




On irreducible representations of Fuchsian groups

Vikraman Balaji  and Yashonidhi Pandey

To Apurv Pandey

Abstract. Let $\mathcal{R} \subset \mathbb{P}_{\mathbb{C}}^1$ be a finite subset of markings. Let G be an almost simple simply-connected algebraic group over \mathbb{C} . Let K_G denote the compact real form of G . Suppose for each lasso l around the marked point, a conjugacy class C_l in K_G is prescribed. The aim of this paper is to give verifiable criteria for the existence of an *irreducible* homomorphism of $\pi_1(\mathbb{P}_{\mathbb{C}}^1 \setminus \mathcal{R})$ into K_G such that the image of l lies in C_l .

1 Introduction

Let G be an almost simple simply-connected algebraic group over \mathbb{C} . Let K_G denote a maximal compact subgroup. Let $\mathcal{R} \subset \mathbb{P}_{\mathbb{C}}^1$ be a finite subset of distinct closed points or markings. Recall that the fundamental group $\pi_1(\mathbb{P}_{\mathbb{C}}^1 \setminus \mathcal{R})$ is a free group on $s = \|\mathcal{R}\|$ -number of generators $\gamma_1, \dots, \gamma_s$ such that $\gamma_1 \dots \gamma_s = 1$. Recall that a subset $H \subset K_G$ is called *irreducible* if the $\{Y \in \text{Lie}(G) \mid \text{adh}(Y) = Y, \forall h \in H\} = \text{center of Lie}(G) = 0$ and a homomorphism $\rho : \pi_1(\mathbb{P}_{\mathbb{C}}^1 \setminus \mathcal{R}) \rightarrow K_G$ is called *irreducible* if the image $\rho(\pi_1(\mathbb{P}_{\mathbb{C}}^1 \setminus \mathcal{R})) \subset K_G$ is irreducible (see Ramanathan [16]). For $i \geq 3$, let $\{C_i \mid 1 \leq i \leq s\}$ denote a prescribed set of conjugacy classes in K_G . The aim of this paper is to give verifiable criteria for the existence of an *irreducible* homomorphism $\rho : \pi_1(\mathbb{P}_{\mathbb{C}}^1 \setminus \mathcal{R}) \rightarrow K_G$, such that the conjugacy class of $\rho(\gamma_j)$ lies in C_j .

The multiplicative Horn problem asks whether there exists a set of lifts $\{c_i \in C_i\}$ satisfying $\prod c_i = 1$. S. Bauer [4] was the first to relate the representation question to standard algebro-geometric objects. For $G = SU_n$ such a criteria was obtained independently by Agnihotri–Woodward [1] and P. Belkale [5]. Teleman and Woodward [19] gave numerical criteria for this problem for arbitrary G . We note that the additive Horn problem was solved in the late nineties independently by A.A. Klyachko [9] and Knutson and Tao [10].

By Balaji–Seshadri [3, Theorem 8.1.7 and Corollary 8.1.8] for finite-order conjugacy classes and by [2, Corollary 10.6] for arbitrary ones, the existence of an irreducible

Received by the editors April 25, 2023; revised December 18, 2023; accepted May 14, 2024.

Published online on Cambridge Core August 27, 2024.

The support of Science and Engineering Research Board under Mathematical Research Impact Centric Support File number: MTR/2017/000229 is gratefully acknowledged.

AMS subject classification: 14L15, 14D23, 14D20.

Keywords: Bruhat–Tits group scheme, parahoric group, Moduli stack, Gromov–Witten, stability.



set of lifts is equivalent to the existence of a stable torsor under a suitable parahoric Bruhat–Tits group scheme on $\mathbb{P}^1_{\mathbb{C}}$. When $K_G = U_n$, by Mehta–Seshadri [12] this problem is equivalent to the existence of a stable parabolic vector bundle on $\mathbb{P}^1_{\mathbb{C}}$.

From the perspective of the root system of G , we recall that conjugacy classes in K_G are parameterized precisely by the points of the Weyl alcove \mathfrak{a}_0 (see [14, p. 151]). In this setting, our aim is to give a numerical verifiable criteria for the existence of such an irreducible set of lifts in terms of the points of the Weyl alcoves determined by the $\{C_i\}$. More precisely, let \mathfrak{a}_0 denote the points of the closed Weyl alcove. Let Δ^s denote the set of points $\theta = \{\theta_x\}_{x \in \mathcal{R}} \in \text{Maps}(\mathcal{R}, \mathfrak{a}_0)$ such that there exists a stable parahoric torsor on \mathbb{P}^1 with weight θ . In this note, we want to describe the stable polytope $\Delta^s \subset \text{Maps}(\mathcal{R}, \mathfrak{a}_0)$. One defines the semistability polytope Δ^{ss} similarly.

Such criteria were obtained by I. Biswas [6] for U_2 and later [7] for U_n , by P. Belkale [5] for SU_n , and by Y. Pandey [15] for the maximal compact subgroups of $SO_n(\mathbb{C})$ and $Sp_{2n}(\mathbb{C})$.

Returning to the setting of [3], let $\mathcal{M}_{\mathbb{P}^1}(\mathcal{G})$ denote the moduli stack of \mathcal{G} -torsors on $\mathbb{P}^1_{\mathbb{C}}$, where \mathcal{G} is a Bruhat–Tits group scheme on $\mathbb{P}^1_{\mathbb{C}}$ at a fixed set of marked points on $\mathbb{P}^1_{\mathbb{C}}$ given by a choice of weights θ . Let $\mathcal{M}_{\mathbb{P}^1}(\mathcal{G}^{\Gamma})$ be the moduli stack of torsors with Iwahori structures at these marked points. Recall that the points of $\mathcal{M}_{\mathbb{P}^1}(\mathcal{G}^{\Gamma})$ can be viewed as principal G -bundles with parabolic structures given by the Borel B at points $x \in \mathcal{R}$, analogous to vector bundles with full-flag parabolic structures. Under this identification, the set consisting of the trivial G -bundle with varying B -structures, gives a subset of the points of $\mathcal{M}_{\mathbb{P}^1}(\mathcal{G}^{\Gamma})$.

Denoting the moduli stack of principal G -bundles by $\mathcal{M}_X(G)$ for an arbitrary curve X , it can be seen that these fit in together in the following Hecke-modification diagram:

$$(1.0.1) \quad \begin{array}{ccc} & \mathcal{M}_X(\mathcal{G}^{\Gamma}) & \\ & \swarrow p \quad \searrow q & \\ \mathcal{M}_X(\mathcal{G}) & & \mathcal{M}_X(G), \end{array}$$

where the morphism q is simply the one which forgets the flag structures (see the discussion after (2.1.3) for details).

In Section 5, we explain the main construction of this paper generalizing the completing flag construction of [5, Appendix]. For each representation ρ of G , this construction extends weights θ on \mathcal{G} -torsors to \mathcal{G}^{Γ} -torsors. Recall that if V_* and W_* are two parabolic vector bundles, then the quasi-parabolic structure underlying their tensor product depends on the weights and is not determined by the quasi-parabolic structures underlying V_* and W_* . Keeping this feature in mind, as it happens in [2, Section 4.2], in order to carry the construction out for each point $x \in \mathcal{R}$, we need to make the choice of a smaller facet $\mathfrak{a}_\rho^{\circ, x}$ (see Definition 5.2.1). Then in Section 6, given a choice of weights θ for \mathcal{G} , we show how one can derive an extended set of weights $(\theta, \{\mathfrak{a}_\rho^{\circ, x}\}_{x \in \mathcal{R}})$ for \mathcal{G}^{Γ} -torsors \mathcal{E}^{Γ} such that the stability condition for a \mathcal{G} torsor \mathcal{E} with weights θ becomes equivalent to an intrinsic stability condition for all the \mathcal{G}^{Γ} torsors \mathcal{E}^{Γ} with weights $(\theta, \{\mathfrak{a}_\rho^{\circ, x}\}_{x \in \mathcal{R}})$ sitting above \mathcal{E} under the map p (see Proposition

6.5.1). Thus, for varying choices of $\{\mathfrak{a}_\rho^{o,x}\}_{x \in \mathcal{R}}$, the $(\mathcal{E}^\perp, \theta, \{\mathfrak{a}_\rho^{o,x}\}_{x \in \mathcal{R}})$ are (semi)stable or not simultaneously. We turn this observation into a definition (see 6.5.2). The equivalence of stability of parahoric torsors to that of usual parabolic G -bundles but for *extended weights* is the main point of Sections 5 and 6 and is the technical heart of this work.

As we noted above in (1.0.1), through q the stability condition can alternatively be seen as an extended weight θ stability condition on the underlying parabolic G -bundle. Denoting by Ad the adjoint representation, we prove the following theorem.

Theorem 1.0.1 *Let $X = \mathbb{P}^1$. The open sub-stack $\mathcal{M}_{\mathbb{P}^1}(\mathcal{G})^\circ$ of $\mathcal{M}_{\mathbb{P}^1}(\mathcal{G})$ consisting of stable torsors is non-empty if and only if the trivial G -bundle with generic B -structures and extended weight θ (see 6.5.2) is stable as a point of $\mathcal{M}_{\mathbb{P}^1}(\mathcal{G}^\perp)$.*

The setting is as in [19], and by Proposition 6.5.4, the sought-after criterion now gets translated into one in terms of Gromov–Witten numbers. We describe the stable polytope Δ^s in Corollary 3.1.1 and Corollary 3.1.2 shows that the difference between Δ^{ss} and Δ^s is at the boundary of $\text{Maps}(\mathcal{R}, \mathfrak{a}_0)$.

Let \mathcal{E}^\perp be the *trivial* G -bundle with parabolic structures of the full-flag type, i.e., B -structures at the marked points \mathcal{R} . For a parabolic subgroup $P \subset G$, let \mathcal{E}_P^\perp be a reduction of structure group to P . We then have an inclusion of Lie algebra bundles $\mathcal{E}_P^\perp(\mathfrak{p}) \subset \mathcal{E}^\perp(\mathfrak{g})$. Observe that the associated Lie algebra bundle $\mathcal{E}^\perp(\mathfrak{g})$ gets canonical parabolic structures at the marked points (these will not be full-flag types though). We denote this Lie algebra bundle with parabolic structures by $\mathcal{E}^\perp(\mathfrak{g})_*$. The sub-bundle $\mathcal{E}_P^\perp(\mathfrak{p})$ gets the canonical induced parabolic structures and we have similarly $\mathcal{E}_P^\perp(\mathfrak{p})_* \subset \mathcal{E}^\perp(\mathfrak{g})_*$.

Say a P -reduction $\mathcal{E}_P^\perp \subset \mathcal{E}^\perp$ is of the *minus 1 type* if the parabolic degree of the quotient $\mathcal{E}^\perp(\mathfrak{g})_*/\mathcal{E}_P^\perp(\mathfrak{p})_*$ is 0 and further, the degree of the vector bundle underlying the quotient $\mathcal{E}^\perp(\mathfrak{g})_*/\mathcal{E}_P^\perp(\mathfrak{p})_*$ is -1 . We prove the following theorem.

Theorem 1.0.2 *A point $\theta \in \Delta^{ss}$ lies in Δ^s if and only if the trivial G -bundle \mathcal{E}^\perp with generic B -structures and extended weight $(\theta, \{\mathfrak{a}_{Ad}^{o,x}\}_{x \in \mathcal{R}})$ does not have any P -reduction \mathcal{E}_P^\perp of the minus 1 type.*

Proposition 7.0.1 reduces the condition in the above theorem to Gromov–Witten numbers. This gives new verifiable criteria for points in Δ^{ss} to lie in Δ^s .

1.1 Comparison with [19]

The inequalities in Corollary 3.1.1 determining Δ^s are strict versions of those in [19, Proposition 4.4] determining Δ^{ss} . A point to be noted is that, whereas [19] had an underlying principal G -bundle to work with, in general, we do not have such a bundle. In fact, the extending weight construction and Theorem 1.0.1 fill the void left by the nonexistence of an underlying principal G -bundle. The bundle-theoretic description of difference between points in Δ^{ss} and Δ^s sheds some light on the role played by them.

1.2 Some remarks on the far wall and stability

We conclude by giving a few words of justification on why the far wall cannot be avoided for the stability question (although it can be avoided for semistability *in the very special case of* $G = \mathrm{GL}(n)$ because of the presence of an underlying $\mathrm{GL}(n)$ -bundle). Let us mention some difficulties. First, in [15, Section 7], some examples of stable parahoric symplectic and (special orthogonal) torsors are shown to lie on the product of far walls. Second, Belkale has shown that $(\Delta^{ss})^\circ \subset \Delta^s$ (see [15, Proposition 7.0.5]). So they have the same closures in $\mathrm{Maps}(\mathcal{R}, \mathfrak{a}_0)$. Also the origin in $\mathrm{Maps}(\mathcal{R}, \mathfrak{a}_0)$ lies in $\Delta^{ss} \setminus \Delta^s$ because it corresponds to the case of principal G -bundles with trivial parabolic structures. Finally, Meinrenken and Woodward (see [13, Corollary 4.13]) have shown that Δ^{ss} is a closed convex polytope of maximal dimension inside $\mathrm{Maps}(\mathcal{R}, \mathfrak{a}_0)$ and to the best of our knowledge, for stability, no such argument is known. Thus, it does not seem possible to reduce the problem of determining Δ^s to the case of generic weights, i.e., the interior of $\mathrm{Maps}(\mathcal{R}, \mathfrak{a}_0)$. We are forced to consider $\mathrm{Maps}(\mathcal{R}, \mathfrak{a}_0)$ fully and directly. Now weight tuples, one of whose factor lies on the far wall of \mathfrak{a}_0 , correspond to strictly parahoric (non-parabolic) torsors under parahoric group schemes. These need to be reckoned with in the sense there is no underlying principal G -bundle. Consequently, one cannot deform to the trivial bundle without going through Heckemodifications. In Corollary 3.1.2, we find that the difference between Δ^{ss} and Δ^s is at the boundary of $\mathrm{Maps}(\mathcal{R}, \mathfrak{a}_0)$.

1.3 Some remarks on nonexistence of underlying bundle and Hecke modification

We carry out the technique of Hecke modification in this paper for the following reason. In [5] or [15], one finds that for Δ^s , the corresponding hyperplanes are not merely the strict versions of the hyperplanes for Δ^{ss} . Indeed, this is in fact expected, because for stability, unlike for semistability, one cannot restrict oneself only to the case when the Gromov–Witten invariant is one. But, even if one allows for higher Gromov–Witten numbers, as we do in this paper, the formulation of the slope inequalities for stability in [5] could be done because in the case $G = \mathrm{SL}_n$, by implicitly extending structure group to GL_n , there was an underlying parabolic vector bundle to work with and the stability of the parahoric torsor, when $G = \mathrm{SL}_n$, is equivalent to that of the parabolic vector bundle. However, in general, for an arbitrary G taking an associated vector bundle under a faithful representation *does not preserve stability*.

The hyperplanes defining the semistability polytope (see [5, 19] (from which even the stability polytope may be deduced)) arise by a translation of semistability conditions on the *trivial principal* G -bundle with generic parabolic structures. Further, the reduction to this special case relies on the existence of an underlying G -bundle to work with. For these reasons, for stability, strict versions of slope inequalities, seem inadequate to address the situation for weight tuples with at least one coordinate in the far wall.

Lastly, the reduction to Gromov–Witten inequalities works when one has a trivial principal G -bundle but in the parahoric situation, *with weights constrained to lie on the far wall*, there is no reduction to anything analogous to the trivial bundle.

It might seem that parahoric weights from the far wall can still be handled by going to an equivariant bundle as in [3]. But again, in the equivariant setup, there is no analogue of Ramanathan's theorem [17] on deformations of principal G -bundles on \mathbb{P}^1 . In this context, we wish to clarify that in [15, Section 4.2, p. 109], for the case of classical groups G of B_n, C_n , and D_n type, the second-named author found a Hecke modification allowing to pass from parahoric torsors to usual parabolic G -bundles preserving (semi)stability. Such a route seems more elusive for the case of exceptional G . In this note, we give a unifying argument in the general case. We also wish to point out that whereas in [5, 15], the weights do change under Hecke modifications, they do not in this note. In terms of line bundles, we are merely pulling them back under p of (1.0.1) and then viewing them through q .

1.4 Layout

We develop notions over a general smooth projective curve X over an algebraically closed field k of arbitrary characteristic throughout the paper and specialize to the case $X = \mathbb{P}^1$ and $k = \mathbb{C}$ only to prove the main theorems in Sections 3 and 7. In Section 2, we explain our basic setup. Then after recalling the main consequences of our construction, we prove our first main theorem in Section 3 and derive the stable polytope in Corollary 3.1.1. In Section 4 after recalling [5, Appendix], we recast it in our setup of alcoves, weights, facets, and Hecke-modification diagram. The introduction of Section 5 explains the main constructions of the paper. It also has a few examples serving to highlight the key issues. In Section 6, we show the equivalence of (semi)stability of usual parahoric torsors (\mathcal{E}, θ) with that of extended weight parahoric torsors $(\mathcal{E}^\mathbb{I}, \theta, \{\mathbf{a}_p^{\circ, x}\}_{x \in \mathcal{R}})$. In Section 7, we prove the second main theorem.

2 The moduli stack $\mathcal{M}_X(\mathcal{G})$

2.1 Local group theoretical data of parahoric group schemes

We will write k instead of \mathbb{C} whenever the results we use holds for an algebraically closed field of arbitrary characteristic. Let $A := k[[t]]$ and $K := k((t)) = k[[t]][t^{-1}]$, where t denotes a uniformizing parameter. Let G be an *almost simple simply connected affine algebraic group* defined over k . We now want to consider the group $G(K)$.

We shall fix a maximal torus $T \subset G$. Let $R = R(T, G)$ denote the root system of G (see [18, p. 125]). Let $Y(T) = \text{Hom}(\mathbb{G}_m, T)$ denote the group of all one-parameter subgroups of T . The *standard affine apartment* \mathcal{A}_T is an affine space under $Y(T) \otimes_{\mathbb{Z}} \mathbb{R}$. We may identify \mathcal{A}_T with $Y(T) \otimes_{\mathbb{Z}} \mathbb{R}$ (see [3, Section 2]) by choosing a point $v_0 \in \mathcal{A}_T$. This v_0 is also called an origin. For a root r of G and an integer $n \in \mathbb{Z}$, we get an affine functional

$$(2.1.1) \quad \alpha = r + n : \mathcal{A}_T \rightarrow \mathbb{R}, x \mapsto r(x - v_0) + n.$$

These are called the *affine roots* of G . For any point $x \in \mathcal{A}_T$, let Y_x denote the set of affine roots vanishing on x . For an integer $n \geq 0$, define

$$(2.1.2) \quad \mathcal{H}_n = \{x \in \mathcal{A}_T \mid |Y_x| = n\}.$$

A facet σ of \mathcal{A}_T is defined to be a connected component of \mathcal{H}_n for some n . The dimension of a facet is its dimension as a real manifold. We refer the reader to [2, Section 3.2] for the definition of the parahoric subgroup of $G(K)$ corresponding to a facet.

The subgroup $G(A) \subset G(K)$ is an example of a maximal parahoric subgroup. We have a natural evaluation map $ev : G(A) \rightarrow G(k)$ and the inverse image $\mathbb{I} := ev^{-1}(B)$ of the standard Borel subgroup $B \subset G$ is called the standard Iwahori subgroup. Any parahoric subgroup contains a $G(K)$ -conjugate of the standard Iwahori subgroup \mathbb{I} . In this paper, Θ will always be either a facet or a point of \mathcal{A}_T . By [8, Section 1.7], we have an affine flat smooth group scheme $\mathcal{G}_\Theta \rightarrow \text{Spec}(A)$ called the *parahoric group scheme* associated with Θ . It is uniquely determined by its A -valued points which equals the parahoric group corresponding to Θ . In particular, the group scheme whose A -valued points is \mathbb{I} is called the standard Iwahori group scheme. For a facet $\sigma \subset \mathcal{A}_T$, let $\mathcal{G}_\sigma \rightarrow \text{Spec}(A)$ be the parahoric group scheme defined by σ .

2.1.1 Alcove

We choose a Borel B in G/k containing T . This determines a choice of positive roots. Let \mathfrak{a}_0 denote the unique closed alcove in \mathcal{A}_T whose closure contains ν_0 and is contained in the finite Weyl chamber determined by positive simple roots. We will denote its interior by \mathfrak{a}_0° . It is the facet corresponding to the standard Iwahori subgroup. The affine walls defining \mathfrak{a}_0 determine a set S of simple *affine roots*. We will denote these simple roots by the symbols $\{\alpha_i\}$.

2.1.2 The parahoric Bruhat–Tits group scheme

For an arbitrary closed point $y \in \mathcal{R}$, let $\mathbb{D}_y := \text{Spec}(\hat{\mathcal{O}}_y)$, let K_y be the quotient field of $\hat{\mathcal{O}}_y$. Let $\mathcal{R} \subset X$ be a non-empty finite set of closed points. For each $x \in \mathcal{R}$, we choose a facet $\sigma_x \subset \mathcal{A}_T$. Let $\mathcal{G}_{\sigma_x} \rightarrow \mathbb{D}_x$ be the parahoric group scheme corresponding to σ_x . Let $X^\circ = X \setminus \mathcal{R}$. In this paper, by a *Bruhat–Tits group scheme* $\mathcal{G} \rightarrow X$, we shall mean that \mathcal{G} restricted to X° is isomorphic to the trivial constant group scheme $X^\circ \times G$ on X° , and for any closed point $x \in X$, \mathcal{G} restricted to \mathbb{D}_x is a parahoric group scheme \mathcal{G}_{σ_x} such that the gluing functions take values in $\text{Mor}(\mathbb{D}_x^\circ, G) = G(K_x)$. This is also the setup of [3, Definition 5.2.1]. Thus, the $\hat{\mathcal{O}}_y$ -points of the restriction of \mathcal{G} to this disk give parahoric subgroups of $G(K)$.

We also suppose that the facets $\{\sigma_x\}_{x \in \mathcal{R}}$ lie in \mathfrak{a}_0 because it can easily be seen that for results and constructions in this note the general case of arbitrary facets reduces to this one.

Remark 2.1.1 The group scheme \mathcal{G} depends on the gluing data. But if \mathcal{G} and \mathcal{G}' are two parahoric group schemes on X which differ only in their gluing data, then it is straightforward to check that the stacks $\mathcal{M}_X(\mathcal{G})$ and $\mathcal{M}_X(\mathcal{G}')$ are isomorphic. For this reason, we fix one gluing data to get \mathcal{G} and work with this.

We use the notation $X \times G$ to denote the trivial group scheme on X . Let $\mathcal{G}^\mathbb{I} \rightarrow X$ (resp. $\mathcal{G}_{tr}^\mathbb{I} \rightarrow X$) be the group scheme obtained by gluing $X^\circ \times G$ with the standard Iwahori group scheme $\mathcal{G}_{\mathfrak{a}_0^\circ}$ at each parabolic point $x \in \mathcal{R}$ using the same gluing

functions as \mathcal{G} (resp. the identity in $G(K_x)$ as a gluing function). For each $x \in \mathcal{R}$, the inclusions $\mathbb{I} \subset \mathcal{G}_{D_x}(\check{\mathcal{O}}_x)$ (resp. $\mathbb{I} \subset G(\check{\mathcal{O}}_x)$) induce morphisms of group schemes $\mathcal{G}^\mathbb{I} \rightarrow \mathcal{G}$ (resp. $\mathcal{G}_{tr}^\mathbb{I} \rightarrow X \times G$) over the whole of X .

2.1.3 Parahoric torsors

Let $\mathcal{G} \rightarrow X$ be a group scheme as in Section 2.1.2. A *quasi-parahoric* torsor \mathcal{E} is a \mathcal{G} -torsor on X . This means that $\mathcal{E} \times_X \mathcal{E} \simeq \mathcal{E} \times_X \mathcal{G}$ and there is an action map $a : \mathcal{E} \times_X \mathcal{G} \rightarrow \mathcal{E}$ which satisfies the usual axioms for principal G -bundles. A *parahoric torsor* is a pair (\mathcal{E}, θ) consisting of the pair of a quasi-parahoric torsor and weights $\theta = \{\theta_x | x \in \mathcal{R}\} \in (Y(T) \otimes \mathbb{R})^m$ such that θ_x lies in the facet σ_x (see Section 2.1.2) and $m = |\mathcal{R}|$. Let $\mathcal{M}_X(\mathcal{G})$ denote the moduli stack of \mathcal{G} -torsors on X . The natural morphisms of group schemes seen above induces the following morphisms of stacks:

$$(2.1.3) \quad \mathcal{M}_X(\mathcal{G}) \leftarrow \mathcal{M}_X(\mathcal{G}^\mathbb{I}) \xrightarrow{2.1.1} \mathcal{M}_X(\mathcal{G}_{tr}^\mathbb{I}) \rightarrow \mathcal{M}_X(G).$$

In particular, the morphism $\mathcal{M}_X(\mathcal{G}^\mathbb{I}) \rightarrow \mathcal{M}_X(G)$ induced by the morphism $\mathcal{G}^\mathbb{I} \rightarrow X \times G$ can be viewed as follows. The points of the stack $\mathcal{M}_X(\mathcal{G}^\mathbb{I})$ are G -bundles on X with B -structures at the marked points \mathcal{R} . The morphism $\mathcal{M}_X(\mathcal{G}^\mathbb{I}) \rightarrow \mathcal{M}_X(G)$ forgets the B -structures. Thus, $\mathcal{M}_X(\mathcal{G}^\mathbb{I})$ seen from the standpoint of $\mathcal{M}_X(G)$ is the analogue of the moduli stack of vector bundles with full-flag structures at the marked points. We will call morphisms in the diagram (1.0.1) as Hecke modification.

Although in the literature, a sequence of flip-flop is called a Hecke modification, we wish to emphasize that often only a *single* morphism as above will be required for the proofs in this paper. For the usual case of parabolic vector bundles, these one-step modification morphisms correspond to usual Hecke modifications. For torsors, we will call them both by the same name following Balaji–Seshadri [3].

3 Main theorem

In this section, we suppose that $X = \mathbb{P}^1$. We wish to show that after general results proved in later sections, our main result follows by standard arguments well-known to experts. Let us begin by the steps of this reduction:

Step 1: Let (\mathcal{E}, θ) be a parahoric torsor. Under $p : \mathcal{M}_{\mathbb{P}^1}(\mathcal{G}^\mathbb{I}) \rightarrow \mathcal{M}_{\mathbb{P}^1}(\mathcal{G})$, let $\mathcal{E}^\mathbb{I}$ be an arbitrary $\mathcal{G}^\mathbb{I}$ -torsor that maps to \mathcal{E} and consider the Hecke-modification diagram (1.0.1). Given a parabolic vector bundle with possibly partial flags, a construction called *completing flags* is described in [5, Appendix]. In an analogous fashion (with a somewhat involved “parahoric” adaptation), in Section 5, we explain how after choosing any finer facet $\mathfrak{a}_{Ad}^{o,x} \subset \mathfrak{a}^o$, in whose closure θ_x lies, θ may be extended as a weight $(\theta, \{\mathfrak{a}_{Ad}^{o,x}\}_{x \in \mathcal{R}})$ (see (5.2.1)) on $\mathcal{E}^\mathbb{I}$.

Step 2: We extend the definition of (semi)stability for such objects and call this construction *extending weights* (see (5.2.1)). Then in Proposition 6.5.1, we show that (\mathcal{E}, θ) is stable if and only if $(\mathcal{E}^\mathbb{I}, \theta, \{\mathfrak{a}_{Ad}^{o,x}\}_{x \in \mathcal{R}})$ is stable as a extended weight parahoric torsor. This result justifies Definition 6.5.2 where we say that $(\mathcal{E}^\mathbb{I}, \theta)$ is stable if for some (and therefore all) choice of $\{\mathfrak{a}_0^{o,x}\}_{x \in \mathcal{R}}$, $(\mathcal{E}^\mathbb{I}, \theta, \{\mathfrak{a}_{Ad}^{o,x}\}_{x \in \mathcal{R}})$ is stable. Now we view $\mathcal{E}^\mathbb{I}$ as a parabolic G -bundle with additional parabolic structures at \mathcal{R} .

Proof of Theorem 1.0.1 Since G is simply-connected and $X = \mathbb{P}^1$, so by [17, Theorem 7.4], the principal G -bundle E underlying \mathcal{E}^Γ may be put in a family $\mathbf{E} \rightarrow \mathbb{P}^1 \times T$, where the generic bundle is the trivial G -bundle and T is affine. Consider $T_1 := T \times_{\mathcal{M}_{\mathbb{P}^1}(G)} \mathcal{M}_{\mathbb{P}^1}(\mathcal{G}^\Gamma)$ corresponding to the classifying map $T \rightarrow \mathcal{M}_{\mathbb{P}^1}(G)$ of \mathbf{E} . The family $\mathbf{E} \rightarrow \mathbb{P}^1 \times T$ can be used to make a T_1 -family of parabolic principal G -bundles $(\mathbf{E}^\Gamma, \boldsymbol{\theta}) \rightarrow \mathbb{P}^1 \times T_1$ with extended weights. Thus, we have a degeneration to \mathcal{E}^Γ , where the underlying bundle of the generic object is trivial. Under the morphism $\mathcal{M}_{\mathbb{P}^1}(\mathcal{G}^\Gamma) \rightarrow \mathcal{M}_{\mathbb{P}^1}(\mathcal{G})$, let $\mathbf{E}^\Gamma \rightarrow \mathbb{P}^1 \times T_1$ give the family $\mathbf{E}_1 \rightarrow \mathbb{P}^1 \times T_1$ of \mathcal{G} -torsors. It degenerates to \mathcal{E} and we view it as a family with weight $\boldsymbol{\theta}$. Further, by [15, Proposition 6.1.2] stability is an open property of parahoric torsors. Therefore, by Proposition 6.5.1 for generic $t \in T_1$, $(\mathbf{E}^\Gamma, \boldsymbol{\theta})_t \rightarrow \mathbb{P}^1$ is stable. So by q (see (1.0.1)), the trivial G -bundle with extended weight $\boldsymbol{\theta}$ and generic quasi-parabolic structure is stable. ■

3.1 Gromov–Witten numbers and the stability polytope

By Proposition 6.5.4, the above result on parahoric torsors can be interpreted back in the setting of parabolic G -bundles. With notations as in [19, p. 716], let us denote the Gromov–Witten number as

$$(3.1.1) \quad n_d(w_x | x \in \mathcal{R}).$$

It counts the number of regular maps $\phi : X \rightarrow G/P$ of degree d such that for $x \in \mathcal{R}$, $\phi(x)$ lies in a generic translate of the Schubert variety $Y_{w_x} \subset G/P$ corresponding to $w_x \in W$. By Remark 6.5.3, for computing the slope inequality of extended weights parahoric torsors, we may switch from our definition to that in [19] including the far wall. Then by repeating the arguments exactly as in [19, p. 741, (13)], we get the following checkable corollary which agrees with [5, 15].

Corollary 3.1.1 *The polytope Δ^s is the set of points $\boldsymbol{\theta}$ satisfying the inequality*

$$(3.1.2) \quad \sum_{x \in \mathcal{R}} (w_x \omega_P, \theta_x) < d$$

for all maximal parabolic subgroups $P \subset G$ and nonnegative integers d such that the Gromov–Witten invariant (see (3.1.1)) $n_d(w_x | x \in \mathcal{R}) \neq 0$.

Corollary 3.1.2 *The interior of Δ^{ss} is contained in Δ^s . Its complement is the intersection of Δ^s with the boundary of $\text{Maps}(\mathcal{R}, \mathbf{a}_0)$.*

Proof Let $\boldsymbol{\theta} \in (\Delta^{ss})^\circ$. Consider a Euclidean ball B in $(\Delta^{ss})^\circ$ about $\boldsymbol{\theta}$. Thus, B is also a ball in the interior of $\text{Maps}(\mathcal{R}, \mathbf{a}_0)$ which equals $\text{Maps}(\mathcal{R}, \mathbf{a}_0^\circ)$. Observe if one of the inequalities in (3.1.2) is non-strict for $\boldsymbol{\theta}$, then points in one of the open hemisphere of B cannot satisfy (3.1.2). Thus, all inequalities must be strict for $\boldsymbol{\theta}$, i.e., $\boldsymbol{\theta}$ lies in Δ^s . We now prove the second statement. The intersection of the boundary of $\text{Maps}(\mathcal{R}, \mathbf{a}_0)$ with $(\Delta^{ss})^\circ$ is of course empty. We now show the inclusion of $\Delta^s \setminus (\Delta^{ss})^\circ$ in the boundary of $\text{Maps}(\mathcal{R}, \mathbf{a}_0)$. Since Δ^s is an open polytope in the polytope $\text{Maps}(\mathcal{R}, \mathbf{a}_0)$, we have $\Delta^s \cap \text{Maps}(\mathcal{R}, \mathbf{a}_0)^\circ = (\Delta^s)^\circ \subset (\Delta^{ss})^\circ$. Therefore, $\Delta^s \setminus (\Delta^{ss})^\circ$ is contained in the boundary of $\text{Maps}(\mathcal{R}, \mathbf{a}_0)$. ■

4 Filtrations associated with parabolic vector bundles

In Sections 4–6, the results are of a general nature and so X will be an *arbitrary smooth projective curve of genus $g \geq 0$* .

4.1 Completing flags [5, Appendix]

For simplicity, we will first assume that we are working with one parabolic point x . Recall a quasi-parabolic structure is giving a possibly partial filtration

$$(4.1.1) \quad \dots \supset E = F_0(E) \supset F_1(E) \supset \dots \supset F_{l-1}(E) \supset F_l(E) = E(-\mathcal{R}) \supset \dots$$

by subsheaves, which can be continued infinitely in both directions. Here, l is called the length of the filtration. It can at most be the rank of E . It is called a parabolic sheaf if it has a system of weights $\alpha_0, \dots, \alpha_{l-1}$ such that

$$(4.1.2) \quad 0 \leq \alpha_0 < \alpha_1 < \dots < \alpha_{l-1} < 1.$$

The weight α_i is called the weight of the subsheaf $F_i(E)$. A given filtration (4.1.1) need not be full. By choosing any complete flag for a given parabolic bundle, in [5], the notion of \mathbb{R} -filtration of [11] is extended to complete flag parabolic vector bundles with extended weights in [5, Appendix]. This process is carried out as follows. One considers a filtration

$$(4.1.3) \quad \dots \supset E_n \supset E_{n+1} \supset \dots$$

of sheaves with strict inclusions as in (4.1.1) parameterized by \mathbb{Z} together with weights $\{\alpha_n\}$ in \mathbb{R} , which are allowed to coincide now. Thus, (4.1.2) has become non-strict and is extended by the law:

$$(4.1.4) \quad \alpha_{k+ml} = \alpha_k + m.$$

The constructions in [5] extend in an obvious way to multiple parabolic points as well as to non-complete flag parabolic vector bundles, just that the indices are harder to write because there may be jumps because of partial flags. Note that, as subsheaves become smaller, their weights become larger.

4.2 Construction inverse to Section 4.1, sliding weights

In 4.1.3, if we forget sheaves E_j for which there exists a bigger sheaf with the same weight, then the reduced subset of $\{E_n\}$, together with the corresponding weights, which are now distinct, correspond to (4.1.1). On any term E_m of the filtration (4.1.3), we can induce the structure of a parabolic vector bundle by using the l successive subsheaves in (4.1.1) to get the flags; their corresponding weights may lie outside of $[0, 1)$, but, after subtracting α_m from each of them the weight of E_m becomes zero and the remaining will lie in $[0, 1)$. This will be denoted E_{m*} . Conversely, E_{m*} gives (4.1.1) up to shifting indices, and the same weights up to a constant. Let us call the process of adding an arbitrary constant $a \in \mathbb{R}$ to all the weights at a point $x \in \mathcal{R}$ as *sliding weights*. Sliding weights adds a to the parabolic slope of the bundle or any of its parabolic sub-bundle. Thus, it leaves (semi)stability invariant. Therefore, up to sliding weights, the formation of E_{m*} is the *inverse construction* to making the filtration 4.1.3 with weights.

4.3 Key takeaway on degree computation of sub-bundles from [5]

For simplicity, we first work in the setting of [5] which involves one parabolic point. Now weights may now lie outside $[0, 1)$. We will denote this as E_{m^*} . The weights are defined by (4.1.3) and (4.1.4) in such a way that the parabolic degree of E_{m^*} becomes independent of $m \in \mathbb{Z}$ (see [5, p. 83 last para]). Further, on [5, p. 84] for any $m_1, m_2 \in \mathbb{Z}$ a natural procedure is explained to go from sub-bundles of $E_{m_1^*}$ to $E_{m_2^*}$. By [5, Lemma 8], this procedure preserves parabolic degree of sub-bundles too. Thus, $E_{m_1^*}$ is (semi)stable if and only if $E_{m_2^*}$ is (semi)stable. These results generalize to multiple parabolic points also.

4.4 Interpretation of passage from $E_{m_1^*}$ to $E_{m_2^*}$ in our setup of alcoves, weights, facets, and Diagram 1.0.1

To enable us to adapt aspects of this process in the setting of parahoric torsors, we need to interpret it in the language of alcoves.

Let us consider the case of $SL(n)$. Let us label the vertices of \mathfrak{a}_0 by integers $\{0, \dots, n - 1\}$. Any facet σ in \mathcal{A}_T of dimension d determines a set of $d + 1$ vertices. Let us call *the far wall of σ* as the codimension one facet determined by forgetting the smallest vertex. Define alcove \mathfrak{a}_{k+1} inductively by reflecting the alcove \mathfrak{a}_k along the far wall and label the new vertex by $n + k$. Let us view the weights of E_{k^*} (4.1.3) as a point in \mathfrak{a}_k by taking barycentric coordinates $\{\alpha_{E_{k+1}} - \alpha_{E_k}, \dots, \alpha_{E_{k+n}} - \alpha_{E_{k+n-1}}\}$. When we pass from E_{m^*} to E_{m+1^*} , it follows from (4.1.4) that the weights of E_{m+1^*} are obtained by reflecting the weights of E_{m^*} along the far wall of \mathfrak{a}_m . Thus, in terms of barycentric coordinates, as a set they remain the same, just that their indexing is shifted by $-1 \pmod n$, respectively.

Let σ be a facet in the closure of \mathfrak{a}_0 of codimension one where only the affine root α_d vanishes. Then the morphism $\mathcal{M}_X(\mathcal{G}^\Gamma) \rightarrow \mathcal{M}_X(\mathcal{G}^\sigma)$ corresponds to forgetting subsheaves in the \mathbb{Z} -filtration whose index is $d \pmod n$. In terms of complete flag parabolic vector bundles, this corresponds to forgetting exactly one term for $d \pmod n \neq 0$ and a Hecke modification by E_0/E_1 for $d = 0$ which gives a shift by one. These facets are of course much more general than those of \mathfrak{a}_0 and its facets. They hold for any pair of facet σ_1 and its codimension one subfacet σ . Going to far wall of σ_1 corresponds to a Hecke modification by a sky-scraper sheaf while forgetting other vertices corresponds merely to forgetting flags in $\mathcal{M}_X(\mathcal{G}^{\sigma_1})$. The above process also suitably generalizes to the graph of the hyperplane structure. More precisely, for any two facets (σ_1, σ) , where σ lies in the closure of σ_1 , the path we take to come from σ_1 to σ is not important, i.e., the processes of forgetting terms in flags and Hecke modifications by sky-scraper sheaves commute.

5 Extending weights on \mathcal{G}^Γ torsors

The curve X is arbitrary. For simplicity of notation, we further assume that only one parabolic point $x \in X$ is fixed. It will become clear to the reader that, for all that is done, the processes can be carried out independently at several points. However, for the main application, the final conclusions will be made in terms of multiple points

on X . In this section, completing flags with induced weights construction of [5] is generalized to *extending weights for $\mathcal{G}^\mathbb{I}$* . Recall that similar to the definition of Mehta–Seshadri, in [3] weights have been defined for parahoric torsors to be points lying in the facets (see Section 2.1.3). Consider the morphism of stacks $p : \mathcal{M}_X(\mathcal{G}^\mathbb{I}) \rightarrow \mathcal{M}_X(\mathcal{G})$. As in Section 2.1.3, suppose that we are given weights $\theta = \{\theta_x | x \in \mathcal{R}\} \in (Y(T) \otimes \mathbb{R})^m$ such that θ_x lies in the facet σ_x and $\sigma_x \subset \mathfrak{a}_0$ for all $x \in \mathcal{R}$.

In [2, Section 5], given a representation $\rho : G \rightarrow SL(V)$ and a parahoric Bruhat–Tits torsors \mathcal{E} , the parabolic vector bundle $(\mathcal{E}(V)_*, \theta_V)$ has been constructed. A priori, a naive approach would be to take the parabolic bundle $(\mathcal{E}(V)_*, \theta_V)$ and carry out a process as in [5], of deforming the underlying bundle after possibly some Hecke modifications, to get one with a full-flag and suitable schema of weights. But the serious obstruction is that, the new parabolic vector bundle obtained by the deformation need not come as an extension of structure group from any parahoric torsor via the representation ρ .

5.1 Two problems that arise when we try to extend the weight θ for $\mathcal{M}_X(\mathcal{G}^\mathbb{I})$.

First, the weights θ_x only belong to \mathfrak{a}_0 and not to its interior \mathfrak{a}_0° . So the setup of [2] does not apply. Second, in order to apply the associated construction of [2], even if we take a weight θ_V in \mathfrak{a}_0 arbitrarily close to θ , already the quasi-parabolic structure of $(\mathcal{E}^\mathbb{I}(V)_*, \theta_V)$ is sensitive to the choice of θ_V (see Example 5.2.6 which shows that even the underlying vector bundle depends on the choice of weight). On weights θ_V , we are forced to consider the equivalence relation that arises from the quasi-parabolic structure.

We address these problems *by choosing for each $x \in \mathcal{R}$ a finer ρ -facet $\mathfrak{a}_\rho^{\circ,x}$ (see Section 5.2) in whose closure θ_x lies. These are defined by the requirement that all points in $\mathfrak{a}_\rho^{\circ,x}$ under $\rho : \mathcal{A}_T \rightarrow \mathcal{A}_{T_{SL(V)}}$ go to a fixed open facet of $SL(V)$, of dimension at most the dimension of T , in whose closure $\rho(\theta_x)$ lies. Now, the flag structure on $(\mathcal{E}(V)_*, \theta_V)$ of [2, Section 5.1] or $(\mathcal{E}^\mathbb{I}, \theta, \{\mathfrak{a}_\rho^{\circ,x}\})$ (see 5.2.1) may not be full since it will have at most $\dim(T)$ many distinct flags (or weights). More importantly, unlike [5] the vector bundle underlying it may only be related to the one underlying $(\mathcal{E}(V)_*, \theta_V)$ by a Hecke modification. So instead of completing flags, we call this construction *extending weights for parahoric torsors*. In the setup of [5], we have $\rho = Id$. This reflects the facts that a parabolic vector bundle determines a choice of an alcove which itself is a finer ρ -facet. The adjoint representation being in general the most canonical choice, in the applications of the constructions carried out here, we will mostly have to take $\rho = Ad$ and so $V = \mathfrak{g}$.*

5.2 Extending weights construction for $\mathcal{G}^\mathbb{I}$ -torsors with respect to a representation ρ

Let \mathcal{E} be a \mathcal{G} -torsor, and let $\mathcal{E}^\mathbb{I}$ be a $\mathcal{G}^\mathbb{I}$ -torsor lying in the fiber of $\mathcal{M}_X(\mathcal{G}^\mathbb{I}) \rightarrow \mathcal{M}_X(\mathcal{G})$. To lighten the notation, it suffices to treat the case of one parabolic point, i.e., $\mathcal{R} = \{x\}$. For a representation $\rho : G \rightarrow SL(V)$, we choose tori $T_G \subset G$ and $T_{SL} \subset SL(V)$ such that ρ maps T_G to T_{SL} . Thus, we get a linear map

$$(5.2.1) \quad \rho : \mathcal{A}_T \rightarrow \mathcal{A}_{T_{SL}}$$

between the apartments. In [2, BBP], the usual definition of facet is generalized to facets associated with a homomorphism ρ as follows. By a generalized affine functional on \mathcal{A}_T , we mean affine functionals for G together with those of $\mathcal{A}_{T_{SL}}$ viewed as functionals on \mathcal{A}_T . For any point $x \in \mathcal{A}_T$, let Y_x^g denote the set of generalized affine functionals vanishing on x . For an integer $n \geq 0$, define

$$(5.2.2) \quad \mathcal{H}_n^g = \{x \in \mathcal{A}_T \mid |Y_x^g| = n\}.$$

A ρ -facet σ of \mathcal{A}_T corresponding to a representation ρ is defined to be a connected component of \mathcal{H}_n^g for some n . The dimension of a ρ -facet is its dimension as a real manifold. The finer facets satisfy the property that, for any two weights belonging to it, the parabolic vector bundles associated with ρ have the same quasi-parabolic structure.

For each $x \in \mathcal{R}$, we choose a ρ -facet $\mathfrak{a}_\rho^{\circ,x} \subset \mathfrak{a}_0$ whose closure contains θ_x . Then, given a weight θ_x , we choose a sequence of rational weights $\theta_{x,n}$ lying in our chosen alcove $\mathfrak{a}_\rho^{\circ,x}$ and converging to θ_x . Thus, the quasi-parabolic structure of $(\mathcal{E}^\perp(V)_*, \rho(\theta_{x,n}))$ is independent of n and is also independent of the choice of the limiting sequence $\{\theta_{x,n}\}$. Keeping this quasi-parabolic structure fixed, the weight $\rho(\theta_{x,n}) \in \mathcal{A}_{T_{SL}}$ equips the vector space G_x^j of the flag at x with a real number $\alpha_{x,n}^j$. We set

$$(5.2.3) \quad \alpha_x^j = \lim \alpha_{x,n}^j.$$

By linearity of (5.2.1), this process is independent of the choice of weights $\{\theta_{x,n}\}$ and depends only on $\mathfrak{a}_\rho^{\circ,x}$ and θ_x .

Definition 5.2.1 Let (\mathcal{E}, θ) be a parahoric torsor. With notations as above, extending weights for a \mathcal{G}^\perp -torsor \mathcal{E}^\perp with respect to a given representation $\rho : G \rightarrow SL(V)$ is giving the triple $(\mathcal{E}^\perp, \theta, \{\mathfrak{a}_\rho^{\circ,x}\}_{x \in \mathcal{R}})$. The quasi-parabolic vector bundle $(\mathcal{E}^\perp(V)_*, \rho(\theta_n))$ associated with $\theta_n = \{\theta_{x,n}\}_{x \in \mathcal{R}}$ endowed with weights $\{\alpha_x^j\}$ is a PVB which we will also, by an abuse of notation, denote as the triple $(\mathcal{E}^\perp, \theta, \{\mathfrak{a}_\rho^{\circ,x}\}_{x \in \mathcal{R}})$.

Remark 5.2.2 Say \mathcal{R} is a single point. A generic point θ in the interior of the Weyl alcove \mathfrak{a}^x , lies in a single ρ -facet $\mathfrak{a}_\rho^{\circ,x}$. In this case, θ determines $\{\mathfrak{a}_\rho^{\circ,x}\}_{x \in \mathcal{R}}$. Thus, $(\mathcal{E}^\perp, \theta, \{\mathfrak{a}_\rho^{\circ,x}\})$ is equivalent to the associated construction $(\mathcal{E}^\perp(V)_*, \theta)$ of [2]. Belkale’s completion of flag in [5] is precisely extending weights for the case θ lies in $\mathfrak{a}_0 \setminus \{\text{far wall}\}$. This is enough to determine the semistability polytope Δ^{ss} .

Example 5.2.3 In [5], we have $G = SL_n, \rho = \text{Id}$ and so $\mathfrak{a}_\rho^{\circ,x}$ is the alcove \mathfrak{a}_0° of SL_n . For simplicity, let $\mathcal{R} = \{x\}$. Let θ_d be the vertex of the alcove where only the affine root α_d does not vanish for $0 \leq d < n$. For $G = SL_2, \rho = \text{Id}$ and only one parabolic point x consider a weight $\theta \in [0, 1)$ and the parabolic vector bundle V_* given by $\mathcal{O}_X^{\oplus 2}$ with one flag at x of weight θ . Doing the extending weight construction for the pair $(\theta_1, \mathfrak{a}_\rho^{\circ,x} := \mathfrak{a}_0^\circ)$, taking limit as θ tends to θ_1 , the flag acquires weight one. For $G = SL_n, \rho = \text{Id}$ weights (b_0, b_1, \dots, b_n) in barycentric coordinates correspond to weights $(0, b_1, b_1 + b_2, \dots, b_1 + \dots + b_n)$. In particular, for $\mathfrak{a}_\rho^{\circ,x} = \mathfrak{a}_0^\circ$, θ_d corresponds to vector bundle of degree $-d$. Further, for $d \geq 1$, $\rho(\theta_d)$ does lie on the far wall.

Let us contrast with the case when $\rho(\theta_d)$ does *not* lie on the far wall of the chosen $\mathfrak{a}_\rho^{\circ,x}$. For instance, suppose $\rho = Id$, $G = SL_2$, and $\theta_d = 1$, but we choose $\mathfrak{a}_\rho^{\circ,x} = (1, 2)$ instead of the standard $(0, 1)$. In this case, the extended weight torsor $(\mathcal{E}^\Gamma, \theta, \{\mathfrak{a}_\rho^{\circ,x}\})$ corresponds to a vector bundle $V \rightarrow X$ of determinant $-d$, and full-flag $0 \subset F_x^1 \subset F_x^2 \subset \dots \subset F_x^n = V_x$ at V_x with extended weights d/n and $\rho(\theta_d)$ is *not* on the far wall of $\mathfrak{a}_\rho^{\circ,x}$. This happens because the flags are of V which is not a principal SL_n -bundle.

Remark 5.2.4 We illustrate sliding of weights (see Section 4.2) for the situation when $\mathcal{R} = \{x\}$, $G = SL_3$, $\rho = Id$. Let $\theta \in \mathfrak{a}_0^\circ$ tend to a point θ_1 on the far wall with barycentric coordinates $(0, b_1, b_2)$. Hence $b_2 = 1 - b_1$. Doing the extending weight construction for the pair $(\theta_1, \mathfrak{a}_\rho^{\circ,x} := \mathfrak{a}_0^\circ)$, we see that rank three vector bundle with full flags acquire weights $(0, b_1, b_1 + b_2)$. On the other hand, θ_1 corresponds to rank three vector bundles with a single flag of dimension two with weight $1 - b_1$. This corresponds to the fact that $\theta_1 = (b_1, b_2)$ in the barycentric coordinates of the far wall. The general case of sliding of weights is only notationally harder to write.

Remark 5.2.5 We acquire weight 1 exactly when $\rho(\theta_x)$ lies on the far wall of the facet corresponding to $\mathfrak{a}_\rho^{\circ,x}$.

Example 5.2.6 Let V_* be as in Example 5.2.3. Now, $Ad : SL_2 \rightarrow SL_3$ corresponds to $V_* \mapsto \text{Sym}^2(V_*)$. Now, $\text{Sym}^2(V_*)$ is the PVB with underlying bundle $\mathcal{O}_X^{\oplus 3}$ with weights $\{\theta, 2\theta\}$ if $\theta \in [0, 1/2)$ or $\mathcal{O}_X^{\oplus 2} \oplus \mathcal{O}_X(x)$ with weights $\{2\theta - 1, \theta\}$ if $\theta \in [1/2, 1)$. When $\theta \in [0, 1/2)$, then $\text{Sym}^2(V_*)$ corresponds to $\mathfrak{a}_0 \setminus \{\text{far wall}\}$ and thus does not have a map forgetting the flags to torsors on the far wall. When $\theta \in [1/2, 1)$, then the underlying degree of $\text{Sym}^2(V_*)$ is not congruent to zero modulo three, and it corresponds to a parahoric SL_3 torsor which maps to torsors on the far wall. Let $W = \mathcal{O}_X \oplus \mathcal{O}_X(x)$. It corresponds to the far wall of SL_2 but $\text{Sym}^2(W) = \mathcal{O}_X \oplus \mathcal{O}_X(x) \oplus \mathcal{O}_X(2x)$ corresponds to an affine Weyl group translate of the origin of SL_3 , i.e., $\text{Sym}^2(W) \otimes \mathcal{O}_X(-x)$ is a principal SL_3 -bundle. We see that $\text{Sym}^2(W)$ and the bundle underlying $\text{Sym}^2(V_*)$ are related by a Hecke modification when $\theta \in [1/2, 1)$. In this sense as θ tends to 1, V_* tends to W . This observation is formalized in the proposition below.

Proposition 5.2.7 *The vector bundles underlying $(\mathcal{E}^\Gamma, \theta, \{\mathfrak{a}_\rho^{\circ,x}\})$ and $(\mathcal{E}(V), \rho(\theta))$ are related by a Hecke modification and are comparable under inclusion.*

Proof By construction, the quasi-parabolic structure of $(\mathcal{E}^\Gamma, \theta, \{\mathfrak{a}_\rho^{\circ,x}\})$ is the same as that of $(\mathcal{E}^\Gamma(V), \rho(\theta_n))$. Notice that for each $x \in \mathcal{R}$, the weights $\{\rho(\theta_{x,n})\}$ lie in a fixed facet σ_{SL}^x of $SL(V)$ in whose closure $\rho(\theta_x)$ lies. So considering the quasi-parabolic structures associated with these weights, we are in the situation of a *single Hecke-modification morphism* between the stacks associated with $\{\sigma_{SL}^x\}_{x \in \mathcal{R}}$ and θ as in Diagram 1.0.1. Equivalently, we have a morphism of stacks of quasi-parabolic vector bundles

$$(5.2.4) \quad QPVB(\rho(\theta_{x,n}), x \in \mathcal{R}) \rightarrow QPVB(\rho(\theta_x), x \in \mathcal{R}).$$

Under this morphism, the underlying vector bundles are related by a Hecke modification (or are the same if the morphism (5.2.4) corresponds merely to forgetting flags) and are comparable under inclusion. ■

Remark 5.2.8 In the following proposition, we show that the filtration (4.1.3) of $(\mathcal{E}(V)_*, \rho(\theta))$ is refined by that of $(\mathcal{E}^\mathbb{T}, \theta, \{\mathbf{a}_\rho^{\circ,x}\}_{x \in \mathcal{R}})$ up to (possibly) shifting of indices, the weights are also preserved up to sliding by a real number (see Section 4.2) and it forgets only those sheaves which do not matter for parabolic degree computations of these bundles as well as their sub-bundles as it happens in (4.3). We assume that $\mathcal{R} = \{x\}$ because the following argument can be applied point by point in the general case.

Proposition 5.2.9 Assume $\mathcal{R} = \{x\}$. Let U (resp. $U^\mathbb{T}$) be the vector bundles underlying $(\mathcal{E}(V)_*, \rho(\theta))$ (resp. $(\mathcal{E}^\mathbb{T}, \theta, \{\mathbf{a}_\rho^{\circ,x}\})$). Consider the filtration (4.1.3) of $(\mathcal{E}^\mathbb{T}, \theta, \{\mathbf{a}_\rho^{\circ,x}\})$ at x . Then U is the m -term for $0 \leq m \leq$ the dimension of the facet of $SL(V)$ containing $\rho(\mathbf{a}_\rho^{\circ,x})$.

Proof The underlying bundle is the 0th term of (4.1.1). Further, by Proposition 5.2.7, U is a term in the infinite filtration (4.1.3) of $(\mathcal{E}^\mathbb{T}, \theta, \{\mathbf{a}_\rho^{\circ,x}\}_{x \in \mathcal{R}})$ because it is related to $U^\mathbb{T}$ by a Hecke modification while being comparable to it under inclusion. It is the 0-term if and only if U is obtained from $U^\mathbb{T}$ only by forgetting flags, but if U is obtained by a nontrivial Hecke modification of vector bundles, then U will be the m th term for $m \geq 1$ as described above because U may correspond to any flag at x and the flag length l_x is given by the dimension of the facet of $SL(V)$ containing $\rho(\mathbf{a}_\rho^{\circ,x})$. ■

Proposition 5.2.10 The notations are as in Section 4.2. We carry out the following three steps. (i) We slide weights so that the bundle U of (5.2.9) has weight zero. (ii) Then, we discard sheaves for which there is a bigger sheaf with the same weight. (iii) We shift indices so that U index zero. Then, we recover the filtration (4.1.1) for $(\mathcal{E}(V)_*, \rho(\theta))$ at x .

Proof We slide the weights (see (4.2)) to make U have weight zero. Under the morphism $\mathcal{M}_X(\mathcal{G}^\mathbb{T}) \rightarrow \mathcal{M}_X(\mathcal{G})$ for each $x \in \mathcal{R}$ depending on the facet in $\mathcal{A}_{T_{SL(V)}}$ containing $\rho(\theta_x)$, we forget the corresponding terms in the filtration. These are exactly the sheaves in the infinite filtration (4.1.3) for which there is a bigger sheaf with the same weight. In particular, we forget all subsheaves of U containing $U(-x)$ which are different from these and which have weight zero or one. Now U_* has weights lying in $[0, 1)$ because the formation of U_* ignores $U(-x)$. Thus, U_* is the parabolic vector bundle corresponding to $(\mathcal{E}(V)_*, \rho(\theta))$. Further, we get the filtration corresponding to $(\mathcal{E}(V)_*, \rho(\theta))$ if we shift indices so that the index of U becomes zero. ■

6 (Semi)-stability of extended weight torsors

The curve X is arbitrary. The aim of this section is to formulate a notion of extended weight θ (semi)stability for \mathcal{E}^I , i.e., the case when θ does not lie in $\text{Maps}(\mathcal{R}, \mathbf{a}_0^\circ)$ but only in its closure. We do this by showing the equivalence of (semi)stability of (\mathcal{E}, θ)

with that of $(\mathcal{E}^\perp, \theta, \{\mathfrak{a}_\rho^{\circ, x}\}_{x \in \mathcal{R}})$ as defined in (5.2.1). In this section, we work with $\rho = Ad : G \rightarrow SL(\mathfrak{g})$, the “adjoint” representation of G .

6.1 Invariant direct image functor

We briefly summarize [2, Section 3.1]. Let $p : W \rightarrow U$ be a finite flat surjective morphism of normal integral Noetherian schemes that is Galois with Galois group Γ . Let \mathcal{H} be an affine group scheme on W . Assume further that \mathcal{H} is equipped with an action of Γ lifting the one on W , so that “mult” and “inverse” maps are Γ -equivariant.

Definition 6.1.1 The invariant direct image $p_*^\Gamma(\mathcal{H})$ of \mathcal{H} is the group scheme on U whose valued points for any U -scheme S are given by $p_*^\Gamma(\mathcal{H})(S) = \mathcal{H}(S \times_U W)^\Gamma$.

Further, the invariant direct image functor commutes with the Lie-algebra functor in the following sense:

$$(6.1.1) \quad \text{Lie}(p_*^\Gamma(\mathcal{H})) = p_*^\Gamma(\text{Lie}(\mathcal{H})).$$

More generally, the invariant direct image may be defined for any *affine* scheme over W together with a lift of Γ -action.

6.2 Rational weight parahoric torsors as $\Gamma - G$ bundles

We briefly recall some results from [3, Section 5]. Let $\mathcal{G} \rightarrow X$ be a parahoric group scheme as in Section 2.1. Say θ is a weight such that each θ_x is a rational point of the facet σ_x corresponding to the restriction of \mathcal{G} at the formal disk \mathbb{D}_x . By [3, Theorem 5.3.1], there exists a finite Galois cover $p : Y \rightarrow X$ branched over \mathcal{R} with Galois group Γ and a principal G -bundle F (see [3, Notation. 5.1.0.1]) equipped with a left action of Γ such that if $\text{Isom}_Y(F, F)$ denotes the adjoint group scheme of F then taking the invariant direct image sets up a canonical isomorphism of group schemes:

$$(6.2.1) \quad p_*^\Gamma(\text{Isom}_Y(F, F)) = \mathcal{G}.$$

Let $\mathcal{R}_Y = p^{-1}(\mathcal{R}) \subset Y$ be the ramification points of the covering p . For each $y \in \mathcal{R}_Y$, let $\Gamma_y \subset \Gamma$ denote the isotropy subgroup that fixes y . Let $\tau_y : \Gamma_y \rightarrow \text{Aut}(F_y)$ be the action on the fiber of y . We denote its conjugacy class as $[\tau_y]$. By the type τ of F one means the set $\tau = \{[\tau_y] \mid y \in \mathcal{R}_Y\}$ of conjugacy classes. Let $\mathcal{M}_Y^\tau(\Gamma, G)$ denote the moduli stack of $(\Gamma - G)$ bundles on Y of type τ . We have an isomorphism of algebraic stacks

$$(6.2.2) \quad \alpha_F : \mathcal{M}_Y^\tau(\Gamma, G) \rightarrow \mathcal{M}_X(\mathcal{G}),$$

given by F as follows: denote by $\text{Isom}_Y(E, F)$ the sheaf of local isomorphisms

$$(6.2.3) \quad E \mapsto p_*^\Gamma(\text{Isom}_Y(E, F)).$$

The inverse map is given by $\mathcal{E} \mapsto p^*(\mathcal{E}) \times_{p^*(\mathcal{G})} F$.

6.3 Definition of (semi)stability for a parahoric torsor (\mathcal{E}, θ) with rational weight θ

Keeping all the notations and the setup as in Section 6.2, we make [2, Section 6] more precise using the notion of *parabolically associated constructions*. Let $\mathcal{E}(\mathfrak{g})_* =$

$(\mathcal{E}(\mathfrak{g}), \boldsymbol{\theta})$ denote the associated parabolic vector bundle ([2, Section 5]). Let $\mathcal{E}_\theta^{\text{par}}(\mathcal{G})$ denote the *parabolically associated adjoint group scheme* of \mathcal{E} defined as follows: let F and E be a principal $\Gamma - G$ bundles on Y such that

$$p_*^\Gamma(\text{Isom}_Y(F, F)) = \mathcal{G} \quad \text{and} \quad \alpha_F(E) = \mathcal{E}.$$

Let $E(G) = \text{Isom}_Y(E, E)$ denote the adjoint group scheme of E . We define

$$(6.3.1) \quad \mathcal{E}_\theta^{\text{par}}(\mathcal{G}) := p_*^\Gamma(E(G)).$$

Let $E(\mathfrak{g})$ denote the Lie algebra bundle of E defined by associated constructions as follows: $E \times_{G, \text{Ad}} \mathfrak{g}$. By (6.1.1), we define the *parabolically associated Lie algebra bundle* $\text{Lie}(\mathcal{E}_\theta^{\text{par}}(\mathcal{G}))$ of $(\mathcal{E}, \boldsymbol{\theta})$ as

$$(6.3.2) \quad \text{Lie}(\mathcal{E}_\theta^{\text{par}}(\mathcal{G})) = \mathcal{E}_\theta^{\text{par}}(\mathfrak{g}) := p_*^\Gamma(\text{Lie}(E(G))) = p_*^\Gamma(E(\mathfrak{g})).$$

The Lie algebra bundle $\mathcal{E}_\theta^{\text{par}}(\mathfrak{g})$ is given the structure of a parabolic Lie algebra bundle by identifying it with the vector bundle underlying $\mathcal{E}(\mathfrak{g})_*$ (see also [2, Sections 5 and 6]).

Let η be the generic point of the curve X . Let $\mathcal{E}_\theta^{\text{par}}(\mathcal{G})_\eta$ denote the restriction of $\mathcal{E}_\theta^{\text{par}}(\mathcal{G})$ to η . Let $\mathcal{P}_\eta \subset \mathcal{E}_\theta^{\text{par}}(\mathcal{G})_\eta$ be a parabolic subgroup scheme. Taking the flat closure of \mathcal{P}_η in $\mathcal{E}_\theta^{\text{par}}(\mathcal{G})$ we get the subgroup scheme $\mathcal{P}_\theta \subset \mathcal{E}_\theta^{\text{par}}(\mathcal{G})$. The Lie algebra bundle $\text{Lie}(\mathcal{P}_\theta)$ is a sub-bundle of $\text{Lie}(\mathcal{E}_\theta^{\text{par}}(\mathcal{G}))$, and we give it the *canonical induced parabolic structure* to get a parabolic Lie subbundle $\text{Lie}(\mathcal{P}_\theta)_*$ of $\mathcal{E}(\mathfrak{g})_*$.

Definition 6.3.1 [2, Definition 6.1] One calls a parahoric torsor $(\mathcal{E}, \boldsymbol{\theta})$ (semi)stable if for every generic parabolic subgroup scheme $\mathcal{P}_\eta \subset \mathcal{E}_\theta^{\text{par}}(\mathcal{G})_\eta$ as above, we have

$$\text{pardeg}(\text{Lie}(\mathcal{P}_\theta)_*) < 0 \quad (\text{resp. } \text{pardeg}(\text{Lie}(\mathcal{P}_\theta)_*) \leq 0).$$

In Remark 6.4.3, we show how to extend this definition to real weights.

6.4 Definition of (semi)stability for extended real weights

Let $(\mathcal{E}, \boldsymbol{\theta})$ be a parahoric torsor where $\boldsymbol{\theta} = \{\theta_x | x \in \mathcal{R}\}$ and θ_x are real weights. Under $p : \mathcal{M}_X(\mathcal{G}^\mathbb{I}) \rightarrow \mathcal{M}_X(\mathcal{G})$, let $\mathcal{E}^\mathbb{I}$ map to \mathcal{E} . For each $x \in \mathcal{R}$, we will fix an Ad -facet $\mathfrak{a}_{Ad}^{\circ, x}$ in whose closure θ_x lies. In each $\mathfrak{a}_{Ad}^{\circ, x}$, we pick a sequence of *rational points* $\theta_{x, n}$ converging to θ_x . We denote by $\boldsymbol{\theta}_n$ the rational weight $\{\theta_{x, n} | x \in \mathcal{R}\}$. Let $\mathcal{E}_{\boldsymbol{\theta}_n}^{\mathbb{I}, \text{par}}(\mathcal{G}^\mathbb{I})$ be the parabolically associated adjoint group scheme (see 6.3.1) of $(\mathcal{E}^\mathbb{I}, \boldsymbol{\theta}_n)$.

Proposition 6.4.1 *The vector bundle underlying $(\mathcal{E}^\mathbb{I}, \boldsymbol{\theta}, \{\mathfrak{a}_{Ad}^{\circ, x}\})$ identifies naturally with the Lie algebra bundle $\text{Lie}(\mathcal{E}_{\boldsymbol{\theta}_n}^{\mathbb{I}, \text{par}}(\mathcal{G}^\mathbb{I}))$ of $\mathcal{E}_{\boldsymbol{\theta}_n}^{\mathbb{I}, \text{par}}(\mathcal{G}^\mathbb{I})$.*

Proof For simplicity, we may suppose that $\mathcal{R} = \{x\}$. By the construction in Definition 5.2.1, the quasi-parabolic structure of $(\mathcal{E}^\mathbb{I}, \boldsymbol{\theta}, \{\mathfrak{a}_{Ad}^{\circ, x}\})$ and $(\mathcal{E}^\mathbb{I}(\mathfrak{g})_*, \text{Ad}(\theta_{x, n}))$ are the same. Since for varying n the $\theta_{x, n}$ all lie in the same Ad -facet $\mathfrak{a}_{Ad}^{\circ, x}$, the vector bundle underlying $(\mathcal{E}^\mathbb{I}(\mathfrak{g})_*, \text{Ad}(\theta_{x, n}))$ is independent of n . Further, just as $\mathcal{E}_\theta^{\text{par}}(\mathfrak{g})$ identifies with the vector bundle underlying $\mathcal{E}(\mathfrak{g})_*$ by (6.1.1), $\text{Lie}(\mathcal{E}_{\boldsymbol{\theta}_n}^{\mathbb{I}, \text{par}}(\mathcal{G}^\mathbb{I}))$ identifies with the vector bundle underlying $(\mathcal{E}^\mathbb{I}(\mathfrak{g})_*, \text{Ad}(\theta_{x, n}))$. ■

We induce the parabolic structure on $(\mathcal{E}^\perp, \theta, \{\mathbf{a}_{Ad}^{\circ,x}\})$ to $\text{Lie}(\mathcal{E}_{\theta_n}^{\perp,par}(\mathcal{G}^\perp))$ and, by an abuse of notation forgetting the smaller facets, denote it by $\text{Lie}(\mathcal{E}_{\theta}^{\perp}(\mathcal{G}^\perp))_*$. We observe the independence with respect to n of the following:

$$(6.4.1) \quad \text{Lie}(\mathcal{E}_{\theta_n}^{\perp,par}(\mathcal{G}^\perp)) \quad \text{and} \quad \mathcal{E}_{\theta_n}^{\perp,par}(\mathcal{G}^\perp)_\eta.$$

The latter equals $\mathcal{E}_{\theta}^{par}(\mathcal{G})_\eta$. Let $\mathcal{P}_\eta \subset \mathcal{E}_{\theta}^{par}(\mathcal{G})_\eta$ be a parabolic subgroup scheme. We denote by $\text{Lie}(\mathcal{P}^\perp)$ the sheaf that is the closure of $\text{Lie}(\mathcal{P}_\eta)$ in $\text{Lie}(\mathcal{E}_{\theta_n}^{\perp,par}(\mathcal{G}^\perp))$ with torsion-free quotient. Thus, $\text{Lie}(\mathcal{P}^\perp)$ is a sub-bundle of $\text{Lie}(\mathcal{E}_{\theta_n}^{\perp,par}(\mathcal{G}^\perp))$. We endow $\text{Lie}(\mathcal{P}^\perp)$ with the *canonical induced parabolic structure* from $(\mathcal{E}^\perp, \theta, \{\mathbf{a}_{Ad}^{\circ,x}\}_{x \in \mathbb{R}})$ and forgetting the smaller facets denote the associated PVB by

$$(6.4.2) \quad \text{Lie}(\mathcal{P}^\perp)_*.$$

Definition 6.4.2 Let (\mathcal{E}, θ) be a parahoric torsor with real weights. Under $p : \mathcal{M}_X(\mathcal{G}^\perp) \rightarrow \mathcal{M}_X(\mathcal{G})$, let \mathcal{E}^\perp map to \mathcal{E} . We say that the parahoric torsor with extended weights $(\mathcal{E}^\perp, \theta, \{\mathbf{a}_{Ad}^{\circ,x}\})$ (see 5.2.1) is (semi)stable if for every generic parabolic subgroup scheme $\mathcal{P}_\eta \subset \mathcal{E}_{\theta_n}^{\perp,par}(\mathcal{G}^\perp)_\eta$, we have

$$(6.4.3) \quad \text{pardeg}(\text{Lie}(\mathcal{P}^\perp)_*) < 0 \quad (\text{resp.} \quad \text{pardeg}(\text{Lie}(\mathcal{P}^\perp)_*) \leq 0).$$

Remark 6.4.3 If for each $x \in \mathbb{R}$ instead of the Ad -facets $\mathbf{a}_{Ad}^{\circ,x}$, we had chosen simply the unique Ad -facet in which θ_x lies, and instead of \mathcal{E}^\perp we worked with the quasi-parahoric torsor \mathcal{E} , then the construction in this subsection recovers the extension [2, Definition 6.1] of Definition 6.3.1 to real weights.

6.5 Equivalence of (semi)stability

Proposition 6.5.1 *The parahoric torsor (\mathcal{E}, θ) is (semi)stable (see 6.4.3) if and only if the extended weight parahoric torsor $(\mathcal{E}^\perp, \theta, \{\mathbf{a}_{Ad}^{\circ,x}\}_{x \in \mathbb{R}})$ is (semi)stable. The (semi)stability of $(\mathcal{E}^\perp, \theta, \{\mathbf{a}_{Ad}^{\circ,x}\}_{x \in \mathbb{R}})$ is independent of the choices of $\{\mathbf{a}_{Ad}^{\circ,x}\}_{x \in \mathbb{R}}$.*

Proof By Proposition 5.2.7, the Lie algebra bundles $\text{Lie}(\mathcal{E}_{\theta_n}^{\perp,par}(\mathcal{G}^\perp))$ and $\text{Lie}(\mathcal{E}_{\theta}^{par}(\mathcal{G}))$, being the vector bundles underlying $(\mathcal{E}^\perp(\mathfrak{g}), \theta)$ and $(\mathcal{E}(\mathfrak{g}), \theta)$, respectively, are related by a Hecke modification and they are comparable under inclusion. In Proposition 5.2.9, we denoted them by U^I and U , respectively. Let a denote the difference between the weights attached to U and U^I in (4.1.3). Sliding of weights (see Section 4.2) by a real number a only changes the parabolic slope by a . So by Remark 5.2.8 if we slide weights a , then we have

$$\text{par}\mu(\text{Lie}(\mathcal{E}_{\theta_n}^{\perp,par}(\mathcal{G}^\perp))_*) - \text{par}\mu(\text{Lie}(\mathcal{E}_{\theta}^{par}(\mathcal{G}))_*) = a.$$

Let us consider a generic parabolic subgroup scheme $\mathcal{P}_\eta \subset \mathcal{E}_{\theta_n}^{\perp,par}(\mathcal{G}^\perp)_\eta = \mathcal{E}_{\theta}^{par}(\mathcal{G})_\eta$.

We have the natural identification $\text{Lie}(\mathcal{P}^\perp)_\eta = \text{Lie}(\mathcal{P}^\perp_\eta) = \text{Lie}(\mathcal{P}_\eta) = \text{Lie}(\mathcal{P}_\theta)_\eta$. The parabolic structure on $\text{Lie}(\mathcal{P}^\perp)_*$ is induced from $(\mathcal{E}^\perp, \theta, \{\mathbf{a}_{Ad}^{\circ,x}\}_{x \in \mathbb{R}})$. So from the infinite filtration (4.1.3) of $\text{Lie}(\mathcal{P}^\perp)_*$ we can extract, like in Remark 5.2.8, the infinite

filtration of $\text{Lie}(\mathcal{P}_\theta)_*$ by forgetting some sheaves which turn out to be only those that do not matter critically for parabolic degree computations. Thus

$$\text{par}\mu(\text{Lie}(\mathcal{P}_\theta^\mathbb{I})_*) - \text{par}\mu(\text{Lie}(\mathcal{P}_\theta)_*) = a.$$

This shows the first assertion. Now the second statement follows. ■

We turn the independence observed above into a definition.

Definition 6.5.2 We say that a $\mathcal{G}^\mathbb{I}$ -torsor $\mathcal{E}^\mathbb{I}$ is (semi)stable with extended weight θ if for some choice of facets $\{\mathbf{a}_{Ad}^{o,x}\}_{x \in \mathcal{R}}$ (and therefore any by (6.5.1)) the torsor $(\mathcal{E}^\mathbb{I}, \theta, \{\mathbf{a}_{Ad}^{o,x}\}_{x \in \mathcal{R}})$ is (semi)stable in the sense of (6.4.2).

Remark 6.5.3 The (semi)stability Definition [19, Definition 2.2] for parabolic principal G -bundle is for the product of alcoves without their far walls (see [19, Definition 2.1]). By continuity, it may be naturally extended to the product of closed Weyl alcoves.

Via the map $q : \mathcal{M}(\mathcal{G}^\mathbb{I}) \rightarrow \mathcal{M}(G)$ of (1.0.1), a $\mathcal{G}^\mathbb{I}$ -torsor $\mathcal{E}^\mathbb{I}$ with extended weight θ may be viewed as a parabolic G -bundle but with *extended weights*, especially in the sense that some weights may become equal and may lie on the boundary of $\text{Maps}(\mathcal{R}, \mathfrak{a}_0)$. The following proposition shows that [19, Definition 2.2] agrees with 6.5.2 even for extended weights.

Proposition 6.5.4 A $\mathcal{G}^\mathbb{I}$ -torsor $\mathcal{E}^\mathbb{I}$ with extended weights θ is (semi)stable (see 6.5.2) if and only if it is (semi)stable as a parabolic G -bundle (see 6.5.3).

Proof In the case of parahoric $\mathcal{G}^\mathbb{I}$ torsors, the Definition 6.5.2 reduces to Definition 6.3.1. Viewing parahoric $\mathcal{G}^\mathbb{I}$ torsors as parabolic G -bundles, (6.3.1) in terms of slopes of the adjoint PVB with respect to reductions of structure group of G to parabolic subgroups is *equivalent* to the standard definition (see [19, Definition 2.2]). When we take limits of weights (5.2.3), this equivalence extends between $\mathcal{G}^\mathbb{I}$ torsors equipped with extended weights and their associated PVBs in the sense of (6.5.2) and parabolic G -bundles with weights lying in the boundary of the space of weights, which is a product of alcoves. ■

7 Some deformation theory and the proof of Theorem 1.0.2

We are now back in the case $X = \mathbb{P}^1$. Let (\mathcal{E}, θ) be a parahoric \mathcal{G} -torsor on \mathbb{P}^1 with parahoric structure on the marked points \mathcal{R} . Recall that if $\mathcal{E}(\mathfrak{g})$ denotes the Lie algebra bundle underlying the parabolic bundle $\mathcal{E}(\mathfrak{g})_*$, the first-order deformations of (\mathcal{E}, θ) are controlled by the cohomology space $H^1(\mathbb{P}^1, \mathcal{E}(\mathfrak{g}))$.

Let $\mathcal{E}^\mathbb{I}$ be a trivial bundle with generic B -structures (B being a fixed Borel subgroup of G) and *extended weight* θ as in Theorem 1.0.1. In Section 5.2, after choosing smaller Ad -facets, we have explained the construction of the parabolic vector bundle V_* associated with it by the Ad representation. We further observe that if \mathcal{E} is a torsor for the Iwahori group scheme, then there is an underlying principal G -bundle with

standard parabolic structures with fibers B at the marked points. Under these conditions, the (semi)stability conditions in Section 6.3 can be rephrased in terms of the usual (semi)stability of principal G -bundles but carrying along the Iwahori structures. In other words, \mathcal{E} is (semi)stable if and only if for every parabolic subgroup $P \subset G$ and reduction of structure group \mathcal{E}_P to P , we have $\text{pardeg}(\mathcal{E}_P(\mathfrak{p})_*) \leq 0 (< 0)$, where $\mathcal{E}_P(\mathfrak{p})_* \subset \mathcal{E}(\mathfrak{g})_*$ gets the canonical induced parabolic structure. This definition coincides with the one in [19].

With these notions in place, we now complete the proof of Theorem 1.0.2.

Proof of Theorem 1.0.2 \implies If $\theta \in \Delta^s$, by Theorem 1.0.1, \mathcal{E}^\perp , the trivial bundle with generic B -structure with extended weights θ , is stable. So, owing to stability, it has no sub-bundles whose associated parabolic vector bundle has degree zero.

\impliedby Since $\theta \in \Delta^{ss}$, so by Theorem 1.0.1 the trivial bundle with generic B -structure \mathcal{E}^\perp is semistable. Now, the stack of B -structures on the trivial bundle is algebraic, smooth, and irreducible. Therefore, we have a smooth and irreducible versal space \mathcal{T} . Let η denote its generic point, and let \mathcal{E}^\perp be a versal torsor on \mathcal{T} . If \mathcal{E}^\perp is only semistable and not stable at η , then in the setting of Section 6.3, by restricting \mathcal{T} if necessary, we may assume that for all $t \in \mathcal{T}$, the family $\mathcal{E}_t^\perp(\mathfrak{g})_*$ of torsors admits parabolic reductions $\mathcal{E}_P^\perp(\mathfrak{p})_{t,*}$ with $\text{pardeg}(\mathcal{E}_P^\perp(\mathfrak{p})_{t,*}) = 0$.

At a point $t \in \mathcal{T}$ corresponding to \mathcal{E}_t^\perp with generic B -structures, let $\mathcal{E}_{t,P}^\perp$ be a parabolic reduction. Let us consider the map $\phi_{\mathcal{E}_{t,P}^\perp}$ from $\{\text{deformations of } \mathcal{E}_{t,P}^\perp\}$ to $\{\text{deformations of } \mathcal{E}_t^\perp\}$. We have the following exact sequence of parabolic bundles:

$$(7.0.1) \quad 0 \rightarrow \mathcal{E}_{t,P}^\perp(\mathfrak{p})_* \rightarrow \mathcal{E}_t^\perp(\mathfrak{g})_* \rightarrow \mathcal{E}_t^\perp(\mathfrak{g})_*/\mathcal{E}_{t,P}^\perp(\mathfrak{p})_* \rightarrow 0.$$

By assumption on \mathcal{E}_t^\perp , no P -reduction $\mathcal{E}_{t,P}^\perp$ is of the minus 1 type. So the quotient $\mathcal{E}_t^\perp(\mathfrak{g})_*/\mathcal{E}_{t,P}^\perp(\mathfrak{p})_*$ has $\text{pardeg} = 0$ but the degree of the underlying vector bundle is not -1 . Hence, it has a nontrivial H^1 . Thus, $\phi_{\mathcal{E}_{t,P}^\perp}$ is not surjective. Therefore, $\mathcal{E}_{t,P}^\perp$ does not deform to the generic point of the versal space. And this holds for all parabolic reductions of \mathcal{E}_t^\perp . So \mathcal{E}_t^\perp has no destabilizing $\mathcal{E}_{P,\eta}^\perp$ arising as a deformation from a closed point of \mathcal{T} . However, any $\mathcal{E}_{P,\eta}^\perp$ of \mathcal{E}_η spreads to a Zariski neighborhood of η in \mathcal{T} . So \mathcal{E} must be stable. Hence $\theta \in \Delta^s$. ■

Proposition 7.0.1 *The condition “no P -reduction \mathcal{E}_P^\perp is of the minus 1 type” of Theorem 1.0.2 can be formulated in terms of vanishing of Gromov–Witten numbers.*

Proof For parabolic vector bundles, one considers the trivial bundle with generic quasi-parabolic structures of a fixed type. Then Gromov–Witten input data exactly corresponds to the triples of rank, degree, and type of induced parabolic structure on sub-bundles. Recall that this generalizes suitably also for principal G -bundles (see [19]). Consider any P -reduction of structure group \mathcal{E}_P^\perp of \mathcal{E}^\perp . By associated constructions, it leads to a sub-PVB $\text{Lie}(\mathcal{P}_\theta^\perp)_*$ in (6.4.2). We have also denoted it as $\mathcal{E}_P^\perp(\mathfrak{p})_*$ above. Notice that for $x \in \mathcal{R}$, the local parabolic degree of $\text{Lie}(\mathcal{P}_\theta^\perp)_*$ gets determined by \mathcal{E}_P^\perp locally around x of which there are only finitely many possibilities analogous to the induced flag types in the case of PVBs. Further, if $\text{Lie}(\mathcal{P}_\theta^\perp)_*$ happens

to have the same slope as $\mathcal{E}^\pm(\mathfrak{g})_*$, then its underlying degree, say d , gets determined as well. Thus, the set of input data $\{d\}$ and $\{w_x | x \in \mathcal{R}\}$ for Gromov–Witten numbers of sub-bundles that could potentially violate stability gets determined and is finite. We now further observe that these input data also determine the underlying degree of the quotient bundle $\mathcal{E}^\pm(\mathfrak{g})_*/\text{Lie}(\mathcal{P}_\theta^\pm)_*$. Therefore, the condition “no P -reduction \mathcal{E}_p^\pm is of the *minus 1* type” can be formulated in terms of vanishing of Gromov–Witten numbers. ■

Thus, Theorem 1.0.2 gives verifiable criteria for points in Δ^{ss} to lie in Δ^s .

Acknowledgments We wish to sincerely thank the anonymous referee for a careful reading of the manuscript and for suggesting improvements. In fact, Corollary 3.1.2 was formulated in response to a question raised by the referee. We thank ICTS, Bangalore for excellent hospitality where this work was finally accomplished.

References

- [1] S. Agnihotri and C. Woodward, *Eigenvalues of products of unitary matrices and quantum Schubert calculus*. Math. Res. Lett. 5(1998), no. 6, 817–836.
- [2] V. Balaji, I. Biswas, and Y. Pandey, *Connections on parahoric torsors on curves*. Publ. Res. Inst. Math. Sci. 53(2017), 551–585.
- [3] V. Balaji and C. S. Seshadri, *Moduli of parahoric \mathfrak{G} -torsors on a compact Riemann surface*. J. Algebraic Geom. 24(2015), no. 1, 1–49.
- [4] S. Bauer, *Parabolic bundles, elliptic surfaces and $SU(2)$ -representation spaces of genus zero Fuchsian groups*. Math. Ann. 290(1991), no. 3, 509–526.
- [5] P. Belkale, *Local systems on $\mathbb{P}^1 - S$ for S a finite set*. Compos. Math. 129(2001), no. 1, 67–86.
- [6] I. Biswas, *A criterion for the existence of a parabolic stable bundle of rank two over the projective line*. Internat. J. Math. 9(1998), no. 5, 523–533.
- [7] I. Biswas, *On the existence of unitary flat connections over the punctured sphere with given local monodromy around the punctures*. Asian J. Math. 3(1999), 333–344.
- [8] F. Bruhat and J. Tits, *Groupes réductifs Sur un corps local. II. Schémas en groupes. Existence d’une donnée radicielle valuée*. Inst. Hautes Études Sci. Publ. Math. 60(1984), 197–376.
- [9] A. A. Klyachko, *Stable bundles, representation theory and Hermitian operators*. Selecta Math. 4(1998), 419–445.
- [10] A. Knutson and T. Tao, *The honeycomb model of $GL_n(\mathbb{C})$ tensor products. I. Proof of the saturation conjecture*. J. Amer. Math. Soc. 12(1999), no. 4, 1055–1090.
- [11] M. Maruyama and K. Yokogawa, *Moduli of parabolic stable sheaves*. Math. Ann. 293(1992), no. 1, 77–99.
- [12] V. B. Mehta and C. S. Seshadri, *Moduli of vector bundles on curves with parabolic structures*. Math. Ann. 248(1980), no. 3, 205–239.
- [13] E. Meinrenken and C. Woodward, *Hamiltonian loop group actions and Verlinde factorization*. J. Differential Geom. 50(1998), no. 3, 417–469.
- [14] J. W. Morgan, *Holomorphic bundles over elliptic manifolds*. In: Lothar Götsche (ed.), *School on algebraic geometry (Trieste, 1999)*, ICTP Lecture Notes, 1, Abdus Salam International Centre for Theoretical Physics, Trieste, 2000, pp. 135–203.
- [15] Y. Pandey, *Criteria for existence of stable parahoric SO_n , Sp_n and spin bundles on \mathbb{P}^1* . J. Ramanujan Math. Soc. 29(2012), no. 1, 93–117.
- [16] A. Ramanathan, *Stable principal bundles on a compact Riemann surface*. Math. Ann. 213(1975), 129–152.
- [17] A. Ramanathan, *Deformations of principal bundles on the projective line*. Invent. Math. 71(1983), no. 1, 165–191.
- [18] T. A. Springer, *Linear algebraic groups*. 2nd ed., Modern Birkhäuser Classics, Birkhäuser Boston, Inc., Boston, MA, 2009.
- [19] C. Teleman and C. Woodward, *Parabolic bundles, products of conjugacy classes and Gromov–Witten invariants*. Ann. Inst. Fourier (Grenoble). 53(2003), no. 3, 713–748.

Chennai Mathematical Institute, H1 Sipcot IT Park, Siruseri, Kelambakkam 603103, India
e-mail: balaji@cmi.ac.in

Indian Institute of Science Education and Research Mohali, Mohali Knowledge city, Sector 81, SAS Nagar, Manauli PO 140306, India
e-mail: ypandey@iisermohali.ac.in yashonidhipandey@yahoo.co.uk