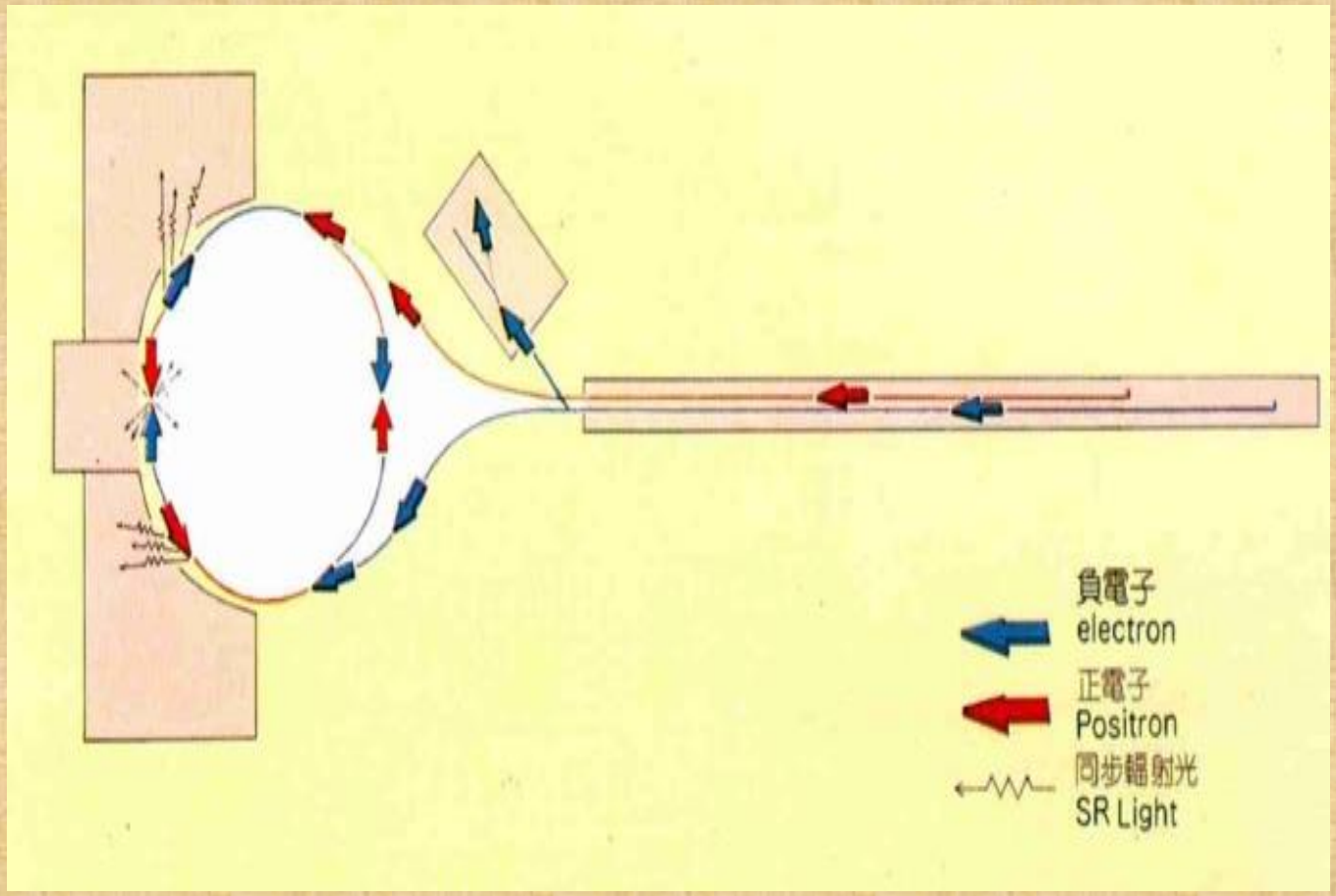
BES III future prospects in exotic hadron spectroscopy

Kai ZHU (IHEP) on behalf of BESIII

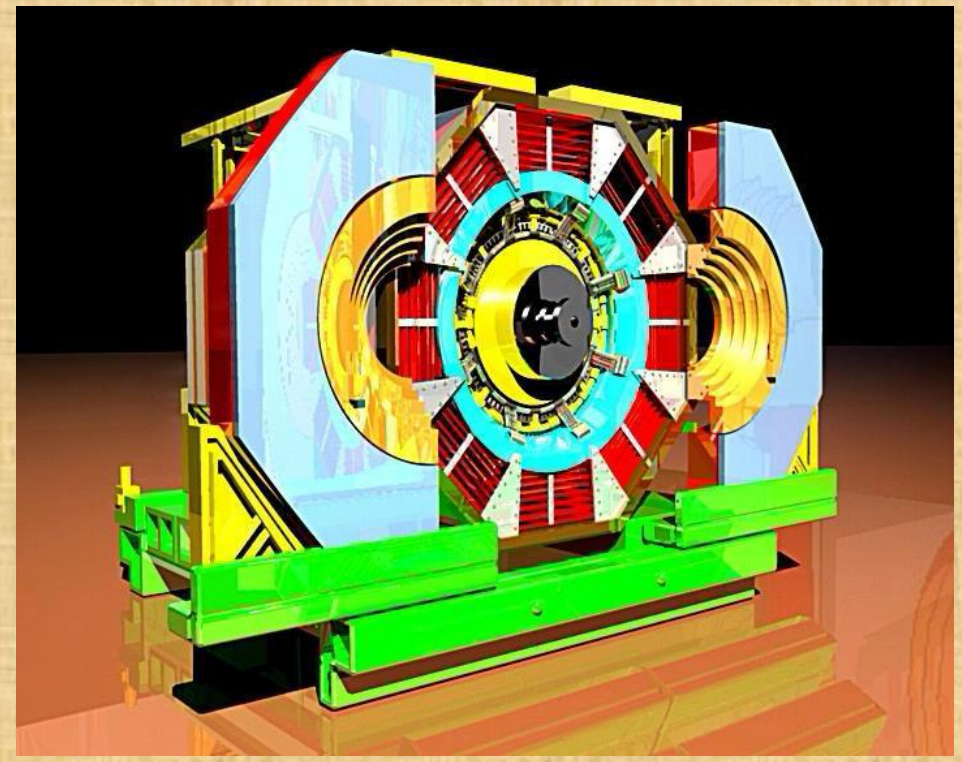
6th International conference on New Frontiers in Physics (ICNFP 2017)
Workshop on exotic hadrons
17-29 August 2017, Kolymbari, Crete, Greece

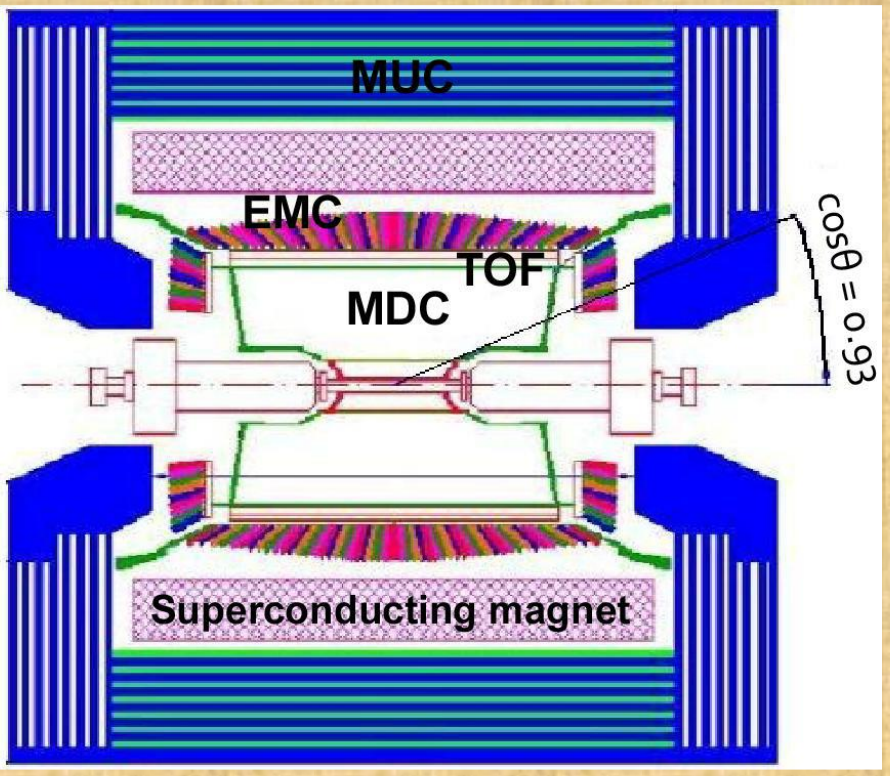
BEPCII: Beijing Electron-Positron Collider II
北京　电子 - 正电子 对撞机 II



CMS energy： $2.0 \sim 4.6$ **GeV；** **Luminosity:** $1 \times 10^{33} cm^{-2} s^{-1}$

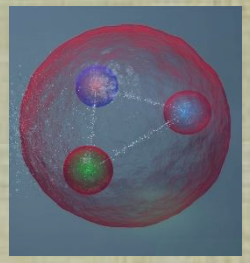
BESIII: BEijing Spectrometer III
北京 谱仪 III



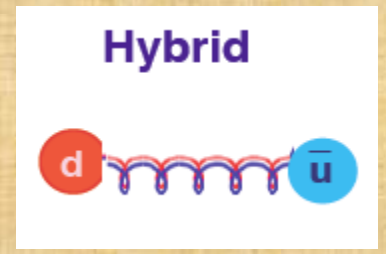


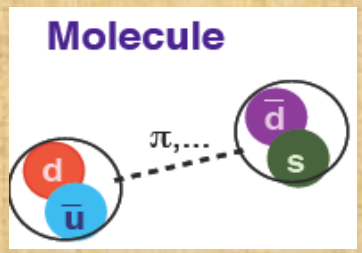
Physics: light hadron, charmonium, charm, R-value & QCD, new physics

“Normal” hadrons



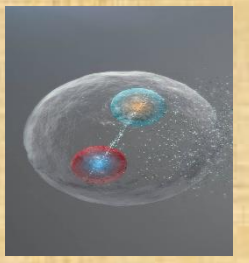
- **Exotic candidates**

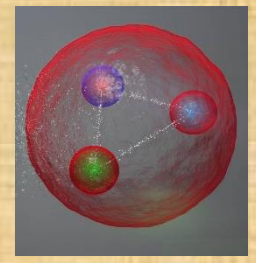




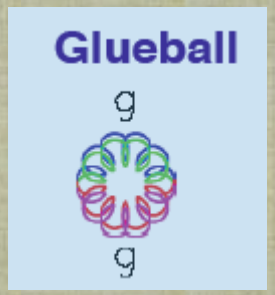
figures from arXiv:1403.1254, S. Olsen

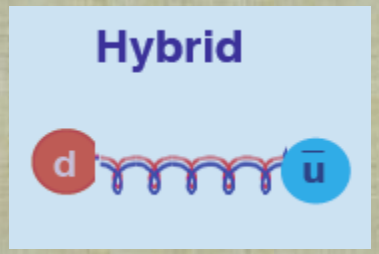
“Normal” hadrons

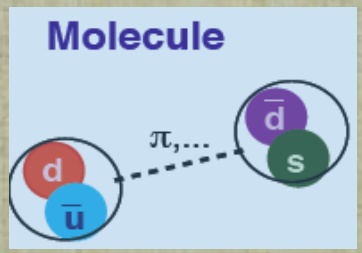




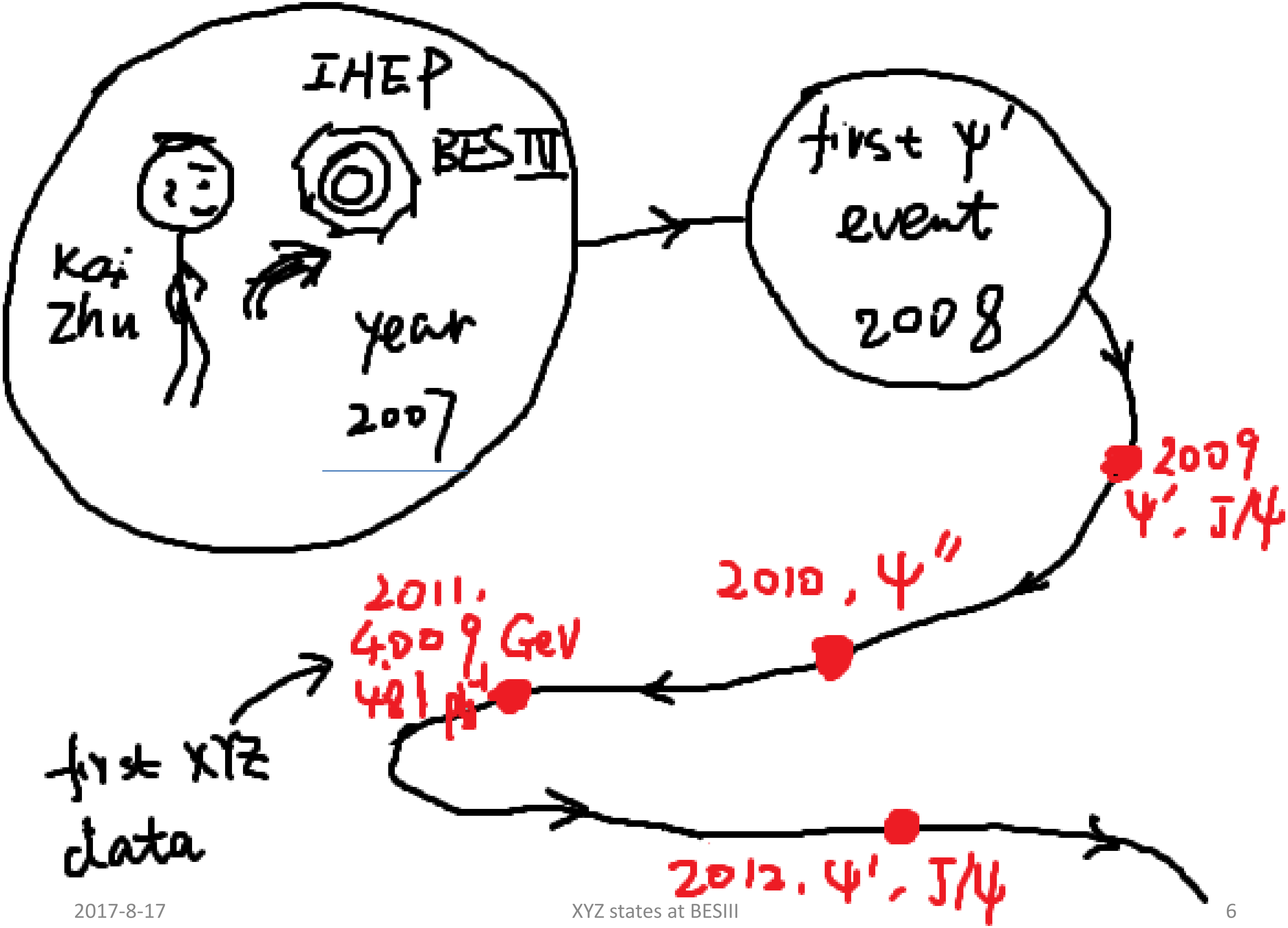
- **Exotic candidates**

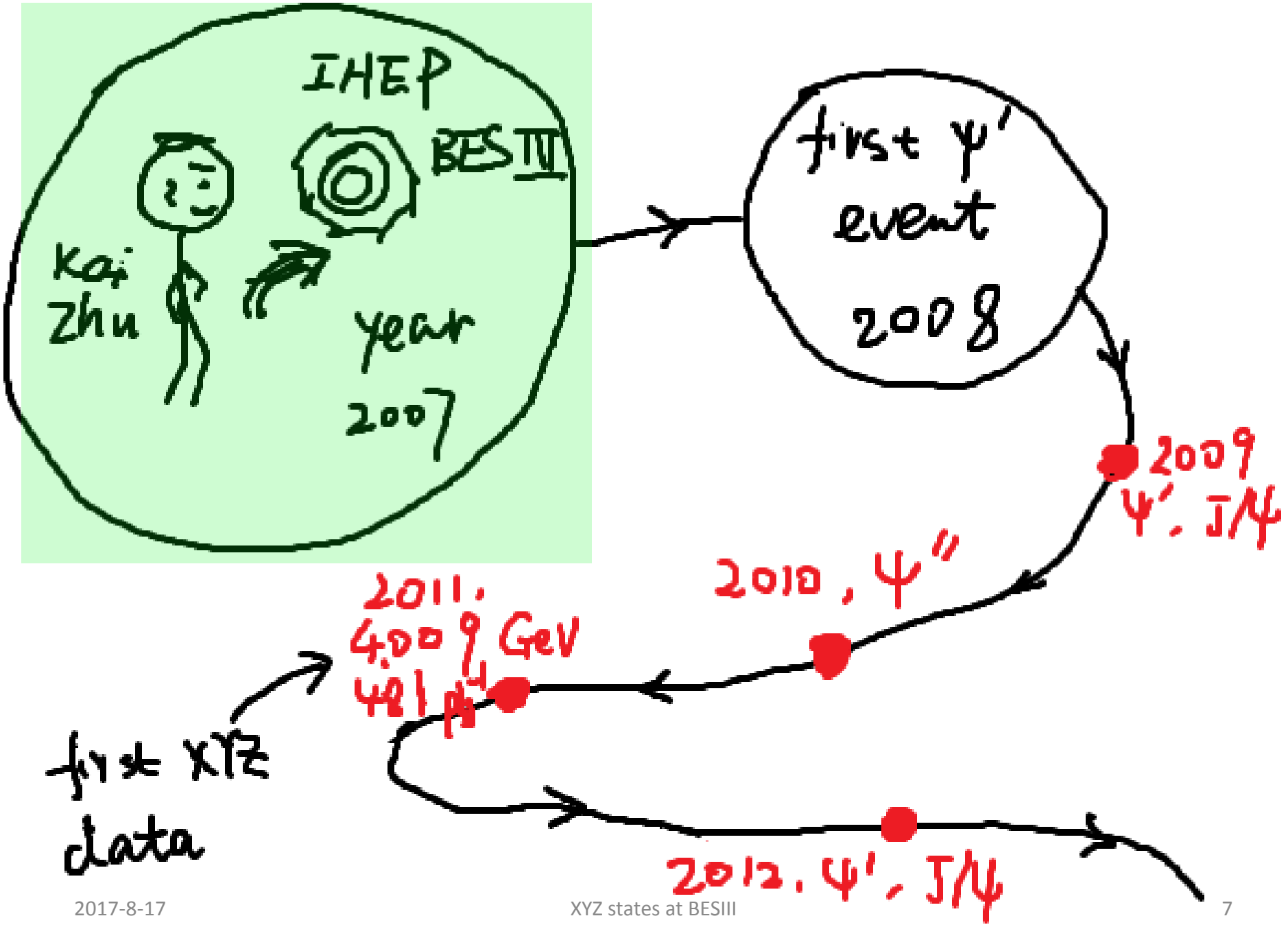


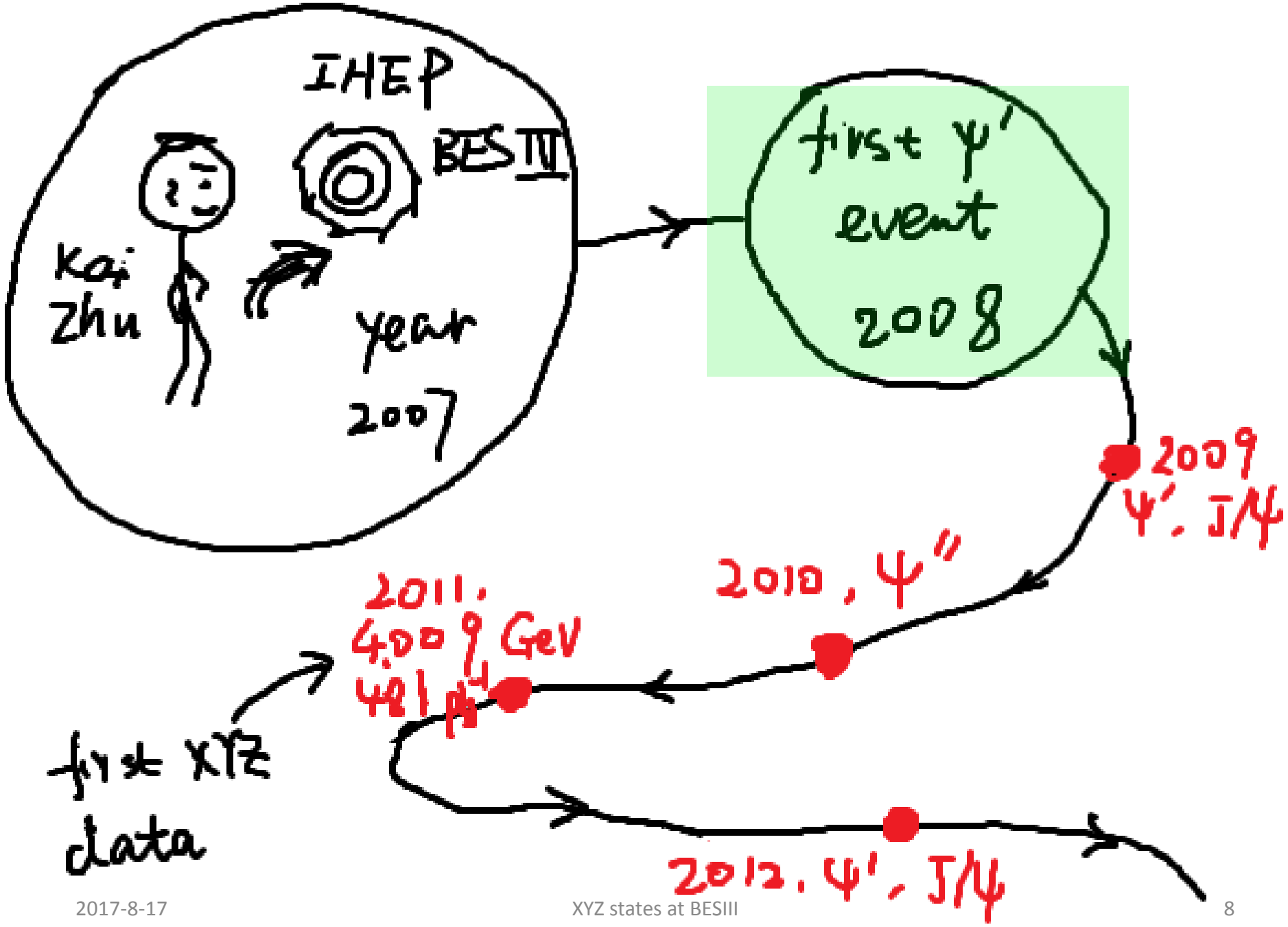


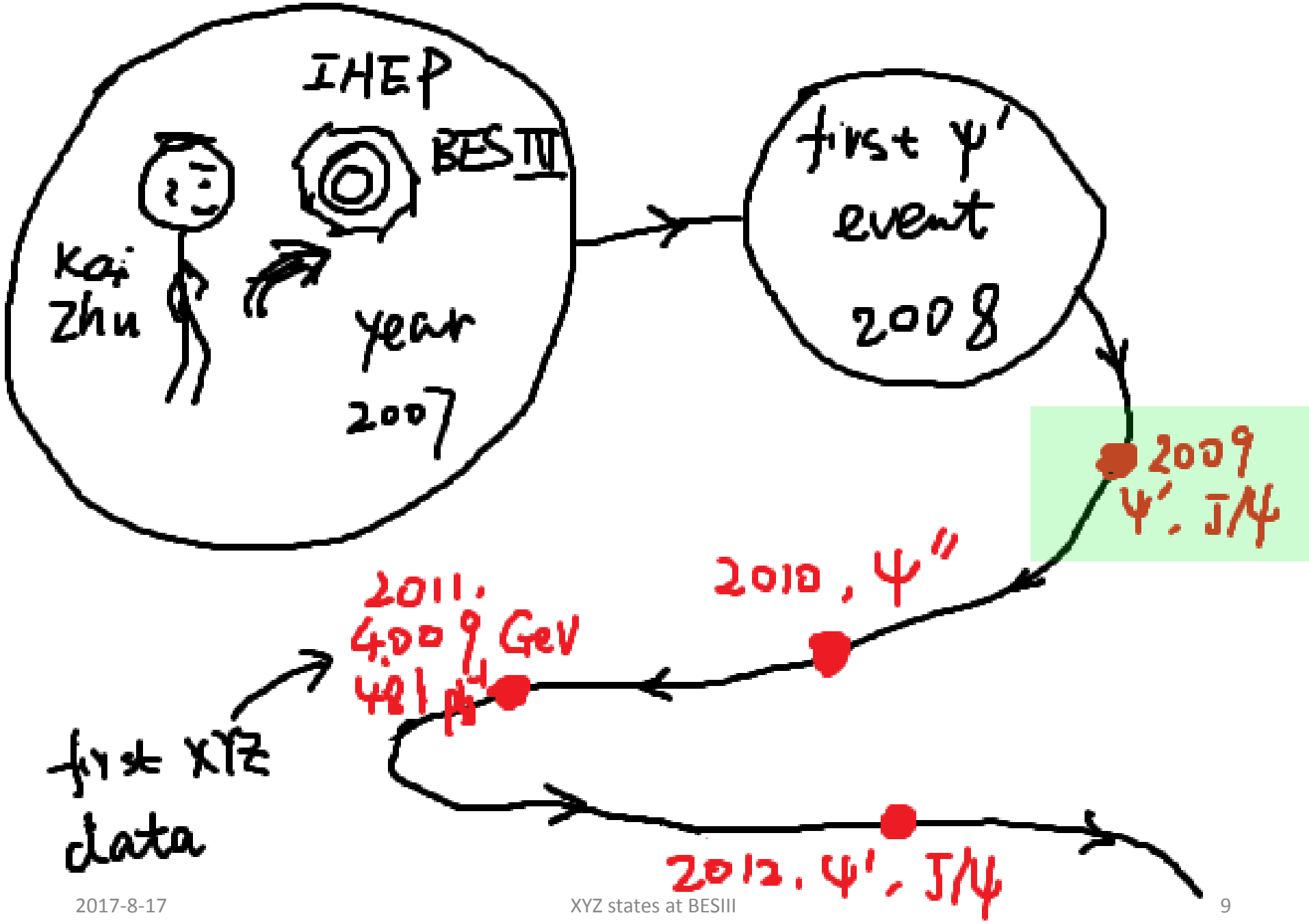


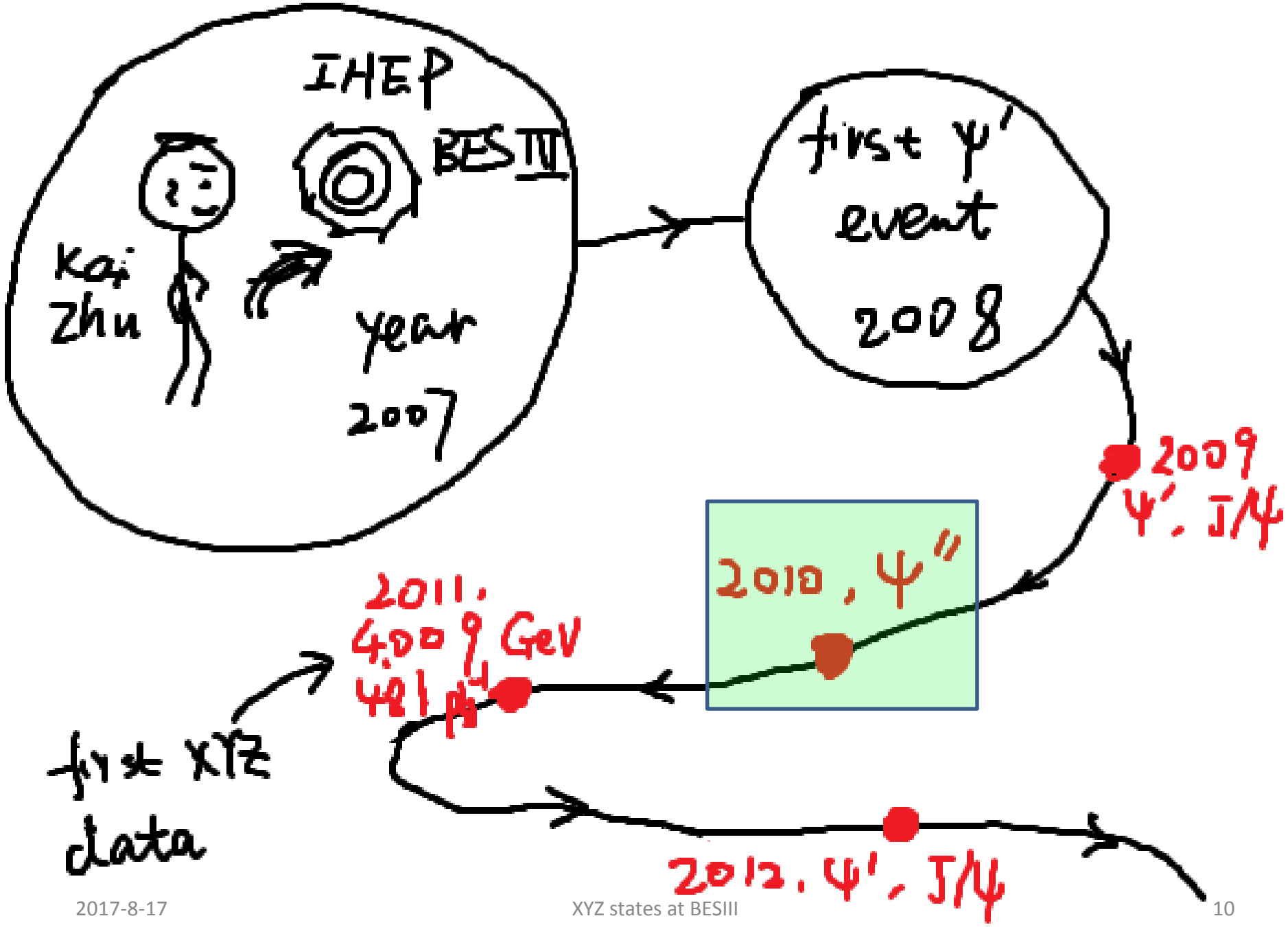
figures from arXiv:1403.1254, S. Olsen

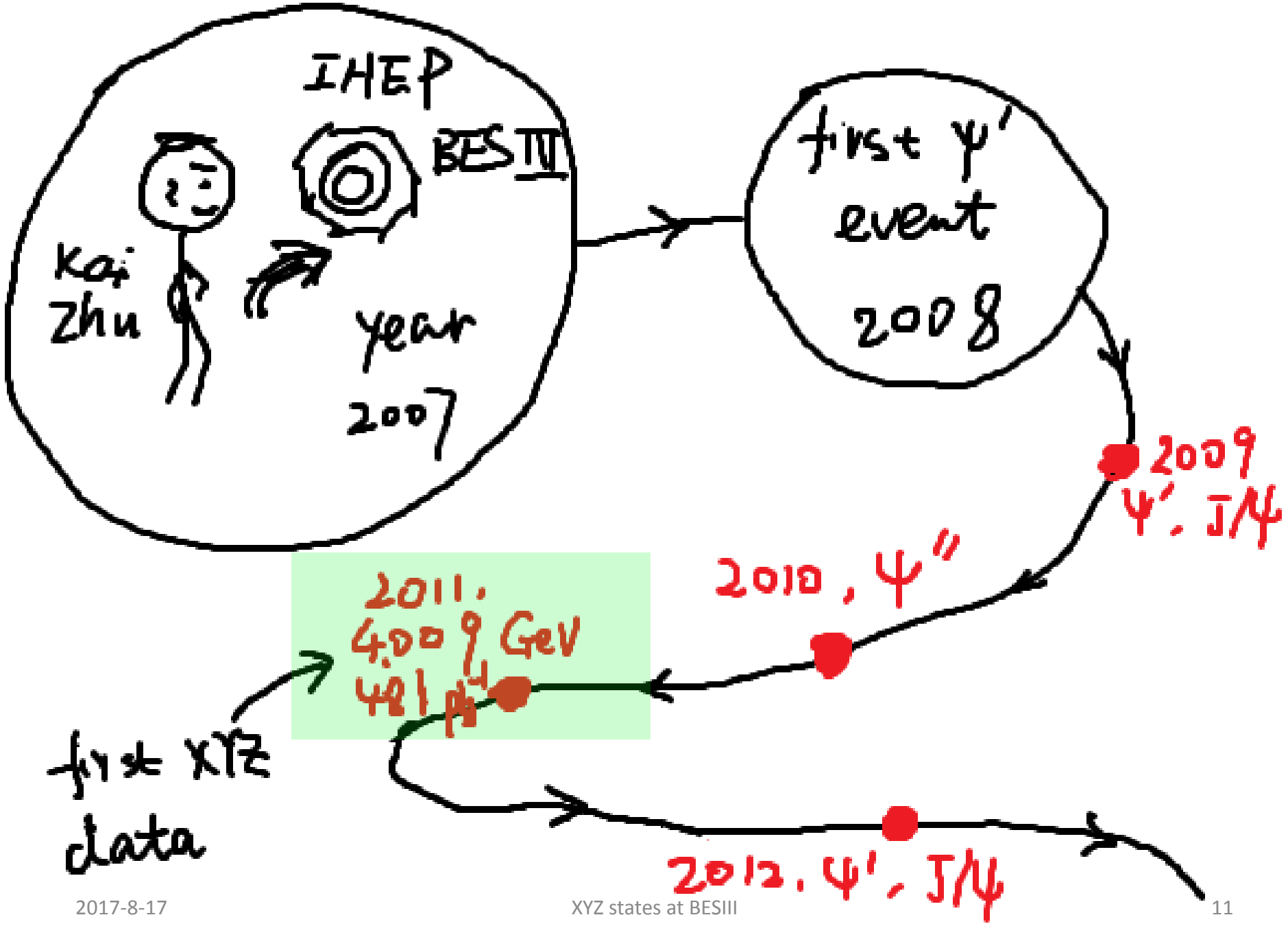

IHEP
BESIII
Kai Zhu
year 2007
first ψ' event 2008
2009 ψ', J/ψ
2010, ψ''
2011, 4.009 GeV 481 pb⁻¹
first XYZ data
2012, ψ', J/ψ

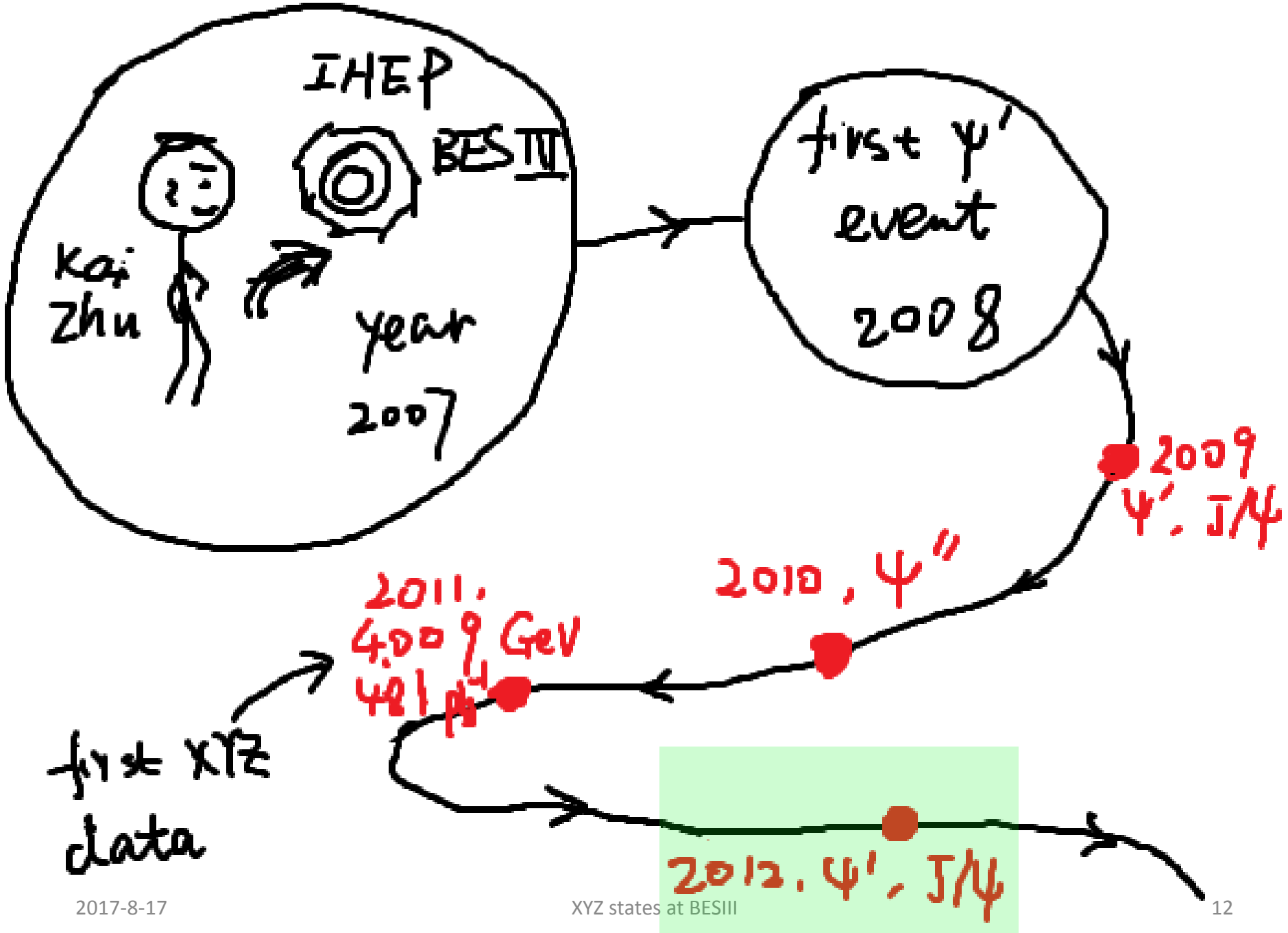

IHEP
BESIII
Kai Zhu
year 2007
first ψ' event 2008
2009 ψ', J/ψ
2010, ψ''
2011, 4009 GeV 4181 pb⁻¹
first XYZ data
2012, ψ', J/ψ

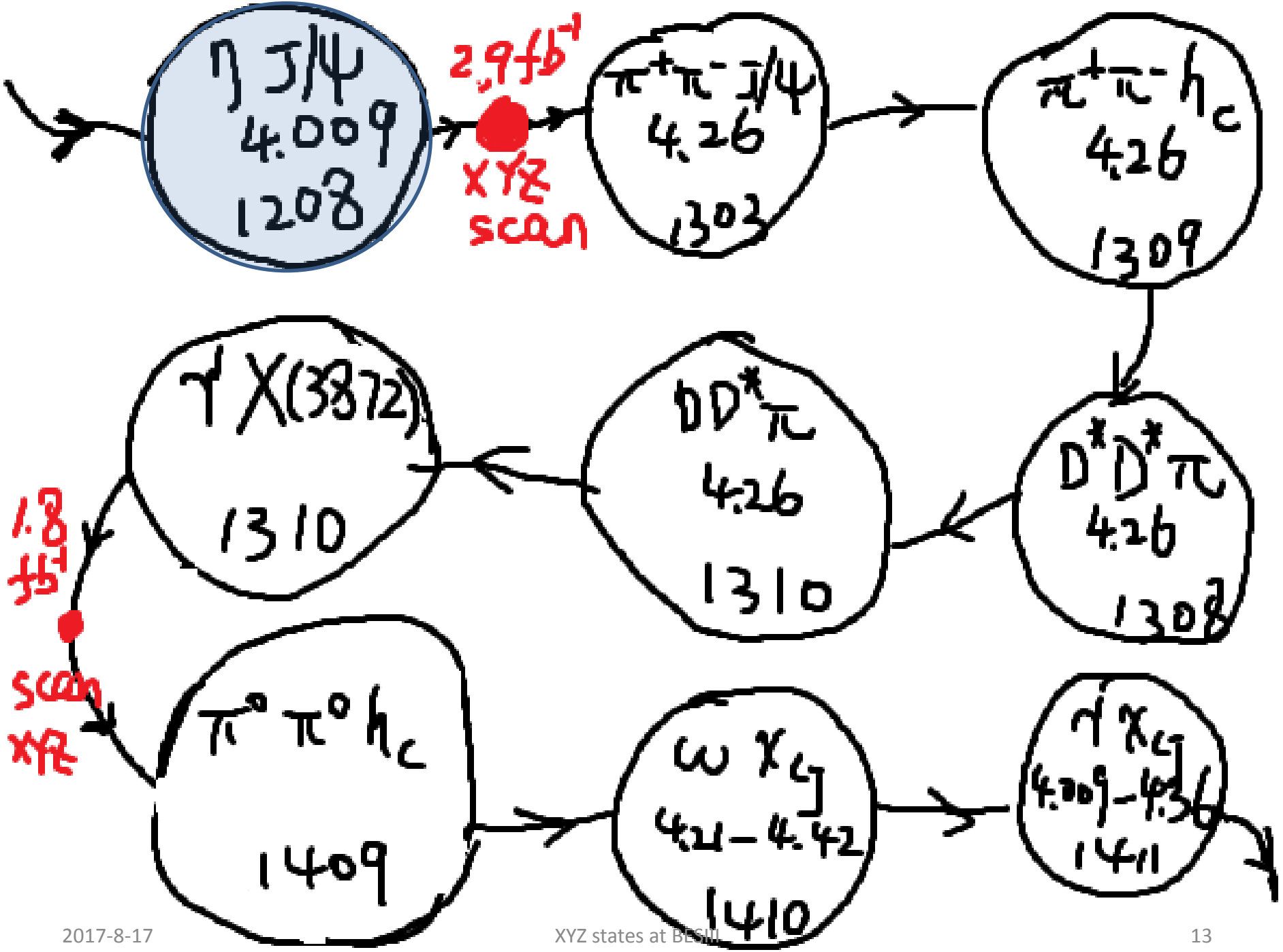

IHEP
BESIII
Kai Zhu
year 2007
first ψ' event 2008
2009 ψ', J/ψ
2010, ψ''
2011, 4009 GeV 4181 pb⁻¹
first XYZ data
2012, ψ', J/ψ

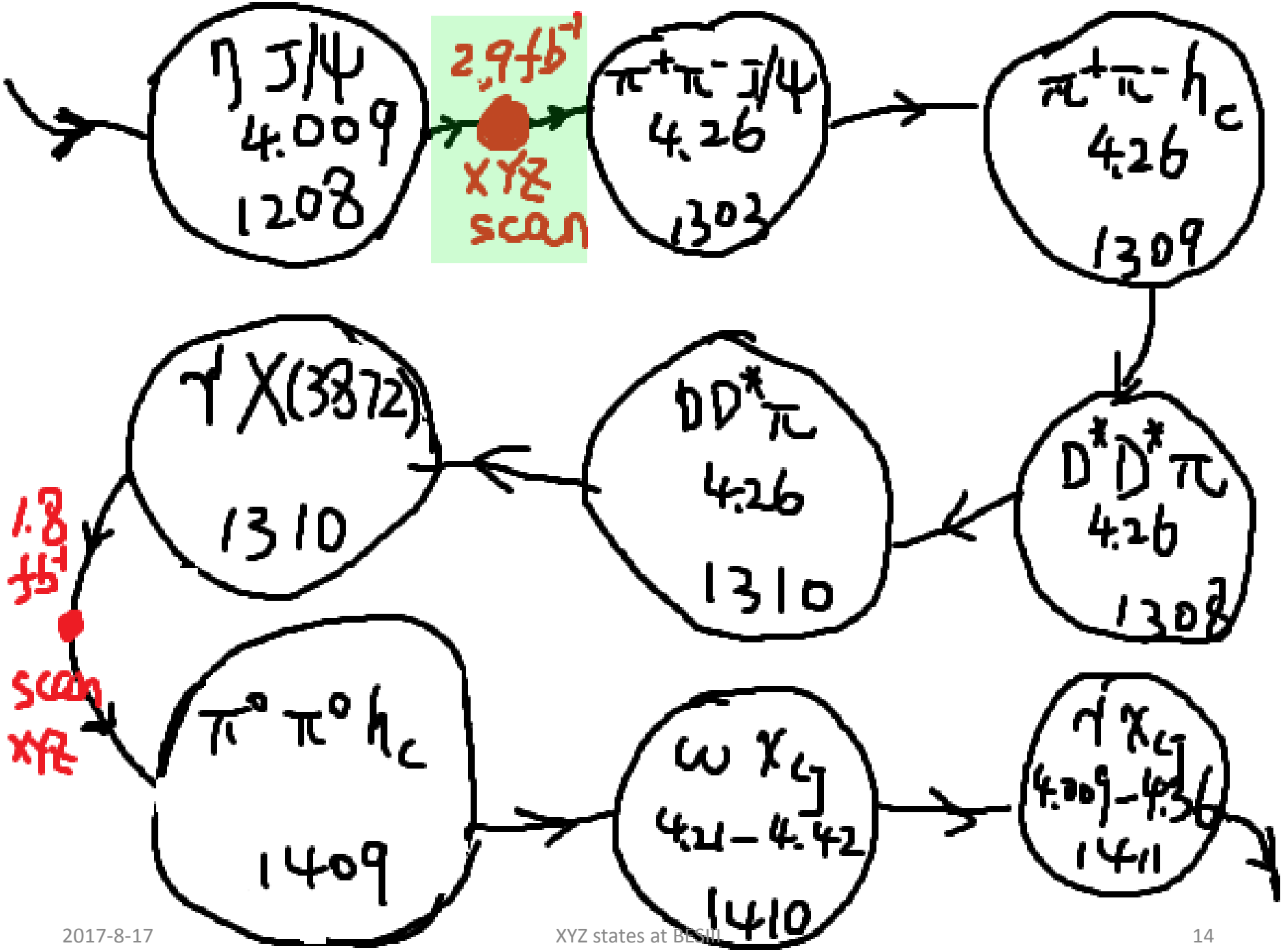

IHEP
BESIII
Kai Zhu
year 2007
first ψ' event 2008
2009 ψ', J/ψ
2010, ψ''
2011, 4.009 GeV 4.1 fb⁻¹
first XYZ data
2012, ψ', J/ψ

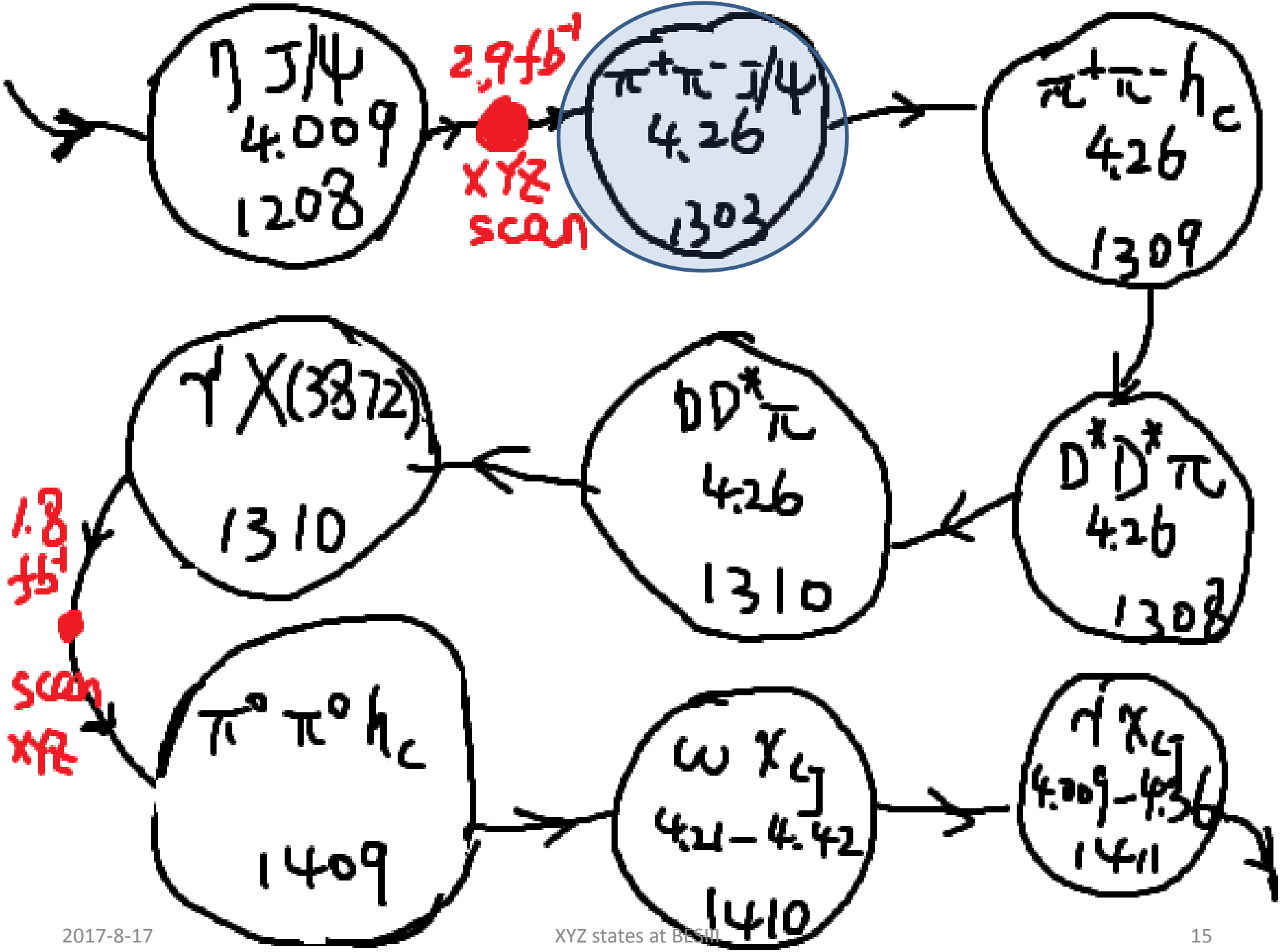

IHEP
BESIII
Kai Zhu
year 2007
first ψ' event 2008
2009 ψ', J/ψ
2010, ψ''
2011, 4009 GeV 4181 pb⁻¹
first XYZ data
2012, ψ', J/ψ


IHEP
BESIII
Kai Zhu
year 2007
first ψ' event 2008
2009 ψ', J/ψ
2010, ψ''
2011, 4009 GeV 4181 pb⁻¹
first XYZ data
2012, ψ', J/ψ

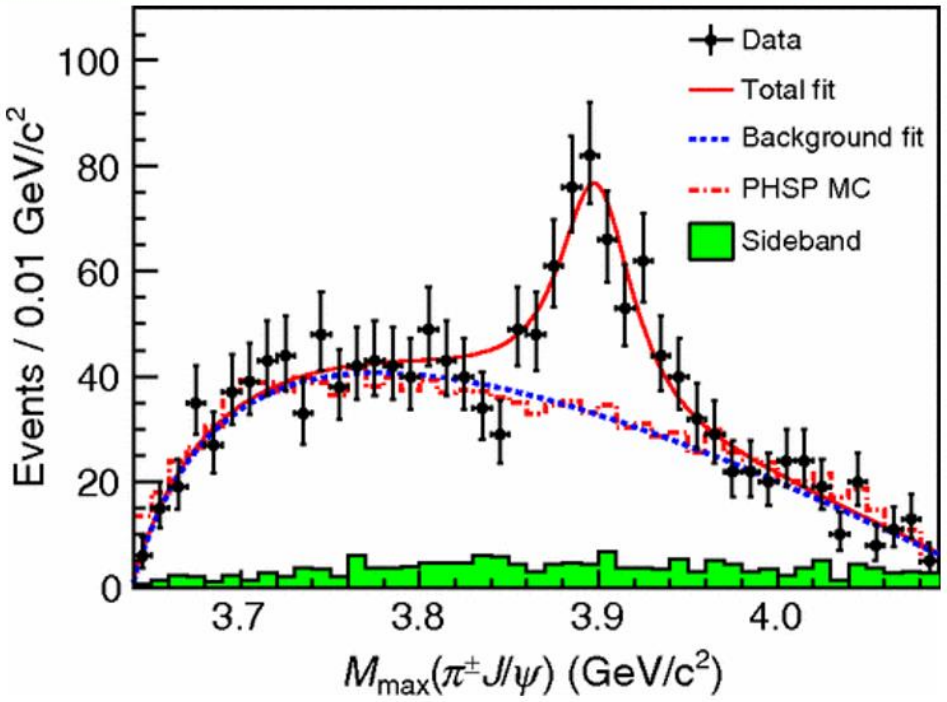

IHEP
BESIII
Kai Zhu
year 2007
first ψ' event 2008
2009 ψ', J/ψ
2010, ψ''
2011, 4.009 GeV 4.181 fb⁻¹
first XYZ data
2012, ψ', J/ψ


η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ h_c
4.26
1309
D* D̄* π
4.26
1308
D D̄* π
4.26
1310
γ X(3872)
1310
1.8 fb⁻¹
scan
XYZ
π⁰ π⁰ h_c
1409
ω χ_cJ
4.21-4.42
1410
γ χ_cJ
4.009-4.36
1411


η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ
scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
D* D* π
4.26
1308
D D* π
4.26
1310
γ X(3872)
1310
1.8 fb⁻¹
scan
XYZ
π⁰ π⁰ hc
1409
ω χc1
4.21-4.42
1410
γ χc1
4.009-4.36
1411

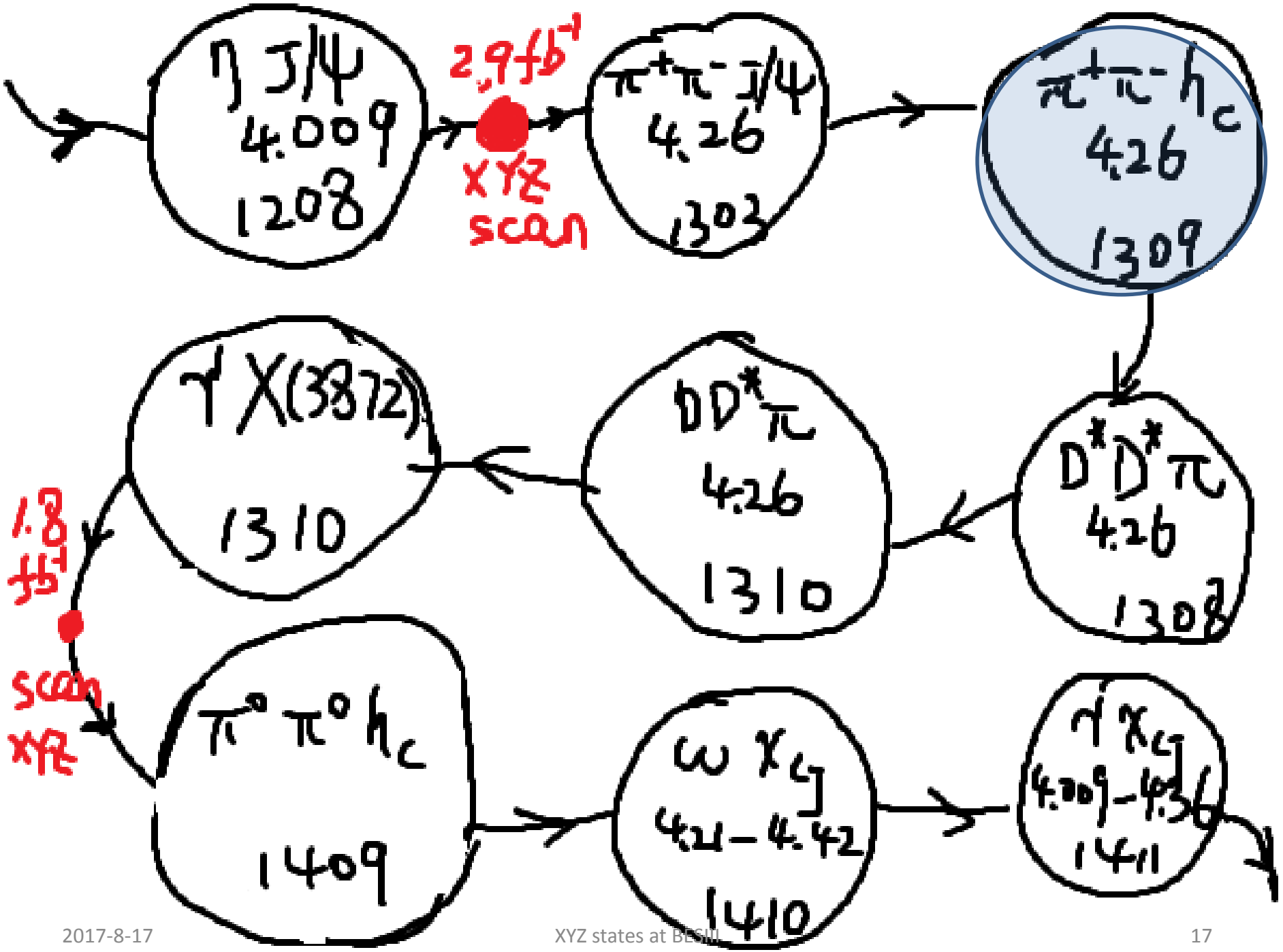

η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
D*D*π
4.26
1308
DD*π
4.26
1310
γ X(3872)
1310
1.8 fb⁻¹
scan
XYZ
π⁰π⁰ hc
1409
ω χc1
4.21-4.42
1410
γ χc1
4.009-4.36
1411

Discovery of the $Z_c(3900)$ in $\pi^+\pi^- J/\psi$
PRL 110, 252001 (2013)

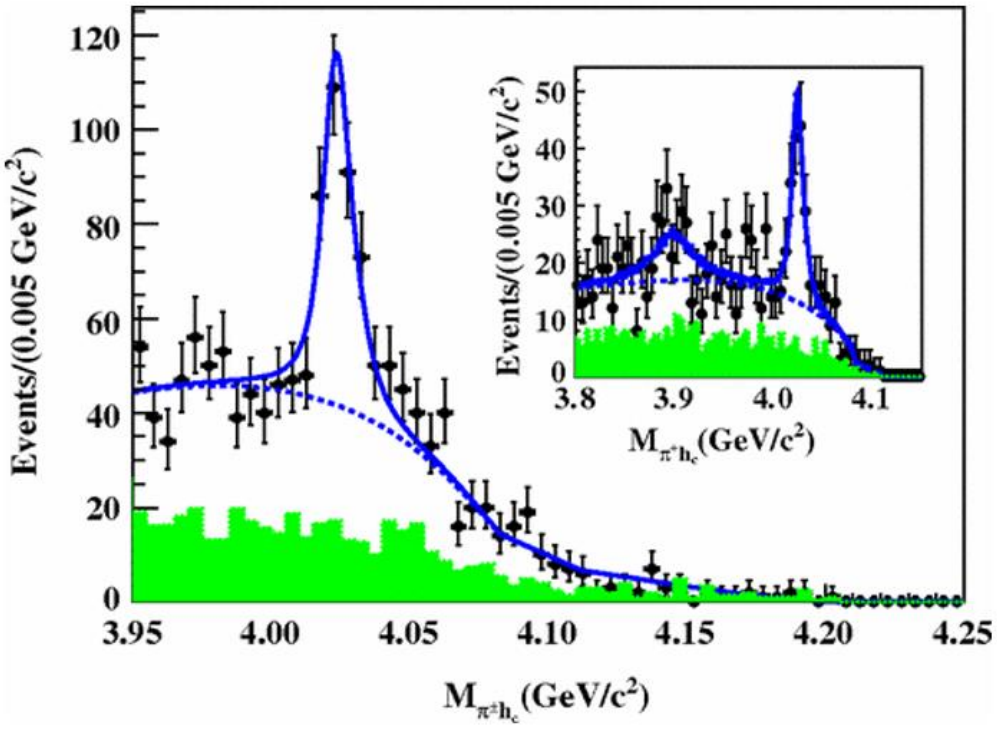


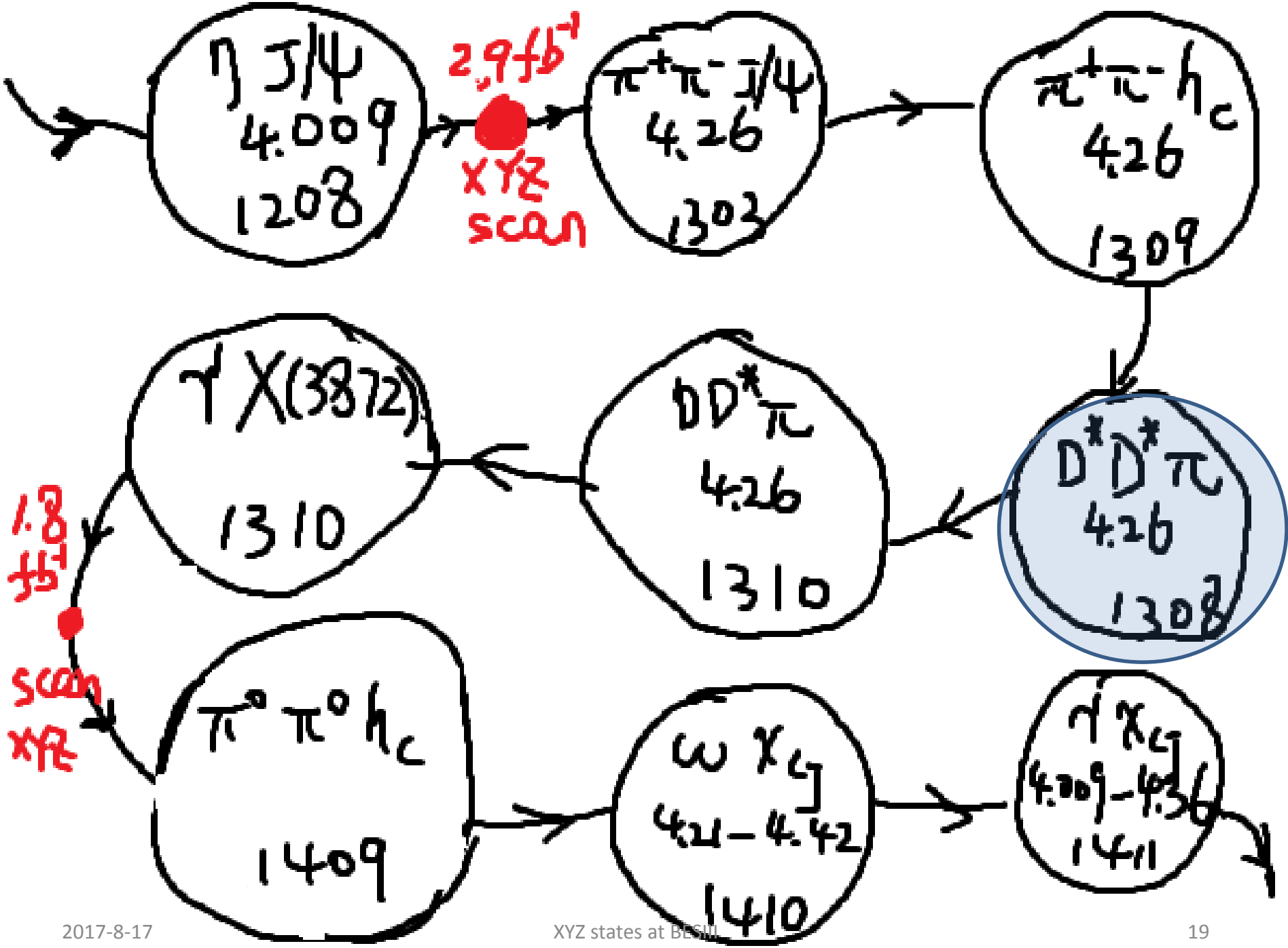
- Couples to $c\bar{c}$
- Has charge
- At least 4-quarks

- DD^* molecule?
- Tetraquark?
- Cusp?
- Threshold effect?
- Mixing ?
- …

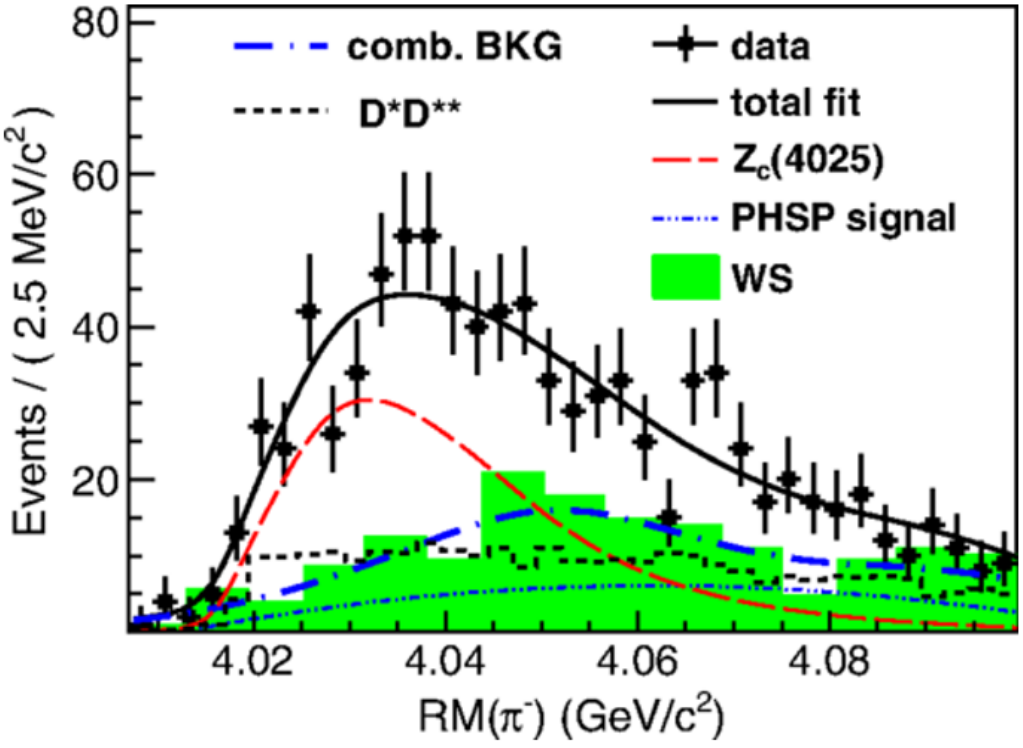

η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ
scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
γ X(3872)
1310
DD*π
4.26
1310
D*D*π
4.26
1308
1.8 fb⁻¹
scan
XYZ
π⁰π⁰ hc
1409
ω χc1
4.21-4.42
1410
γ χc1
4.009-4.36
1411

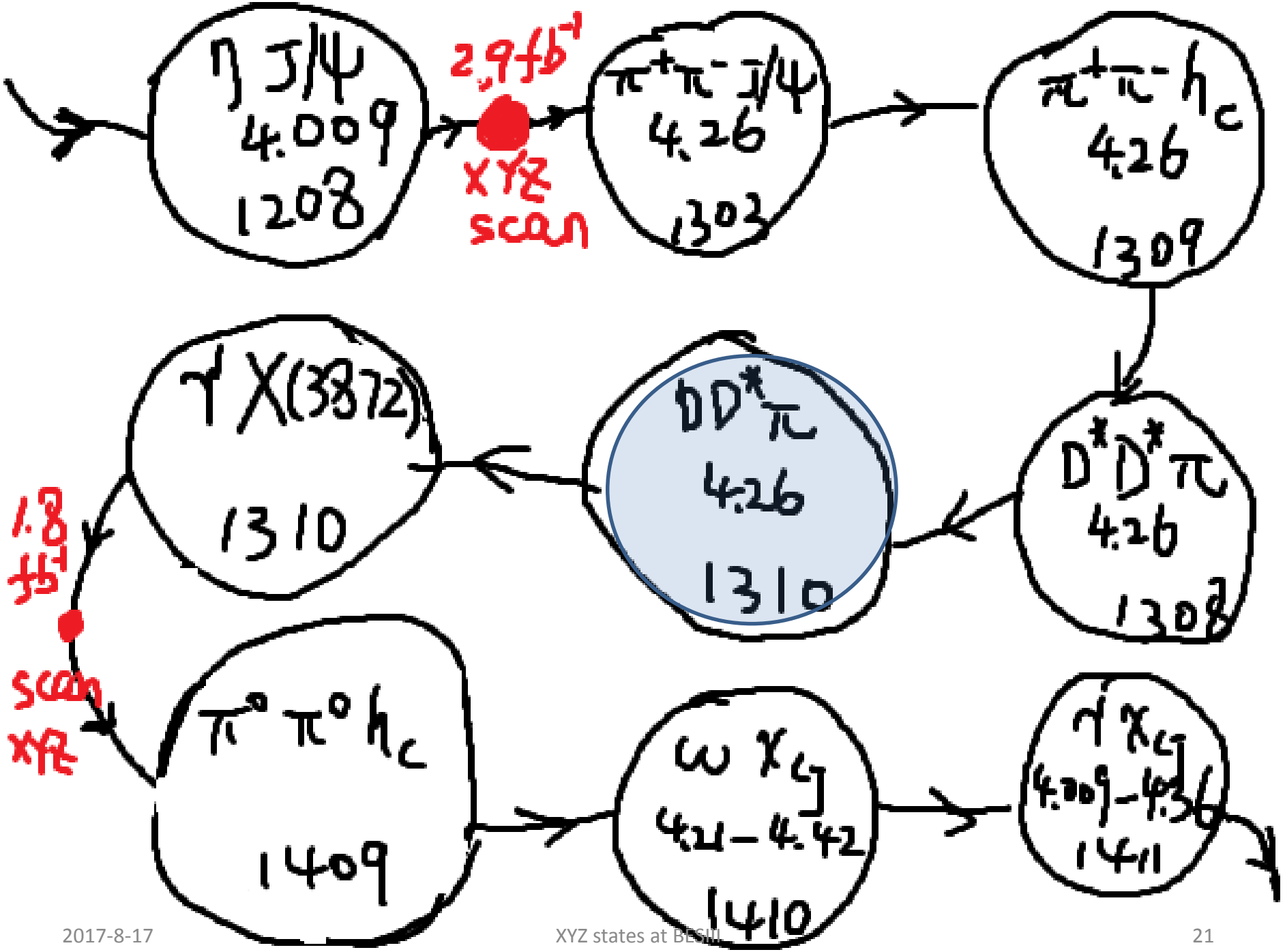
Discovery of $Z_c(4020)$ in $\pi^+\pi^- h_c$
PRL 111, 242001 (2013)



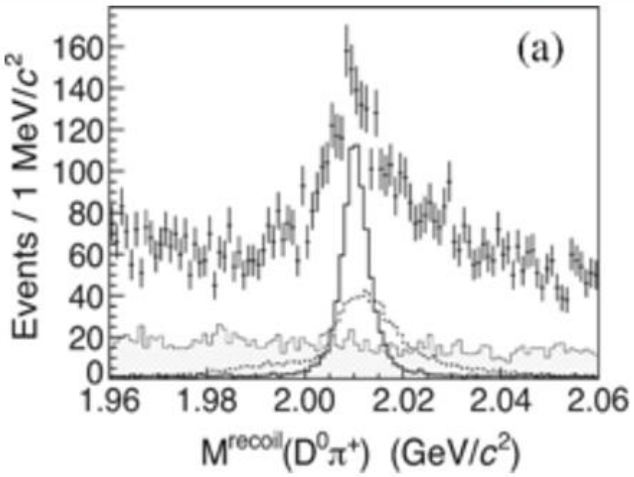

η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ
scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
γ X(3872)
1310
DD*π
4.26
1310
D*D*π
4.26
1308
1.8 fb⁻¹
scan
XYZ
π⁰π⁰ hc
1409
ω χc1
4.21-4.42
1410
γ χc1
4.009-4.36
1411

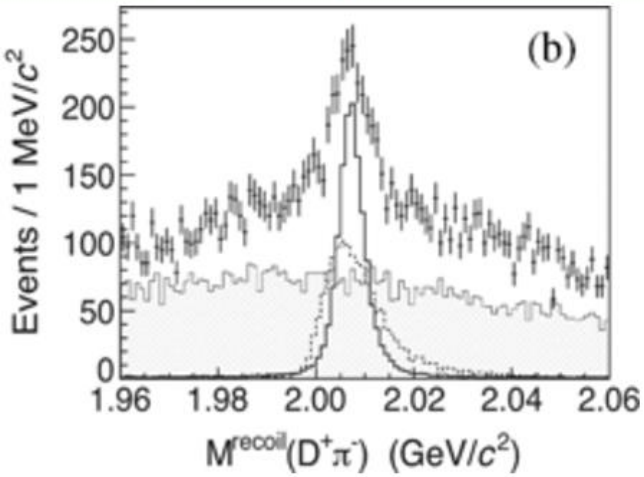
Discovery of $Z_c(4025)$ in D^*D^*
PRL 112, 132001 (2014)

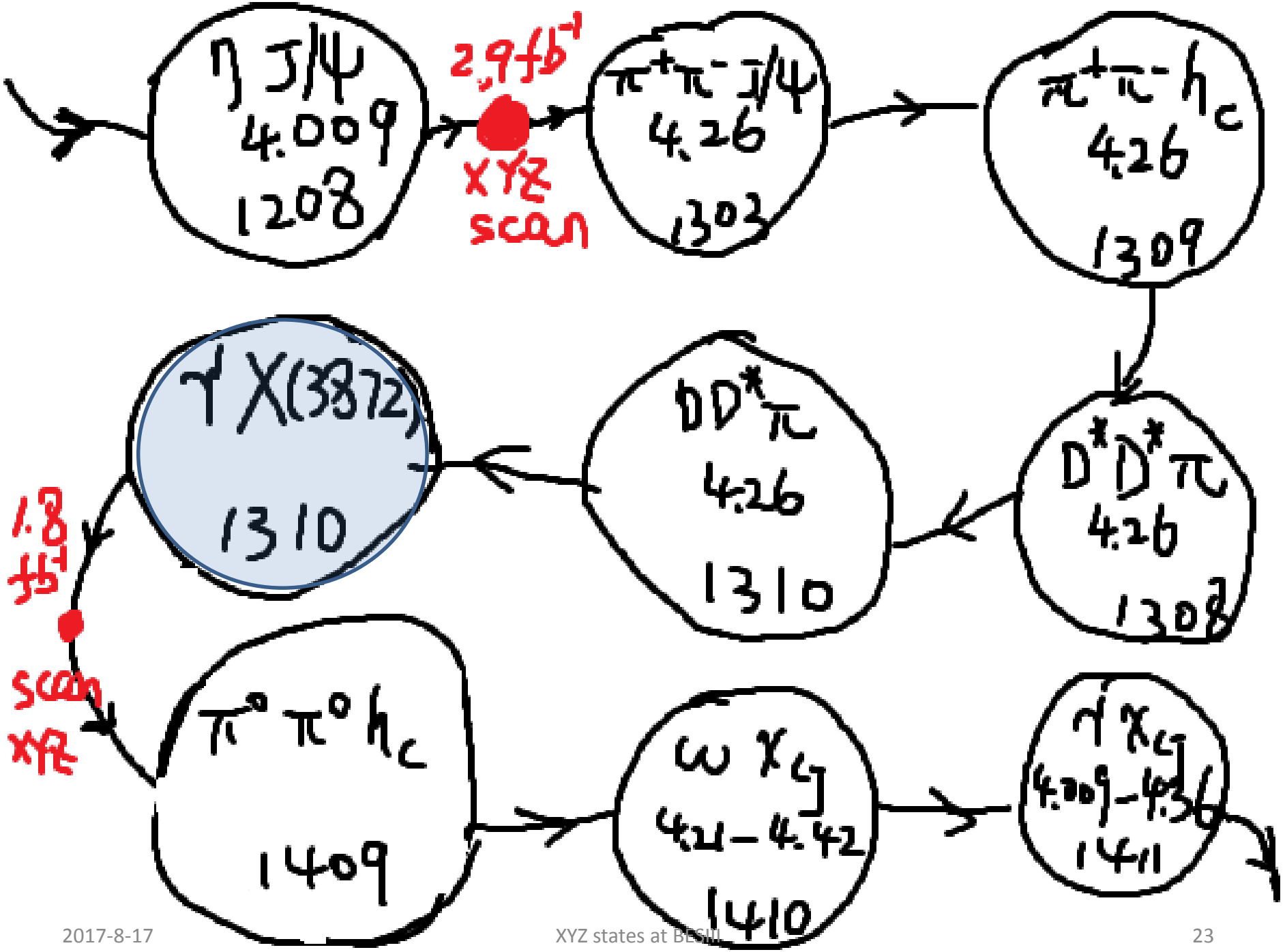



η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ
scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
γ X(3872)
1310
DD*π
4.26
1310
D*D*π
4.26
1308
1.8 fb⁻¹
scan
XYZ
π⁰π⁰ hc
1409
ω χc1
4.21-4.42
1410
γ χc1
4.009-4.36
1411

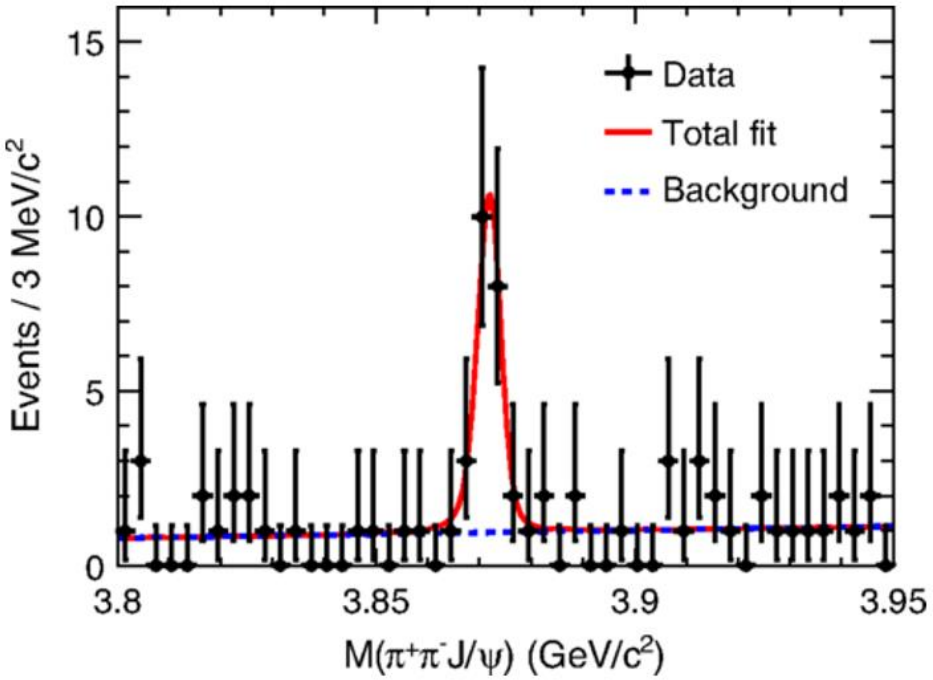
Discovery $Z_c(3885)$ in DD^* model
PRL 112, 022001 (2014)

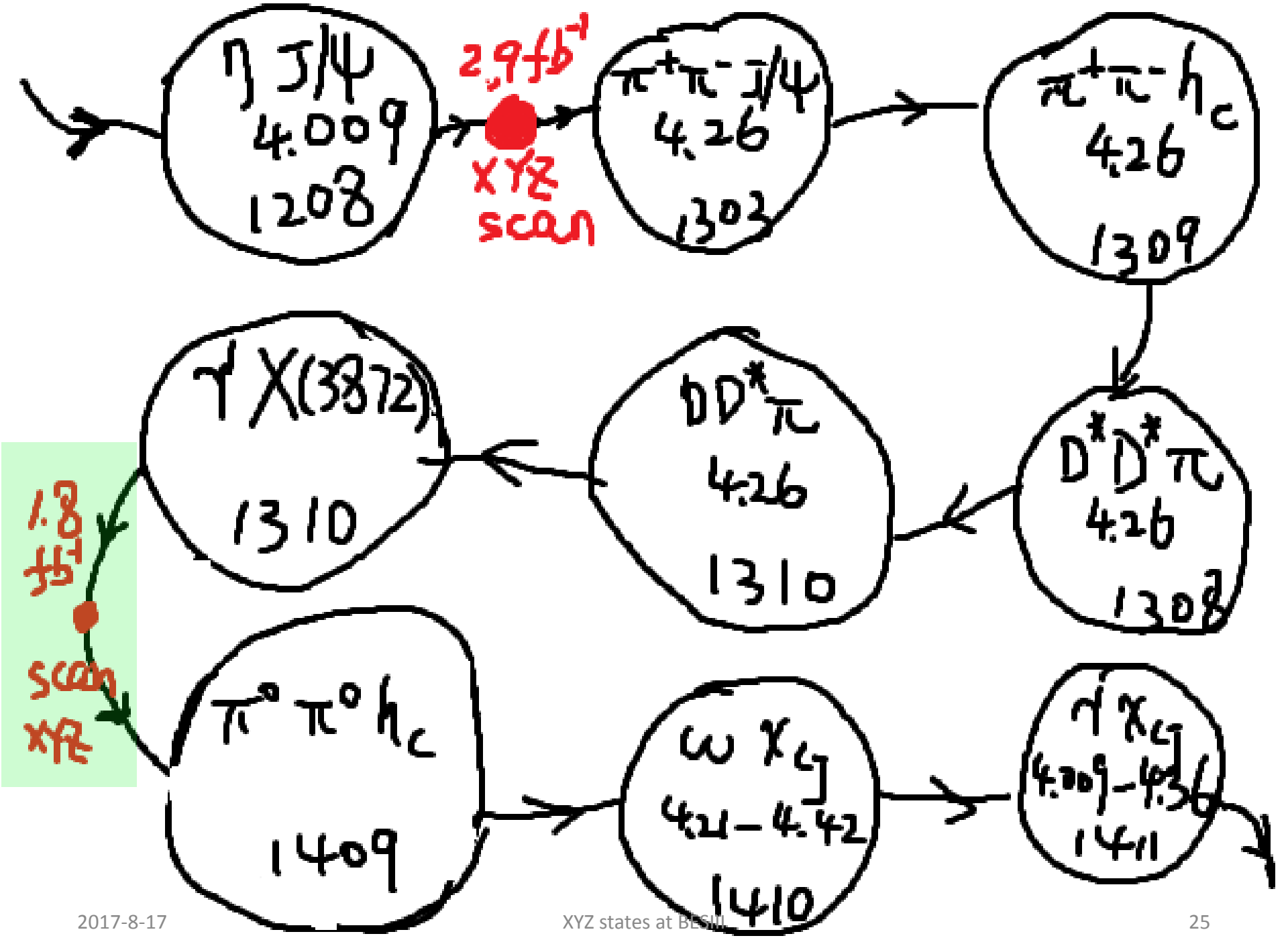


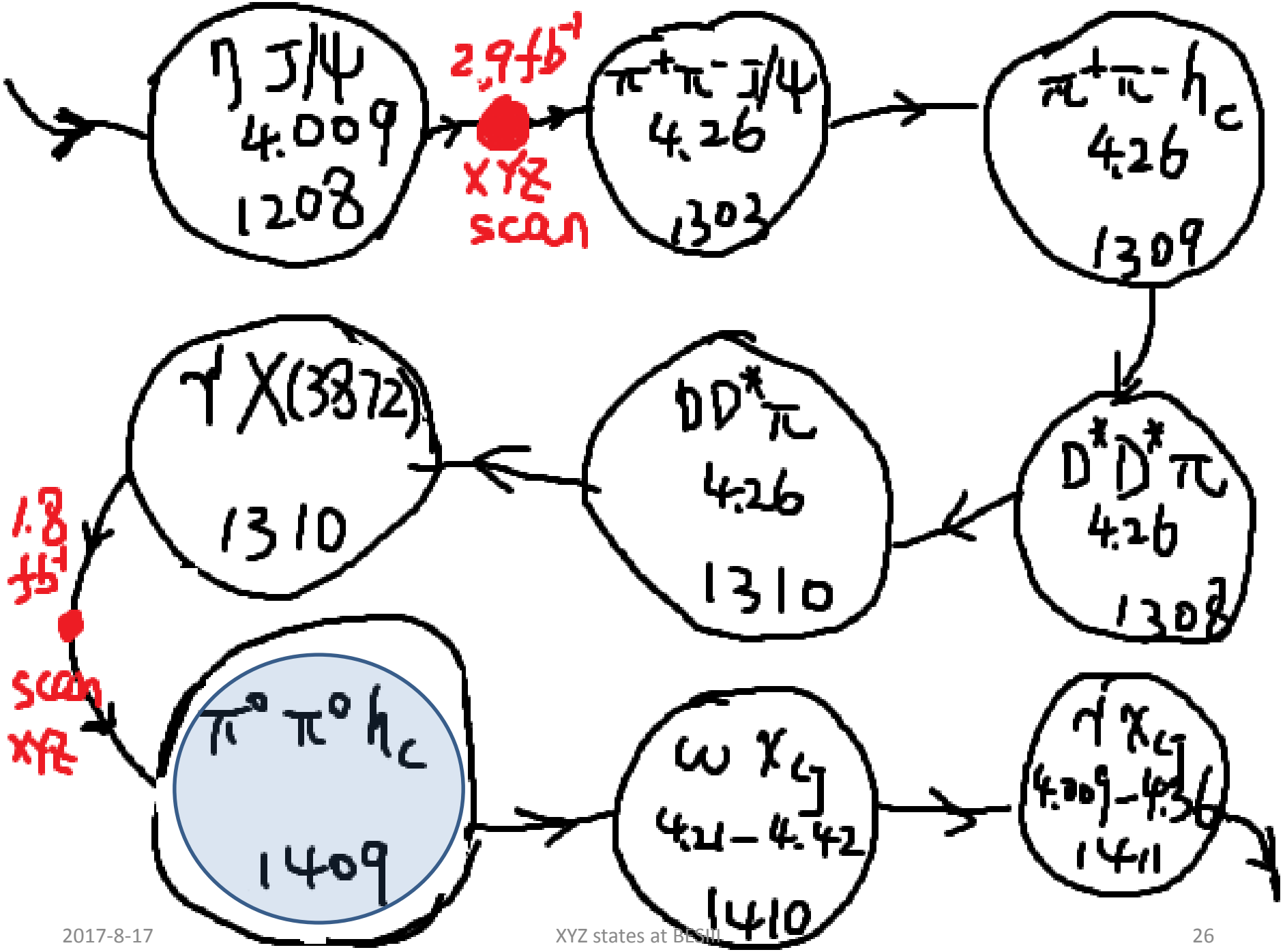



η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ
scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
γ X(3872)
1310
DD*π
4.26
1310
D*D*π
4.26
1308
1.8 fb⁻¹
scan
XYZ
π⁰π⁰ hc
1409
ω χc1
4.21-4.42
1410
γ χc1
4.009-4.36
1411

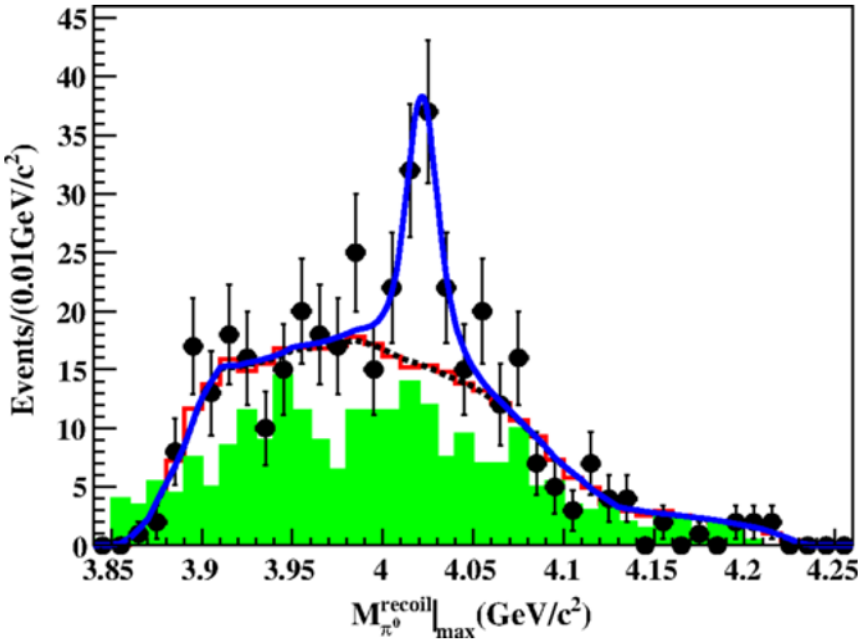
Observation of $e^+e^- \to \gamma X(3872)$
PRL 112, 092001 (2014)

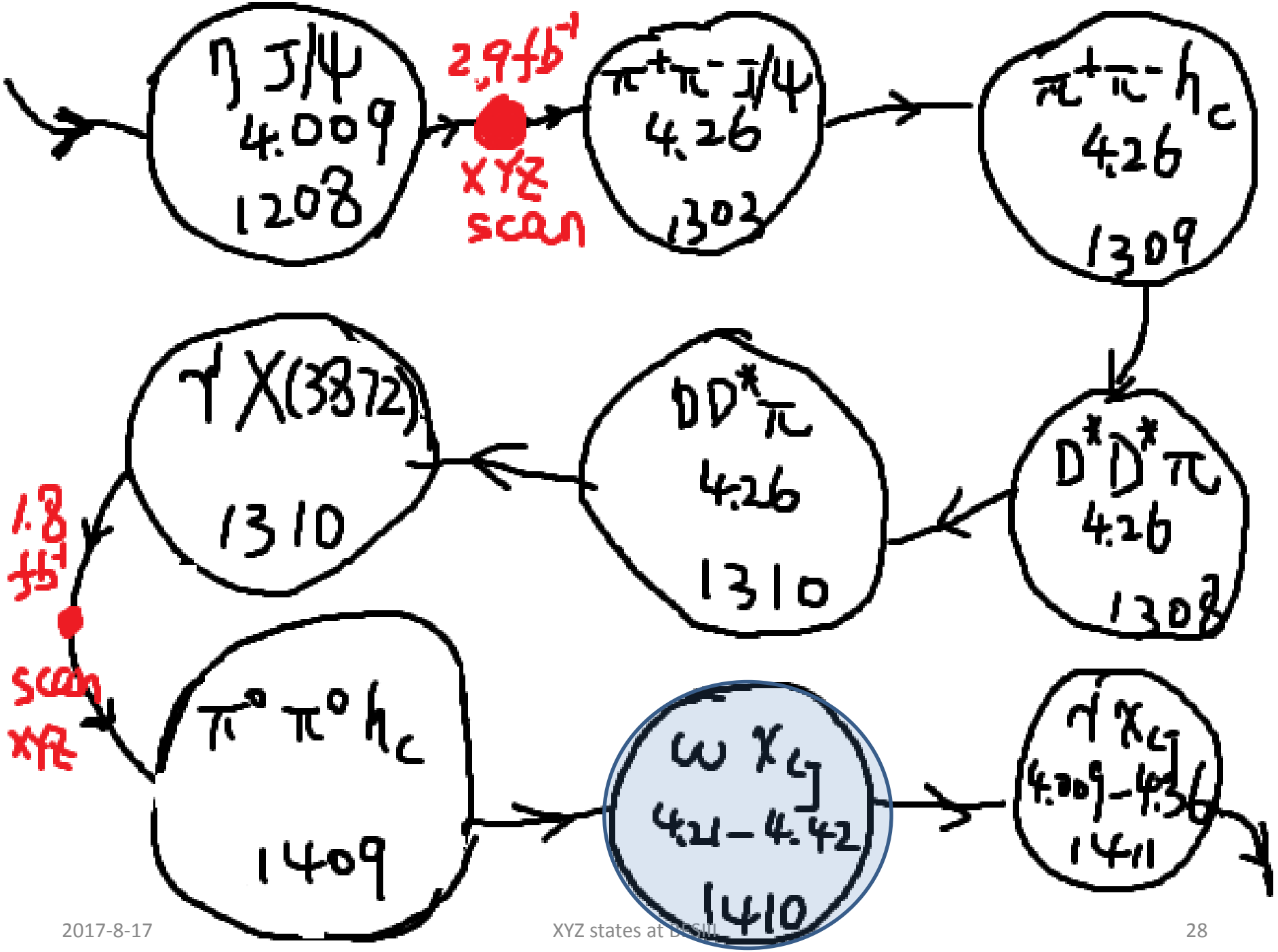



η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ
scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
D*D*π
4.26
1308
DD*π
4.26
1310
γ X(3872)
1310
1.8 fb⁻¹
scan
XYZ
π⁰π⁰ hc
1409
ω χc1
4.21-4.42
1410
η χc1
4.009-4.36
1411

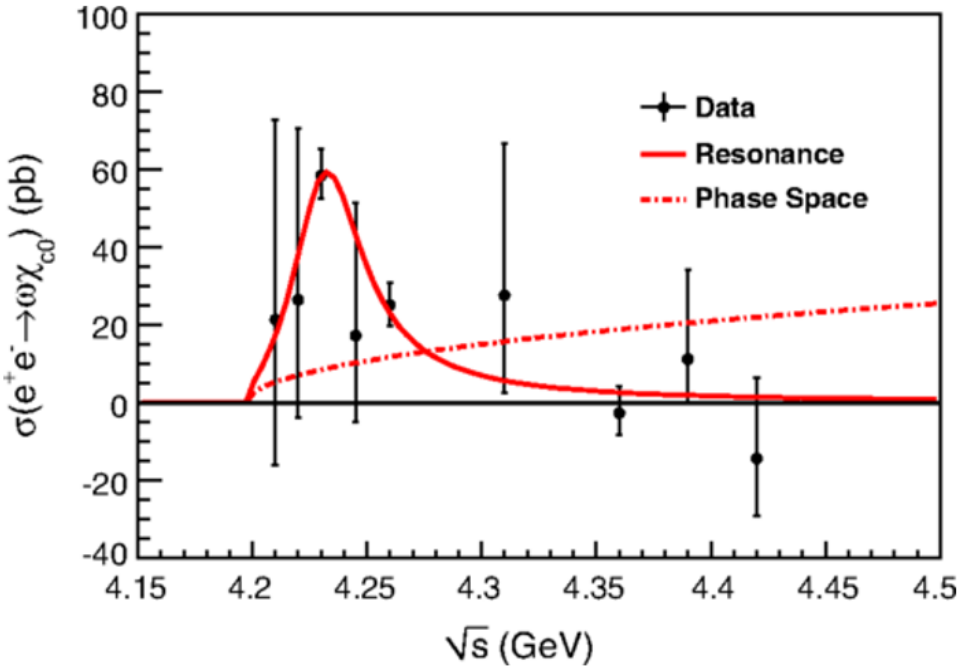

η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ
scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
D* D* π
4.26
1308
DD* π
4.26
1310
γ X(3872)
1310
1.8 fb⁻¹
scan
XYZ
π⁰ π⁰ hc
1409
ω χc1
4.21-4.42
1410
γ χc1
4.009-4.36
1411

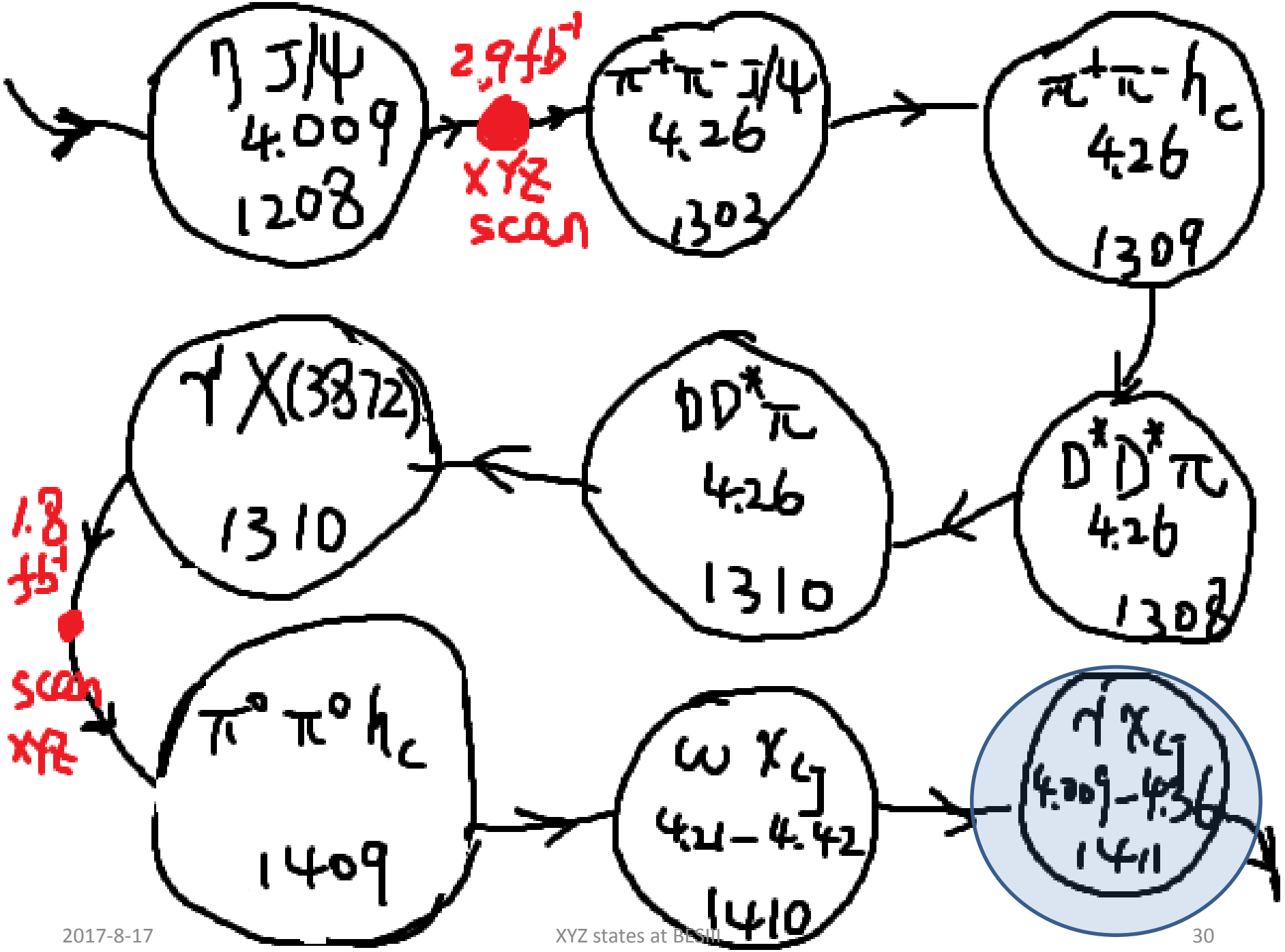
Neutral $Z_c^0(4020)$ in $\pi^0\pi^0 h_c$
PRL 113, 212002 (2014)



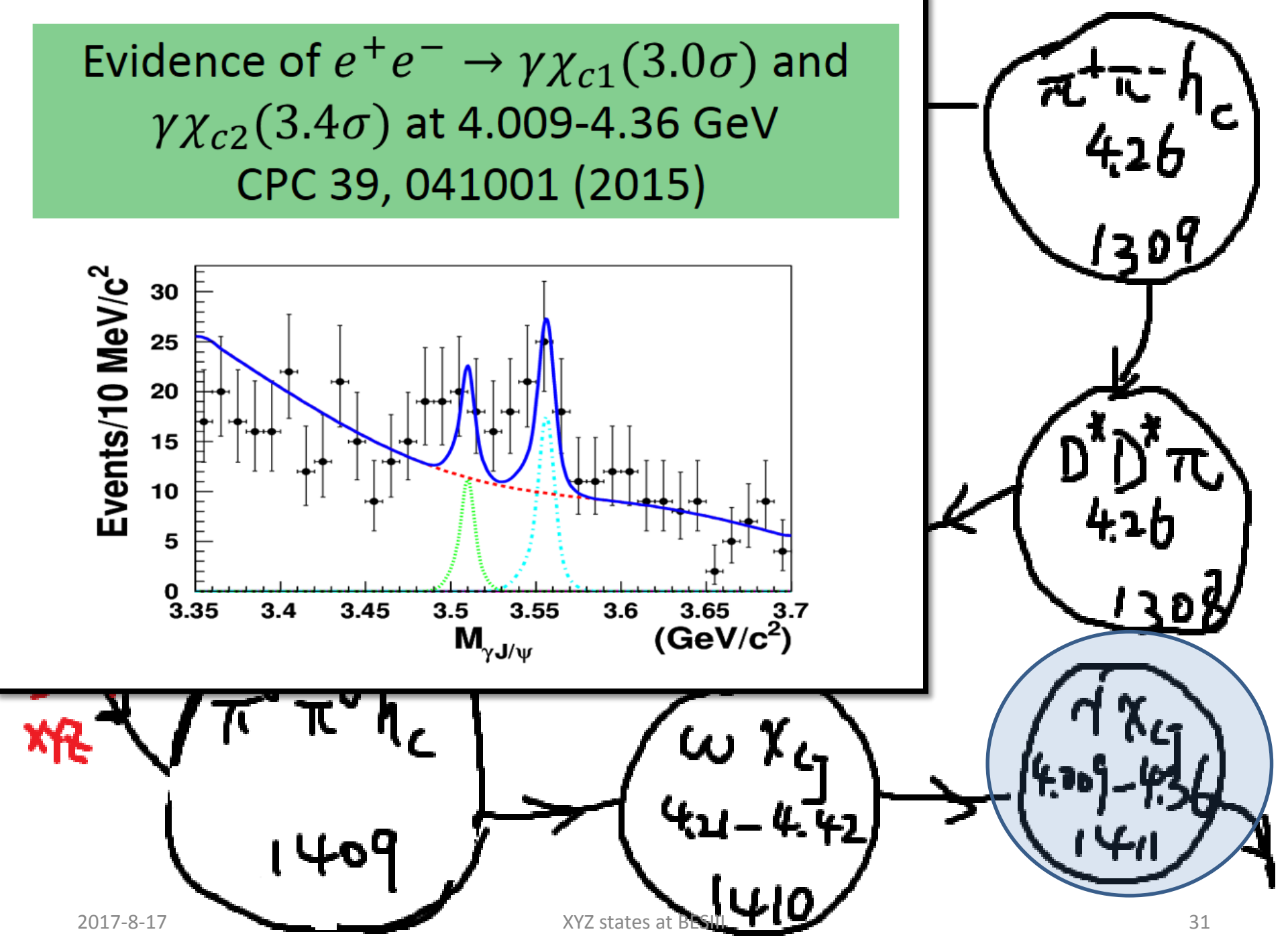

η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ
scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
γ X(3872)
1310
DD*π
4.26
1310
D*D*π
4.26
1308
1.8 fb⁻¹
scan
XYZ
π⁰π⁰ hc
1409
ω χc1
4.21-4.42
1410
γ χc1
4.009-4.36
1411

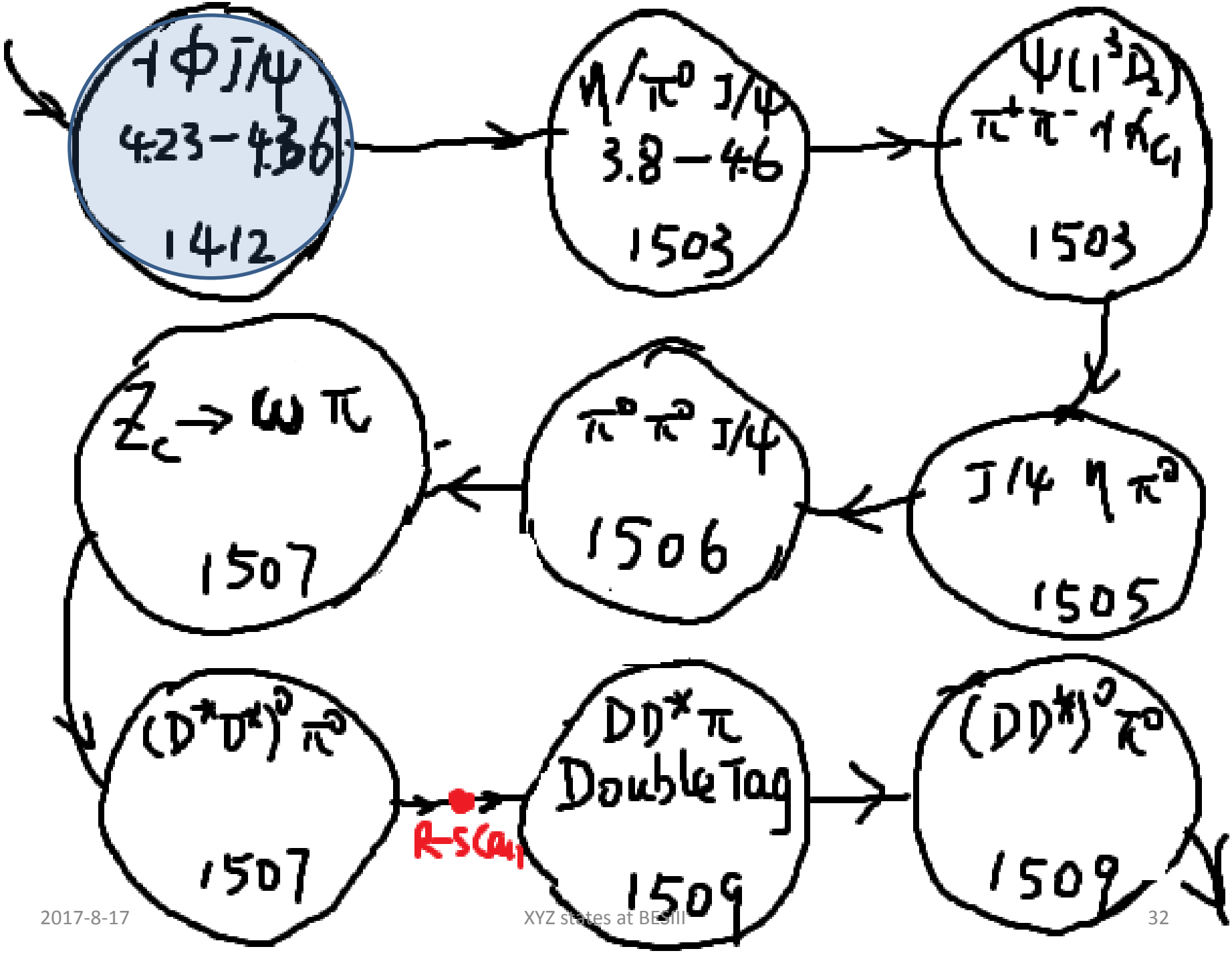
Discovery of a peak in $e^+e^- \to \omega\chi_{c0}$
PRL 114, 092003 (2015)




η J/ψ
4.009
1208
2.9 fb⁻¹
XYZ
scan
π⁺π⁻ J/ψ
4.26
1303
π⁺π⁻ hc
4.26
1309
D*D*π
4.26
1308
DD*π
4.26
1310
γ X(3872)
1310
1.8 fb⁻¹
scan
XYZ
π⁰π⁰ hc
1409
ω χc1
4.21-4.42
1410
γ χc1
4.009-4.36
1411

Evidence of $e^+e^- \to \gamma\chi_{c1}(3.0\sigma)$ and $\gamma\chi_{c2}(3.4\sigma)$ at 4.009-4.36 GeV
CPC 39, 041001 (2015)




γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γK_S
1503
J/ψ η π⁰
1505
π⁰π⁰ J/ψ
1506
Z_c → ωπ
1507
(D*D*)⁰π⁰
1507
DD*π
DoubleTag
1509
(DD*)⁰π⁰
1509
R-Scan

$\gamma\phi J/\psi$
4.23-4.36
1412

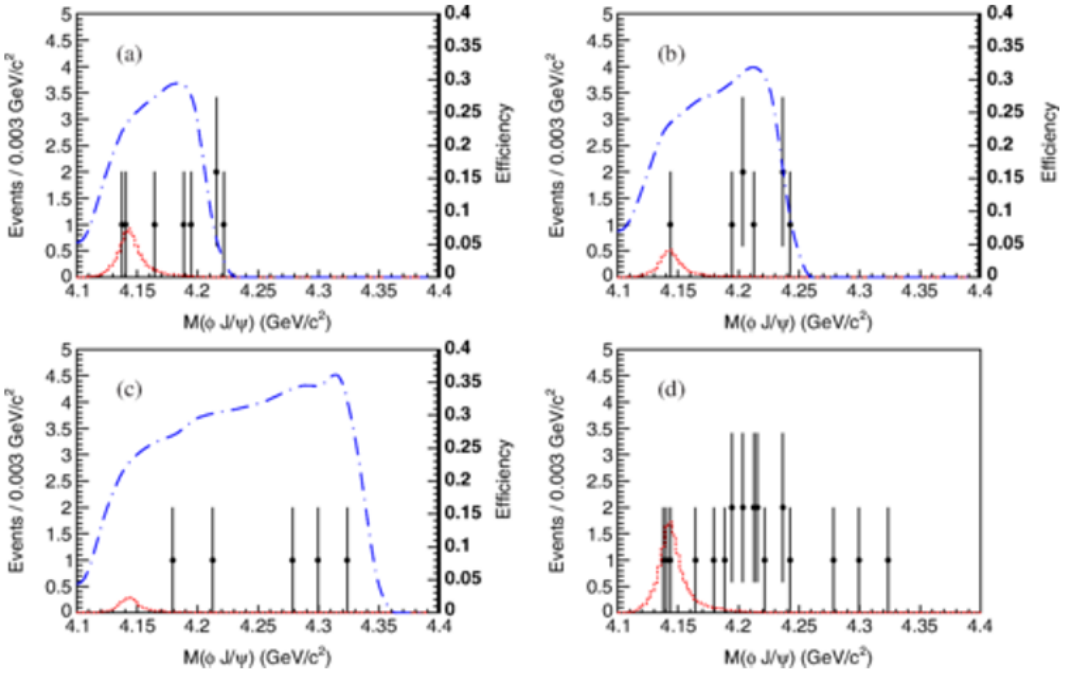
$\eta/\pi^0\, J/\psi$
3.8-4.6
1503

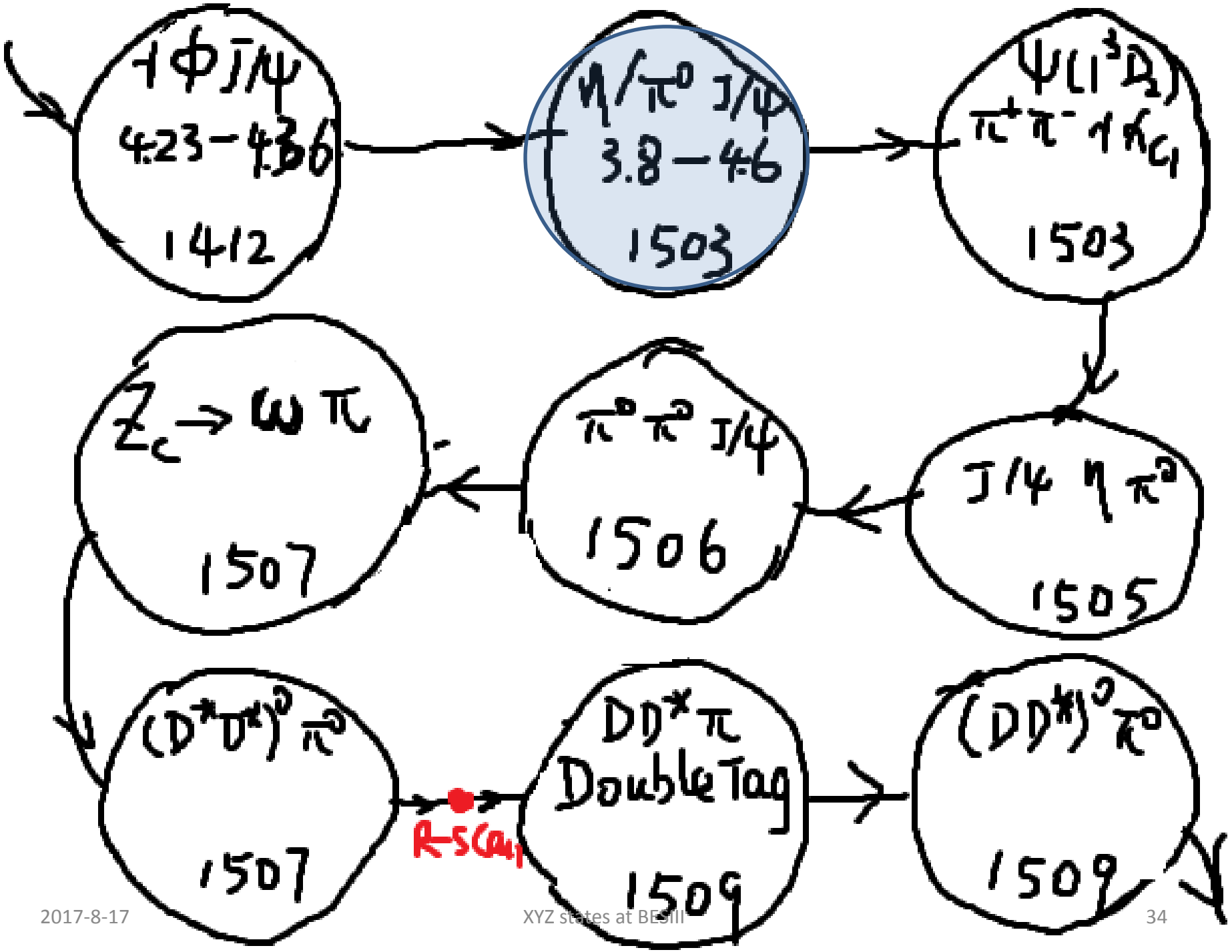
$\psi(1^3D_2)$
$\pi^+\pi^-\gamma K_S$
1503

$Z_c \to \omega$
1507

$(D^*D^*)^0\pi$
1507

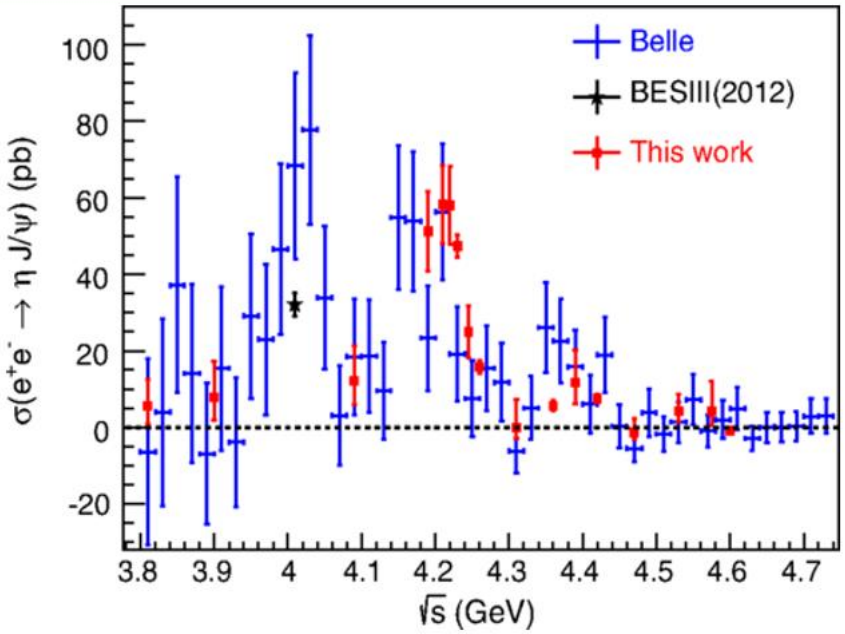
No significant signal of Y(4140) is observed via $\gamma\phi J/\psi$ at 4.23-4.36 GeV
PRD 91, 032002 (2015)

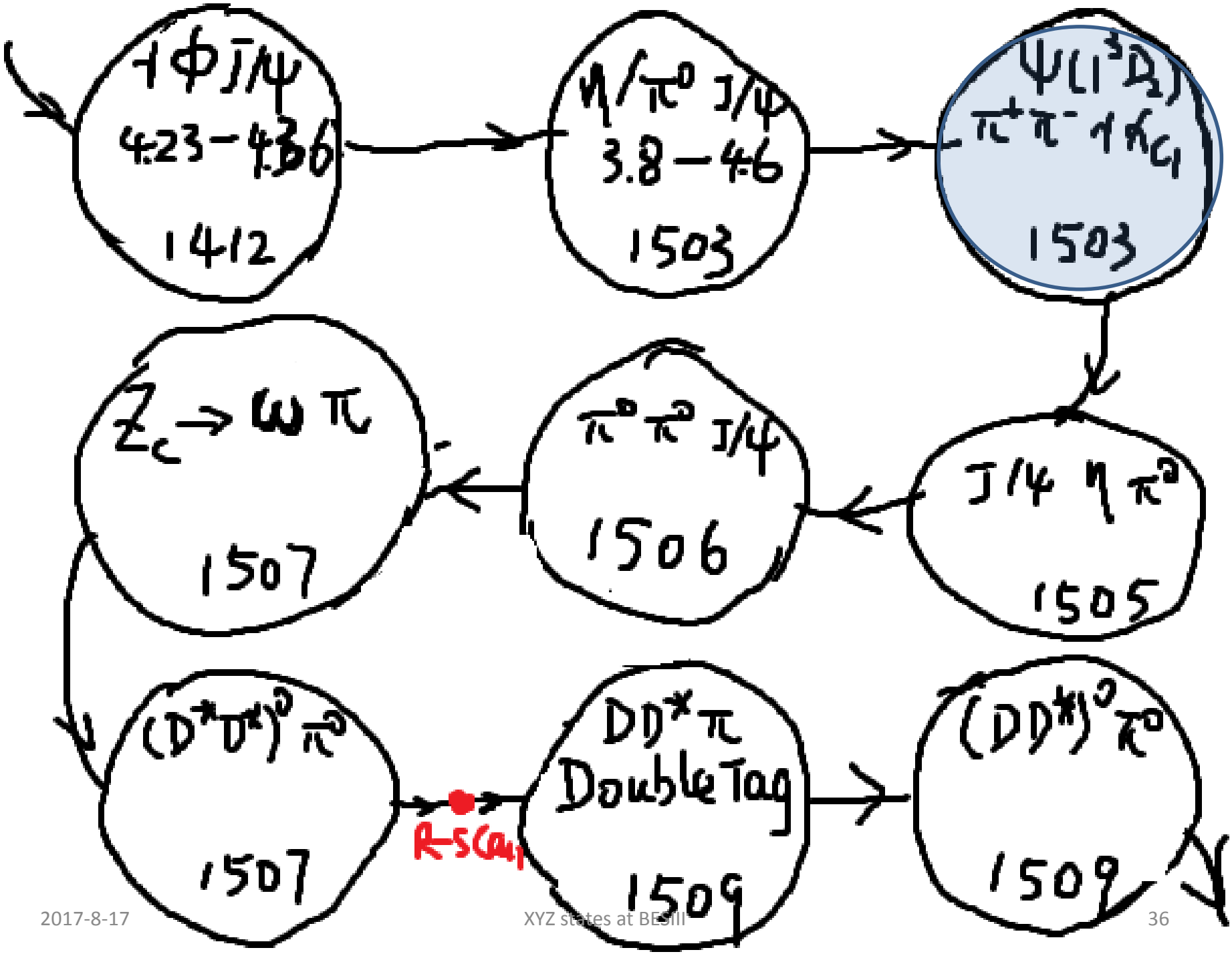


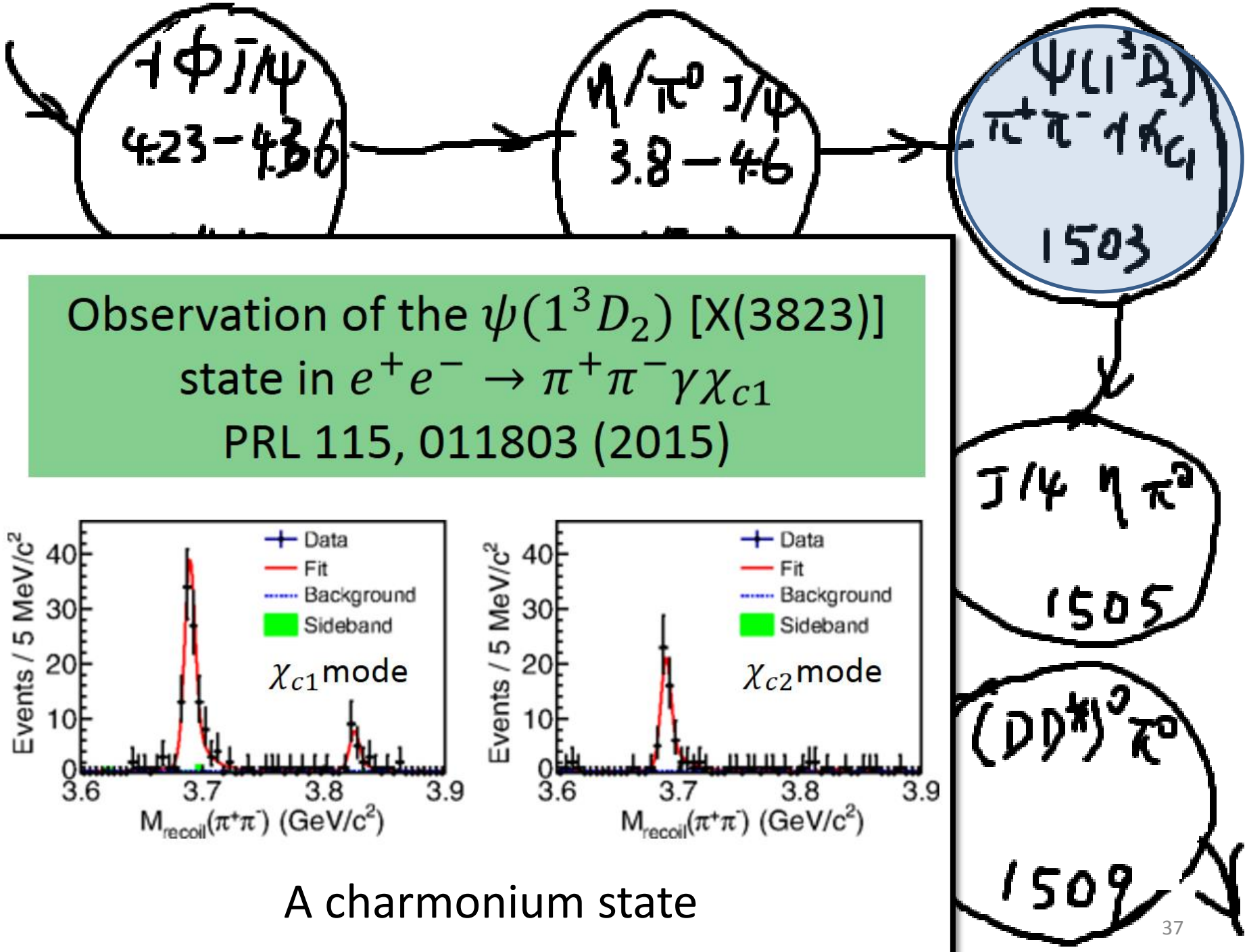

γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γK_L
1503
Z_c → ωπ
1507
π⁰π⁰ J/ψ
1506
J/ψ η π⁰
1505
(D*D*)⁰π⁰
1507
DD*π
DoubleTag
1509
(DD*)⁰π⁰
1509
R-Scan

Enhancement is observed near 4.2 GeV in the line-shape of $e^+e^- \to \eta J/\psi$

PRD 91, 112005 (2015)

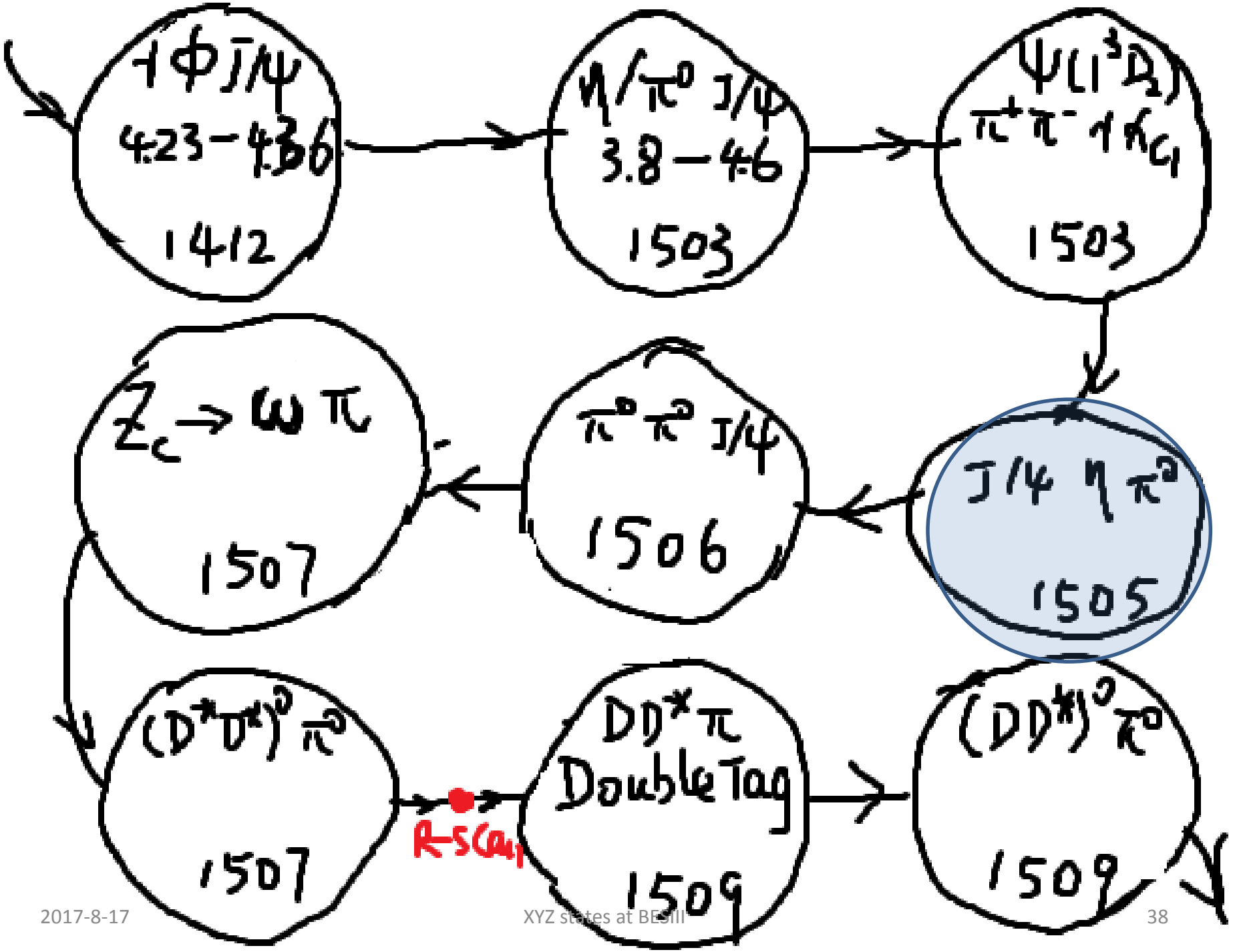



γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γK_S
1503
Z_c → ωπ
1507
π⁰π⁰ J/ψ
1506
J/ψ η π⁰
1505
(D*D*)⁰π⁰
1507
DD*π
Double Tag
1509
(DD*)⁰π⁰
1509
R-S(a)

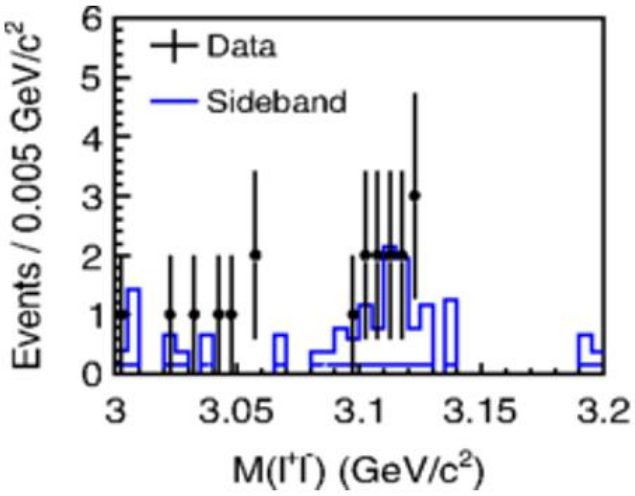


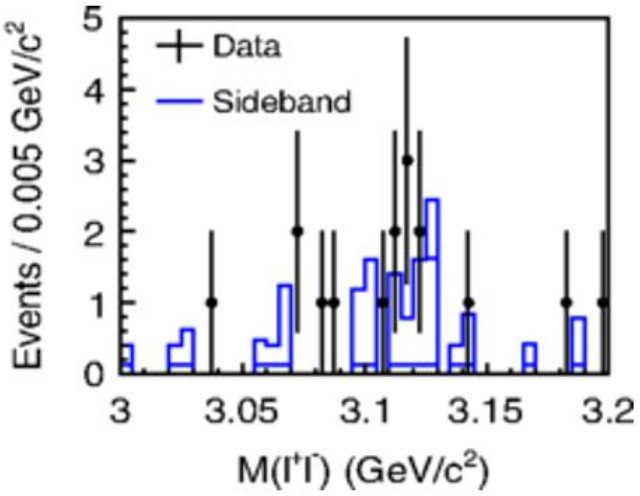
Observation of the $\psi(1^3D_2)$ [X(3823)] state in $e^+e^- \to \pi^+\pi^-\gamma\chi_{c1}$
PRL 115, 011803 (2015)

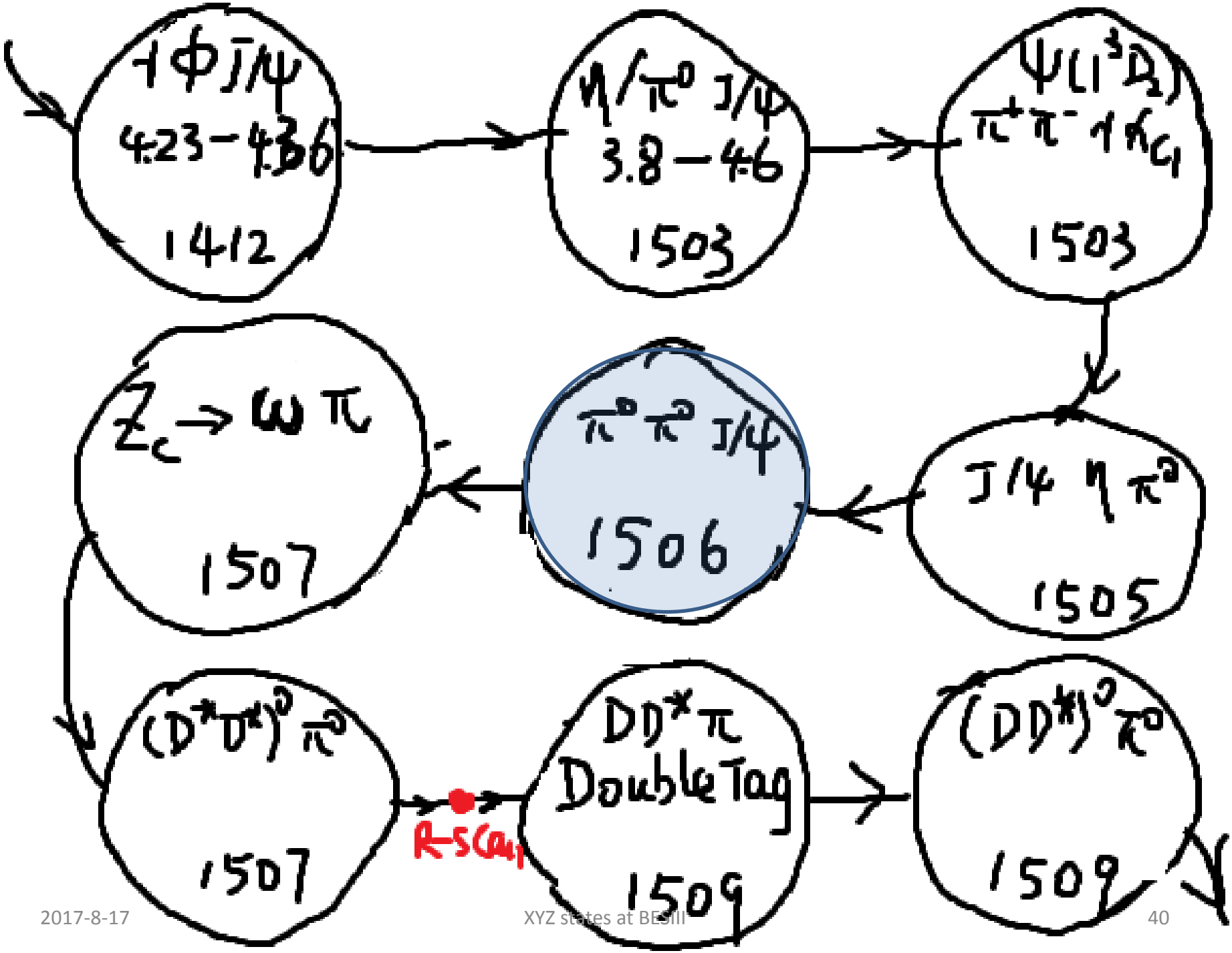
A charmonium state


γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γK_L
1503
Z_c → ωπ
1507
π⁰π⁰ J/ψ
1506
J/ψ η π⁰
1505
(D*D*)⁰π⁰
1507
DD*π
DoubleTag
1509
(DD*)⁰π⁰
1509
R-Scan

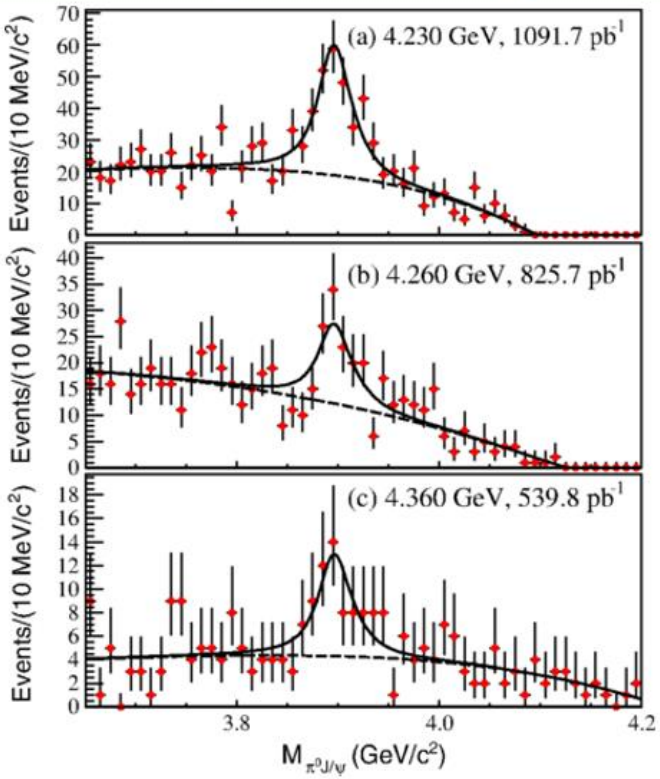
No significant signal of
$Y(4260) \to \eta\pi^0 J/\psi$ is observed
PRD 92, 012008 (2015)

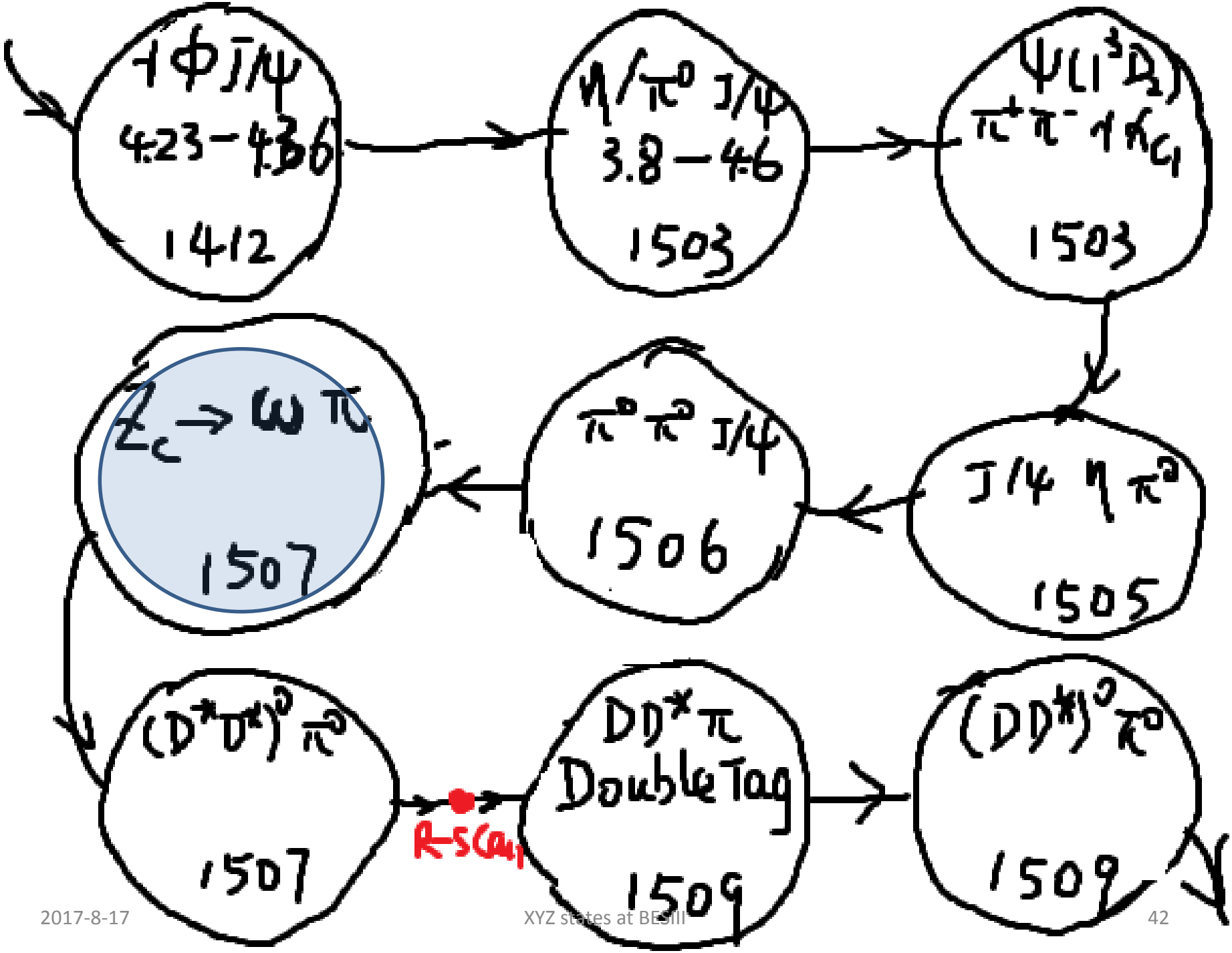




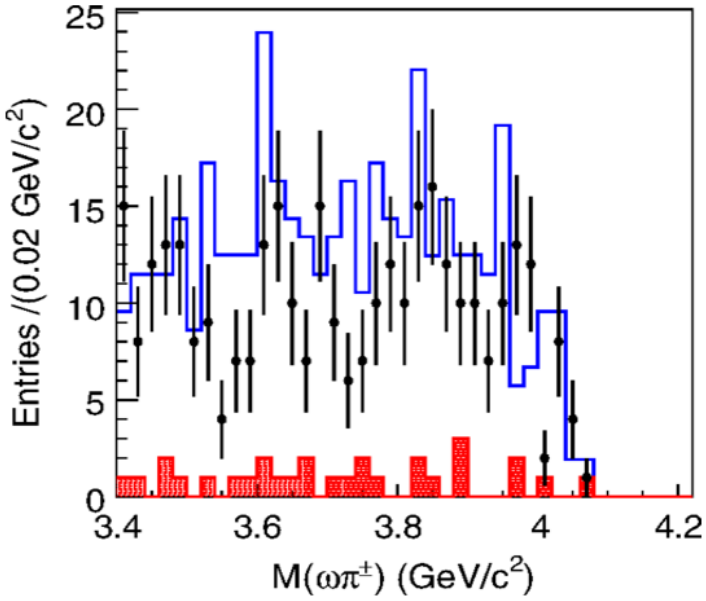

γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γK_S
1503
Z_c → ωπ
1507
π⁰π⁰ J/ψ
1506
J/ψ η π⁰
1505
(D*D*)⁰π⁰
1507
DD*π
Double Tag
1509
(DD*)⁰π⁰
1509
R-S(a)

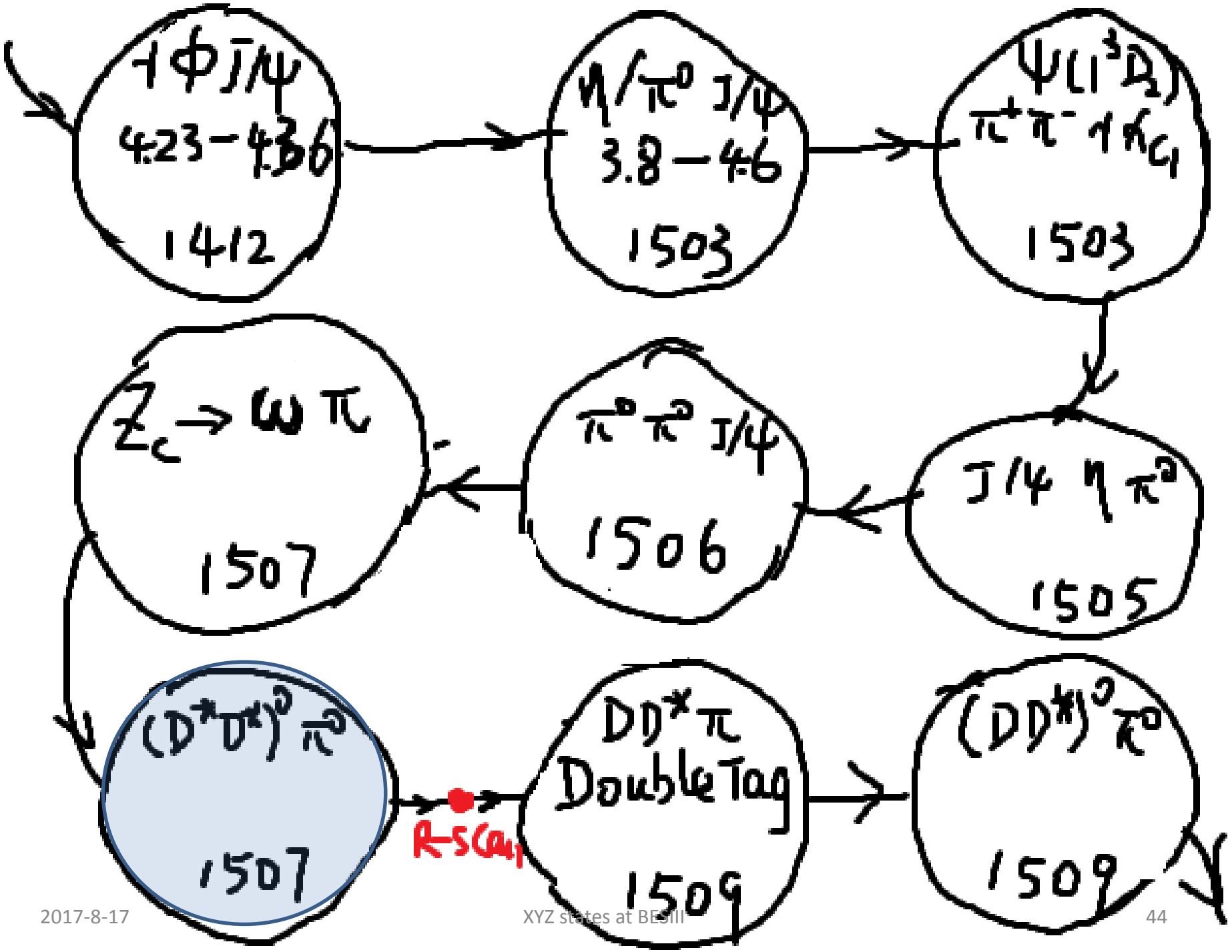
Neutral $Z_c(3900)$ in $\pi^0\pi^0 J/\psi$
PRL 115, 112003 (2015)



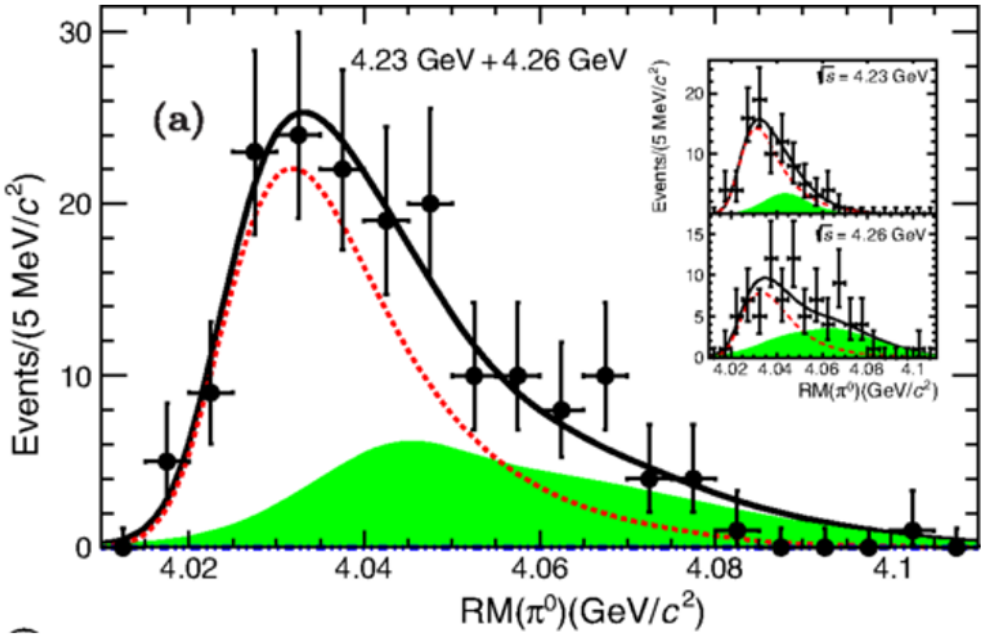

γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γK_L
1503
Z_c → ωπ
1507
π⁰π⁰ J/ψ
1506
J/ψ η π⁰
1505
(D*D*)⁰π⁰
1507
DD*π
Double Tag
1509
(DD*)⁰π⁰
1509
R-Scan

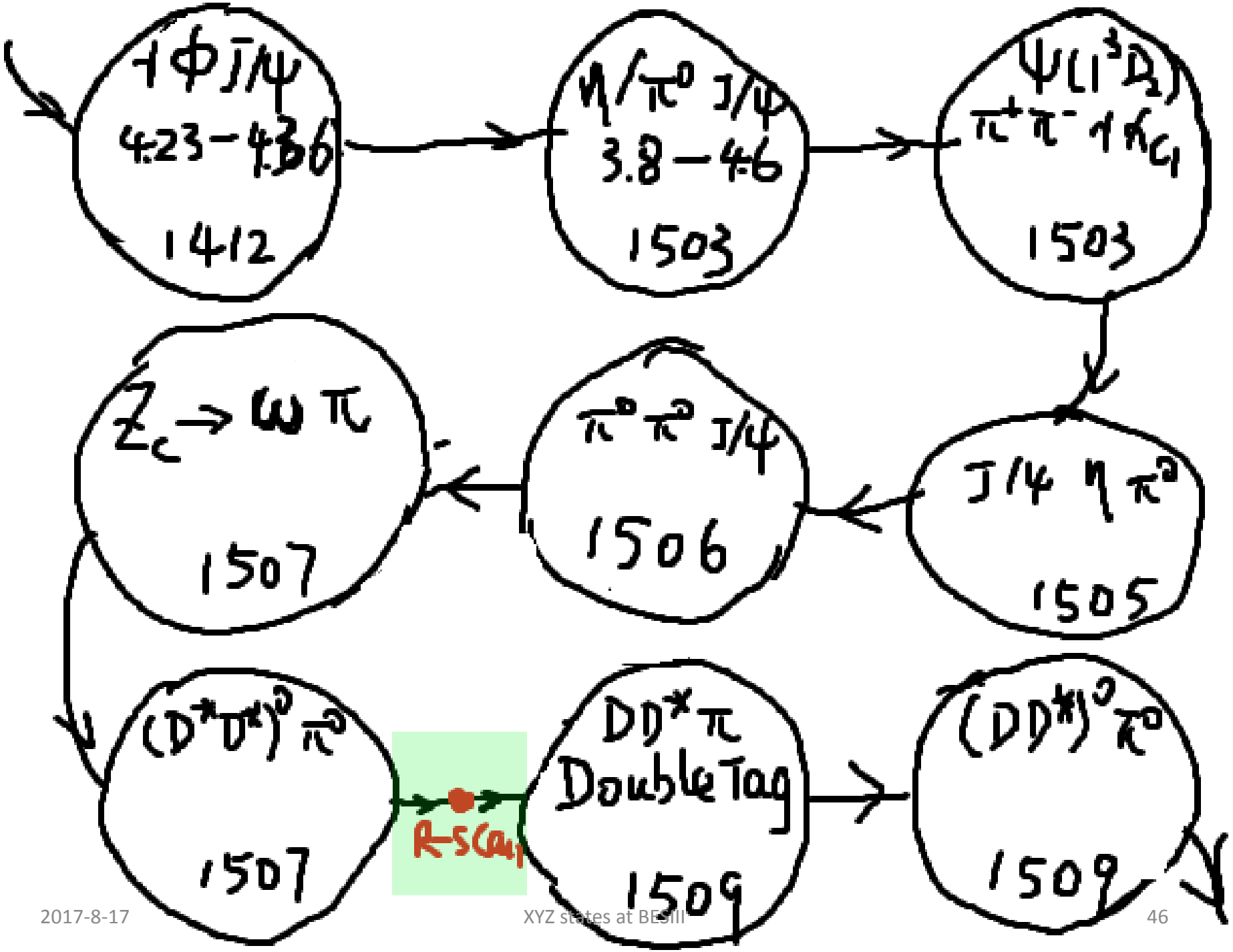
No significant signal of
$Z_c(3900)^{\pm} \to \omega\pi^{\pm}$ is observed
PRD 92, 032009 (2015)

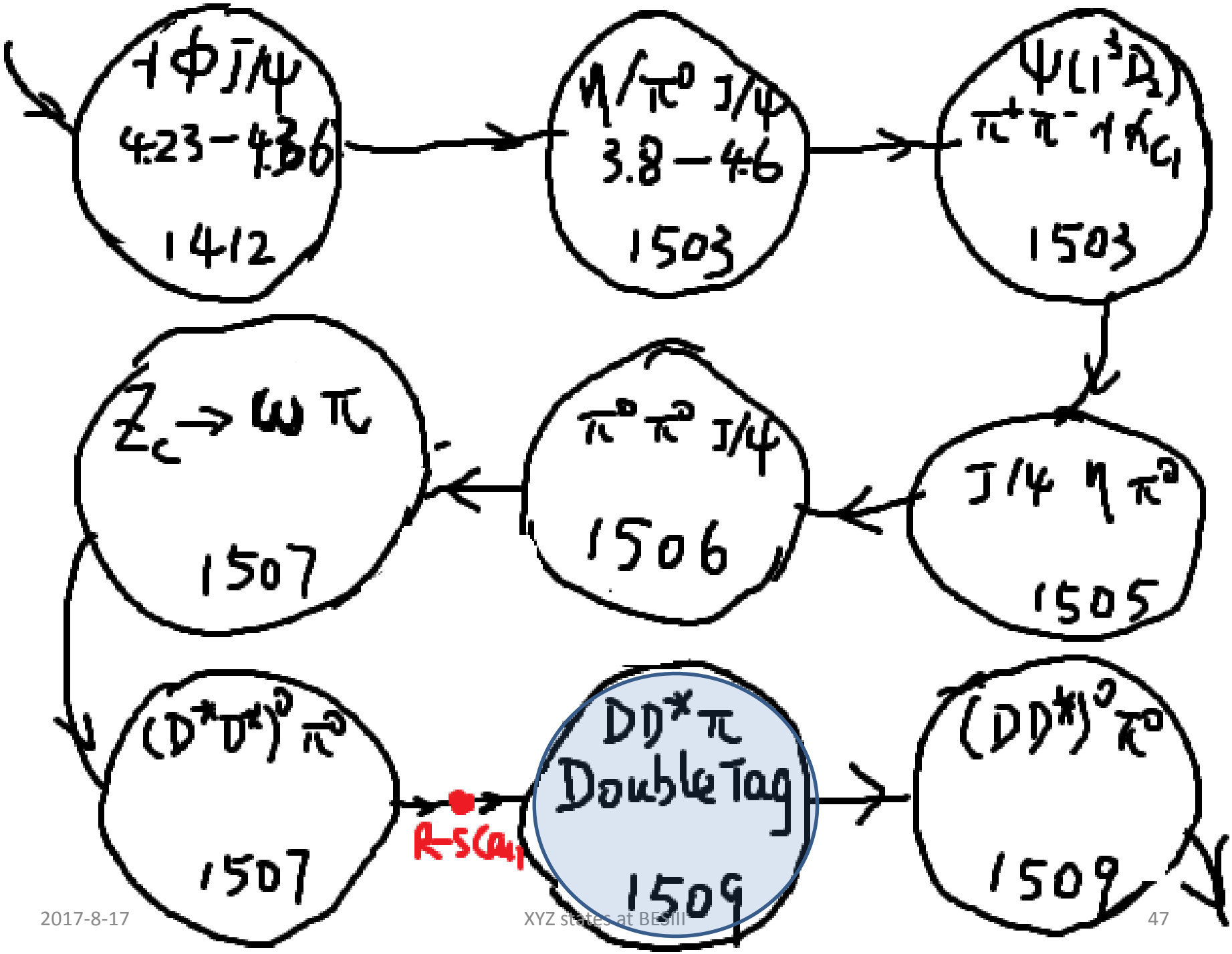


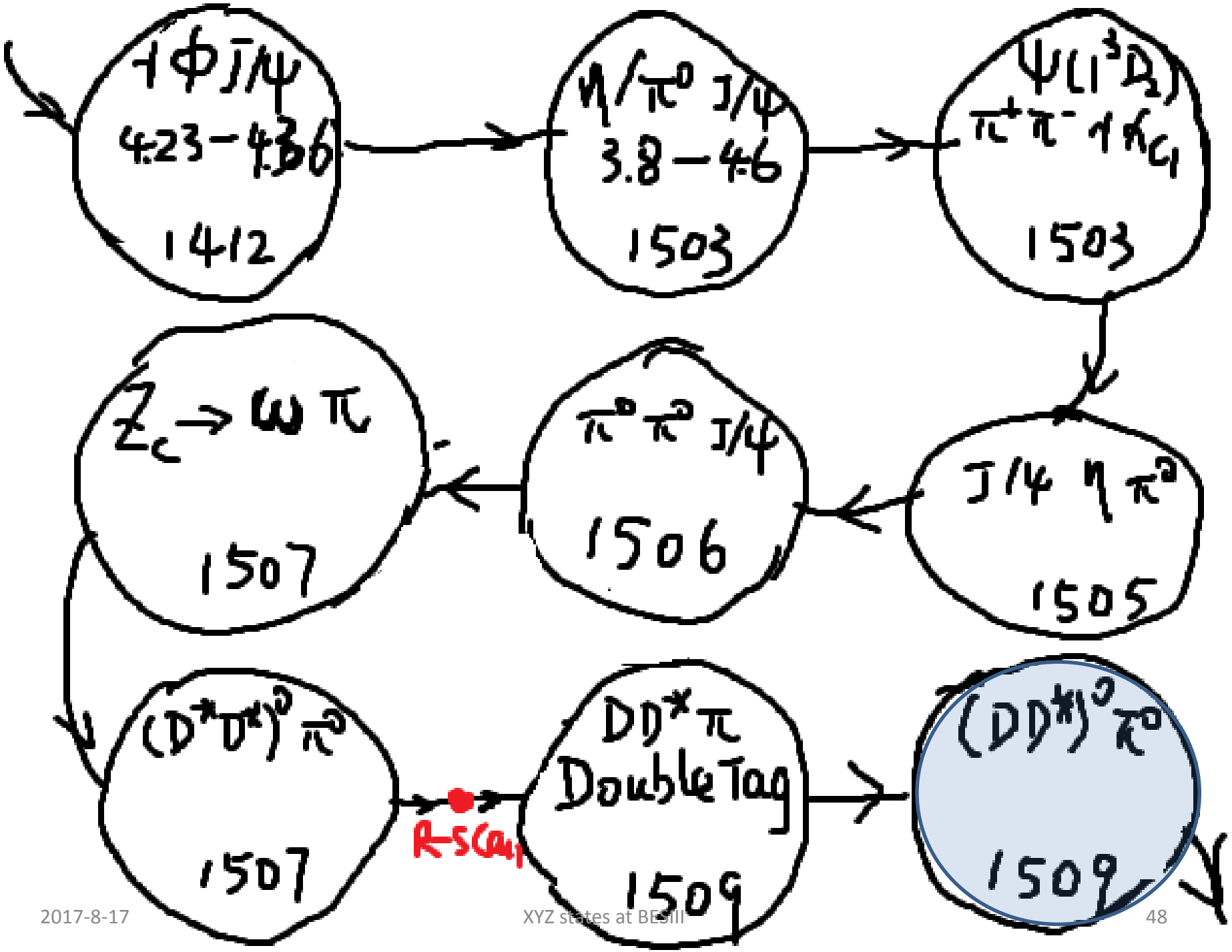

γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γK_S
1503
Z_c → ωπ
1507
π⁰π⁰ J/ψ
1506
J/ψ η π⁰
1505
(D*D*)⁰π⁰
1507
R-S(a)
DD*π
DoubleTag
1509
(DD*)⁰π⁰
1509

Neutral $Z_c(4025)$ in D^*D^* mode
PRL 115, 182002 (2015)

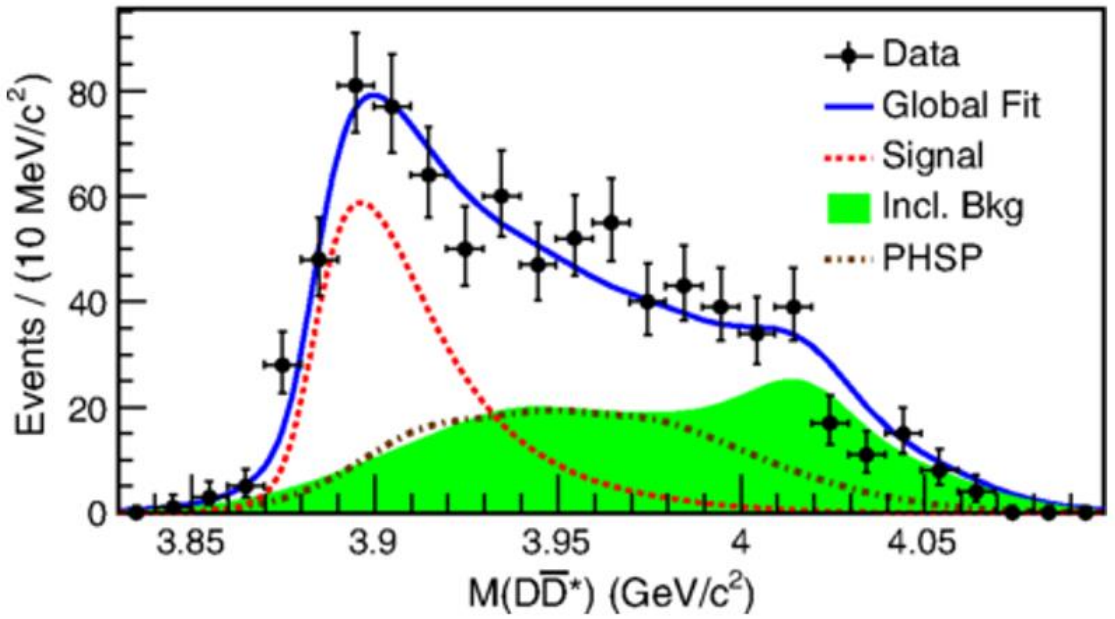


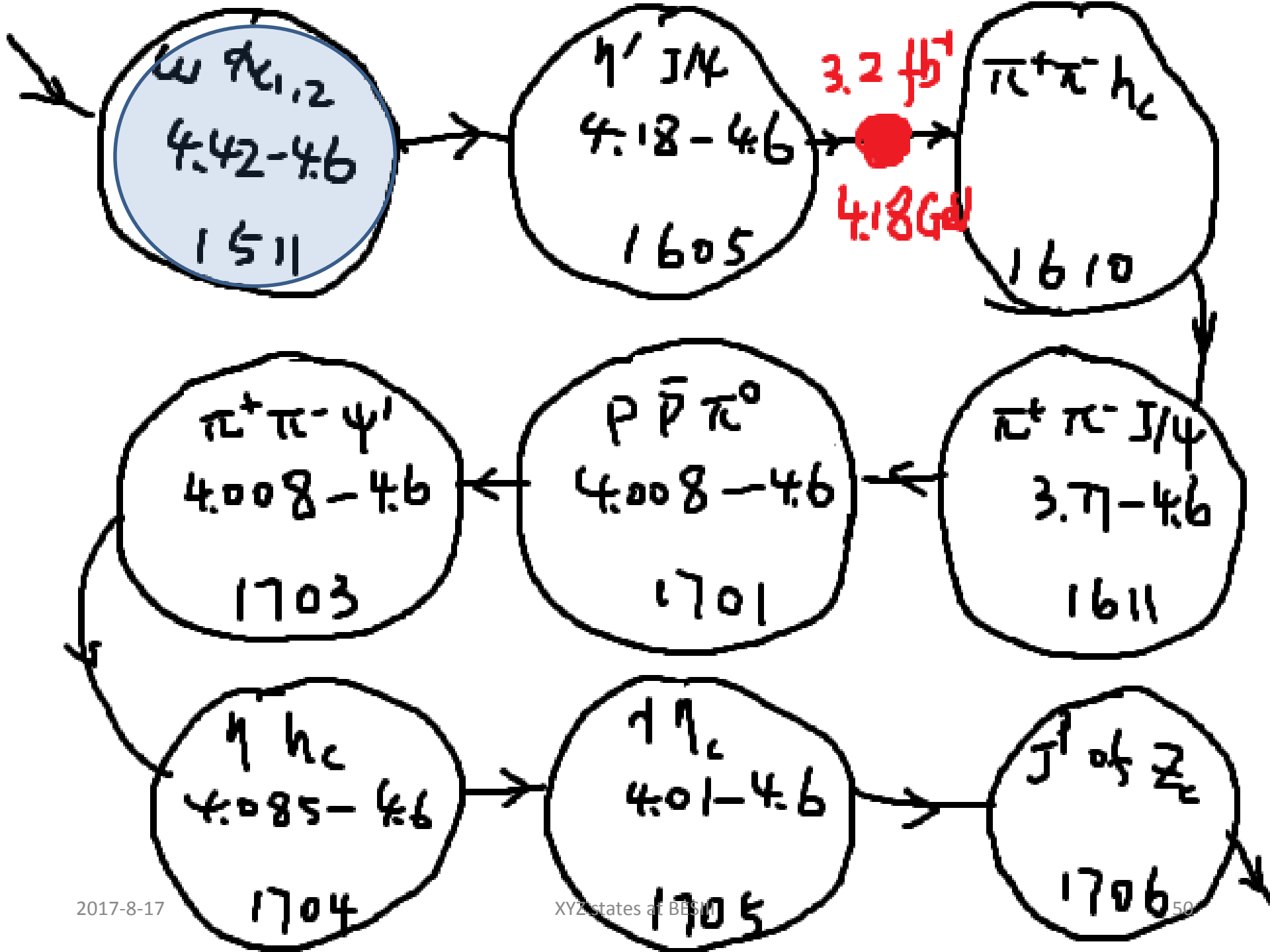

γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γK_S1
1503
J/ψ η π⁰
1505
π⁰π⁰ J/ψ
1506
Z_c → ωπ
1507
(D*D*)⁰π⁰
1507
R-S(a)
DD*π
DoubleTag
1509
(DD*)⁰π⁰
1509


γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γχc1
1503
Zc→ωπ
1507
π⁰π⁰ J/ψ
1506
J/ψ η π⁰
1505
(D*D*)⁰π⁰
1507
R-Sca
DD*π
DoubleTag
1509
(DD*)⁰π⁰
1509


γφJ/ψ
4.23-4.36
1412
η/π⁰ J/ψ
3.8-4.6
1503
ψ(1³D₂)
π⁺π⁻γK_S
1503
J/ψ η π⁰
1505
π⁰π⁰ J/ψ
1506
Z_c → ωπ
1507
(D*D*)⁰π⁰
1507
R-Scan
DD*π
DoubleTag
1509
(DD*)⁰π⁰
1509

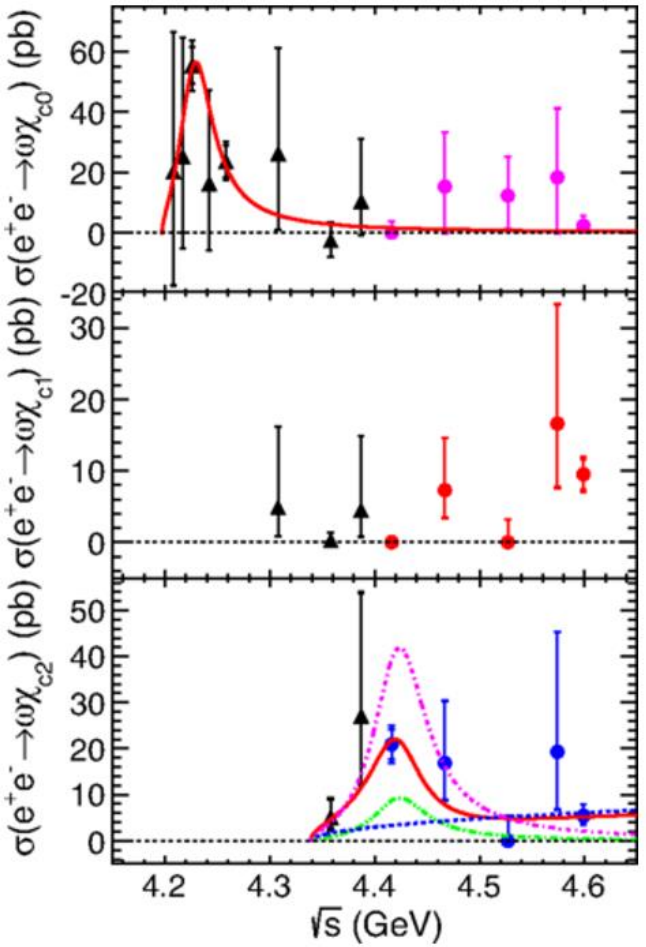
Neutral $Z_c(3885)$ in DD^* mode
PRL 115, 222002 (2015)

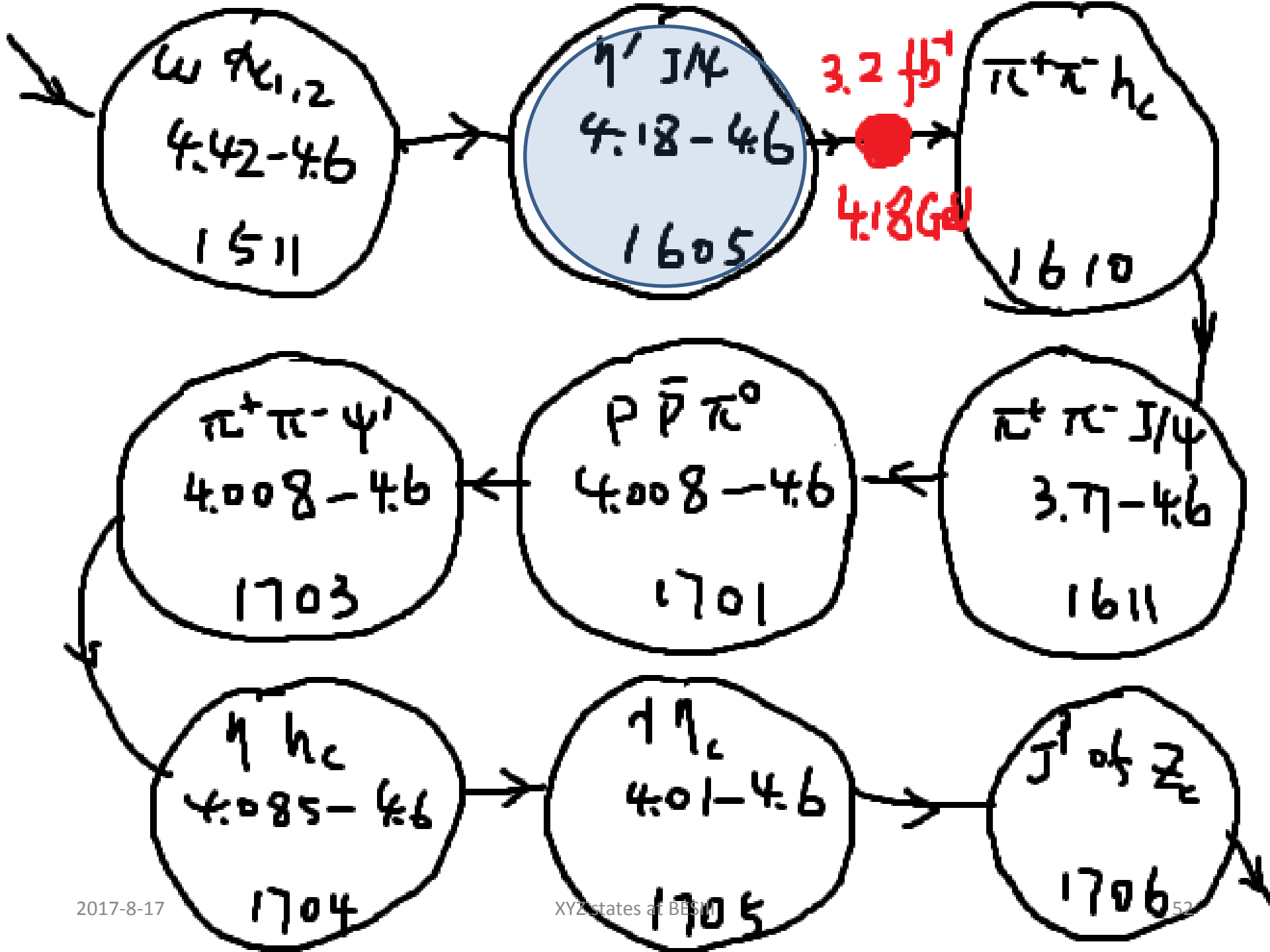



ω χc1,2
4.42-4.6
1511
η' J/ψ
4.18-4.6
1605
3.2 fb⁻¹
4.18GeV
π⁺π⁻ hc
1610
π⁺π⁻ J/ψ
3.77-4.6
1611
p p̄ π⁰
4.008-4.6
1701
π⁺π⁻ ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J^PC of Zc
1706

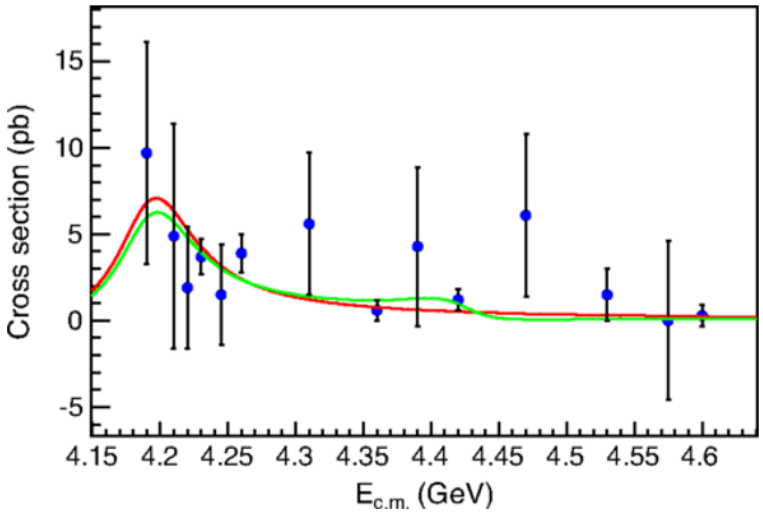
Clear signals of $e^+e^-\omega\chi_{c1,2}$ are observed at $\sqrt{s} > 4.4$ GeV

PRD 93, 011102(R) (2016)



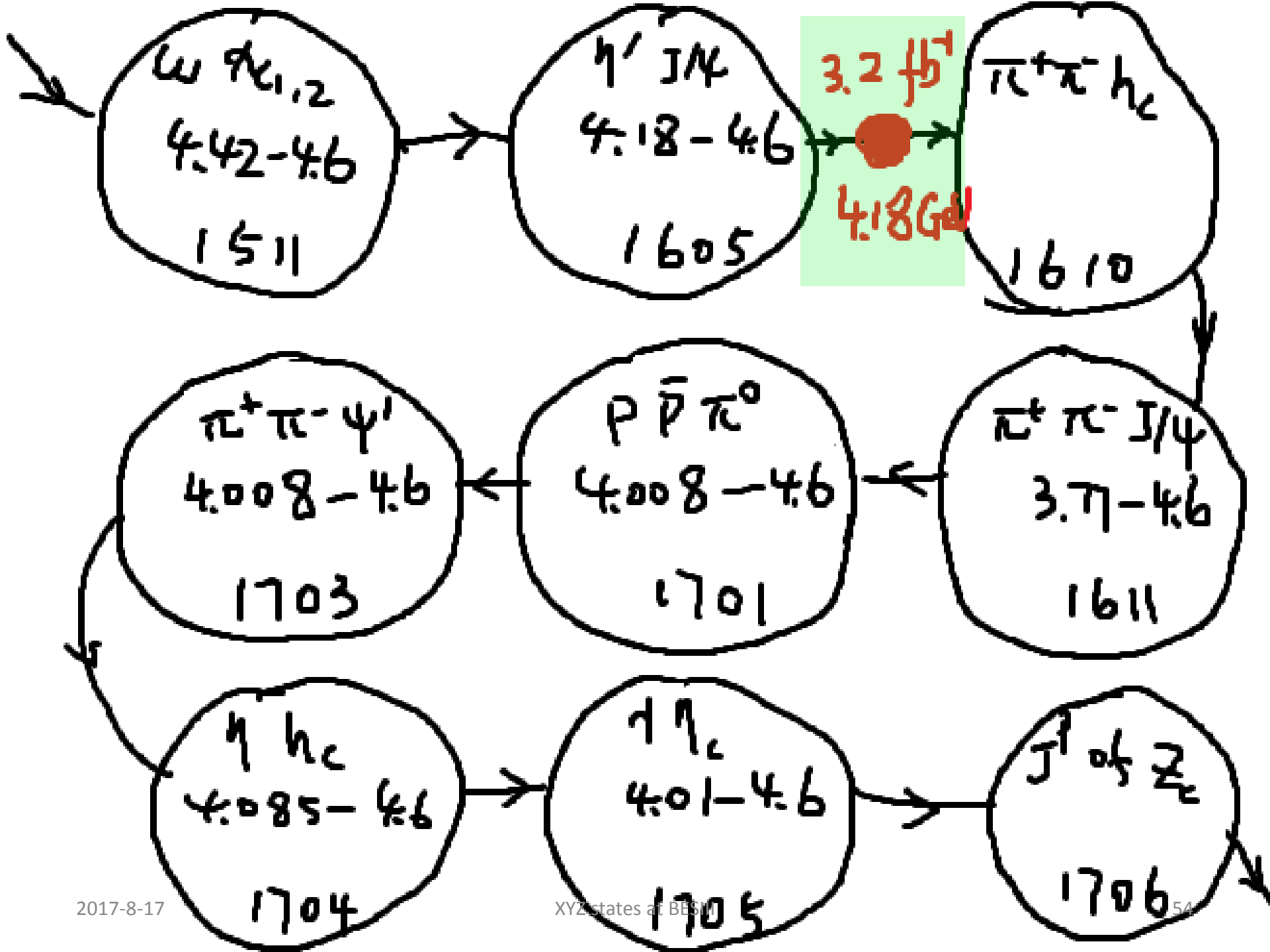

ω χc1,2
4.42-4.6
1511
η' J/ψ
4.18-4.6
1605
3.2 fb⁻¹
4.18GeV
π⁺π⁻ hc
1610
π⁺π⁻ J/ψ
3.77-4.6
1611
p p̄ π⁰
4.008-4.6
1701
π⁺π⁻ ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J^PC of Zc
1706

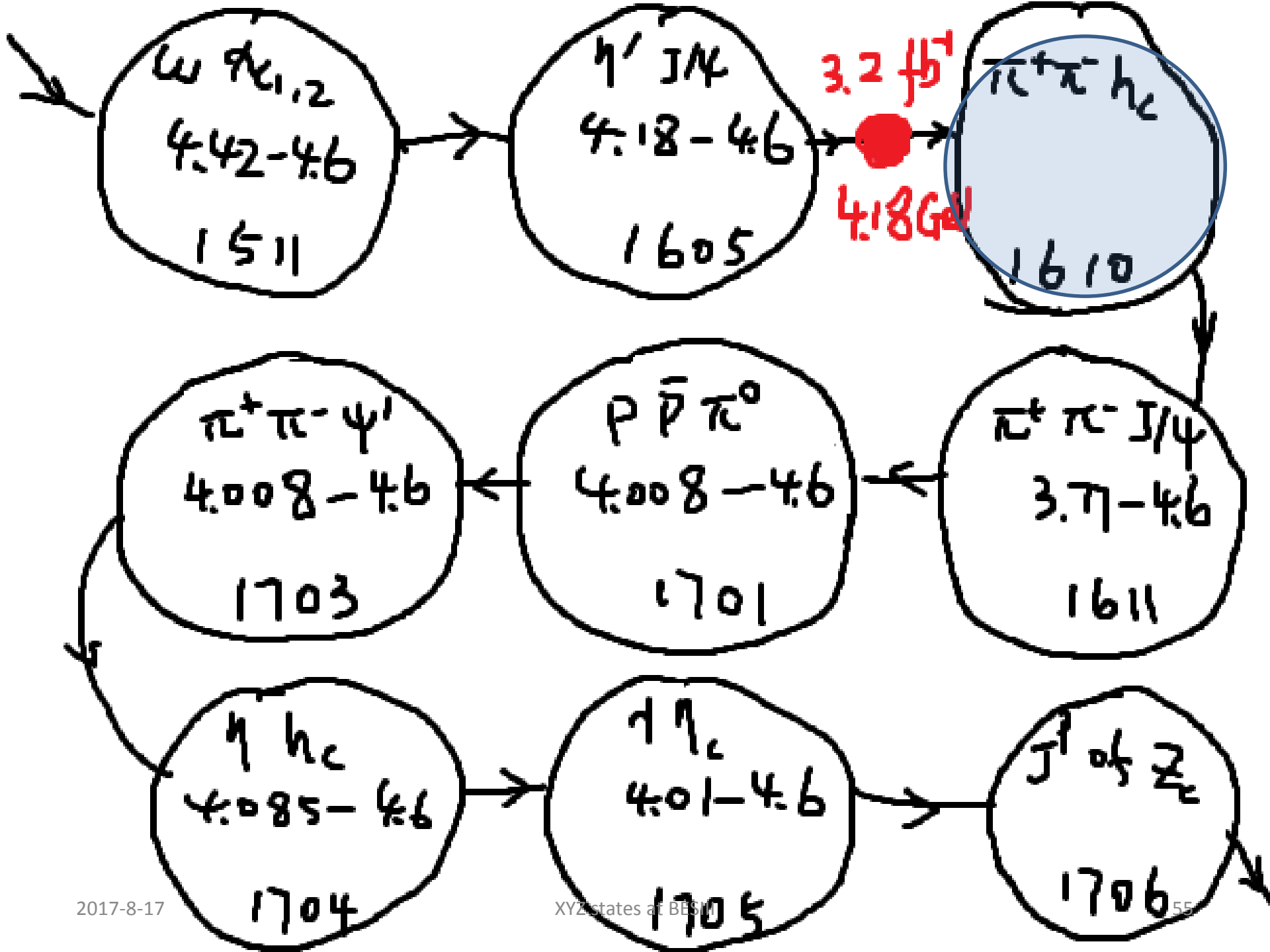
$e^+e^- \to \eta' J/\psi$ is observed at 4.23 GeV (8.6σ) and 4.26 GeV (7.3σ)
PRD 94, 032009 (2016)



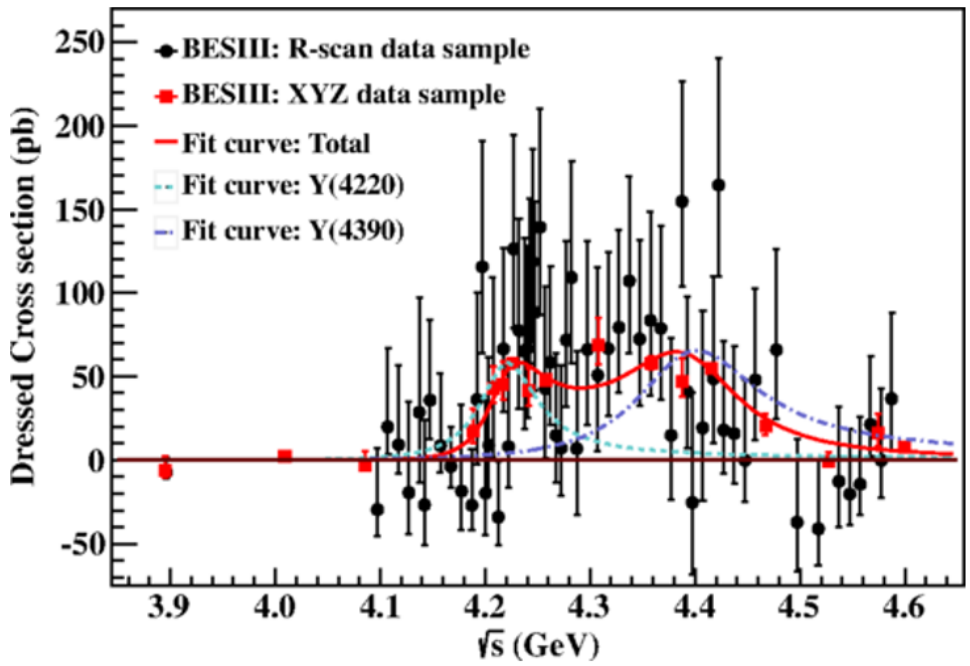
Red curve: $\psi(4160)$

Green curve: $\psi(4160) + \psi(4415)$

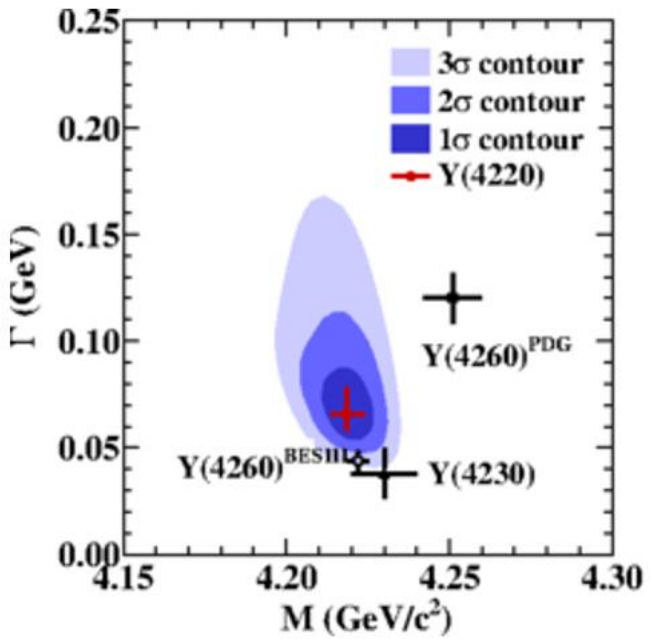

ω χc1,2
4.42-4.6
1511
η' J/ψ
4.18-4.6
1605
3.2 fb⁻¹
4.18GeV
π⁺π⁻ hc
1610
π⁺π⁻ J/ψ
3.77-4.6
1611
p p̄ π⁰
4.008-4.6
1701
π⁺π⁻ ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J/ψ γ χc
1706

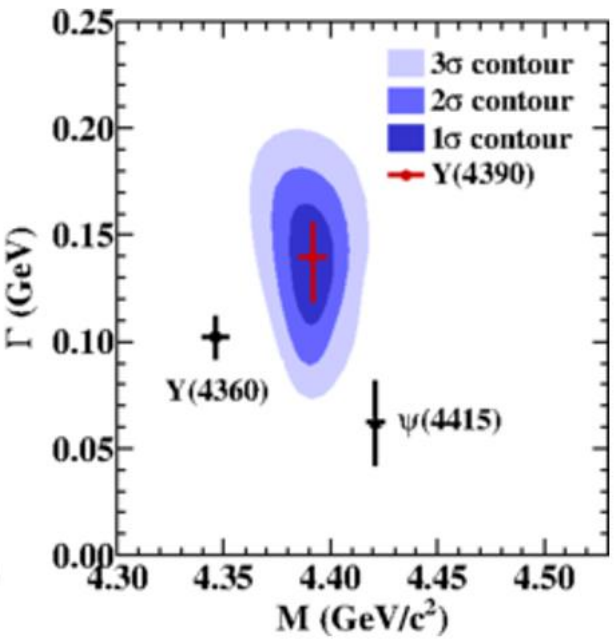

ω χc1,2
4.42-4.6
1511
η' J/ψ
4.18-4.6
1605
3.2 fb⁻¹
4.18GeV
π⁺π⁻ hc
1610
π⁺π⁻ J/ψ
3.77-4.6
1611
p p̄ π⁰
4.008-4.6
1701
π⁺π⁻ ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J^PC of Zc
1706

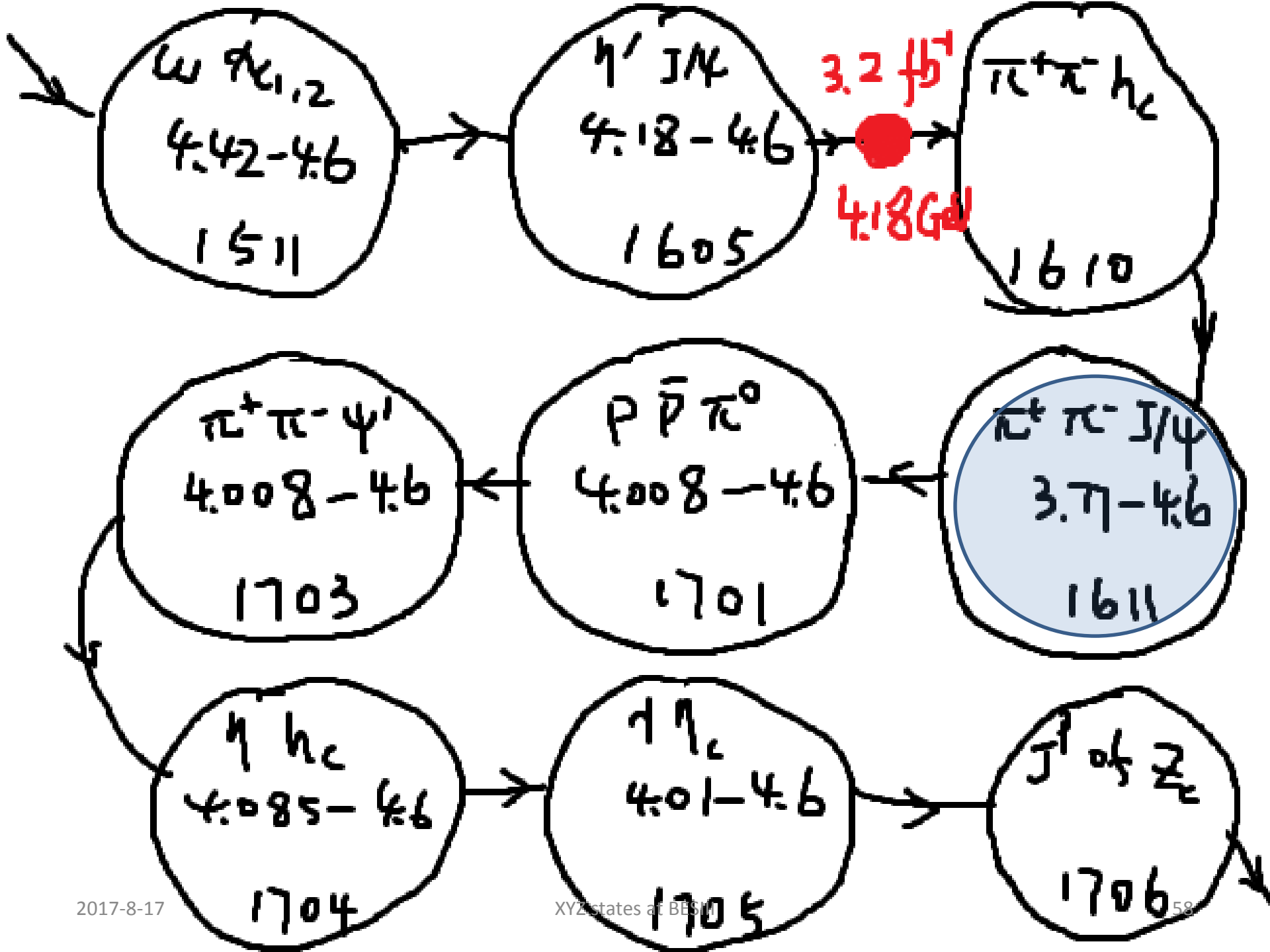
Observation of Y(4390) in $e^+e^- \to \pi^+\pi^- h_c$
PRL 118, 092002 (2017)



Observation of Y(4390) in $e^+e^- \to \pi^+\pi^- h_c$
PRL 118, 092002 (2017)





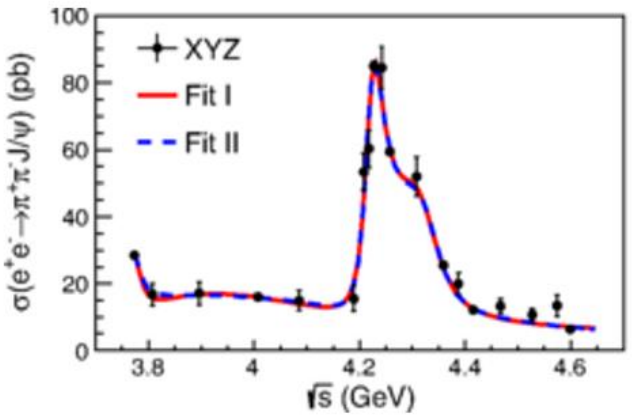

ω χc1,2
4.42-4.6
1511
η' J/ψ
4.18-4.6
1605
3.2 fb⁻¹
4.18GeV
π⁺π⁻ hc
1610
π⁺π⁻ J/ψ
3.77-4.6
1611
p p̄ π⁰
4.008-4.6
1701
π⁺π⁻ ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J/ψ γγ
1706

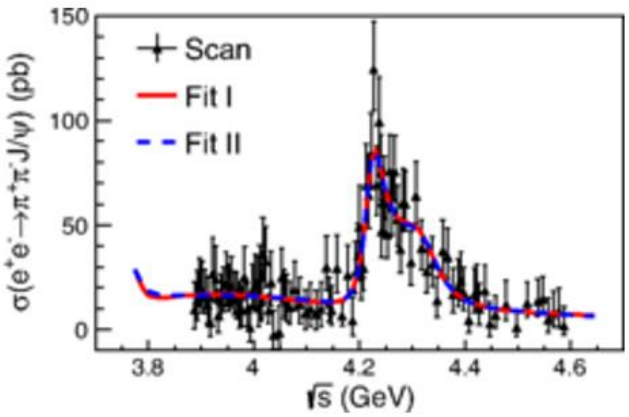
Y(4260) and Y(4360) are observed in

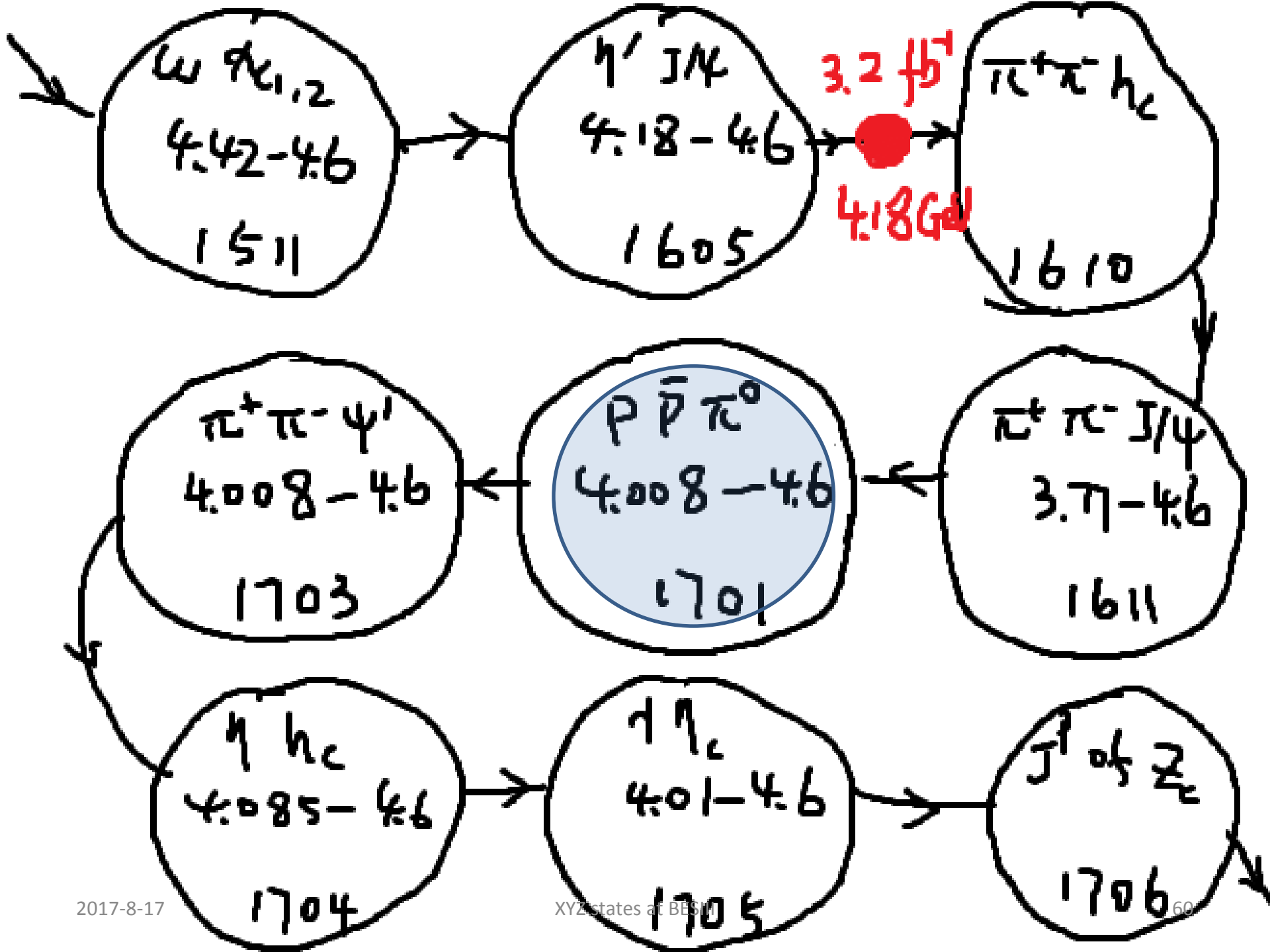
$e^+e^- \to \pi^+\pi^- J/\psi$

Y(4008) is not confirmed

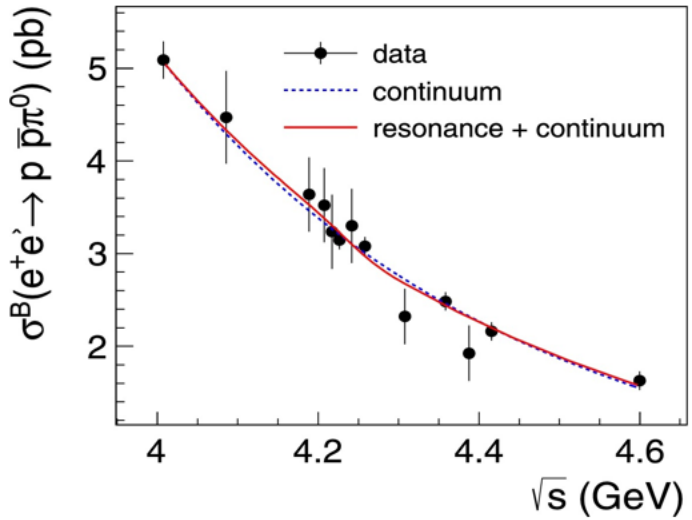
PRL 118, 092001 (2017)

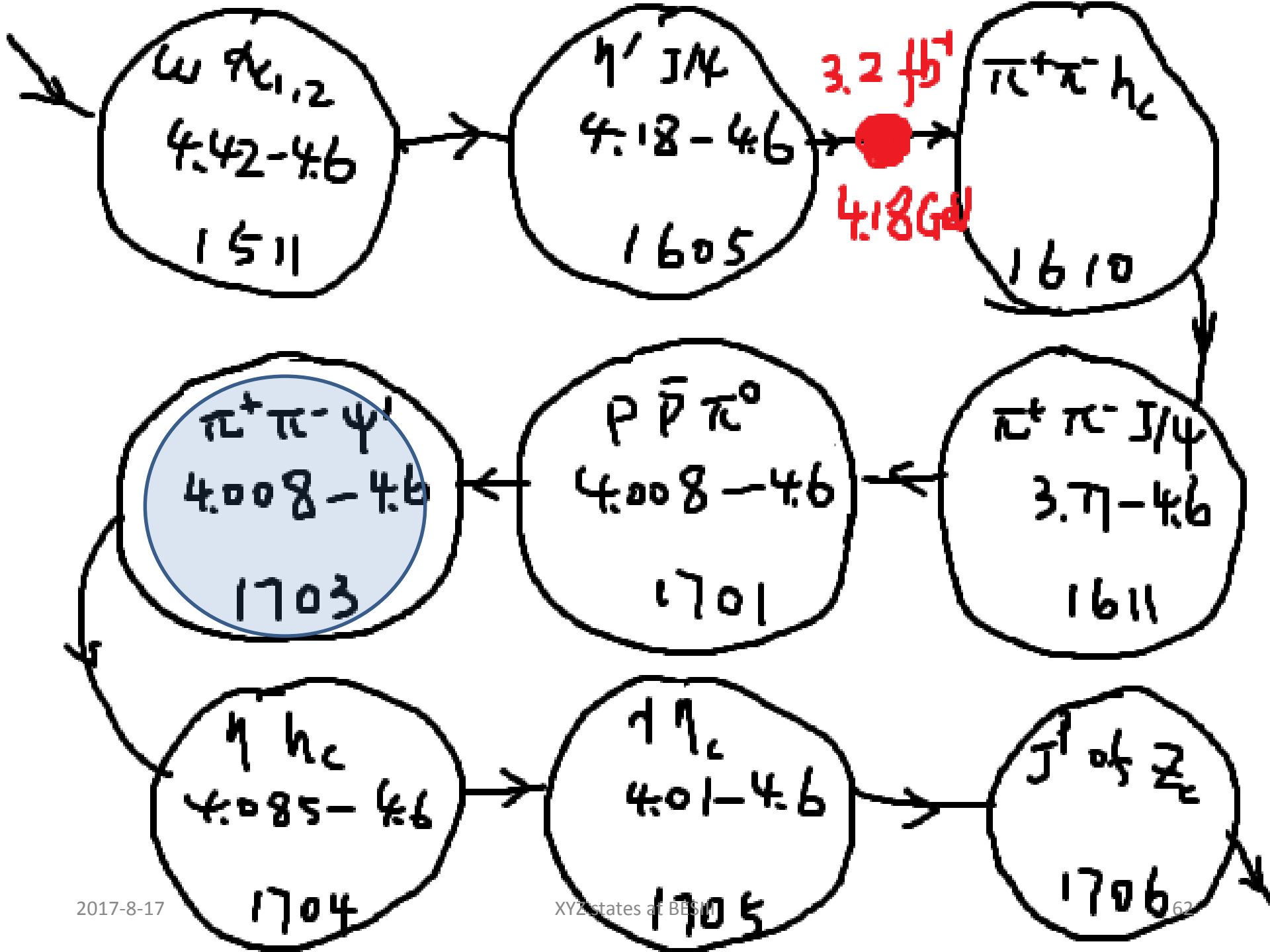





ω χc1,2
4.42-4.6
1511
η' J/ψ
4.18-4.6
1605
3.2 fb⁻¹
4.18GeV
π⁺π⁻ hc
1610
π⁺π⁻ J/ψ
3.77-4.6
1611
p p̄ π⁰
4.008-4.6
1701
π⁺π⁻ ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J^PC of Zc
1706

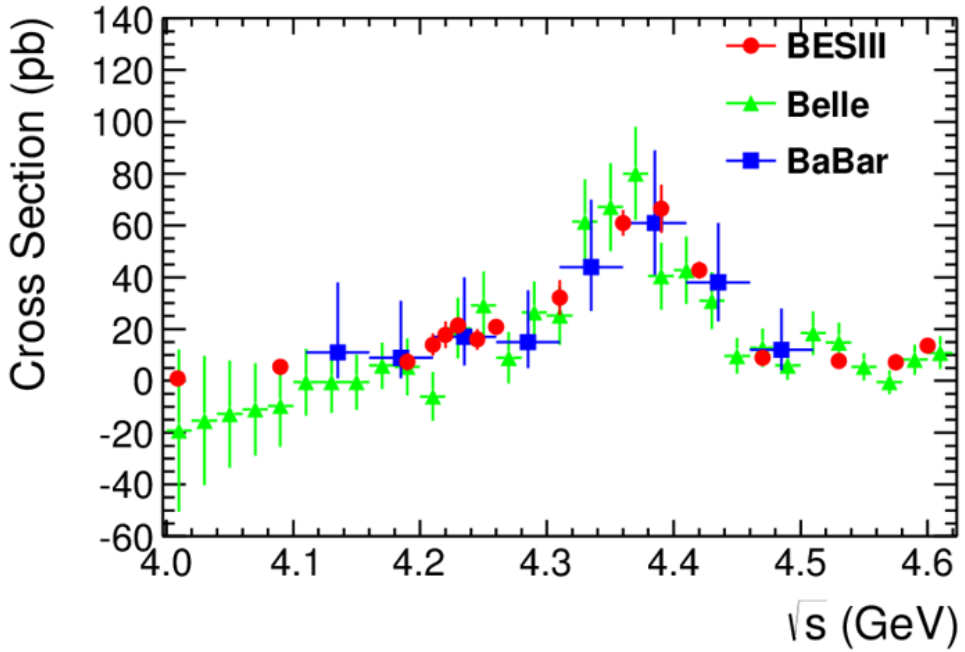
No significant resonance structure is observed in $e^+e^- \to p\bar{p}\pi^0$
PLB 771, 45-51 (2017)




ω χc1,2
4.42-4.6
1511
η' J/ψ
4.18-4.6
1605
3.2 fb⁻¹
4.18GeV
π⁺π⁻ hc
1610
π⁺π⁻ J/ψ
3.77-4.6
1611
p p̄ π⁰
4.008-4.6
1701
π⁺π⁻ ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J/ψ γ χc
1706

Cross section of $e^+e^- \to \pi^+\pi^-\psi'$

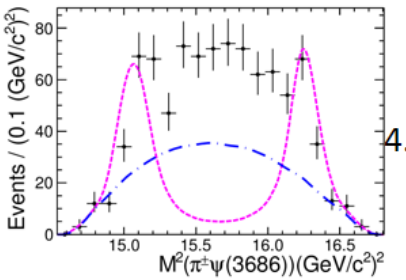
arXiv: 1703.08787, Accepted by PRD



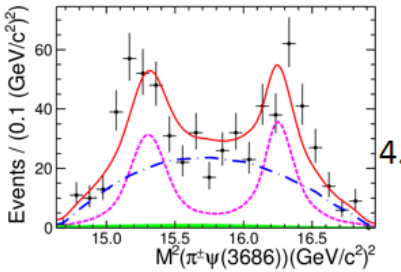
Charged structures in $e^+e^- \to \pi^+\pi^-\psi'$

Unresolved discrepancies between the fit model (theory input) and data (stat.)

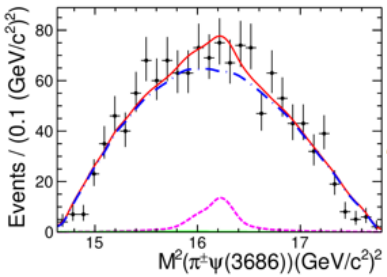
arXiv: 1703.08787, Accepted by PRD



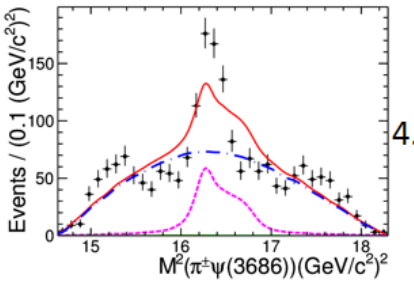
4.23 GeV



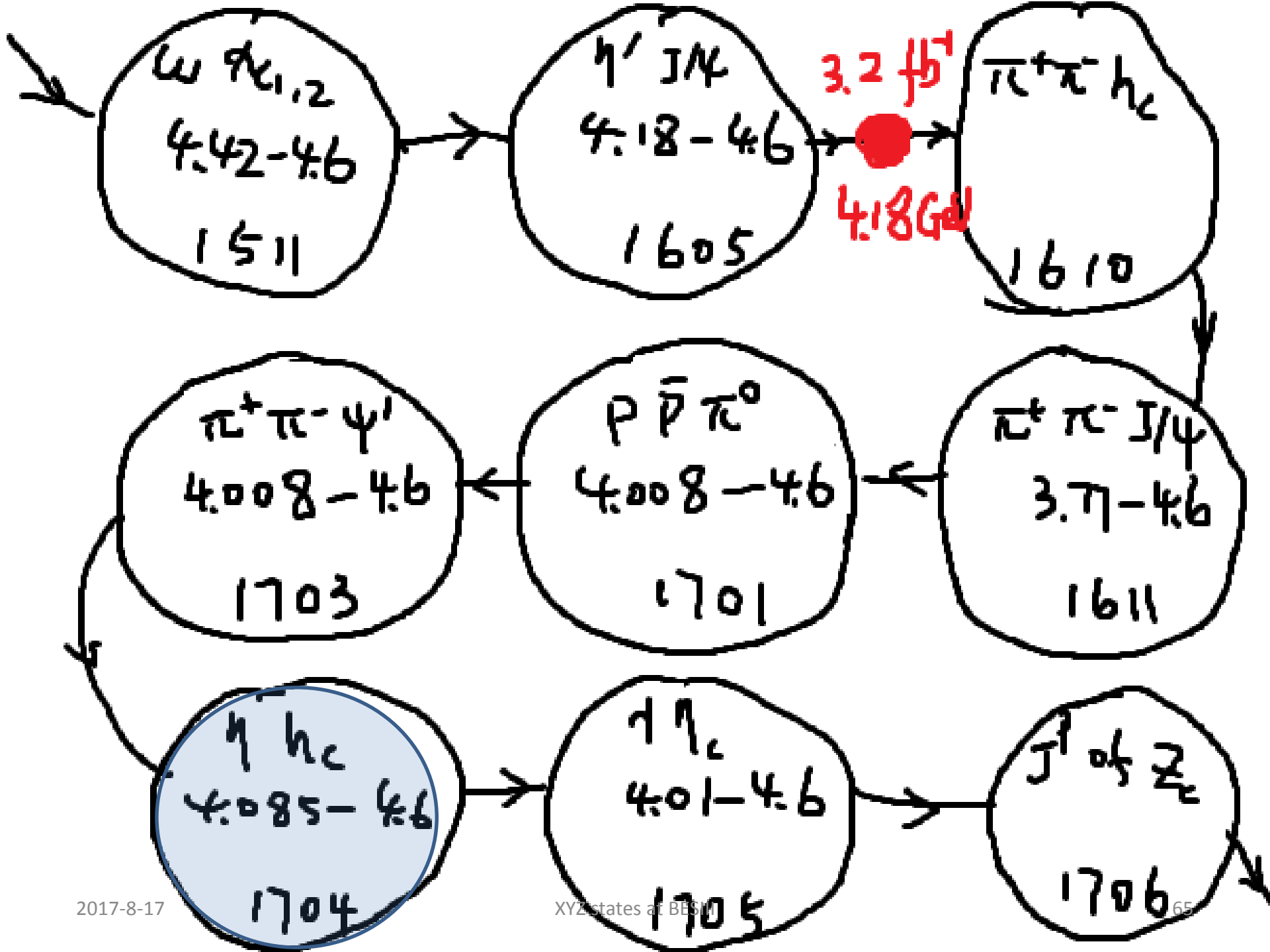
4.26 GeV



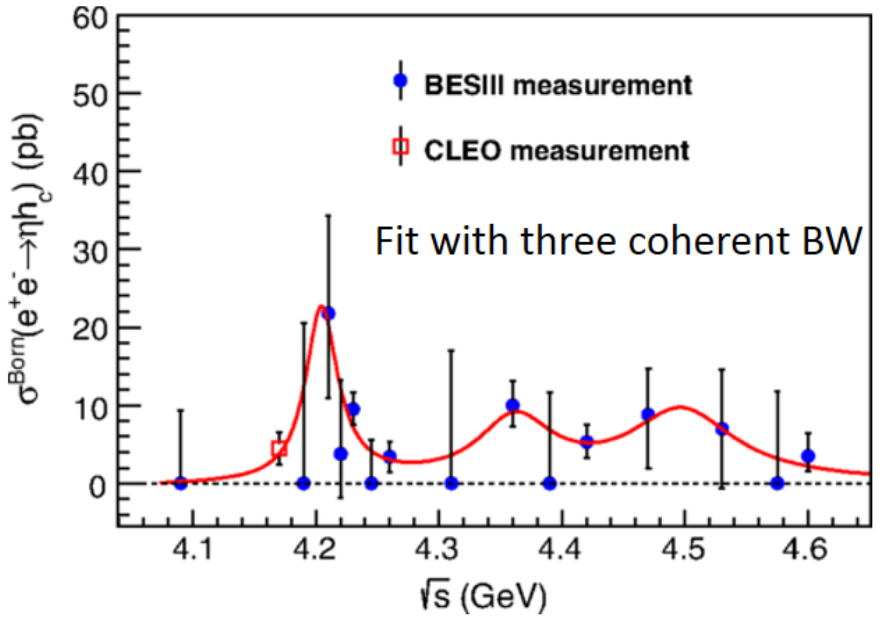
4.36 GeV

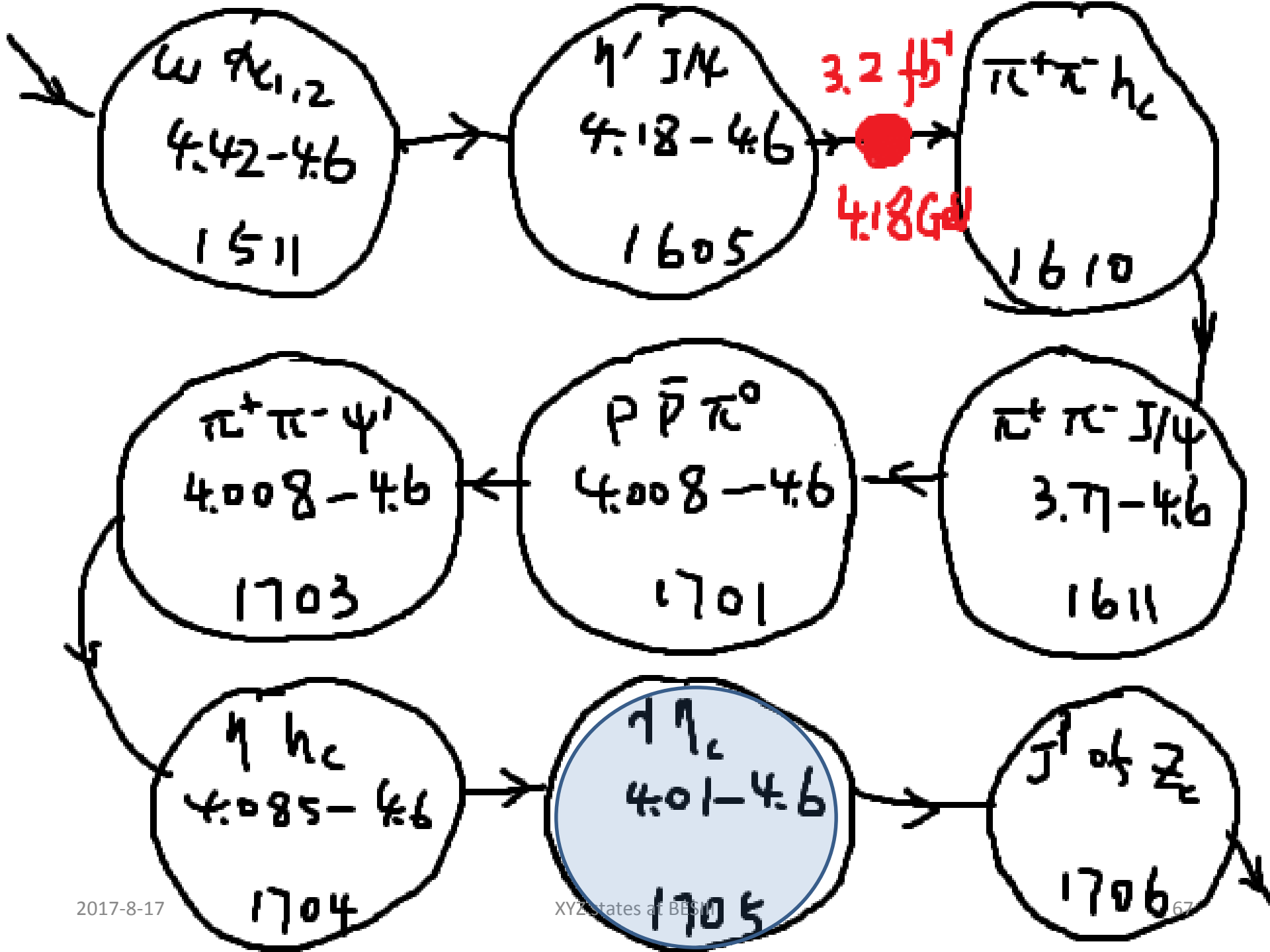


4.42 GeV

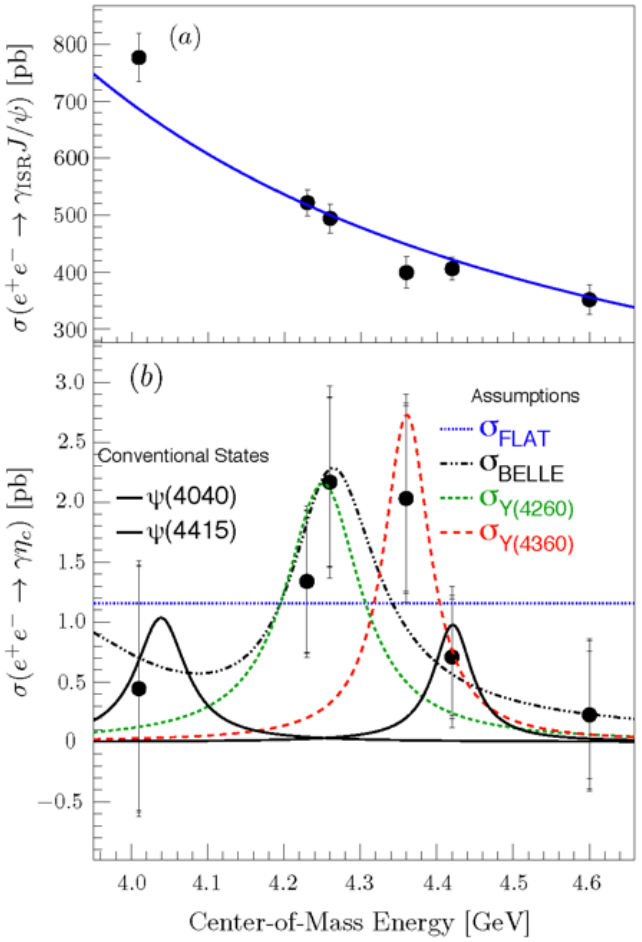

ω χc1,2
4.42-4.6
1511
η' J/ψ
4.18-4.6
1605
3.2 fb⁻¹
4.18GeV
π⁺π⁻ hc
1610
π⁺π⁻ J/ψ
3.77-4.6
1611
p p̄ π⁰
4.008-4.6
1701
π⁺π⁻ ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J/ψ γχc
1706

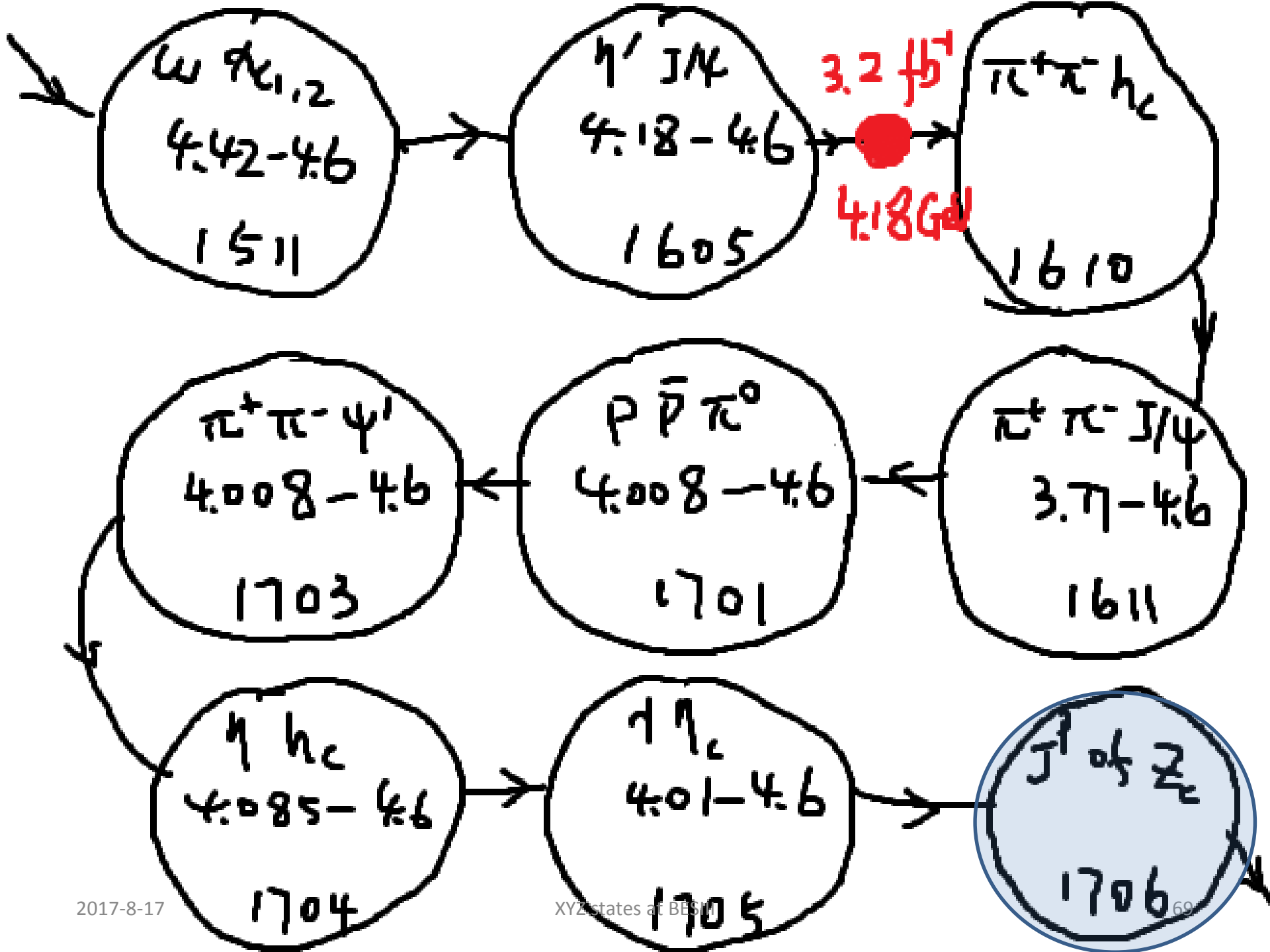
Observation of $e^+e^- \to \eta h_c$ from 4.085 GeV to 4.6 GeV PRD 96, 012001 (2017)




ω χc1,2
4.42-4.6
1511
η' J/ψ
4.18-4.6
1605
3.2 fb⁻¹
4.18GeV
π⁺π⁻ hc
1610
π⁺π⁻ J/ψ
3.77-4.6
1611
p p̄ π⁰
4.008-4.6
1701
π⁺π⁻ ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J/ψ γχc
1706

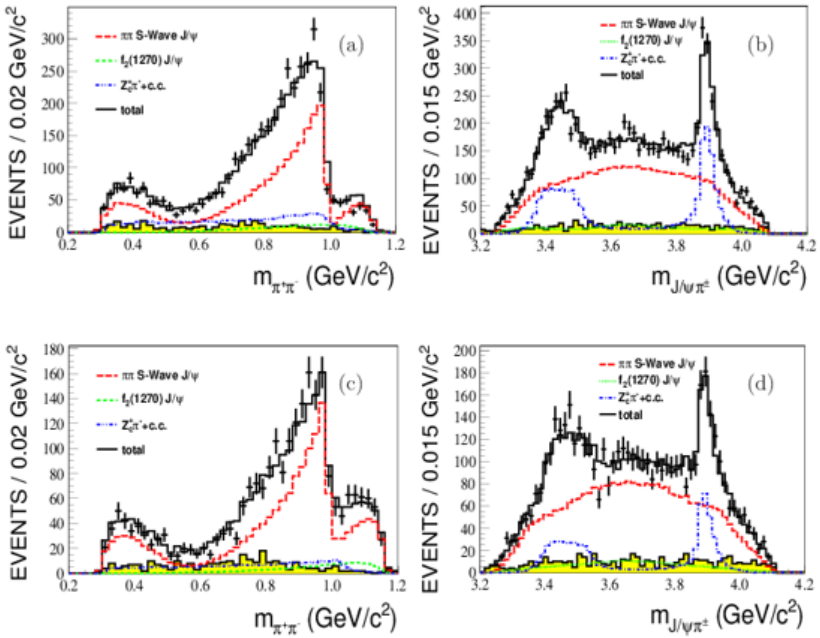
Evidence of $e^+e^- \to \gamma\eta_c$ arXiv: 1705.06853 Acceptec by PRD (R)

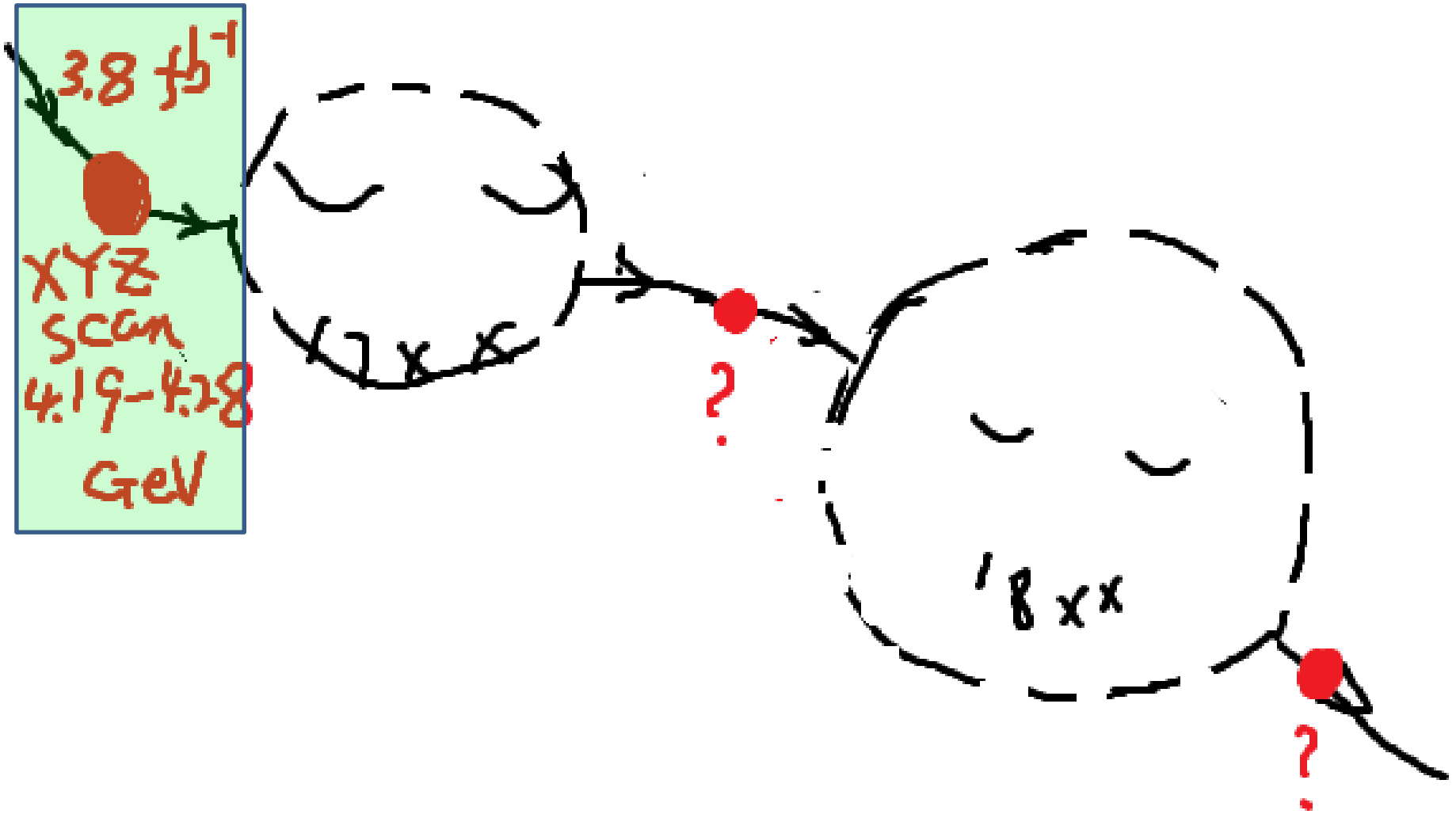


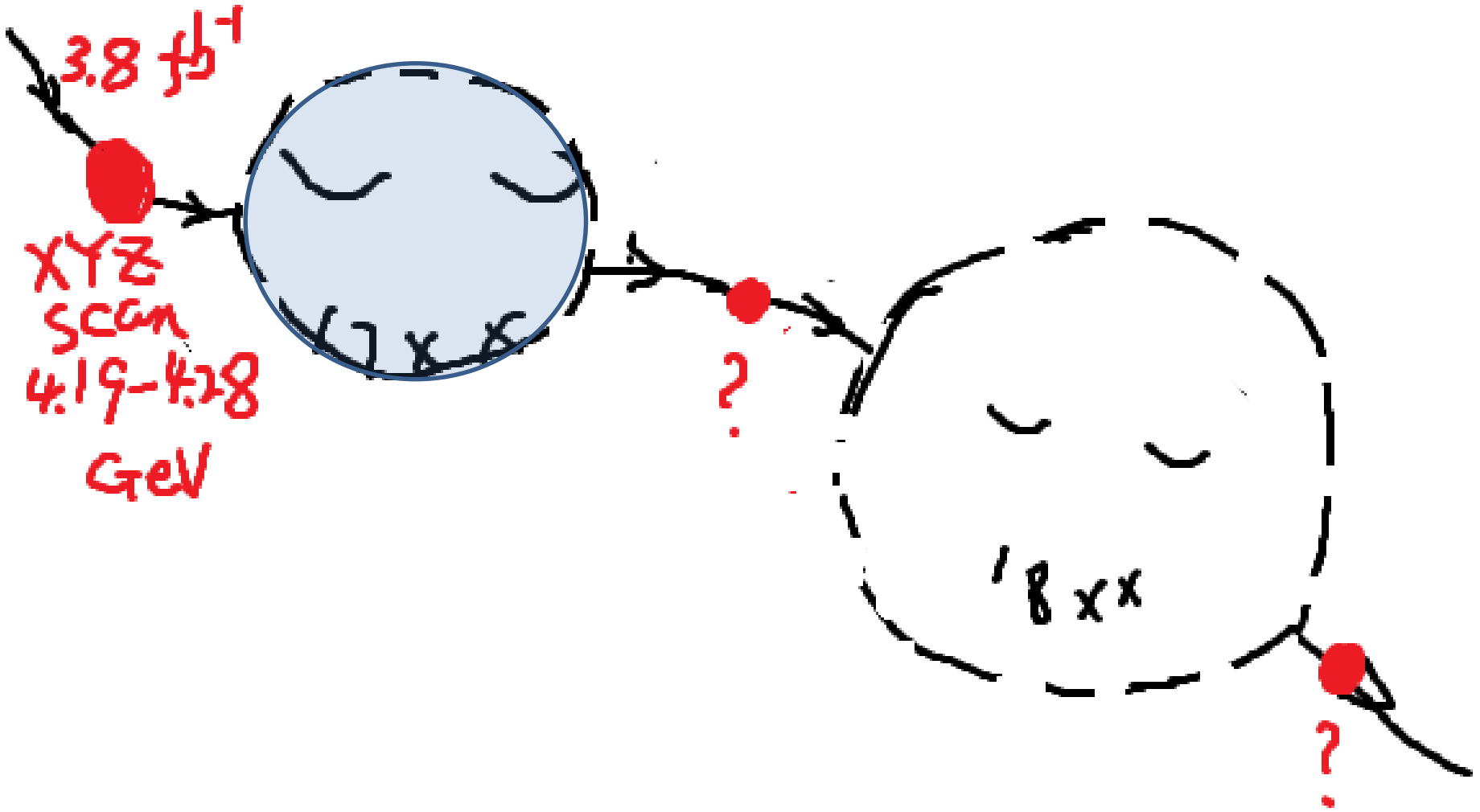

ω χc1,2
4.42-4.6
1511
η' JN
4.18-4.6
1605
3.2 fb-1
4.18GeV
π+π- hc
1610
π+π- J/ψ
3.77-4.6
1611
p p̄ π0
4.008-4.6
1701
π+π- ψ'
4.008-4.6
1703
η hc
4.085-4.6
1704
η ηc
4.01-4.6
1705
J1 of Zc
1706

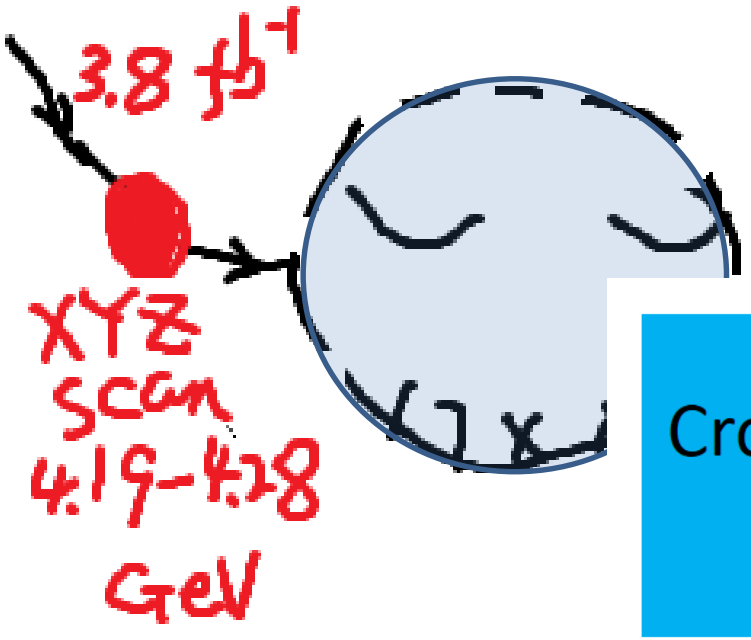
$J^P = 1^+$ for $Z_c(3900)^\pm$ and the pole mass and width

PRL 119, 072001 (2017)

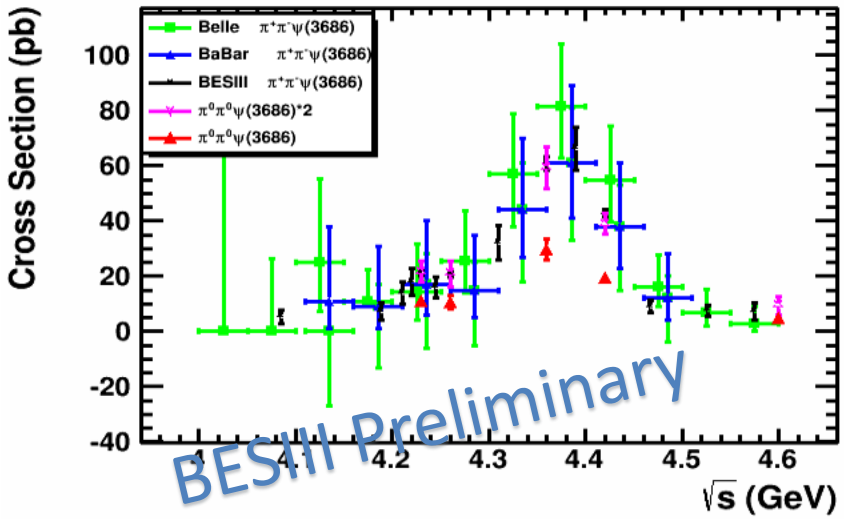


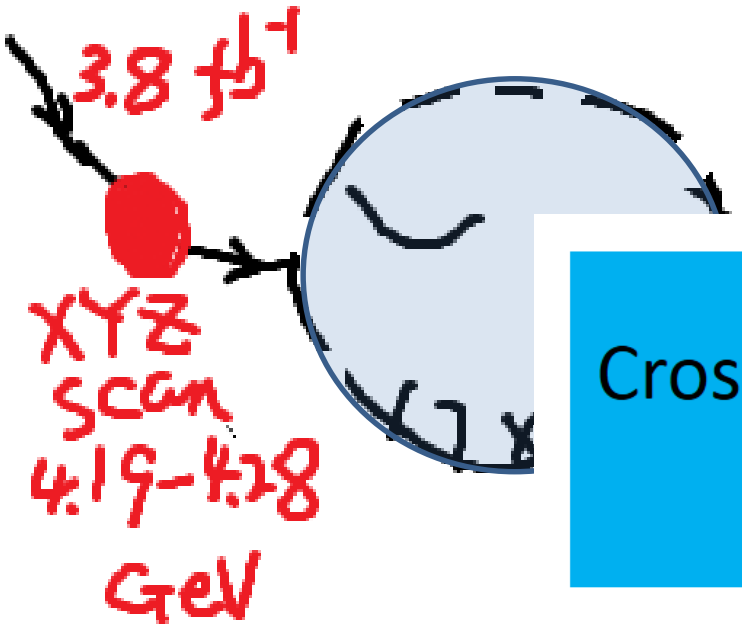

3.8 fb-1
XYZ
scan
4.19-4.28
GeV
?
?


3.8 fb-1
XYZ
scan
4.19-4.28
GeV
?
?

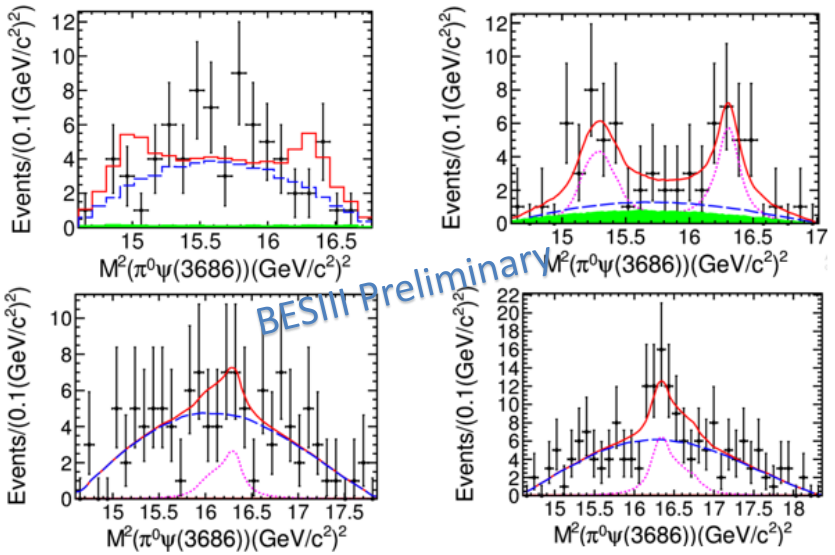


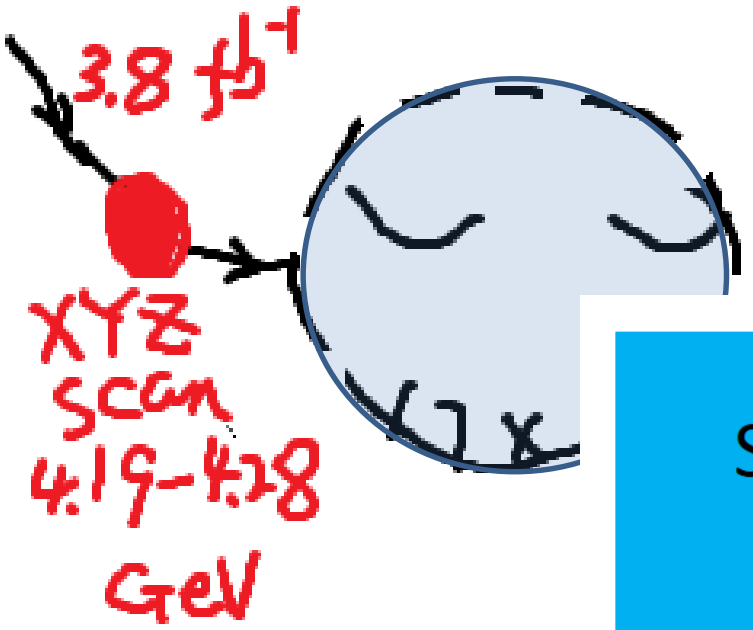
Cross sections and neutral structure in $e^+e^- \to \pi^0\pi^0\psi(3686)$



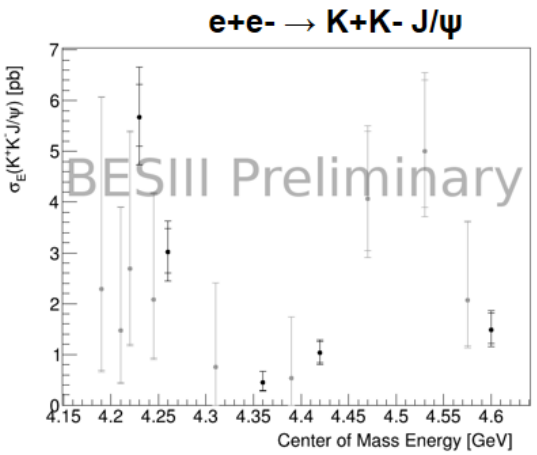


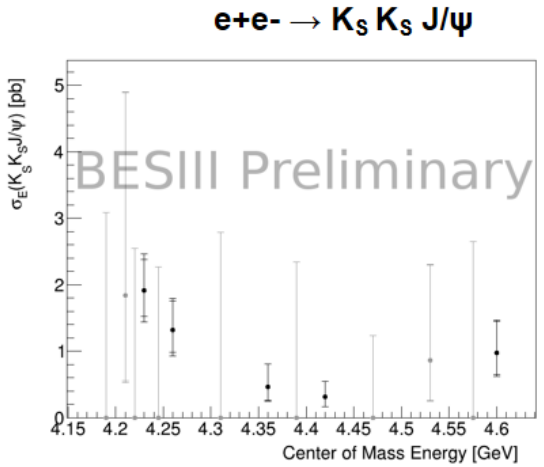
Cross sections and neutral structure in $e^+e^- \to \pi^0\pi^0\psi(3686)$

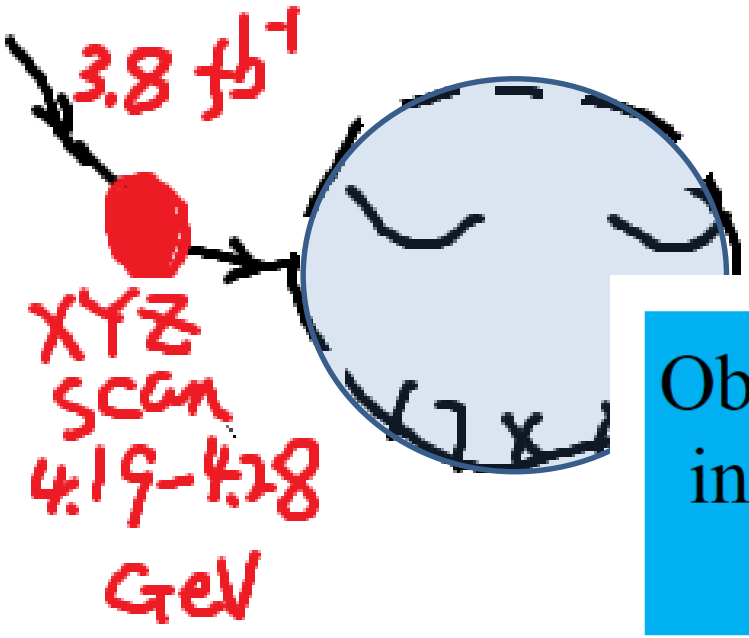




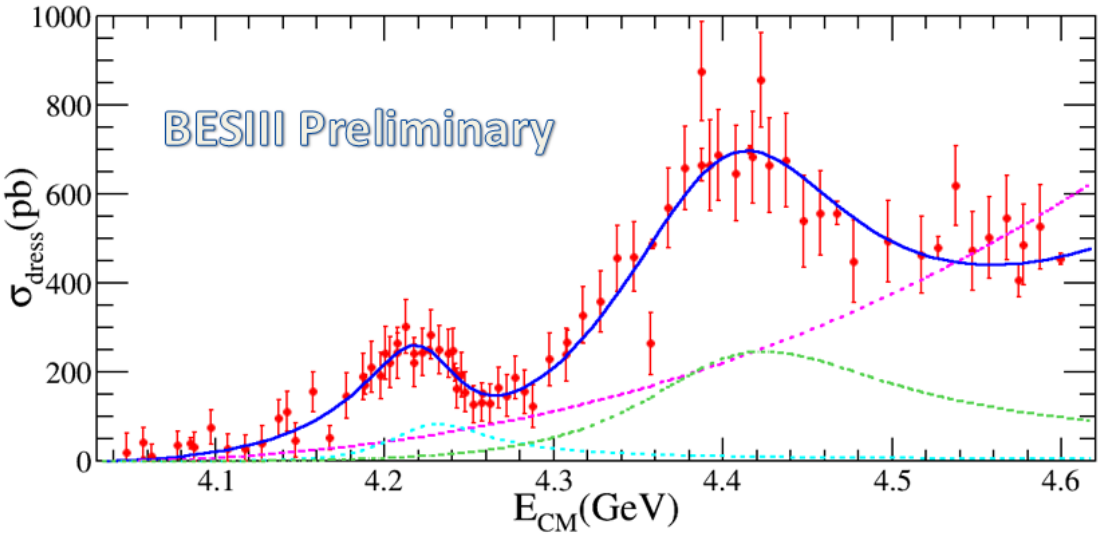
Structures in the line-shape of $e^+e^- \to KKJ/\psi$







Observation of Y(4220) and Y(4390) in $e^+e^- \to \pi^+ D^0 D^{*-}$ cross section between 4.05 and 4.60 GeV



$e^+e^- \to \gamma X(3872)$
$\pi^+\pi^- X(3823)$

X

$Y(4260), Y(4360)$ in
$e^+e^- \to \omega\chi_{cJ}, \gamma\chi_{cJ}$
$\eta J/\psi, \eta' J/\psi, \eta h_c$
$\pi\pi h_c, \pi\pi J/\psi, \gamma\eta_c$

Y

Z

$Z_c(3900)^{\pm,0}$ $[\pi J/\psi, DD^*]$
$Z_c(4240)^{\pm,0}$ $[\pi h_c, D^*D^*]$
Complex structured observed in $\pi\psi(3686)$.

No light hadron final states from XYZ decay is observed.

Characteristics and trends in XYZ study at BESIII

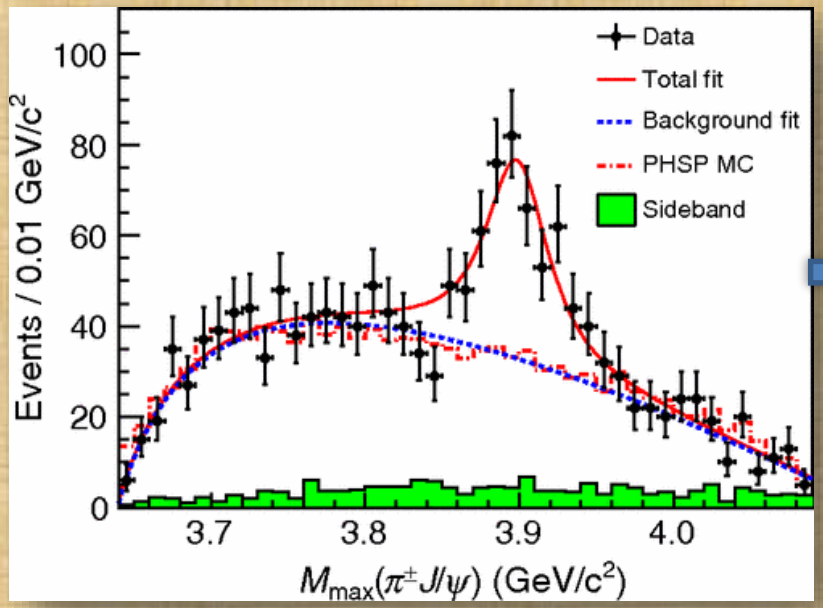
- Systematic

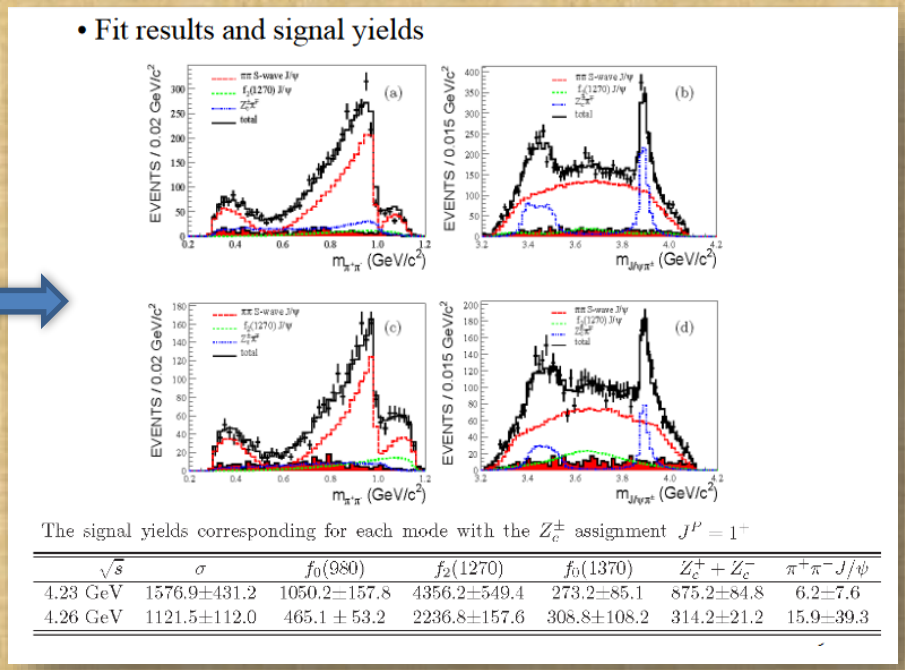
Ex.

$$\gamma \times \begin{pmatrix} \pi^0 \\ \eta \\ \eta' \\ \pi^+\pi^- \\ \eta\eta \\ \pi^+\pi^-\pi^0(\omega) \\ \eta\pi\pi \\ \pi^0\pi^0 \\ K^+K^-(\phi) \end{pmatrix} \times \begin{pmatrix} \eta_c \\ J/\psi \\ \chi_{cJ} \\ h_c \\ \psi' \\ D^{(*)}D^{(*)} \end{pmatrix}$$

Characteristics and trends in XYZ study at BESIII

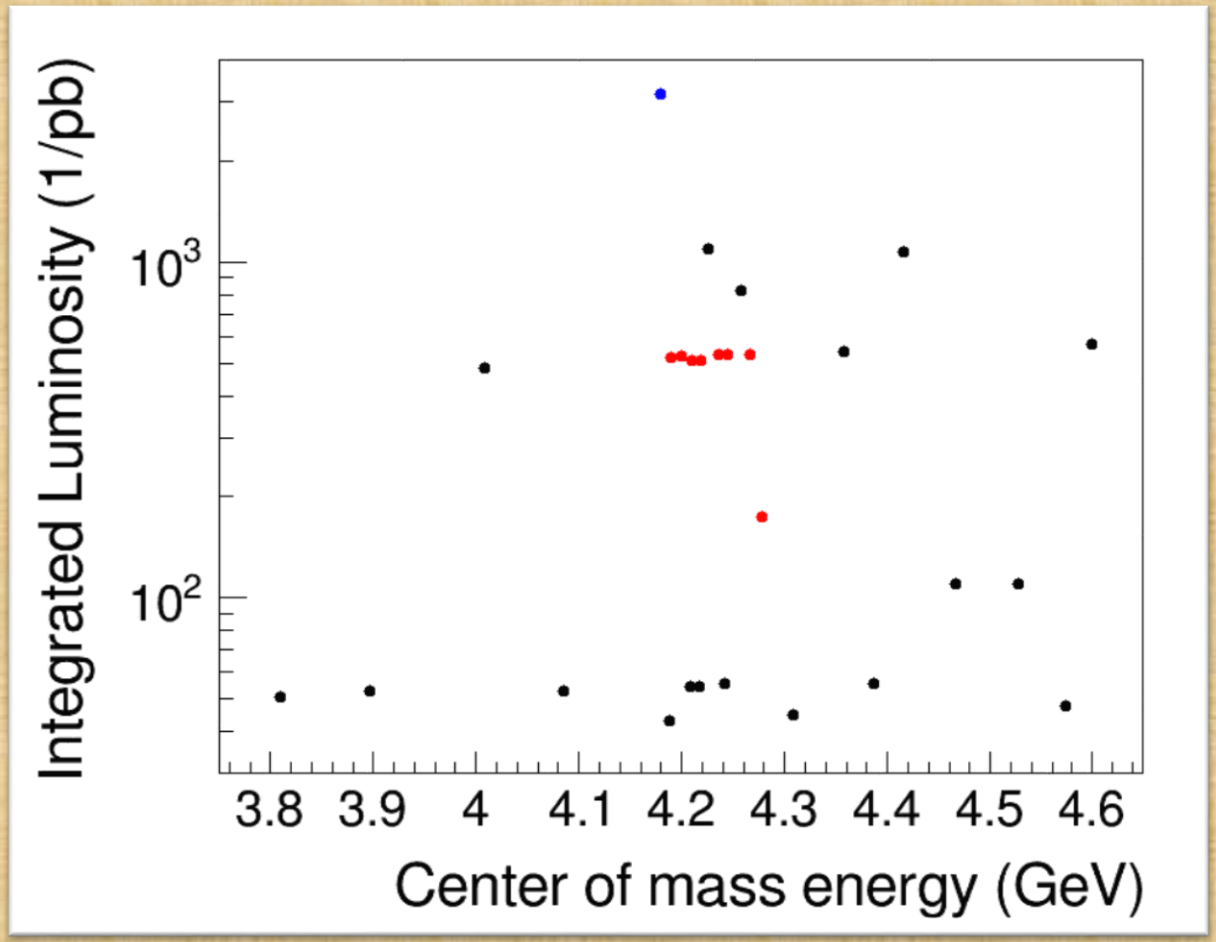
- More amplitude analyses





$\sqrt{s}$	σ	$f_0(980)$	$f_2(1270)$	$f_0(1370)$	$Z_c^+ + Z_c^-$	$\pi^+\pi^- J/\psi$
4.23 GeV	1576.9±431.2	1050.2±157.8	4356.2±549.4	273.2±85.1	875.2±84.8	6.2±7.6
4.26 GeV	1121.5±112.0	465.1 ± 53.2	2236.8±157.6	308.8±108.2	314.2±21.2	15.9±39.3

XYZ Data: we already have ~12 fb^{-1}



+ R-scan data sets

A big plan for XYZ

- Start from 4.0 GeV up to the maximum energy BEPCII can reach (≥ 4.6 GeV)
- 10 MeV step (slight adjust ~ thresholds, skip those 6 points we have already collected large samples)
- 500 pb^{-1}/point (from the size of the existing samples!)

- Year 1: 4.0-4.1 GeV
- Year 2: 4.1-4.2 GeV
- Year 3: 4.2-4.3 GeV
- Year 4: 4.3-4.4 GeV
- Year 5: 4.4-4.5 GeV
- Year 6: 4.5-4.6 GeV
- Years 7, 8, ...: >4.6 GeV

- ~ 4.5/fb per year!
- A bit conservative than BEPCII design luminosity (5/fb/yr)!
- Top-up injection allows more integrated luminosity!
- If "Year 1" = 2015, we finish 4.6 GeV data taking in 2021!

Further plan

- A few high statistics points (around 4.2, 4.3 4.4 GeV?)
  - Primary focus: further study on Z_c states.
- More high energy data (between 4.5 and 4.6 GeV?)
  - Primary focus: line-shapes, $\Lambda_c\Lambda_c$ threshold, more phase space
- > 4.6 GeV (the present upper energy of BEPCII)
  - R&D is on-going
- Others (suggestions from theorists?)
  - Specific predictions are extremely welcome.

XYZ in the future at BESIII

- BESIII has observed/measured XYZ states.
  - From experiment side, $Z_c(3900)$, $Z_c(4020)$, and $Y(4260)$ are solidly established based on BESIII measurements.
- Our knowledge of XYZ has been significantly improved. However, there are still many puzzles
  - One or two states when two resonances are close?
  - Complex structures are observed and difficult to describe.
  - Some expected states or decay modes have not been observed.
  - Nature of these states.
  - …
- With more data and inputs from theorists, we will better understand these exotic states.


Thank you!