An introduction to heavy flavour physics at hadron machines, e^+e^- colliders, & elsewhere

Bruce Yabsley

University of Sydney Particle Physics Group
ARC Centre of Excellence for Particle Physics at the Terascale
(http://www.coepp.org.au/)

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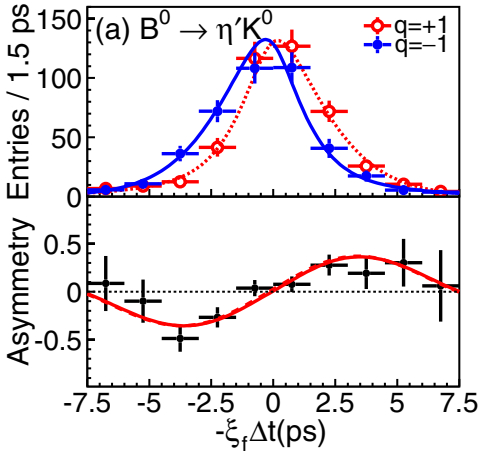

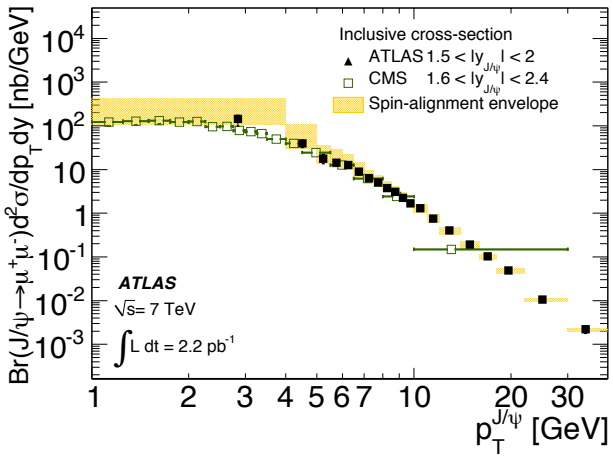

Outline

What we mean by "heavy flavour"

- the term is somewhat flexible in practice
- my working definition:
  "a fermion with mass greater than the hadronic scale is involved . . . "
- the original extra flavour, strangeness, doesn't count
  - the strange quark is not quite heavy enough
  - but there are some common features (*cf.* ϕ, K^*, . . .)
- *charm* does count, but is more complicated than you think
- *beauty* is the ideal case, and has a rich phenomenology
- top is different again: decays too quickly to hadronise
- in this talk, I will leave out τ, which does not form bound states, although there are common features with b and c
- so we should add another clause:
  ". . . and is at least potentially part of a bound state"

Open flavour states

Heavy quark symmetry

D^+	1869.6 MeV
D^0	1864.9 MeV
D_s^+	1968.5 MeV
Λ_c^+	2286.5 MeV
Ξ_c^0	2470.9 MeV
Ξ_c^+	2467.8 MeV
Ω_c^0	2695 MeV

B^+	5279.3 MeV
B^0	5279.6 MeV
B_s^0	5366.8 MeV
Λ_b^0	5619.4 MeV
Ξ_b^0	5788 MeV
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HQS: $m_Q \to \infty$, universal behaviour; heavy $\vec{s}_Q$ and light $\vec{j}_q$ decouple;
predictive — narrow and broad states, nontrivial $\vec{L}$ of decays, ...

Lifetimes of heavy hadrons

. . . and at leading order in an expansion in Λ_{QCD}/m_Q,
all heavy hadrons of a given flavour should have *the same lifetime*,
driven by the decay of the free quark

	τ
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  (similarly for both B^+ and B^0, $\Gamma_{X\ell\nu} \sim 0.135\,\mathrm{ps}^{-1}$)

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- notice that $\tau \sim 1.6\,ps \longrightarrow c\tau \sim 500\,\mu\mathrm{m}$:
  foundation of open-heavy flavour measurement in many experiments

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- beauty heavy enough to undergo baryonic decay, $\mathrm{B} \to \mathfrak{B}\overline{\mathfrak{B}}X$;
  complex effects are possible — active area of study

Loops and all that

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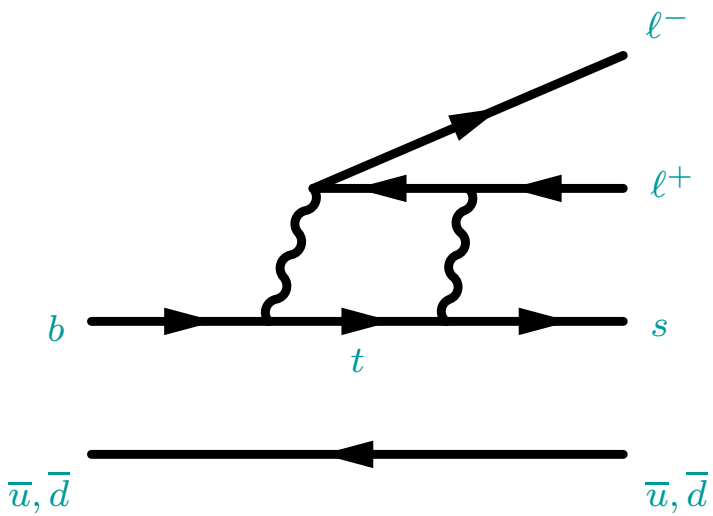

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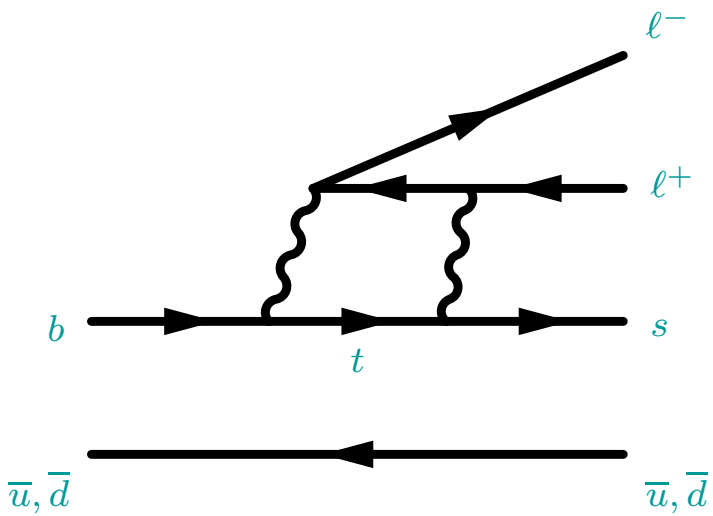

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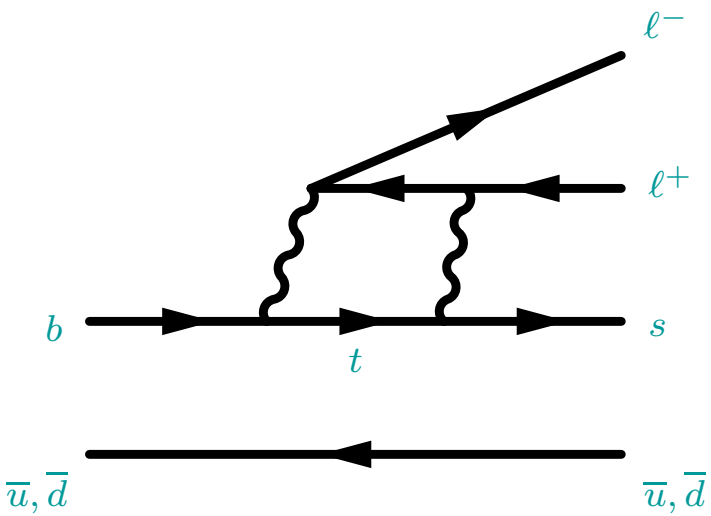

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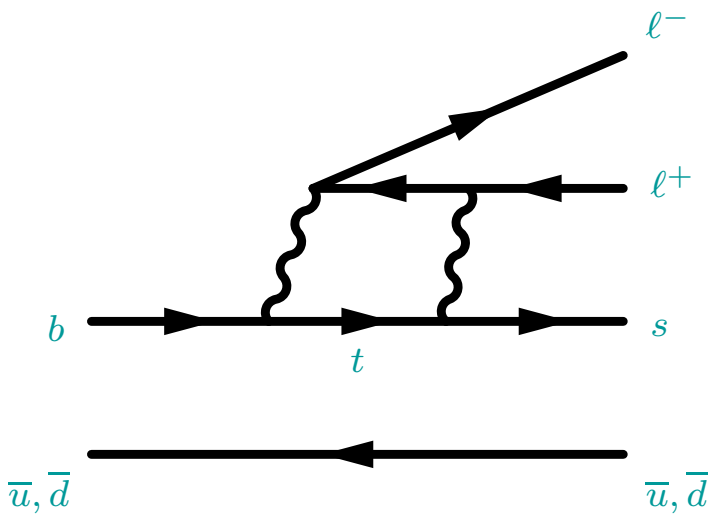

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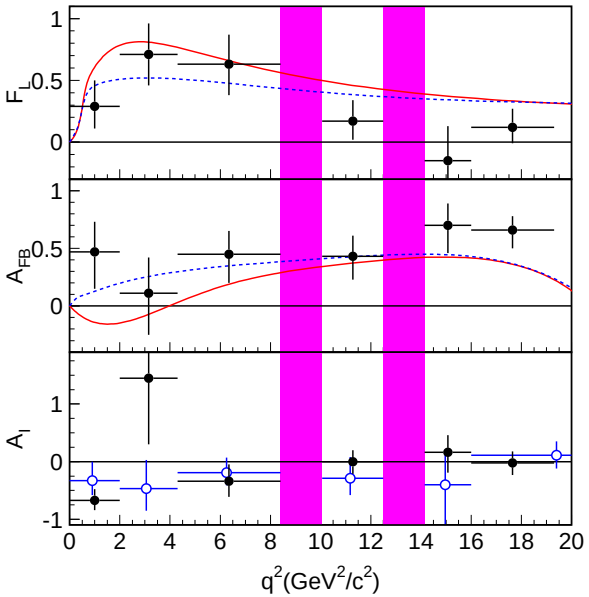

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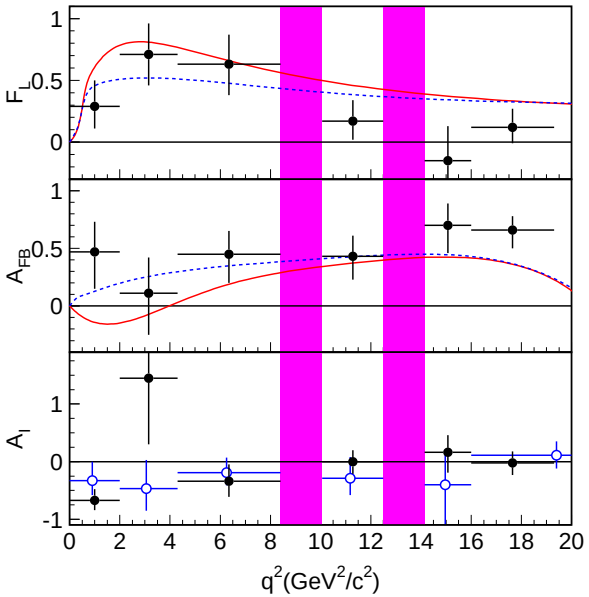

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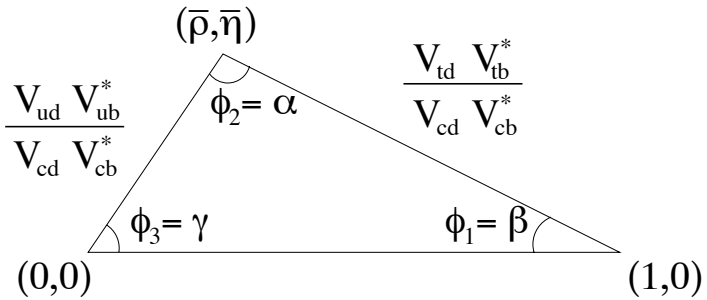

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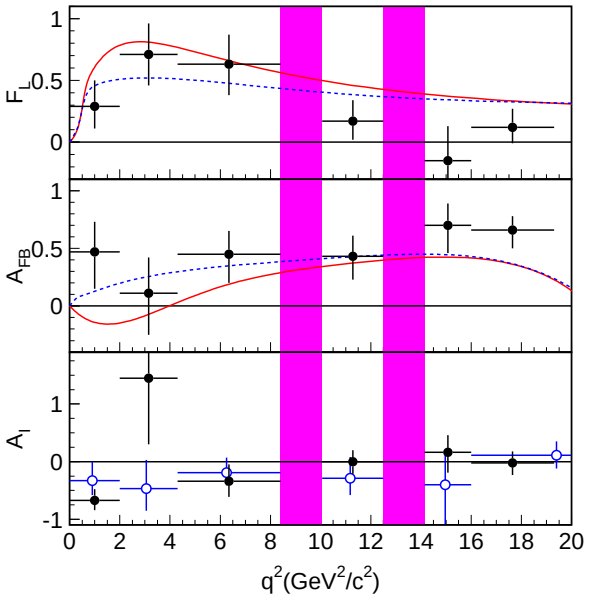

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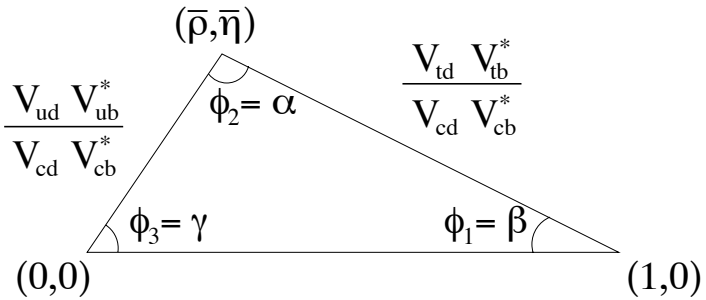

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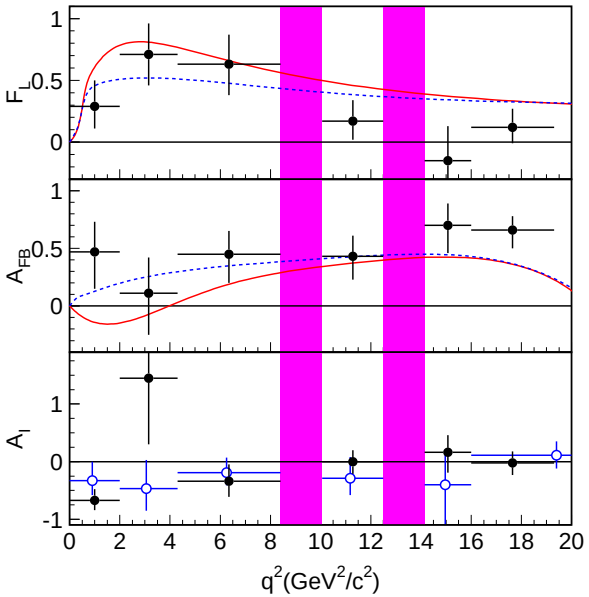

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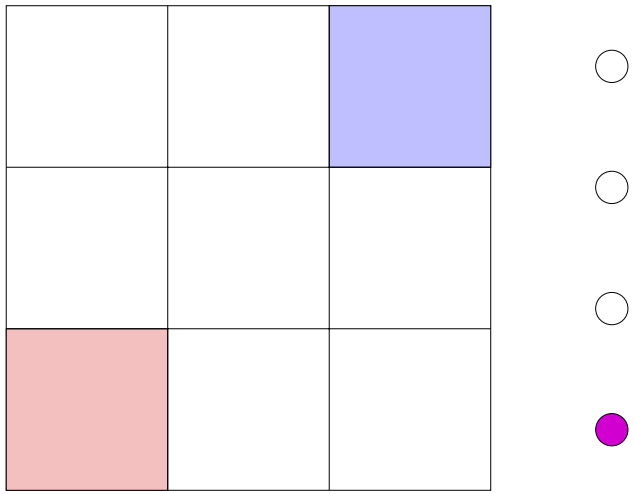
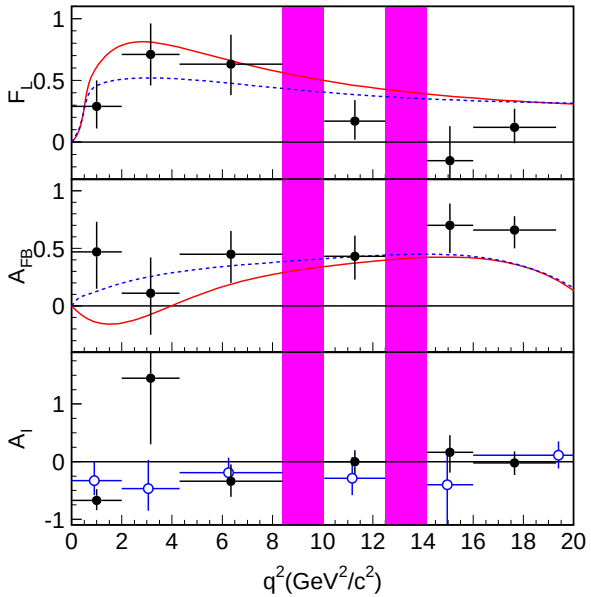
- open unitarity triangle: large effects
- confirmed KM picture of CPV



Loops and all that

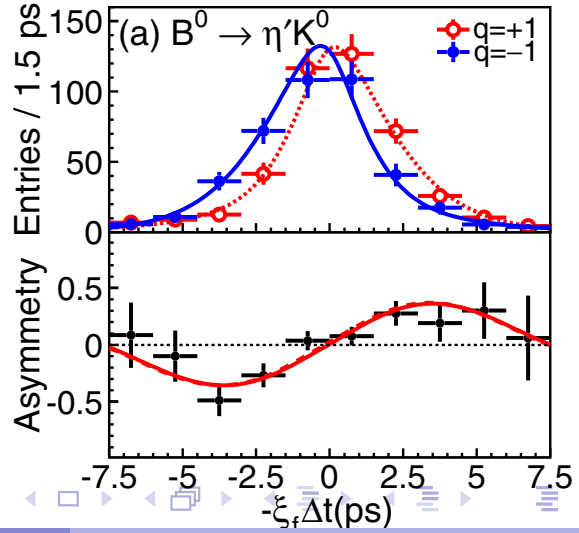
Much of the history and the current interest in open heavy flavour comes from loop effects:

- no FCNC $\Longrightarrow \exists$ charm
- B mixing $\Longrightarrow$ large m_t
- loops such as $b \to s\ell^+\ell^-$ are likewise sensitive to further new (heavy) particles, incl. those beyond current direct reach



B-factories' flagship programme: time-dependent CP violation analyses

- CPV in interf. of decay & mixing (loops!)
- open unitarity triangle: large effects
- confirmed KM picture of CPV
- searches for non-SM effects due to competing (mostly loop) amplitudes



Hidden flavour states

Heavy quarks and quarkonium spectroscopy

Image credit: Tord Johansson (Uppsala), Excited QCD 2012

quarks explain eightfold way *etc.* . . . and are manifest in DIS [$\sim$ '70]

Heavy quarks and quarkonium spectroscopy

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quarks explain eightfold way *etc.* . . . and are manifest in DIS [$\sim$ '70]

charm explains ~~FCNC~~ . . . and is seen as an active flavour ['76];

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positronium-like $c\overline{c}$ states, charmonium, also form ['75]:

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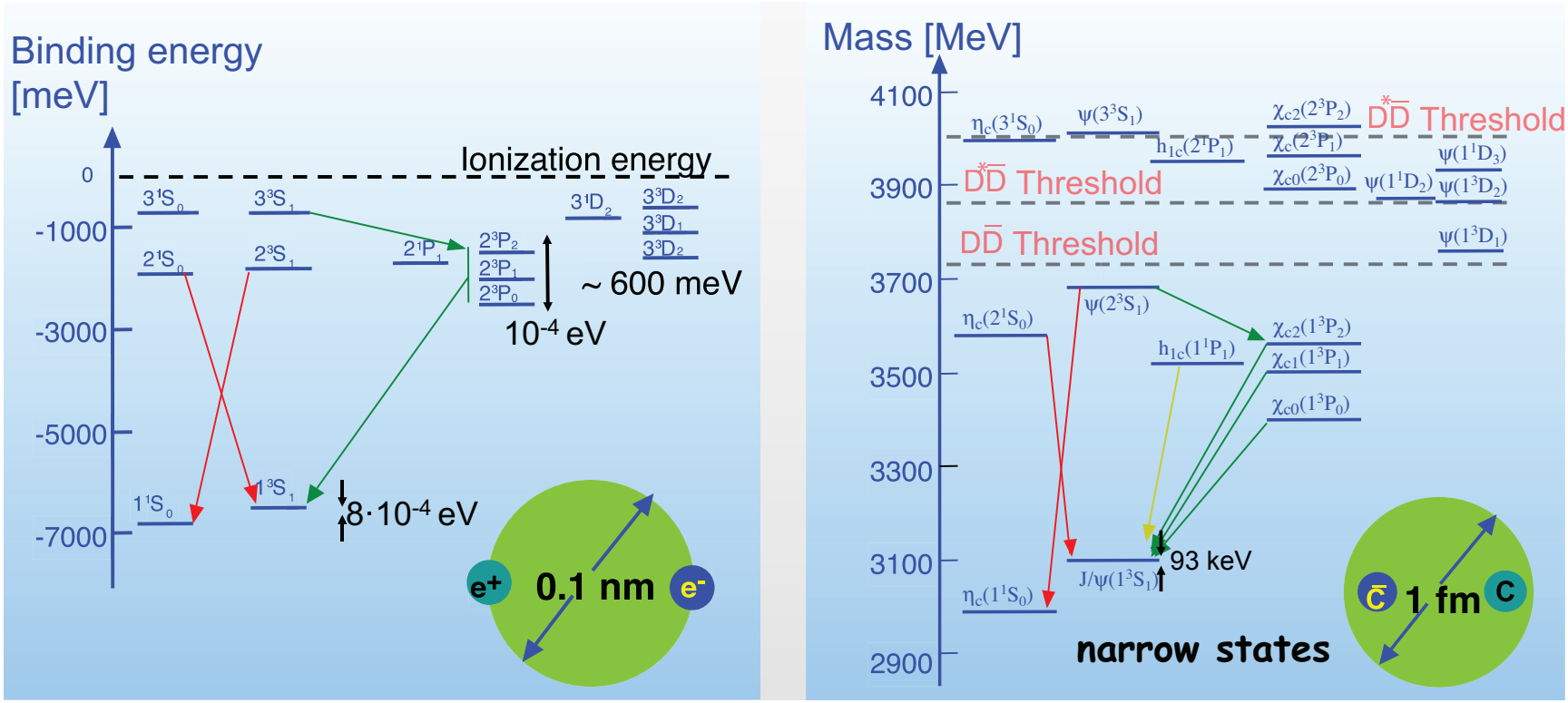

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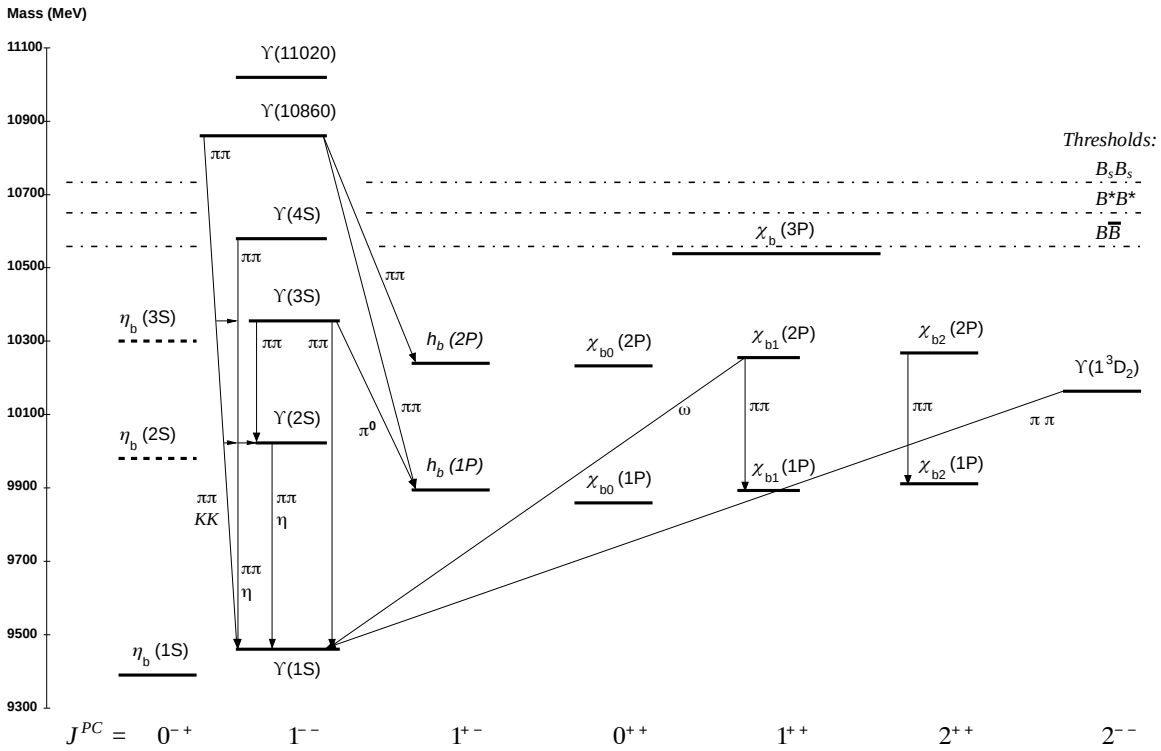


beauty similarly forms $b\bar{b}$, "bottomonium" (!) states ['77]

Quarkonium as a tool

$e^+e^- \to \gamma^* \to (Q\overline{Q})_{(res)}$ can be used to produce other states:

$\Upsilon(4S)$	$\to B^+B^-$, $B^0\overline{B}{}^0$ (coherent) for B, CPV studies	[Belle and BaBar]
$\psi(3770)$	equivalent D^+D^-, $D^0\overline{D}{}^0$ programme	[CLEO-c, BESIII]
J/ψ, $\psi(2S)$	study of decays and transitions to other $c\overline{c}$	[BESII/III, ...]
$\Upsilon(2S, 3S)$	decays and transitions; NP searches	[CLEO, Belle, BaBar]
$\Upsilon(5S)$	$B_s^0\overline{B}_s^0$ physics programme, incl. CPV	[Belle]

The $\{\psi, \Upsilon\} \to \ell^+\ell^-$ signature is self-tagging:

- triggering
- b-hadron physics analyses

X(3872), Y(4260): anomalous hidden-charm (1)

from my review for Beauty 2006 / Oxford

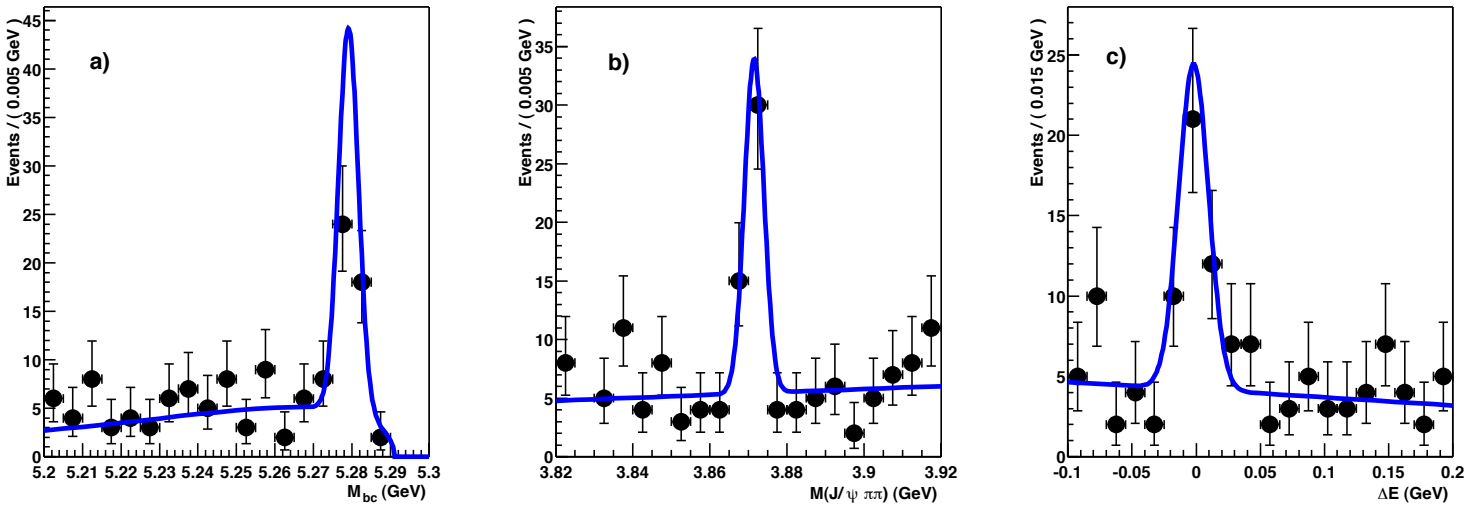
"solved" subject for two decades, until unexpected states $\to \pi^+\pi^-\psi$ seen:

Belle: S.-K.Choi, S.L.Olsen, *et al.*, *PRL* **91**, 262001 (2003)

3D fits to ψ' (to fix params) & $M_{\pi^+\pi^- J/\psi} \in [3770, 3970]$ MeV (to extract signal)

signal region proj^{ns} and the UML $(M_{bc}, M(\pi^+\pi^- J/\psi), \Delta E)$ fit

beam-constrained mass | invariant mass | energy difference



confirmations of narrow X	
CDF	*PRL* **93**, 072001 (2004)
D0	*PRL* **93**, 162002 (2004)
BaBar	*PRL* **71**, 071103 (2005)

substructure

concentration $\to$ high $M(\pi^+\pi^-)$

favouring $X(3872) \to \rho J/\psi$

and hence $C = +1$

X(3872), Y(4260): anomalous hidden-charm (1)

from my review for Beauty 2006 / Oxford

"solved" subject for two decades, until unexpected states $\to \pi^+\pi^-\psi$ seen:

MESON 2004: "Search for a charmonium assignment for the $X(3872)$"
Int. J. Mod. Phys. **A20**, 240–249 (2005) [arXiv:hep-ex/0407033]

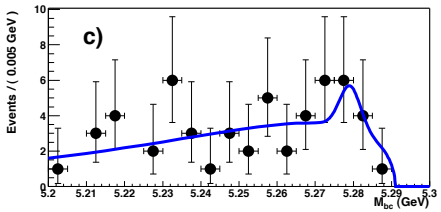
- X is narrow & $X \not\to D\overline{D}$ [R. Chistov *et al.*, *PRL* **93**, 051803 (2004)] disfavours $J^{PC} = 0^{++}, 1^{--}, 2^{++}, \ldots$ [N.B. $0^{+-}, 1^{-+}, \ldots$ exotic]
- run through low-J charmonia with unnatural J^P:

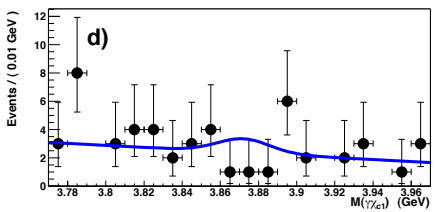
state	alias	J^{PC}	M_{pred}	Γ_{pred}	comment
1^3D_2	ψ_2	2^{--}	3838	0.7	Mass wrong; $\Gamma_{\gamma\chi_{c1}}$ too small
2^1P_1	h_c'	1^{+-}	3953	1.6	Ruled out by $\lvert\cos\theta_{J/\psi}\rvert$ distribution
1^3D_3	ψ_3	3^{--}	3849	4.8	M, Γ wrong; $\Gamma_{\gamma\chi_{c2}}$ too small; J too high
1^1D_2	η_{c2}	2^{-+}	3837	0.9	$\mathcal{B}(\pi^+\pi^- J/\psi)$ expected to be very small
2^3P_1	χ_{c1}'	1^{++}	3956	1.7	"$\Gamma_{\gamma J/\psi}$ too small"
3^1S_0	η_c''	0^{-+}	4060	~ 20	Mass and width are wrong

$$\frac{\Gamma(X \to \gamma\chi_{c1})}{\Gamma(X \to \pi\pi\psi)} < 0.89\ (90\%)$$

cf. ψ_2: > 1.6

[potential / ψ'' Wigner-Eckart]





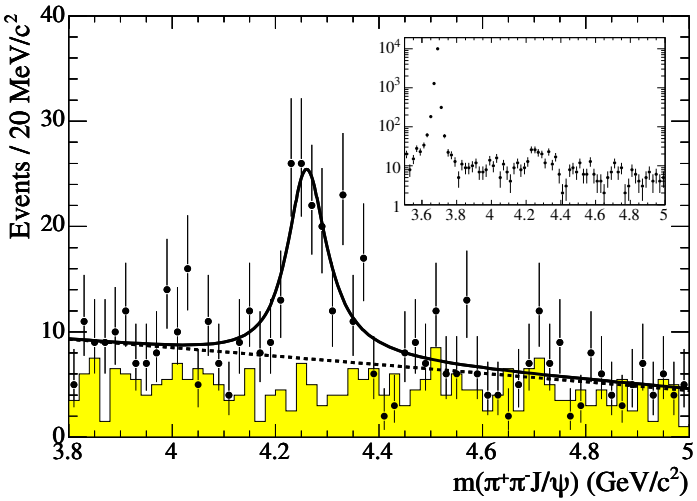
X(3872), Y(4260): anomalous hidden-charm (1)

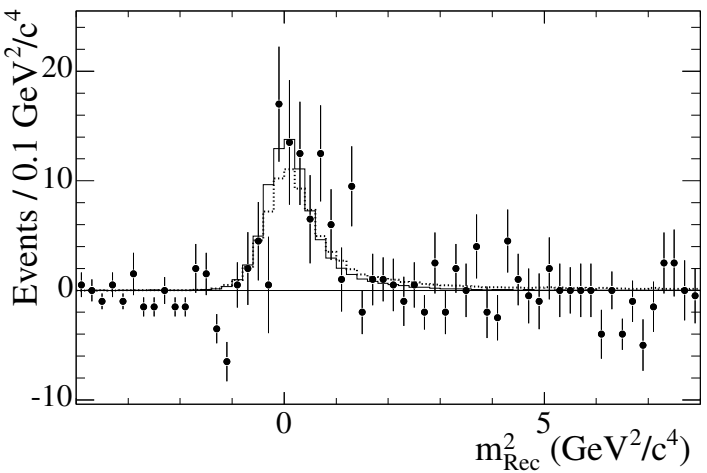
from my review for Beauty 2006 / Oxford

"solved" subject for two decades, until unexpected states $\to \pi^+\pi^-\psi$ seen:

BaBar: B. Aubert *et al.*, *PRL* **95**, 142001 (2005)

$\pi^+\pi^-\ell^+\ell^-$ vtx, ψ-mass constraint $M(\pi^+\pi^- J/\psi) \sim 4260\,\text{MeV}$; $-$ sideband





BW fit; can't rule out > 1 state

125 ± 23 events

$M = (4259 \pm 8^{+2}_{-6})\,\text{MeV}$

$\Gamma = (88 \pm 23^{+6}_{-4})\,\text{MeV}$

$M^2_{\text{recoil}} \in [-1.04, +3.27]\,\text{GeV}^2$ (e^+e^-)

$M_{\text{recoil}} \in [-1.04, +1.25]\,\text{GeV}^2$ $(\mu^+\mu^-)$

other dist^{ns} studied . . .

. . . good agreement with MC

$\Gamma(Y(4260) \to e^+e^-) \times \mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi) = (5.5 \pm 1.0^{+0.8}_{-0.7})\,\text{eV}$

X(3872), Y(4260): anomalous hidden-charm (2)

from my review for QWG 2011 / Darmstadt

industry in study of $X(3872)$; there are still important unknowns

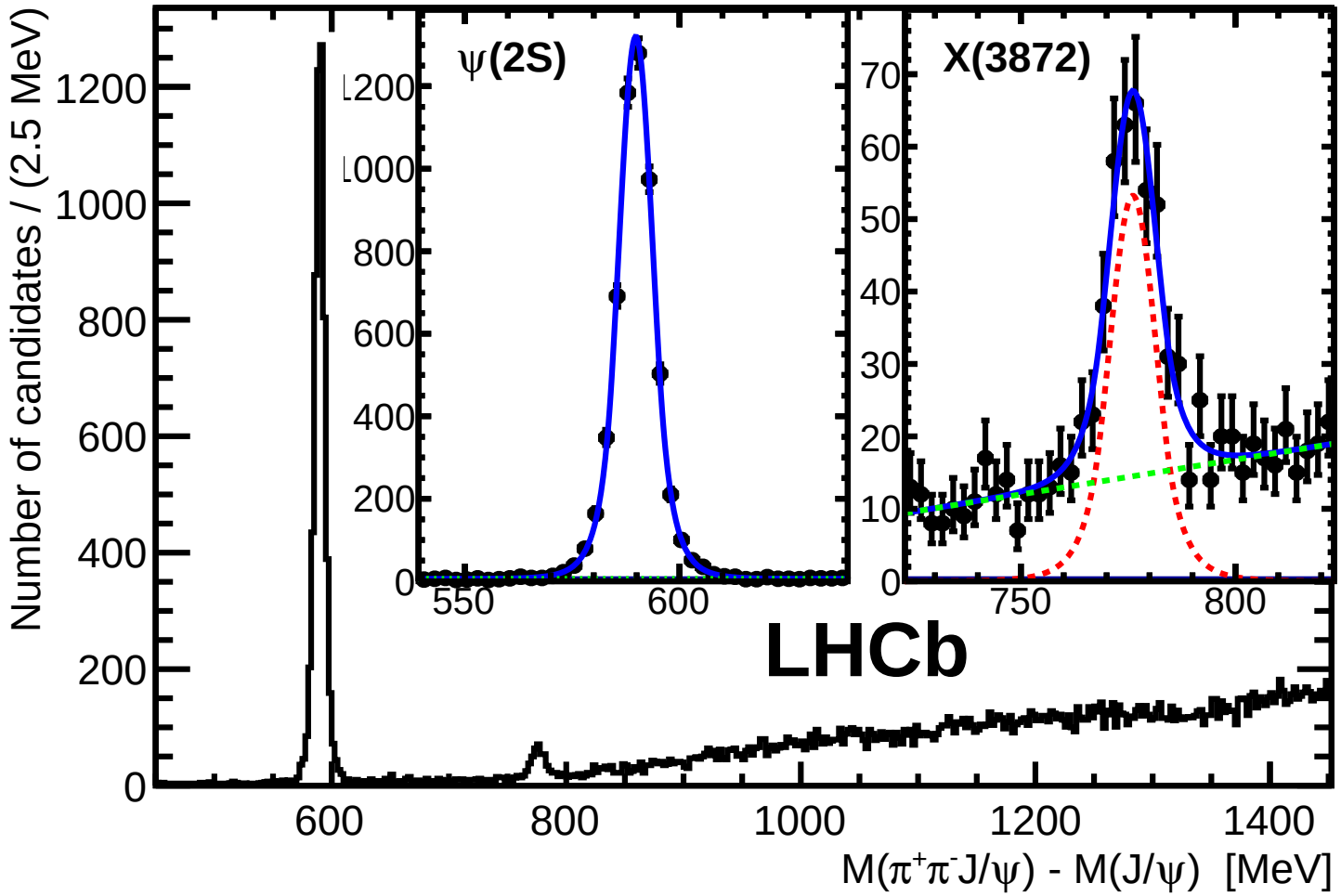
- narrow; prominent $\pi^+\pi^-\psi$ decay [Belle discovery; CDF, D0, BaBar]
  - $\mathcal{B}(X \to \pi^+\pi^-\psi) > 4.2\%$ [BaBar inclusive, *PRD* **71**, 031501]
  - $\Gamma < 1.2\,\mathrm{MeV}$ (90% C.L.) [Belle *PRD* **84**, 052004]
- $M = (3871.71 \pm 0.19)\mathrm{MeV} \overset{\Delta \ll \sigma}{=} (m_{\mathrm{D}^0} + m_{\mathrm{D}^*})$ [private WA; $S < 1$]
- $\mathrm{p\overline{p}}$ prod^n: $(16 \pm 5 \pm 2)\%$ b-decay, rest prompt; "ψ'-like" [CDF]
- $X^\pm$ still not seen: not an isovector [BaBar; Belle *PRD* **84**, 052004]
- C-even, from $X \to \gamma\psi$ [Belle, BaBar] and $\pi^0\pi^+\pi^-\psi$ [Belle]
  - $X \to \rho\psi$ dominates, $L = 0, 1$ [CDF & Belle $M(\pi^+\pi^-)$]
  - $J^{PC} = 1^{++}$ or 2^{-+} [CDF & Belle angular; note BaBar $\pi^0\pi^+\pi^-\psi$]
- B^+ *vs* $\mathrm{B}^0 \to \mathrm{K}\,X$: ΔM disfavoured [BaBar & Belle]
- large $\mathcal{B}(X \to (\{\gamma, \pi^0\}\mathrm{D}^0)_{\mathrm{D}^{*0}}\overline{\mathrm{D}}{}^0)$ [Belle & BaBar]
- loose ends: $\pi^0\pi^0\psi$, $\gamma\psi'$, $\pi^+\pi^-\eta_c$, $\{\gamma, \pi^0\}\mathrm{D}\overline{\mathrm{D}}$ lineshape

— radiative (disputed) & lineshape crucial for structure

X(3872), Y(4260): anomalous hidden-charm (3)

LHCb resolution of J^{PC} question, arXiv:1302.6269 [hep-ex] $\rightarrow$ PRL

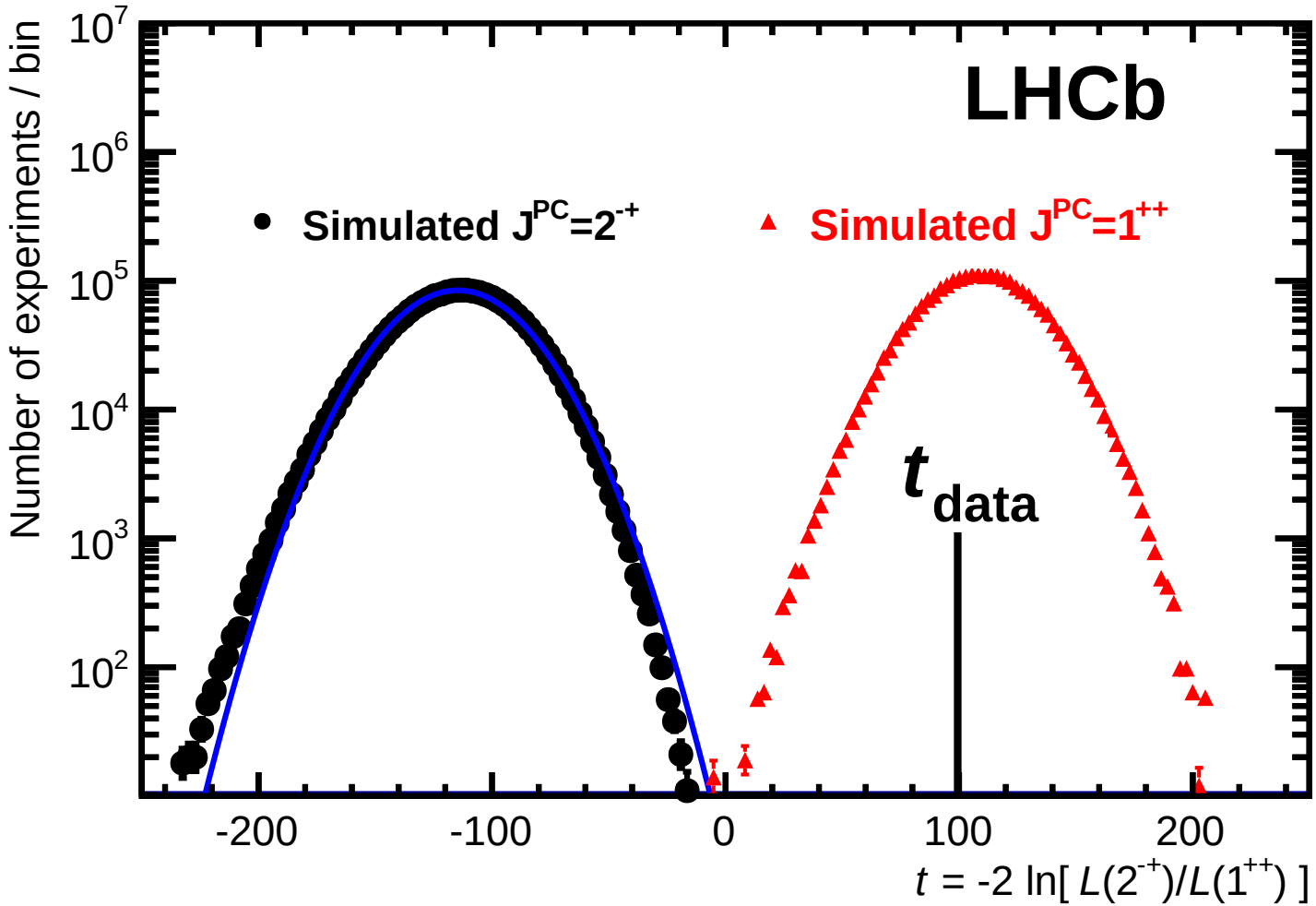
313 ± 26 $B^+ \rightarrow K^+ X(3872)$ events



X(3872), Y(4260): anomalous hidden-charm (3)

LHCb resolution of J^{PC} question, arXiv:1302.6269 [hep-ex] $\rightarrow$ PRL

$\mathcal{L}$ ratio test statistic from 5D angular dist^n, accumulated over those events



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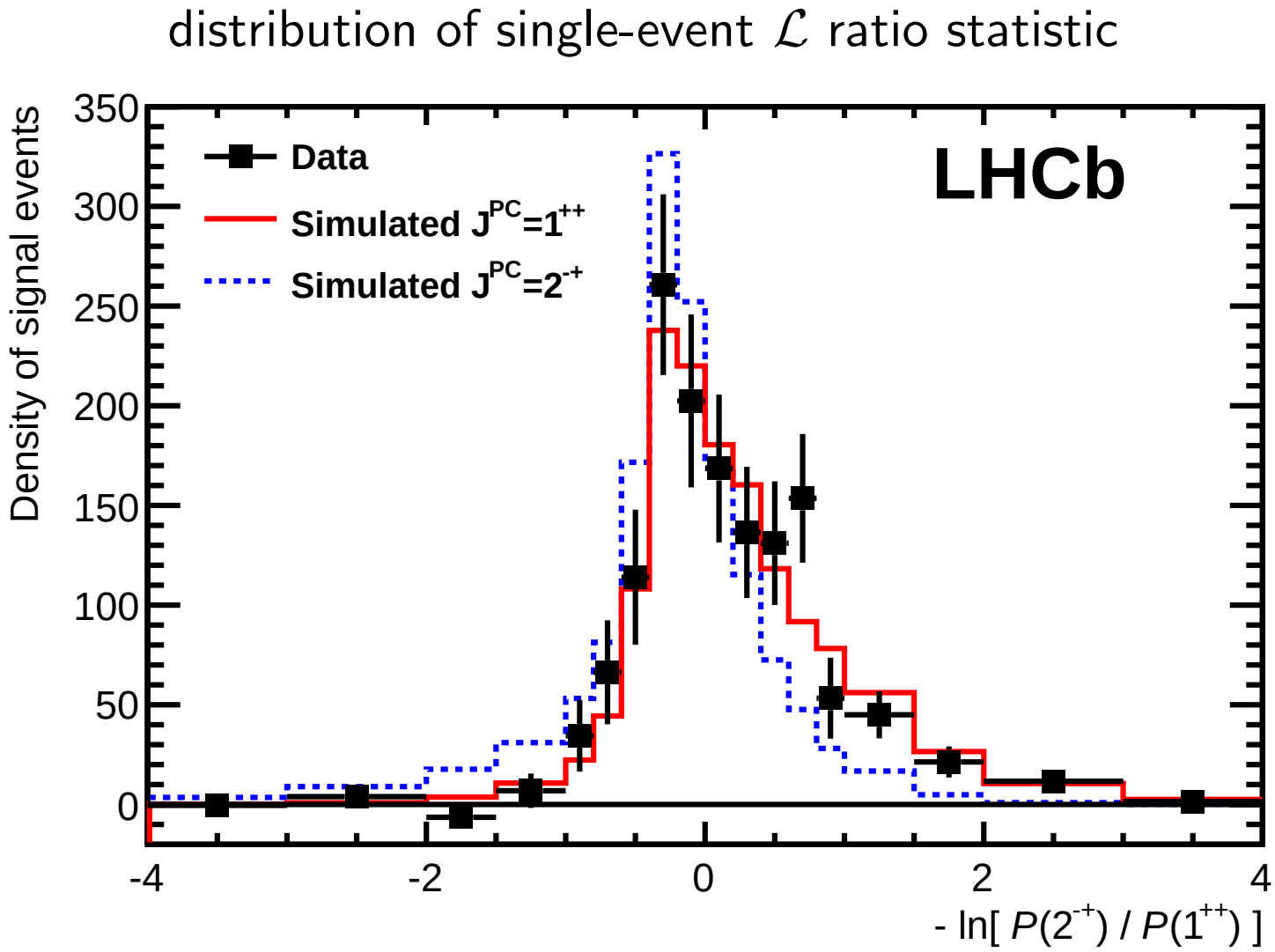

"XYZ": "Jefe, what is a plethora?"

current listing, from Christian Hambrock (Dortmund), at Beauty 2013

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Also observed by
					e^+e^- (ISR)	
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	$J/\psi \to \eta Y_s(2175)$	BaBar*, BESII
				$\pi^+\pi^- J/\psi$,		BaBar
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\gamma J/\psi, D\bar{D}^*$	$B \to KX(3872), p\bar{p}$	CDF, D0
$Z(3900)$	3899 ± 6	46 ± 22	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(3900)\pi$	BESIII*
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$	
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$	
				$D\bar{D}^*$ (not $D\bar{D}$		
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$	
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$	BaBar
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	BaBar*, CLEO
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	BaBar*
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^- (ISR)	
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$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$	
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$	
$Z_b(10610)$	$10,607 \pm 2$	18.4 ± 2.4	1^+	$\pi^\pm h_b(1,2P), \pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10610)\pi$	
$Z_b(10650)$	$10,652 \pm 2$	11.5 ± 2.2	1^+	$\pi^\pm h_b(1,2P), \pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10650)\pi$	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$	

note in particular charged and hidden beauty final states

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note in particular charged and hidden beauty final states

"XYZ": Corrolaries

There are *many* explanations for these states; this is lovely.
However all such explanations have further consequences:

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  a *forest* of new states

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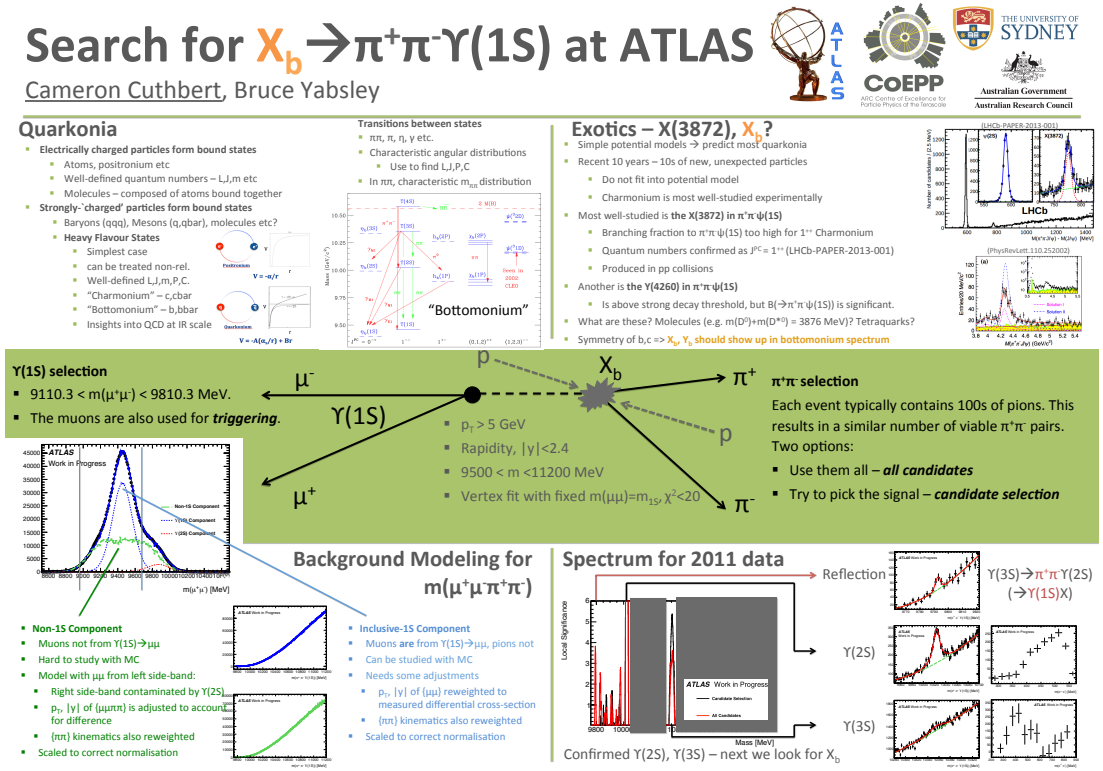
- hidden beauty analogues expected: PhD project of Cameron Cuthbert



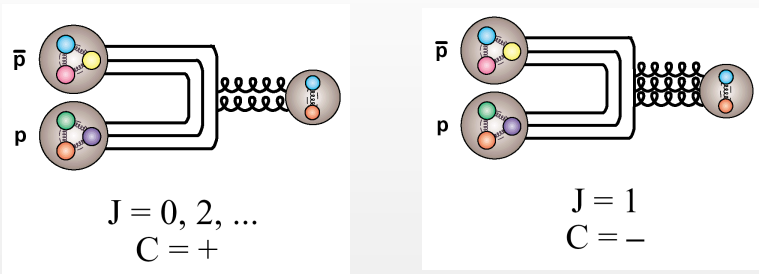
"XYZ": Corrolaries

There are *many* explanations for these states; this is lovely.
However all such explanations have further consequences:

- molecules $\mathrm{D}^*\overline{\mathrm{D}}$: more
- tetraquarks $c\bar{c}q\bar{q}$:
  a *forest* of new states
- hidden beauty analogues
  expected: PhD project of
  Cameron Cuthbert
- hybrids: many partners;
  some manifestly exotic
  $(0^{+-}, 1^{-+}, 2^{+-}, \ldots)$;
  hard to see — look in $p\overline{p}$

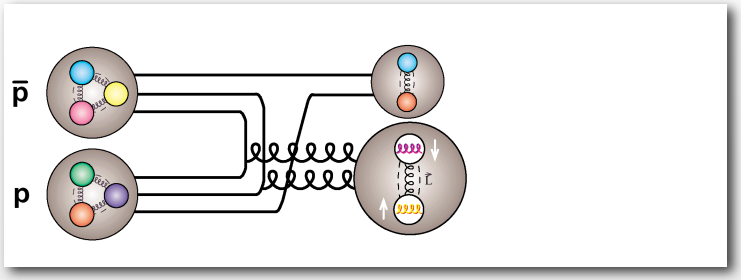
Particle production in $\bar{p}p$ interaction

Formation:



All J^{PC} allowed for $(q\bar{q})$ are accessible in $\bar{p}p$

Production:



J^{PC} not allowed for $(q\bar{q})$ possible

"XYZ": What counts as an exotic state?

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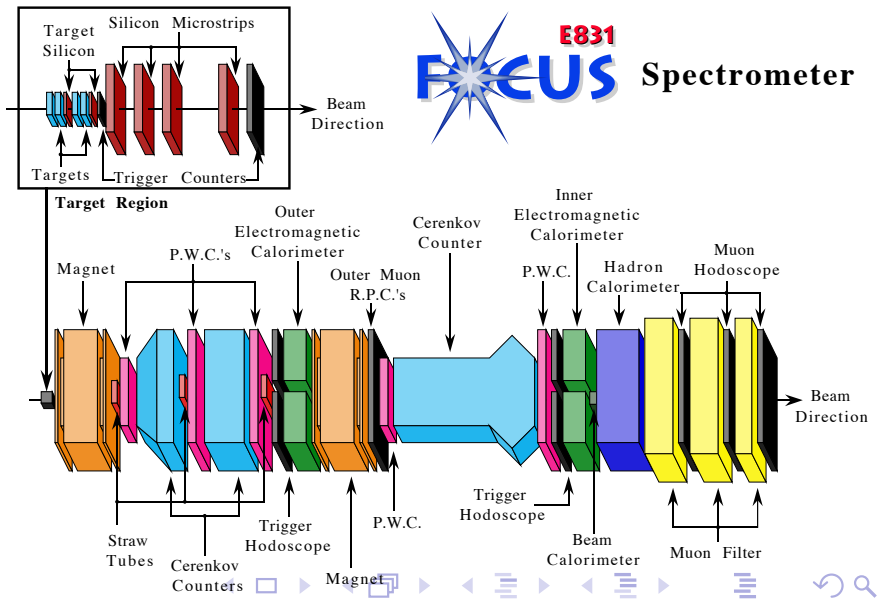
- there are varying degrees of *plausibility*:
  new tetraquark candidates speculative until we're sure we've seen *one*
- relatively little is known about production mechanism

Facilities for heavy flavour studies

Fixed-target experiments

- classic environment for heavy flavour production
- density of solid target $\rightarrow$ huge equivalent luminosity, so preferable to colliders for many measurements
- forward-boosted decay products: long, multi-element spectrometers
- high boost: good decay-time resolution even with older technology (first D-mixing evidence came from FOCUS)

- attention to triggering required
- challenging to reconstruct neutrals
- $\exists$ some sophisticated facilities: FOCUS used a tagged-γ beam



Hadron colliders

Messy environment, but large cross-sections for $c\bar{c}$, $b\bar{b}$ production

- increase in energy has made beauty accessible
  (*cf.* mostly charm at earlier facilities)
- advantage to working in the *forward region*,
  as flavour production concentrated at high-y $\longrightarrow$ LHCb
- background is an issue, esp. for multi-track / hadronic signatures
- triggering a challenge:

CDF made themselves a power in charm studies with a displaced-track trigger

ATLAS relies on $\{\psi, \Upsilon\} \to \ell^+\ell^-$; high-$p_T$ thresholds limit this $\longrightarrow$ move to 3ℓ, 4ℓ, *etc.*

LHCb makes powerful use of displaced vertices, impact param.

e^+e^- colliders

Clean environment for physics, with knowledge of the initial state.
Reconstruction of neutral decay products & 4-momentum balance possible.
Various ways to produce hidden flavour:

- EM coupling
  - flavour physics at LEP
  - B-mixing at ARGUS and CLEO
  - $e^+e^- \to c\bar{c}$ continuum at Belle/BaBar
- $e^+e^- \to \gamma^* \to 1^{--}$ resonance: $\Upsilon(4S)$ and friends
- initial state radiation: α discount, then continuous $\sqrt{s}$ spectrum
- 2-photon physics: $e^+e^- \to e^+e^-\gamma\gamma^{(*)}[\to X]$
- relatively *open trigger*:
  track multiplicity, angular distribution, E_{cal} enough
  to separate interesting events from {Bhabha, beam-gas, ...}

∼ Fixed-target $p\bar{p}$ at few-GeV energies: P̄ANDA

from Tord Johansson (Uppsala), for P̄ANDA, at Excited QCD 2012

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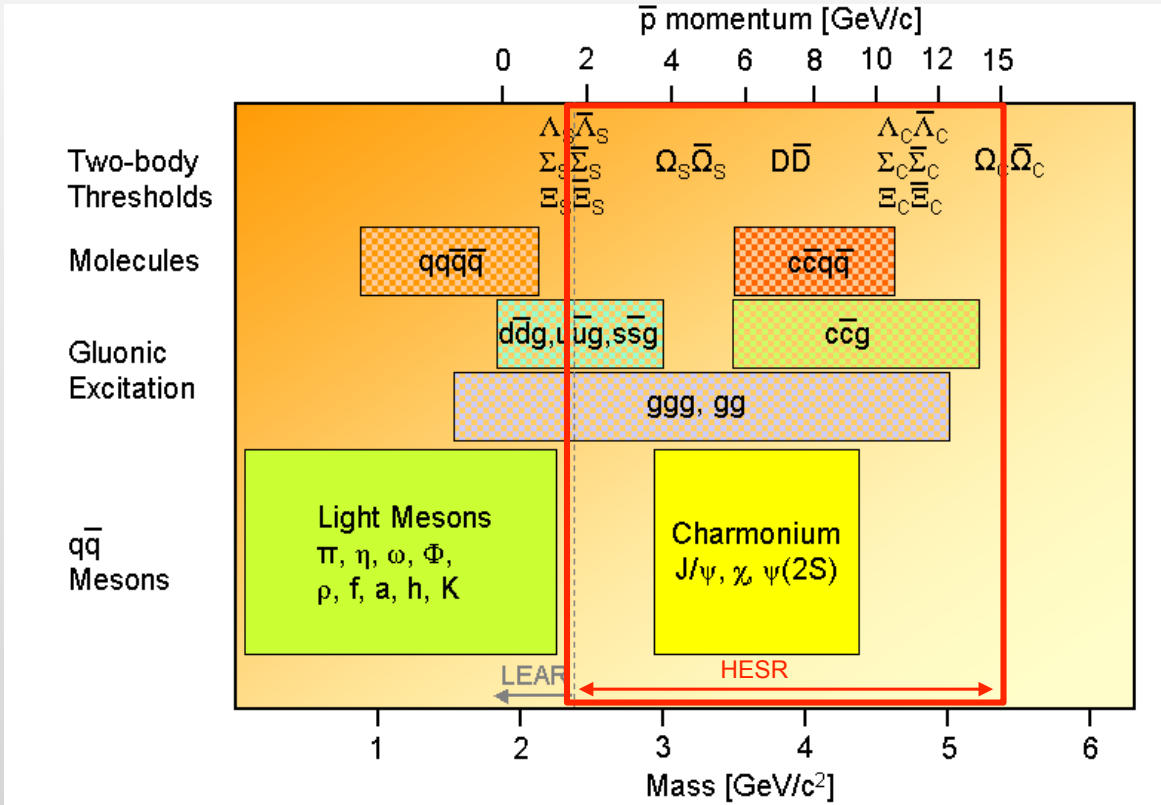
Physics with antiprotons:

- hadron spectroscopy
- hadron structure
- interaction of hadrons



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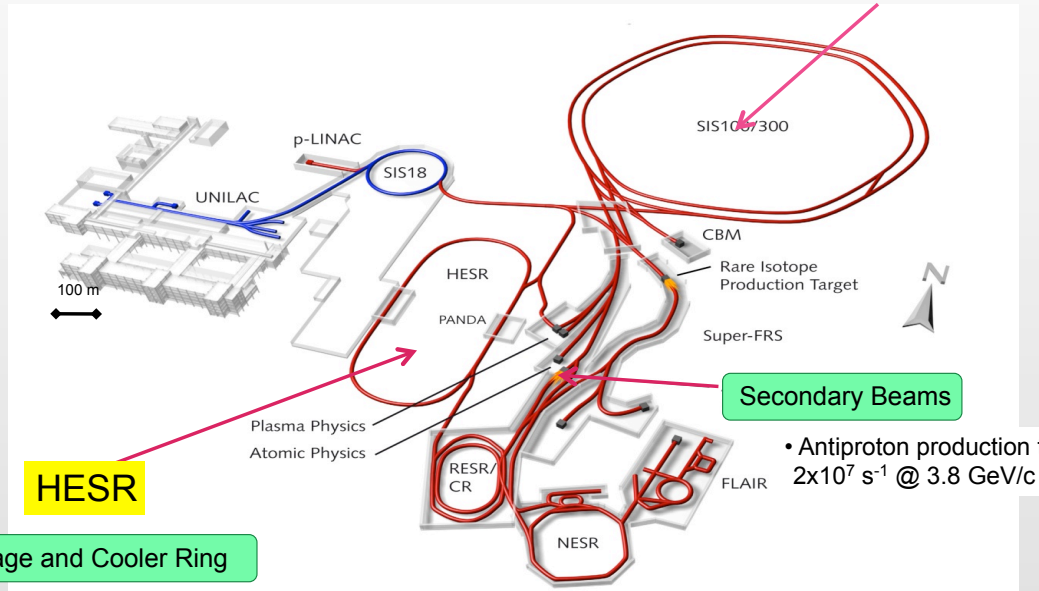
Facility for Antiproton and Ion Research FAIR

Primary Beams

•30 GeV protons 2(4)x10^{13} s^{-1}



• Antiproton production target 2x10^{7} s^{-1} @ 3.8 GeV/c

Storage and Cooler Ring

• 10^{11} stored and cooled 1.5 - 14.5 GeV/c antiprotons

High resolution mode

• $\delta p/p$ < 2x10^{-5} (electron cooling)
• Luminosity = 2x10^{31} cm^{-2} s^{-1}

High luminosity mode

• Luminosity = 2 x 10^{32} cm^{-2} s^{-1}
• $\delta p/p$ ~ 10^{-4} (stochastic cooling)

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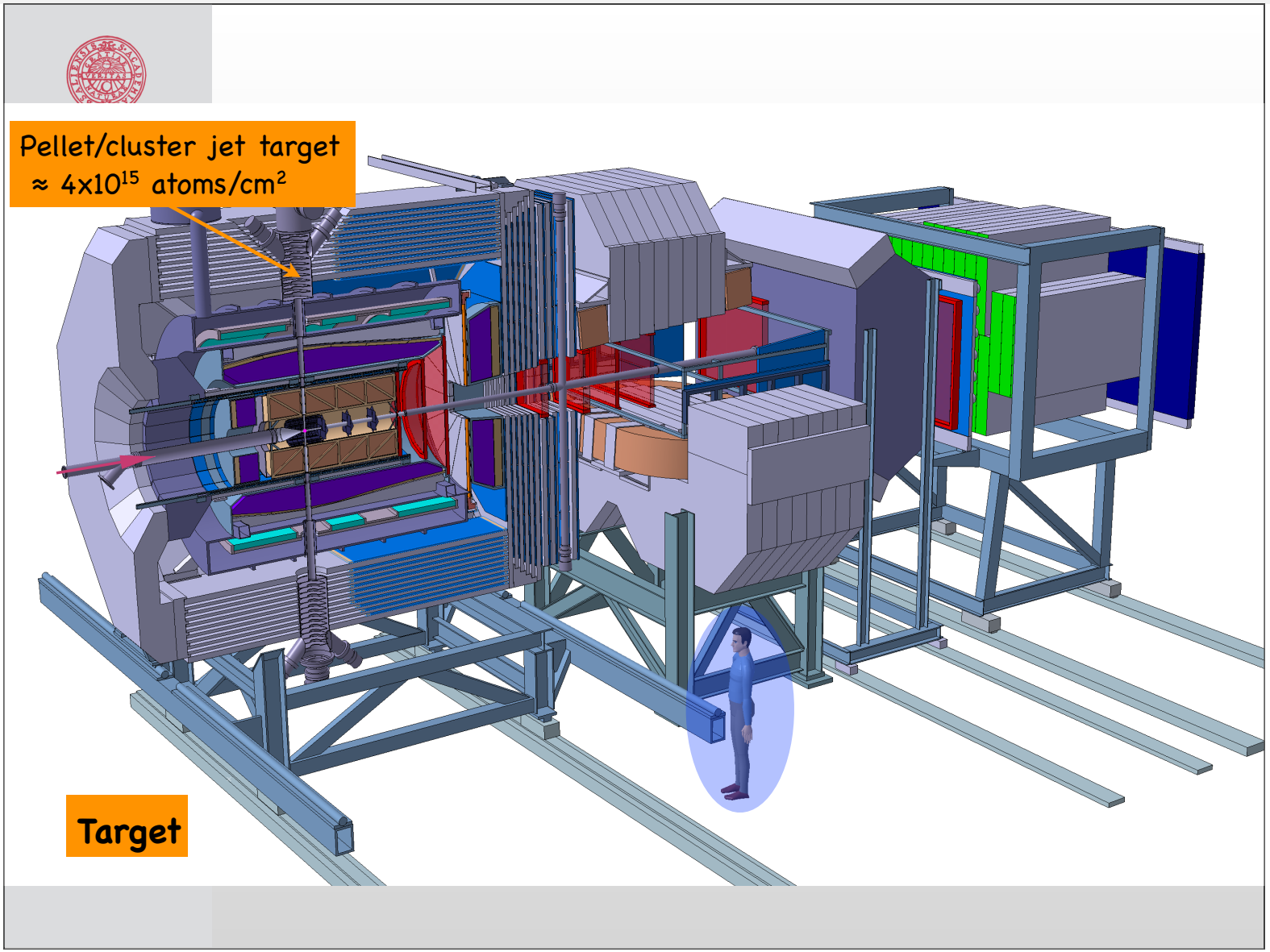

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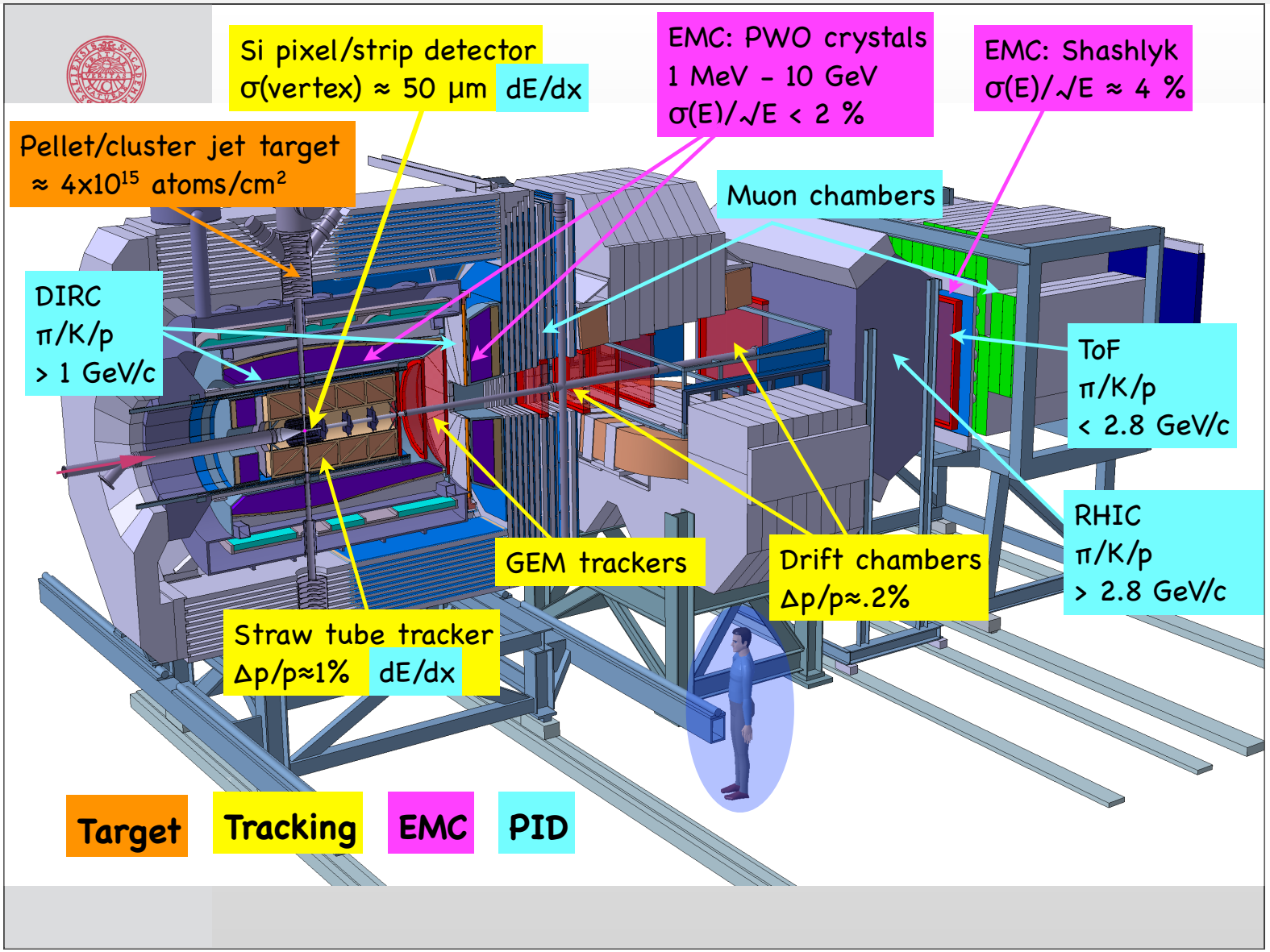

Summary

- heavy flavour is useful as a tool, and interesting in itself
- it provides a window on QCD, CPV, new heavy states
- open and hidden flavour physics analyses are underway at $\mathrm{e}^+\mathrm{e}^-$ machines, ATLAS, CMS, LHCb
- Belle II is under construction
- $\bar{\mathrm{P}}$ANDA, with unique capabilites, will come online late this decade
- I am offering two new PhD projects in hidden flavour:
  1. XYZ associated production at ATLAS
  2. $X(3872) \to \{\gamma, \pi^0\}\mathrm{D}\overline{\mathrm{D}}$ lineshape at Belle II / $\bar{\mathrm{P}}$ANDA

  Please chat if you or your colleagues are interested.