

On quasi-tame Looijenga pairs

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We prove a conjecture of Bousseau, van Garrel and the first-named author relating, under suitable positivity conditions, the higher genus maximal contact log Gromov–Witten invariants of Looijenga pairs to other curve counting invariants of Gromov–Witten/Gopakumar–Vafa type. The proof consists of a closed-form q -hypergeometric resummation of the quantum tropical vertex calculation of the log invariants in presence of infinite scattering. The resulting identity of q -series appears to be new and of independent combinatorial interest.

1. Introduction

1.1. Quasi-tame Looijenga pairs

A Looijenga pair $Y(D) := (Y, D)$ is the datum of a smooth rational complex projective surface Y and an anticanonical singular curve $D \in |-K_Y|$. A Looijenga pair $Y(D)$ is called *nef* if the singular curve D is a simple normal crossings divisor $D = \cup_{i=1}^l D_i$ with each D_i smooth, irreducible, and nef¹ for all $i = 1, \dots, l$. A *tame* Looijenga pair is a nef pair with either $l > 2$, or $D_i^2 > 0$ for all i . Writing $E_{Y(D)} := \text{Tot}(\oplus_i (\mathcal{O}_Y(-D_i)))$, we will say that a nef pair $Y(D)$ is *quasi-tame* if there exists a tame pair $Y'(D')$ such that $E_{Y(D)}$ is deformation-equivalent to $E_{Y'(D')}$. By definition, there is an obvious sequence of nested inclusions

nef Looijenga pairs \supset quasi-tame Looijenga pairs \supset tame Looijenga pairs .

Looijenga pairs have been the focus of much attention lately due to their intertwined role in mirror symmetry for surfaces [2–4, 20, 23, 36, 42, 43] and the study of cluster varieties [19, 37, 45]. In a recent series of papers [7–9], the log Gromov–Witten theory of quasi-tame pairs was further conjectured to be at the centre of a web of correspondences relating it to several enumerative theories. We recall the relevant context and fix notation below.

¹Since we require D to be singular, an l -component nef Looijenga pair must have $l > 1$.

1.2. Enumerative theories

The authors of [7] consider four different geometries, and associated enumerative invariants, attached to the datum of a quasi-tame Looijenga pair $Y(D)$:

1. the log Calabi–Yau surface obtained by viewing $Y(D)$ as a log-scheme for the divisorial log structure induced by D . For a given genus g and effective curve class $d \in H_2(Y, \mathbb{Z})$ with $d \cdot D_i > 0$ for all $i = 1, \dots, l$, the corresponding set of invariants are the log Gromov–Witten invariants [1, 10, 22] of $Y(D)$ with maximal tangency at each component D_i , $l - 1$ point insertions on the surface, and one insertion of the top Chern class of the Hodge bundle:

$$(1) \quad N_{g,d}^{\log}(Y(D)) := \int_{[\mathcal{M}_{g,l-1}^{\log}(Y(D),d)]^{\text{vir}}} \prod_{i=1}^{l-1} \text{ev}_i^*[\text{pt}_Y] (-1)^g \lambda_g,$$

or equivalently, their all-genus generating function

$$(2) \quad N_d^{\log}(Y(D))(\hbar) := \left(2 \sin \left(\frac{\hbar}{2} \right) \right)^{2-l} \sum_{g \geq 0} N_{g,d}^{\log}(Y(D)) \hbar^{2g-2+l};$$

2. the quasi-projective Calabi–Yau variety $E_{Y(D)}$, and its genus zero local Gromov–Witten invariants [11, 12]

$$(3) \quad N_d(E_{Y(D)}) := \int_{[\mathcal{M}_{0,l-1}(E_{Y(D)},d)]^{\text{vir}}} \prod_{i=1}^{l-1} \text{ev}_i^*[\text{pt}_Y]$$

and local Gopakumar–Vafa invariants [24, 27]

$$(4) \quad \text{GV}_d(E_{Y(D)}) := \sum_{k|d} \frac{\mu(k)}{k^{4-l}} N_d(E_{Y(D)})$$

where μ is the Möbius function;

3. the quasi-projective Calabi–Yau threefold $\text{Tot}(\mathcal{O}_{Y \setminus \cup_{i < l} D_i}(-D_l))$ equipped with a disjoint union of $l - 1$ Lagrangians L_i fibred over real curves in D_i , $i < l$, as defined in [7, Construction 6.4]:

$$Y^{\text{op}}(D) := \left(\text{Tot} \left(\mathcal{O}(-D_l) \rightarrow Y \setminus (D_1 \cup \dots \cup D_{l-1}) \right), L_1 \sqcup \dots \sqcup L_{l-1} \right),$$

The respective invariants, for a given relative homology degree $d \in H_2(Y^{\text{op}}(D), \mathbb{Z})$, are the open Gromov–Witten counts

$$\begin{aligned}
 O_{g,d}(Y^{\text{op}}(D)) &:= \int_{[\mathcal{M}_g(Y^{\text{op}}(D),d)]^{\text{vir}}} 1, \\
 \textcircled{O}_d(Y^{\text{op}}(D))(\hbar) &:= \sum_{g \geq 0} \hbar^{2g+l-3} O_{g,d}(Y^{\text{op}}(D))
 \end{aligned}
 \tag{5}$$

virtually enumerating genus- g open Riemann surfaces with $l - 1$ connected components of the boundary ending on the Lagrangians L_i , $i = 1, \dots, l - 1$. Under relatively lax conditions², $Y^{\text{op}}(D)$ can be deformed to a singular Harvey–Lawson (Aganagic–Vafa) Lagrangian pair with $L_i \simeq \mathbb{R}^2 \times S^1$, for which open GW counts can be defined in the algebraic category [26, 34] (see also [14, 33]). Denoting by $w_i(d)$ the winding number of a relative degree- d open stable map to $Y^{\text{op}}(D)$ around the non-trivial homology circle in L_i , we will also consider the corresponding genus zero/all-genus Labastida–Mariño–Ooguri–Vafa invariants [31, 32, 41]

$$\begin{aligned}
 \text{LMOV}_{0,d}(Y^{\text{op}}(D)) &= \sum_{k|d} \frac{\mu(k)}{k^{4-l}} O_{0,d/k}(Y^{\text{op}}(D)), \\
 \text{LMOV}_d(Y^{\text{op}}(D))(\hbar) &= [1]_q^2 \prod_{i < l} \frac{w_i(d)}{[w_i(d)]_q} \sum_{k|d} \frac{\mu(k)}{k} \textcircled{O}_{d/k}(Y^{\text{op}}(D))(k\hbar),
 \end{aligned}
 \tag{6}$$

where $[n]_q := q^{n/2} - q^{-n/2}$, and $q = e^{\hbar}$;

4. for $l = 2$, a symmetric quiver $\mathbf{Q}(Y(D))$ with adjacency matrix determined by $Y(D)$ [7, Thm. 7.3]. For a given charge vector d , the corresponding numbers are the numerical Donaldson–Thomas invariants $\text{DT}_d^{\text{num}}(\mathbf{Q}(Y(D)))$, defined as the formal Taylor coefficients of (the plethystic logarithm of) the generating series of Euler characteristics on the stack of representations of $\mathbf{Q}(Y(D))$.

The constructions of [7] in particular identify the absolute homology of $Y(D)$, the relative homology of $Y^{\text{op}}(D)$, and the free abelian group over the

²This was formalised as “Property O” in [7, Definition 6.3]: this is equivalent to requiring that $E_{Y(D)}$ is deformation-equivalent to $E_{Y'(D')}$ with Y' a toric weak Fano surface, D'_i a prime toric divisor for $i < l$, and D'_l nef. All quasi-tame pairs with $l = 2$ satisfy Property O, and all non-tame quasi-tame pairs have $l = 2$, so this is safely assumed to hold throughout this paper.

set of vertices of $\mathbf{Q}(Y(D))$,

$$d \in H_2(Y(D), \mathbb{Z}) \simeq H_2(E_{Y(D)}, \mathbb{Z}) \simeq H_2^{\text{rel}}(Y^{\text{op}}(D), \mathbb{Z}) \simeq \mathbb{Z}^{|\mathbf{Q}(Y(D))_{\text{ol}}|}.$$

Under these identifications, the authors of [7] propose that the invariants above are essentially the same, as follows.

Conjecture 1.1 (The genus zero log/local/open correspondence, [7, 16, 35]). *The genus zero log, local, and open Gromov–Witten invariants associated to a quasi-tame Looijenga pair $Y(D)$ are related as*

$$(7) \quad N_d(E_{Y(D)}) = O_{0,d}(Y^{\text{op}}(D)) = \left(\prod_{j=1}^l \frac{(-1)^{d \cdot D_j - 1}}{d \cdot D_j} \right) N_{0,d}^{\text{log}}(Y(D)),$$

and, for the associated BPS invariants,

$$(8) \quad \text{GV}_d(E_{Y(D)}) = \text{LMOV}_{0,d}(Y^{\text{op}}(D)) \in \mathbb{Z}.$$

Moreover, if $l = 2$,

$$(9) \quad \text{DT}_d^{\text{num}}(\mathbf{Q}(Y(D))) = |\text{GV}_d(E_{Y(D)})|.$$

In [7, Conj. 1.3], the above is further extended to an identity between all-genus Gromov–Witten generating functions.

Conjecture 1.2 (The higher genus log/open correspondence). *The higher genus log and open Gromov–Witten invariants associated to a quasi-tame Looijenga pair $Y(D)$ are related as*

$$(10) \quad \mathbb{O}_d(Y^{\text{op}}(D))(\hbar) = \left(\prod_{j=1}^{l-1} \frac{(-1)^{d \cdot D_j - 1}}{d \cdot D_j} \right) \frac{(-1)^{d \cdot D_l - 1}}{[d \cdot D_l]_q} \mathbb{N}_d^{\text{log}}(Y(D))(\hbar).$$

Moreover,

$$(11) \quad \begin{aligned} \text{LMOV}_d(Y^{\text{op}}(D))(\hbar) &= [1]_q^2 \left(\prod_{i=1}^l \frac{1}{[d \cdot D_i]_q} \right) \\ &\times \sum_{k|d} \frac{(-1)^{d/k \cdot D + l} \mu(k)}{[k]_q^{2-l} k^{2-l}} \mathbb{N}_{d/k}^{\text{log}}(Y(D))(k\hbar) \\ &\in \mathbb{Z}[q, q^{-1}]. \end{aligned}$$

Conjecture 1.1 was proved in [7, Thm. 1.4–1.6]. Conjecture 1.2 was proved in [7, Thm. 1.5 and 1.7] for tame $Y(D)$, and formulated as a conjecture for quasi-tame $Y(D)$ in [7, Conj. 4.8]. Two non-tame, quasi-tame cases of this conjecture were subsequently proved in [30].

In this paper, we establish a stronger statement from which Conjecture 1.2 follows for any quasi-tame Looijenga pair $Y(D)$. We will provide a closed-form calculation and comparison of both sides of (10), returning the two equalities in Conjecture 1.2 as a corollary. Since the tame setting was already dealt with in [7], we may restrict our attention here to non-tame, quasi-tame pairs alone, for which $l = 2$. We give here a slightly discursive version of the main result of this paper (see Propositions 2.3, 2.5 and 2.7 for precise statements, and e.g. (12) and (14) for explicit formulas).

Theorem 1.3. *Let $Y(D)$ be a non-tame, quasi-tame Looijenga pair $Y(D)$ and $d \in H_2(Y, \mathbb{Z})$. The log and open higher genus generating functions $\mathbb{N}_d^{\log}(Y(D))(\hbar)$ and $\mathbb{O}_d(Y^{\text{op}}(D))(\hbar)$ are rational functions of $q = e^{\hbar}$, with zeroes and poles only at $q = 0, \infty$, or at roots of unity. Furthermore, Conjecture 1.2 holds.*

1.3. Strategy of the proof

Our task is simplified by a number of circumstances, which reduce Theorem 1.3 to the computation of *one single example*. As explained in [15] and [7, Prop. 2.2], $Y(D)$ is fully determined by the self-intersections (D_1^2, D_2^2) , and when considering specific examples we will shorten notation by writing $Y(D_1^2, D_2^2)$ for $Y(D)$. Let $\pi : d\mathbb{P}_r \rightarrow \mathbb{P}^2$ be the blow-up of the plane at $r \geq 0$ points $\{P_1, \dots, P_r\}$, and write $H := \pi^*c_1(\mathcal{O}_{\mathbb{P}^2}(1))$, $E_i := [\pi^{-1}(P_i)]$. Up to deformation and permutation of D_1, D_2 and E_1, \dots, E_r , there is a unique non-tame, quasi-tame pair of maximal Picard number given by $Y = d\mathbb{P}_3$ and $D_1 = H - E_1$, $D_2 = 2H - E_2 - E_3$, so that $(D_1^2, D_2^2) = (0, 2)$.

By [7, Prop 2.2], any other non-tame, quasi-tame pair $Y(D)$ is the result of a toric contraction $\pi' : d\mathbb{P}_3(0, 2) \rightarrow Y(D)$. Therefore, as we recall in Proposition 2.3 below, the blow-up formulas for log and open invariants [7, Prop. 4.3 and 6.9] imply that it suffices to check that Conjecture 1.2 holds for the single case $Y(D) = d\mathbb{P}_3(0, 2)$. The l.h.s. of (10) in that case was computed in [7, Sec. 6.3.1] to be

$$\begin{aligned}
 \mathbb{O}_d(d\mathbb{P}_3^{\text{op}}(0, 2)) &= (-1)^{d_1+d_2+d_3} \frac{[d_1]_q}{d_1[d_0]_q[d_1+d_2+d_3-d_0]_q} \begin{bmatrix} d_3 \\ d_0-d_1 \end{bmatrix}_q \\
 (12) \quad &\times \begin{bmatrix} d_3 \\ d_0-d_2 \end{bmatrix}_q \begin{bmatrix} d_0 \\ d_3 \end{bmatrix}_q \begin{bmatrix} d_1+d_2+d_3-d_0 \\ d_3 \end{bmatrix}_q,
 \end{aligned}$$

where we decomposed $d = d_0(H - E_1 - E_2 - E_3) + d_1E_1 + d_2E_2 + d_3E_3$ in terms of generators $\{H - E_1 - E_2 - E_3, E_1, E_2, E_3\}$ of $H_2(\mathrm{dP}_3, \mathbb{Z})$, and for non-negative integers n, m we denoted³

$$(13) \quad [n]_q! := \prod_{i=1}^n [i]_q, \quad \begin{bmatrix} n \\ m \end{bmatrix}_q := \begin{cases} \frac{[n]_q!}{[m]_q! [n-m]_q!} & 0 \leq m \leq n, \\ 0 & \text{otherwise.} \end{cases}$$

The first equality (10) in Conjecture 1.2 is then a consequence of the following

Proposition 1.4 (=Propositions 2.5 and 2.7). *With the conventions above, we have*

$$(14) \quad \begin{aligned} \mathbb{N}_d^{\log}(\mathrm{dP}_3(0, 2))(\hbar) &= \frac{[d_1]_q [d_2 + d_3]_q}{[d_0]_q [d_1 + d_2 + d_3 - d_0]_q} \begin{bmatrix} d_3 \\ d_0 - d_1 \end{bmatrix}_q \begin{bmatrix} d_3 \\ d_0 - d_2 \end{bmatrix}_q \\ &\times \begin{bmatrix} d_0 \\ d_3 \end{bmatrix}_q \begin{bmatrix} d_1 + d_2 + d_3 - d_0 \\ d_3 \end{bmatrix}_q. \end{aligned}$$

Indeed, comparing (12) with (14) we see that these generating series are related as in (10). The second statement, equation (11), then also follows from Proposition 1.4 combined with the BPS integrality result of [7, Thm. 8.1] for $l = 2$, whose proof applies identically to this case.

We will show Proposition 1.4 in two main steps. We will first construct a toric model for $\mathrm{dP}_3(0, 2)$ in the sense of [20], and then compute the λ_g -log Gromov–Witten invariants (1) from the corresponding quantum scattering diagram and algebra of quantum broken lines [4–6, 13, 17, 18, 38, 40]. The lack of tameness is epitomised by the existence of infinite scattering when two quantum walls meet, and the resulting sum over quantum broken lines leads to the intricate-looking multi-variate generalised hypergeometric sum in (19). The second step consists of proving that this sum admits a closed-form q -hypergeometric resummation given by (14). To our knowledge, this has not previously appeared in the literature, with the exception of the special cases $d_3 = d_2 = d_0$ and $d_3 = d_0 = d_1 + d_2$ considered in [30]. To prove it, we first establish a difference equation satisfied by a 1-parameter deformation of (19), and then show inductively that the resulting recursion has a unique closed-form solution compatible with (19) by repeated use of Jackson’s q -analogue of the Pfaff–Saalschütz summation for the ${}_3\varphi_2$ -hypergeometric function.

³By [7, Prop. 2.5], the effectiveness of d implies that all arguments of the q -binomial expressions in (12) are non-negative integers.

2. Proof of Conjecture 1.2

2.1. Log GW invariants from the quantum tropical vertex

We start off by giving a summary of the combinatorial setup for the calculation of the higher genus log GW invariants (2) from the associated quantum scattering diagram, referring the reader to [7, Sec. 4.2] for a more extensive treatment.

2.1.1. Toric models Two birational operations on log Calabi–Yau surfaces $Y(D)$ will feature prominently in the rest of the paper.

- If \tilde{Y} is the blow-up of Y at a node of D and \tilde{D} is the preimage of D in \tilde{Y} we say $\tilde{Y}(\tilde{D})$ is a *corner blow-up* of $Y(D)$.
- In case \tilde{Y} is the blow-up of Y at a smooth point in D and \tilde{D} is the strict transform of D in \tilde{Y} we say $\tilde{Y}(\tilde{D})$ is an *interior blow-up* of $Y(D)$.

Starting from a Looijenga pair $Y(D)$, we will seek to construct pairs $\tilde{Y}(\tilde{D})$ and $\bar{Y}(\bar{D})$ fitting into a diagram

$$(15) \quad \begin{array}{ccc} & \tilde{Y}(\tilde{D}) & \\ \varphi \swarrow & & \searrow \pi \\ Y(D) & & \bar{Y}(\bar{D}) \end{array}$$

where φ is a sequence of corner blow-ups and π is a *toric model*, meaning that \bar{Y} is toric, \bar{D} is its toric boundary and π is a sequence of interior blow-ups. By [20, Prop. 1.3] such a diagram always exists. We will write ρ_{D_i} for the generator of the ray in the fan $\bar{\Sigma}$ of \bar{Y} associated to the toric prime divisor which is the push-forward along π of the strict transform of D_i under φ .

Given a toric model $\pi : \tilde{Y}(\tilde{D}) \rightarrow \bar{Y}(\bar{D})$ as in (15) we can associate a *consistent quantum scattering diagram* \mathfrak{D} to it, which is what we discuss next.

2.1.2. Quantum scattering and higher genus invariants The scattering diagram \mathfrak{D} is defined on the lattice $N_{\mathbb{Z}} \cong \mathbb{Z}^2$ of integral points of the fan $\bar{\Sigma}$ of \bar{Y} , as follows: assume that π is a sequence of blow-ups of distinct smooth points P_1, \dots, P_s of \bar{D} and denote $\mathcal{E}_1, \dots, \mathcal{E}_s$ the exceptional divisors in \tilde{Y} associated to these blow-ups. Further, write ρ_j for the primitive generator of the ray associated to the toric prime divisor which P_j is an element of. For each $j \in \{1, \dots, s\}$ we introduce a wall $\mathfrak{d}_j := \mathbb{R}\rho_j$ decorated with

wall-crossing functions $f_{\mathfrak{d}_j} := 1 + t_j z^{-\rho_j} \in \mathbb{C}[[t_1, \dots, t_s]][[N_{\mathbb{Z}}]]$. We will often write $z^\rho =: x^a y^b$ if $\rho = (a, b)$. Then \mathfrak{D} is the unique (up to equivalence) completion of the initial scattering diagram $\mathfrak{D}_{\text{in}} := \{(\mathfrak{d}_j, f_{\mathfrak{d}_j})\}_{j \in \{1, \dots, s\}}$ in the sense of [4, 5, 21, 29]. Such a completion can be found algorithmically by successively adding new rays whenever two walls meet, as we now describe.

First of all, after perturbing the diagram \mathfrak{D}_{in} we may assume that walls intersect in codimension at least one and that no more than two walls meet in a point. Now suppose two walls $\mathfrak{d}^1, \mathfrak{d}^2$ intersect. Denote by $-\rho^i$ a primitive integral direction of \mathfrak{d}^i and assume $f_{\mathfrak{d}^i} = 1 + c_i z^{\rho^i}$. For our purpose the relevant scattering processes are:

- $\det(\rho^1, \rho^2) = \pm 1$ (*simple scattering*): the algorithm tells us to add a ray \mathfrak{d} emanating from the intersection point $\mathfrak{d}^1 \cap \mathfrak{d}^2$ in the direction $-\rho^1 - \rho^2$ decorated with $1 + c_1 c_2 z^{\rho^1 + \rho^2}$.
- $\det(\rho^1, \rho^2) = \pm 2$ (*infinite scattering*): the algorithm creates three types of walls. First, there is a central wall in the direction $-\rho^1 - \rho^2$ decorated with a wall-crossing function whose explicit shape is not of interest in the subsequent analysis and hence omitted. Further – and most relevant for us later – one needs to add walls $\mathfrak{d}_1, \dots, \mathfrak{d}_n, \dots$ with slope $-(n + 1)\rho^1 - n\rho^2$ decorated with

$$1 + c_1^{n+1} c_2^n z^{(n+1)\rho^1 + n\rho^2}$$

and last a collection ${}_1\mathfrak{d}, \dots, {}_n\mathfrak{d}, \dots$ of walls respectively having slope $-n\rho^1 - (n + 1)\rho^2$ and decorated with

$$1 + c_1^n c_2^{n+1} z^{n\rho^1 + (n+1)\rho^2}.$$

Adding new walls to the scattering diagram possibly creates new intersection points. Perturbing the diagram if necessary and repeating the above described process for each newly created intersection point yields a consistent scattering diagram \mathfrak{D} .

We now introduce the final combinatorial object we require for our computation of log Gromov–Witten invariants. Let $N_{\mathbb{R}} := N_{\mathbb{Z}} \otimes_{\mathbb{Z}} \mathbb{R}$. Given $p \in N_{\mathbb{R}}$ and $m \in N_{\mathbb{Z}}$, a *quantum broken line β with ends p and m* consists of

1. a continuous piece-wise straight path $\beta : (-\infty, 0] \rightarrow B \setminus \bigcup_{\mathfrak{d} \in \mathfrak{D}} \partial\mathfrak{d} \cup \bigcup_{\mathfrak{d}^1 \neq \mathfrak{d}^2} \mathfrak{d}^1 \cap \mathfrak{d}^2$ intersecting walls transversely;
2. a labelling L_1, \dots, L_n of the successive line segments with L_n ending at p such that each intersection point $L_i \cap L_{i+1}$ lies on a wall;
3. an assignment $a_i z^{m_i}$ to each line segment L_i such that

- $a_1 z^{m_1} = z^m$,
- if $L_i \cap L_{i+1} \subset \mathfrak{d}$ with $f_{\mathfrak{d}} = \sum_{r \geq 0} c_r z^{r\rho_{\mathfrak{d}}}$ and $\rho_{\mathfrak{d}}$ chosen primitive then $a_{i+1} z^{m_{i+1}}$ is a monomial occurring in the expansion of

$$(16) \quad a_i z^{m_i} \prod_{\ell = -\frac{1}{2}(|\det(\rho_{\mathfrak{d}}, m_i)| - 1)}^{\frac{1}{2}(|\det(\rho_{\mathfrak{d}}, m_i)| - 1)} \left(\sum_{r \geq 0} c_r q^{r\ell} z^{r\rho_{\mathfrak{d}}} \right),$$

- L_i is directed in direction $-m_i$.

For such a quantum broken line β call $a_{\beta, \text{end}} := a_n$ the end-coefficient and write $m_{\beta, \text{end}} := m_n$. Moreover, we will often refer to $a_{\beta, \text{end}} z^{m_{\beta, \text{end}}}$ as the end-monomial and to z^m as the asymptotic monomial of β . We remark that for $f_{\mathfrak{d}} = 1 + cz^{\rho_{\mathfrak{d}}}$ the product in (16) takes the form

$$(17) \quad \prod_{\ell = -\frac{1}{2}(|\det(\rho_{\mathfrak{d}}, m_i)| - 1)}^{\frac{1}{2}(|\det(\rho_{\mathfrak{d}}, m_i)| - 1)} (1 + cq^{\ell} z^{\rho_{\mathfrak{d}}}) = \sum_{k=0}^{|\det(\rho_{\mathfrak{d}}, m_i)|} \left[\begin{matrix} |\det(\rho_{\mathfrak{d}}, m_i)| \\ k \end{matrix} \right]_q c^k z^{k\rho_{\mathfrak{d}}}.$$

Now given two lattice vectors $m_1, m_2 \in N_{\mathbb{Z}}$, define

$$(18) \quad C_{p; m_1, m_2}^{\mathfrak{D}}(q) := \sum_{\substack{\beta_1, \beta_2 \\ \text{Ends}(\beta_i) = (p, m_i) \\ m_{\beta_1, \text{end}} + m_{\beta_2, \text{end}} = 0}} a_{\beta_1, \text{end}} a_{\beta_2, \text{end}}$$

to be the sum of products of all end-coefficients of quantum broken lines β_1 and β_2 with asymptotic monomials z^{m_1} , resp. z^{m_2} , meeting in a common point p and with opposite exponents of their end-monomials. This sum is a polynomial in the variables t_j with coefficients in $\mathbb{Z}[q^{\pm \frac{1}{2}}]$. It turns out that the definition of $C_{p; m_1, m_2}^{\mathfrak{D}}(q)$ is mostly independent of p .

Proposition 2.1. [38, Proposition 2.13 & 2.15] *The sum in (18) is finite and as long as p is chosen generic, $C_{p; m_1, m_2}^{\mathfrak{D}}(q)$ is independent of the choice of p .*

Moreover, we remark that according to the same proposition [38, Proposition 2.15] $C_{p; m_1, m_2}^{\mathfrak{D}}(q)$ enjoys the interpretation as being the constant term in the product of two theta functions. However, most crucial for us, this quantity gives us a way to extract the higher genus, maximal contact log Gromov–Witten invariants (2) of a Looijenga pair $Y(D)$ from the scattering diagram associated to its toric model, as per the following

Proposition 2.2 ([7, 39]). *Let $Y(D)$ be a 2-component Looijenga pair, i.e. $D = D_1 + D_2$, $\pi : Y(\widetilde{D}) \rightarrow \overline{Y}(\overline{D})$ a toric model for it as in (15), and \mathfrak{D} the corresponding consistent quantum scattering diagram. For $d \in H_2(Y, \mathbb{Z})$ an effective curve class, set $m_i := (d \cdot D_i)\rho_{D_i}$. Then $\mathbb{N}_d^{\log}(Y(D))(\hbar)$ is the coefficient of $\prod_{j=1}^s t_j^{d \cdot \varphi_* \mathcal{E}_j}$ in*

$$C_{p; m_1, m_2}^{\mathfrak{D}}(q) \Big|_{q=e^{i\hbar}}.$$

2.1.3. Birational invariance Suppose now that $Y(D)$ is a 2-component quasi-tame Looijenga pair and $\pi : Y'(D') \rightarrow Y(D)$ is a sequence of interior blow-ups such that $Y'(D')$ is also quasi-tame. The following compatibility statement explains how the higher genus log-open correspondence interacts with this type of birational transformations.

Proposition 2.3. [7, Prop. 4.3 and 6.9] *Let $\pi : Y'(D') \rightarrow Y(D)$ be an interior blow-up, with both $Y'(D')$ and $Y(D)$ 2-component quasi-tame Looijenga pairs. Then $\mathbb{N}_d^{\log}(Y(D)) = \mathbb{N}_{\pi^*d}^{\log}(Y'(D'))$, $\mathbb{O}_d(Y^{\text{op}}(D)) = \mathbb{O}_{\pi^*d}(Y'^{\text{op}}(D'))$ for all $d \in H_2(Y, \mathbb{Z})$.*

The comparison statement of Proposition 2.3 for log invariants is easy to visualise in genus 0, where the invariants $N_{0,d}^{\log}(Y(D))$ are enumerative [39]: since blowing up a point away from the curves does not affect the local geometry, the corresponding counts are invariant, a property also reflected in the broken lines calculations of the scattering diagrams of Section 2.1.2. The corresponding statement for the open invariants is a non-trivial consequence of the invariance of the topological vertex under flops [25, 28].

By the classification theorem of nef Looijenga pairs in [7, Prop. 2.2], any non-tame, quasi-tame Looijenga pair $Y(D)$ is obtained up to deformation as a sequence of $m \geq 0$ interior blowings-down of $dP_3(0, 2)$. It follows from Proposition 2.3 that proving Conjecture 1.2 for $Y(D) = dP_3(0, 2)$ implies that the same statement *a fortiori* holds for any other non-tame, quasi-tame pair (and indeed any 2-component quasi-tame pair with Picard number lower than four).

2.2. The case of maximal Picard number

Let us then specialise to $Y(D) = dP_3(0, 2)$. Throughout this section we will write $d = d_0(H - E_1 - E_2 - E_3) + \sum_{i=1}^3 d_i E_i$ for a curve class $d \in H_2(dP_3, \mathbb{Z})$. If $d \cdot D_1$ or $d \cdot D_2$ vanishes, then $\mathbb{N}_d^{\log}(dP_3(0, 2))(\hbar) = 0$. In case the intersection numbers are strictly positive, we may use the scattering diagram of $dP_3(0, 2)$ to compute the invariants.

2.2.1. Constructing the toric model First, we recall from [7, Sec. 4.4] the construction of a toric model of $\mathbb{P}^2(D_1 \cup D_2)$, with D_1 a line and D_2 a smooth conic intersecting D_1 in two distinct points P_1 and P_2 . Let \mathcal{E} denote the tangent line through P_1 to D_2 . In the following we will always identify D_1, D_2, \mathcal{E} , and some yet to be defined divisors F_1, F_2 with their strict transforms, resp. push-forwards, under blow-ups, resp. blow-downs.

Blow up the point P_1 , and write F_1 for the exceptional divisor, and then blow up the intersection point of F_1 with D_2 and denote the exceptional curve by F_2 . Under these blow-ups, the strict transform of \mathcal{E} is a (-1) -curve intersecting F_2 in one point and can therefore be blown down. This blow-down results in the log Calabi–Yau surface $(\overline{\mathbb{P}^2(D)}, \overline{D})$ with anti-canonical divisor $\overline{D} = D_1 \cup F_1 \cup F_2 \cup D_2$ where F_1 is a curve with self-intersection -2 , D_2 has self-intersection 2 , and D_1, F_2 zero. Therefore, since the irreducible components of \overline{D} form a necklace with the same self-intersections as the toric boundary of \mathbb{F}_2 , we already must have $\overline{\mathbb{P}^2(D)} = \mathbb{F}_2$ with \overline{D} the toric boundary by [15, Lemma 2.10] and hence we have constructed a toric model for $\mathbb{P}^2(D)$. From the discussion of the previous Section, at a tropical level the fact that we blew down \mathcal{E} amounts to adding a wall \mathfrak{d}_{F_2} emanating from a *focus-focus singularity* on the ray corresponding to F_2 in the fan of \mathbb{F}_2 .

The above construction results in a toric model for $d\mathbb{P}_3(0, 2)$, as displayed in Figure 1: we blow up an interior point on D_1 and two interior points on D_2 and take the proper transforms, which at the fan level leads to the addition of focus-focus singularities on the rays corresponding to D_1 and D_2 (indicated with crosses in Figure 1). We denote by \mathcal{E}_1 , resp. by $\mathcal{E}_2, \mathcal{E}_3$ the exceptional loci that result from blowing up a point in D_1 , resp. two points on D_2 .

2.2.2. The quantum scattering diagram We now follow the construction outlined in Section 2.1.2 to derive the quantum scattering diagram \mathfrak{D} of the toric model of $d\mathbb{P}_3(0, 2)$ (Figure 2). We shoot out walls $\mathfrak{d}_{F_2}, \mathfrak{d}_{D_1}, \mathfrak{d}_{D_2,1}, \mathfrak{d}_{D_2,2}$ emanating from the focus-focus singularities in the direction $-\rho$, where ρ is the respective generator of the ray in the fan. We send the singularities to infinity and perturb the walls as indicated in Figure 2. From these initial walls we now want to construct a consistent scattering diagram. However, since in our subsequent analysis we will only be interested in walls with slope lying in the cone generated by $(0, -1)$ and $(1, 2)$, we will restrict the discussion to such walls only. As $|\rho_{F_2} \wedge \rho_{D_1}| = 2$ there is infinite scattering in the sense of Section 2.1.2 between the walls \mathfrak{d}_{F_2} and \mathfrak{d}_{D_1} . This results in walls $\mathfrak{d}_2, \mathfrak{d}_3, \dots$ with slope $-\rho_{F_2} - (n - 1)\rho_{D_1} = (1, -2(n - 1))$ decorated with wallcrossing functions $1 + t^n t_1^{n-1} x^{-1} y^{2(n-1)}$ where $n > 1$. For conformity, let us write $\mathfrak{d}_1 := \mathfrak{d}_{F_2}$. Now for all $n \geq 1$ each wall \mathfrak{d}_n intersects both $\mathfrak{d}_{D_2,1}$

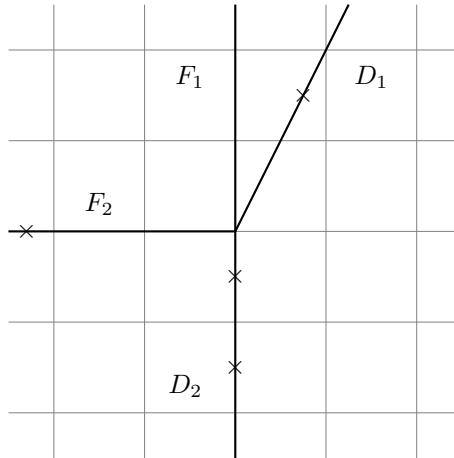


Figure 1: The toric model of $dP_3(0, 2)$.

and $\mathfrak{d}_{D_2,2}$. Luckily, in this case we only have simple scattering resulting in walls with slope $(1, -2n+3)$ and wallcrossing functions $1 + t^n t_1^{n-1} t_i x^{-1} y^{2n-3}$ where $i \in \{2, 3\}$. Lastly, we notice that the wall which is the result of scattering between \mathfrak{d}_n and $\mathfrak{d}_{D_2,1}$ intersects $\mathfrak{d}_{D_2,2}$ thus producing a wall with slope $(1, -2n + 4)$ and wallcrossing function $1 + t^n t_1^{n-1} t_2 t_3 x^{-1} y^{2n+4}$ attached to it. Let us call this wall $\mathfrak{d}_n^{D_2, D_2}$. The whole construction is summarised in Figure 2.

We collect the walls constructed above into 4-tuples labelled by an integer $n > 0$ as depicted in Figure 3. The n th tuple consists of the wall \mathfrak{d}_n , the walls which are the result of scattering between \mathfrak{d}_n and $\mathfrak{d}_{D_2,1}$, resp. $\mathfrak{d}_{D_2,2}$, and lastly the wall $\mathfrak{d}_{n+1}^{D_2, D_2}$.

2.2.3. Higher genus log GW invariants In this section we will apply Proposition 2.2 to obtain the log Gromov–Witten invariants of $dP_3(0, 2)$. For this we need to determine $C_{p; m_1, m_2}^{\mathfrak{D}}(q)$, where $m_i := (d \cdot D_i) \rho_{D_i}$ and p is a generically chosen point. First, let us characterise all quantum broken lines which contribute to this sum.

Lemma 2.4. *Choose p in the lower right quadrant so that it lies to the right of $\mathfrak{d}_{D_2,2}$ and that below p there are only walls belonging to the n th 4-tuple of walls with $n \geq d \cdot D_2 + 2$. Then the following statements hold:*

1. *If β_2 is a quantum broken line with ends (p, m_2) then either it is a straight line and thus $m_{\beta_2, \text{end}} = m_2$ or $m_{\beta_2, \text{end}}$ lies in the half open cone $\{-a_1 \rho_{D_1} - a_2 \rho_{D_2} \mid a_1 > 0, a_2 \geq 0\}$.*

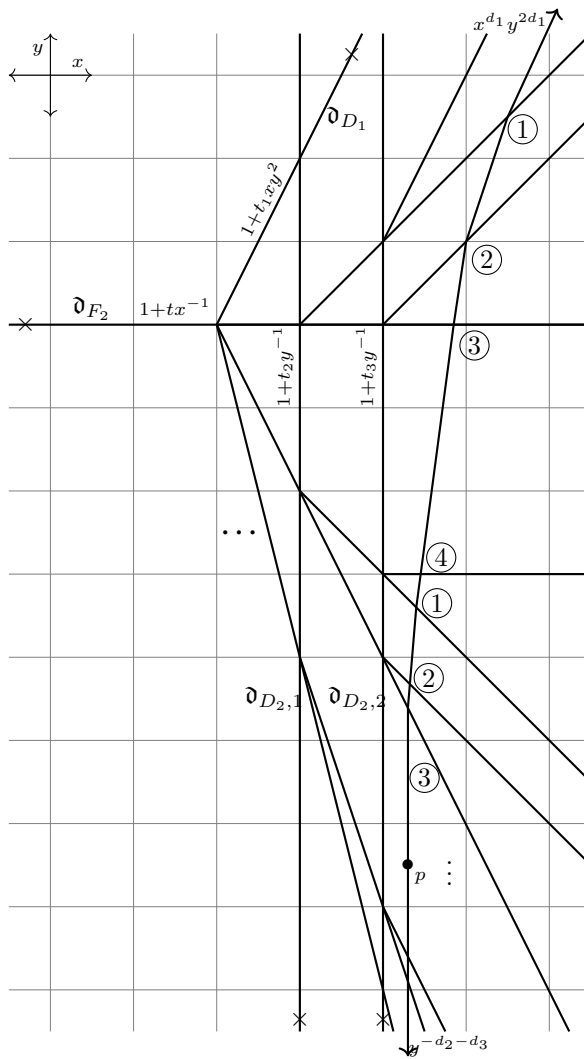


Figure 2: The quantum scattering diagram of $dP_3(0, 2)$.

2. If β_1 and β_2 are quantum broken lines with ends (p, m_1) and (p, m_2) respectively such that

$$m_{\beta_1, \text{end}} + m_{\beta_2, \text{end}} = 0$$

then β_2 is a straight line and β_1 may only bend at walls to the right of $\partial_{D_2, 2}$ as in Figure 2.

Proof. Statement 1. can be proven by a straightforward, but tedious case-by-case analysis. Since this proof is barely enlightening we omit it here, and only explain how 1. implies 2. Indeed, suppose β_2 is not a straight line. Then by 1. we must have $m_{\beta_1, \text{end}} \in \{a_1 \rho_{D_1} + a_2 \rho_{D_2} \mid a_1 > 0, a_2 \geq 0\}$. However, this means that β_1 only crosses walls at which it may pick up a contribution that bends it further into the the lower right quadrant. In particular, such a quantum broken line cannot have asymptotic monomial z^{m_1} , leading to a contradiction. Hence, β_2 must be a straight line. \square

Having Lemma 2.4 at hand, we are now equipped to determine the log Gromov–Witten invariants of $d\mathbb{P}_3(0, 2)$ via Proposition 2.2.

Proposition 2.5. *Let d be an effective curve class with $d \cdot D_1, d \cdot D_2 > 0$. Then*

$$(19) \quad \mathbb{N}_d^{\text{log}}(d\mathbb{P}_3(0, 2))(\hbar) = \sum_{\substack{\forall (i, n) \in \{1, 2, 3, 4\} \times \mathbb{Z}_{>0}: \\ k_{i, n} \geq 0 \\ d_0 = \sum_{n \geq 1} \sum_{i=1}^4 (n + \delta_{i,1}) k_{i, n} \\ d_1 = \sum_{n \geq 1} \sum_{i=1}^4 k_{i, n} \\ d_0 - d_2 = \sum_{n \geq 1} (k_{1, n} + k_{4, n}) \\ d_0 - d_3 = \sum_{n \geq 1} (k_{1, n} + k_{3, n})}} \prod_{n \geq 1} \prod_{i=1}^2 \left[d_2 + d_3 - \sum_{m \geq 1} \sum_{j=1}^4 (2m - \delta_{j,3} - \delta_{j,4}) k_{j, n+m} \right]_q \times \left[d_2 + d_3 - \sum_{m \geq 0} \sum_{j=1}^4 (2m + \delta_{j,1} + \delta_{j,2}) k_{j, n+m} \right]_q.$$

Proof. In order to compute $\mathbb{N}_d^{\text{log}}(d\mathbb{P}_3(0, 2))$ we choose a point p as specified in Lemma 2.4 and consider quantum broken lines β_i with ends $(p, z^{(d \cdot D_i) \rho_{D_i}})$, where $i \in \{1, 2\}$, so that the sum of the exponents of their end-monomials at p vanishes. As stated in Proposition 2.2, we then obtain the desired log Gromov–Witten invariant by taking the product of the two end-coefficients, summing this over all such pairs of quantum broken lines and extracting the coefficient of the monomial $t^{d \cdot \varphi_* \mathcal{E}} \prod_{i=1}^3 t_i^{d \cdot \varphi_* \mathcal{E}_i}$.

Let us then analyse a quantum broken line β_1 coming from the direction D_1 with asymptotic monomial $z^{(d \cdot D_1) \rho_{D_1}} = x^{d_1} y^{2d_1}$ ending at p which only bends at walls to the right of $\mathfrak{d}_{D_2, 2}$ as illustrated in Figure 2. We claim that its end-monomial is of the form

$$a_{\beta_1, \text{end}} z^{m_{\beta_1, \text{end}}} = \prod_{n=1}^N \prod_{i=1}^2 \left[2nd_1 - \sum_{l=1}^n \sum_{j=1}^4 (2(n-l) - \delta_{j,3} - \delta_{j,4}) k_{j, l} \right]_q \times \left[(2n-1)d_1 - \sum_{l=1}^{n-1} \sum_{j=1}^4 (2(n-l) - \delta_{j,1} - \delta_{j,2}) k_{j, l} \right]_q$$

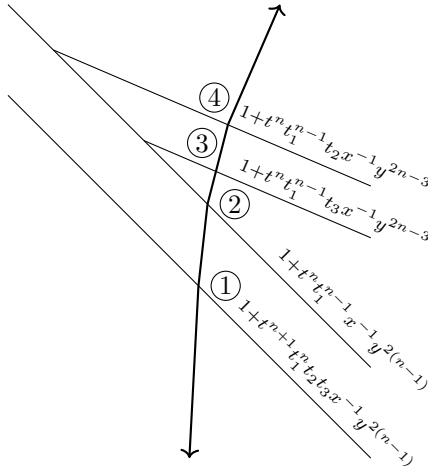


Figure 3: The n th 4-tuple of walls.

$$\begin{aligned}
 & \times t^{\sum_{n=1}^N \sum_{j=1}^4 (n+\delta_{j,1})k_{j,n}} t_1^{\sum_{n=1}^N \sum_{j=1}^4 (n-1+\delta_{j,1})k_{j,n}} \\
 & \times t_2^{\sum_{n=1}^N (k_{1,n}+k_{4,n})} t_3^{\sum_{n=1}^N (k_{1,n}+k_{3,n})} x^{d_1 - \sum_{n=1}^N \sum_{j=1}^4 k_{j,n}} \\
 (20) \quad & \times y^{2d_1 + \sum_{n=1}^N (2n-2)(k_{1,n}+k_{2,n}) + \sum_{n=1}^N (2n-3)(k_{3,n}+k_{4,n})}
 \end{aligned}$$

for some $k_{j,n} \geq 0$ where we set $N = d \cdot D_2 + 1$. Indeed, suppose that after passing the first $(n-1)$ 4-tuples of walls β_2 carries the monomial $a_{n-1} x^{b_{n-1}} y^{c_{n-1}}$. Then crossing wall ④ of the n th 4-tuple displayed in Figure 3 we see that by the defining property 3 of a quantum broken line and formula (17) the monomial carried by the quantum broken line must now be

$$\begin{aligned}
 a_{n-1} x^{b_{n-1}} y^{c_{n-1}} & \xrightarrow{\textcircled{4}} a_{n-1} \begin{bmatrix} (2n-3)b_{n-1} + c_{n-1} \\ k_{4,n} \end{bmatrix}_q t^{nk_{4,n}} t_1^{(n-1)k_{4,n}} \\
 (21) \quad & \times t_2^{k_{4,n}} x^{b_{n-1} - k_{4,n}} y^{c_{n-1} + (2n-3)k_{4,n}}
 \end{aligned}$$

for some $k_{4,n} \geq 0$. Similarly, after passing the next three walls, which together with ④ form the n th 4-tuple of walls, the quantum broken line carries the monomial

$$a_{n-1} \begin{bmatrix} (2n-3)b_{n-1} + c_{n-1} \\ k_{4,n} \end{bmatrix}_q t^{nk_{4,n}} t_1^{(n-1)k_{4,n}} t_2^{k_{4,n}} x^{b_{n-1} - k_{4,n}} y^{c_{n-1} + (2n-3)k_{4,n}}$$

$$\begin{aligned}
 & \xrightarrow{\textcircled{3}} a_{n-1} \left[\begin{matrix} (2n-3)b_{n-1} + c_{n-1} \\ k_{3,n} \end{matrix} \right]_q \left[\begin{matrix} (2n-3)b_{n-1} + c_{n-1} \\ k_{4,n} \end{matrix} \right]_q \\
 & \quad \times t^{n(k_{3,n}+k_{4,n})} t_1^{(n-1)(k_{3,n}+k_{4,n})} t_2^{k_{4,n}} t_3^{k_{3,n}} \\
 & \quad \times x^{b_{n-1}-k_{3,n}-k_{4,n}} y^{c_{n-1}+(2n-3)(k_{3,n}+k_{4,n})} \\
 \\
 & \xrightarrow{\textcircled{2}} a_{n-1} \left[\begin{matrix} (2n-2)b_{n-1} + c_{n-1} + (k_{3,n} + k_{4,n}) \\ k_{2,n} \end{matrix} \right]_q \\
 & \quad \times \left[\begin{matrix} (2n-3)b_{n-1} + c_{n-1} \\ k_{3,n} \end{matrix} \right]_q \left[\begin{matrix} (2n-3)b_{n-1} + c_{n-1} \\ k_{4,n} \end{matrix} \right]_q \\
 & \quad \times t^{\sum_{j=2}^4 nk_{j,n}} t_1^{\sum_{j=2}^4 (n-1)k_{j,n}} t_2^{k_{4,n}} t_3^{k_{3,n}} \\
 & \quad \times x^{b_{n-1}-\sum_{j=2}^4 k_{j,n}} y^{c_{n-1}+(2n-2)k_{2,n}+(2n-3)(k_{3,n}+k_{4,n})} \\
 \\
 & \xrightarrow{\textcircled{1}} a_{n-1} \left[\begin{matrix} (2n-2)b_{n-1} + c_{n-1} + (k_{3,n} + k_{4,n}) \\ k_{1,n} \end{matrix} \right]_q \\
 & \quad \times \left[\begin{matrix} (2n-2)b_{n-1} + c_{n-1} + (k_{3,n} + k_{4,n}) \\ k_{2,n} \end{matrix} \right]_q \\
 & \quad \times \left[\begin{matrix} (2n-3)b_{n-1} + c_{n-1} \\ k_{3,n} \end{matrix} \right]_q \left[\begin{matrix} (2n-3)b_{n-1} + c_{n-1} \\ k_{4,n} \end{matrix} \right]_q \\
 & \quad \times t^{\sum_{j=1}^4 (n+\delta_{j,1})k_{j,n}} t_1^{\sum_{j=1}^4 (n-1+\delta_{j,1})k_{j,n}} t_2^{k_{1,n}+k_{4,n}} t_3^{k_{1,n}+k_{3,n}} \\
 (22) \quad & \quad \times x^{b_{n-1}-\sum_{j=1}^4 k_{j,n}} y^{c_{n-1}+(2n-2)(k_{1,n}+k_{2,n})+(2n-3)(k_{3,n}+k_{4,n})} .
 \end{aligned}$$

Since we know that $(b_0, c_0) = m_1 = (d_1, 2d_1)$, by induction we can deduce that

$$b_n = d_1 - \sum_{l=1}^n \sum_{j=1}^4 k_{j,l}, \quad c_n = 2d_1 + \sum_{l=1}^n (2l-2)(k_{1,l}+k_{2,l}) + \sum_{l=1}^n (2l-3)(k_{3,l}+k_{4,l}) .$$

Substituting this into the binomial coefficients in the last line of (22) and noting that

$$(2n-3)b_{n-1} + c_{n-1} = (2n-1)d_1 - \sum_{l=1}^{n-1} (2(n-l)-1)(k_{1,l} + k_{2,l})$$

$$(23) \quad - \sum_{l=1}^{n-1} 2(n-l)(k_{3,l} + k_{4,l})$$

and

$$(24) \quad \begin{aligned} (2n-2)b_{n-1} + c_{n-1} + (k_{3,n} + k_{4,n}) &= 2nd_1 - \sum_{l=1}^n 2(n-l)(k_{1,l} + k_{2,l}) \\ &- \sum_{l=1}^n (2(n-l) - 1)(k_{3,l} + k_{4,l}) \end{aligned}$$

we indeed see that the end-monomial $a_{\beta_1, \text{end}} z^{m_{\beta_1, \text{end}}}$ is of the form (20).

Now by definition, $C_{p; m_1, m_2}^{\mathfrak{D}}(q)$ is the sum of $a_{\beta_1, \text{end}} a_{\beta_2, \text{end}}$ over all quantum broken lines β_i , $i \in \{1, 2\}$, with ends (p, m_i) such that

$$(25) \quad m_{\beta_1, \text{end}} + m_{\beta_2, \text{end}} = 0.$$

Since by Lemma 2.4 β_2 must be a straight line, we have $m_{\beta_2, \text{end}} = (d \cdot D_2) \rho_{D_2} = (0, -d_2 - d_3)$ and thus (25) translates into the conditions

$$(26) \quad d_1 = \sum_{n=1}^N \sum_{i=1}^4 k_{i,n},$$

$$(27) \quad d_2 + d_3 = \sum_{n=1}^N (2n(k_{1,n} + k_{2,n}) + (2n-1)(k_{3,n} + k_{4,n})).$$

Hence, plugging $a_{\beta_2, \text{end}} = 1$ and (20) into the defining expression (18) for $C_{p; m_1, m_2}^{\mathfrak{D}}(q)$ we get

$$\begin{aligned} C_{p; m_1, m_2}^{\mathfrak{D}}(q) &= \sum_{\substack{\forall (i,n) \in \{1,2,3,4\} \times \{1, \dots, N\}: \\ k_{i,n} \geq 0 \\ d_1 = \sum_{n=1}^N \sum_{i=1}^4 k_{i,n} \\ d_2 + d_3 = \sum_{n=1}^N \sum_{i=1}^4 (2n - \delta_{i,3} - \delta_{i,4}) k_{i,n}}} t^{\sum_{n=1}^N \sum_{j=1}^4 (n + \delta_{j,1}) k_{j,n}} t_1^{\sum_{n=1}^N \sum_{j=1}^4 (n-1 + \delta_{j,1}) k_{j,n}} \\ &\quad \times t_2^{\sum_{n=1}^N (k_{1,n} + k_{4,n})} t_3^{\sum_{n=1}^N (k_{1,n} + k_{3,n})}, \\ &\quad \times \prod_{n=1}^N \prod_{i=1}^2 \left[2nd_1 - \sum_{l=1}^n \sum_{j=1}^4 (2(n-l) - \delta_{j,3} - \delta_{j,4}) k_{j,l} \right]_q \end{aligned}$$

$$\times \left[\begin{matrix} (2n-1)d_1 - \sum_{l=1}^{n-1} \sum_{j=1}^4 (2(n-l) - \delta_{j,1} - \delta_{j,2})k_{j,l} \\ k_{2+i,n} \end{matrix} \right]_q.$$

Using the sum conditions (26) and (27) we can simplify the arguments of the q -binomials to bring the sum into the form

(28)

$$\begin{aligned} C_{p; m_1, m_2}^{\mathfrak{D}}(q) = & \sum_{\substack{\forall (i,n) \in \{1,2,3,4\} \times \{1, \dots, N\}: \\ k_{i,n} \geq 0 \\ d_1 = \sum_{n=1}^N \sum_{i=1}^4 k_{i,n} \\ d_2 + d_3 = \sum_{n=1}^N \sum_{i=1}^4 (2n - \delta_{i,3} - \delta_{i,4})k_{i,n}}} t^{\sum_{n=1}^N \sum_{j=1}^4 (n + \delta_{j,1})k_{j,n}} t_1^{\sum_{n=1}^N \sum_{j=1}^4 (n-1 + \delta_{j,1})k_{j,n}} \\ & \times t_2^{\sum_{n=1}^N (k_{1,n} + k_{4,n})} t_3^{\sum_{n=1}^N (k_{1,n} + k_{3,n})} \\ & \times \prod_{n=1}^N \prod_{i=1}^2 \left[\begin{matrix} d_2 + d_3 - \sum_{m=1}^{N-n} \sum_{j=1}^4 (2m - \delta_{j,3} - \delta_{j,4})k_{j,n+m} \\ k_{i,n} \end{matrix} \right]_q \\ & \times \left[\begin{matrix} d_2 + d_3 - \sum_{m=0}^{N-n} \sum_{j=1}^4 (2m - \delta_{j,1} - \delta_{j,2})k_{j,n+m} \\ k_{2+i,n} \end{matrix} \right]_q \end{aligned}$$

We can now apply Proposition 2.2 which states that $\mathbb{N}_d^{\log}(\mathrm{dP}_3(0, 2))$ is the coefficient of

$$(29) \quad t^{d \cdot \varphi_* \mathcal{E}} \prod_{i=1}^3 t_i^{d \cdot \varphi_* \mathcal{E}_i} = t^{d_0} t_1^{d_0 - d_1} t_2^{d_0 - d_2} t_3^{d_0 - d_3}.$$

in (28). Here, φ is the sequence of corner blow-ups $\widetilde{\mathrm{dP}}_3(\widetilde{D}) \rightarrow \mathrm{dP}_3(D)$ and $\mathcal{E}, \mathcal{E}_1, \mathcal{E}_2, \mathcal{E}_3$ are the exceptional curves we introduced in Section 2.2.1. The above identity follows from the fact that $[\varphi_* \mathcal{E}] = H$ and $[\varphi_* \mathcal{E}_i] = E_i$. Now picking the coefficient of (29) in (28) we obtain that $\mathbb{N}_d^{\log}(\mathrm{dP}_3(0, 2))$ is the sum of

(30)

$$\begin{aligned} & \prod_{n \geq 1} \prod_{i=1}^2 \left[\begin{matrix} d_2 + d_3 - \sum_{m=1}^{N-n} (2m(k_{1,n+m} + k_{2,n+m}) + (2m-1)(k_{3,n+m} + k_{4,n+m})) \\ k_{i,n} \end{matrix} \right]_q \\ & \times \left[\begin{matrix} d_2 + d_3 - \sum_{m=0}^{N-n} ((2m+1)(k_{1,n+m} + k_{2,n+m}) + 2m(k_{3,n+m} + k_{4,n+m})) \\ k_{2+i,n} \end{matrix} \right]_q \end{aligned}$$

over $k_{j,n} \geq 0$, $j \in \{1, \dots, 4\}$ and $n \in \{1, \dots, N\}$ subject to the conditions (26), (27) and

$$(31) \quad d_0 = \sum_{n=1}^N \left(k_{1,n} + n \sum_{i=1}^4 k_{i,n} \right),$$

$$(32) \quad d_0 - d_1 = \sum_{n=1}^N \left(k_{1,n} + (n-1) \sum_{i=1}^4 k_{i,n} \right),$$

$$(33) \quad d_0 - d_2 = \sum_{n=1}^N (k_{1,n} + k_{4,n}),$$

$$(34) \quad d_0 - d_3 = \sum_{n=1}^N (k_{1,n} + k_{3,n}).$$

Notice here that (31), (33), and (34) together imply (27), and that (32) follows from subtracting (26) from (31). Hence, it is sufficient to impose conditions (26), (31), (33), and (34) only. Note that these constraints are exactly the ones appearing in the sum in (19). Moreover, (30) exactly matches the summand on the right-hand side of (19) and hence the claimed formula is proven. \square

Remark 2.6. It is easy to convince oneself that there are actually only finitely many summands contributing to (19), due to the finite number of choices $(k_{i,n})$ satisfying the summation conditions. Moreover, the product in each of these summands is well-defined since the first sum condition forces $k_{i,n} = 0$ for all $n > d_0$. Thus, only a finite number of binomials can be different from one and therefore the whole expression becomes well-defined.

To prove that the right-hand side of (19) returns (14), it will be helpful to consider a 1-parameter deformation of (19), as follows. For non-negative integers a, b, c, d, e , we write

$$(35) \quad G(a, b, c, d, e) := \sum_{\substack{\forall (i,n) \in \{1,2,3,4\} \times \mathbb{Z}_{>0}: k_{i,n} \geq 0 \\ a = \sum_{n \geq 1} \sum_{i=1}^4 (n + \delta_{i,1}) k_{i,n} \\ b = \sum_{n \geq 1} \sum_{i=1}^4 k_{i,n} \\ c = \sum_{n \geq 1} (k_{1,n} + k_{4,n}) \\ d = \sum_{n \geq 1} (k_{1,n} + k_{3,n})}} \prod_{n \geq 1} \prod_{i=1}^2 \left[e - \sum_{m \geq 1} \sum_{j=1}^4 \frac{(2m - \delta_{j,3} - \delta_{j,4}) k_{j,n+m}}{k_{i,n}} \right]_q \times \left[e - \sum_{m \geq 0} \sum_{j=1}^4 \frac{(2m + \delta_{j,1} + \delta_{j,2}) k_{j,n+m}}{k_{2+i,n}} \right]_q.$$

By (19), our sought-for log Gromov–Witten generating function is obtained from (35) via the restriction

$$(36) \quad \mathbb{N}_d^{\log}(\mathrm{dP}_3(0, 2)) = G(d_0, d_1, d_0 - d_2, d_0 - d_3, d_2 + d_3).$$

We claim that (35) has a simple closed-form summation, as follows.

Proposition 2.7. *For all $a, b, c, d, e \in \mathbb{Z}_{\geq 0}$ we have that*

$$(37) \quad G(a, b, c, d, e) = \begin{bmatrix} b - a + e \\ b - c \end{bmatrix}_q \begin{bmatrix} c - a + d + e \\ c \end{bmatrix}_q \begin{bmatrix} a - c \\ d \end{bmatrix}_q \begin{bmatrix} a - d \\ b - d \end{bmatrix}_q \\ - \begin{bmatrix} b - a + e - 1 \\ b - c \end{bmatrix}_q \begin{bmatrix} c - a + d + e - 1 \\ c \end{bmatrix}_q \begin{bmatrix} a - c - 1 \\ d \end{bmatrix}_q \begin{bmatrix} a - d - 1 \\ b - d \end{bmatrix}_q.$$

In particular, from (36), it follows that

$$(38) \quad \mathbb{N}_d^{\log}(\mathrm{dP}_3(0, 2))(\hbar) = \frac{[d_1]_q [d_2 + d_3]_q}{[d_0]_q [d_1 + d_2 + d_3 - d_0]_q} \begin{bmatrix} d_3 \\ d_0 - d_1 \end{bmatrix}_q \begin{bmatrix} d_3 \\ d_0 - d_2 \end{bmatrix}_q \\ \times \begin{bmatrix} d_0 \\ d_3 \end{bmatrix}_q \begin{bmatrix} d_1 + d_2 + d_3 - d_0 \\ d_3 \end{bmatrix}_q.$$

We will give an inductive proof of Proposition 2.7 in the next Section by seeking a suitable recursive relation in the parameter a , broadly following the lead of [30]. The proof is composed of three main steps:

1. We first establish (37) for the base cases $a = 0$ and $b = 0$ by a direct analysis of the quantum broken line sum in (35), which in these cases is either vanishing, or reduces to a single summand (Lemma 2.8).
2. We then establish, for $a, b > 0$, a difference equation satisfied by $G(a, b, c, d, e)$ in the parameters a, b, c and d . This equation recursively and uniquely determines $G(a, b, c, d, e)$ from the knowledge of the base case $G(a', b', c', d', e)$ with $0 \leq a' < a$ (Lemma 2.9).
3. We finally check that the r.h.s. of (37) is also a solution of the difference equation, and conclude by uniqueness (Proposition 2.11). The proof is fundamentally based on a classical q -hypergeometric summation result in the form of the q -Pfaff–Saalschütz formula (Lemma 2.10).

2.2.4. Proof of Proposition 2.7 We start by considering the base cases $a = 0$ and $b = 0$ in the induction procedure.

Lemma 2.8. *We have that*

$$(39) \quad G(0, b, c, d, e) = \delta_{b,0} \delta_{c,0} \delta_{d,0}, \quad G(a, 0, c, d, e) = \delta_{a,0} \delta_{c,0} \delta_{d,0}.$$

In particular, Proposition 2.7 holds when $a = 0$ or $b = 0$.

Proof. Both equalities are implied by the conditions on the range of summation of (35): setting $a = 0$ or $b = 0$ implies that $k_{i,n} = 0$ for all $(i, n) \in \{1, 2, 3, 4\} \times \mathbb{Z}_{>0}$. In this case the r.h.s. of (35) is equal to one for $c = d = 0$, while if either $c \neq 0$ or $d \neq 0$ it vanishes being an empty sum.

To see that (39) agrees with (37), note that when $a = 0$ the second summand in (37) must always vanish, while the first one is non-zero only if $b = c = d = 0$, in which case it is equal to 1. Likewise, when $b = 0$, the right-hand side of (37) can only be non-zero if $c = d = 0$: this is equal to 1 for $a = 0$ by the previous analysis, and for $a > 0$ the contributions from the two summands cancel each other, since

$$\begin{aligned} & \begin{bmatrix} e - a \\ -c \end{bmatrix}_q \begin{bmatrix} c - a + d + e \\ c \end{bmatrix}_q \begin{bmatrix} a - c \\ d \end{bmatrix}_q \begin{bmatrix} a - d \\ -d \end{bmatrix}_q \\ & - \begin{bmatrix} e - a - 1 \\ -c \end{bmatrix}_q \begin{bmatrix} c - a + d + e - 1 \\ c \end{bmatrix}_q \begin{bmatrix} a - c - 1 \\ d \end{bmatrix}_q \begin{bmatrix} a - d - 1 \\ -d \end{bmatrix}_q \\ & = \delta_{c,0} \delta_{d,0} - \delta_{c,0} \delta_{d,0} = 0. \end{aligned} \quad \square$$

Lemma 2.9. *For $a, b \in \mathbb{Z}_{>0}$, $c, d, e \in \mathbb{Z}_{\geq 0}$, $G(a, b, c, d, e)$ satisfies the following recursion in (a, b, c, d) :*

$$(40) \quad G(a, b, c, d, e) = \sum_{k_{j,1} \geq 0} \prod_{i=1}^2 \begin{bmatrix} e - 2a + 2b + c + d - k_{3,1} - k_{4,1} \\ k_{i,1} \end{bmatrix}_q \begin{bmatrix} e - 2a + b + c + d \\ k_{i+2,1} \end{bmatrix}_q$$

$$G(a - b - k_{1,1}, b - k_{1,1} - k_{2,1} - k_{3,1} - k_{4,1}, c - k_{1,1} - k_{4,1}, d - k_{1,1} - k_{3,1}, e).$$

Proof. Looking at the defining equation (35) for $G(a, b, c, d, e)$, we see that the sum conditions imply that

$$\begin{aligned} & \sum_{m \geq 1} (2m(k_{1,1+m} + k_{2,1+m}) + (2m - 1)(k_{3,1+m} + k_{4,1+m})) \\ & = 2a - 2b - c - d + k_{3,1} + k_{4,1} \end{aligned}$$

and

$$\sum_{m \geq 0} ((2m + 1)(k_{1,1+m} + k_{2,1+m}) + 2m(k_{3,1+m} + k_{4,1+m})) = 2a - b - c - d.$$

Hence, they allow us to rewrite the four q -binomial coefficients that correspond to the factor $n = 1$ in the product over $n \geq 1$ in (35) as

$$\begin{aligned} & \prod_{i=1}^2 \left[\begin{matrix} e - \sum_{m \geq 1} (2m(k_{1,1+m} + k_{2,1+m}) + (2m - 1)(k_{3,1+m} + k_{4,1+m})) \\ k_{i,n} \end{matrix} \right]_q \\ & \times \left[\begin{matrix} e - \sum_{m \geq 0} ((2m + 1)(k_{1,1+m} + k_{2,1+m}) + 2m(k_{3,1+m} + k_{4,1+m})) \\ k_{2+i,n} \end{matrix} \right]_q \\ & = \prod_{i=1}^2 \left[\begin{matrix} e - 2a + 2b + c + d - k_{3,1} - k_{4,1} \\ k_{i,1} \end{matrix} \right]_q \left[\begin{matrix} e - 2a + b + c + d \\ k_{i+2,1} \end{matrix} \right]_q. \end{aligned}$$

This factor is independent of all $k_{i,n}$ with $n > 1$ and hence in (35) we can factor it out of the sum over these integers which gives us

$$\begin{aligned} (41) \quad & G(a, b, c, d, e) = \\ & \sum_{k_{j,1} \geq 0} \prod_{i=1}^2 \left[\begin{matrix} e - 2a + 2b + c + d - k_{3,1} - k_{4,1} \\ k_{i,1} \end{matrix} \right]_q \left[\begin{matrix} e - 2a + b + c + d \\ k_{i+2,1} \end{matrix} \right]_q \\ & \times \sum_{\substack{\forall (i,n) \in \{1,2,3,4\} \times \mathbb{Z}_{>1}: k_{i,n} \geq 0 \\ a = \sum_{n \geq 1} \sum_{i=1}^4 (n + \delta_{i,1}) k_{i,n} \\ b = \sum_{n \geq 1} \sum_{i=1}^4 k_{i,n} \\ c = \sum_{n \geq 1} (k_{1,n} + k_{4,n}) \\ d = \sum_{n \geq 1} (k_{1,n} + k_{3,n})}} \prod_{n \geq 2} \prod_{i=1}^2 \left[\begin{matrix} e - \sum_{m \geq 1} \sum_{j=1}^4 (2m - \delta_{j,3} - \delta_{j,4}) k_{j,n+m} \\ k_{i,n} \end{matrix} \right]_q \\ & \times \left[\begin{matrix} e - \sum_{m \geq 0} \sum_{j=1}^4 (2m + \delta_{j,1} + \delta_{j,2}) k_{j,n+m} \\ k_{2+i,n} \end{matrix} \right]_q. \end{aligned}$$

Now using (35) again in order to explicitly write out

$$\begin{aligned} (42) \quad & G(a - b - k_{1,1}, b - k_{1,1} - k_{2,1} - k_{3,1} - k_{4,1}, c - k_{1,1} - k_{4,1}, d - k_{1,1} - k_{3,1}, e) = \\ & \sum_{\substack{\forall (i,n) \in \{1,2,3,4\} \times \mathbb{Z}_{>1}: \\ k_{i,n} \geq 0 \\ a - b - k_{1,1} = \sum_{n \geq 2} \sum_{i=1}^4 (n - 1 + \delta_{i,1}) k_{i,n} \\ b - \sum_1 k_{1,1} = \sum_{n \geq 2} \sum_{i=1}^4 k_{i,n} \\ c - k_{1,1} - k_{4,1} = \sum_{n \geq 2} (k_{1,n} + k_{4,n}) \\ d - k_{1,1} - k_{3,1} = \sum_{n \geq 2} (k_{1,n} + k_{3,n})}} \prod_{n \geq 2} \prod_{i=1}^2 \left[\begin{matrix} e - \sum_{m \geq 1} \sum_{j=1}^4 (2m - \delta_{j,3} - \delta_{j,4}) k_{j,n+m} \\ k_{i,n} \end{matrix} \right]_q \\ & \times \left[\begin{matrix} e - \sum_{m \geq 0} \sum_{j=1}^4 (2m + \delta_{j,1} + \delta_{j,2}) k_{j,n+m} \\ k_{2+i,n} \end{matrix} \right]_q. \end{aligned}$$

we notice that the sum conditions in (42) are actually equivalent to the ones in the third line of (41). Hence, we can identify (42) with line three and four of (41) and so we arrive at the recursion formula (40). \square

Define now

$$(43) \quad \tilde{G}(a, b, c, d, e) := \begin{bmatrix} b - a + e \\ b - c \end{bmatrix}_q \begin{bmatrix} c - a + d + e \\ c \end{bmatrix}_q \begin{bmatrix} a - c \\ d \end{bmatrix}_q \begin{bmatrix} a - d \\ b - d \end{bmatrix}_q,$$

so that the right-hand side of (37) equates to $\tilde{G}(a, b, c, d, e) - \tilde{G}(a - 1, b, c, d, e - 2)$. We shall make extensive use of Jackson’s q -analogue of the Pfaff–Saalschütz summation in the form it is stated in [44, Equation (1q)].

Lemma 2.10 (The q -Pfaff–Saalschütz Theorem, [44]). *For integers $A, B, C, D \geq 0$ we have*

$$(44) \quad \sum_{k \geq 0} \frac{[A + B + C + D - k]_q!}{[k]_q! [A - k]_q! [B - k]_q! [C - k]_q! [D + k]_q!} = \begin{bmatrix} A + B + D \\ B \end{bmatrix}_q \begin{bmatrix} A + C + D \\ A \end{bmatrix}_q \begin{bmatrix} B + C + D \\ C \end{bmatrix}_q.$$

Proposition 2.11. *Let $a, b \in \mathbb{Z}_{>0}$ and $c, d, e \in \mathbb{Z}_{\geq 0}$. Then $\tilde{G}(a, b, c, d, e)$ satisfies the same recursion (40) as $G(a, b, c, d, e)$, i.e.*

$$(45) \quad \tilde{G}(a, b, c, d, e) = \sum_{k_1, k_2, k_3, k_4 \geq 0} \prod_{i=1}^2 \begin{bmatrix} e - 2a + 2b + c + d - k_3 - k_4 \\ k_i \end{bmatrix}_q \begin{bmatrix} e - 2a + b + c + d \\ k_{i+2} \end{bmatrix}_q \times \tilde{G}(a - b - k_1, b - k_1 - k_2 - k_3 - k_4, c - k_1 - k_4, d - k_1 - k_3, e).$$

Proof. In order to prove (45) we will repeatedly use Lemma 2.10. We start from the right-hand side of (45), plug in the definition of \tilde{G} given in (43), expand the binomials, and collect all factorials involving k_1 and k_2 . Doing so one finds for the r.h.s. of (45) that

$$\sum_{k_3, k_4 \geq 0} \begin{bmatrix} b - 2a + c + d + e \\ k_3 \end{bmatrix}_q \begin{bmatrix} b - 2a + c + d + e \\ k_4 \end{bmatrix}_q \times \frac{[a - b - d + k_3]_q! [2b - 2a + c + d + e - k_3 - k_4]_q!^2 [a - b - c + k_4]_q!}{[b - a + d + e - k_3]_q! [b - a + c + e - k_4]_q!}$$

$$\begin{aligned} & \times \sum_{k_1 \geq 0} \frac{[b - a + c + d + e - k_1 - k_3 - k_4]_q!}{[k_1]_q! [c - k_1 - k_4]_q! [d - k_1 - k_3]_q!} \\ & \times \frac{1}{[2b - 2a + c + d + e - k_1 - k_3 - k_4]_q! [a - b - c - d + k_1 + k_3 + k_4]_q!} \\ & \times \sum_{k_2 \geq 0} \frac{[2b - a + e - k_2 - k_3 - k_4]_q!}{[k_2]_q! [b - c - k_2 - k_3]_q! [b - d - k_2 - k_4]_q!} \\ & \times \frac{1}{[2b - 2a + c + d + e - k_2 - k_3 - k_4]_q! [a - 2b + k_2 + k_3 + k_4]_q!}. \end{aligned}$$

We can now use (44) to perform the sum over k_1 and k_2 . Collecting the factorials depending on k_3 and k_4 in the resulting expression, we get

$$\begin{aligned} & \frac{[a - b]_q! [a - c - d]_q! [b - 2a + c + d + e]_q!^2}{[b - a + e]_q! [c - a + d + e]_q!} \\ & \sum_{k_3 \geq 0} \frac{[b - a + d + e - k_3]_q!}{[k_3]_q! [d - k_3]_q! [b - c - k_3]_q! [b - 2a + c + d + e - k_3]_q! [a - b - d + k_3]_q!} \\ & \sum_{k_4 \geq 0} \frac{[b - a + c + e - k_4]_q!}{[k_4]_q! [c - k_4]_q! [b - d - k_4]_q! [b - 2a + c + d + e - k_4]_q! [a - b - c + k_4]_q!}. \end{aligned}$$

Thus, we can use (44) again to carry out the sums over k_3 and k_4 to deduce that the right-hand side of (45) equals

$$\frac{[a - c]_q! [a - d]_q! [b - a + e]_q! [c - a + d + e]_q!}{[a - b]_q! [b - c]_q! [c]_q! [b - d]_q! [a - c - d]_q! [d]_q! [c - a + e]_q! [d - a + e]_q!}.$$

The above is exactly the expansion of $\tilde{G}(a, b, c, d, e)$ into factorials, proving (45). □

Using Proposition 2.11 we can conclude the proof of Proposition 2.7.

Proof of Proposition 2.7. By (40), for $a > 0$ and $b > 0$, $G(a, b, c, d, e)$ is determined by the value of $G(a', b', c', d', e)$ for $0 \leq a < a'$. This means that $G(a, b, c, d, e)$ is the unique solution of (40) compatible with the boundary value in (39) for $G(0, b, c, d, e)$. By the second part of Lemma 2.8, the r.h.s. of (37) indeed returns the correct value of $G(0, b, c, d, e)$ and $G(a, 0, c, d, e)$ from (35), so all that is left to do is to check that it solves (40), and conclude by uniqueness.

To this aim, it is sufficient to argue using Proposition 2.11: note first of all that the coefficients of the recursion are invariant under the shift

$(a, e) \rightarrow (a - 1, e - 2)$. Therefore, since $\tilde{G}(a, b, c, d, e)$ is a solution of (40) by Proposition 2.11, then so is $\tilde{G}(a - 1, b, c, d, e - 2)$. Furthermore, since (40) is linear in G , their difference is also a solution. But by (43) this is exactly the claimed expression for $G(a, b, c, d, e)$ in (37), which concludes the proof. \square

Corollary 2.12. *Conjecture 1.2 holds for any quasi-tame pair $Y(D)$.*

Proof. The tame case having been treated in [7], it suffices to restrict to non-tame, quasi-tame pairs. Taking the specialisation (36) of (37) leads to (14), which together with (12) establishes the first equality of Conjecture 1.2 for $Y(D) = \mathrm{dP}_3(0, 2)$. Since $\mathbb{O}_d(\mathrm{dP}_3^{\mathrm{op}}(0, 2)) = \mathbb{O}_d(\mathrm{dP}_3^{\mathrm{op}}(1, 1))$ [7, Sec. 6.3.1], the BPS integrality statement in the second equality further follows without any modification from the proof of [7, Thm. 8.1] for $l = 2$. Finally, since every non-tame, quasi-tame pair $Y(D)$ is related to $\mathrm{dP}_3(0, 2)$ by a series of $m \geq 0$ iterated interior blow-ups at general points of D [7, Prop. 2.2], Proposition 2.3 further implies that Conjecture 1.2 holds for any such pair. \square

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