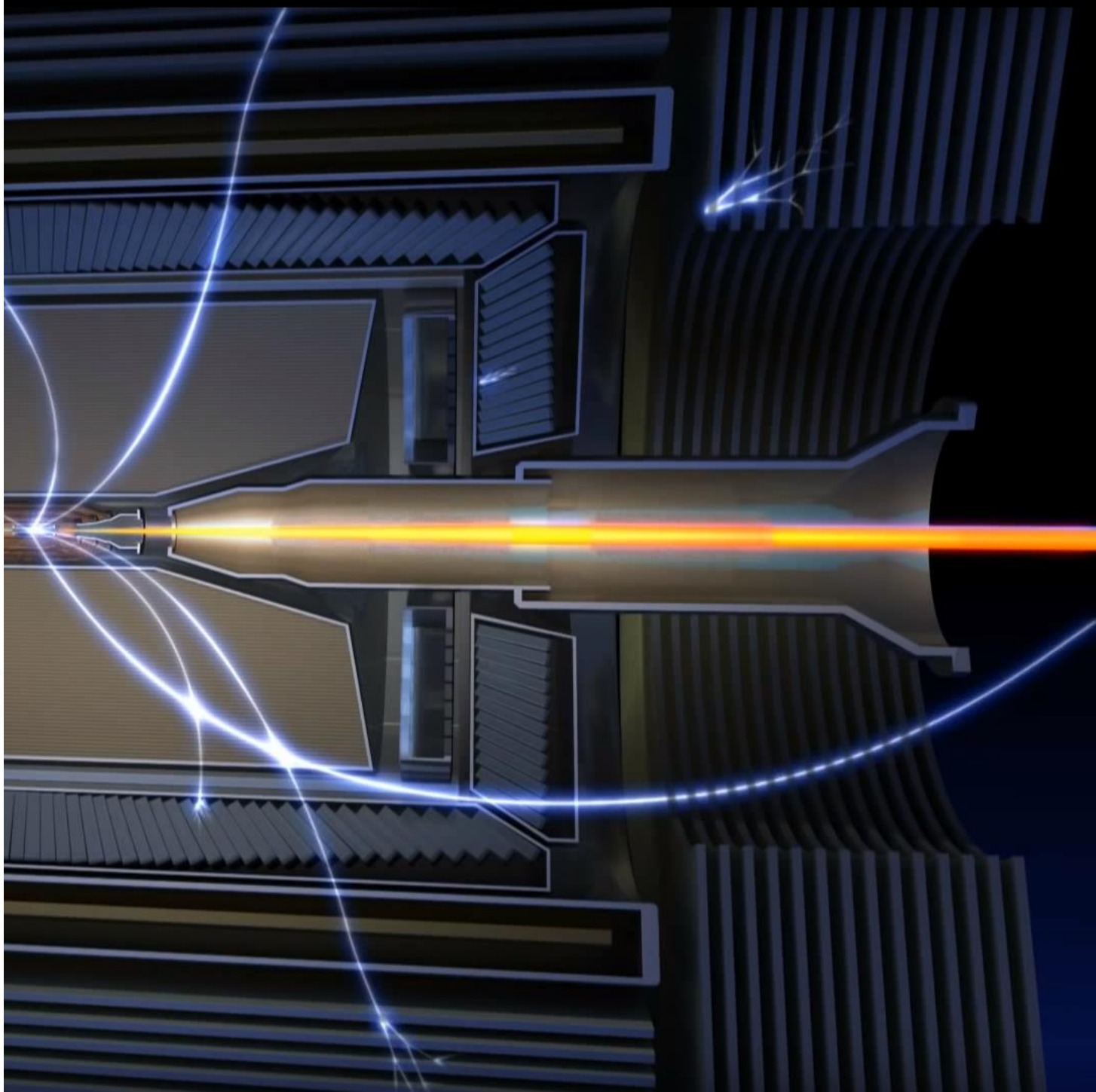
Pacific Northwest
NATIONAL LABORATORY

Hadron spectroscopy

July 08, 2020

Bryan Fulsom (PNNL)

Preparatory Joint Sessions on
“Open questions and New Ideas”



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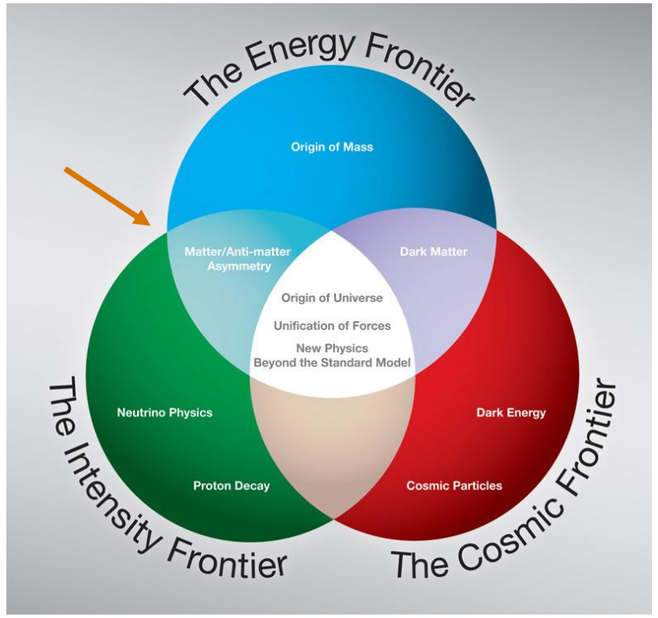
Introduction

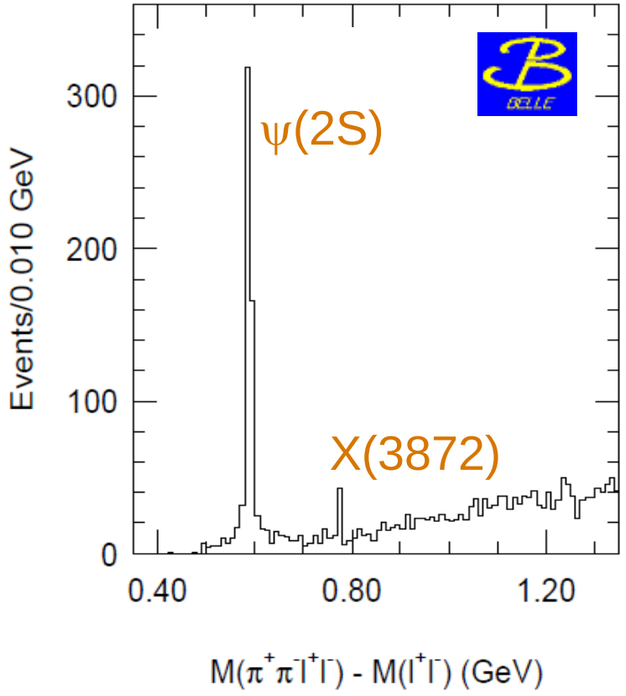
- “Hadron spectroscopy at future and upgraded facilities”
- Summary of EF06 subtopic meeting
  - June 24 (https://indico.fnal.gov/event/43796/)
  - >60 attendees, 7 talks
  - LHC, e+e-, fixed target, theory review
- Frontier overlap with “Rare Processes and Precision”

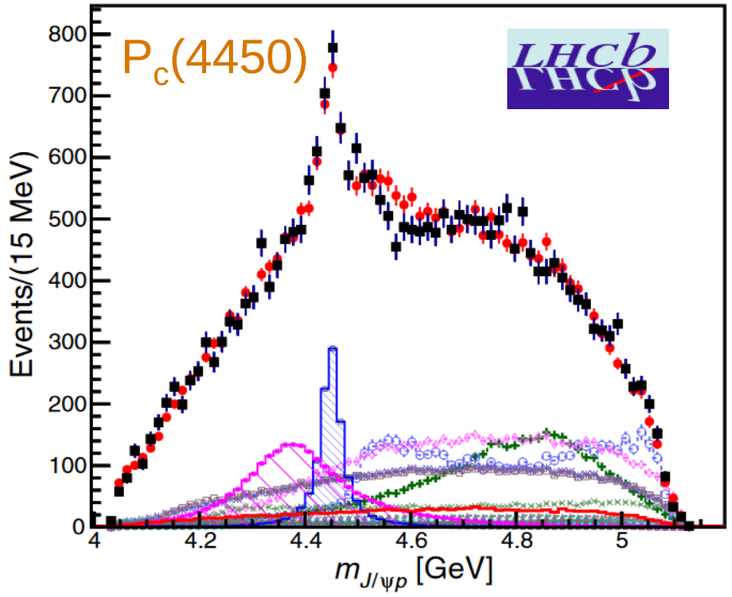


- Why we care: driven by experimental discoveries, the field of hadron spectroscopy is in the midst of a major revolution

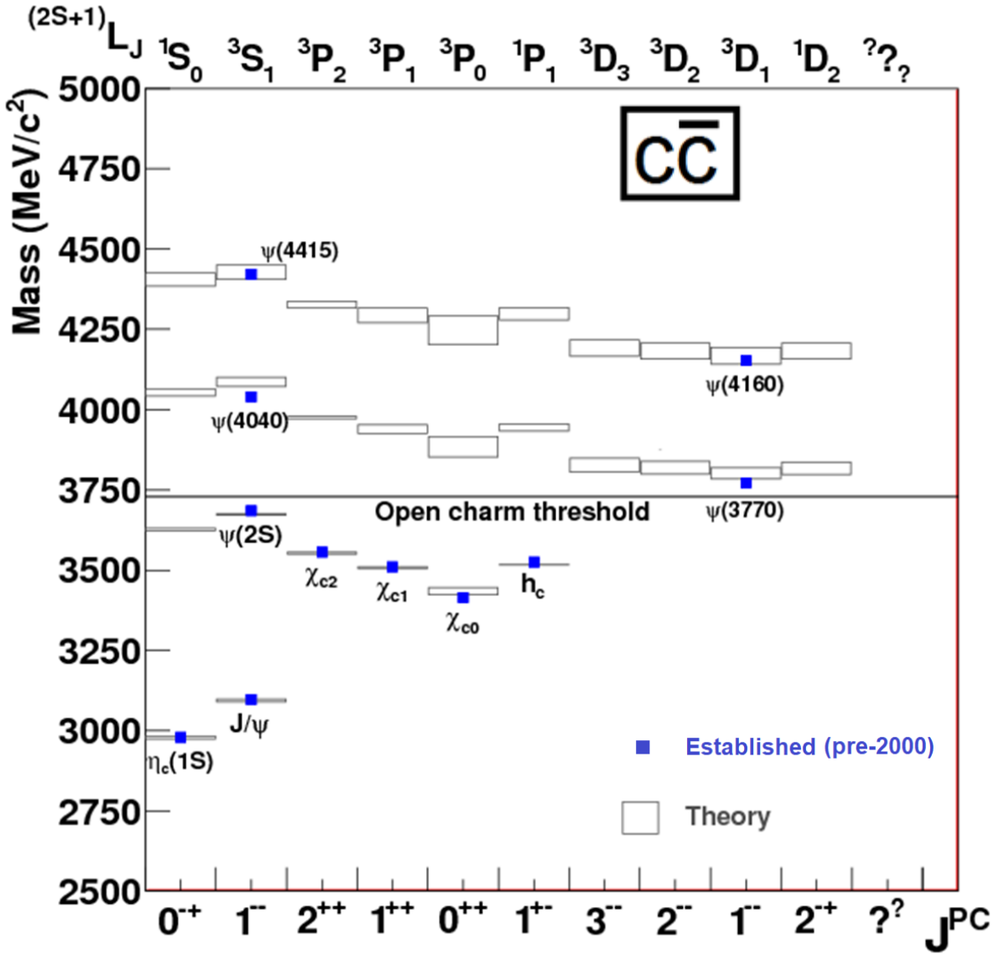
Brief history

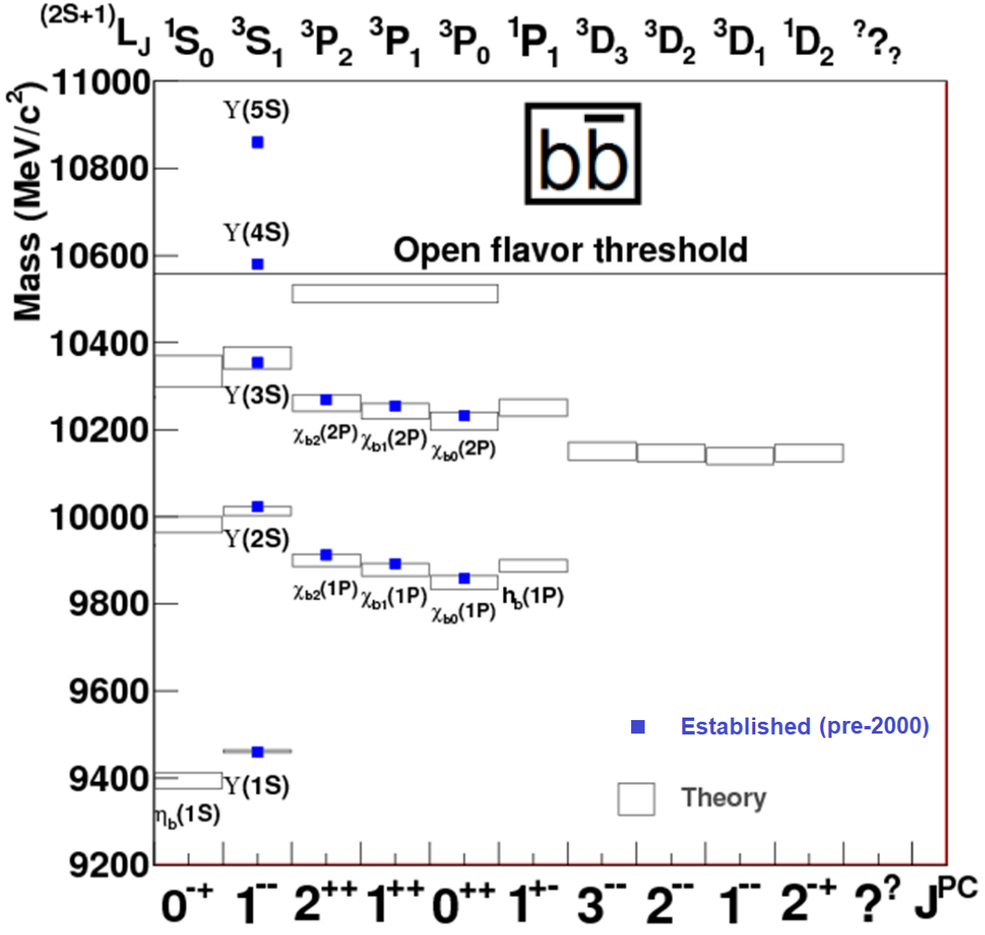
- 2000: quarkonium picture thought to be complete
- 2003: Discovery of X(3872) **PRL 91, 262001 (2003)**
- 2005-2020: Proliferation of “XYZ” states
- 2015: Discovery of P_c pentaquarks **PRL 115, 072001 (2015)**
- 2020 (1 week ago): Discovery of $T_{cc\bar{c}\bar{c}}$?



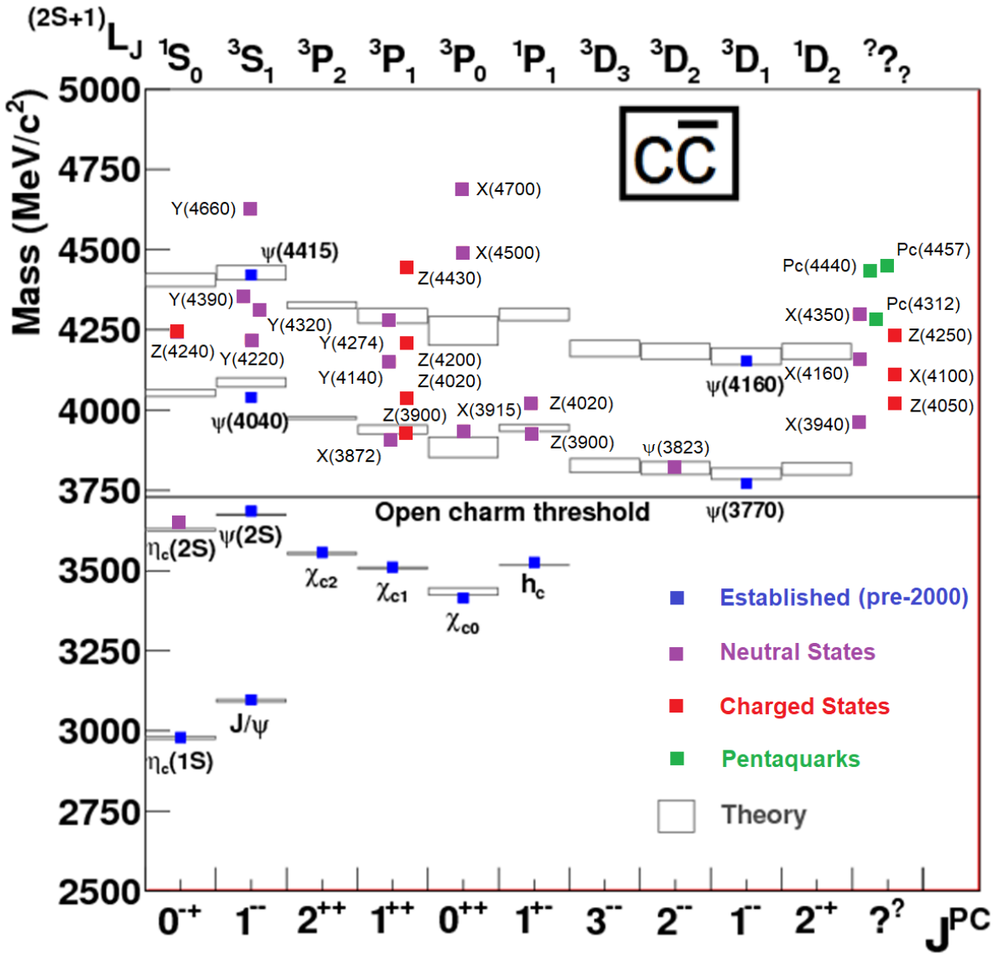


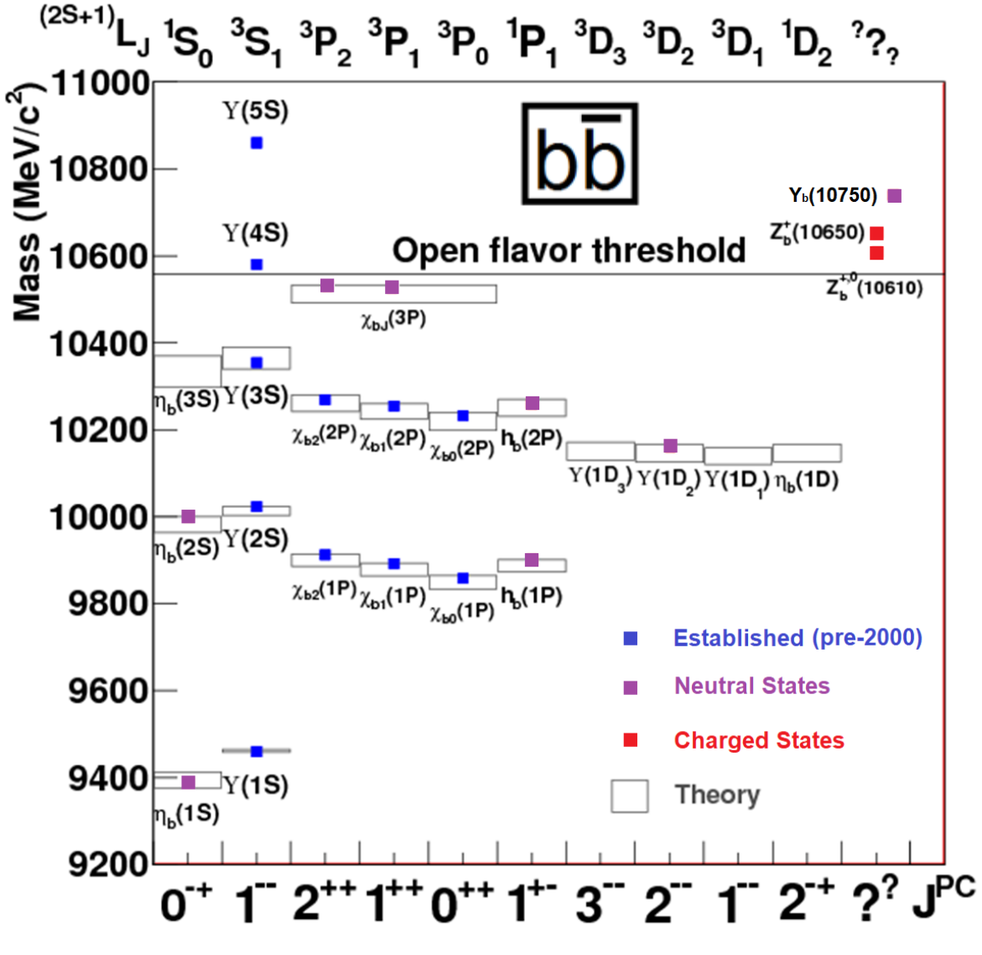
That was then… (circa 2000)





…this is now


$(2S+1)L_J$ $^1S_0$ $^3S_1$ $^3P_2$ $^3P_1$ $^3P_0$ $^1P_1$ $^3D_3$ $^3D_2$ $^3D_1$ $^1D_2$??
Mass (MeV/c²)
5000
4750
4500
4250
4000
3750
3500
3250
3000
2750
2500
$c\bar{c}$
Y(4660)
ψ(4415)
Y(4390)
Y(4320)
Z(4240)
Y(4220)
ψ(4040)
Y(4274)
Y(4140)
X(4700)
X(4500)
Z(4430)
Z(4200)
Z(4020)
Z(3900)
X(3872)
X(3915)
Z(4020)
Z(3900)
ψ(3823)
ψ(4160)
ψ(3770)
Pc(4440)
Pc(4457)
X(4350)
Pc(4312)
Z(4250)
X(4160)
X(4100)
Z(4050)
X(3940)
Open charm threshold
$\eta_c(2S)$
ψ(2S)
χ_{c2}
χ_{c1}
χ_{c0}
h_c
J/ψ
$\eta_c(1S)$
Established (pre-2000)
Neutral States
Charged States
Pentaquarks
Theory
0^{-+} 1^{--} 2^{++} 1^{++} 0^{++} 1^{+-} 3^{--} 2^{--} 1^{--} 2^{-+} ?? J^{PC}


$(2S+1)L_J$ $^1S_0$ $^3S_1$ $^3P_2$ $^3P_1$ $^3P_0$ $^1P_1$ $^3D_3$ $^3D_2$ $^3D_1$ $^1D_2$??
Mass (MeV/c²)
11000
10800
10600
10400
10200
10000
9800
9600
9400
9200
$b\bar{b}$
Y(5S)
Y(4S)
Open flavor threshold
$Y_b(10750)$
$Z_b^+(10650)$
$Z_b^{+,0}(10610)$
$\chi_{bJ}(3P)$
$\eta_b(3S)$
Y(3S)
$\chi_{b2}(2P)$
$\chi_{b1}(2P)$
$\chi_{b0}(2P)$
$h_b(2P)$
$Y(1D_3)$
$Y(1D_2)$
$Y(1D_1)$
$\eta_b(1D)$
$\eta_b(2S)$
Y(2S)
$\chi_{b2}(1P)$
$\chi_{b1}(1P)$
$\chi_{b0}(1P)$
$h_b(1P)$
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Established (pre-2000)
Neutral States
Charged States
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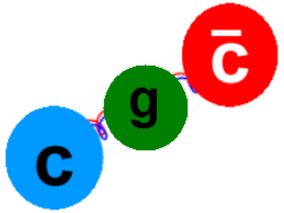
0^{-+} 1^{--} 2^{++} 1^{++} 0^{++} 1^{+-} 3^{--} 2^{--} 1^{--} 2^{-+} ?? J^{PC}

Interpreting new forms of matter

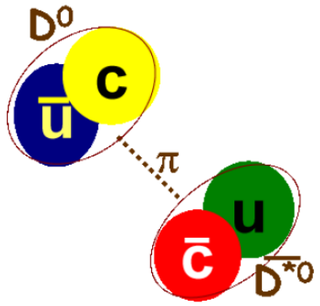
See EF06 talk by R. Lebed

- Hadronic Molecules
  - Weakly bound state of mesons/baryons
- Tetraquarks/Pentaquarks
  - Di-quarks bound directly by strong force
- Other exotica
  - Hybrids: quarkonium with bound excited gluon
  - Hadroquarkonium: $q\bar{q}$-light hadron interaction
- "Nothing special"
  - Kinematic effects / standard quarkonium
- Lattice QCD
  - Challenging calculation, but some progress underway

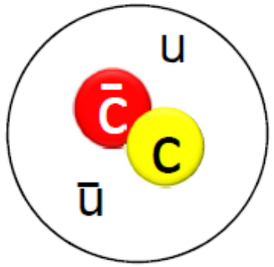
diquark-diantiquark



$q\bar{q}$-gluon"hybrid"

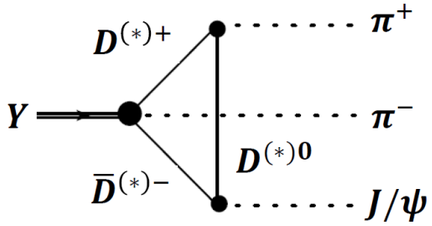


X3872: D^0D^{0*} "molecule"
P_c pentaquark: $\Sigma_c D^{(*)}$?



hadroquarkonium

conventional quarkonium

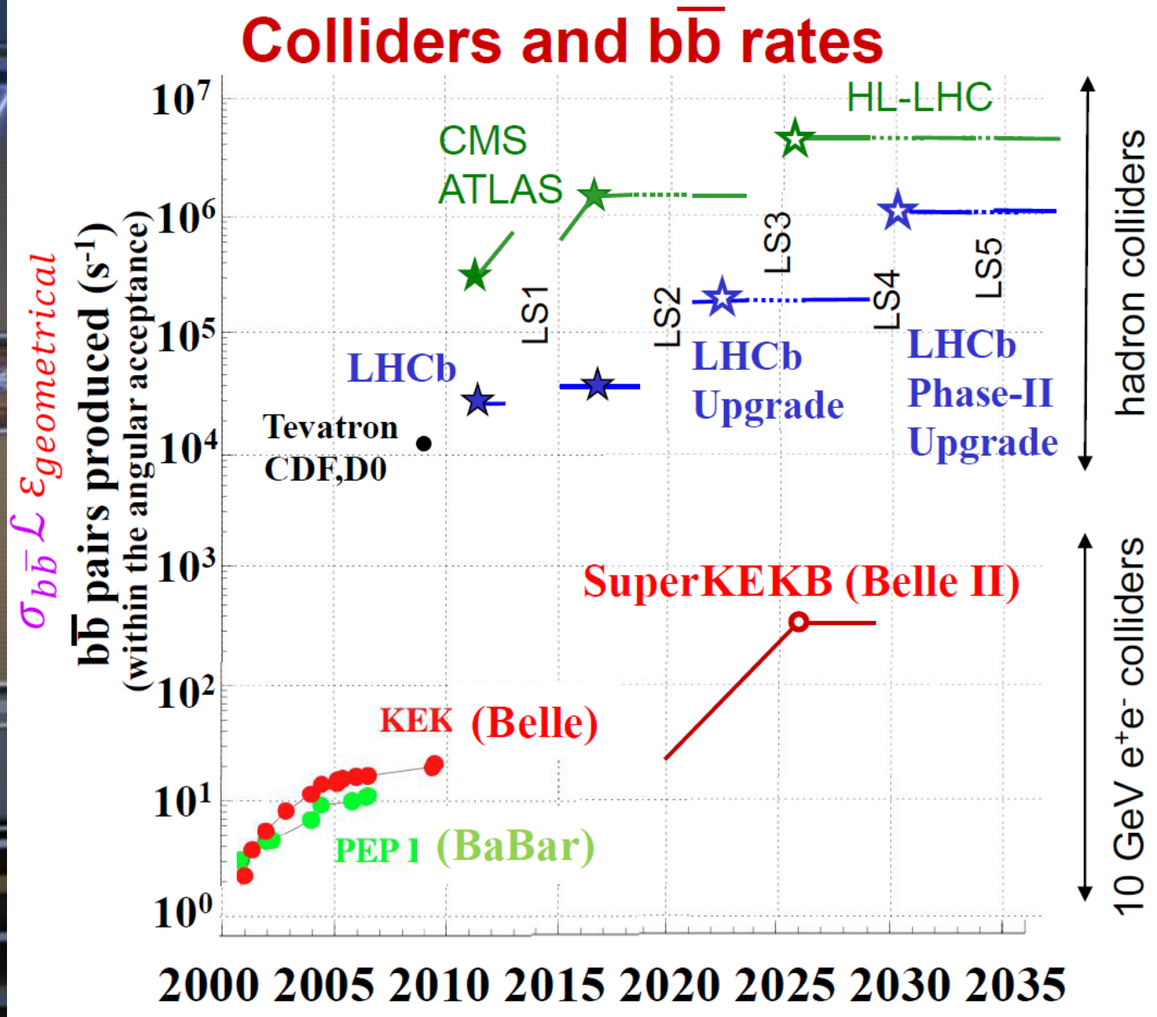


threshold/rescattering/cusp effect

Adapted from Godfrey & Olsen, Ann. Rev. Part. Sci. 58 (2008) 51

It is becoming increasingly clear that no single theoretical paradigm explains all > 40 heavy-quark exotics

Importance of Energy Frontier flavor production



- Tremendous rate potential
  - σ_{bb}~500000x higher than B-Factories
  - Backgrounds pose trigger challenges
  - Physics determined by detector capability
- Production mechanisms
  - All b-hadron species: B_d, B_s, B_c, b-baryons
  - ~10x charm prod. rate (prompt and b-decay) enables charm meson/baryon spectroscopy
  - Central, forward, and heavy-ion-collision

$\int \mathcal{L}\,dt$

CDF 10 fb^{-1} , D0 8 fb^{-1}

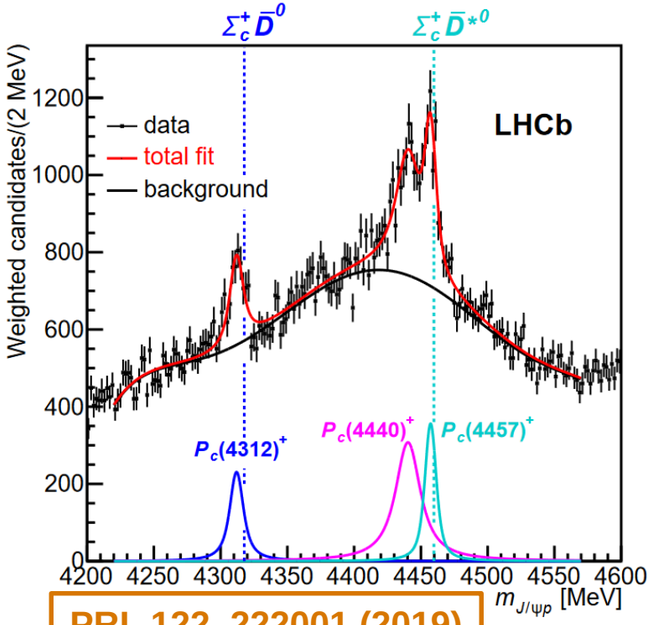
now

	Run I	Run II	Run III	Run IV	Run V+VI
LHCb	3 fb^{-1}	6 fb^{-1}	50 fb^{-1}		300 fb^{-1}
ATLAS,CMS	25 fb^{-1}	450 fb^{-1}	3000 fb^{-1}		

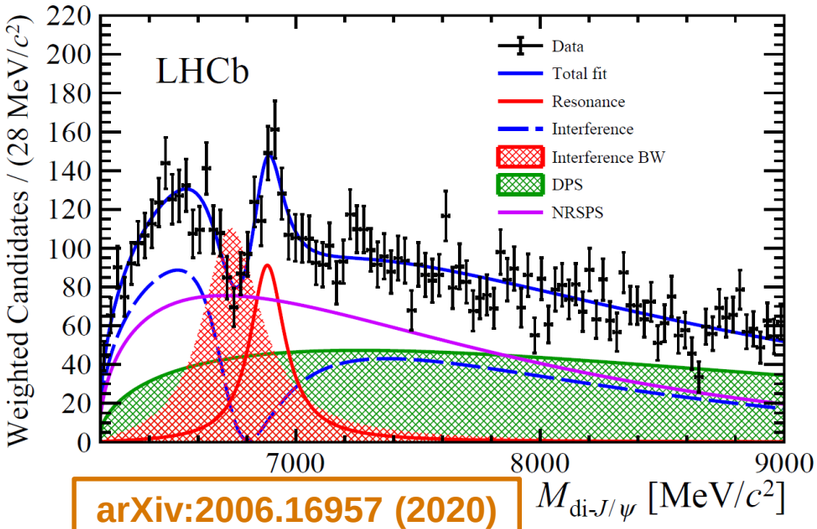
LHCb

See EF06 talk by T. Skwarnicki

- First hadron collider experiment optimized for heavy flavor physics
- Advantages
  - Dedicated trigger bandwidth
  - Lower p_T reach
  - Charged/hadron ID capabilities
  - Huge production cross section
- Landmark achievements
  - pJ/ψ pentaquarks
  - Doubly-charmed baryons
  - J/ψJ/ψ doubly heavy tetraquark?



PRL 122, 222001 (2019)



arXiv:2006.16957 (2020)

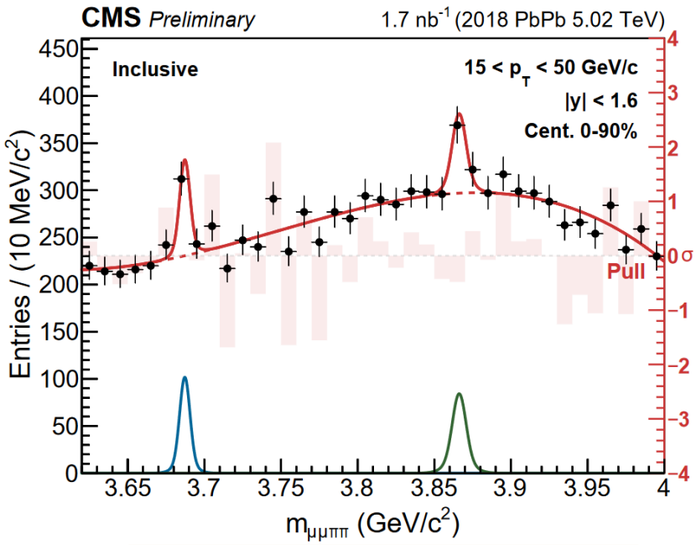
- Future upgrades
  - Run 3/4 (now): ~5x luminosity, faster readout, finer tracking
  - Run 5/6 (~2030): ~6x luminosity, timing and segmentation, ECAL upgrade?

ATLAS/CMS

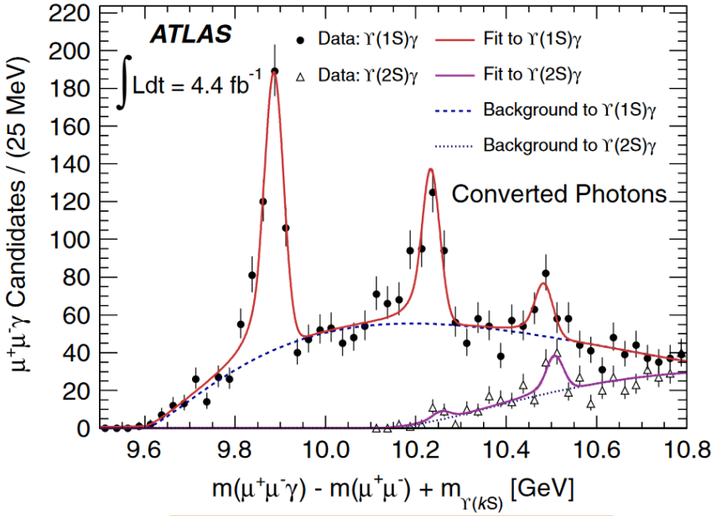
See EF06 talk by A. Pompili

- Both experiments have active conventional and exotic spectroscopy programs

- Key contributions
  - X(3872) production (pp and HI)
  - Observation of $\chi_b(3P)$
  - Observation of $B_c^{(*)}(2S)$



CMS PAS HIN-19-005 (2019)



PRL 108, 152001 (2012)

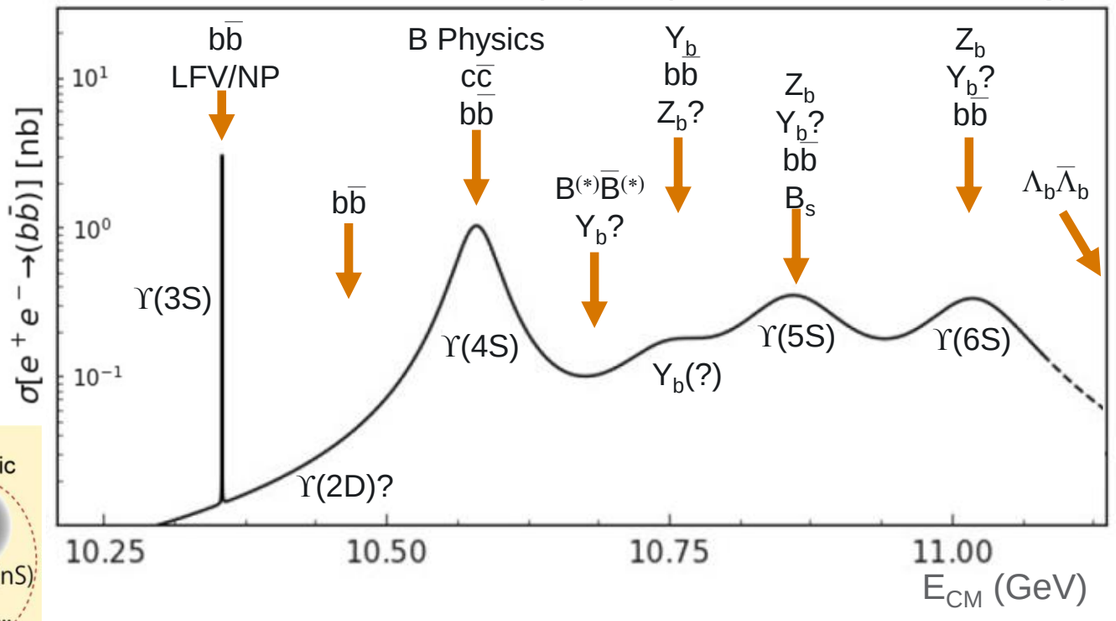
- Future potential
  - Further exploitation of existing Run-II data
  - Development/deployment of effective trigger strategies as luminosity increases

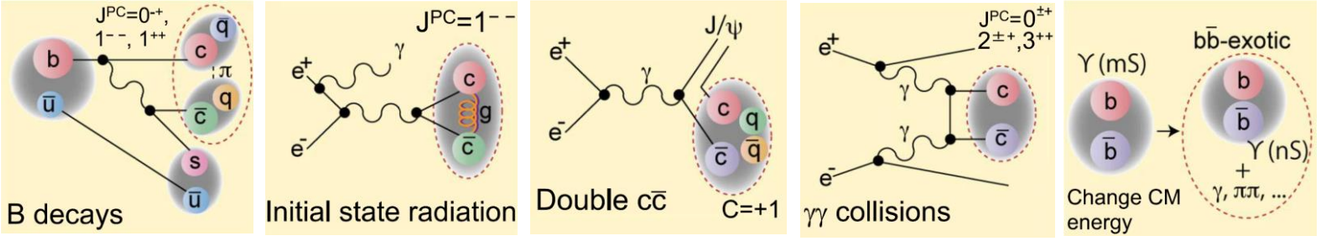
Belle II

See EF06 talk by B. Fulsom

- Belle opened the new era of XYZ studies; Belle II is the next generation
- ~10 year program with rebuilt accelerator/detector started last year
- Instantaneous luminosity record (June 15)
- Advantages
  - 50x luminosity
  - Clean, fully-reconstructed events
  - Final states with neutrals/missing energy
  - $\sqrt{s}$ up to ~11 GeV
  - Unique production methods

Belle II $b\bar{b}$ cross section and physics potential vs. beam energy

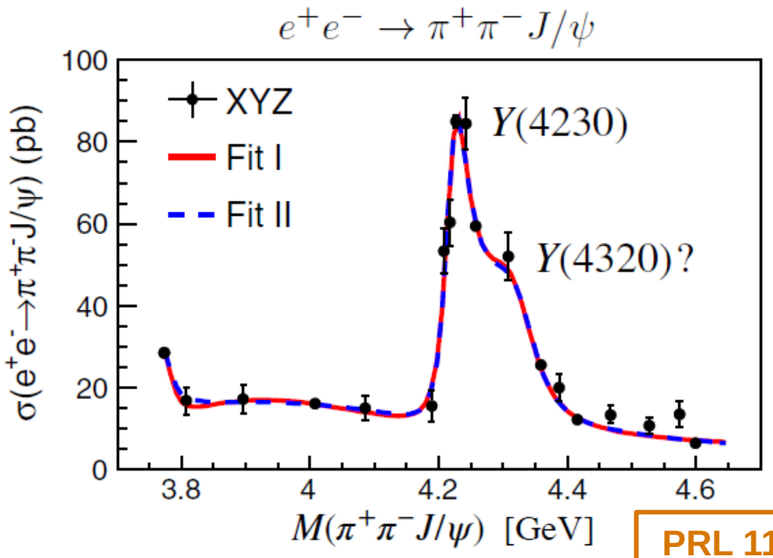




BES III

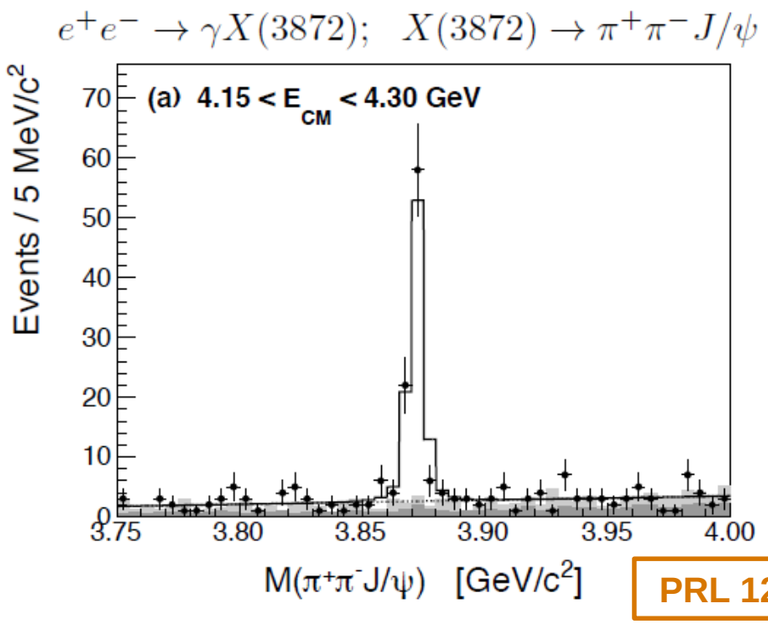
See EF06 talk by R. Mitchell

- Focus on:
  - light quark spectroscopy
  - precision charmonium measurements
  - XYZ states



PRL 118, 092001 (2017)

- Advantages/key contributions
  - Large J/ψ, ψ(2S) samples
  - E_{CM} scan: direct production of Y states
  - Connection between XYZ via decay



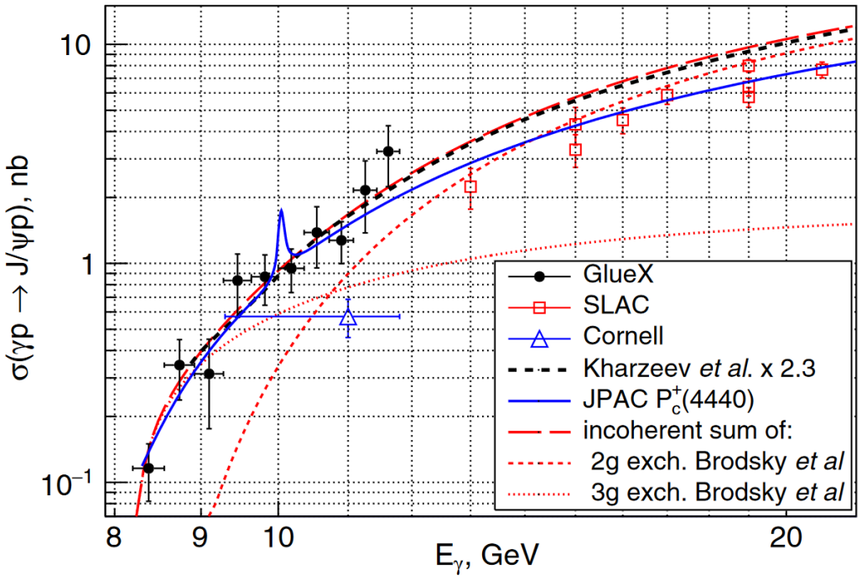
PRL 122, 202001 (2019)

- Future plans
  - Energy upgrade to 4.9 GeV
  - Continue operation for ~5-10 years
  - Charm-tau factories (50-100x luminosity, $2<E_{CM}<7$ GeV)?

JLab & EIC

See EF06 talk by J. Stevens

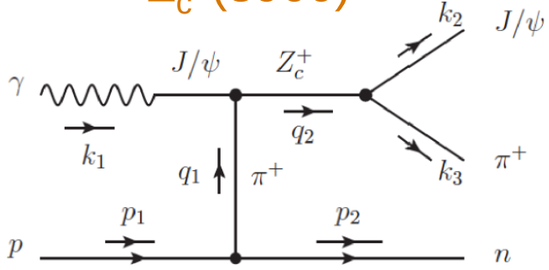
- JLab 12 GeV e- beam
- GlueX: light meson/exotics studies
  - Hybrid meson searches
  - $\gamma p \rightarrow pJ/\psi$ limits on P_c



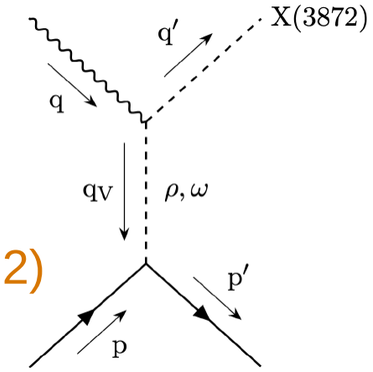
PRL 123, 072001 (2019)

- EIC development (~2030)
  - Exotic photoproduction mechanisms?

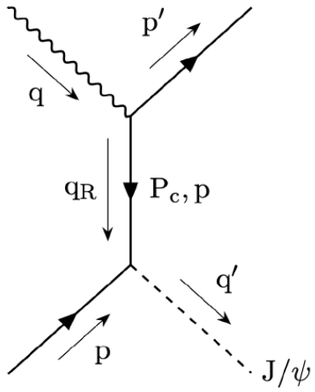
$Z_c^+(3900)$



X(3872)



P_c^+



Future facilities?

- Hadron spectroscopy program yet to be defined at future new facilities (ILC/CLIC, FCC-ee/CEPC, FCC-hh, …)
- Energy and Intensity Frontier machines both make significant complementary contributions to flavor physics and hadron spectroscopy
- This is an open question we need/intend to explore

- Experiment has led theory: difficult to predict the future
  - No initial X(3872) or P_c experimental programs → did not know they existed!
- Not unreasonable to expect more surprises in the future

Summary: Open Questions / New Ideas

- Extensive experimental and theoretical program, complementary across frontiers, needed to discover/confirm/understand/classify 40+ new states

- LHC
  - Future LHCb upgrades to exploit LHC luminosity increase
  - Development of trigger/operating strategies to take full advantage of ATLAS/CMS
  - What can we learn from heavy ion studies (combined EF07 effort)?
- Existing e+e- colliders
  - Support (personnel, detector/machine/E_{CM} upgrades) to fully pursue these topics
- Future facilities
  - EIC: new exotics production mechanisms
  - All: Hadron spectroscopy potential and requirements to be defined

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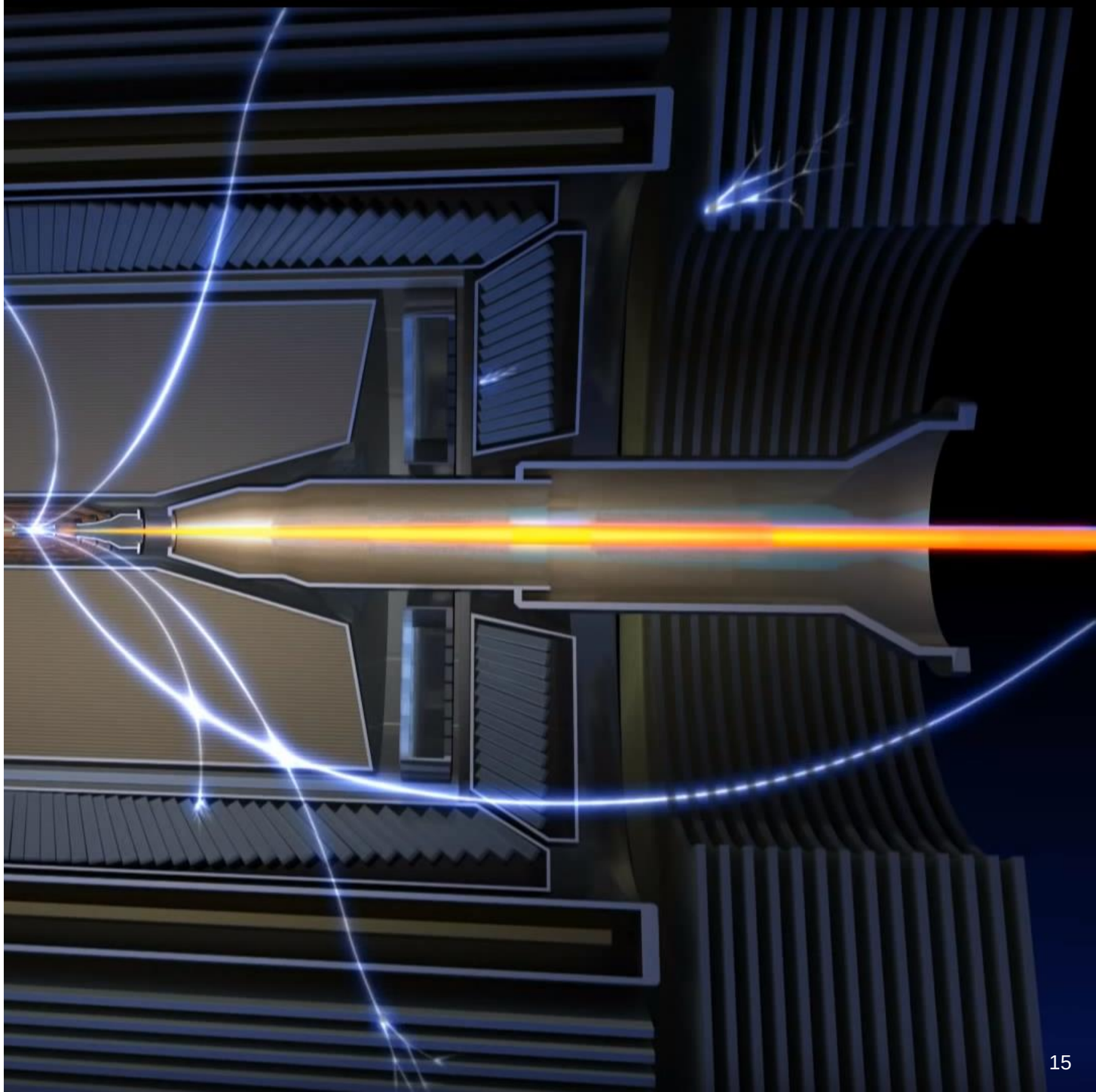
Thank you