Hadron physics at Belle II

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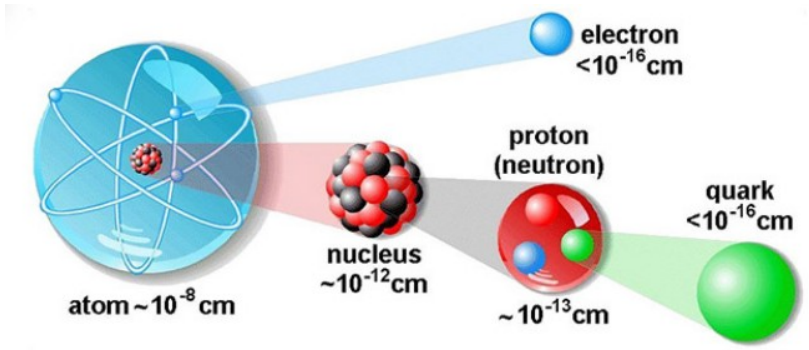

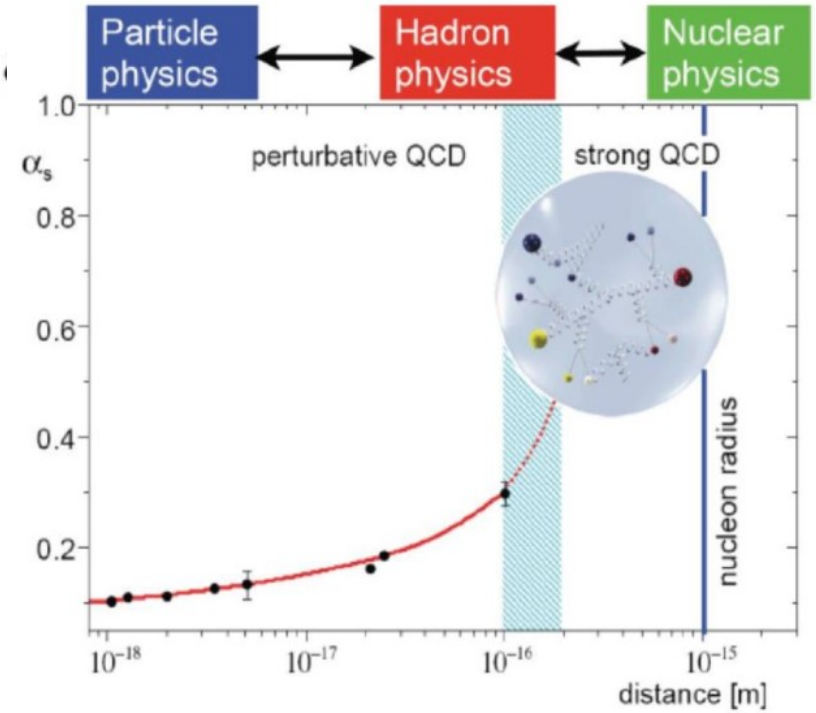

- Physics of the hadrons: composite, color neutral systems of quarks

- Explores the first level of complexity of strongly interacting particles

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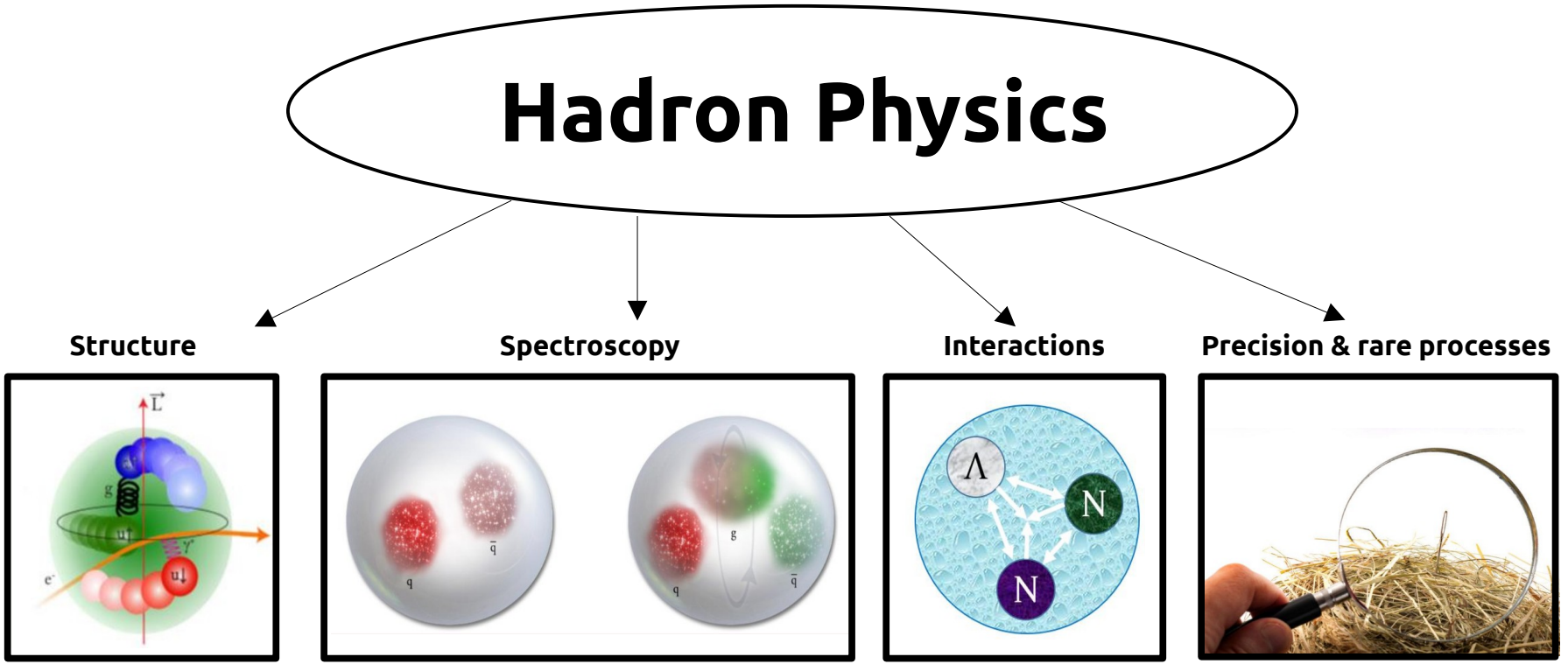

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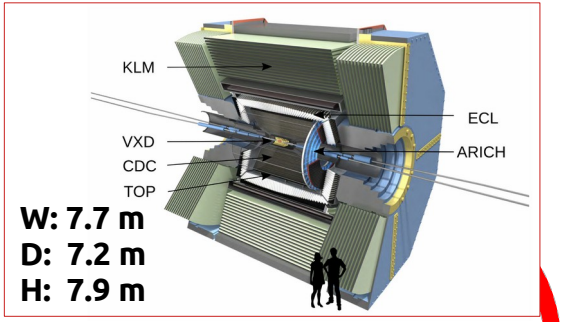
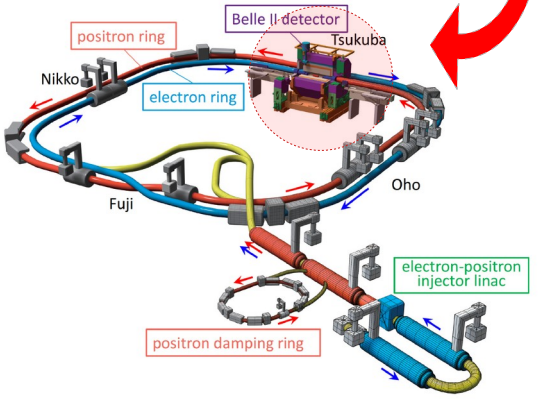
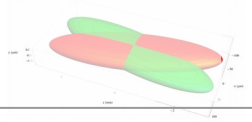
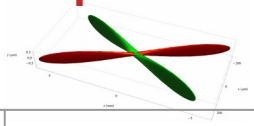
Hadron physics at Belle II

Belle II: particle physics experiment designed to study the properties of B mesons and other particles (B-Factory)

SuperKEKB: accelerator complex in which the Belle II experiment operates, located at KEK (High Energy Accelerator Research Organization) in Tsukuba, Japan





	KEKB	SuperKEKB
Sketch of the Interaction region		
$\int L\,dt$	1 ab^{-1}	794 fb^{-1} {50 ab^{-1}}
L_{peak} [$cm^{-2}\,s^{-1}$]	2.1 x 10^{34}	5.24 x 10^{34} (WR) {60 x 10^{34}}

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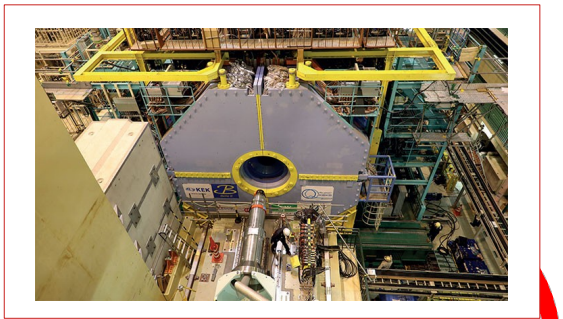
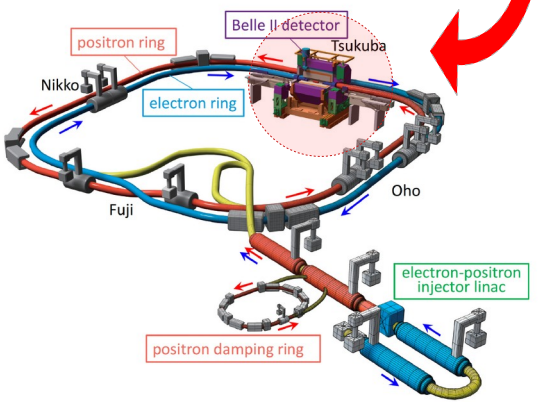
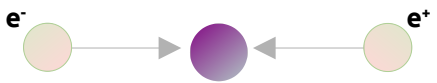




Hadron physics at Belle II

B-Factory: particle collider experiment designed to produce and detect a large number of B mesons so that their properties and behavior can be measured with small statistical and systematic uncertainties

$e^- e^+$ collisions → direct production of $J^{PC}=1^-$ states



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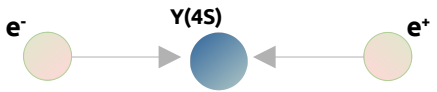

$e^- e^+$ collisions → direct production of $J^{PC}=1^{--}$ states

$\sqrt{s}$ = 10.58 GeV (= $m_{Y(4S)}$)

Y(4S): $b\bar{b}$ meson, $J^{PC} = 1^{--}$
Γ : 20.5 MeV
$m_{Y(4S)}$: 10.58 GeV
→ right above the $B\bar{B}$ production threshold (10.56 GeV)

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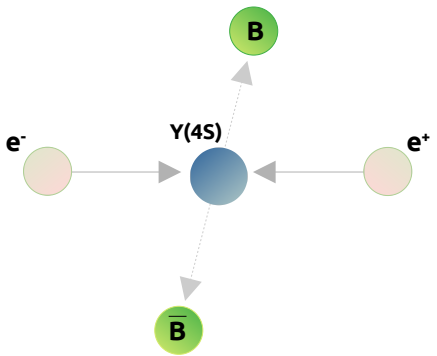

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BR(Y(4S) → $B\bar{B}$) > 96%

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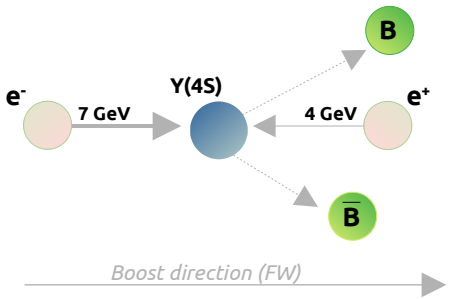

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Asymmetric collisions → boosted collision products

Intermezzo: Belle II physics potential

Belle II operates mainly at $\sqrt{s}$ = 10.58 GeV:

- $\sigma(e^+ e^- \rightarrow b\bar{b}) \sim 1.1$ nb [$L_{peak} = 2.7\ 10^{34} cm^{-2}\ s^{-1} \rightarrow 30\ B\bar{B}/s$]

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- $\sigma(e^+e^- \to \tau\tau) \sim 0.9$ nb

- $\sigma(e^+e^- \to c\bar{c}) \sim 1.3$ nb

→ *B* & τ & *c* factory

- $\sigma(e^+e^- \to e^+e^-) \sim 125/294$ nb (strongly depends on the acceptance angle)

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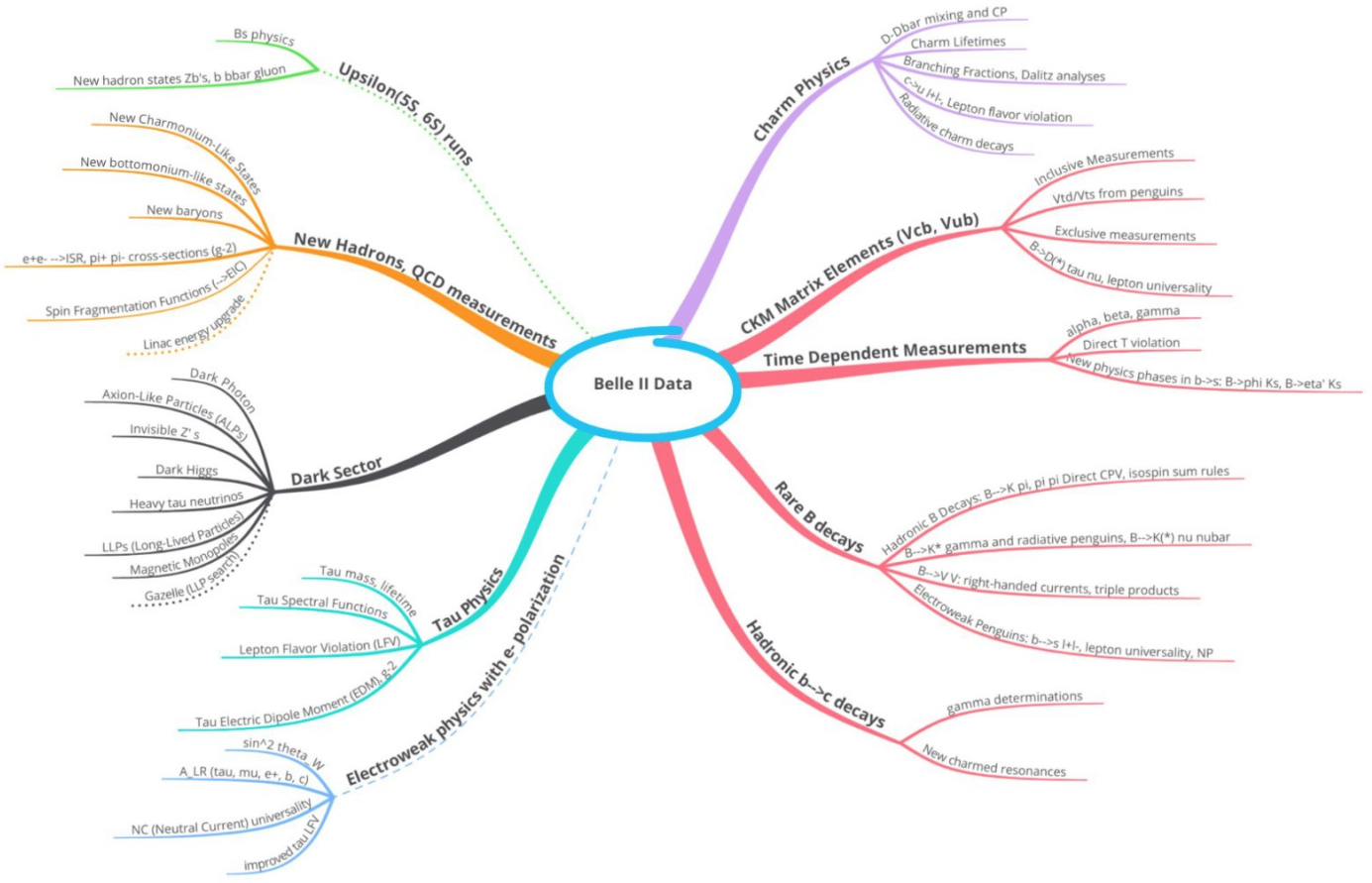
It is possible to change the √s:

In 2019 unique energy scan sample collected at ~10.75 GeV

Intermezzo: Belle II physics program

[See: BIITIP, Snowmass Whitepaper]



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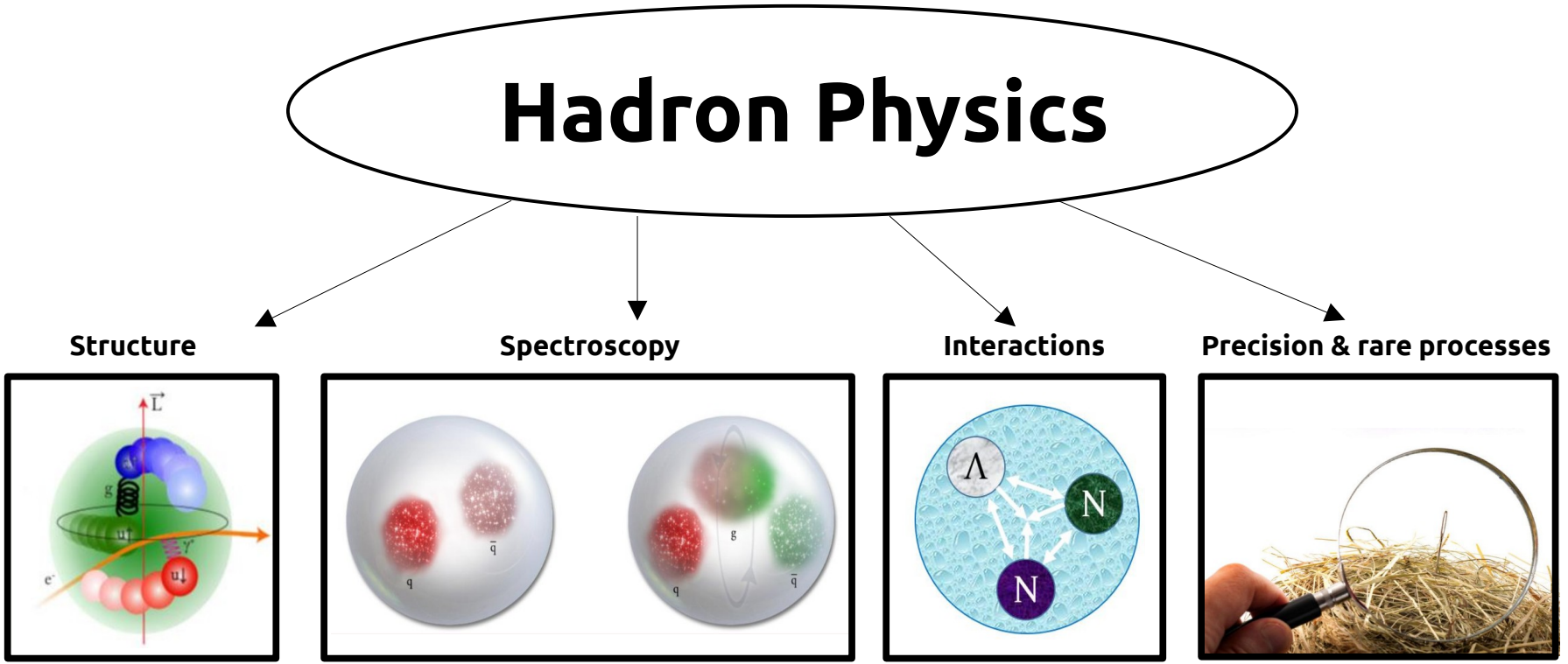

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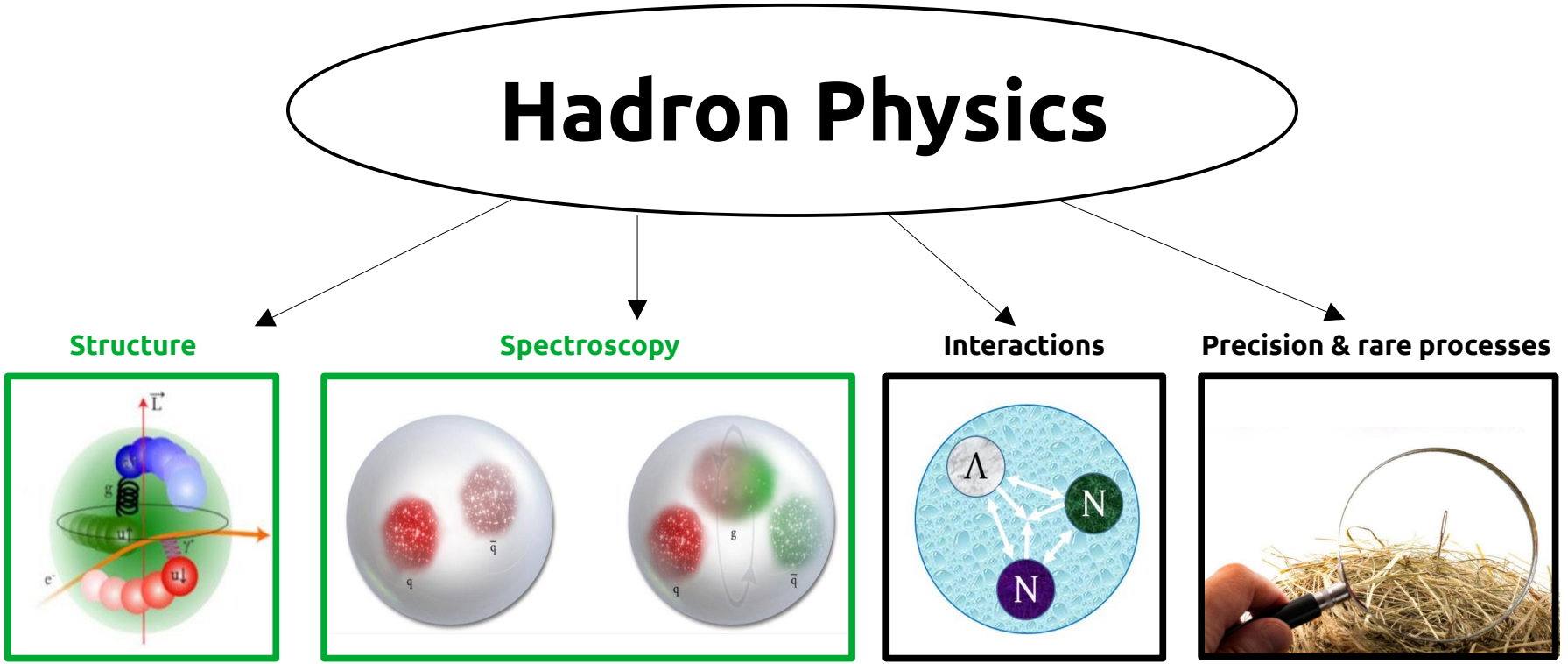

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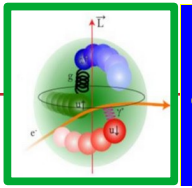
1. Hadron formation



Belle II

Hadronization: how particular hadrons are formed from scattered quarks and gluons (partons)

- Fragmentation functions: probability distribution of a parton fragmenting into a specific hadron
- Transverse momentum dependent (TMD): spin-momentum correlations

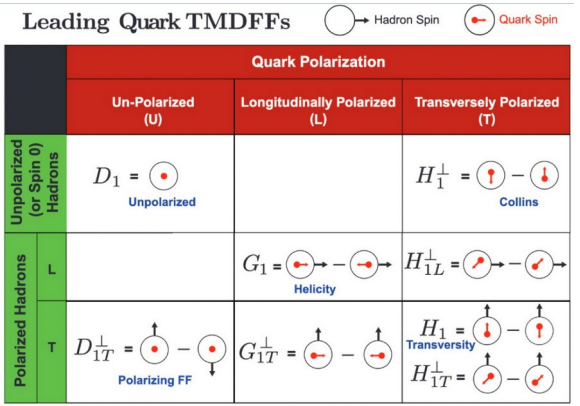
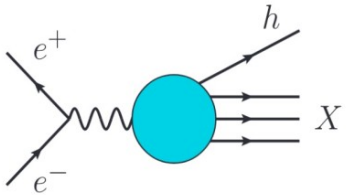
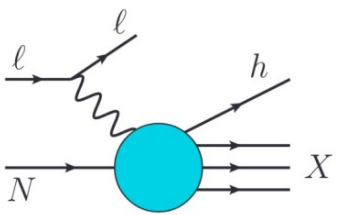


Image from arXiv:2304.03302v1

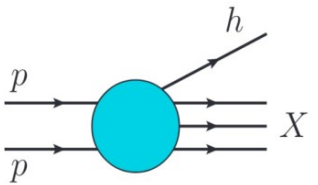
$$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes FF$$



$$\sigma^{lN\to lhX} = PDF \otimes \hat{\sigma} \otimes FF$$



$$\sigma^{pp\to hX} = PDF \otimes PDF \otimes \hat{\sigma} \otimes FF$$



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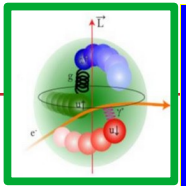
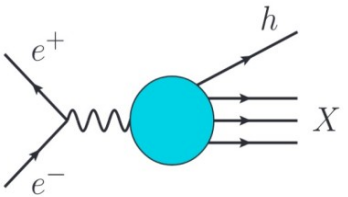


Belle II

Belle II can offer high precision, comprehensive measurements important for understanding hadronization dynamic

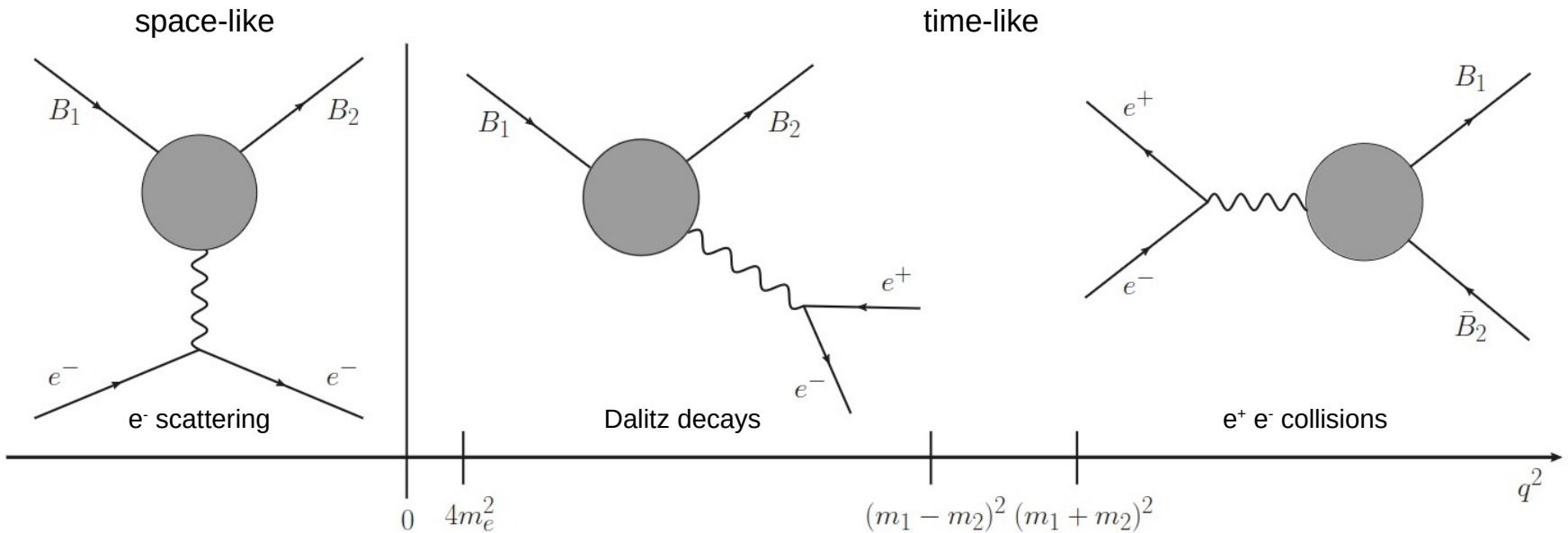
$$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes FF$$



- Clean environment for detailed studies of hadronic final states
- Multi-dimensional analyses of fragmentation functions correlations, heavy flavor, hadronization effects in jets
- Essential for understanding transverse momentum of partons in measurements of PDFs and spin structure of nucleons (e.g. EIC)
- Many analysis ongoing
  → Di-hadron fragmentation functions, Lambda polarization, TMD jet functions, ..

2. Hadron structure

Electromagnetic Form Factors (EMFFs): momentum-dependent functions that map the spatial distribution of electric charge and magnetization, deviating from point-like behavior



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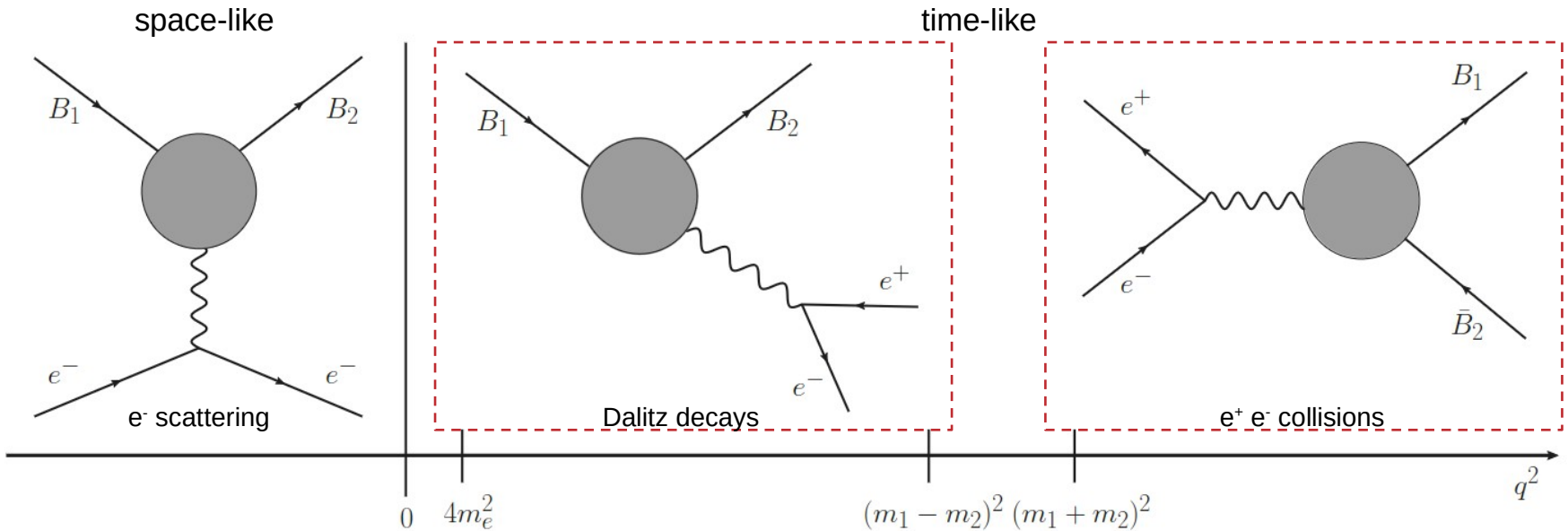

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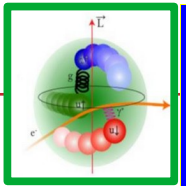
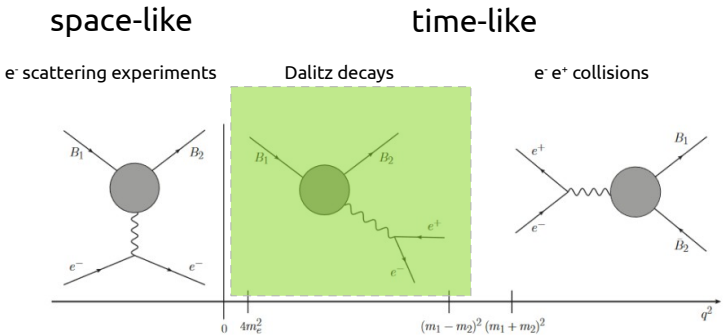


Belle II

Hyperons transition form factor using **Dalitz decays**

$\Sigma^0 \to \Lambda\, e^+ e^-$: predicted BR: 0.5 %

- $q^2 < 77$ MeV
- Extrapolate TFF to ɣ point → magnetic moment
- Increase predictive power of dispersion theory



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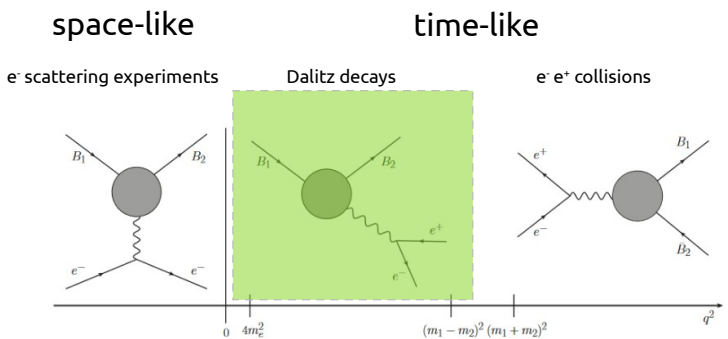
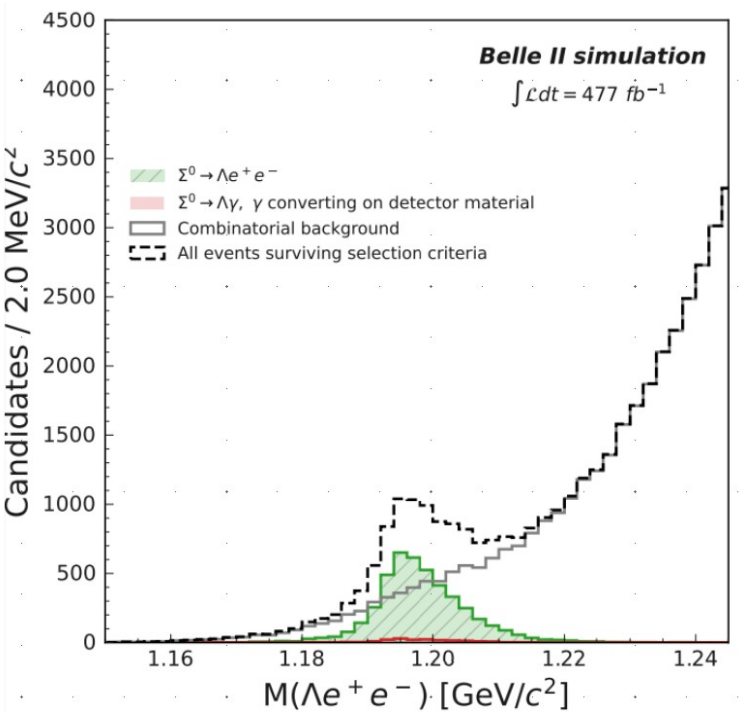
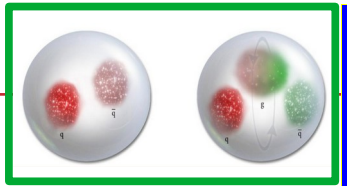




3. Hadron spectroscopy



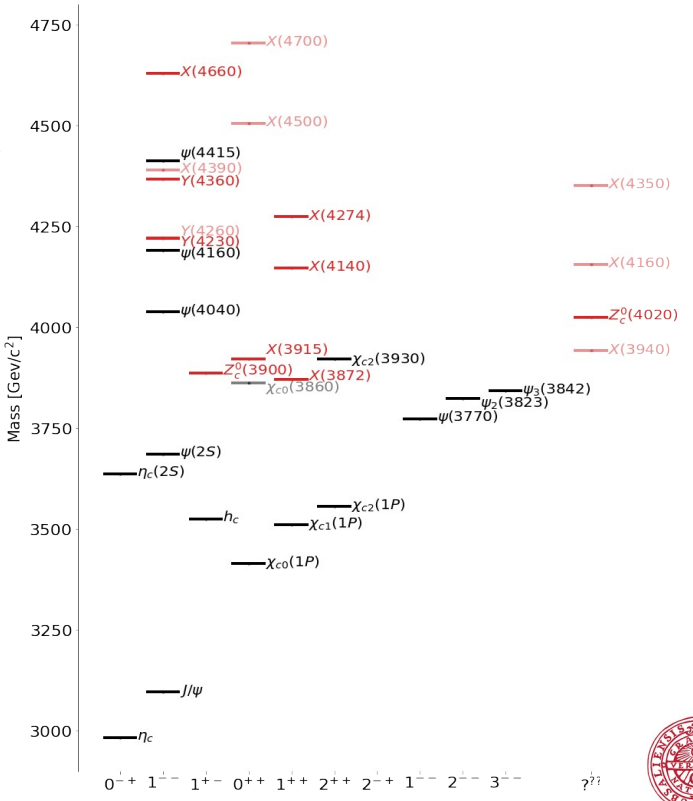
Belle II

$q\bar{q}$ and qqq are not the only color singlets,
we are now sure that there is much more

Full, neutral charmonium-like spectrum

- In 15 years we discovered:
  - ~30 exotics in charmonia
  - 3 exotics in bottomonium
  - 5 pentaquarks

→ **The question is not if they exists,**
but what they are



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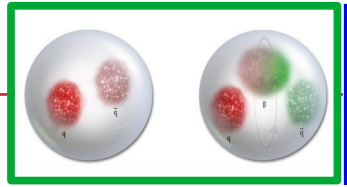
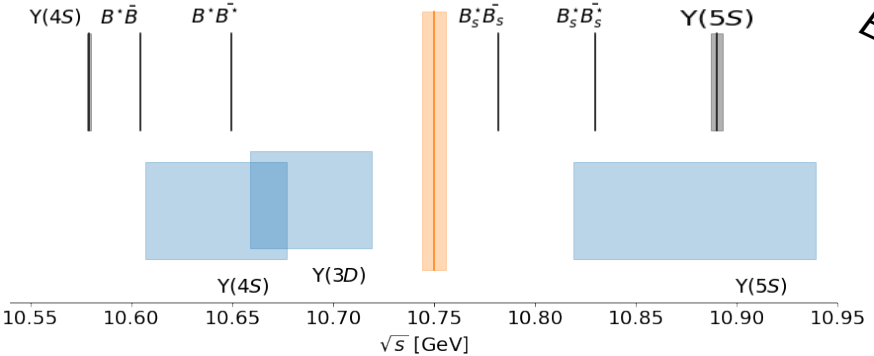


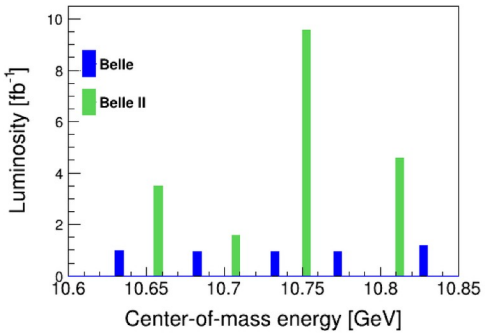
Belle II

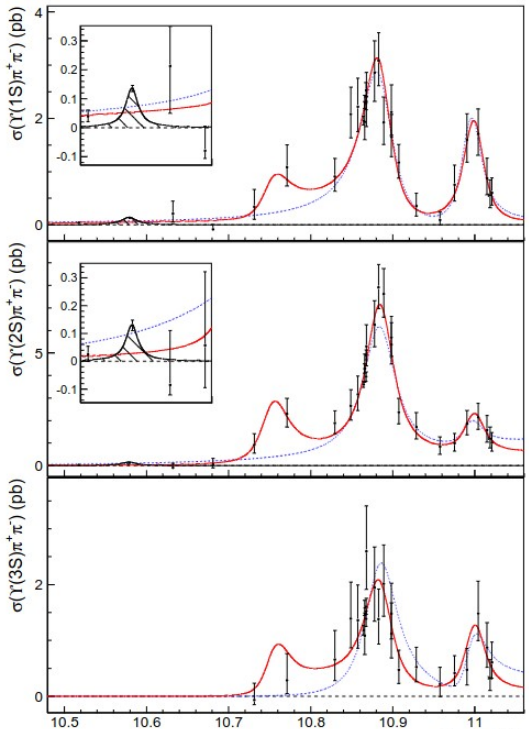
Unexpected vector state around 10.750 GeV (Belle)



Experiment

Quark model





[JHEP 10 (2019) 220]

- Dedicated Belle II data taking
  - 4 energy points
  - 19 fb^{-1} in total

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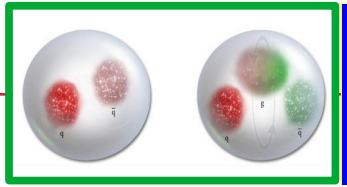
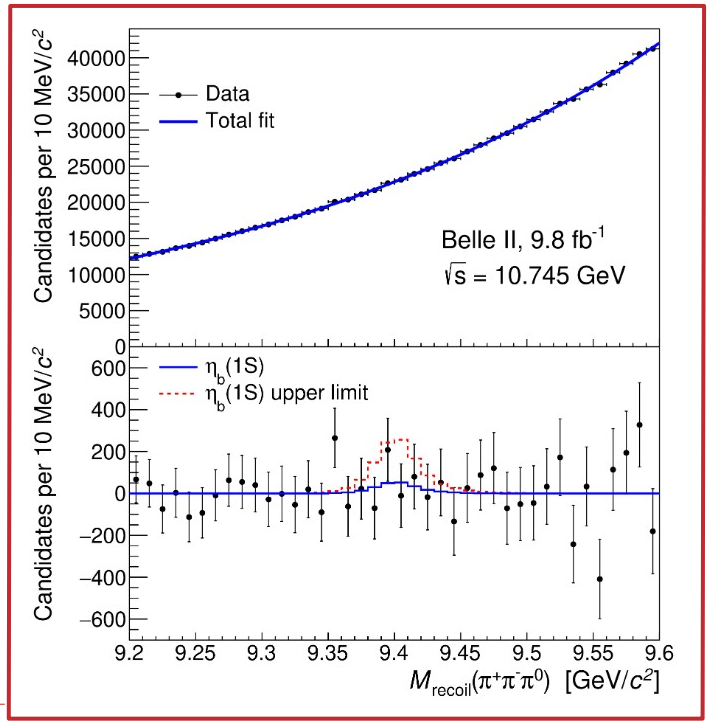


- Di-pion transitions $e^+ e^- \to \Upsilon(nS)\, \pi^+ \pi^-$ *[JHEP 07 (2024) 116]*
  → No f_0 contribution in the di-pion mass
- 3-π transitions $e^+e^- \to X_{bJ}(1P)\, \pi^+ \pi^- \pi^0$ *[Preliminary]*
  → Large w VS non-w differences
- $e^+e^- \to \Upsilon(nS)\, \eta$ *[ArXiv 2509.01917]*
  → Hint of another resonant state?
- $e^+e^- \to B(*)B(*)$ *[JHEP 10 114 (2024)]*
  → Indication of a B*B* bound state
  see *[Salnikov, Nucl. Phys. A 1041 (2024) 122764]*
- $e^+e^- \to \omega\eta_b(1S)$ *[PRD 109, 072013 (2024)]*
  → **favoured in tetraquark models, not observed**



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- Lots of measurement opportunities, with several current ongoing analyses underway

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Thank you for your attention!

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