QED in the quark level
  - more comprehensively reflect the inner structure than nonperturbative strong decay
- **Width of them can not be measured currently.**
  - The width of $D_s(2317)^+$ is unknown: $\Gamma(D_s(2317)^+) < 3.8$ MeV @95% CL.

Partial decay widths:
unique in discriminating between various models

$D^*_{s0}(2317)^{\pm}$ **DECAY MODES**
$D^*_{s0}(2317)^-$ modes are charge conjugates of modes below.

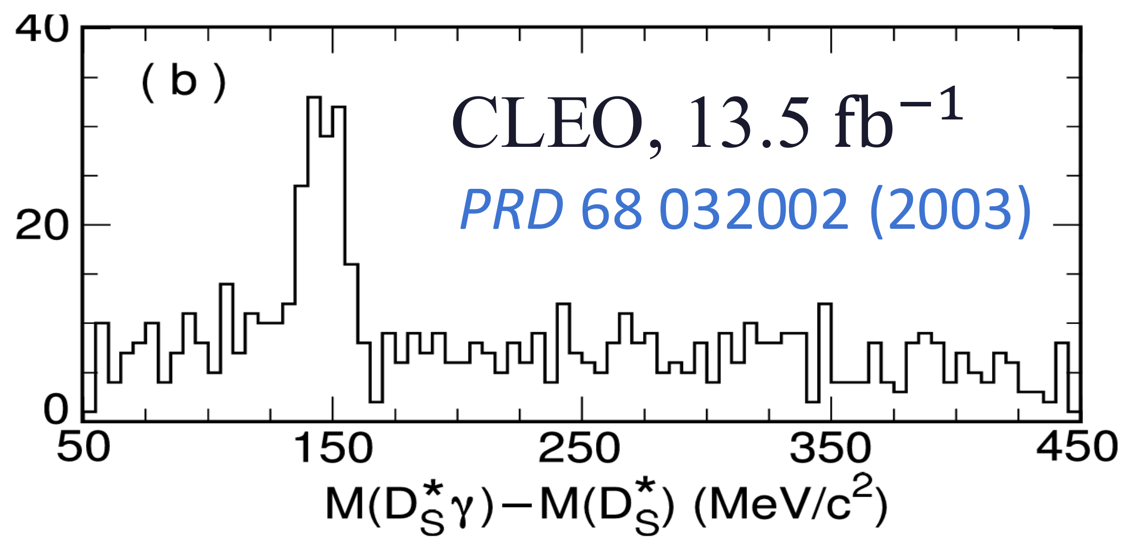
Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D_s^+\pi^0$	(100^{+0}_{-20}) %		298
Γ_2	$D_s^+\gamma$	<5 %	CL=90%	323
Γ_3	$D_s^*(2112)^+\gamma$	<6 %	CL=90%	
Γ_4	$D_s^+\gamma\gamma$	<18 %	CL=95%	323
Γ_5	$D_s^*(2112)^+\pi^0$	<11 %	CL=90%	
Γ_6	$D_s^+\pi^+\pi^-$	$< 4 \times 10^{-3}$	CL=90%	194
Γ_7	$D_s^+\pi^0\pi^0$	not seen		205

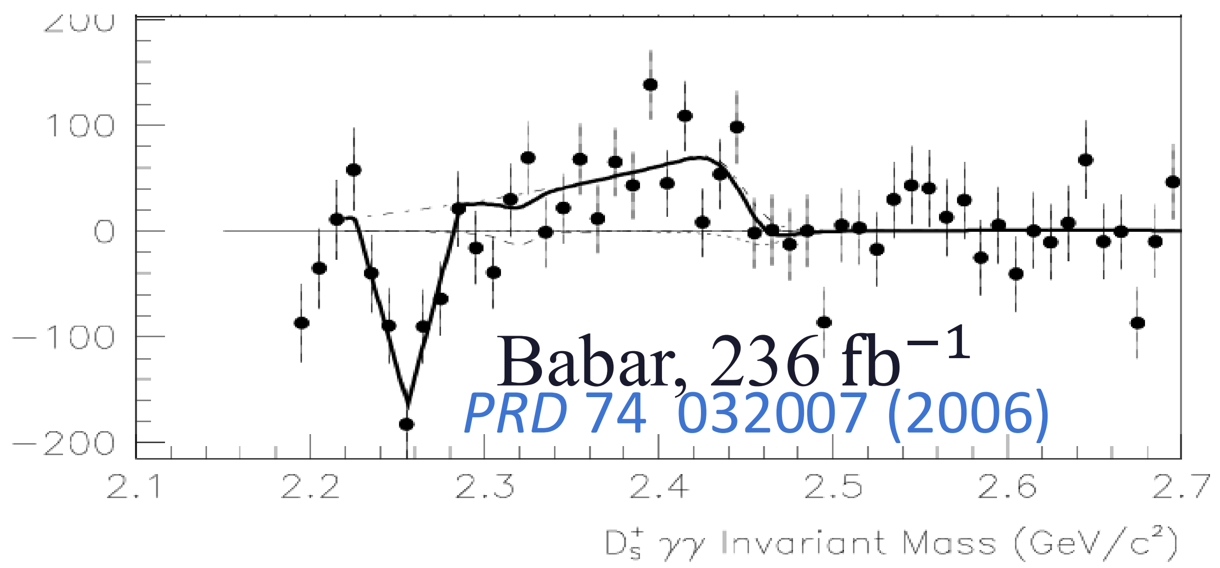
$D_{s1}(2460)^+$ **DECAY MODES**
$D_{s1}(2460)^-$ modes are charge conjugates of the modes below.

Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D_s^{*+}\pi^0$	(48 ± 11) %		297
Γ_2	$D_{s+}\gamma$	(18 ± 4) %		442
Γ_3	$D_{s+}\pi^+\pi^-$	(4.3 ± 1.3) %	S=1.1	363
Γ_4	$D_s^{*+}\gamma$	<8 %	CL=90%	323
Γ_5	$D^*_{s0}(2317)^+\gamma$	$(3.7^{+5.0}_{-2.4})$ %		138

Radiative decay of $D_{s0}(2317)^+$ and $D_{s1}(2460)^+$

- Precise absolute branching fraction is unknown: $\mathcal{B}(D_s(2317)^+ \to D_s^+\pi^0) = (100^{+0}_{-20})\%$
- The radiative decay of $D_{s0}(2317)^+$ has not been founded.
  - $\mathcal{R} < 0.059$ @ 90% CL from CLEO, $\mathrm{N}(\mathrm{D_s}(2317)^+ \to \mathrm{D_s^{*+}}\gamma) = -6.5 \pm 5.2$





$D_{s0}(2317)^+$ Decay mode	J^p transition	Possible wave
$D_s^+\gamma$	$0^+ \to 0^-1^-$	Forbidden
$D_s^{*+}\gamma$	$0^+ \to 1^-1^-$	$L = 0, 2$ ★

Eg. $\frac{\Gamma(D_{s1}(2460)^+ \to D_s^{*+}\gamma)}{\Gamma(D_{s1}(2460)^+ \to D_s^{+}\gamma)} = \frac{4.2}{7.3}\tan^2\theta$

PRD72, 094004 (2005)

Radiative decay:

1. $\Delta J = 0, \pm 1$(But not $0 \to 0$)
2. sign of P $\begin{cases} \text{change: E1 transition} \\ \text{unchange: M1 transition} \end{cases}$

$D_{s1}(2460)^+$ Decay mode	J^P transition	Transition
$D_s^+\gamma$	$1^+ \to 0^-1^-$	E1
$D_s^{*+}\gamma$	$1^+ \to 1^-1^-$	
$D_{s0}^*(2317)^+\gamma$	$1^+ \to 0^+1^-$	M1

- $D_{s1}(2460)^+ \to D_s^+\gamma$ is observed but $D_s^{*+}\gamma$ not
  - $D_{s1}(2460)^+$ state has the components with both **S = 0** ($^1P_1$ state) and **S = 1** ($^3P_1$ state)
    $D_{s1}(2460)^+ = \sin\theta|{}^1P_1\rangle + \cos\theta\,|{}^3P_1\rangle$
  - For E1 transition, $\Delta S = 0$, So, it is useful to **measure $D_s^+\gamma$ and $D_s^{*+}\gamma$ decay ratio**

Radiative decay of $D_{s0}(2317)^+$ and $D_{s1}(2460)^+$

Table I: The theoretical predictions of the $\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^{*+}\gamma)/\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^+\pi^0)$ ($\mathcal{R}$

Reference	$D_{s0}^*(2317)^+$ Structure	Approach	Radiative Decay Width (keV)	Hadronic Decay Width (keV)	$\mathcal{R}(\%)$
Godfrey [40]	$c\bar{s}$ state	quark model	1.9	$\sim$10	19
Ke [41]		light front quark mode	1.71 ± 2.9	-	$> (0.45 \pm 0.11$
Bardeen [18]		chiral theory	1.74	21.5	8.1
Faessler [42]	molecule state	effective Lagrangian	$0.55 \sim 1.41$	79.6 ± 33	$0.5 \sim 3.0$
Fu [44]		heavy quark flavor symmetry	3.7 ± 0.3	132 ± 7	2.8 ± 0.9
Lutz [45]		chiral theory	1.94 or 6.47	140	1.35 or 4.57

The branching fraction ratio of $\mathcal{R} = \frac{\mathcal{B}(D_s(2317)^+ \to D_s^{*+}\gamma)}{\mathcal{B}(D_s(2317)^+ \to D_s^+\pi^0)}$ and $\mathcal{R} = \frac{\mathcal{B}(D_s(2460)^+ \to D_s^{*+}\gamma)}{\mathcal{B}(D_s(2460)^+ \to D_s^+\gamma)}$ are the probe of the $D_{s0}(2317)^+$ and $D_{s1}(2460)^+$ internal structure

Table I: Summary of theoretical predictions for the radiative partial widths of $D_{s1}(2460)^+ \to D_s^{*+}\gamma$ and $D_{s1}(2460)^+ \to D_s^+\gamma$, and for their ratio, under different interpretations of the $D_{s1}(2460)^+$. All partial widths are given in keV.

References	Interpretations	$\Gamma(D_{s1}^+ \to D_s^{*+}\gamma)$	$\Gamma(D_{s1}^+ \to D_s^+\gamma)$	$\frac{\Gamma(D_{s1}^+\to D_s^{*+}\gamma)}{\Gamma(D_{s1}^+\to D_s^+\gamma)}$
Godfrey [13]	$c\bar{s}$	5.5	6.2	0.89
Bardeen *et al.* [14]	$c\bar{s}$	4.66	5.08	0.92
Ferrandes [15]	$c\bar{s}$	1.5	3.3	0.45
Radford *et al.* [18]	$c\bar{s}$	11.0	8.3	1.33
Green *et al.* [21]	$c\bar{s}$	5.40	15.2	0.36
Bondar *et al.* [40]	$c\bar{s}$	104	297	0.35
Colangelo *et al.* [41]	$c\bar{s}$	0.6–1.1	19–29	0.021–0.058
Close *et al.* [42]	$c\bar{s}$	$4.2\sin^2\theta_s$	$7.3\cos^2\theta_s$	$(4.2/7.3)\tan^2\theta_s$
	D^*K	~ 30	~ 30	~ 1
Fu *et al.* [43]	D^*K	13 ± 2	42 ± 4	0.31 ± 0.06
Zhang *et al.* [44]	D^*K	1.65/1.60/1.17	5.58/15.36/16.26	0.30/0.10/0.07
	$c\bar{s} + D^*K$	1.74/2.19/2.75	0.98/6.41/6.99	1.78/0.34/0.39
Lutz *et al.* [45]	hadrogenesis	21.8/12.47	44.50/45.14	0.49/0.28

Radiative decay of $D_{s0}(2317)^+$ and $D_{s1}(2460)^+$

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Decay chain: $e^+e^- \to c\bar{c} \to D_{s0}(2317)^+ +$ anythings

$D_{s0}(2317)^+ \to D_s^+[\phi\pi, K^*K]\,\pi^0$ **Reference channel**

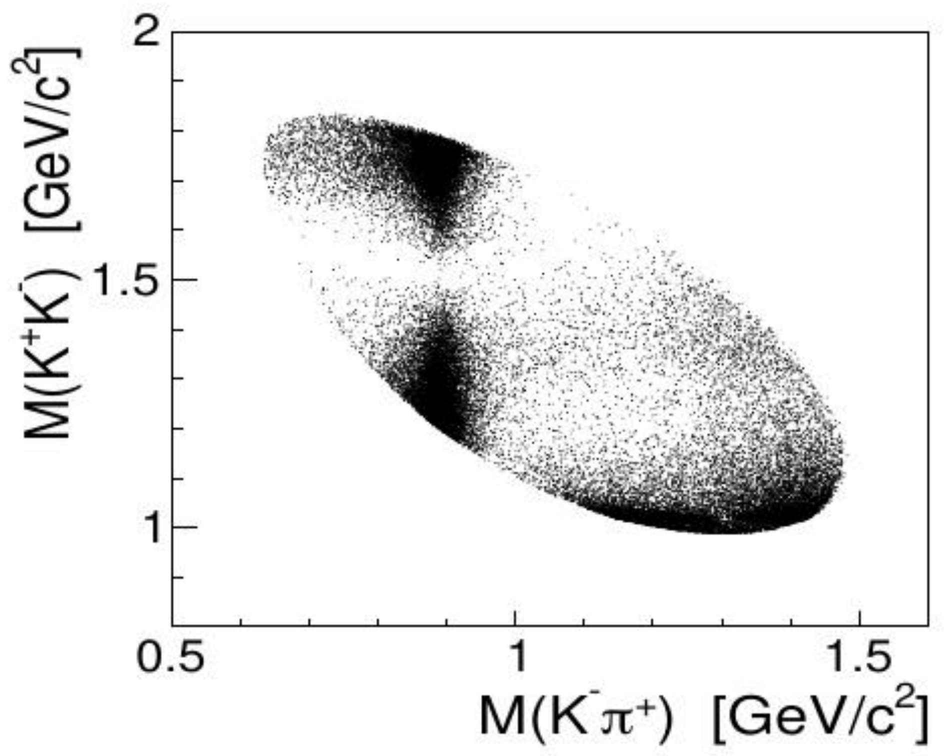
$\to D_s^{*+}[D_s^+\gamma]\gamma$ **Signal Mode**

Datasets:

- All Belle data: 980 fb^{-1}
- All Belle II data: 428 fb^{-1}

Signal MC:

- $e^+e^- \to c\bar{c}$: Pythia
- $D_s(2317)^+ \to D_s^+\pi^0, D_s^{*+}\gamma$: PHSP (S-Wave)
- $D_s^{*+} \to D_s^+\gamma$: VSP
- $D_s^+ \to KK\pi$: Dalitz



Pre-selection:

Photon:

- π^0 veto: the invariant mass of any combination of one signal γ_{sig} with one γ_{roe} in rest of event should not in the region of $|M(\gamma_{sig}\gamma_{roe}) - m(\pi^0)| < 15\ \mathrm{MeV}/c^2$

Radiative decay of $D_{s0}(2317)^+$

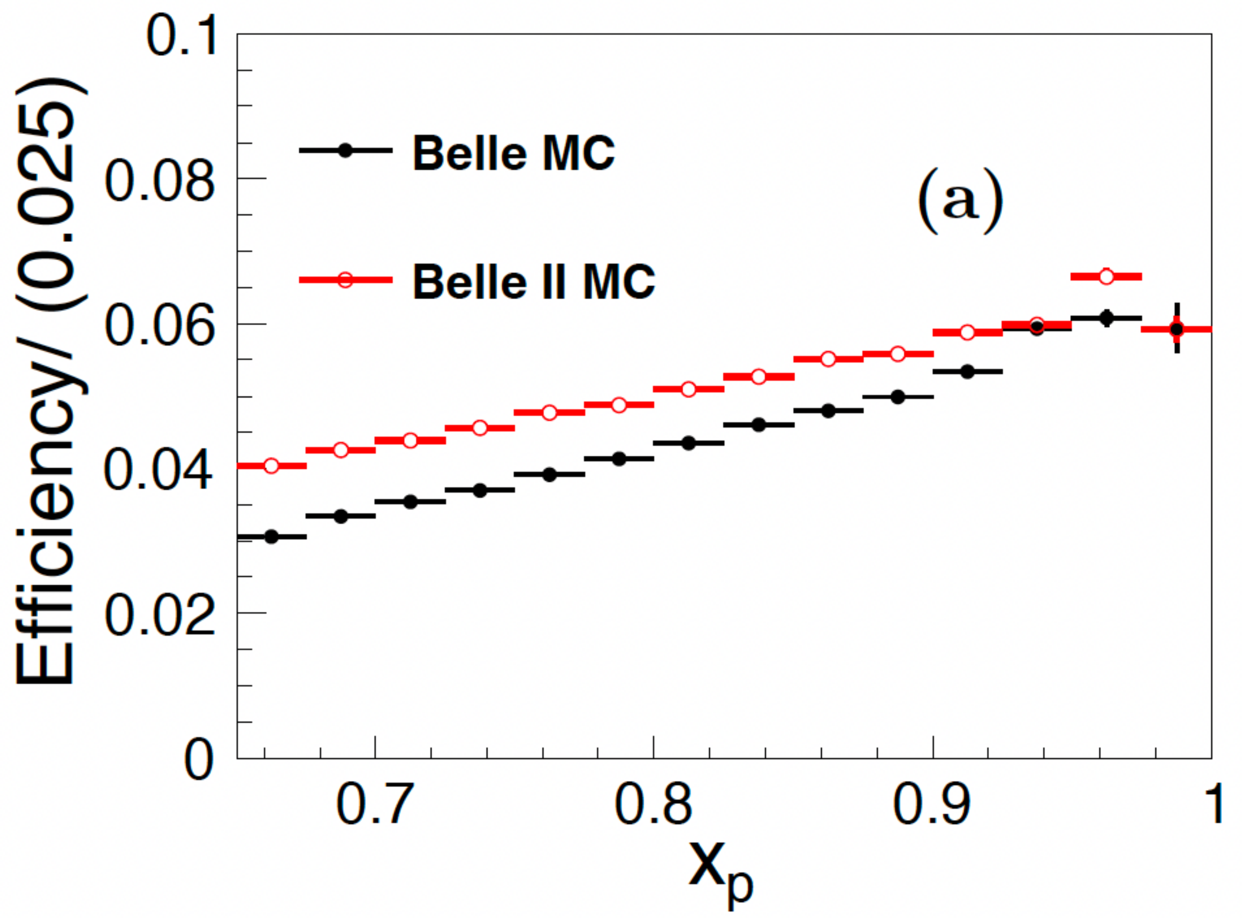
The correction of x_p distribution: get the correct efficiency

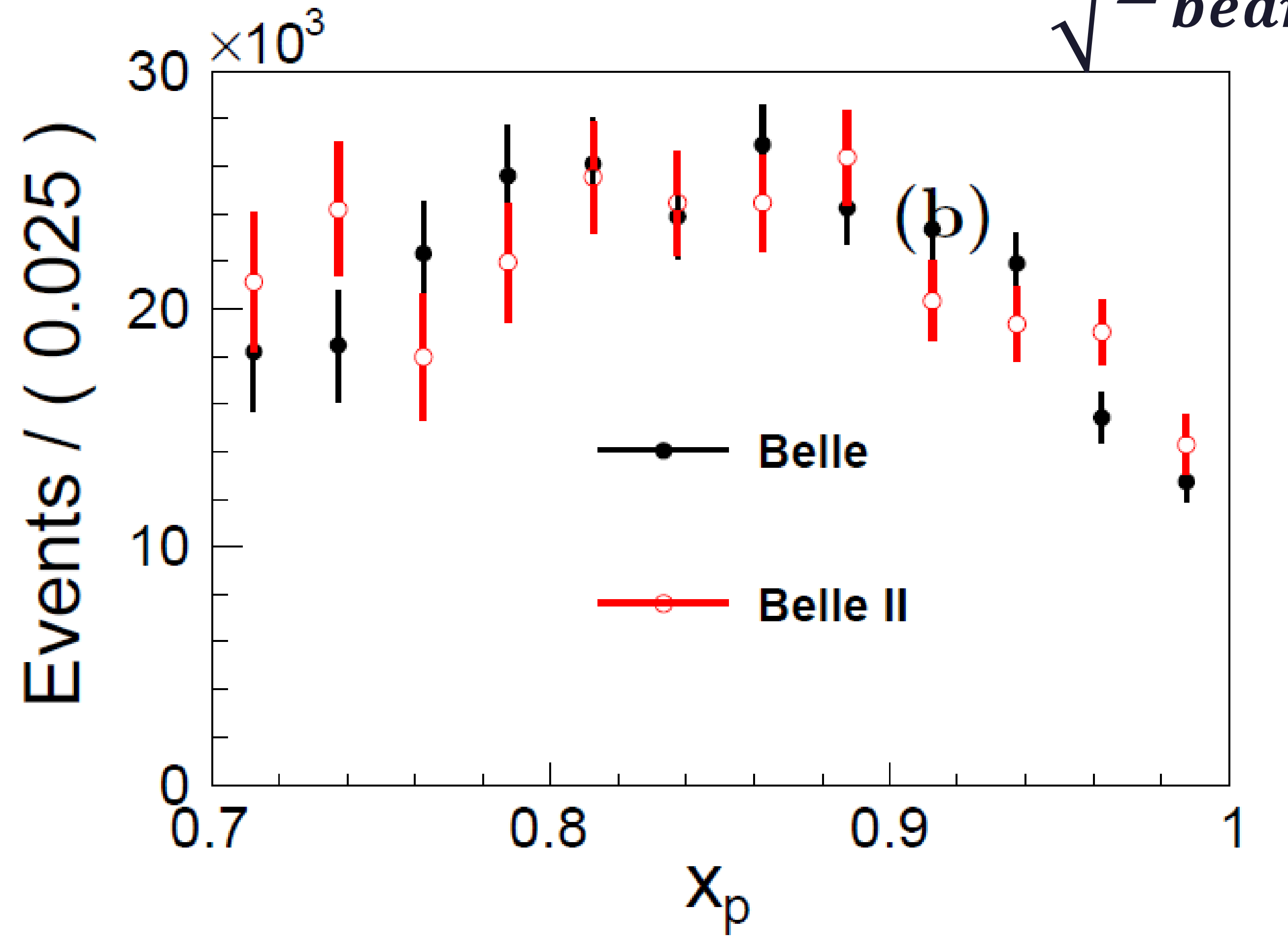
$$xp = \frac{p^*_{D_s^*\gamma}}{\sqrt{E^2_{beam} - M^2_{D_s^*\gamma}}}$$

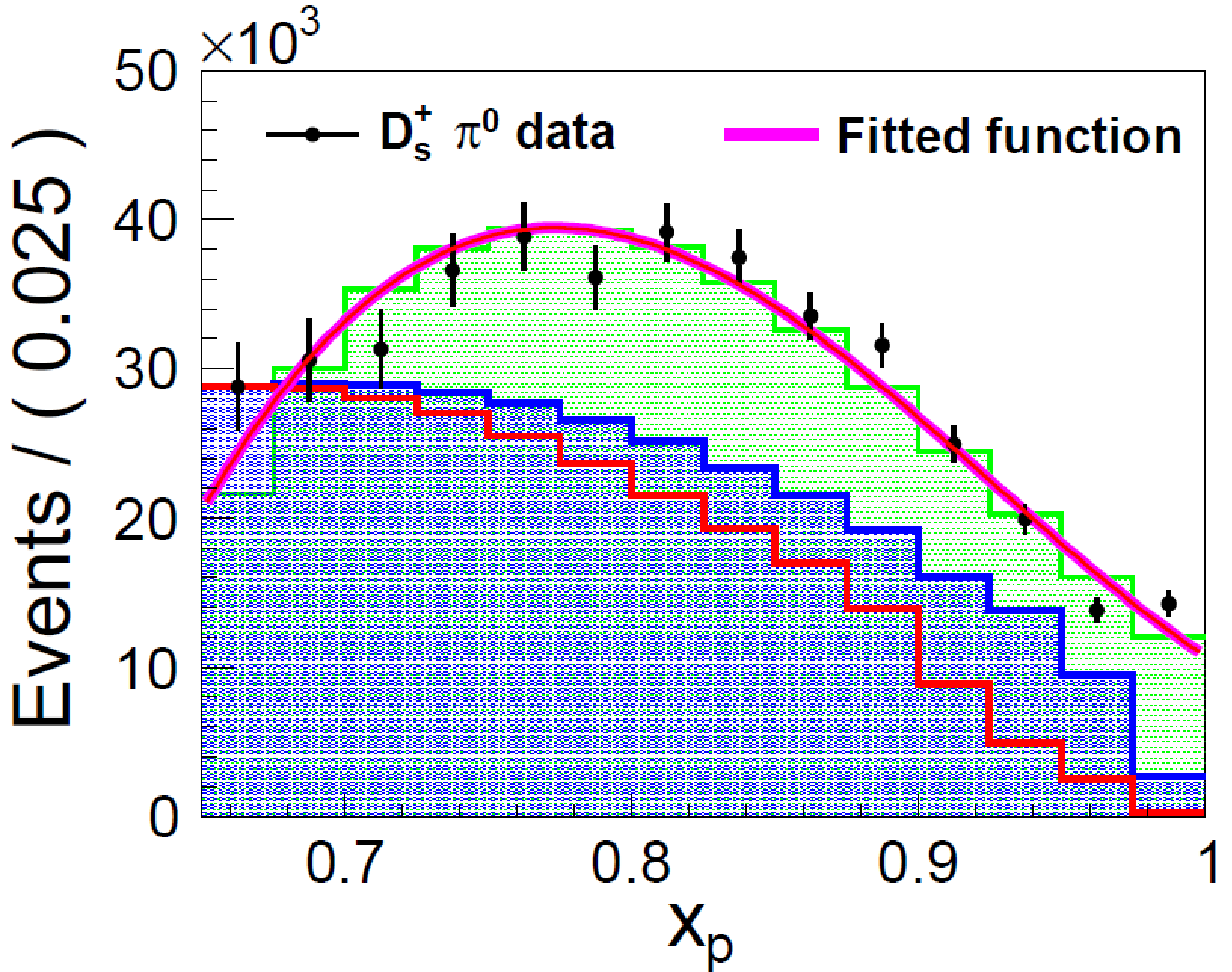
Dots:
Efficiency-corrected from combined Belle and Belle II data

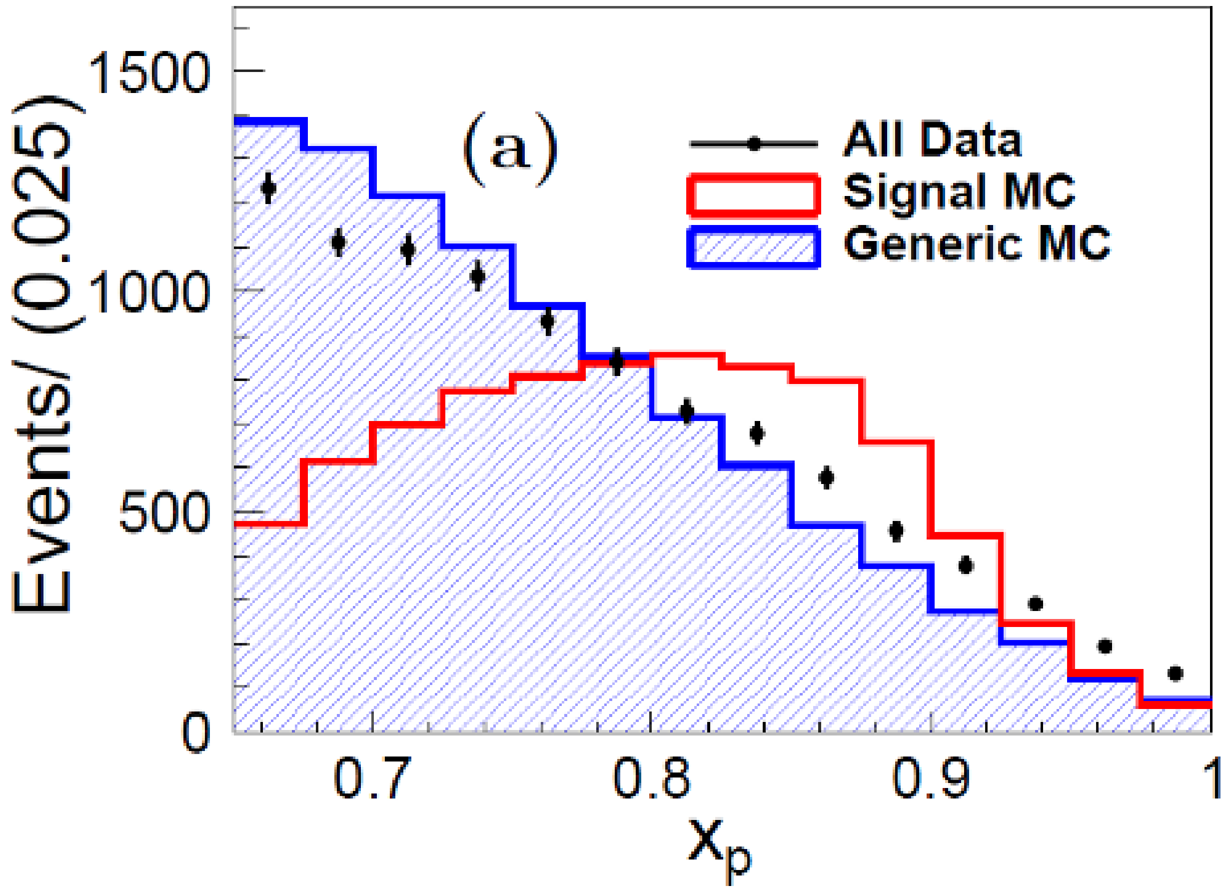
Histograms:
Simulated distributions from
- Original Belle MC samples
- Original Belle II MC samples
- Reweighted MC samples

Only background from $e^+e^- \to q\bar{q}$
Apply cut: $x_p > 0.7$



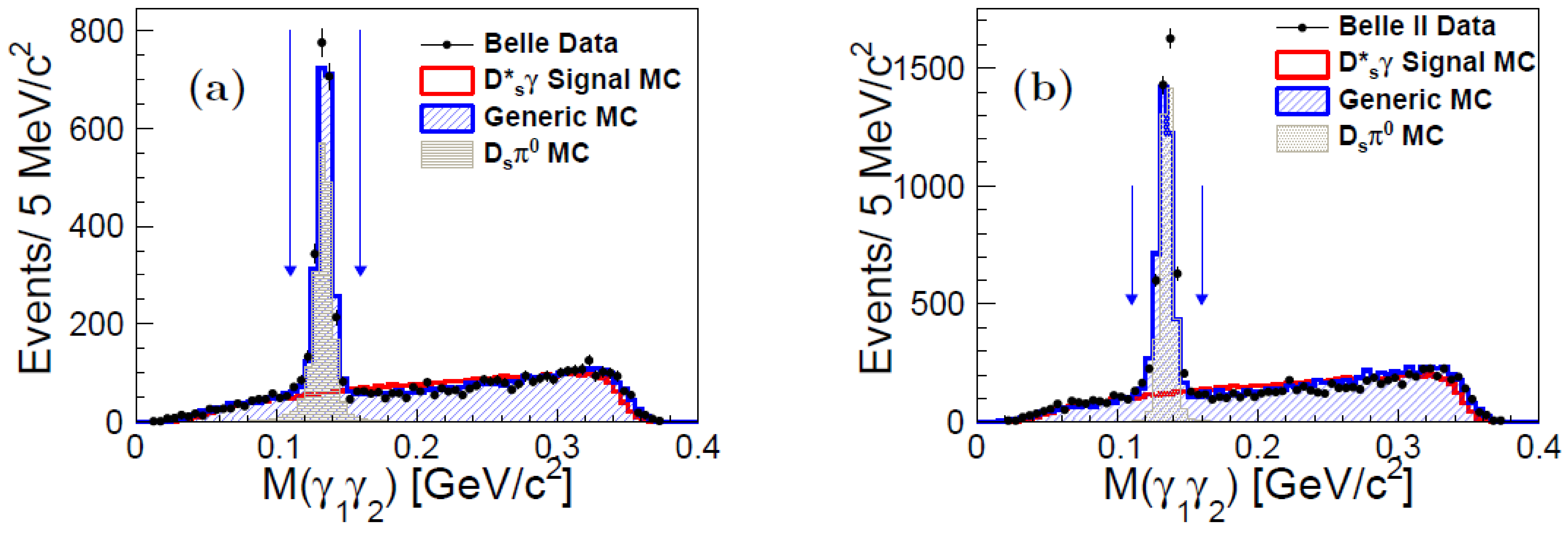


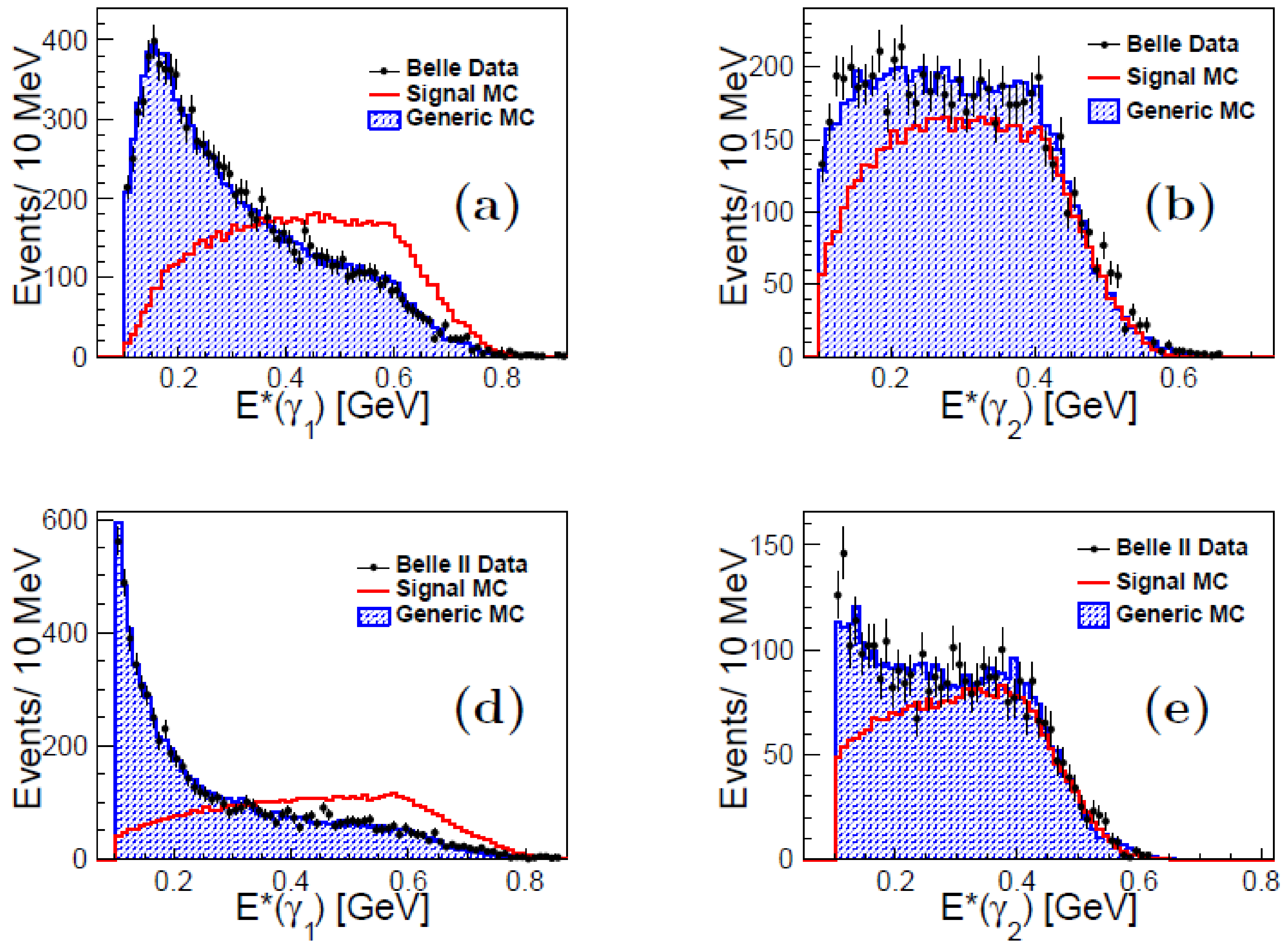




Radiative decay of $D_{s0}(2317)^+$

γ selection: $D_s(2317)^+ \rightarrow [D_s^{*+} \rightarrow D_s^+ \gamma_2]\gamma_1$





Veto events in the region:

$$0.100 < |M(\gamma_1\gamma_2)| < 0.160 \text{ GeV}/c^2$$

To suppress the contributions from the $D_s(2317)^+ \rightarrow D_s^+\pi^0$ decay

Apply:

$$E^*(\gamma_1) > 0.22 \text{ GeV}$$
$$E^*(\gamma_2) > 0.10 \text{ GeV}$$

Radiative decay of $D_{s0}(2317)^+$

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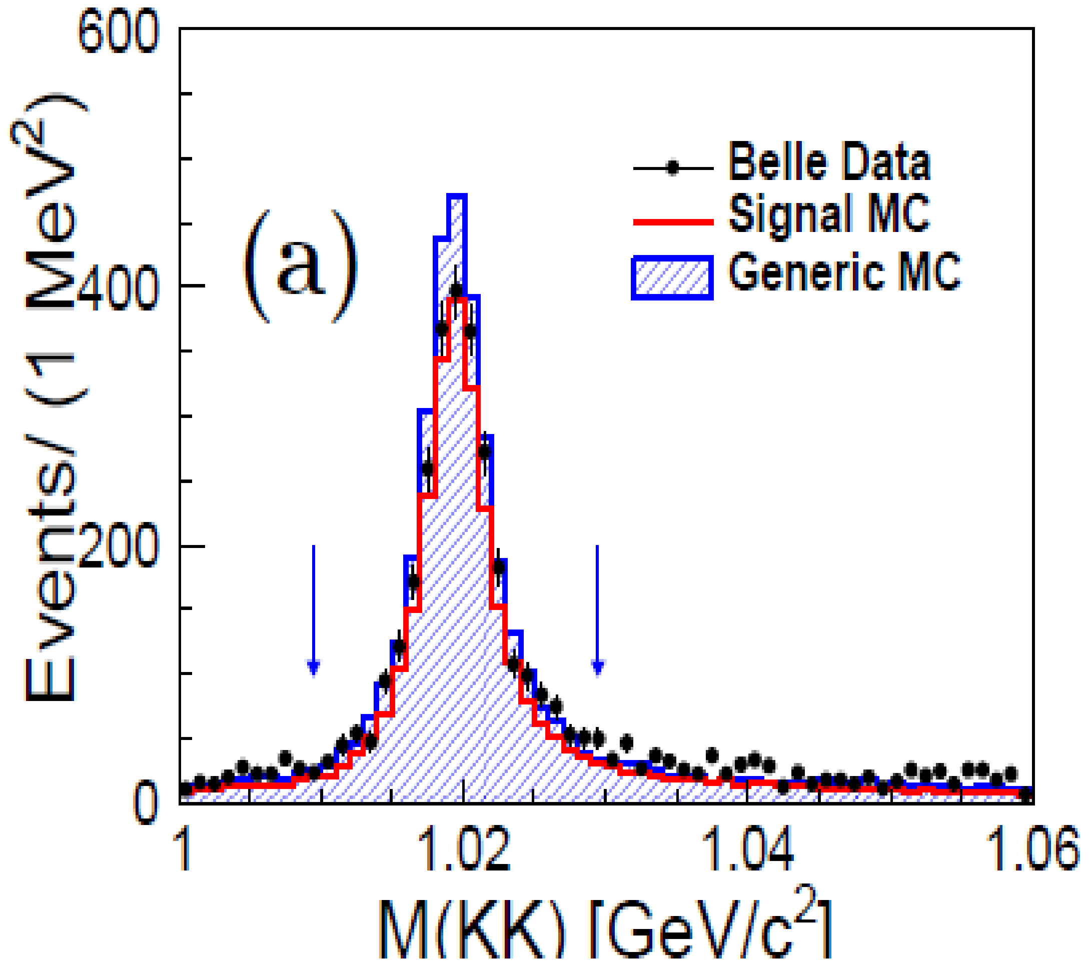
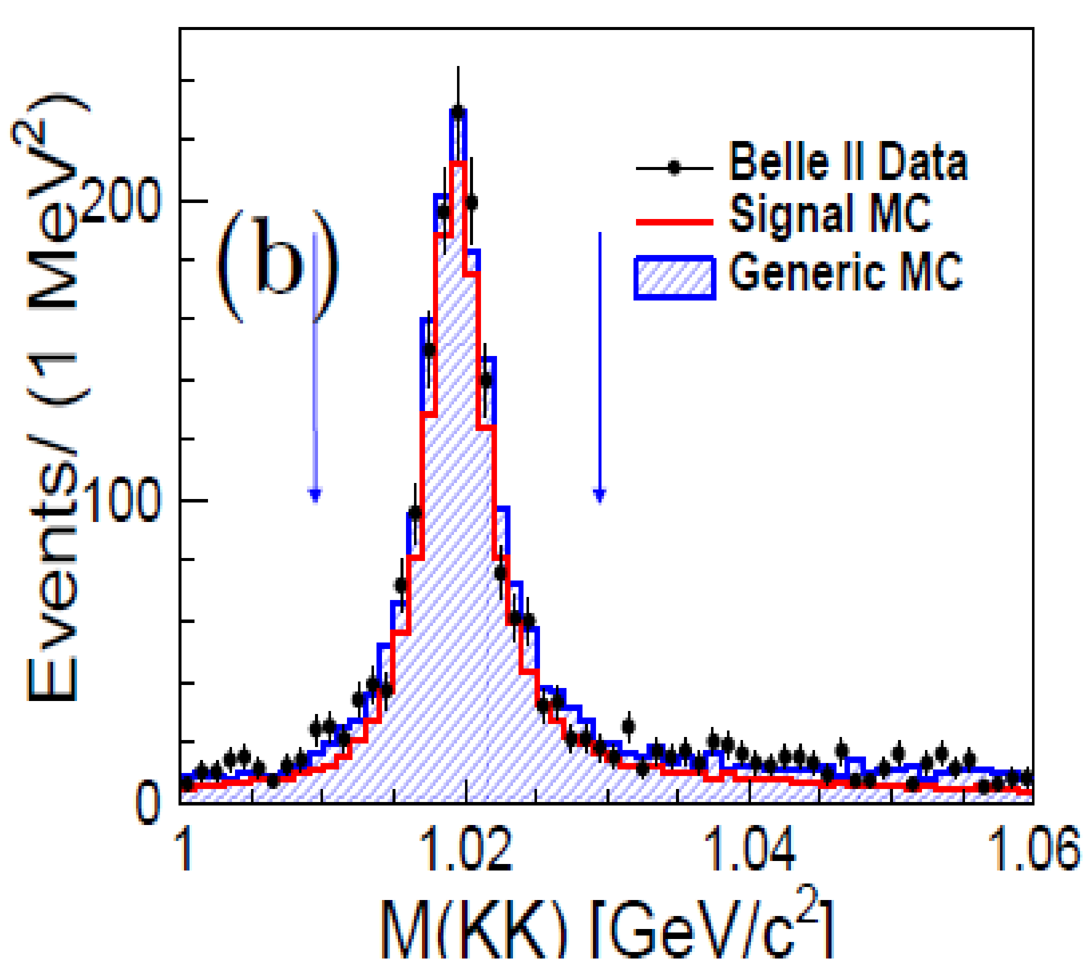
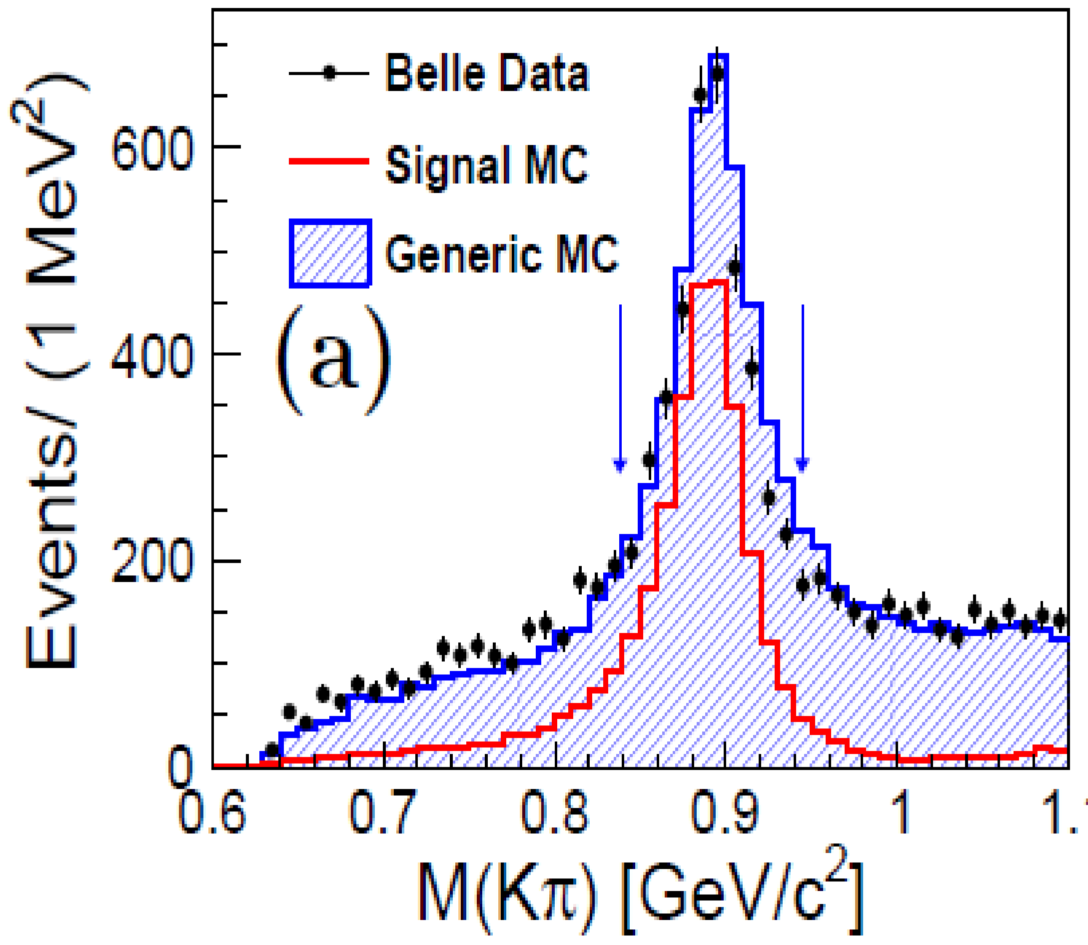
ϕ selection:

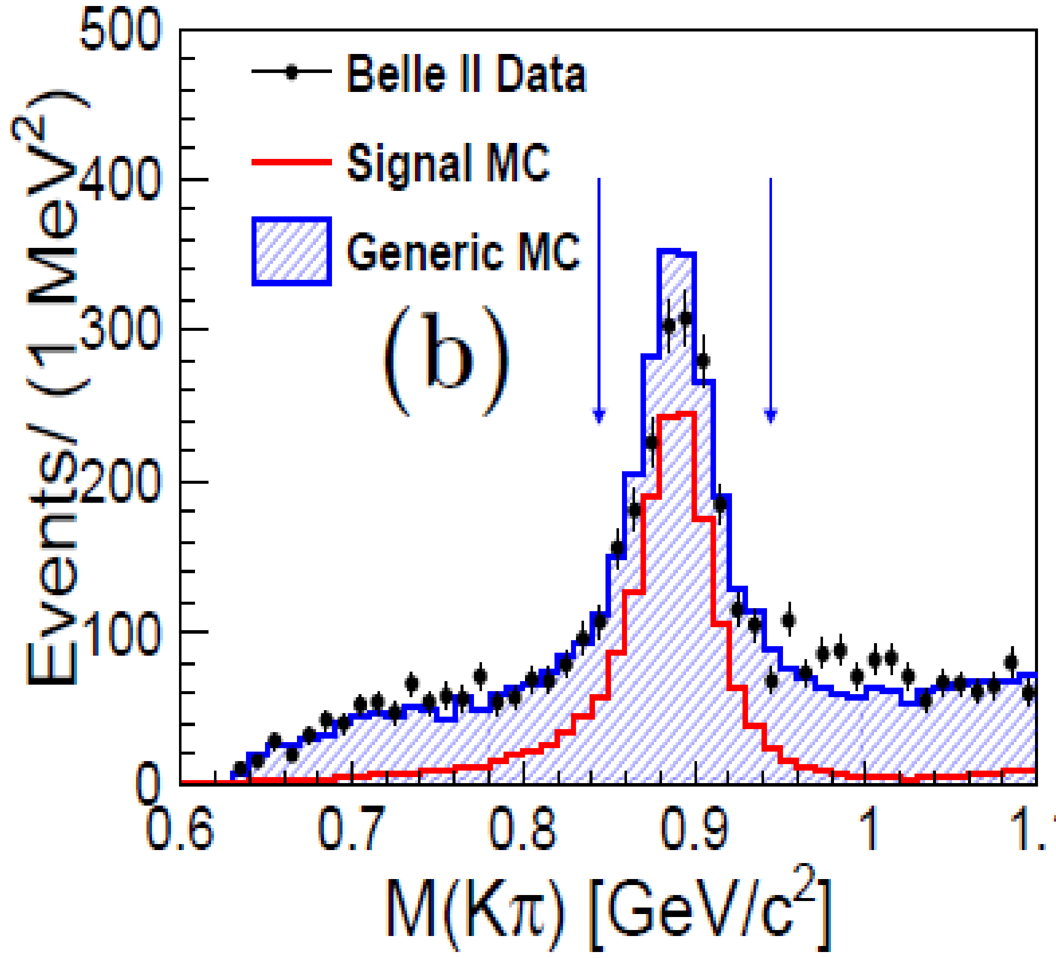




Apply:
$|M(K^+K^-) - m(\phi)| < 10\ \mathrm{MeV}/c^2$

$\bar{K}^{*0}$ selection:

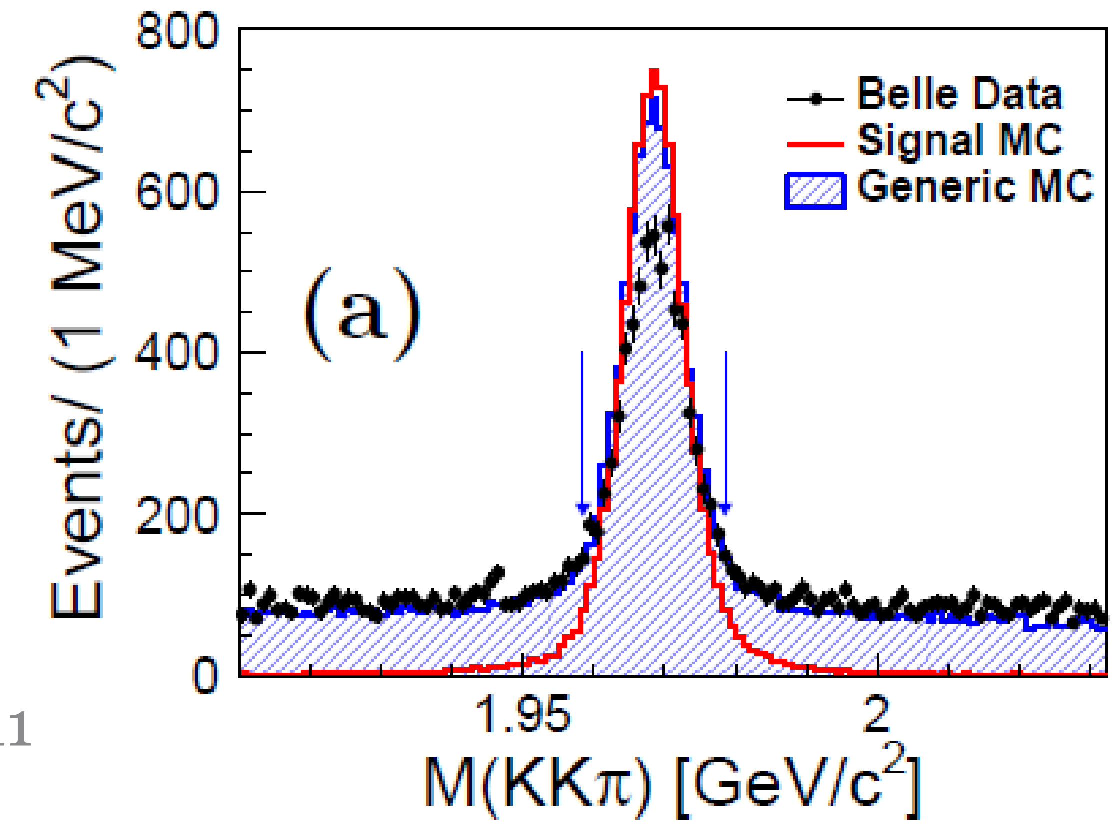


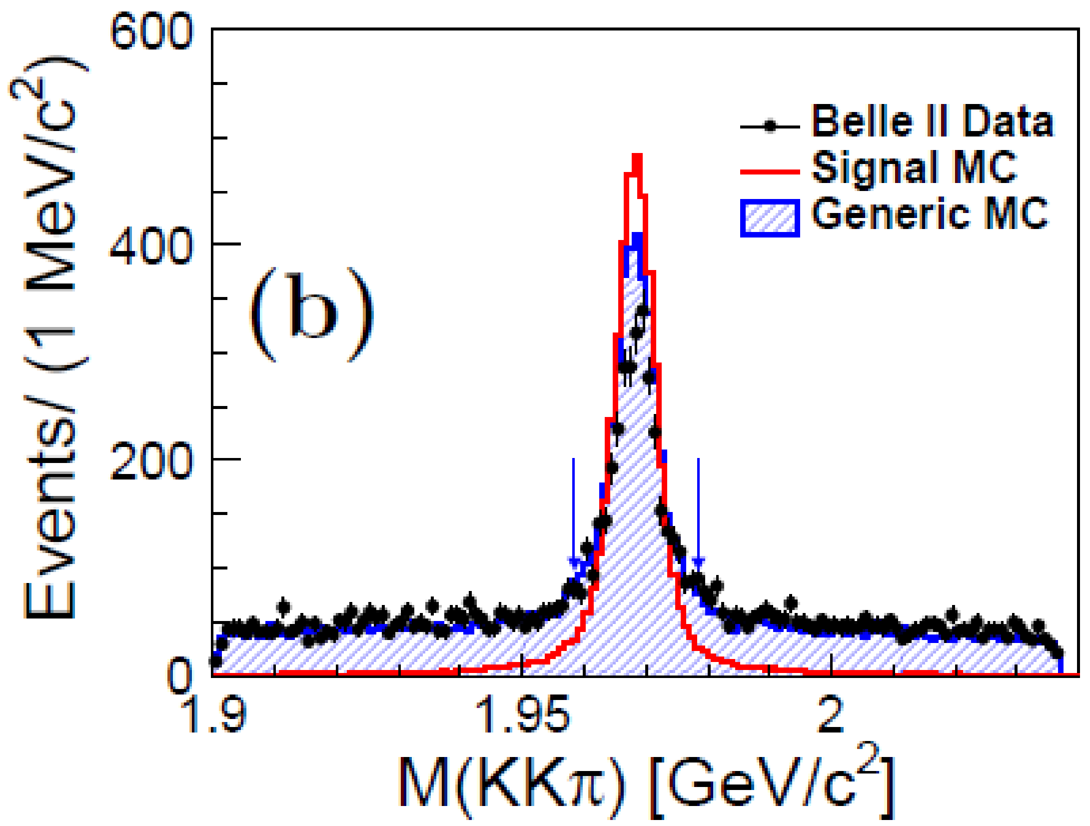


Apply:
$|M(K\pi) - m(\bar{K}^*)| < 50\ \mathrm{MeV}/c^2$

D_s^+ selection:

Mass window :
$|M(K^+K^-\pi^+) - m(D_s^+)| < 10\ \mathrm{MeV}/c^2$





Radiative decay of $D_{s0}(2317)^+$

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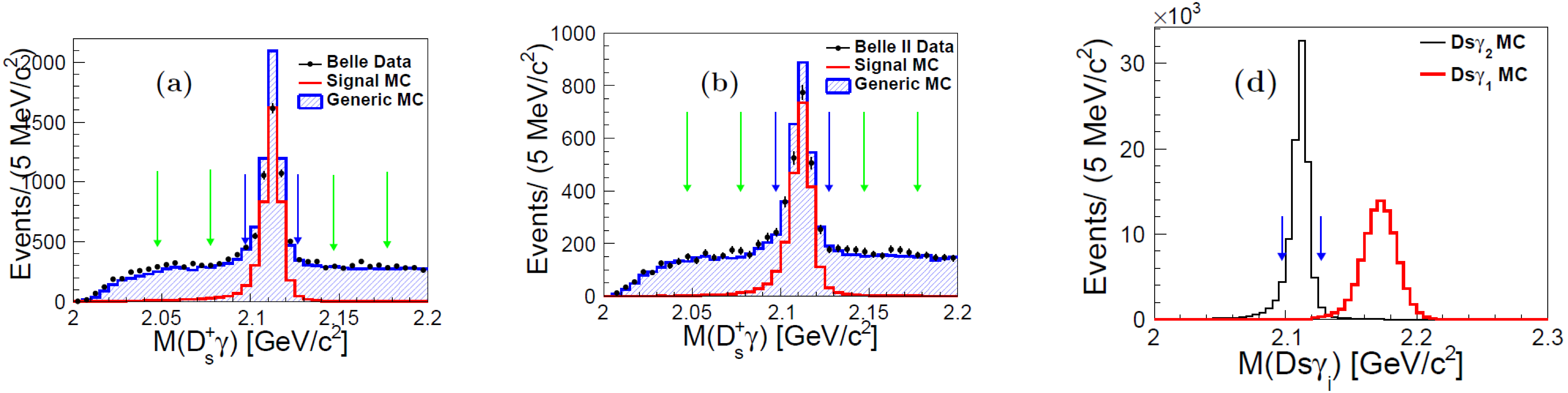
D_s^{*+} selection:

$D_s(2317)^+ \to [D_s^{*+} \to D_s^+ \gamma_2]\gamma_1$

To reduce the resolution of $m(D_s^+)$:

$$M(D_s^+\gamma) = M^{rec}(D_s^+\gamma) - M(K^+K^-\pi^+) + m(D_s^+)$$



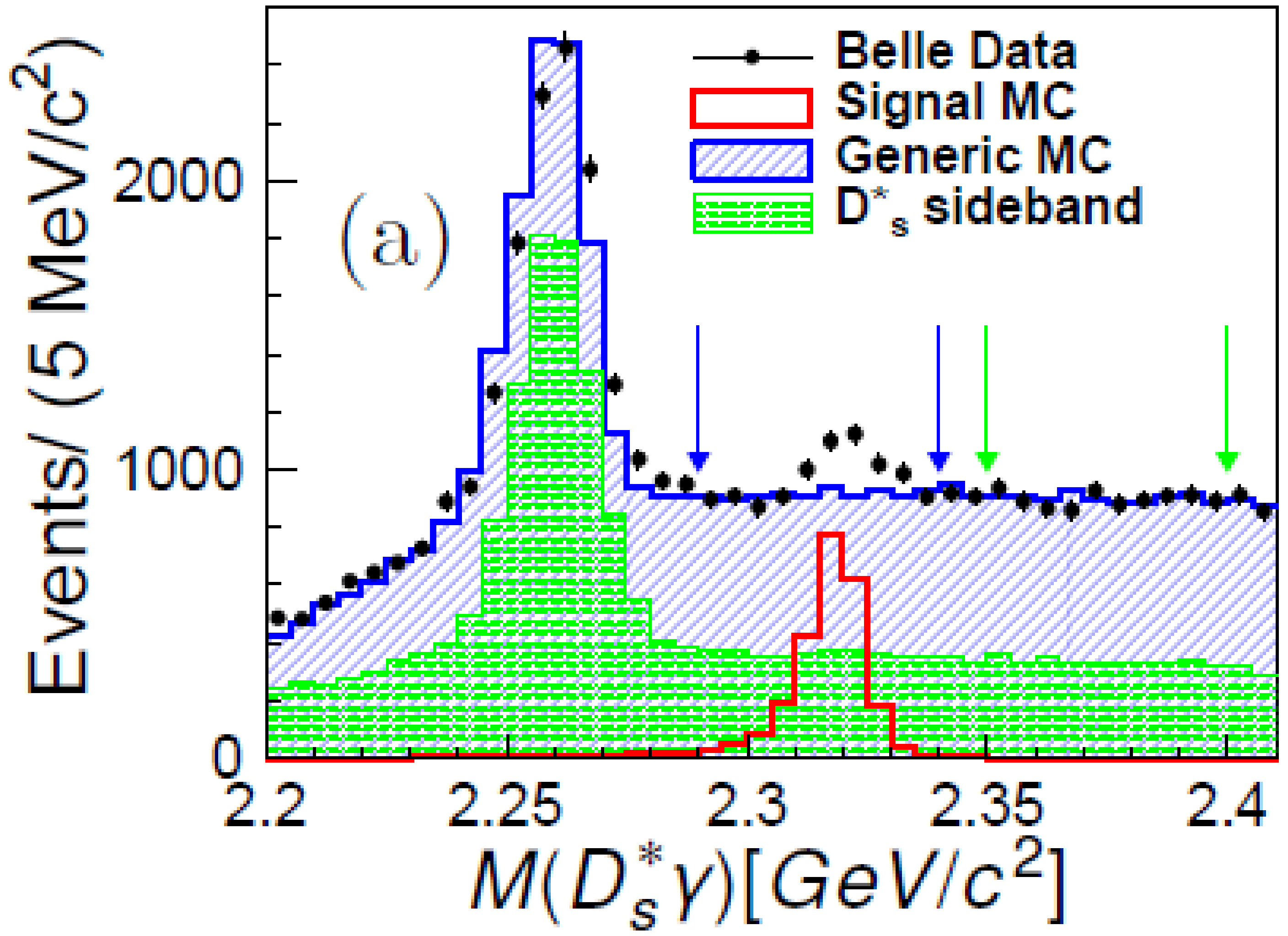
Signal window:
$|M(D_s^+\gamma) - m(D_s^{*+})| < 0.015\ \mathrm{GeV}/c^2$

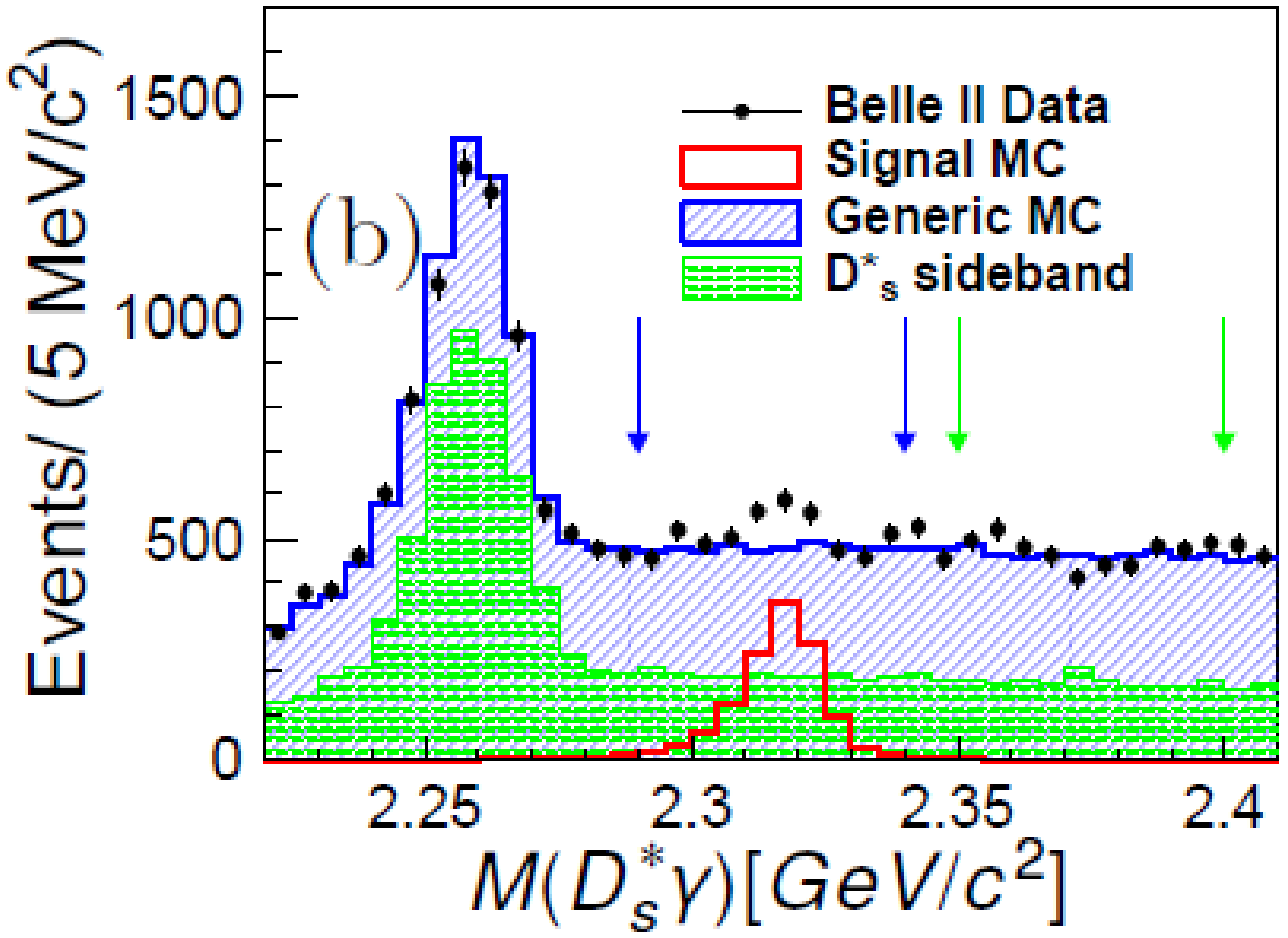
Sideband:
$|M(D_s^+\gamma) - m(D_s^{*+}) \pm 0.05| < 0.015\ \mathrm{GeV}/c^2$

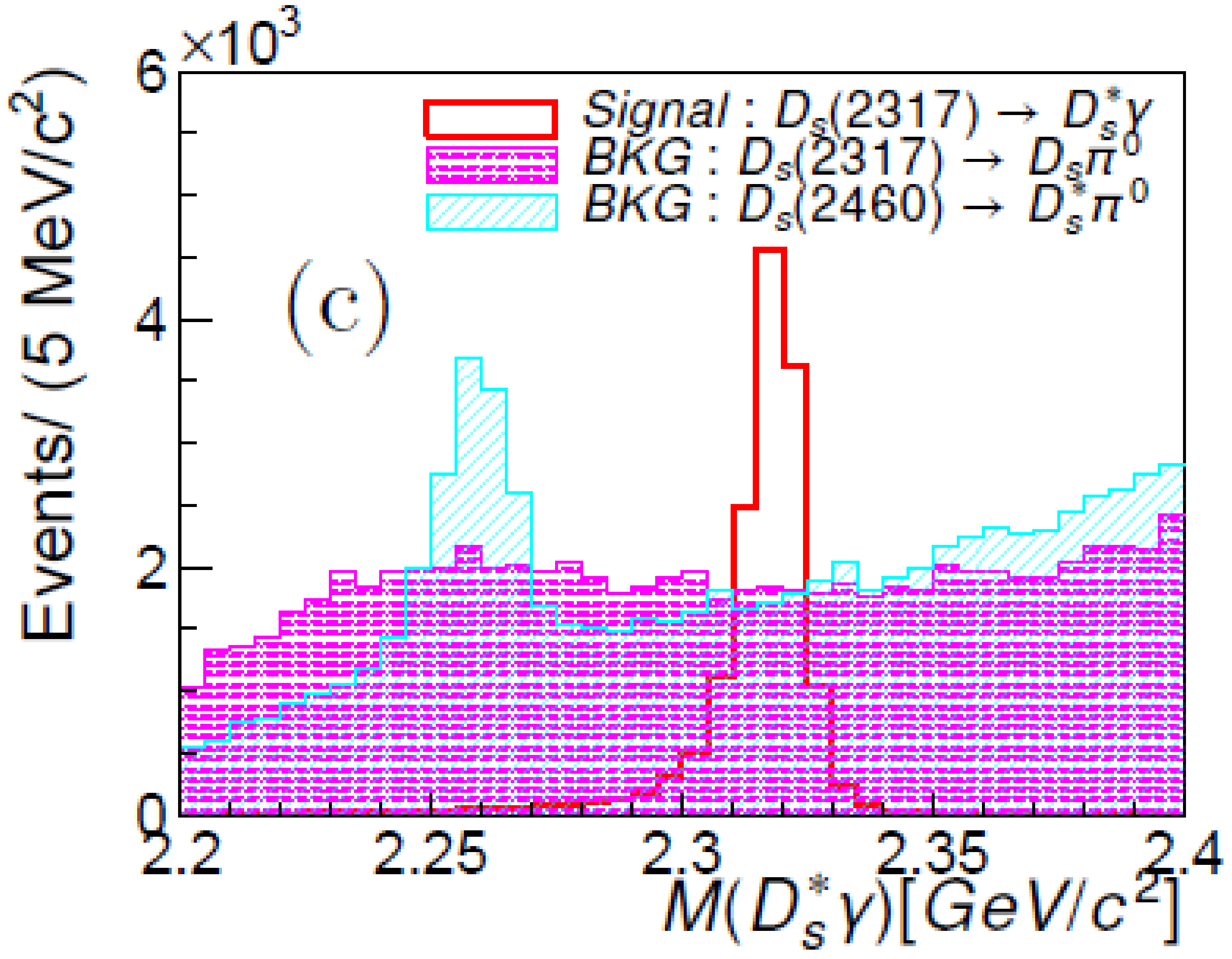
Radiative decay of $D_{s0}(2317)^+$

$D_s(2317)^+ \to [D_s^{*+} \to D_s^+ \gamma_2]\gamma_1$

$D_s(2317)$ distributions:



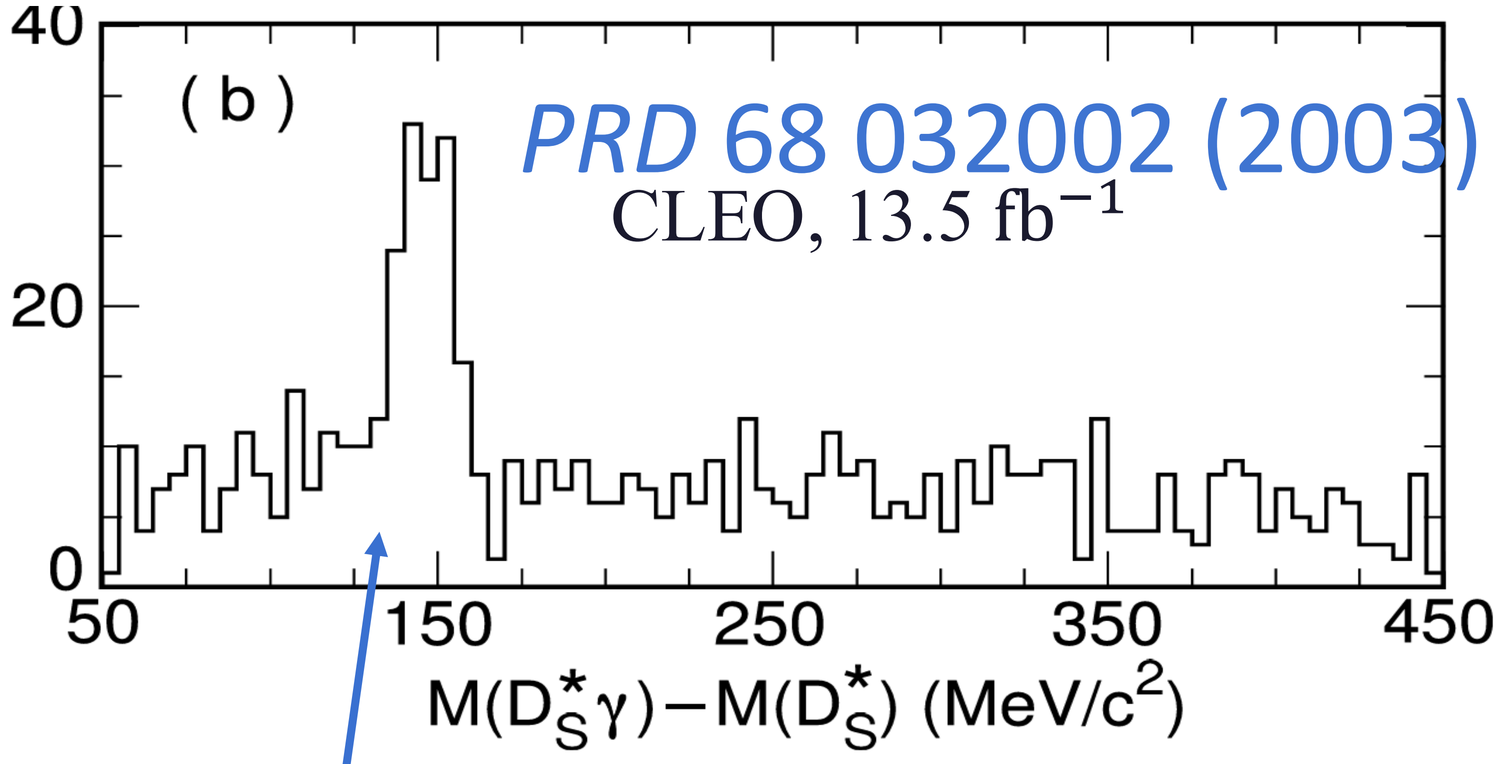




To reduce the resolution of $M(D_s^{*+})$:

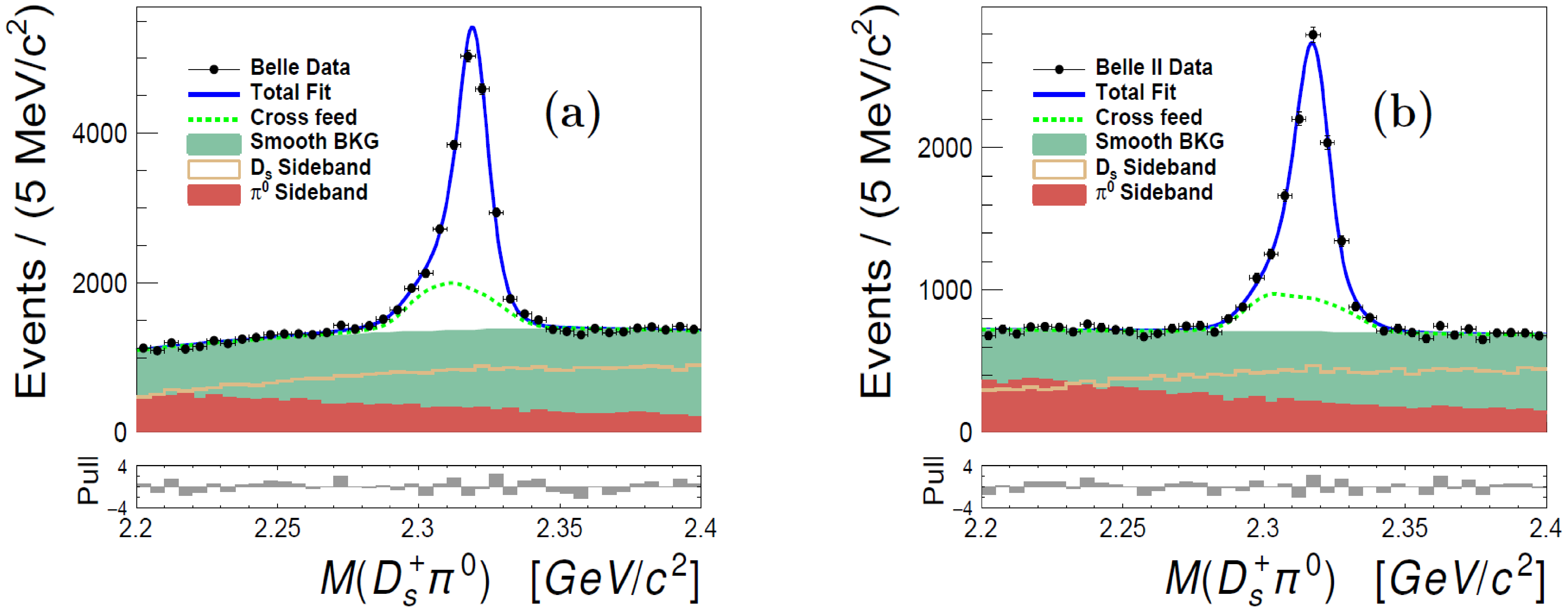
$$M(D_s^{*+}\gamma) = M^{rec}(D_s^{*+}\gamma_1) - M^{rec}(D_s^+\gamma_2) + m(D_s^{*+})$$

- **Clear $D_s(2317)$ signal peaks**
- **Flat background:** from both D_s^* sideband and generic MC
- Peaks around 2.26 GeV$/c^2$ are from $D_s^* + \gamma_{\text{free}}$ (same as CLEO)



The same conclusion holds for the $D_s^*\gamma$ final state, shown in Fig. 3(b), where we combine selected D_s^* candidates with photons of energy above 150 MeV. The peak in the $\Delta M(D_s^*\gamma)$ spectrum in Fig. 3(b) near 150 MeV$/c^2$ is due to real $D_s^{*+} \to D_s^+\gamma$ decays in which a random photon has been combined with the D_s^+ candidate to form the D_s^* candidate, and the actual photon from this transition is combined with this system to form the D_{sJ}^* candidate. There

Radiative decay of $D_{s0}(2317)^+$



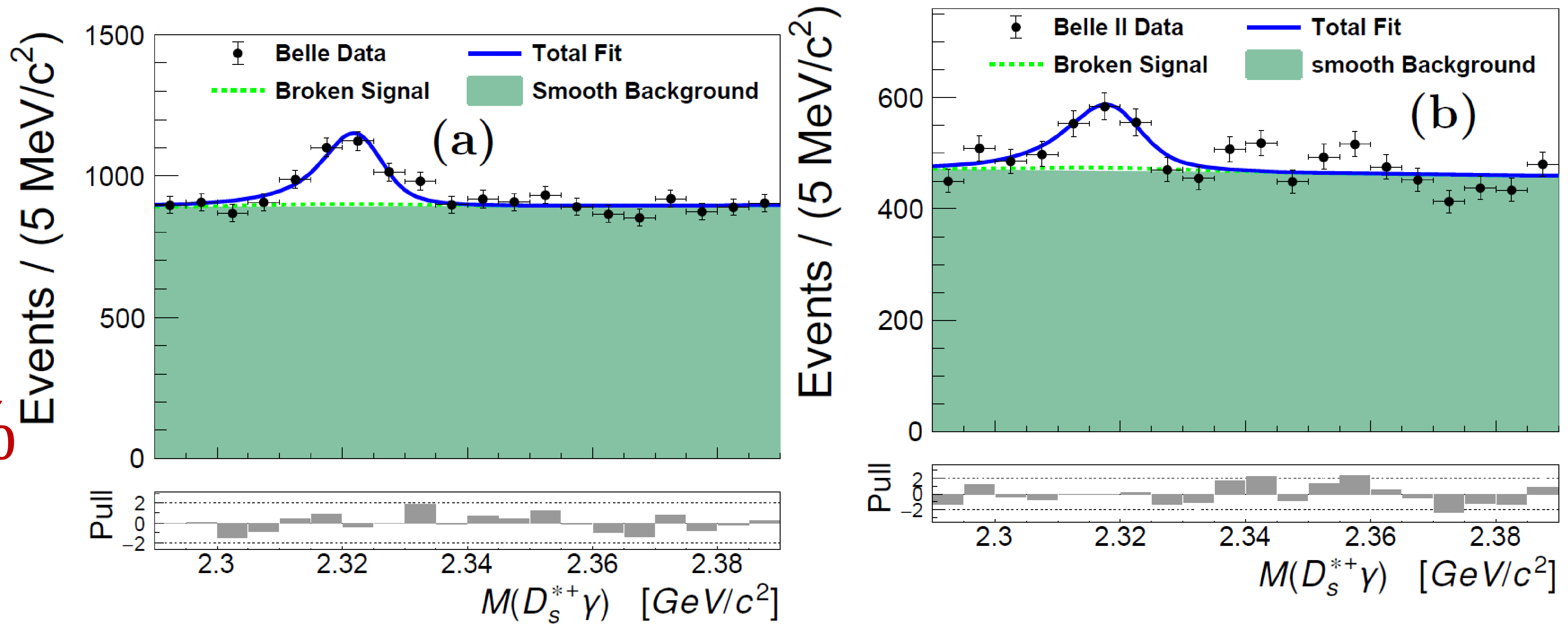
Separate fit to extract $D_s(2460)^+ \to D_s\pi^0$ yields

- Signal: Crystal Ball convoluted with triple-Gaussian
- Broken Signal: asymmetry Gaussian
- Smooth Background: 2nd order polynomial
- cross feed: $D_s(2460)^+ \to D_s^{*+}\pi^0$, (i.e. missing one photon)

Simultaneous fit to extract $\mathcal{R}$

- $N_{\exp}(D_s^{*+}\gamma) = \mathcal{R}\dfrac{N_{\exp}^{\mathrm{fit}}(D_s^+\pi^0)\varepsilon_{\exp}(D_s^{*+}\gamma)}{\varepsilon_{\exp}(D_s^+\pi^0)}$,

  exp represents Belle or Belle II.
- $\mathcal{R} = [7.13 \pm 0.70(stat.) \pm 0.23(syst.)]\%$
- Significance: 10.1σ, with syst. Uncertainty included.



Radiative decay of $D_{s0}(2317)^+$

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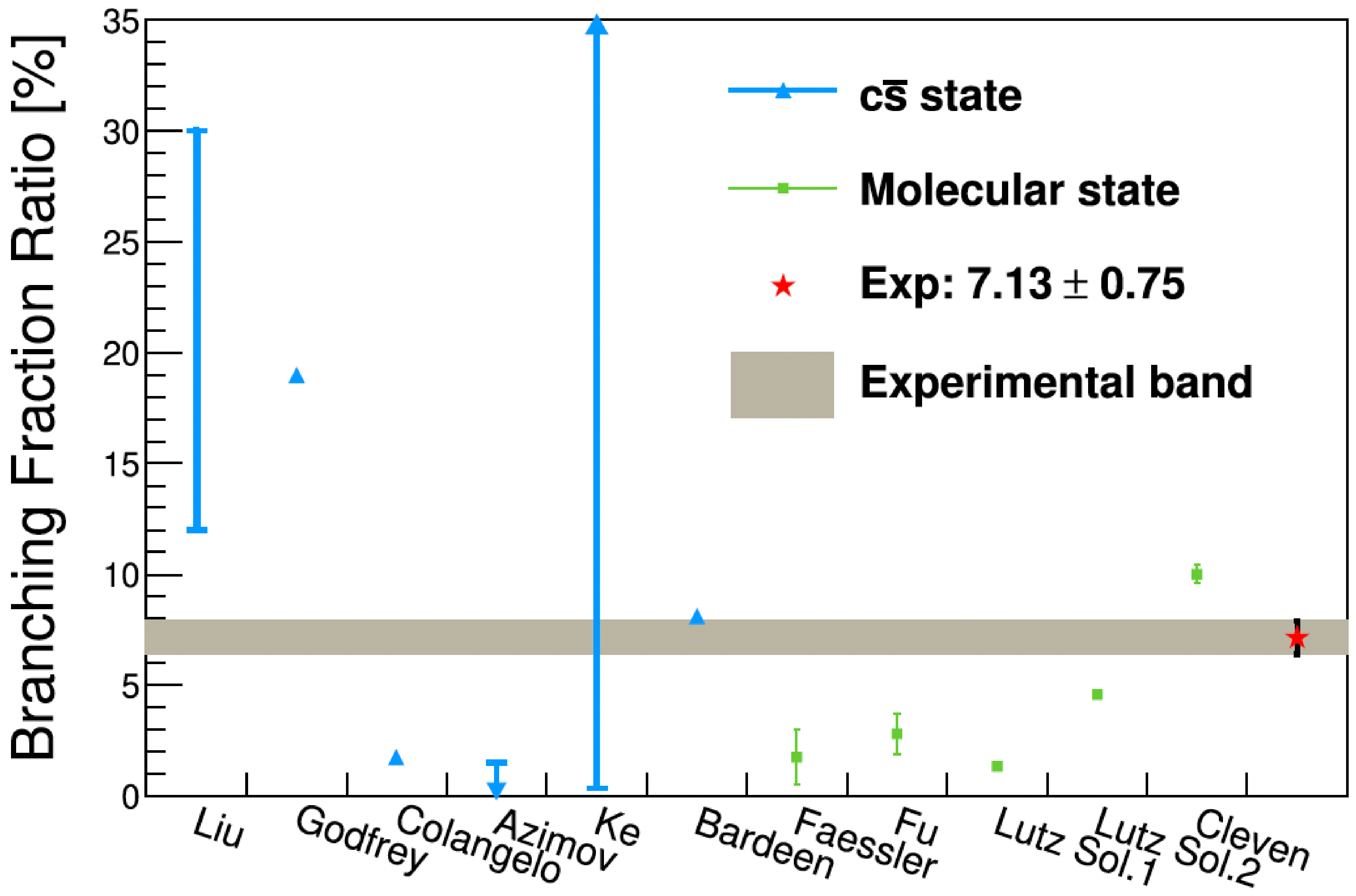
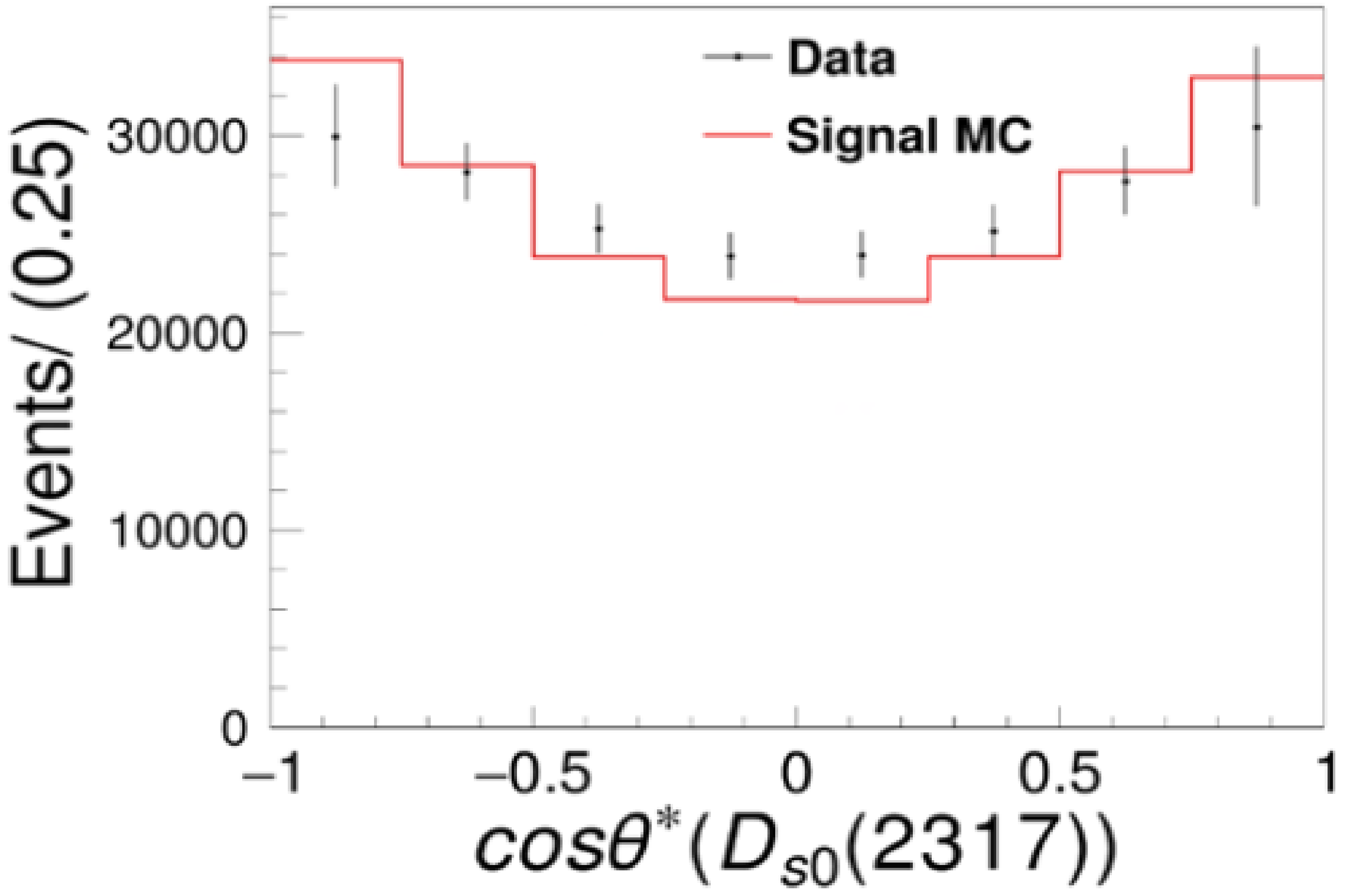
Systematic uncertainty

Source	$D_s^+\pi^0$	$D_s^{*+}\gamma$
Fit region and background pdf	0.8	1.3
Fixed pdf parameters	0.7	2.5
Cross-feed or broken signal	0.6	0.7
x_p reweighting	0.5	
$\boxed{\cos\theta_{\gamma_1\gamma_2}\text{ reweighting} \quad 1.7}$	1.7	
MC sample size	0.5	
Sum	3.6	





Reweight MC as:

$I(\cos\theta) \propto 1 + \cos\theta_{\gamma\gamma}$, where $\theta_{\gamma\gamma}$ is the angle between the two photons in the D_s^{*+} rest frame.

θ^*: polar angle of the $\boldsymbol{D_{s0}(2317)^+}$ in center-of-mass system

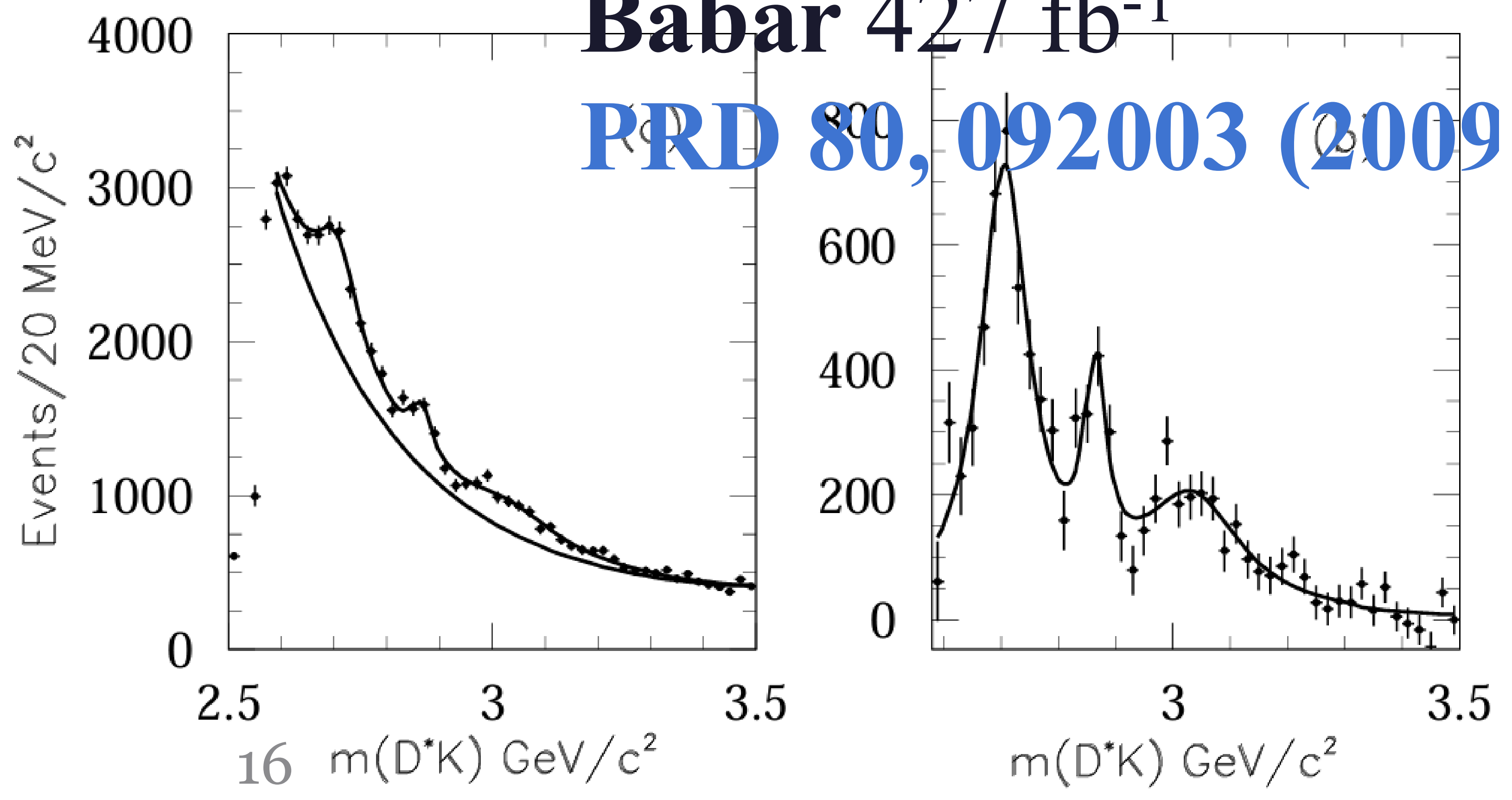
Summary

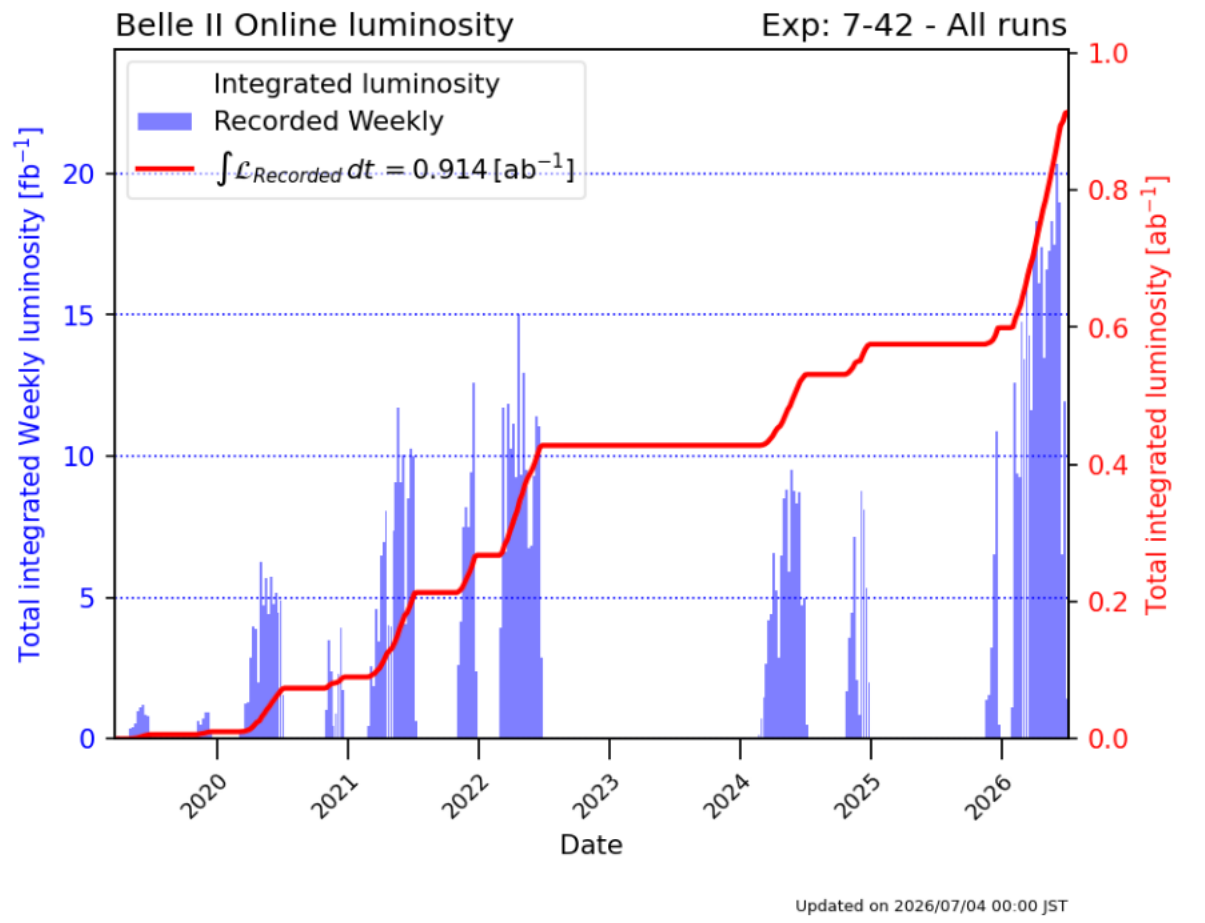
- Using all Belle data (983 fb^{-1}) and Belle II data (427 fb^{-1} +xxx)
- **Observed $D_{s0}(2317)^+ \to D_s^{*+}\gamma$ decay for the first time with 10.1σ**
- $\mathcal{R} = \frac{\mathcal{B}(D_s(2317)^+ \to D_s^{*+}\gamma)}{\mathcal{B}(D_s(2317)^+ \to D_s^{+}\pi^0)} = [7.14 \pm 0.70(stat.) \pm 0.23(syst.)]\%$
  - **uncertainty dominated by Statistical error of $D_s(2317)^+ \to D_s^{*+}\gamma$**
  - higher than the molecular assumption for $D_{s0}(2317)^+$
  - possible interpretation: $D_{s0}(2317)^+$ could be the mixture state of pure $c\bar{s}$ and molecular state

- **Analysis of $D_{s1}(22460)^+ \to D_s^{*+}\gamma$ is ongoing.**
- **More analysis can be done:**
  - **XYZ → $D_{sJ}XXX$**
  - **Higher excited states**

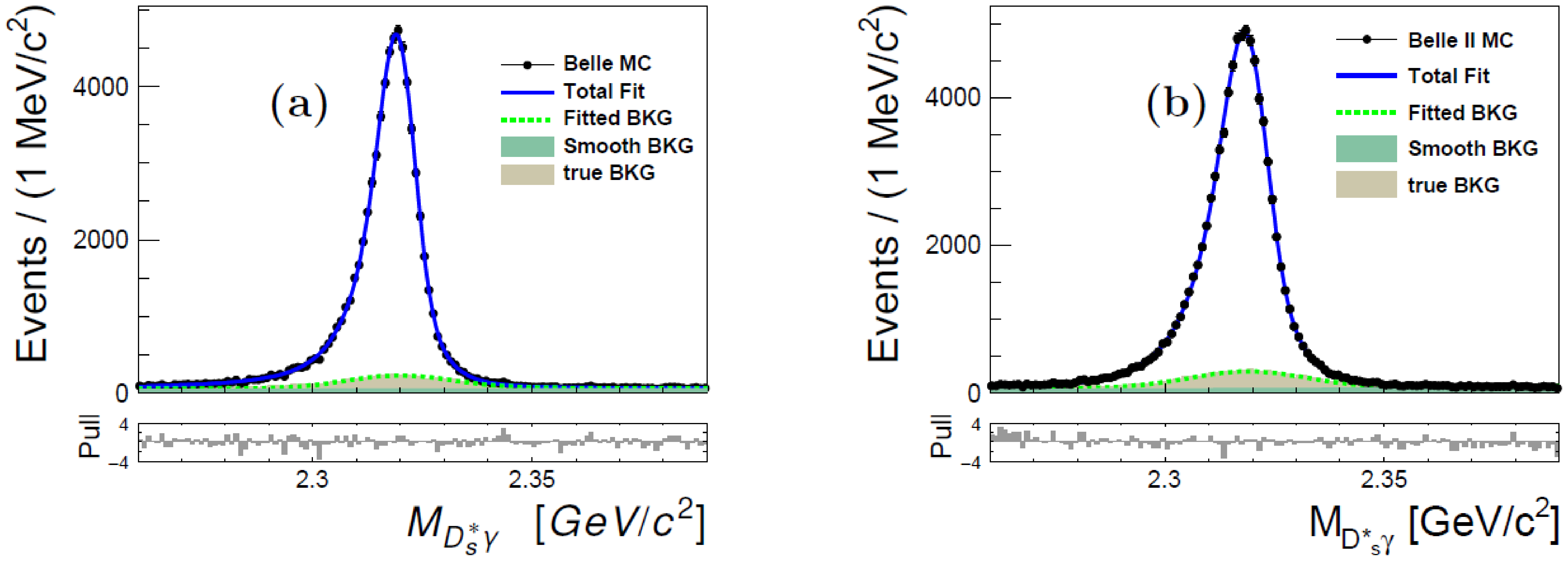
Babar 427 fb^{-1}

PRD 80, 092003 (2009





$D_s(2317)$ MC distributions



- Signal: Crystal Ball convoluted with triple-Gaussian
- Broken Signal: asymmetry Gaussian
- Smooth Background: 2nd order polynomial
- All parameters free to float in the fits

Experiments	Belle	Belle II
N^{fit}	$(6.44 \pm 0.02) \times 10^4$	$(8.00 \pm 0.03) \times 10^4$
Truth yields	64,508	80,154

The IO checks are OK for the signal MC samples

$$N_{\rm exp}(D_s^{*+}\gamma) = \mathcal{R}\,\frac{N_{\rm exp}^{\rm fit}(D_s^+\pi^0)\,\varepsilon_{\rm exp}(D_s^{*+}\gamma)}{\varepsilon_{\rm exp}(D_s^+\pi^0)}$$

Systematic Uncertainty Study

- The systematic uncertainties due to D_s and **photon** selection, and cut on x_p are cancelled
- x_p **reweighting:**
  - ➢Change the order of the polynomial used to fit x_p distribution
  - ➢Redo the reweighting to get the new detection efficiency $\varepsilon_{\rm exp}$
  - ➢Fit $\mathcal{R}$ again

Uncertainties on $\mathcal{R}$:
Difference in Fit $\mathcal{R}$

- $D_{s0}(2317) \to D_s\pi^0$ **mode:**

In the fits to $M(D_s^+\pi^0)$ spectra, By

1. Changing the fit region, order of background polynomial
2. Enlarging the widths of Gaussians by 1σ (gotten from fits to signal MC)
3. Using the shapes of $M(D_s\pi)$ from $D_s(2460)^+ \to D_s^{*+}\pi^0$ MC directly

➢ Differences in the fitted signal yields: Uncertainties ($\Delta_{\rm exp}^{N(D_s^+\pi^0)}$) of $N_{\rm exp}^{\rm fit}(D_s^+\pi^0)$

Then, in the simultaneous fit to $M(D_s^{*+}\gamma)$ spectra,

By varying the $N_{\rm exp}^{\rm fit}(D_s^+\pi^0)$ based on Gaussian($N_{\rm exp}^{\rm fit}(D_s^+\pi^0)$, $\Delta_{\rm exp}^{N(D_s^+\pi^0)}$) in the fits

Widths of the distributions of fitted values of $\mathcal{R}$:
Uncertainties on $\mathcal{R}$:

Systematic Uncertainty Study

- $D_{s0}(2317) \to D_s^{*}\gamma$ **mode:**

In the simultaneous fit to $M(D_s^{*+}\gamma)$ spectra, by:

1. Changing the fit region, order of background polynomial
2. Enlarging the widths of Gaussian by 1σ (gotten from fits to signal MC)
3. Changing resolutions of broken signal by 2σ
4. Changing ratios of broken signal to signal yields by 2σ

➢Fit $\mathcal{R}$ again

Uncertainties on $\mathcal{R}$:
Difference in Fit $\mathcal{R}$

Source	$D_s^+\pi^0$	$D_s^{*+}\gamma$
Fit region and background pdf	0.8	1.3
Fixed PDF parameters	0.7	2.5
Cross-feed or broken signal	0.6	0.7
x_p reweighting	0.5	
MC statistic	0.5	
Sum	3.2	

Assuming all systematic uncertainties are independent