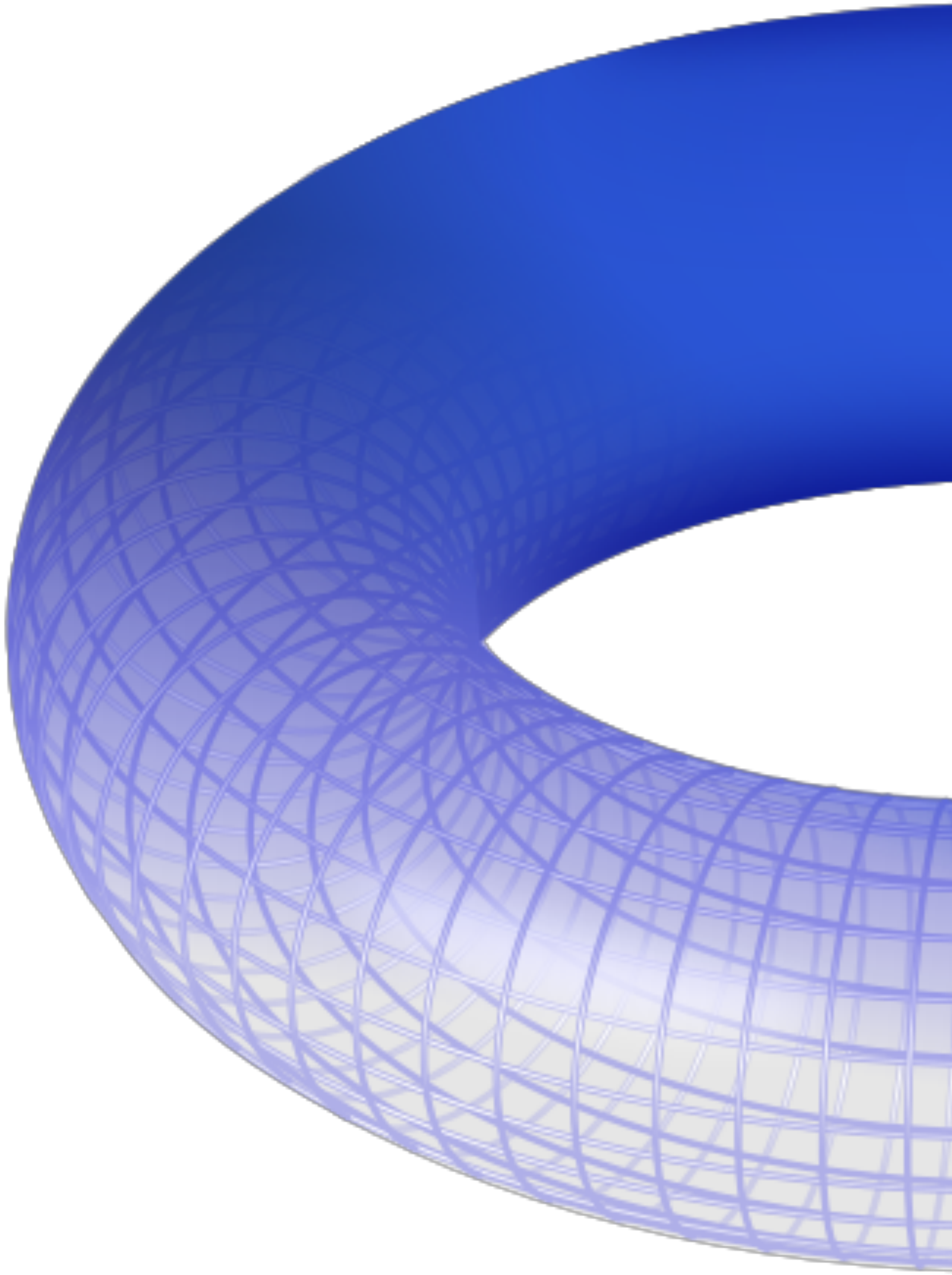
FEYNMAN INTEGRALS AND HIGHER GENUS SURFACES



In collaboration with:

J. Brödel, F. Dulat, C. Duhr, B. Penante

Theory seminar

Università di Genova 5/12/2018

Lorenzo Tancredi - CERN TH

INTRODUCTION

Precision physics @ the LHC, means (mainly) **precision in QCD**, in a very **dirty environment**! **How precise can we hope to get?**

$$pp \to HX \to l_1\bar{l}_1 + l_2\bar{l}_2 + X$$

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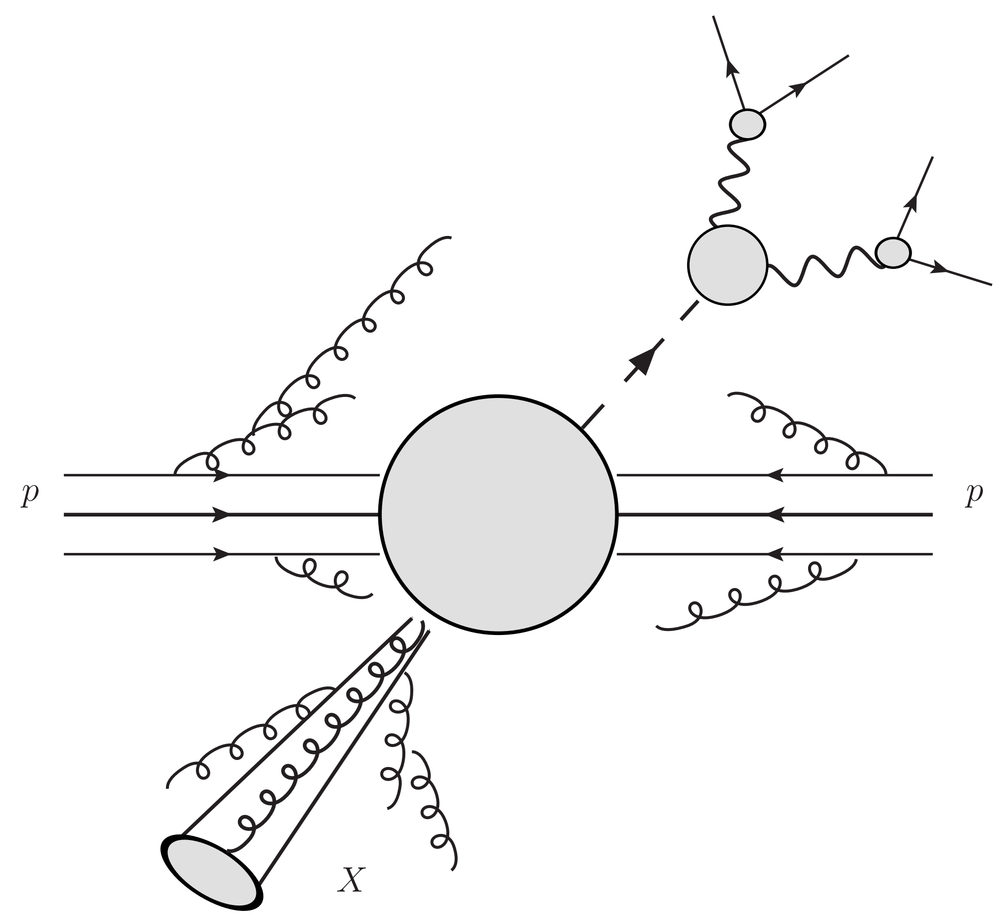

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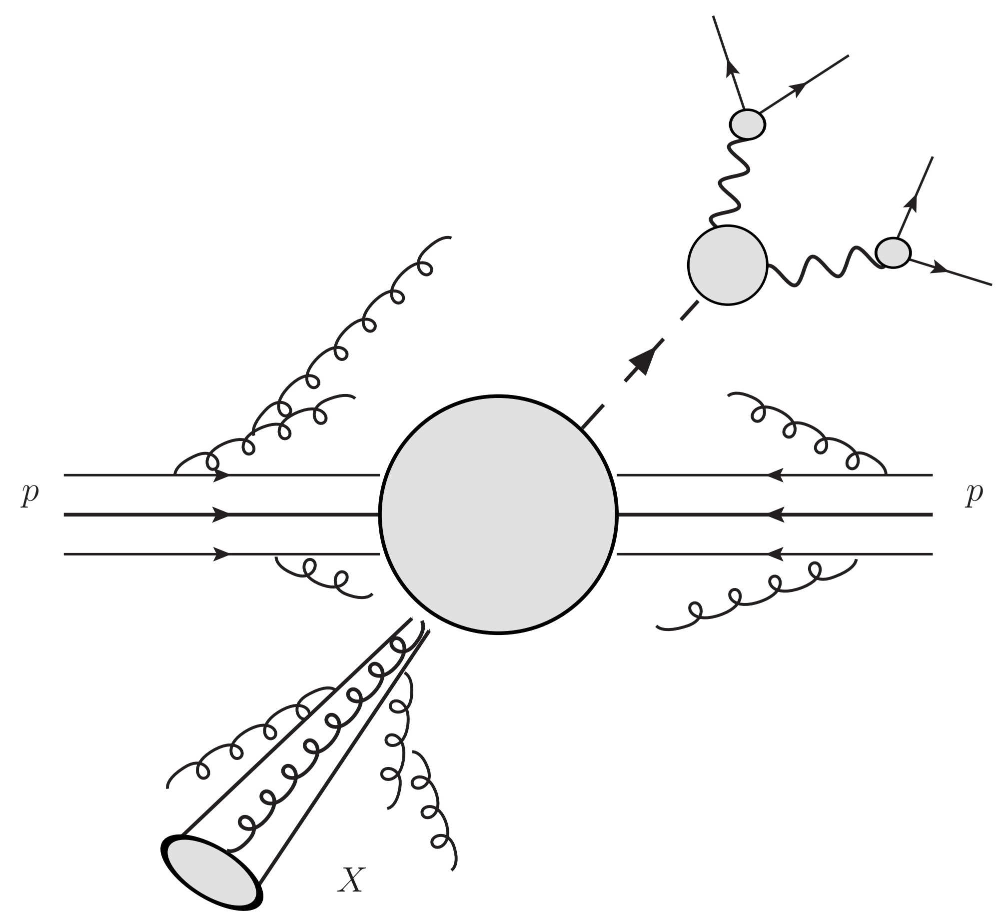
Factorisation of long and short range physics

Non perturbative corrections

$\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right) \sim$ few percent?



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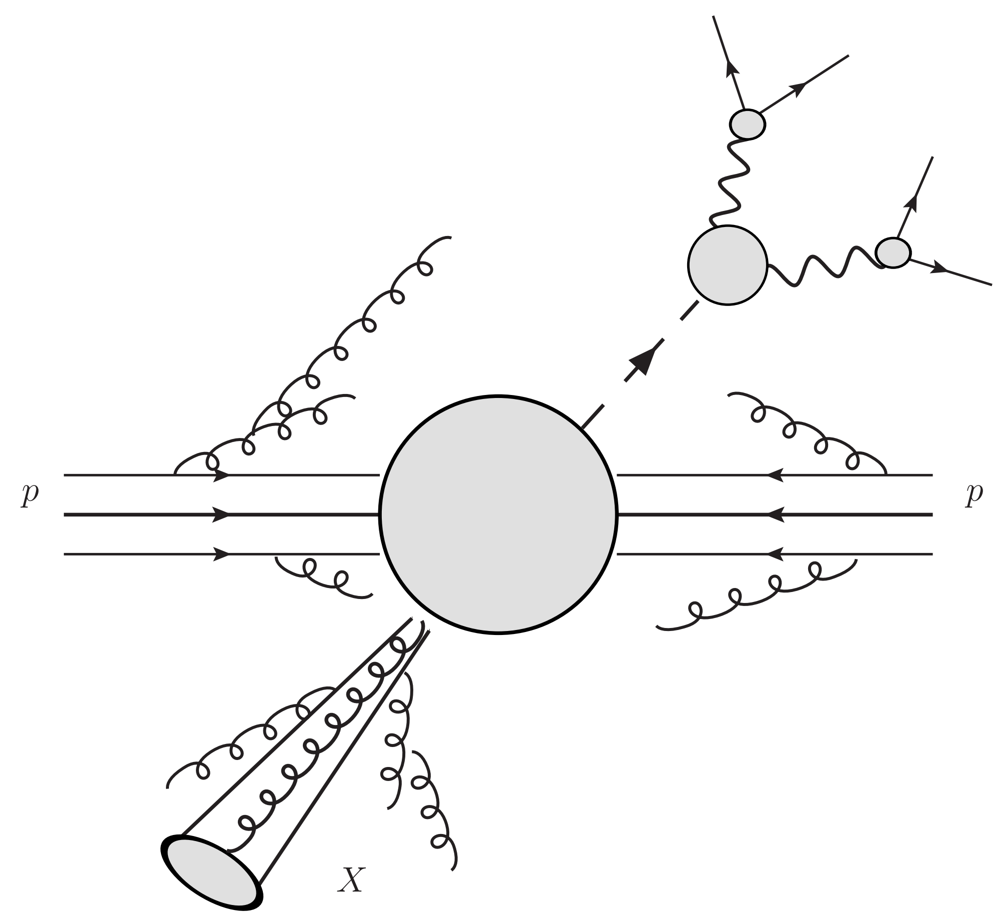

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PDFs Currently known at level $\sim$ few % for LHC

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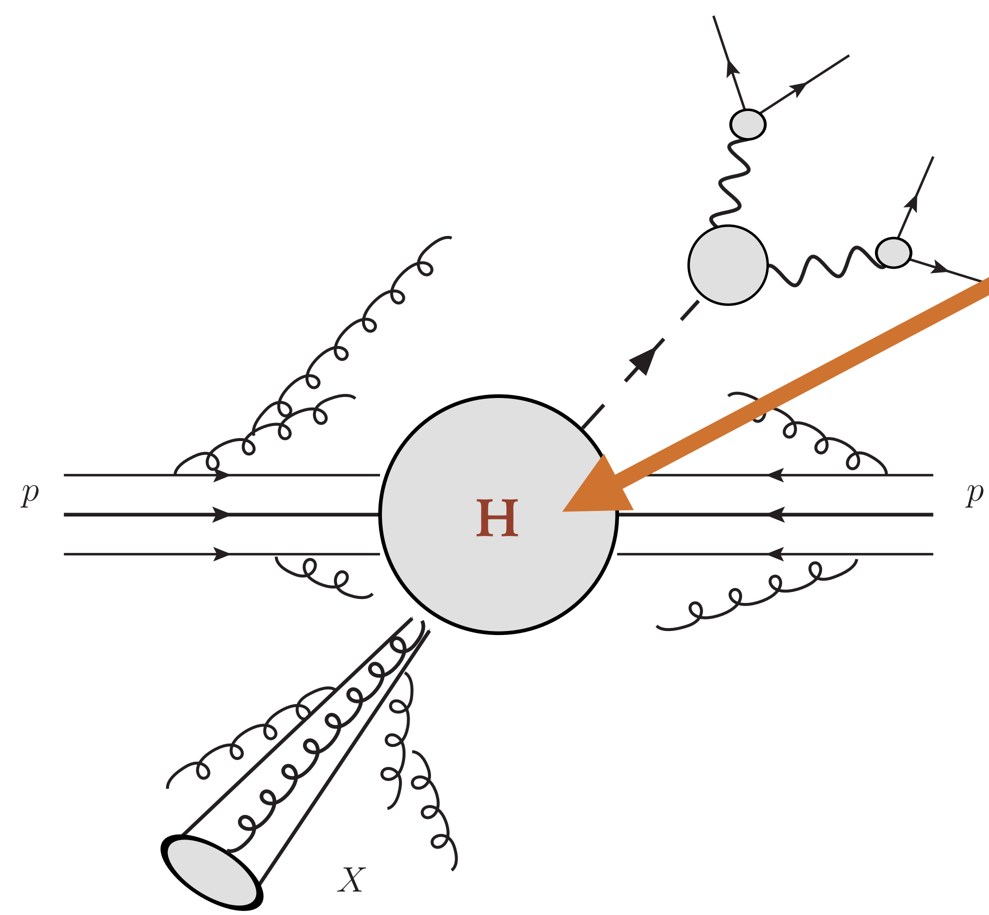

Hard scattering process

Aim to $\sim$ **few % precision**

Precise determination of **parton content of proton**

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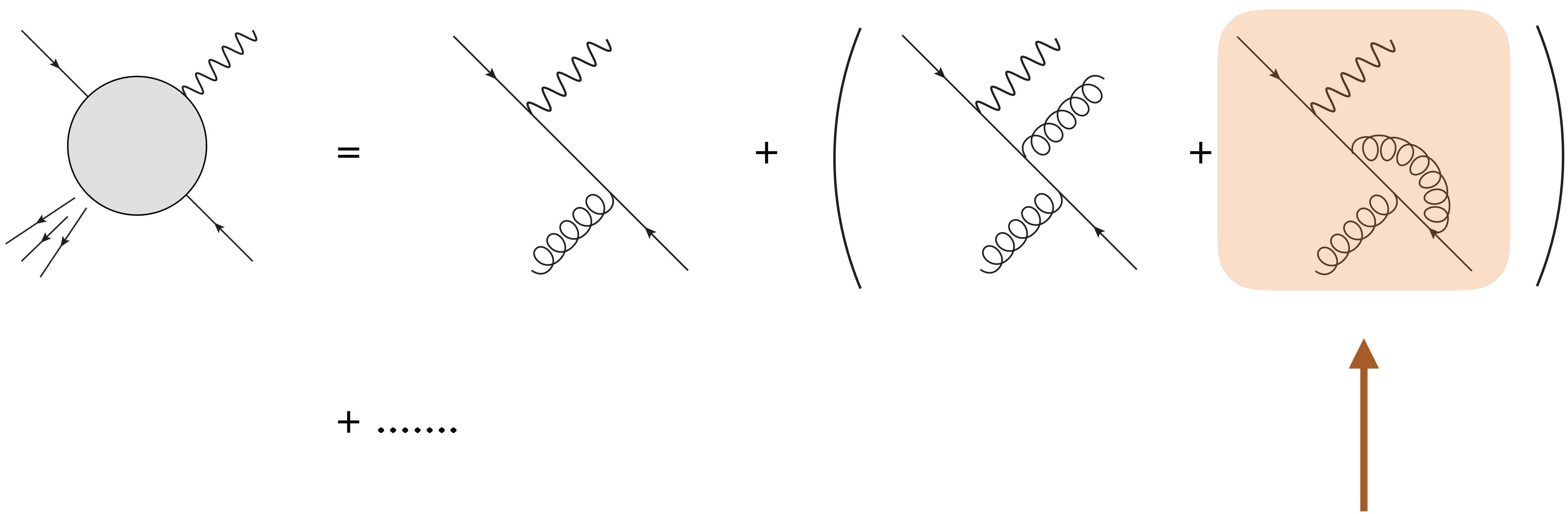
INTRODUCTION

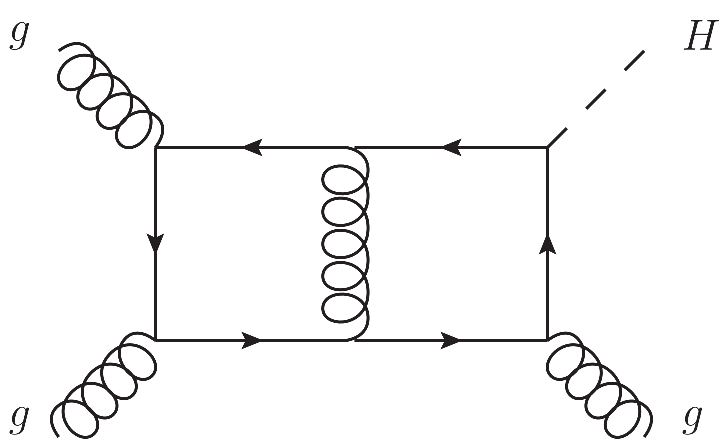
Scattering amplitudes are computed in Quantum Field Theory as a perturbative expansion. **Pictorial representation** in **Feynman Diagrams:**

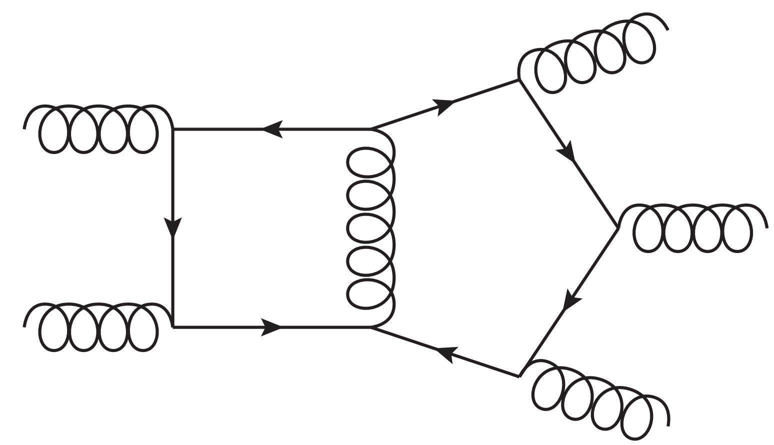


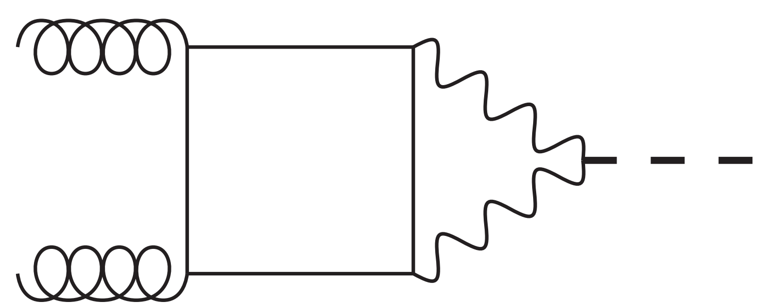
Each of these “diagrams” represents a complicated set of **integrals** that must be computed

INTRODUCTION

% precision physics in the **hard scattering** typically means computing **two-loop Feynman integrals**!







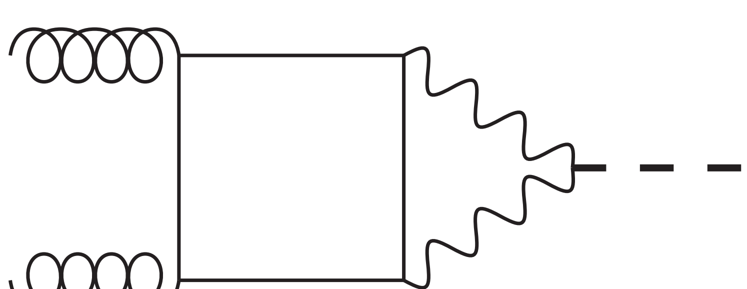
In the last 15 years we have witnessed impressive advancements in our ability of computing these integrals

INTRODUCTION

Rule of thumb: **Masses** and **scales** ***REMAIN difficult***.

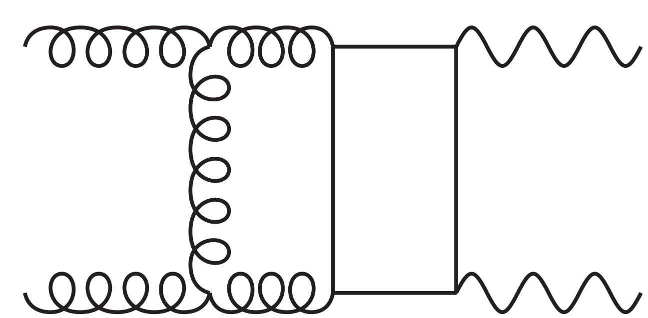
@ 2 loops, we have good understanding of:

$2 \to 1$



Different internal and external particles

$2 \to 2$



Mainly ***massless internal particles***. Up to ***2 massive external particles (HH, WZ,…)***

HOW DID WE GET THERE

- Development of the **differential equation method** [Kotikov '90; Remiddi '97; Gehrmann Remiddi '00]
- Definition of the **Harmonic Polylogarithms (HPLs)** and discovery of their *large applicability in high energy physics* [Remiddi, Vermaseren '99]
- Generalization to **Multiple Polylogarithms (MPLs)**, well known to the mathematicians [Kummer 1840; Lappo-Danilevsky 1954; Gehrmann, Remiddi '01]
- Development of routines for their **numerical evaluation** [Vollinga, Weinzierl '04]
- Study of their **analytical and algebraic properties** (*Symbols and Co-action* for MPLs and Feynman integrals) [Goncharov '01,…, Duhr, Gangl, Rhodes '13,…]
- Finally, discovery of **Canonical Bases**. Close the circle with the differential equations method. FIs that fulfil DEs in canonical basis can be straightforwardly solved in terms of MPLs… ***well not quite, but often…*** [Henn '13]

WHAT WE CAN DO

LHC phenomenology had a lot to gain from these developments…

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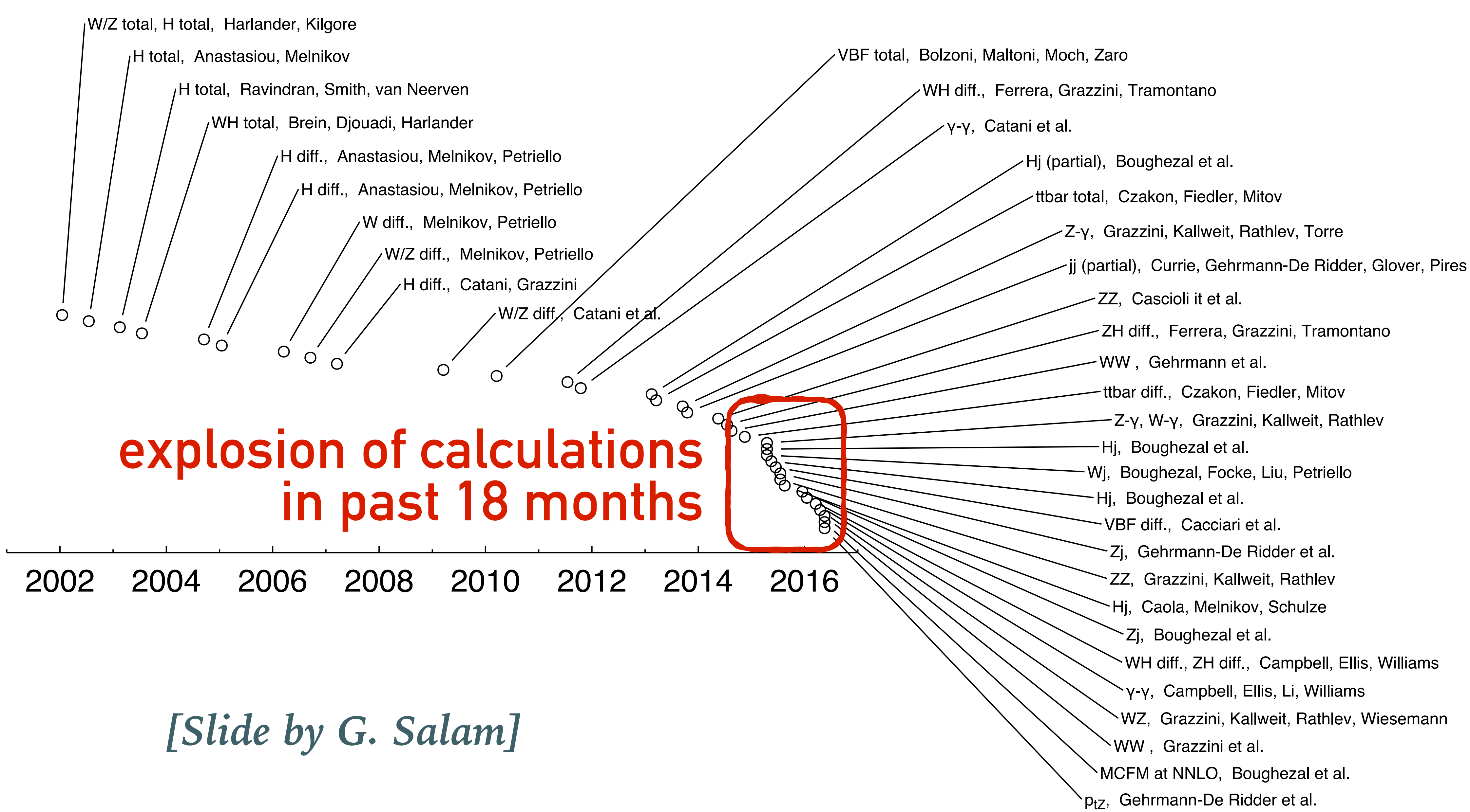
NNLO calculations: the status around the beginning of 2017

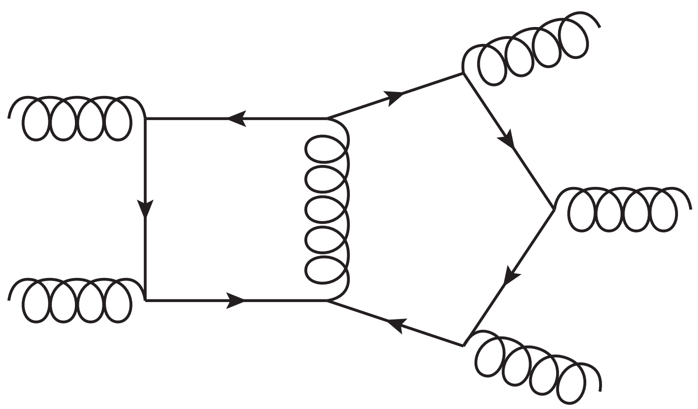


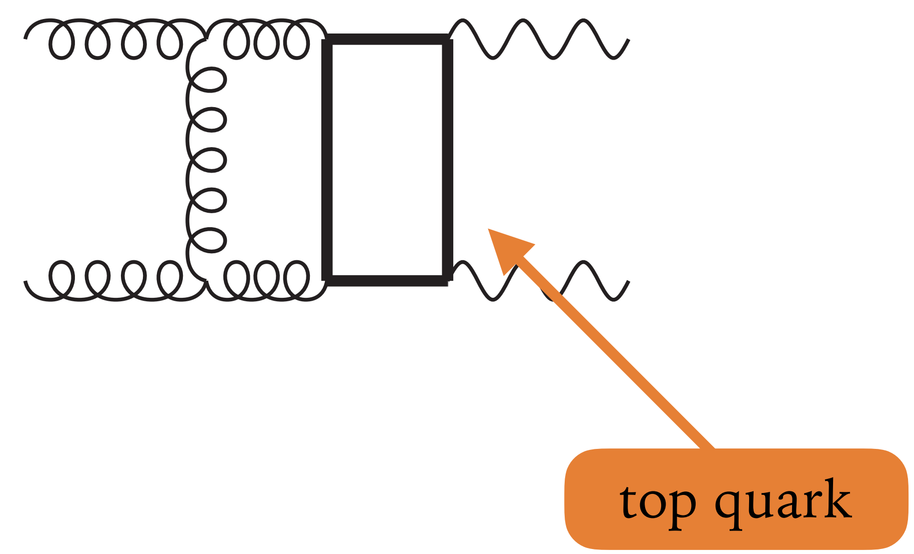
[Slide by G. Salam]

WHAT WE CANNOT DO (YET…)

There is a lot that we can (could?) do, but we are not quite there yet…

Properly modelling LHC processes with high precision requires ***more external particles*** and ***massive internal states***





What are we fighting against?

Algebraic complexity

Analytical complexity

New mathematical insight needed to tame these processes!

TOWARDS MULTIPLE POLYLOGARITHMS

Most of what we can do is expressible as so-called **Multiple Polylogarithms**

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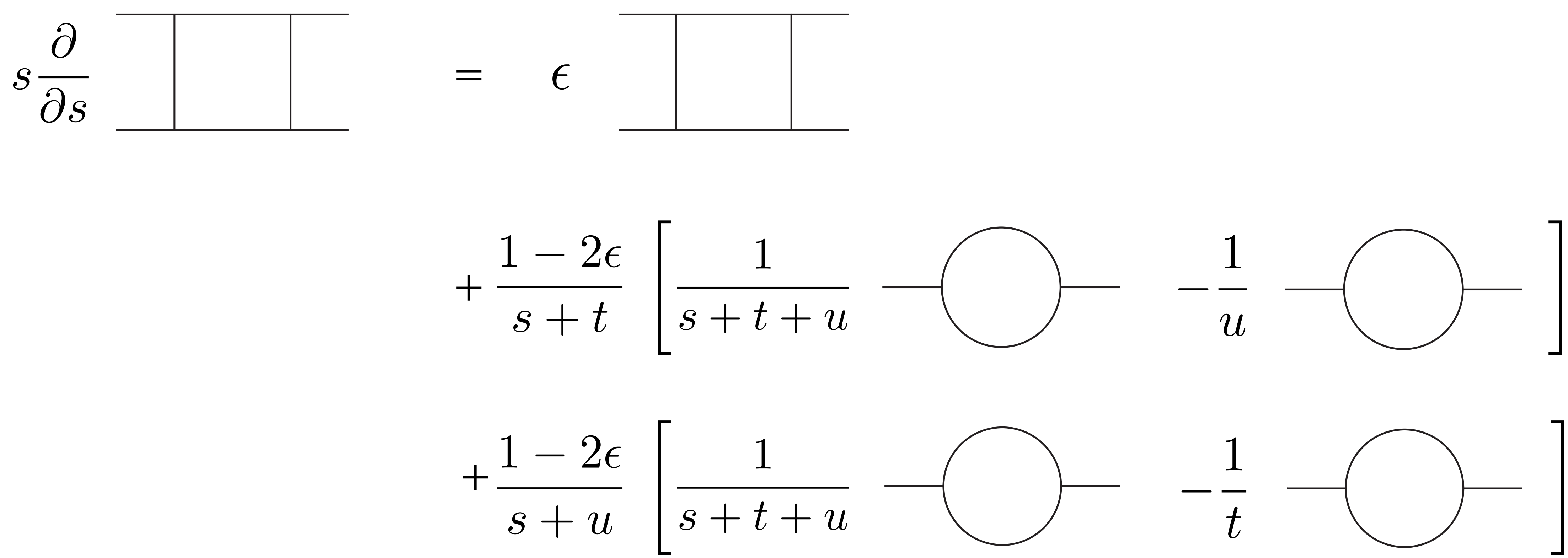
1) Feynman integrals fulfil **differential equations** with **rational coefficients**

[Kotikov, Remiddi, Gehrmann, ...]



Solution *(as Laurent series in epsilon)*, naturally expressed as **iterated integrals over rational functions**!

TOWARDS MULTIPLE POLYLOGARITHMS

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2) Feynman/Schwinger parameters

$$\mathcal{I} = \int \prod_i (dx_i \, x_i^{a_i - 1}) \frac{\mathcal{U}^{a-(N+1)D/2}}{\mathcal{F}^{a-ND/2}} \delta\left(1 - \sum_i x_i\right)$$

U and F are polynomials -> **U/F is a rational function in the xs**

By Laurent-expanding in epsilon, if I am lucky enough, I could get again **iterated integrals over rational functions at every step of the integration**

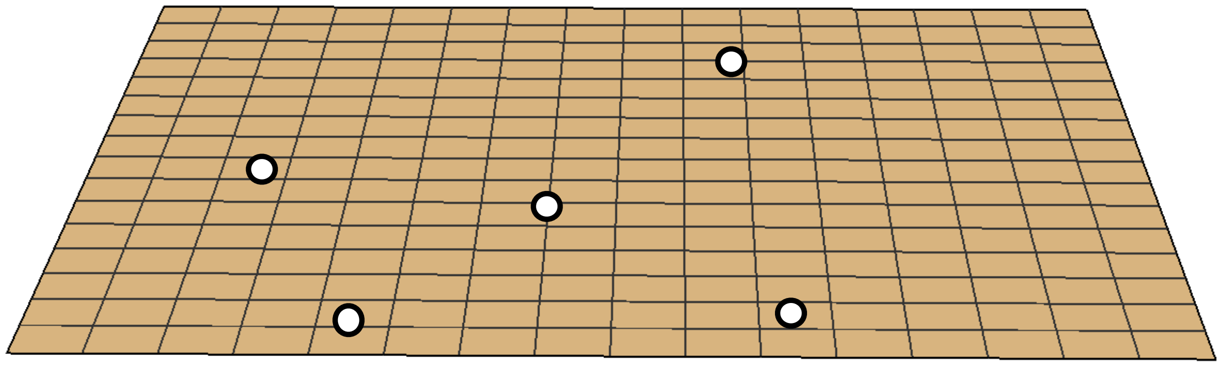
[Linear Reducibility, F. Brown]

A GEOMETRICAL POINT OF VIEW

Dealing with complex functions, the natural concept: **Riemann surface**

$$R(z) = \frac{P(z)}{Q(z)}$$

$$\begin{cases} P(z) & = a_n z^n + \ldots + 1 \\ Q(z) & = b_m z^m + \ldots + 1 \end{cases}$$



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But it has **poles**

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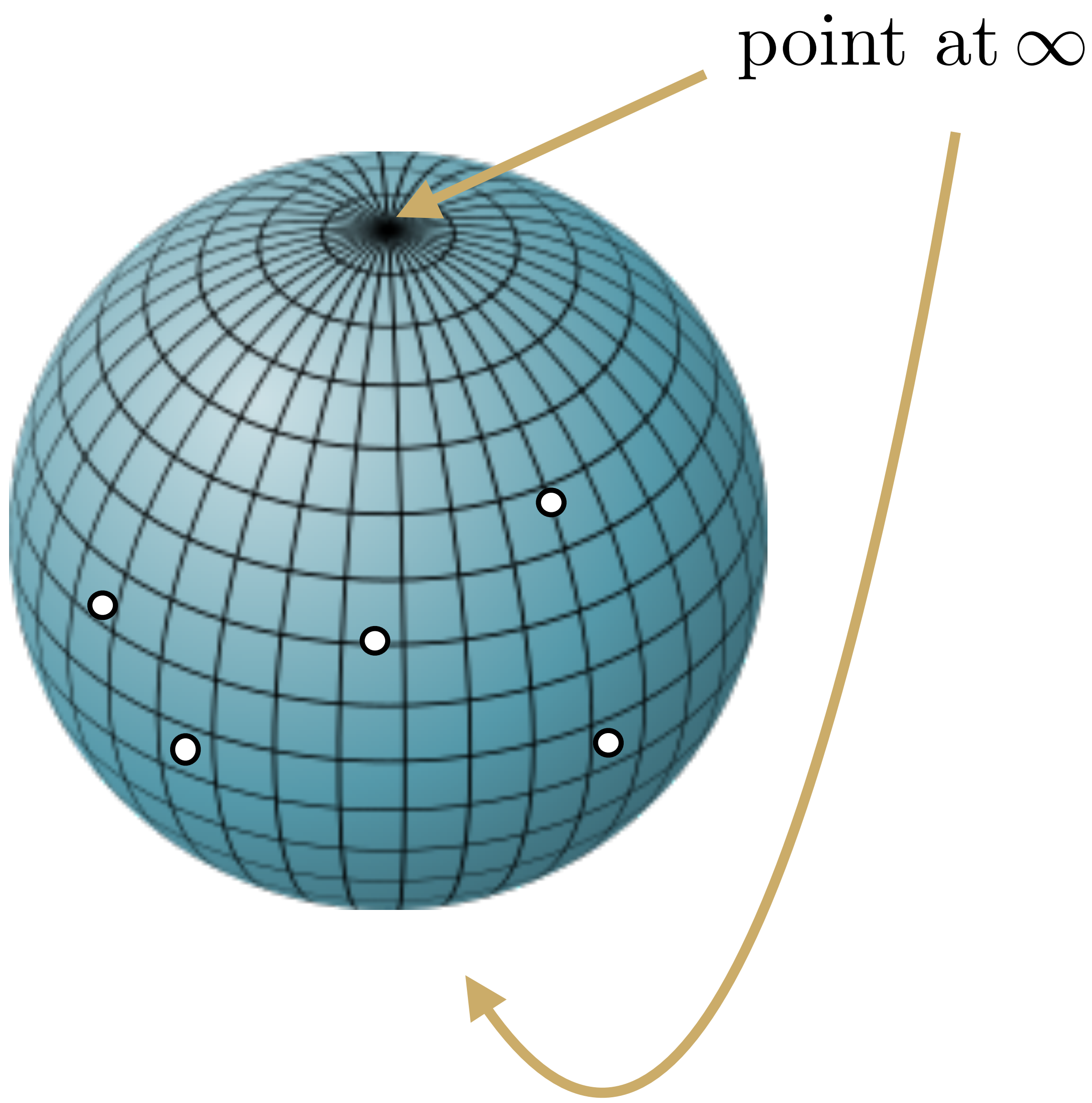

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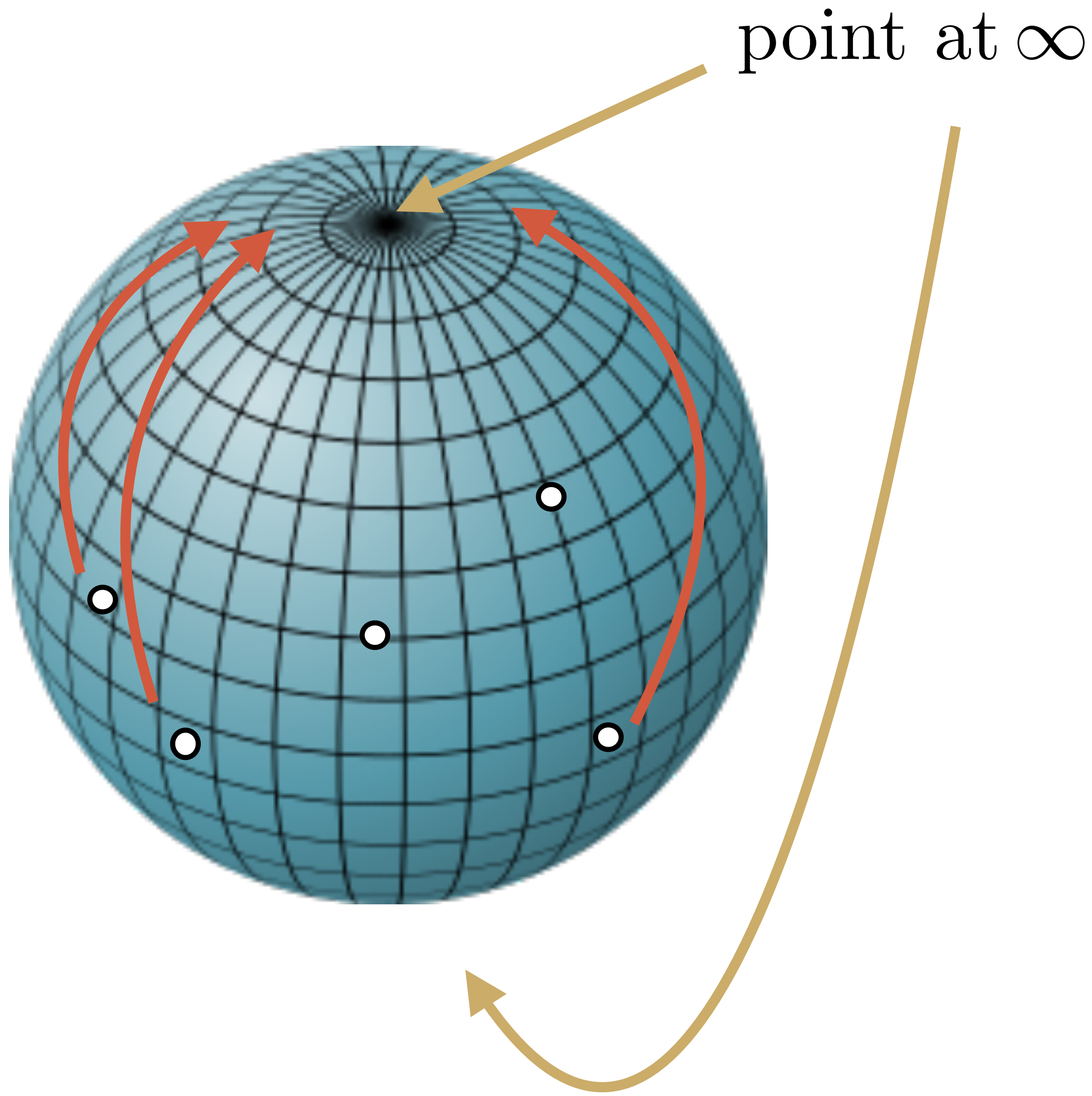

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RESULTS ON MPLS

Given any rational function R(x), by **factorizing poles** and **partial fractioning** I get

$$\int dx\, R(x) = \int dx\, \frac{p(x)}{q(x)} \sim \left\{ \int dx\, x^n \quad , \quad \int \frac{dx}{(x-c)^k} \right\}$$

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simple pole

$$\oint_{\gamma_c} \frac{dx}{x-c} = 2\pi i \quad \rightarrow$$

Residue non zero => **multivalued function**

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$$\int^{x} \frac{dx_1}{(x_1-c_1)^{k_1}} \int^{x_1} \frac{dx_2}{(x_2-c_2)^{k_2}} \cdots \int^{x_{n-1}} \frac{dx_n}{(x_n-c_n)^{k_n}} \rightarrow \begin{cases} \textit{Rational functions} \\ + \\ \textit{MPLs (generalized logs...)} \end{cases}$$

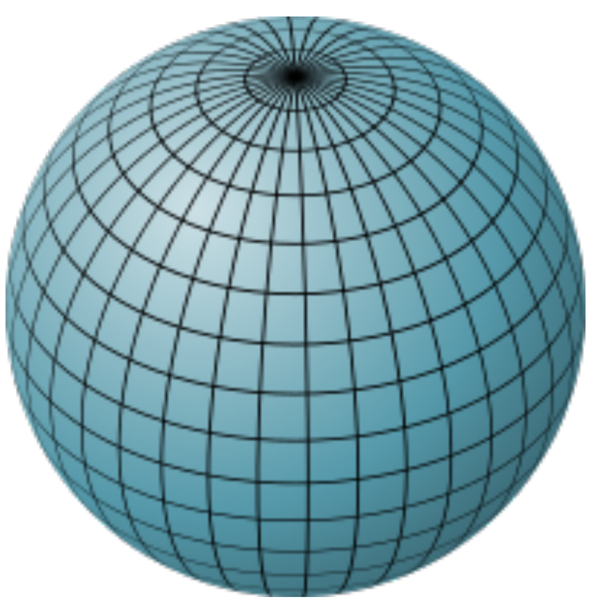
MPLS: INTEGRATING ON THE RIEMANN SPHERE

$$G(c_1, c_2, ..., c_n, x) = \int_0^x \frac{dt_1}{t_1 - c_1} G(c_2, ..., c_n, t_1)$$

$$= \int_0^x \frac{dt_1}{t_1 - c_1} \int_0^{t_1} \frac{dt_2}{t_2 - c_2} \cdots \int_0^{t_{n-1}} \frac{dt_n}{t_n - c_n}$$

We integrate **rational functions**

The singularities are generically **complex numbers**!

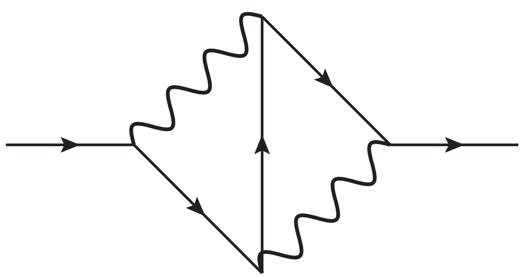


BEYOND GENUS ZERO

THE ELLIPTIC WORLD: THE SUNRISE AND HIS FRIENDS

At **two loops**, MPLs with their beautiful properties are not enough.

Electron self-energy in QED @ 2 loops *(computation attempted in 1961 by A. Sabry!)*



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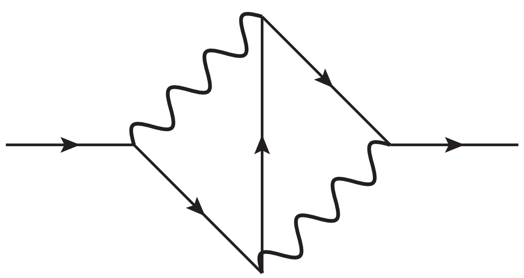
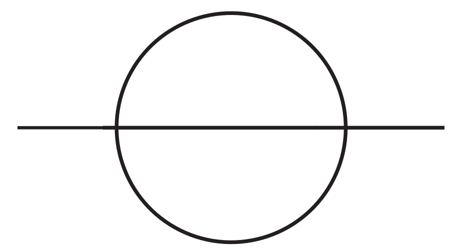
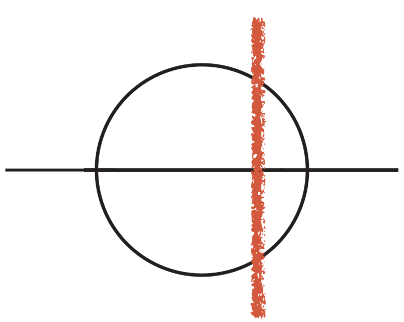




The sunrise integral



$$= \frac{1}{\sqrt{(3m-\sqrt{s})(\sqrt{s}+m)^3}}\,\mathrm{K}\left(\frac{16m^3\sqrt{s}}{(3m-\sqrt{s})(\sqrt{s}+m)^3}\right)$$

Elliptic Integral of the first kind:

$$\mathrm{K}(x) = \int_0^1 \frac{dz}{\sqrt{(1-z^2)(1-x\,z^2)}}$$

A NEW GEOMETRY

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These integrals "live" in a new geometry:

Consider the function

$$y(z) = \sqrt{(1-z^2)(k^2-z^2)} \quad \text{with} \quad k^2 = \frac{1}{x} > 1$$

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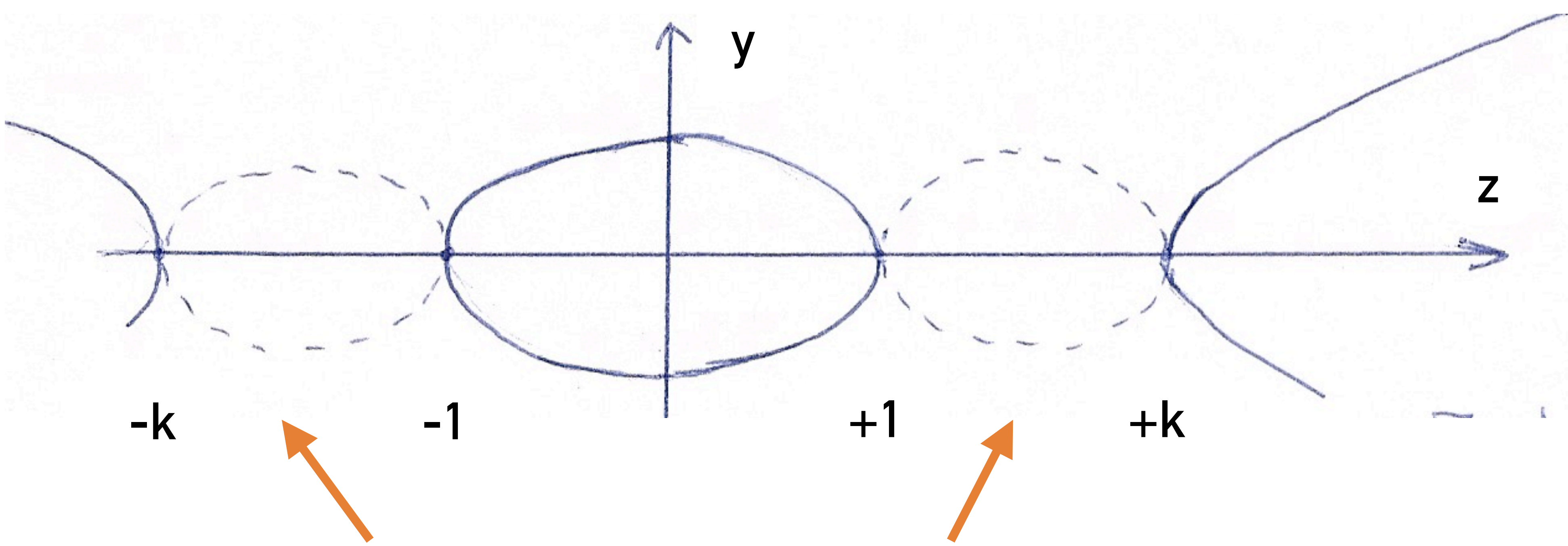
This algebraic equation defines geometrically ***an elliptic curve***



here y becomes imaginary

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In contrast with rational functions, this defines (on the complex plane) a multi-valued function due to the ***branches of the square-root***

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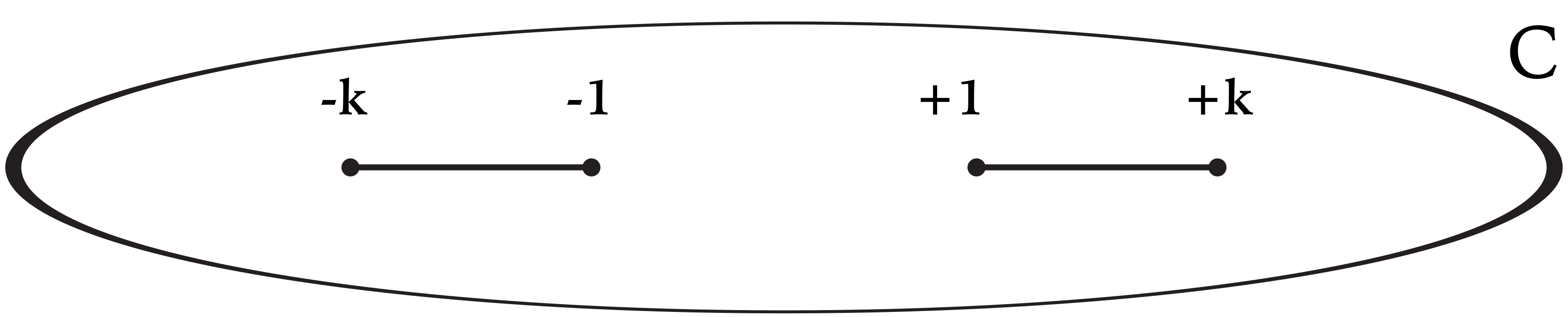
In contrast with rational functions, this defines (on the complex plane) a multi-valued function due to the ***branches of the square-root***

The usual trick is: restrict the function to be valid on its own graph -> **“Riemann Surface”**

$$T = \left\{(z,y) \in \mathbb{C}^2 \,|\, y^2 = (1-z^2)(z^2-k^2)\right\}$$

The 4 points **z={-1,+1,-k,+k},** are branching points for y(z) (the argument changes sign). In order to get a continuous branch, we need to cut the complex plane!



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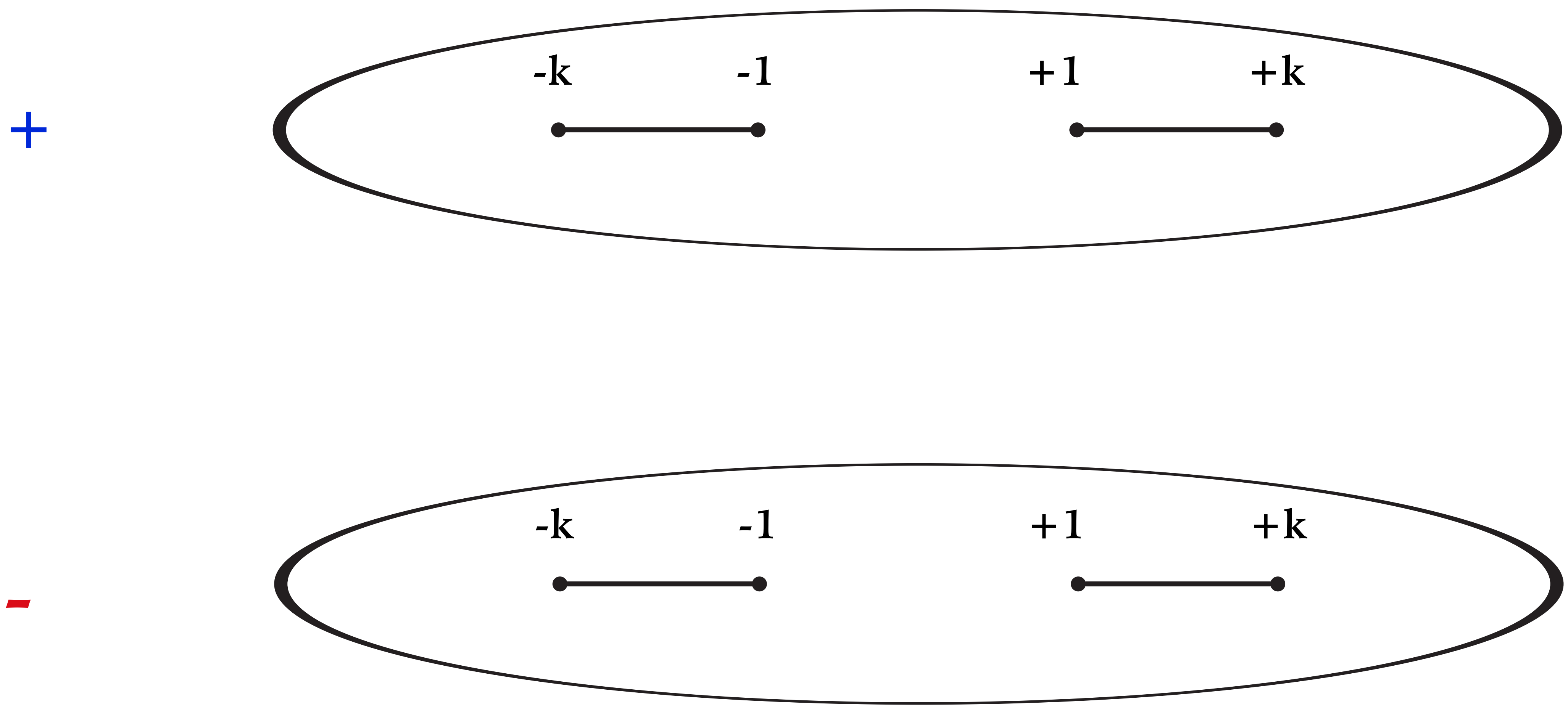
But one copy of the complex plane is not enough. **For every z,** except the branching points, **there are two choices for y** (two signs of the square root!).

Plus ***two signs on each side of the branches!***



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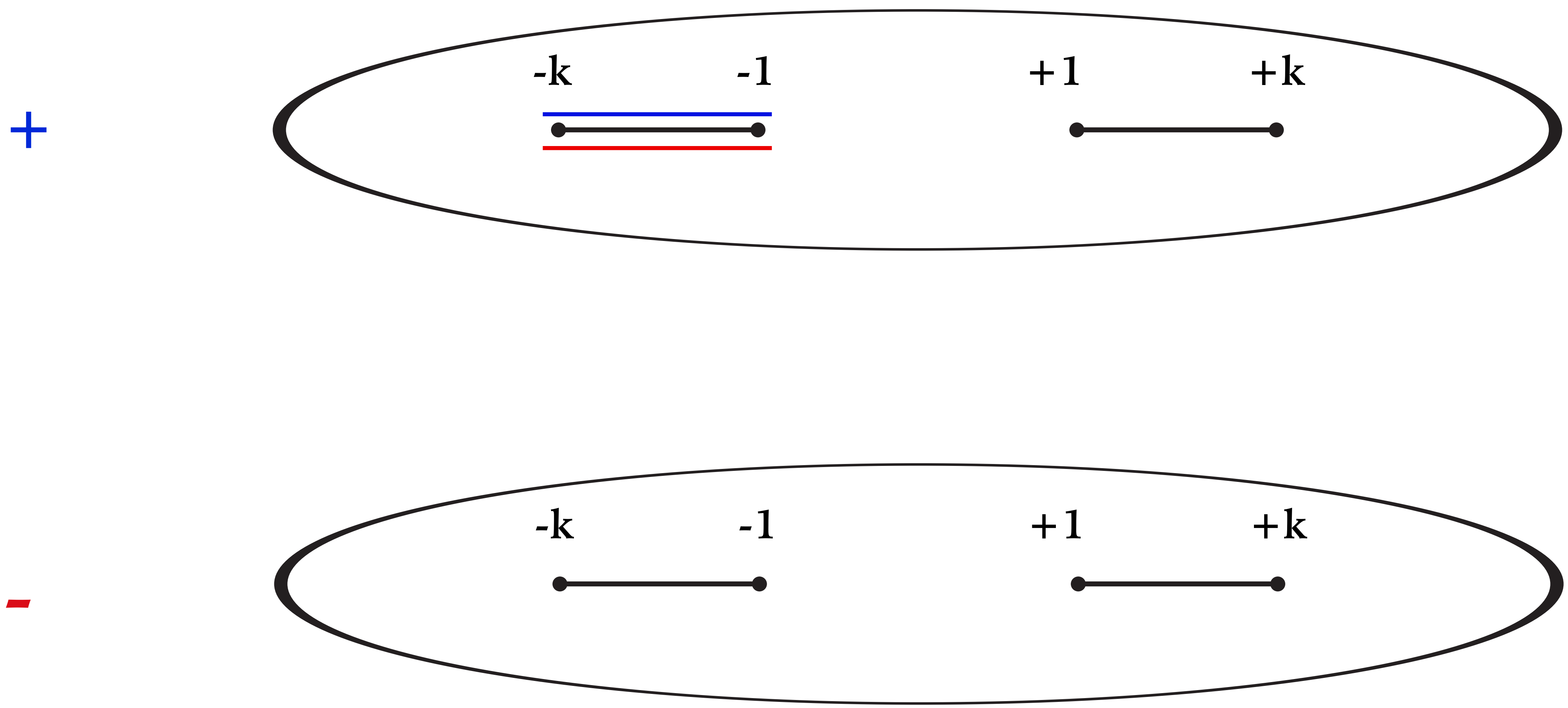

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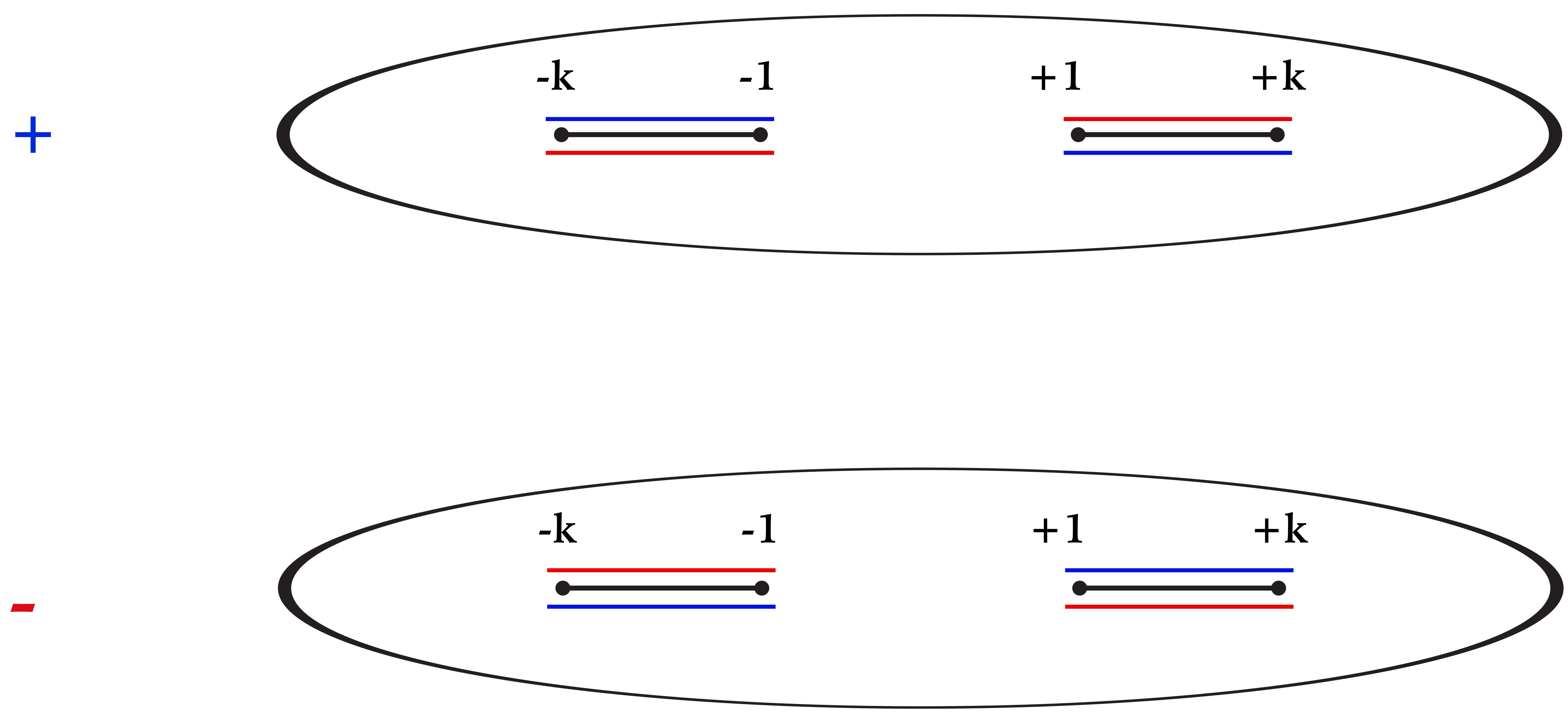

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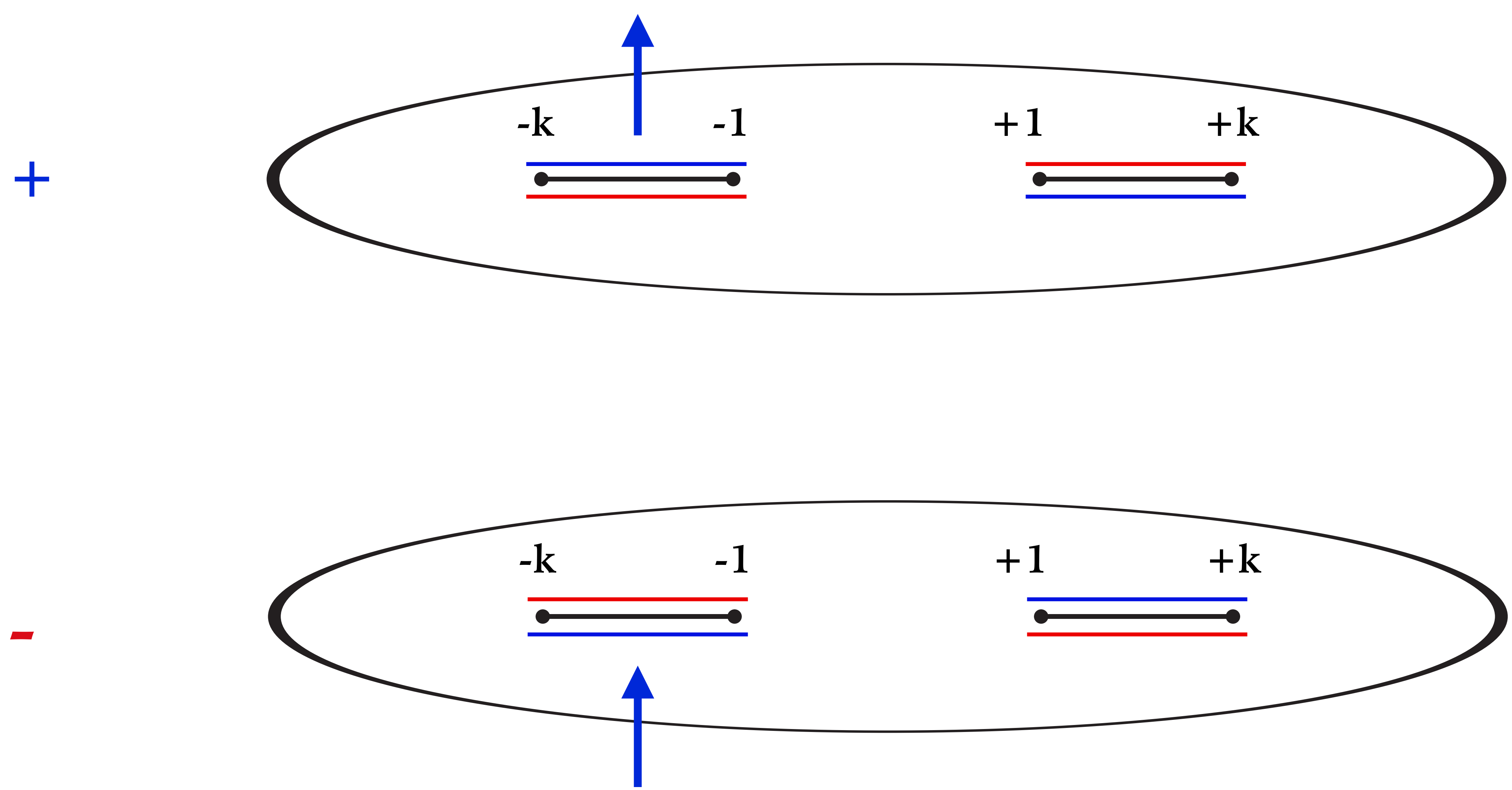

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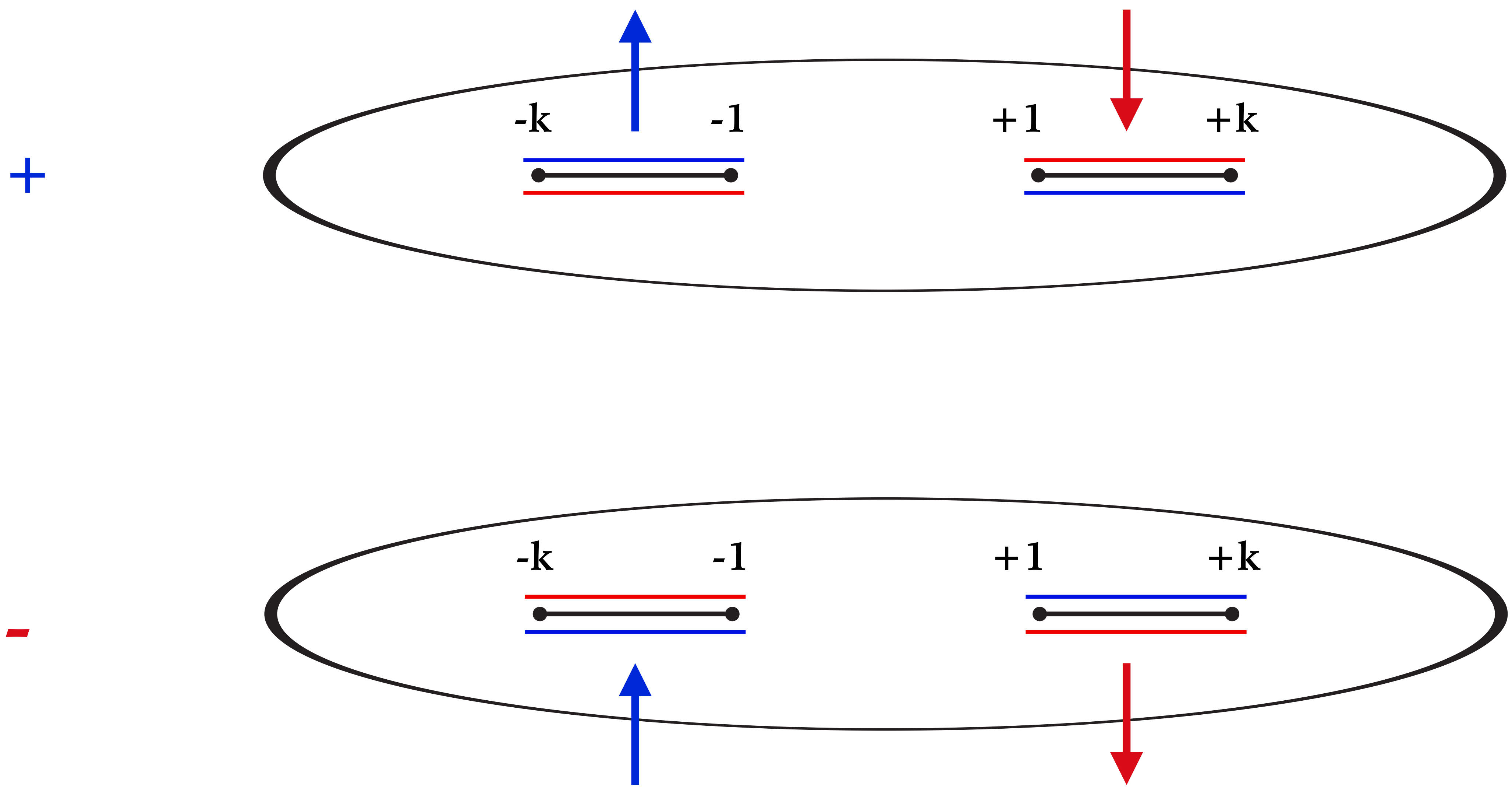

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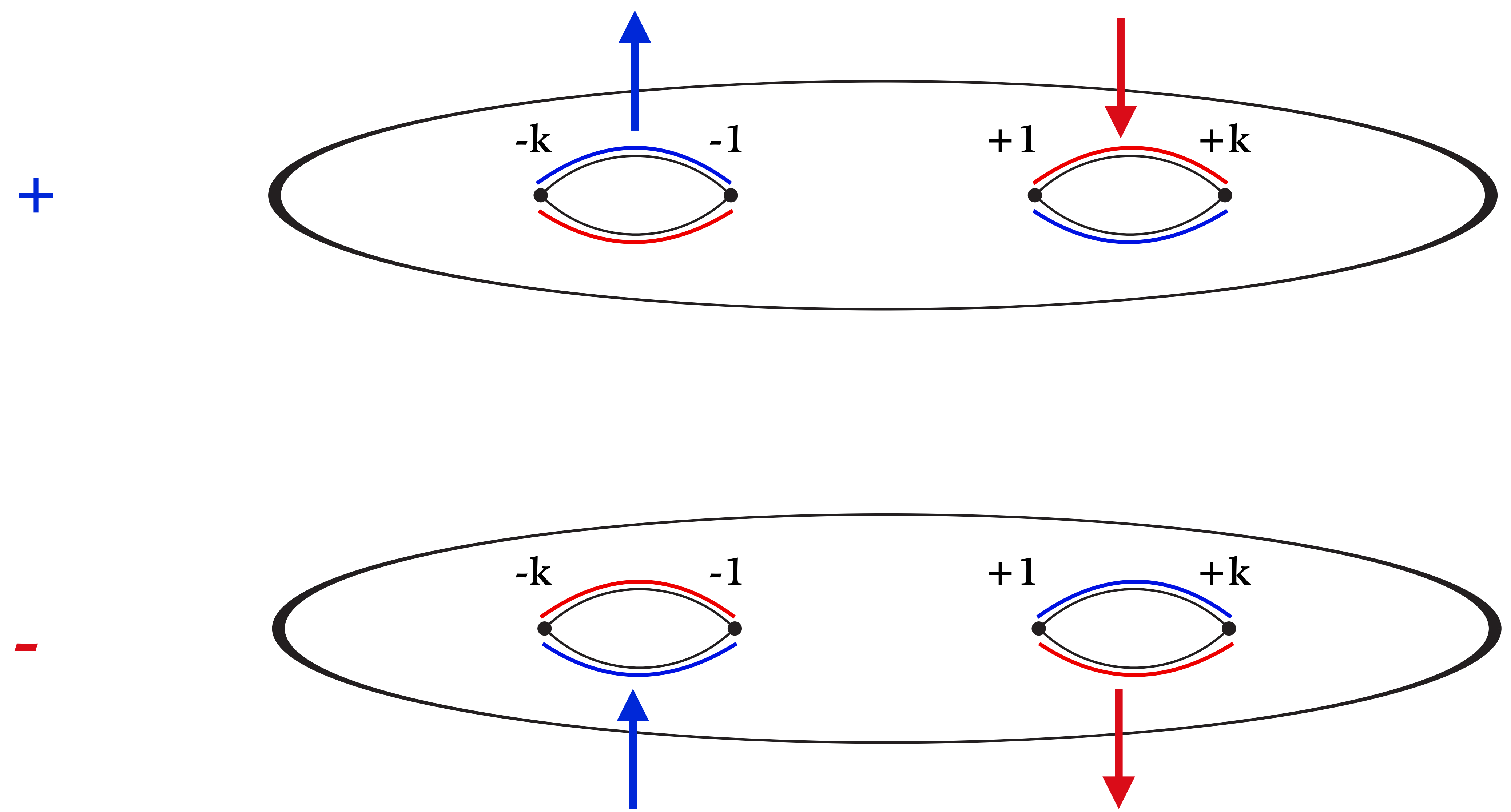
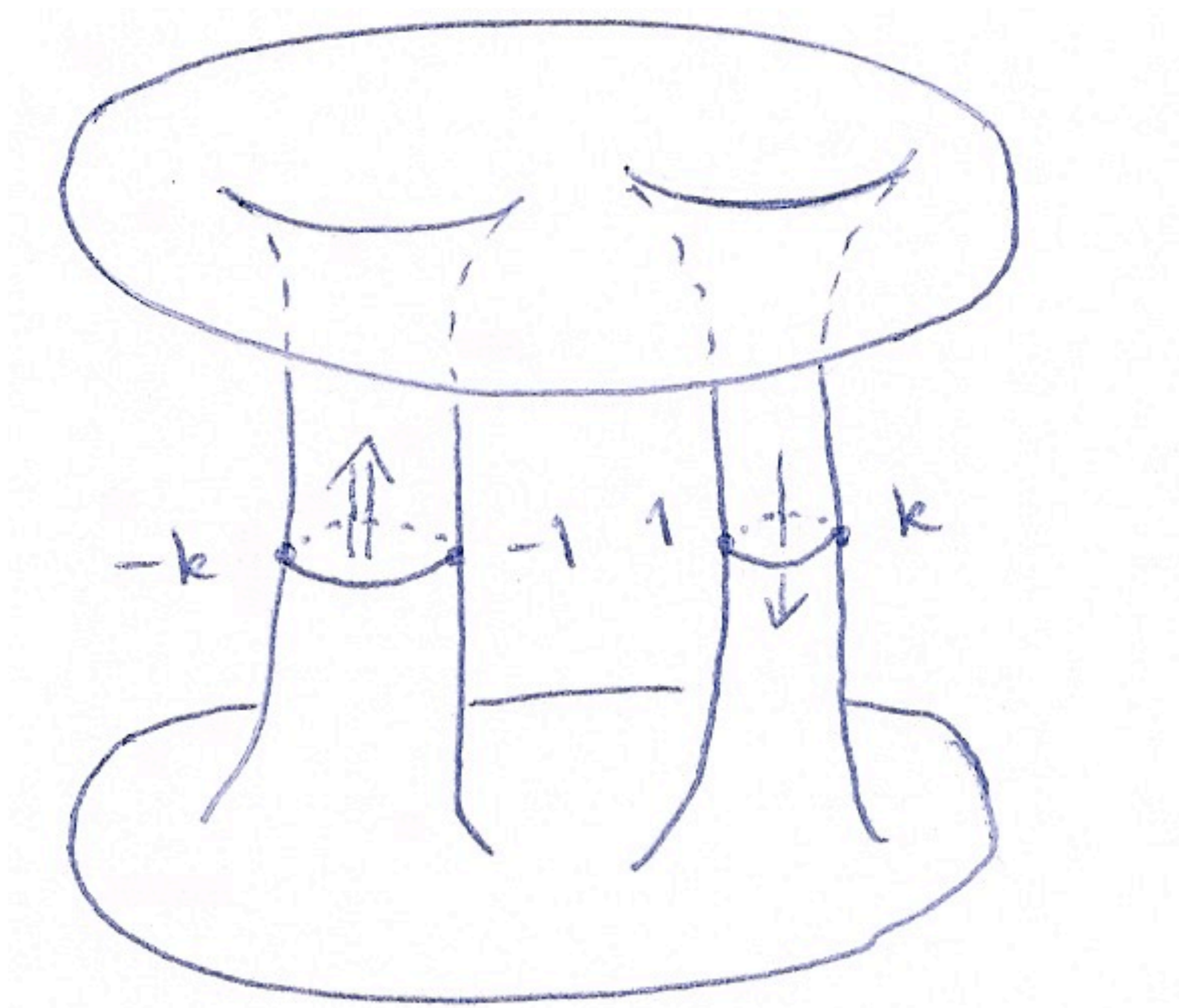


A NEW GEOMETRY

To obtain a ***continuous determination of y***, I need to glue together the two planes.

Flip one plane along x axis, and ***glue + with +, and - with -***



[Drawings by C. Teleman, Riemann Surfaces]

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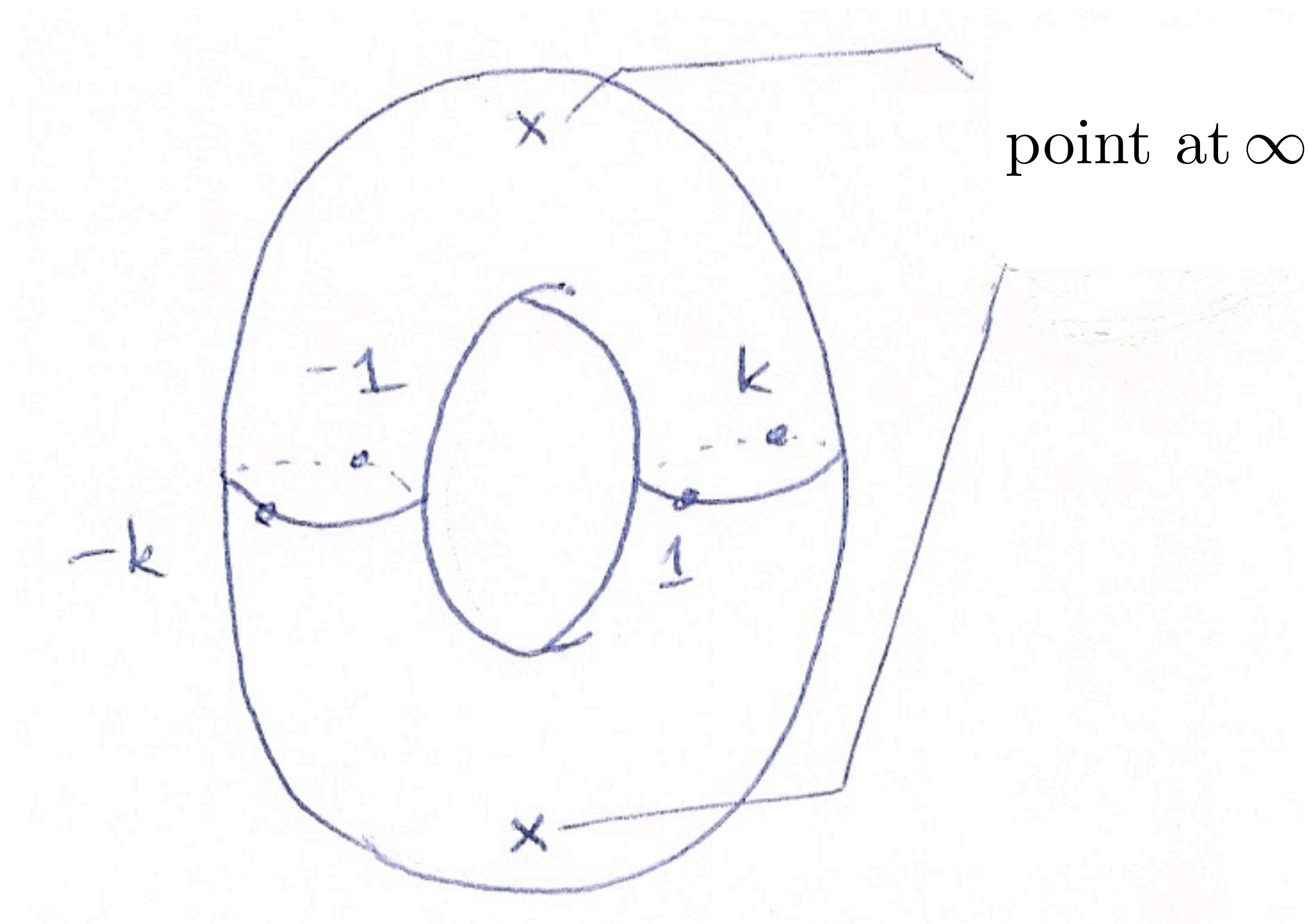

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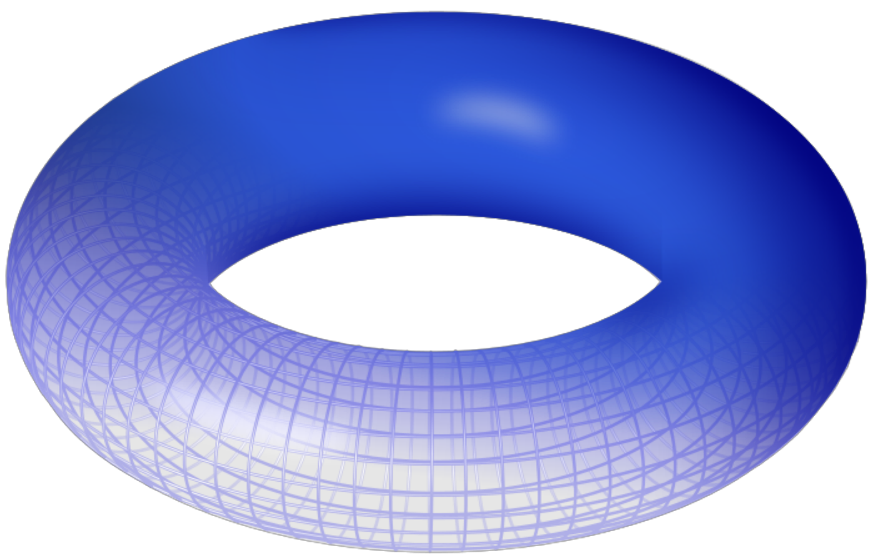
In conclusion, the **Riemann surface** associated to the algebraic equation that defines an **elliptic curve** is a **complex Torus!**



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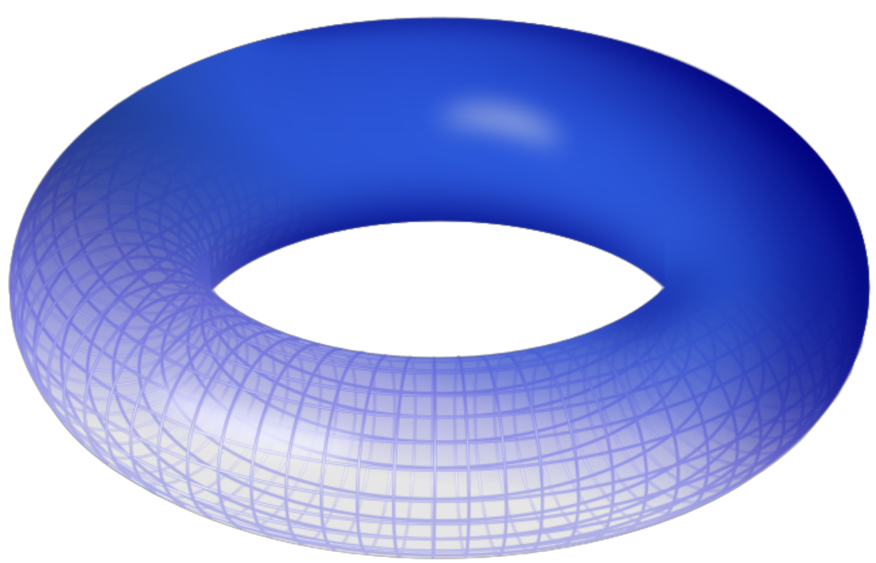

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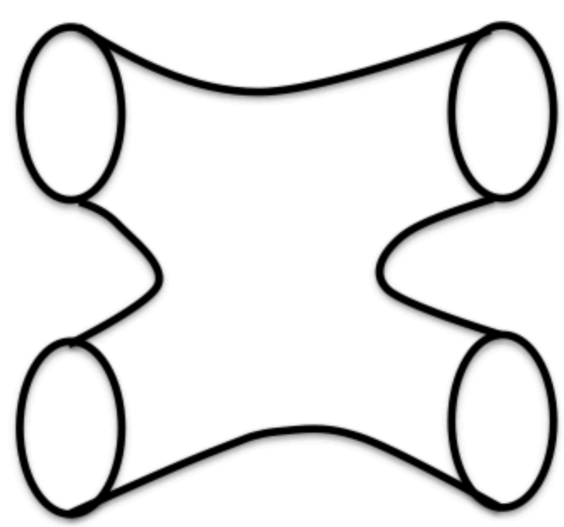
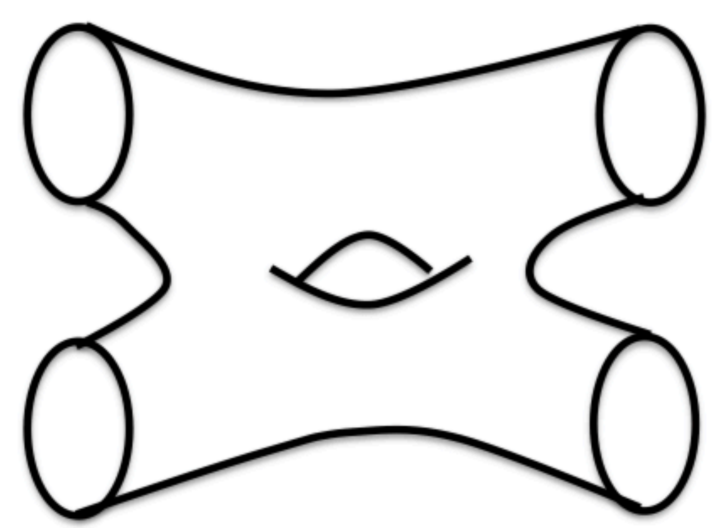
Easy to see why the same structures appear in one-loop string theory amplitudes!





ELLIPTIC MULTIPLE POLYLOGARITHMS

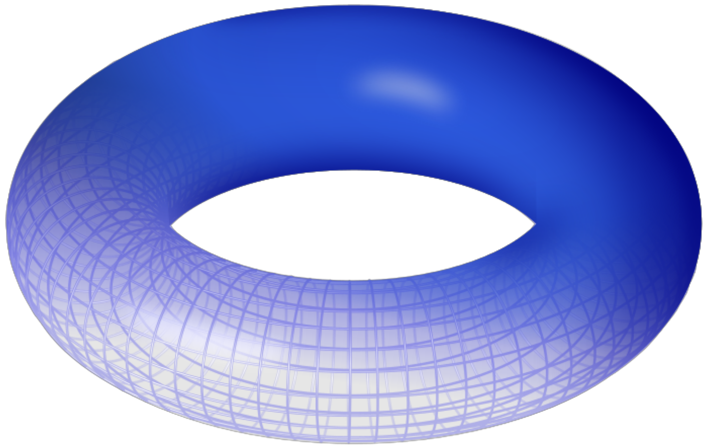
Some definitions. Take a completely general elliptic curve:

$$y^2 = (x-a_1)(x-a_2)(x-a_3)(x-a_4)$$

We define the two periods as

$$\omega_1 = 2c_4 \int_{a_2}^{a_3} \frac{dx}{y} = 2\,\mathrm{K}(\lambda)\,, \quad \omega_2 = 2c_4 \int_{a_1}^{a_2} \frac{dx}{y} = 2\,i\,\mathrm{K}(1-\lambda)\,,$$

$$\lambda = \frac{(a_1-a_4)(a_2-a_3)}{(a_1-a_3)(a_2-a_4)}\,, \quad c_4 = \frac{1}{2}\sqrt{(a_1-a_3)(a_2-a_4)}$$



ELLIPTIC MULTIPLE POLYLOGARITHMS

Some definitions. Take a completely general elliptic curve:

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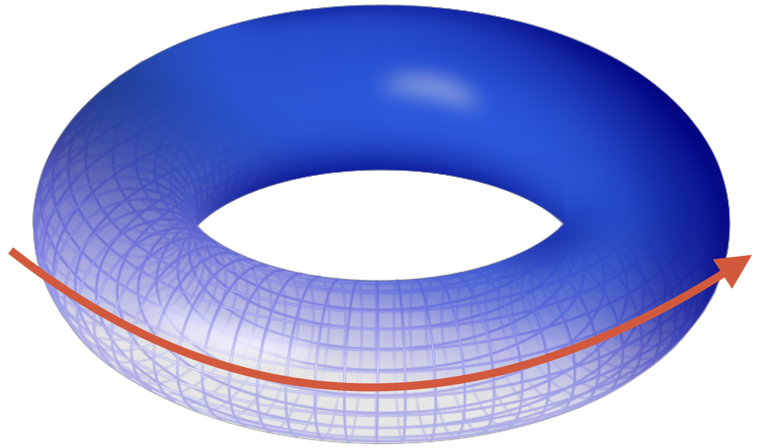

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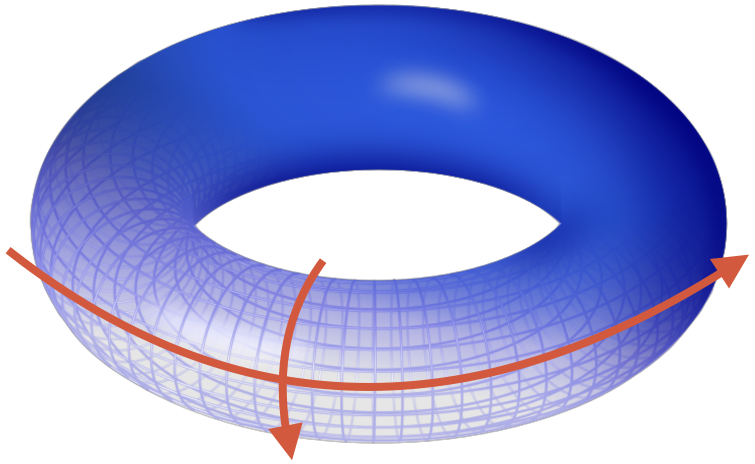
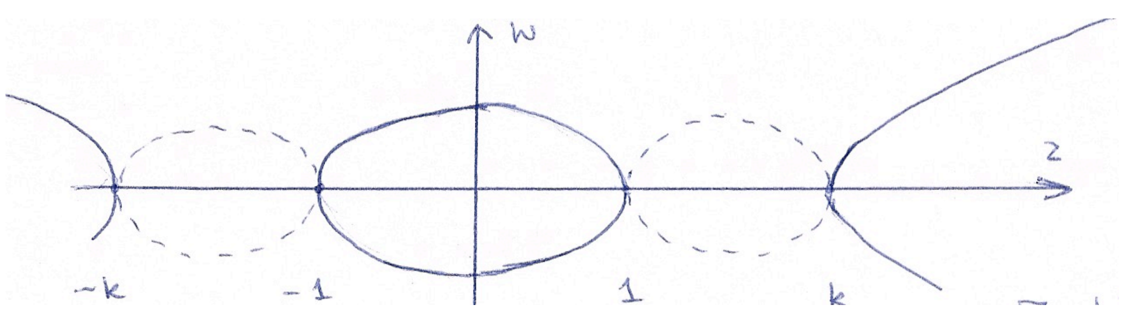


ELLIPTIC MULTIPLE POLYLOGARITHMS

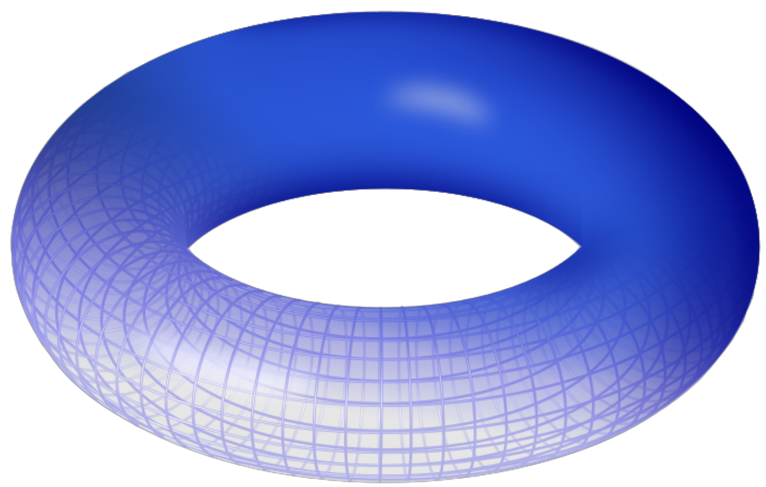
Dual description of the same problem

Elliptic curve as algebraic equation

$$y^2 = (x - a_1)(x - a_2)(x - a_3)(x - a_4)$$



Genus one complex surface - Torus



Move between the two using ***Abel's Map***

$$z_x = \frac{c_4}{\omega_1} \int_{a_1}^{x} \frac{dt}{y(t)}$$

ELLIPTIC MULTIPLE POLYLOGARITHMS

Iterated integrals on the Torus have been defined and studied by mathematicians

[Brown, Levin '11]

The elliptic curve representation is easier to relate directly to **Feynman diagrams!**
So can we construct **elliptic polylogarithms** on the elliptic curve?

What are **rational functions** on the elliptic curve?

ELLIPTIC MULTIPLE POLYLOGARITHMS

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[Brown, Levin ’11]

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So can we construct **elliptic polylogarithms** on the elliptic curve?

What are **rational functions** on the elliptic curve?

$$R(x,y) \text{ subject to } \; y^2 = P(x) = (x-a_1)(x-a_2)(x-a_3)(x-a_4)$$

$$R(x,y) = \frac{p_1(x) + p_2(x)\, y}{q_1(x) + q_2(x)\, y} = \frac{p_1(x) + p_2(x)\, \sqrt{P(x)}}{q_1(x) + q_2(x)\, \sqrt{P(x)}} = R_1(x) + \frac{1}{\sqrt{P(x)}} R_2(x)$$

ELLIPTIC MULTIPLE POLYLOGARITHMS

So we need to study iterated integrals of this form

$$\int dx \left(R_1(x) + \frac{1}{\sqrt{P(x)}} R_2(x) \right) = \ ?$$

ELLIPTIC MULTIPLE POLYLOGARITHMS

So we need to study iterated integrals of this form

$$\int dx \left(R_1(x) + \frac{1}{\sqrt{P(x)}} R_2(x) \right) = \; ?$$

Integrals of the kind:

$$\int \frac{dx}{(x-c_i)^k} \qquad \text{from} \quad R_1(x)$$

$$\int \frac{dx}{y} x^k \,, \quad \int \frac{dx}{y(x-c_i)^k} \,, \qquad \text{from} \quad \frac{1}{y} R_2(x)$$

Integrations by part reduce everything to

$$\int \frac{dx}{x-c}\,, \quad \int \frac{dx}{y}\,, \quad \int \frac{x\,dx}{y}\,, \quad \int \frac{x^2\,dx}{y}\,, \quad \int \frac{dx}{y(x-c)}$$

ELLIPTIC MULTIPLE POLYLOGARITHMS

Still something is not optimal. MPLs defined as iterated integrals over kernels with simple poles —> logarithmic singularities in scattering amplitudes!

$$\int \frac{dx}{x-c}\,, \quad \int \frac{dx}{y}\,, \quad \int \frac{x\,dx}{y}\,, \quad \int \frac{x^2\,dx}{y}\,, \quad \int \frac{dx}{y(x-c)}$$

This guy here has a double pole at infinity!!

ELLIPTIC MULTIPLE POLYLOGARITHMS

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$$\int \frac{dx}{x-c}, \quad \int \frac{dx}{y}, \quad \int \frac{x\,dx}{y}, \quad \int \frac{x^2\,dx}{y}, \quad \int \frac{dx}{y(x-c)}$$

This guy here has a double pole at infinity!!

Only way to get a full set of kernels with simple poles is to introduce a transcendental kernel! **Choose its primitive.**

$$Z_4(x) \sim \int^x \frac{x^2\,dx}{y}$$

ELLIPTIC MULTIPLE POLYLOGARITHMS

Fundamental differences with MPLs:

1. Impossible to find a basis of kernels which are **algebraic** and only with **simple poles**
2. We seem to need an **infinite tower** of integration kernels to span the whole space

ELLIPTIC MULTIPLE POLYLOGARITHMS

$$G(c_1, ..., c_k; x) = \int_0^x dt\, r(c_1, t) G(c_2, ..., c_k; t)\,, \quad r(c, t) = \frac{1}{t - c} \quad c \in \mathbb{C}$$

ELLIPTIC MULTIPLE POLYLOGARITHMS

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$$\mathrm{E}_4\left(\begin{smallmatrix} n_1 & \cdots & n_k \\ c_1 & \cdots & c_k \end{smallmatrix}; x\right) = \int_0^x dt\, \psi_{n_1}(c_1, t)\, \mathrm{E}_4\left(\begin{smallmatrix} n_2 & \cdots & n_k \\ c_2 & \cdots & c_k \end{smallmatrix}; t\right)$$

$$\begin{aligned}
\psi_0(0,x) &= \frac{c_4}{y}\,, \\
\psi_1(c,x) &= \frac{1}{x-c}\,, \qquad \psi_{-1}(c,x) = \frac{y_c}{y(x-c)}\,, \\
\psi_1(\infty,x) &= \frac{c_4}{y}\, Z_4(x)\,, \qquad \psi_{-1}(\infty,x) = \frac{x}{y}\,, \\
\psi_{-n}(\infty,x) &= \frac{x}{y}\, Z_4^{(n-1)}(x) - \frac{\delta_{n2}}{c_4}\,, \\
\psi_n(c,x) &= \frac{1}{x-c}\, Z_4^{(n-1)}(x) - \delta_{n2}\, \Phi_4(x)\,, \\
\psi_n(\infty,x) &= \frac{c_4}{y}\, Z_4^{(n)}(x)\,, \qquad \psi_{-n}(c,x) = \frac{y_c}{y(x-c)}\, Z_4^{(n-1)}(x)\,,
\end{aligned}$$

ELLIPTIC MULTIPLE POLYLOGARITHMS

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$$\psi_{-n}(\infty,x) = \frac{x}{y} Z_4^{(n-1)}(x) - \frac{\delta_{n2}}{c_4}\,,$$

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$$\psi_n(\infty,x) = \frac{c_4}{y} Z_4^{(n)}(x)\,, \qquad \psi_{-n}(c,x) = \frac{y_c}{y(x-c)} Z_4^{(n-1)}(x)\,,$$

ELLIPTIC MULTIPLE POLYLOGARITHMS

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ARE THEY REALLY USEFUL?

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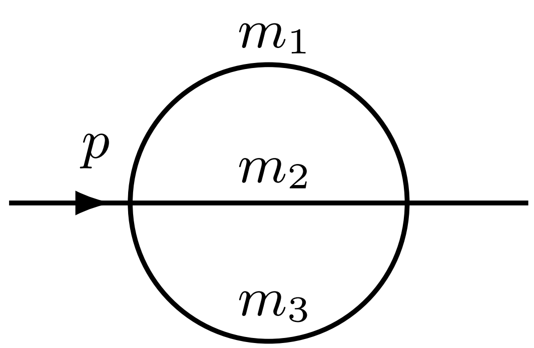
The Sunrise graph *(QED, massive QCD, every EW calculation…)*



$p^2 = -S$

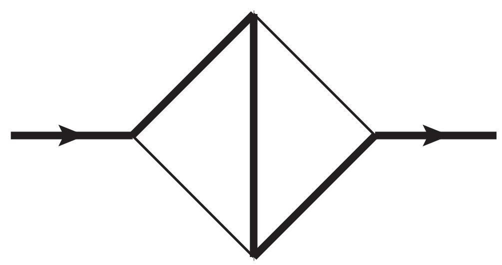
In the **equal-mass case**, particularly compact expression

$$S_{111}(S, m^2)\Big|_{\epsilon^0} = \frac{1}{(m^2+S)c_4}\left[\frac{1}{c_4}\,\mathrm{E}_4\!\left(\begin{smallmatrix}0 & 0\\ 0 & 0\end{smallmatrix};1\right) - 2\,\mathrm{E}_4\!\left(\begin{smallmatrix}0 & -1\\ 0 & \infty\end{smallmatrix};1\right) - \mathrm{E}_4\!\left(\begin{smallmatrix}0 & -1\\ 0 & 0\end{smallmatrix};1\right)\right.$$
$$\left. - \,\mathrm{E}_4\!\left(\begin{smallmatrix}0 & -1\\ 0 & 1\end{smallmatrix};1\right) - \mathrm{E}_4\!\left(\begin{smallmatrix}0 & 1\\ 0 & 0\end{smallmatrix};1\right)\right].$$

Different mass case can also be expressed in terms of the same functions

ARE THEY REALLY USEFUL?

A first generalisation: the Kite integral

$K_{11111}(p^2, m^2) =$  $\qquad z = \dfrac{p^2}{m^2}$

$$= \frac{1}{z}\Big[2\pi^2 G(0,z) - 2\pi^2 G(1,z) + 3G(0,0,0,z) - 6G(0,1,0,z) - 24\zeta(3)$$

$$+12G(0,1,1,z) - 3G(1,0,0,z) - 6G(1,0,1,z) + 6G(1,1,0,z) + \ldots\Big]$$

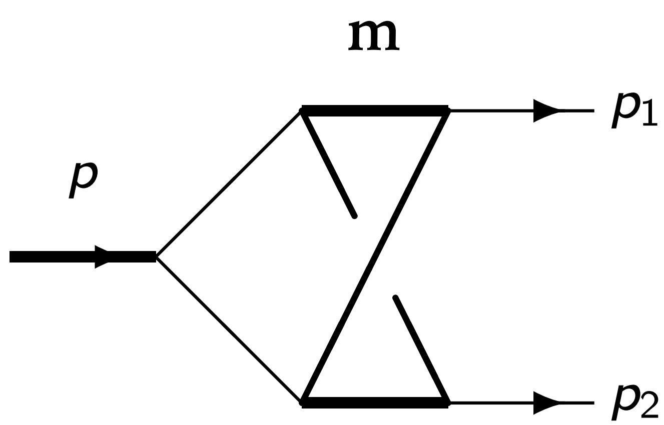
$$+ \frac{1+z}{(a_1-a_3)^2(1-z)z}\Big[\mathrm{E}_4\left(\begin{smallmatrix}0&0&1\\0&0&1\end{smallmatrix};1\right) + \mathrm{E}_4\left(\begin{smallmatrix}0&1&0\\0&1&0\end{smallmatrix};1\right) - \mathrm{E}_4\left(\begin{smallmatrix}1&0&0\\0&0&0\end{smallmatrix};1\right)\Big]$$

$$+ \frac{1+z}{(a_1-a_3)(1-z)z}\Big[\mathrm{E}_4\left(\begin{smallmatrix}0&-1&1\\0&0&1\end{smallmatrix};1\right) + \mathrm{E}_4\left(\begin{smallmatrix}0&-1&1\\0&1&1\end{smallmatrix};1\right)$$

$$+2\mathrm{E}_4\left(\begin{smallmatrix}0&-1&1\\0&\infty&1\end{smallmatrix};1\right) + \mathrm{E}_4\left(\begin{smallmatrix}0&1&1\\0&0&1\end{smallmatrix};1\right) + \ldots\Big] + 79 \text{ more } \mathrm{E}_4 s$$

ARE THEY REALLY USEFUL?

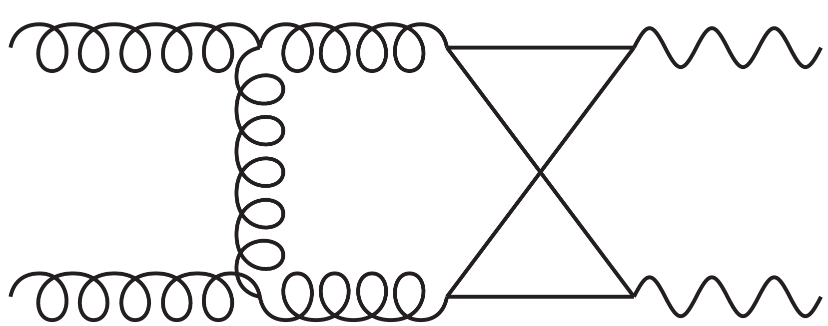
A three point function



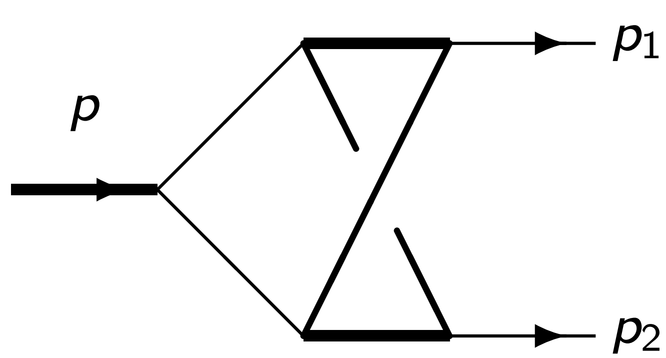
$$a = \frac{p^2}{m^2}$$

$$r_{-\pm} = \frac{1}{2}(1 - \sqrt{1 \pm 4a}), \quad r_{+\pm} = 1 - r_{-\pm} \ .$$

Relevant for QCD and EW theory *(ttb, gg, 2jet, HH, Hj production,…)*



ARE THEY REALLY USEFUL?



$$a = \frac{p^2}{m^2}$$

$$r_{-\pm} = \frac{1}{2}\left(1 - \sqrt{1 \pm 4a}\right), \quad r_{+\pm} = 1 - r_{-\pm} \; .$$

$$\begin{aligned}
I = \frac{2a^2}{c_4^2}\Bigg[& 5\mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & r_{-+} \end{smallmatrix}; 1\right) + 5\mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & r_{++} \end{smallmatrix}; 1\right) + 5\mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & r_{-+} \end{smallmatrix}; 1\right) + 5\mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & r_{++} \end{smallmatrix}; 1\right) \\
& - 3\mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & r_{--} & 0 \end{smallmatrix}; 1\right) - 3\mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & r_{--} & 1 \end{smallmatrix}; 1\right) - 3\mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & r_{+-} & 0 \end{smallmatrix}; 1\right) - 3\mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & r_{+-} & 1 \end{smallmatrix}; 1\right) \\
& + 3\log a \left(\mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 \\ 0 & 0 & r_{--} \end{smallmatrix}; 1\right) + \mathrm{E}_4\left(\begin{smallmatrix} 0 & 0 & 1 \\ 0 & 0 & r_{+-} \end{smallmatrix}; 1\right)\right)\Bigg] \\
- \frac{4a^2}{c_4}\Bigg[& 5\mathrm{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & 0 & r_{-+} \end{smallmatrix}; 1\right) + 5\mathrm{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & 0 & r_{++} \end{smallmatrix}; 1\right) + 5\mathrm{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & 1 & r_{-+} \end{smallmatrix}; 1\right) + 5\mathrm{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & 1 & r_{++} \end{smallmatrix}; 1\right) \\
& - 3\mathrm{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & r_{--} & 0 \end{smallmatrix}; 1\right) - 3\mathrm{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & r_{--} & 1 \end{smallmatrix}; 1\right) - 3\mathrm{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & r_{+-} & 0 \end{smallmatrix}; 1\right) - 3\mathrm{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & r_{+-} & 1 \end{smallmatrix}; 1\right) \\
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\end{aligned}$$

SUMMARIZING

The properties of these functions are currently under study, many recent developments:

- Study of the **algebra** generated by these functions following [Brown '14]
- We developed a set of tools which works very well for direct integration of FIs *(like before 1999 for MPLs and FIs…)* [Gehrmann, Remiddi '00]
- Connection to the differential equation method is non-trivial. Understood for the special case of ***Iterated integrals over modular forms***
- **Most recently** "concept of **purity**". Rotation in the basis of E4 functions to obtain a class of functions of "pure transcendental weight"

Soon more examples to come, in particular also **four point functions** and the **<u>first physical results</u>**!

CONCLUSIONS

- We have built a class of functions which span the space generated by **repeated integrations** of *rational functions on an elliptic curve*
- The functions span the **same space of the eMPLs defined by mathematicians and string theorists on the Torus**. We have highlighted the <u>connection between the two formalisms</u>
- We have showed how many **physically relevant FIs can be expressed in terms of these functions**
- We can associate to them a concept of transcendental weight and we ***recover an idea of "purity" associated to some classes of FIs***

Still to do:

- Understand the connection with the <u>**differential equations method**</u>
- Study general algorithm for their numerical evaluation
- <u>**Finally, use them to do some real physics!**</u>

Stay tuned!

THANK YOU!

BACK UP

PURE ELLIPTIC MULTIPLE POLYLOGARITHMS

$$\mathcal{E}_4\left(\begin{smallmatrix} n_1 & \ldots & n_k \\ c_1 & \ldots & c_k \end{smallmatrix}; x, \vec{a}\right) = \int_0^x dt\, \Psi_{n_1}(c_1, t, \vec{a})\, \mathcal{E}_4\left(\begin{smallmatrix} n_2 & \ldots & n_k \\ c_2 & \ldots & c_k \end{smallmatrix}; t, \vec{a}\right)$$

$$\Psi_1(c, x, \vec{a}) = \frac{1}{x-c}$$

$$\Psi_0(0, x, \vec{a}) = \frac{1}{\omega_1}\, \psi_0(0, x, \vec{a}) = \frac{c_4}{\omega_1\, y}$$

$$\Psi_{-1}(c, x, \vec{a}) = \psi_{-1}(c, x, \vec{a}) + Z_4(c, \vec{a})\, \psi_0(0, x, \vec{a}) = \frac{y_c}{y(x-c)} + Z_4(c, \vec{a})\, \frac{c_4}{y}\,,$$

$$\Psi_1(\infty, x, \vec{a}) = -\psi_1(\infty, x, \vec{a}) = -Z_4(x, \vec{a})\, \frac{c_4}{y}\,,$$

EXAMPLE KITE OR SUNRISE

$$S_1(p^2, m^2) = -\frac{\omega_1}{(p^2+m^2)\, c_4}\, T_1(p^2, m^2)\,,$$

$$\begin{aligned}
T_1^{(0)} &= 2\mathcal{E}_4\left(\begin{smallmatrix}0 & -1\\ 0 & \infty\end{smallmatrix}; 1, \vec{a}\right) + \mathcal{E}_4\left(\begin{smallmatrix}0 & -1\\ 0 & 0\end{smallmatrix}; 1, \vec{a}\right) + \mathcal{E}_4\left(\begin{smallmatrix}0 & -1\\ 0 & 1\end{smallmatrix}; 1, \vec{a}\right)\ ,\\
T_1^{(1)} &= -4\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_3 & \infty\end{smallmatrix}; 1, \vec{a}\right) - 4\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_1 & \infty\end{smallmatrix}; 1, \vec{a}\right) - 4\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_4 & \infty\end{smallmatrix}; 1, \vec{a}\right) - 4\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_2 & \infty\end{smallmatrix}; 1, \vec{a}\right)\\
&- 2\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_3 & 0\end{smallmatrix}; 1, \vec{a}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_3 & 1\end{smallmatrix}; 1, \vec{a}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_1 & 0\end{smallmatrix}; 1, \vec{a}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_1 & 1\end{smallmatrix}; 1, \vec{a}\right)\\
&- 2\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_4 & 0\end{smallmatrix}; 1, \vec{a}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_4 & 1\end{smallmatrix}; 1, \vec{a}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_2 & 0\end{smallmatrix}; 1, \vec{a}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & a_2 & 1\end{smallmatrix}; 1, \vec{a}\right)\\
&+ 2\mathcal{E}_4\left(\begin{smallmatrix}0 & -1 & 1\\ 0 & \infty & 0\end{smallmatrix}; 1, \vec{a}\right) + 2\mathcal{E}_4\left(\begin{smallmatrix}0 & -1 & 1\\ 0 & \infty & 1\end{smallmatrix}; 1, \vec{a}\right) + 6\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & 0 & \infty\end{smallmatrix}; 1, \vec{a}\right) + 6\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & 1 & \infty\end{smallmatrix}; 1, \vec{a}\right)\\
&- 2\mathcal{E}_4\left(\begin{smallmatrix}0 & -1 & 1\\ 0 & 0 & 0\end{smallmatrix}; 1, \vec{a}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix}0 & -1 & 1\\ 0 & 0 & 1\end{smallmatrix}; 1, \vec{a}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix}0 & -1 & 1\\ 0 & 1 & 0\end{smallmatrix}; 1, \vec{a}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix}0 & -1 & 1\\ 0 & 1 & 1\end{smallmatrix}; 1, \vec{a}\right)\\
&+ 6i\pi\mathcal{E}_4\left(\begin{smallmatrix}0 & 0 & 1\\ 0 & 0 & 0\end{smallmatrix}; 1, \vec{a}\right) + 6i\pi\mathcal{E}_4\left(\begin{smallmatrix}0 & 0 & 1\\ 0 & 0 & 1\end{smallmatrix}; 1, \vec{a}\right) + 3\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & 0 & 0\end{smallmatrix}; 1, \vec{a}\right) + 3\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & 0 & 1\end{smallmatrix}; 1, \vec{a}\right)\\
&+ 3\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & 1 & 0\end{smallmatrix}; 1, \vec{a}\right) + 3\mathcal{E}_4\left(\begin{smallmatrix}0 & 1 & -1\\ 0 & 1 & 1\end{smallmatrix}; 1, \vec{a}\right) + \zeta_2\, \mathcal{E}_4\left(\begin{smallmatrix}0\\ 0\end{smallmatrix}; 1, \vec{a}\right)\ .
\end{aligned}$$

A PURE VERSION OF THE TRIANGLE

$$I = \frac{32\omega_1}{q^2(1+\sqrt{1-16a})}\left[T_0(a) + 3T_-(a) + 5T_+(a) + \mathcal{O}(\epsilon)\right]$$

$$\begin{aligned}
T_a \;=\; & -\mathcal{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & 0 & 0 \end{smallmatrix}; 1\right) - \mathcal{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & 0 & 1 \end{smallmatrix}; 1\right) - \mathcal{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & 1 & 0 \end{smallmatrix}; 1\right) - \mathcal{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 & 1 \\ 0 & \infty & 1 & 1 \end{smallmatrix}; 1\right) + \\
& \log(a)\left[\mathcal{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 \\ 0 & \infty & 0 \end{smallmatrix}; 1\right) + \mathcal{E}_4\left(\begin{smallmatrix} 0 & -1 & 1 \\ 0 & \infty & 1 \end{smallmatrix}; 1\right)\right] + \frac{1}{2}\mathcal{E}_4\left(\begin{smallmatrix} 0 & -1 \\ 0 & \infty \end{smallmatrix}; 1\right)\left(\zeta_2 - \log^2(a)\right)
\end{aligned}$$

$$\begin{aligned}
T_- \;=\; & -\frac{3}{2}\zeta_2\,\mathcal{E}_4\left(\begin{smallmatrix} -1 \\ \infty \end{smallmatrix}; r_{--}\right) + \zeta_2\mathcal{E}_4\left(\begin{smallmatrix} -1 & 0 \\ \infty & 0 \end{smallmatrix}; r_{--}\right) - 2\mathcal{E}_4\left(\begin{smallmatrix} -1 & -1 \\ \infty & \infty \end{smallmatrix}; r_{--}\right)\mathcal{E}_4\left(\begin{smallmatrix} 0 & -1 \\ 0 & \infty \end{smallmatrix}; 1\right) \\
& + \mathcal{E}_4\left(\begin{smallmatrix} -1 & 0 & 1 & 1 \\ \infty & 0 & 0,0 & \end{smallmatrix}; r_{--}\right) + \mathcal{E}_4\left(\begin{smallmatrix} -1 & 0 & 1 & 1 \\ \infty & 0 & 0 & 1 \end{smallmatrix}; r_{--}\right) - \mathcal{E}_4\left(\begin{smallmatrix} -1 & 0 & 1 & 1 \\ \infty & 0 & 1 & 0 \end{smallmatrix}; r_{--}\right) - \mathcal{E}_4\left(\begin{smallmatrix} -1 & 0 & 1 & 1 \\ \infty & 0 & 1 & 1 \end{smallmatrix}; r_{--}\right) \\
& + \mathcal{E}_4\left(\begin{smallmatrix} -1 & 1 & 0 & 1 \\ \infty & 0 & 0 & 1 \end{smallmatrix}; r_{--}\right) - \mathcal{E}_4\left(\begin{smallmatrix} -1 & 1 & 0 & 1 \\ \infty & 1 & 0 & 0 \end{smallmatrix}; r_{--}\right) + \mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 & 0 & 1 \\ 0 & \infty & 0 & 1 \end{smallmatrix}; r_{--}\right) - \mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 & 0 & 1 \\ 1 & \infty & 0 & 0 \end{smallmatrix}; r_{--}\right) \\
& - \mathcal{E}_4\left(\begin{smallmatrix} -1 & 0 & 1 \\ \infty & 0 & 1 \end{smallmatrix}; r_{--}\right)\log(r_{--}) + \mathcal{E}_4\left(\begin{smallmatrix} -1 & 0 & 1 \\ \infty & 0 & 0 \end{smallmatrix}; r_{--}\right)\log(1-r_{--})
\end{aligned}$$

$$\begin{aligned}
T_+ \;=\; & \frac{i\pi}{4}\left(\mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 \\ 0 & \infty \end{smallmatrix}; r_{-+}\right) + \mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 \\ 1 & \infty \end{smallmatrix}; r_{-+}\right) - 4\left(\mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 & 0 \\ 0 & \infty & 0 \end{smallmatrix}; r_{-+}\right) + \mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 & 0 \\ 1 & \infty & 0 \end{smallmatrix}; r_{-+}\right)\right)\right) \\
& - \mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 & 0 & 1 \\ 0 & \infty & 1 & 0 \end{smallmatrix}; r_{-+}\right) + \mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 & 0 & 1 \\ 0 & \infty & 0 & 1 \end{smallmatrix}; r_{-+}\right) - \mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 & 0 & 1 \\ 1 & \infty & 1 & 0 \end{smallmatrix}; r_{-+}\right) + \mathcal{E}_4\left(\begin{smallmatrix} 1 & -1 & 0 & 1 \\ 1 & \infty & 0 & 1 \end{smallmatrix}; r_{-+}\right)
\end{aligned}$$