CONTENTS

➤ Motivations

➤ MATRIX

➤ My PhD Project

➤ Conclusions
HEAVY QUARK PRODUCTION AT THE LHC
HEAVY QUARK PRODUCTION AT THE LHC

- **Heavy quark** → Top quark
  
  *Third family quark, heaviest particle of the SM*
HEAVY QUARK PRODUCTION AT THE LHC

➤ Heavy quark → Top quark
   Third family quark, heaviest particle of the SM

➤ Production → Pair production
   $t\bar{t}$ production is the main source of top quark events in the SM
HEAVY QUARK PRODUCTION AT THE LHC

➤ Heavy quark → Top quark
   *Third family quark, heaviest particle of the SM*

➤ 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?
WHY TOP QUARK?

➤ Heaviest elementary particle known so far ($m_t \approx 173$ GeV)

*Strong coupling with the Higgs Boson*

*Study of $t \bar{t}$ production can shed light on electroweak symmetry breaking mechanism*
WHY TOP QUARK?

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

- 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

<table>
<thead>
<tr>
<th>arXiv id</th>
<th>Observable</th>
<th>t(\bar{t}) background?</th>
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<td>1802.08168</td>
<td>Missing Transverse Momentum</td>
<td>✔</td>
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<tr>
<td>1802.09572</td>
<td>t(\bar{t}) production</td>
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<tr>
<td>1802.06572</td>
<td>H → cc</td>
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<td>1802.03388</td>
<td>H → ZX/XX → 4 (\ell)</td>
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<td>1802.03158</td>
<td>Supersymmetry</td>
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<td>Tetraquark</td>
<td>❌</td>
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<td>1801.08769</td>
<td>q(\bar{q}) + γ or jet</td>
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<td>1801.07893</td>
<td>W′ → t b</td>
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<td>1801.06992</td>
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<td>t(\bar{t}) production</td>
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</tr>
<tr>
<td>1712.08891</td>
<td>pp → t(\bar{t}) H</td>
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*Zurich PhD Seminars, 09.03.18 - Simone Devoto*
# Most Recent ATLAS Papers

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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
HOW DO WE DESCRIBE TOP PAIR PRODUCTION?

➤ Perturbation theory → Feynman diagrams

Leading Order (LO)

$LO \rightarrow \text{order of magnitude prediction}$
HOW DO WE DESCRIBE TOP PAIR PRODUCTION?

➤ Perturbation theory → Feynman diagrams

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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Higher Orders (NLO - NNLO)

➤ They are necessary to obtain a reliable prediction
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Higher Orders (NLO - NNLO)

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QCD CORRECTIONS
They are challenging because of IR divergences!
WHY ARE QCD CORRECTIONS CHALLENGING?

Real

Virtual

\( q \rightarrow t \rightarrow g \rightarrow \bar{t} \)

\( \bar{q} \rightarrow t \rightarrow g \rightarrow q \)
WHY ARE QCD CORRECTIONS CHALLENGING?

Real

Virtual

IR Divergent

IR Divergent

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WHY ARE QCD CORRECTIONS CHALLENGING?

Real

Virtual

IR Divergent

IR Divergent

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

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

\[
\sigma^{NLO} = \int d\sigma^{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V
\]

Divergent \hspace{2cm} Divergent
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SUBTRACTION METHODS

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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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Convergent!

Convergent!

Divergent

Divergent

SUBTRACTION METHODS
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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MATRiX

Version: 1.0.0
Reference: arXiv:1711.06631

Munich — the MULTI-chanNeled Integrator at swiss (CH) precision —
Automates qT-subtraction and Resummation to Integrate X-sections

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 [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 qT subtraction.

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

- The computational framework MATRIX simplifies the evaluation of fully differential cross sections for a wide range of processes at hadron colliders.
- It utilizes $q_T$ subtraction to achieve next-to-next-to-leading order (NNLO) QCD accuracy.

**MATRIX**

**Description:**

**Version:** 1.0.0  
**Reference:** arXiv:1711.06631

**Munich — the MULTI-chAnnel Integrator at swiss (CH) precision —** Automates $q_T$-subtraction and Resummation to Integrate X-sections

**Authors:**
- M. Grazzini  
- S. Kallweit  
- M. Wiesemann

**MATRX 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.**

**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.**

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<td>ppw01</td>
<td>$p p \to W^+$</td>
<td>on-shell $W^+$ production with CRM</td>
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<tr>
<td>ppw01</td>
<td>$p p \to W^-$</td>
<td>on-shell $W^-$ production with CRM</td>
</tr>
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<td>$p p \to e^- e^+$</td>
<td>$Z$ production with decay</td>
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<tr>
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<td>$p p \to e^+ e^-$</td>
<td>$Z$ production with decay</td>
</tr>
<tr>
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<td>$p p \to e^- e^-  e^+ e^+$</td>
<td>$W^+$ production with decay and CRM</td>
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MY PhD PROJECT
MY PHD PROJECT

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

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

Coloured final state $\rightarrow$ QCD corrections also from the final state
To compute the missing ingredient to implement $t\bar{t}$ production at NNLO in MATRIX

Coloured final state → QCD corrections also from the final state
MY PHD PROJECT

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

Coloured final state → QCD corrections also from the final state
MY PHD PROJECT

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

Coloured final state  \rightarrow  QCD corrections also from the final state

\[ q \rightarrow q \]
\[ \bar{q} \rightarrow t \]
\[ \bar{q} \rightarrow \bar{t} \]
**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.

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

Can be computed with NLO subtraction techniques
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.

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

Can be computed with NLO subtraction techniques

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

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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.

\[
d\sigma_{Q\bar{Q}}^{NNLO} = H_{Q\bar{Q}}^{NNLO} \otimes d\sigma_{LO}^{Q\bar{Q}} + \left[ d\sigma_{Q\bar{Q}+\text{jet}}^{NLO} - d\sigma_{CT}^{NNLO} \right]
\]

**HARD VIRTUAL COEFFICIENT**

- Needs to be computed!

**Can be computed with NLO subtraction techniques**

**IR behaviour known from studies in $q_t$ resummation**

WHAT DO I NEED TO COMPUTE?

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:
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:

➤ proportional to the number of light quark flavours $n_f$;
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:

➤ proportional to the number of light quark flavours $n_f$;

➤ not proportional to the number of light quark flavours $n_f$. 
N\textsubscript{f} CONTRIBUTION

One has to consider:

➤ Soft quark pair production;

➤ NNLO contribution to single gluon emission;

➤ 2 loop contribution.
**N_f CONTRIBUTION**

One has to consider:

➤ 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!**
Nf CONTRIBUTION

Most tricky part: soft quark pair production.

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

Soft Limit

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

\[
k = q_1 + q_2 \quad J^\mu = T_i \frac{p_i^\mu}{p_i \cdot q} \quad \Pi^{\mu\nu}(q_1, q_2) = \frac{T_R}{(q_1 \cdot q_2)^2} (-g^{\mu\nu} q_1 \cdot q_2 + q_1^\mu q_2^\nu + q_1^\nu q_2^\mu)
\]

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

One has to consider:

➤ Double real contribution;
➤ Real - virtual contribution;
➤ 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: \[ a_1(p_1^\mu) a_2(p_2^\mu) \rightarrow Q(p_3^\mu) \bar{Q}(p_4^\mu) g(q_1^\mu) g(q_2^\mu) \]

**Soft Limit**

\[
J^{a_1 a_2}_{\mu \nu}(q_1, q_2) g^{\sigma \mu} g^{\rho \nu} J^{a_1 a_2}_{\sigma \rho}(q_1, q_2) = \frac{1}{2} \left\{ J^2(q_1), J^2(q_2) \right\} - C_A \sum_{i,j=1}^{n} T_i \cdot T_j S_{ij}(q_1, q_2)
\]

\[
S_{ij}(q_1, q_2) = S_{ij}^{m=0}(q_1, q_2) + \left( m_i^2 S_{ij}^{m\neq 0}(q_1, q_2) + m_j^2 S_{ji}^{m\neq 0}(q_1, q_2) \right)
\]

\[
\left| \mathcal{M}_{a_1 a_2 \rightarrow Q\bar{Q}gg} \right|^2 = (\alpha_0 \mu_0^2 \epsilon)^q (4\pi \alpha_0 \mu_0^2 \epsilon) \left\langle \mathcal{M}^{(0)} \right| J^{a_1 a_2}_{\mu \nu}(q_1, q_2) g^{\sigma \mu} g^{\rho \nu} J^{a_1 a_2}_{\sigma \rho}(q_1, q_2) \left| \mathcal{M}^{(0)} \right\rangle
\]

Need to compute:

\[
\int d^n q_1 \, d^n q_2 \, J^{a_1 a_2}_{\mu \nu}(q_1, q_2) g^{\sigma \mu} g^{\rho \nu} J^{a_1 a_2}_{\sigma \rho}(q_1, q_2)
\]

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DOUBLE GLUON EMISSION

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

\[
S_{ij}^{m\neq0}(q_1, q_2) = \frac{p_i \cdot p_j p_j \cdot (q_1 + q_2)}{2 p_i \cdot q_1 p_j \cdot q_2 p_i \cdot q_2 p_j \cdot q_1 p_i \cdot (q_1 + q_2)} \\
- \frac{1}{2 q_1 \cdot q_2 p_i \cdot (q_1 + q_2) p_j \cdot (q_1 + q_2)} \left( \frac{(p_j \cdot q_1)^2}{p_i \cdot q_1 p_j \cdot q_2} + \frac{(p_j \cdot q_2)^2}{p_i \cdot q_2 p_j \cdot q_1} \right)
\]
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*