PROCEEDINGS OF SCIENCE

The Super$B$ Project

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Super$B$ is a major new European e^+e^- collider facility to be built at the recently-approved Nicola Cabibbo Laboratory on the campus of the University of Tor Vergata, Rome. The facility will enable the precise study of the structure of New Physics beyond the Standard Model at energy scales above the LHC. In this article, I review the physics opportunities, the status of the accelerator and detector studies, and the future plans.

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1. Introduction

A super-flavour factory will be able to improve the precision and sensitivity of the previous generation of e^+e^- flavour factories by factors of five to ten. The sides and angles of the Unitarity Triangle will be determined to an accuracy of $\sim 1\%$. Limits on Lepton Flavour Violation (LFV) in τ decays will be improved by two orders of magnitude. It will become feasible to search for CP violation (CPV) in τ decays and charm mixing. New precision measurements of electroweak properties, such as the running of the weak mixing angle $\sin^2\theta_W$ with energy, should become possible. But the primary goal will be the search for New Physics (NP) signatures at energy scales that exceed the direct search capabilities of the LHC.

Figure 1 illustrates the current situation (summer 2011) in the search for the Higgs boson and supersymmetry (SUSY). The LHC detectors are beginning to exclude the standard model Higgs with mass from $\sim 150\,\mathrm{GeV}/c^2$ to $\sim 450\,\mathrm{GeV}/c^2$ and searches for SUSY particles suggest that some are quite massive, possibly nearer $1\,\mathrm{TeV}/c^2$ than $100\,\mathrm{GeV}/c^2$. A low mass Higgs ($\sim 120\,\mathrm{GeV}/c^2$) is compatible with both the standard model and SUSY, while a high mass Higgs or no Higgs at all indicates the need to probe higher mass scales for NP. The SUSY results indicate that "trivial" SUSY models may need to include more parameters.

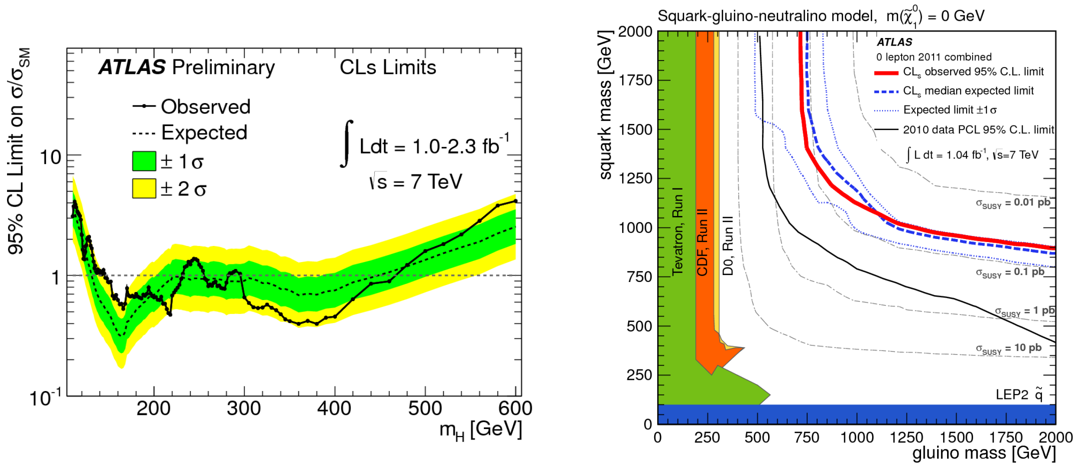

Figure 1: (left) 95% confidence level (CL) upper limit on the standard model Higgs as a function of the Higgs mass (solid black line) from ATLAS [1]; (right) The median observed 95% CL limit (red/solid line) for a simplified SUSY model (also from ATLAS) [2].

Flavour physics is an ideal tool for indirect searches for NP. Both flavour mixing and CPV in B and D mesons occur at the loop level in the Standard Model (SM) and therefore can be subject to NP corrections. New virtual particles occurring in the loops ("penguins") or tree diagrams can also change the predicted branching fractions or angular distributions of rare decays. Current experimental limits indicate NP with trivial flavour couplings has a scale in the 10-100 TeV range, which is much higher than the 1 TeV scale suggested by SM Higgs physics. We are therefore presented with a scenario in which either the NP scale can not be seen in direct searches at the LHC or the NP scale is close to 1 TeV and therefore the flavour structure of the NP must be very complex. In either case, indirect searches provide a way of understanding the new phenomena in great detail.

Super*B* is an asymmetric e^+e^- collider with a 1.3 km circumference. The design calls for 6.7 GeV positrons colliding with 4.18 GeV electrons at a centre of mass energy $\sqrt{s} = 10.58$ GeV. The boost $\beta\gamma = 0.238$ is approximately half the value used at BABAR [3] to keep the power consumption low (< 20 MW). The design luminosity $\mathscr{L}$ is $10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and data taking is expected to start in the latter part of this decade with a delivered integrated luminosity of 75 ab^{-1} over five years. Confidence is high that the baseline luminosity specification can be exceeded, leading to the prospect of collecting 20-40 ab^{-1} per year in later years.

In the following sections, I discuss the physics potential of some of the key measurements to be made at the Super*B* factory with an integrated luminosity of 75 ab^{-1}. In addition, there is a comprehensive program for B_s at the $\Upsilon(5S)$ resonance, B and D mesons Dalitz analyses, lepton number violation [4], bottomium and charmonium spectroscopy, exotic resonances, and two-photon interactions, to name just a few.

2. The CKM matrix and CP Violation

The complex 3×3 Cabibbo-Kobayashi-Maskawa (CKM) unitary matrix V_{ckm} maps the weak eigenstates of the quarks to their mass eigenstates. The complex phase in the CKM matrix can explain CP Violation. Multiplying together the first and third columns forms the Unitarity Triangle relationship $V_{\mathrm{ud}}V^*_{\mathrm{ub}} + V_{\mathrm{cd}}V^*_{\mathrm{cb}} + V_{\mathrm{td}}V^*_{\mathrm{tb}} = 0$ which can be displayed as a triangle in the complex plane with three internal angles α, β and γ [5].

Both BABAR and Belle [6] have successfully measured the Unitarity Triangle sides and angles [5]. Although there are discrepancies in some measurements, overall everything is consistent to a few sigma. Increasing the statistics will show if these tensions are real and possible signs of NP. It will be possible to measure the angles α and γ to $1-2\%$, and β to 0.1%. $|V_{cb}|$ and $|V_{ub}|$ can be measured to 1% and 2% accuracy, respectively, in both inclusive and exclusive semileptonic decays. Figure 2a shows constraints on the Unitarity Triangle in the $\overline{\rho}$-$\overline{\eta}$ plane with current experimental measurements and Figure 2b shows what the $\overline{\rho}$-$\overline{\eta}$ plane will look like with Super*B* statistics, assuming the current measurements maintain their central values.

3. New Physics (NP) Searches

In parallel with improved determination of the Unitarity Triangle, Super*B* will make precision measurements of a series of “Golden Modes”. The SM predictions for these modes are well calculated and they can be cleanly measured experimentally. NP scenarios can be differentiated by comparing the measured values with NP predictions. Table 1 shows just some of the key measurements and a sample of NP models.

In 2-Higgs-doublet (2HDM-II) and MSSM models, the decay $B\to\tau\nu$ is sensitive to the presence of a charged Higgs H^- replacing the SM W^-. The region of charged Higgs mass versus $\tan\beta$ that can be excluded is shown in Figure 3. This includes a 20% uncertainty from the form factor f_b and CKM matrix element V_{ub} that can be expected to be much reduced in the future.

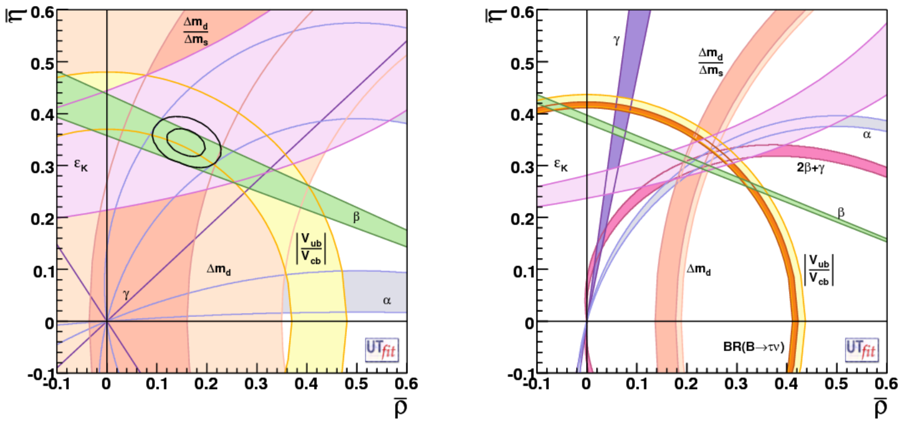

Figure 2: Regions corresponding to 95% probability for $\overline{\rho}$ and $\overline{\eta}$ with current measurements (left) and with Super*B* precision assuming the current central values (right). The Unitarity Triangle has a base of unit length along $\overline{\rho}$ and the black ellipses show the current best estimate of the apex.

	H^+ high tanβ	MFV	non-MFV	NP Z-penguins	Right-hand currents	LTH	SUSY models AC	RVV2	AKM	δLL	FBMSSM
$\mathscr{B}(\tau \to \mu\gamma)$							$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$	$\star\star\star$
$\mathscr{B}(\tau \to \mu\mu\mu)$						$\star\star\star$					
$\mathscr{B}(B \to \tau\nu, \mu\nu)$	$\star\star\star$-CKM										
$\mathscr{B}(B \to K^{(*)}\nu\overline{\nu})$			$\star$	$\star\star\star$			$\star$	$\star$	$\star$	$\star$	$\star$
$S_{K_S^0\pi^0\gamma}$					$\star\star\star$						
Angle β (ΔS)			$\star\star\star$-CKM		$\star\star\star$		$\star\star\star$	$\star\star$	$\star$	$\star\star\star$	$\star\star\star$
$A_{CP}(B \to X_s\gamma)$			$\star\star\star$		$\star\star$		$\star$	$\star$	$\star$	$\star\star\star$	$\star\star\star$
$\mathscr{B}(B \to X_s\gamma)$		$\star\star\star$	$\star$		$\star$						
$\mathscr{B}(B \to X_s ll)$			$\star$	$\star$	$\star$						
$A_{FB}(B \to K^{(*)}ll)$							$\star$	$\star$	$\star$	$\star\star\star$	$\star\star\star$
Charm mixing							$\star\star\star$	$\star$	$\star$	$\star$	$\star$
CPV in Charm	$\star\star\star$									$\star\star\star$	

Table 1: The golden matrix of observables versus a sample of NP scenarios. MFV is a representative Minimal Flavour Violation model; LTH is a Littlest Higgs Model with T Parity. A number of explicit SUSY models are included [7]. $\star\star\star$ denotes a large effect, $\star$ a measurable effect and $\star\star\star$-CKM indicates a measurement that requires precise measurement of the CKM matrix. ΔS is the difference in the angle β between $b \to s$ penguin-dominated transitions and $b \to c\bar{c}s$ tree-dominated decays.

Super*B* can access the off-diagonal elements of generic squark mass matrices in the MSSM model using the mass insertion approximation. These can not be seen by the LHC general purpose detectors. Considering decays like $b \to s\gamma$ and $b \to sl^+l^-$, the dark (red) region in Figure 4 shows the region sensitive to non-zero values of the absolute value of the matrix element $(\delta^d_{23})_{LR}$ as a function of the gluino mass. SUSY mass scales in the range 1-10 TeV can be measured.

4. τ Physics

An almost equal number of $\tau^+\tau^-$ pairs are produced as $B\bar{B}$ pairs at the $\Upsilon(4S)$ resonance. Current experimental 90% confidence level upper limits on τ LFV are in the $10^{-8} - 10^{-7}$ range

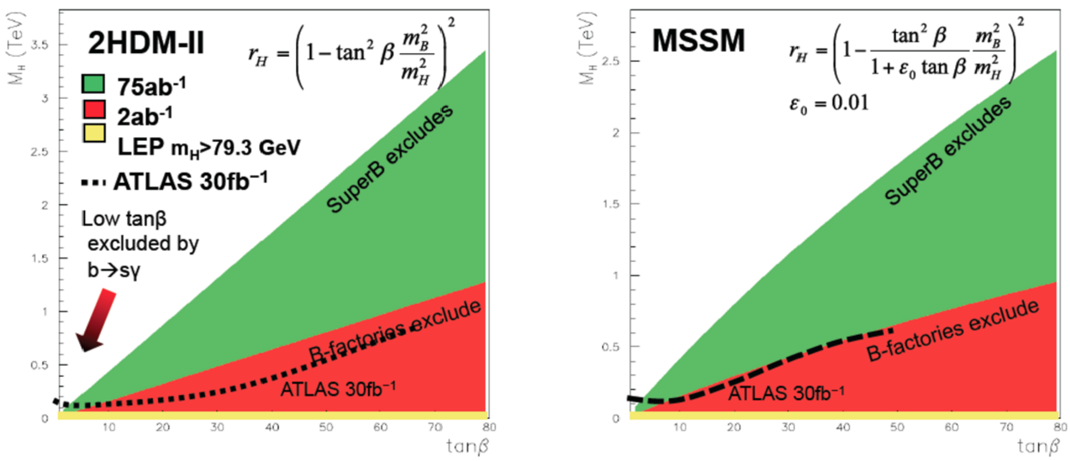

Figure 3: The mass of the charged Higgs versus $\tan\beta$ from $B \to \tau\nu$ decays for a 2HDM-II (left) and MSSM (right) model. The dark (red) region is excluded assuming the *BABAR* and Belle datasets are combined and the light (green) region shows the exclusion potential of Super*B*.

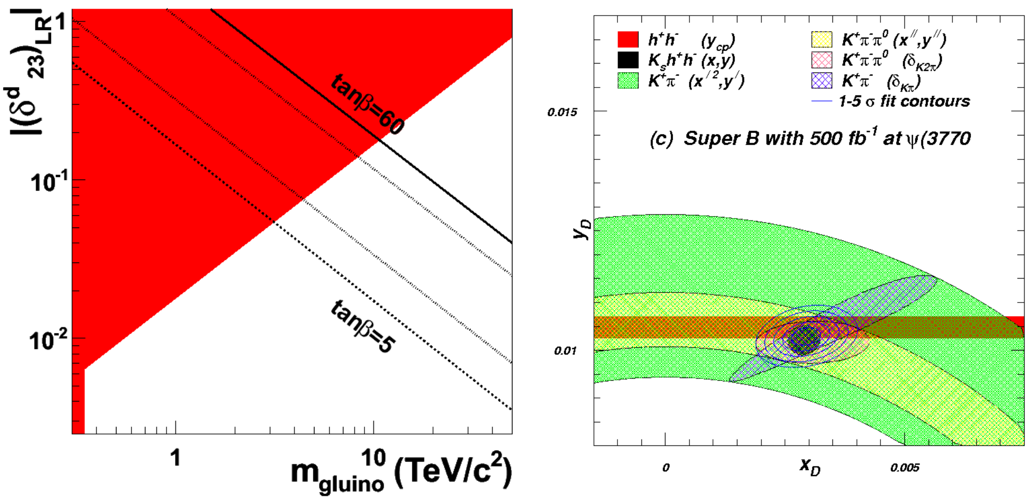

Figure 4: Left: The shaded (red) region shows where a measurement can be made (defined as a 3σ significance) of the matrix element $(\delta^d_{23})_{LR}$ as a function of gluino mass in an MSSM model from measurements involving a $b \to s$ transition. Right: the expected precision on charm mixing parameters from combining BES-III and Super*B* $\psi(3770)$ and $\Upsilon(4S)$ data.

depending on the decay. In the very clean environment of Super*B*, upper limits on τ LFV can be achieved down to a level of 2×10^{-10} for $\tau \to \mu\mu\mu$. This is illustrated in Figure 5, which compares current *BABAR* and Belle measurements [8] with some predictions for Super*B*. Background-free modes should scale with the luminosity $\mathscr{L}^{-1}$ while other modes will scale with $\mathscr{L}^{-1/2}$ or better, thanks to re-optimized analysis techniques. In $\tau \to \mu\gamma$ for example, LFV is predicted at the level $10^{-10} - 10^{-7}$ depending on the NP model. Figure 6 shows the predicted branching fraction $\mathscr{B}(\tau \to$

$\mu\gamma$) in an SU(5) SUSY GUT model as a function of the NP phase. The expected Super*B* sensitivity of 2×10^{-9} covers the majority of the parameter space. These τ measurements are complementary to the measurement of θ_{13} in ν experiments and LFV in $\mu \to e\gamma$.

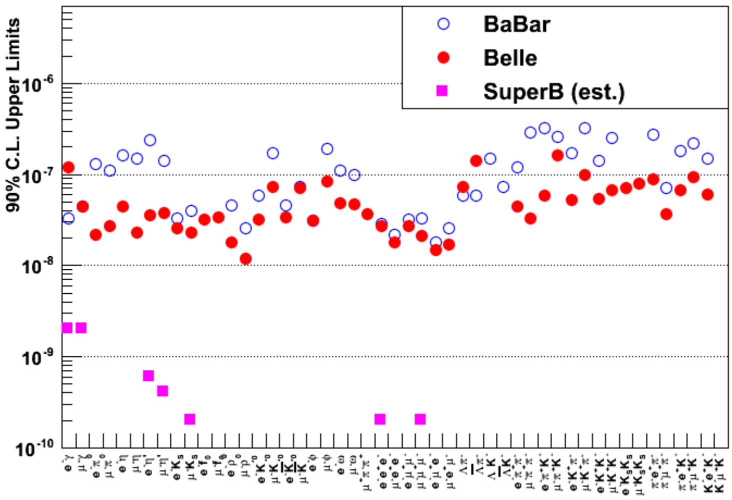

Figure 5: Current 90% confidence limits on branching fractions $\mathscr{B}$ for τ LFV decays from *BABAR* and Belle compared to predictions for Super*B*. The majority of the modes will be measurable at Super*B*.

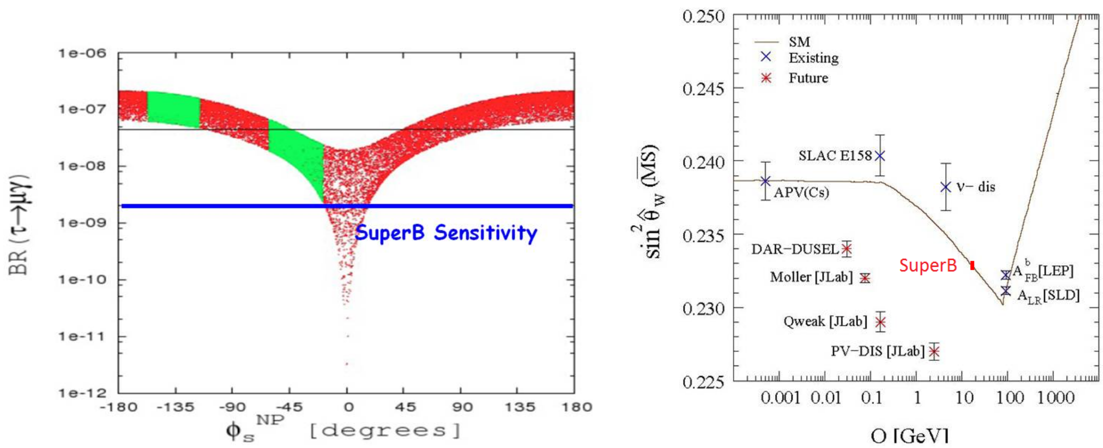

Figure 6: Left: $\mathscr{B}(B \to \mu\gamma)$ in an SU(5) SUSY GUT model as a function of parameter space and NP phase ϕ_S^{NP}. Right: Measurements of $\sin^2\theta_w$ as a function of energy. The size of the bar at an energy ~ 10.6 GeV representing the Super*B* measurement is approximately the same size as the error.

5. Charm Physics

CPV in charm decays is expected to be very low in the SM ($< 1\%$) so its detection would be a clear indicator of NP [9]. Current values for the mixing parameters x and y from HFAG [5] fits give

$(0.63 \pm 0.20)\%$ and $(0.75 \pm 0.12)\%$, allowing for CPV [5]. At Super$B$, the errors should reduce to 0.07% and 0.02%, respectively. If the results are combined with expected results from BES-III and a dedicated Super$B$ 500 fb^{-1} run ($\sim$ 4 months) at the $D\,\bar{D}$ threshold, the BES-III/CLEO-c physics programme can be repeated leading to a further reduction in these errors to 0.02% and 0.01%, respectively. This is shown in the right-hand plot of Figure 4.

6. Electroweak Physics

If a polarised electron beam is available, many of the upper limits on τ LFV modes can be improved by an additional factor of two. The polarisation also allows for the search for τ EDM at a level of $2 \times 10^{-19} e\,$cm and measurement of $\Delta\alpha_\tau$ with an error of 10^{-6}. The value of $\sin^2\theta_w$ can be measured with an accuracy $\pm 1.8 \times 10^{-4}$ at $Q = 10.58\,$GeV and so help understand the discrepancy in the measurements from LEP, SLD and NuTev [10]. This is shown in right-hand plot of Figure 6 where the size of the bar represents the expected error on the Super$B$ measurement.

7. Exotics and Charmonium

The B-Factories and the Tevatron have discovered heavy bound states that do not fit into the conventional meson interpretation. However, apart from some exceptions like the $X(3872)$, they have only been observed in a single decay channel with a significance only just above 5σ. Figure 7 shows some of the newly discovered states. Possible explanations include hybrids, molecules, tetraquarks and threshold effects. Super$B$'s ability to run at the $\Upsilon(nS)$ resonances and charm threshold provides a unique opportunity for testing low- and high-energy QCD predictions. Predicting the expected rates for poorly measured resonances is of course hard and work is on-going to improve the extrapolations. The $B \to X(3872)K$ decays should produce $\sim 2k - 10k$ events in each of their main decay channels. $Y(4260) \to J/\psi\,\pi^+\pi^-$ will have $\sim 45k$ events, while $\sim 4.5k$ events can be expected for both $Y(4350)$ and $Y(4660)$ decaying to $\psi(2S)\pi^+\pi^-$. It should be possible to confirm the existence of the $Z_1^+(4050)$, $Z^+(4430)$ and $Z_2^+(4430)$ as Super$B$ will collect between $150k - 2M$ events of the relevant fully reconstructed final states $J/\psi\,\pi^+K$, $\psi(2S)\pi^+K$, and $\chi_{cJ}\pi^+K$.

8. Status of the project

The physics potential [7], and the detector [11] and accelerator [12] plans have been extensively documented. The detector will reuse a large part of the BABAR detector. Major upgrades and options include the vertex detector, the tracking chamber, forward and rear calorimetry, and enhanced particle identification. The accelerator parameters are close to final for operating in the $\psi(3770)$ to $\Upsilon(5S)$ energy range and the accelerator will reuse large parts of the SLAC PEP-II hardware. A 30 hectare site on the campus of Tor Vergata University, Rome, was selected at the end of May 2011 and the new "Nicola Cabibbo Laboratory" was approved at the beginning of October 2011. Data taking should start within six years after construction begins.

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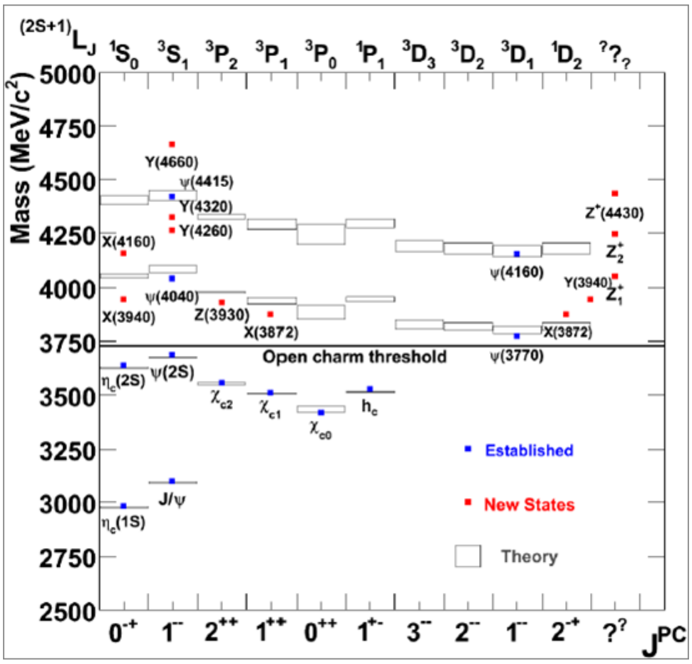

Figure 7: Measured masses of newly observed states positioned according to their most likely quantum numbers.

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