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New results on the $X(3872)$ from CDF

Michal Kreps, University of Karlsruhe

for the CDF Collaboration

bmb+f - Förderschwerpunkt
Elementarteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

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The X(3872)

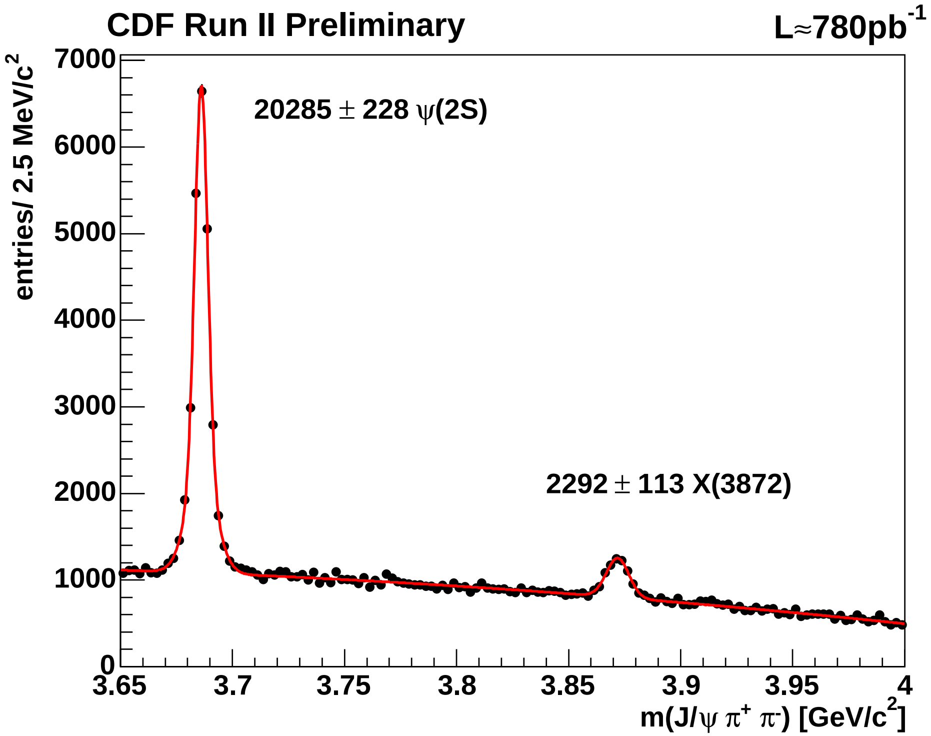
- discovered 2003 by Belle in search for charmonium states
- $m = 3871.3 \pm 0.7 \pm 0.4 \mathrm{MeV/c^2}$

  CDF PRL 93, 072001 (2004)
- $\Gamma < 2.3 \mathrm{MeV/c^2}$

  Belle PRL 91, 26001 (2003)
- No X^{++} or X^{--}

  CDF PRL 93, 072001 (2004)
- No iso-partner $X^{\pm}$

  BaBar PRD 71, 031501 (2005)
- Evidence for $X \to J/\psi\gamma$, $J/\psi\omega$ Belle, hep-ex/0505037

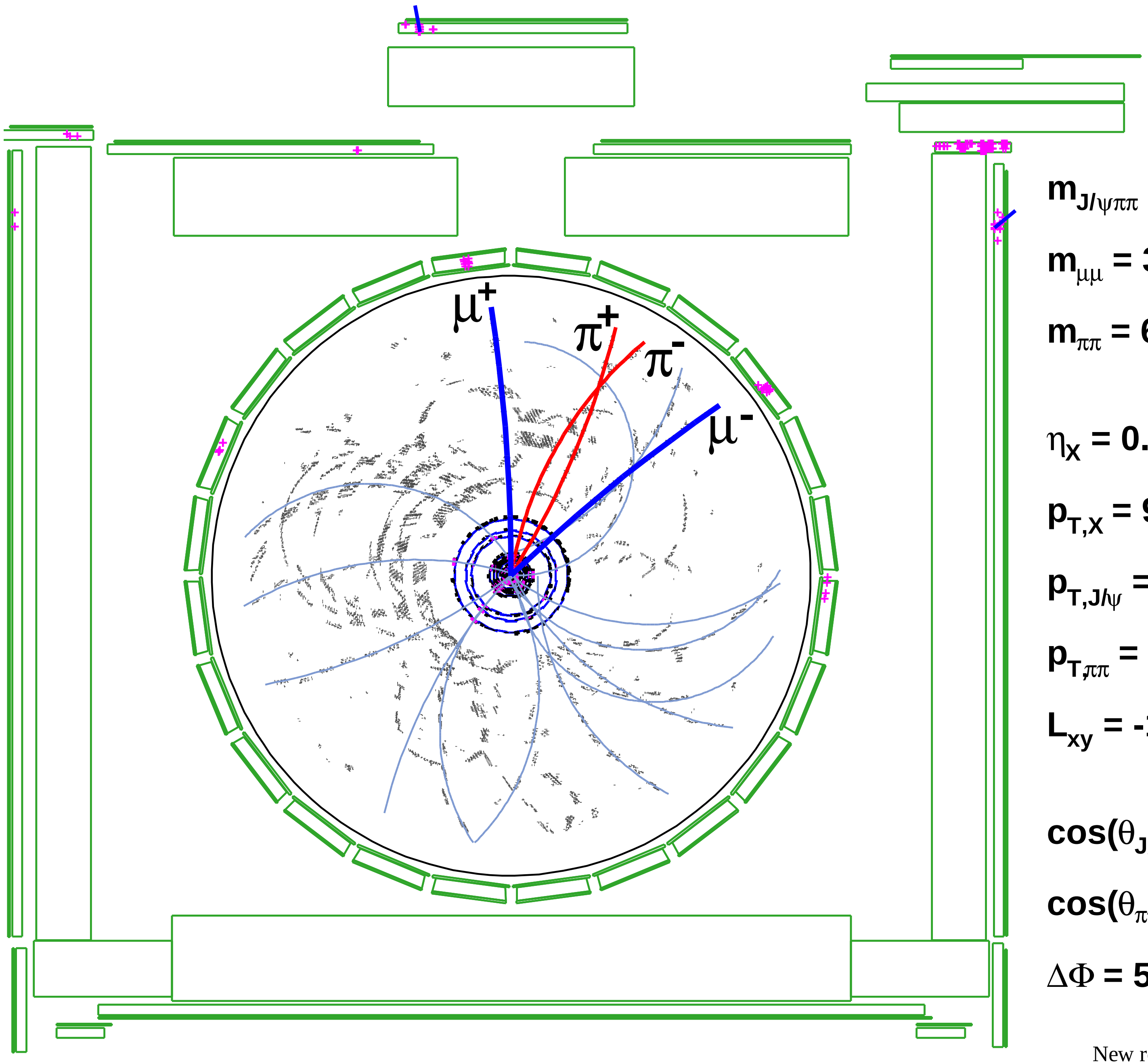


$\Rightarrow$ What is the $X(3872)$? Charmonium? Exotic?

$\rightarrow$ determine quantum numbers J^{PC}

- $m(\pi^+\pi^-)$
- distribution of angles between decay particles

Typical X(3872) event



$m_{J/\psi\pi\pi}$ = 3872 MeV/c^2

$m_{\mu\mu}$ = 3072 MeV/c^2

$m_{\pi\pi}$ = 698 MeV/c^2

η_X = 0.14

$p_{T,X}$ = 9.3 GeV/c

$p_{T,J/\psi}$ = 6.7 GeV/c

$p_{T,\pi\pi}$ = 2.6 GeV/c

L_{xy} = -148 μm

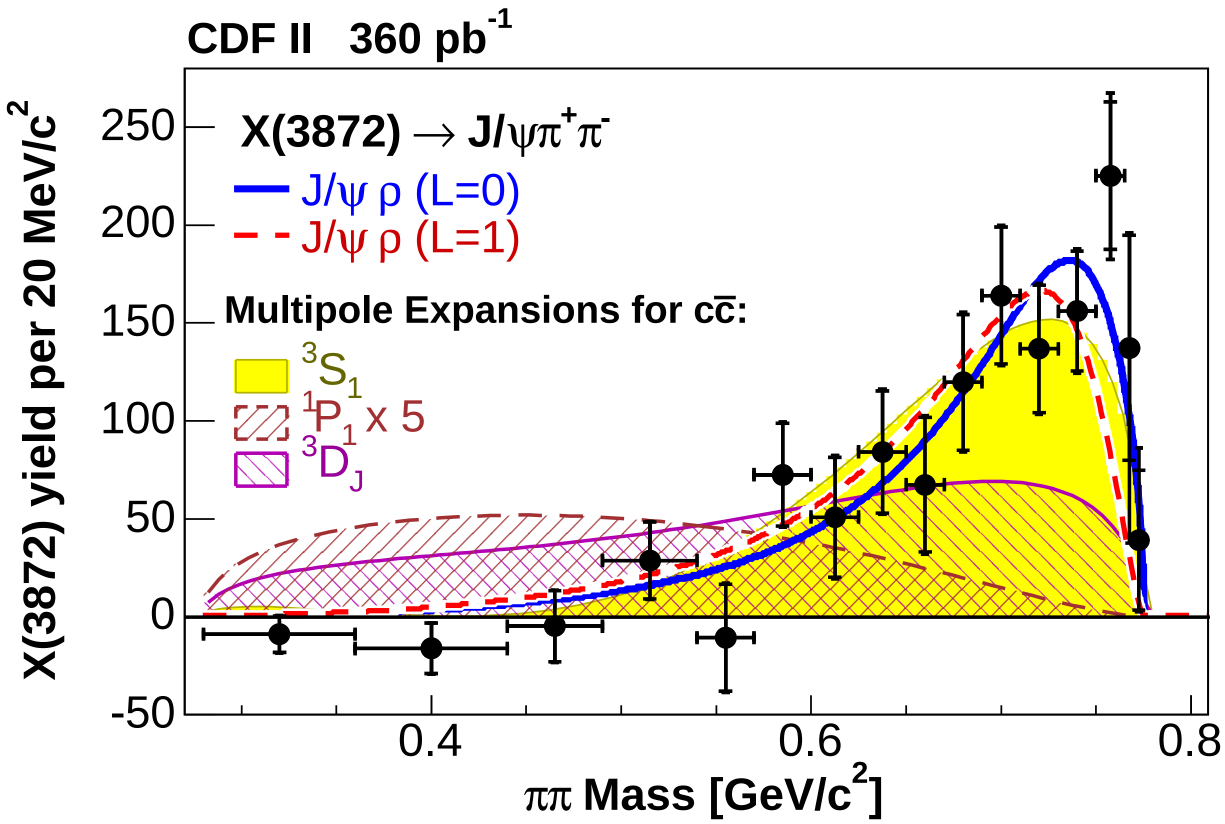
cos($\theta_{J/\psi}$) = -0.29

cos($\theta_{\pi\pi}$) = 0.56

ΔΦ = 5.95

$m(\pi^+\pi^-)$ distribution for $X(3872)$

- Mass spectrum sensitive to J^{PC}
- If $(\pi^+\pi^-)$ in s-wave: needs modelling, e.g. multipole expansion
- If $(\pi^+\pi^-)$ in p-wave: shape from Breit-Wigner



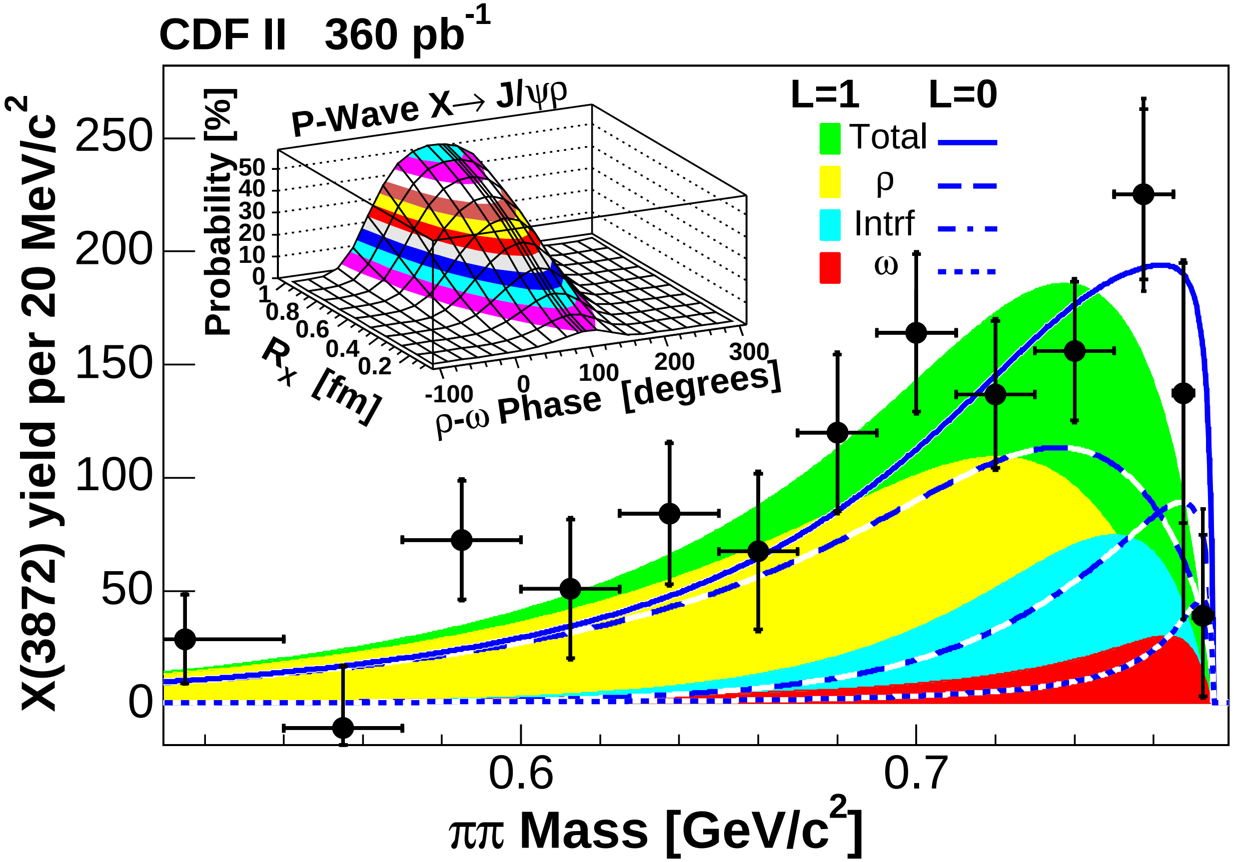
- $m(\pi^+\pi^-)$ favours high end of spectrum

  $\Rightarrow$ Compatible with intermediate ρ^0 resonance
- Also $^3S_1$ multipole expansion possible
  - no $c\bar{c}$ candidate at this mass
  - $^3S_1$ has $J^{PC} = 1^{--}$ but non-observation by BES

$\mathrm{m}(\pi^+\pi^-)$ distribution for $\mathrm{X}(3872)$

- for broad resonances
  - $\rightarrow$ kinematic quantities vary across width
  - $\rightarrow$ introduce form factor Blatt-Weisskopf depends on L and effective range R

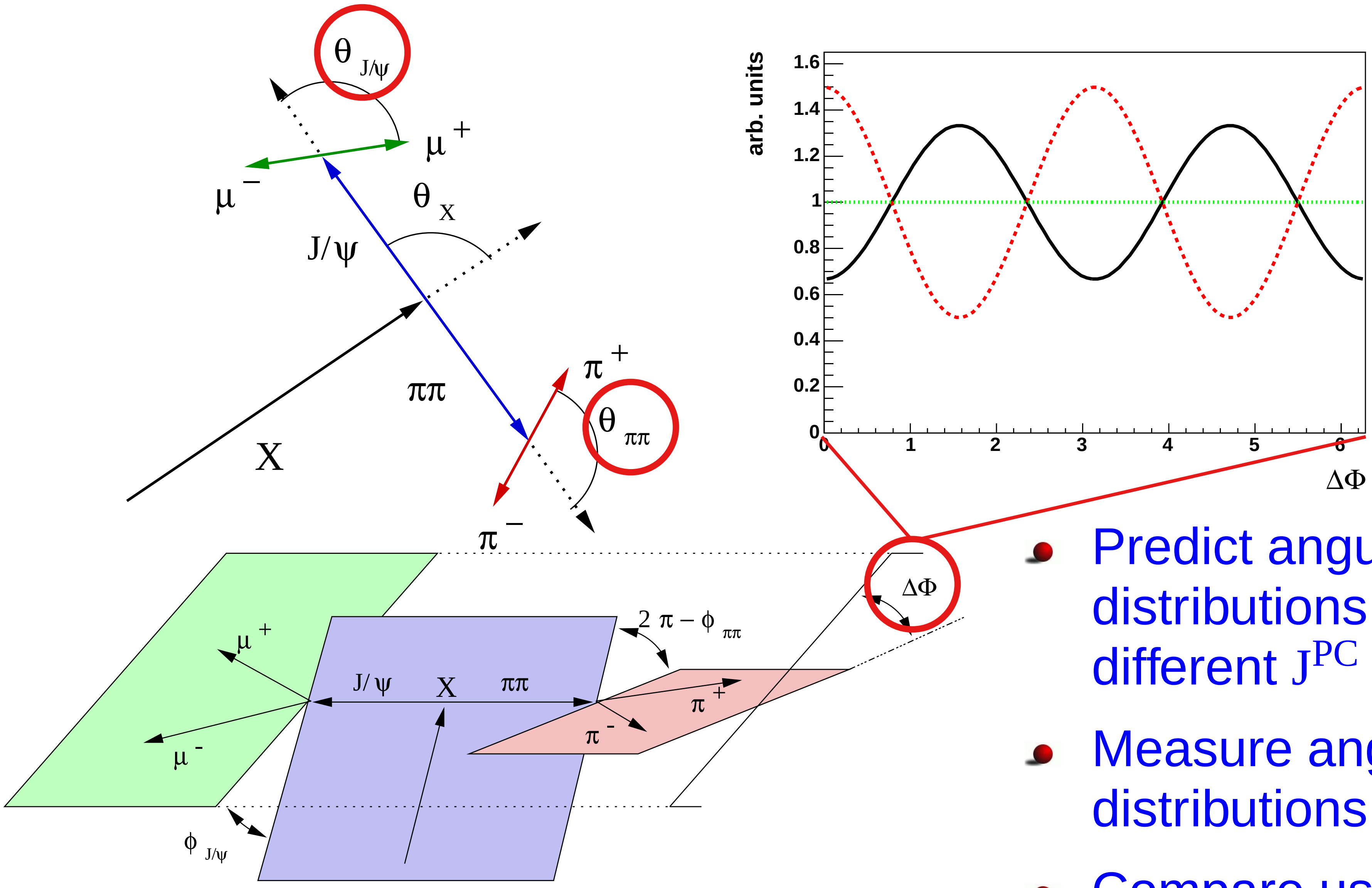
    [Belle doesn't use it]



- Possible ρ^0-ω mixing
  - Both $\mathrm{L}=0$ and $\mathrm{L}=1$ compatible with data
  - ρ/ω mixing improves agreement even more for L=1

$\Rightarrow$ To get more information, do angular analysis

Angular analysis

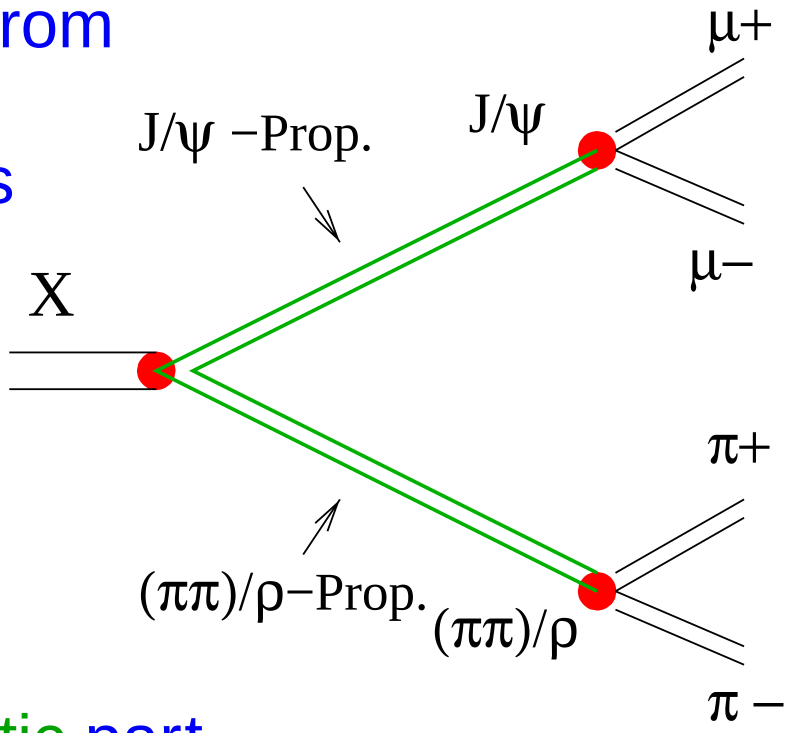


- Predict angular distributions for different J^{PC}
- Measure angular distributions in data
- Compare using χ^2

Angular analysis - predictions

Predictions for kinematic decay quantities from
helicity formalism
$\Rightarrow$ decay chain as sequential 2-body decays

$$X(3872) \to J/\psi(\pi^+\pi^-)_{s,p} \to \mu^+\mu^-\pi^+\pi^-$$



We need:

- one matrix element per decay vertex
- propagators to connect vertices

$$M \propto M_X \cdot (P_{J/\psi} \cdot M_{J/\psi}) \cdot (P_{\pi\pi} \cdot M_{\pi\pi})$$

matrix elements consist of angular and kinetic part

$$M = A_{J_i,\lambda_i}(\theta,\phi) \cdot T(|\vec{p}|, L)$$

$\Rightarrow$ J/ψ propagator $\Leftrightarrow$ PDG mass
$\Rightarrow$ $(\pi^+\pi^-)_{s,p}$ propagator model dependent
Assume lowest L to be dominant $\Rightarrow$ neglect others
Make dedicated simulation for each J^{PC} hypothesis

Angular analysis - predictions

Limitations from helicity formalism:

- No model independent description of $\pi^+\pi^-$ s-wave
- Breit-Wigner for $\rho^0 \rightarrow \pi^+\pi^-$ depends on form-factor details

$\rightarrow$ fix $m_{\pi\pi}$ distribution to describe data

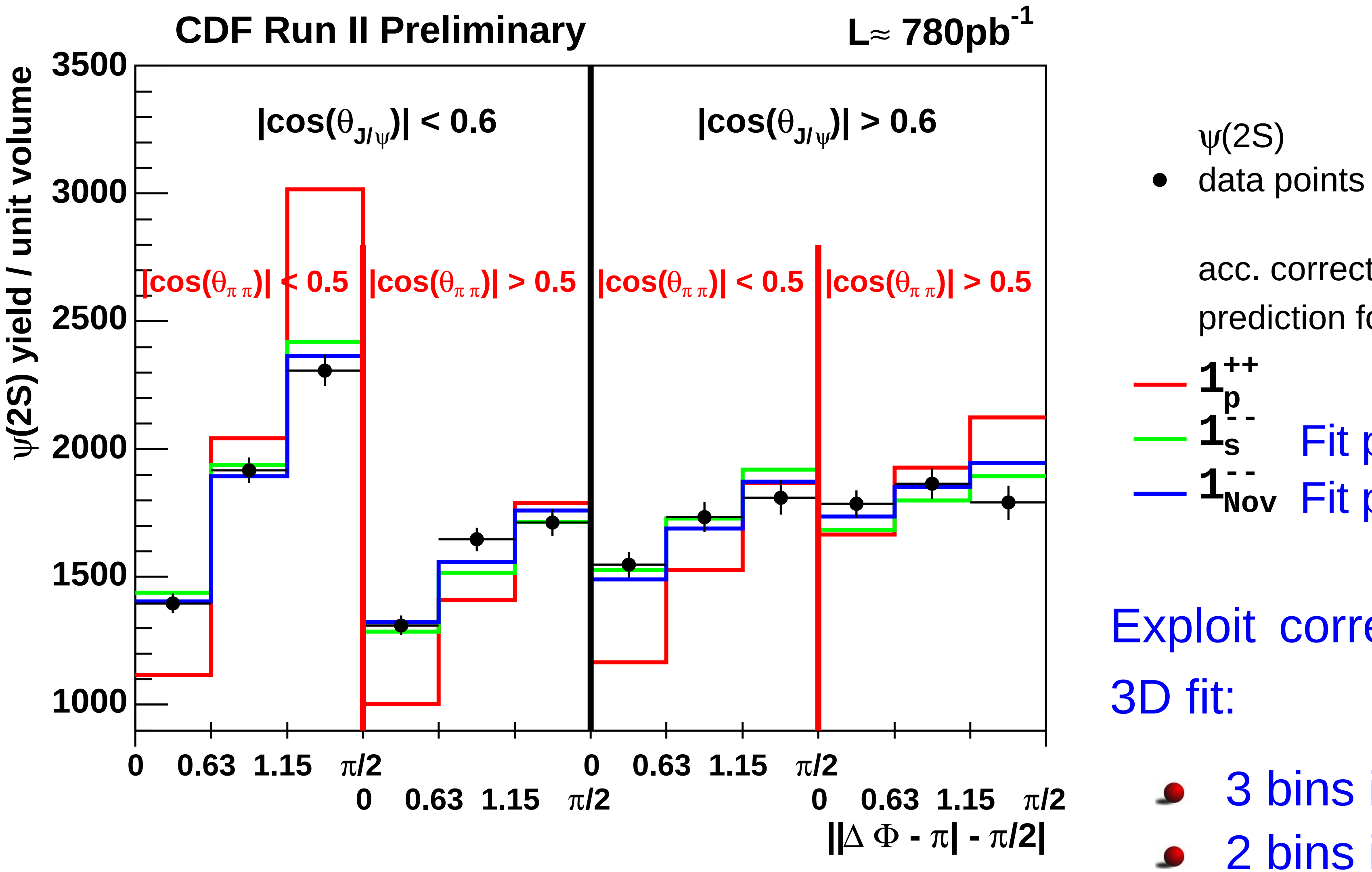
$\rightarrow$ Use angular distributions only

- $\mathrm{J}^{\mathrm{PC}} = 1^{-+}$ and 2^{-+}: multiple sub-states with same L contribute

$$M(1^{-+}) = r_0 \mathrm{e}^{i\phi_0} M(1^{-+}_{S=0}) + r_1 \mathrm{e}^{i\phi_1} M(1^{-+}_{S=1}) + r_2 \mathrm{e}^{i\phi_2} M(1^{-+}_{S=2})$$

$\Rightarrow$ Can arbitrary mixture describe the data?

Cross-check on $\psi(2S)$



Fit prob. 1.5%

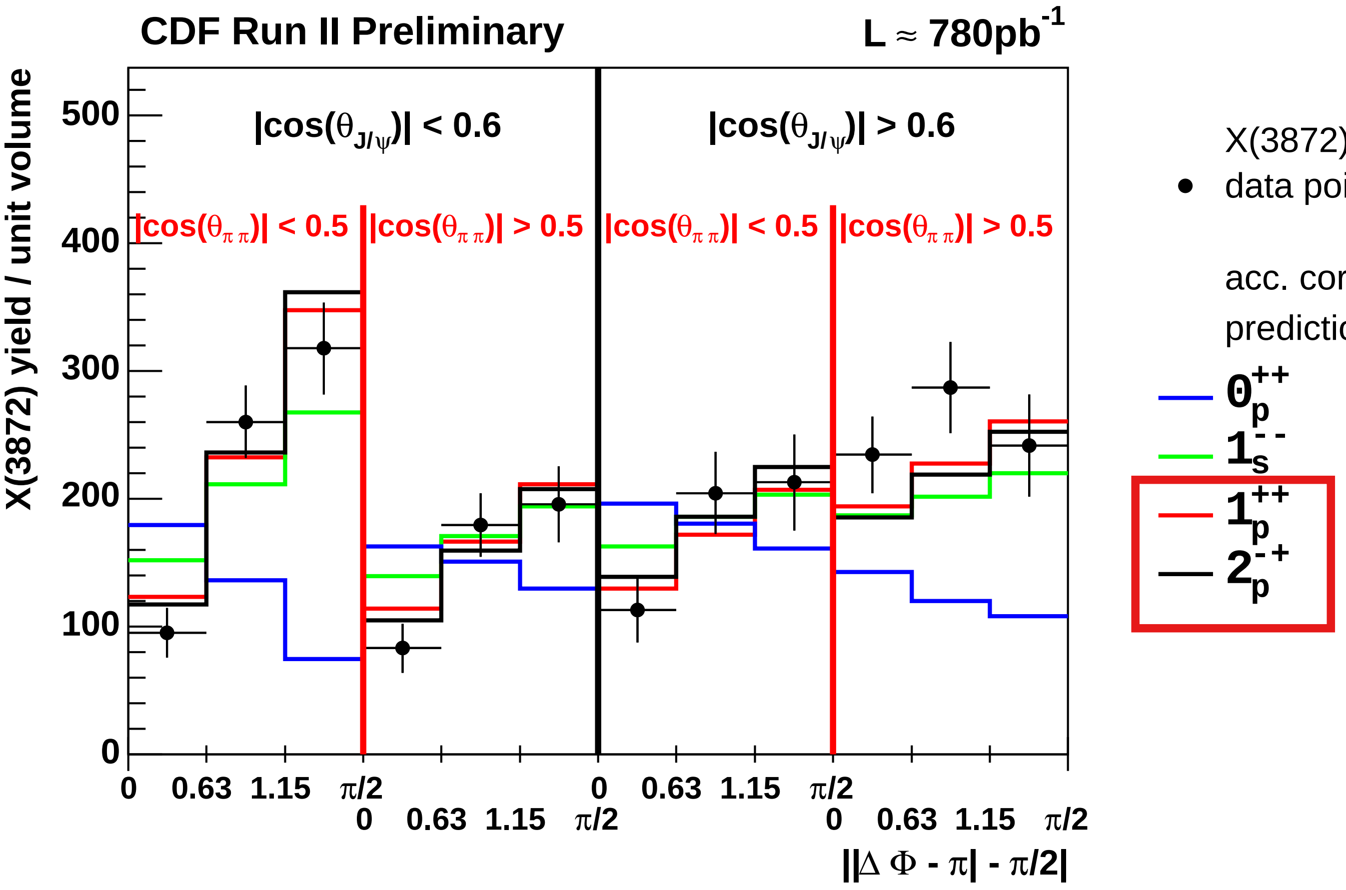
Fit prob. 17.9%

Exploit correlations via 3D fit:

- 3 bins in $\Delta\phi$
- 2 bins in $\theta_{J/\psi}$
- 2 bins in $\theta_{\pi\pi}$

Obtained correct result $J^{PC} = 1^{--}$

Result for X(3872)



hypothesis	χ^2 prob.
1^{++}	27.8%
2^{-+}	25.8%
1^{--}	0.02%
2^{+-}	$5.5 \cdot 10^{-5}$
1^{+-}	$3.8 \cdot 10^{-5}$
2^{--}	$3.8 \cdot 10^{-5}$
3^{+-}	$3.8 \cdot 10^{-5}$
3^{--}	$2.4 \cdot 10^{-5}$
2^{++}	$1.1 \cdot 10^{-5}$
1^{-+}	$4.1 \cdot 10^{-6}$
0^{-+}	$3.5 \cdot 10^{-17}$
0^{+-}	$\leq 1 \cdot 10^{-20}$
0^{++}	$\leq 1 \cdot 10^{-20}$

Only $J^{PC} = 1^{++}$ and 2^{-+} compatible with data!
All other hypothesis excluded by more than 3σ

What is the $X(3872)$?

- Charmonium?

  Potential candidates:
  - $\chi_c^{'}$ $({}^3P_1 \ \mathrm{J^{PC}} = 1^{++})$
  - η_{c2} $({}^1D_2 \ \mathrm{J^{PC}} = 2^{-+})$

  But:
  - Decay via ρ violates isospin
  - Mass predictions from potential models $\approx 50\text{-}100\, MeV/c^2$ off

- Exotic?
  - $m(X) \approx m(D^0) + m(D^{0*}) \rightarrow$ coincidence?
  - evidence for $X(3872) \rightarrow D^0\overline{D}^0\pi^0$ by Belle [hep-ex/0606055]
  - charmed molecule? $c\bar{c}q\bar{q}$ or $D^0\overline{D}^{0*}$ or ...
  - hybrid state ? $c\bar{c}g$, but expected above $\approx 4\, GeV/c^2$
  - mainly charmonium - but interaction with $D^0\overline{D}^{0*}$?

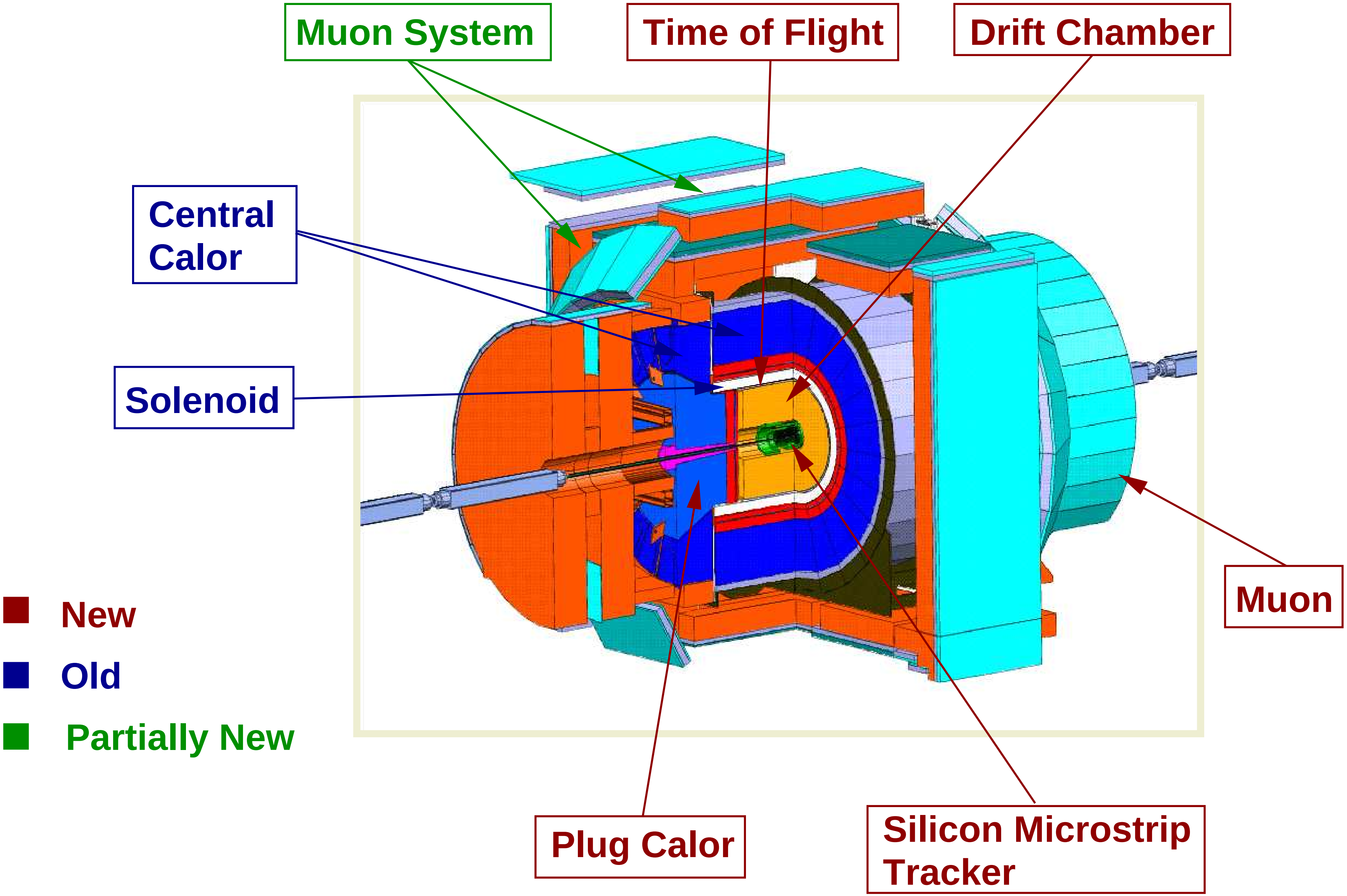
Conclusions

- New results on properties of the $X(3872)$ by CDF
- $m(\pi^+\pi^-)$
  - Both L=0 and L=1 transitions via ρ compatible with data
  - $\Rightarrow$ Cannot exclude J^{-+} hypothesis from $m(\pi^+\pi^-)$
  - Using same model as Belle, L=1 can be excluded, but is that correct model?
- 3D angular analysis
  - Stay as model independent as possible
  - Only $\mathrm{J}^{\mathrm{PC}} = 1^{++}$ or 2^{-+} describes data
  - Other hypothesis excluded at 3σ level

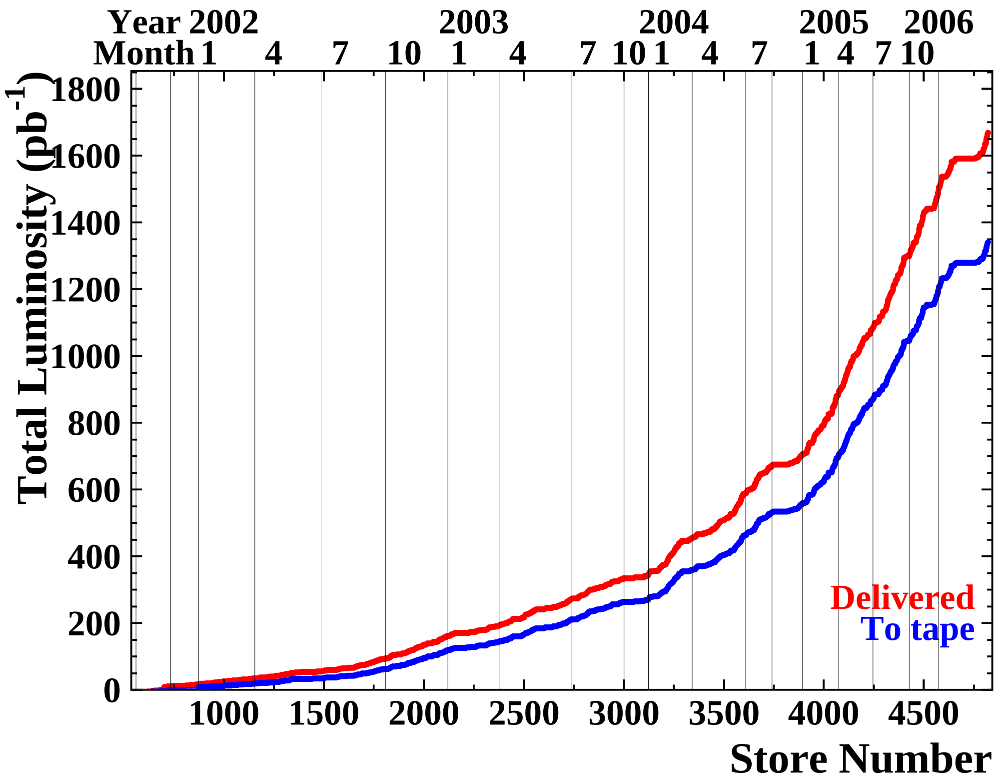
$\Rightarrow$ Both, charmonium and exotic interpretations still "in the game"

Backup

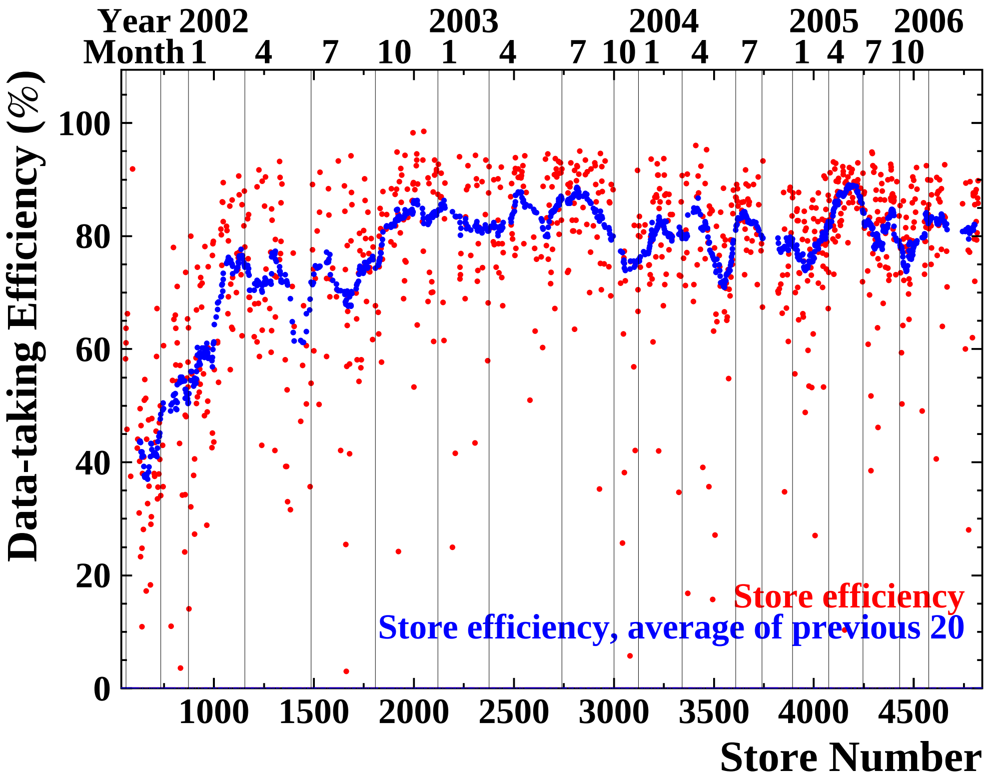
CDF Detector



Luminosity



Year 2002
2003
2004
2005
2006
Month 1
4
7
10
1
4
7
10
1
4
7
1
4
7
10
Total Luminosity (pb^{-1})
1800
1600
1400
1200
1000
800
600
400
200
0
1000
1500
2000
2500
3000
3500
4000
4500
Store Number
Delivered
To tape



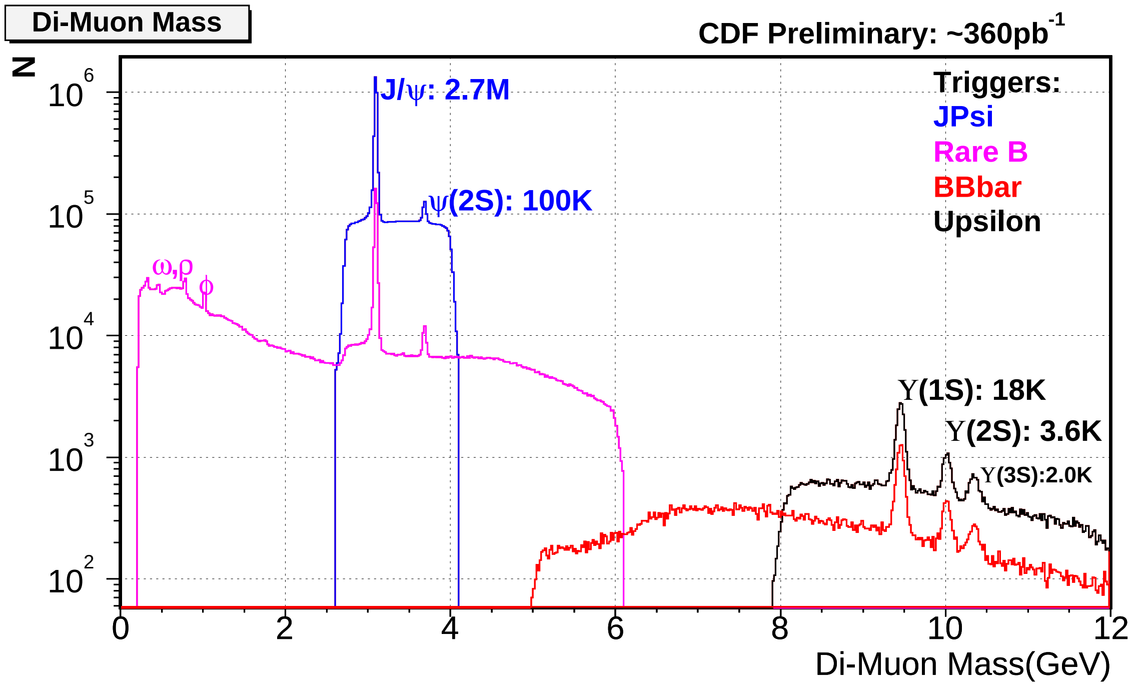
Year 2002
2003
2004
2005
2006
Month 1
4
7
10
1
4
7
10
1
4
7
1
4
7
10
Data-taking Efficiency (%)
100
80
60
40
20
0
1000
1500
2000
2500
3000
3500
4000
4500
Store Number
Store efficiency
Store efficiency, average of previous 20

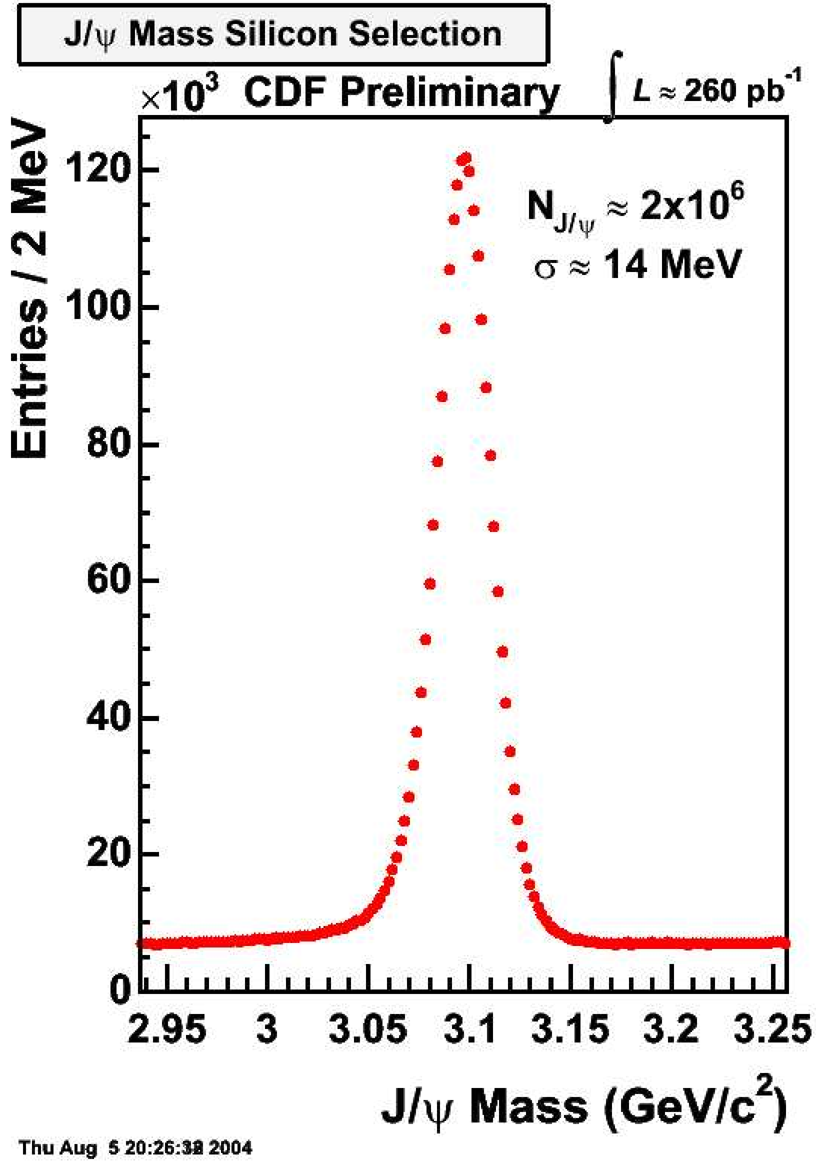
$J/\psi \to \mu^+\mu^-$ Trigger

Evaluate muon chamber info on trigger level:

Select events with $m(\mu\mu)$ aroung $m(J/\psi)$

- $\longrightarrow$ high purity
- $\longrightarrow$ high statistics

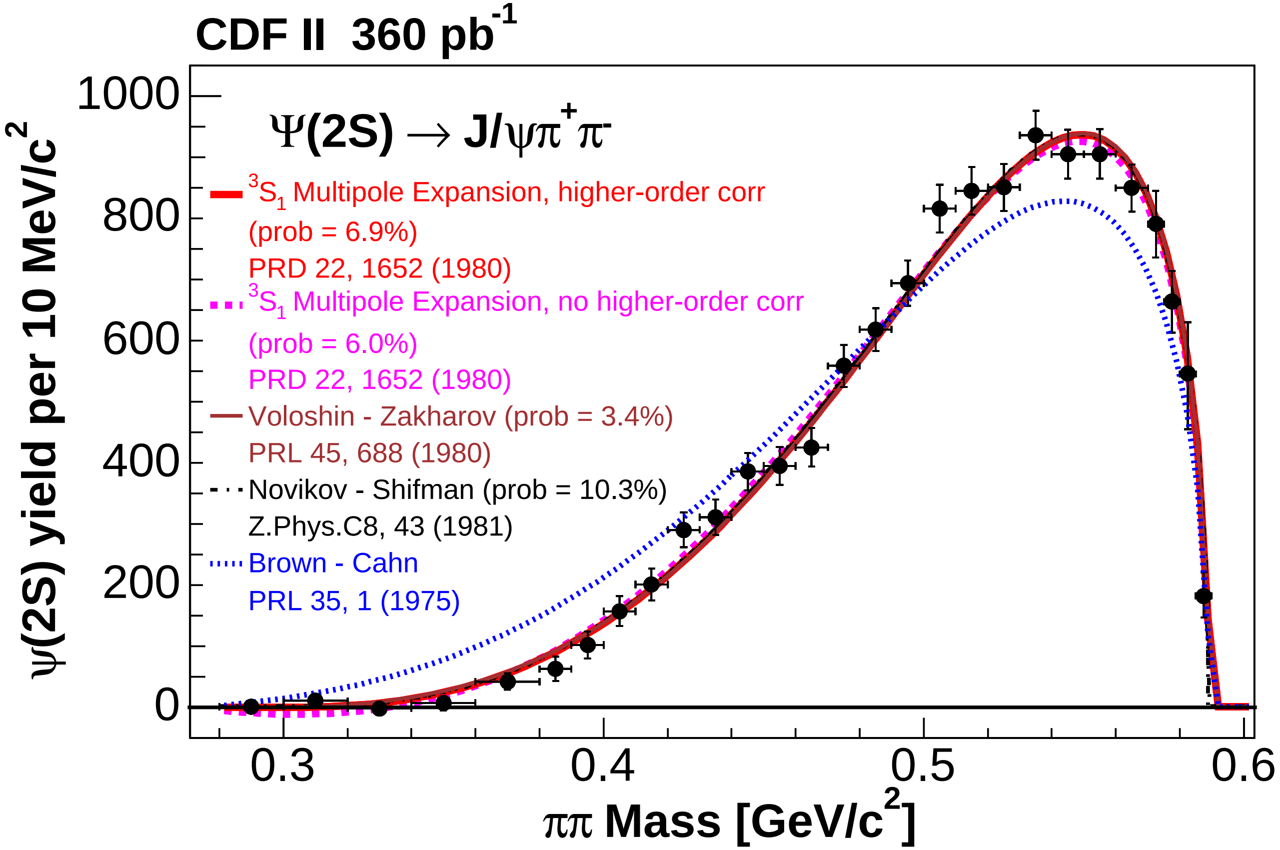




$m(\pi^+\pi^-)$ distribution for $\psi(2S)$

- Same exclusive final state
- High statistics
- Known properties

$\Rightarrow$ Can test methods



- High precision data by CDF
- Allows to discriminate between models
- Correct models are preferred

The m($\pi^+\pi^-$) mass spectrum

Ambiguity in modelling $m(\pi^+\pi^-)$ spectrum:

- No prefered model for $(\pi^+\pi^-)$ system in s-wave
- For $(\pi^+\pi^-)$ system in p-wave use ρ Breit-Wigner

$$\frac{d\Gamma_X}{dm_{\pi\pi}} = 2m_{\pi\pi}\frac{\Gamma_{X\to J/\psi\rho}(m_{\pi\pi})\cdot 2m(\pi\pi)\Gamma_{\rho\to\pi\pi}}{(m_{\pi\pi}^2 - m_\rho^2)^2 + m_\rho^2\Gamma_\rho^2(m_{\pi\pi})}$$

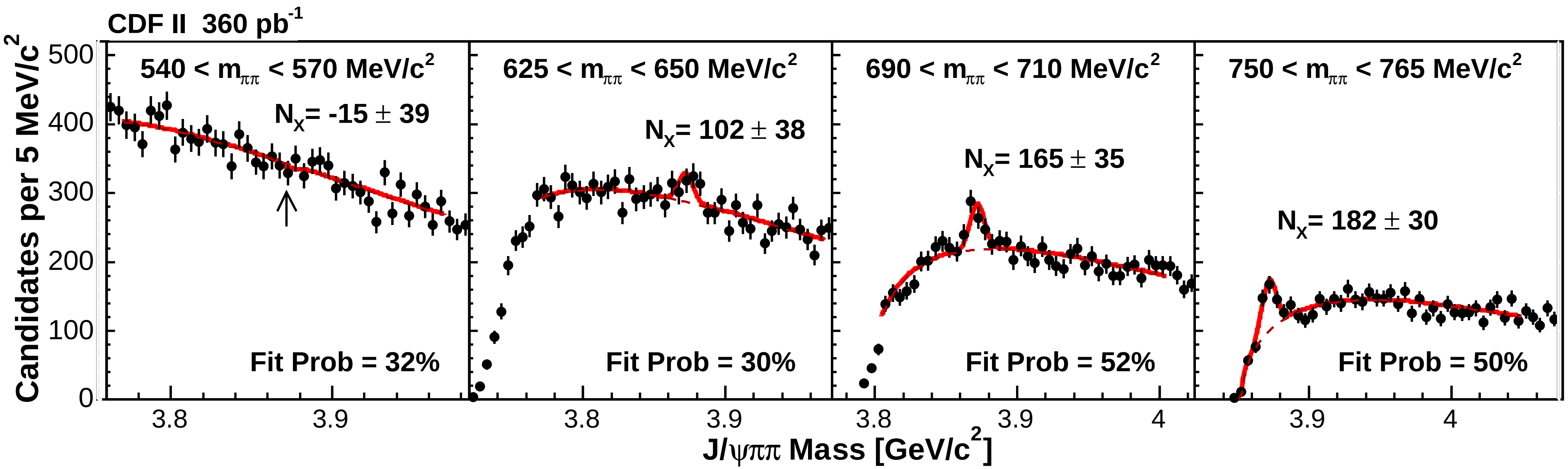
For broad resonance as ρ

$$\Gamma_{A\to BC} = \Gamma_{0,A\to BC}\left(\frac{k^*}{k_0^*}\right)^{2L+1}\left(\frac{f(k^*)}{f(k_0^*)}\right)^2\left(\frac{m}{m_0}\right)$$

Form-factor

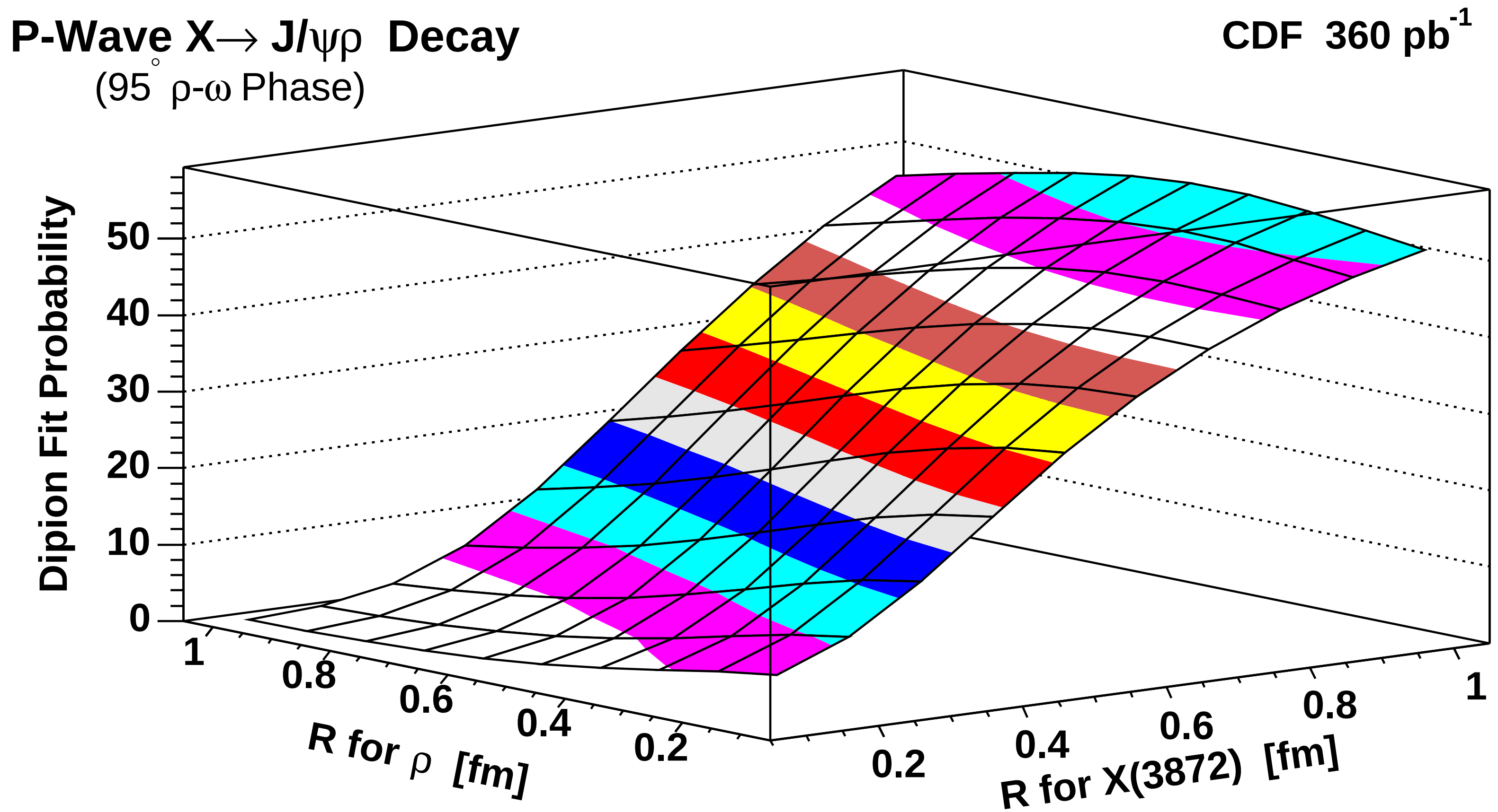
The m$(\pi^+\pi^-)$ mass spectrum

Challenge: Large background, low $X(3872)$ yield
$\rightarrow$ sideband subtraction difficult $\Rightarrow$ use slicing technique

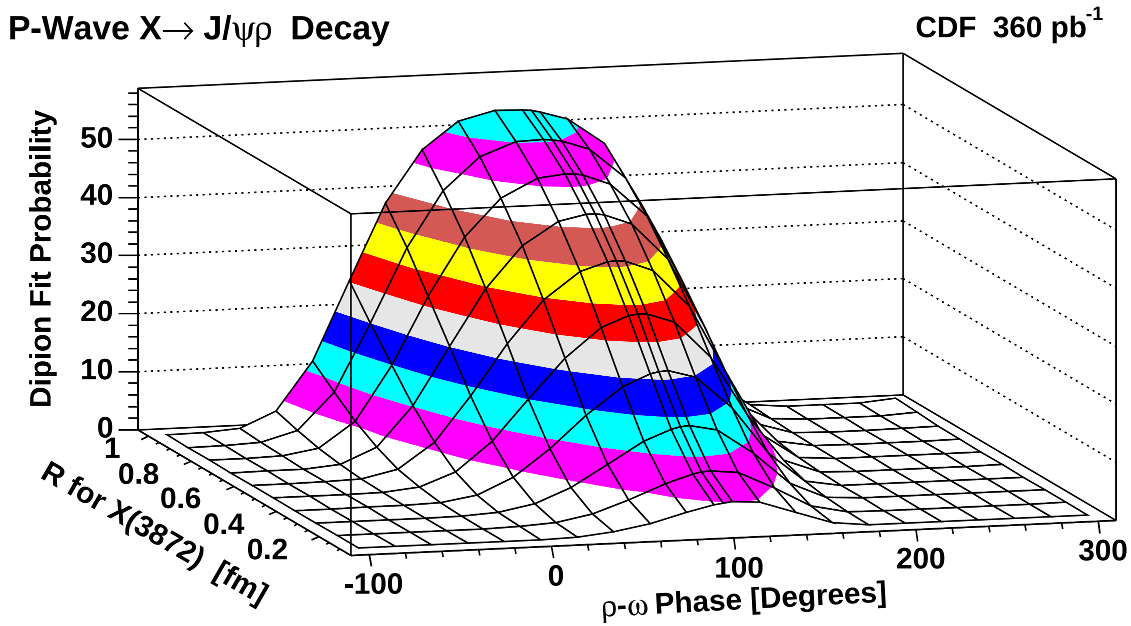


Effect of form factor on $\mathbf{m}(\pi^+\pi^-)$

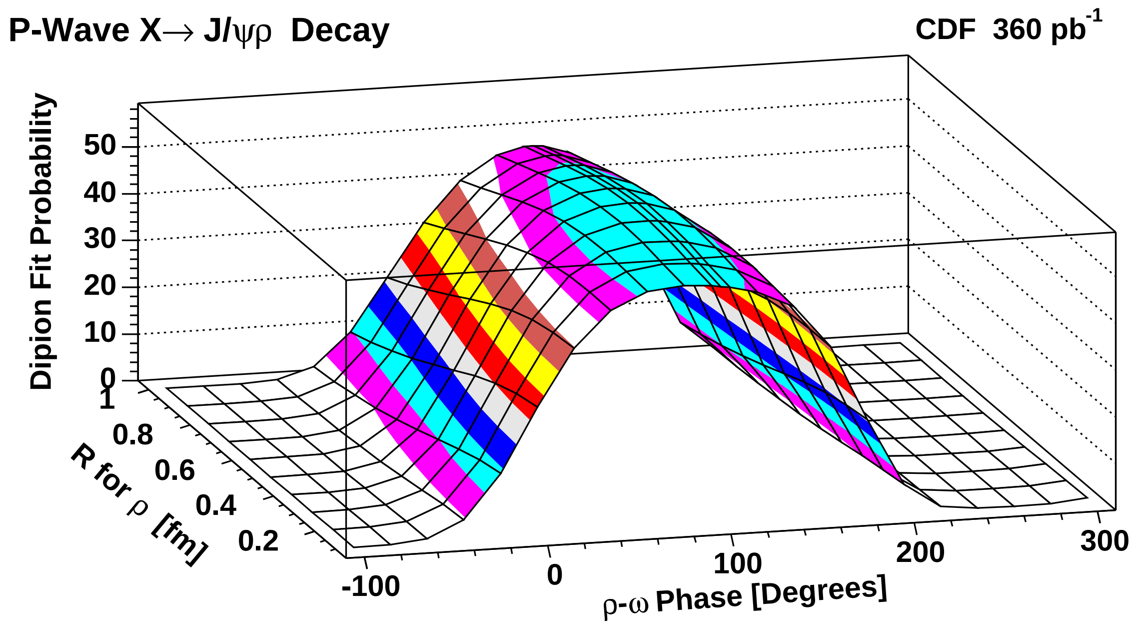
Use model from Blatt-Weiskopp for form-factor
Free parameter R determines effective size, no unique choice



Mixing phase between ρ and ω

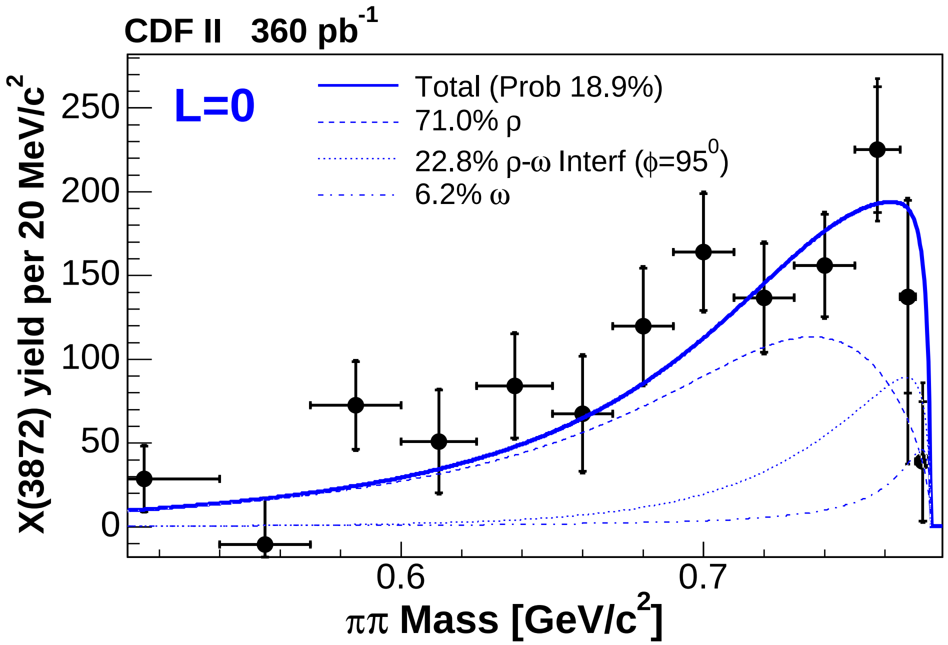


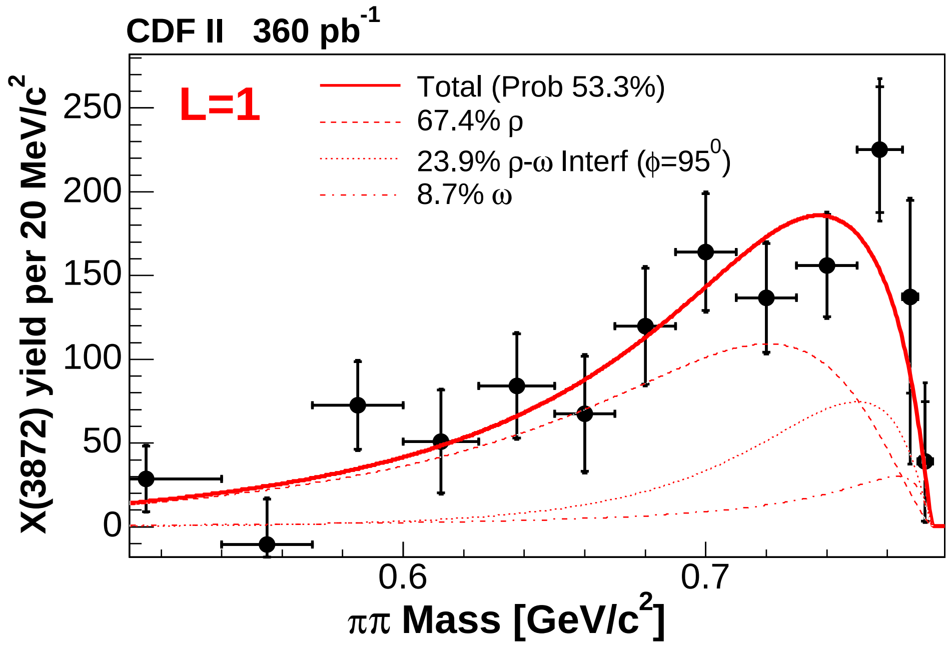
good fit probability for relative phase 95°



Small influence by ρ radius, large effect from $X(3872)$ radius

Effect of ρ-ω mixing





Both L=0 and L=1 describe $m(\pi^+\pi^-)$ data

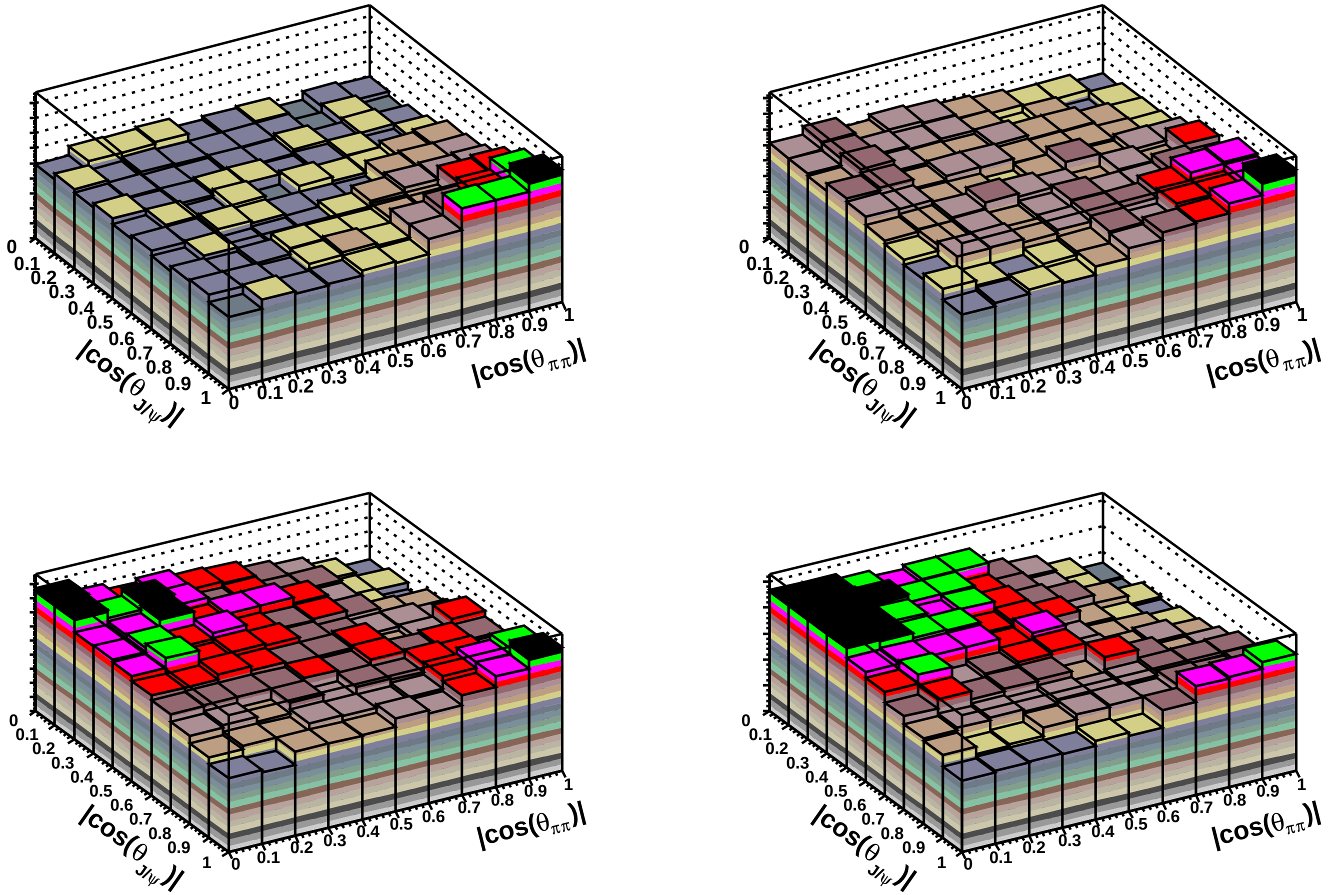
Cannot be ruled out based on $m(\pi^+\pi^-)$

Illustration of angular correlation

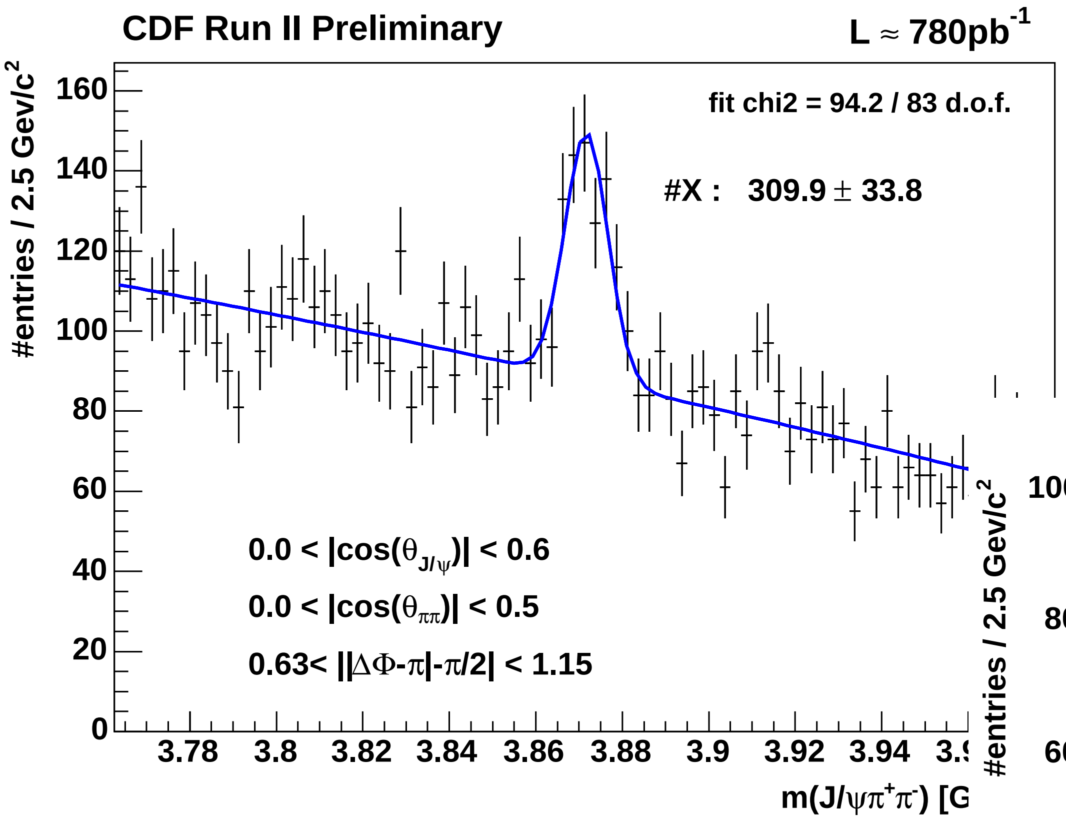
Example for $J^{PC} = 1^{++}$

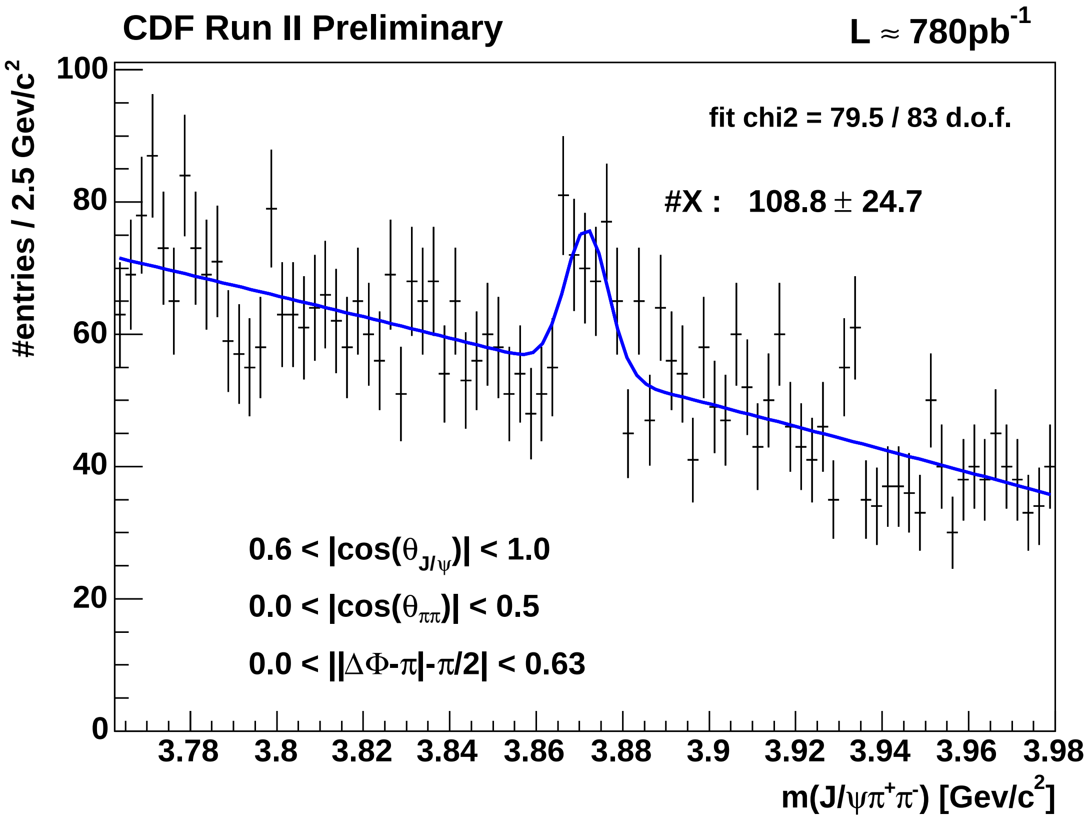
$0 < \Delta\Phi < \frac{\pi}{8}$ $\frac{\pi}{8} < \Delta\Phi < \frac{\pi}{4}$

$\frac{\pi}{4} < \Delta\Phi < \frac{3\pi}{8}$ $\frac{3\pi}{8} < \Delta\Phi < \frac{\pi}{2}$



Typical fits for angular analysis





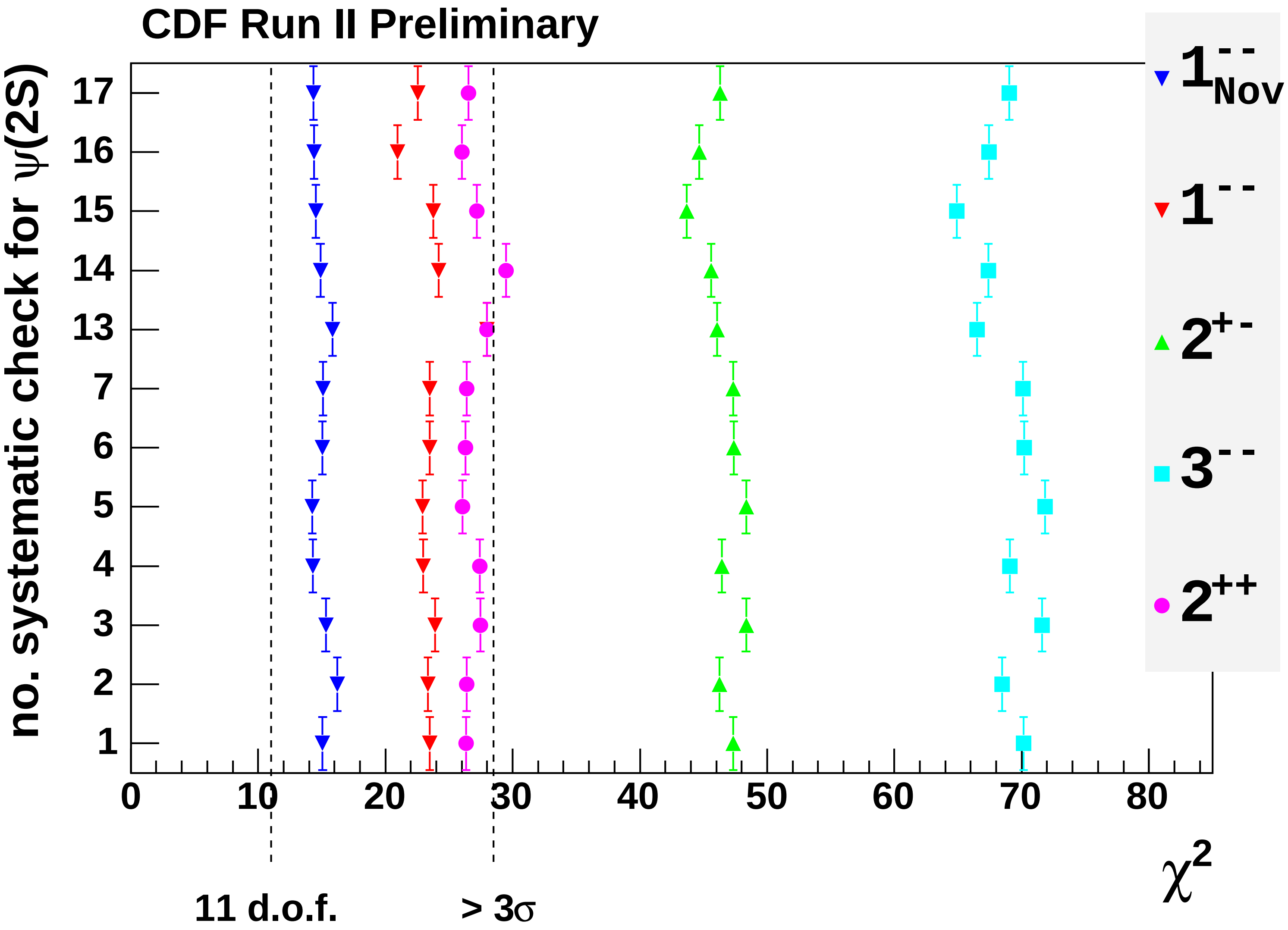
$\psi(2S)$ result

hypothesis	3D χ^2 / 11 d.o.f.	χ^2 prob.
$1^{--}_{Novikov}$	15.1	17.9%
1^{--}_{s}	23.5	1.5%
2^{++}_{p}	26.3	0.58%
2^{+-}_{s}	47.4	$1.9 \cdot 10^{-6}$
3^{--}_{s}	70.2	$1.2 \cdot 10^{-10}$
1^{++}_{p}	399.5	$\leq 1 \cdot 10^{-20}$
3^{+-}_{s}	504.8	$\leq 1 \cdot 10^{-20}$
2^{--}_{s}	504.8	$\leq 1 \cdot 10^{-20}$
1^{+-}_{s}	504.8	$\leq 1 \cdot 10^{-20}$
2^{-+}_{p}	505.1	$\leq 1 \cdot 10^{-20}$
1^{-+}_{p}	516.5	$\leq 1 \cdot 10^{-20}$
0^{++}_{p}	1500.3	$\leq 1 \cdot 10^{-20}$
0^{+-}_{s}	1847.0	$\leq 1 \cdot 10^{-20}$
0^{-+}_{p}	3169.2	$\leq 1 \cdot 10^{-20}$

X(3872) result

hypothesis	3D χ^2 / 11 d.o.f.	χ^2 prob.
1^{++}	13.2	27.8%
2^{-+}	13.6	25.8%
1^{--}	35.1	0.02%
2^{+-}	38.9	$5.5{\cdot}10^{-5}$
1^{+-}	39.8	$3.8{\cdot}10^{-5}$
2^{--}	39.8	$3.8{\cdot}10^{-5}$
3^{+-}	39.8	$3.8{\cdot}10^{-5}$
3^{--}	41.0	$2.4{\cdot}10^{-5}$
2^{++}	43.0	$1.1{\cdot}10^{-5}$
1^{-+}	45.4	$4.1{\cdot}10^{-6}$
0^{-+}	103.6	$3.5{\cdot}10^{-17}$
0^{+-}	129.2	$\leq 1{\cdot}10^{-20}$
0^{++}	163.1	$\leq 1{\cdot}10^{-20}$

$\psi(2S)$ systematics



13-17:
details of MC

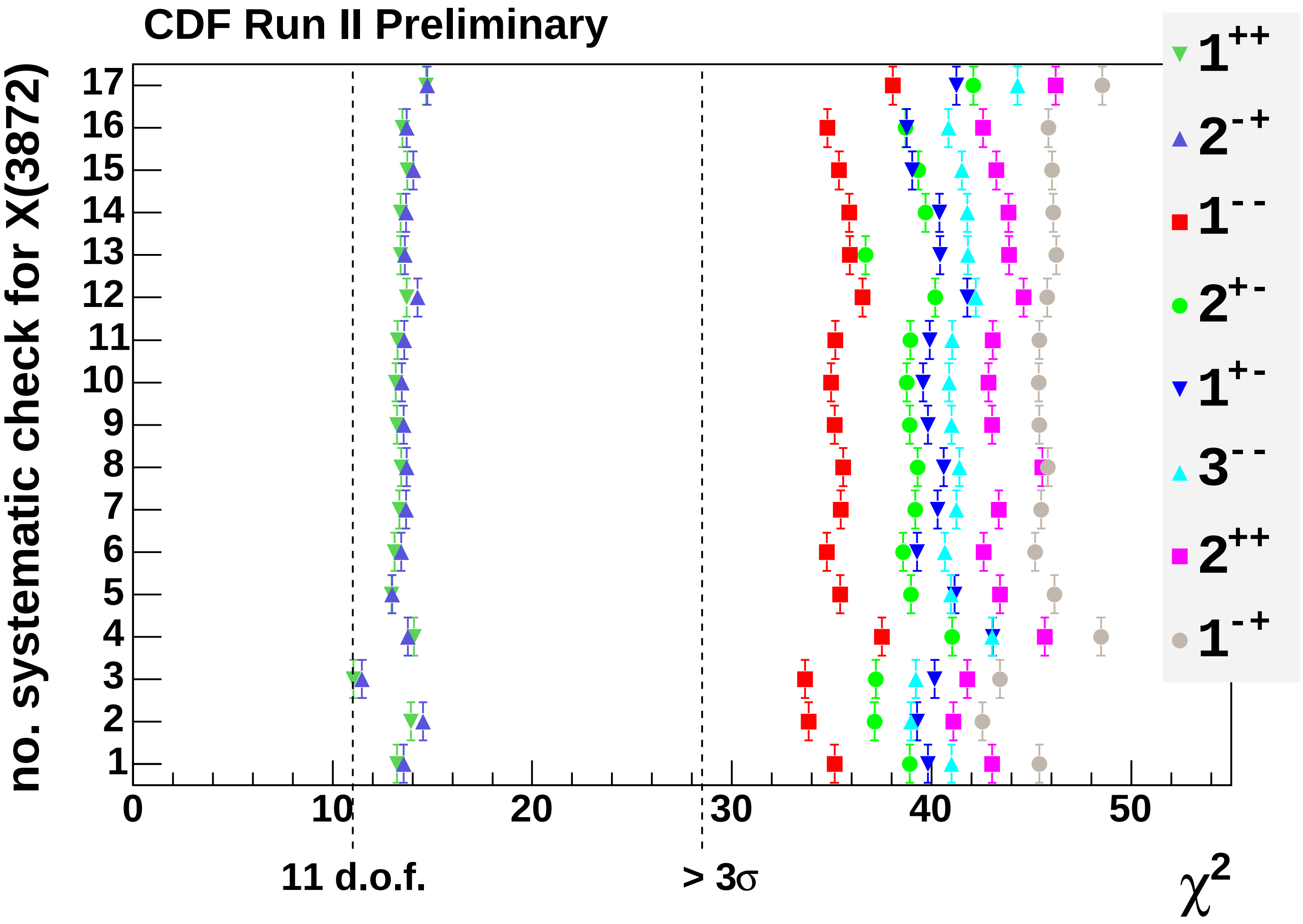
6,7:
vary $\psi(2S)$ mass and width

4,5:
vary histogram bin width

2,3:
vary $\psi(2S)$ fi t window

1: default result

Systematic checks



13-17:
details of MC

12:
phase-space to describe $m(\pi\pi)$

10,11:
vary ρ^0 form-factor

6-9:
vary $X(3872)$ mass and width

4,5:
vary histogram bin width

2,3:
vary $X(3872)$ fi t window

1: default result

No change in the result

Detector effects