Observation of the Direct Production of χ_{c1} in e^+e^- Annihilation at BESIII

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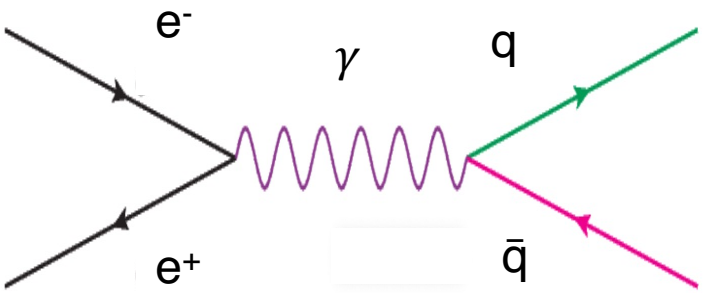
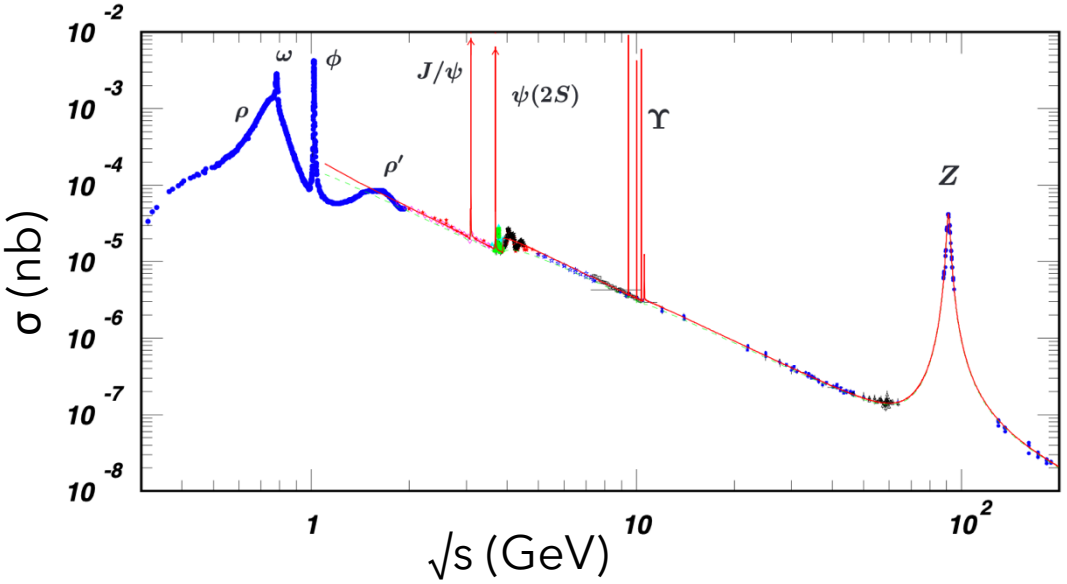
Final States in e^+e^- Collisions

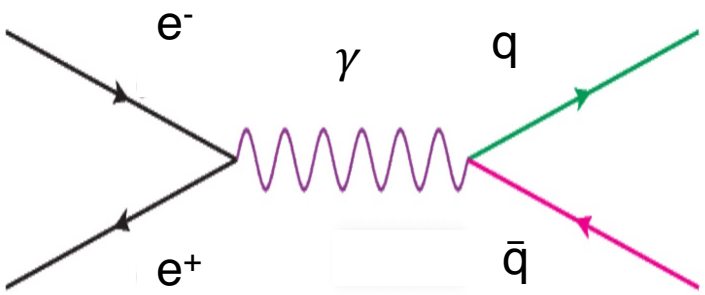
At e^+e^- machines vector states are produced

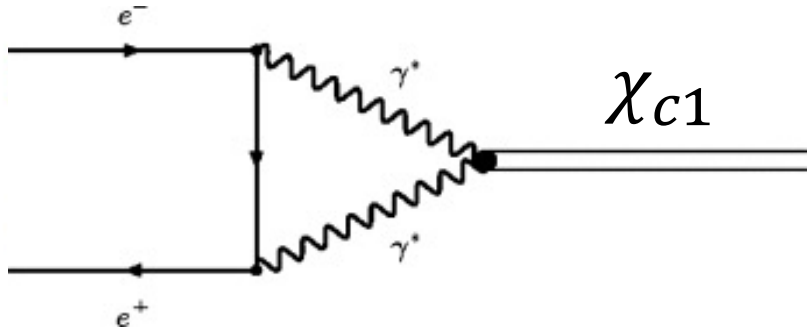
- Annihilation into single photon ($J^{PC} = 1^{--}$)
- EM process: C and P are conserved
- Discovery of J/ψ and ϒ





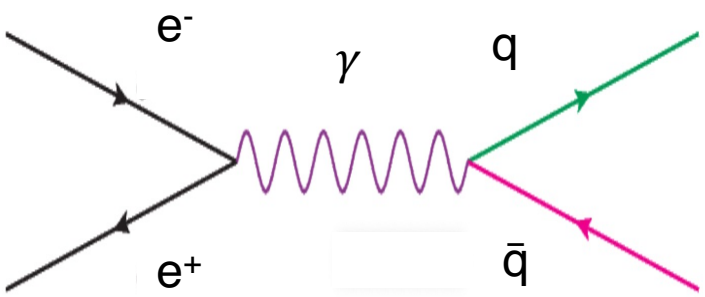
Final States in e^+e^- Collisions

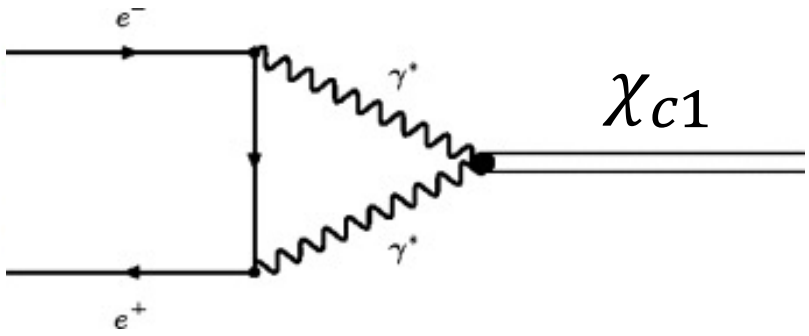




- **Production** of axial-vector mesons **forbidden at tree level** (**$J^{PC}=1^{++}$**)
- **Two-photon** transition **allowed**!
- However, **no** definitive **observation until now**:
  - Several channels tested without success: η, η′, f_0, a_0, a_2
  - First hint from SND on $f_1(1285)$ (2 events, 2.5σ) [SND *Ph.Lett.B 800 (2020)*]
- The **χ_{c1}** is a **promising channel** to look for at BESIII

Final States in e^+e^- Collisions





- **Cross section** proportional to electronic width (**Γ_{ee}**)
- Several theoretical predictions:
  - **Unitarity limit: $\Gamma_{ee} > 0.044$ eV** [Kaplan et al, Phys. Lett. B78 (1978)]
  - **Vector Dominance Model**: $\Gamma_{ee} = 0.46$ eV or $\Gamma_{ee} \sim 0.1$ eV. [Kühn et al, Nucl. Phys. B157 (1979) , Denig et al, Phys. Lett. B736 (2014)]
  - **NRQCD**: $\Gamma_{ee} \sim 0.1$ eV [Kivel et al, J. High. Energy Phys. 2 (2016)]
  - **Latest prediction**: **$\Gamma_{ee} = 0.43$** **[Czyz et al, Phys. Rev. D94 (2016)]**

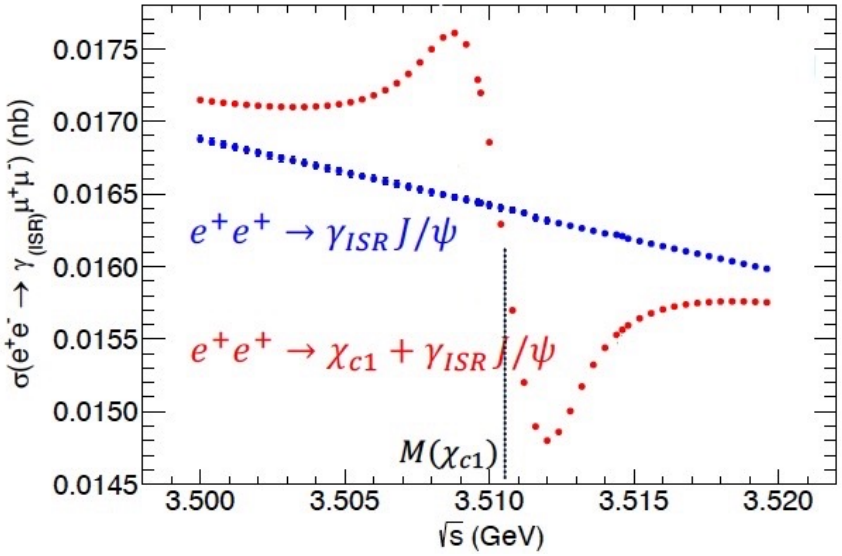
The Role of Interference

Latest prediction: Γ_{ee} **= 0.43** [Czyz et al, Phys. Rev. D94 (2016)]

- Include **interference** between

  $e^+e^- \rightarrow \boldsymbol{\chi_{c1}} \rightarrow \boldsymbol{\gamma J/\psi} \rightarrow \gamma\mu^+\mu^-$ and $\boldsymbol{e^+e^- \rightarrow \gamma\, J/\psi} \rightarrow \gamma\mu^+\mu^-$

- **Distortion** of the total **line shape** (phase angle **ϕ**)



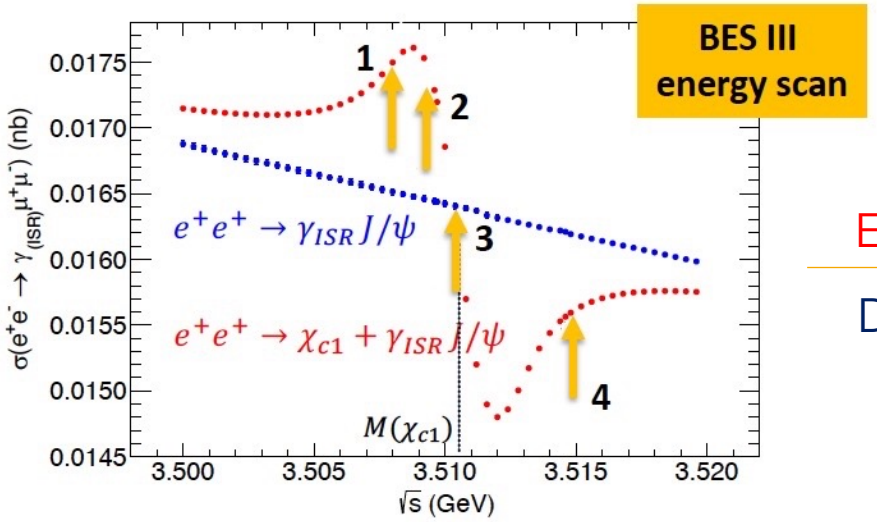
Implemented within the Phokhara generator

The Role of Interference

Experimentally:

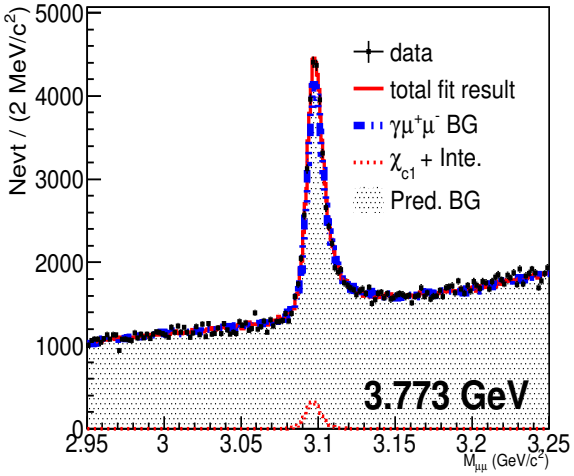
- Scan energy region around χ_{c1} mass (≈450 pb^{-1} at 4 E_{cms} points)
- Energy resolution ≈50 keV (BEMS)
- Look for predicted interference pattern

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



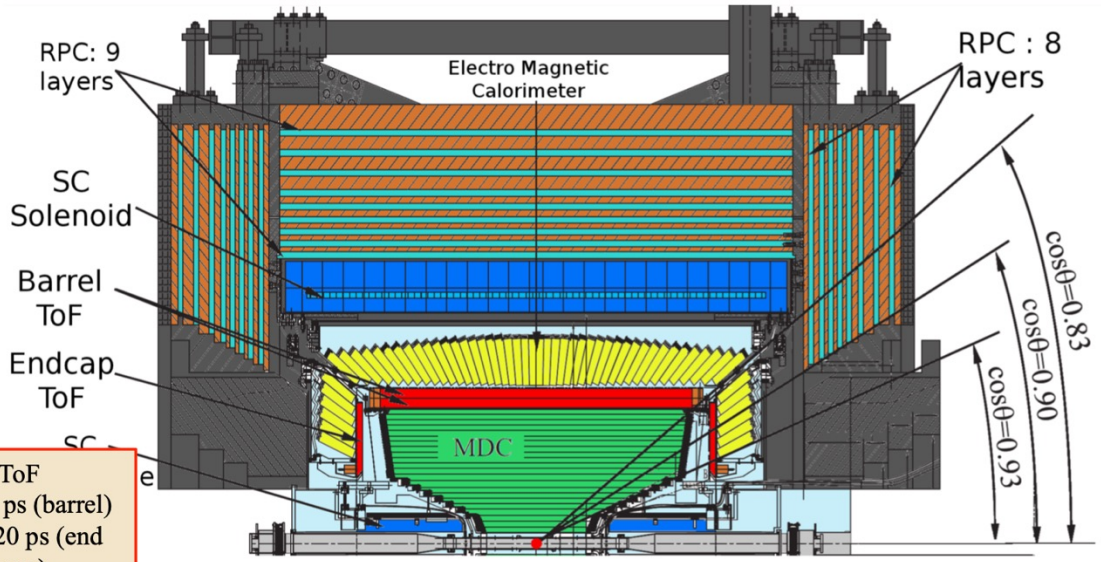
Excess

Deficit



The BESIII Experiment (1)

[NIM A614 (2010) 345]



- Located at the BEPCII collider (Beijing, China)
- Symmetric e^+e^- beams
- ECM between 2-4.95 GeV
- Maximum luminosity: 1 nb^{-1}/s
- 93% coverage of the solid angle

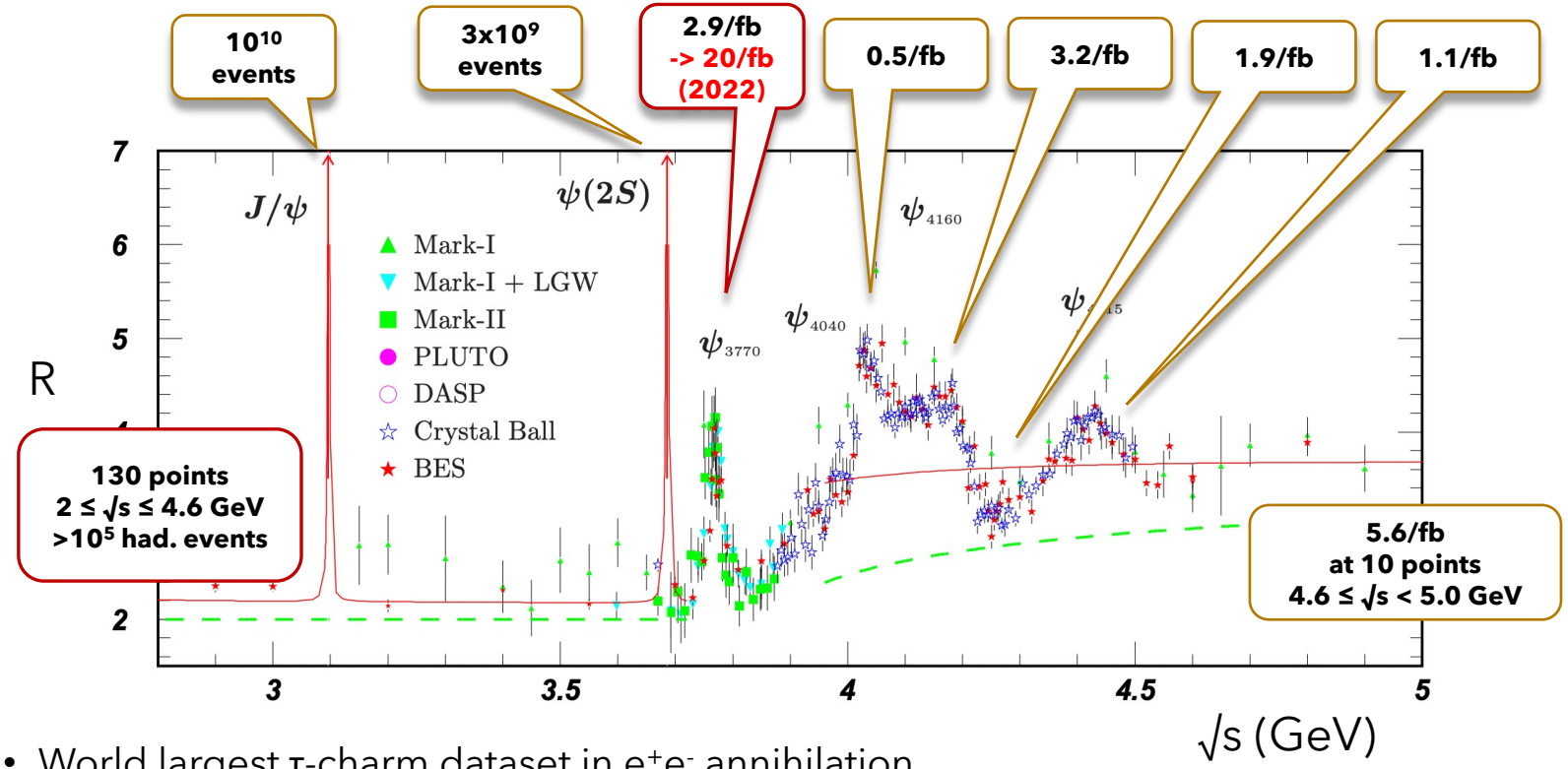
ToF
$\sigma_t \sim 90$ ps (barrel)
$\sigma_t \sim 120$ ps (end caps)

Drift Chamber
$\sigma_{r\phi} \sim 130$ μm (single wire)
$\sigma_{pt}/p_t \sim 0.5$ % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} \sim (6\text{ mm})/E^{1/2}$ @ 1 GeV

RPC Muon Detector
$\Delta\Omega/4\pi = 93\%$

The BESIII Experiment (2)



- World largest τ-charm dataset in e^+e^- annihilation
- Detailed studies in:
  - Charmonium spectroscopy and charm physics
  - Light hadron dynamics
  - τ-physics
  - R-scan

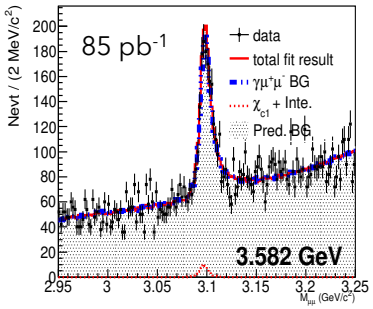
Analysis Strategy

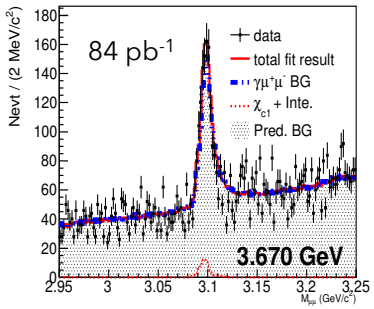
1. Select events with:
   - 2 oppositely charged tracks
   - Identified as muons (E_{EMC}< 400 MeV)
   - At least 1 photon
2. Kinematic fit (4C):
   - Beam energy-momentum conservation of μμγ system
   - Test all reconstructed photons
   - Select photon with best χ^2
3. Best photon in central region ($|\cos\theta_\gamma|<0.8$)
4. 2D Fit to ($M_{\mu\mu}$,$|\cos\theta_\mu|$) distribution
   - Templates from simulation
   - Obtain N_{sig} and N_{bkg}
   - Interference parameters from dedicated scan

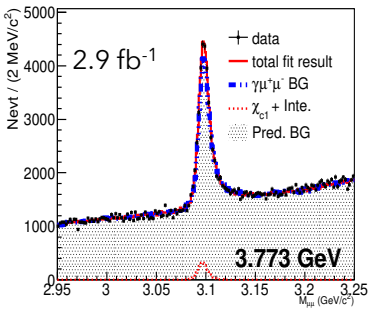
Signal Everywhere? MC Validation

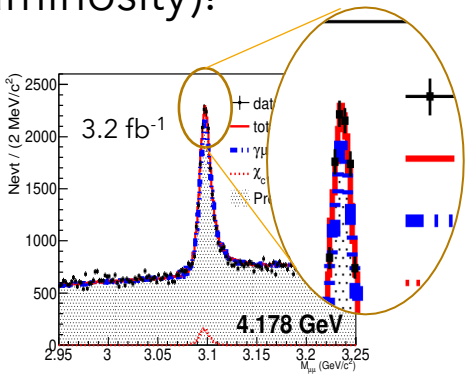
Test the analysis strategy on control samples

- Up to 2.3σ significance (scaled to 180 pb^{-1} integrated luminosity)!



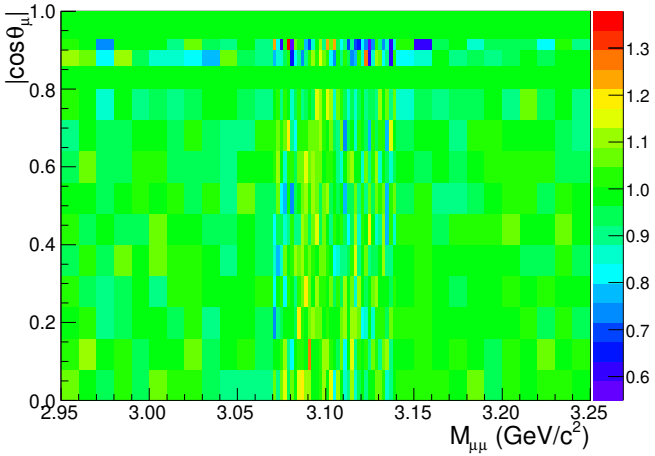






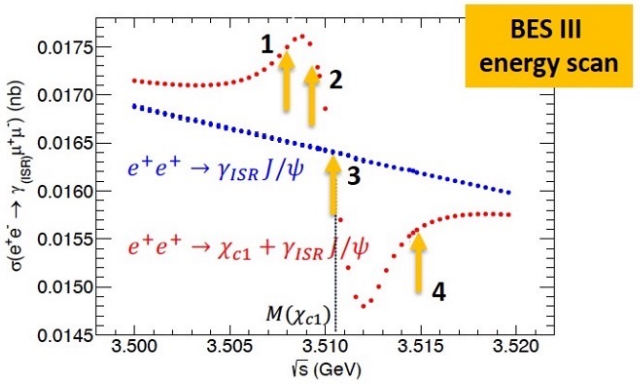
Corrections to 2D distribution

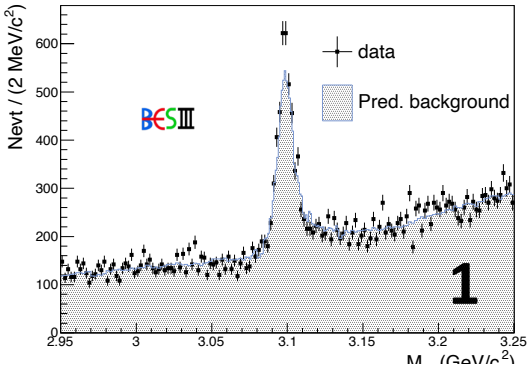
- Evaluated on 3.773 and 4.178 GeV samples
- Cross check (use different corrections)
- Significance always below 1σ!

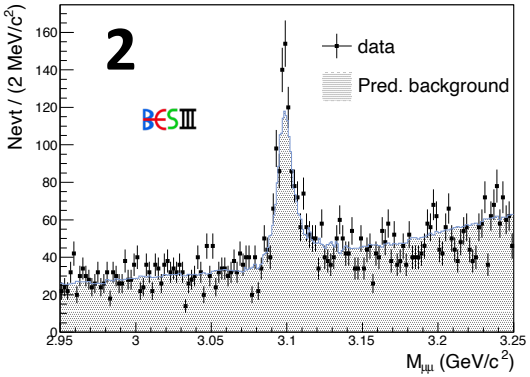


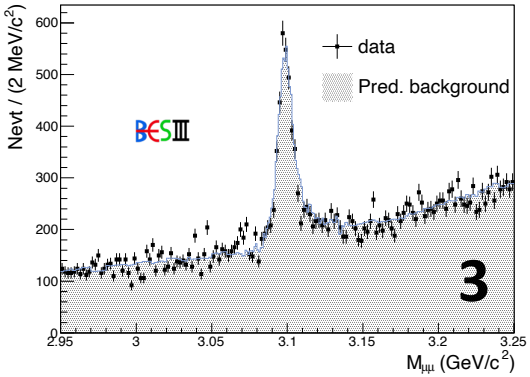
Signal Extraction

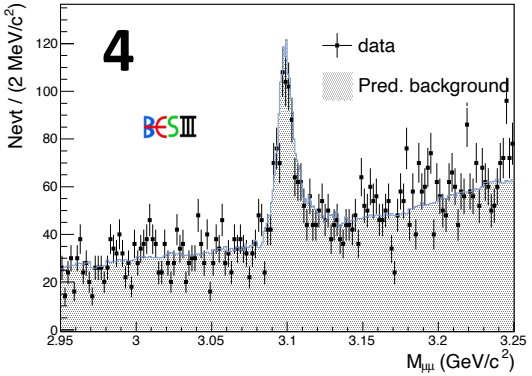
- After corrections, fit 2D ($M_{\mu\mu}$,$|\cos\theta_{\mu}|$) distribution at each scan data point











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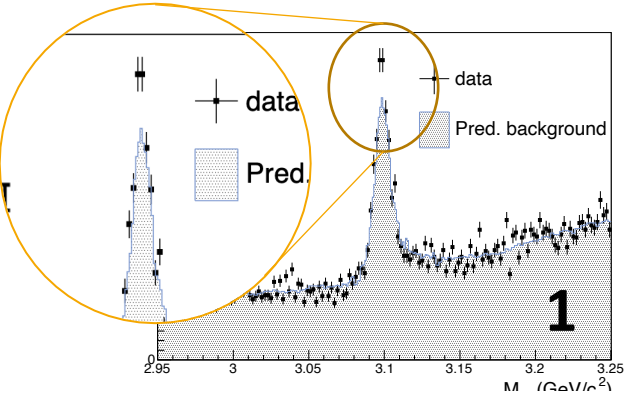
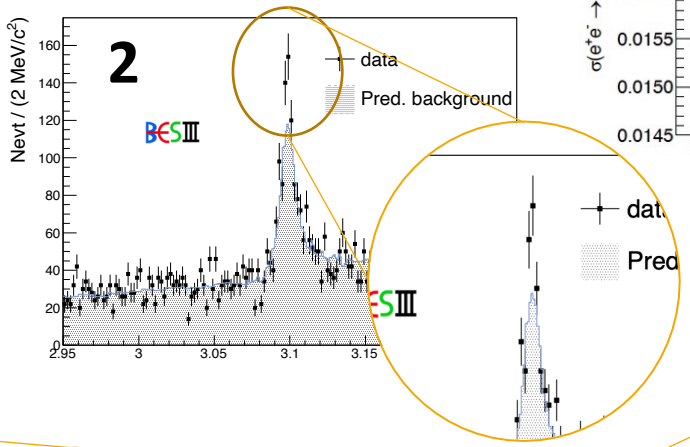
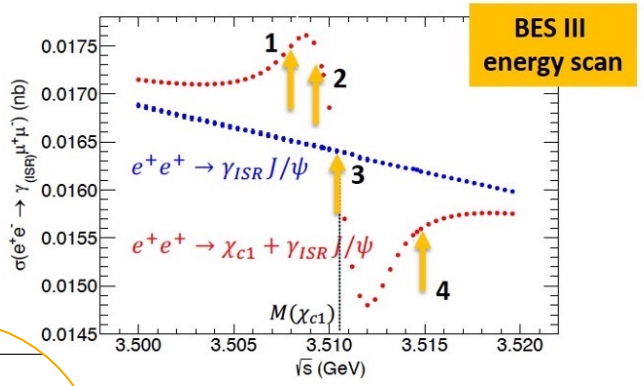
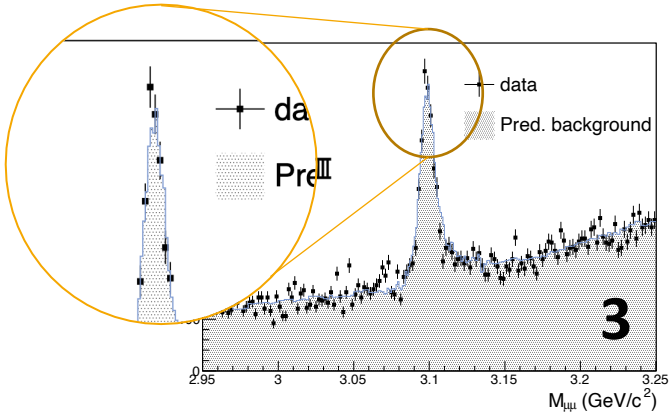
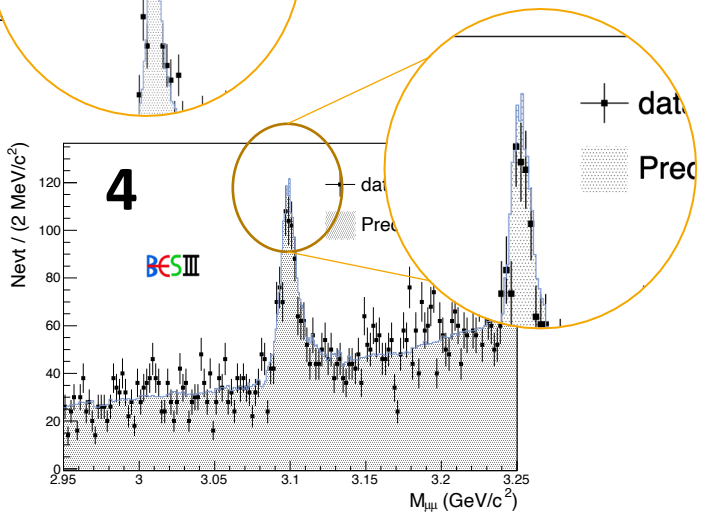




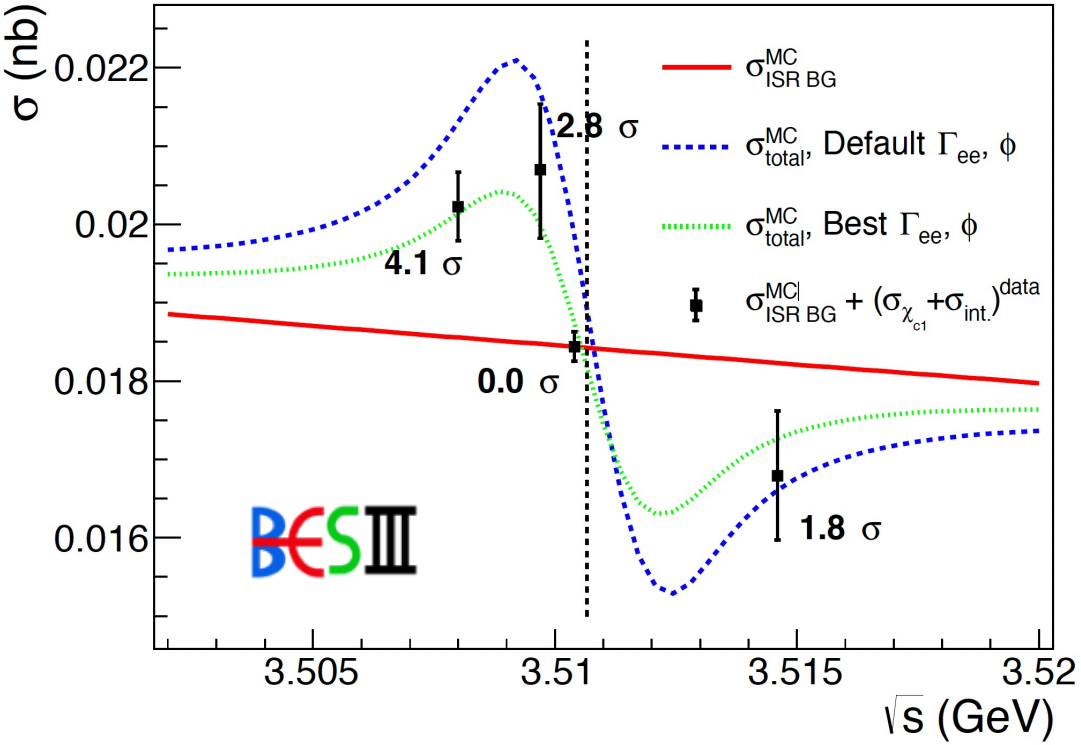






First Observation!

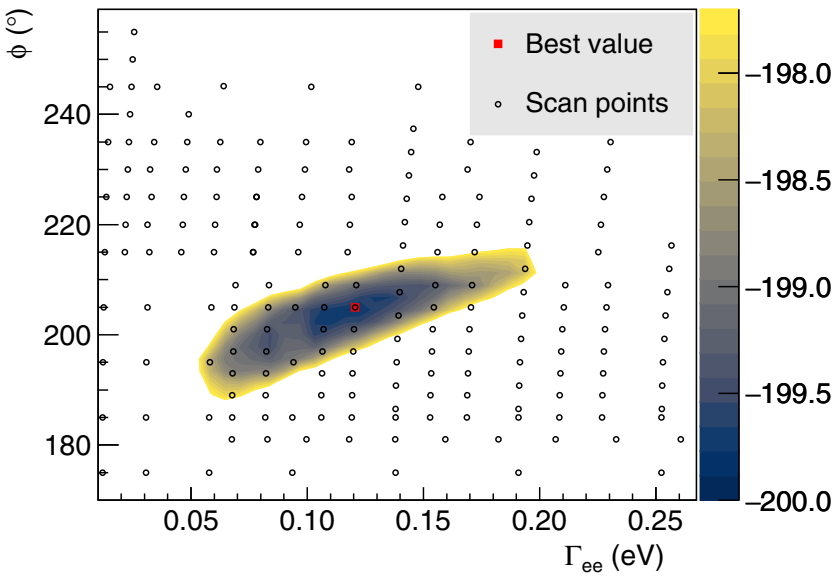
Combining the 4 energy points: **5.1σ** global **significance**

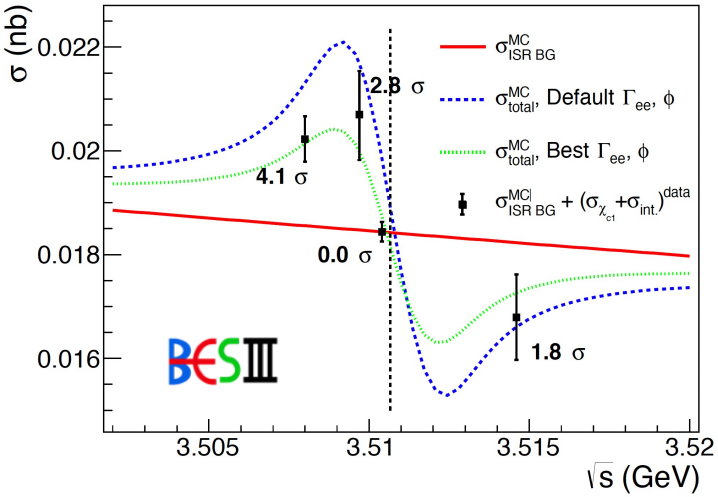


Discrepancy wrt. predicted interference parameters

First Observation!

Combining the 4 energy points: **5.1σ** global **significance**





$$\Gamma_{ee} = \left(0.12^{+0.08}_{-0.07}\right)\ \text{eV}$$

$$\Phi = \left(205^{+10}_{-17}\right)^{\circ}$$

First measurement of χ_{c1} electronic width!

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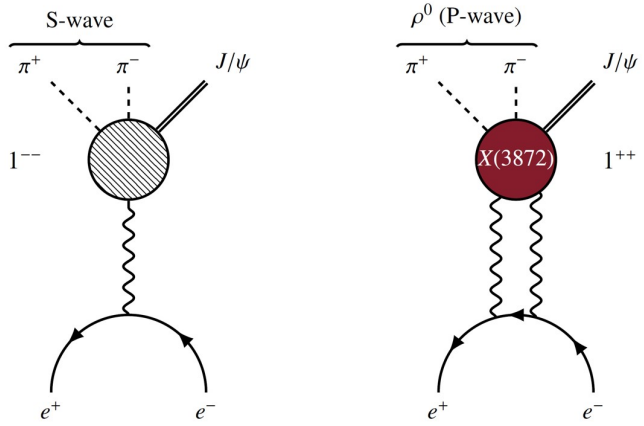
Conclusion and Outlook

- Final states with $\mathbf{J^{PC} \neq 1^{--}}$ **can be produced in** $\mathbf{e^+e^-}$-annihilations
- **First observation** of direct production **of** $\boldsymbol{\chi_{c1}}$ (5.1σ)
  - **Interference** pattern between $\mathbf{e^+e^- \rightarrow \gamma J/\psi}$ and $\boldsymbol{\chi_{c1} \rightarrow \gamma J/\psi}$
  - First measurement of χ_{c1} **electronic width**
- **New technique** to investigate properties of conventional/**exotic** mesons in e^+e^--collisions
- Investigation of $\boldsymbol{\chi_{c2}}$ **direct production** foreseen
  - Different quantum numbers
  - **Validation of the technique**

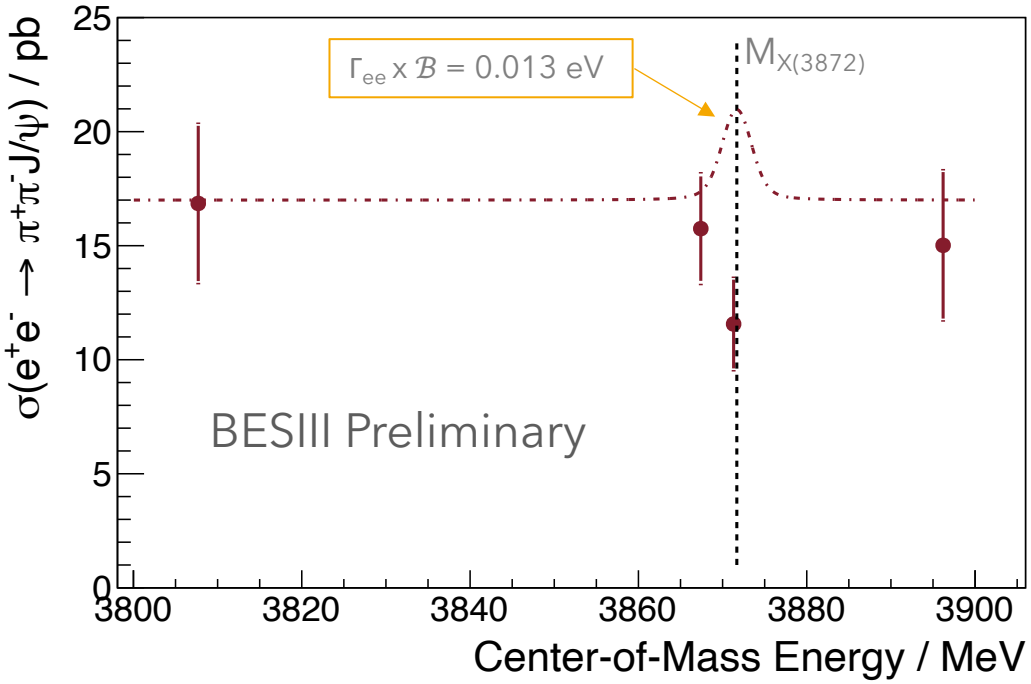
Search for X(3872) in e^+e^- annihilations

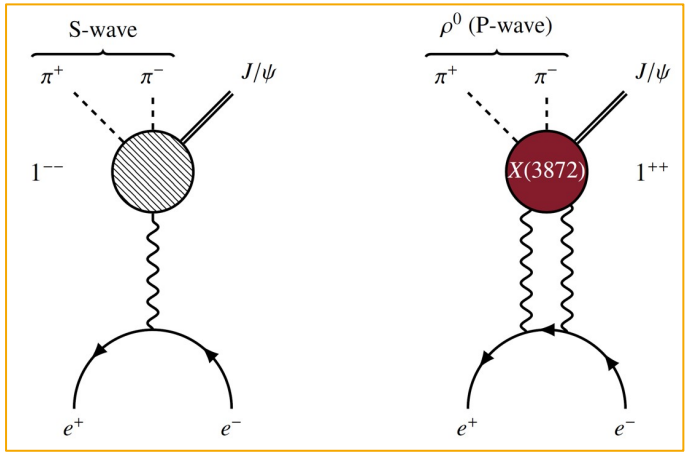
- VMD prediction: $\Gamma_{ee} \gtrsim 0.036$ eV [Denig et al, Phys. Lett. B736 (2014)]
- Look for signal in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
- No interference expected!
- 4 energy points (> 300 pb^{-1})
  - 1 at X(3872) mass
  - 3 off-resonance



Point	E_{cms} (MeV)	$\mathcal{L}_{int}$ (pb^{-1})
1	3807.7	50.5
2	3867.4	108.9
3	3871.3	110.3
4	3896.2	52.6

Search for X(3872) in e^+e^- annihilations





- **No signal observed**: $\Gamma_{ee} \times \mathcal{B} < 0.75 \times 10^{-3}$ eV @ 90% CL

Submitted to PRD (arXiv: 2209.12007)