XYZ Overview—Vector-Vector final states

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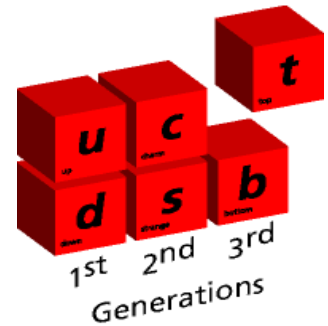
5th workshop on XYZ particles, 19-23 Oct, 2018, Zhengzhou, China

Outline

- *Introduction*
- *The first structure(s) in $J/\psi\phi$ mass spectrum at CDF*
- *The $J/\psi\phi$ structure(s) from other experiments*
- *Other final states*
- *Summary*

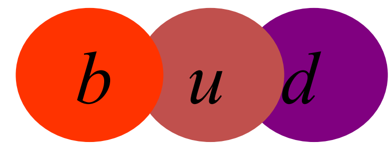
Quark model

- *The birth of quark model (M. Gell-Mann & G. Zweig):*
  M. Gell-Mann, Phys. Lett. 8, 214 (1964)



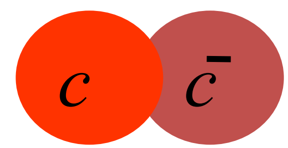
- *Heavy top decays before forming bound states*
  light quarks exist as bound states

  – *Baryons:* (qqq)



  – *Mesons:* $(q\bar{q})$

  quarkonia: $(s\bar{s})$, $(c\bar{c})$ $(b\bar{b})$



- *J/ψ turned the quark model into reality*

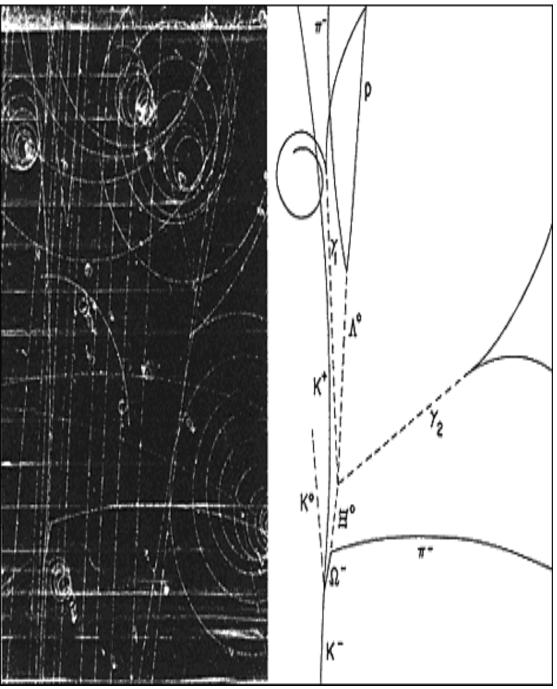
- *Gell-Mann also suggested exotic states* $(qq\bar{q}\bar{q})$, $(\bar{q}qqqq)$ *at the birth of quark model, but evidence has never been solidly established*

Revitalized by the discovered charmonium-like states, i.e., X(3872)
despite a decade, still mysterious!

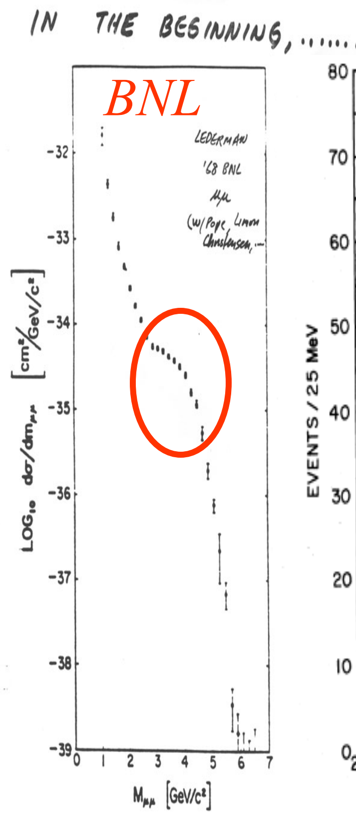
History—from strange to bottom discovery

Ω⁻ discovery *J/ψ ($\bar{c}c$) discovery* *ϒ ($\bar{b}b$) discovery*

BNL

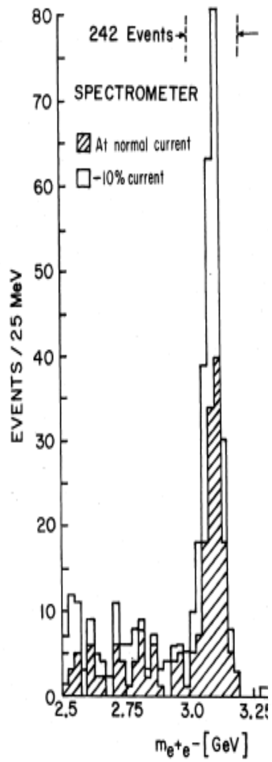


1964



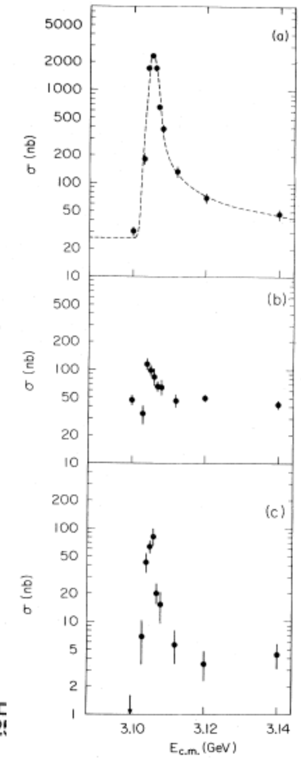
1968

BNL



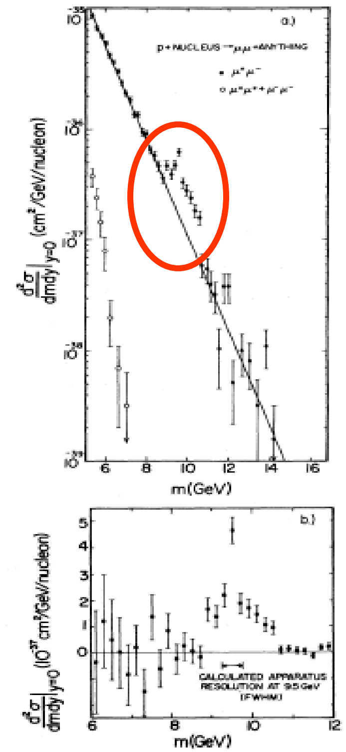
1974

SLAC



1974

FNAL

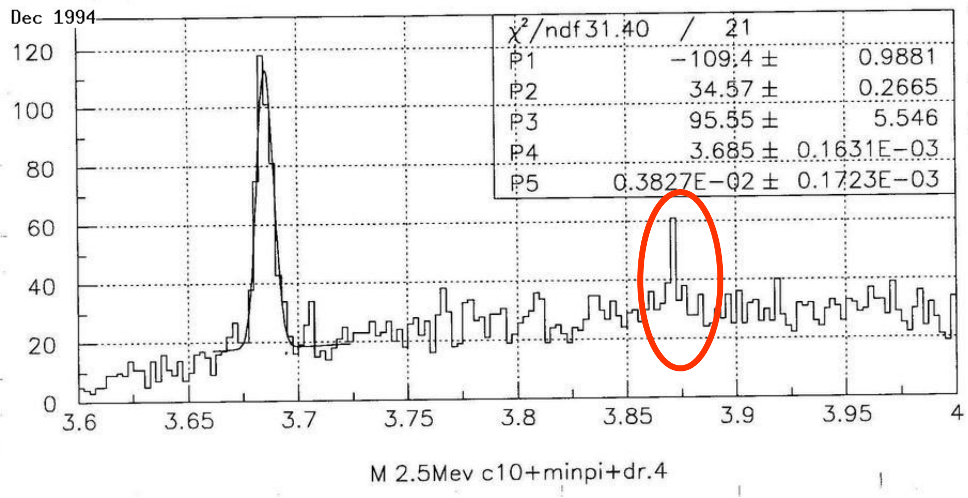


1977

Heavy flavor spectroscopy helped turn quarks into a reality!

Hints before the discovery of $X(3872) \to J/\psi\pi^+\pi^-$

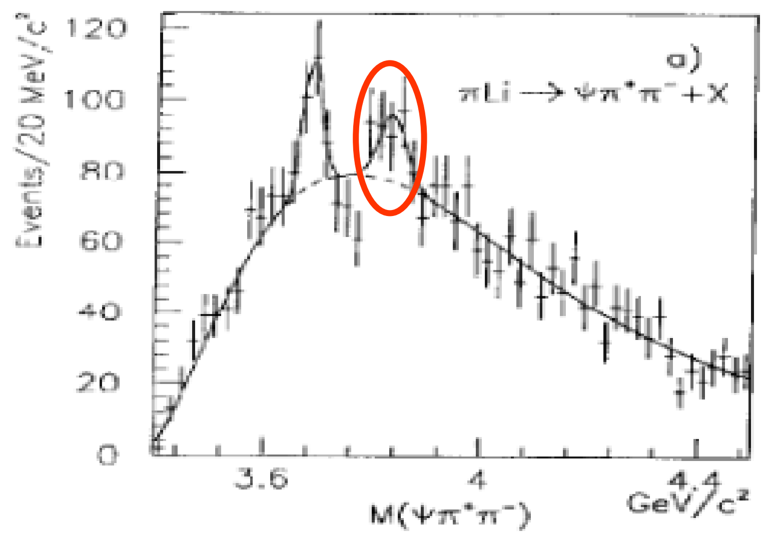
CDF internal, 1994



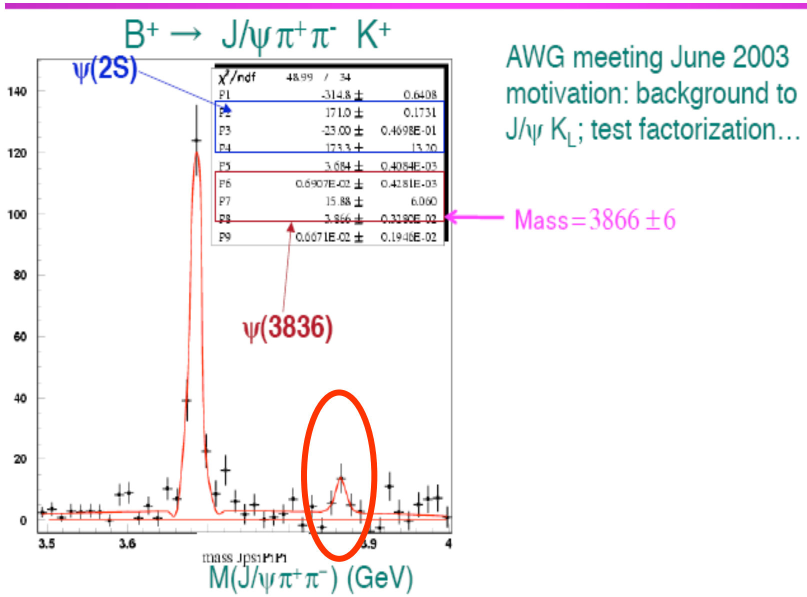
E705, PRD 50, 4258 (1994)

E705 saw $\psi(3836)$ (2^{--}) in 1994, 3.836 ± 0.013 GeV

PRL 115 011803, PRL 111 032001



BaBar internal, 2003



AWG meeting June 2003
motivation: background to J/ψ K_L; test factorization…

From BaBar B-Factory Symposium (C. Hearty)

http://www-conf.slac.stanford.edu/b-factory-symposium/talks.asp

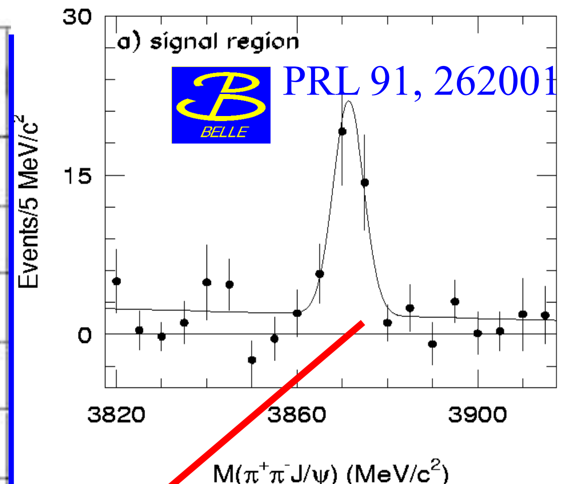
CDF saw a hint in 1994, unpublished

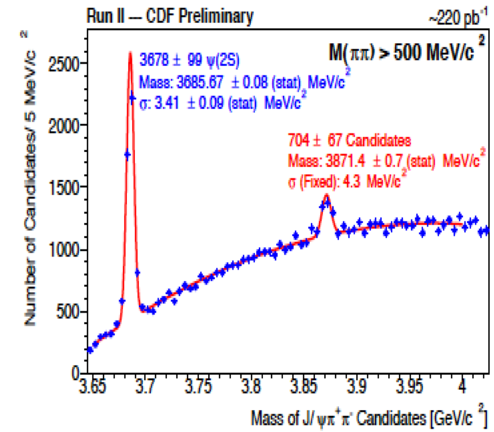
BaBar saw a hint in 2003, unpublished

Both CDF and Babar spotted hints of X(3872) before its discovery!

X(3872) (Belle)--2003

$N\,^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I=1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I=0$	$C\bar{C}$ $c\bar{c}$ $I=0$
$1\,^1S_0$	0^{-+}	π	η, η'	$\eta_c(1S)$
$1\,^3S_1$	1^{--}	ρ	ω, ϕ	$J/\psi(1S)$
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$h_1(1170)$, $h_1(1380)$	$h_c(1P)$
$1\,^3P_0$	0^{++}	$a_0(1450)^*$	$f_0(1370)^*$, $f_0(1710)^*$	$\chi_{c0}(1P)$
$1\,^3P_1$	1^{++}	$a_1(1260)$	$f_1(1285)$, $f_1(1420)$	$\chi_{c1}(1P)$
$1\,^3P_2$	2^{++}	$a_2(1320)$	$f_2(1270)$, $f_2'(1525)$	$\chi_{c2}(1P)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$\eta_2(1645)$, $\eta_2(1870)$	
$1\,^3D_1$	1^{--}	$\rho(1700)$	$\omega(1650)$	$\psi(3770)$
$1\,^3D_2$	2^{--}			??
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$\omega_3(1670)$, $\phi_3(1850)$	
$1\,^3F_4$	4^{++}	$a_4(2040)$	$f_4(2050)$, $f_4(2220)$	
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$\eta(1295)$, $\eta(1440)$	$\eta_c(2S)$
$2\,^3S_1$	1^{--}	$\rho(1450)$	$\omega(1420)$, $\phi(1680)$	$\psi(2S)$
$2\,^3P_2$	2^{++}	$a_2(1700)$	$f_2(1950)$, $f_2(2010)$	
$3\,^1S_0$	0^{-+}	$\pi(1800)$	$\eta(1760)$	





mass ~70 MeV > 1^3D_2 charmonium, $J^{PC} = 1^{++}$ or 2^{-+}

$M(\pi^+\pi^-)$ peaks as a ρ, C=+, isospin=1 (charmonium--0)

Decays to $J/\psi\gamma$ & $\psi'\gamma$, suppressed for 2^{-+}

Mass close to DD, molecule etc are speculated…*

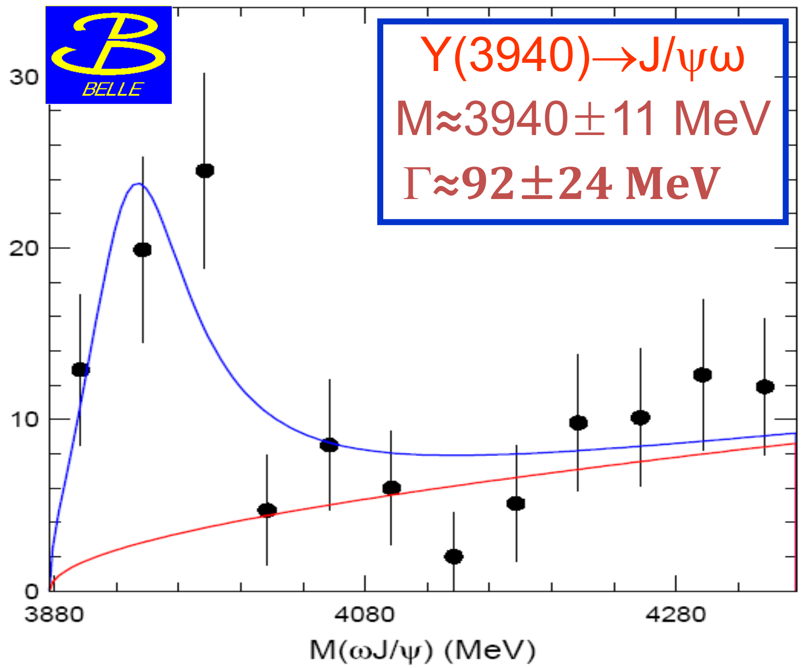
2017 Laureates

"…The X(3872) was discovered by Dr. Sookyung Choi and Dr. Stephen Olsen with their colleagues in the Belle experiment among the final states of the decay of B mesons. The X(3872) was confirmed by seven other experimental groups thereafter and is the first example of a new type of XYZ meson and the most well-established state among them. …"

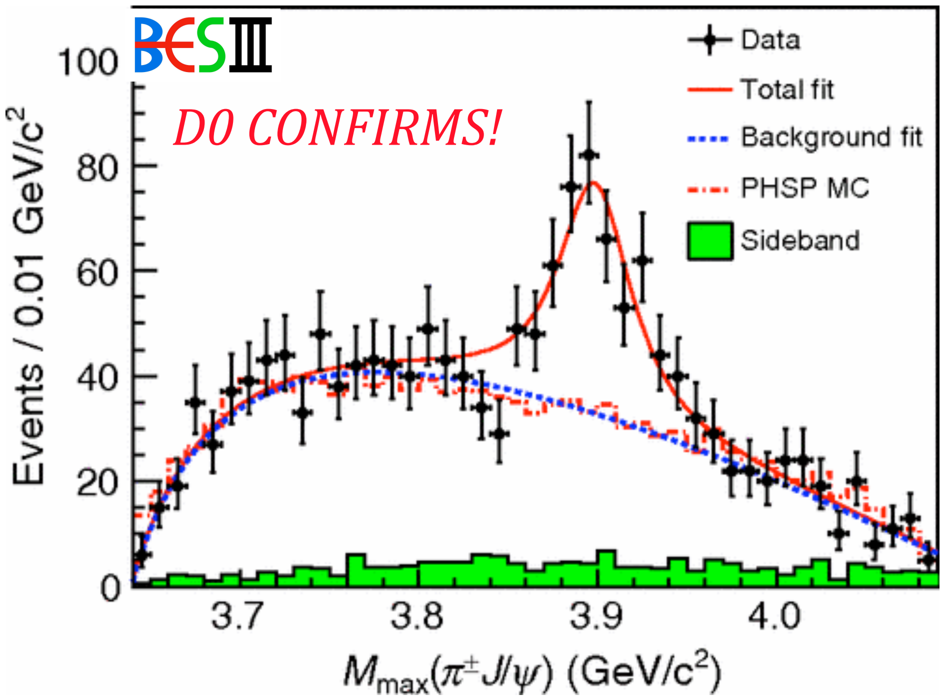
2017 Korean Ho-Am Science Prize

$Y(3940)\to J/\psi\omega$, $Z_c^+(3900)\to J\psi\pi^+$

PRL 94, 182002 (2005)



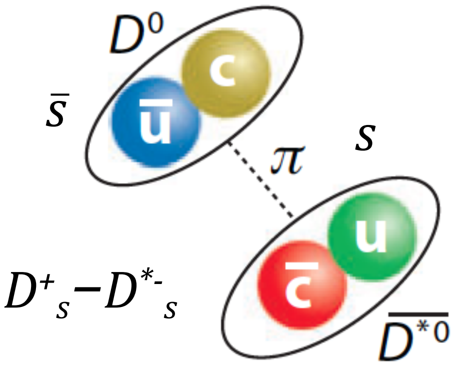
PRL 110, 252001 (2015)



Above $\overline{D}D$ & $D\overline{D}^*$ threshold,
Tiny branching fraction expected
mass and width from BaBar:
$M\approx 3919.1^{+3.8}_{-3.4}\pm2.0$, $\Gamma\approx 31^{+10}_{-8}\pm5$ MeV
arXiv:1012.0074 [hep-ex]
at the $J/\psi\omega$ threshold ***?***

It is Charged! from Y(4260)
No charge for normal charmonium
Immediately confirmed by BELLE
J^{PC}=? In the same time, $Z^+(4430)$
(Found in 2006) is confirmed by LHCb

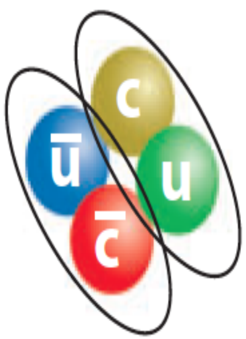
Exotic models-I



D^0–$\overline{D}^{*0}$ "molecule"

Molecular

*Loosely bound state of a pair of mesons. The dominant binding mechanism should be **pion exchange**. Being weakly bound the mesons tend to decay as if they were free*



Diquark–diantiquark

Tetraquark

Bound state of four quarks, i.e. $\boldsymbol{qq\bar{q}\bar{q}}$ in which the quarks group into color triplet scalar or vector clusters

Strong decays proceed via rearrangement processes

Distinctive features of multi-quark picture with respect to charmonium:

- prediction of many new states

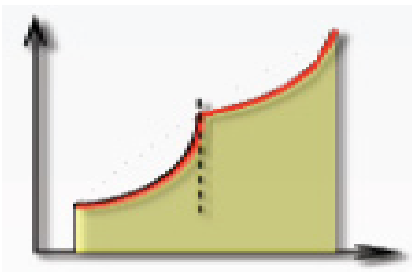
- possible existence of states with non-zero charge, strangeness, or both

Exotic models-II

Charmonium hybrids

States with excited gluonic degrees of freedom;
exotic $J^{PC}=0^{+-}$, 1^{-+}, 2^{+-}... not allowed for charmonium.
Smoking gun for exotic states.

Lattice QCD for 1^{-+}: $m \sim 4.3 \pm 0.05$ GeV (C. Thomas)



Threshold, cusp, or coupled-channel effect giving a cross section enhancement which may not correspond to resonance production at all

Hadro-charmonium

Light hadrons bounded by van der Waals force to a charmonium core in the case where the light hadron is a highly excited resonance.

We know something is going on even though we do not know exactly what!

New kind(s) of spectroscopy with complex binding forces?

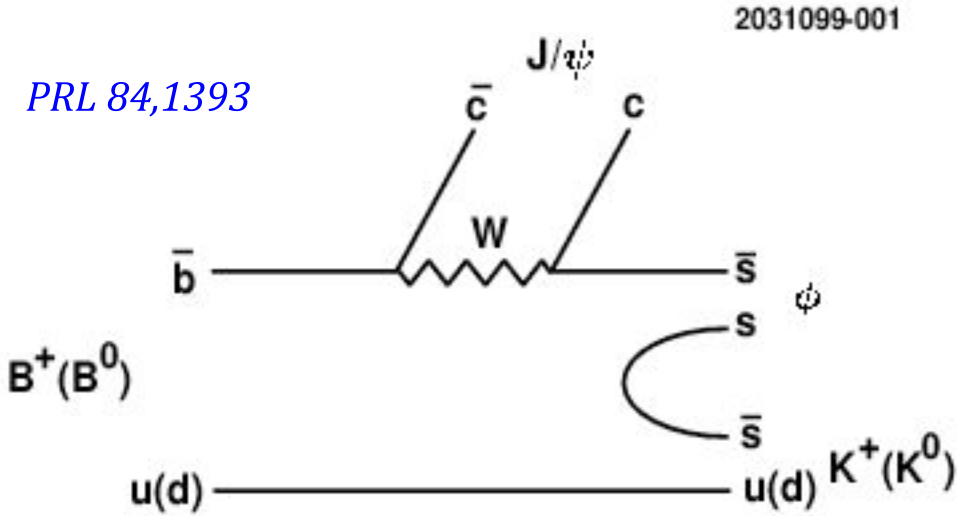
A good place to explore--J/ψϕ system:

no light quarks; (threshold @4.116 GeV, VV, C=+); (cc) with a mass above 4.116 GeV, expect tiny branching fraction to J/ψϕ.

Search structures in J/$\psi\phi$ through B decays

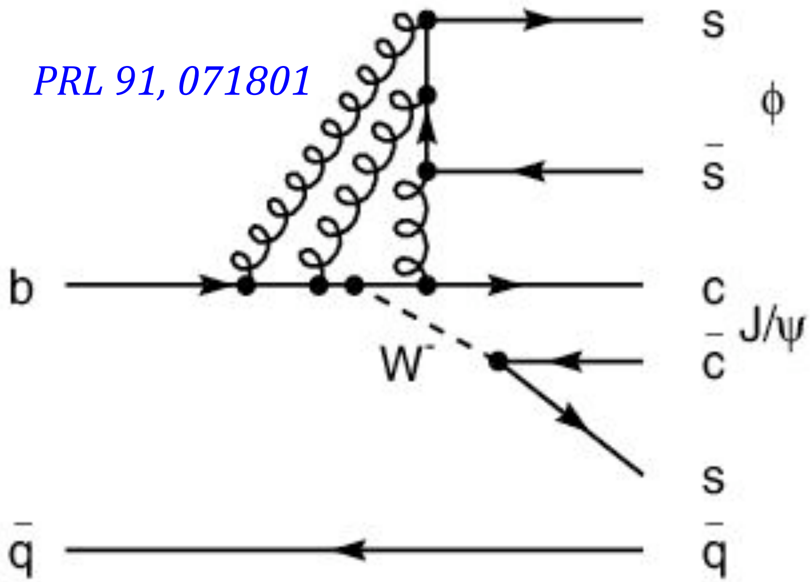
- *Experimentally attractive to search through the clean $B \to J/\psi\phi K$ channel*
  -- taking advantage of the B lifetime and narrow B mass window
  -- $B \to J/\psi\phi K$ is OZI suppressed, so low rate from phase space decays

PRL 84,1393



vacuum polarization

PRL 91, 071801

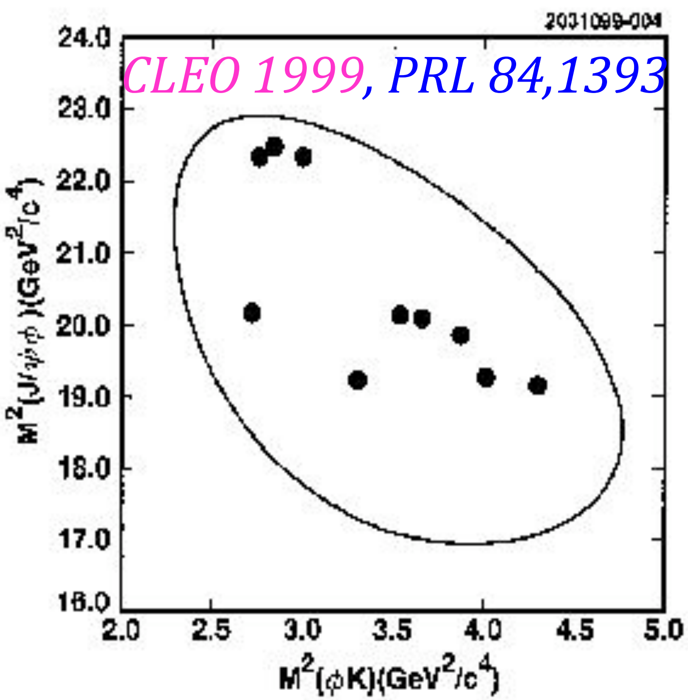


gluon coupling

The status before original CDF report

- *The **status** through $B \to J/\psi\phi K$:*

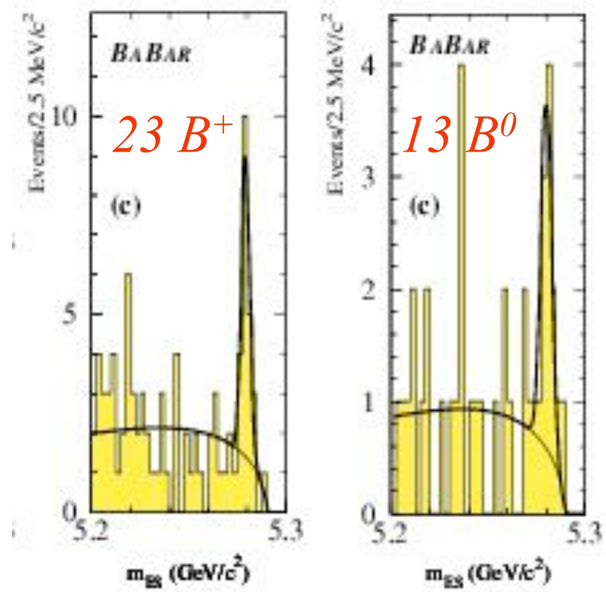
CLEO 1999, PRL 84,1393



$J/\psi \to \mu\mu$ and ee, 10 B^+ and B^0

BaBar 2003, PRL 91, 071801

23 B^+ *13 B^0*



$J/\psi \to \mu\mu$ and ee

- *statistically limited, no structures seen*

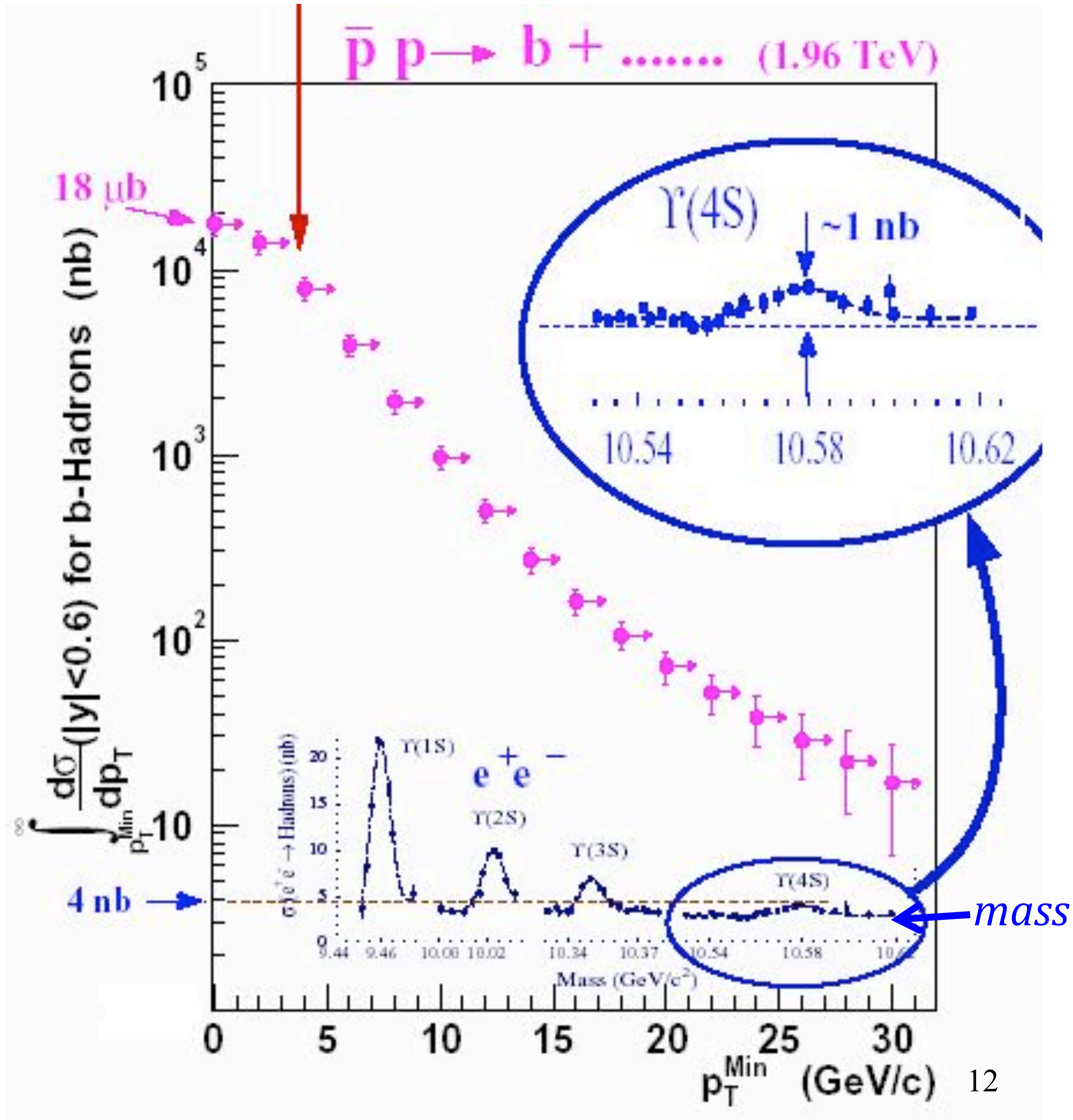
Why search at CDF and LHC?

B hadrons at Tevatron are:

- *copiously produced*
- *boosted*
  --vertex separation
  --boost low p_T daughters

CDF has:

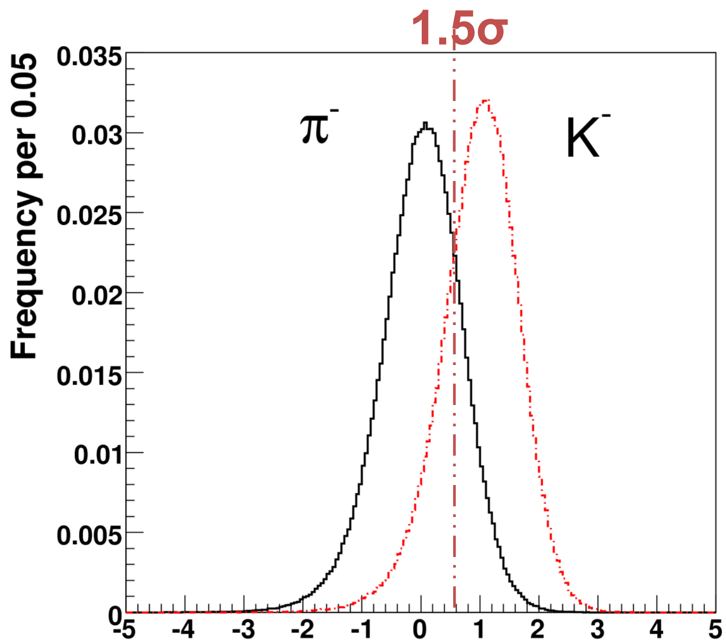
- *excellent mass resolution*
- *excellent vertex resolution*
- *reasonable hadron PID*



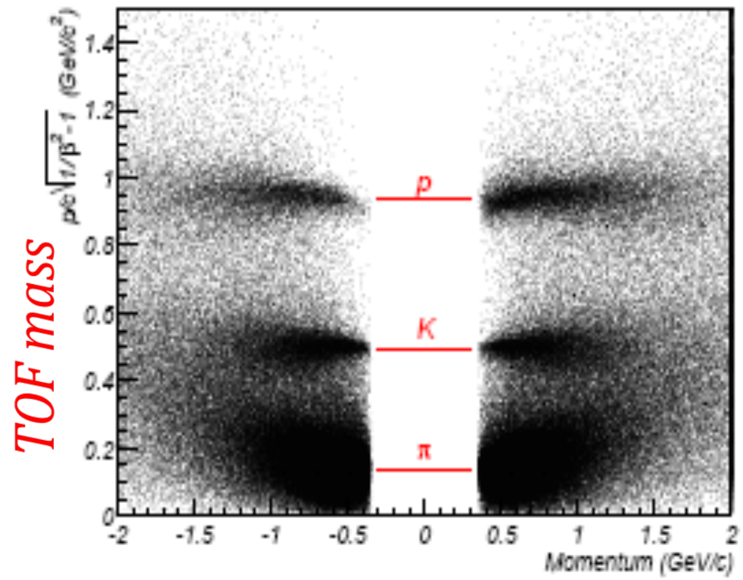
CDF hadron PID

Main background: prompt pions. Need PID to suppress

dE/dx residual



CDF Time-of-flight: Tevatron store 860-12/23/2001



dE/dx parameterized using$^{\kappa}$
$D^{*+(-)} \rightarrow D^0 \pi^{+(-)}$ sample

Excellent resolution

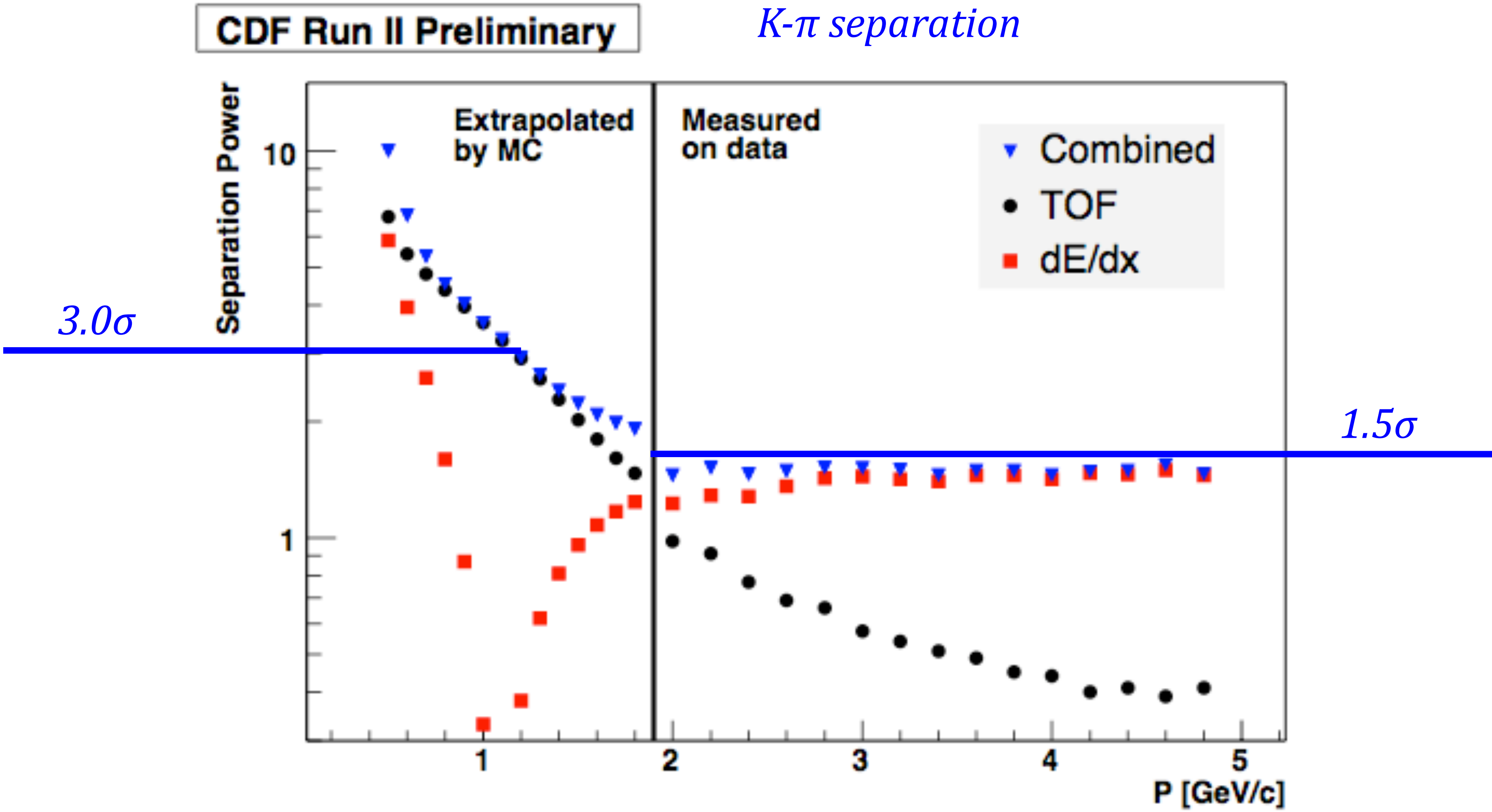
dE/dx efficiency ~100%

Time-of-Flight acceptance+efficiency ~60%

Make use of both dE/dx and ToF for hadron PID
summarizing dE/dx and ToF into a log-likelihood ratio

CDF hadron PID

K-π separation



Typical B decay daughter momentum ~GeV

CDF hadron PID

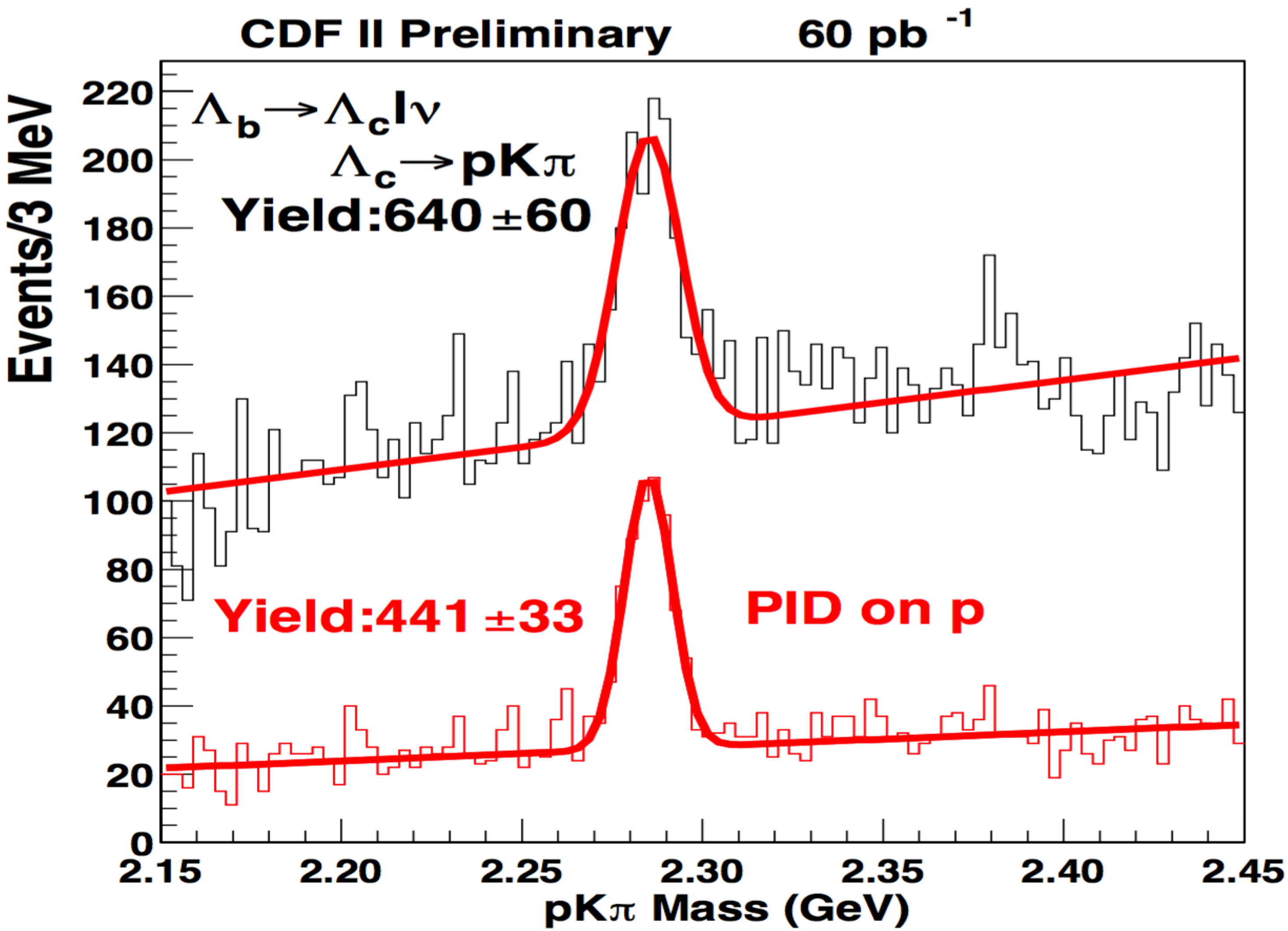


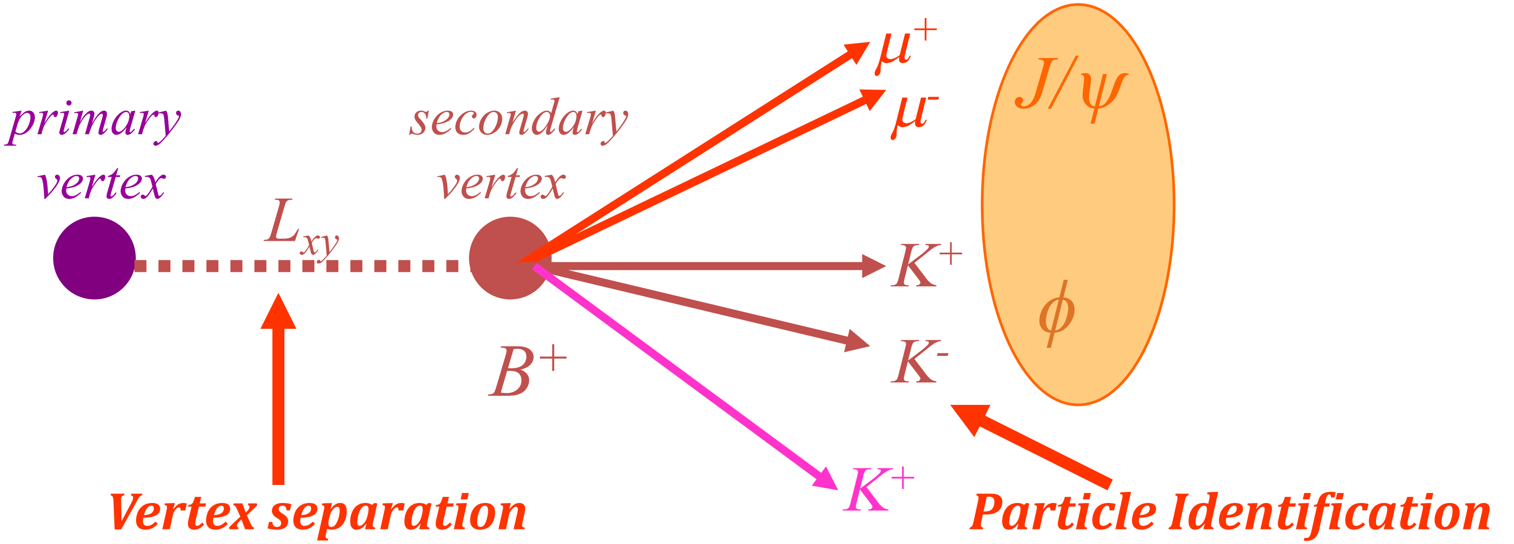
Figure 3.21: $pK\pi$ invariant mass from Λ_b without(top) proton identification and with(bottom) proton identification.

Analysis strategy

- *I) Reconstruct B^+ as:*

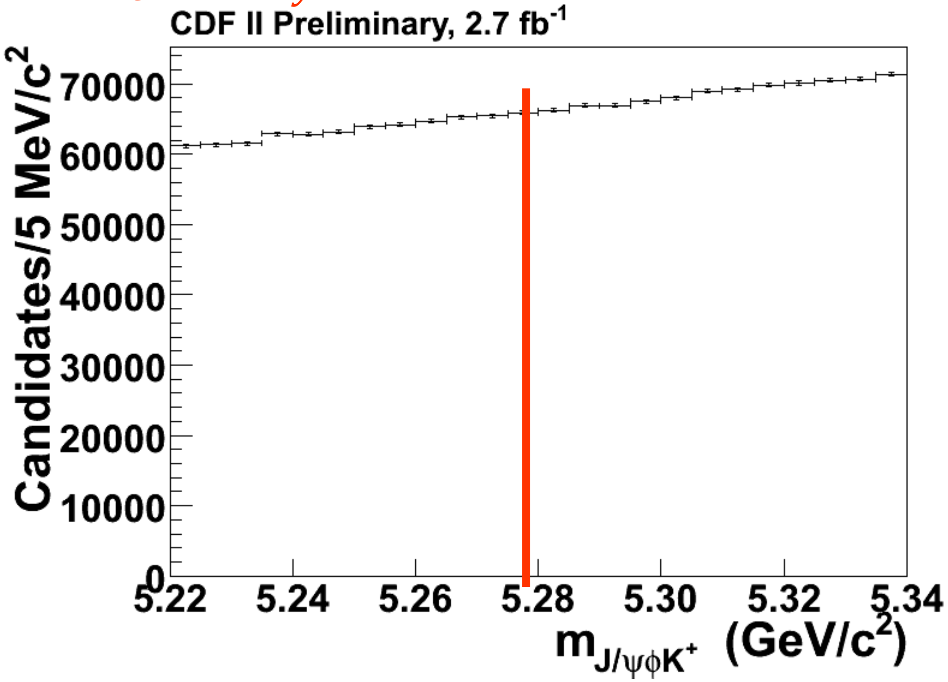
$$B^+ \to J/\psi\phi\, K^+$$
$$J/\psi \to \mu^+\mu^-$$
$$\phi \to K^+K^-$$

- *II) Search for structure in $J/\psi\phi$ mass spectrum inside B^+ mass window*

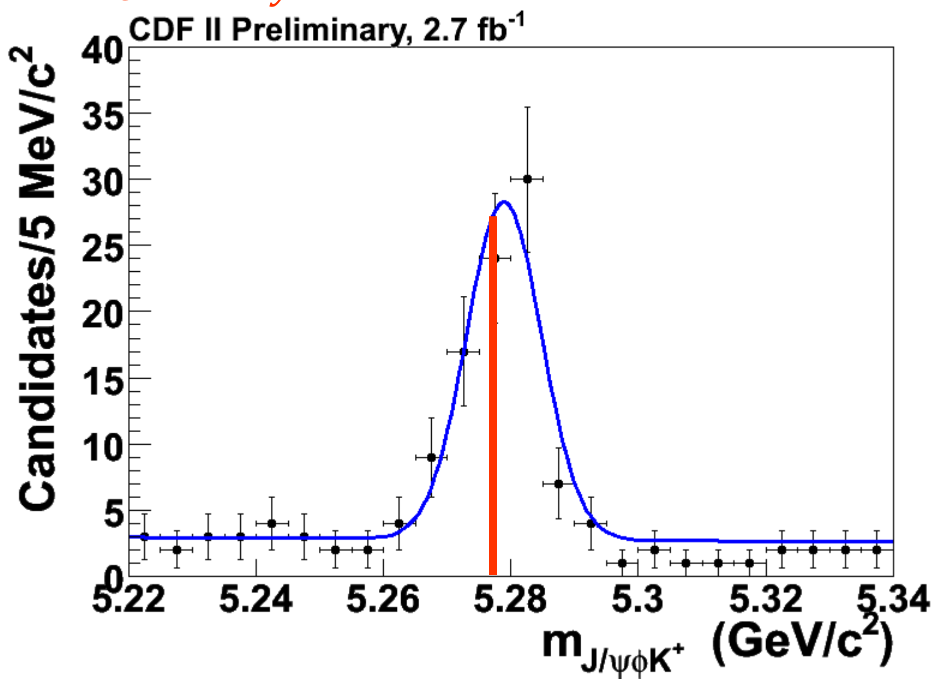


Background reduction factor

Before L_{xy}>500 μm, kaon LLR>0.2



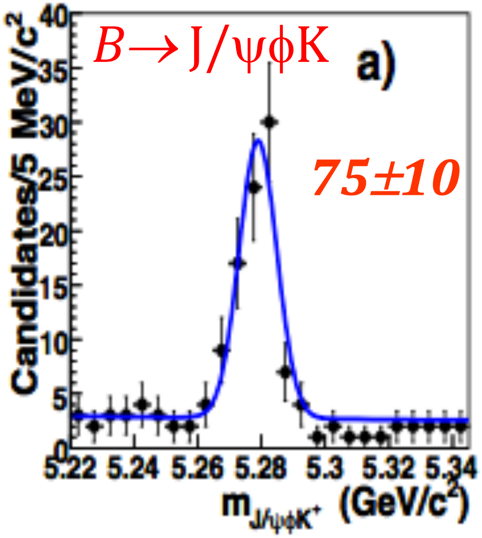
After L_{xy}>500 μm, kaon LLR>0.2

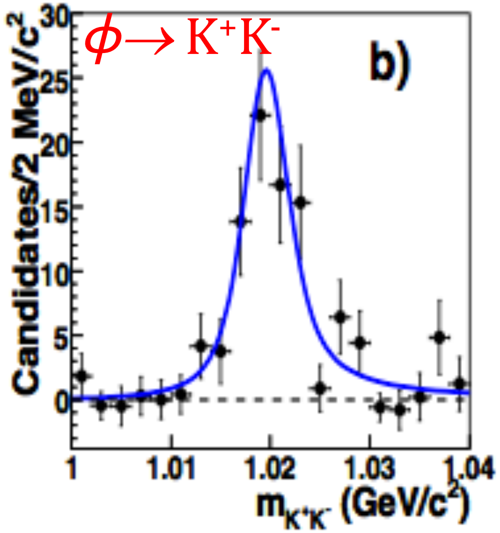


Reduce background by a factor of ***20 000*** *by using L_{xy} and kaon PID cuts while keeping about* ***20%*** *of signal as estimated by control channels.*

There is also a nice ϕ line-shape

First report by CDF w/ 2.7 fb^{-1} (2009)

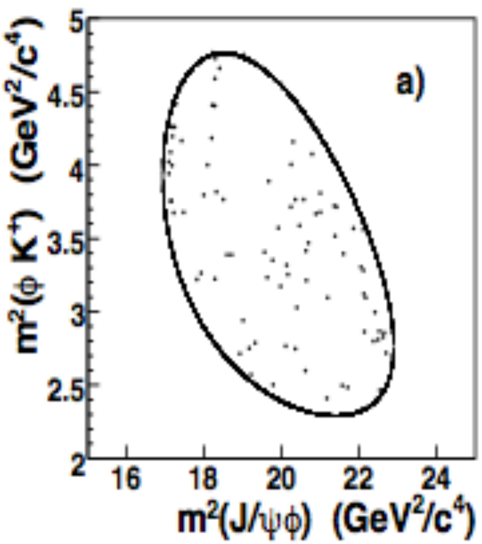


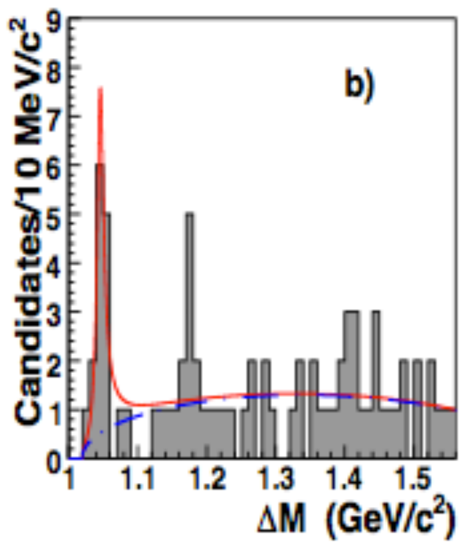


PRL 102:242002, 2009

Purity ~80% in B^+ region

Nice ϕ shape





Dalitz plot

$\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$

Near threshold peak, called Y(4140)

Significance: ~4σ

Yield =14±5

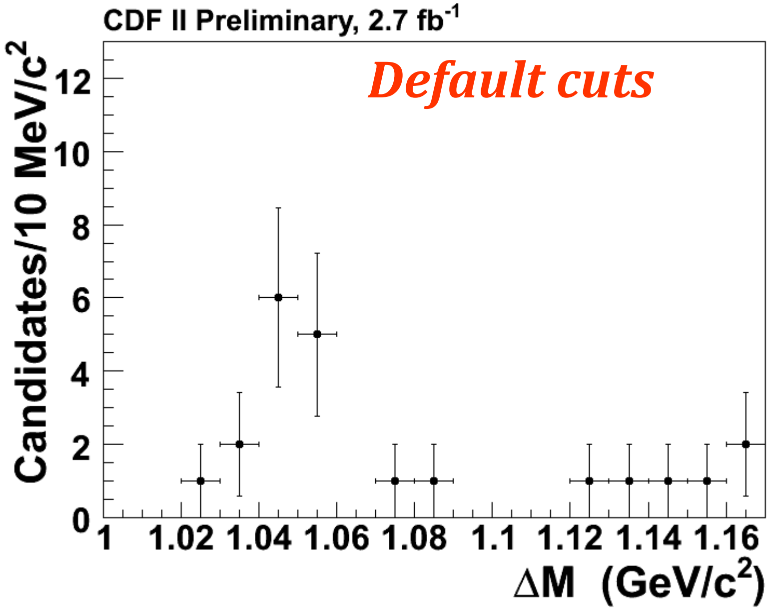
M= 4143.0 ± 2.9 (stat) ± 1.2 (syst) MeV

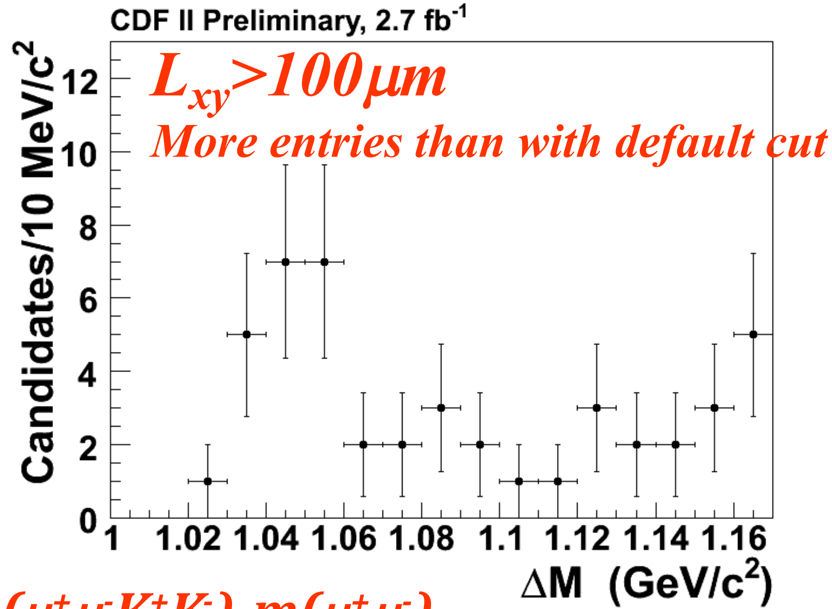
Γ = 11.7 $^{+8.3}_{-5.0}$ (stat) ± 3.7(syst) MeV

Not likely to be charmonium:

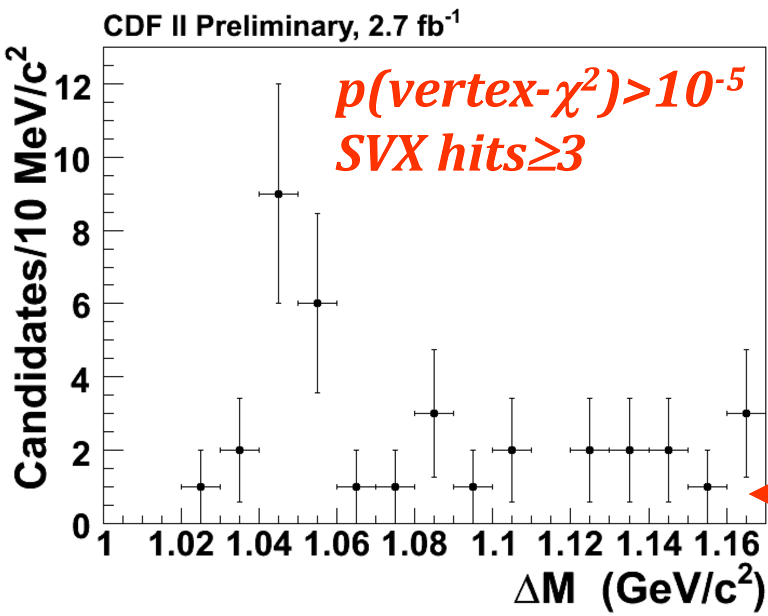
High mass w/ narrow width

Robustness test





$\Delta M = m(\mu^+\mu^- K^+K^-) - m(\mu^+\mu^-)$



- *Extensive cross checks by varying L_{xy}, kaon PID LLR, B^+ mass window, vertex probability, # of silicon hits,…*

  Robust against variations

  More signal but with more background

Reflection in three-body decays

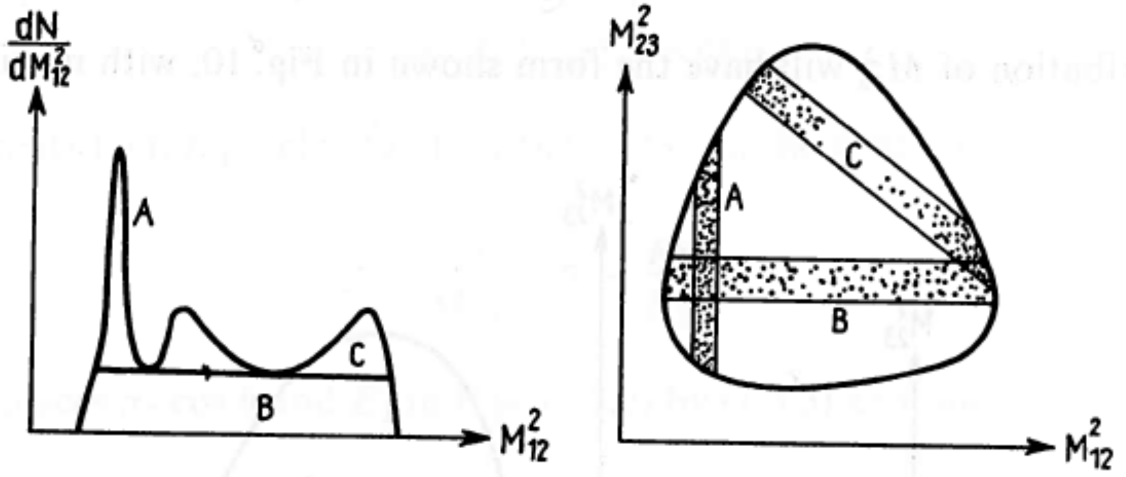


Fig. 11

Three resonances:

A ➔ M_{12}
B ➔ M_{23}
C ➔ M_{13}

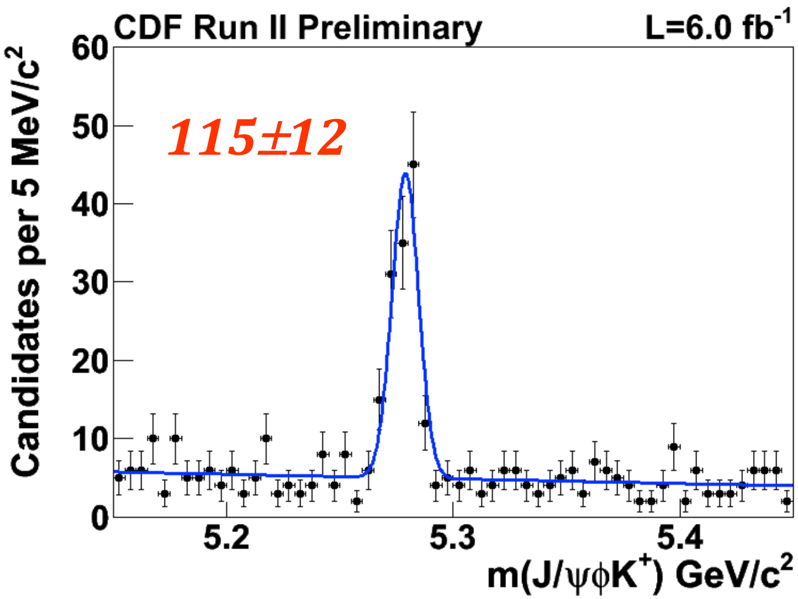
Examples: ρ^+, N^{*++}, N^{*+} in $\pi^+ + p \rightarrow \pi^+ + \pi^0 + p$

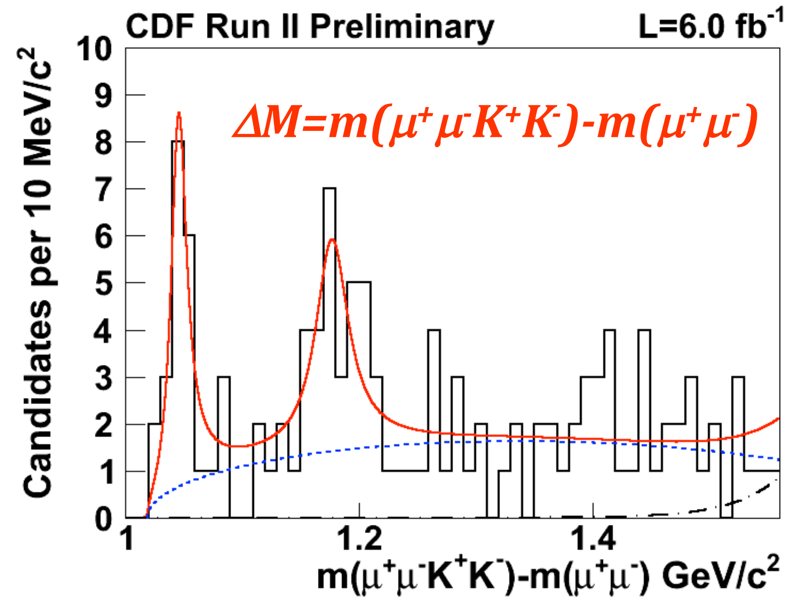
Depending on J^{PC}, B&C can be structure-less or structures in M_{12}. In this example, B shows flat distribution in M_{12} and C shows two structures in M_{12}.

There are no established resonances in $m(\phi K^+)$ (possible hint for K_1&K_2) and $M(J/\psi K^+)$, CDF was limited by statistics, and stated:

"We find no evidence for any other structure in the ϕK^+ and $J/\psi K^+$ spectrum; the only structure [i.e. $K_2(1770)$] that has been claimed in the ϕK^+ spectrum by previous experiments is too broad to alter our analysis"

Update from CDF w/ 6.0 fb^{-1} (2010)





arXiv:1101.6058 [hep-ex], Mod.Phys.Lett. A32 (2017) no.26, 1750139

$Yield_1$ = 19±6; >5σ

$Yield_2$ = 22±8; 3.1σ

$M_1 = 4143.4^{+2.9}_{-3.0}\,(stat) \pm 0.6\,(syst)$ MeV

$M_2 = 4277.4^{+8.4}_{-6.7}\,(stat) \pm 1.9\,(syst)$ MeV

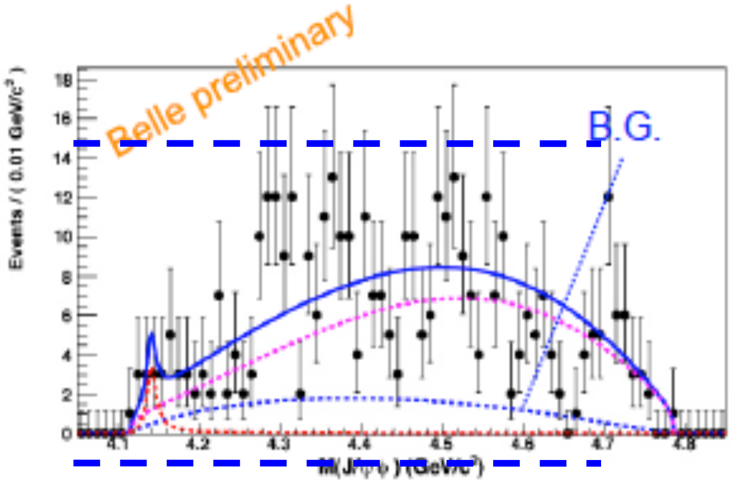
$\Gamma_1 = 15.3^{+10.4}_{-6.1}\,(stat) \pm 2.5(syst)$ MeV

$\Gamma_2 = 32.3.7^{+21.9}_{-15.3}\,(stat) \pm 7.6(syst)$ MeV

χ^2/dof between old and new Δm is 7.2/3, p-value=6.5% w/ four regions

$$\frac{\mathcal{B}(B^+ \to Y(4140)K^+, Y(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} = 0.149 \pm 0.039(\mathrm{stat}) \pm 0.034(\mathrm{syst})$$

Belle: Confirm or refute? (2009, 2010)



Y(4140): 7.5 +4.9/-4.4events
Statistical significance: 1.9σ
Signal could not be identified.

Summary

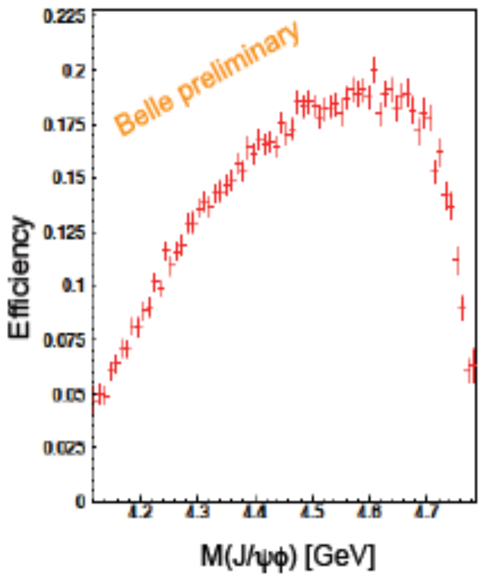
–B factories suffer from low pt track efficiency
–Belle cannot confirm or deny the existence of Y(4140)

–Tevatron edge over B factories:
Low p_T kaons are boosted from B momentum

no statement from Babar until 2015

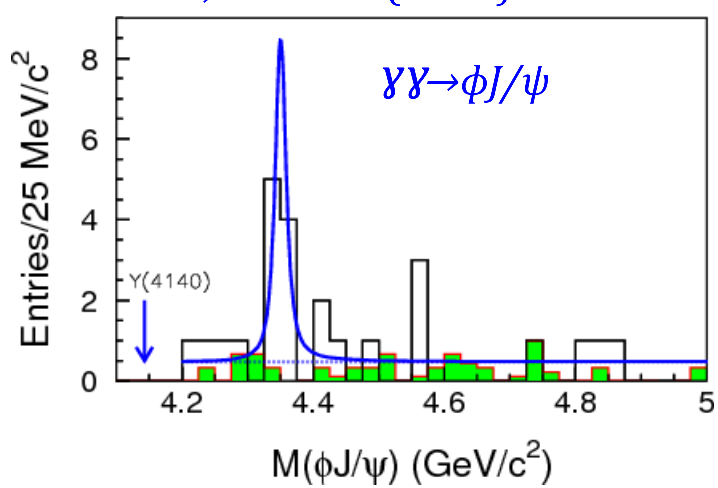
QWG 2010

Kenkichi Miyabayashi
(Nara Women's Univ.)
2010 May QWG7

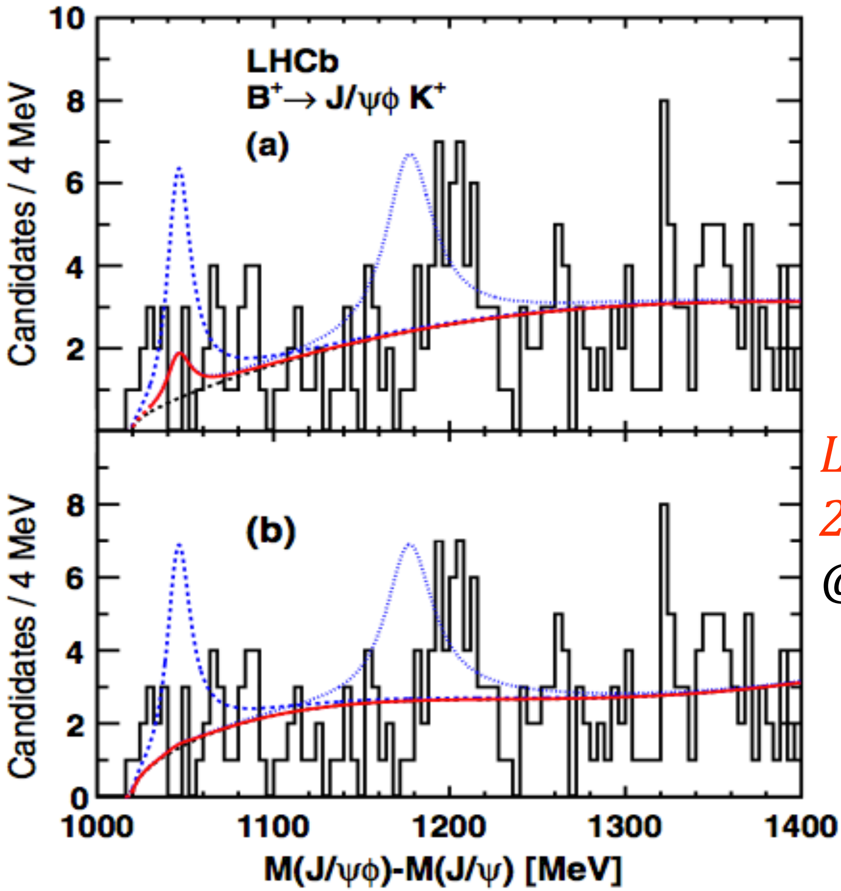


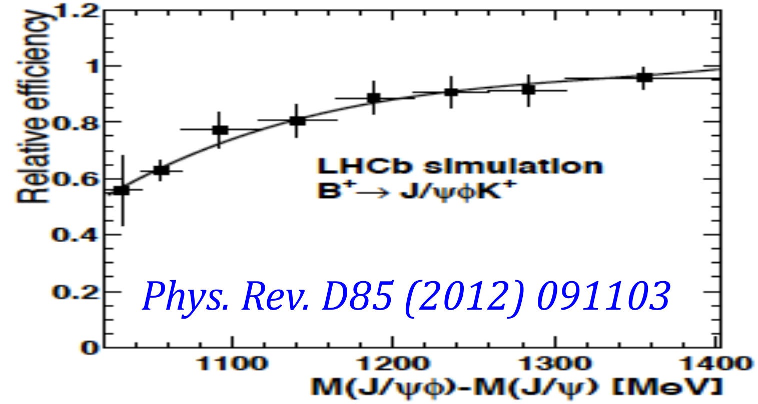
Note: CDF and Belle do not contradict each other.
In Belle, B meson at rest on ϒ(4S) rest frame, Kaon momentum from φ decay is low, especially just above J/ψφ threshold
→ lower reconstruction efficiency.

Belle, PRL 104 (2010) 112004



LHCb: contests CDF report (2011)





Phys. Rev. D85 (2012) 091103

LHCb confirms neither structure(s)

2.4σ disagreement with CDF measurement

@90% CL (PDG changed the name to be X(4140)):

$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\,\phi)}{\mathcal{B}(B^+ \to J/\psi\,\phi K^+)} < 0.07.$$

$$\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\,\phi)}{\mathcal{B}(B^+ \to J/\psi\,\phi K^+)} < 0.08$$

LHCb Versus CDF: Two Punches In The Face!

By Tommaso Dorigo | July 27th 2011 05:48 AM | 10 comments | Print | E-mail | Track

The first is the tentative observation ofa new hadron, called

Y(4140), a bump observed in the invariant mass of pairs of

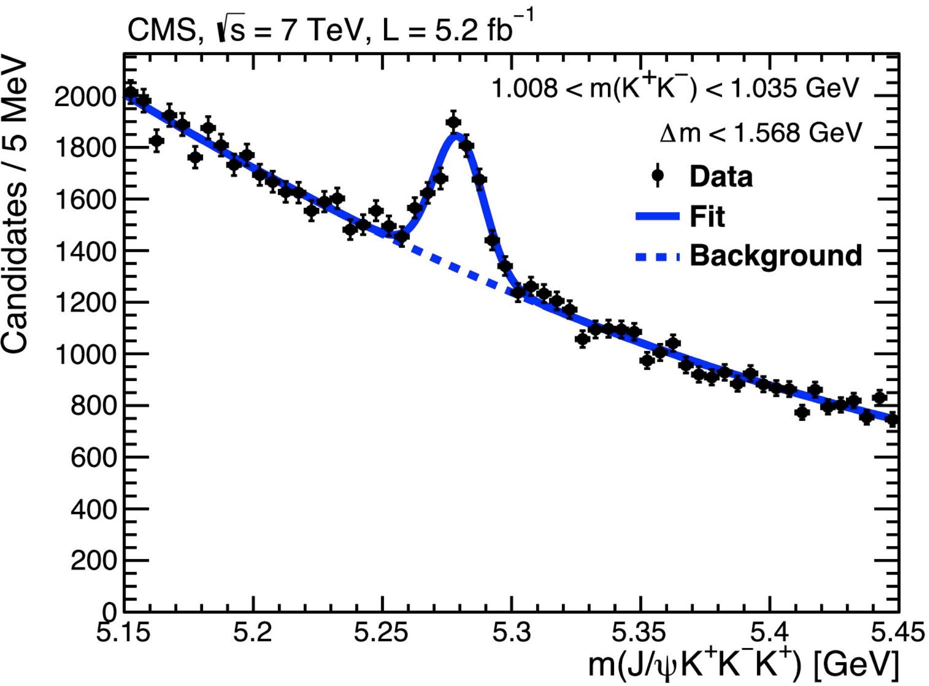
result. Note that, as reported in the figure, if the CDF signal were as estimated by CDF, LHCb would have been able to fit 39+-9+-6 events. The Y(4140) is on very shaky ground at the moment, and the new PDG will likely change its status in the particle zoo... This is punch number 1.

The B signal (CMS 2012)

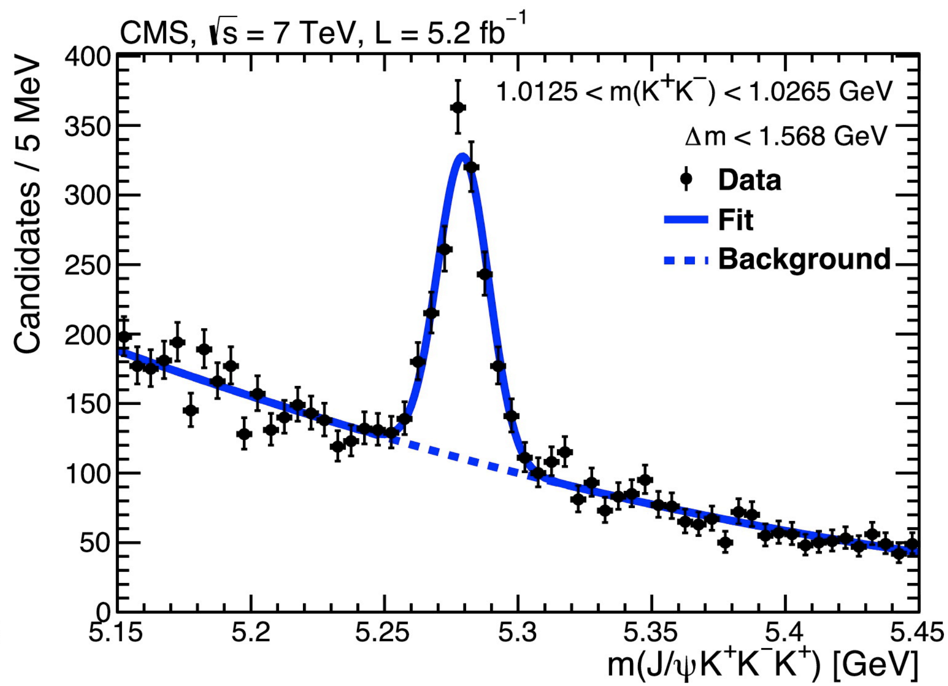
$B^+ \rightarrow J/\psi\phi\ K^+$ decay

PLB 734 261 (2014)

Default selection: 2340±120 events



Tight selection: ~1000 events

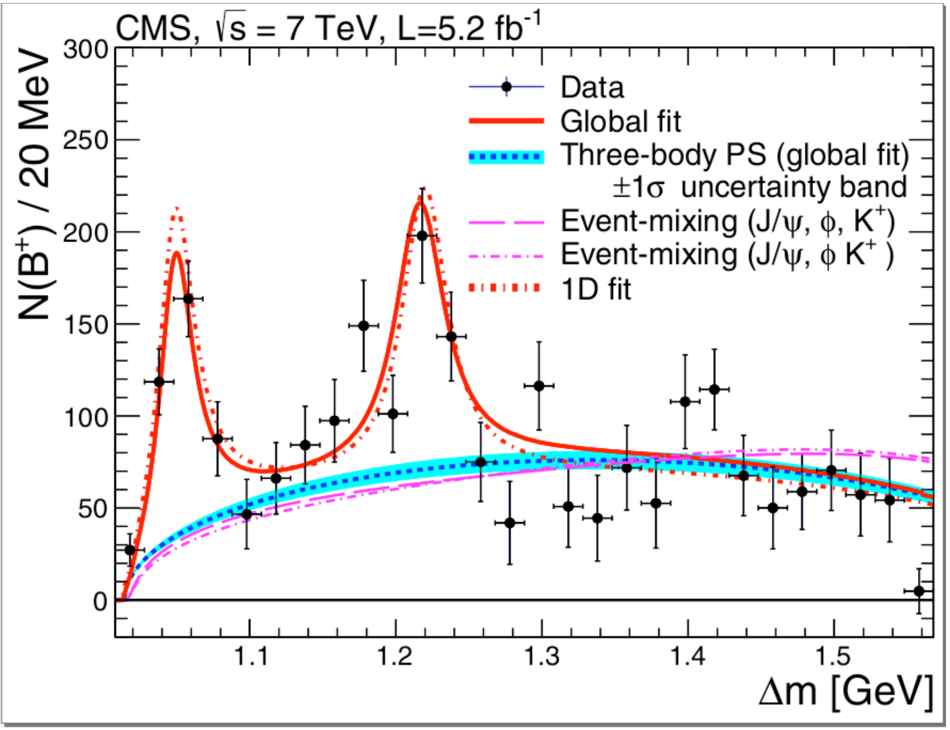


Signal--Gaussian, Background—2nd polynomial, Width--MC

Largest $B^+ \rightarrow J/\psi\phi\ K^+$ sample collected in the world up to date

~20 times of CDF statistics (115±12); ~7.2 of LHCb statistics (346±20)

Background shape studies(CMS 2012)



Event mixing to study the Δm shape

--J/ψ, ϕ, K^+ from different events

--ϕ, K^+ from the same event, J/ψ from different events. This is to get the impact on Δm from possible ϕK^+ resonances

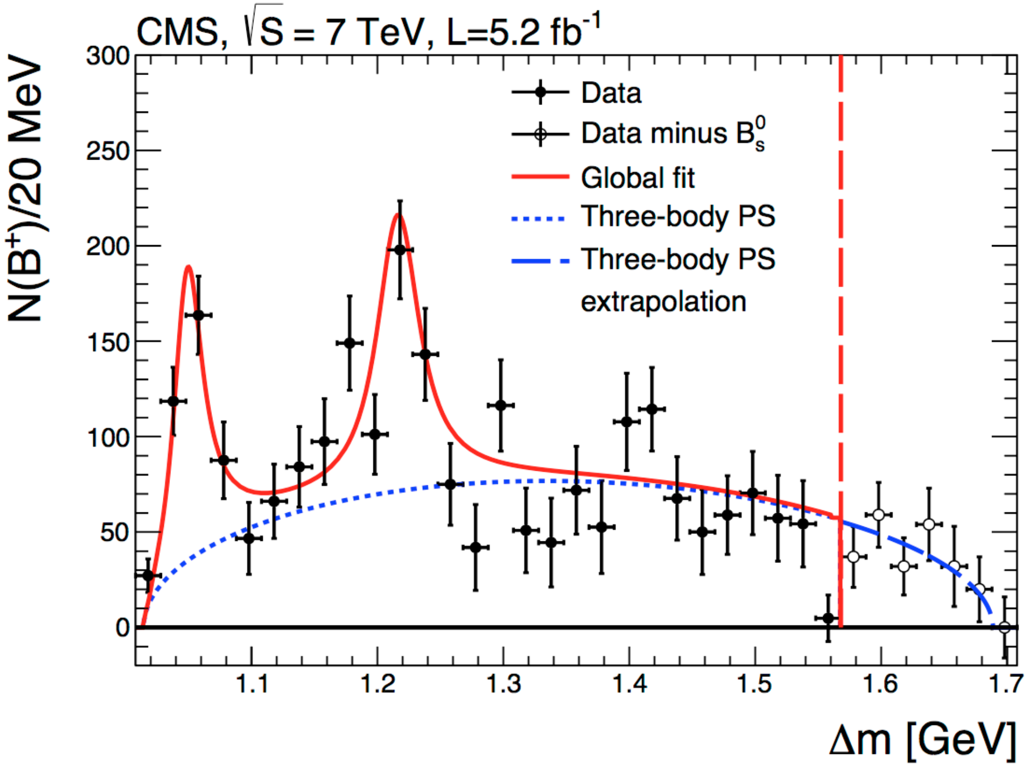
Require the J/ψϕK^+ mass around B mass

Event-mixing Δm shapes are slightly distorted compared to three-body phase space

However, the possible effect is in the high Δm region and the three-body phase space shape is more conservative in the low Δm region, where the two structures are observed.

Result from CMS

- *A global fit to all Δm bins to extract parameter*



Δm_1=1051.3±2.4(stat)MeV,
Γ_1=28_{-11}^{+15}(stat) MeV, 310±70 events

Δm_2=1217.1±5.3(stat)MeV,
Γ_2=38_{-15}^{+30}(stat) MeV, 418±170 events

m_1= 4148.0±2.4(stat)±6.3 (syst) MeV
Γ_1= 28_{-11}^{+15}(stat)±19 (syst) MeV

m_2= 4313.8±5.3(stat)±7.3 (syst) MeV
Γ_2= 38_{-15}^{+30}(stat)±16 (syst) MeV

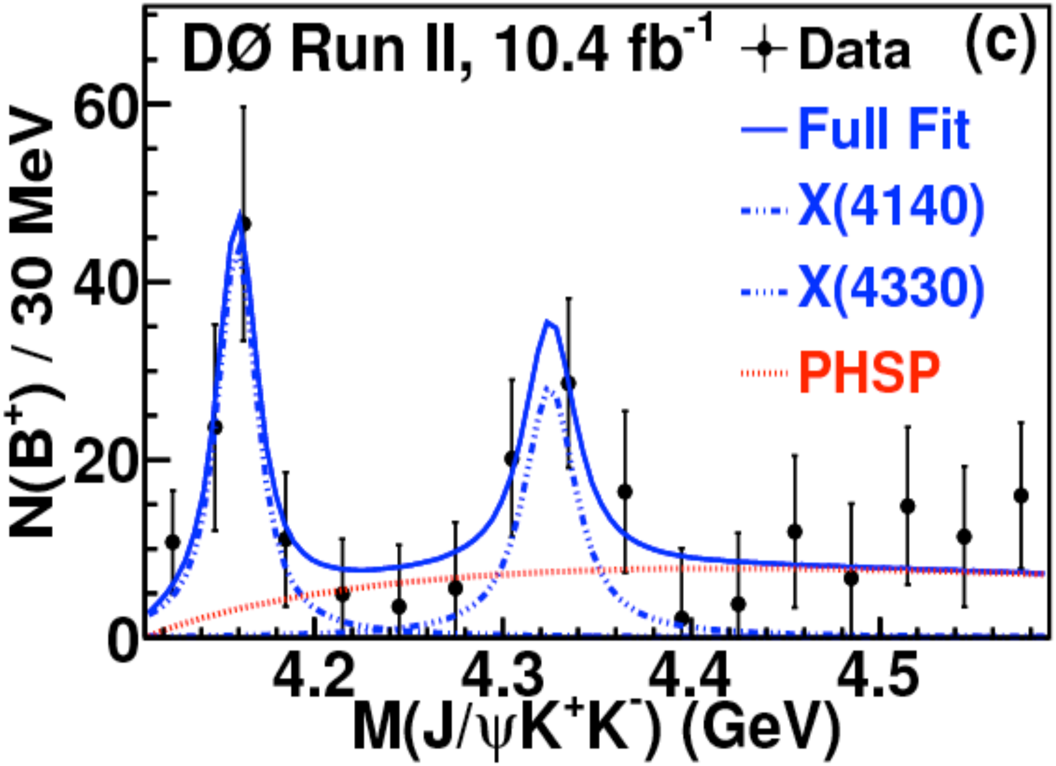
- *observed a $J/\psi\phi$ structure at 4148MeV with a significance greater than 5σ*

confirms the existence of Y(4140) for the first time from another experiment

CDF Y(4140): m=$4143.4^{+2.9}_{-3.0}$ (stat) ± 0.6 (syst)

- *evidence for a second structure at ~4317MeV in the same mass spectrum*

Y(4140) @ D0 (2013)



PRD 89, 012004 (2014)

M_1=4159.0±4.3(stat)±6.6(syst) MeV

M_2=4328.5±12.0(stat) MeV

Γ_1=19.9±12.6(stat)$^{+1.0}_{-8.0}$(syst) MeV

Γ_2=? MeV

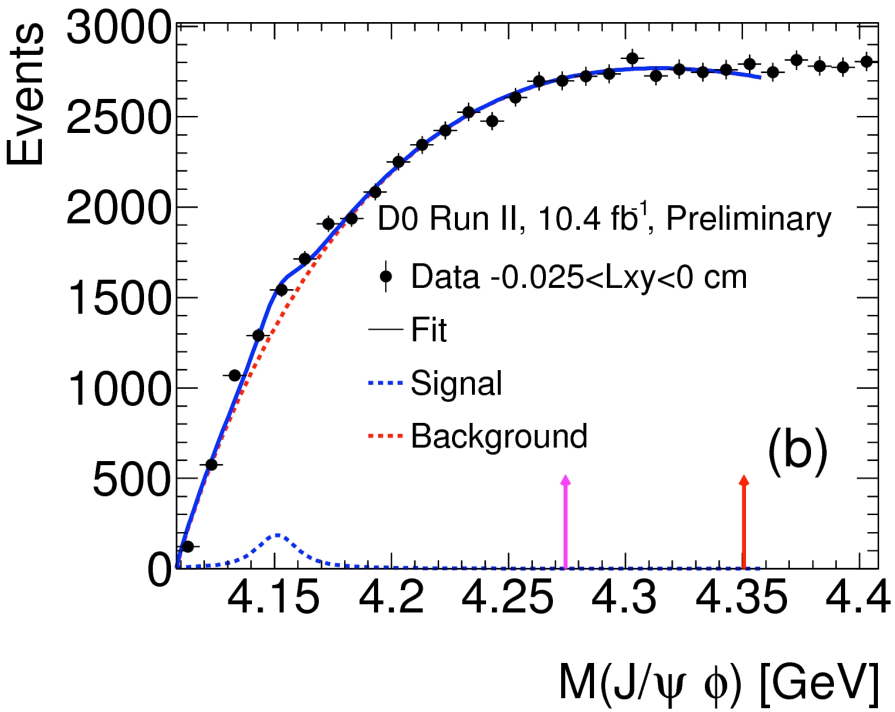
Y(4140)—Evidence (3.1σ), consistent with CDF Y(4140) result

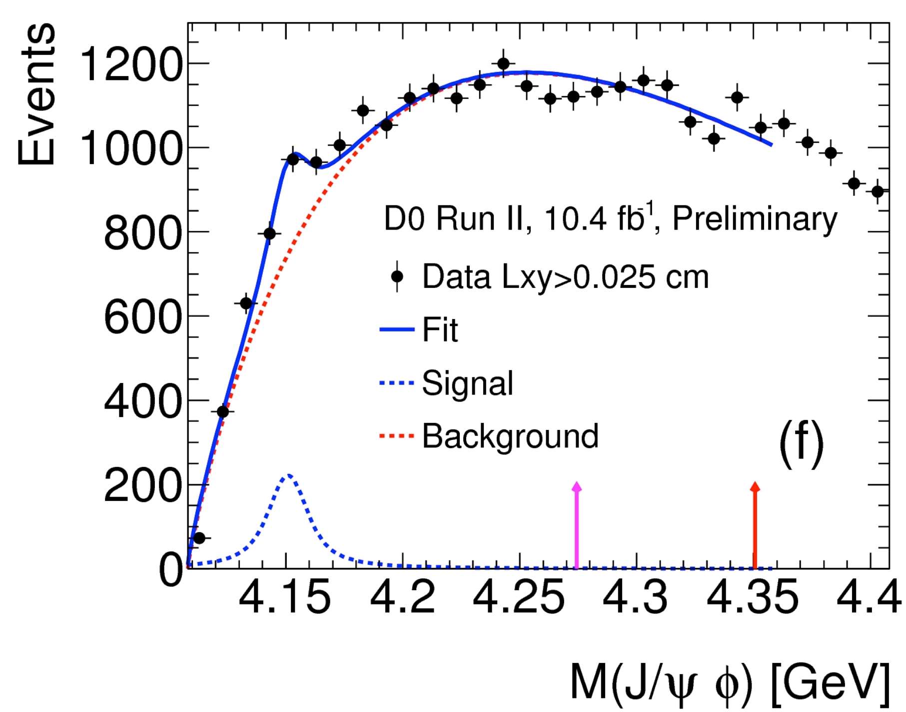
Peak2 — hint w/ fixed width

D0 provides the second independent confirmation of Y(4140) with 3.1σ significance
Later D0 also confirmed the Y(4140) using the inclusive channel.

Inclusive Y(4140) @ D0 (2015)

PRL 115(2015) no. 23, 232001





significance: >> 5σ, there are 1964 ± 248 signal events

$m = 4152.5 \pm 1.7(stat)^{+4.7}{}_{-3.6}(syst)$ MeV

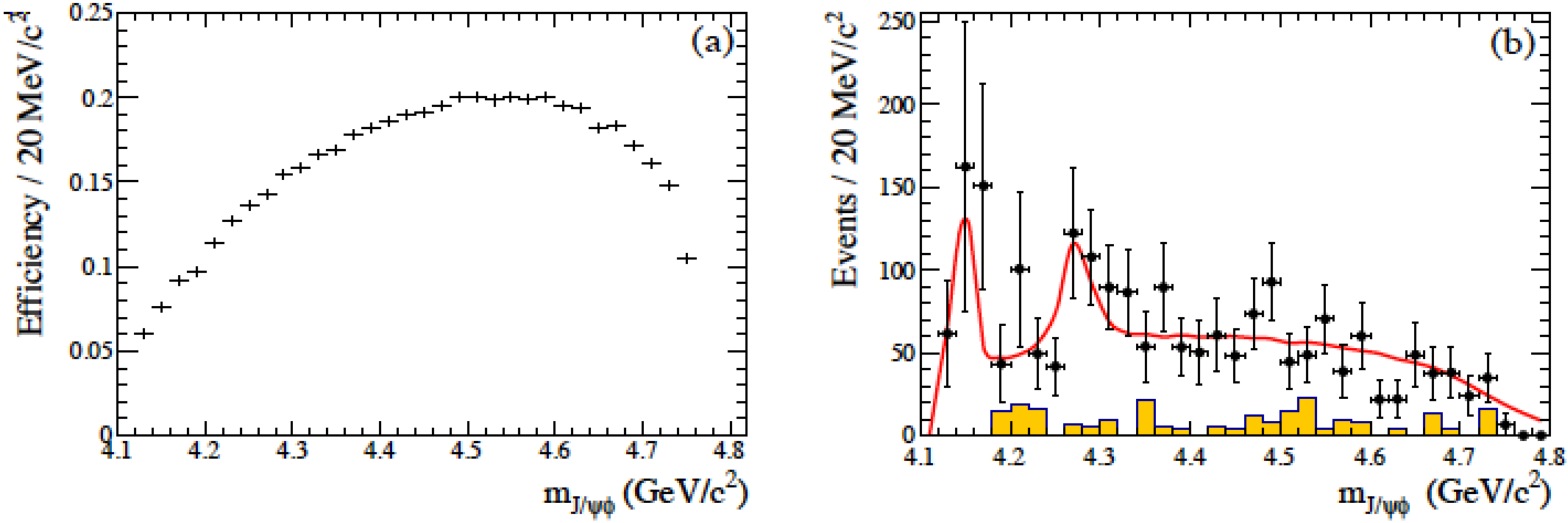
$\Gamma = 16.3 \pm 5.6\ (stat) \pm 10.3\ (syst)$ MeV

(consistent with their previous measurements and CDF/CMS

B production fraction: 0.39 ± 0.07 (stat) ±0.10 (syst).

Y(4140) @ BaBar (2015)

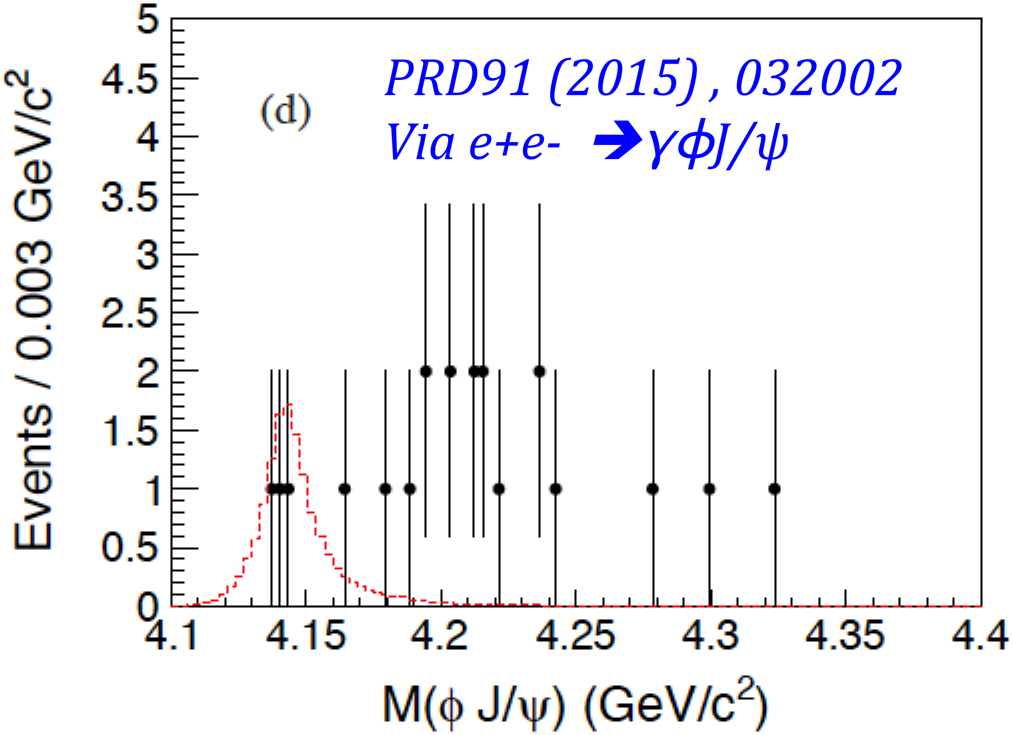
PRD91 (2015), 012003



The same searches via B decays
Mass & width are fixed to CDF values
No significance for both structures even though there are hints
Babar sets limits for both, compatible with all experiments

BaBar provides useful information even though there is no significant signal

Y(4140) @ BES (2015)



No sensitivity for Y(4140)

Three events @4.15 GeV

BES sets limits, cannot compare because it is from a different process

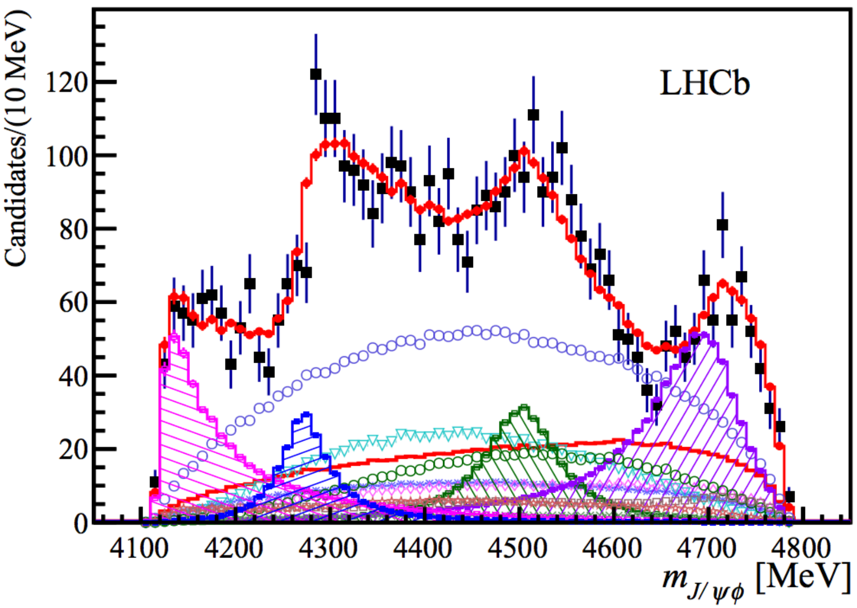
BES provides additional information: under the assumption of molecule interpretation, the BF of Y(4140)→J/ψϕ is estimated to be about 30%

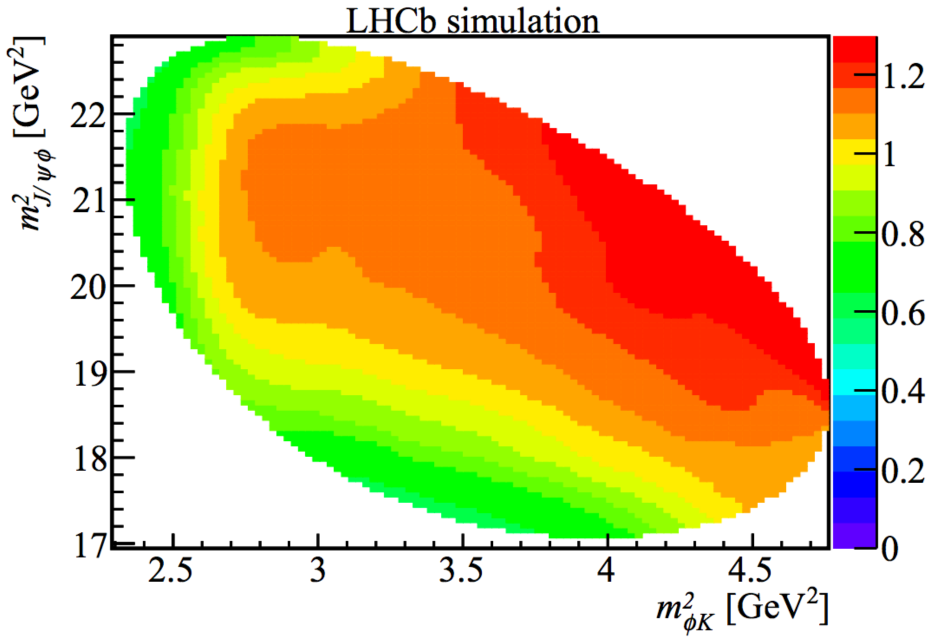
Mini summary of Y(4140) before LHCb new result :

Signal seen by CDF, CMS, D0
No significant signal from Belle, Babar, BES, but no conflicts
2.4σ tension between LHCb (0.3 fb^{-1} data) and CDF

Results from LHCb (2016)

LHCb, PRL 118 (2017) no.2, 022003; PRD 95 (2017) no. 1, 012002





- *LHCb confirmed both X(4140) and X(4274), X(4140) with significant wider width*
- *LHCb found two additional resonances in the same mass spectrum*
- *This amplitude analysis is 7 years after the first report from CDF*
- *LHCb also determined the J^{PC} of the four states*

- *PDG renamed them as X.*

Results from LHCb (2016)

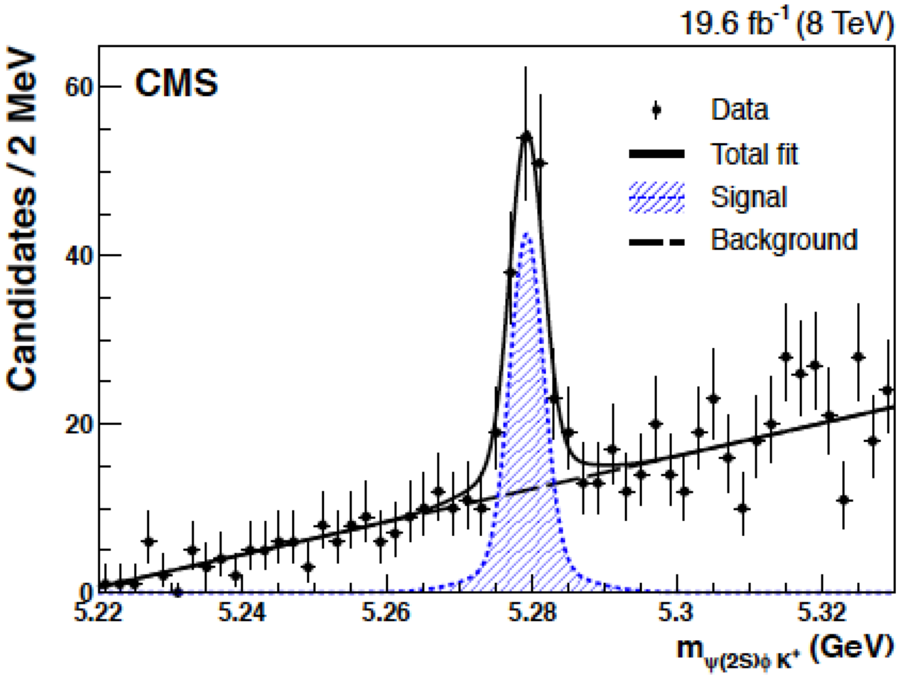
LHCb, PRL 118 (2017) no.2, 022003; PRD 95 (2017) no. 1, 012002

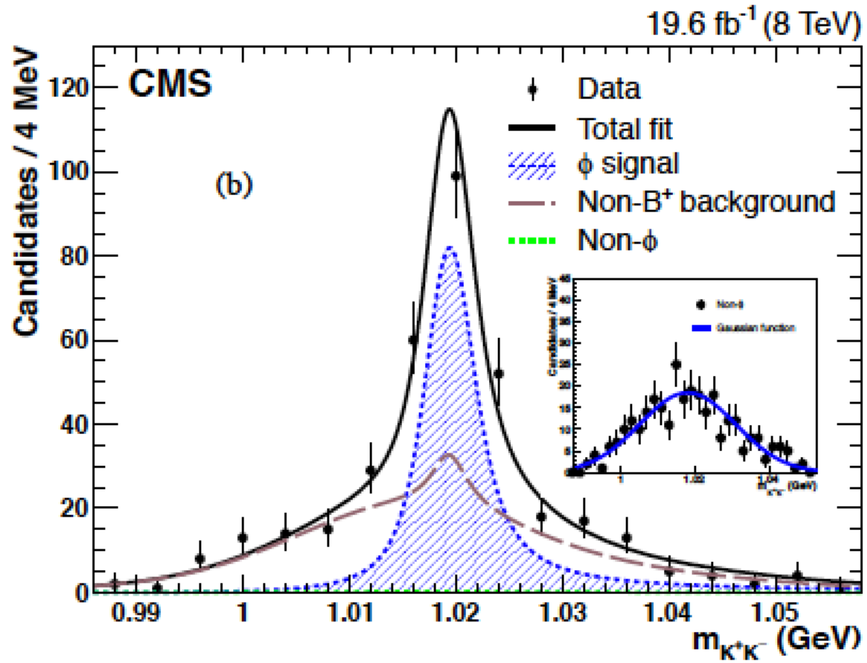
All $X(1^+)$				$16\pm3\ {}^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13.0\pm3.2\,^{+4.7}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ 3.6}$	$56\pm11\,^{+\ 8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF	[26]	$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
CMS	[23]	$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
$\mathrm{NR}_{J/\psi\,\phi}$	6.4σ			$46\pm11\ {}^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\ {}^{+\ 9}_{-\ 5}$

- *LHCb explained X(4140) as a possible CUSP due to their measured wide width.*
- *Currently the width of X(4140) from LHCb is significantly larger than all measurements from other experiments*
- *The width can be measured more precisely? i.e., by Belle II?*
- *These states have no light quark components, add an important piece to the exotic meson family, and demand a theoretical explanation!*

Anything at $\psi(2S)\phi$?

[Phys.Lett. B 764 (2017) 66]



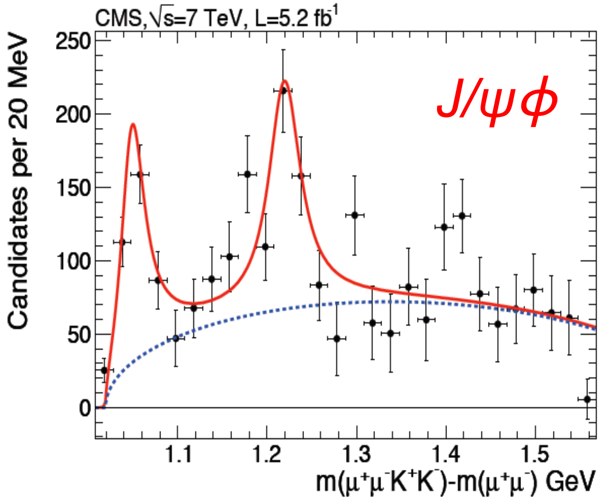


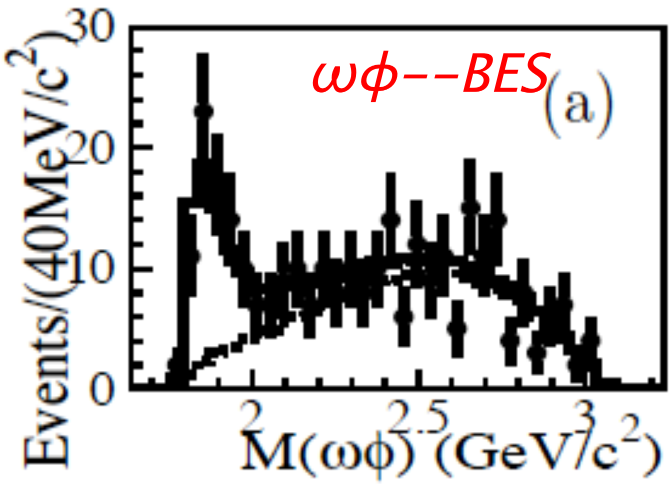
$$\mathcal{B}(B^+ \to \psi(2S)\phi K^+)$$

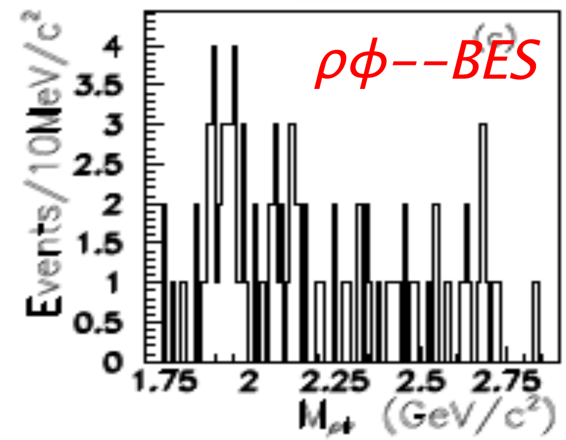
$$(4.0 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.2\,(\mathcal{B})) \times 10^{-6},$$

$B^+ \to \psi(2S)\phi K^+$ signal is clearly observed at CMS, no report on possible sub-structures—very narrow phase space.

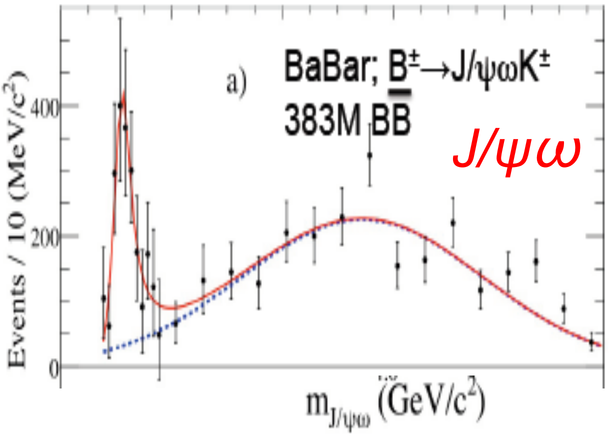
From J/ψϕ to four-lepton states

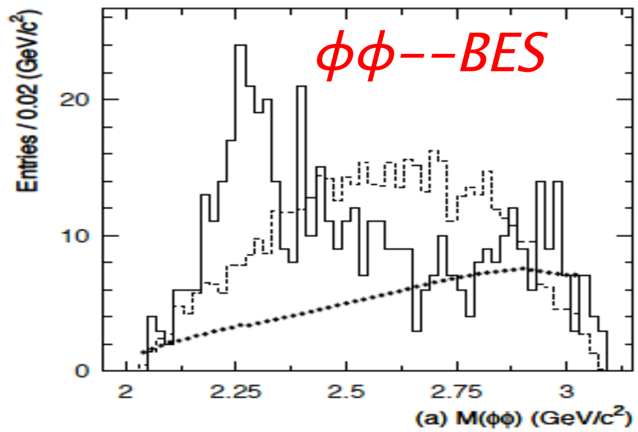


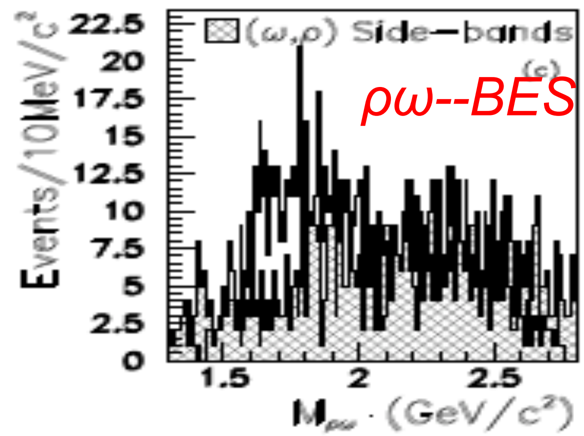




PRD 77, 012001(2008)







--Observed near threshold narrow V(I=0)V (I=0) enhancement

--No clear enhancement if one of the V (I!=0) or due to wide width of ρ

How about J/ψJ/ψ, J/ψϒ*, ϒϒ* threshold? And four-lep final state? Note that CMS and ATLAS do not have hadron PID, but excellent with lepton ID and mass resolution, and easier to trigger!*

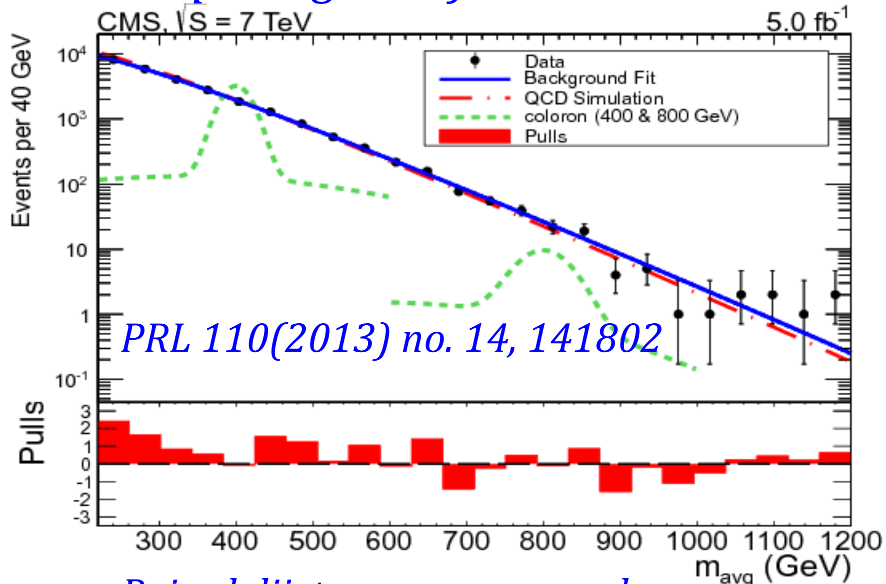
Experimental review of structures in the J/ψϕ mass spectrum, Int.J.Mod.Phys. A28 (2013) 1330020

Example: CMS detector performance

Excellent muon/silicon detectors:

- Muon system
  - High-purity muon identification
  - $\Delta m / m \sim 0.6\%$ at J/Ψ mass range
- Silicon Tracking detector
  - $\Delta p_T / p_T \sim 1\%$
  - excellent vertex reconstruction and impact parameter resolution

Comparing to dijet resolution: >10%

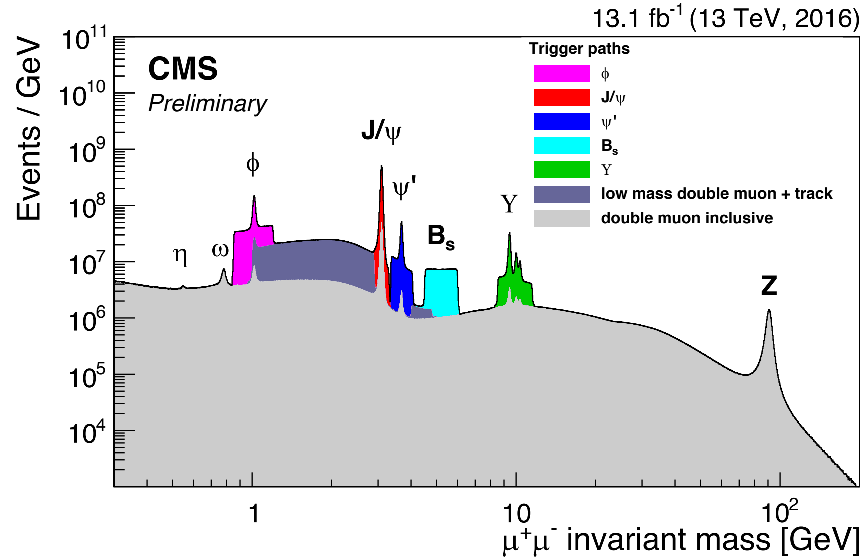


PRL 110(2013) no. 14, 141802

Paired dijet resonance searches

LHC luminosity and trigger:

- *LHC will have ~100 fb^{-1} by this year*
- *Relatively easy for lepton trigger, i.e., dimuon trigger. However becoming more difficult*



never fully explored (GeVs-Z mass) Multiple-lepton final states

http://arxiv.org/abs/hep-ph/0312114

Experiment	E_{cm} [GeV]
* ADONE-MEA	2.23
BEPC-BES	2.0 - 4.8
BEPC-BES	2.6 - 5.0
* SPEAR-SMAG †	2.4 - 5.0
* SPEAR-SMAG+LGW	3.598 - 3.886
SPEAR-Crystal Ball	3.670 - 4.496
SPEAR-Crystal Ball	5.0 - 7.4
SLAC-MARK-II	3.670 - 3.872
DORIS-DASP	3.6025 - 5.1950
DORIS-II-LENA	7.440 - 9.415
* DORIS-II-ARGUS	9.360
DORIS-II-Crystal Ball	9.39 - 9.46
* DORIS-II-DHHM	9.45 - 10.04
DORIS-II-DASP	9.51
VEPP-4-MD1	7.30 - 10.29
CESR-CUSB	10.43 - 11.09
CESR-CLEO	10.49
CESR-CLEO ††	10.60 - 11.20
CESR-CLEO II	10.52
DORIS/PETRA-PLUTO	3.6 - 30.8
* PETRA-TASSO	12.0 - 41.4
* PETRA-TASSO	12.00 - 31.25
* PETRA-TASSO	14.03 - 43.70
PETRA-TASSO	41.45 - 44.20
PETRA-JADE	12.00 - 46.47
PETRA-MARK-J	12.00 - 46.47
* PETRA-MARK-J	31.57
* PETRA-MARK-J	34.85
PETRA-CELLO	14.0 - 46.6
PEP-MAC	29.0
* PEP-MARK-II	29.0
* TRISTAN-AMY	50.0 - 61.4
* TRISTAN-TOPAZ	50.0 - 61.4
* TRISTAN-TOPAZ	57.77
* TRISTAN-TOPAZ	57.37 - 59.84
* TRISTAN-VENUS	50.0 - 52.0
* TRISTAN-VENUS	63.6 - 64.0

A) Not enough energy
VV OR VV states can not be directly produced via e^+e^-, need higher energy. The highest e^+e^- energy before LEP/SLC was 64 GeV.*

B) Not enough int. luminosity
LEP/Tevatron not enough luminosity.

C) Opportunity comes with LHC
Enough energy and luminosity

D) Rich physics motivation + curiosity,
BSM—new scalar, Higgs-like,…
QCD—new dynamics, 4b bound states,…
anything else unexpected?

Motivation—heavy tetra-quark states

- ***Heavy-quark tetra-quark states*** *Phys. Rev. D 86, 034004 (2012)*

---There are quite some new development recently, here shows the first prediction.

$c\bar{c}c\bar{c}$

$0^{++'}$: $M = 5.966\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -228.\,\mathrm{MeV}$,
$1^{+-'}$: $M = 6.051\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -142.\,\mathrm{MeV}$,

Below double J/ψ threshold
*Search via J/ψl⁺l⁻, J/ψ**

2^{++} : $M = 6.223\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = 29.5\,\mathrm{MeV}$.

Above double J/ψ threshold
Search via J/ψJ/ψ

$bc\bar{b}\bar{c}$

$0^{++}a$: $M = 12.359\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -191.\,\mathrm{MeV}$
$0^{++}b$: $M = 12.471\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -78.7\,\mathrm{MeV}$,
$1^{+-}a$: $M = 12.424\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -126.\,\mathrm{MeV}$
$1^{+-}b$: $M = 12.488\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -62.5\,\mathrm{MeV}$,
1^{++} : $M = 12.485\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -64.9\,\mathrm{MeV}$,

Below double B_c threshold
J/ψY(1S) threshold
? …

2^{++} : $M = 12.566\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = 16.1\,\mathrm{MeV}$.

Above double B_c threshold
J/ψY(1S) threshold
Search via the above two channels

$b\bar{b}b\bar{b}$

$0^{++'}$: $M = 18.754\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -544.\,\mathrm{MeV}$,
$1^{+-'}$: $M = 18.808\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -490.\,\mathrm{MeV}$,
2^{++} : $M = 18.916\,\mathrm{GeV}$, $M - M_{\mathrm{th}} = -382.\,\mathrm{MeV}$.

Below double Y(1S) threshold
Search via Y(1S)l⁺l⁻

Will be a breakthrough for exotic mesons if established

Arguable to call below J/ψ mass events as J/ψ since J/ψ is very narrow, same for Y**

Tetra-charm-quark states (1980) and positronium molecule (2007)

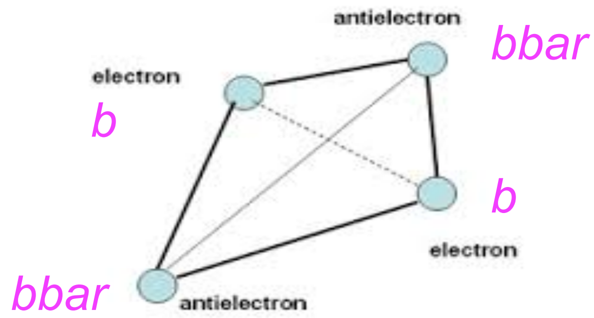
FERMILAB-Pub-80/70-THY
August 1980

The (cc) - $(\overline{cc})$ (Diquark-Antidiquark) States in e^+e^- Annihilation

KUANG-TA CHAO
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
and
Department of Physics, Peking University, Beijing

ABSTRACT

The mass spectrum and decay modes of the (cc) - $(\overline{cc})$ states are estimated in a quark-gluon model. We argue that the peculiar resonance-like structures of $R(e^+e^- \rightarrow \text{hadrons})$ for $\sqrt{s} = 6$–7 GeV may be due to production of the P-wave (cc) – $(\overline{cc})$ states. They are predicted to lie in the range 6.4 - 6.8 GeV and mainly decay into charmed mesons.



Vol 449 | 13 September 2007 | doi:10.1038/nature06094 nature

Nature letter

LETTERS

The production of molecular positronium

D. B. Cassidy[1] & A. P. Mills Jr[1]

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Last Updated: Wednesday, 12 September 2007, 17:03 GMT 18:03 UK

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Mirror particles form new matter

By Jonathan Fildes
Science and technology reporter, BBC News

Fragile particles rarely seen in our Universe have been merged with ordinary electrons to make a new form of matter.

Antiparticles are the mirror image of ordinary particles

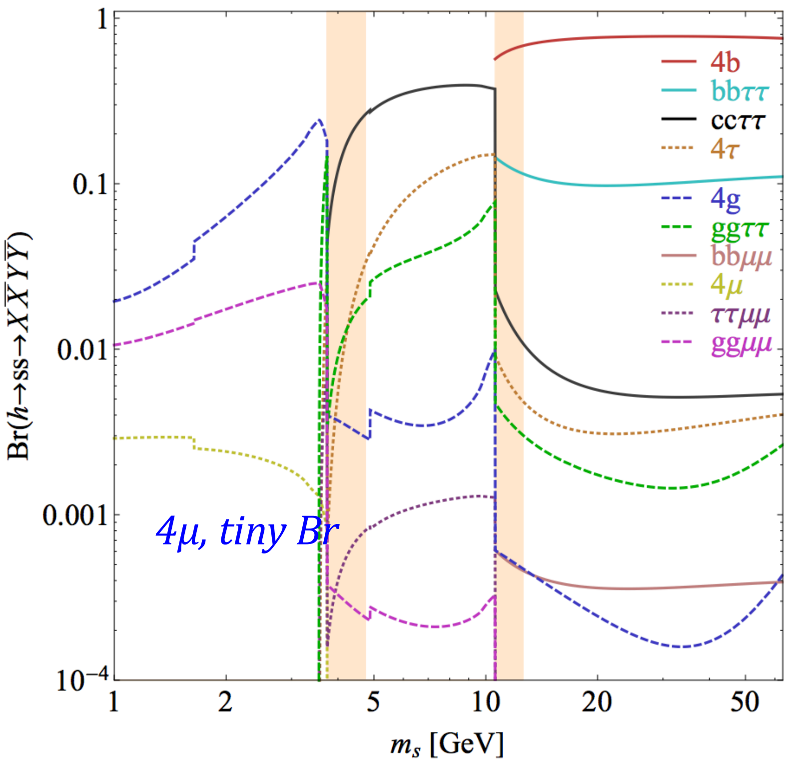
Di-positronium, as the new molecule is known, was predicted to exist in 1946 but has remained elusive to science.

Now, a US team has created thousands of the molecules by merging electrons with their antimatter equivalent: positrons.

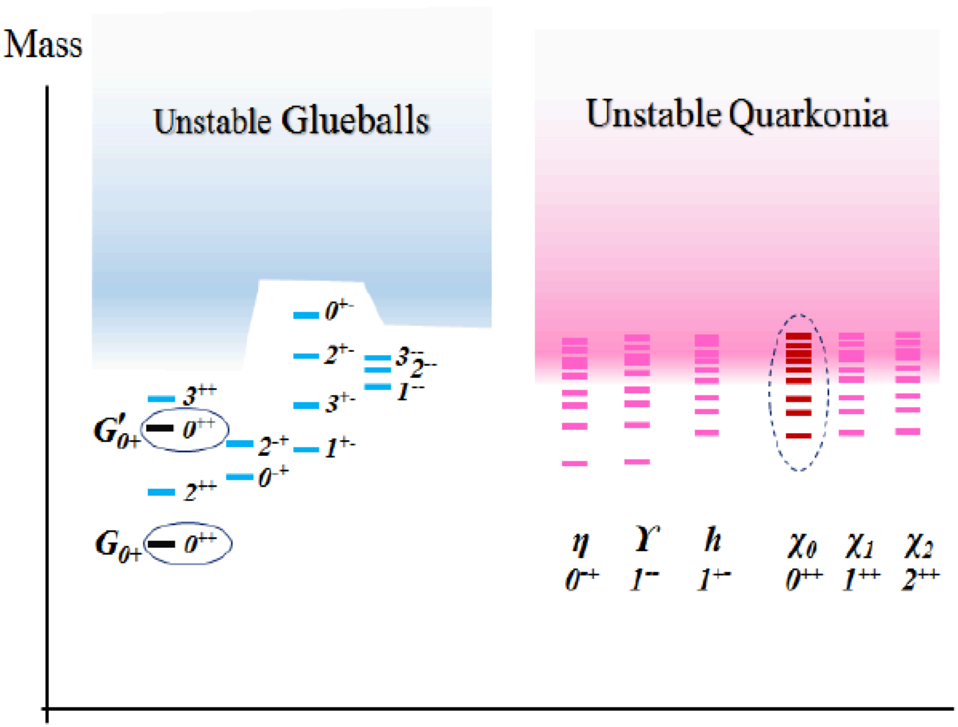
The discovery, reported in the journal Nature, is a key step in the creation of ultra-powerful lasers known as gamma-ray annihilation lasers.

Examples of new physics from GeVs-Z mass

A light scalar,
PRD 90 (2014), 075004



Twin hadron spectrum, hidden valley
*JHEP **07** (2015) 105,*



Many new physics models in this region
Many different decay modes
We can investigate if sensible multiple-lepton channels decay rate exists

Let's start to explore

Motivation for VV production cross section

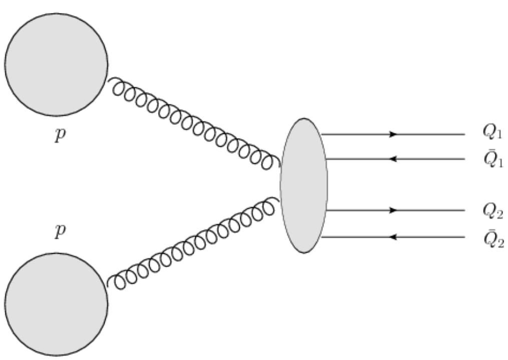
- The production of J/ψJ/ψ, YJ/ψ, YY are the benchmark measurements to evaluate the sensitivity of possible tetra-quark states composed of all heavy quarks at LHC

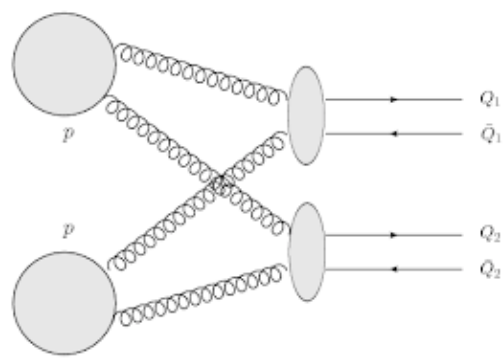
- On the other hand, the measurement of quarkonium and double quarkonium provide insight to the production mechanism.
  - Single Parton Scattering (SPS)
  - Double Parton Scattering (DPS)

- DPS production is expected to be significant at LHC

- Only SPS is relevant to the production of exotic mesons, DPS contributes as background events

SPS

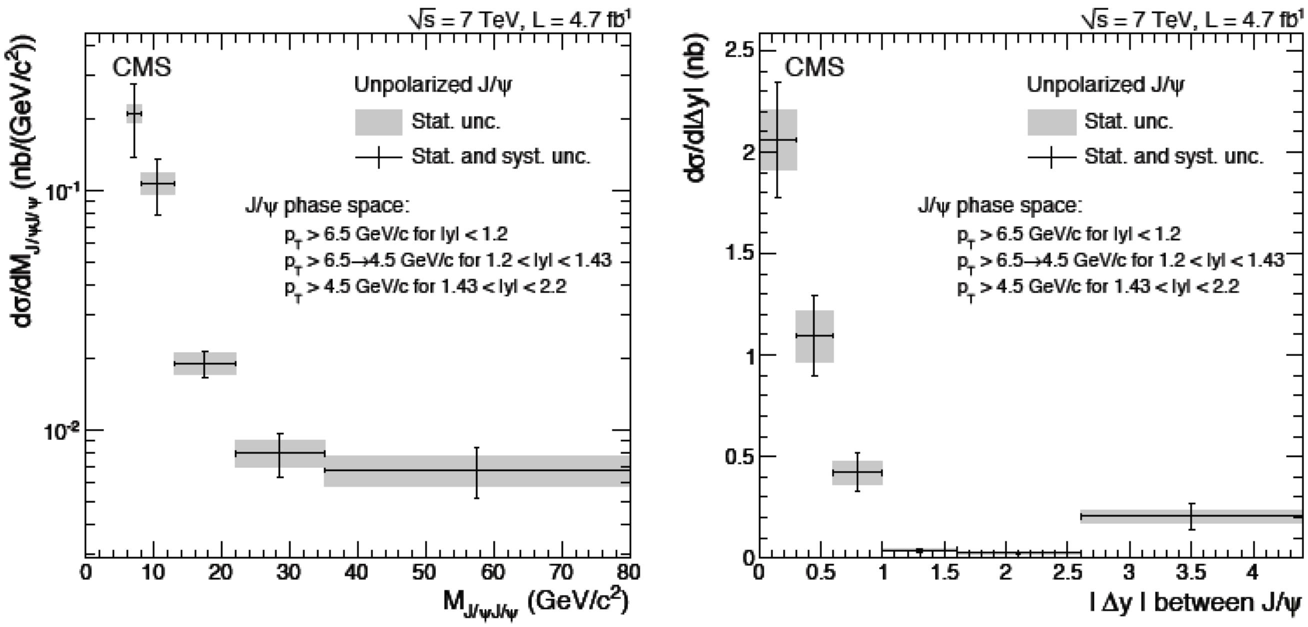




DPS

Double J/ψ cross section

JHEP 1409 (2014) 094



$\sigma_{tot} = 1.49 \pm 0.07(stat) \pm 0.13(syst)$ nb, prompt component

We have observed double J/ψ events and measured its production cross section
Dominated by SPS, hint of DPS.

How about an upsilon pair?

Observation of $\Upsilon(1S)\Upsilon(1S) \to \mu^+\mu^-\mu^+\mu^-$

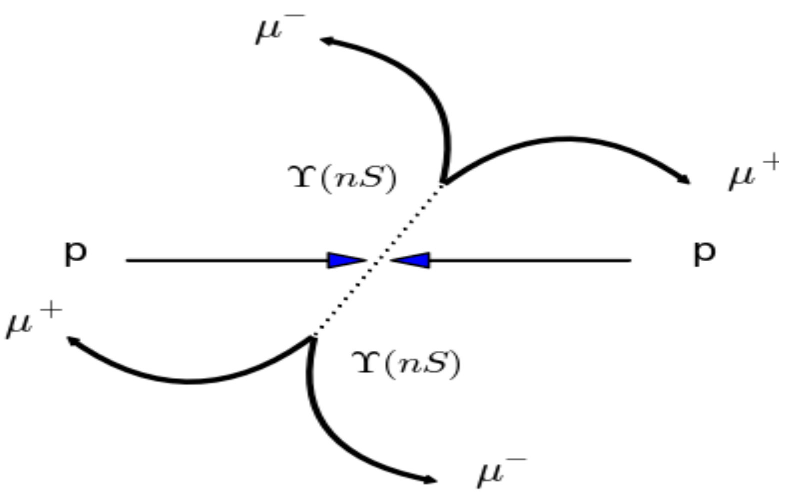
JHEP 1705 (2017) 013

Motivation:

--Interest to investigate production mechanism:
Single-Parton-Scattering--SPS vs Double-Parton-Scattering (DPS)

--Benchmark measurement for 4b bound and BSM states searches

A good start point for 4-lepton mass spectrum



$$pp \to \Upsilon\Upsilon$$
$$\Upsilon \to \mu^+\mu^-$$

Main selections:

--muon p_T >3.5 GeV, pseudorapidity within 2.4

--Upsilon pseudo-rapidity within 2.0

--four-muons come from the same vertex: vertex-probability>5%

Two-dimensional scatter plot

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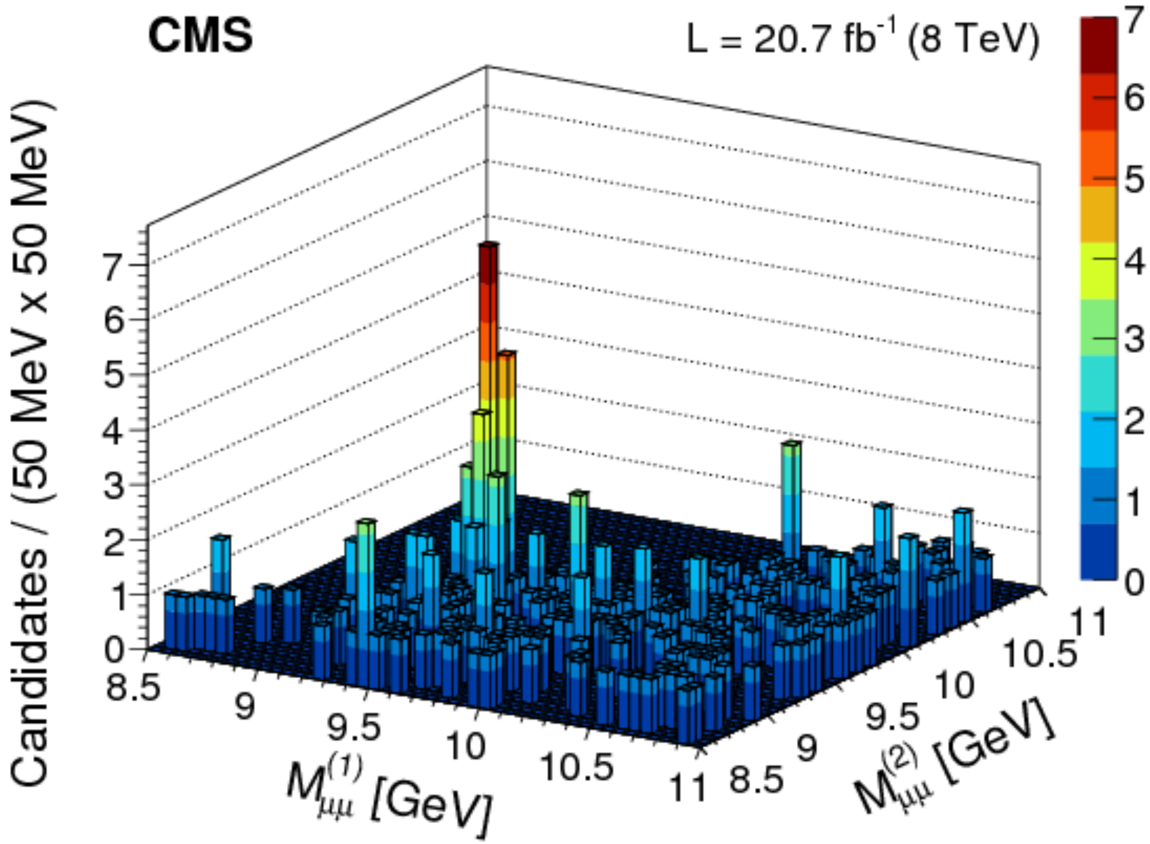

Two dimensional scatter plot of selected events,
Striking peaks at 9.5 GeV from both dimensions.

Scatter plot projection

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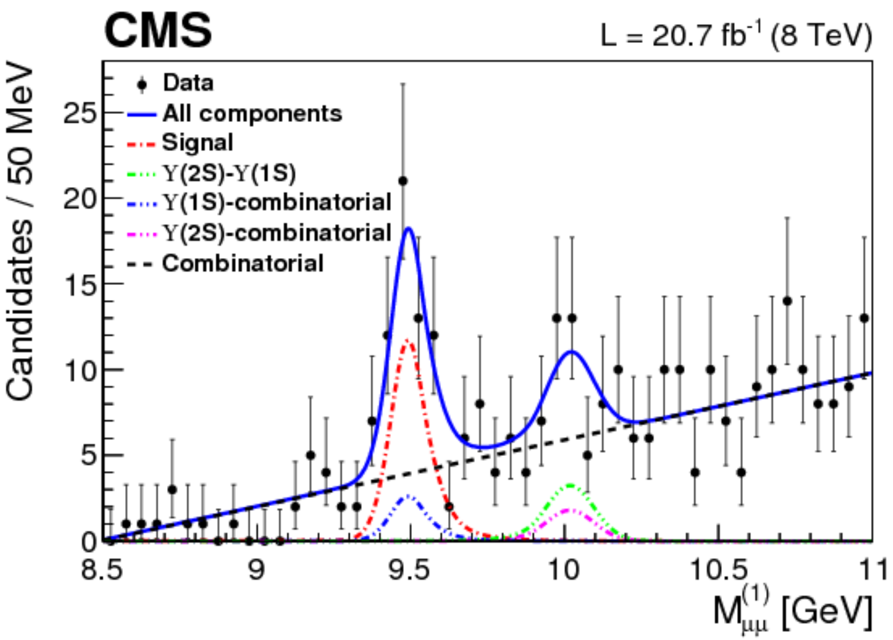
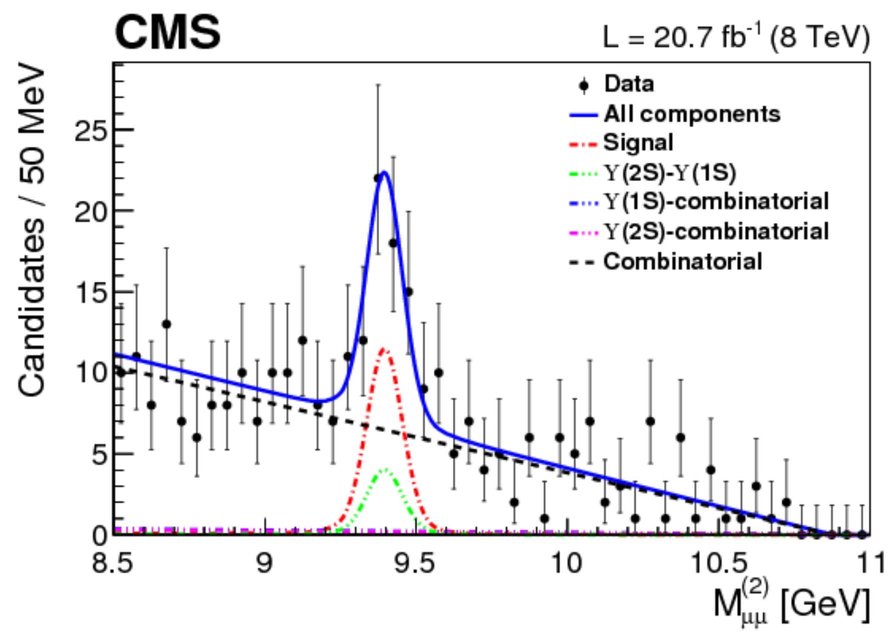




Main selections: Yield extraction from maximizing 2D likelihood PDF
--signal is modeled by two Crystal-ball functions
--background is modeled as 1st order polynomial

Number of Y(1S)Y(1S): 38±7
Significance: >>5sigma
Also see a hint of (Y(1S)Y(2S)

First time observation in the world

Υ(1S)Υ(1S) Cross section @ 8 TeV

Assuming unpolarized production of Υ(1S) meson, the cross section of Υ(1S)Υ(1S) with pseudorapidity within 2.0 for each Υ(1S), and p_T *less than 50 GeV at 8 TeV is measured as:*

$$\sigma(pp \to \Upsilon\Upsilon) = 68.8 \pm 12.7(stat) \pm 7.4(syst) \pm 2.8(BR)pb$$

Different assumptions of Υ(1S) polarization gives the total cross section uncertainty between -38% and 36%

No enough statistics to separate SPS and DPS fractions.

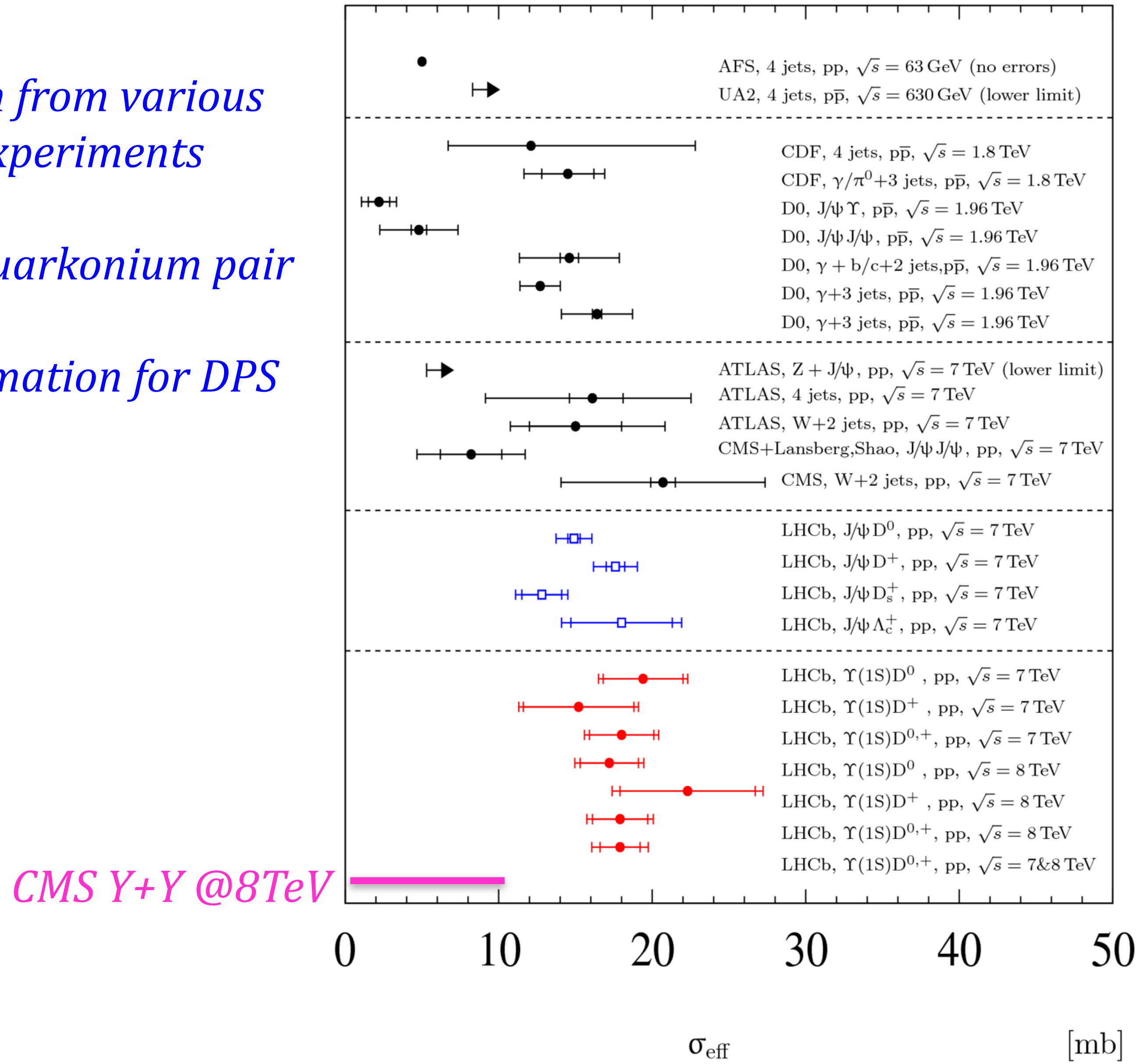
The effective cross section can be calculated by:

$$\sigma_{\mathrm{eff}} = \frac{[\sigma(\Upsilon)]^2}{2\, f_{\mathrm{DPS}}\, \sigma_{\mathrm{fid}}\, [\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)]^2}.$$

The effective cross section is between 6.6 and 1.32 mb assuming 10%-50% f_{DPS}

Comparison with other channels

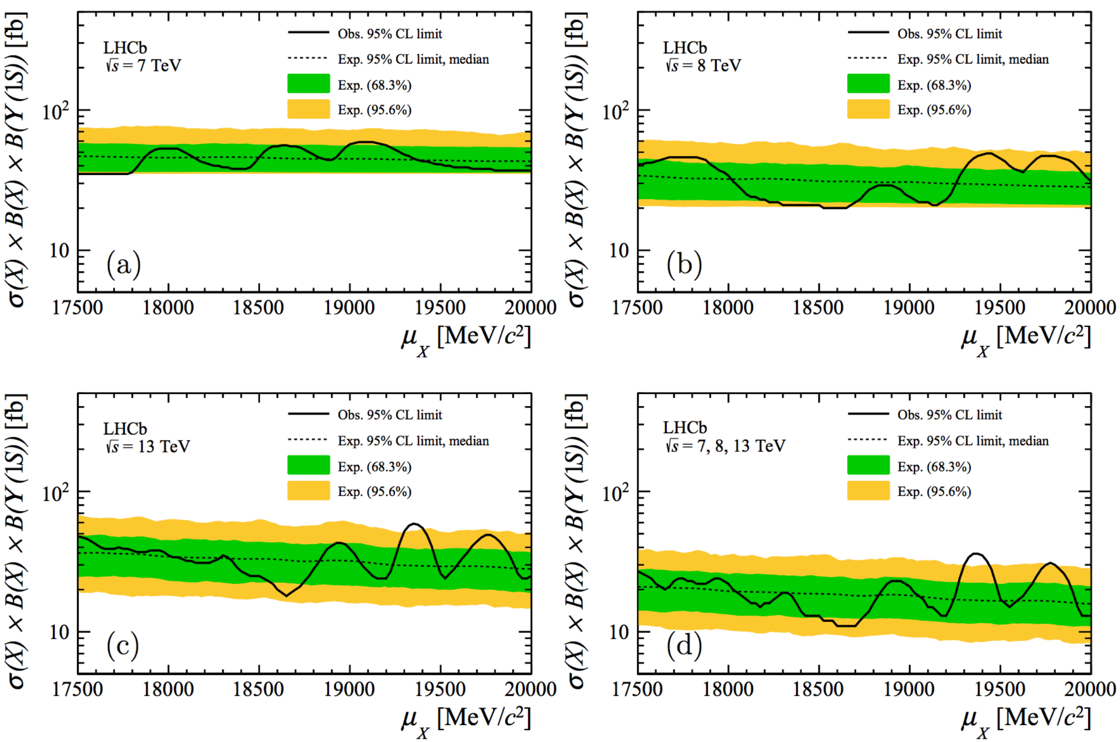
- *effective cross section from various channels at different experiments*
- *relatively small for quarkonium pair*
- *provide insight information for DPS*



Y(1S)Y(1S) SPS Cross section @ 8 TeV

Assuming f_{DPS} to be 10%-50%, the SPS cross section @8 TeV in CMS can be as large as [34,62] pb

CMS will be sensitive if tetra-quark state cross section is close to pb level @CMS.



LHCb limit in the kinematic region:
All muon eta in range: [2,5],
X in rapidity range: [2,4.5]
X p_T < 15 GeV

arXiv:1806.09707 [hep-ex]

No upsilon pair cross section reported from LHCb yet

Summary

- *Hadron colliders have made significant contributions to the ongoing XYZ saga—X(3872), X(4140), X(4274), Zc^{+}(3900),..*

- *CMS observed the upsilon pair production for the first time*

- *The fiducial cross section is measured as:*
$\sigma(pp \rightarrow YY) = 68.8 \pm 12.7(stat) \pm 7.4(syst) \pm 2.8(BR)pb$

- *provide insight to upsilon pair production mechanism*

- *The SPS cross section can be as large as 34-62 pb, sensitive to 4b states at cross section of pb level*

Stay tuned!

Backup