Search for exotic charmonium states

on behalf of the *BABAR* and *BELLE* Collaborations

August 25th, 2014 | Elisabetta Prencipe(*), Forschungszentrum Jülich (Germany) | HQL 2014, Mainz (Germany)

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Introduction

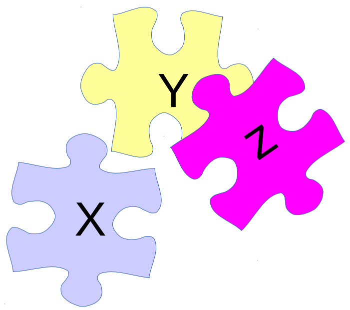
- Exciting time to study exotic states using the full ***BABAR*** and ***BELLE*** dataset.
- How many *charmonium(-like)* states can we count?

So many! CERN Yellow Report http://arxiv.org/abs/hep-ph/0412158

unexpected but found, expected and not found, controversial claims...

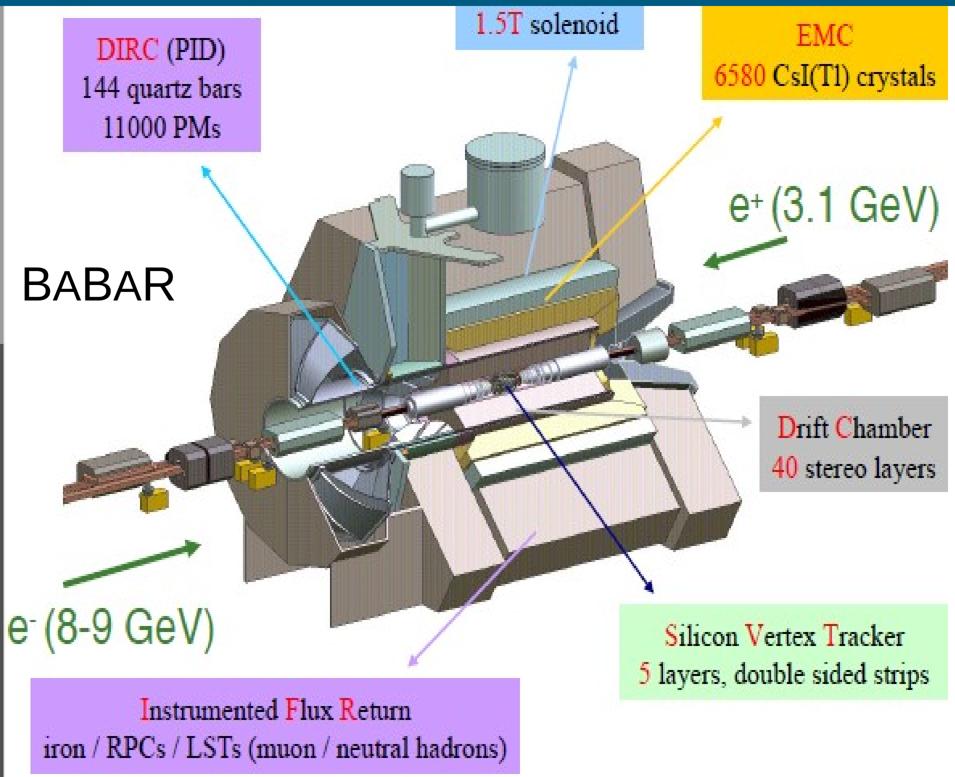
- 2014: 50th anniversary of CP violation discovery. Much progress thanks to the B-factories!
- 2014: 11 years after the observation of the unexpected X(3872).

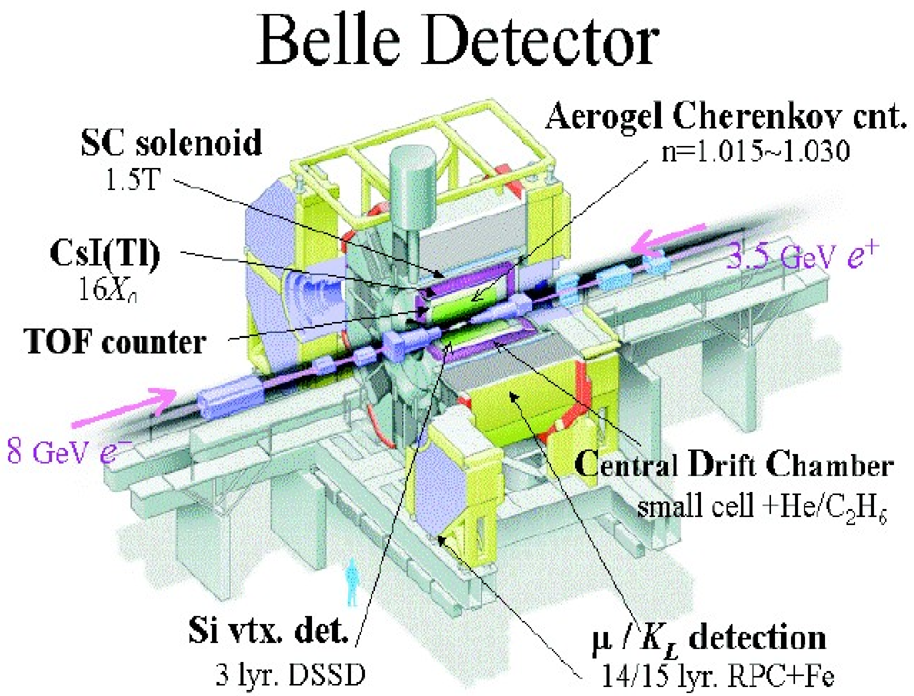
QUESTION: What have we understood?



- This talk is mainly focused on:
  - Analysis of the invariant mass $J/\psi\omega$
  - Analysis of the invariant mass $J/\psi\phi$ more recent result

The BABAR and BELLE detectors





- Located at SLAC (California, USA)
- Runs: from 1999 to 2008
- e+e- asymmetric collider

$$-0.9 < \cos\theta^* < 0.85$$

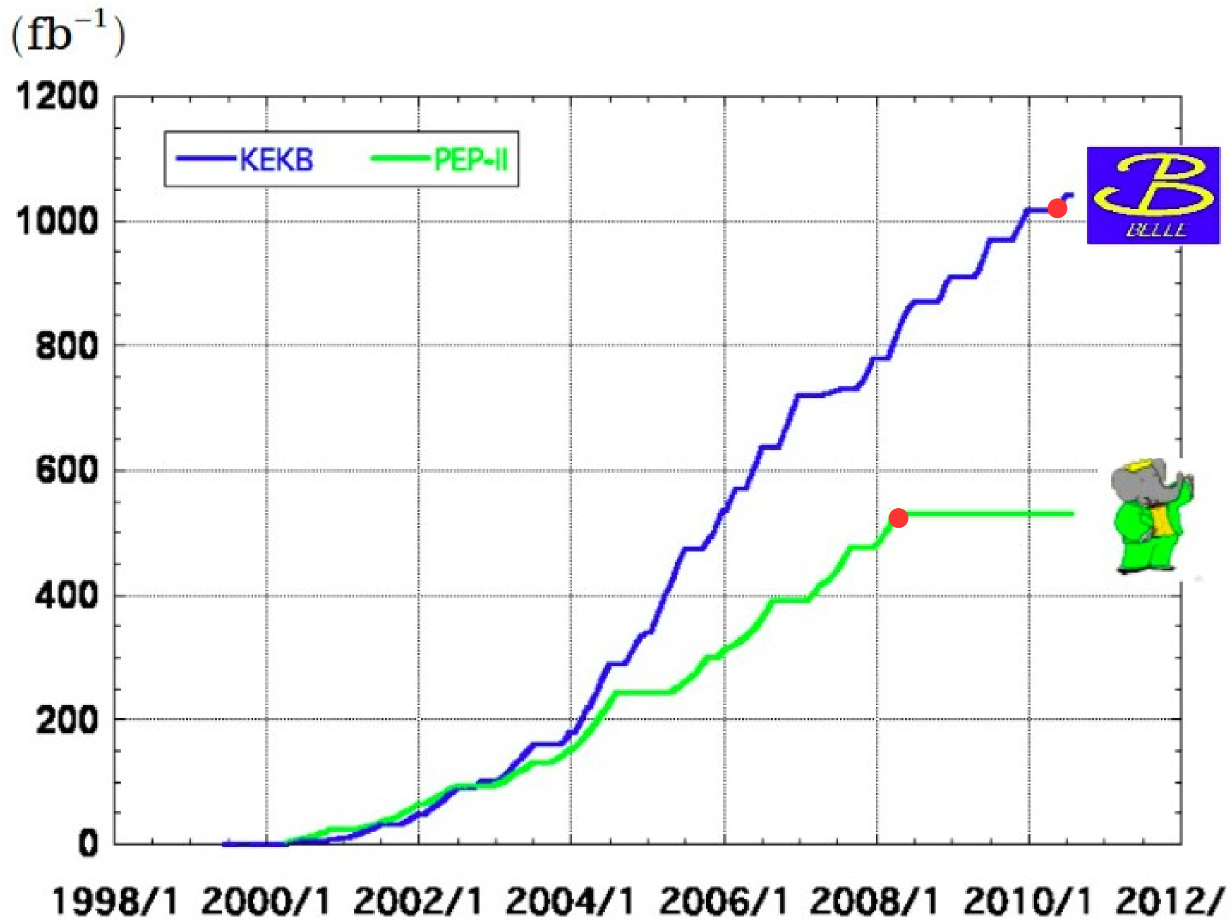
operating at the c.m. energy of Y(4S), then Y(2S) and Y(3S).

- Located at KEK (Japan)
- Runs: from 1999 to 2010
- e+e- asymmetric collider

$$-0.86 < \cos\theta < 0.95$$

operating at the c.m. energy of Y(4S), then Y(1S), Y(2S), Y(3S), Y(5S).

The BABAR and BELLE luminosity



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

513.7 ± 1.8 fb–1

On resonance:

$\Upsilon(4S)$: 424 fb^{-1}, 471 M

$\Upsilon(3S)$: 28 fb^{-1}, 122 M

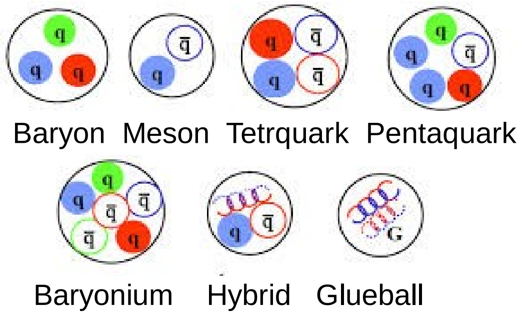
$\Upsilon(2S)$: 14 fb^{-1}, 99 M

Off resonance: 48 fb^{-1}

- Optimized for studies of CP violation
- High luminosity achieved ⇨ rare decay studies
- High production rate of $c\bar{c}$ ⇨ charmonium studies
- Run at Y(nS) ⇨ bottomonium studies

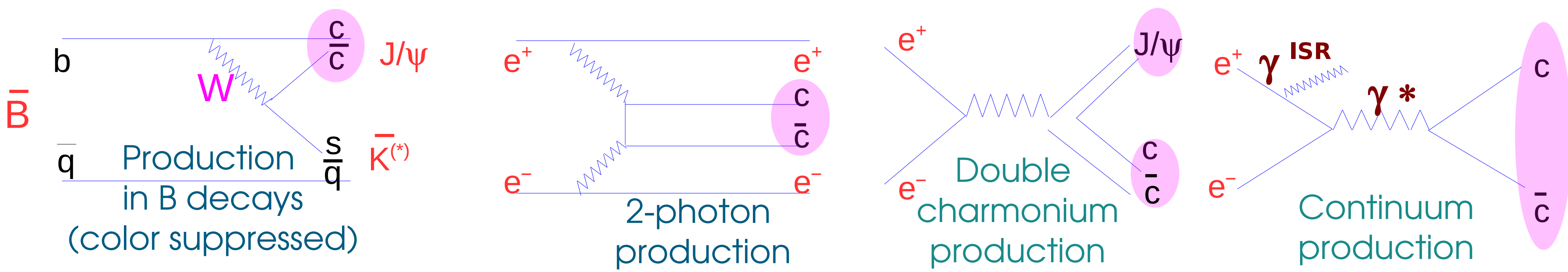
Experimental approach

- **Why** should we look for new resonant states?
  - Elementary particles exist; then:
  - Mesons (2 quarks: one quark and one antiquark)
  - Baryons (3 quarks)
  - More complicated aggregations of matter:
    tetraquarks, hybrids, molecular states, and more...



Need to understand these forms of aggregation of matter

- **Where** shall we look for new resonant states?
  - Several theoretical approaches.
  - The systems of $J/\psi\pi\pi$, $J/\psi\pi\pi\pi^0$ prove to be rich sources of information: still under study.
  - What about $J/\psi KK$ (strangeness in charmonium)? Recently (partially) covered



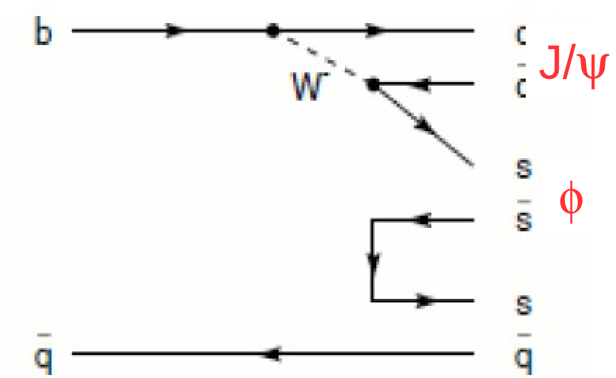
Strangeness in Charmonium

$b \rightarrow c\bar{s}s$

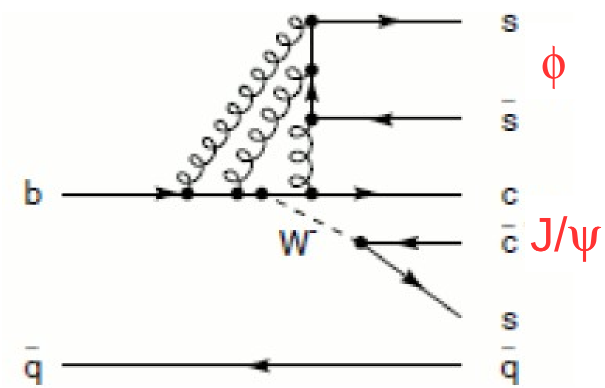
(suppressed B decays)

Analysis $B \to J/\psi KK(K)$: motivation

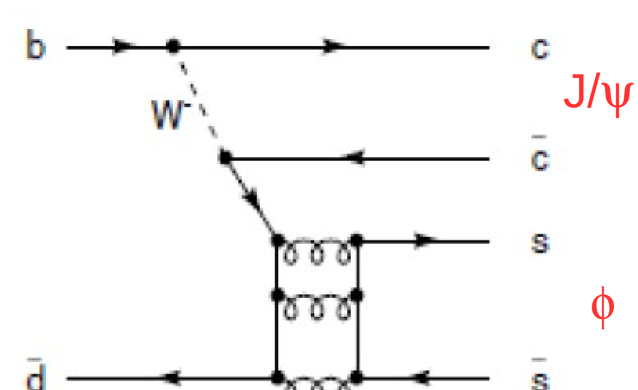
- $B \to J/\psi$ K K K: rare B decay, Cabibbo suppressed, predicted BF ~10^{-5}
- K^+K^- contribution expected to be dominated from ϕ [BF($\phi \to K^+K^-$) ~49.5%]
- $B \to J/\psi\, \phi$ K: three body decay, gluon rich process ⇒ ideal place to look for exotics
- It could proceed also via quasi-2-body decay, $B \to Y_g (c\bar{c}s\bar{s})K$, $Y_g \to J/\psi\phi$
- If any Y_g exists, expected mass < 4.3 GeV/c^2 (threshold DD^{**})
- $B^0 \to J/\psi\phi$: transition $b\bar{d} \to c\bar{c}s\bar{s}$ rescattering process ⇒ no signal expected



B →J/ψϕK via strange sea quark



B →J/ψϕK via gluon coupling



$B^0 \to J/\psi\phi$: rescattering diagram

Analysis $B \to J/\psi KK(K)$: "old" measurements

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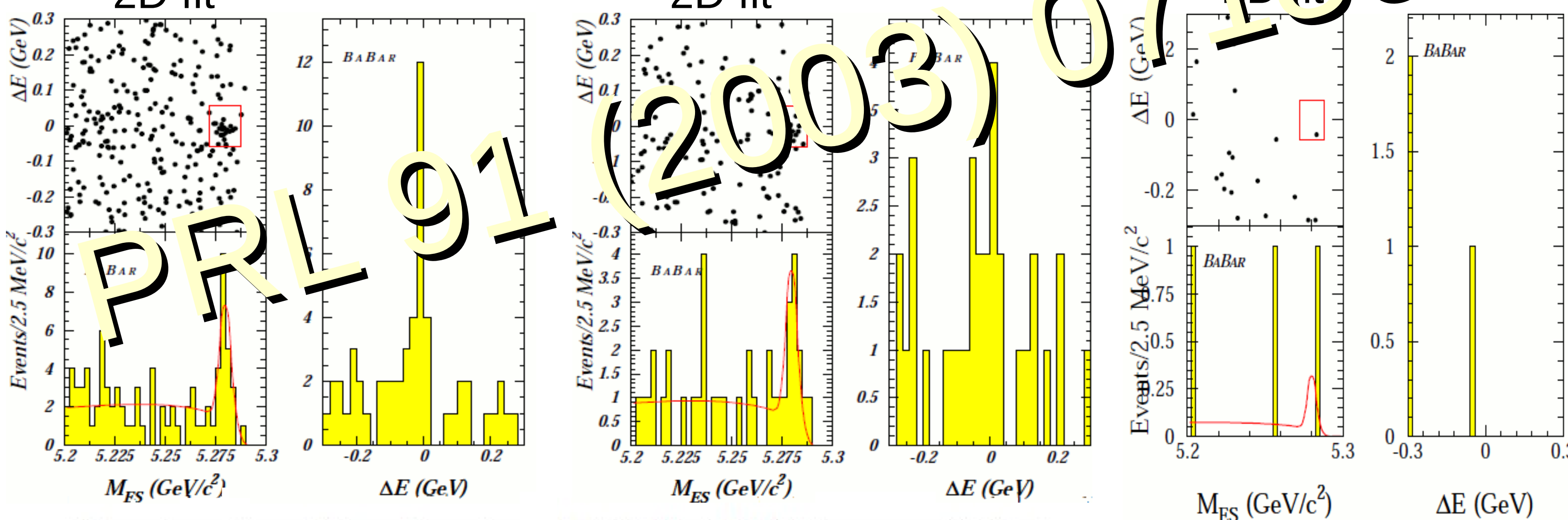
- Old BaBar publication: PRL 91 (2003) 071801, 51 fb^{-1}
- Today: 424 fb^{-1}, 470M $B\bar{B}$: expected much higher precision in BF measurements, and possibility to look at the invariant mass distributions

2D fit | 2D fit | 2D fit



Experiment	Channel	B.R. (10^{-5})	PDG12 average (10^{-5})
BaBar	$B^{\pm} \to J/\psi\phi K^{\pm}$	$4.4 \pm 1.4 \pm 0.5$	5.2 ± 1.7
CLEO-II		$8.8^{+3.5}_{-3.0} \pm 1.3$	
BaBar	$B^{0} \to J/\psi\phi K^{0}$	$10.2 \pm 3.8 \pm 1.0$	9.4 ± 2.6
CLEO-II		$8.8^{+3.5}_{-3.0} \pm 1.3$	

$B^0 \to J/\psi\phi$ UL<9.2 * 10^{-6}

No update until 2014!

BaBar measurements dominate the PDG measurements since 2003

$B \to J/\psi KK(K)$: BF strategy

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- B channels under study : $B^{\pm}$ and B^0
- K^+K^- invariant mass in the full range [0.98;1.69] GeV/c^2

PDG2012

decay channel	BR	J^G (J^{PC})
$a_0(980) \to K^+K^-$	seen	$1^-(0^{++})$
$f_0(980) \to K^+K^-$	seen	$0^+(0^{++})$
$\phi(1020) \to K^+K^-$	$(48.9 \pm 0.5)\%$	$0^-(1^{--})$
$f_2(1270) \to K^+K^-$	$(4.6 \pm 0.4)\%$	$0^+(2^{++})$
$a_2(1320) \to K^+K^-$	$(4.9 \pm 0.8)\%$	$1^-(2^{++})$
$f_2'(1525) \to K^+K^-$	$(88.8 \pm 3.1)\%$	$0^+(2^{++})$
$\phi(1680) \to K^+K^-$	seen	$0^-(1^{--})$

Several resonant states decaying to K^+K^-.
Expected dominant meson ($\to K^+K^-$) in these B decays: ϕ

- Measurement of BFs:
  – blind analysis (large MC samples) to check consistency of fit methods
  – unbinned maximum likelihood fit of m_{ES} (gaussian fit for signal yield; Argus function to parametrize the background). Double check with ΔE fit is performed

$$m_{ES} = \sqrt{E^{*}_{beam} - p^{*}_{beam}} \qquad \Delta E = E^{*}_{beam} - \sqrt{s}/2$$

  – K^+K^- invariant mass in the full range, then we restrict to the ϕ mass region
- J/ψ reconstructed to e^+e^- and $\mu^+\mu^-$; mass constrained

B → J/ψKKK: fits for BF measurements

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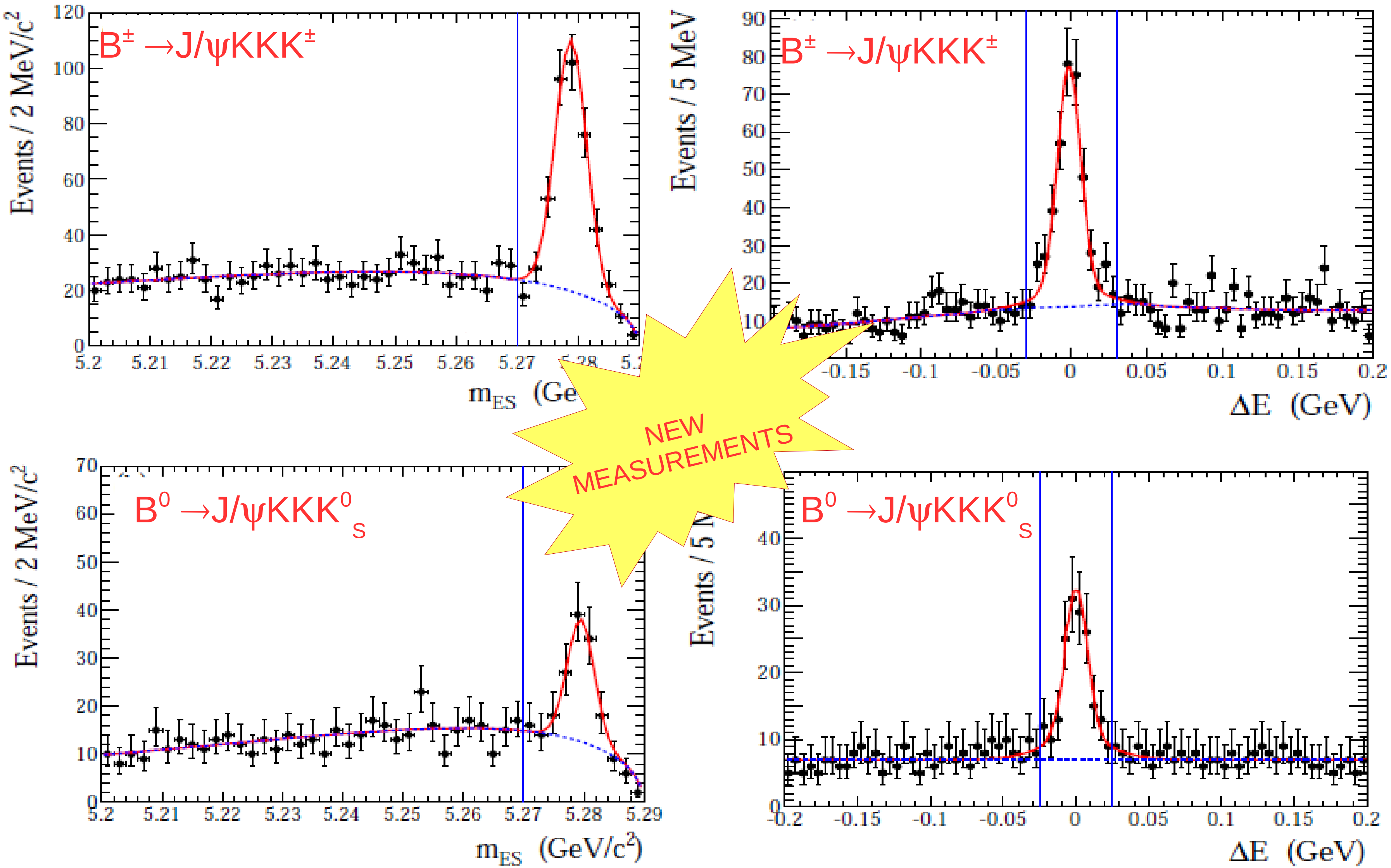
Submitted to PRD

- No BF measurements in the PDG until 2014



K^+K^- invariant mass

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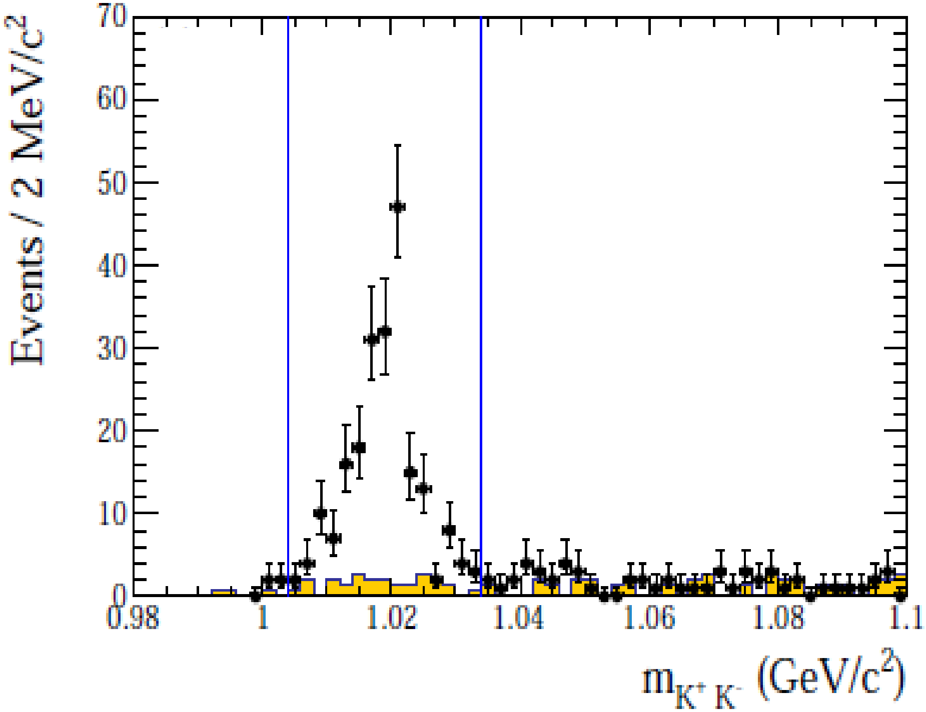
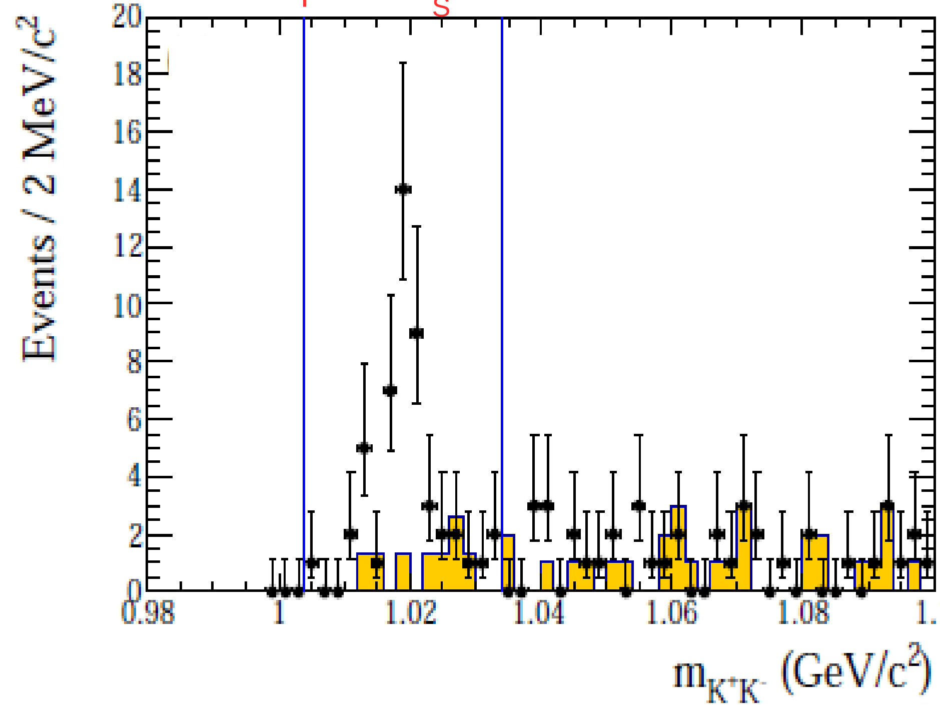
$B^\pm \rightarrow J/\psi KKK^\pm$



$B^0 \rightarrow J/\psi KKK^0_S$



- ϕ mass region selected to study $B \rightarrow J/\psi\phi K$
- ϕ meson dominant over the other K^+K^- combinations
- One-to-one correspondence between B candidate and ϕ candidate
- Observation of good signal, small background

B → J/ψϕ(K): fits for BF measurements

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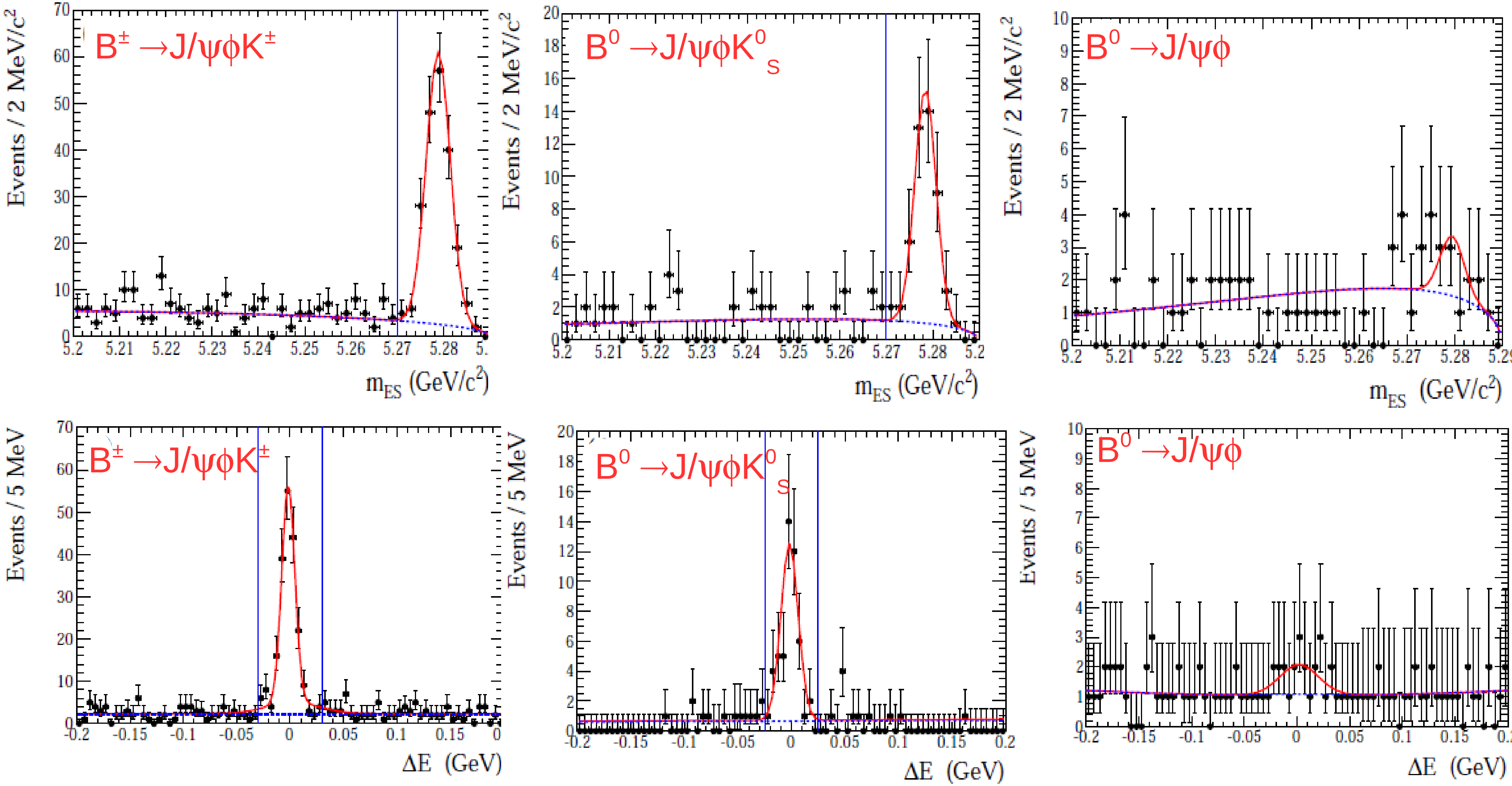

$B \to J/\psi KK(K)$: BF results

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TABLE I: Event yields, BF measurements ($\mathcal{B}$) and efficiencies (ϵ) for the different final states. The yields re-weighted by the average efficiency ($\bar{\epsilon}$) evaluated on PHSP MC distributions, and the yields re-weighted by the efficiency from the Dalitz plots (ϵ_D) are reported. BF measurements with the two different efficiency methods are compared for the channel $B^+ \to J/\psi K^+K^-K^+$ (B^+_{KKK}), $B^+ \to J/\psi \phi K^+$ ($B^+_{\phi K}$), $B^0 \to J/\psi K^-K^+K^0_S$ ($B^0_{KKK_S}$), and $B^0 \to J/\psi \phi K^0_S$ ($B^0_{\phi K_S}$). The $B^0 \to J/\psi \phi$ (B^0_ϕ) UL at 90% c.l. is listed at the end of the table.

B channel	Event yield	$\bar{\epsilon}$ (%)	Corrected yield ($\bar{\epsilon}$)	Corrected yield (ϵ_D)	Case A $\mathcal{B}$ ($\times 10^{-5}$) calculated with $\bar{\epsilon}$	Case B $\mathcal{B}$ ($\times 10^{-5}$) calculated with ϵ_D
B^+_{KKK}	290±22	17.96±0.04	1615±122	1904±144	5.86±0.44 (stat)±0.24 (sys)	6.91±0.52 (stat)±0.28 (sys)
$B^+_{\phi K}$	189±14	16.28±0.04	1161± 86	1396±103	4.21±0.31 (stat)±0.13 (sys)	5.06±0.37 (stat)±0.15 (sys)
$B^0_{KKK_S}$	68±13	11.31±0.04	586±115	639±125	3.07±0.59 (stat)±0.13 (sys)	3.35±0.66 (stat)±0.15 (sys)
$B^0_{\phi K_S}$	41± 7	10.73±0.04	382± 65	406± 69	2.00±0.34 (stat)±0.05 (sys)	2.13±0.36 (stat)±0.06 (sys)
B^0_ϕ	6 ± 4	31.12±0.07	19 ± 13	–	< 0.101	–

- The difference between the case A) and B) is due to the K^+K^- correction in the Dalitz structure

B → J/ψKKK: non-resonant contribution

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$$R_+ = \frac{\mathcal{B}(B^+ \to J/\psi K^+ K^- K^+)}{\mathcal{B}(B^+ \to J/\psi \phi K^+)} = 1.39 \pm 0.15 \pm 0.07$$

$$R_0 = \frac{\mathcal{B}(B^0 \to J/\psi K^+ K^- K^0_s)}{\mathcal{B}(B^0 \to J/\psi \phi K^0_s)} = 1.54 \pm 0.40 \pm 0.08$$

$$R_\phi = \frac{\mathcal{B}(B^0 \to J/\psi \phi K^0_s)}{\mathcal{B}(B^+ \to J/\psi \phi K^+)} = 0.48 \pm 0.09 \pm 0.02$$

$$R_{2K} = \frac{\mathcal{B}(B^0 \to J/\psi K^+ K^- K^0_s)}{\mathcal{B}(B^+ \to J/\psi K^+ K^- K^+)} = 0.52 \pm 0.09 \pm 0.03$$

- BFs in agreement with the prediction of the quark spectator model
- K^+K^- contribution to BFs outside the ϕ mass region: first measurement
- Old Babar measurement on B →J/ψϕK confirmed, now with >4 times precision

⇨ currently highest world precision of these BF measurements!

$B \to J/\psi KKK$: search for exotics

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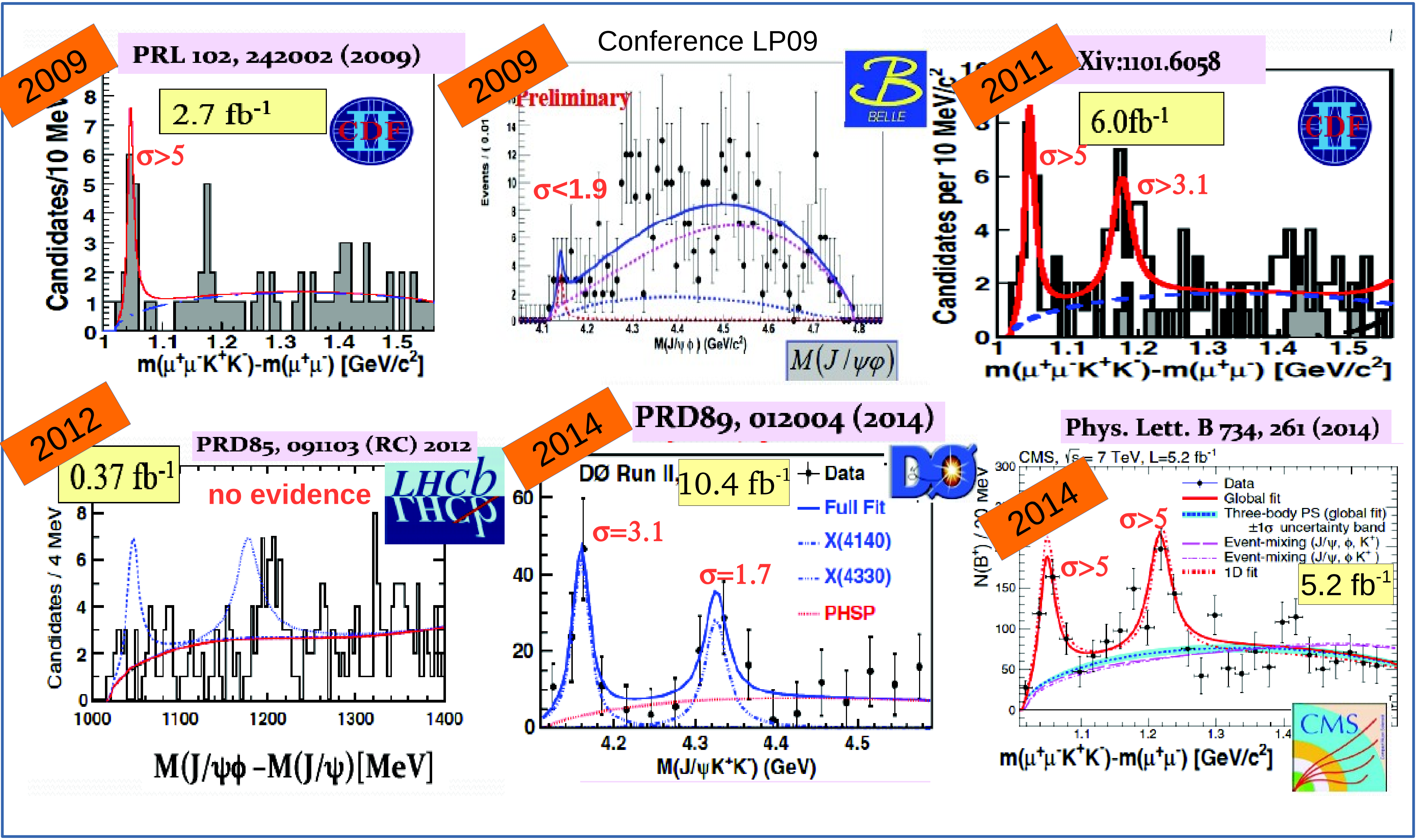
- Signal box selected: m_{ES}>5.27 GeV/c^2; |ΔE|<30 MeV ($B^{\pm}$) and |ΔE|<25 MeV (B^0)
- Mass resolution at the $J/\psi\phi$ threshold: 2 MeV/c^2
- Search for resonant states in $J/\psi KK$, $J/\psi K$, KKK
- $J/\psi\phi$ invariant mass gained more attention because of several recent publications
- J/ψ and ϕ are **vectors**: high spin contribution expected
- Efficiency as function of the invariant mass must be taken into account
- In our fit: mass and width fixed to the CDF values (first publication on res. structure)

Experiment	ref	$M_{X(4140)}$ [MeV/c^2]	$\Gamma_{X(4140)}$ [MeV]	
CDF	PRL102.242002(2009)	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{5.0} \pm 3.7$	OBSERVATION
CDF	arXiv:1101.6058	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.2^{+10.4}_{6.1} \pm 2.5$	
LHCb	PRD85,091103(2012)	-	-	NO EVIDENCE
CMS	PRB734,261(2014)	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	OBSERVATION
D0	PRD89,012004(2014)	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	EVIDENCE
		$M_{X(4270)}$ [MeV/c^2]	$\Gamma_{X(4270)}$ [MeV]	
CDF	arXiv:1101.6058	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32.3^{+21.1}_{15.3} \pm 7.6$	EVIDENCE
LHCb	PRD85,091103(2012)	-	-	NO EVIDENCE
CMS	PRB734,261(2014)	$4313.8 \pm 5.3 \pm 7.3$	$38^{+30}_{-15} \pm 16$	OBSERVATION
D0	PRD89,012004(2014)	≈ 4360	$30(\textit{fixed})$	NO EVIDENCE, but BETTER FIT

The controversial picture of $m_{J/\psi\phi}$



$B \to J/\psi\phi K$: reconstruction efficiency

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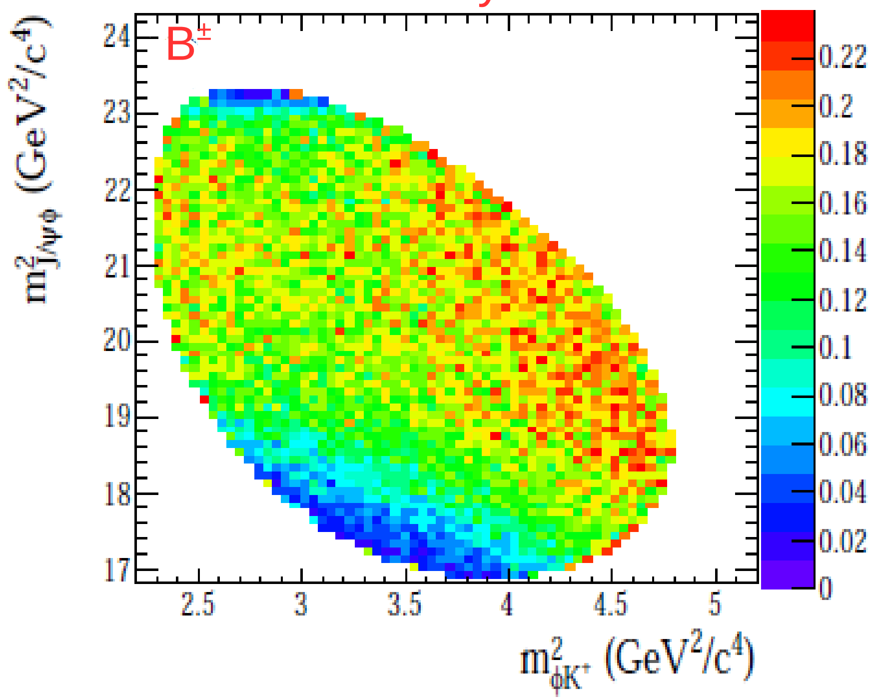
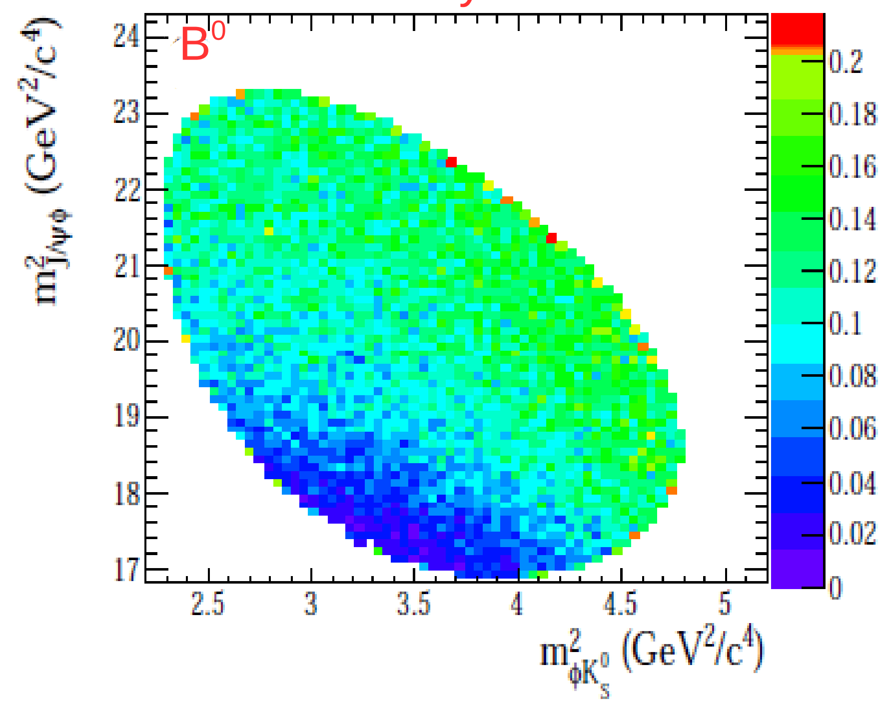
- Efficiency lower at the $J/\psi\phi$ mass threshold due to the difficulty to reconstruct low momentum kaon
- Charged B channel more sensitive to the efficiency change at the $J/\psi\phi$ threshold compared to B^0 channel; poorer ϕ ($\to K^+K^-$) reconstruction

MC efficiency



MC efficiency



$B \to J/\psi\phi K$: invariant mass fit

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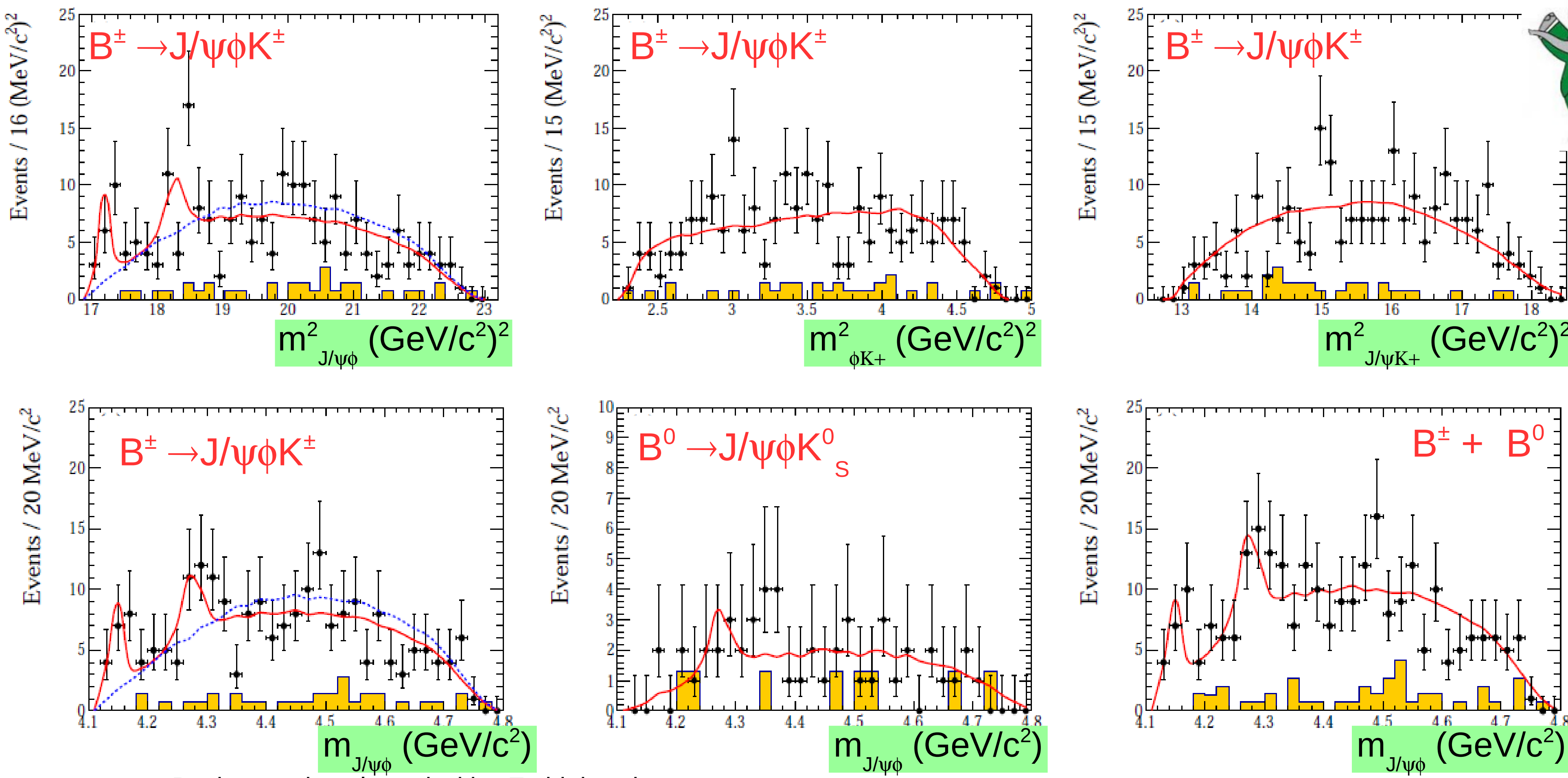
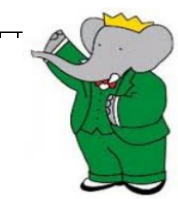
- **Unbinned maximum likelihood fit**
- Central value and width of the Breit-Wigners are fixed in the fit
- 2 Breit-Wigner + PHSP function re-weighted by 2D-efficiency map from **Dalitz plots**
- Background estimated from ΔE sidebands





Background evaluated with ΔE sidebands

$B \to J/\psi\phi K$: mass fit results

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Channel	Fit	$f_{X(4140)}(\%)$	$f_{X(4270)}(\%)$	2D χ^2/ν	1D χ^2/ν
B^+	A	9.2 ± 3.3	10.6 ± 4.8	12.7/12	6.5/20
	B	9.2 ± 2.9	0.	17.4/13	15.0/17
	C	0.	10.0 ± 4.8	20.7/13	19.3/19
	D	0.	0.	26.4/14	34.2/18
$B^0 + B^+$	A	7.3 ± 3.8	12.0 ± 4.9	8.5/12	15.9/19

- These results are background corrected.
- Small background: purity 89% ($B^\pm$) and 82% (B^0)
- χ^2 of fits acceptable in all cases: no hypothesis should be rejected

Our fit:

– S-wave relativistic Breit-Wigners;

– non-resonant contribution represented by a constant term;

– no interference allowed between the fit components;

– small bkg from ΔE sidebands, consistent with PHSP behavior (incorporated in the non-resonant PHSP term);

– high spin contribution expected, but angular term non included due to poor statistics (we assume that the resonances decay isotropically)

fit without resonances (phase space): $\chi^2/\text{ndof} =$ 26.4/14

fit with two resonances (parameters fixed to CDF) : $\chi^2/\text{ndof} =$ 12.7/12

$f_{X(4140)} = (9.2 \pm 3.3 \pm 4.7)\%$, $f_{X(4270)} = (10.6 \pm 4.8 \pm 7.1)\%$ — Parameters fixed to the CDF values — PRL102,242002(2009)

$f_{X(4140)} = (13.2 \pm 3.8 \pm 6.8)\%$, $f_{X(4270)} = (10.9 \pm 5.2 \pm 7.3)\ \%$ — Parameters fixed to the CMS values — PLB734,261(2014)

$B \to J/\psi\phi K$: fractions

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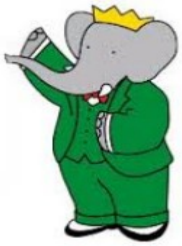
$$\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\,\phi)/\mathcal{B}(B^+ \to J/\psi\,\phi K^+) < 0.135$$
$$\mathcal{B}(B^+ \to X(4270)K^+) \times \mathcal{B}(X(4270) \to J/\psi\,\phi)/\mathcal{B}(B^+ \to J/\psi\,\phi K^+) < 0.184$$

U.L. @ 90% c.l.

X(4140) and X(4270) on 422.5 fb^{-1} integrated luminosity: <2σ effect (within sys. uncertainties)

No additional structures are shown in the other invariant mass systems



Experiment	ref	$f_{X(4140)}$ [%]
CDF	PRL102.242002(2009)	-
CDF	arXiv:1101.6058	$14.9 \pm 2.9 \pm 2.4$
LHCb	PRD85,091103(2012)	< 7
CMS	**PLB734,261(2014)**	13.4 ± 3.0
D0	PRD89,012004(2014)	$19 \pm 7 \pm 4$
		$f_{X(4270)}$ [%]
CDF	arXiv:1101.6058	-
LHCb	PRD85,091103(2012)	< 8
CMS	**PRB734,261(2014)**	18.0 ± 7.3
D0	PRD89,012004(2014)	-

$B \to J/\psi\phi K$: BABAR re-weighted data

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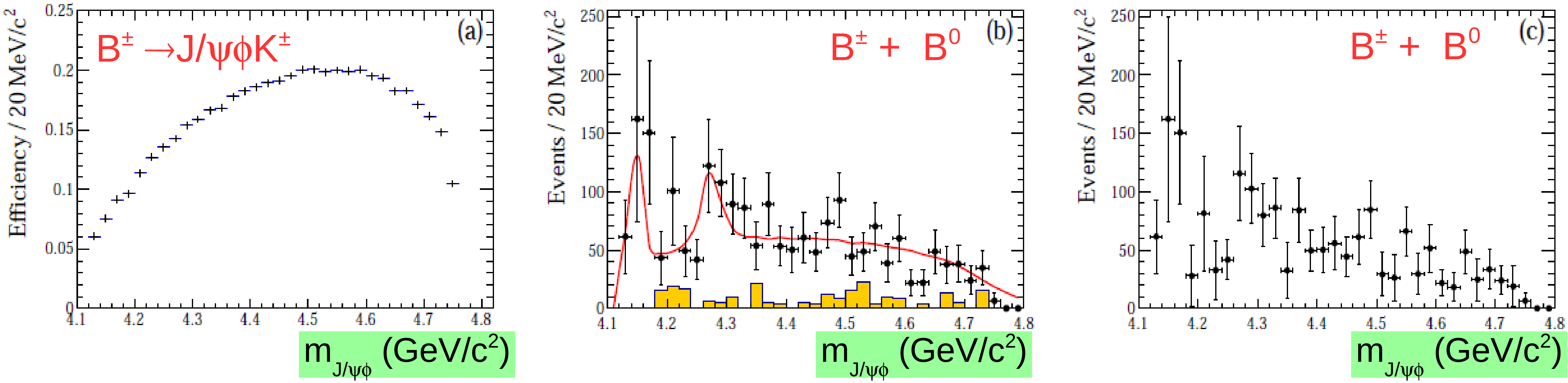
- What happens if we re-weight data (not the fit function) by the Dalitz efficiency?



(a) Average efficiency distribution as a function of the $J/\psi\phi$ mass for $B^+ \to J/\psi\phi K^+$

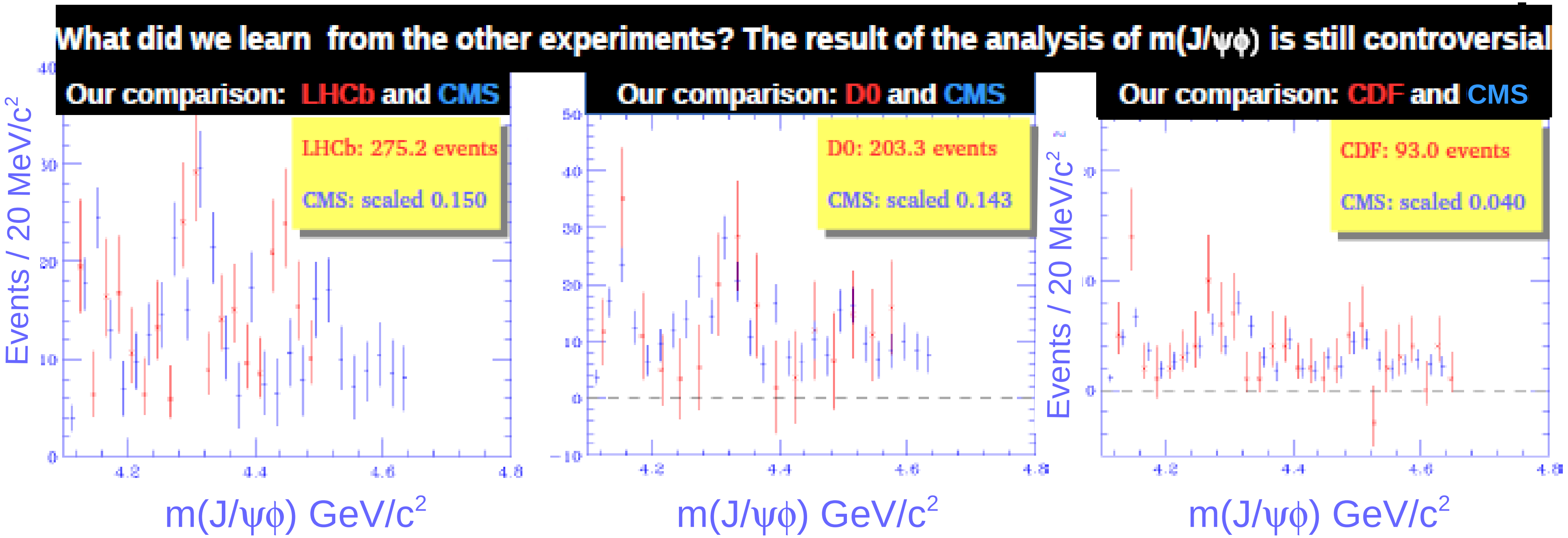
(b) Efficiency corrected $J/\psi\phi$ for the combined B^+ and B^0 samples

(c) Efficiency corrected and background subtracted $J/\psi\phi$ mass spectrum for the combined B^+ and B^0 samples

Significance < 2 σ within systematic uncertainties

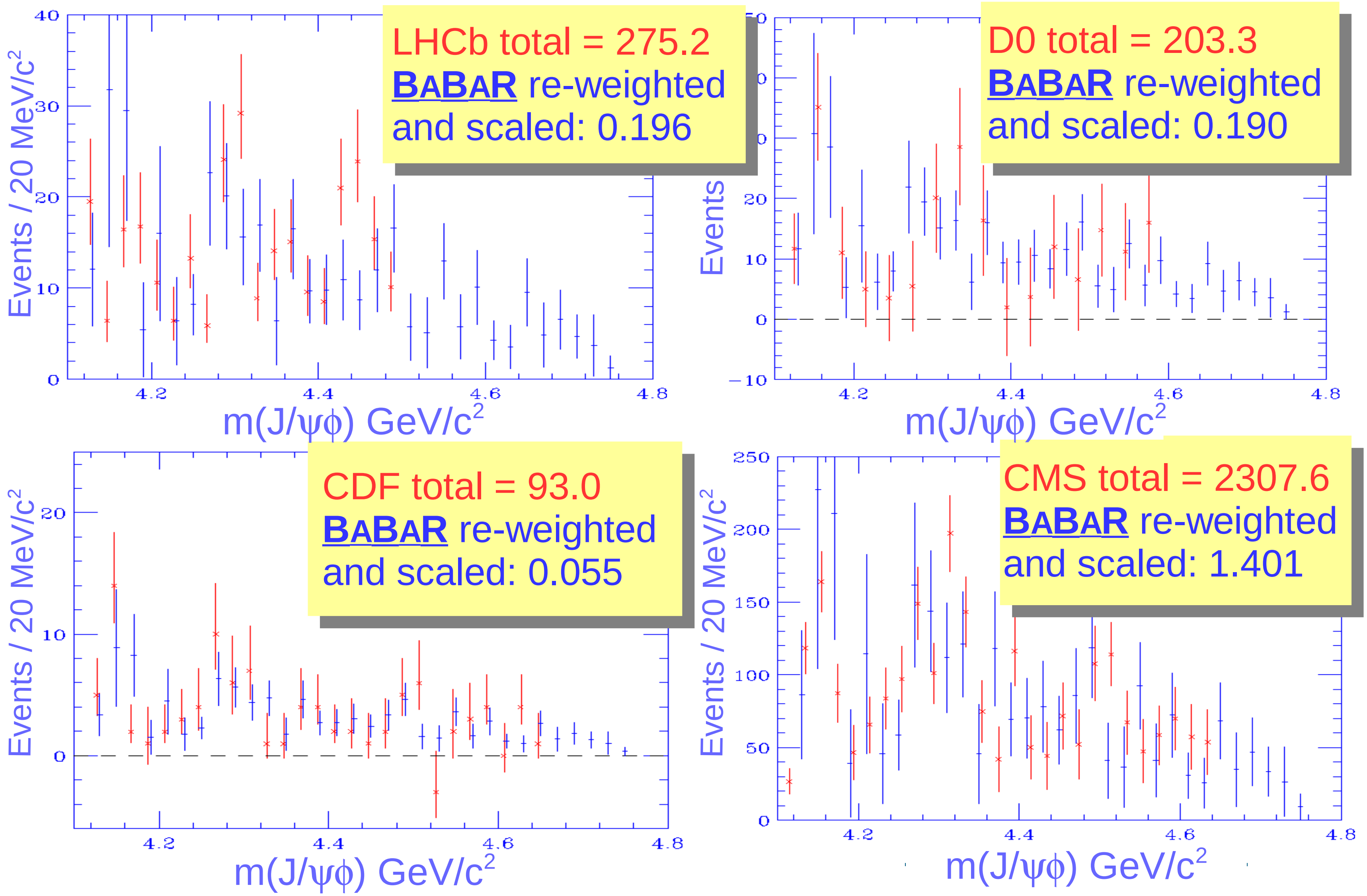
B → J/ψϕK: comparison (I)

- Let's try to combine properly results and try to understand:



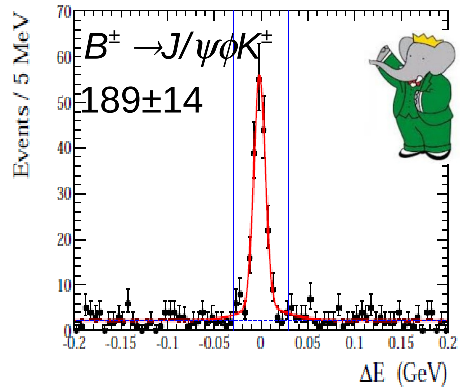
CDF Coll., PRL 102, 242002 (2009); LHCB Coll., PRD 85, 091103 (2010); D0 Coll., PRD 89, 012004 (2014); CMS Coll., PRB 734, 261 (2014)

$B \to J/\psi\phi K$: comparison (II)



<u>Note</u>: BABAR re-weighed data (B^0 + $B^{\pm}$); other experiments: <u>only</u> $B^{\pm}$, <u>only</u> $J/\psi \to \mu\mu$

$B \to J/\psi\phi K$: comparison (III)



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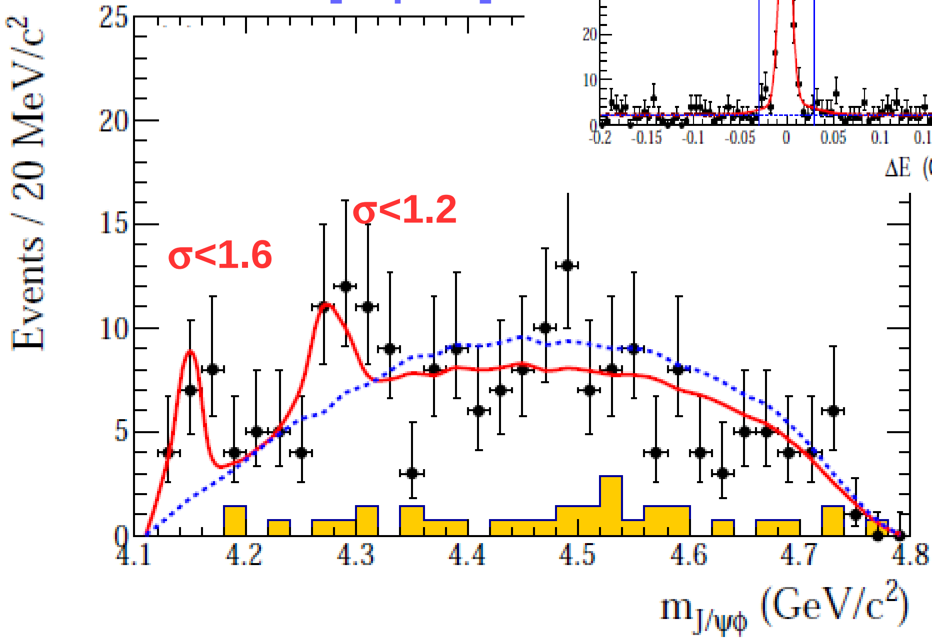
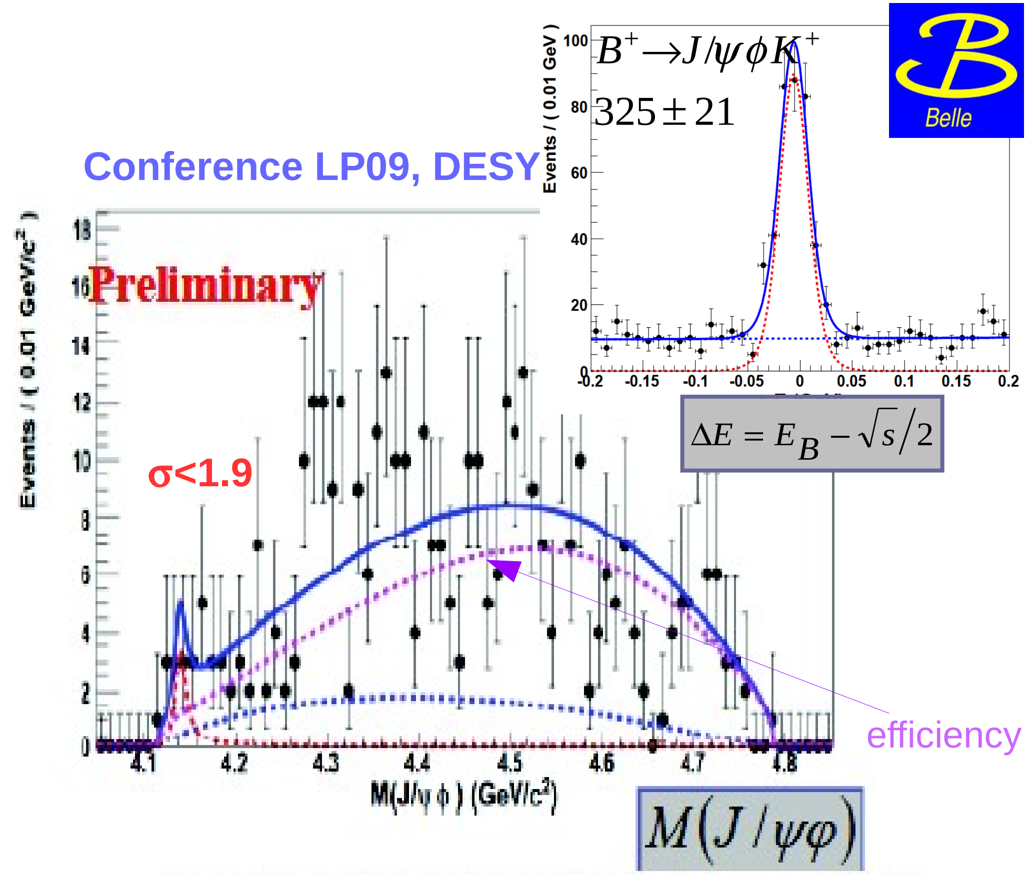


Conference LP09, DESY



NOTE: Significance is evaluated after re-weighting *pdf* by 2D-efficiency + systematic uncertainties are included

Br($B^+ \to X(4140)K^+$, $X \to J/\psi\phi$) $<5.7 \times 10^{-6}$ @90%*C.L.*

Br($B^+ \to X(4140)K^+$, $X \to J/\psi\phi$) $<6 \times 10^{-6}$ @90%*C.L.*

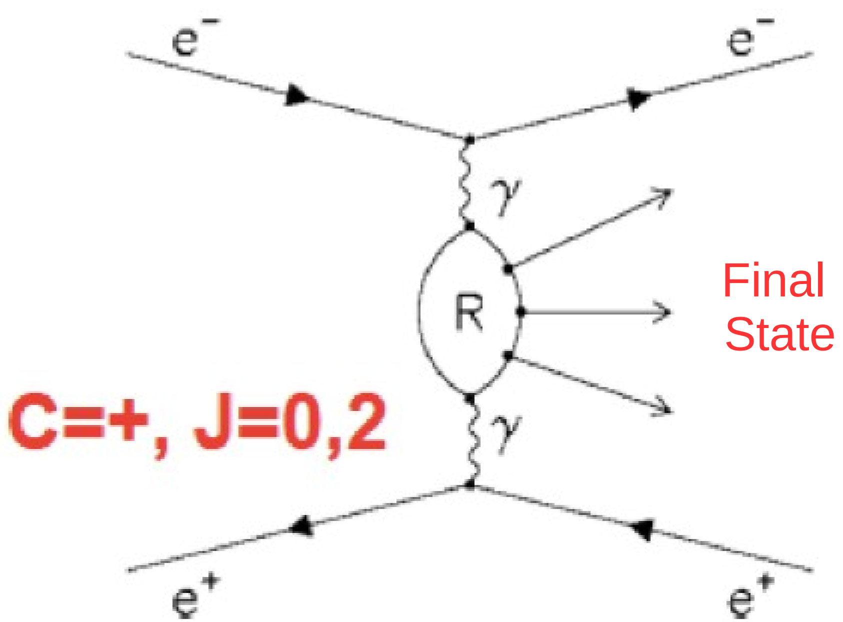
Consistency!

Search for new resonances via $\gamma\gamma$ interactions

$X(4140)\rightarrow J/\psi\phi$

$X(3915)\rightarrow J/\psi\omega$

2-photon interactions



- 2-photon interactions:
  e^+e^- interact and emit a quasi-real photon, which can form resonances.
- Clear signature: $J=0^{\pm},2^{\pm}$, ... ;
  the resonant state (if any) cannot be vector
- In BABAR resonant states are observed in 2-photon interactions: X(3915), ...
- Low p_t with respect to the beam axis
- Final state emitted along the beam direction

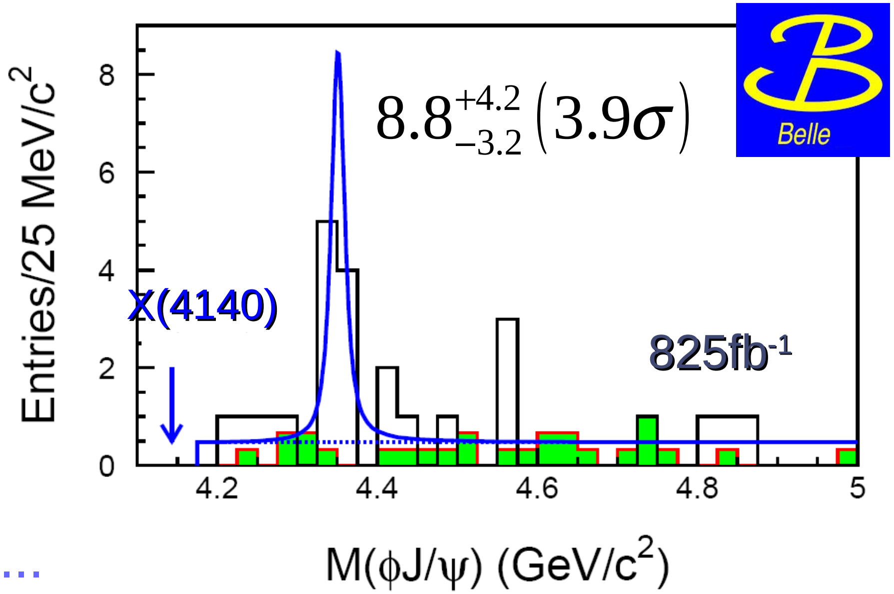
Search for exotic states in $J/\psi\phi$ via $\gamma\gamma$

PRL 104, 112004 (2010)

$e^+e^- \to J/\psi\phi$

$$M = 4350.6^{+4.6}_{-5.1} \pm 0.7\,MeV$$
$$\Gamma = 13.3^{+17.9}_{-9.1} \pm 4.1\,MeV$$

$$\Gamma_{\gamma\gamma} Br(Y(4350) \to J/\varphi\psi) = \begin{cases} 6.4^{+3.1}_{-2.3} \pm 1.1\,eV \text{ for } J^P = 0^+ \\ 1.5^{+0.7}_{-0.5} \pm 0.3\,eV \text{ for } J^P = 2^+ \end{cases}$$



No evidence for Y(4140) and/or Y(4270)!

...indeed hint of a new resonant state is found...

- X(4140) and X(4270), after 5 years of discussions and search in several modes, are not observed in any other decay mode, except m($J/\psi\phi$) in B^+, with $J/\psi \to \mu^+\mu^-$ only
- Not all experiments confirm their observation, neither evidence in some cases. Are they real resonances?

Remarks on X(4140)

- No evidence in BABAR and BELLE, in B decays, with $J/\psi \to e^+e^-$ and $\mu^+\mu^-$
- BABAR data reweighted by efficiency: $<2\sigma$ within systematic effects, on 468 M $B\bar{B}$
- BABAR and BELLE consistent in UL to the presence of a new Y state in $m(J/\psi\phi)$
- THE BABAR UL is consistent with what was published from other experiments.
- BABAR and BELLE show the same efficiency behaviour at threshold of $m(J/\psi\phi)$: poorer ϕ reconstruction
- BELLE showed that in $J/\psi\phi$ invariant mass (via $\gamma\gamma$) no resonant state compatible with Y(4140): if any, then we cannot exclude any J^{PC} hypothesis
- No experiment showed additional decay mode for Y(4140).

So:

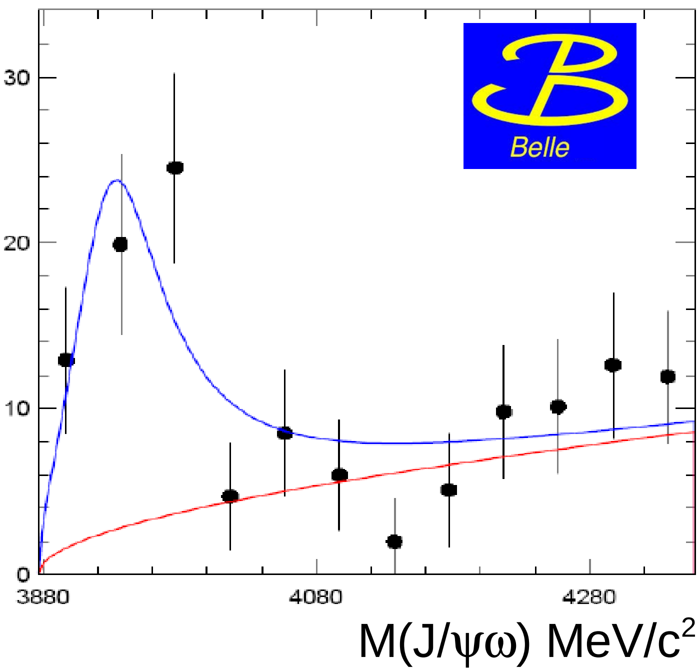
- All experiments agree that the inv. mass system $J/\psi\phi$ cannot be simply described by PHSP
- 2 vectors can be polarized: need full Dalitz analysis and higher statistics
- "*Enhancements*" does not mean only new resonant state!
  If real resonance, would expect to be seen in different decay modes
- B^+: controversial interpretation of $m(J/\psi\phi)$;
- B^0: no evidence of Y(4140) and Y(4270) in BABAR and LHCb (x20 statistics)

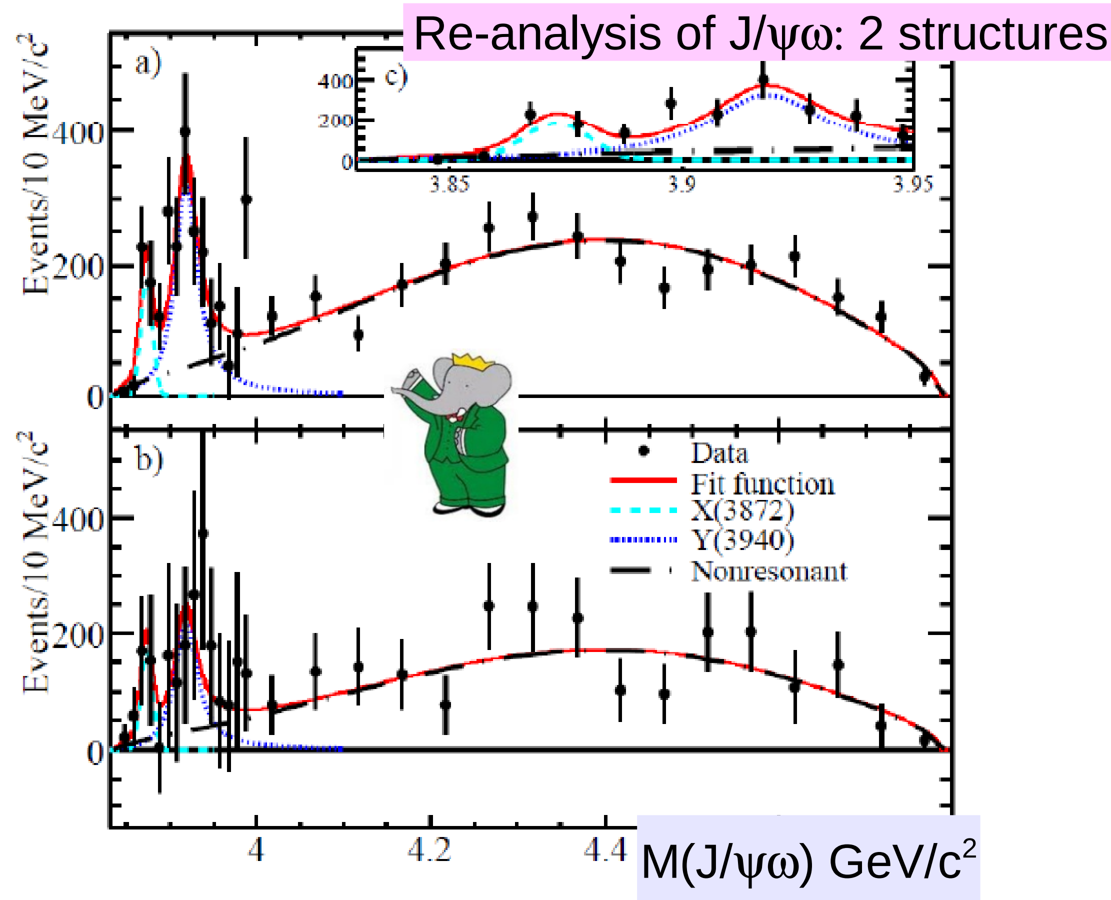
From X $\rightarrow$ J/ψϕ...

...to X $\rightarrow$J/ψω

Invariant mass of J/ψω (B decays)

- Analysis: $B^+ \to J/\psi \omega K^+$
  $\omega \to \pi\pi\pi^0$
- First observation of **Y(3940)** [X(3915)]





PRL 94, 182002 (2005)

PRL 101, 082001 (2008)
PRD 82, 011101 (2010)

	Mass (MeV)	Γ (MeV)
Belle 253 fb^{-1}	$3943 \pm 11(stat) \pm 13(syst)$	$87 \pm 22(stat) \pm 26(syst)$
BaBar 350 fb^{-1}	$3914.6^{+3.8}_{-3.4} \pm 2.0$	$34^{+12}_{-8} \pm 5$

What is X(3915)?

- Several analyses show enhancements at a mass value compatible with X(3915):
  – B decays (BABAR and BELLE in agreement, mostly)
  – double-charmonium, $e^+e^- \rightarrow J/\psi D^*\bar{D}$ (PRL 98, 082001 (2007), BELLE)
  – $\gamma\gamma$ interactions: $e^+e^- \rightarrow D\bar{D}$ (PRL 96, 082003 (2006) BELLE; PRD 81, 092003 BABAR)

⇩

Consequence: X(3915), Y(3940), X(3940), Z(3930) observed. Are they the same state?

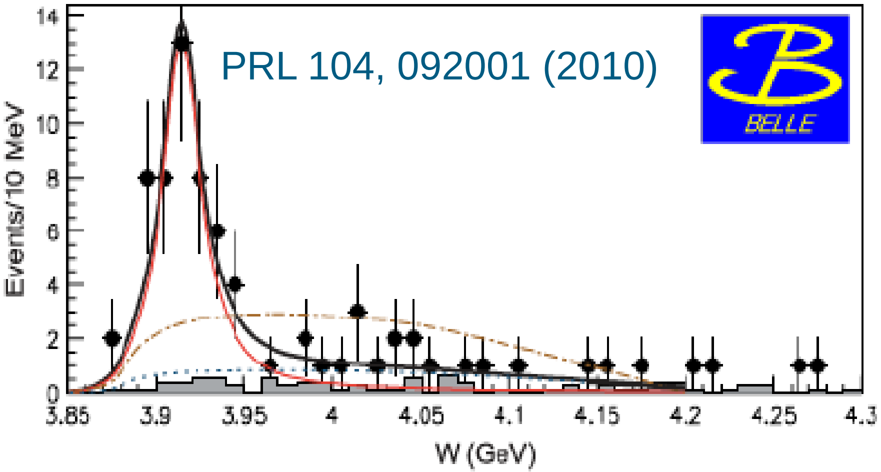
Unlikely....

⇩

- The analysis via $\gamma\gamma$ interaction is performed to gain more information on the invariant mass system of $J/\psi\omega$.
  – **Z(3930)** to $D\bar{D}$, via $\gamma\gamma$: angular distribution analysis supports J=2 ⇨ $\boldsymbol{\chi_{c2}}$**(2P)**?
  – **X(3940)**: possible interpretation as $\boldsymbol{\eta_c}$**(3S)**; χ_{c0}(2P) cannot decay to $D^*\bar{D}$
  – **X(3915)** → $J/\psi\omega$: analysis via $\gamma\gamma$ needed to establish J^{PC}: if J=0, could it be $\boldsymbol{\chi_{c0}}$**(2P)**?

Invariant mass system of $J/\psi\omega$ (via $\gamma\gamma$)

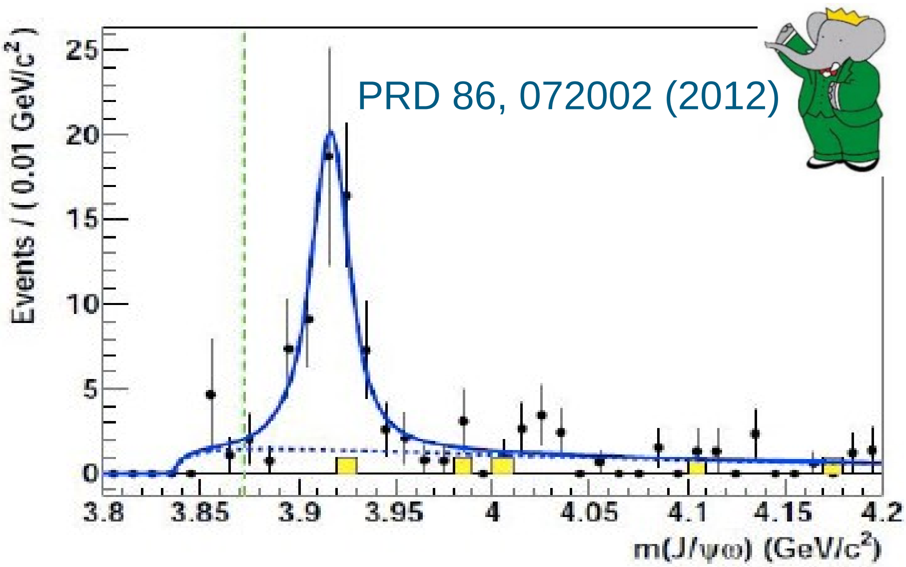
$$M = 3915 \pm 3 \pm 2 \text{ MeV}/c^2$$
$$\Gamma = 17 \pm 10 \pm 3 \text{ MeV}$$
$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 61 \pm 17 \pm 8 \text{ eV} \quad (J=0)$$
$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 18 \pm 5 \pm 2 \text{ eV} \quad (J=2)$$



CONSISTENCY!

- Confirmation from BABAR:

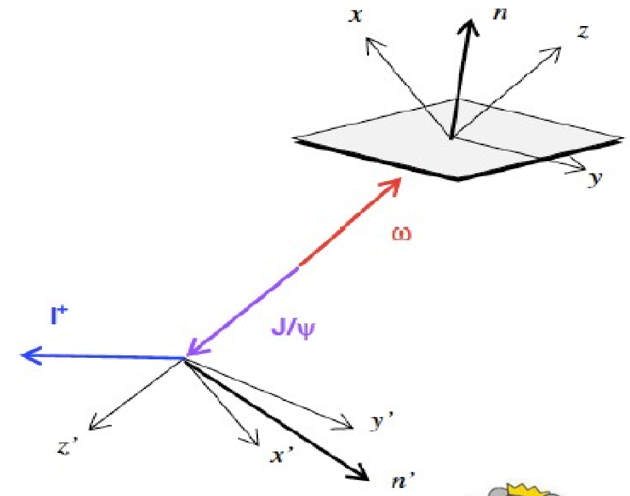
$$M = 3919.4 \pm 2.2 \pm 1.6 \text{ MeV}/c^2$$
$$\Gamma = 13 \pm 6 \pm 3 \text{ MeV}$$
$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 52 \pm 10 \pm 3 \text{ eV} \quad (J=0)$$
$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 10.5 \pm 1.9 \pm 0.6 \text{ eV} \quad (J=2)$$



- If $\Gamma_{\gamma\gamma} = \mathcal{O}(1 \text{ keV})$ (typical $c\bar{c}$), then $\mathcal{B}(J/\psi\omega) > (1-6)\%$

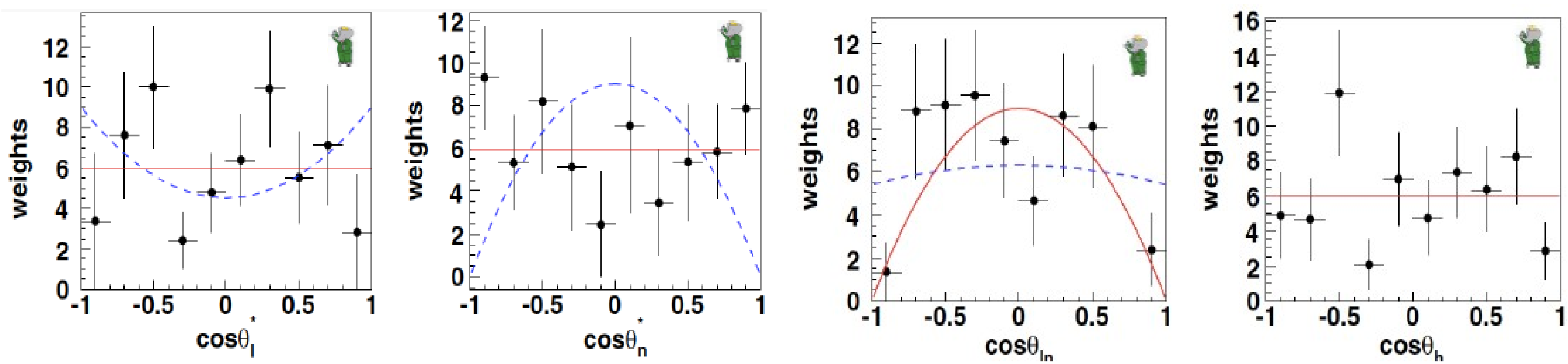
$J/\psi\omega$ angular analysis (via $\gamma\gamma$)

- Theoretical input: PRD 70, 094023 (2004), J.L. Rosner



- Events have low p_t ⇨ γγ collision axis along beam axis
- Angles are defined in 3 different c.m. frames: J/ψω, J/ψ, and ω.
- The normal to the ω decay plane defines the axis orientation
- No background subtraction: all events in 3890< M(J/ψω)<3950 MeV/c^2 come from X(3915) decay

PRD, 072002 (2012)

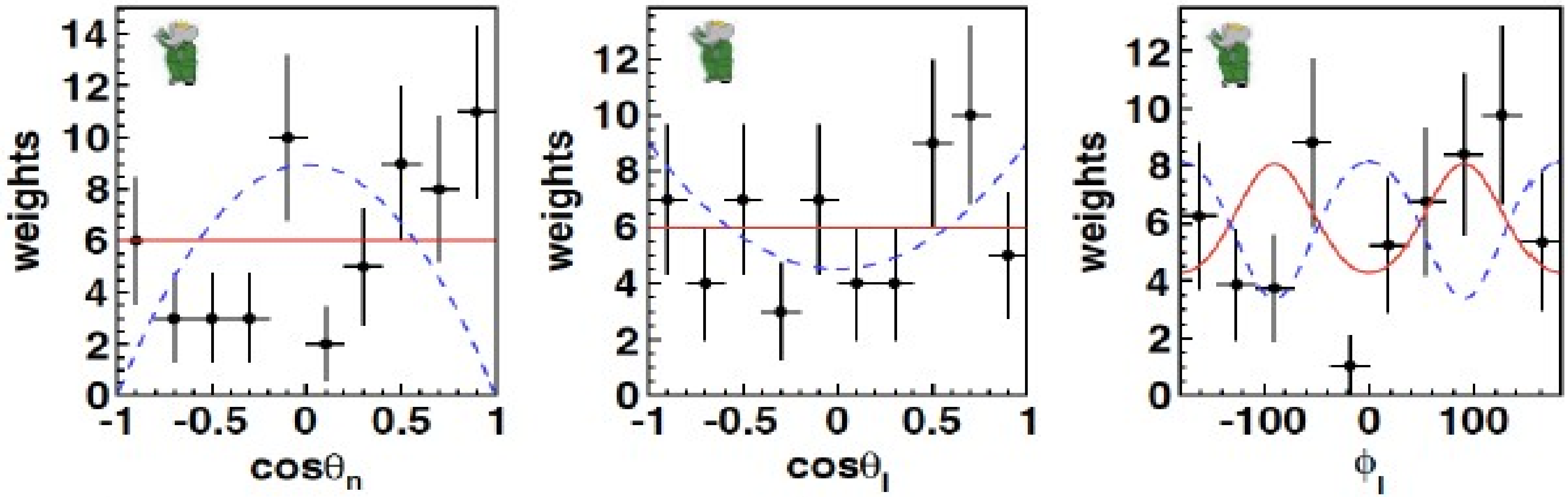


(efficiency corrected distributions)

- Result: **J = 0** strongly preferred over J = 2

X(3915): 0^+ or 0^-?

PRD, 072002 (2012)



Angle	$J^P = 0^-$	$J^P = 0^+$
θ_n	$\sin^2\theta_n$	1
χ^2	77.6	16.3
θ_l	$1 + \cos^2\theta_l$	1
χ^2	8.7	8.3
ϕ_l	$2 - \cos(2\cos\phi_l)$	$2 + \cos(2\cos\phi_l)$
χ^2	21.7	9.6

0^+ favored over 0^-

Strong implication:

$\chi_{c0}(2P)$ **candidate?**

Remarks on X(3915)

- Y(3940) [X(3915)] was observed from BABAR and BELLE in $B \to J/\psi\omega K$
- X(3940) was observed from BELLE in the recoil of J/ψ (double charmonium)
- X(3915) was observed from BABAR and BELLE in $\gamma\gamma$ interactions

NO DOUBT: X(3915) EXISTS!

⇩

X(3915) cannot have J = 1 (seen in $\gamma\gamma$ interactions)

- Angular analysis in BABAR: $J = 0^+$ ⇨ in favor of $\chi_{c0}(2P)$ interpretation

Is this the only possible interpretation?

- Argument against $X(3915) = \chi_{c0}(2P)$:
- in the potential model: unlikely to explain $\chi_{c0}(2P)$ = X(3915) and $\chi_{c2}(2P)$=Z(3930).
- M(Z(3930)) = 3927.2 ± 2.6 MeV/c^2. PRL 96, 082003 (2006) BELLE; PRD 81, 092003 BABAR
  In this picture, the mass difference between $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ is ~10 MeV/c^2 only, for an excitation from J=0 to J=2.
- For comparison, $\chi_{cJ}(1P)$ mass difference is ~142 MeV/c^2...

Summary

- Study of B decays: $B^{\pm,0} \to J/\psi KKK^{\pm,0}$ (charged and neutral B) for the first time: observation
  - – K^+K^- inv mass restricted to ϕ meson in [1.004;1.034] GeV/c^2:
  - – $J/\psi K$ and KKK systems PHSP distributed; $J/\psi\phi$ system shows a non-PHSP behaviour
- Search for X(4140) and X(4270) in $J/\psi\phi$ inv mass system: no evidence (BABAR and BELLE)
- Interpretation of $J/\psi\phi$ inv mass system is difficult, because:
  - – dynamics of J/ψ and ϕ (vectors) interaction is complicated: full Dalitz analysis needed;
  - – different hypotheses for explaining the presence of a non-PHSP behavior at the threshold
  - – BABAR results consistent with other experiments within uncertainties.

- Non resonant K^+K^- contribution to the BF of $B \to J/\psi KKK$: first measurement

- Information on X(3915) from different analyses:
  - – B decay (BABAR and BELLE)
  - – double charmonium (BELLE; BABAR coming soon)
  - – $\gamma\gamma$ interactions (BABAR and BELLE)

- BABAR and BELLE have plenty of results in search for exotic charmonium states:
  time to combine results and understand what we reached

Thank you for your attention!

Back up slides

Summary of Charmonium states at the B factories

Z(3930) → $\chi_{c2}(2P, 3927)$

State	J^{PC}	Process
$\eta_c(2S, 3639)$	0^{-+}	$B \to K(K_S K \pi)$
$\psi(3820)$	2^{--}	$B \to \chi_{c1}\gamma K$
$X(3872)$	$1^{++}/2^{-+}$	$B \to K(J/\psi \pi^+\pi^-)$
$G(3900)$	1^{--}	$e^+e^- \to \gamma(D\bar{D})$
$X(3915)$	$0/2^{?+}$	$B \to K(J/\psi \omega)$
$\chi_{c2}(2P, 3927)$	2^{++}	$\gamma\gamma \to D\bar{D}$
$X(3940)$	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Y(4008)$	1^{--}	$e^+e^- \to \gamma(J/\psi \pi^+\pi^-)$
$Z_1(4050)^+$	?	$B \to K(\chi_{c1}(1P)\pi^+)$

State	J^{PC}	Process
$X(4160)$	$?^{?+}$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$
$Z_2(4250)^+$	?	$B \to K(\chi_{c1}(1P)\pi^+)$
$Y(4260)$	1^{--}	$e^+e^- \to \gamma(J/\psi \pi^+\pi^-)$
$X(4350)$	$0/2^{++}$	$\gamma\gamma \to J/\psi\phi$
$Y(4360)$	1^{--}	$e^+e^- \to \gamma(\psi(2S)\pi^+\pi^-)$
$Z(4430)^+$	?	$B \to K(\psi(2S)\pi^+)$
$Y(4630)$	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	1^{--}	$e^+e^- \to \gamma(\psi(2S)\pi^+\pi^-)$