QCD, hadron spectroscopy, exotics

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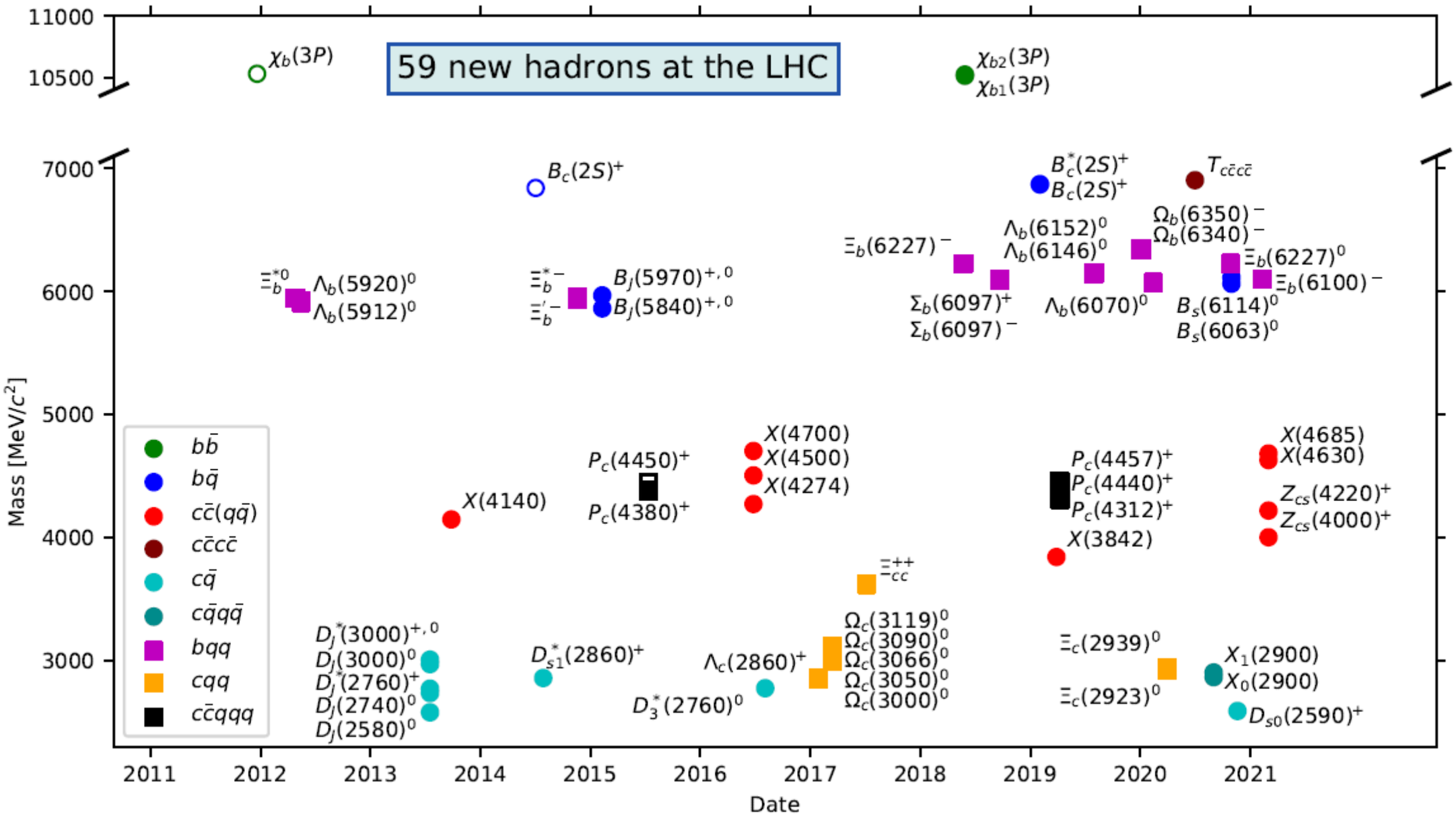
Justin Stevens WILLIAM & MARY CHARTERED 1693

Intersections in hadron spectroscopy

	Heavy quarks	Light quarks
Electromagnetic probes	e^+e^-    	γp   
Hadronic probes	$\bar{p}p$   pp   	$\bar{p}p$  πp 

prolific hadron discoveries

Gary Robertson



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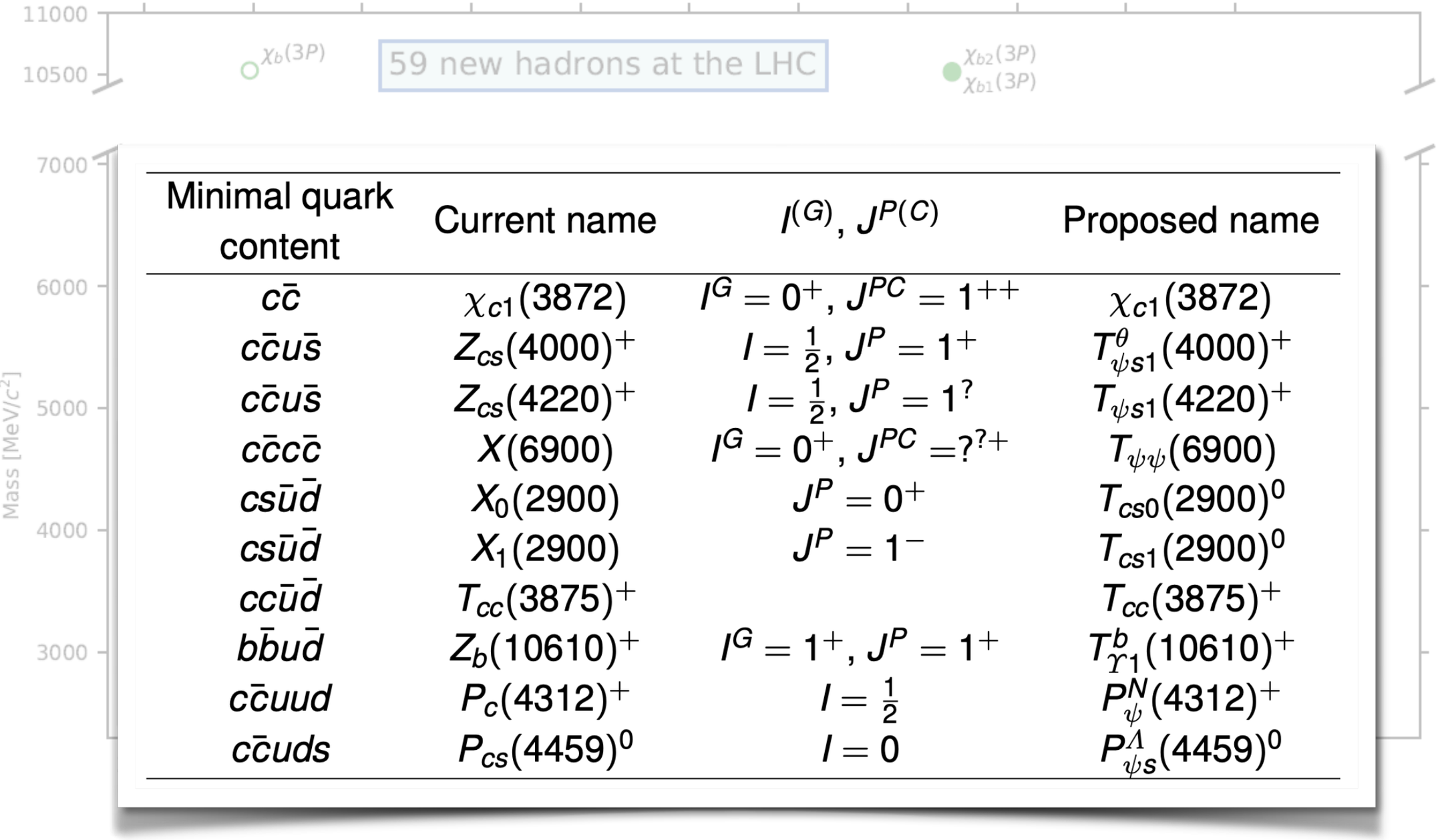
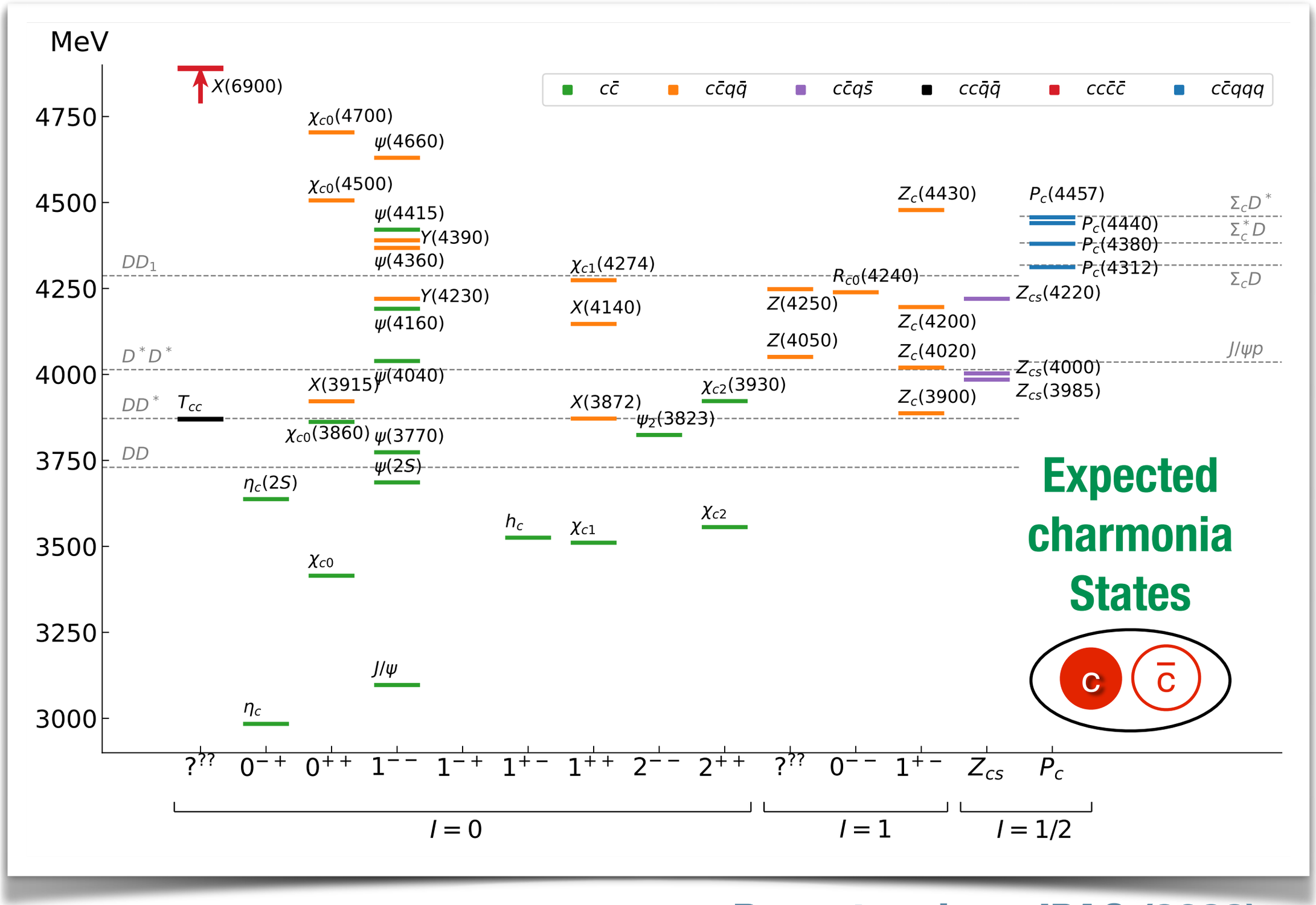


Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^{\theta}_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}$, $J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+$, $J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_{\psi}(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^{\Lambda}_{\psi s}(4459)^0$

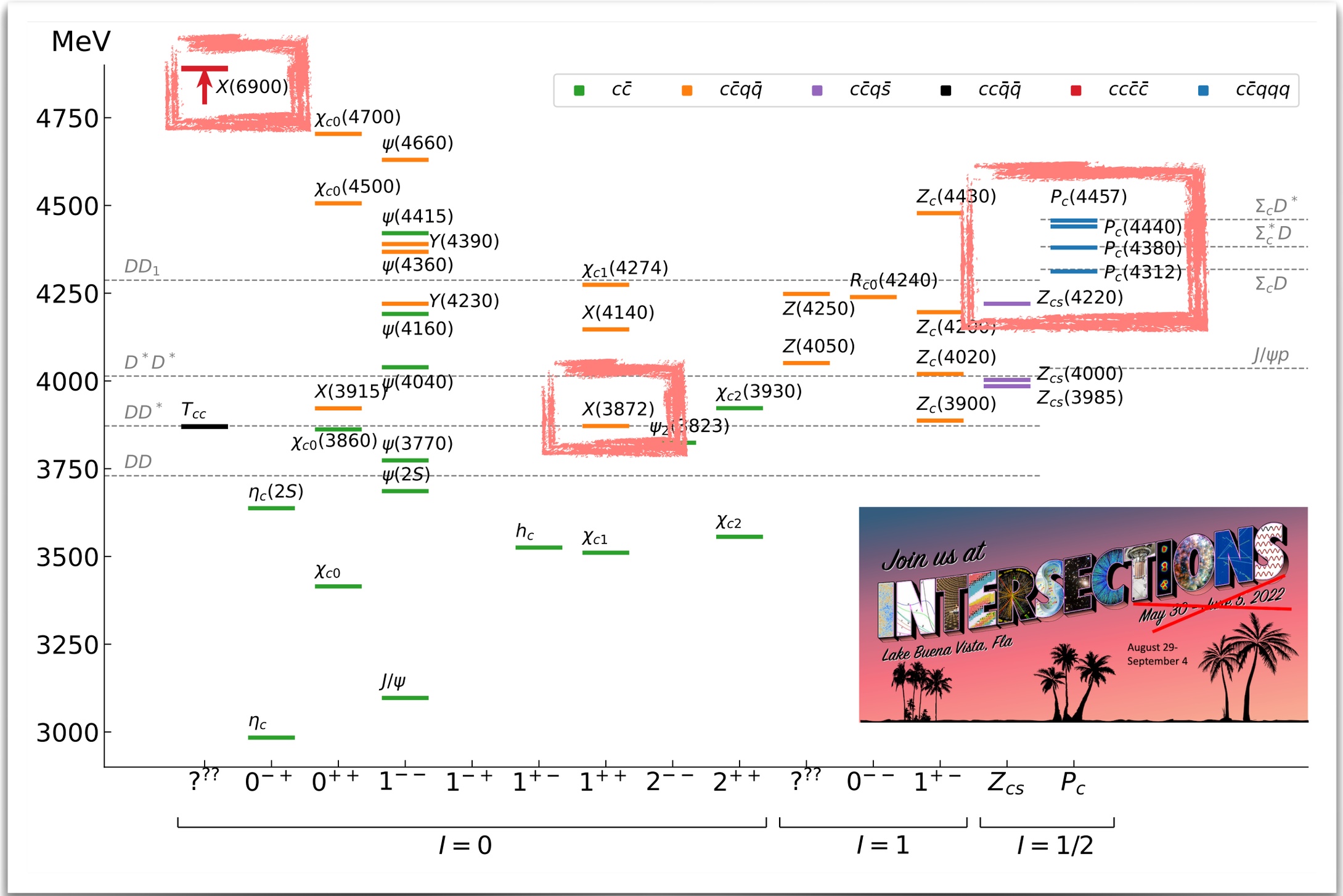
- So many new observed states: proposed new naming scheme to provide consistent descriptions arXiv:2206.15233

Recent discoveries in charm sector



Recent review: JPAC (2022)

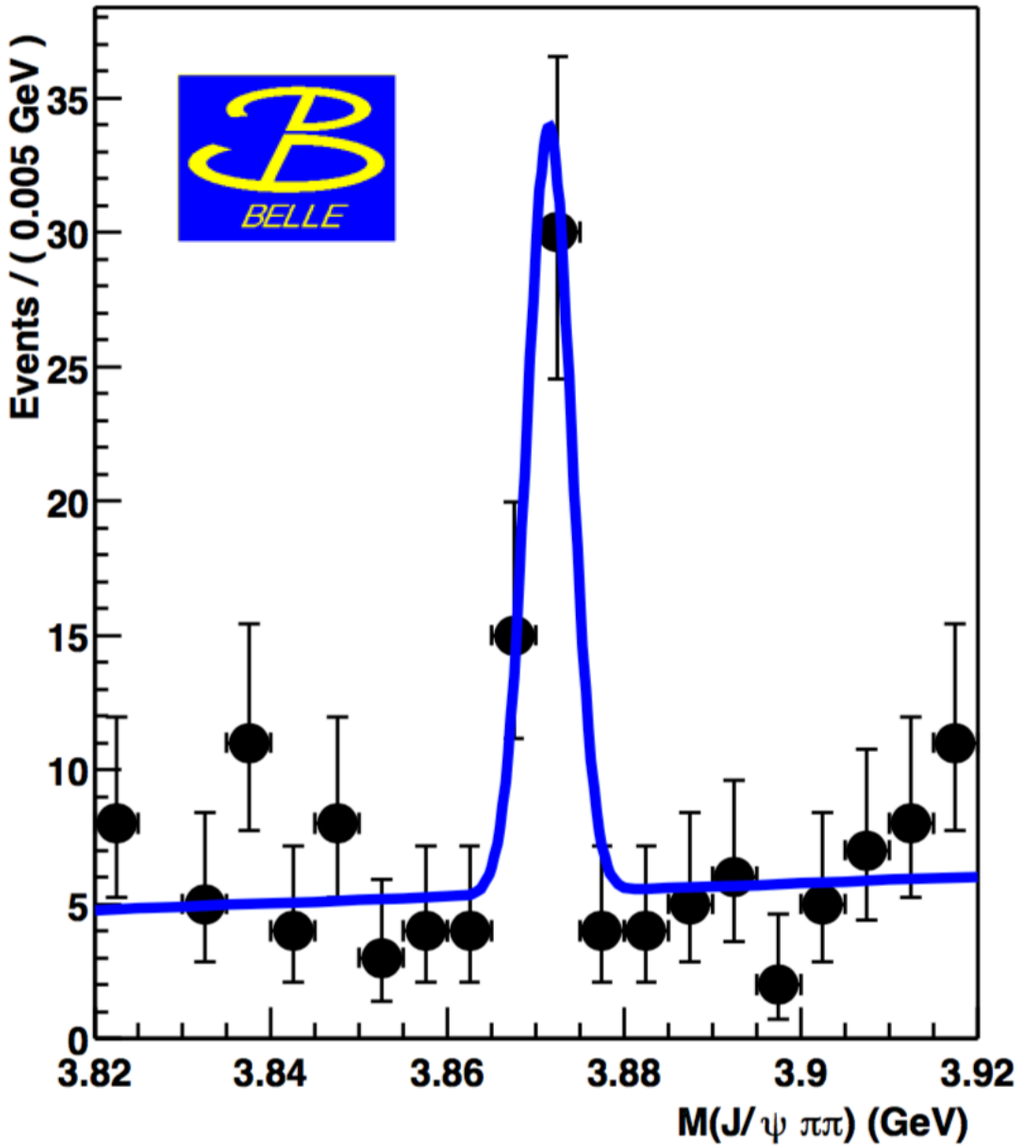
Recent discoveries in charm sector

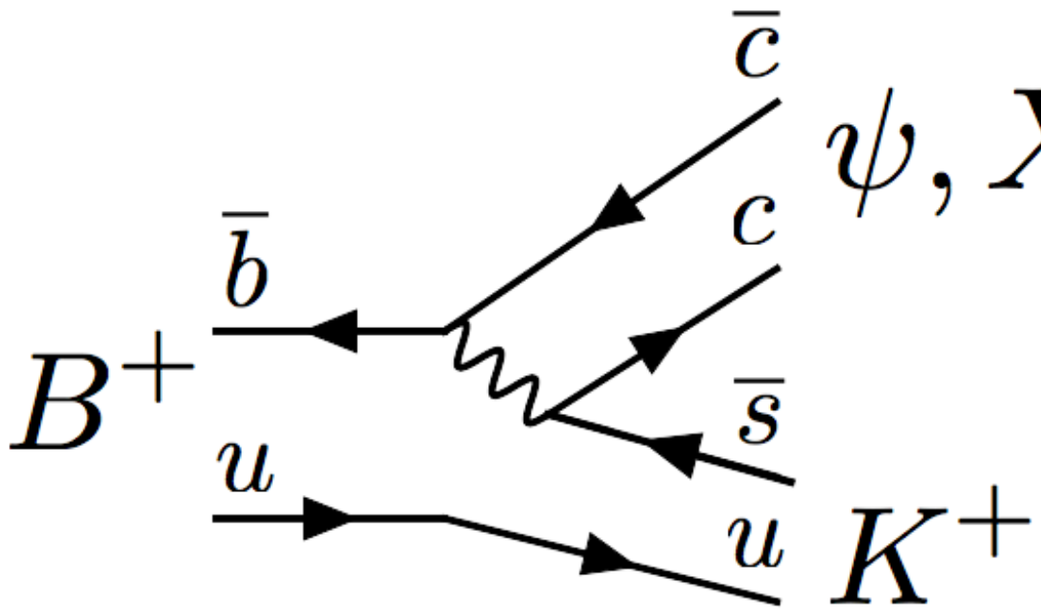


Recent review: JPAC (2022)

A charming surprise: $X(3872)$ or $\chi_{c1}(3872)$

$$X \to \pi^+\pi^- J/\psi$$





PRL 91, 262001 (2003)

A charming surprise: $\chi_{c1}(3872)$

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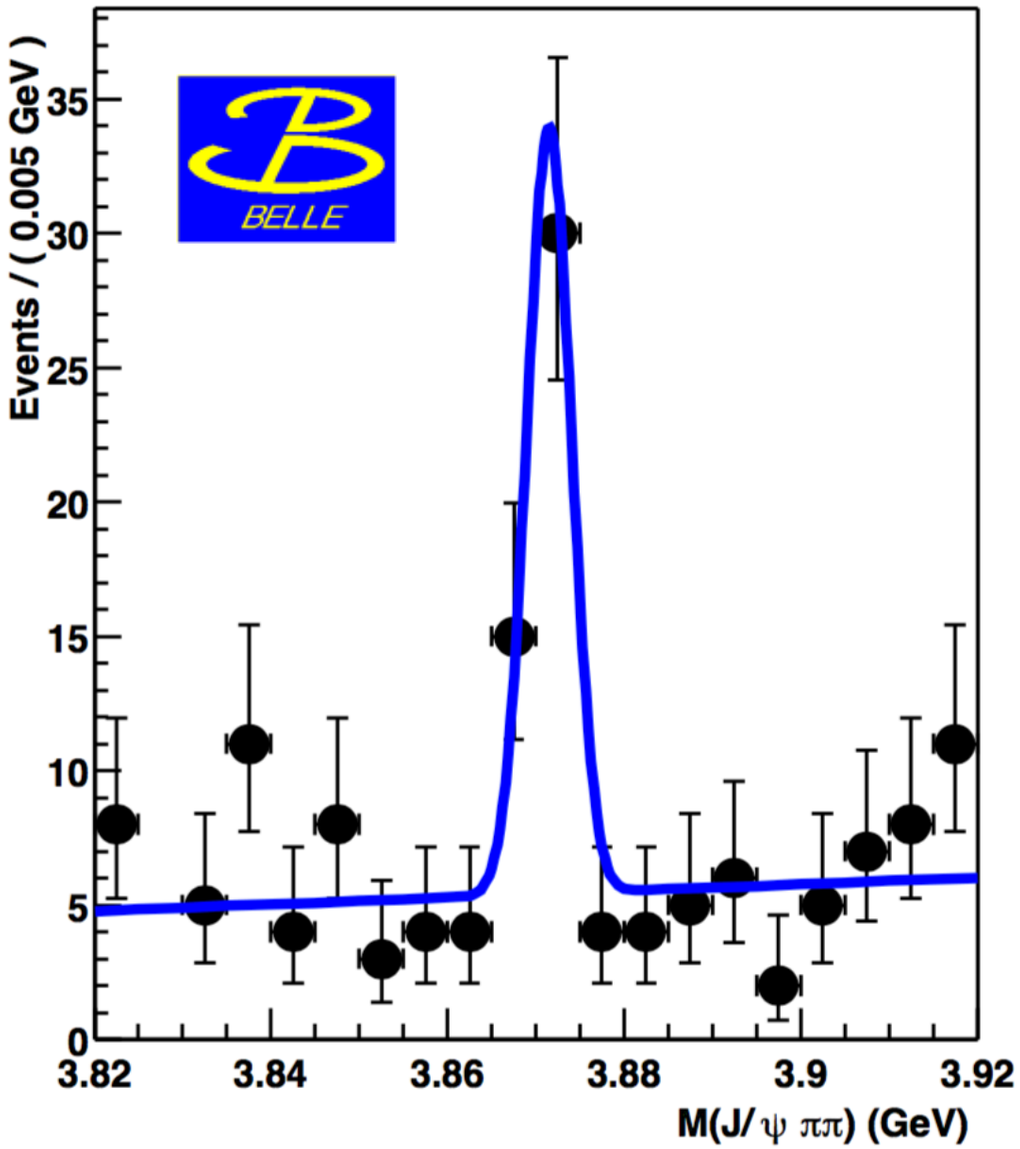
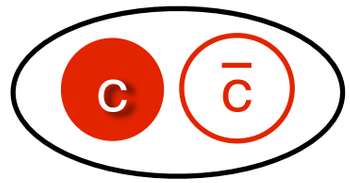


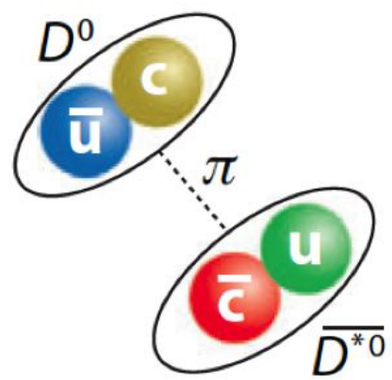
PRL 91, 262001 (2003)

Interpretation?

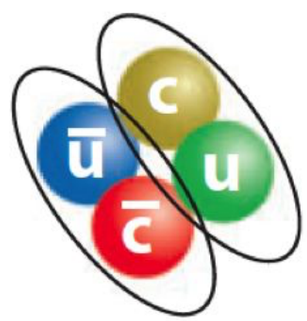
Conventional



Molecule

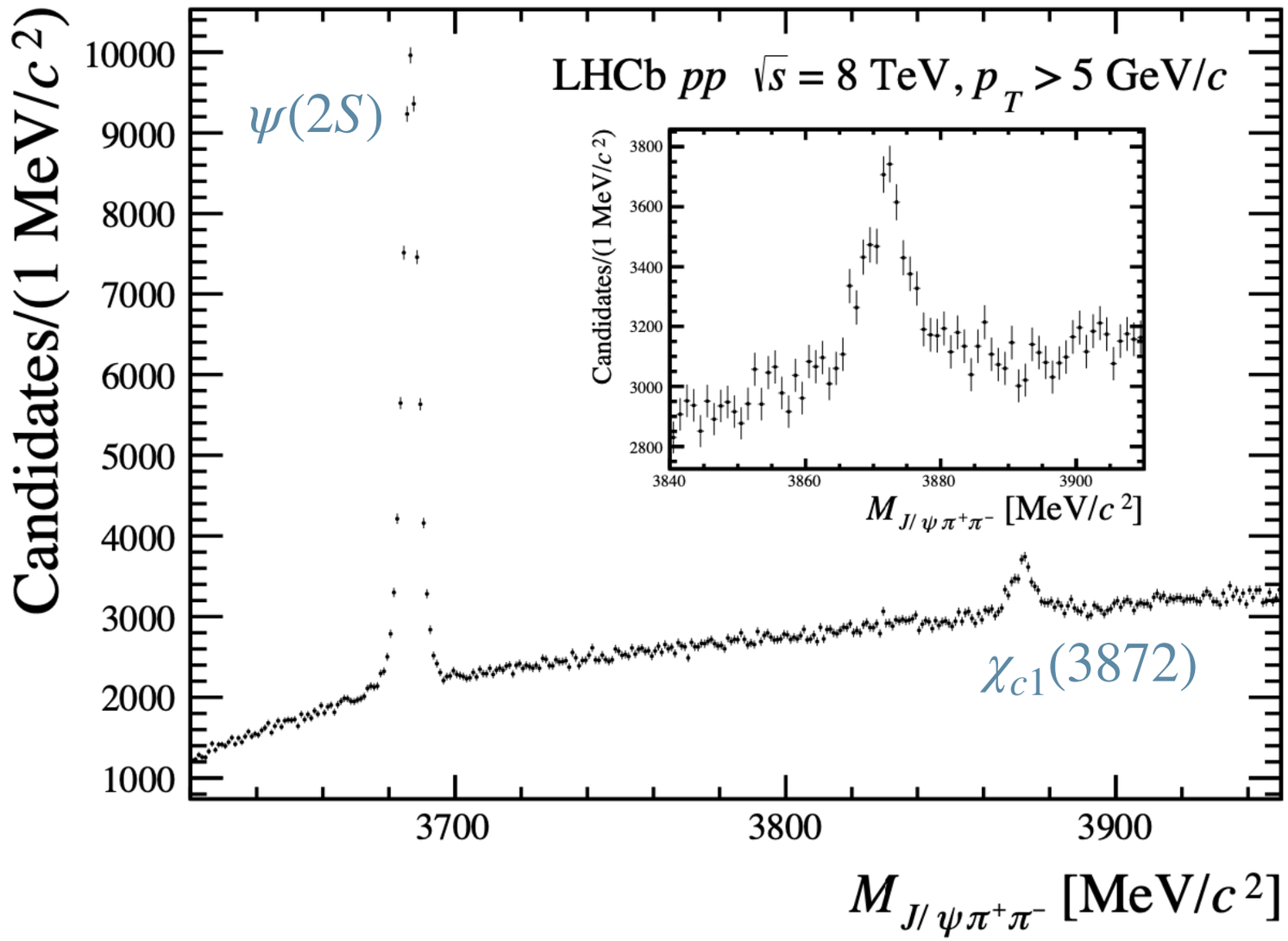


Compact Tetraquark



$\chi_{c1}(3872)$ compared to $\psi(2S)$

Thomas Boettcher



LHCb: PRL 126 (2021) 9, 092001

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \frac{\mathrm{BR}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\mathrm{BR}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

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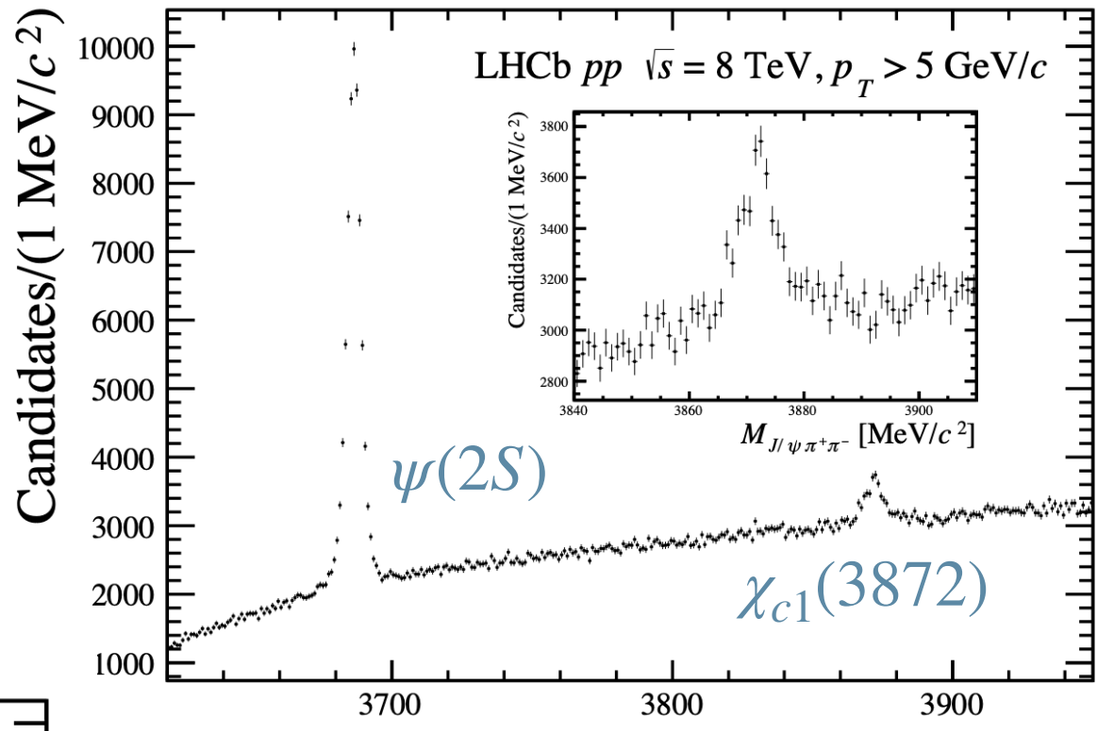

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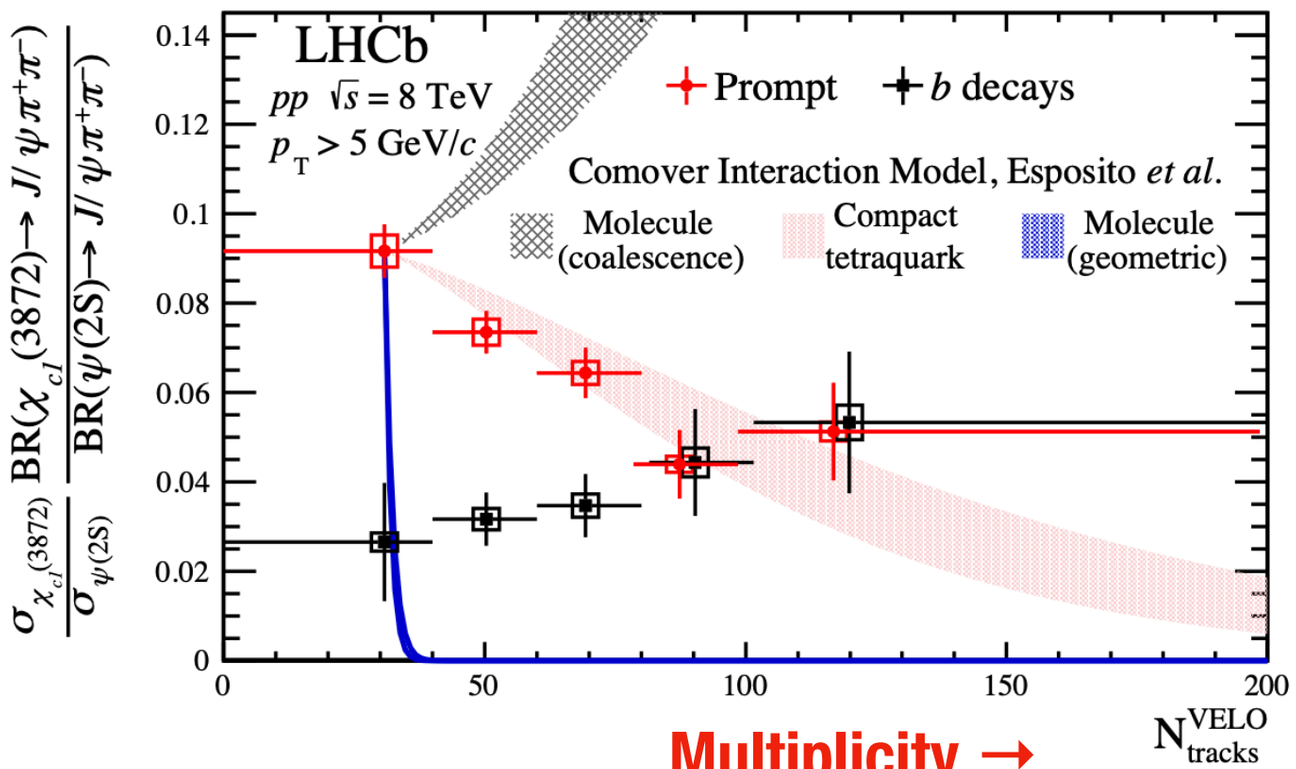

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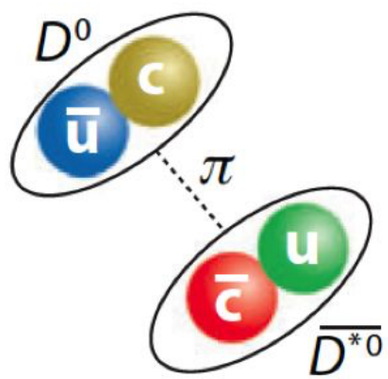

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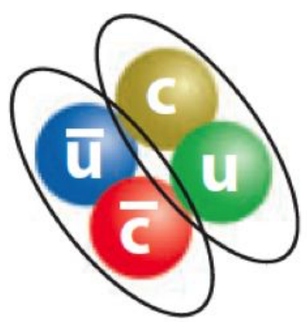

$\chi_{c1}(3872)$ in heavy ion collisions

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- First observation of prompt $\chi_{c1}(3872)$ in PbPb at CMS not suppressed relative to $\psi(2S)$

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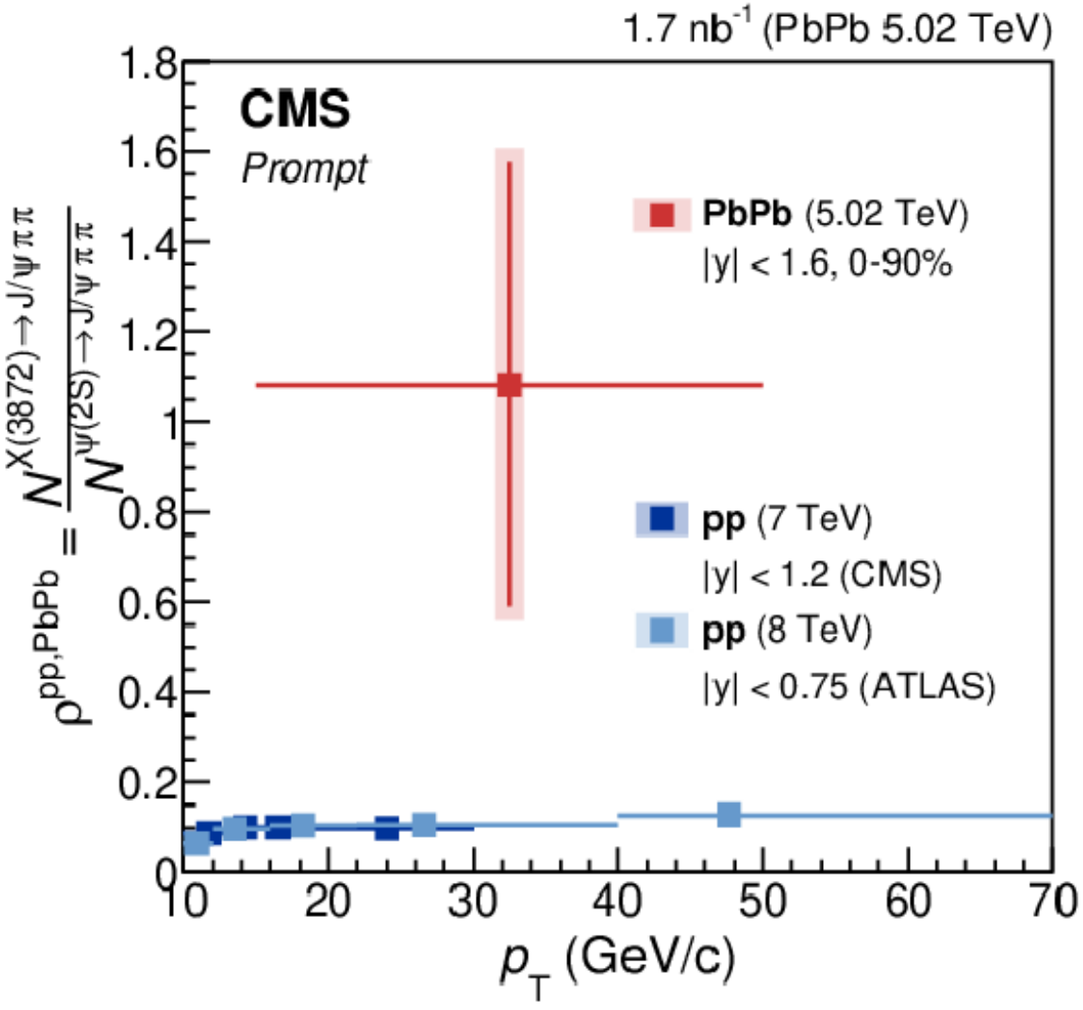

CMS: PRL 128 (2022) 3, 032001

$\chi_{c1}(3872)$ in heavy ion collisions

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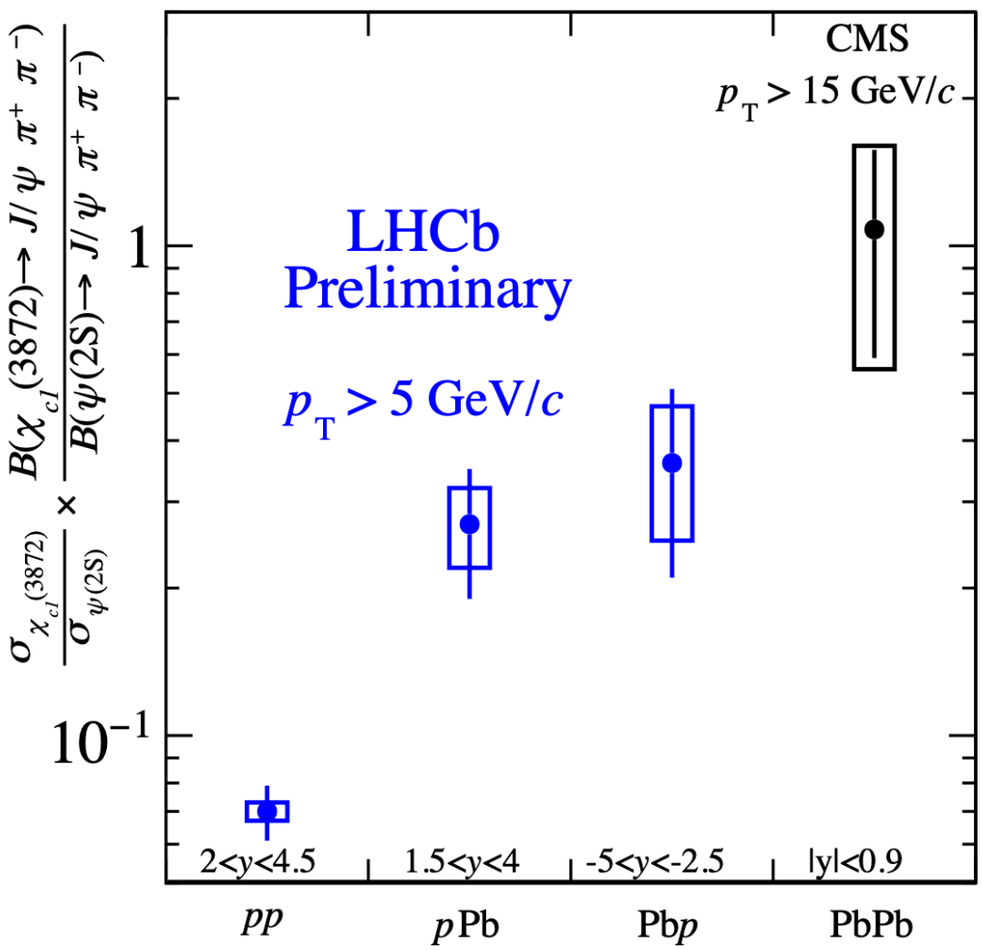
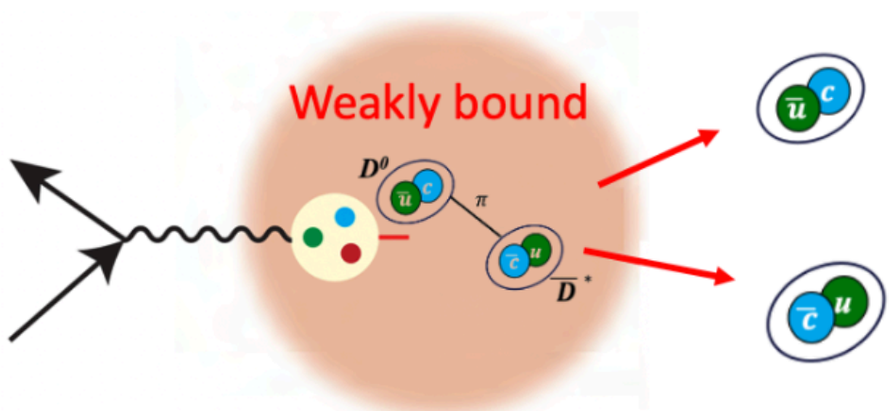
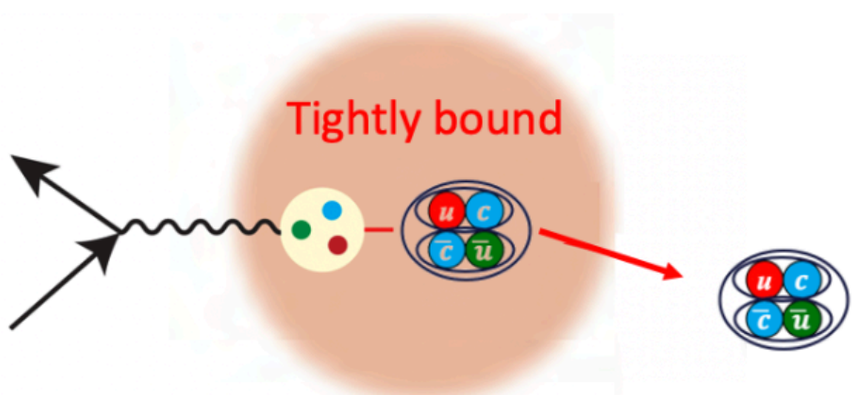
- Recent LHCb results in pp show prompt $\chi_{c1}(3872)$ decreases with multiplicity
- First observation of prompt $\chi_{c1}(3872)$ in PbPb at CMS not suppressed relative to $\psi(2S)$
- Enhancement in pPb relative to pp, increase with system size

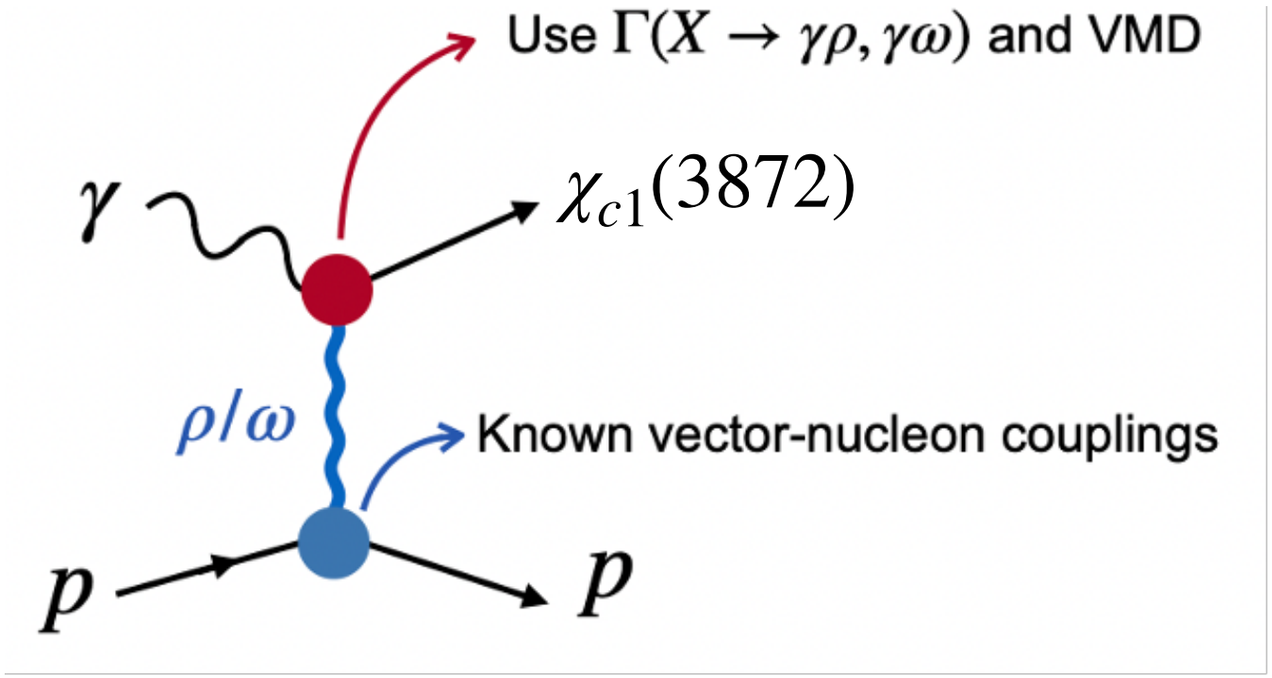






$\chi_{c1}(3872)$ future opportunities

$\gamma p \to p J/\psi \pi^+ \pi^-$



Alternative production mechanism:
free of rescattering effects and
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JPAC : PRD 102, 114010 (2020)

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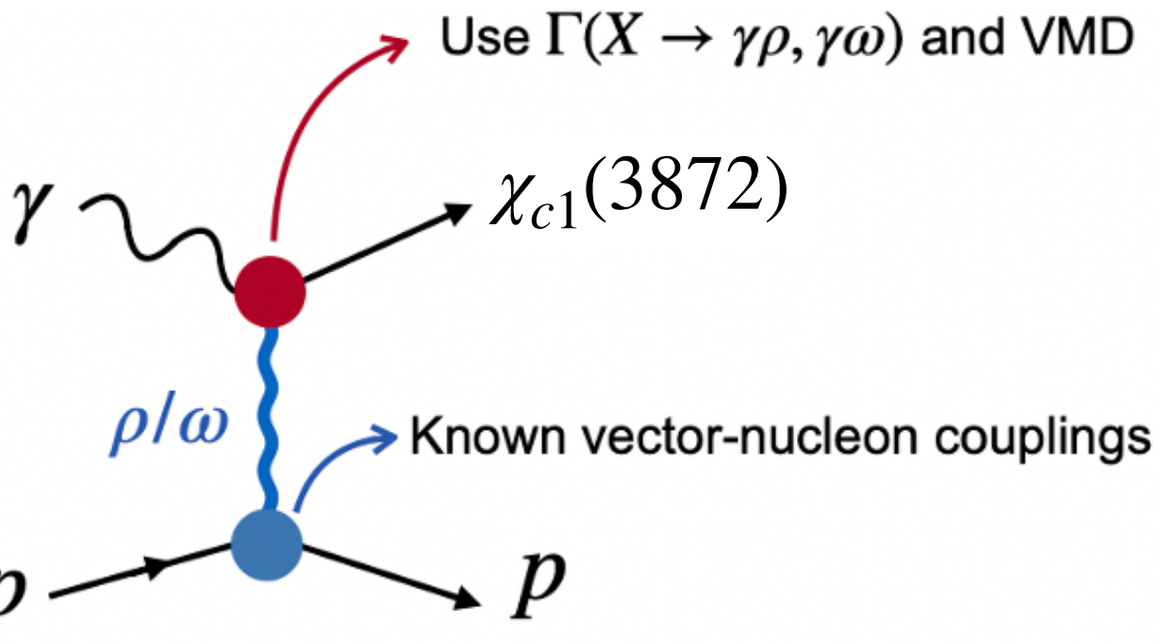

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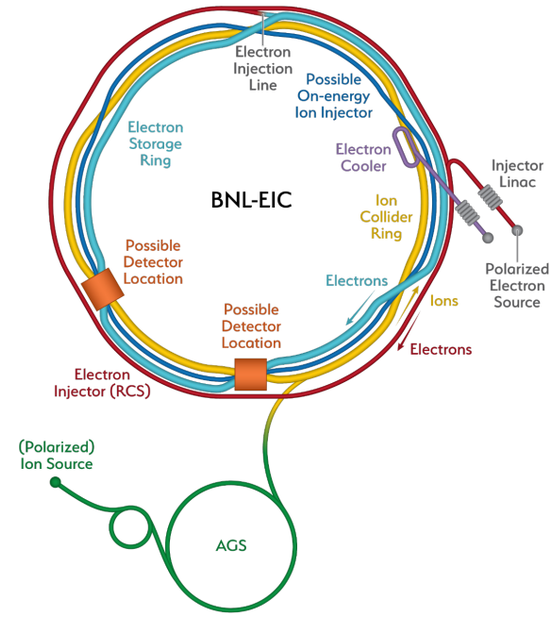
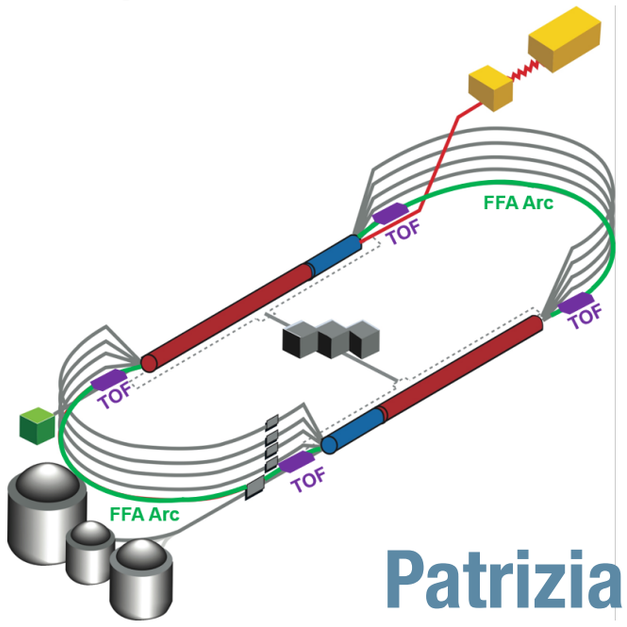
Electron Ion Collider (EIC)



Jefferson Lab upgrade:
E_e = 12 → 22 GeV



Patrizia Rossi

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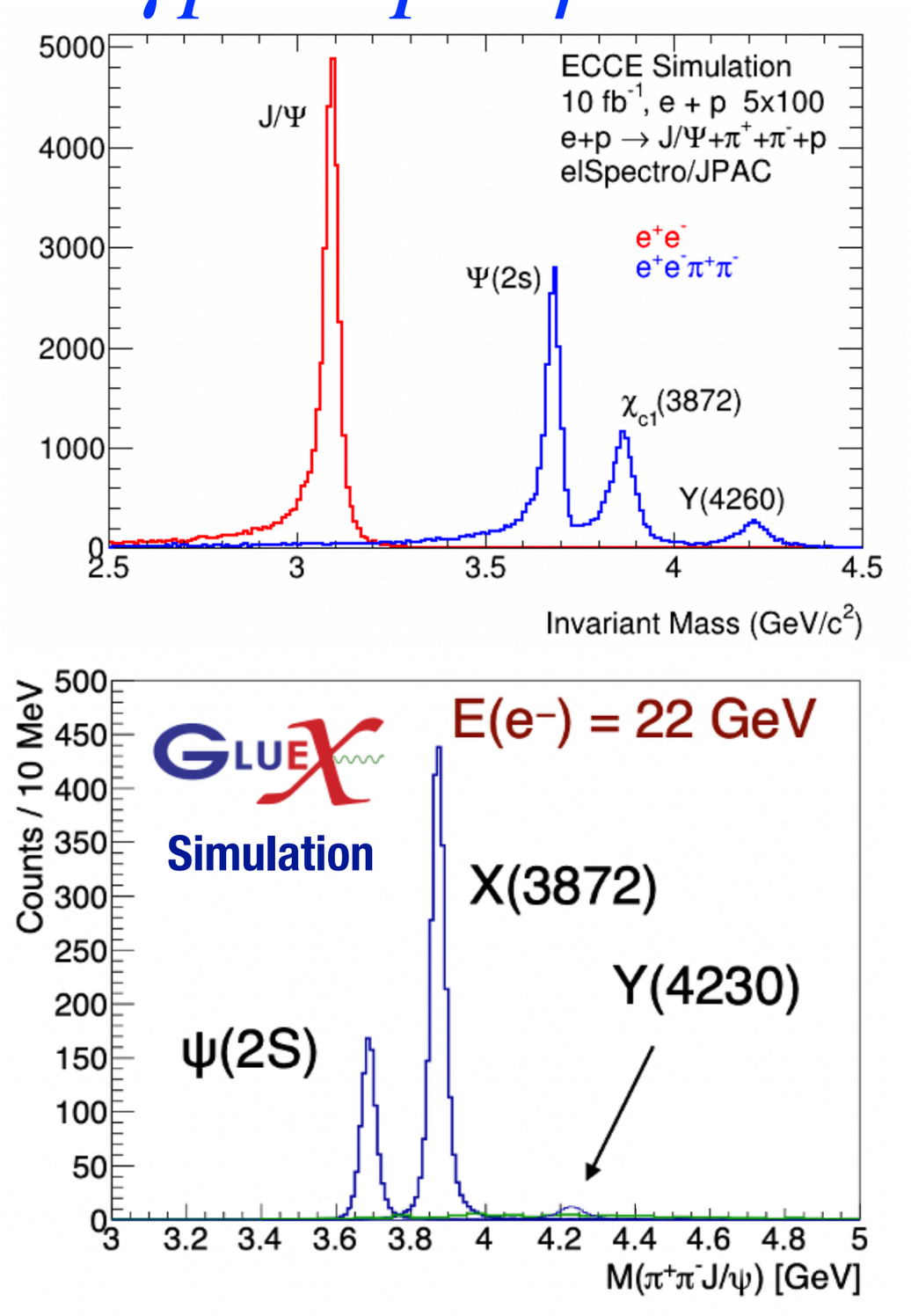

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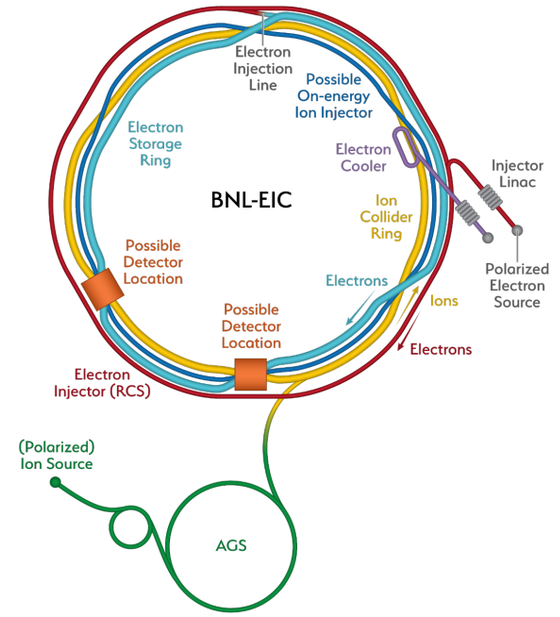

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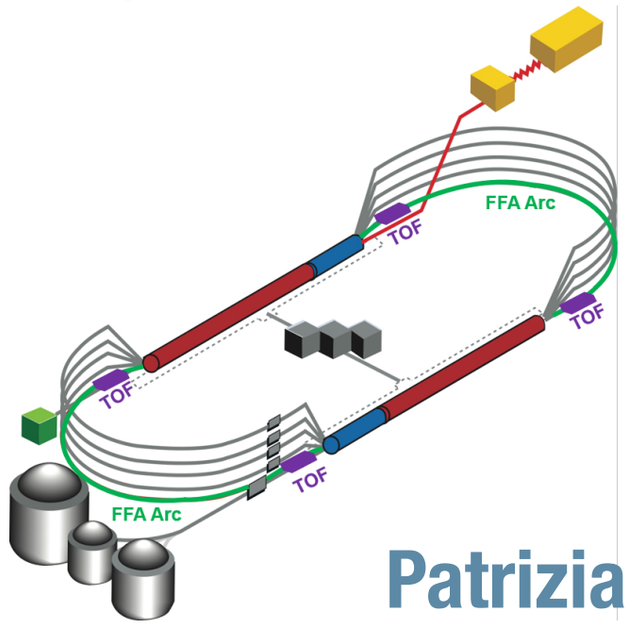

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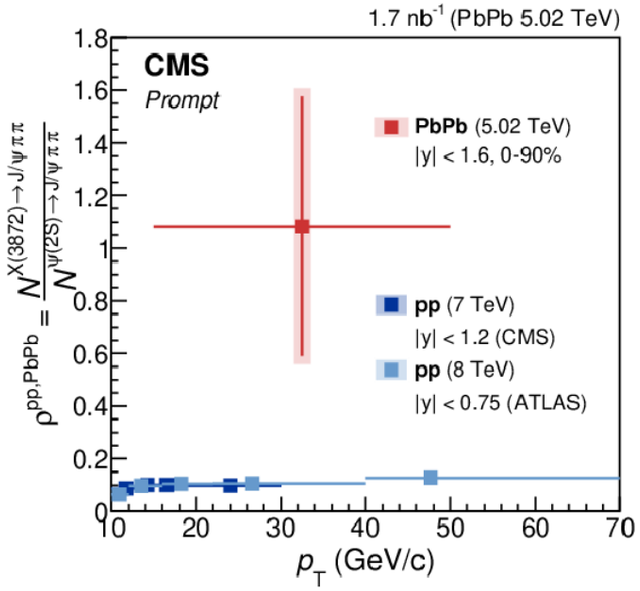
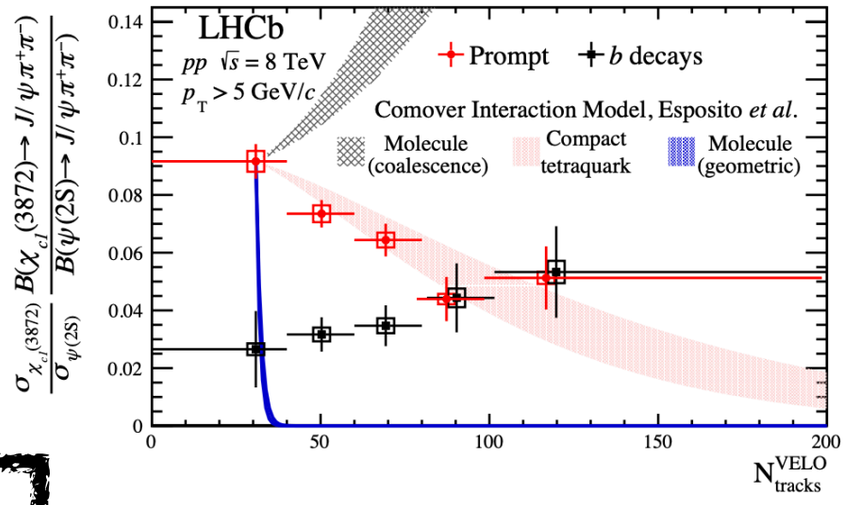
$\chi_{c1}(3872)$:  particle & nuclear

Heavy Ion: Coalescence

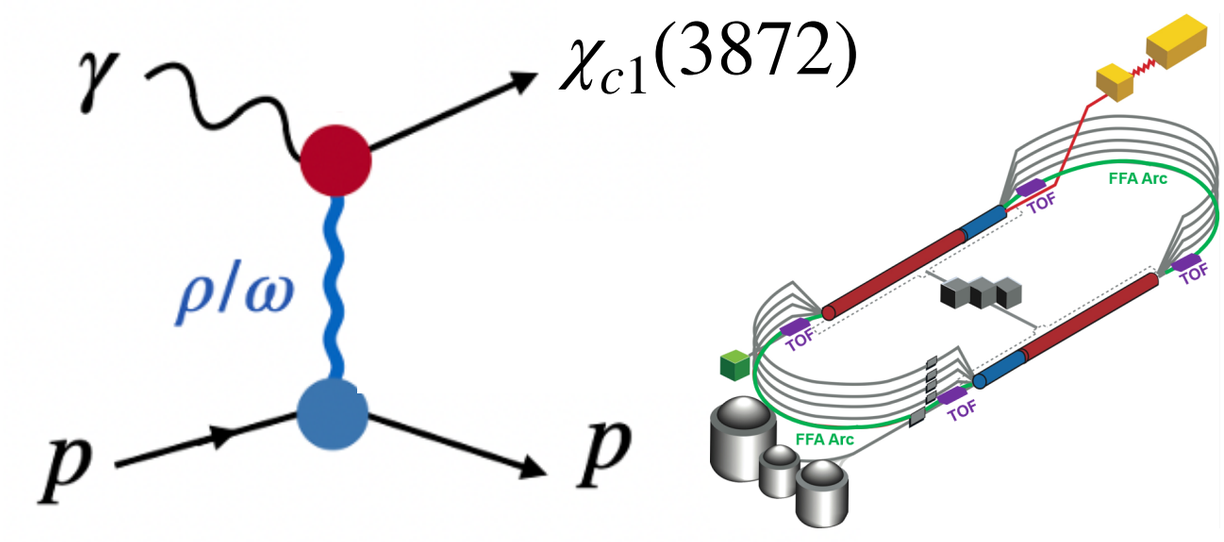


High energy: prompt vs b-decay

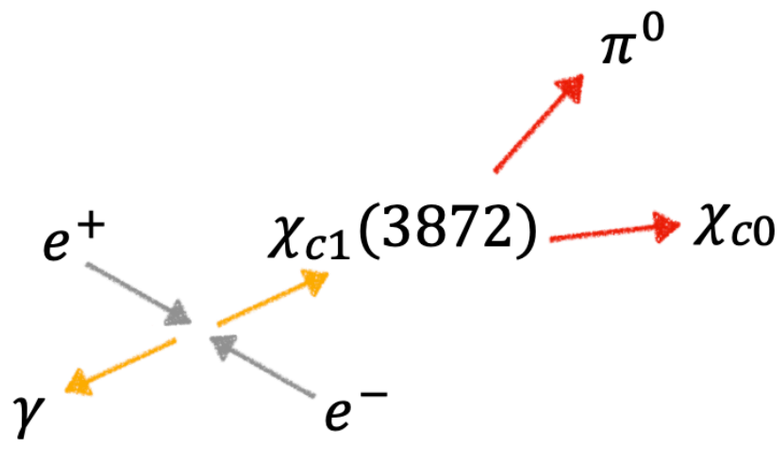


$\chi_{c1}(3872)$

Future: photoproduction



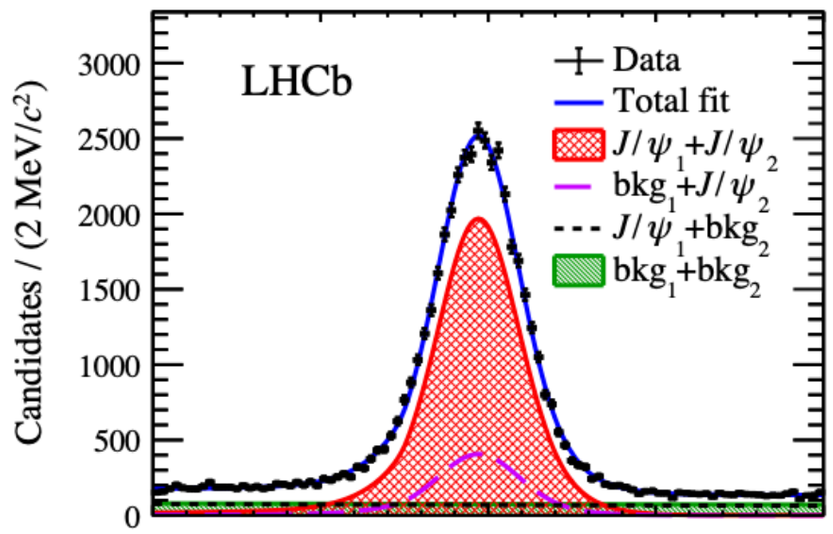
Alternate decay modes: e+e-

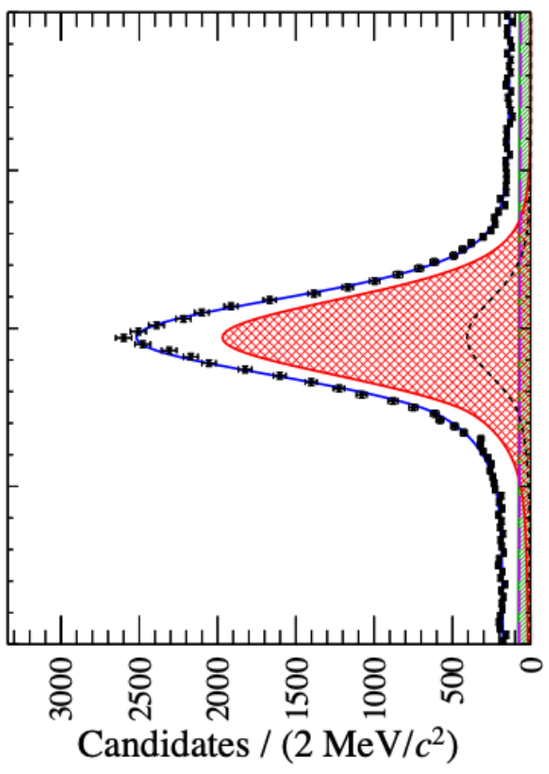


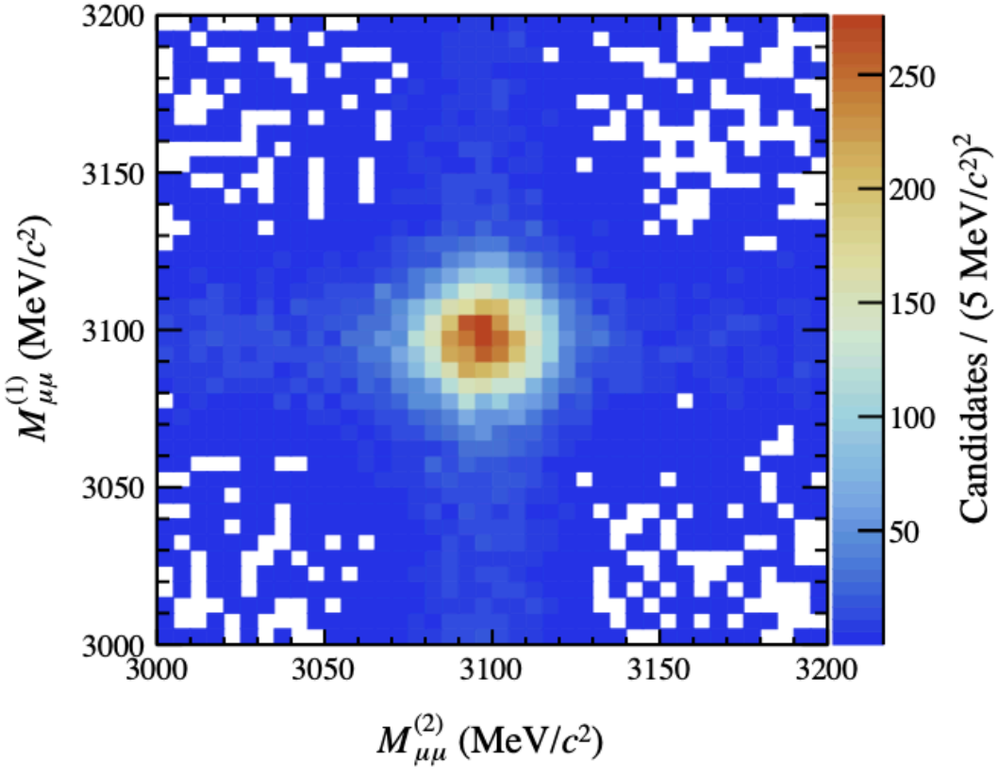
More surprises: **di-J/ψ**

Jane Nachtman

$$pp \to J/\psi J\psi + X$$







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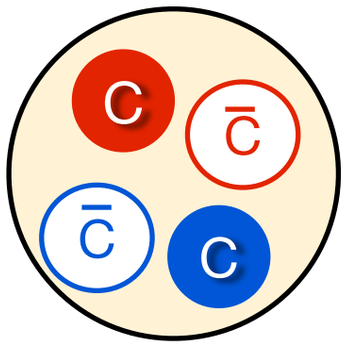

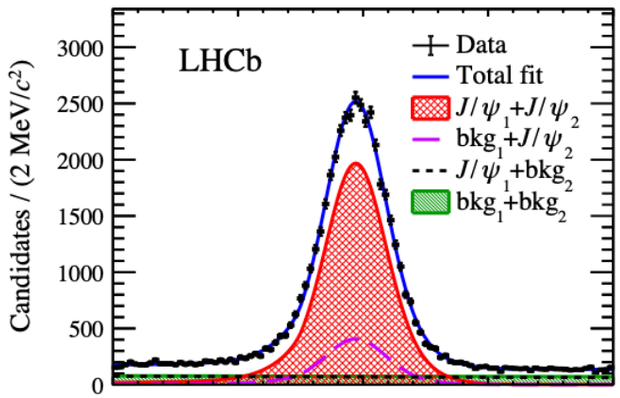

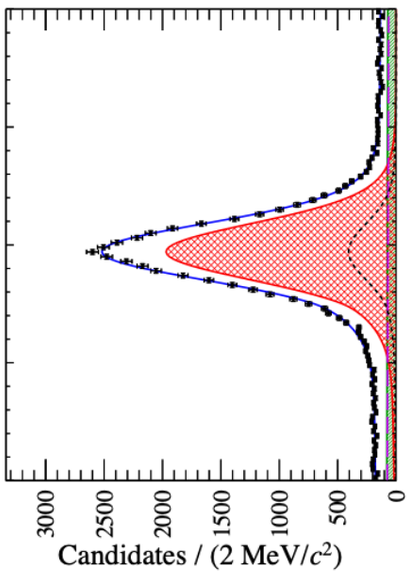

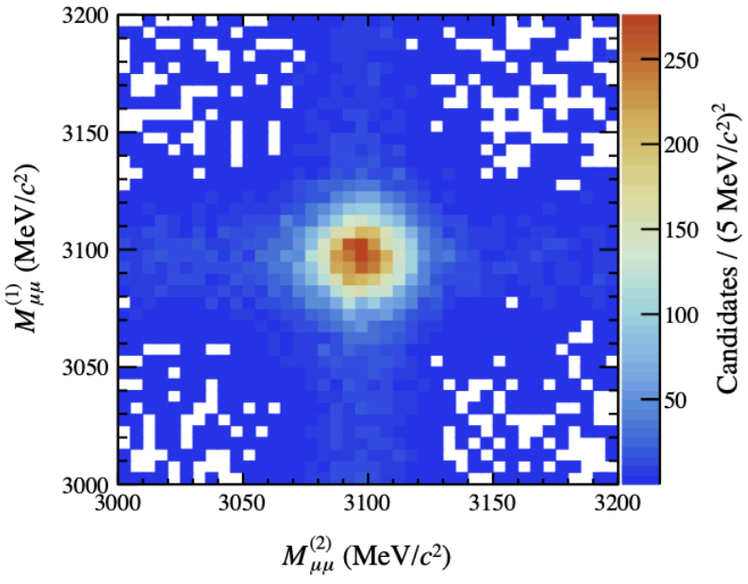

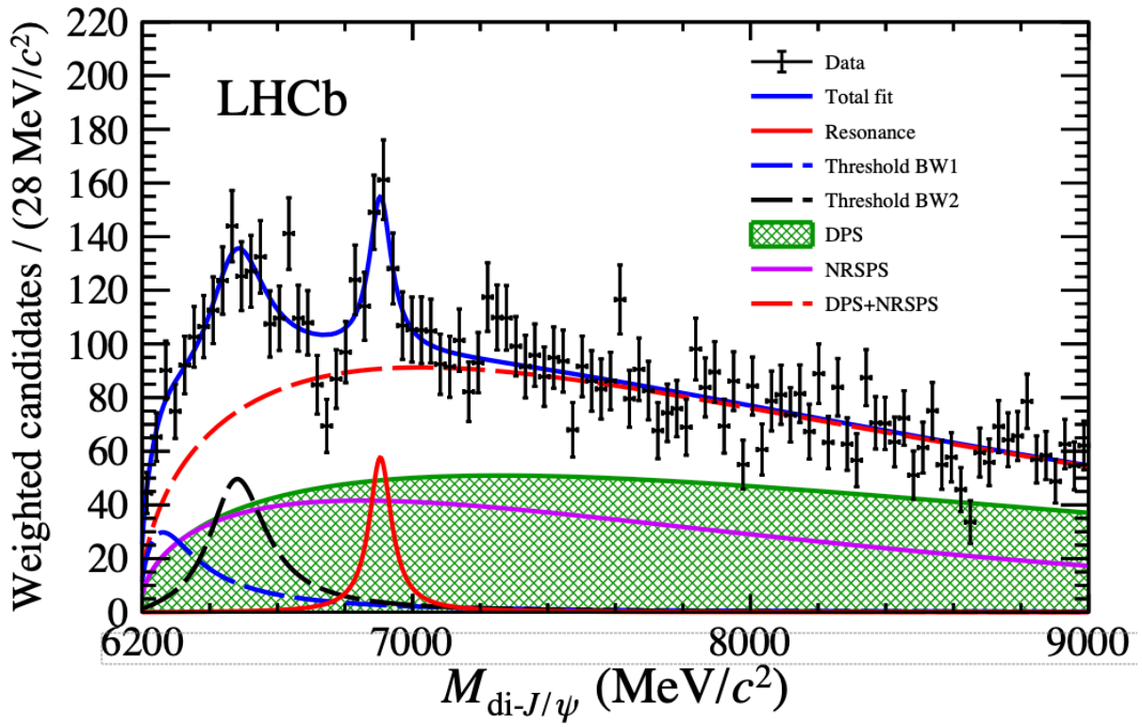

Science Bulletin 65 (2020) 1983–1993

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Article

Observation of structure in the J/ψ-pair mass spectrum

LHCb collaboration [1]

- All-heavy tetraquark: first mentioned in 1975 (1 year after J/ψ discovery)
- Complicated structures, challenging to describe with simple Breit-Wigners

More surprises: di-J/ψ

Jane Nachtman

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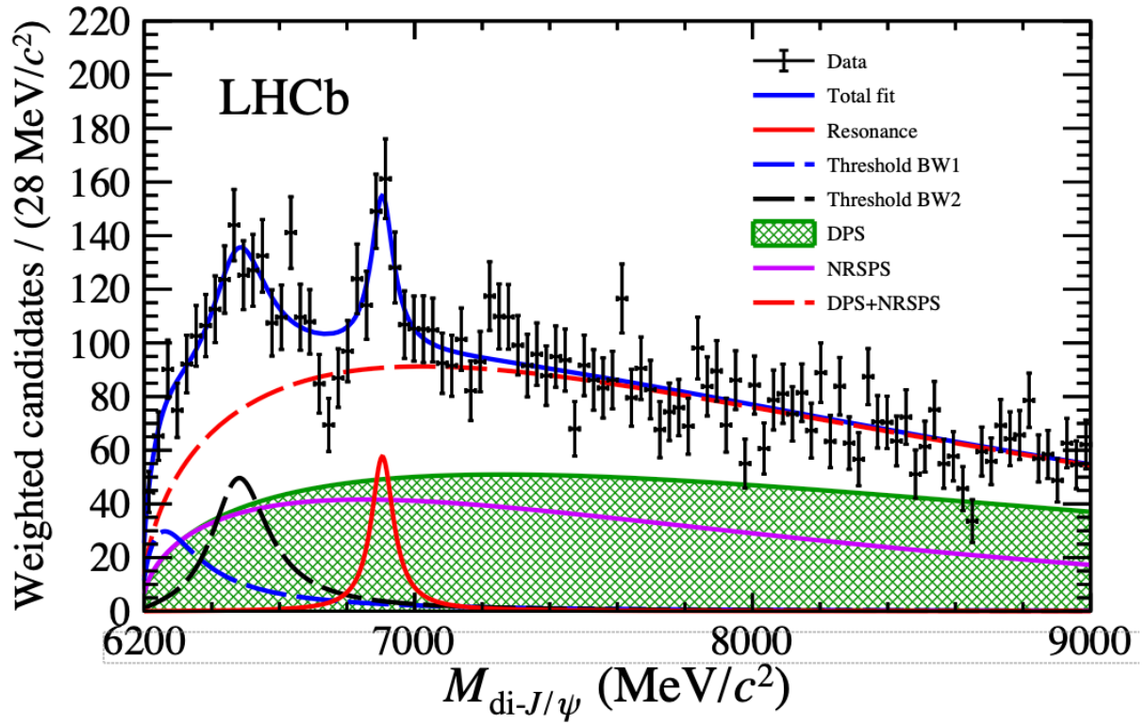
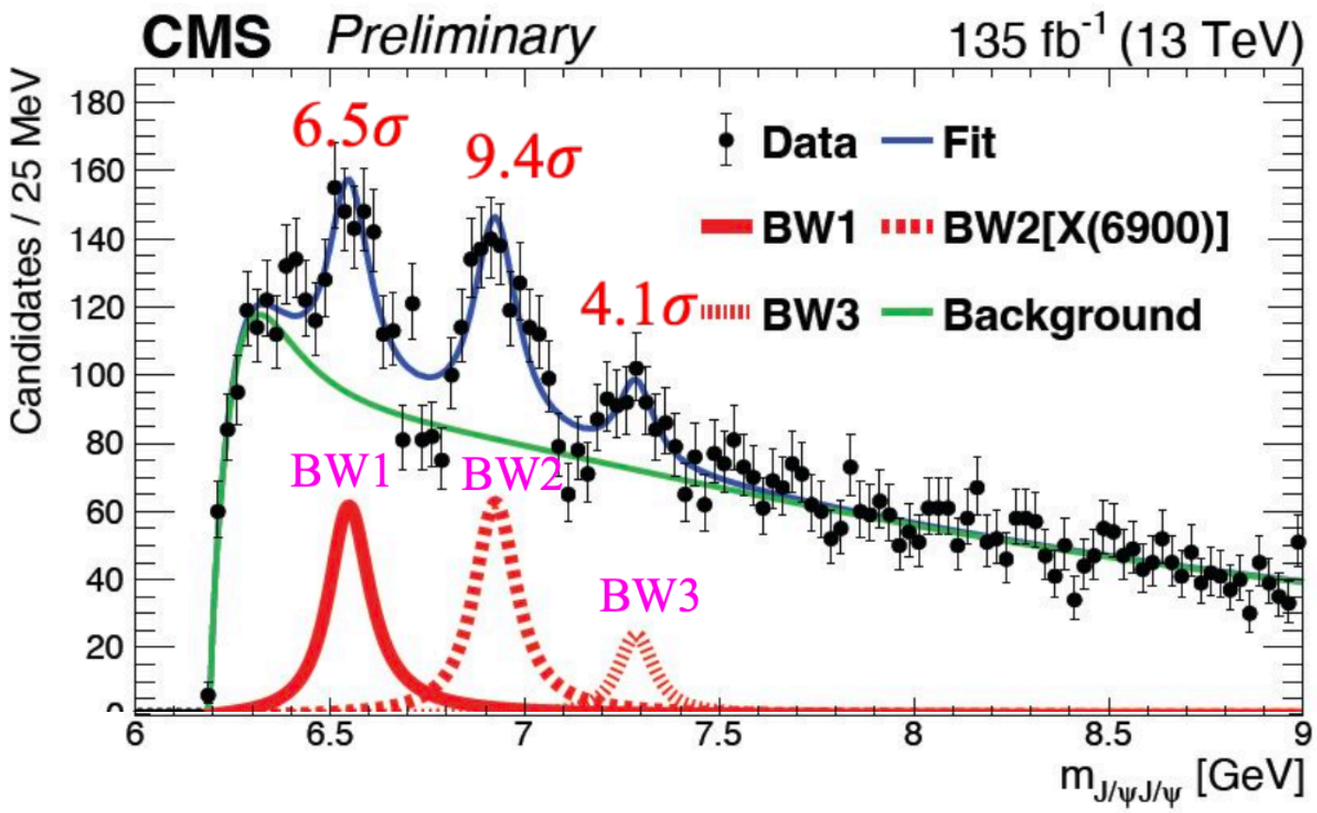
- Many recent theoretical studies for both charm and bottom





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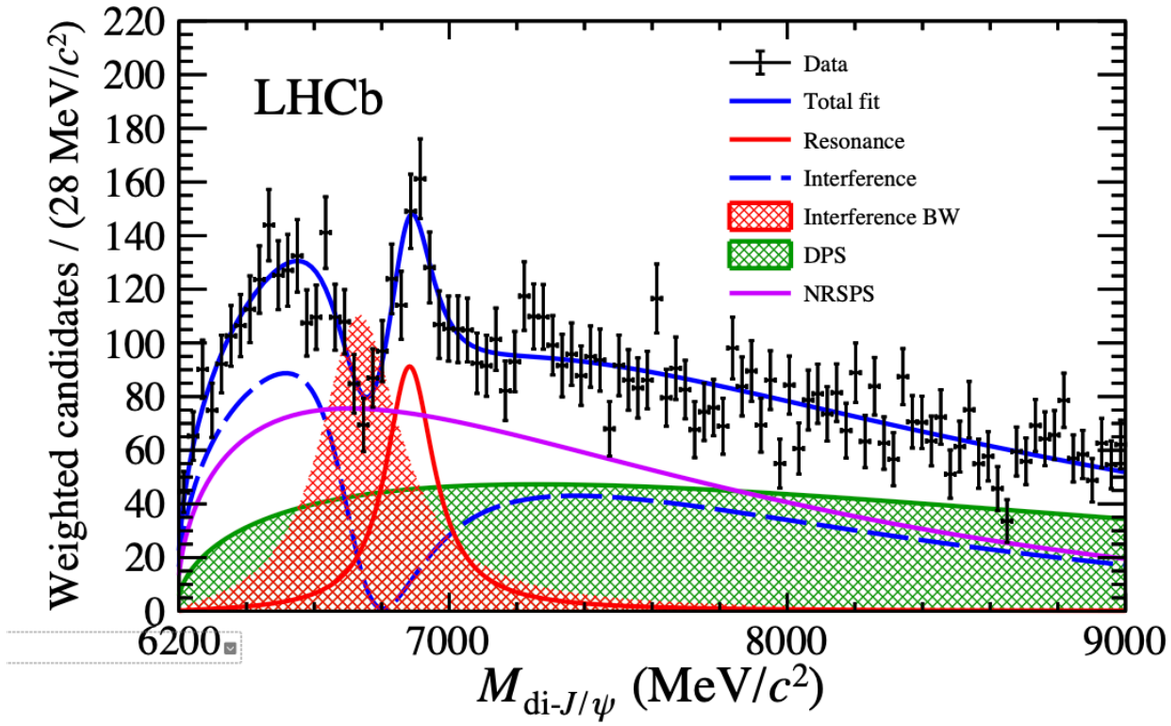
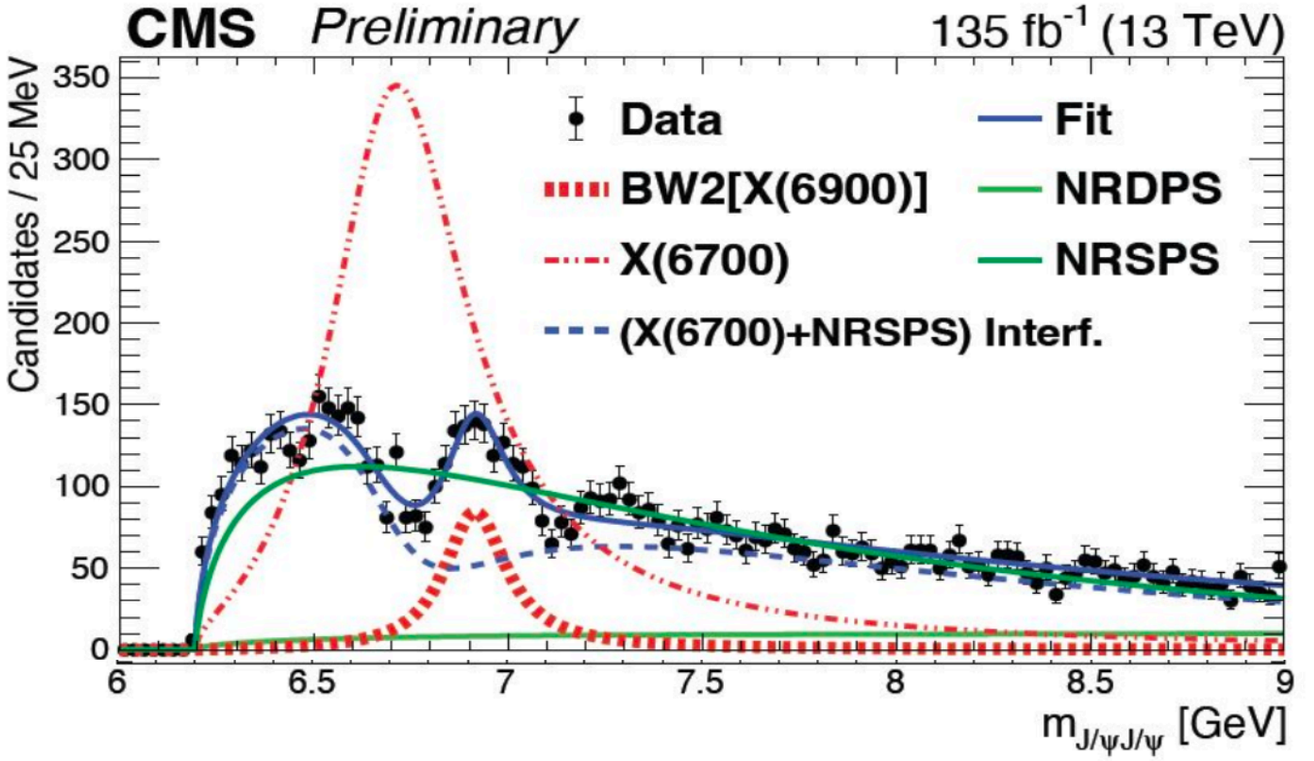
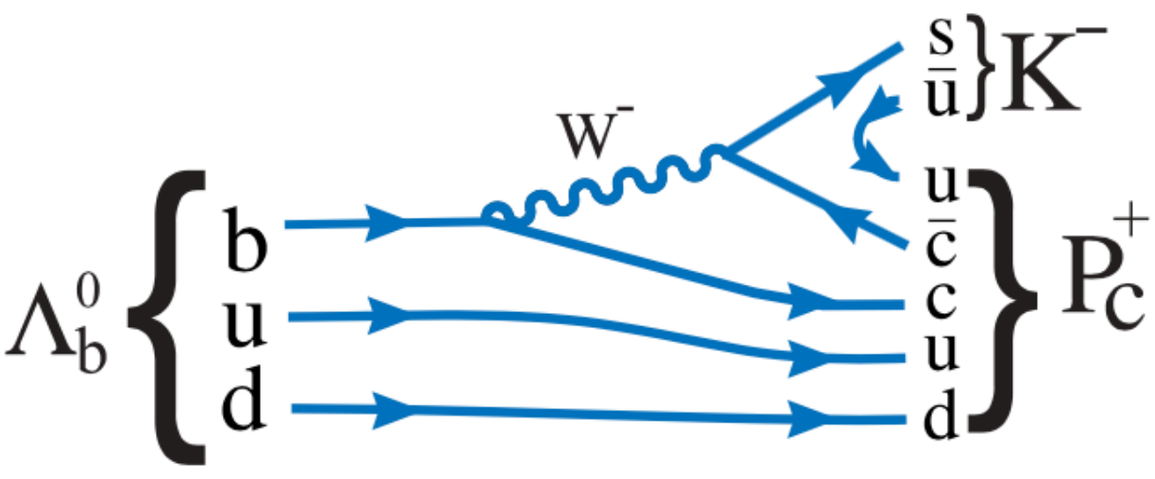
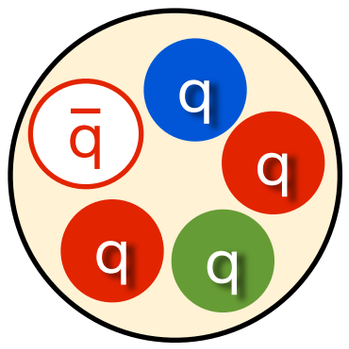




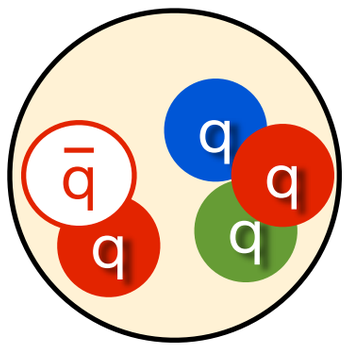
Pentaquarks

Sylvester Joosten



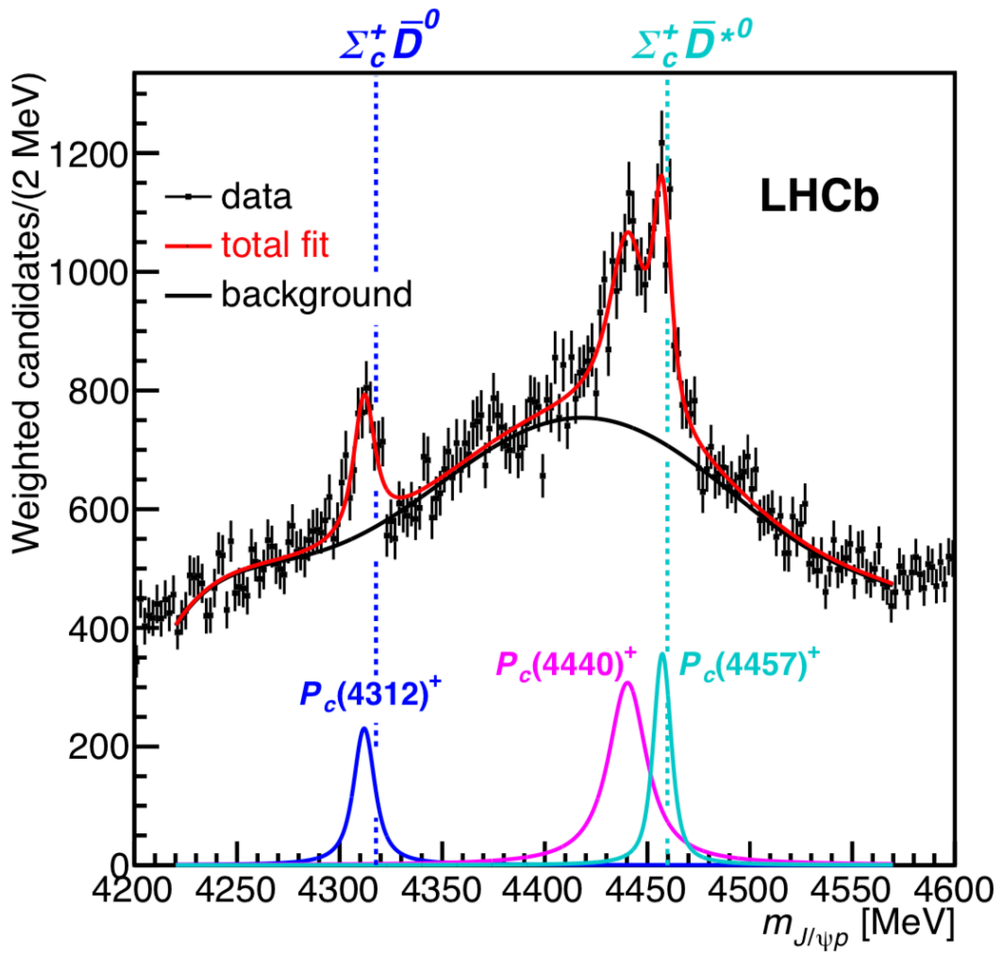


pentaquark



Molecular

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

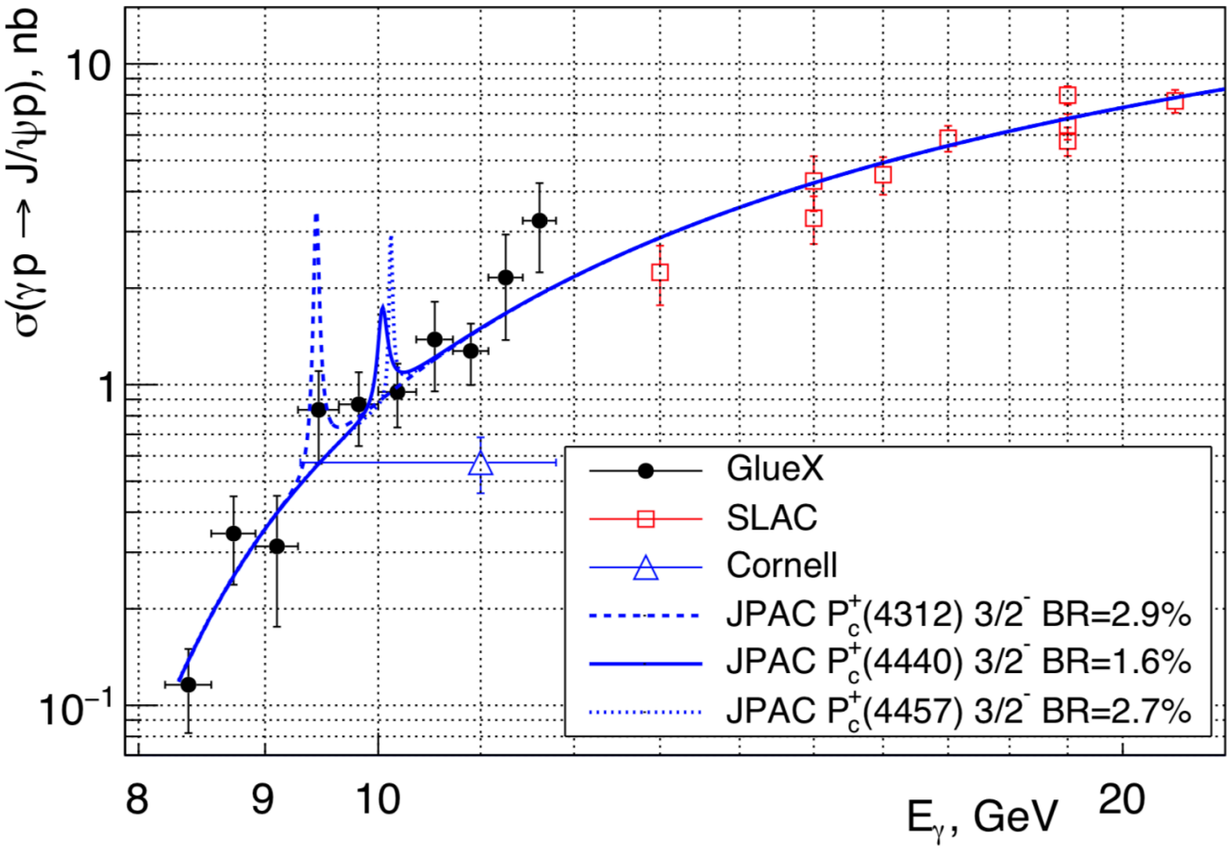


PRL 122, 222001 (2019)

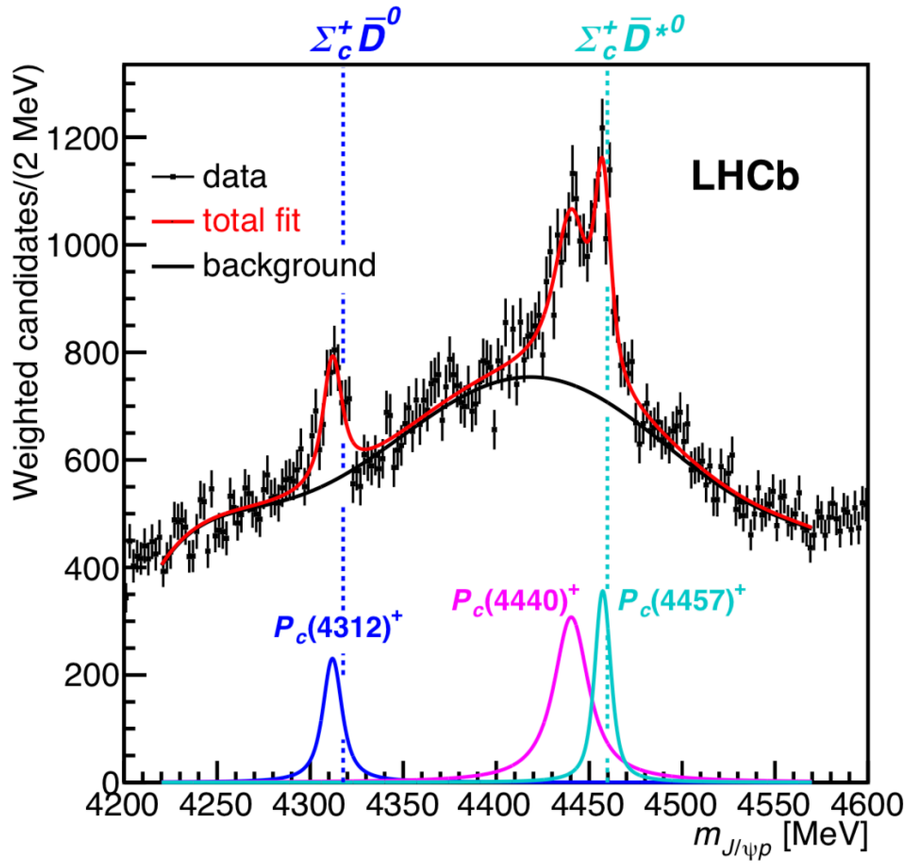
Pentaquark photoproduction

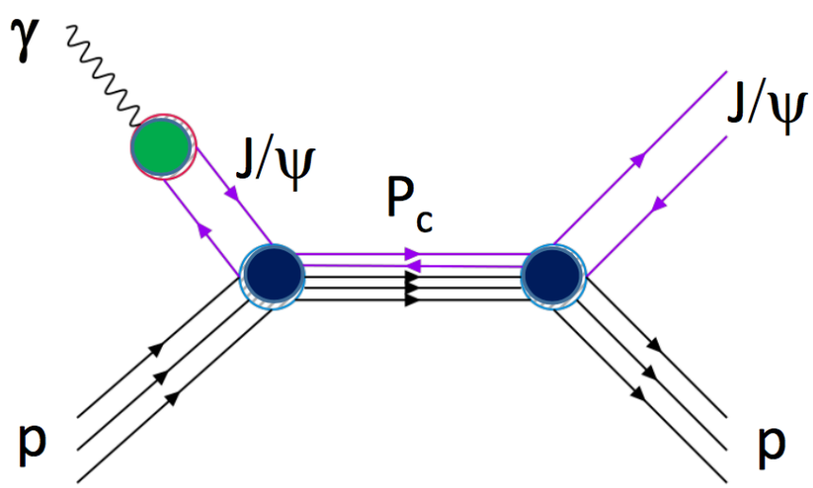
Sylvester Joosten

GLUEX **PRL 123, 072001 (2019)**



Limits BR($P_c \to J/\psi p$) < 2-4%, providing additional model constraints



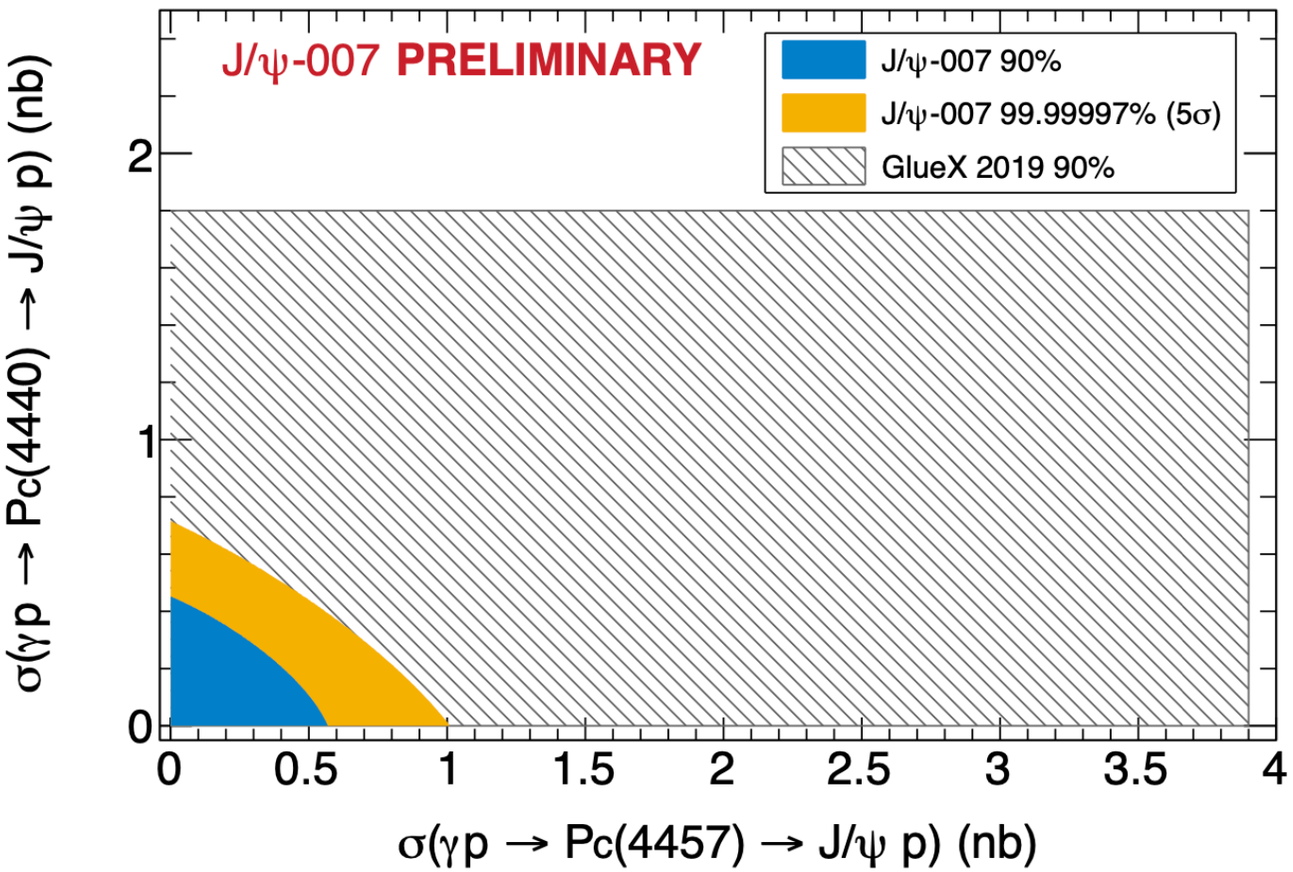


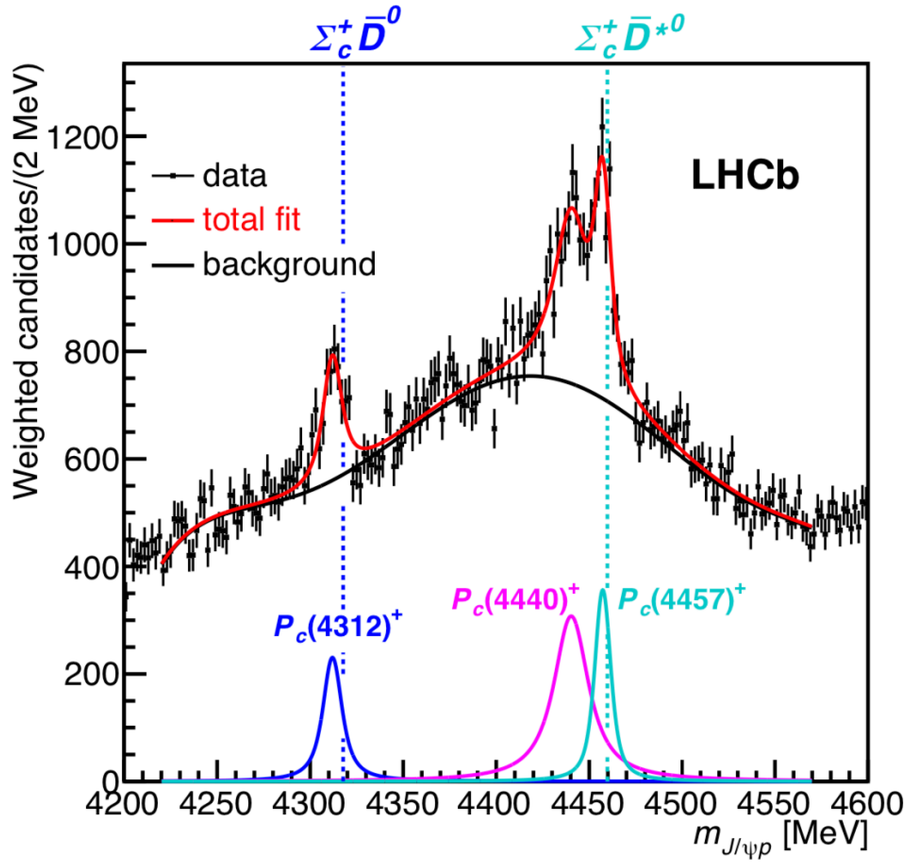
- Proportional to BR($P_c \to J/\psi p$)^2

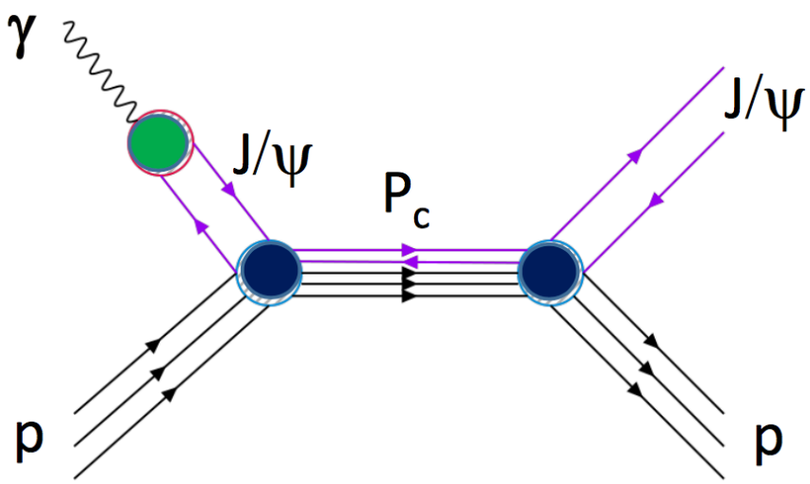
Pentaquark photoproduction

Sylvester Joosten

Hall C: J/ψ-007 experiment



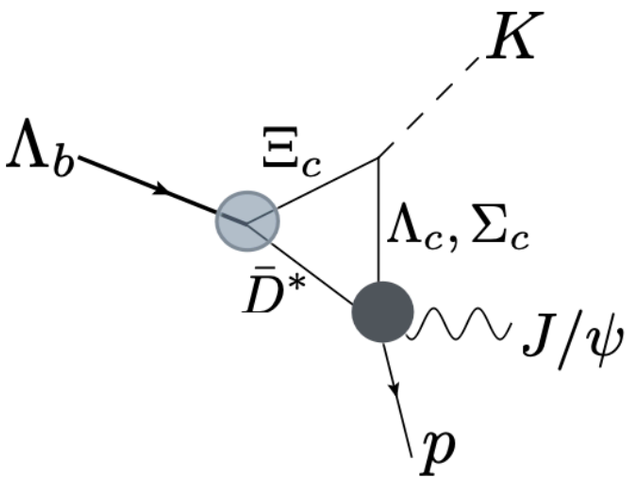


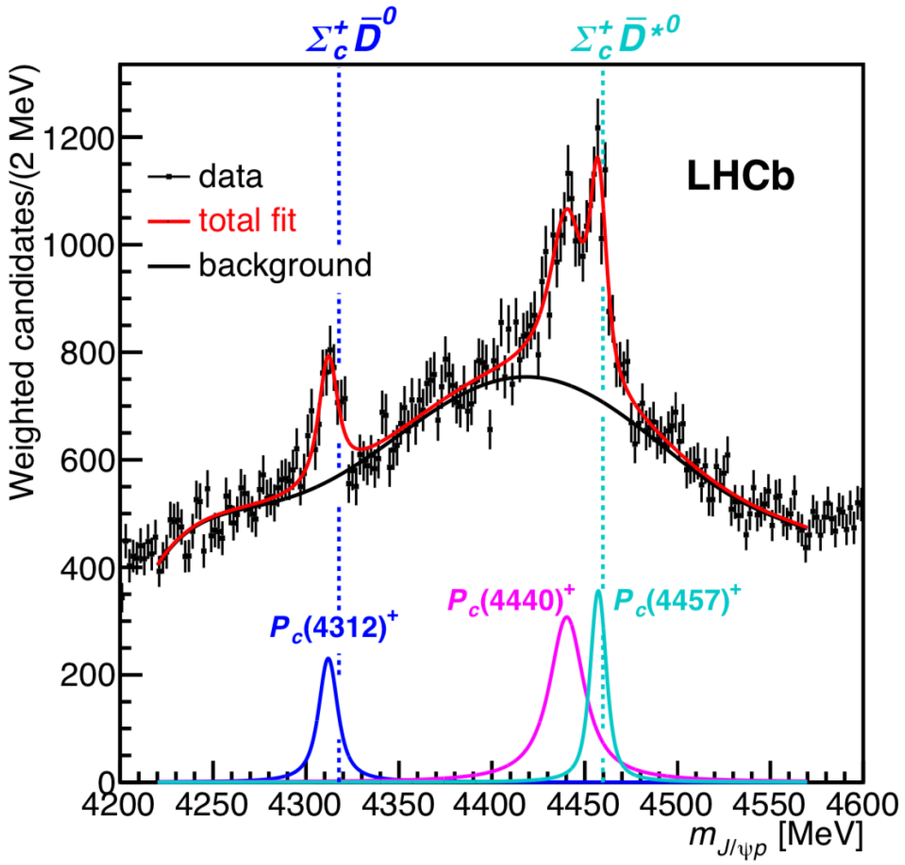


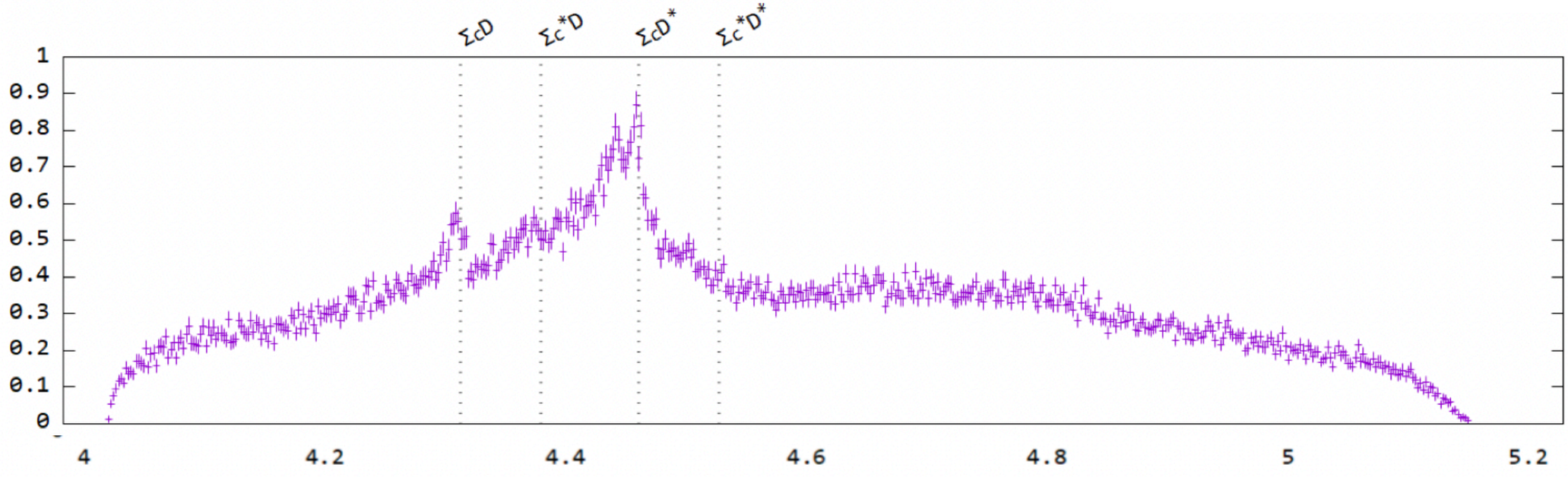
Even stricter limits on BR($P_c \to J/\psi p$): consistent with 5-quark picture?

Possible pentaquark interpretation

Eric Swanson

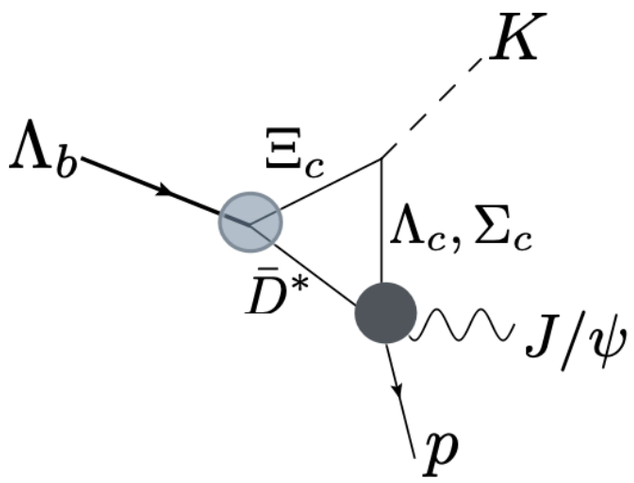


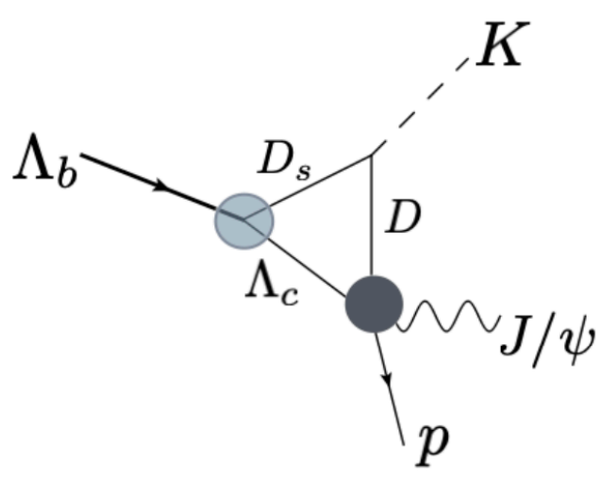


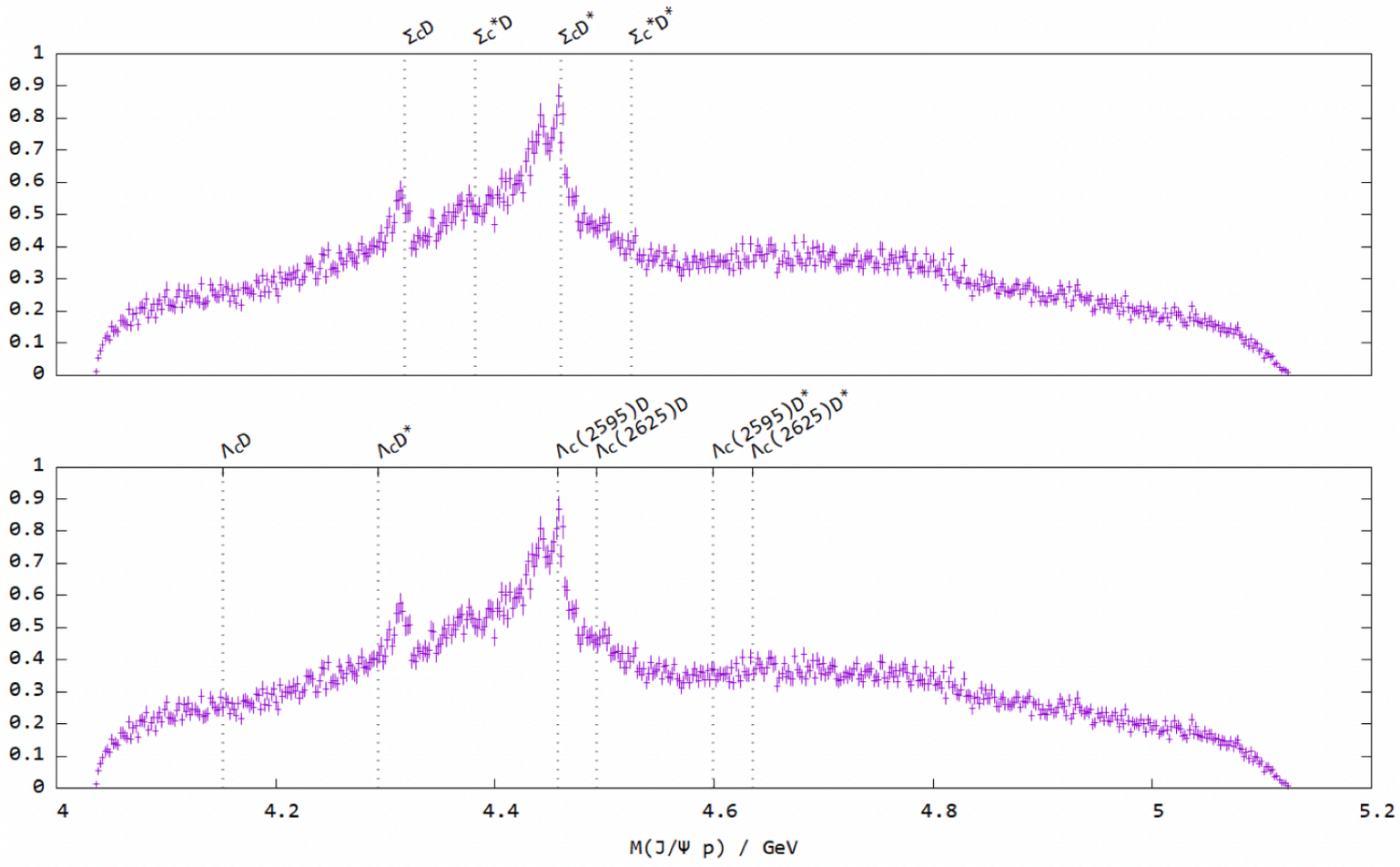


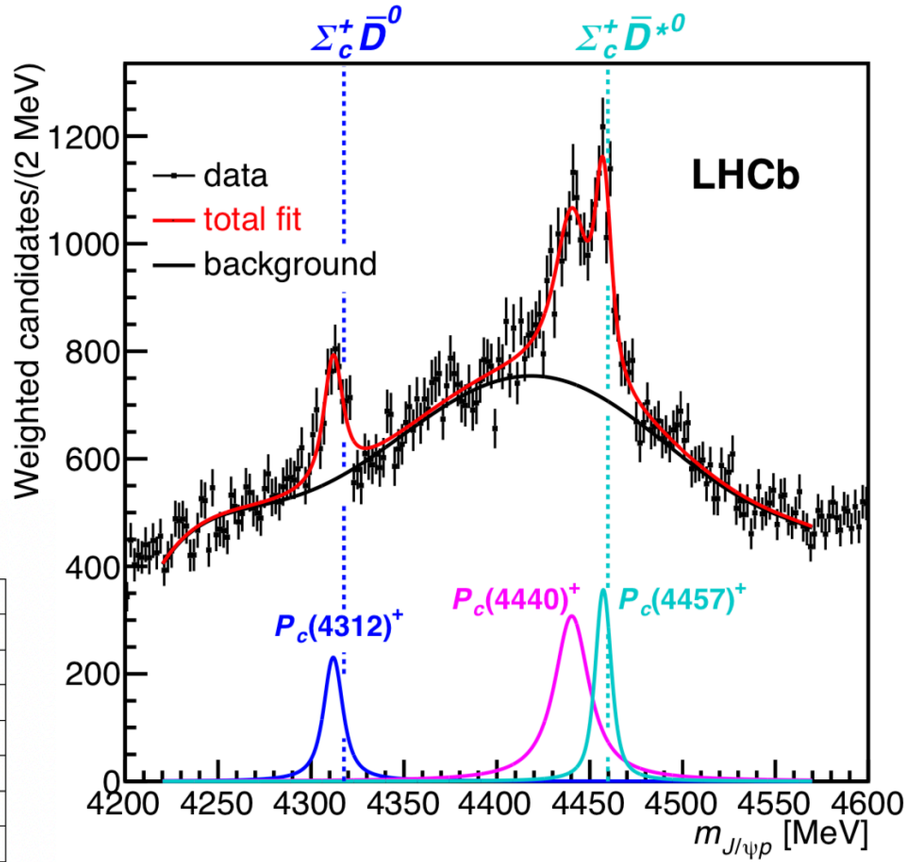
Possible pentaquark interpretation

Eric Swanson



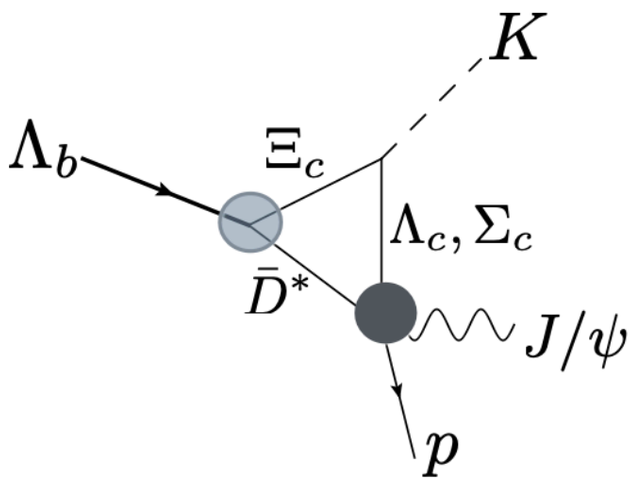


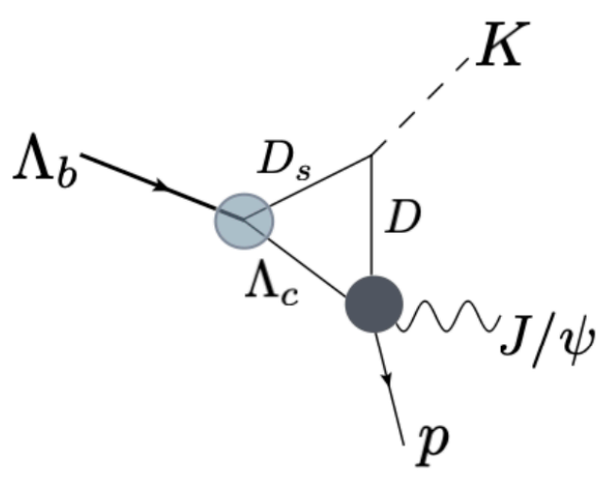


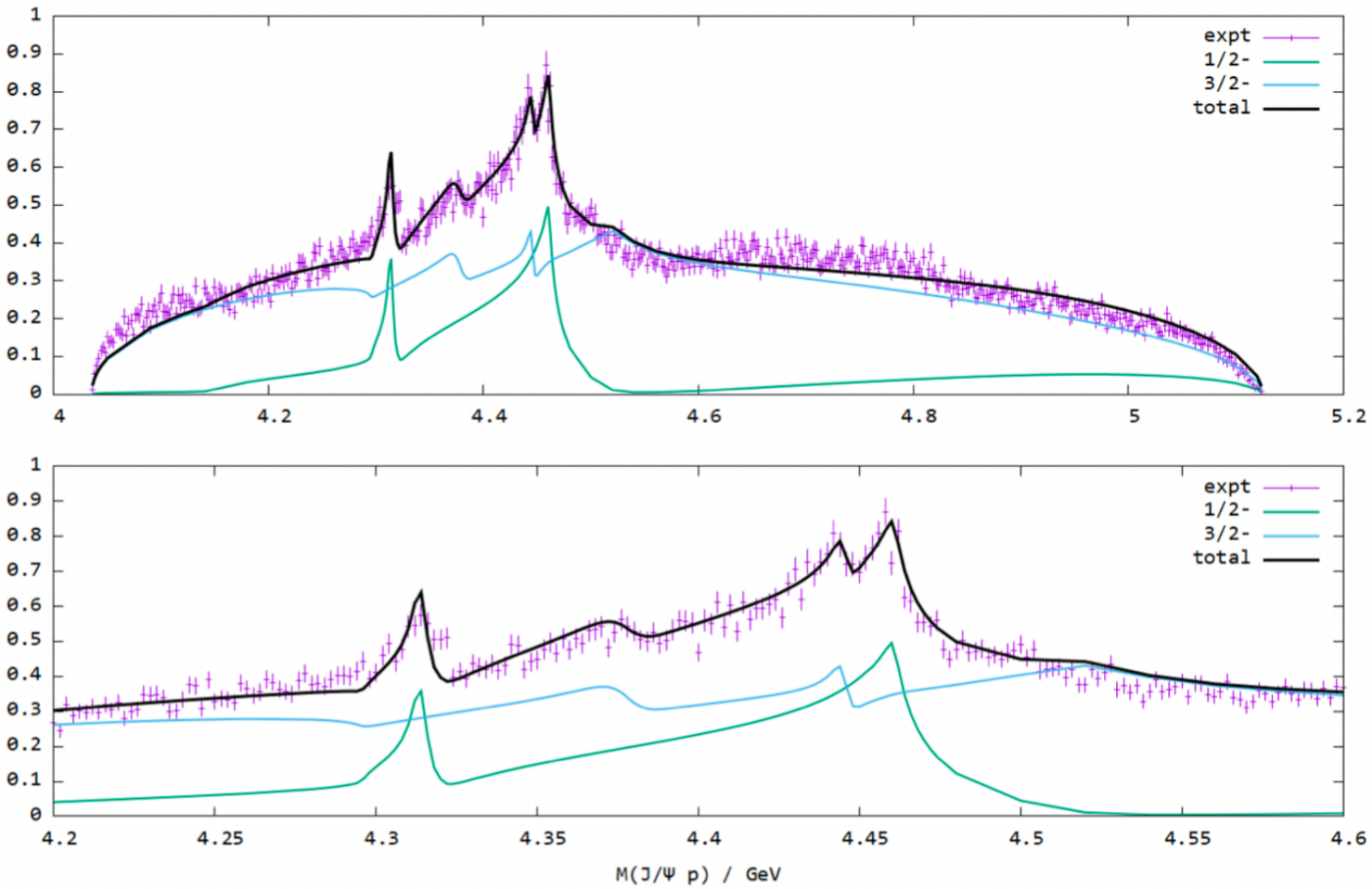


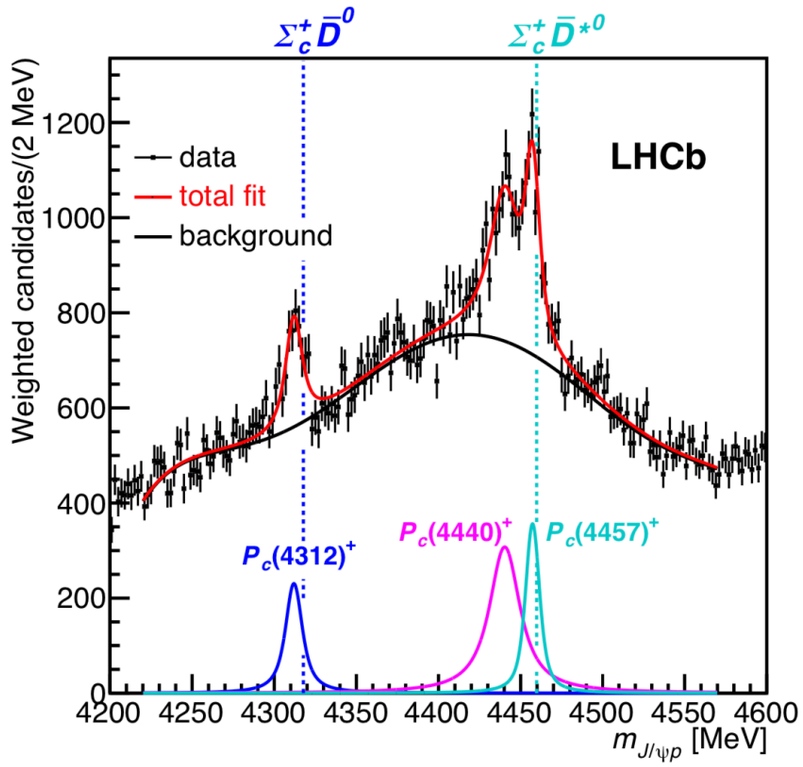
Possible pentaquark interpretation

Eric Swanson







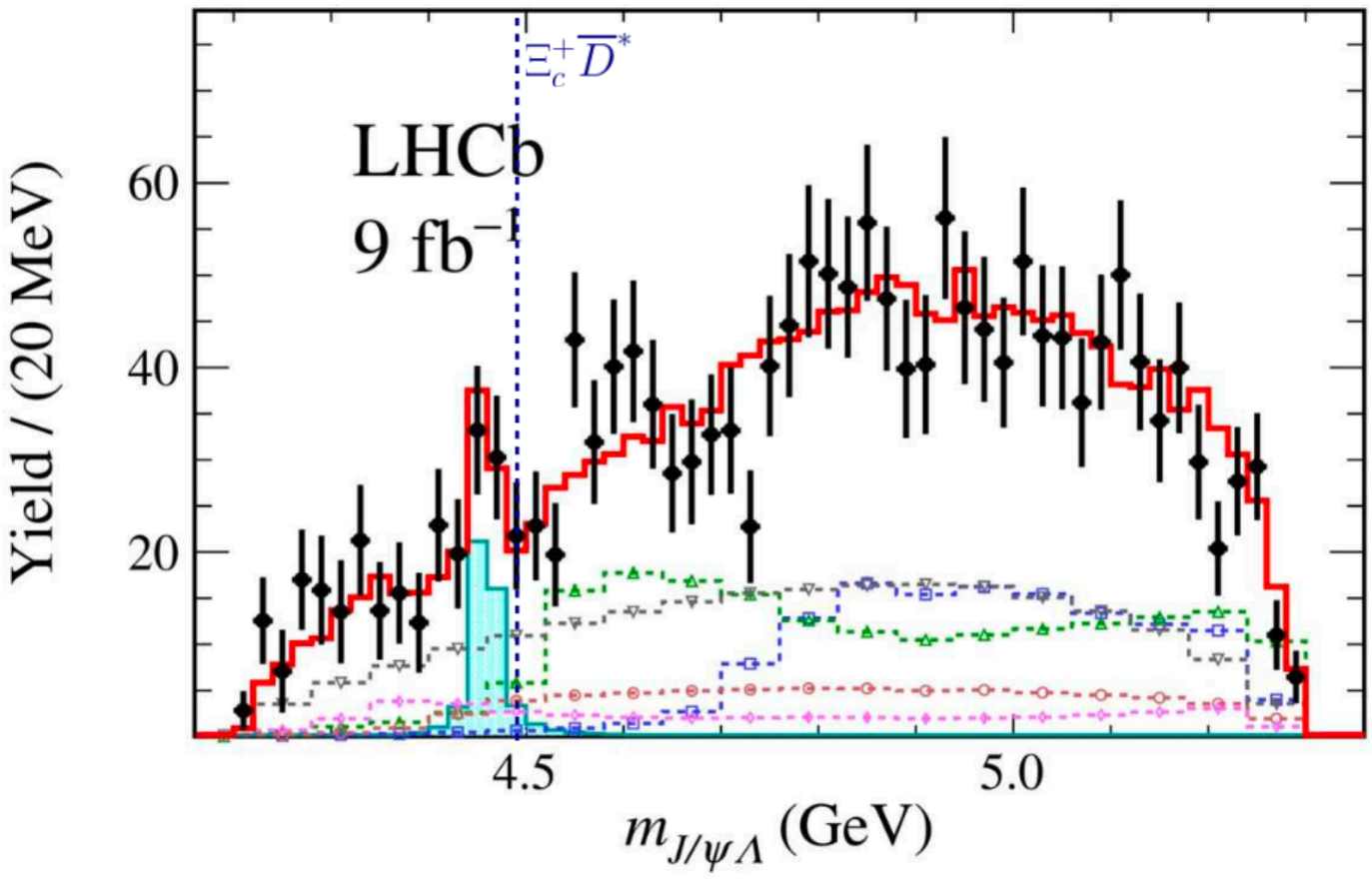


- Fit full spectrum with all possible threshold openings
- Molecular + cusp interpretation, still consistent with JLab non-observation

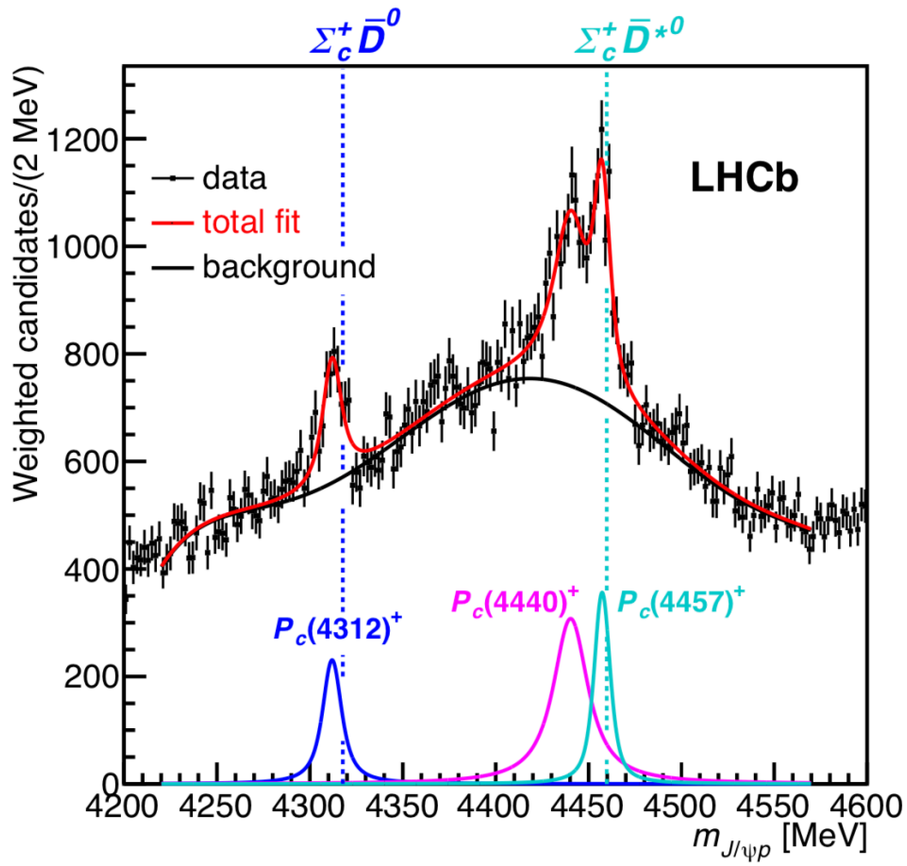
Pentaquarks get *stranger*

Gary Robertson

$$\Xi_b^- \to J/\psi \Lambda K^-$$



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



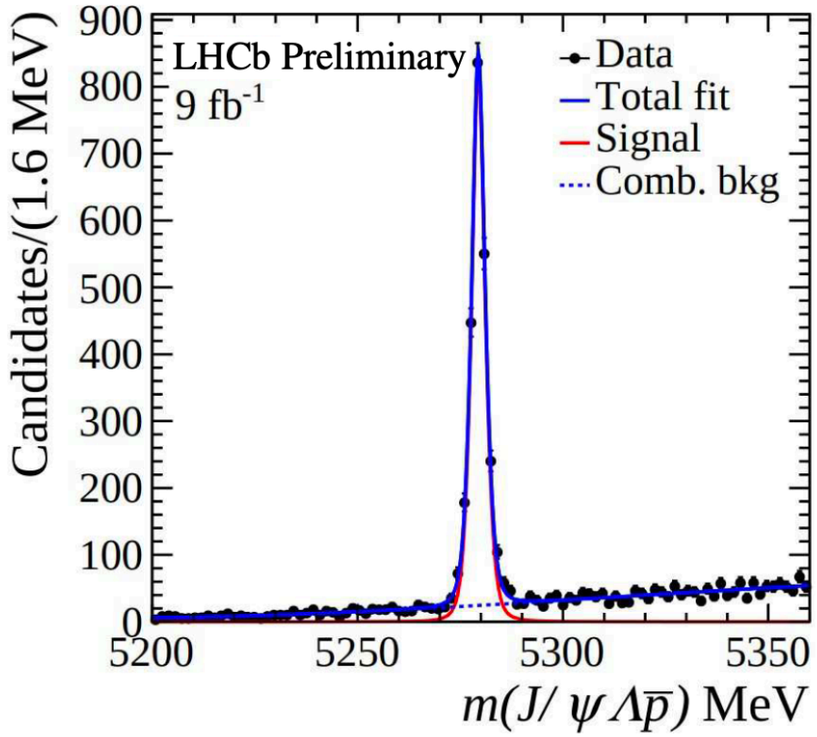
- Other b hadron decays provide opportunity for pentaquark with strangeness $P_{cs} = P^{\Lambda}_{\psi s} = \bar{c}ccuds$

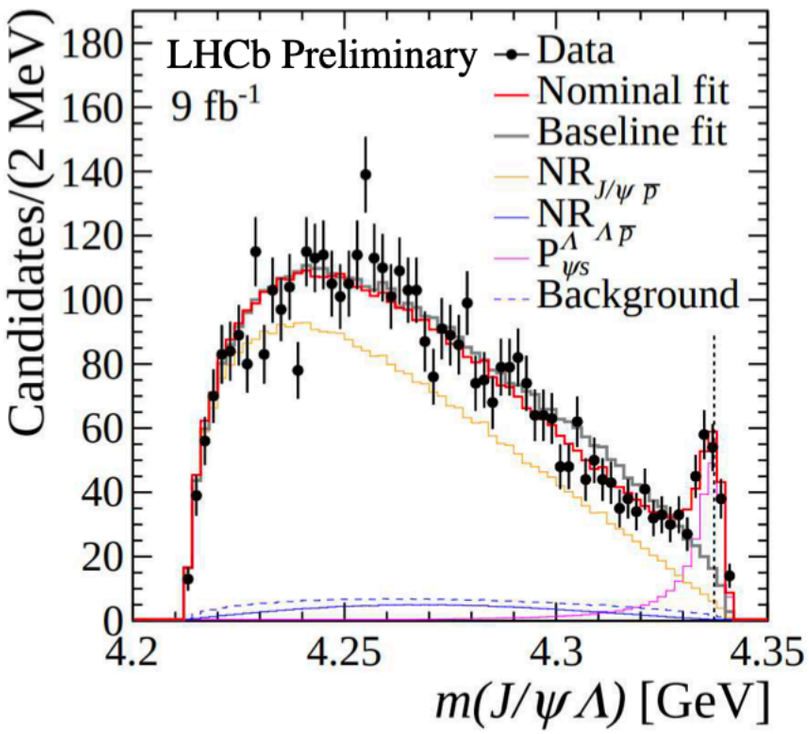
Pentaquarks get *stranger*

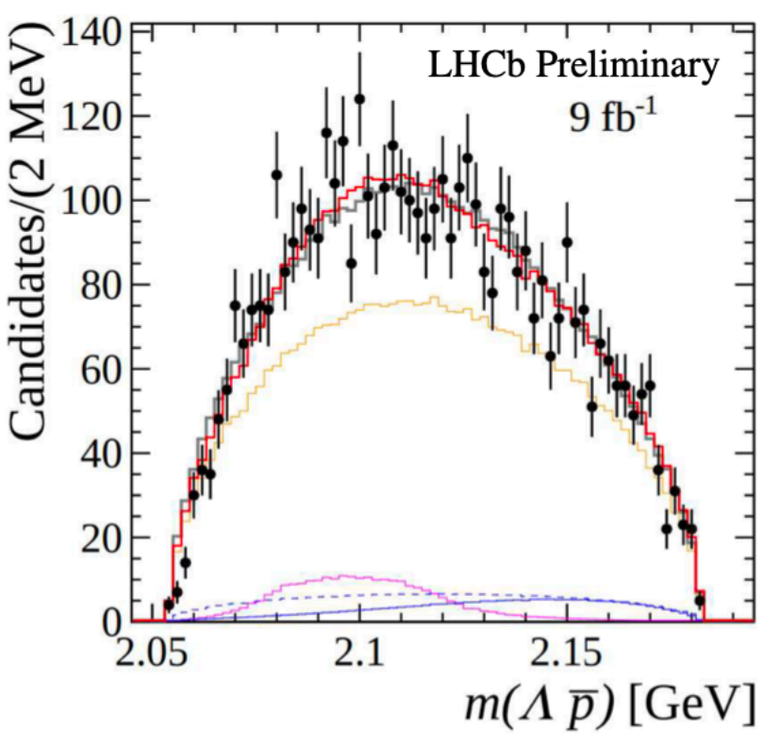
Gary Robertson

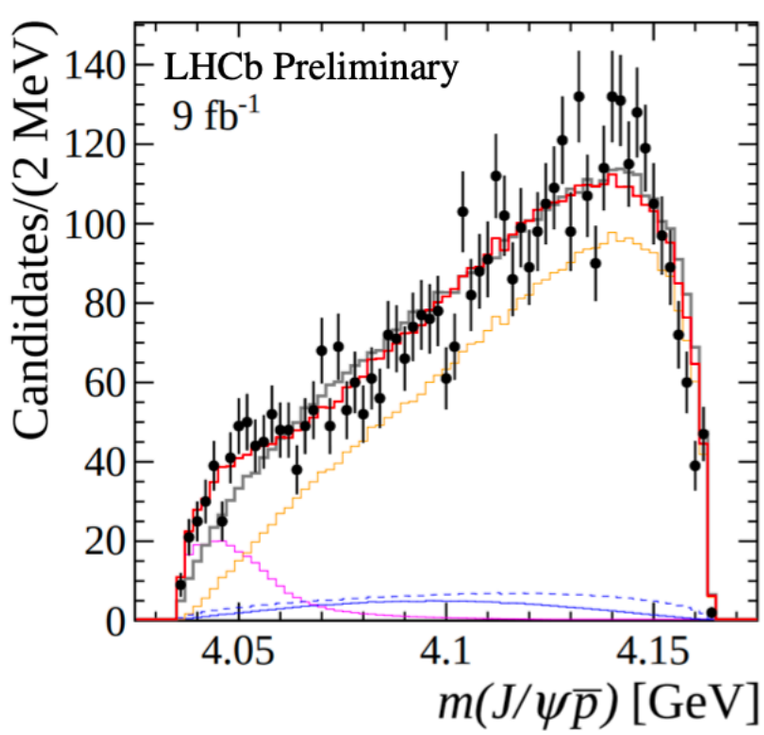
$$B^- \to J/\psi \Lambda \bar{p}$$

- Recent studies with B- meson requires $P^{\Lambda}_{\psi s}$ contribution with slightly smaller mass



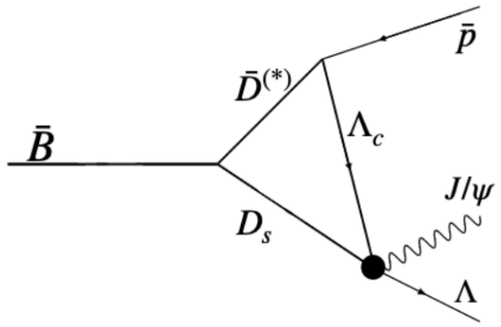


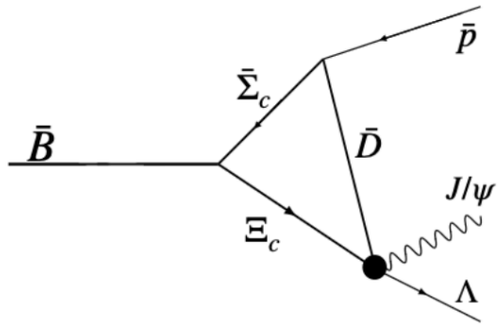


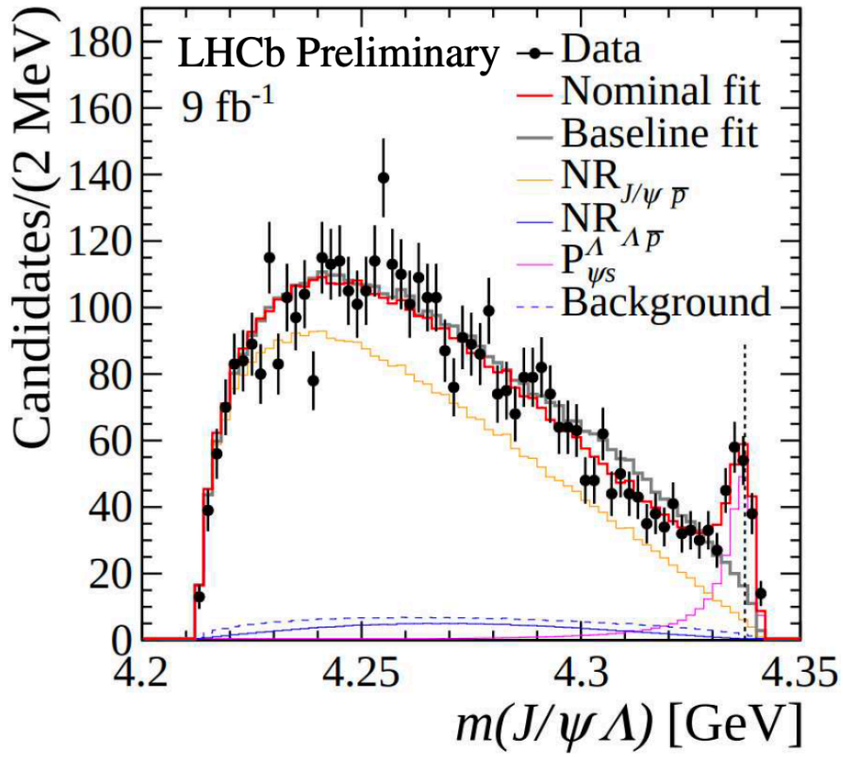


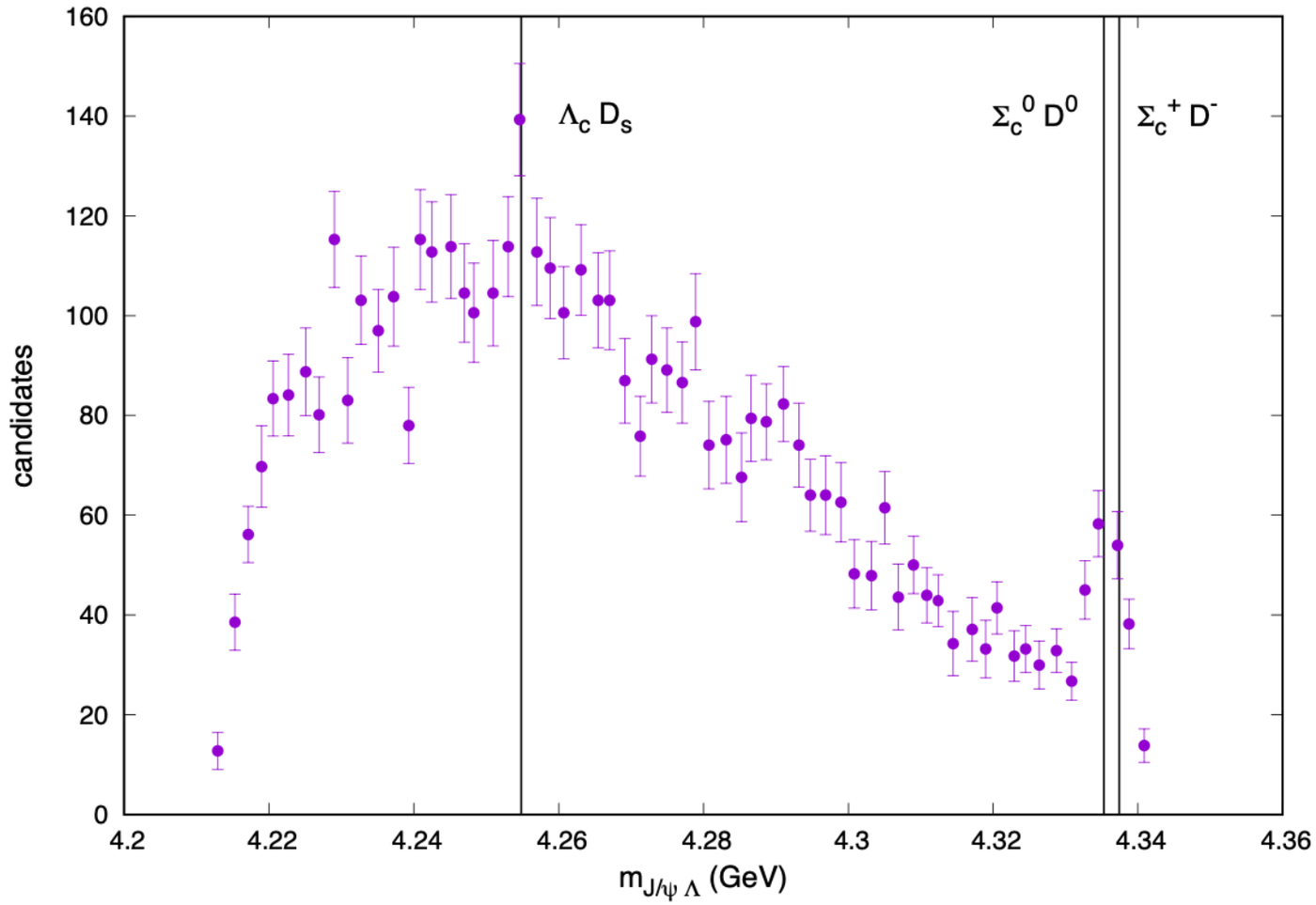
Possible pentaquark interpretation

Eric Swanson





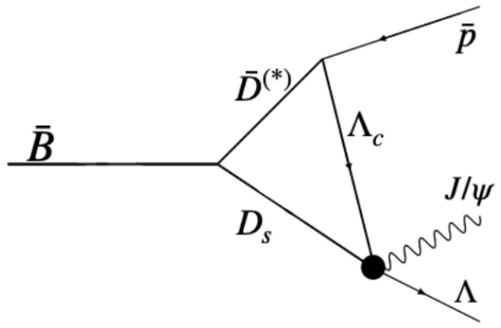


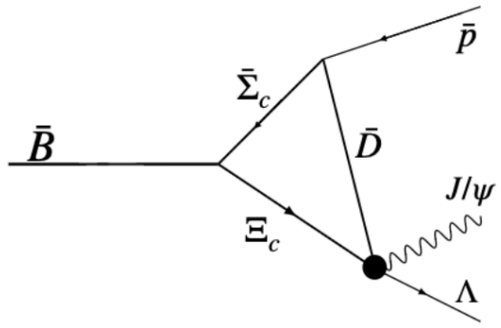


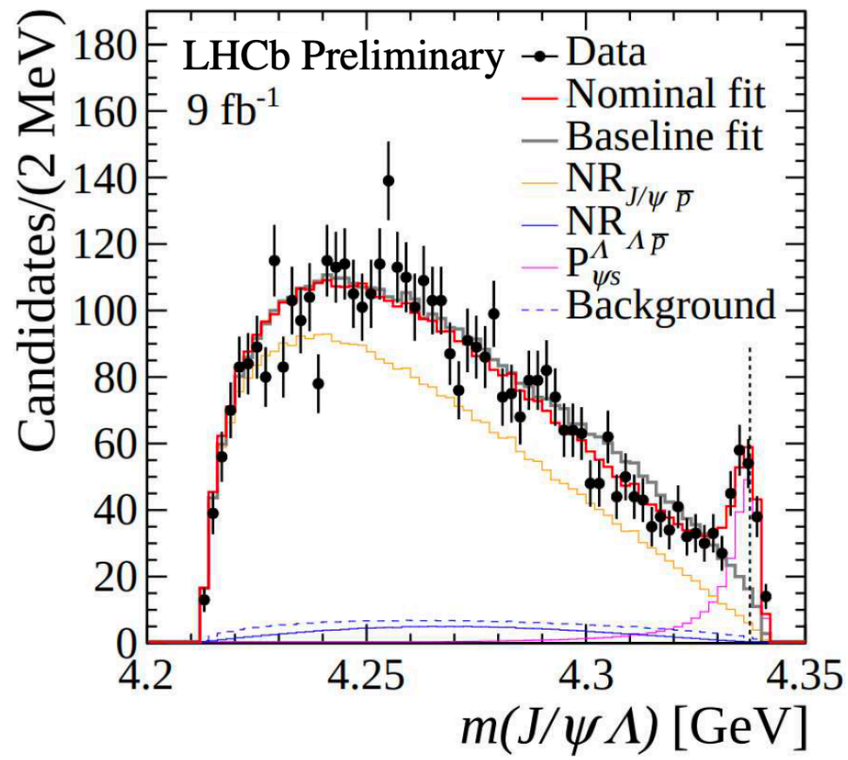
- Again, fit full spectrum with molecular + cusp interpretation
- Models not yet "predictive" to suggest rescattering in other decays

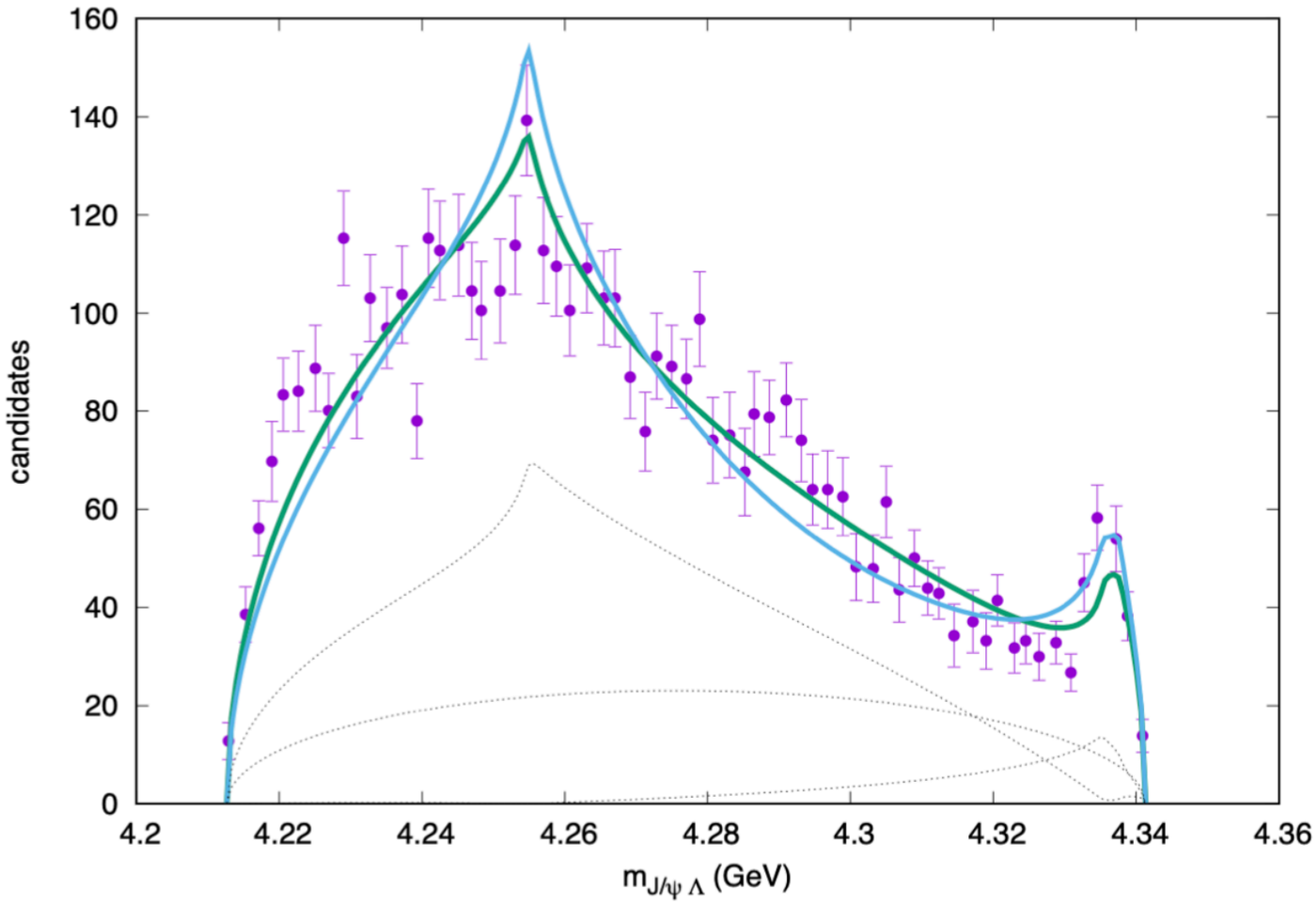
Possible pentaquark interpretation

Eric Swanson





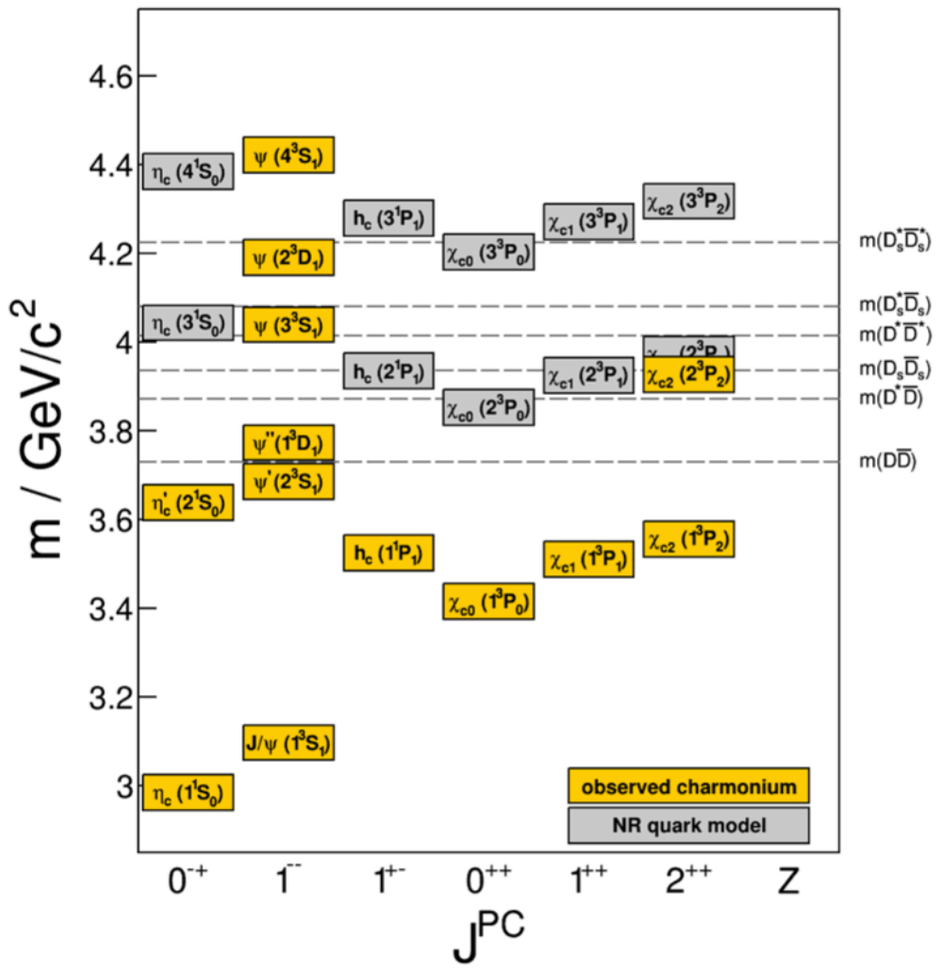




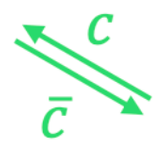
- Again, fit full spectrum with molecular + cusp interpretation
- Models not yet "predictive" to suggest rescattering in other decays

Charmonium

Nils Hueksen



- conventional charmonia ($c\bar{c}$) fit well with potential model calculations



$$V_{c\bar{c}} = -\frac{4}{3}\cdot\frac{\alpha_s(r)}{r} + k\cdot r$$

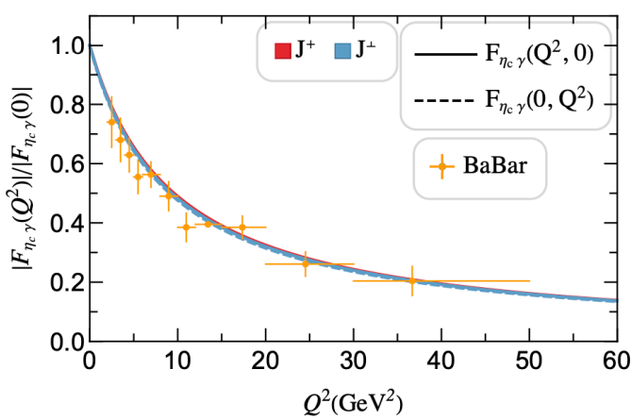
+ spin-dependent terms

Basis Light Front Quantization

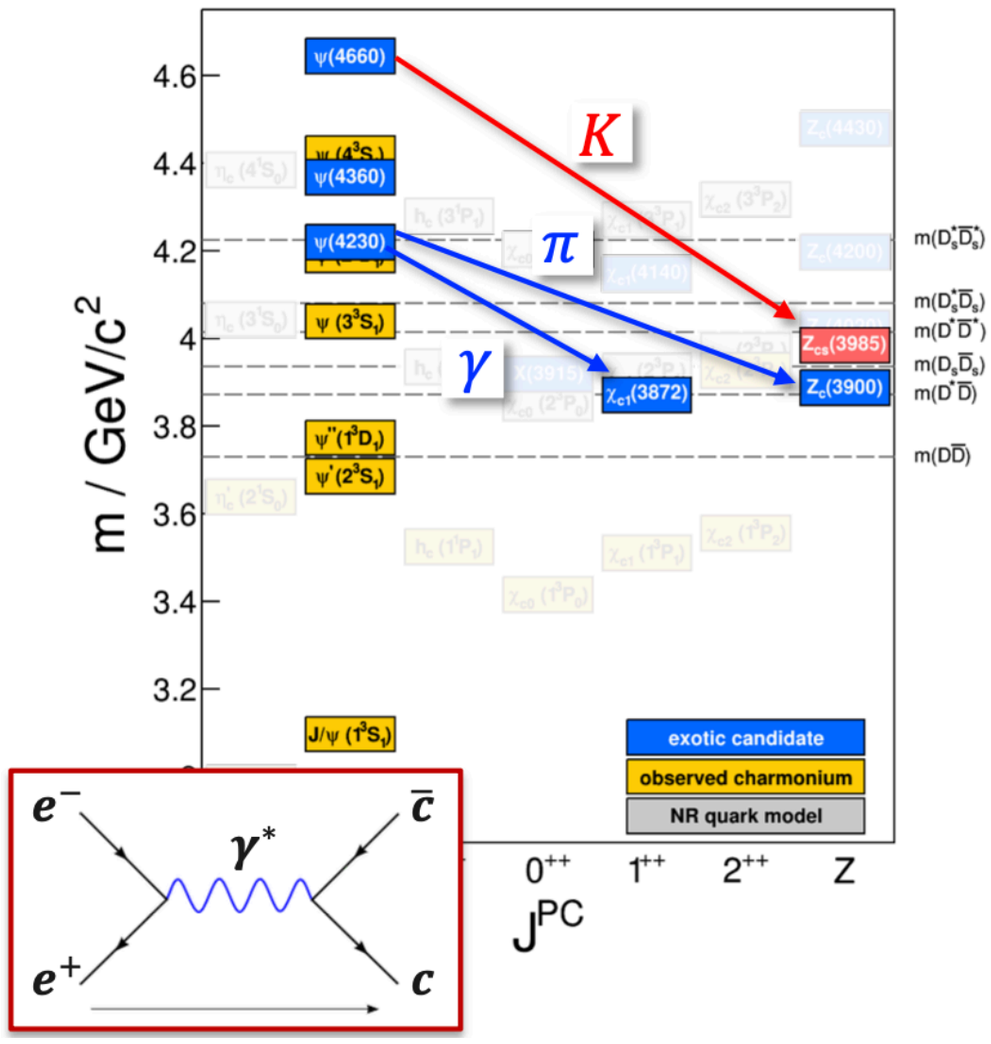
$$H_{\text{eff}} = \underbrace{\frac{\vec{k}_\perp^2 + m_q^2}{z(1-z)}}_{\text{LF kinetic energy}} + \underbrace{\kappa^4\zeta_\perp^2 - \frac{\kappa^4}{4m_q^2}\partial_z\left[z(1-z)\partial_z\right]}_{\text{confinement}} - \underbrace{\frac{C_F 4\pi\alpha_s}{Q^2}\bar{u}_{s'}(k')\gamma_\mu u_s(k)\bar{v}_{\bar{s}}(\bar{k})\gamma^\mu v_{\bar{s}'}(\bar{k}')}_{\text{one-gluon exchange}}$$

Wavefunctions for Conventional charmonium

Guangyao Chen

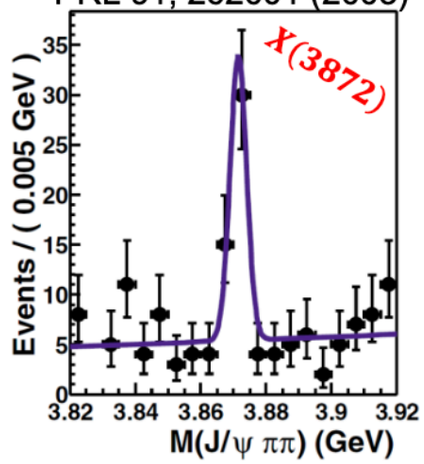


Charmonium-like states

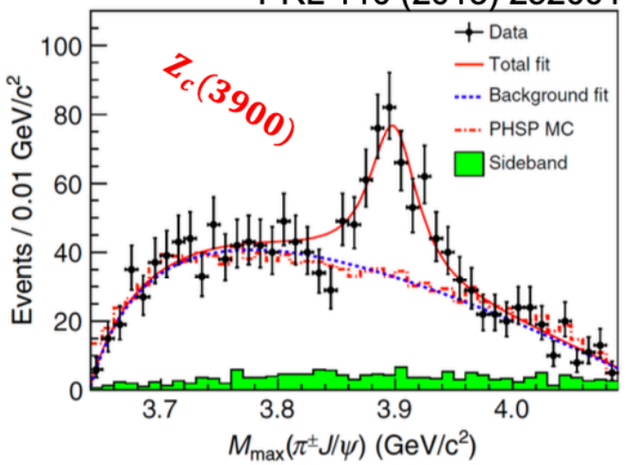


- several unexpected states observed

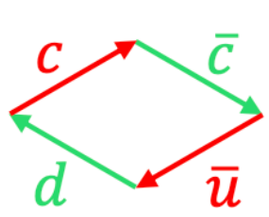
PRL 91, 262001 (2003)



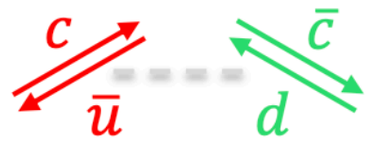
PRL 110 (2013) 252001



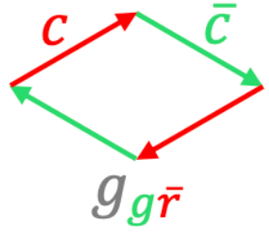
- their nature is still unclear



tetraquark



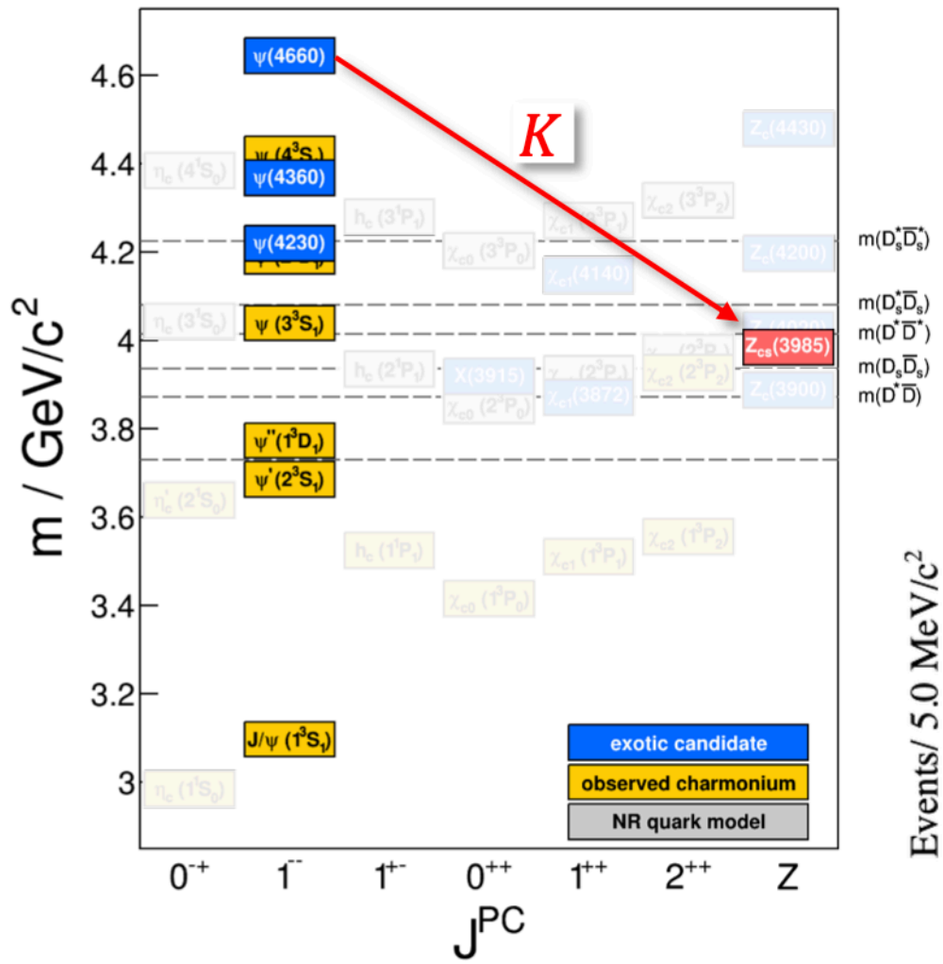
molecular state



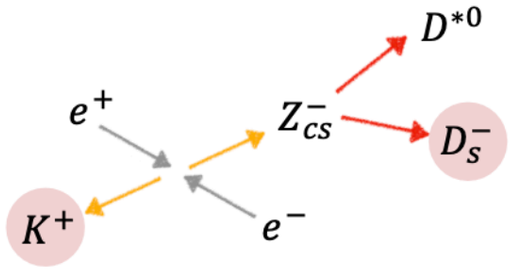
hybrid meson

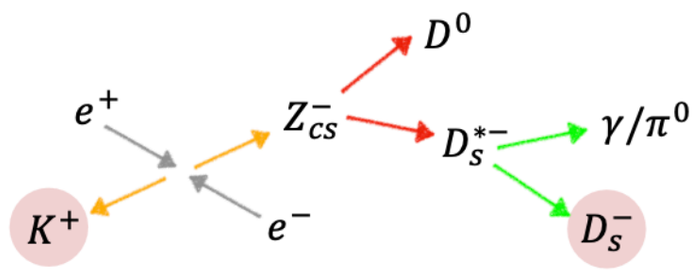
Nils Hueksen

Charged charmonium-like states

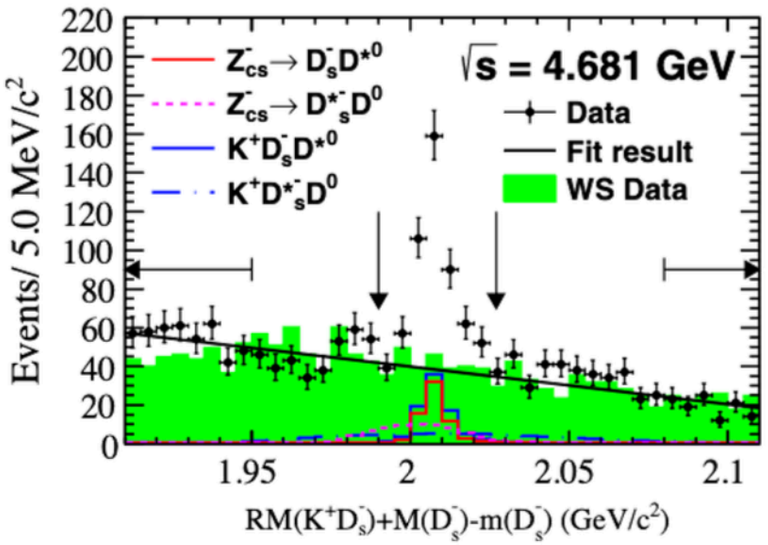


- search for an open-strange $c\bar{c}s\bar{q}$ partner Z_{cs}



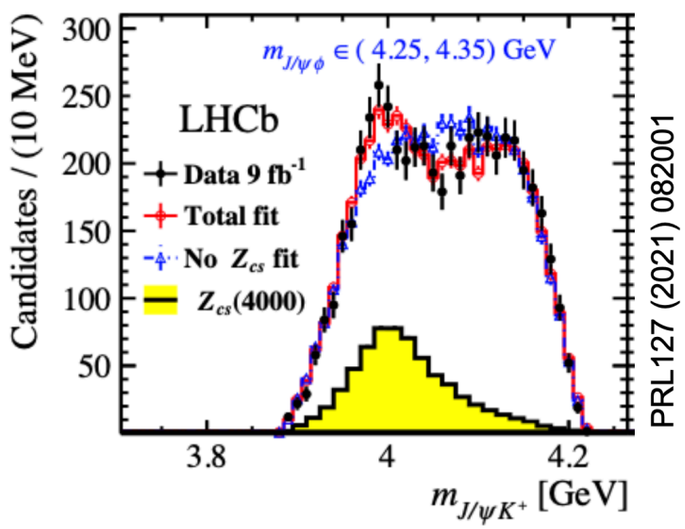


partial reconstruction method: K^+, D_s^-



- Observation of narrow $Z_{cs}^+ = T_{\psi s}^+ = \bar{c}cq\bar{s}$ near threshold

- LHCb observes a much wider candidate in $J/\psi K^-$



What about the gluons?

Matt Shepherd
Andrew Jackura

The Quark Model

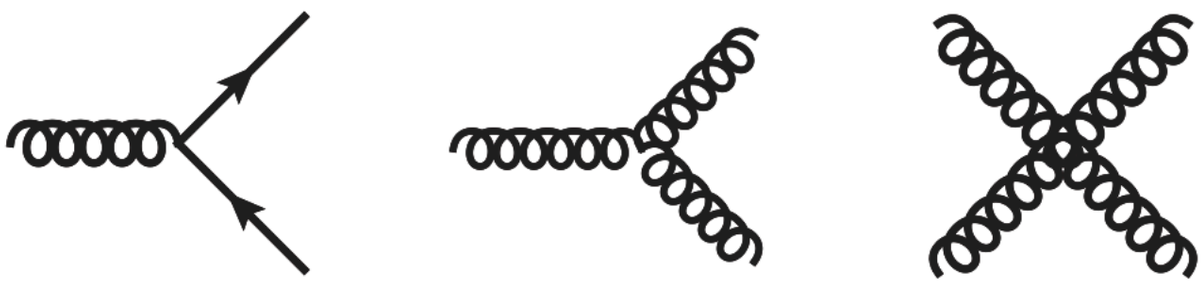
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

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

Phys. Lett. 8 (1964) 214

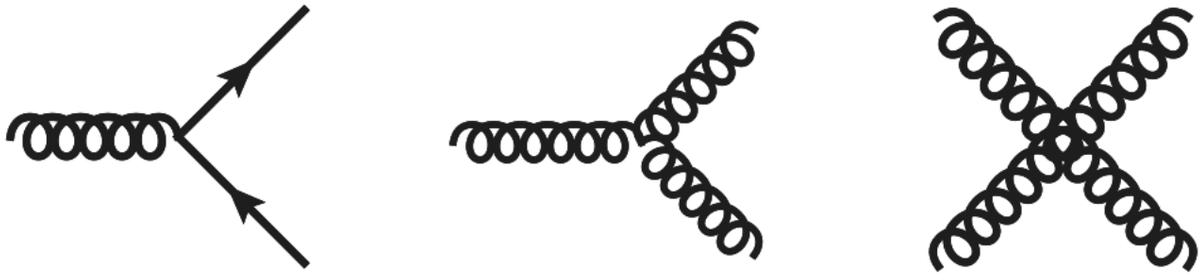
Quantum Chromodynamics

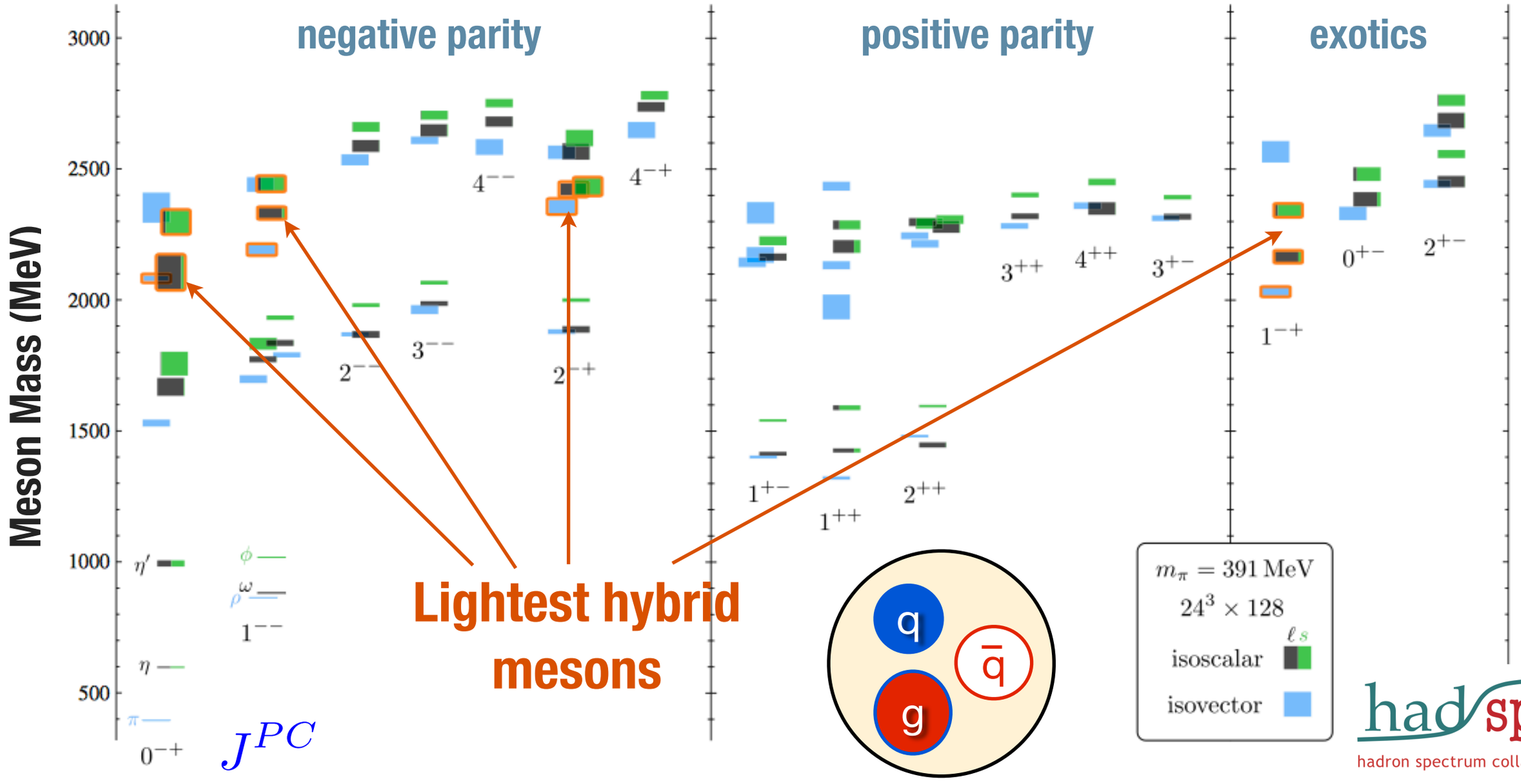


Lattice QCD

Andrew Jackura

Quantum Chromodynamics

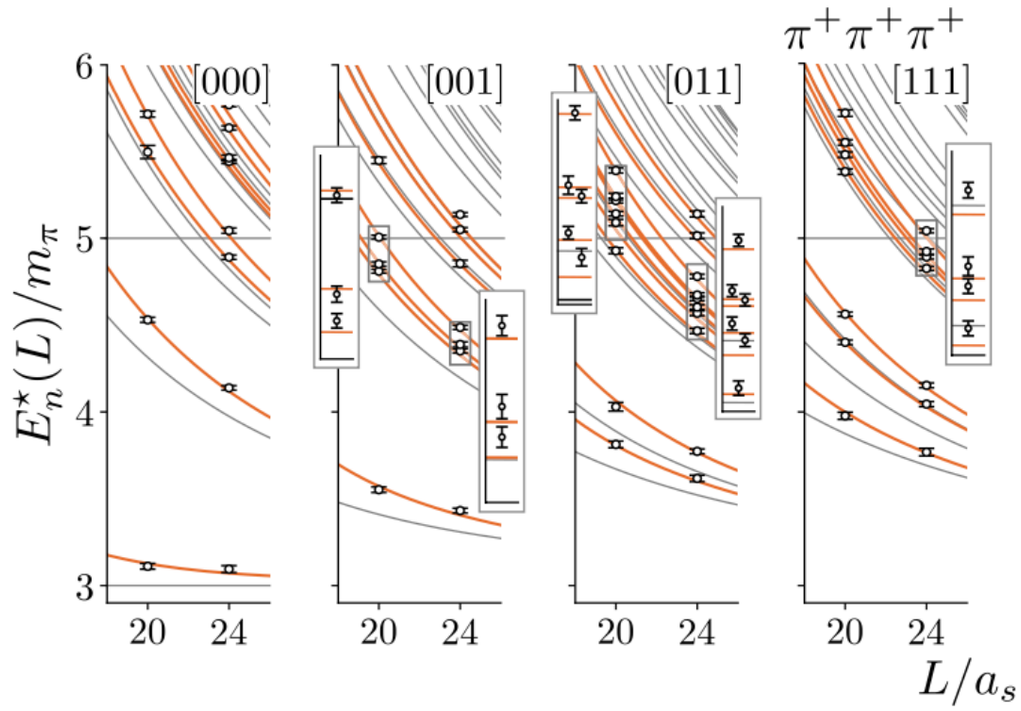


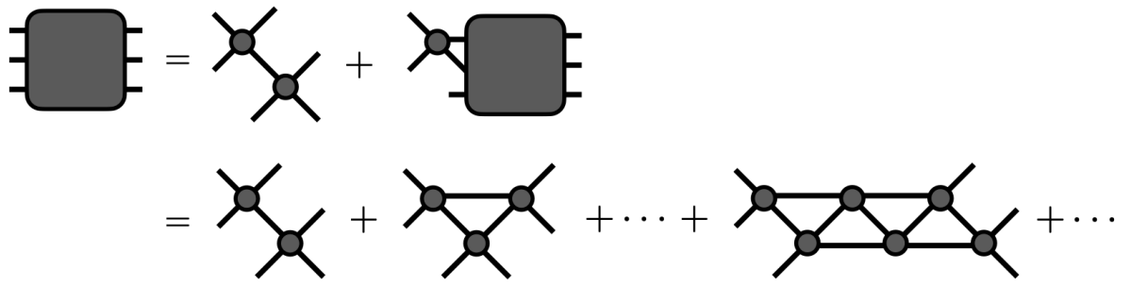


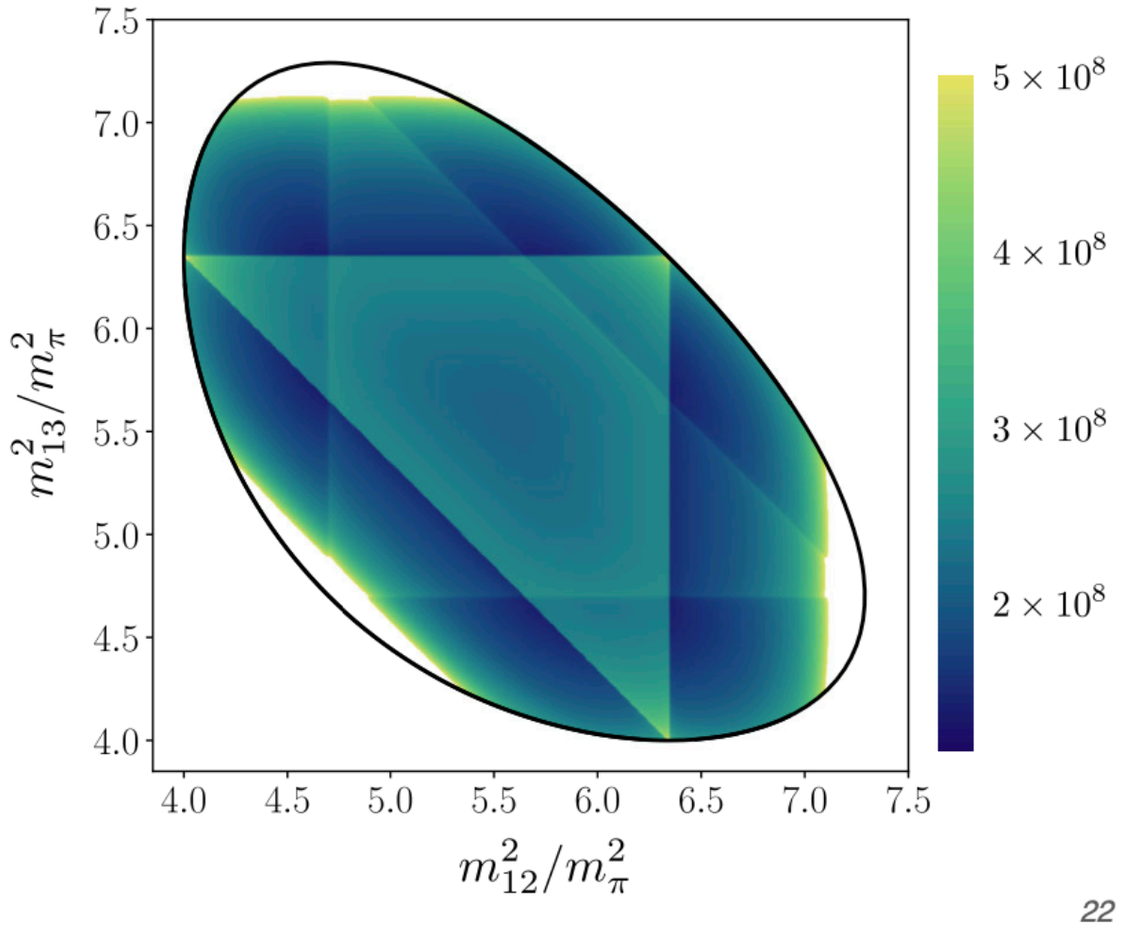
Lattice QCD

Andrew Jackura

Applications to $3\pi^+$





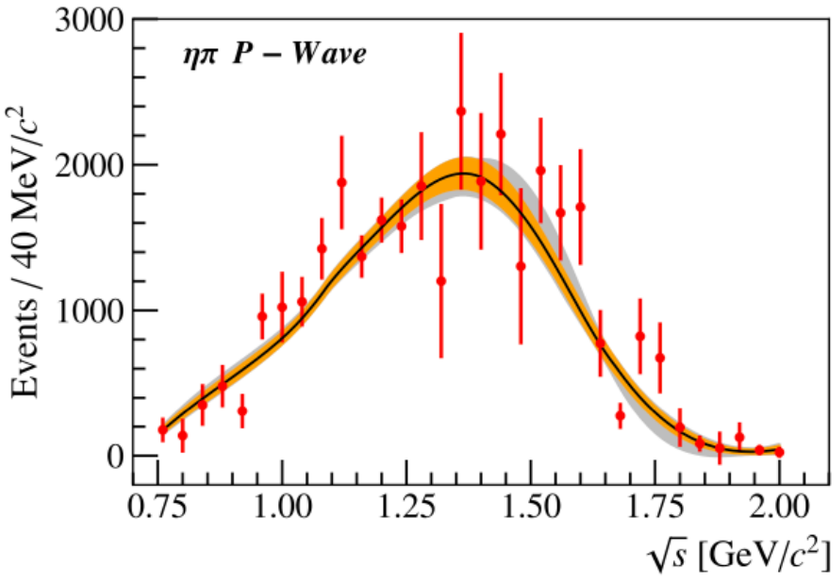


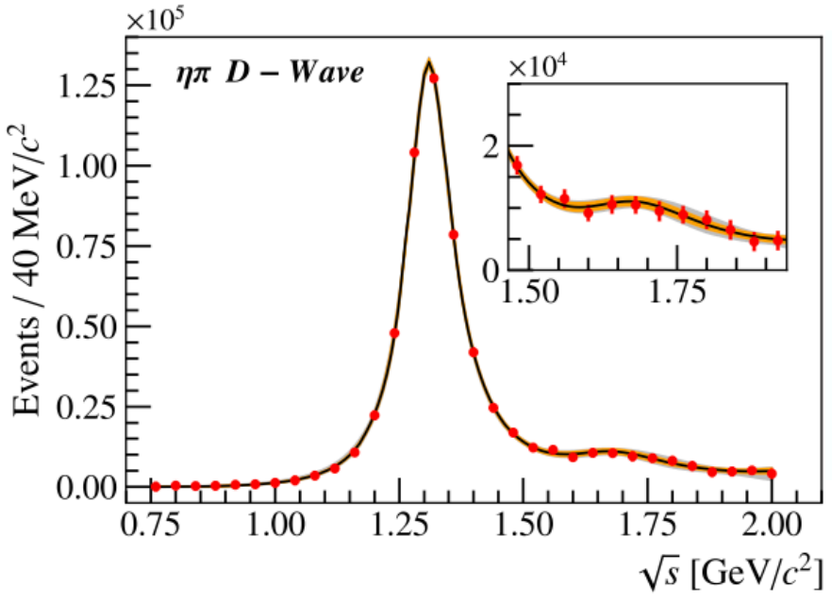
- Hadron scattering on the lattice: energy levels → resonances
- Complications with 3-body dynamics, much recent progress

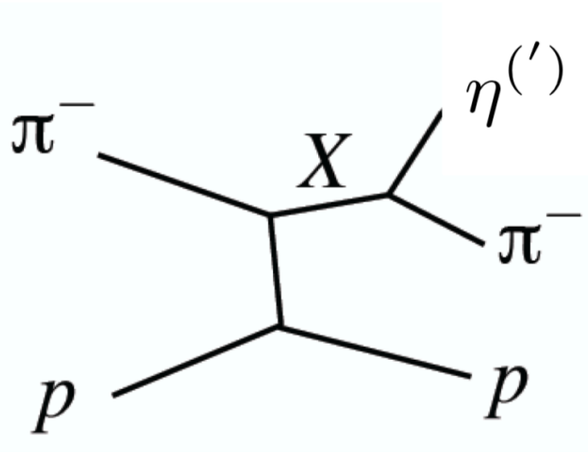
M. Hansen et al. [HadSpec]
Phys. Rev. Lett. **126**, (2021) 012001

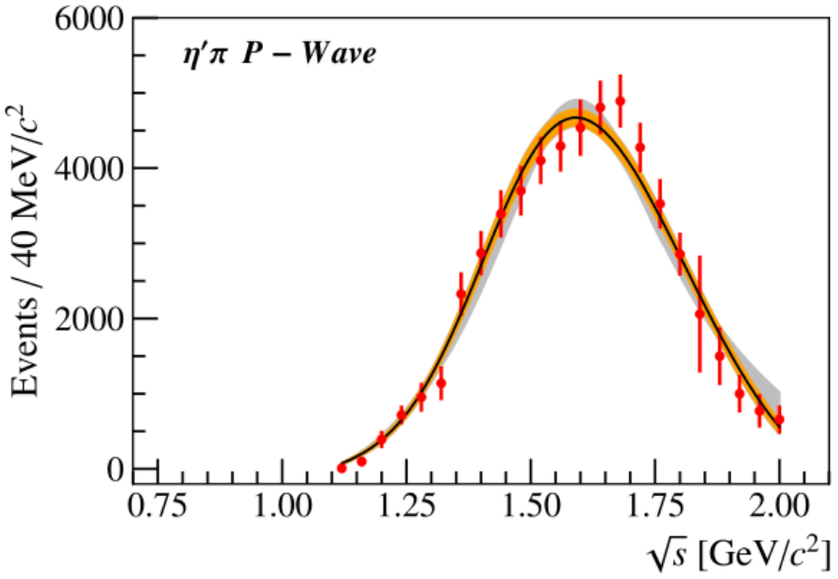
Exotic hybrid mesons

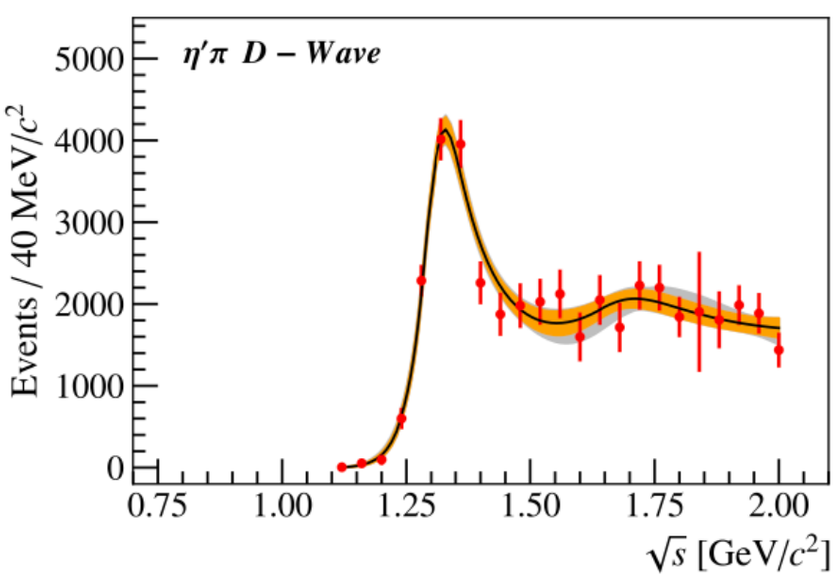
Malte Albrecht





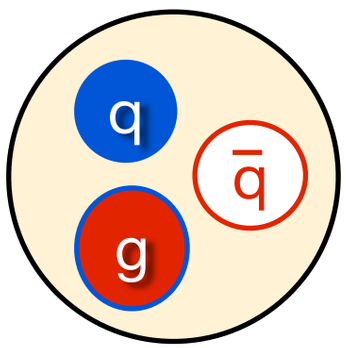






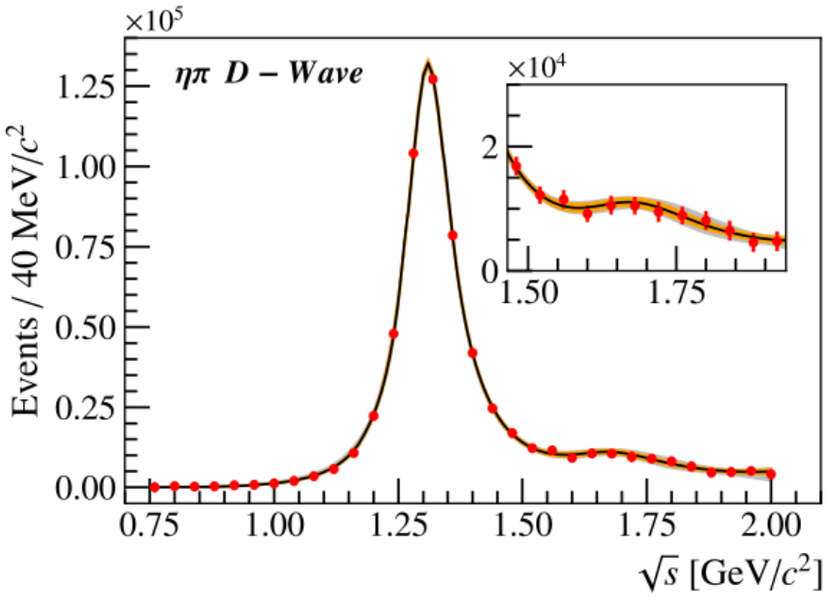
$\pi_1(1600)$ with exotic quantum numbers

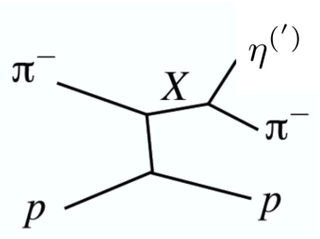
$J^{PC} = 1^{-+}$



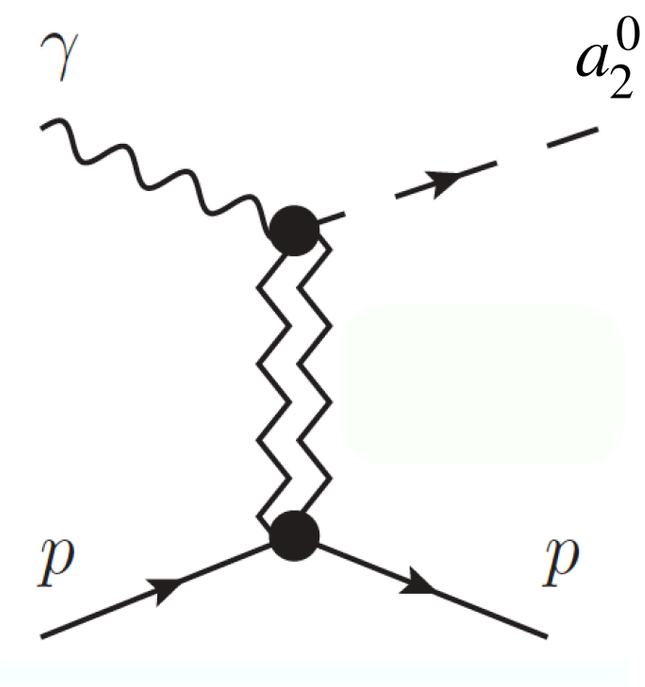
$\eta\pi$ photoproduction at GlueX

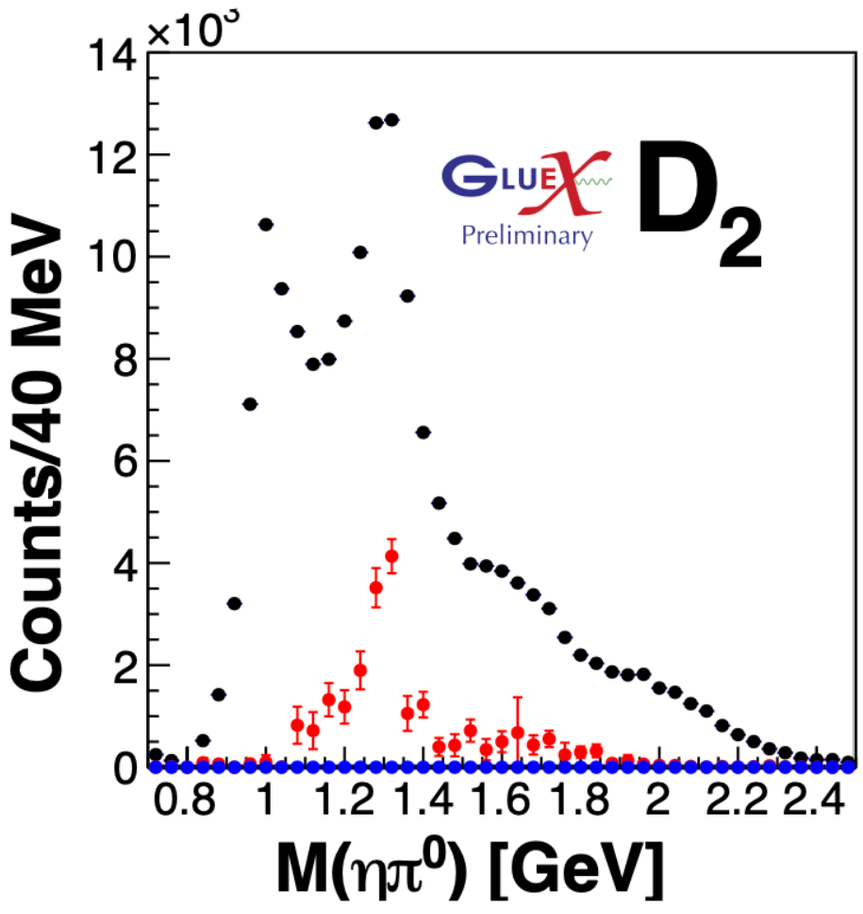
Malte Albrecht

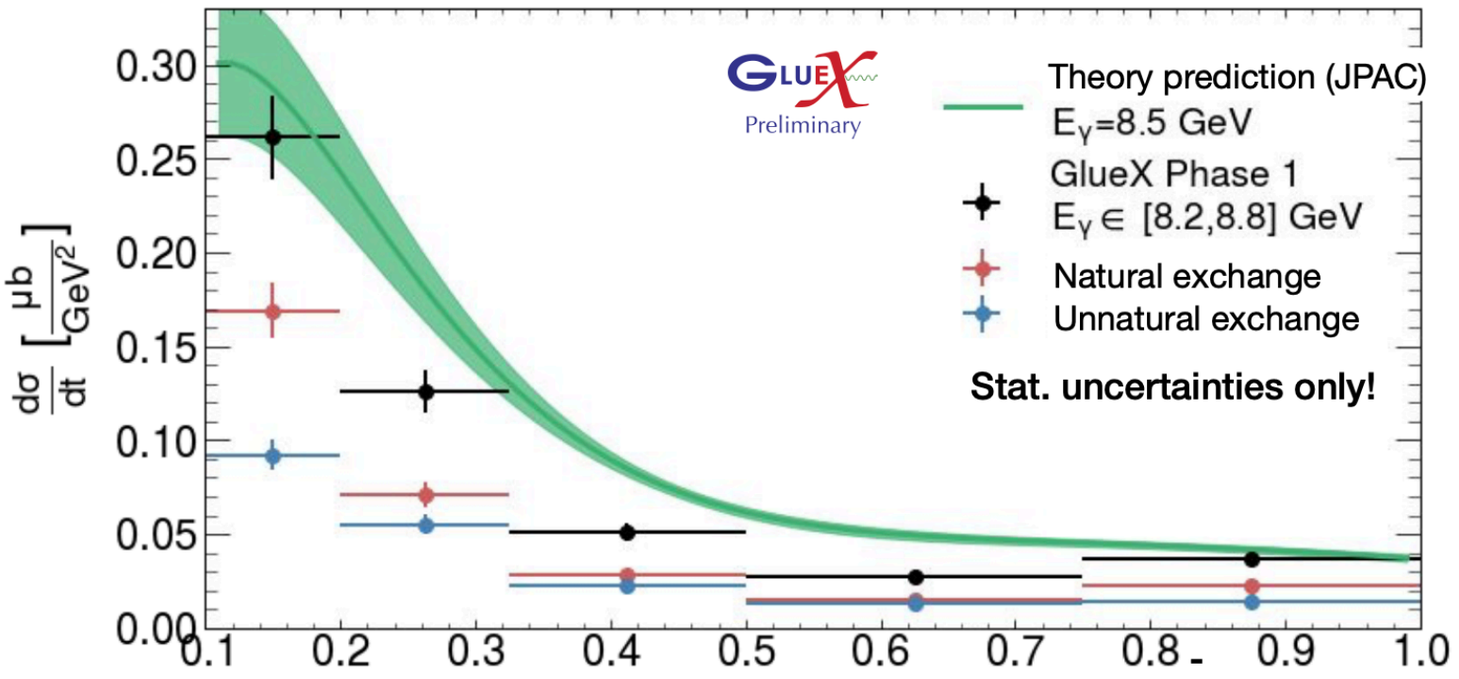




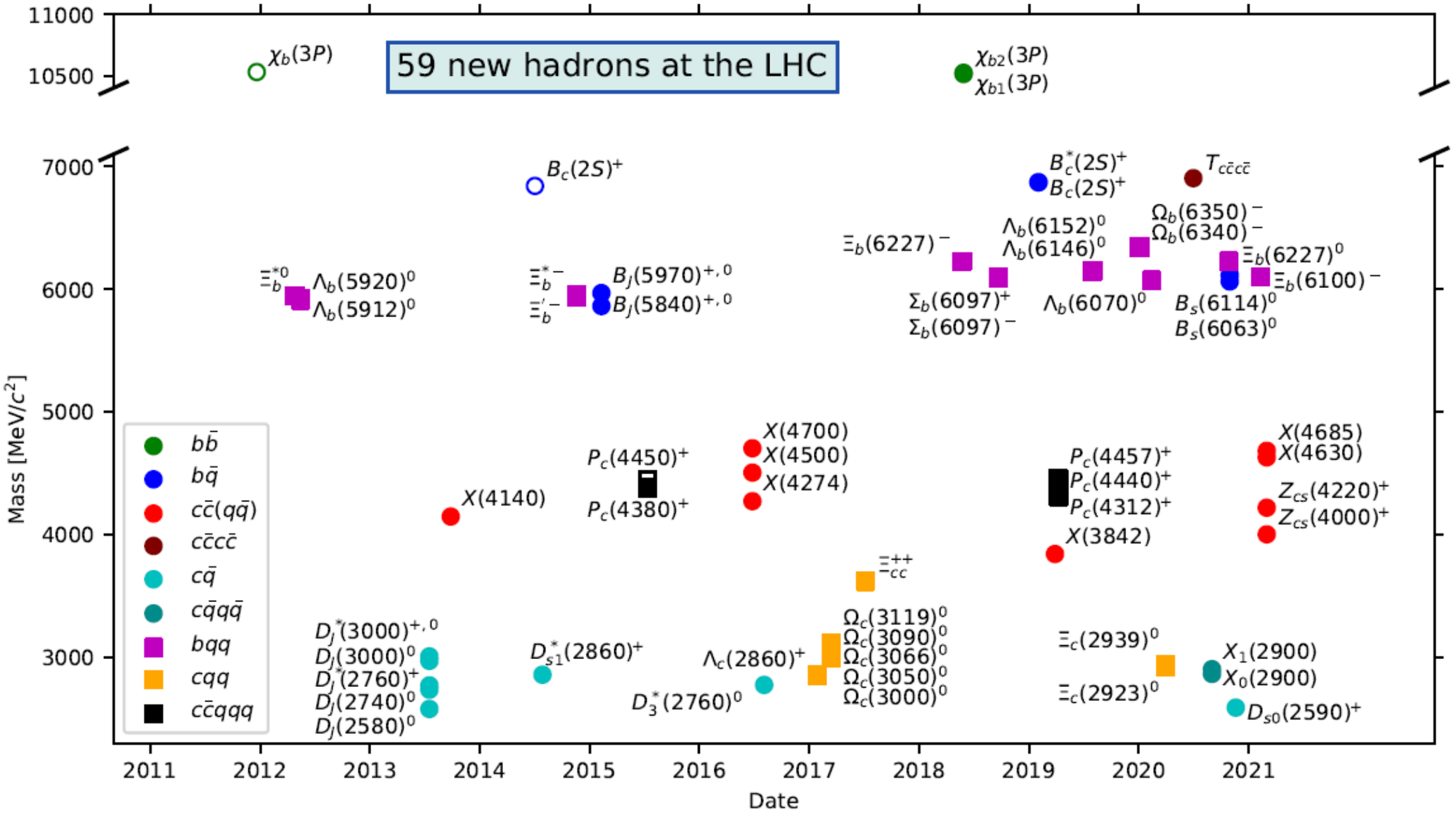
COMPASS





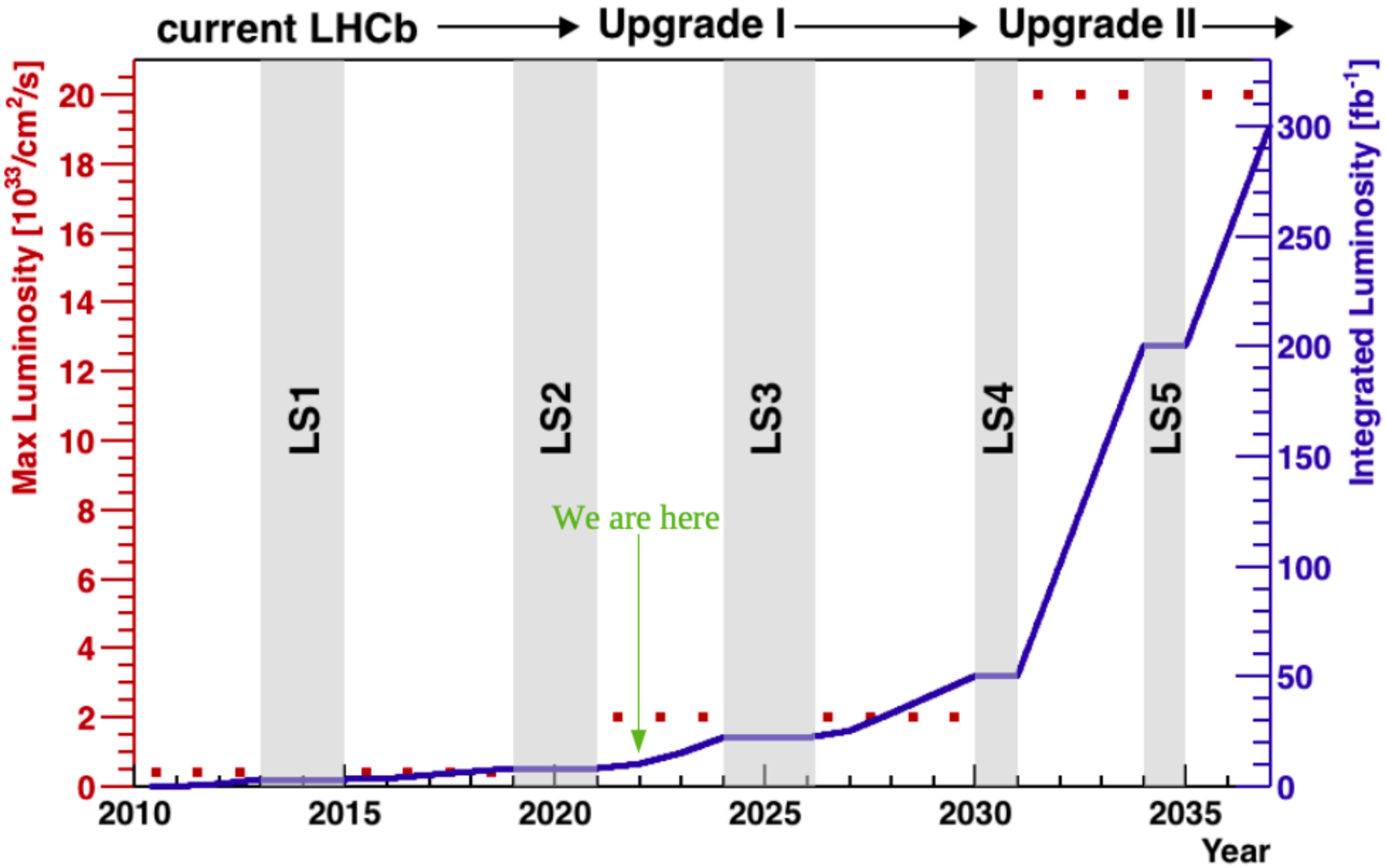


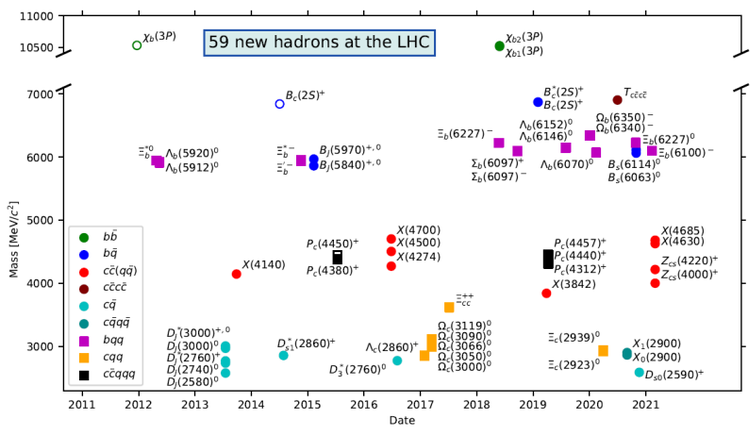
Outlook for spectroscopy/exotics?



LHCb reminder: new hadrons from Run 1+2

Outlook for spectroscopy/exotics?

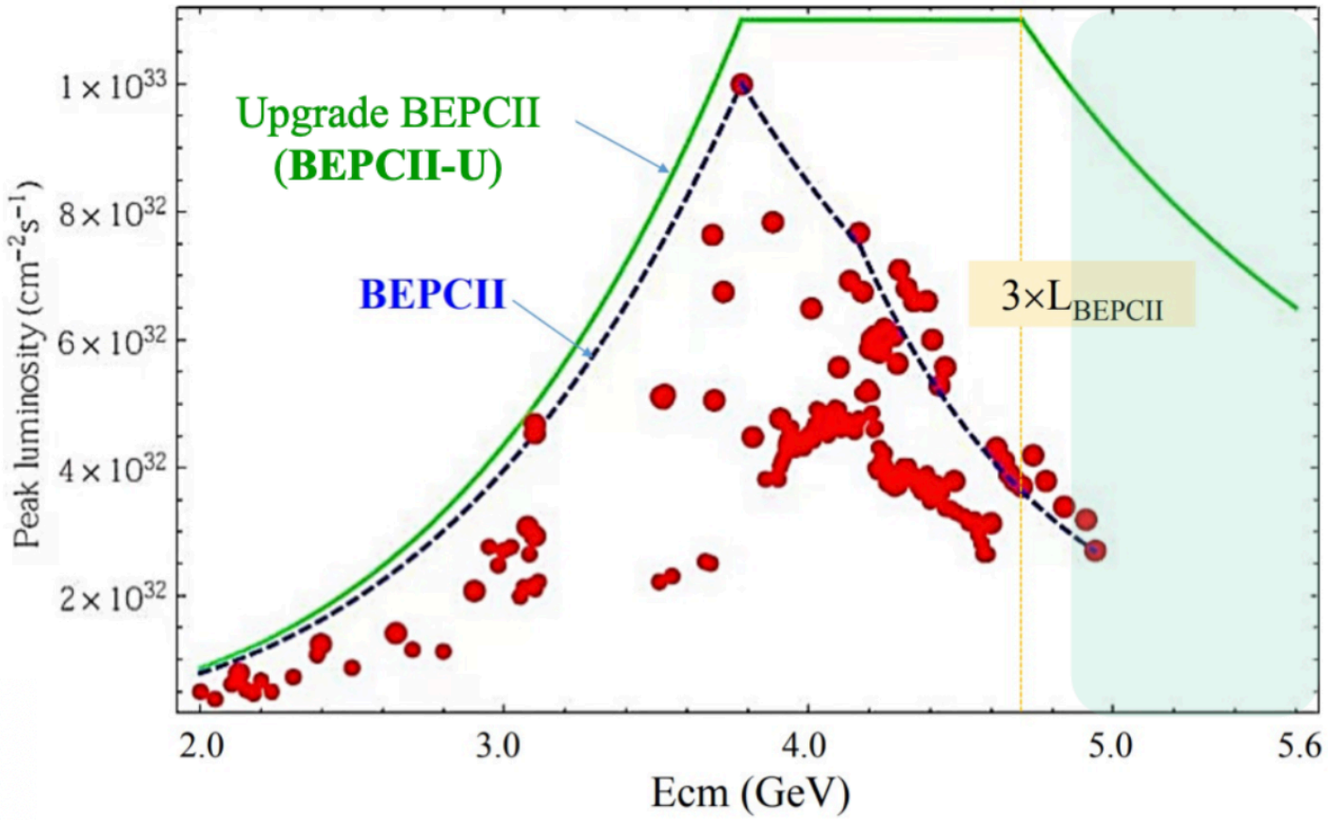


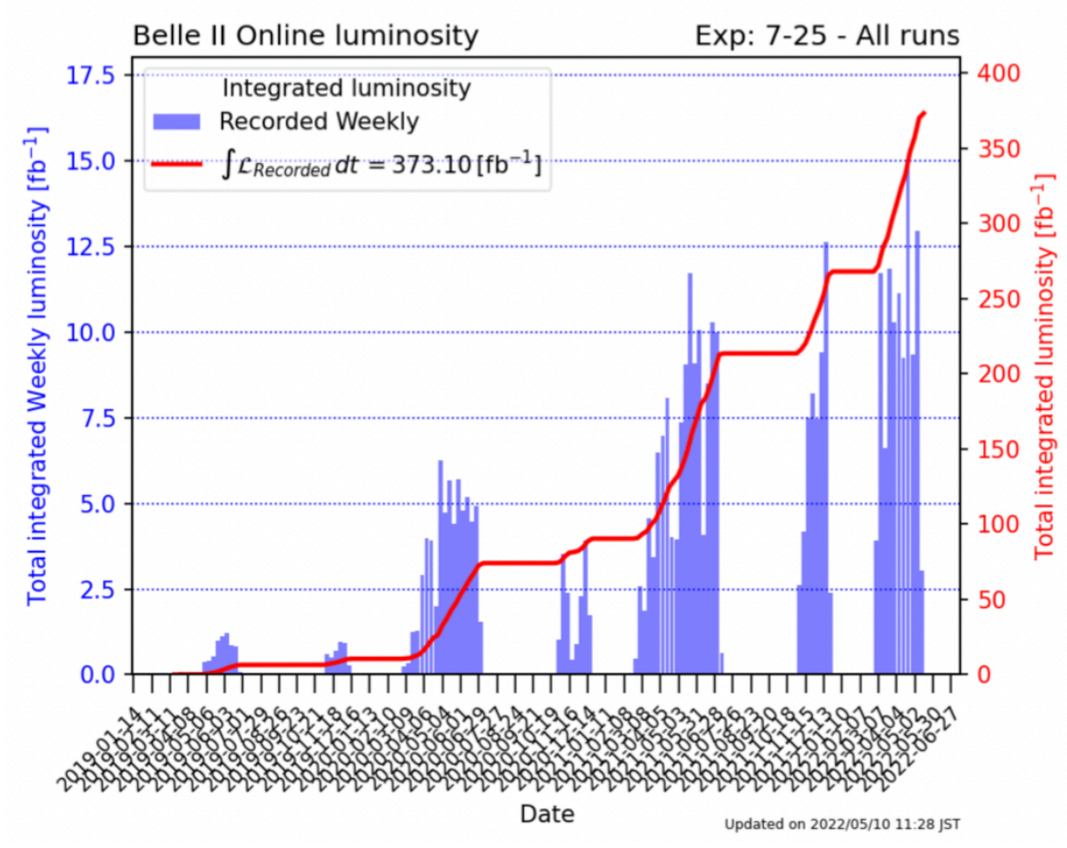


LHCb: ~10x more larger dataset in Run 3+4

Outlook for spectroscopy/exotics?

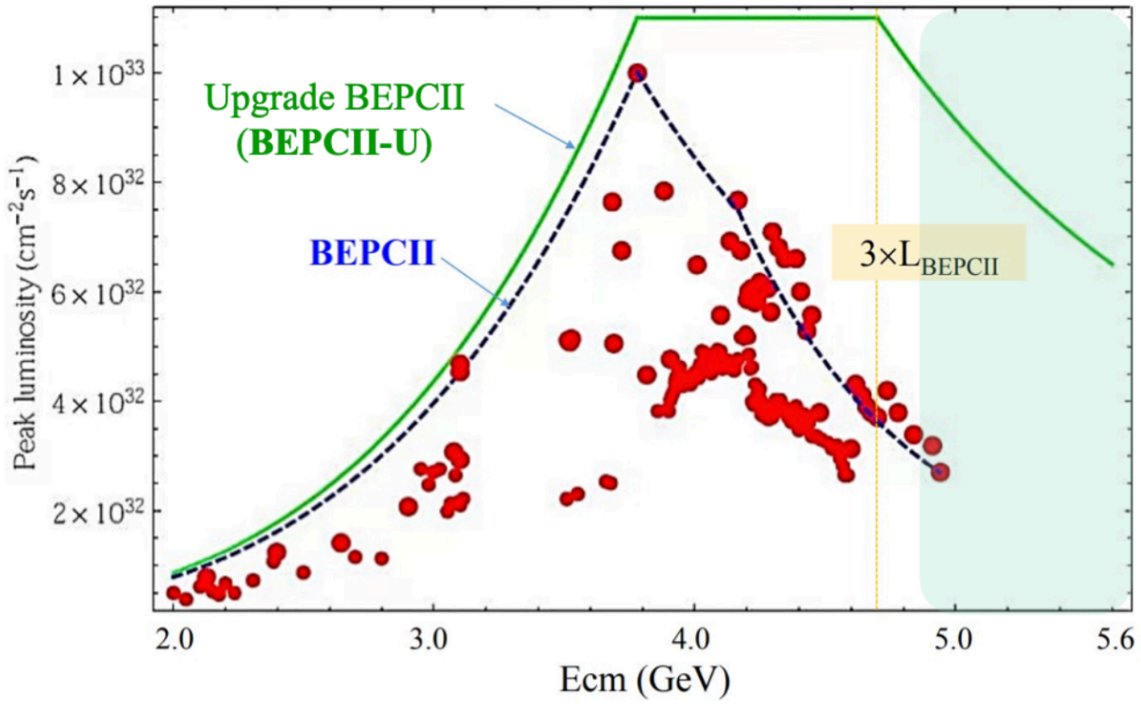
- BESIII: e+e- energy and luminosity upgrades
- Belle II: e+e- 50 ab^{-1}



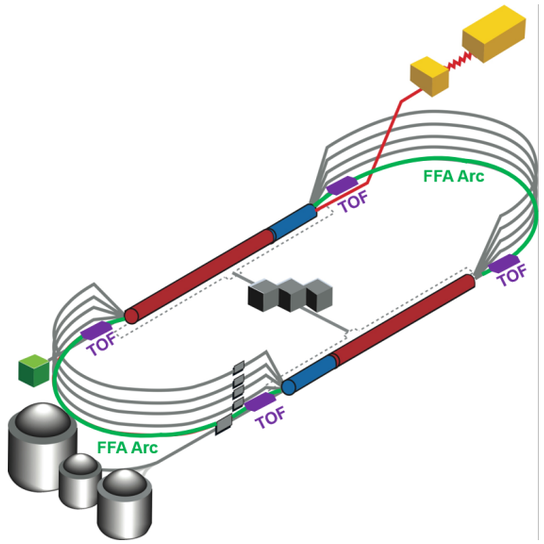


Outlook for spectroscopy/exotics?

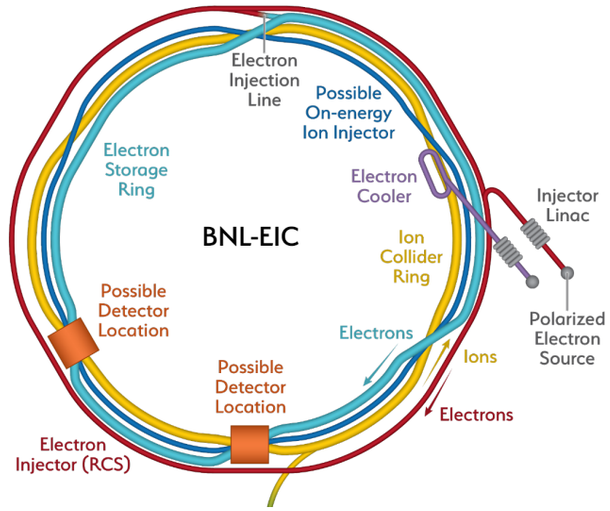
- BESIII: e+e- energy and luminosity upgrades
- Belle II: e+e- 50 ab^{-1}
- Photoproduction:
  - Light quark hybrids @ GlueX/CLAS12
  - Heavy quarks @ EIC & JLab20+



Jefferson Lab upgrade:
E_e = 12 → 22 GeV



Electron Ion Collider (EIC)



Outlook for spectroscopy/exotics?

- BESIII: e+e- energy and luminosity upgrades
- Belle II: e+e- 50 ab^{-1}
- Photoproduction:
  - Light quark hybrids @ GlueX/CLAS12
  - Heavy quarks @ EIC & JLab20+
- Far future: ~1 TeV Muon Ion Collider?