BABAR Achievements beyond CKM

Claudia Patrignani

Università di Bologna and I.N.F.N.

Claudia.Patrignani@bo.infn.it

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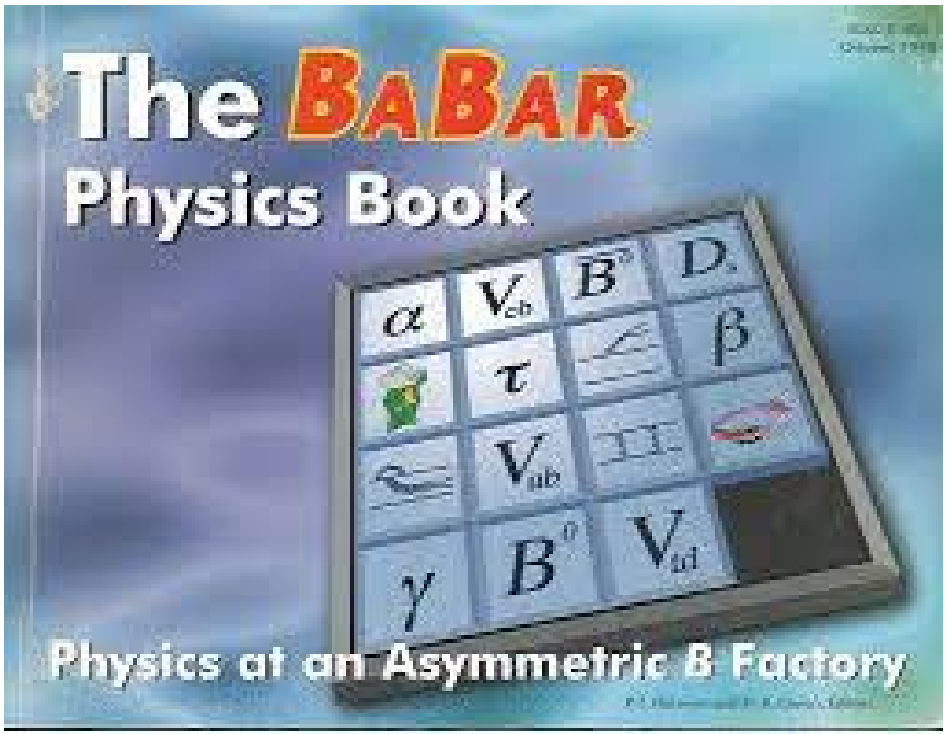
The *BABAR* legacy beyond CP violation and CKM

DISCLAIMER: too many results to cover them all!

A (personal) selection

- Charmed mesons spectroscopy
- ~~Charmed baryons~~ — no time!
  Check it out in the *"Physics of the B-Factories"*
- Charmonium-like mesons
- Bottomonium
- hadronic cross sections via ISR method

Some of the opportunities outside CKM had been already considered in the Physics Book SLAC-R-504



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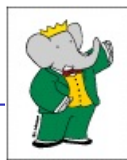
P.S.: ISR only considered as source of background



Charmed hadrons at B factories

Charmed hadrons can be produced in

- $e^+e^- \to c\bar{c}$
- $e^+e^- \to B\bar{B}$ with $B \to \text{charm had.} + X$

that means HUGE yields:

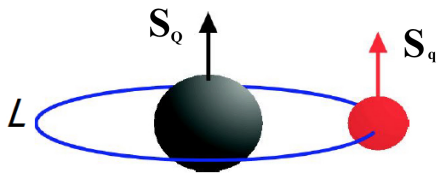
- 1.3 M $c\bar{c}$/ fb^{-1} $\approx 700M$ in entire *BABAR* dataset
- 1 M $b\bar{b}$/ fb^{-1} $\approx 550M$ in entire *BABAR* dataset

$e^+e^- \to$	Cross-section (nb)
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	~ 40

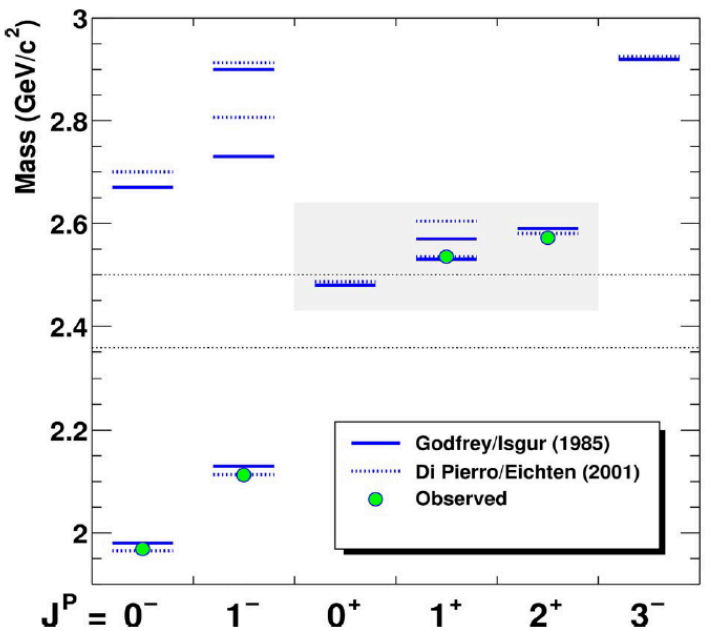
Charmed meson spectroscopy

Heavy quark symmetry: $Q\bar{q}$ mesons classified in doublets of j_q angular momentum of the light quark "orbiting" around the heavy one

$\Longrightarrow$ "hydrogen atom"



Status pre-2003



- $M_Q \to \infty$: S_Q fixed
- $\Longrightarrow j = L + S_q$ conserved
- Notation: ${}^{j}L_J$

$J = j + S_Q$

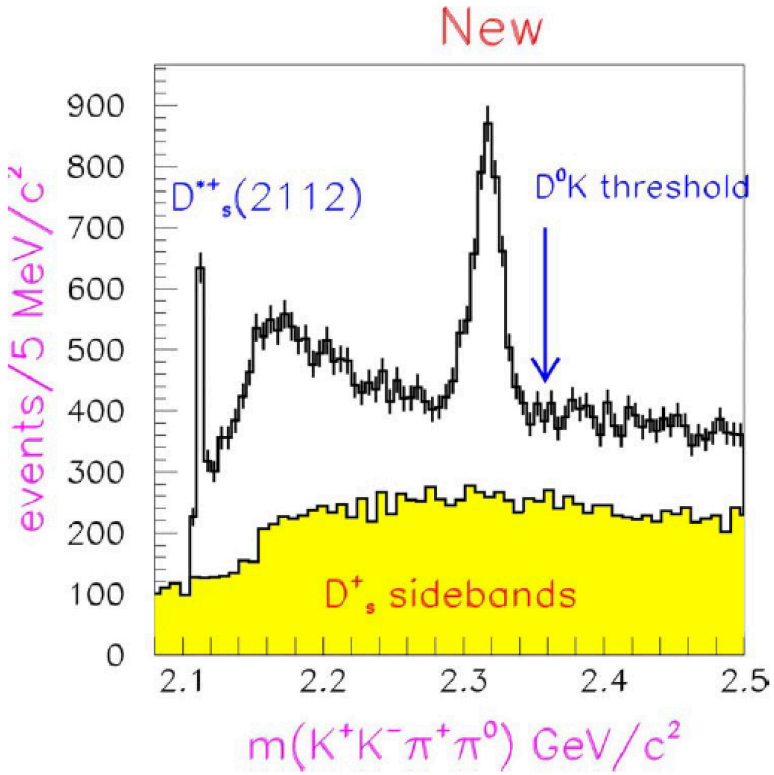
j conserved

$j = 1/2$: large widths to charm+light mesons (above threshold)

$j = 3/2$: no S-wave decay – expected to be narrow

The first surprise: $D^*_{s0}(2137)^+$

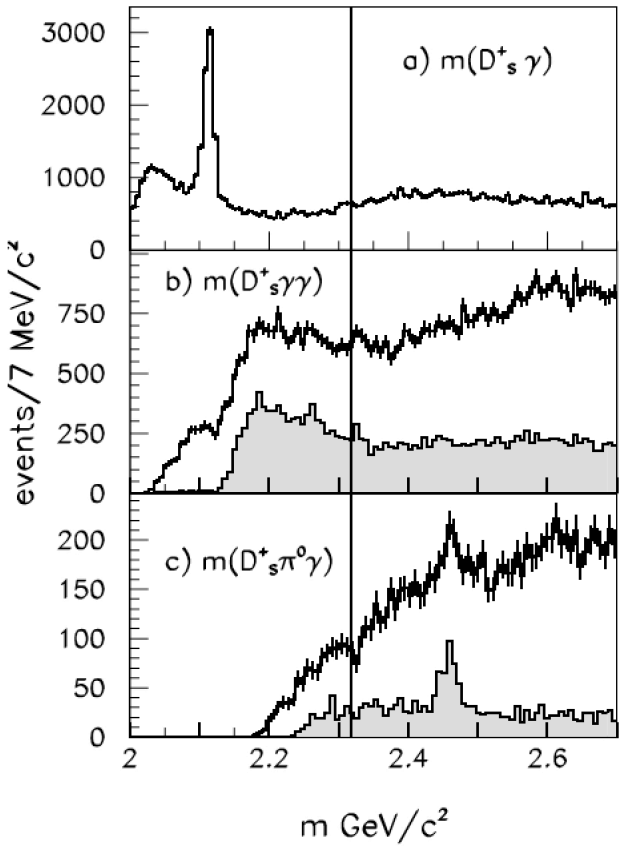
reconstruct $D_s^+ \to K^+K^-\pi^+$ and pair it to a π^0 PRL 90, 242001 (2003)



- decay to two $J^P = 0^-$ mesons $\Longrightarrow$ natural spin-parity $(0^+; 1^-; 2^+; \ldots)$
- mass below threshold for decay to D^0K^+
- if $c\bar{s}$ then the decay violate I-spin: can be narrow
- ... but mass is $\approx 170\ \mathrm{MeV}/c^2$ below prediction for 0^+ $c\bar{s}$

(non) discovery of $D_{s1}(2460)^+$

PRL 90, 242001 (2003) also reports a peak at 2.46 GeV/c^2 in $M(D_s^*(2112)\pi^0)$



However, the mass splittings in the two chains are very close

- $D_{sJ}(2458)^+ \to D_s^*(2112)^+ \pi^0$ Δm = 346 MeV/c²
  $D_s^*(2112)^+ \to D_s(1968)^+ \gamma$ Δm = 144 MeV/c²

- $D_{sJ}(2458)^+ \to D_{sJ}^*(2317)^+ \gamma$ Δm = 141 MeV/c²
  $D_{sJ}^*(2317)^+ \to D_s(1968)^+ \pi^0$ Δm = 349 MeV/c²

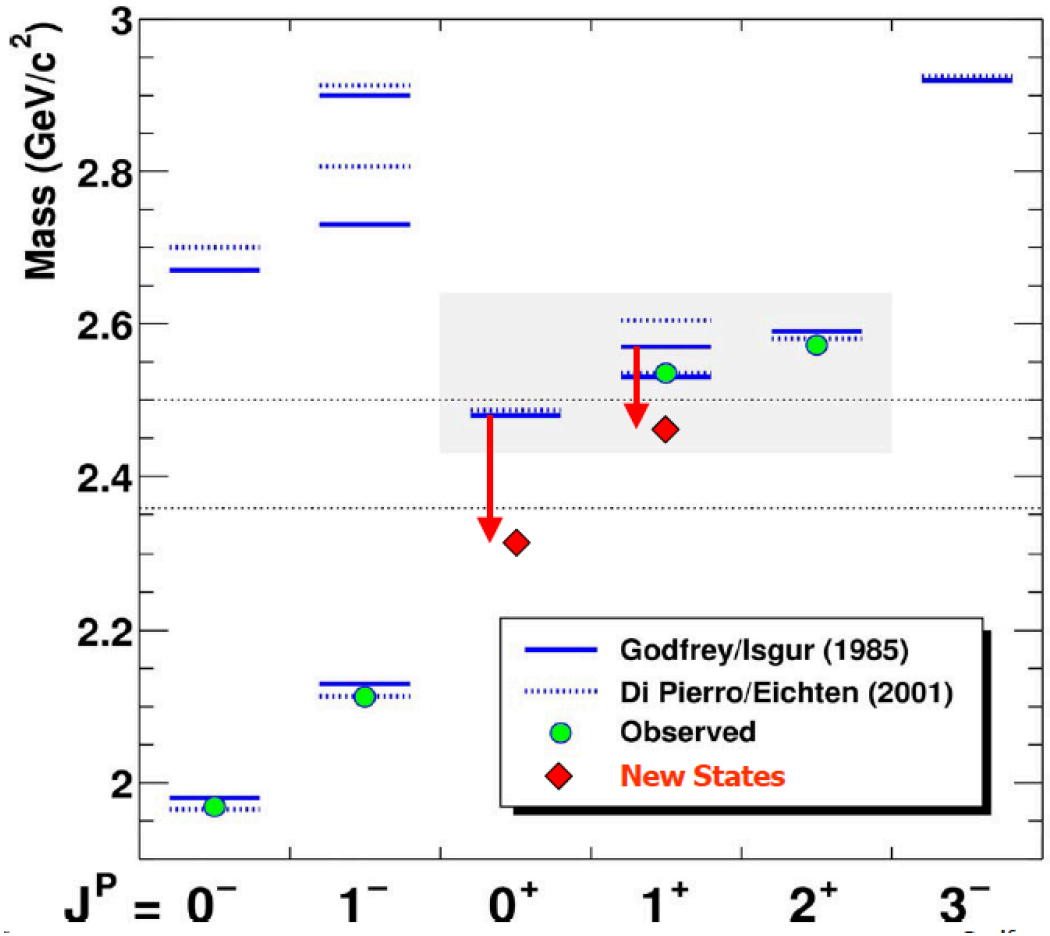
so

Although we rule out the decay of a state of mass 2.46 GeV/c^2 as the sole source of the $D_s^+\pi^0$ mass peak corresponding to the $D_{sJ}^*(2317)^+$, such a state may be produced in addition to the $D_{sJ}^*(2317)^+$. However, the complexity of the overlapping kinematics of the $D_s^*(2112)^+ \to D_s^+\gamma$ and $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ decays requires more detailed study, currently underway, in order to arrive at a definitive conclusion.

The $D_{s1}(2460)^+$ was later established by CLEO PRD 68, 032002 (2003)

What's so exciting?

i.e: . . . so what if potential model does not work?

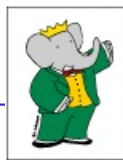


- it seems to work well for other $c\bar{s}$ both above and below thresholds
- both new states are $\approx 40\ \mathrm{MeV}/c^2$ below corresponding strong decay threshold

  just an accident?
- narrow
- I-spin violating decay

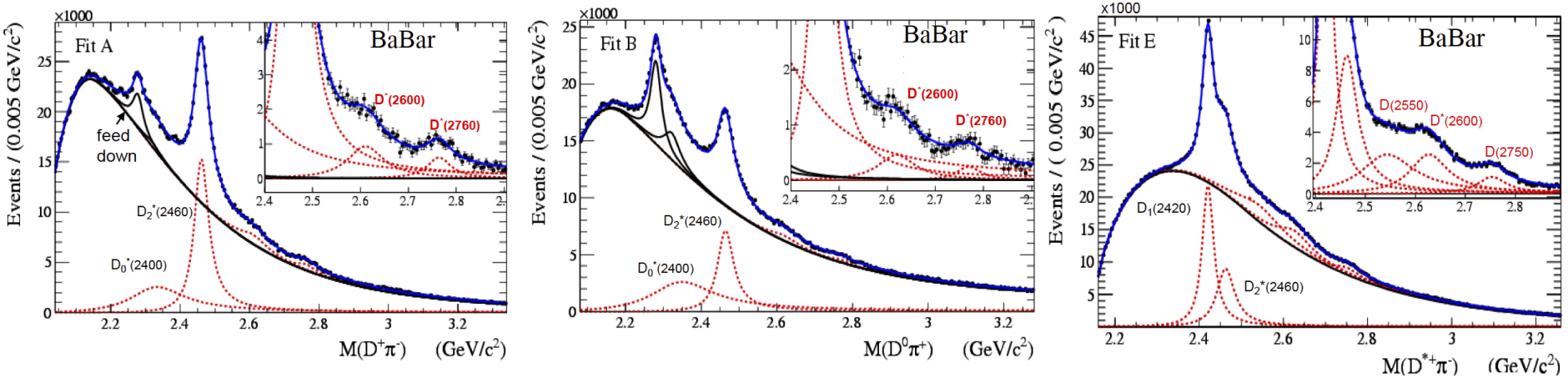
can they be something more than just $q\bar{q}$?

. . . issue not yet settled 15 years later . . .

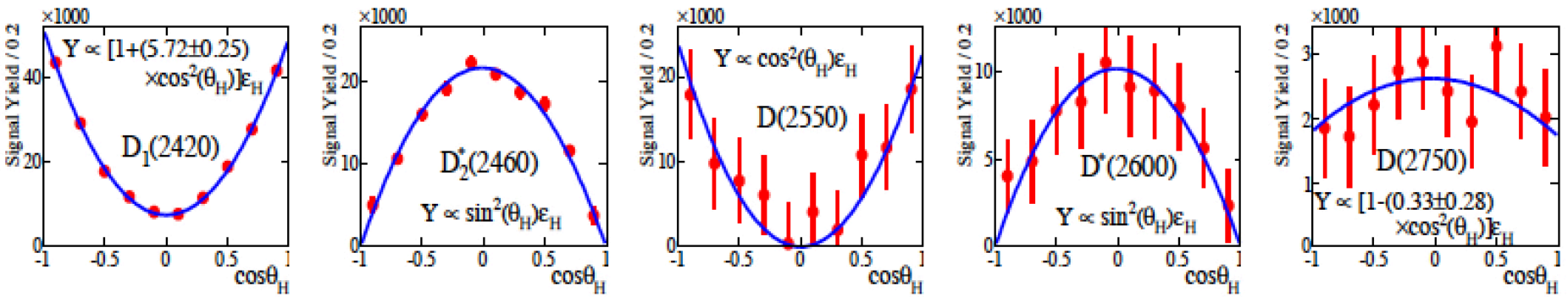


Excited D mesons in inclusive production

Reconstruct events with $D^+\pi^-$ (left) ; $D^0\pi^+$ (center); $D^{*+}\pi^-$ (right)

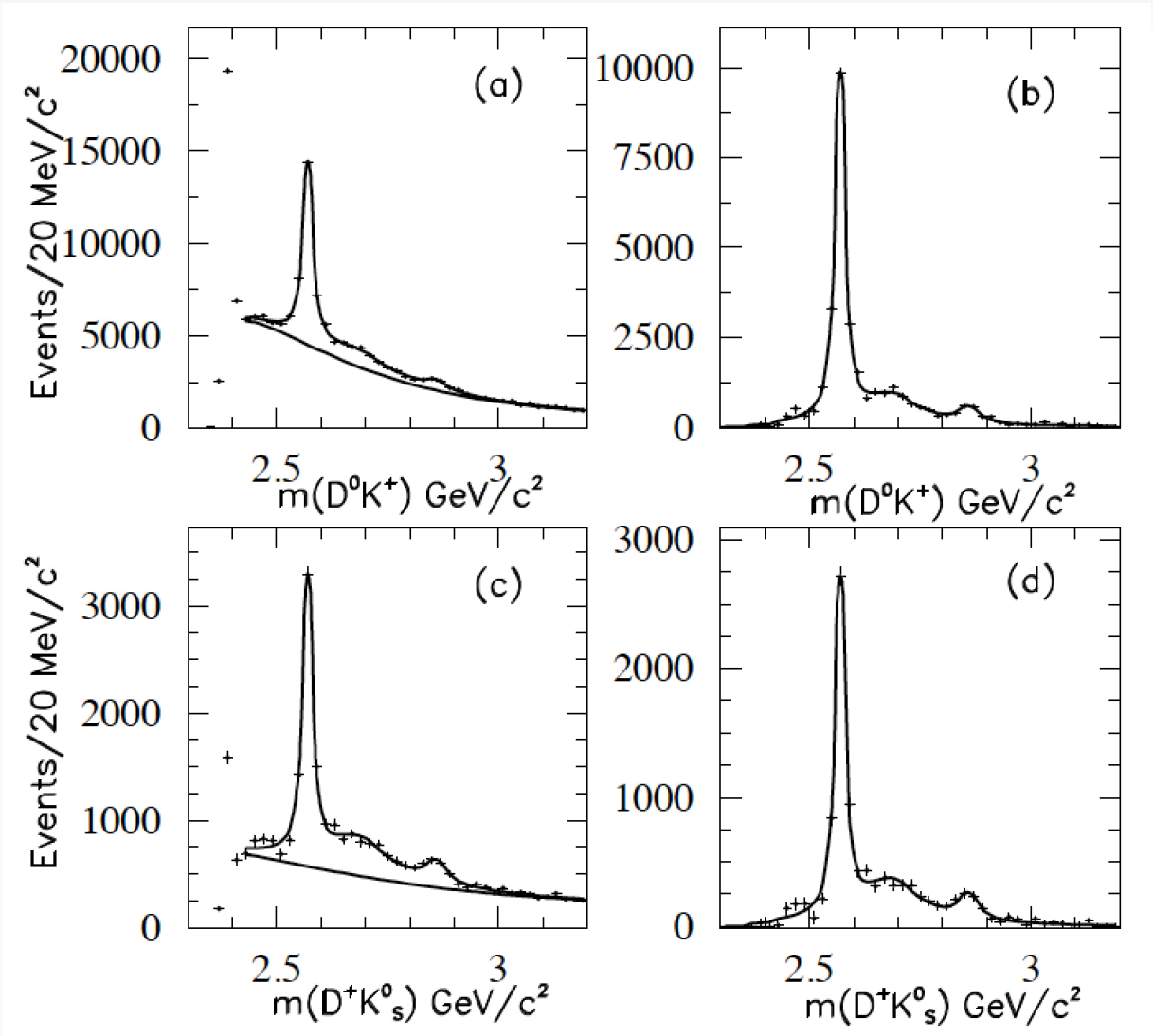


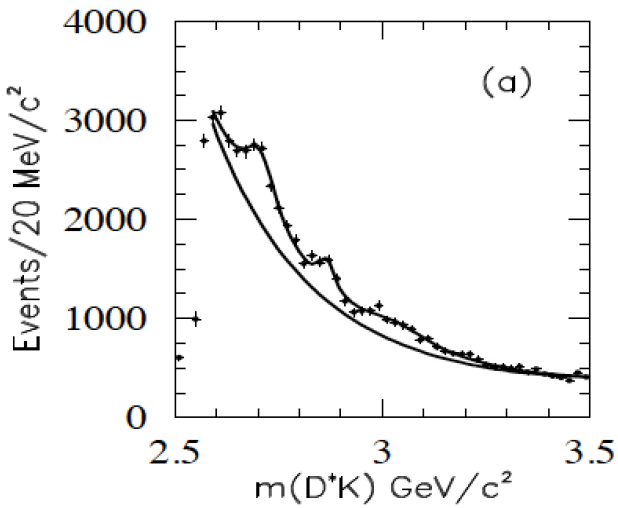
From the yields for each component in each helicity angle bin extract distribution $\Longrightarrow$ allows to test quantum numbers



(D^{**} also studied in Dalitz plot of $B^+ \to D^+\pi^+\pi^-$ PRD79, 112004 (2009))

Excited D_s mesons in inclusive production

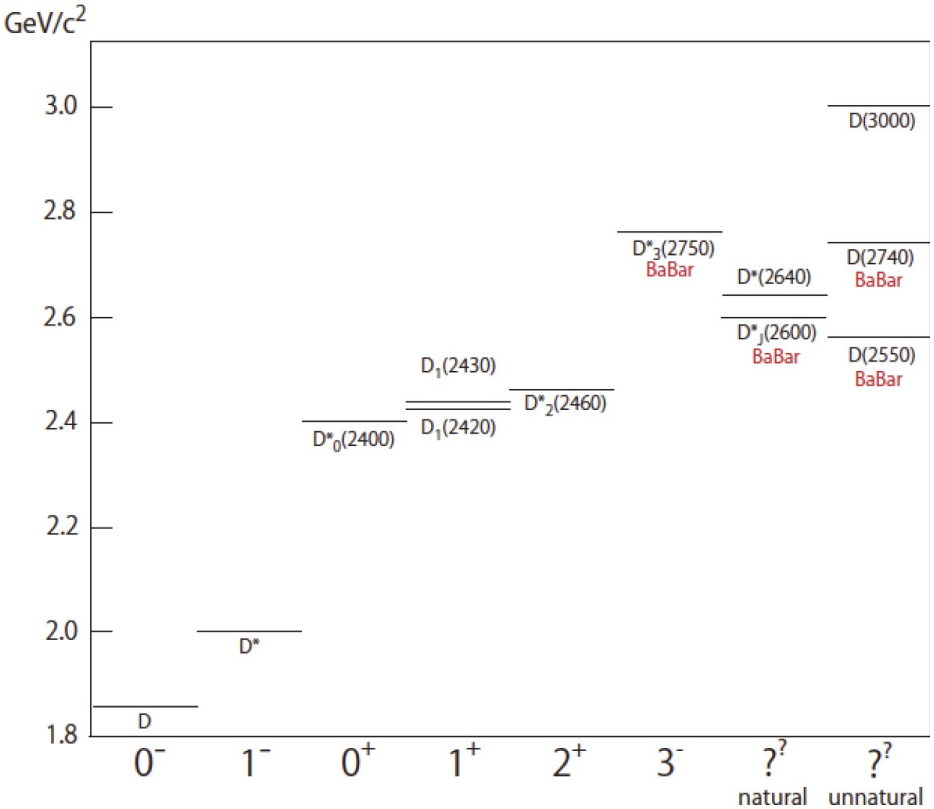




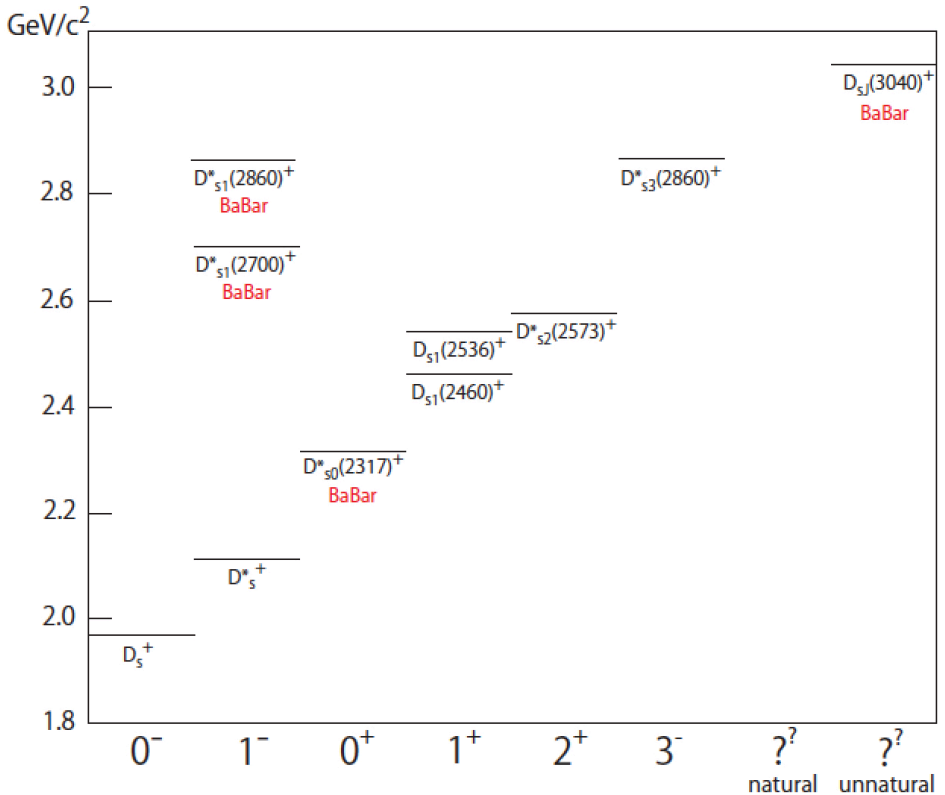
PRD 80, 092003 (2009)

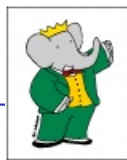
BABAR legacy in charmed mesons

Observed $D^{(*)}$ spectrum



Observed $D_s^{(*)}$ spectrum

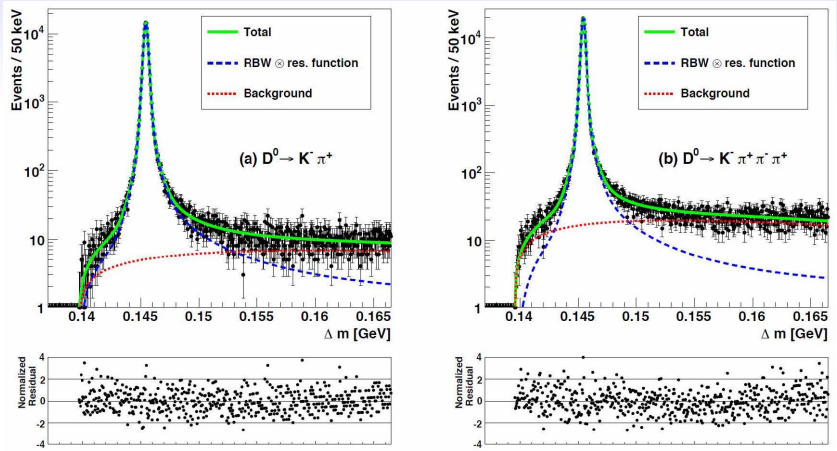




Precision parameter determination

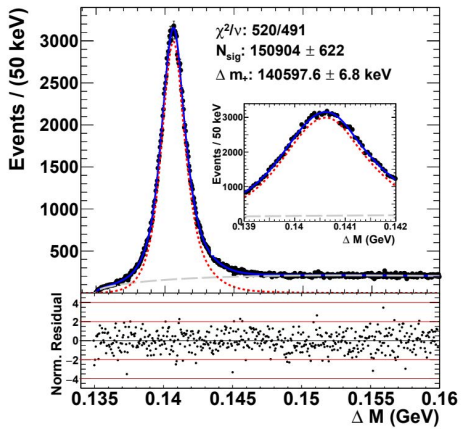
- $\Delta m_0 = M(D^{*+}) - M(D^0)$

PRL 111, 111801 (2013)



- $\Delta m_+ = M(D^{*+}) - M(D^+)$

PRL 119, 202003 (2017)



Combining: $M(D^+) - M(D^0) = (4824.9 \pm 6.8 \pm 12.9)$ keV

Precise D^0 mass measurement PRD 88, 071104 (2013)

Quarkonium physics

$c\bar{c}$; $b\bar{b}$ bound states: heavy quarks $\Rightarrow$ non relativistic

relativistic corrections in $b\bar{b}$ smaller than in $c\bar{c}$

Potential model ("Cornell": coulomb+linear) or more modern Lattice NRQCD, pNRQCD (α_s, m_q; spacing...)

$\Longrightarrow$ predictions for masses (fine and hyperfine splitting), partial widths; radiative and hadronic transitions

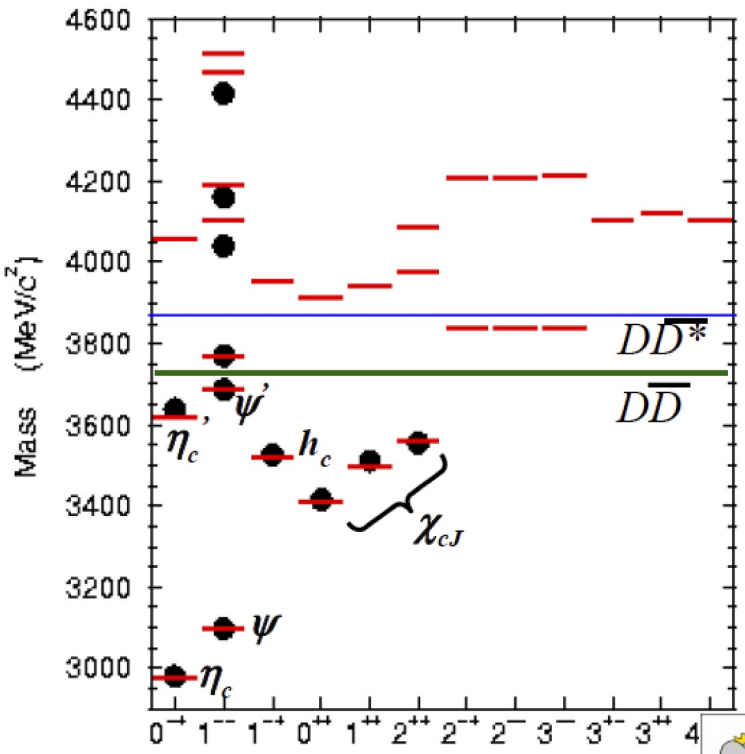
$n^{2S+1}L_J \; P = (-1)^{L+1}; \quad C = (-1)^{L+S}$

$\Upsilon(nS); \psi(nS) \equiv n^3S_1 \;\; \eta_c(nS); \eta_b(nS) \equiv n^1S_0$

$\chi_{cJ}(nP); \chi_{bJ}(nP) \equiv n^3P_J; \; h_c(nP); h_b(nP) \equiv n^1P_1$

by the time of first collisions in *BABAR* the spectrum below the $D\bar{D}$ threshold was (sufficiently?) well known

- reasonable agreement with theory



... interest fading

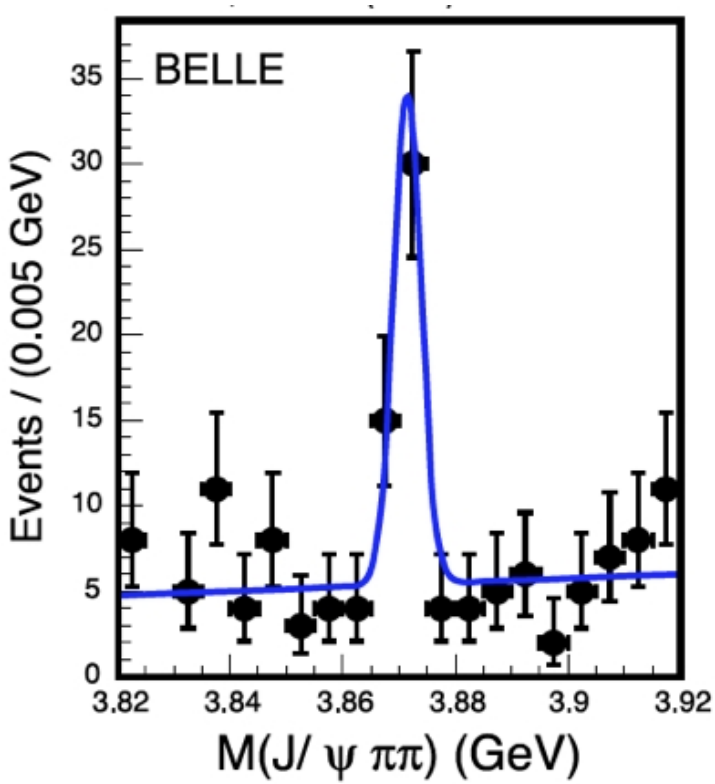
Early *BABAR* contributions to charmonium physics

With the first data (before circa 2005) already a few significant contributions

- PRD 65, 031101 (2002): Branching ratios for $\psi(2S) \to e^+e^-$ and $\mu^+\mu^-$
  Reference mode for final states including $\psi(2S)$
- PRL 92, 142002 (2004): $\eta_c(1S)$ mass and width measured in $\gamma\gamma \to K\bar{K}\pi$
  Γ larger than (most) previous determinations – later confirmed by others
- in the same paper $\eta_c(2S)$ is also observed, confirming Belle's observation at a much larger mass than previously believed (based on a Crystal Ball paper)
- PRD 69, 011103 (2004): Indirect determination of J/ψ width from $\Gamma_{ee} \cdot \mathcal{B}_{\mu\mu}$ measured in ISR
  Confirm the value directly measured at FNAL E760/E835 (30% larger than previous indirect determinations)
- PRL 96, 052002 (2006): Absolute measurement of $\mathcal{B}(B^+ \to K^+ + c\bar{c})$ in the K spectrum in the recoil of fully reconstructed B's allows INDIRECT determination of $\eta_c(nS)$ branching ratios for final states observed in exclusive B decays

The $X(3872)$ [now $\chi_{c1}(3872)$]

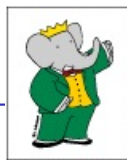
Soon after the excitement of $D_{s0}^{*}(2137)^{+}$ and $D_{s1}(2460)^{+}$ a new striking surprise



Narrow peak in $J/\psi\pi^{+}\pi^{-}$ invariant mass observed by Belle in $B^{+} \to (J/\psi\pi^{+}\pi^{-})K^{+}$ decays PRL 91, 262001 (2003)

Almost spot on $D^{*0}\bar{D}^{0}$ threshold

thanks to LHCb we now know that $J^{PC} = 1^{++}$ PRL 110, 222001 (2013)



BABAR papers on $\chi_{c1}(3872)$ aka $X(3872)$

- confirmation of existence PRD 71, 071103 (2005) constraint/rule out some 4-quark models
- limit on $B^+ \to K^+ \chi_{c1}(3872))$ PRL 96, 052002 (2006)
  lower limits on $\chi_{c1}(3872)$ BRs
- radiative decay to $J/\psi\,\gamma$ PRD 74, 071101 (2006)
  Establish $C = +$
- radiative decay to $\psi(2S)\gamma$ PRL 102, 132001 (2009)
  challenge molecular models
- observe $D^{*0}\bar{D}^0$ decay; not $D^0\bar{D}^0$ PRD 77, 011102 (2008)
- I-spin violating (sub-threshold) $J/\psi\,\omega$ decay PRD 82,011101(2010)

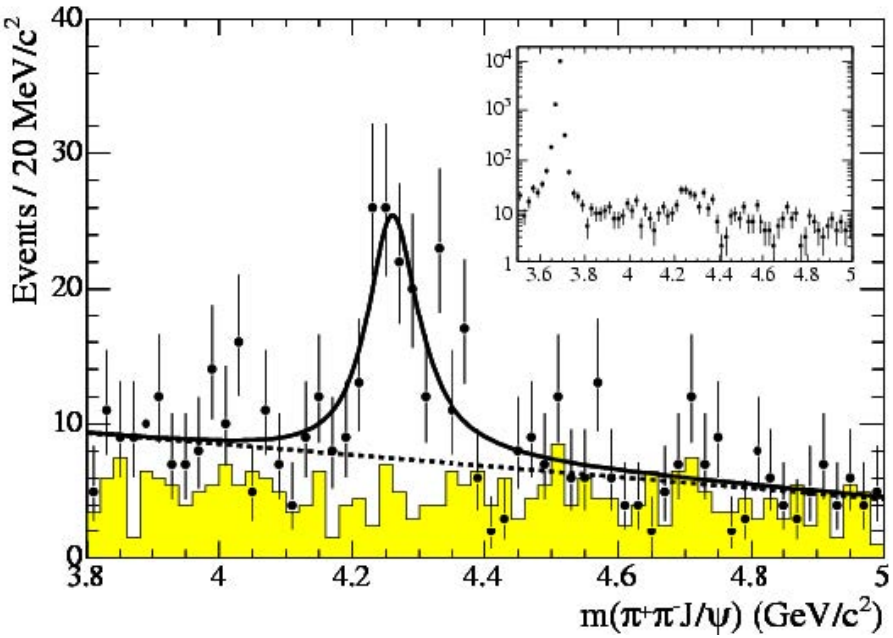
plus: D^0 mass measurement PRD 88, 071104 (2013)
crucial to determine distance from $D^{*0}\bar{D}^0$ threshold

Another state decaying to $J/\psi\ \pi^+\pi^-$!
$\psi(4260)$ aka $Y(4260)$

Very large peaking structure at 4.26 GeV/c^2 observed in

$$e^+e^- \to (\gamma_{ISR})J/\psi\,\pi^+\pi^-$$

PRL 95, 142001 (2005)



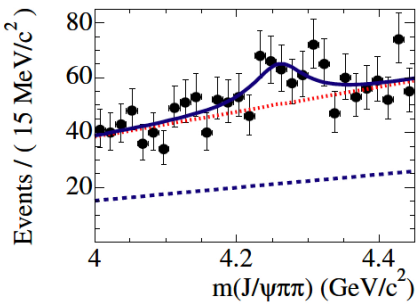
very strange indeed

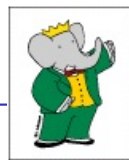
- $c\bar{c}$ states with 1^{--} states accounted for

  not really a strong argument ...

- the hadronic cross section has a minimum at that energy
  implies HUGE
  $\Gamma_{ee} > 1\ \mathrm{MeV}/c^2$

No significant signal found by *BABAR* in $B^+ \to J/\psi\,\pi^+\pi^-\,K^+$ decays PRD 73, 011101 (2006)

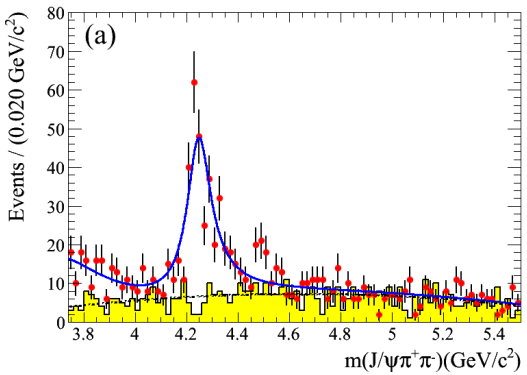




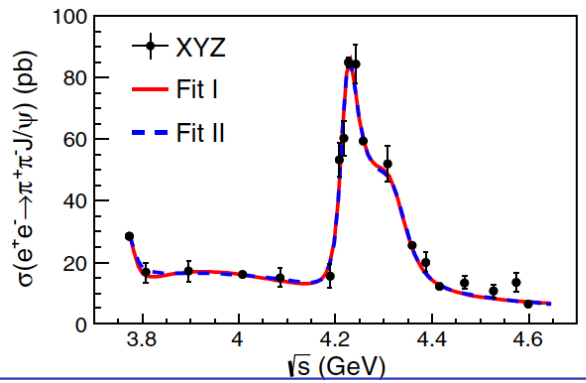
Two states?

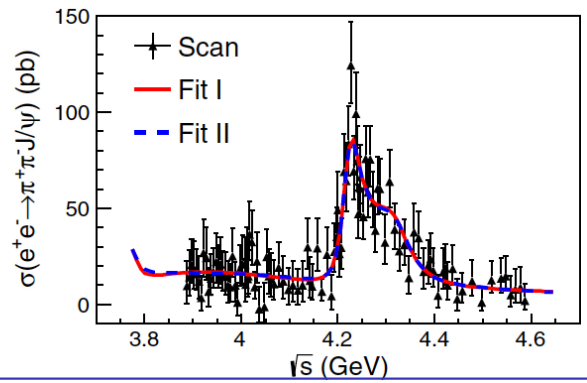
The structure soon confirmed in ISR and on-peak by CLEO PRL 96, 162003 (2006) and by Belle in ISR PRL 99, 182004 (2007) .

- not seen in $D\bar{D}$
- nor in many exclusive hadronic modes
- $\pi^+\pi^-$ spectrum peaking around $f_0(980)$ (Belle PRL 99, 182004 (2007))
- *BABAR* PRD 86, 051102 (2012) measures that $f_0(980)$ is not dominant but also suggest that the lineshape is not well described by a BW
- $\pi^0\pi^0/\pi^+\pi^-$ consistent with I=0 (CLEO)



Scans performed by BES III PRL 118,092001 (2017) resolve two structures: $\psi(4220)$ and $\psi(4320)$



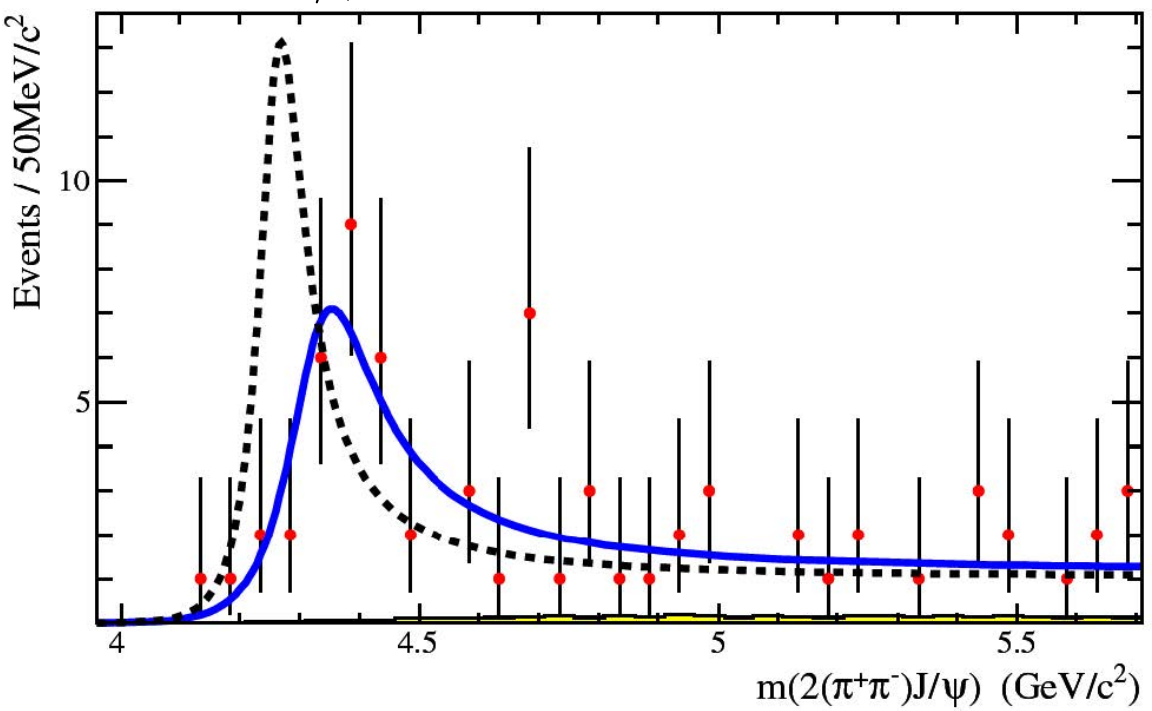


. . . and one more structure in $\psi(2S)\pi^+\pi^-$!

Since the structure at 4260 MeV/c^2 is way above the threshold for $\psi(2S)\pi^+\pi^-$, *BABAR* searched for a signal in this final state, again in ISR

PRL 98, 212001 (2007)

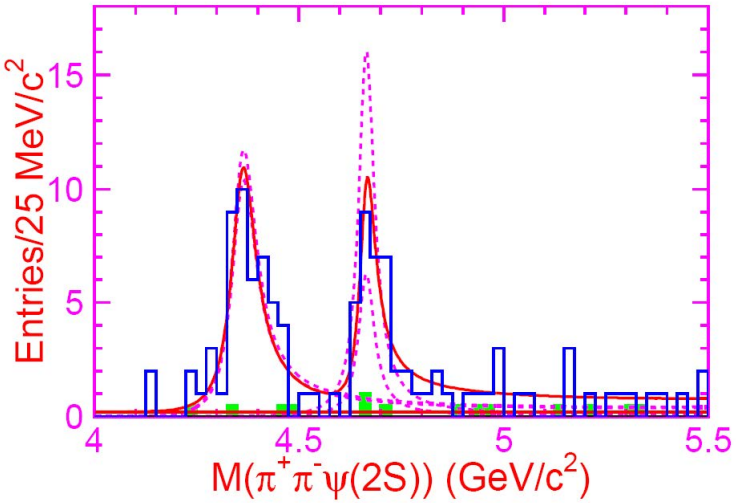
and indeed a signal is found, only it's not compatible with the parameters of the structure seen in $J/\psi\,\pi^+\pi^-$!



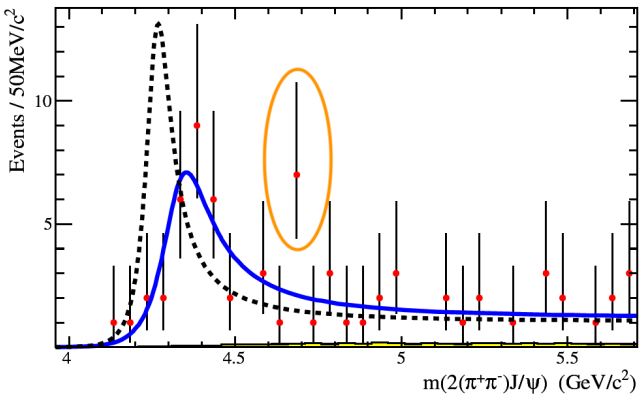
. . . and one more! $\psi(4660)$ discovered by Belle

Belle confirmed the structure around 4350 MeV/c^2 . . . and found one more (at the "high" point in the original *BABAR* paper!)

PRL 99, 142002 (2007) (Belle)

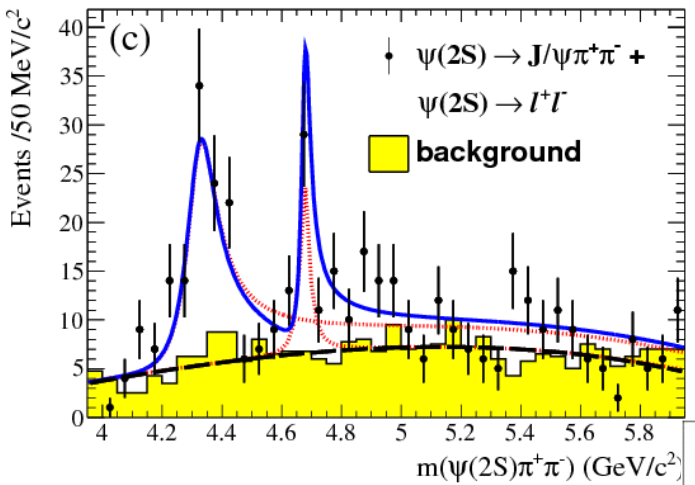


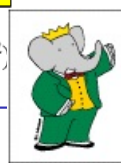
PRL 98, 212001 (2007)



The *BABAR* update with entire dataset confirms the structure at 4660 MeV/c^2

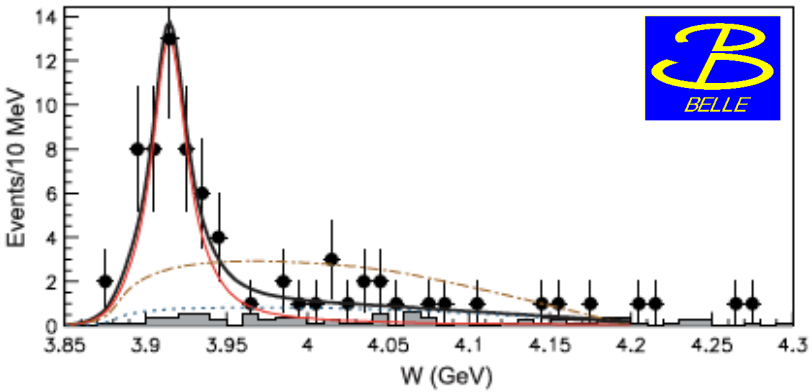
PRD 89, 111103 (2014)



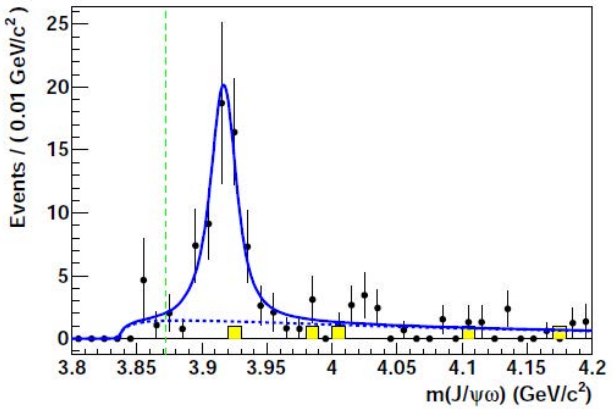


$X(3915) \to J/\psi\,\omega$

Observed by Belle in $\gamma\gamma$ reactions



PRL 104, 092001 (2010)



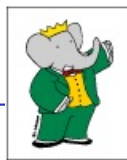
confirmed by *BABAR*

PRD 86, 072002 (2012)

Angular distribution strongly favors $J = 0$ in the assumption of helicity-2 dominance in $\gamma\gamma$.

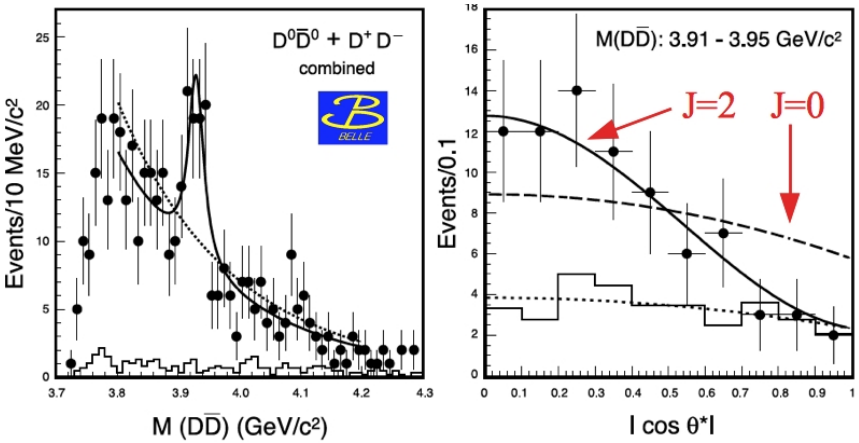
Possibly the same state seen earlier in $B \to J/\psi\,\omega K$ by Belle

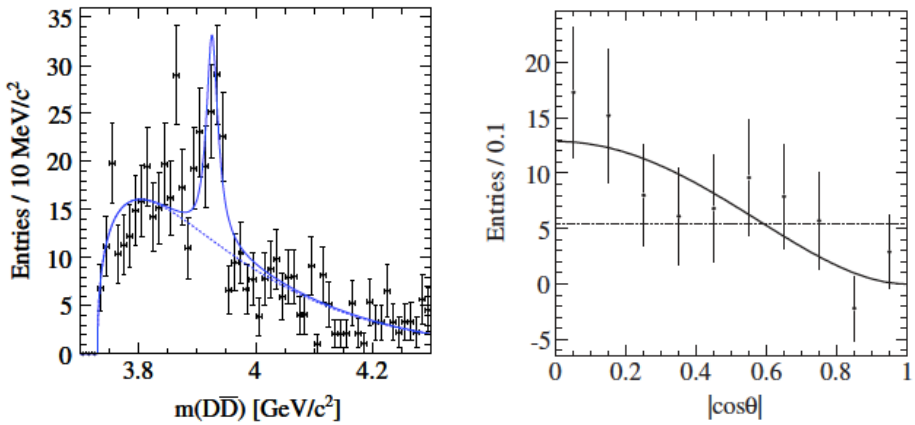
PRL 94, 182002 (2005) and later confirmed by *BABAR* PRD 82, 011101 (2010)



$\chi_{c2}(3930) \to D\bar{D}$

Observed by Belle





PRL 96, 082003 (2006)

confirmed by *BABAR* PRD 81, 092003 (2010)

NOT seen in $D\bar{D}^*$

Angular distribution strongly favors $J = 2$: generally identified as $\chi_{c2}(2P)$ candidate

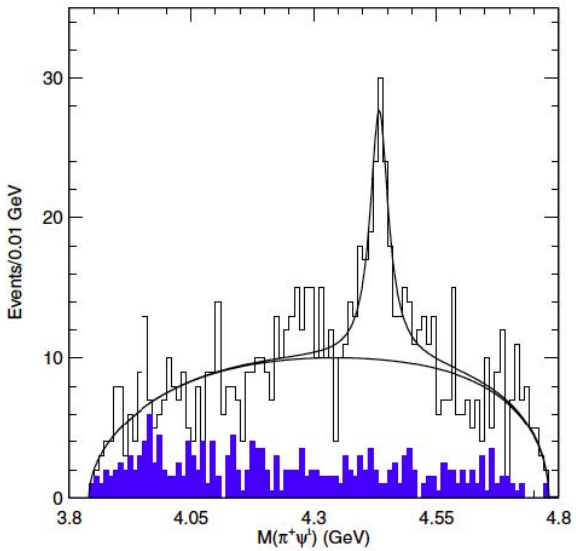
Mass lower by $\approx 50\ \mathrm{MeV}/c^2$ but Γ, $\Gamma_{\gamma\gamma}$ and $\mathcal{B}(D\bar{D})$ consistent with expectations

BABAR also set upper limits for a few exclusive modes: $K\bar{K}\pi$, $K^+K^-\pi^+\pi^-\pi^0$ PRD 84, 012004 (2011) and $\eta_c\pi^+\pi^-$ PRD 86, 092005 (2012)

Charged charmonium? $Z(4430)^{\pm} \to \psi(2S)\pi^{\pm}$

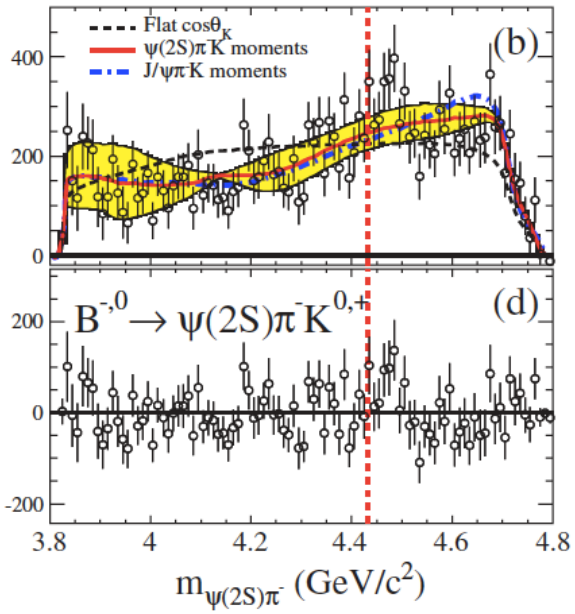
Observed by Belle in
$\bar{B}^0 \to K^+\psi(2S)\pi^-$
PRL 100, 142001 (2008)

quark content at least $c\bar{c}u\bar{d}$



confirmed in a Dalitz re-analisis by Belle PRD 80, 031104 (2009)
(not strictly independent)

no evidence in *BABAR*
PRD 79, 112001 (2009)
(model independent approach)

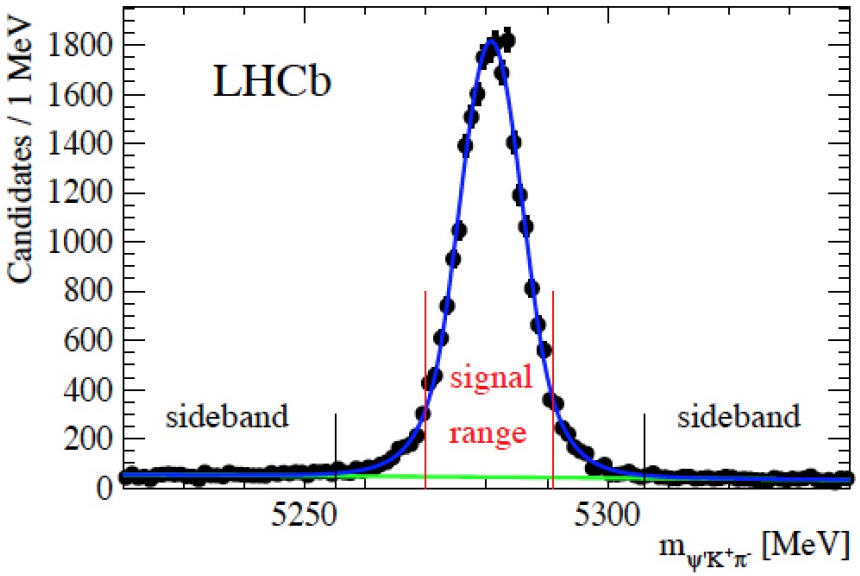


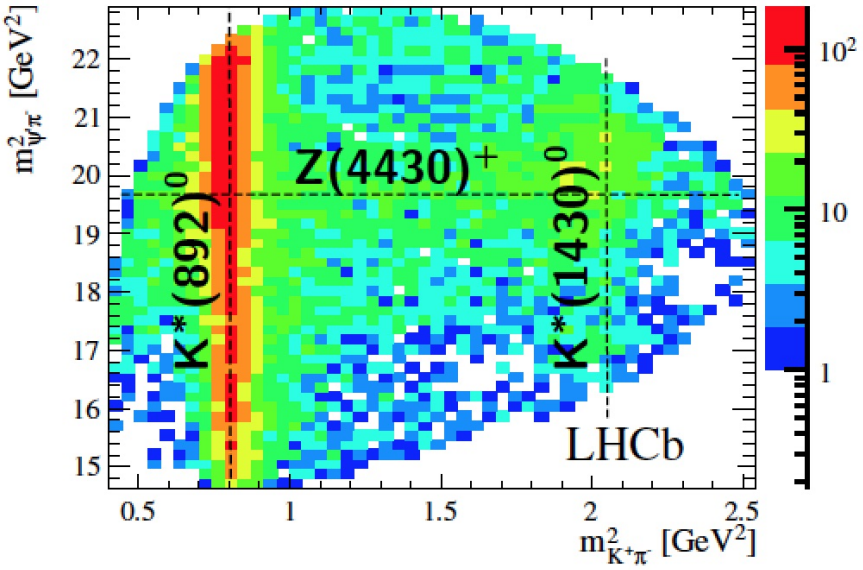
data can be described within errors by $K\pi$ reflections without additional resonances

$Z(4430)^+ \to J/\psi\pi^+$ seen by Belle PRD 90, 112009 (2014)

$Z_c(4430)^+$ in $B^0 \to \psi(2S)K^+\pi^-$ at LHCb

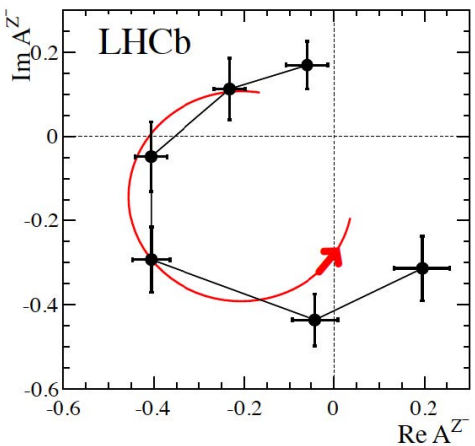
$\approx$ 25k $B^0 \to \psi(2S)K^+\pi^-$ with $\approx$ 4% combinatorial background





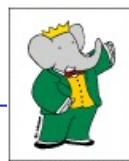
perform 4D amplitude analysis PRL 112, 222002 (2014)

- $J^P = 1^+$
- Argand plot shows resonant behaviour



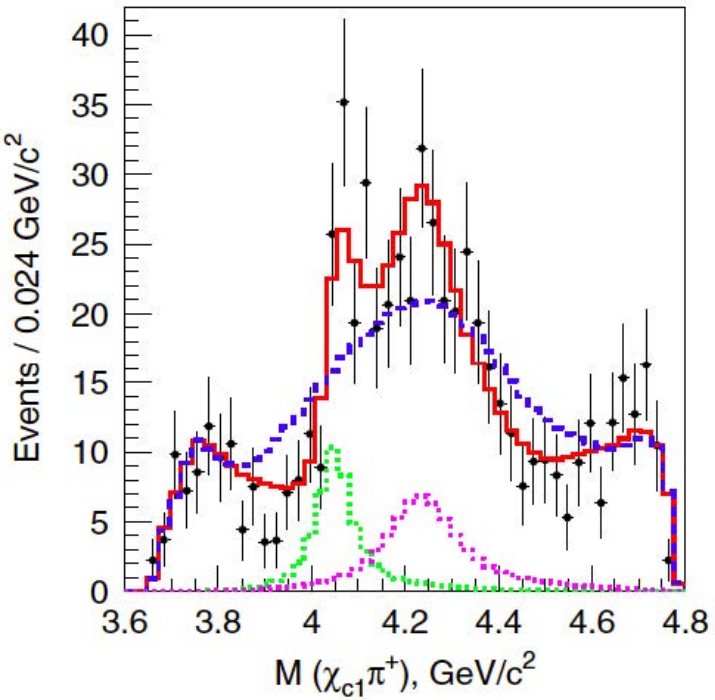
with the larger statistics the $Z_c(4430)^+$ is observed also with the model-independent approach adopted by *BABAR*

PRD 92, 112009 (2015)

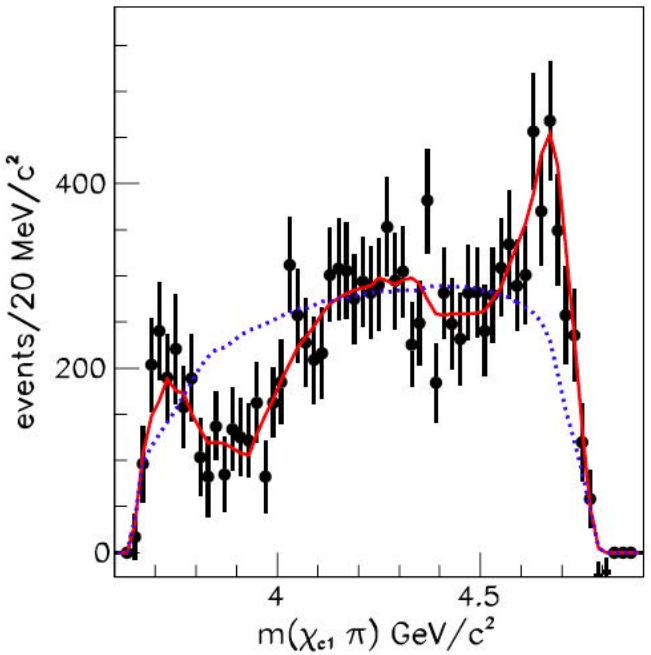


More charged states in $B^0 \to \chi_{c1}\pi^+K^-$

Two new peaks in $\chi_{c1}\gamma$ invariant mass reported by Belle $Z_1(4050)^+$ and $Z_2(4250)^+$

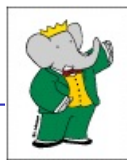


PRD 78, 072004 (2008)



PRD 85, 052003 (2012)

also in this case *BABAR* finds that within errors data can be described in a model independent approach by $K\pi$ substructures without introducing new resonances

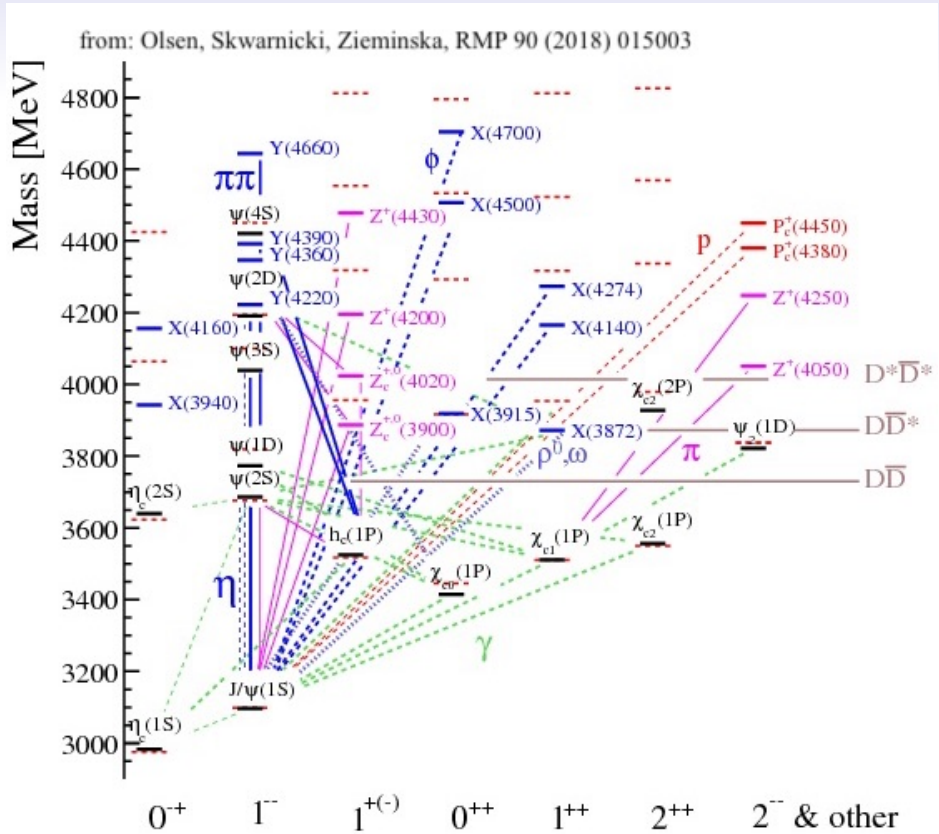


Today: states with hidden charm

A deluge of new states!

more states being discovered at BES III and LHC

- overpopulated spectrum wrt to conventional $Q\bar{Q}$
- candidates with manifestly exotic quantum numbers

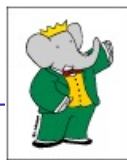


from: Olsen,Skwarniki, Zieminska RMP 90, 015003 (2018)

Nothing "exceptional"; non-$q\bar{q}$ configurations allowed in quark model right from the start!

States with the same quantum numbers can mix

does it make sense to "label" them by anything different than $J^{P(C)}$?

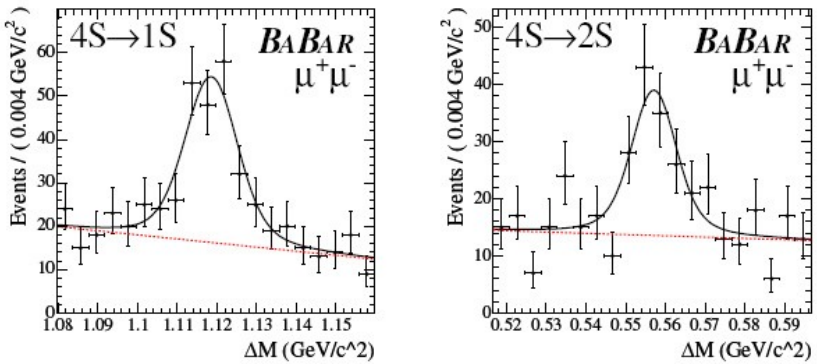


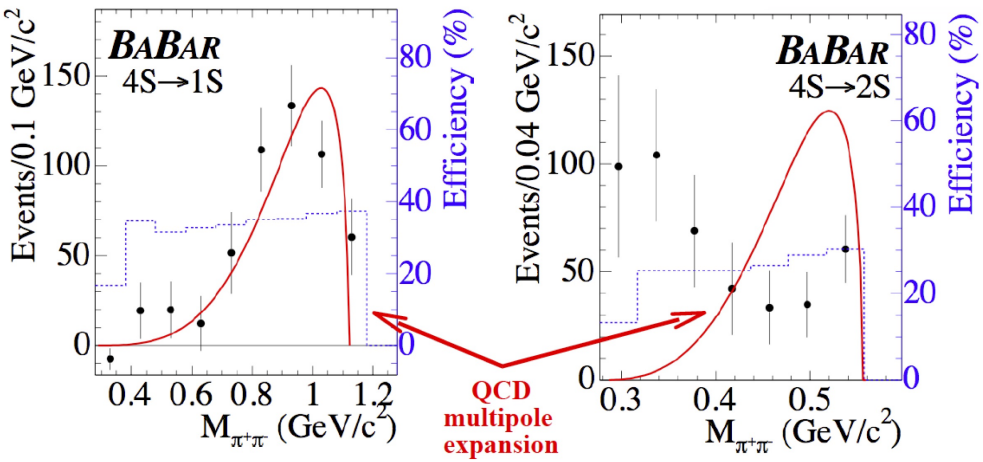
Bottomonium studies while running at $\Upsilon(4S)$

$\mathcal{B}(\Upsilon(4S) \to B\bar{B}) \approx 100\%$ – with several 10^8 $\Upsilon(4S)$ non-$B\bar{B}$ decays become accessible, with some surprises

$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(nS)$

PRL 96, 232001 (2006))



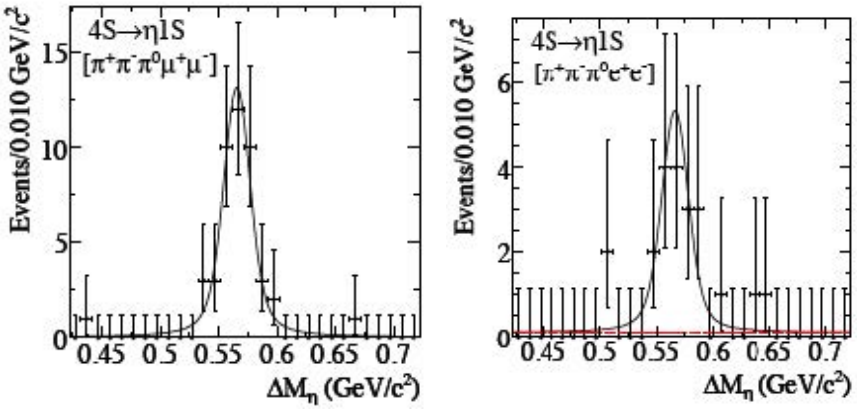


THIS is a surprise.!

"Double bump" structure?

$\Upsilon(4S) \to \eta\Upsilon(nS)$

PRD 78, 112002 (2008)

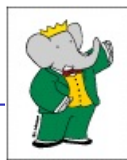


surprisingly large!

- ISR emission reduces the e^+e^- collision energy

$\Longrightarrow$ the $\Upsilon(4S)$ data sample used also to study hadronic transitions between narrow Υ states

PRD 78, 112002 (2008)



Run 7

i.e.: a disaster turned overnight into an opportunity

- Dec. 15th: first collisions at Υ(4S) energy
- Dec. 19th: FY08 Budget Disaster

  faced with immediate shutdown of PEP-II

  BaBar proposed to run at Υ(3S) energy by reducing the HER(e-) energy
- Dec. 21st,1:30PM: PEPII-BaBar mtg.

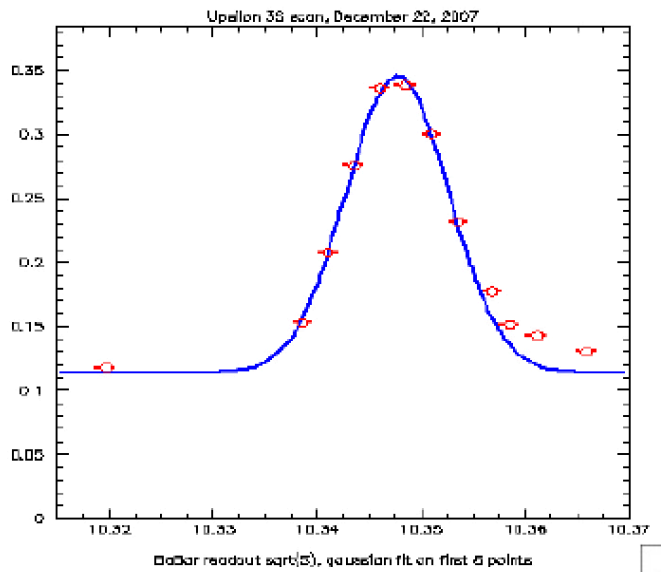
  Decision to move to Υ(3S)
- Dec. 22nd ,7:00 PM :

  Υ(3S) scan completed!
  - moved to Υ(3S) peak
  - initial luminosity at 3.5 x 10^{33}
- Move to Υ(2S) energy in March (in 10 hrs)
- Scan above Υ(4S) for 10 days

- Last data taken on Apr. 7, 2008

The goal was to double the integrated luminosity at the Υ(4S)

Changes to machine operation, trigger, reconstruction and simulation software implemented over Xmas



Run 7 physics goals

Explore bottomonium physics with unprecedented statistics:

	CLEO III	BaBar	BELLE
Υ(1S)	20 M	--	100 M
Υ(2S)	9 M	100 M	160 M
Υ(3S)	6 M	120 M	11 M

(Belle data at $\Upsilon(2S)$ taken after the end of *BABAR*)

- "New physics":
  search for light Higgs, light Dark Matter

- Bottomonium physics:
  search for $b\bar{b}$ singlet states: $\eta_b(1S)$, $\eta_b(2S)$, $h_b(1P)$

  first priority

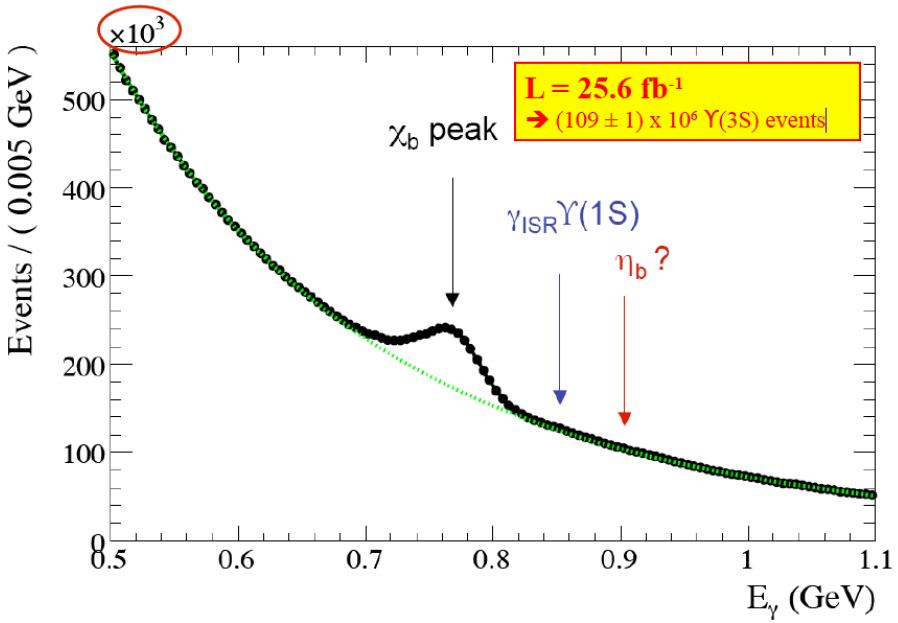
  precision measurements
  of radiative and hadronic transitions...

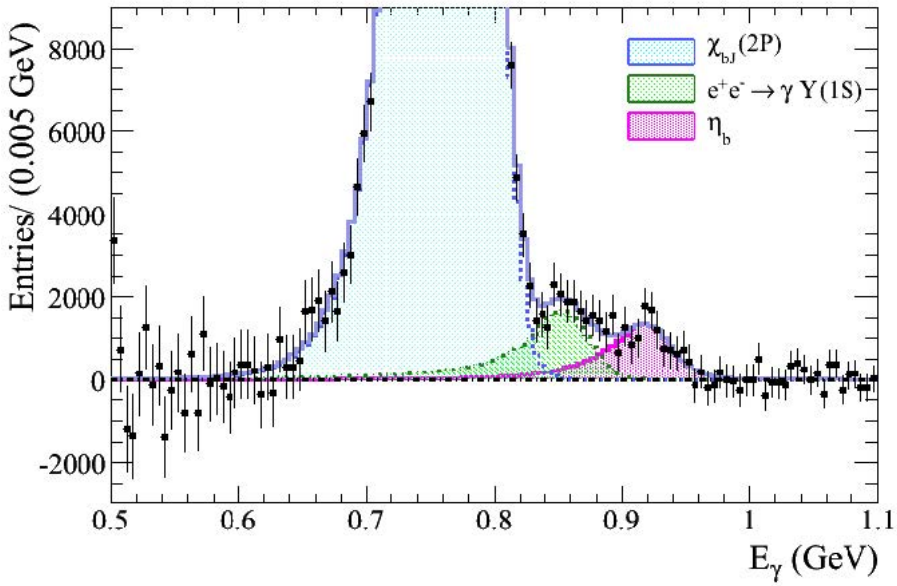
Observation of $\Upsilon(3S) \to \gamma\eta_b(1S)$

$\eta_b(1S)$ decay modes unknown $\Longrightarrow$ search for $\Upsilon(3S) \to \gamma\eta_b(1S)$ in inclusive photon spectrum PRL 101, 071801(2008)

... barely six months after start of data taking!

fit and subtract non-peaking background

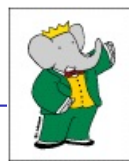




significance of $\eta_b(1S)$ signal $> 8\,\sigma$

$$M(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV}/c^2$$
$$M(\Upsilon(1S))\text{-}M(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7 \text{ MeV}/c^2$$

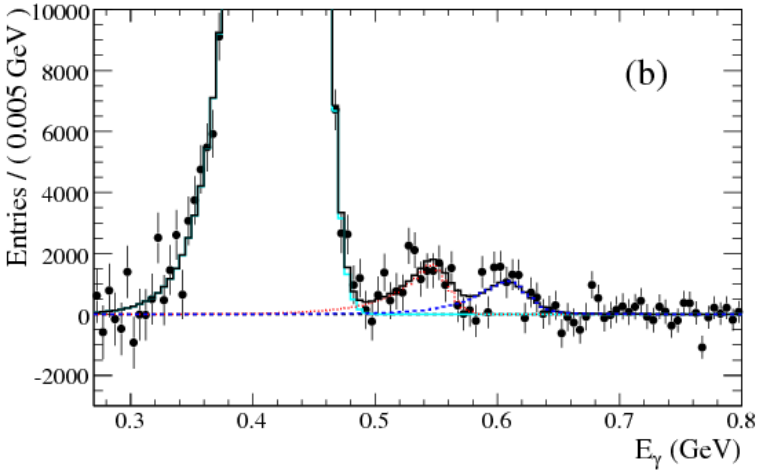
$\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b(1S)) = (4.5 \pm 0.5 \pm 1.2) \times 10^{-4}$



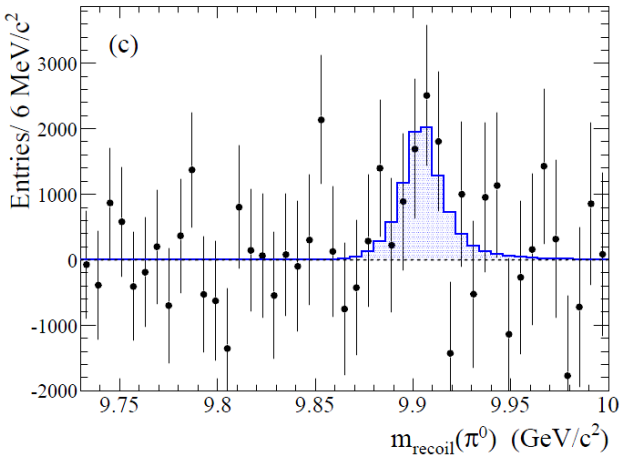
Other *BABAR* inclusive searches

Evidence for $\Upsilon(2S) \to \gamma\eta_b(1S)$

PRL 103, 161801 (2009)

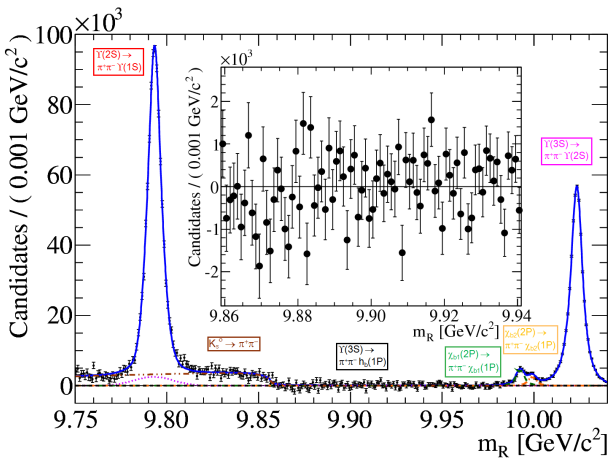


Evidence for $\Upsilon(3S) \to \pi^0 h_b(1P)$



PRD 84, 091101 (2011)

Search for $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$



PRD 84, 011104 (2011)

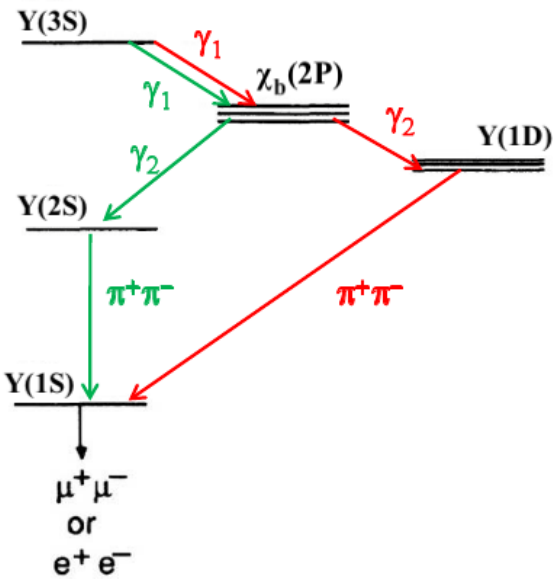
$\Upsilon(1^3D_J) \to \pi^+\pi^-\Upsilon(1S)$

Produced in $\chi_b(2P)$ radiative decay

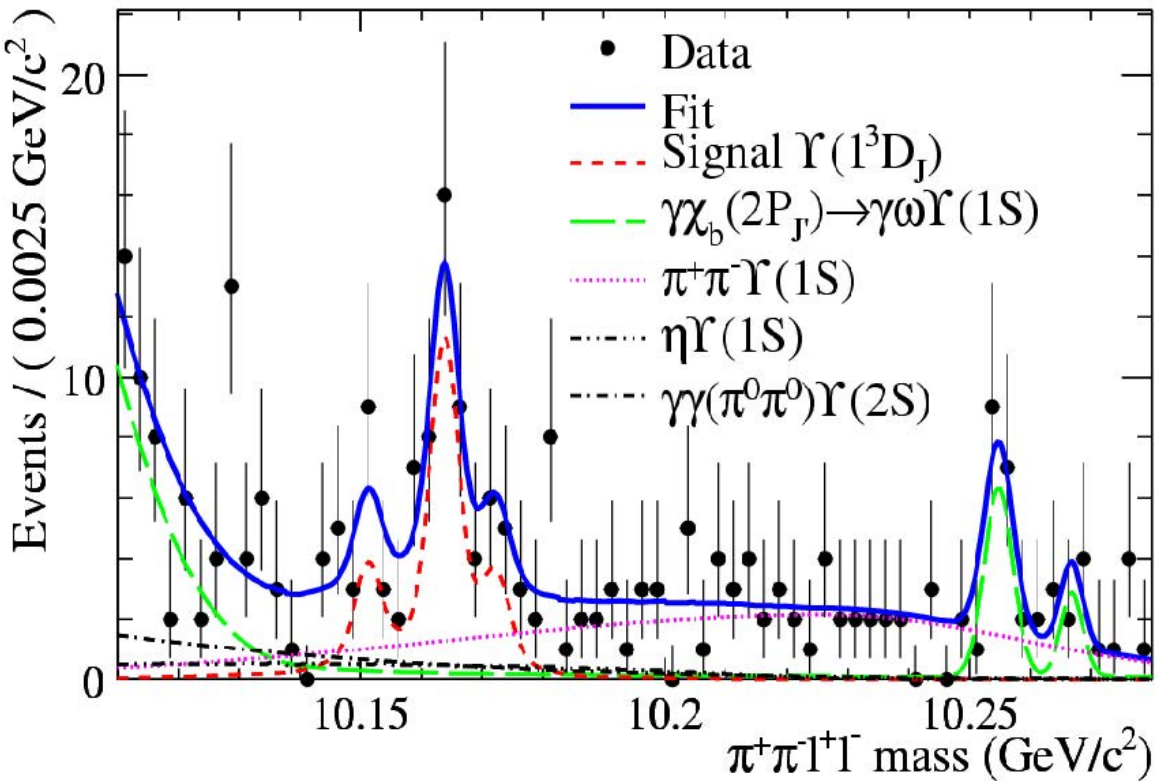
PRD 82, 111102 (2010)

Fully reconstruct the event

- 6 different cascades for $\Upsilon(1D)$



- many others with same final state



Observe $\Upsilon(1^3D_J)$ hadronic transitions;

$\Upsilon(1^3D_2)$ signal 5.8σ

Radiative transitions with converted photons

PRD 84, 072002 (2011)

Goals: search for η_b and measure the hindered E1 transitions

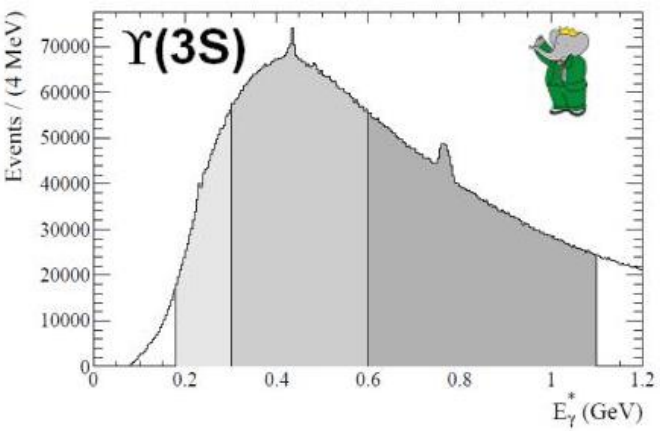
$\Upsilon(3S) \rightarrow \chi_{bJ}(1P)$, $\chi_{bJ}(2P) \rightarrow \Upsilon(1S)$

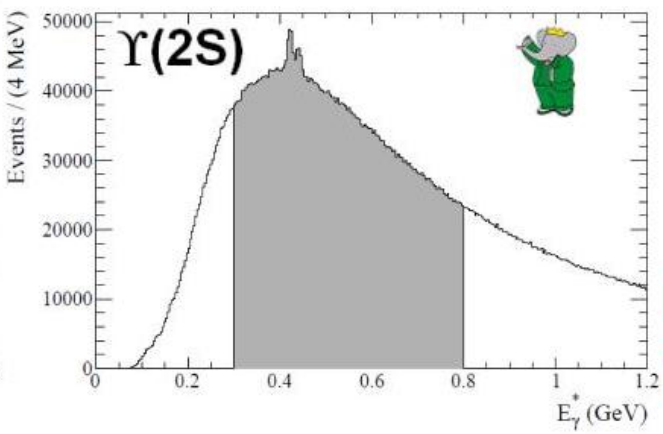
Rates generally phenomenologically well-predicted

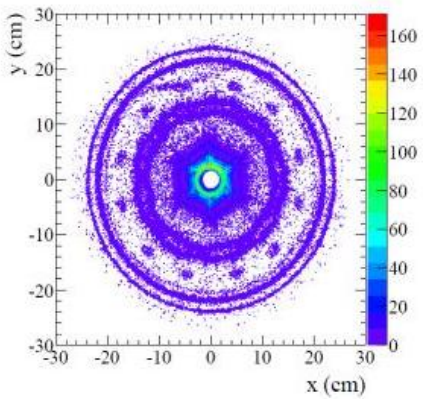
For some of these transitions the photons are in the same energy range
"overlapping" due to Doppler broadening and detector resolution

Use converted photons ($\gamma \rightarrow e^+e^-$) to improve resolution (e.g.: 25 → 5 MeV)

Price: efficiency (0.1÷2.5)% (depending on energy)



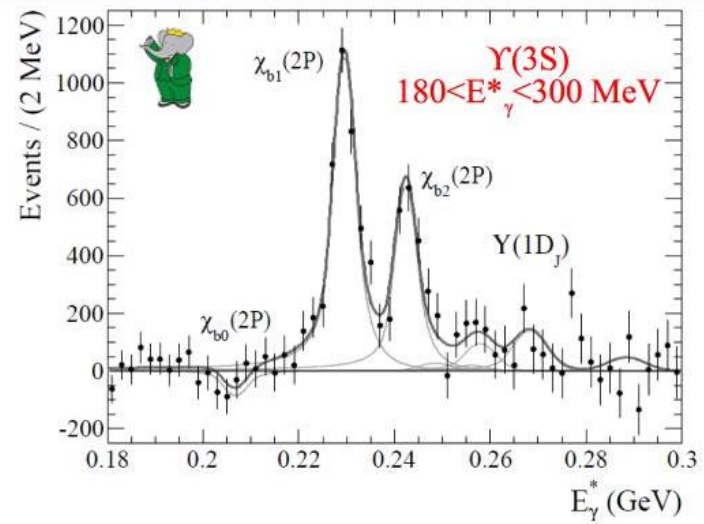


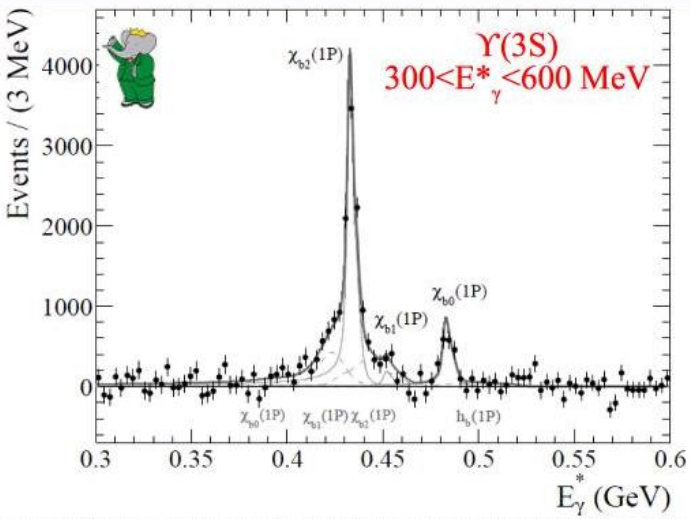


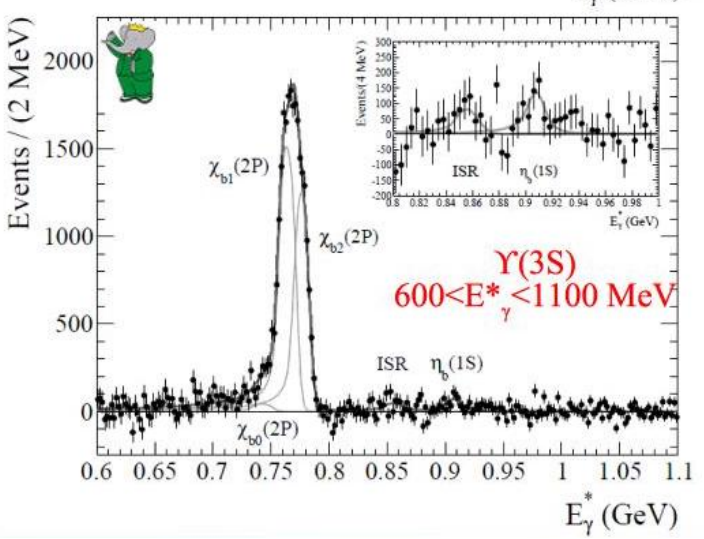
Fit the E^*_γ spectrum in 4 regions of interest

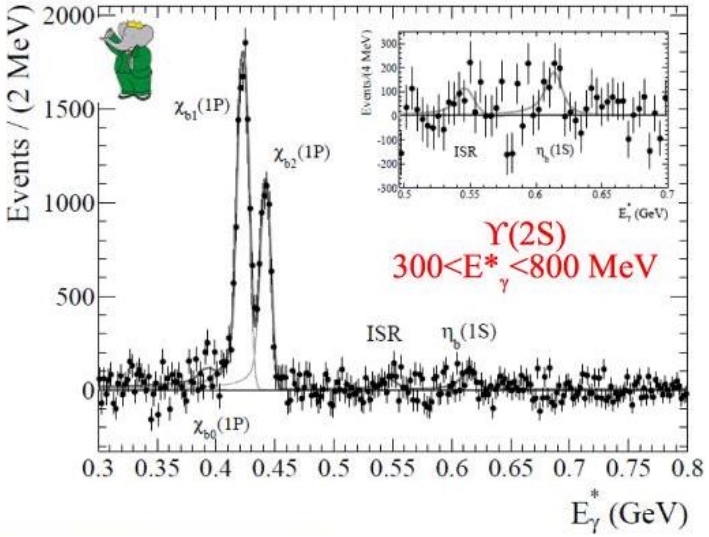
Background subtracted photon spectra

PRD 84, 072002 (2011)









Radiative transitions also studied without conversions
(larger statistics – broader resolution)

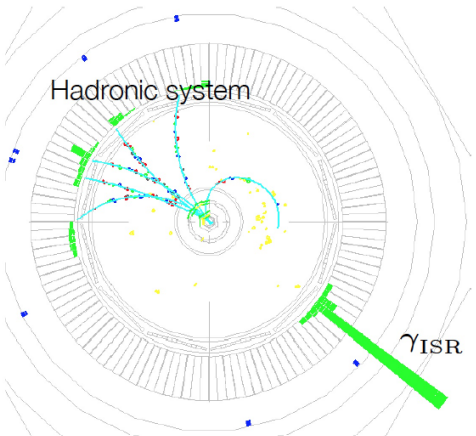
PRD 90, 112010 (2014)

The ISR method

Initial State Radiation from e^+e^- allows to measure cross sections at all center-of-mass energies $\sqrt{s'}$ below the nominal $\sqrt{s}$ of the beams

$$\frac{\mathrm{d}\sigma(s;s';\theta_\gamma)}{\mathrm{d}s'\mathrm{d}\theta_\gamma} = W(s;s';\theta_\gamma) \cdot \sigma_x(s')$$

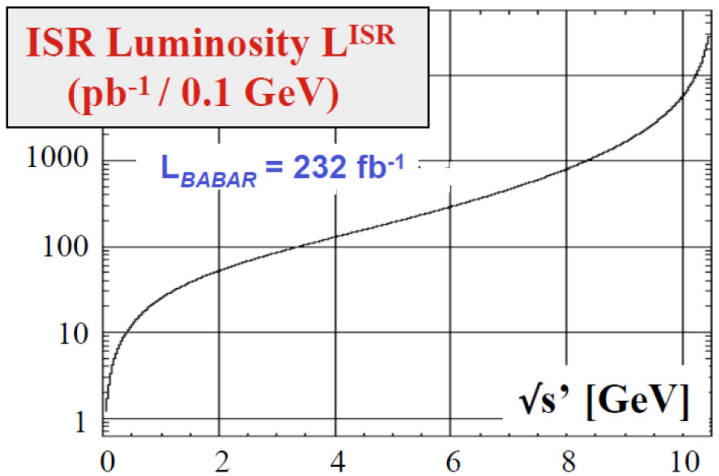
tag photon to identify ISR events



- hadrons in fiducial detector region
- fully reconstruct the final state
- kinematic fit: energy resolution

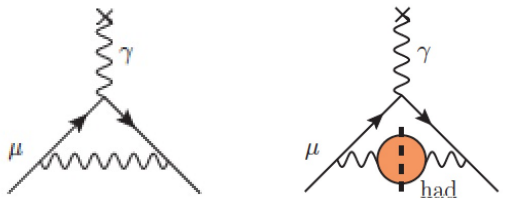
boost $\Longrightarrow$ harder momentum spectrum for daughter particles

- cross sections down to threshold
- measure σ at all $\sqrt{s}$ simultaneously
- large "effective" luminosity

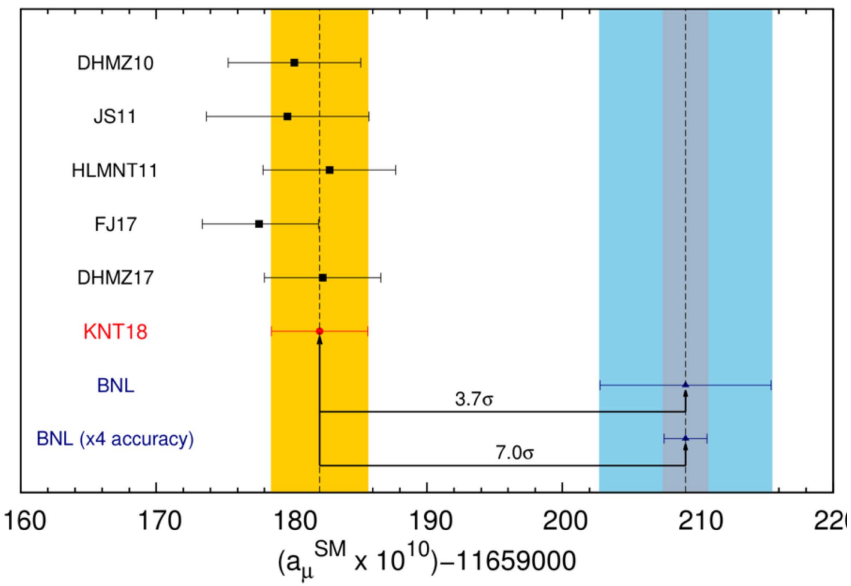


$a_\ell = \frac{1}{2}(g-2)_\ell$ precision test of QED

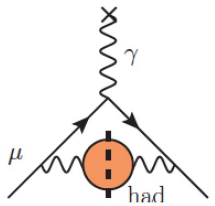
- OK for electrons
- long-standing $\approx 3\,\sigma$ discrepancy for muons



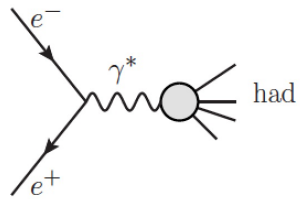
need experimental input for hadronic vacuum polarization



Keshavarzi et al. PRD 97 114025 (2018)



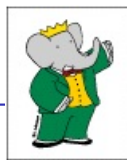
dispersion relation



$K(s)$: analytically known kernel function

$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} \mathrm{d}s \, \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$ experimental input



Low energy hadronic cross sections and a_μ

The dominant correction and error from hadronic vacuum polarization

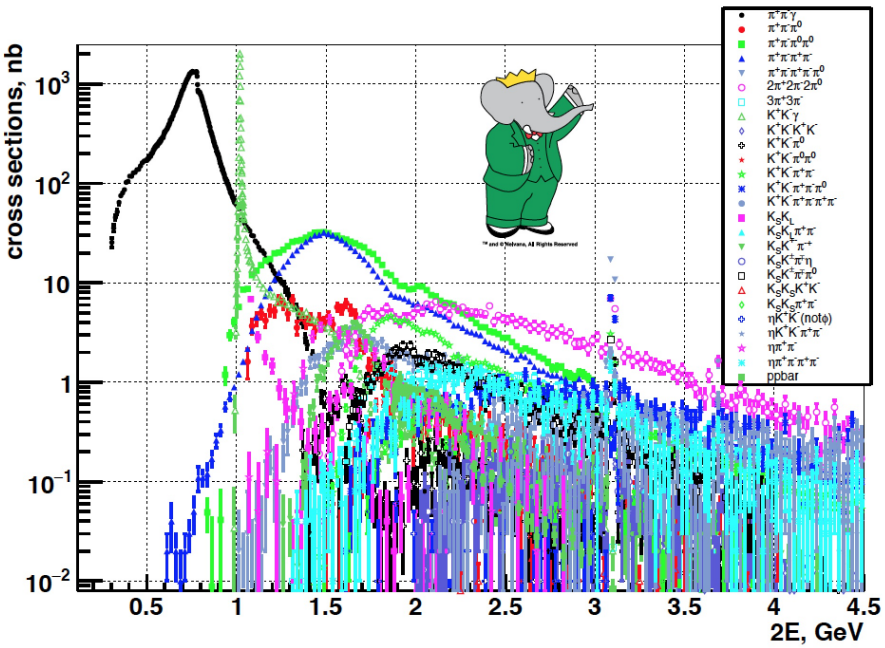
Individual SM contributions $\times 10^{-10}$

a_μ^{QED}	11658471.895 ± 0.008
a_μ^{EW}	15.4 ± 0.1
$a_\mu^{had,LO-VP}$	692.6 ± 3.3
$a_\mu^{had,HO-VP}$	-8.63 ± 0.09
$a_\mu^{had,LbLs}$	10.5 ± 2.6

Comparison with measurement

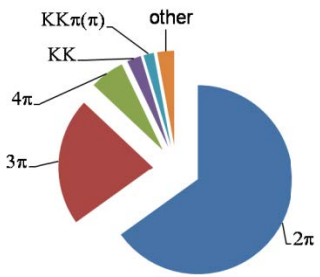
$a_\mu^{total-SM}$	11659181.7 ± 4.2
$a_\mu^{BNL-E821}$	11659209.1 ± 6.3
Data - SM	27.4 ± 7.6 (3.6σ)

Davier et al; EPJC 77, 827 (2017)



at low energies total hadronic cross section determined from (finite) sum of exclusive modes

$\sigma^2(a_\mu^{had,LO-VP})$



More than 30 exclusive modes measured by *BABAR* with the ISR method, the latest ones

- $\pi^+\pi^-\pi^0\pi^0$
- $\pi^+\pi^-\eta$
- $K_S^0 K_L^0 \pi^0$; $K_S^0 K_L^0 \eta$; $K_S^0 K_L^0 \pi^0\pi^0$
- $K_S^0 K^+\pi^+\pi^0$; $K_S^0 K^+\pi^+\eta$

BABAR papers on light hadron cross sections in ISR

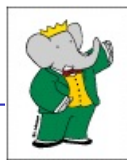
- $\pi^+\pi^-\eta$ PRD 97, 052007 (2018)
- $\pi^+\pi^-\pi^0\pi^0$ PRD 96, 092009 (2017)
- $K^0_S K^\pm\pi^\mp\pi^0$ and $K^0_S K^\pm\pi^\mp\eta$ PRD 95, 092005 (2017)
- $K^0_S K^0_L\pi^0$, $K^0_S K^0_L\eta$, and $K^0_S K^0_L\pi^0\pi^0$ PRD 95, 052001 (2017)
- $\mu^+\mu^-$ and $\pi^+\pi^-$ ISR-FS interference PRD 92, 072015 (2015)
- $K^0_S K^0_L$, $K^0_S K^0_L\pi^+\pi^-$, $K^0_S K^0_S\pi^+\pi^-$, and $K^0_S K^0_S K^+K^-$ PRD 89, 092002 (2014)
- K^+K^- PRD 88, 032013 (2013)
- $p\bar{p}$ PRD 87, 092005 (2013)
- $\pi^+\pi^-$ PRD 86, 032013 (2012)
- $\pi^+\pi^-\pi^+\pi^-$ PRD 85, 112009 (2012)
- $K^+K^-\pi^+\pi^-$, $K^+K^- - \pi^0\pi^0$, and $K^+K^-K^+K^-$ PRD 86, 012008 (2012)
- $\pi^+\pi^-$ PRL103, 231801 (2009)
- $K^+K^-\eta$, $K^+K^-\pi^0$ and $K^0_s K^\pm\pi^\mp$ PRD 77, 092002 (2008)
- $\Lambda\bar{\Lambda}$, $\Lambda\bar{\Sigma}^0$, $\Sigma^0\bar{\Sigma}^0$ PRD 76, 092006 (2007)
- $2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $K^+K^-\pi^+\pi^-\pi^0$ and $K^+K^-\pi^+\pi^-\eta$ PRD 76, 092005 (2007)
- $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$ and $K^+K^-K^+K^-$ PRD 76, 012008 (2007)
- $3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0)$ and $K^+K^-2(\pi^+\pi^-)$ PRD 73, 052003 (2006)
- $p\bar{p}$ PRD 73, 012005 (2006)
- $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, and $K^+K^-K^+K^-$ PRD 71, 052001 (2005)
- $\pi^+\pi^-\pi^0$ PRD 70, 072004 (2004)

Conclusions

BABAR has been a treasure trove for a variety of physics topics!

designed for *CKM*, gave new insight into QCD (and QCD corrections)

the devilish detail in precision test of SM..

- excellent detector performance
- great community!

It's been fun!