NLO corrections to massive vector color octet pair production

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Fig.1 A multi-loop correction to a tree

Based on arXiv:1705.xxxx

with A. Freitas

NLO – the Why, the What and the How

- the Why
  - QCD corrections can be **sizeable** $O(10-20\%)$
  - **Unphysical** μ_R/μ_F dependence is more suppressed
- the What
  - massive Vector Color Octets prominent feature (e.g. **UED**)
  - Appropriate low-energy theory (**Coloron**[1]) renormalizable without knowing UV
- the How
  - Massless particles lead to **Infrared/Collinear Divergencies**
  - Use **Two Cutoff Phase Space Slicing**
  -
  - FeynArts/FeynCalc had (until now) no Coloron model/QCD@NLO toolbox

[1] E.Simmons, A. Atre, R. Chivukula et al hep-ph/1304.0255

QCD@NLO: Divergencies

$$|\langle in|out\rangle|^2 = \left|\sum_n \alpha_s^n \mathcal{M}_n\right|^2 = \alpha_s^2|\mathcal{M}_{LO}|^2 + 2\alpha_s^3\,\mathrm{Re}|\mathcal{M}_{LO}\mathcal{M}_{NLO}| + \cdots$$

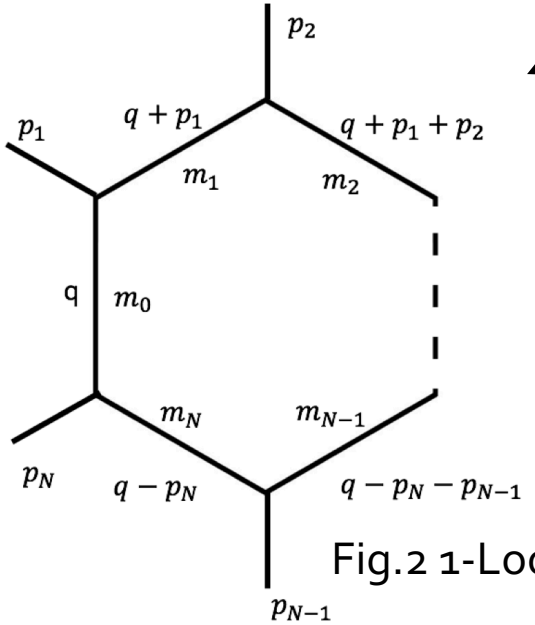
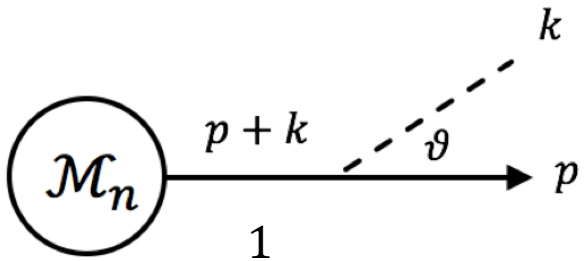


Fig.2 1-Loop conventions

Same order in

perturbation theory

Fig.3 Final state real emission



$$\frac{1}{2(p\cdot k)} = \frac{1}{2E_k\left(E_p - |\vec{p}|\cos\vartheta\right)}$$

But…

$$T_N^{\mu_1\mu_2\ldots\mu_k} = \frac{(2\pi\mu)^{4-D}}{i\pi^2}\int d^Dq\,\frac{q^{\mu_1}q^{\mu_2}\,\ldots\,q^{\mu_k}}{(q^2-m_0^2)\left((q+p_1)^2-m_1^2\right)\ldots\left((q-p_N)^2-m_N^2\right)}$$

Kinoshita-Lee-Nauenberg: The NLO observables are IR-finite order by order in perturbation theory

Two Cutoff Phase Space Slicing

$$\sigma_{2\to3} = \int \sum |M_{2\to3}|^2 d\Gamma_3 = \int_{Soft} \sum |M_{2\to3}|^2 d\Gamma_3 + \int_{HC} \sum |M_{2\to3}|^2 d\Gamma_3 + \int_{HNC} \sum |M_{2\to3}|^2 d\Gamma_3$$

<u>Soft/Collinear Region</u>

$$0 \le E_g \le \delta_s \frac{\sqrt{s}}{2}$$

$$d\sigma_{soft} = \frac{\alpha_s}{2\pi} \frac{\Gamma(1-\varepsilon)}{\Gamma(1-2\varepsilon)} \left(\frac{4\pi\mu^2}{s}\right)^{\varepsilon} d\sigma_{LO} \times \sum_{f,f'} \underbrace{\int dS \frac{-p_f \cdot p_{f'}}{(p_f \cdot k)(p_{f'} \cdot k)}}_{I_D^{(k,l)}}$$

→ Factorization for **color subamplitudes**

→ Regularized angular integrals scattered through literature

<u>Hard/Collinear Region</u>

$$0 \le -\left(p_i - p_g\right)^2 = \sqrt{s} E_g (1 - \cos\vartheta) \le \delta_c s$$

$$d\sigma_{coll} = \frac{\alpha_s}{2\pi} \frac{\Gamma(1-\varepsilon)}{\Gamma(1-2\varepsilon)} \left(\frac{4\pi\mu^2}{s}\right)^{\varepsilon} \left(-\frac{1}{\varepsilon}\right) \delta_c^{-\varepsilon} \times \left\{ \int_0^{1-\delta_s} \frac{dz}{z} \left[\frac{1-z}{z} \frac{s}{\mu_F^2} \delta_c\right]^{-\varepsilon} P_{ii'}(z) d\sigma_{LO}^{ji'} + (i \leftrightarrow j) \right\}$$

Altarelli-Parisi Kernel

→ Redefine **Parton Density Functions** to absorb the Pole

$$\tilde{\mathcal{F}}(x, \mu_F) = \frac{\alpha_s}{2\pi} \sum_k \int_x^{1-\delta_s} \frac{dz}{z} \mathcal{F}_k\left(\frac{x}{z}\right) \left[P_{ik}(z) \log\left(\frac{s}{\mu_F^2} \frac{1-z}{z} \delta_c\right) - P'_{ik}(z)\right]$$

[1] B. Harris, J. Owens hep-ph/0102128

Master formula for any 2→2 process in QCD@NLO

$$\sigma_{NLO} = \sum_{i,j} \int dx_1 dx_2 \mathcal{F}_i(x_1,\mu_f)\mathcal{F}_j(x_2,\mu_f)\left[\sigma_{LO}^{ij}(x_1,x_2,\mu) + \sigma_{Virt}^{ij}(x_1,x_2,\mu) + \sigma_{soft}^{ij}(x_1,x_2,\mu)\right]$$

$$+\frac{\alpha_s}{2\pi}\sum_{i,j}\int dx_1 dx_2 \int_{x_1}^{1-\delta_s} \frac{dz}{z}\left[\mathcal{F}_i\left(\frac{x_1}{z},\mu_f\right)\mathcal{F}_j(x_2,\mu_f) + \mathcal{F}_i(x_2,\mu_f)\mathcal{F}_j\left(\frac{x_1}{z},\mu_f\right)\right]$$

$$\times\sigma_{LO}^{ij}\left[P_{ik}(z)\log\left(\frac{s(1-z)\delta_c}{z\mu_F^2}\right) - P'_{ik}(z)\right] + (i \leftrightarrow j) + \int_{HNC} \sum |M_{2\to3}|^2 d\Gamma_3$$

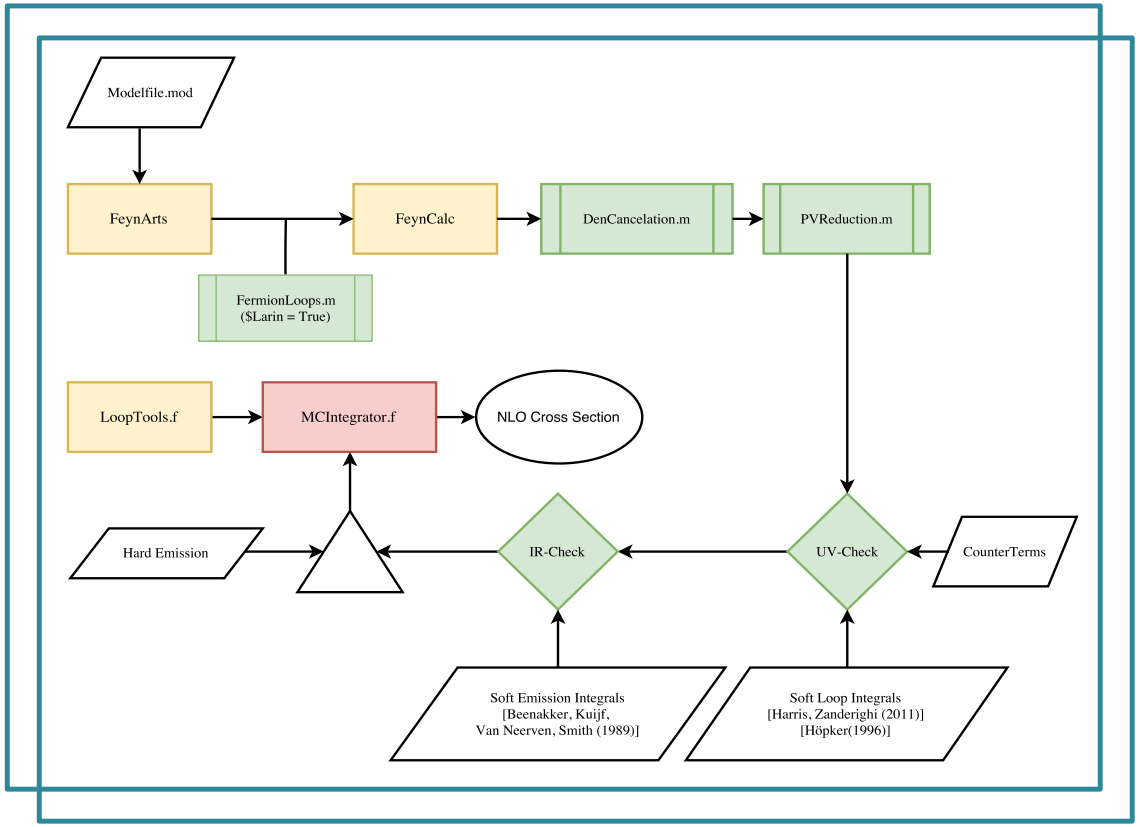
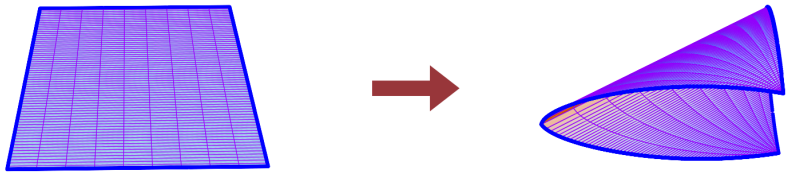
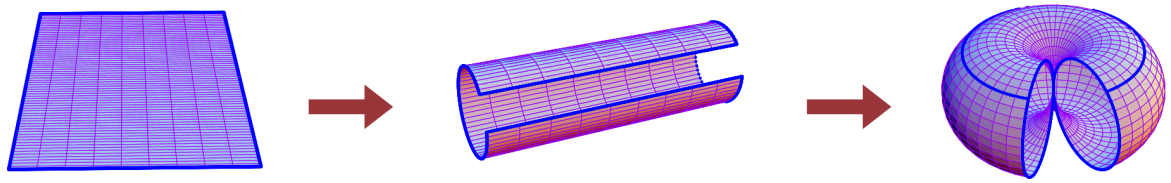


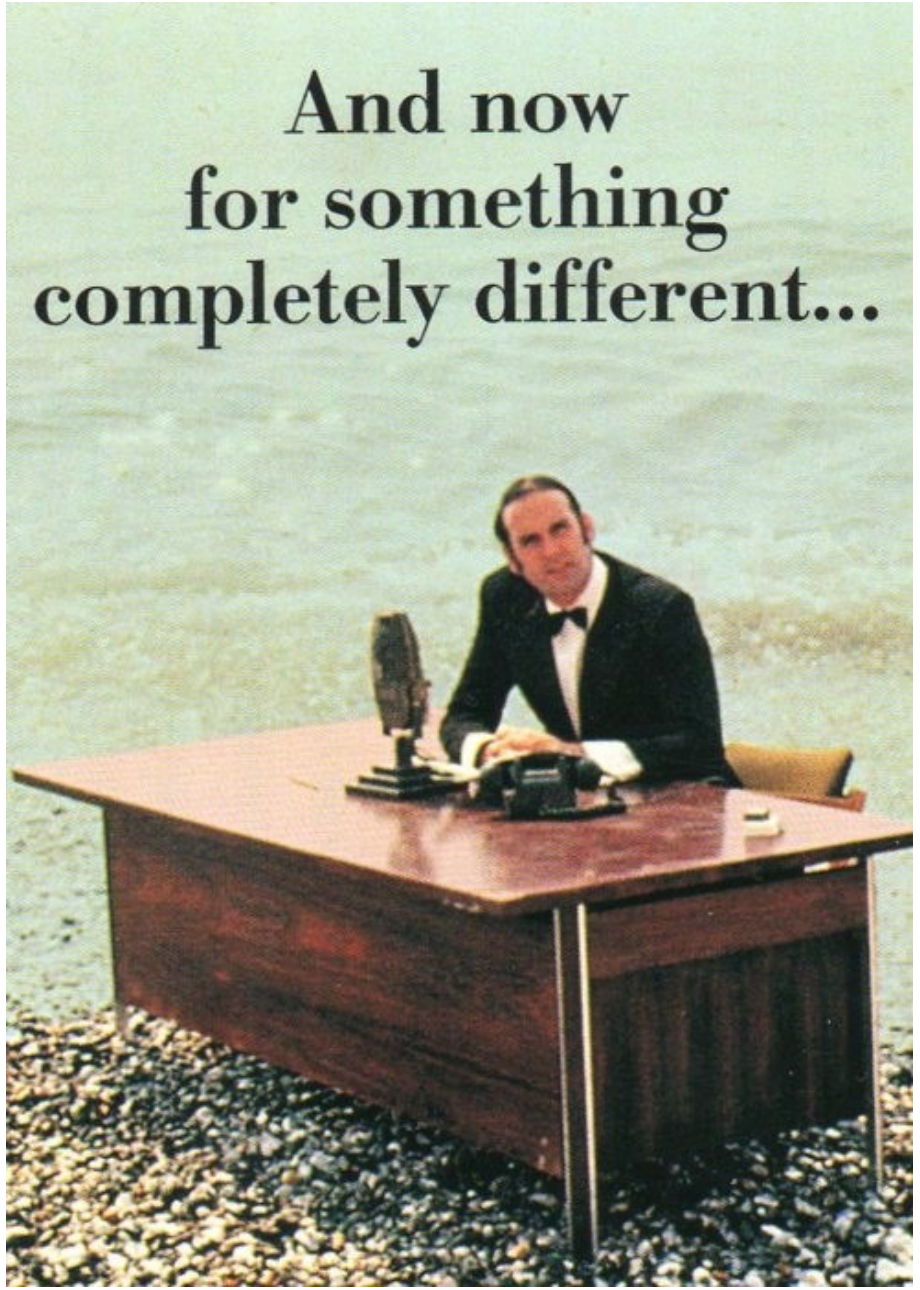
Fig.4 The production pipeline showing the implementation in the FeynArts/FeynCalc framework

1) T. Hahn hep-ph/0012260
2) T. Hahn hep-ph/1006.2231



Extra Dimensions and Colorons





Universal Extra Dimensions (UED)

Universal Extra Dimensions:

- Assume five-dimensional spacetime manifold
- To explain four-dimensional world impose boundary conditions (Kaluza Klein Compactification/**Orbifolding**)
- Fields $\Psi(x^\mu, y)$ propagating can be decomposed into Fourier modes
- ψ_0 are the standard model modes, ψ_n a tower of additional (heavy) excitations of mass $M = \frac{n}{R}$

$$\Psi(x^\mu, y) = \frac{1}{\sqrt{\pi R}}\psi_0(x) + \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty}\psi_n(x)\cos\frac{ny}{R}$$

(Current Limit: $M \geq 1400\text{GeV}$ with $\Lambda R \sim 10^{1,2,3}$ @LO)

$$A_M^a(x,y) \quad \rightarrow \quad A_M^a(x,y) + \partial_M\Theta^a(x,y) - g_5 f^{abc}\Theta^a(x,y)A_M^c(x,y)$$

$$\rightarrow \quad A_\mu^{0,a} \rightarrow A_\mu^{0,a} + \partial_\mu\Theta^{0,a} - \frac{1}{2}\frac{g_5}{\sqrt{2\pi R}}f^{abc}\sum_m 2^{1-\delta_{m,0}}(1+\delta_{m,0})\Theta^{m,b}\,A_\mu^{m,c}$$

$$\rightarrow \quad A_\mu^{n,a} \rightarrow A_\mu^{n,a} + \partial_\mu\Theta^{n,a} - \frac{1}{2}\frac{g_5}{\sqrt{2\pi R}}f^{abc}\sum_m \sqrt{2}^{1-\delta_{m,0}}\Theta^{m,b}\left(\sqrt{2}^{\delta_{m,n}}(1+\delta_{m,n})A_\mu^{m-n,c} + A_\mu^{m+n,c}\right)$$

$\longrightarrow$ Truncation breaks gauge invariance!

1) N. Deutschmann, T.Flacke, J. Kim hep-ph/1702.00401

2) K. Matchev, A.Datta et al hep-ph/1702.00413

3) ATLAS hep-ex/1501.03555

Building a Non-Linear Sigma Model

$SU(3)_1 \times SU(3)_2 \times SU(2)_W \times U(1)_Y$

$\langle \chi_a \rangle = v\, \mathbb{1}_a$

$SU(3)_C \times SU(2)_W \times U(1)_Y$

$SU(3)_C \times U(1)_{EM}$

With massless gauge bosons A_1^μ , A_2^μ

Introduce a Σ field that transforms **non-linearly** under the full group

$$\Sigma \to U_1\, \Sigma U_2^\dagger \qquad\qquad \Sigma = \exp\left({}^{i\chi_a T^a}\!/_{f}\right)$$

With the vev of the Goldstone Boson χ_a breaking the $SU(3)_1 \times SU(3)_2$

For which we can built a Lagrangian that respects the symmetry

$$\mathcal{L}_\Sigma = \frac{f^2}{2} Tr\left[\left(D_\mu \Sigma\right)^\dagger D^\mu \Sigma\right] - \frac{1}{4} Tr\left[F_1^{\mu\nu} F_{1,\mu\nu}\right] - \frac{1}{4} Tr\left[F_2^{\mu\nu} F_{2,\mu\nu}\right]$$

Diagonalized mass terms reveals a massive and a massless vector octet

$$C^\mu = \sin\alpha\, A_1^\mu + \cos\alpha\, A_1^\mu$$
$$g^\mu = \sin\alpha\, A_2^\mu - \cos\alpha\, A_1^\mu$$

$$\tan(\alpha) = \frac{g_2}{g_1} = 1$$

"coupling universality"

"KK parity "

$\mathbb{Z}_2$ Symmetry: $G_1^\mu \leftrightarrow G_2^\mu$ becomes $g^\mu \to g^\mu \quad C^\mu \to -C^\mu \quad \Sigma \to \Sigma^\dagger$

Additionally introduce gauge-fixing and ghosts $\mathcal{L}_{GF} = -\frac{1}{2\xi_g}\left(\partial_\mu g^\mu\right)^2 - \frac{1}{2}\left(\frac{1}{\sqrt{\xi_{G1}}}\partial_\mu C^\mu - \sqrt{\xi_{G2}} M \chi\right)^2$

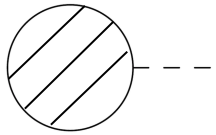
Renormalization

Fields and Masses

$$\delta Z_{GG} = -\mathrm{Re}\,\frac{\partial \Sigma^T_{GG}(p^2)}{\partial p^2}\bigg|_{p^2=M^2} \qquad \delta Z_{gg} = -\mathrm{Re}\,\frac{\partial \Sigma^T_{gg}(p^2)}{\partial p^2}\bigg|_{p^2=0} \qquad \delta M^2_{kk} = -\mathrm{Re}\Sigma^T_{kk}(M^2)$$

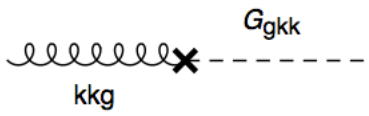
On-Shell conditions

Tadpoles

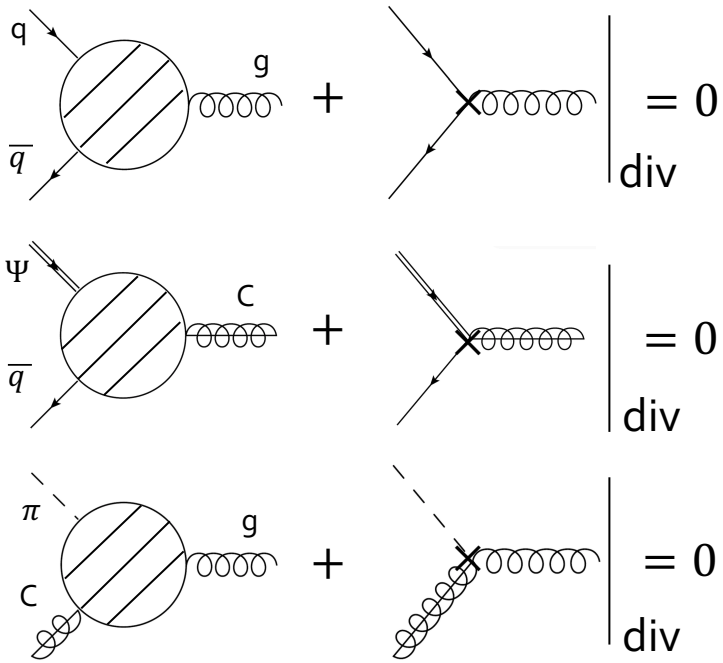


$$= i\,Tad = i\,\Sigma_{GB}(p^2)\Big|_{p^2=0}$$

Ending up in a **Goldstone/Coloron mixing** term



Couplings ($\overline{MS}$)



Same coupling
Different CT
Different Running

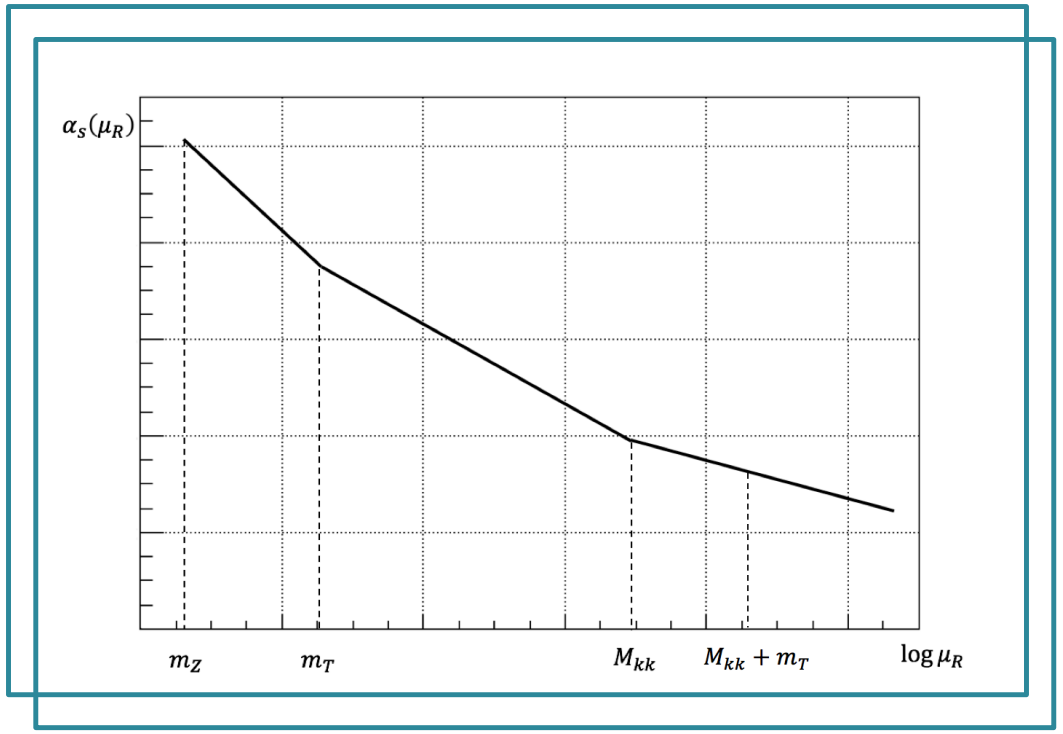
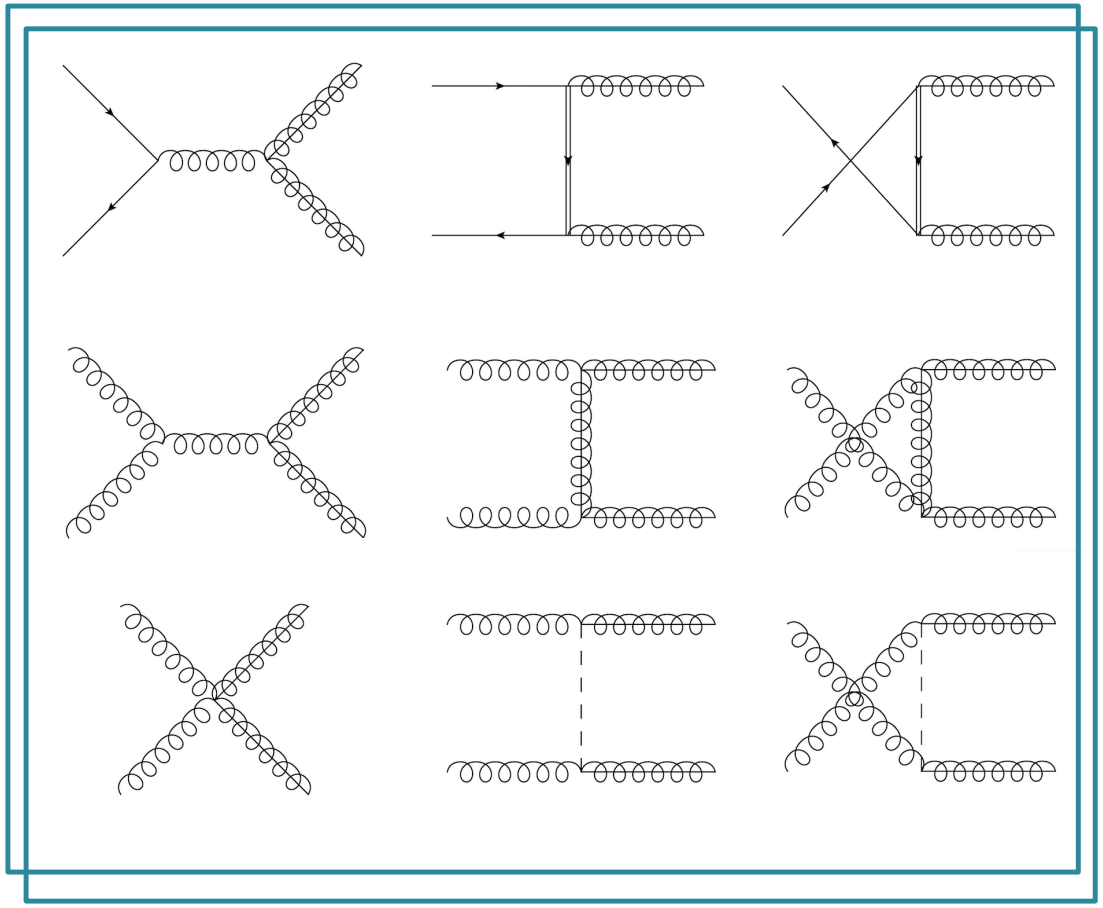


Fig.5 Decoupling of heavy particles in α_s

Coloron Production at LHC

Fig.6 Diagrams contributing to
the Born cross section



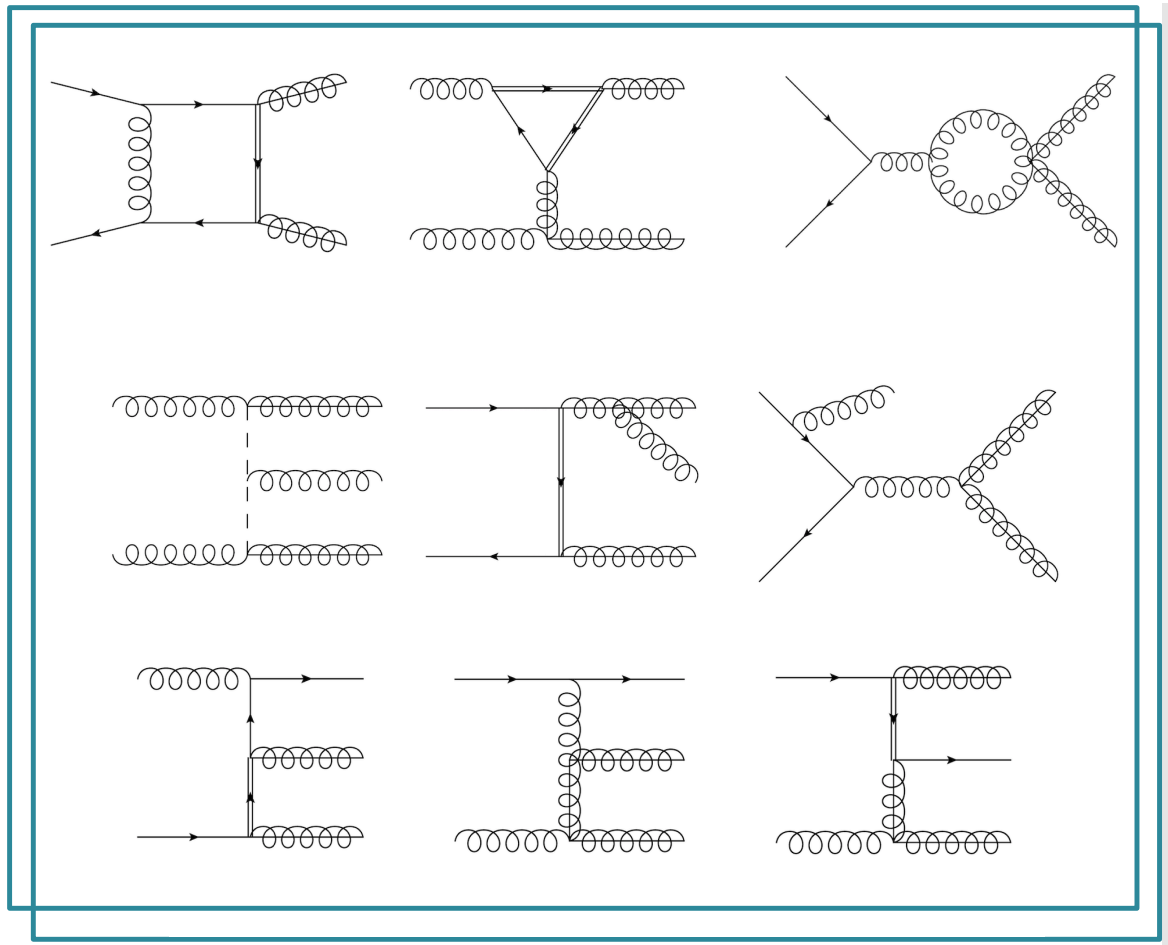


Fig.7 Diagrams contributing to
A) the virtual cross section
B) Real emission part
C) quark-gluon channel

Cutoff Dependence

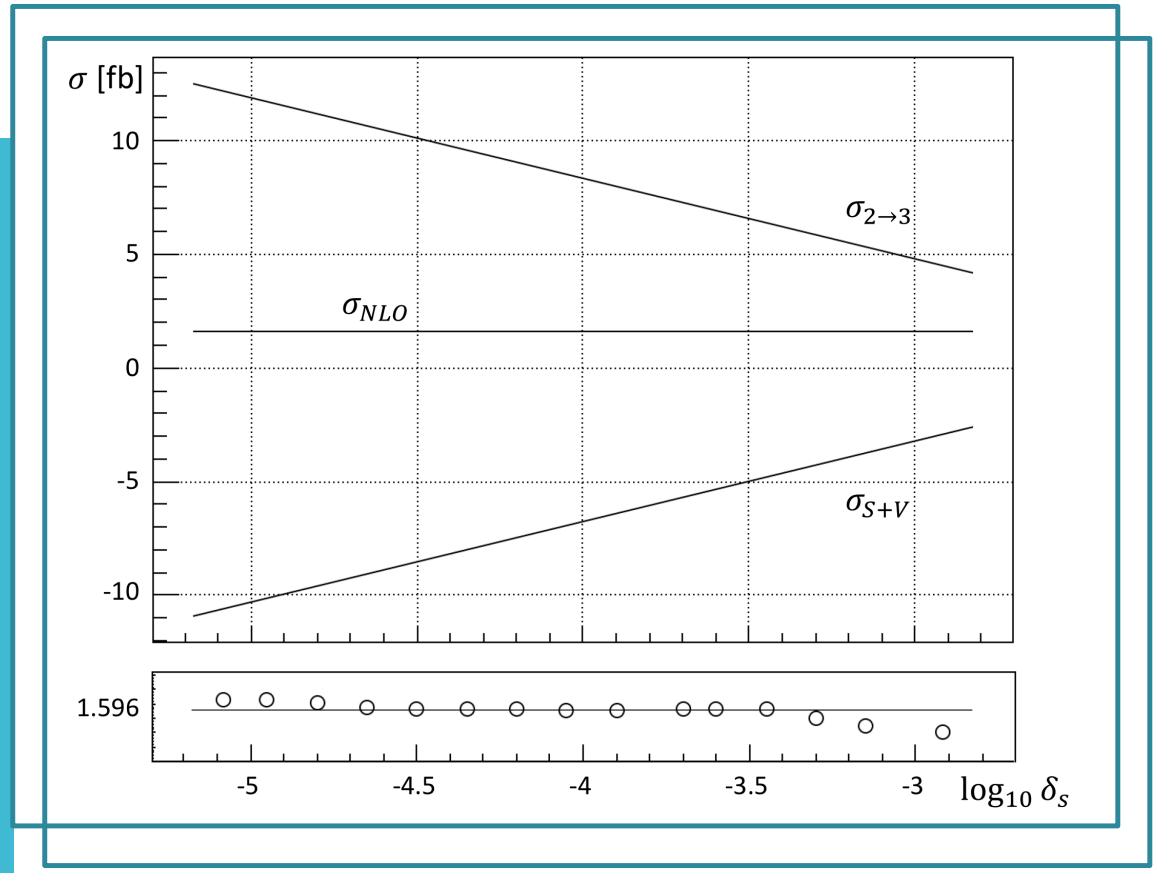
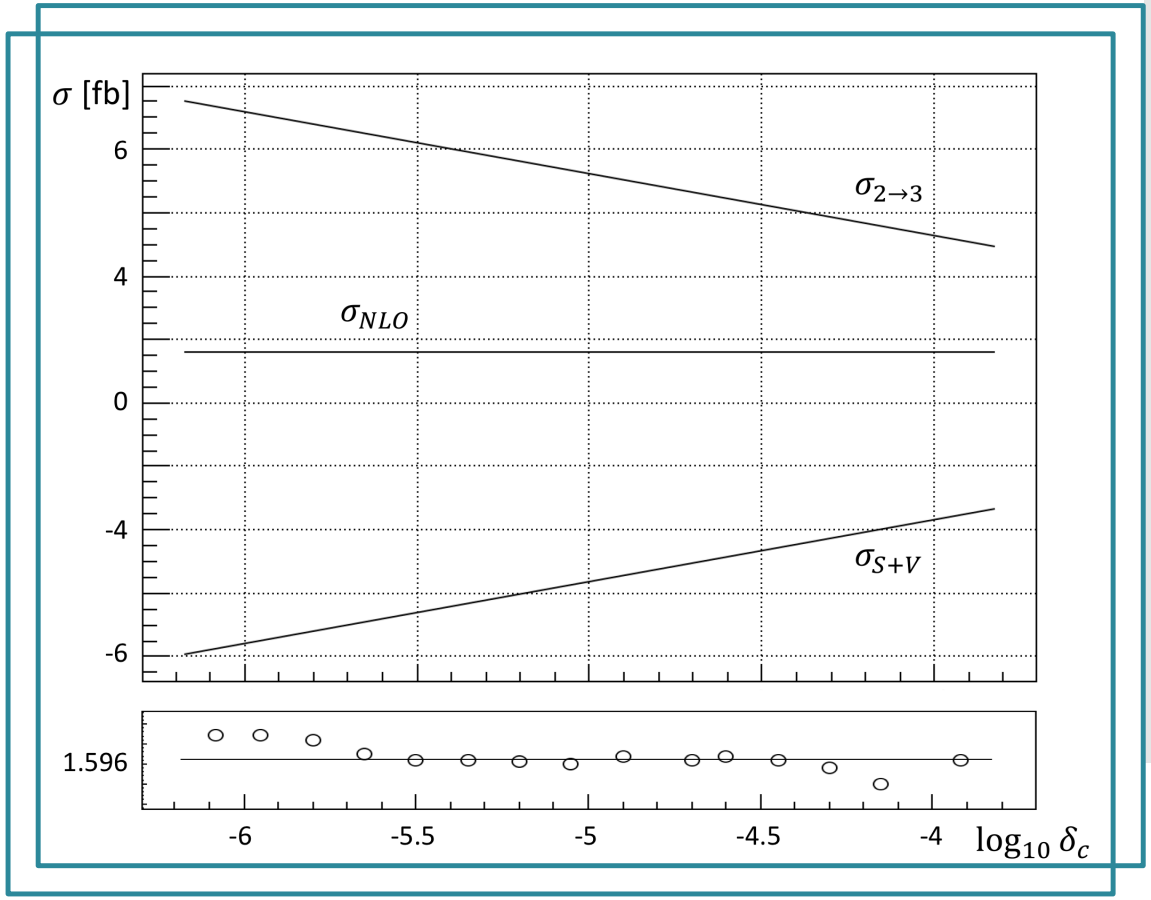


Fig.8 δ_s dependence of σ_{NLO}
($M_{kk} = \mu_R = \mu_f = 1\text{TeV}$, $\delta_c = 7\times10^{-6}$,
$\sqrt{s} = 14\text{TeV}$)

Fig.9 δ_c dependence of σ_{NLO}
($M_{kk} = \mu_R = \mu_f = 1\text{TeV}$, $\delta_s = 7\times10^{-6}$,
$\sqrt{s} = 14\text{TeV}$)



Scale Dependence

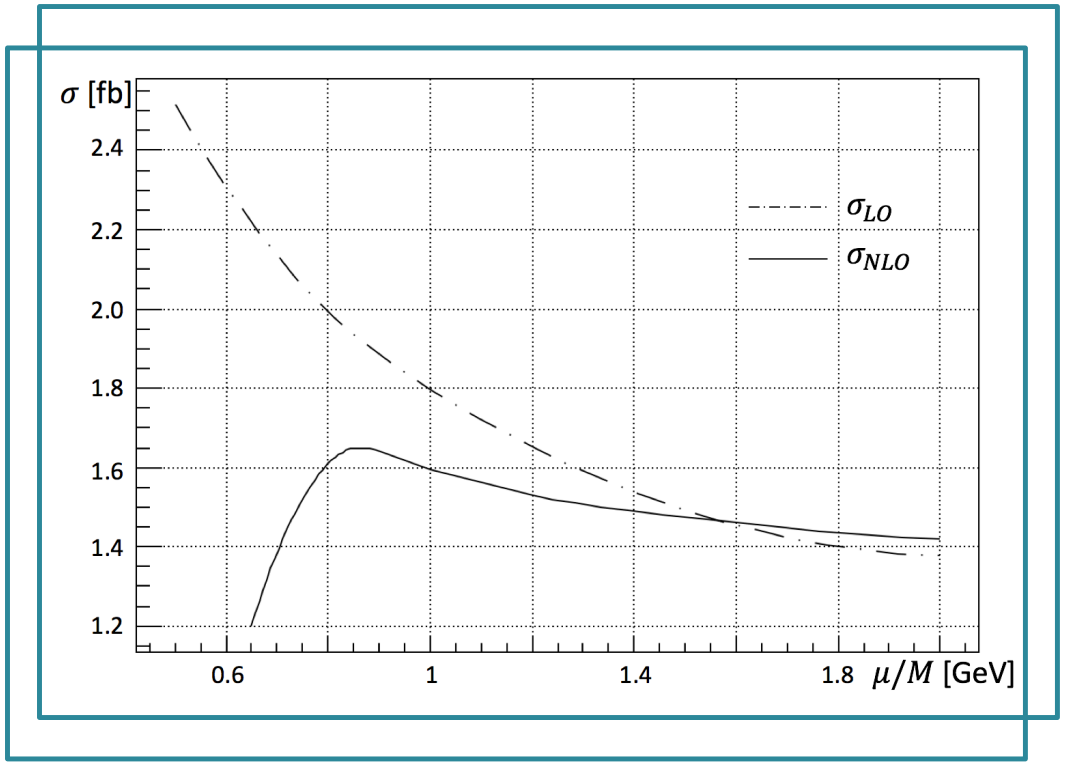
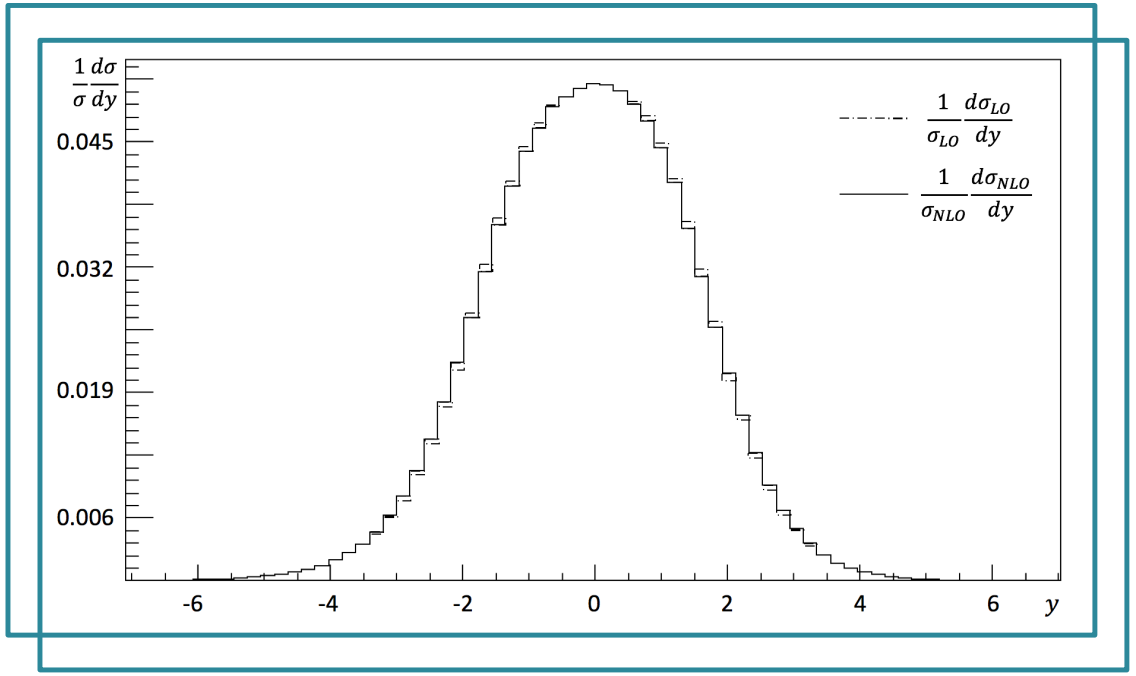


Fig.10 Variation of the scales ($\mu_R = \mu_F$) for 1TeV Colorons

Fig.11 Rapidity distribution of the Colorons ($M = \mu_{R/F} = 1$ TeV)



Mass Dependence

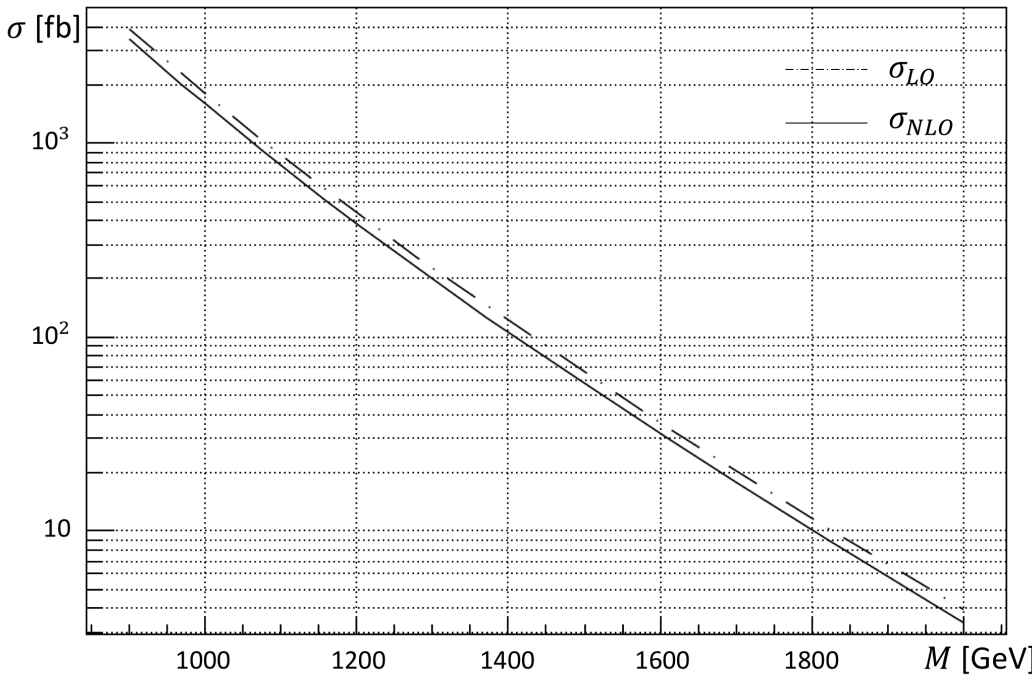
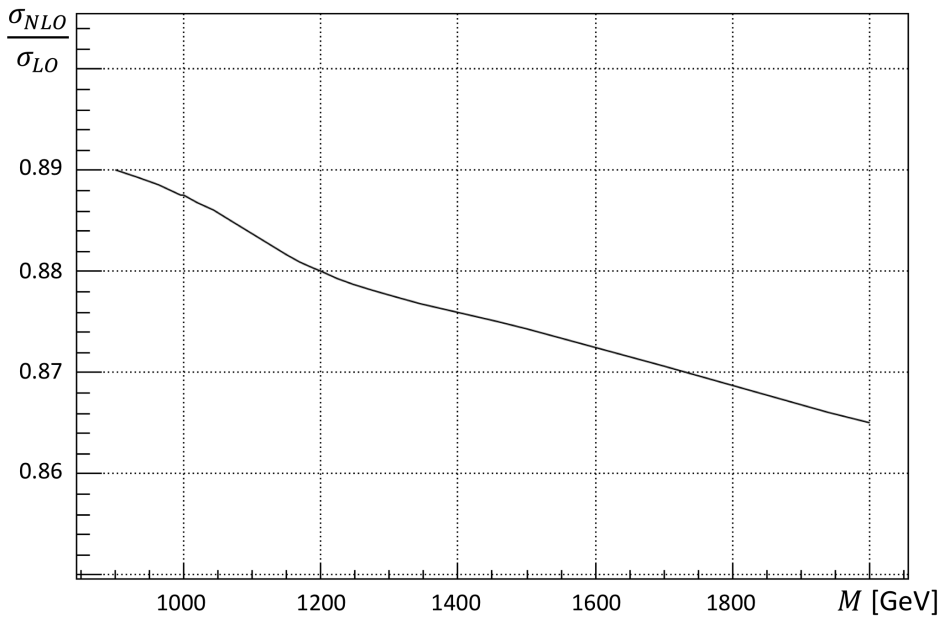


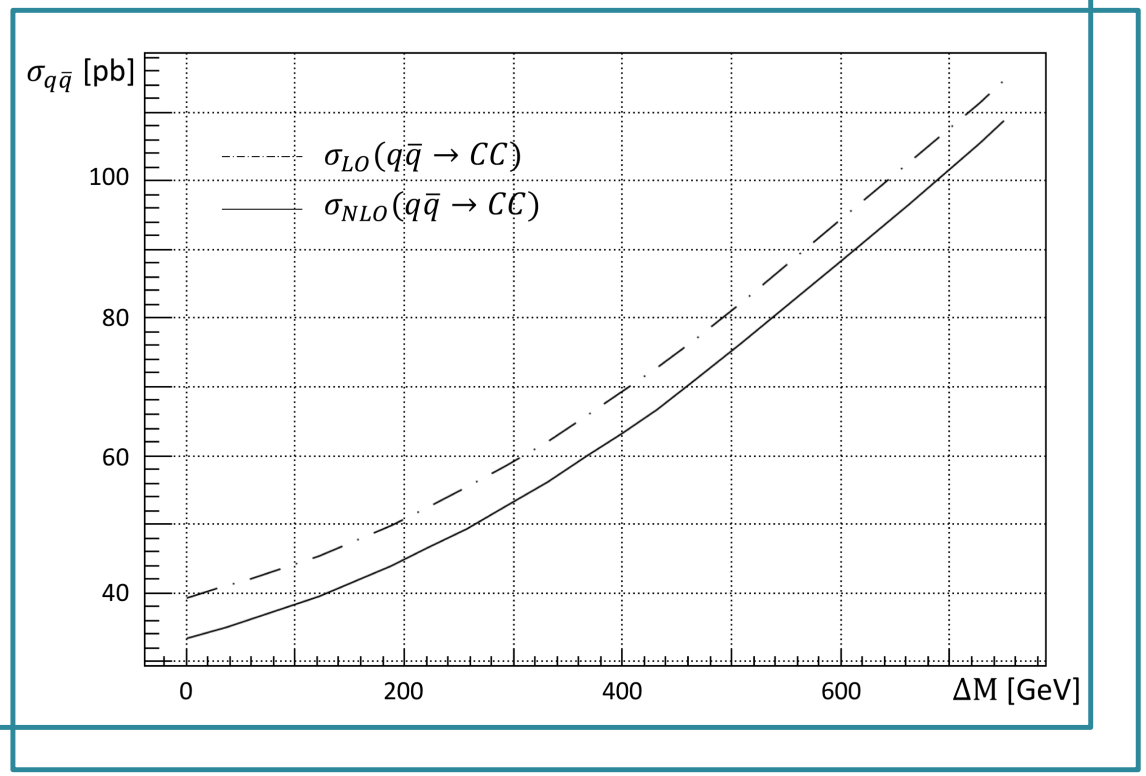
Fig.12 Mass dependence of the NLO cross section

Fig.13 Mass dependence of the κ-Factor



Mass Splitting

Fig.14 Mass splitting of the NLO cross section vs LO (quark channel only)



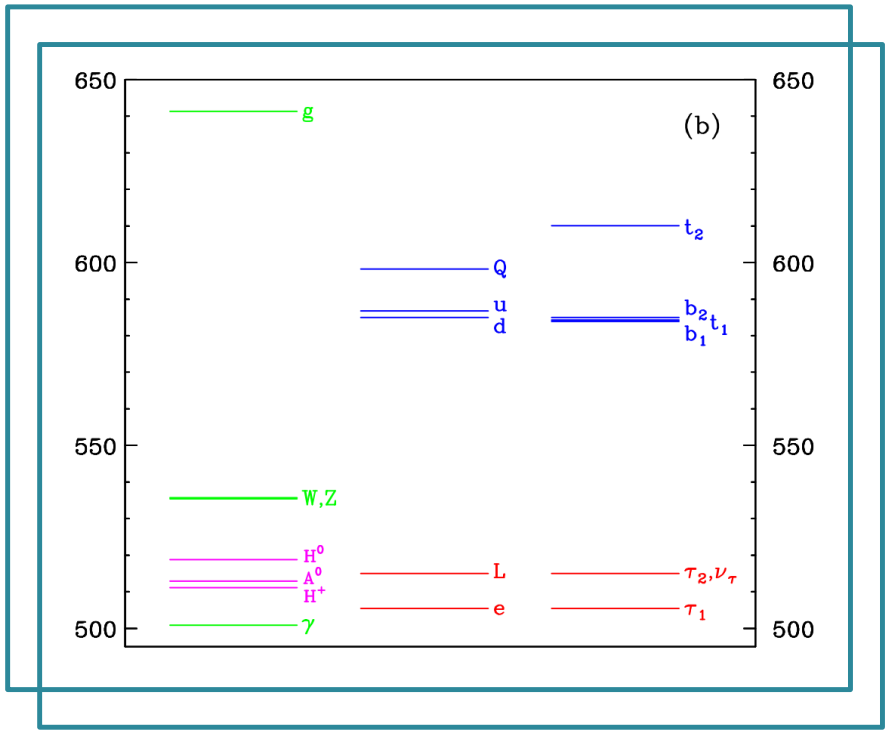


Fig.15 Radiative Corrections to the KK 1-modes[1]

UED: Masses largely degenerate ⟹receive radiate corrections (**Bulk** and **Boundary** terms)

Coloron: Masses independent parameters ⟹ Mimic UED

$$\Delta M = \delta M_C - \delta M_Q = \frac{\alpha_s}{4\pi} M^2 \left[-\frac{3}{2}\frac{\xi(3)}{\pi} + \frac{17}{2}\ln\left(\frac{\Lambda^2}{\mu^2}\right) \right]$$

1) H. Cheng, K. Matchev, M. Schmaltz hep-ph/0204342

...and now what?

We amended the FeynCalc/FeynArts package to properly include QCD corrections with dimensionally regularized Soft/Collinear divergencies

Pro

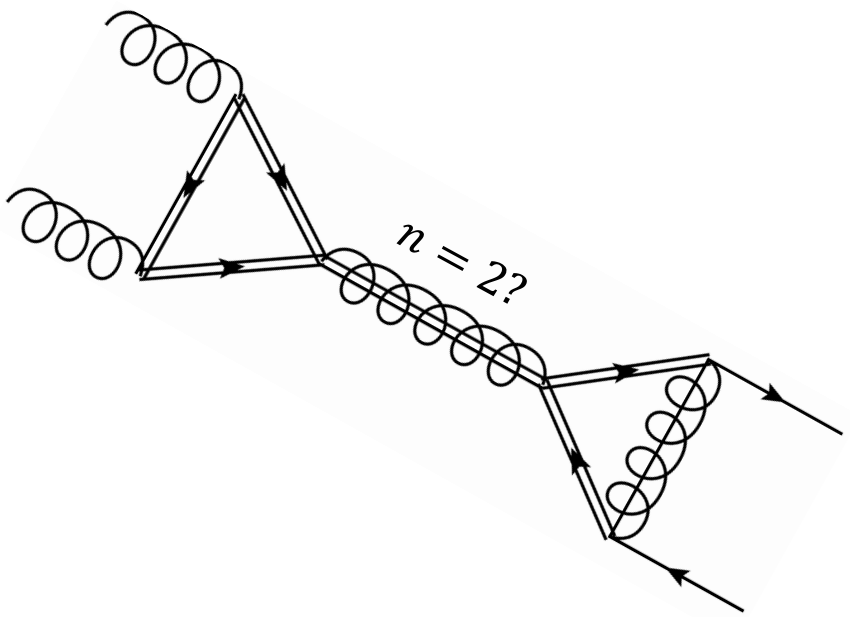
- Very modular procedure for different models and different processes

Con

- Time intensive ME for large number of diagrams/external legs

Follow-up/Work in Progress:

- Signature/Coloron decay? Update Limits?
- Understand higher modes/UV sensitivity?



Thanks!