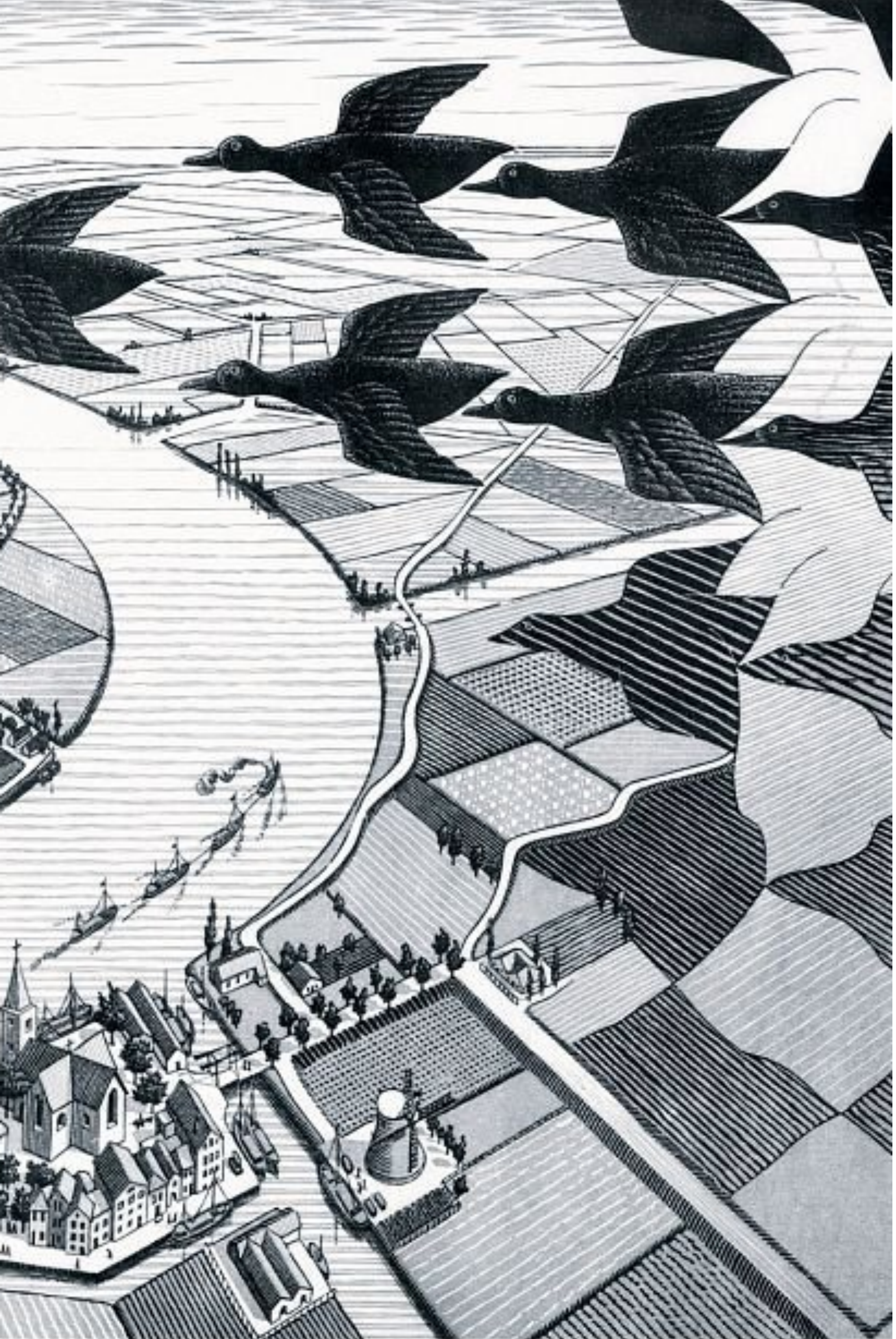
HEAVY QUARK PRODUCTION AT THE LHC

Simone Devoto
Advisor: Massimiliano Grazzini

Zurich PhD Seminars, 09.03.18



CONTENTS

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- **Production** → Pair production
  $t\bar{t}$ *production is the main source of top quark events in the SM*

- **At the LHC** → Large Hadron Collider
  The world's largest and most powerful particle collider

WHY TOP QUARK?

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- Heaviest elementary particle known so far ($m_t \simeq 173$ GeV)
  Strong coupling with the Higgs Boson
  Study of $t\bar{t}$ production can shed light on electroweak symmetry breaking mechanism

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- Top quarks are abundantly produced at the LHC
  Its production is an important background both for NP model and SM precision measurements
  Experimental measurements require reliable predictions of $t\bar{t}$ production

MOST RECENT ATLAS PAPERS

arXiv id	Observable	$t\bar{t}$ background?
1802.08168	Missing Transverse Momentum	✓
1802.09572	$t\bar{t}$ production	✓
1802.06572	$H \rightarrow cc$	✓
1802.03388	$H \rightarrow ZX/XX \rightarrow 4\ell$	✓
1802.03158	Supersymmetry	✓
1802.01840	Tetraquark	✗
1802.04146	$H \rightarrow \gamma\gamma$	✓
1801.08769	$q\bar{q} + \gamma$ or jet	✓
1801.07893	$W' \rightarrow t\,b$	✓
1801.06992	$X \rightarrow \tau\,\nu$	✓
1801.02052	$t\bar{t}$ production	✓
1712.08891	$pp \rightarrow t\bar{t}H$	✓

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11/12 REQUIRE THEORETICAL PREDICTION OF $T\bar{T}$ PRODUCTION!

…

HOW DO WE DESCRIBE TOP PAIR PRODUCTION?

- Perturbation theory → Feynman diagrams

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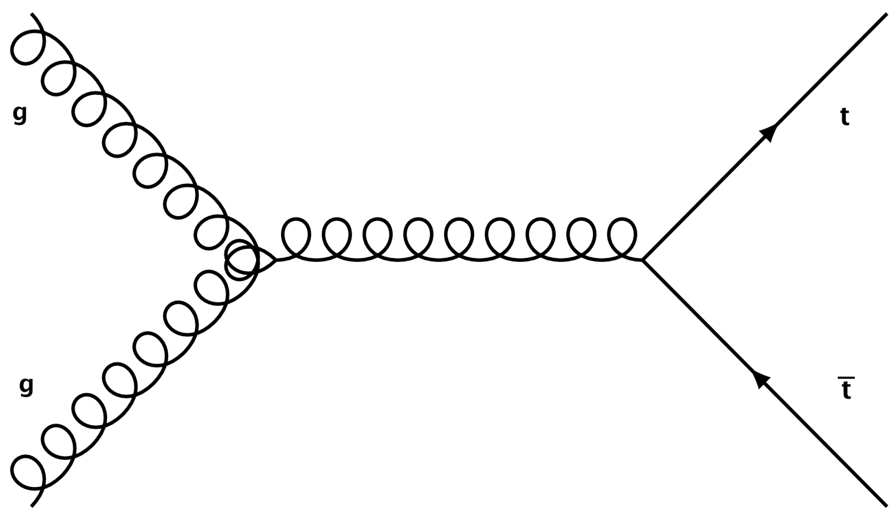
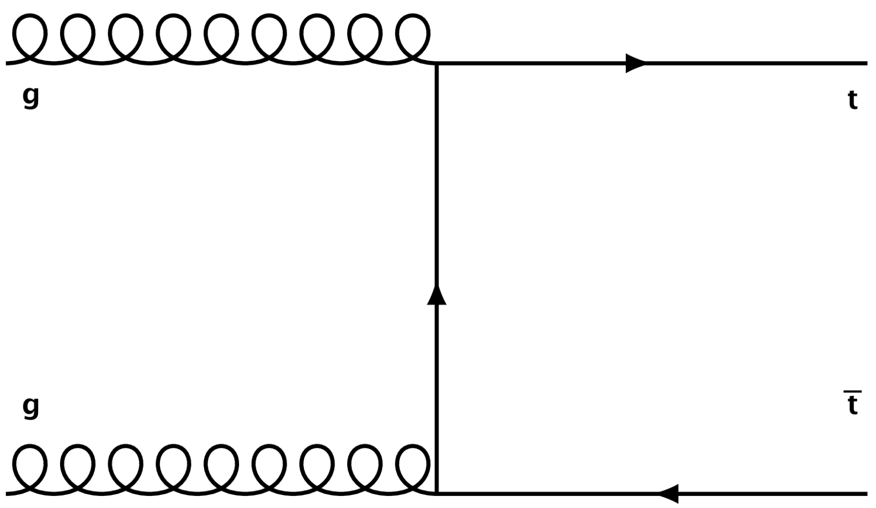
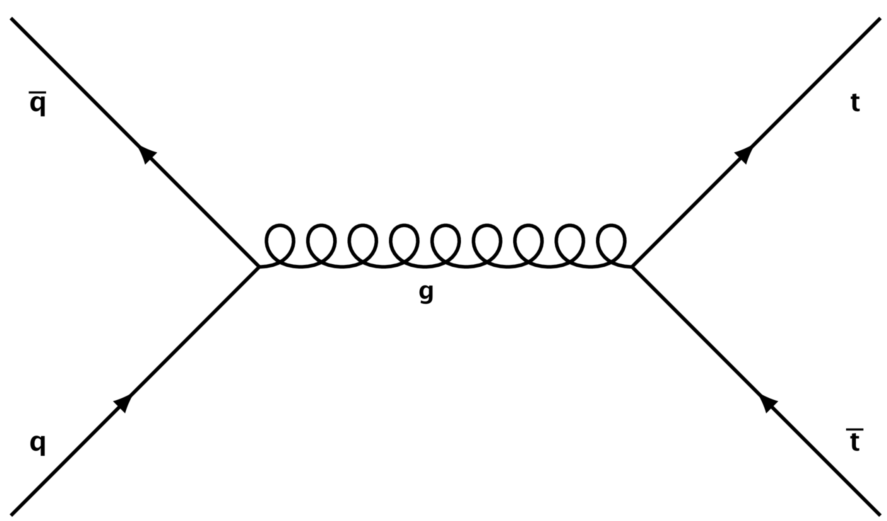
Leading Order (LO)







LO → order of magnitude prediction

HOW DO WE DESCRIBE TOP PAIR PRODUCTION?

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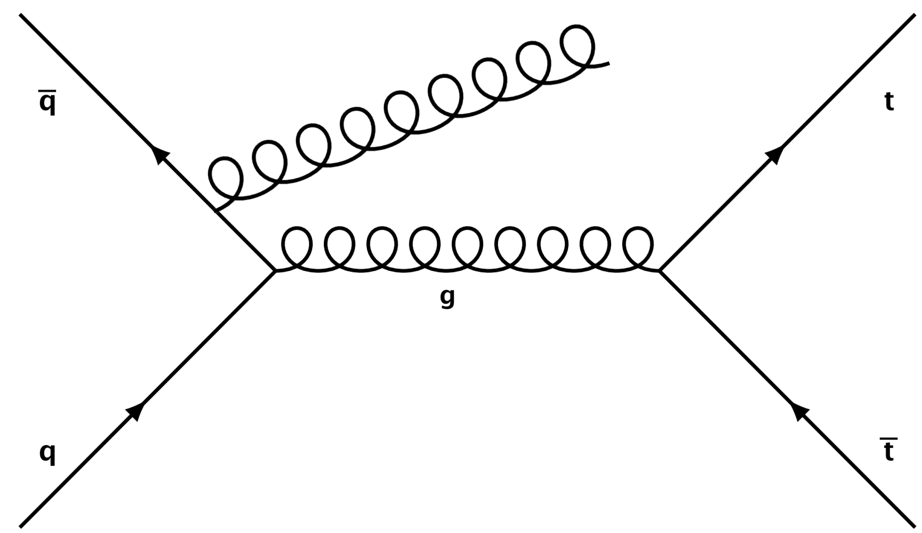
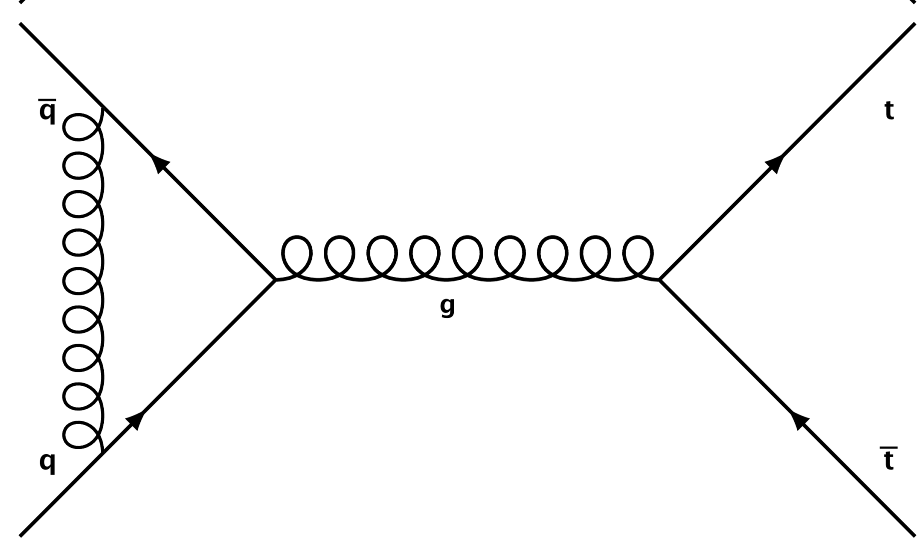
Next to Leading Order (NLO)

Two types of corrections:

- Real



- Virtual



HOW DO WE DESCRIBE TOP PAIR PRODUCTION?

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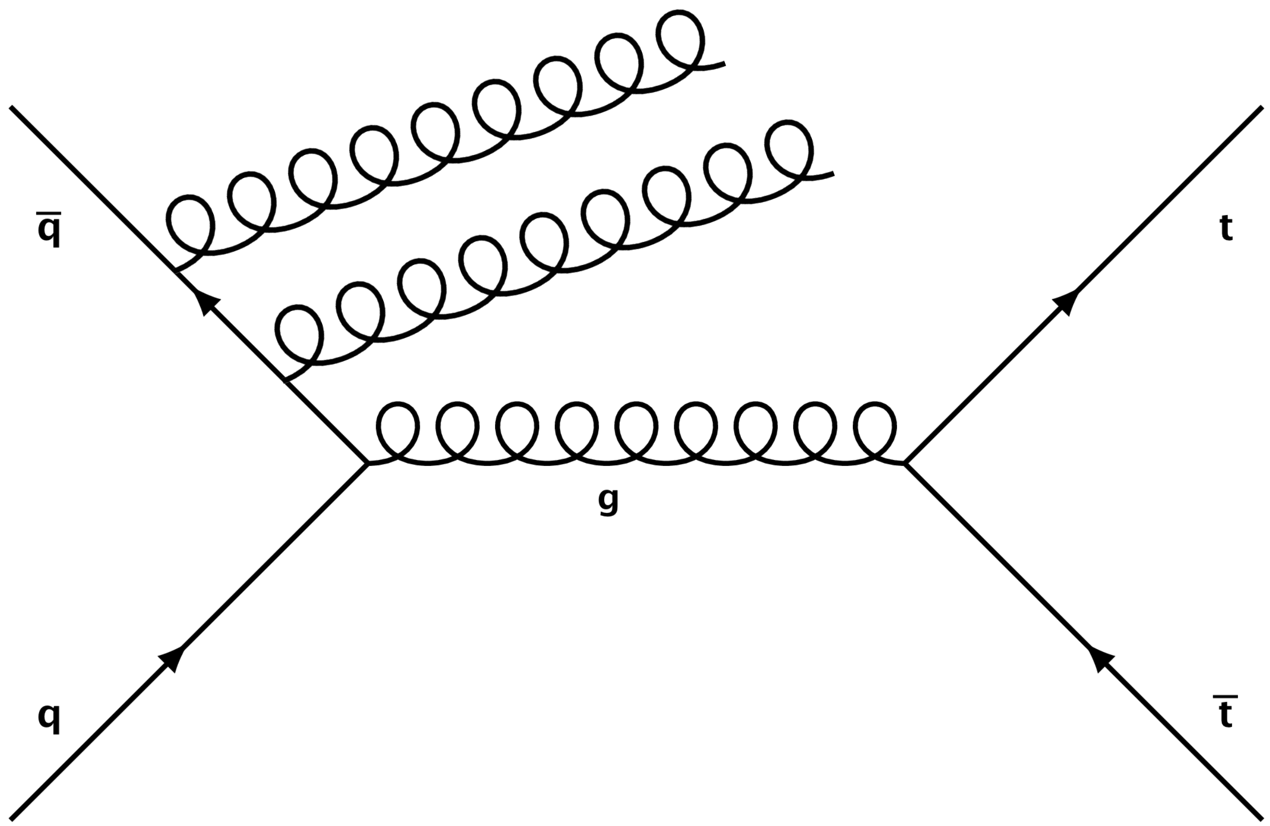
Next to Next to Leading Order (NNLO)

Three types of corrections:

- Double real
- Single real at 1 loop
- 2 loop Virtual



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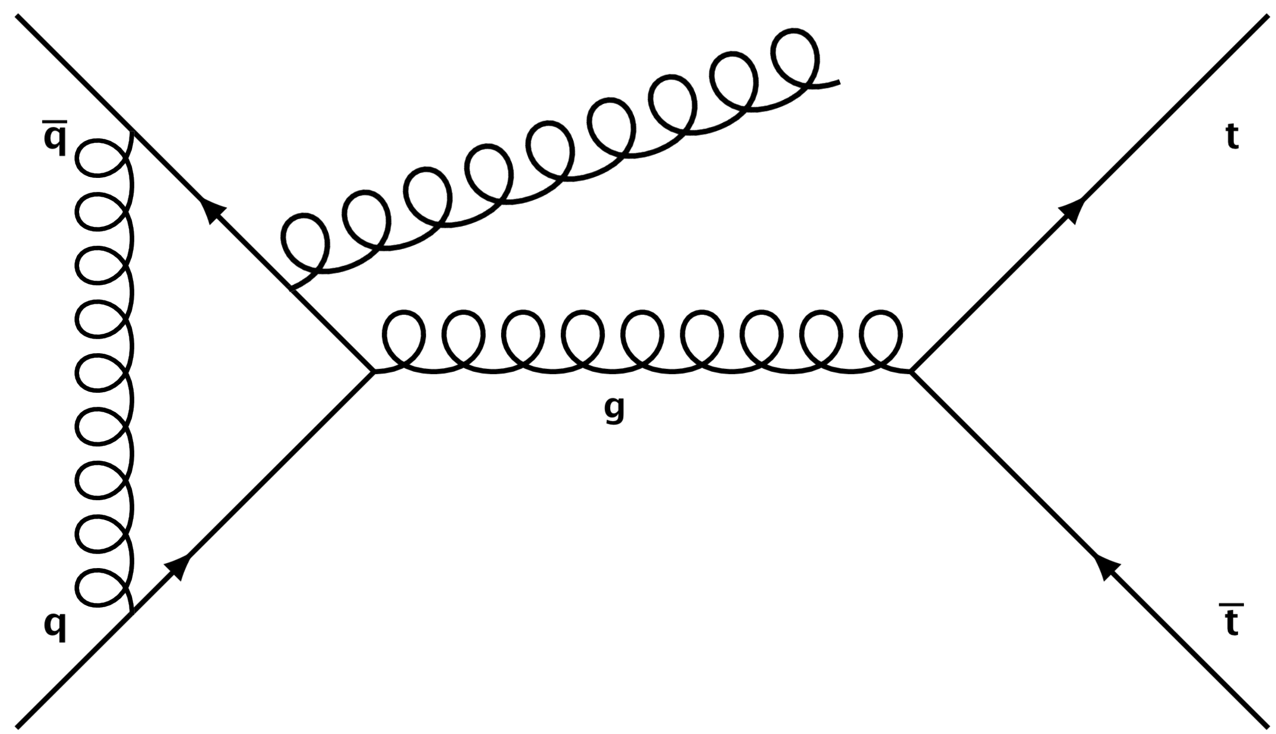

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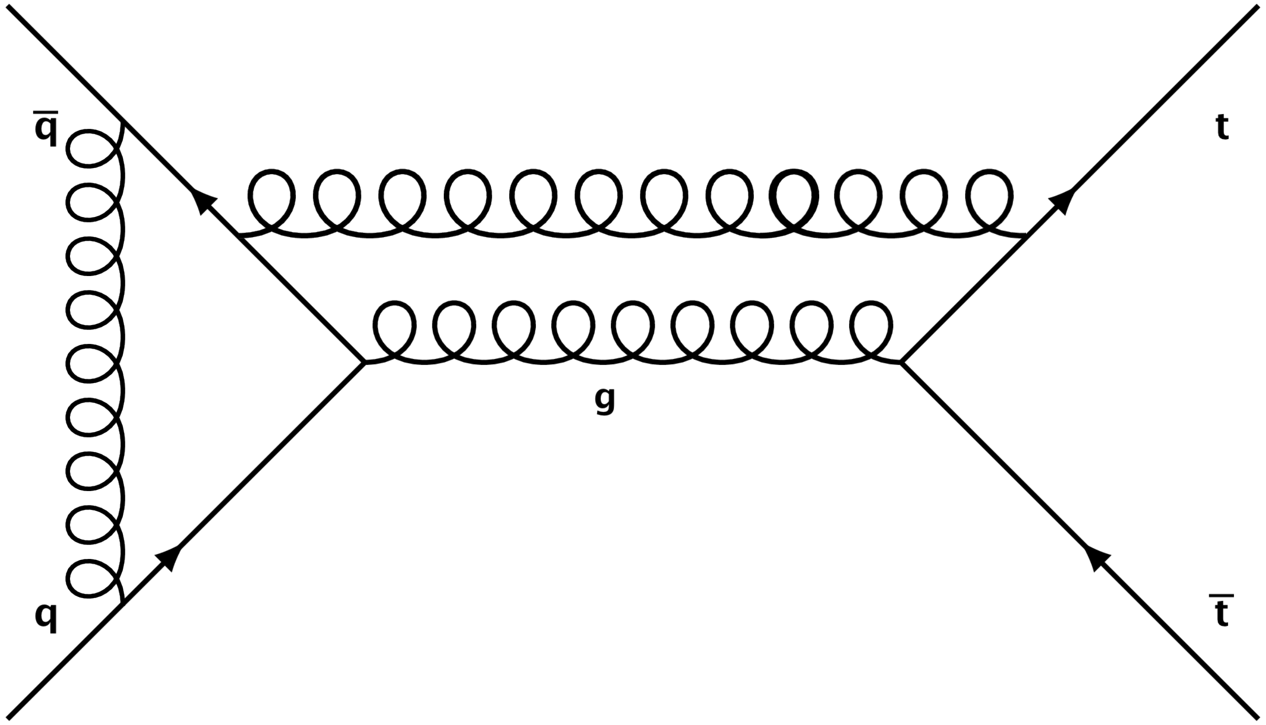

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Higher Orders (NLO - NNLO)

- They are necessary to obtain a reliable prediction

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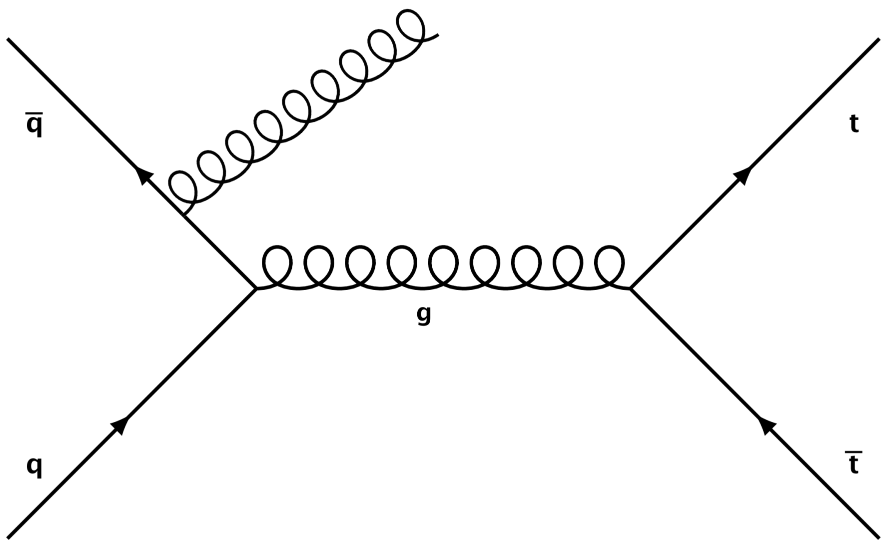
↓

QCD CORRECTIONS

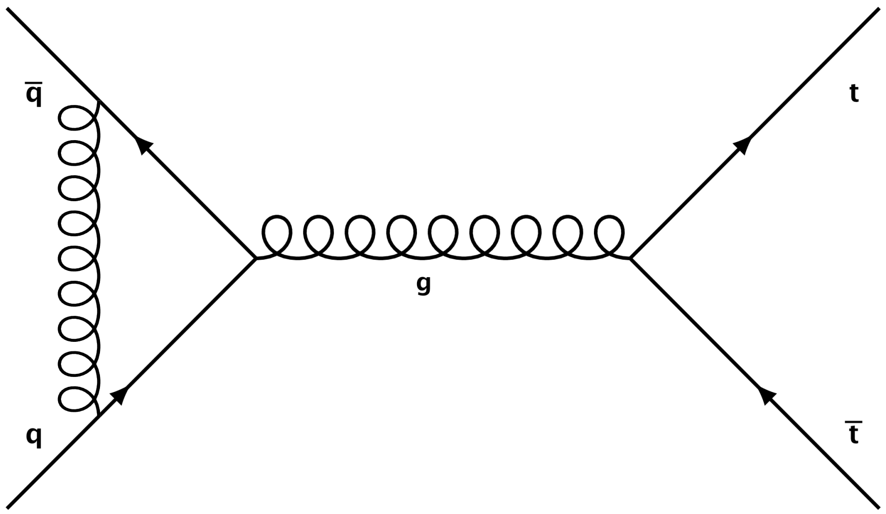
They are challenging because of IR divergences!

WHY ARE QCD CORRECTIONS CHALLENGING?

Real



Virtual



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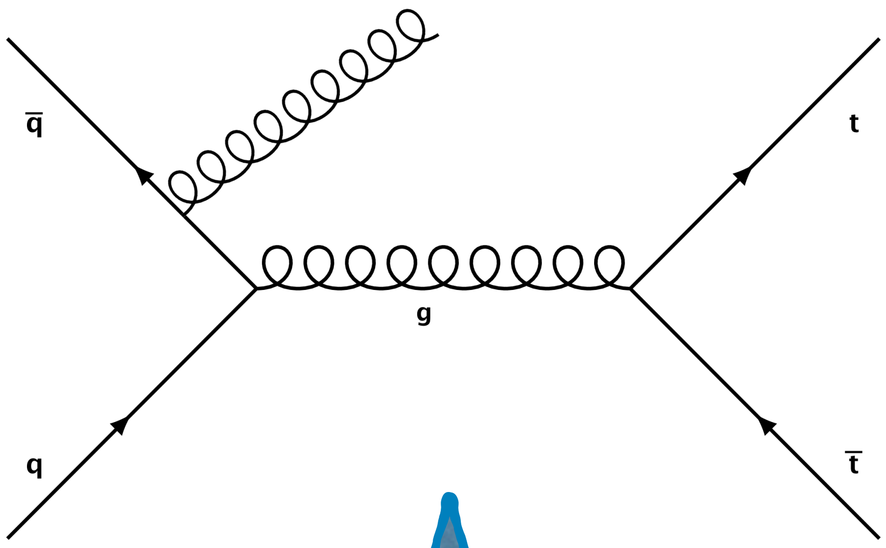
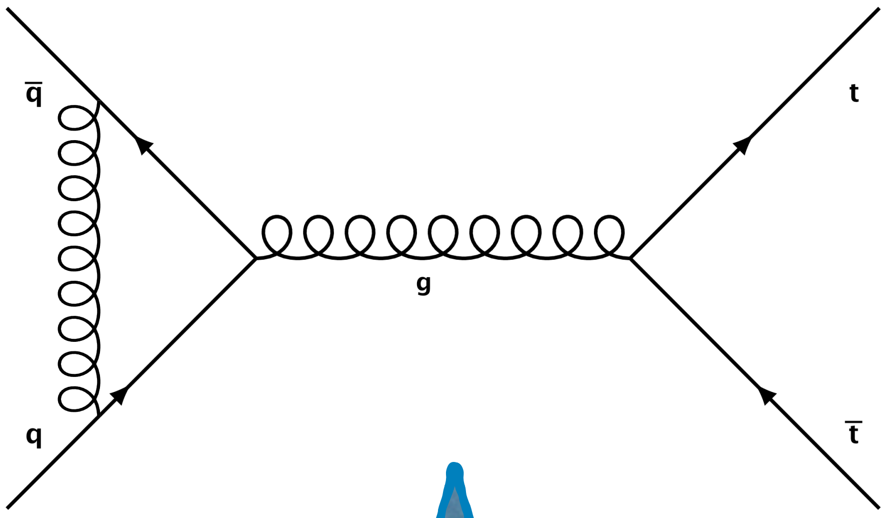


IR Divergent

Virtual



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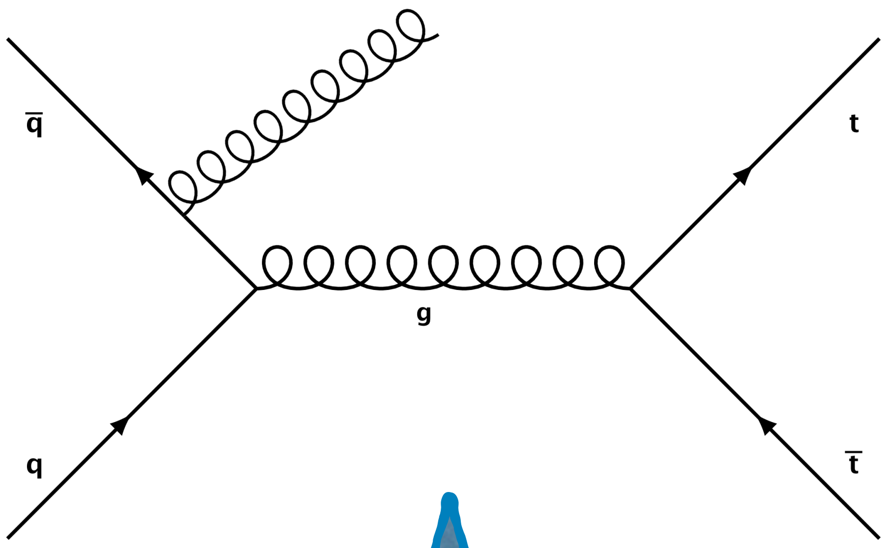

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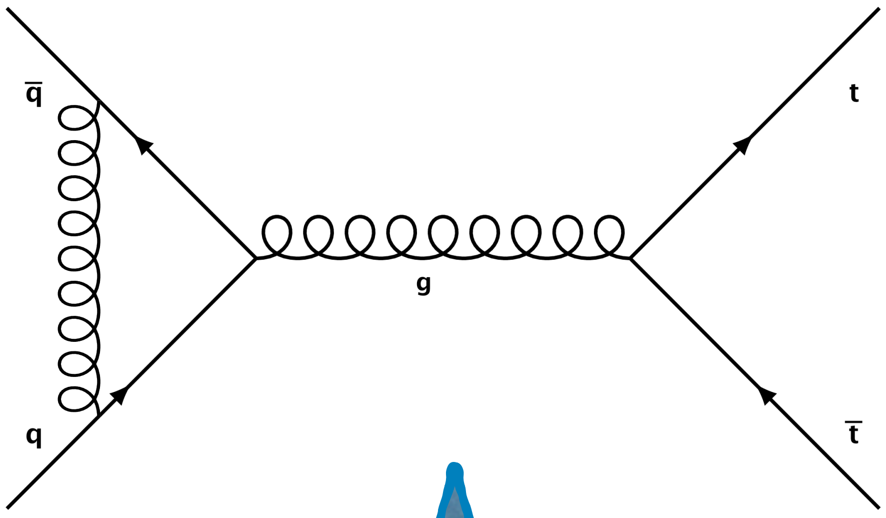

IR Divergent

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IR divergences are guaranteed to cancel out for inclusive observables after summing real and virtual contributions (KLN Theorem)

WHY ARE QCD CORRECTIONS CHALLENGING?

Presence of IR divergences at intermediate steps of the computation of QCD higher order corrections does not allow a straightforward implementation of numerical techniques.

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SUBTRACTION METHODS

$$\sigma^{NLO} = \int d\sigma^{NLO} = \int_{m+1} d\sigma^{R} + \int_{m} d\sigma^{V}$$

Divergent *Divergent*

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$$\sigma^{NLO} = \int d\sigma^{NLO} = \int_{m+1} \left[d\sigma^R - d\sigma^{CT} \right] + \int_m \left[d\sigma^V + \int_1 d\sigma^{CT} \right]$$

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~~Divergent~~ ~~Divergent~~

Convergent! **Convergent!**

WHY ARE QCD CORRECTIONS CHALLENGING?

Subtraction methods:

➤ **NLO:**

- *Catani-Seymour dipole subtraction* *[S. Catani, M. Seymour (1996)]*
- *FKS subtraction* *[S. Frixione, Z. Kunszt, A. Signer (1996)]*

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  - *Colourful subtraction* *[G. Somogyi, Z. Trocsanyi, V. Del Luca (2005)]*
  - *Antenna subtraction* *[T. Gehrmann, A. Gehrmann-De Ridder, N. Glover (2005)]*
  - *Stripper formalism* *[M. Czakon (2010); Boughezal et al (2011)]*
  - q_T *subtraction formalism* *[S. Catani, M. Grazzini]*
  - *N-jettiness subtraction* *[Boughezal, Focke, Liu, Petriello (2015); Gaunt, Stahlhofen, Tackmann, Walsh (2015)]*

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```
[devoto:/mnt/runs2/devoto/MATRIX_v1.0.0] ./matrix
```

MATRIX

[arXiv 1711.06631]

MATRIX *[arXiv 1711.06631]*

Computational framework which allows us to evaluate fully differential cross sections for a wide class of processes at hadron colliders where the final state is a colour singlet in next-to-next-to-leading order (NNLO) QCD by using q_T subtraction.

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```
[devoto:/mnt/runs2/devoto/MATRIX_v1.0.0] ./matrix

 /------------------------------------------------------------------\
 |                                                                  |
 |     __  __     ___     ____     ___     _    _    __            |
 |    | _\/_ |   / _ \   |____|   / _ \   ||    \\  //             |
 |    || \/ ||   | |_| |    ||    ||_||   ||     \\//              |
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 |    ||    ||   ||   ||    ||    || \\   ||    //  \\             |
 |                                                                  |
 |    Version: 1.0.0                                 Nov 2017      |
 |    Reference: arXiv:1711.06631                                  |
 |                                                                  |
 | Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision -- |
 | Automates qT-subtraction and Resummation to Integrate X-sections |
 |                                                                  |
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 | /         /          /         /         /          /            |
 |                                                                  |
 | M. Grazzini                              (grazzini@physik.uzh.ch) |
 | S. Kallweit                             (stefan.kallweit@cern.ch) |
 | M. Wiesemann                           (marius.wiesemann@cern.ch) |
 |------------------------------------------------------------------|
 | MATRIX is based on a number of different computations and tools  |
 | from various people and groups. Please acknowledge their efforts |
 | by citing the list of references which is created with every run. |
 \------------------------------------------------------------------/

<<MATRIX-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                available processes. Try pressing TAB for auto-completion. Type
                "exit" or "quit" to stop.
|============>> list
------------------------------------------------------------------------------------------
process_id     ||   process                             ||   description
------------------------------------------------------------------------------------------
pph21          >>   p p --> H                           >>   on-shell Higgs production
ppz01          >>   p p --> Z                           >>   on-shell Z production
ppw01          >>   p p --> W^-                         >>   on-shell W- production with CKM
ppwx01         >>   p p --> W^+                         >>   on-shell W+ production with CKM
ppeex02        >>   p p --> e^- e^+                     >>   Z production with decay
ppnenex02      >>   p p --> v_e^- v_e^+                 >>   Z production with decay
ppenex02       >>   p p --> e^- v_e^+                   >>   W- production with decay and CKM
ppexne02       >>   p p --> e^+ v_e^-                   >>   W+ production with decay and CKM
ppaa02         >>   p p --> gamma gamma                 >>   gamma gamma production
ppeexa03       >>   p p --> e^- e^+ gamma               >>   Z gamma production with decay
ppnenexa03     >>   p p --> v_e^- v_e^+ gamma           >>   Z gamma production with decay
ppenexa03      >>   p p --> e^- v_e^+ gamma             >>   W- gamma production with decay
ppexnea03      >>   p p --> e^+ v_e^- gamma             >>   W+ gamma production with decay
ppzz02         >>   p p --> Z Z                         >>   on-shell ZZ production
ppwxw02        >>   p p --> W^+ W^-                     >>   on-shell WW production
ppemexmx04     >>   p p --> e^- mu^- e^+ mu^+           >>   ZZ production with decay
ppeeexex04     >>   p p --> e^- e^- e^+ e^+             >>   ZZ production with decay
ppeexnmnmx04   >>   p p --> e^- e^+ v_mu^- v_mu^+       >>   ZZ production with decay
ppemxnmnex04   >>   p p --> e^- mu^+ v_mu^- v_e^+       >>   WW production with decay
ppeexnenex04   >>   p p --> e^- e^+ v_e^- v_e^+         >>   ZZ/WW production with decay
ppemexnmx04    >>   p p --> e^- mu^- e^+ v_mu^+         >>   W-Z production with decay
ppeeexnex04    >>   p p --> e^- e^- e^+ v_e^+           >>   W-Z production with decay
ppeexmxnm04    >>   p p --> e^- e^+ mu^+ v_mu^-         >>   W+Z production with decay
ppeexexne04    >>   p p --> e^- e^+ e^+ v_e^-           >>   W+Z production with decay
|============>>
```

MATRIX

[arXiv 1711.06631]

Computational framework which allows us to evaluate f… s… p… s… w… c… r… (NNLO) QCD by using q_T subtraction.

WHAT ABOUT $t\bar{t}$ PRODUCTION?

MY PHD PROJECT

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To compute the missing ingredient to implement $t\bar{t}$ production at NNLO in MATRIX

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Coloured final state → *QCD corrections also from the final state*

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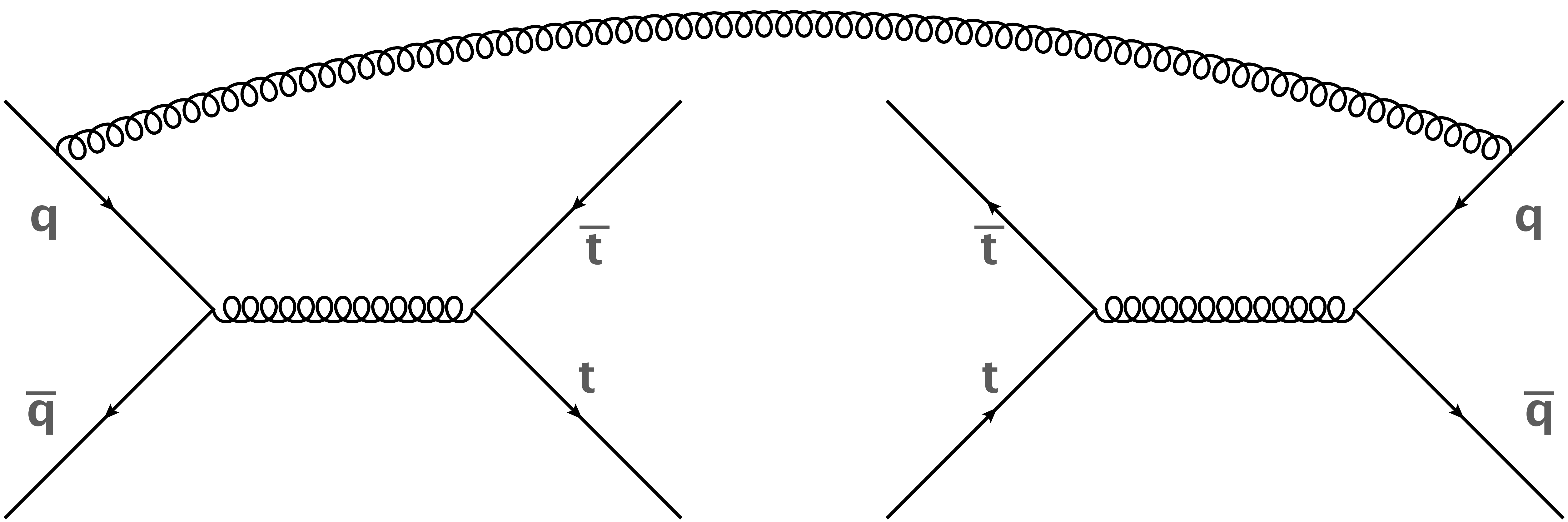

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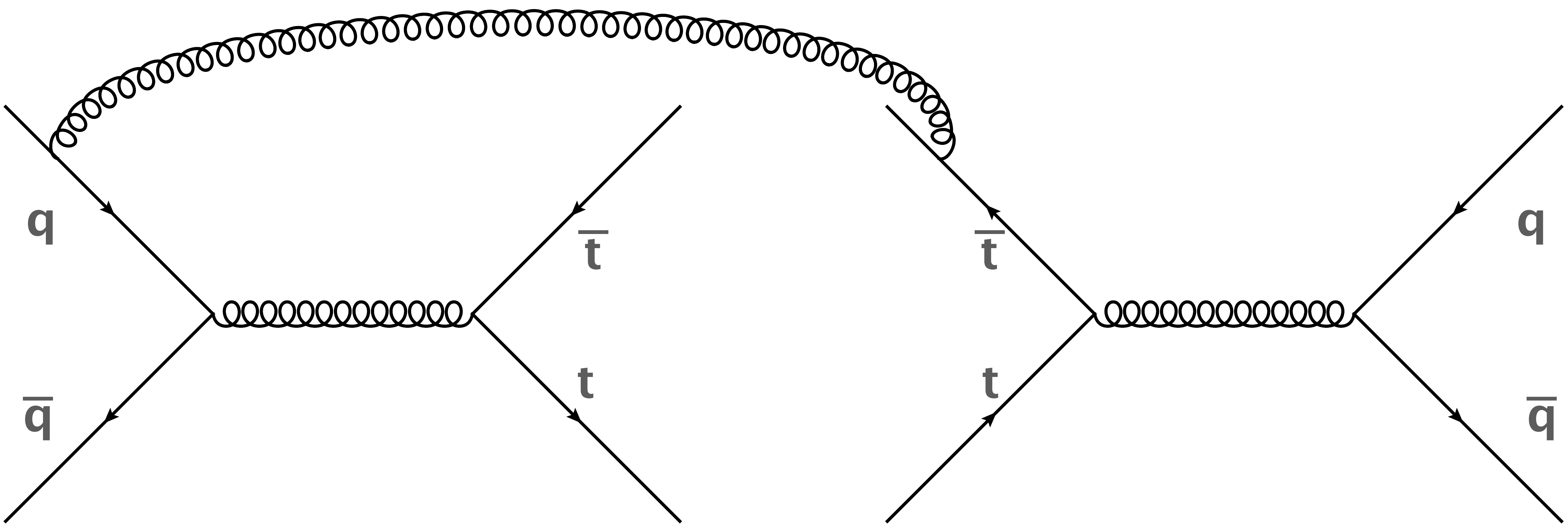

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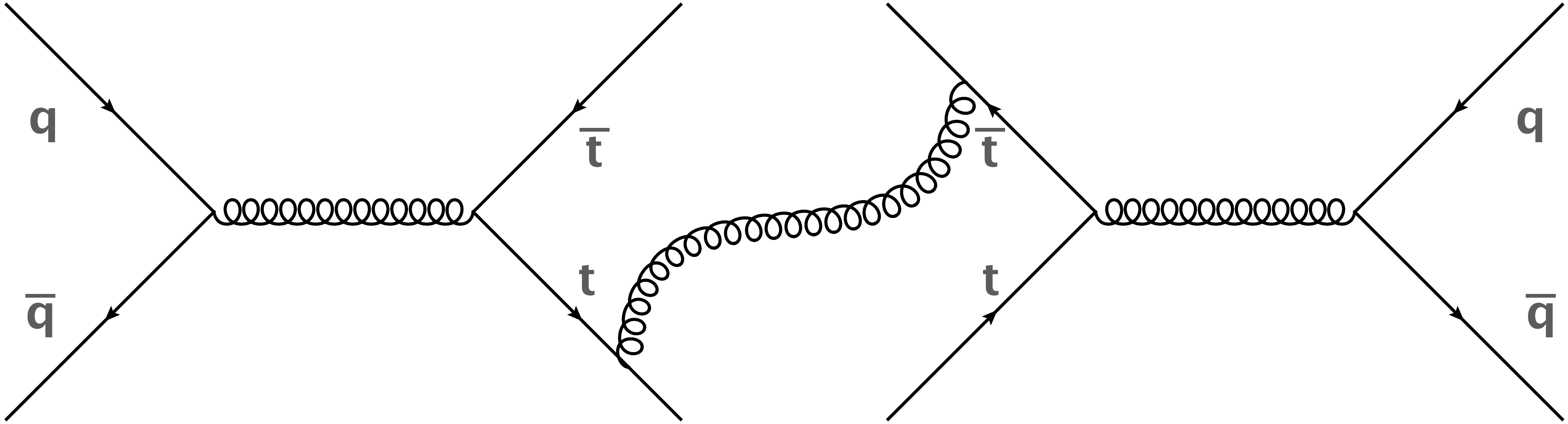

WHAT IS q_T SUBTRACTION?

q_T subtraction exploits the fact that the behaviour of the q_T distribution at small q_T has a universal structure known from transverse momentum resummation formalism to construct a process independent counterterm.

$$d\sigma^{Q\bar{Q}}_{NNLO} = \mathcal{H}^{Q\bar{Q}}_{NNLO} \otimes d\sigma^{Q\bar{Q}}_{LO} + \left[d\sigma^{Q\bar{Q}+\mathrm{jet}}_{NLO} - d\sigma^{CT}_{NNLO}\right]$$

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HARD VIRTUAL COEFFICIENT

Needs to be computed!

Can be computed with NLO subtraction techniques

IR behaviour known from studies in q_t resummation [arXiv:1408.4564; arXiv:1508.03585]

WHAT DO I NEED TO COMPUTE?

Hard Virtual Coefficient

To obtain this goal, one has to:

- Integrate the NNLO matrix elements for the real contribution in the soft limit (subtraction operator).
- Add them to the virtual contribution.
- Check the cancellation of the IR poles, keep the finite part.

WHAT DO I NEED TO COMPUTE?

Computation of the soft emission → *Integration of the NNLO soft currents (eikonal currents)*

We can distinguish between two classes of contribution:

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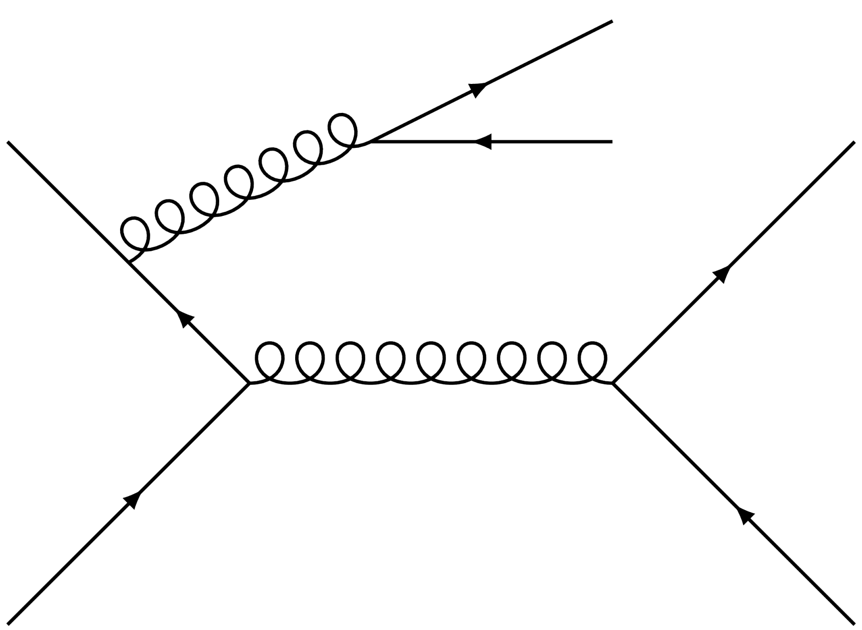
- proportional to the number of light quark flavours n_f ;



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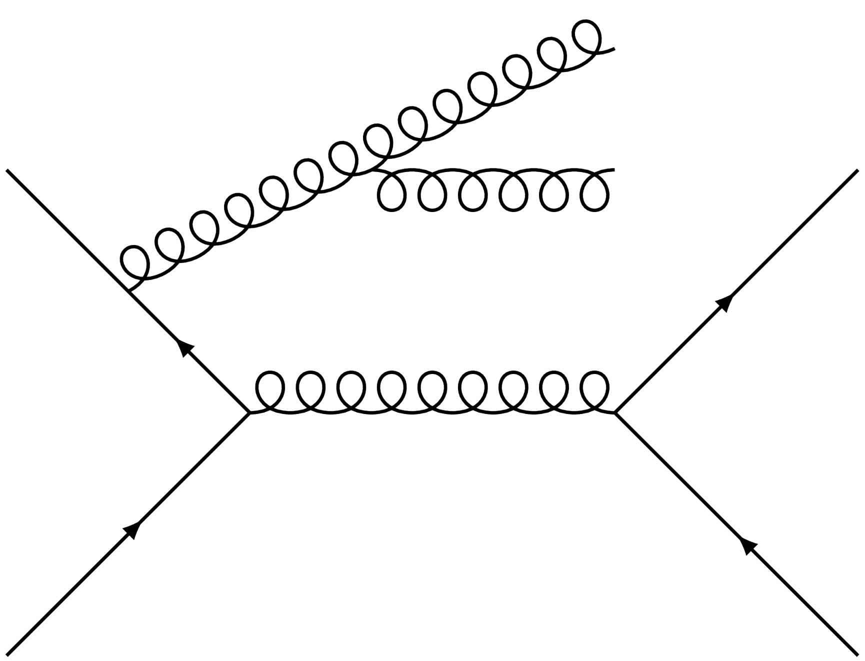
Computation of the soft emission → *Integration of the NNLO soft currents (eikonal currents)*

We can distinguish between two classes of contribution:

- proportional to the number of light quark flavours n_f;
- **not** proportional to the number of light quark flavours n_f.



N_f CONTRIBUTION

One has to consider:

- Soft quark pair production;
- NNLO contribution to single gluon emission;
- 2 loop contribution.

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- Soft quark pair production;
- NNLO contribution to single gluon emission;
- 2 loop contribution.

We computed the missing terms and combined them together.

We observed a complete cancellation of the poles and we extracted the finite part.

Full result for the n_f contribution!

N_f CONTRIBUTION

Most tricky part: soft quark pair production.

Process: → $a_1(p_1^\mu)a_2(p_2^\mu) \quad \to \quad Q(p_3^\mu)\bar{Q}(p_4^\mu)[g \to q(q_1^\mu)\bar{q}(q_2^\mu)]$

Soft Limit

$$\left|\mathcal{M}_{a_1 a_2 \to Q\bar{Q}q\bar{q}}\right|^2 = (\alpha_0 \mu_0^{2\epsilon})^q (4\pi\alpha_0\mu_0^{2\epsilon})^2 \left\langle \mathcal{M}^{(0)} \middle| J_\mu(k)\Pi^{\mu\nu}(q_1,q_2)J_\nu(k) \middle| \mathcal{M}^{(0)} \right\rangle$$

$$k = q_1 + q_2 \qquad J^\mu = T_i \frac{p_i^\mu}{p_i \cdot q} \qquad \Pi^{\mu\nu}(q_1,q_2) = \frac{T_R}{(q_1 \cdot q_2)^2}\left(-g^{\mu\nu} q_1 \cdot q_2 + q_1^\mu q_2^\nu + q_1^\nu q_2^\mu\right)$$

Need to compute: →

$$\int d^n q_1 \int d^n q_2 J_\mu(k)\Pi^{\mu\nu}(q_1,q_2)J_\nu(k)$$

DOUBLE GLUON EMISSION

One has to consider:

- Double real contribution;
- Real - virtual contribution;
- 2 loop virtual contribution.

DOUBLE GLUON EMISSION

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- Double real contribution;
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- 2 loop virtual contribution.

Current status:

We started the computation of the most tricky part, double real contribution (double gluon emission).

DOUBLE GLUON EMISSION

Process: $a_1(p_1^\mu)a_2(p_2^\mu) \quad \to \quad Q(p_3^\mu)\bar{Q}(p_4^\mu)g(q_1^\mu)g(q_2^\mu)$

Soft Limit

$$J^{a_1a_2}_{\mu\nu}(q_1,q_2)g^{\sigma\mu}g^{\rho\nu}J^{a_1a_2}_{\sigma\rho}(q_1,q_2) = \frac{1}{2}\left\{\mathbf{J}^2(q_1),\mathbf{J}^2(q_2)\right\} - C_A\sum_{i,j=1}^{n}\mathbf{T}_i\cdot\mathbf{T}_j\,\mathcal{S}_{ij}(q_1,q_2)$$

$$\mathcal{S}_{ij}(q_1,q_2) = \mathcal{S}^{m=0}_{ij}(q_1,q_2) + \left(m_i^2\,\mathcal{S}^{m\neq0}_{ij}(q_1,q_2) + m_j^2\,\mathcal{S}^{m\neq0}_{ji}(q_1,q_2)\right)$$

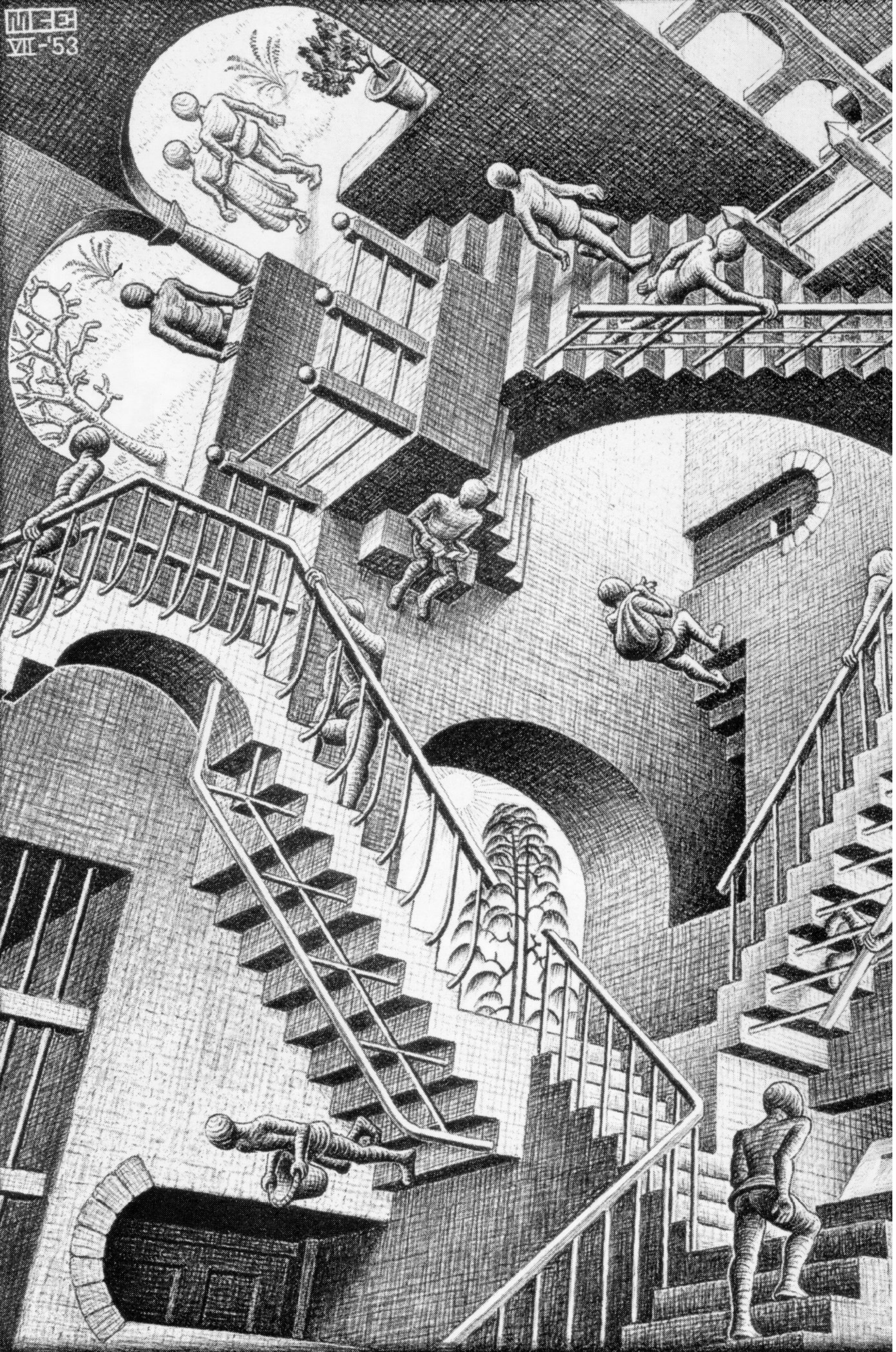
$$\left|\mathcal{M}_{a_1a_2\to Q\bar{Q}gg}\right|^2 = (\alpha_0\mu_0^{2\epsilon})^q(4\pi\alpha_0\mu_0^{2\epsilon})\left\langle\mathcal{M}^{(0)}\right|J^{a_1a_2}_{\mu\nu}(q_1,q_2)g^{\sigma\mu}g^{\rho\nu}J^{a_1a_2}_{\sigma\rho}(q_1,q_2)\left|\mathcal{M}^{(0)}\right\rangle$$

Need to compute: $\int d^nq_1\,d^nq_2\,J^{a_1a_2}_{\mu\nu}(q_1,q_2)g^{\sigma\mu}g^{\rho\nu}J^{a_1a_2}_{\sigma\rho}(q_1,q_2)$

DOUBLE GLUON EMISSION

$$\mathcal{S}_{ij}^{m=0}(q_1,q_2) = \frac{(1-\epsilon)}{(q_1\cdot q_2)^2}\frac{p_i\cdot q_1\, p_j\cdot q_2 + p_i\cdot q_2\, p_j\cdot q_1}{p_i\cdot(q_1+q_2)\, p_j\cdot(q_1+q_2)}$$
$$- \frac{(p_i\cdot p_j)^2}{2\, p_i\cdot q_1\, p_j\cdot q_2\, p_i\cdot q_2\, p_j\cdot q_1}\left[2 - \frac{p_i\cdot q_1\, p_j\cdot q_2 + p_i\cdot q_2\, p_j\cdot q_1}{p_i\cdot(q_1+q_2)\, p_j\cdot(q_1+q_2)}\right]$$
$$+ \frac{p_i\cdot p_j}{2\, q_1\cdot q_2}\left[\frac{2}{p_i\cdot q_1\, p_j\cdot q_2} + \frac{2}{p_j\cdot q_1\, p_i\cdot q_2} - \frac{1}{p_i\cdot(q_1+q_2)\, p_j\cdot(q_1+q_2)}\right.$$
$$\left.\times\left(4 + \frac{(p_i\cdot q_1\, p_j\cdot q_2 + p_i\cdot q_2\, p_j\cdot q_1)^2}{p_i\cdot q_1\, p_j\cdot q_2\, p_i\cdot q_2\, p_j\cdot q_1}\right)\right]$$

$$\mathcal{S}_{ij}^{m\neq 0}(q_1,q_2) = \frac{p_i\cdot p_j\, p_j\cdot(q_1+q_2)}{2\, p_i\cdot q_1\, p_j\cdot q_2\, p_i\cdot q_2\, p_j\cdot q_1\, p_i\cdot(q_1+q_2)}$$
$$- \frac{1}{2\, q_1\cdot q_2\, p_i\cdot(q_1+q_2)\, p_j\cdot(q_1+q_2)}\left(\frac{(p_j\cdot q_1)^2}{p_i\cdot q_1\, p_j\cdot q_2} + \frac{(p_j\cdot q_2)^2}{p_i\cdot q_2\, p_j\cdot q_1}\right)$$



CONCLUSIONS

- What?

  Computation of the hard virtual coefficient for $t\bar{t}$ production.

- Why?

  To implement q_t subtraction for coloured final state.

- Done:

  Computation of the n_f contribution

- To do:

  Complete the computation for the double gluon emission contribution