June, 2024

Heavy Quark Exotics

Eric Swanson

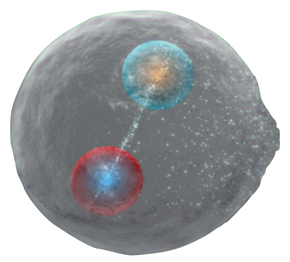
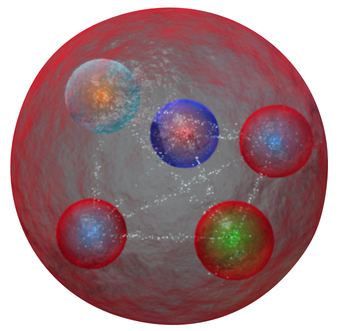
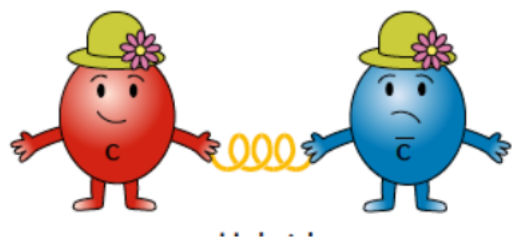
ExoHad
Exotic Hadrons Topical Collaboration

tl;dl

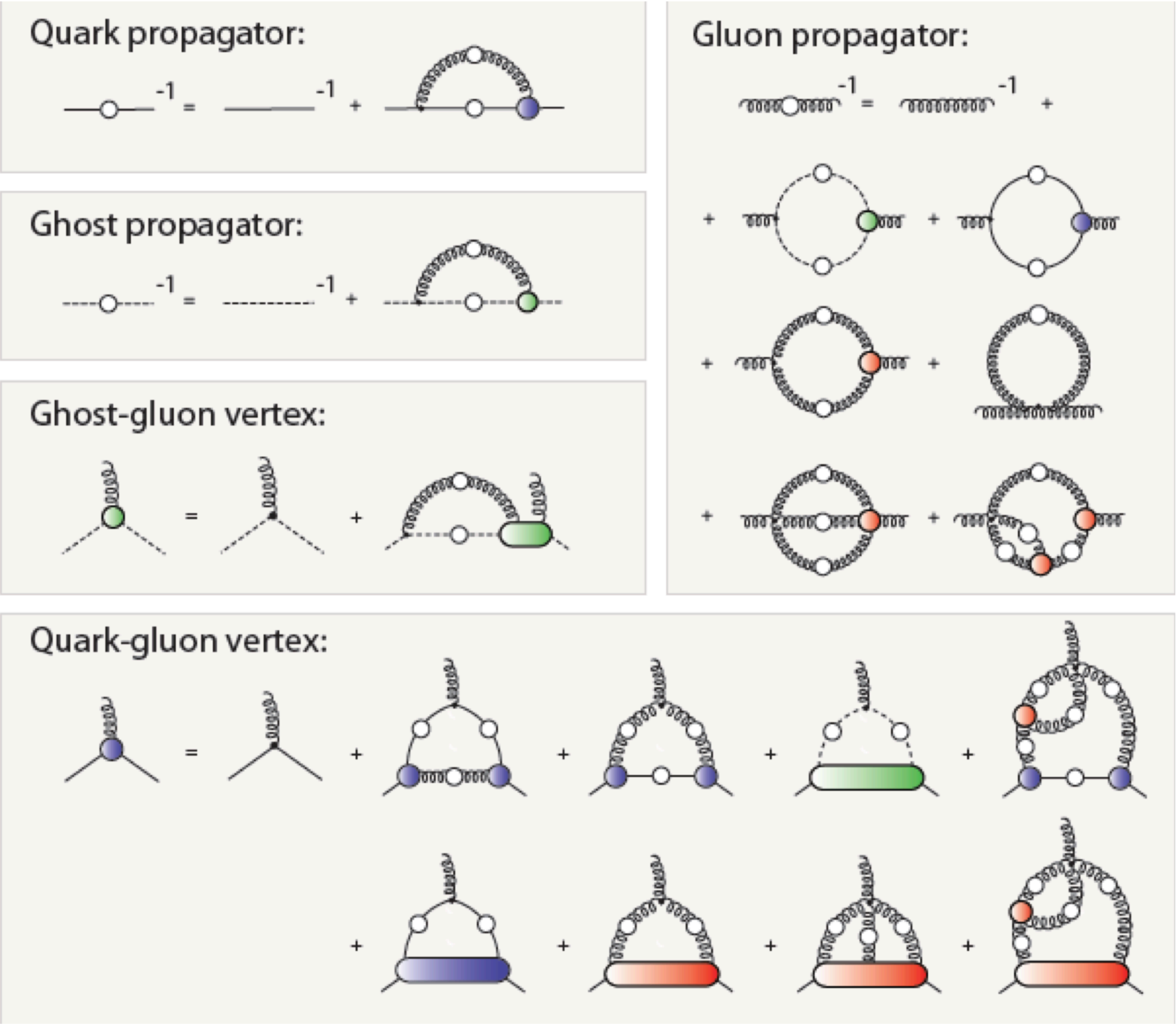
- no shortage of anomalies & multiquark candidates
- definite shortage of hybrid candidates!
- naive analysis can create states ⚠
- many "states" can appear to due to production (near) singularities, cusps, interferences ⚠
- much work remains to be done!

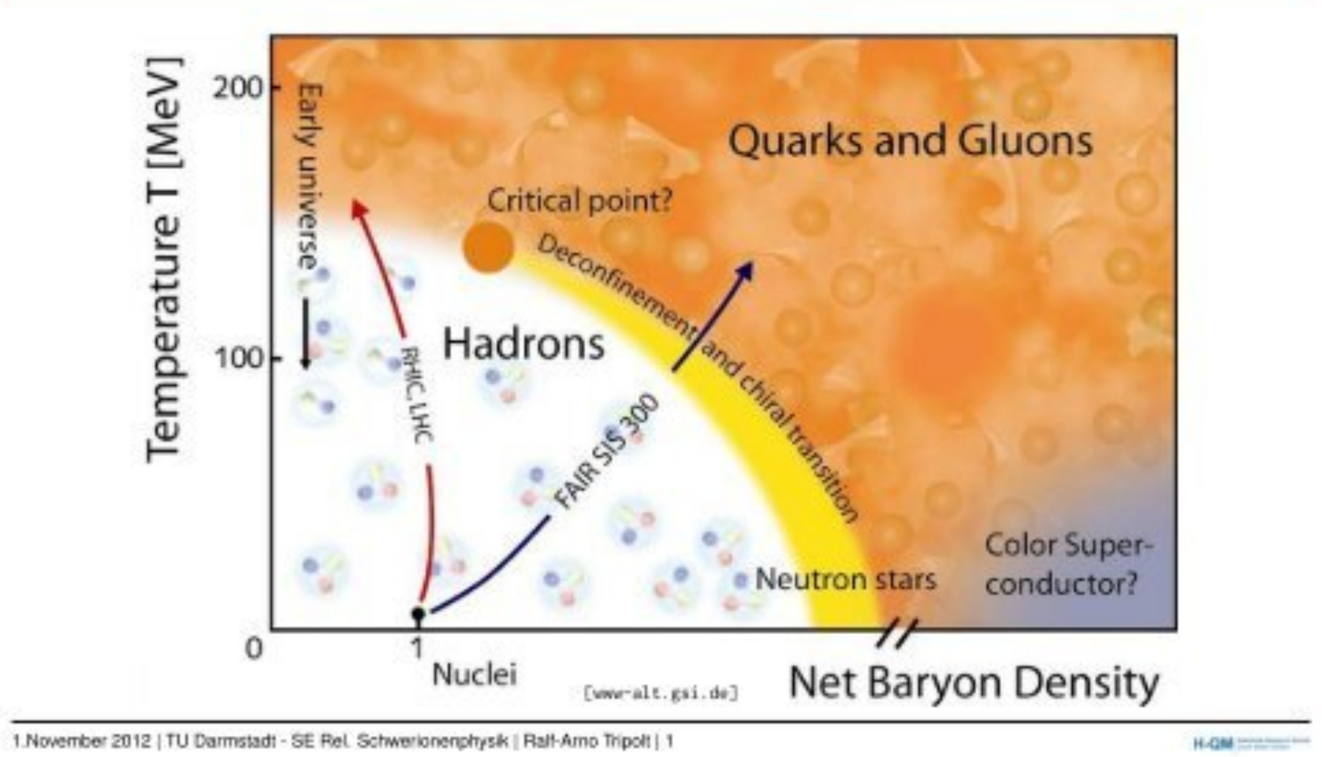
Rumsfeld hadronic matrix

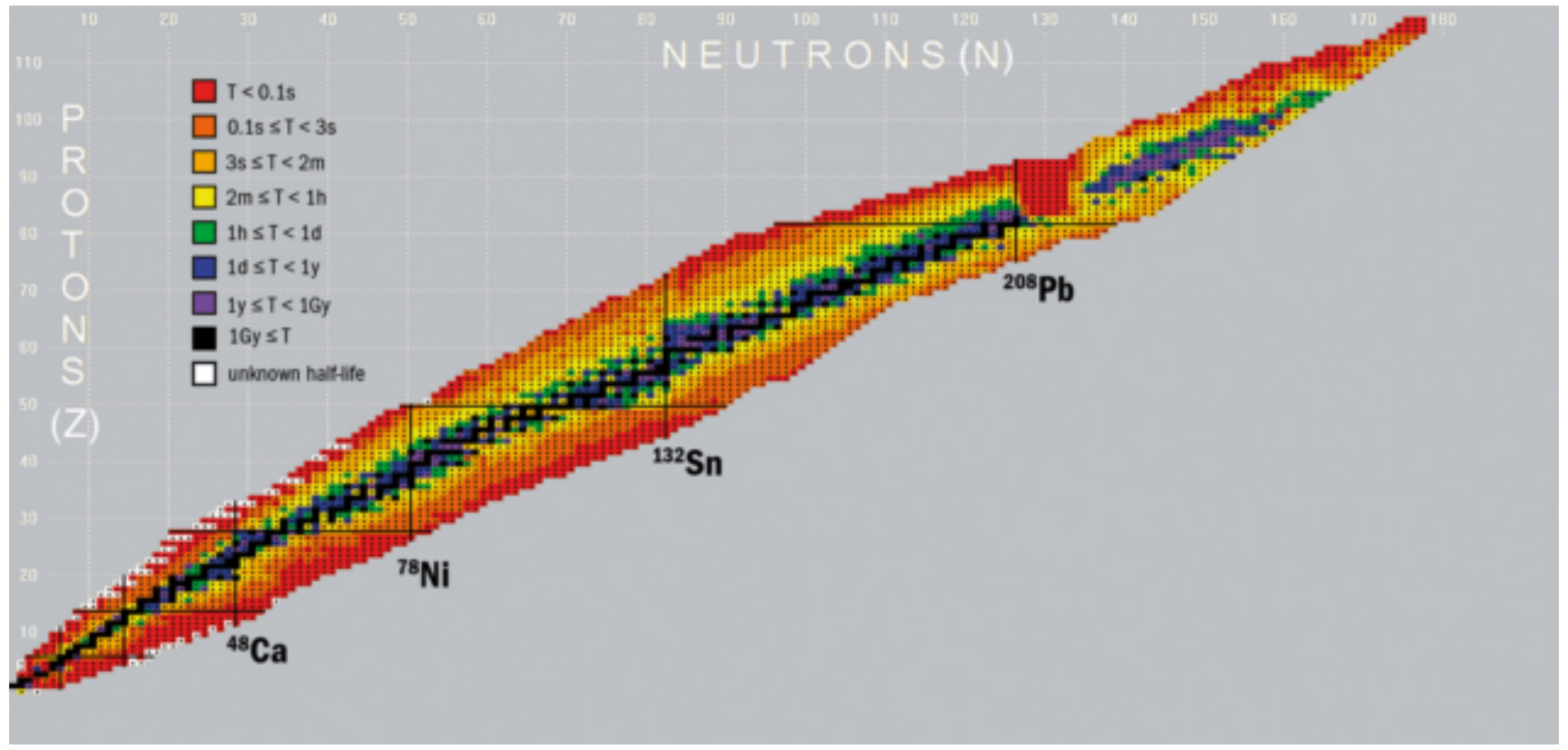
understood

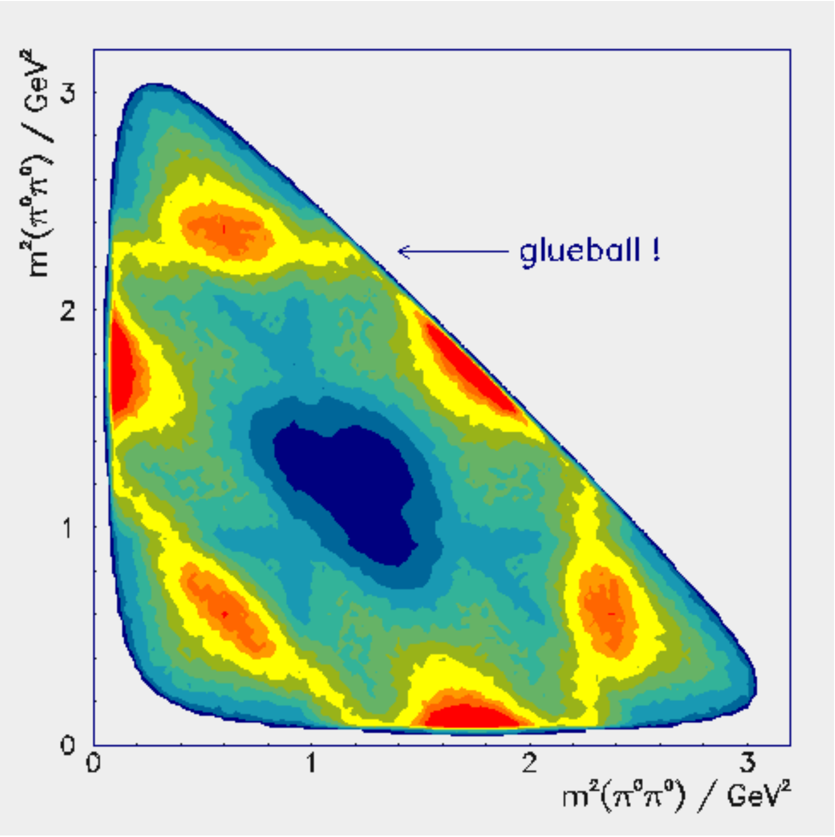
	expected	unexpected
seen		
not seen		?

The QCD Panoply


Quark propagator:
-1
=
-1
+
Ghost propagator:
-1
=
-1
+
Ghost-gluon vertex:
=
+
Gluon propagator:
-1
=
-1
+
Quark-gluon vertex:
=
+


Temperature T [MeV]
200
100
0
1
Early universe
Quarks and Gluons
Critical point?
Hadrons
RHIC, LHC
Deconfinement and chiral transition
FAIR SIS 300
Neutron stars
Color Super-conductor?
Nuclei
Net Baryon Density
1.November 2012 | TU Darmstadt - SE Rel. Schwerionenphysik | Ralf-Arno Tripolt | 1

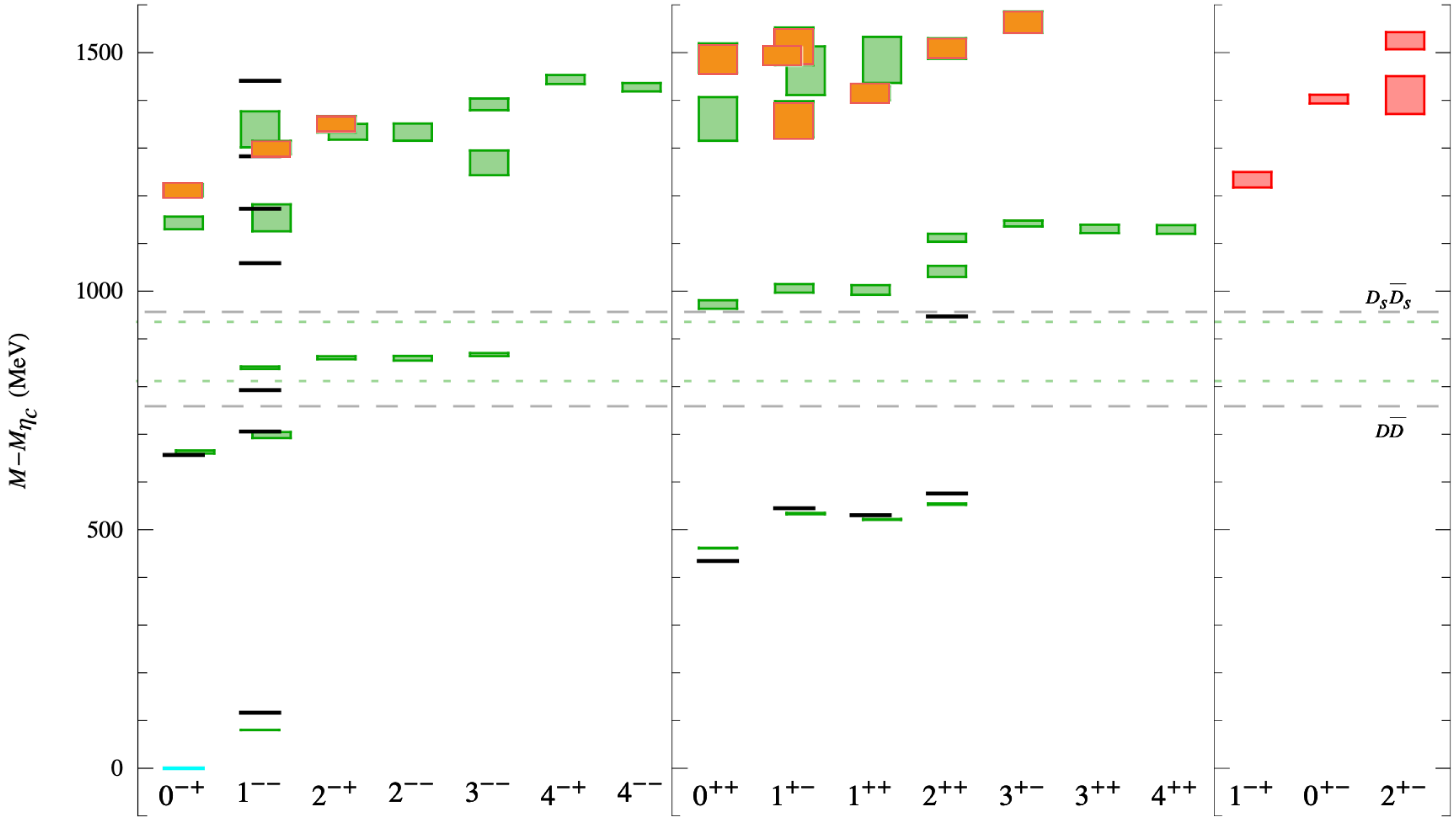

NEUTRONS (N)
PROTONS (Z)
T < 0.1s
0.1s ≤ T < 3s
3s ≤ T < 2m
2m ≤ T < 1h
1h ≤ T < 1d
1d ≤ T < 1y
1y ≤ T < 1Gy
1Gy ≤ T
unknown half-life
208Pb
132Sn
78Ni
48Ca


glueball !
m²(π⁰π⁰) / GeV²
m²(π⁰π⁰) / GeV²
0
1
2
3

Multi-quark States

“Vi har nu en model, der på smukke ste vis forklarer data og for første gang indeholder alle de begrænsninger, data giver,” sagde fysikeren Tim Burns fra Swansea University ved offentliggørelsen.

Gluonic Excitations

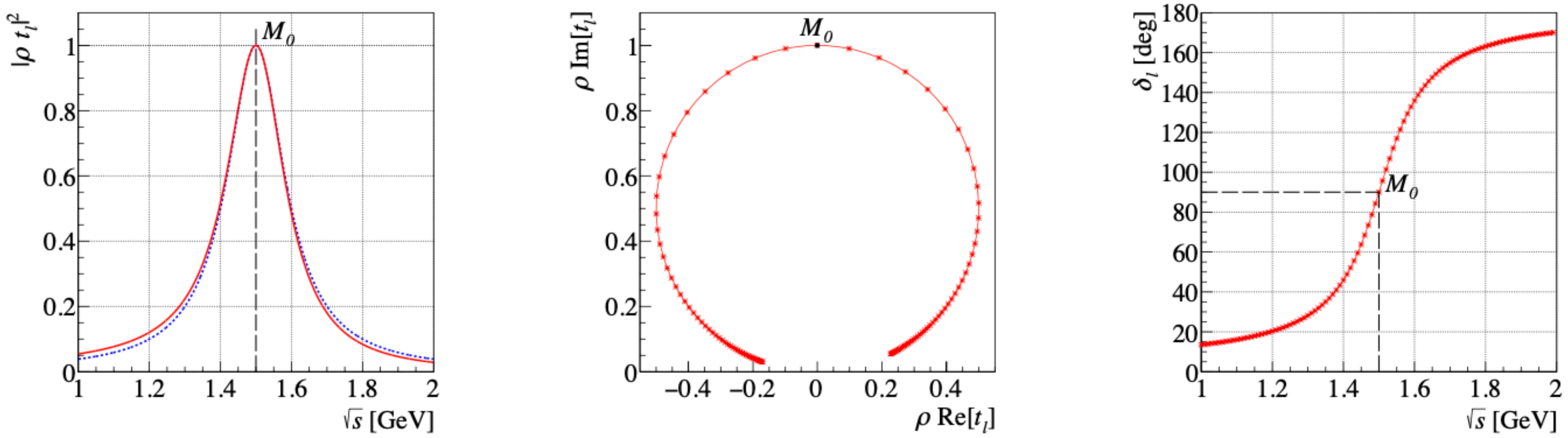


HadSpec, 1204.5425

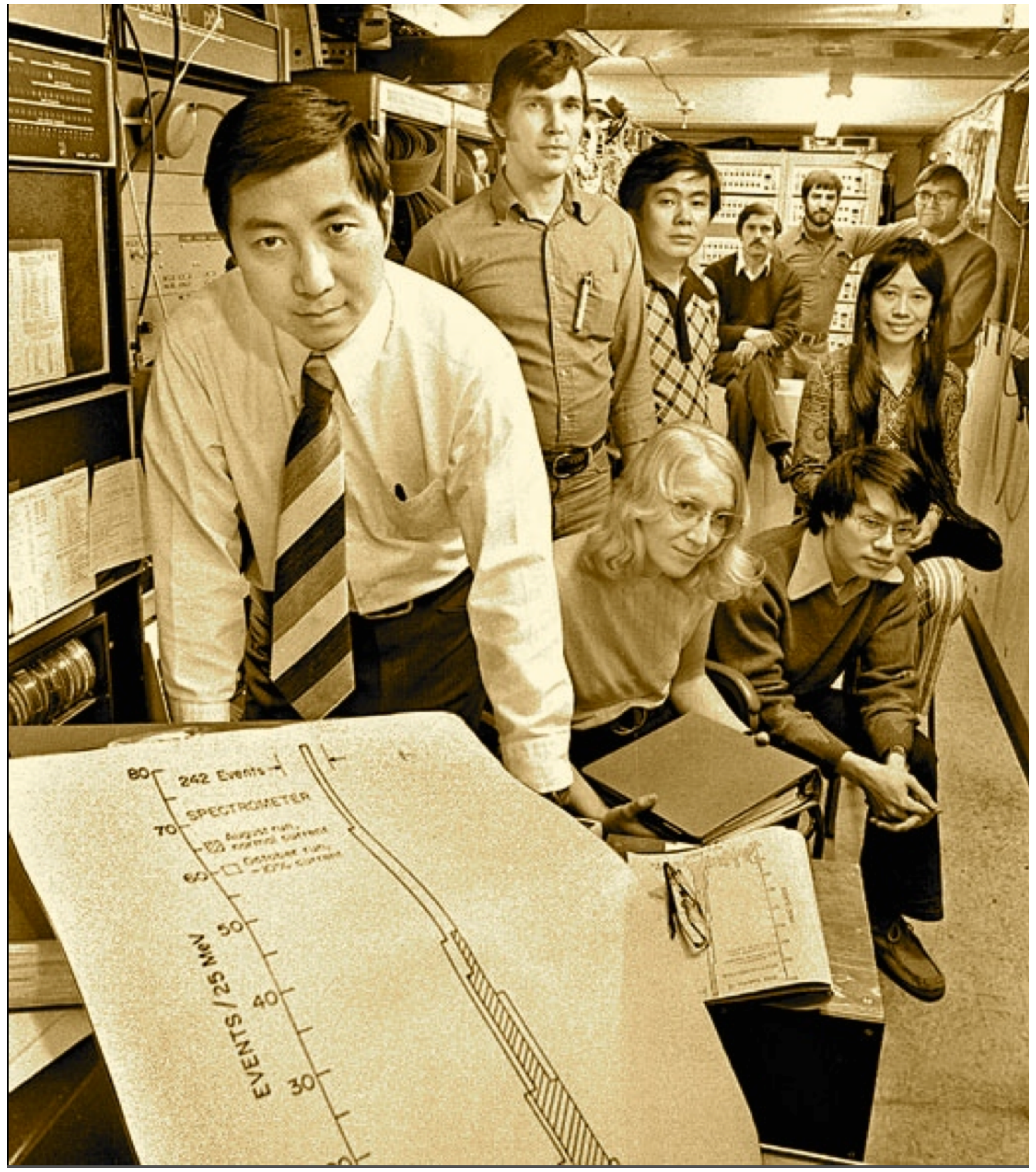
Comments on "Fitting"

"Not every bump is a resonance, not every resonance is a bump" - R. G. Moorhouse (1960s)

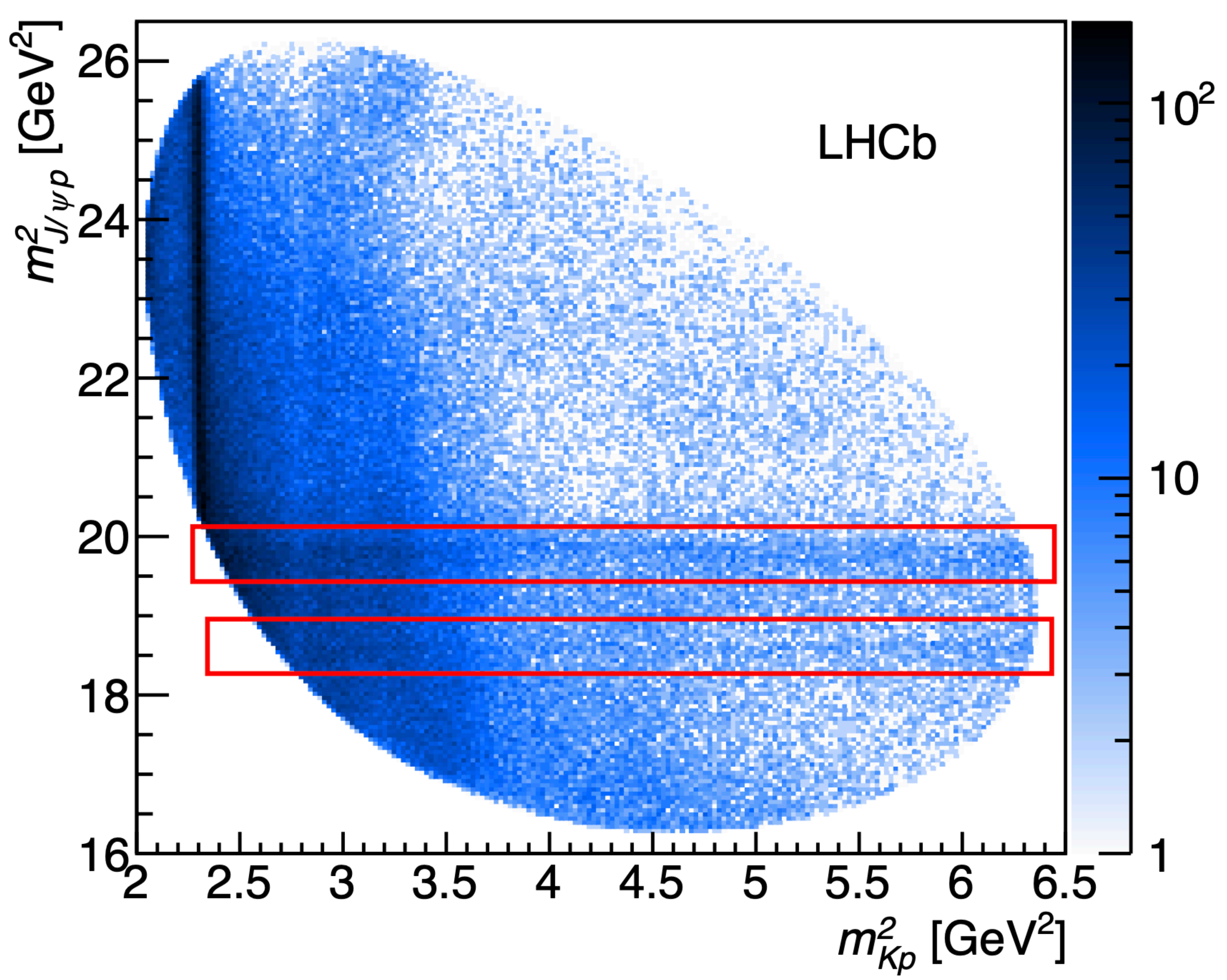
These days are over.

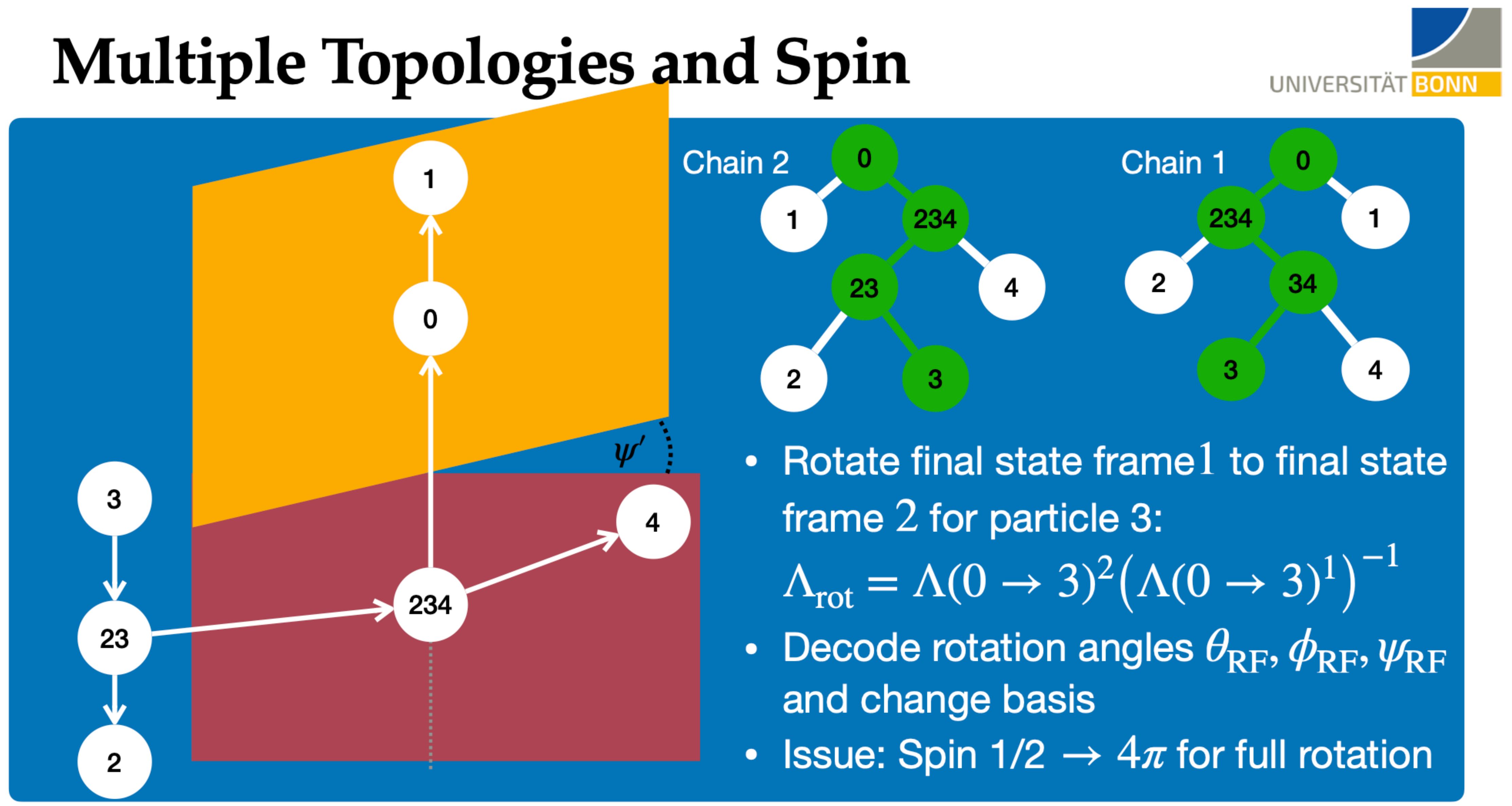


(a) (b) (c)

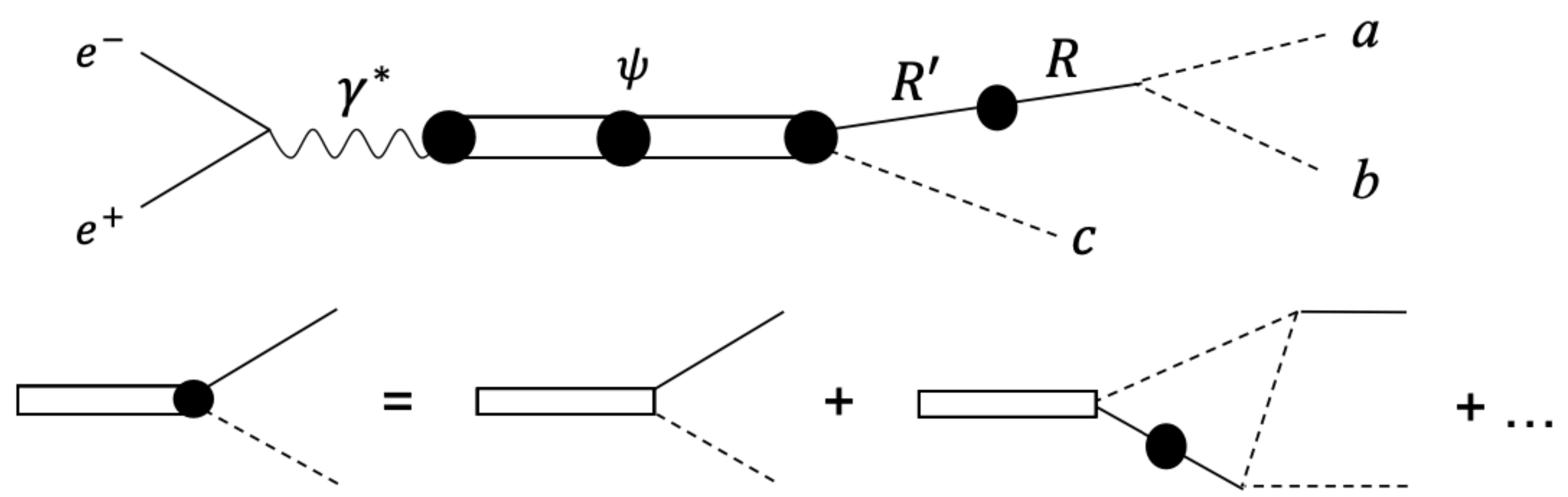


Present reality.



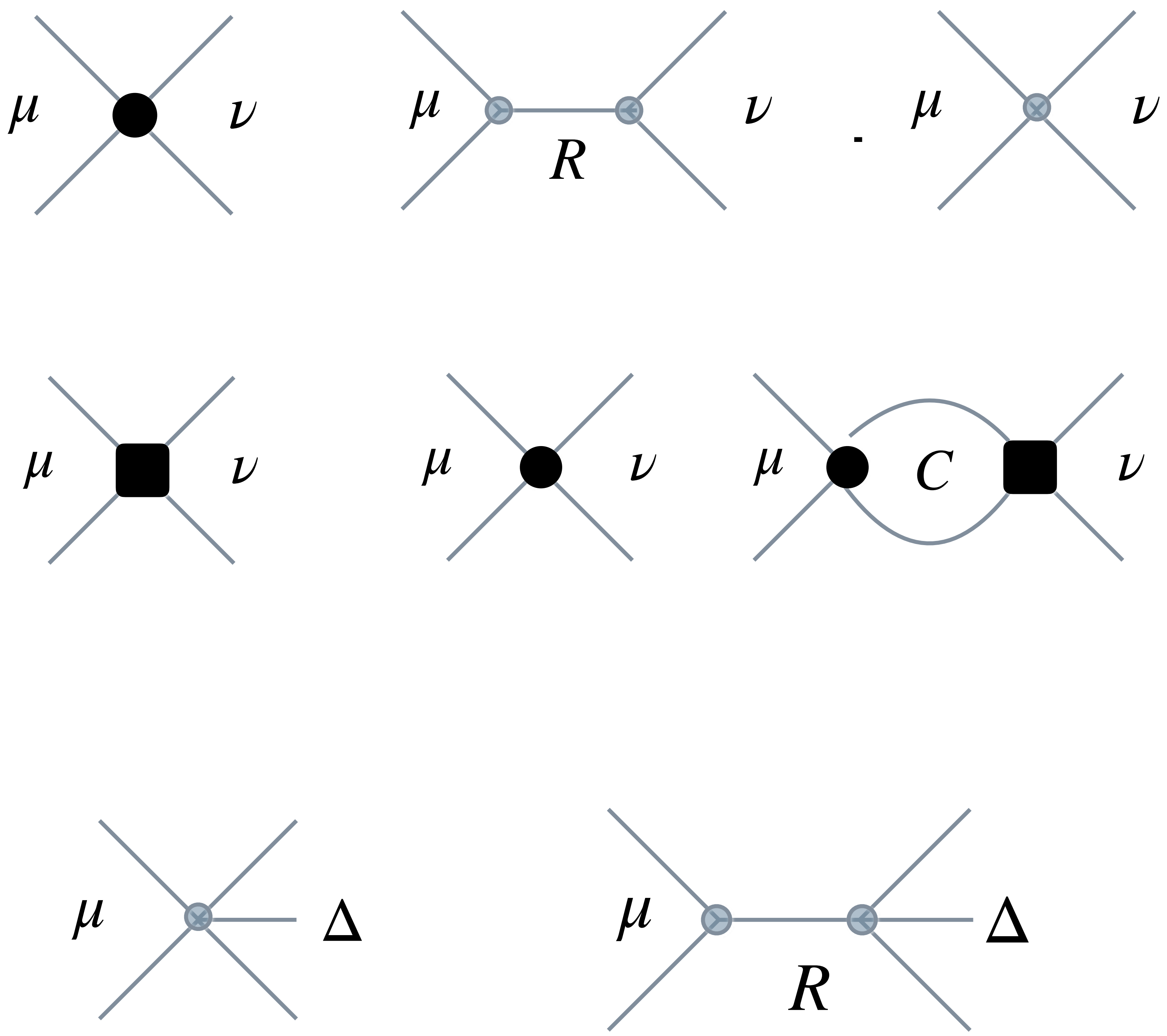


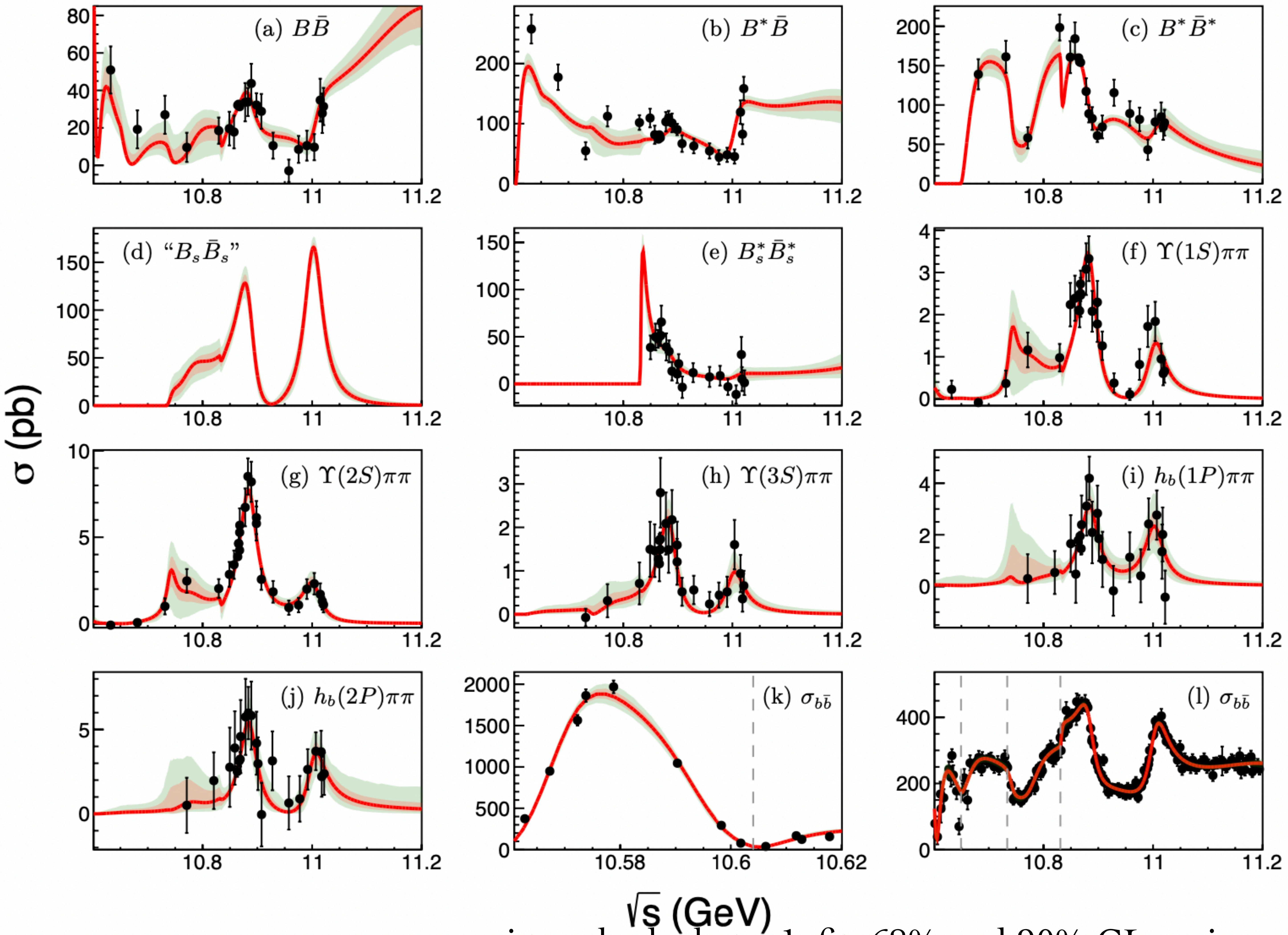
$$I(\Omega,\Phi) = 2\kappa \sum_k \Bigg\{ (1-P_\gamma) \Big| \sum_{\ell,m} [\ell]^{(-)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)] \Big|^2 + (1-P_\gamma) \Big| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Im}[Z^m_\ell(\Omega,\Phi)] \Big|^2 +$$
$$(1+P_\gamma) \Big| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)] \Big|^2 + (1+P_\gamma) \Big| \sum_{\ell,m} [\ell]^{(-)}_{m;k} \mathrm{Im}[Z^m_\ell(\Omega,\Phi)] \Big|^2 \Bigg\}$$



Vector Bottomonium

Coupled channel K-matrix

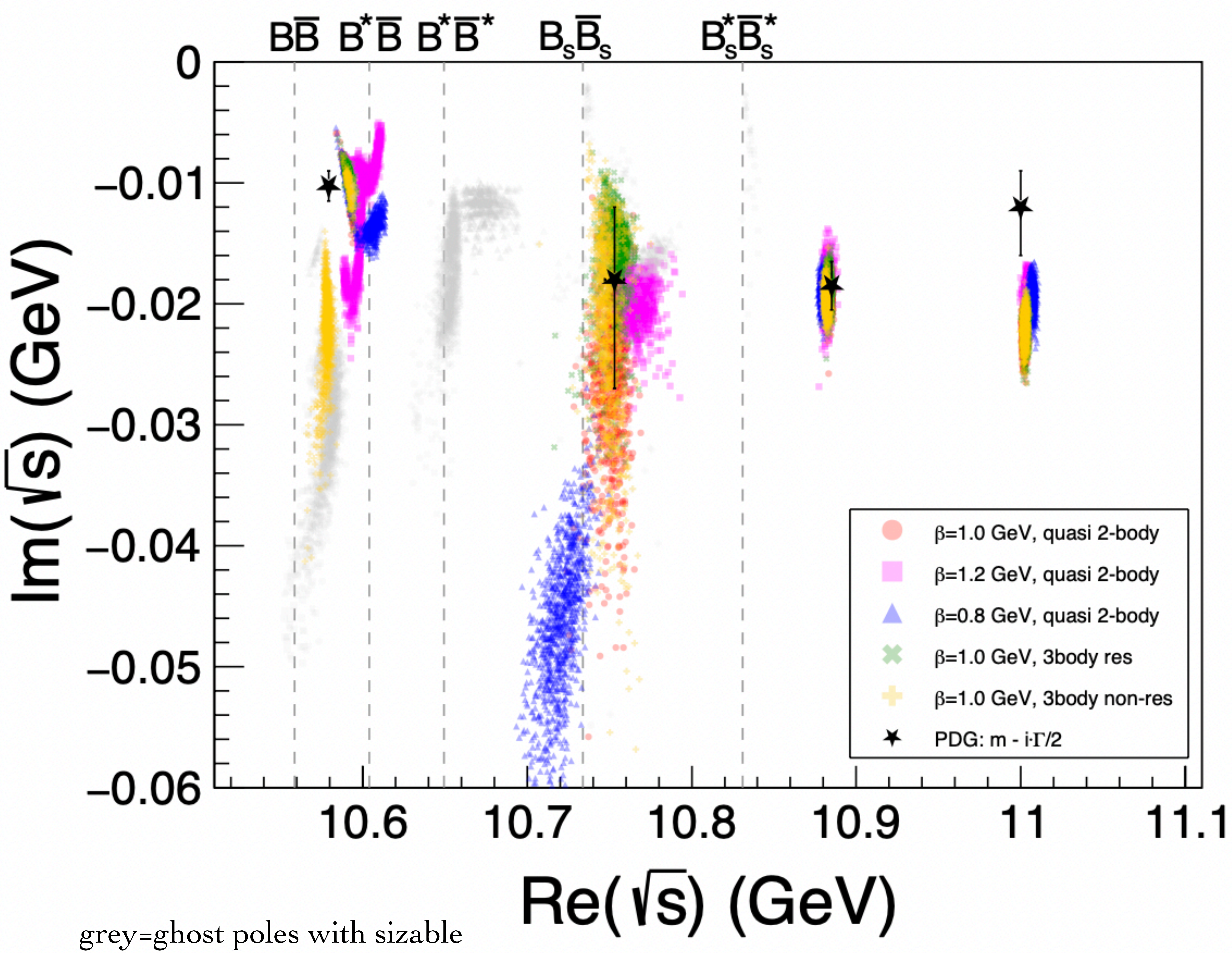




quasi two-body, beta=1, fit+68% and 90% CL regions

N. Hüsken, R.E. Mitchell, E.S. Swanson, 2204.11915

pole positions (+ 1000 bootstrap datasets)



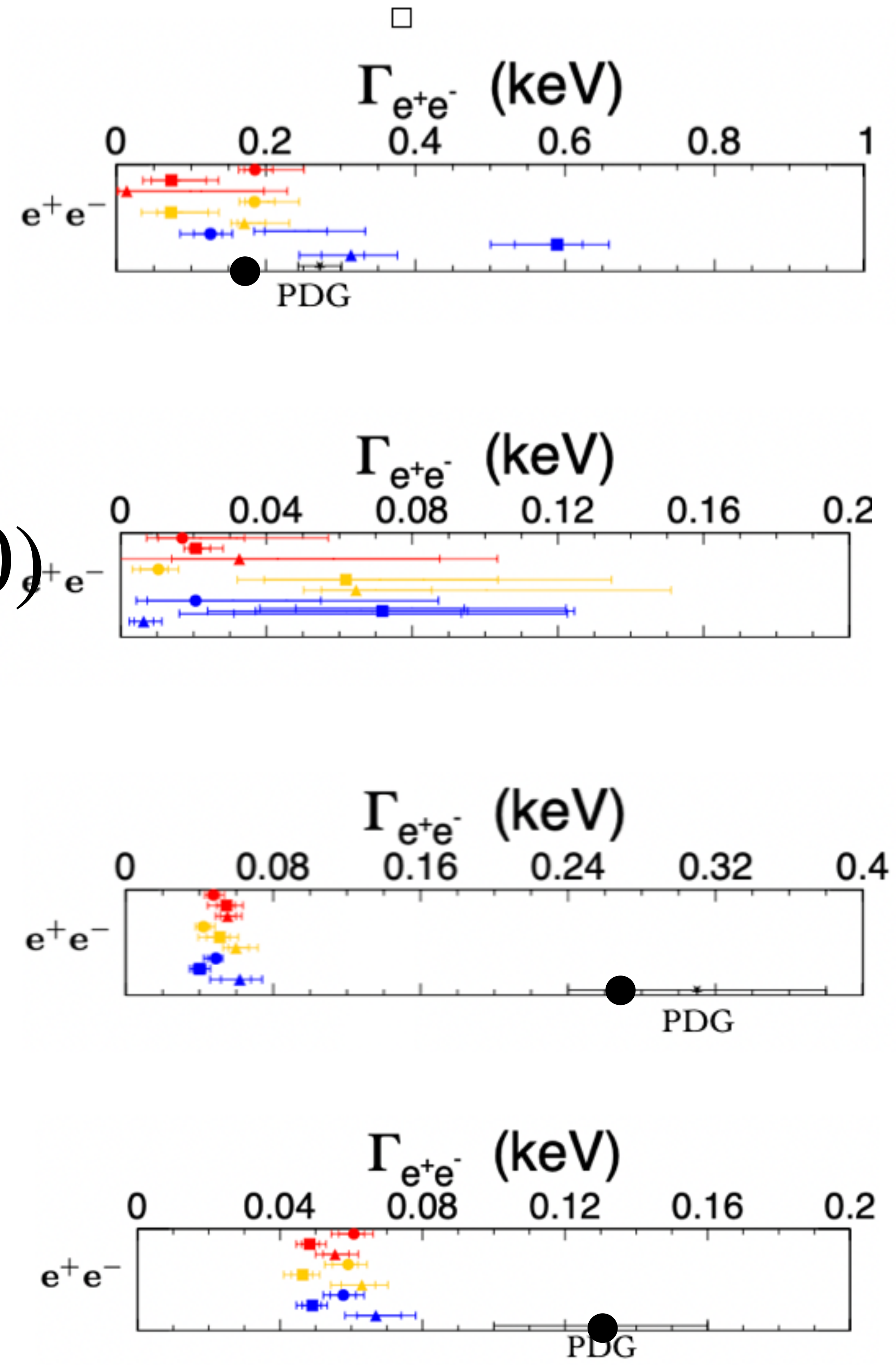
grey=ghost poles with sizable residues

$\Upsilon(4S)$

$\Upsilon(10750)$

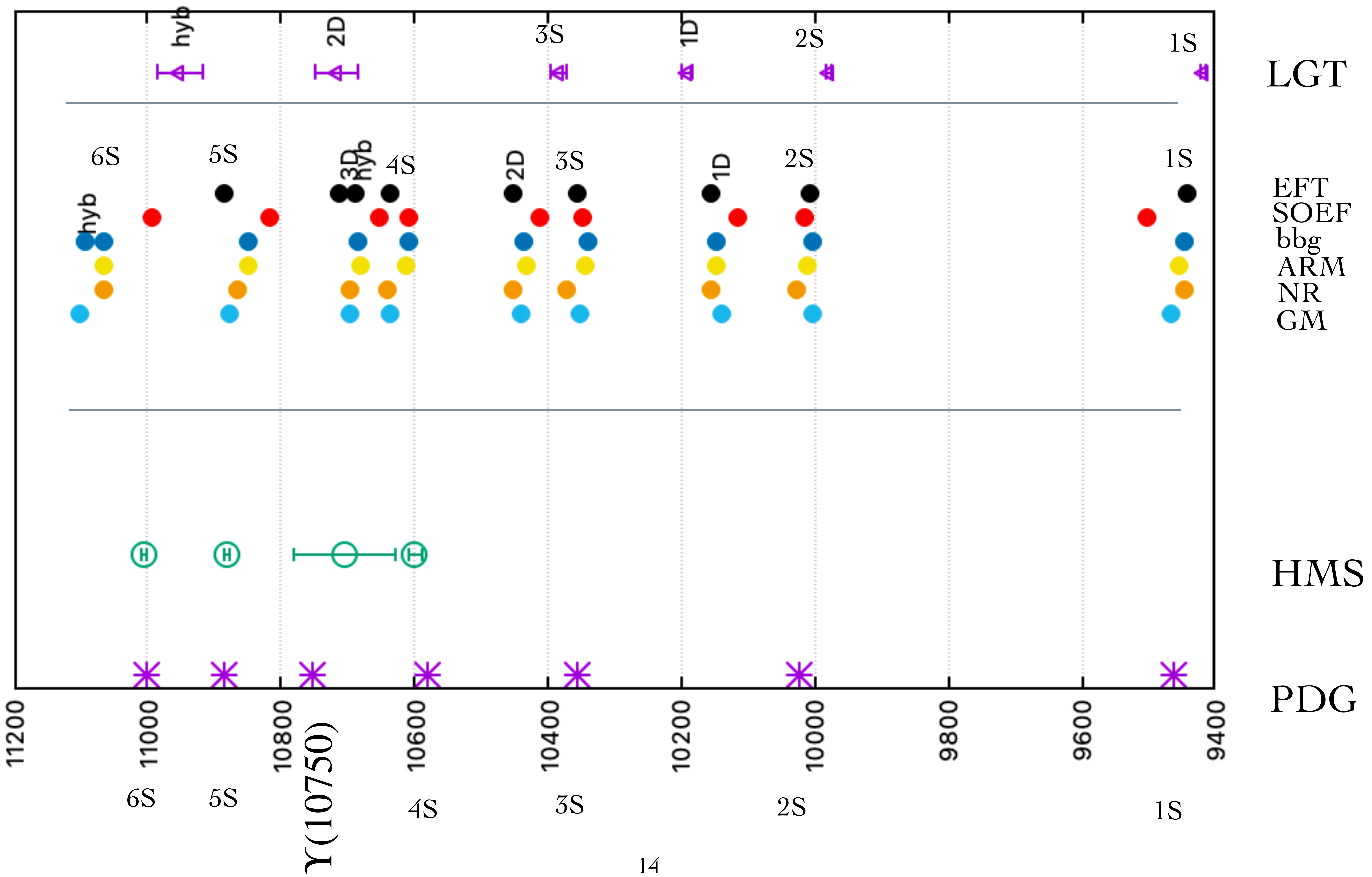
$\Upsilon(5S)$

$\Upsilon(6S)$

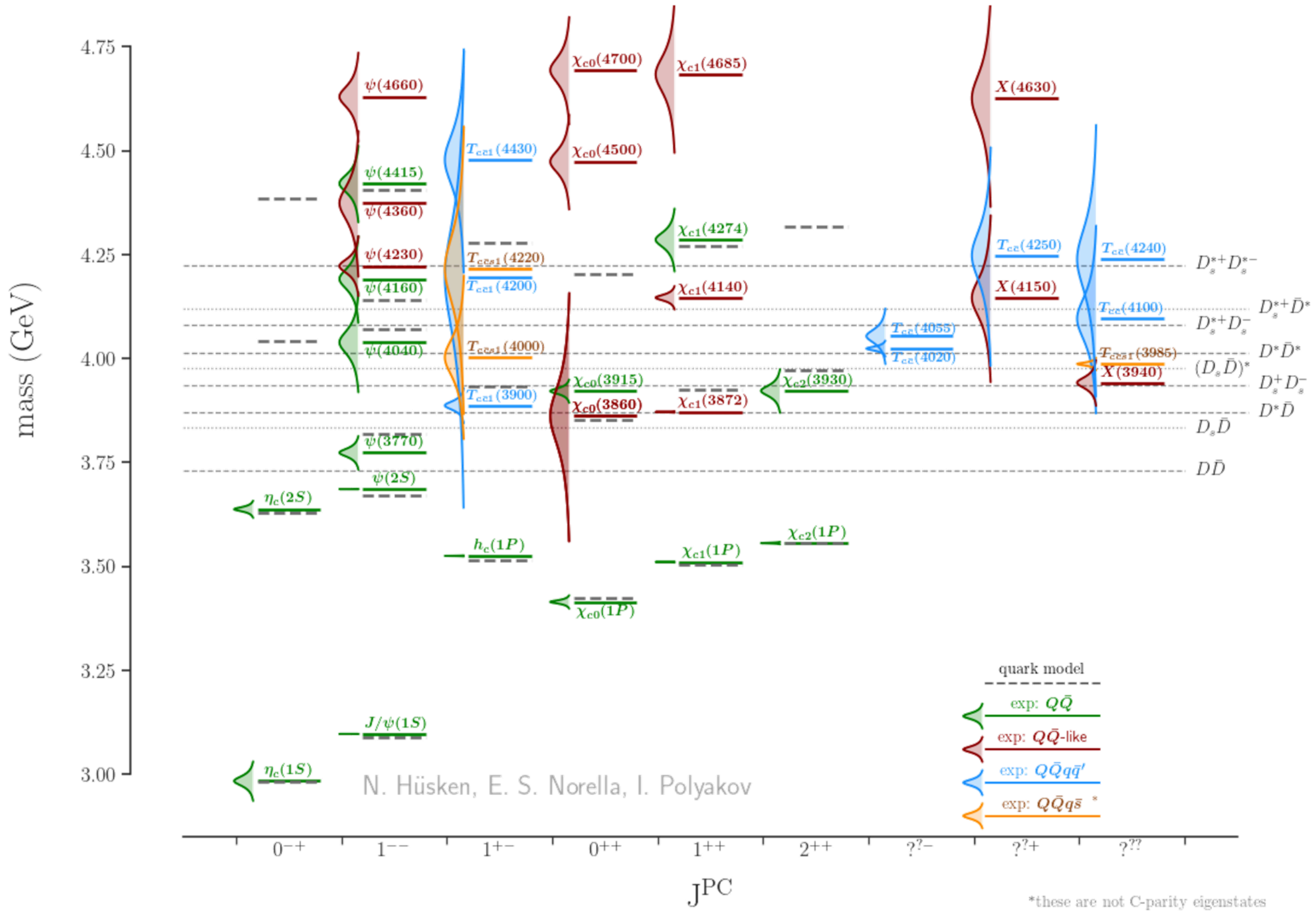


"masses"

[BW params, poles, quark model eigenvalues, LGT plateaus]



Charmonia



mass (GeV)
J^PC
0−+
1−−
1+−
0++
1++
2++
??−
??+
???
ηc(1S)
ηc(2S)
J/ψ(1S)
ψ(2S)
ψ(3770)
ψ(4040)
ψ(4160)
ψ(4230)
ψ(4360)
ψ(4415)
ψ(4660)
hc(1P)
Tcc̄1(3900)
Tcc̄s1(4000)
Tcc̄1(4200)
Tcc̄s1(4220)
Tcc̄1(4430)
χc0(1P)
χc0(3860)
χc0(3915)
χc0(4500)
χc0(4700)
χc1(1P)
χc1(3872)
χc1(4140)
χc1(4274)
χc1(4685)
χc2(1P)
χc2(3930)
Tcc̄(4020)
Tcc̄(4055)
X(4150)
Tcc̄(4250)
X(4630)
X(3940)
Tcc̄s1(3985)
Tcc̄(4100)
Tcc̄(4240)
DD̄
DsD̄
D*D̄
Ds+Ds−
(DsD̄)*
D*D̄*
Ds*+Ds−
Ds*+D̄*
Ds*+Ds*−
quark model
exp: QQ̄
exp: QQ̄-like
exp: QQ̄qq̄′
exp: QQ̄qs̄ *
N. Hüsken, E. S. Norella, I. Polyakov
*these are not C-parity eigenstates

The R(3900) [prev. G(3900)]

$e^+e^- \to D\bar{D}$

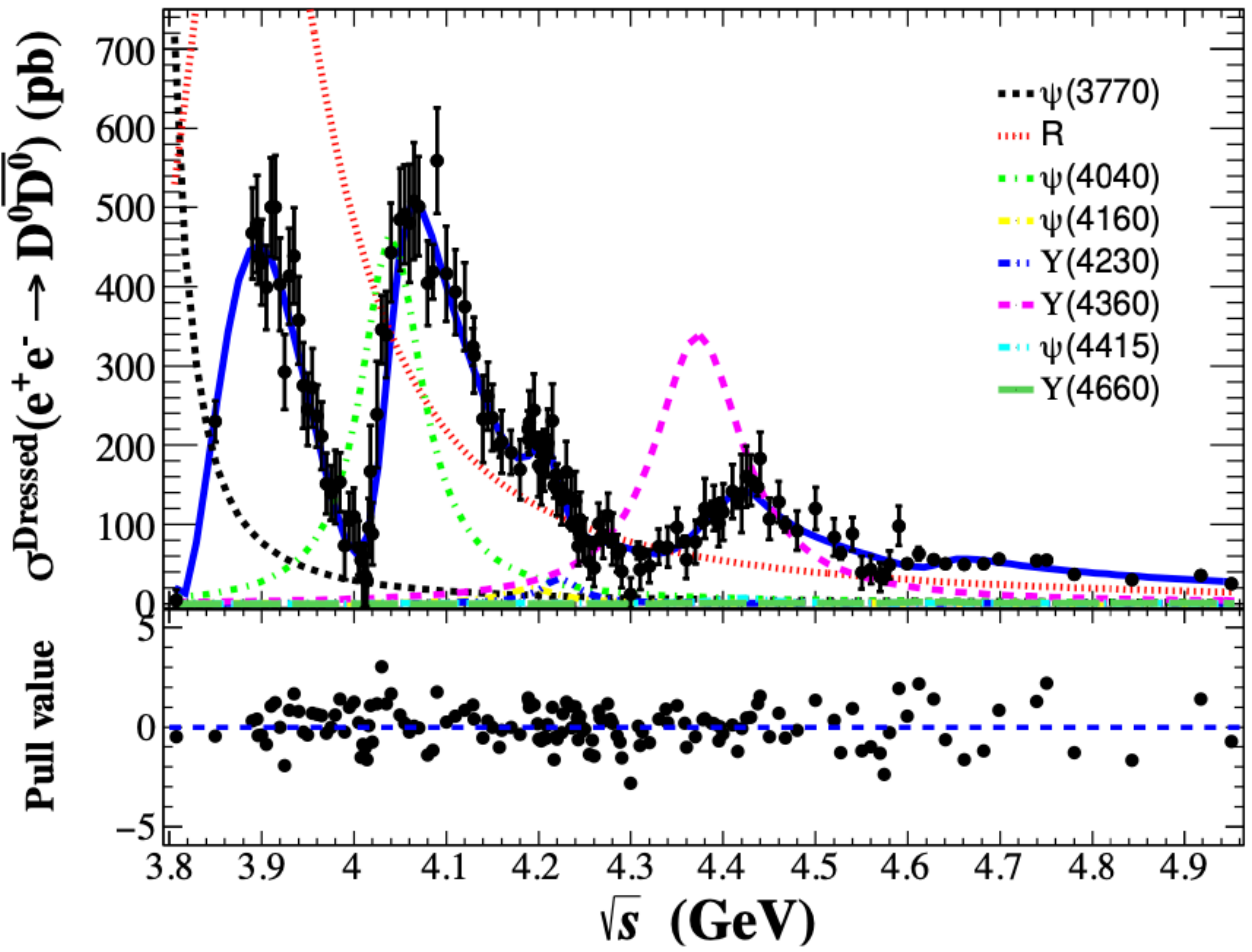


TABLE I. Fit results of the Born cross section, where the first uncertainties are the statistical and the second are systematic and S denotes the significance.

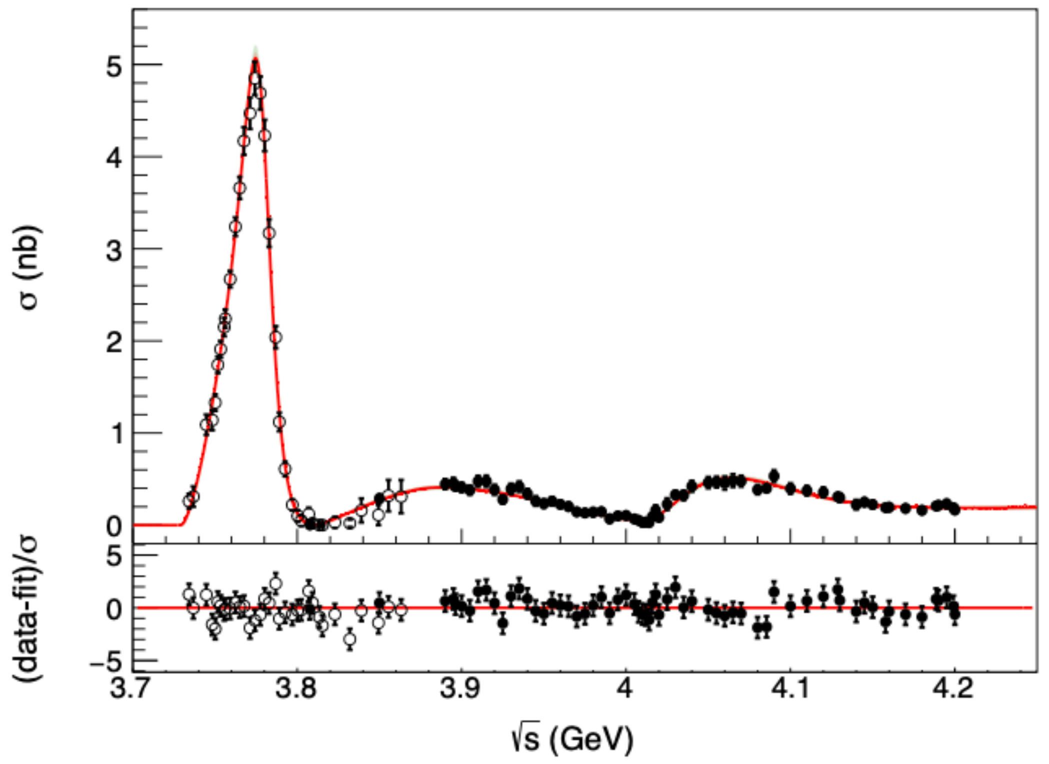
	$e^+e^- \to D\bar{D}$							
Resonance	$\psi(3770)$	R	$\psi(4040)$	$\psi(4160)$	$Y(4230)$	$Y(4360)$	$\psi(4415)$	$Y(4660)$
Mass (MeV/c^2)	3773.7 (fixed)	3872.5±14.2±3.0	4039 (fixed)	4191 (fixed)	4222.5 (fixed)	4374 (fixed)	4421 (fixed)	4630 (fixed)
Width (MeV/c^2)	87.6 (fixed)	179.7±14.1±7.0	80 (fixed)	70 (fixed)	48 (fixed)	118 (fixed)	62 (fixed)	72 (fixed)
$\Gamma_{ee}\mathcal{B}$ (eV)	95-106	202-292	41-44	1-2	1-2	50-144	0-2	0-1
S(σ)	10	>20	13	7	11	11	4	8
χ^2/d.o.f = 346/275				p-value = 0.002				

BESIII, 2402.03829

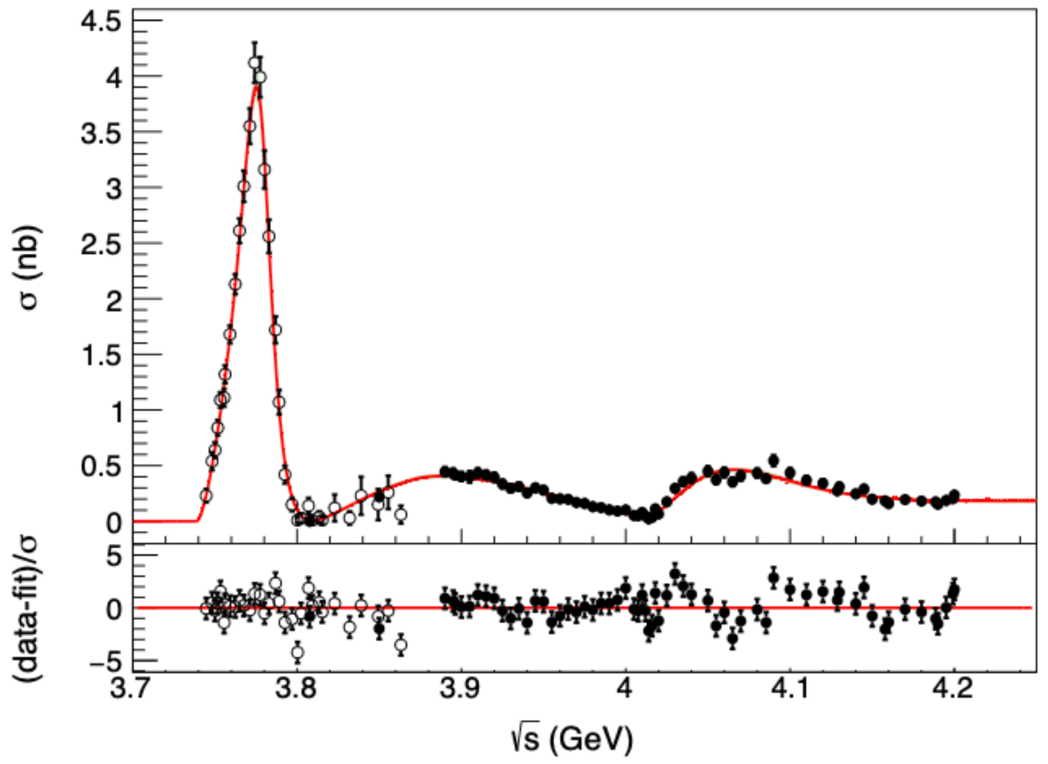
Analyse coupled channels with K-matrix

Feature is explained by channel threshold & interference

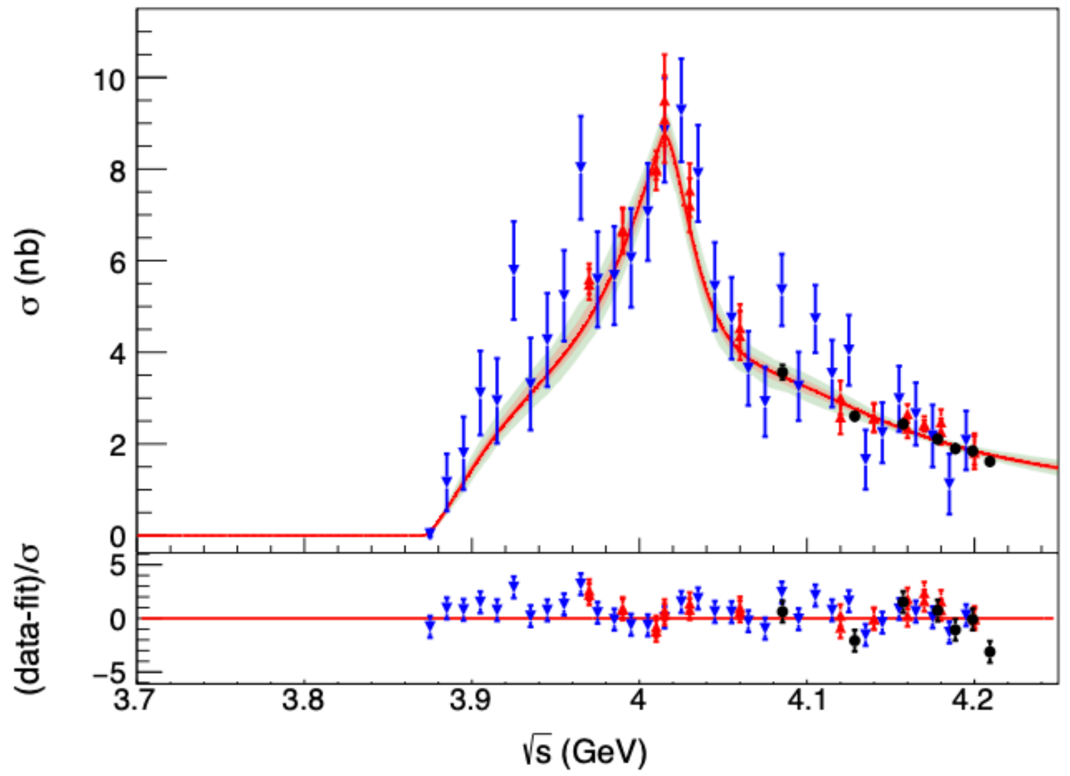
$e^+e^- \to D^0\bar{D}^0$



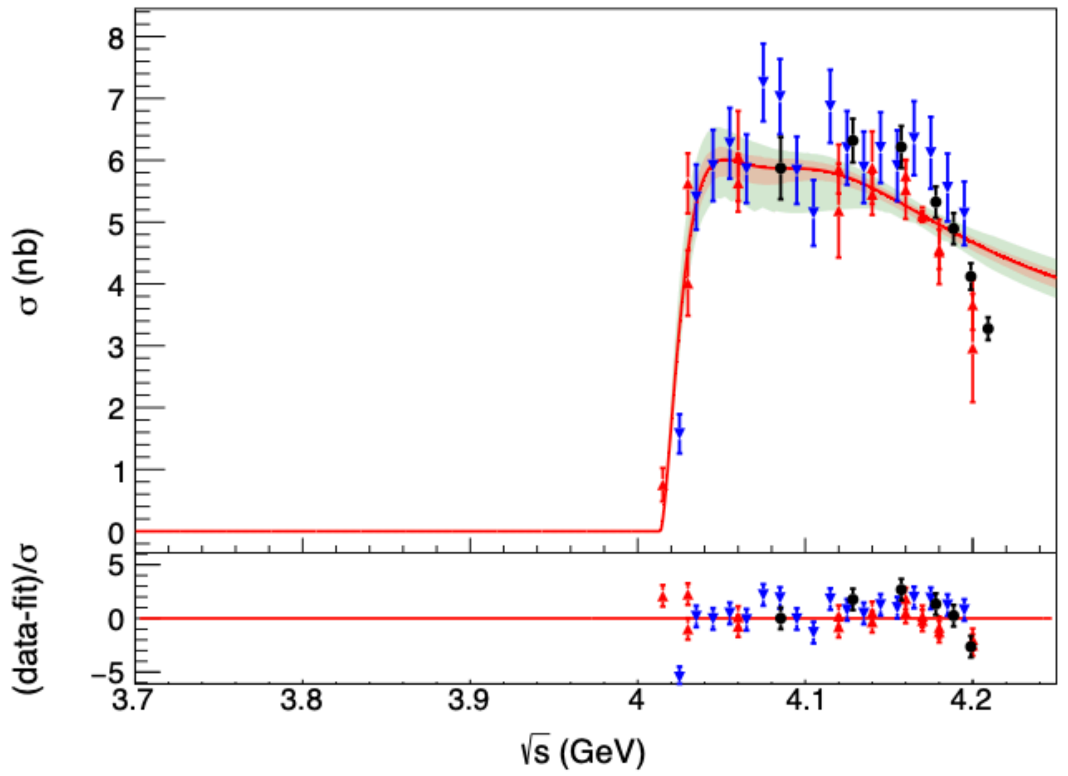
$e^+e^- \to D^+D^-$



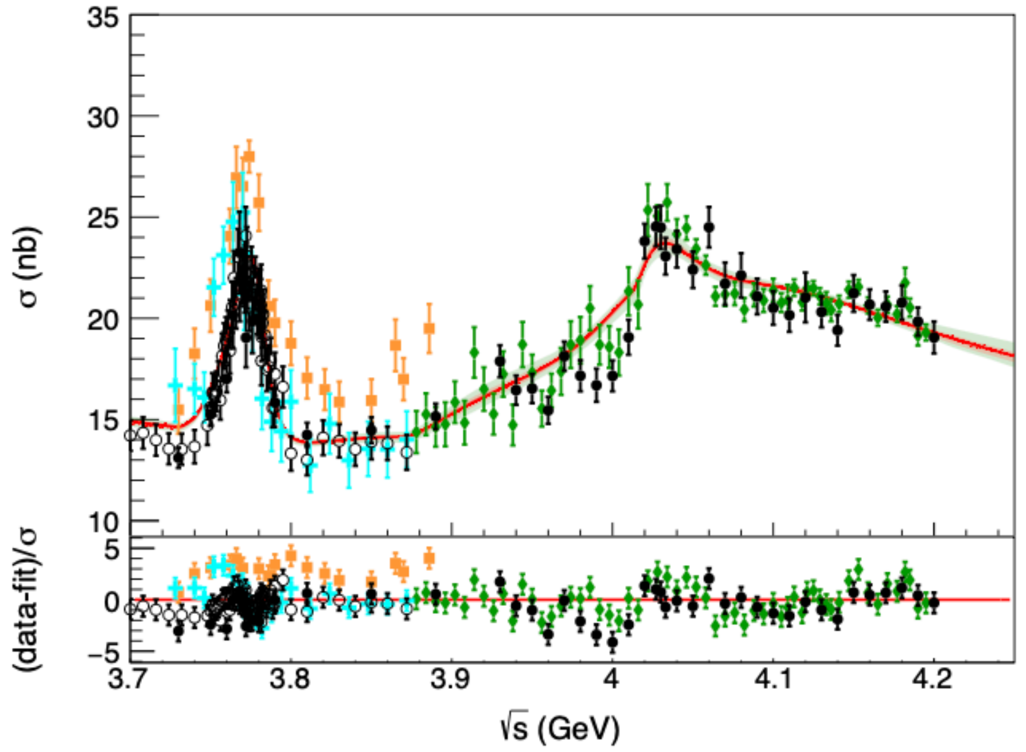
$e^+e^- \to D^*\bar{D}$

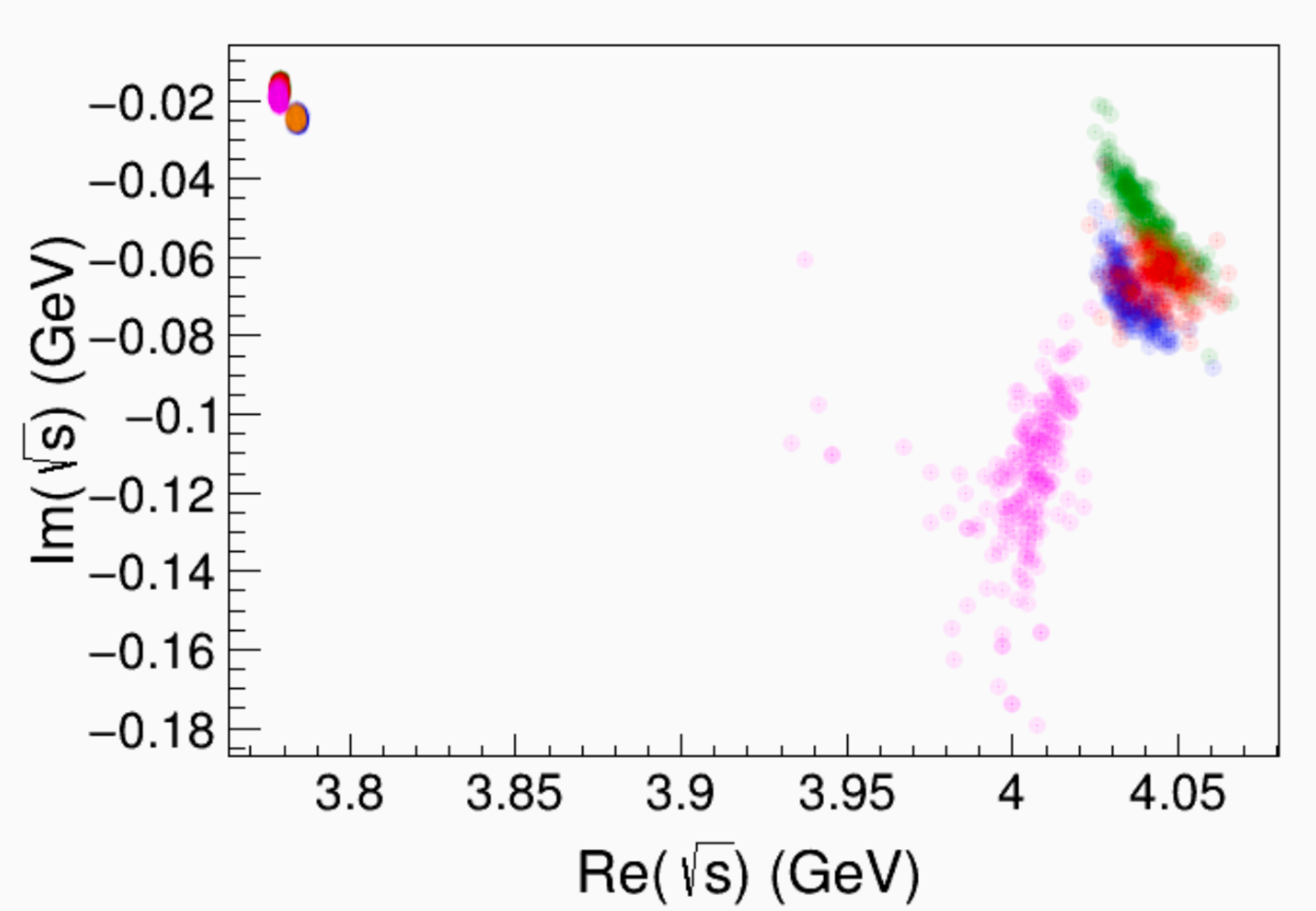


$e^+e^- \to D^*\bar{D}^*$



$e^+e^- \to$ hadrons





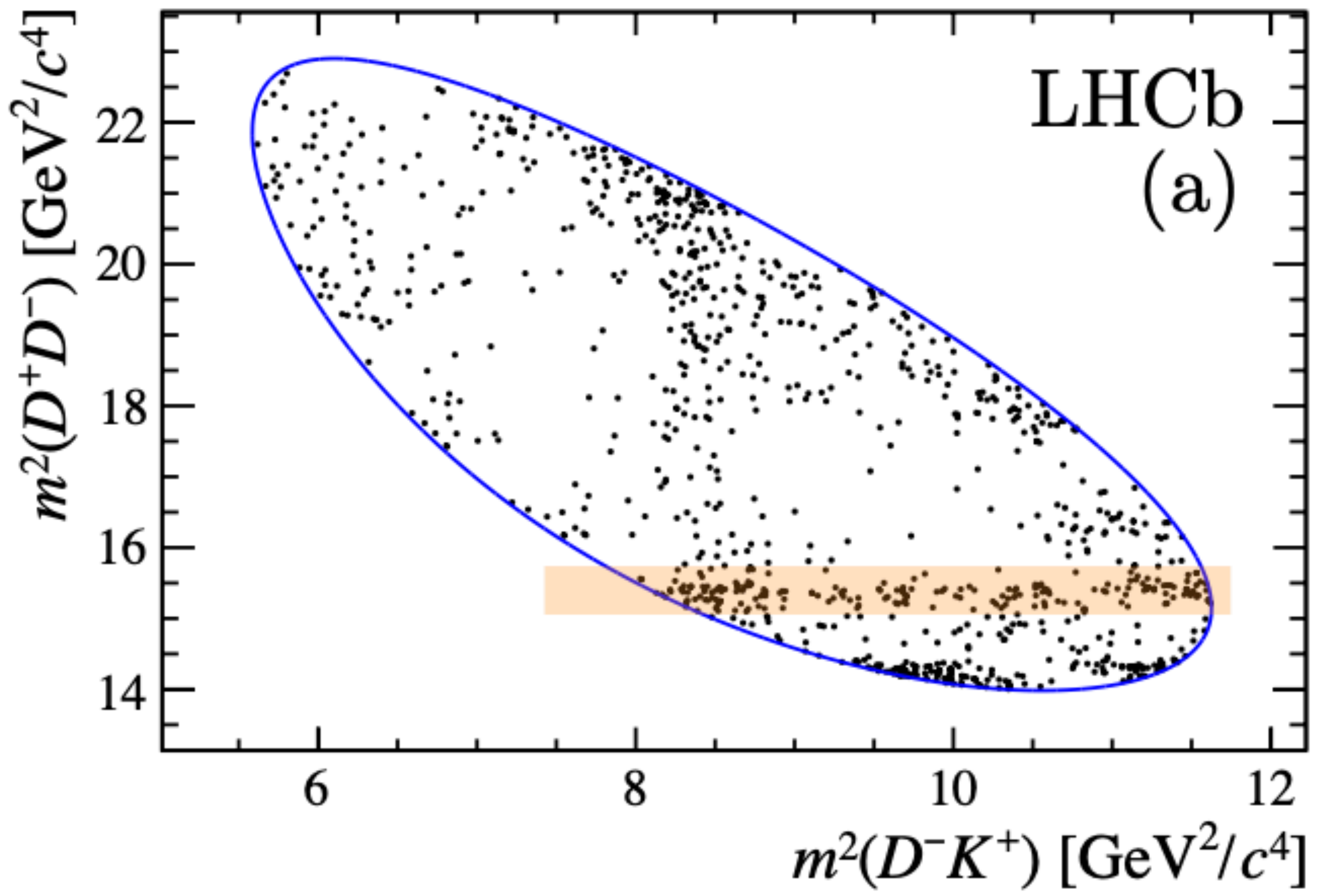
Nils Hüsken, Richard F. Lebed, Ryan E. Mitchell, Eric S. Swanson, Ya-Qian Wang. 2404.03896

Canonical Charmonia

$\chi_{c0}(3930)$ & $\chi_{c2}(3930)$

LHCb: PRL 125 (2020) 242001
LHCb: PRD 102 (2020) 112003

$B^+ \to D^+D^-K^+$ Dalitz Plot

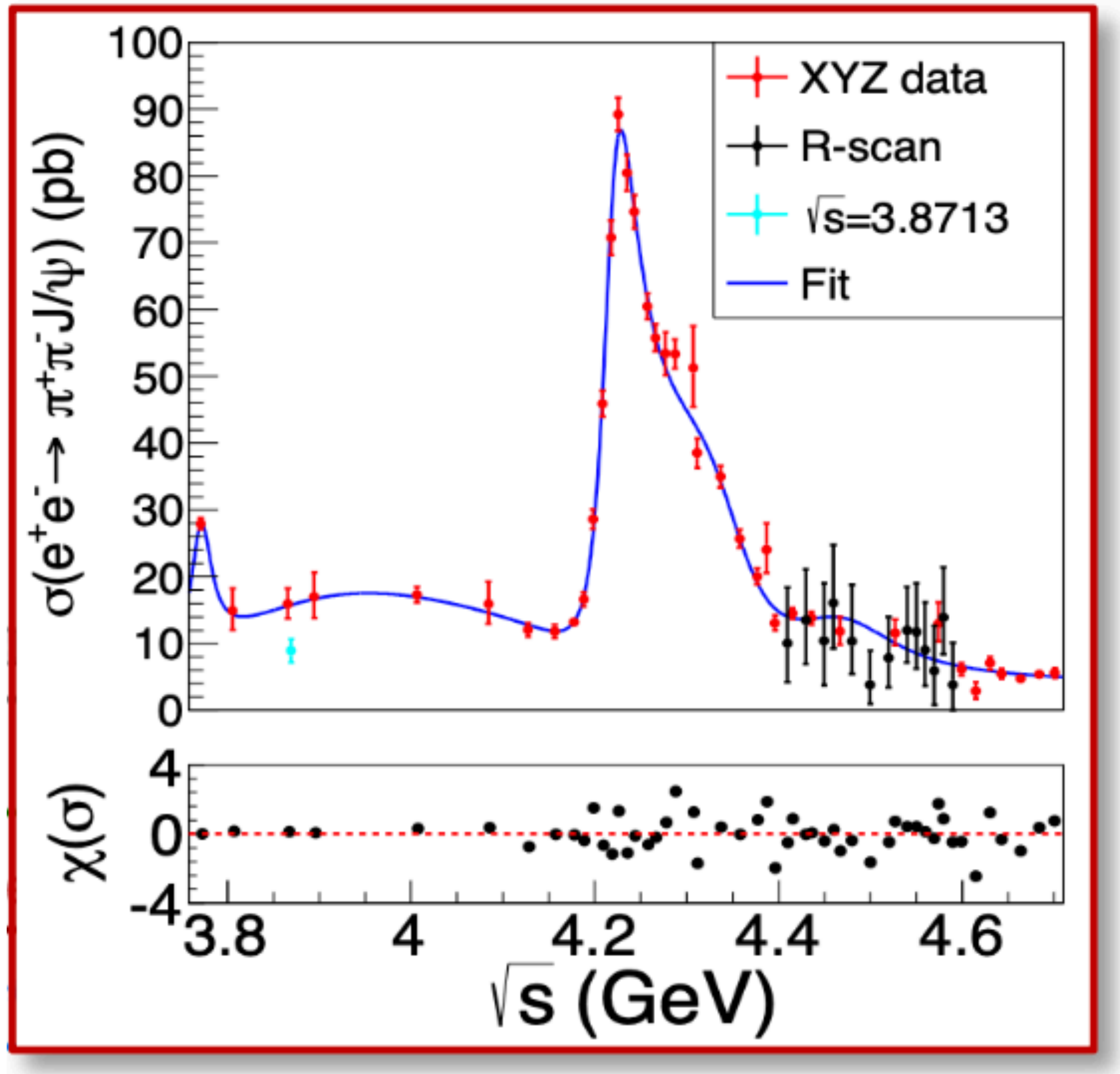


Previously observed $\chi_c(3930)$ seen as two states

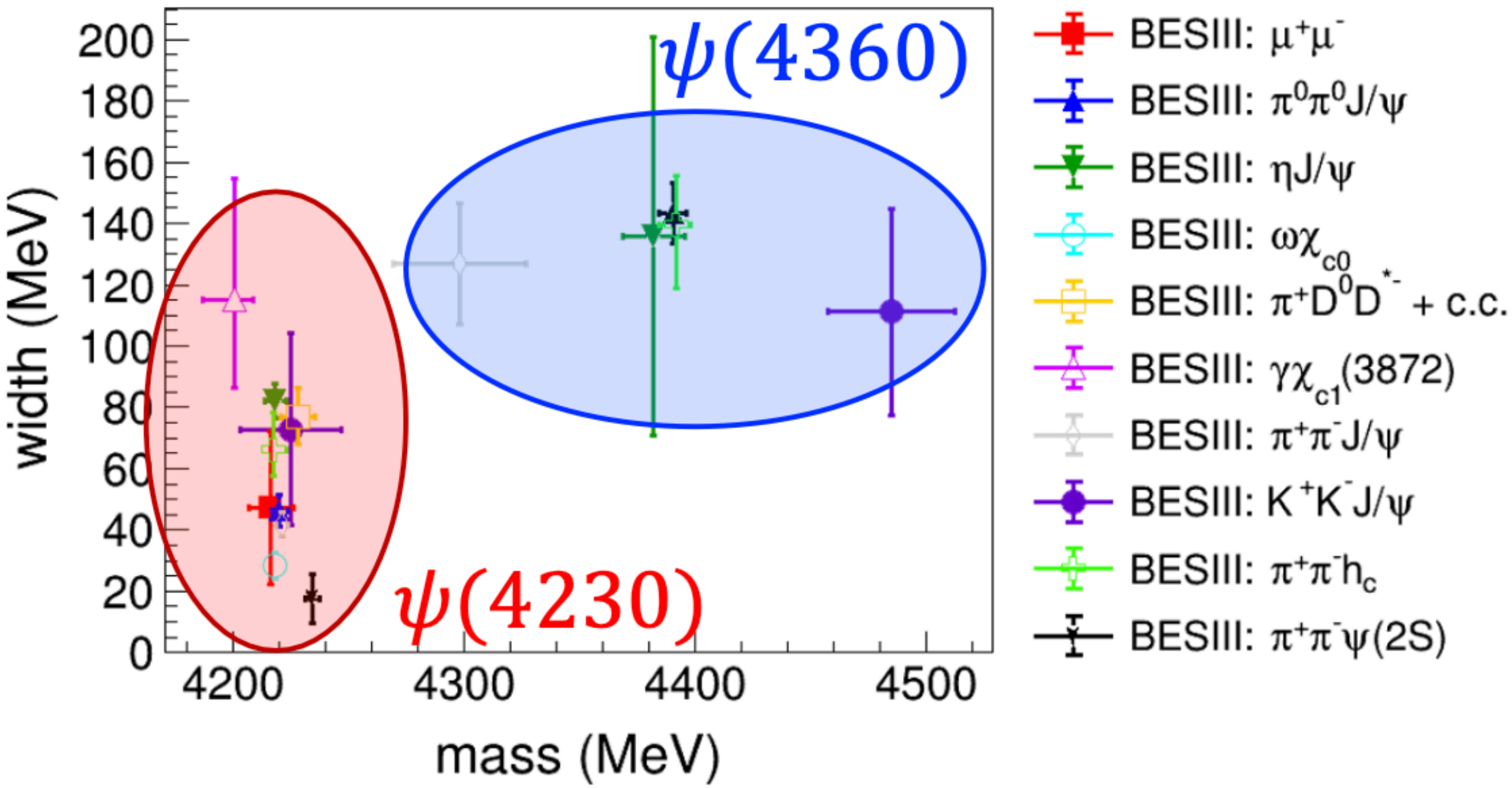
$\chi_{c0}(3930)$

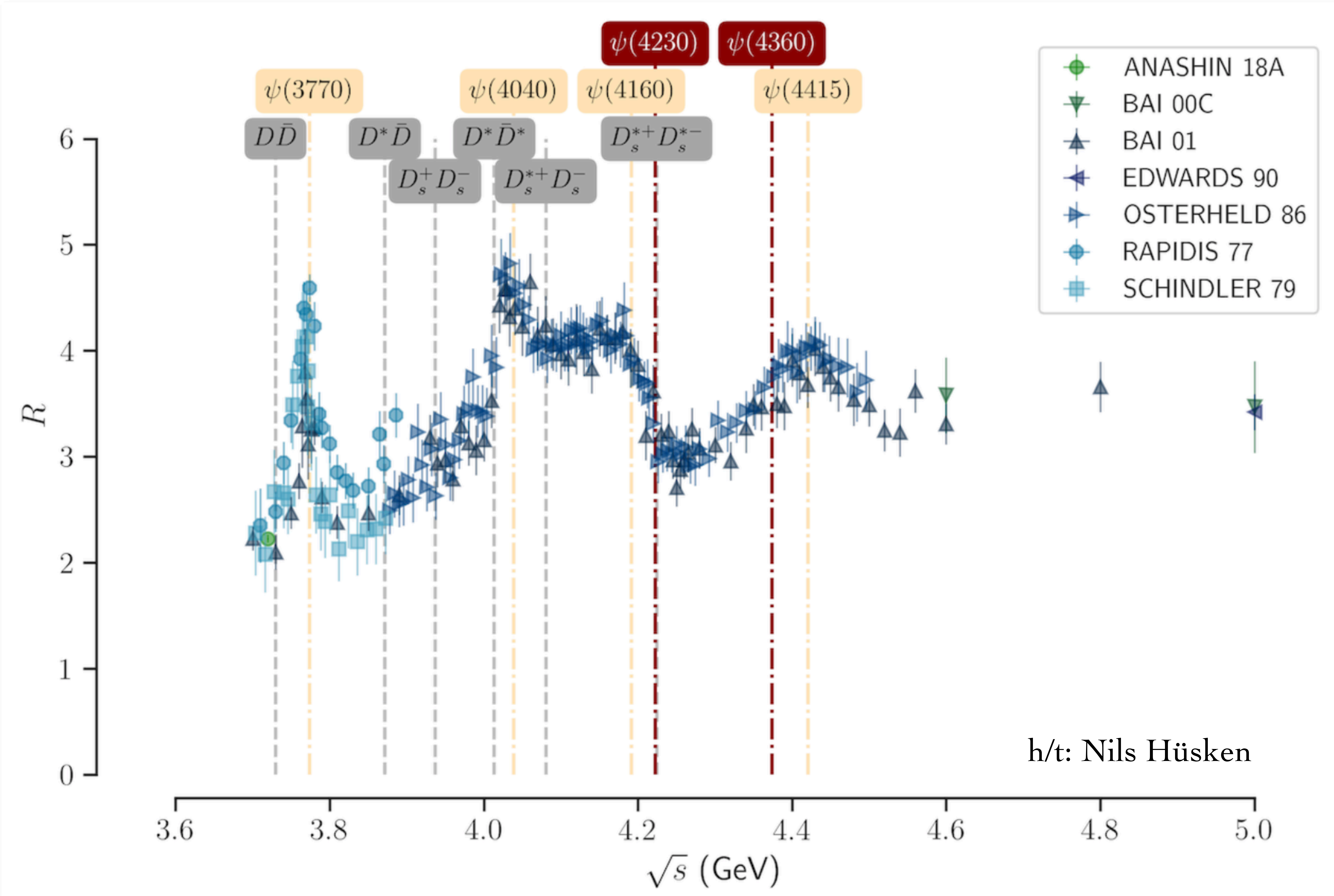
$\chi_{c2}(3930)$

$\psi(4320)$ & $\psi(4360)$



PRD 106 (2022) 7, 072001



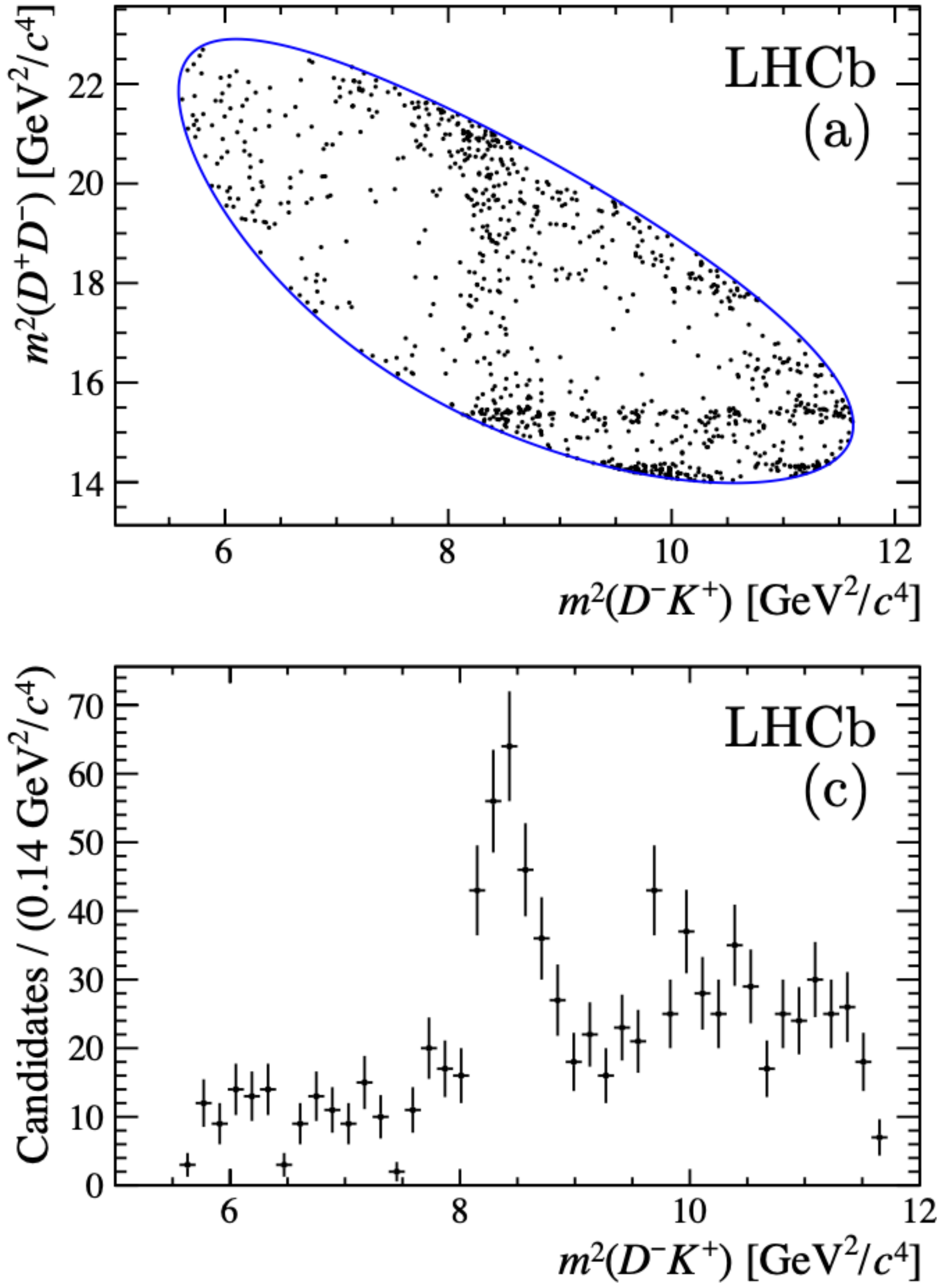


The situation is even worse: we rely on R for much information! This is not reliable!

Tetraquarks

X(2900)

$B^+ \to D^+ D^- K^+$

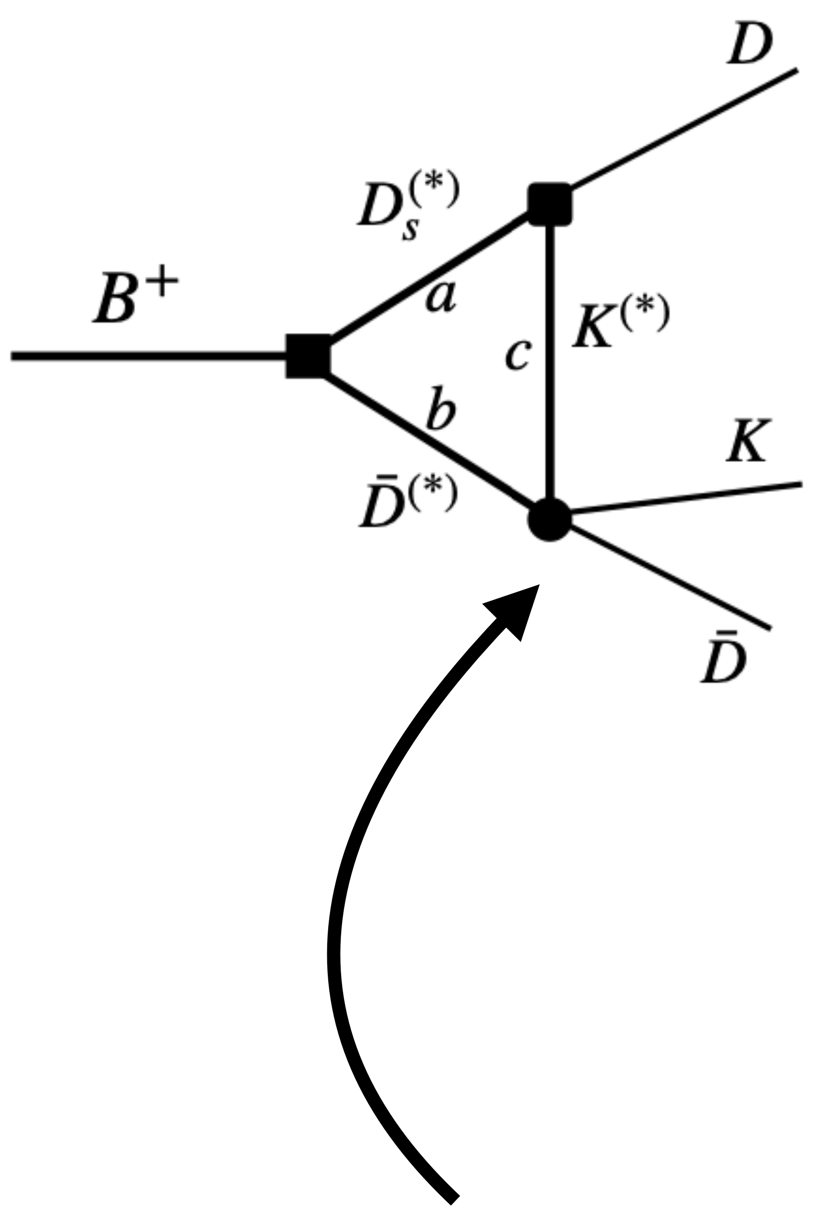


LHCb, arXiv:2009.00026.

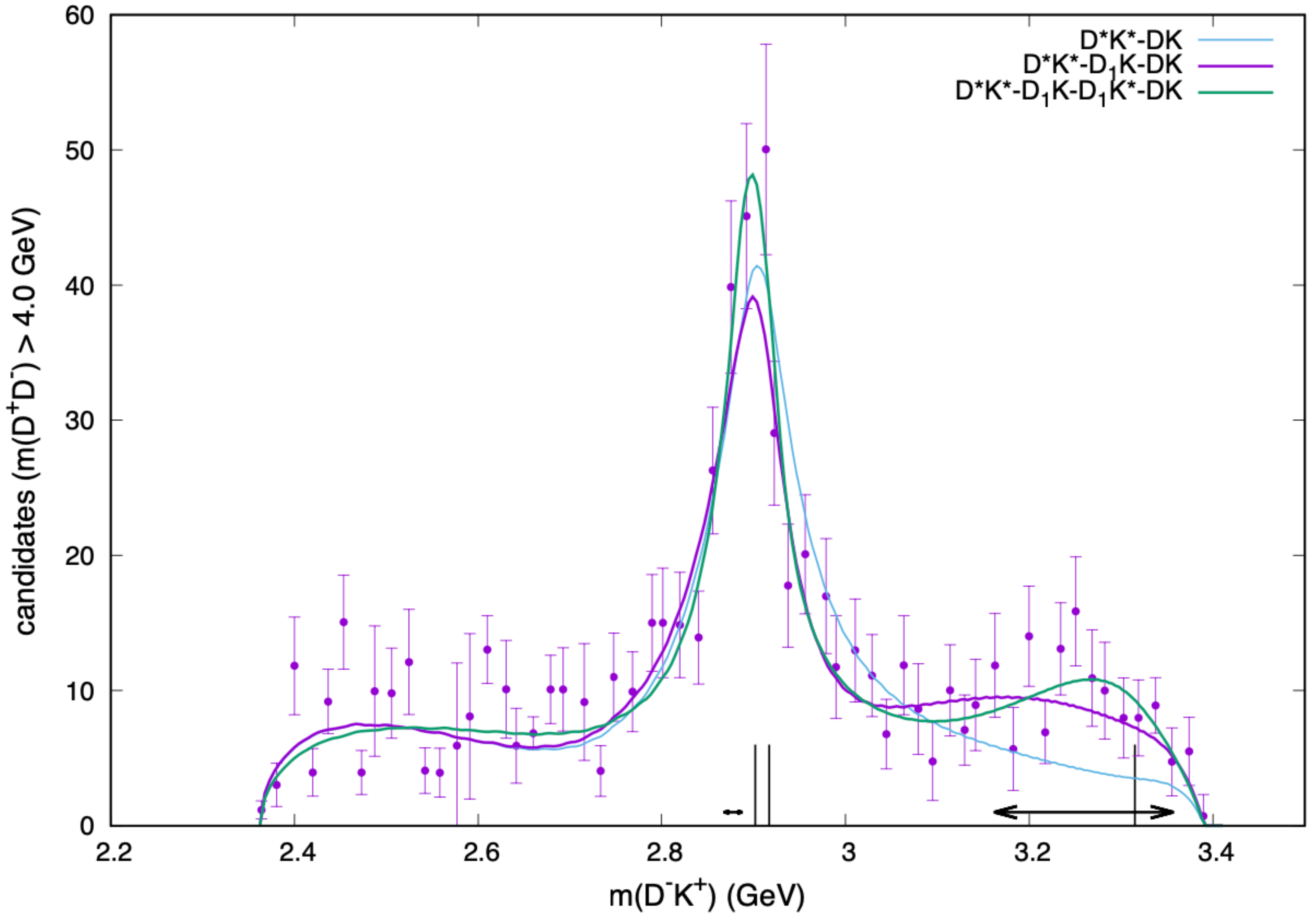
X_0 $\quad M = 2.866 \pm 0.007 \pm 0.002$ GeV, $\Gamma = 57 \pm 12 \pm 4$ MeV,

X_1 $\quad M = 2.904 \pm 0.005 \pm 0.001$ GeV, $\Gamma = 110 \pm 11 \pm 4$ MeV.

manifestly exotic channel $ud\bar{s}\bar{c}$



$\boldsymbol{\lambda}(1^-)$	$\bar{D}^*K^*\vert_P$	$\bar{D}_1K\vert_S$	$\bar{D}_1K^*\vert_S$	$\bar{D}K\vert_P$
$\bar{D}^*K^*\vert_P$	C_1	C_2	C_3	C_4
$\bar{D}_1K\vert_S$		0	C_5	0
$\bar{D}_1K^*\vert_S$			C_6	0
$\bar{D}K\vert_P$				0



thresholds: $\bar{D}^*K^*$, $\bar{D}_1K$ $\bar{D}_1K^*$

resonances: 2849 - i 23 MeV 3173 - i 236 MeV

$\bar{D}^*K^* - \bar{D}_1K$ $\bar{D}_1K^*$

Production matters!

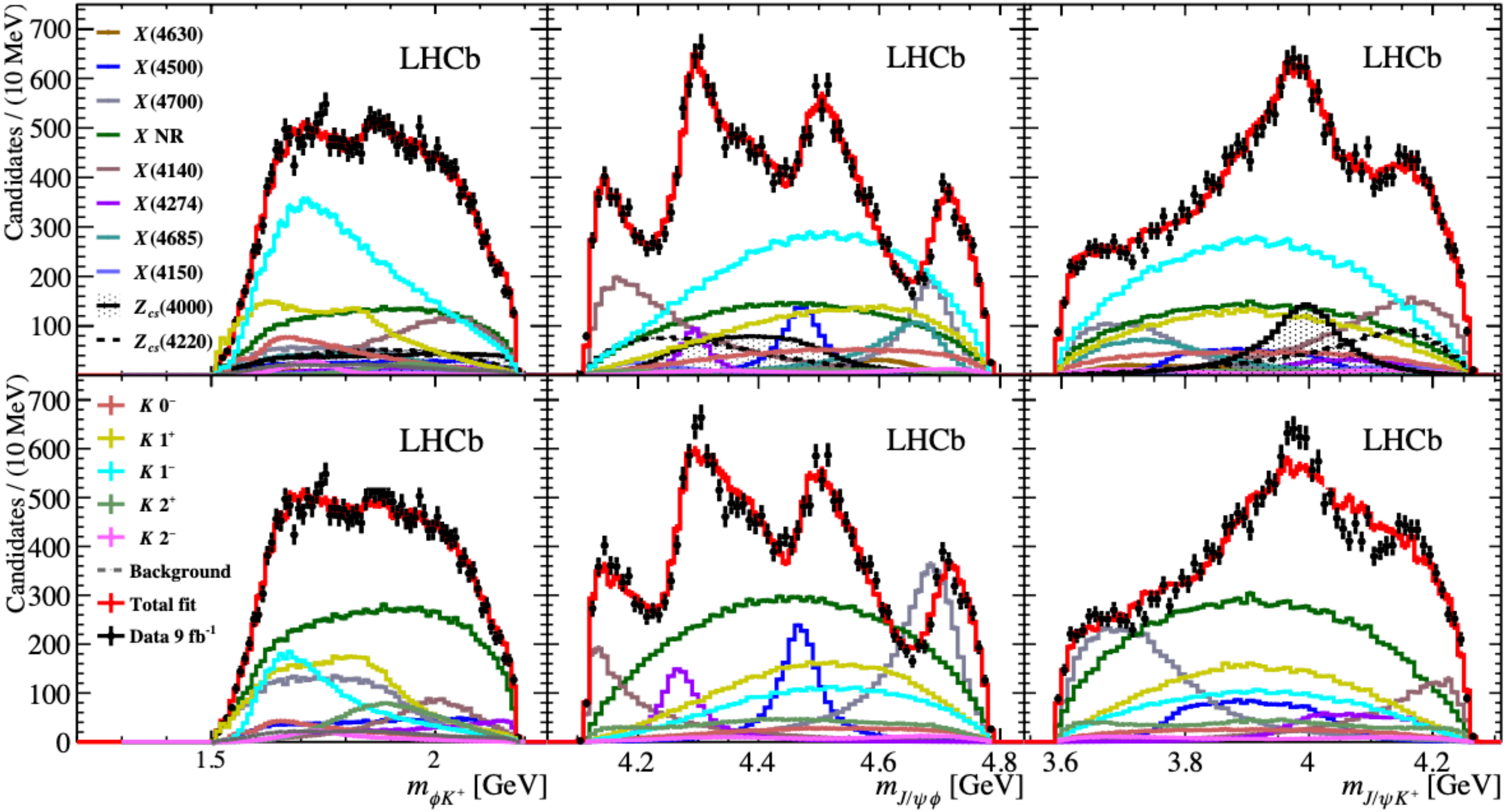
a resonance interpretation is possible, but has weak evidence

T.J. Burns and E.S. Swanson, 2008.12838, 2009.05352.

$$Z_{cs}(4000), Z_{cs}(4220), X(4140), X(4150), X(4274)$$

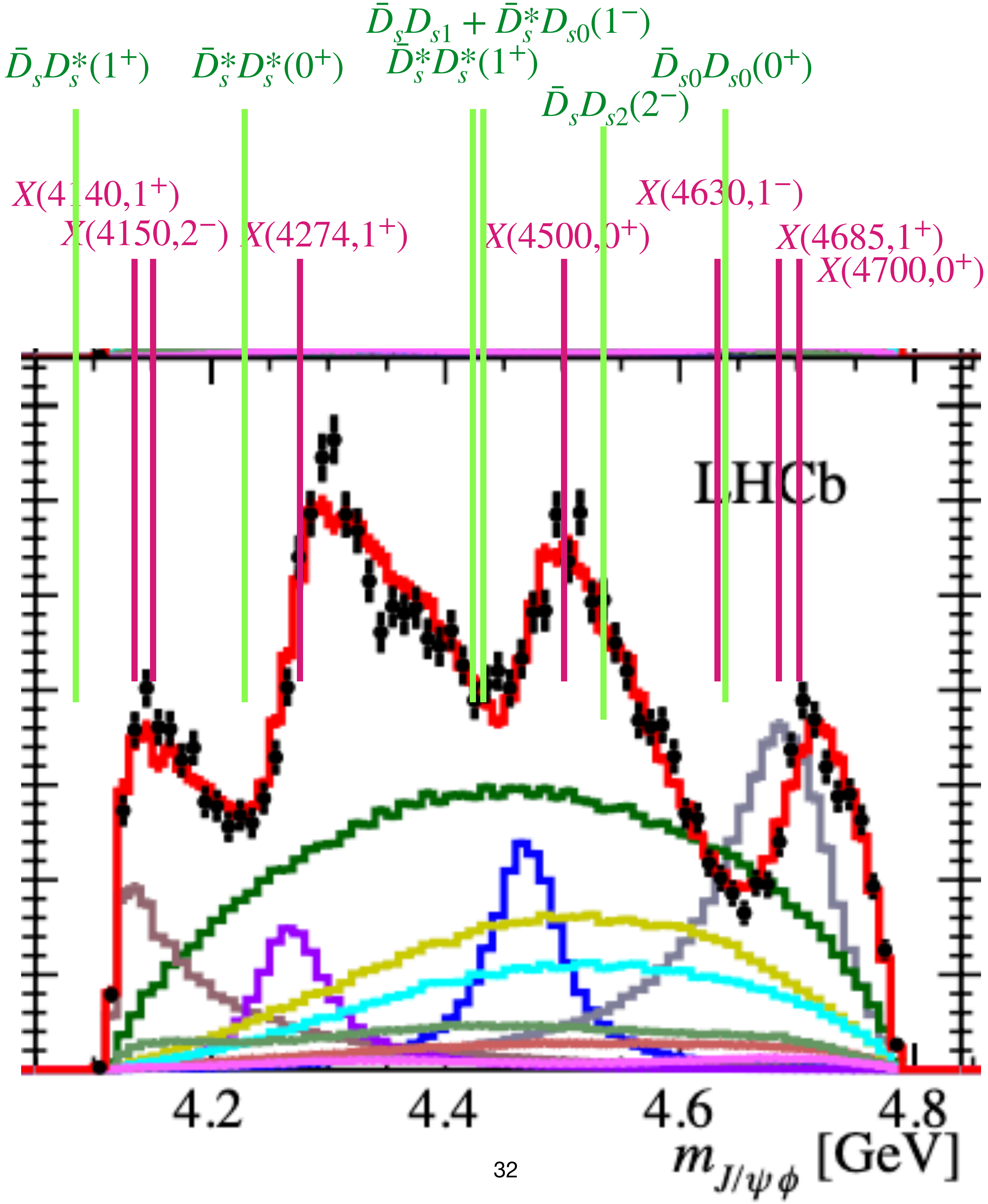
$$X(4500), X(4630), X(4685), X(4700)$$

$B^+ \to J/\psi \phi K^+$



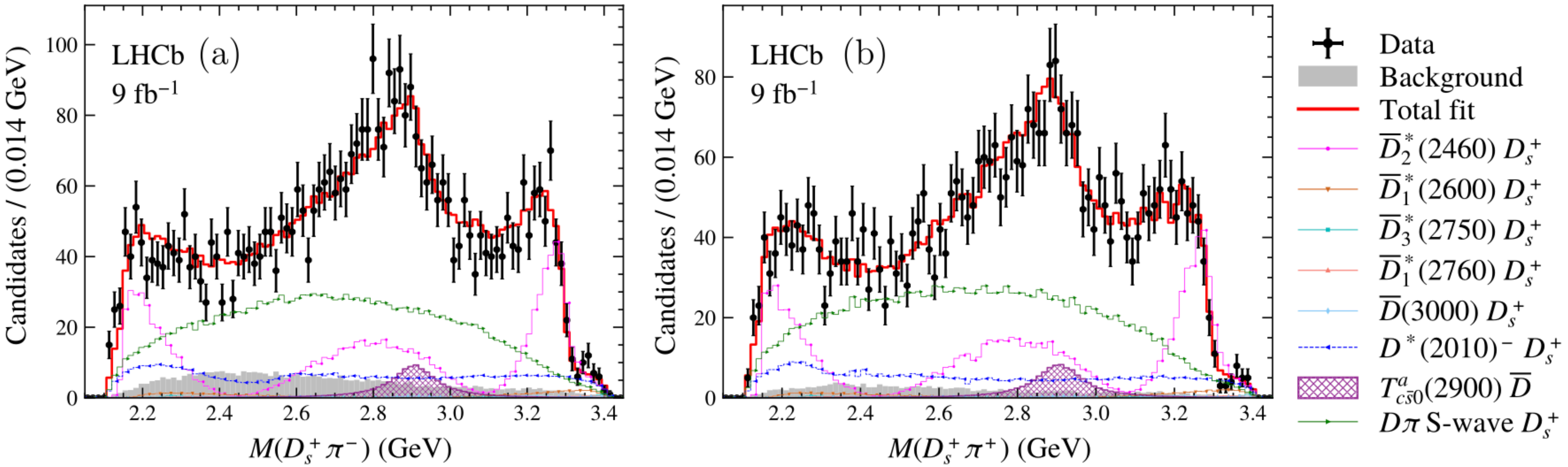
LHCb, 2103.01803

X Thresholds

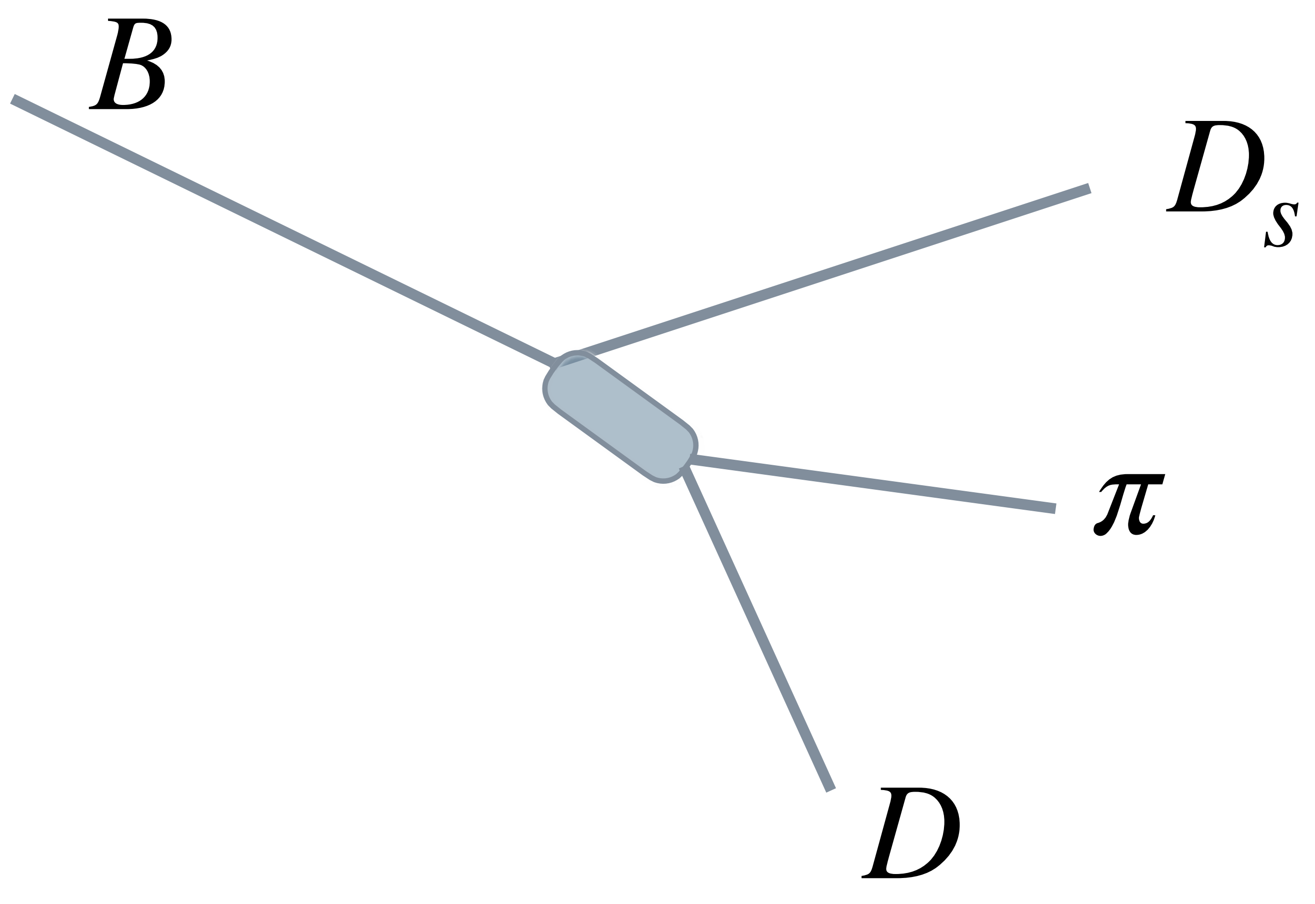


$T_{c\bar{s}0(2908)}$

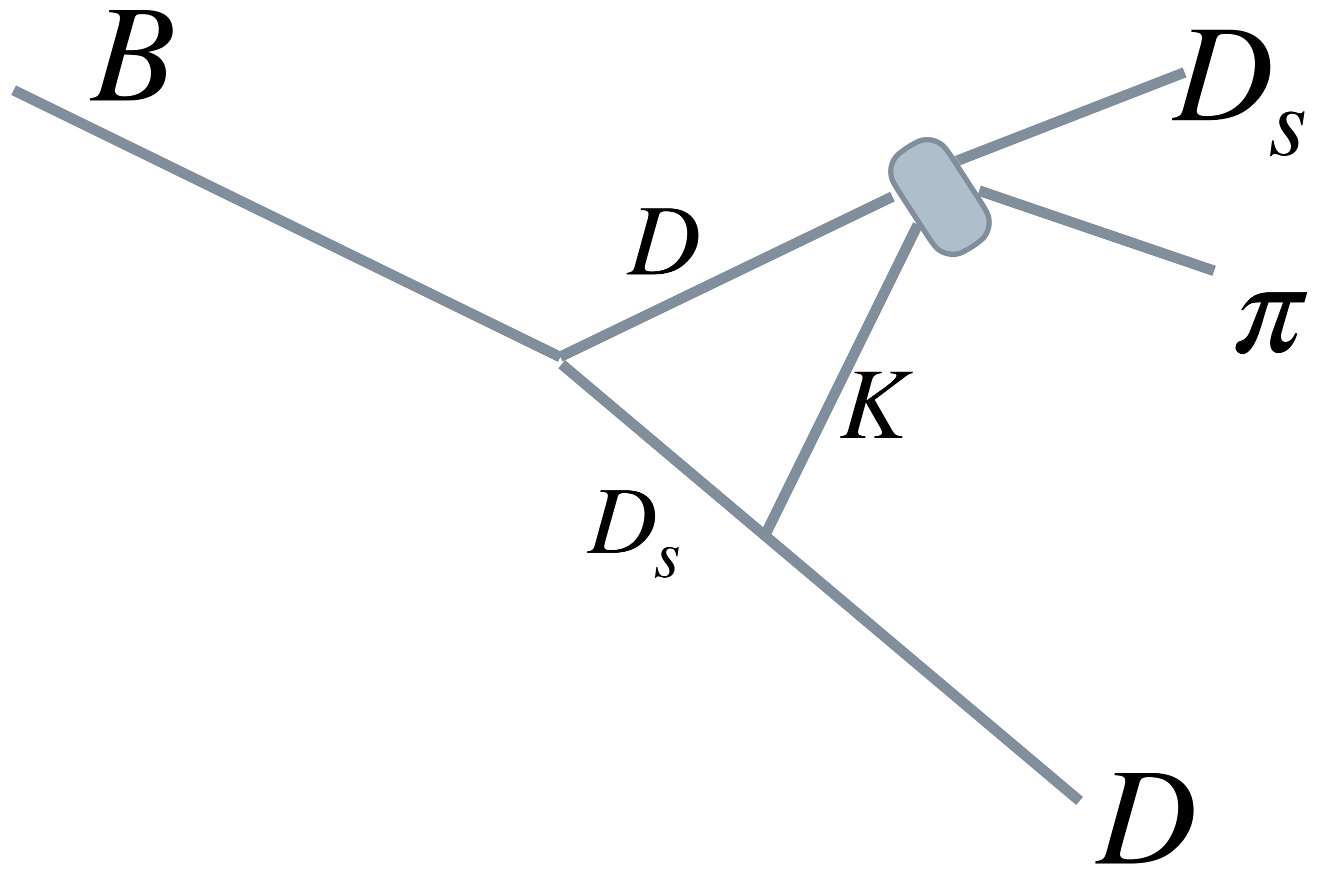
$B^0 \to \bar{D}^0 D_s^+ \pi^-$ $\qquad$ $B^+ \to D^- D_s^+ \pi^+$



BESIII, PRL**131**, 041902 (2023)

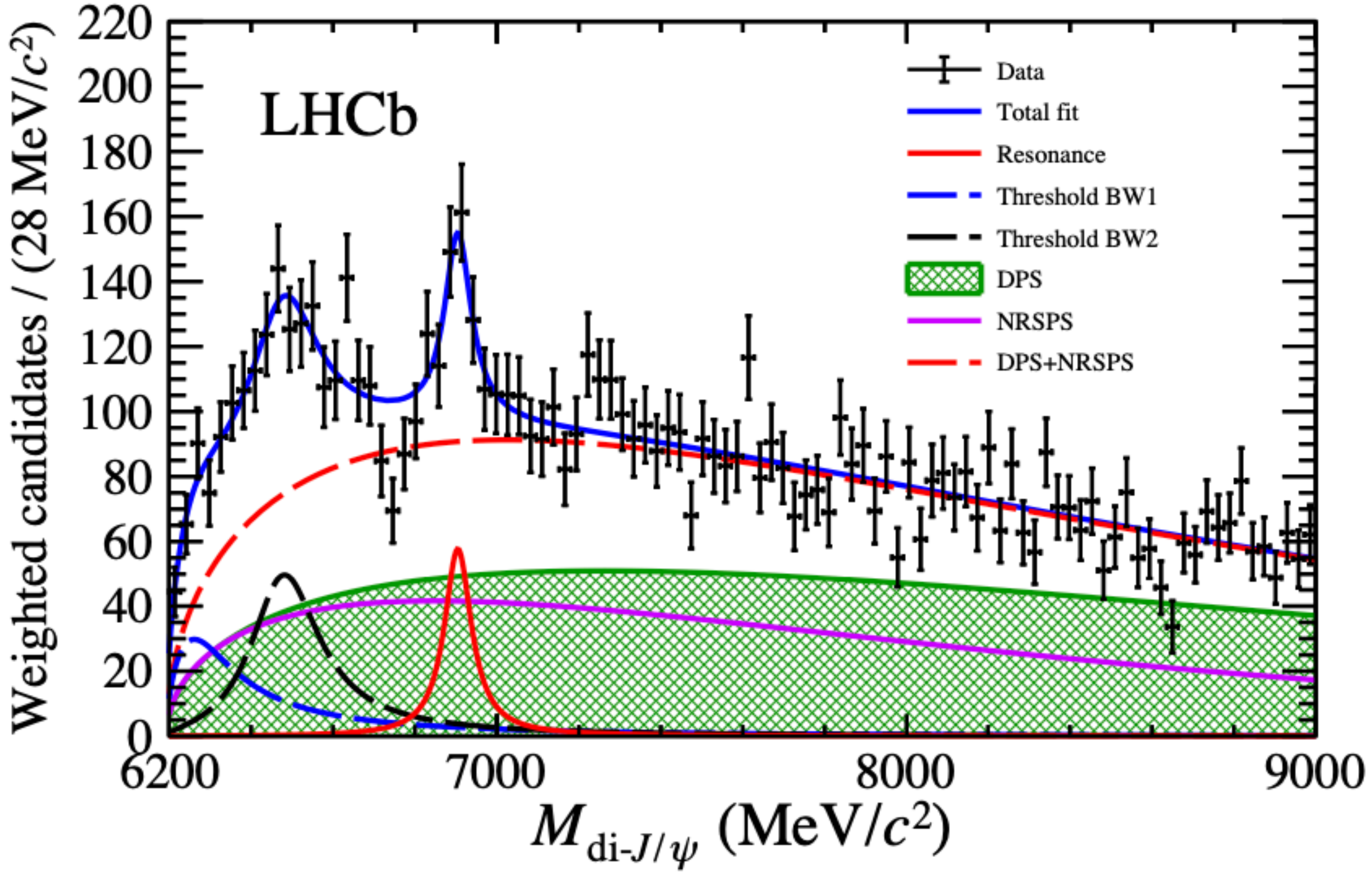


tree order process exists

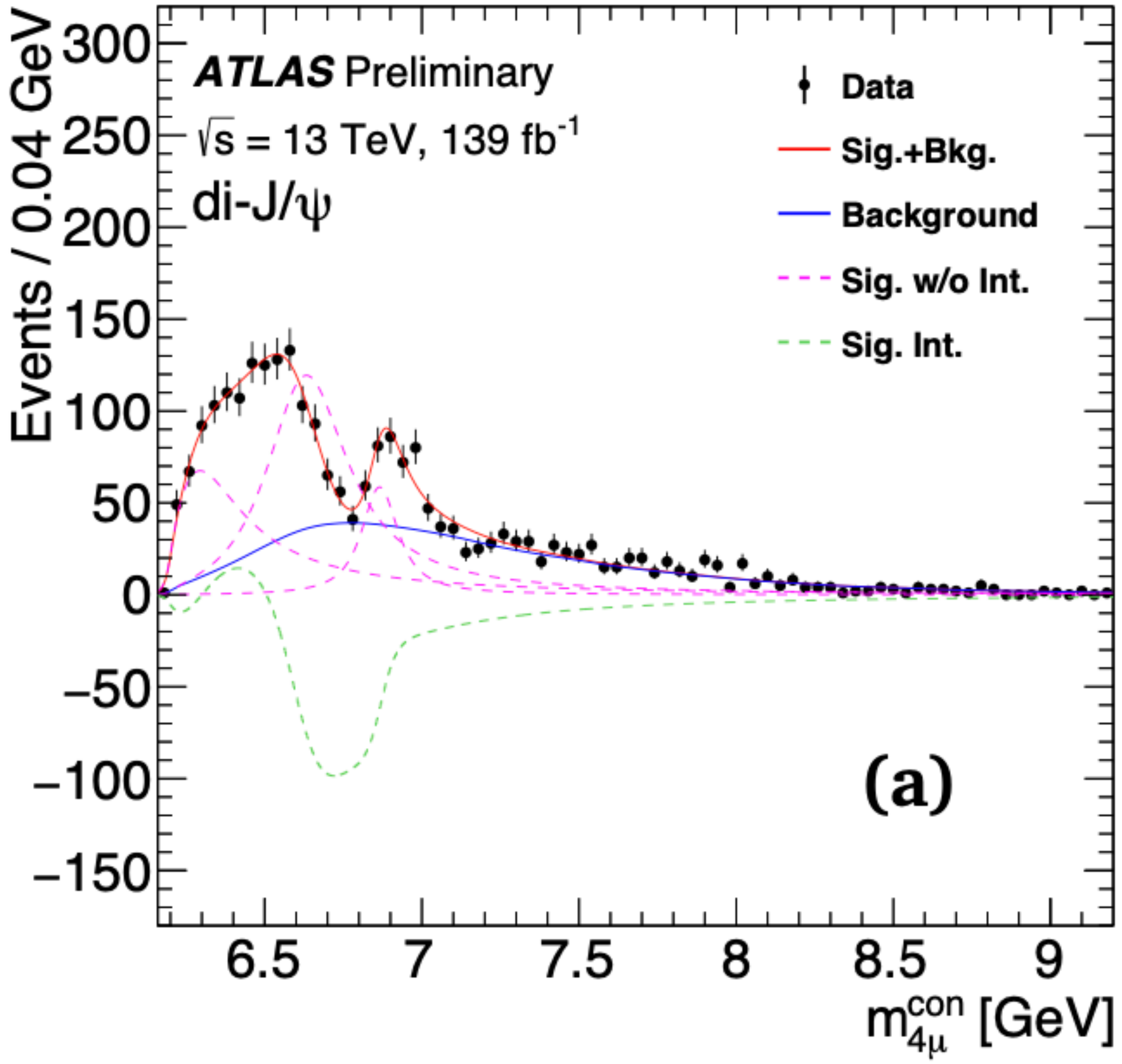


masses don't align

$$T_{\psi\psi}(6200), T_{\psi\psi}(6600), T_{\psi\psi}(6900), T_{\psi\psi}(7200)$$



LHCb, 2006.16957



ATLAS, 2209.12173

Pentaquarks

$P_{\psi s}^{\Lambda}(4338)$

Discussion on the new J/ψΛ state

For theoretical interpretation

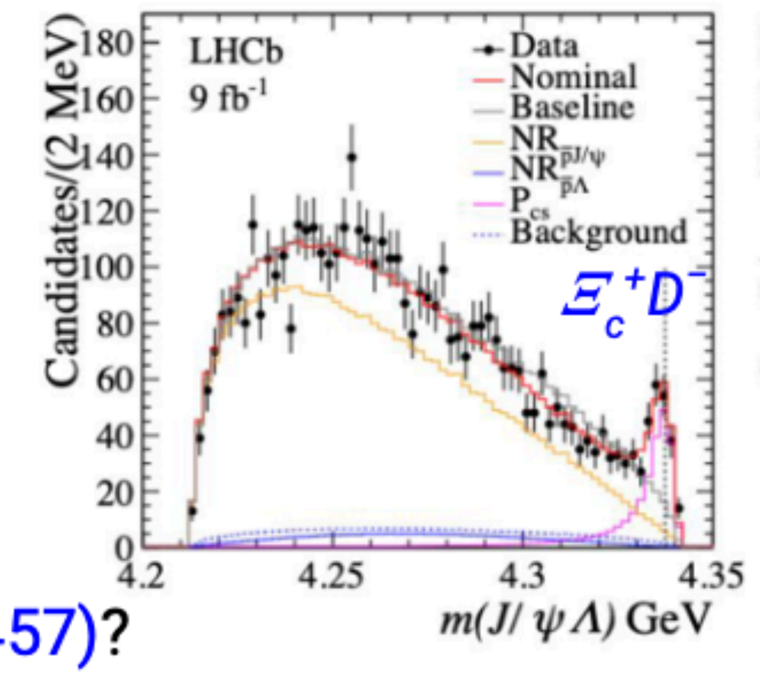
First pentaquark candidate $P^{\Lambda}_{\psi s}(4338)$ with strange quark content $c\bar{c}uds$,

$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}$$

$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$$

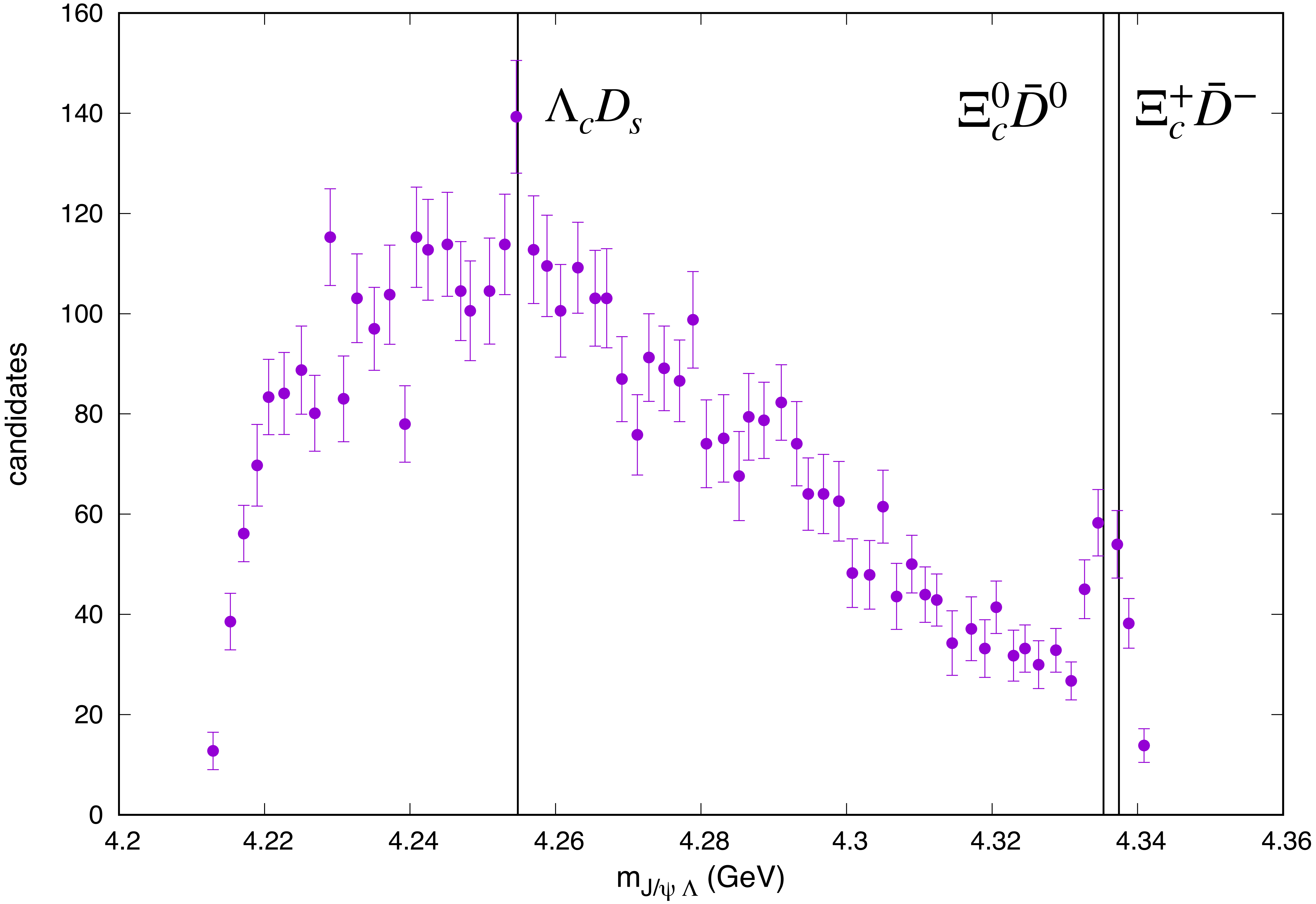
⇒ first pentaquark with spin assigned $J^P = ½^-$

- ✓ narrow, close to $\Xi_c^+ D^-$ threshold and in S-wave
- ✓ pentaquark with strangeness, due to SU(3) symmetry
- ✓ at same mass of $P^N_{\psi}(4337)$: analogy to $P^{\Lambda}_{\psi s}(4459)$ & $P^N_{\psi}(4457)$?



Can fit in SU(3) multiplets or are more likely molecular states?

Relevant Thresholds



Is a $\Xi_c D$ bound state plausible?

Heavy quark symmetry implies $\Xi_c D^*$ partners

$$V(\Xi_c \bar{D}, 1/2^-) = V(\Xi_c \bar{D}^*, 1/2^-) = V(\Xi_c \bar{D}^*, 3/2^-),$$

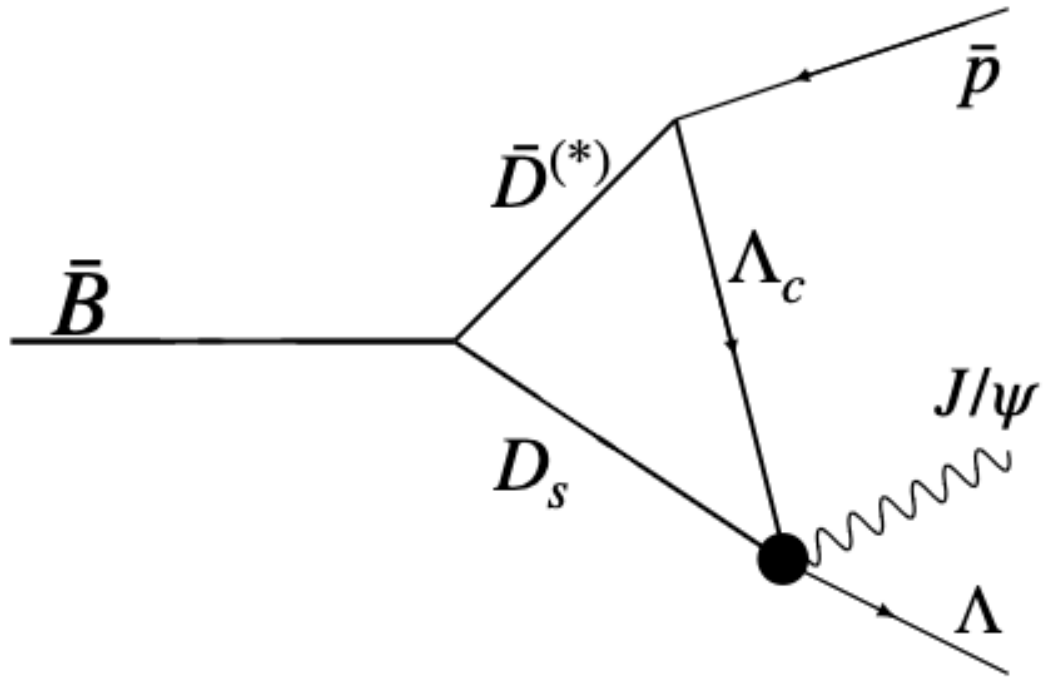
Possible partner state is the $P_{cs}(4459)$, but the binding energy is ~19 MeV, not ~0.

The $P_{\psi s}^{\Lambda}$ is 1-3 MeV *above* threshold.

Production

the tree-level diagrams for the $J/\psi\ \Lambda\ \bar{p}$ final state are color-suppressed; hence it is natural to assume that the color-favored triangle diagram is a dominant contribution.

dominant mechanism



Production

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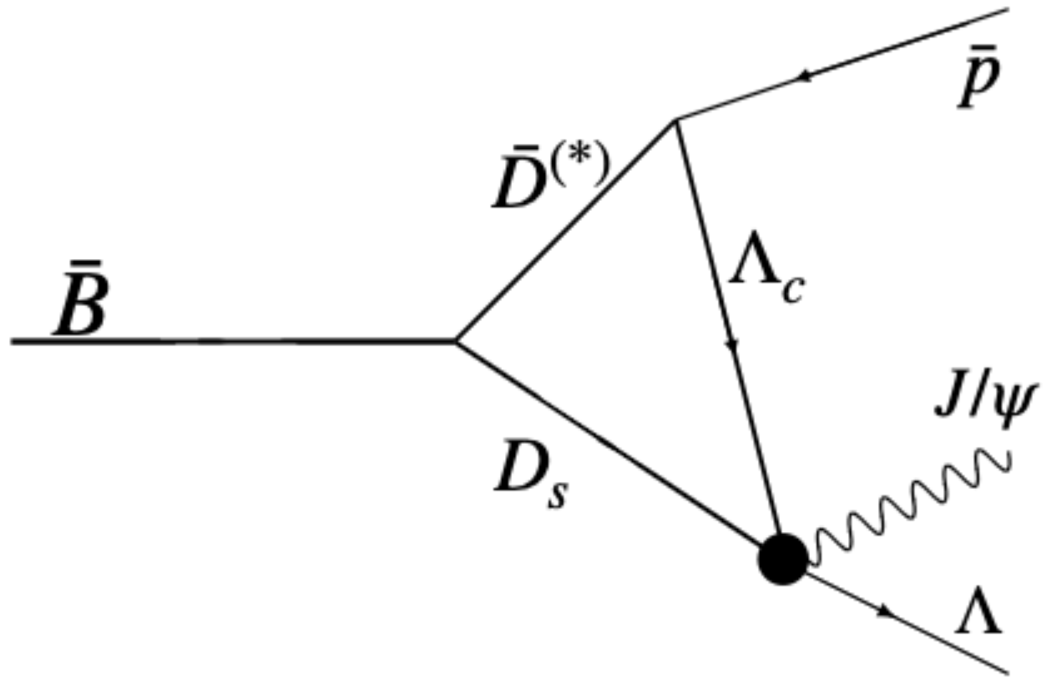
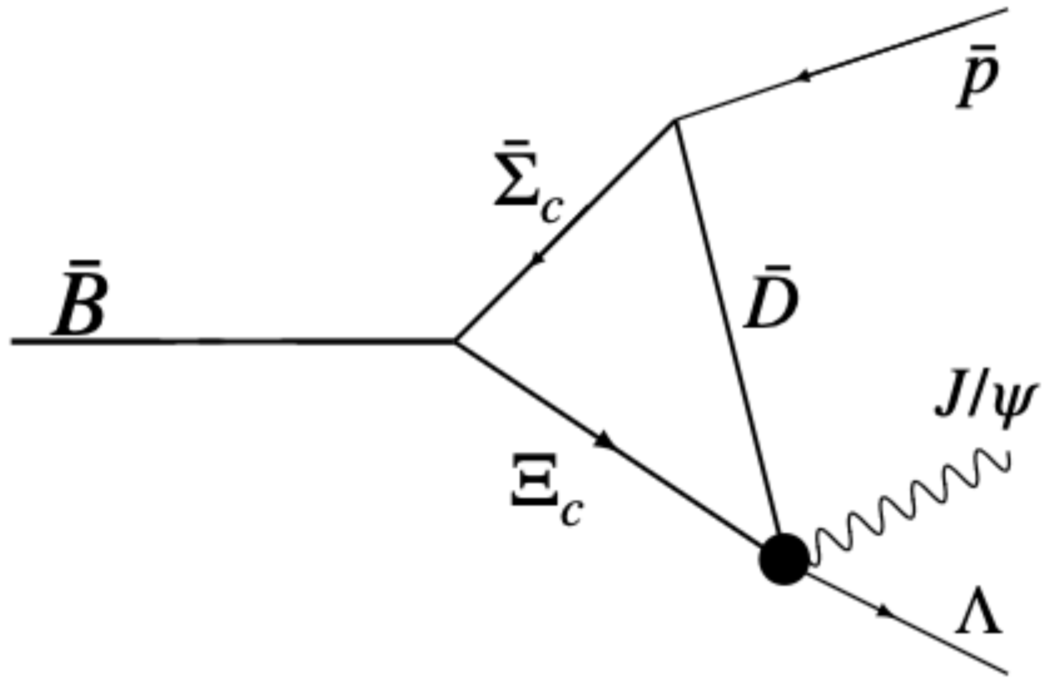
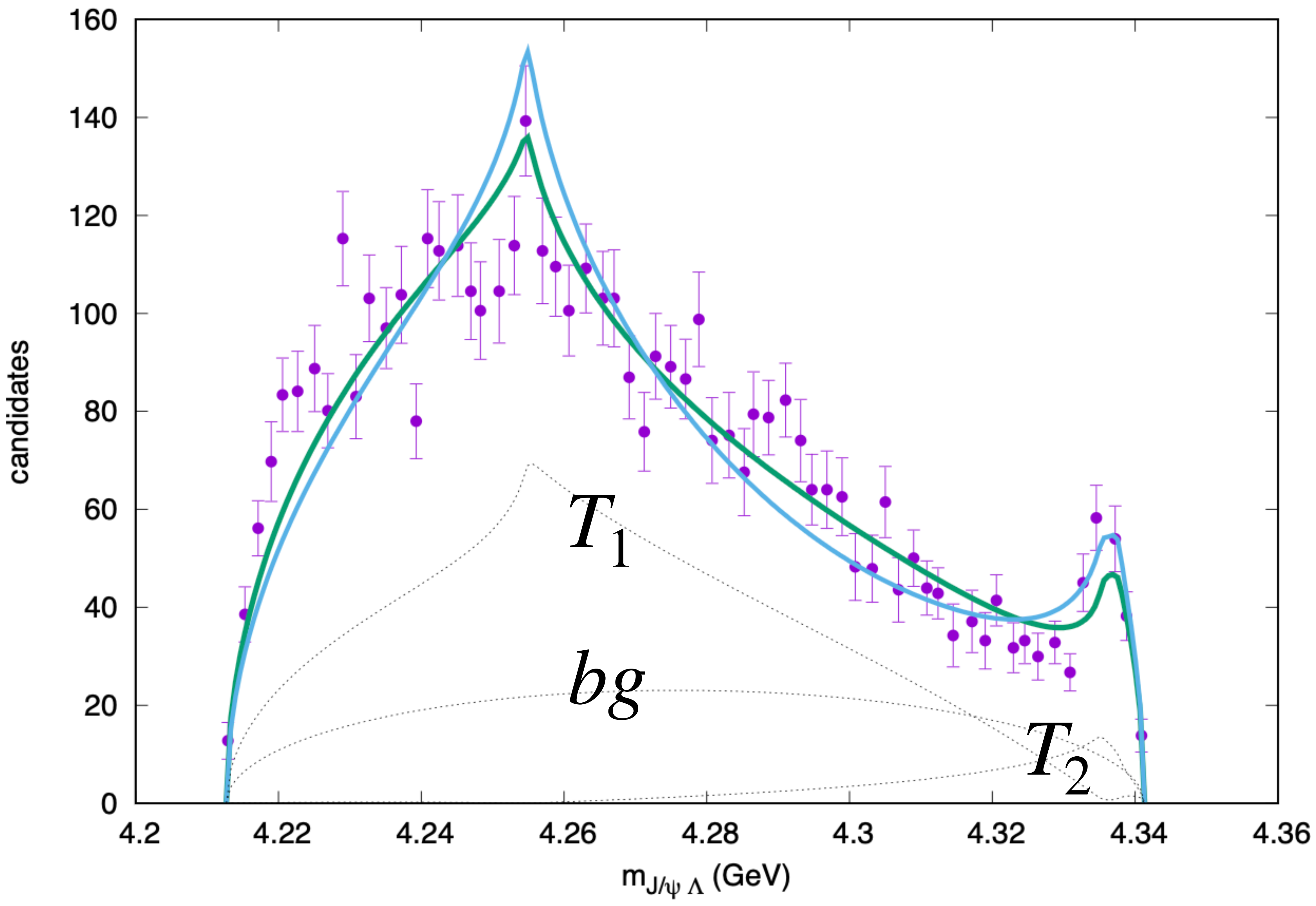
dominant mechanism





but this can be comparable if the Landau conditions are ~ satisfied



$\Lambda_c D_s$ $\Xi_c^+ \bar{D}^-$ $\Xi_c^0 \bar{D}^0$

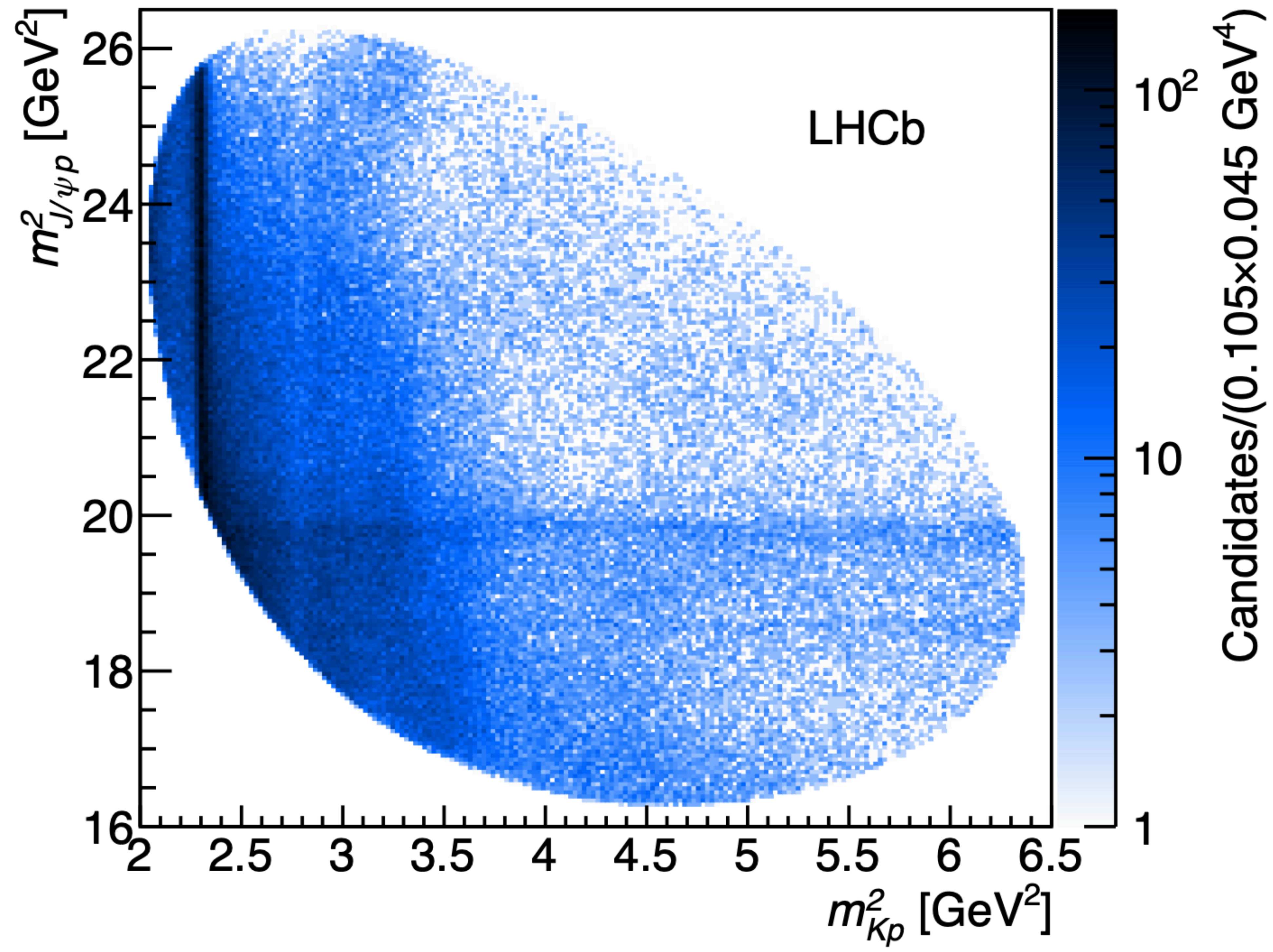
$$\mathcal{A} = b + g_1 T_1 + g_2 \frac{1}{\sqrt{6}} \left[2T_2^{(--)} - T_2^{(-)} \right]$$

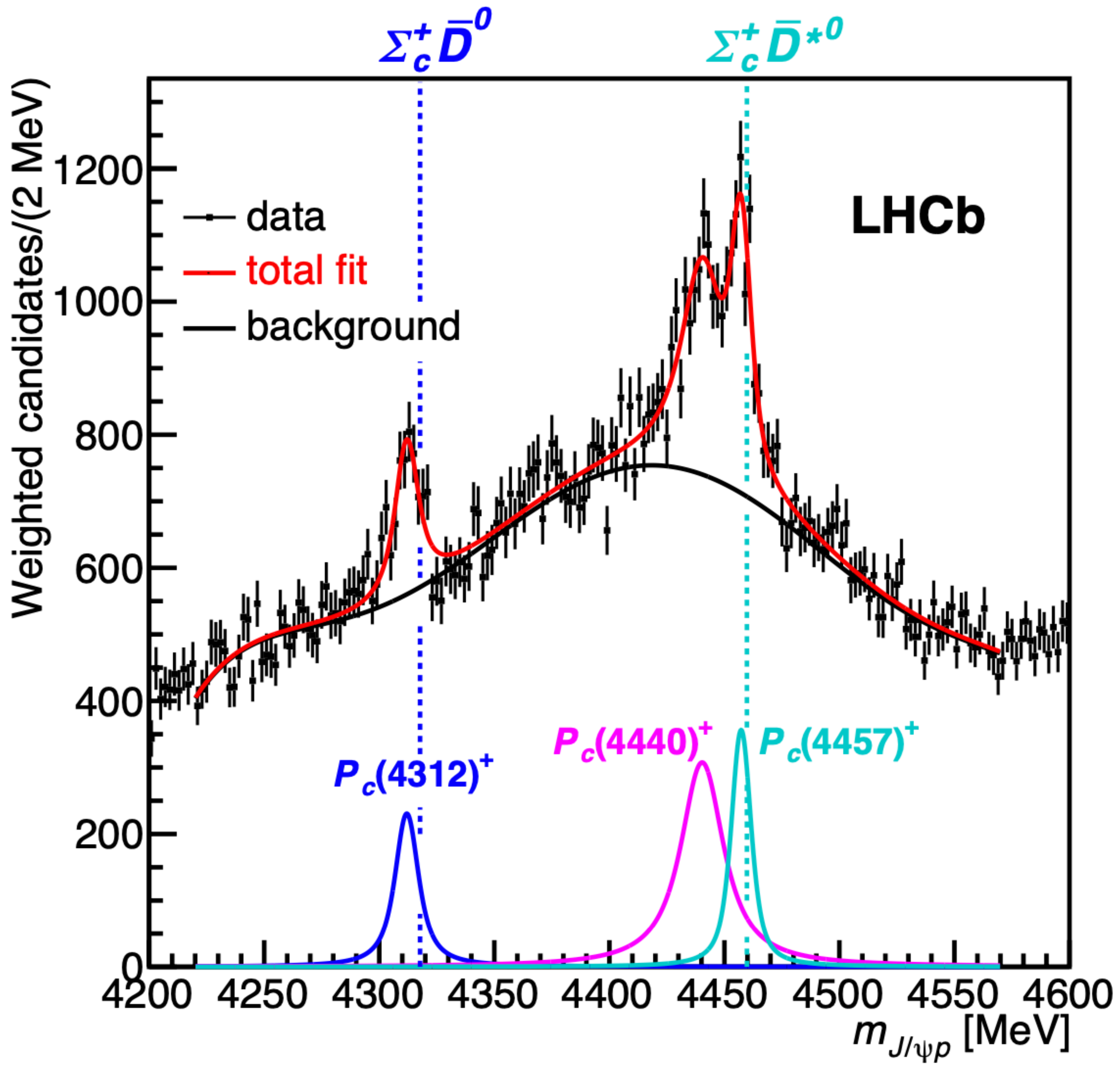
$g_2 \ll g_1$ ✓

T.J. Burns and E.S. Swanson, 2208.05015

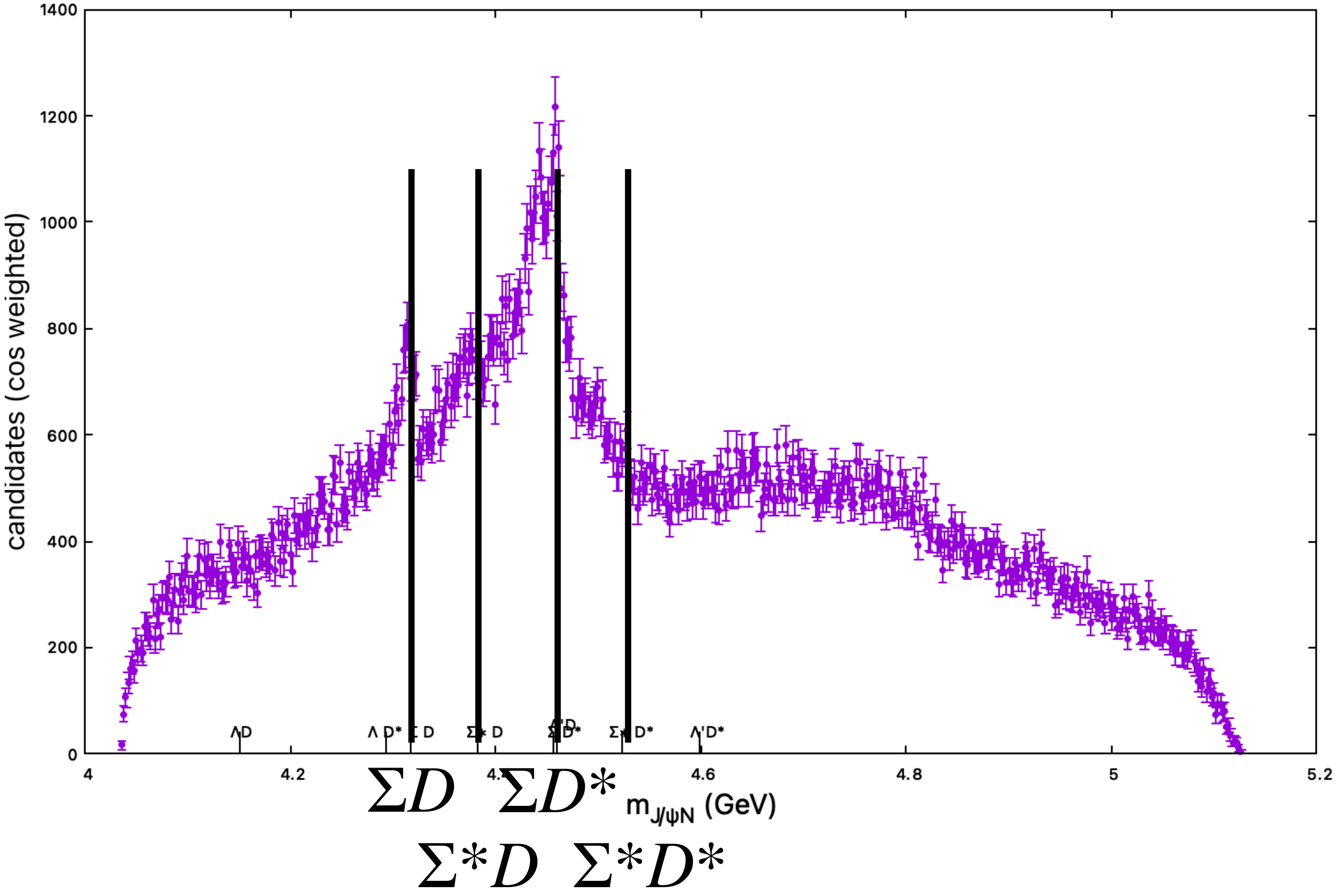
Pc(4312), (Pc(4380)), Pc(4440), Pc(4457)

$\Lambda_b^0 \to J/\psi p K^-$

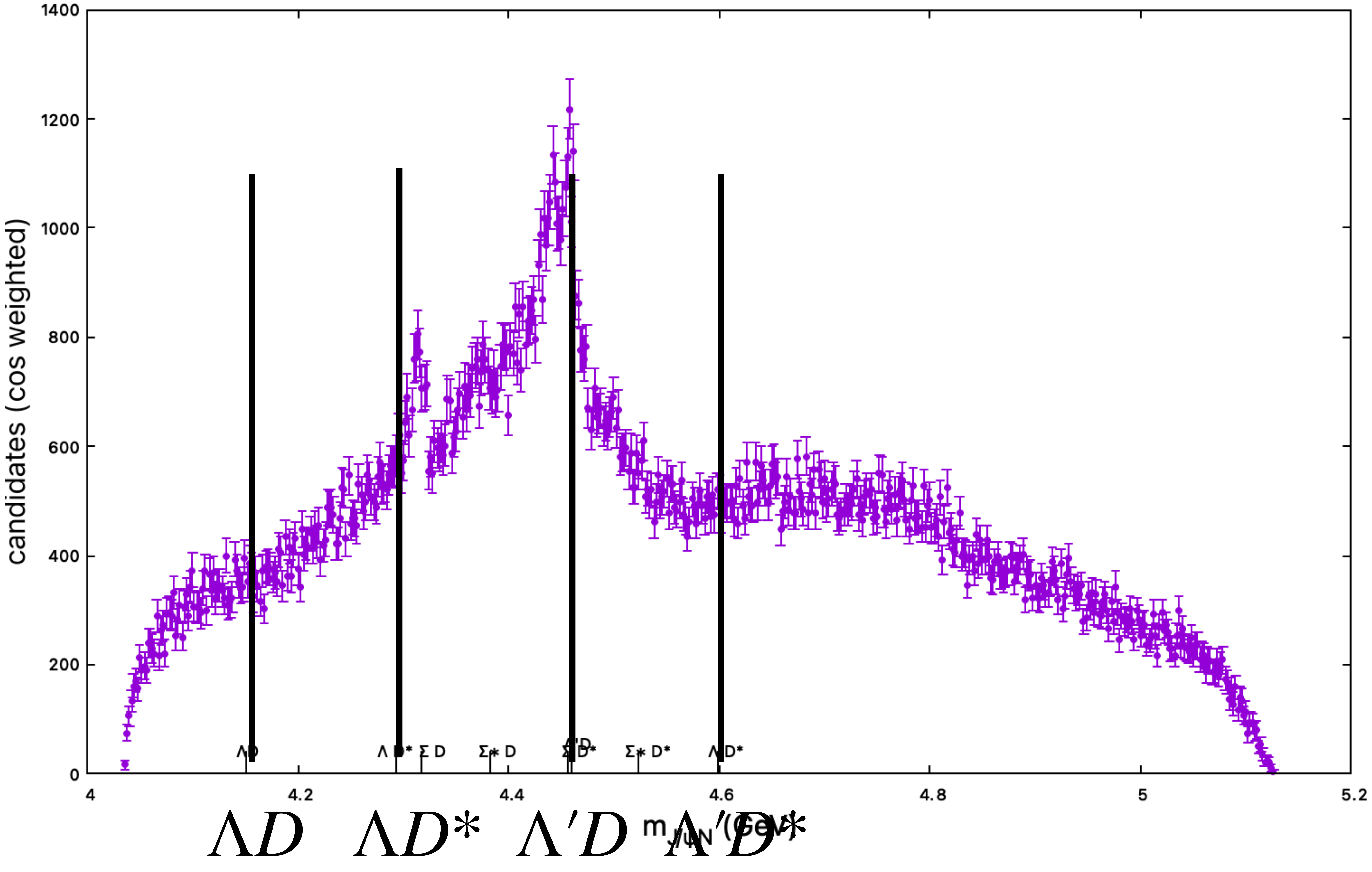




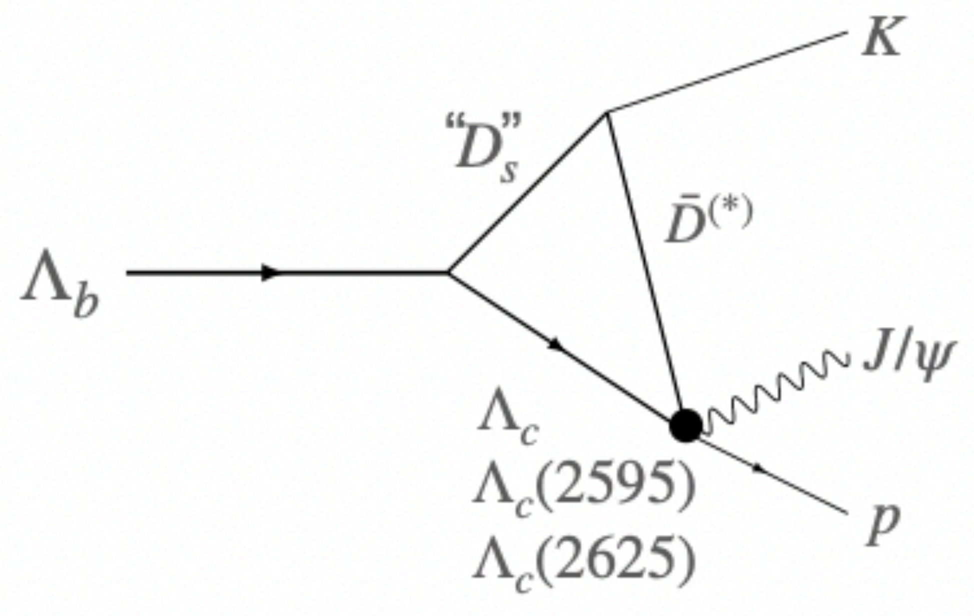
A Look at the Data (LHCb cos weighted)

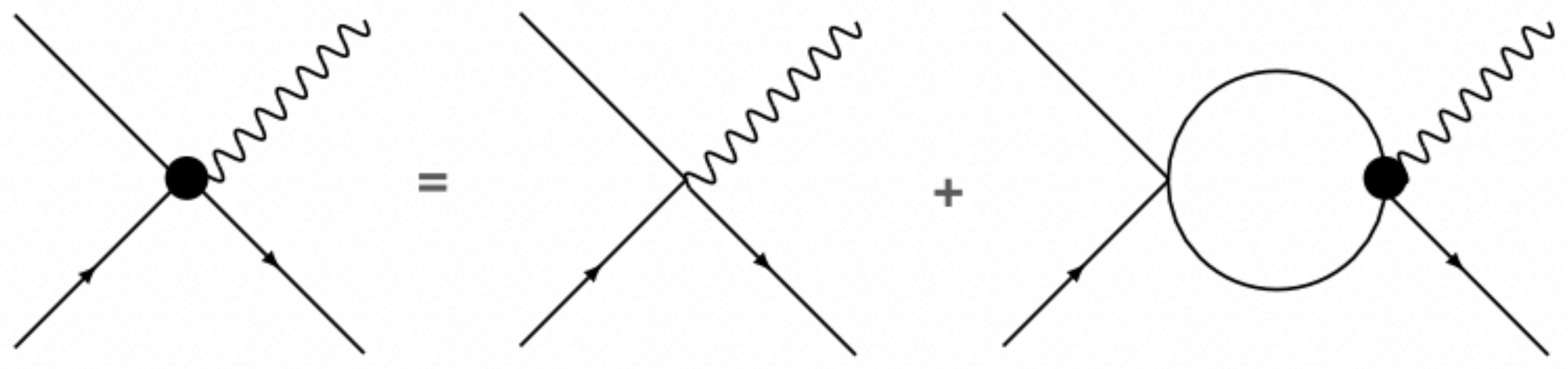


A Look at the Data (LHCb cos weighted)



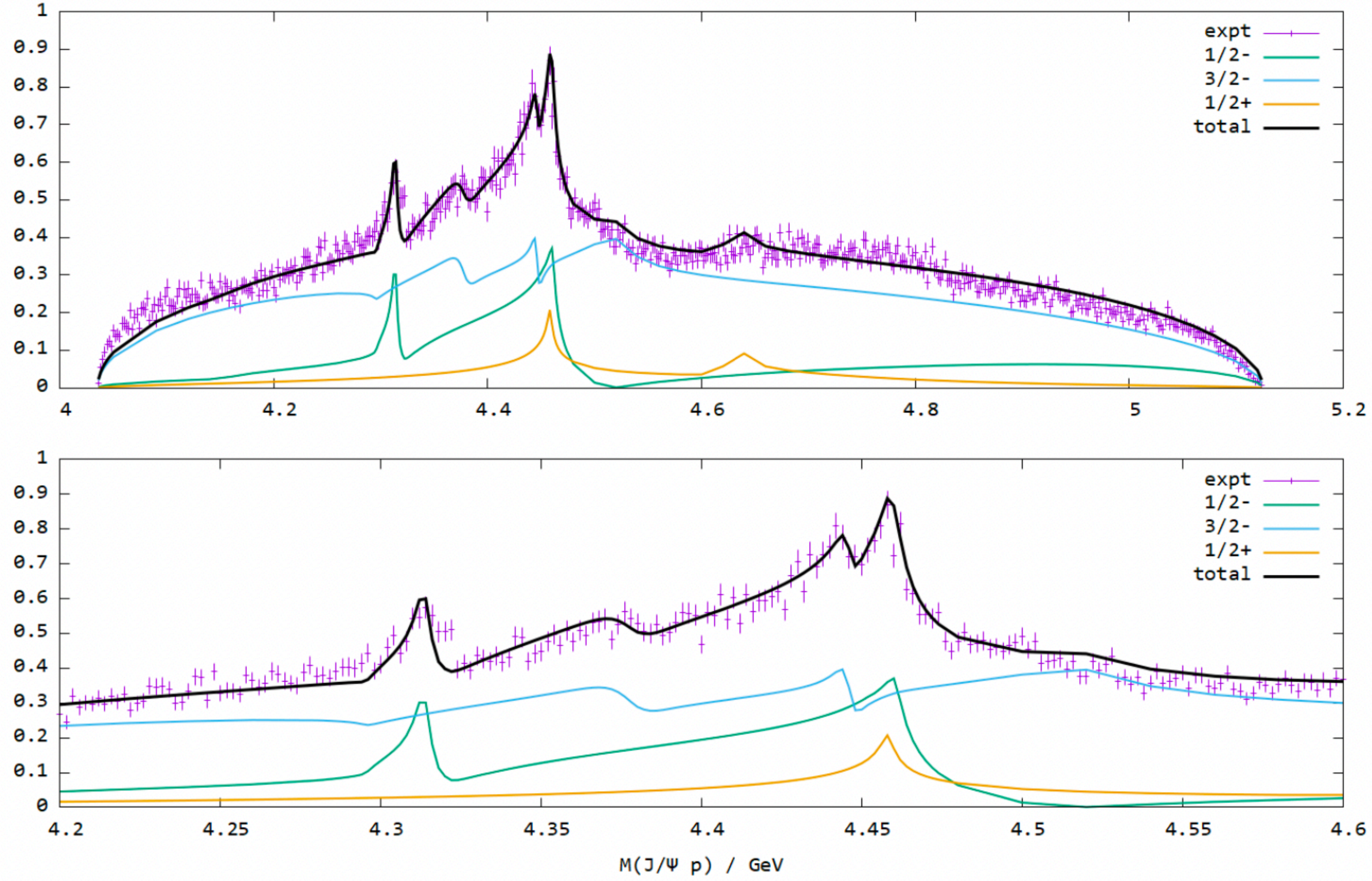
A Production/ Rescattering Model for Pentaquarks





- bound/resonance states
- threshold cusps
- triangle singularities

Model Fit

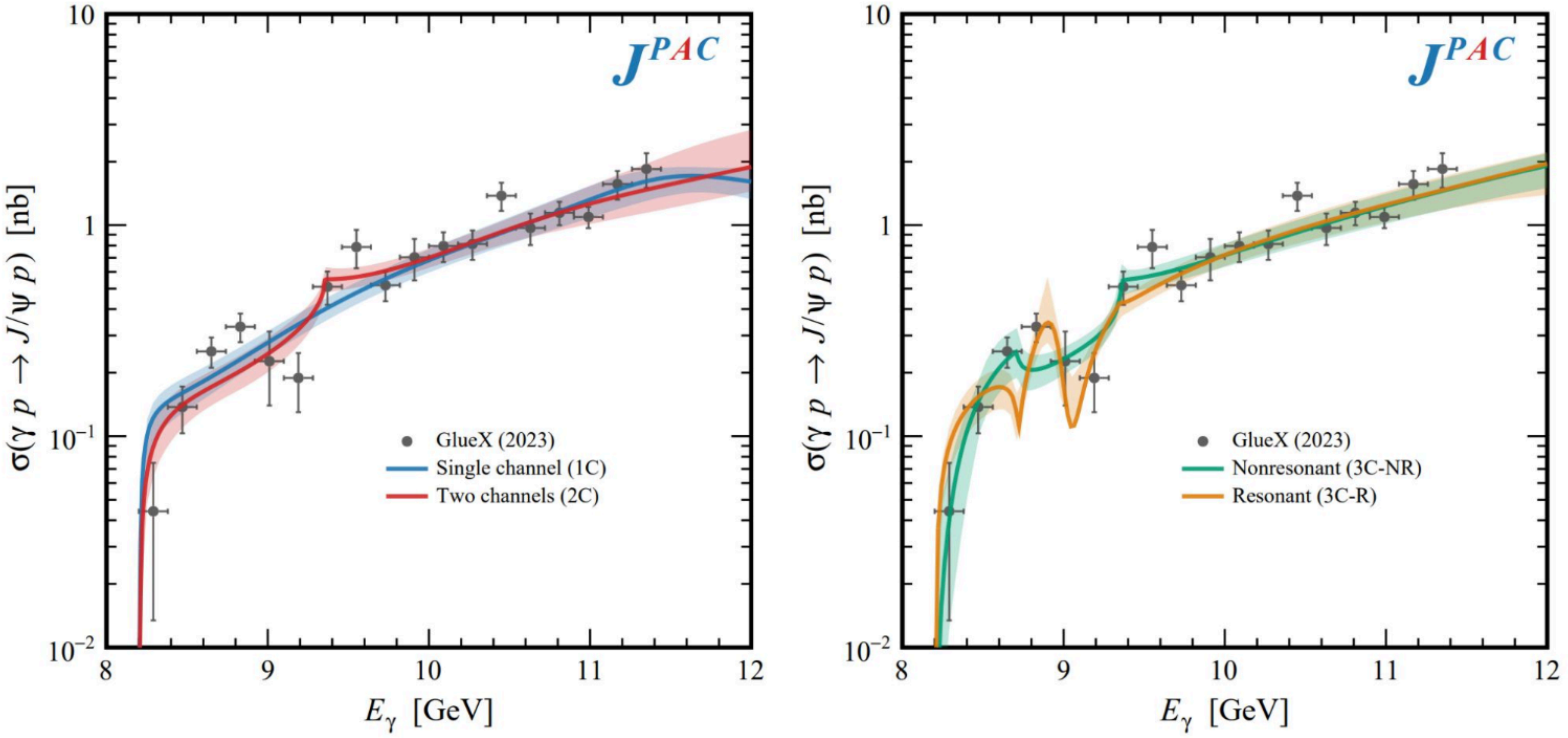


T.J. Burns and E.S. Swanson, 2112.11527, 2207.00511

- 4312 ($\Sigma_c D$, 1/2-)
- 4380 ($\Sigma_c^* D$, 3/2-)
- 4440 ($\Sigma_c D^*$, 3/2-)
- 4457(1/2-$\Sigma_c D^*$ threshold cusp / 1/2+ triangle)
- 4508 ($\Sigma_c^* D^*$, 5/2-)

Non Sighting i

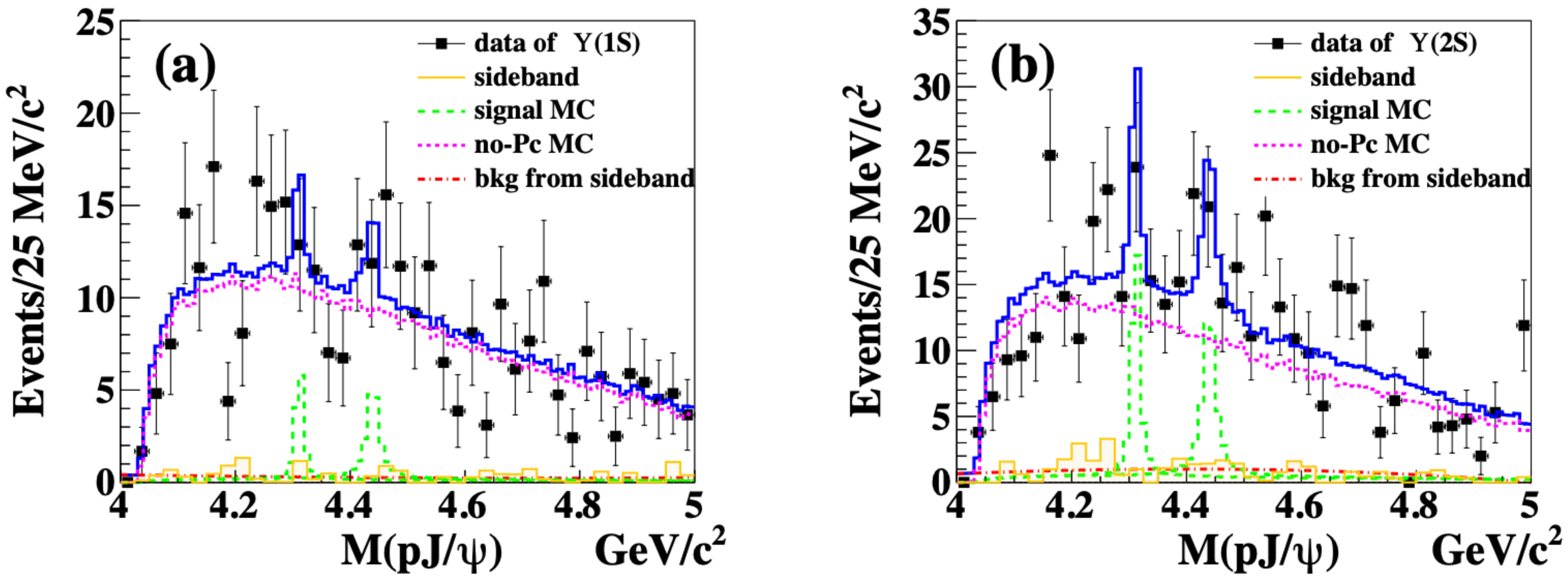
Four solutions with different dynamical pictures found to be consistent with full data with similar statistical significance.



JPAC, PRD108, 5, (2023)

Non Sighting ii

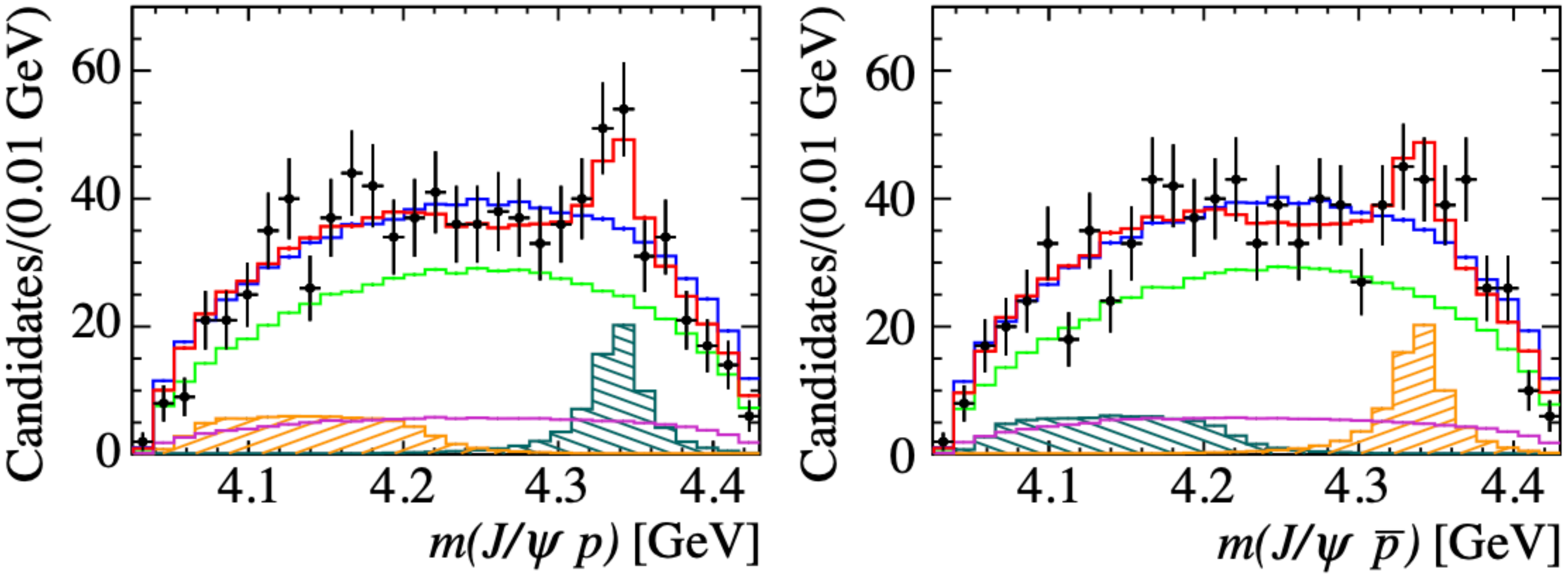
No evidence for Pc(4312), Pc(4440), Pc(4457) in $\Upsilon(1S)$ or $\Upsilon(2S)$ decays



Belle arXiv:2403.04340v2

$P_{c\bar{c}}(4337)$

$B \to J/\psi p\bar{p}$



integrated luminosity of 9 fb^{-1}. No evidence is seen for either a P_c state at a mass of 4312 MeV [2] or the glueball state $f_J(2220)$ predicted in Ref. [11]. Unlike in other B

LHCb, PRL128, 062001 (2022)

Conclusions

tl;dl

- no shortage of anomalies & multiquark candidates
- definite shortage of hybrid candidates!
- naive analysis can create states ⚠
- many "states" can appear to due to production (near) singularities, cusps, interferences ⚠
- much work remains to be done!

✢ ÆRIC MEC HEHT GEWYRCAN