Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Belle II

Plans for exotic bottomonium-like states at Belle II

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INFN - Sezione di Torino

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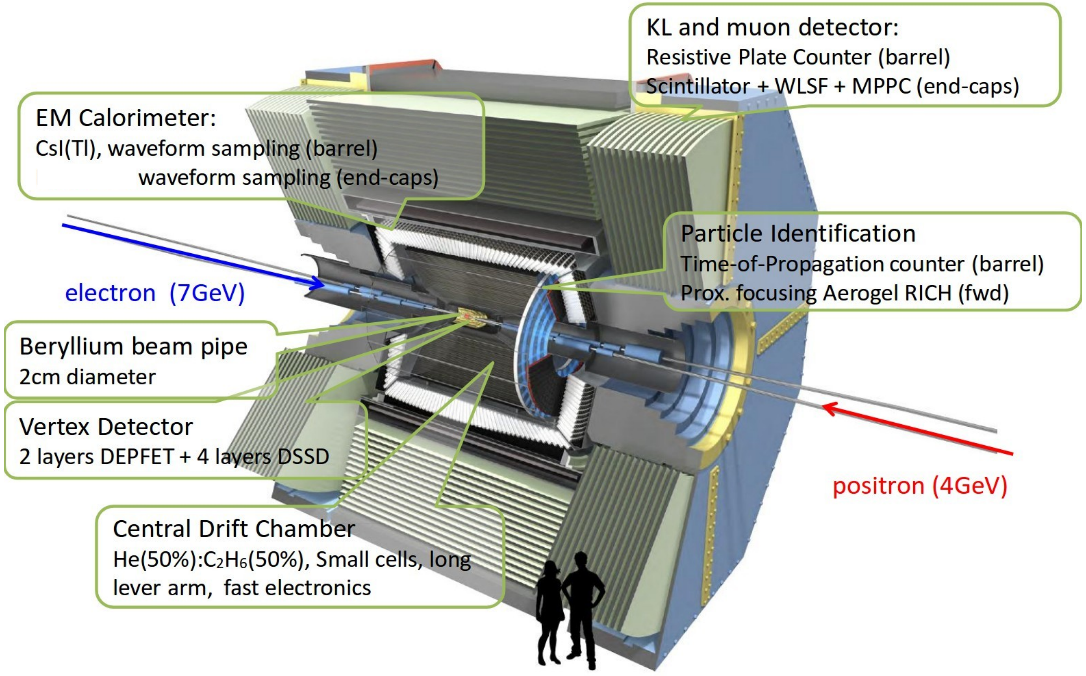
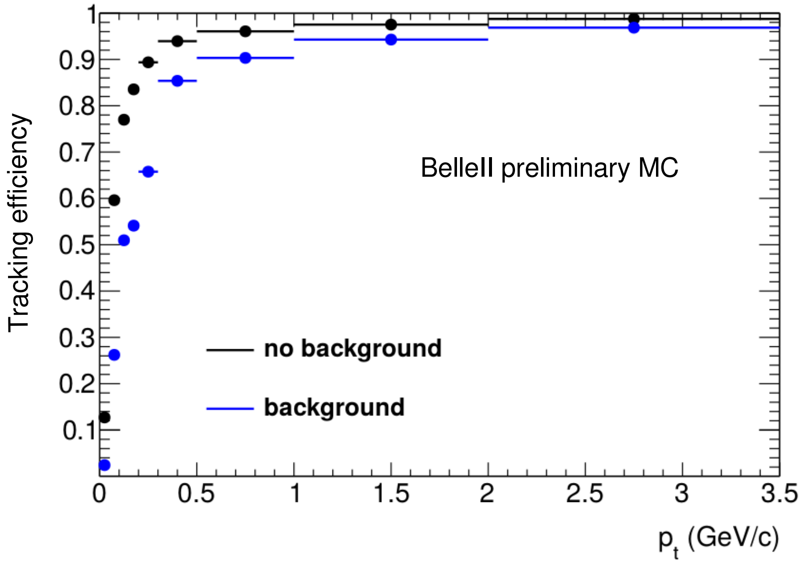
Part I. Accelerator and Detector

Belle II : the detector





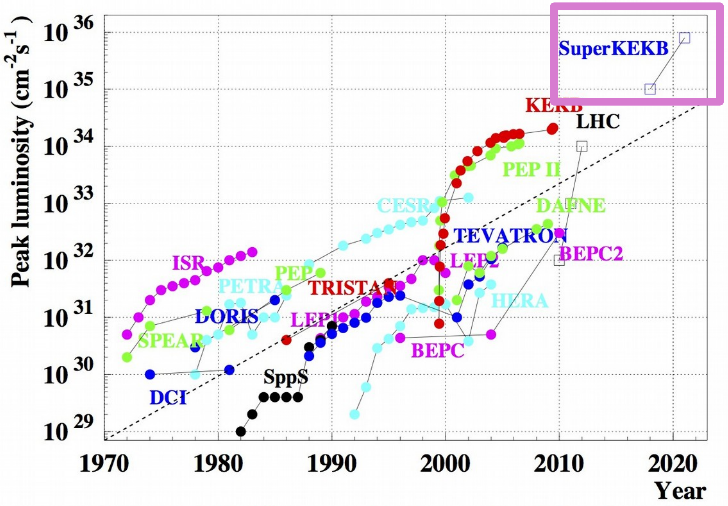
Translated into performances for ππ transitions...

Channel	BaBar	BelleII	BaBar	BelleII
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$	≈ 4 MeV/c^2	2.5 MeV/c^2	17%	45%
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	≤ 4 MeV/c^2	1.8 MeV/c^2	42%	63%

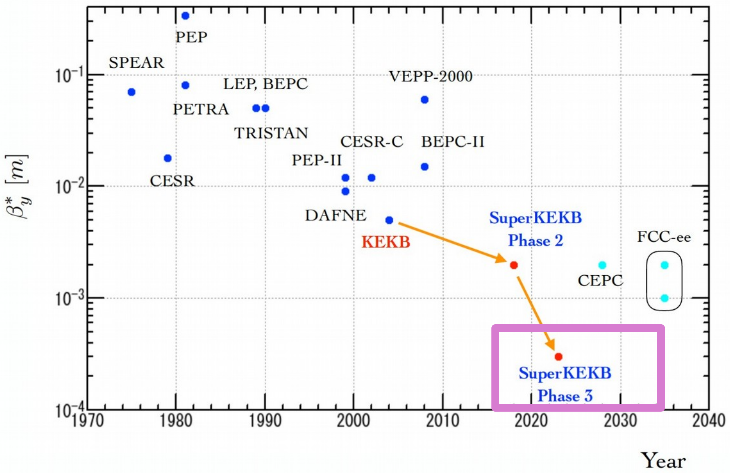
BaBar: Phys. Rev. D 84, 011104 (2011)
BelleII: preliminary MC

Super-KEKB

Super-KEKB aims for **8 x 10^{35} cm^{-2} s^{-1}**

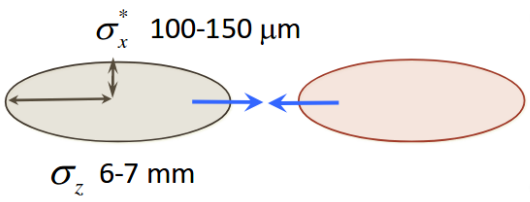


SuperKEKB will try to make the smallest β_y* in the world !



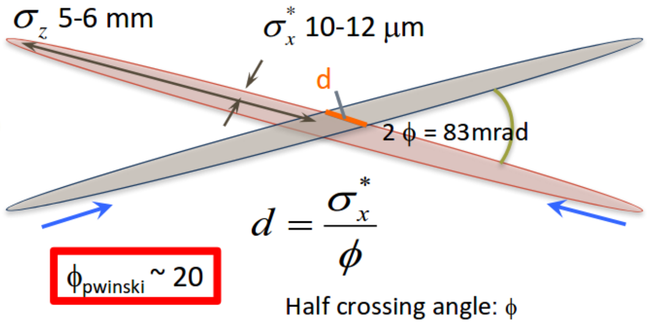
P. Raimondi

KEKB head-on (crab crossing)



interaction region = bunch length

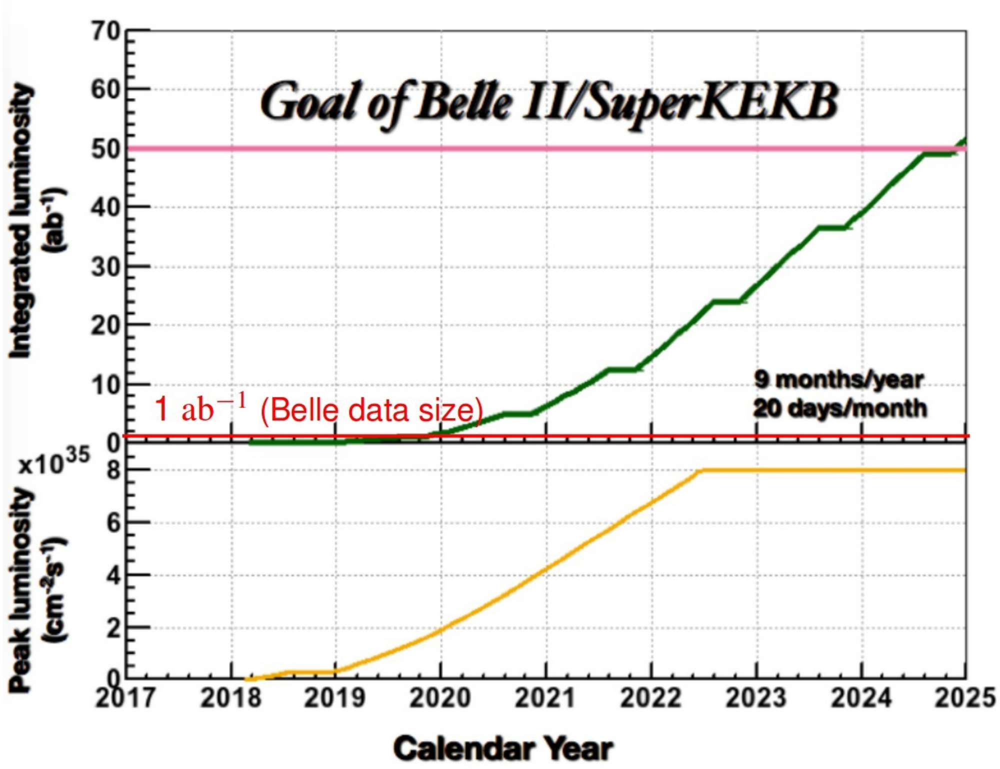
Nano-Beam Scheme SuperKEKB



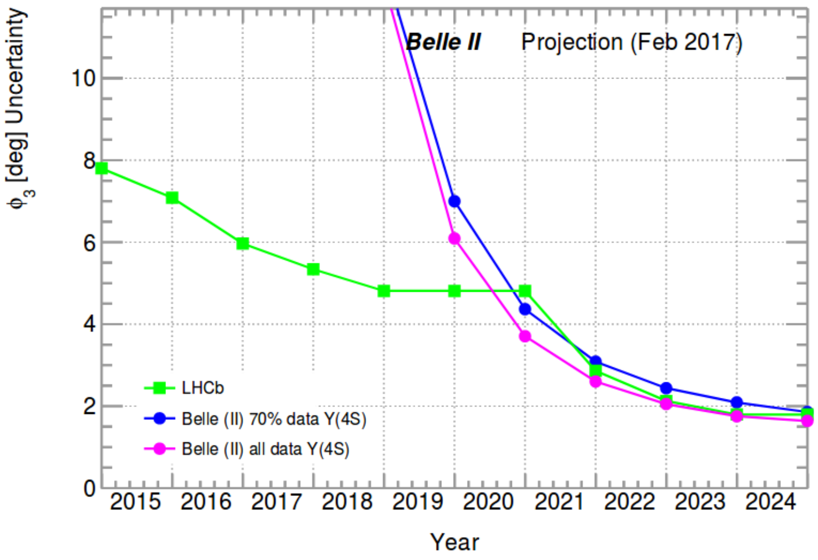
interaction region << bunch length

Super-KEKB

Super-KEKB aims for **8 x 10^{35} cm^{-2} s^{-1}**



Competition with LHCb is quite pressing!

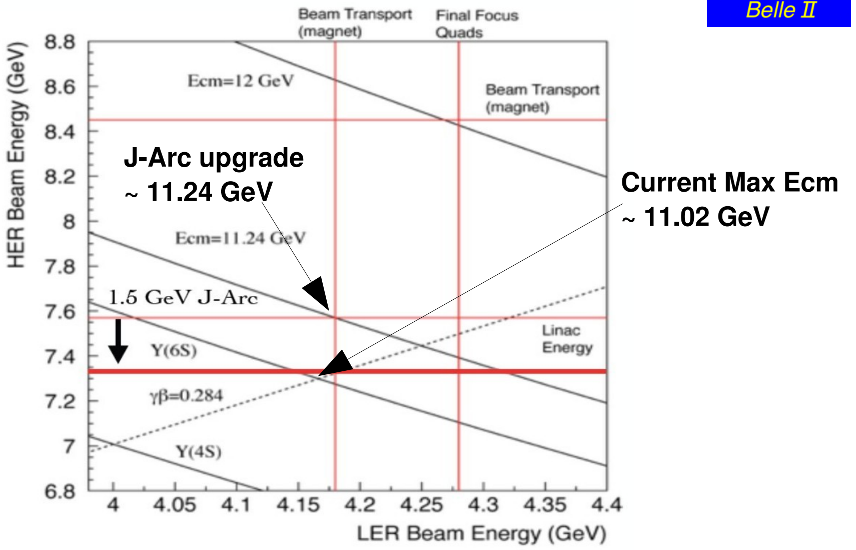


A reasonable non-Y(4S) request:

1 ab^{-1} @ Y(5S)
100 fb^{-1} @ Y(6S)
300 fb^{-1} @ Y(3S) (1.2 Billions)
400 fb^{-1} scan (?)

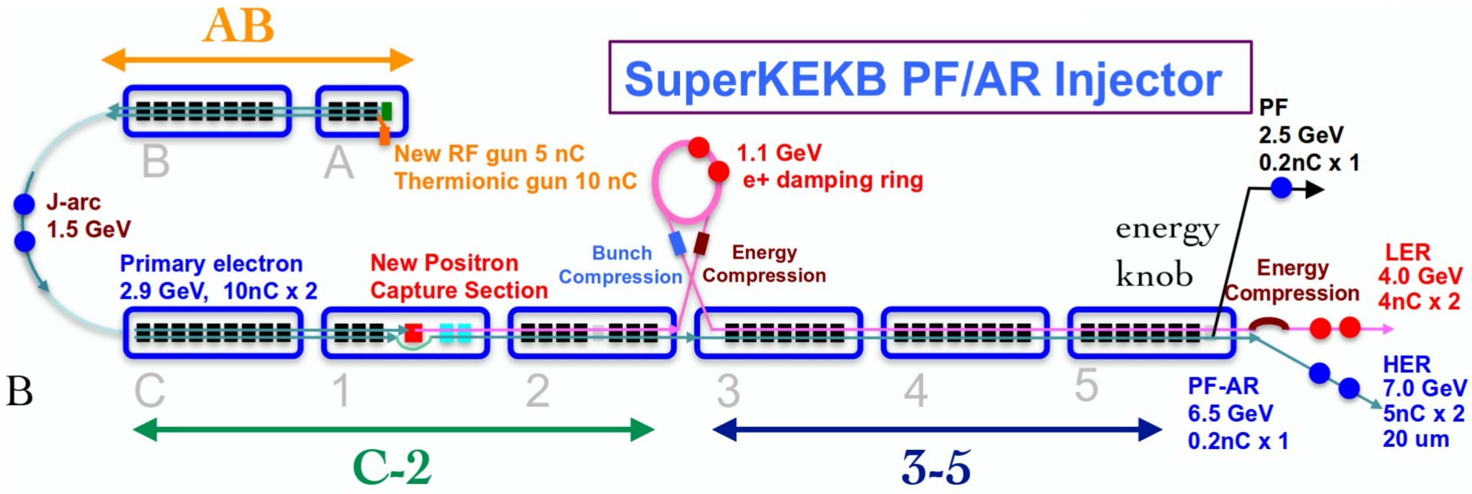
Super-KEKB: energy and limitations

Super-KEKB is technically an accumulation ring
- → All the acceleration phase is carried out in the LINAC
- → RF cavities in the ring only to sustain the beams
- → Continuous injection



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

Possible max E_{cm} = ~ 11.24 GeV, at $\Lambda_b\bar{\Lambda}_b$ threshold



Part II. Bottomonium physics

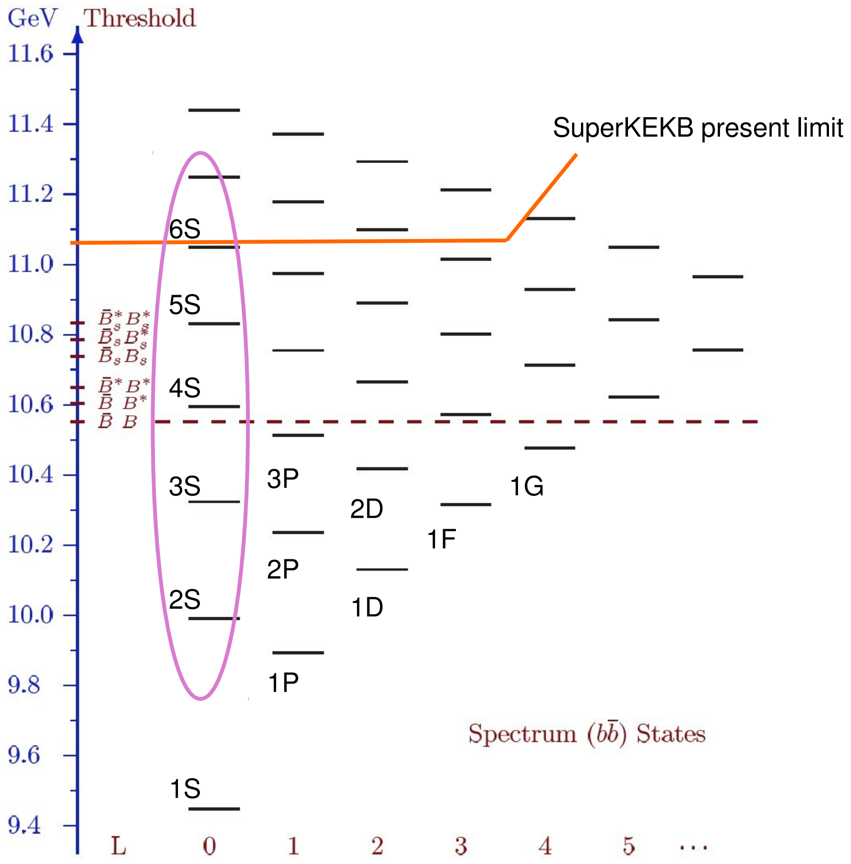
→ *Hadronic transitions*
→ *Scan opportunities*

Bottomonia: what we've learned

An "light quark" effect can enhance a transition and lead to the discovery of a conventional state

→ **Constraint on the initial state ($J^{PC} = 1^{--}$)**

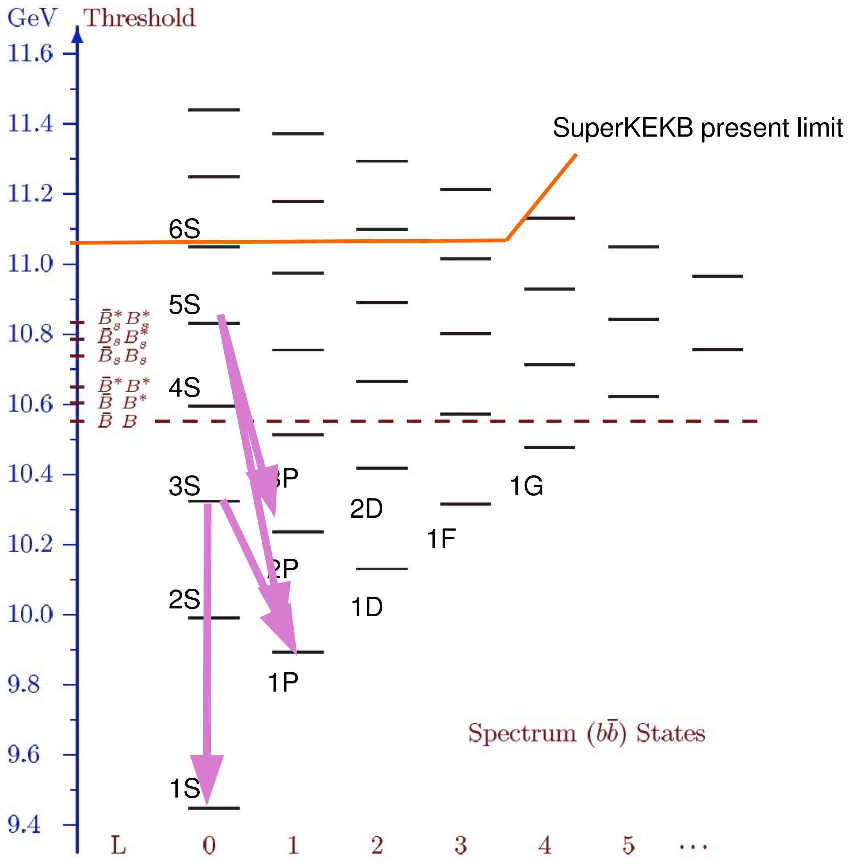
→ All the bottomonium studies are studies of transitions



Predictions on the exotics production modes and rates are as important as the ones on the decays

Discoveries: missing transitions

Transitions to/from known states



Extrapolations from Belle/BaBar

Missing Υ(3S) transitions (300 fb^{-1}):

BF [Υ(3S) → η Υ(1S)] > 2 x 10^{-5}
BF [Υ(3S) → ππ h_b(1P)] > 5 x 10^{-5}

Missing Υ(5S) transitions (1 ab^{-1}):

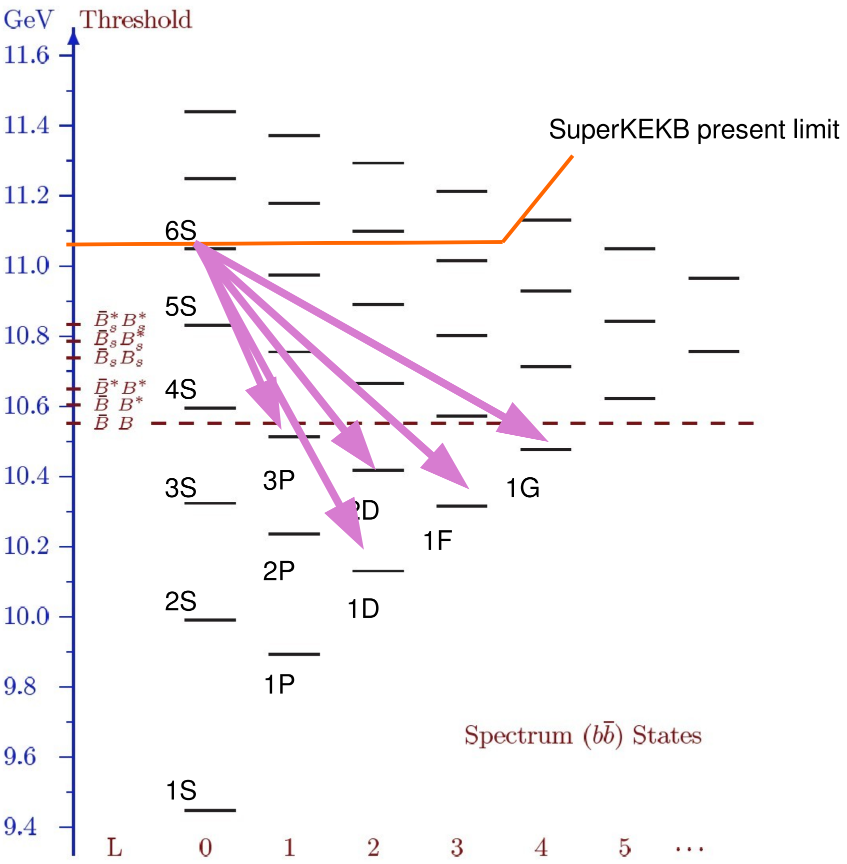
BF [Υ(5S) → η h_b(1P, 2P)] > 3 x 10^{-3}

Other opportunities

A Very large set of h_b(nP) will be available using Υ(4S, 5S) → ππ/η h_b(1P, 2P).
→ Predictions/ideas on transitions from the h_b(nP)?
→ h_b(2P) → η Υ(1S) ?

Discoveries: new states

Most of the discovery of new states requires to run at the largest possible E_{cm}

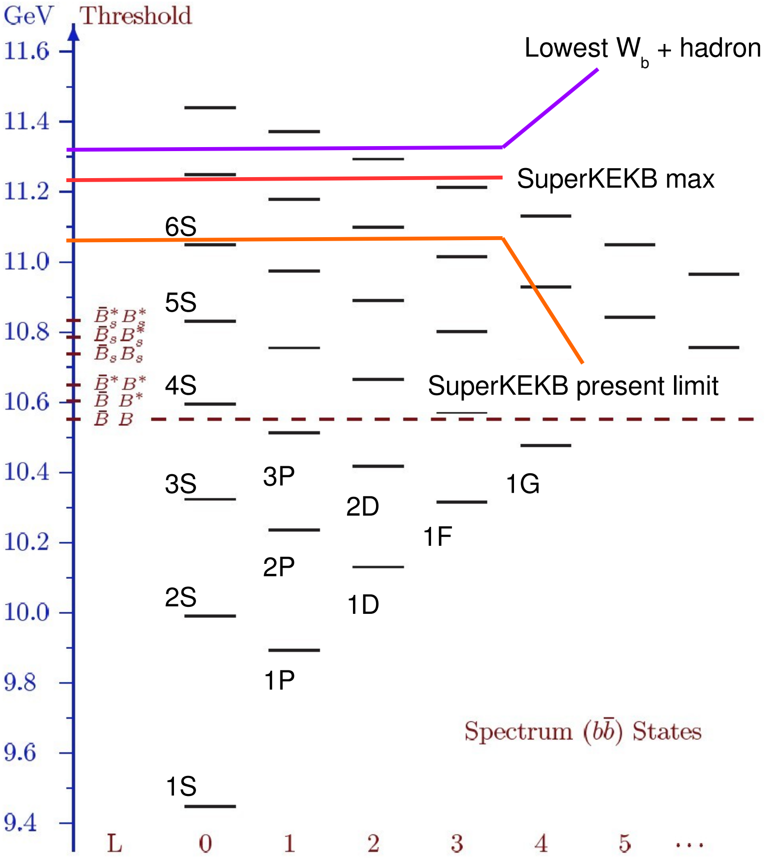


Name	L	S	J^{PC}	Emitted hadrons [Threshold, GeV/c^2]
$\eta_b(3S)$	0	0	0^{-+}	ω [11.12], ϕ [11.36]
$h_b(3P)$	1	0	1^{+-}	$\pi^+\pi^-$ [10.82], η [11.09], η' [11.50]
$\eta_{b2}(1D)$	2	0	2^{-+}	ω [10.93], ϕ [11.17]
$\eta_{b2}(2D)$	2	0	2^{-+}	ω [11.23], ϕ [11.47]
$\Upsilon_J(2D)$	2	1	$(1,2,3)^{--}$	$\pi^+\pi^-$ [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]

No sensitivity predictions yet... stay tuned!

Discoveries: new exotica on thresholds

Most of the discovery of new states requires to run at the largest possible E_{cm}

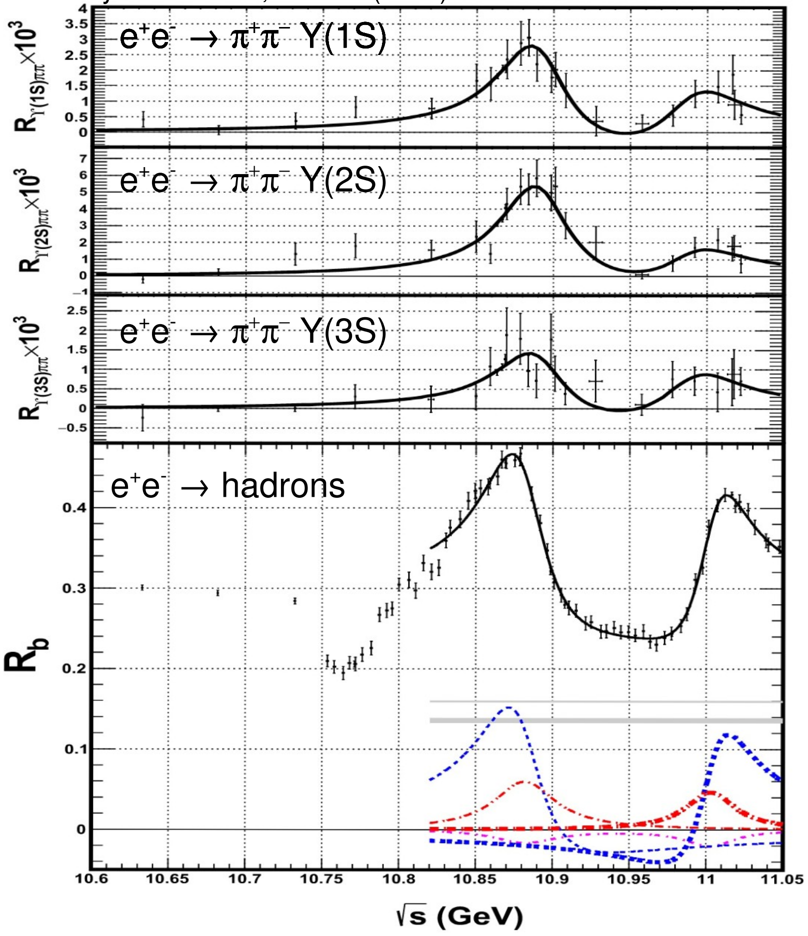


$I^G(J^P)$	Name	Composition	Co-produced particles [Threshold, GeV/c^2]	Decay channels
$1^+(1^+)$	Z_b	$B\bar{B}^*$	π [10.75]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^+(1^+)$	Z_b'	$B^*\bar{B}^*$	π [10.79]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^-(0^+)$	W_{b0}	$B\bar{B}$	ρ [11.34], γ [10.56]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(0^+)$	W_{b0}'	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(1^+)$	W_{b1}	$B\bar{B}^*$	ρ [11.38], γ [10.61]	$\Upsilon(nS)\rho$
$1^-(2^+)$	W_{b2}	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$
$0^-(1^+)$	X_{b1}	$B\bar{B}^*$	η [11.15]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^-(1^+)$	X_{b1}'	$B^*\bar{B}^*$	η [11.20]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^+(0^+)$	X_{b0}	$B\bar{B}$	ω [11.34], γ [10.56]	$\Upsilon(nS)\omega$, $\eta_b(nS)\eta$
$0^+(0^+)$	X_{b0}'	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\eta_b(nS)\eta$
$0^+(1^+)$	X_b	$B\bar{B}^*$	ω [11.39], γ [10.61]	$\Upsilon(nS)\omega$
$0^+(2^+)$	X_{b2}	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$

Predictions on the production rates?

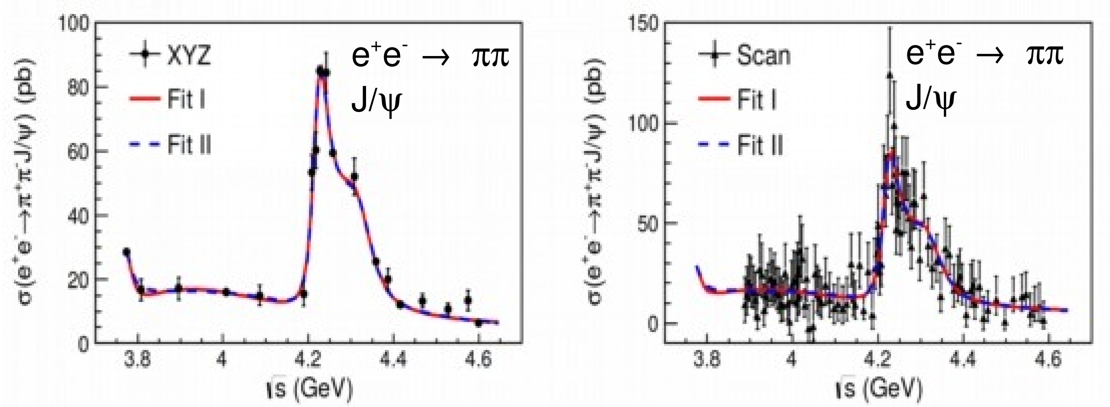
Precision studies: Υ(5S-6S) scans

Phys. Rev. D 93, 011101 (2016)



… with an eye on what happens in charmonia...

BESIII scan: Phys. Rev. Lett. 118, 092001



BelleII prospects

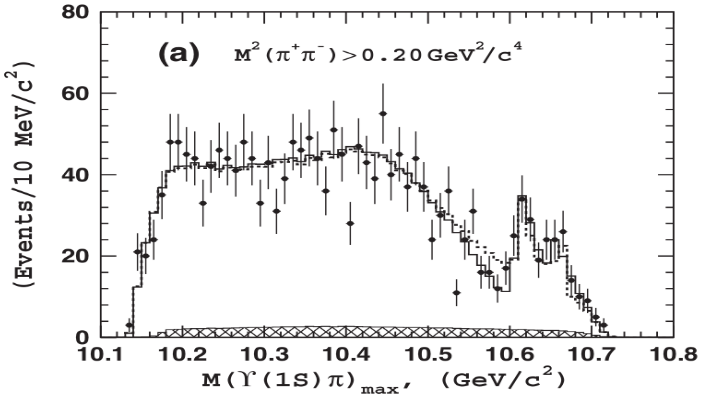
→ Beam energy spread 5 MeV

→ 10 fb^{-1} per point, 10 MeV steps (10x Belle)

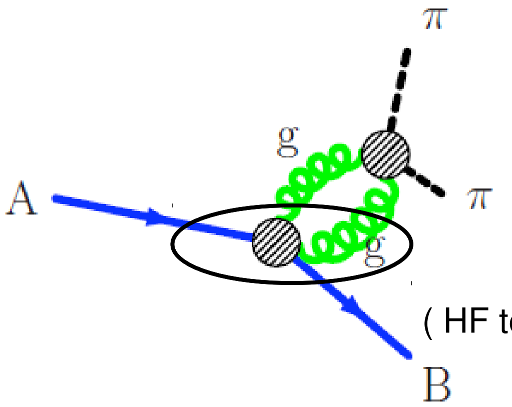
→ Almost 0.5 ab^{-1}: needs <u>strong</u> theoretical motivation

Precision studies: Di-pion transitions

Belle Υ(5S) → ππ Υ(1S)



A QCDME diagram (purely as example)

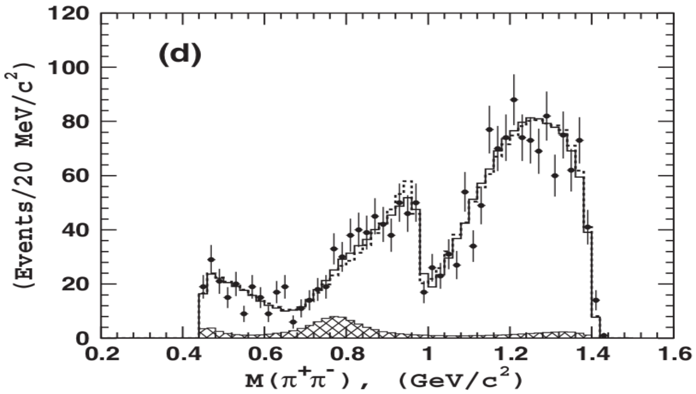


Heavy vertex

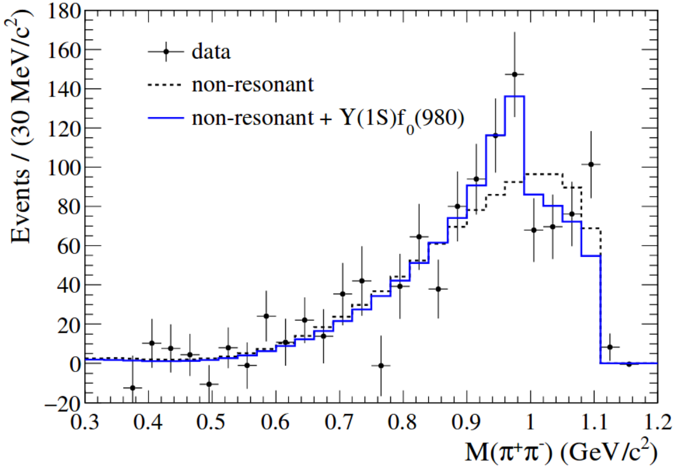
(HF tetraquarks, molecules, hybrids)

Precision studies: Di-pion transitions

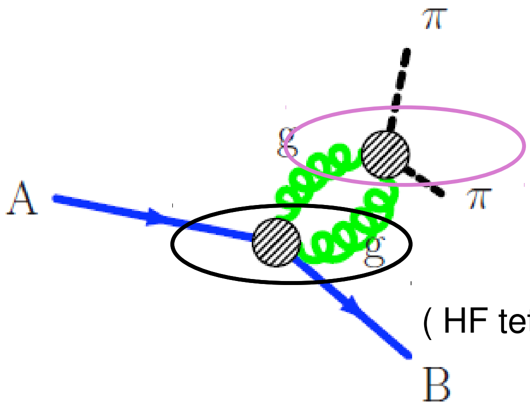
Belle Υ(5S) → ππ Υ(1S)



Belle Υ(4S) → ππ Υ(1S) (*Elisa Guido's talk*)



A QCDME diagram (purely as example)



Light vertex
(LF tetraquarks, molecules, hybrids...)

Heavy vertex
(HF tetraquarks, molecules, hybrids)

Study of scalar mesons using di-pion transitions is not a new idea, but we lacked of statistics *H.W. Ke et al, PRD 76 (2007) 074035*

Actually, also Zb's can contribute to Υ(3S) → ππ Υ(1S) !
Y.H. Chen et al, PRD93 (2016) 03403, F.K. Guo's talk

BelleII prospects

→ High-statistic full PWA of the di-pion transitions
→ Confirm Exotica as contributors to transitions below threshold!
→ Hunt for CP = ++ contributions: σ, f_2… *Liu et al,EPJC73, 2284 (2013)*
→ ππ scattering length from Υ(3S) → ππ Υ(2S)

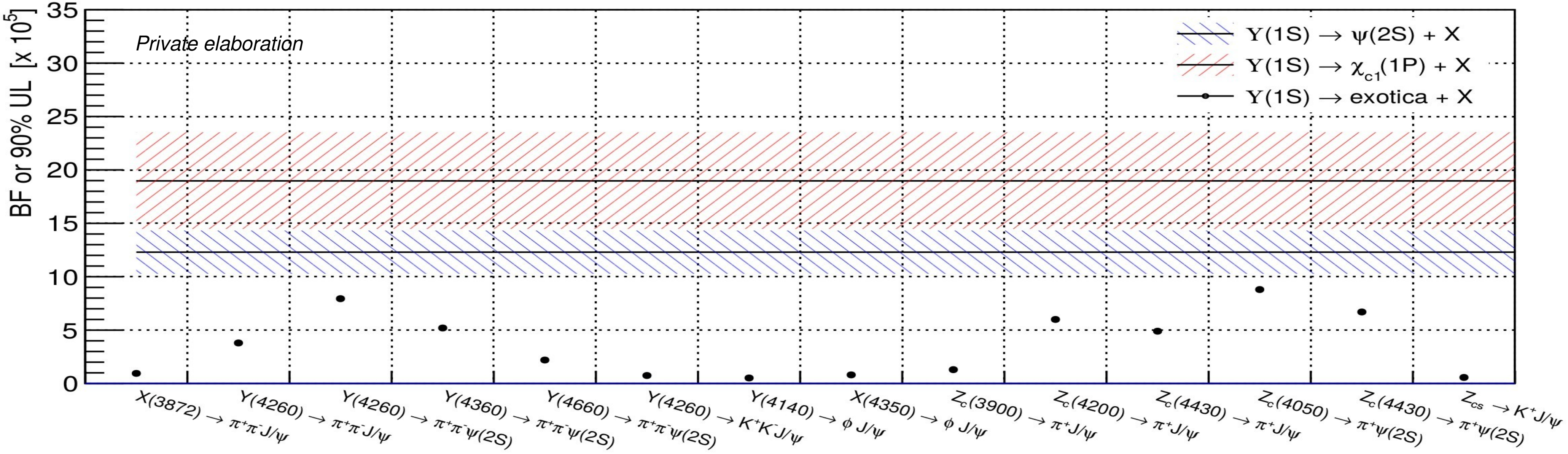
Part III. Beyond bottomonia

→ *Light meson effects in transitions*
→ *Bottomonium annihilations*

Charmonia in production

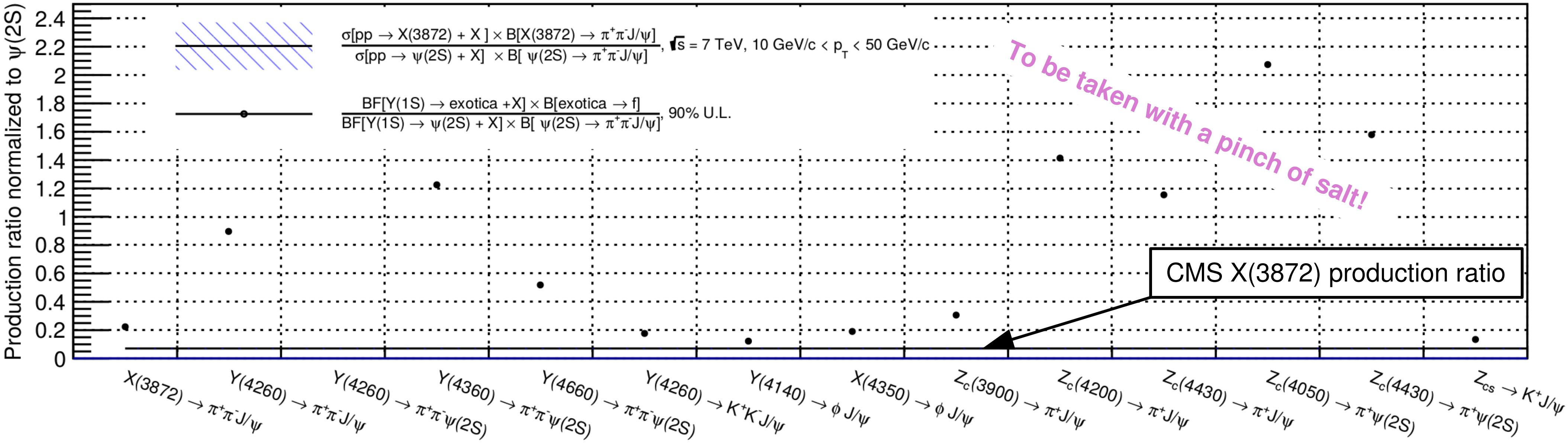
Lots of observation of exotica, but quite few completely independent confirmations
→ Usually structures in one (or few...) Dalitz plot with limited Q.
→ Only X(3872) has been seen in prompt production (in $p\bar{p}$ and pp collisions)
→ Production is debated *A. Pilloni's talk on Wednesday (look for the backup slides...)*

Belle, Phys. Rev. D 93, 112013, S.Eidelman's talk



Charmonia: pp and e^+e^- compared

A tentative comparison between Belle and CMS.



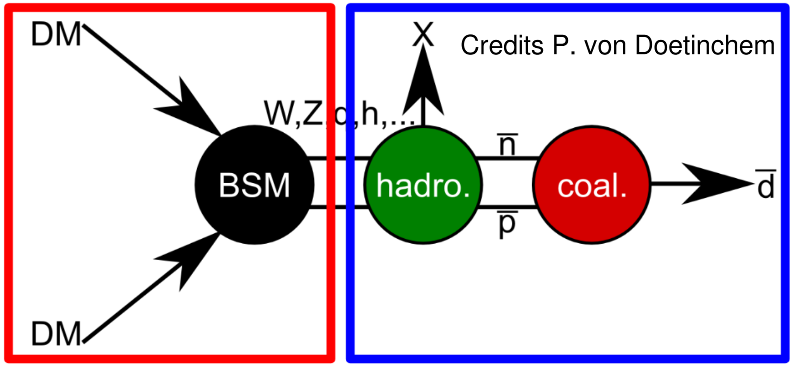
Bellell prospects

→ 3-5 x sensitivity in inclusive production from Υ(3S)
→ 10-15 x sensitivity in double charmonium
→ Theoretical predictions, at least for X(3872)?

→ Directly from this conference: DD* correlation in Υ(3S) → DD* + hadrons

Deuteron production: bottomonium for DM

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



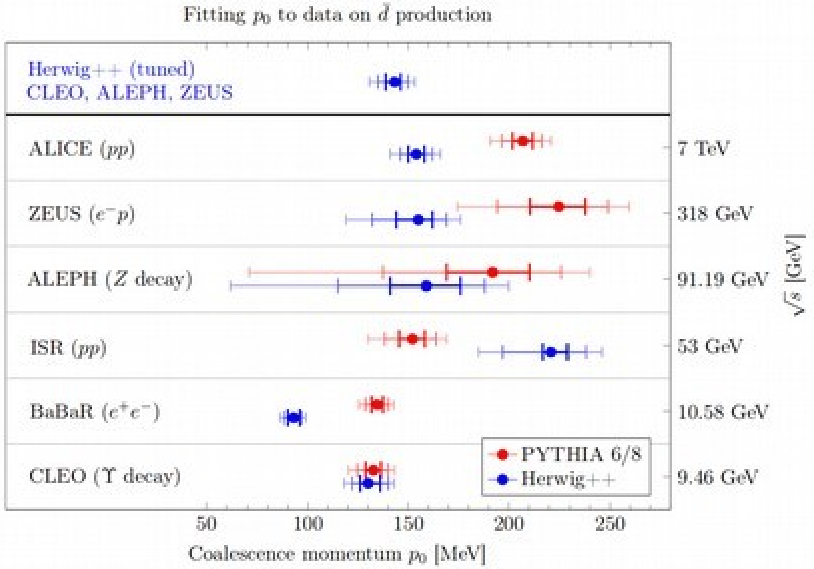
dark matter

conventional production
(e.g., p+ISM) & dark matter

Original idea:
Donato, Fornengo, Salati, PRD 62, 043003 (2000)

Recent review:
Aramaki et al. Phys. Rept. 618 (2016) 1-37

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

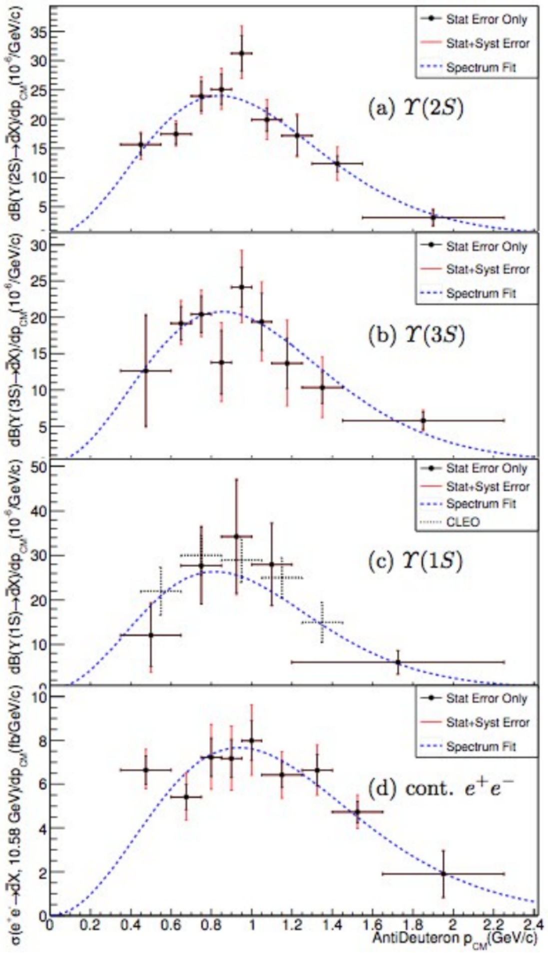


Production at B-factories highlights:
→ No in-medium and extended source corrections
→ Complete access to the rest of event
→ BelleII is made for PID...

Deuteron from Υ(3S)

With no dedicated PID or tracking, BaBar and CLEO measured the $\bar{d}$ spectrum *Phys.Rev. D89 (2014) no.11, 111102*

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



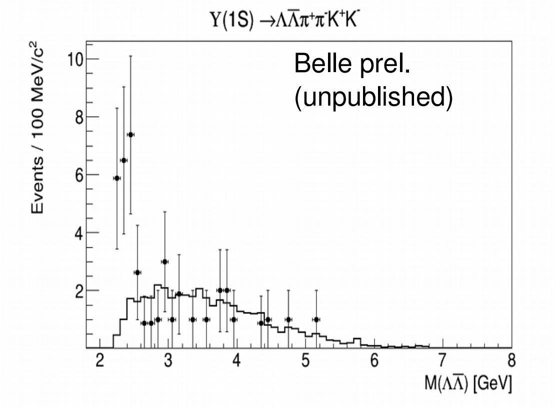
BelleII prospects

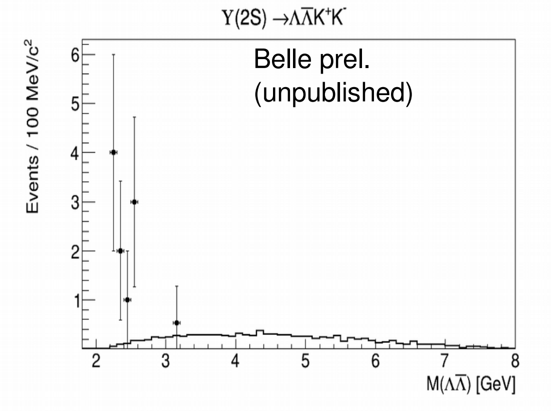
→ Collect ~30000 $\bar{d}$, with dedicated tracking and PID
→ Get the world best estimate of the coalescence parameter
→ Simultaneous fit of the proton spectrum
→ $d\bar{d}$ associated production
→ Search for excited nucleons: d* → d ππ

Probing the ΛΛ interaction

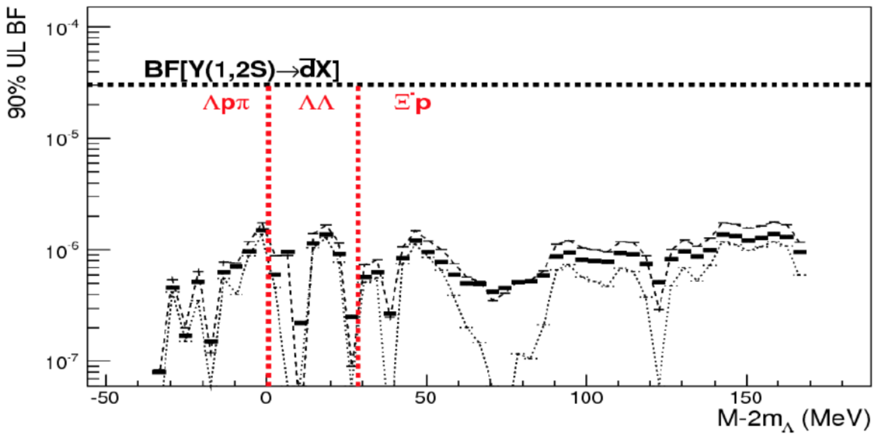
Belle left two main results on ΛΛ pairs (More to come!)

Near-threshold enhancement in exclusive Y annihilations





No sign of weakly bound H-dibaryon



BelleII prospects

→ Rough extrapolation for 1.2 B Y(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

→ search for H di-baryon in missing mass from Y(3S) → H ΛΛ + hadrons

→ Extract the ΛΛ potential from correlation functions (no in-medium corrections!)

Wrapping it up

Belle II offers:

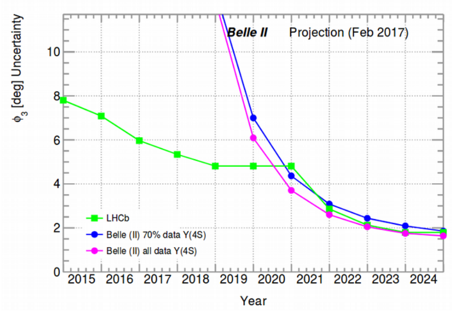
→ Improved tracking (efficiency and resolution)
→ Improved hermeticity (smaller boost)
→ 8-10x Belle statistics
→ 10 MeV-wide cross section scans

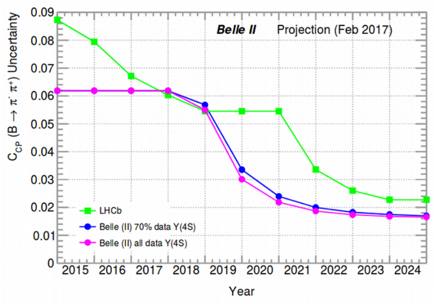
Belle II could take

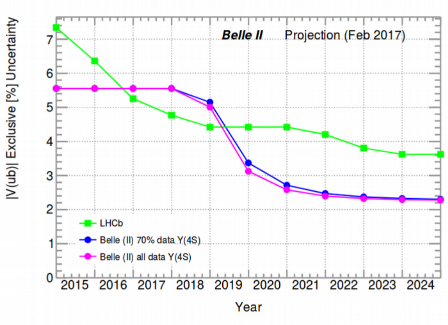
→ O(ab-1) at Υ(5S)
→ Fine-grained scan around Υ(5S) and Υ(6S)
→ O(1 B) Υ(3S)

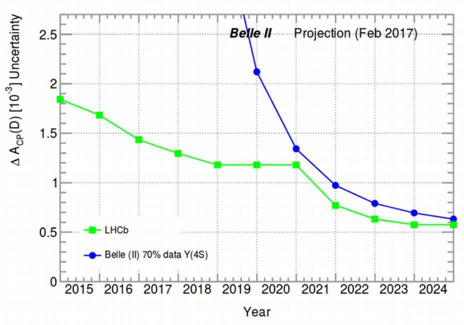
Unfortunately, nothing comes for free

→ BelleII is mainly focused on BSM physics in the weak sector
→ Most of the data taking will take place at Υ(4S) for B physics: max 30% of data off-Υ(4S), including continuum
→ Competition with LHCb is pressing









Support and inputs from **all** the QCD communities are welcome!

Backup

Light mesons: the π scattering lenght

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

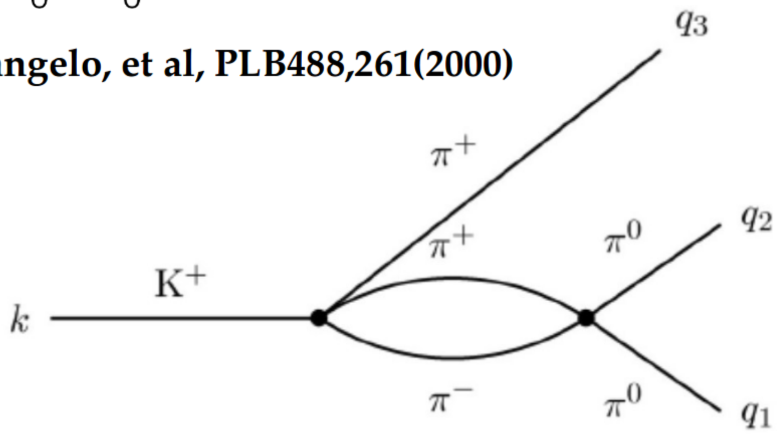
$$a_0^0 = \frac{7M_\pi^2}{32\pi F_\pi^2} + \mathcal{O}(m_q^2) \qquad a_0^2 = -\frac{M_\pi^2}{16\pi F_\pi^2} + \mathcal{O}(m_q^2)$$

Weinberg, PRL17,616(1966)

Using ChPT, theory predicts:

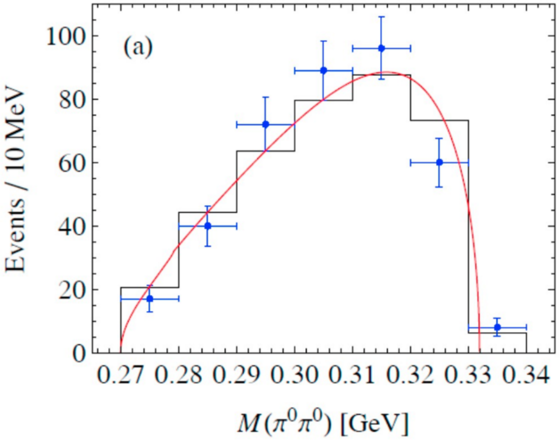
$$a_0^0 - a_0^2 = 0.265 \pm 0.004$$

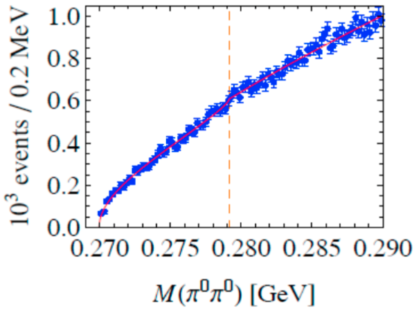
Colangelo, et al, PLB488,261(2000)

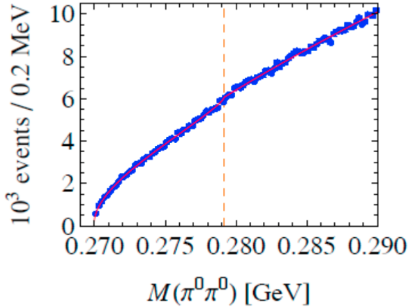


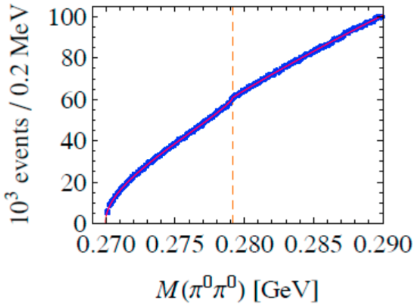
Q-value for Y(3S) → ππ Y(2S) is only 50 MeV

Liu et al,EPJC73, 2284 (2013)









Rare decays as BSM probes

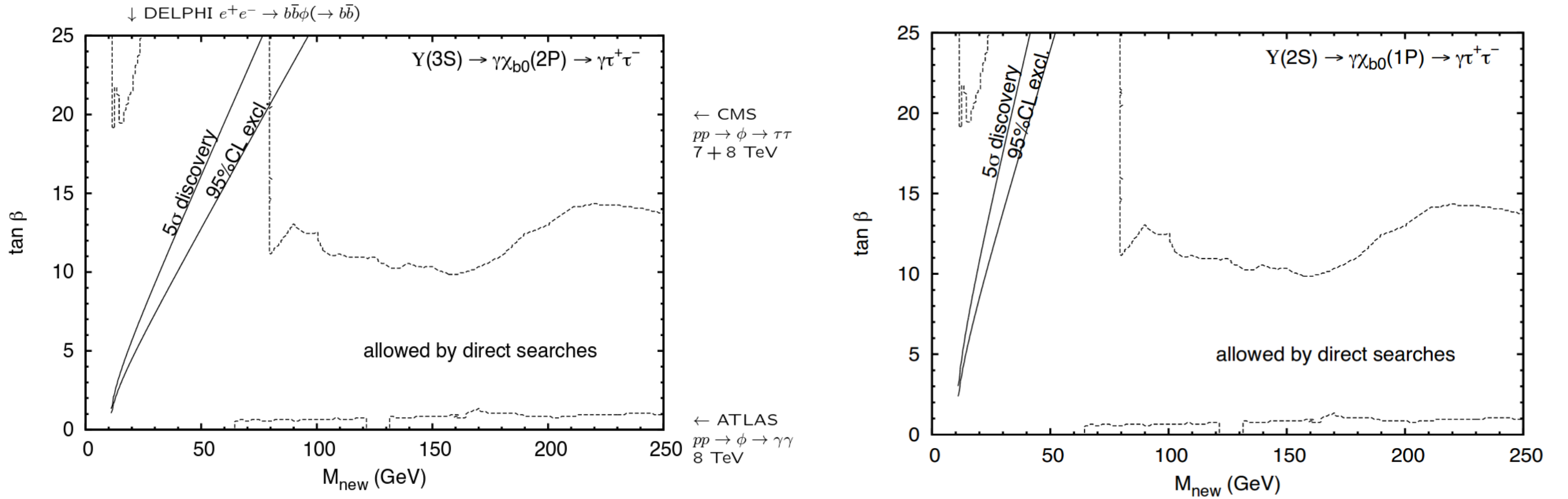
Godfrey and Logan, Phys. Rev. D 93, 055014 (2016)

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

$$\left.\begin{array}{l} \mathrm{BR}^H(\chi_{b0}(1P) \to \tau\tau) = 3.1 \times 10^{-13} \\ \mathrm{BR}^H(\chi_{b0}(2P) \to \tau\tau) = (1.9 \pm 0.5) \times 10^{-12} \end{array}\right\} \times \left[1 + \frac{M^2_{H_{125}} \tan^2\beta}{M^2_{\mathrm{new}} - M^2_{\chi_{b0}}}\right]^2$$

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: $\Upsilon(3S)$



BelleII prospects:

→ Collect 300fb^{-1} at Y(3S) only, and run both fully inclusive and fully exclusive analysis

→ Challenging background from QED ee → γττ