

# From HERA to the LHC

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## Abstract

Some personal comments are given on some of the exciting interfaces between the physics of HERA and the LHC. These include the quantitative understanding of perturbative QCD, the possible emergence of saturation phenomena and the Colour-Glass Condensate at small  $x$  and large  $Q^2$ , the link between forward physics and ultra-high-energy cosmic rays, and new LHC opportunities opened up by the discovery of rapidity-gap events at HERA, including the search for new physics such as Higgs bosons in double-diffraction events.

## 1 Preview

There are many exciting interfaces between physics at HERA and the LHC, and I cannot do justice to all of them in this talk. Therefore, in this talk I focus on a few specific subjects that interest me personally, starting with the LHC's 'core business', namely the search for new physics at the TeV scale, notably the Higgs boson(s) and supersymmetry [1]. Identifying any signals for such new physics will require understanding of the Standard Model backgrounds, and QCD in particular. I then continue by discussing some other topics of specific interest to the DESY community.

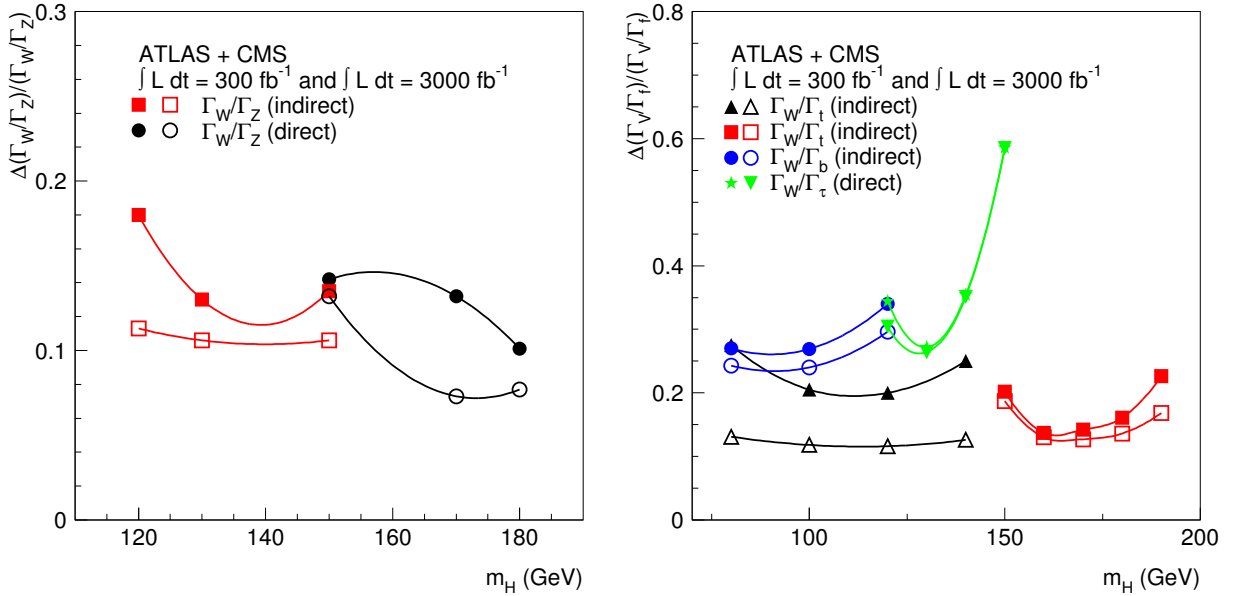
- The understanding of QCD will be important for making accurate studies of any such new physics. Perturbative QCD at moderate  $x$  and large  $p_T$  is quite well understood, with dramatic further progress now being promised by novel calculational techniques based on string theory [2].
- Novel experimental phenomena are now emerging at RHIC at small  $x$ , following harbingers at HERA. The parton density saturates, and a powerful organizational framework is provided by the Colour-Glass Condensate (CGC) [3]. Forward measurements at the LHC will provide unique opportunities for following up on this HERA/RHIC physics.
- Forward physics at the LHC will also provide valuable insight into the interpretation of ultra-high-energy cosmic rays (UHECRs) [4]. One of the principal uncertainties in determining their energy scale is the modeling of the hadronic showers they induce, and the LHC will be the closest laboratory approximation to UHECR energies.
- Looking further forward, there is increasing interest in exploring at the LHC the new vistas in hard and soft diffraction opened up by the discovery of rapidity-gap events at HERA [5]. One particularly interesting possibility is quasi-exclusive diffractive production of Higgs bosons or other new particles at the LHC [6]. This is particularly interesting in supersymmetric extensions of the Standard Model, notably those in which CP is violated [7].

## 2 Prospects in Higgs Physics

Many studies have given confidence that the Standard Model Higgs boson will be found at the LHC, if it exists [8]. Moreover, there are some chances that it might be found quite quickly, in particular if its mass is between about 160 GeV and 600 GeV. However, discovering the Higgs boson will take rather longer if its mass is below about 130 GeV, as suggested in the minimal supersymmetric extension of the Standard Model (MSSM) [9]. In this case, the Higgs signal would be composed of contributions from several different production and decay channels, notably including  $gg \rightarrow H \rightarrow \gamma\gamma$ .

Understanding the gluon distribution at  $x \sim 10^{-2}$  is therefore a high priority, and one to which HERA measurements of processes involving gluons have been playing key roles [10]. Perturbative corrections to the  $gg \rightarrow H$  production process need to be understood theoretically, as do the corrections to  $H \rightarrow \gamma\gamma$  decay. Resummation of the next-to-next-to-leading logarithms has by now reduced these uncertainties to the 10% level, and further improvements may be possible with the string-inspired calculational techniques now being introduced [11].

Fig. 1 shows estimates of the accuracy with which various Higgs couplings may be determined at the LHC, also if the luminosity may be increased by an order of magnitude (SLHC) [12] [see also [13]]. There are interesting prospects for measuring the couplings to  $\tau\tau$ ,  $\bar{b}b$ ,  $WW$ ,  $ZZ$  and  $\bar{t}t$  as well as the total Higgs decay width, though not with great accuracy. Measurements at the ILC would clearly be much more powerful for this purpose [13].



**Fig. 1:** Illustrations of the accuracy with which Higgs couplings could be measured at the LHC with the planned luminosity and with a possible upgrade by a factor of ten (SLHC) [12].

### 3 Theorists are Hedging their Bets

The prospect of imminent Higgs discovery is leading theorists to place their last bets on the LHC roulette wheel, and many are hedging their bets by proposing and discussing alternatives to the Standard Model or the MSSM. Composite Higgs models are not greatly favoured, since they have a strong tendency to conflict with the precision electroweak data [14]. This problem has led some theorists to question the interpretation of the electroweak data, which are normally taken to favour  $m_H < 300$  GeV, debating their consistency and even arguing that some data should perhaps be discounted [15]. Personally, I see no strong reason to doubt the hints from the electroweak data. An alternative corridor leading towards higher Higgs masses is provided by including higher-dimensional operators in the electroweak data analysis [16]: this would require some fine-tuning, but cannot be excluded. An even more extreme alternative that has been re-explored recently is that of Higgsless models [17]. However, these lead to strong  $WW$  scattering and conflict with the available electroweak data. These problems are alleviated, but not solved, by postulating extra dimensions at the TeV scale [18].

One of the least unappetizing alternatives to the supersymmetric Higgs paradigm is offered by little Higgs models [19]. Their key idea is to embed the Standard Model in a larger gauge group, from which the Higgs boson emerges as a relatively light pseudo-Goldstone boson. The one-loop quadratic

divergence due to the top quark:

$$\delta m_{H,top}^2(SM) \sim (115 \text{ GeV})^2 \left( \frac{\Lambda}{400 \text{ GeV}} \right)^2$$

is cancelled by the contribution of a new heavy  $T$  quark:

$$\delta m_{H,top}^2(LH) \sim \frac{6G_F m_t^2}{\sqrt{2}\pi^2} m_T^2 \log \frac{\Lambda}{m_T}$$

Additionally, there are new gauge bosons and exotic Higgs representations. The Standard-Model-like Higgs boson is expected to be relatively light, possibly below  $\sim 150$  GeV, whereas the other new particles are expected to be heavier:

$$\begin{aligned} M_T &< 2 \text{ TeV} (m_h/200 \text{ GeV})^2 \\ M'_W &< 6 \text{ TeV} (m_h/200 \text{ GeV})^2 \\ M_{H^{++}} &< 10 \text{ TeV} \end{aligned}$$

Certainly the new  $T$  quark, probably the  $W'$  boson and possibly even the doubly-charged Higgs boson will be accessible to the LHC. Thus little Higgs models have quite rich phenomenology, as well being decently motivated. However, they are not as complete as supersymmetry, and would require more new physics at energies  $> 10$  TeV.

Depending on the mass scale of this new physics, there may be some possibility for distinguishing a little Higgs model from the Standard Model by measurements of the  $gg \rightarrow H \rightarrow \gamma\gamma$  process at the LHC. However, the ILC would clearly have better prospects in this regard [13].

## 4 Supersymmetry

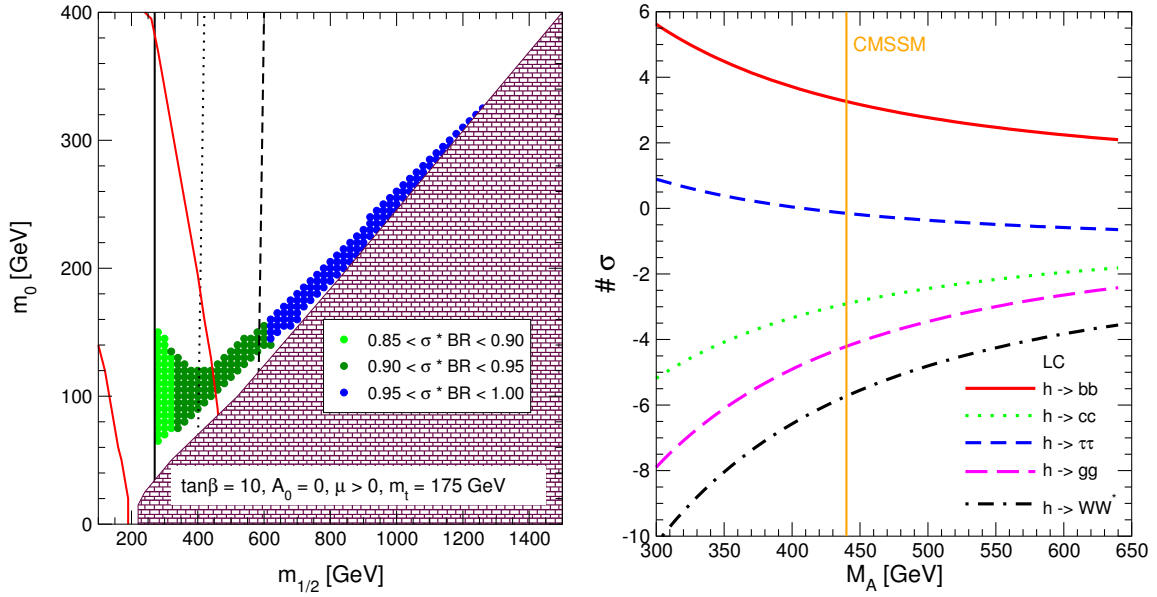
No apologies for repeating the supersymmetric mantra: it resolves the naturalness aspect of the hierarchy problem by cancelling systematically the quadratic divergences in all loop corrections to the Higgs mass and hence stabilizes the electroweak scale [20], it enables the gauge couplings to unify [21], it predicts  $m_H < 150$  GeV [9] as suggested by the precision electroweak data [14], it stabilizes the Higgs potential for low Higgs masses [22], and it provides a plausible candidate [23] for the dark matter that astrophysicists and cosmologists claim clutters up the Universe.

However, all we have from accelerators at the moment are lower limits on the possible supersymmetric particle masses, most notably from the absence of sparticles at LEP:  $m_{\tilde{\ell}}, m_{\chi^\pm} > 100$  GeV and the Tevatron collider:  $m_{\tilde{g}}, m_{\tilde{q}} > 300$  GeV, the LEP lower limit  $m_H > 114.4$  GeV, and the consistency of  $b \rightarrow s\gamma$  decay with the Standard Model. However, if we assume that the astrophysical cold dark matter is largely composed of the lightest supersymmetric particle (LSP), and require its density to lie within the range allowed by WMAP et al [24]:

$$0.094 < \Omega_\chi h^2 < 0.129,$$

we obtain upper as well as lower limits on the possible sparticle masses. The anomalous magnetic moment of the muon,  $g_\mu - 2$ , provides intermittent hints on the supersymmetric mass scale [25]: these are lower limits if you do not believe there is any significant discrepancy with the Standard Model prediction, but also an upper limit if you do not believe that the Standard Model can fit the data, as is indicated by the current interpretation of the  $e^+e^-$  data used to calculate the Standard Model prediction.

If one compares the production of the lightest neutral Higgs boson in the constrained MSSM (CMSSM) in which all the soft supersymmetry-breaking scalar masses  $m_0$  and gaugino masses  $m_{1/2}$  are assumed to be universal, the *good news* is that the rate for  $gg \rightarrow h \rightarrow \gamma\gamma$  is expected to be within 10% of the Standard Model value, as seen in Fig. 2(a) [26]. On the other hand, the *bad news* is the rates

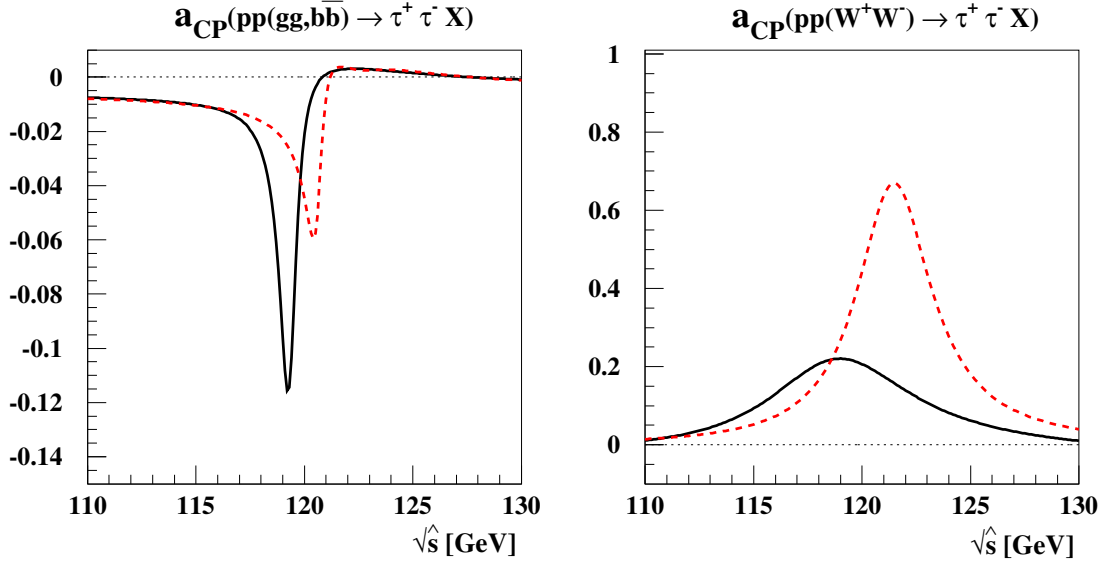


**Fig. 2:** Left panel: The cross section for production of the lightest CP-even MSSM Higgs boson in gluon fusion and its decay into a photon pair,  $\sigma(gg \rightarrow h) \times \mathcal{B}(h \rightarrow \gamma\gamma)$ , normalized to the Standard Model value with the same Higgs mass, is given in the  $(m_{1/2}, m_0)$  plane for  $\mu > 0$ ,  $\tan\beta = 10$ , assuming  $A_0 = 0$  and  $m_t = 175$  GeV [26]. The diagonal (red) solid lines are the  $\pm 2 - \sigma$  contours for  $g_\mu - 2$ . The near-vertical solid, dotted and dashed (black) lines are the  $m_h = 113, 115, 117$  GeV contours. The (brown) bricked regions are excluded since in these regions the LSP is the charged  $\tilde{\tau}_1$ . Right panel: The numbers of standard deviations by which the predictions of the MSSM with non-universal Higgs masses may be distinguished from those of the Standard Model in different channels by measurements at the ILC [27]. The predictions with the CMSSM values of  $M_A$  and  $\mu$  are indicated by light vertical (orange) lines. The other parameters have been chosen as  $m_{1/2} = 300$  GeV,  $m_0 = 100$  GeV,  $\tan\beta = 10$  and  $A_0 = 0$ .

are so similar that it will be difficult to distinguish a CMSSM Higgs boson from its Standard Model counterpart. This would be much easier at the ILC, as seen in Fig. 2(b) [27].

One of the distinctive possibilities opened up by the MSSM is the possibility of CP violation in the Higgs sector, induced radiatively by phases in the gaugino masses and the soft supersymmetry-breaking trilinear couplings. Fig. 3 displays CP-violating asymmetries that might be observable in the  $gg, \bar{b}b \rightarrow \tau^+\tau^-$  and  $W^+W^- \rightarrow \tau^+\tau^-$  processes at the LHC, in one particular CP-violating scenario with large three-way mixing between all three of the neutral MSSM Higgs bosons [28].

A typical supersymmetric event at the LHC is expected to contain high- $p_T$  jets and leptons, as well as considerable missing transverse energy. Studies show that the LHC should be able to observe squarks and gluinos weighing up to about 2.5 TeV [8], covering most of the possibilities for astrophysical dark matter. As seen in Fig. 4(a) [1], the dark matter constraint restricts  $m_{1/2}$  and  $m_0$  to narrow strips extending to an upper limit  $m_{1/2} \sim 1$  TeV. As seen in Fig. 4(b), whatever the value of  $m_{1/2}$  along one of these strips, the LHC should be able to observe several distinct species of sparticle [1]. In a favourable case, such as the benchmark point B in Fig. 4(a) (also known as SPS Point 1a), experiments at the LHC should be able to measure the CMSSM parameters with sufficient accuracy to calculate the supersymmetric relic density  $\Omega_\chi h^2$  (blue histogram) with errors comparable to the present astrophysical error (yellow band) as seen in Fig. 4(c) [1]. Fig. 4(d) summarizes the capabilities of the LHC and other accelerators to detect various numbers of sparticle species. We see that the LHC is almost guaranteed to discover supersymmetry if it is relevant to the naturalness of the mass hierarchy. However, there are some variants of the CMSSM, in particular at the tips of the WMAP strips for large  $\tan\beta$ , that might escape detection at the LHC.



**Fig. 3:** Numerical estimates of differential CP asymmetries as functions of the effective reduced centre-of-mass energy  $\sqrt{\hat{s}}$  in a CP-violating three-Higgs mixing scenario with gaugino phase  $\Phi_3 = -90^\circ$  (solid lines) and  $\Phi_3 = -10^\circ$  (dashed lines) [28].

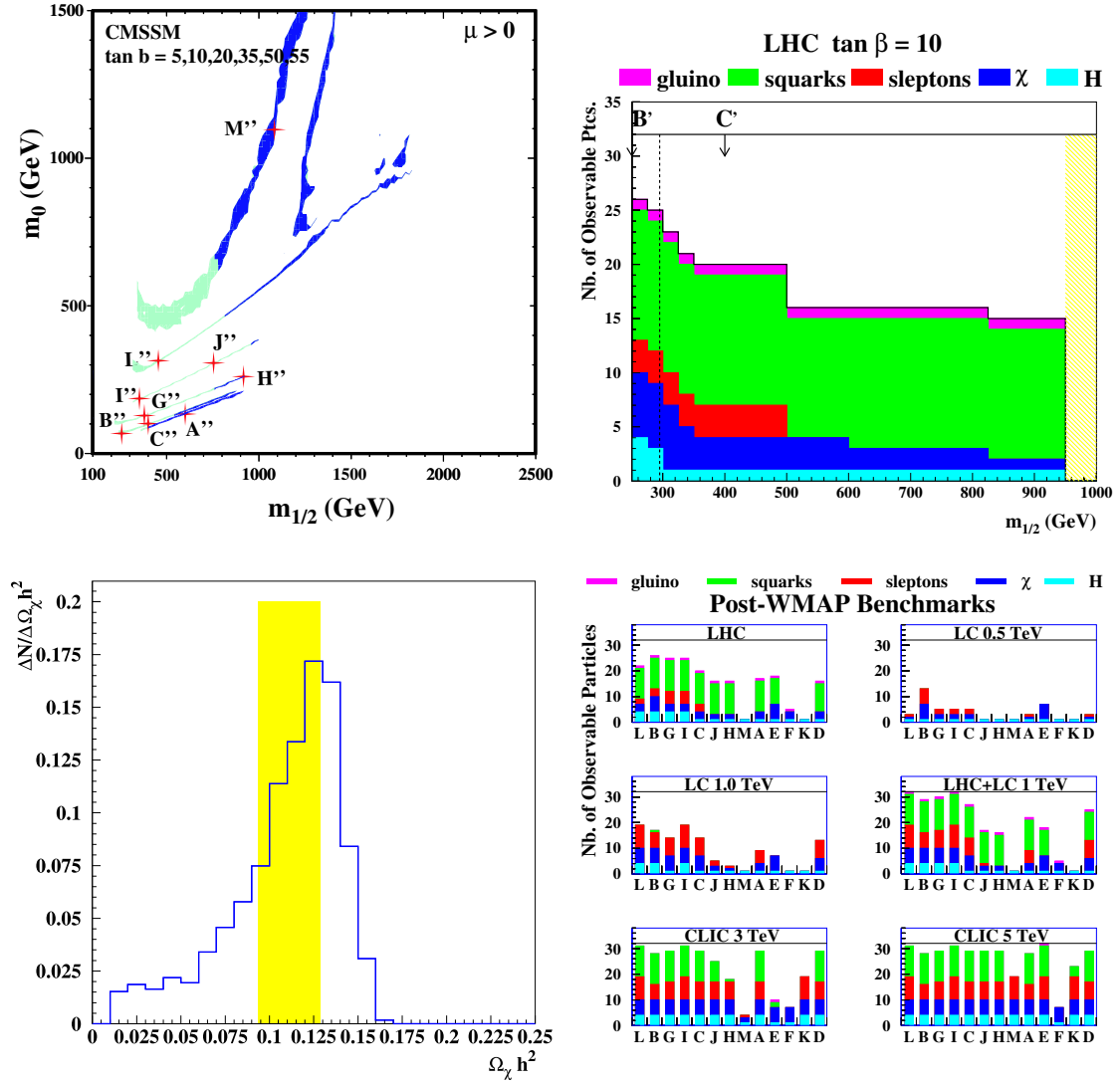
As we also see in Fig. 4(d), linear colliders would be able to observe a complementary subset of sparticles, particularly sleptons, charginos and neutralinos [1]. A linear collider with a centre-of-mass energy of 1 TeV would have comparable physics reach to the LHC, but a higher centre-of-mass energy, such as the 3 TeV option offered by CLIC [29], would be needed to complete the detection and accurate measurement of all the sparticles in most variants of the CMSSM.

We have recently evaluated whether precision low-energy observables currently offer any hint about the mass scale of supersymmetric particles, by exploring their sensitivities to  $m_{1/2}$  along WMAP lines for different values of the trilinear supersymmetry-breaking parameter  $A_0$  and the ratio of Higgs v.e.v's,  $\tan \beta$  [31]. The measurements of  $m_W$  and  $\sin^2 \theta_W$  each currently favour  $m_{1/2} \sim 300$  GeV for  $\tan \beta = 10$  and  $m_{1/2} \sim 600$  GeV for  $\tan \beta = 50$ . The agreement of  $b \rightarrow s\gamma$  decay with the Standard Model is compatible with a low value of  $m_{1/2}$  for  $\tan \beta = 10$  but prefers a larger value for  $\tan \beta = 50$ , whereas  $B_s \rightarrow \mu^+ \mu^-$  decay currently offers no useful information on the scale of supersymmetry breaking [30]. The current disagreement of the measured value of the anomalous magnetic moment of the muon,  $g_\mu - 2$ , also favours independently  $m_{1/2} \sim 300$  GeV for  $\tan \beta = 10$  and  $m_{1/2} \sim 600$  GeV for  $\tan \beta = 50$ . Putting all these indications together, as seen in Fig. 5, we see a preference for  $m_{1/2} \sim 300$  GeV when  $\tan \beta = 10$ , and a weaker preference for  $m_{1/2} \sim 600$  GeV when  $\tan \beta = 50$  [31]. At the moment, this preference is far from definitive, and  $m_{1/2} \rightarrow \infty$  is excluded at less than  $3 \sigma$ , but it nevertheless offers some hope that supersymmetry might lurk not far away.

As seen in Fig. 6, the likelihood function for  $m_{1/2}$  can be converted into the corresponding likelihood functions for the masses of various species of sparticles. The preferred squark and gluino masses lie below 1000 GeV for  $\tan \beta = 10$ , with somewhat heavier values for  $\tan \beta = 50$ , though still well within the reach of the LHC [31].

## 5 Gravitino Dark Matter

The above analysis assumed that the lightest supersymmetric particle (LSP) is the lightest neutralino  $\chi$ , assuming implicitly that the gravitino is sufficiently heavy and/or rare to have been neglected. This implicit assumption may or may not be true in a minimal supergravity model, where the gravitino mass

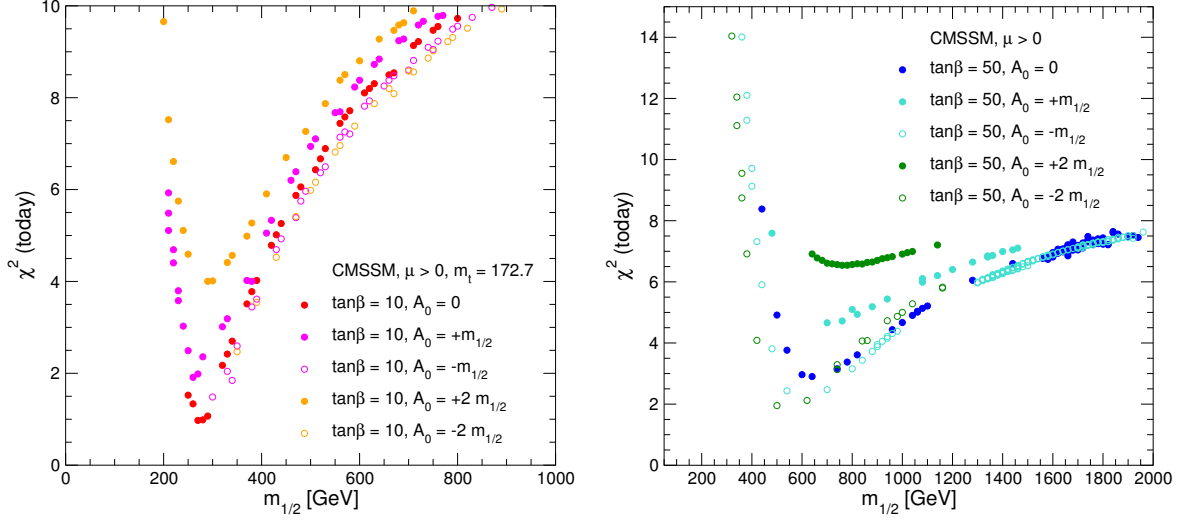


**Fig. 4:** Top left panel: The strips of CMSSM parameter space allowed by WMAP and other constraints, with specific benchmark scenarios indicated by (red) crosses. Top right panel: The numbers of MSSM particle species observable at the LHC as a function of  $m_{1/2}$  along the WMAP strip for  $\tan \beta = 10$  [26]. Bottom left panel: The accuracy with which the relic dark matter density could be calculated using LHC measurements at benchmark point B, compared with the uncertainty provided by WMAP and other astrophysical data. Bottom right panel: The numbers of MSSM particle species observable in the benchmark scenarios at the LHC and  $e^+e^-$  colliders with different centre-of-mass energies [27].

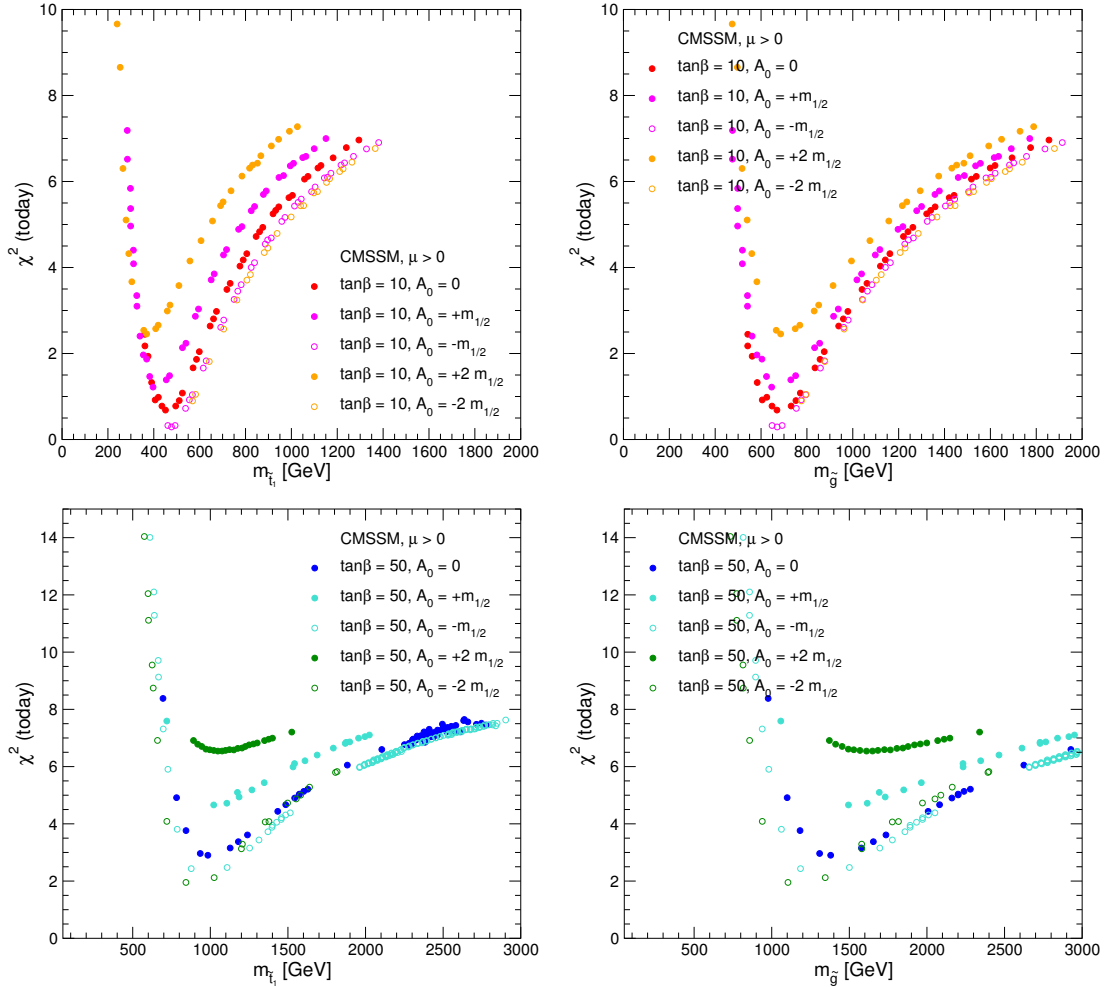
$m_{3/2} = m_0$ , as seen in Fig. 7<sup>1</sup> [32]. In this model, the gravitino mass is fixed throughout the  $(m_{1/2}, m_0)$  plane: there is a familiar WMAP strip where the  $\chi$  is the LSP, but there is also a wedge of parameter space where the LSP is the gravitino. There is no way known to detect such astrophysical gravitino dark matter (GDM), since the gravitino has very weak interactions.

However, the LHC may have prospects for detecting GDM indirectly [33–35]. In the GDM region, the lighter stau,  $\tilde{\tau}_1$ , is expected to be the next-to-lightest sparticle (NLSP), and may be metastable with a lifetime measurable in hours, days, weeks, months or even years. The  $\tilde{\tau}_1$  would be detectable in CMS or ATLAS as a slow-moving charged particle. Staus that are sufficiently slow-moving might be stopped in

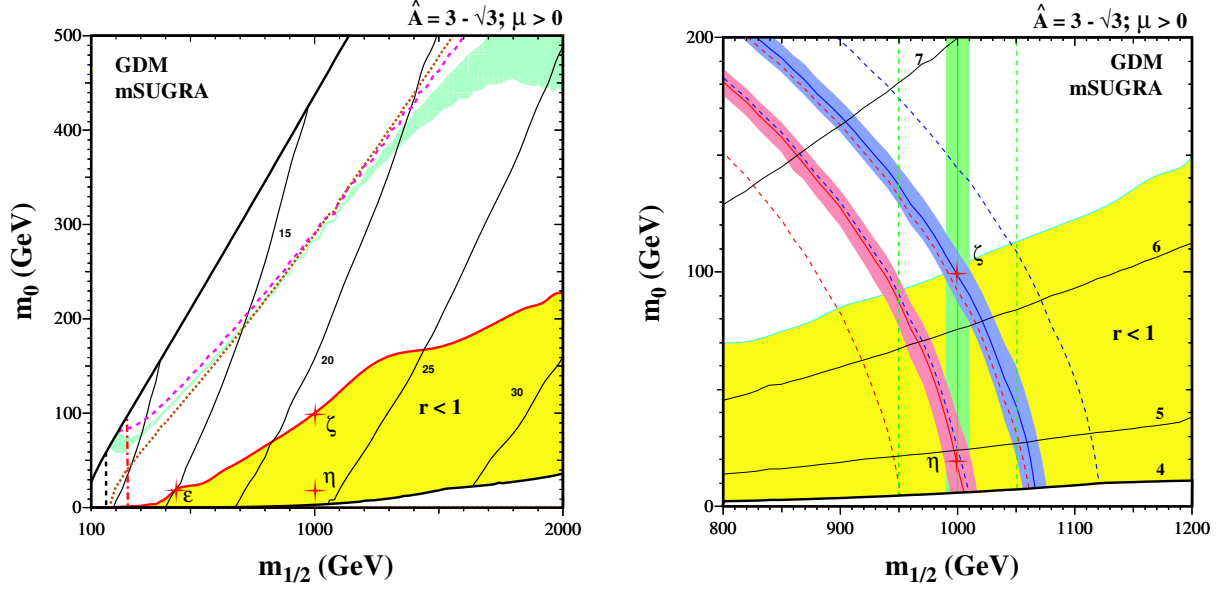
<sup>1</sup>Minimal supergravity also relates the trilinear and bilinear supersymmetry-breaking parameters:  $A_0 = B_0 + 1$ , thereby fixing  $\tan \beta$  as a function of  $m_{1/2}, m_0$  and  $A_0$ , see the contours in Fig. 7(b).



**Fig. 5:** The results of  $\chi^2$  fits based on the current experimental results for the precision observables  $M_W$ ,  $\sin^2 \theta_{weff}$ ,  $(g-2)_\mu$  and  $b \rightarrow s\gamma$  are shown as functions of  $m_{1/2}$  in the CMSSM parameter space with WMAP constraints for different values of  $A_0$  and (left)  $m_t = 172.7 \pm 2.9$  GeV and  $\tan \beta = 10$  and (right)  $m_t = 178.0 \pm 4.3$  GeV and  $\tan \beta = 50$  [31].



**Fig. 6:** The  $\chi^2$  contours in the CMSSM with  $\tan \beta = 10$  for the lighter stop (left) and gluino (right) masses, assuming  $\tan \beta = 10$  (top) and  $\tan \beta = 50$  (bottom) [31].



**Fig. 7:** Left panel: The allowed region in the  $(m_{1/2}, m_0)$  planes for minimal supergravity (mSUGRA) with a gravitino LSP [light (yellow) shaded regions labelled  $r < 1$ ], for  $A \equiv \hat{A}m_0 : \hat{A} = 3 - \sqrt{3}$ . The red crosses denote the benchmark GDM models  $\epsilon, \zeta$  and  $\eta$  [35]. Right panel: The potential impacts on the determination of GDM parameters in the mSUGRA framework of prospective measurement errors of 1% and 5% for  $m_{\tilde{\tau}_1}$  (diagonal bands and lines) and  $m_{1/2}$  (vertical bands and lines), shown as constraints in the  $(m_{1/2}, m_0)$  plane [35]. The smaller errors would enable the benchmark scenarios  $\zeta$  and  $\eta$  to be distinguished, and the possible NLSP lifetime to be estimated. The near-horizontal thin solid lines are labelled by the logarithm of the NLSP lifetime in seconds.

the detector itself, in some external detection volume designed to observe and measure their late decays into GDM [33, 34], or in the walls of the caverns surrounding the detectors [35].

## 6 The LHC and Ultra-High-Energy Cosmic Rays

Historically, the two experiments with (until recently) the largest statistics for ultra-high-energy cosmic rays (UHECRs), AGASA [36] and HiRes [37], have not agreed on their energy spectra above about  $10^{19}$  eV and, specifically, whether there is a significant number of events beyond the GZK cutoff due to interactions of primary UHECRs with the cosmic microwave background radiation. The Auger experiment now has the second-largest statistics but does not yet have sufficient data to settle the issue [38], though these should soon be forthcoming. If there are super-GZK events, they might be due either to nearby astrophysical sources that have not yet been identified, or (more speculatively) to the decays of metastable superheavy particles [39]. Normalizing the energies of UHECRs requires understanding of the development of extensive air showers. At the moment, this is not very well known, and models of shower development are not even able to tell us the composition of cosmic rays with lower energies between  $10^{15}$  and  $10^{19}$  eV [4].

The LHC is the accelerator that comes closest to reproducing the UHECR energy range, with a centre-of-mass energy corresponding to  $4 \times 10^{17}$  eV, in the range where the cosmic-ray composition is still uncertain. This uncertainty would be reduced by better modelling of hadronic showers, which would in turn benefit from measurements in the forward direction [4].

Unfortunately, the LHC is currently not equipped to make good measurements in this kinematic region, where most of the centre-of-mass energy is deposited. More instrumentation in the forward direction would be most welcome in both CMS and ATLAS. This region is also of fundamental importance for our understanding of QCD, as I now explain.

## 7 Back to Forward QCD

We discussed earlier the success of perturbative QCD, and the accuracy with which it could be used to calculate high- $p_T$  physics, thanks to the structure functions provided by HERA data [10], in particular. The simple parton description is expected, however, to break down at ‘small’  $x$  and ‘large’  $Q^2$ , due to saturation effects. At small  $x$ , there is a large probability to emit an extra gluon  $\sim \alpha_s \ln(1/x)$ , and the number of gluons grows in a limited transverse area. When the transverse density becomes large, partons of size  $1/Q$  may start to overlap, and non-linear effects may appear, such as the annihilation of low- $x$  partons. The Malthusian growth in the number of gluons seen at HERA is eventually curbed by these annihilation effects when  $\ln(1/x)$  exceeds some critical  $x$ -dependent saturation value of  $Q^2$ . At larger values of  $x$ , the parton evolution with  $Q^2$  is described by the usual DGLAP equations, and the evolution with  $\ln(1/x)$  is described by the BFKL equation. However, at lower values of  $x$  and large  $Q^2$ , a new description is needed for the saturated configuration, for which the most convincing proposal is the Colour-Glass Condensate (CGC) [3].

According to the CGC proposal, the proton wave function participating in interactions at low  $x$  and  $Q^2$  is to be regarded as a classical colour field that fluctuates more slowly than the collision time-scale. This possibility may be probed in Gold-Gold collisions at RHIC and proton-proton collisions at the LHC: the higher beam energy of LHC compensates approximately for the higher initial parton density in Gold-Gold collisions at RHIC. At central rapidities  $y \sim 0$ , effects of the CGC are expected to appear only when the parton transverse momentum  $< 1$  GeV. However, CGC effects are expected to appear at larger parton transverse momenta in the forward direction when  $y \sim 3$ . Lead-Lead collisions at the LHC should reveal even more important saturation effects [40].

What is the experimental evidence for parton saturation? First evidence came from HERA, and Fig. 8(a) displays an extraction of the saturation scale from HERA data [41]. At RHIC, in proton-nucleus collisions one expects the suppression of hard particles at large rapidity and small angle compared to proton-proton collisions, whereas one expects an enhancement at small rapidity, the nuclear ‘Cronin effect’. The data [42] from the BRAHMS collaboration at RHIC shown in Fig. 8(b) are quite consistent with CGC expectations [43], but it remains to be seen whether this approach can be made more quantitative than older nuclear shadowing ideas.

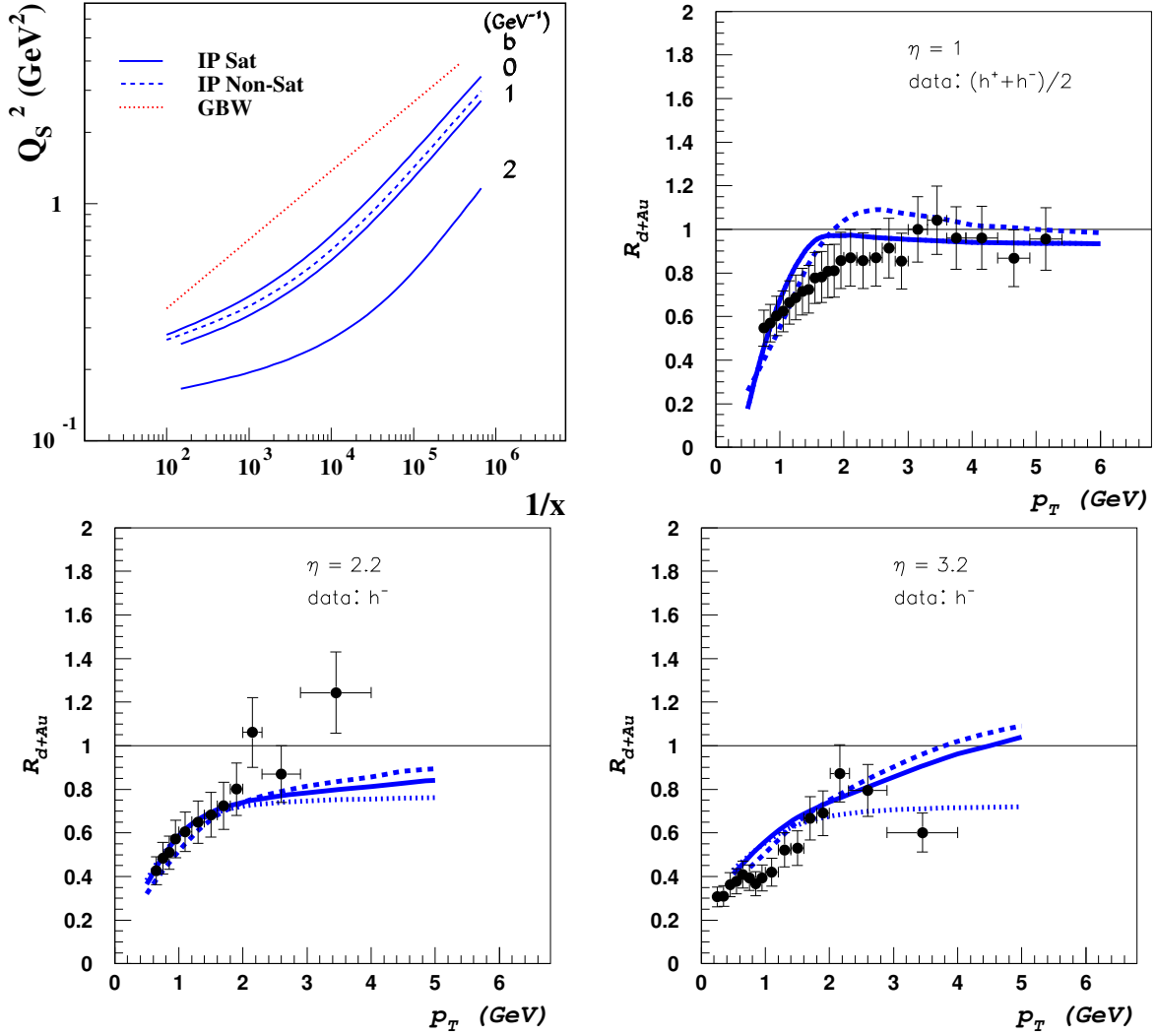
## 8 New Physics in Diffraction?

HERA has revealed a menagerie of different diffractive phenomena, opening up a Pandora’s box of possible new physics at the LHC. Classically one had soft diffraction dissociation in peripheral proton-proton collisions, in which one (or both) of the colliding protons would dissociate into a low-mass system (or systems). HERA discovered an additional class of diffractive events [5], which may be interpreted [44] as a small colour dipole produced by an incoming virtual photon penetrates the proton and produces a high-mass system. Additionally, one expects at the LHC soft double diffraction, in which a peripheral proton-proton collision produces a low-mass central system separated from each beam by a large rapidity gap. Events with mixed hard and soft diffraction are also possible at the LHC, as are events with multiple large rapidity gaps. The LHC will certainly provide good prospects for deepening our understanding of diffraction, building upon the insights being gained from HERA.

Double diffraction also offers the possibility of searching for new physics in a relatively clean experimental environment containing, in addition to Higgs boson or other new particle, only a couple of protons or their low-mass diffraction-dissociation products<sup>2</sup>. The leading-order cross-section formula (nominal values of the diffractive parameters are quoted in the brackets) is [6]:

$$M^2 \frac{\partial^2 \mathcal{L}}{\partial y \partial M^2} = 4.0 \times 10^{-4} \left[ \frac{\int_{\ln Q_{min}}^{\ln \mu} F_g(x_1, x_2, Q_T, \mu) d \ln Q_T}{\text{GeV}^{-2}} \right]^2 \left( \frac{\hat{S}^2}{0.02} \right) \left( \frac{4}{b \text{GeV}^2} \right)^2 \left( \frac{R_g}{1.2} \right)^4 .$$

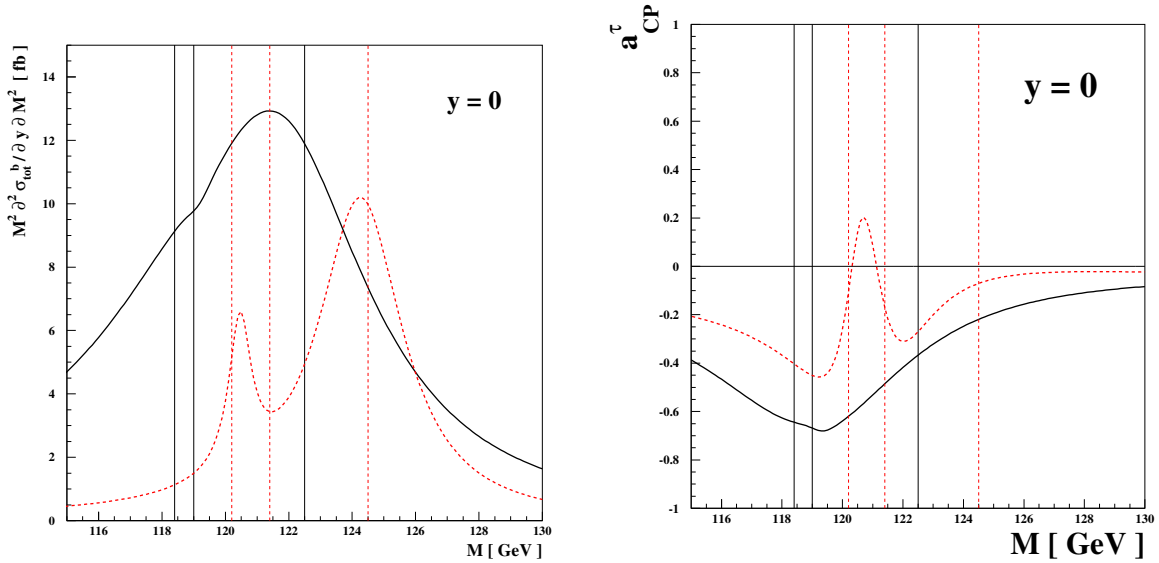
<sup>2</sup>New physics might also be produced in other classes of diffractive events, but with less distinctive signatures.



**Fig. 8:** Top left panel: The parton saturation scale as a function of Bjorken  $x$ , extracted from HERA data in [41]. Other three panels: Nuclear modification factor  $R_{dAu}$  of charged particles for rapidities  $\eta = 1, 2.2, 3.2$  [42], compared with calculations from [43].

The gluon collision factor is currently inferred from HERA data via different parameterizations of the integrated gluon distribution function, and has an uncertainty of a factor of about two [6]. Further analyses of HERA data, as well as future LHC data, would enable the determination to be refined.

The observation of diffractive Higgs production at the LHC would be a challenge in the Standard Model, but the cross section is expected to be considerably larger in the MSSM, particularly at large  $\tan \beta$ . One of the enticing possibilities offered by supersymmetry is a set of novel mechanisms for CP violation induced by phases in the soft supersymmetry-breaking parameters [7]. These would show up in the MSSM Higgs sector, generating three-way mixing among the neutral MSSM Higgs bosons. This might be observable in inclusive Higgs production at the LHC [7], but could be far more dramatic in double diffraction. Fig. 9(a) displays the mass spectrum expected in double diffraction in one particular three-way mixing scenario [45]: it may exhibit one or more peaks that do not coincide with the Higgs masses. Analogous structures may also be seen in CP-violating asymmetries in  $H_i \rightarrow \tau^+ \tau^-$  decay, as seen in Fig. 9(b). These structures could not be resolved in conventional inclusive Higgs production at the LHC, but may be distinguished in exclusive double diffraction by exploiting the excellent missing-mass resolution  $\sim 2$  GeV that could be provided by suitable forward spectrometers [46].



**Fig. 9:** Left panel: The hadron-level cross section for the double-diffractive production of Higgs bosons decaying into  $b$  quarks. CP-violating three-way mixing scenarios have been taken, with the gluino phase  $\Phi_3 = -90^\circ$  (solid lines) and  $\Phi_3 = -10^\circ$  (dotted line). The vertical lines indicate the three Higgs-boson pole-mass positions. Right panel: The CP-violating asymmetry  $a_{\text{CP}}^\tau$  observable in three-way mixing scenarios when Higgs bosons decay into  $\tau$  leptons, using the same line styles [45].

## 9 Summary

We do not know what the LHC will find - maybe there will be no supersymmetry and we will observe mini-black-hole production instead! However, whatever the physics scenario, HERA physics will provide crucial inputs, for example via measuring the parton distributions that will be crucial for searches for new physics such as the Higgs boson, or via the observation of saturation effects that will be important for forward physics, or via measurements of diffraction.

Forward physics is a potentially exciting area of LHC physics that is not covered by the present detectors. HERA and RHIC suggest that parton saturation and the Colour Glass Condensate may be observable here, understanding of forward physics is essential for the modelling of cosmic-ray air showers and hence determining the spectrum of ultra-high-energy cosmic rays, and diffractive events related to those observed by HERA may be a valuable tool for discovering new physics such as Higgs production. There is still plenty of room at the LHC for novel experimental contributions [46].

## References

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