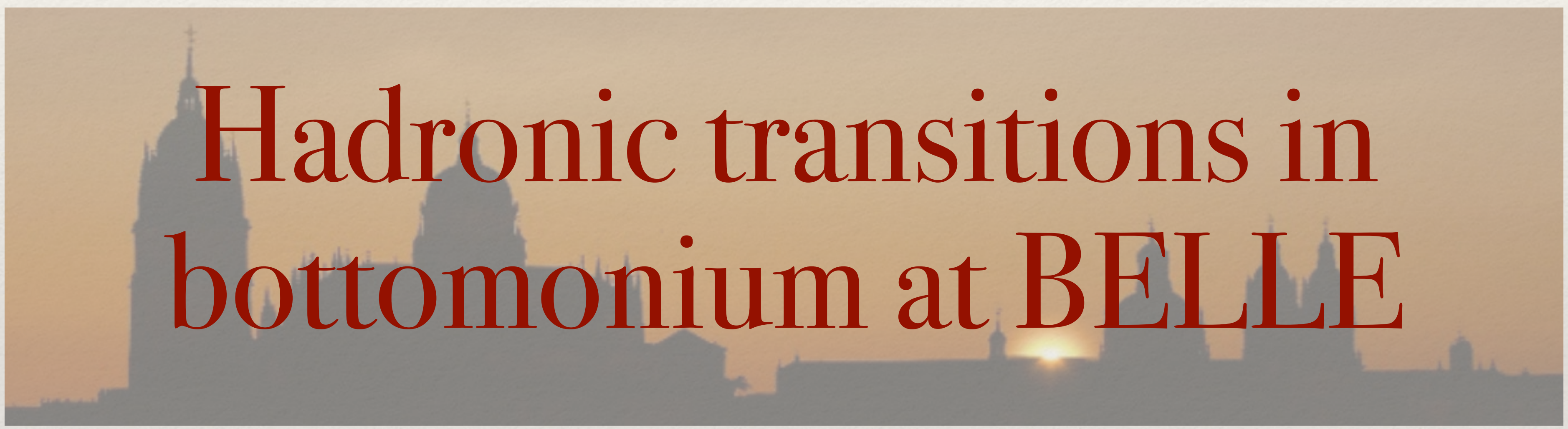
XVII International Conference on Hadron Spectroscopy and Structure
27 September 2017, Salamanca



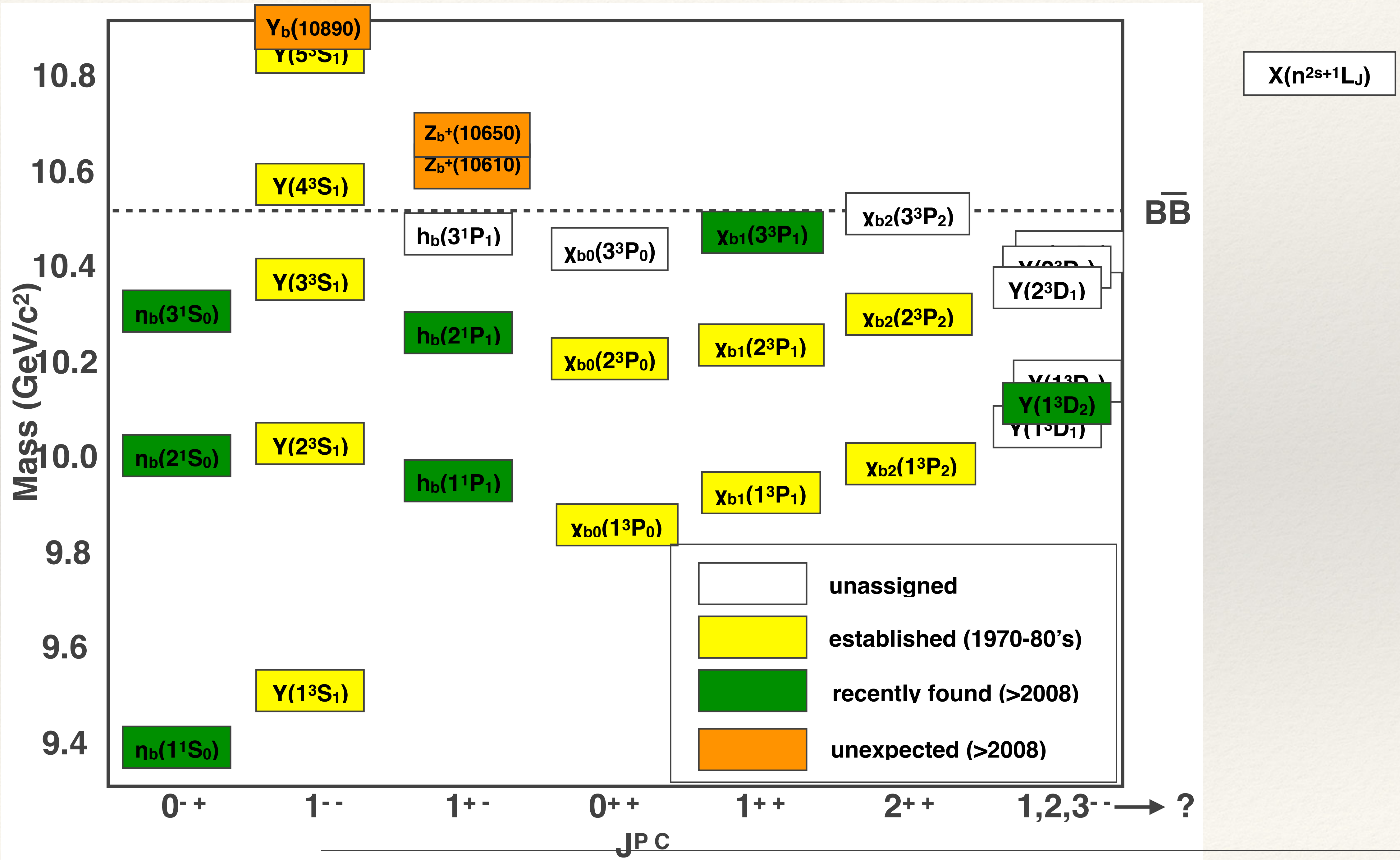
Hadronic transitions in bottomonium at BELLE

Elisa Guido - INFN Torino

(on behalf of the Belle Collaboration)

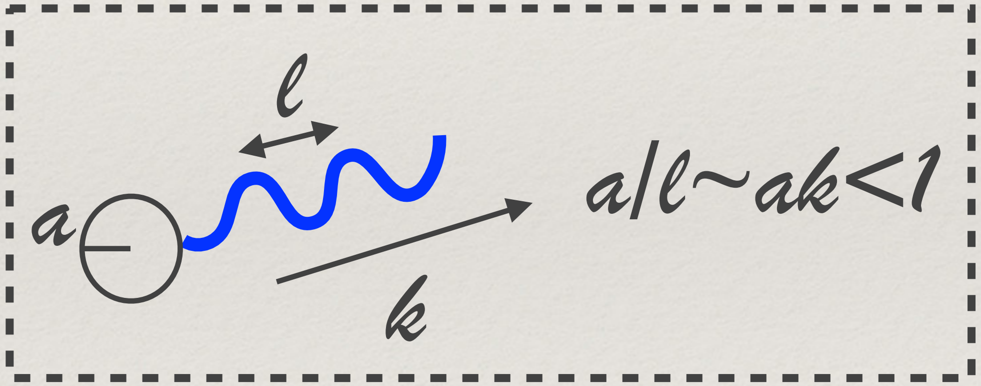
Hadronic transitions

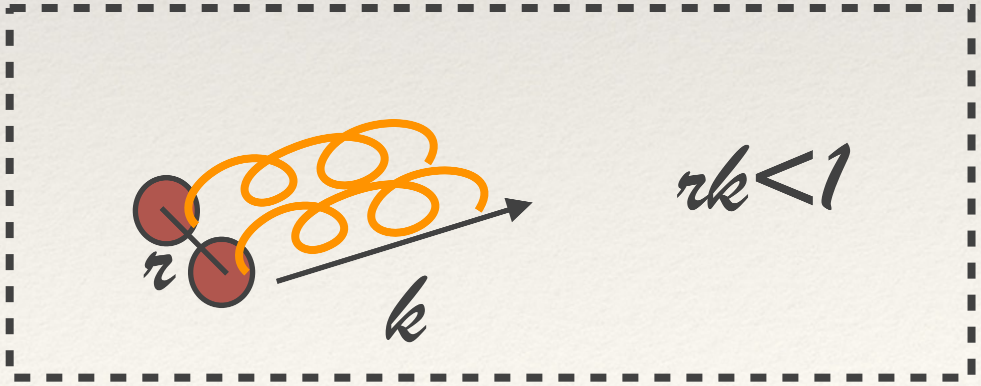
- Last decade has been a fertile era for bottomonium spectroscopy: many missing states and exotica



Hadronic transitions

- Last decade has been a fertile era for bottomonium spectroscopy: many missing states and exotica
- Important informations on bottomonium given also by the **study of transitions** between its states
- These transitions can be predicted by effective potential models, rather well established in the case of the dominant radiative transitions
- Instead, BRs not well predicted in particular in the 2-body hadronic transitions (η, π^0)
- In quarkonia below threshold, should be explained by **QCDME** (analogy with the QED multiple expansion) in terms of momentum of the emitted gluons
- Gluons emitted in pairs, either **E1** (no spin-flipping) or **M1** (spin-flipping)
- Expectations:
    - **suppression of spin-flipping transitions** (i.e. mS—>η nS wrt mS—>$\pi^+\pi^-$ nS, and mS—>$\pi^+\pi^-$ nP wrt mS—>$\pi^+\pi^-$ nS)
    - **further suppression of isospin-violating transitions** (i.e. mS—>π^0 nS wrt others)





η transitions: experimental status

Transition	CLEO	Year	BaBar	Year	Belle	Year
$\Upsilon(4S) \to \eta \Upsilon(1S)$	-		1.96±0.26±0.09	2008	1.70±0.23±0.08	2017
$\Upsilon(3S) \to \eta \Upsilon(1S)$	<1.8 (*)	2008	<1.0 (*)	2011	-	
$\Upsilon(2S) \to \eta \Upsilon(1S)$	$2.1^{+0.7}_{-0.6}\pm0.3$	2008	2.39±0.31±0.14	2011	3.57±0.25±0.21	2013
$\Upsilon(4S) \to \eta h_b(1P)$	-		-		21.8±1.1±1.8	2015

[in units of 10^{-4}]

(*) all ULs are at 90% CL

BaBar Coll. PRD 78 (2008) 112002
CLEO Coll. PRL 101 (2008) 192001
BaBar Coll. PRD 84 (2011) 092003
Belle Coll. PRL 115 (2015) 142001
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$\Upsilon(4S) \to \eta h_b(1P)$	-		-		21.8±1.1±1.8	2015

>2 times larger than dipion transition!

$[B(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)) = (0.81\pm0.06)\ 10^{-4}]$

→ no spin-flipping suppression, due to effects next to threshold?

[in units of 10^{-4}]

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$\Upsilon(4S) \to \eta h_b(1P)$	-					2015

~2 times smaller than theoretical prediction!

[in units of 10^{-4}]

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CLEO Coll. PRL 101 (2008) 192001
BaBar Coll. PRD 84 (2011) 092003
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$\Upsilon(4S) \longrightarrow \eta h_b($					21.8±1.1±1.8	2015

yet unobserved!

Tension with theoretical prediction
Spin-flip suppression still holds,
but BRs not well predicted

[in units of 10^{-4}]

(*) all ULs are at 90% CL

CLEO Coll. PRL 101 (2008) 192001
BABAR Coll. PRD 84 (2011) 092003

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$\Upsilon(2S) \rightarrow \eta\Upsilon(1S)$	2.1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]±0.21	2013
$\Upsilon(4S) \rightarrow \eta h_b(1P)$	-		-		21.8±1.1±1.8	2015

the largest non-BB transition from the Υ(4S)!

In agreement with prediction

Guo et al. PRL 105 (2010) 162001

[in units of 10^{-4}]

(*) all ULs are at 90% CL

Belle Coll. PRL 115 (2015) 142001

η transitions from Υ(5S)

- Dipion transitions from **Υ(5S)** enhanced due to the Z_b's…

Belle Coll. PRL 100 (2008) 112001
Belle Coll. PRL 108 (2012) 032001

Transition	**Belle**	Year
Υ(5S) —>ππΥ(1S)	5.3±0.6	2008
Υ(5S) —>ππΥ(2S)	7.8±1.3	2008
Υ(5S) —>ππh_b(1P)	$3.5^{+1.0}_{-1.3}$	2012
Υ(5S) —>ππh_b(2P)	$5.7^{+1.7}_{-2.1}$	2012

[in units of 10^{-3}]

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- …but η transitions are NOT suppressed!
- Observation of **Υ(5S)—>ηΥ(1D)!**

Belle Coll. preliminary @LaThuile2012
Belle Coll. preliminary @DIS2014

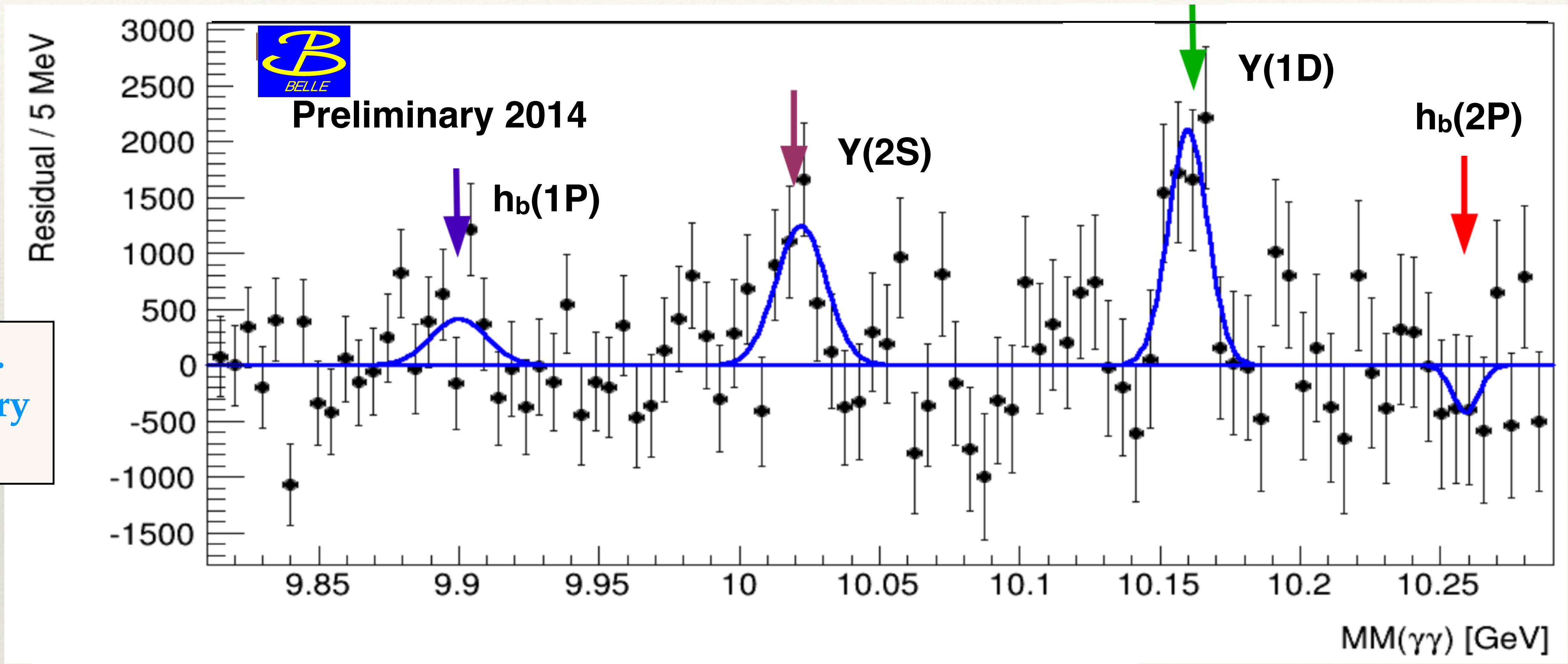
Belle Coll. PRL 100 (2008) 112001
Belle Coll. PRL 108 (2012) 032001

[in units of 10^{-3}] (*) ULs are at 90% CL

Transition	**Belle**	Year
Υ(5S) —>ηΥ(1S)	0.73±0.16±0.8	2012 (prel.)
Υ(5S) —>ηΥ(2S)	2.1±0.7±0.3	2014 (prel.)
Υ(5S) —>ηh_b(1P)	<3.3 (*)	2014 (prel.)
Υ(5S) —>ηh_b(2P)	<3.7 (*)	2014 (prel.)
Υ(5S) —>ηΥ(1D)	2.8±0.7±0.4	2014 (prel.)

η transitions from Υ(5S)

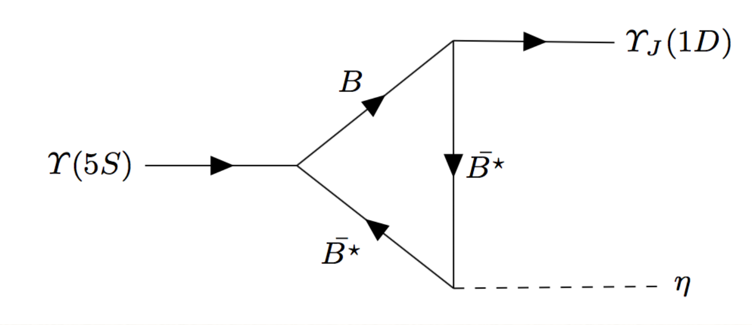
- η reconstructed in η⟶γγ, look at the missing mass spectrum, after combinatorial background subtraction



Belle Coll.
preliminary
@DIS2014

- In particular, BR(Υ(5S) —>ηΥ(1D)) is compatible with the prediction (via triangular meson loops)

Wang et al. PRD 94 (2016) 094039



- Now finalizing the result on the branching fractions (to be published soon)

Investigations on the Υ(1D) triplet

NEW!

$$\mathcal{F}_{1D} = \frac{N_{1D}}{1+f_1+f_3}\cdot[\mathcal{C}_2(m_2)+f_1\mathcal{C}_1(m_1)+f_3\mathcal{C}_3(m_3)]$$

- Not resolving the Υ(1D) triplet (resolution ~mass splitting)
- Signal in MM(γγ): 3 Crystal Ball functions, with free relative fractions f_1, f_3 that are precisely predicted in: **Wang et al. PRD 94 (2016) 094039**

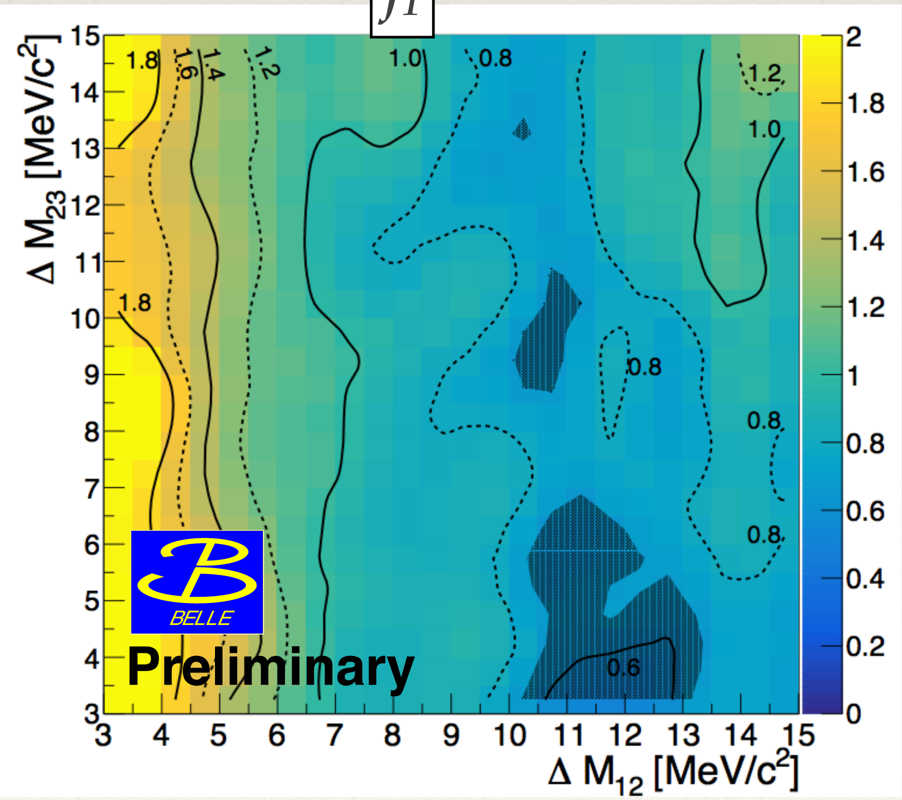
$$f_1 = \frac{\mathcal{B}[\Upsilon(5S)\to\eta\Upsilon(1D_1)]}{\mathcal{B}[\Upsilon(5S)\to\eta\Upsilon(1D_2)]} = 0.68$$

and

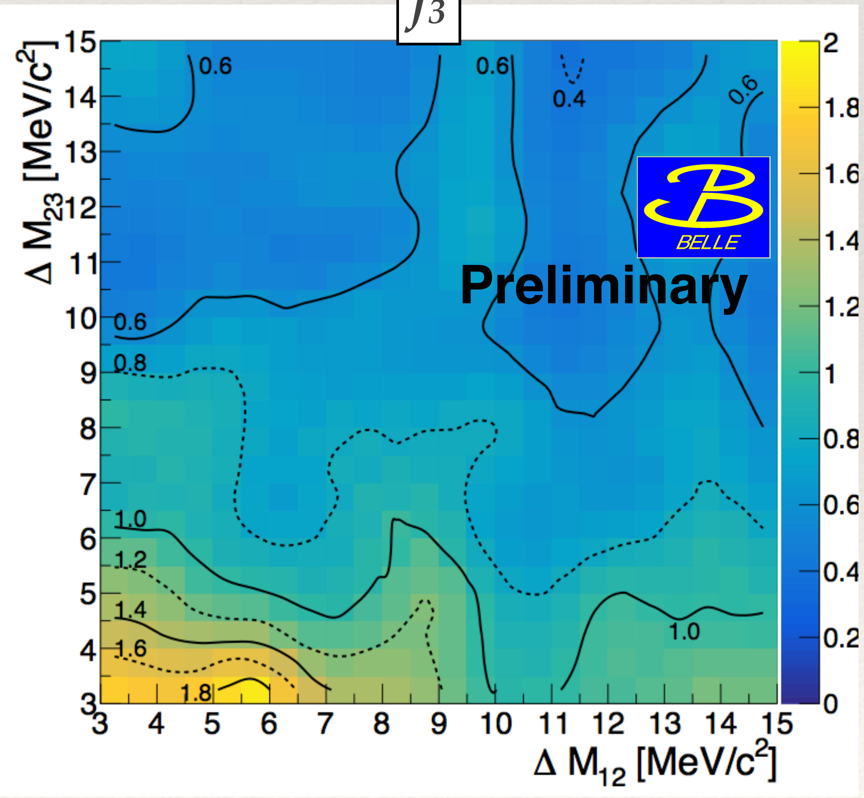
$$f_3 = \frac{\mathcal{B}[\Upsilon(5S)\to\eta\Upsilon(1D_3)]}{\mathcal{B}[\Upsilon(5S)\to\eta\Upsilon(1D_2)]} = 0.13.$$

- m_2 fixed to world average, ΔM_{ij} fixed to different values between 3 and 15 MeV/c² (reasonable according to calculations and observations)
- Values returned by the fit in any of these configurations are compatible with 0
- 90% CL ULs on f_1, f_3 as a function of ΔM_{12} and ΔM_{23}
- f_1 favored value excluded in 3 regions where **10< ΔM_{12} <13 MeV/c²**

f_1



f_3

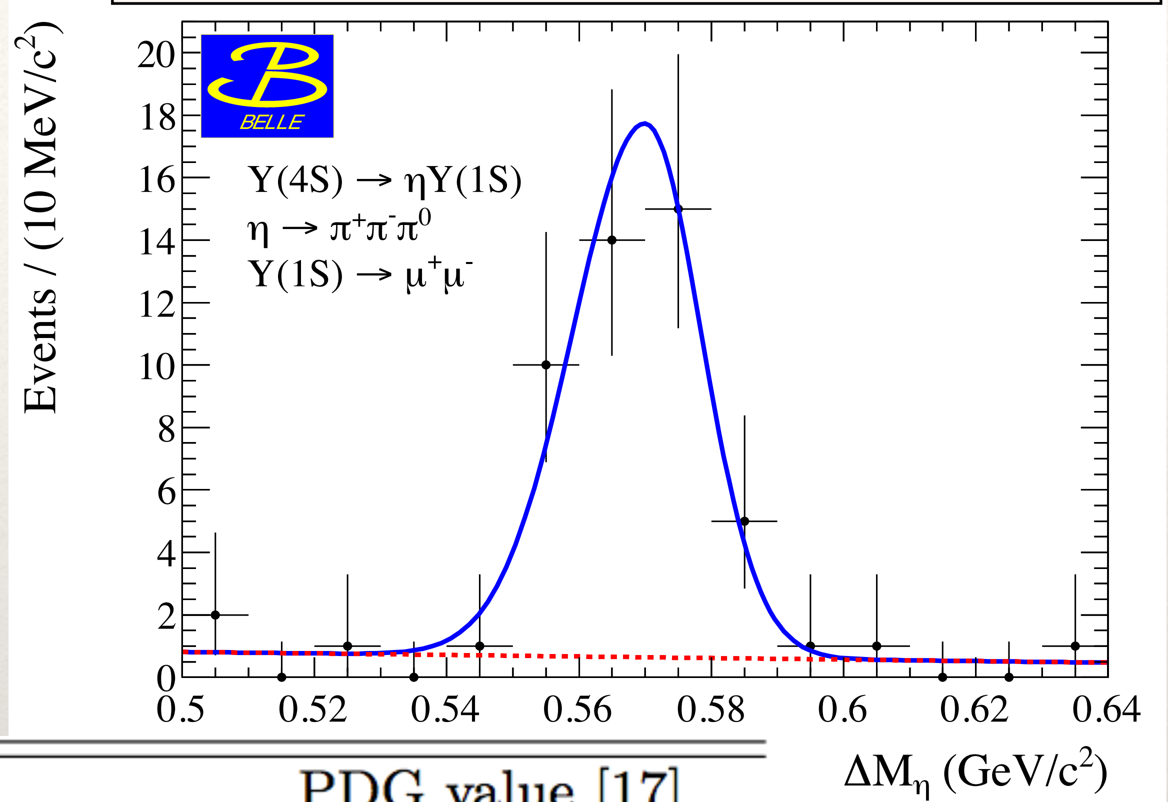


Υ(4S) ⟶η Υ(1S)

- $\eta \to \pi^+\pi^-\pi^0$ and $\pi^0 \to \gamma\gamma$, $\Upsilon(1S) \to \mu^+\mu^-$
- Fit to $\Delta M_\eta = M(\pi\pi\gamma\gamma\mu\mu) - M(\mu\mu) - M(\pi\pi\gamma\gamma)$
- Confirmation of the enhancement with respect to dipion transition

$$\mathcal{R} = \frac{\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))}{\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))}$$

Belle Coll. arXiv:1707.04973 (accepted by PRD)



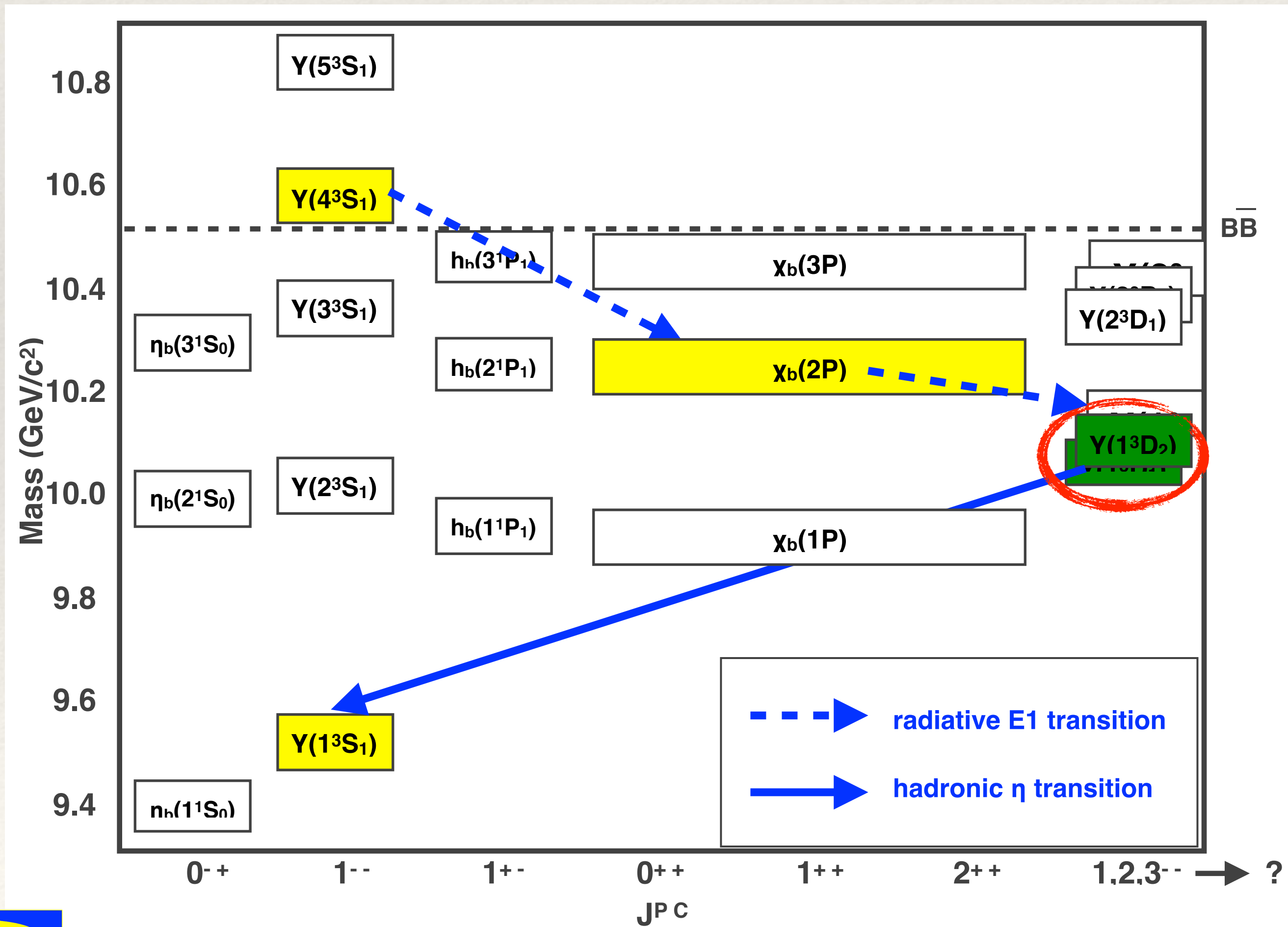
Measurement	Result	PDG value [17]
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$	$(8.2 \pm 0.5 \pm 0.4) \times 10^{-5}$	$(8.1 \pm 0.6) \times 10^{-5}$
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))$	$(7.9 \pm 1.0 \pm 0.4) \times 10^{-5}$	$(8.6 \pm 1.3) \times 10^{-5}$
$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))$	$(1.70 \pm 0.23 \pm 0.08) \times 10^{-4}$	$(1.96 \pm 0.28) \times 10^{-4}$
$\mathcal{R}$	$2.07 \pm 0.30 \pm 0.11$	2.41 ± 0.42
Measurement	Result	Expected value [12]
$\sigma_{\rm ISR}(\Upsilon(2S))$	$(17.36 \pm 0.19 \pm 0.69)$ pb	(17.1 ± 0.3) pb
$\sigma_{\rm ISR}(\Upsilon(3S))$	$(28.9 \pm 0.5 \pm 1.3)$ pb	(28.6 ± 0.5) pb

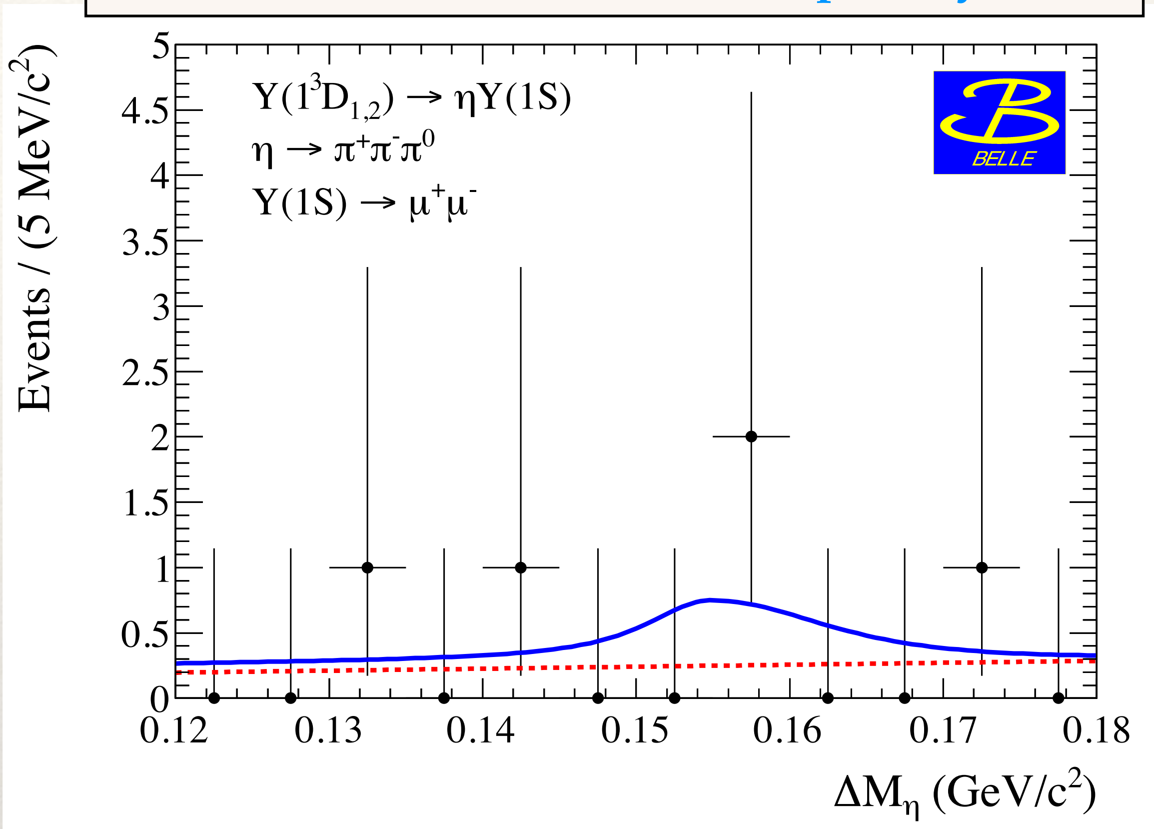
Υ(1D) ⟶η Υ(1S)

Belle Coll. arXiv:1707.04973 (accepted by PRD)

- With the same approach and a similar event selection, we look for **Υ(1D)⟶ηΥ(1S)**
- Predicted to be enhanced with respect to the transition Υ(1D)⟶$\pi^+\pi^-$Υ(1S) by the axial anomaly in QCD

Voloshin PLB 562 (2003) 68

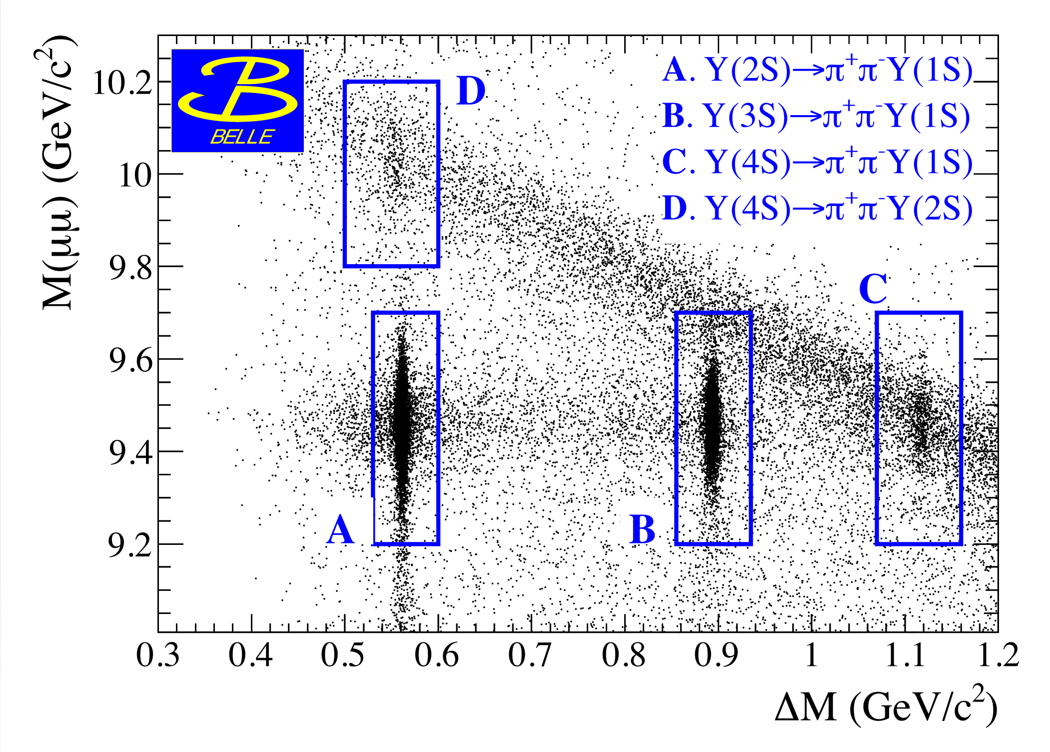


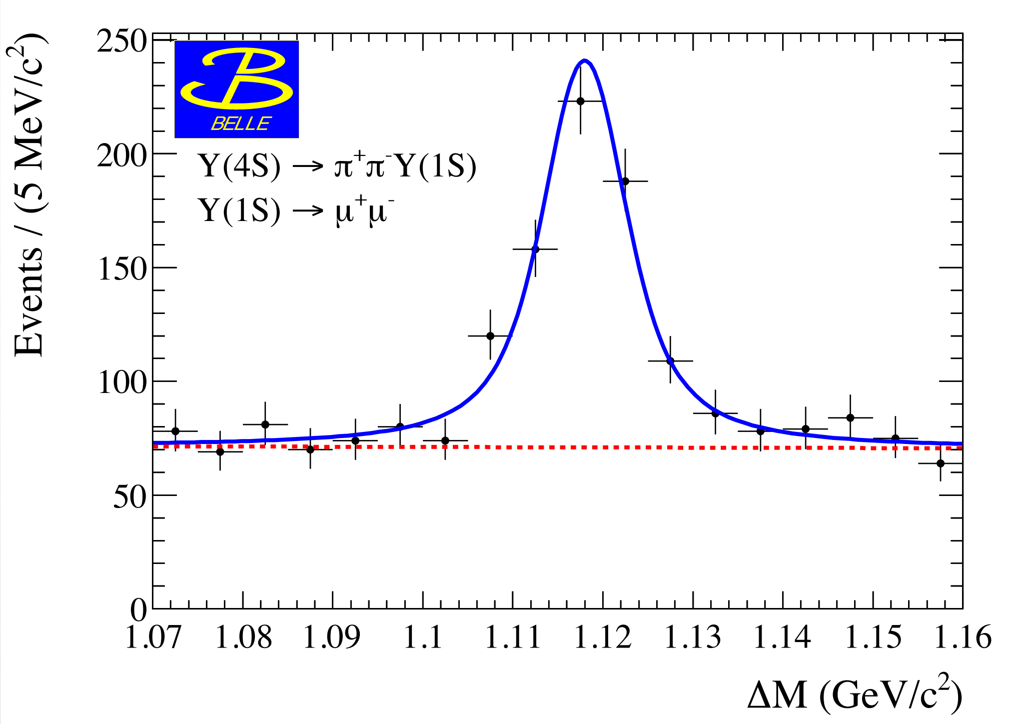


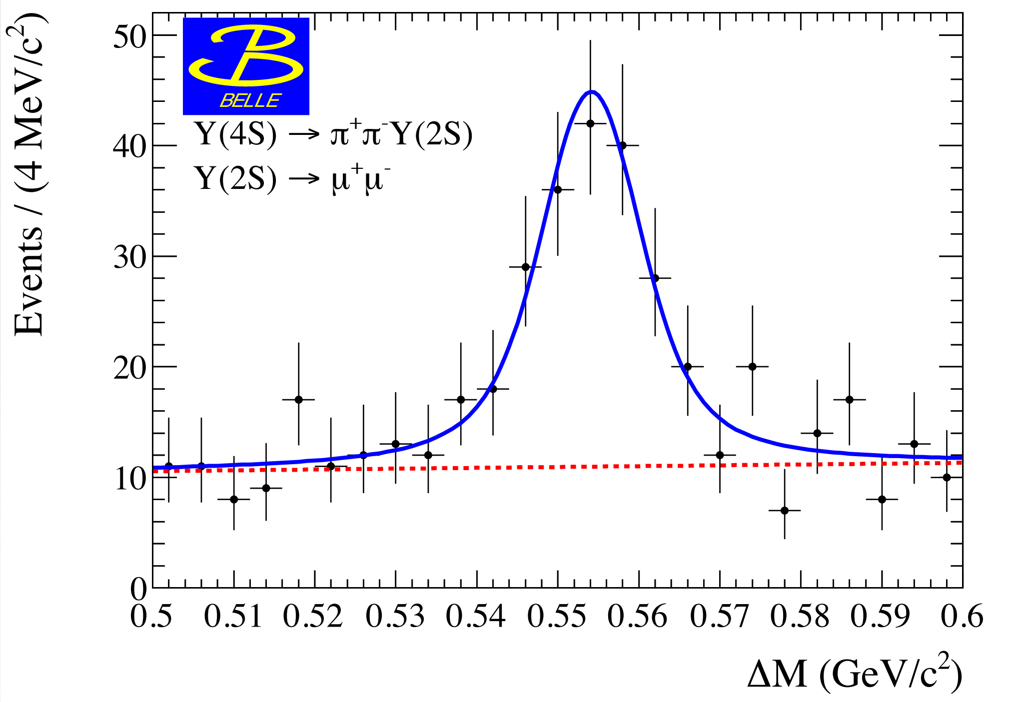
- Υ(1D) possibly produced via double-radiative transitions from Υ(4S) through χ_{bJ}(2P) states
- $\mathcal{B}(\Upsilon(4S) \to \gamma\gamma\Upsilon(1D)) \times$ $\times\, \mathcal{B}(\Upsilon(1D) \to \eta\Upsilon(1S)) < 2.3 \times 10^{-5}$

Dipion transitions

- Measurement of dipion transitions also provided
- Fit to: $\Delta M = M(\pi\pi\mu\mu) - M(\mu\mu)$







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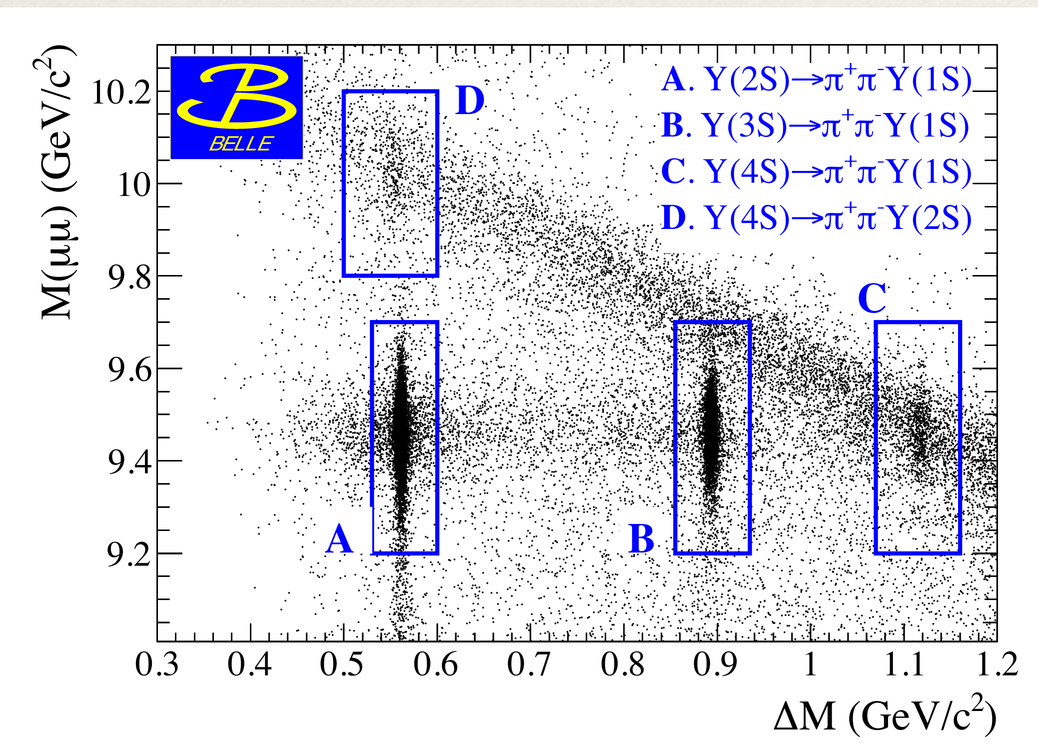

Belle Coll. arXiv:1707.04973 (accepted by PRD)

- Improved BR results for transitions from Υ(4S)

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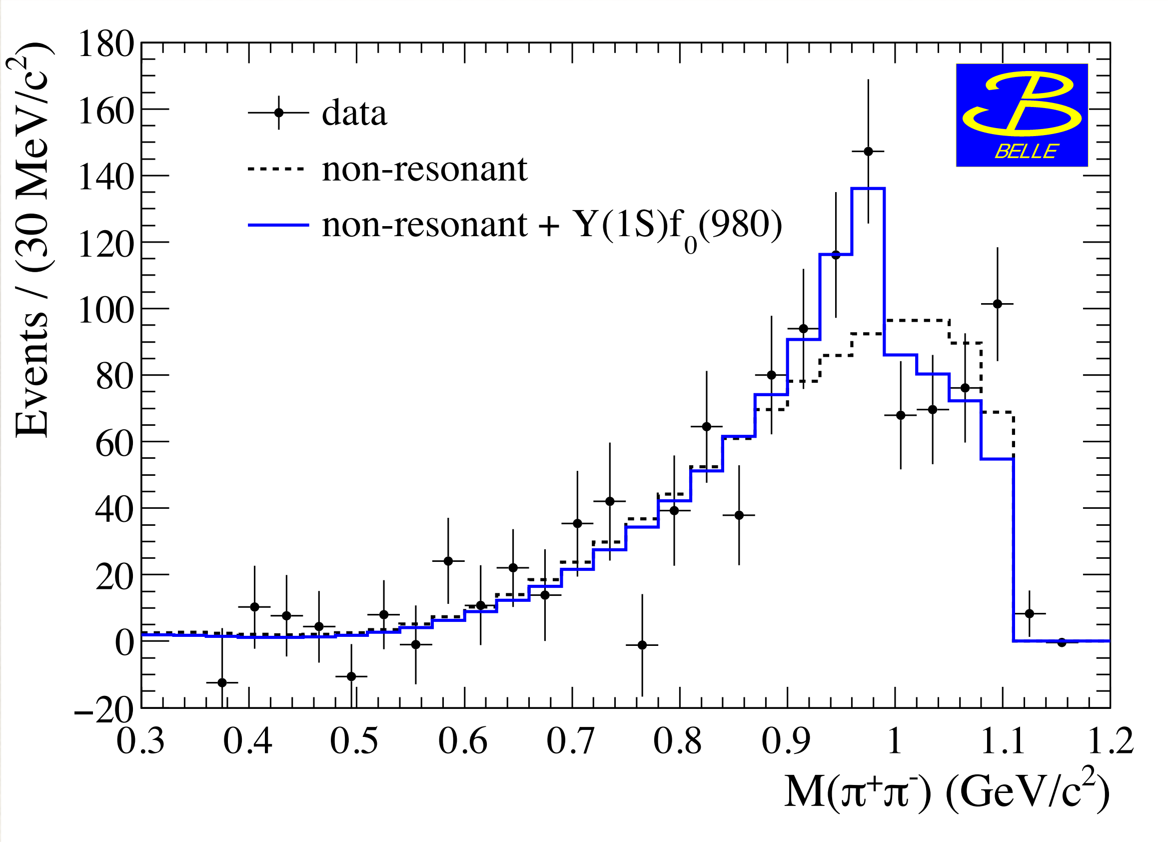
uncertainty on $\Gamma(\Upsilon(2S,3S) \to e^+e^-)$

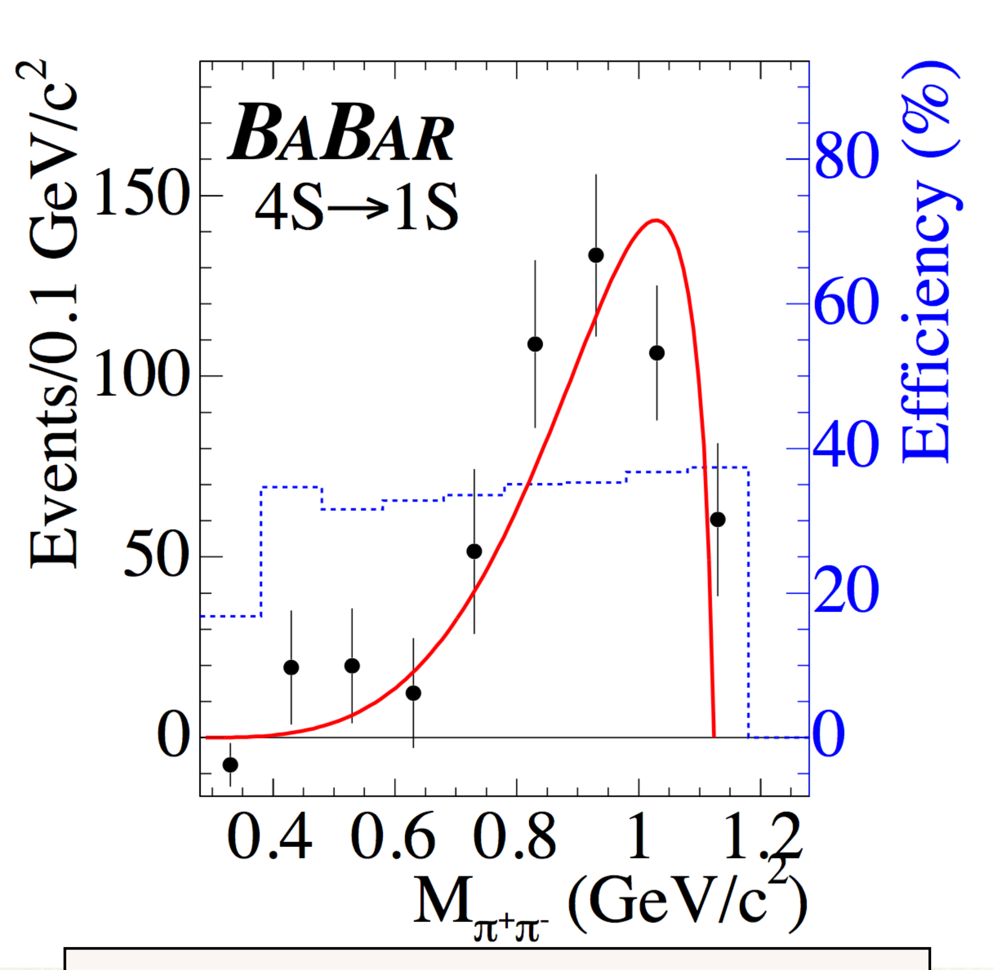
Benayoun et al. Mod.Phys.Lett. A 14 (1999) 2605

Dipion transitions

- Distributions of $M(\pi^+\pi^-)$ and $\cos\vartheta_{hel}(\pi^+)$ for the signal components unfolded from the data using the *sPlot* technique, for all the transitions (see backup)
- Major interest comes from $\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)$ dipion invariant mass
  - Behaviour not seen in previous data at the $\Upsilon(4S)$:



Belle Coll. arXiv:1707.04973 (accepted by PRD)



BABAR Coll. PRL 96 (2006) 232001

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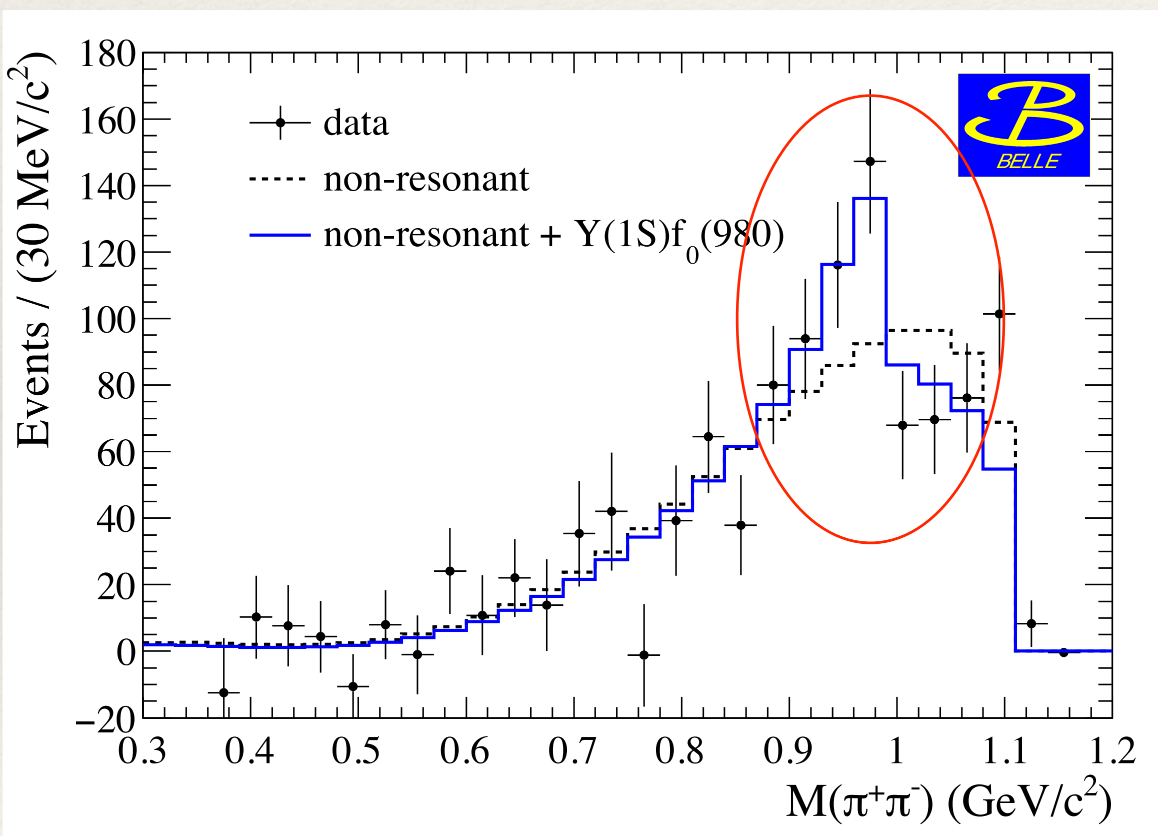
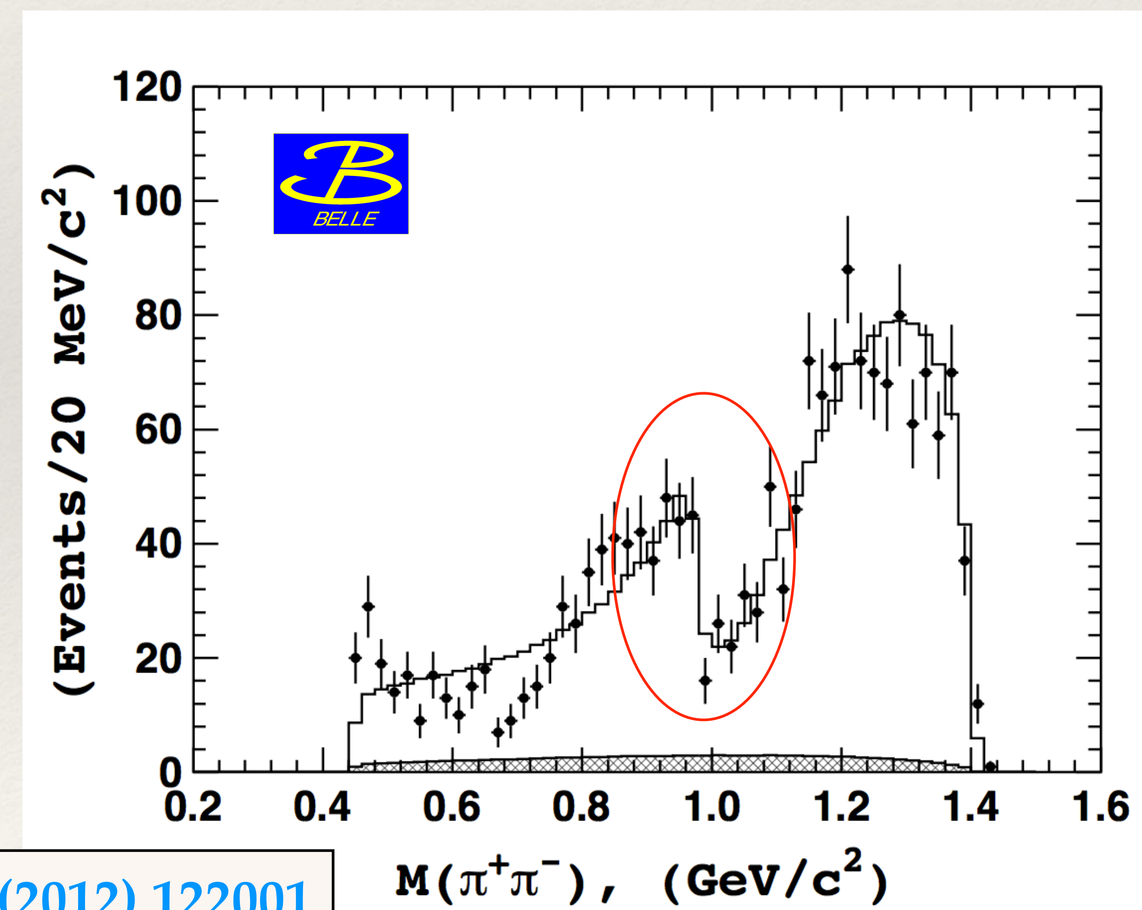


Belle Coll. arXiv:1707.04973 (accepted by PRD)

- Behaviour not seen in previous data at the $\Upsilon(4S)$ and very similar to what observed at the $\Upsilon(5S)$:



Belle Coll. PRL 108 (2012) 122001

Dipion transitions

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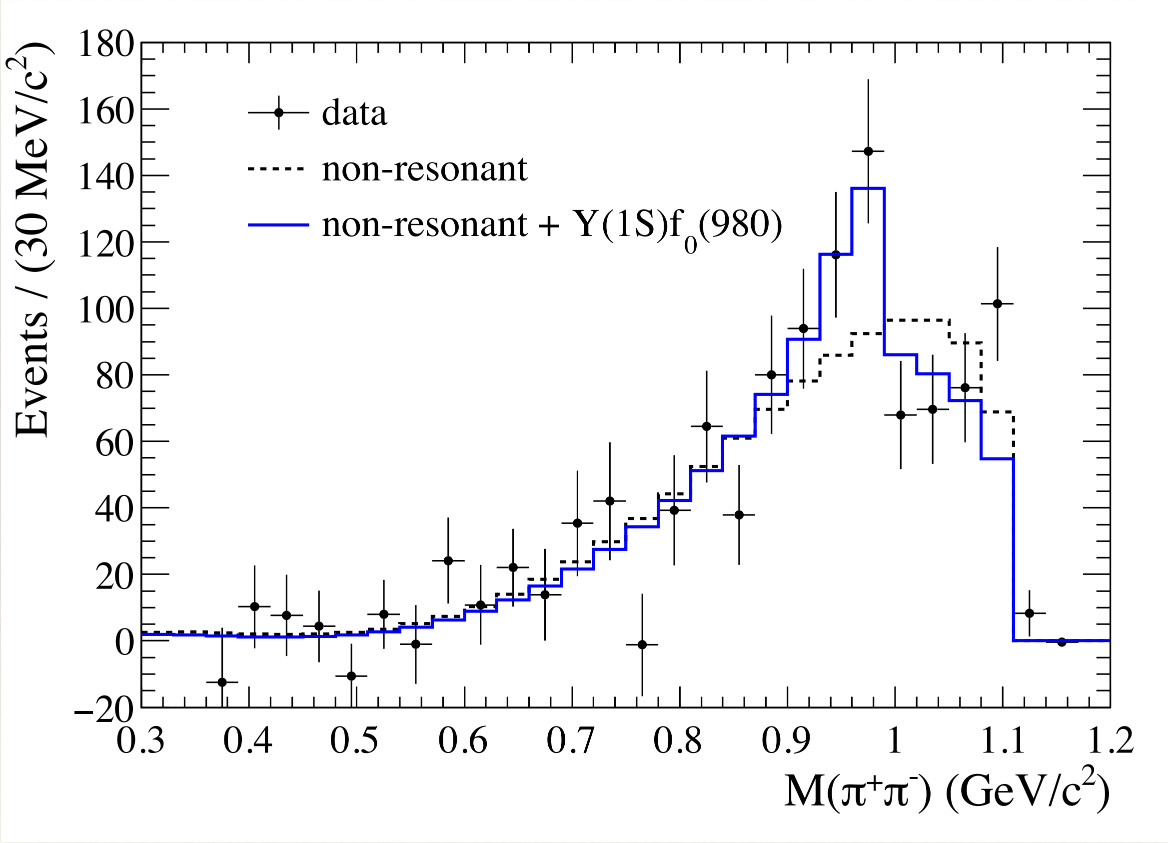


Belle Coll. arXiv:1707.04973 (accepted by PRD)

- Behaviour not seen in previous data at the $\Upsilon(4S)$ and very similar to what observed at the $\Upsilon(5S)$
- <u>Recently predicted by theory:</u>

Chen et al. PRD 95 (2017) 034022

- An amplitude model including a resonant **f_0(980)** contribution is preferred by data (**2.8σ**)
- Addition of f_2(1270) does not improve the description

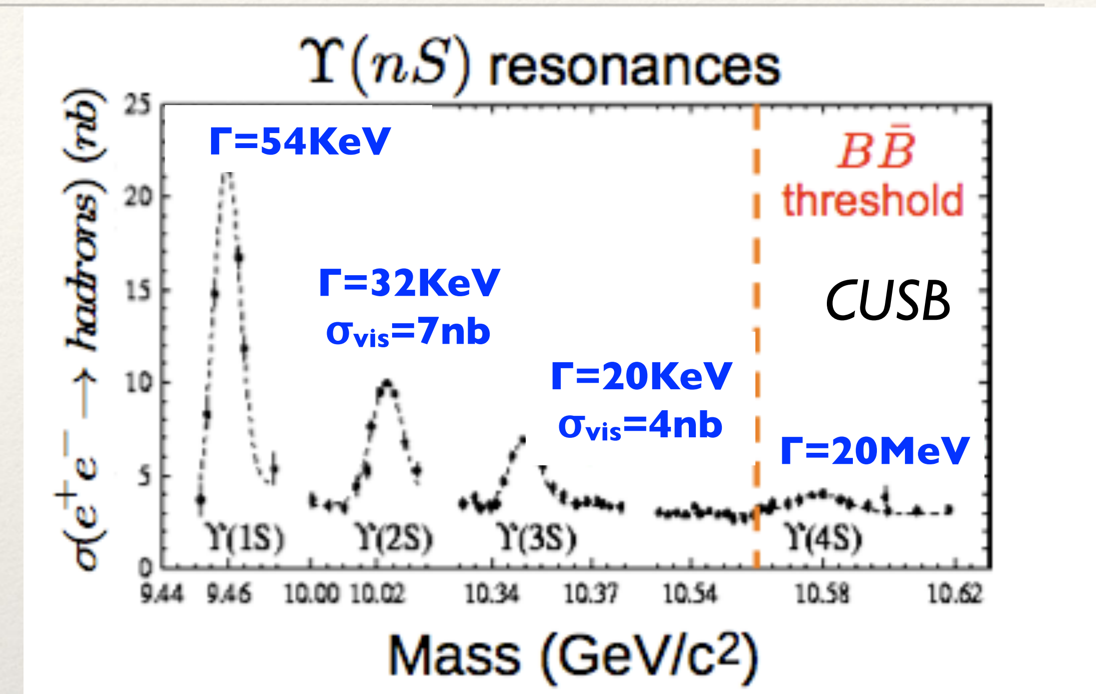
Conclusions

- Hadronic transitions are a key ingredient in understanding bottomonium and QCD description of matter
- Belle has recently given a solid contribution, with many achievements in the topic:
  - Observation of $\Upsilon(4S) \longrightarrow \eta h_b(1P)$
  - Observation of $\Upsilon(5S) \longrightarrow \eta \Upsilon(1D)$
  - Confirmation of the enhancement of $\Upsilon(4S) \longrightarrow \eta \Upsilon(1S)$ with respect to $\Upsilon(4S) \longrightarrow \pi^+\pi^-\Upsilon(1S)$
  - Measurement of/search for other η transitions
  - Precise measurement of $\Upsilon(4S)$ dipion transitions and first indication for a resonant contribution in $\Upsilon(4S) \longrightarrow \pi^+\pi^-\Upsilon(1S)$
- And many more results are likely to come in the future with Belle2 (see U.Tamponi's talk in Exotic states and candidates on Friday morning)

Backup

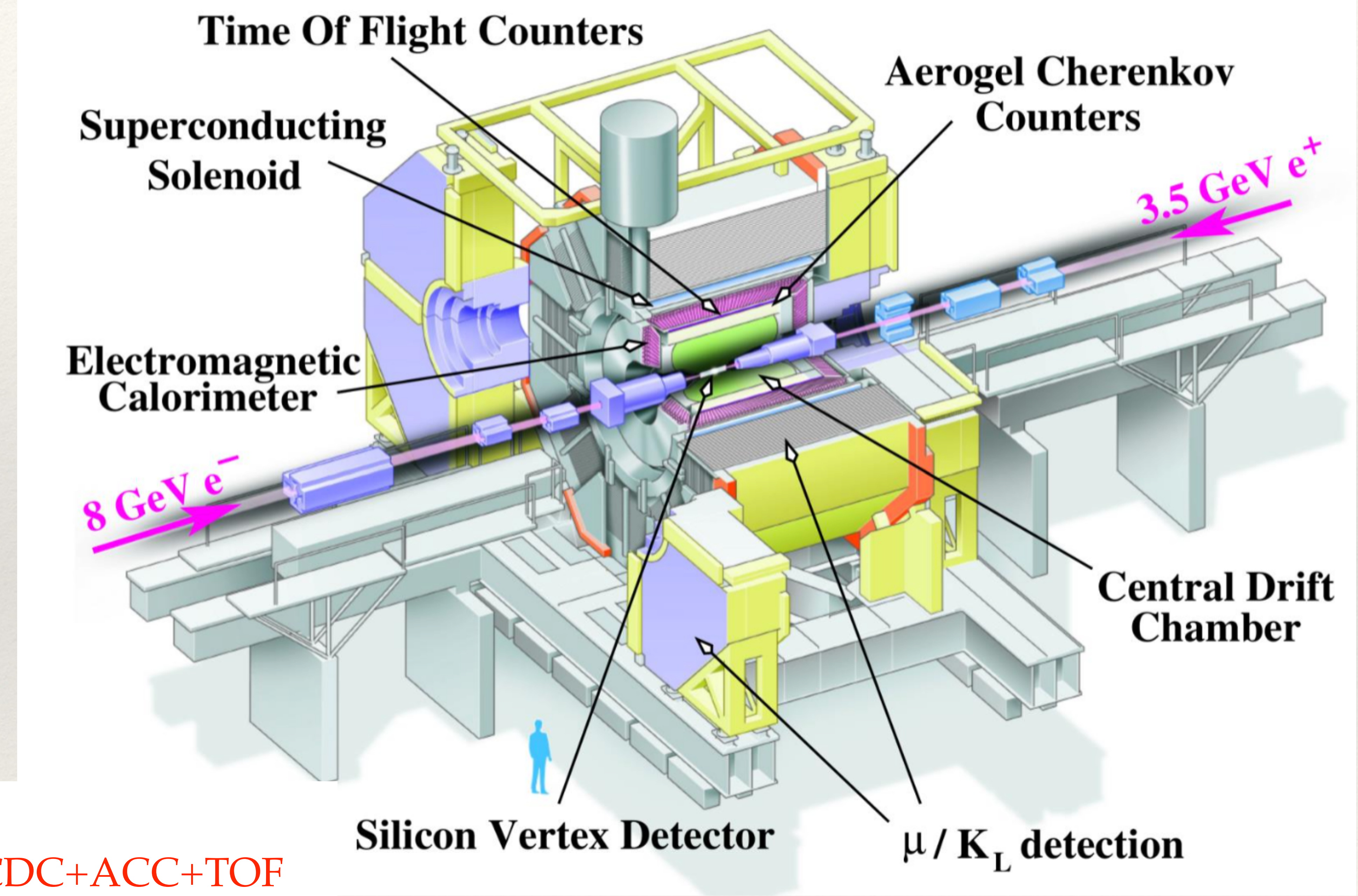
The BELLE experiment

- Operated at **KEKB** asymmetric e^+e^- collider, run at the energies of the different Υ resonances (below and above $B\bar{B}$ threshold)
- Collected the largest data samples at almost all of these energies (the only exception being $\Upsilon(3S)$)



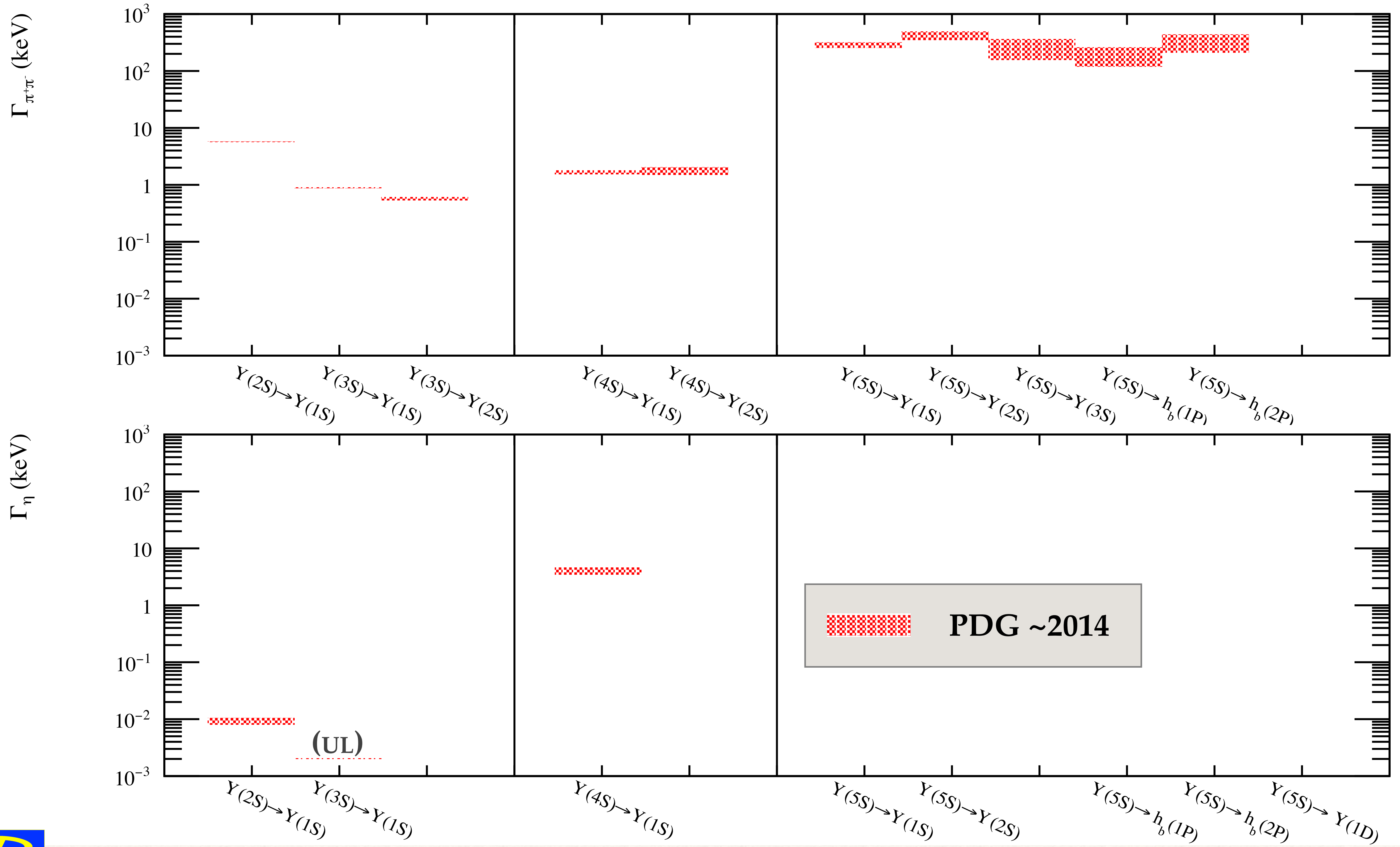
- **711 fb^{-1}** at $\Upsilon(4S)$
- **3 fb^{-1}** at $\Upsilon(3S)$
- **24 fb^{-1}** at $\Upsilon(2S)$
- **6 fb^{-1}** at $\Upsilon(1S)$
- **~100 fb^{-1}** off resonance/scan above threshold
- **121 fb^{-1}** at $\Upsilon(5S)$

The BELLE detector

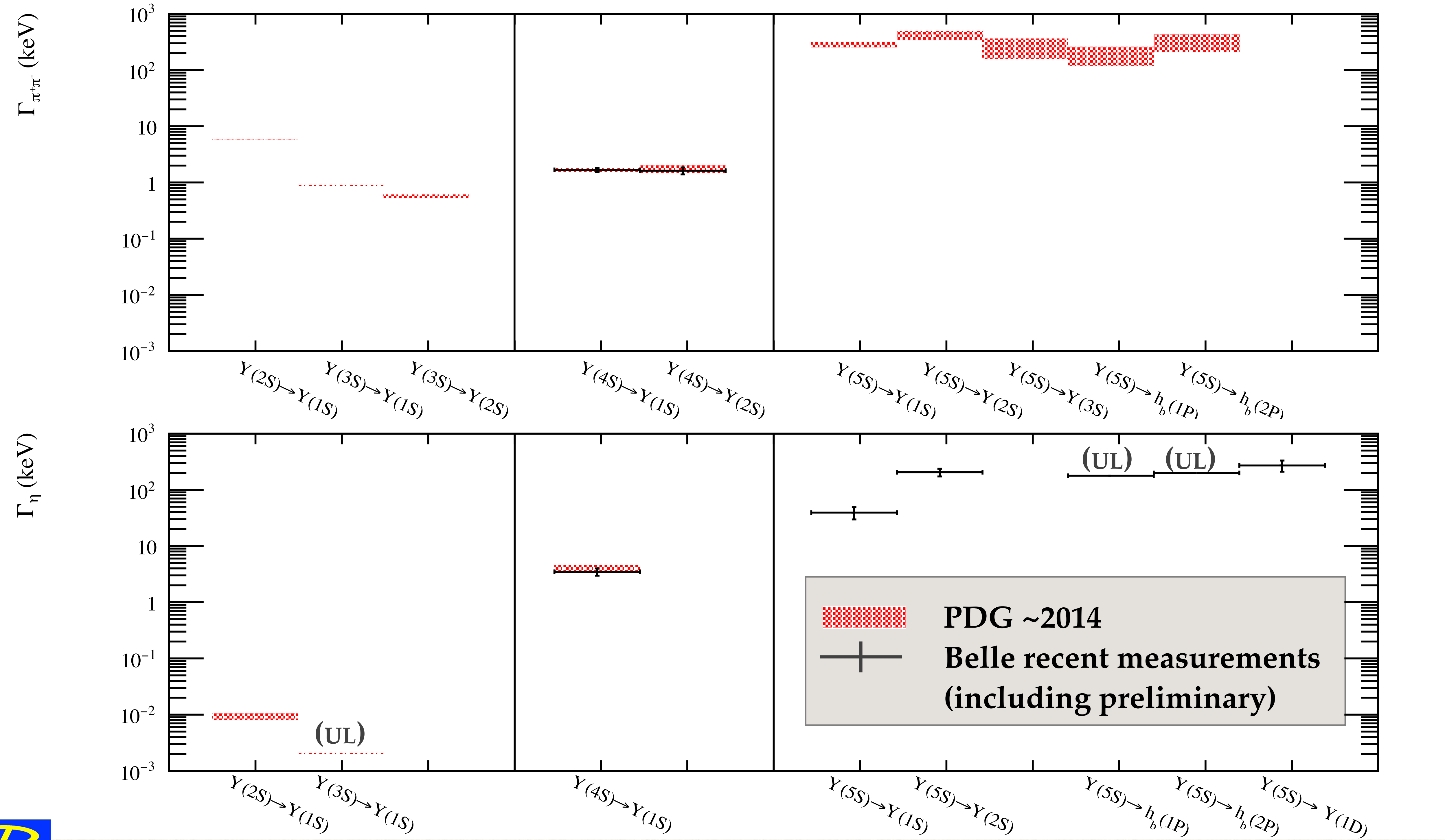


- Tracking : SVD+CDC
- Particle Identification: CDC+ACC+TOF
- Calorimetry: (CsI(Tl) crystal)

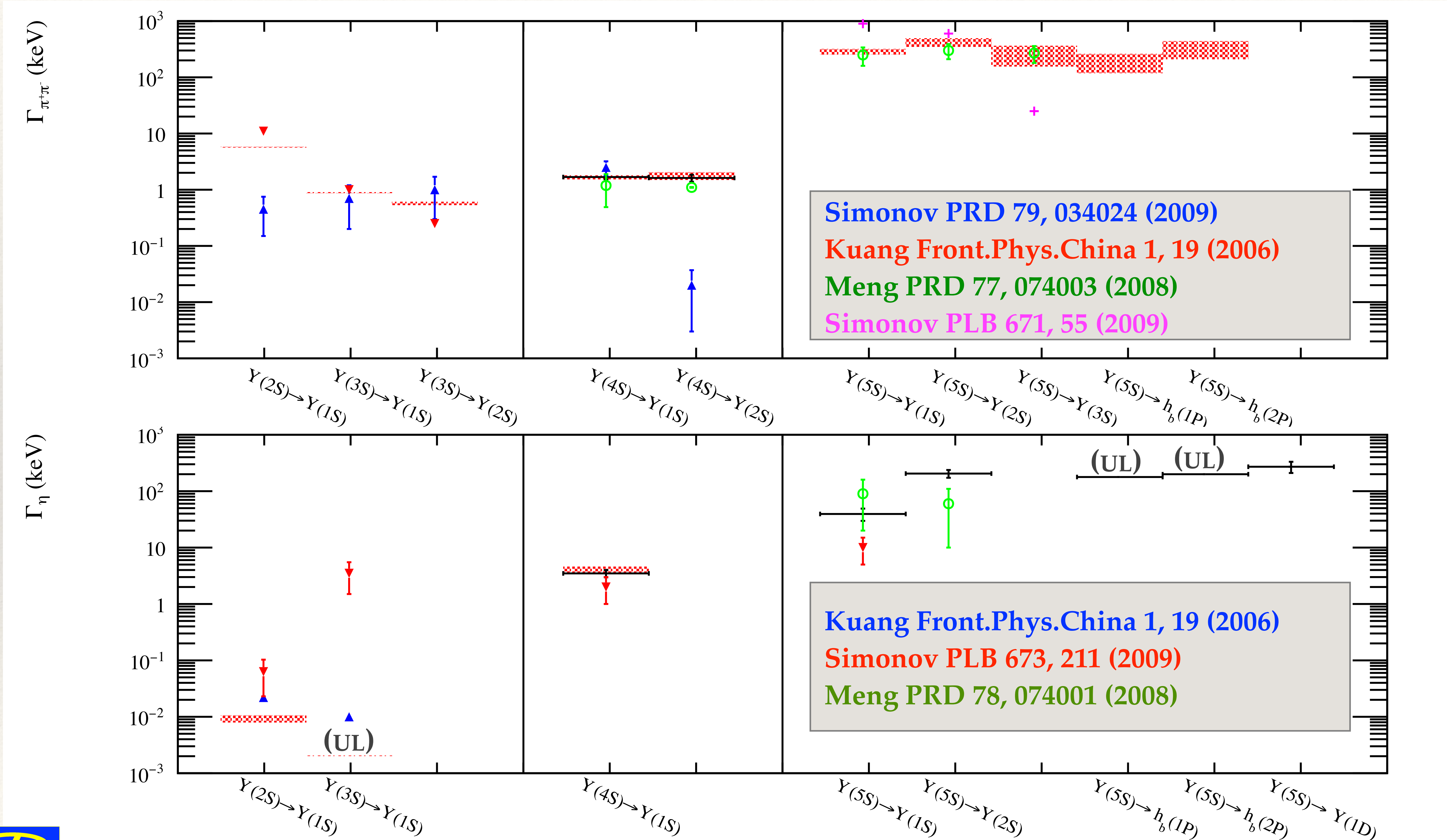
Hadronic transitions: exp vs. theory



Hadronic transitions: exp vs. theory



Hadronic transitions: exp vs. theory

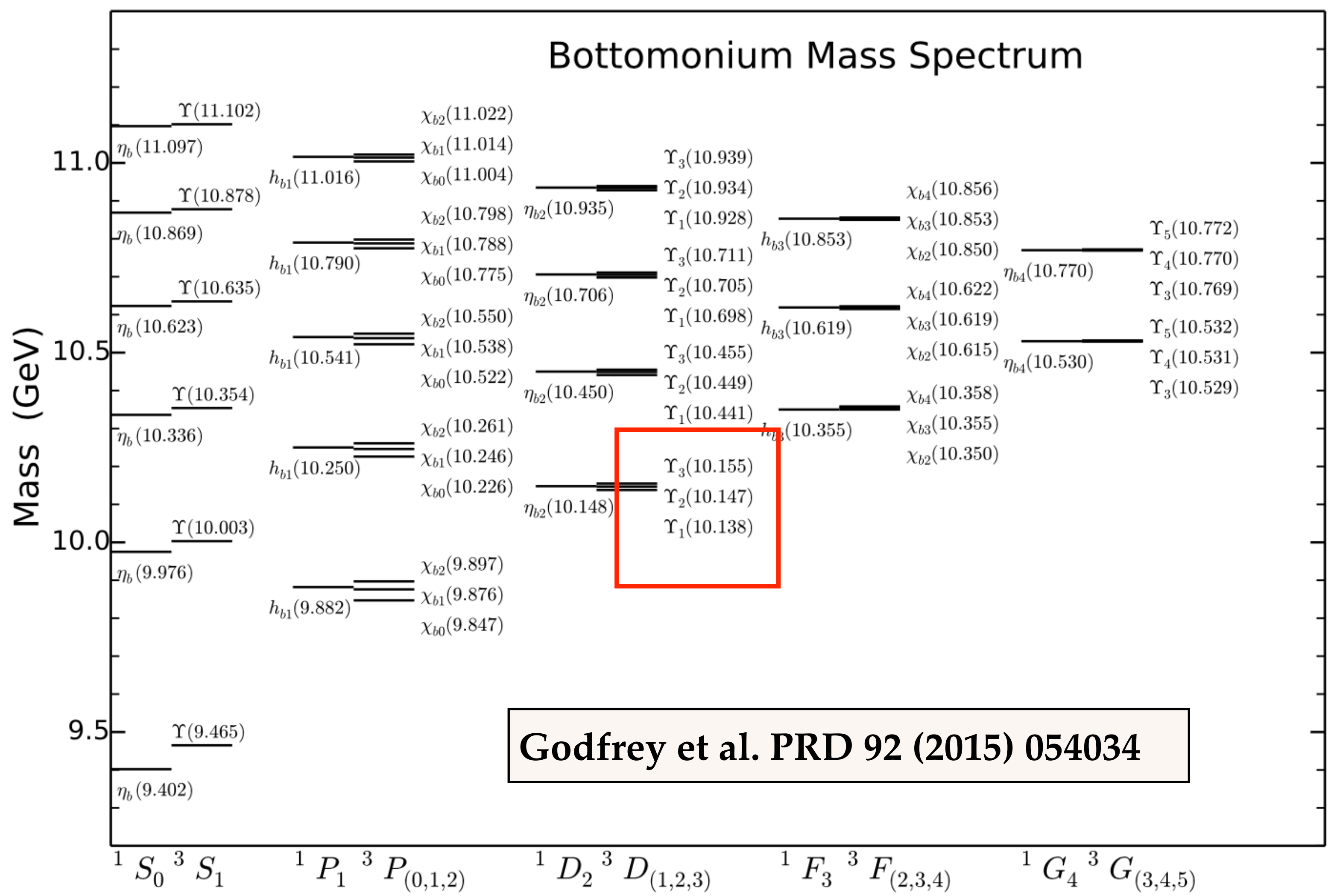


π^0 transitions: experimental status

Transition	CLEO	Year	BaBar	Year	Belle	Year
$\Upsilon(3S) \longrightarrow \pi^0 h_b(1P)$	-		7.4±2.2±1.4	2011b	-	
$\Upsilon(2S) \longrightarrow \pi^0 \Upsilon(1S)$	<1.8	2008	-		<0.41	2013

CLEO Coll. PRL 101 (2008) 192001
BaBar Coll. PRD 84 (2011) 112007
Belle Coll. PRD 87, 011104(R) (2013)

Calculations of ΔM_{ij}



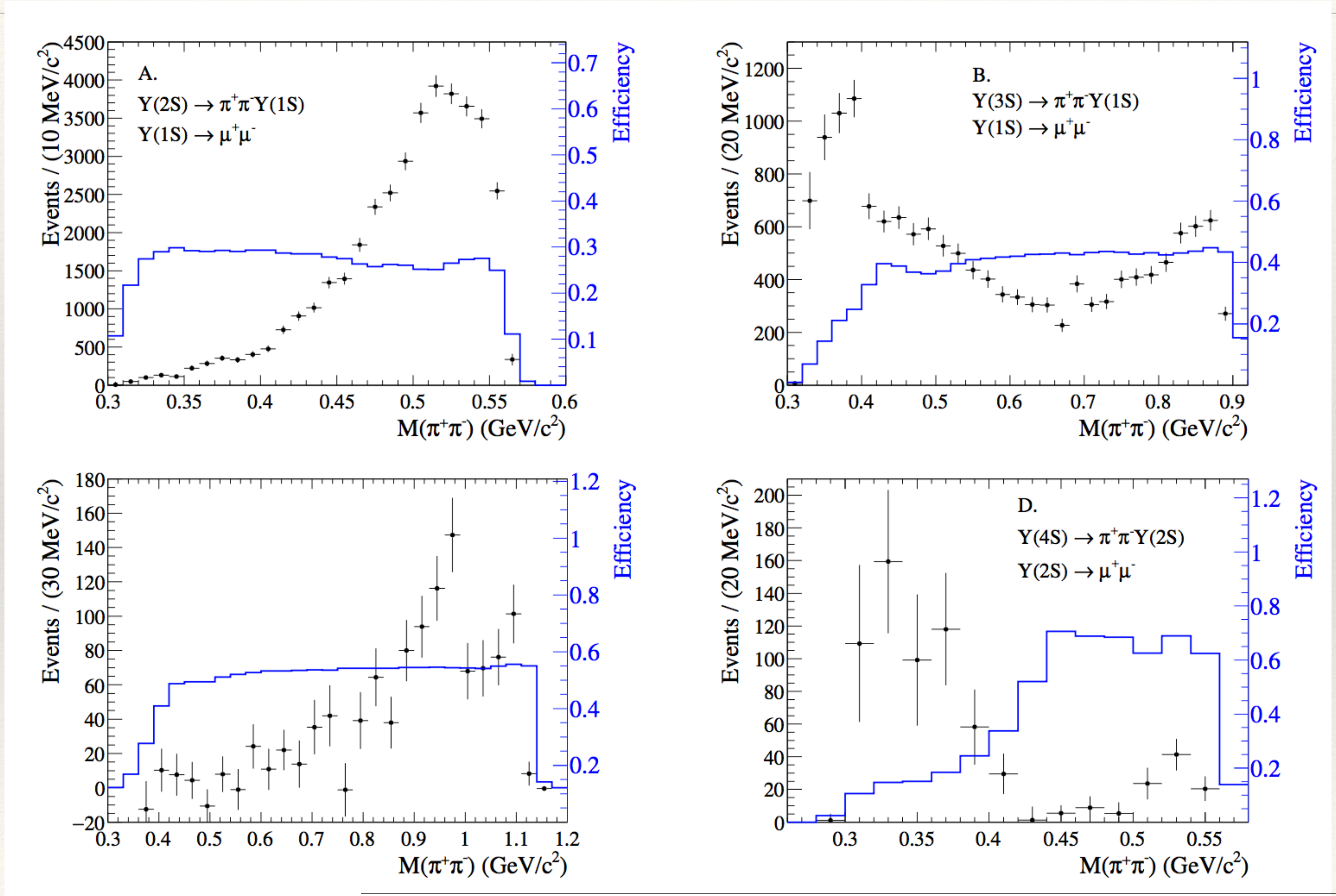
Godfrey et al. PRD 92 (2015) 054034

FIG. 1: The $b\bar{b}$ mass spectrum as predicted by the relativized quark model [11].

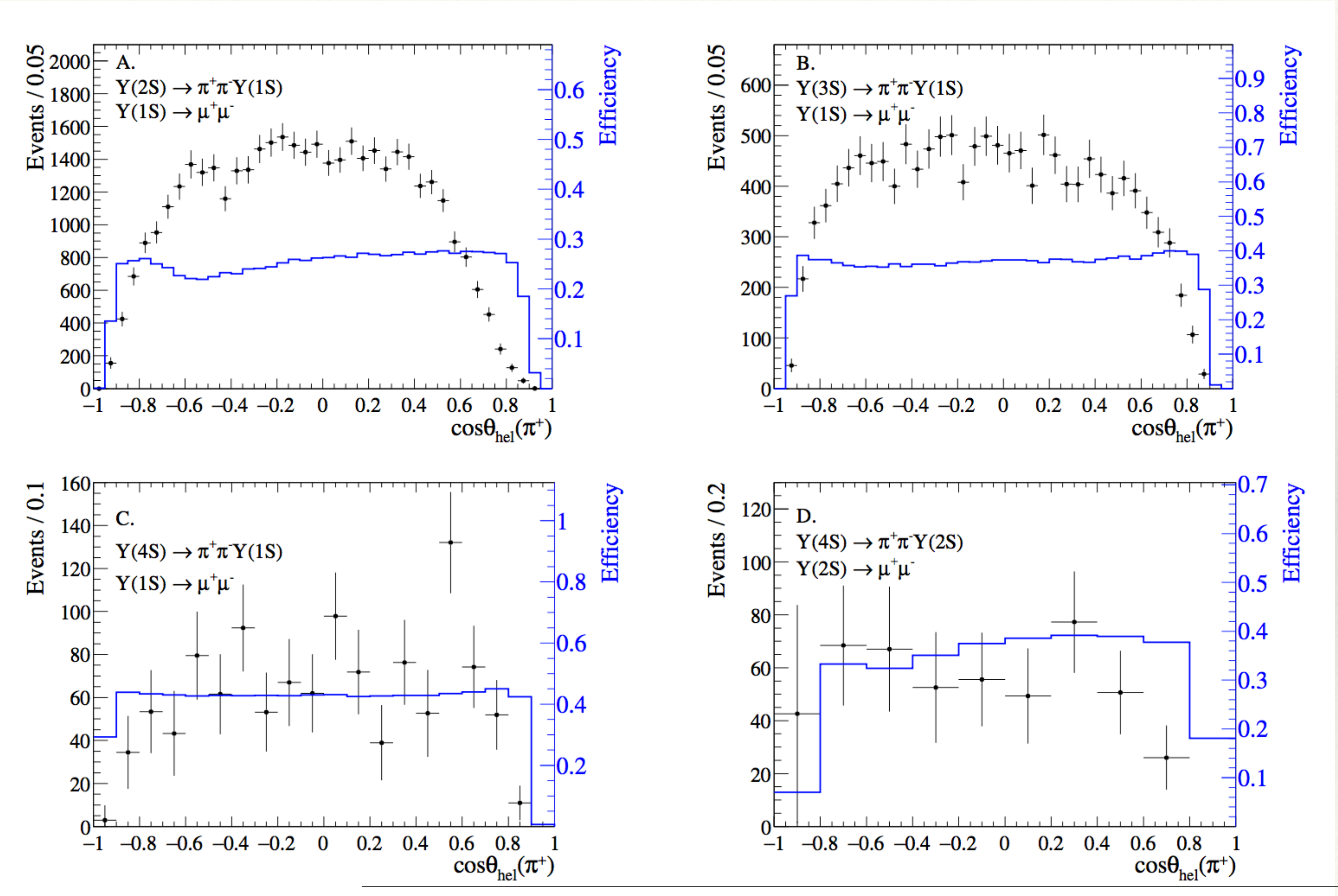
Liu et al. EPJC 72 (2012) 1981

	$\Upsilon(1\,^3D_2)$	$\Upsilon(1\,^3D_1)$	$\Upsilon(1\,^3D_3)$
BB	0	13.077	10.995
B^*B	40.776	11.968	27.296
B^*B^*	42.213	57.205	45.513
B_sB_s	0	1.817	2.088
$B_s^*B_s$	6.763	1.703	5.272
$B_s^*B_s^*$	7.941	11.023	7.531
δM	97.692	96.793	98.696
M_0	10242.3	10234.9	10248.0
M_{th}	10144.6	10138.1	10149.3
M_{ex}	10164.5		
$P_{b\bar{b}}$	0.870	0.872	0.869

Y(4S) analysis: Dipion transitions



Y(4S) analysis: Dipion transitions



Υ(4S) analysis: Systematic uncertainties

Source	$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$	$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$	$\Upsilon(4S) \to \eta\Upsilon(1S)$
Number of $\Upsilon(4S)$	1.4	1.4	1.4	1.4	1.4
Secondary BRs	2.5	2.7	2.0	2.0	$2.0 \oplus \underline{1.2}$
Tracking	1.4	1.4	1.4	1.4	1.4
μ-identification	1.1	1.1	1.1	1.1	1.1
Signal extraction	1.9	2.7	$\underline{2.7}$	2.7	$\underline{2.8}$
Acceptance	1.0	1.0	$\underline{3.1}$	3.3	-
π^0 reconstruction	-	-	-	-	$\underline{1.4}$
Total	4.0	4.5	5.1	5.2	4.5