Сессия-конференция Секции ядерной физики ОФН РАН,
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Измерение энергетической зависимости сечений $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ в эксперименте Belle

JHEP 1910, 220 (2019)

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Bottomonium-like states

Above $B\bar{B}$ threshold there are 5 hadrons containing $b\bar{b}$ quarks:

$Z_b(10610)^+$, $Z_b(10650)^+$ $\Rightarrow$ exotic quark content: $|b\bar{b}u\bar{d}\rangle$

$\Upsilon(4S)$, $\Upsilon(5S)$, $\Upsilon(6S)$ $\Rightarrow$ properties unexpected for $b\bar{b}$:

Enhanced hadronic transitions to lower bottomonia:

$$\Gamma[\,\Upsilon(5S) \to \Upsilon(1S,2S,3S)\,\pi^+\pi^-\,] = 240{,}430{,}150\ \text{MeV}$$

c.f. $\Gamma[\,\Upsilon(2S) \to \Upsilon(1S)\,\pi^+\pi^-\,] = 6$ MeV,

$\Gamma[\,\Upsilon(3S) \to \Upsilon(1S,2S)\,\pi^+\pi^-\,] = 0.9,\ 0.6$ MeV.

η transitions are not suppressed w.r.t. $\pi^+\pi^-$ transitions:

$$\Gamma[\,\Upsilon(4S) \to \Upsilon(1S)\,\eta\,] \,/\, \Gamma[\,\Upsilon(4S) \to \Upsilon(1S)\,\pi^+\pi^-\,] = 2.4$$

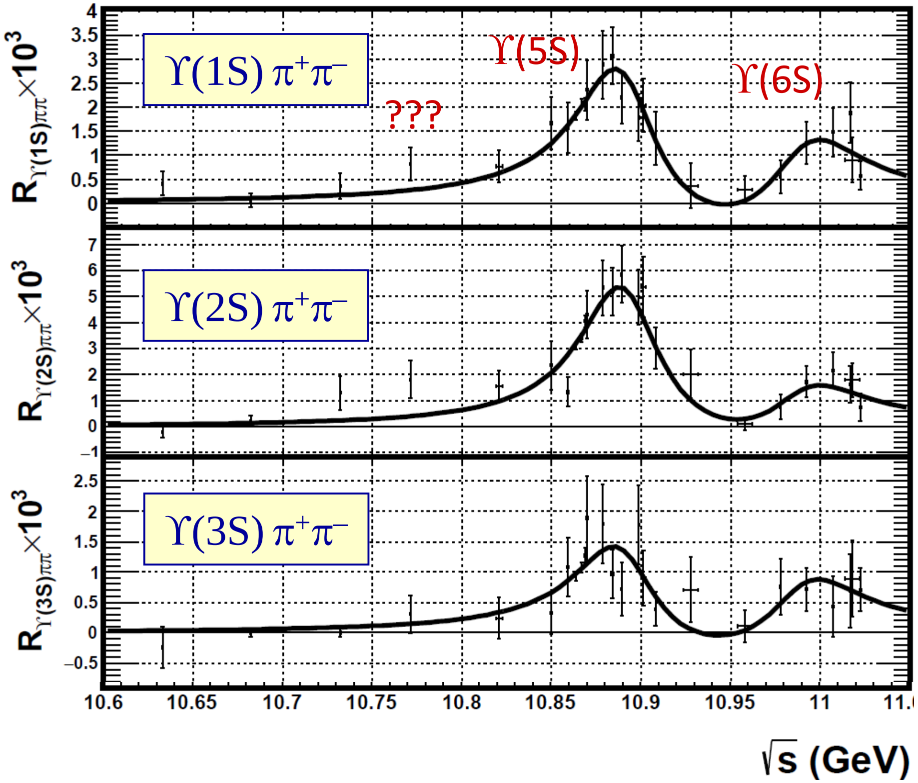
c.f. $\Gamma[\,\Upsilon(2S) \to \Upsilon(1S)\,\eta\,] \,/\, \Gamma[\,\Upsilon(2S) \to \Upsilon(1S)\,\pi^+\pi^-\,] = 1.6 \times 10^{-3}$,

$\Gamma[\,\Upsilon(3S) \to \Upsilon(1S)\,\eta\,] \,/\, \Gamma[\,\Upsilon(3S) \to \Upsilon(1S)\,\pi^+\pi^-\,] < 2 \times 10^{-3}$.

Structure of $\Upsilon(4S)$, $\Upsilon(5S)$, $\Upsilon(6S)$ states
is more complicated than pure $b\bar{b}$ pair.

Previous measurement

Belle PRD93,011101(2016)



Clear signals of $\Upsilon(5S)$, $\Upsilon(6S)$. Excess near 10.77 GeV ?

Which vector states are expected in this energy range?

Badalian,Bakker,Danilkin
PAN73,138(2010)

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

Exotic states: hadrobottomonia, compact tetraquarks

$\Rightarrow$ 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 $\times 1\ \mathrm{fb}^{-1}$

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

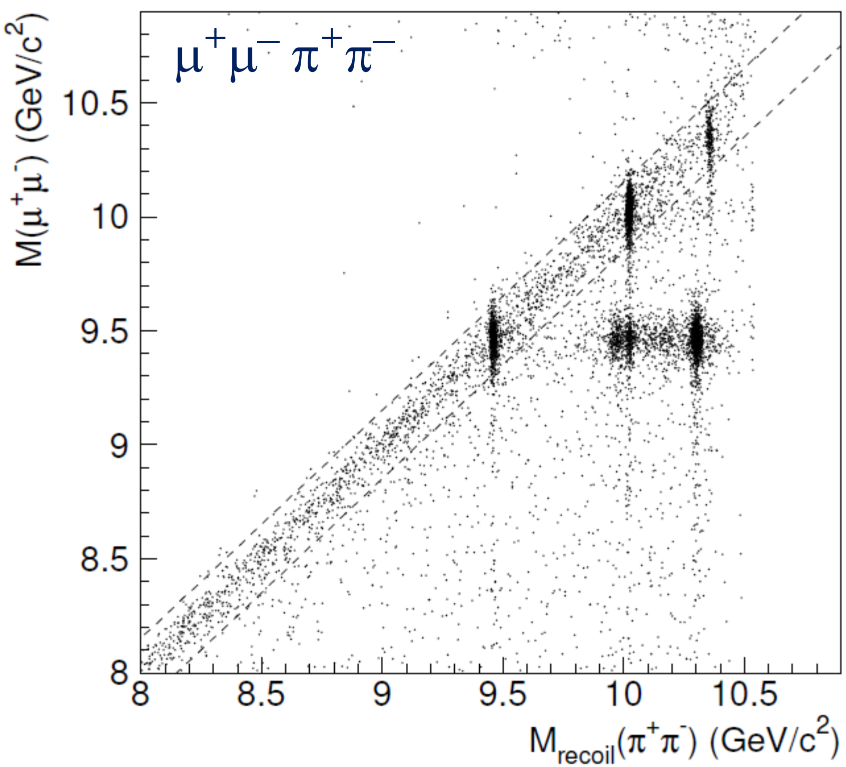
Continuum data, 10.52GeV: $61\ \mathrm{fb}^{-1}$

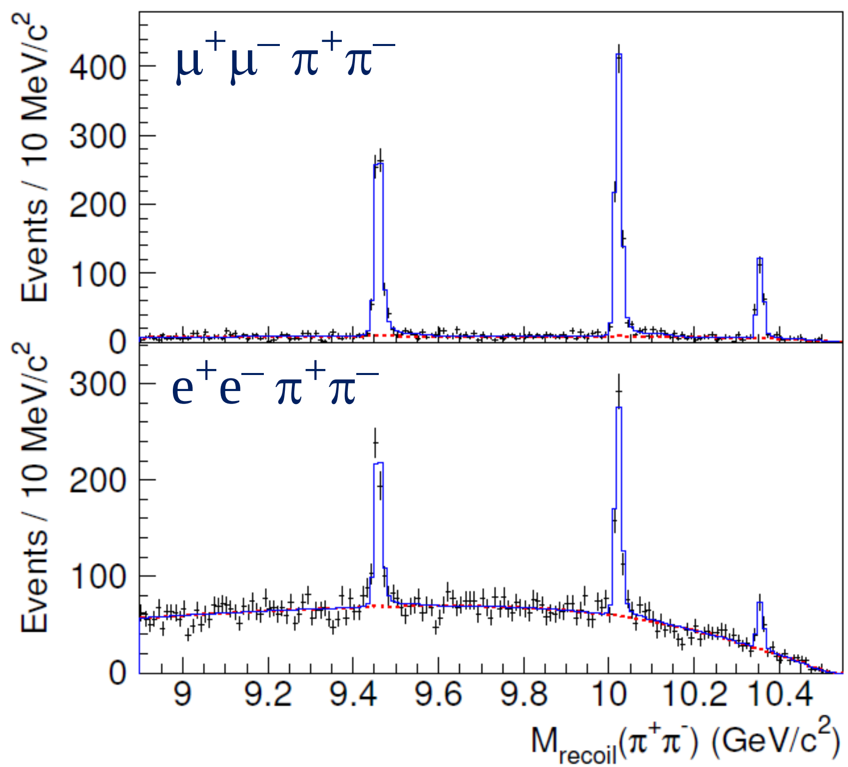
Selection requirements

$\mu^+\mu^-\pi^+\pi^-$ / $e^+e^-\pi^+\pi^-$ 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 $\otimes$ ISR

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

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

$\otimes$ Ecm spread $\times$ ε of energy balance requirement

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

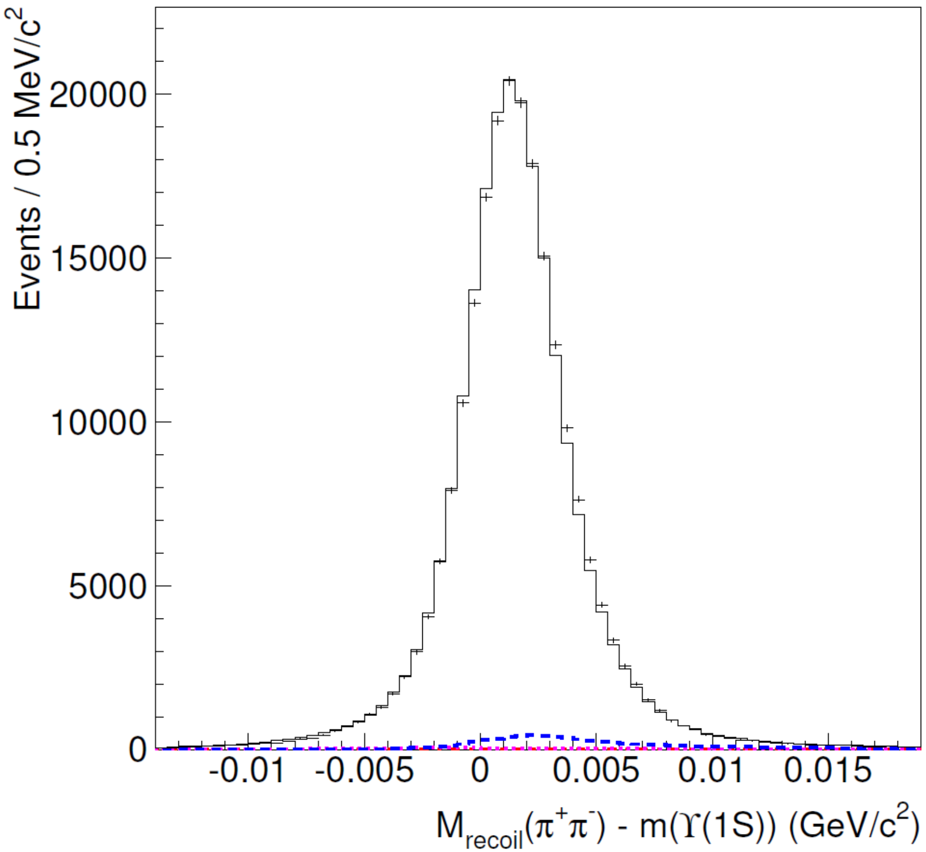
soft cut-off at ~200 MeV

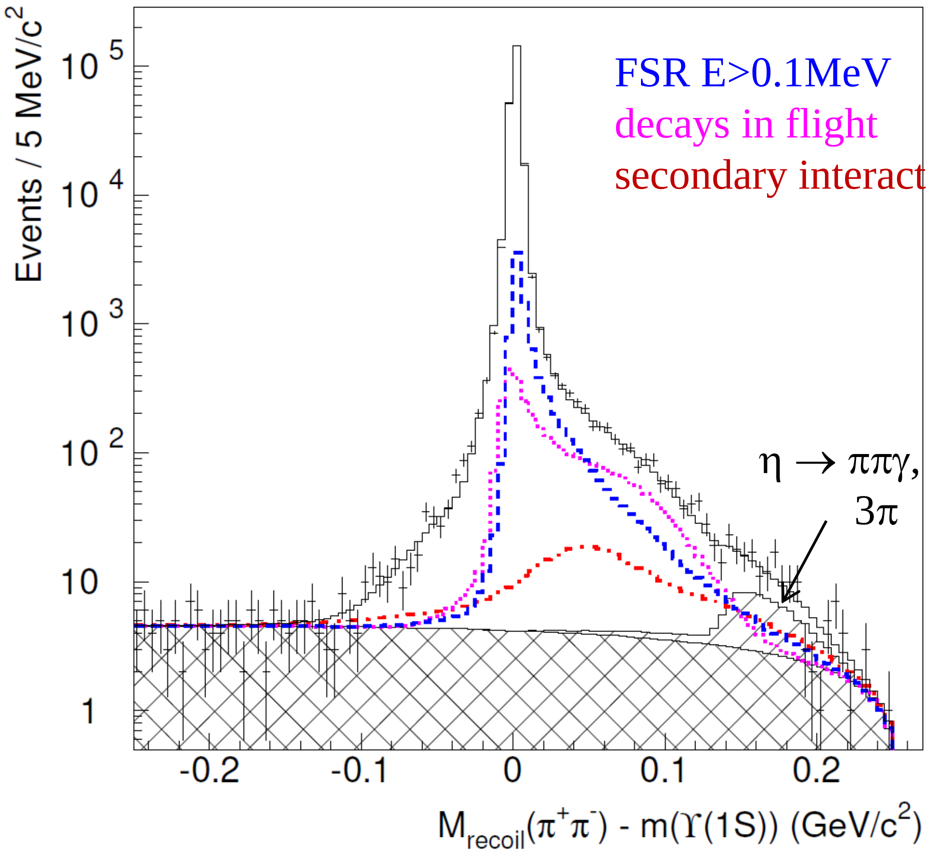
$\sigma(E_{cm})$ is being measured $\Rightarrow$ iterations

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

Verification of signal shape

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

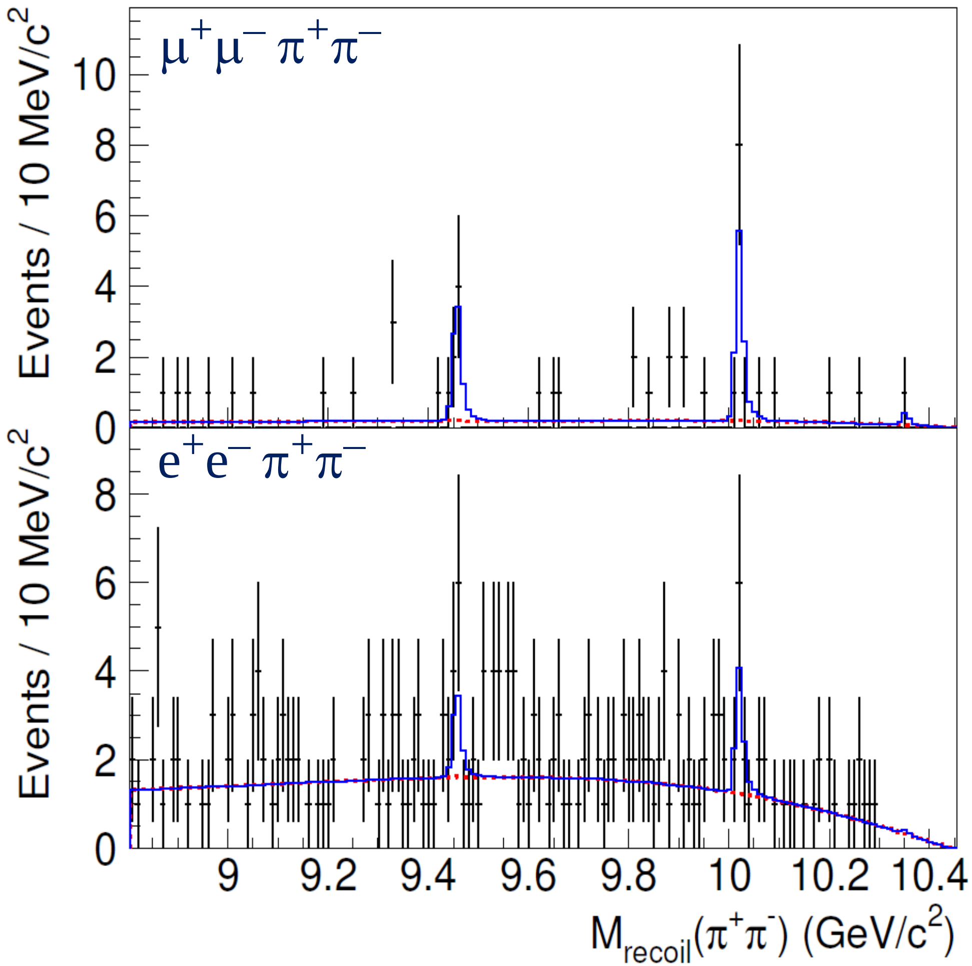




Shapes from MC; floated parameters are yield, overall shift and momentum resolution fudge factor $f = 1.160 \pm 0.003$

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

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



Signal:

fix ratio of $ee/\mu\mu$ yields,
float $\mu\mu$ yields and overall shift

$\Rightarrow E_{cm}$ calibration

Non-peaking background:

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

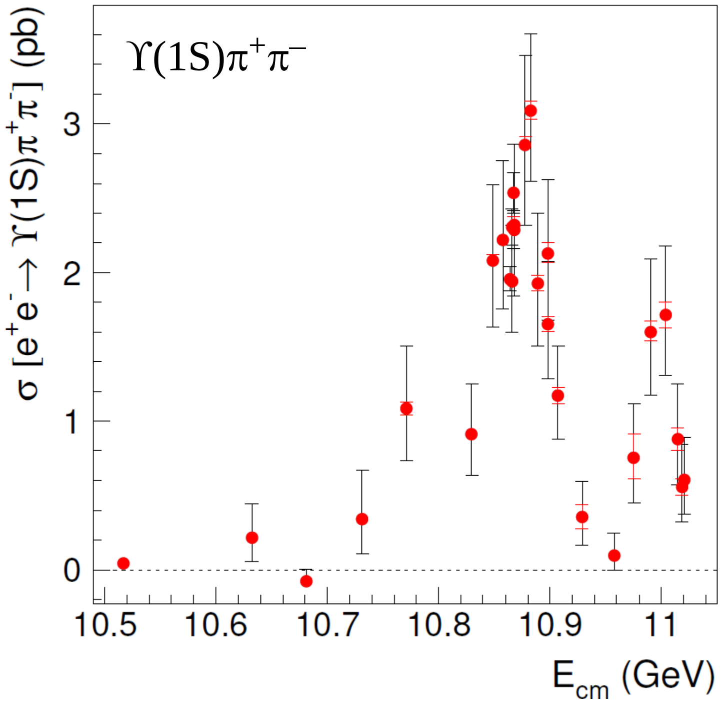
Peaking background:

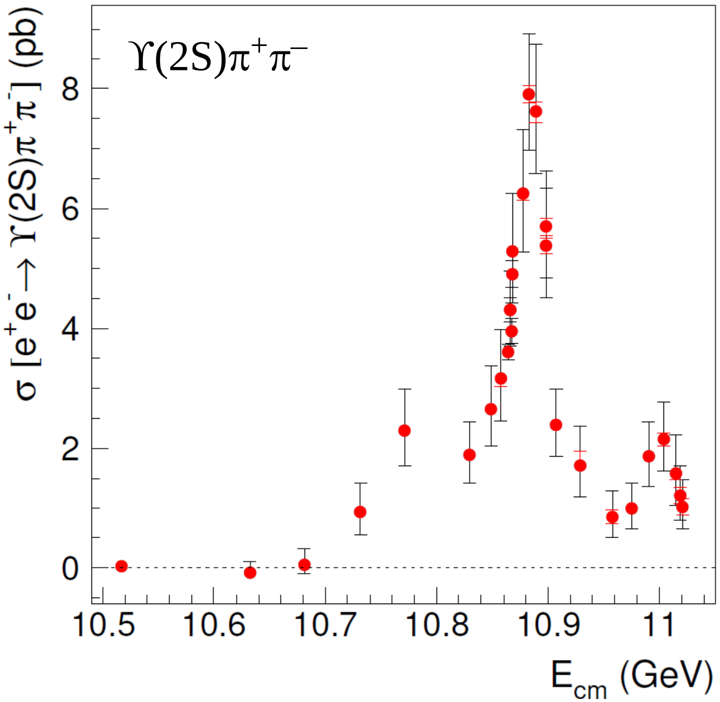
e.g. $e^+e^- \to \gamma^*\gamma^* \to \Upsilon(nS)\,\pi^+\pi^-$, $\Upsilon(nS) \to \mu^+\mu^-$

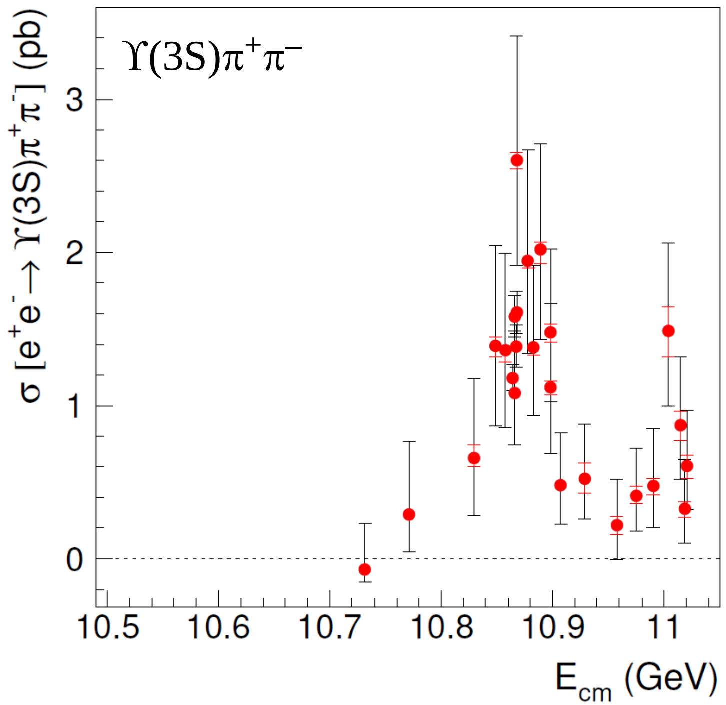
from MC, small contribution

Krachkov, Milstein, Rezanova, Shamov,
EPJ Web Conf. 212, 04010 (2019)

Born cross sections







errors: stat. , uncor. syst.

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

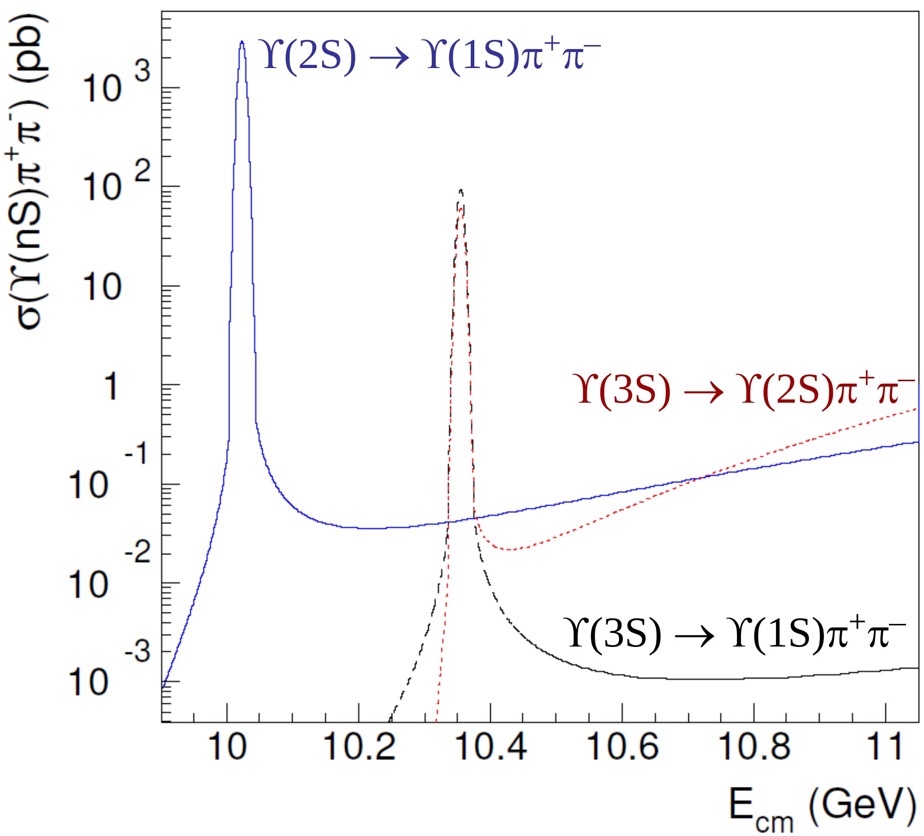
Continuum below $\Upsilon(4S)$

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, Γ, Γ_{ee}, B_f from PDG.

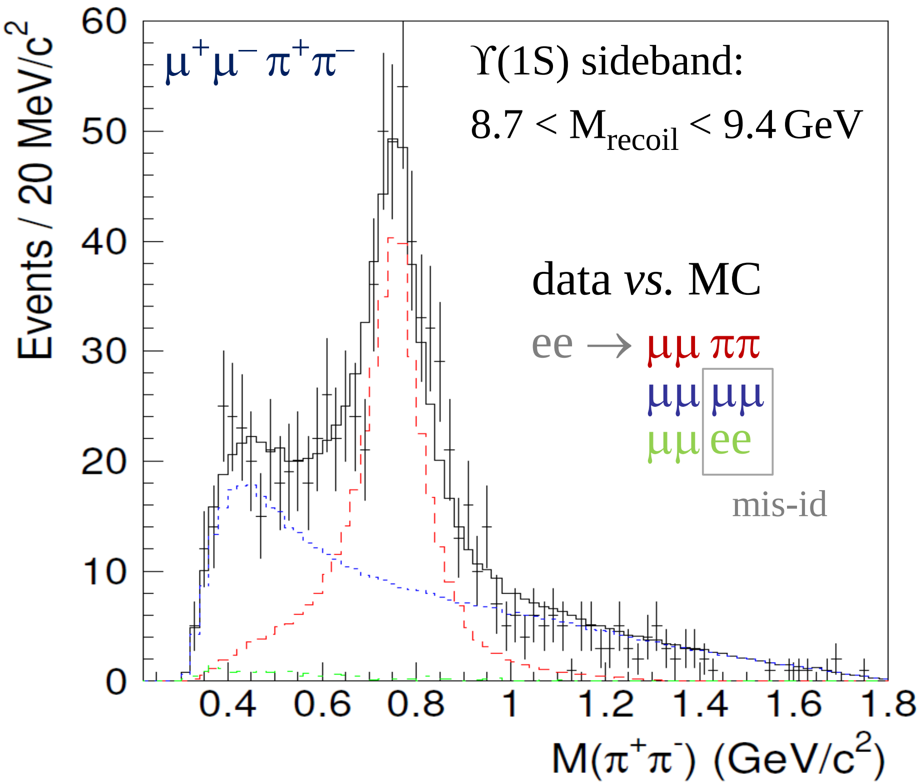
$\Gamma_f(s)$: integrate ME over Dalitz plot.

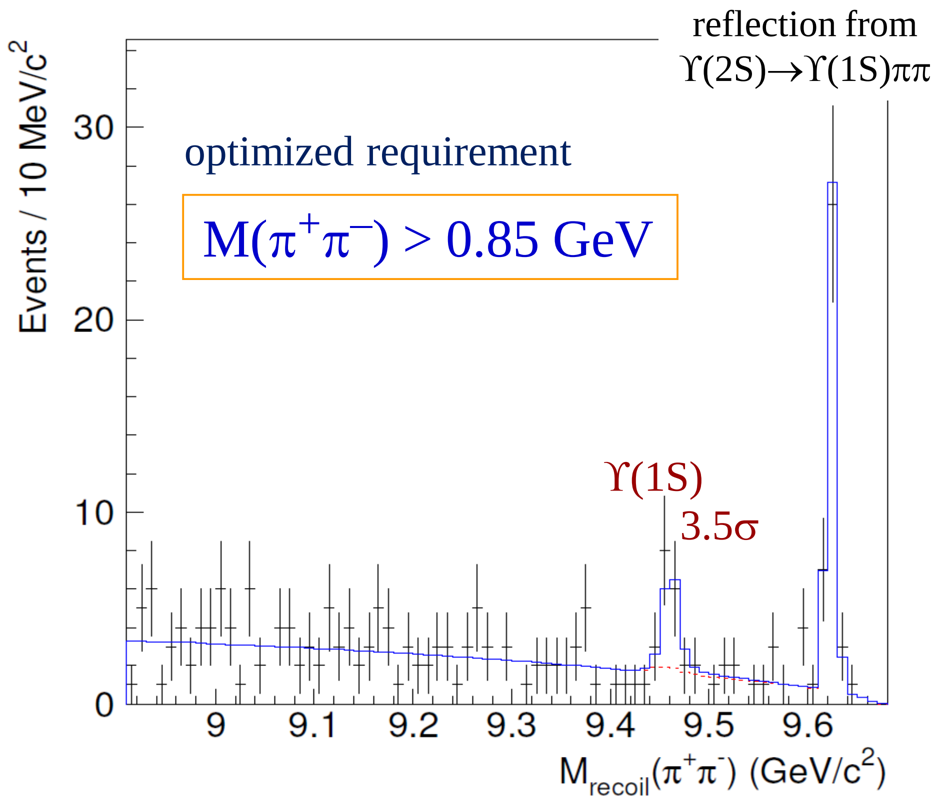
ME rapidly increase with $M(\pi^+\pi^-)$ $\Rightarrow$ BW tails increase with energy

$\Rightarrow$ 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	agree	40^{+21}_{-19} fb
stat.		

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 $\Leftarrow$ similar line shape, phase motion.

$\Rightarrow$ 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

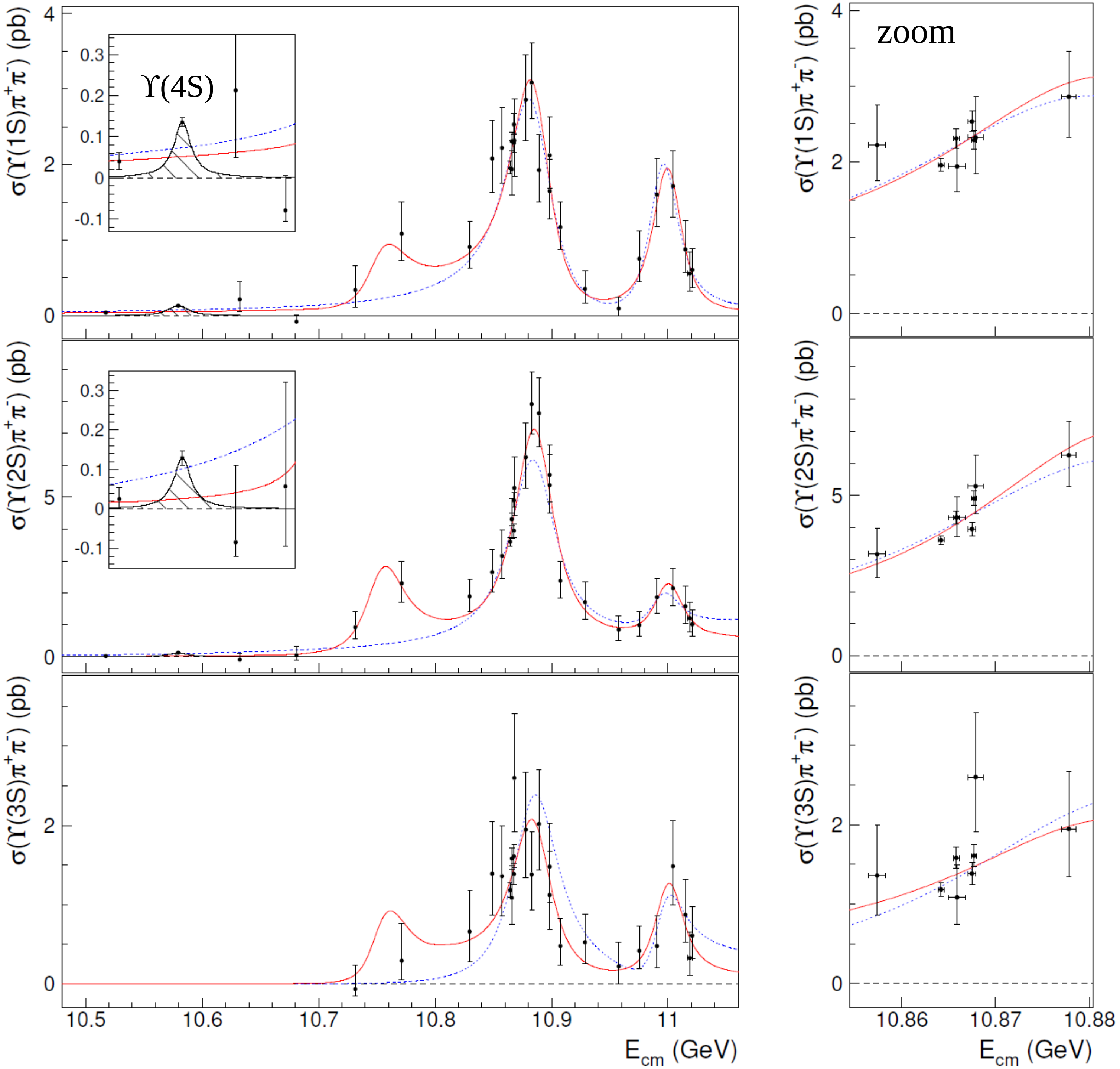
New structure

$\Upsilon(1S)\pi\pi$ 2.4σ

$\Upsilon(2S)\pi\pi$ 5.1σ

w/ syst.

Combined global significance w/ syst. 5.2σ



Fit

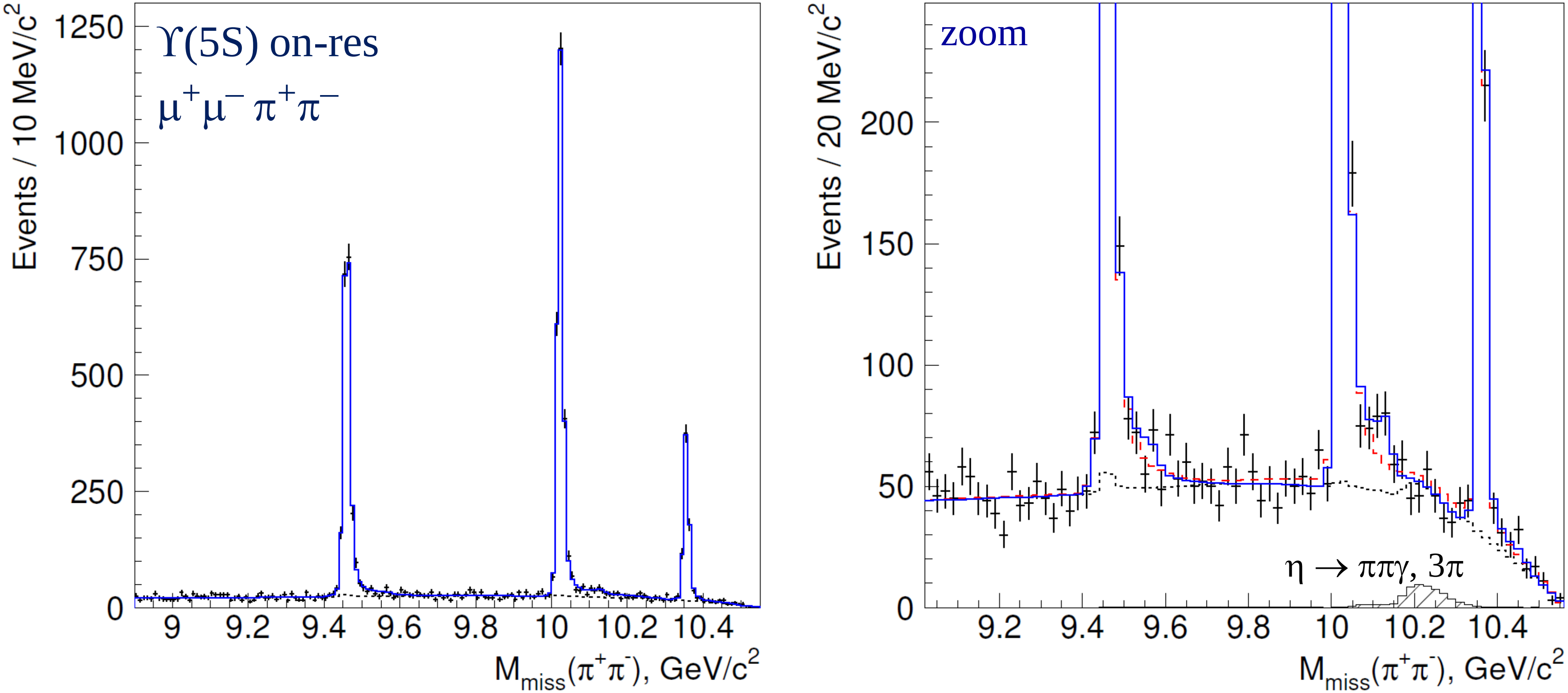
ISR tails of the $\Upsilon(nS)\pi\pi$ signals are sensitive to the cross section shapes.

$\Rightarrow$ 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)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

Previous measurement

	$\Upsilon(10860)$	$\Upsilon(11020)$
M	$10891.1 \pm 3.2^{+0.6}_{-1.7}$	$10987.5^{+6.4}_{-2.5}\,^{+9.0}_{-2.1}$
Γ	$53.7^{+7.1}_{-5.6}\,^{+1.3}_{-5.4}$	$61^{+9}_{-19}\,^{+2}_{-20}$

PRD93,011101(2016)

many differences, e.g.

model: new structure, tails

$\sigma^{vis} \Leftrightarrow \sigma^{B}$

C.f. $h_b\pi\pi$	$\Upsilon(10860)$	$\Upsilon(11020)$	PRL117,142001(2016)
M	$10884.7^{+3.6+8.9}_{-3.4-1.0}$	$10999.0^{+7.3+16.9}_{-7.8-\ 1.0}$	
Γ	$40.6^{+12.7+\ 1.1}_{-\ 8.0-19.1}$	$27^{+27+\ 5}_{-11-12}$	

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)

Ranges:
min – max

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

Υ(4S)

Implications?

Belle PRD96,052005(2017)

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

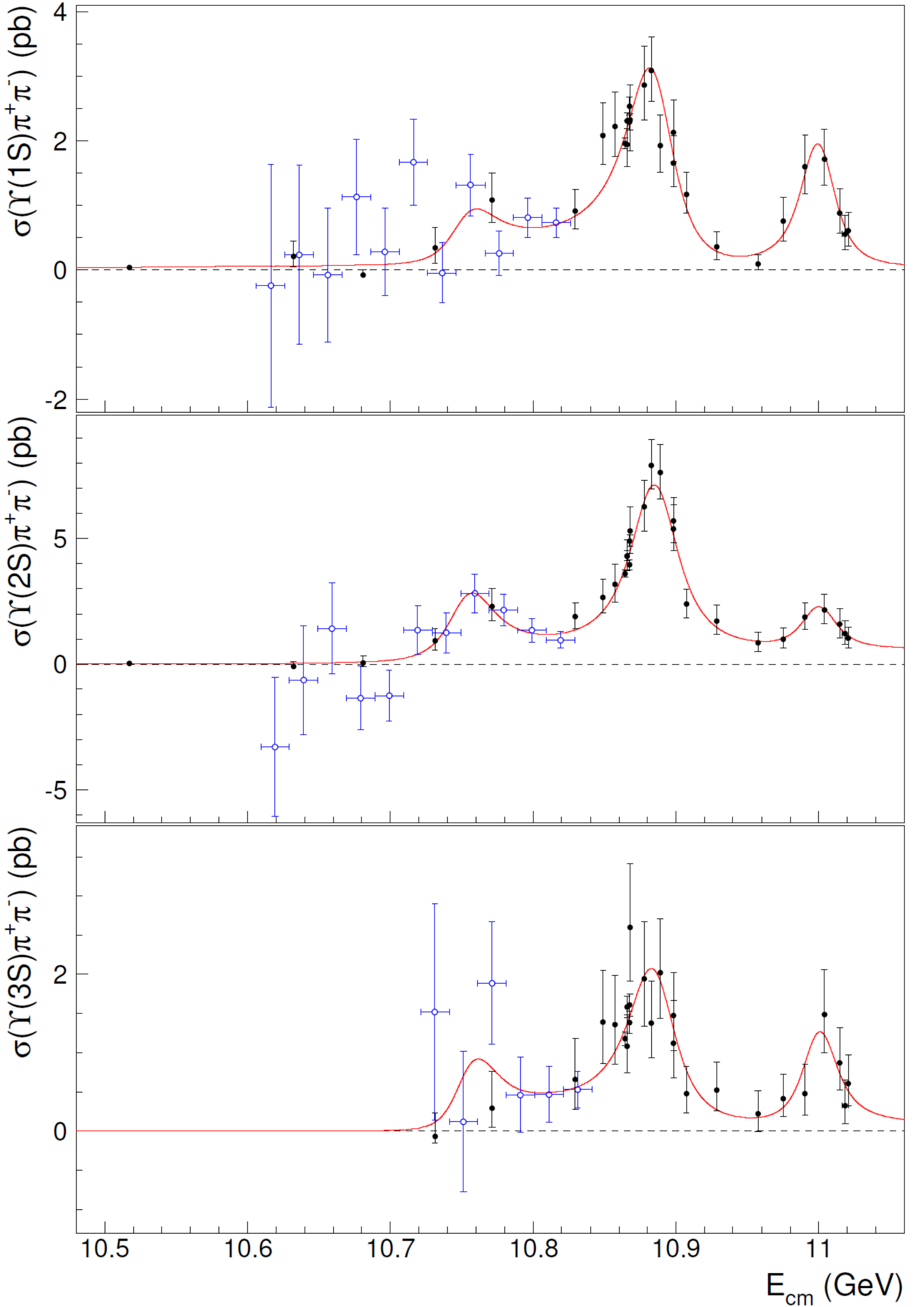
Include Υ(4S) in the fit, scan FCN in B $\Rightarrow$ $(1.2 - 16) \times 10^{-5}$, $(1.3 - 9.6) \times 10^{-5}$ 67% C.L.

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

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

Global significance including systematics: 5.2σ.

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

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

Belle JHEP 1910, 220 (2019)

Interpretation?

2 1 2 1

Resonance? $\Upsilon(3D)$, $\Upsilon(4D)$, compact tetraquark, hybrid, hadrobottomonium,..

0

Non-resonant effect? Complicated rescattering,..

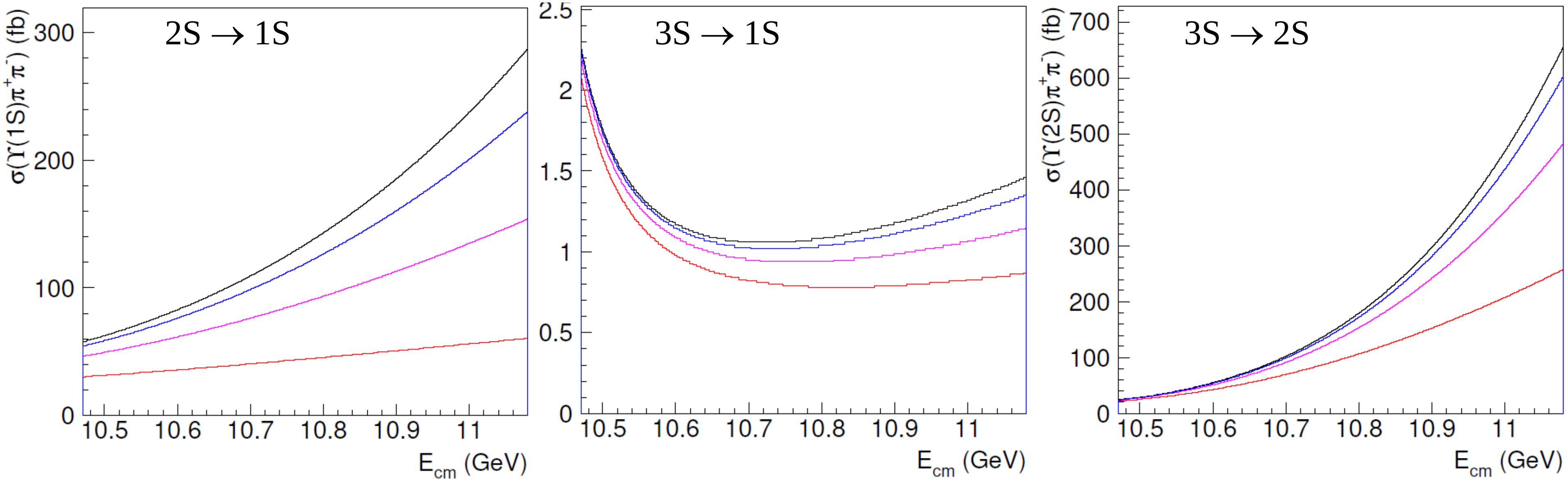
Need information on other channels to clarify the nature.

Back-up

Tails

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

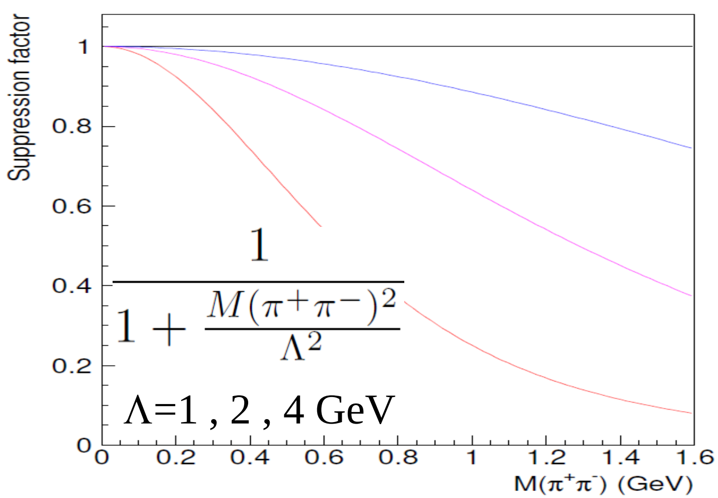
$\Rightarrow$ Contributions rise quickly as PHSP grows with c.m. energy



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: $\Delta(-2\ln L) = 66.$

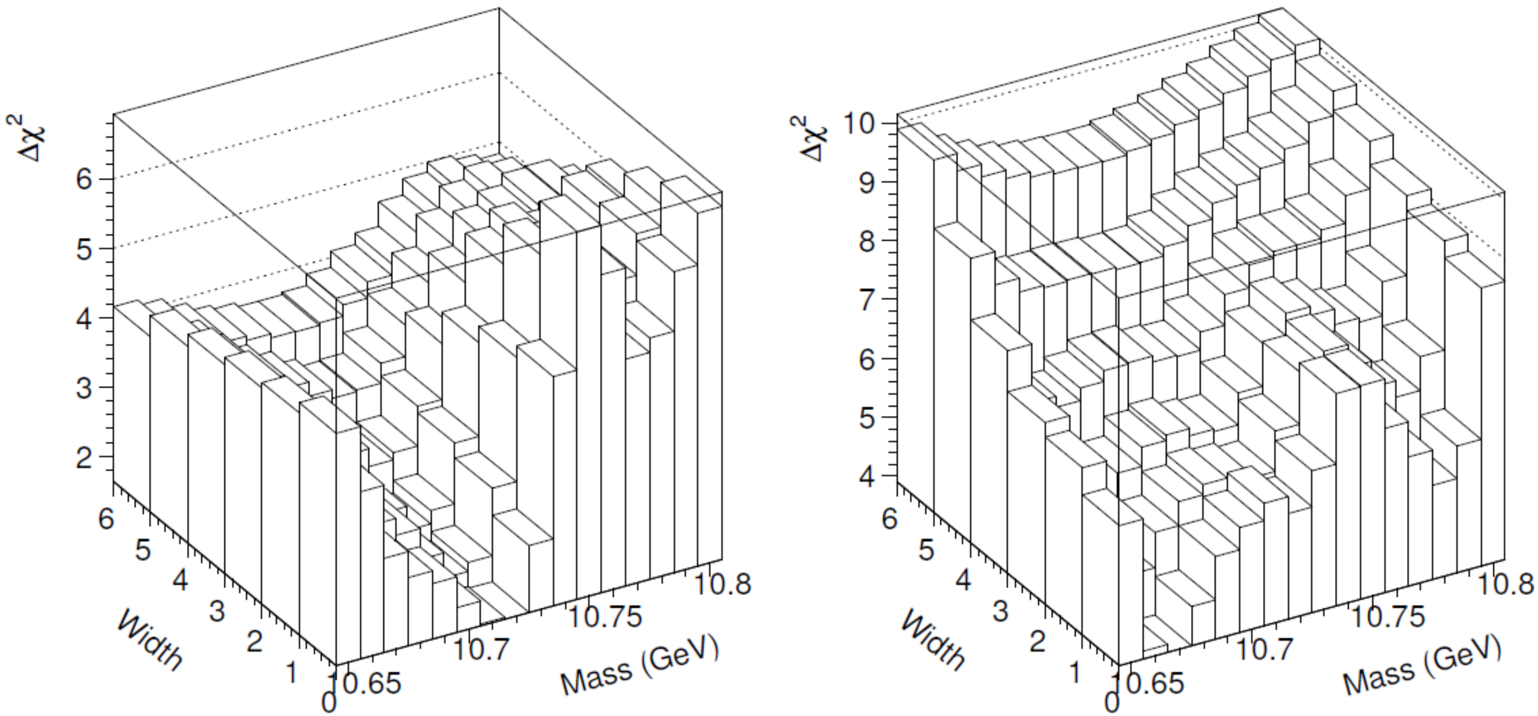
52. – cross sections
14. – recoil mass

local significance 7.0σ

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

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

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