Measurement of the Dipion Mass Spectrum in the Decay $X(3872) \to J/\psi\, \pi^+\pi^-$ at the CDF II Experiment

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Thesis Defense

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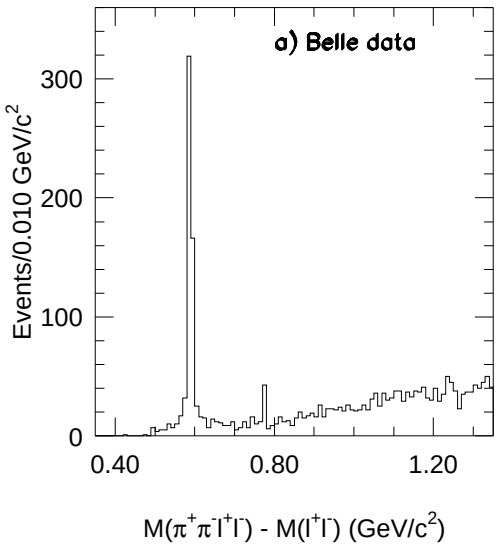
http://www-cdf.fnal.gov/~rakitin/defense.pdf

Introduction

New narrow resonance $X(3872)$, discovered by Belle, in $B^+ \to X(3872)K^+$ $\to J/\psi\,\pi^+\pi^-K^+$ decay in August 2003 [hep-ex/0308029]:



Discovery confirmed by CDF, D0 and BaBar (in order of appearance)

The nature of $X(3872)$ is puzzling:

- new charmonium state $c\bar{c}$?
- so-called *hybrid* meson $c\bar{c}g$?
- deuteron-like "molecule" D^0-$\bar{D}^{*0}$?

Are we opening new chapter in heavy flavor spectroscopy?

Belle speculated: $X(3872) \to J/\psi\,\pi^+\pi^-$ via $J/\psi\,\rho^0$?

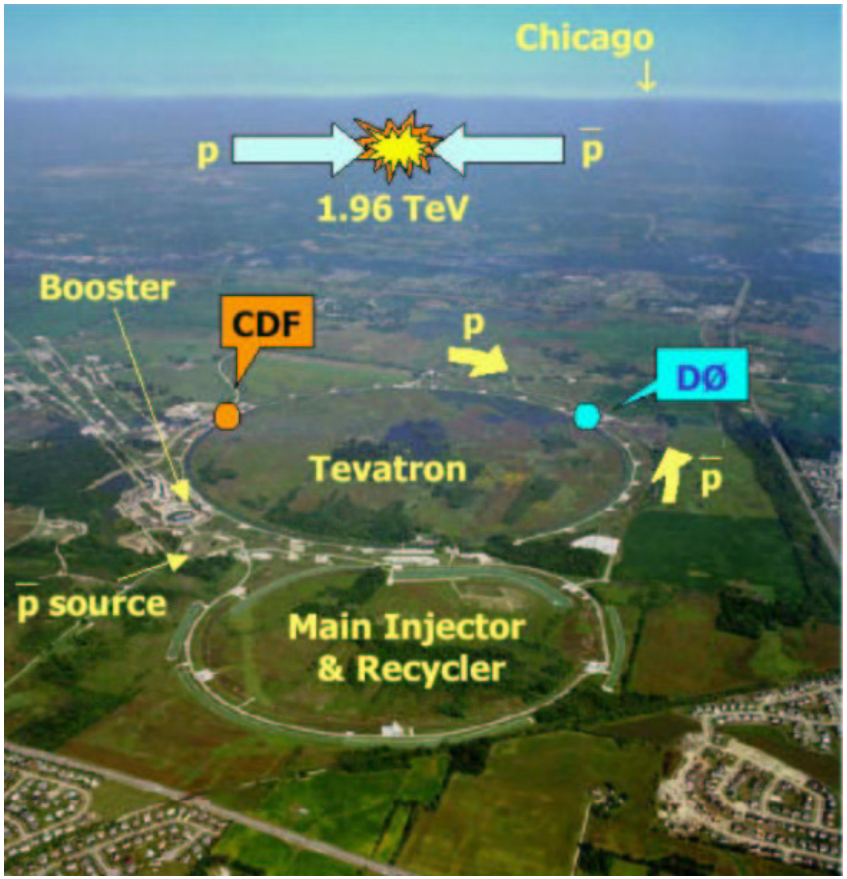
- isospin-violating for charmonium
- if ρ^0 found $\Rightarrow X(3872)$ is molecule?

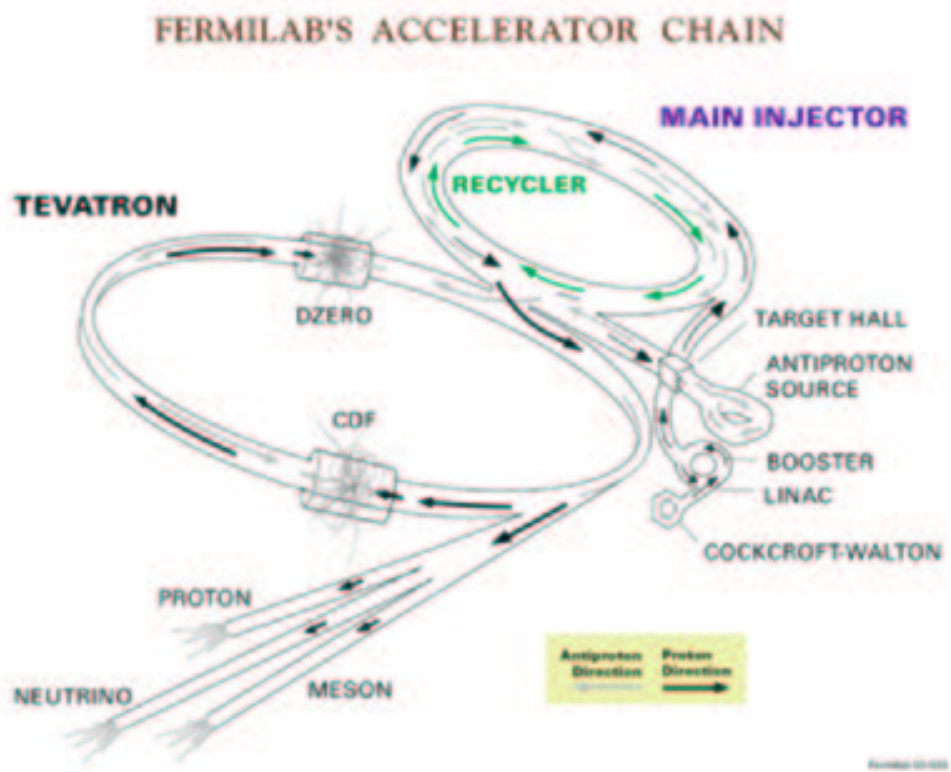
Shape of dipion mass spectrum may help to know this.

Purpose of our analysis:

- obtaining the dipion mass spectrum
- comparing to theoretical predictions
- understanding $X(3872)$ properties/identity

Tevatron Collider at Fermilab: short overview





- 36×36 $p\bar{p}$ bunches, 10^{12} (10^{10}) p ($\bar{p}$) per bunch
- bunches collide every 396 ns at CM energy 1.96 TeV
- record $\mathcal{L}_{inst} = 10.7 \times 10^{31}$ cm^{-2} sec^{-1}
- total integrated $\mathcal{L} = 1$ fb^{-1} ($\sim$800 pb^{-1} on tape, $\sim$360 pb^{-1} used)
- high energy physics frontier until LHC turn-on

CDF Experiment: short overview

CDF is a multi-purpose detector

Silicon Vertex Detector

- up to 8 layers of silicon
  - layers in r-ϕ & r-z planes

Central Outer Tracker (COT)

- 96 layer drift wire chamber
  - *axial* & *stereo* layers
- coverage $|\eta| \equiv |\text{-ln}(\tan\frac{\theta}{2})| < 1$
- $\sigma(\text{hit}) \sim 150\ \mu\text{m}$
- $\frac{\sigma(p_t)}{p_t} \sim 0.15\%\ p_t$

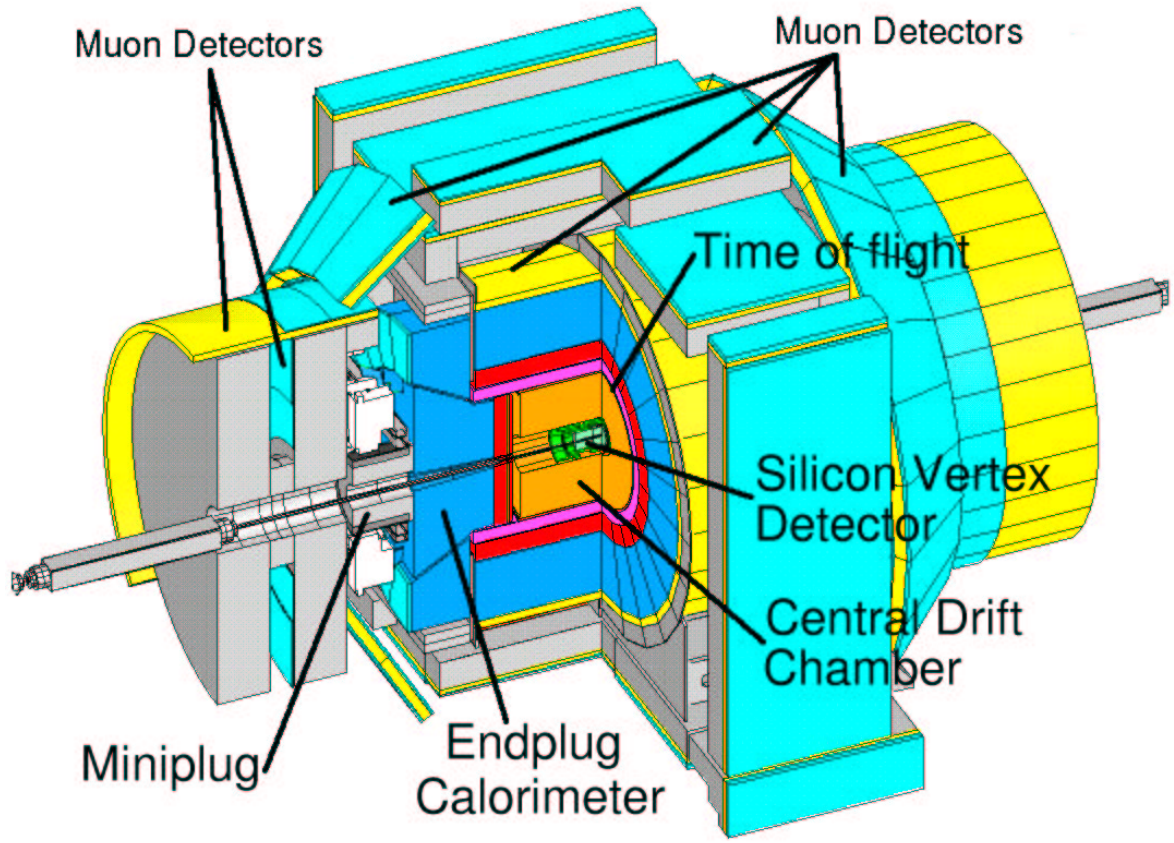
Time-of-Flight system

Calorimeters: central, wall, plug

- coverage $|\eta| < 3.6$

Muon chambers

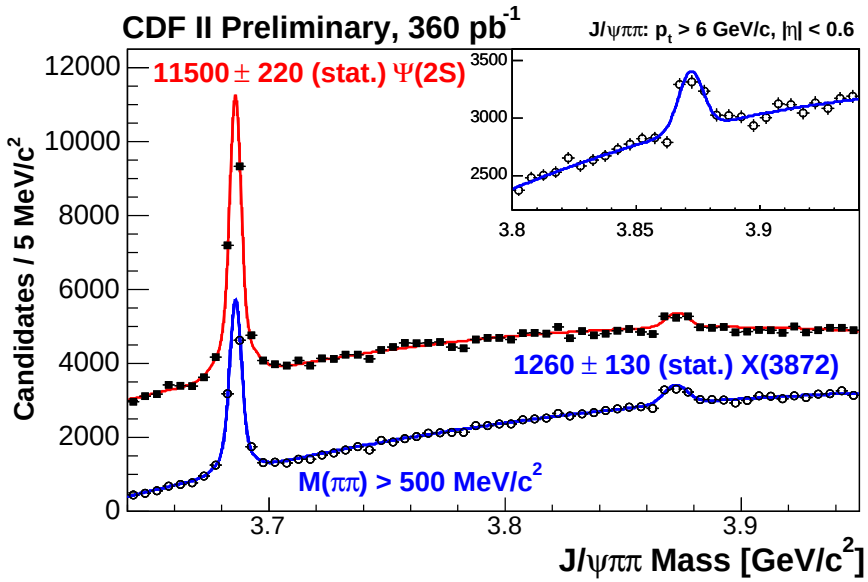
- coverage $|\eta| < 1.5$



Components important for analysis are highlighted in red

Data Selection

- Data sample obtained via J/ψ trigger
  - 2 tracks with matching muon stubs
  - mass of $\mu^+\mu^-$ around J/ψ mass
- Luminosity: 360 pb^{-1}
- All tracks:
  - 10+ axial & 10+ stereo COT hits, 3+ Si r-ϕ hits
  - $p_t > 400$ MeV/c
- Single muons:
  - $p_t > 1.5$ GeV/c
- J/ψ selection:
  - $p_t(J/\psi) > 4$ GeV/c
  - Vertex fit $\chi^2(\mu^+\mu^-) < 15$
  - $\left|\mathrm{m}(\mu^+\mu^-) - \mathrm{m}(J/\psi)\right| < 60$ MeV/c^2
- Cone around $J/\psi\,\pi^+\pi^-$ momentum with both pions, $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.7$
- Vertex fit $\chi^2(J/\psi\,\pi^+\pi^-) < 25$



Upper graph: reconstructed $J/\psi\,\pi^+\pi^-$

Lower graph and inset: additional cut $m_{\pi\pi} > 500$ MeV/c^2 improves signal-to-noise ratio for $X(3872)$ peak

Fiducial cuts for detector efficiency corrections: $p_t(J/\psi\,\pi^+\pi^-) > 6$ GeV/c, $|\eta(J/\psi\,\pi^+\pi^-)| < 0.6$

Analysis Strategy:

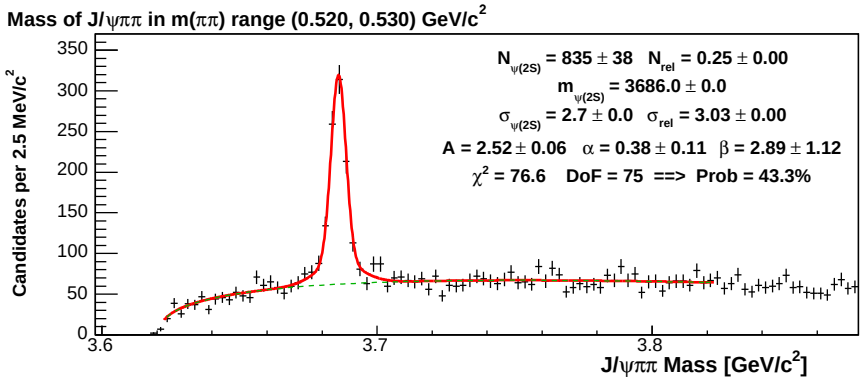
Analysis performed for $\psi(2S)$ first and then for $X(3872)$

- divide J/ψ sample into $m_{\pi\pi}$ slices
- fit $J/\psi\,\pi^+\pi^-$ mass in $m_{\pi\pi}$ slices $\Rightarrow$ get yield in each slice $\Rightarrow$ obtain $m_{\pi\pi}$ spectrum
- correct $m_{\pi\pi}$ spectrum for detector efficiency (from Monte Carlo), to be able to compare to other experiments
- compare corrected $m_{\pi\pi}$ spectrum to various theoretical predictions
  - **Does $X(3872) \to J/\psi\,\pi^+\pi^-$ decay go via $J/\psi\,\rho^0$?**
  - **What is the $X(3872)$?**

$J/\psi\,\pi^+\pi^-$ mass fit in $m_{\pi\pi}$ slice

$\psi(2S)$

520 MeV/c^2 < $m_{\pi\pi}$ < 530 MeV/c^2



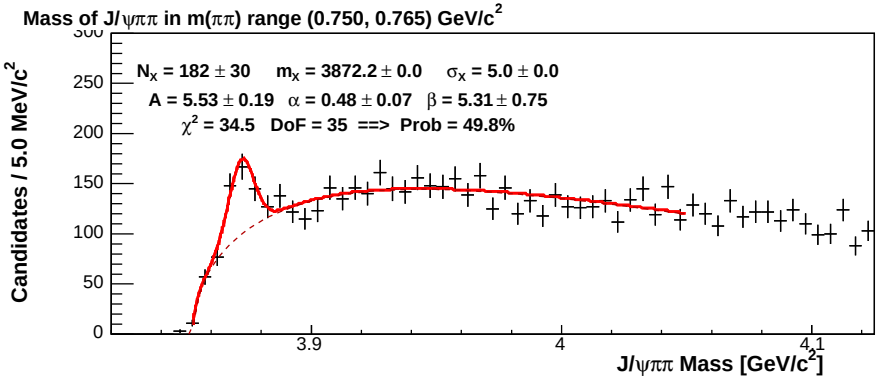
Signal: di-Gaussian with common mean

Mean, N_{rel}, σ and σ_{rel} fixed

by fit of full sample

$X(3872)$

750 MeV/c^2 < $m_{\pi\pi}$ < 765 MeV/c^2



Signal: single Gaussian

Mean and width fixed by

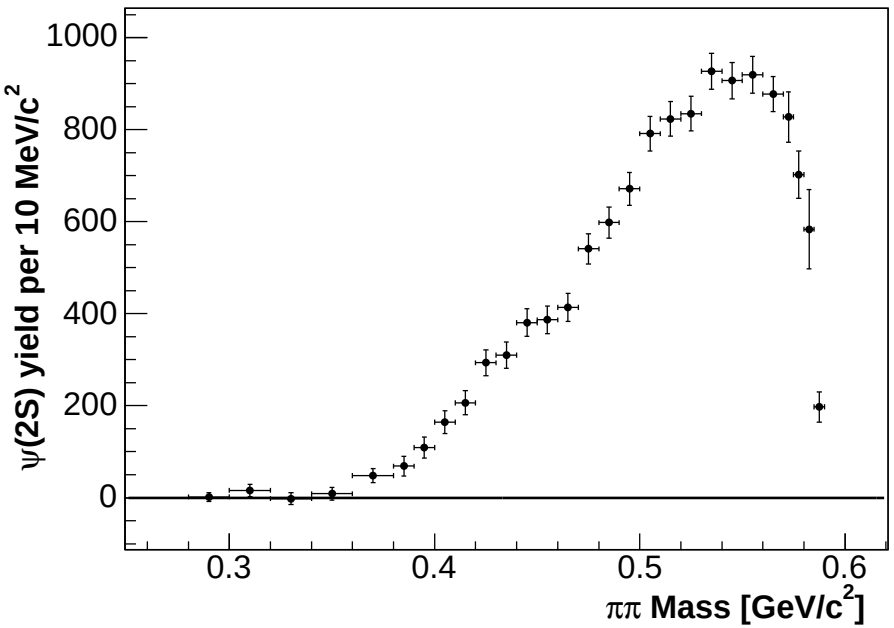
fit of sample after $m_{\pi\pi}$ > 500 MeV/c^2 cut

Background: $A(x - x_0)^\alpha \exp(-\beta x)$

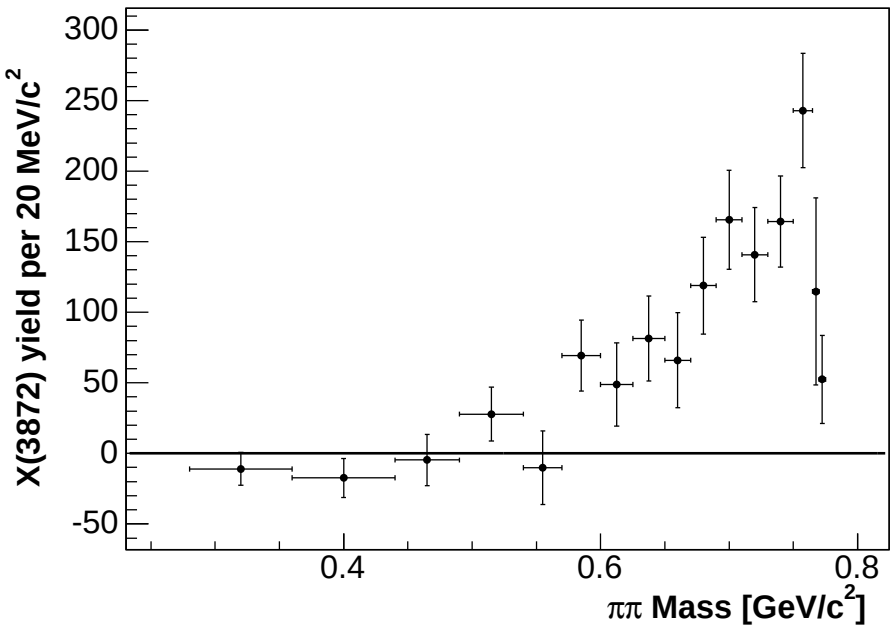
- $m_{\pi\pi} \longrightarrow x$
- fit parameters $\longrightarrow A,\ x_0,\ \alpha,\ \beta$

Dipion mass spectra

$\psi(2S)$



$X(3872)$



	$\psi(2S)$	$X(3872)$
Sum of yields in each bin	11523 ± 166	1079 ± 149
Yield from full-sample mass fit	11503 ± 221	929 ± 154

Detector corrections

CDF detector does not find all X's $\Rightarrow$ need *acceptance* and *efficiency corrections*.

1. Generate MC matching data in p_t, η and $m_{\pi\pi}$ in fiducial region

- nature of $X(3872)$ = nature of $\psi(2S)$? Cannot use $p_t(\psi(2S))$ for X

  $\Rightarrow$ Need $p_t(X)$ from data
- use S-wave $m_{\pi\pi}$ parametrization for $\psi(2S)$ PRL 68, 282 (1992)
- do not know *exact* $m_{\pi\pi}$ spectrum for $X(3872)$

  $\Rightarrow$ bootstrap ourselves by assuming S-wave for $X(3872)$
  - good approximation, no need to iterate further
  - assign systematic uncertainty for it

2. Calculate ratio of $m_{\pi\pi}$ spectra before and after detector
3. Use this ratio to correct data

Step 1: Generation of MC matching data

Make sure MC p_t and η match data by iterations:

- input – flat p_t-η distribution
- **fiducial cuts:** $p_t > 6$ GeV/c, $|\eta| < 0.6$
- events go through MC simulation of detector, trigger and reconstruction
- output p_t-η distribution – detector *efficiency curve*
- multiply input p_t by ratio data/output $\Rightarrow$ corrected p_t
- presume corrected η to be flat in fiducial region
- use corrected p_t-η distribution as input for next MC iteration
- stop when iterations converge
- they converge after first one $\Rightarrow$ corrected p_t = true p_t

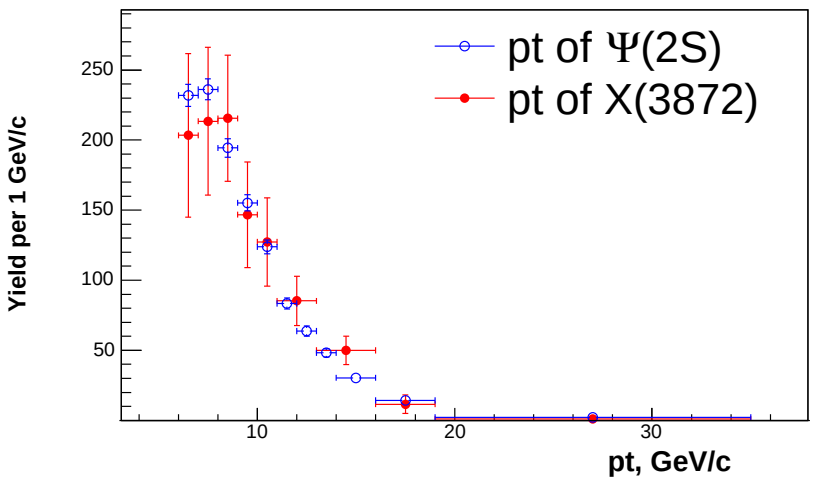
Getting p_t for $\psi(2S)$ and $X(3872)$ from data

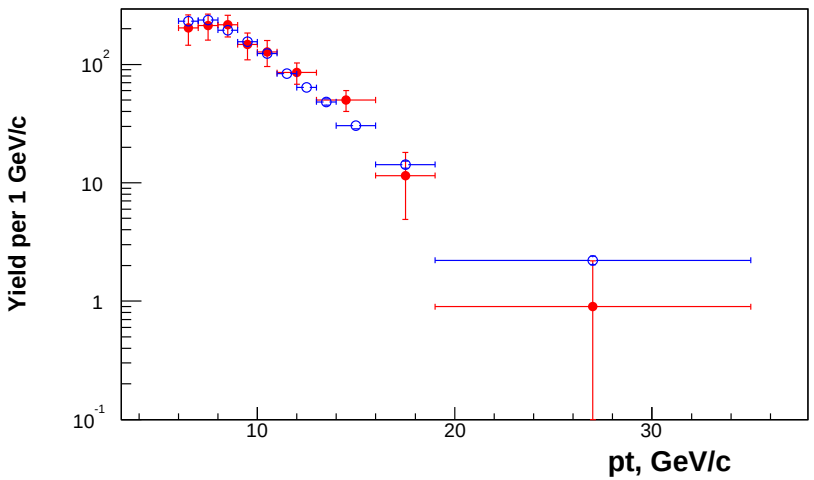
Same slicing technique:

- Divide sample into p_t slices
- Fit $\psi(2S)$ or $X(3872)$ mass in each slice
- Plot $\psi(2S)$ and $X(3872)$ yields versus p_t

$\Rightarrow$ same p_t spectra for $X(3872)$ and $\psi(2S)$ within uncertainties.

If $X(3872)$ is a fragile molecule, one might not expect them to be the same

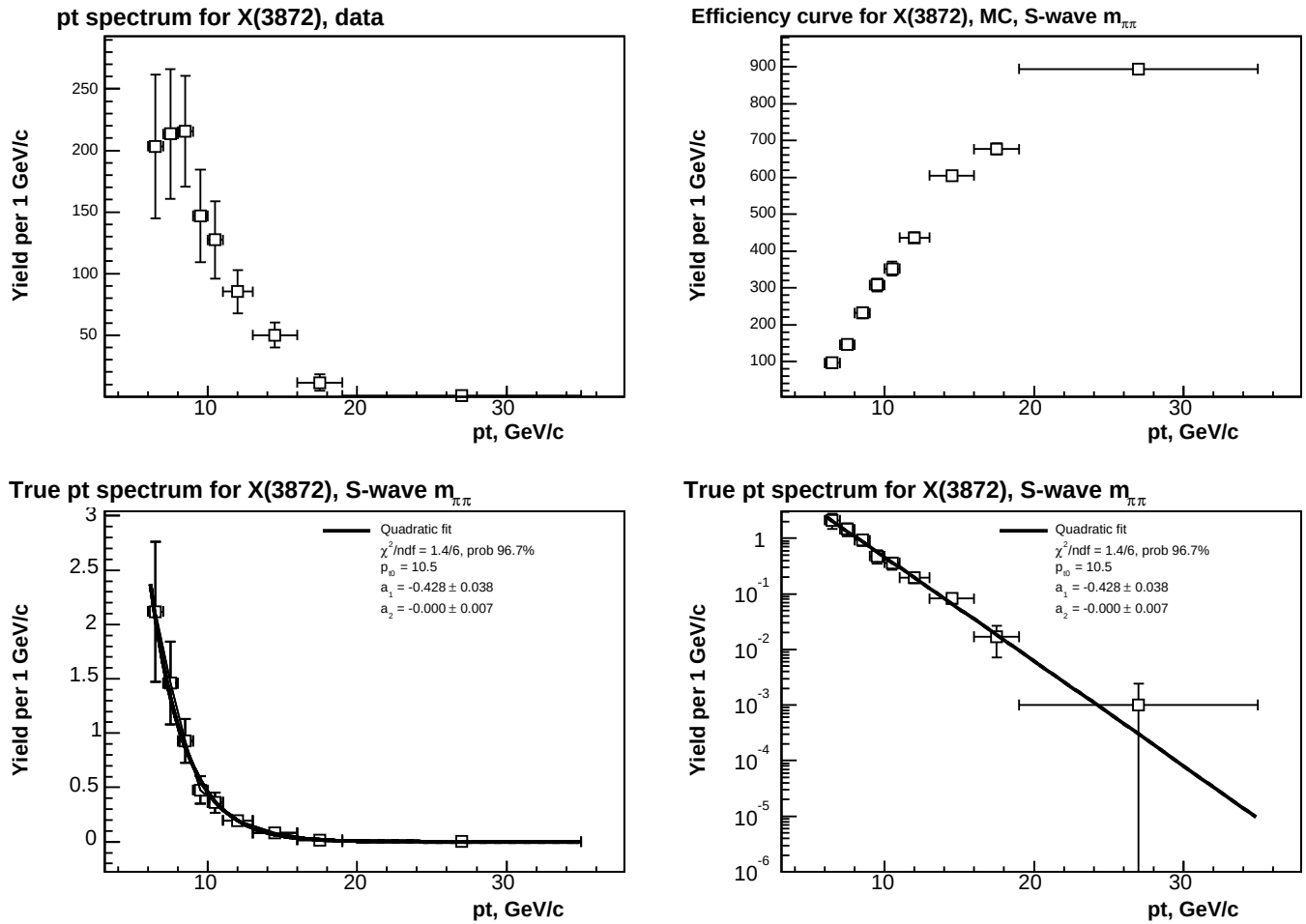




Getting corrected p_t of $X(3872)$

Upper left: $X(3872)$ p_t from data

Upper right: Detector efficiency curve (MC output from flat p_t-η input)

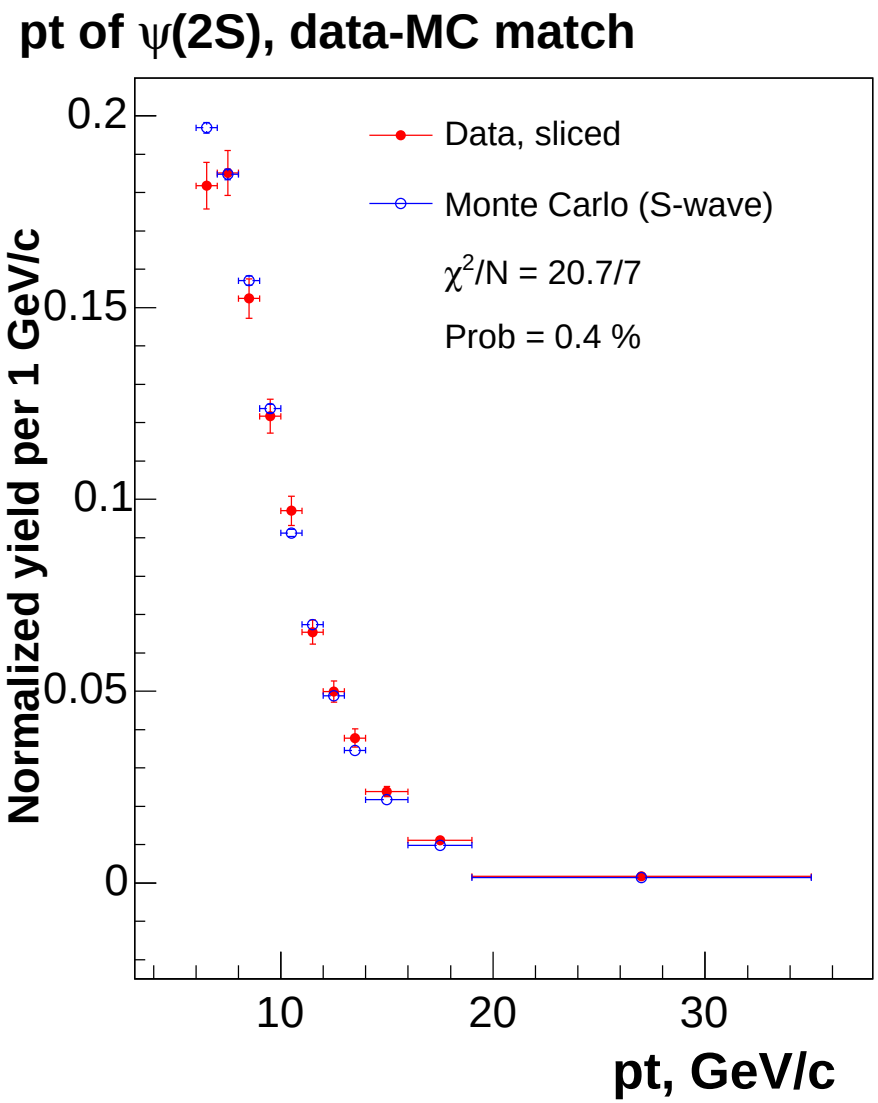


Lower plots: $X(3872)$ p_t from data divided by eff. curve $\Rightarrow$ fit with $\exp(a_0 + a_1 p_t + a_2 p_t^2)$

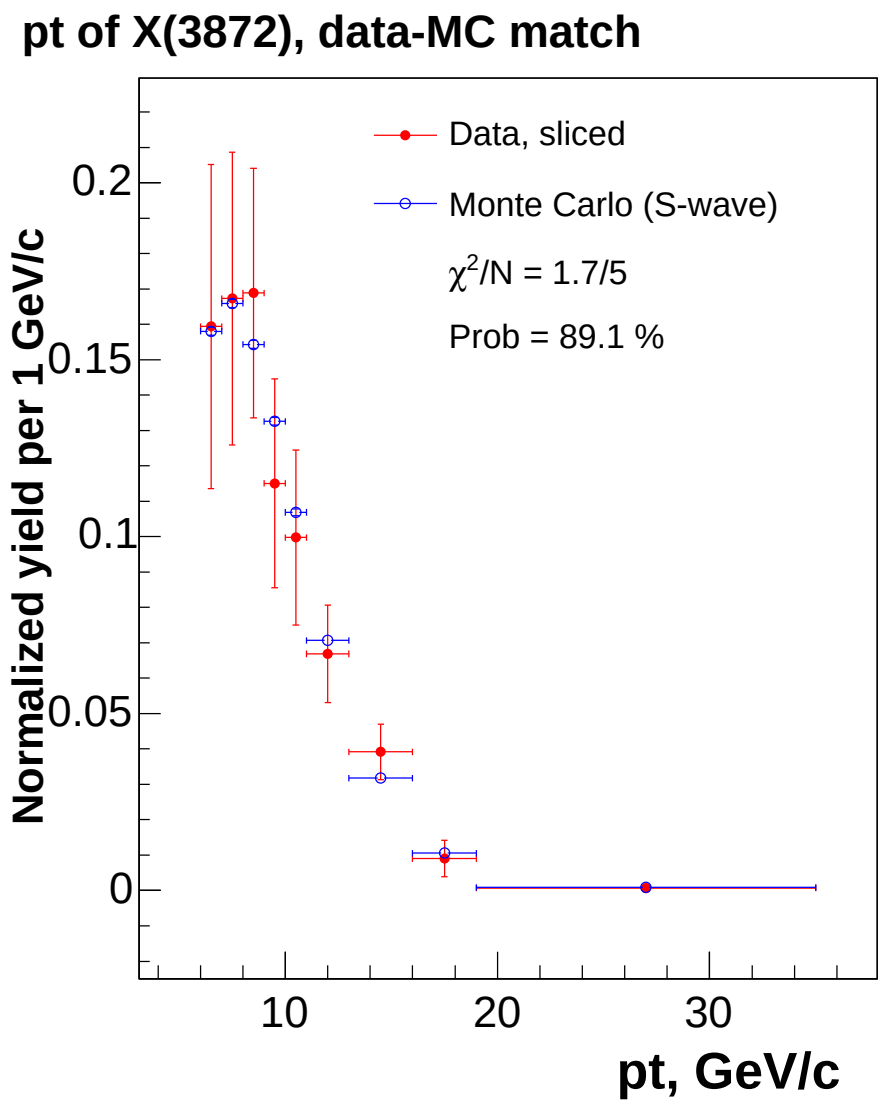
$$a_1 = 0.428 \pm 0.038, \quad a_2 = 0.000 \pm 0.007$$

Data-MC match for p_t

$\psi(2S)$

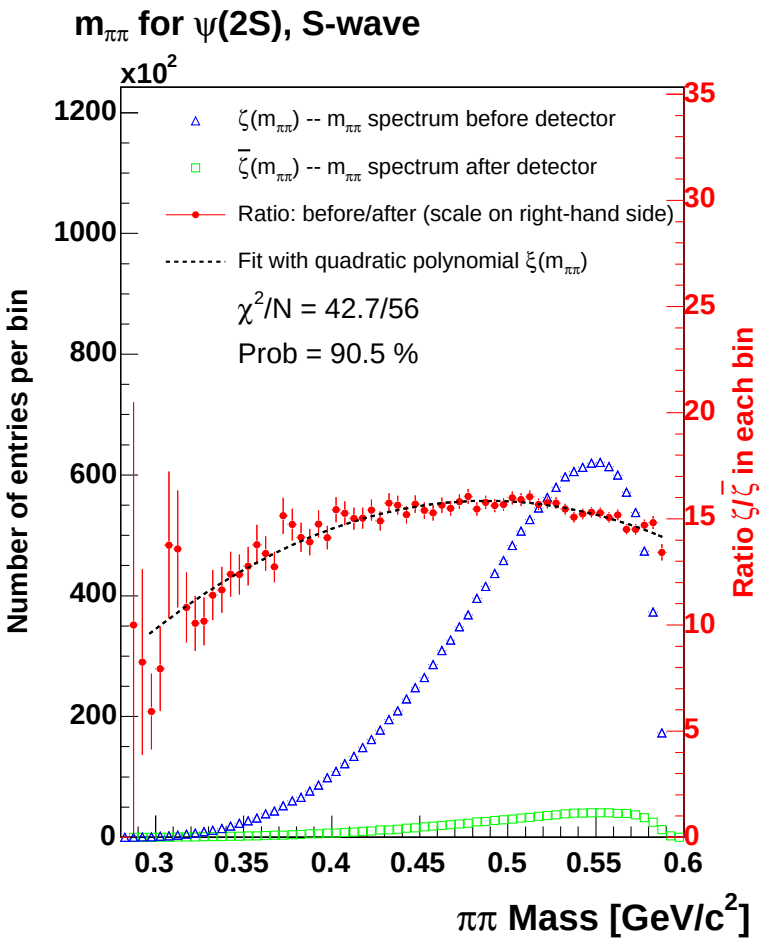


$X(3872)$

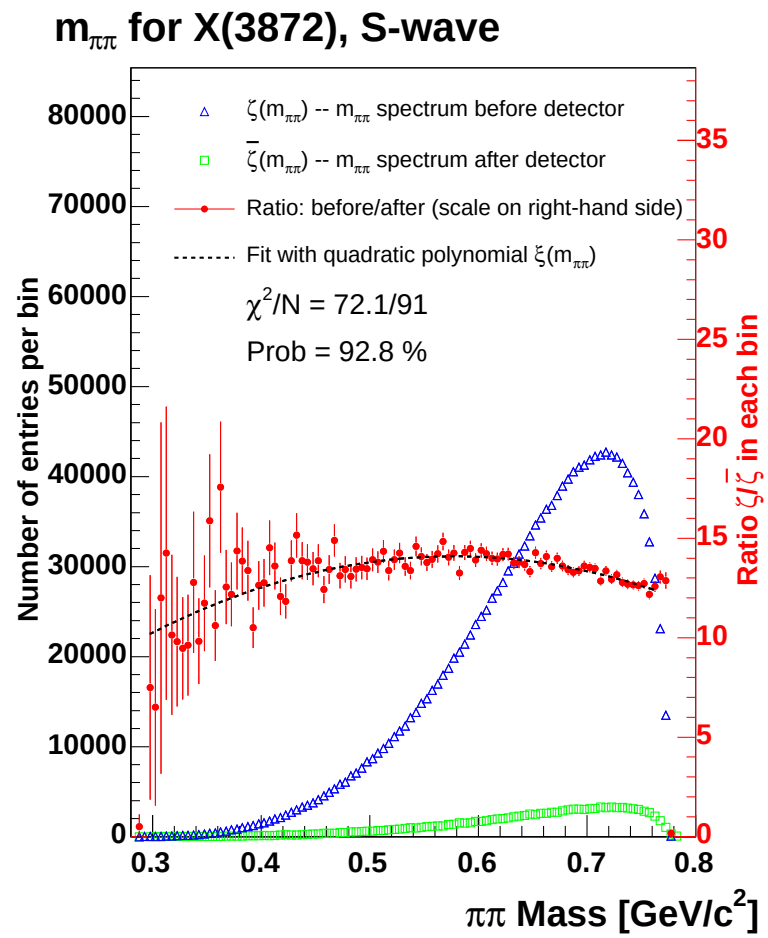


Step 2: Obtain detector corrections

$\psi(2S)$



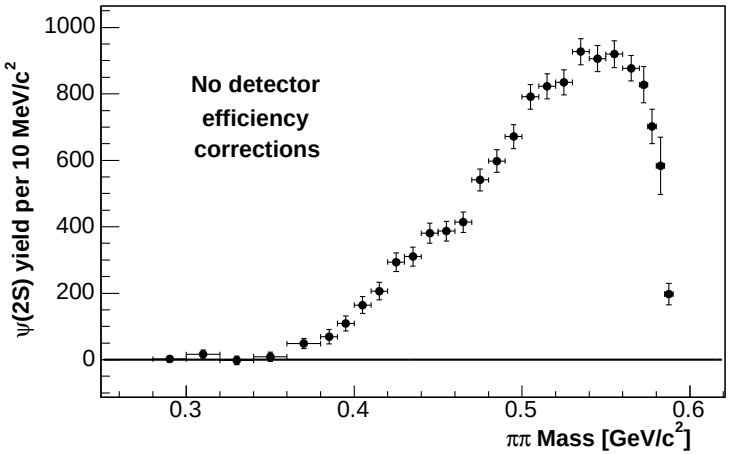
$X(3872)$

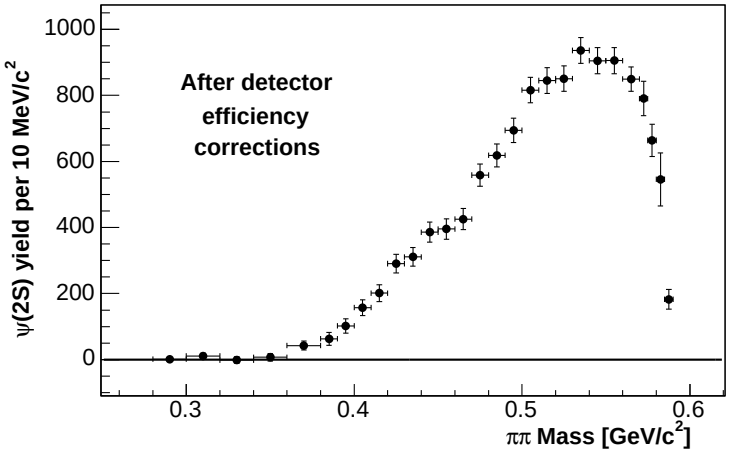


- Relatively flat efficiency corrections for high $m_{\pi\pi}$ (region of interest)
- Flatter for $X(3872)$ than for $\psi(2S)$

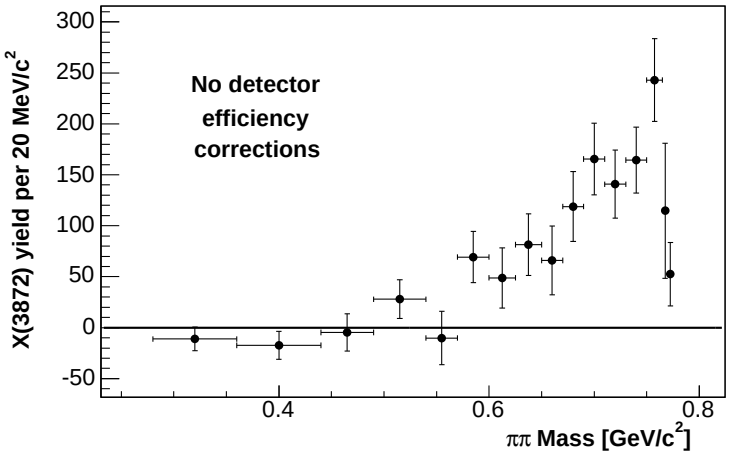
Step 3: Apply corrections

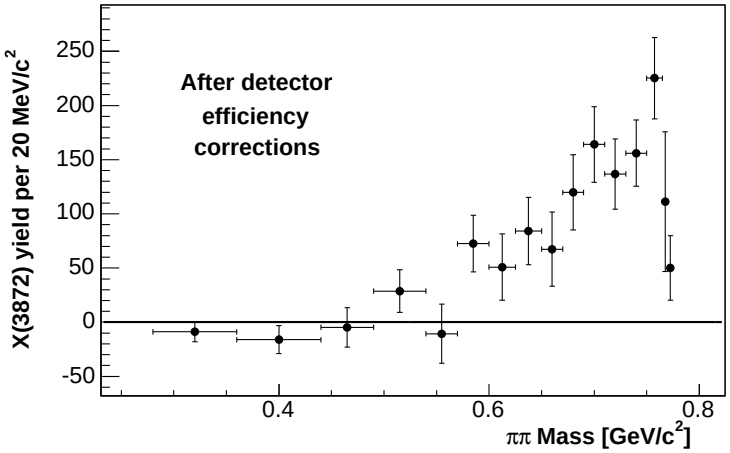
$\psi(2S)$





$X(3872)$

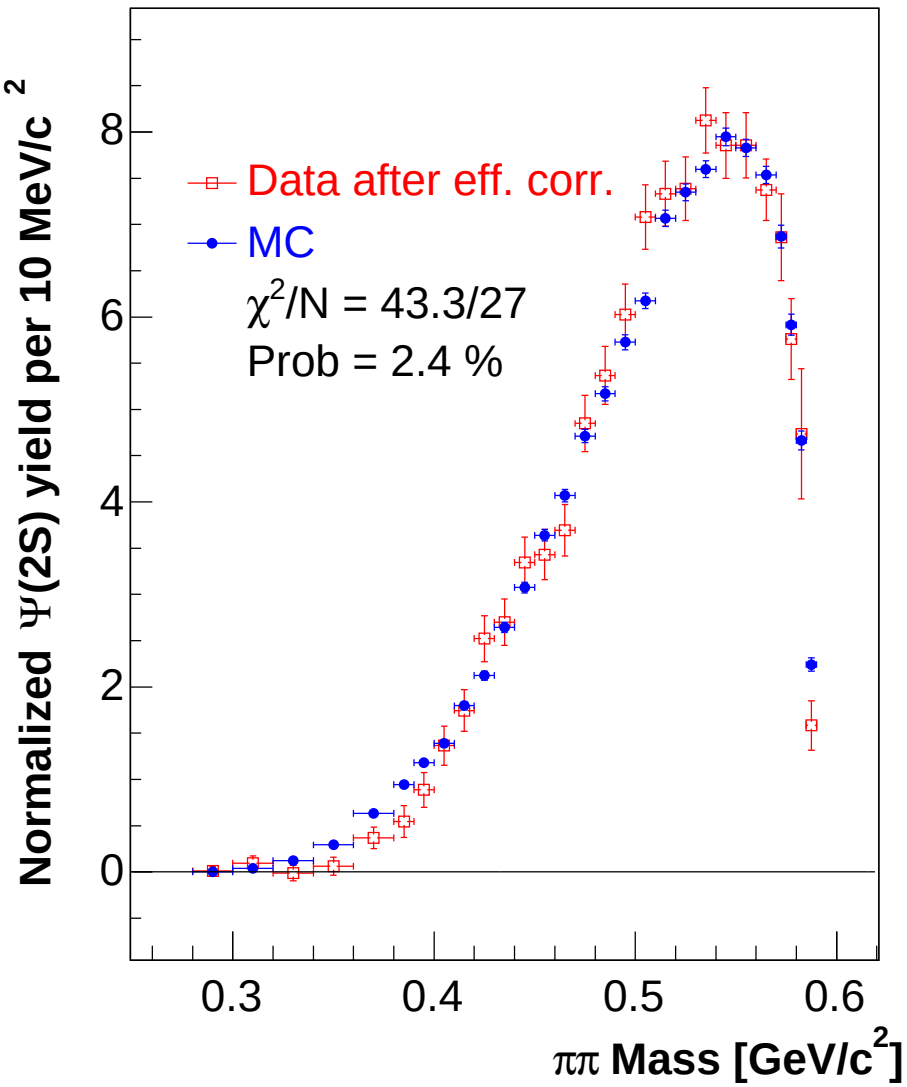




No visible shape difference – detector efficiency corrections are almost negligible

Data-MC match for $m_{\pi\pi}$ spectrum for $\psi(2S)$

Compare *S*-wave $m_{\pi\pi}$ parametrization for $\psi(2S)$ Monte Carlo to corrected data – see reasonable match



Systematics

For i-th $m_{\pi\pi}$ slice $N_i^{corr} = N_i^{raw} \times \xi_i$

Systematics on yields N^{raw}:

- signal shape description
- background shape description

Systematics on detector efficiency corrections ξ:

- $m_{\pi\pi}$ spectrum parametrization

  (unknown true shape for $X(3872)$)

- p_t spectrum parametrization

  (large errors on p_t spectrum from data)

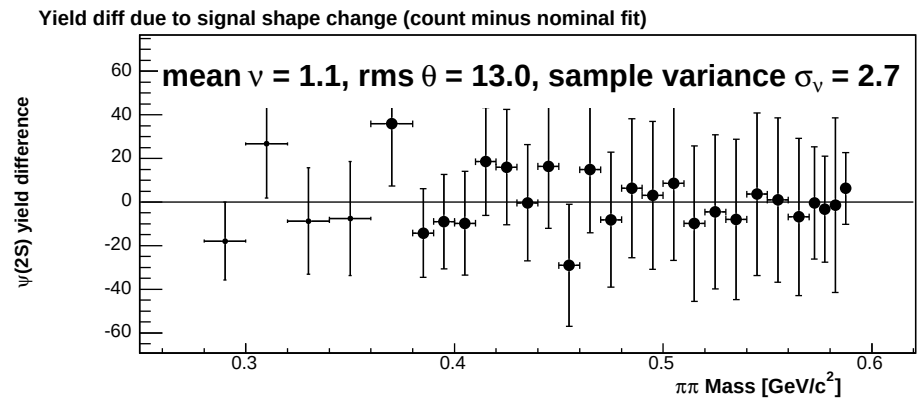
Systematics on yields

- change signal or background description
- compare nominal and changed yields for each $m_{\pi\pi}$ slice
- plot yield differences versus $m_{\pi\pi}$ — see if there is a trend
- if no apparent trend:
  - calculate mean ν, RMS θ and sample variance $\sigma_\nu = \frac{\theta}{\sqrt{N-1}}$
  - systematics cannot be determined better than $\nu \pm \sigma_\nu$

Systematics on yields

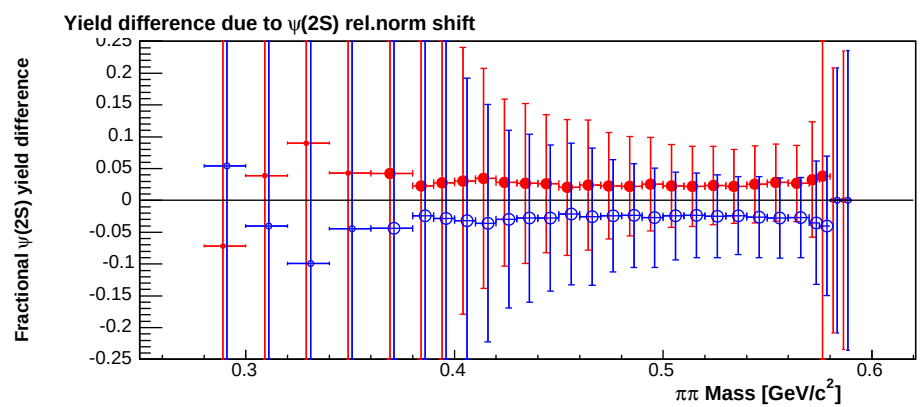
Example: count # of entries in peak

- plot $N_{counted} - N_{fitted}$
- ignore first four slices with no $\psi(2S)$ yield
- systematics smaller than 1.1 ± 2.7
- $\Rightarrow$ use 2.7 cand. as upper limit



Another example: shift N_{rel} by $\pm 1\sigma$

- **uniform** $\sim$2.7% **relative** change in yield
- no change in shape $\Rightarrow$ discard it



- total $\psi(2S)$ yield syst. = 2.7 $\oplus$ similarly obtained bkg. syst. 2.4 $\Rightarrow$ 3.6 cand.
- same thing for $X(3872)$ $\Rightarrow$ total $X(3872)$ yield systematics is 8.4 cand.
- systematic uncertainty is small

High $m_{\pi\pi}$ masses – special treatment

Normally fix $\psi(2S)$ mass & width,

but could let them float $\Rightarrow$

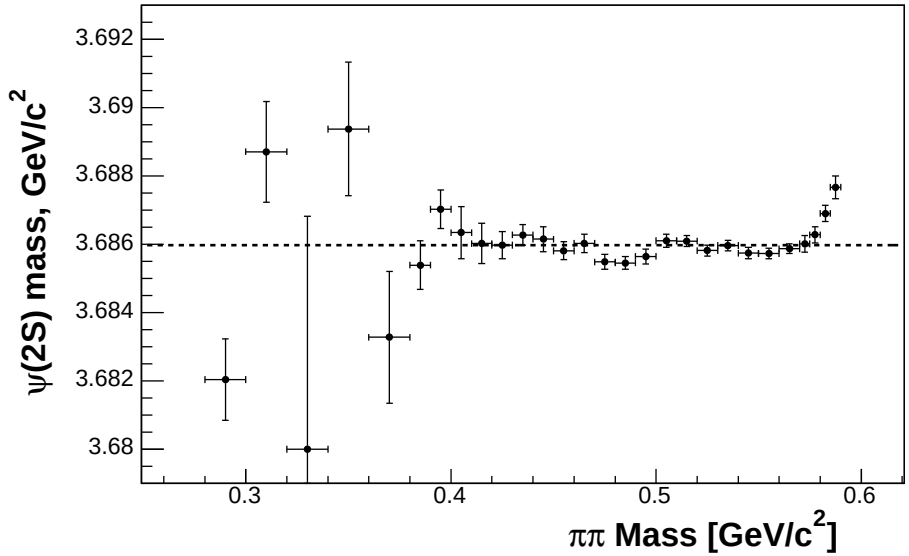
Both quite flat, except for last few slices:

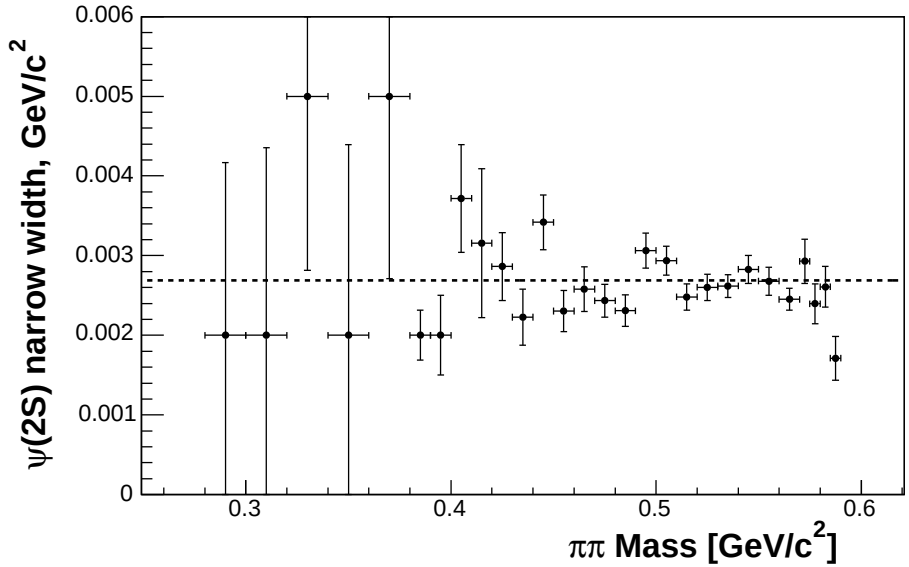
- smearing at $m_{\pi\pi}$ kinematic limit
- peak is close to background turn-on

$\Rightarrow$ Let $\psi(2S)$ mass and width float for last two slices

Similar problems for $X(3872)$:

- use different combinations of fixed/floating mass and width
  $\Rightarrow$ Let $X(3872)$ width float for last three slices
- difficult for fit to determine turn-on
  $\Rightarrow$ constrain from lower $m_{\pi\pi}$ slices





Special systematics for high $m_{\pi\pi}$ masses

Due to special treatment, use special syst. variations, in addition to regular ones:

- turn-on parameter x_0 shift by $\pm 1\sigma$
- fit range change by $\pm$ 50 MeV/c^2
- fix $\psi(2S)$ mass, and $\psi(2S)$ and $X(3872)$ width
- let $X(3872)$ mass float
- asymmetric Gaussian to fit the very last point for $\psi(2S)$

Compare yield variations with respect to nominal yields $\Rightarrow$ derive systematics:

$$N_X^{last-2} = 182 \pm 30(\text{stat.})^{+15}_{-16}(\text{syst.})$$

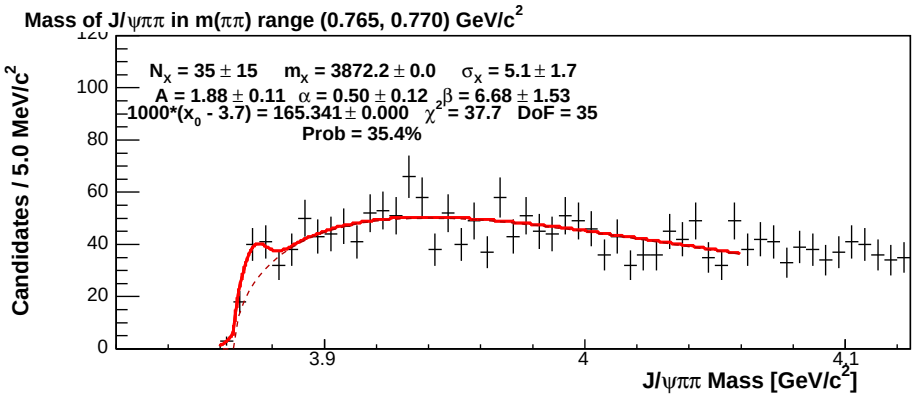
$$N_X^{last-1} = 35 \pm 15(\text{stat.})^{+3}_{-21}(\text{syst.})$$

$$N_X^{last} = 10 \pm 9(\text{stat.})^{+8}_{-2}(\text{syst.})$$

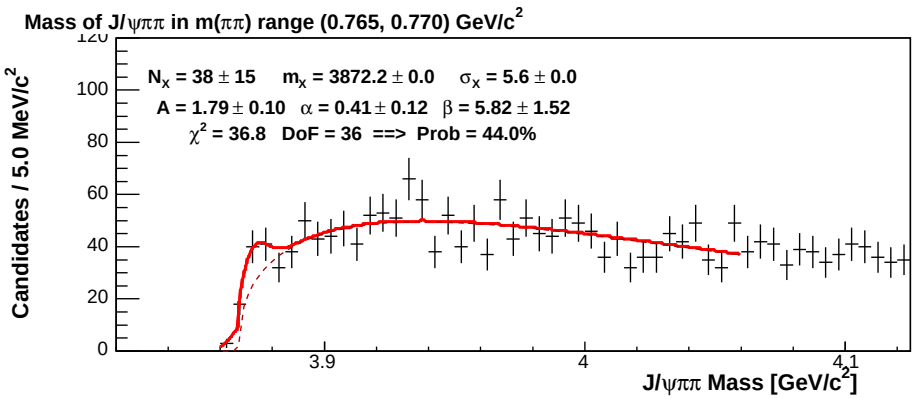
$$N_{\psi(2S)}^{last-1} = 292 \pm 43(\text{stat.})^{+12}_{-22}(\text{syst.})$$

$$N_{\psi(2S)}^{last} = 99 \pm 16(\text{stat.})^{+13}_{-10}(\text{syst.})$$

Example – syst. on 2nd to last $X(3872)$ slice



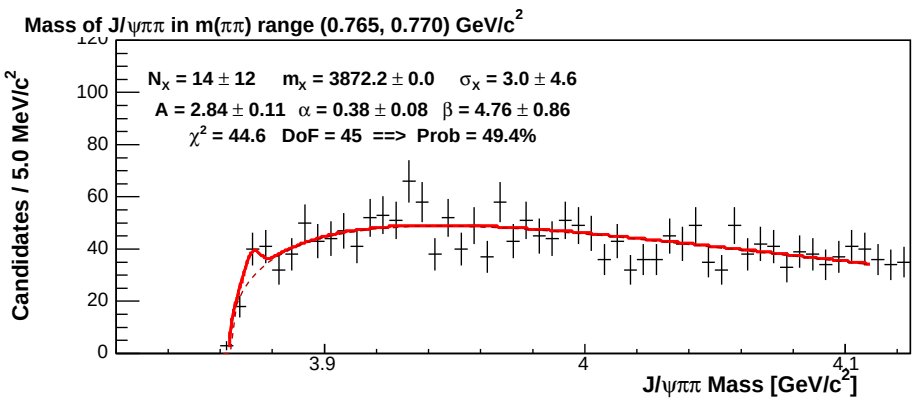
Nominal fit: $N_X = 35 \pm 15$



$X(3872)$ width shifted by $+1\sigma$:

$N_X = 38 \pm 15$

(largest yield increase)



Fit range +50 MeV/c^2:

$N_X = 14 \pm 12$

(largest yield decrease)

Systematics

For i-th $m_{\pi\pi}$ slice $N_i^{corr} = N_i^{raw} \times \xi_i$

Systematics on yields N^{raw}:

- signal shape description
- background shape description

Systematics on detector efficiency corrections ξ:

- $m_{\pi\pi}$ spectrum parametrization

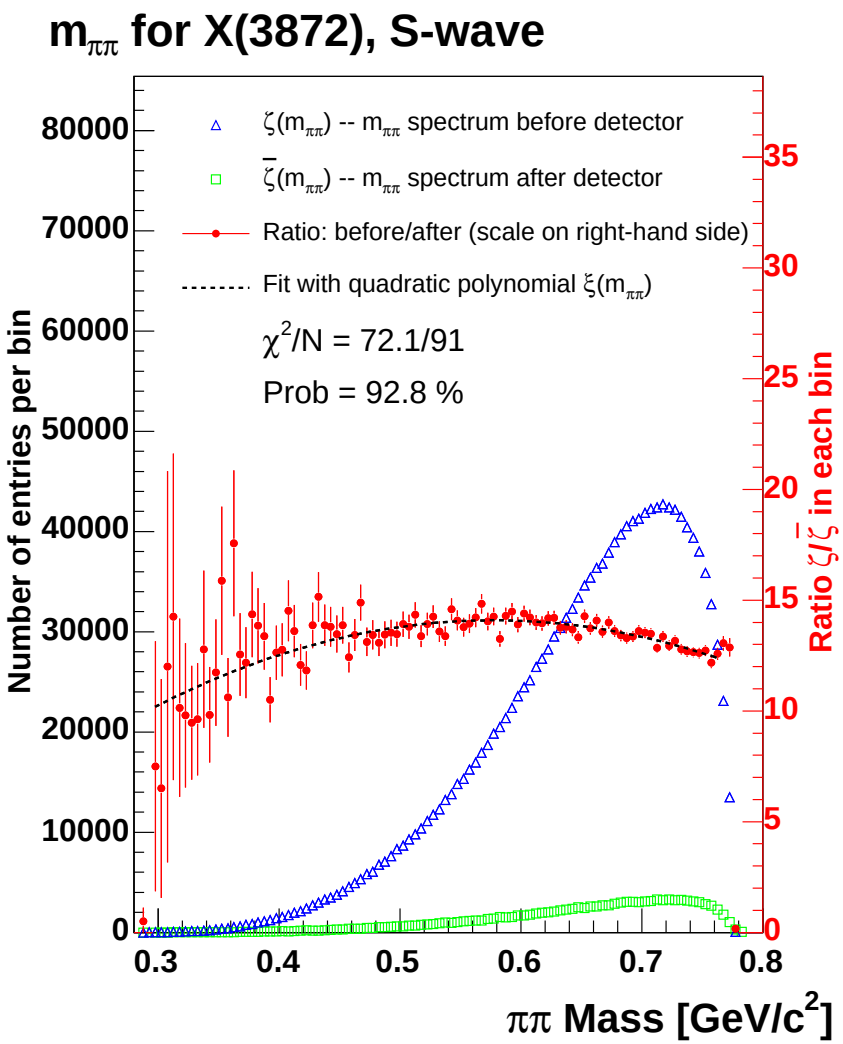
  (unknown true shape for $X(3872)$)

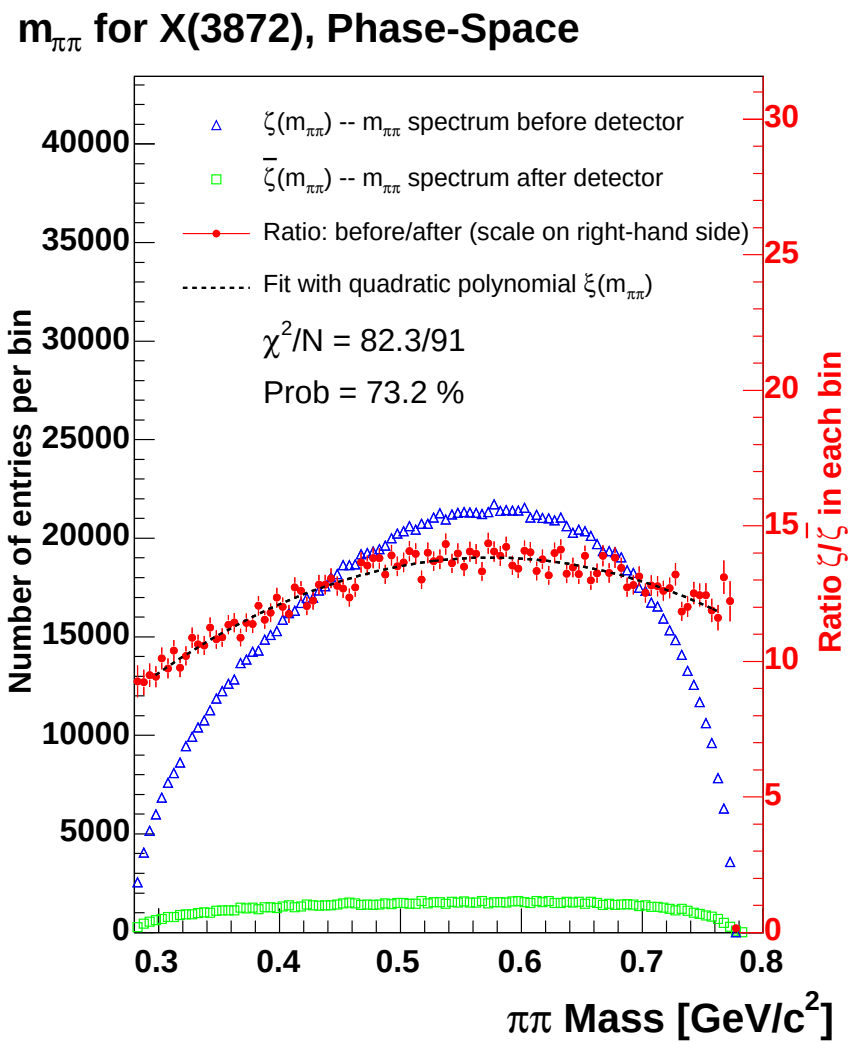
- p_t spectrum parametrization

  (large errors on p_t spectrum from data)

Systematics from $m_{\pi\pi}$ shape for $X(3872)$

Big change of nominal (*S*-wave) $m_{\pi\pi}$ spectrum: phase-space (Same for $\psi(2S)$)



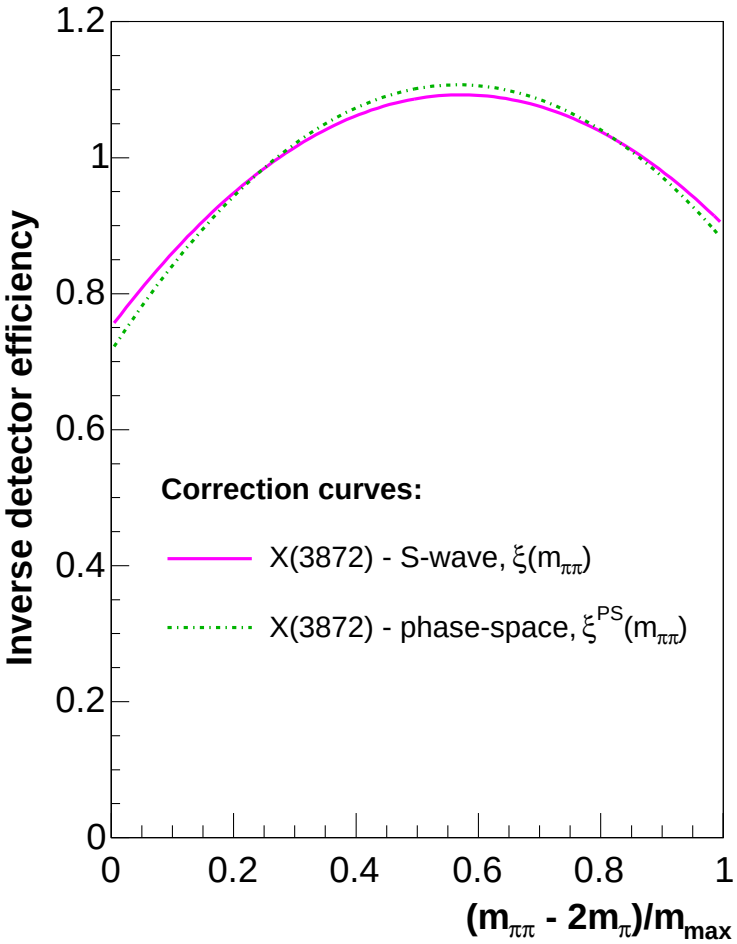


Nominal (*S*-wave) det. eff. corr. curve

Phase-space det. eff. corr. curve

Systematics from $m_{\pi\pi}$ shape for $X(3872)$

Curve comparison

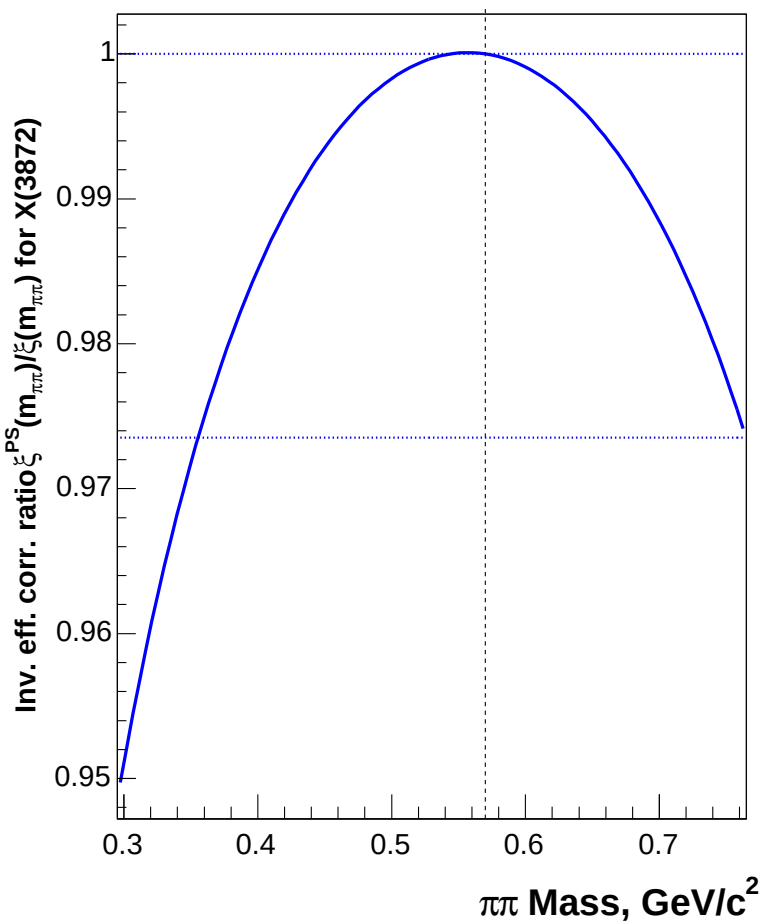


Efficiency corrections

not very sensitive

to $m_{\pi\pi}$ shape

Ratio $\gamma^{PS}(m_{\pi\pi}) = \frac{\text{phase-space}}{S\text{-wave}}$



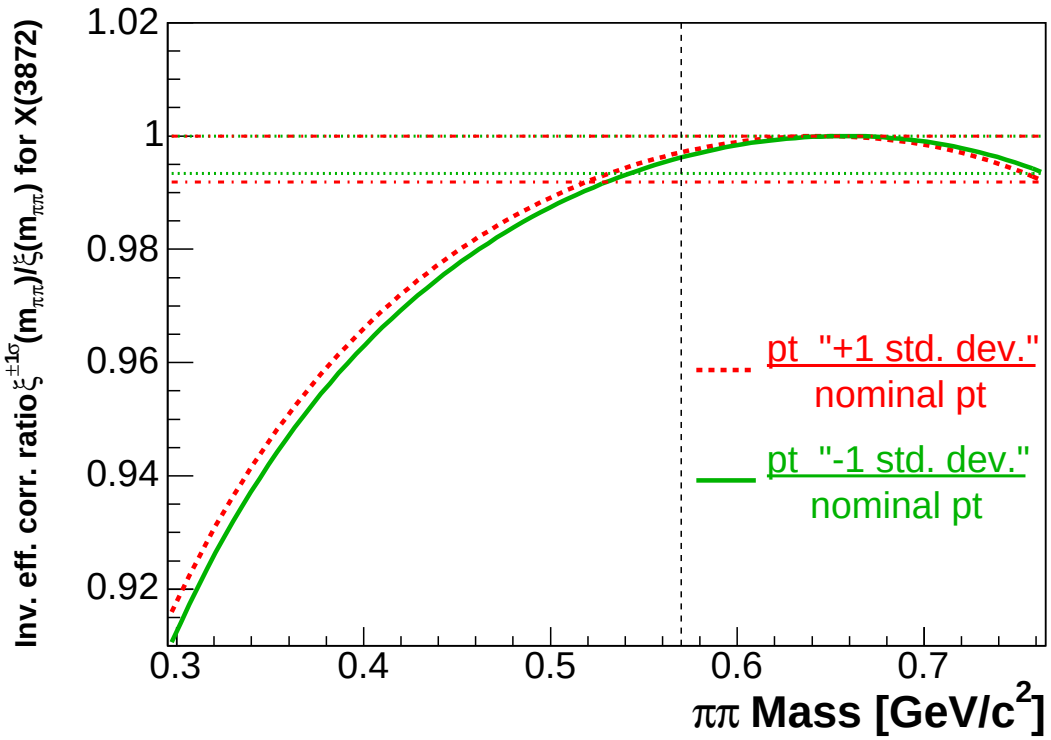
We will include ratio $\gamma^{PS}(m_{\pi\pi})$ into theoretical fit

to see general effect on $m_{\pi\pi}$ shape

(described later)

Systematics from p_t shape for $X(3872)$

- parametrize p_t shape as $\exp(a_0 + a_1 p_t + a_2 p_t^2)$
- shift a_1 up and down by one sigma
- generate new MC with shifted a_1
- get "shifted" efficiency correction curves, divide them by nominal one



- include ratio function $\gamma^{\pm 1\sigma}(m_{\pi\pi})$ into theoretical fit to see general effect on $m_{\pi\pi}$ shape

$\Rightarrow$ same thing for $\psi(2S)$

Include detector eff. corr. into χ^2

Naïve and simple

$$\chi^2_{\text{naïve}} = \sum \left(\frac{N_i \xi_i - T_i}{\sigma(N_i)\xi_i} \right)^2$$

- $N_i \pm \sigma(N_i)$ – raw yield in i-th point
- ξ_i – nominal detector efficiency correction function (integrated over i-th bin)
- T_i – theoretical function (integrated over i-th bin)

Include $m_{\pi\pi}$ and p_t systematics (*i.e.* γ_i^{PS} and $\gamma_i^{\pm 1\sigma}$ ratio functions) into χ^2 with floating coefficients a and b:

$$\chi^2 = \sum \left(\frac{N_i \xi_i \left[1 + a(\gamma_i^{PS} - 1)\right] \left[1 + b(\gamma_i^{\pm 1\sigma} - 1)\right] - T_i}{\sigma(N_i)\xi_i \left[1 + a(\gamma_i^{PS} - 1)\right] \left[1 + b(\gamma_i^{\pm 1\sigma} - 1)\right]} \right)^2 + \left(\frac{a - 0}{1} \right)^2 + \left(\frac{b - 0}{1} \right)^2$$

$a = 0$ – nominal (S-wave) $m_{\pi\pi}$ parametrization $\xi(m_{\pi\pi})$

$a = 1$ – changed (phase-space) $m_{\pi\pi}$ parametrization $\xi^{PS}(m_{\pi\pi})$

b – similar for p_t shape

Last two terms: a and b are expected to have central value of 0 and standard deviation of 1

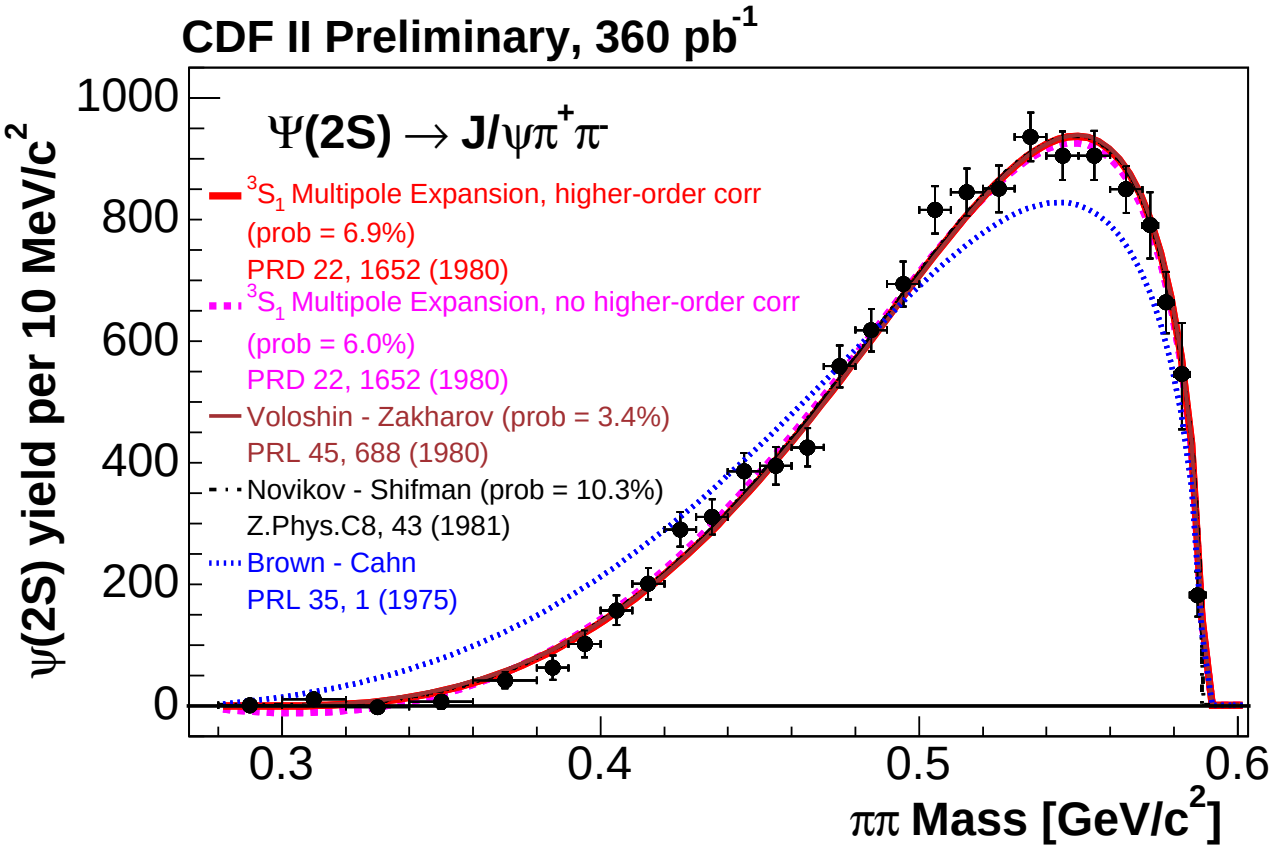
Theory models for $\psi(2S)$ + prior expt. data

$\psi(2S)$ is well studied both theoretically and experimentally:

- lots of theoretical models for $m_{\pi\pi}$ spectrum shape - use them to fit data
- large BES data sample (23k $\psi(2S)$) available - compare with our fits

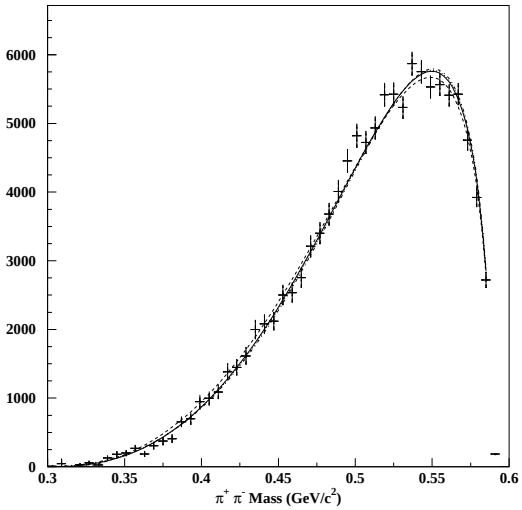
Model	Short description
Yan, [PRD22 1652 (1980)]	Multipole Expansion of QCD Lagrangian: – for $^3S_1$ charmonium state – for $^3S_1$ state with higher-order corection
Voloshin-Zakharov [PRL45, 688 (1980)]	Chiral limit $m_\pi = 0$ plus phen. term λm_π^2
Novikov-Shifman [Z.Phys.C8, 43 (1981)]	Elaborate VZ model
Brown-Cahn [PRL35, 1 (1975)]	Neglect chiral symmetry breaking, no strong angular correlations

Theoretical fits for $\psi(2S)$



BES data

[PRD62, 032002 (2000)]:



- first four models describe the data well
- Brown – Cahn model does not work so well, because it neglects term correspponding to angular correlations between pions

Fit results for $\psi(2S)$

Each model has a fit parameter:

Model	CDF fit	Result from BES	Diff.
Yan $^3S_1$-state with higher-order corr.	$B/A = -0.342 \pm 0.022$ $\chi^2/NDF = 37/26$ CL = 6.9%	$B/A = -0.336 \pm 0.009 \pm 0.019$ $\chi^2/NDF = 60/45$ CL = 6.4%	0.2σ
Yan $^3S_1$-state without higher-order corr.	$B/A = -0.245 \pm 0.011$ $\chi^2/NDF = 38/26$ CL = 6.0%	$B/A = -0.225 \pm 0.004 \pm 0.028$ $\chi^2/NDF = 84/45$ CL = 0.02%	0.7σ
Voloshin-Zakharov	$\lambda = 4.34 \pm 0.15$ $\chi^2/NDF = 41/26$ CL = 3.4%	$\lambda = 4.35 \pm 0.06 \pm 0.17$ $\chi^2/NDF = 69/45$ CL = 1.0%	0.04σ
Novikov-Shifman	$\kappa = 0.189 \pm 0.007$ $\chi^2/NDF = 35/26$ CL = 10.3%	$\kappa = 0.186 \pm 0.003 \pm 0.006$ $\chi^2/NDF = 55/45$ CL = 14.6%	0.3σ
Brown-Cahn	$\chi^2/NDF = 226/27$	–	

CDF consistent with BES within 0.7σ for all fits

Which models to use for $X(3872)$?

Consider J^{PC} of dipion system in $X(3872) \to J/\psi\,\pi^+\pi^-$ decay.
For pions $S = 0 \Rightarrow$ for dipion $P = C = (-1)^L = (-1)^I$. Two states possible:

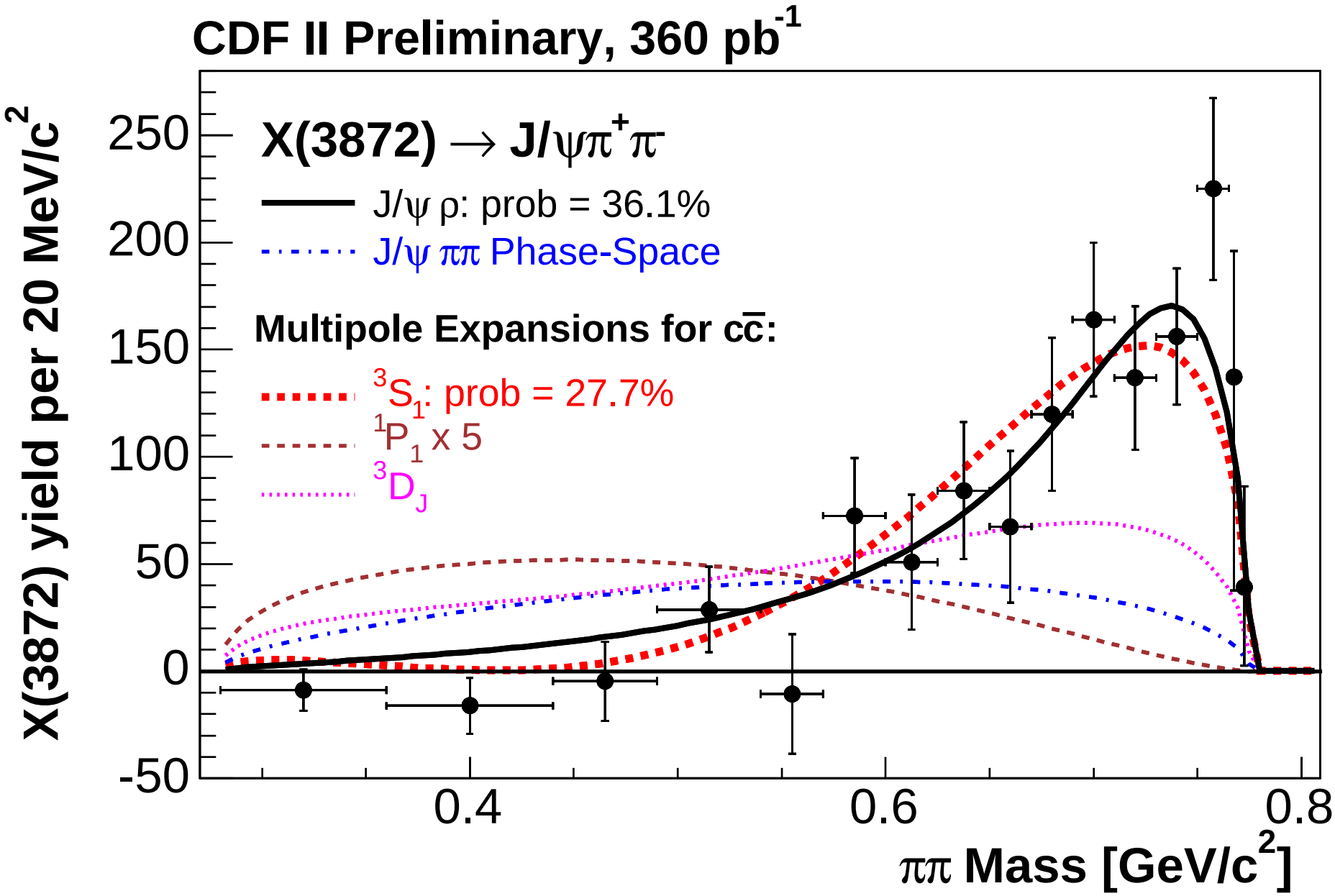
0^{++} dipion:

- isospin $I = 0 \Rightarrow$ good for charmonium assignment
- charmonium: Yan model for $^3S_1$, $^1P_1$ and ^3D_J decaying into $^3S_1\,\pi^+\pi^-$ (multipole expansion)

1^{--} dipion:

- isospin $I = 1 \Rightarrow$ isospin breaking if charmonium
  Note: virtual coupling to $D^0\overline{D}^{*0}$ may "bypass" isospin conservation
- decay must proceed via $\boldsymbol{J/\psi\rho^0}$
- use Breit-Wigner modified by 3-body $J/\psi\,\pi^+\pi^-$ phase space,
  $\frac{\Gamma}{(m_{\pi\pi}-M_\rho)^2+\Gamma^2/4} \times (\textbf{\textit{Phase}} - \textbf{\textit{Space}})$

Theoretical fits for $X(3872)$



Charmonium options for $X(3872)$

0^{++} dipion: Multipole Expansion predictions for $^3S_1$, $^1P_1$, $^3D_{1,2,3}$ (Yan):

- compatible with $^3S_1$, but no viable $^3S_1$ candidate available
- incompatible with $^1P_1$ or $^3D_{1,2,3}$

1^{--} dipion: $J/\psi\rho^0$ model: Breit-Wigner $\times$ PS

- compatible with $J/\psi\,\rho^0$

Three candidates can be excluded:

- $2\,^3P_0$ and $2\,^3P_2$: $X(3872)$ was not seen in $\gamma\gamma$ fusion
- $3\,^1S_0$: too heavy, must be close to $3\,^3S_1 = \psi(4040)$

Two viable charmonium candidates remain:

$1\,^1D_2$ and $2\,^3P_1$ — both decay into $J/\psi\,\pi^+\pi^-$ with isospin violation

$n\,^{2s+1}\ell_{J^{PC}}$	Known	Dipion J^{PC} in decay into $J/\psi\,\pi^+\pi^-$	Compatible with data?
$1\,^1S_{0^{-+}}$	$\eta_c(1S)$	1^{--}	
$1\,^3S_{1^{--}}$	J/ψ	0^{++}	
$1\,^1P_{1^{+-}}$	$h_c(1P)$	0^{++}	
$1\,^3P_{0^{++}}$	$\chi_{c0}(1P)$	1^{--}	
$1\,^3P_{1^{++}}$	$\chi_{c1}(1P)$	1^{--}	
$1\,^3P_{2^{++}}$	$\chi_{c2}(1P)$	1^{--}	
$1\,^1D_{2^{-+}}$		**1^{--}**	**Yes**
$1\,^3D_{1^{--}}$	$\psi(3770)$	0^{++}	
$1\,^3D_{2^{--}}$		0^{++}	No
$1\,^3D_{3^{--}}$		0^{++}	No
$2\,^1S_{0^{-+}}$	$\eta_c(2S)$	1^{--}	
$2\,^3S_{1^{--}}$	$\psi(2S)$	0^{++}	
$2\,^1P_{1^{+-}}$		0^{++}	No
$2\,^3P_{0^{++}}$		1^{--}	Yes
$2\,^3P_{1^{++}}$		**1^{--}**	**Yes**
$2\,^3P_{2^{++}}$		1^{--}	Yes
$3\,^1S_{0^{-+}}$		1^{--}	Yes
$3\,^3S_{1^{--}}$	$\psi(4040)$	0^{++}	

Exotic options for $X(3872)$

Most popular non-charmonium option for $X(3872)$ is a D^0-$\overline{D}^{*0}$ "molecule".

Example: Swanson model [PLB588, 189 (2004)] – mixture of D^0-$\overline{D}^{*0}$, $J/\psi\,\omega$, $J/\psi\,\rho^0$, D^+-D^{*-}

For different dipion J^{PC}:

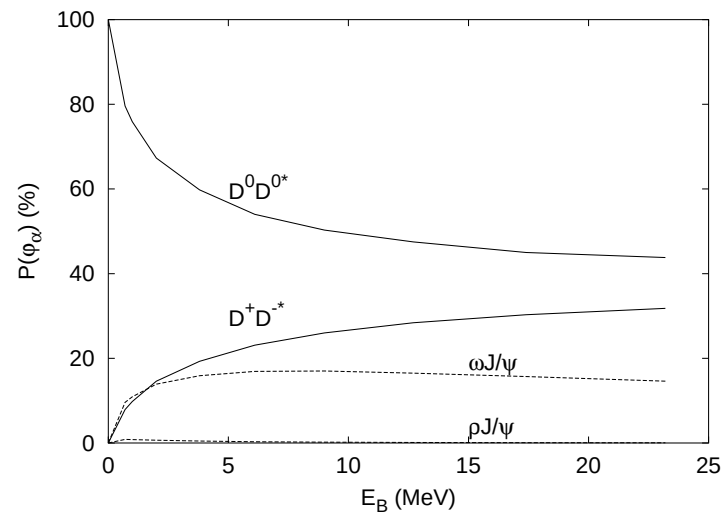
0^{++} dipion

- no predictions for $m_{\pi\pi}$ spectrum shape

1^{--} dipion

- decay proceeds via $J/\psi\,\rho^0$

  $\Rightarrow$ compatible with data

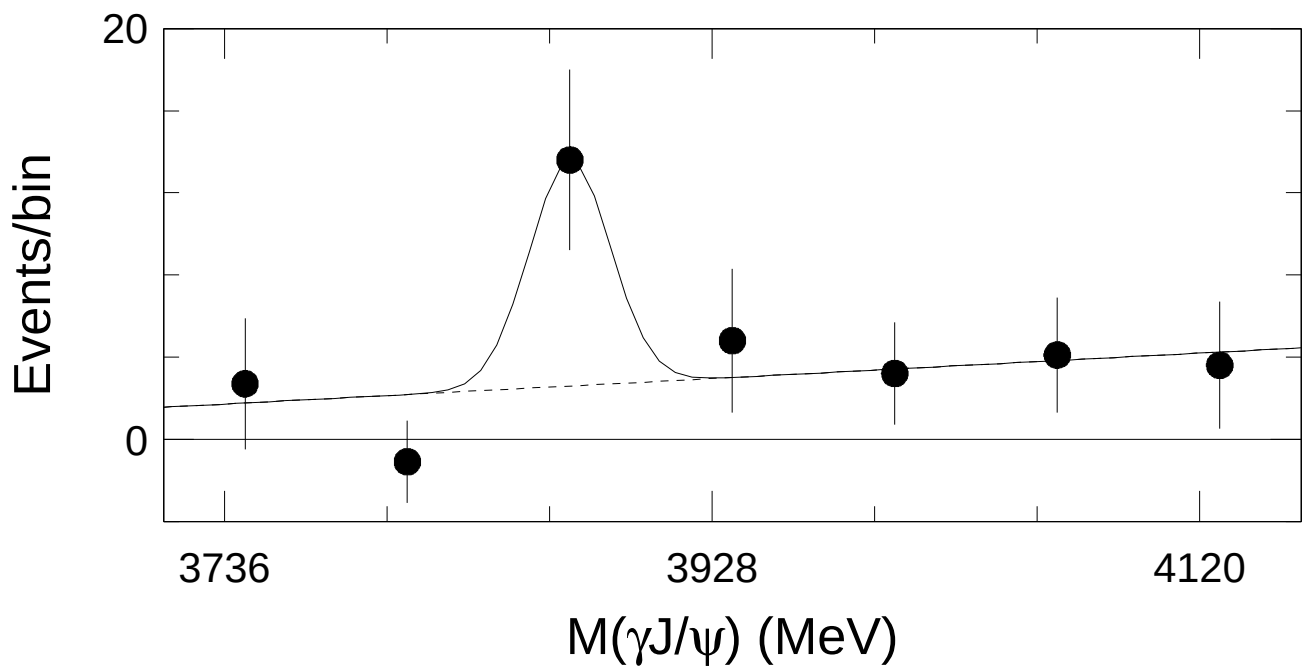


Relative contribution of each component versus binding energy

C-parity of $X(3872)$

Whatever $X(3872)$ is, $\mathbf{1}^{--}$ dipion implies C-positive $X(3872)$:

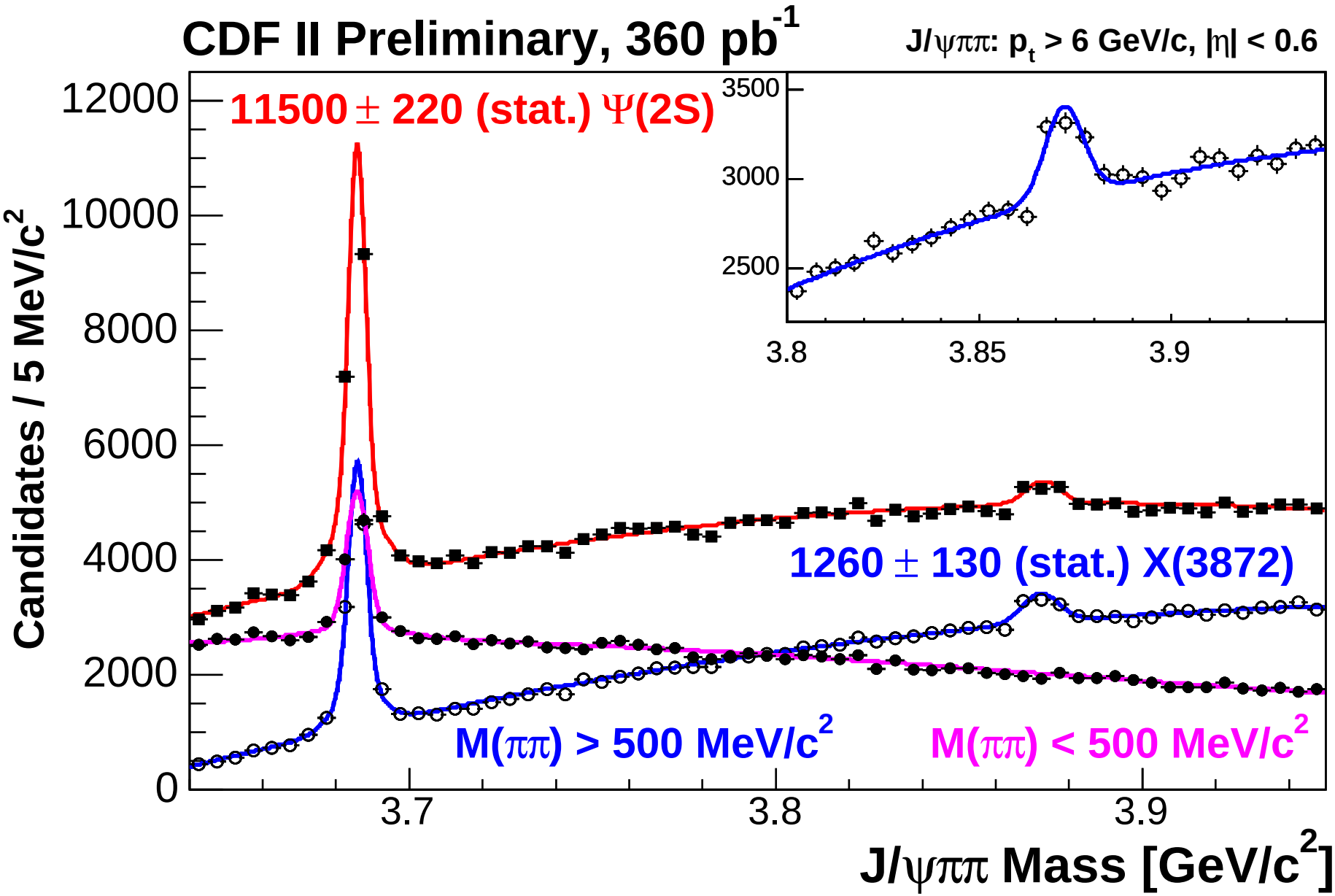
- compatible with CDF data
- supported by recent Belle's observations of $X(3872) \to J/\psi\,\omega$ and $X(3872) \to J/\psi\,\gamma$



Conclusion:

- measured dipion mass spectrum in $X(3872) \to J/\psi\,\pi^+\pi^-$ decay
- good agreement for $m_{\pi\pi}$ spectrum shape for $\psi(2S)$ with large data sample from BES
- $m_{\pi\pi}$ spectrum shape for $X(3872)$:
  - compatible with C-negative $^3S_1$-state (no viable $^3S_1$-state available)
  - compatible with C-positive $J/\psi\rho^0$ hypothesis
  - positive C-parity consistent with Belle's observations of $X(3872) \to J/\psi\,\omega$ and $X(3872) \to J/\psi\,\gamma$
- $X(3872)$ nature from $m_{\pi\pi}$ spectrum shape:
  - charmonium: $1\,^1D_2$ or $2\,^3P_1$, with isospin violating decay to $J/\psi\,\pi^+\pi^-$
  - could be exotics, such as D^0-$\overline{D}^{*0}$ molecule
  - exotic interpretation: new chapter in heavy flavor spectroscopy?

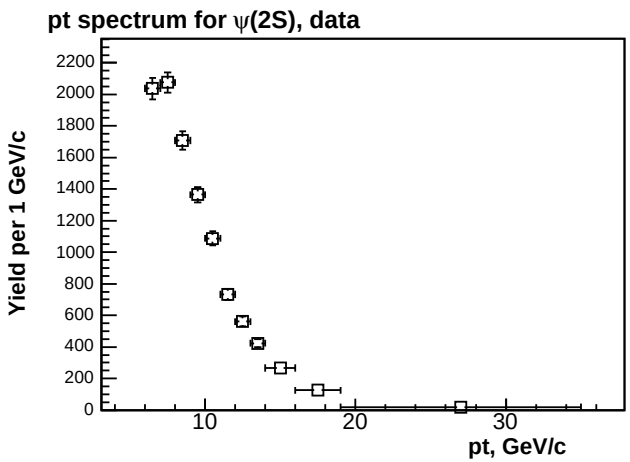
Backup

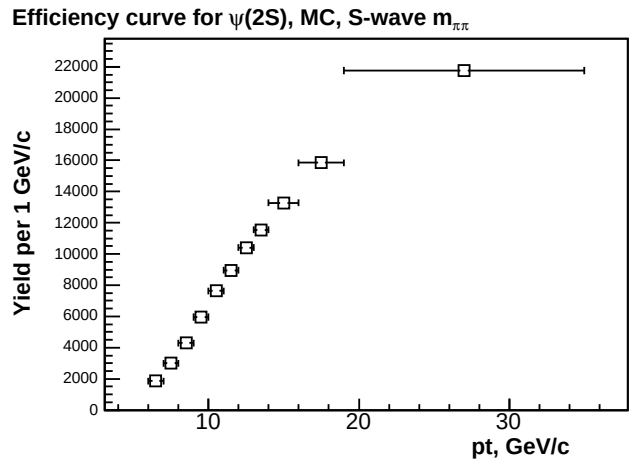

CDF II Preliminary, 360 pb^{-1}
J/ψππ: p_t > 6 GeV/c, |η| < 0.6
11500 ± 220 (stat.) Ψ(2S)
1260 ± 130 (stat.) X(3872)
M(ππ) > 500 MeV/c^2
M(ππ) < 500 MeV/c^2
Candidates / 5 MeV/c^2
J/ψππ Mass [GeV/c^2]
0
2000
4000
6000
8000
10000
12000
3.7
3.8
3.9
2500
3000
3500

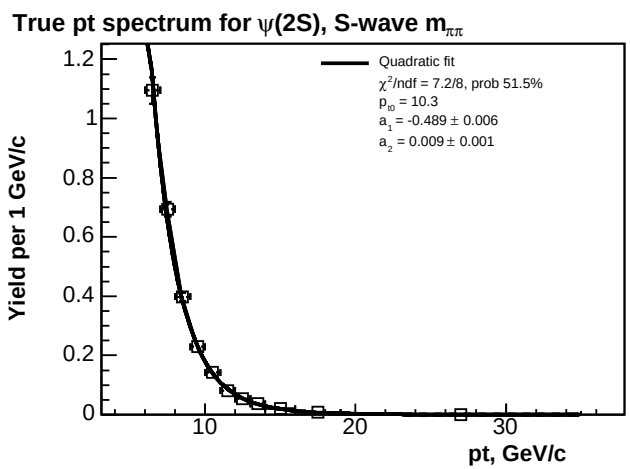
Getting corrected p_t of $\psi(2S)$

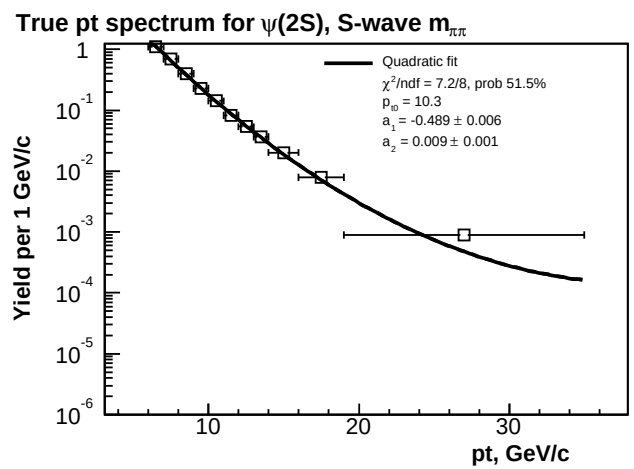
Upper left: $\psi(2S)$ p_t from data

Upper right: Detector efficiency curve (MC output from flat p_t-η input)





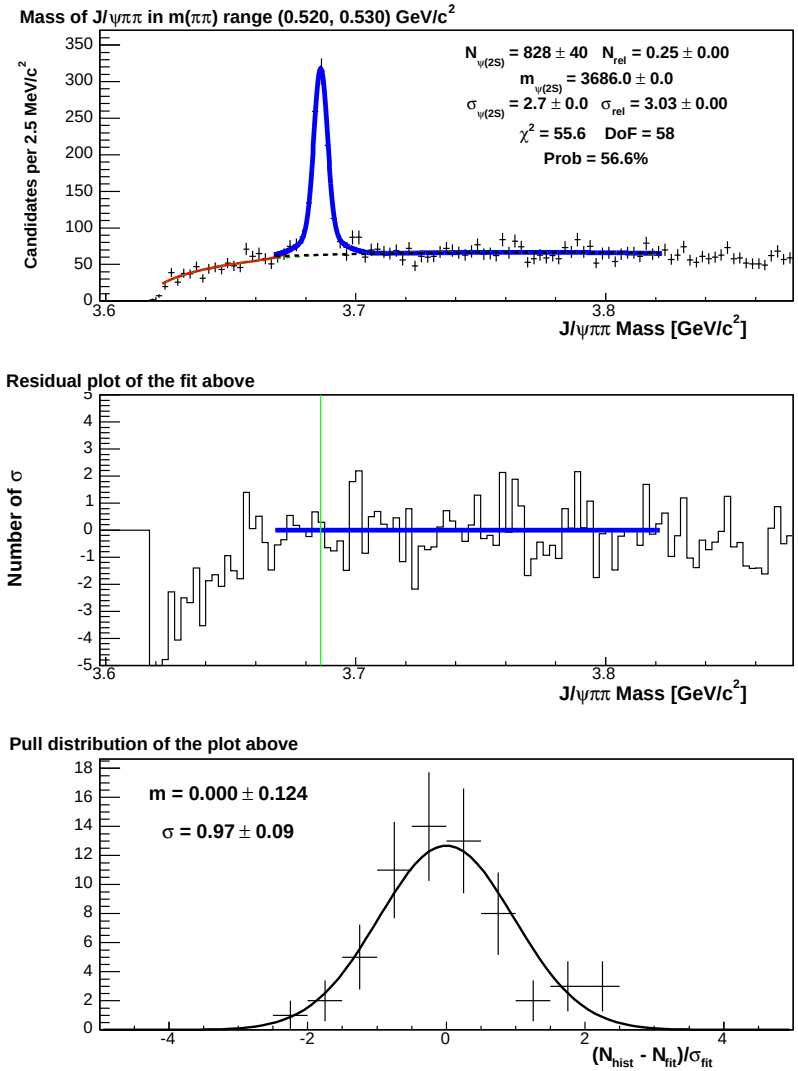




Lower plots: $X(3872)$ p_t from data divided by eff. curve $\Rightarrow$ Parametrized with $e^{a_0+a_1 p_t+a_2 p_t^2}$

$$a_1 = 0.489 \pm 0.008, \quad a_2 = 0.009 \pm 0.001$$

$\psi(2S)$ mass fit with different bkg. model



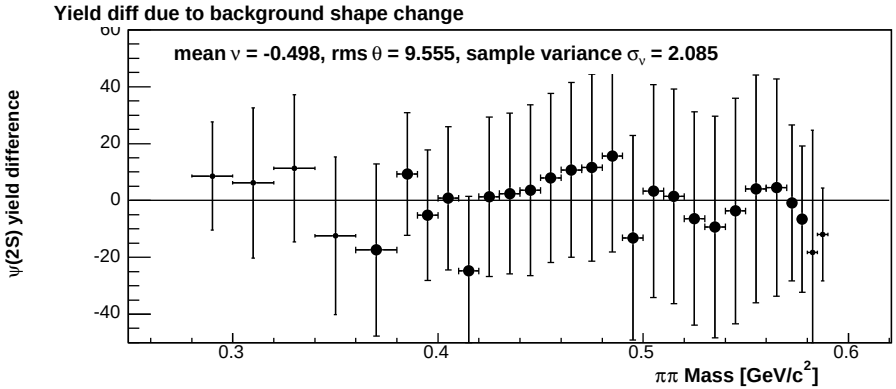
$520\ \mathrm{MeV}/c^2 < m_{\pi\pi} < 530\ \mathrm{MeV}/c^2$

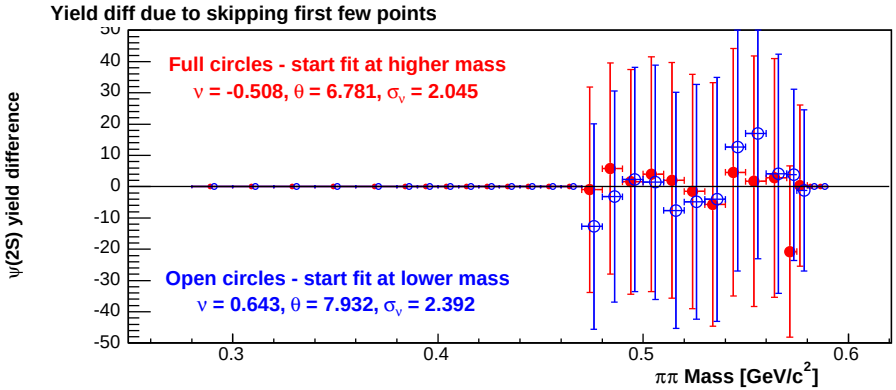
Diff. bkg: polynomial instead of $A(x - x_0)^{\alpha} \exp(-\beta x)$

High-side bkg defines shape

	$N_{\psi(2S)}$	fit prob
Nominal fit	835 ± 38	43.3%
Diff. bkg fit:	828 ± 40	56.6%

$\psi(2S)$ mass fit with different bkg. model





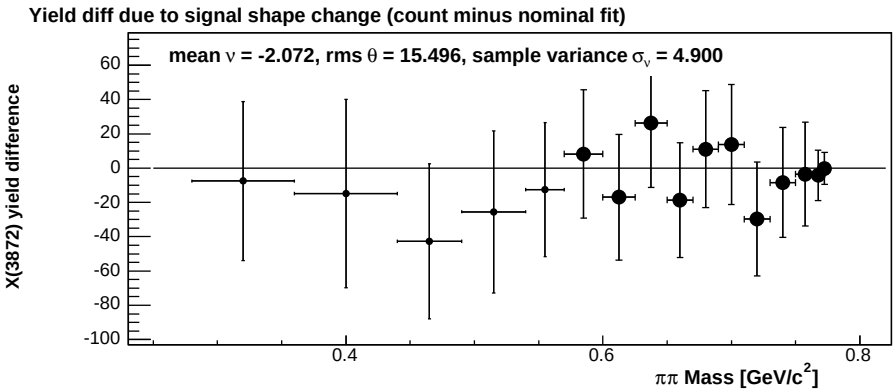
- Use polynomial bkg. instead of $A(x - x_0)^{\alpha} \exp(-\beta x)$
- Plot $N_{diff.bkg.} - N_{normal}$
- Can't claim syst. smaller 0.498 ± 2.085
- $\Rightarrow$ use 2.1 cand. as systematics

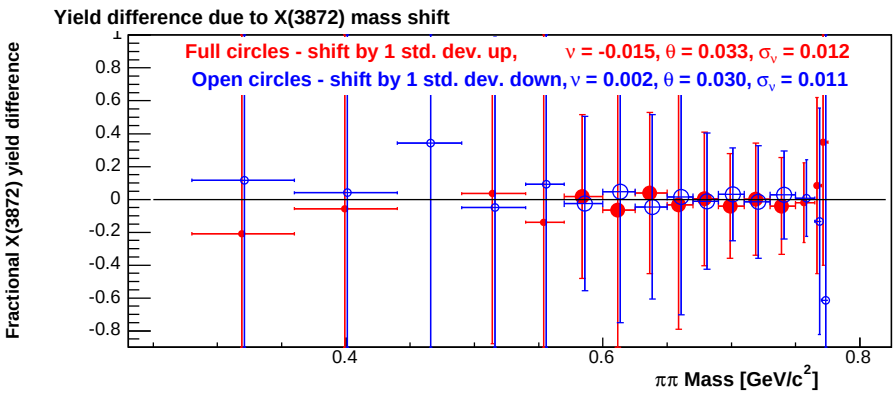
- Another bkg variation: add/skip a few points near background turn-on
- $\Rightarrow$ use 2.4 cand. as systematics

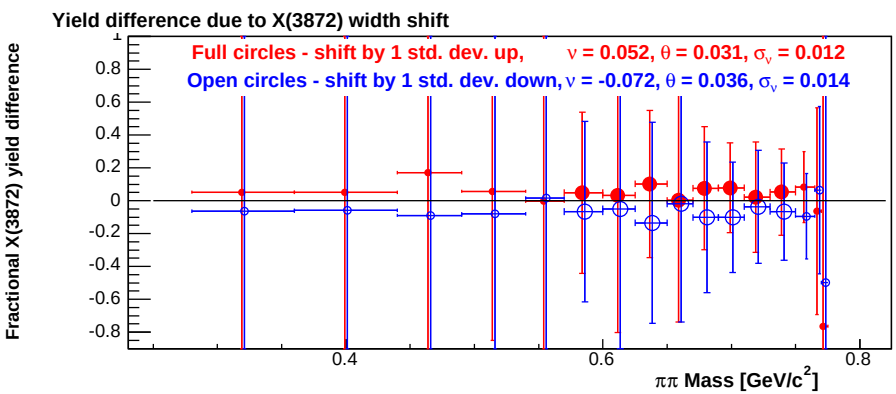
Use 2.4 as $\psi(2S)$ bkg syst

Use 3.6 as **total** $\psi(2S)$ yield systematics

$X(3872)$ mass fit with different signal model







First five slices have no $X(3872)$ yield

$\Rightarrow$ ignore them (smaller points)

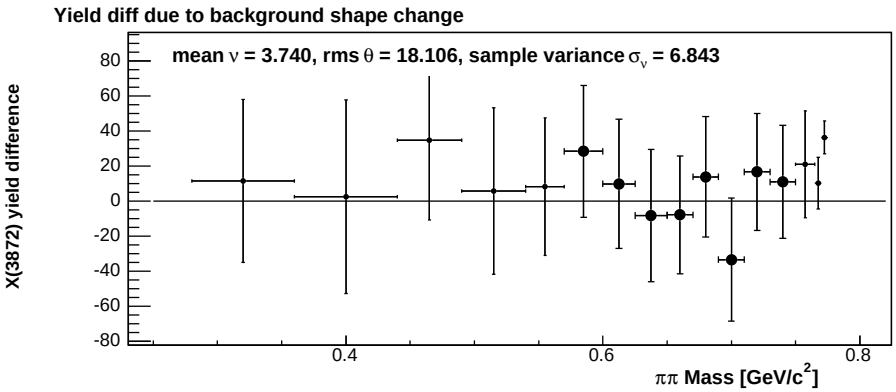
- Count # of entries in peak
- Plot $N_{counted} - N_{fitted}$
- No apparent systematic trend
- Can't claim syst. smaller -2.072 ± 4.900
- Use 4.9 cand. as systematics

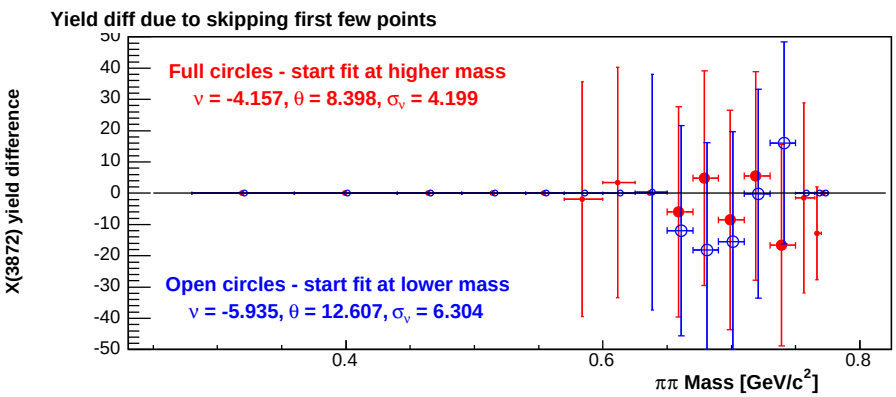
- Shift $X(3872)$ mass by $\pm 1\sigma$
- ~ 1.5% relative change in yield
- Discard it

- Shift $X(3872)$ width by $\pm 1\sigma$
- ~ 7.2% relative change in yield
- Discard it

Use 4.9 as $X(3872)$ signal syst

$X(3872)$ mass fit with different bkg. model





- Use polynomial bkg. instead of $A(x - x_0)^{\alpha} \exp(-\beta x)$
- Plot $N_{diff.bkg.} - N_{normal}$
- Can't claim syst. smaller 3.740 ± 6.843
- $\Rightarrow$ 6.8 cand. as systematics

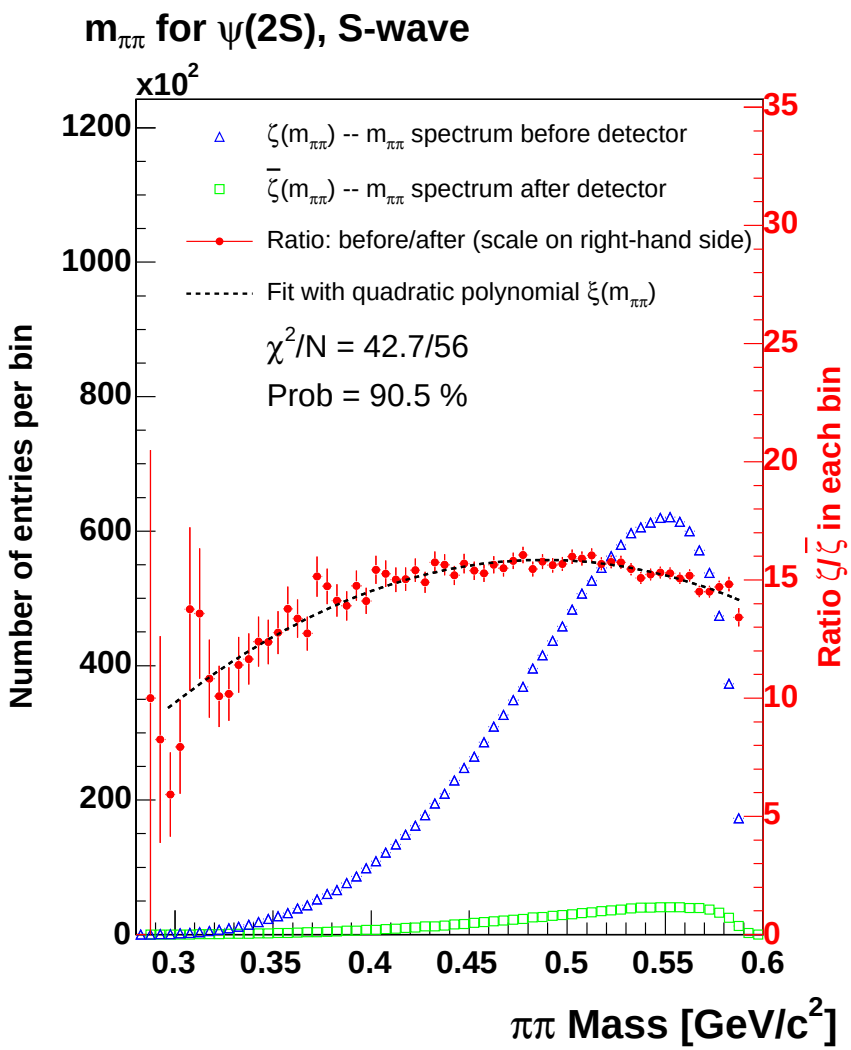
- Add/skip a few points near turn-on
- $\Rightarrow$ 6.3 cand. as systematics

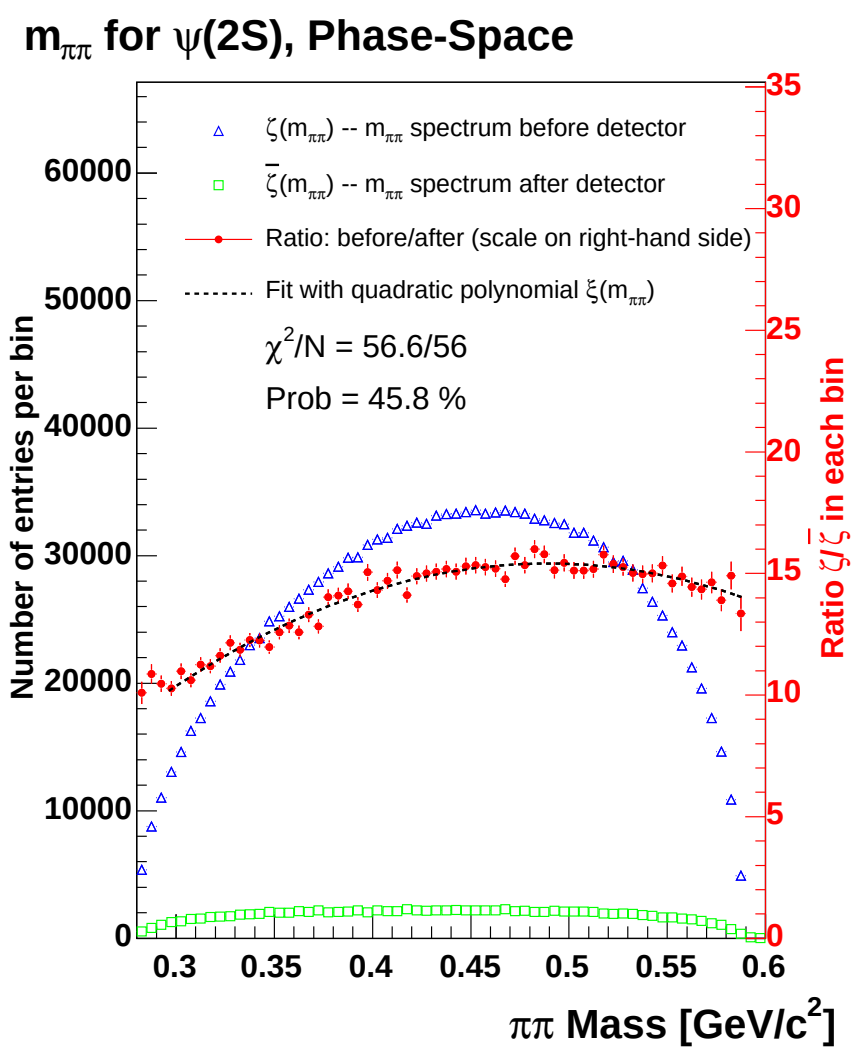
Use 6.8 as $X(3872)$ bkg syst

Use 8.4 as **total** $X(3872)$ systematics

Systematics from $m_{\pi\pi}$ shape for $\psi(2S)$

Estimate this uncertainty by comparing *S*-wave to phase-space



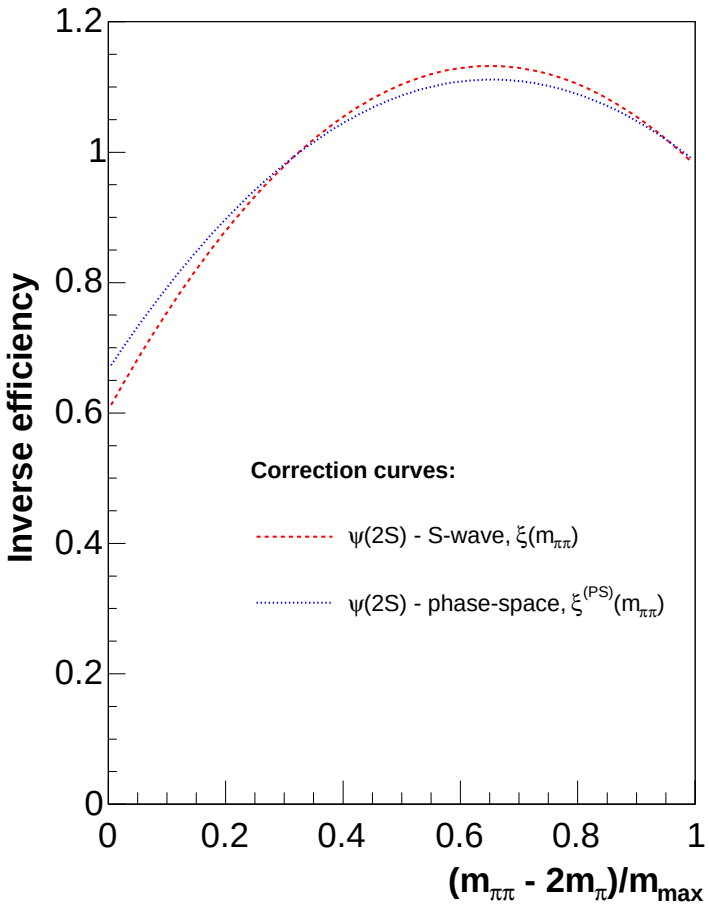


Nominal (*S*-wave) det. eff. corr. curve

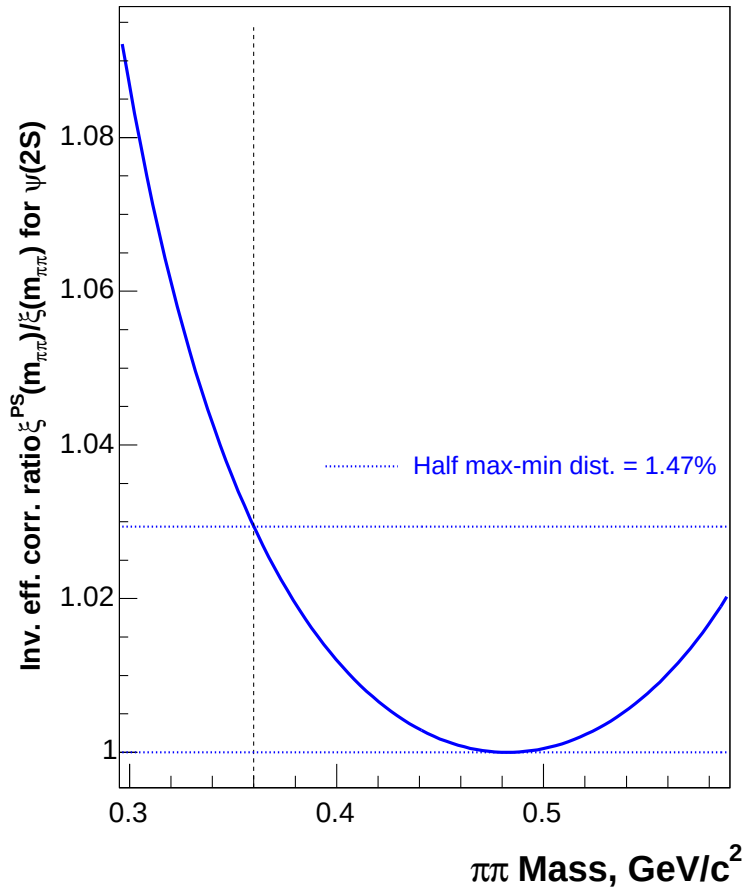
Phase-space det. eff. corr. curve

Systematics from $m_{\pi\pi}$ shape for $\psi(2S)$

Curve comparison



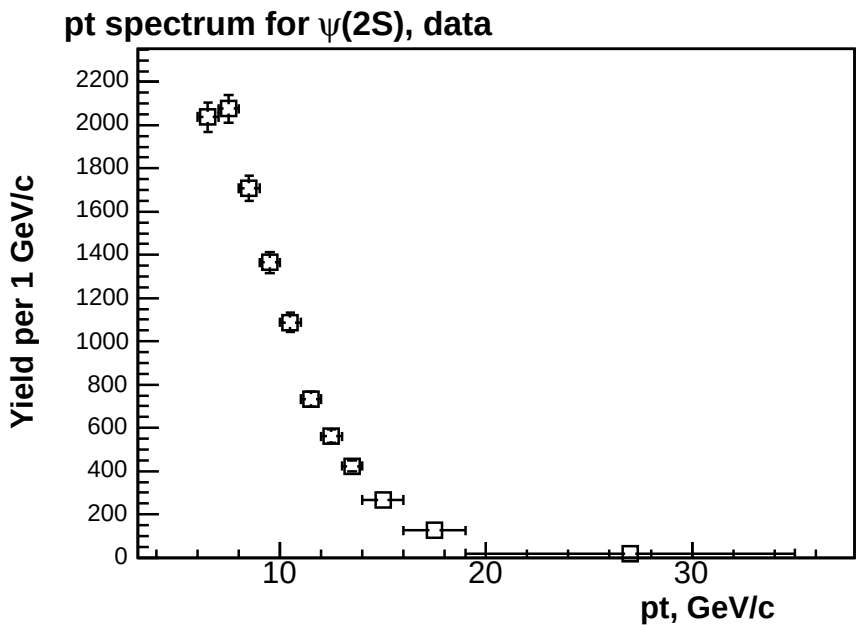
Curve ratio: phase-space/*S*-wave

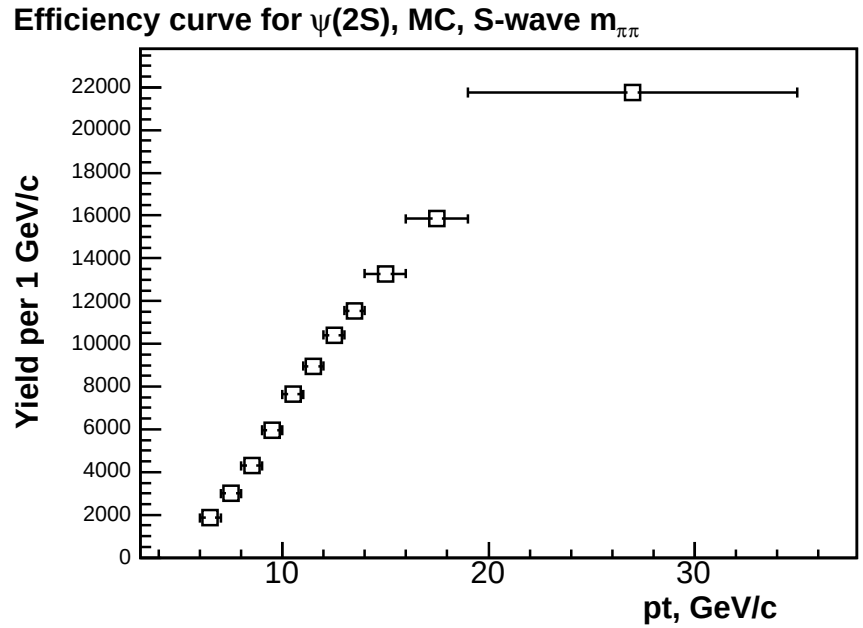


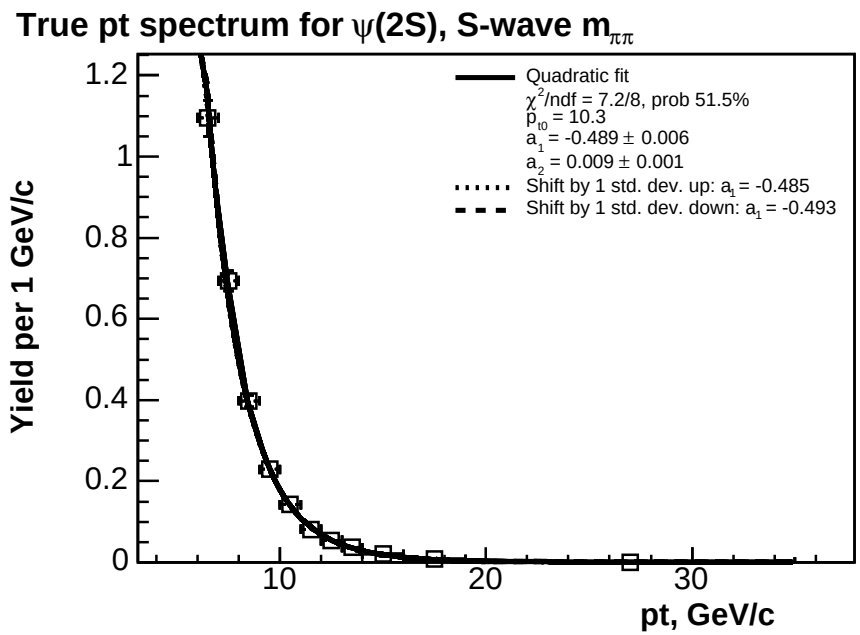
Efficiency corrections
not very sensitive to $m_{\pi\pi}$ shape

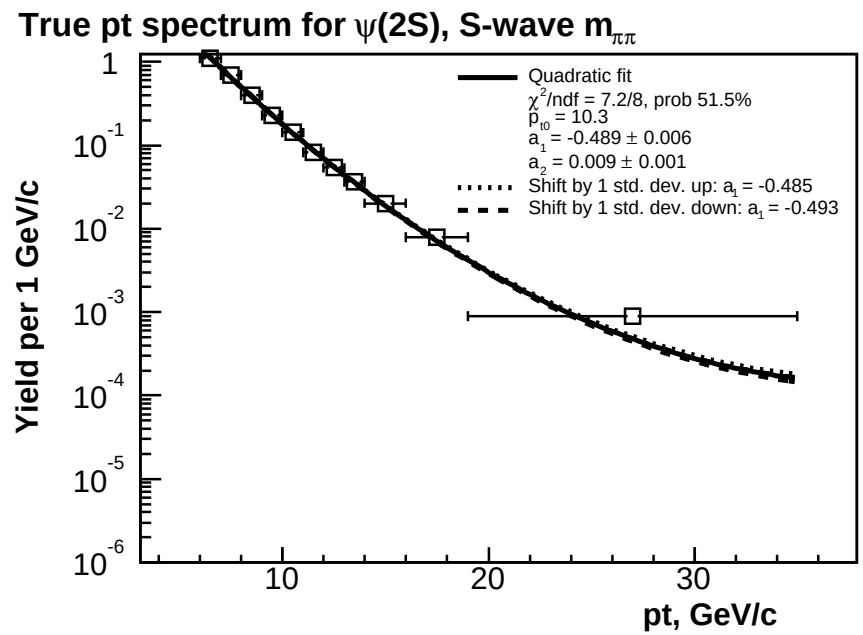
We will include ratio function into theoretical fit
to see general effect on $m_{\pi\pi}$ shape

Syst. from p_t shape for $\psi(2S)$– input for MC

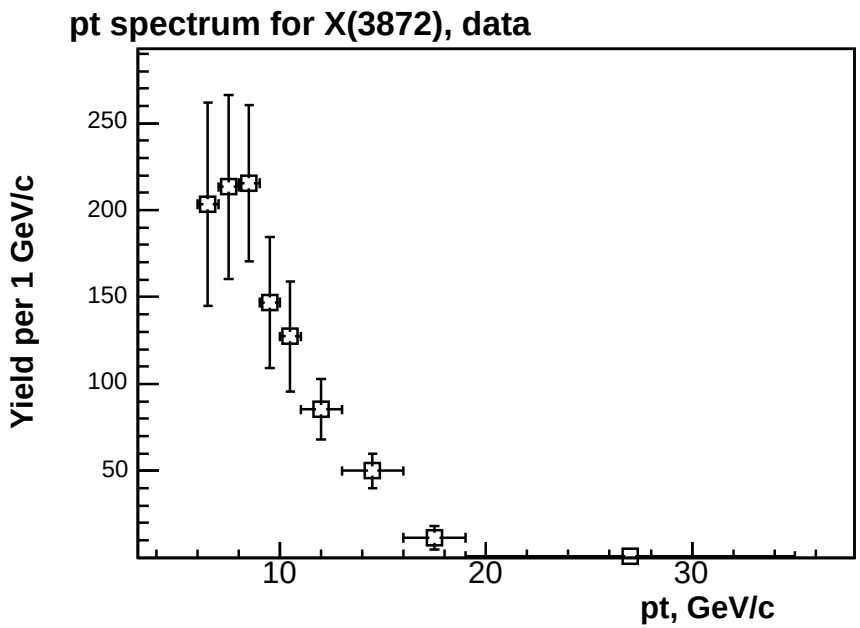


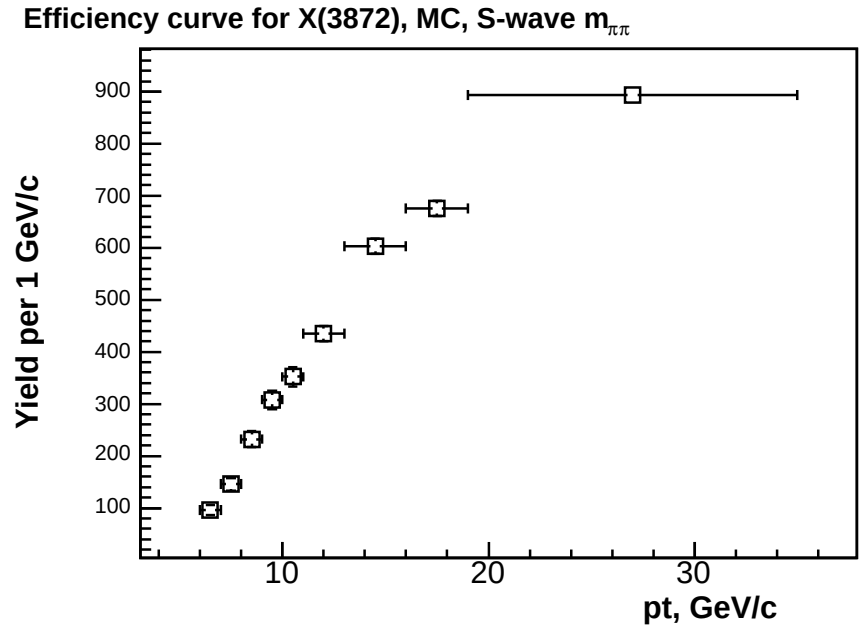


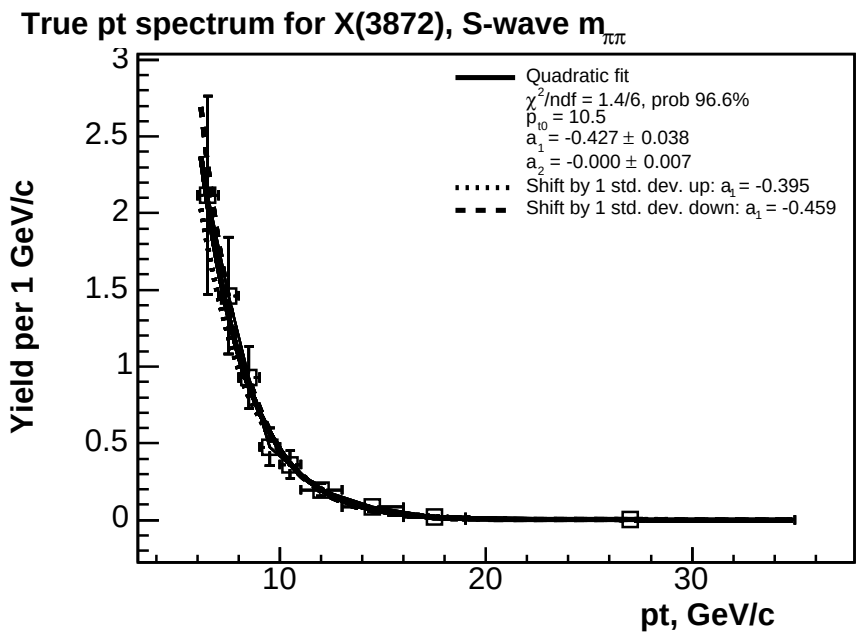


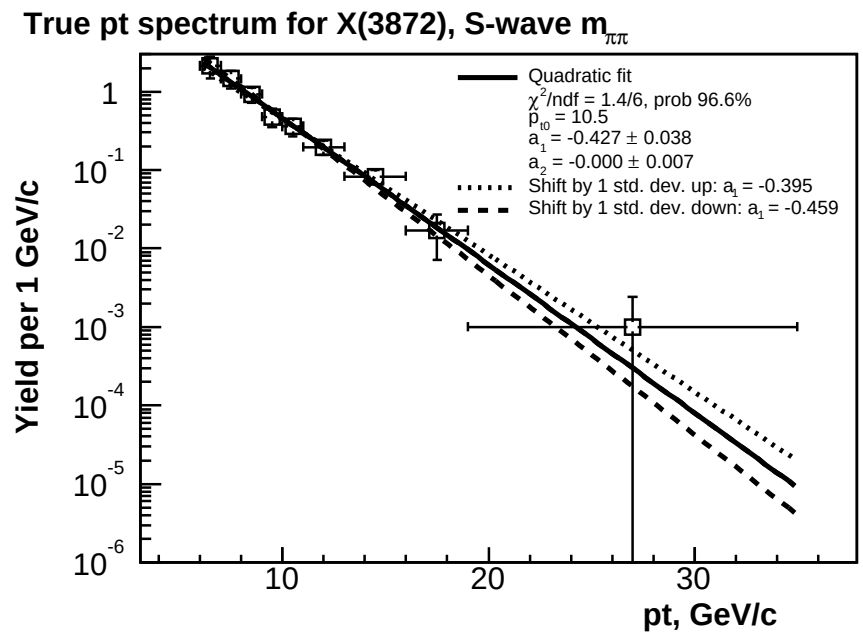


Syst. from p_t shape for X – input for MC

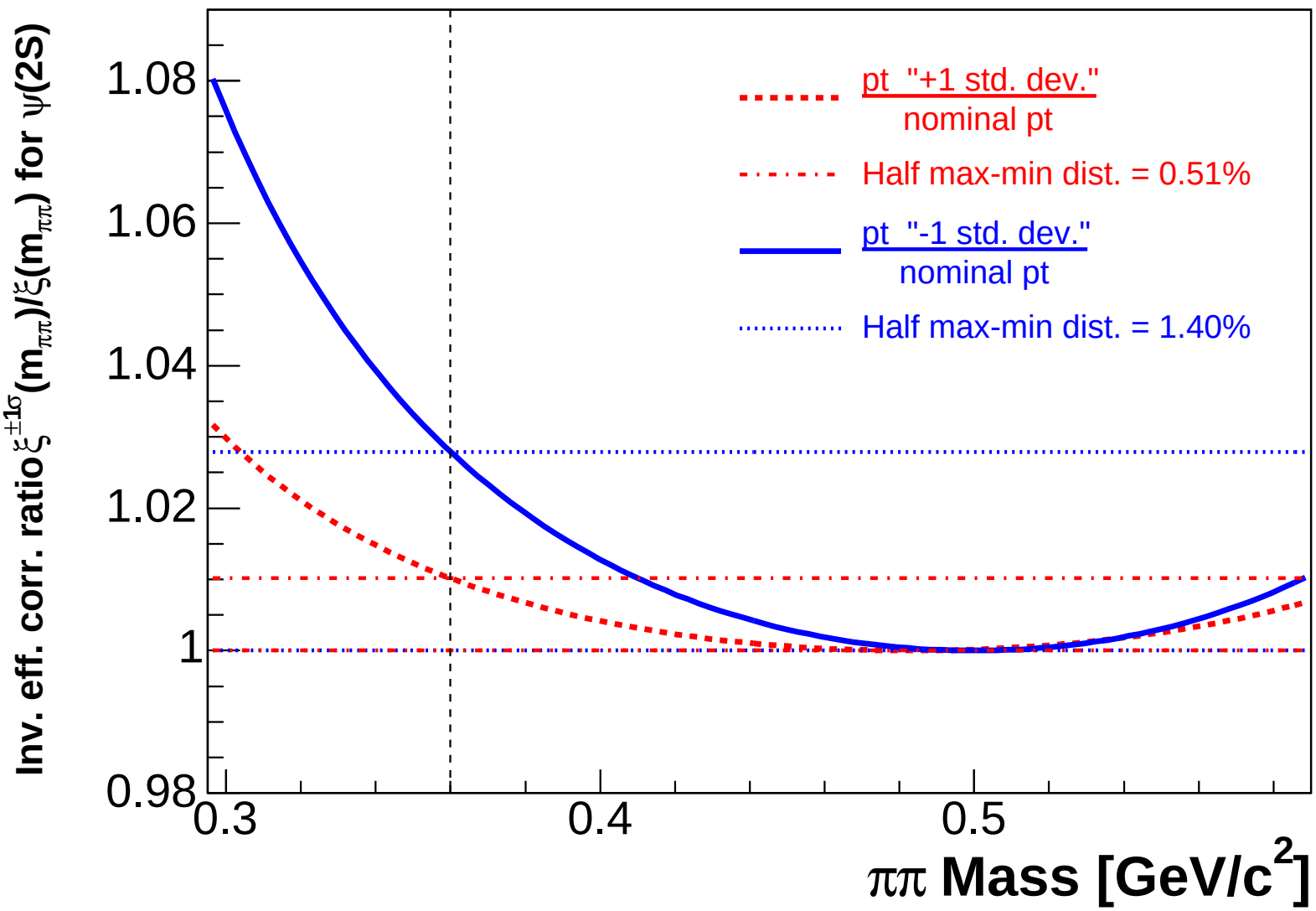


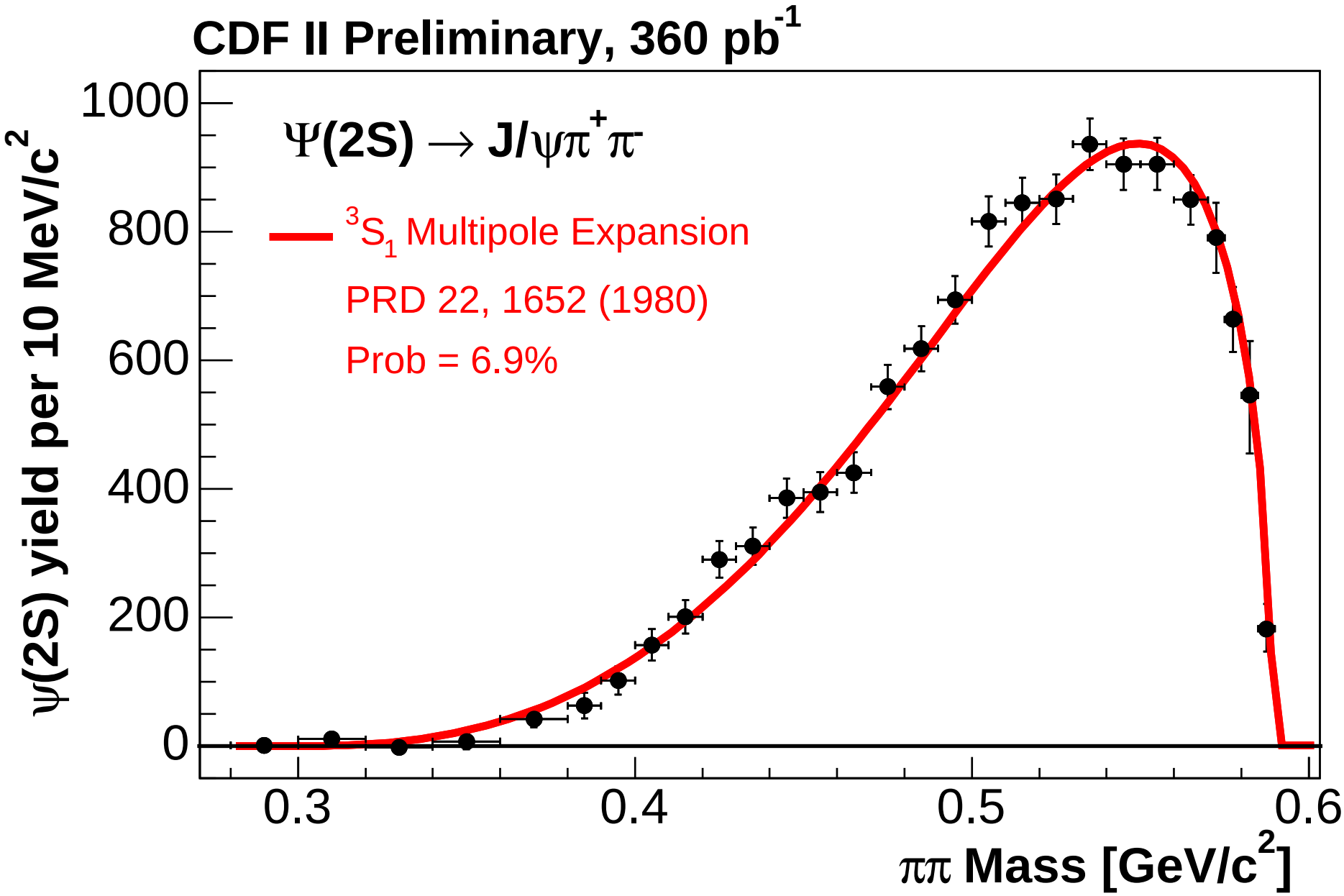


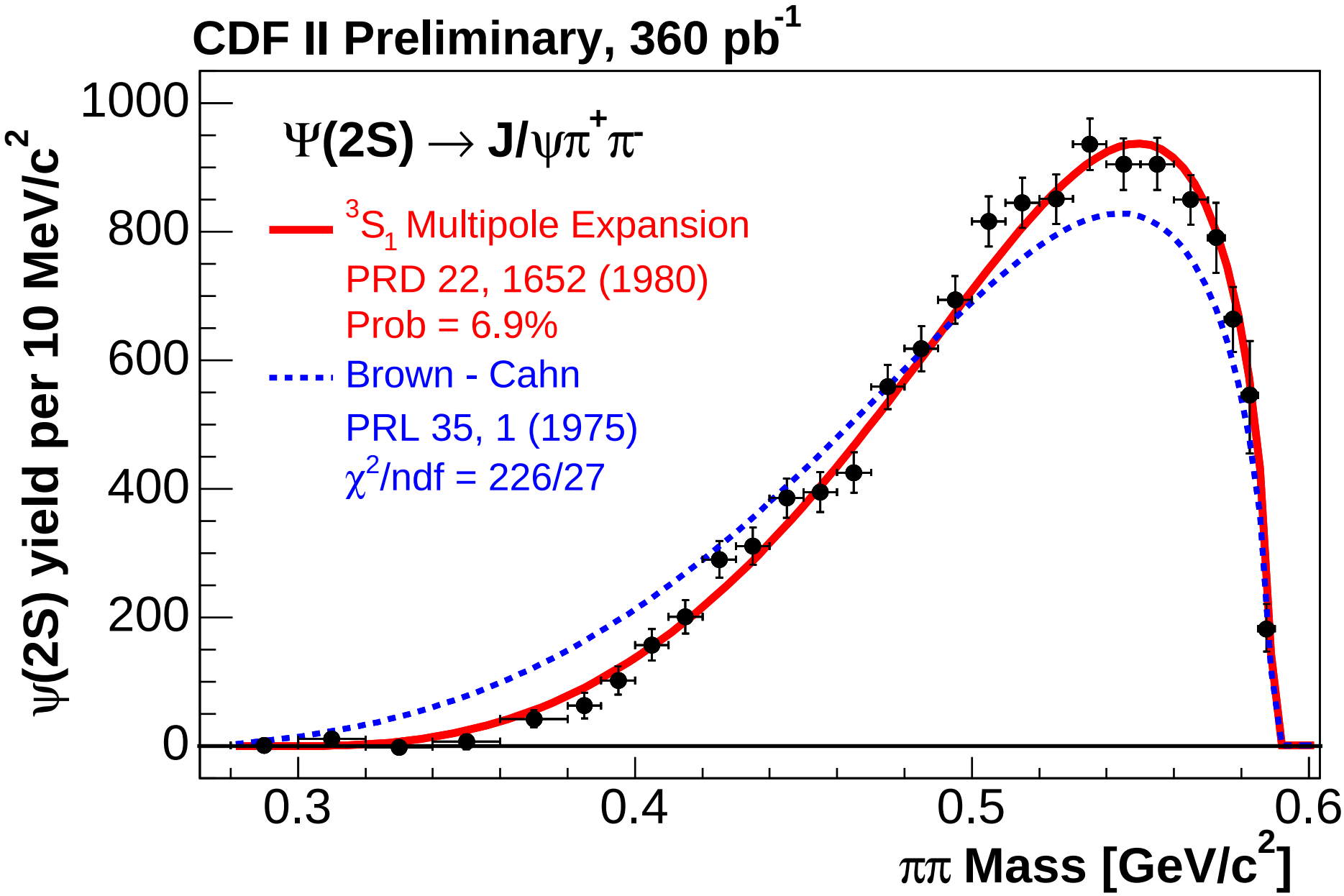




Systematics from p_t shape for $\psi(2S)$




CDF II Preliminary, 360 pb-1
Ψ(2S) → J/ψπ+π-
3S1 Multipole Expansion
PRD 22, 1652 (1980)
Prob = 6.9%
ψ(2S) yield per 10 MeV/c2
1000
800
600
400
200
0
0.3
0.4
0.5
0.6
ππ Mass [GeV/c2]

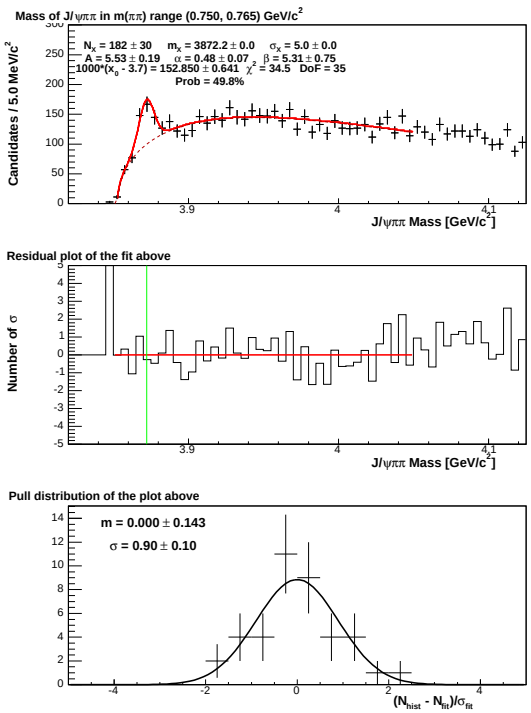

CDF II Preliminary, 360 pb^{-1}
$\Psi(2S) \rightarrow J/\psi\pi^+\pi^-$
$^3S_1$ Multipole Expansion
PRD 22, 1652 (1980)
Prob = 6.9%
Brown - Cahn
PRL 35, 1 (1975)
χ^2/ndf = 226/27
$\psi(2S)$ yield per 10 MeV/c^2
$\pi\pi$ Mass [GeV/c^2]
0
200
400
600
800
1000
0.3
0.4
0.5
0.6

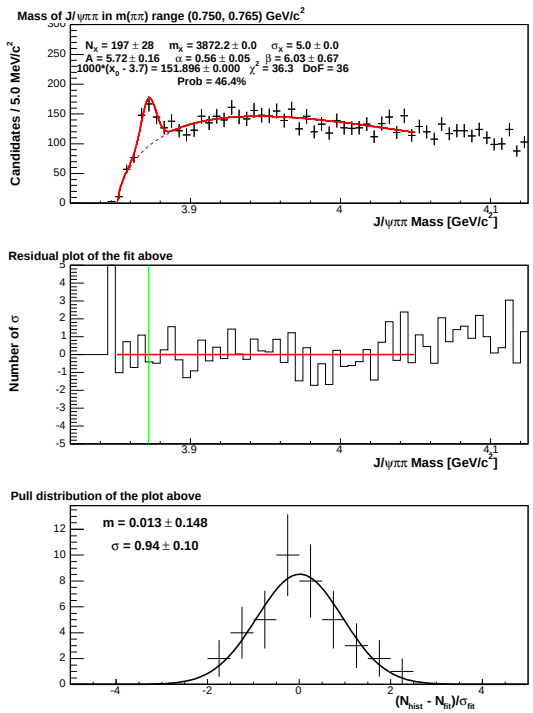
CDF II Preliminary, $360\ \mathrm{pb}^{-1}$

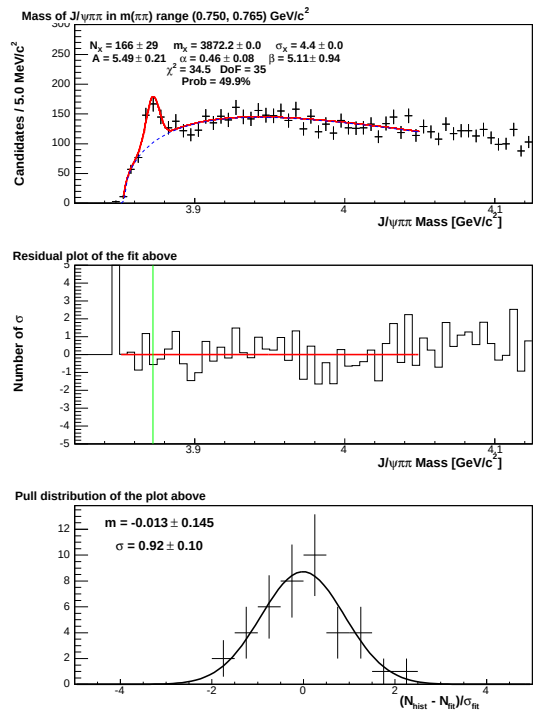
Model		$X(3872)$ Fit
Multipole Expansion for $c\bar{c}$	$^3S_1$ (higher-order corr.) Yan: PRD**22** 1652 (1980)	$B/A = -0.584 \pm 0.111$ $\chi^2/NDF = 17/14$ CL $= 27.7\%$
	$^1P_1$ Kuang *et al.*: PRD**37** 1210 (1988)	$\chi^2/NDF = 127/15$
	^3D_J Yan: PRD**22** 1652 (1980)	$\chi^2/NDF = 76/15$
	$J/\psi\pi\pi$ Phase-Space (PS)	$\chi^2/NDF = 102/15$
	$X(3872) \to J/\psi\rho$ (Breit-Wigner $\times$ PS)	$\chi^2/NDF = 16/15$ CL $= 36.1\%$

Systematics on third to last $X(3872)$ slice

Nominal fit	“Projected” turn-on	$X(3872)$ width -1σ
$N_X = 182 \pm 30$	$N_X = 197 \pm 28$	$N_X = 166 \pm 29$

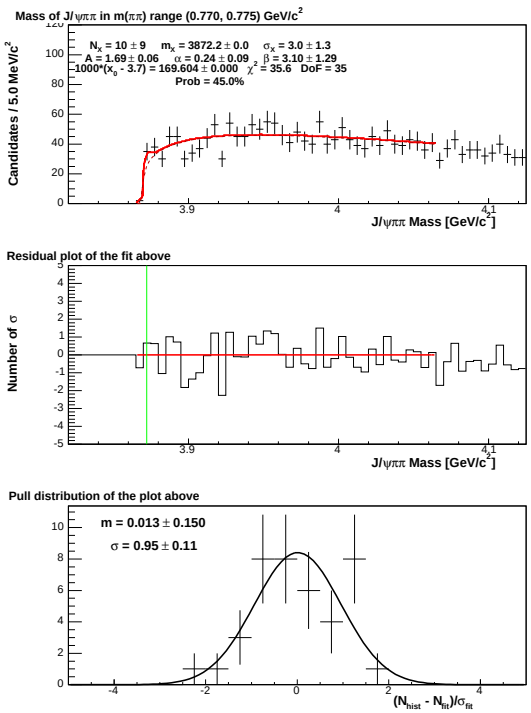


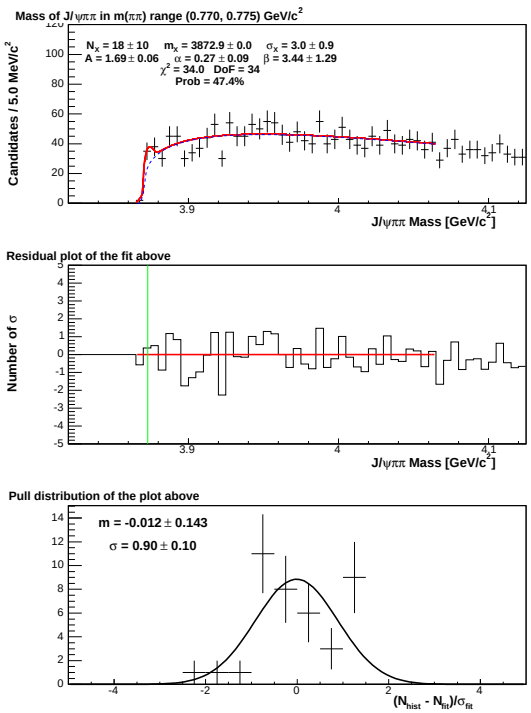


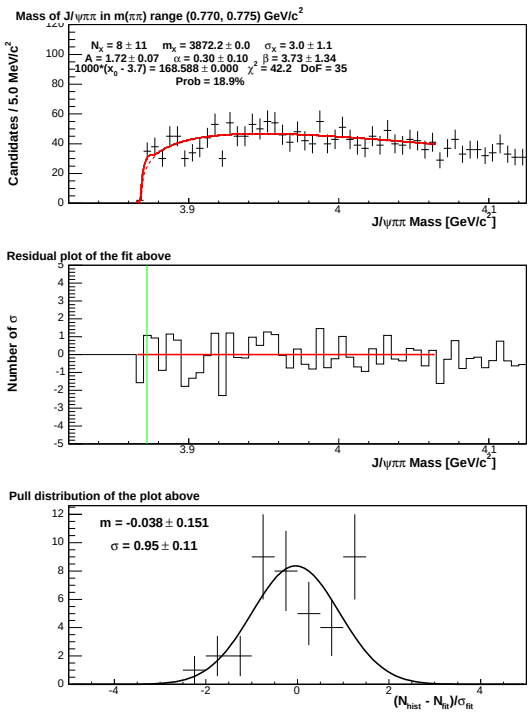


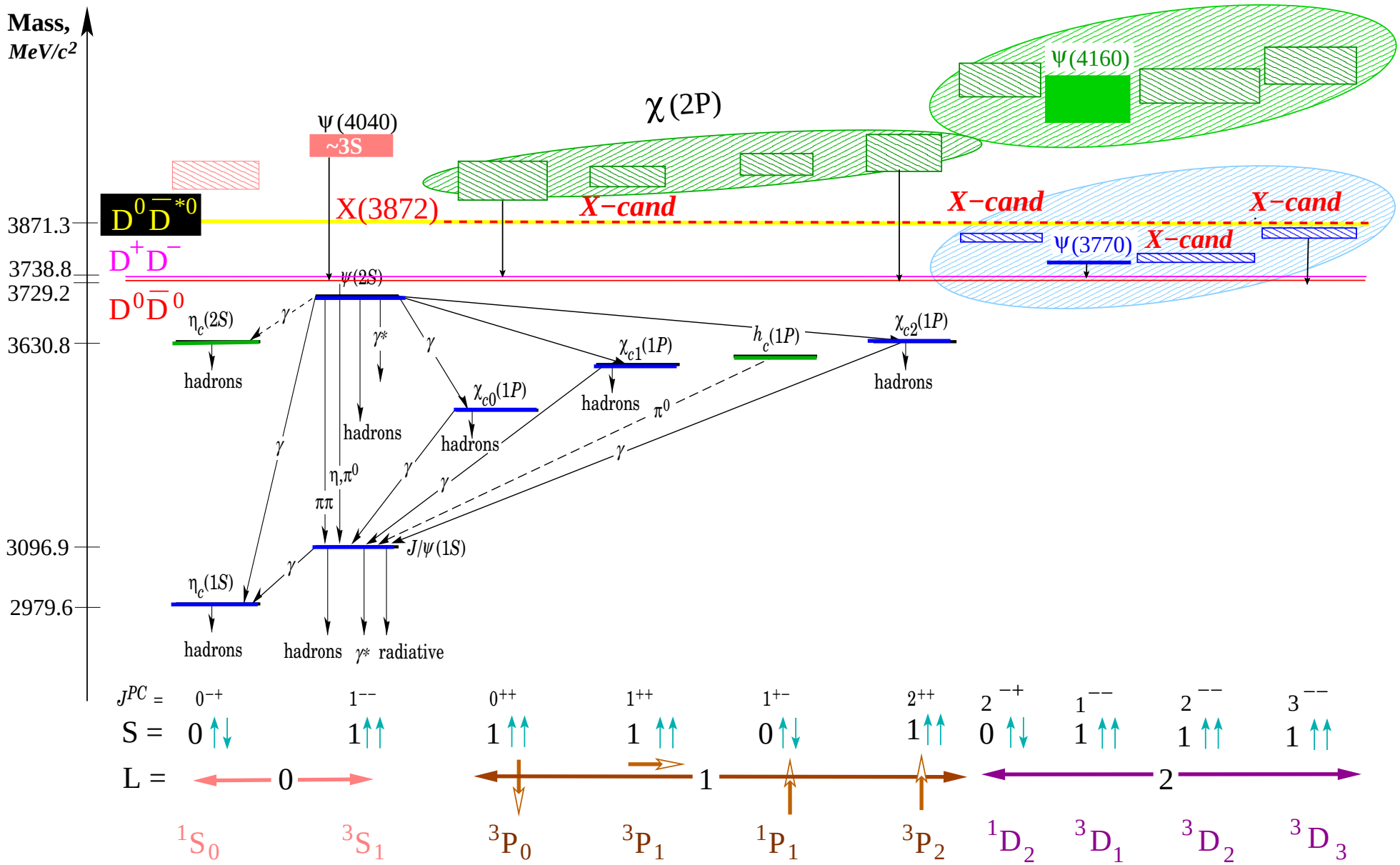
Systematics on last $X(3872)$ slice

Nominal fit	$X(3872)$ width $+1\sigma$	Turn-on -1σ
$N_X = 18 \pm 10$	$N_X = 18 \pm 10$	$N_X = 8 \pm 11$








Mass, MeV/c²
3871.3
3738.8
3729.2
3630.8
3096.9
2979.6
D⁰D̄*⁰
D⁺D⁻
D⁰D̄⁰
ψ(4040)
~3S
X(3872)
χ(2P)
ψ(4160)
X−cand
X−cand
X−cand
X−cand
ψ(3770)
ψ(2S)
η_c(2S)
χ_c0(1P)
χ_c1(1P)
h_c(1P)
χ_c2(1P)
J/ψ(1S)
η_c(1S)
hadrons
γ
γ*
π⁰
η,π⁰
ππ
radiative
J^PC =
0⁻⁺
1⁻⁻
0⁺⁺
1⁺⁺
1⁺⁻
2⁺⁺
2⁻⁺
1⁻⁻
2⁻⁻
3⁻⁻
S =
L =
¹S₀
³S₁
³P₀
³P₁
¹P₁
³P₂
¹D₂
³D₁
³D₂
³D₃