Pentaquarks, Hypernuclei, and Things that Go Clump in Upsilonia

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Exotic States in QCD

- QCD predicts states beyond the mesons ($q\bar{q}$) and baryons (qqq):
  Glueballs (gg or ggg), Hybrids ($q\bar{q}g$), Tetraquarks ($qq\bar{q}\bar{q}$),
  Pentaquarks ($qqqq\bar{q}$), Hexaquarks (qqqqqq; di-baryons), etc.

- Glueballs (gg)
  - Extensively searched in radiative J/psi decays (and rad. Upsilon decays)
  - Many candidates, $\iota(1440)$, $\theta(1720)$, $\xi(2220)$, but not truly convincing…
  - Observation of too many states beyond the expected meson spectrocopy, not a strong evidence…

- Search for Hybrids (e.g. GlueX at JLab)

- <u>A key is to find states with J^{PC} not accessible by $q\bar{q}$ or qqq</u>

X Y Z States

- First evidence for 4-quark states ($c\bar{c}q\bar{q}$) ? (Belle)

- Z^+ states: Charmonium-like, but charged!
  $Z^+(4430)$, $Z_1^+(4050)$, $Z_2^+(4250)$ Belle
  $Z^+(3900)$, $Z^+(4020)$ BESIII
  Z_b states also observed in the bottomonium mass range

- Possible Interpretations:
  Conventional Quarkonium States,
  Hybrids
  Multiquark States: Molecule, Tetraquark, or Diquark-onium

For review, see Exotic Hadrons: What's New in an Old Spectroscopy?
(Steve Godfrey; UofH Physics Colloquium, Feb. 2015)

Pentaquarks

- Previous round of Pentaquark observations were not verified by other experiments

  $\Theta^+ \rightarrow K^0 p$, $K^+ n$ from LEPS at SPring-8 (M=1.54 GeV, Γ=10 MeV)

  $\Theta_c^0 \rightarrow D^{*-} p$ from H1 at HERA (M =3.10 GeV, Γ=12 MeV)

  $\Xi^{--} \rightarrow \Xi^- \pi^-$ NA-49 at CERN SPS (M =1.862 GeV, Γ<18 MeV)

* Searches by BaBar/Belle in B decays and e^+e^- continuum yielded no signal
"Prospects for Pentaquark Production at Meson Factories"
(Browder, Klebanov, Marlow) http://arxiv.org/abs/hep-ph/0401115

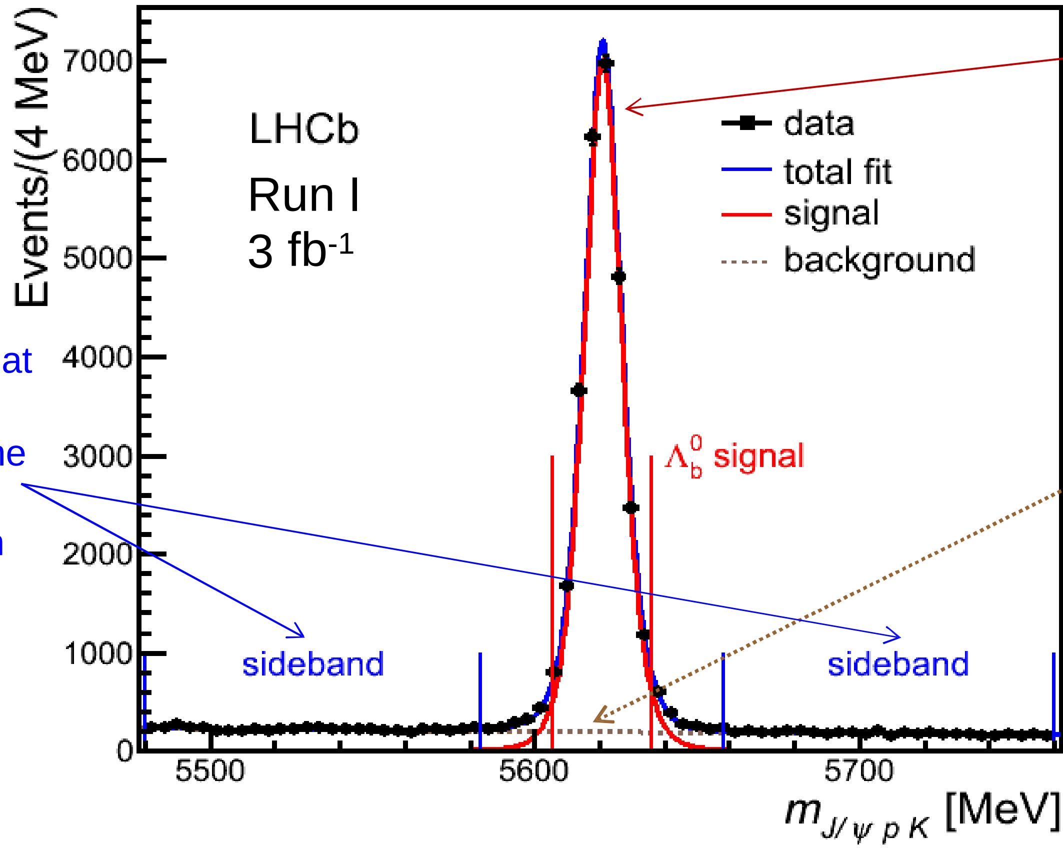
* Theoretical (model) calculation of narrow widths can spur Exp. activity

The Rise and Fall of Pentaquarks in Experiments, R. Schumacher, AIP Conf. Proc. 842, 409 (2006); On the conundrum of the pentaquarks, K.Hicks, Eur. Phys. J. H37 (2012) 1.

Pentaquarks appeared to be avoiding detection, until…

LHCb $\Lambda_b^0 \rightarrow J/\psi\ p K^-$

LHCb-PAPER-2015-029, arXiv:1507.03414, PRL 115, 07201



26,007±166 Λ_b^0 candidates

The sideband distributions are flat → no major reflections from the other b-hadrons after the selection

The background is only 5.4% in the signal region!

- The decay first observed by LHCb and used to measure Λ_b^0 lifetime:
  - LHCb-PAPER-2013-032 (PRL 111, 102003)

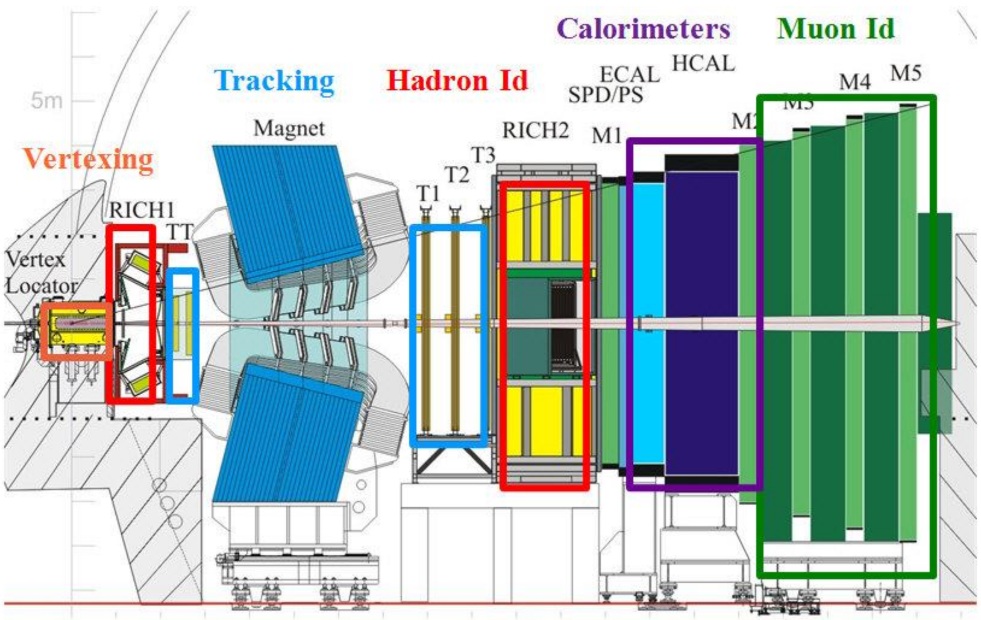
LHCb Detector

Dedicated single-arm Forward spectrometer with $1.8 < \eta < 4.9$.

pp collisions in Run 1:

- 2011: 1/fb at 7 TeV
- 2012: 2/fb at 8 TeV

High $b\bar{b}$ and $c\bar{c}$ cross-sections: $\sigma(pp \to b\bar{b}) = 286\ \mu b$ at 7 TeV



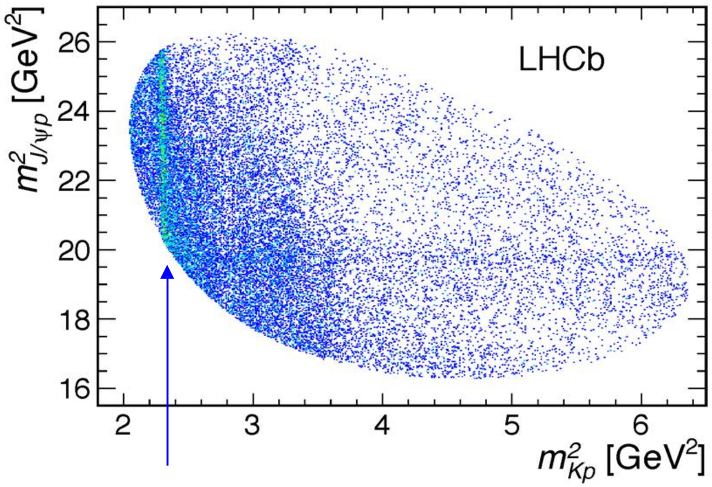
VeLo detector
- Silicon detector with two retractable halves
- 7 mm away from the beam line when closed
- B lifetime resolution: 50 fs

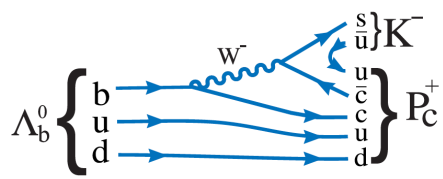
RICH Particle ID
- K/π separation in [2,100] GeV/c

Muon detectors:
- 97% efficiency, $< 2.5\%\ \pi \leftrightarrow \mu$ mis-ID

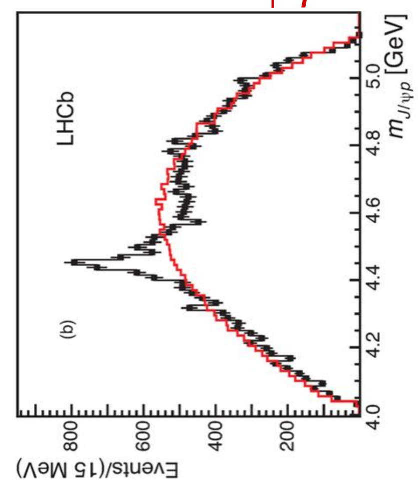
(B. Dey, SSI 2015)

$\Lambda_b^0 \rightarrow J/\psi p K^-$: unexpected structure in $m_{J/\psi\, p}$

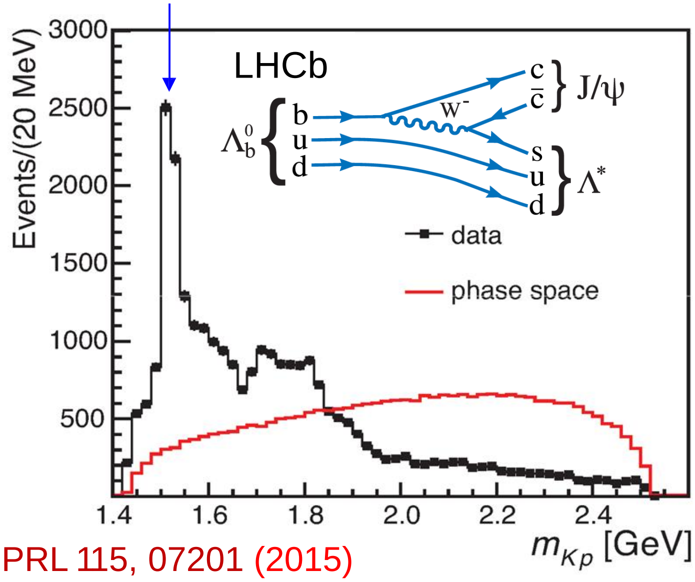




$P_c^+ \rightarrow J/\psi\ p$
?



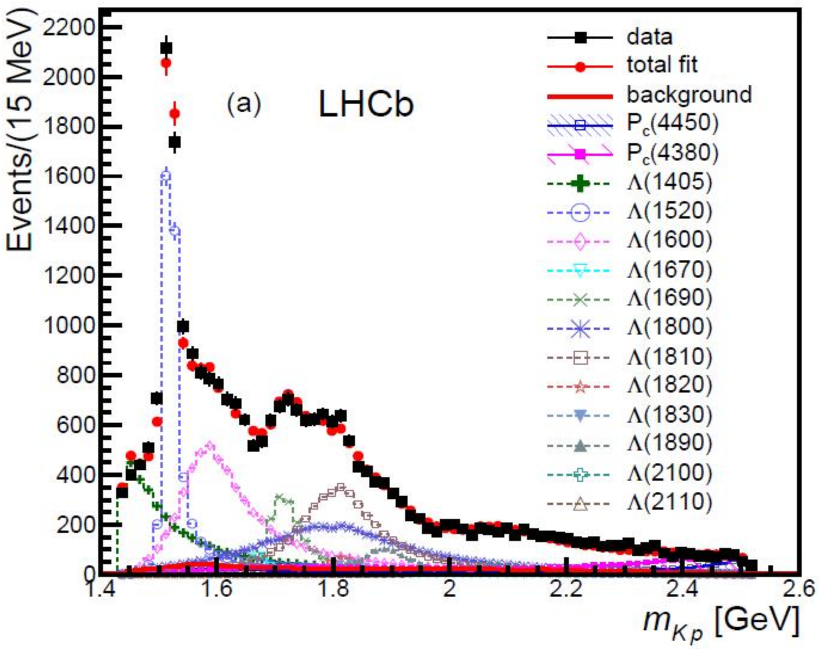
$\Lambda(1520)$ and other Λ^*'s $\rightarrow$ p K^-

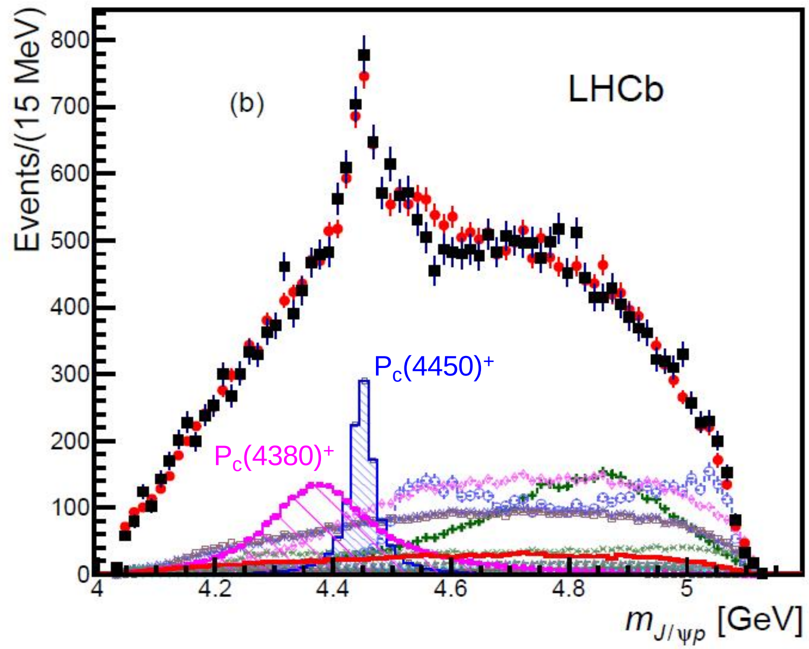


PRL 115, 07201 (2015)

- Unexpected, narrow peak in $m_{J/\psi\, p}$
- Many checks done to ensure it is not an "artifact" of selection:
  - Veto $B_s \rightarrow J/\psi K^- K^+$ & $B^0 \rightarrow J/\psi K^- \pi^+$ after changing p to K, or K to π
  - Clone and ghost tracks carefully eliminated
  - Exclude Ξ_b decays as a possible source
- Could it be a reflection of interfering Λ^*'s $\rightarrow$ p K^- ?
  - Proper amplitude analysis absolutely necessary!

Fit with Λ^*'s and two $P_c^+ \rightarrow J/\psi p$ states



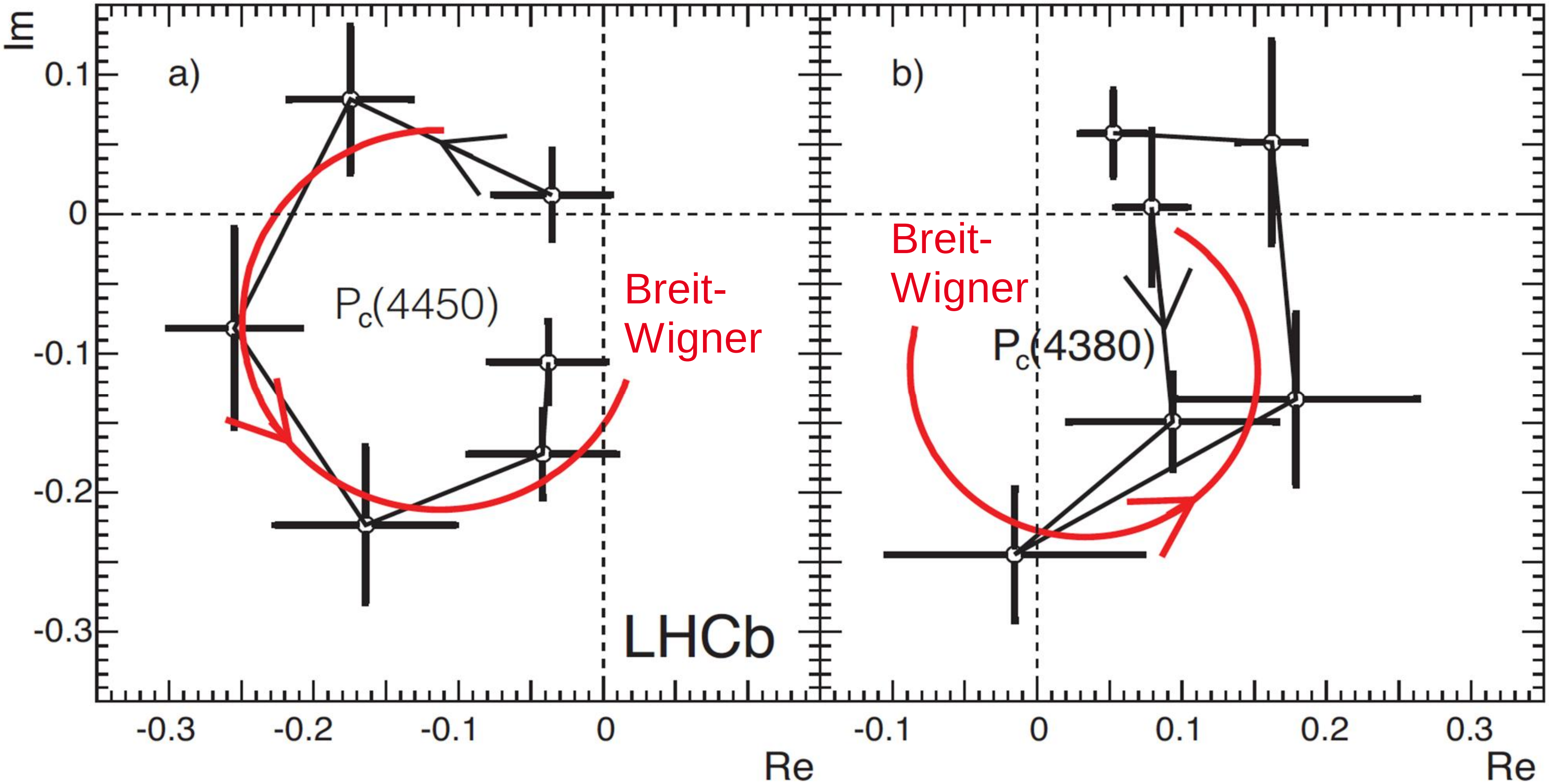


- Max. Likelihood Fit with 2 signal, 12 Λ^* components
- Obtain good fits even with the reduced Λ^* model
- Best fit has J^P=(3/2$^-$, 5/2$^+$), also (3/2$^+$, 5/2$^-$) & (5/2$^+$, 3/2$^-$) are preferred

Argand diagrams

PRL 115, 07201 (2015)

P_c^+ amplitudes for 6 $m_{J/\psi p}$ bins between $+\Gamma$ & $-\Gamma$ around the resonance mass



- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive

Significances and the results

- Fit improves greatly, for 1 P_c $\Delta(-2\ln L)=14.7^2$, adding the 2nd P_c improves by 11.6^2, for adding both together $\Delta(-2\ln L)=18.7^2$
- Simulations of pseudoexperiments are used to turn the $\Delta(-2\ln L)$ values to significances:
  - significance of $P_c(4450)^+$ state is 12σ
  - significance of $P_c(4380)^+$ state is 9σ
  - combined significance of the two P_c^+ states is 15σ
- This includes the dominant systematic uncertainties, coming from difference between extended and reduced Λ^* Model results
- Parameters of the P_c^+ states (and F.F. of well isolated Λ^*'s)

State	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	**4380 ±8±29**	**205±18±86**	**8.4±0.7±4.2**
$P_c(4450)^+$	**4449.8±1.7±2.5**	**39± 5±19**	**4.1±0.5±1.1**
$\Lambda(1405)$			15±1±6
$\Lambda(1520)$	(arXiv:1507.03414, PRL 115, 07201)		19±1±4

Comments and Questions

- Evidence for the 4450 MeV state is strong – a very clear band in Dalitz plot
- Inclusion of $P_c(4380)$ component of large width (200 MeV) is necessitated by desire to fit the data well – "Data demands it".
- Σ Fit Fractions = 125%, with large negative interference between the two signal amplitudes
- Large No. of fit parameters = 64 or 146
- The region right above 4450 GeV has a dip that's not well fitted; Could it be indication of onset of a threshold? Or some interference effect?
- 4450 GeV is near the (χ_{c1} p) threshold; Threshold enhancement rescattering into (J/ψ p) can give an appearance of a resonance pole.

  - arXiv:1507.04950
- Study of the signal line shape is important; More data will help.
- Is it a (compact) Pentaquark, or molecular state? Karliner/Rosner

  Rearrangement of the quarks $\rightarrow \Sigma c\,\bar{D}^*$ (mass threshold = 4.462 GeV)

Search Scenarios at B-factory

- $P_c(4450)$ not accessible in B meson decay; If there exist a family of P_c states, search for $B \to (\eta_c\, p\ \text{p-bar})$ might be worthwhile.

- ISR production of [$P_c(4450)$ p p-bar] at E_CM just above threshold

- Inclusive search for $P_c(4450) \to J/\psi\ p$ in continuum data

- Inclusive search for $P_c(4450) \to J/\psi\ p$ in $\Upsilon(nS)$ data
  - Hadronic decays are dominated by 3-gluon decay
  - No suppression of strange quark or diquark production; high rate of baryons
  - Relative proximity in physical space and momentum & wave function overlap
  - BaBar/Belle: 100's of million events at $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$

- Exclusive search in $\Upsilon(nS)$ data

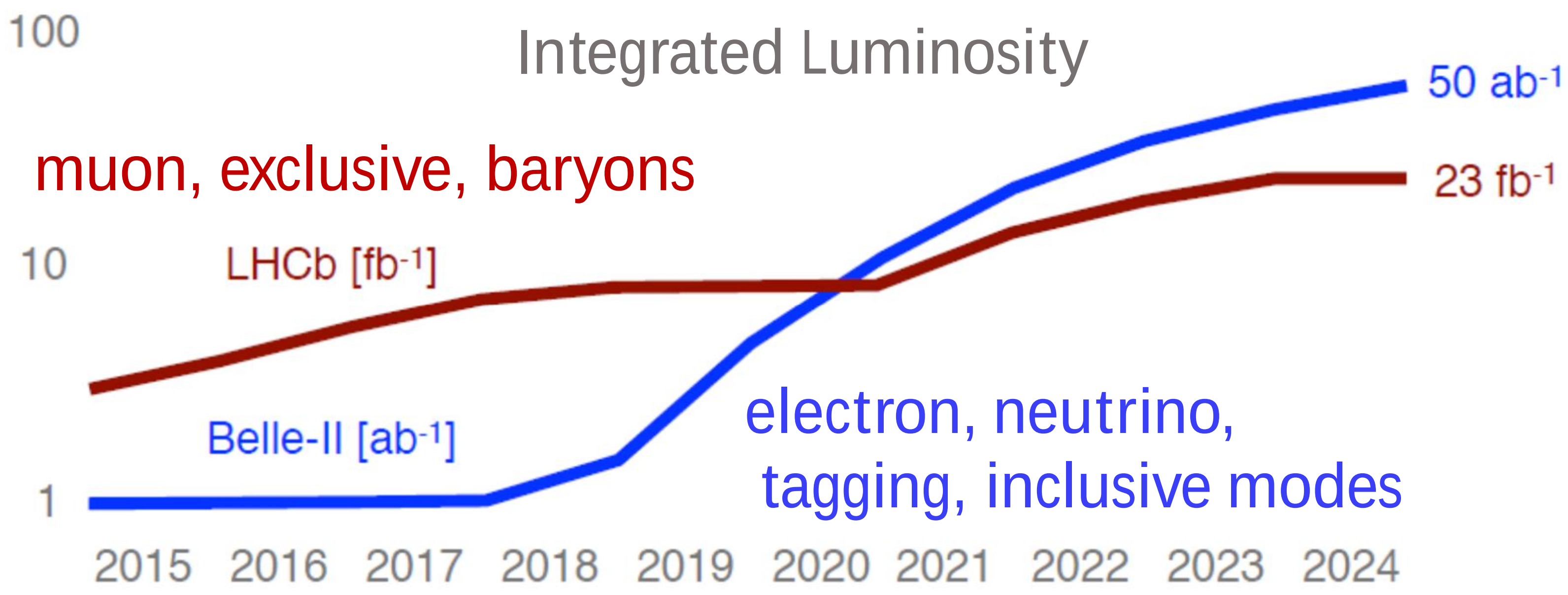
  $\Upsilon(nS) \to J/\psi$ p p-bar

- Repeat the above with $P_c(4450) \to \chi_{c1}\ p$ and $P_c(4450) \to \Sigma c\ \overline{D}^*$

- Search for Θ^+, Θ_c^0 in $\Upsilon(nS)$ data; Belle results from 2012?

LHCb and Belle II

- Complementarity with Belle II. CMS/Atlas also coming into the fold.



Di-baryons

- 64 Combinations from 8 N and Strange baryons:n, p, Λ, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0
- Which are bound?

www.physics.princeton.edu/~mcdonald/examples/dineutron.pdf

www.physics.princeton.edu/~mcdonald/examples/hyperdeuteron.pdf

- Deuteron (*np*): Binding Energy of 2.225 MeV
  - (*pp*) and (*nn*) are not bound.

- Hyper-deuterons: Λp, Σp, Ξp or Λn, Σn, Ξn
  - Extensive study of hyper-nuclei in Nuclear Physics (since 1960's)
    "Hypernuclei", B. Podh, Ann.Rev.Nucl.Part.Sci., 1978.
  - Lowest mass hypernuclei observed is (Λnp)

- H di-baryon ($\Lambda\Lambda$)
- More 6-quark combinations
  e.g., (uuuuuu) – Brodsky, arXiv:1308.6404
- Charmed hyper-nuclei (or Supernuclei): Charm baryon + N

Antideuteron production in Upsilon decay

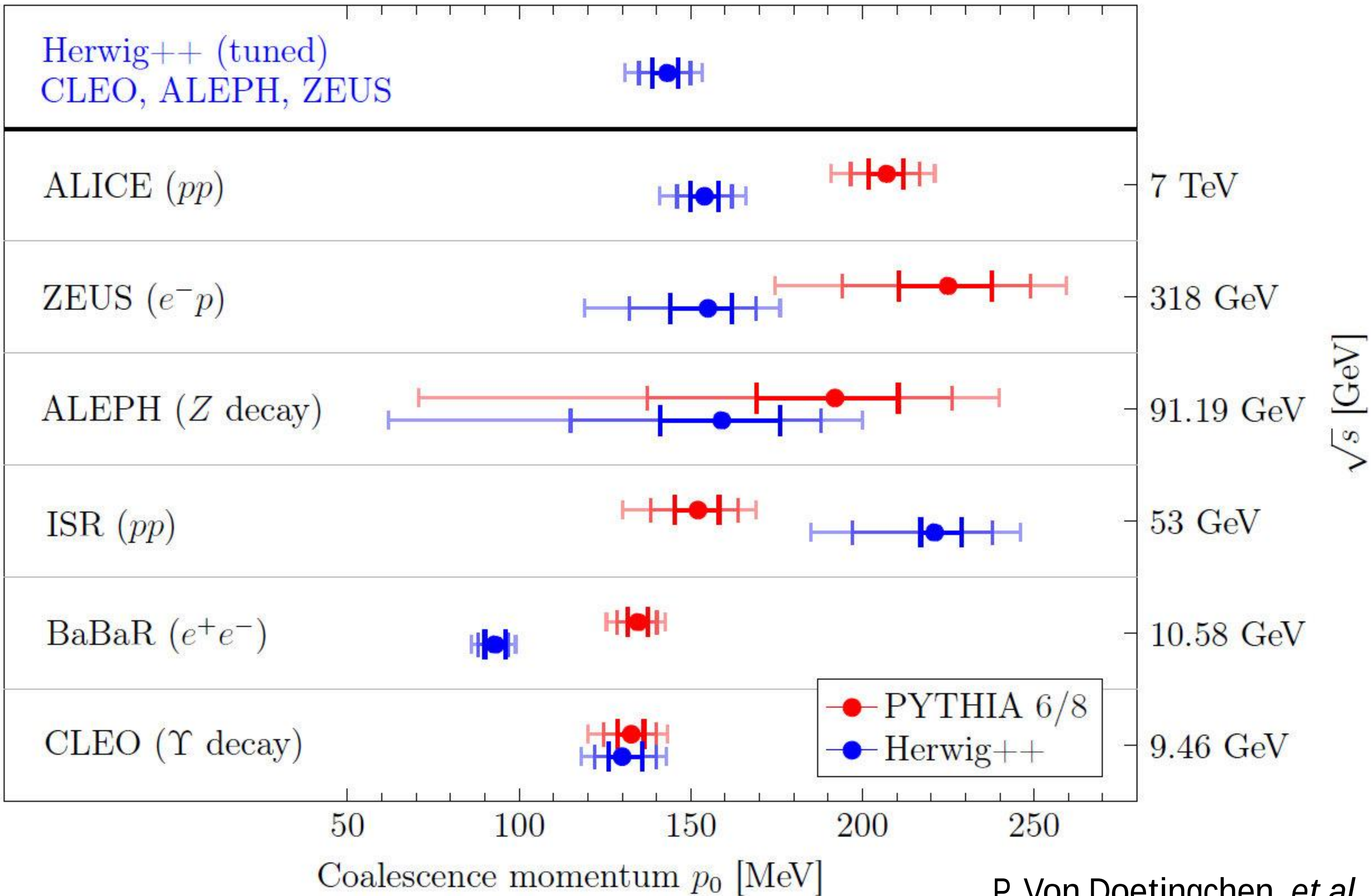
- Antideuterons observed in Υ(nS) data by ARGUS (1985, 1990), CLEO (2007), and BaBar (2014): B.F. of ~2.5×10^{-5} Phys.Rev.D 89, 111102(R)
- Continuum production = 1/10th of the Υ(nS) rates

- Leading theory is deuteron wave-function overalp with the neutron proton pair in close space and momentum ranges, a la coalescence model.
- Theoretical details are uncertain how the 6 quarks are arranged internally; treated as composition of Fock States: p n color singlet state, p n color octet state, $\Delta\Delta$, or multi-diquark state.

- Exp. measurements so far limited to the production rates and momentum spectra (which agrees with coalescence model).

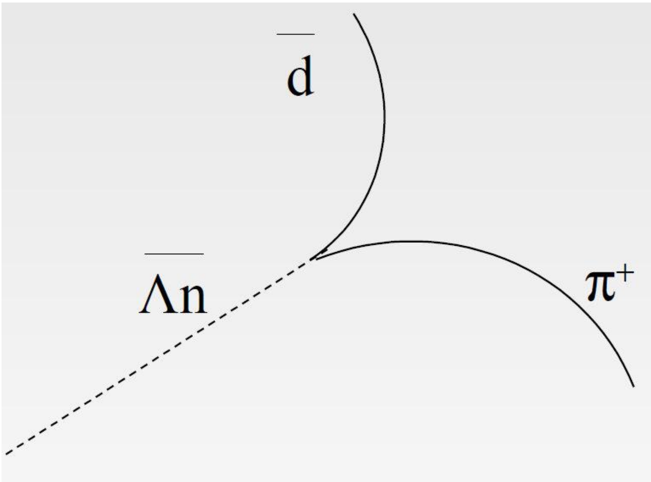
- Q1: What can we learn from full reconstruction of exclusive channels
  such as Υ(1S) -> $\bar{d}$ p p π^- or Υ(1S) -> d $\bar{d}$?
- Q2: Can the antideuteron be daughter particle of a higher mass resonance?
- Q3: What else can get "clumped"?

MC modeling of antideutron production



P. Von Doetingchen, *et al.*
arXiv:1507.02712

Hyper-deutreon(Λn) Search



- Look for a detached secondary vertex
- Current searches are at ion collision experiments

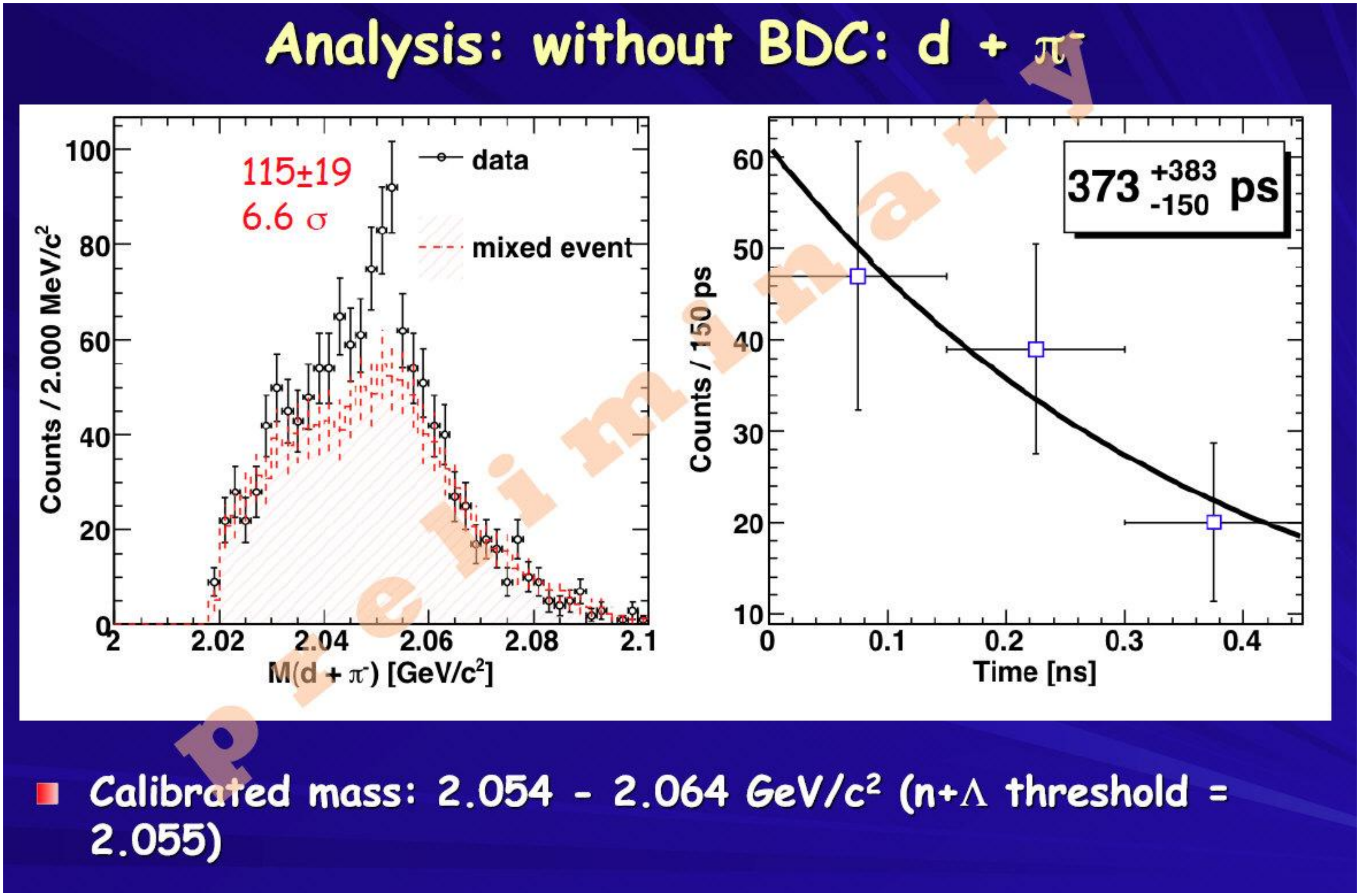
HypHI at GSI – Hints of Hyper-deuteron (2012)

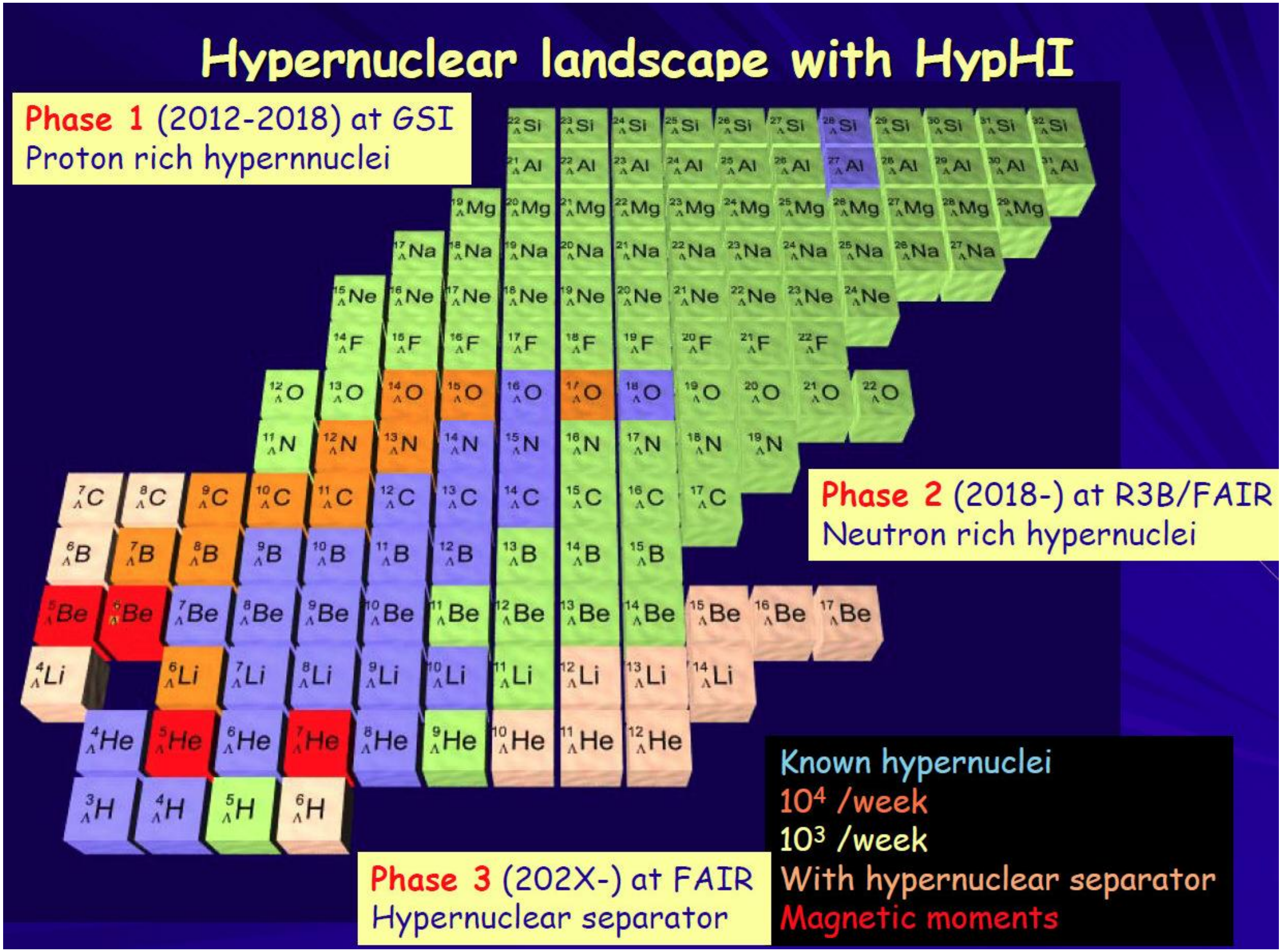
- 5.3 σ excess at M = 2059 MeV
- But, could be the Fermi breakup of excited heavier hyperfragments, and not produced by direct coalescence of a Λ and a neutron

Observation of $_{\Lambda}H^3$*(Λnp) – Hyper-triton*

B. Abelev et al (STAR Collaboration), Science 328, 58 (2010)
J. Adam et al. (ALICE Collaboration), arXiv:1506.08453

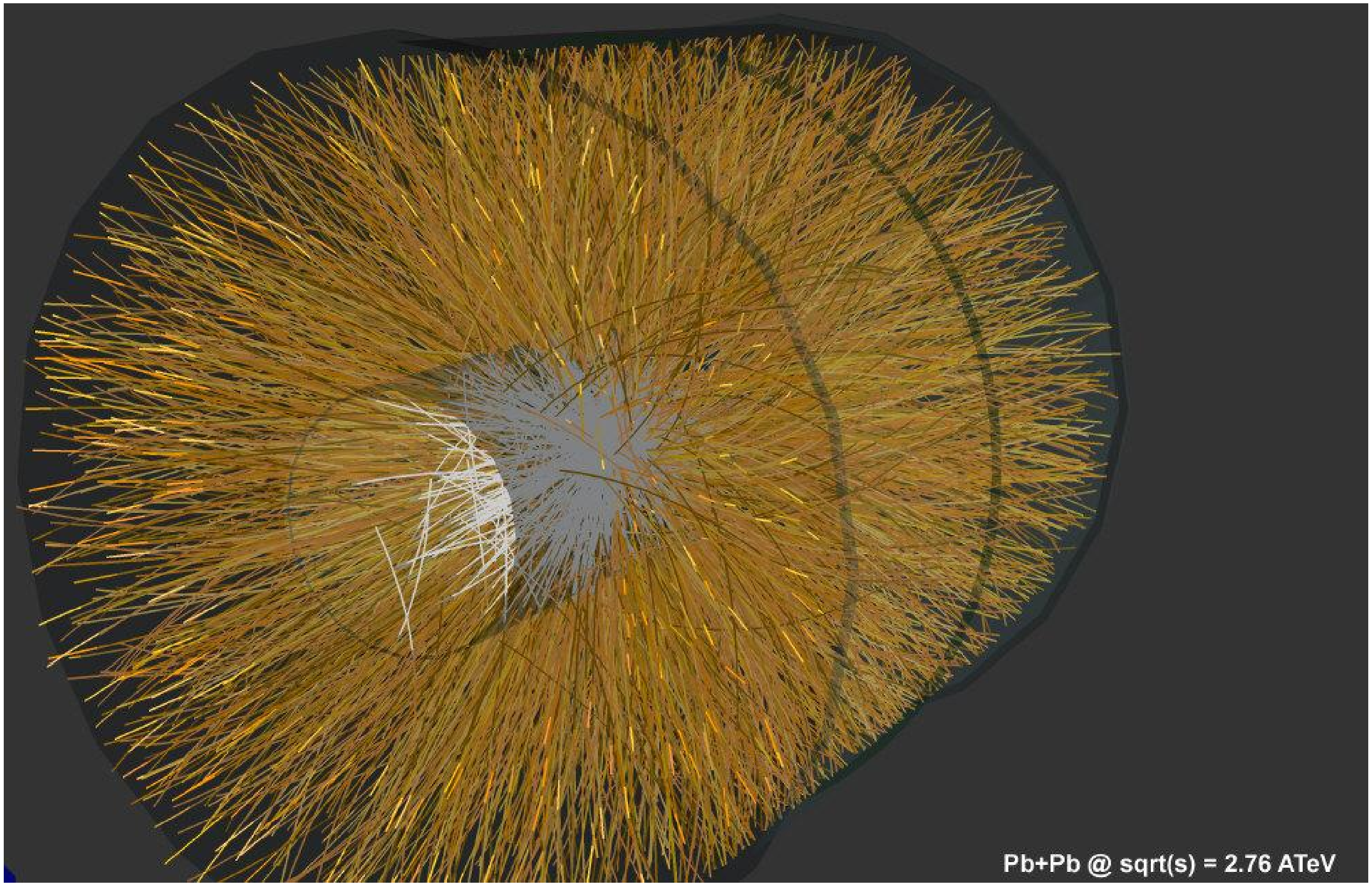
HypHI at GSI


Analysis: without BDC: d + π⁻
115±19
6.6 σ
data
mixed event
Counts / 2.000 MeV/c²
M(d + π⁻) [GeV/c²]
373 +383 -150 ps
Counts / 150 ps
Time [ns]
preliminary
Calibrated mass: 2.054 - 2.064 GeV/c² (n+Λ threshold = 2.055)



T. Saito at Few-Body Problems in Physics (FB20), 2012

Ion Collision event at ALICE



Hyper-deuteron search in Υ(ns) decay

- Should be carried out by BaBar/Belle
- Secondary vertexing with mods to the Kalman filter dE/dx energy; no DOCA cut, but gains from vertexing in background discrimination

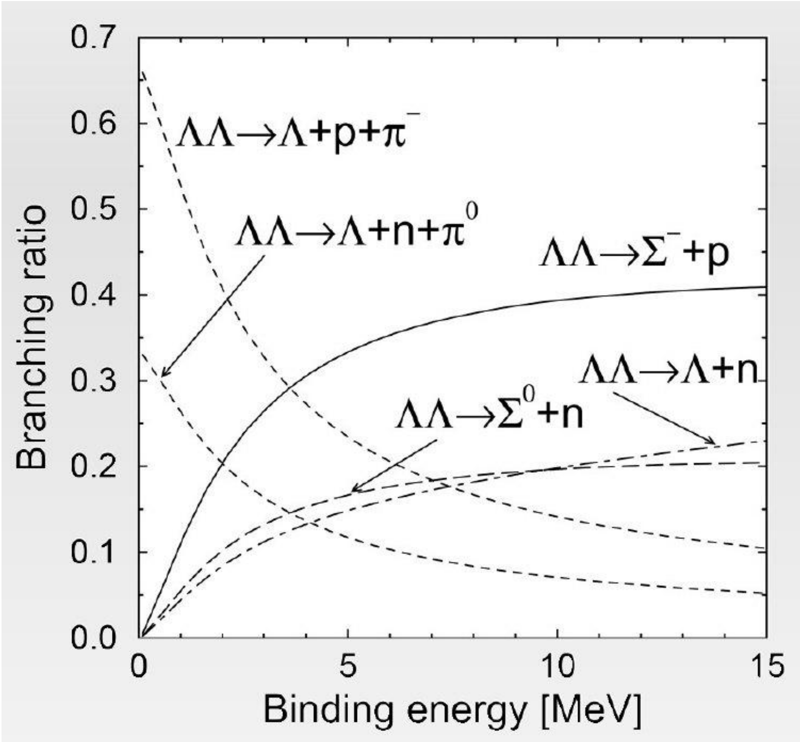
$$\overline{(\Lambda n)} \text{ or } \overline{(\Sigma p)} \rightarrow \bar{d}\,\pi^{+}$$

- Antideuteron yield = ~1500 events / 100 Million Υ(1S)
- A couple month running at Υ(1S) at early stage of Belle-II data taking will be very useful.

- Study of the rest of the event, and reconstruction of exclusive final state could shed light on QCD production process.

H di-baryon

- Searches at fixed target and ion collision experiments, and Belle - PRL 110, 222002 (2013)
  Needs More Υ Data!
- If loosley-bound above threshold, H -> $\Lambda\Lambda$
- If bound tightly, leading decay modes depend on the Binding energy



Schaffner-Bielich et al., PRL 84, 4305 (2000)

If the binding energy is large, M_H = 1.5-1.7 GeV, it becomes very stable
-- Dark Matter candidate (G. Farrar)

Charmed hyper-deuteron

- Bound state of a charm baryon and a nucleon
- First speculations soon after the J/ψ discovery. One possible event at FNAL fixed target emulsion experiment (A.A. Tyapkin, 1975)

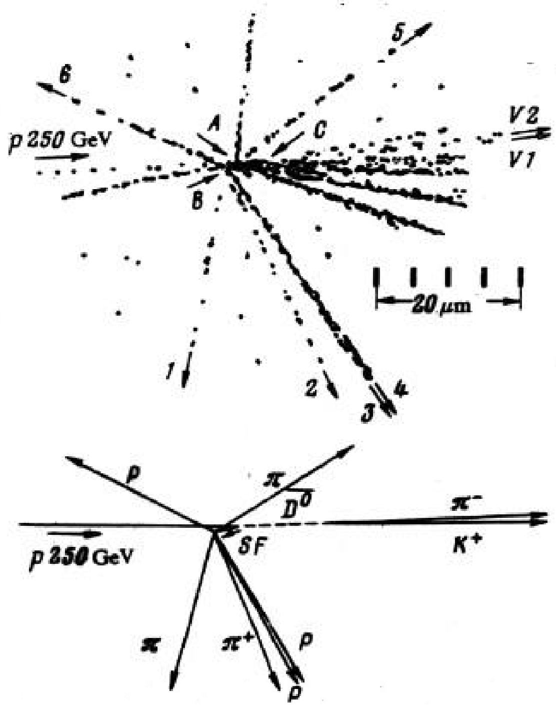
  KEK-PS-E373 emulsion experiments – no signal candidate
- Future Exp.: PANDA at GSI/HESR, GSI-FAIR, J-PARC
- For review, see "Λ_c N bound states revisited", Y. Liu and M. Oka, PRD 85, 013015 (2012).

*** Search in Υ(nS) decay ***

- Large fraction of energy in Υ decay goes to the rest mass of the daughter particles, 6.5 GeV min. (Λ_c^+, p, p-bar, Λ_c^-)
- Anti-charm baryon and p-bar in the rest of the event –> useful selection criteria
- Low multiplicity leads to potential reconstruction of an exclusive channel, either fully or partially.

Charmed nuclei event?

A.A.Tyapkin Yad.Fiz 22('75)181
250GeV/c proton ➔ emulsion
at FNAL



p + Emulsion ➔ "Charmed HY" + $\bar{D}^{o}$ + X
|➔ $K^+\pi^-$

Interpretations

① ${}^{4}_{\Lambda_c^+}\mathrm{Be}$ ➔ $\Lambda^o{}_s\,\pi^+\pi^+\pi^-\,p\,p\,p$

($\Lambda^+{}_c$ ➔ $\Lambda^o{}_s\,\pi^+\pi^+\pi^-$)

Bc = 0 ~ 10 MeV

② ${}^{4}_{\Lambda_c^+}\mathrm{He}$ ➔ $\Lambda^o{}_s\,\pi^+\pi^+\pi^o\,p\,p\,p$

($\Lambda^+{}_c\,n$ ➔ $\Lambda^o{}_s\,p\,\pi^+\pi^+\pi^o$)

⊕ $\pi^o n$ ➔ $\pi^+ p$

Bc = 0 ~ 10 MeV

③ ${}^{6+k}_{\Lambda_c^+}\mathrm{C}$ ➔ $\Lambda\,s\,\pi^+\,\pi^+\,\pi^+\,ppp\;nn + kn$ $(k>=1)$

($\Lambda^+{}_c\,p$ ➔ $\Lambda^o{}_s\,n\,\pi^+\pi^+\pi^o$)

⊕ $\pi^o\,p$ ➔ $\pi^+\,n$

Bc = ?

Nakazawa, Few Body Conf., 2004.

Summary

- Most exotic states predicted in QCD not confirmed, even after ~40 years of success in describing the Strong Interaction
- Many appear to be accessible in hadronic bottomonium decays; Should carry out comprehensive searches with BaBar/Belle data
- Rate-limited modes will get a big boost at Belle-II
- Better understanding of QCD from confinement and binding to formation and decay will lead to consistent theoretical framework for QCD.
- Finding a new particle is fun!