13th International Workshop on Heavy Quarkonium (QWG2019),
13–17 May 2019, Torino

Update on $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ scan at Belle

arxiv:1905.05521

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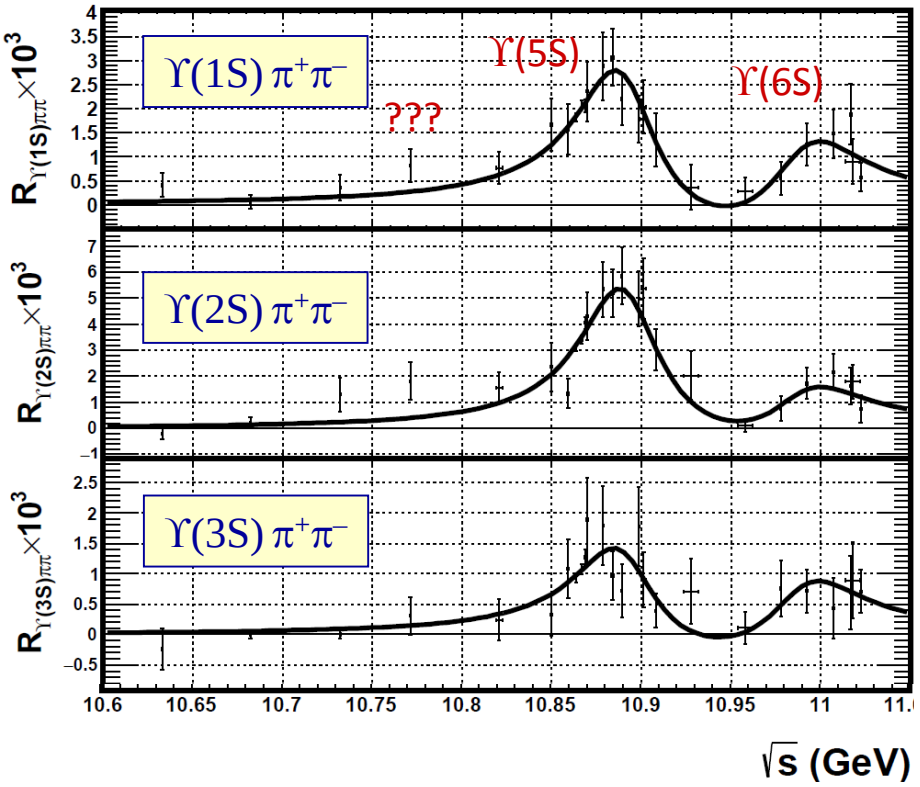
Previous measurement

Belle PRD93,011101(2016)



Clear signals of Υ(5S), Υ(6S). Excess near 10.77 GeV ?

Which vector states are expected in this energy range?

Badalian,Bakker,Danilkin PAN73,138(2010)

Υ(3D) mixed with Υ(4S,5S) mixing could be enhanced due to hadron loops

Exotic states: hadrobottomonia, compact tetraquarks

⇒ Motivation for update.

Changes in the new measurement

The same data samples, improvements in the analysis:

PREVIOUS	NEW
Use more decay channels	
$\Upsilon(nS) \to \mu^+\mu^-$	$\Upsilon(nS) \to \mu^+\mu^-$ and e^+e^-
Improve statistical treatment of data	
Count events in the signal and sideband regions with 1/Efficiency weights	Find signal yield from a fit, then apply efficiency correction Need 3-body matrix element to generate MC PRD91,072003(2015)

accuracy is improved by a factor ~1.3

Use ISR in high statistics $\Upsilon(5S)$ on-resonance data to study cross section energy dependence

Data samples

Scan data: 22 points ×1 fb^{-1}

$\Upsilon(5S)$ on-resonance data: 121 fb^{-1} at 5 points, $E_{max}–E_{min}$= 3MeV

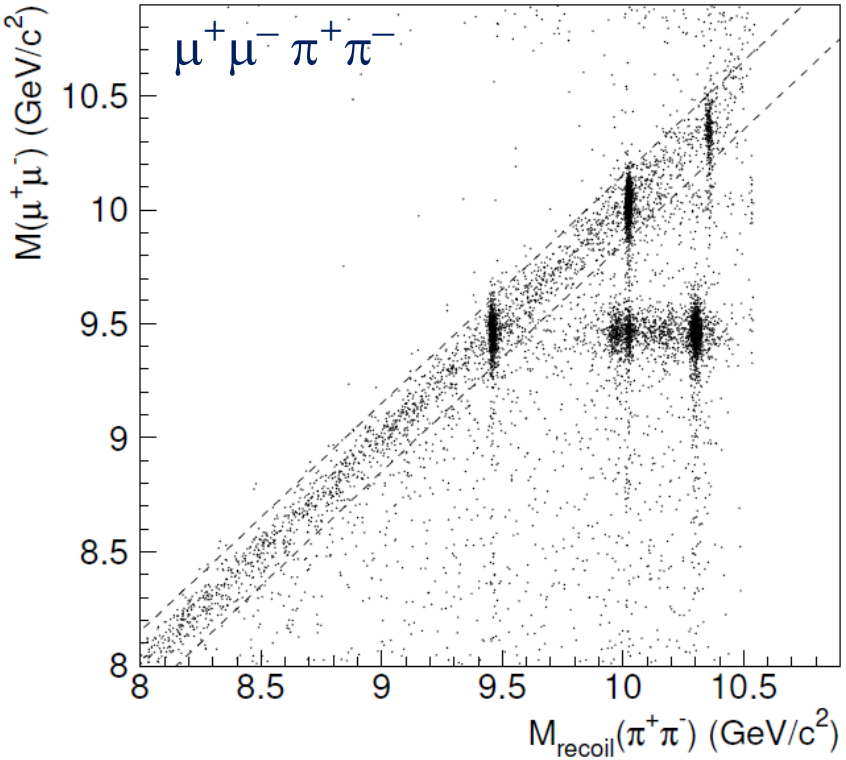
Continuum data, 10.52GeV: 61 fb^{-1}

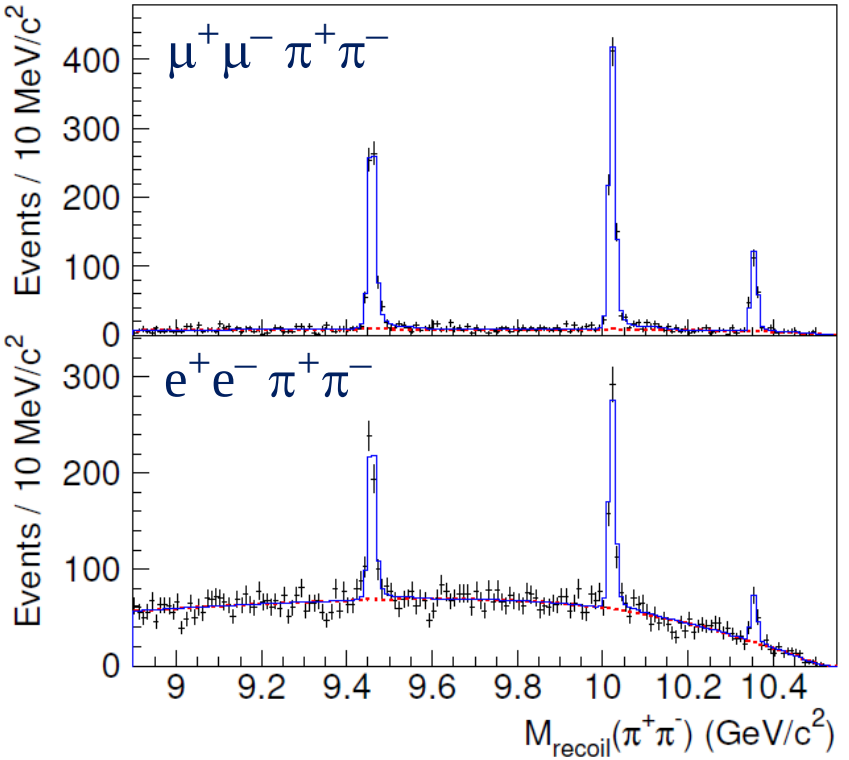
Selection requirements

$\mu^+\mu^-\pi^+\pi^-$ / $e^+e^-\pi^+\pi^-$ require PID, energy balance;

extra in e^+e^- channel: $M_{recoil}(e^+e^-) > 350$ MeV, $\cos\theta_{e-} < 0.82$

Background: QED production of 4 tracks





Signal shape in $M_{recoil}(\pi^+\pi^-)$

Calculation scheme

Momentum resolution ⊗ ISR

includes effects of
- FSR
- decays-in-flight
- secondary interactions

Kuraev-Fadin radiator function
$\times \sigma(E_{cm})$
$\times \varepsilon (E\gamma_{ISR})$

⊗ Ecm spread

Gaussian $\times \sigma(E_{cm})$

5.4 MeV

× ε of energy balance requirement

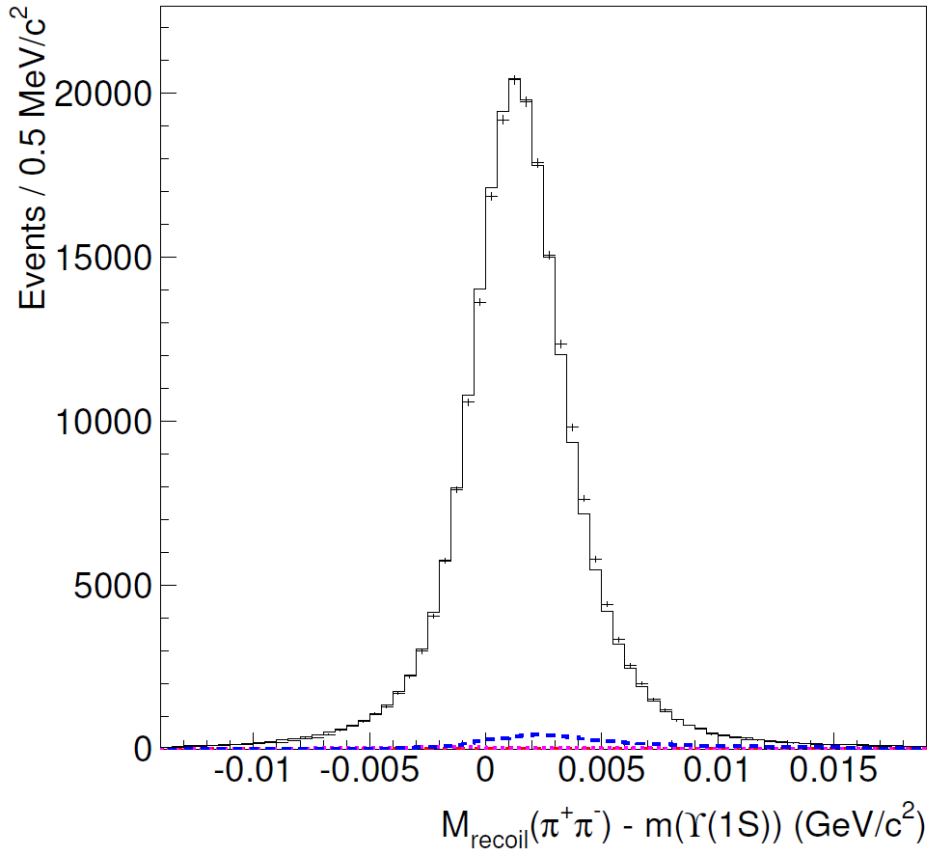
soft cut-off at ~200 MeV

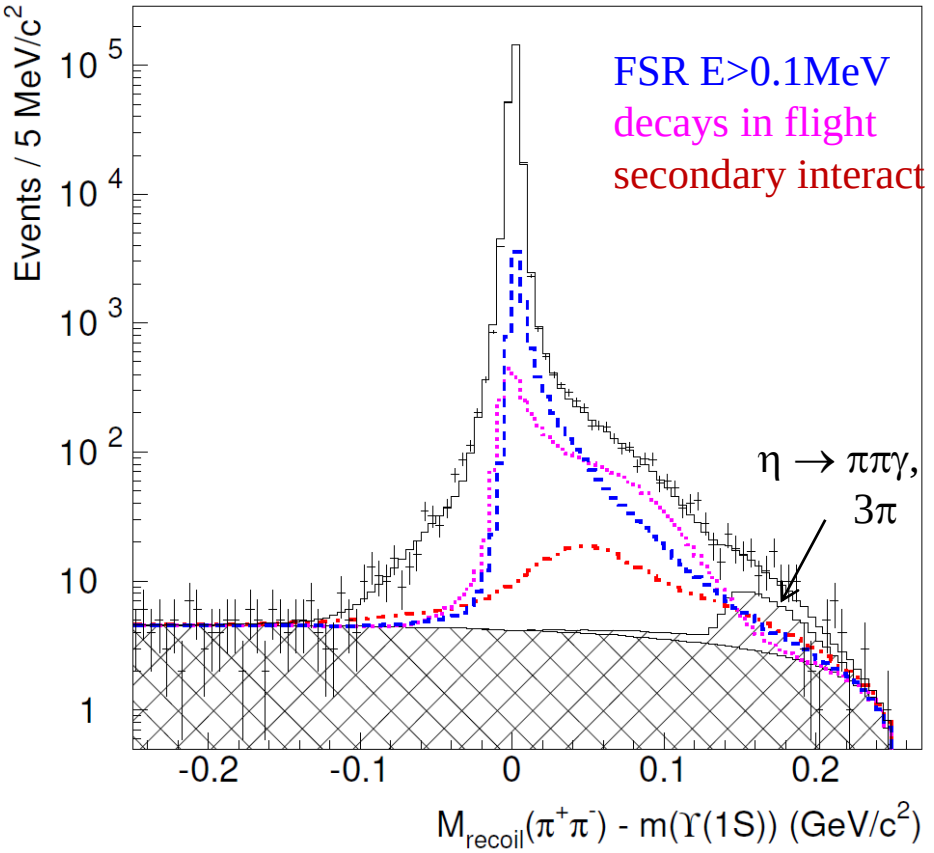
$\sigma(E_{cm})$ is being measured ⇒ iterations

compute signal shapes
↓
measure cross sections
↓
fit energy dependence of cross sections

Verification of signal shape

Υ(2S) data 24fb^{-1} Υ(2S) is narrow $\Rightarrow$ no contributions of ISR and energy spread

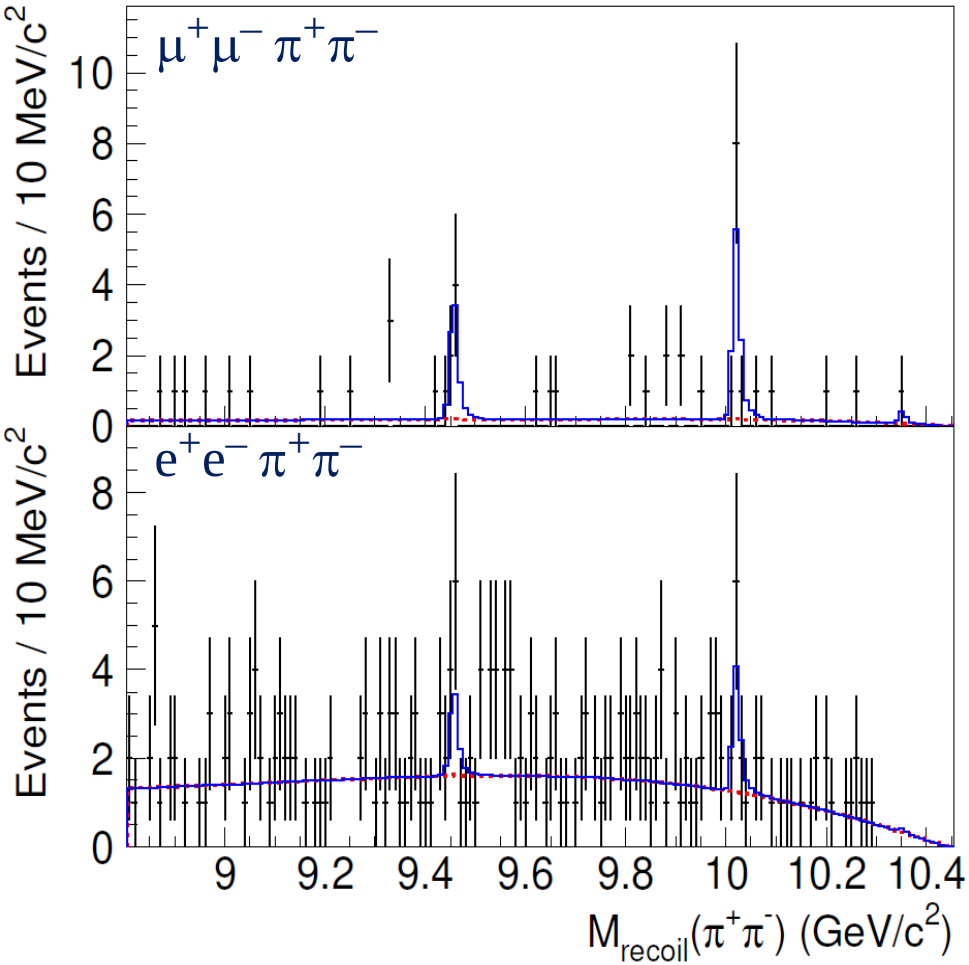




Shapes from MC; floated parameters are yield, overall shift and momentum resolution fudge factor $f = 1.160 \pm 0.003$

Use Υ(3S) data 3fb^{-1} to study energy dependence of f $\Rightarrow$ constant

Fit to $M_{recoil}(\pi^+\pi^-)$



Signal:

fix ratio of ee/μμ yields,
float μμ yields and overall shift

$\Rightarrow E_{cm}$ calibration

Non-peaking background:

$$B(x) = A\,(x - x_0)^p\,P_3(x)$$

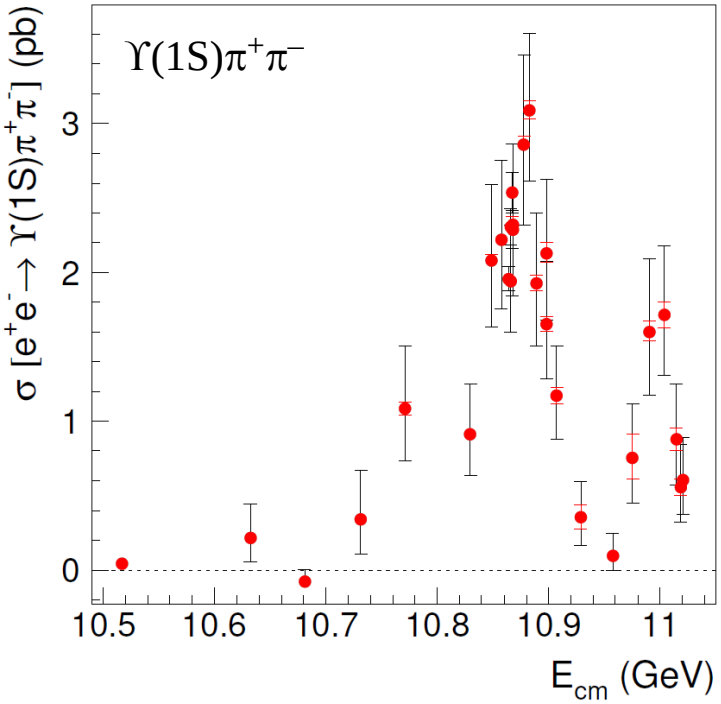
Peaking background:

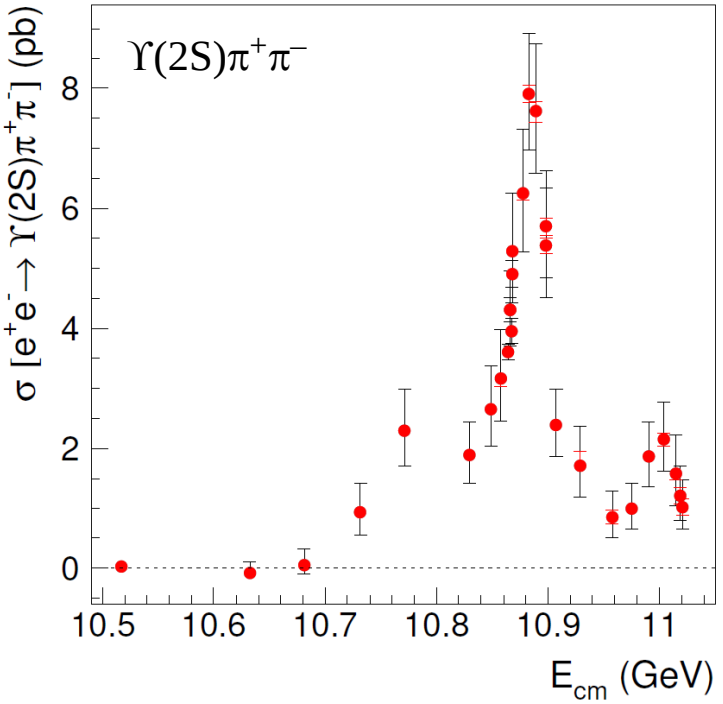
e.g. $e^+e^- \to \gamma^*\gamma^* \to \Upsilon(nS)\,\pi^+\pi^-$
$\hookrightarrow \mu^+\mu^-$

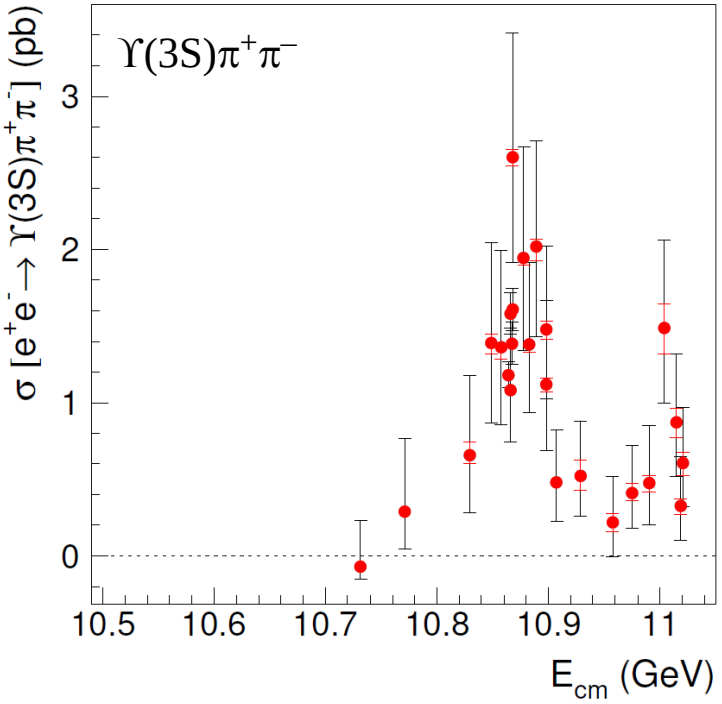
from MC, small contribution

Shamov et al., to be published in proceedings of PhiPsi 2019

Born cross sections







errors: stat. , uncor. syst.

Clear signals of $\Upsilon(5S)$, $\Upsilon(6S)$;
new structure near 10.77 GeV ?

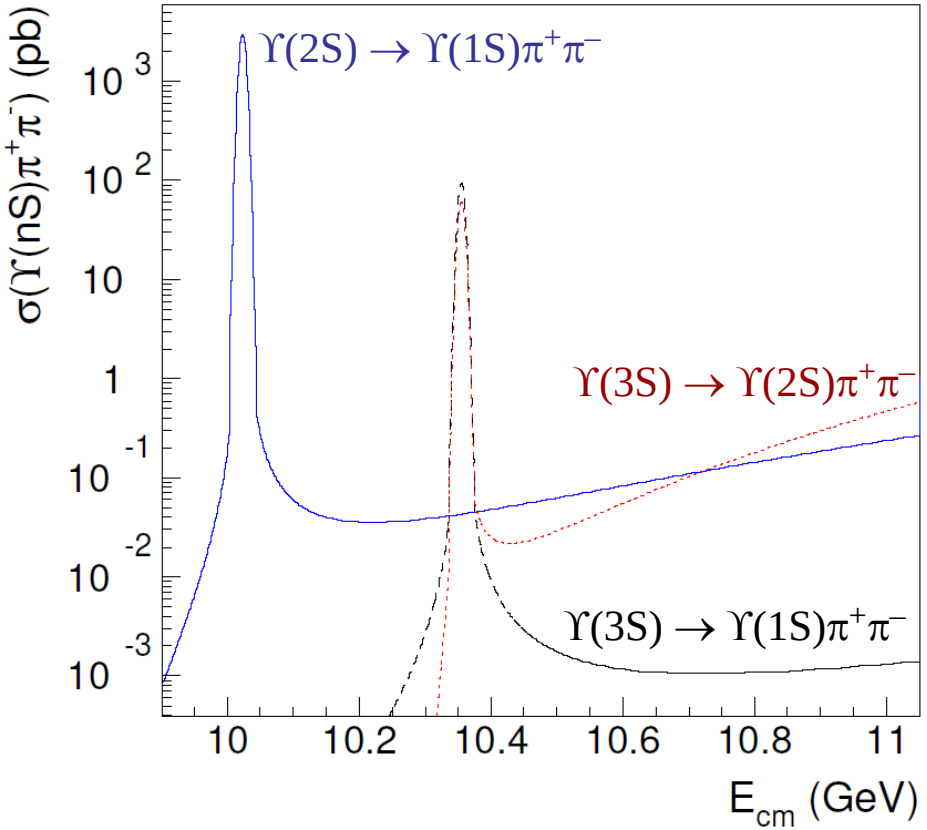
Continuum below $\Upsilon(4S)$

Hints for non-zero values:

$$\sigma[e^+e^- \to \Upsilon(1S)\pi^+\pi^-] = 40^{+21}_{-19}\ \text{fb}$$

$$\sigma[e^+e^- \to \Upsilon(2S)\pi^+\pi^-] = 25^{+29}_{-25}\ \text{fb}$$

What could be the origin?



Expectations:

$$e^+e^- \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^- = 71\text{fb}$$
$$e^+e^- \to \Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^- = 2\ \text{fb}$$
$$e^+e^- \to \Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^- = 35\text{fb}$$

$\Leftarrow$ BW with $M, \Gamma, \Gamma_{ee}, B_f$ from PDG.

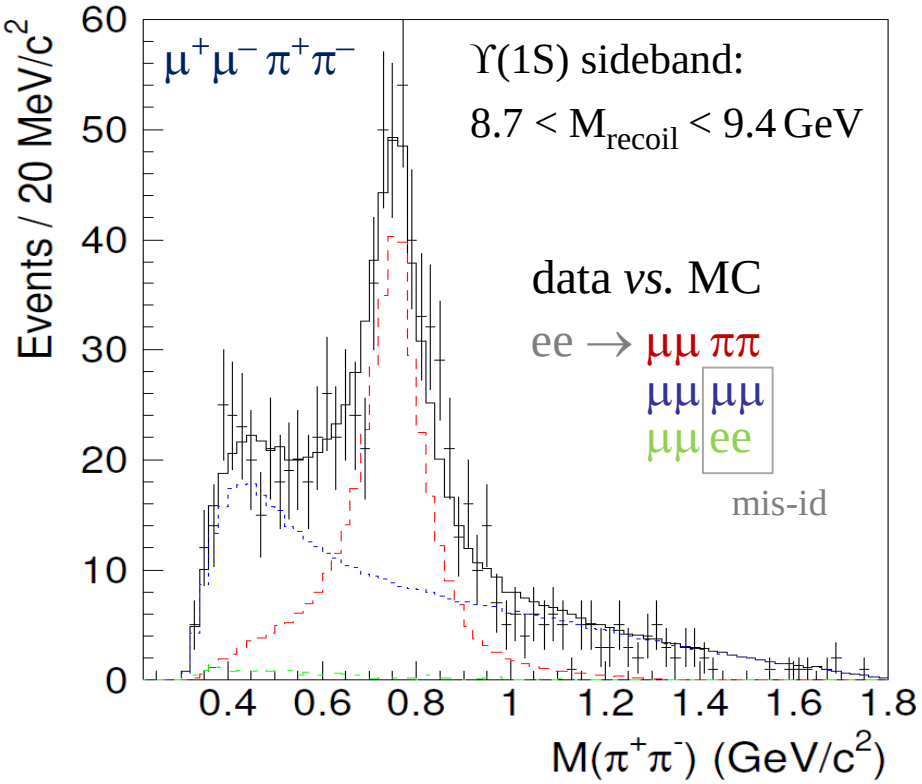
$\Gamma_f(s)$: integrate ME over Dalitz plot.

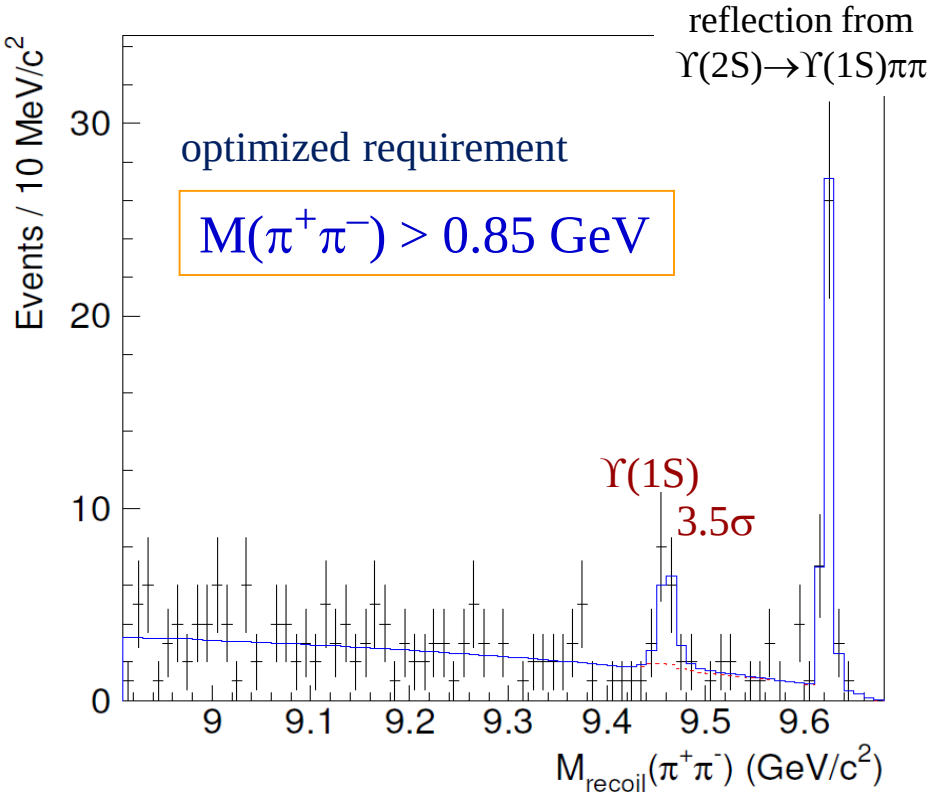
ME rapidly increase with $M(\pi^+\pi^-)$ $\Rightarrow$ BW tails increase with energy

$\Rightarrow$ Large contributions at high energy

Continuum below $\Upsilon(4S)$

$M(\pi^+\pi^-)$ distribution: distinguish signal from background





$\sigma[e^+e^- \to \Upsilon(1S)\pi^+\pi^-] =$

with $M(\pi\pi)$ cut		w/o $M(\pi\pi)$ cut
42^{+17}_{-15} fb (stat.)	agree	40^{+21}_{-19} fb

Evidence for $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$ in continuum at E_{cm}= 10.52 GeV.

Fit to energy dependence of cross sections

Fit function

$$|\mathrm{BW}^{(n)}_{\Upsilon(5S)} + e^{i\alpha_n}\,\mathrm{BW}^{(n)}_{\Upsilon(6S)} + e^{i\beta_n}\,\mathrm{BW}^{(n)}_{\mathrm{new}} + e^{i\gamma_n}\,\mathrm{BW}^{(n)}_{\Upsilon((n+1)S)}|^2 \otimes \mathrm{Gaussian}$$

The new structure might have resonant or non-resonant origin.
The two effects are difficult to distinguish ⇐ similar line shape, phase motion.

⇒ Breit-Wigner – reasonable approximation in both cases.

Bugg EPL96,11002(2011)
…

we do not claim that the new structure is a resonance

$$\mathrm{BW}(s, M, \Gamma, \Gamma^0_{ee} \times \mathcal{B}_f) = \frac{\sqrt{12\pi\ \Gamma\ \Gamma^0_{ee} \times \mathcal{B}_f}}{s - M^2 + iM\Gamma} \sqrt{\frac{\Gamma_f(s)}{\Gamma_f(M^2)}}$$

Floated parameters: M, Γ for Υ(5S), Y(6S), new structure

$\Gamma^0_{ee} \times \mathcal{B}_f$, complex phases for all contributions, for all channels

Fit

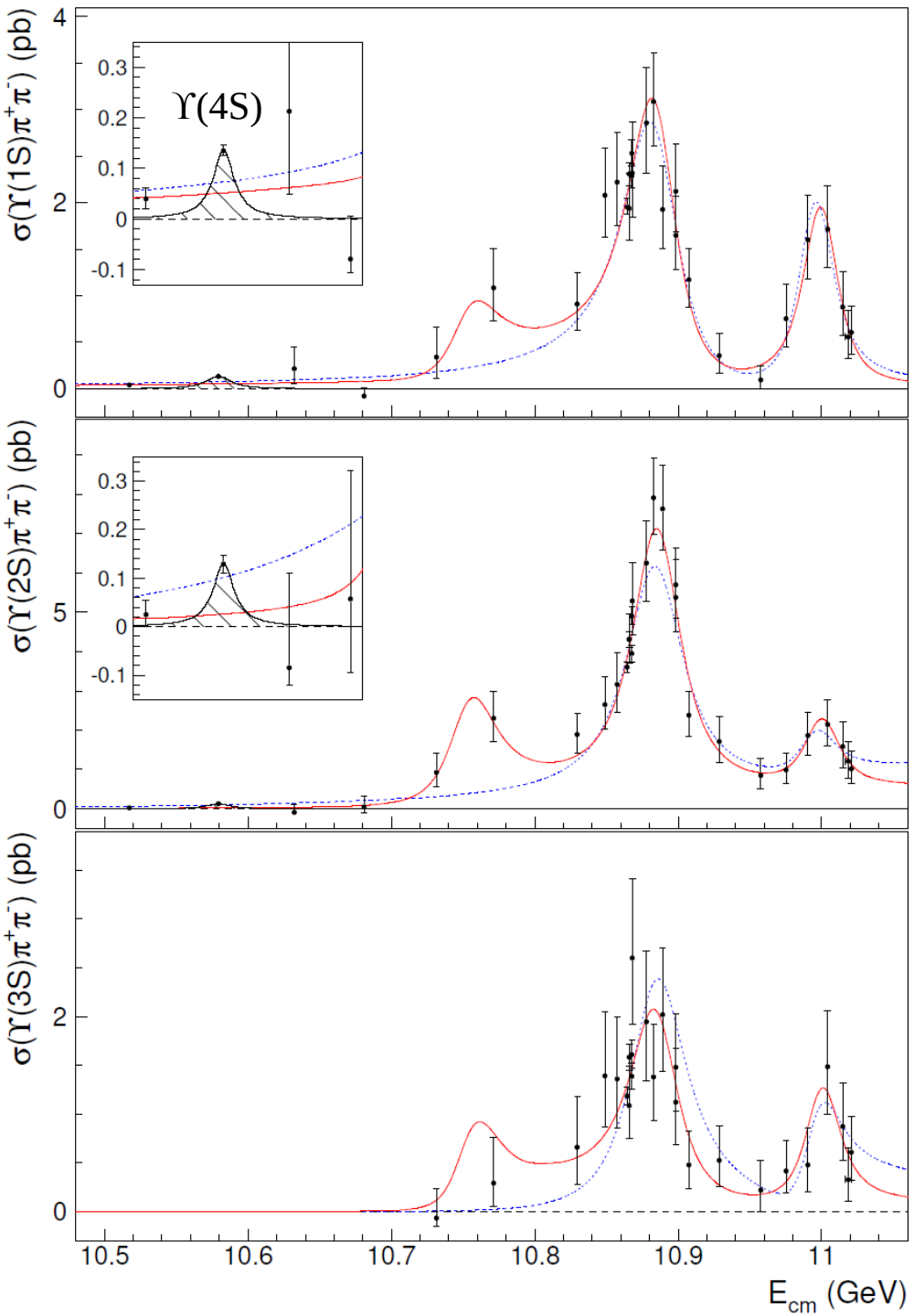
default
w/o new structure

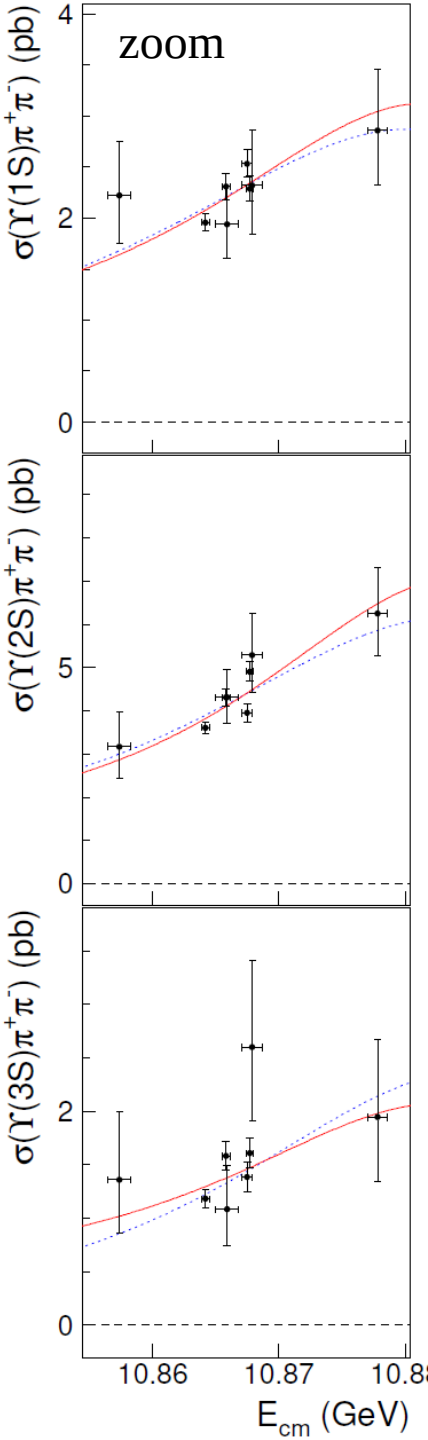
$\Upsilon(4S)$ is shown for illustration

New structure

$\Upsilon(1S)\pi\pi$ 2.4σ
$\Upsilon(2S)\pi\pi$ 5.3σ
w/ syst.

Combined global significance w/ syst. 6.7σ





Fit

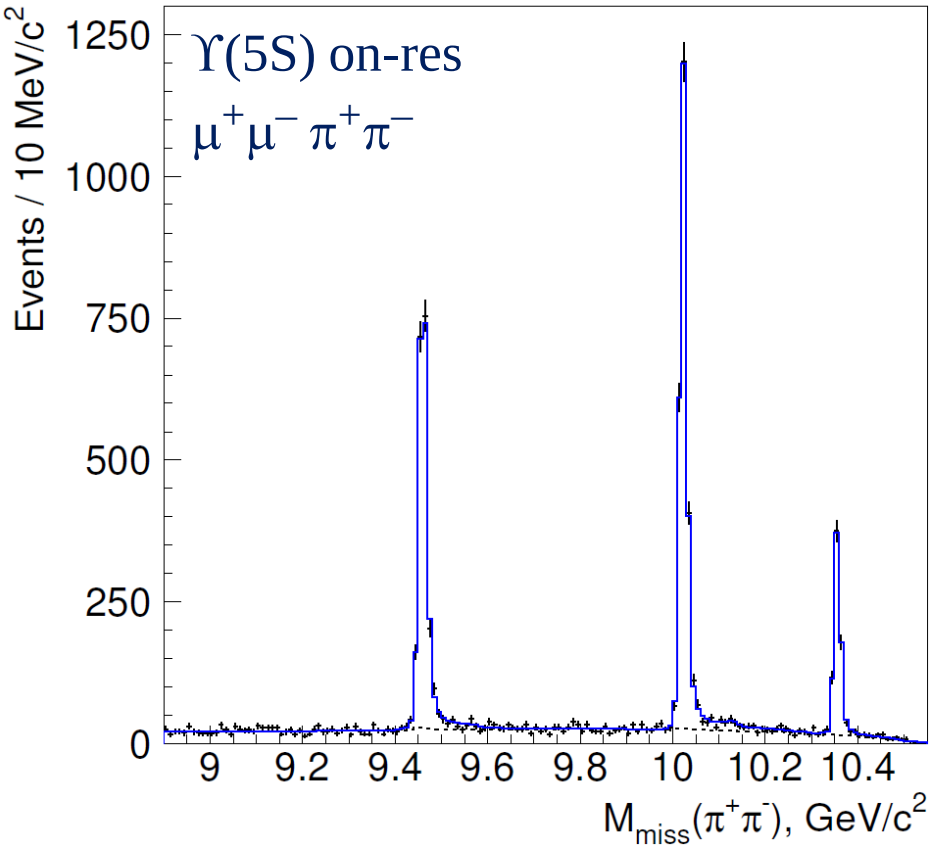
ISR tails of the $\Upsilon(nS)\pi\pi$ signals are sensitive to the cross section shapes.

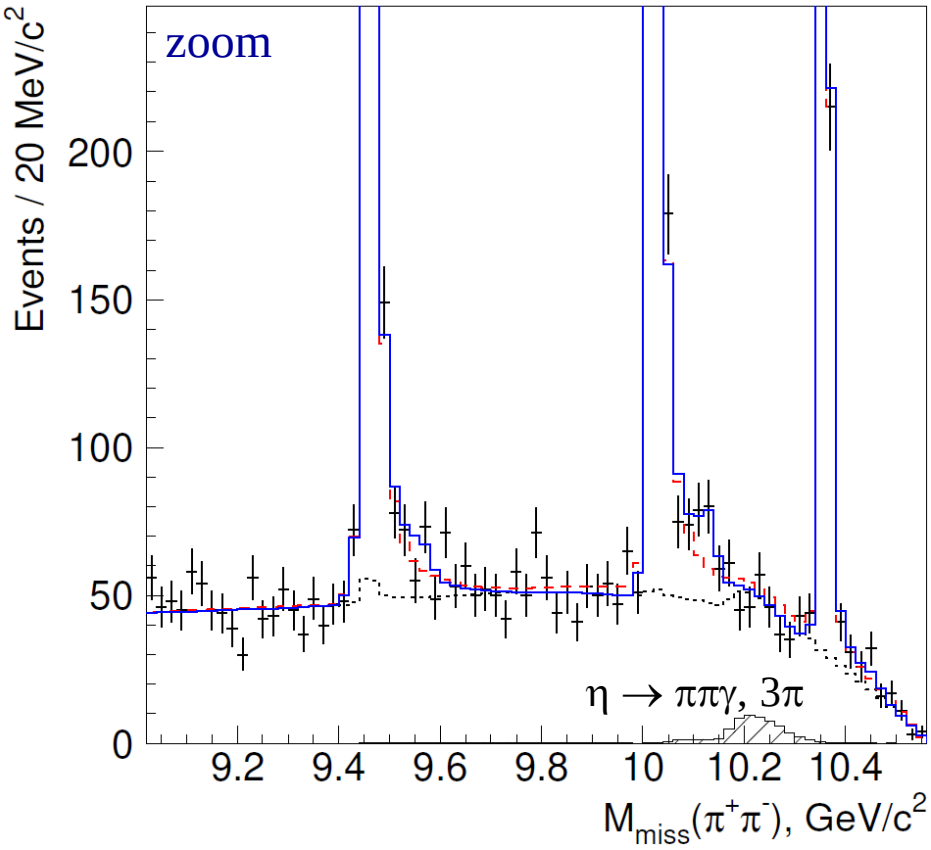
$\Rightarrow$ Include the $M_{recoil}(\pi^+\pi^-)$ distribution into the fit.

simultaneous fit to the cross sections and $M_{recoil}(\pi^+\pi^-)$

default

w/o new structure





Excellent description of ISR tails.

Fit results

	$\Upsilon(10860)$	$\Upsilon(11020)$	new structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\ +1.0}_{-4.5\ -1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\ +0.5}_{-3.9\ -1.1}$	$23.8^{+8.0\ +0.7}_{-6.8\ -1.8}$	$35.5^{+17.6\ +3.9}_{-11.3\ -3.3}$

Previous measurement

$10891.1 \pm 3.2^{+0.6}_{-1.7}$	$10987.5^{+6.4\ +9.0}_{-2.5\ -2.1}$	PRD93,011101(2016)
$53.7^{+7.1\ +1.3}_{-5.6\ -5.4}$	$61^{+9\ +2}_{-19\ -20}$	

many differences, e.g.
model: new structure, tails
$\sigma^{vis} \Leftrightarrow \sigma^{B}$

C.f. $h_b\pi\pi$	$10884.7^{+3.6+8.9}_{-3.4-1.0}$	$10999.0^{+7.3+16.9}_{-7.8-\ 1.0}$	PRL117,142001(2016)
	$40.6^{+12.7+\ 1.1}_{-\ 8.0-19.1}$	$27^{+27+\ 5}_{-11-12}$	

good agreement

Branching fractions

Multiple solutions: sum of N BW amplitudes – 2^{N-1} solutions (4 or 8 in our case)

$\Gamma_{ee} \times \mathcal{B}$ (in eV)

	$\Upsilon(10860)$	$\Upsilon(11020)$	new
$\Upsilon(1S)\pi^+\pi^-$	$0.75 - 1.43$	$0.38 - 0.54$	$0.12 - 0.47$
$\Upsilon(2S)\pi^+\pi^-$	$1.35 - 3.80$	$0.13 - 1.16$	$0.53 - 1.22$
$\Upsilon(3S)\pi^+\pi^-$	$0.43 - 1.03$	$0.17 - 0.49$	$0.21 - 0.26$

Ranges:
min – max

$\Upsilon(4S)$

Implications?

Belle PRD96,052005(2017)

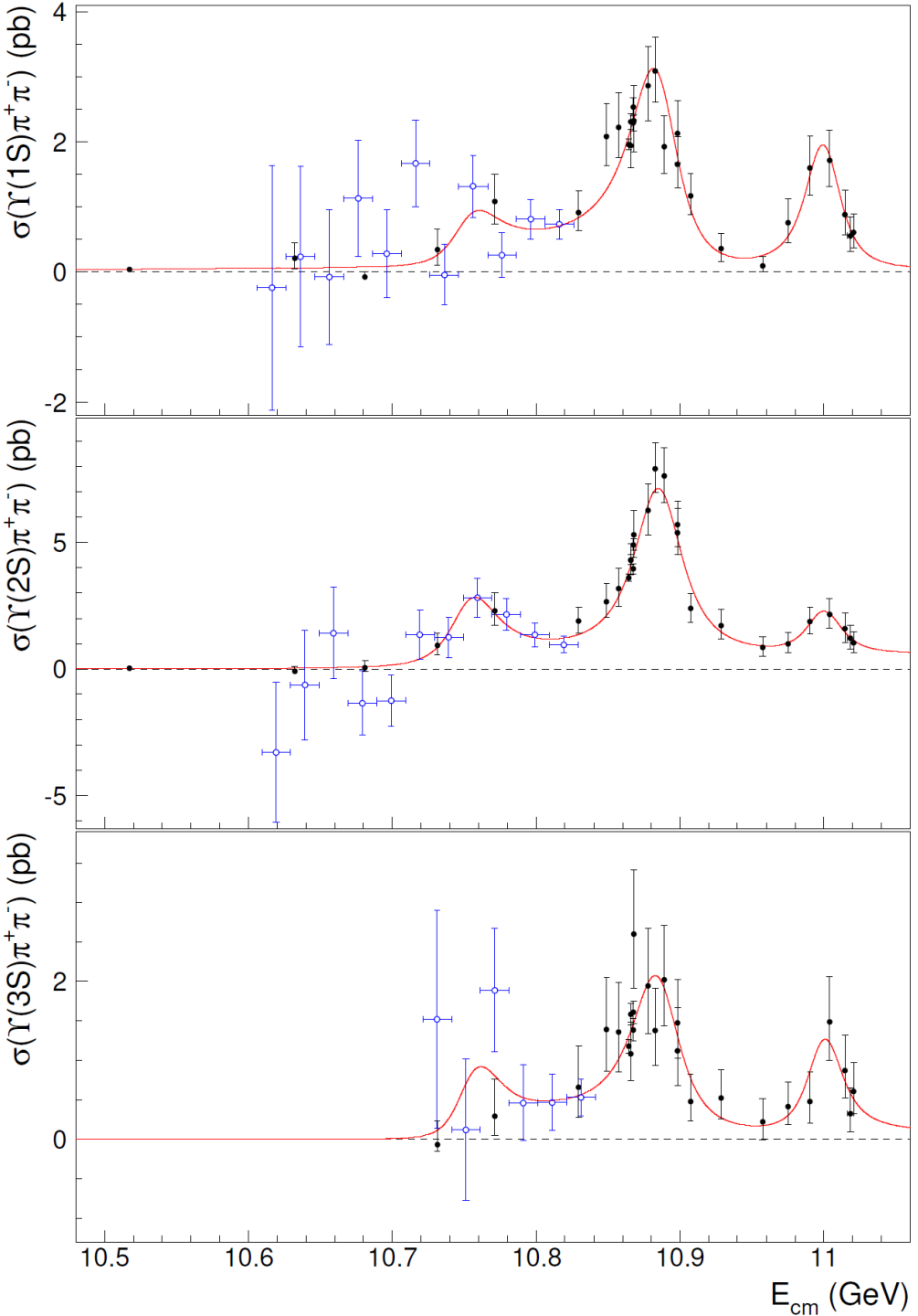
$$\mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) = (8.2 \pm 0.5 \pm 0.4) \times 10^{-5}$$
$$\mathcal{B}(\Upsilon(4S) \to \Upsilon(2S)\pi^+\pi^-) = (7.9 \pm 1.0 \pm 0.4) \times 10^{-5}$$

Include $\Upsilon(4S)$ in the fit, scan FCN in B $\Rightarrow$ $(1.2 - 16) \times 10^{-5}$, $(1.3 - 9.6) \times 10^{-5}$ 67% C.L.

Visualization

Blue points: cross sections
estimated using ISR tails

Not to be used in the fit:
1. Stat. errors only.
2. ISR luminosity changes rapidly
w/ energy ⇒ difficult to estimate
effects of spread & resolution.



Conclusions

Observation of new structure

$$M = 10752.7 \pm 5.9\,^{+0.7}_{-0.4}\ \text{MeV}$$

$$\Gamma = 35.5^{+17.6}_{-11.3} \pm 3.4\ \text{MeV}$$

Global significance including systematics: 6.7σ.

arxiv:1905.05521

Evidence for $e^+e^- \to \Upsilon(1S)\,\pi^+\pi^-$ at E_{cm} = 10.52 GeV

– implications for BF[$\Upsilon(4S) \to \Upsilon(1,2S)\,\pi^+\pi^-$]

All results are preliminary

Interpretation?

Resonance? $\Upsilon(3D)$, exotics,..

Non-resonant effect? Complicated rescattering,..

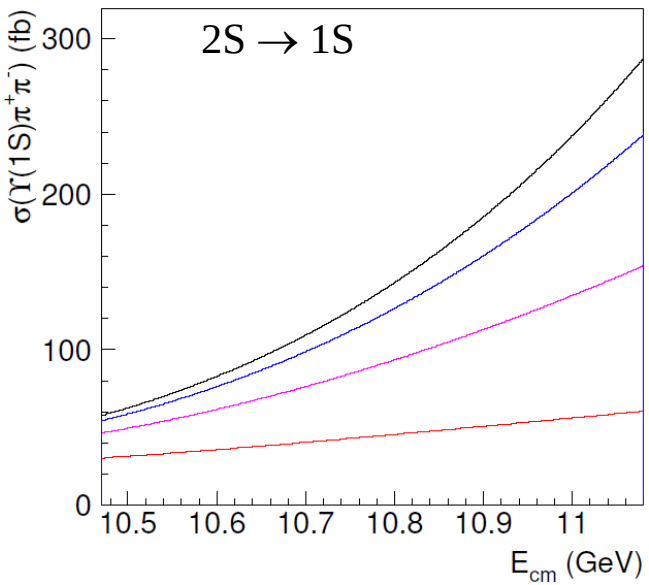
Need information on other channels to clarify the origin.

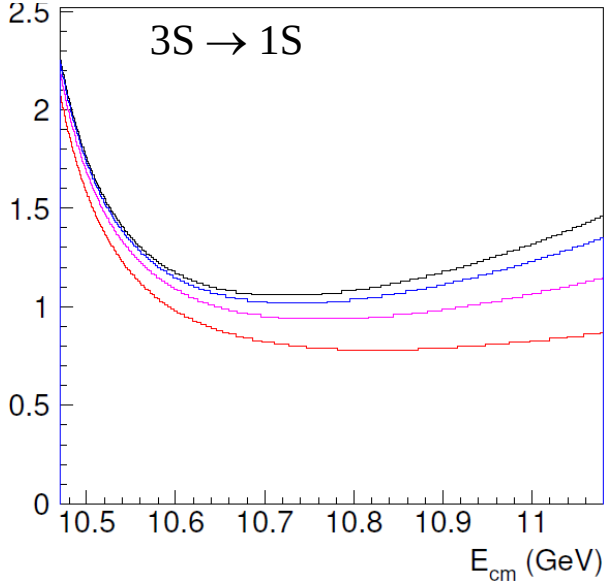
Back-up

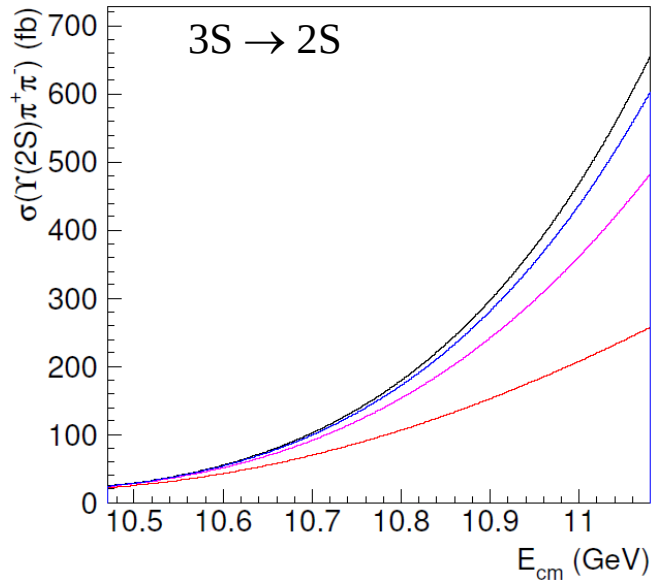
Tails

Matrix elements of $\Upsilon(2S,3S) \to \Upsilon(1S,2S)\pi^+\pi^-$ have terms proportional to $M^2(\pi^+\pi^-)$

$\Rightarrow$ Contributions rise quickly as PHSP grows with c.m. energy



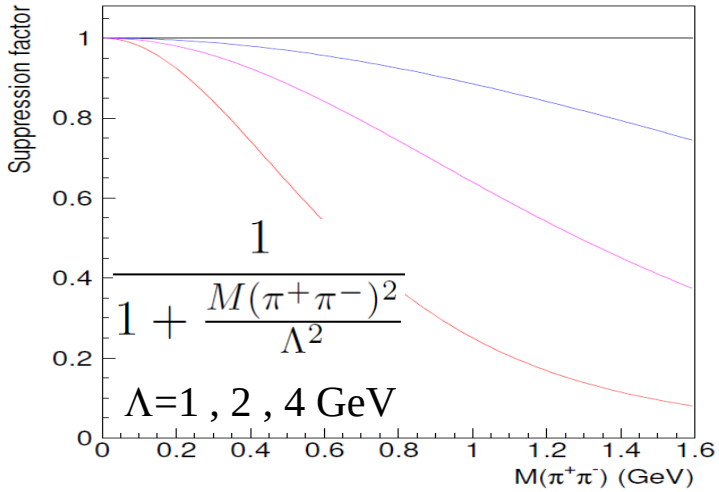




Why could there be deviations from these estimations?

M. Voloshin: high $M(\pi^+\pi^-)$ could be suppressed due to some form factor

$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$ - no sign of suppression



Global significance

Exclude new structure in all channels: $\Delta(-2\ln L) = 66.$

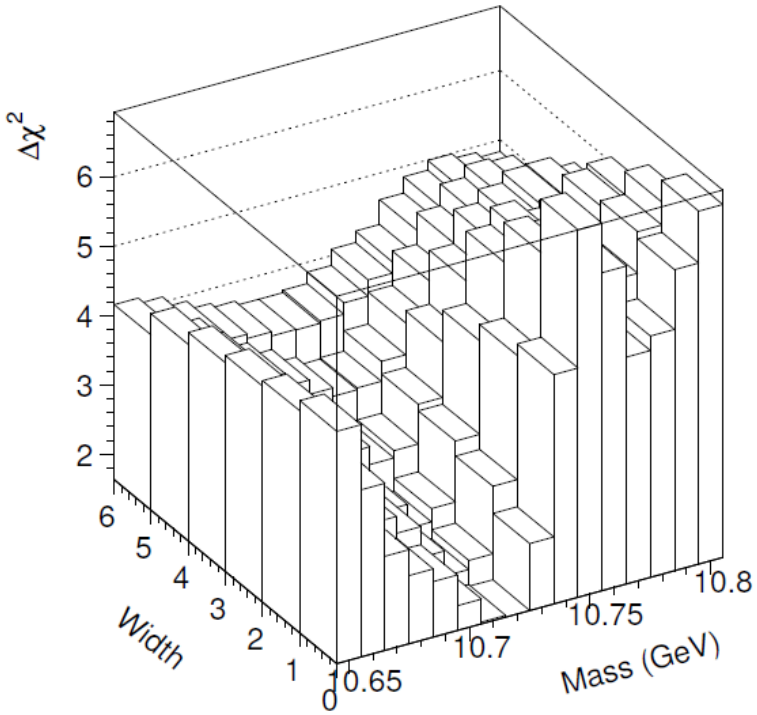
local significance 7.0σ

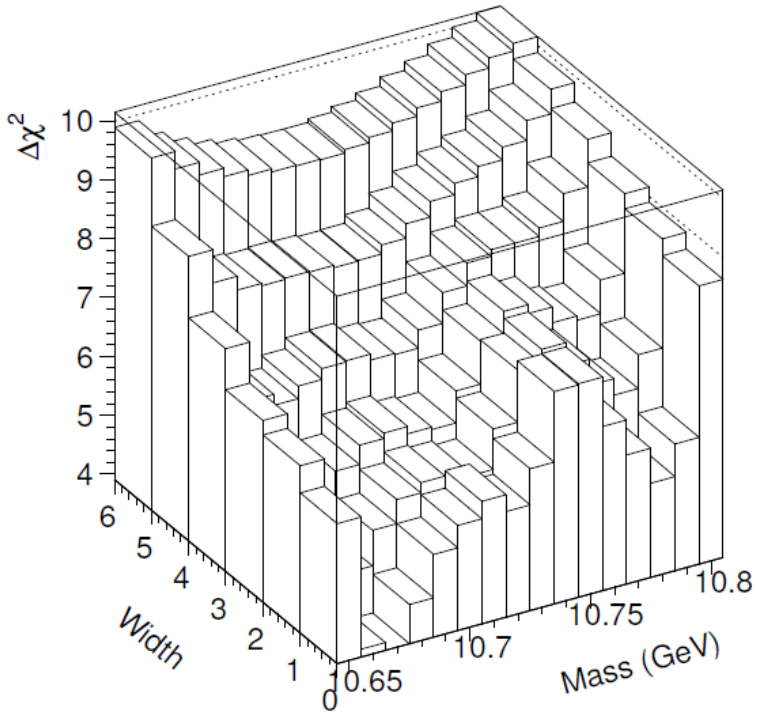
52. – cross sections
14. – recoil mass

global?

Astropart. Phys. **35**, 230 (2011)

Gross-Vitells: toy MC, scan $\Delta(-2\ln L)$ in M, Γ (=30,40,50,70,100,150 MeV)





Euler characteristic

$$p = \chi^2_6(u) + e^{-u/2}\, u^2\, (A\sqrt{u} + B\,(u-5))$$

"Look elsewhere effect": p-value ×4.5, global significance 6.8σ

w/ syst. 6.7σ