Observation of $e^+e^- \to \chi_{c1}$ at BESIII

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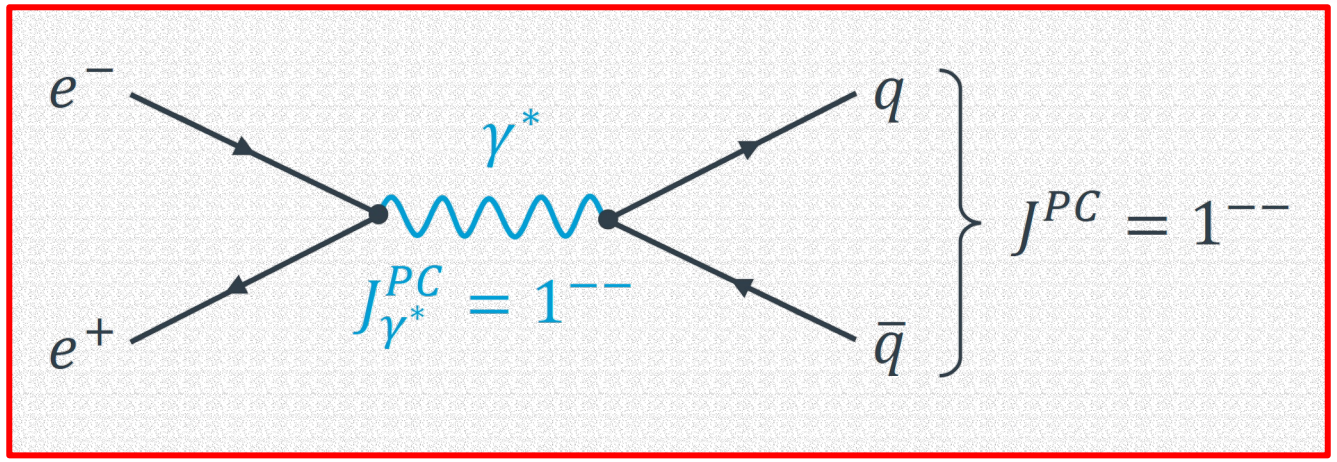
Hadron production in e^+e^- collisions



- e^+e^- pairs mainly annihilate into one virtual photon
- The virtual photon can decay into quark-antiquark pairs
- Direct production of vector meson states with $J^{PC} = 1^{--}$
- Energy scan to estimate the line shape and decay width

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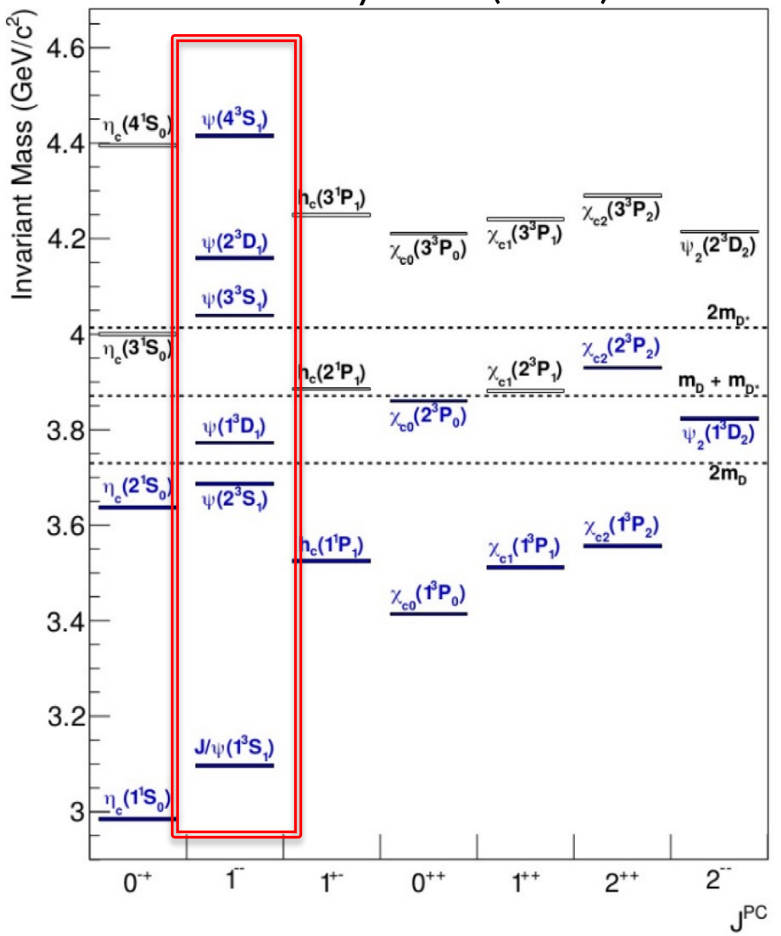
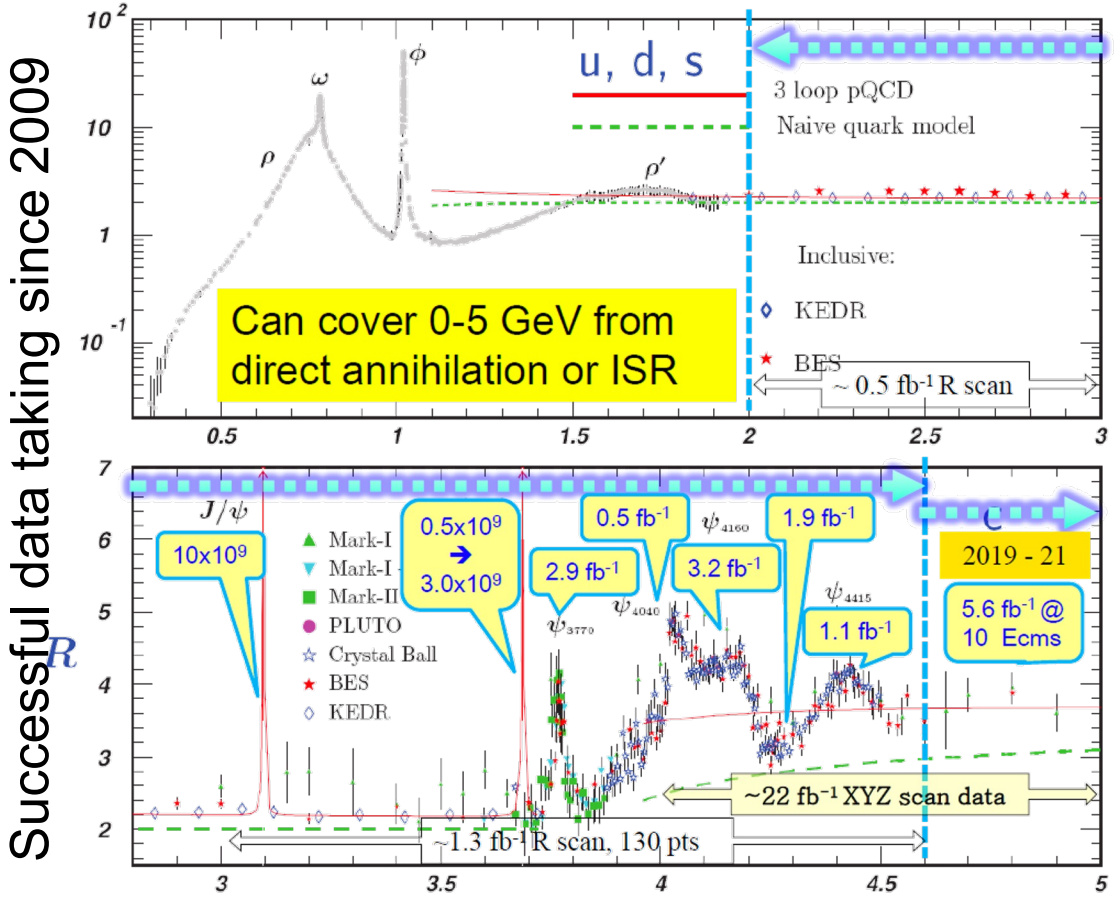


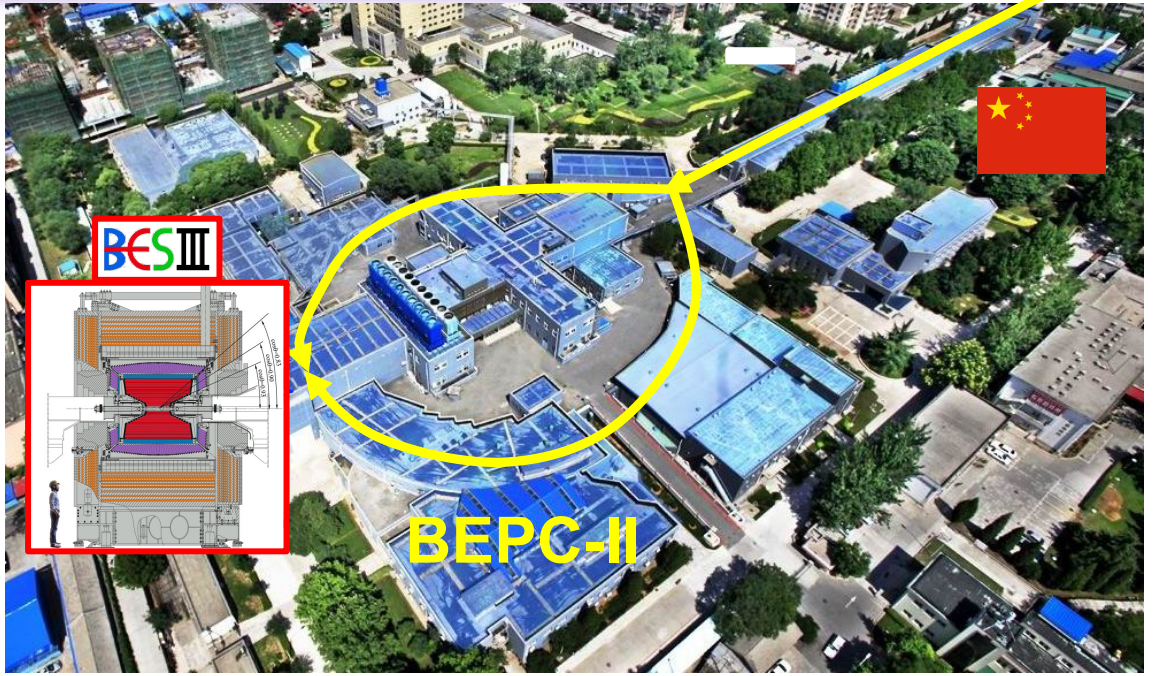
Let's focus on charmonium states

e^+e^- collisions with BEPC-II and BESIII

E_{CM} = 2 - 4.9 GeV

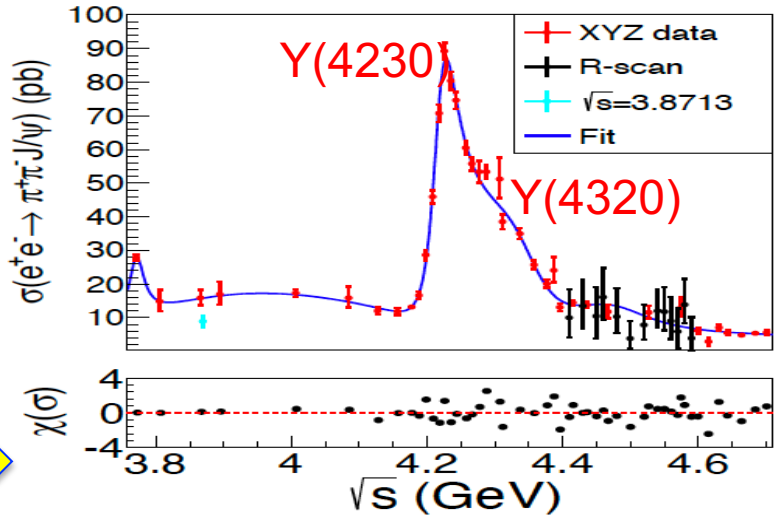
L_{peak} = 1.0 x $10^{33}/cm^2s^{-1}$





Charmonium Spectroscopy

Conventional & Unconventional



Direct Production of C-even resonances (0^{-+}, 0^{++}, 1^{++}, 2^{++}, ...)

Forbidden via one virtual photon

Allowed via two virtual photons or Z° neutral current (1^{++})

Experimental researches so far unsuccessful

ND collaboration

- $\eta', f_0(980), f_0(1300), a_0(980), f_2(1270), a_2(1320)$ at VEPP-2M collider (Vorobev et al. (ND), SJNP48, 273 (1988))

SND collaboration

- $f_2(1270), a_2(1320)$ at VEPP-2M collider (Achasov et al. (SND), PLB492, 8 (2000))
- η at VEPP-2M collider (Achasov et al. (SND), PRD98, 052007 (2018))
- η' at VEPP-2000 collider (Achasov et al. (SND), PRD91, 092010 (2015))
- $f_1(1285)$ at VEPP-2000 collider (Achasov et al. (SND), PLB800, 135074 (2020))

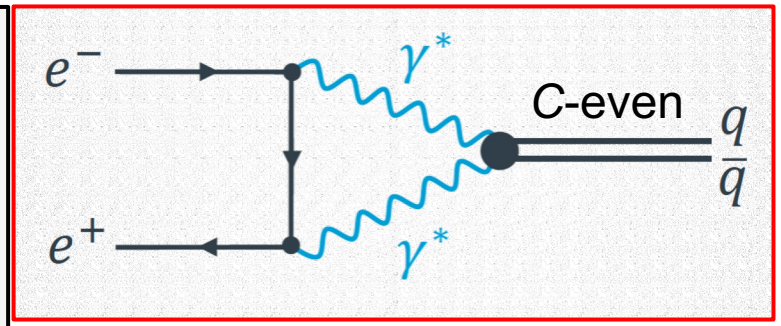
CMD-3 collaboration

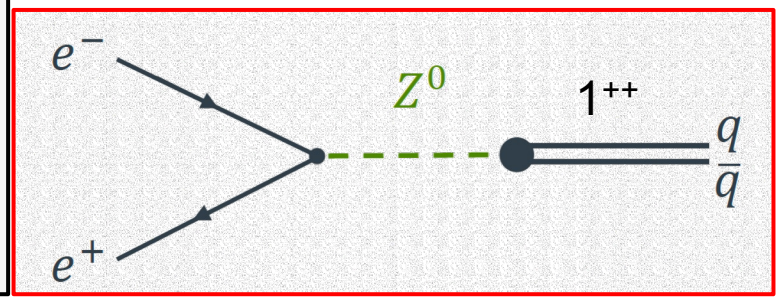
- η' at VEPP-2000 collider (Akhmetshin et al. (CMD-3), PLB740, 273 (2015))

BESIII collaboration

- $\chi_{c1}(3872)$ at BEPCII collider (Ablikim et al. (BESIII), PLB[illegible]414 (2015), Ablikim et al. (BESIII), PRD107, [illegible]2007 (2023))

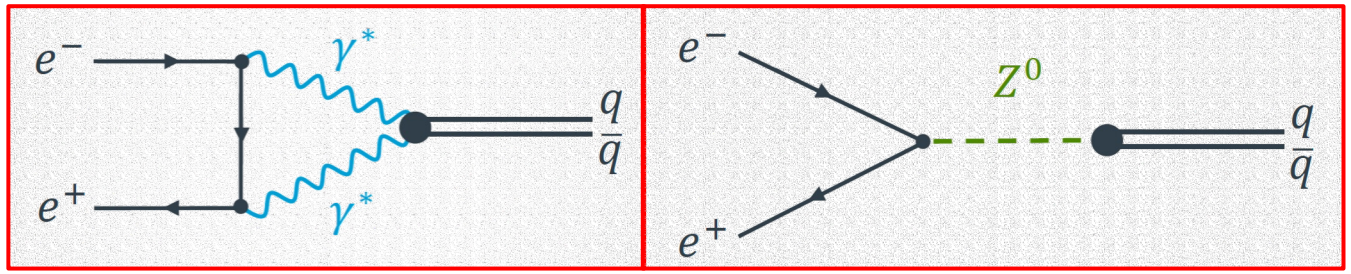
ISR SPOILER





Direct Production of χ_{c1} in e^+e^- collisions

$e^+e^- \to \chi_{c1}$ cross section unknown, proportional to Γ_{ee}



Theoretical predictions for Γ_{ee}:

- Lower limit based on unitarity: $\Gamma_{ee} > 0.044$ eV

  Kaplan *et al.* PLB78 (1978) 252

- Using Vector Meson Dominance Model (VMD): $\Gamma_{ee} = 0.46$ eV

  Kühn *et al.* NPB157 (1979) 125

- More recently using VMD or non-relativistic QCD $\Gamma_{ee} \sim 0.1$ eV

  Denig *et al.* PLB736 (2014) 221, Kivel *et al.* JHEP02 (2016) 032

- Latest prediction: $\Gamma_{ee} = 0.41$ eV – providing analysis strategies and predictions

  Czyz *et al.* PRD94 (2016) 034033

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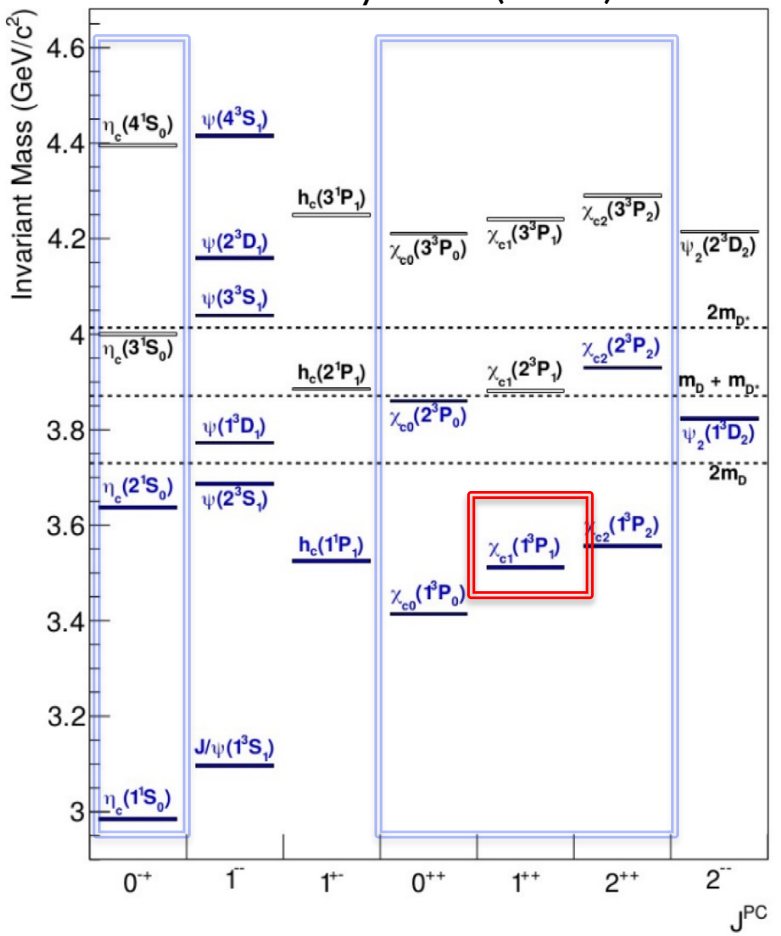
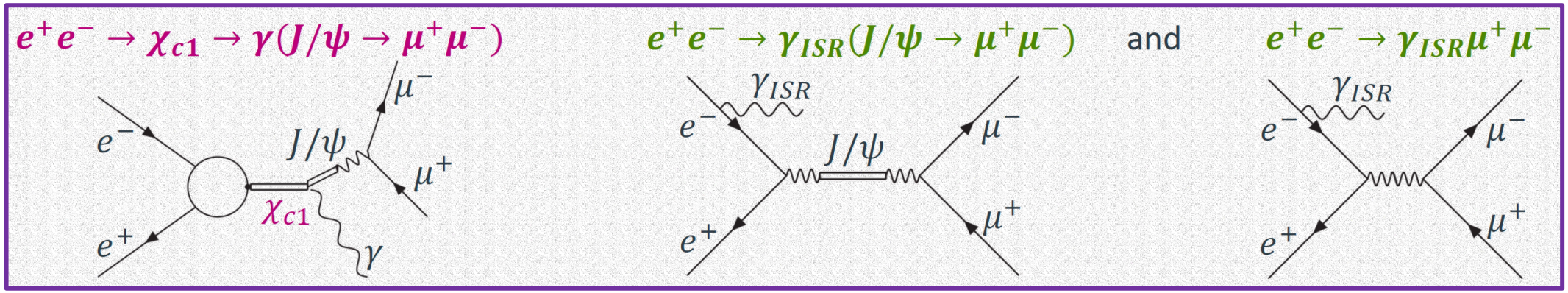
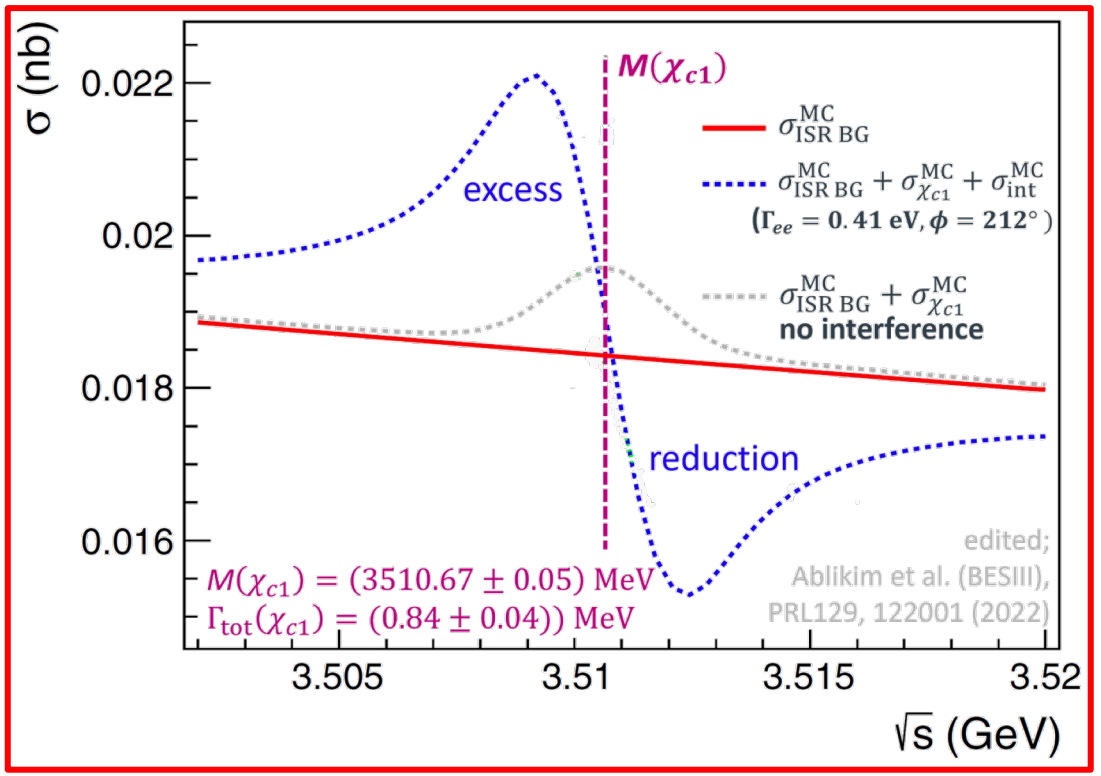


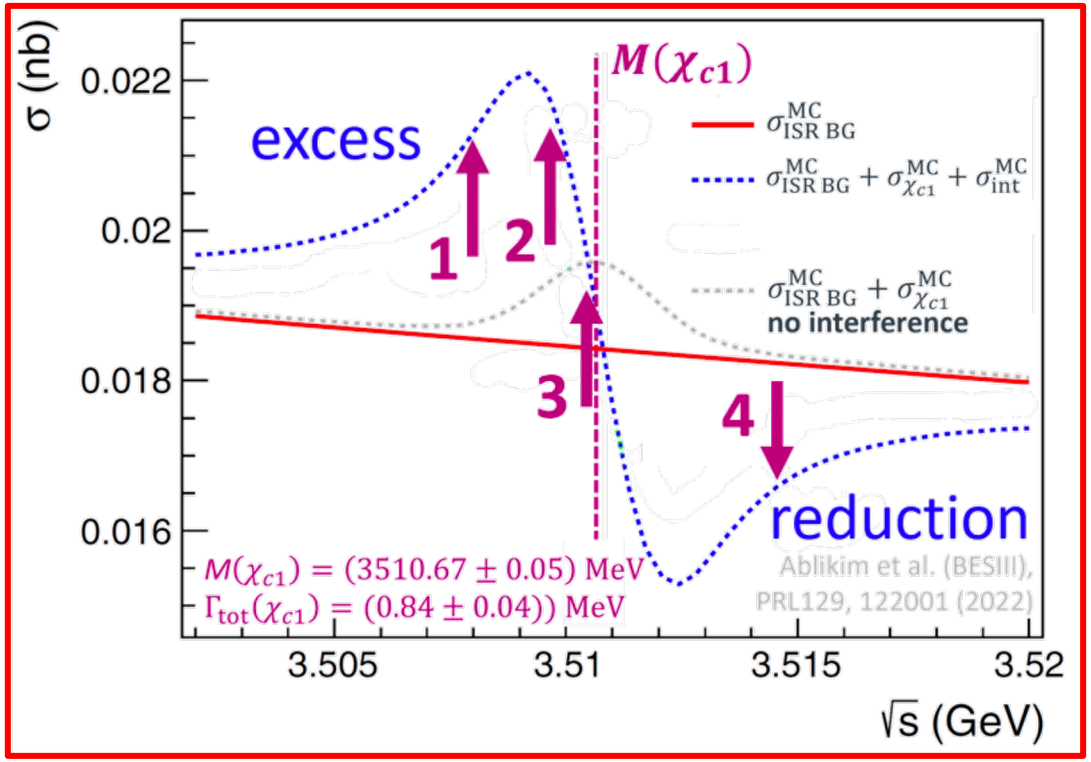
$e^+e^- \to \chi_{c1}$ search proposed by Czyz *et al.*



- Interference between $\chi_{c1} \to \gamma J/\psi$ signal and γ_{ISR} background
- Distortion of the line shape depending on the phase angle ϕ
- Observation of the interference pattern via energy scan around χ_{c1} at BESIII



$e^+e^- \to \chi_{c1}$ at BESIII [PRL129 (2022) 122001]

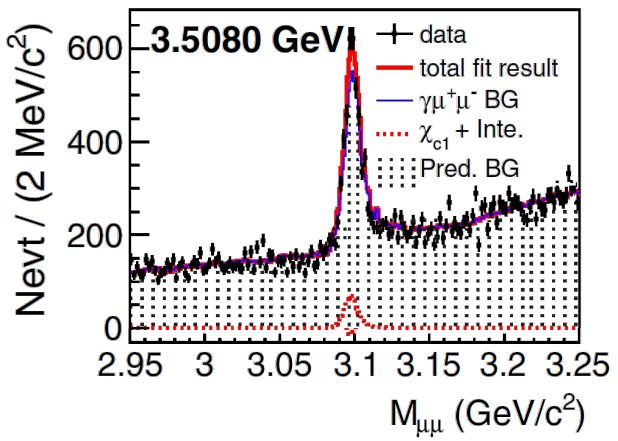


data point	E_{cms} (GeV)	$\mathcal{L}_{int}$ (pb^{-1})
1	3.5080	$181.79 \pm 0.04_{stat} \pm 1.04_{sys}$
2	3.5097	$39.29 \pm 0.02_{stat} \pm 0.22_{sys}$
3	3.5104	$183.64 \pm 0.04_{stat} \pm 1.05_{sys}$
4	3.5146	$40.92 \pm 0.02_{stat} \pm 0.23_{sys}$

- Four data points collected around χ_{c1} in 2017
- Total integrated luminosity 446 pb^{-1}
- Beam energy uncertainty ΔE_{cms} ~ 50 keV

- Search for $e^+e^- \to \chi_{c1} \to \gamma(J/\psi \to \mu^+\mu^-)$
- Looking for excess/reduction in

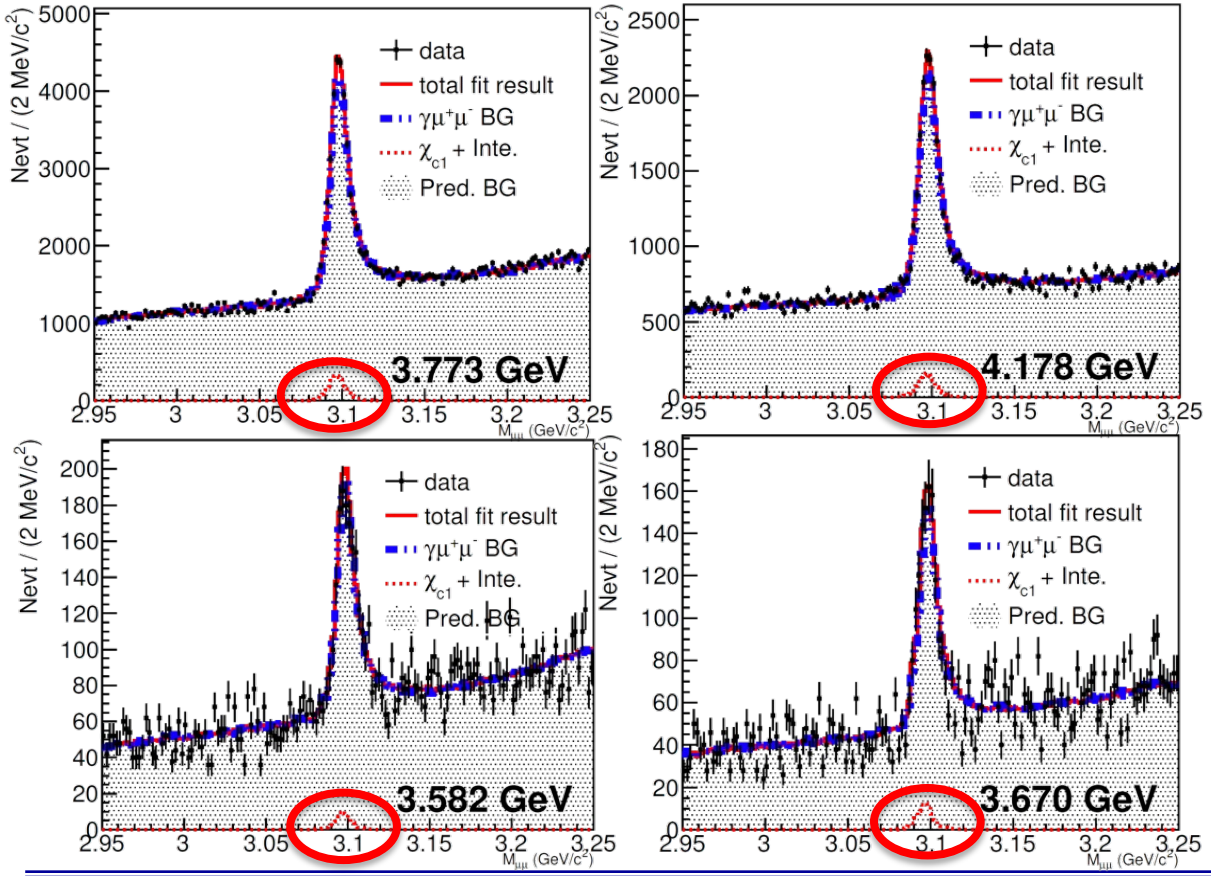
$M_{\mu\mu}$ invariant mass



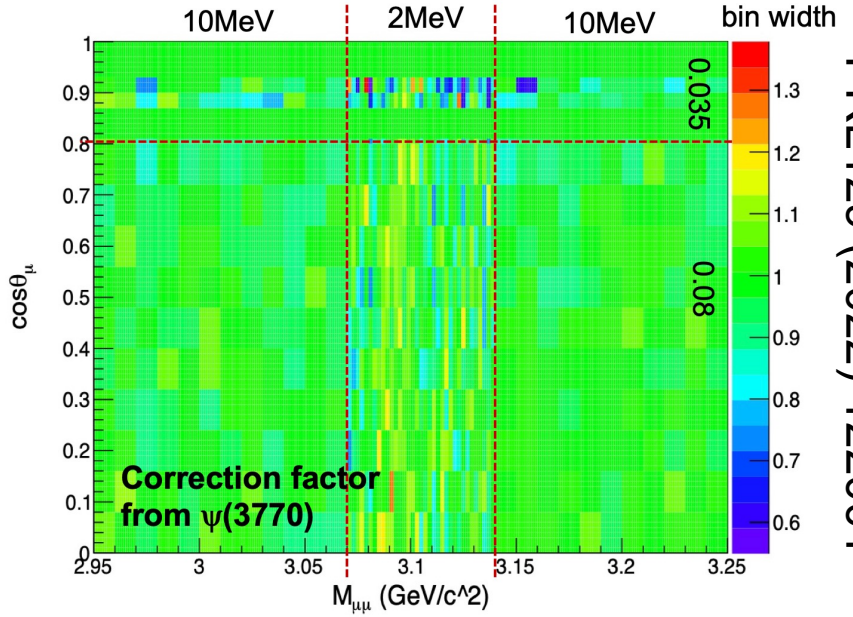
Background Studies and MonteCarlo Tuning

- Control sample: four data points at energies where no χ_{c1} signal ($\mathcal{L}_{int}$ = 6294 pb^{-1})
- ISR simulation using PHOKHARA

data points	E_{cms} (GeV)	$\mathcal{L}_{int}$ (pb^{-1})
two points of $\psi(3686)$ scan	3.581	$85.28 \pm 0.03_{stat} \pm 0.58_{sys}$
	3.670	$83.61 \pm 0.03_{stat} \pm 0.57_{sys}$
$\psi(3770)$	3.773	$2932.39 \pm 0.17_{stat} \pm 12.61_{sys}$
high luminosity	4.178	$3192.49 \pm 0.20_{stat} \pm 15.99_{sys}$



- Data-MC discrepancy (seen χ_{c1} signal)
- Estimated reweight factor $f(M_{\mu\mu}, \cos\theta_\mu)$



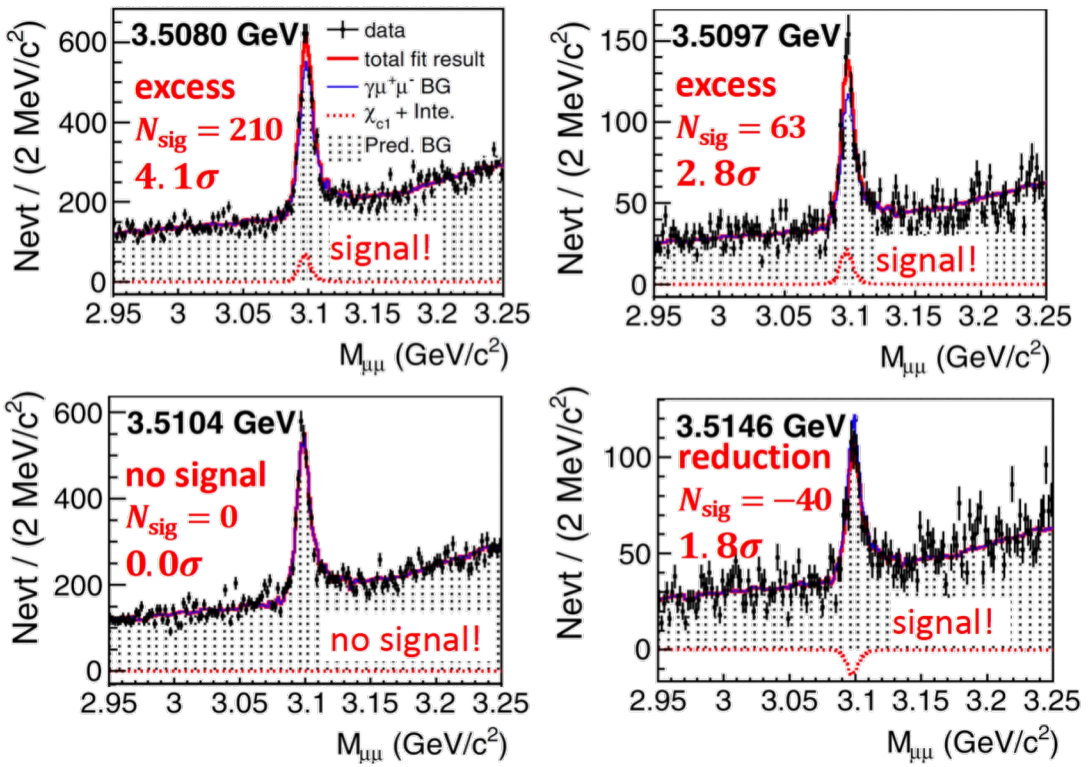
PRL 129 (2022) 122001

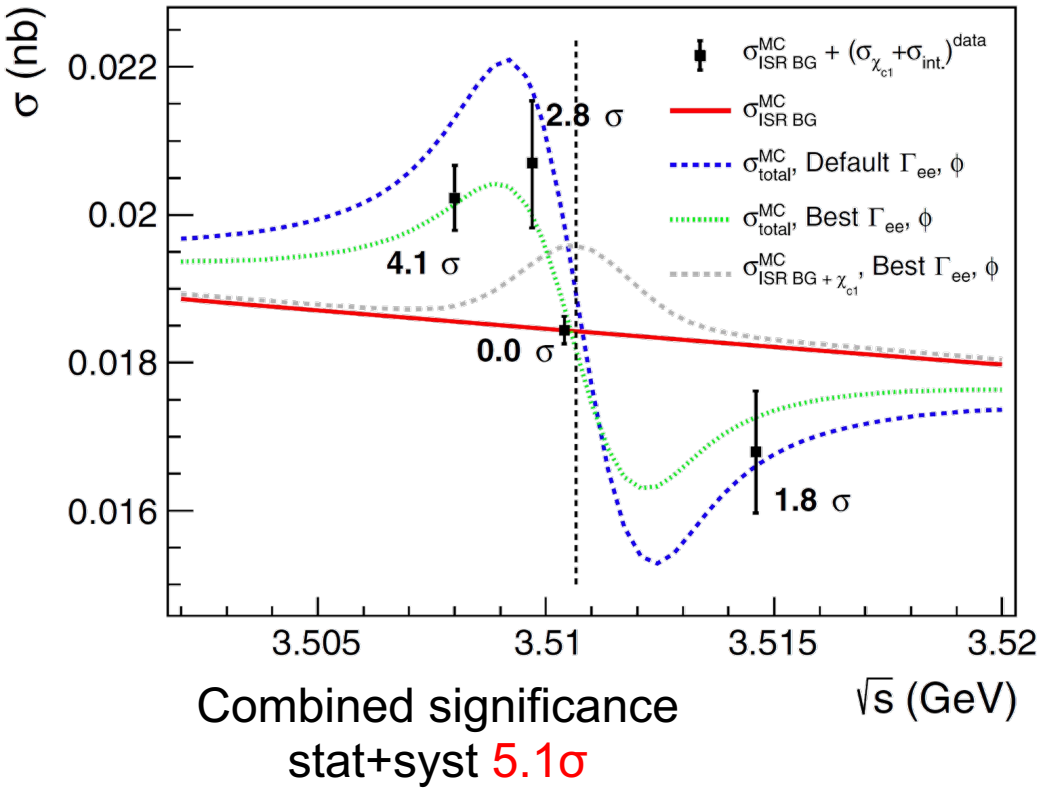
Extraction of χ_{c1} Signal Events

PDF: $N_{\chi_{c1}}\mathbf{MC}_{\chi_{c1}} + N_{bg}\mathbf{MC}_{\text{ISR bg}} + \underbrace{N_{\text{int}}\mathbf{MC}_{\text{int}}}_{\text{interference included}}$

line shapes extracted from binned MC histograms

$$N_{\text{int}} = a(\Gamma_{ee}, \phi) \cdot \sqrt{N_{\chi_{c1}} \cdot N_{\text{bg}}}$$

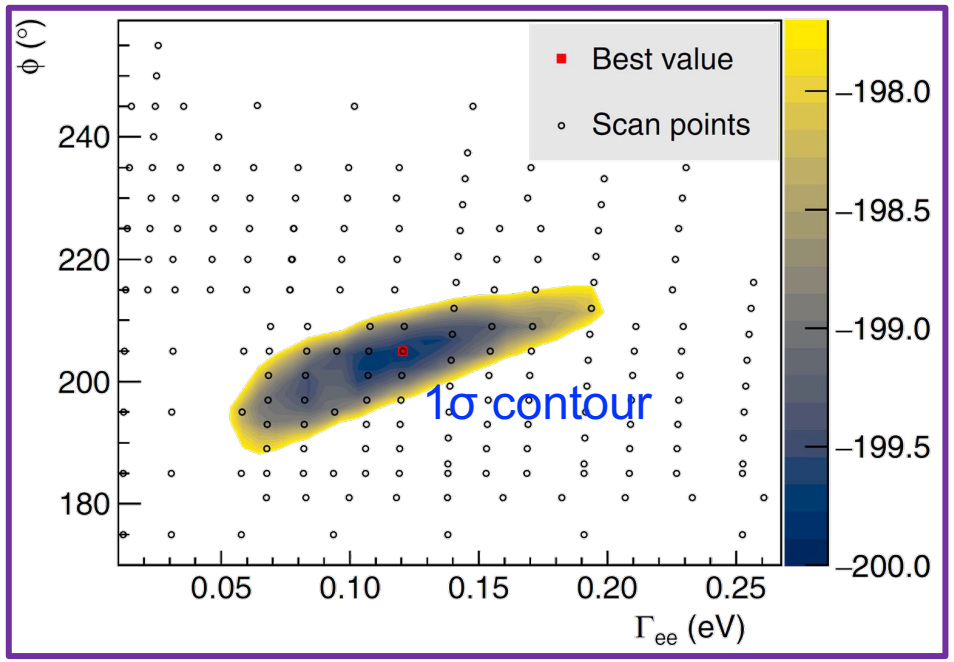




Combined significance
stat+syst 5.1σ

PRL 129 (2022) 122001

Estimation of Γ_{ee} and ϕ values



- best fitted values (**red dot**):

$\Gamma_{ee} = \left(0.12^{+0.13}_{-0.08}\right)$ eV and $\phi = \left(205^{+15.4}_{-22.4}\right)°$

including statistical and systematic uncertainties (are of same order)

- theoretical predictions:

$\Gamma_{ee}^{theo} = 0.41$ eV and $\phi^{theo} = 212°$

First experimental measurement of Γ_{ee} and ϕ

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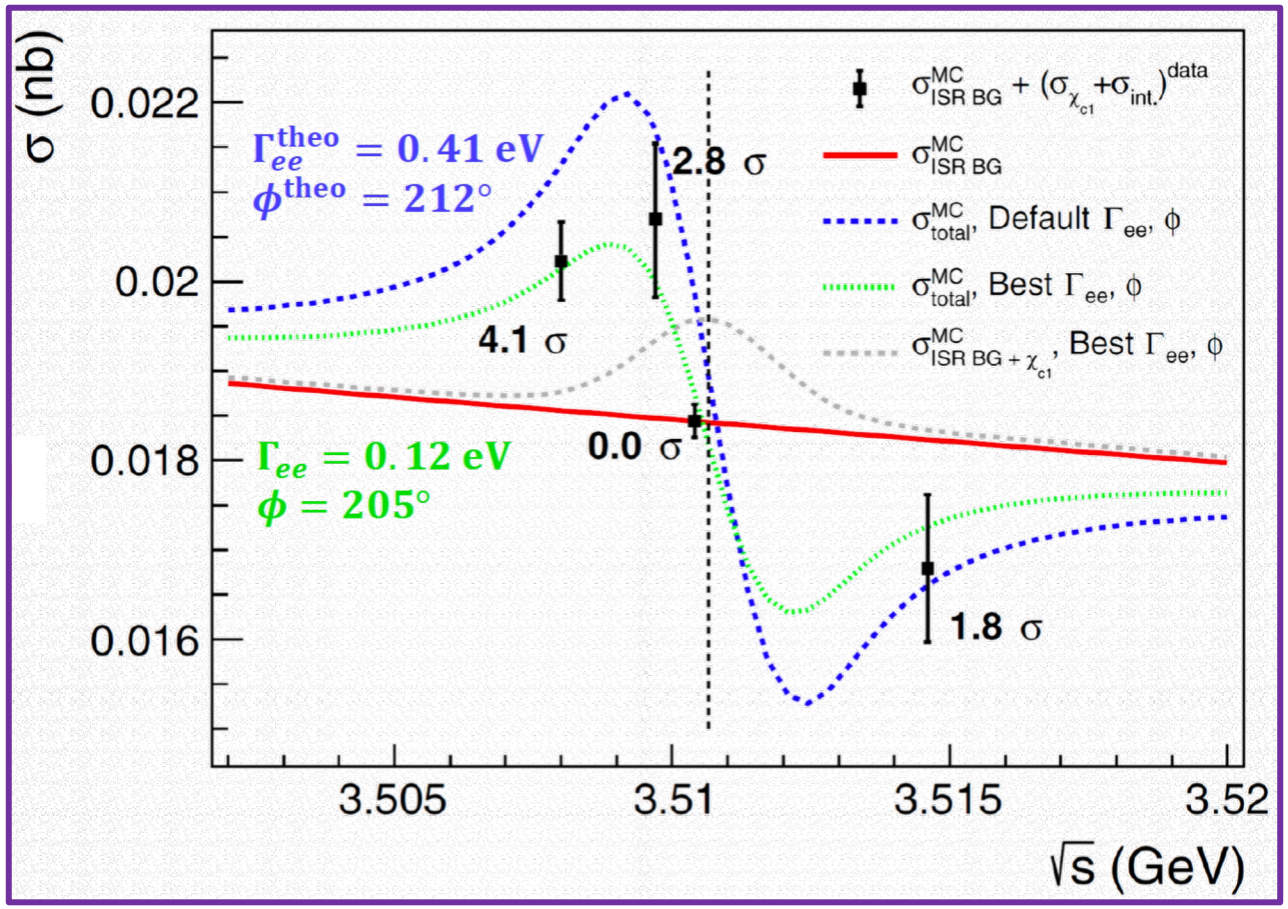
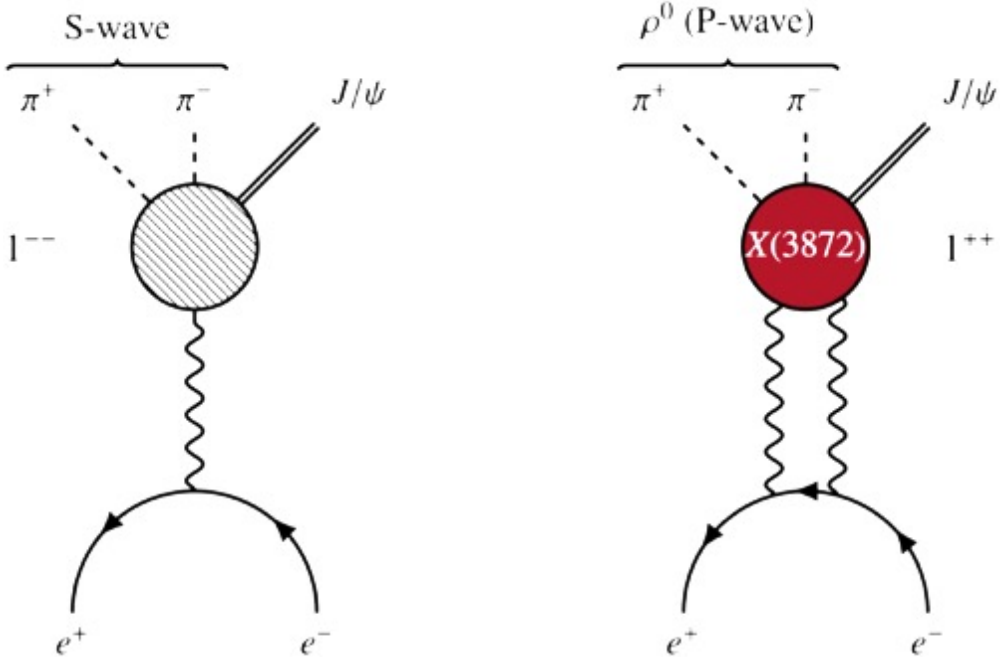
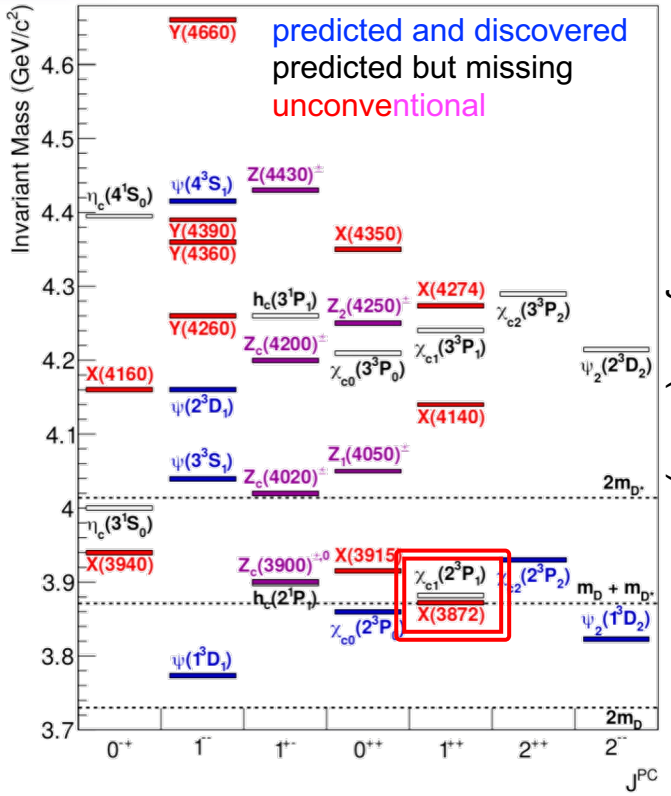


BONUS TRACK: What about X(3872)?

- ✓ aka $\chi_{c1}(3872)$ - $J^{PC} = 1^{++}$
- ✓ Nonconventional charmonium state or mixture
- ✓ Very close to the D^0D^{*0} threshold $\quad M_{X(3872)} - M_{D^0D^{*0}} = 0.01 \pm 0.14 MeV$
- ✓ Very narrow: $\quad \Gamma^{BW}_{X(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21 MeV$
- ✓ Large part of the decay width still unmeasured





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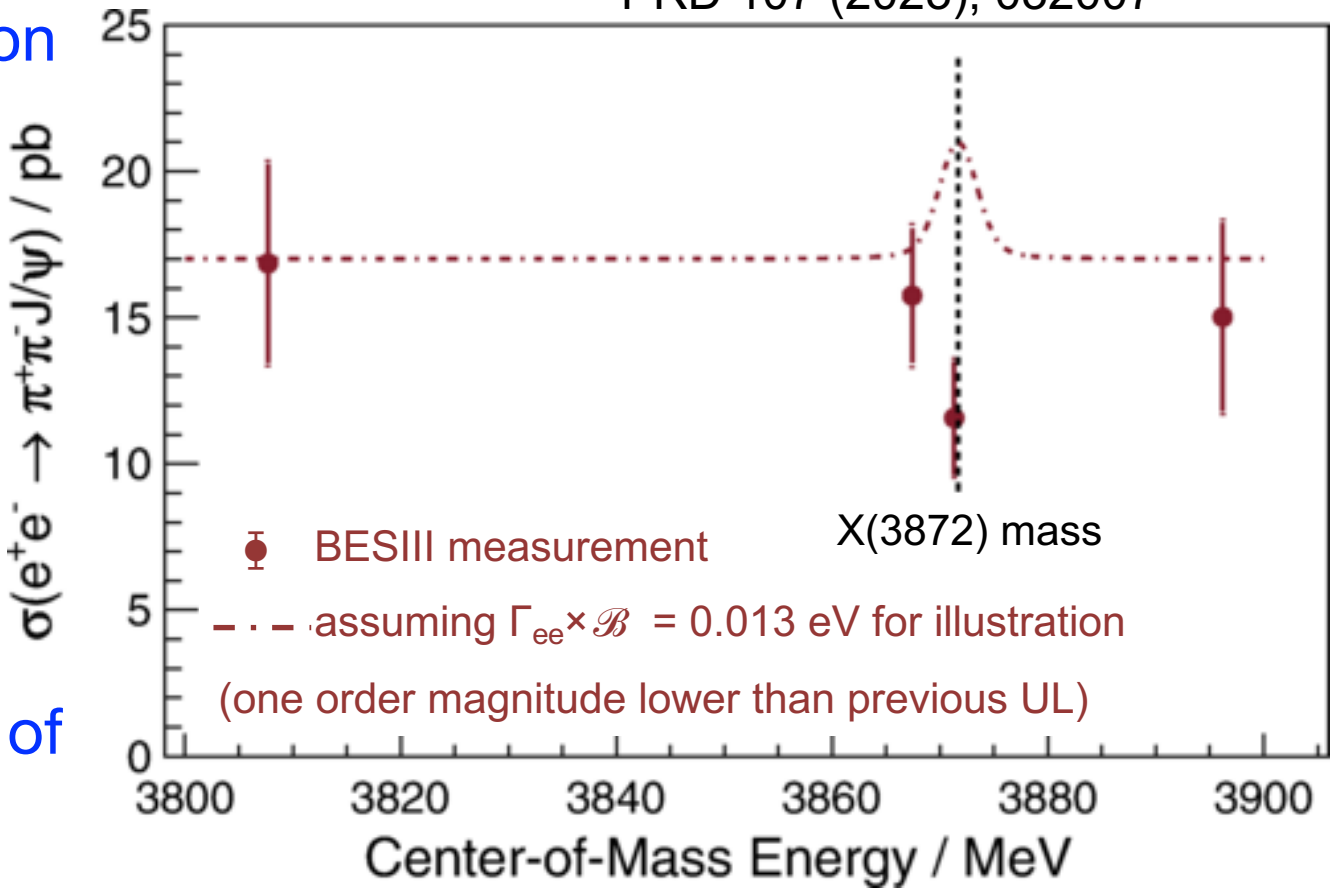
- ➢ Main decay channel: $X(3872) \rightarrow \pi^+\pi^- J/\psi$
- ➢ No interference is expected
- ➢ VMD prediction: $\Gamma_{ee} \gtrsim 0.03$ eV — Denig *et al.*, PLB736, 221 (2014)
- ➢ Energy scan to search for direct production at BESIII

Search for $e^+e^- \to X(3872) \to \pi^+\pi^- J/\psi$

- Measured $e^+e^- \to \pi^+\pi^- J/\psi$ cross section around the X(3872) mass
- No enhancement of the cross section around X(3872)
- Small dip around X(3872) mass but not significant (consistent with flat)
- Estimated upper limits (improvement of a factor ~ 17)

PRD 107 (2023), 032007



$\Gamma_{ee} \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 7.5 \times 10^{-3}$ eV @ 90% C.L.

$\Gamma_{ee} < 0.32$ eV @ 90% CL (assuming total width Γ = 1.19 MeV)

previous UL: $\Gamma_{ee} \times \mathcal{B} < 0.13$ eV
BESIII, PLB749 (2015), 414

In Summary

Energy scan at BESIII: Search for $J^{PC} = 1^{++}$ states

- First observation (5.1σ) of direct production of χ_{c1} resonance in e^+e^- collisions
- Interference pattern observed with ISR processes
- First measurement of χ_{c1} electronic width
- No observation of X(3872) direct production

Starting from the next year crucial upgrades will improve BESIII capabilities

- Increase in maximum CMS energy
- Increase in integrated luminosity in XYZ region
- New CGEM inner tracker