

Hadron physics experimental overview

-- Selected Aspects of Production and Spectroscopy

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**38th INTERNATIONAL CONFERENCE
ON HIGH ENERGY PHYSICS**

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Disclaimer

Due to the lack of time, (there are ~15 talks with wide range topics), I left out:

- Hadron production in media
- Conventional hadron decays
- Gluonic excitations
- Fragmentations

[1644] Exotic hadrons at the LHC (25' + 5')	ZHANG, Liming
[1645] Exotic hadrons at the Tevatron (15' + 5')	ZIEMINSKA, Daria
[1646] b-hadron production at ATLAS and CMS (20' + 5')	DE LA CRUZ BURELO, Eduard
[1647] b-hadron production at LHCb (15' + 5')	ARTUSO, Marina
[1648] charm-hadron production at BES-III (15' + 5')	WATSON, Miriam
[1652] Hadron spectroscopy at BES-III (15' + 5')	JIN, Shan
[1653] Results from e+e- collisions at BES-III (15' + 5')	MITCHELL, Ryan
[1654] Production of exotic hadrons and charmonium at Belle/Babar (12' + 3')	KINOSHITA, Kay
[1287] Charmonia and bottomonia decays at Belle/Babar (12' + 3')	KOWALEWSKI, Bob
[1624] Latest independent measurements of the Collins asymmetries as a function of energy and transverse momentum for kaons and pions at BABAR (8' + 2')	VASSEUR, Georges
[625] First observation of K+ and pi+K- atoms, their lifetime measurement and pi+K- scattering length evaluation. (12' + 3')	MORICCIANI, Dario
[1296] First observation of K+ and pi+K- atoms, their lifetime measurement and pi+K- scattering length evaluation. (12' + 3')	MARCHEVSKI, Radoslav
[122] X(3872) search for its bottomonium counterpart at the LHC (20' + 5')	AFANASYEV, Leonid
[627] Neutral pion form factor measurement by the NA62 experiment (12' + 3')	TOMS, Konstantin
	GOUDZOVSKI, Evgueni

- ✓ Cross section measurements
 - Quarkonium polarization
 - Associate production
 - Dependence of multiplicity

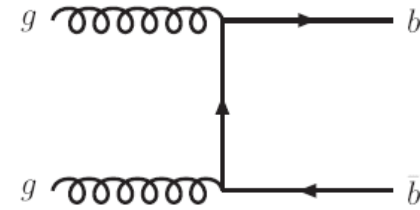
Stay tuned for Halina' s talk

HEAVY-FLAVOR PRODUCTION

- Probe both perturbative and non-perturbative aspects of QCD calculations
- Crucial to modeling backgrounds for precise measurements & discoveries

Charmonium production

Non-prompt (from B-hadron decays) – probes open b quark production, fragmentation and B-decay kinematics



Theoretical approaches for open-heavy-flavor production:

FONLL: matched NLO+NLL (“massive” NLO + resummation) *perturbative*

GM-VFNS: (“massless” NLO + mass-dependent terms)

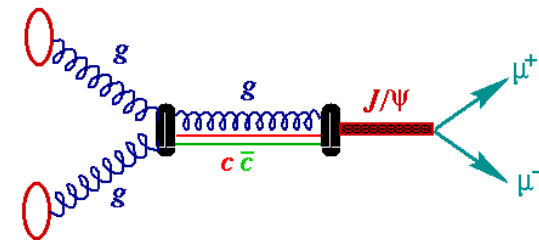
Prompt (Produced directly or through feed-down decays from higher charmonium states) – probes specific mechanisms of $Q\bar{Q}$ system production and transformation to a meson

Theoretical approaches for Quarkonium production:

NRQCD: Color Singlet (CS) and Color Octet (CO) terms. Long-distance matrix elements (LDME) determined from experimental data

Color Singlet Model (CSM): only CS diagrams

Color Evaporation Model (CEM): only one LDME

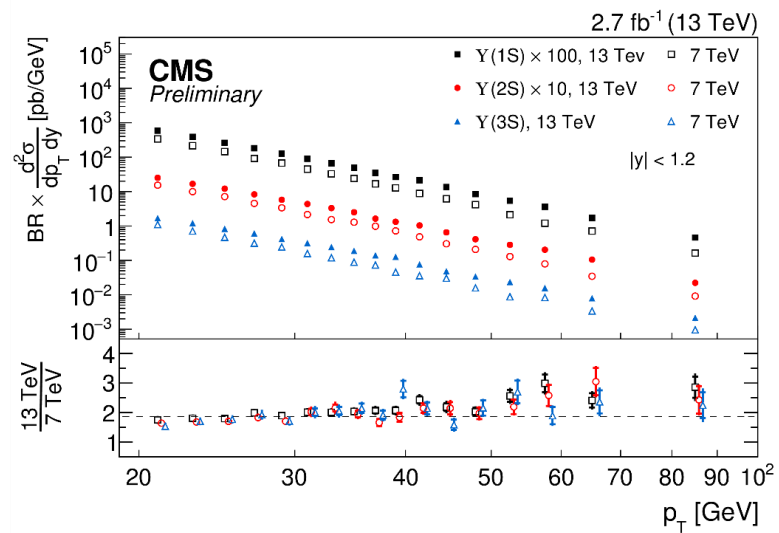
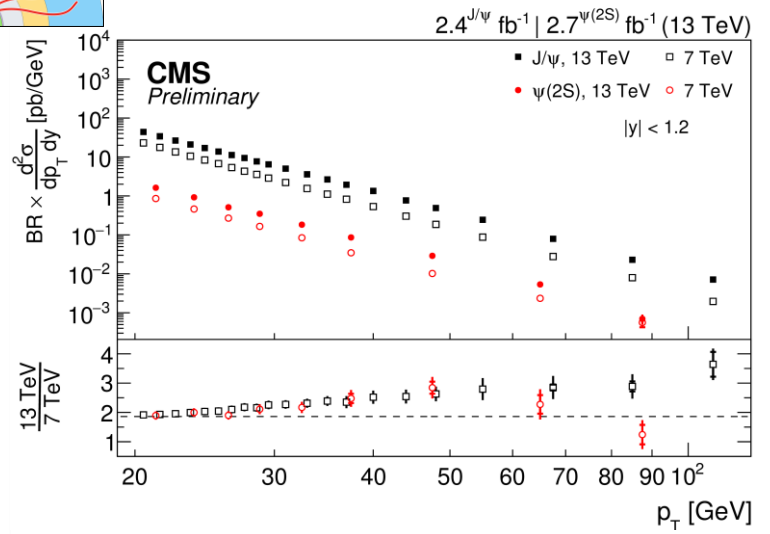


Factorization between a $Q\bar{Q}$ pair production (perturbative) and its binding (non-perturbative)

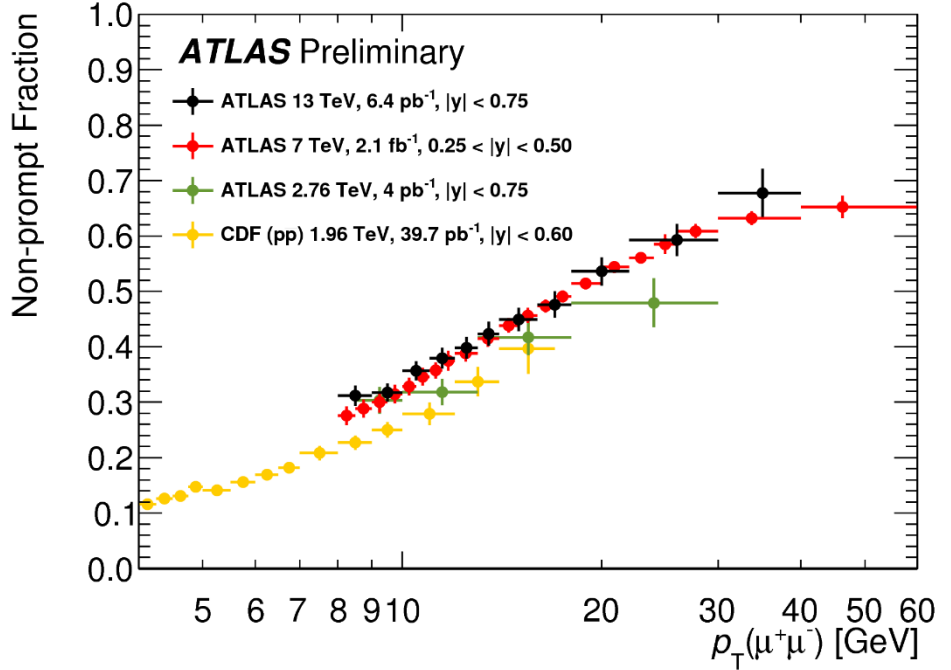
Quarkonium cross section and non-prompt fraction, 13 TeV



CMS-PAS-BPH-15-005



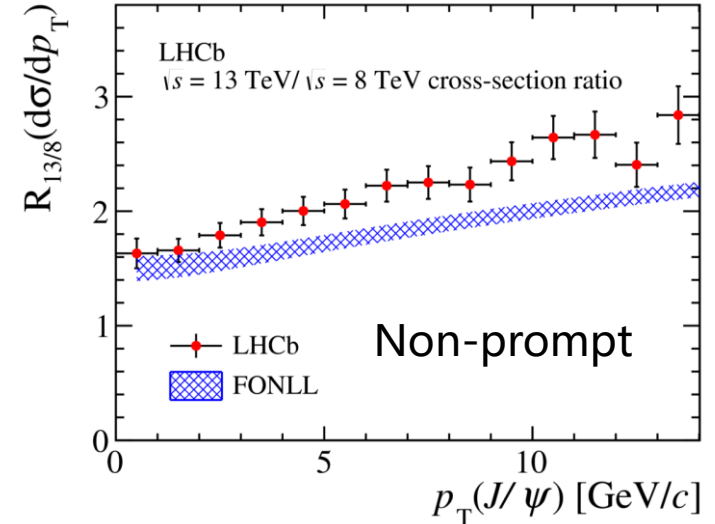
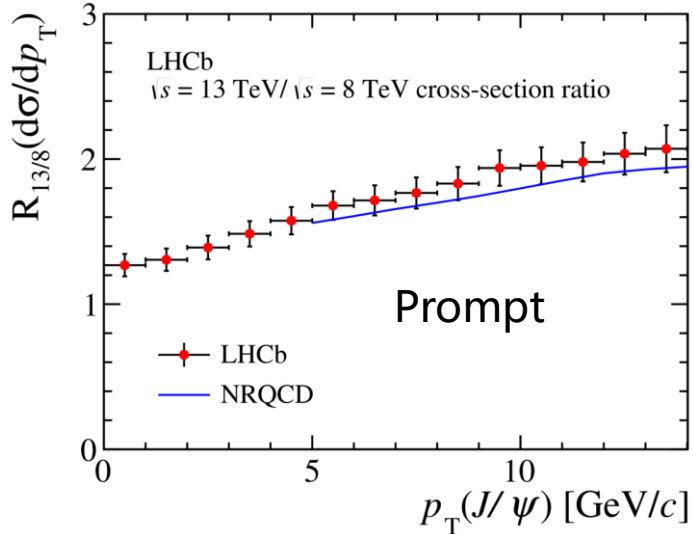
ATLAS-CONF-2015-030



Test factorization and NRQCD Constraints for PDFs

Forward J/ψ production at 13 TeV

JHEP10(2015)172

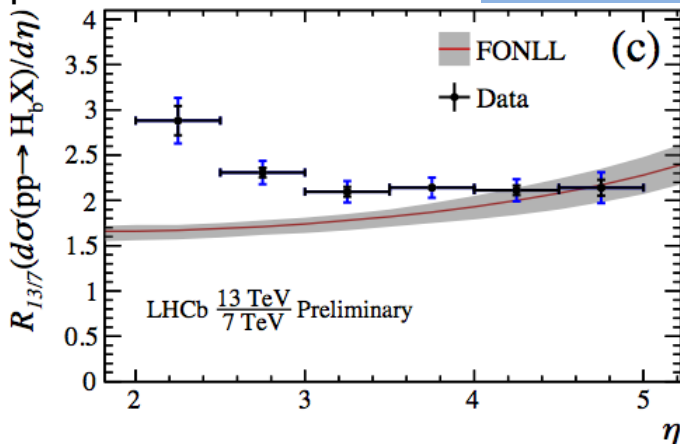


13 TeV / 8 TeV: NRQCD reasonable agreement, FONLL below data

$b\bar{b}$ cross-section at 13 TeV from $b \rightarrow X_c \mu \nu X$

LHCb-paper-2016-031
 In preparation

[Artuso](#)



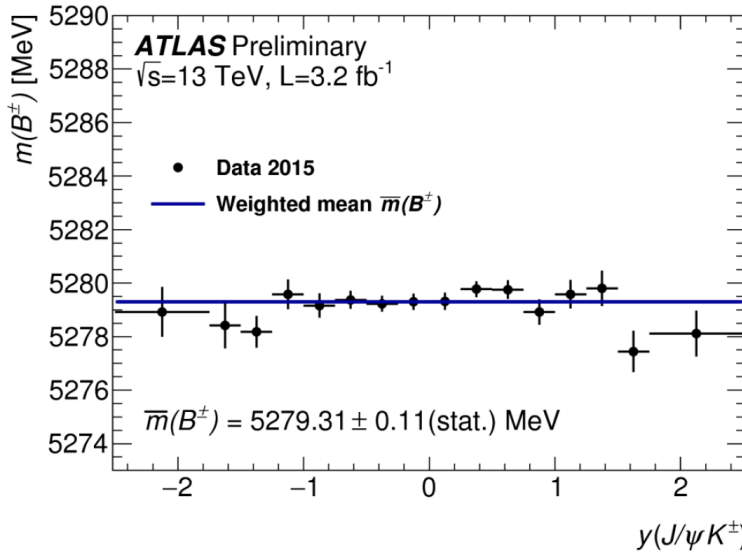
Measured ratio	Predicted ratio (FONLL)
$2.30 \pm 0.25 \pm 0.19$	$1.79^{+0.21}_{-0.15}$

Some theory-experiment tensions in cross-section ratios at low η

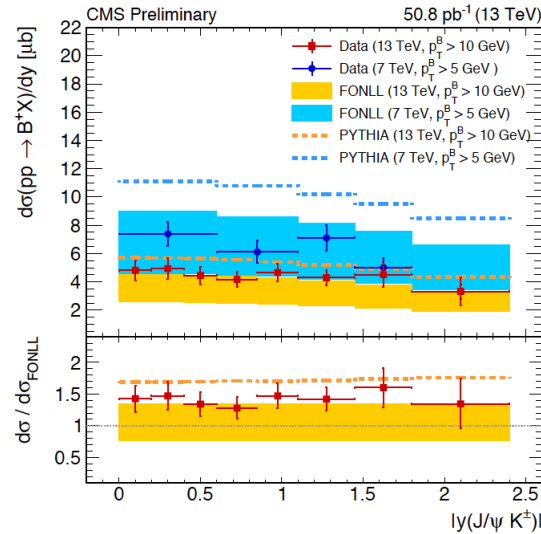
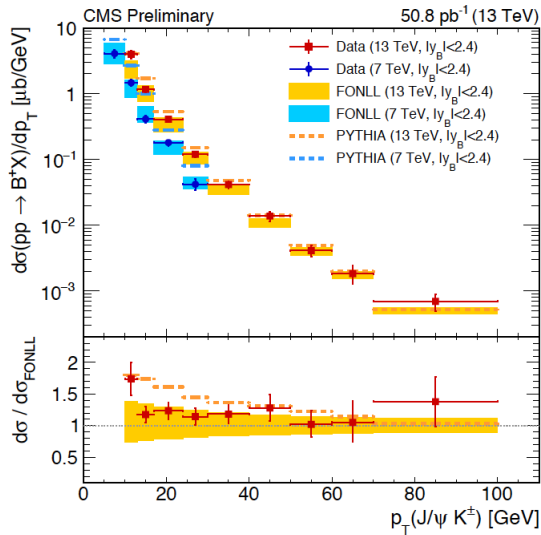
Beauty meson production: $B^+ \rightarrow J/\psi K^+$, 13 TeV



ATLAS-CONF-2015-064



Fit	B^\pm mass [MeV]	Fit error [MeV]
Default Fit	5279.31	0.11 (stat.)
$L_{xy} > 0.2$ mm	5279.34	0.09 (stat.)
World Average fit	5279.29	0.15
LHCb	5279.38	0.11 (stat.) \pm 0.33 (syst.)



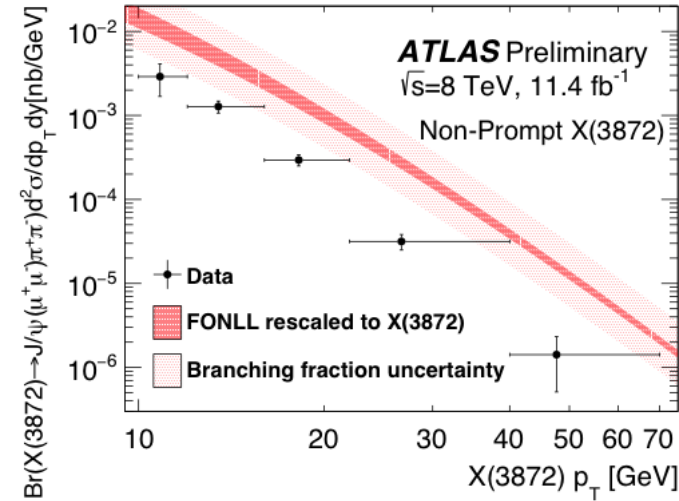
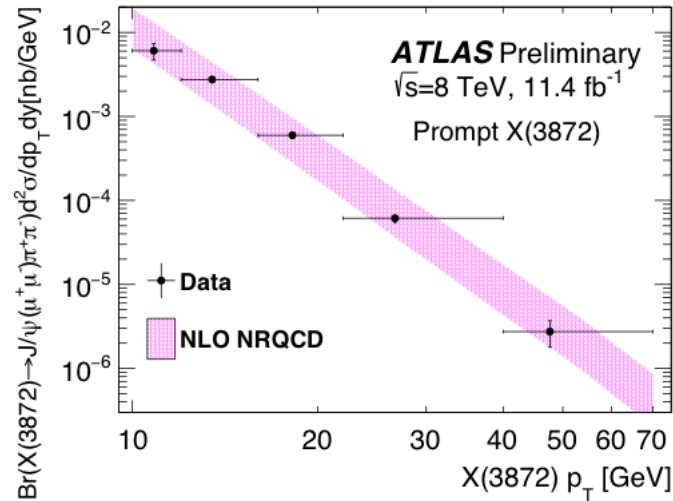
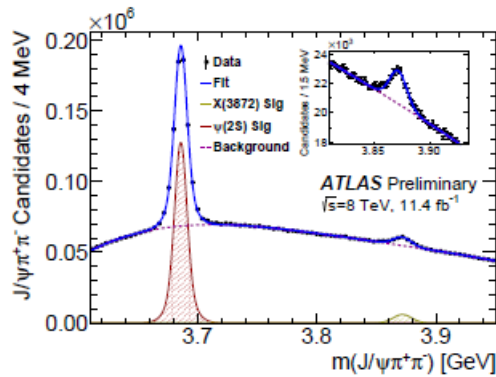
CMS-PAS-BPH-15-004



Reasonable agreement with FONLL and with PYTHIA

X(3872) production at 8 TeV

ATLAS-CONF-2016-028



NRQCD ($\chi_{c1}(2P)$ dominance) agrees

FONLL is higher and harder

$$R_B^{2L} = \frac{Br(B \rightarrow X(3872))Br(X(3872) \rightarrow J/\psi\pi^+\pi^-)}{Br(B \rightarrow \psi(2S))Br(\psi(2S) \rightarrow J/\psi\pi^+\pi^-)} = (3.57 \pm 0.33(\text{stat}) \pm 0.11(\text{sys}))\%$$

Smaller than $18 \pm 8 \%$ estimated from Tevatron data

$$\frac{\sigma(pp \rightarrow B_c)Br(B_c \rightarrow X(3872))}{\sigma(pp \rightarrow \text{non-prompt } X(3872))} = (25 \pm 13(\text{stat}) \pm 2(\text{sys}) \pm 5(\text{spin}))\%$$

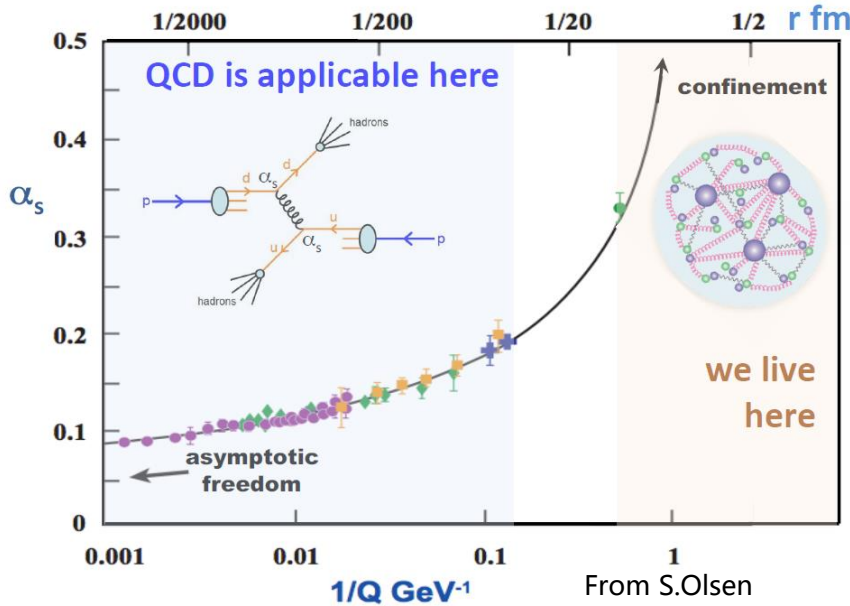
Non-prompt X(3872) production suggests enhanced B_c contribution

Searches for X_b -- the b-partner of X(3872)

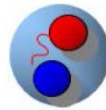
- Non-observation in $\Upsilon(1S)\pi\pi$ at CMS and Atlas
- Non-observation in $\Upsilon(1S)\omega$ at Belle

Conventional hadrons

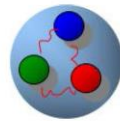
QCD Exotic hadrons



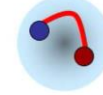
Meson



Baryon



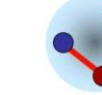
Hybrid



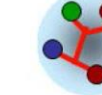
Glueball



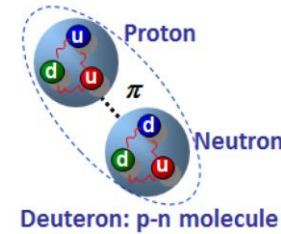
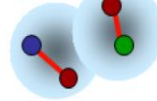
Tetraquark



Pentaquark



Hadronic molecule



Color singlet beyond quark model

SPECTROSCOPY

- Hadron spectroscopy is a key tool to access non-perturbative QCD in confinement regime
- New forms of hadronic matter provide crucial insights of the effective degrees of freedom of QCD

XYZ states:

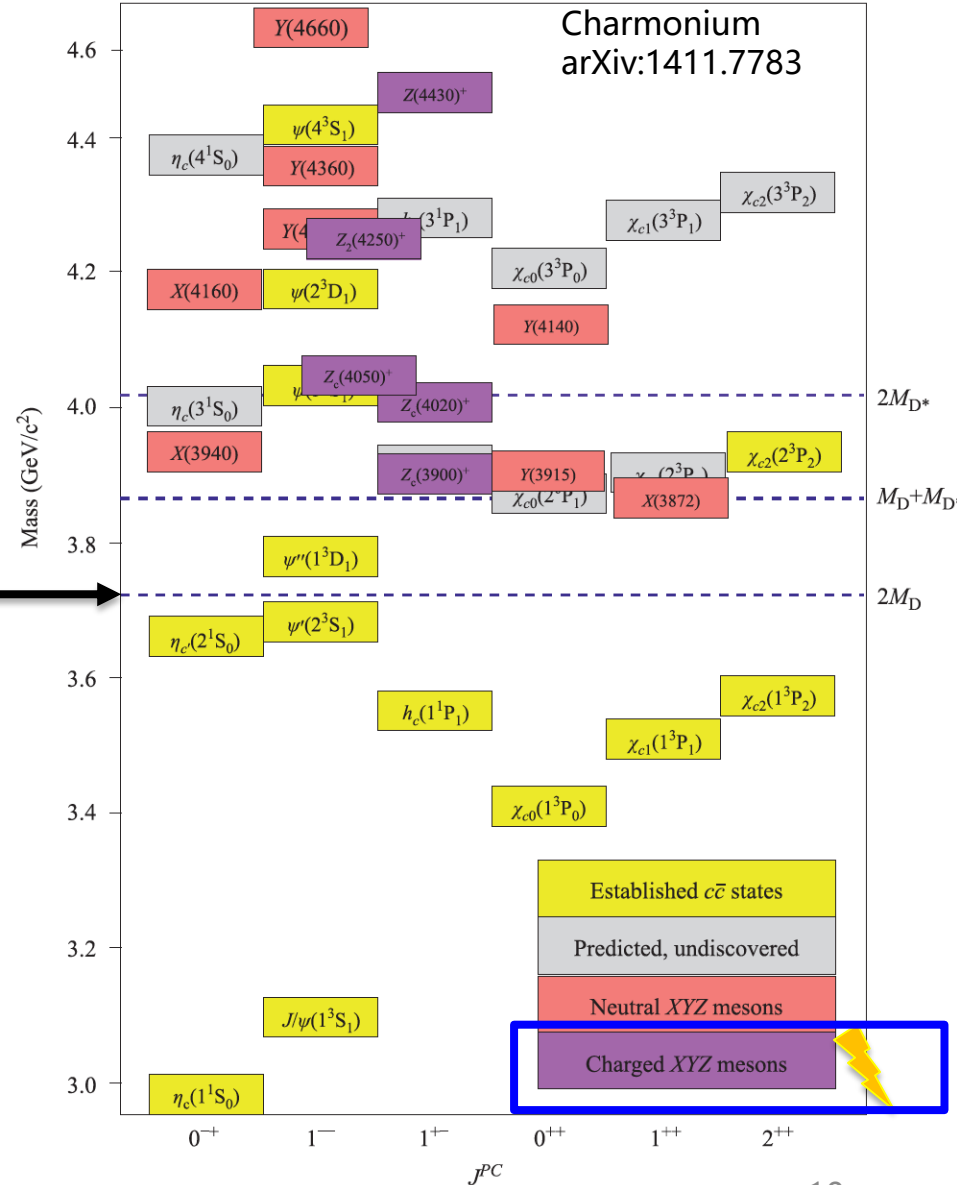
Cannot fit in the spectrum of conventional heavy quarkonia

Additional degree of freedom from light quarks and gluons?

Open charm threshold

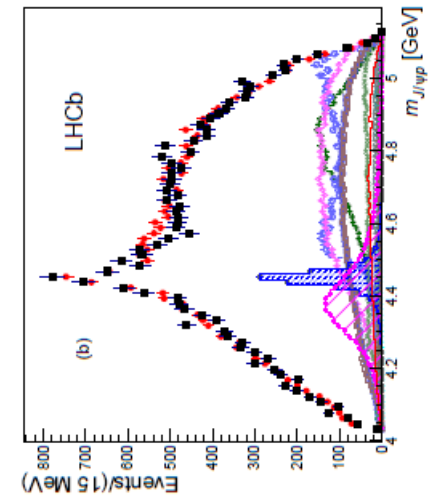
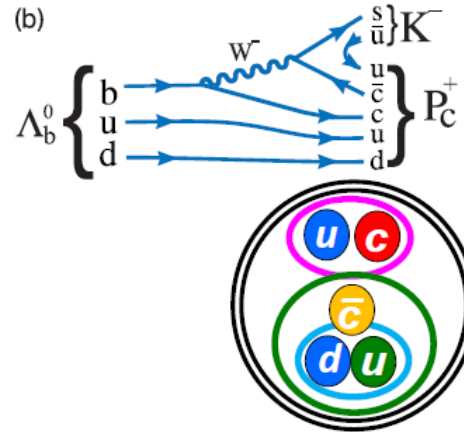
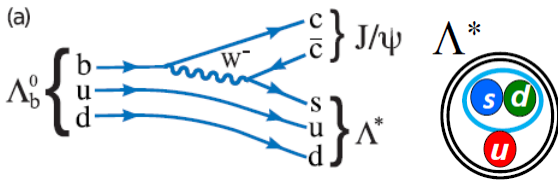
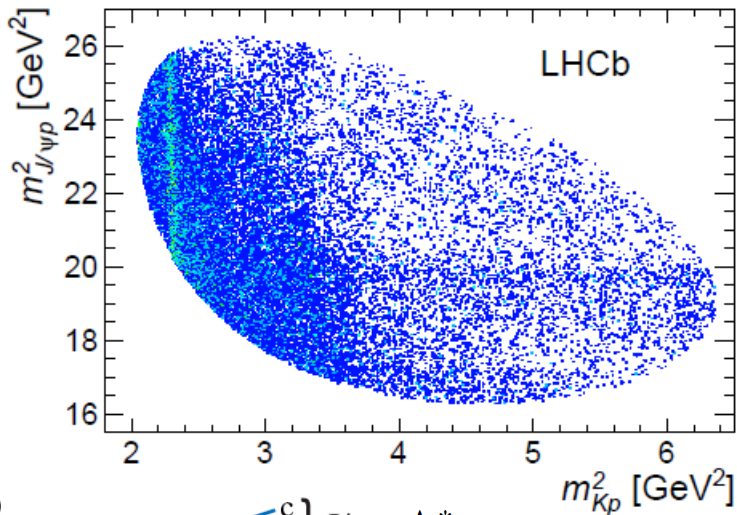
c- and b-quark are heavy
Non-relativistic QM applies

NRQCD approach is a spectacular success, validated by the consistency between $(c\bar{c})$ and $(b\bar{b})$

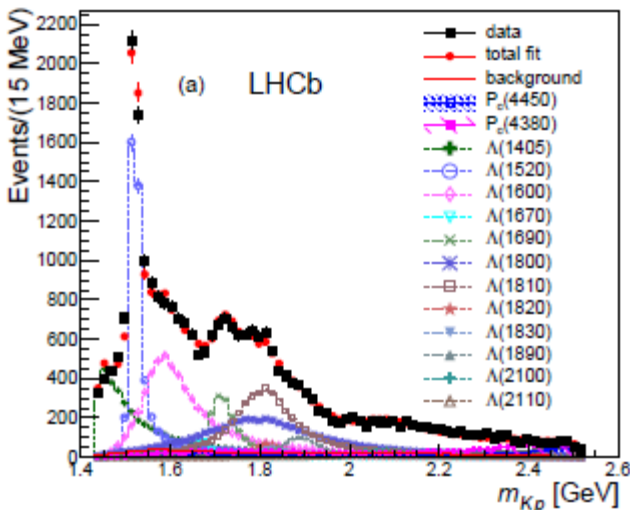


P_c : unexpected structures in $m_{J/\psi p}$

Pentaquark? Hadroquarkonium? Molecule? Threshold effect?



PRL 115, 072001 (2015)

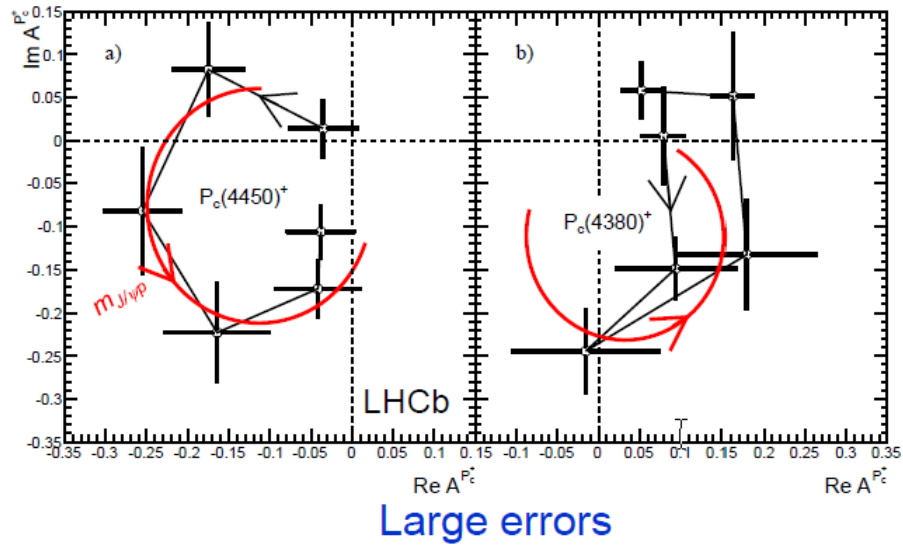


State	Mass (MeV)	Width (MeV)	Fit fract. (%)	Sig.
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$	12σ
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$	9σ

- Best fit has $J^P = (3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred. $(5/2^-, 3/2^+)$ cannot be ruled out within systematics

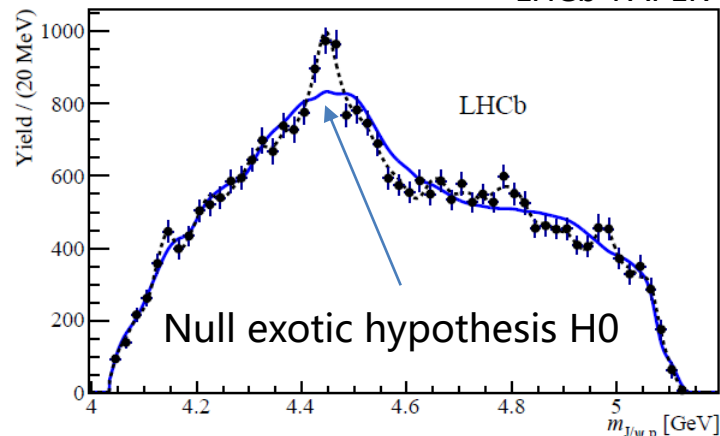
$\Lambda_b \rightarrow J/\psi p K^-$

Argand plots:
Amplitudes of P_c without BW assumption



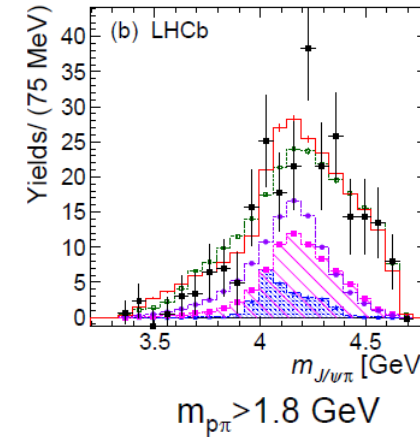
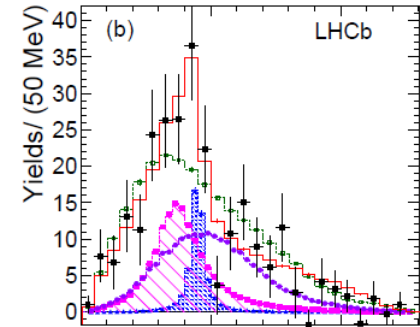
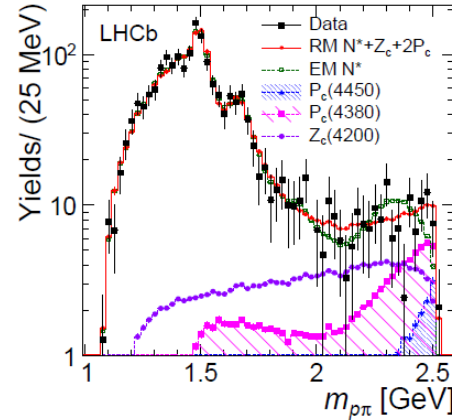
Model independent proof based on angular moments

arXiv:1604.05708
LHCb-PAPER-2016-009



$\Lambda_b \rightarrow J/\psi p \pi^-$: Cabibbo Suppressed

LHCb-PAPER-2016-015
arXiv: 1606.06999



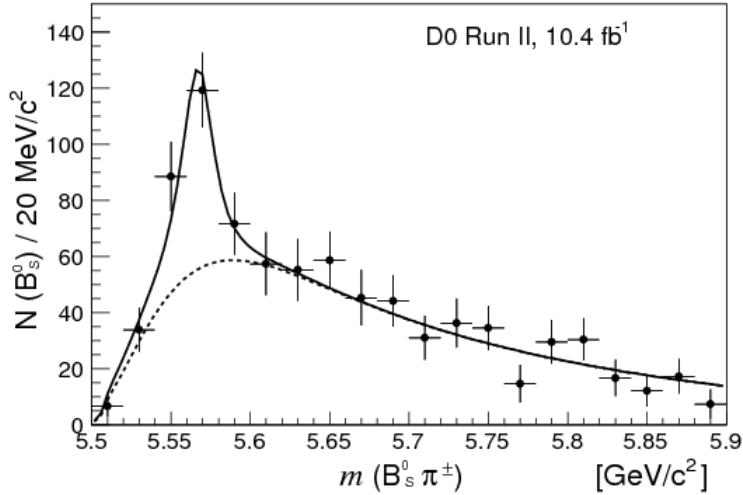
Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is **3.1σ**

Consistent with the P_c production rates from $\Lambda_b \rightarrow J/\psi p K^-$ & Cabibbo suppression

$B_S^0 \pi$ spectroscopy: $X(5568)$ [b,s,u,d]?



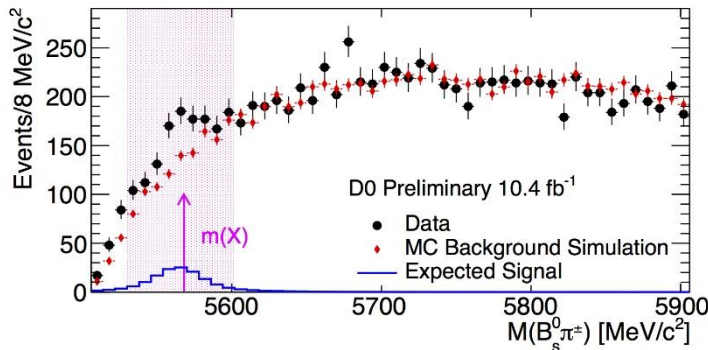
Phys. Rev. Lett. 117, 022003 (2016).



$$\rho_X^{D0} \equiv \frac{\sigma(p\bar{p} \rightarrow X + \text{anything}) \times \mathcal{B}(X \rightarrow B_S^0 \pi)}{\sigma(p\bar{p} \rightarrow B_S^0 + \text{anything})} \Big|_{D0Acc.}$$

$$= (8.6 \pm 1.9 \pm 1.4)\%$$

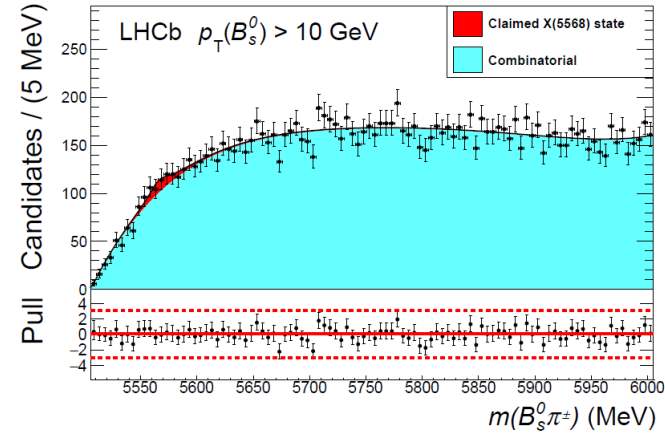
New DØ Note 6488-CONF



Similar results with $B_S^0 \rightarrow D_S \mu \nu$



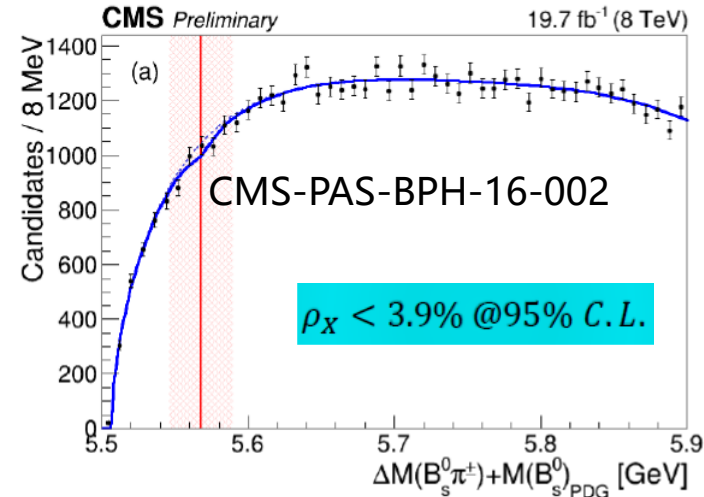
LHCb-PAPER-2016-029



$$\rho_X^{LHCb}(p_T(B_S^0) > 5 \text{ GeV}) < 0.011 (0.012),$$

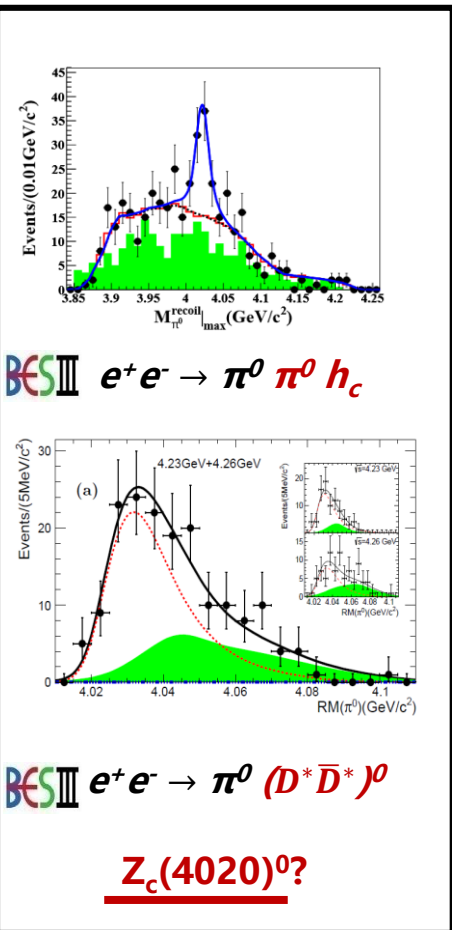
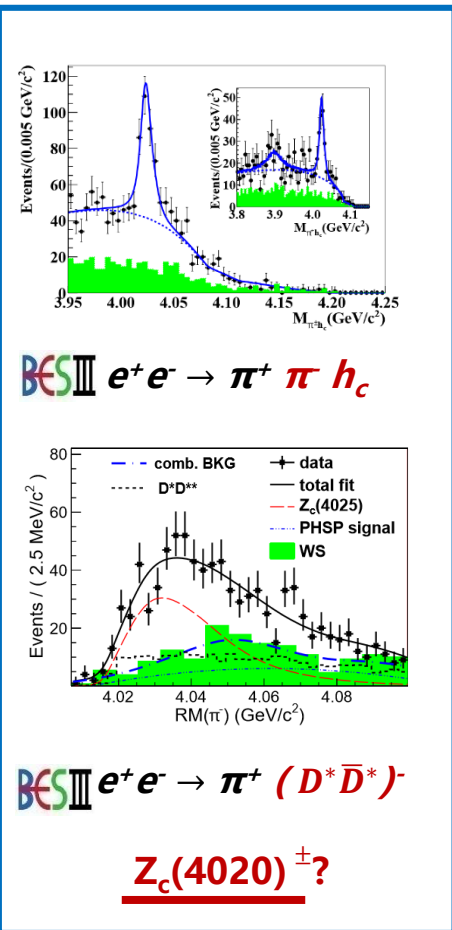
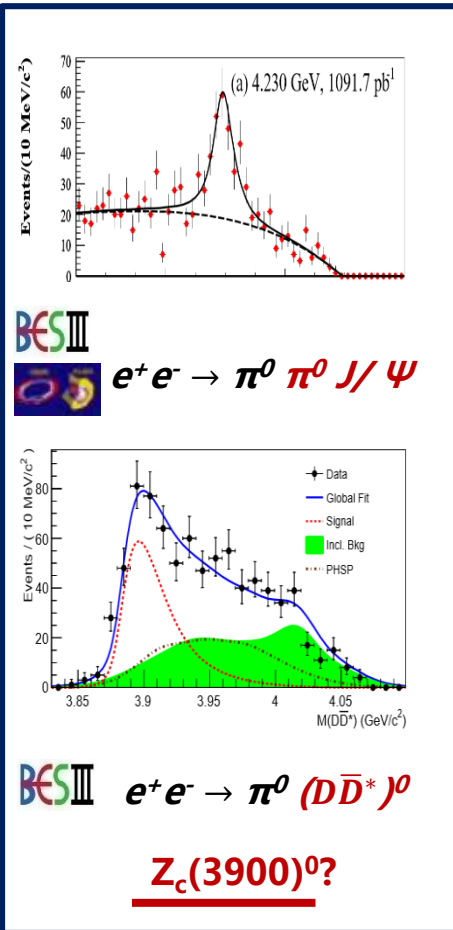
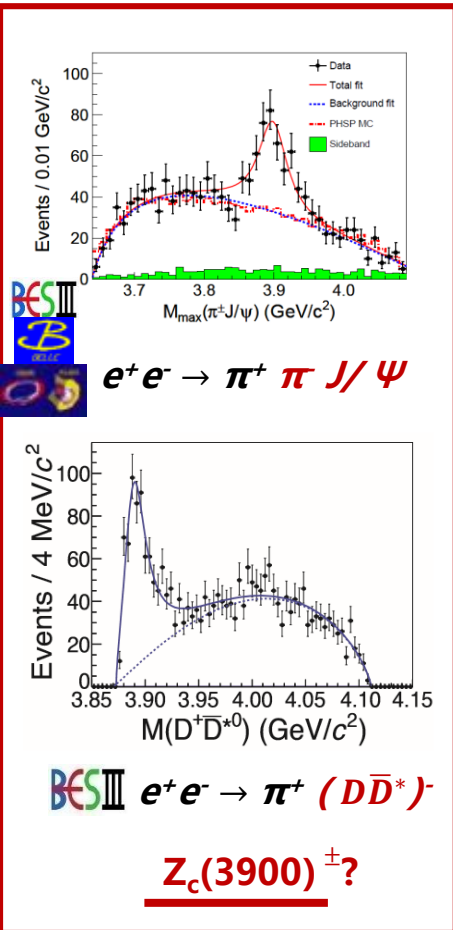
$$\rho_X^{LHCb}(p_T(B_S^0) > 10 \text{ GeV}) < 0.021 (0.024),$$

$$\rho_X^{LHCb}(p_T(B_S^0) > 15 \text{ GeV}) < 0.018 (0.020).$$

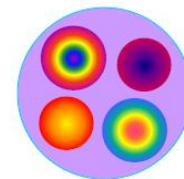


$$\rho_X < 3.9\% @95\% C.L.$$

Observations of Z_c



Tetraquark? Hadroquarkonium?
Molecule? Threshold effect?



Summary of the Z_c at BESIII

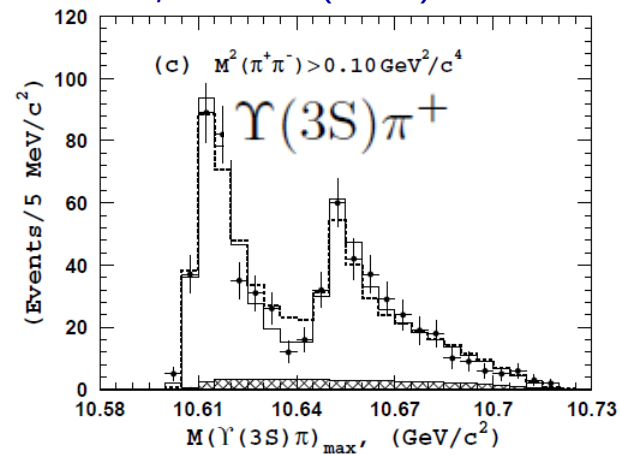
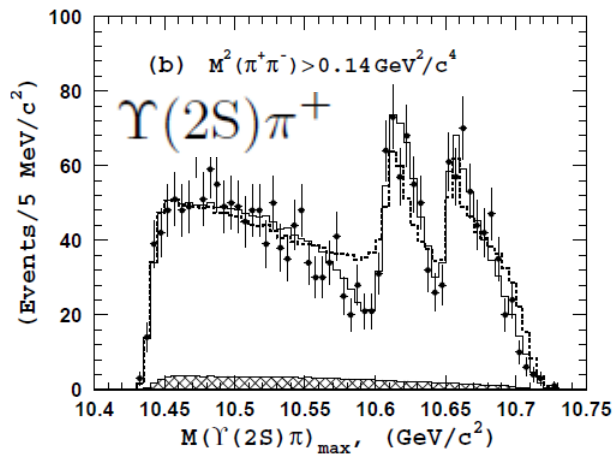
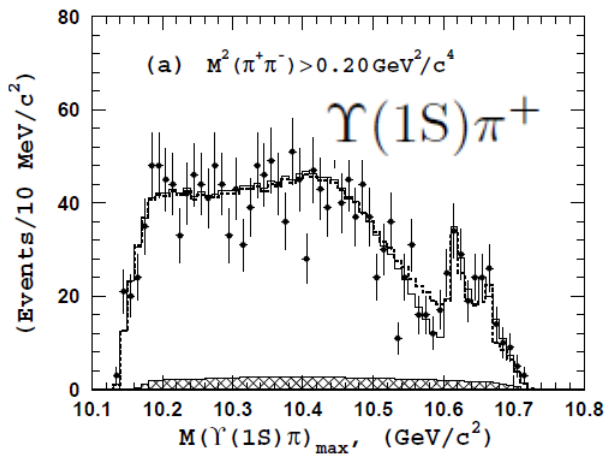
$Z_c^\pm(3900)$	$Z_c^\pm(4020)$	DD* threshold (3875 MeV) D*D* threshold (4017 MeV)
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ M=3899.0±3.6±4.9 MeV $\Gamma = 46 \pm 10 \pm 20$ MeV	$e^+e^- \rightarrow \pi^+\pi^- h_c$ M= 4022.9±0.8±2.7 MeV $\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV	
$Z_c^0(3900)$	$Z_c^0(4020)$	Two isospin triplets established
$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$ M=3894.8±2.3 MeV $\Gamma = 29.6 \pm 8.2$ MeV	$e^+e^- \rightarrow \pi^0\pi^0 h_c$ M=4023.9±2.2±3.8 MeV Γ Fixed at $Z_c^\pm(4020)$	
$Z_c^\pm(3885)$	$Z_c^\pm(4025)$	Mass/width difference in two modes to be understood
$e^+e^- \rightarrow \pi(D\bar{D}^*)^\pm$ M=3882.2±1.1±1.5 MeV $\Gamma = 26.5 \pm 1.7 \pm 2.1$ MeV	$e^+e^- \rightarrow \pi(D^*\bar{D}^*)^\pm$ M= 4026.3±2.6±3.7 MeV $\Gamma = 24.8 \pm 5.6 \pm 7.7$ MeV	
$Z_c^0(3885)$	$Z_c^0(4025)$	
$e^+e^- \rightarrow \pi^0(D\bar{D}^*)^0$ M=3885.7±5.7±8.4 MeV $\Gamma = 35 \pm 12 \pm 15$ MeV	$e^+e^- \rightarrow \pi^0(D^*\bar{D}^*)^0$ M= 4025.5±4.7±3.1 MeV $\Gamma = 23.0 \pm 6.0 \pm 1.0$ MeV	

- J^P of $Z_c(3900)=1^+$ determined from PWA
- DD* dominates $Z_c(3900)$ decays and D*D* dominates $Z_c(4025)$ decays
- No significant $Z_c(3900) \rightarrow h_c\pi, Z_c(4020) \rightarrow J/\psi\pi$

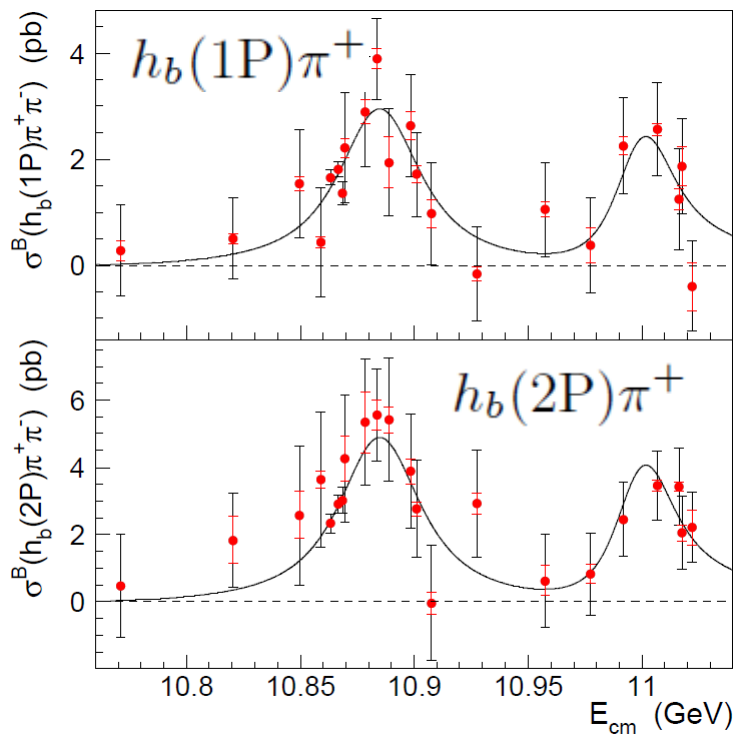


Observations of Z_b

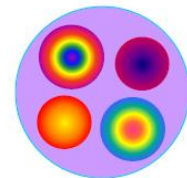
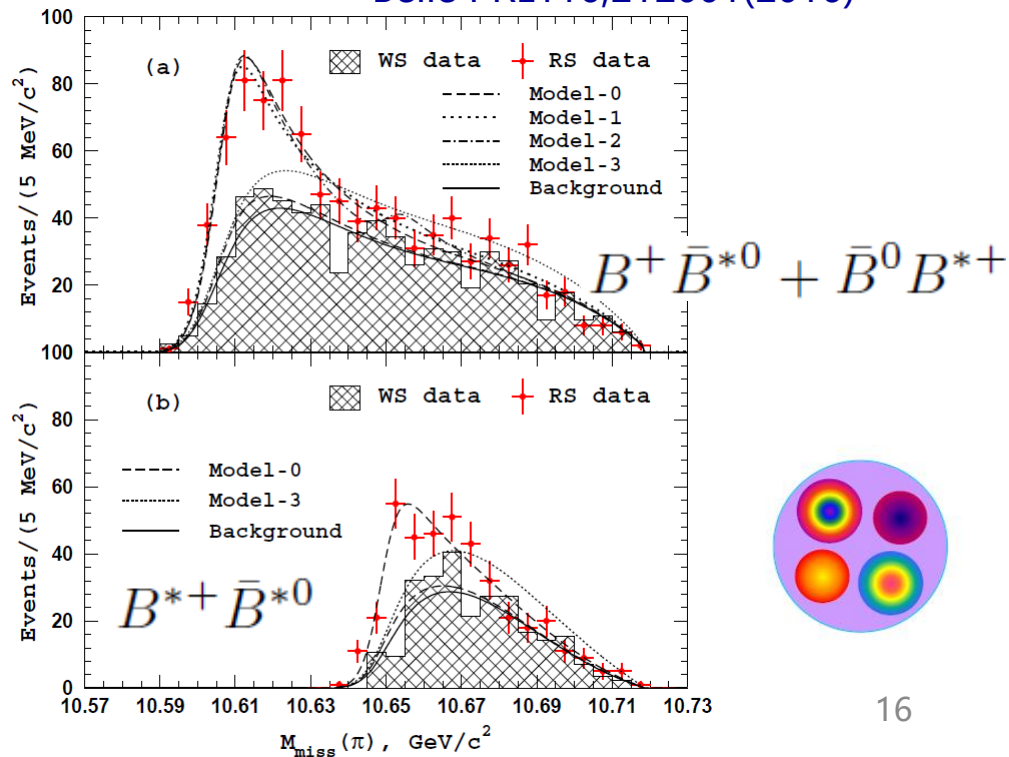
Belle: PRD91, 072003 (2015)



arXiv:1508.06562



Belle PRL116,212001(2016)



Observations of Z_b



$B^*B^{(*)}$ dominate Z_b channels observed so far

PRD93,011101(2016)
arXiv:1508.06562
PRL116,212001(2016)

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$...
$B^{*+}\bar{B}^{*0}$...	$73.7^{+3.4+2.7}_{-4.4-3.5}$

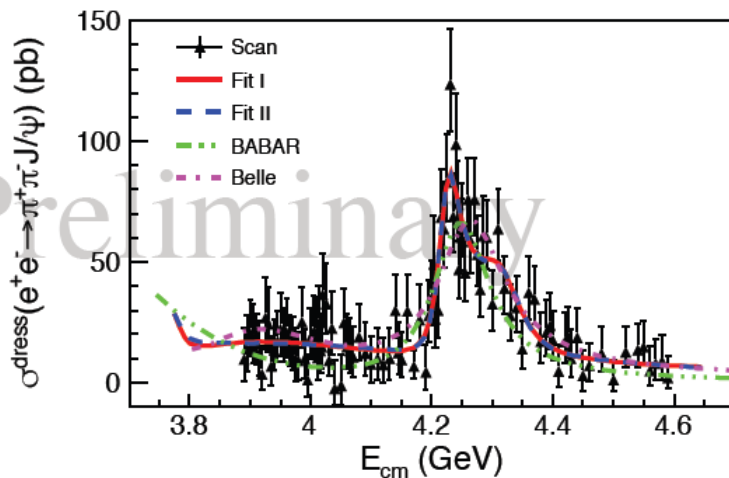
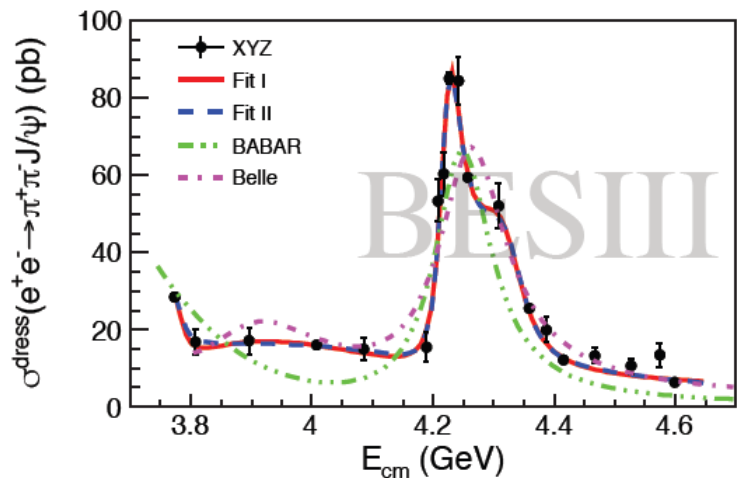
- Z_b are very close to $\bar{B}B^*$, $B^*\bar{B}^*$ threshold
- $I^G J^{P(C)} = 1^+ 1^+ (-)$
- Observed both in the hidden-bottom modes: $\pi Y(1S, 2S, 3S)$, $\pi h_b(1P, 2P)$ and open-bottom modes: $\bar{B}B^*$, $B^*\bar{B}^*$

Favors "meson molecule" configuration
[Voloshin PRD 87, 091501 (2013)]

Cross sections and Y(4260) at BESIII

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at BESIII (direct) **BESIII**

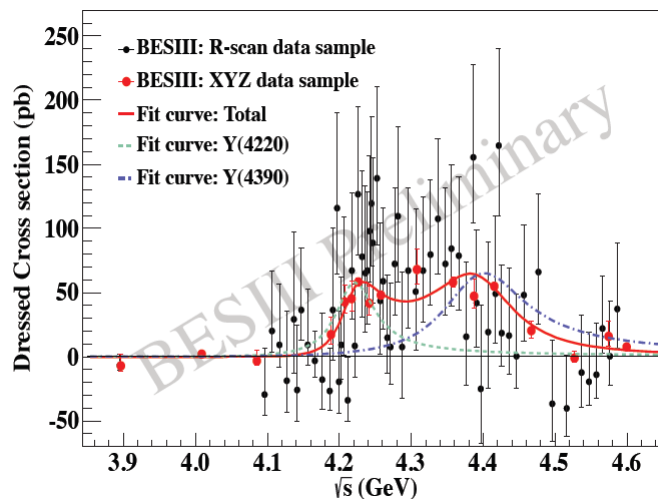
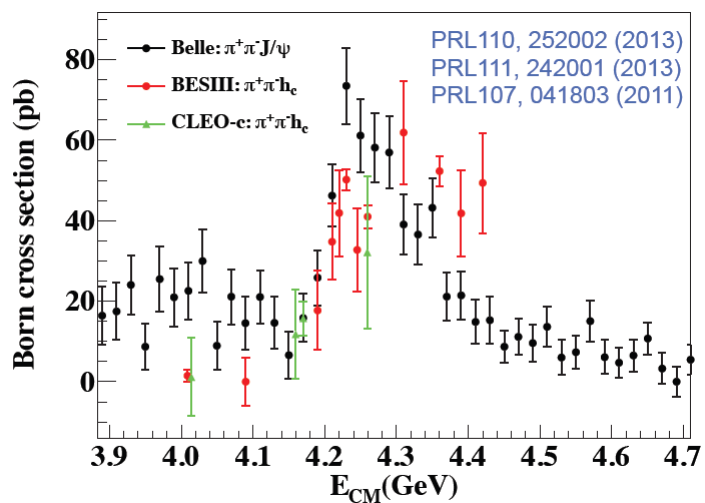
Inconsistent with a single BW of Y(4260)



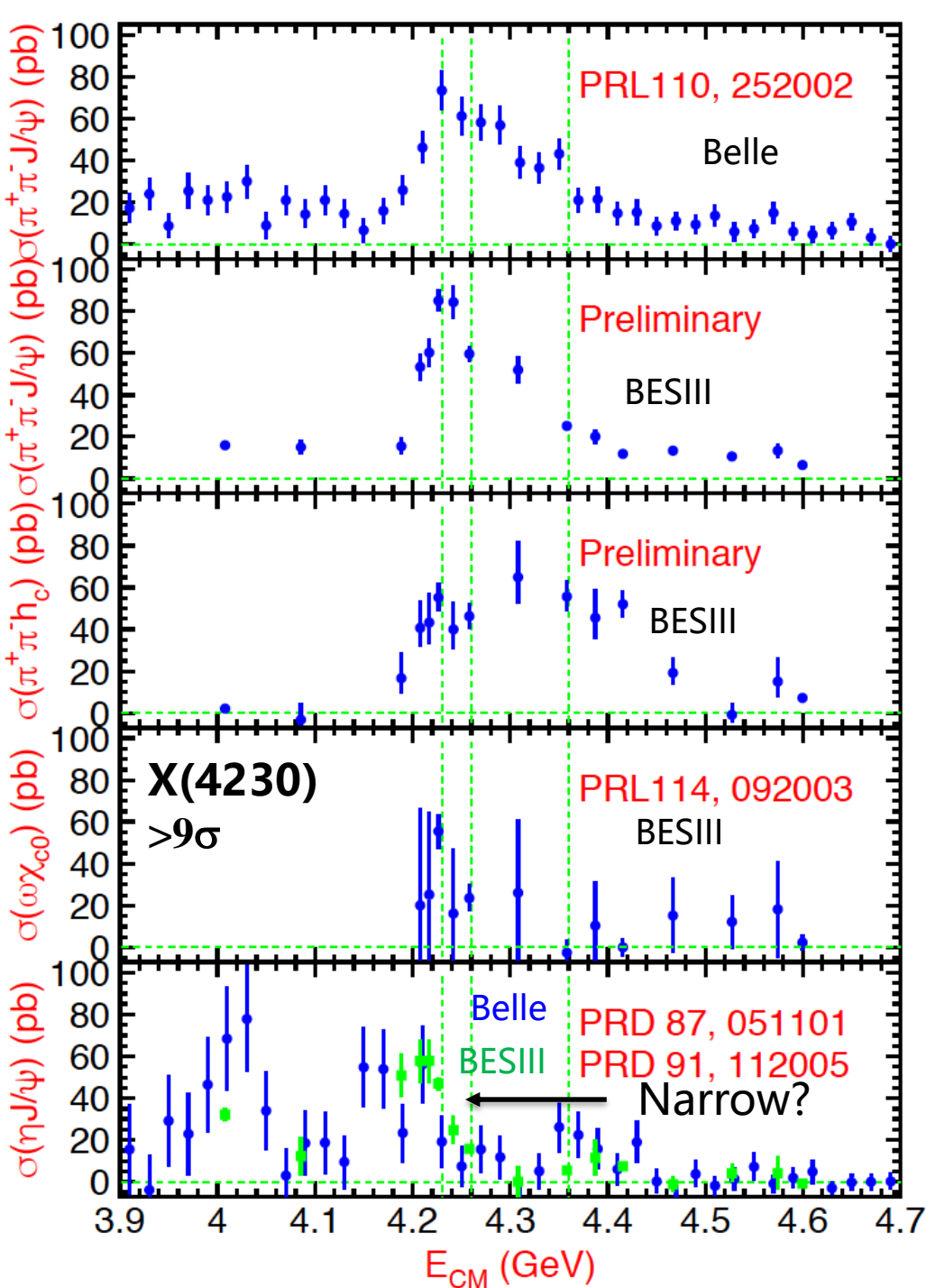
significance of an additional narrow structure $> 7 \sigma$

$e^+e^- \rightarrow \pi^+\pi^- h_c$ at BESIII (direct) **BESIII**

Clearly different from $\pi\pi J/\psi$



significance of two structures assumption over one structure $> 10 \sigma$



$Y(4260) \rightarrow \pi^+\pi^-J/\psi$ is observed by Babar (2005) and confirmed by Belle, known for its anomaly large decay width to $\pi^+\pi^-J/\psi$

Revisit the $Y(4260)$

-- with improved cross section measurements

Not a single/simple BW?

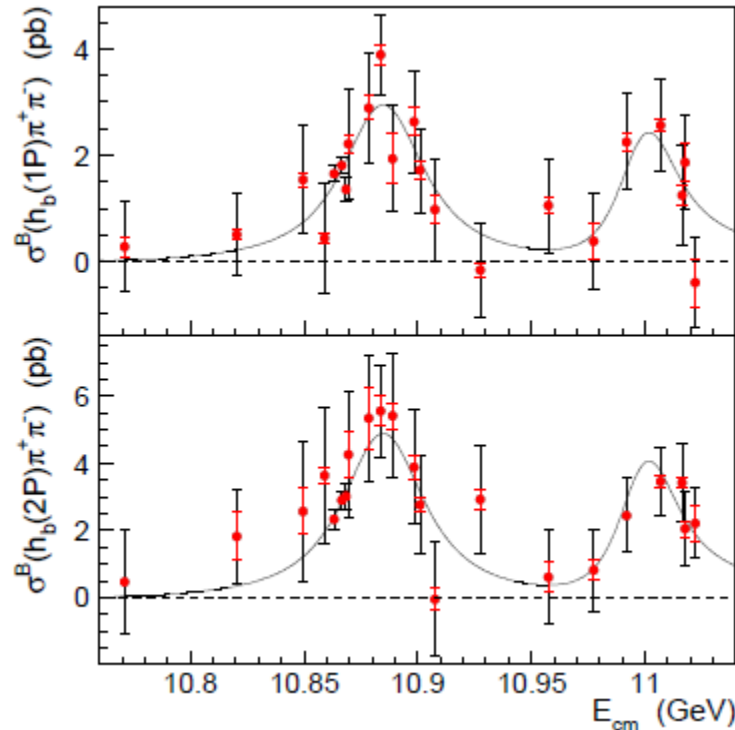
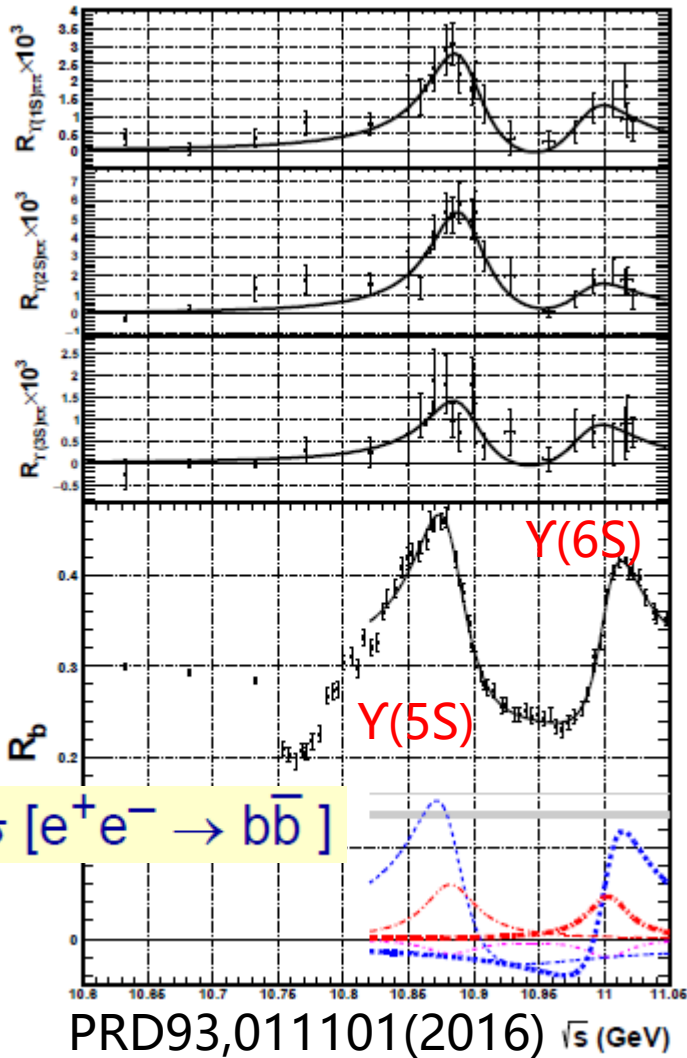
Is there any connection to $\bar{D}_s^* D_s^*$ threshold (4224 MeV) ?

Cross sections and Υ' s at Belle



$$\sigma [e^+e^- \rightarrow \Upsilon(nS) \pi^+ \pi^-]$$

$$\sigma [e^+e^- \rightarrow h_b(nP) \pi^+ \pi^-]$$



arXiv:1508.06562

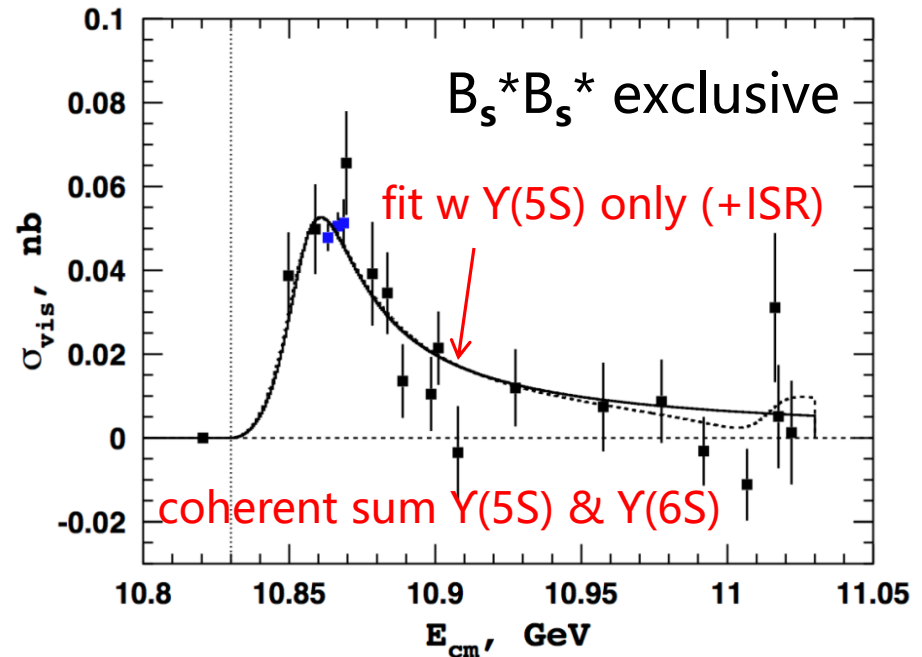
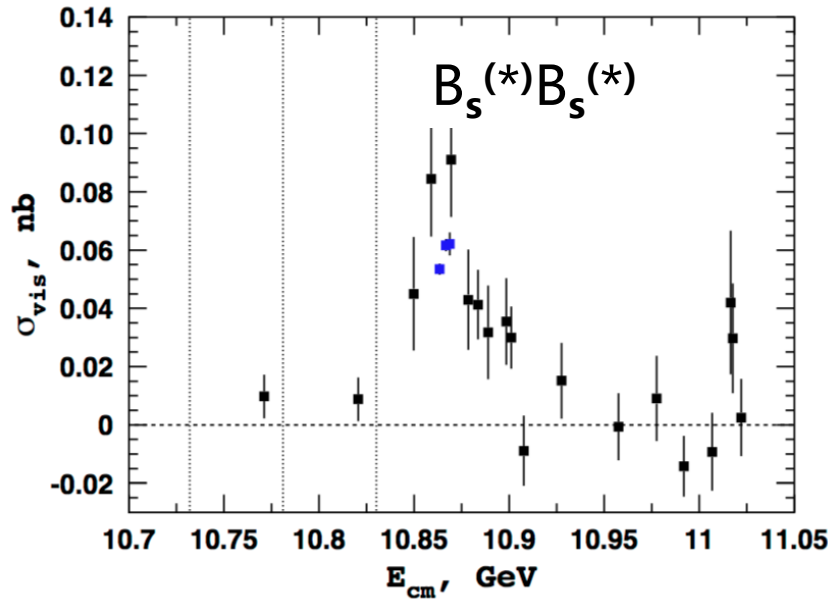
- **“No continuum”** : expect same for other Z_b -dominated events– $h_b(mP)\pi\pi$, $B^*B^{(*)}\pi$
- $\Upsilon(nS)\pi\pi + h_b(mP)\pi\pi + BB^*\pi + B^*B^*\pi$ saturate “ $\Upsilon(5S)$ ”
- **Different from $c\bar{c}$**

Cross sections and Υ' s at Belle



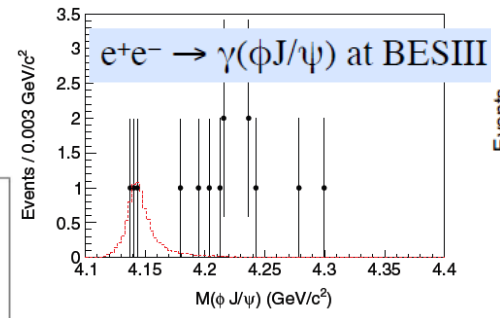
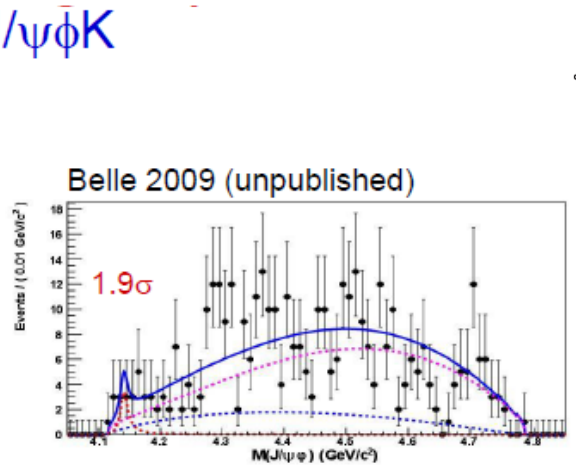
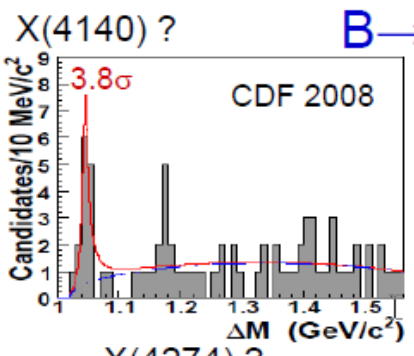
- B_s cross section vs CMS energy

NEW

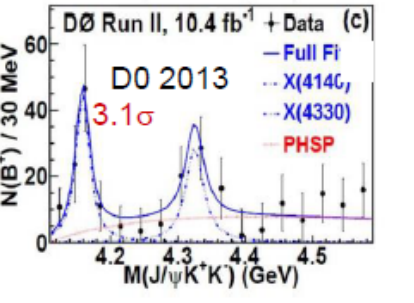
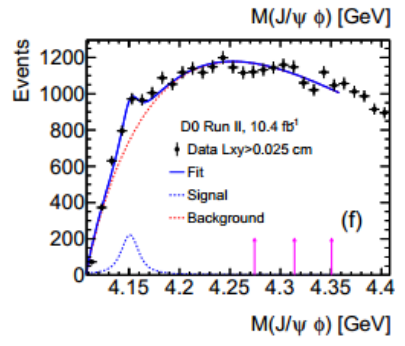
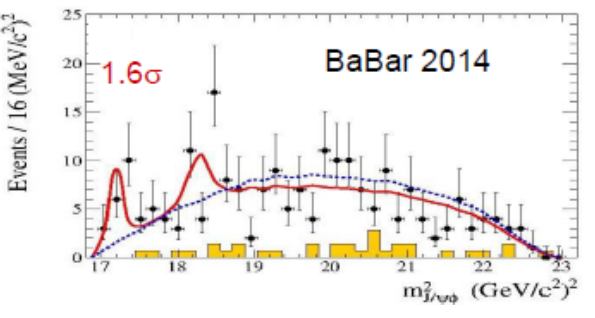
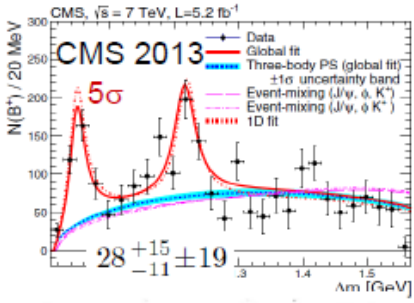
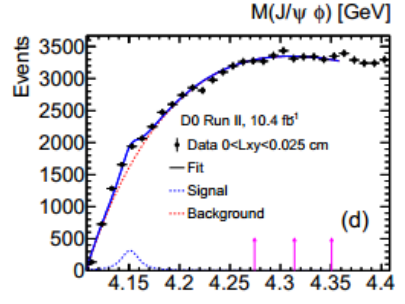
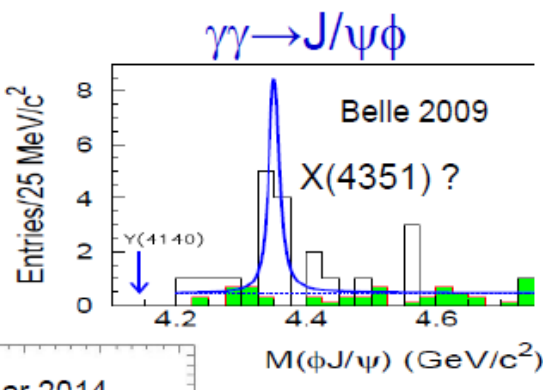
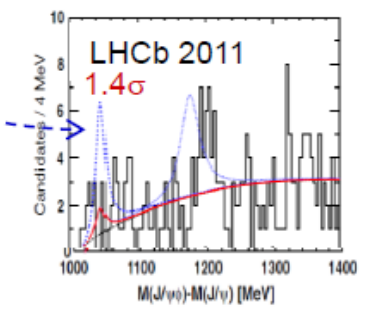
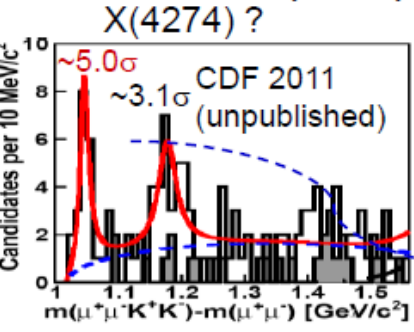
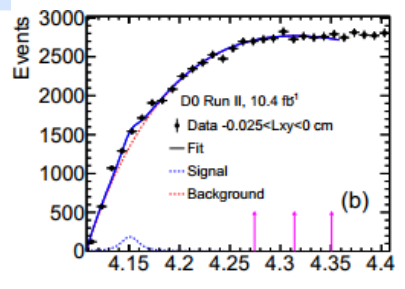


- Consistent with no continuum production
- Clear peak at the $\Upsilon(5S)$
- $\Upsilon(6S)$ signal is considerably weaker

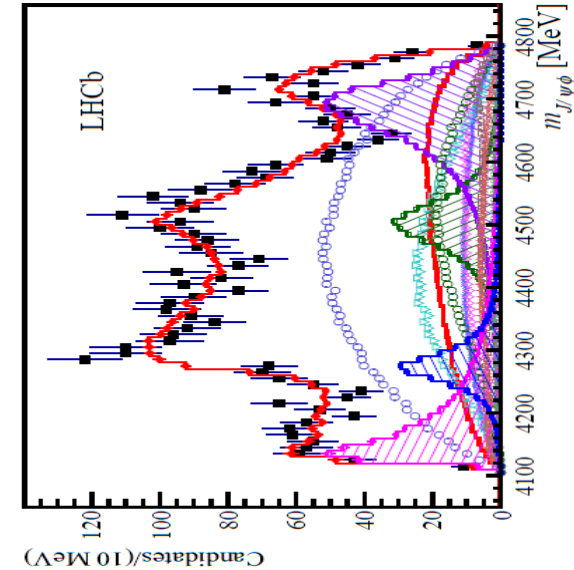
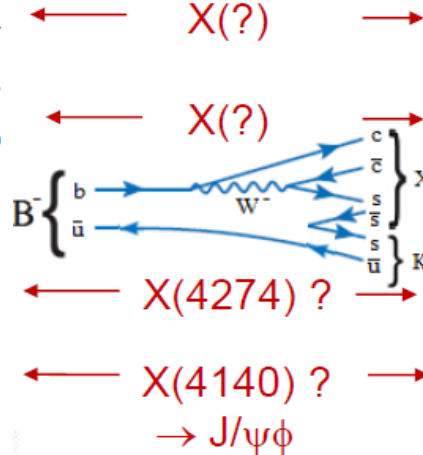
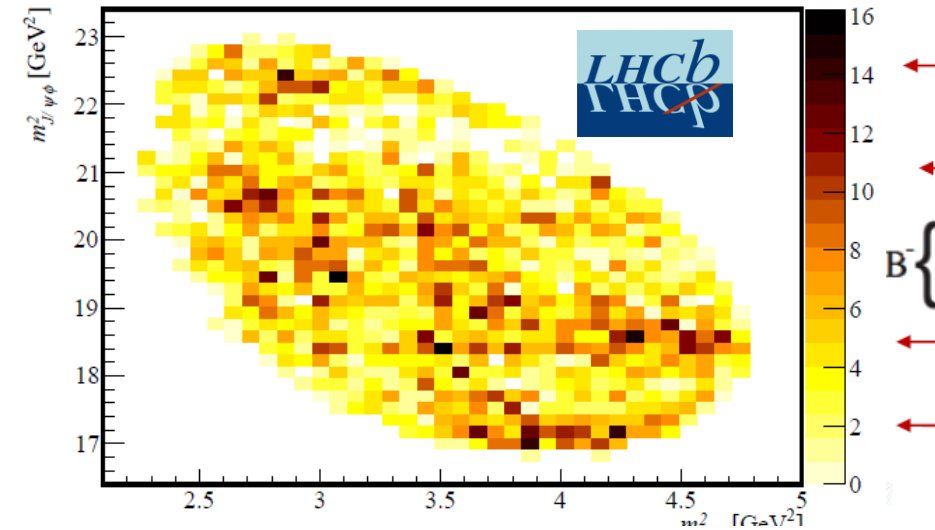
$X \rightarrow J/\psi\phi$ structures: confusing history



Inclusive production at D0



$X \rightarrow J/\psi\phi$ structures: New observations from LHCb



Contribution	sign. or Ref.	M_0 [MeV]	Γ_0 [MeV]	Fit results FF %
All $X(1^+)$				16 ± 3 $^{+6}_{-2}$
$X(4140)$	8.4σ	4146.5 ± 4.5 $^{+4.6}_{-2.8}$	83 ± 21 $^{+21}_{-14}$	13 ± 3.2 $^{+4.8}_{-2.0}$
ave.	Table 1	4143.4 ± 1.9	15.7 ± 6.3	
$X(4274)$	6.0σ	4273.3 ± 8.3 $^{+17.2}_{-3.6}$	56 ± 11 $^{+8}_{-11}$	7.1 ± 2.5 $^{+3.5}_{-2.4}$
CDF	[28]	4274.4 $^{+8.4}_{-6.7} \pm 1.9$	32 $^{+22}_{-15} \pm 8$	
CMS	[25]	$4313.8 \pm 5.3 \pm 7.3$	38 $^{+30}_{-15} \pm 16$	

Contribution	sign. or Ref.	M_0 [MeV]	Γ_0 [MeV]	Fit results FF %
All $X(0^+)$				$28 \pm 5 \pm 7$
$NR_{J/\psi\phi}$	6.4σ			46 ± 11 $^{+11}_{-21}$
$X(4500)$	6.1σ	4506 ± 11 $^{+12}_{-15}$	92 ± 21 $^{+21}_{-20}$	6.6 ± 2.4 $^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	4704 ± 10 $^{+14}_{-24}$	120 ± 31 $^{+42}_{-33}$	12 ± 5 $^{+9}_{-5}$

Significance of $J^{PC} = 1^{++}$:
 $X(4140)$: 5.7σ $X(4274)$: 5.8σ

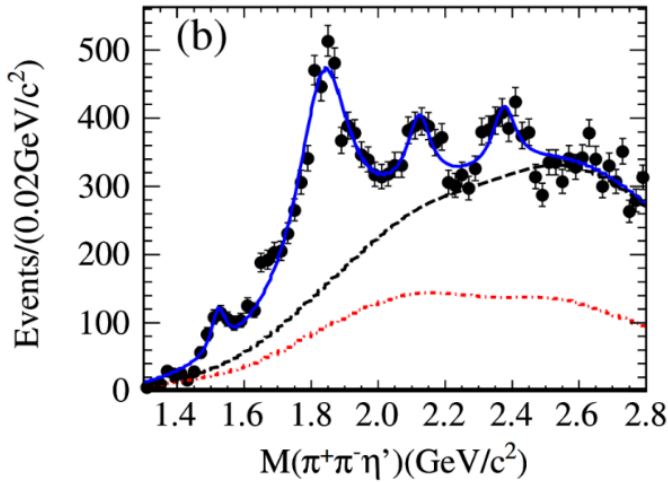
Significance of $J^{PC} = 0^{++}$:
 $X(4500)$: 4.0σ $X(4700)$: 4.5σ

$D_S^* \bar{D}_S^*$ Molecule is expected to be $0^+/2^+$
 $D_S^* \bar{D}_S^*$ Cusp can be 1^+ ← A cusp is preferred by 1.6 σ over a BW for $X(4140)$

Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold: connection between $X(1835)$ and $X(p\bar{p})$

$X(1835)$ observed in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

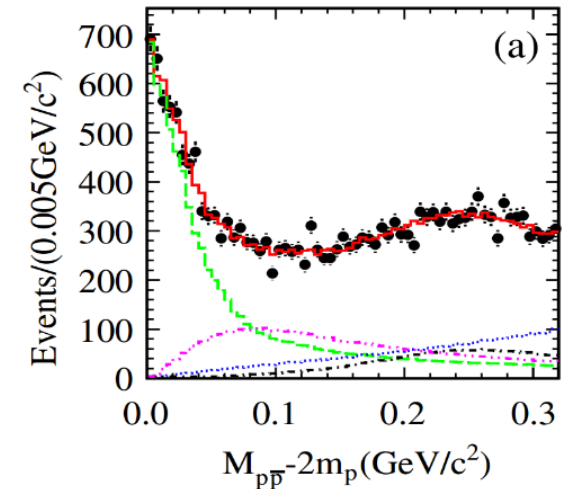
BESIII PRL 106, 072002 (2011), PRL 115, 091803 (2015)



$X(1835) J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25} \text{ MeV}/c^2$
$\Gamma = 192^{+20+62}_{-17-43} \text{ MeV}/c^2$
$X(p\bar{p}) J^{PC}=0^{-+}$
$M = 1832^{+19+18}_{-5-17} \pm 19 \text{ MeV}/c^2$
$\Gamma = 13 \pm 19 \text{ MeV}/c^2$ ($< 76 \text{ MeV}/c^2$ @ 90% C.L.)

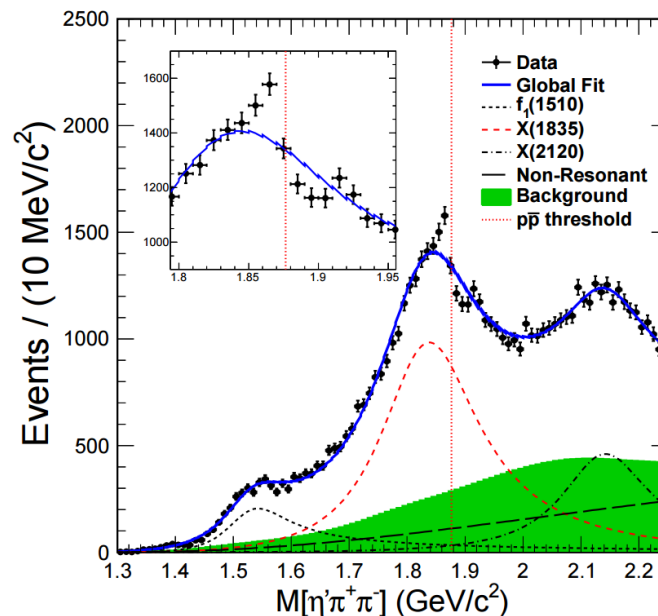
$X(p\bar{p})$ observed in $J/\psi \rightarrow \gamma p\bar{p}$

BESIII PRL 108, 112003 (2012)



Connection is emerging

BESIII PRL 117, 042002 (2016)

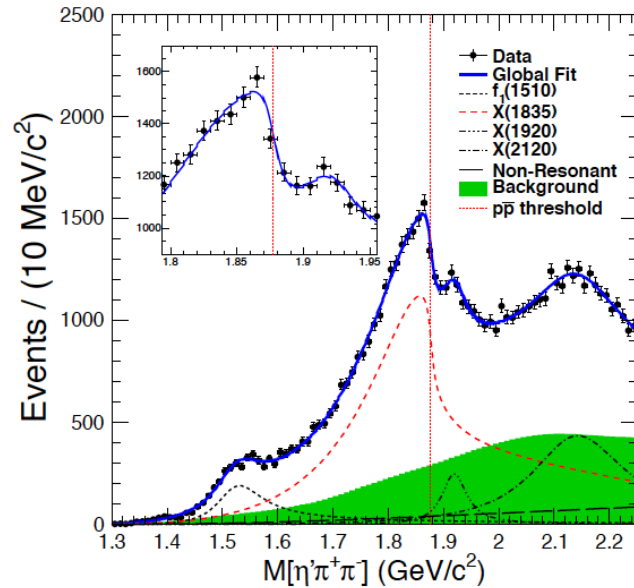


BES III

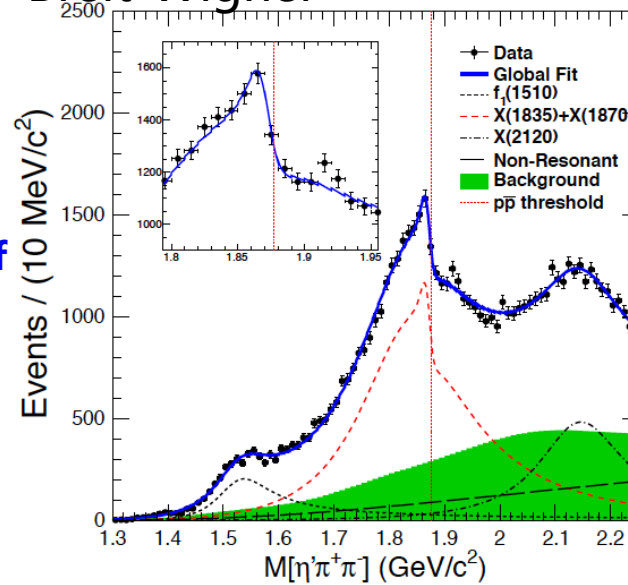
Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold: connection between $X(1835)$ and $X(p\bar{p})$

Model1: Flatté formula

Model2: coherent sum of two Breit-Wigner



Significance of non-zero coupling to $p\bar{p}$ $> 7\sigma$



Significance of narrow $X(1870)$ $> 7\sigma$

The state around $1.85 \text{ GeV}/c^2$

$g_{p\bar{p}}^2/g_0^2$	$2.31^{+0.37+0.83}_{-0.37-0.60}$
$M_{\text{pole}} (\text{MeV}/c^2) *$	$1909.5^{+15.9+9.4}_{-15.9-27.5}$
$\Gamma_{\text{pole}} (\text{MeV}/c^2) *$	$273.5^{+21.4+6.1}_{-21.4-64.0}$

$X(1870)$

$M (\text{MeV}/c^2)$	$1870.2^{+2.2+2.3}_{-2.3-0.7}$
$\Gamma (\text{MeV}/c^2)$	$13.0^{+7.1+2.1}_{-5.5-3.8}$

The anomalous line shape can be modeled with equally good fit quality

- Suggest the existence of a state, either a **broad state with strong couplings to $p\bar{p}$** , or a **narrow state just below the $p\bar{p}$ mass threshold**
- Support the existence of a **$p\bar{p}$ molecule-like state** or **bound state**

Multiquark Hybrid
Hadrocharmonium
Molecule
Threshold effects
Cusps...

States or/and interactions

What is the role of threshold

--Many new observations near thresholds: P_c , Z_b , Z_c , ...

See reviews by Swanson (Hadron2015) , Eichten (QWG2016), Zhao(MENU2016) and ref. within

* Phase variations appear in many process: not unique for resonance

To have a complete picture, more clues are needed

- Energy-dependence
 - Patterns in productions and decays
- Pole properties** **For XYZ, the picture is still unclear**

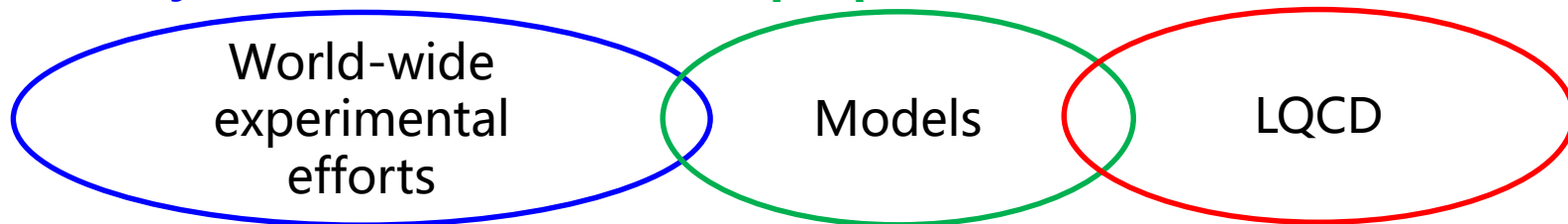
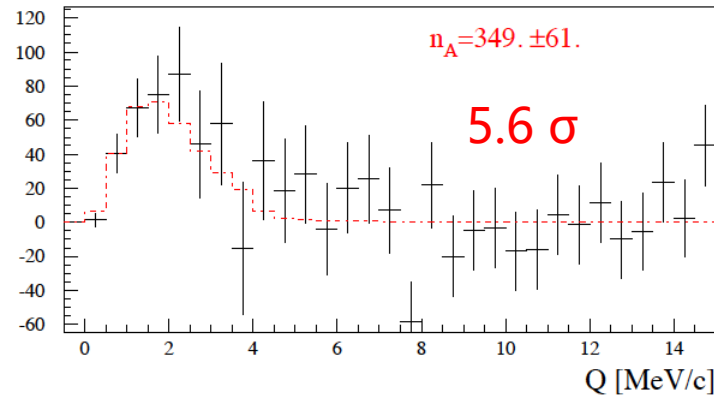
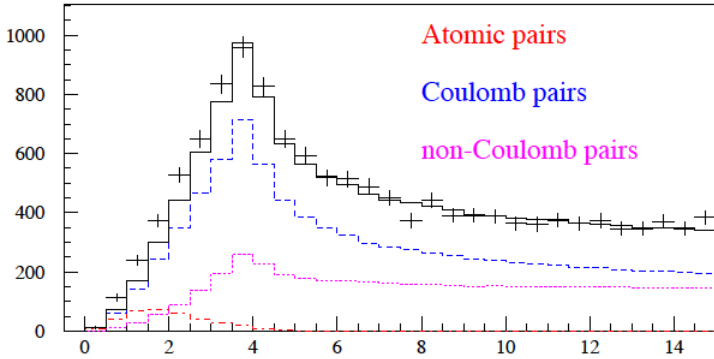


Photo-productions are proposed to test the contribution of threshold effects [arXiv:1508.00339, 1508.00888, 1508.01496]

Other highlights from low energy

The observation of hydrogen-like πK atoms, DIRAC

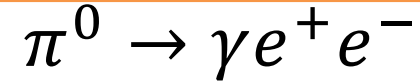
arXiv:1605.06103



$$\tau = (3.8^{+3.3}_{-2.0}|_{stat} \ 1.0|_{syst}) \text{ fs} = (3.8^{+3.5}_{-2.1}|_{tot}) \text{ fs}$$

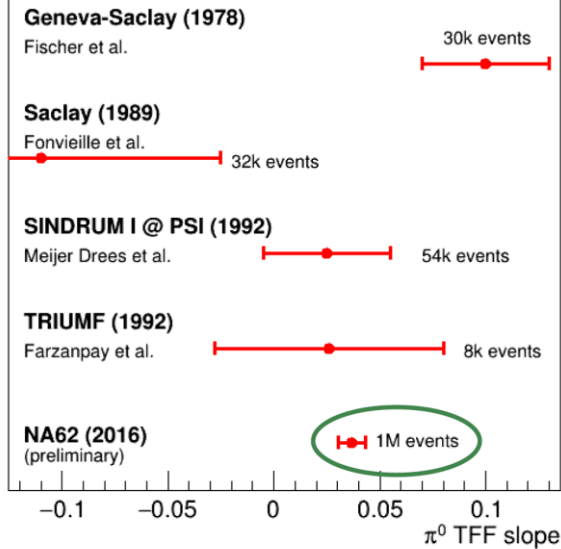
$$|a_0^-| M_\pi = 0.087^{+0.043}_{-0.024}$$

π^0 form factor
NA62- R_K



Dark photon exclusion
NA48/2 PLB746 (2015) 178

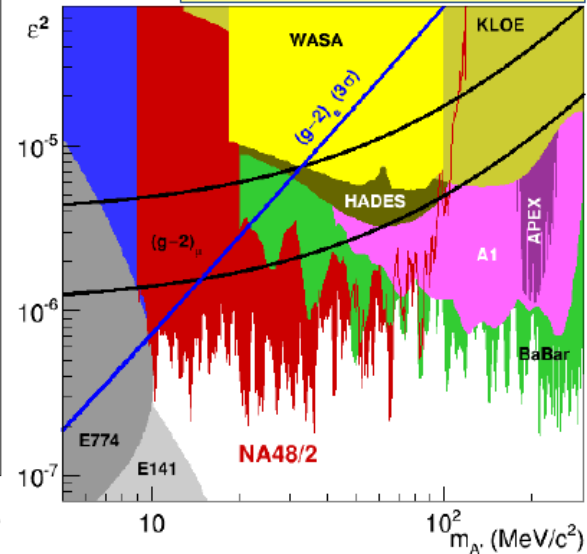
World data: π^0 TFF slope measurement with π^0_D decays



NA62- R_K preliminary result:

$$a = (3.70 \pm 0.53|_{stat} \pm 0.36|_{syst}) \times 10^{-2}$$

DP exclusion summary: all results published by 2015



Summary

- Probe QCD to a new level with hadron productions and decays
- Hadron Spectroscopy enters the new region
-- the picture is still incomplete
- We need new theoretical tools for analysis
- We can expect much more from the ongoing and future experiments

Thanks