Exotic vectors in the Quarkonium region

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JPAC

ExoHad
Exotic Hadrons Topical Collaboration

States above $\Upsilon(4S)$ ($J^{PC} = 1^{--}$)

- First observations in '80s at CLEO, CUSB in e^+e^- annihilation
- Coupled-channel models used to extract open-bottom contributions

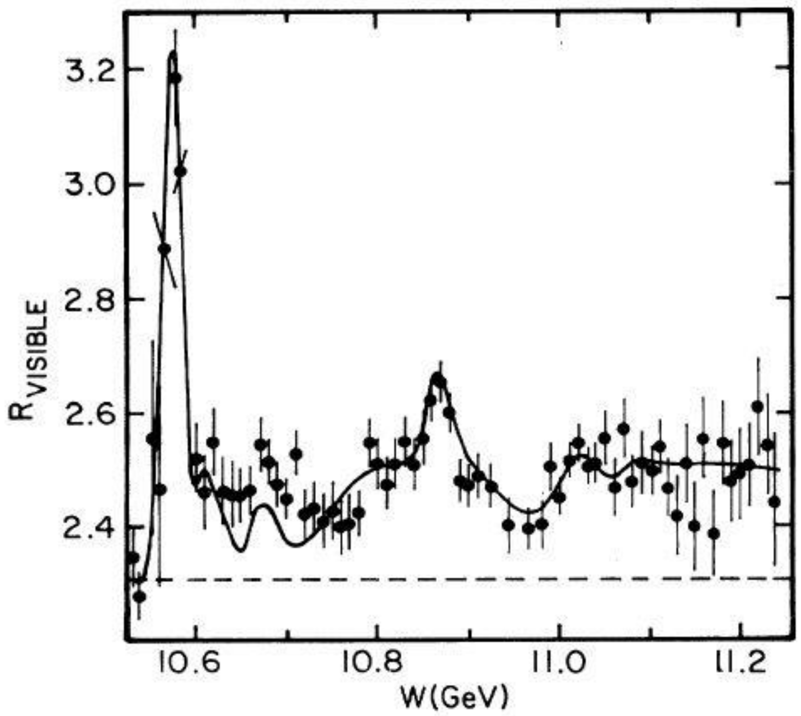


FIG. 2. Model calculation superimposed on data.

Lovelock et al. 1985

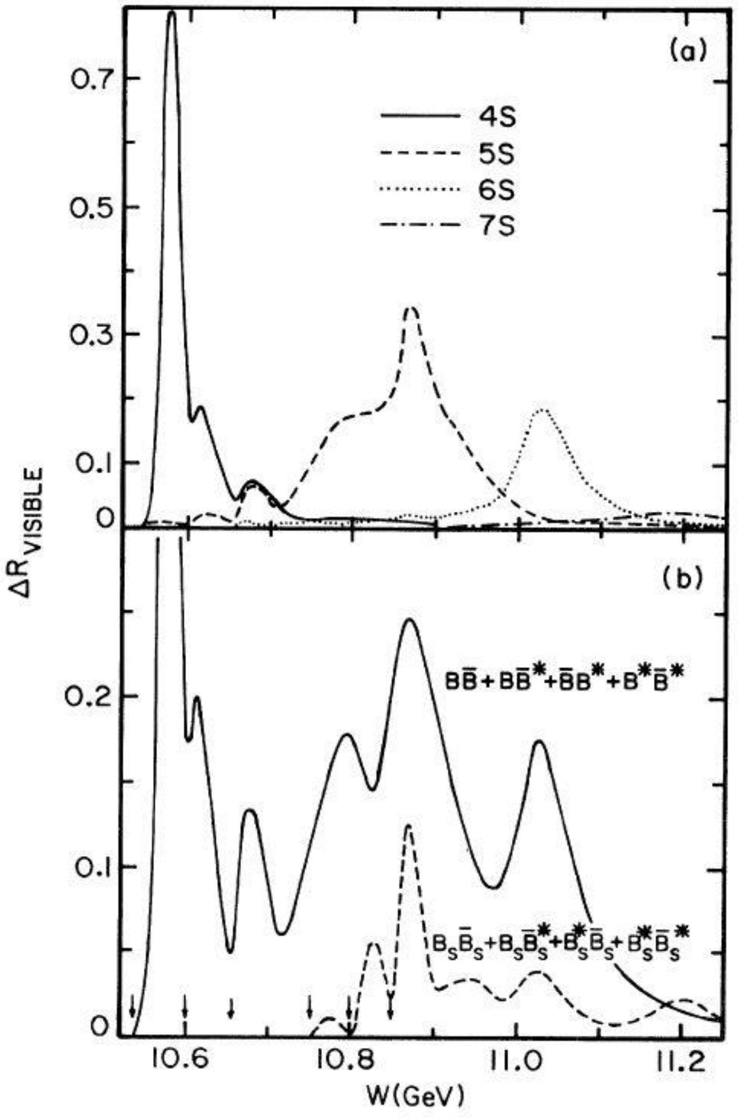


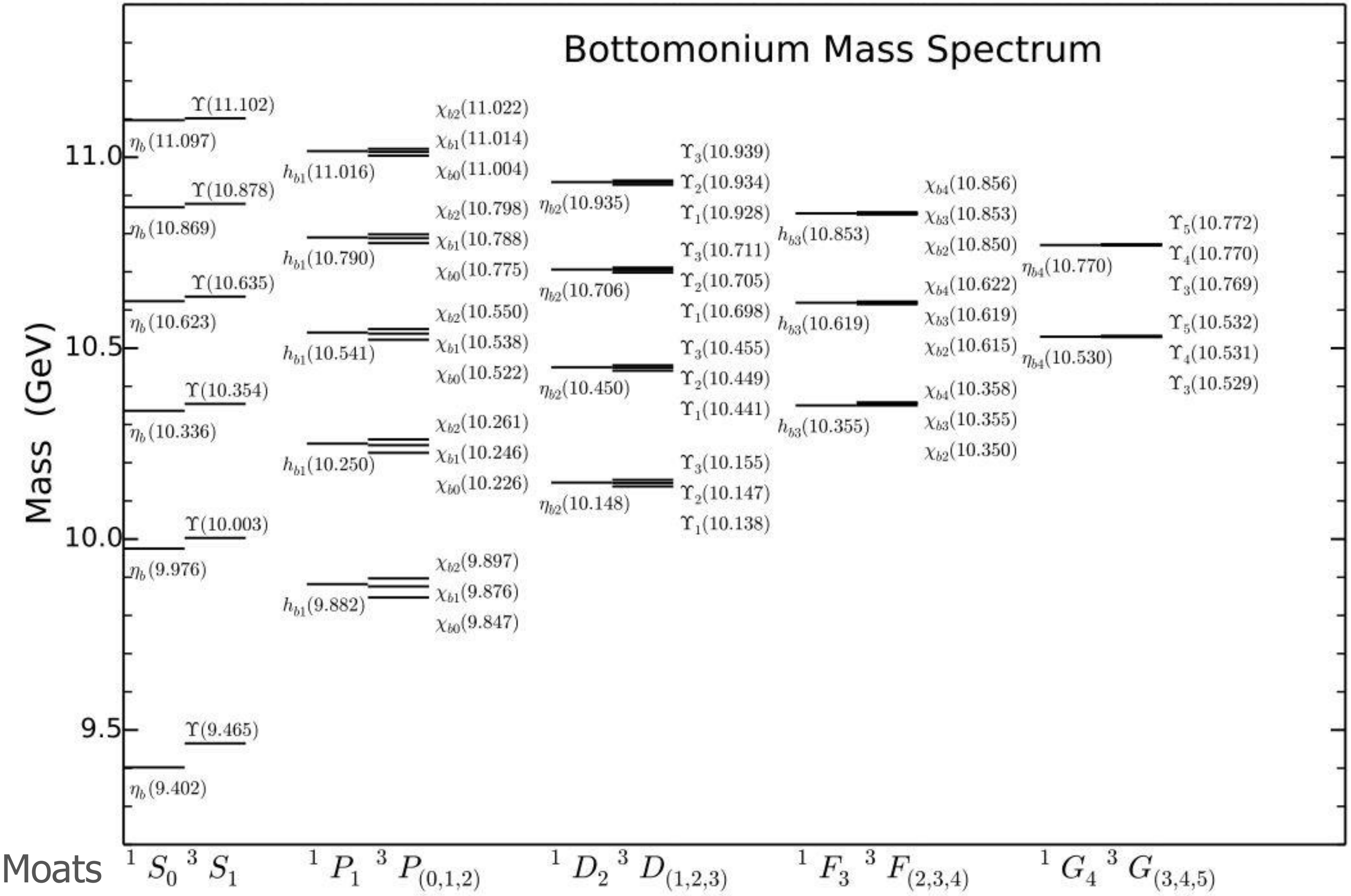
FIG. 3. (a) Contributions of the four Υ's to R, for two-body decays. (b) Contribution to R from B mesons (solid curve) and strange B mesons (dashed curve). Arrows indicate thresholds: $B\bar{B}$(10.545 GeV), $B\bar{B}^*$(10.600 GeV), $B^*\bar{B}^*$(10.655 GeV), $B_s\bar{B}_s$(10.751 GeV), $B_s\bar{B}_s^*$(10.801 GeV), $B_s^*\bar{B}_s^*$(10.851 GeV).

- Spectrum predictions based on relativized quark model
- Cornell potential from LQCD takes care of confinement

$$V(r) = A + \frac{B}{r} + \sigma r$$

TABLE I: Masses and effective harmonic oscillator parameter values (β) for S-, P- and D-wave Bottomonium mesons.

Meson	M_{theo} (MeV)	M_{exp} (MeV)	β (GeV)
$\Upsilon(1^3S_1)$	9465	9460.30 ± 0.26 [a]	1.157
$\eta_b(1^1S_0)$	9402	9398.0 ± 3.2 [a]	1.269
$\Upsilon(2^3S_1)$	10003	10023.26 ± 0.31 [a]	0.819
$\eta_b(2^1S_0)$	9976	$9999.0 \pm 3.5^{+2.8}_{-1.9}$ [a]	0.854
$\Upsilon(3^3S_1)$	10354	10355.2 ± 0.5 [a]	0.698
$\eta_b(3^1S_0)$	10336	10337 [b]	0.719
$\Upsilon(4^3S_1)$	10635	10579.4 ± 1.2 [a]	0.638
$\eta_b(4^1S_0)$	10623	10567 [b]	0.654
$\Upsilon(5^3S_1)$	10878	10876 ± 11 [a]	0.600
$\eta_b(5^1S_0)$	10869	10867 [b]	0.615
$\Upsilon(6^3S_1)$	11102	11019 ± 8 [a]	0.578
$\eta_b(6^1S_0)$	11097	11014 [b]	0.593



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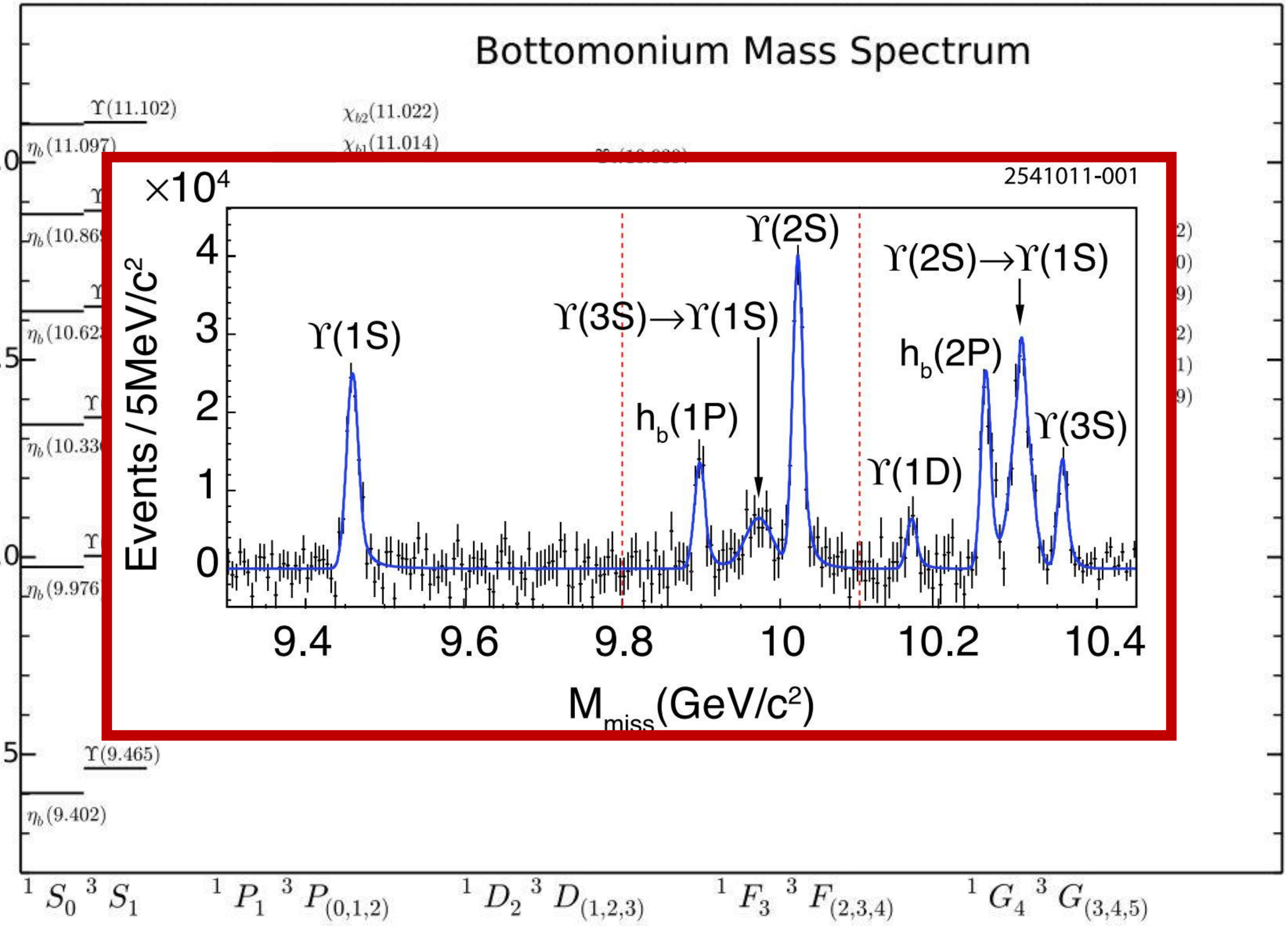

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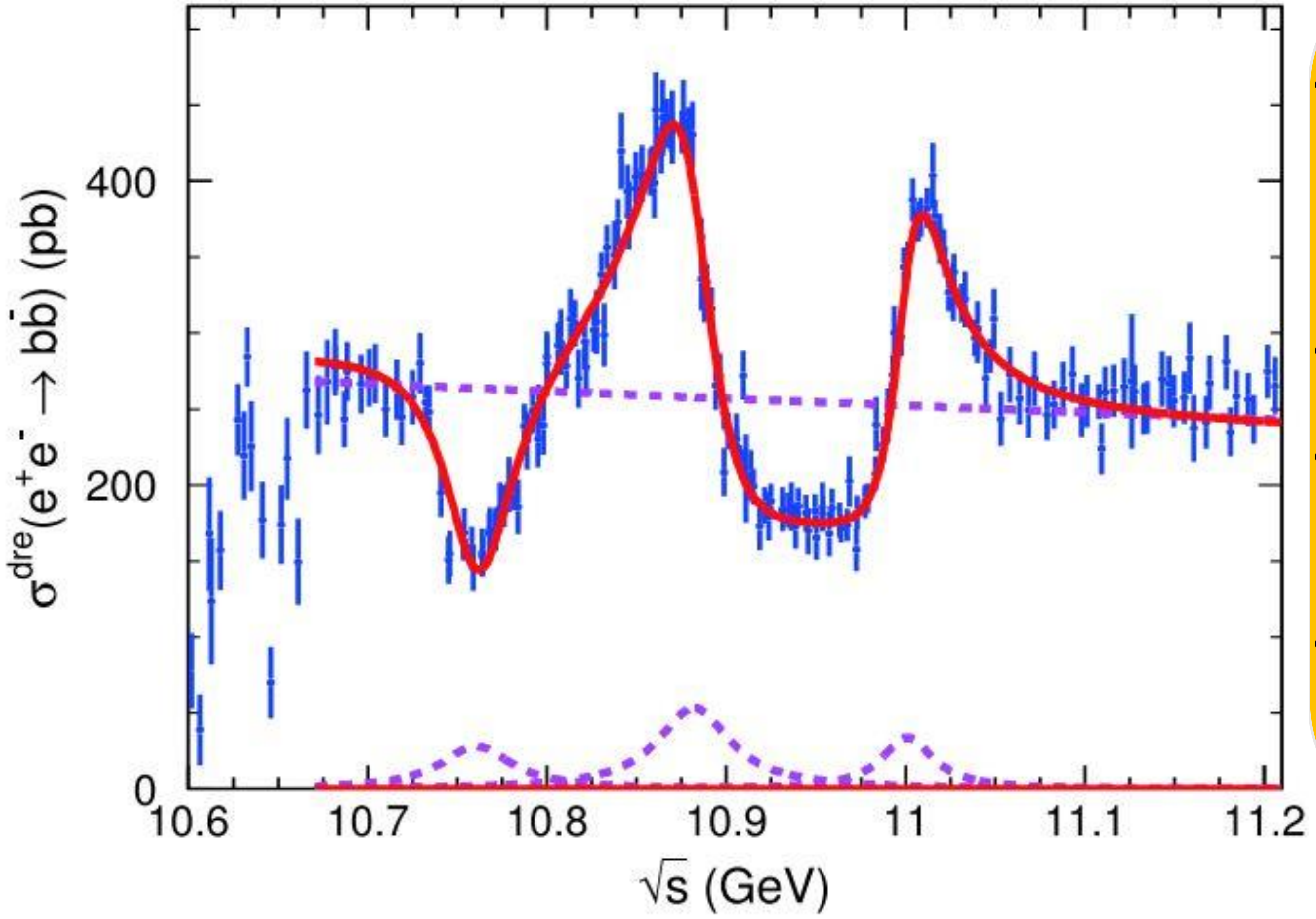
New Data!



- New data from BaBar (2009), Belle (2016) show unexplained structure above $\Upsilon(4S)$
- New resonance $\Upsilon(10750)$
- states renamed $\Upsilon(5S) \rightarrow \Upsilon(10860)$ and $\Upsilon(6S) \rightarrow \Upsilon(11020)$
- PDG Branching ratios still based on Breit-Wigner parameterizations

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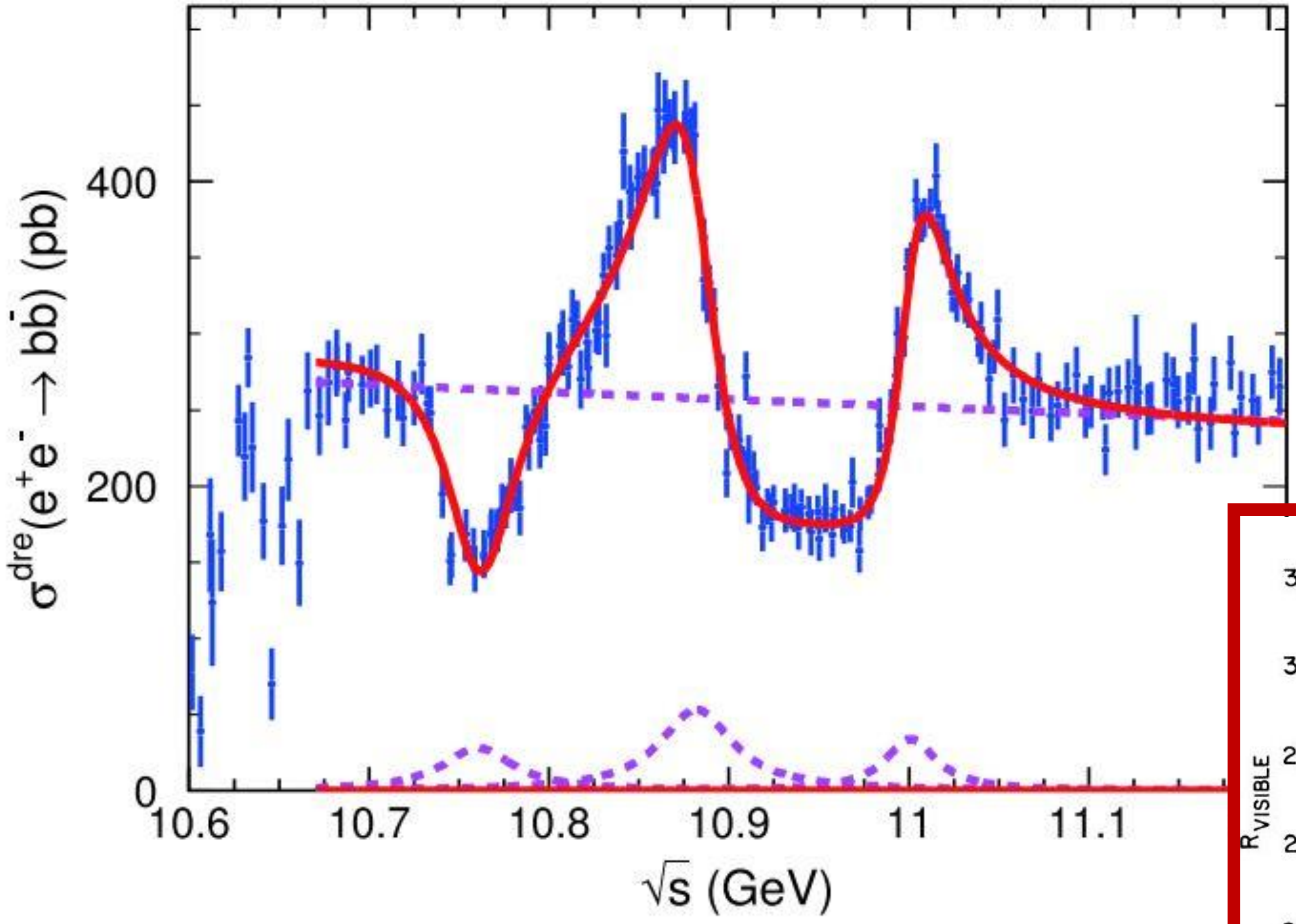

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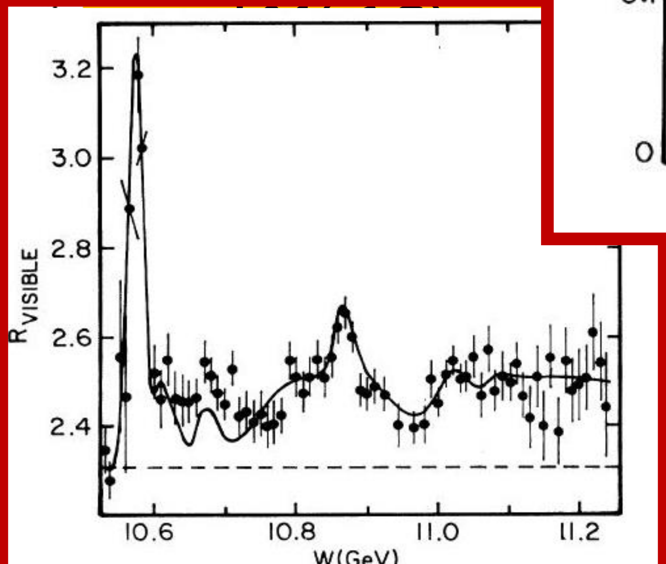

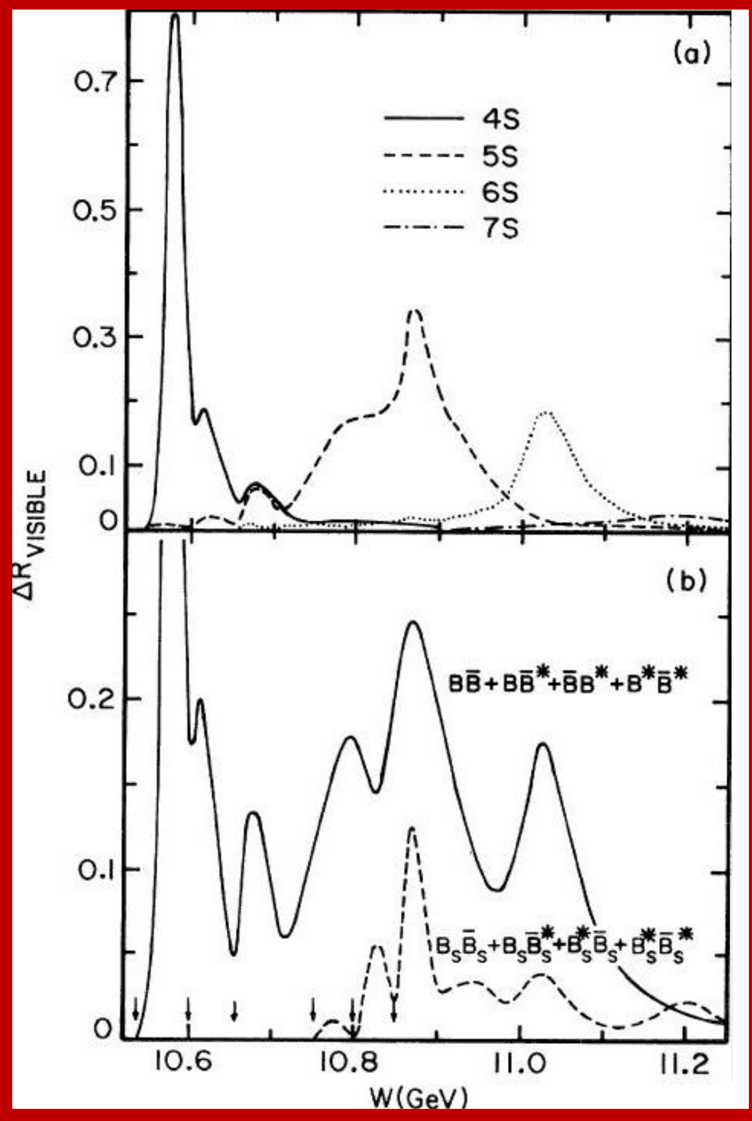

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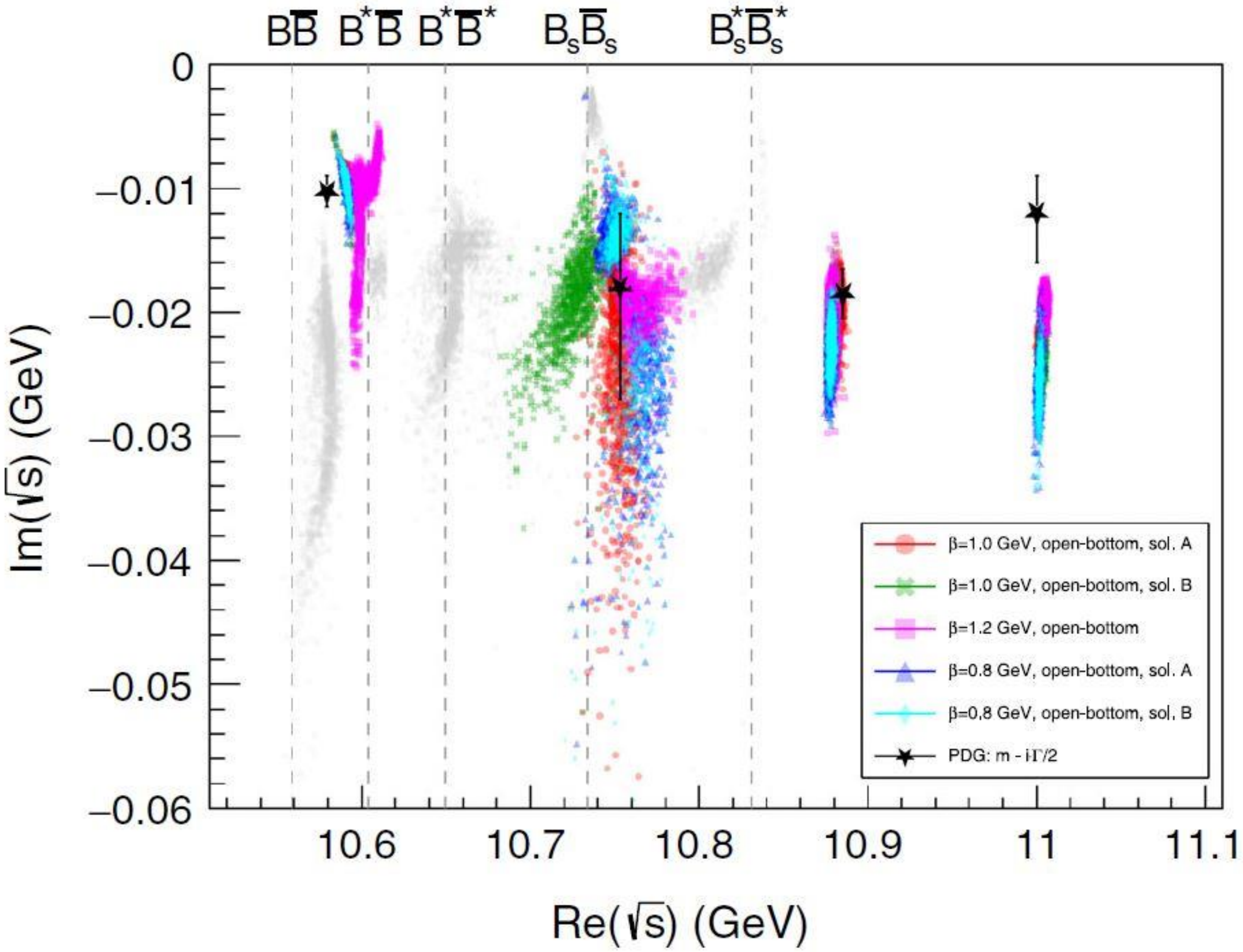
K-Matrix Analysis

- Systematic uncertainties seem to be large
- Complicated analytic behavior from amplitude parameterization
- Quasi 3-body channels $\Upsilon(nS)\pi^+\pi^-, h_b(nP)\pi^+\pi^-$
- Need to assess systematics better by including more model variation and making use of analytic properties



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K-Matrix Analysis

- Significant difference in branching ratios from PDG

TABLE IX. $\Upsilon(6S)$ branching ratios (%).

Channel	RPP	Our estimate	GM	SOEF
$B\bar{B}$	...	(0.8–8.6)	3.9	5.3
$B^*\bar{B}$	...	(1.9–12)	22.4	19.6
$B^*\bar{B}^*$	...	(0.2–6.2)	17.4	15.0
"$B_s\bar{B}_s$"	...	(70–90)	...	...
$B_s^*\bar{B}_s^*$	...	(0.04–9.7)	0.9	2.6
$\Upsilon(1S)\pi\pi$	...	(0.3–1.2)	...	0.35
$\Upsilon(2S)\pi\pi$	...	(0.3–2.9)	...	8.0×10^{-3}
$\Upsilon(3S)\pi\pi$	...	(0.2–1.0)	...	0.049
$h_b(1P)\pi\pi$	...	(0.5–2.1)	...	...
$h_b(2P)\pi\pi$	...	(0.2–4.3)	...	...

TABLE VIII. $\Upsilon(5S)$ branching ratios (%).

Channel	RPP[a]	Our estimate	GM	SOEF
$B\bar{B}$	5.5	(0.6–31)	19.5	22.3
$B^*\bar{B}$	14	(0.03–3.2)	60.6	42.4
$B^*\bar{B}^*$	38	(2.9–17)	8.8	0.3
"$B_s\bar{B}_s$"	[25]	(31–77)	...	...
$B_s^*\bar{B}_s^*$	18	(0.9–33)	7.3	27.4
$\Upsilon(1S)\pi\pi$	0.53	(0.6–2.5)	...	0.023
$\Upsilon(2S)\pi\pi$	0.78	(1.6–5.2)	...	0.033
$\Upsilon(3S)\pi\pi$	0.48	(0.2–1.7)	...	0.01
$h_b(1P)\pi\pi$	0.35	(0.3–2.8)	...	...
$h_b(2P)\pi\pi$	0.57	(0.9–4.0)	...	...

[a]Obtained using ratios of cross sections near the $\Upsilon(5S)$ mass.

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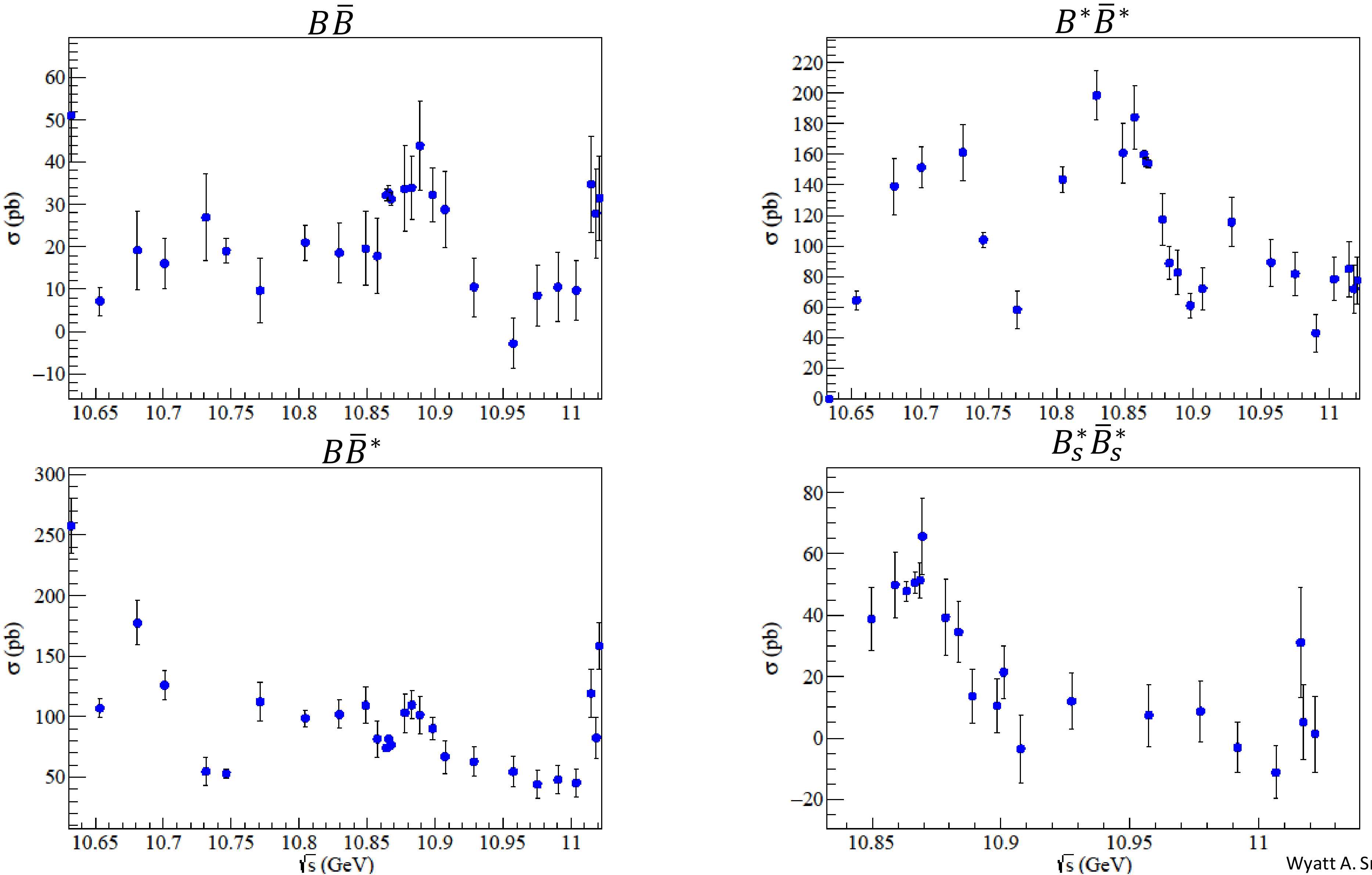
- Even more new data now available for exclusive cross sections! (Belle, 2023 Preliminary)



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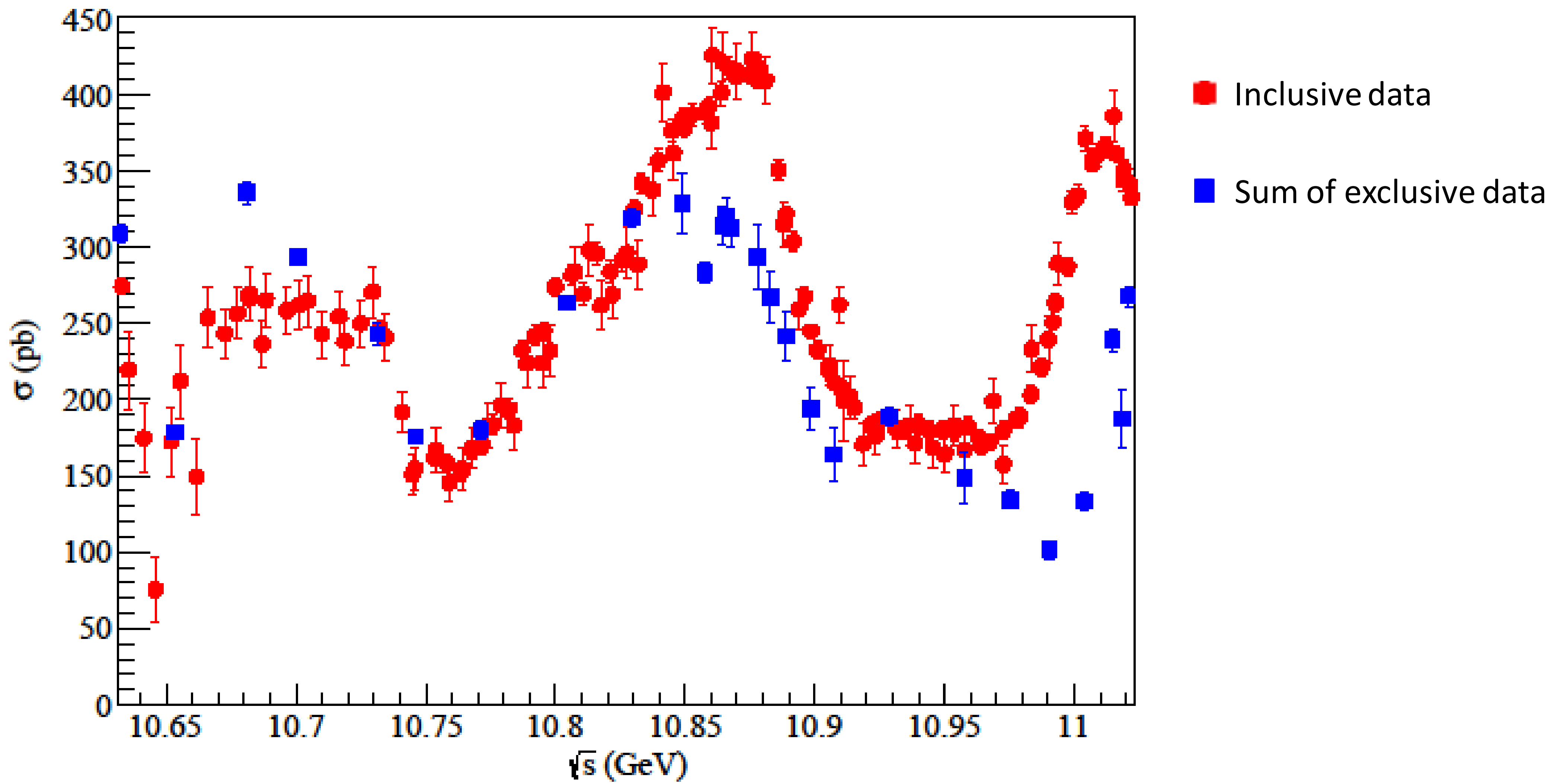


Coupled Channel N/D Model

$$A_i^J = \kappa p_i^J \sum_k n_k^J(s)\,{(D^J)_{ki}}^{-1}$$

- Basic idea is to separate left-hand and right-hand cuts explicitly, to take advantage of analytic properties of the amplitude

$$n_k^J(s) = \sum_{n=0}^{n_{max}} a_n^{J,k} T_n[\omega(s)] \qquad \omega(s) = \frac{s}{s+s_0}$$

- n is parameterized by an effective polynomial expansion, with s_0 as a scale parameter

Coupled Channel N/D Model

$$D^J_{ki}(s) = [K^J(s)^{-1}]_{ki} - \frac{s}{\pi}\int_{m_{th}^2}^{\infty} ds' \frac{\rho N^J_{ki}(s')}{s'(s'-s-i\epsilon)}$$

- D is parameterized by a K-matrix and dispersive integral

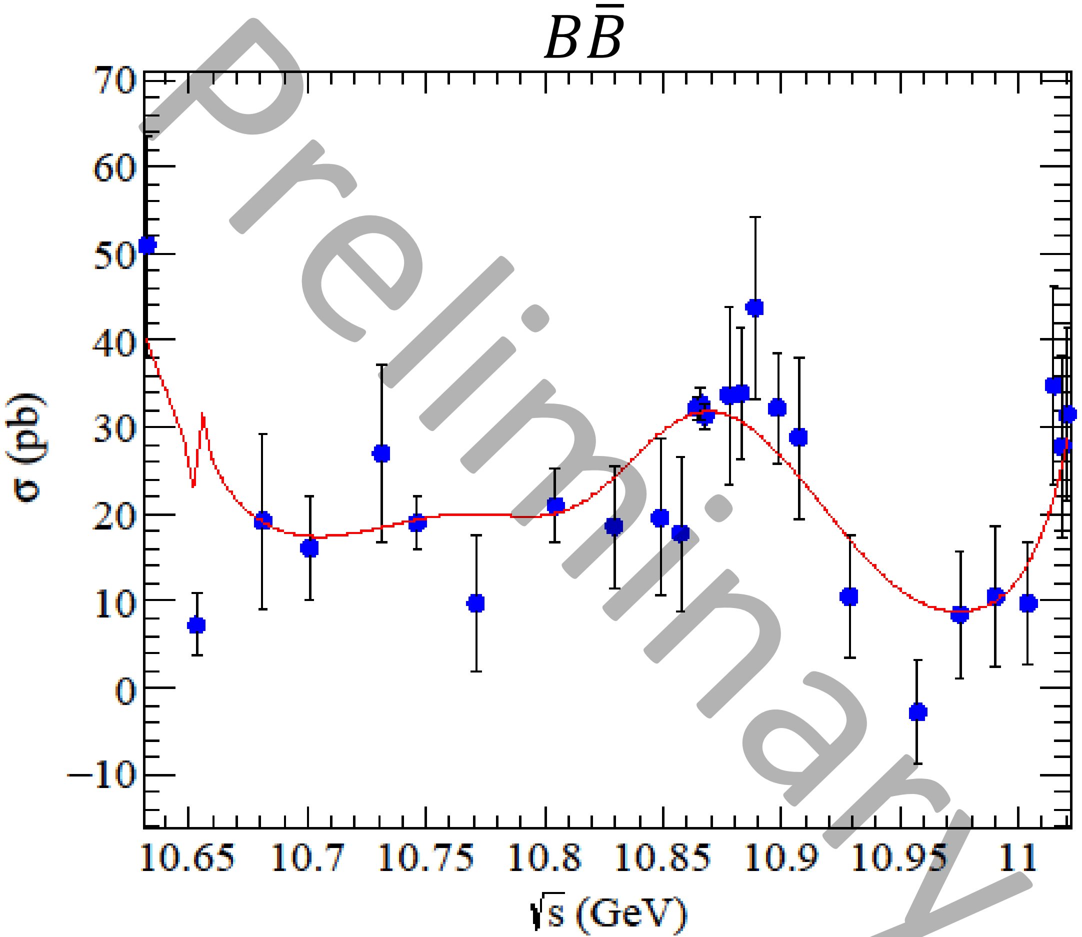
$$\rho N^J_{ki}(s') = \delta_{ki}\frac{(2p_i)^{2J+1}}{(s'+s_L)^{2J+\alpha}}$$

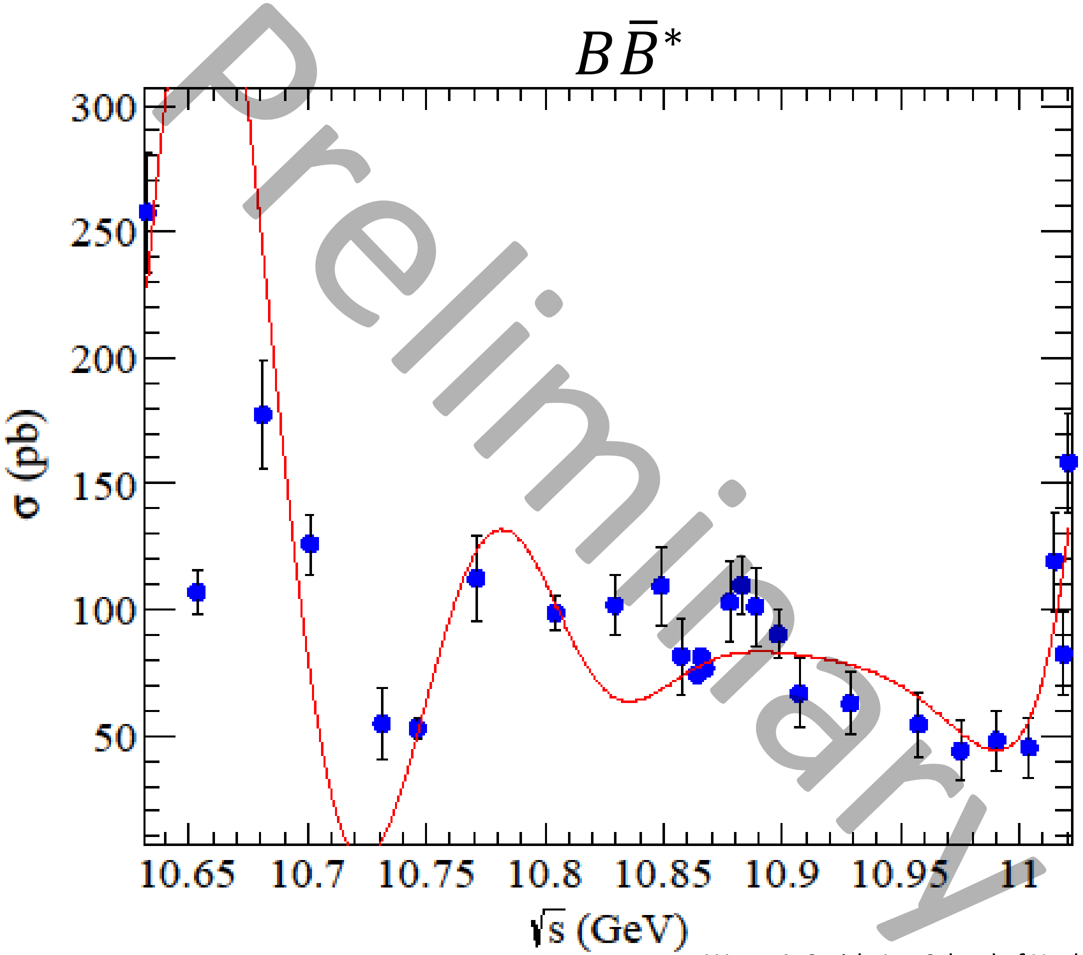
$$K^J_{ki}(s) = \sum_R \frac{g_k^{J,R} g_i^{J,R}}{m_R^2 - s} + c^J_{ki} + d^J_{ki}s$$

- s_L controls position of left hand poles
- α controls asymptotic behavior of integrand
- $g's$ are couplings of K-matrix resonances to the channels
- c, d are nonresonant terms from subtraction of the dispersion relation

(very) Preliminary Fits

- Exclusive fits to $B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$





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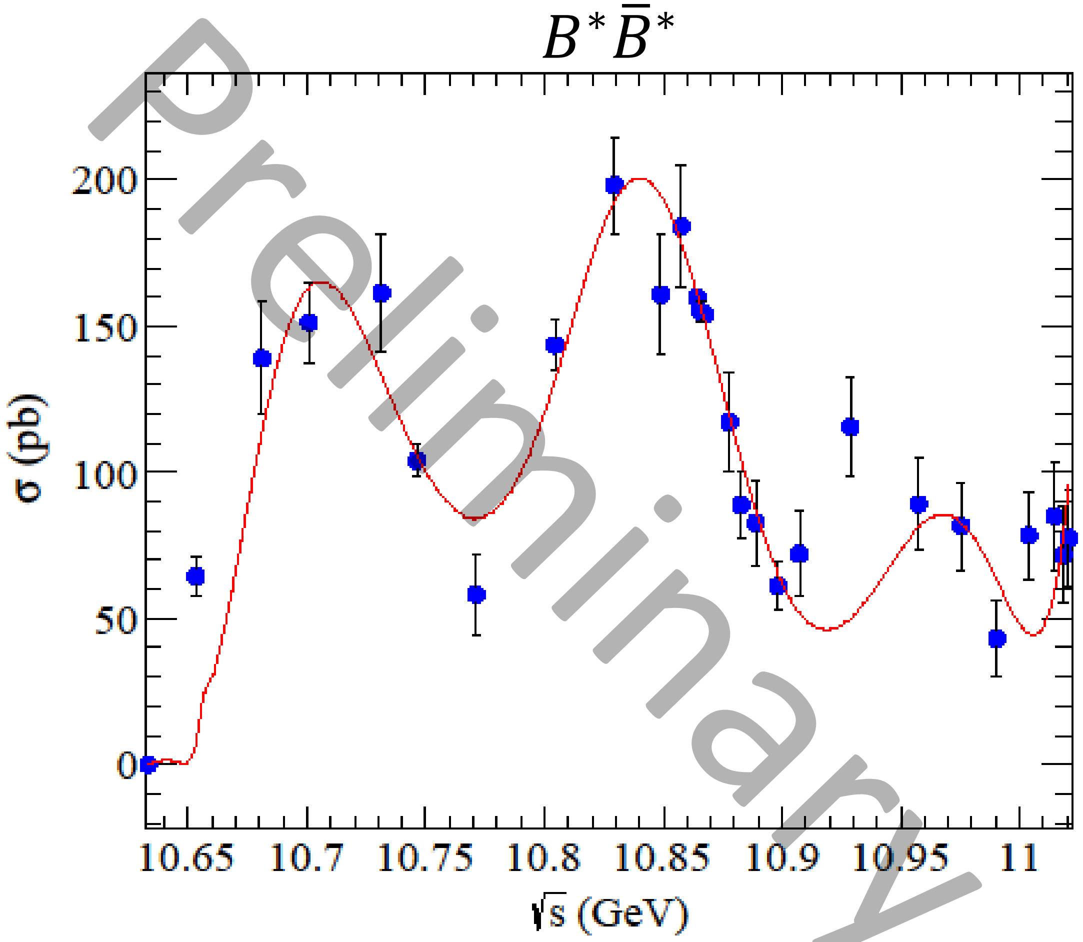
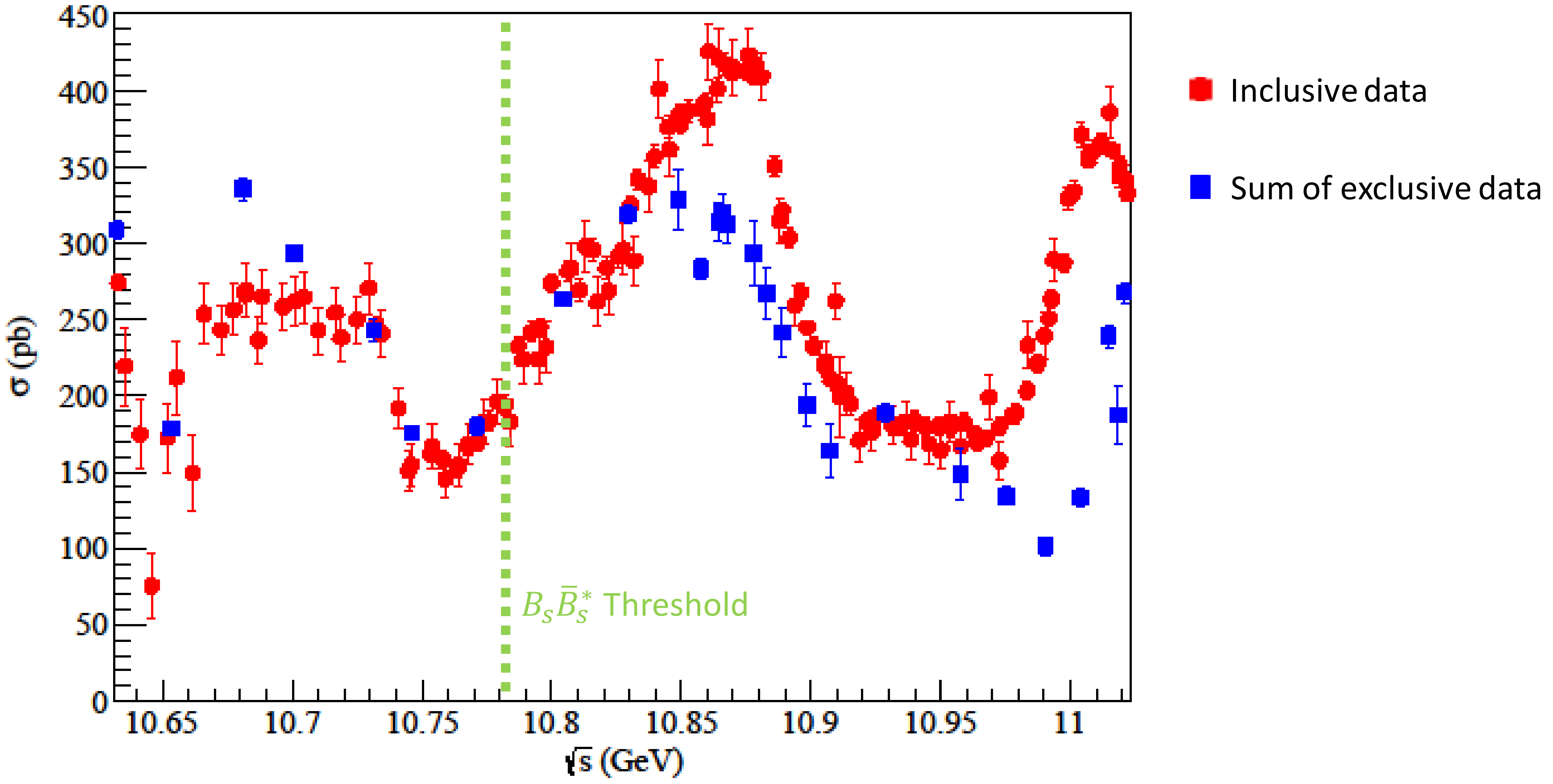


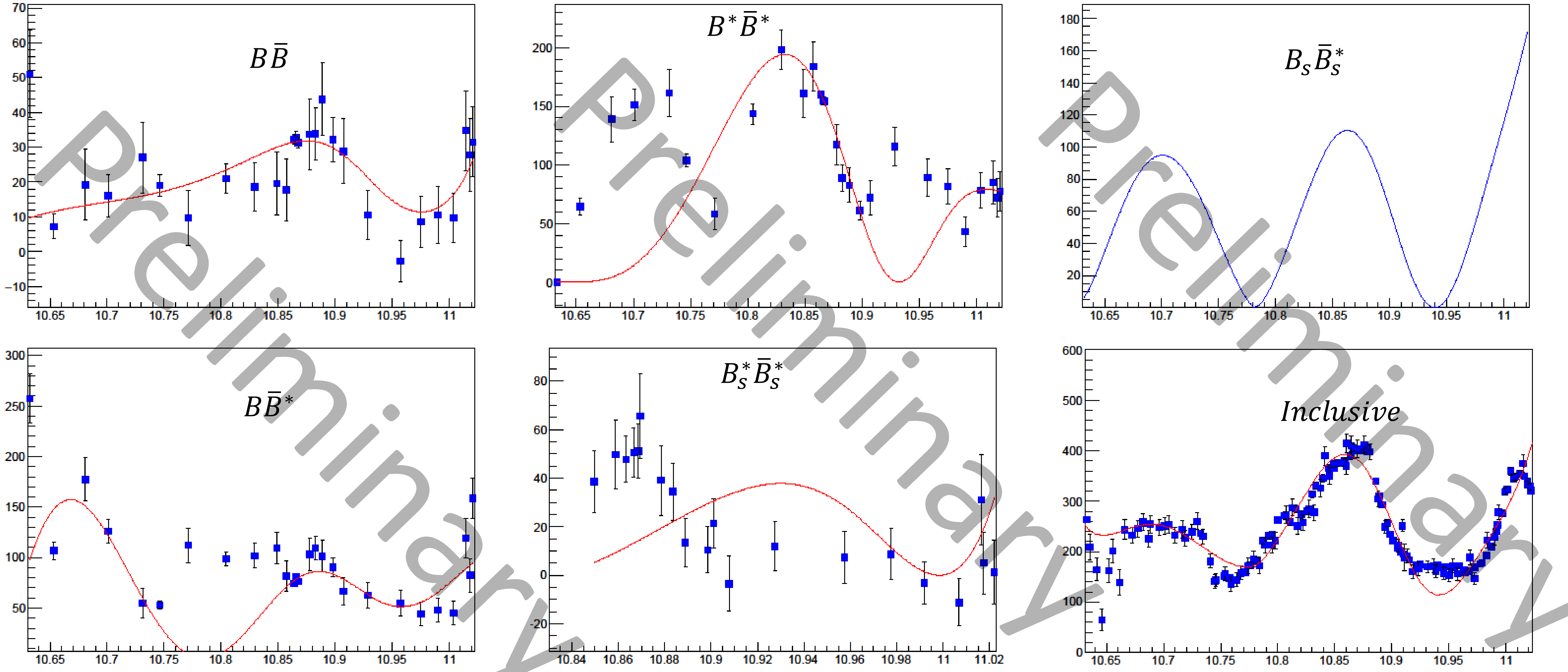
(very) Preliminary Fits

- Closest channel to visible difference between inclusive, sum of exclusive data is $B_s\bar{B}_s^*$ → add it to absorb differences



(very) Preliminary Fits

- Simultaneous fits to inclusive data and $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$, $B_s^*\bar{B}_s^*$, and $B_s\bar{B}_s^*$



Summary

- Bottomonium spectrum above $\Upsilon(4S)$ not so simple!
- Breit-Wigners don't cut it—need coupled channel analysis
- Need better assessment of systematics, more model variation
- 3-body channels?
- Analysis in progress (stay tuned!)