Study of the $e^+e^- \to \pi^+\pi^-\psi(2S)$ reaction at $\sqrt{s} > 4.600$ GeV and search for the charged $Z_c(4430)$ exotic state

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FE

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BESIII Experiment

BESIII (BEijing Spectrometer III) is an experiment located at the BEPCII (Beijing Electron Positron Collider II) at IHEP (Institute of High Energy Physics)

Being **BEPCII** an **e^+e^- collider**, BESIII can profit from **direct production** of **vector states** ($J^{PC} = 1^{--}$)

The **statistics of the ψ(nS)** decays allows to probe and study with **high precision** also the non vector states

BESIII has also **unique opportunities** with datasets **above 3.8 GeV**

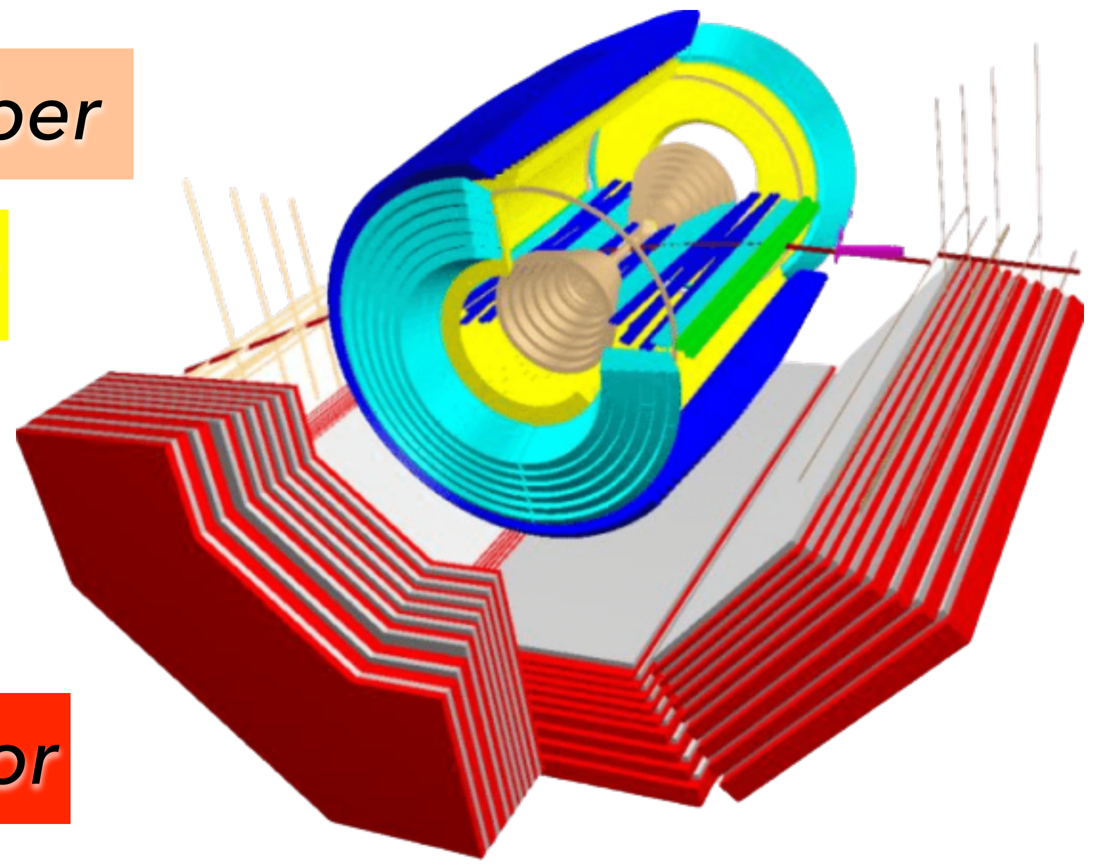
Multi-layer Drift Chamber

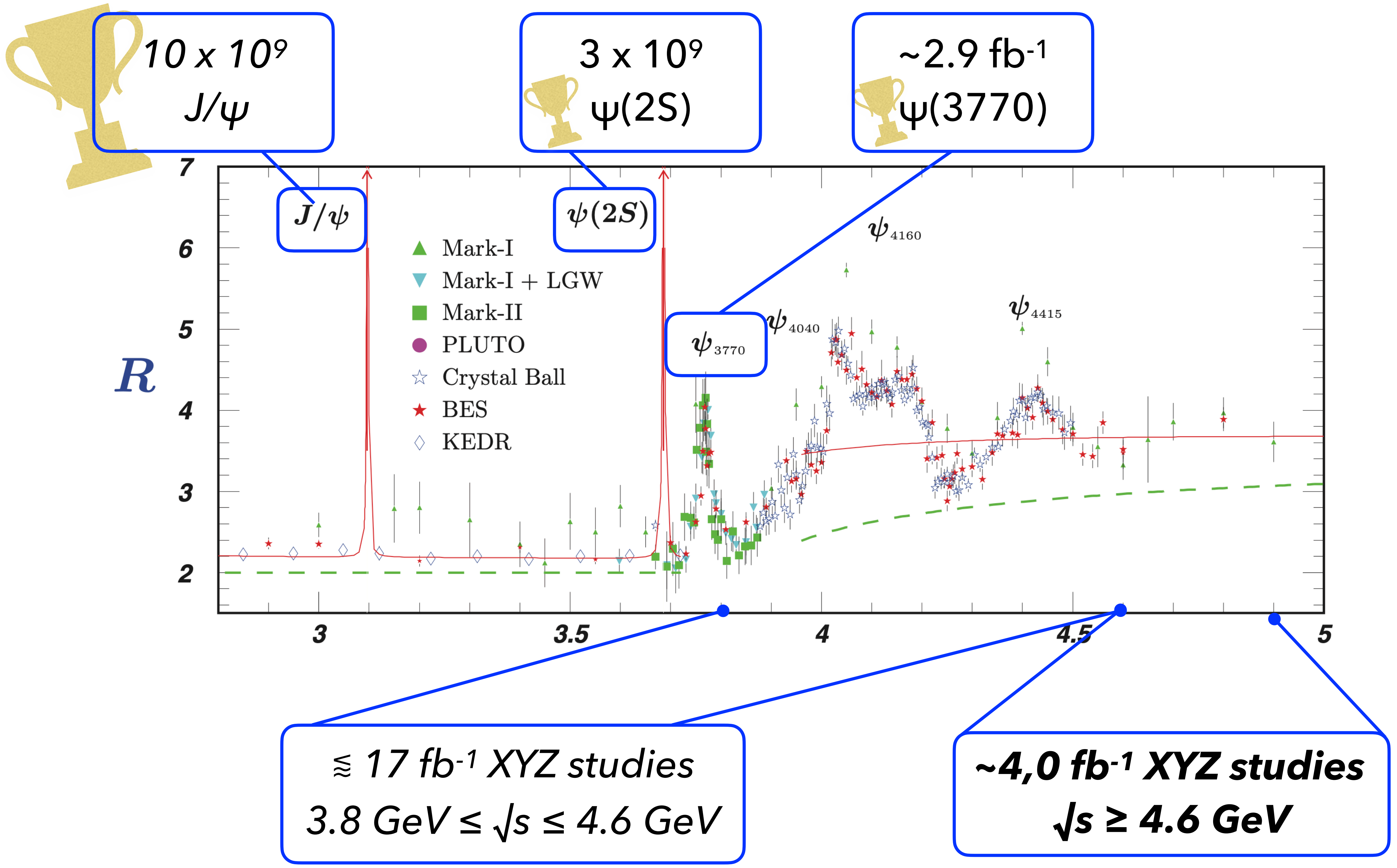
Time of Flight Detector

EM Calorimeter

1T Solenoidal Magnet

Muon Detector





τ-charm factory 2.0 GeV ≤ $\sqrt{s}$ ≤ 4.9 GeV with a 10^{33} $cm^{-2}s^{-1}$ designed luminosity @ $\sqrt{s}$ = 3.77 GeV

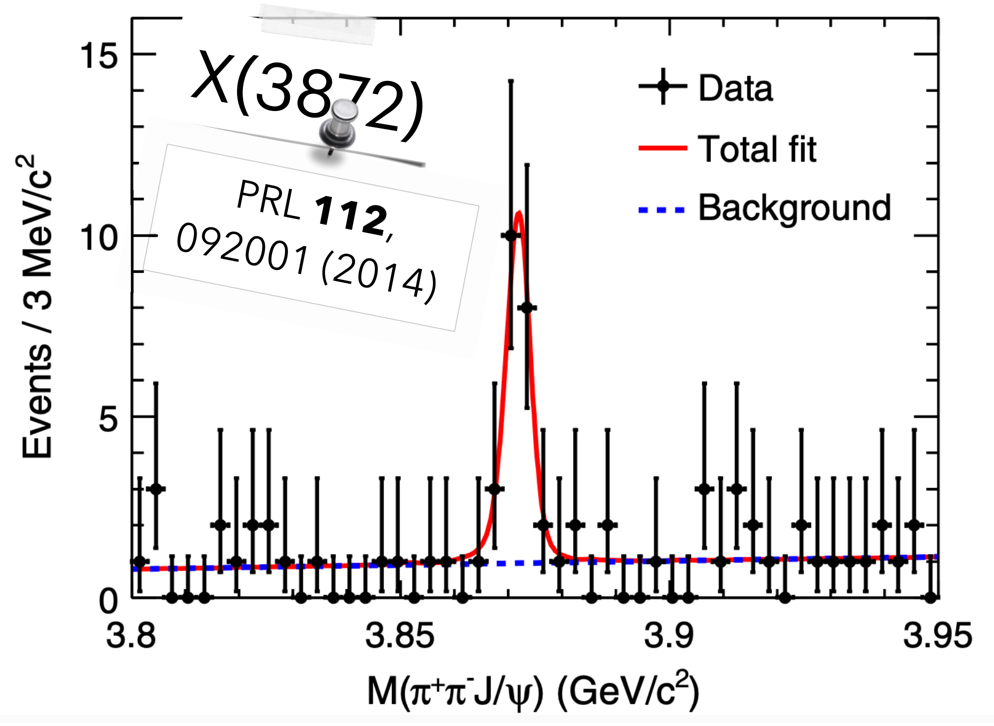
Charmonium (-like) States

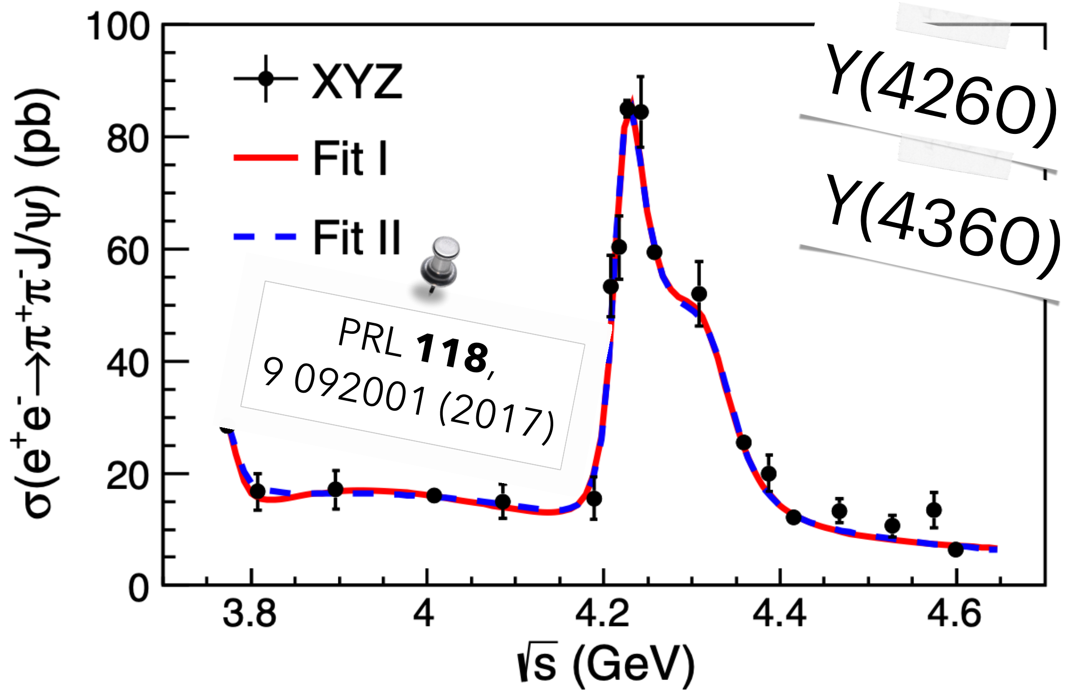
Charmonium resonances are located in the **transition region** of perturbative and non-perturbative **QCD**

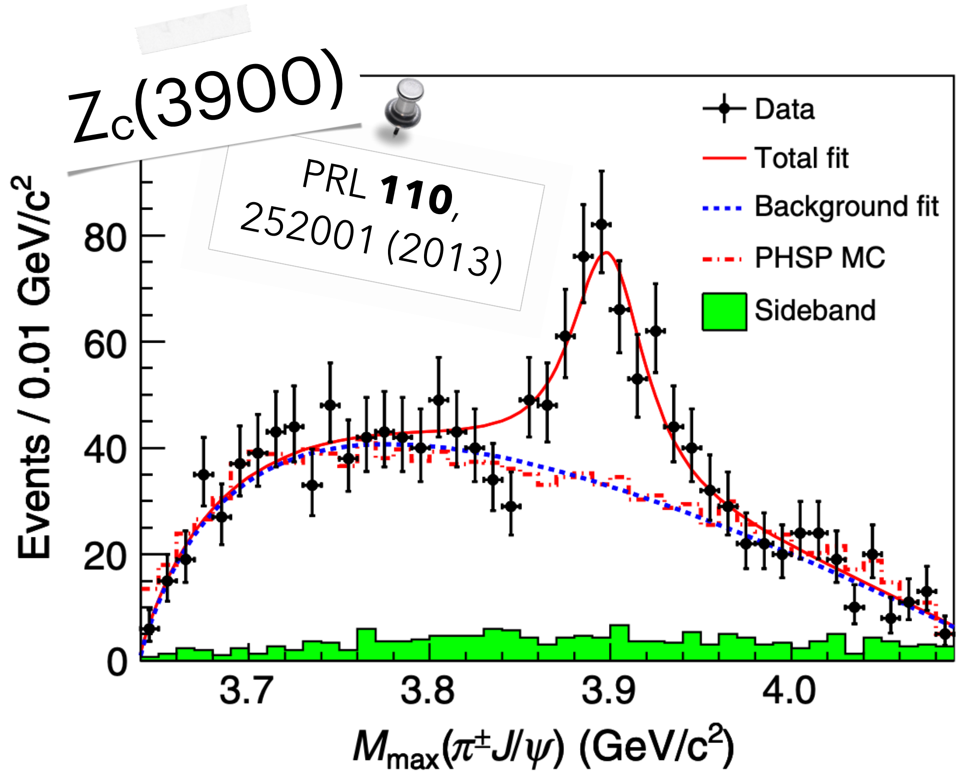
Despite **conventional charmonia fit** fairly well potential model **predictions**, **non-vector** states are still **not** entirely **known**

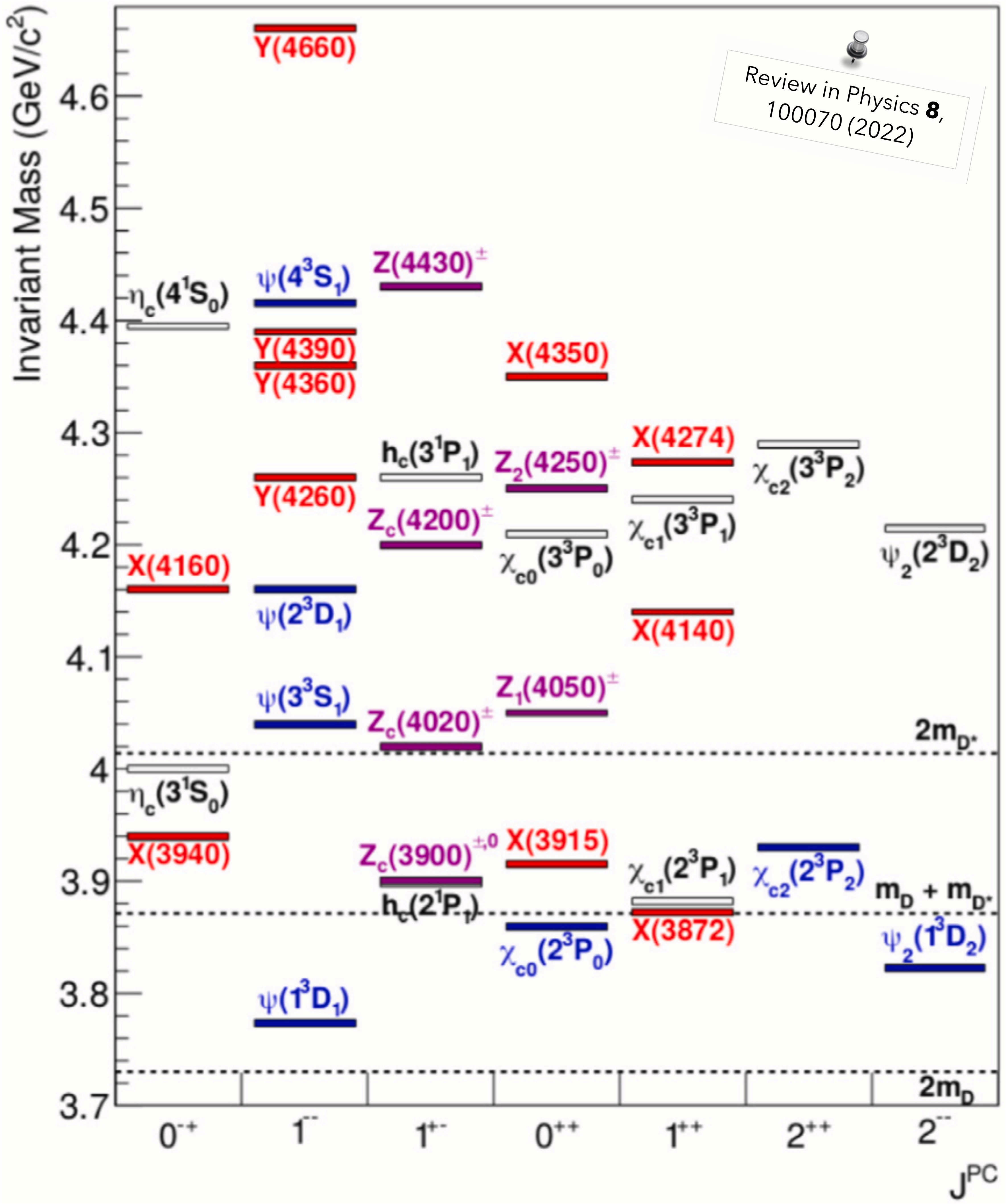
$c\bar{c}$ spectrum features **supernumerary (XYZ) states**, (1) **not fitting** potential model **predictions**, (2) showing strong couplings to hidden charm states, and (3) can exhibit a non-zero charge

The **nature** of these exotic states is **not** yet **clear** (*hybrids*, *mesonic molecules*, *tetraquarks*…)









Charmonium (-like) States

Some of the exotic **candidates** are **close to open-flavour thresholds**, the **presence** of which might induce kinematic **enhancements**[I, II]; also, the **XYZ states could** emerge as **interference effects** of various standard quarkonia

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[II] Int. J. Mod. Phys. E **25**, 07 1642010 (2016)

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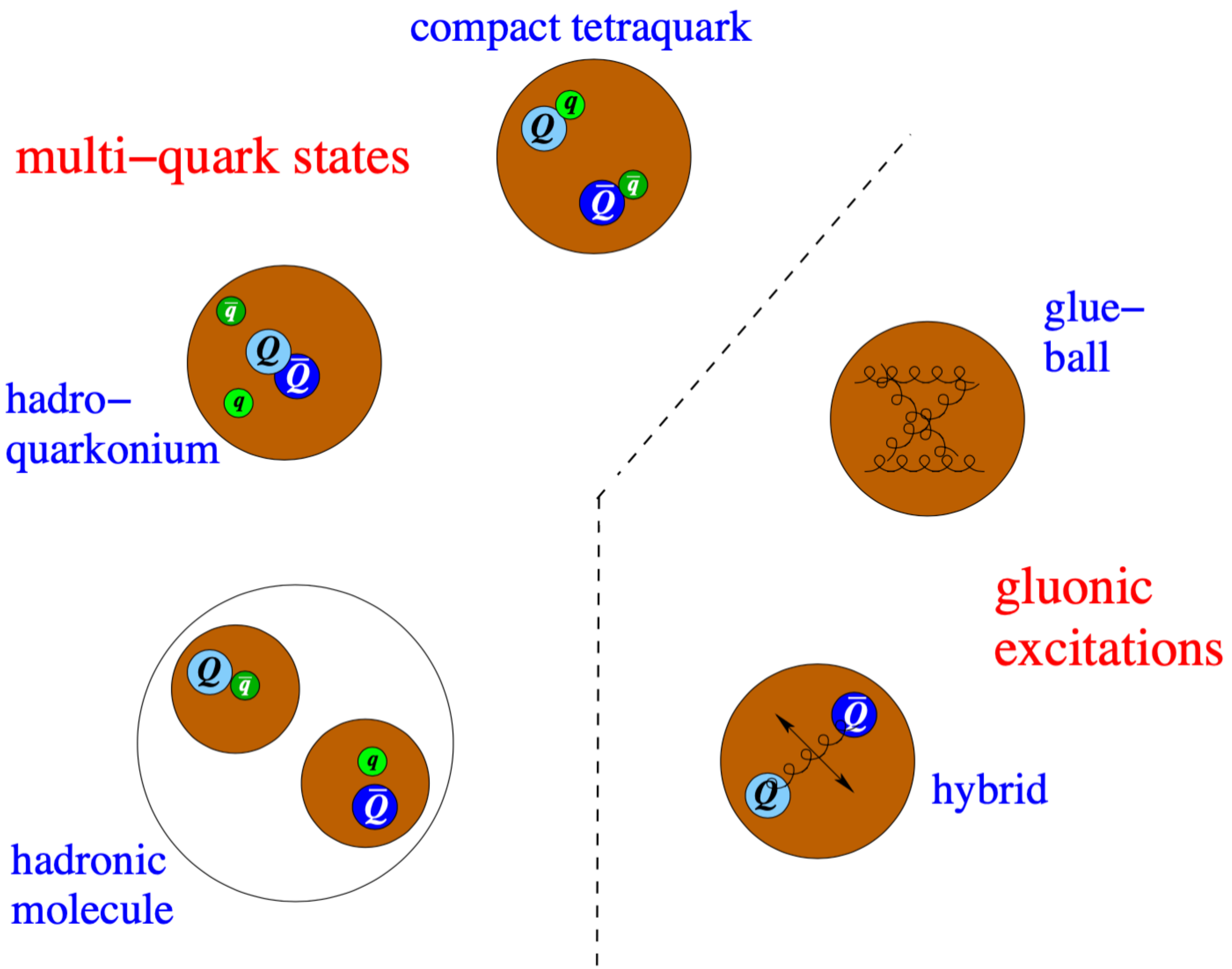
Assuming a novel physical origin, **exotic hadrons** can be grouped into **two families following their valence content** with respect to the standard meson-baryon picture



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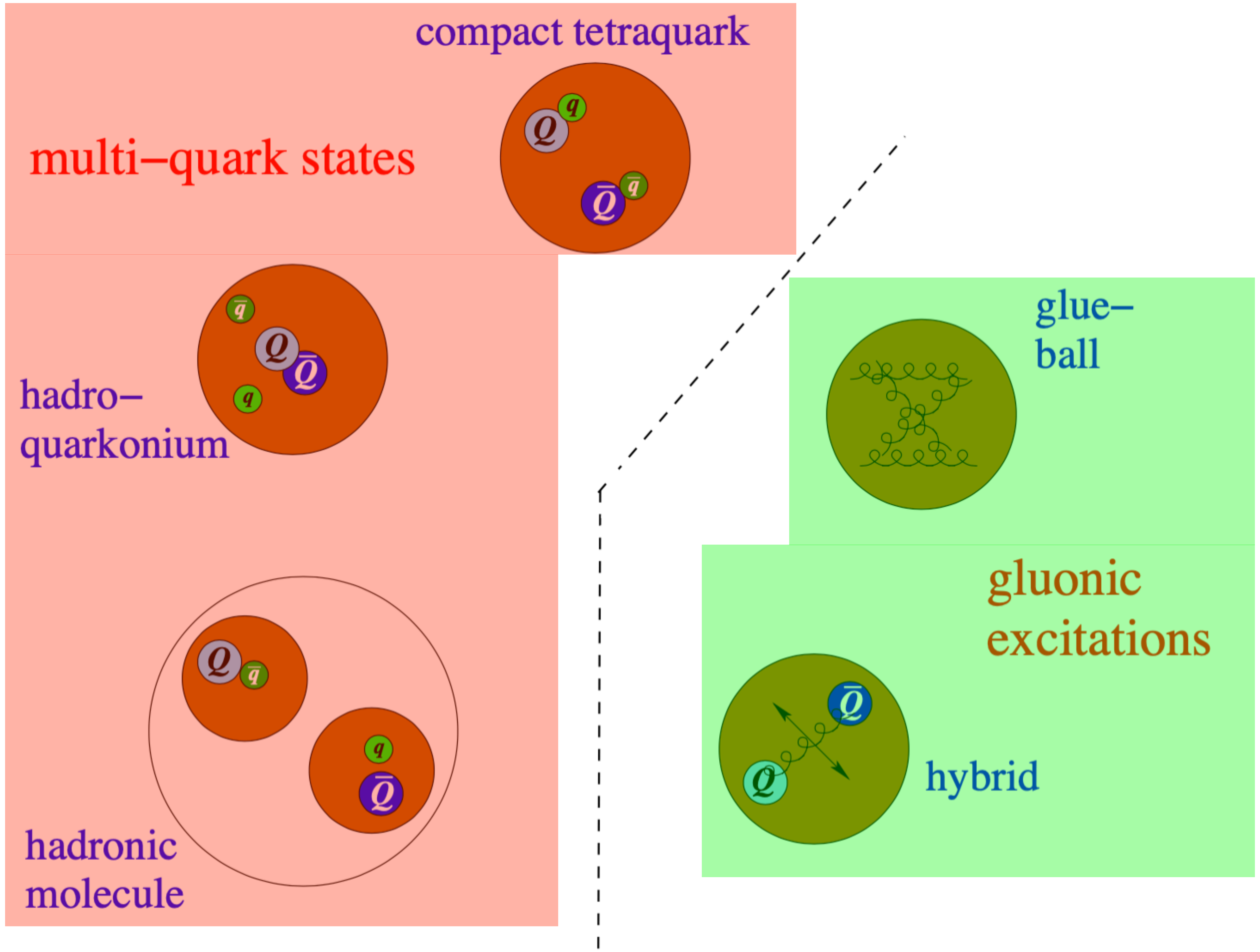

Assuming a novel physical origin, **exotic hadrons** can be grouped into **two families following their valence content** with respect to the standard meson-baryon picture:

* they might contain additional (or only) valence gluons
* they can be multi-quark states

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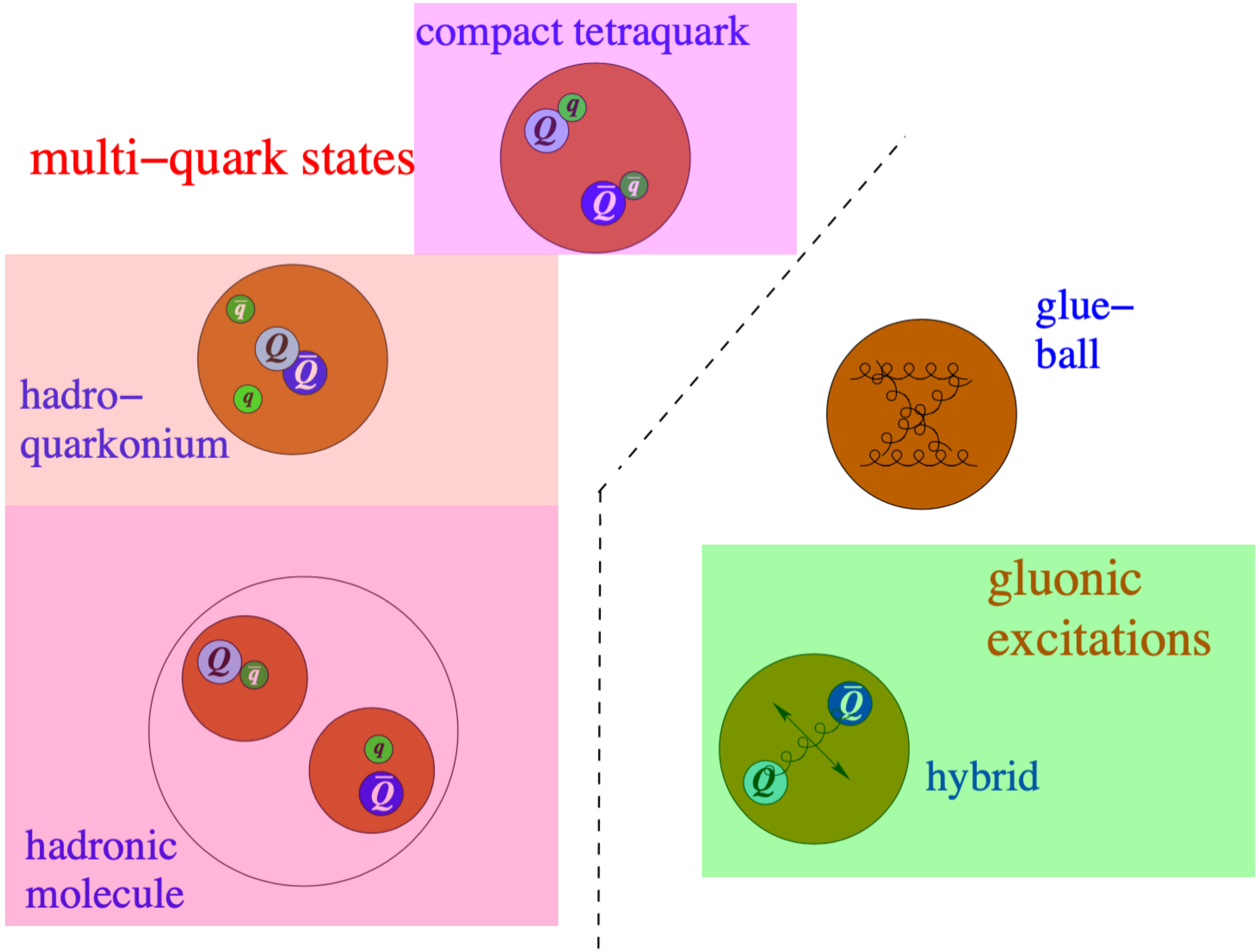
Charmonium (-like) States

BESIII has recently discovered the **η(1855)** hadron, an **exotic isoscalar** state **consistent with** lattice QCD[III] **calculations for** the $J^{PC} = 1^{-+}$ **hybrid**

Y states can be described as **hadroquarkonia**
Ref. [IV] suggests that the **Y (4230)** resonance might be a **mixture of two hadrocharmonia**

The **X(3872)** state is **claimed**[V] to be a **DD* molecule**
The **Y (4230)** resonance is **suggested**[V] to have a **$D_1\bar{D}$ molecular nature**

A candidate for a **compact tetraquark** is the **Z_c(3900)** hadron, following Ref. [VI]



[III] Phys. Rev. D **88**, 094505 (2013)
[IV] Mod. Phys. Lett. A **29**, 12 1450060 (2014)
[V] Phys. Rev. D **90**, 074039 (2014)
[VI] Phys. Lett. B **746**, 194-201 (2015)

Preamble

What and Why

The **$e^+e^- \to \pi^+\pi^-\psi(2S)$** reaction offers the possibility to probe the ***XYZ* sector**, via the investigation of 2 exotic states

The **Y(4660)** via the $e^+e^- \to [\pi^+\pi^-/f_0(980)]\psi(2S)$

Y(4660), **observed by BaBar**[1], **BELLE**[2], and **BESIII**[3] hypothesised to be a **baryonium**[4], a **molecule**[5], or a **tetraquark**[6]

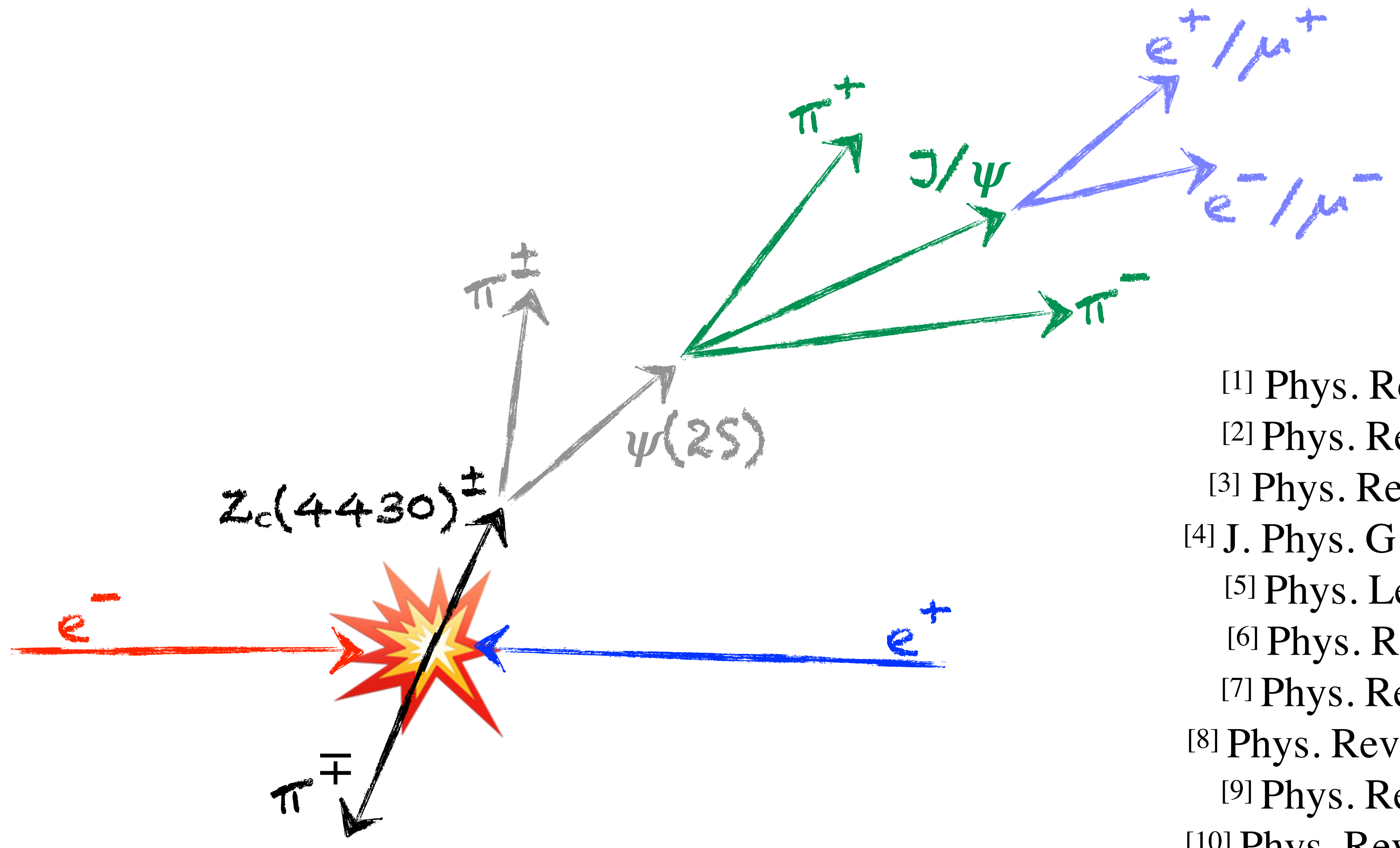
Study of the exotic $Z_c(4430)$ state through the $e^+e^- \to \pi^\pm Z_c(4430) \to \pi^+\pi^-\psi(2S)$

Z^+_c(4430) was **observed** and studied in the *B*-decays in the $\pi\psi(2S)$ invariant mass **by BELLE**[7] (and **by LHCb**[8])

Motivation

In Refs. [9, 10], the $Z_c(3900)^\pm$ state is seen both in $\pi\psi(2S)$ and $\pi J/\psi$, and in relation with the Y(4260) resonance

Ref. [10] finds $R = \sigma(\pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi)/\sigma(\pi^+\pi^- J/\psi) \sim 22\%$, neglecting the the J/ψ to $\psi(2S)$ PHSP change, ~100 events are expected around Y (4660)



[1] Phys. Rev. D **89**, 111103
[2] Phys. Rev. D **91**, 112007
[3] Phys. Rev. D **104**, 052012
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[5] Phys. Lett. B **665**, 26-29
[6] Phys. Rev. D **89**, 114010
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[8] Phys. Rev. Lett. **112**, 222002
[9] Phys. Rev. D **96**, 032004
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Preamble

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Study of the exotic $Z_c(4430)$ state through the $e^+e^- \to \pi^\pm Z_c(4430) \to \pi^+\pi^-\psi(2S)$

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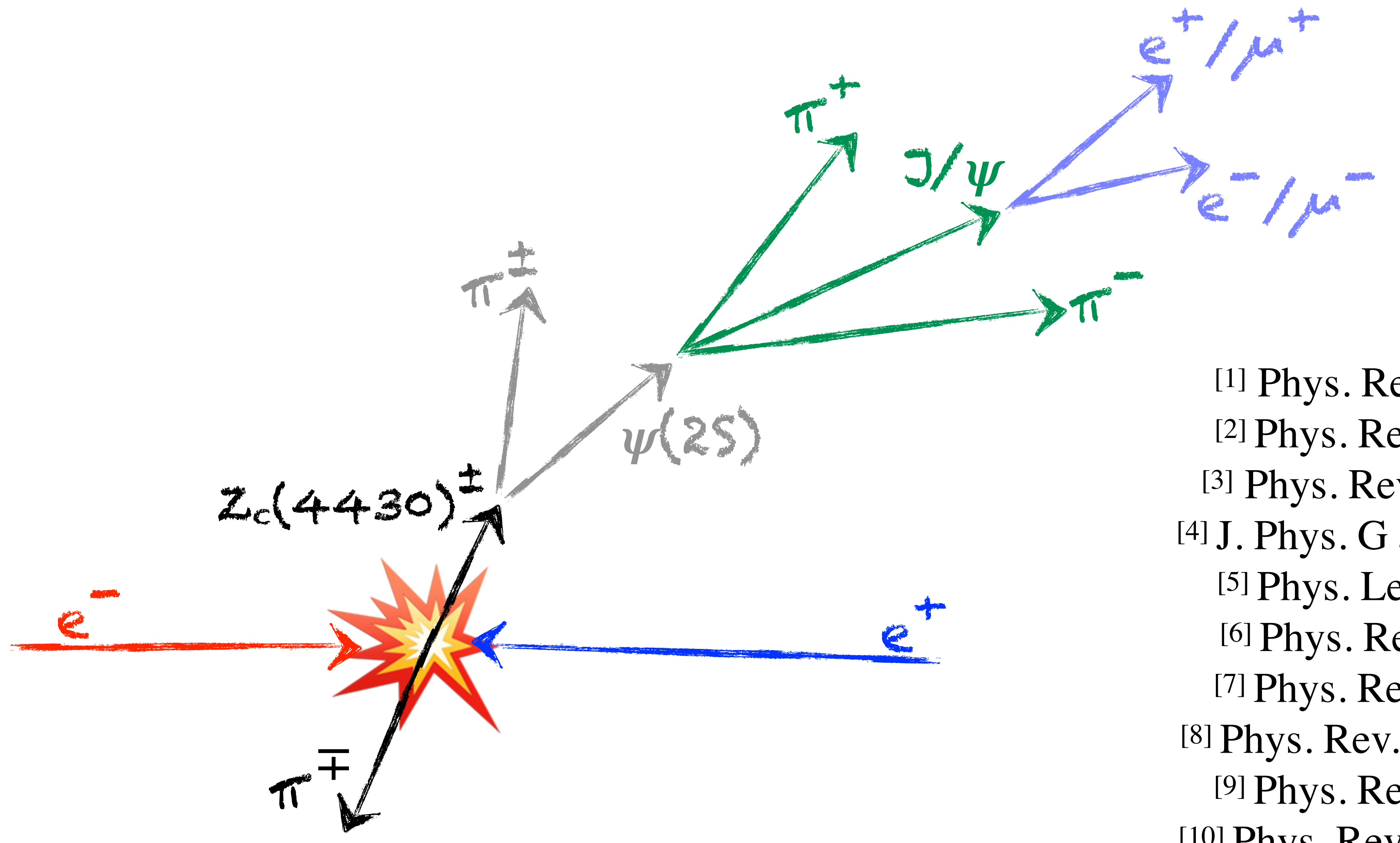
How

The study will make use of the **~5 fb^{-1}** data @$\sqrt{s}$ > 4.6 GeV

No $Z_c(4430)$ **signal** was observed in the **mono-energetic datasets**[11], so the main idea is to merge all the data @$\sqrt{s}$ > 4.6 GeV to use the whole statistics



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Event Selection

Signal MC sample
300k events

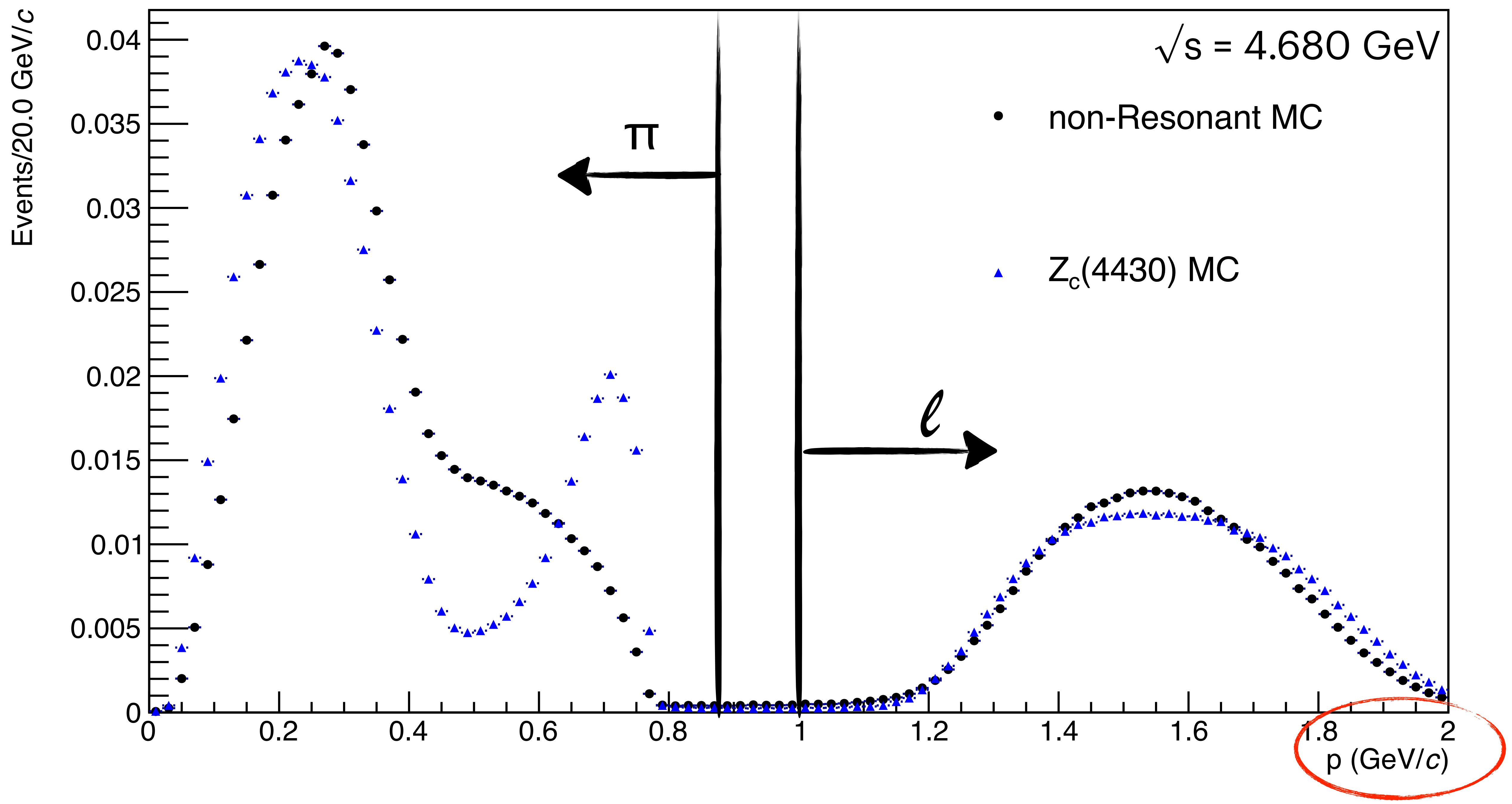
Goodness Cuts

Vertex: $R_{xy} < 1$cm & $R_z < 10$ cm

Polar angle: $|\cos\theta| < 0.93$

Channel ID

Leptons	Pions
p > 1 GeV E/p (e) > 0.7 E/p (μ) < 0.6	p < 0.85 GeV



2 good charged topologies

$2\ell\ 3\pi$

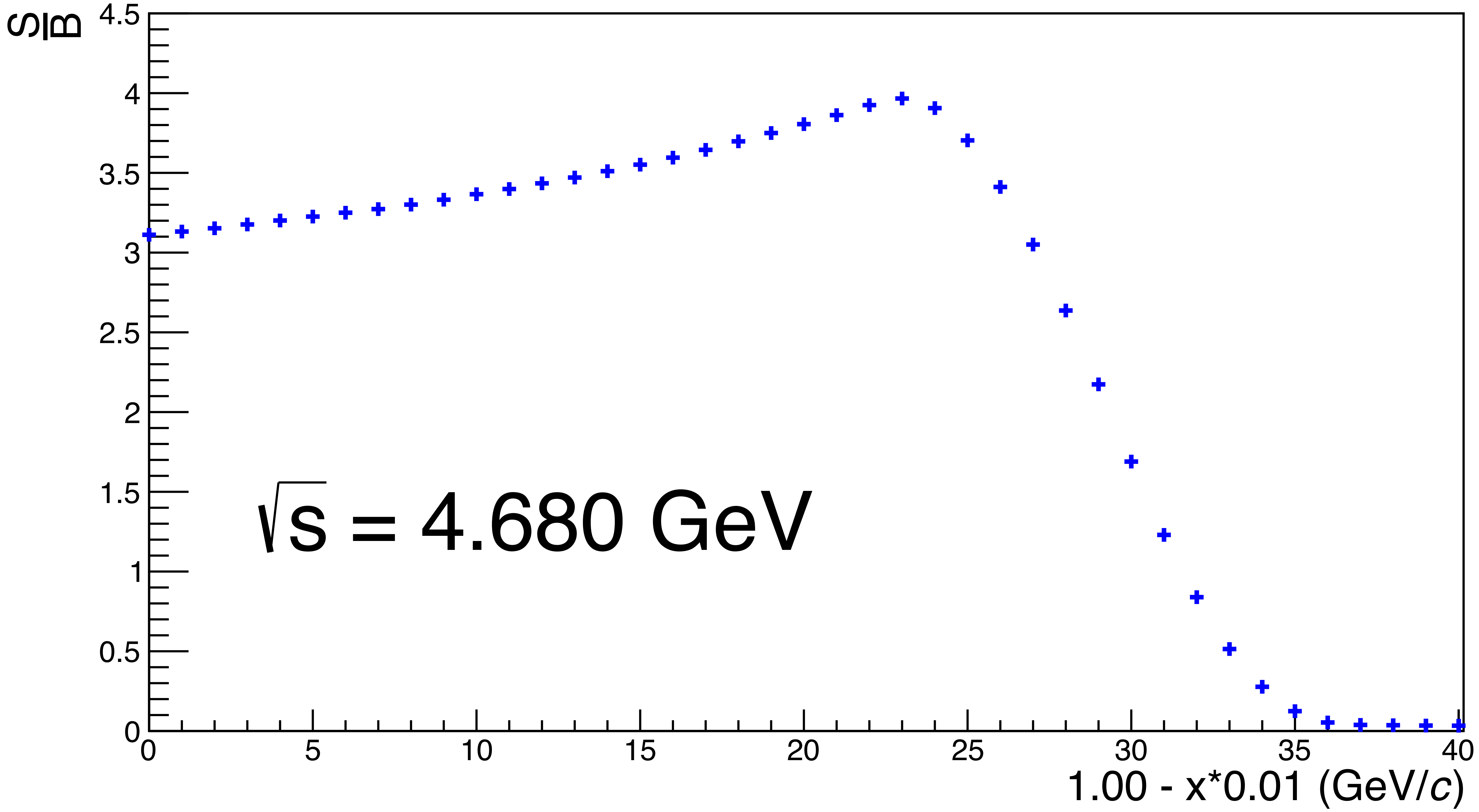
$2\ell\ 4\pi$

Event Selection

Charged Particles Momentum Optimisation

S(Sig$_{MC}$ Z$_c$)/B(Inc$_{MC}$) optimisation
∀ √s and using only MC datasets

√s	p_{ch} [GeV/c]
4.612	0.72
4.626	0.73
4.640	0.74
4.660	0.75
4.680	0.77
4.700	0.78



Event Selection

Topology-dependent Kinematic Fits

$2\ell 4\pi$

6-constraint (6C) kinematic fit

1C on the $M_{J/\psi}$
1C on the $M_{\psi(2S)}$
4C on the $p_{Tot} = (0.051, 0, 0, M_{\sqrt{s}})$

The $\pi\pi$ couples are selected via the best χ^2

$2\ell 3\pi$

6-constraint (6C) kinematic fit

1C on the $M_{J/\psi}$
1C on the $M_{\psi(2S)}$
4C on the $p_{Tot} = (0.051, 0, 0, M_{\sqrt{s}})$

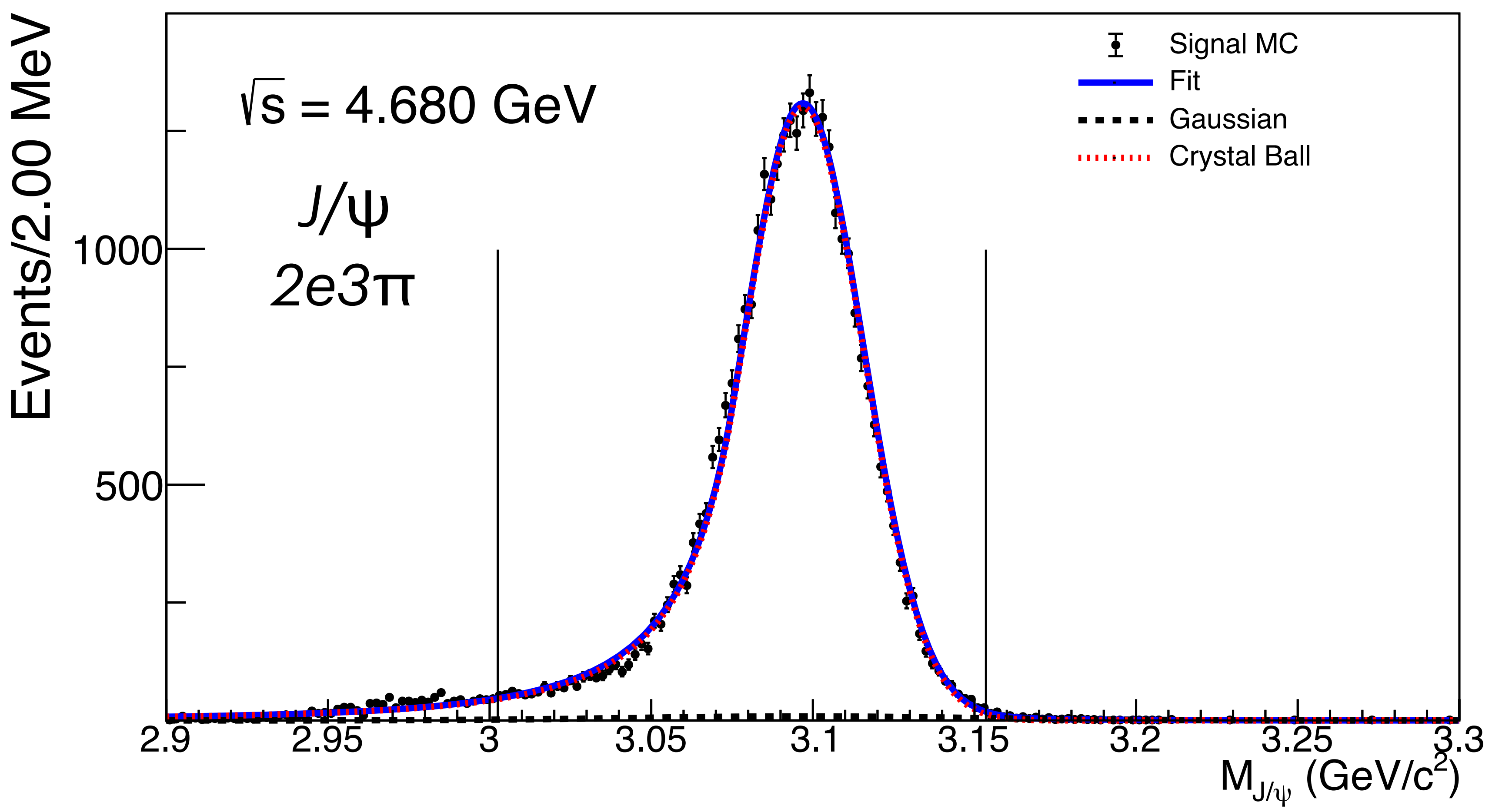
π_{Miss} either from prompt production or from $\psi(2S)$ decay, but not from $Z_c(4430)$

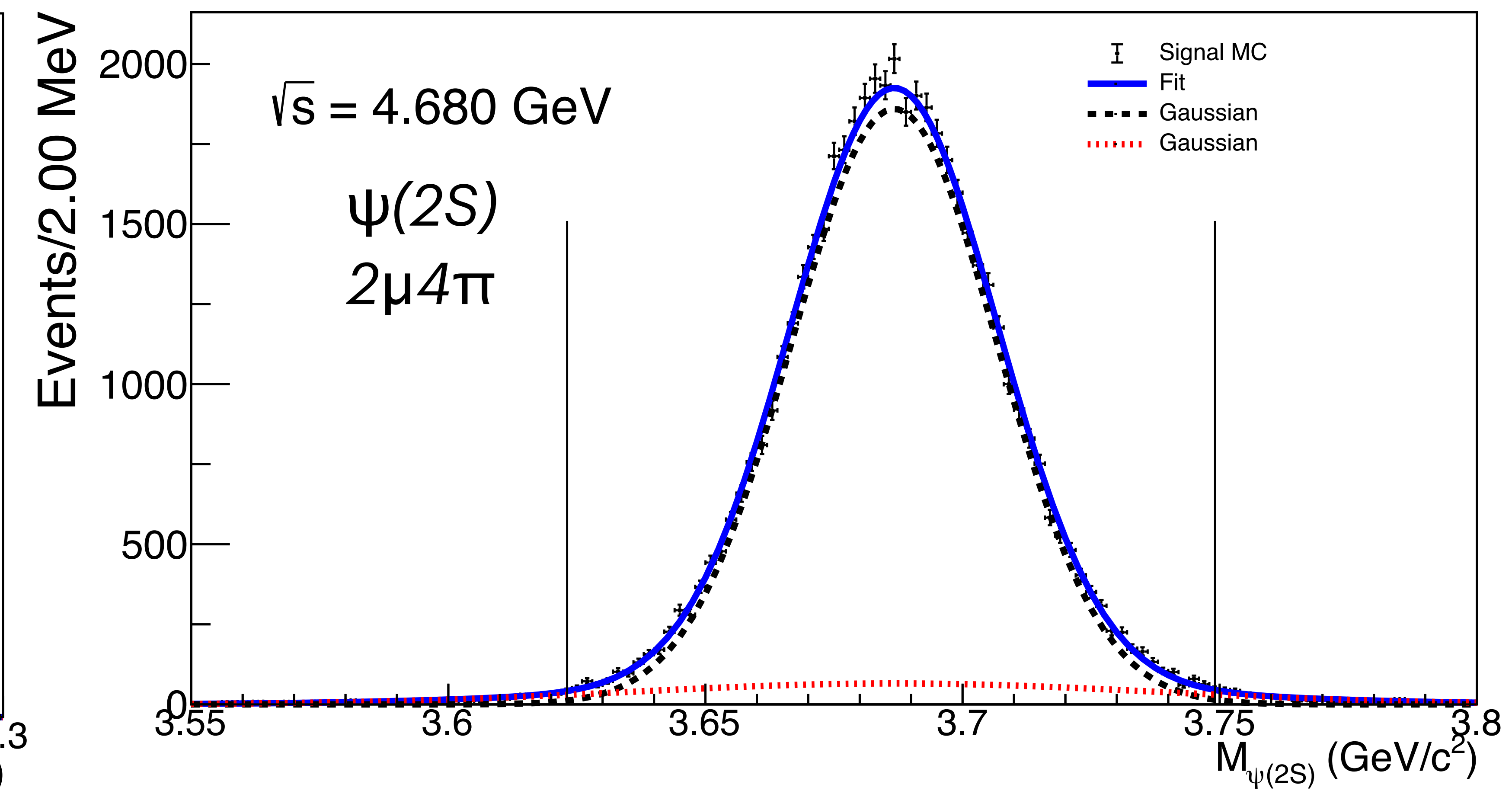
$\pi\pi$ and $\pi\pi_{Miss}$ couples are selected by minimising $M^{Reco}_{\psi(2S)}$-$M^{PDG}_{\psi(2S)}$

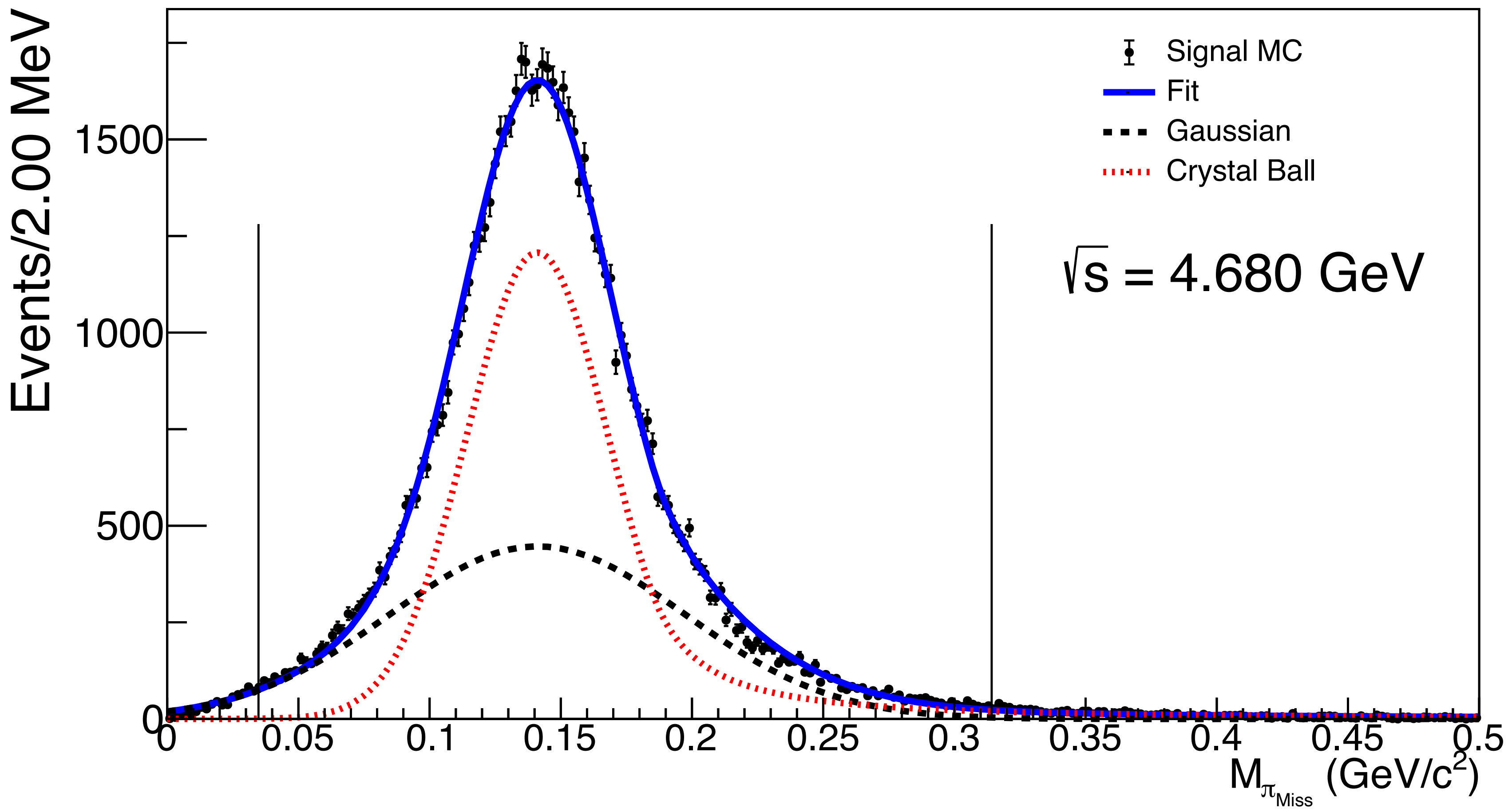
Event Selection

Signal MC sample
300k events

Just a bit more… Signal Windows







Selection performed on

$M(\psi(n))$ both for 2l 4π and 2l 3π
$M_{Miss}(\pi)$ for 2l 3π

Given the width (σ) of the distribution:

ee channel: $-5\sigma < M < +3\sigma$
μμ channel: $-3(5)\sigma < M < +3\sigma$
Miss mass: $-3\sigma < M < +5\sigma$

Background Rejection

Inclusive MC sample
10x $\mathcal{L}$ data

From 1.3 billion inclusive MC events, **28136 survive**, with a survival rate of ~ O(10ppm)

Virtually **only hadron component** is surviving after the selection criteria

Background Rejection

Inclusive MC sample
10x $\mathscr{L}$ data

Index (i)	Decay tree	N_{Evts}	$\sum_i^{Tot} N_{Evts}$
1	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	3389	3389
2	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	2983	6372
3	$e^+e^- \to \pi^+\pi^-\psi'\gamma^I, \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	2875	9247
4	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	2528	11775
5	$e^+e^- \to \pi^+\pi^-\psi'\gamma^I, \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	2499	14274
6	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	2313	16587
7	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	1346	17933
8	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	1249	19182
9	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	1037	20219
10	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	907	21126
11	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	307	21433
12	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	289	21722
13	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	276	21998
14	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	245	22243
15	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	240	22483
16	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	197	22680
17	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	188	22868
18	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	161	23029
19	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	156	23185
20	$e^+e^- \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	144	23329
21	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	132	23461
22	$e^+e^- \to \pi^+\pi^-\psi',, \psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	109	23570
23	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	104	23674
24	$e^+e^- \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\gamma^I$	103	23777
25	$e^+e^- \to \pi^+\pi^-\psi', \psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	96	23873
26	...	...	...

From 1.3 billion inclusive MC events, **28136 survive**, with a survival rate of ~ O(10ppm)

Virtually **only hadron component** is surviving after the selection criteria

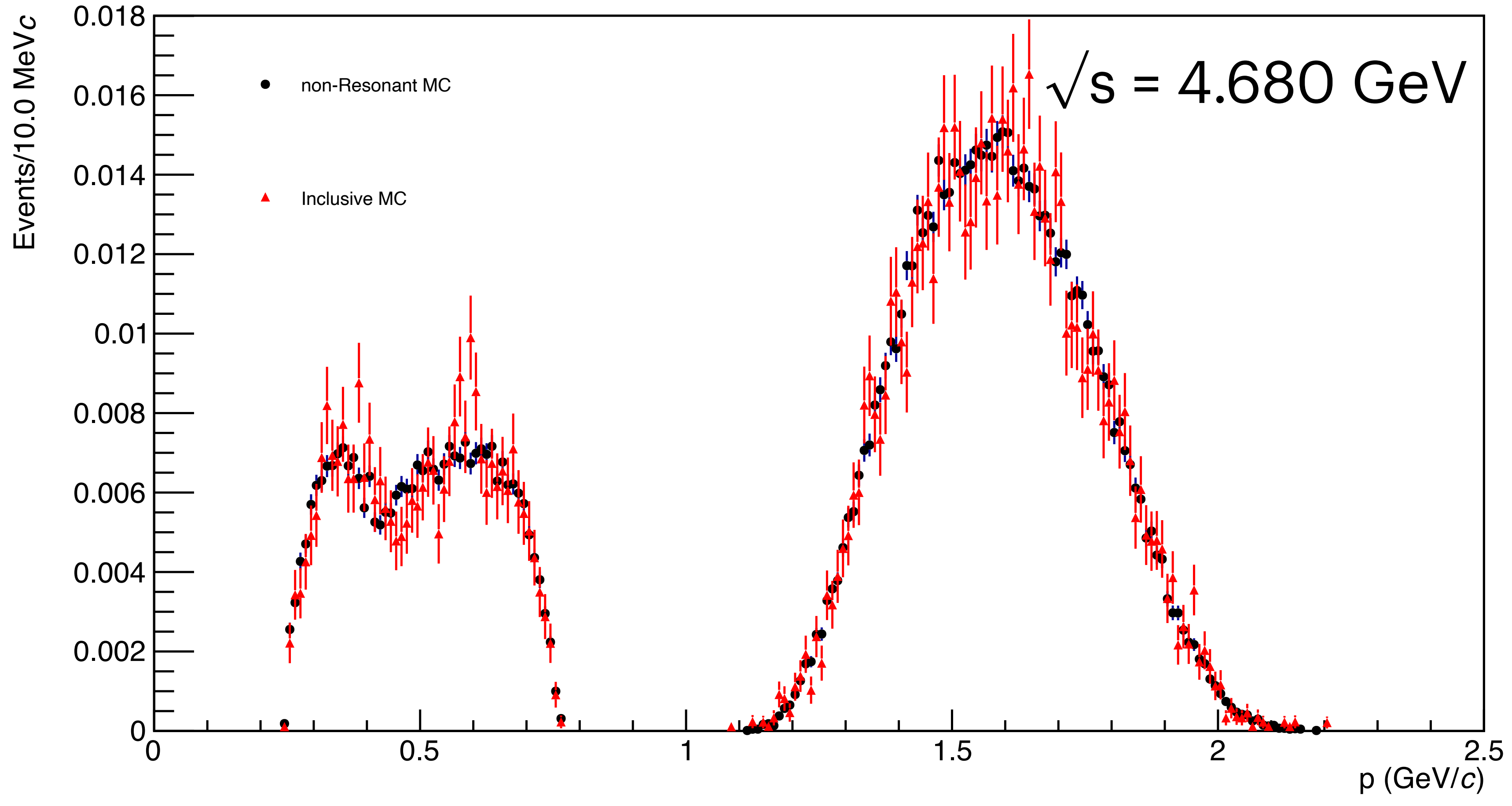
Out of 28136 total **IncMC events**, more of the **90%** of events are from

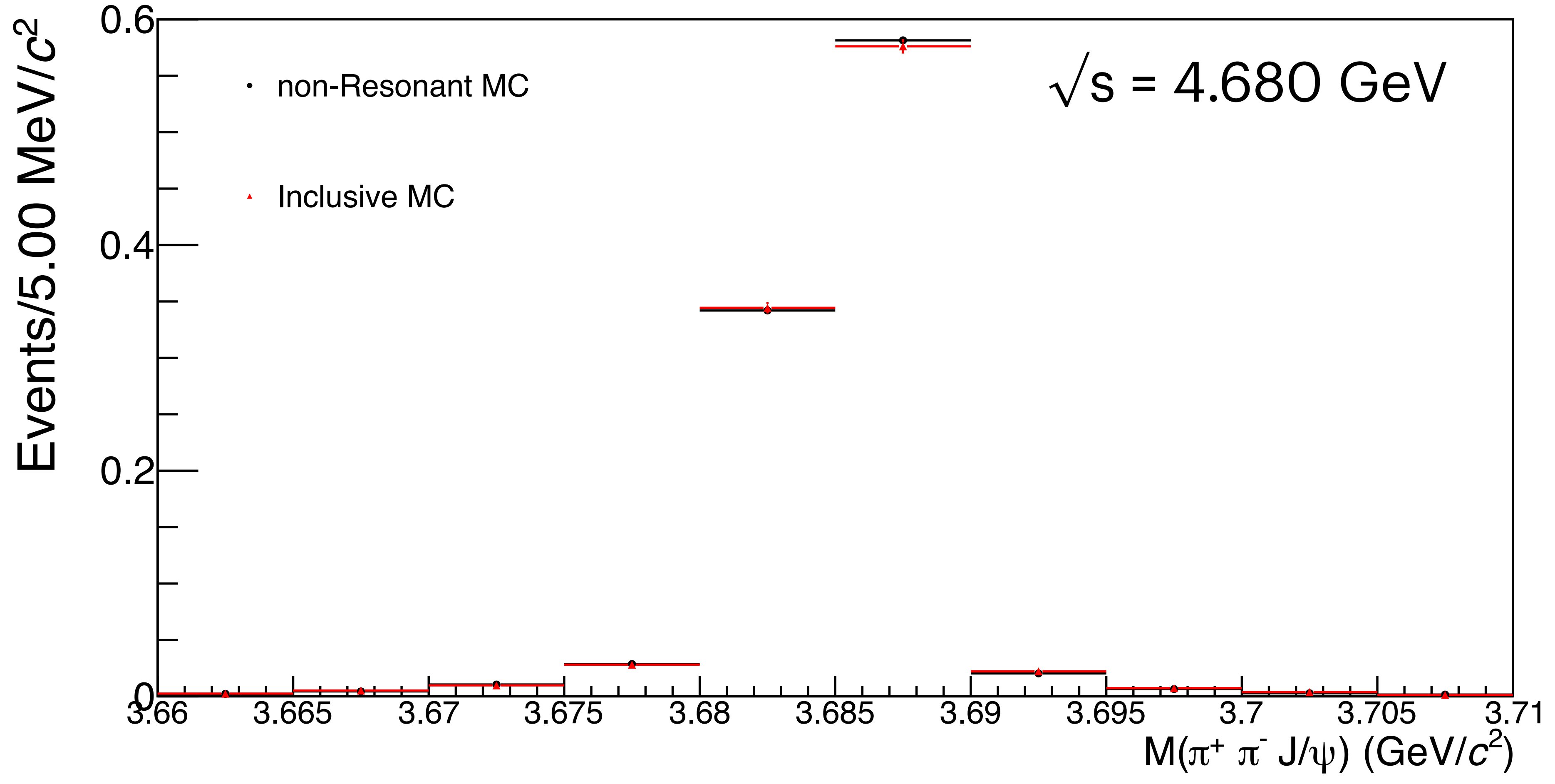
- Non-resonant **ππ ψ(2S)** signal
- Multi-π states

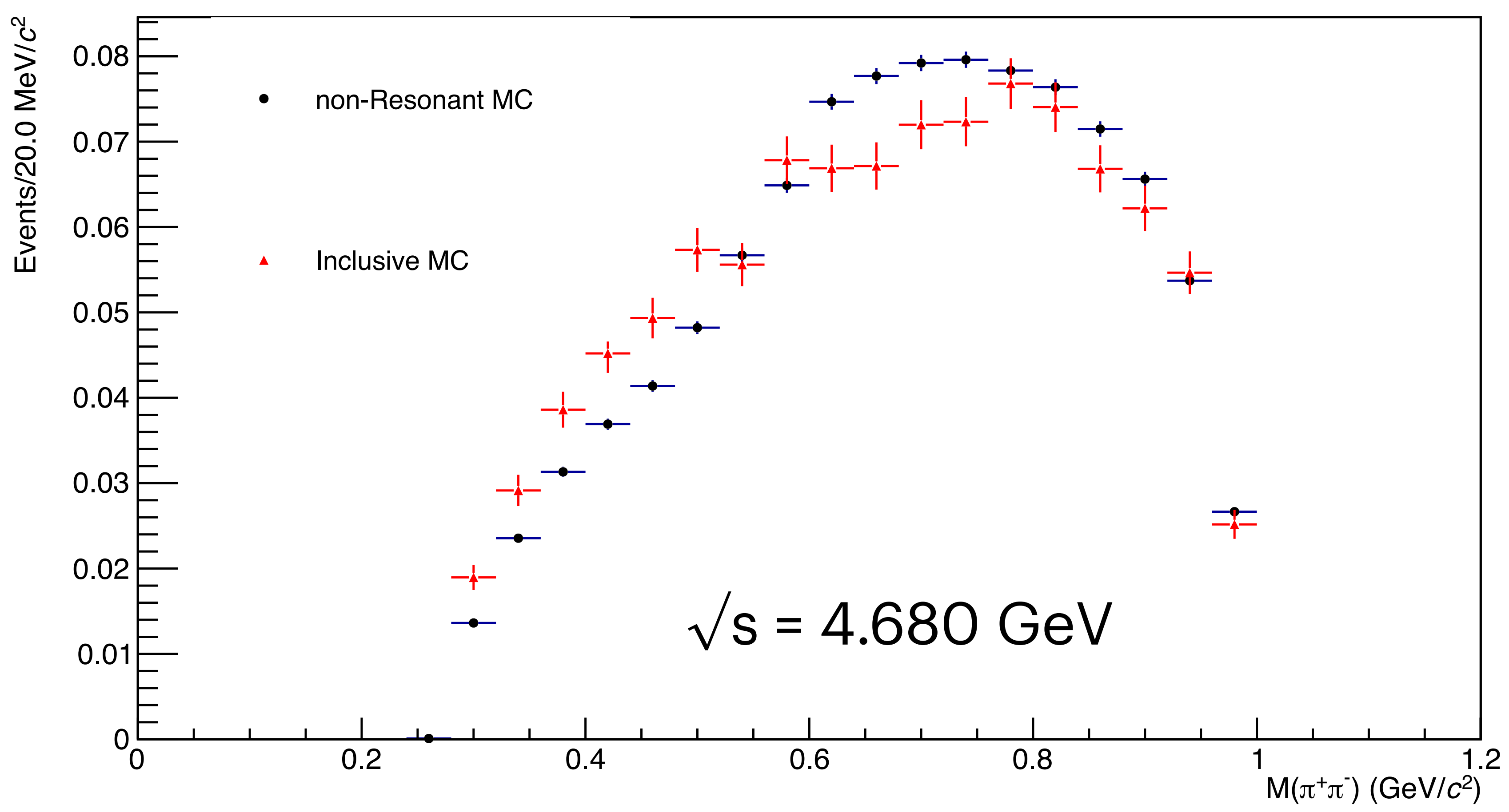
MC Studies

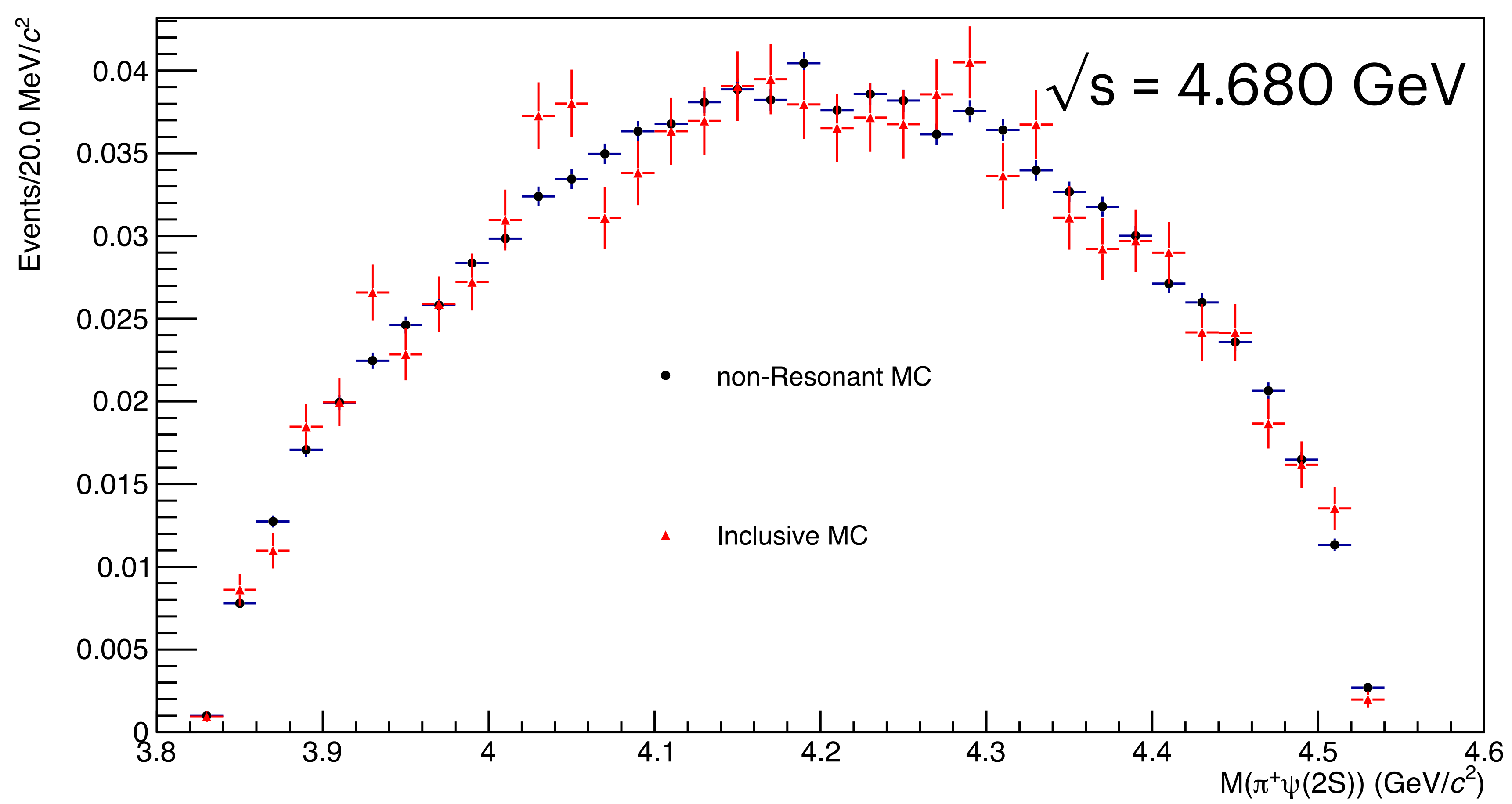
Inclusive / Non-resonant

MC Comparison



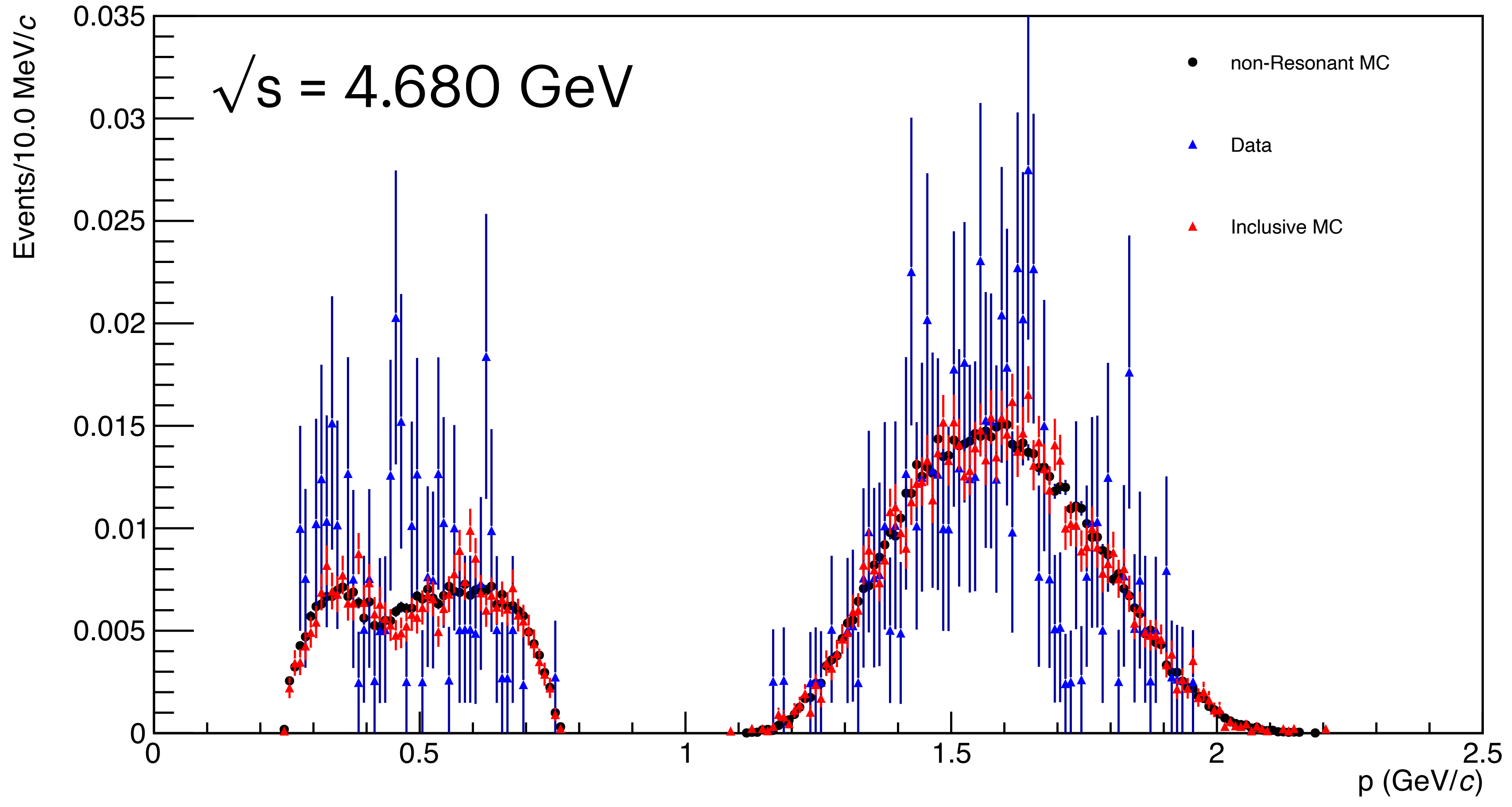


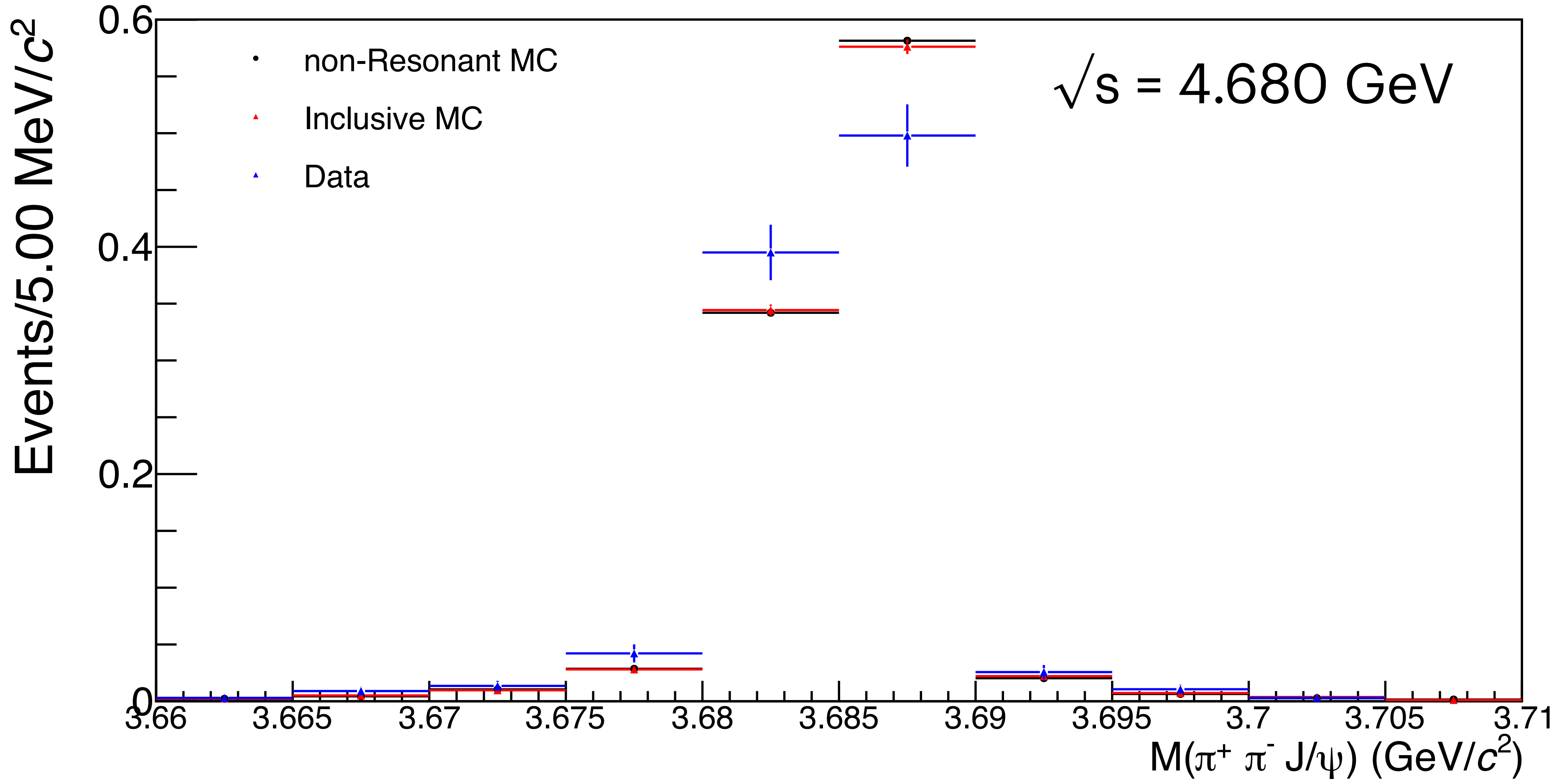


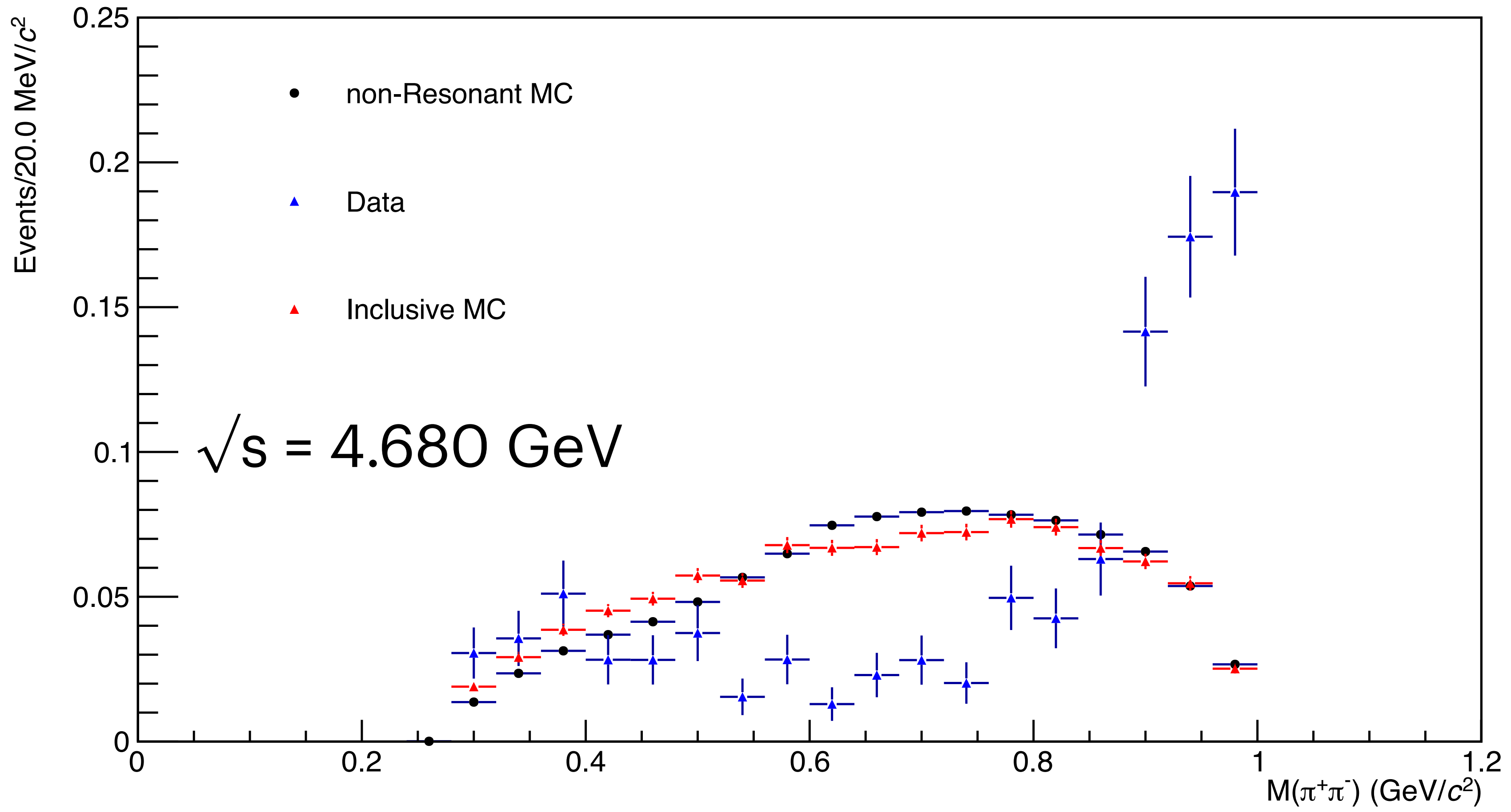


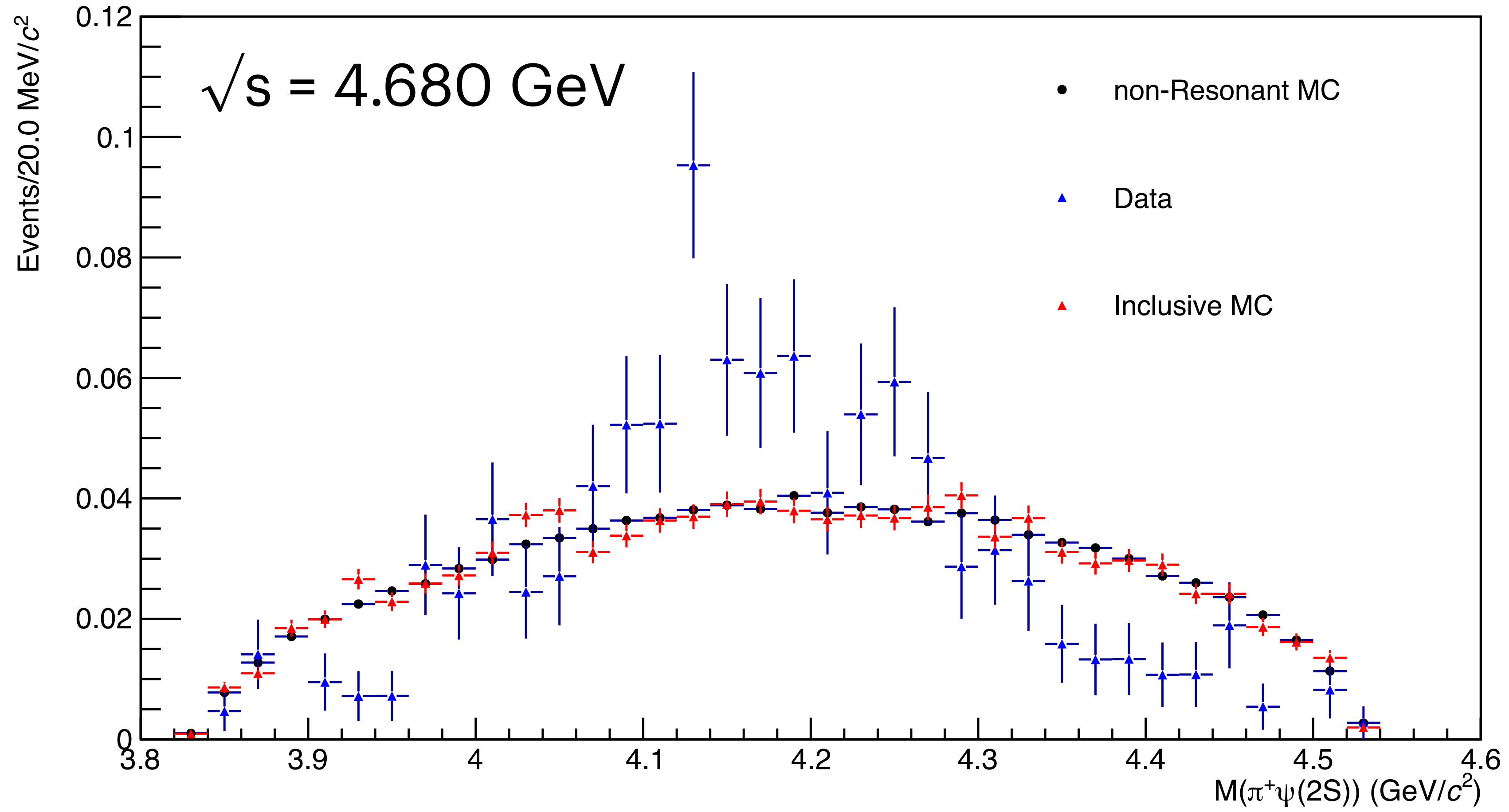
MC Studies

Inclusive MC / Non-resonant MC/ Data Comparison





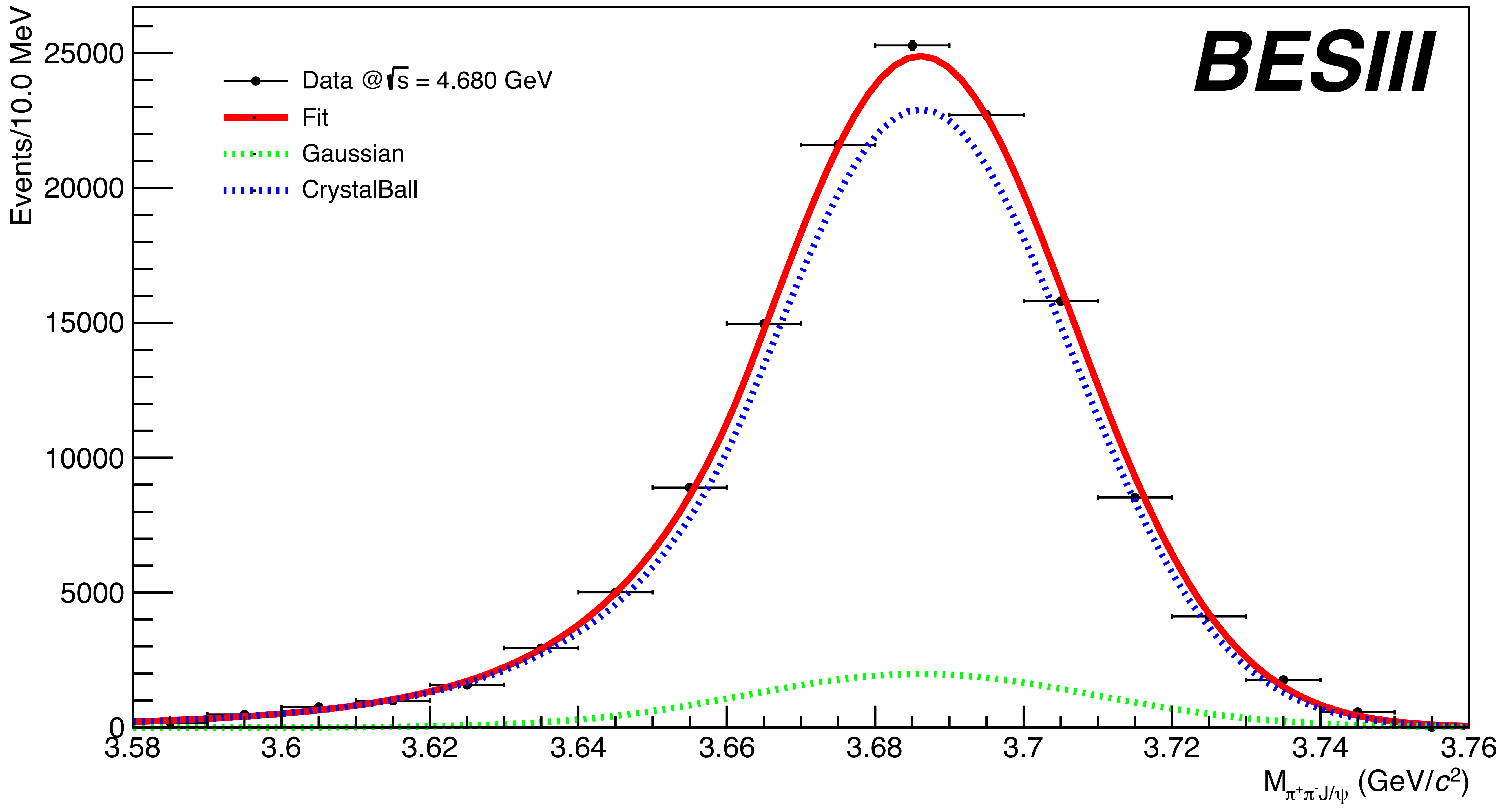




Extraction of the $\sigma(\pi\pi\,\psi(2S))$

Extraction of the σ(ππ ψ(2S))

ππ ψ(2S) cross-section

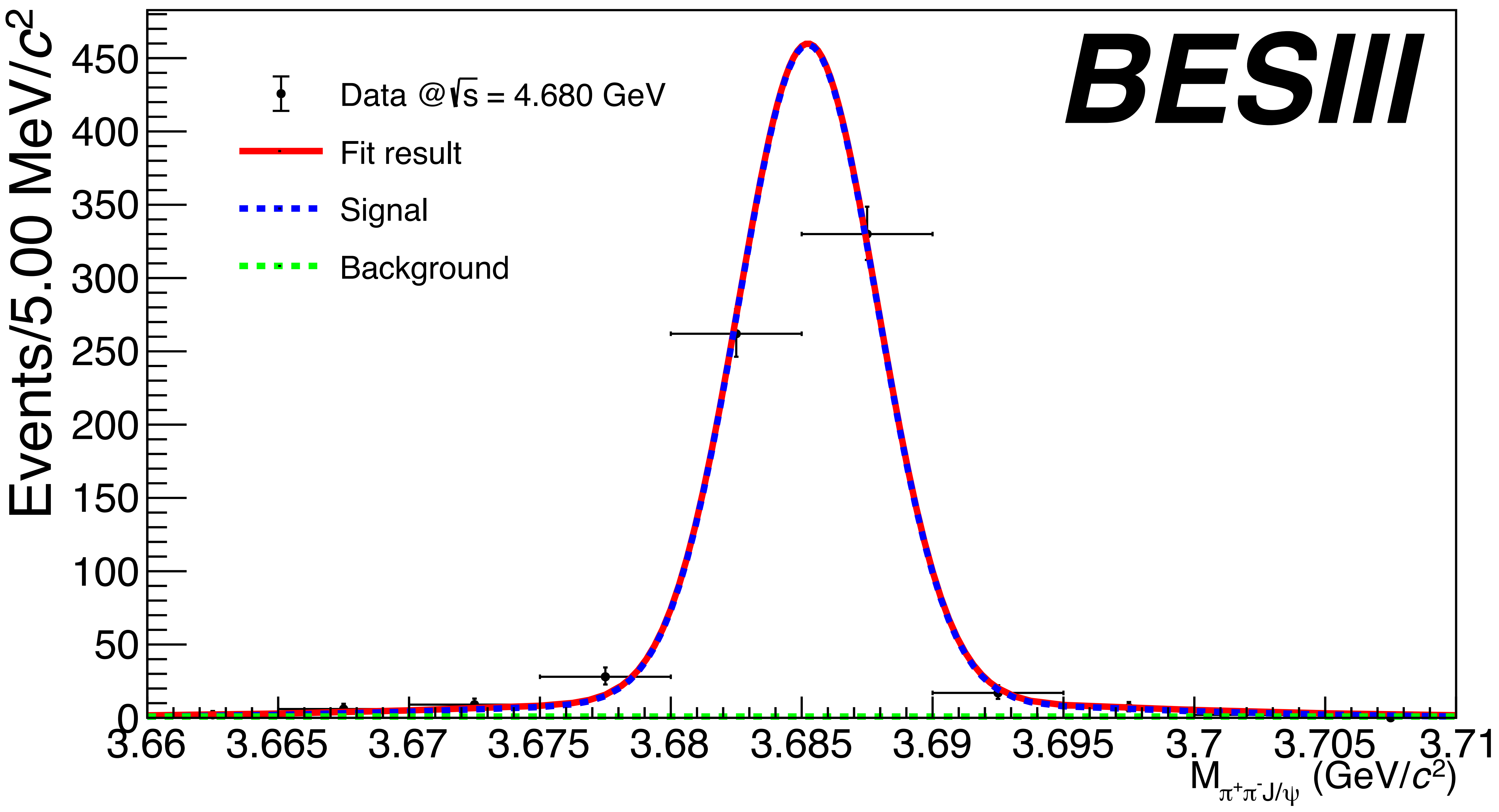


For **each √s**, the **signal** is modelled via a signal MC sample with a **sum of Gaussian and Crystal Ball** functions

√s [GeV]	Efficiency [%]
4.612	38.90
4.626	40.45
4.640	41.59
4.660	41.54
4.680	40.72
4.700	39.16

Extraction of the σ(ππ ψ(2S))

ππ ψ(2S) cross-section



For **each √s**, the ππψ(2S) contribution is extracted by **fitting the M(ππJ/ψ)** invariant spectrum

The **signal** is modelled with a **sum of Gaussian and Crystal Ball** functions

A **polynomial** function is used to describe the **background**

Extraction of the σ(ππ ψ(2S))

ππ ψ(2S) cross-section

$$\sigma_{\text{Born}} = \frac{N_{\text{Obs}}}{\mathcal{L}(1+\delta)\frac{1}{|1-\Pi^2|}\epsilon\mathcal{B}}$$

Extraction of the σ(ππ ψ(2S))

ππ ψ(2S) cross-section

Number of Observed events

$$\sigma_{\text{Born}} = \frac{N_{\text{Obs}}}{\mathcal{L}(1+\delta)\frac{1}{|1-\Pi^2|}\epsilon\mathcal{B}}$$

Extraction of the $\sigma(\pi\pi\,\psi(2S))$

$\pi\pi\,\psi(2S)$ cross-section

Number of Observed events

$$\sigma_{\text{Born}} = \frac{N_{\text{Obs}}}{\mathcal{L}(1+\delta)\frac{1}{|1-\Pi^2|}\epsilon\mathcal{B}}$$

Integrated Luminosity

Branching Fractions of the sub-decays

Efficiency

Extraction of the σ(ππ ψ(2S))

ππ ψ(2S) cross-section

Number of Observed events

$$\sigma_{\text{Born}} = \frac{N_{\text{Obs}}}{\mathcal{L}(1+\delta)\frac{1}{|1-\Pi^2|}\epsilon\mathcal{B}}$$

Integrated Luminosity

ISR Corrections

Vacuum Polarisation Correction

Efficiency

Branching Fractions of the sub-decays

Extraction of the σ(ππ ψ(2S))

ππ ψ(2S) cross-section

Number of Observed events

$$\sigma_{\text{Born}} = \frac{N_{\text{Obs}}}{\mathcal{L}(1+\delta)\frac{1}{|1-\Pi^2|}\epsilon\mathcal{B}}$$

Integrated Luminosity

ISR Corrections

Vacuum Polarisation Correction

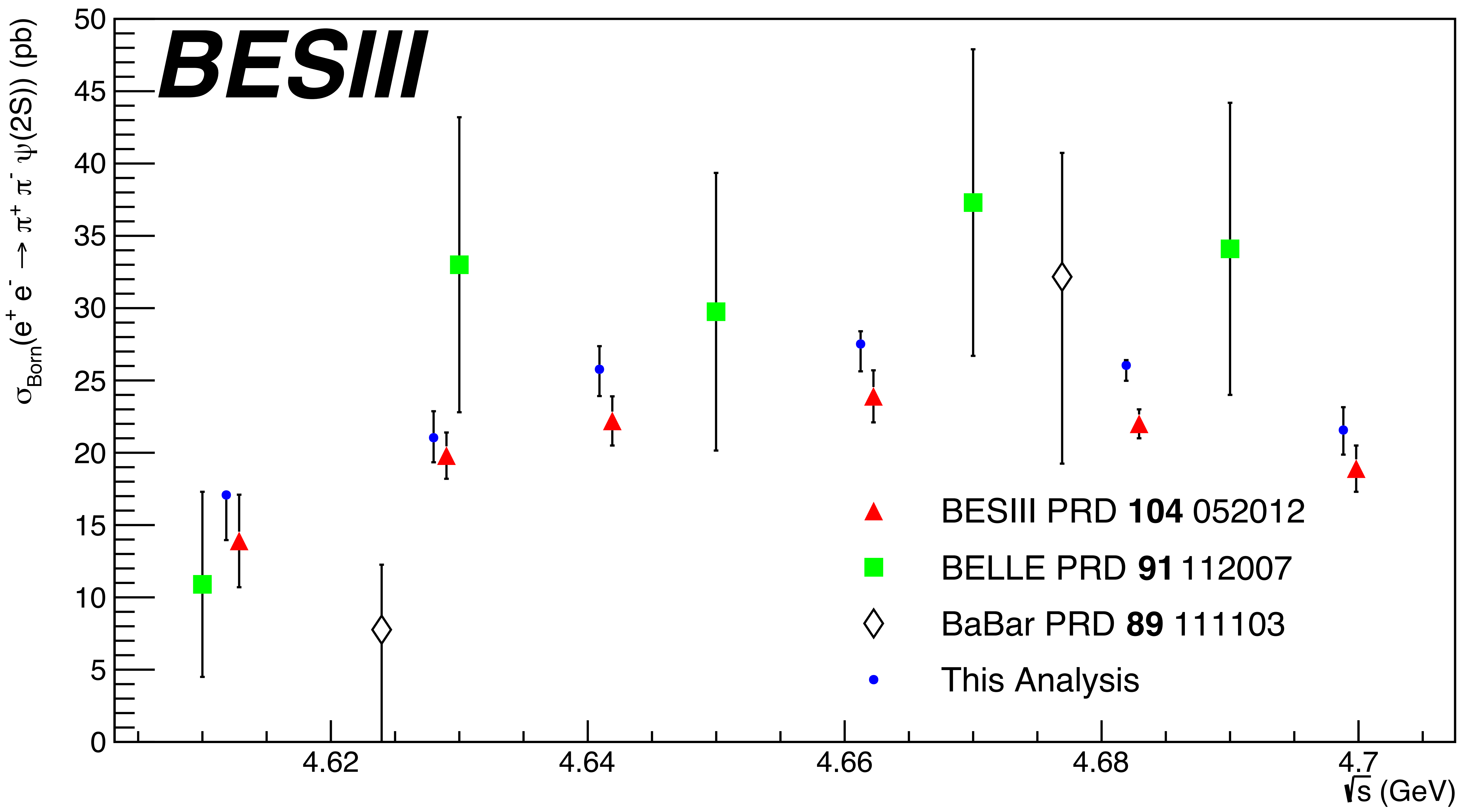
Efficiency

Branching Fractions of the sub-decays

Estimated via CONEXC

Extraction of the σ(ππ ψ(2S))

ππ ψ(2S) cross-section



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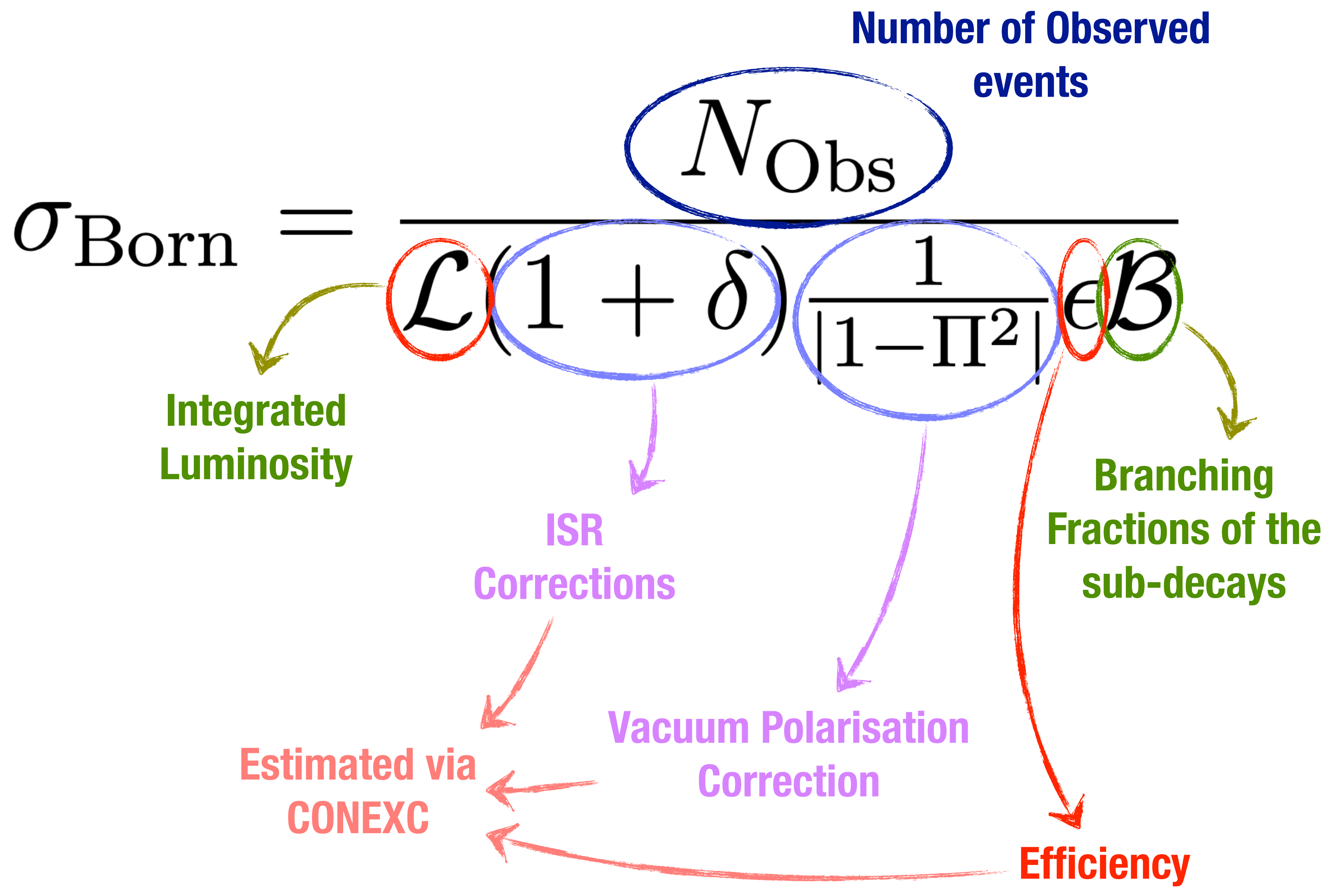
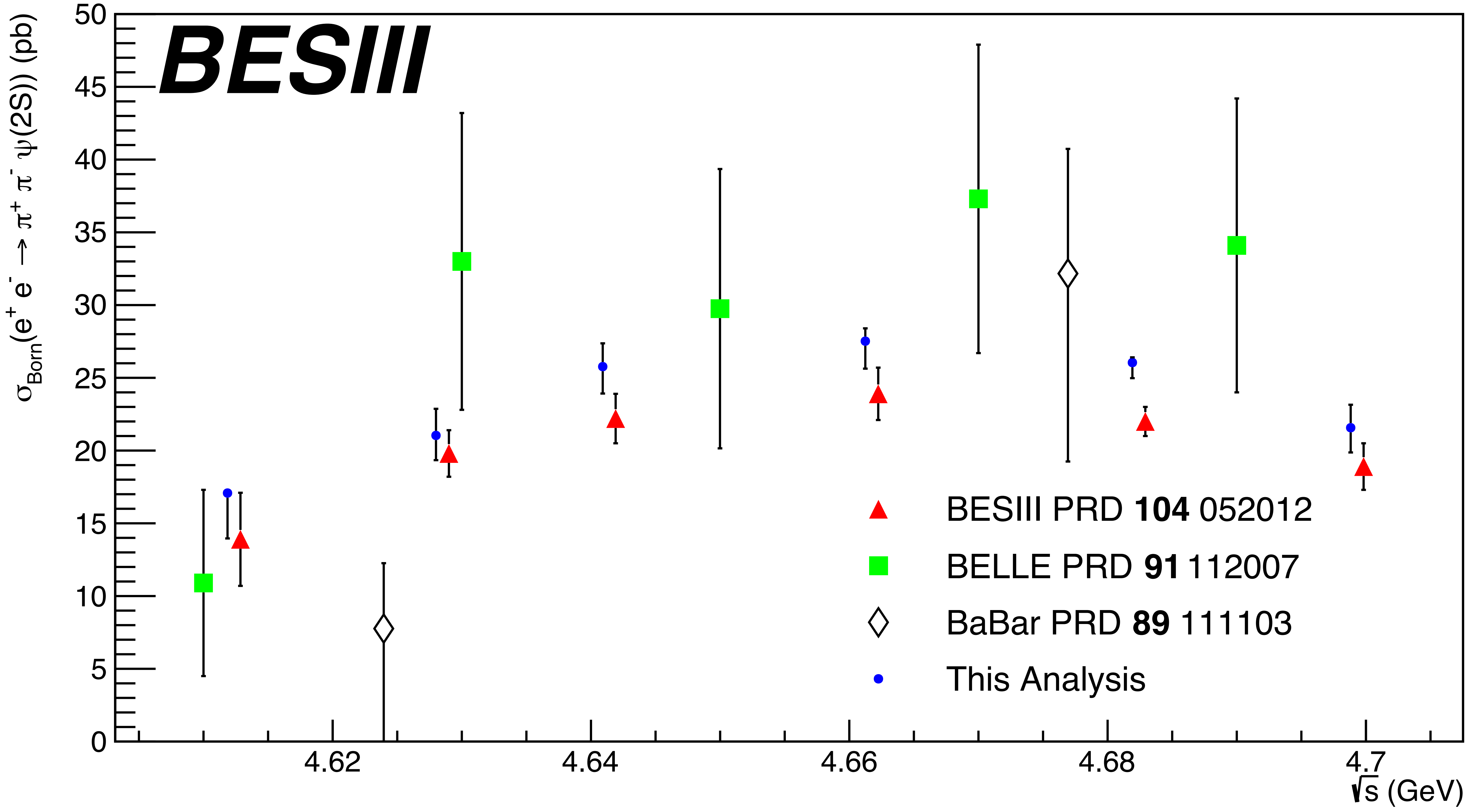


Extraction of the $\sigma(\pi\pi\,\psi(2S))$

$\pi\pi\,\psi(2S)$ cross-section



$$\sigma_{\text{Born}} = \frac{N_{\text{Obs}}}{\mathcal{L}(1+\delta)\frac{1}{|1-\Pi^2|}\epsilon\mathcal{B}}$$

The observed **cross-section** is **compatible with** the previous result of **Ref. [11]**

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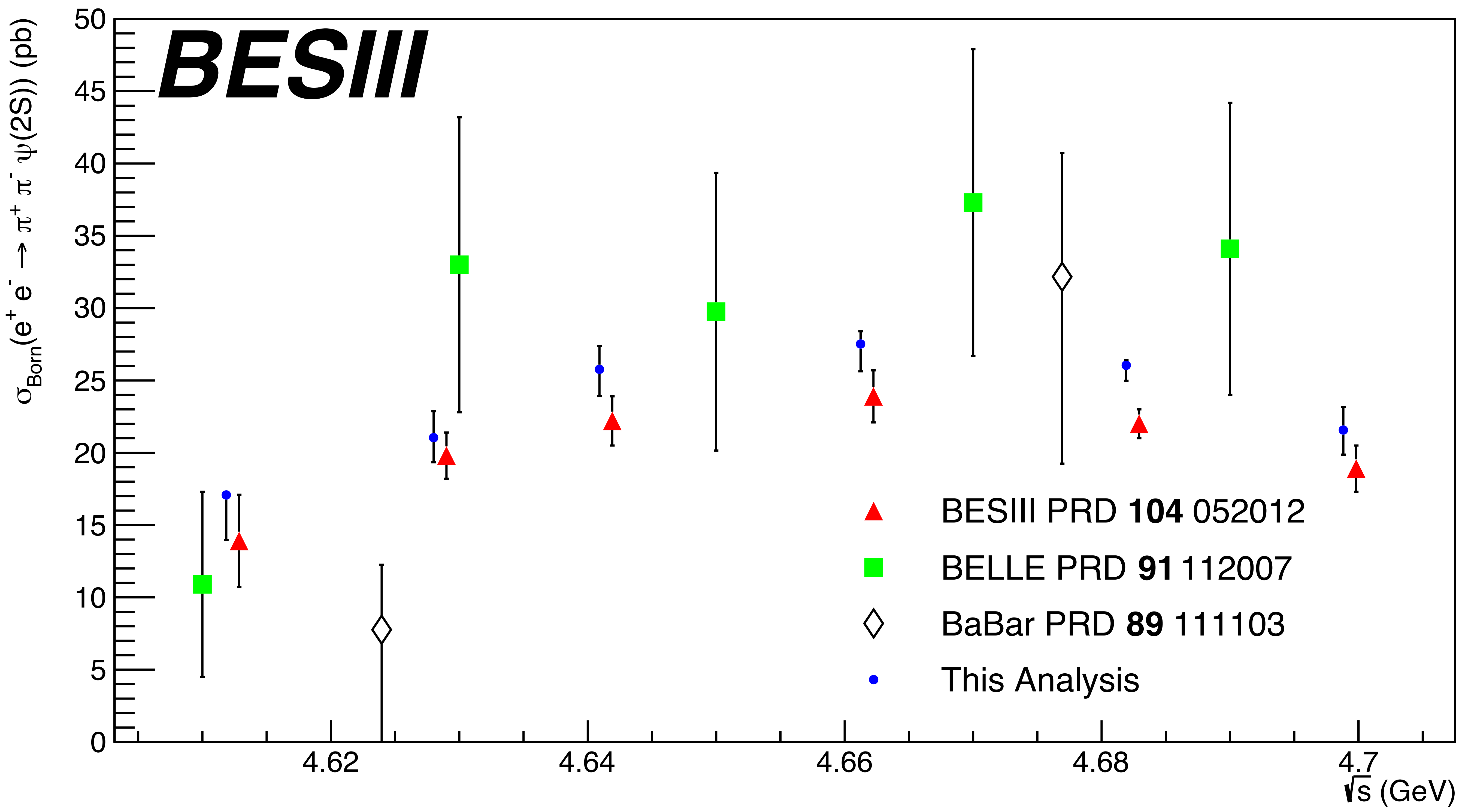

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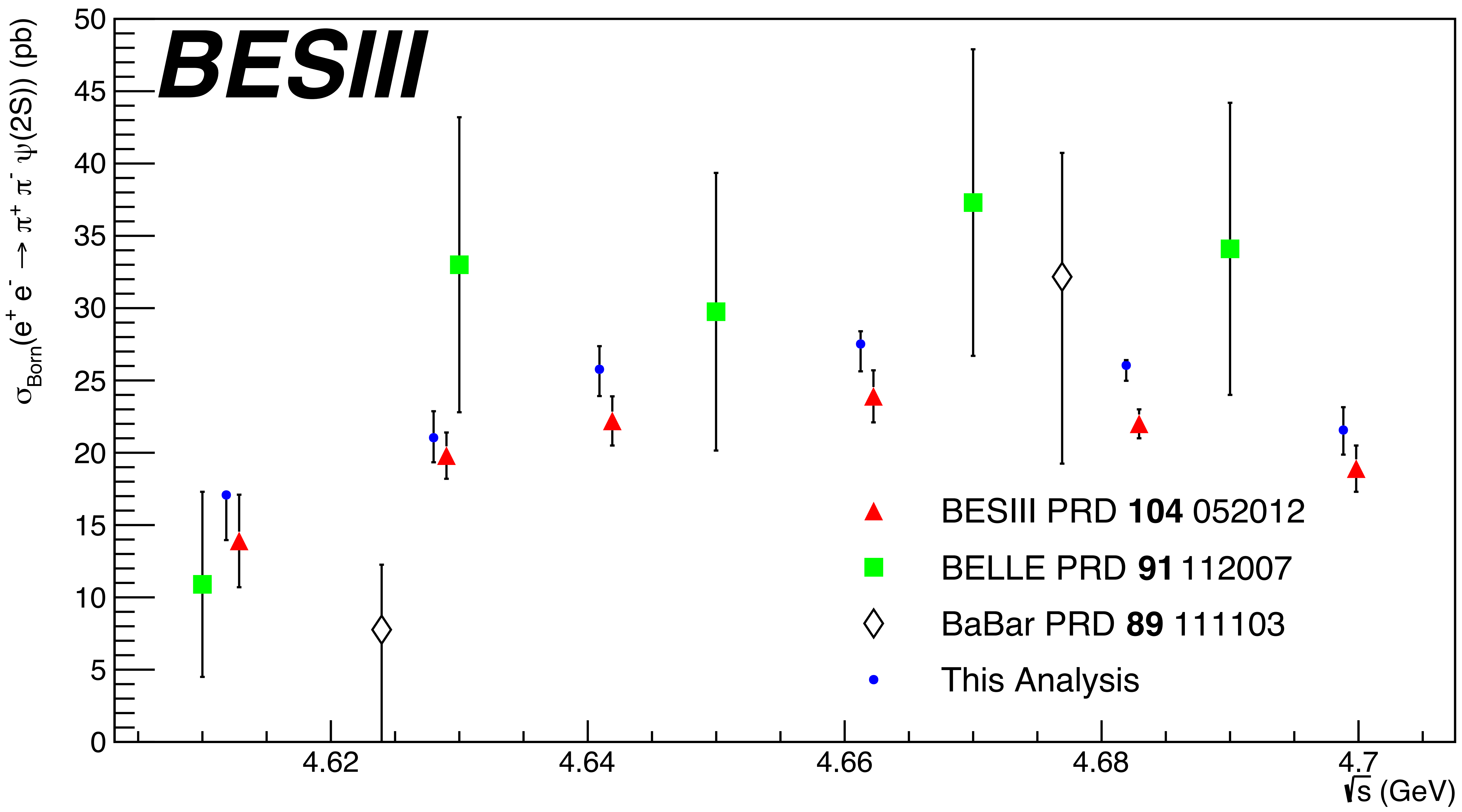

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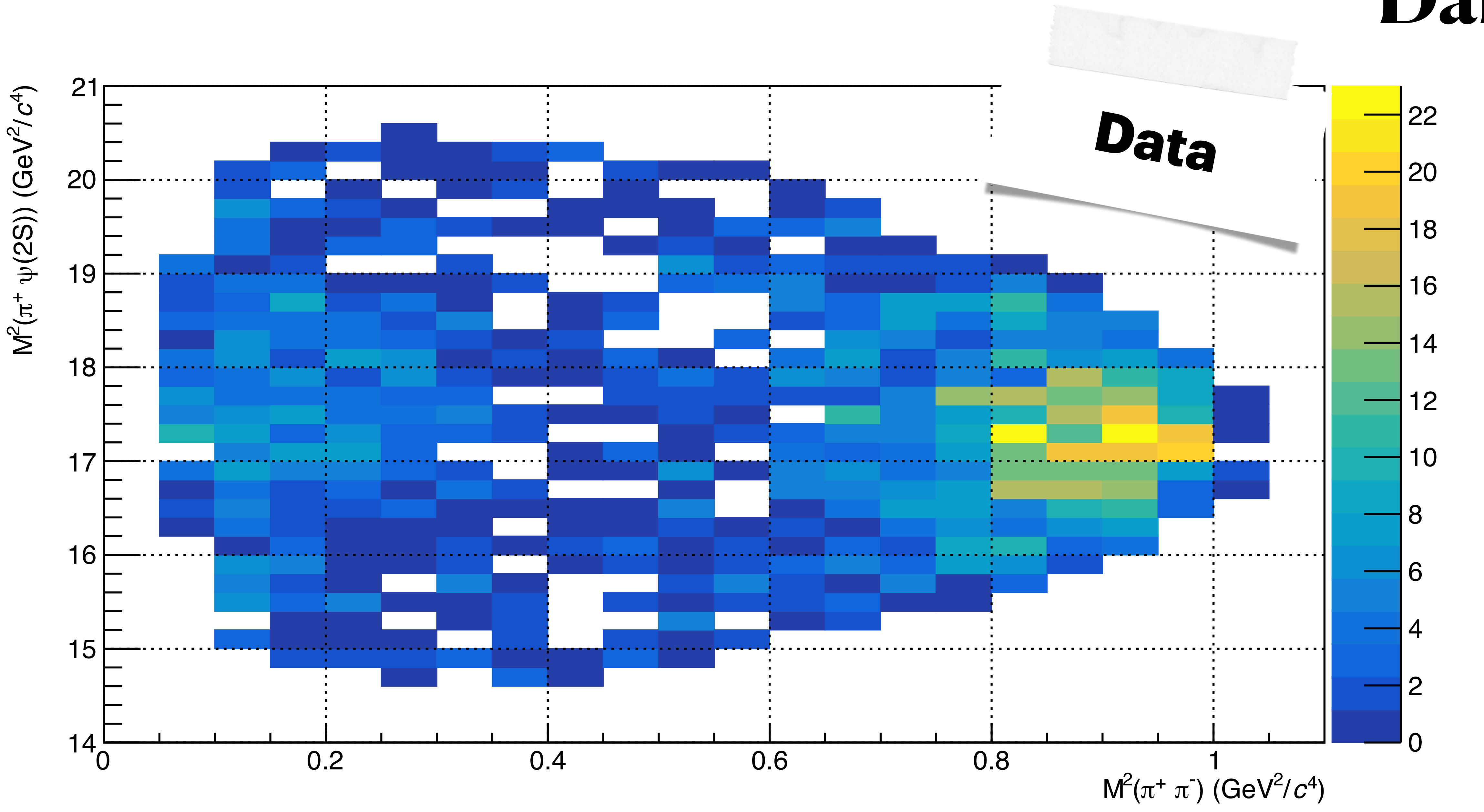
Results from BELLE and BaBar are reported too, further **confirming the compatibility** of this thesis' results with the published literature

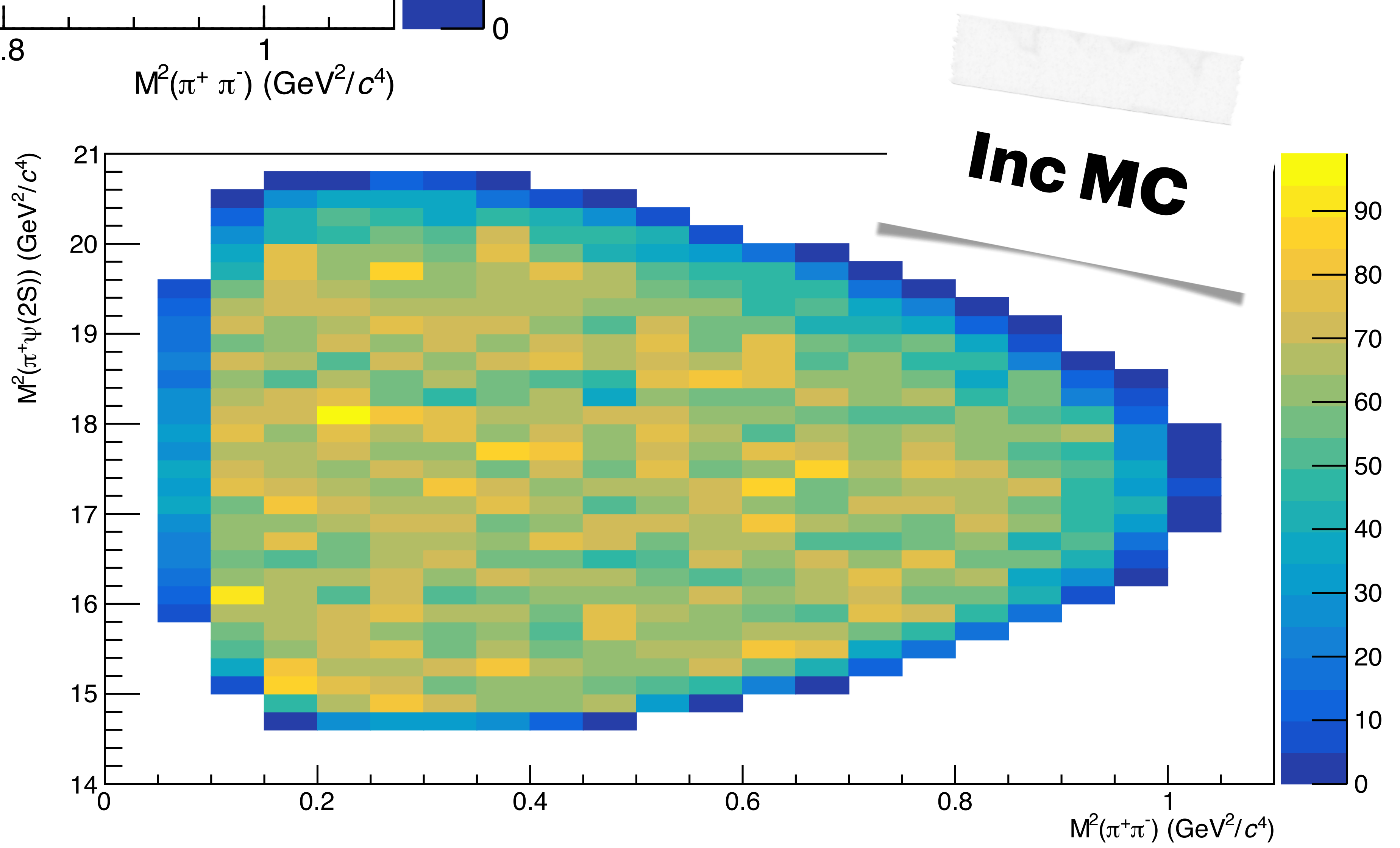
Thus **validating** the **following results** and analyses

Study of the Intermediate States

Study of the Intermediate States

Dalitz Plots



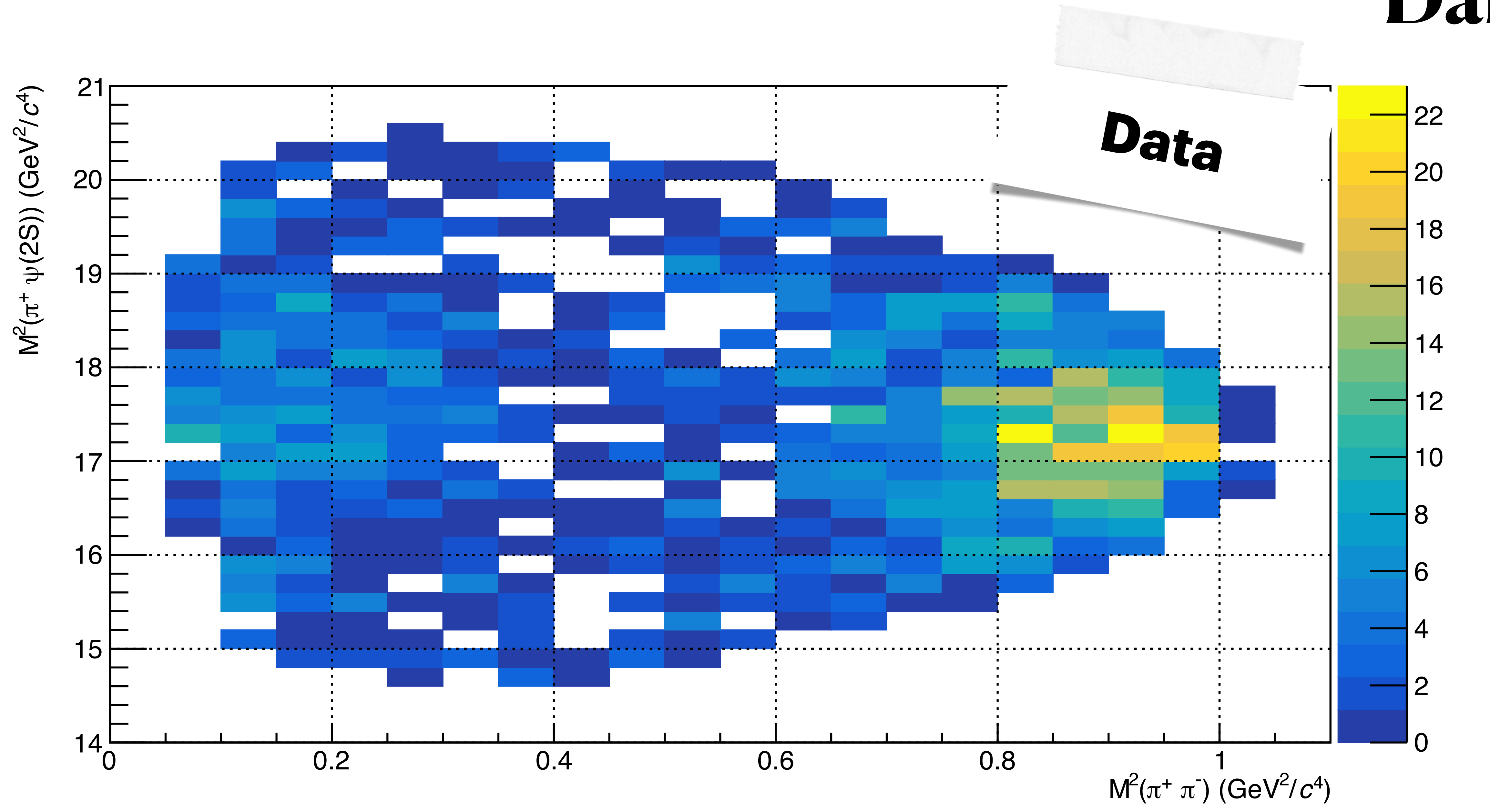


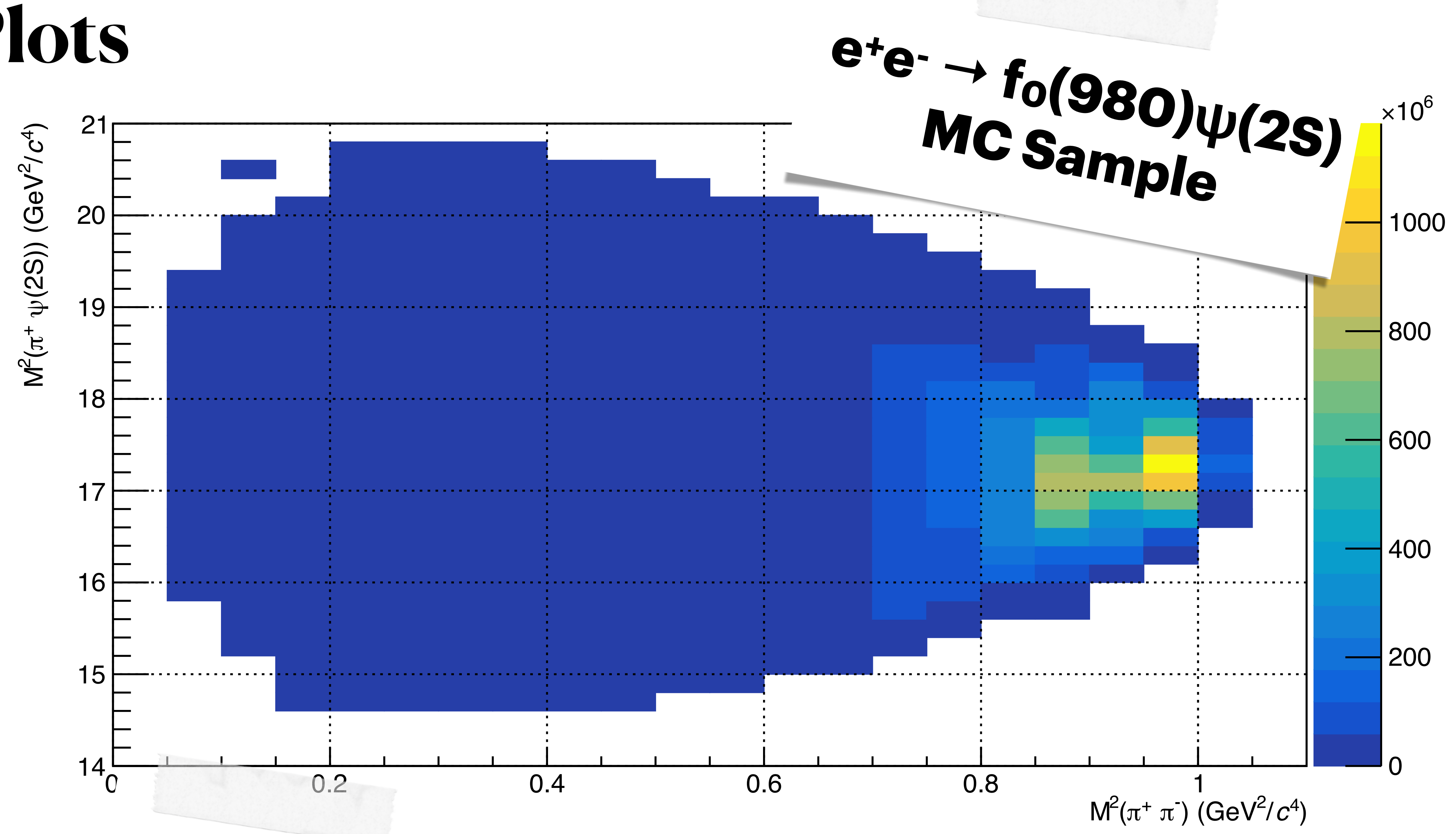
In **Ref.[11]**, a **simplified PWA** performed on the data sets highlighted **f_0(500)** and **f_0(980)** contributions

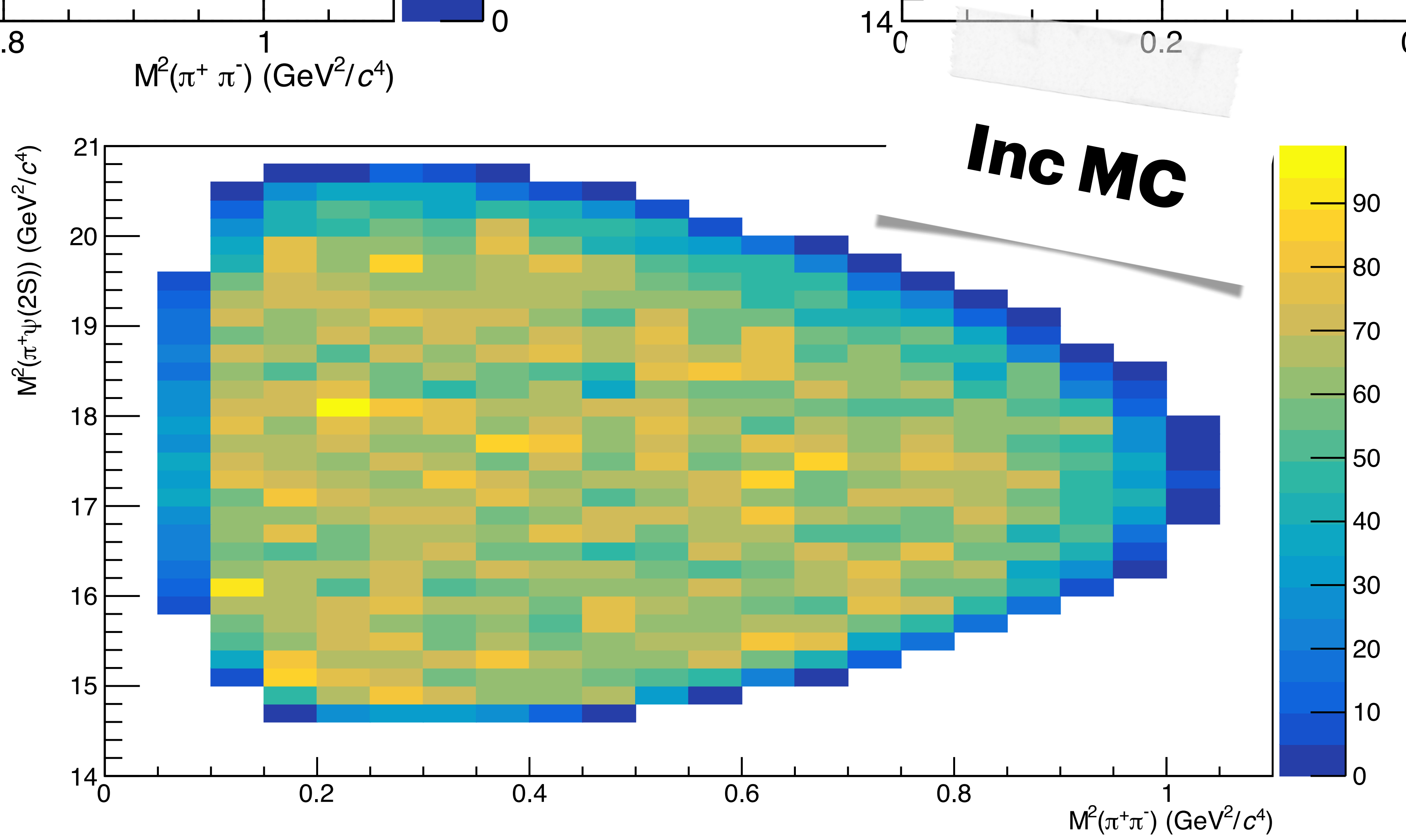
The six **data samples** are **merged together** to have more statistical significance

Study of the Intermediate States

Dalitz Plots







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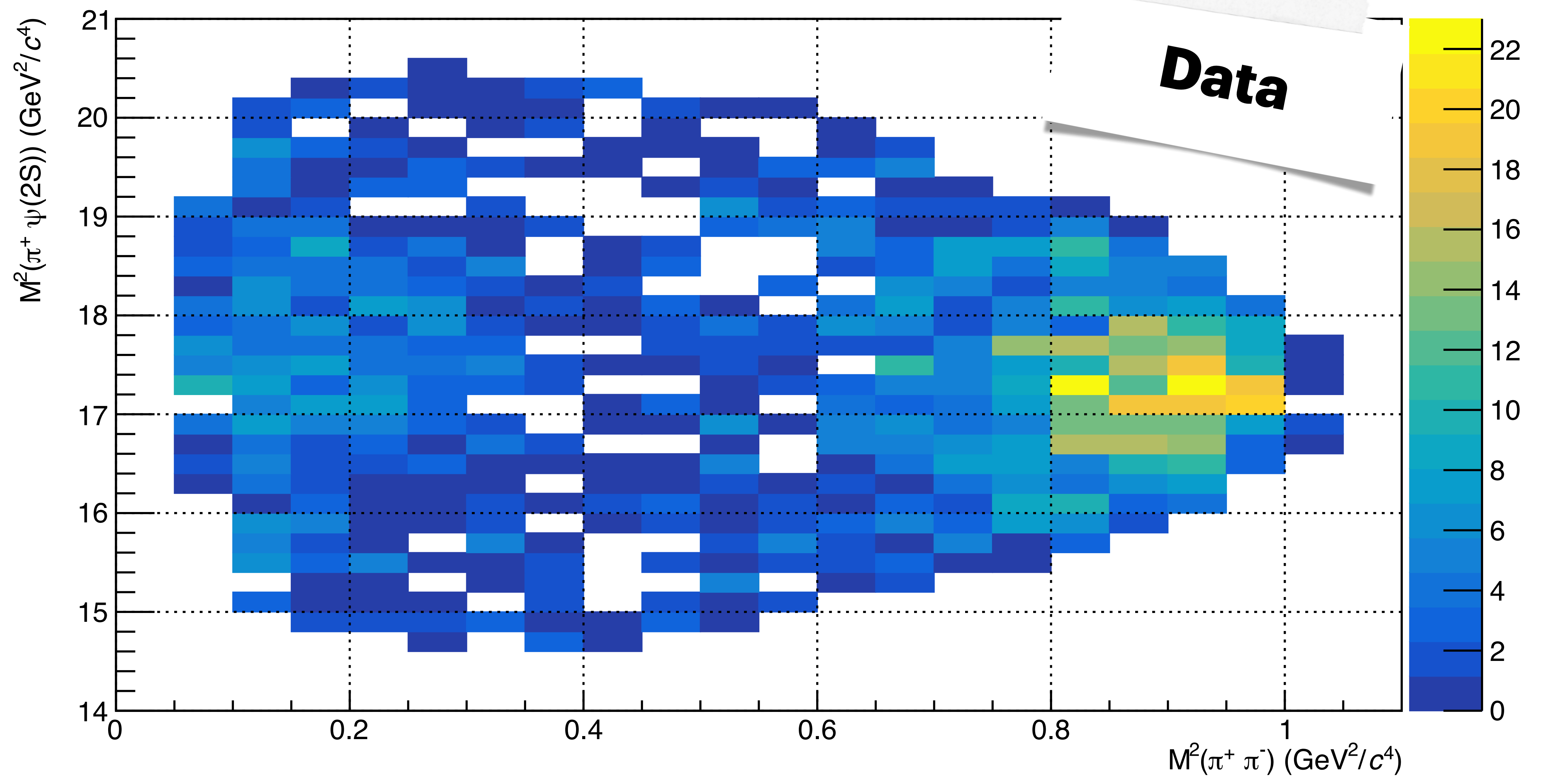

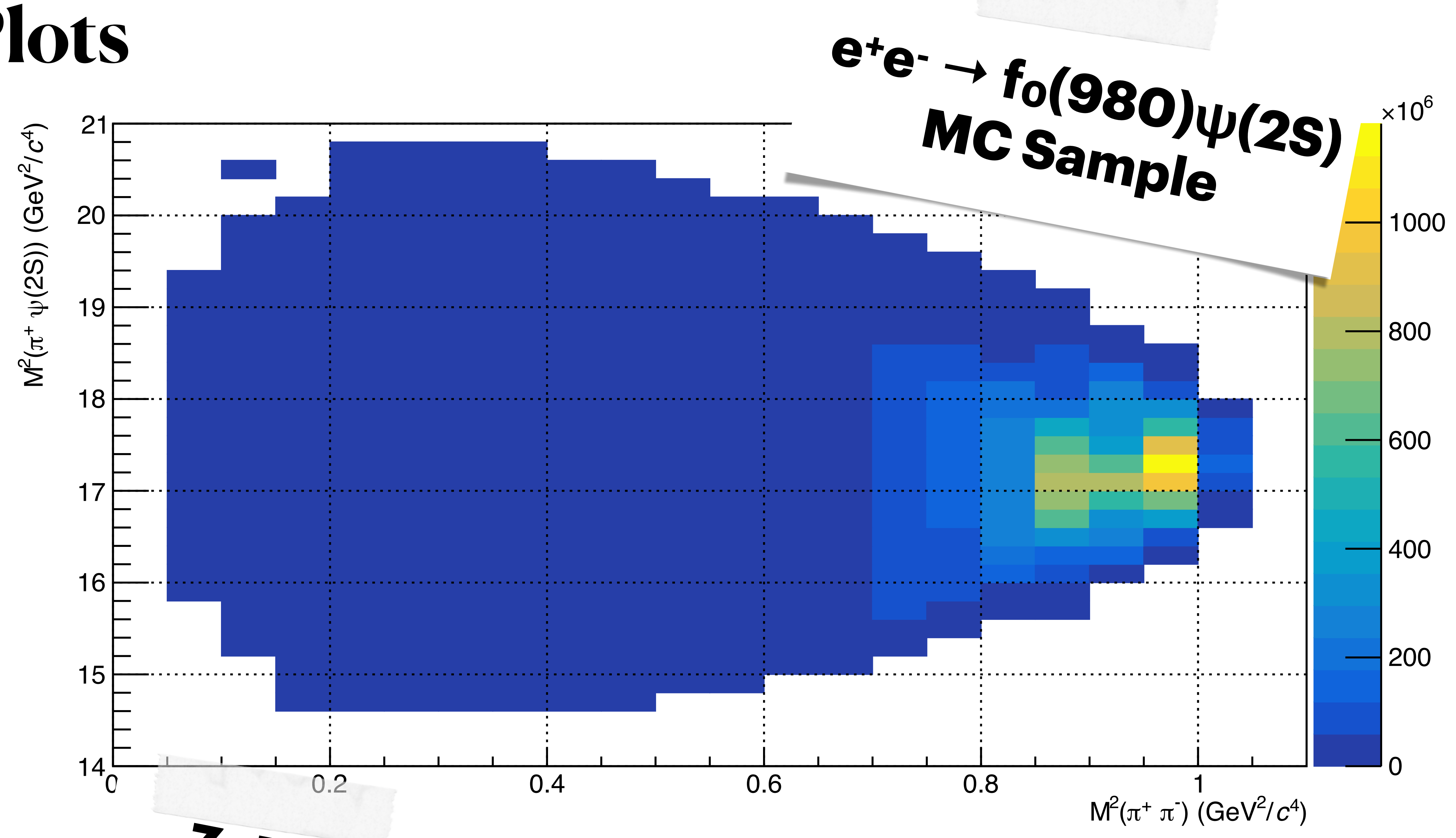

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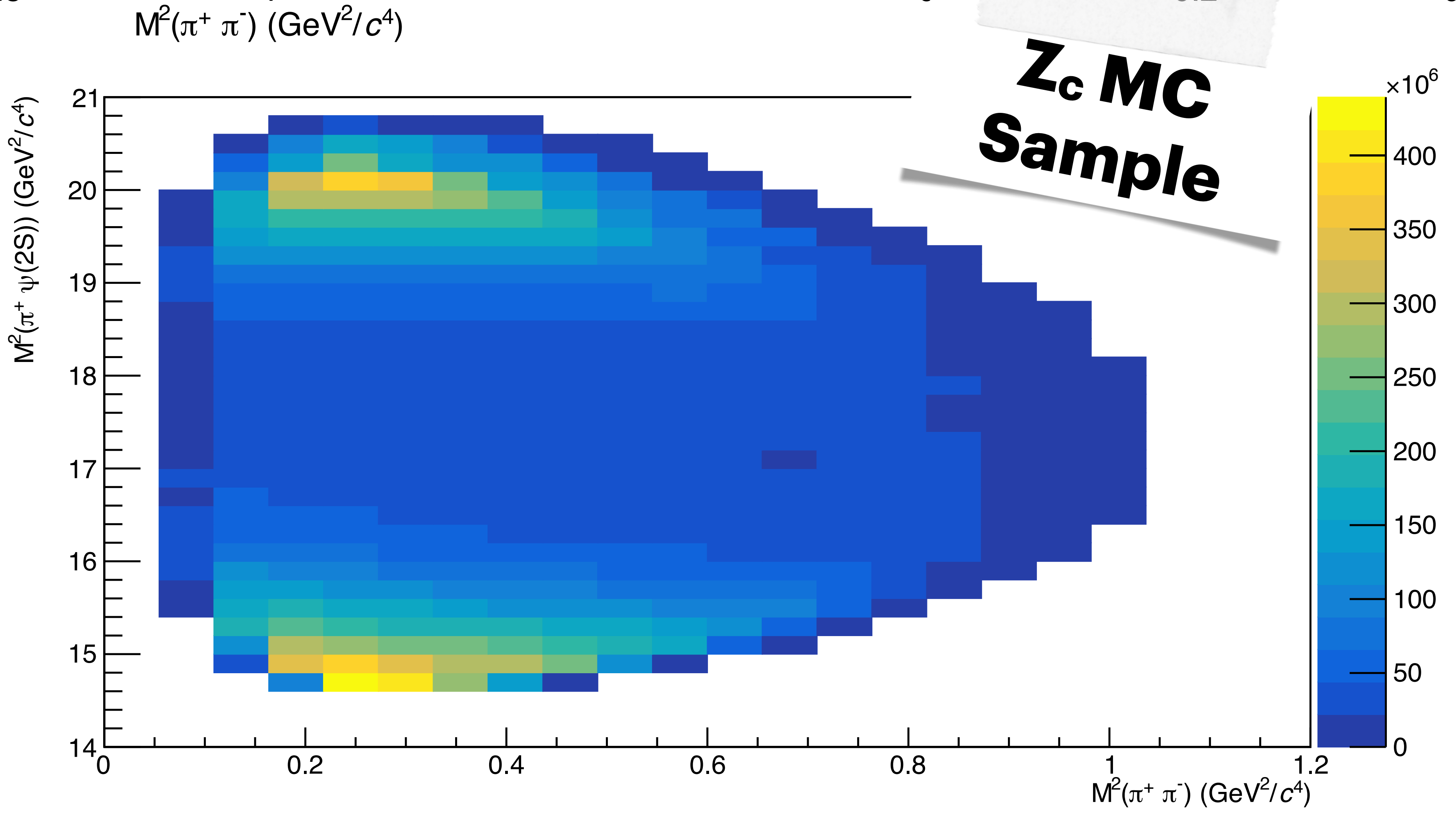

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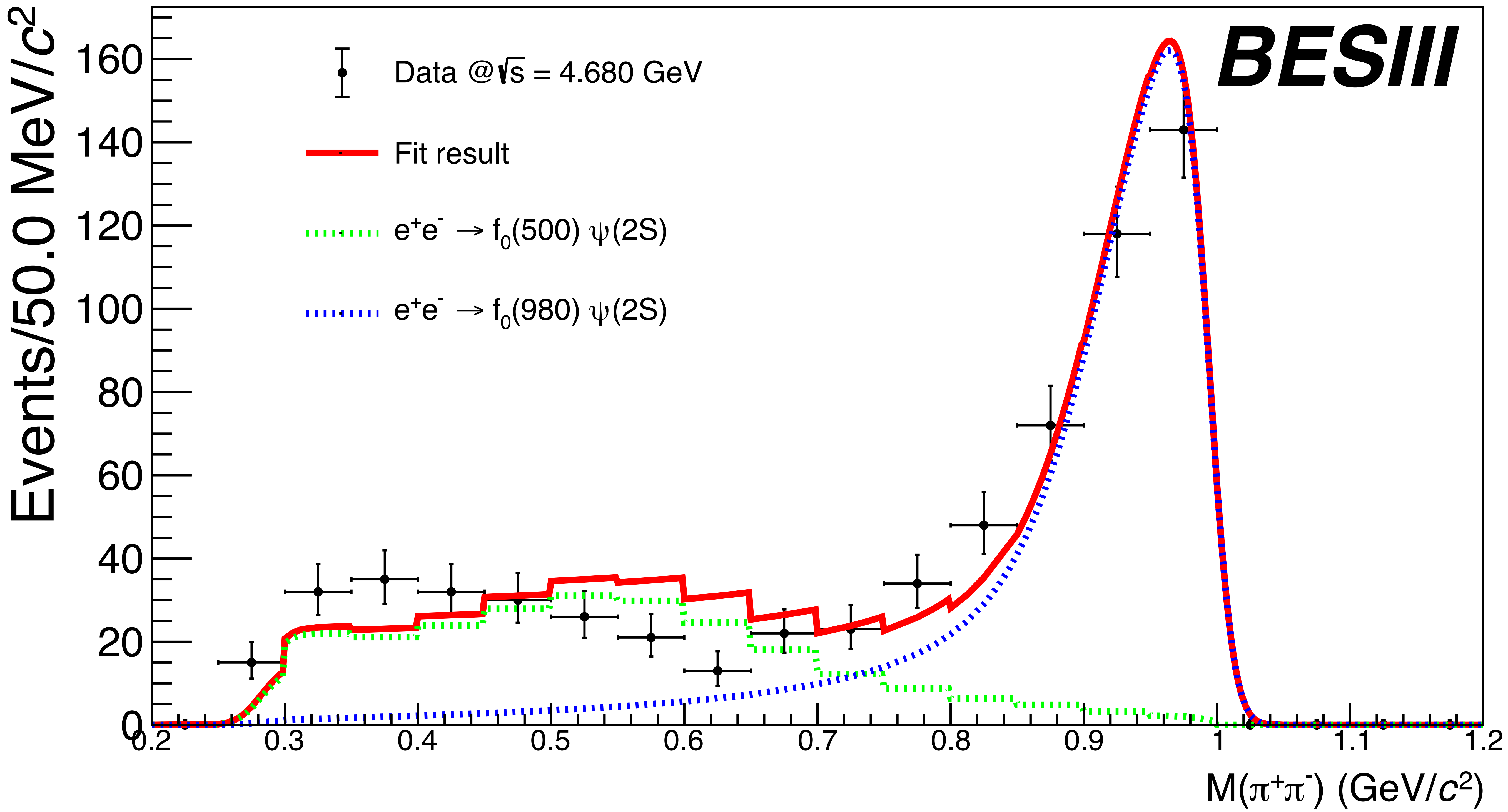
Extraction of the $\sigma(f_0(980)\,\psi(2S))$

$f_0(980)$ contribution



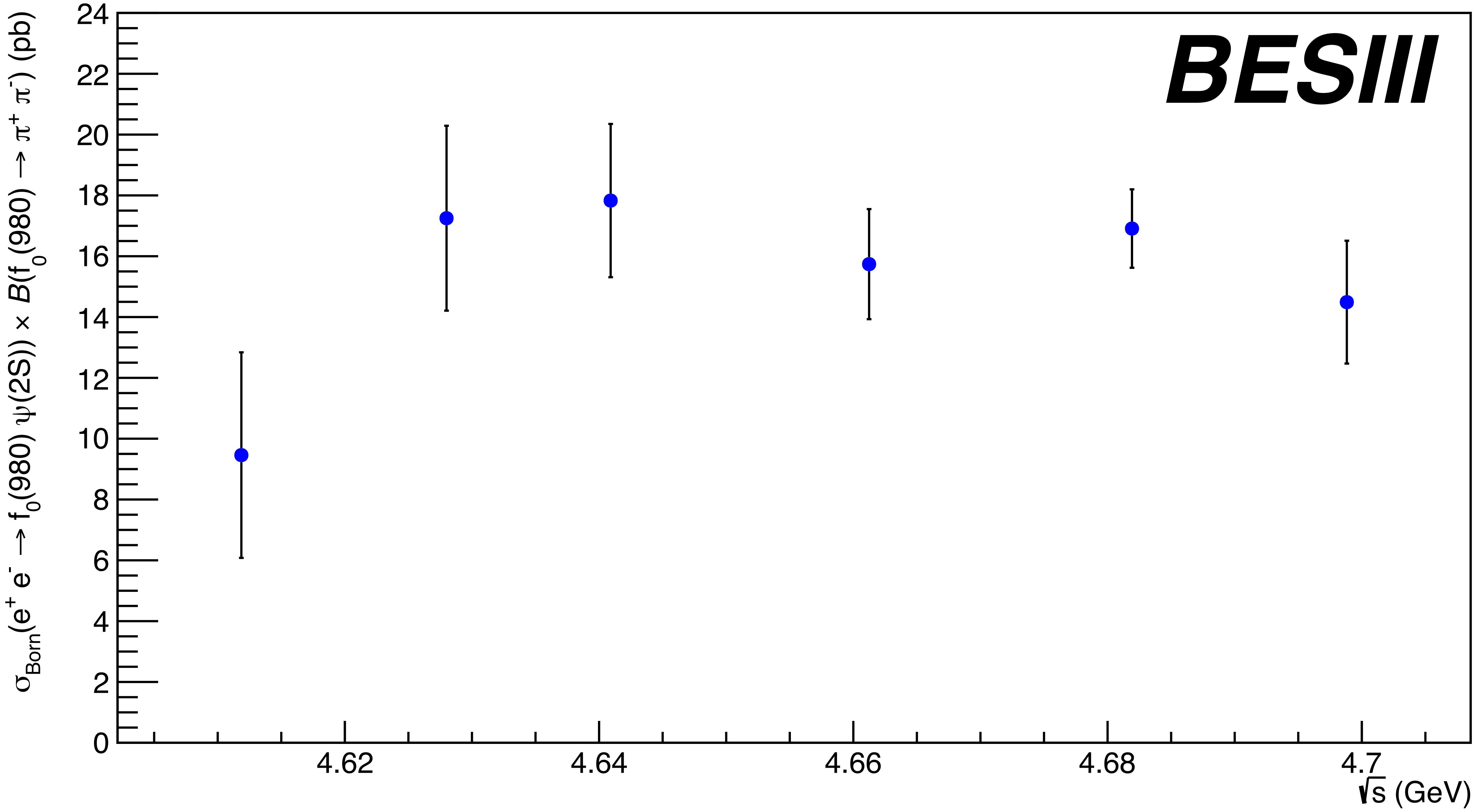
For **each $\sqrt{s}$**, the **$f_0(980)$** contribution is extracted by fitting the m(ππ) invariant distribution

The signal is a **Flatté smeared by a Gauss(0, σ) multiplied by a threshold**

The **$f_0(500)$** contribution is modelled using a **MC shape**

Extraction of the $\sigma(f_0(980)\,\psi(2S))$

$f_0(980)$ contribution

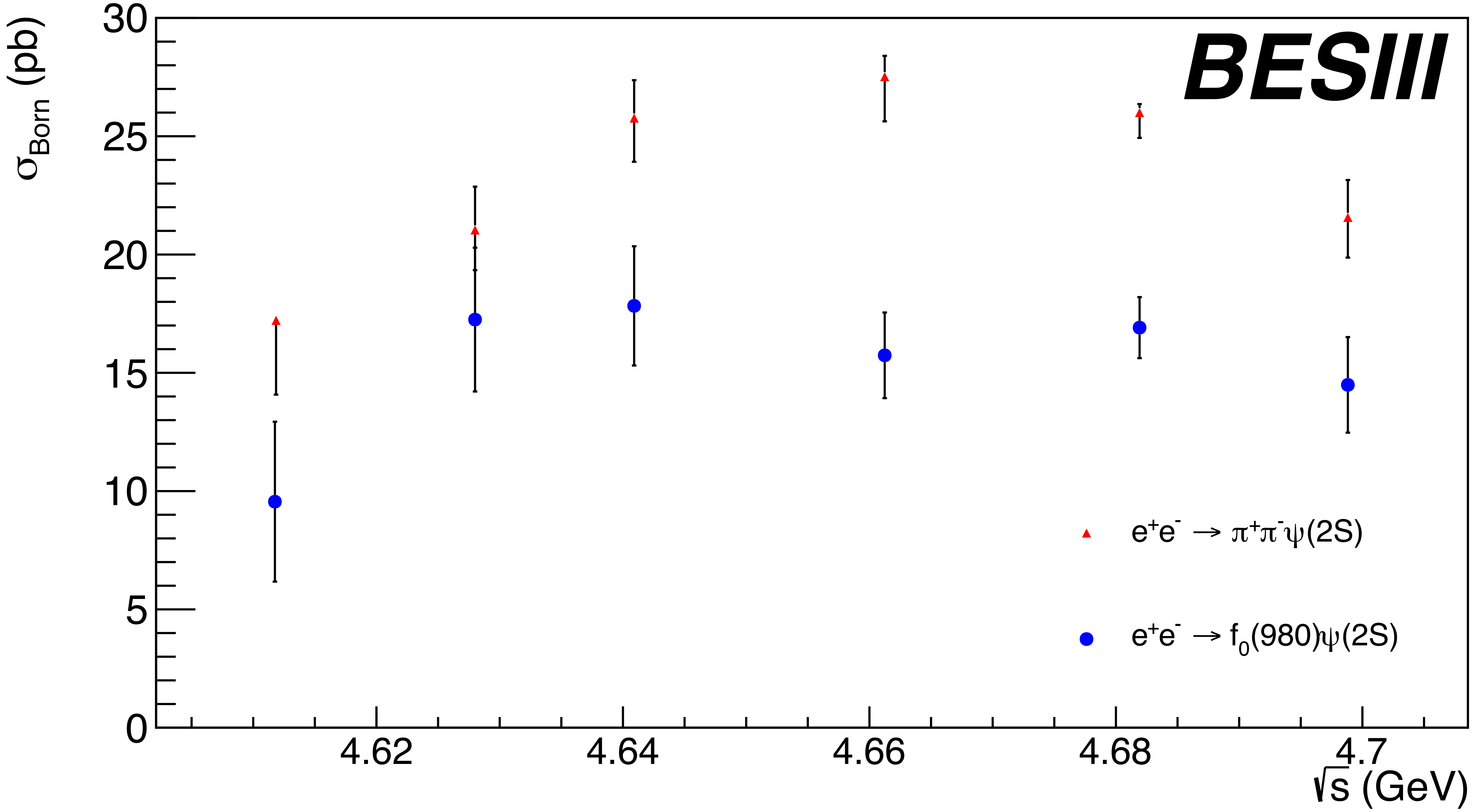


Product of the **f_0(980) → $\pi^+\pi^-$ branching fraction and** the **Born cross-section** of the $e^+e^- \to f_0(980)\psi(2S)$ process

$$\mathcal{B}(f_0(980) \to \pi^+\pi^-) \times \left(\frac{N_{\text{Obs}}^{f_0(980)}}{\mathcal{L}(1+\delta)\frac{1}{|1-\Pi^2|}\epsilon^{f_0(980)}\mathcal{B}} \right)$$

Extraction of the $\sigma(f_0(980)\,\psi(2S))$

$f_0(980)$ contribution

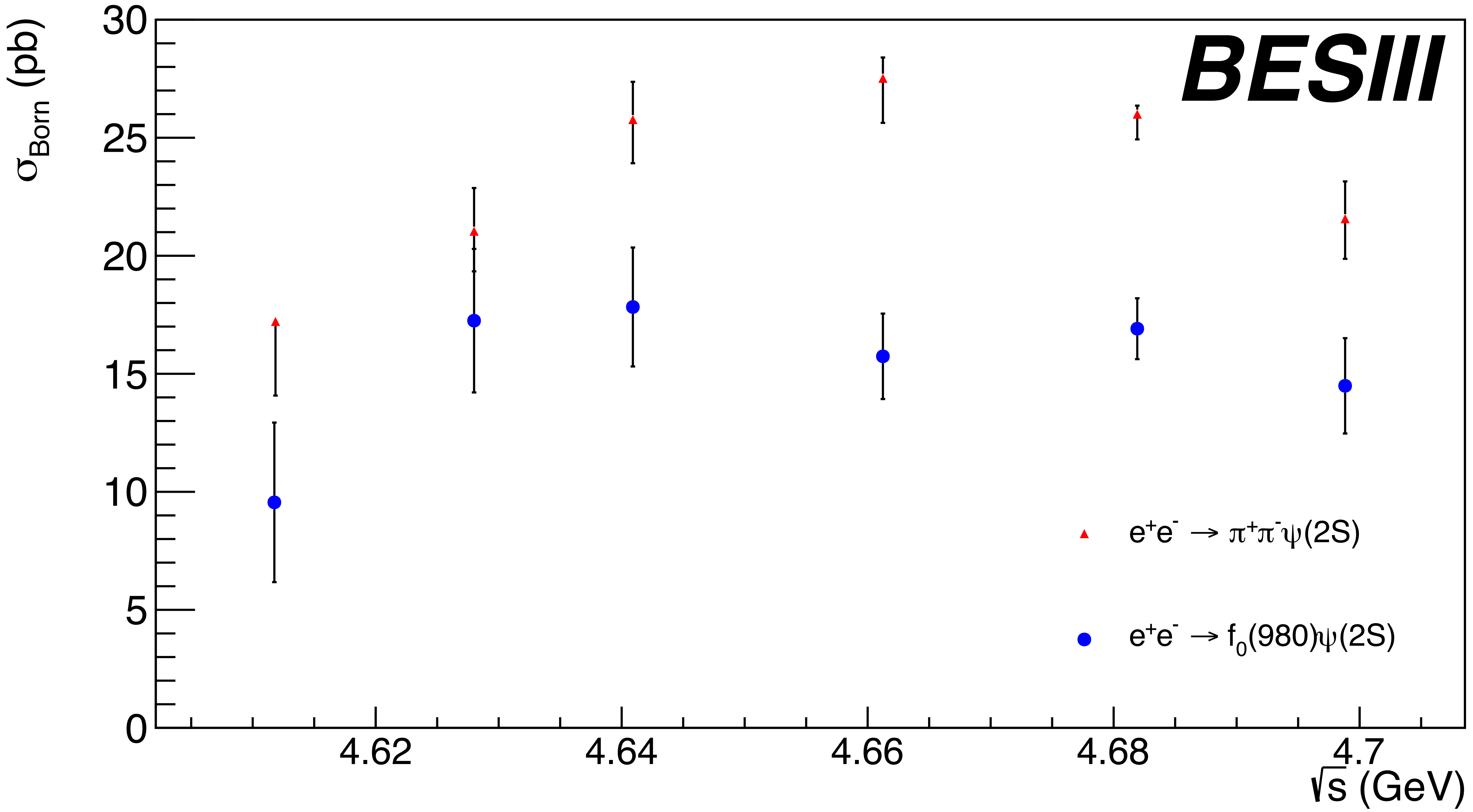


Product of the **$f_0(980) \to \pi^+\pi^-$ branching fraction and** the **Born cross-section** of the $e^+e^- \to f_0(980)\psi(2S)$ process

No particular structures can be recognised

Extraction of the $\sigma(f_0(980)\,\psi(2S))$

$f_0(980)$ contribution



No particular structures can be recognised

Within the statistical uncertainty, $\boldsymbol{\sigma_{Born}}$ ***x* B** is **flat** compared to $\sigma_{Born}(\pi\pi\psi(2S))$

Thus one **cannot confirm** the hypothesis of Ref. [12] for the **Y(4660)** being an ***f_0(980) - ψ(2S)* molecule**

[12] Phys. Lett. B 665, 26-29 (2008)

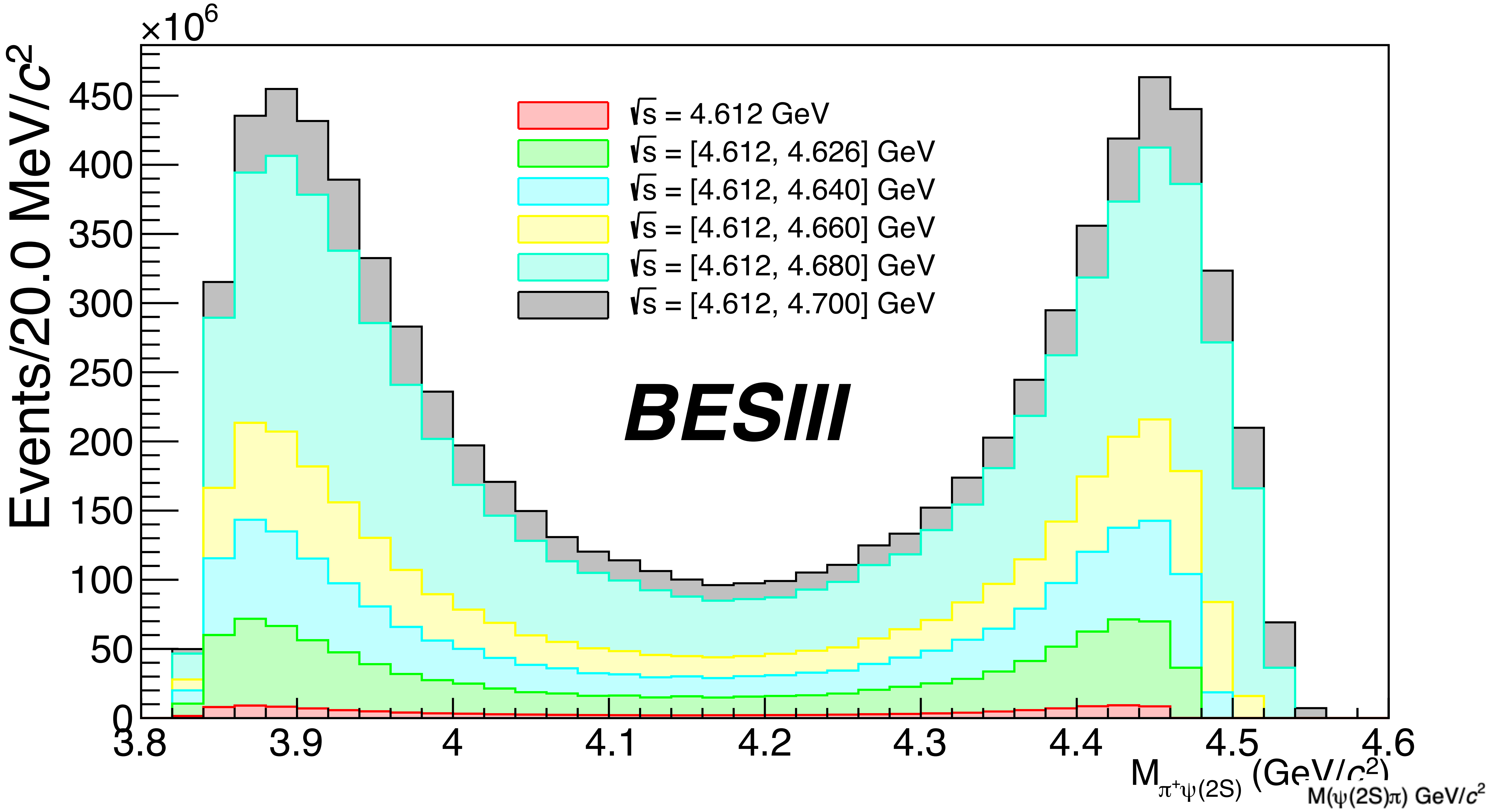
Analysis of the $\pi^{\pm}\psi(2S)$ Invariant Mass

Analysis of the π±ψ(2S) Invariant Mass

Signal MC Shape Extraction

Z_c Signal MC sample
300k events

√s [GeV]	$w_{Normalised} = (\sigma \times \mathcal{L})/(\sigma \times \mathcal{L})\|_{4.680}$	Resolution [MeV/c^2]	Efficiency [%]
4.612	0,04	— —	53.96
4.626	0.28	2.33	53.68
4.640	0.32	0.77	53.97
4.660	0.35	0.69	53.96
4.680	1.00	0.67	54.56
4.700	0.27	0.74	54.38

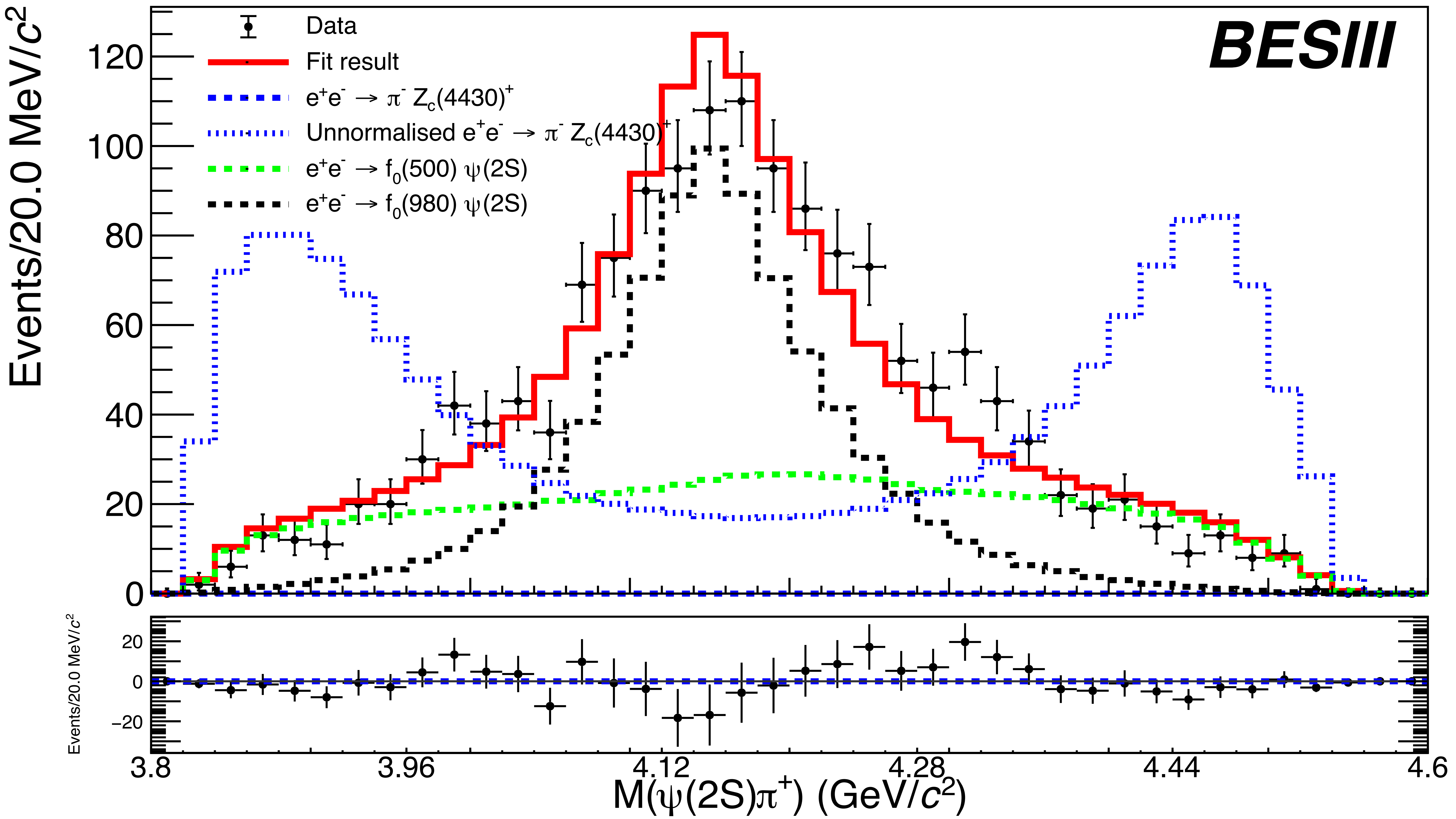


Signal function
MC Signal Shape

Analysis of the $\pi^{\pm}\psi(2S)$ Invariant Mass

In accordance with Ref.[11] and the Dalitz plots only f_0 contributions are considered

No evident $Z_c(4430)$ contribution is present (0 ± 4)



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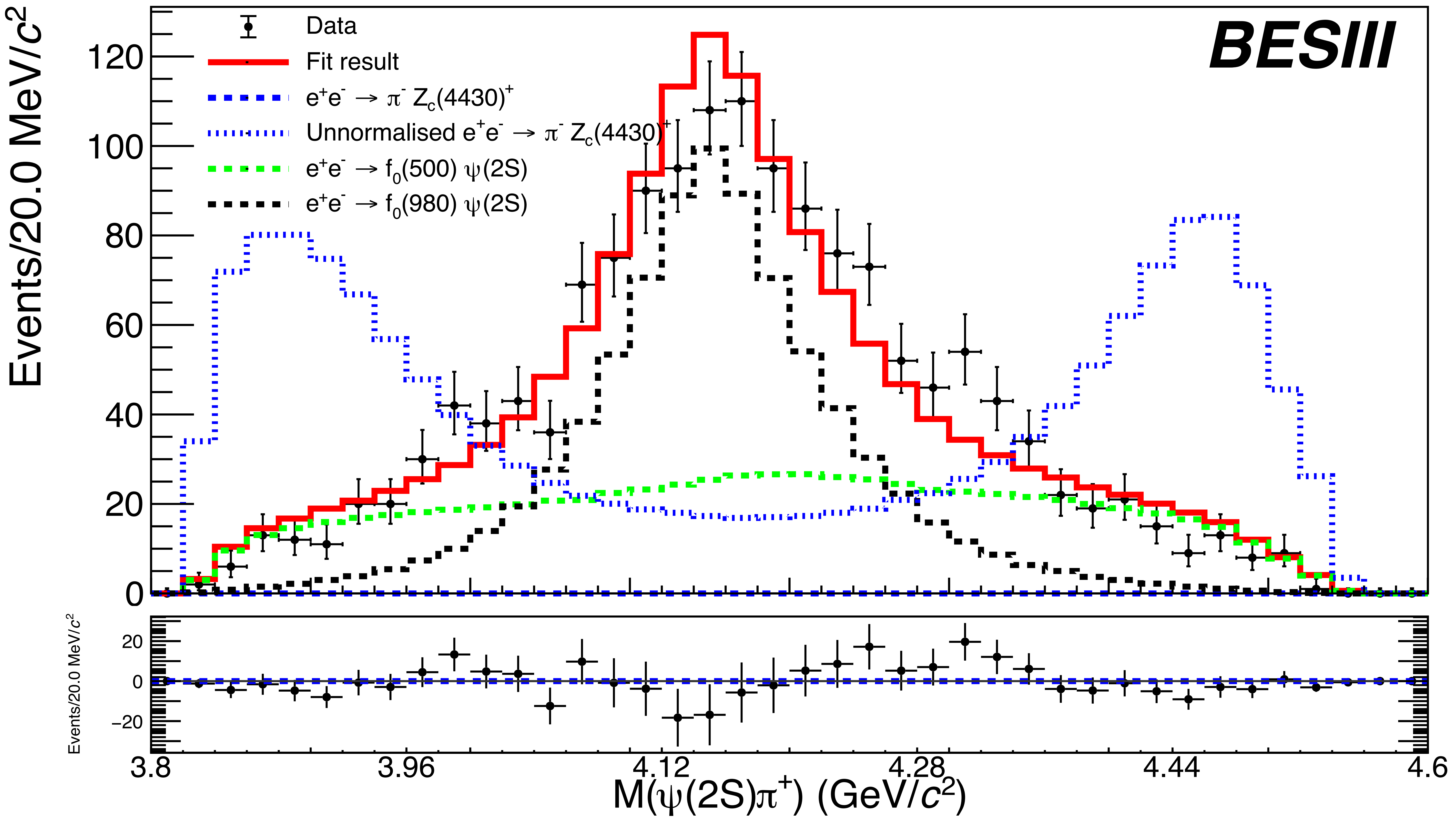
Bayesian U.L. @90%
$N(Z_c(4430)) < 16$



Analysis of the $\pi^{\pm}\psi(2S)$ Invariant Mass

Production Ratio Estimation

Bayesian U.L. @90%
$N(Z_c(4430)) < 16$

$$R = \frac{\sigma_{\text{Born}}(e^+e^- \to \pi^{\pm} Z_c(4430)^{\mp} \to \pi^+\pi^-\psi(2S))}{\sigma_{\text{Born}}(e^+e^- \to \pi^+\pi^-\psi(2S))}$$

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When **compared with Ref. [10]** (used as the motivation for this search), the **$Z_c(4430)^{\pm}$** state **production** in the $e^+e^- \to \pi^+\pi^-\psi(2S)$ channel is **suppressed by** at least **20 times with respect of** that of the **$Z_c(3900)^{\pm}$** hadron in the $e^+e^- \to \pi^+\pi^- J/\psi$ transition

Systematic Uncertainties

On the **cross-sections**, the systematic uncertainties come from the **selection efficiencies**, the integrated **luminosity**, the **vacuum polarisation**, the ISR **radiative corrections**, the **tracking efficiency**, and residual sources

- *Luminosity*: 1% as from Ref. [13]
- *Vacuum polarisation*: 0.5% from Ref. [14]
- *ISR radiative corrections*: Difference in the $(1 + \delta)$ between the last two iterations
- *Tracking efficiency*: 1.0% per track[10], 2.0% (leptons) and 3.5% (average of 2 pion-topologies)
- *Intermediate states* branching fractions: from PDG
- *Lepton separation*, *trigger efficiency*, and *FSR*: 1.0% from Ref. [11]

[13] Chin. Phys. C **46**, 11, 113003
[14] Sov. J. Nucl. Phys **41**, 466-472

Systematic Uncertainties

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Source	4.610	4.630	4.640	4.660	4.680	4.700
Luminosity	0.17	0.21	0.26	0.28	0.26	0.22
Vacuum polarisation	0.09	0.11	0.13	0.14	0.13	0.11
ISR corrections	0.07	0.07	0.00	0.03	0.03	0.02
Tracking efficiency	0.60	0.74	0.90	0.96	0.91	0.75
Intermediate states branching fractions	0.16	0.20	0.25	0.26	0.25	0.21
Other sources	0.17	0.21	0.26	0.28	0.26	0.22
Total systematic uncertainty	0.68	0.83	1.01	1.08	1.02	0.85

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Systematic Uncertainties

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Sample	$\sigma_{\rm Born}(\pi^+\pi^-\psi(2S))$	$\sigma_{\rm Born}(f_0(980)\psi(2S))\times \mathcal{B}(f_0(980)\to\pi^+\pi^-)$
4.610	$17.19^{+0.15}_{-3.14} \pm 0.68$	$6.88^{+2.46}_{-2.46} \pm 0.37$
4.630	$21.04^{+1.83}_{-1.70} \pm 0.83$	$12.48^{+2.20}_{-2.20} \pm 0.68$
4.640	$25.77^{+1.60}_{-1.85} \pm 1.01$	$14.24^{+2.01}_{-2.01} \pm 0.70$
4.660	$27.52^{+0.88}_{-1.89} \pm 1.08$	$13.66^{+1.56}_{-1.56} \pm 0.62$
4.680	$26.00^{+0.36}_{-1.07} \pm 1.02$	$14.48^{+1.09}_{-1.09} \pm 0.67$
4.700	$21.57^{+1.58}_{-1.70} \pm 0.85$	$12.18^{+1.69}_{-1.69} \pm 0.57$

[13] Chin. Phys. C **46**, 11, 113003
[14] Sov. J. Nucl. Phys **41**, 466-472

Systematic Uncertainties

The systematic sources **on the Z_c(4430) U.L.** come from the fitting procedure and choices, such as the **binning**, the **signal range**, and the **parametrisation of the signal and background**

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The **$Z_c(4430)^{\pm}$** number of events is also affected by the **same systematic sources as $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$** cross-section, so…

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$N(Z_c(4430)^{\pm}) < 17$

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Bayesian U.L. @90%
$N(Z_c(4430)^{\pm}) < 17$

Additional systematic uncertainties come from the **number and** selection **efficiency** of ***$e^+e^- \to \pi^+\pi^-\psi(2S)$*** events for the production ratio estimation
$R < 1.1\%$ at 90% C.L.

Conclusions

The **results found** in this analysis **confirm Ref.[11]** and compatible with the published literature

The **f_0(500)/f_0(980) contributions** to the $\pi^+\pi^-\psi(2S)$ cross-section are highlighted despite **no conclusion** can be drawn **on** the account of the **Y(4660) being an *$f_0(980)$-$\psi(2S)$* molecule**

A **search for the Z_c(4430)** exotic state is performed via the **$e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$** reaction, **no evident Z_c(4430)** is found and a U.L. at 90% C.L. is set

Outlook

The collaboration proposed to **extend the studies at $\sqrt{s} > 4.7$ GeV**, data of which have been recently gathered and reconstructed

This will allow ameliorating the analysis with some fine-tuning features…

For the **$Z_c(4430)^{\pm}$** signal shape, a **fitting model** can be chosen **following a PWA-motivated** generated signal **MC sample**

Implementation of an **analytical $f_0(500)$** shape

Interference term **between** the **two f_0 states**

Thanks for your attention!

Back-up Slides

DEC Cards

Z_c Resonant

```
noPhotos
Particle vpho 4.680 0

Decay vpho
  0.5000 dummy10_1 pi- PHSP;
  0.5000 anti-dummy10_1 pi+ PHSP;
Enddecay

Decay dummy10_1
  1.0000 pi+ psi(2S) PHSP;
Enddecay

Decay anti-dummy10_1
  1.0000 pi- psi(2S) PHSP;
Enddecay

Decay psi(2S)
  1.0000 J/psi pi+ pi- JPIPI;
Enddecay

Decay J/psi
  0.5000 e+ e- PHOTOS VLL;
  0.5000 mu+ mu- PHOTOS VLL;
Enddecay

End
```

$Z_c(4430)$
$M_{Zc} = 4478^{+15}_{-18}$ MeV
$\sigma_{Zc} = 181 \pm 31$ MeV

Signal MC samples
300k events

BOSS Release
7.0.6

non-Resonant

```
Particle vpho 4.6812 0.0
Decay vpho
  1.0000 ConExc -2 100443 211 -211;
Enddecay

Decay vhdr
  1.0000 psi(2S) pi+ pi- VVPIPI;
Enddecay

Decay psi(2S)
1.000 J/psi pi+ pi- JPIPI;
Enddecay

Decay J/psi
  0.5000 e+ e- PHOTOS VLL;
  0.5000 mu+ mu- PHOTOS VLL;
Enddecay

End
```

Signal MC Studies

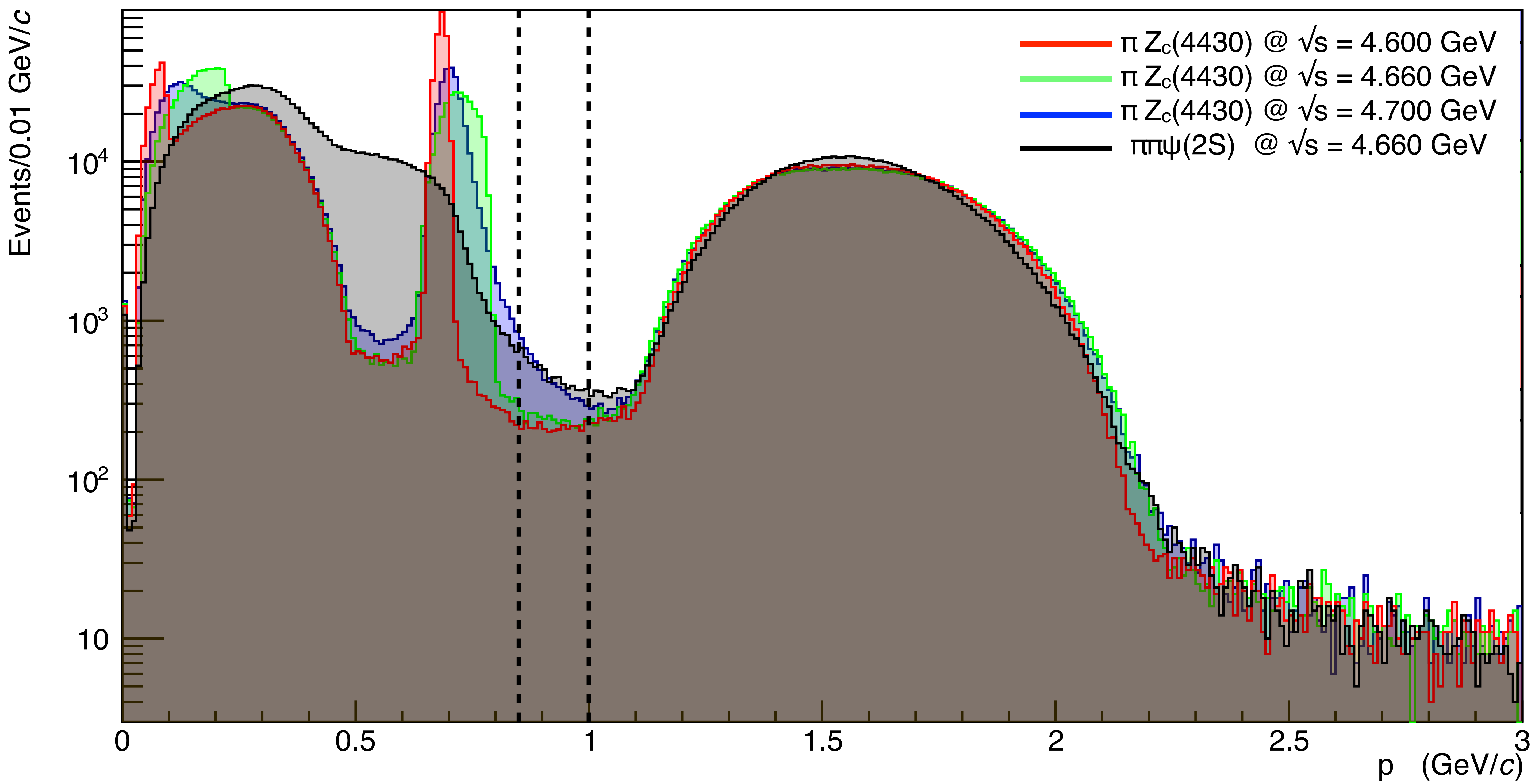
Signal MC sample
300k events

Charged Particles Momentum Comparison

Let's check it in more detail… the upper bound for p_{π} (< 0.85 GeV) can be improved?

↓

S(Sig$_{MC}$ Z$_c$)/B(Inc$_{MC}$) optimisation



Signal MC Studies

Signal MC sample
300k events

Event Selection

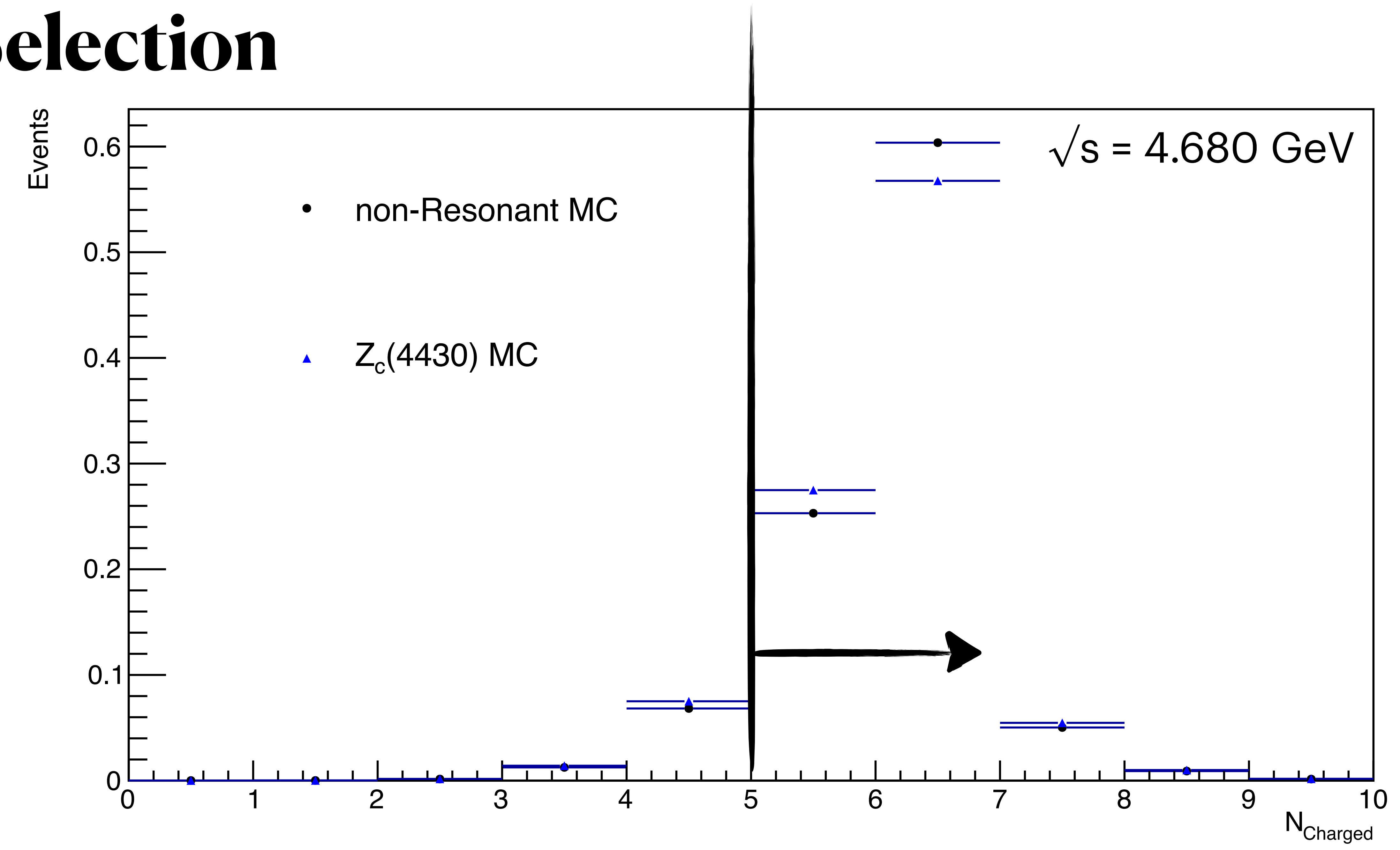
Goodness Cuts

Vertex: R_{xy} < 1cm & R_z < 10 cm

Polar angle: |cos θ| < 0.93

Channel ID

charged tracks > 4



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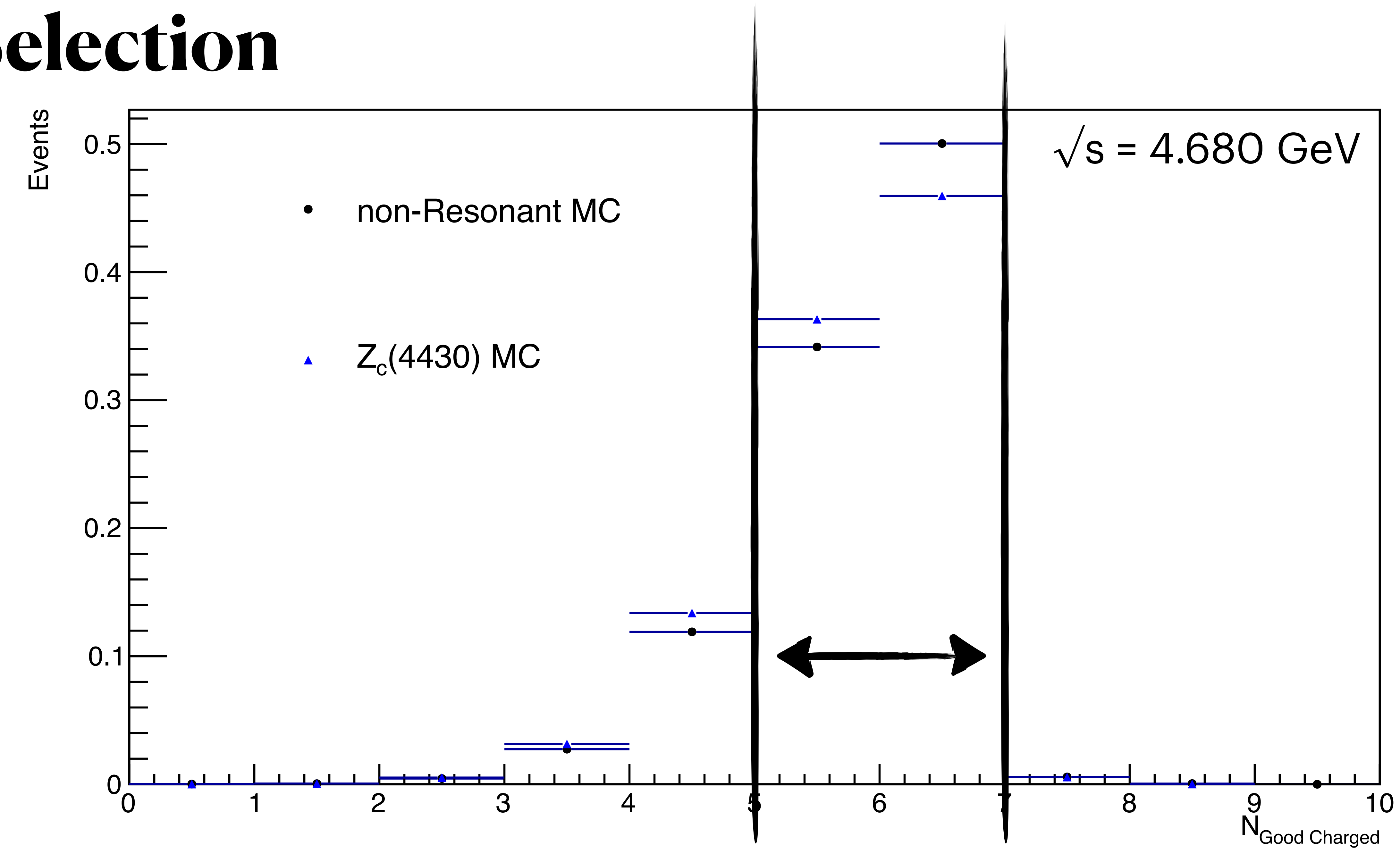

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Polar angle: $|\cos\theta| < 0.93$

Channel ID

charged tracks > 4

2 good charged topologies

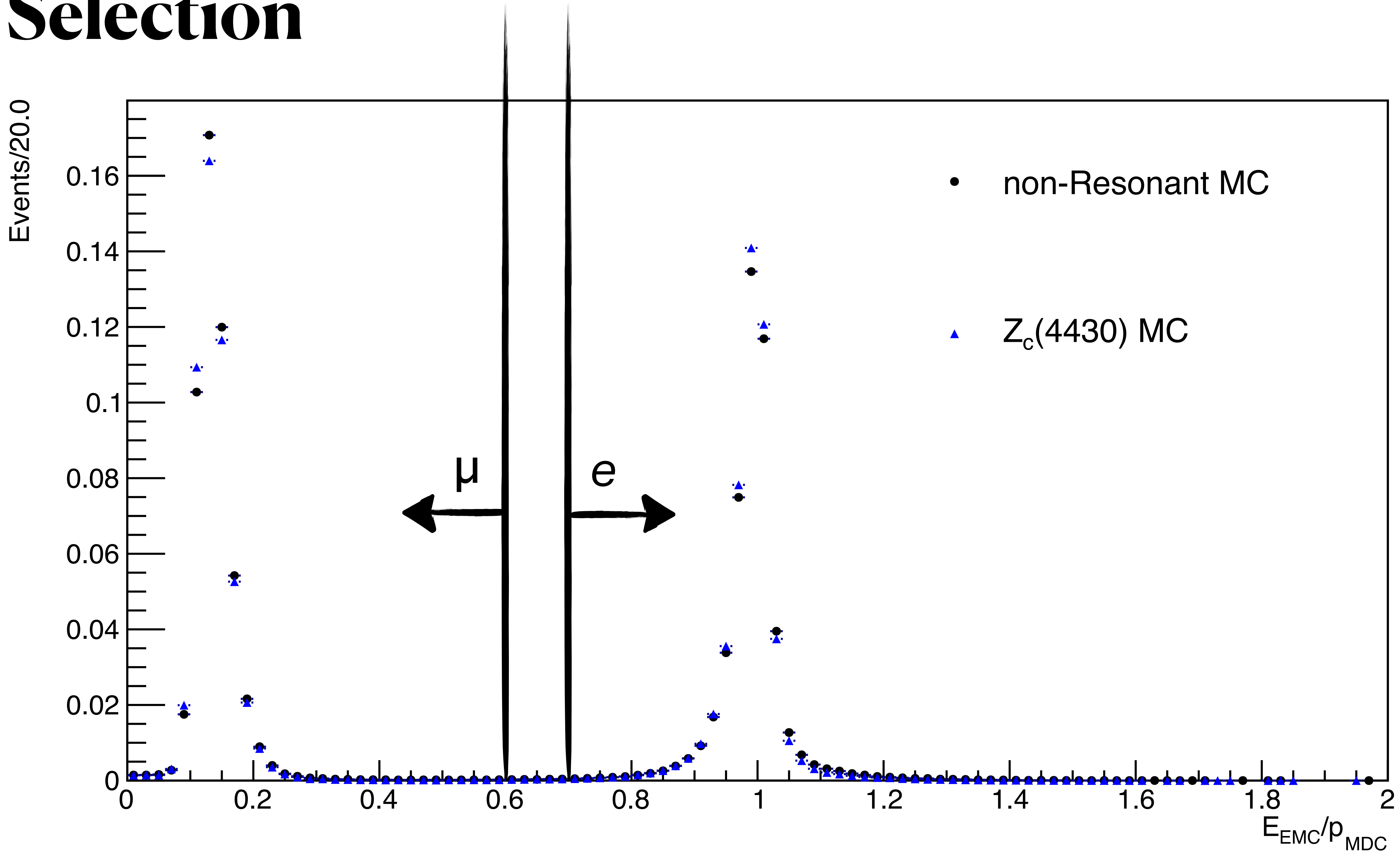
$2\ell\, 3\pi$

$2\ell\, 4\pi$

Signal MC Studies

Signal MC sample
300k events

E/p Selection



Goodness Cuts

Vertex: $R_{xy} < 1$cm & $R_z < 10$ cm

Polar angle: $|\cos\theta| < 0.93$

Channel ID

charged tracks > 4

Leptons	Pions
$p_T > 1$ GeV	$p_T < 0.85$ GeV
E/p (e) > 0.7	
E/p (μ) < 0.6	

2 good charged topologies

$2\ell\,3\pi$

$2\ell\,4\pi$

Signal MC Studies

Event Selection

Topology dependent KALMAN Fits

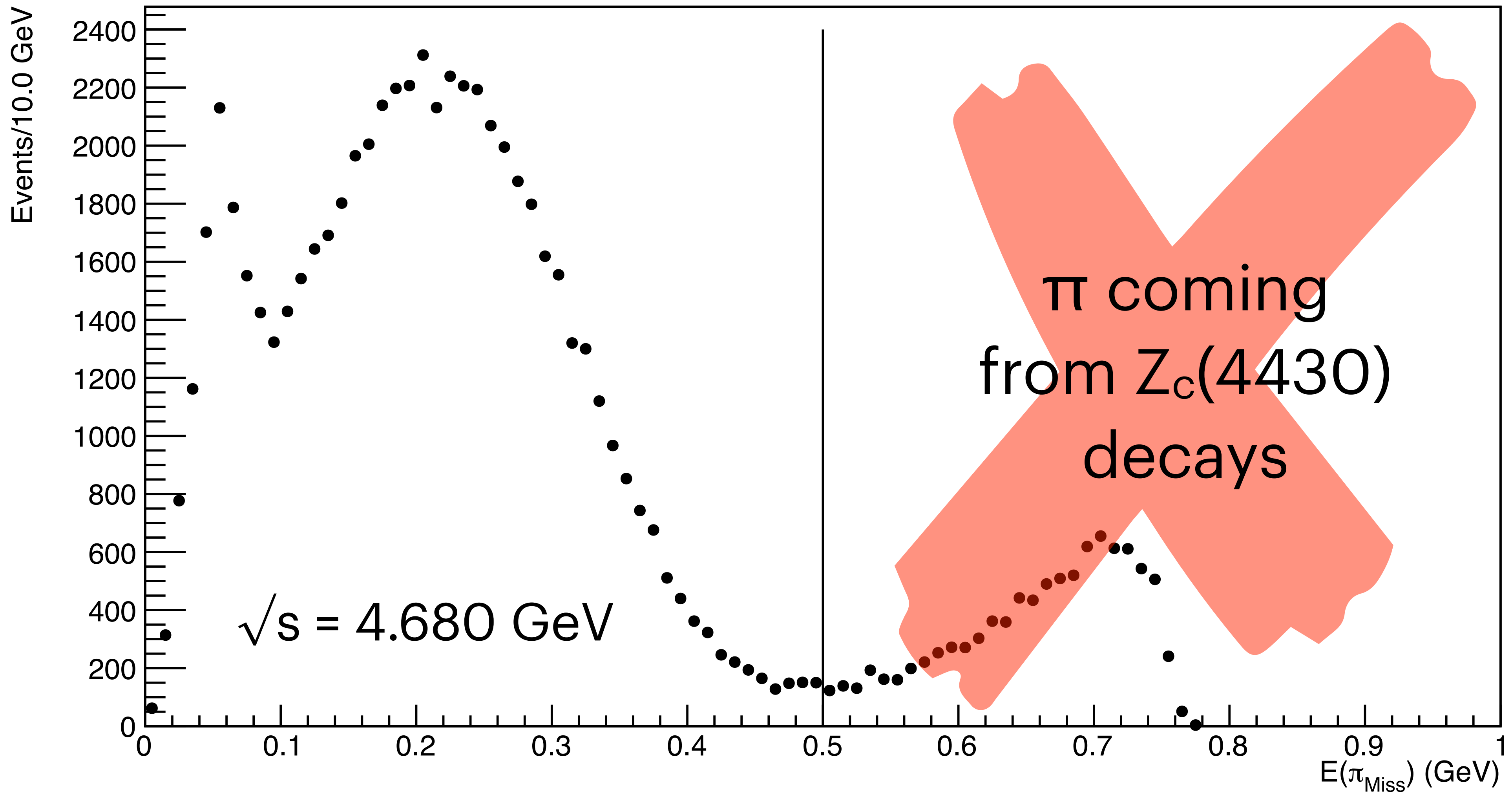
$2\ell 4\pi$

6C Kalman fit

1C on the $M_{J/\psi}$
1C on the $M_{\psi(2S)}$
4C on the p_{Tot} = (0.051, 0, 0, $M_{\sqrt{s}}$)

The $\pi\pi$ couples are selected via the best χ^2

$2\ell 3\pi$

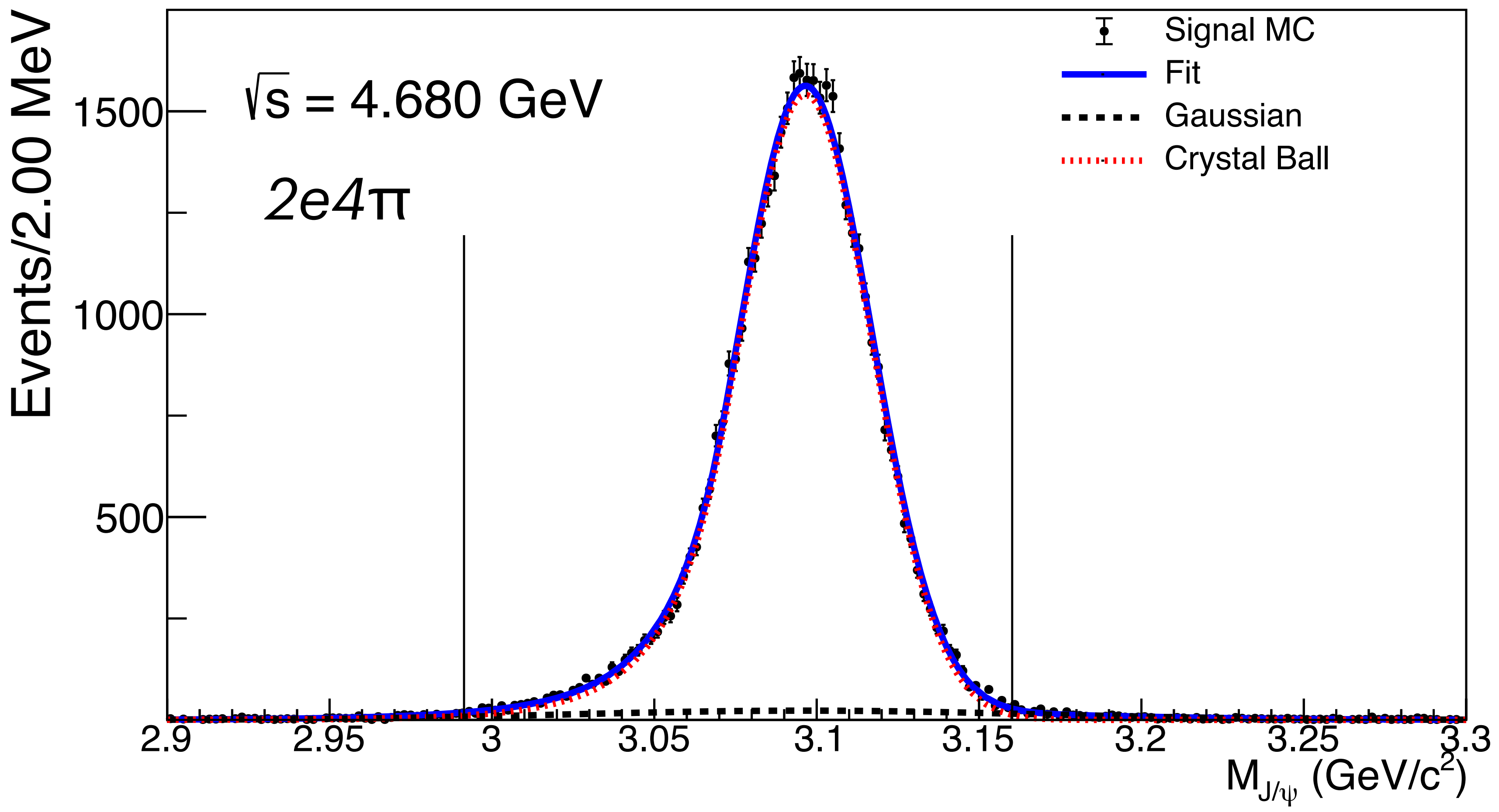


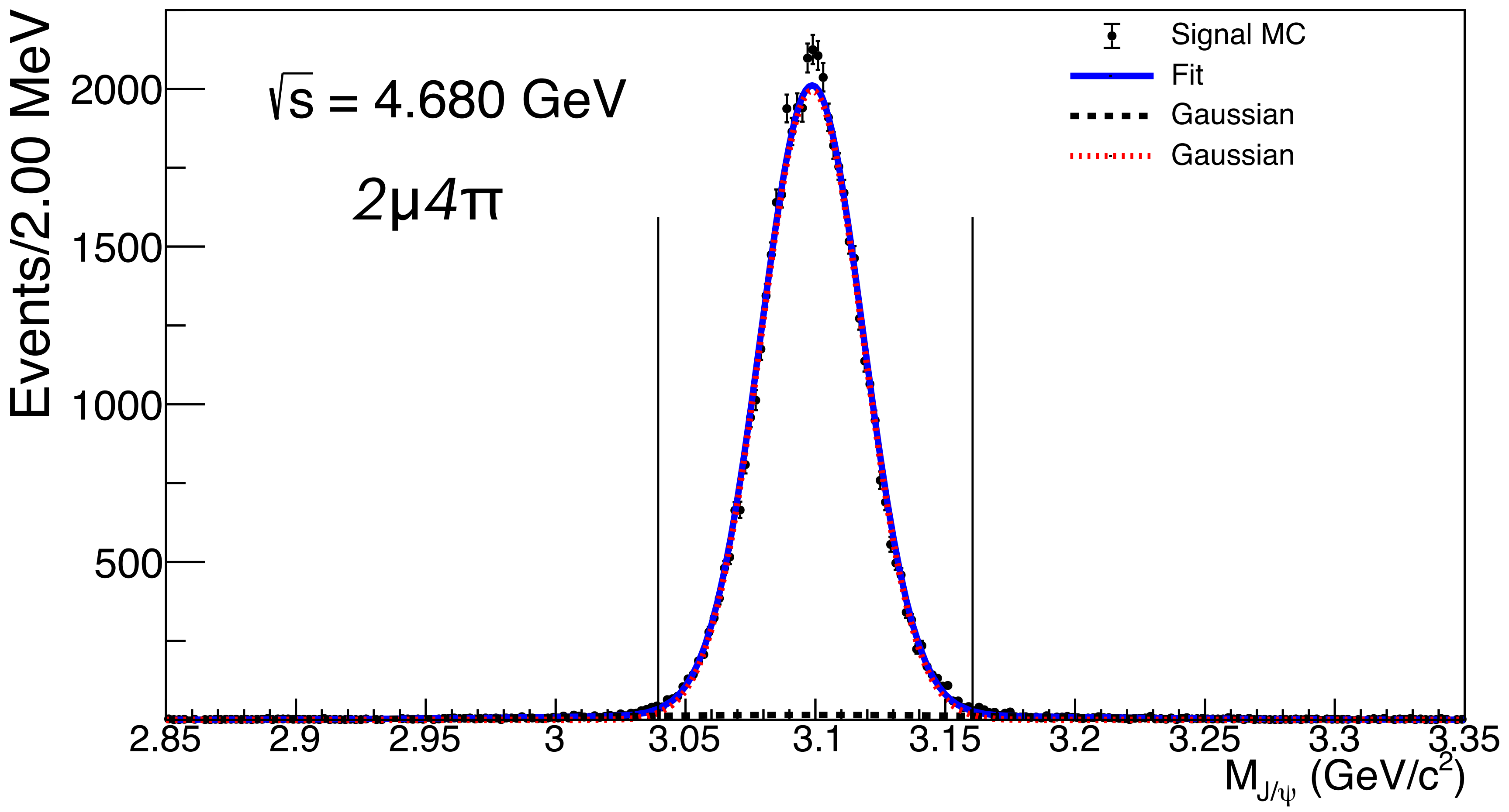
$\pi\pi$ and $\pi\pi_{Miss}$ couples are selected by minimising $M^{Reco}_{\psi(2S)}$-$M^{PDG}_{\psi(2S)}$

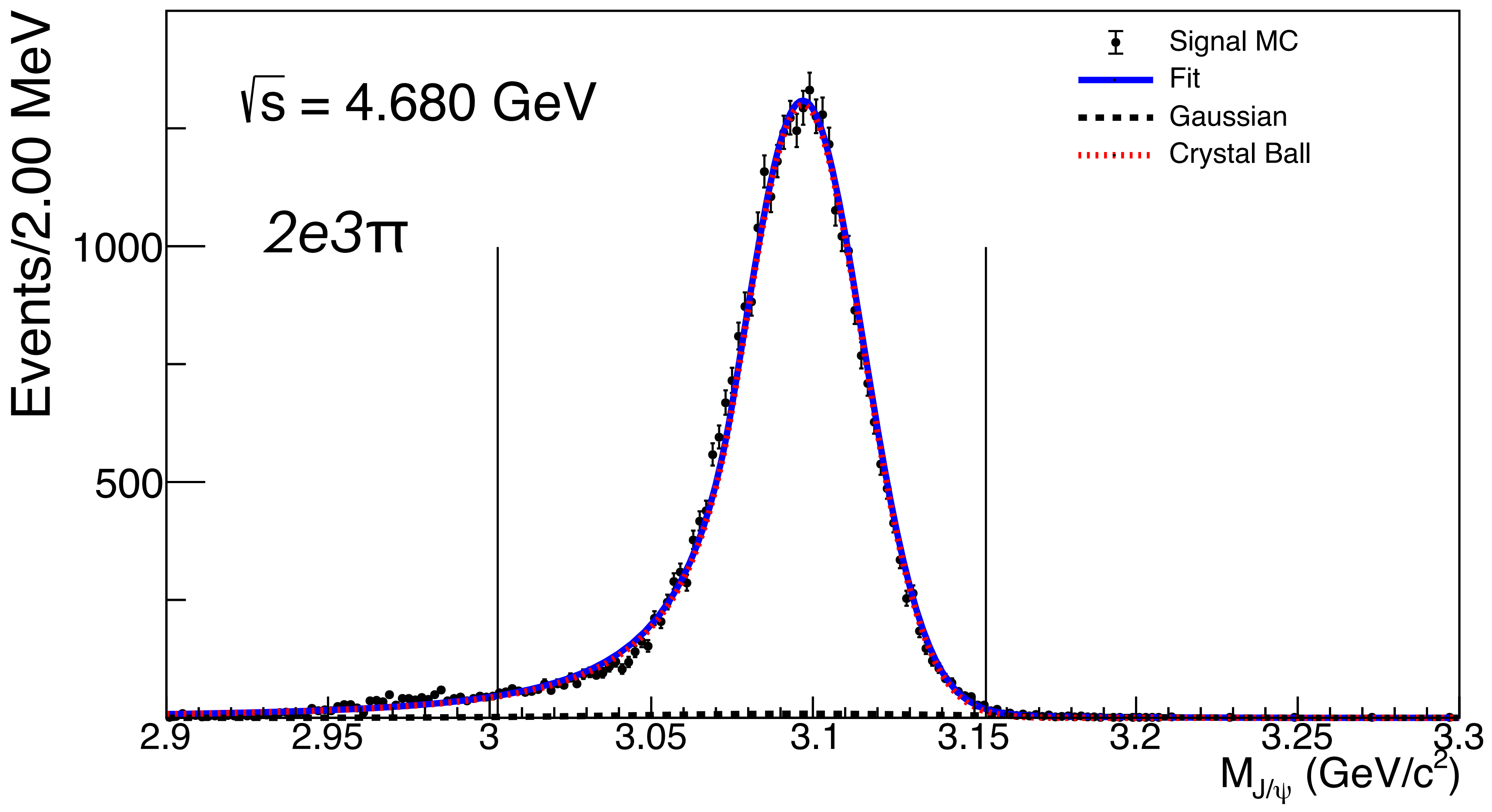
Event Selection

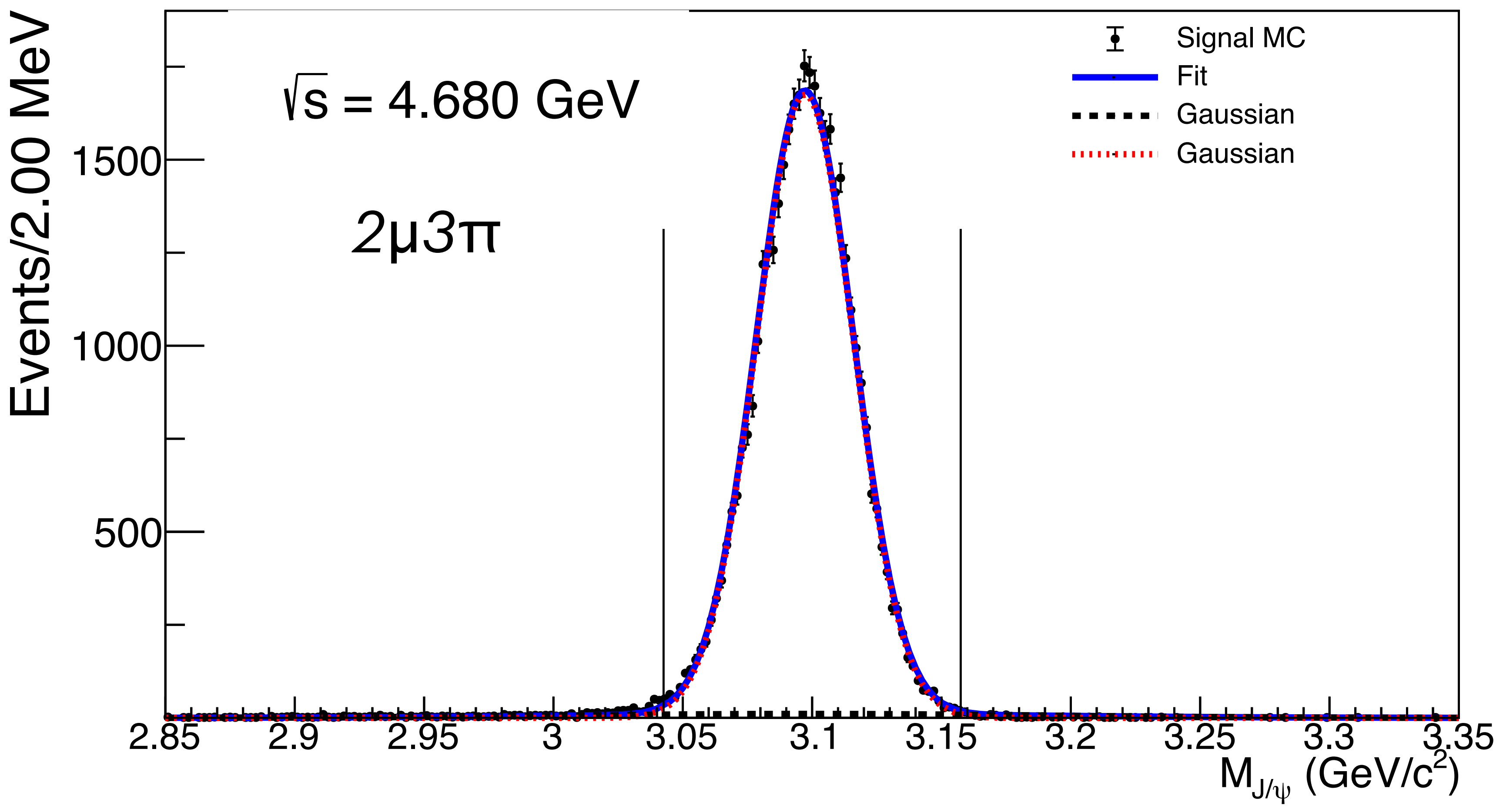
Signal MC sample
300k events

Just a bit more... $M_{J/\psi}$ Signal Windows









Selection on

M(ψ(n)) both for **2ℓ4π** and **2ℓ3π**

$M_{Miss}(\pi)$ for 2ℓ3π

Given the width (σ) of the distribution:

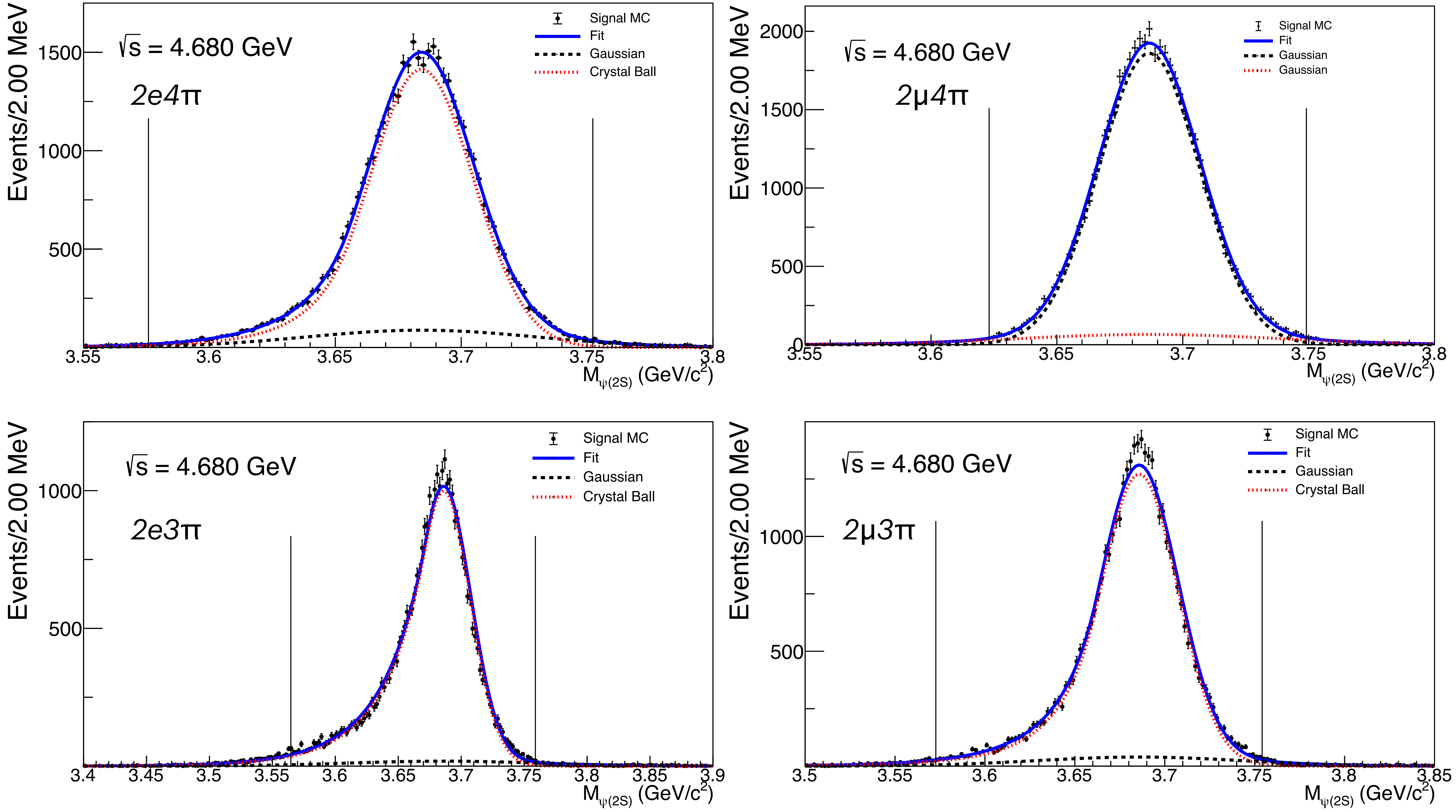
ee channel: -5σ < M < +3σ

μμ channel: -3(5)σ < M < +3σ

Event Selection

Just a bit more… $M_{\psi(2S)}$ Signal Windows

Signal MC sample
300k events



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Event Selection

Just a bit more... $M_{Miss}(\pi)$ for $2\ell 3\pi$ Signal Window

Signal MC sample
300k events

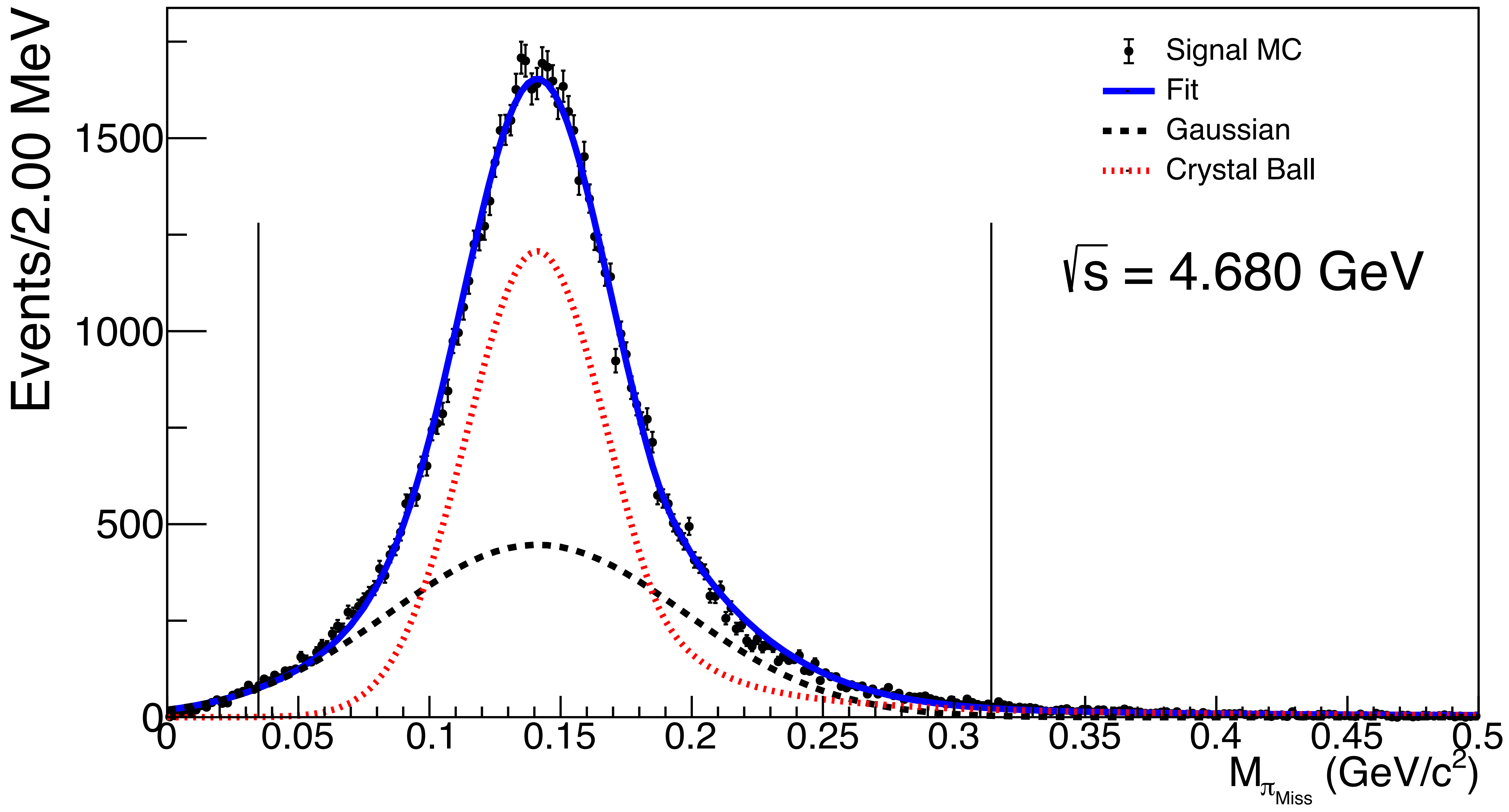
Given the width (σ) of the distribution, ∀ $\sqrt{s}$:

$$-3\sigma < M < +5\sigma$$

√s	σ(Miss-π) [MeV/c^2]
4.612	29
4.626	30
4.640	32
4.660	34
4.680	35
4.700	37

$M_{Miss}(\pi) = \pi\pi^+\pi^-\ell^+\ell^-$ recoil mass

Fit function: sum of Gaussian and Crystal Ball



Background Rejection

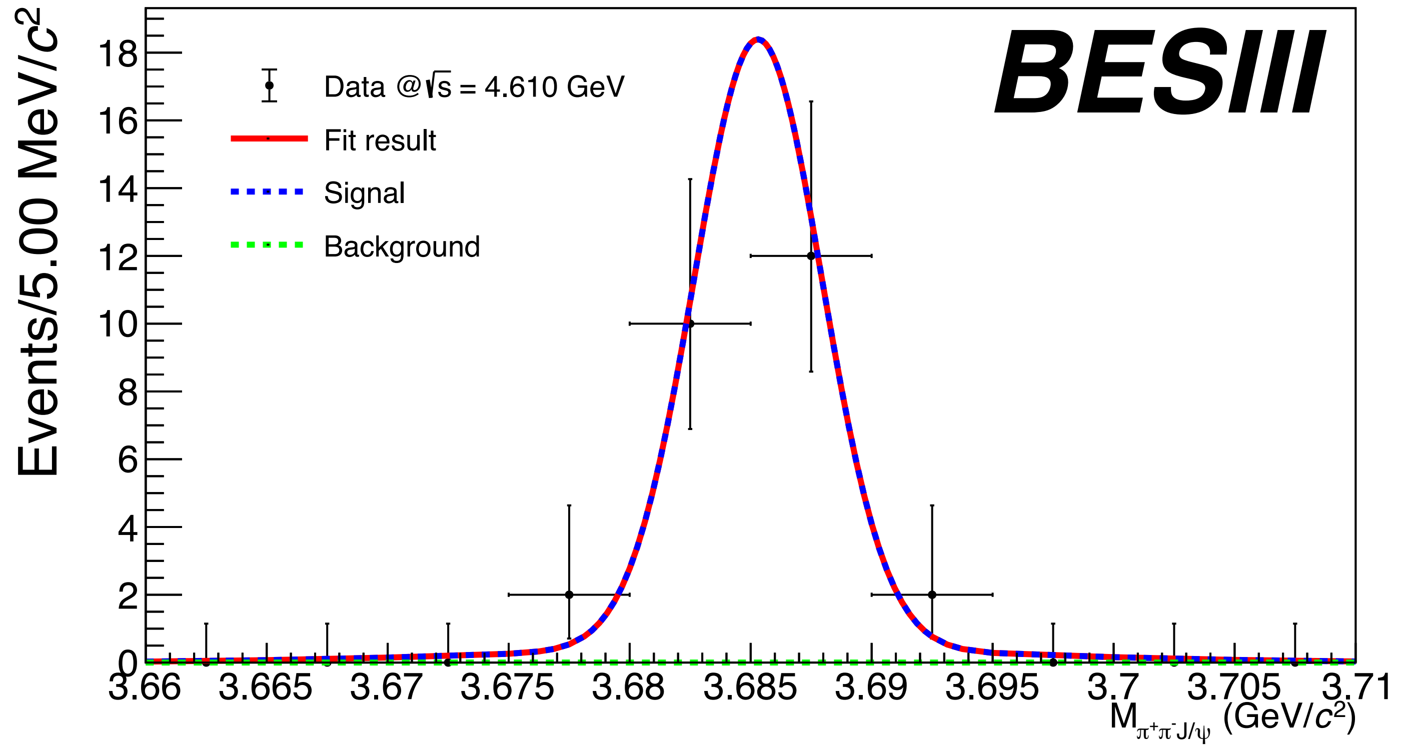
Inclusive MC sample
10x $\mathcal{L}$ data

From 1.3 billion inclusive MC events, **28136 survive**, with a survival rate of ~ O(10ppm)

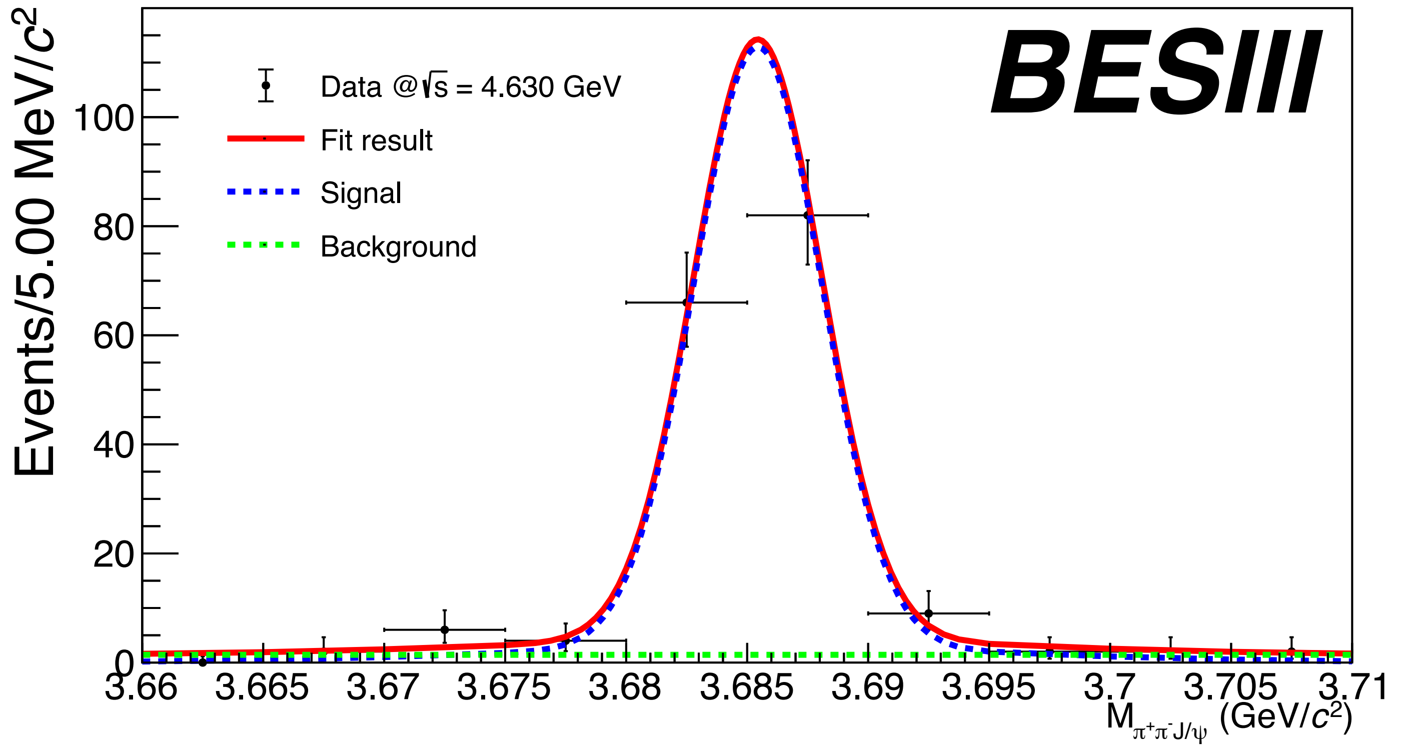
Virtually **only hadron component** is surviving after the selection criteria

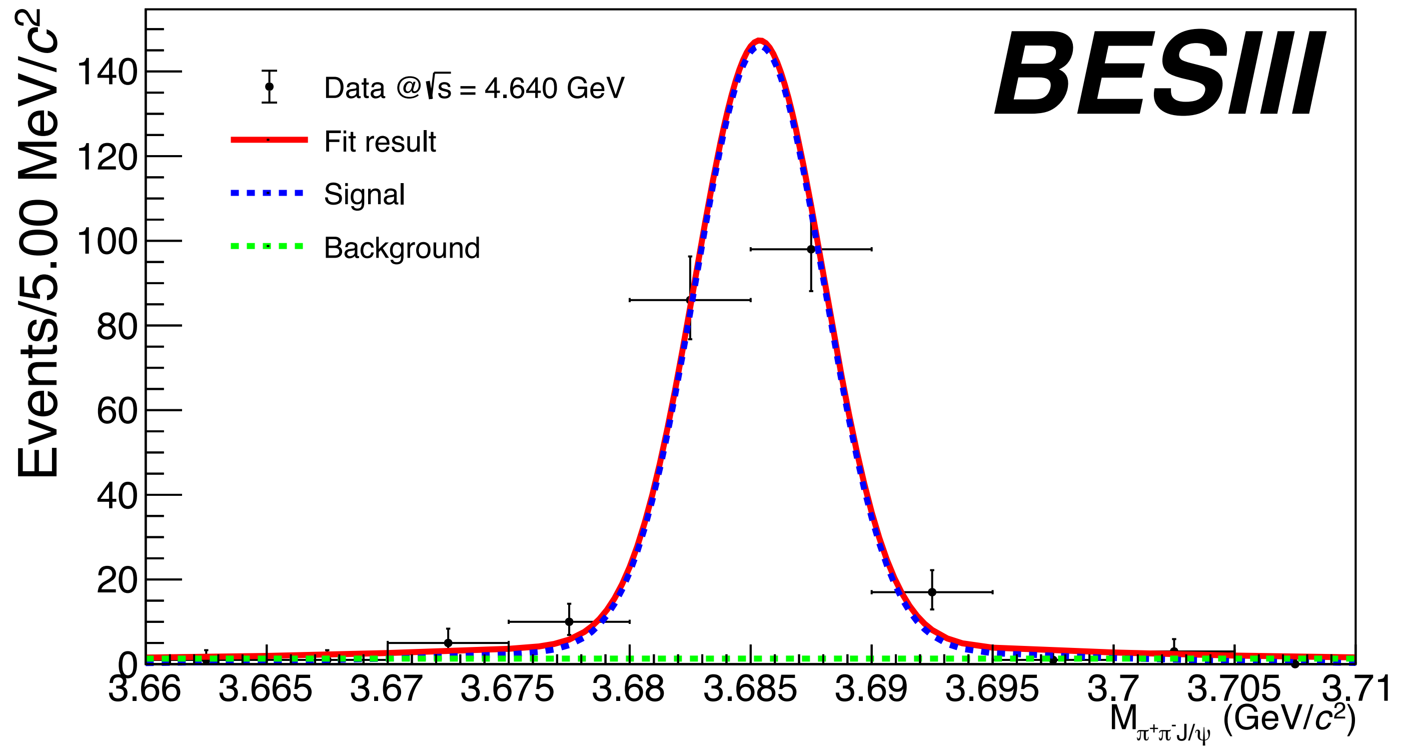
√s 4.680 GeV	$\Lambda_c\Lambda_c$	ττ	Hads	μμ	ee	γγ	Tot	Eff. [%]
NTot	35047250	56093530	287911230	69508120	55673000	10815600	515048730	100,0000
NCutCh	152301	751	97416298	930	1513908	3877322	102961510	19,9906
NCutGoodCh	243	238	1034648	315	19755	442	1055641	0,2050
NCut_5trks	0	1	5585	1	0	0	5587	0,0011
NCut_6trks	0	0	8786	0	0	0	8786	0,0017
NCut_Alltrks	0	1	14371	1	0	0	14373	0,0028

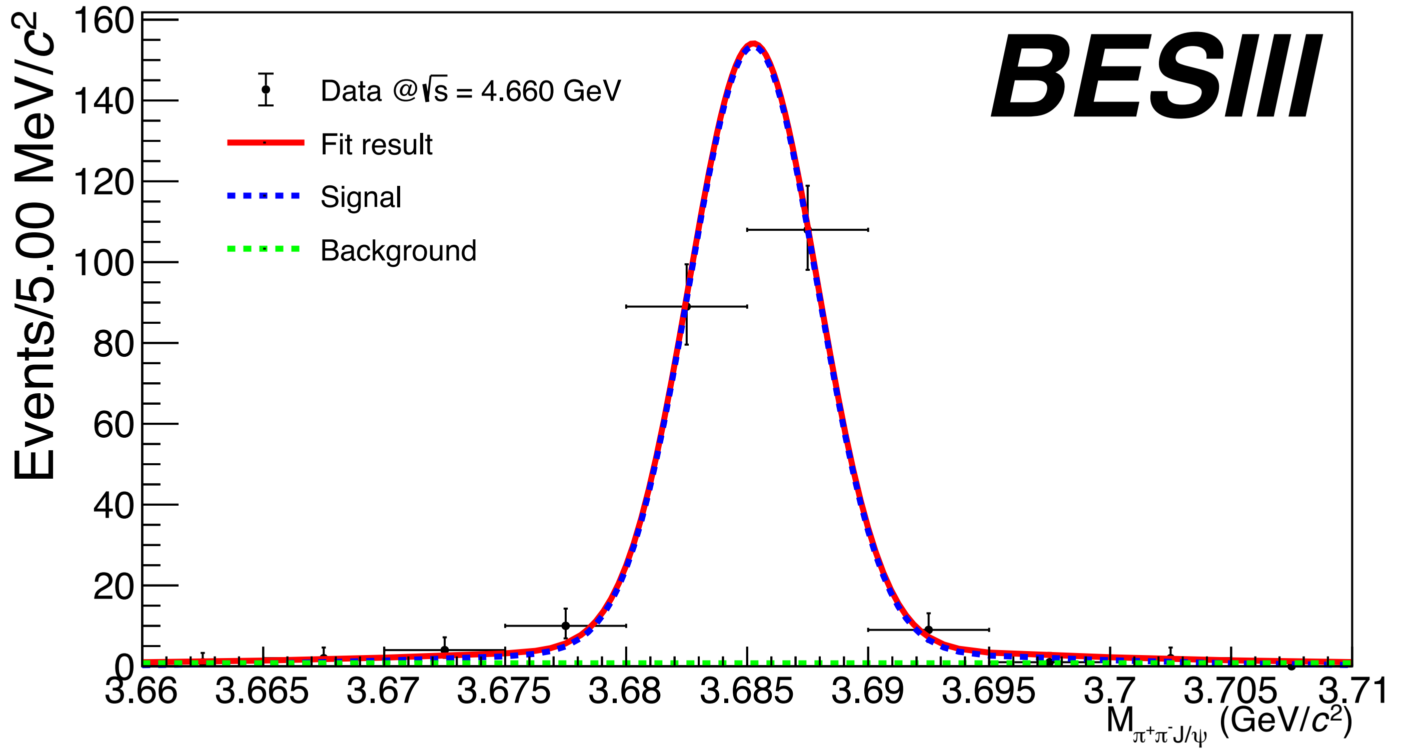
Extraction of the σ(ππ ψ(2S))

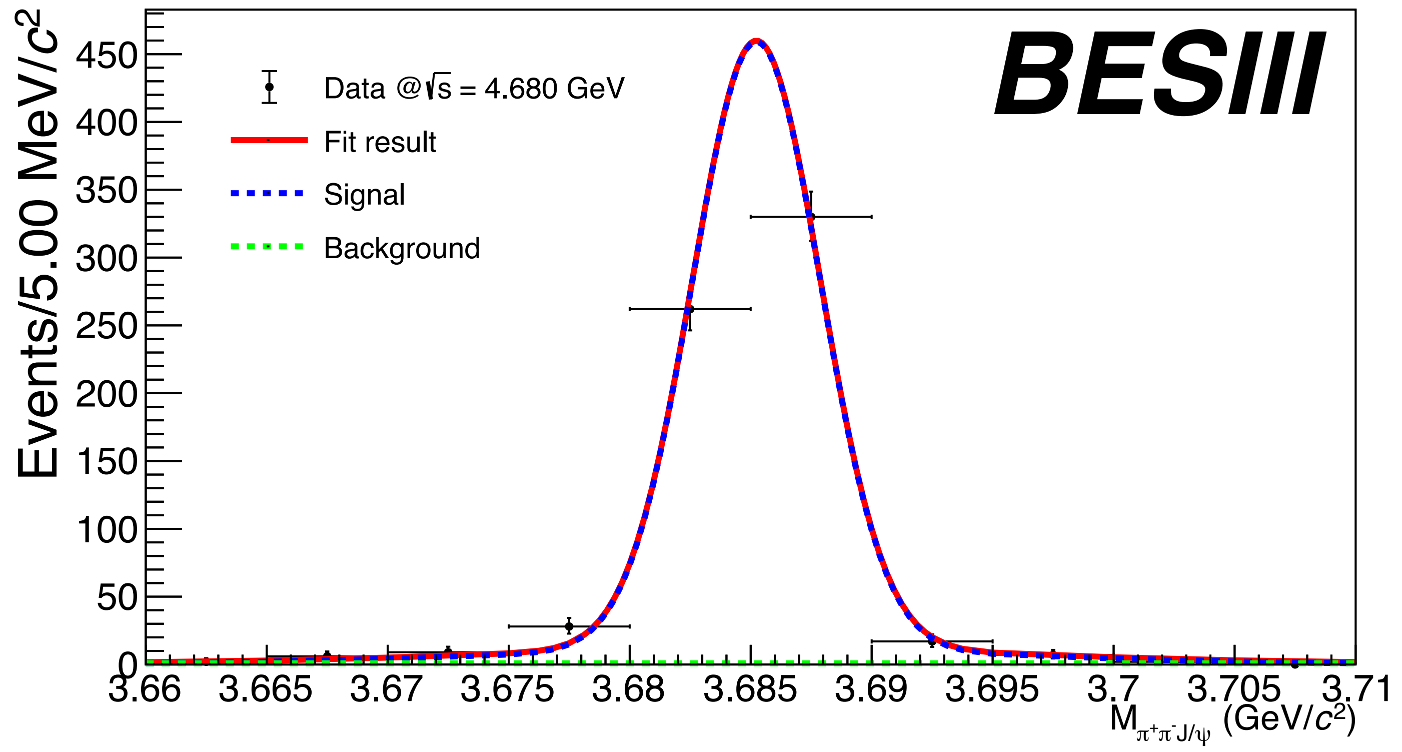


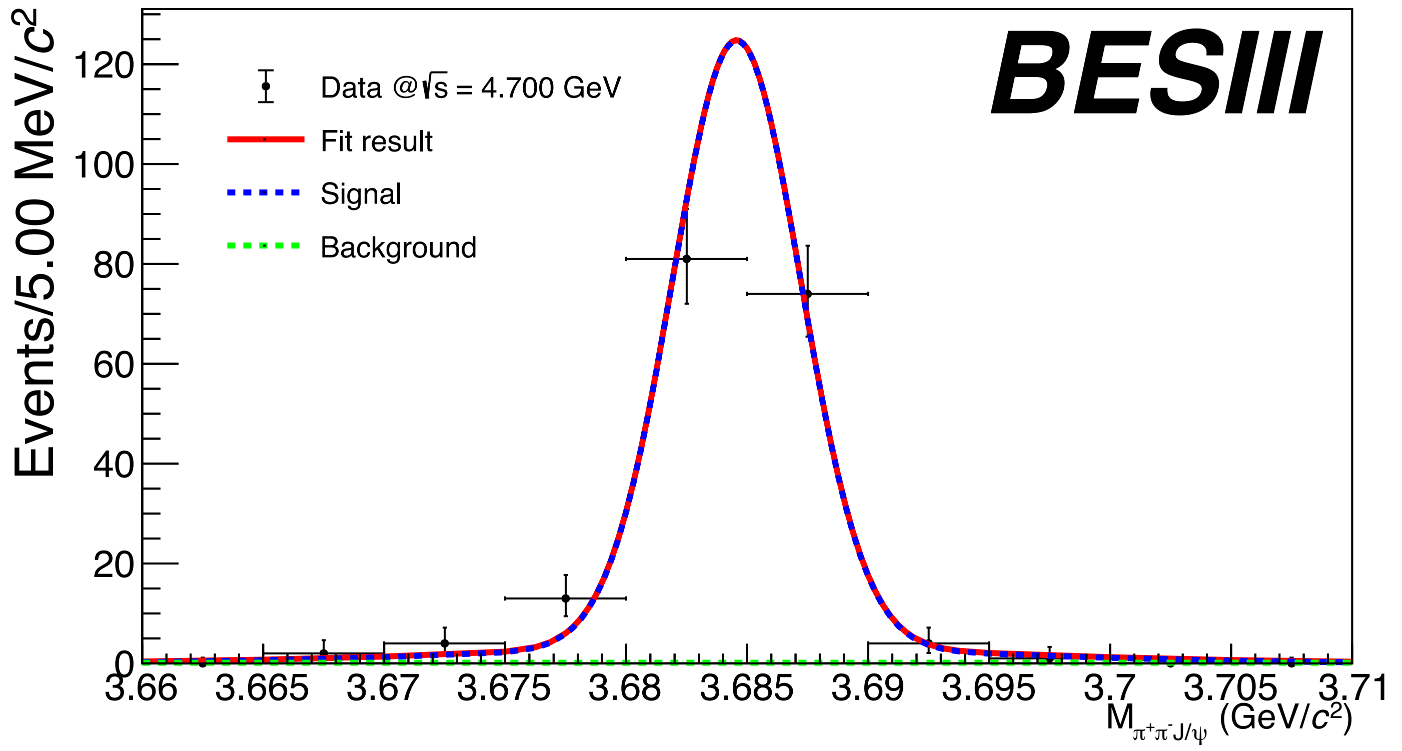
ππ ψ(2S) cross-section











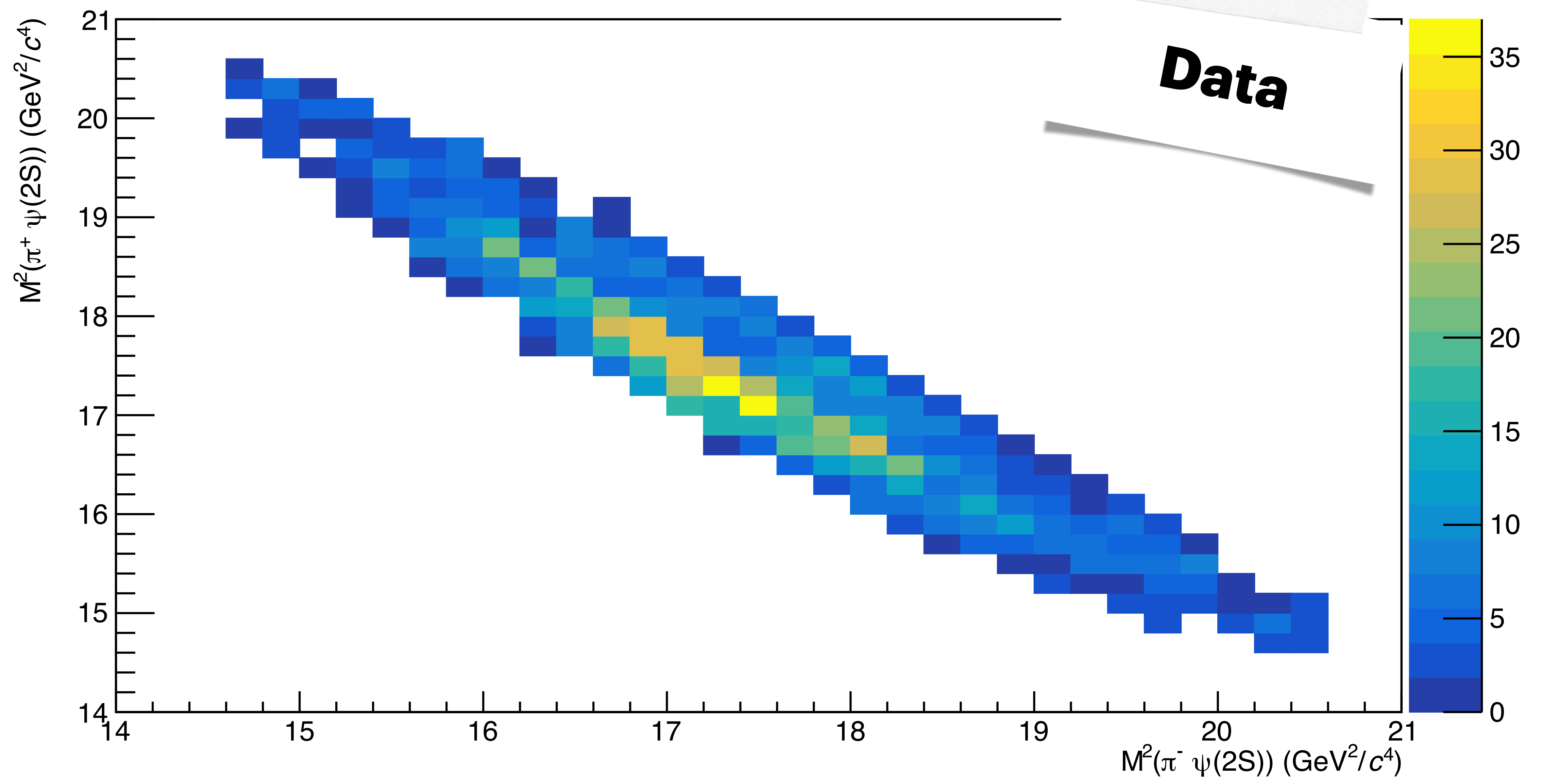
Extraction of the σ(ππ ψ(2S))

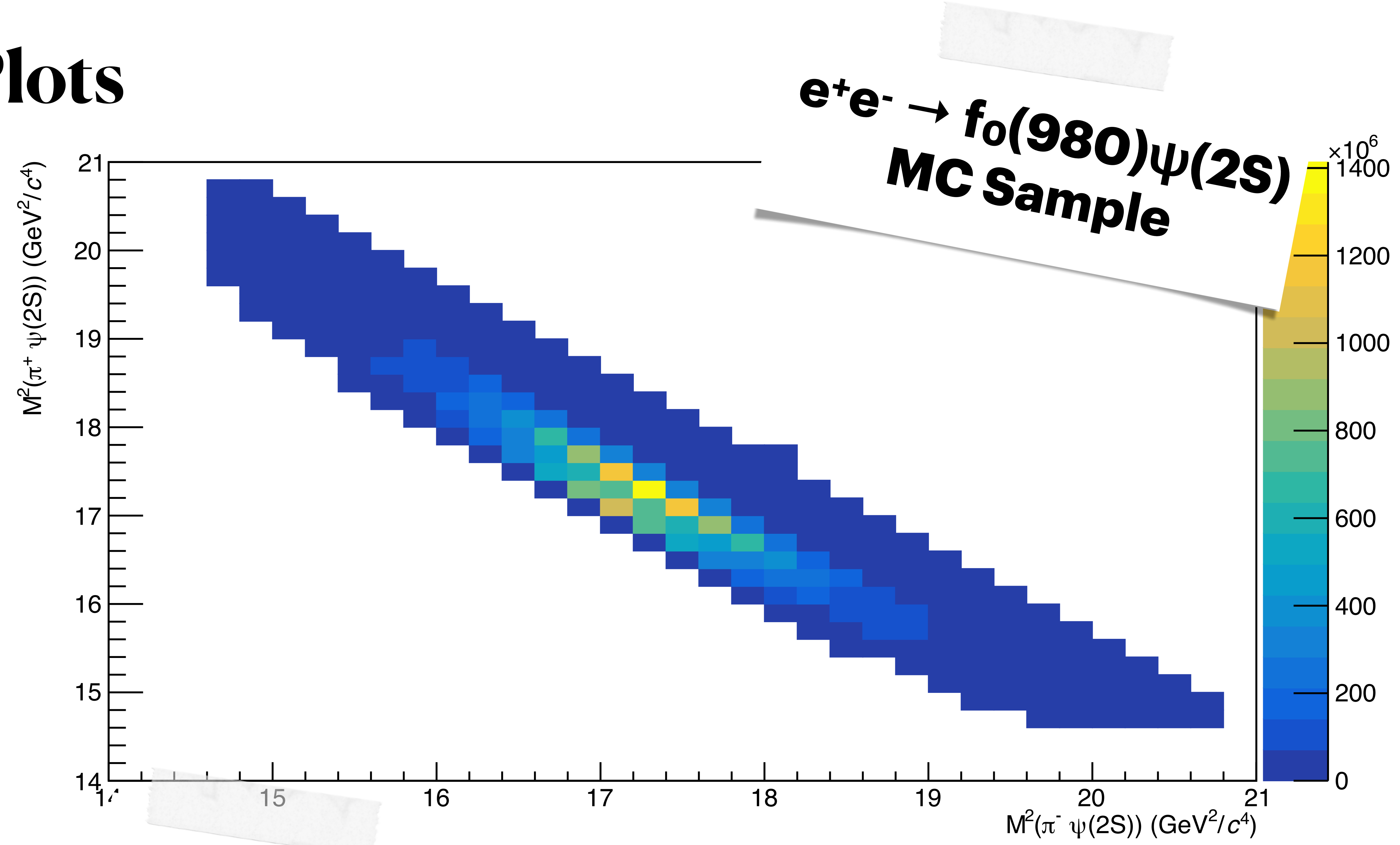
ππ ψ(2S) cross-section

E_{CoM} (MeV)	$\mathcal{L}$ (pb^{-1})	N_{Obs}	ϵ (%)	$\sigma_{Observed}$	$(1+\delta)$	$\frac{1}{\lvert 1-\Pi \rvert^2}$	σ_{Born}
4611.86	103.83	24^{+2}_{-5}	38.90 ± 0.11	$16.28^{+0.14}_{-2.98}$	0.898	1.05453	$17.19^{+0.15}_{-3.14}$
4628.00	521.52	155^{+18}_{-18}	40.45 ± 0.12	$19.46^{+1.69}_{-1.57}$	0.877	1.05444	$21.04^{+1.83}_{-1.70}$
4640.91	552.41	193^{+27}_{-29}	41.59 ± 0.12	$23.20^{+1.44}_{-1.66}$	0.854	1.05442	$25.77^{+1.60}_{-1.85}$
4661.24	529.63	202^{+20}_{-20}	41.54 ± 0.12	$25.15^{+0.80}_{-1.72}$	0.867	1.05441	$27.52^{+0.88}_{-1.89}$
4681.92	1669.31	563^{+46}_{-46}	40.72 ± 0.12	$24.60^{+0.34}_{-1.02}$	0.897	1.05448	$26.00^{+0.36}_{-1.07}$
4698.82	536.45	162^{+16}_{-16}	39.16 ± 0.11	$21.59^{+1.58}_{-1.70}$	0.949	1.05453	$21.57^{+1.58}_{-1.70}$

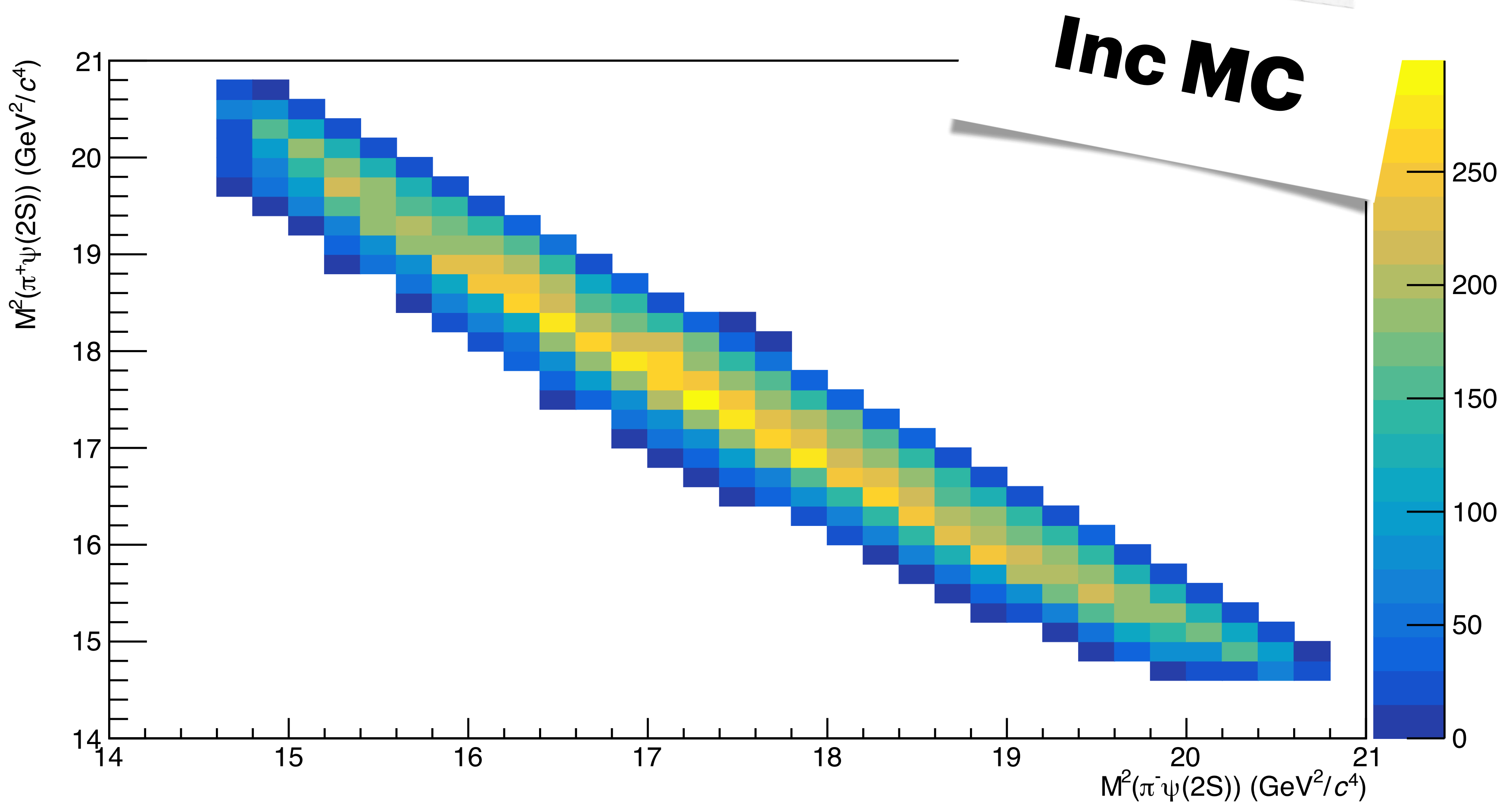
Study of the Intermediate States

Dalitz Plots





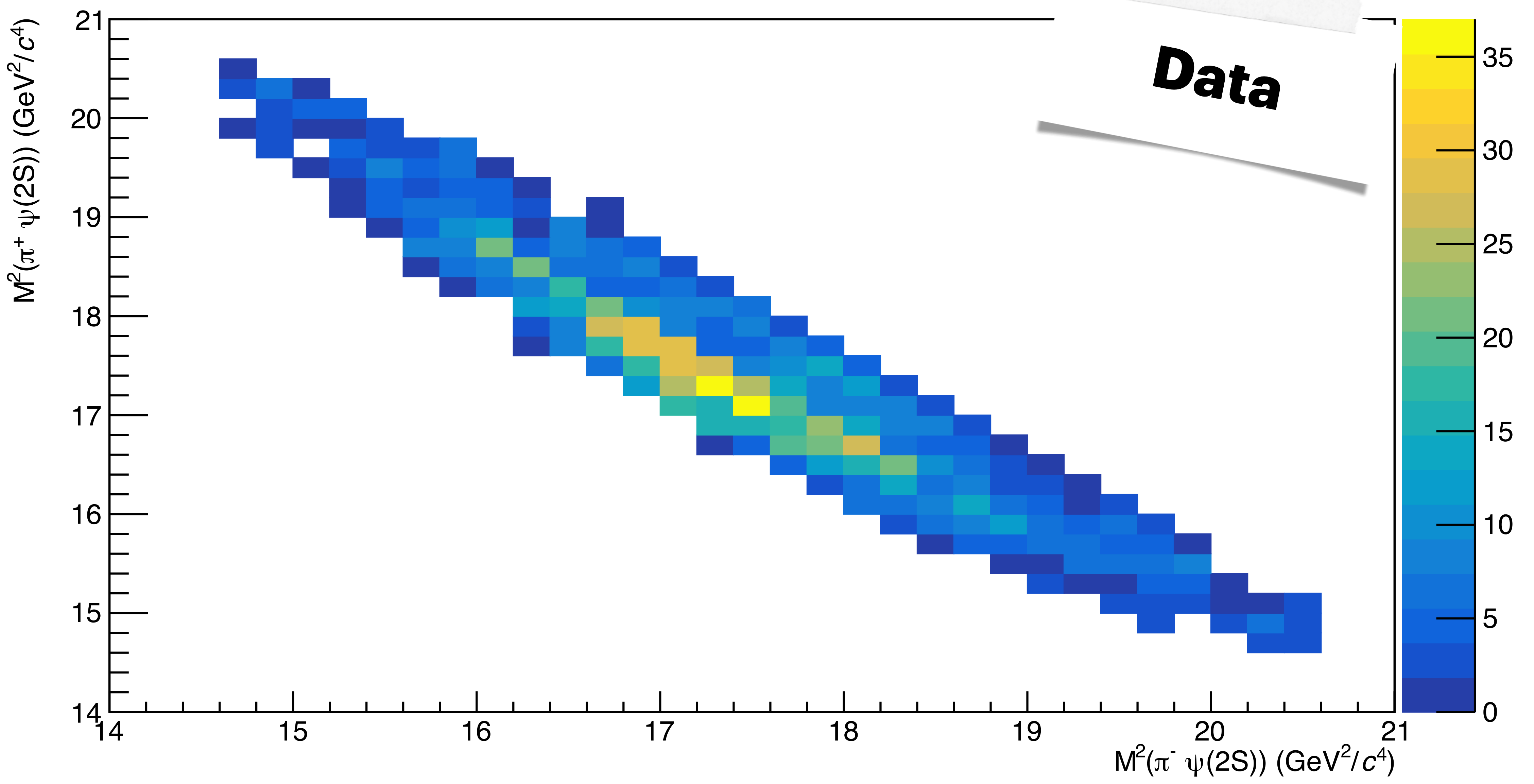
In **Ref.[11]**, a **simplified PWA** performed on the data sets highlighted **f_0(500)** and **f_0(980)** contributions

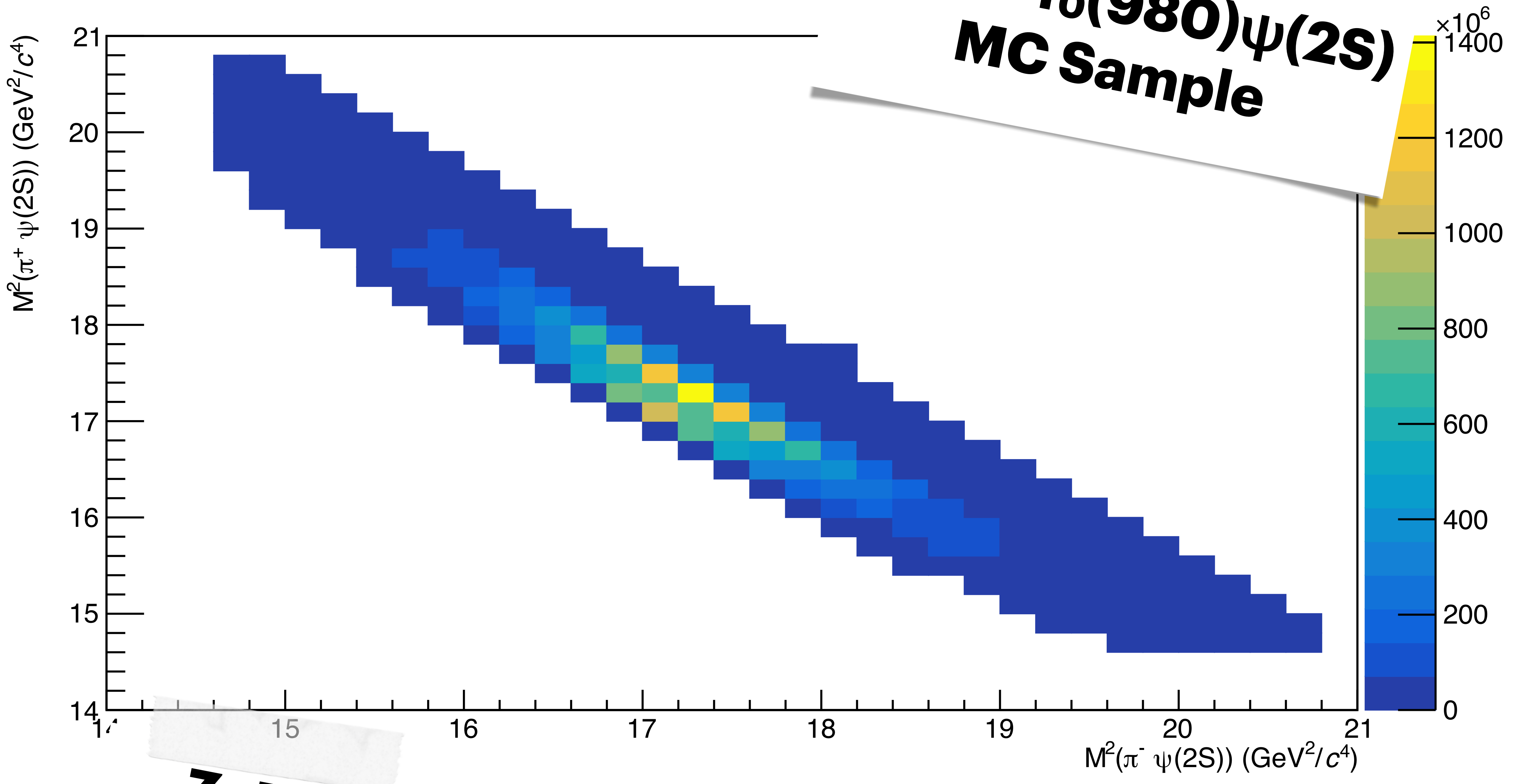


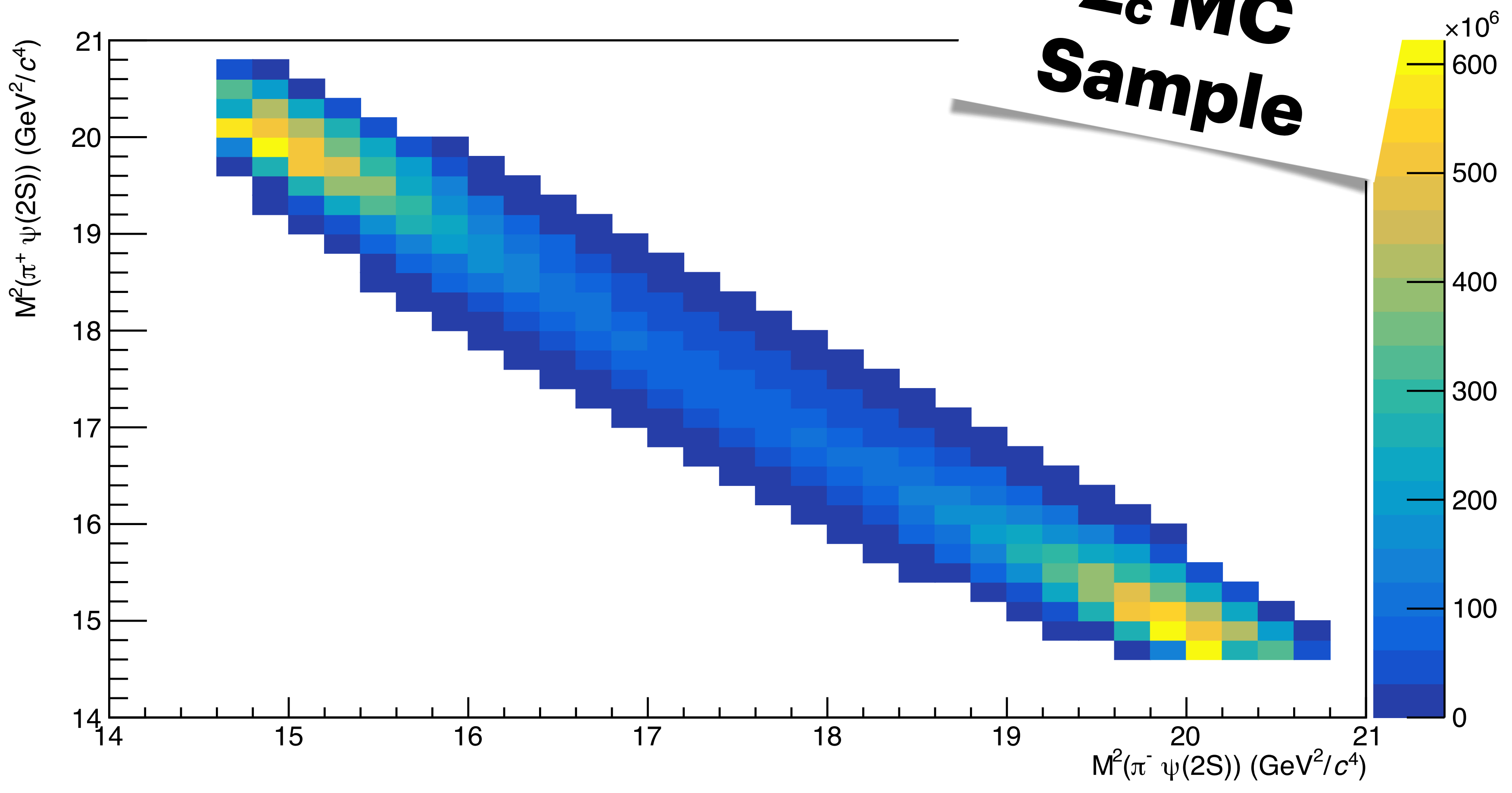
The six **data samples** are **merged together** to have more statistical significance

Study of the Intermediate States

Dalitz Plots







In **Ref.[11]**, a **simplified PWA** performed on the data sets highlighted **f_0(500)** and **f_0(980)** contributions

The six **data samples** are **merged together** to have more statistical significance

MC Studies

Efficiency

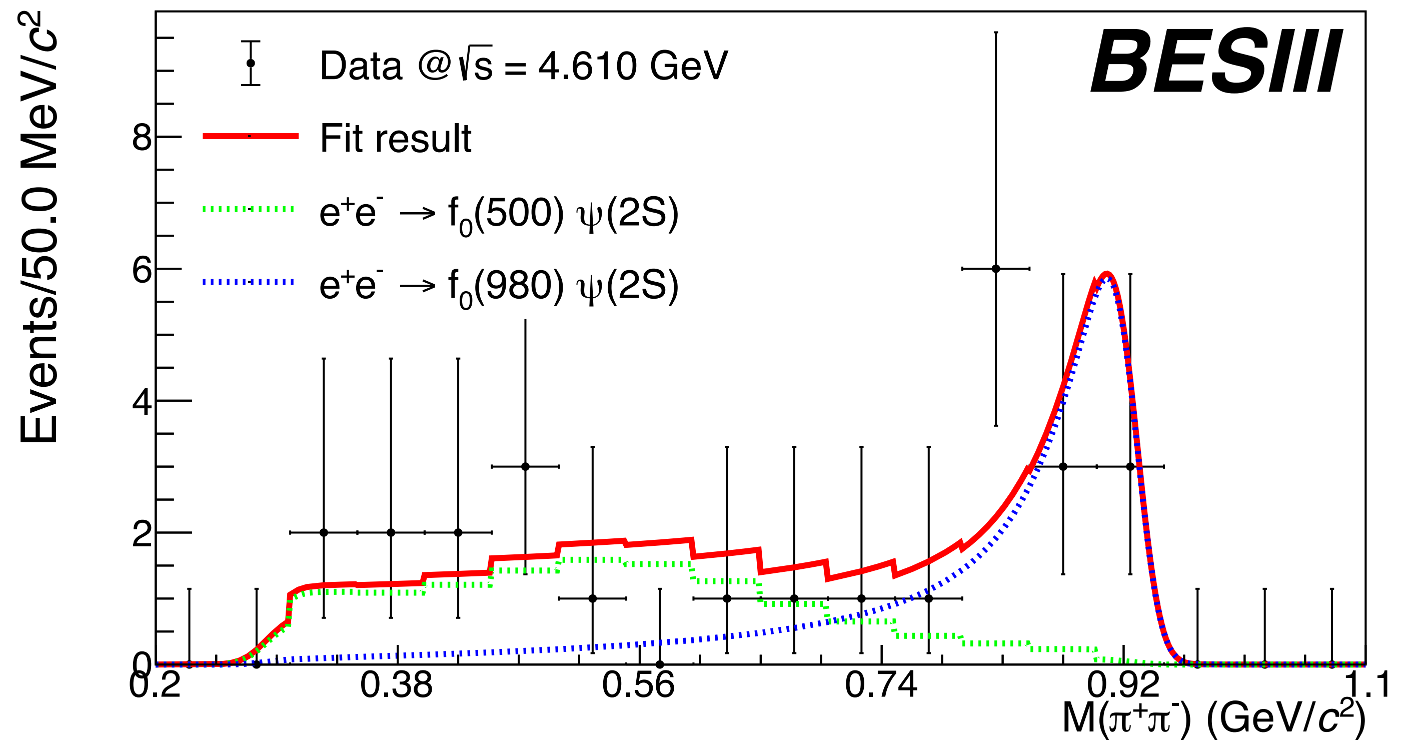
$f_0(980)$
Signal MC sample
300k events

CONEXC

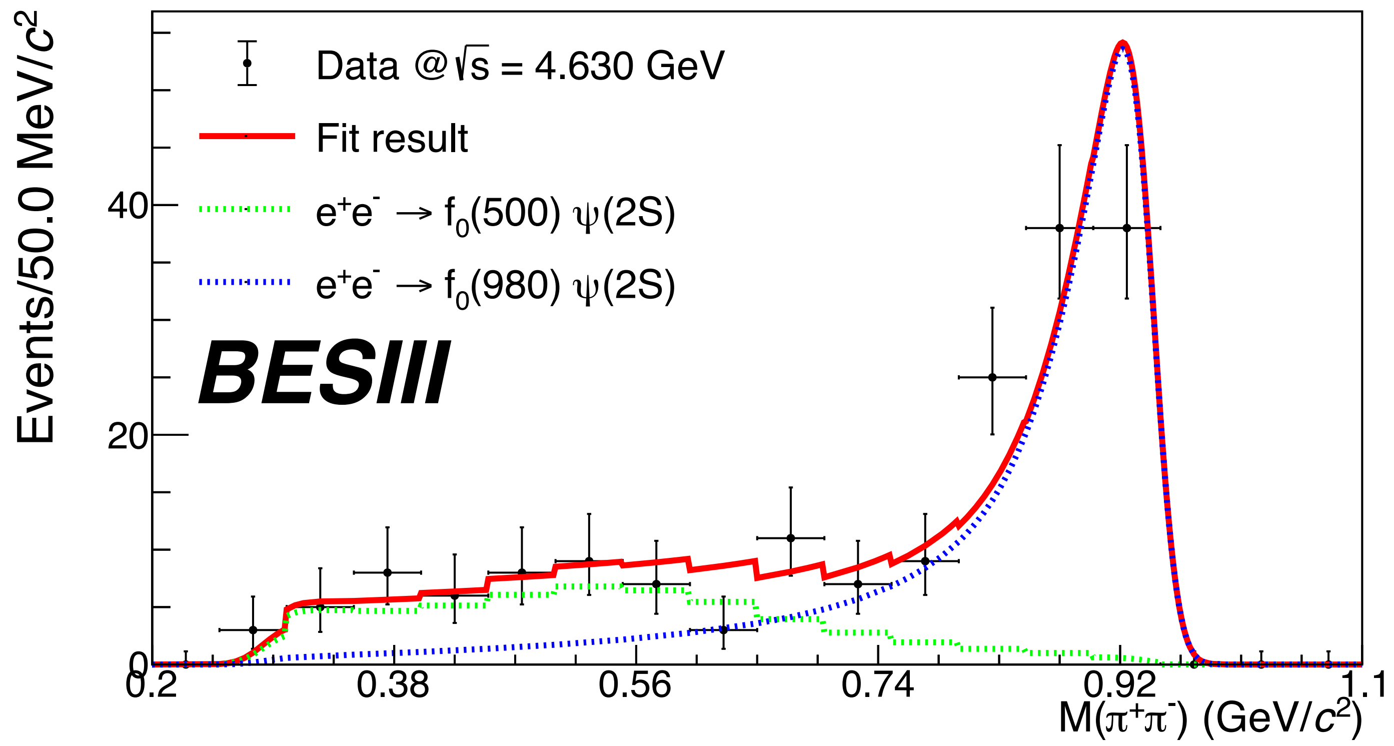
5 iterations

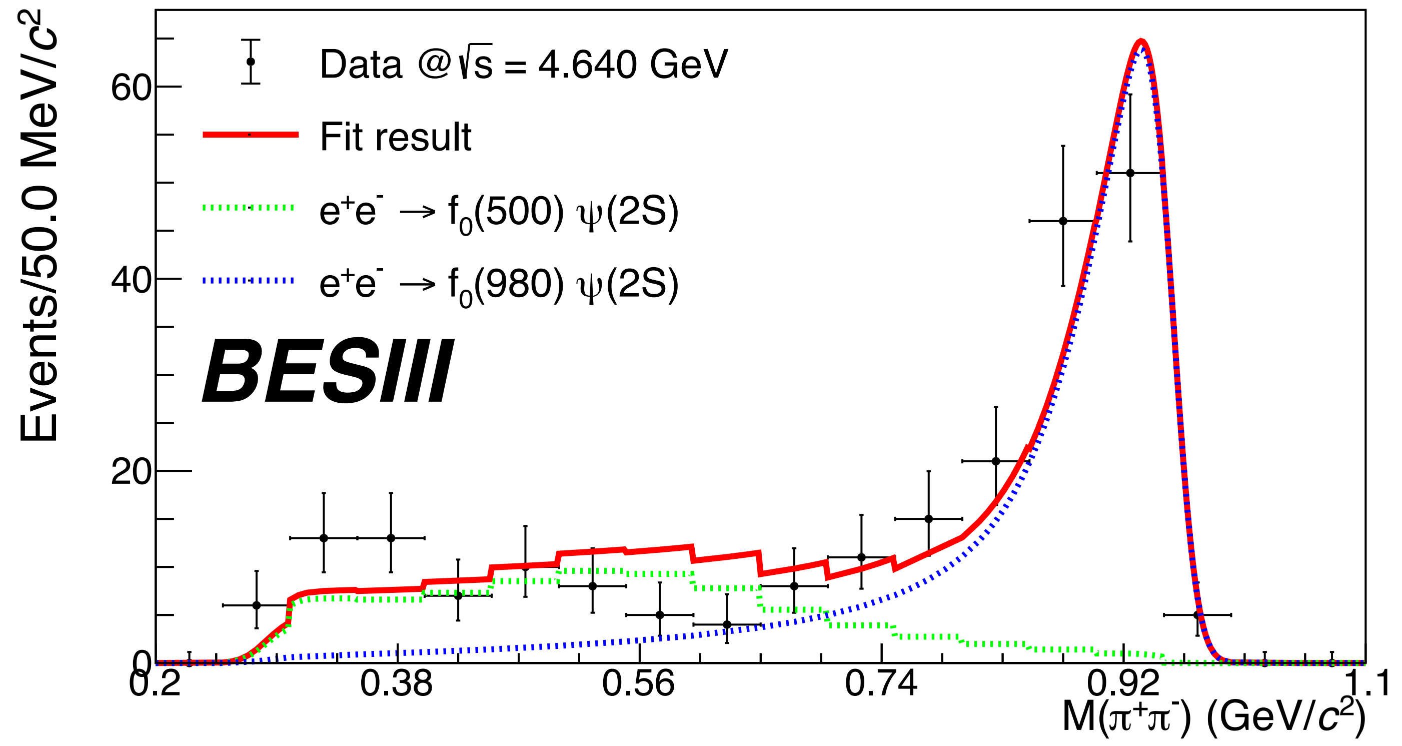
Sample	Efficiency [%]	ISR*VP Corr. Factor.	*d*(ISR*VP) Corr. Factor.	VP Corr. Factor
4,612	49,57	0,7281	0,0001	1,05453
4,626	48,99	0,7234	0,0002	1,05444
4,640	48,30	0,7984	0,0003	1,05442
4,660	45,76	0,8676	0,0004	1,05441
4,680	44,86	0,8531	0,0004	1,05448
4,700	44,83	0,8404	0,0005	1,05453

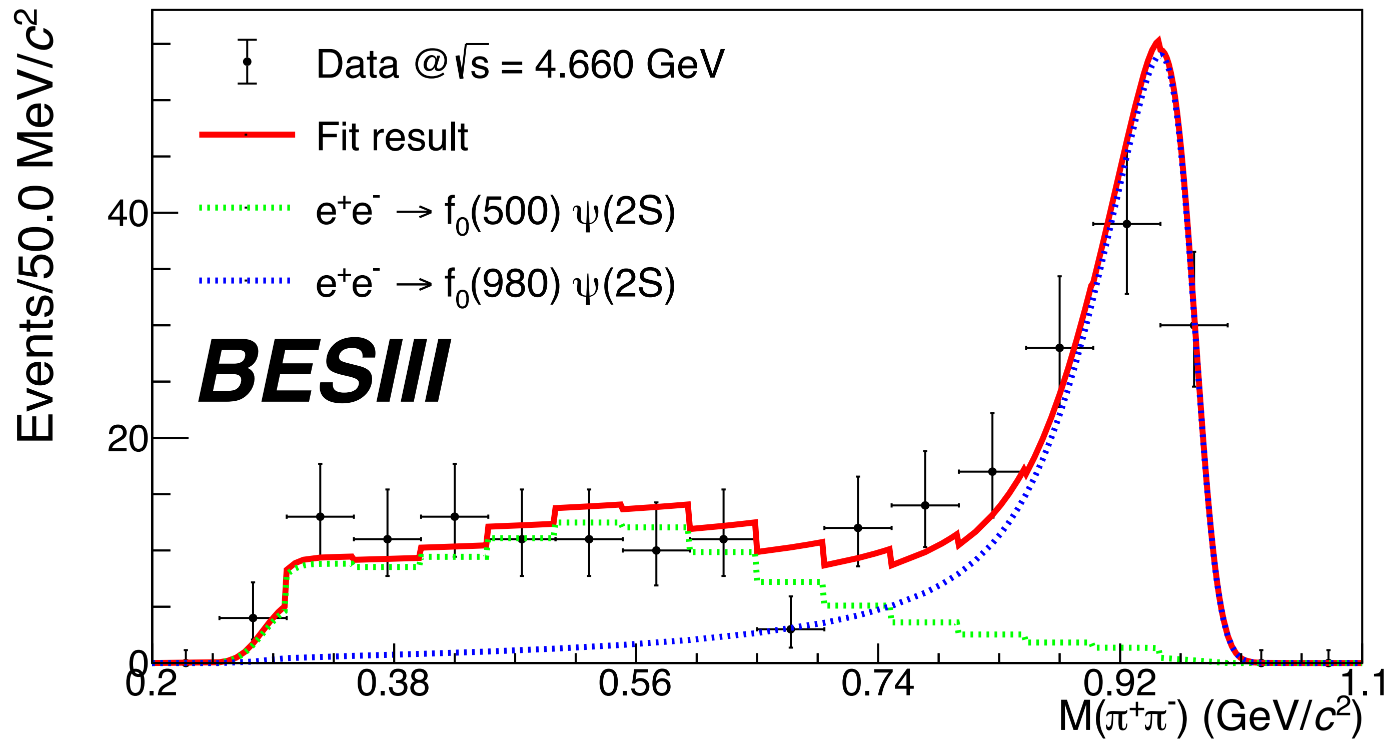
Extraction of the $\sigma(f_0(980)\,\psi(2S))$

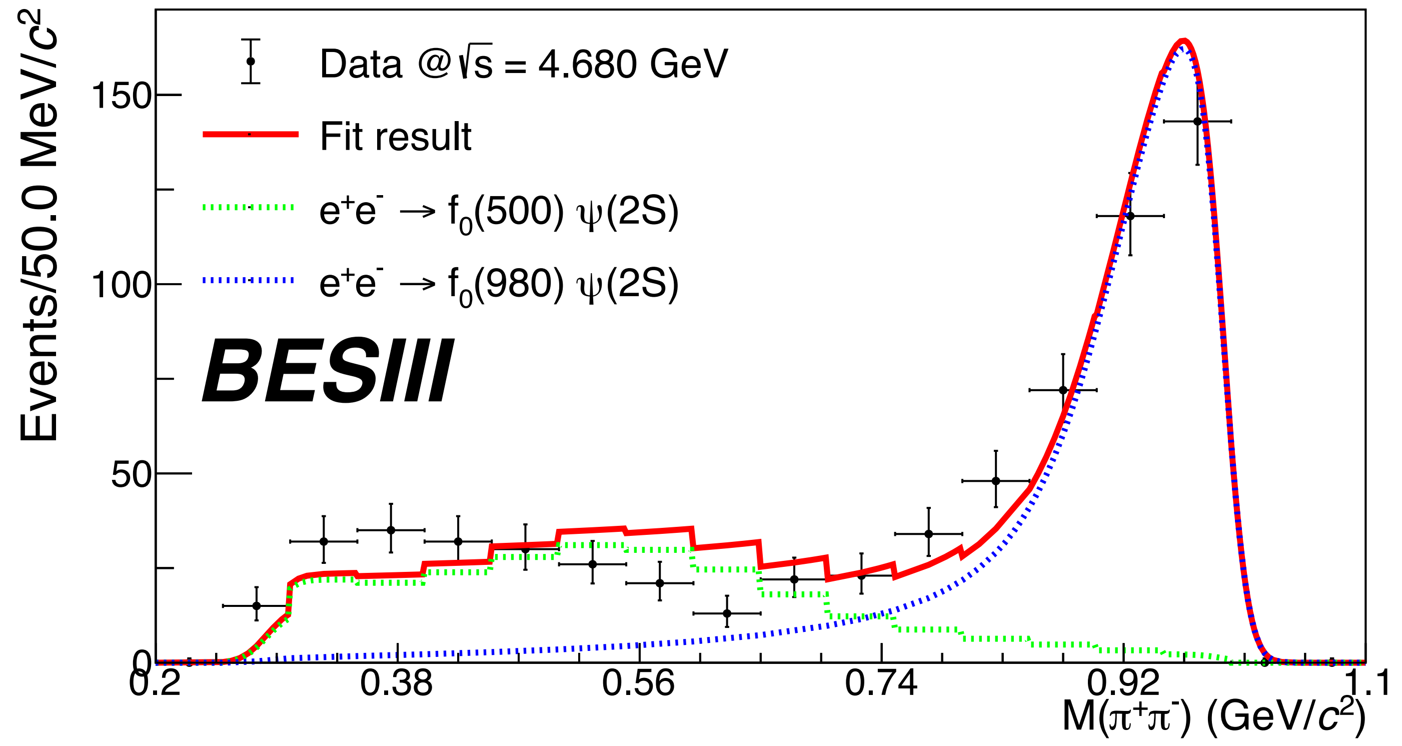


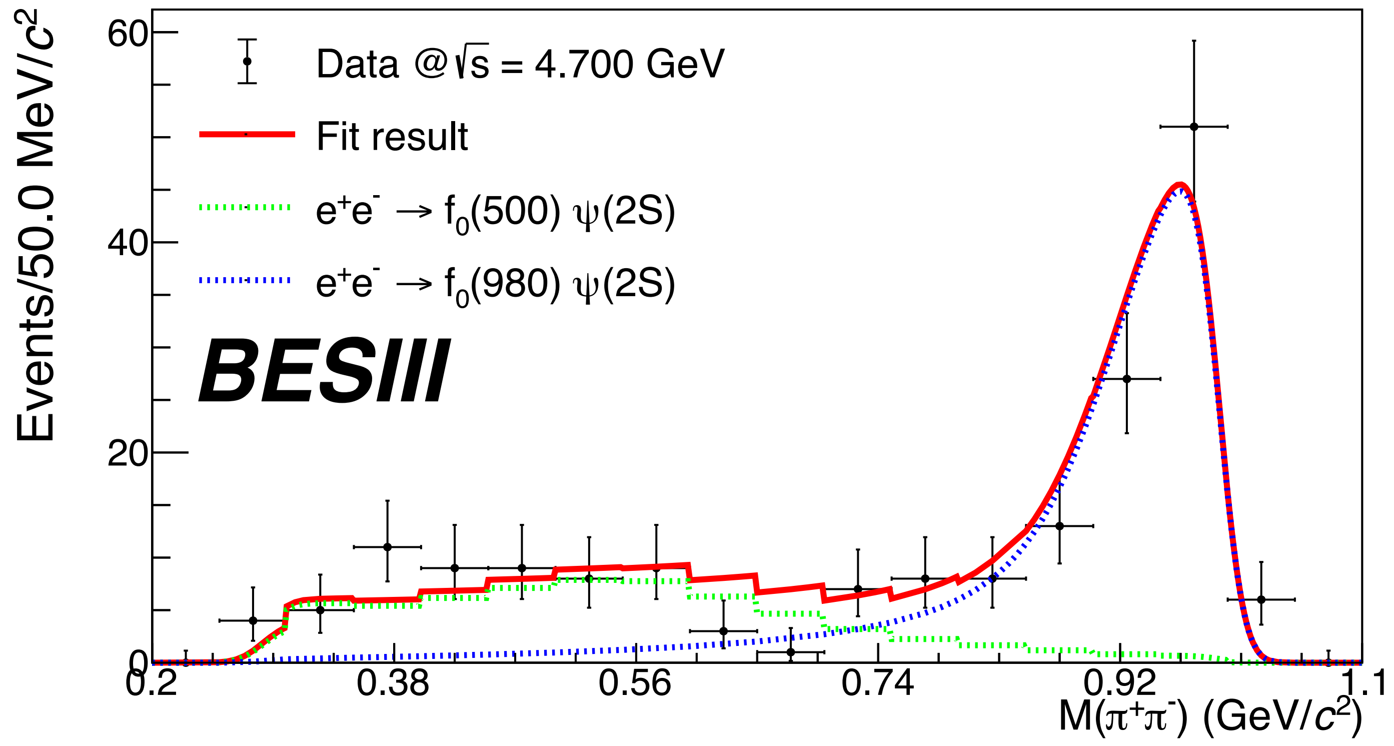
$f_0(980)$ contribution











Extraction of the σ(f_0(980) ψ(2S))

f_0(980) contribution

E_{CoM} (MeV)	$N_{\text{Obs}}^{f_0(980)}$	$\epsilon^{f_0(980)}$ (%)	$(1+\delta)$	$\frac{1}{\lvert 1-\Pi \rvert^2}$	$\sigma \times \mathcal{B}$
4611.86	14 ± 5	49.57 ± 0.13	0.690	1.05453	9.46 ± 3.38
4628.00	125 ± 22	48.99 ± 0.13	0.686	1.05444	17.25 ± 3.04
4640.91	149 ± 21	48.30 ± 0.13	0.757	1.05442	17.83 ± 2.52
4661.24	131 ± 15	45.76 ± 0.12	0.823	1.05441	15.74 ± 1.81
4681.92	424 ± 32	44.86 ± 0.12	0.809	1.05448	16.91 ± 1.29
4698.82	115 ± 16	44.83 ± 0.12	0.797	1.05453	14.49 ± 2.02

Analysis of the $\pi^{\pm}\psi(2S)$ Invariant Mass

Efficiency and Cut-flow

Z_c Signal MC sample
300k events

√s = 4.680 GeV	Events	Efficiency [%]
NTot	300000	100
NCutCh	248899	82,97
NCutGoodCh	215894	71,96
NCut_5trks	62850	20,95
NCut_6trks	100828	33,61
NCut_Alltrks	163678	54,56

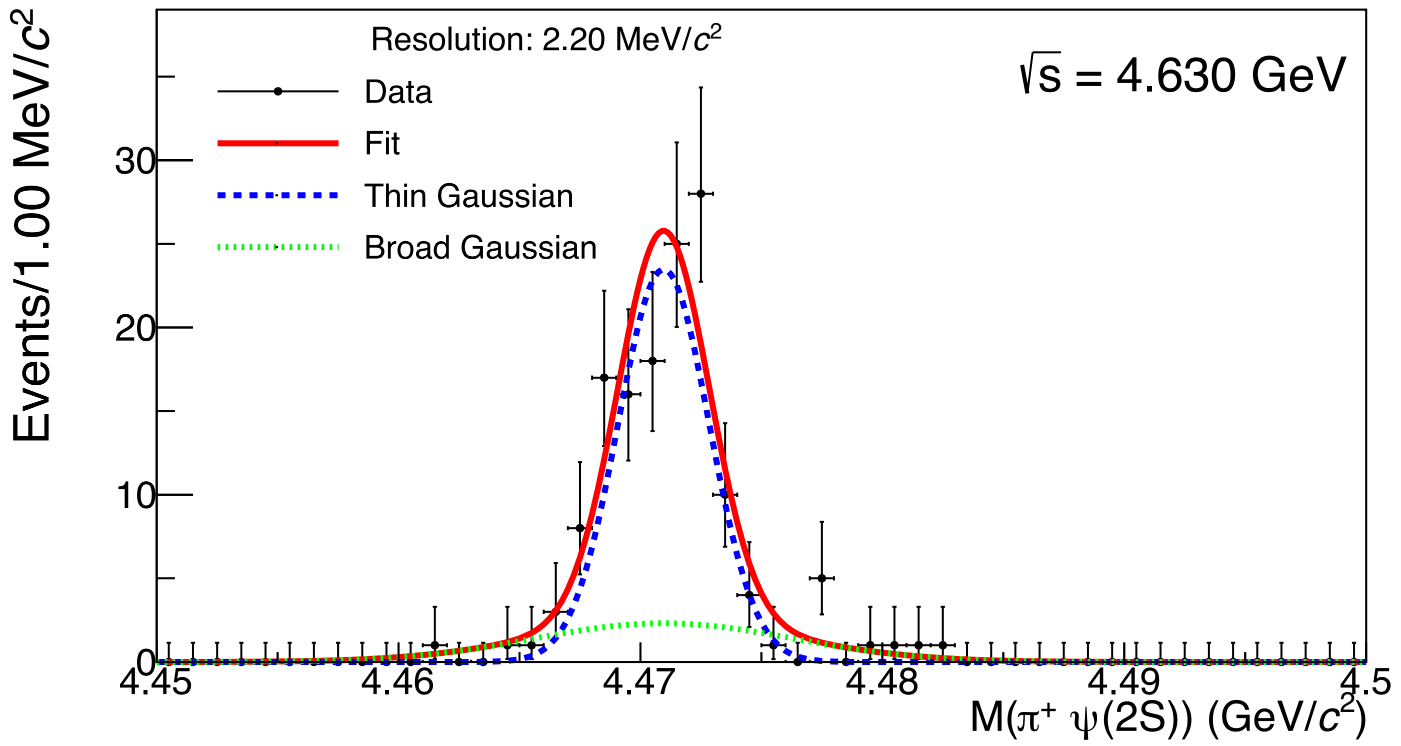
Explicative sample (@$\sqrt{s}$ = 4.680 GeV)

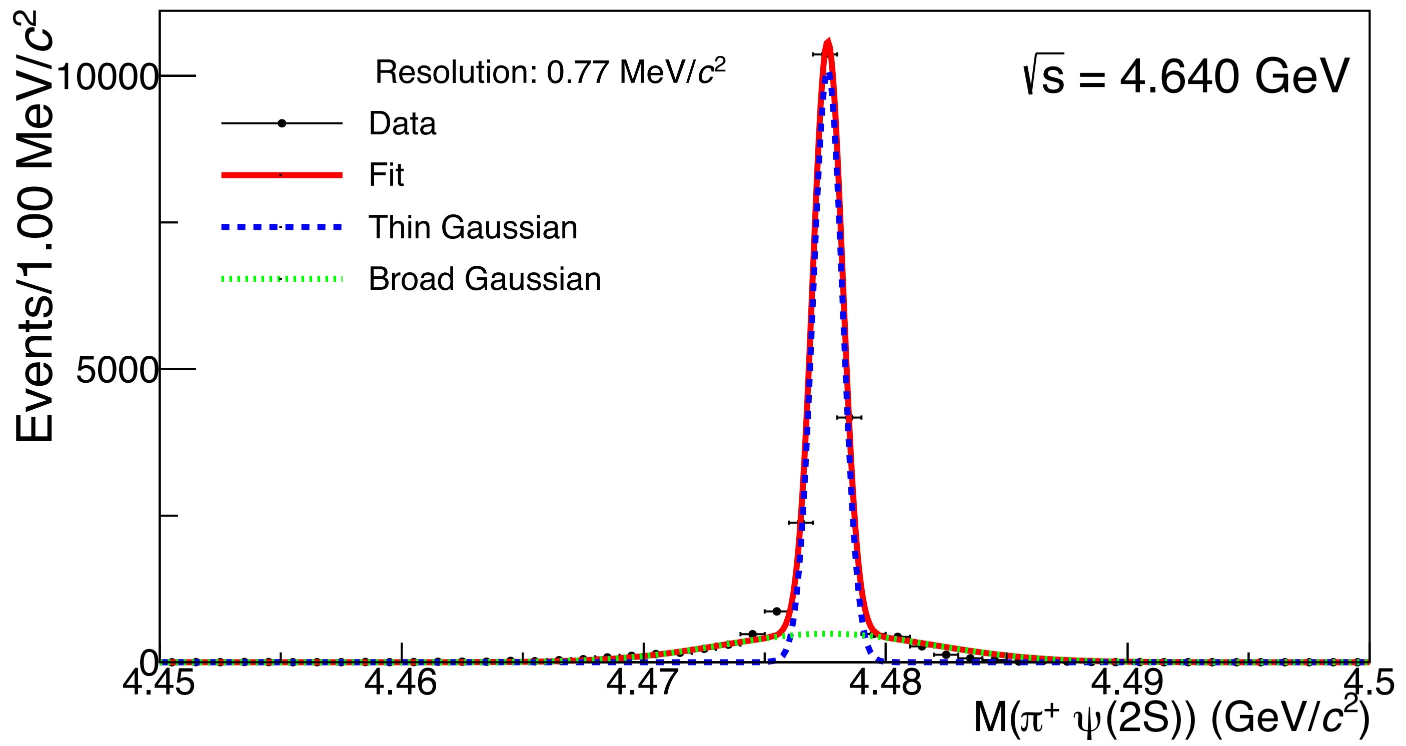
But overall efficiency ~ 50% ∀ $\sqrt{s}$

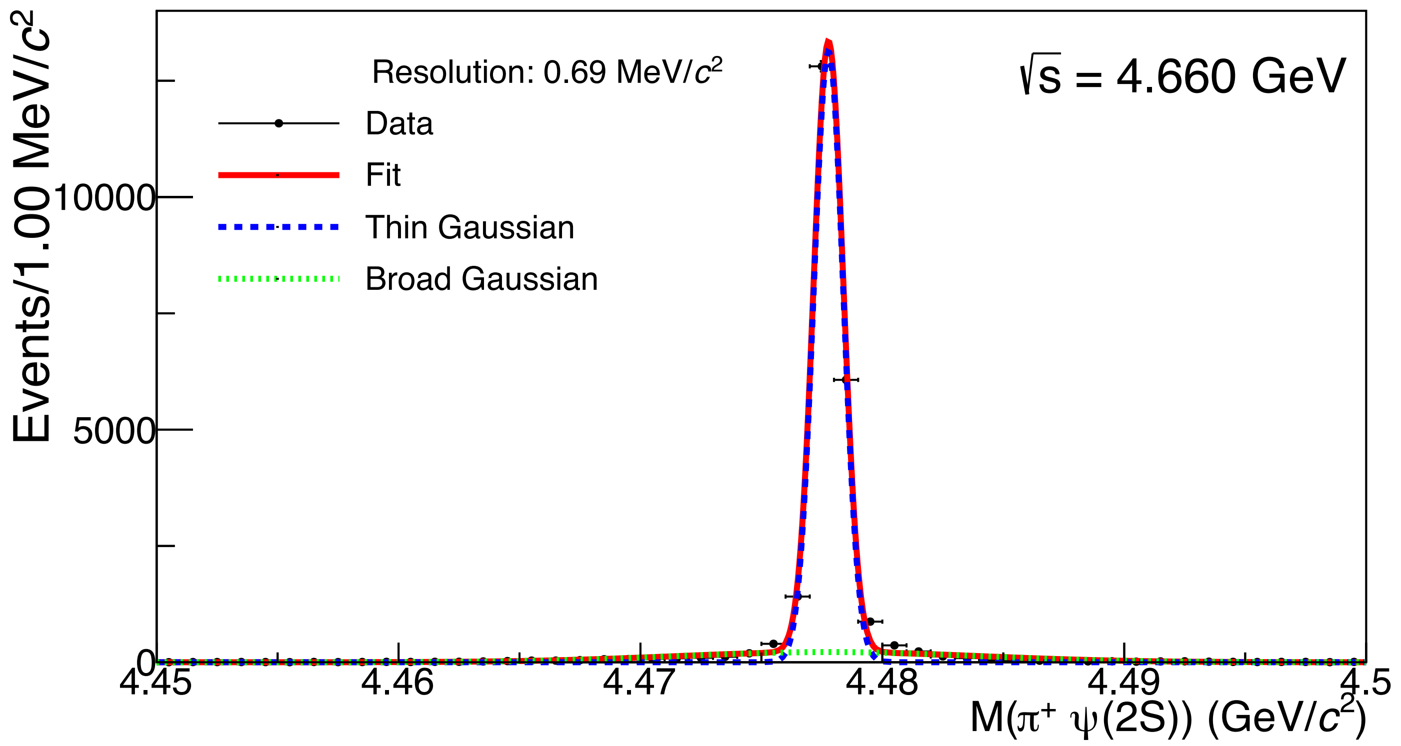
No assumption is made on the production cross-section

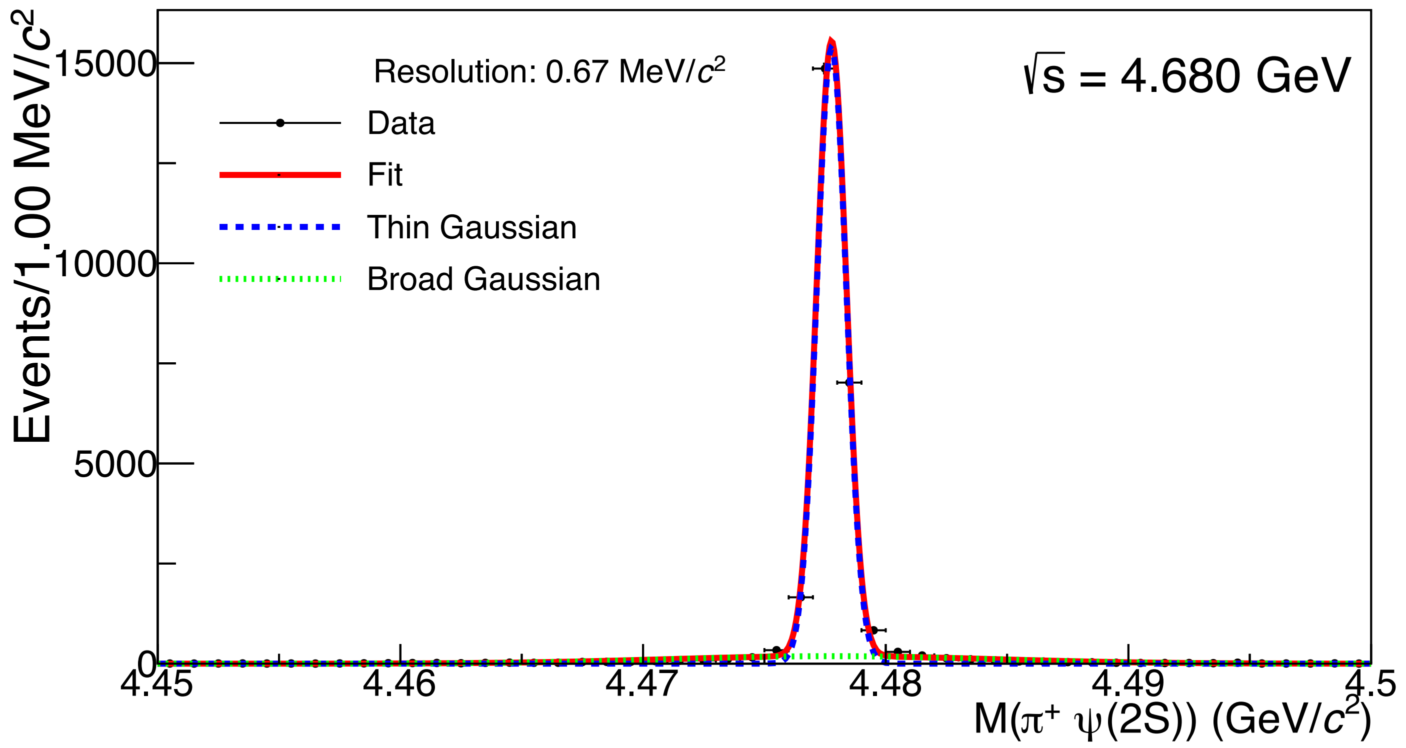
Resolution Studies

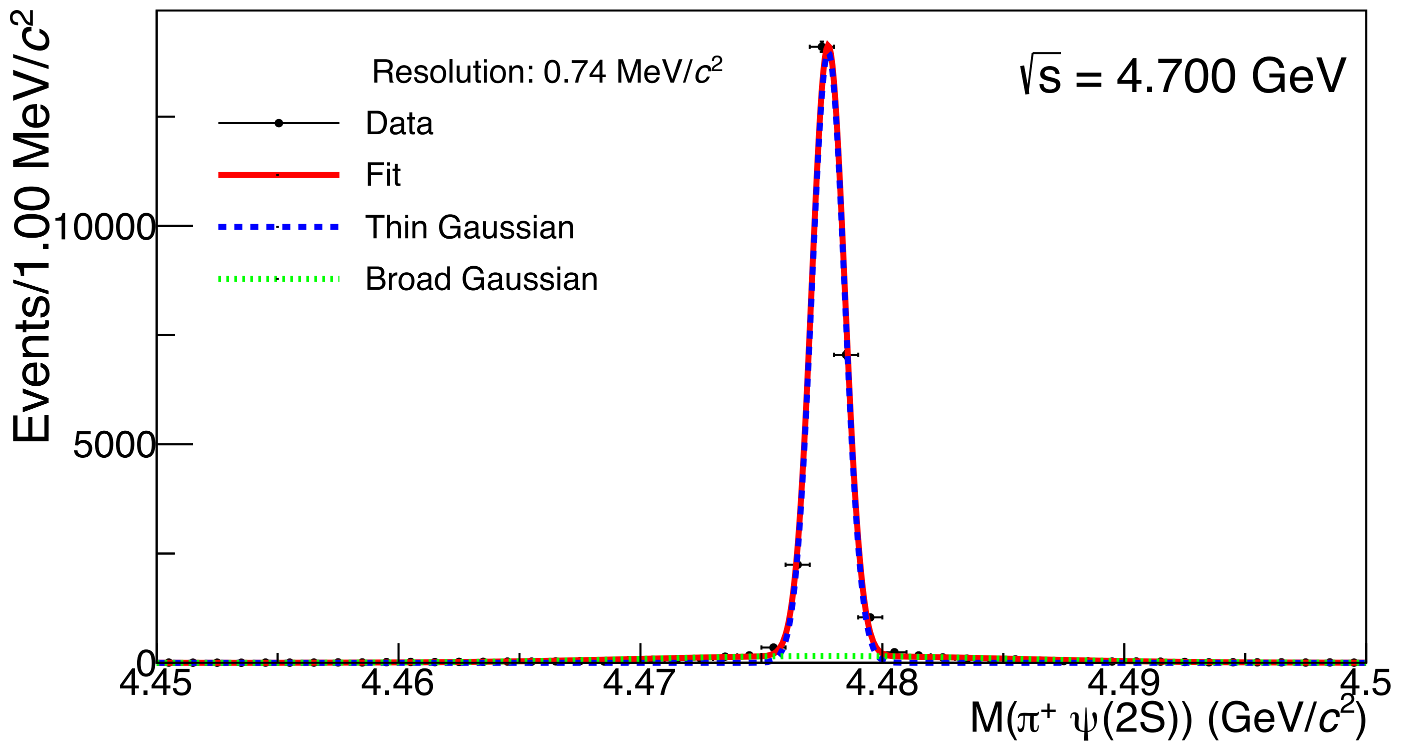
$\pi^\pm\psi(2S)$ Invariant Mass





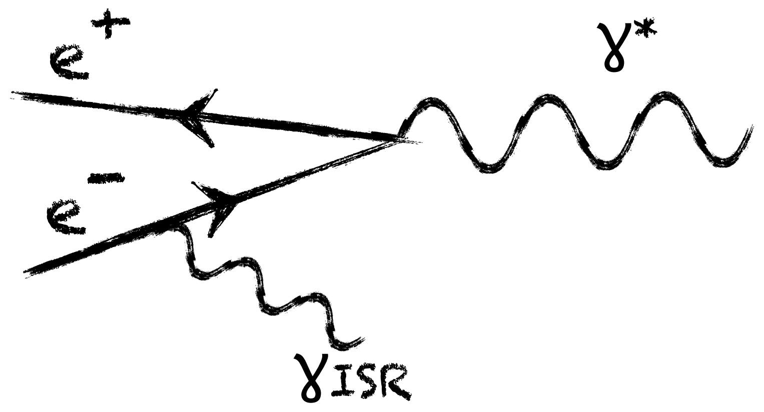






CONEXC Generator

Initial State Radiation (ISR): the emission of a photon by a leptonic beam in e^+e^- colliders



ISR reduces beam energy, hence CONEXC is a SW specifically that calculates ISR corrections up to the second order

Input
Measured σ_{Born}

$$\sigma_{e^+e^-\to\gamma X}(s) = \int dm \frac{2m}{s} W(s,x) \frac{\sigma_{exp}(m)}{[1+\Pi(m)]^2}$$

Radiator function

Probability of a transition to occur at lower centre-of-mass energy

Vacuum Polarisation Correction

Tabulated

If neglected…

$$\epsilon_{effective} = \frac{N_{Rec}}{N_{Gen}} = \frac{\int dx\ \epsilon(x)\ \sigma_{e^+e^-\to\gamma X}(s)\ W(s,x)}{\int dx\ \sigma_{e^+e^-\to\gamma X}(s)\ W(s,x)}$$

Efficiency at @$\sqrt{s_{ISR}}$

$$1+\delta = \int dx \frac{\sigma_{e^+e^-\to\gamma X}(s)}{\sigma_{exp}} W(s,x)$$

ISR Correction