Exotic Spectroscopy in the Heavy and Light Sectors

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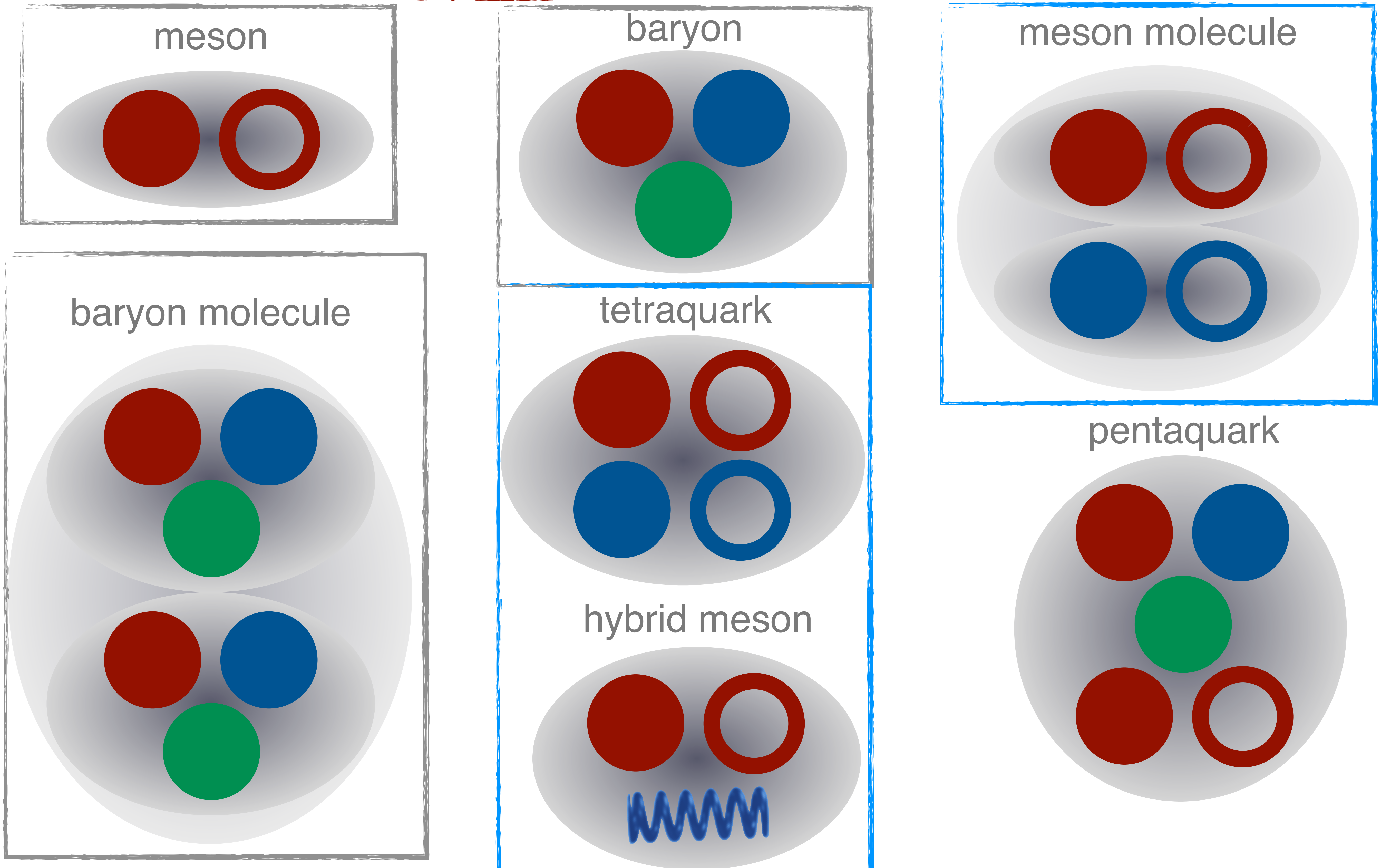
APS GHP
April 10, 2015

Baryons can now be constructed from quarks by using the combinations qqq, $qqq\bar{q}q$, etc, while mesons are made out of $q\bar{q}$, $q\bar{q}q\bar{q}$, etc.

Murray Gell-Mann

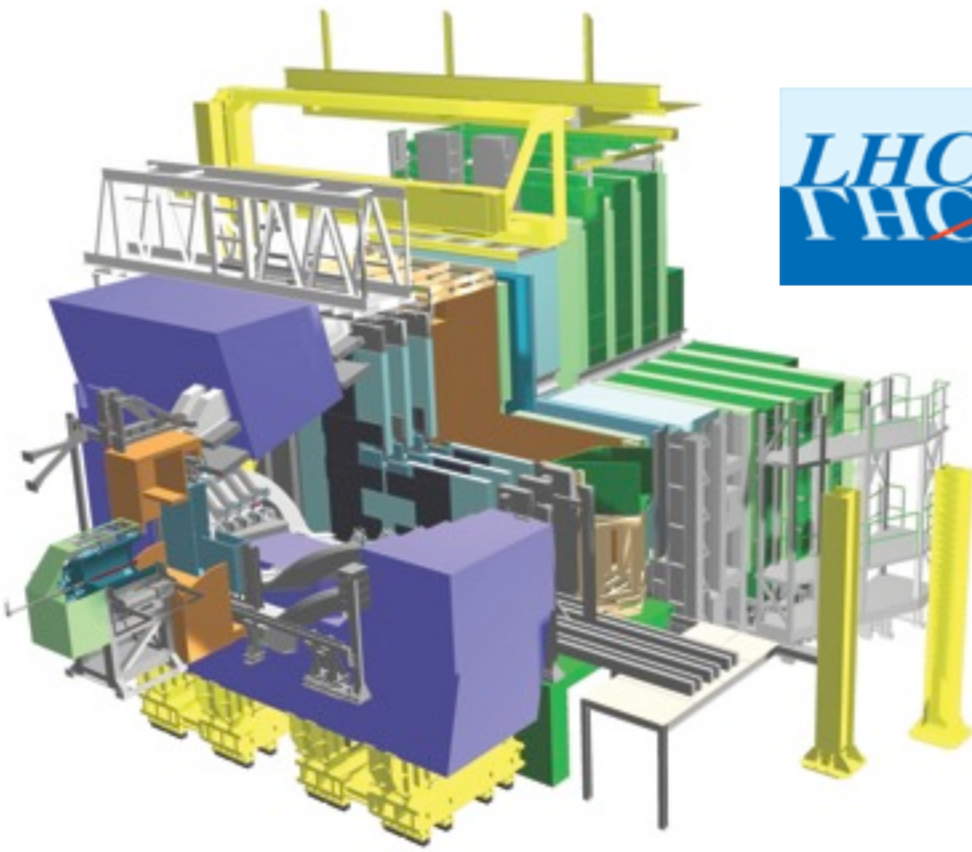
Hadrons



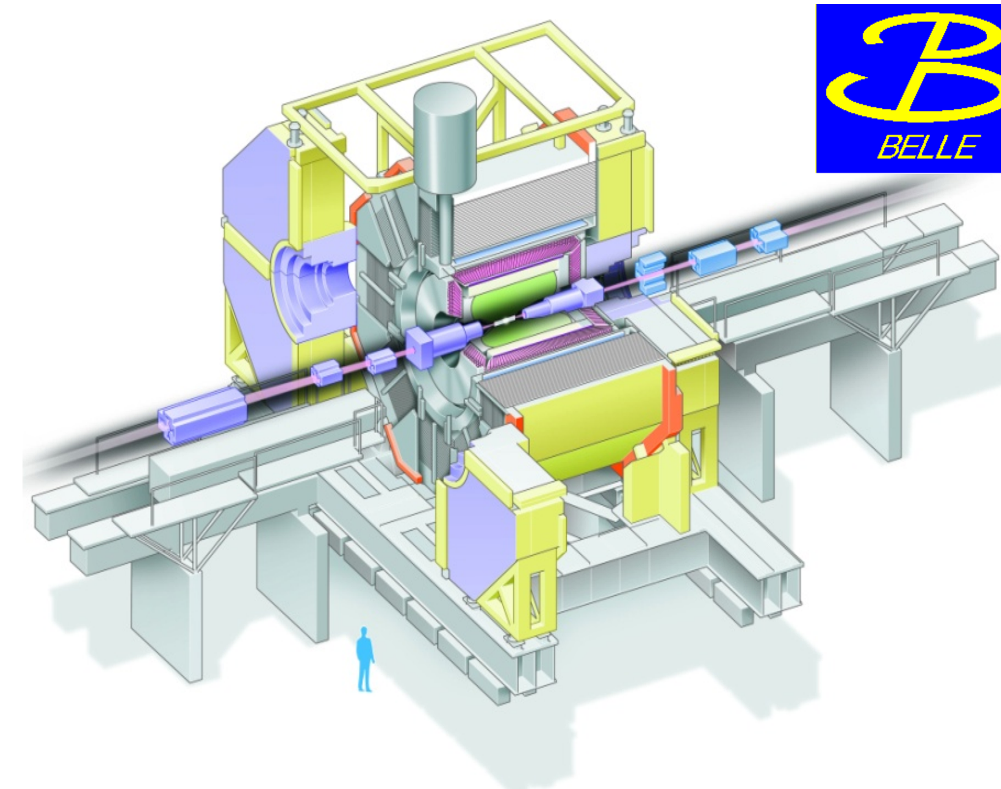
meson
baryon
meson molecule
baryon molecule
tetraquark
hybrid meson
pentaquark

Heavy-Quark Sector

Experiments



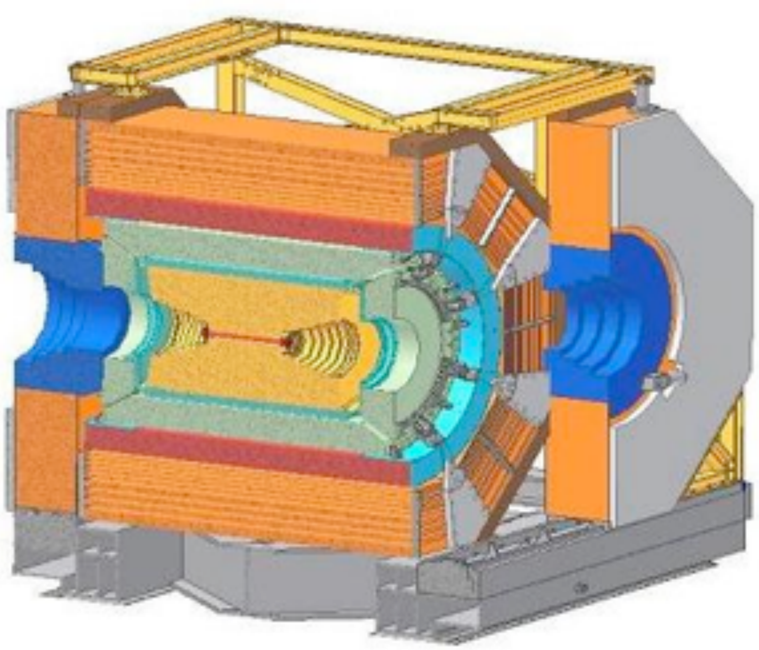
LHCb



BELLE

CDF II

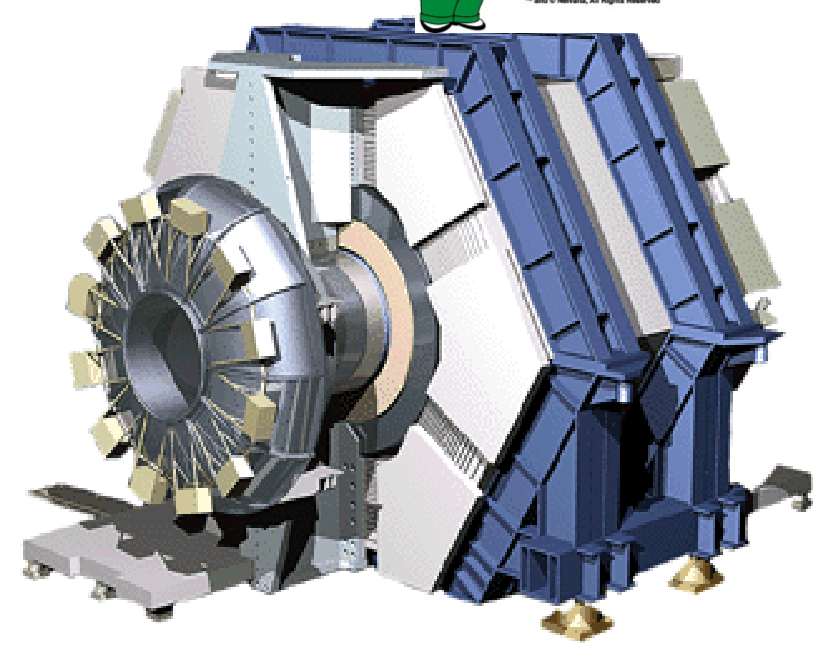
BESIII



DØ

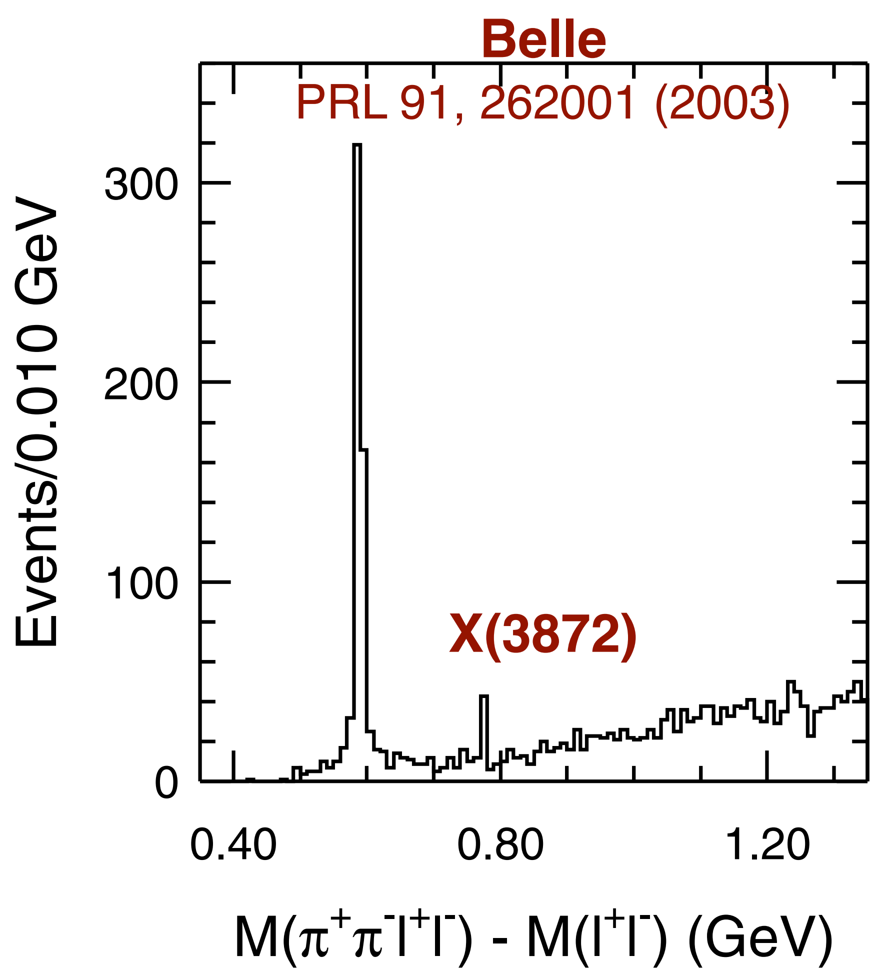
CMS Compact Muon Solenoid

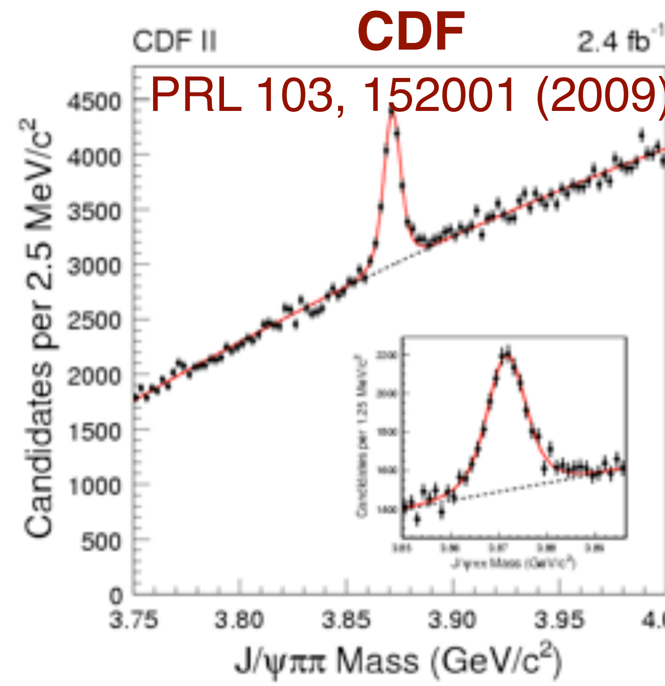
BABAR

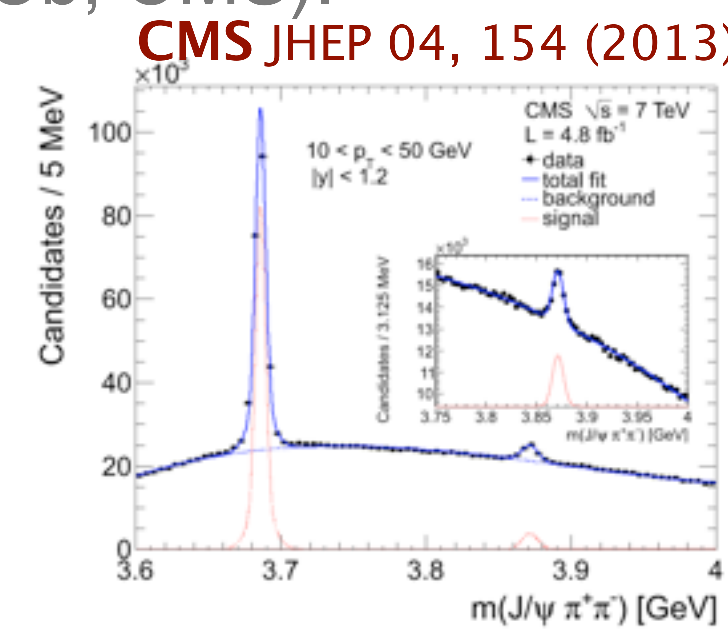


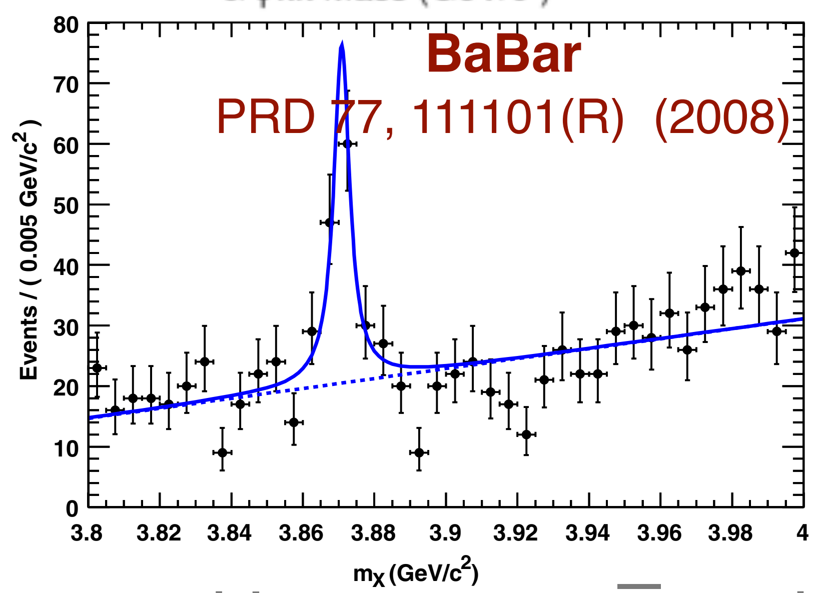
X(3872)

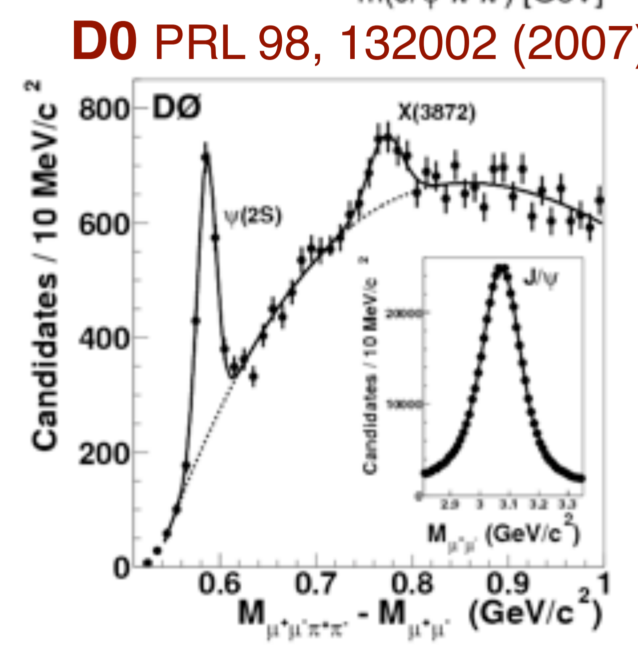
First observed by Belle in 2003 using the decay B→(J/ψππ)K and has now been seen by 6 experiments (Belle, BaBar, CDF, D0, LHCb, CMS).











The X is seen in both B decays and in prompt $p\bar{p}$ and pp production.

X(3872)

Properties of the X(3872):

isospin violation → $J/\psi\rho$, $J/\psi\omega$

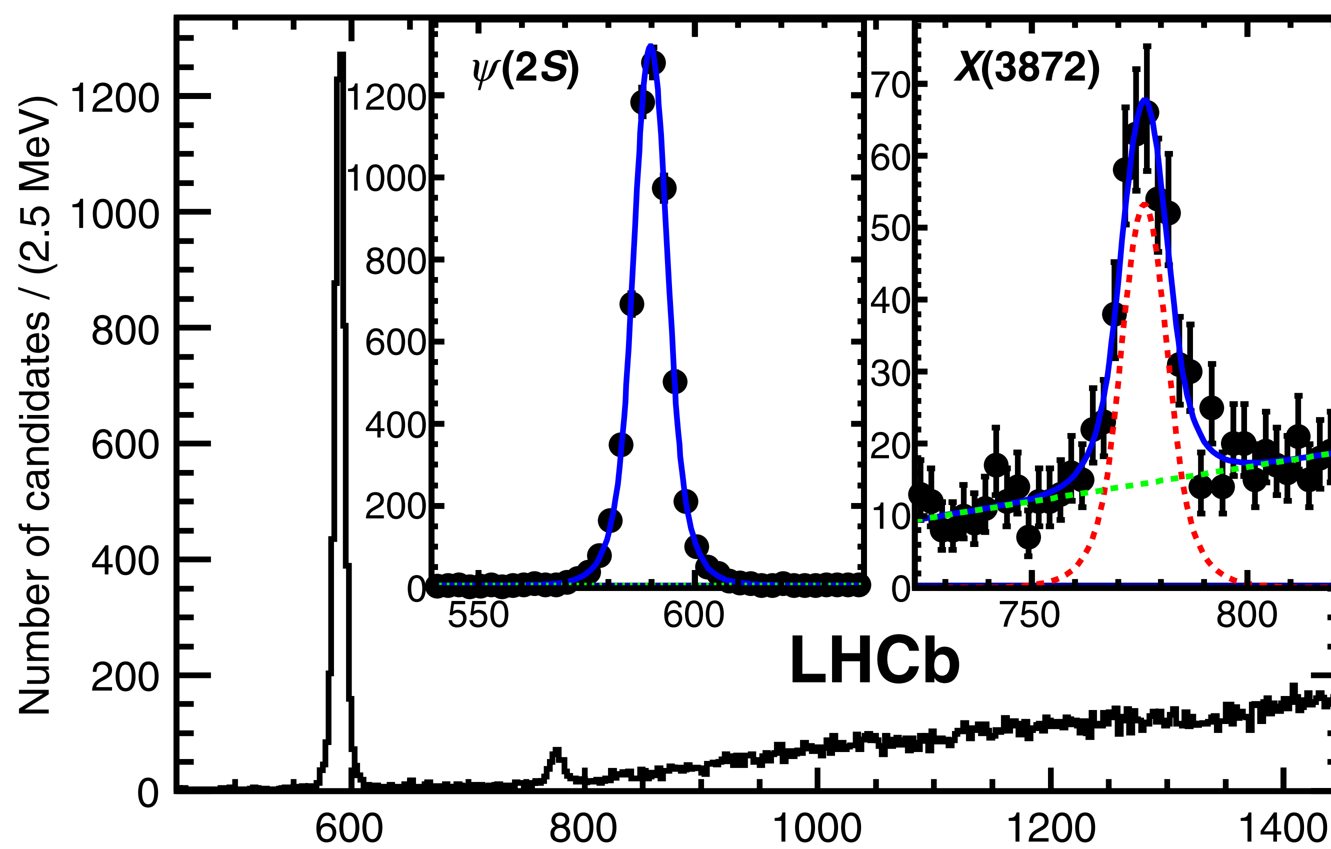
C=+ → $J/\psi\gamma$, $\psi(2S)\gamma$

- Seen decaying into $J/\psi\pi\pi$ (mostly $J/\psi\rho$), $J/\psi\omega$, $D^{*0}D^0$, $J/\psi\gamma$, $\psi(2S)\gamma$.
- M = 3871.68±0.17 MeV [c.f. M(D*)+M(D)=3871.85±0.20 MeV].
- Γ < 1.2 MeV (very narrow).

CDF angular analysis of the decay $B \to X(J/\psi\pi\pi)K$ rules out all but J^{PC} = 1++ and 2-+. PRL 98, 132002 (2007)

LHCb determined the quantum numbers via angular analysis of the decay $B \to X(J/\psi\pi\pi)K$ to be $J^{PC}=1^{++}$.

PRL 110, 222001 (2013) [LHCb-PAPER-2013-001]

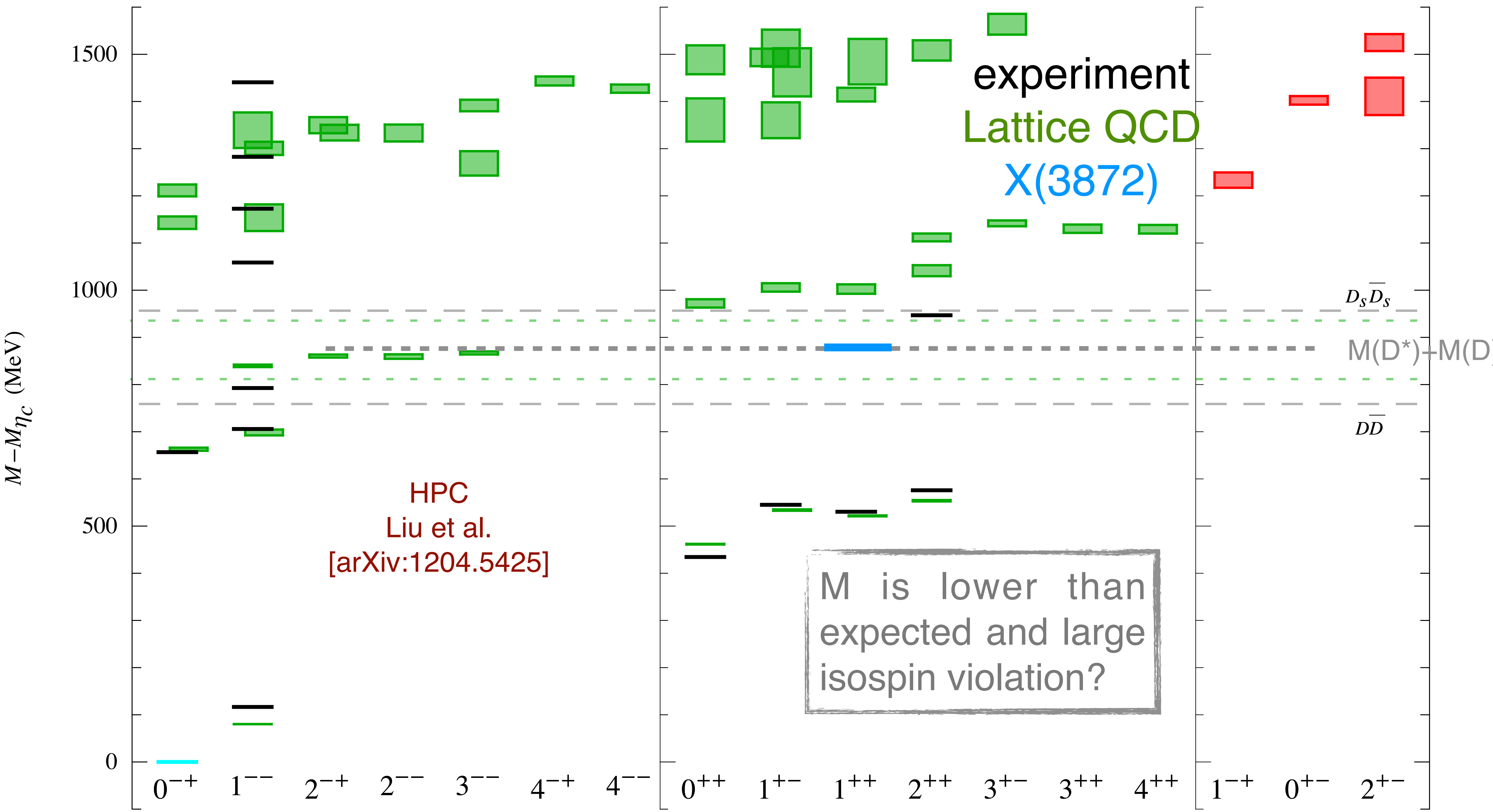


$M(\pi^+\pi^- J/\psi)$ - $M(J/\psi)$ [MeV]

Confirmed this year that higher L states don't spoil this. [LHCb-PAPER-2015-015]

Charmonium

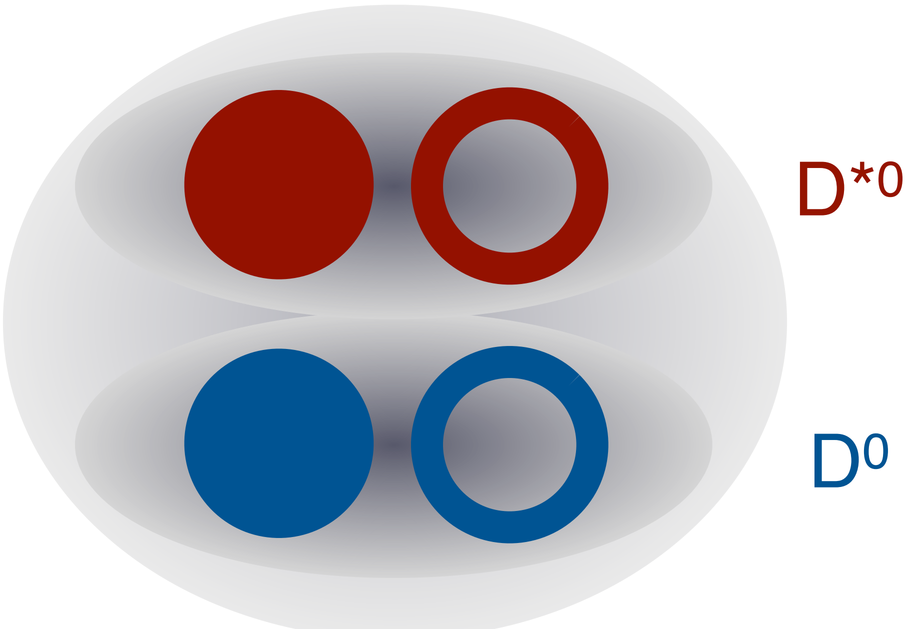
Recent LQCD predictions for the charmonium spectrum:



Not a perfect fit but could be charmonium. Other options?

Molecule

Recall that M(X) = 3871.68±0.17 MeV, while M(D*)+M(D)=3871.85±0.20 MeV. The similarity here immediately sparked interest in the idea that the X is really a meson molecule.

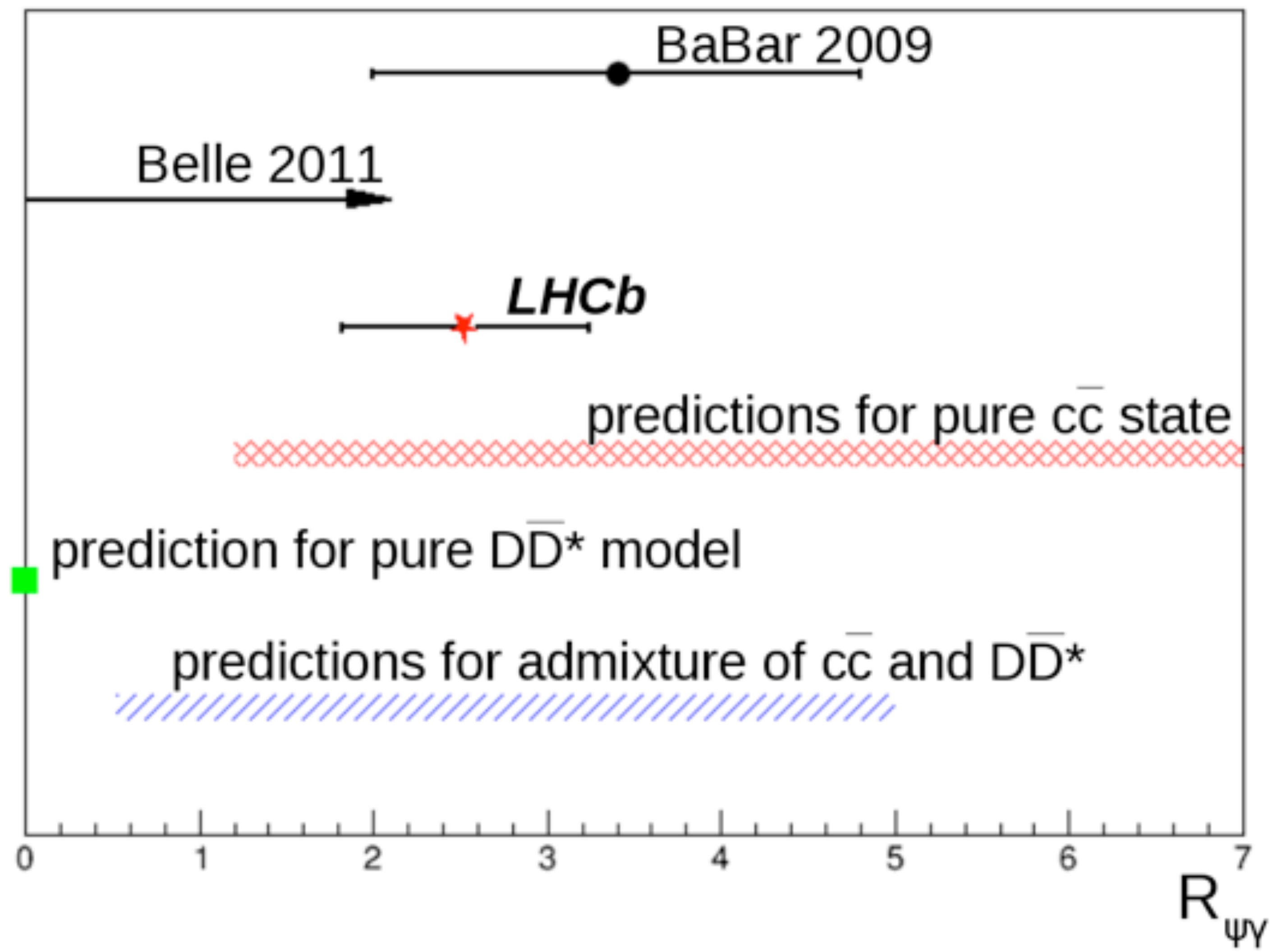


If it is a molecule the binding energy is only 0.17±0.26 MeV ... which means it's huge (bigger than Pb). The quantum numbers are what is needed for this interpretation (prompt production suggestive this is not the true X nature).

Radiative Decays

The ratio $\Gamma(X \to \psi(2S)\gamma)/\Gamma(X \to J/\psi\gamma)$ is a good probe of the internal structure.

LHCb result rules out the pure molecule interpretation of the X(3872).



PRL 102, 132001 (2009)

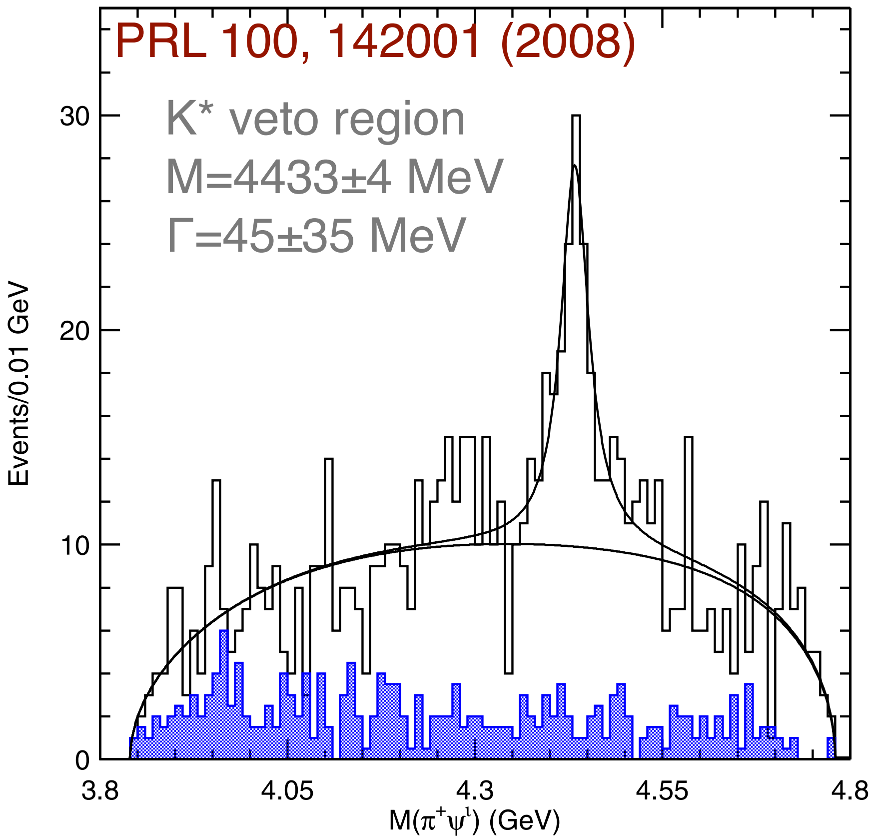
PRL 107, 091803 (2011)

[LHCb-PAPER-2014-008]

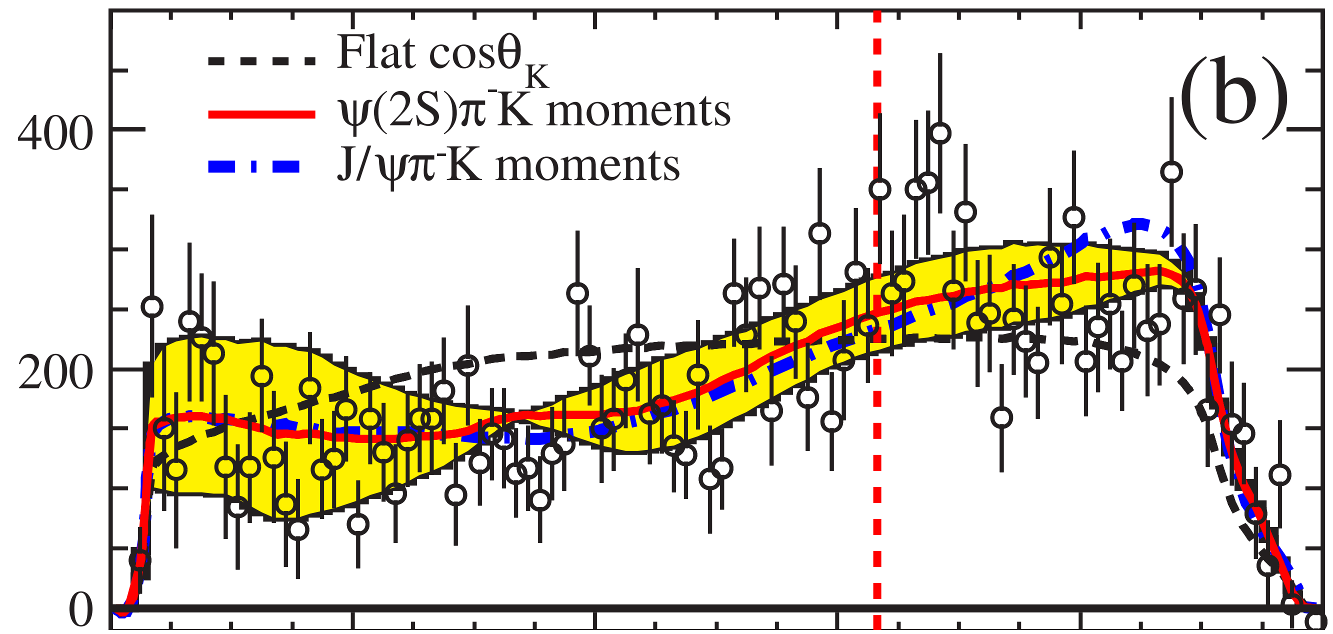
Unlikely to be a tetraquark (where charged partners?), possibly cc+cusp/molecule? See talk by D. Mohler (yesterday) for details on very recent studies of the X(3872) on the lattice.

$Z(4430)^{\pm}$

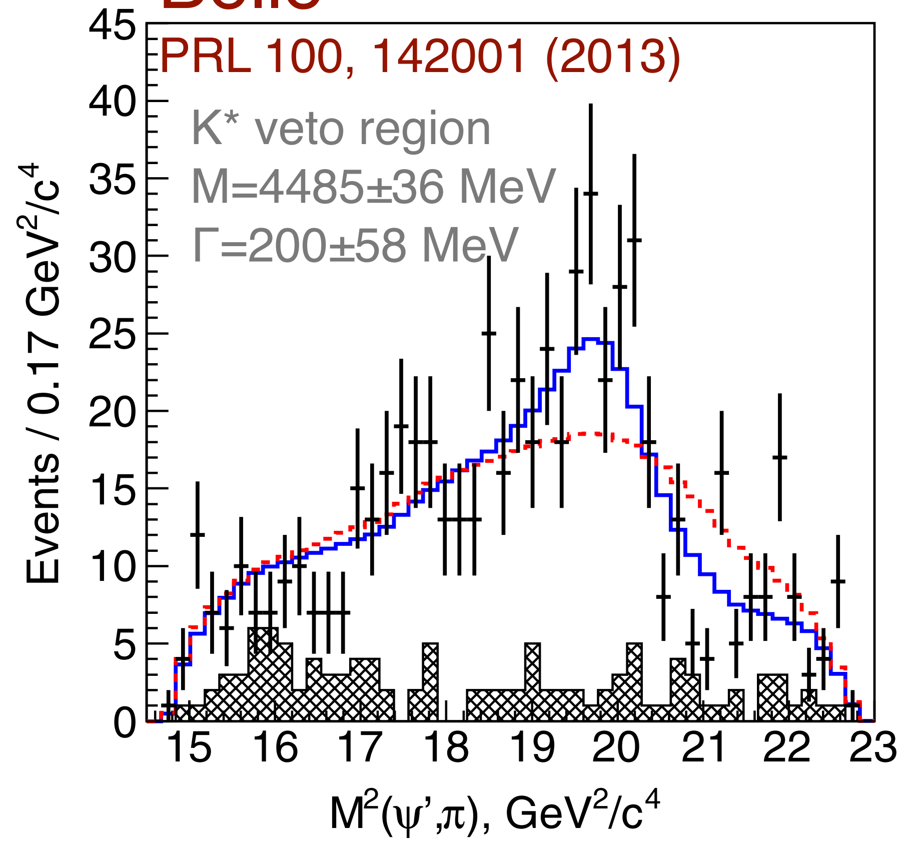
Belle



BaBar, PRD 79, 112001 (2009)



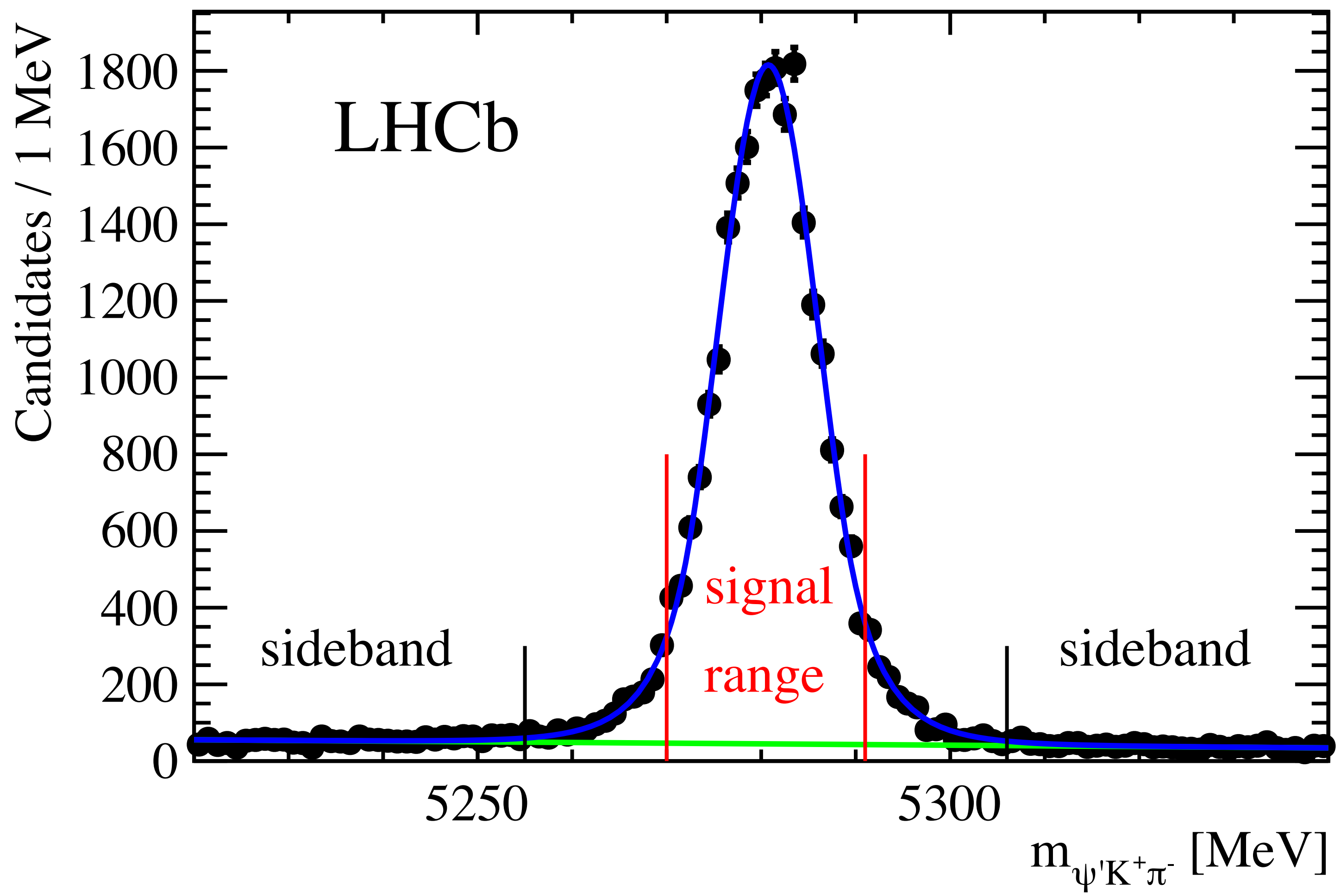
Belle



First seen by Belle in 2008 but not confirmed by BaBar. More recent result from Belle still sees state but looks much different. Model-dependent amplitude analysis prefers $J^P=1^+$ (doesn't rule out all other options).

LHCb has 125k signal candidates (~12x more stats than Belle or BaBar):

$B^0 \rightarrow \psi(2S)K^+\pi^-$ (+c.c.)

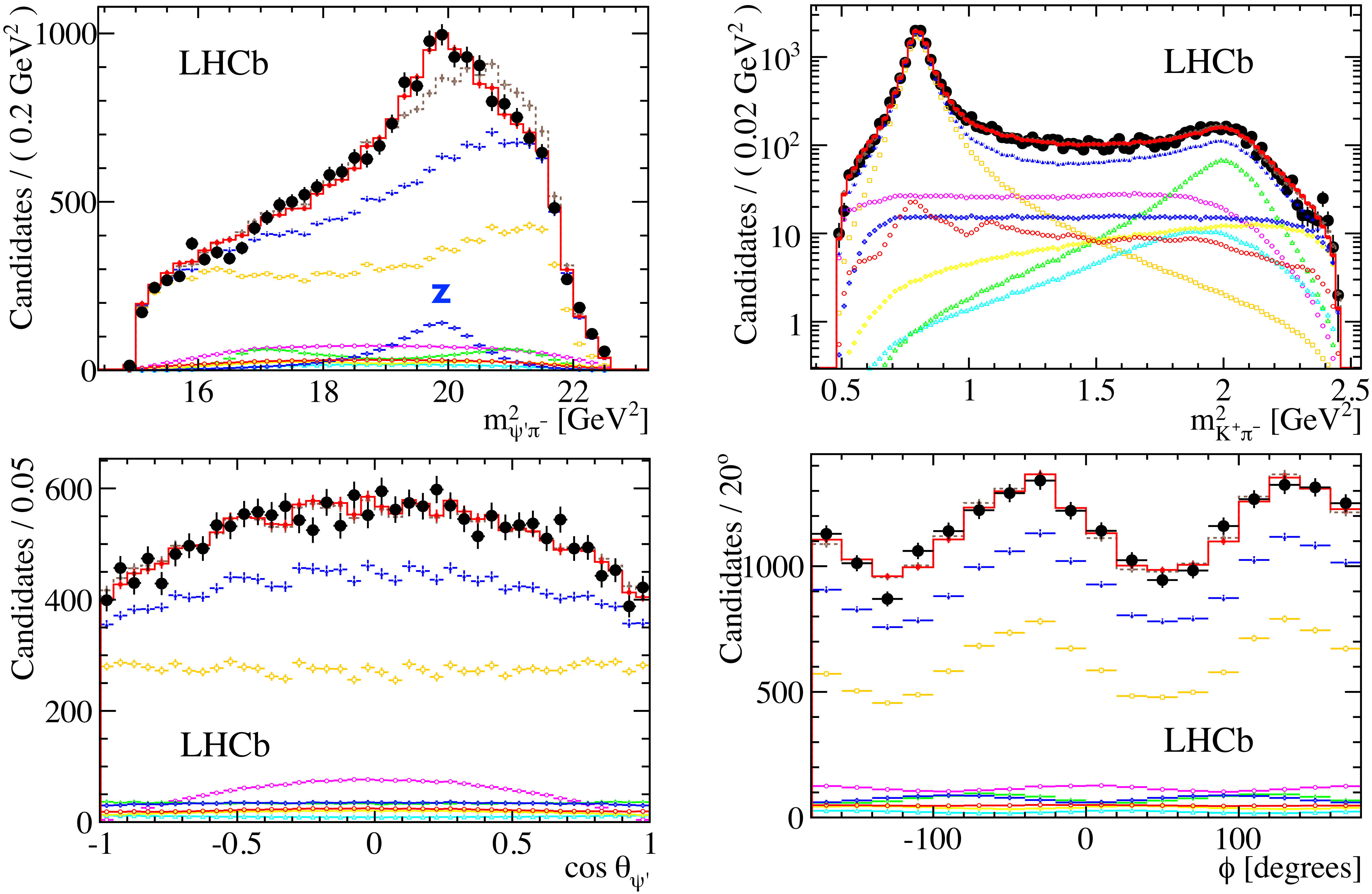


[LHCb-PAPER-2014-014]

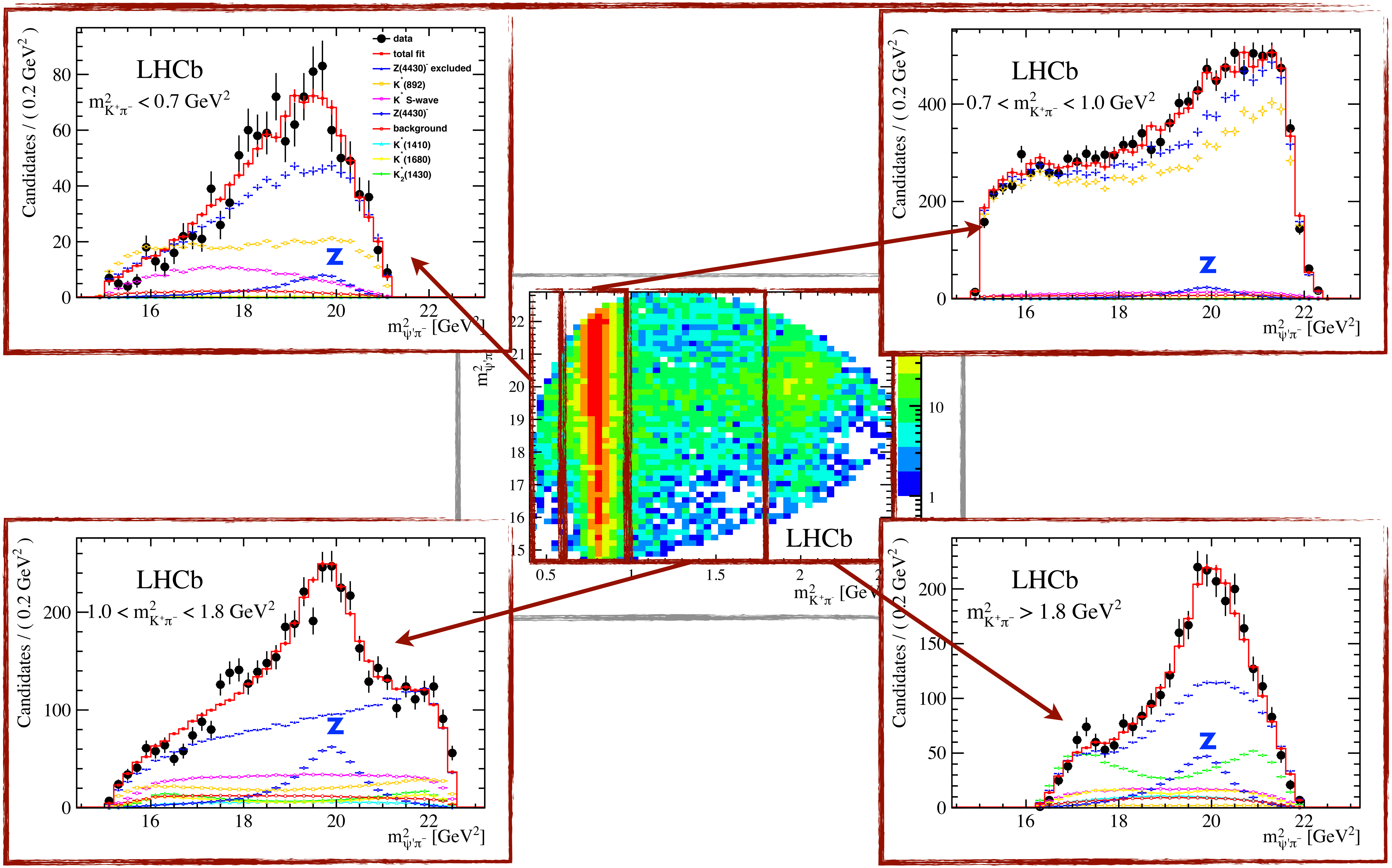
Smaller background than B factories in hostile LHC environment!

Z(4430)±@LHCb

Fit with Z(4430) in (4-D p-value 10^{-6} → 12%):



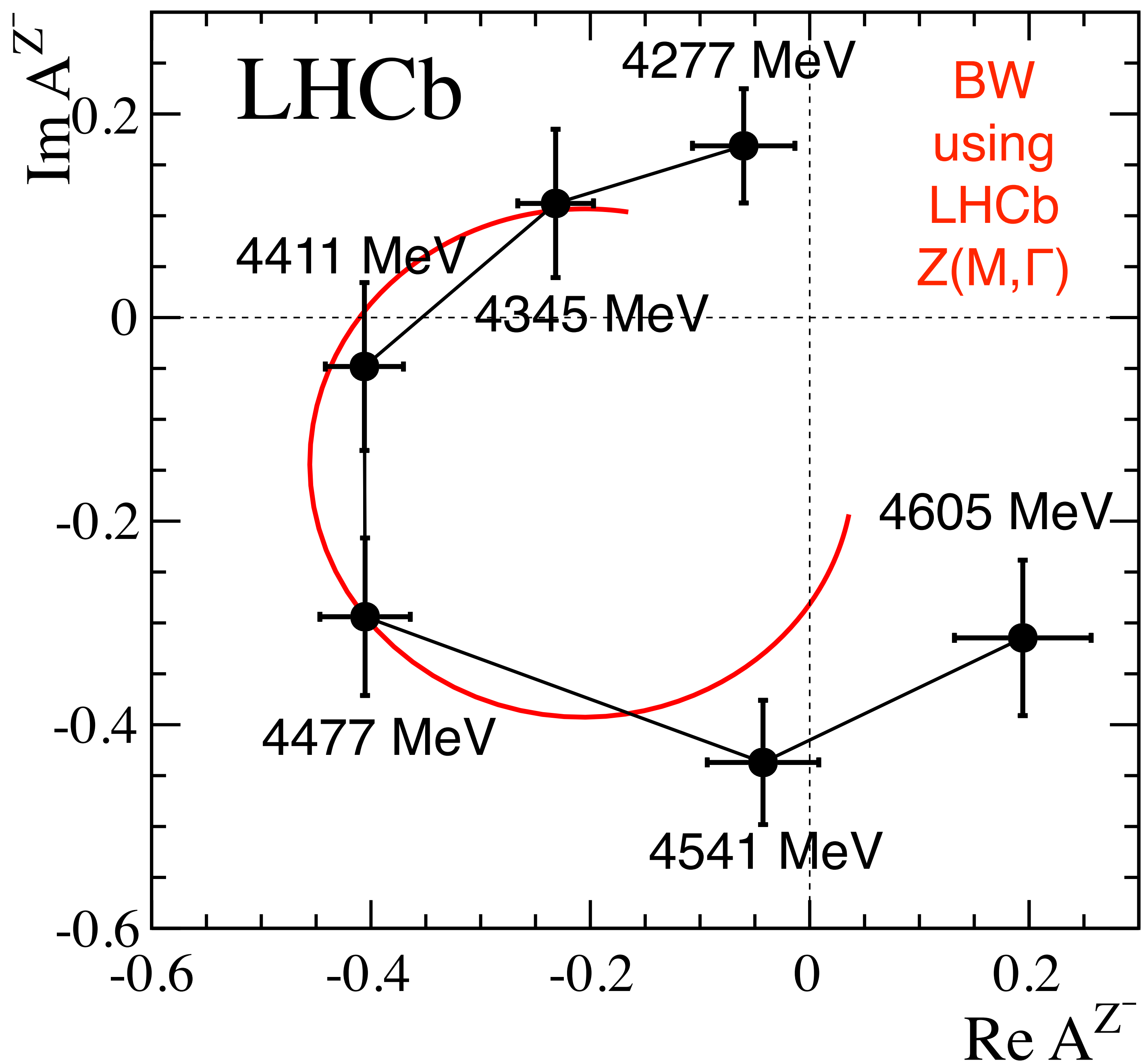
Z(4430)±@LHCb



LHCb
m²K⁺π⁻ < 0.7 GeV²
Candidates / (0.2 GeV²)
m²ψ'π⁻ [GeV²]
data
total fit
Z(4430)⁻ excluded
K*(892)
K* S-wave
Z(4430)⁻
background
K*(1410)
K*(1680)
K*2(1430)
Z
LHCb
0.7 < m²K⁺π⁻ < 1.0 GeV²
Candidates / (0.2 GeV²)
m²ψ'π⁻ [GeV²]
Z
LHCb
1.0 < m²K⁺π⁻ < 1.8 GeV²
Candidates / (0.2 GeV²)
m²ψ'π⁻ [GeV²]
Z
LHCb
m²K⁺π⁻ > 1.8 GeV²
Candidates / (0.2 GeV²)
m²ψ'π⁻ [GeV²]
Z
LHCb
m²K⁺π⁻ [GeV²]

Z(4430)$^{\pm}$@LHCb

Model-independent Z amplitude fits:



LHCb: $J^P = 1^+$.

Belle: $J^P=1^+$ preferred, but 0^- and 1^- not excluded.

Argand diagram shows clear resonant behavior!

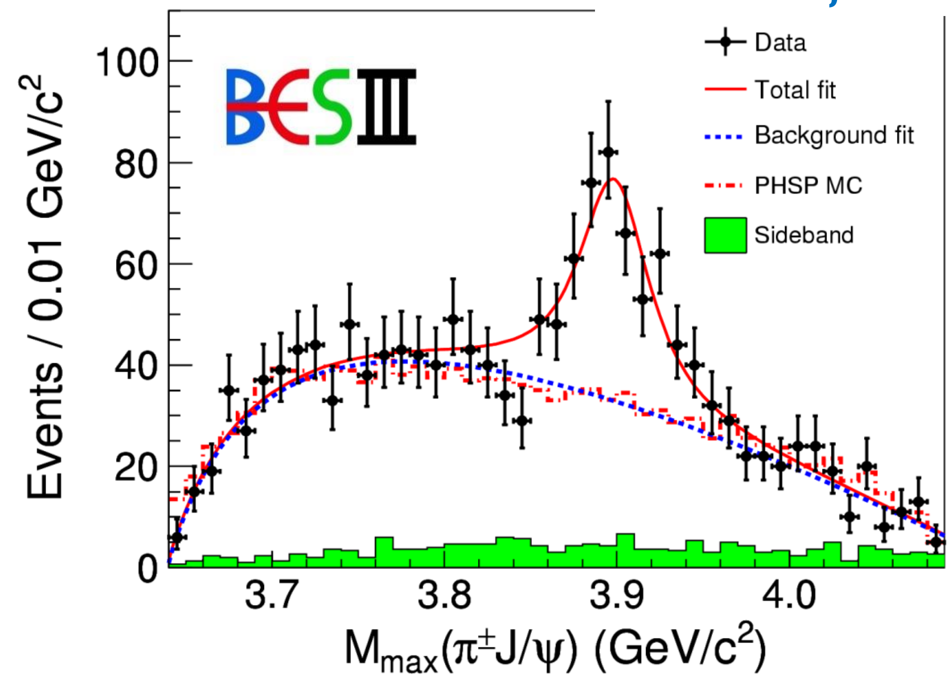
Etc

Many other recent results that I don't have time to cover properly ...

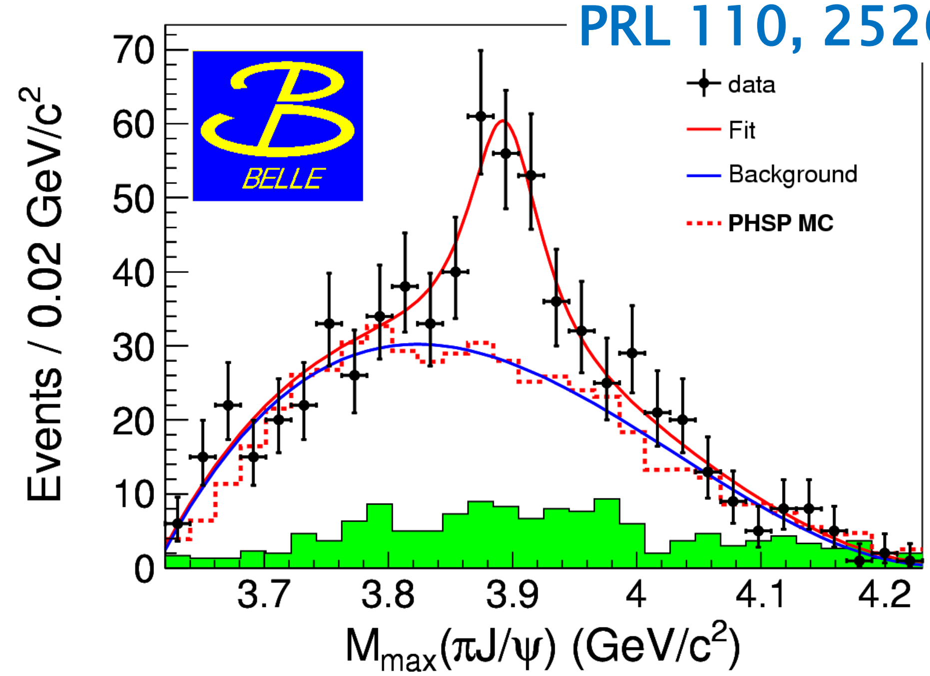
- ❖Belle claims observation of Z(4430)→J/ψπ and a new charged Z(4200) state.
- ❖BES and Belle observe a number of neutral Zc states, e.g., Z(3900).
- ❖Belle also observes Zb states decaying into Υπ and B*B(*).
- ❖Nature of these states is unclear.
- ❖LHCb has observed many new cs, cl, bl and bll (l=u,d) states in largely unexplored territory.

It's Particle_Zoo_v2.0 in heavy flavor ...

PRL. 110, 252001



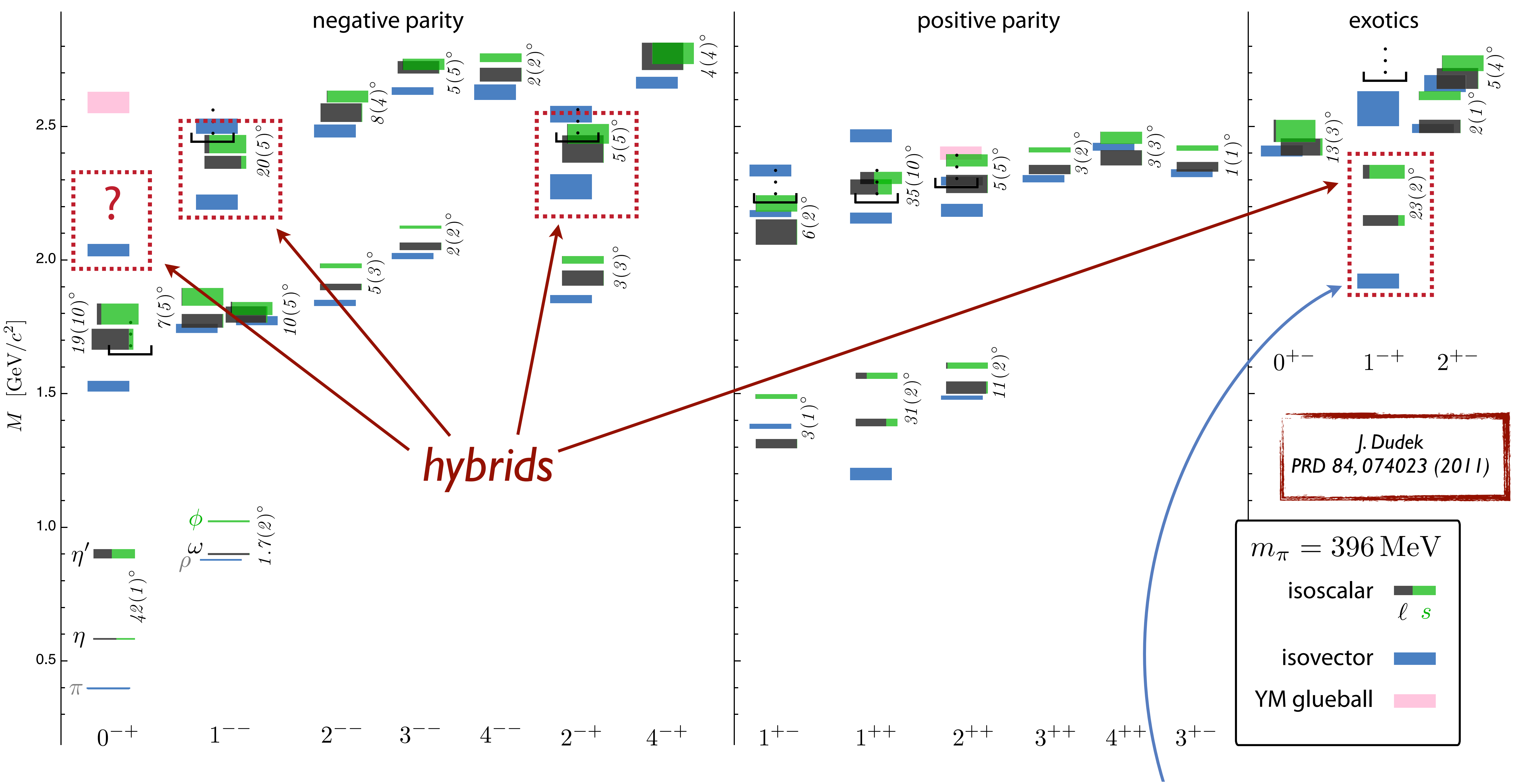
PRL 110, 252002



Light-Quark Sector

Lattice QCD

Hybrids: light-quark sector expect 3 iso-vector + 2 iso-scalar states for each J^P.



Experimental evidence for π_1 pole(s) (see Meyer, Van Haarlem [1004.5516]).

Hybrid Decays

Key exotic hybrid decay modes

LQCD | Models | high-priority modes

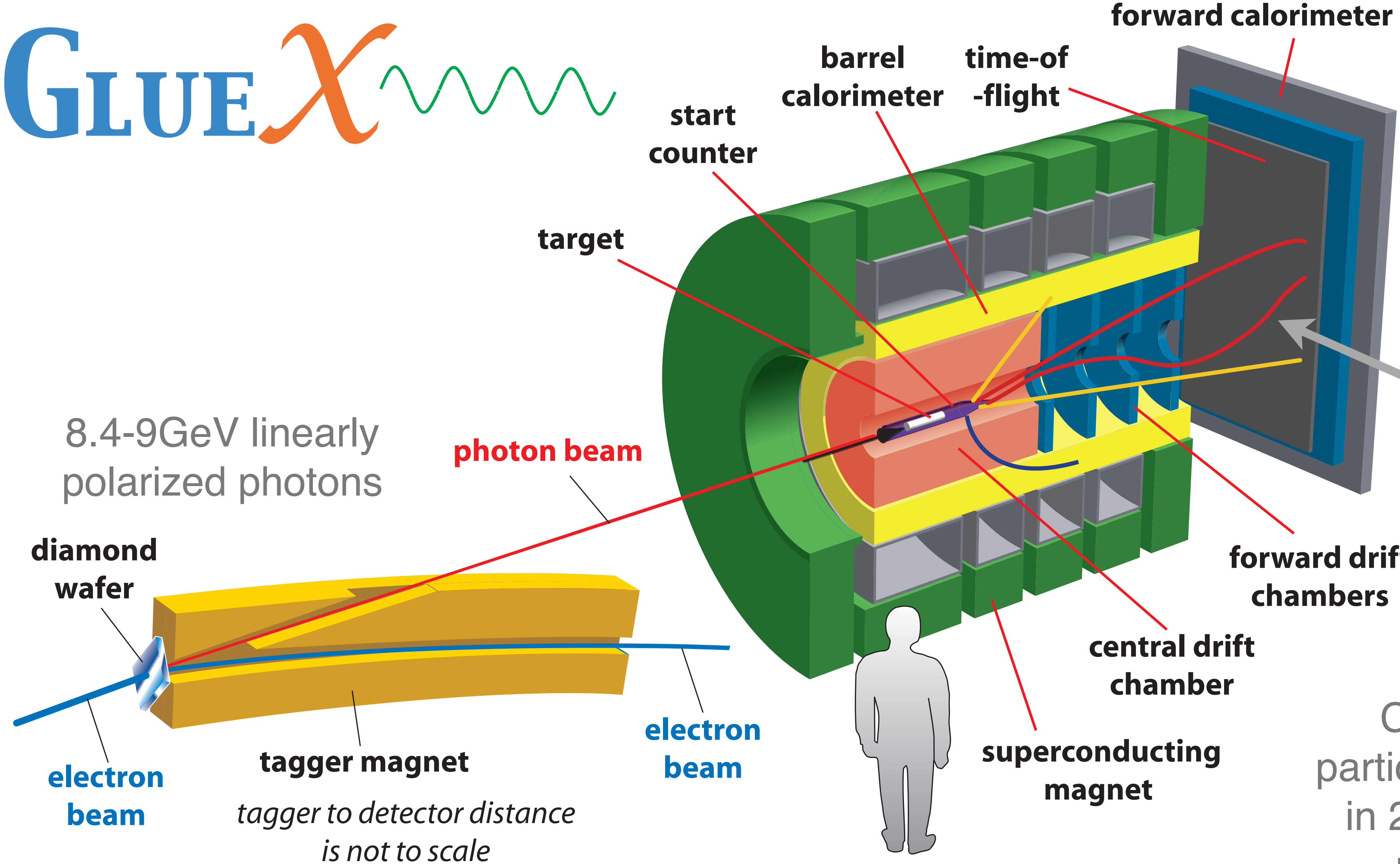
	Approximate Mass (MeV)	J^{PC}	Total Width (MeV) PSS	IKP	Relevant Decays	Final States
π_1	1900	1^{-+}	80 – 170	120	$b_1\pi^\dagger$, $\rho\pi^\dagger$, $f_1\pi^\dagger$, $a_1\eta$, $\eta'\pi^\dagger$	$\omega\pi\pi^\dagger$, $3\pi^\dagger$, 5π, $\eta 3\pi^\dagger$, $\eta'\pi^\dagger$
η_1	2100	1^{-+}	60 – 160	110	$a_1\pi$, $f_1\eta^\dagger$, $\pi(1300)\pi$	4π, $\eta 4\pi$, $\eta\eta\pi\pi^\dagger$
η_1'	2300	1^{-+}	100 – 220	170	$K_1(1400)K^\dagger$, $K_1(1270)K^\dagger$, $K^*K^\dagger$	$KK\pi\pi^\dagger$, $KK\pi^\dagger$, $KK\omega^\dagger$
b_0	2400	0^{+-}	250 – 430	670	$\pi(1300)\pi$, $h_1\pi$	4π
h_0	2400	0^{+-}	60 – 260	90	$b_1\pi^\dagger$, $h_1\eta$, $K(1460)K$	$\omega\pi\pi^\dagger$, $\eta 3\pi$, $KK\pi\pi$
h_0'	2500	0^{+-}	260 – 490	430	$K(1460)K$, $K_1(1270)K^\dagger$, $h_1\eta$	$KK\pi\pi^\dagger$, $\eta 3\pi$
b_2	2500	2^{+-}	10	250	$a_2\pi^\dagger$, $a_1\pi$, $h_1\pi$	4π, $\eta\pi\pi^\dagger$
h_2	2500	2^{+-}	10	170	$b_1\pi^\dagger$, $\rho\pi^\dagger$	$\omega\pi\pi^\dagger$, $3\pi^\dagger$
h_2'	2600	2^{+-}	10 – 20	80	$K_1(1400)K^\dagger$, $K_1(1270)K^\dagger$, $K_2^*K^\dagger$	$KK\pi\pi^\dagger$, $KK\pi^\dagger$

†*experimentally promising: few particles or narrow isobars*

modes where K/π separation is vital

Experimental requirements: ability to identify multi-body final states; large stats; and excellent PID.


Jefferson Lab
Solenoid
BCAL
CDC
FDC
TOF
FCAL



8.4-9GeV linearly polarized photons

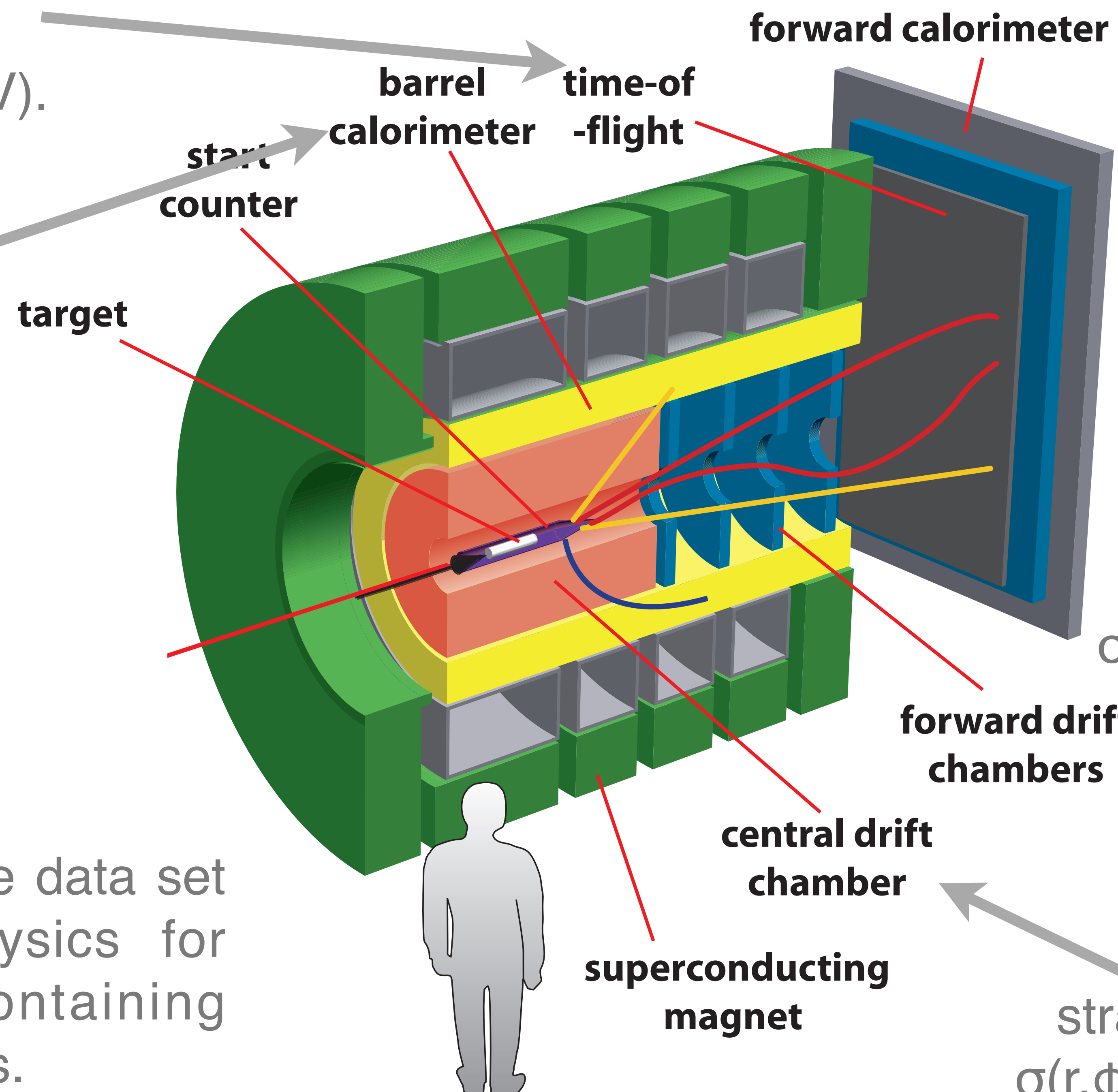
PID upgrade to go here

Charged particle tracking in 2T B field; photon detection.

GlueX

horizontal+vertical scintillator array:
σ = 70 ps
(K/π separation up to ~2.5 GeV).

Pb/scintillating fiber matrix:
σ/E = 5%/√E⊕1%



Pb glass:
σ/E =
6%/√E⊕2%

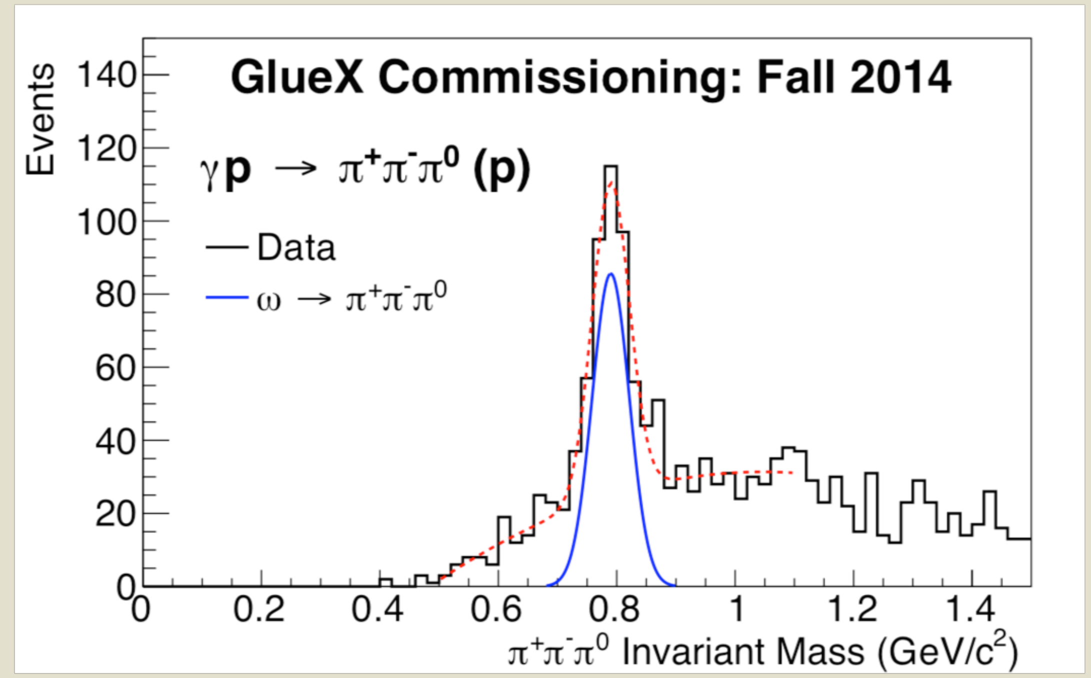
4x6 cells:
σ(x,y)=0.2mm

straw tubes:
σ(r,ϕ)=0.15mm;
σ(z)=1.5mm.

GlueX will provide an immense data set for studying light-quark physics for many-body final states containing charged and/or neutral particles.

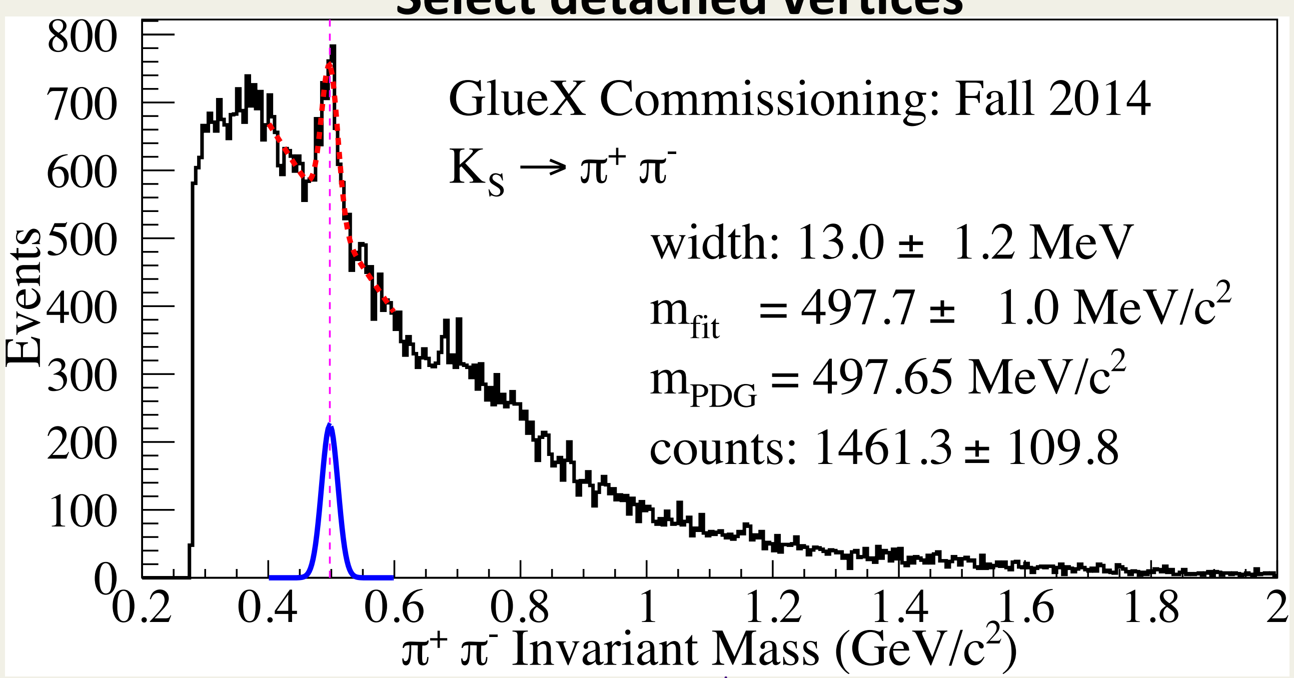
Commissioning

GlueX February 2015

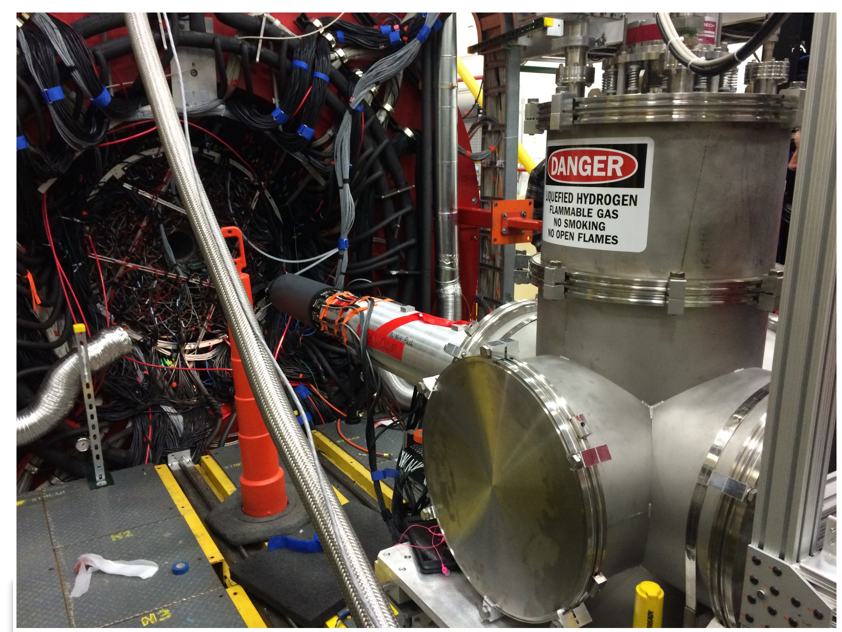


$\omega \to \pi^+\pi^-\pi^0$

Select detached vertices



$K_S \to \pi^+\pi^-$



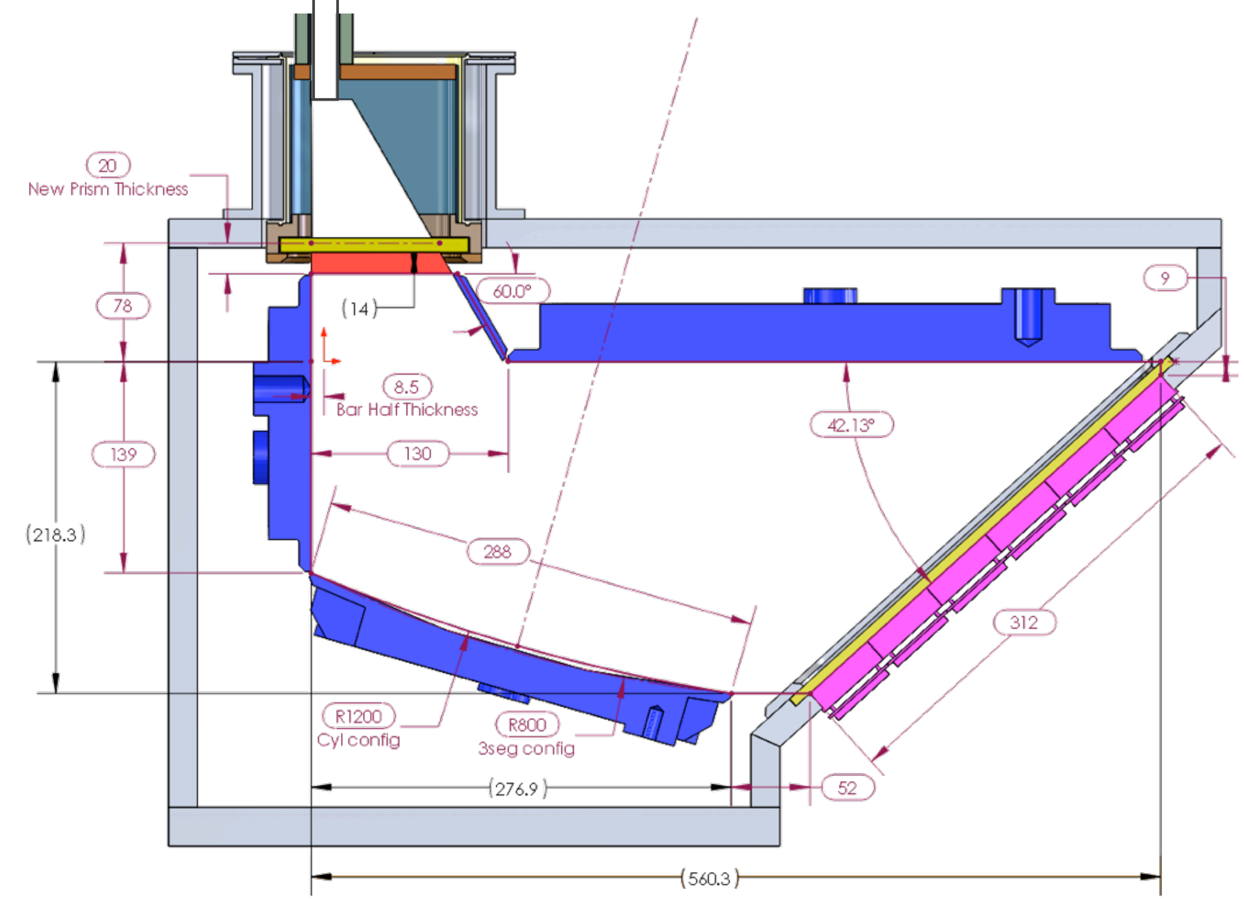
Start Counter mounted to LH2 target prior to installation in GlueX, February 2015

GlueX

Physics data expected this year!

- identify exotic and super-numerary non-exotic mesons in the spectrum;
- measure masses and widths of isovector and isoscalar hybrids;
- study internal quark structure by studying strange and non-strange decay modes;
- provide stringent tests of LQCD and various QCD models.

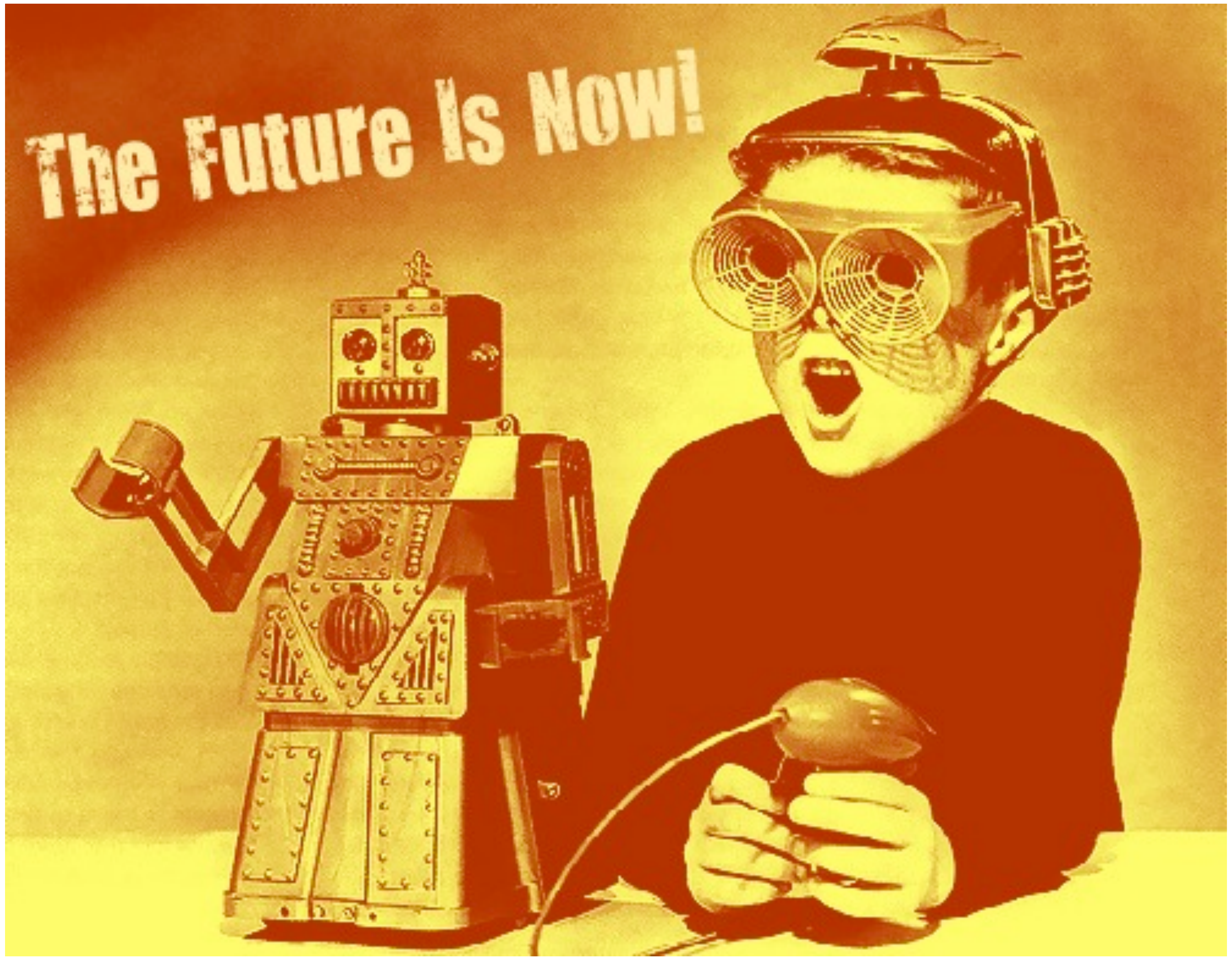
PID upgrade using the BaBar DIRC bars + focusing box.



There are also studies ongoing for an upgraded calorimeter that would expand the physics program to include rare η(‘) decays.

Summary

Many interesting developments in exotic spectroscopy in the heavy-quark sector in the past few years ... and with the LHC turning back on, Belle II soon to take data, and BESIII continuing to run, many more are expected.



A new precision era in light-quark spectroscopy in the “interesting” region (for hybrids) is about to begin at GlueX. The next few years should be interesting!