# MULTIPLE PARTON SCATTERING AND ITS RELEVANCE FOR LHC PHENOMENOLOGY

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# Outline

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# My studies

## Brief history of my education

- 2008-2012 Bachelor in Physics at
  Taras Shevchenko National University of Kyiv
- 2012 - present Master in Physics at
  Taras Shevchenko National University of Kyiv
- 2013 - 2015 Master in Physics at
  Ecole Polytechnique, Paris
- 1st of October 2015 - present PhD at WWU
  Supervisors: Dr. Anna Kulesza, Dr. Ch. Klein-Bösing

# Research expierence

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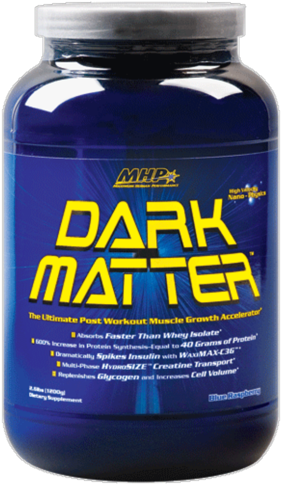
- HBT Correlations (Bachelor thesis):
  The role of HBT correlations in the final for nucleus-nucleus collisions
- Quantum Transport Subject:
  Equilibrium current through the quantum dot
- Quantum Chemistry Subject:
  Ab initial calculations spectra of molecules which belong to family of Phthalocyanines
- Particle Phenomenology (Master thesis):
  Minimal Supersymmetric Standard Model and its phenomenological relevance for dark matter annihilation, (group of Prof. Dr. Klasen)

# Dark Matter Problem




**WIMPs**

Visible matter is only small fraction of the Universe (only about 5%)

Neutralinos are good candidates for WIMPs (weakly interacting massive particles)

Phenomenology of Neutralinos is crucial for understanding true nature of Dark Matter

# The goal of my internship

## Study of neutralino annihilation in a pair of gluons

- In order to compute the relic density the neutralino annihilation cross section is needed
- The precision of measurements (WMAP and Planck satellite experiments) is about 1% now!
- The Next to Leading Order Corrections can give rise a significant contribution to the relic density[1]
- The goal of my internship was to implement all corresponding matrix elements squared (about 100 elements) into a DM@NLO code

[1] Björn Herrmann, Michael Klasen, Karol Kovařík, arXiv:0907.0030v2 [hep-ph]

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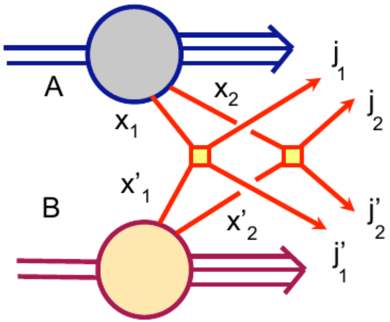
# Multiple Parton Scattering




**What it's all about**

MPI cross sections are suppressed by a factor $\left(\Lambda^2_{QCD}/Q^2\right)^{n-1}$

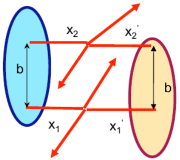
But this suppression factor is absent for the differential cross section

**What it's all about**

Multiple parton scattering is a process when two or more interactions between proton (nucleon) constituents occur at the same time (during one collision)

An important background for High-Precision SM (BSM)

# Multiple Parton Scattering: Factorization




**The "pocket" formula**

$$\sigma_{AB}^{D} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

**The cross section is given by:**

$$\sigma_{AB}^{D} = \frac{m}{2}\sum_{i,j,k,l}\int D_{ij}\hat{\sigma}_{ik}^{A}\hat{\sigma}_{jl}^{B}D_{kl}$$

$$D_{ij}(x_1, x_2; b) \simeq D_i(x_1)\, D_j(x_2)\, F(b) \quad \Longrightarrow \quad \sigma_{AB}^{D} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

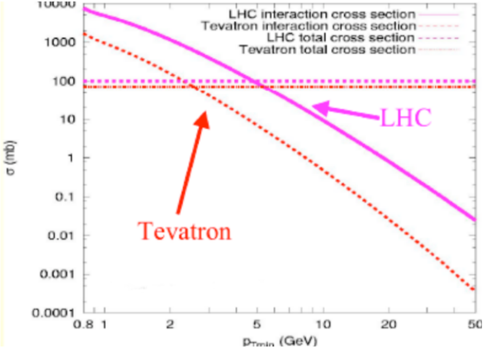
# Research plan

**Research plan:**

- Investigation of theoretical assumptions (factorization) and its impact on LHC phenomenology
- Study of DPS in $pp + pA$ collisions
- Feasible study of DPS measurements with ALICE detector

# Outline

# Multiple Parton Scattering: Unitarity violation




**Why it happens?**

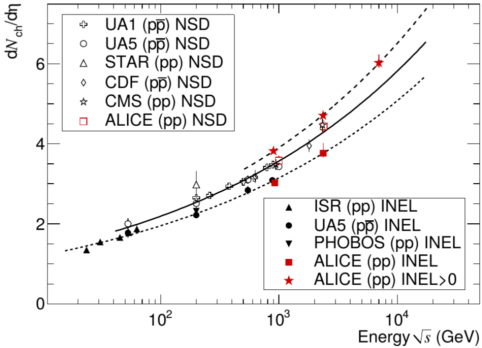
Unitarity is restored by introducing multiple parton interactions

$\sigma_{in} = \sigma_{soft} + \sigma_H$

Where $\sigma_H$ now corresponds to MPI

[2] T. Sjöstrand, P. Skands, arXiv:hep-ph/0402078v2 [hep-ph]

# Multiple Parton Scattering: Scaling violation



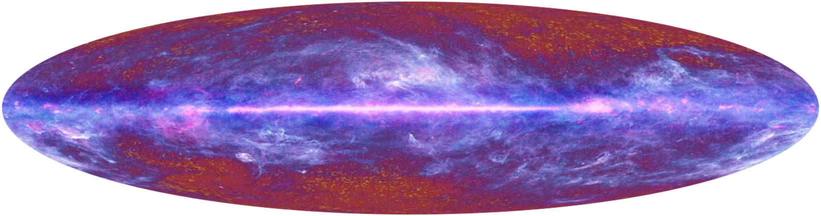

**Multiplicity distribution**

The Feynmann scaling implies that multiplicity distribution should behave like $\sim \ln s$

But experiment shows us that it behaves as $\sim A \ln s + B \ln^2 s$

Multiple scattering provides an additional term $\sim \ln^2 s$

# Relic density



## Relic density of neutralinos:

$\Omega_{\bar{\chi}} \mathrm{h}^2 = \frac{n_0 m_{\bar{\chi}}}{\rho_c}$ $\rho_c = \frac{3\mathrm{H}_0^2}{8\pi \mathrm{G}_N}$

The Boltzmann equation:

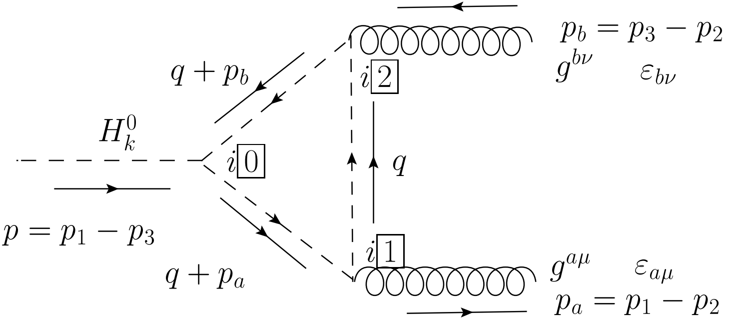
$\frac{\mathrm{d}n_{\bar{\chi}}}{\mathrm{d}t} = -3\mathrm{H} n_{\bar{\chi}} - \langle \sigma_{ann} v \rangle \left( n_{\bar{\chi}}^2 - n_{equ}^2 \right)$

Computing cross section $\langle \sigma_{ann} v \rangle$ and solving the Boltzmann equation, one can find the relic density of neutralinos

# Computational strategy

- Generate all possible one-loop diagrams for $\bar{\chi}\bar{\chi} \to gg$.
- Group all possible one-loop diagrams (about 60 diagrams) by topological classes (19 different topologies).
- Eliminate all topologies with zero contribution (9 topologies).
- Compute the rest (10 topologies) using Passarino-Veltman decomposition.
- Implement obtained results into DM@NLO code, compute the cross section numerically.

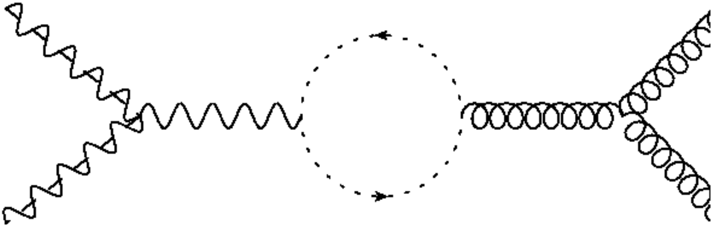
# Passarino-Veltman decomposition




**The Higgs boson decay and the corresponding vertex correction**

$$V_2^{\mu\nu} \sim \int_q \frac{q^\mu q^\nu}{D_0 D_1 D_2} \sim C^{\mu\nu} = g^{\mu\nu} C_{00} + \sum_{i,j=a,b} p_i^\mu p_j^\nu C_{ij}$$

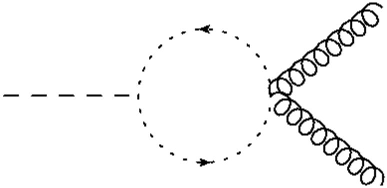
# The topologies with zero contribution



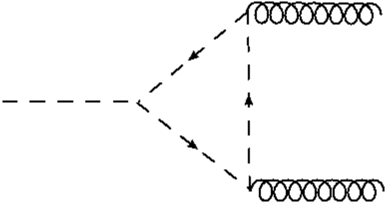
## SU(3) gauge invariance

- In this process all diagrams with intermediate gluon will give a zero contribution
- It is not possible to decompose SU(3) octet into a SU(3) singlet!
- The corresponding color factor $\mathrm{tr}\left(\mathrm{T}^{\mathrm{a}}\right) = 0$ ensures us that the gauge invariance will be preserved

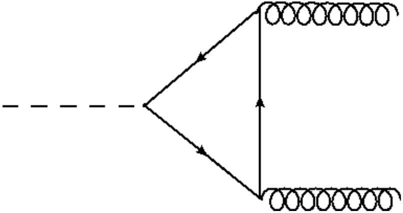
# The Higgs boson decay channel



a)



b)



c)

**Cancellation of UV-divergences**

$$\text{div}\left[V_a^{\mu\nu} + V_b^{\mu\nu}\right] = 0$$
$$\text{div}\left[V_c^{\mu\nu}\right] = 0$$

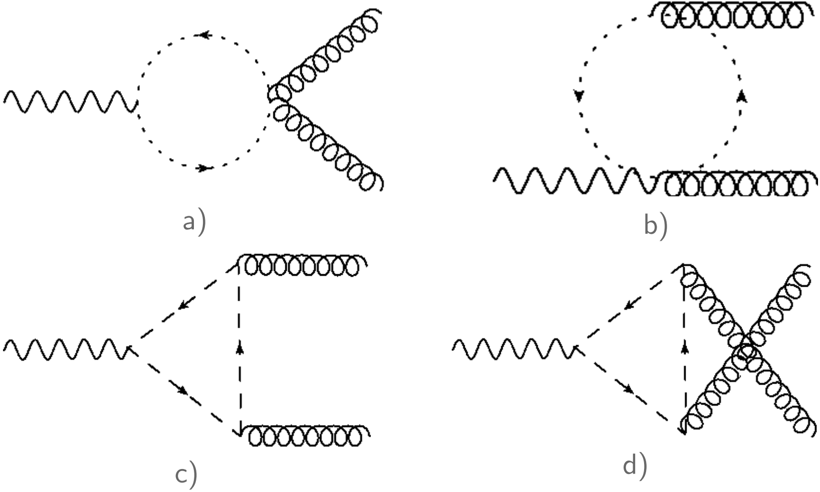
# The Z boson decay channel

## The Z boson decay channels are more interesting

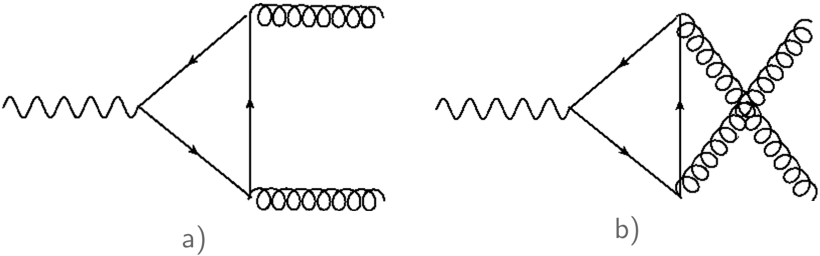
- Landau-Yang theorem does not work for off-shell particles[3]
- The Furry theorem claims that we cannot attach an odd number of "vector" legs to closed fermion loop
- As a consequence the massive off-shell spin one particle with an axial coupling can decay into two a pair of photons (gluons)

[3] S.Moretti, Variations on a Higgs theme, arXiv:1407.3511v1 [hep-ph]

# The Z boson decay channel



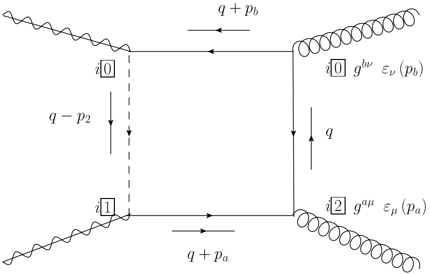
# The Z boson decay channel




## Cancellation of UV-divergences

- Sum of $\mathrm{T}$ and $\mathrm{U}$ channels is UV-finite
- Only axial part of Z boson's coupling $(g_V + g_A\gamma_5)$ remains (due to the Furry theorem)
- $\mathrm{div}\left[V_a^{\mu\nu} + V_b^{\mu\nu}\right] = 0$

# The box-like diagrams




## All box-like diagrams are UV-convergent

$$\frac{\left[\not{q} + \not{p}_a + m_f\right] \gamma^\mu \left[\not{q} + m_f\right] \gamma^\nu \left[\not{q} + \not{p}_b + m_f\right]}{\left[q^2 - m_f^2\right] \left[(p_a + q)^2 - m_f^2\right] \left[(p_b + q)^2 - m_f^2\right] \left[(q - p_2)^2 - m_q^2\right]}$$

# Conclusions

## Conclusions and further steps

- I have computed set of general topologies for $\bar{\chi}\chi \to gg$
- Sum of all topologies is UV-finite
- I have learned how to use Passarino-Veltman technique and also how to use LoopTools, FernCalc and FORM packages for analytical and numerical one-loop computations
- Currently I am working on implementation of matrix elements squared into the DM@NLO code
- General form of computation allows to apply the obtained results for inverse process $gg \to \bar{\chi}\chi$ and also to use them for processes which have common topologies
- As an extension the inverse process can be implemented into RESUMMINO (LHC phenomenology) code