Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

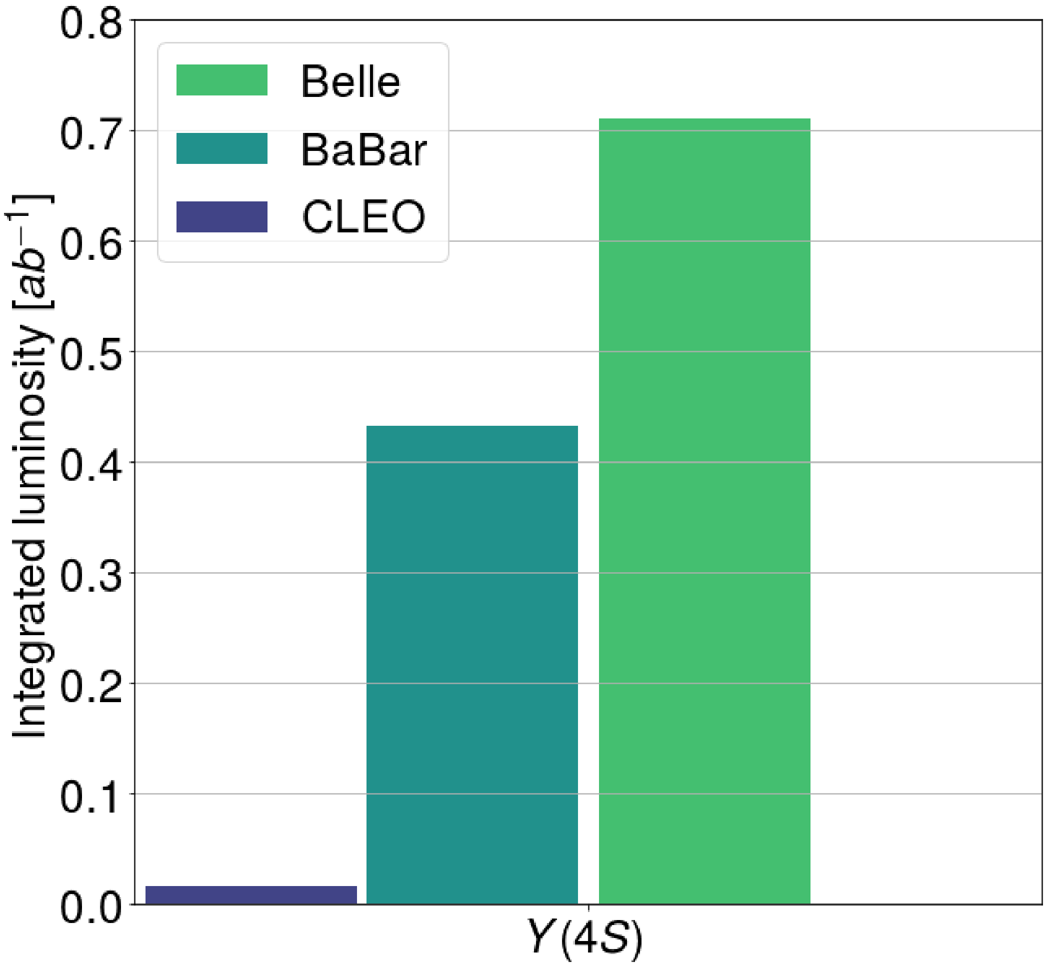
Exotic and Conventional Quarkonium Physics Prospects at Belle II

Umberto Tamponi
tamponi@to.infn.it

LC2019 - QCD on the light cone
Palaiseau, September 19th 2019

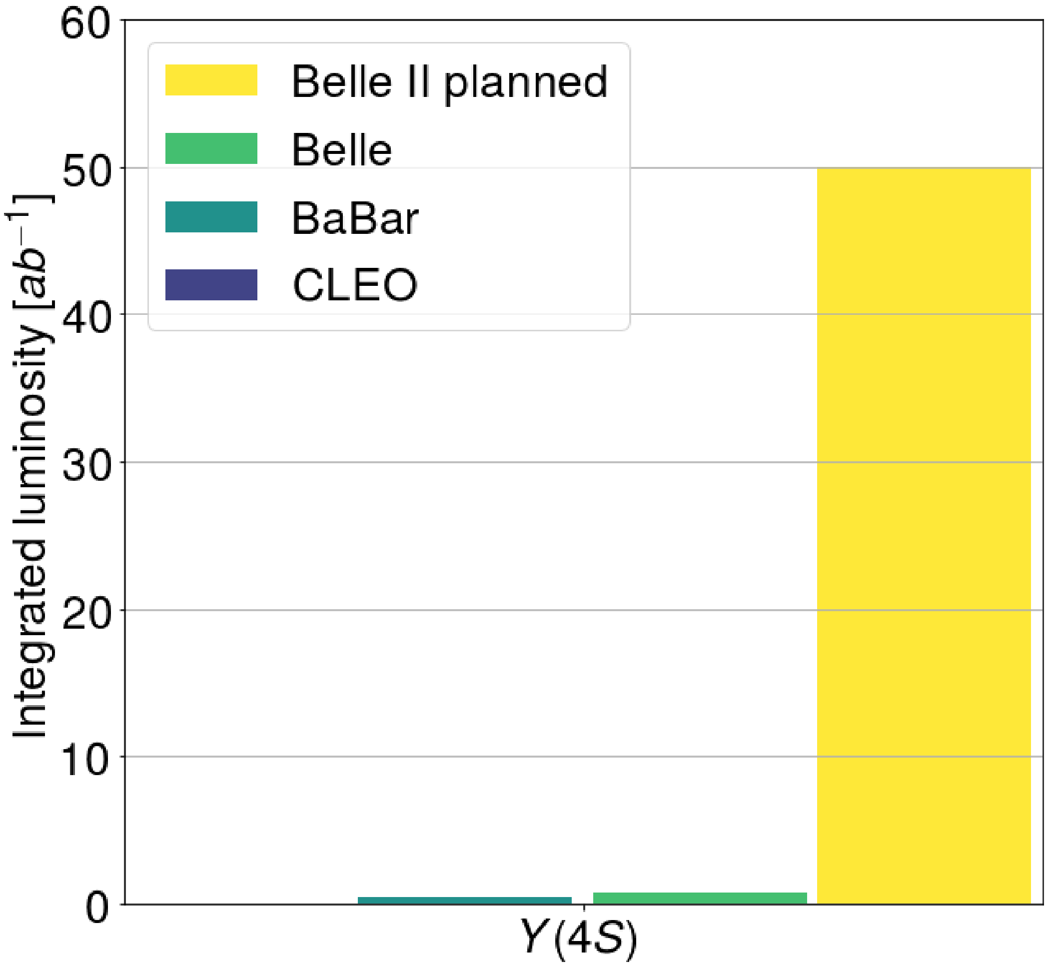
INFN – Sezione di Torino

Belle II: a super-B factory



$\sim$ **10 years of data taking each**

Belle II: a super-B factory



To be done by ~2027

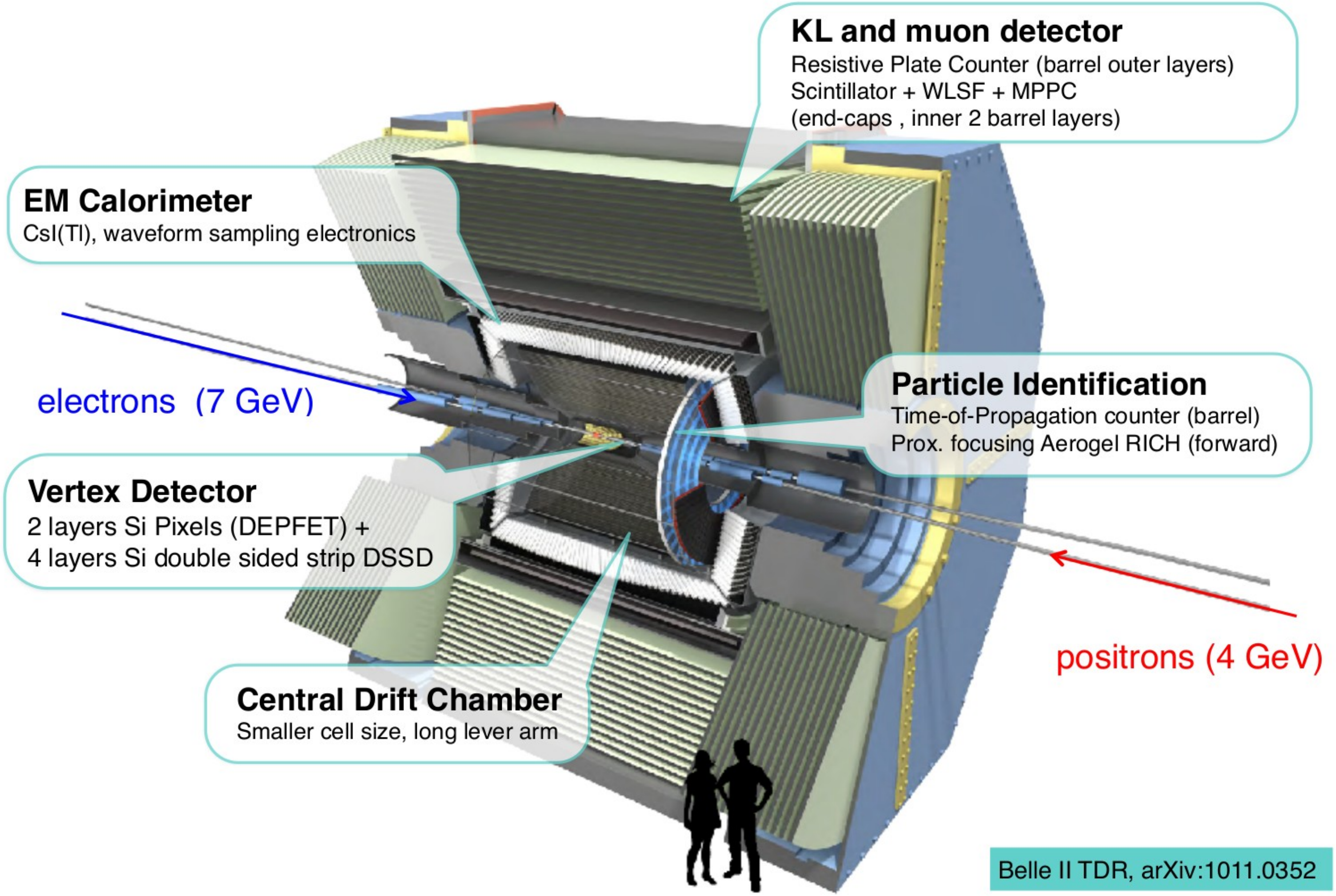
→ 40x instantaneous luminosity

→ 30x trigger rate

→ ~50x computing resources

The toolbox

The Belle II detector



Belle II TDR, arXiv:1011.0352

Belle VS Belle II

arXiv:1808.10567

Tracking and vertexing

→ More precise

Particle identification

→ Much more powerful

Calorimetry

→ ~Unchanged (Better reconstruction, but more backgrounds)

Super-KEKB: the nano-beam scheme

Lorentz factor

Beam current

Beam-beam factor

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

Beam aspect ratio
(flat beam ~ 1-2%)

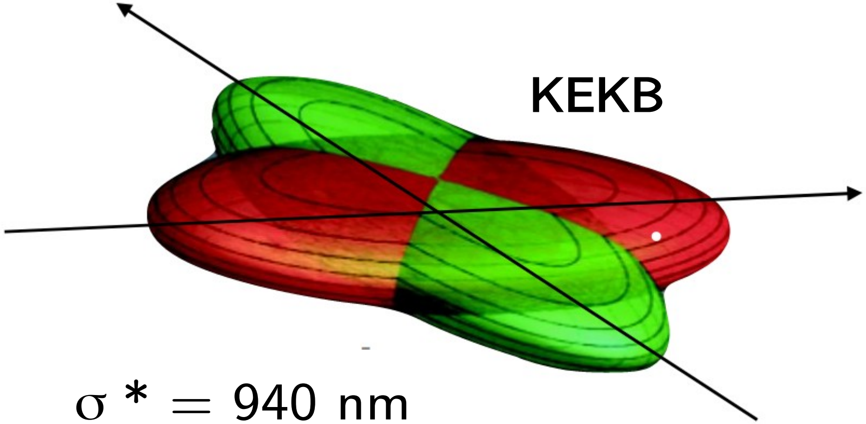
Vertical beta
function at IP

Geometrical corrections
(Hourglass effect...)

Brute force: Increase the current (x2)

Precision: denser beams, smaller β* (x20)

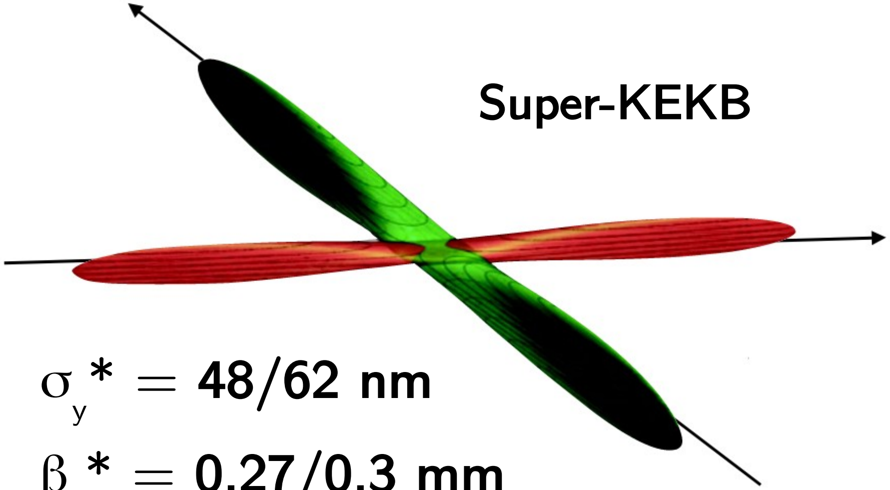
Super-KEKB: the nano-beam scheme



$\sigma_y^* = 940$ nm

$\beta_y^* = 5.9$ mm

$\sigma_x^* = 147/170$ μm



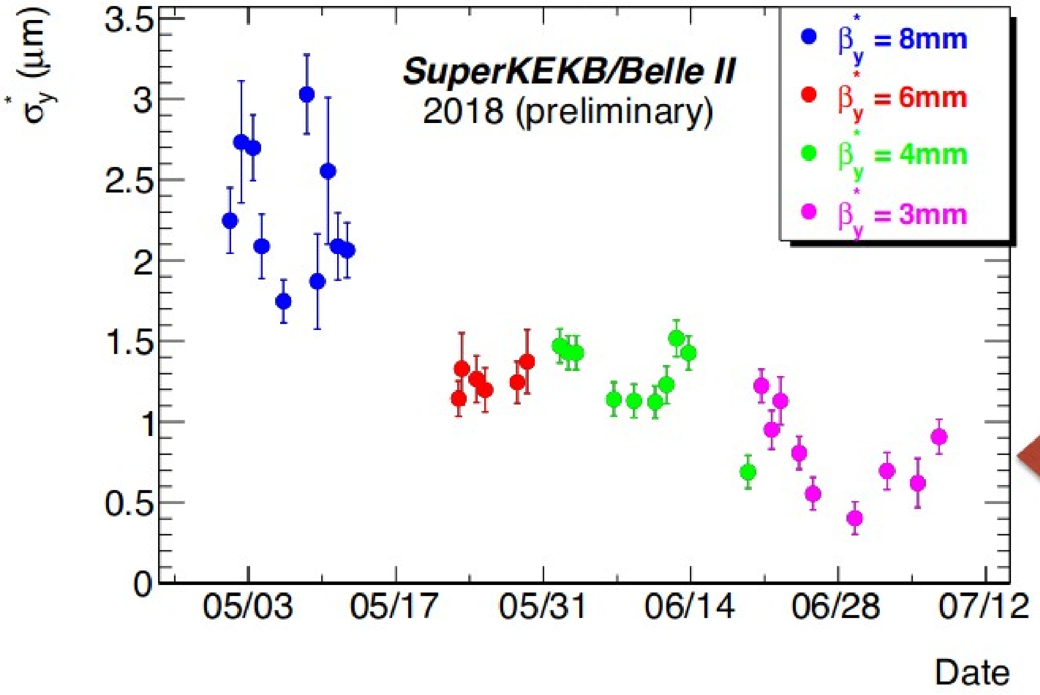
$\sigma_y^* = 48/62$ nm

$\beta_y^* = 0.27/0.3$ mm

$\sigma_x^* = 10.1/10.7$ μm

Measuring a nanometric beam

- How to measure the vertical size of the beams?
  - Measure the luminosity with our fast diamond detector while the machine people moves the beam vertically.



less than 500 nm achieved

Charmonium(-like)

At Belle II, charmonium comes “for free”

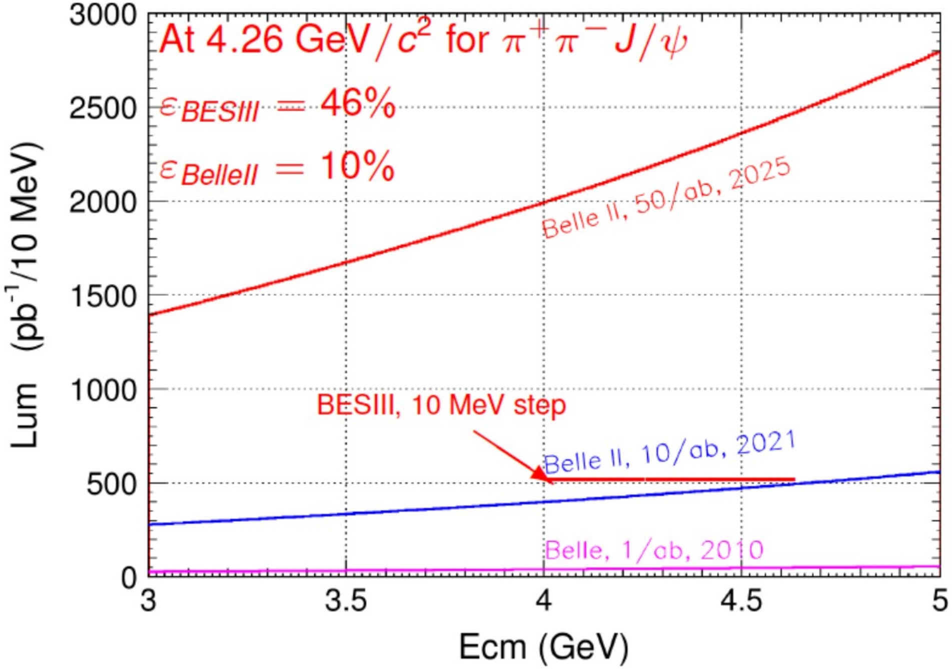
$\rightarrow$ No special triggers needed

$\rightarrow$ No special data taking

Physics program $\sim$ 50x Belle

$\rightarrow$ What does this mean?

ISR with 50 ab^{-1}



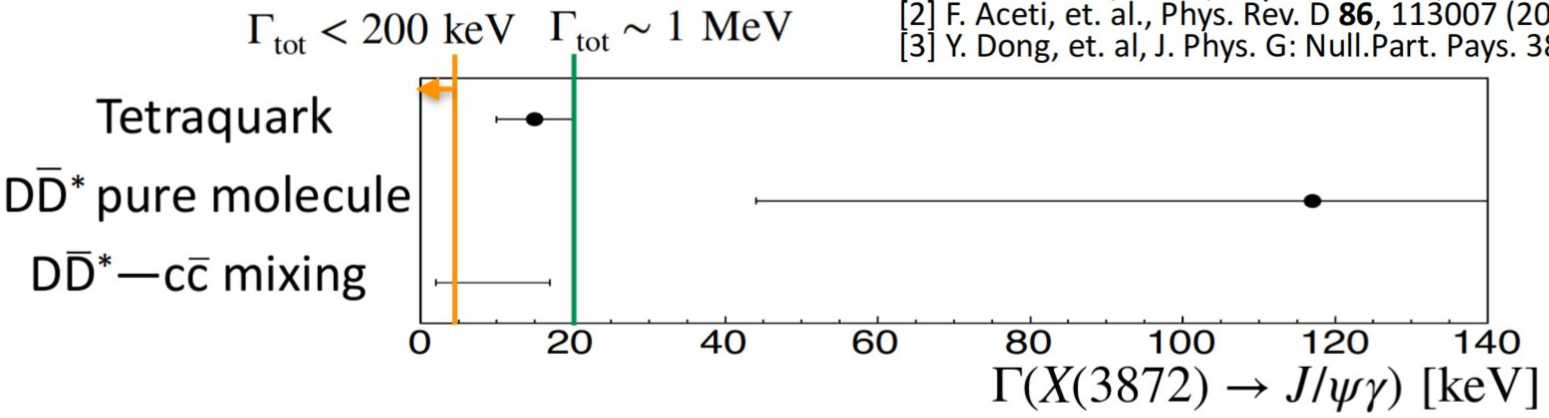
The full Belle II dataset will be equivalent to a 500 pb^{-1}, 10 MeV scan by BESIII

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}

Power of statistics: the X(3872) width

[1] S. Dubnicka, et. al., Phys. Rev. D **81**, 114007 (2010)
[2] F. Aceti, et. al., Phys. Rev. D **86**, 113007 (2012)
[3] Y. Dong, et. al, J. Phys. G: Null.Part. Pays. 38, 015001 (2011)



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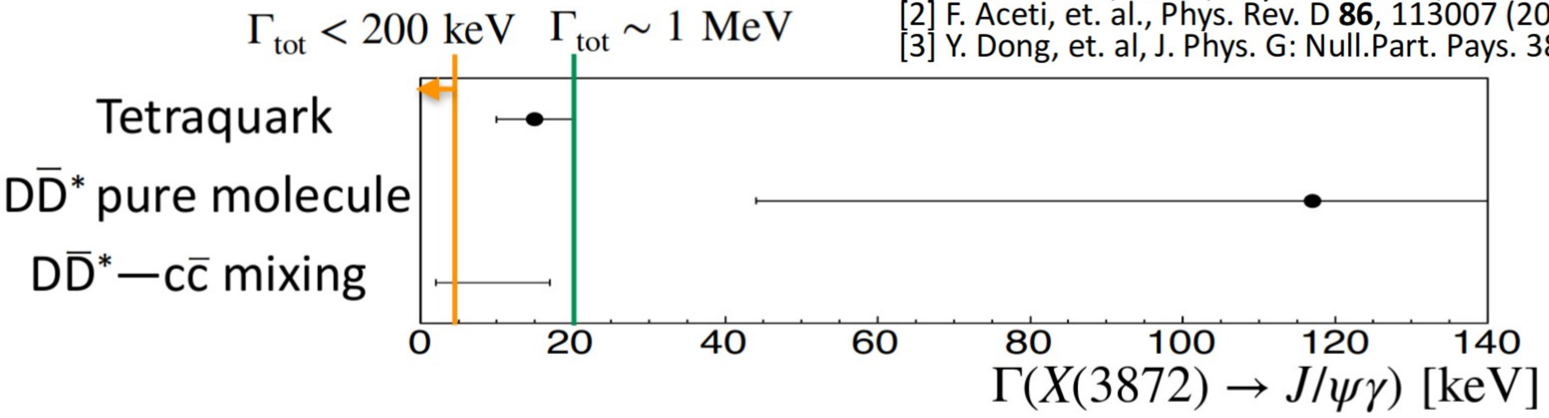
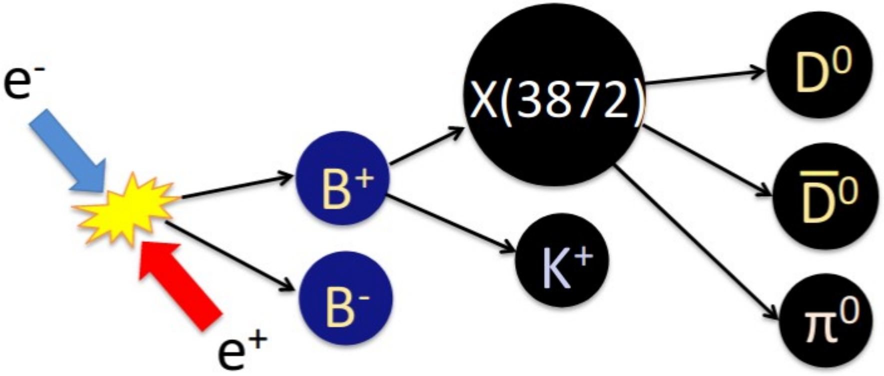


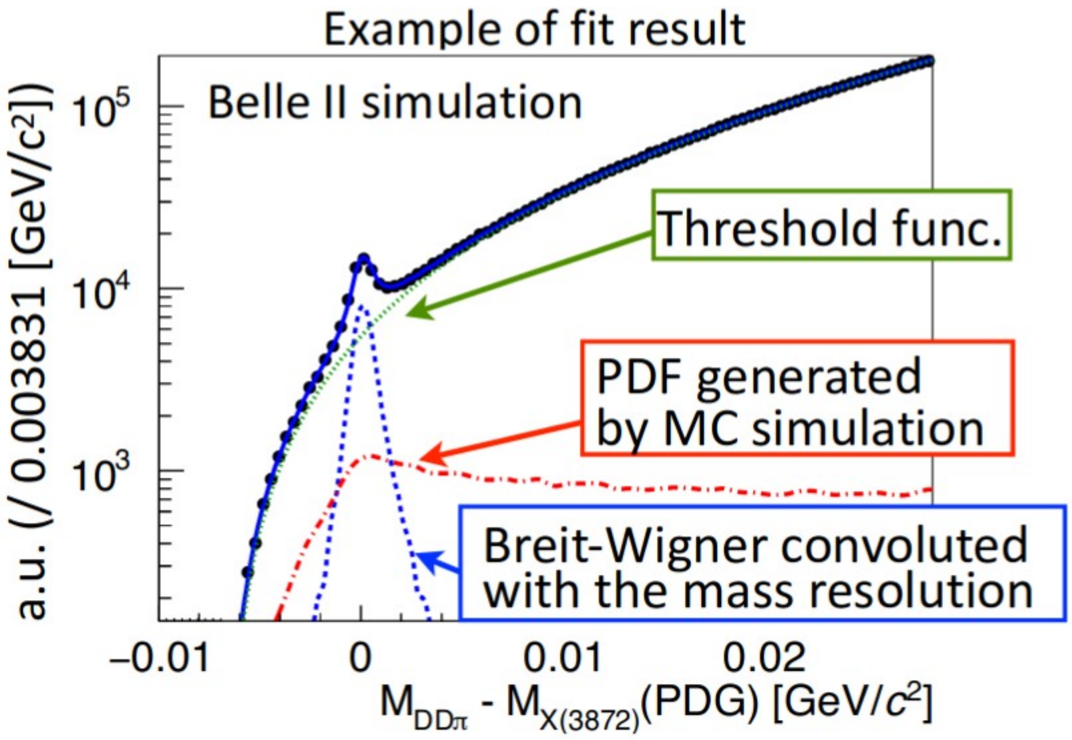
How to measure small widths?

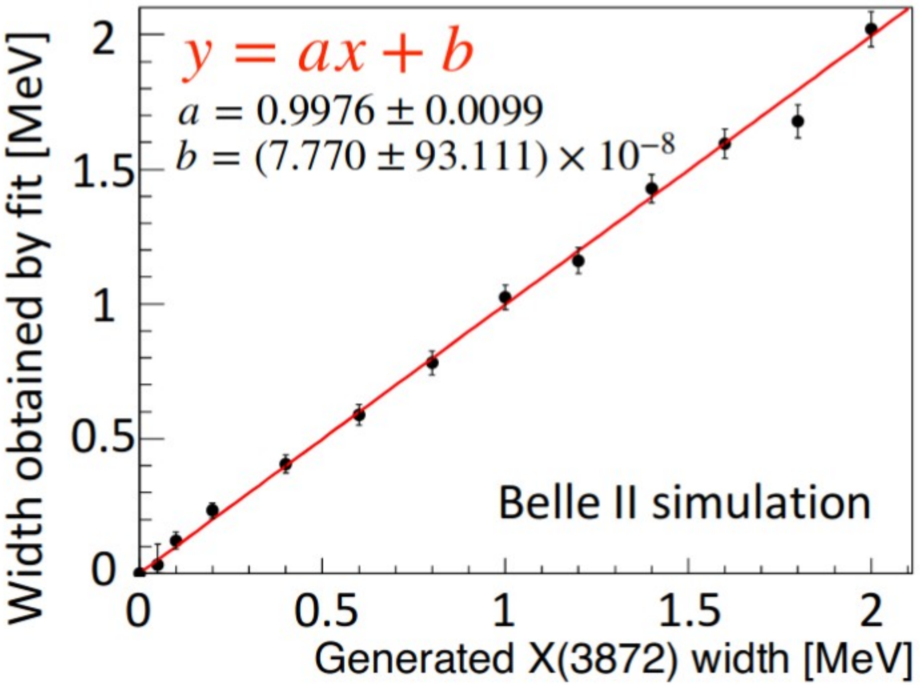
$\to$ Use channels with very small Q-value!



Power of statistics: the X(3872) width

Mass resolution: 684 ± 8 keV





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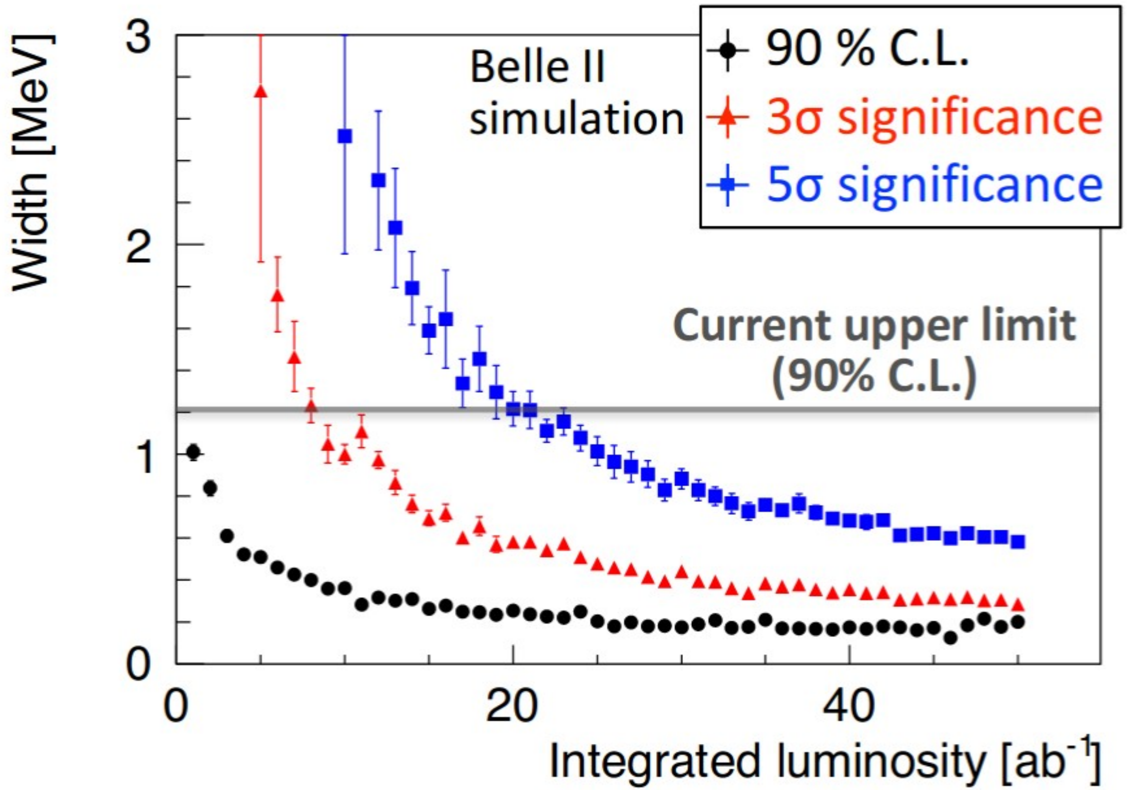


- With the full data sample of Belle II (50 ab^{-1}), total width with values up to

[90% C.L.] ~ 180 keV

[3σ significance] ~ 280 keV

[5σ significance] ~ 570 keV

can be measured.

Assuming a Breit-Wigner shape

Bottomonium-like

Bottomonium

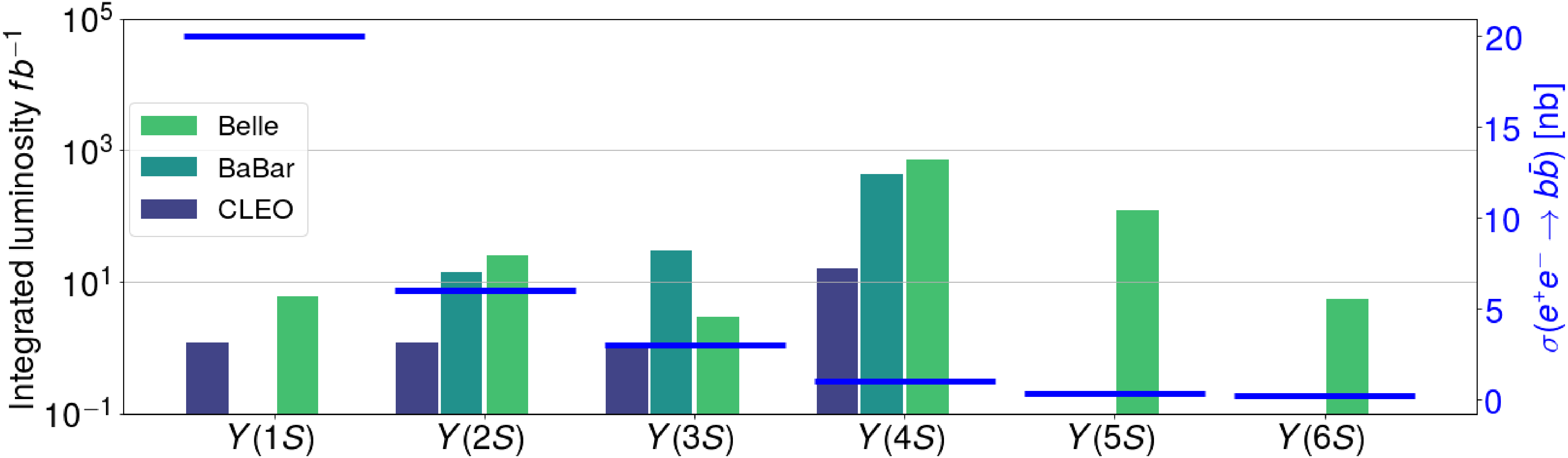
Bottomonium is much less accessible than charmonium

→ Direct production in e^+e^- collisions

→ Prompt production

After Belle II, only the LHC experiments will cover bottomonia with strong limitations

The Belle II bottomonium program



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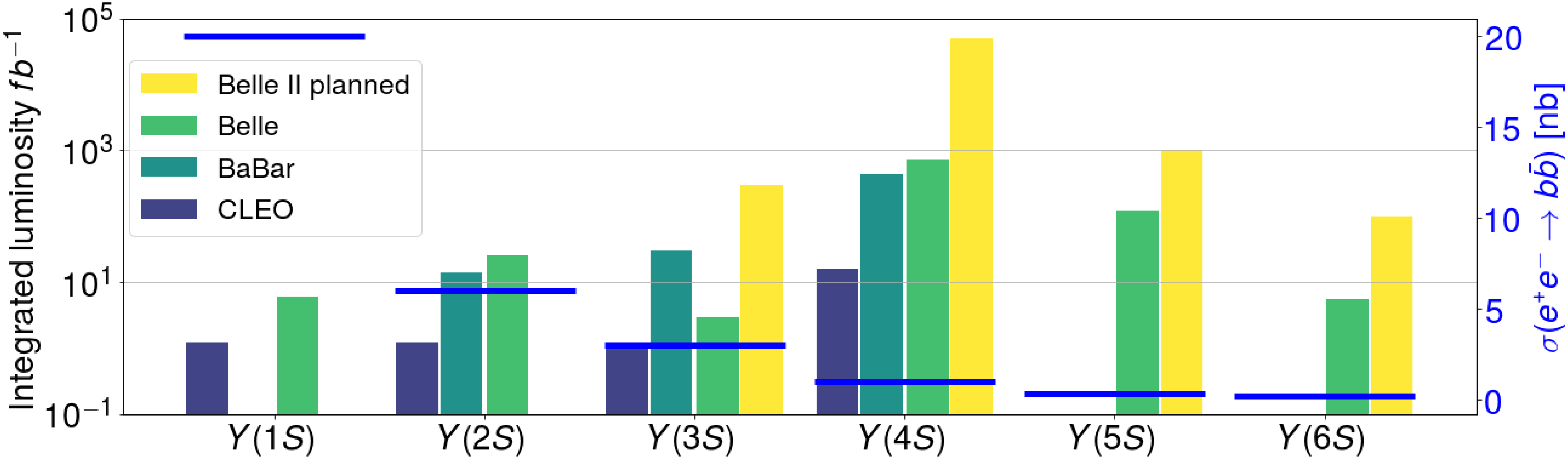

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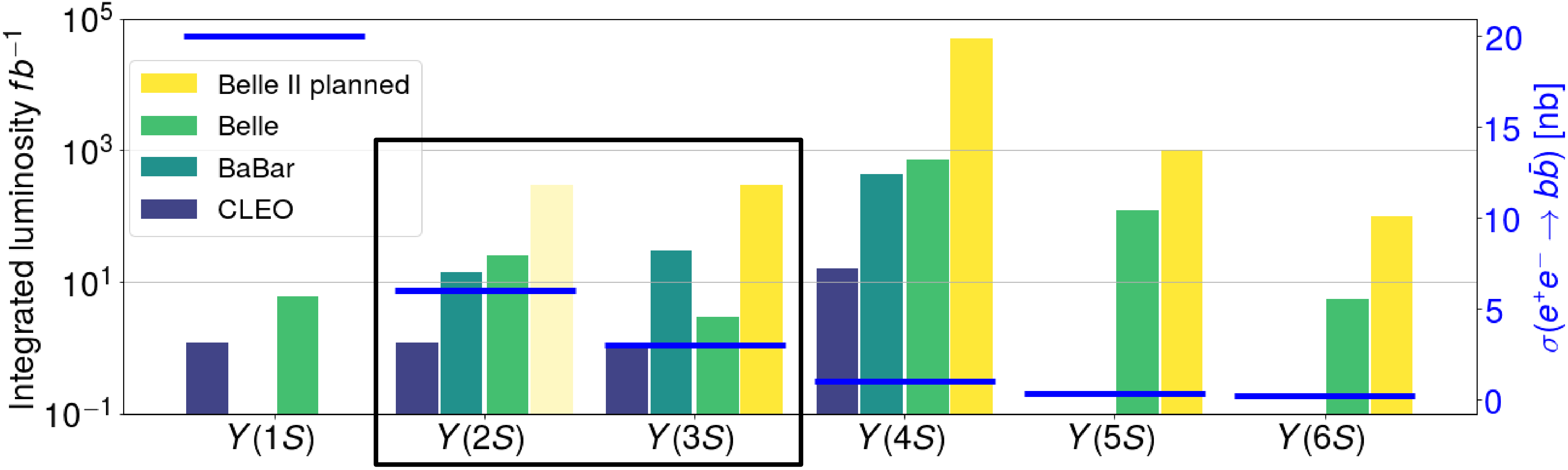
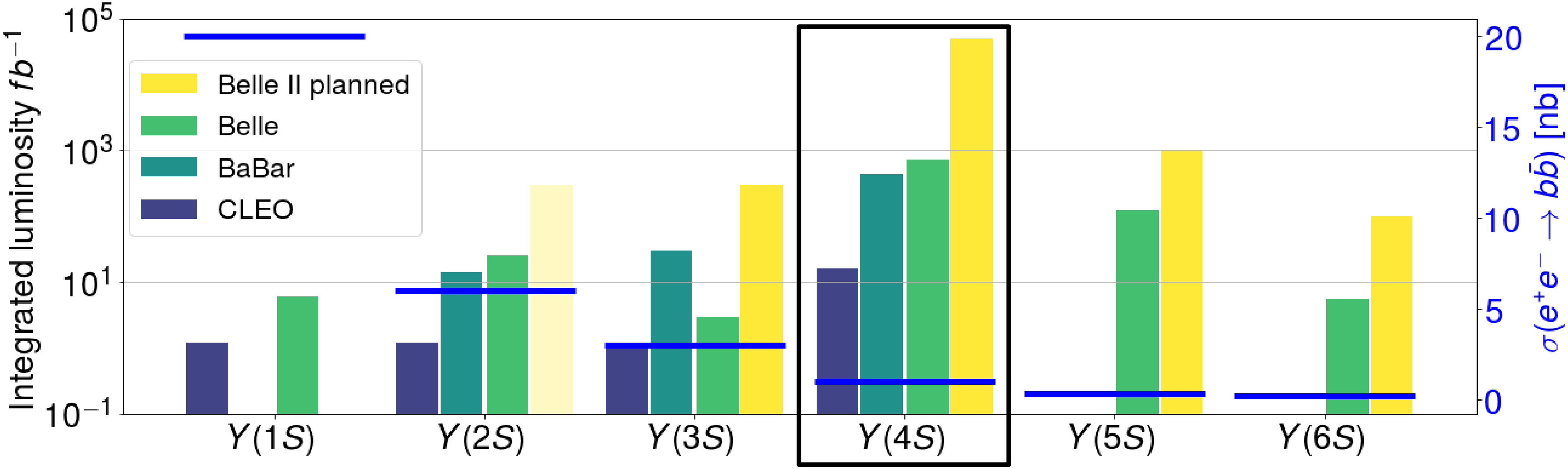


300 fb^{-1} of Y(3S):

- LFV, LUV, invisible decays
- Deuteron formation by coalescence
- Hyperons production and correlation
- Charmonia and di-baryon exotica inclusive production
- Precision QCD in radiative transitions

The Belle II bottomonium program



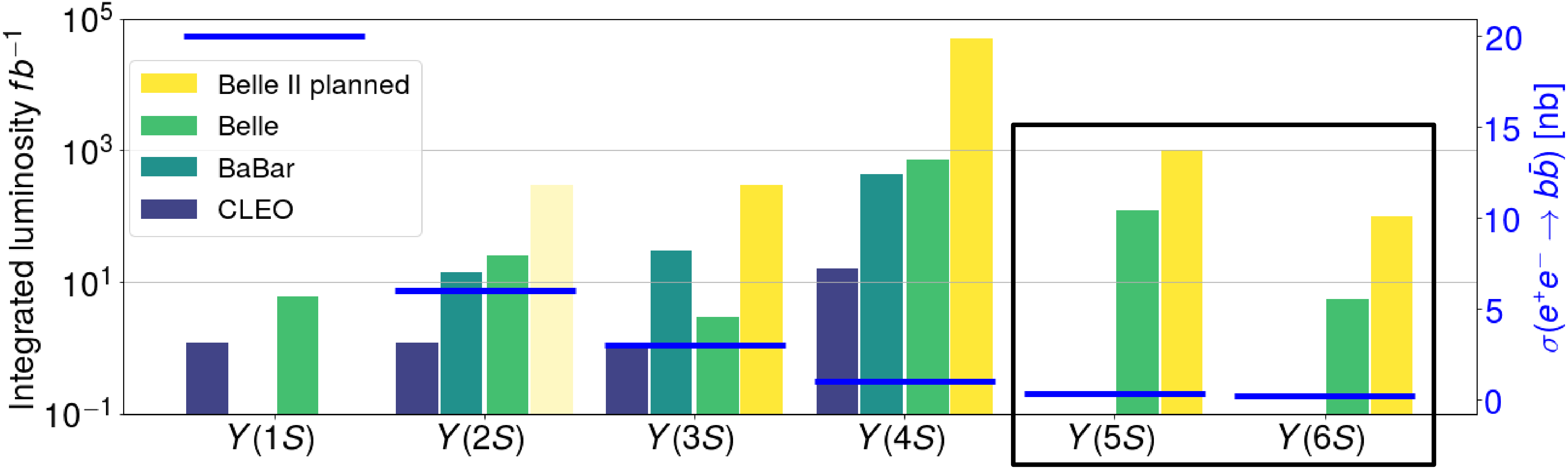
50 ab^{-1} of Y(4S):

ISR

Precision spin-singlet spectroscopy

$\eta_b \to \gamma\gamma$!

The Belle II bottomonium program



1+ ab^{-1} of Y(5S-6S): Exotica

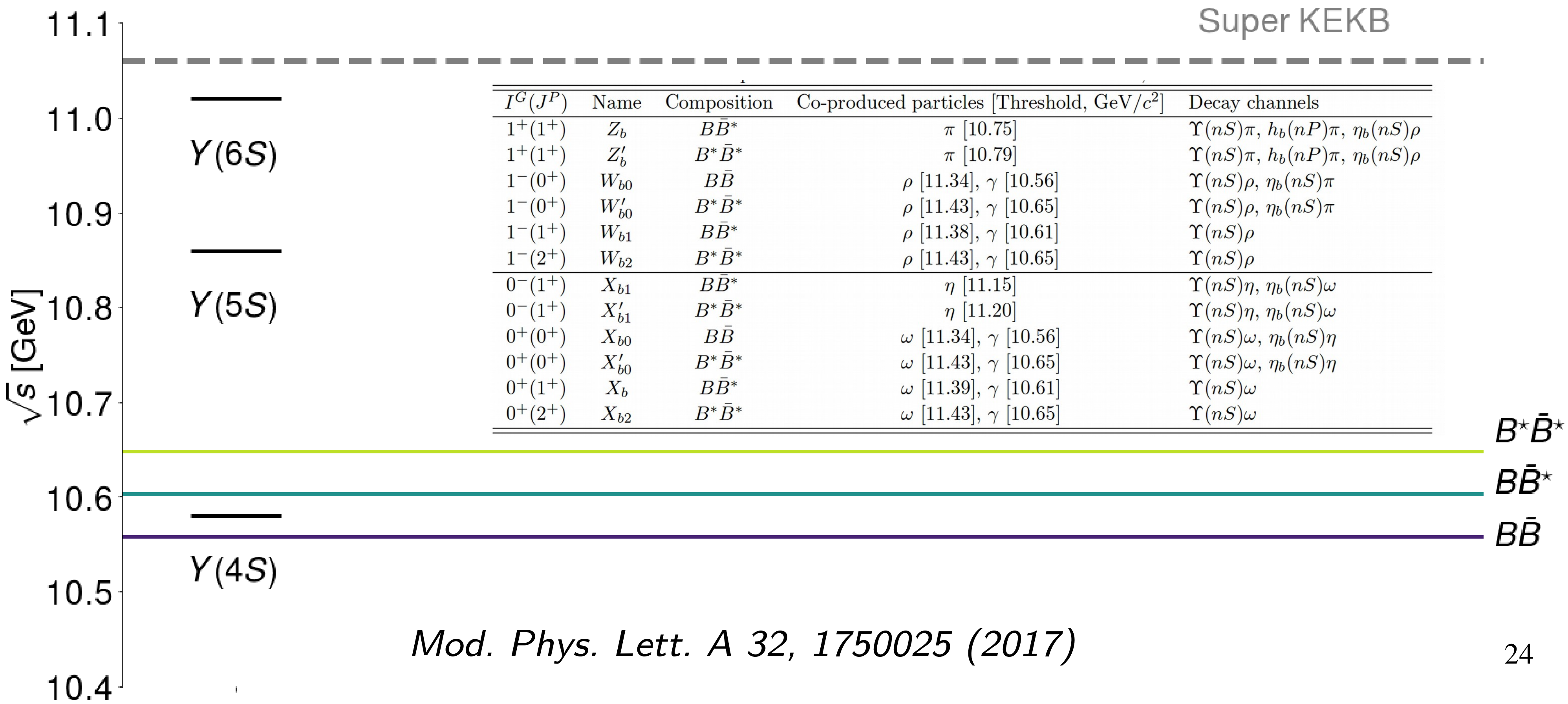
Threshold exploration

Precision spin-singlet spectroscopy

High-statistics scan

Υ(5S) and Υ(6S): new exotica

If the Z_b is a loosely bound state, then several other molecules must appear



$I^G(J^P)$	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]	$\Upsilon(nS)\rho$
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$0^-(1^+)$	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]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
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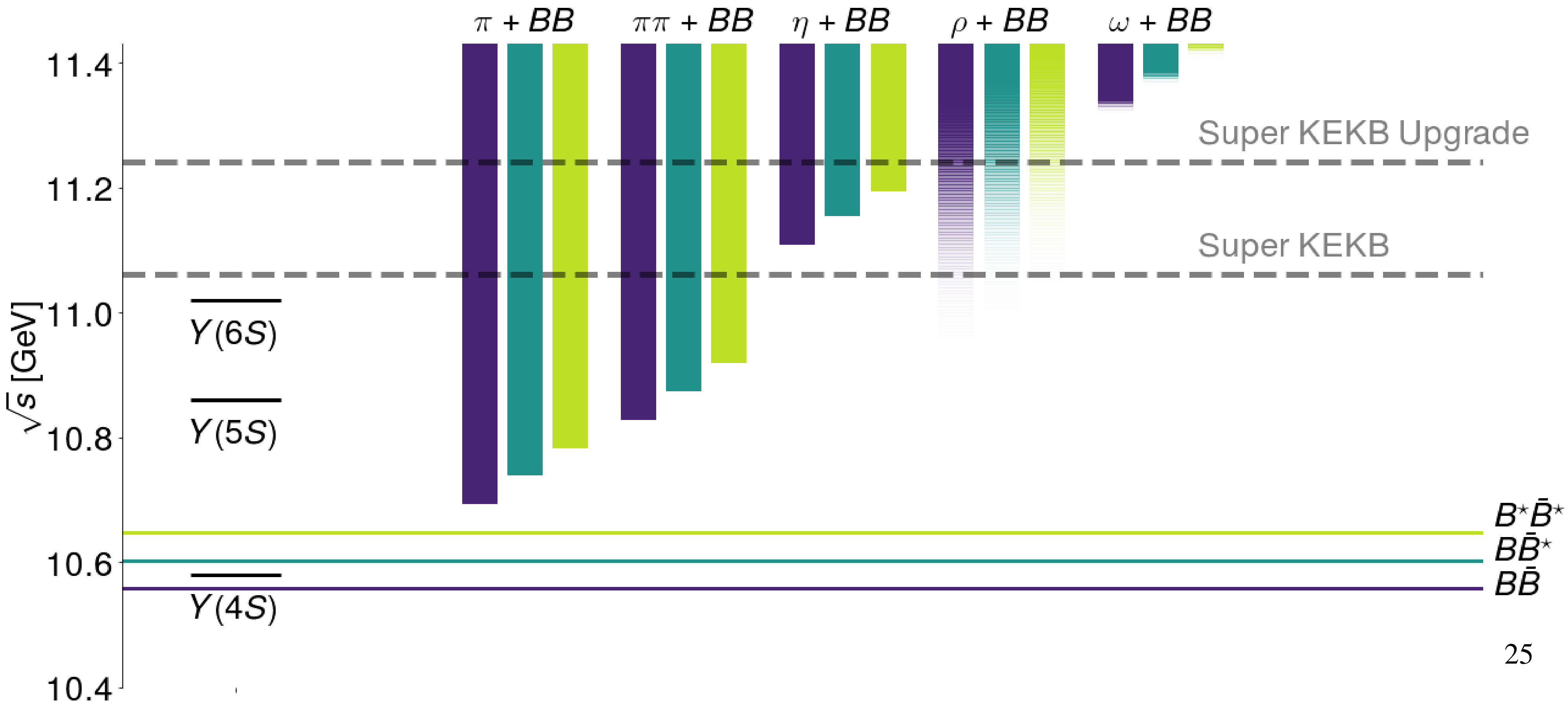
$0^+(1^+)$	X_b	$B\bar{B}^*$	ω [11.39], γ [10.61]	$\Upsilon(nS)\omega$
$0^+(2^+)$	X_{b2}	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$

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

$\Upsilon(5S)$ and $\Upsilon(6S)$: new exotica

Almost all the production thesholds are beyond our reach



Exotica: how you can save the day

1) Calculate the width of the radiative production modes

$\Upsilon(5S) \rightarrow \gamma$ exotica

$e^+e^- \rightarrow \gamma$ exotica

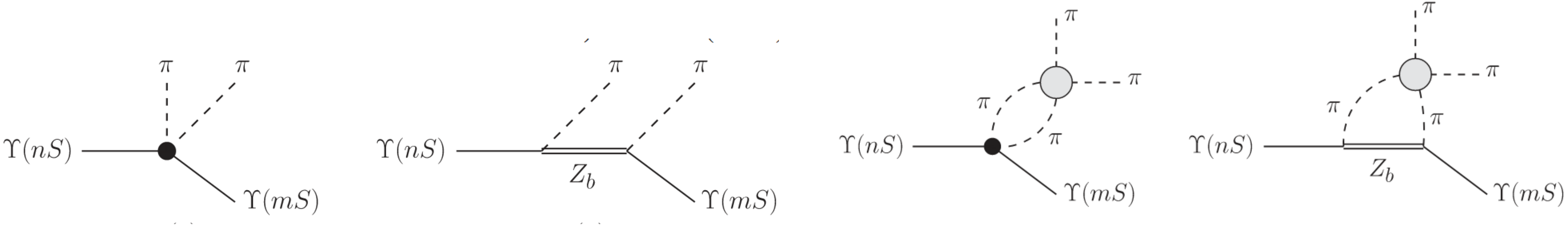
Exotica: how you can save the day

1) Calculate the width of the radiative production modes

$\Upsilon(5S) \to \gamma$ exotica

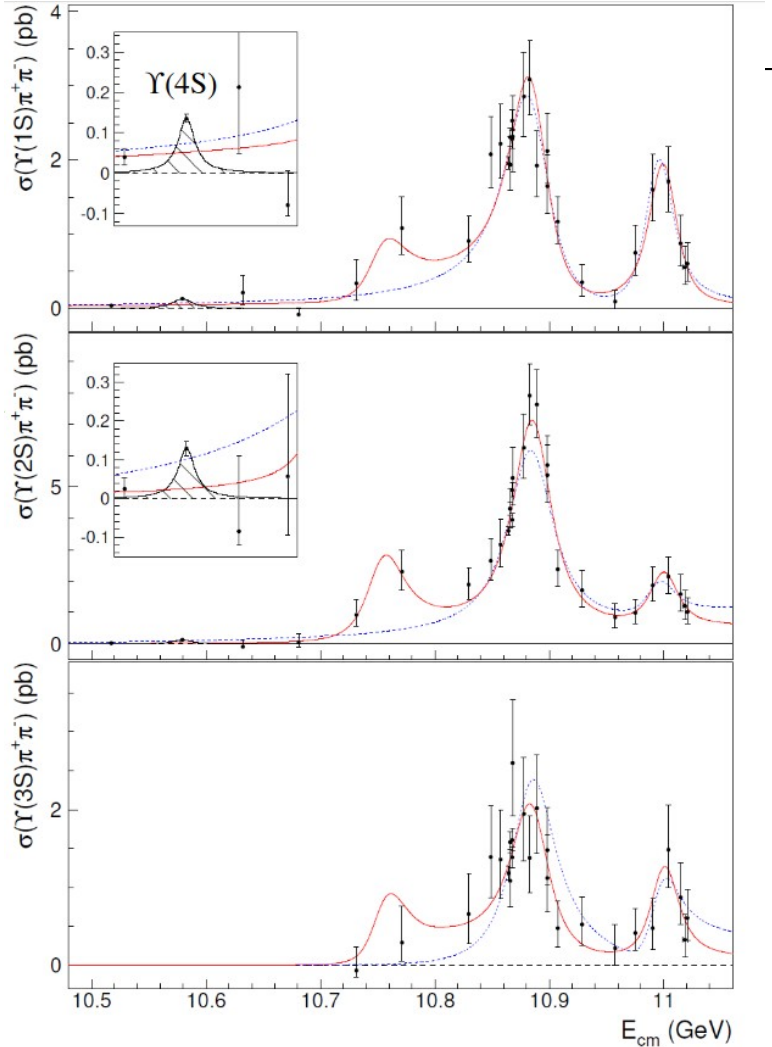
$e^+e^- \to \gamma$ exotica

2) Calculate corrections induced by the exotica to lower energy transitions like $\Upsilon(1S) \to \pi\pi/\eta\ \Upsilon(1S)$



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

More accessible exotica



→ Structure at ~10.75 D wave state or something more?
arXiv:1905.05521

The Belle II scan program (*arXiv:1610.01102*):

→ 50 points
→ 10 fb-1 each (10 times Belle)
→ Average beam energy precision < 1 MeV

Υ(nS) annihilations

Similarities between hadronic collisions and bottomonium annihilations

0) Mostly $\Upsilon \to ggg$

PRD76 012005 (2007)

1) High density

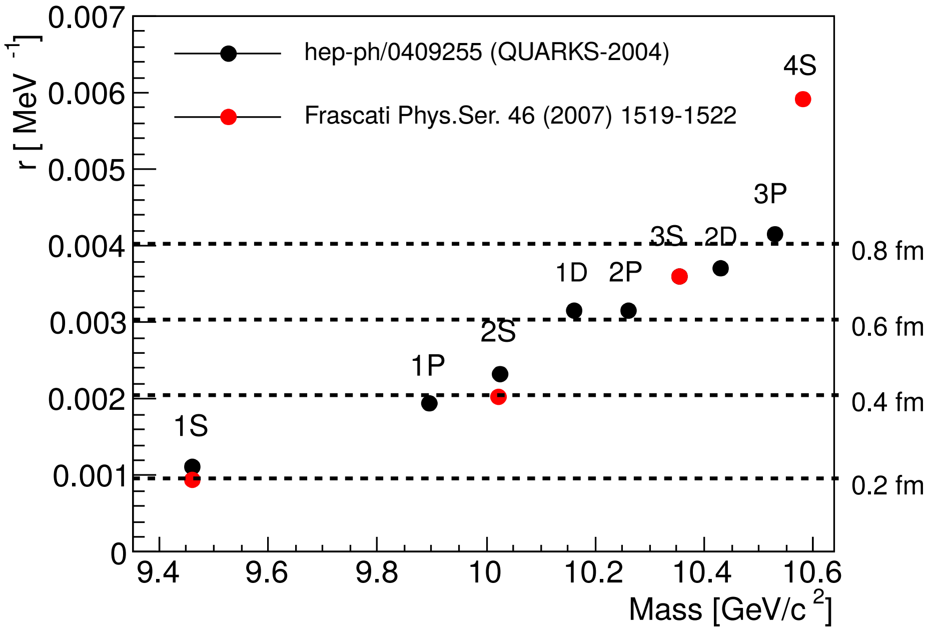
Frascati Phys. Ser. (2007) 1519-1522

2) Baryon and strangeness enhancement

PRD76 012005 (2007)

3) Large Production of anti-nuclei

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



Charmonium from bottomonia

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

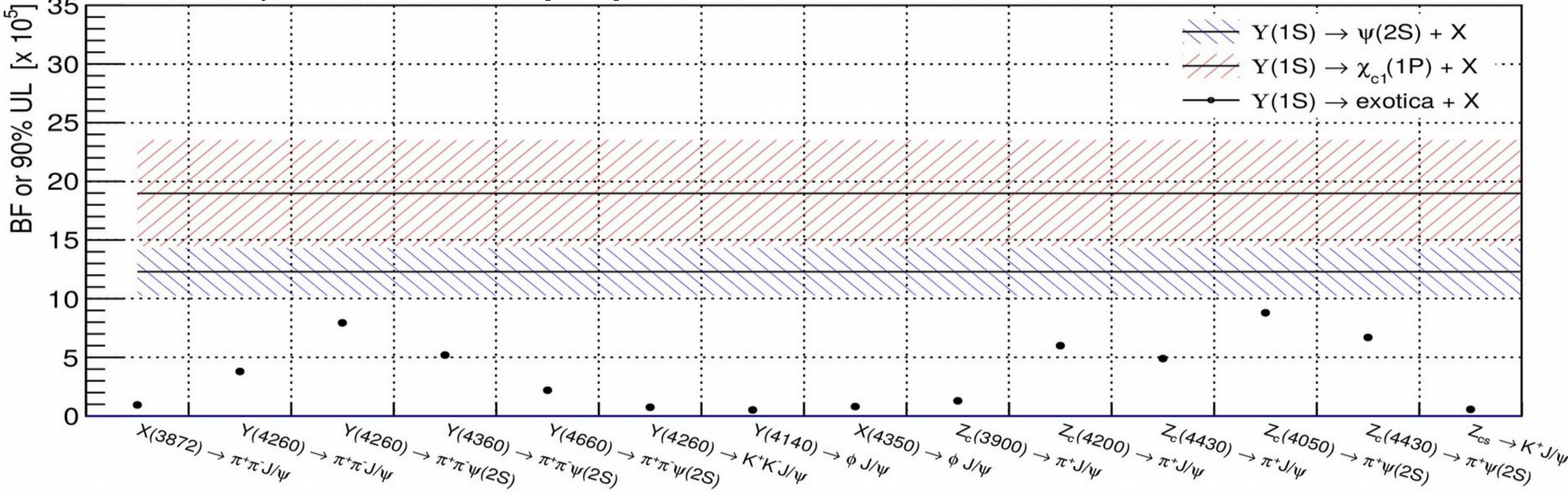
$\rightarrow$ Only X(3872) has been seen in prompt production (in $p\bar{p}$ and pp collisions)

Charmonium from bottomonia

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

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

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



Theoretical predictions on Y → exotica + hadrons?

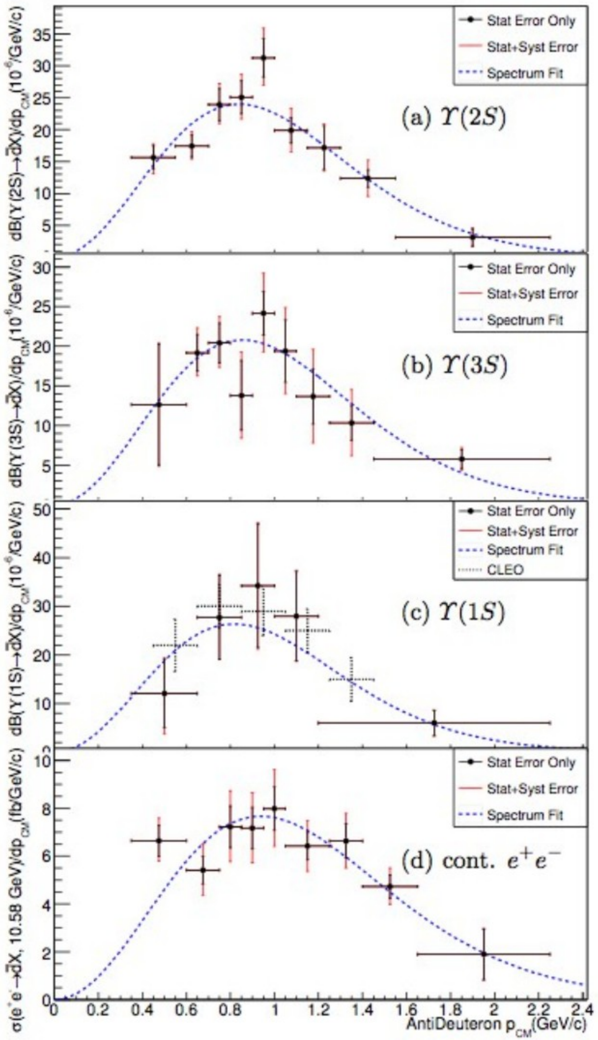
Another feature: deuteron production

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

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

Deuteron production ~ 10 x more likely in Y(nS) than in $q\bar{q}$

Theoretical models for coalescence in very small volumes?



Conclusions

The Belle II experiment has finally started the data taking

The Belle II quarkonium program includes

$\rightarrow$ 50 ab^{-1} for charmonium ISR, double charmonium, $B \rightarrow c\bar{c}\, X$ ...

$\rightarrow$ 500 fb^{-1} of scan above Υ(5S)

$\rightarrow$ 300 fb^{-1} of Υ(3S)

$\rightarrow$ 100 fb^{-1} of Υ(6S)

$\rightarrow$ 1 ab^{-1} of Υ(5S)

… However, the schedule is still under discussion and theoretical support is very welcome…

A very personal wish list

- Lineshape of the $X(3872) \to D\bar{D}\pi$

- $Y(nS) \to (c\bar{c})_{exotic} + \text{hadrons}$

- $(b\bar{b}) \to (c\bar{c})(c\bar{c})$

- Deuteron formation in small volumes

- hyperon-hyperon correlation functions in small volumes

- $Y(5S, 6S) \to \gamma\ (b\bar{b})_{exotic}$

- $\Gamma[\eta_b(1S) \to \gamma\gamma]$

The end

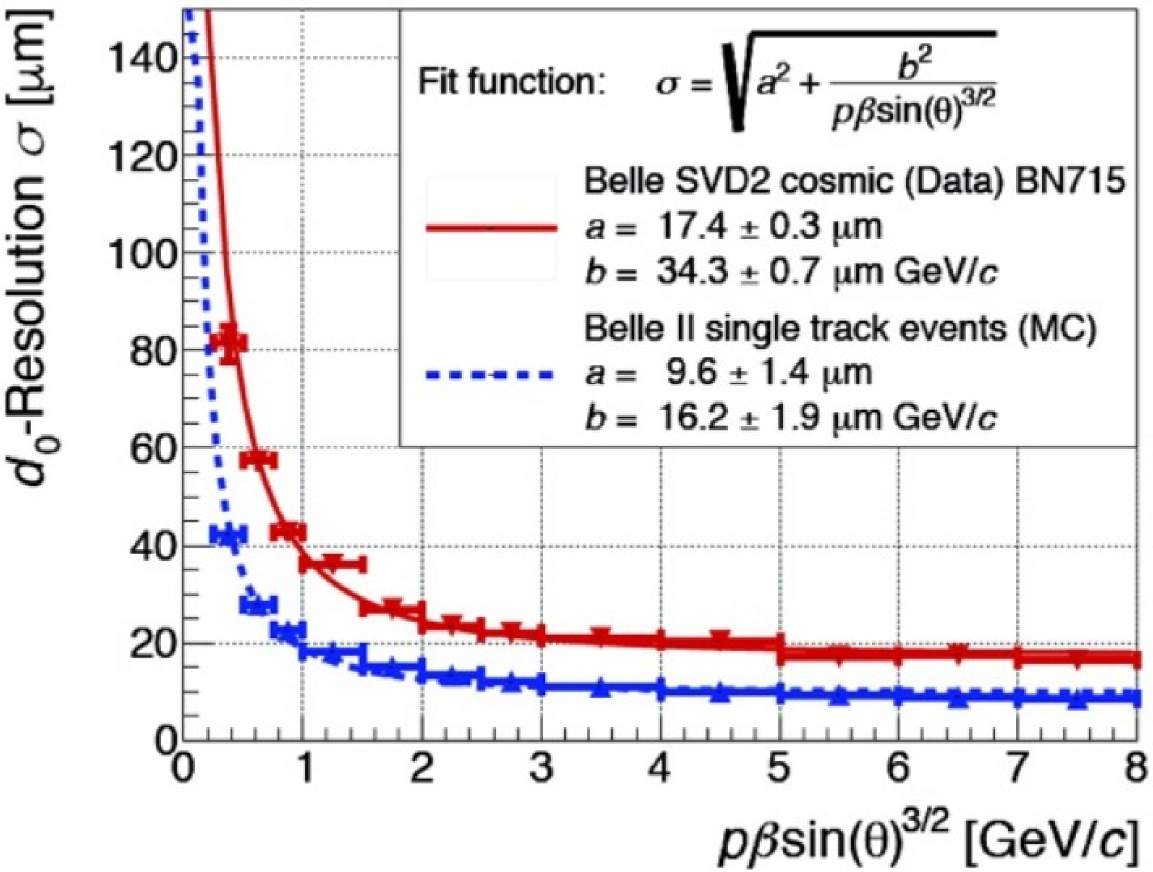
arXiv:1808.10567

Tracking and vertexing

→ More precise

Particle identification

→ Much more powerful



Belle VS Belle II

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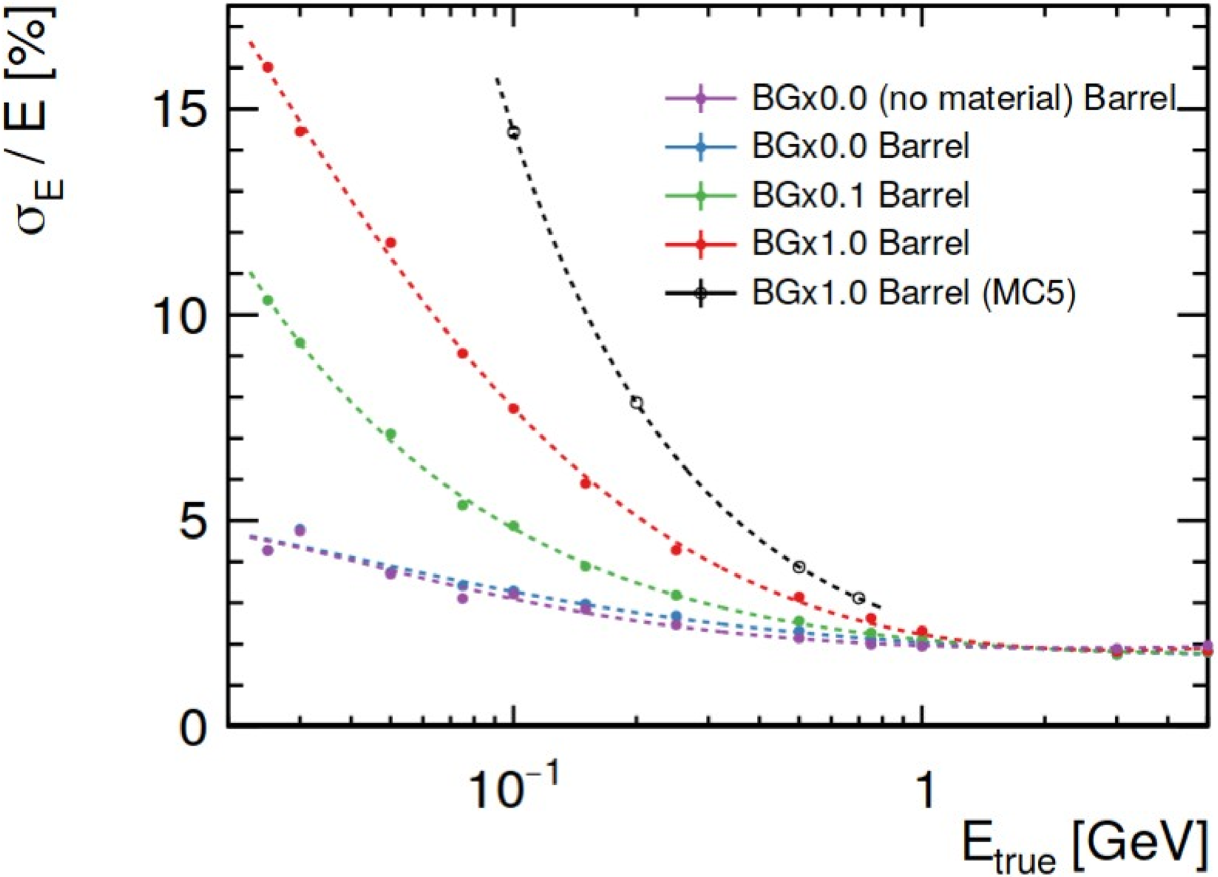
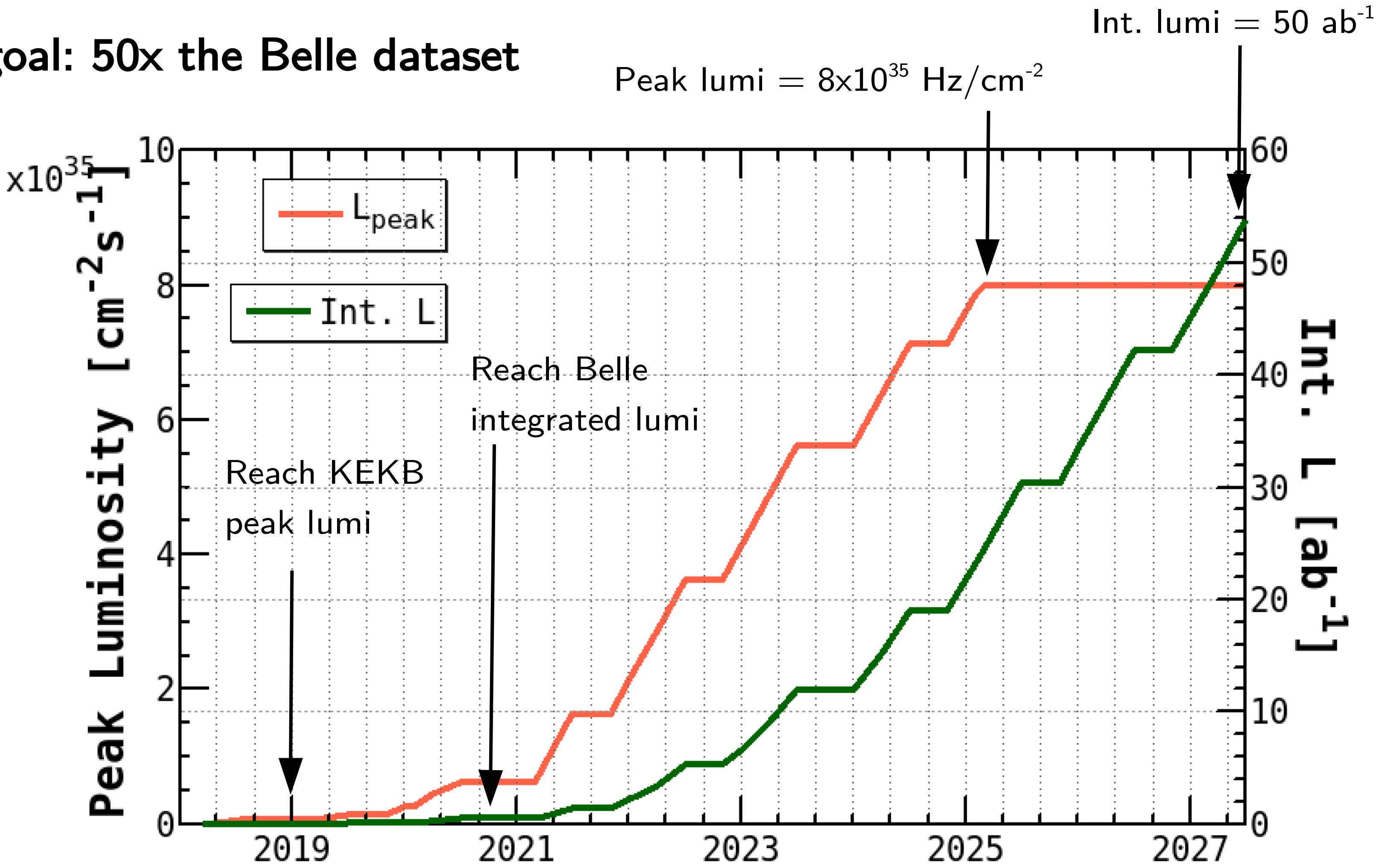


Calorimetry

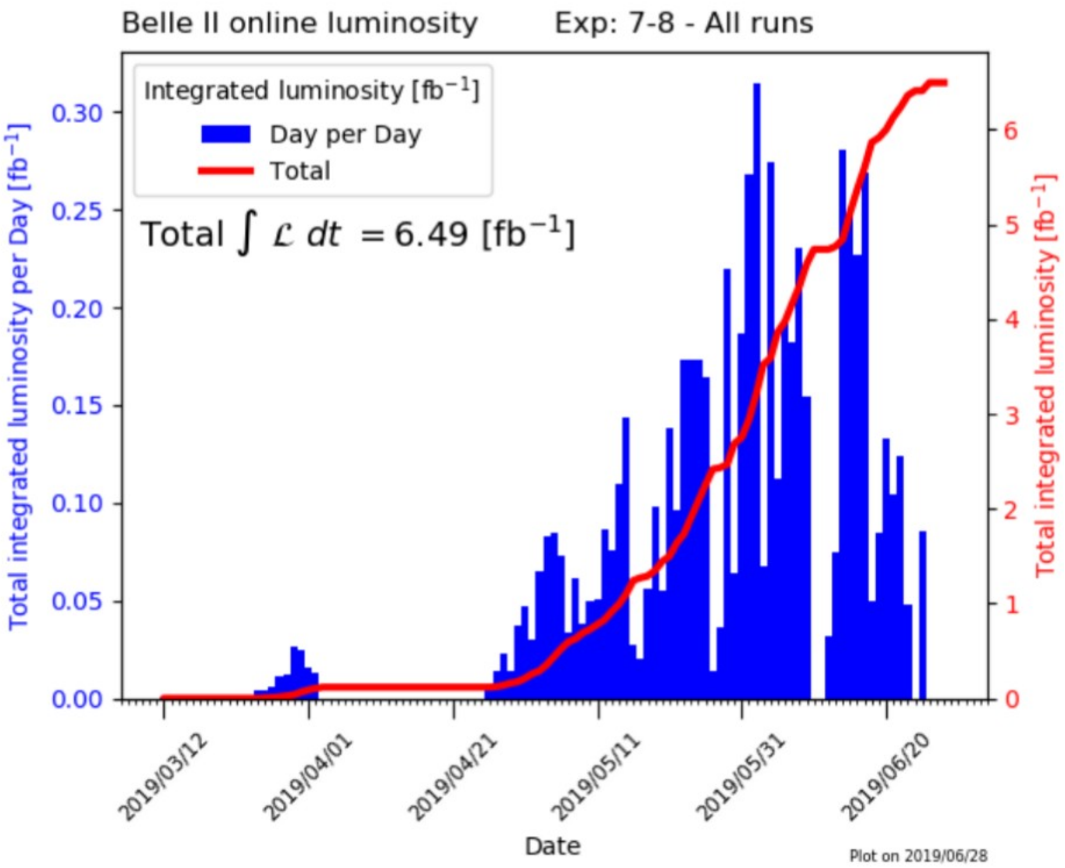
→ Slightly worst (Better reconstruction, but more backgrounds)

Belle II: a super-B factory

Final goal: 50x the Belle dataset



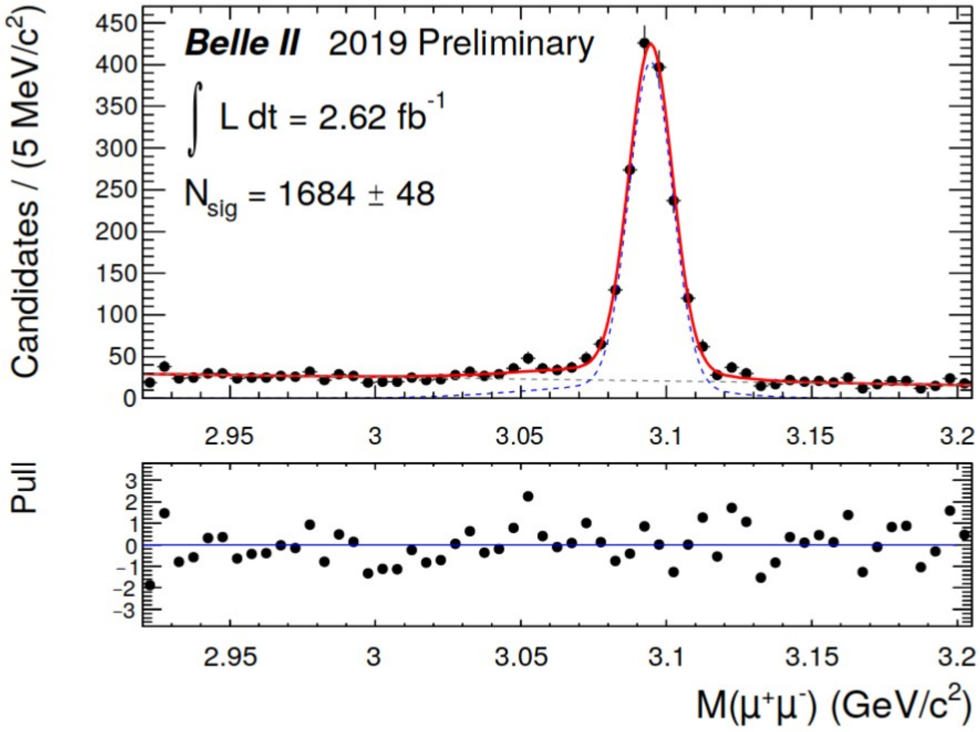
First data with full detector

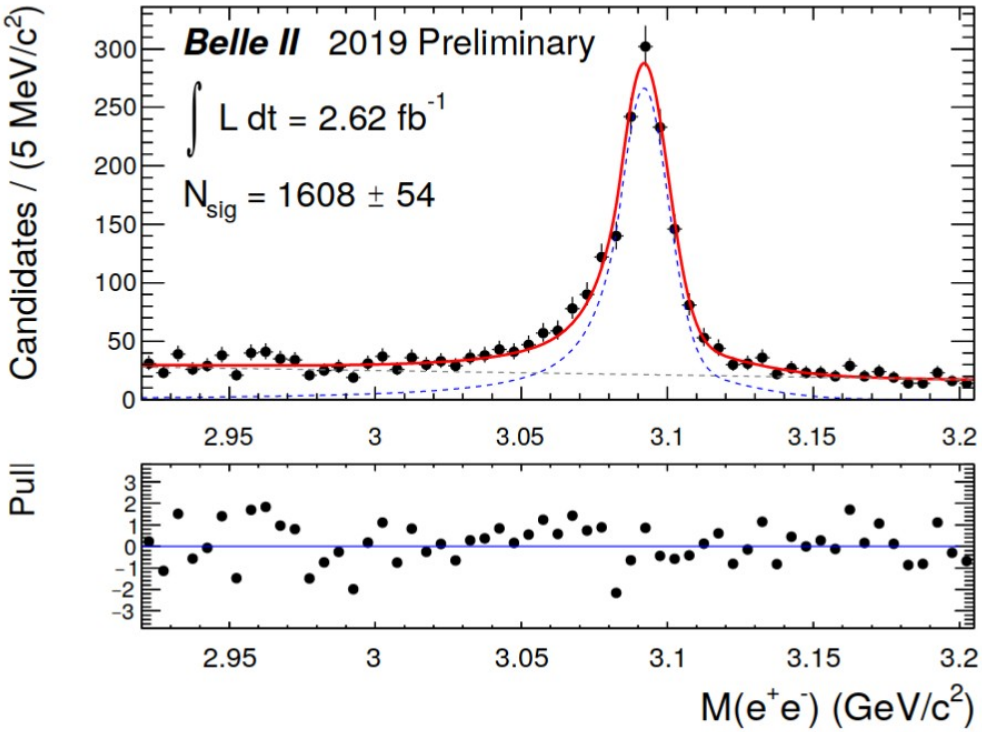


→ ~0.015% of the final goal

→ Only 4S and 4S – 30 MeV

First Quarkonia!





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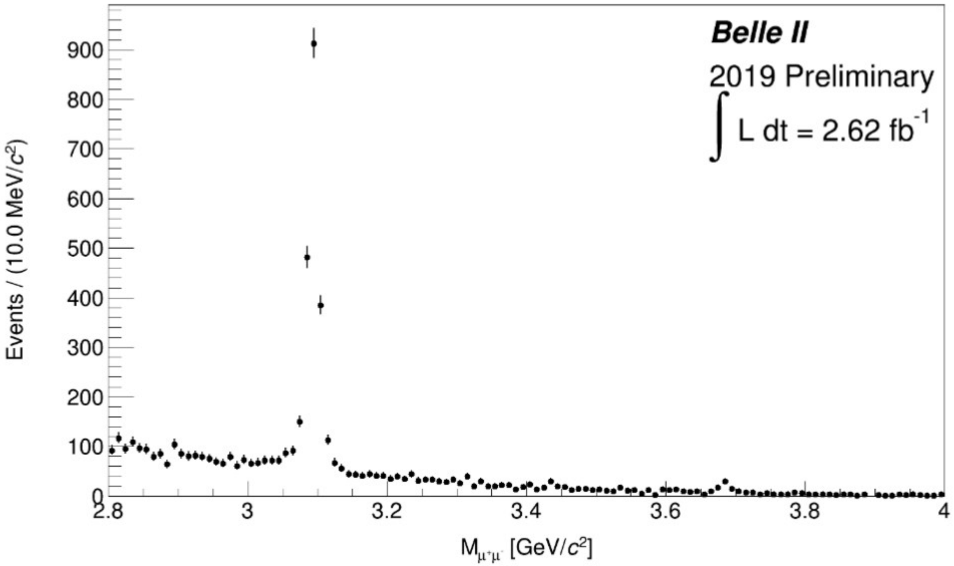
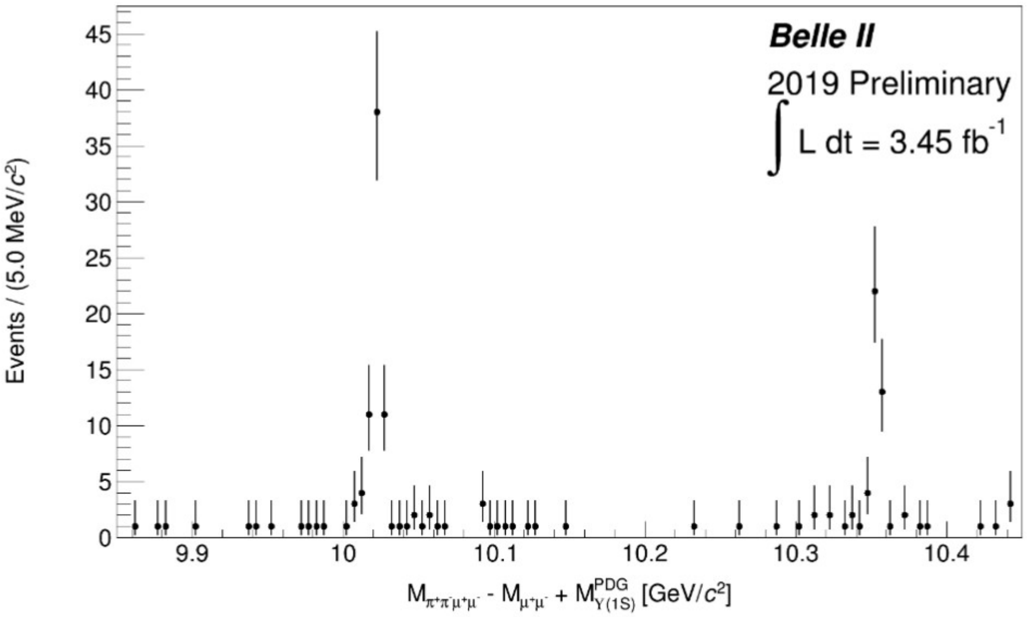
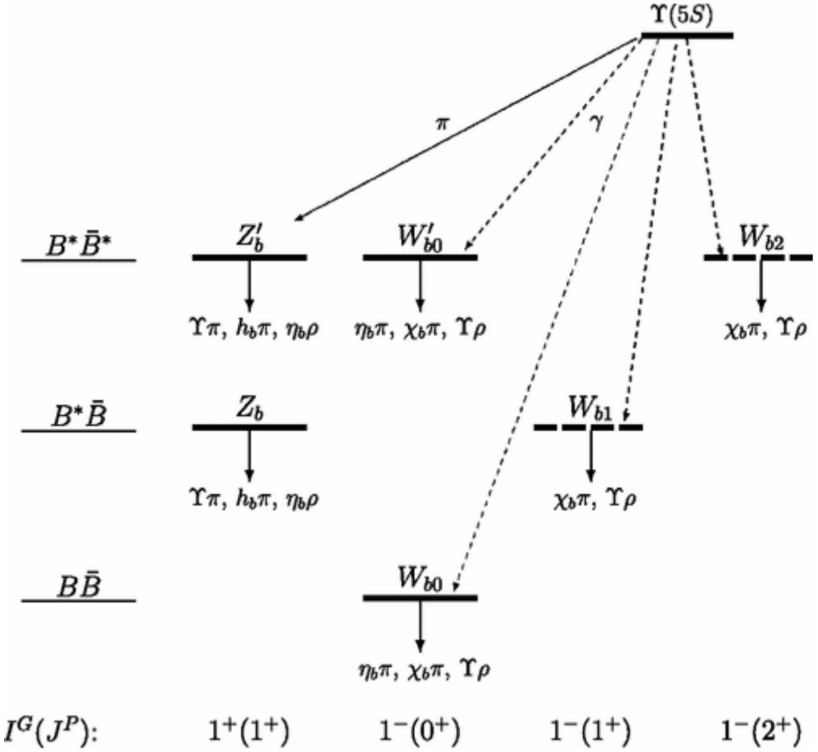




$\Upsilon(5S)$ and $\Upsilon(6S)$: new exotica

→ If the Z_b is a loosely bound state, then several other molecules must appear

→ **No predictions on the production rates**



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

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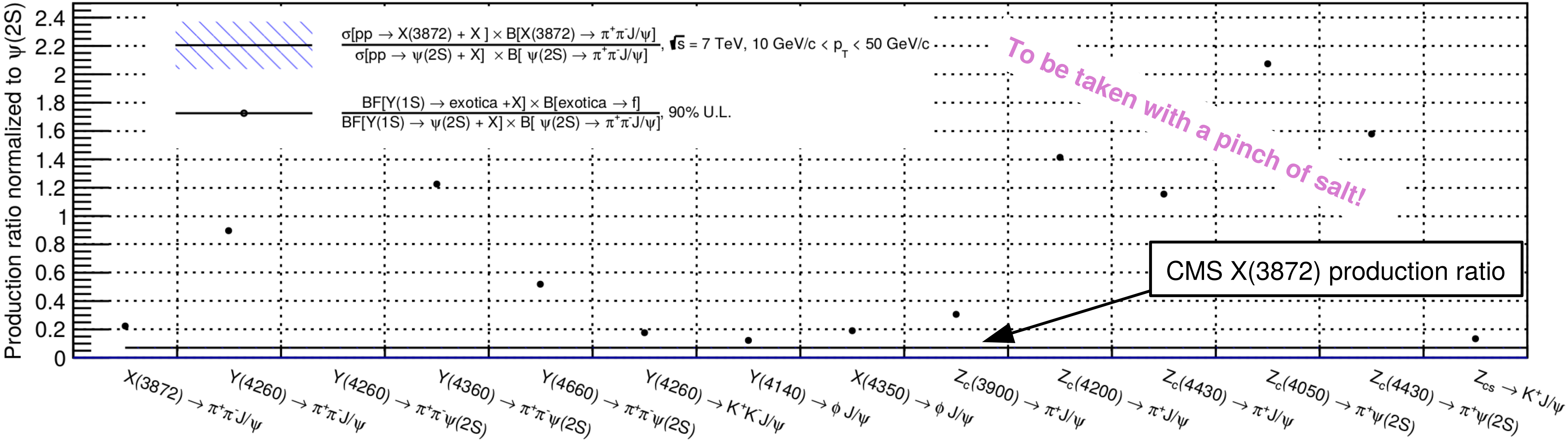
Charmonium from bottomonia

A tentative comparison between Belle and CMS.



Belle II prospects with 300 fb^{-1} of Υ(3S):

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

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

Basic constraints

e^+e^- machines

→ Triggers are quite open

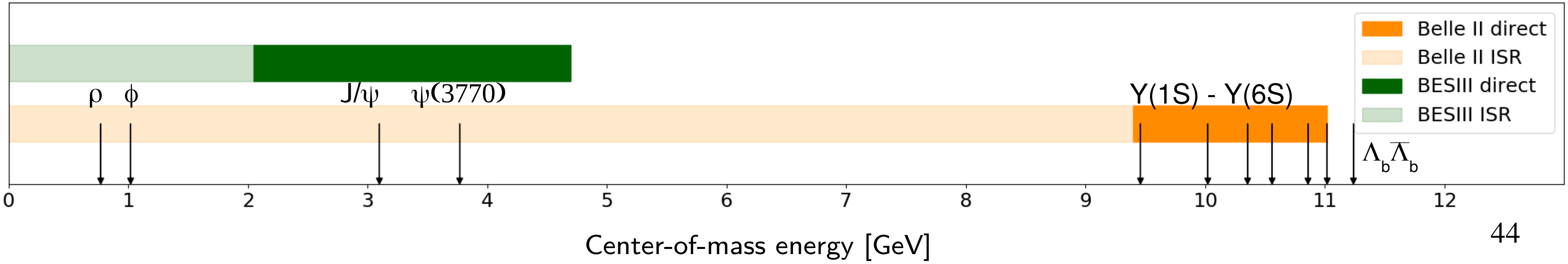
→ High efficiency / Sensitive to very low momentum

→ 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

→ "continuum" Background processes: ee → qq, tt, mm…

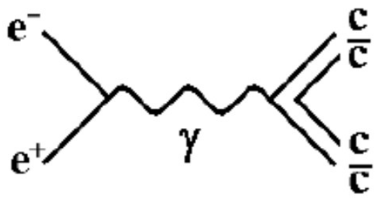


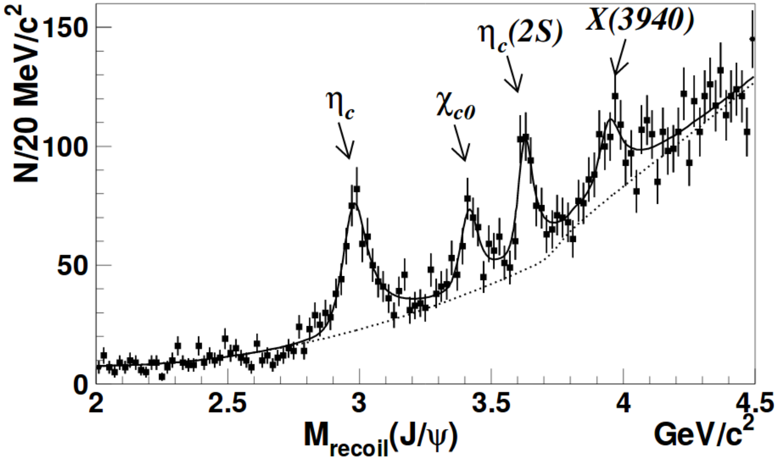
Double charmonium production

Measurable only at Belle II

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

$0^{+/-} + 1^{-/+}$





Belle II prospects (highlights):

→ Inclusive χ_c and η_c recoil to study the vector spectrum

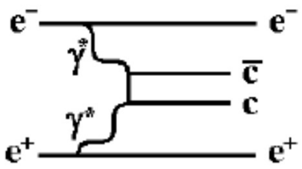
→ η_c branching fractions measurement at 1% precision

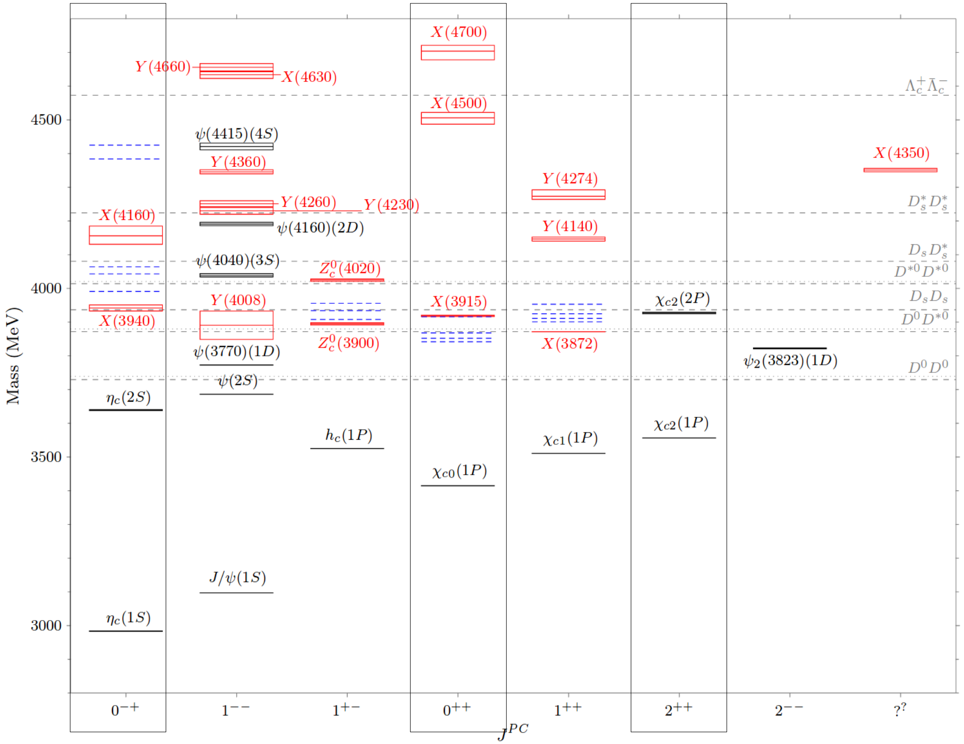
→ J/ψ + D recoil and J/ψ + DD*

Charmonium in $\gamma\gamma$ fusion

$e^+e^- \to (c\bar{c}) \quad e^+ e^-$

$0^{-/+}, 2^+$





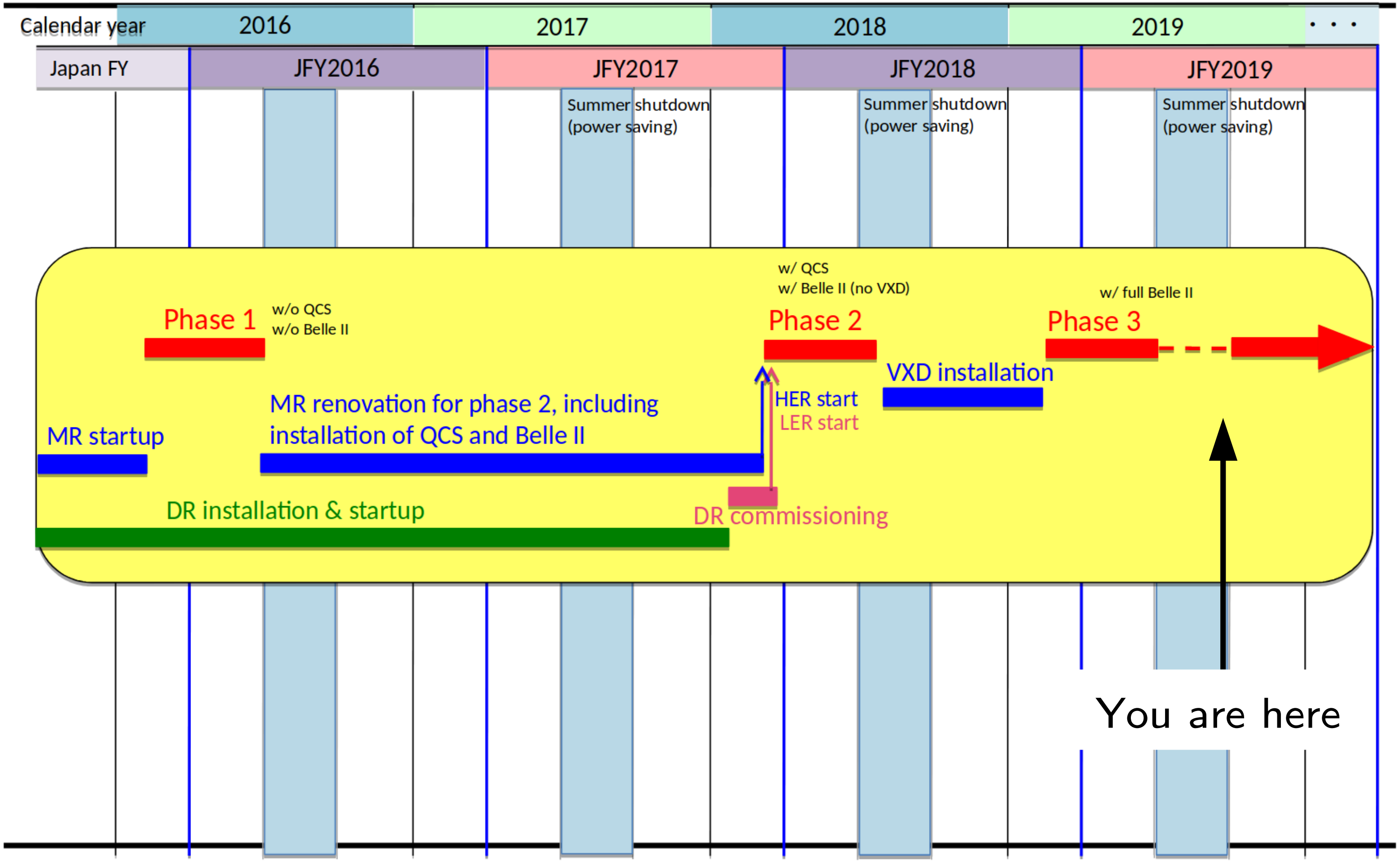
- Measurable only at Belle II
- Gives access to spectrum of the scalar states and $\gamma\gamma^*$ form factors

Belle II prospects:

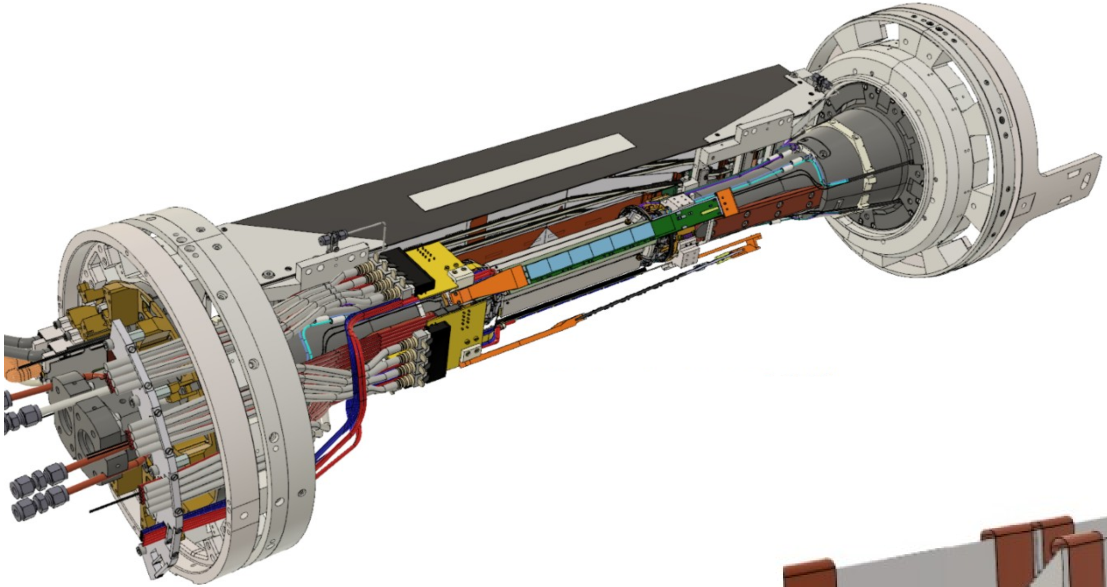
$\to$ Disentangle 2 of the four states seen by LHCb in ϕ J/ψ

$\to$ $\chi_{c0,2}$(2P) properties in $D\bar{D}\gamma$

The Belle II experiment: a timeline



What is "phase 2"?

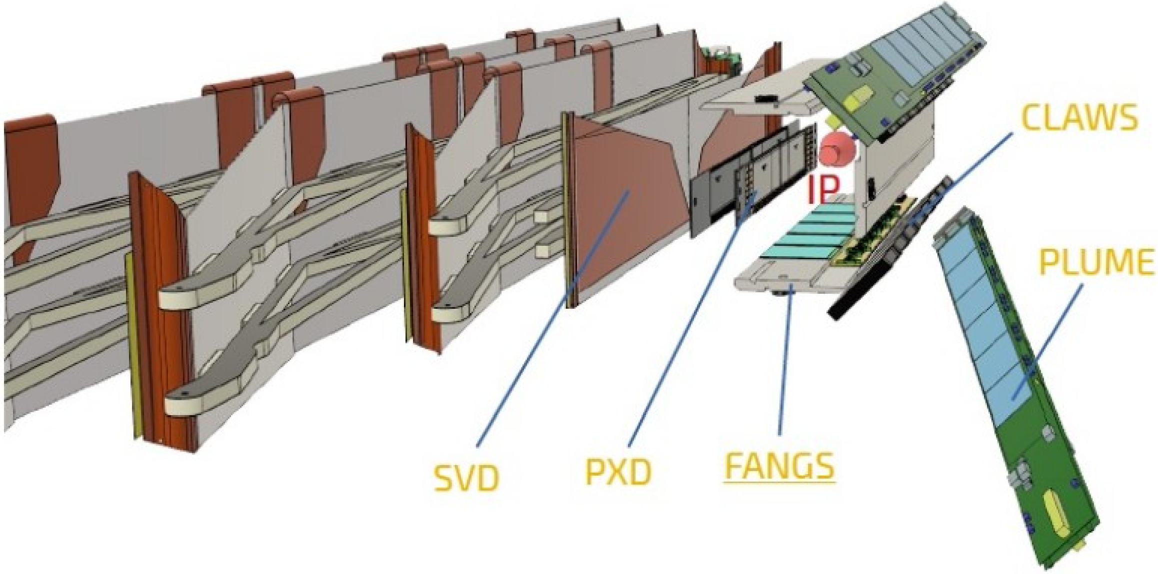


Pilot run with limited vertexing

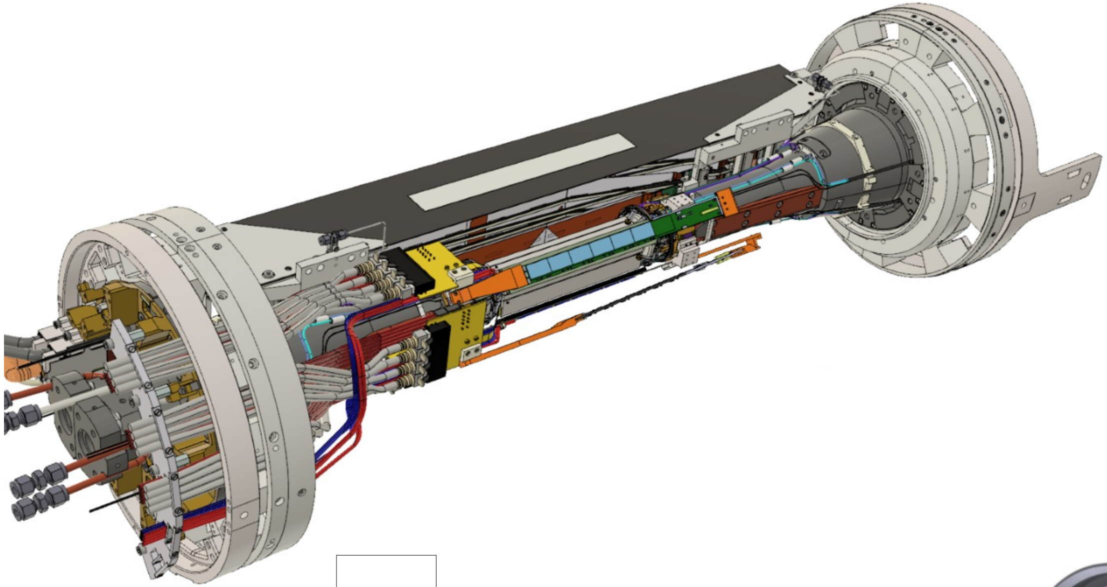
→ Background monitor detectors replacing most of the silicon tracker

→ One full octant of PXD+SVD

(2 + 4 layers)



What is "phase 3"?

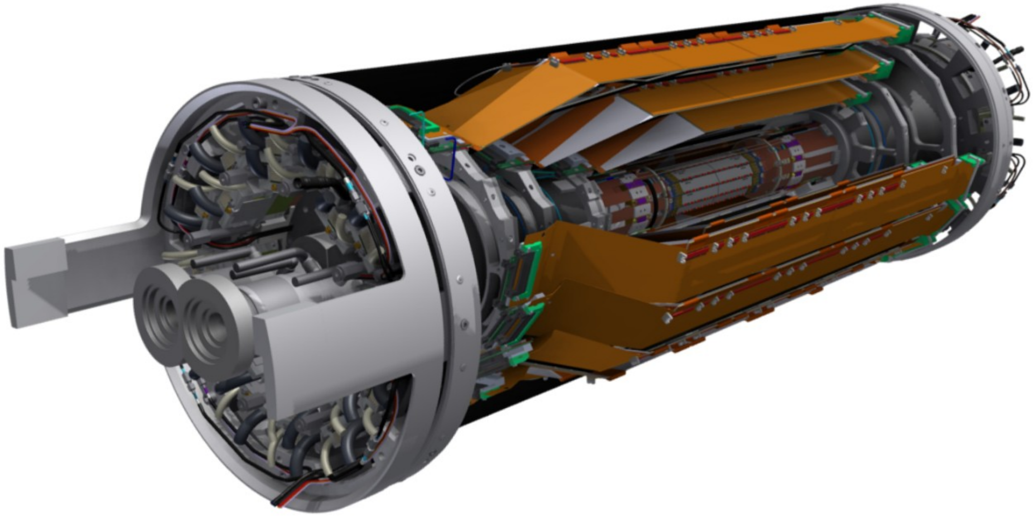


Phase 3 = (almost) final setup for physics

→ 4 full layers of silicon strips

→ 1 + 1/6 full layers of pixel

→ full installation approx in 2020



Nano-beam scheme

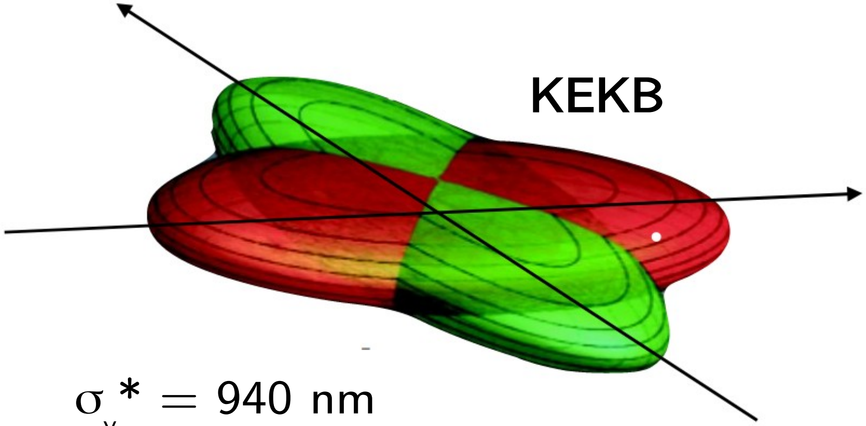
1) Large Piwinski angle by **large θ** and **small σ_x**

$$\phi = \frac{\sigma_z}{\sigma_x} tg\left(\frac{\theta}{2}\right) \approx \frac{\sigma_z}{\sigma_x}\frac{\theta}{2}$$

2) Very small β

$$\beta_y^* \approx \frac{\sigma_x}{\theta} << \sigma_z$$

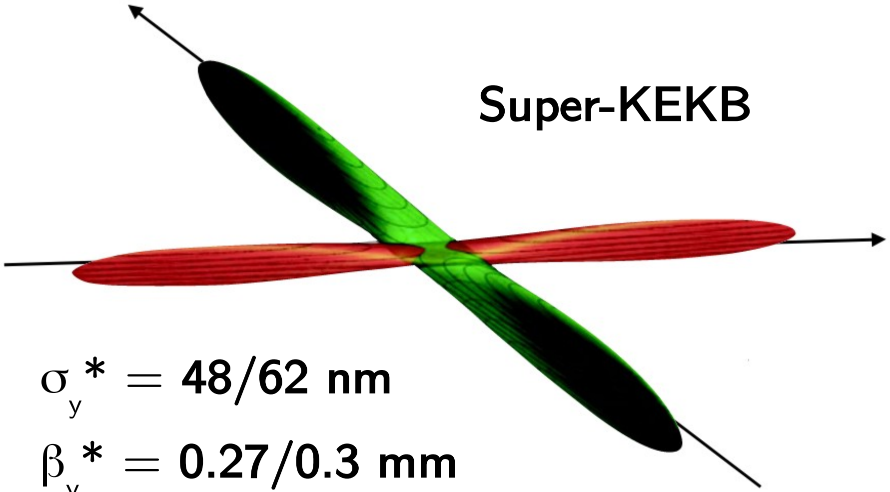
3) Non-linear optics (suppress beam-beam resonances)



$\sigma_y^* = 940$ nm

$\beta_y^* = 5.9$ mm

$\sigma_x^* = 147/170$ μm

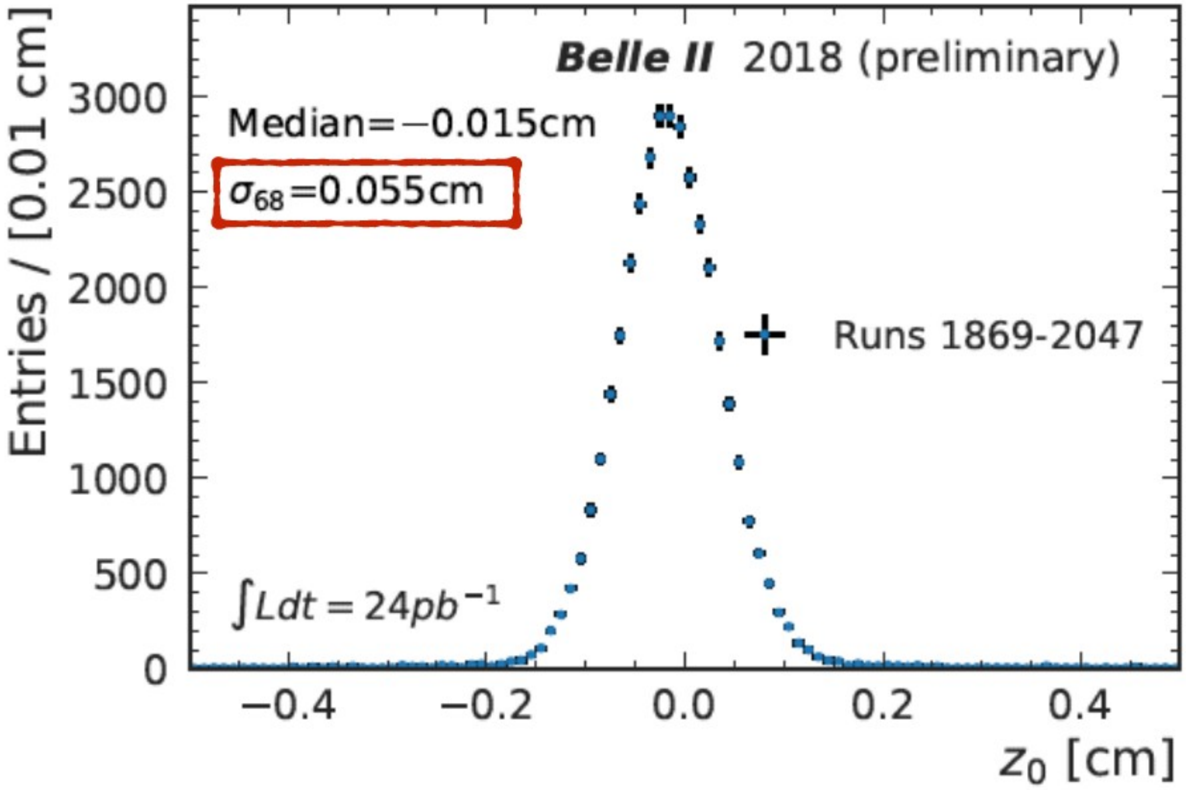


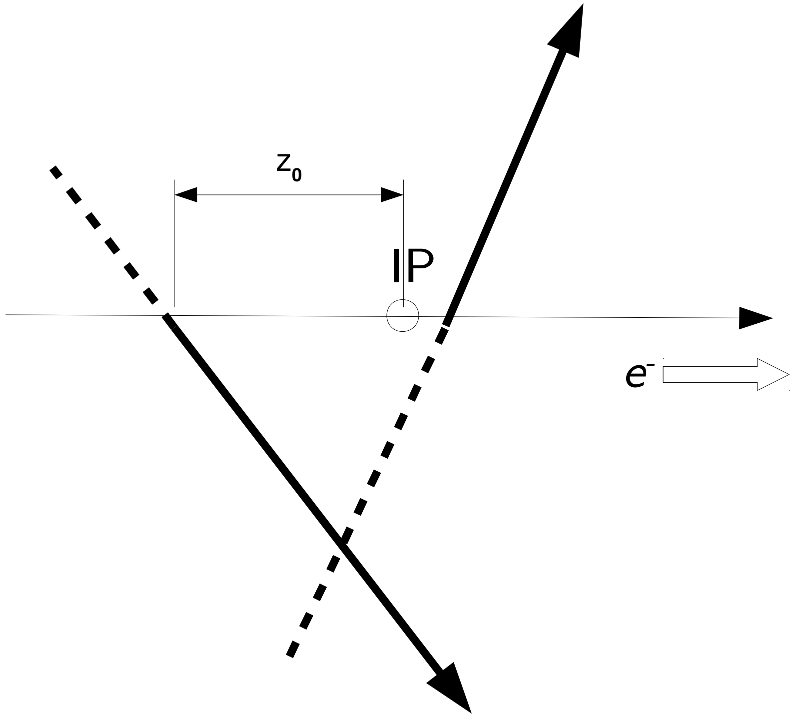
$\sigma_y^* =$ **48/62 nm**

$\beta_y^* =$ **0.27/0.3 mm**

$\sigma_x^* =$ **10.1/10.7 μm**

Interaction region size

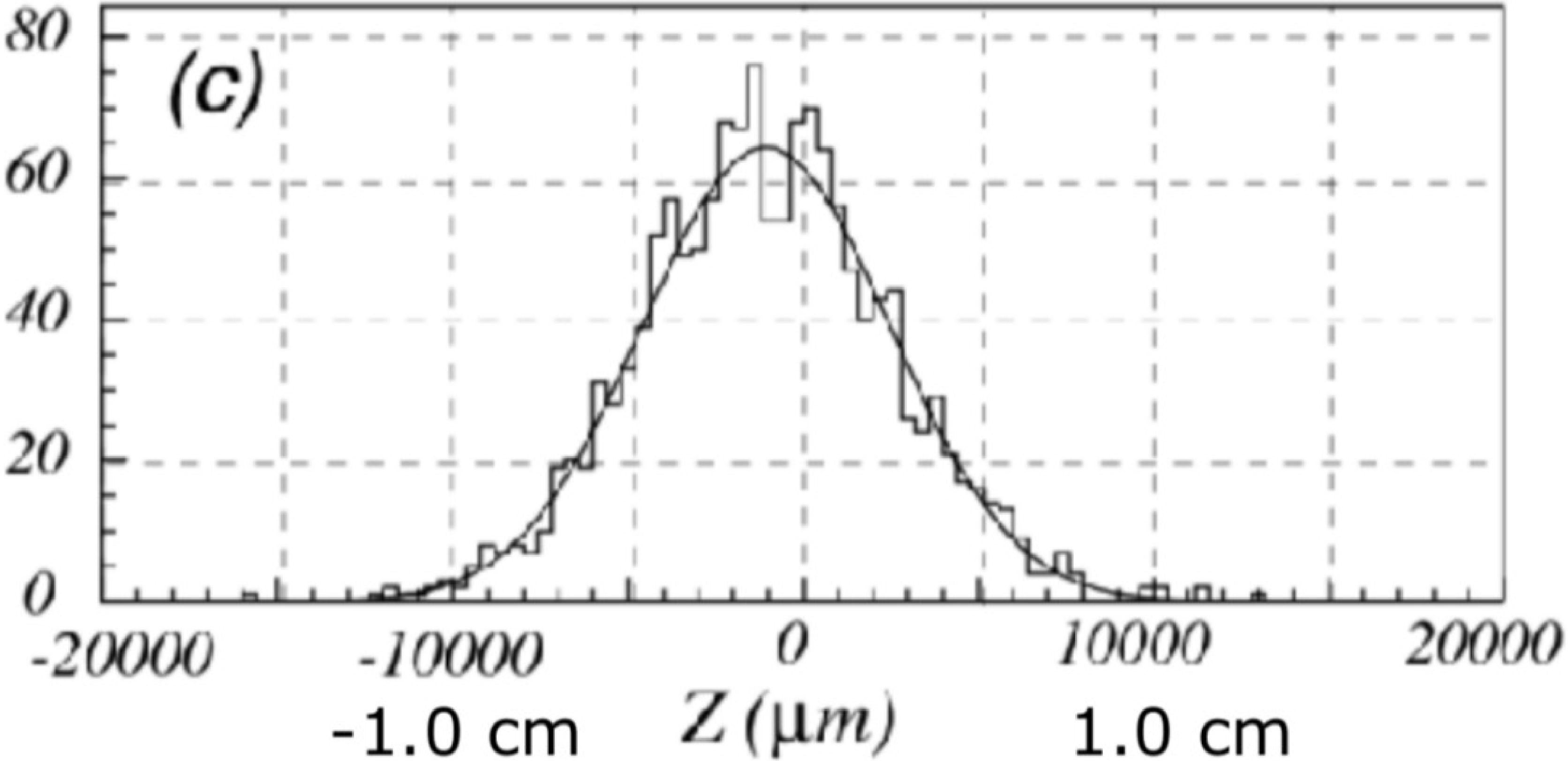




Beam spot ~ 10 times smaller than KEKB

IP size

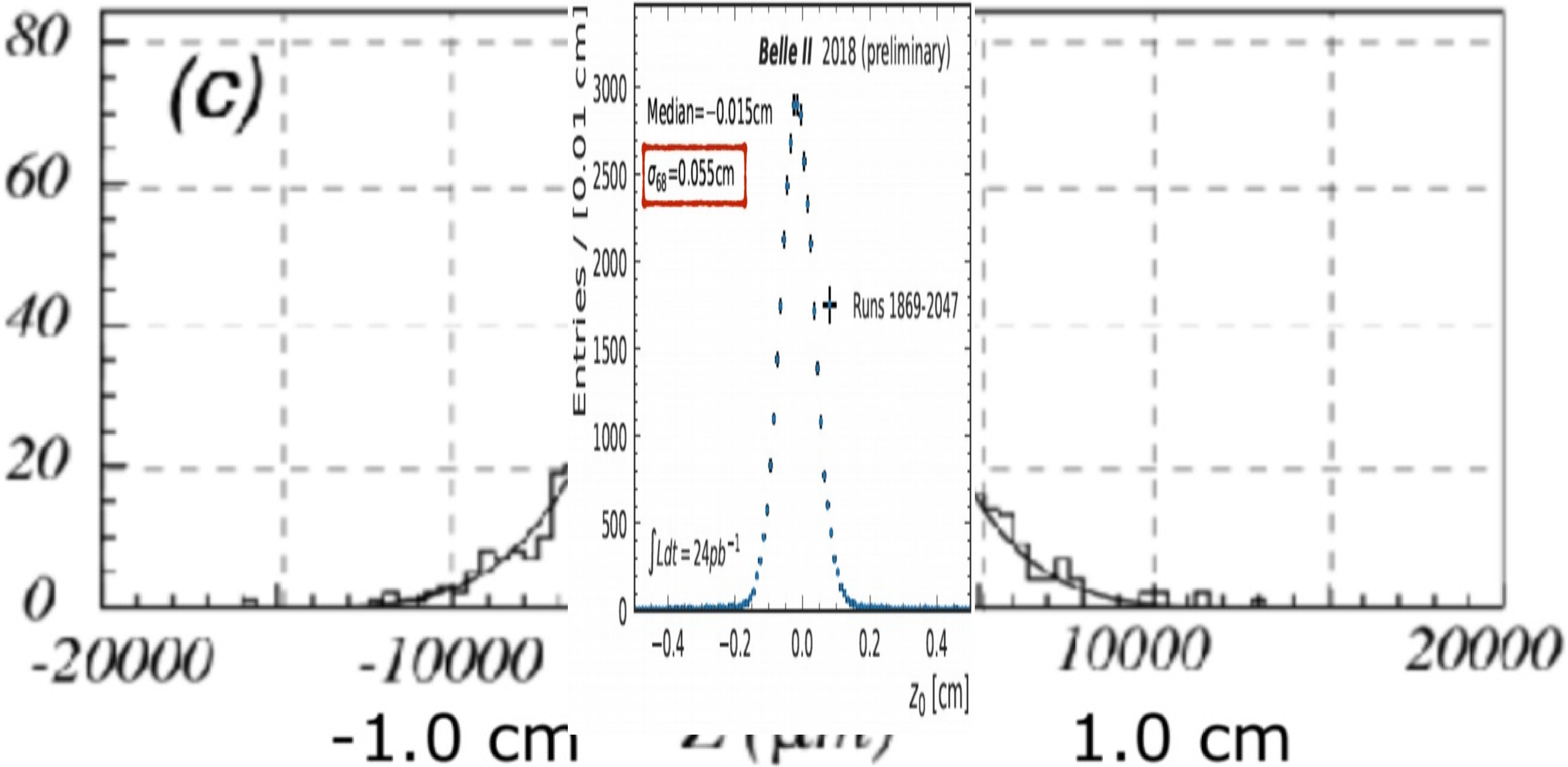
Belle case 1999 data



-1.0 cm 1.0 cm

IP size

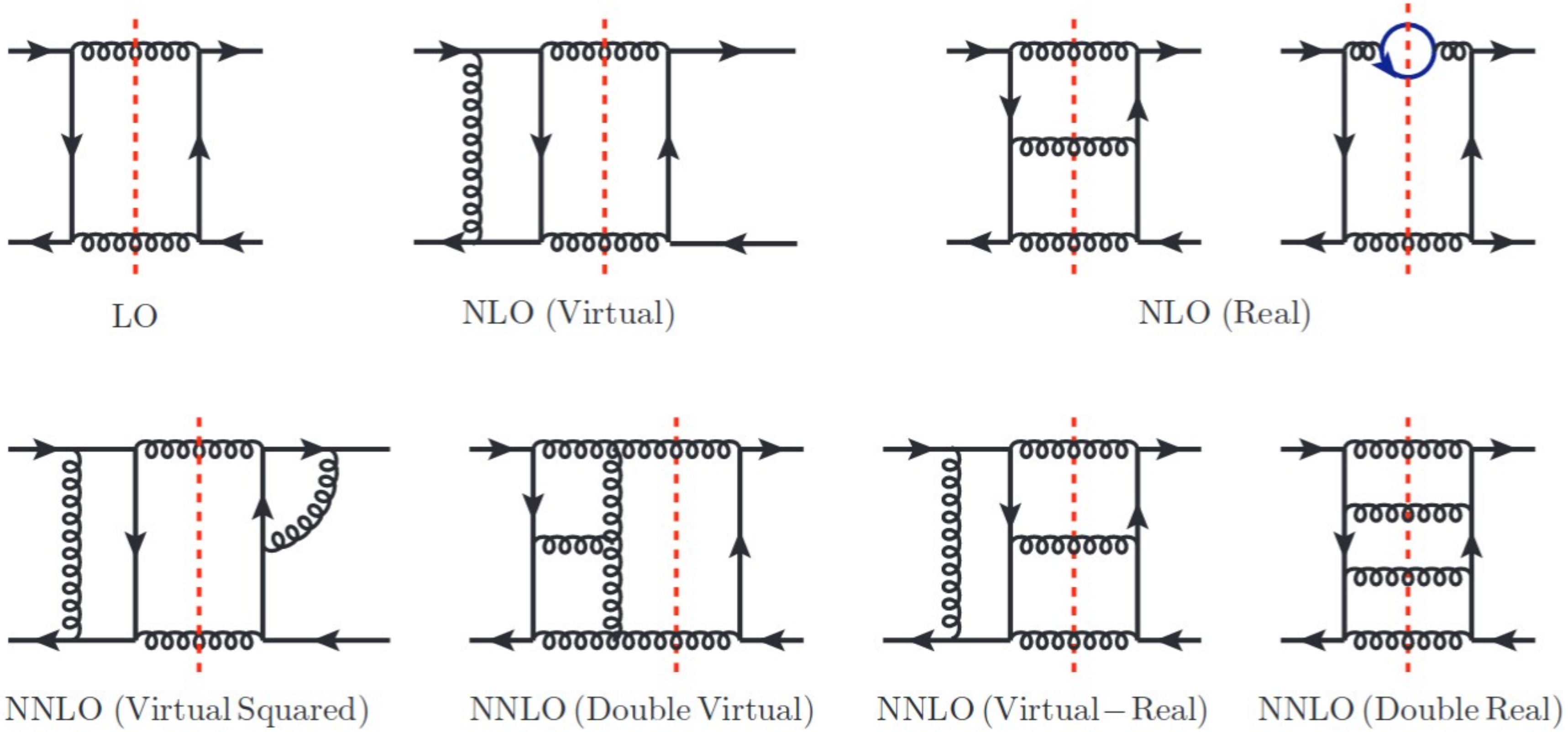
Belle case 1999 data



Ground state width in NRQCD

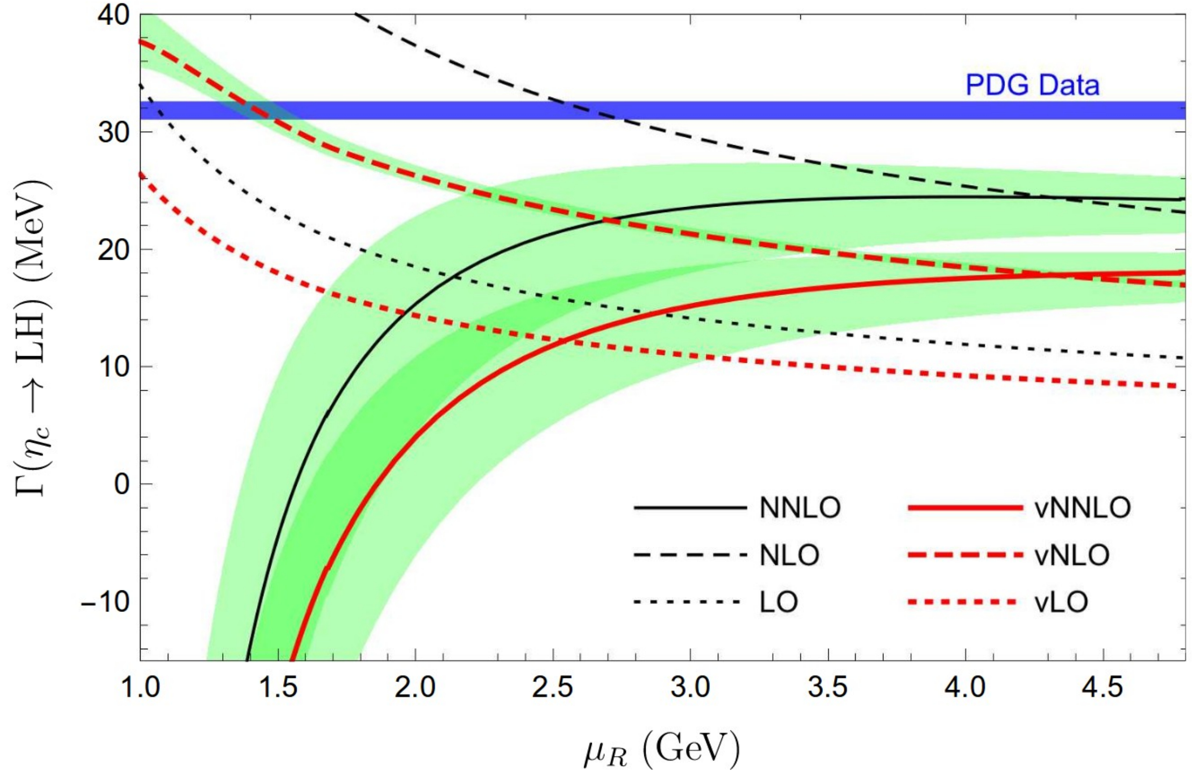
State-of-the art NRQCD: *Phys. Rev. Lett. 119, 252001 (2017)*

$\sim$ 1700 diagrams, $\sim 10^5$ CPU hours of calculation



State of the art results

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



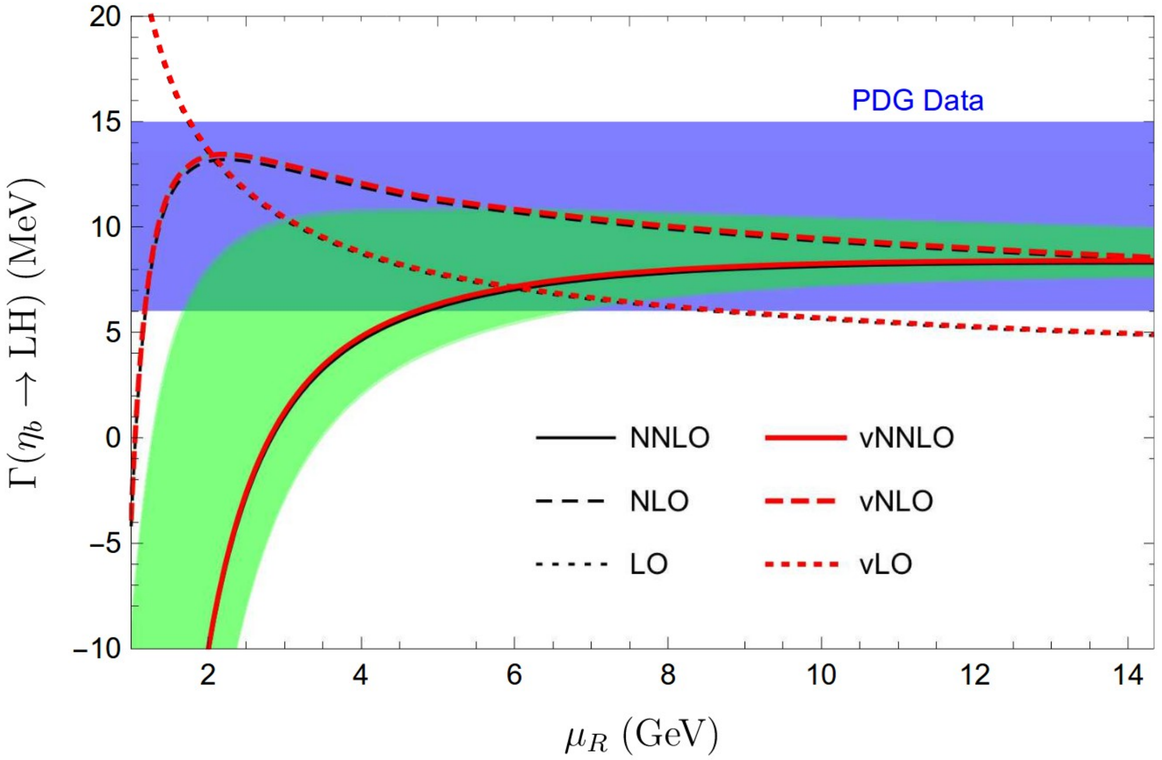
Is charmonium “too relativistic” or is the NRCQD not converging fast enough?

→ **See bottomonium!**

Last Minute note: Brambilla et al. Also find a disagreement between the experiment at their last calculations (arXiv:1810.02586)

State of the art results

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

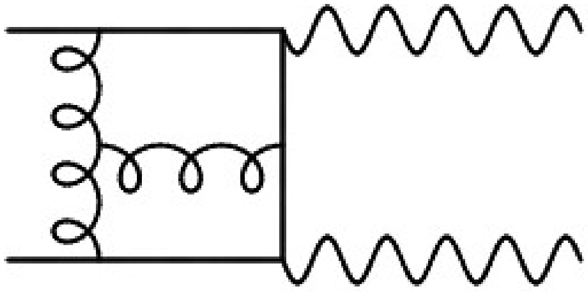


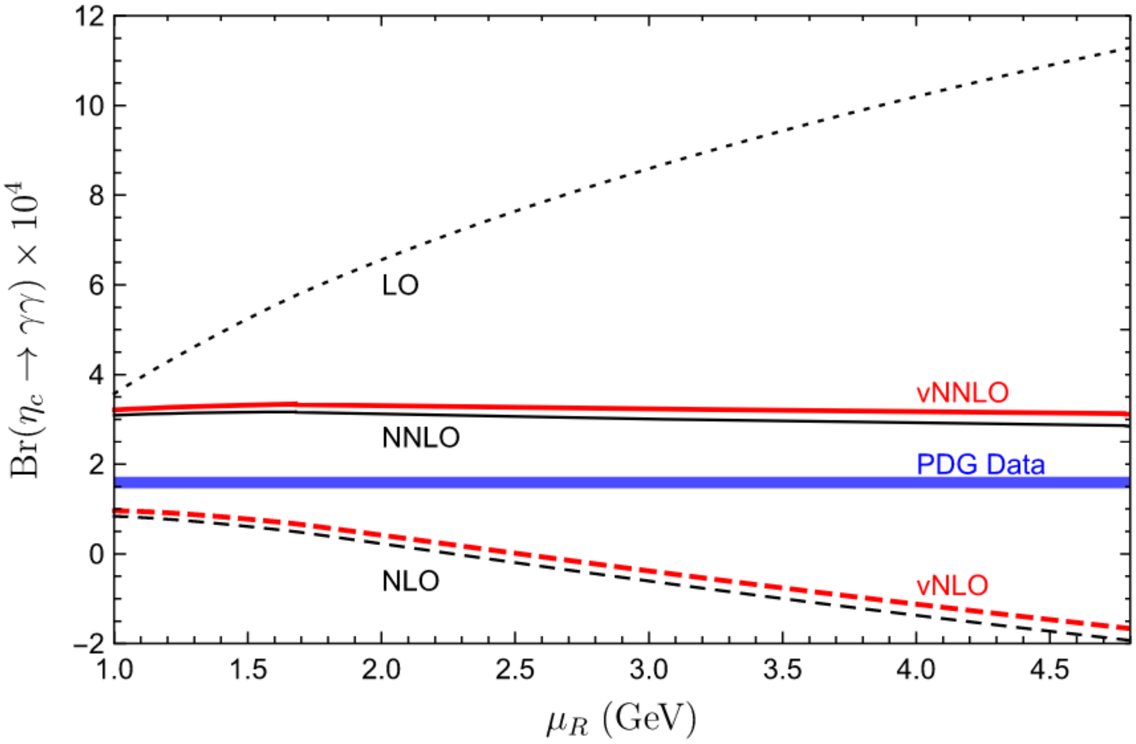
→ **Bottomonium measurements are note yet precise enough!**

The "holy grail" of NRQCD

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

Simpler and cleaner: BR(Ground state $\rightarrow \gamma\gamma$)

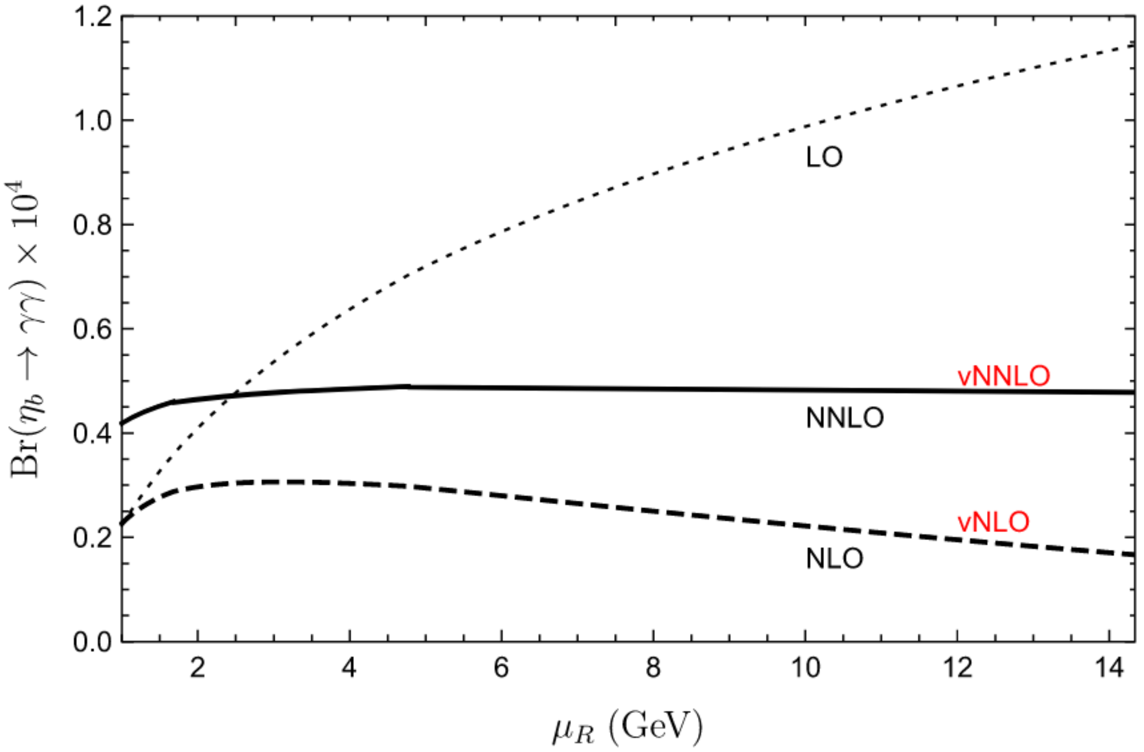




What about the bottomonium?

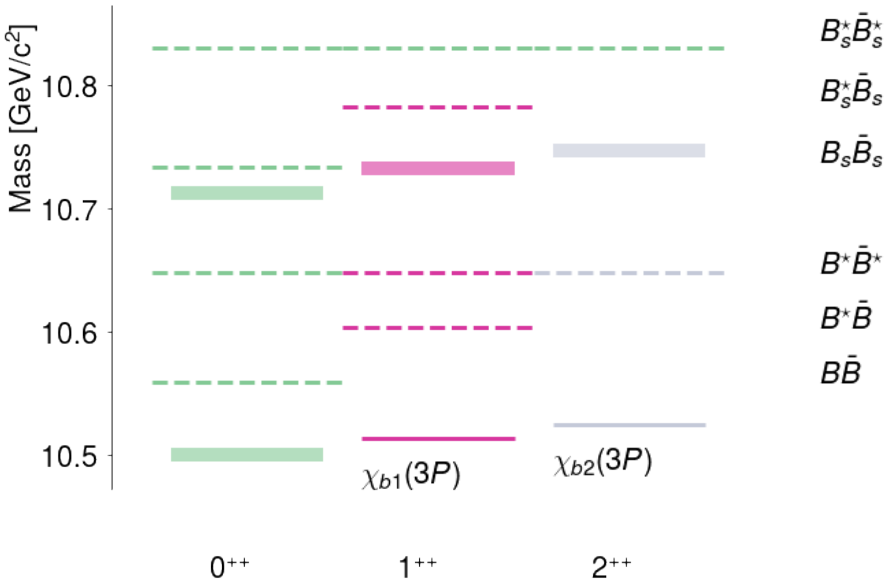
Phys. Rev. Lett. 119, 252001 (2017)

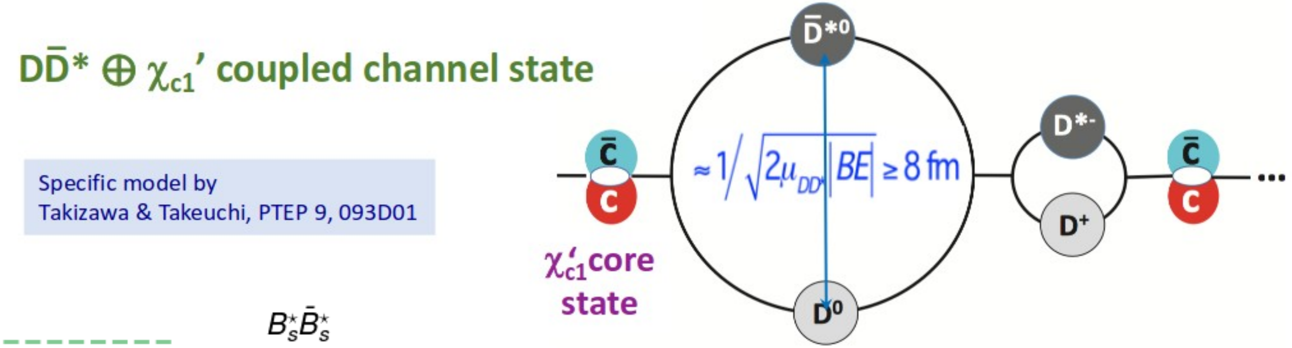
No measurement has been done!



Why no X_b ?

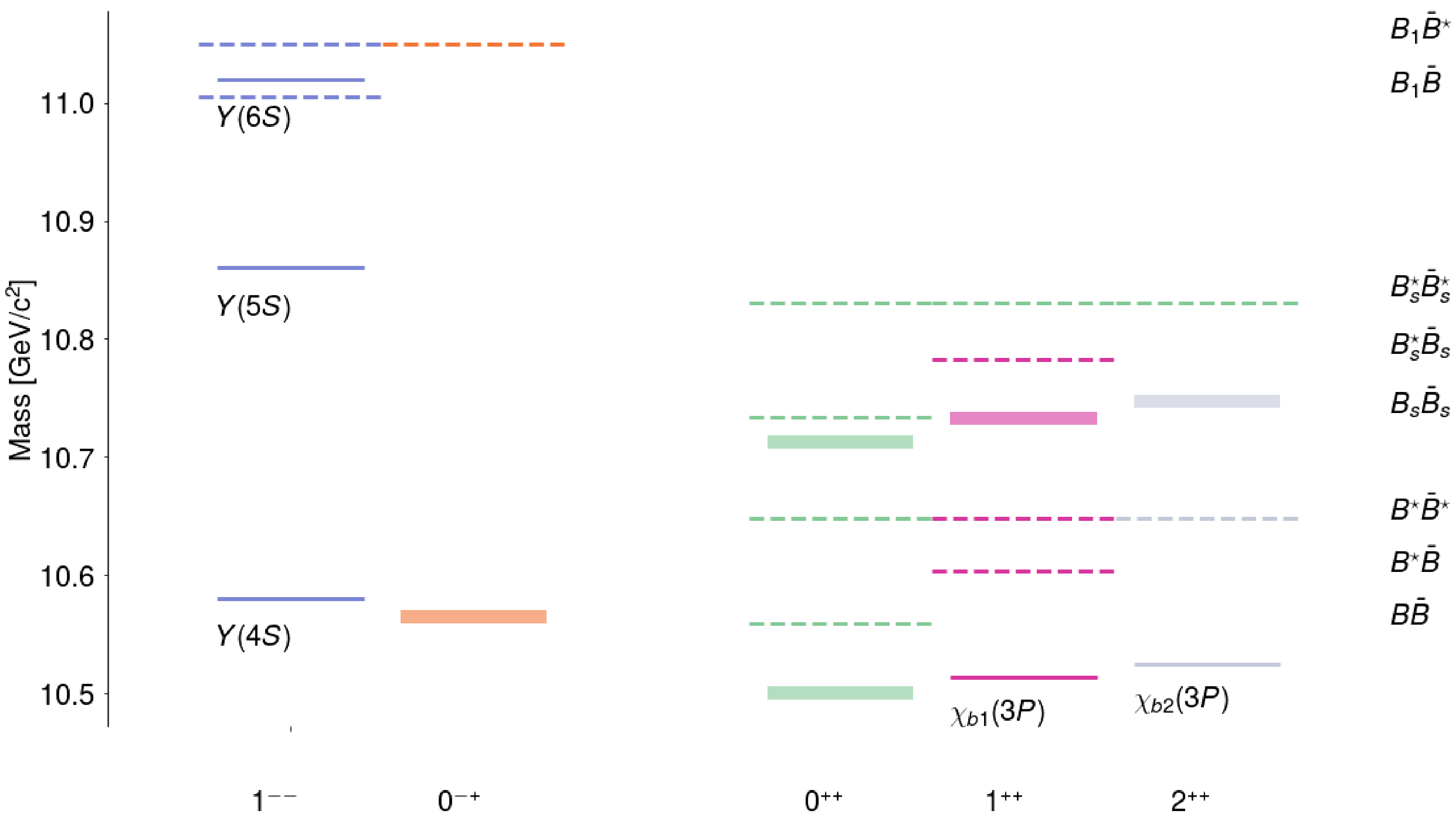
3) The X(3872) is generated by a peculiar coincidence





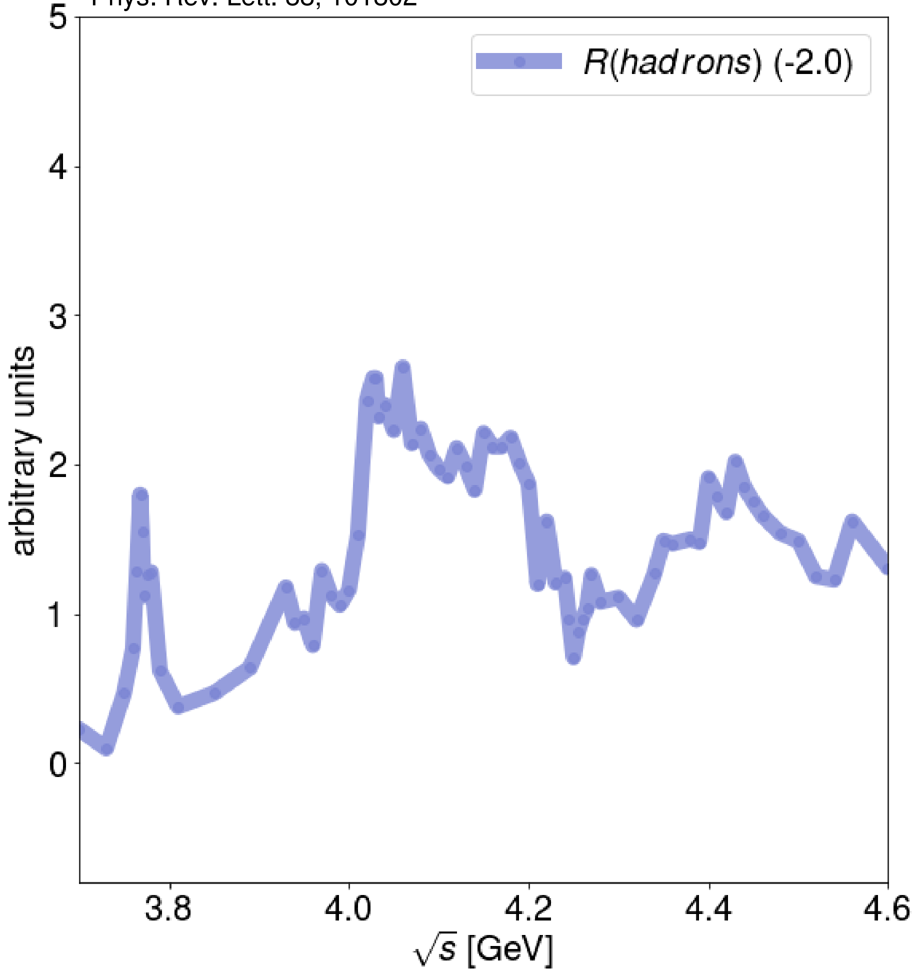
No χ_b is near the BB* threshold, no X_b

A close look at the S-wave thresholds

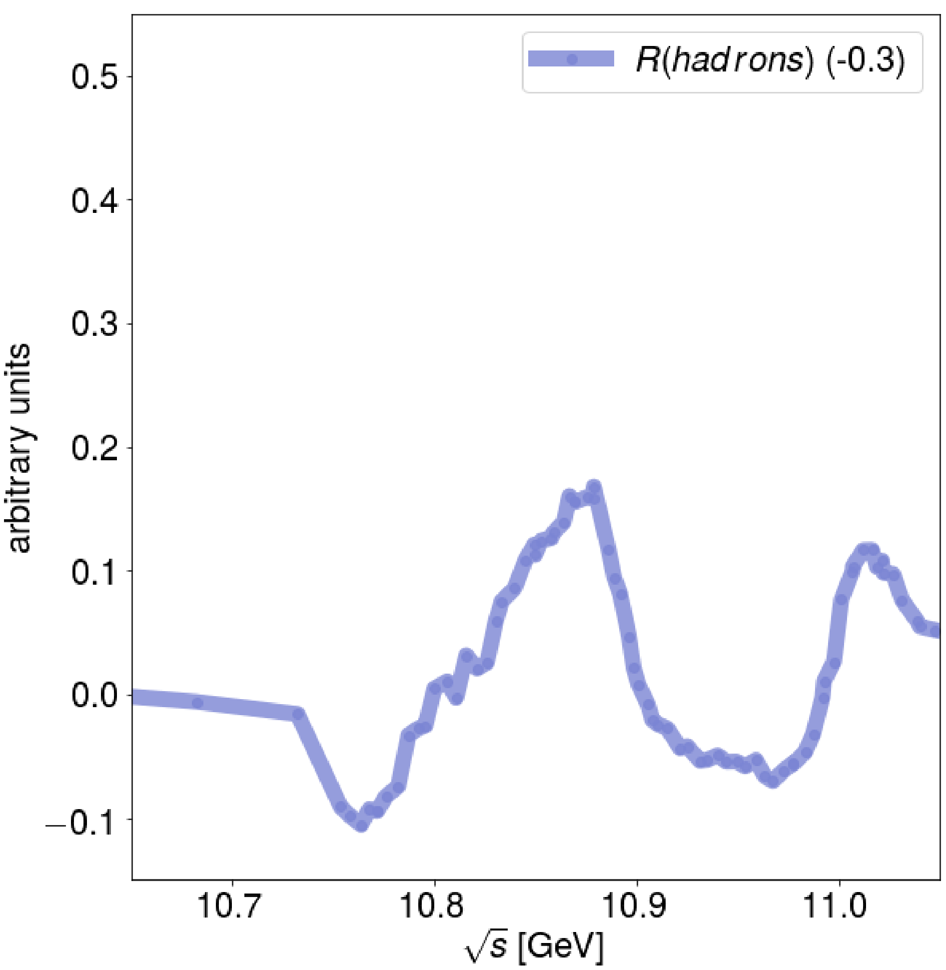


Bottomonium VS charmonium

Phys. Rev. Lett. 88, 101802

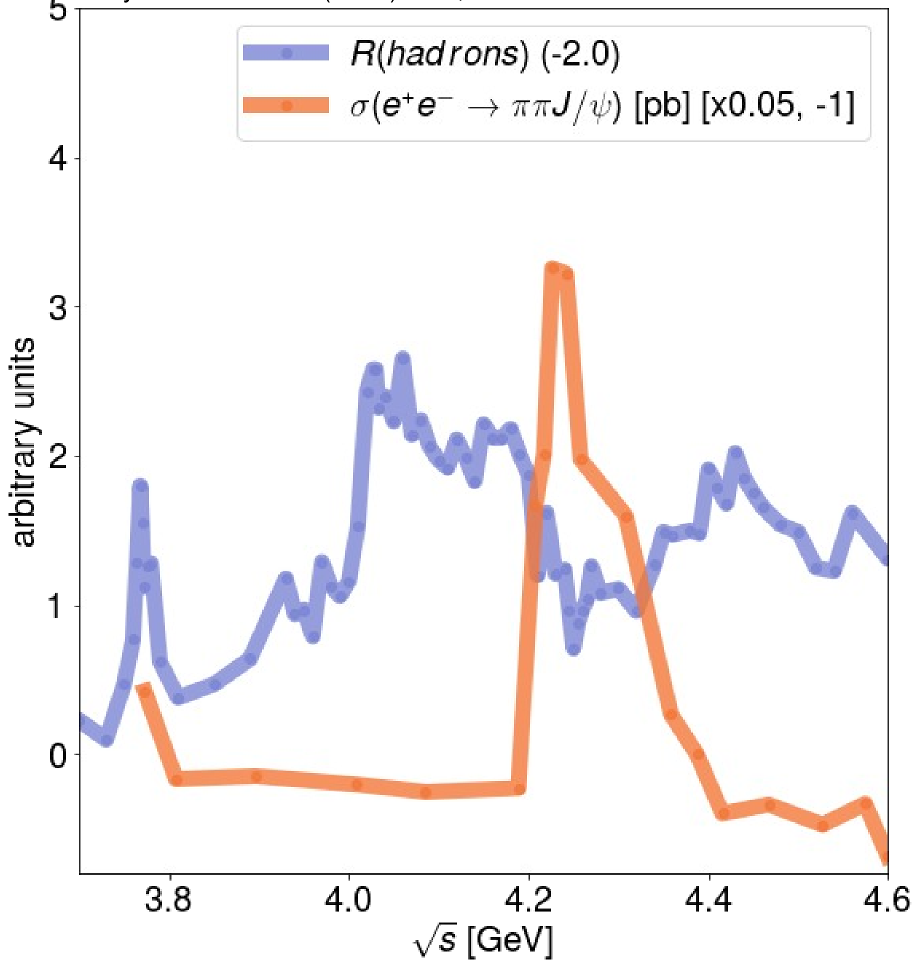


Phys.Rev. D93 (2016) no.1, 011101

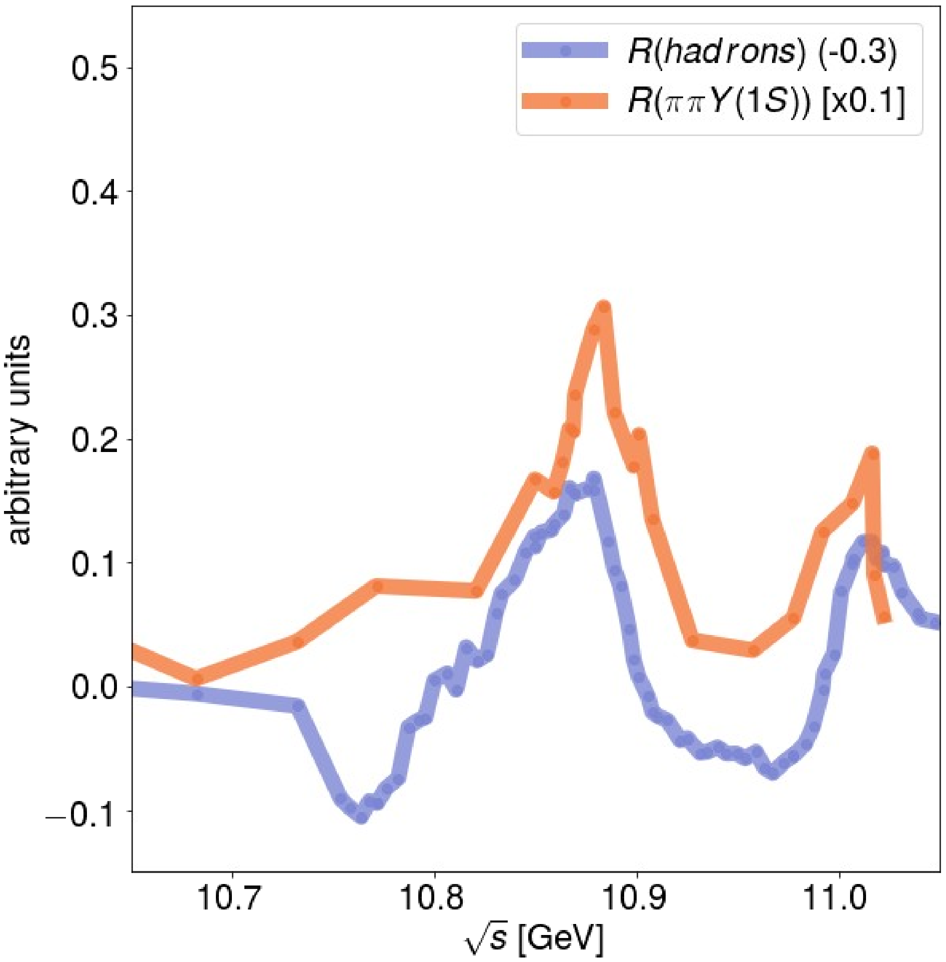


Bottomonium VS charmonium

Phys.Rev.Lett. 118 (2017) no.9, 092001

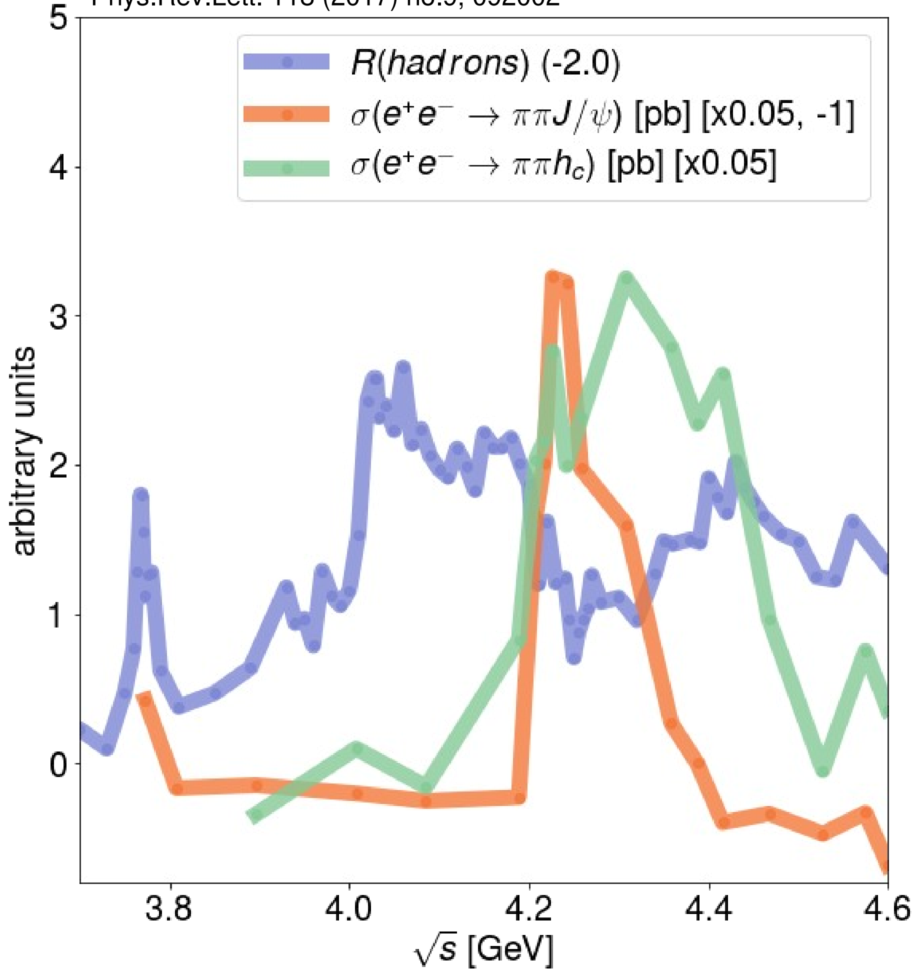


Phys.Rev. D93 (2016) no.1, 011101

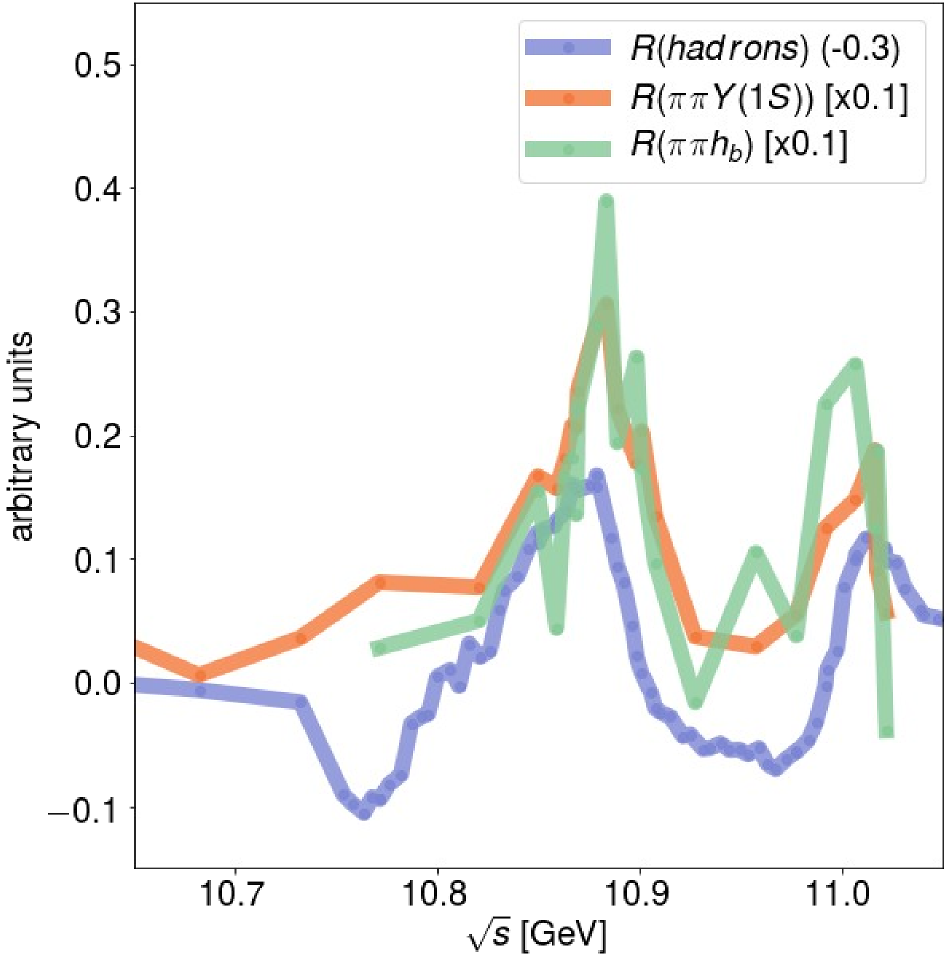


Bottomonium VS charmonium

Phys.Rev.Lett. 118 (2017) no.9, 092002



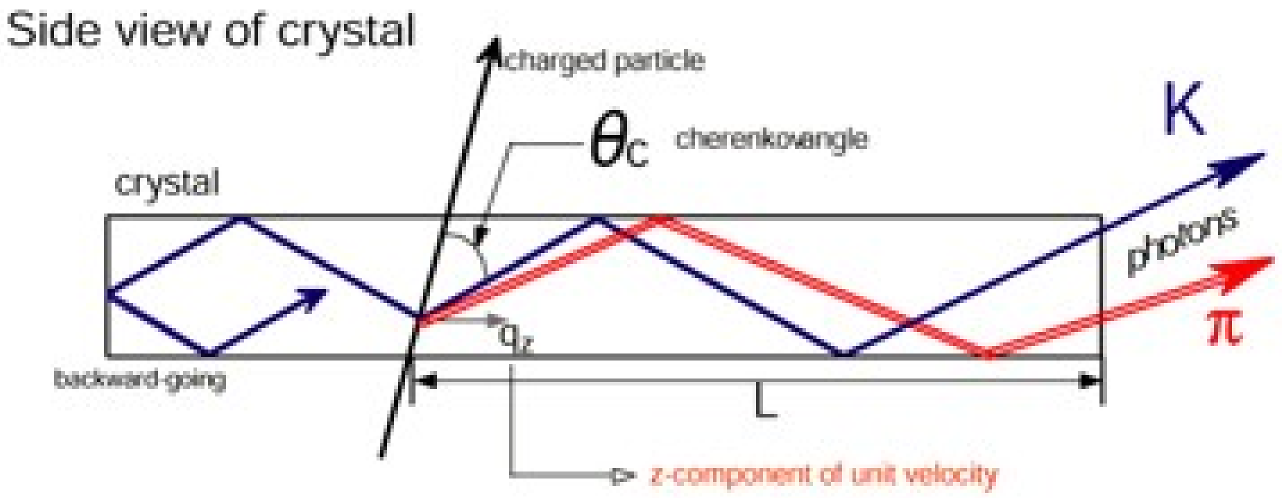
Phys. Rev. Lett. 117, 142001 (2016)



The TOP is a "*DIRC in the time domain*"

→ Cherenkov light trapped and propagated to the readout in a wide bar of fused silica

→ The Cherenkov angle is measured by the **time of propagation** rather than the ring image on the PMT surface



The TOP counter at Belle II

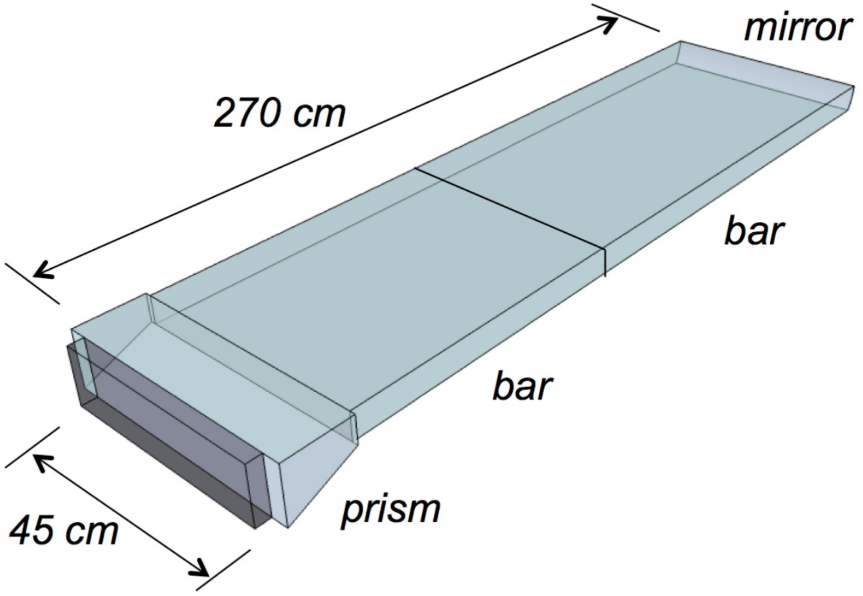
TOP implementation in Belle II:

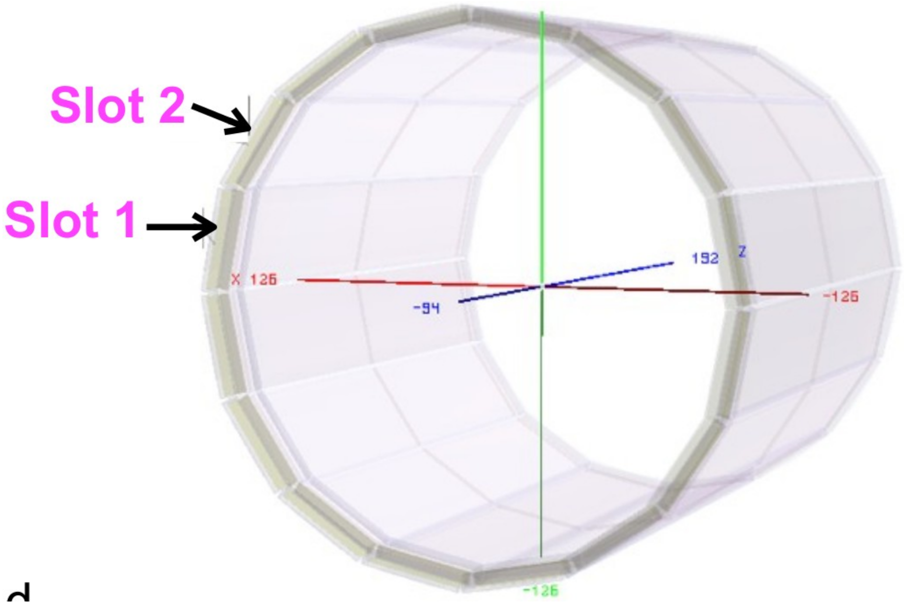
→ 16 modules (or slots) arranged around the interaction point

→ Each module is made of two identical bars of fused silica glued together

→ Backward side: expansion prism, PMTs and readout

→ Forward side: spherical mirror





Visualizing the Cherenkov rings