Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Conventional quarkonia: few experimental ideas

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Bound states in strongly coupled systems

GGI, Firenze, 02/12/2018

Disclaimer

→ I am part of the Belle/Belle II collaborations
→ I've mostly done bottomonium physics in my life
→ This talk contains lots of personal opinions

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I believe that **conventional bottomonia are (experimentally) more important than conventional charmonia** right now:

→ More states
→ More transitions to be explored
→ More almost unexplored topics
→ **Limited time and chances to actually do this physics**

Charmonium: experimental tools

Charmonium is experimentally easy and accessible

→ Direct production in e^+e^- collisions

→ Production in $B \to K\, c\bar{c}$

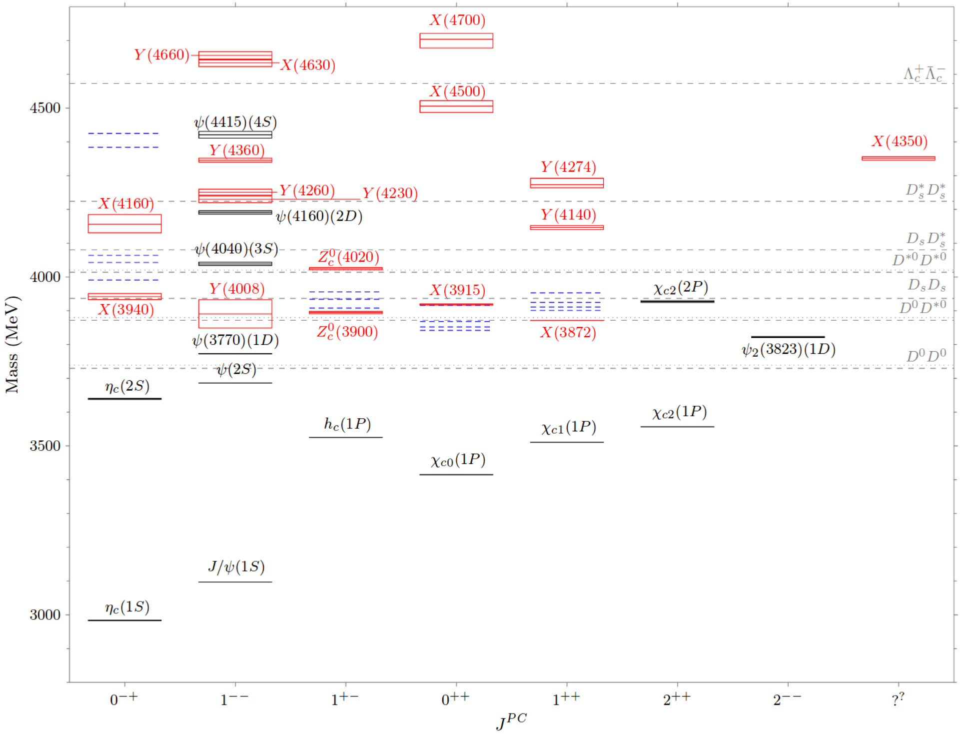
→ Photon-photon scattering $\gamma\gamma^* \to (c\bar{c})$

→ Double Charmonium $e^+e^- \to (c\bar{c})(c\bar{c})$

→ Prompt production

→ Direct production in $p\bar{p}$ (???)

→ A future super-tau-charm factory (???)



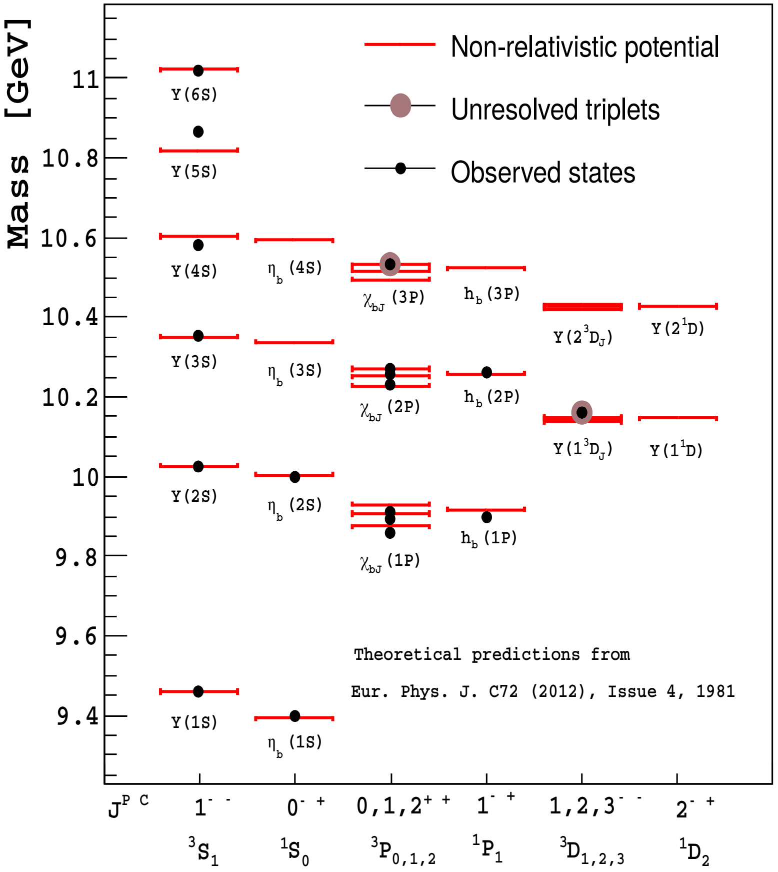
Bottom line: Charmonium will still be fully covered in the next 15 yrs.

Bottomonium: experimental tools

Bottomonium is much less accessible

→ Direct production in e^+e^- collisions

→ Prompt production



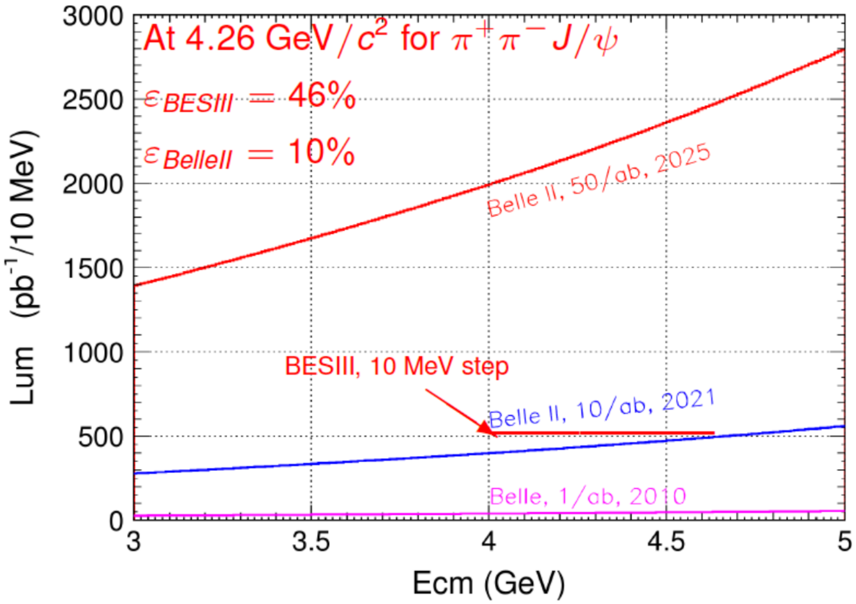
Bottom line: after Belle II, only the LHC experiments will cover bottomonia with strong limitations

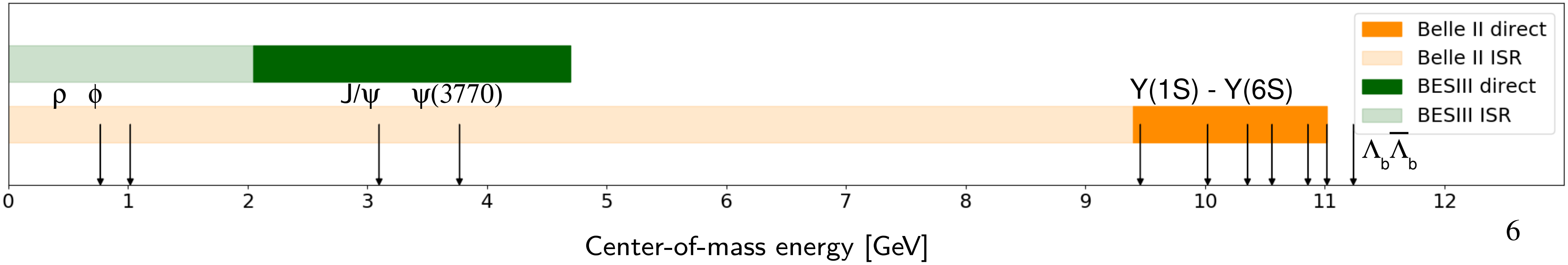
Production is not everything

e^+e^- machines

→ Triggers are quite open
→ High efficiency / Sensitive to very low momentum
→ Unique measurements (double charmonium, $\gamma\gamma^* \to c\bar{c}$)

→ Initial states is always a 1^{--} quarkonium or a B meson
→ CM energy is a limiting factor

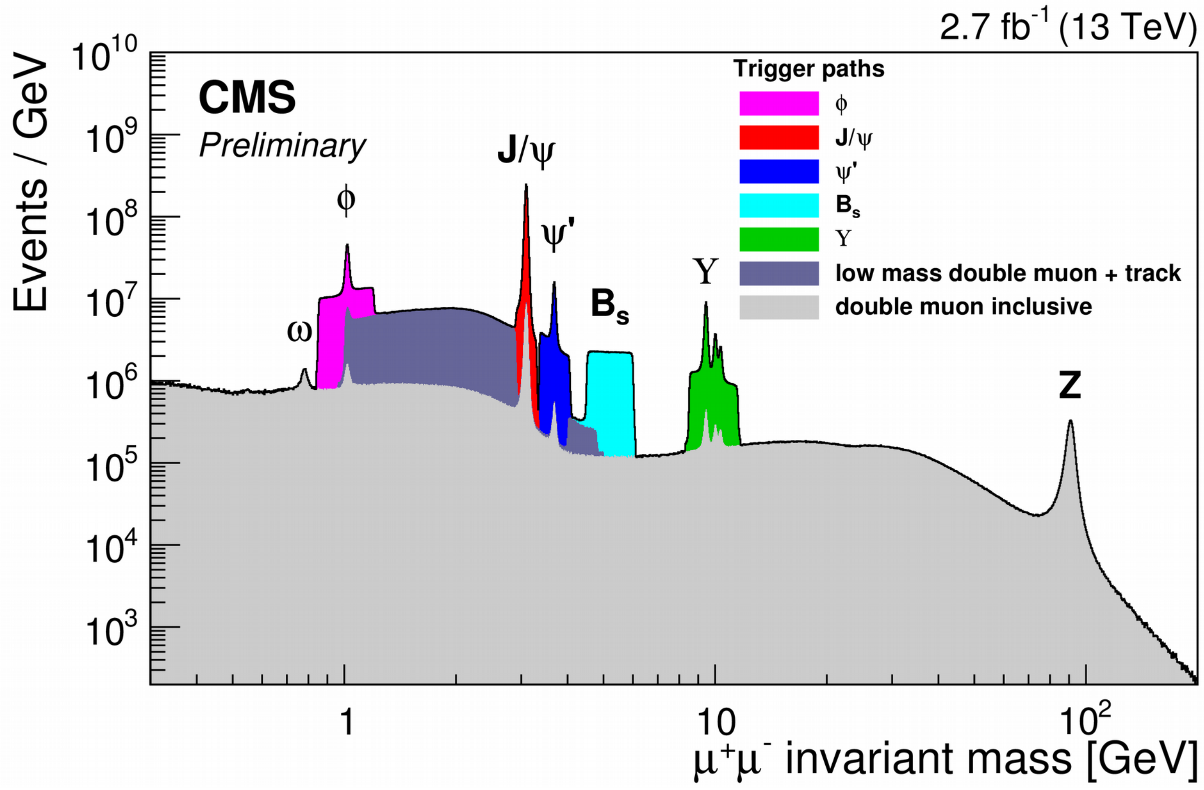




Production is not everything

Hadronic machines

→ Produce any quantum numbers
→ CM energy is not an issue
→ Unique measurements (double Y, polarization, cross sections...)
→ Triggers are a limiting factor
→ No inclusive analysis: only $\mu\mu$, $p\bar{p}$...
→ (No soft photons, no neutral mesons ...)



Production is not everything

Hadronic machines

→ Produce any quantum numbers

→ CM energy is not an issue

→ Unique measurements (double Υ, polarization, cross sections...)

→ Triggers are a limiting factor

→ No inclusive analysis: only $\mu\mu$, $p\bar{p}$...

→ (No soft photons, no neutral mesons ...)

Rule of thumb for <u>bottomonia</u>:

→ Yes to $\pi\pi/\gamma + \mu\mu$ final states

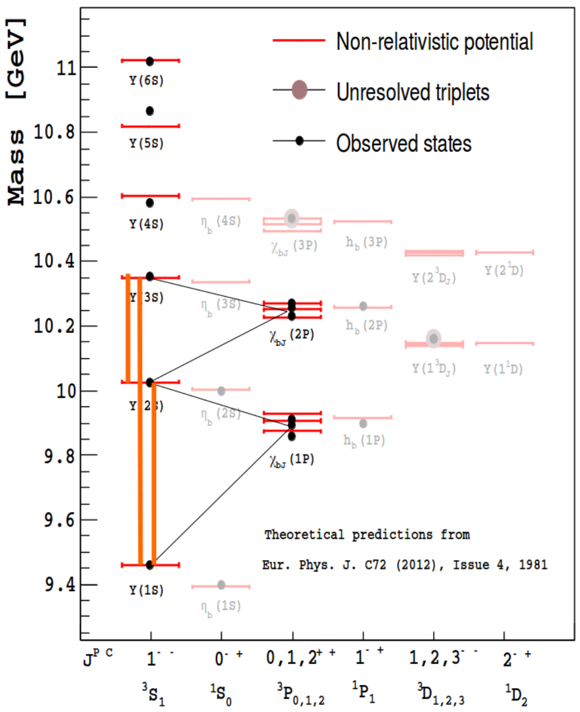
$\Upsilon(nS) \to \pi\pi\ \Upsilon(1S)$

$\chi_b(nP) \to \gamma\ \Upsilon(1S)$

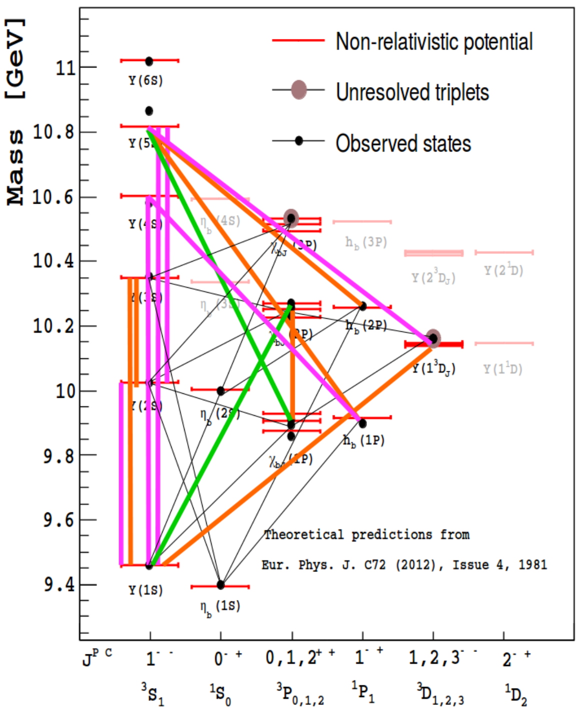
→ No to multi-hadrons final states

$\Upsilon(nS) \to \gamma\, \eta_b(1S)$

Transitions pattern circa year 2005



Transitions pattern year 2016

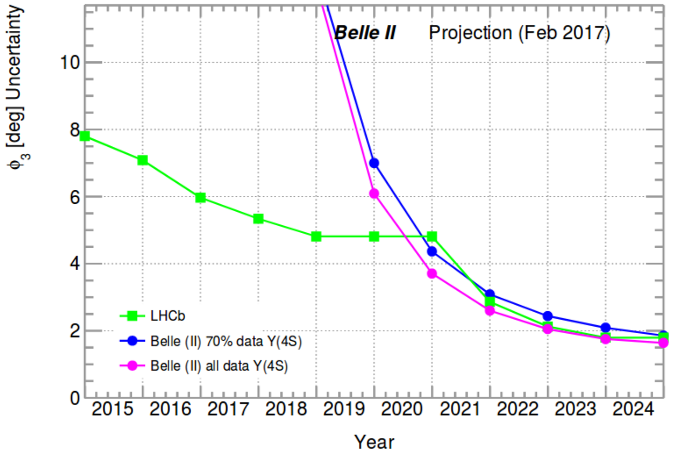


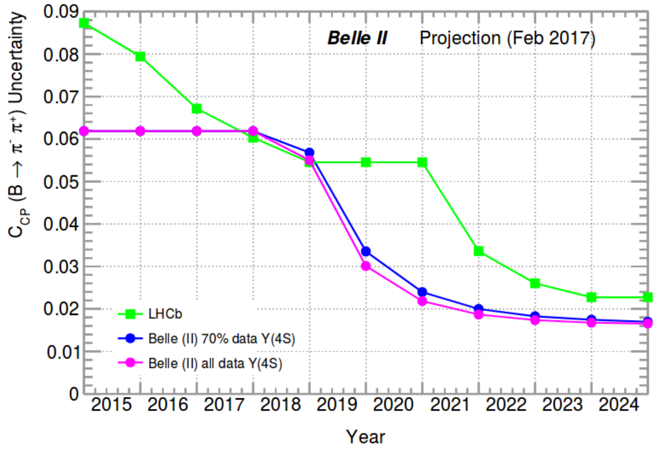
Is Belle II going to take bottomonium data?

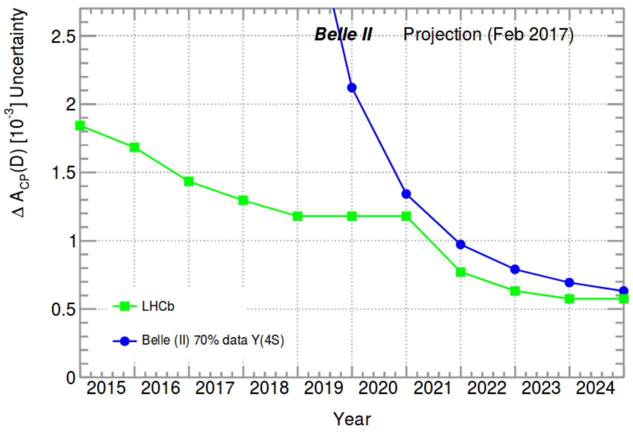
The collaboration considers Y(3S,5S,6S) runs as part of its physics program from the very beginning

$\rightarrow$ Still, the competition with LHCb on CPV is tough

$\rightarrow$ Nothing comes for free: a document for the Y(3S) run should be submitted by Feb. 2019

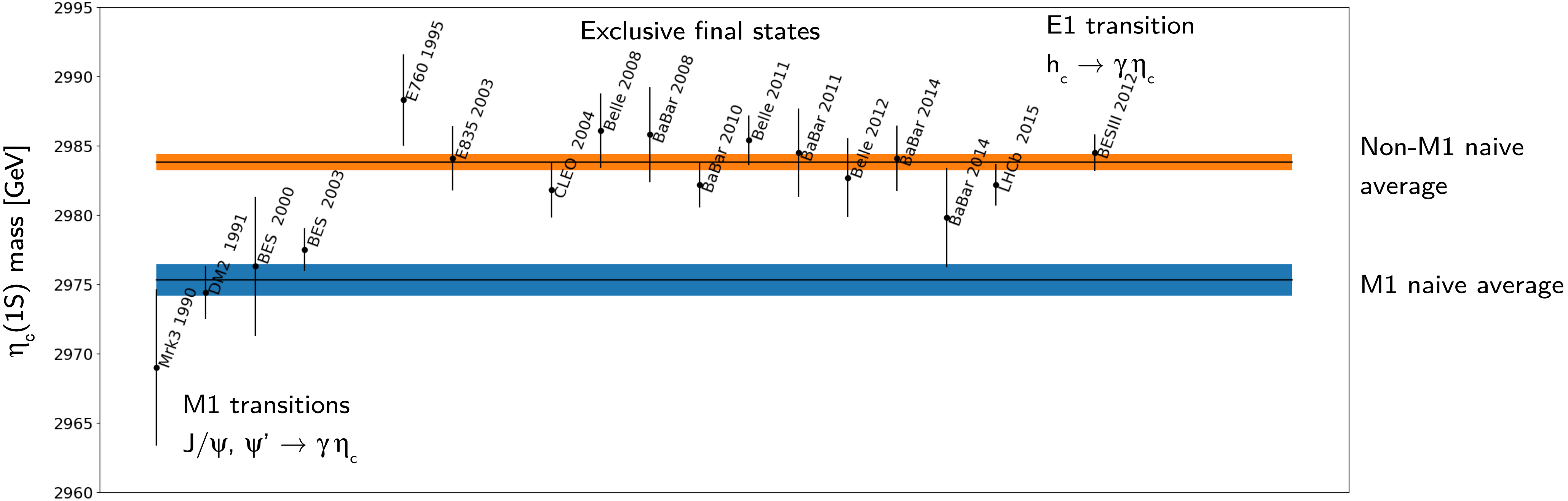






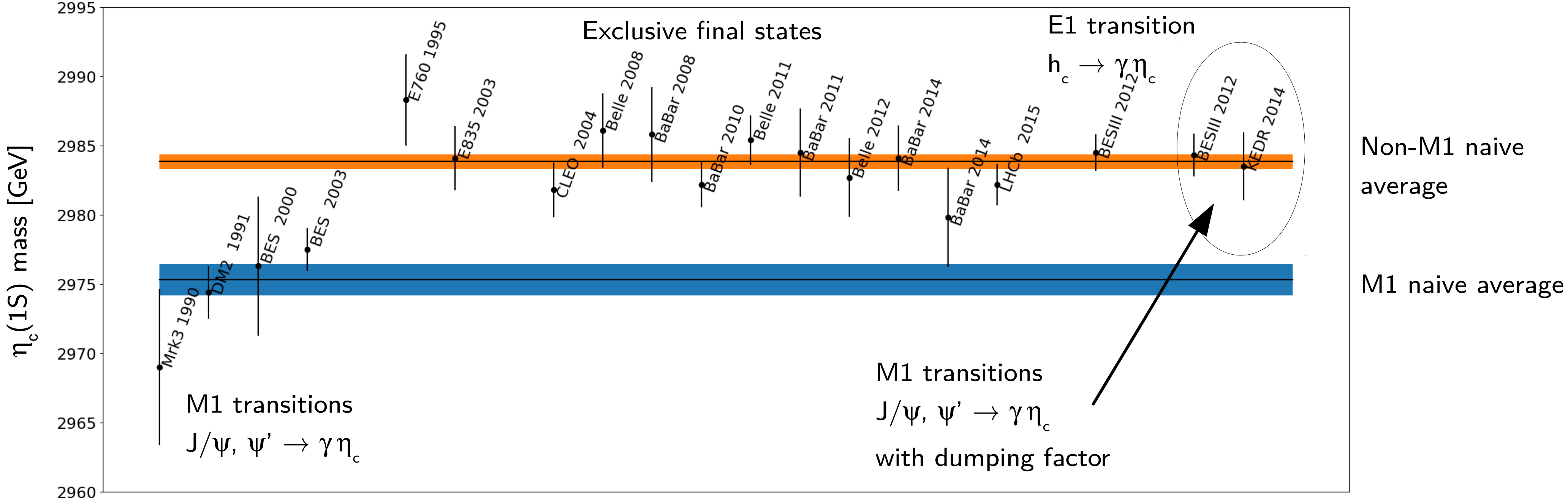
The ground states parameters

The η_c mass conundrum



All the fits are performed using a Breit-Wigner shape

The η_c mass conundrum

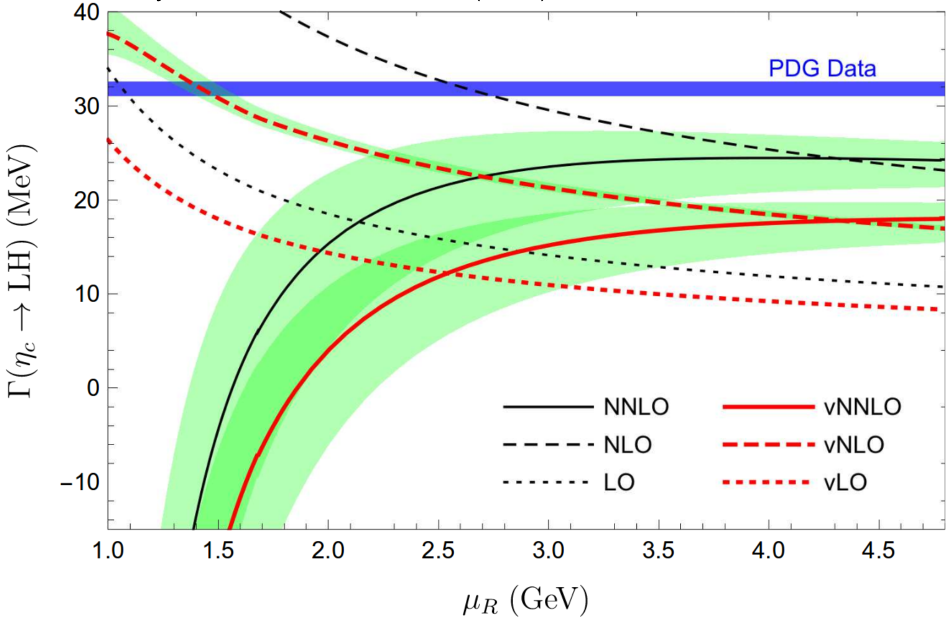


$$\frac{d\Gamma(\omega)}{d\omega} = \frac{4}{3}\alpha\frac{e_c^2}{m_c^2}\omega^3|M|^2\mathrm{BW}(\omega) \longrightarrow \frac{d\Gamma(\omega)}{d\omega} \sim \omega^3 f(\omega)\mathrm{BW}(\omega)$$

What is the proper theoretical shaper for this dumping factor?

The η_c width conundrum

Phys. Rev. Lett. 119, 252001 (2017)



What do I understand from this?

→ NNLO is still not enough

→ Is NRQCD converging fast enough?

→ The problem is not in the experimental resolution

Bottom line:

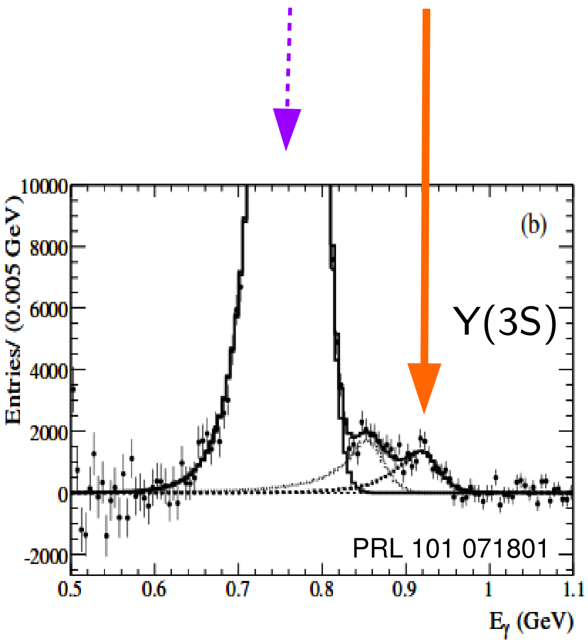
→ New data may be useful, but the problem with the η_c seems to be in the theoretical models rather than in the lack of good data

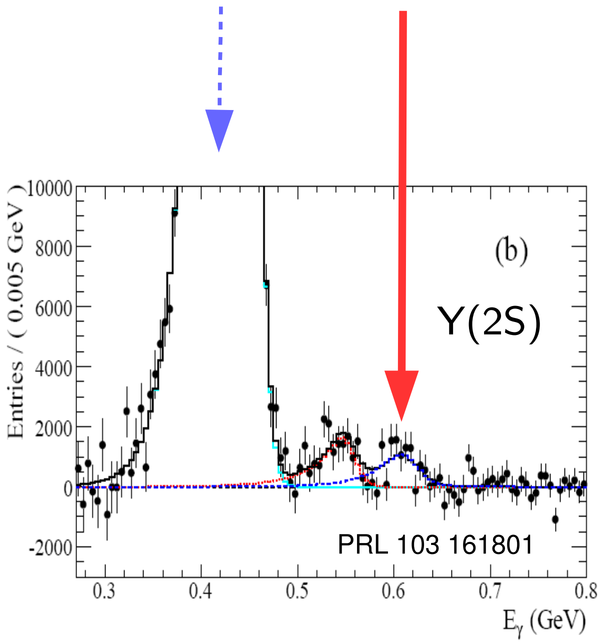
The $\eta_b(1S)$ case

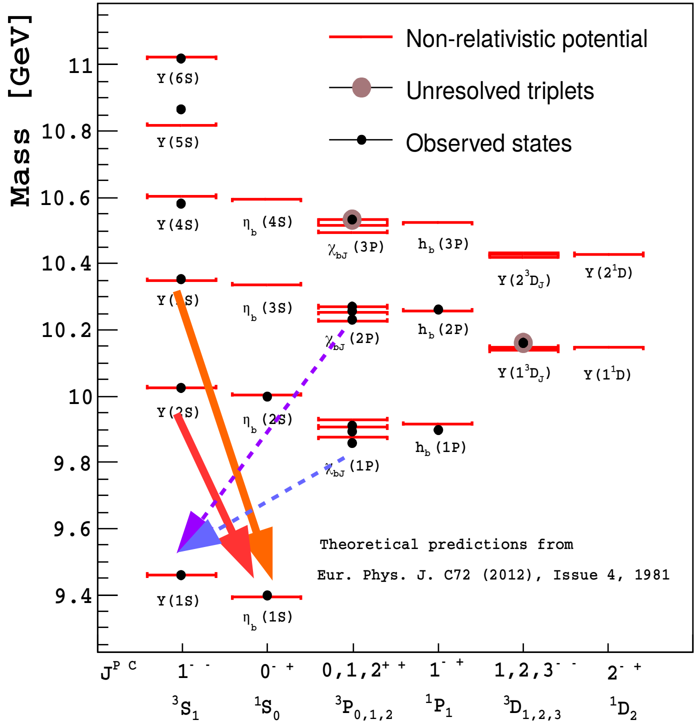
No specific decay of the $\eta_b(1S)$ has been observed so far

→ No (known) way to perform an exclusive reconstruction

→ Can be studied only at B-factories looking at the photon spectrum in $e^+e^- \to$ hadrons @ Υ(2S,3S)





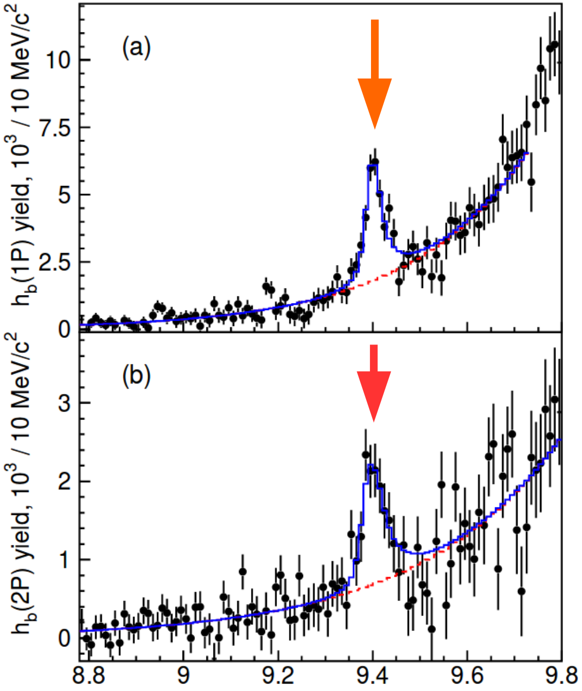


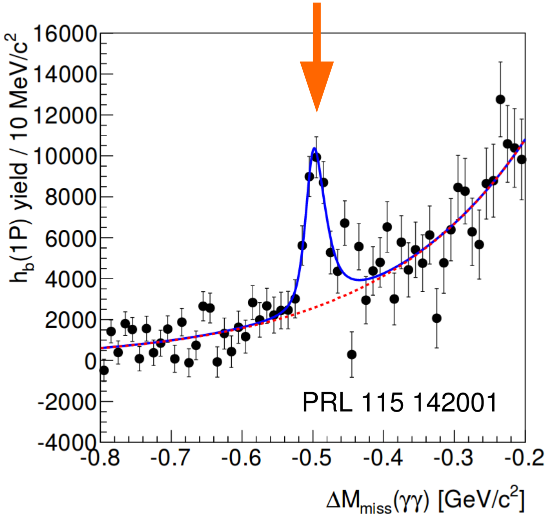
The $\eta_b(1S)$ case

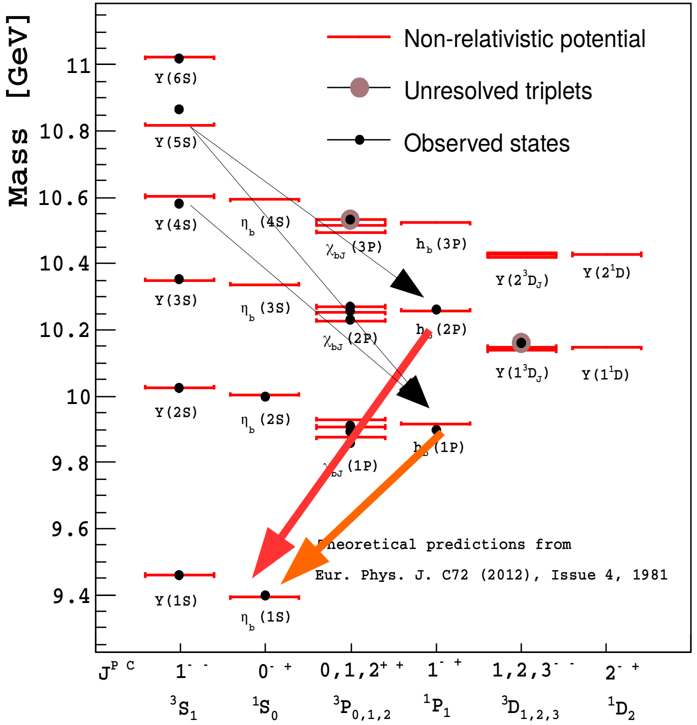
…or by looking at the photon spectrum

in $e^+e^- \to (\pi\pi, \eta)\,\gamma$ + hadrons @ Υ(4S, 5S)

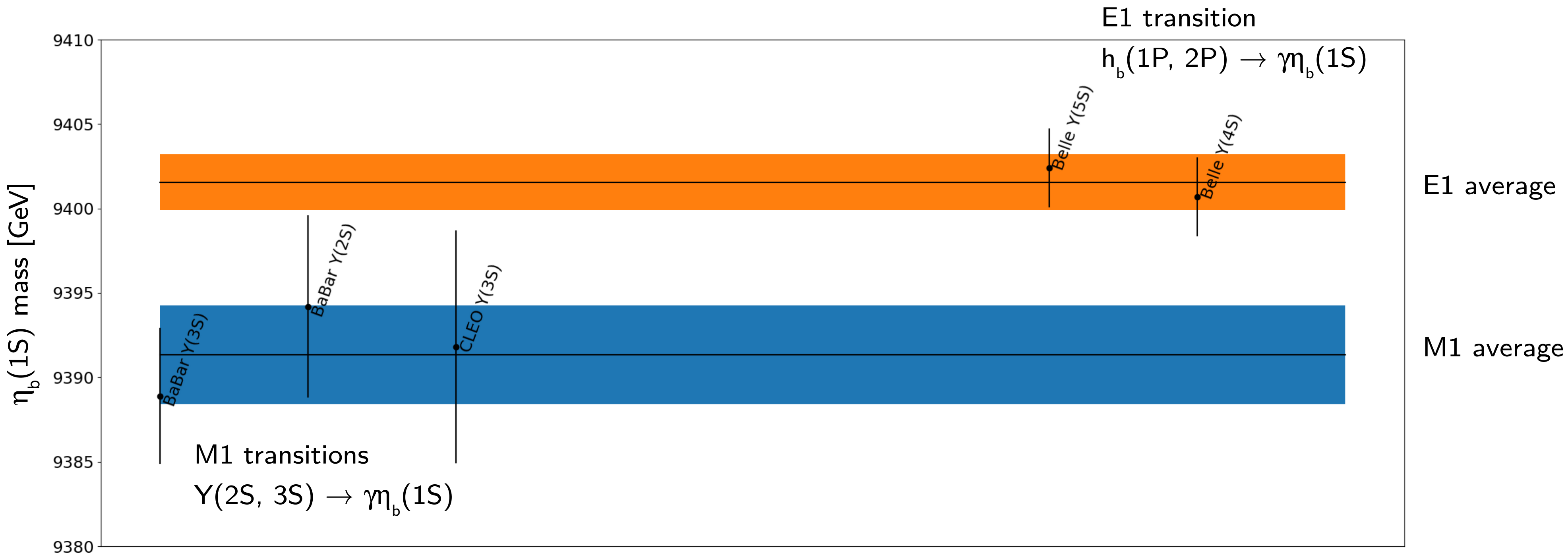
PRL 109 232002







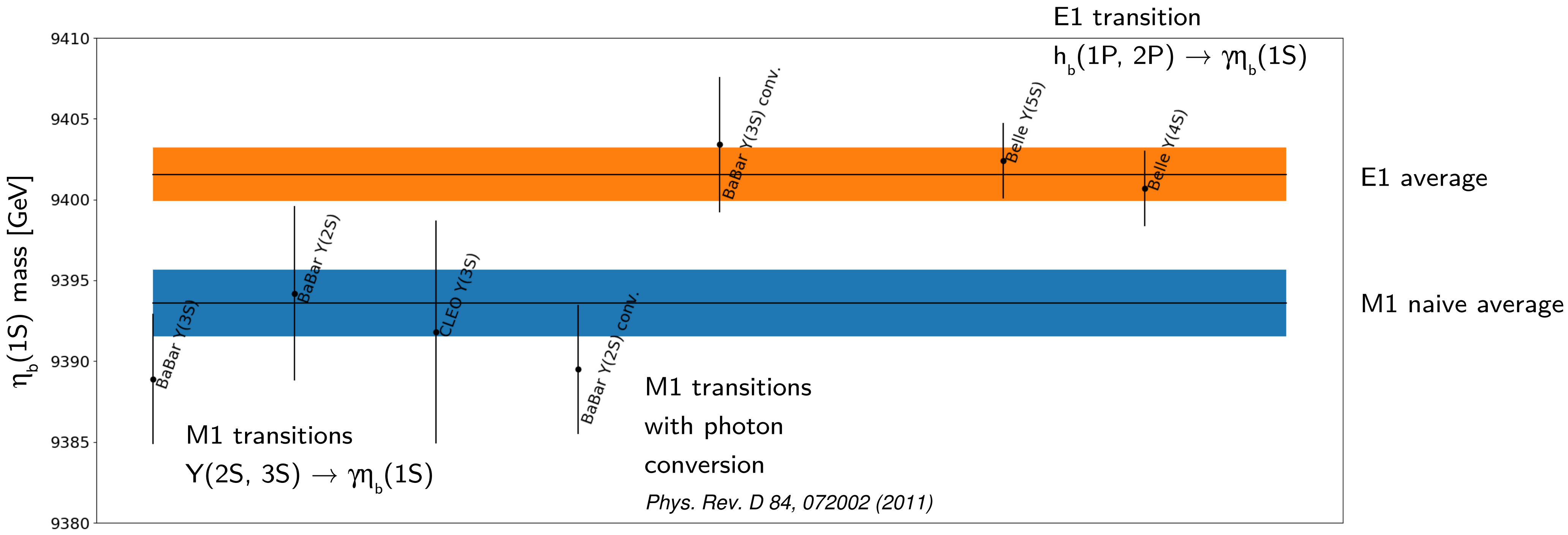
The $\eta_b(1S)$ case



→ No treatment of the dumping factor

→ No full reconstruction!

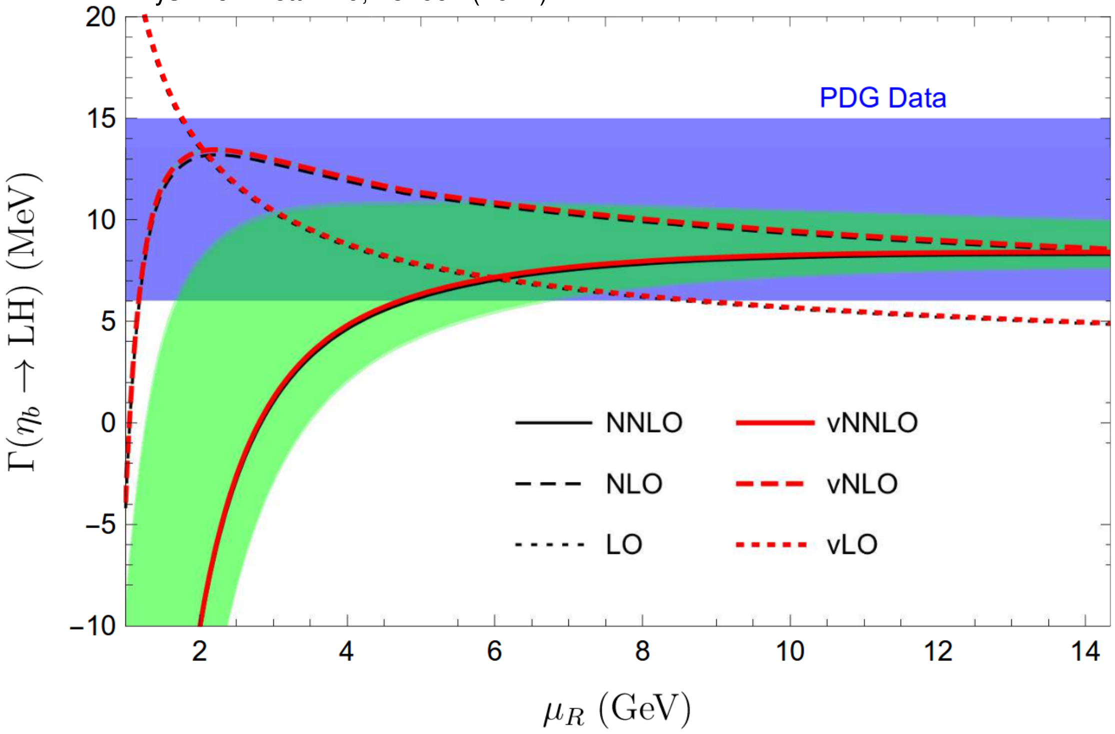
The $\eta_b(1S)$ case



→ The analysis with conversions somehow further confuses the situation

The $\eta_b(1S)$ case

Phys. Rev. Lett. 119, 252001 (2017)



Quite some room for experimental improvements

The $\eta_b(1S)$ at Belle II

Luminosities and number of events

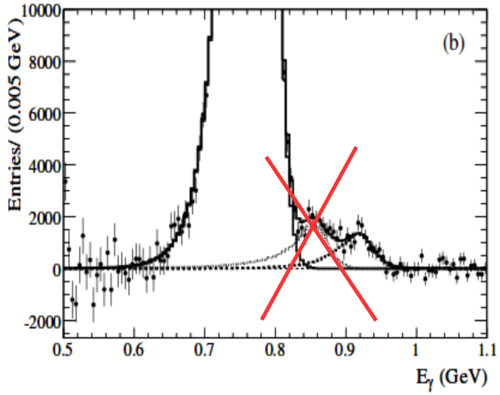
Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
BelleII	-	-	300 (1200)	5×10^4 (5.4×10^4)	1000 (300)	100+400(scan)	3.6%

$\Upsilon(3S) \to \gamma\,\eta_b(1S)$: ~200k evts (~5000 with conversion!)

$\Upsilon(3S) \to \pi\pi\,\Upsilon(2S) \to \pi\pi\gamma\,\eta_b(1S)$: 3000 evts, no ISR background

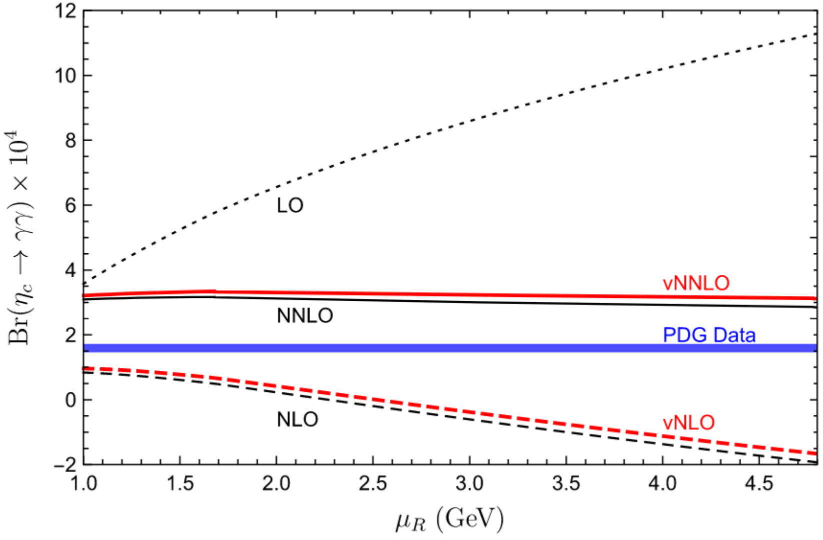
$\Upsilon(4S) \to \eta\,h_b(1P) \to (\gamma\gamma)\gamma\,\eta_b(1S)$: 2.5 Million events

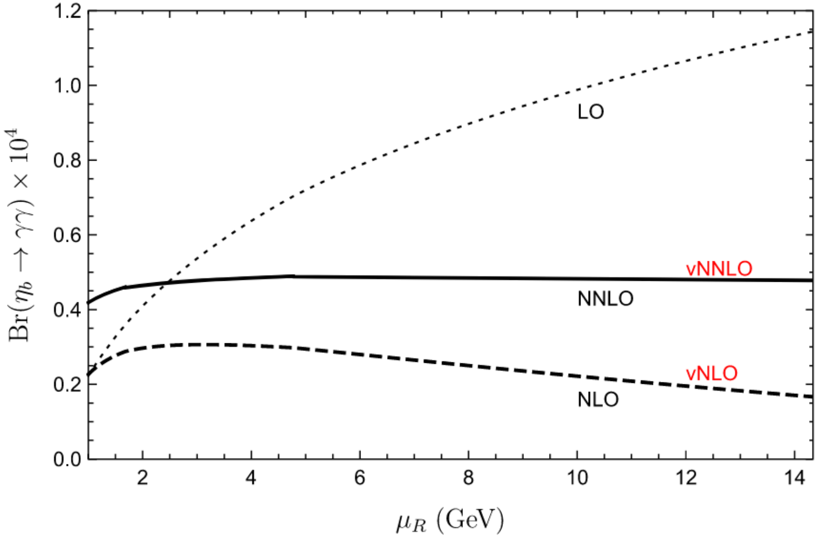
$\Upsilon(5S) \to \pi\pi\,h_b(nP) \to \pi\pi\gamma\,\eta_b(1S, 2S)$: 125k each



Ground state exclusive decays

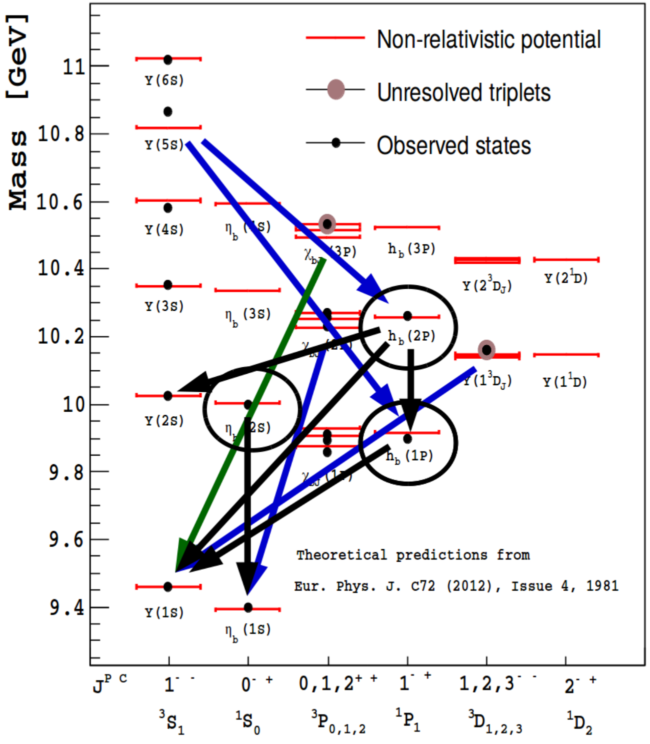
Phys. Rev. Lett. 119, 252001 (2017)





With 50 ab^{-1} of Y(4S) Belle II can measure $\eta_b(1S) \to \gamma\gamma$ with ~20% uncertainty

Di-pion transitions



What we are missing:

$\Upsilon(5S) \to \eta\ hb(1P)$

$\Upsilon(5S) \to \eta\ hb(2P)$ **Belle II**

$\Upsilon(4S) \to \pi\pi\ hb(1P)$

$\chi_b(3P) \to \omega\ \Upsilon(1S)$ **Belle II (?)**

$\chi_b(2P) \to \eta\ \eta_b(1S)$ **Belle II (?)**

$\Upsilon(1D) \to \eta\ \Upsilon(1S)$ **Belle II**

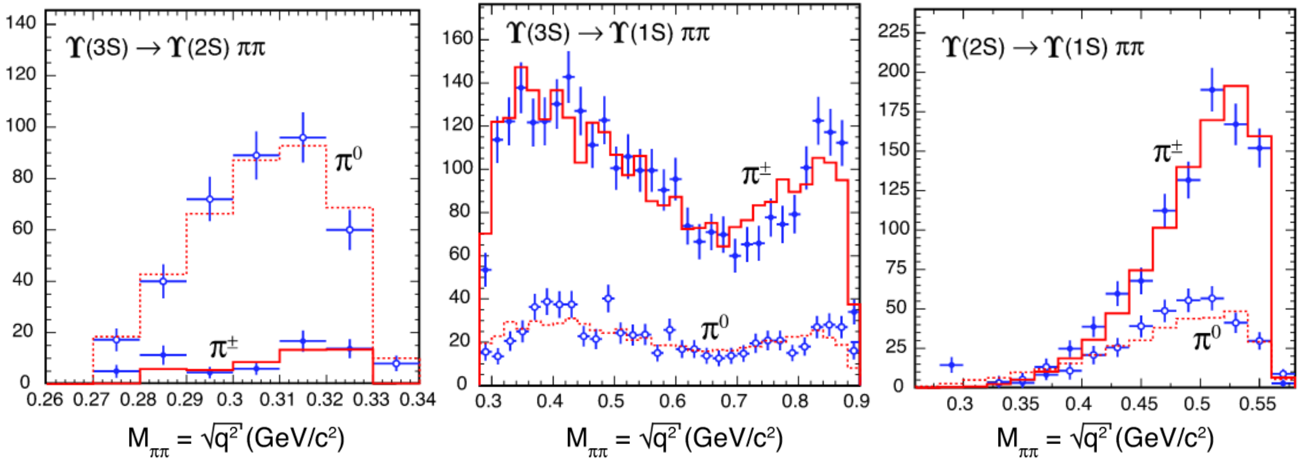
$\Upsilon(3S) \to \eta\ \Upsilon(1S)$ **Belle II**

All the hadronic transitions from Spin singlets states are unknown

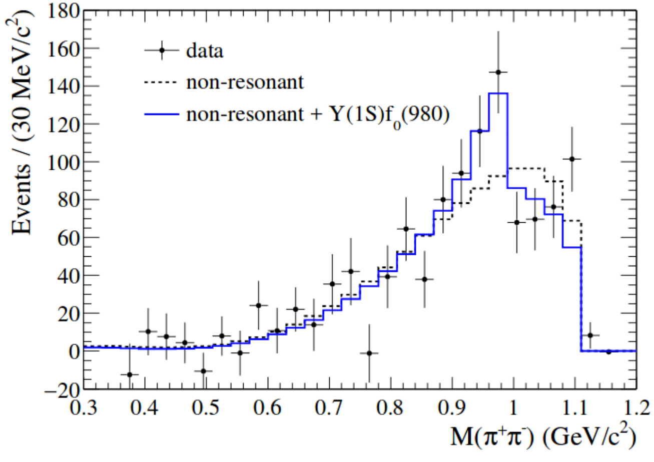
→ Any theoretical prediction is welcome!

Di-pion transitions: a family picture

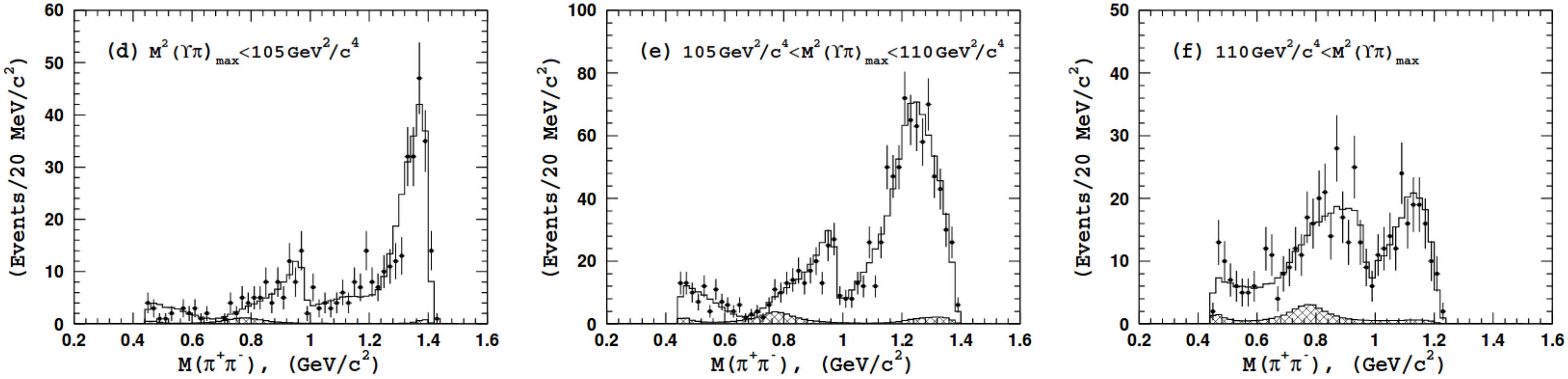
PRD76 072001 (2007)



PoS (hadron2017) 040



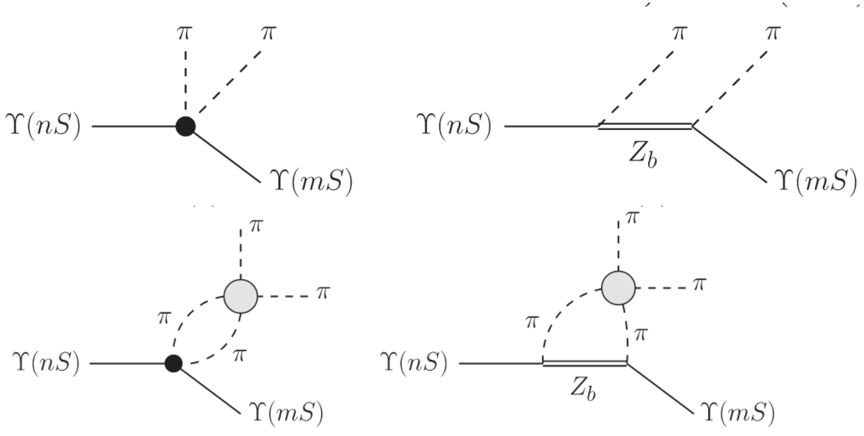
Phys.Rev. D91 (2015) no.7, 072003

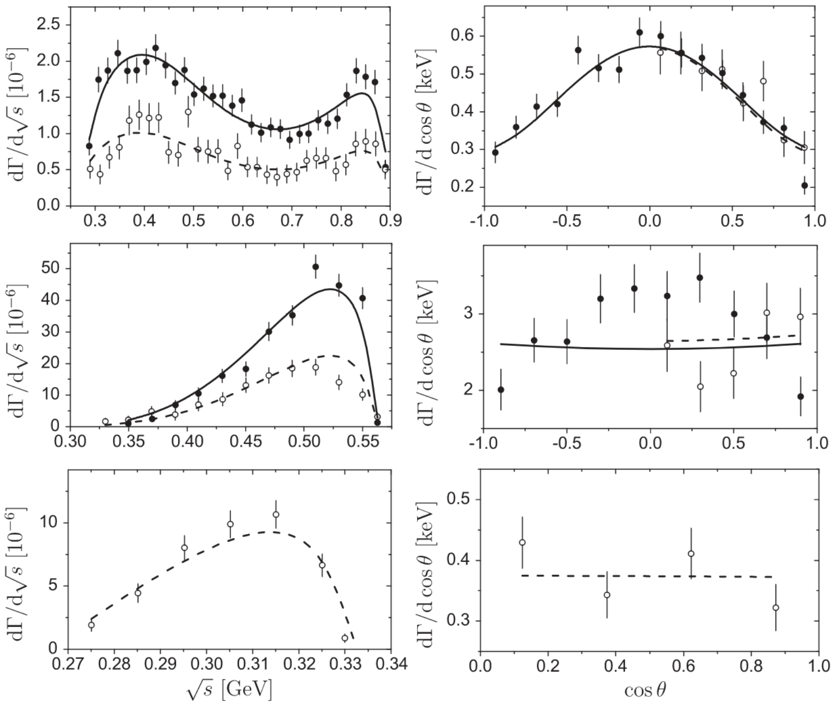


Di-pion transitions

Exotic stats contribute to the hadronic and radiative transitions from narrow quarkonia

Y.H. Chen et al, PRD93 (2016) 034030





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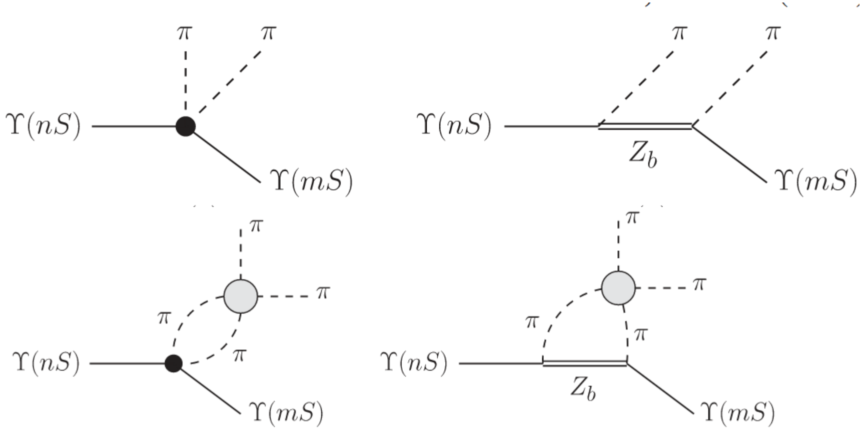
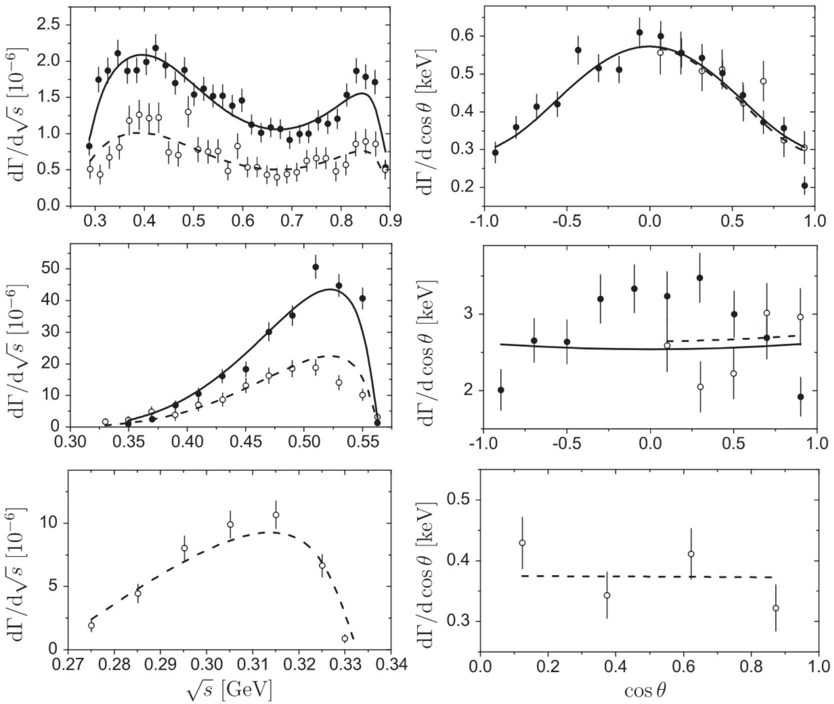




To-do list

Full amplitude analysis of

Y(3S) → ππ Y(1S), Y(2S)

$\chi_b(2P) \rightarrow \pi\pi\ \chi_b(1P)$

LHCb and CMS could contribute here!

Two (or three) ideas to exploit the $\Upsilon(nS)$ annihilations

Υ(nS) annihilations

Υ(nS) annihilations into hadrons are quite peculiar and not very well know

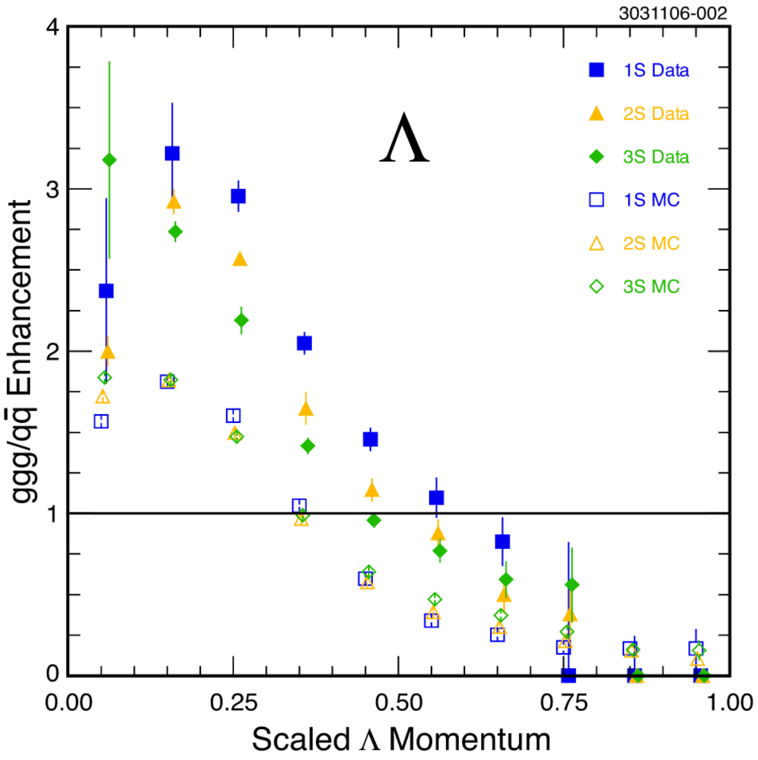
1) Baryon and strangeness enhancement

PRD76 012005 (2007)

CLEO absolute yields

Particle Type	$(ggg)/(q\bar{q})$ [Data]
Λ	$(873600 \pm 1400)/(107300 \pm 600)$
p	$(1399800 \pm 1200)/(295900 \pm 500)$
$\bar{p}$	$(1359500 \pm 1200)/(285400 \pm 500)$
ϕ	$(227900 \pm 1600)/(48300 \pm 800)$
$f_2(1270)$	$(193000 \pm 4000)/(66500 \pm 1800)$

$e^+e^- \rightarrow$ Υ(1S,2S,3S) is a
"low momentum hyperon factory"



Y(nS) annihilations

Y(nS) annihilations into hadrons are quite peculiar and not very well know

1) **Baryon and strangeness enhancement**

PRD76 012005 (2007)

1) **Production of nuclei**

Phys.Rev. D89 (2014) no.11, 111102

Process	**Rate**
$\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$	$(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$	$(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$	$(2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5}$
$\sigma(e^+e^- \to \bar{d}X)$ $[\sqrt{s} \approx 10.58\,\mathrm{GeV}]$	$(9.63 \pm 0.41^{+1.17}_{-1.01})$ fb
$\dfrac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \mathrm{Hadrons})}$	$(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$

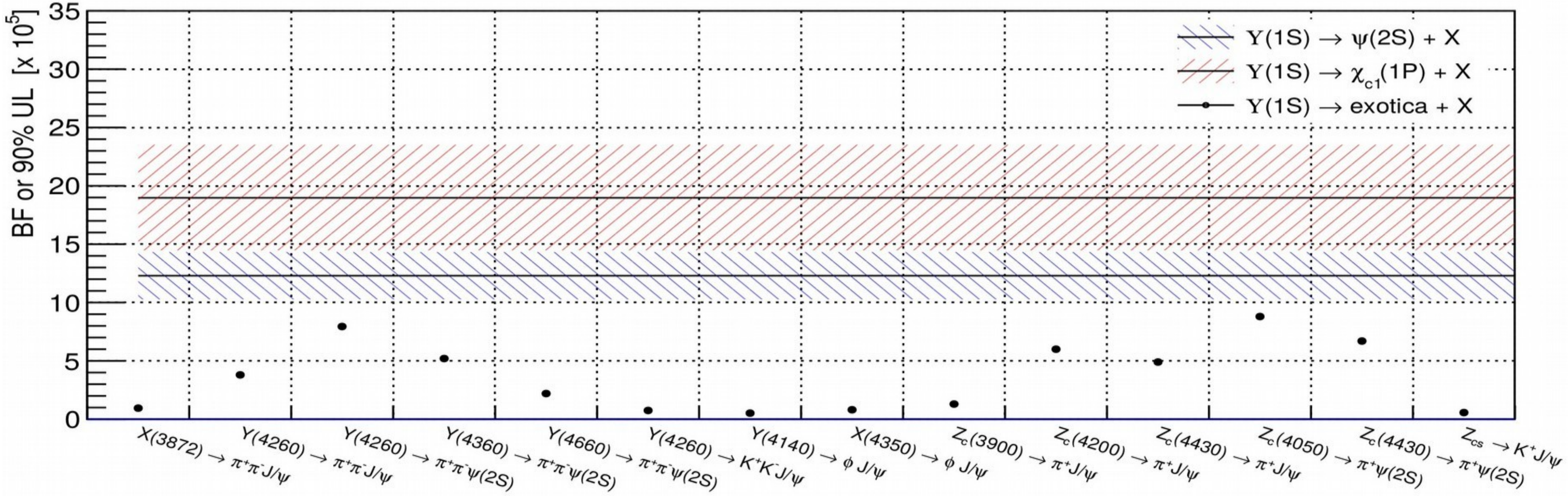
Anti-deuteron is 10 times more abundant in Y(nS) $\to$ ggg than in $e^+e^- \to q\bar{q}$ at the same energy

Idea nr. 1: Y(nS) for exotic charmonia

Lots of observation of exotica, but quite few completely independent confirmations

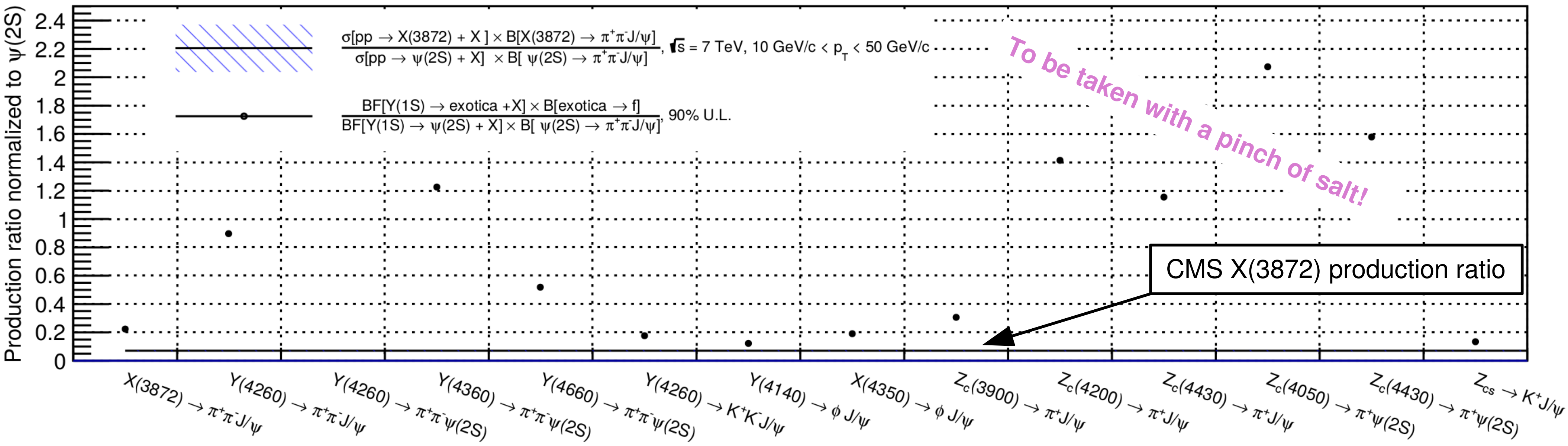
$\rightarrow$ Only X(3872) has been seen in prompt production (in $p\bar{p}$ and pp collisions)

Based on Phys. Rev. D 93, 112013 [Belle]



Idea nr. 1: Υ(nS) for exotic charmonia

A tentative comparison between Belle and CMS.



Belle II prospects with 300 fb^{-1}:

→ 3-5 x sensitivity in inclusive production from Υ(3S)

B[Υ(nS) → X(3872)+had] / B[Υ(nS) → ψ'+had] > 7%

→ 10-15 x sensitivity in double charmonium

Idea nr. 1: Y(nS) for exotic charmonia

BaBar measured a reasonably high production of D* from Y(1S) annihilations

B[Y(nS) $\rightarrow$ D* + X] = 2.5%

Belle II will have:

$\rightarrow$ ~10x the data

$\rightarrow$ Better efficiency at low momenta

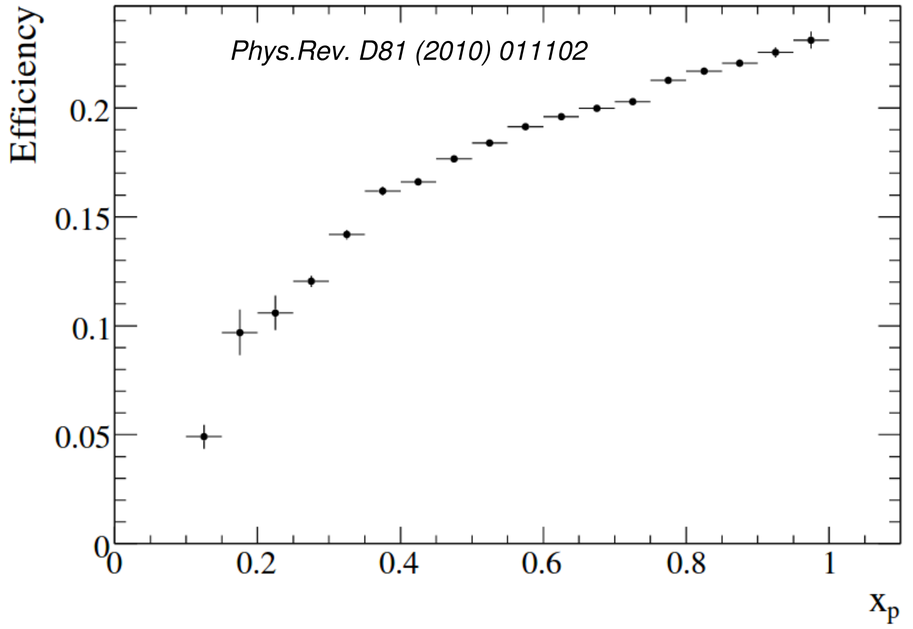


FIG. 3: Reconstruction efficiency for the decay chain $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow D^{*\pm}X$ as a function of the scaled $D^{*\pm}$ momentum x_p.

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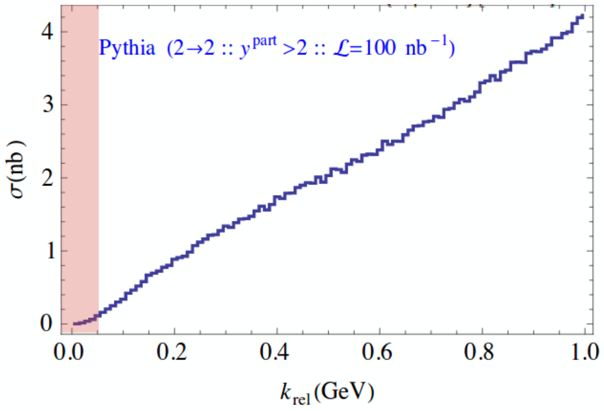
- Production at Colliders speaks against extended objects;
- using Pythia to estimate the probability to find a D-Dbar pair in the relevant phase space, factors of 10^{-2} with respect to the X(3872) cross section measured by CDF (~ 30 nb) are found.

L. Maiani's talk



$\rightarrow$ We can aim for associated DD* and (maybe) DD* correlations

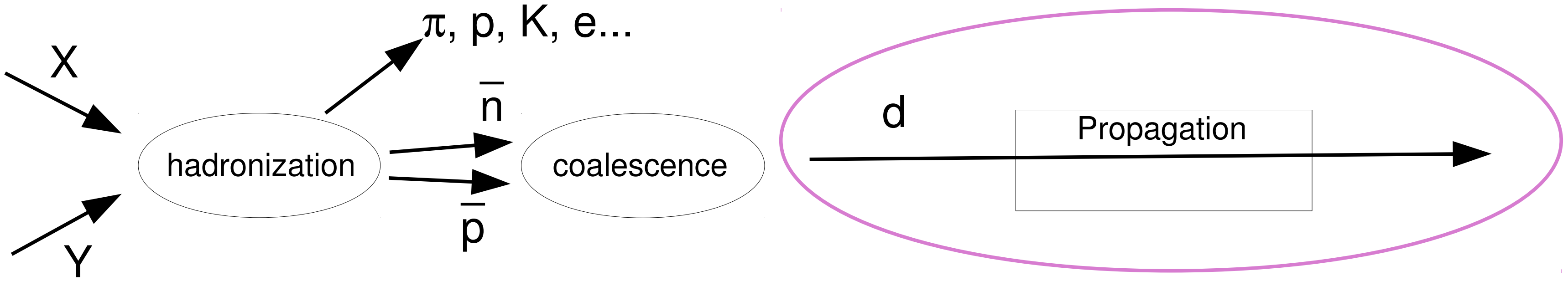
$\rightarrow$ And if we actually observe also the X(3872)…

Idea nr. 2: Bottomonium for astrophysics

Donato, Fornengo, Salati, PRD 62, 043003 (2000)
Aramaki et al. Phys. Rept. 618 (2016) 1-37

$\bar{d}$ detection in cosmic rays is considered since long a probe for low or intermediate mass WIMPs

$\rightarrow$ it's kinematically easier to produce a d from $\chi\chi$ annihilation than from SM processes



Nuclear uncertainties

$\rightarrow$ $\bar{p}$ and $\bar{n}$ production rates

rel. uncertainty ~ 10

$\rightarrow$ $\bar{d}$ production model

rel. uncertainty ~ ~ 50 - 200

Astrophysical uncertainties

$\rightarrow$ Galactic density profile

rel. uncertainty ~ 20

$\rightarrow$ Transport models

rel. uncertainty ~ 500

Idea nr. 2: Bottomonium for astrophysics

Donato, Fornengo, Salati, PRD 62, 043003 (2000)
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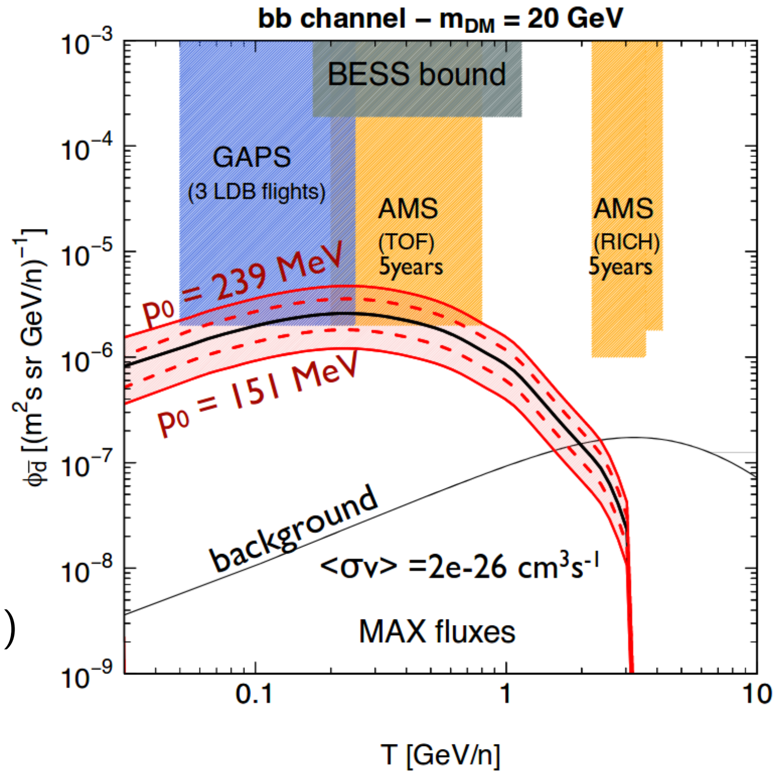
→ Anti-deuteron production is described by **p-n coalescence models tuned on the HEP data**

$$\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6} \frac{m_{\bar{d}}}{m_{\bar{n}} m_{\bar{p}}} \frac{1}{\sqrt{T_{\bar{d}}^2 + 2 m_{\bar{d}} T_{\bar{d}}}} \frac{dN_{\bar{n}}}{dT_{\bar{n}}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}$$



→ Most recent data are from Alice (large final state, MC-driven correction)

→ Strong need to further constrain the $\bar{d}$ production model (new AMS-02 data are coming, **<u>few He3 could have been observed</u>**)

Idea nr. 2: Bottomonium for astrophysics

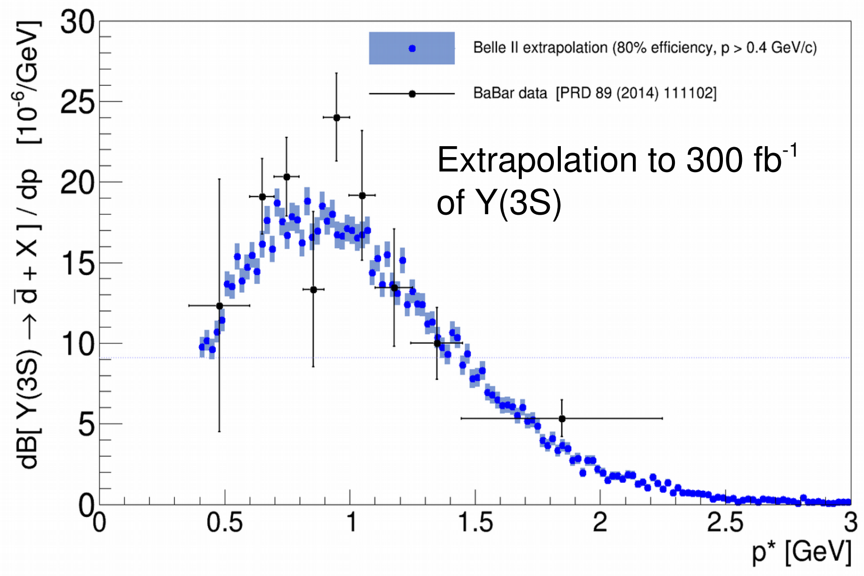
Use the Belle II data to investigate the basic mechanism for d production

→ No final state interaction (complementarity with Alice)

→ Better particle identification than Belle and BaBar

→ Collect ~30000 $\bar{d}$, with dedicated tracking and PID

→ Is coalescence really the whole story?



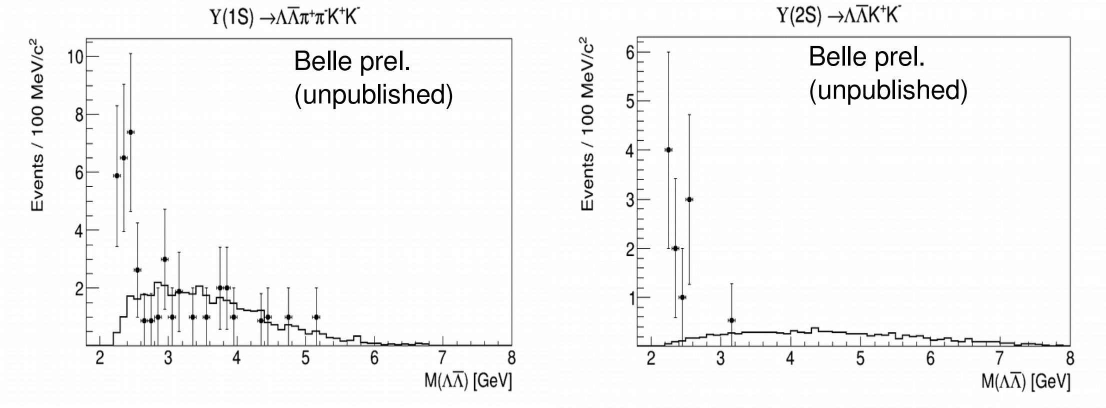
Need for theoretical models!

→ d production models are made for HIC!

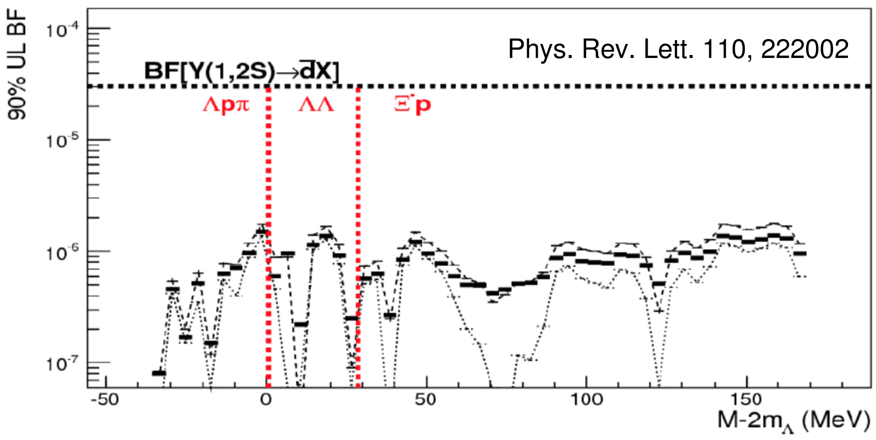
Idea nr. 3: Hyperon-Hyperon interactions

Two results from Belle:

Near-threshold enhancement in exclusive Υ annihilations



No sign of weakly bound H-dibaryon



Rough extrapolation for 300 fb^{-1} Υ(3S)

~60 Million events with one Λ or $\overline{\Lambda}$

~3 Million events with one $\Lambda\overline{\Lambda}$ pair

→ High statistics study near threshold enhancement

→ Stable H di-baryon in missing mass

→ Extract the $\Lambda\Lambda$ potential from correlations?

  → Need for theoretical input on the $\Lambda\Lambda$ correlations in a small volume

Conclusions

This talk was extremely incomplete

$\rightarrow$ Lots of topics has been neglected

The next years can represent our last chance to fully investigate the bottomonium spectrum

$\rightarrow$ Again, lots of topics has been neglected

Hadronic annihilations are a bridge between sectors of low energy QCD that we should exploit

Conclusions

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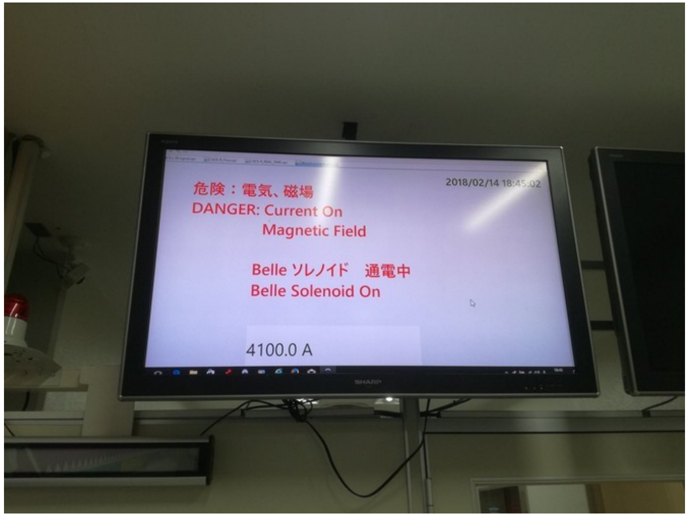
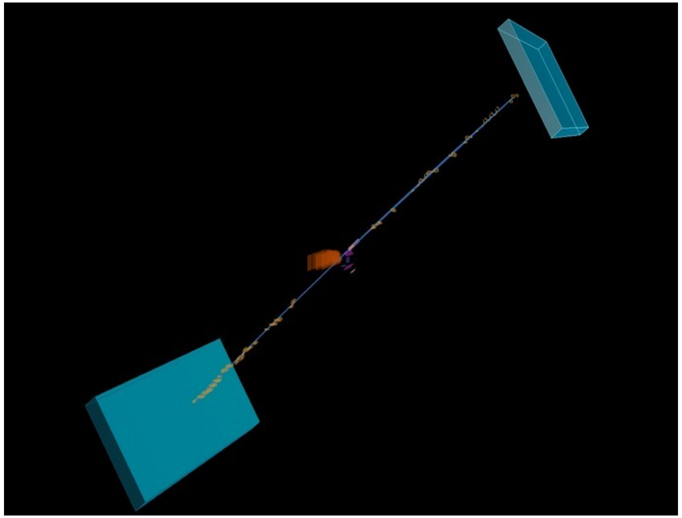
Hadronic annihilations are a bridge between sectors of low energy QCD that we should exploit

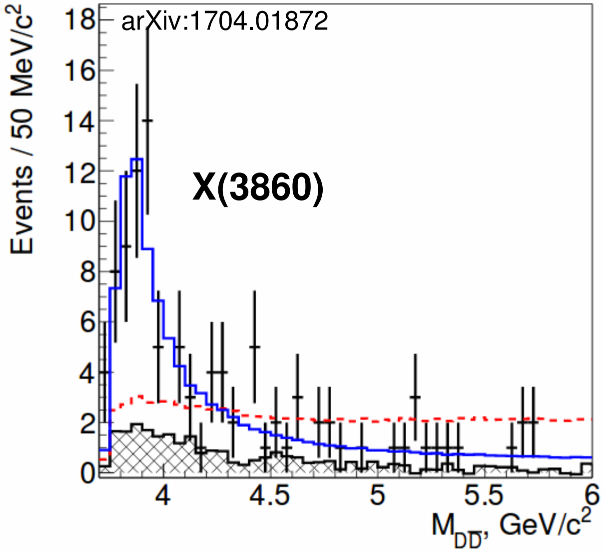




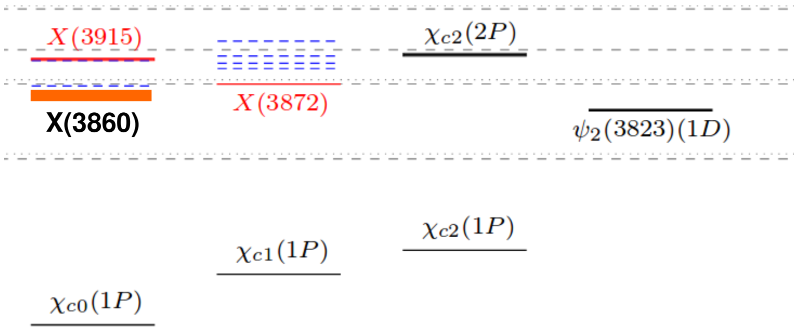
Backup

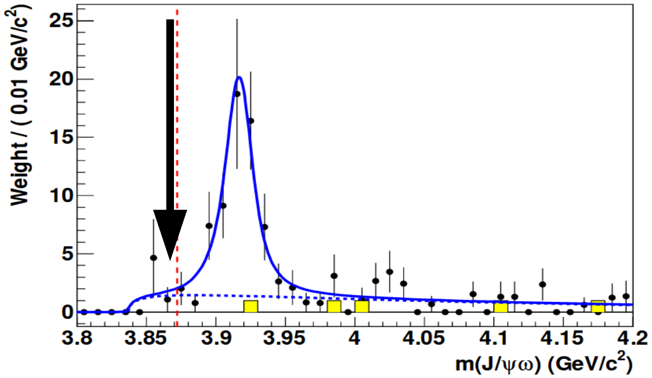
The uniqueness of quarkonia: the X(3915) saga

Belle 2017: New analysis of $e^+e^- \to J/\psi\, D^0\overline{D}^0$: **X(3860)**



χ_{cJ0}(2P) should have:	X(3915)	X(3860)
1) Dominant decay to $D^0\overline{D}^0$	✗	✓
2) Be 80-120 MeV below χ_{cJ2}(2P)	✗	✓
3) $\mathcal{B}(\chi'_{c0} \to \omega J/\psi) < 7.8\%.$	✗	✓

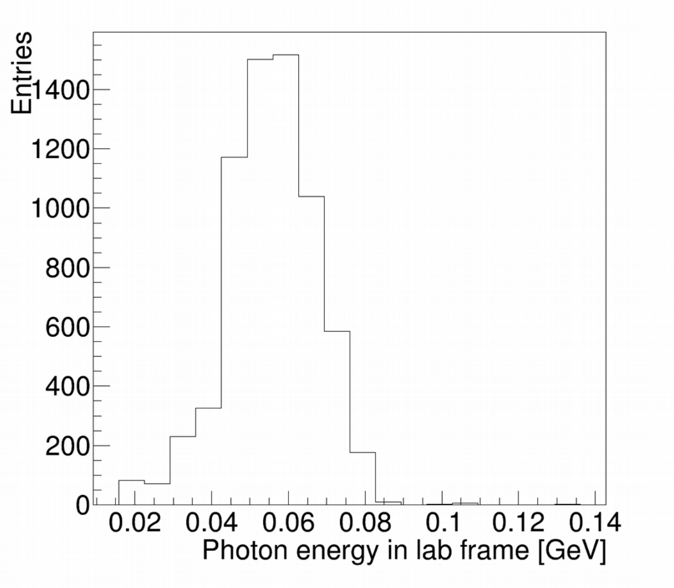


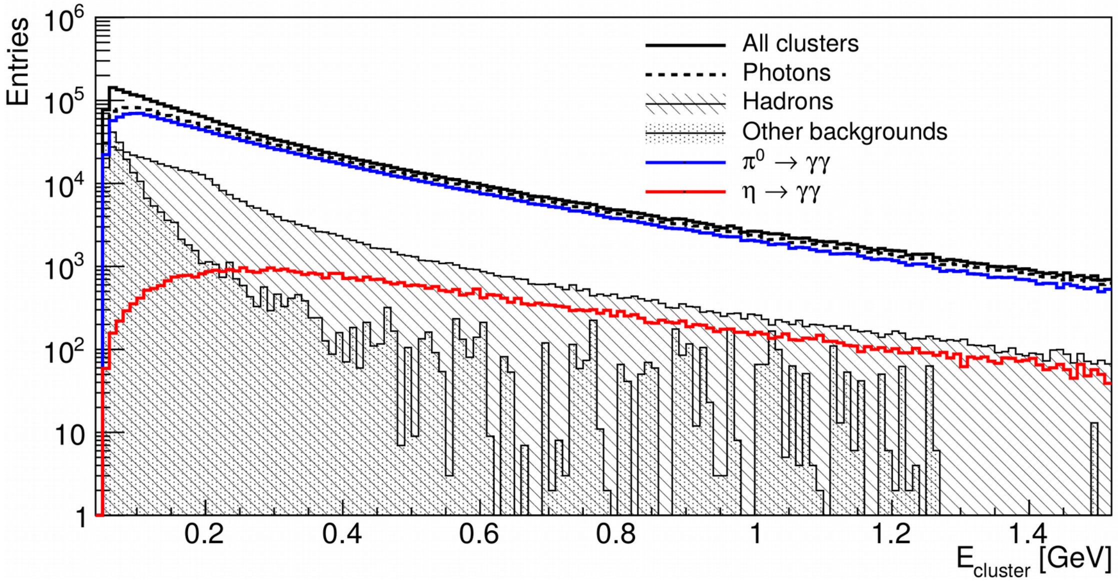


The low-energy radiative transitions

The M1 radiative transition $\Upsilon(1S) \to \eta_b(1S)\gamma$ is the unique electromagnetic decay of $\Upsilon(1S)$ state, which has no experimental information until now.

This is going to be ~~impossible~~ ~~unfeasible~~ ~~just a nightmare~~ very challenging...

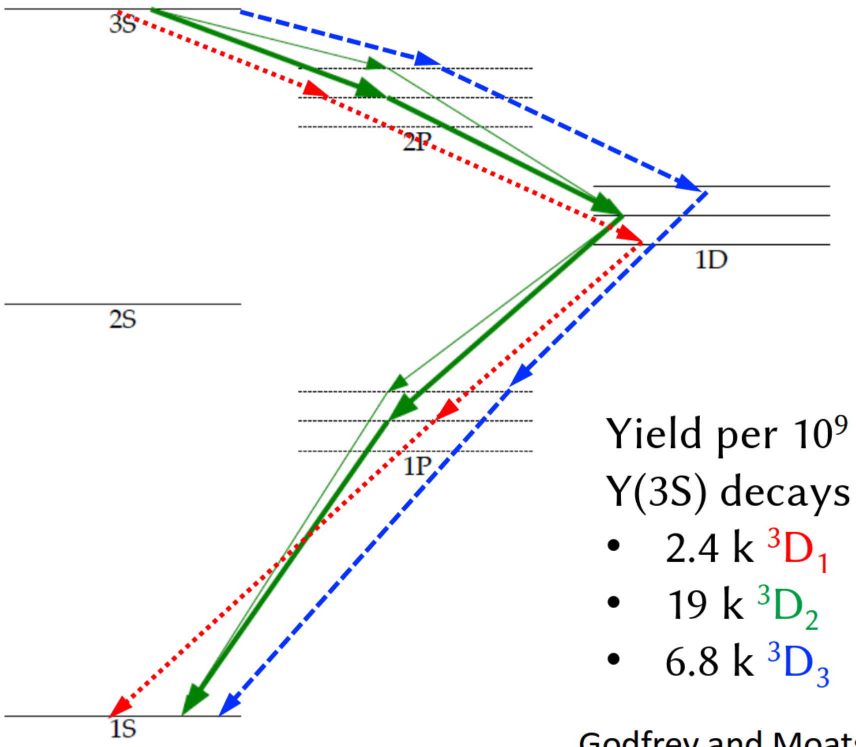




... This of course doesn't mean that we are never going to try do to this analysis

Υ(3S): precision spectroscopy

The components of the Υ(1D) triplet have not been disentagled yet

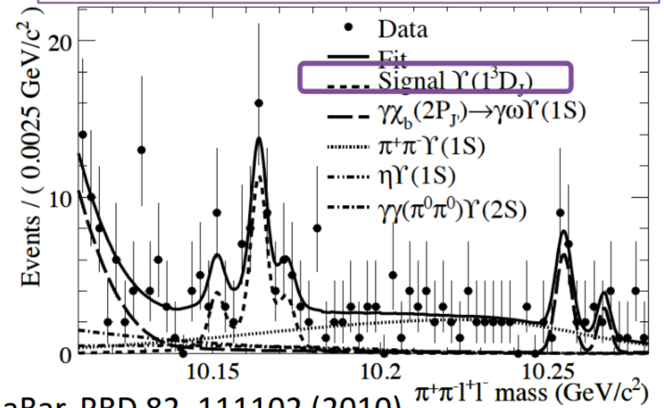


Yield per 10^9 Υ(3S) decays

- 2.4 k $^3D_1$
- 19 k $^3D_2$
- 6.8 k $^3D_3$

Godfrey and Moats, PRD 92, 054034 (2015)

$\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_J) \to \gamma\gamma\pi^+\pi^-\Upsilon(1S)$



BaBar, PRD 82, 111102 (2010)

Belle II prospects with 300 fb^{-1}:

→ Separate the components of the 1D triplet
→ (not shown here) $\eta_b(1S)$ line-shape measurement

Summary and readiness: bottomonium

Competition and complementarity

- **No other experiment, running or planned, can address the open topics in bottomonium physics**
- **Belle II is the last chance we have to make further measurements**
- **>30 unique papers with less than 1 ab^{-1} of data (Υ(3S) and Υ(6S) only)**

CMS energy requirements

- Run at Υ(3S) (200 MeV below nominal energy)
- Run at Υ(6S) (460 MeV above nominal energy)
- Run at Υ(5S) (300 MeV above nominal energy)

Luminosity

- 0.3 ab^{-1} for Υ(3S)
- 0.1 ab^{-1} for Υ(6S)
- 1 ab^{-1} for Υ(5S) (to be used for Bs physics)
- 0.4 ab^{-1} for scans (+ possibility for 20 fb^{-1} in Phase II)
- **These luminosity request are the minimal ones needed to achieve the bottomonium physics program. Any reduction would significantly compromise parts of it, in particular the new physics searches Υ(3S)**

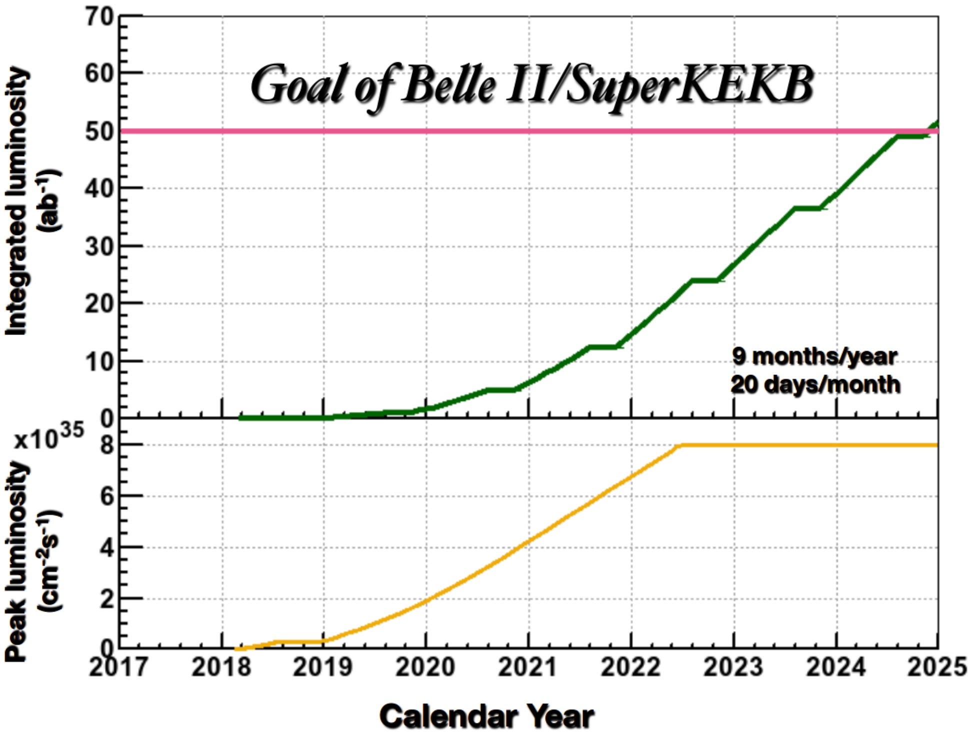
Triggers:

- Special trigger for Υ(1S) → invisible, under development

Summary and readiness: bottomonium

A possible run plan

- Only an hypothesis, still to be discussed with the accelerator group
- Devote the end of each year of data taking to non-Υ(4S) physics (few weeks / year o average, at most)



The Υ(3S) run would require (not including the time needed to change energy and assuming no changes in the luminosity):

$\rightarrow$ few months at 0.5x10^{35} cm^{-2} s^{-1} (~ May 2018)

$\rightarrow$ few weeks at 3x10^{35} cm^{-2} s^{-1} (~ May 2020)

$\rightarrow$ few days at 8x10^{35} cm^{-2} s^{-1} (~ May 2022)

Υ(3S) data should be preferably taken at low luminosity, to fully exploit the di-pion trigger for Υ(1S) $\rightarrow$ invisible

The Υ(6S) scan would require ~2 months independently from the luminosity (40 points, 10 fb^{-1} each)

The Υ(6S) on-resonance would require few days. Possibly split it in 10 fb^{-1} at the very beginning of phase III and the rest afterwards ?

Charmonium at Belle II

Competition and complementarity

- LHCb and BESIII run a parallel program in charmonium physics
- Competition for the vector states (BESIII) and for the $B \to (c\bar{c})\,K$ (LHCb)
- Unique topics: double charmonium (cross section, absolute BF, spectroscopy),
  $\gamma\gamma \to c\bar{c}$ (form factors, spectroscopy)

CMS energy requirements

- The charmonium physics program is part of the Υ(4S) physics program
- Double charmonium, $\gamma\gamma$ fusion and the ISR program can take place at any energy

Luminosity

- No tight requirement for $\gamma\gamma \to c\bar{c}$, precise results starting from 10 ab^{-1}
- As much as possible for double charmonium
- Crucial for ISR and $B \to c\bar{c}\,K$. **Running 6 month/year would pose us significantly beyond BESIII and LHCb.**

Triggers:

- No need for specific triggers, all the final states have several charged tracks

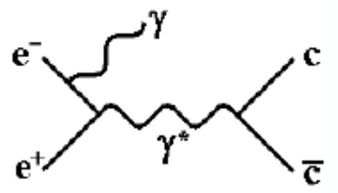
Software:

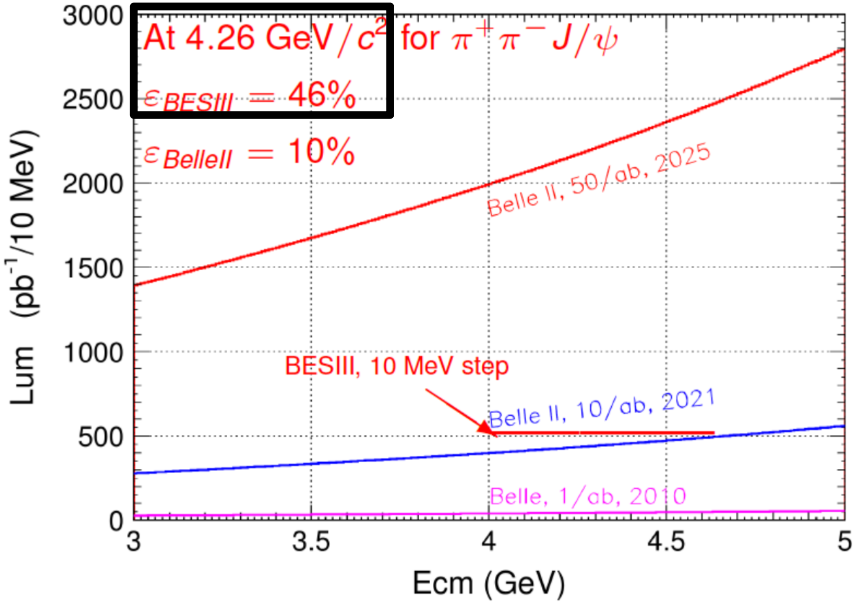
- ISR generators (PHOKARA, KKMC, BABAYAGA...) are part of the generator package
- No need for dedicated analysis or fitting tools

Charmonium in ISR

Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^- \psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$, $Y(4390)$, $Z_c(4020)$, $Z_c(4025)$
$\omega\chi_{c0}$	4.23	35 (15)	$Y(4220)$

10 ab^{-1} 50 ab^{-1}





Belle II prospects:

→ **At 50 ab^{-1}, Belle II would match BESIII on a wider spectrum**

→ Line-shape of the Y(4260)

→ Strange partner of the Z(3900) in KKJ/ψ

→ Cross sections of exclusive ($c\bar{c}$) + hadrons

Bottomonium at Belle II

Current samples in fb^{-1} (millions of events), and the proposal for Belle II

Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
BelleII	-	-	300 (1200)	5×10^4 (5.4×10^4)	1000 (300)	100+400(scan)	3.6%

1.6% for bottomonium only

- Narrow states spectroscopy (Y(1D), χ_b(nP)...)
- **Exotica as virtual contributions to transitions**
- Precision NRQCD test
- **New Physics (DM / light higgs)**
- Missing hadronic and radiative transitions
- Baryon physics (inc. correlations)
- **Anti-nuclei production (with DM applications)**
- Gluon fragmentation
- **Inclusive charmonium production** and $D\bar{D}$ correlations
- LFV and LUV in Y(nS) decays

- Bs physics
- **Exotica discovery**
- Precision Zb mass measurement
- Missing hadronic and radiative transitions
- **Light meson spectroscopy in transitions**

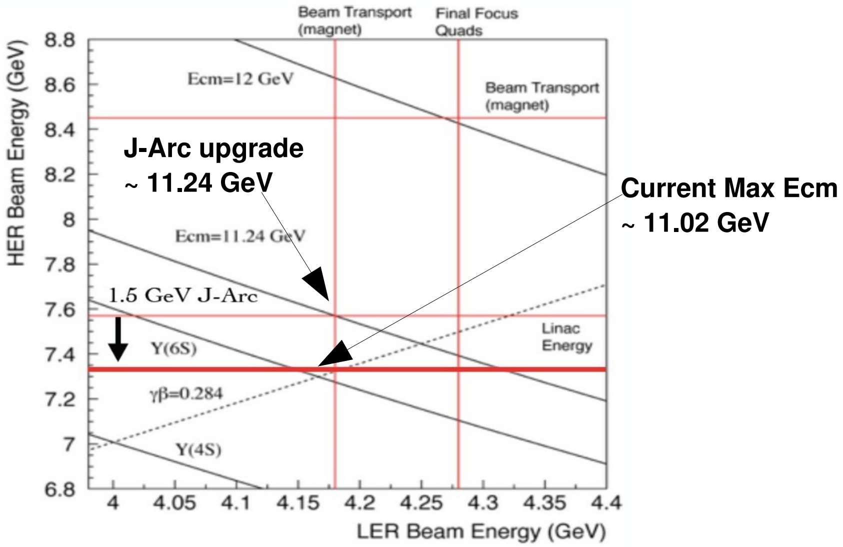
- **Exotica discovery**
- **Y(5S-6S) lineshape**

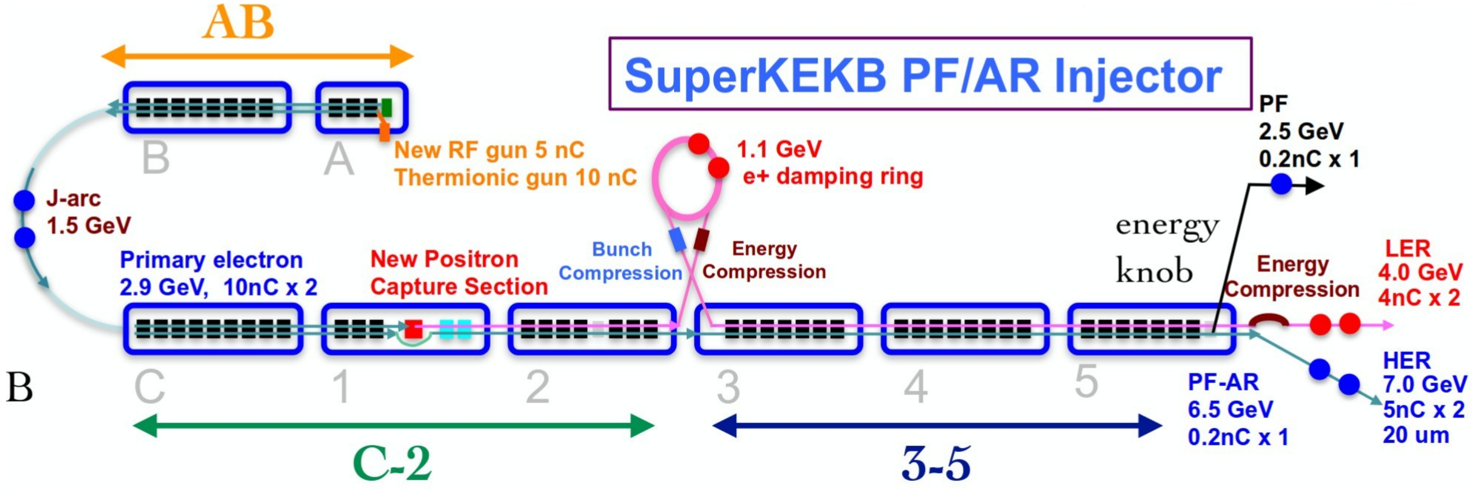
Accelerator requirements for bottomonium

→ Present max E_{cm} = ~ 11.02 GeV, a bit above Υ(6S)

→ Need to run safely at this energy

→ Would greatly profit from a linac upgrade to reach 11.24 GeV (see next slide)



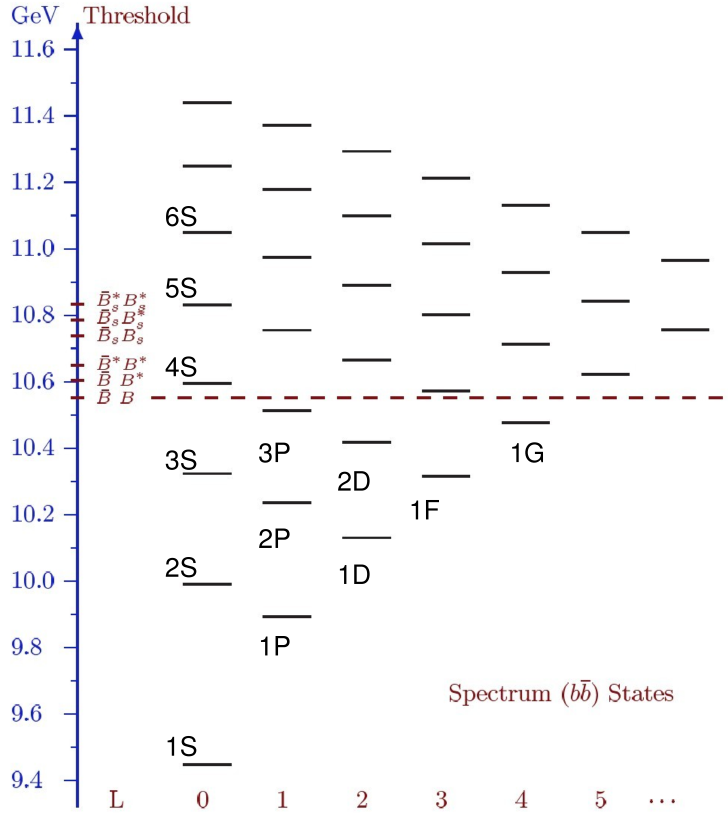


Y(6S) on-resonance run: conventional

→ Y(5S)-Y(6S) are portals to the missing narrow states

→ Y(5S) → η Y(1D) is the largest Y(5S), single-meson transition

→ The conventional spectrum gets contributions from the couple channel effect (again, light quarks...)



Mod. Phys. Lett. A 32, 1750025 (2017)

Name	L	S	J^{PC}	Emitted hadrons [Threshold, GeV/c^2]
$\eta_b(3S)$	0	0	0^{-+}	ω [11.12], ϕ [11.36]
$h_b(3P)$	1	0	1^{+-}	$\pi^+\pi^-$ [10.82], η [11.09], η' [11.50]
$\eta_{b2}(1D)$	2	0	2^{-+}	ω [10.93], ϕ [11.17]
$\eta_{b2}(2D)$	2	0	2^{-+}	ω [11.23], ϕ [11.47]
$\Upsilon_J(2D)$	2	1	$(1,2,3)^{--}$	$\pi^+\pi^-$ [10.73], η [11.00], η' [11.41]
$h_{b3}(1F)$	3	0	3^{+-}	$\pi^+\pi^-$ [10.63], η [10.90], η' [11.31]
$\chi_{bJ}(1F)$	3	1	$(2,3,4)^{++}$	ω [11.14], ϕ [11.38]
$\eta_{b4}(1G)$	4	0	4^{-+}	ω [11.31], ϕ [11.55]
$\Upsilon_J(1G)$	4	1	$(3,4,5)^{--}$	$\pi^+\pi^-$ [10.81], η [11.08], η' [11.49]

Belle II goals:

→ Search for new, predicted, resonances

→ Use both single transitions and double cascades

→ Fill the remaining spectrum to measure the effects of the coupled channels contributions

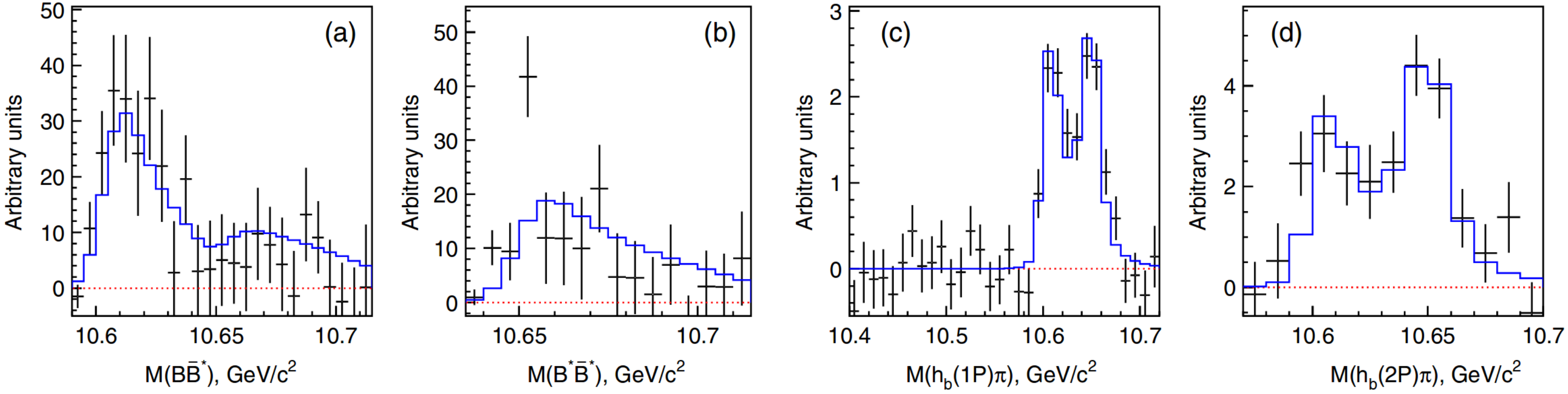
$\Upsilon(5S)$: Zb masses

The measurement of the Zb masses is foundamental to determine their nature: are they above or below the $B^{(*)}B^*$ thresholds?

$\rightarrow$ Equivalent to the X(3872) mass problem: above or below the open threshold?

Phys. Rev. D 93, 074031 (2016)

B



Current best estimate of the Zb location with respect to the thresholds:

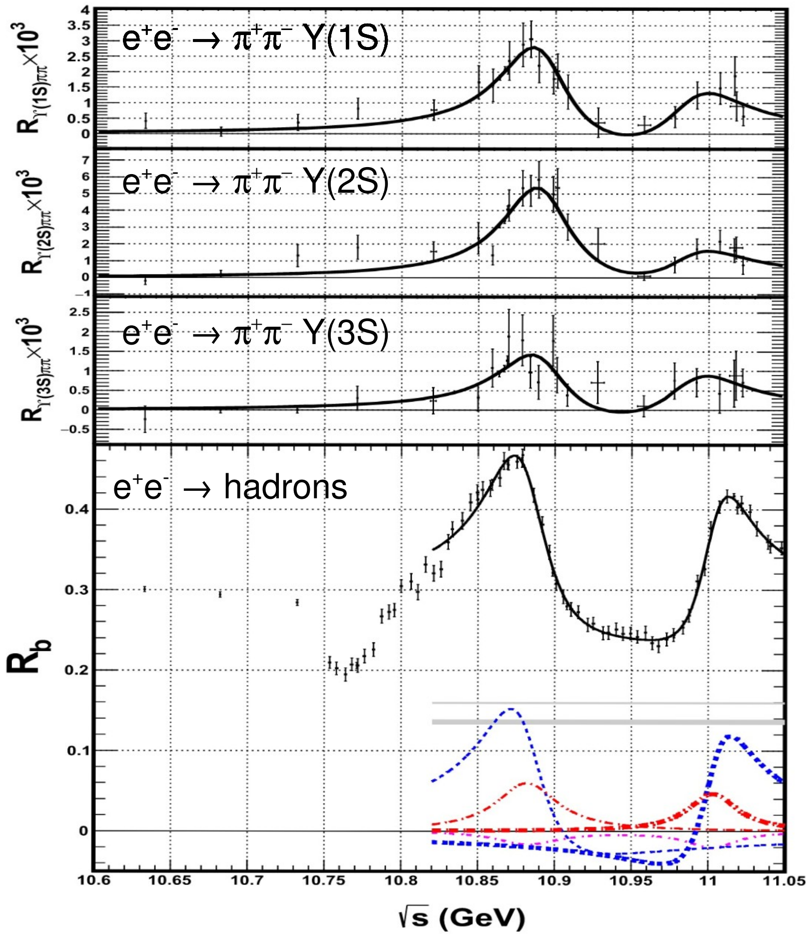
$$\varepsilon_B(Z_b) = (0.60^{+1.40}_{-0.49} \pm i0.02^{+0.02}_{-0.01})\ \text{MeV},$$
$$\varepsilon_B(Z_b{}') = (0.97^{+1.42}_{-0.68} \pm i0.84^{+0.22}_{-0.34})\ \text{MeV},$$

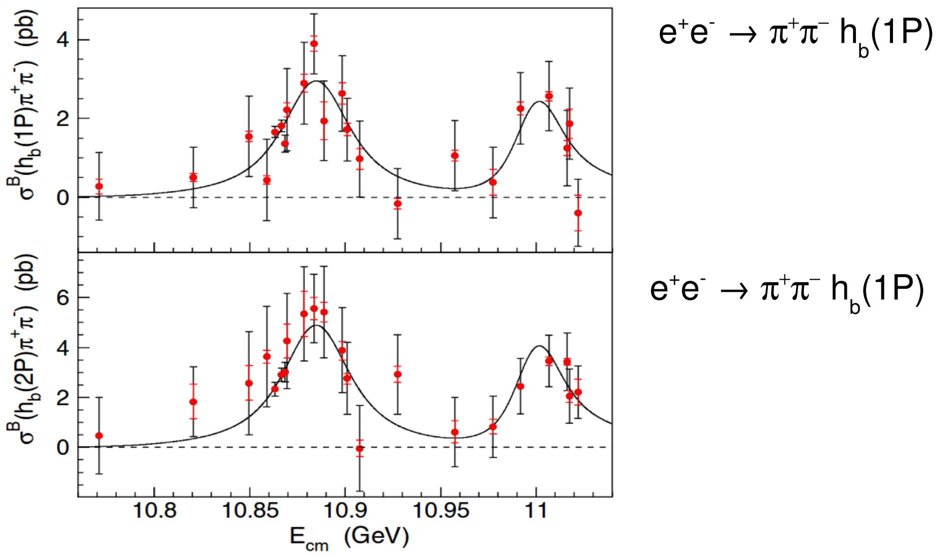
Belle II Goals:

$\rightarrow$ Determine if the Zb are located above or below the open flavour threshold using 1 ab^{-1} of $\Upsilon(5S)$

Y(5S) - Y(6S) scan

Phys. Rev. D 93, 011101 (2016)





Belle II scan goal:

→ Investigate the presence of a broad resonance at 10.750 GeV
→ 10 MeV wide steps, 10 fb^{-1} each (10x Belle scan)
→ Y(5S) and Y(6S) line-shapes in R, $R_{\Upsilon\pi\pi}$ and $R_{h\pi\pi}$
→ Rb decomposition (BB, BB*, B*B*, BB*π, B*B*π, BsBs ...)
→ Overall goal: settle the nature of the Y(5S)

$\Upsilon(3S)$: rare χ_b decays

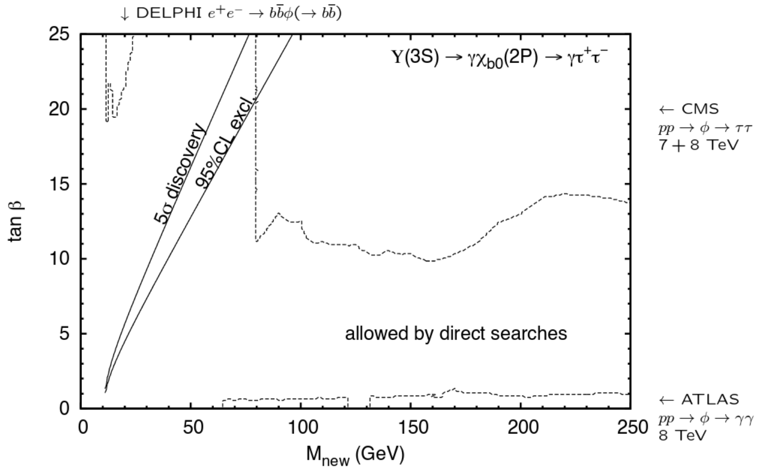
Godfrey and Logan, Phys. Rev. D 93, 055014 (2016)

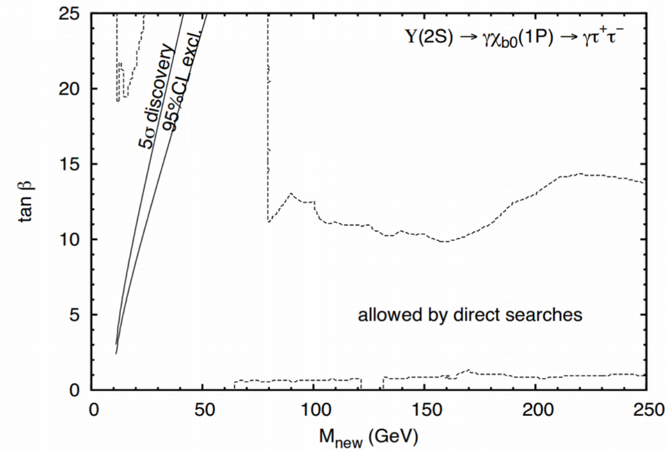
$\chi_b(2P) \rightarrow \tau\tau$ is sensitive to the presence of a CP-even light Higgs (as $B \rightarrow \tau\tau$, $B \rightarrow \tau\nu$...)

$$\left.\begin{array}{l}\mathrm{BR}^H(\chi_{b0}(1P) \to \tau\tau) = 3.1 \times 10^{-13} \\ \mathrm{BR}^H(\chi_{b0}(2P) \to \tau\tau) = (1.9 \pm 0.5) \times 10^{-12}\end{array}\right\} \times \left[1 + \frac{M_{H125}^2 \tan^2\beta}{M_{\mathrm{new}}^2 - M_{\chi_{b0}}^2}\right]^2$$

Will only need $(M_{H_{125}}/M_{H_{\mathrm{new}}}) \tan\beta \sim 30$ for $\mathcal{O}(100)$ signal events in $\Upsilon(3S) \to \gamma\chi_{b0}(2P) \to \gamma\tau\tau$

Results: $\Upsilon(3S)$





Belle II goals:

→ $\chi_{b0}(2P, 1P) \rightarrow \gamma\tau\tau$ inclusive

→ $\chi_{b0}(2P, 1P) \rightarrow \gamma\tau\tau$ per exclusive final state

→ MC studies ongoing

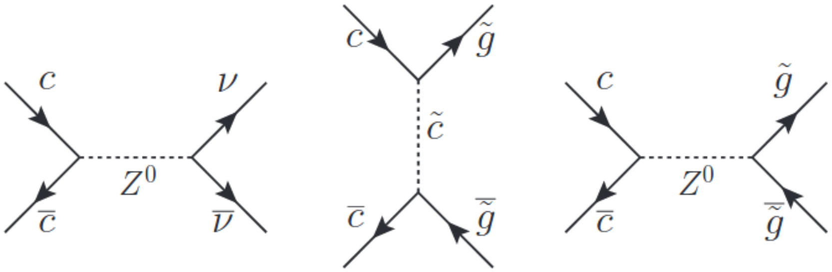
$\Upsilon(1S) \to invisible$

$\Upsilon(1S) \to$ invisible is well calculable in the SM

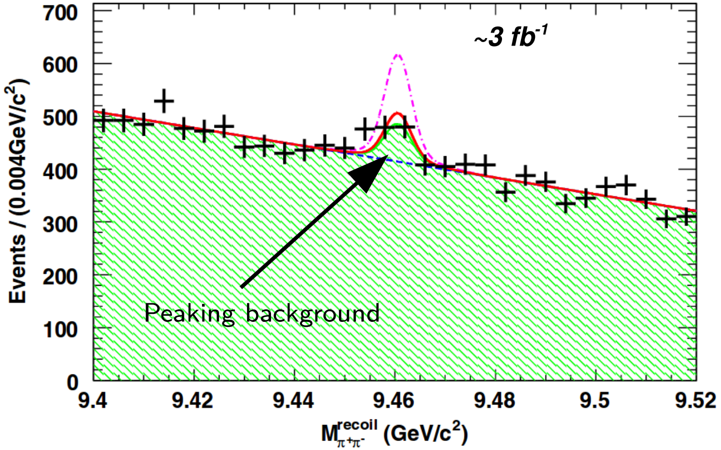
$$\frac{BR(\Upsilon(1S)\to\nu\bar{\nu})}{BR(\Upsilon(1S)\to e^+e^-)} = \frac{27G^2M^4_{\Upsilon(1S)}}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2 = 4.14\times10^{-4}$$

$$BR(\Upsilon(1S)\to\nu\bar{\nu}) \sim 9.9\times10^{-6}$$

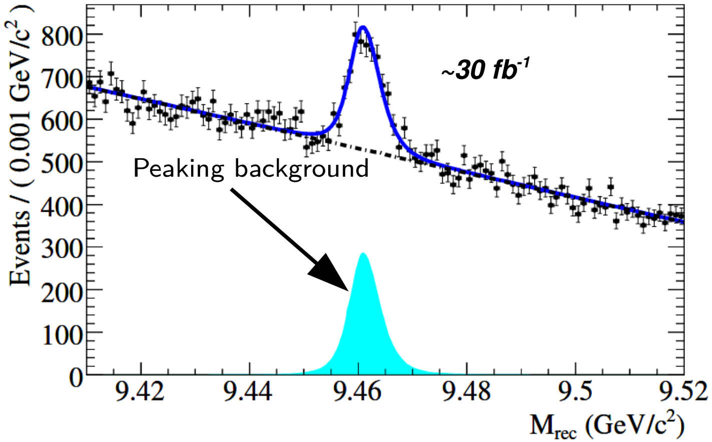
Non-SM contributions from $\Upsilon(1S) \to \chi\chi$



Belle: Phys. Rev. Lett. 98 (2007) 132001



BaBar, Phys. Rev. Lett. 103, 251801 (2009)



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Non-SM contributions from $\Upsilon(1S) \to \chi\chi$

Belle: Phys.Rev.Lett. 98 (2007) 132001

Source	(%)	
Track selection	5.6	
π^0 veto	2.4	
Fisher discriminant	6.1	
Other selection requirements	1.1	
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	7.6	4% in BaBar
Trigger efficiency	8.7	
Fit bias	0.2	
Statistics of control sample	1.4	
$\mathcal{B}(\Upsilon \to \mu^+\mu^-)$	2.0	
Total	14.7	

Belle II prospects

→ 10x dataset w/ respect to BaBar

→ Sensitivity ~1 x 10^{-4} on the BF

→ Reduce the systematic with precision measurement of the pp and gg transitions

→ Trigger is crucial: capability to trigger on 2p + missing energy depends on the BG levels and luminosity

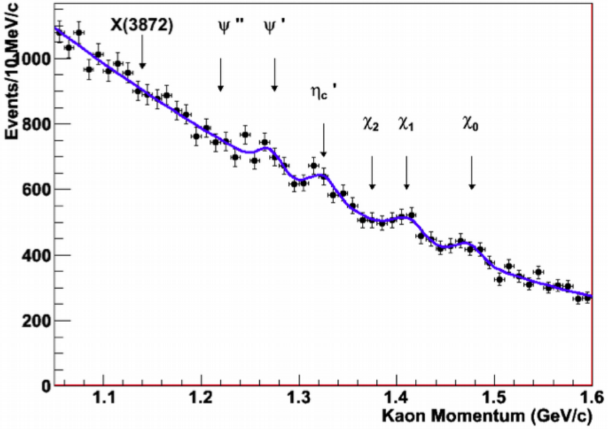
Charmonium from B decay

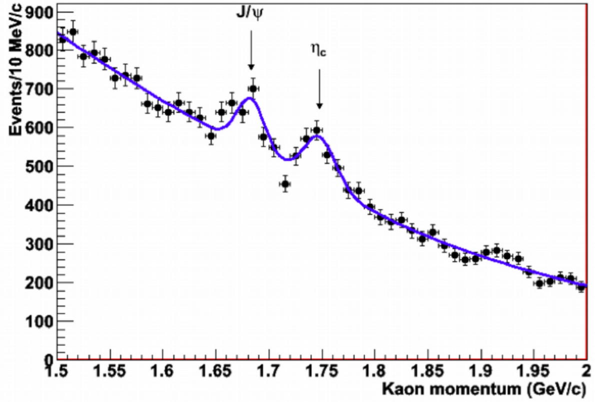
$B \rightarrow K\ (c\bar{c}) \rightarrow K$ (hadrons, hadrons + $\mu\mu$, $n\gamma + \mu\mu$)

$\rightarrow$ Competitive in neutral transitions ($Xc\bar{c} \rightarrow \eta$, π^0, $\omega\ J/\psi$)

$\rightarrow$ Competitive for finals states with large multiplicities (h_c and η_c)

$\rightarrow$ Unique opportunity for inclusive measurements





Belle II prospects:

$\rightarrow$ Discover the η_{c2}(2D), last narrow charmonium missing in $B \rightarrow K\ \gamma\ h_c$

$\rightarrow$ Comprehensive study of $B \rightarrow K\ D\bar{D}$, $KD\bar{D}^*$, $KD^*\bar{D}^*$, $K\bar{D}D^{**}$, $K\bar{D}^*D^{**}$

$\Upsilon(3S)$: $\pi\pi$ scattering length

At low energy the $\pi\pi$ interaction is described by two scattering lengths who vanish in the chiral limit:

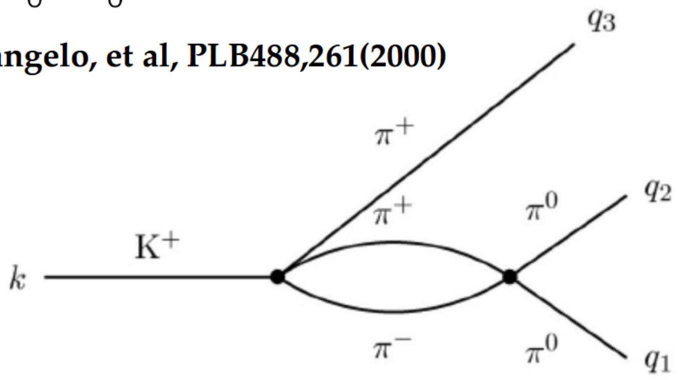
$$a_0^0 = \frac{7M_\pi^2}{32\pi F_\pi^2} + \mathcal{O}(m_q^2) \qquad a_0^2 = -\frac{M_\pi^2}{16\pi F_\pi^2} + \mathcal{O}(m_q^2)$$

Weinberg, PRL17,616(1966)

Using ChPT, theory predicts:

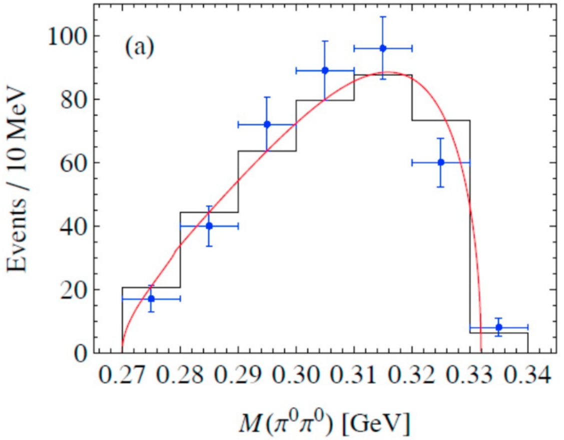
$$a_0^0 - a_0^2 = 0.265 \pm 0.004$$

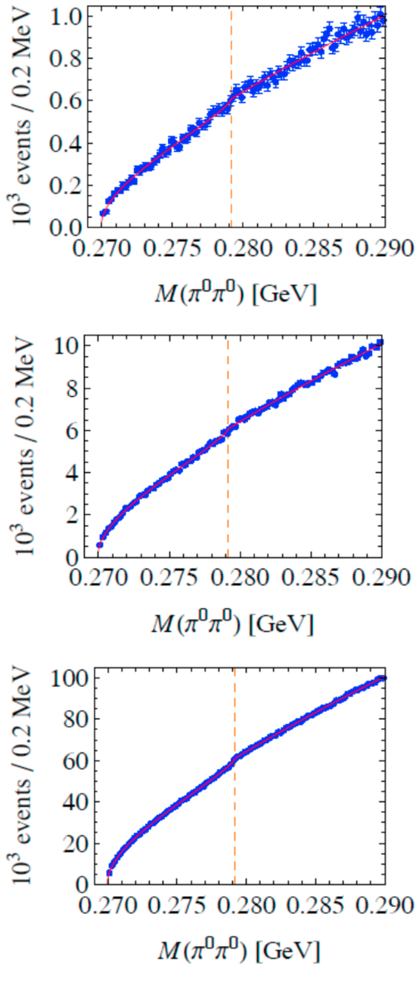
Colangelo, et al, PLB488,261(2000)



Q-value for Y(3S) → ππ Y(2S) is only 50 MeV

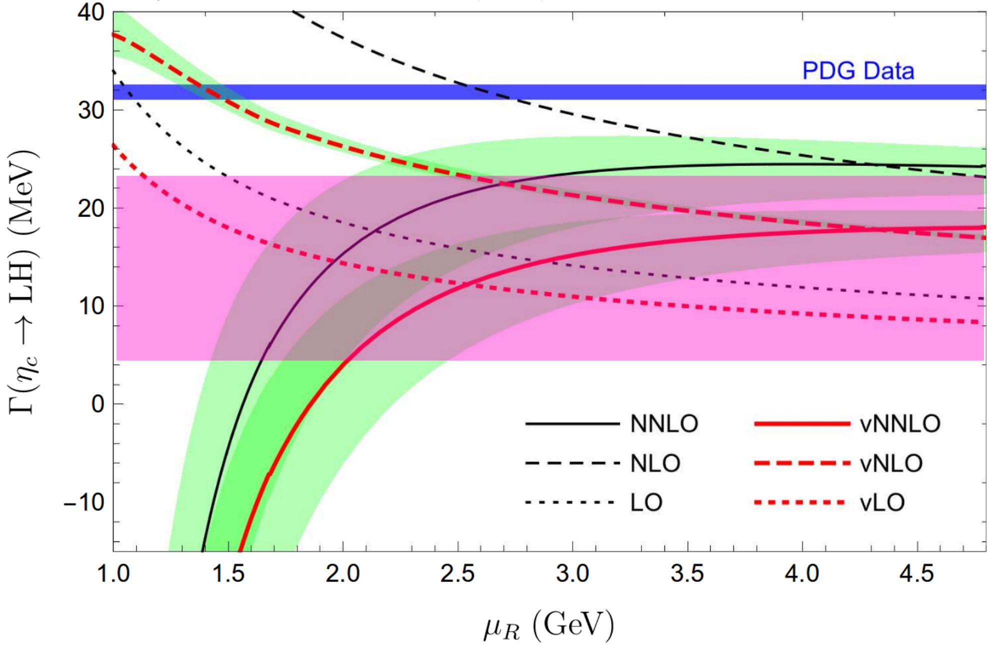
Liu et al,EPJC73, 2284 (2013)





The η_c width conundrum

Phys. Rev. Lett. 119, 252001 (2017)



What do I understand from this?

→ NNLO is still not enough

→ Is NRQCD converging fast enough?

→ The problem is not in the experimental resolution

A funny coincidence: what happens if we take the measurements done with M1 naive fit?

11.5 ± 4.5	GAISER	1986	CBAL	$J/\psi \to \gamma$ X, $\psi(2S) \to \gamma$ X
$11.0 \pm 8.1 \pm 4.1$	12 BAI	2000F	BES	$J/\psi \to \gamma\eta_c$ and $\psi(2S) \to \gamma\eta_c$
$17.0 \pm 3.7 \pm 7.4$	10 BAI	2003	BES	$J/\psi \to \gamma\eta_c$