NLO corrections to massive vector color octet pair production

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@LoopFest 2017

Fig.1 A multi-loop correction to a tree

Based on arXiv:1705.xxxx

with A. Freitas

The Why, the What and the How

the Why

- Colored Scalars and Spinors done at NLO for SUSY searches
- Vector Octets still missing → technology not straightforward!

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

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

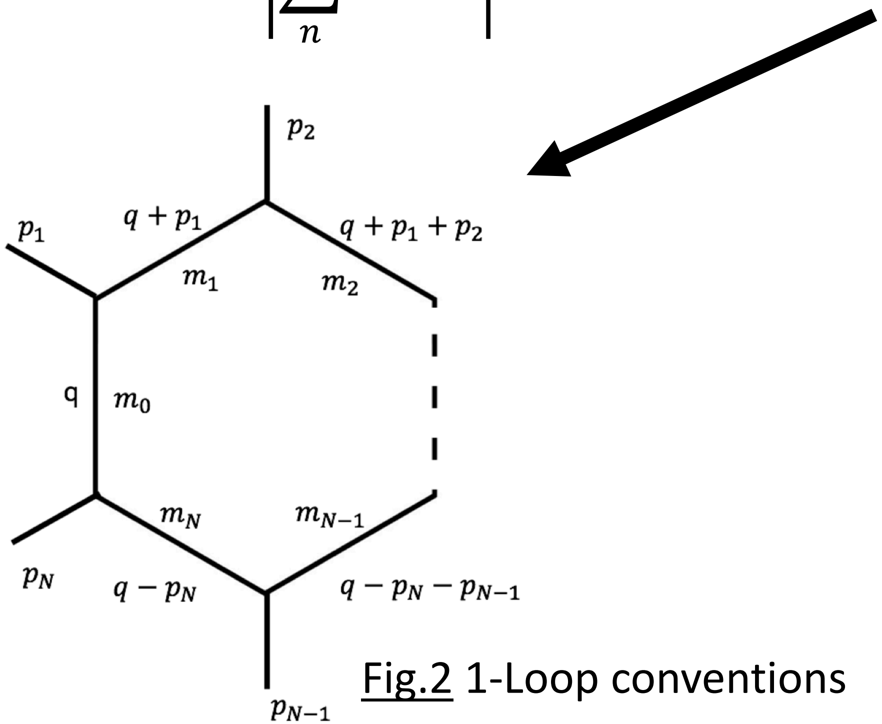

Fig.2 1-Loop conventions

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

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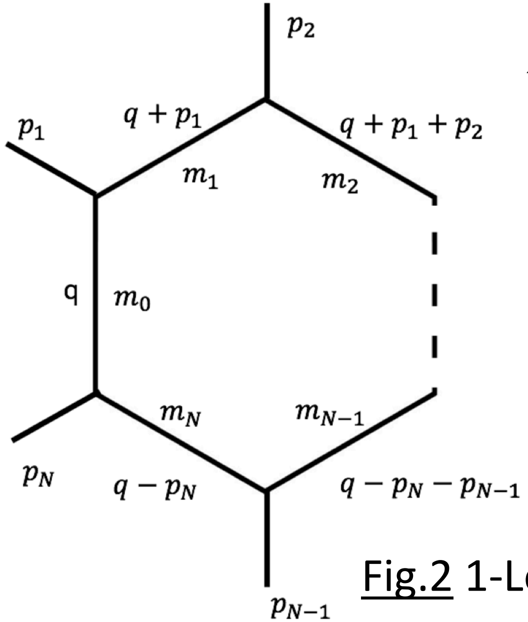
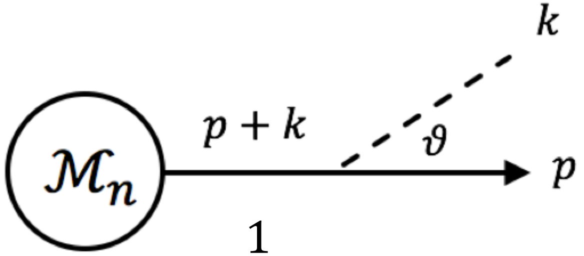


Fig.2 1-Loop conventions

Same order in

perturbation theory

Fig.3 Final state real emission



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

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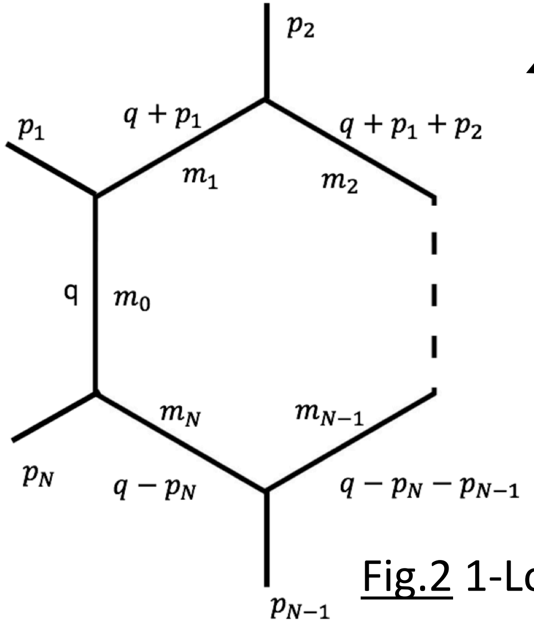

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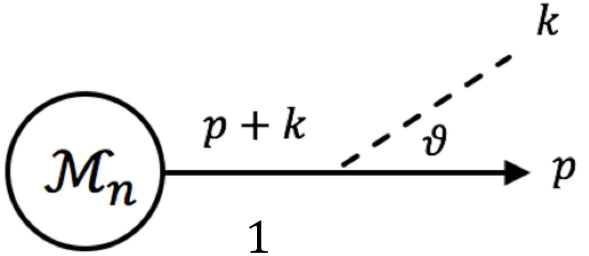


$$\frac{1}{2(p\cdot k)} = \frac{1}{2E_k\left(E_p - |\vec{p}|\cos\vartheta\right)}$$

But…

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

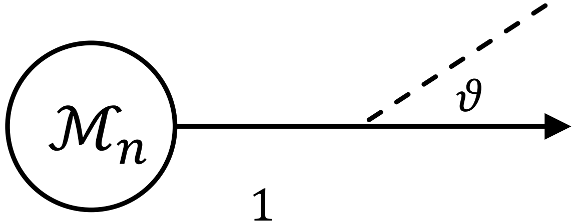
Kinoshita-Lee-Nauenberg: The NLO observables are IR-finite order by order in perturbation theory

Two Cutoff Phase Space Slicing

<u>soft-collinear region</u>

To extract the soft/collinear poles divide the integration region:

$$\sigma_{2\to3} = \int\sum|M_{2\to3}|^2 d\Gamma_3 = \int_{Soft}\sum|M_{2\to3}|^2 d\Gamma_3 + \int_{Hard}\sum|M_{2\to3}|^2 d\Gamma_3 \qquad 0 \le E_g \le \delta_s\frac{\sqrt{s}}{2}$$



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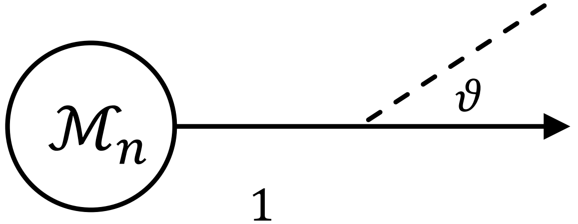
hard-collinear region

$$\int_{Hard}\sum|M_{2\to3}|^2 dLIPS_3 = \int_{HC}\sum|M_{2\to3}|^2 dLIPS_3 + \int_{HNC}\sum|M_{2\to3}|^2 dLIPS_3 \qquad 0 \le -\left(p_i - p_g\right)^2 = \sqrt{s}E_g(1-\cos\vartheta) \le \delta_c s$$



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

The hard-non collinear region does not contain any poles anymore and can be integrated numerically

The Eikonal Limit

Soft/Collinear Region

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

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

→ Factorization for **color subamplitudes**

→ Regularized angular integrals scattered through literature

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

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Hard/Collinear Region

$$(1-\cos\vartheta) \leq \delta_c \sqrt{s}/E_g$$

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

Altarelli-Parisi Kernel

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

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

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

$$\sigma_{NLO} = \sum_{i,j} \int dx_1 dx_2 \mathcal{F}_i(x_1,\mu_f)\mathcal{F}_j(x_2,\mu_f)\left[\sigma_{LO}^{ij}(x_1,x_2,\mu) + \sigma_{Virt}^{ij}(x_1,x_2,\mu) + \sigma_{soft}^{ij}(x_1,x_2,\mu)\right]$$
$$+\frac{\alpha_s}{2\pi}\sum_{i,j}\int dx_1 dx_2 \int_{x_1}^{1-\delta_s} \frac{dz}{z}\left[\mathcal{F}_i\left(\frac{x_1}{z},\mu_f\right)\mathcal{F}_j(x_2,\mu_f) + \mathcal{F}_i(x_2,\mu_f)\mathcal{F}_j\left(\frac{x_1}{z},\mu_f\right)\right]$$
$$\times\sigma_{LO}^{ij}\left[P_{ik}(z)\log\left(\frac{s(1-z)\delta_c}{z\mu_F^2}\right) - P'_{ik}(z)\right] + (i \leftrightarrow j) + \int_{HNC}\sum |M_{2\to3}|^2 d\Gamma_3$$

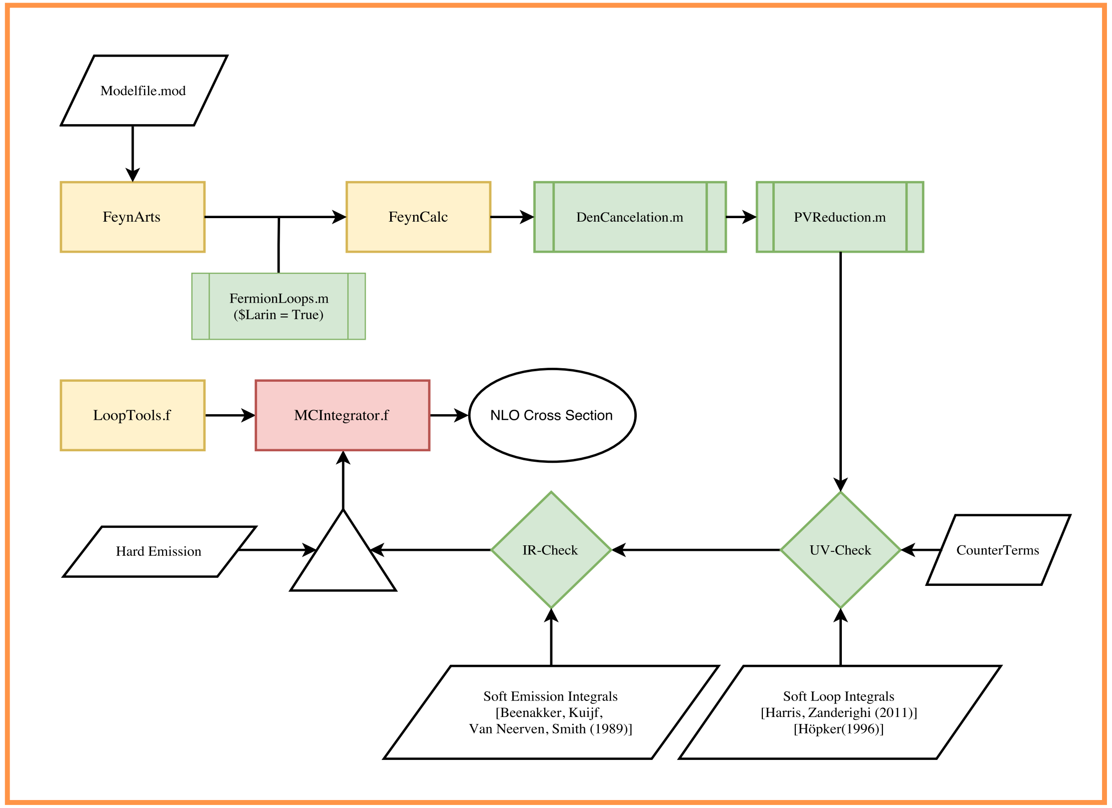
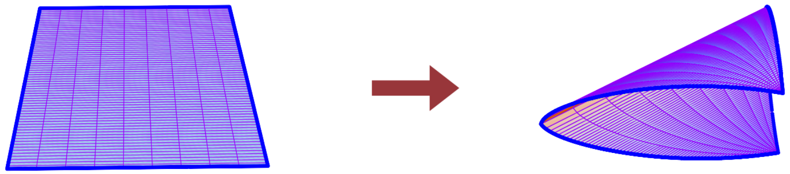


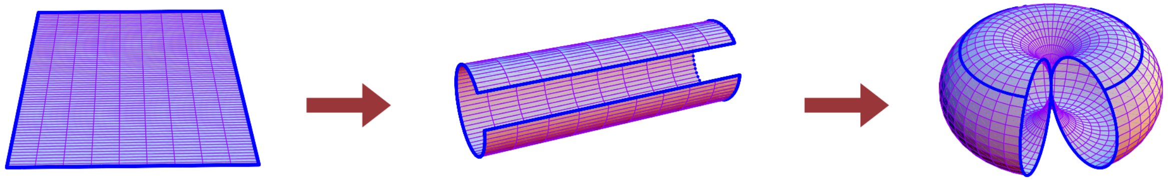
Fig.4 The production pipeline showing the implementation in the FeynArts/FeynCalc framework

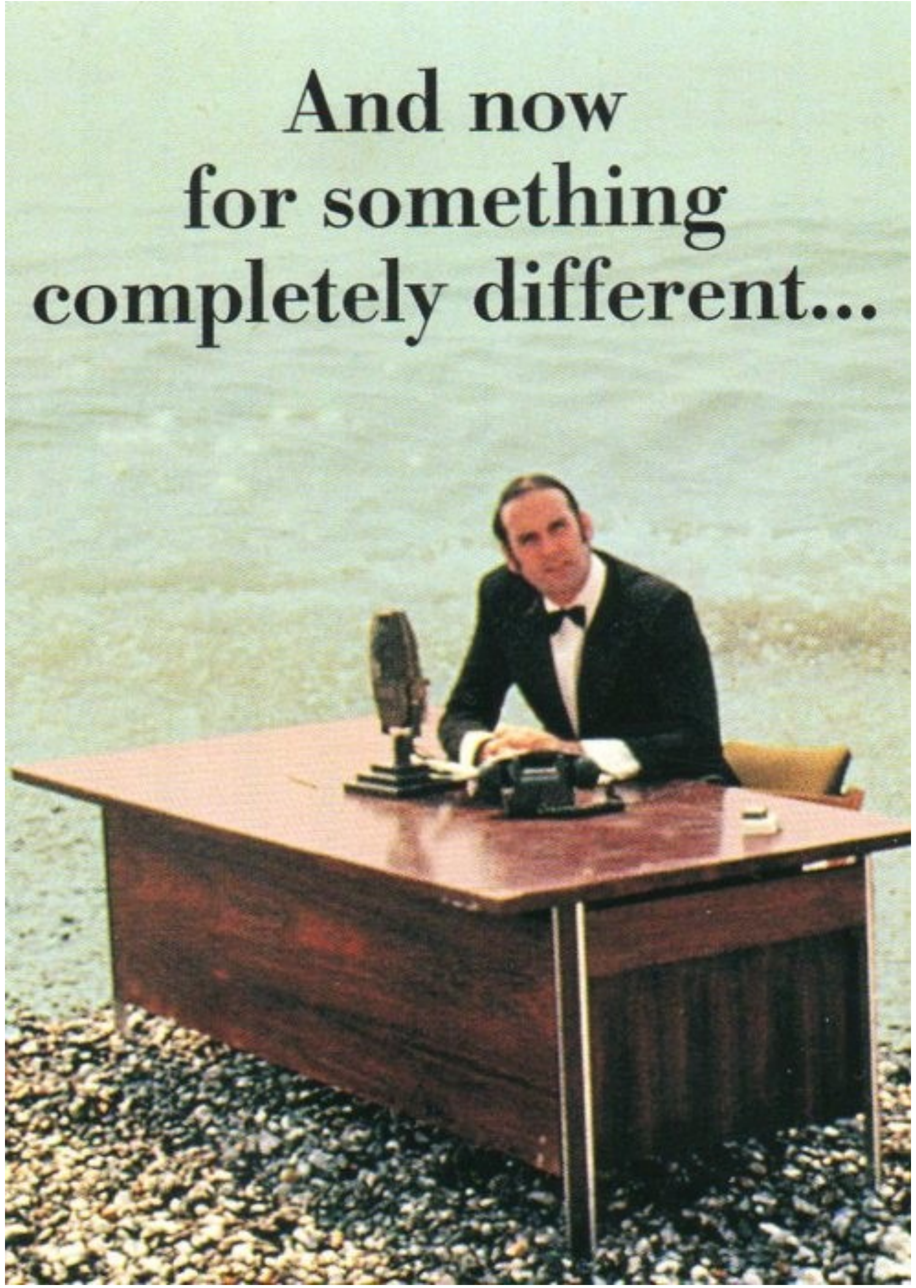
[1] T. Hahn hep-ph/0012260

[2] T. Hahn hep-ph/1006.2231



From Extra Dimensions to 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: $M \geq 1400$GeV with $\Lambda R \sim 10$[1,2,3] @LO)

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

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

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

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

→ Truncation breaks gauge invariance!

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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

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

Additionally introduce gauge-fixing and ghosts

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

Building a Non-Linear Sigma Model

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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 $g^\mu \rightarrow g^\mu \quad C^\mu \rightarrow -C^\mu \quad \Sigma \rightarrow \Sigma^\dagger$

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

Define the renormalization constants in an On-Shell scheme

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

$$\delta Z_F^{L/R} = -\,\mathrm{Re}\Sigma^{L/R}\left(M^2_{kk}\right) - M^2_{kk}\,\frac{\partial}{\partial p^2}\,\mathrm{Re}\left[\Sigma^R(p^2) + \Sigma^L(p^2) + 2\Sigma^S(p^2)\right]\bigg|_{p^2=M^2_{kk}}$$

Demand that the Residue of the propagator remains i

$$\delta M^Q_{kk} = \frac{M_{kk}}{2}\,\mathrm{Re}\left[\Sigma^R(M_{kk}) + \Sigma^L(M_{kk}) + 2\Sigma^S(M_{kk})\right] \qquad \delta M^2_{kk} = -\mathrm{Re}\Sigma^T_{kk}\left(M^2_{kk}\right)$$

Demand that the Pole of the propagator remains at the mass

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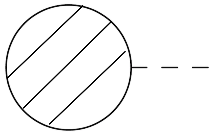
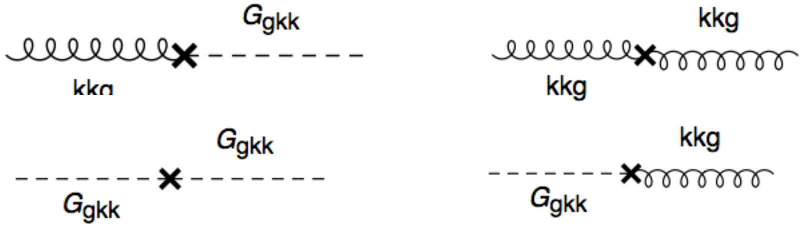
Demand that the Pole of the propagator remains at the mass

N.B.: The tadpole Renormalization in Feynman Gauge demands special attention: We assume a Higgs-like breaking mechanism but the non-linear sigma model integrates out the radial part of the Goldstone Boson



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

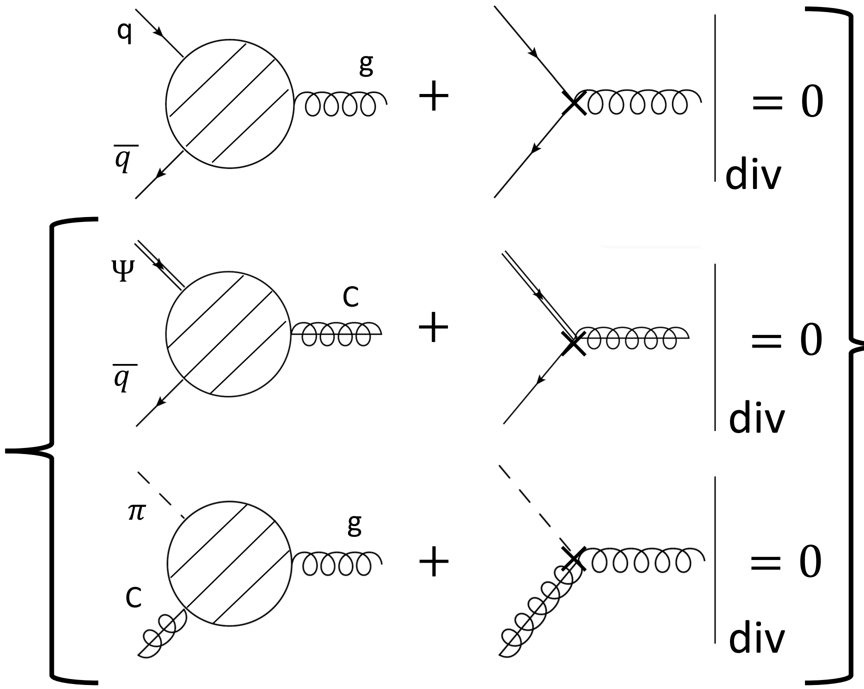


Running of the Couplings

- Choose a 5-flavor Scheme $\overline{MS}$ Scheme
- Fix all couplings at $\mu = M$
- Account for heavy particles with finite log's

$$\hat{g}_s \to g_s(\mu_R^2)\left\{1 + \frac{\alpha_S(\mu_R^2)}{4\pi}\left[\left(-\frac{1}{\tilde{\varepsilon}} + \log\left(\frac{\mu_R^2}{\mu^2}\right)\right)\frac{\beta_0}{2} - \frac{1}{3}\log\left(\frac{m_T^2}{\mu_R^2}\right) + \frac{23}{12}\log\left(\frac{M_{kk}^2}{\mu_R^2}\right) - \frac{2}{3}\log\left(\frac{(M_{kk}+m_T)^2}{\mu_R^2}\right)\right]\right\}$$

Effectively no running $\mu > M$



Same coupling
Different CT
Different Running

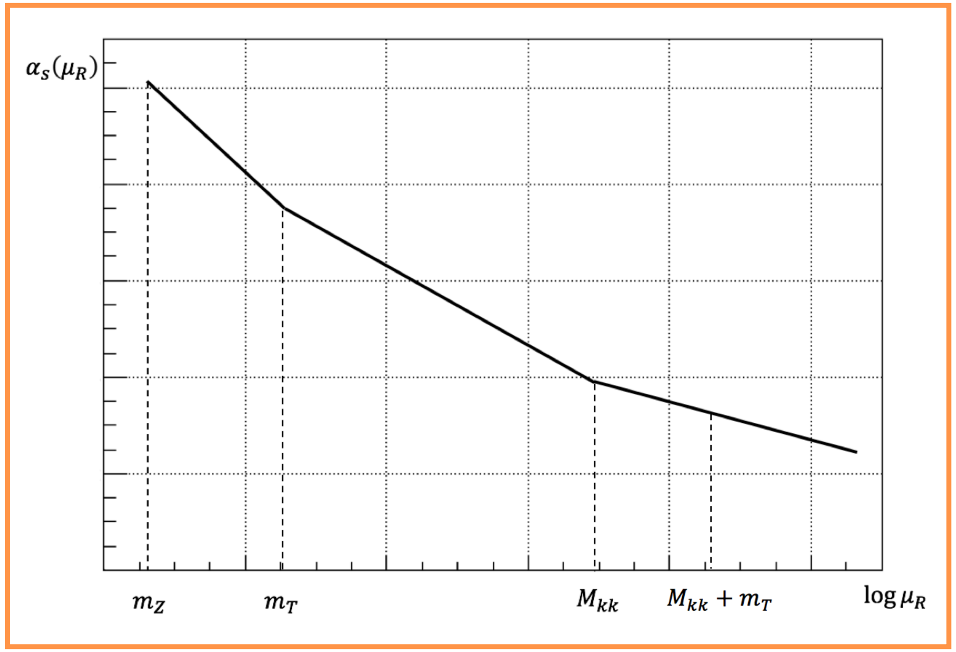
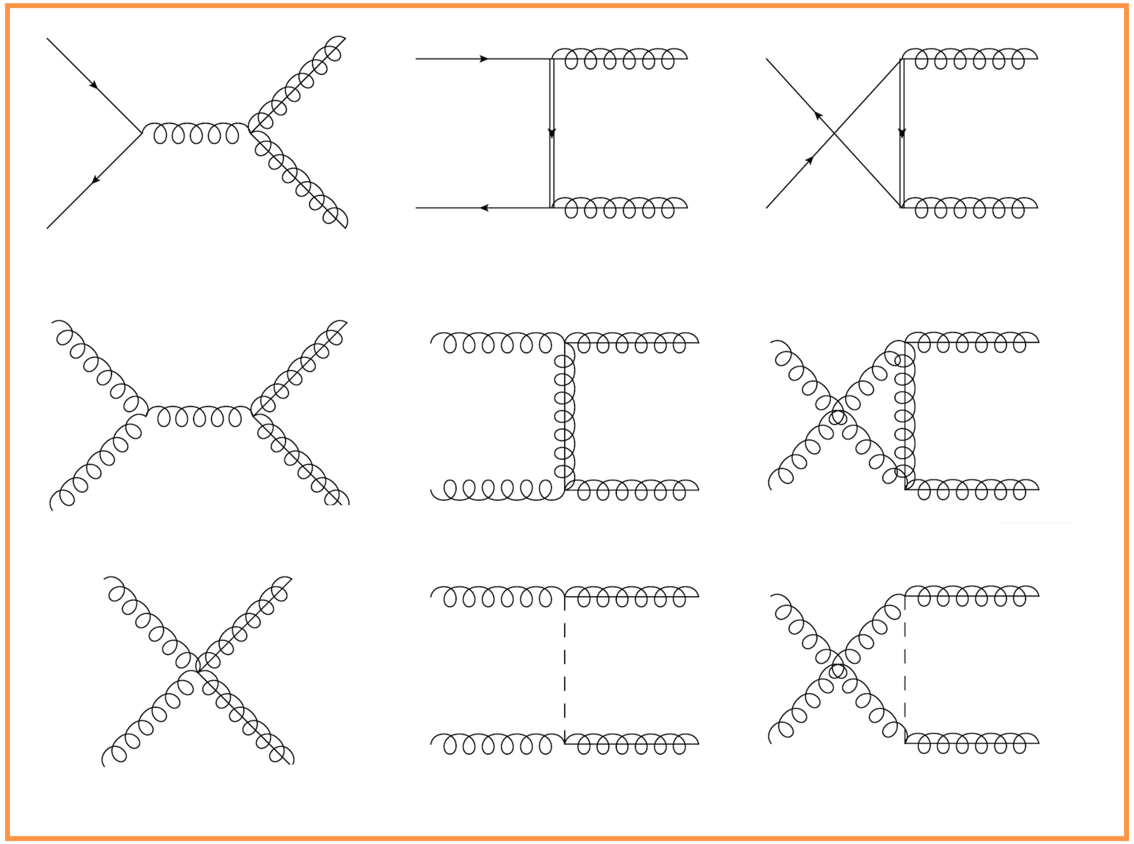


Fig.5 Decoupling of heavy particles in $\alpha_s(\overline{q}qg$ Vertex)

Coloron Production at LHC

Fig.6 Diagrams contributing to the Born cross section



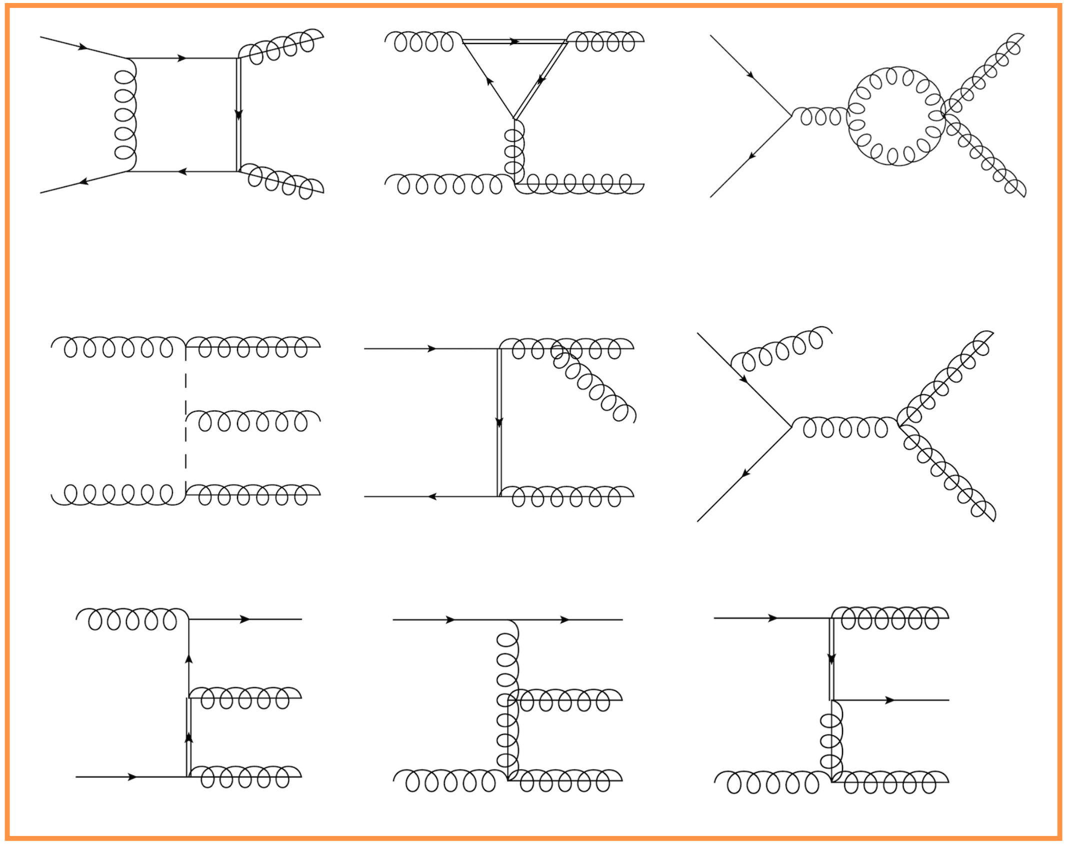
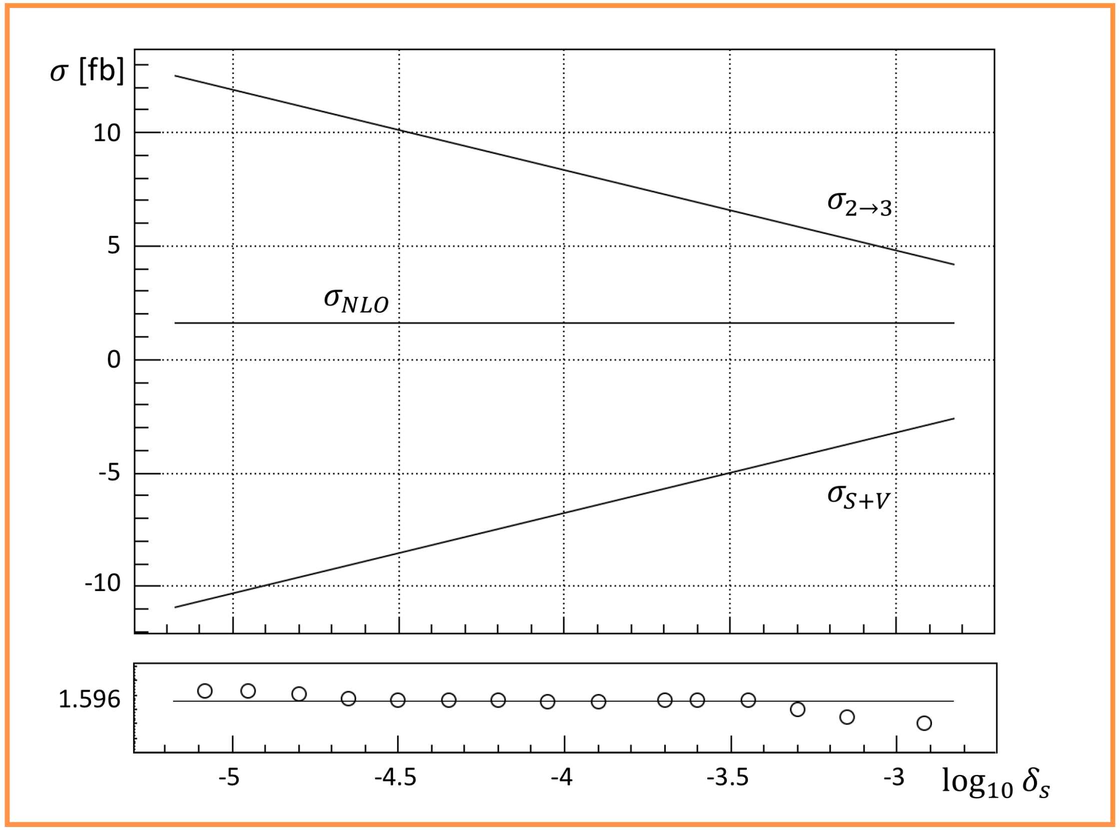


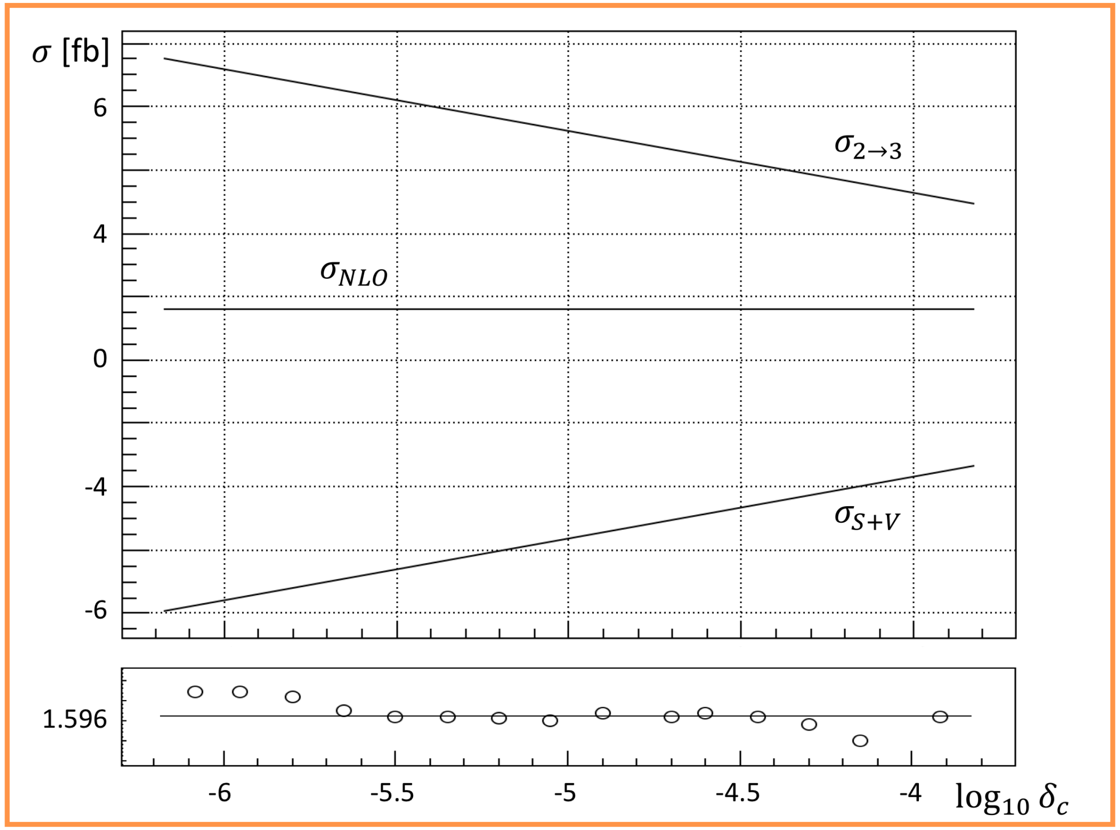
Fig.7 Diagrams contributing to
A) the virtual cross section
B) Real emission part
C) quark-gluon channel

Cutoff Dependence



<u>Fig.8</u> δ_s dependence of σ_{NLO}
($M_{kk} = \mu_R = \mu_f = 1$TeV, δ_c= 7×10^{-6},
$\sqrt{s} = 14$TeV)

<u>Fig.9</u> δ_c dependence of σ_{NLO}
($M_{kk} = \mu_R = \mu_f = 1$TeV, δ_s= 7×10^{-6},
$\sqrt{s} = 14$TeV)



Scale Dependence

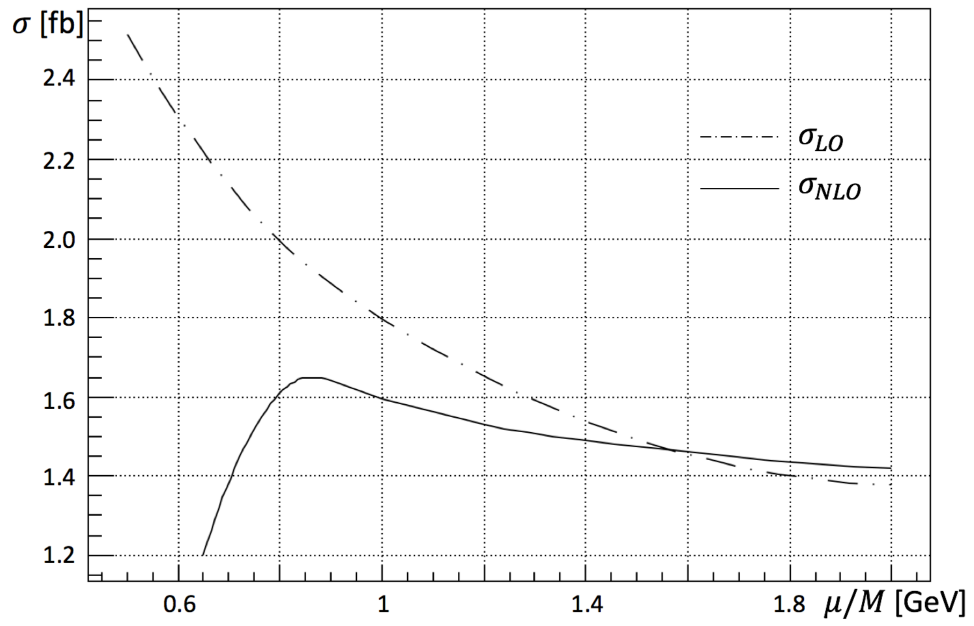
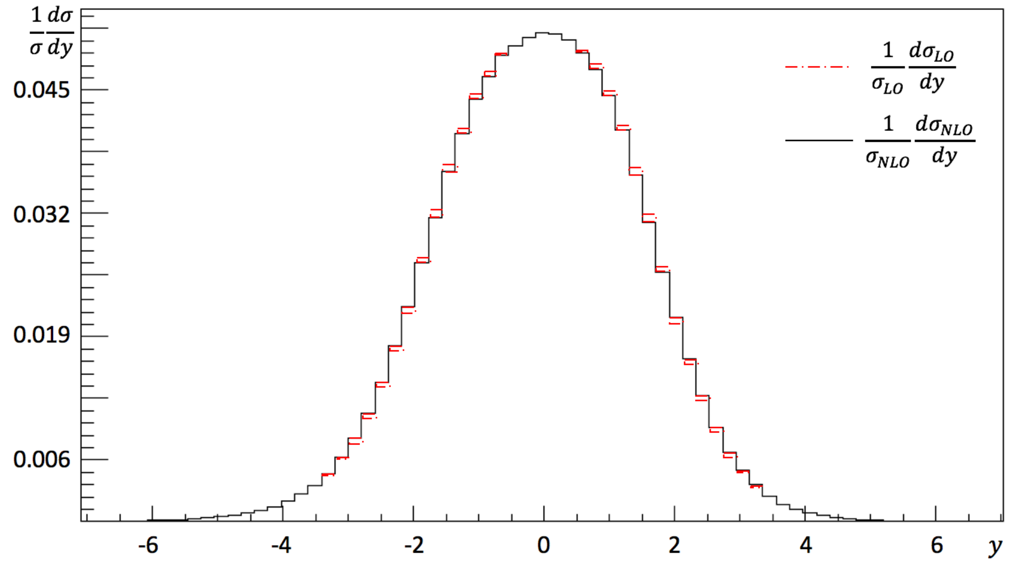


Fig.10 Variation of the scales ($\mu_R = \mu_F$) for 1TeV Colorons

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



Mass Dependence

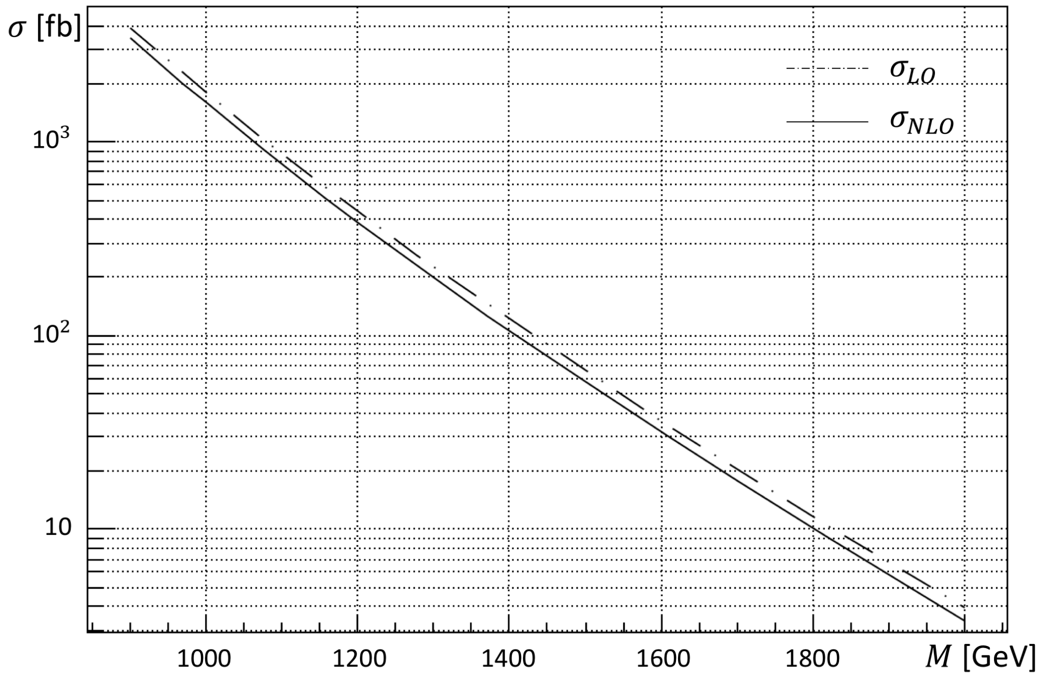
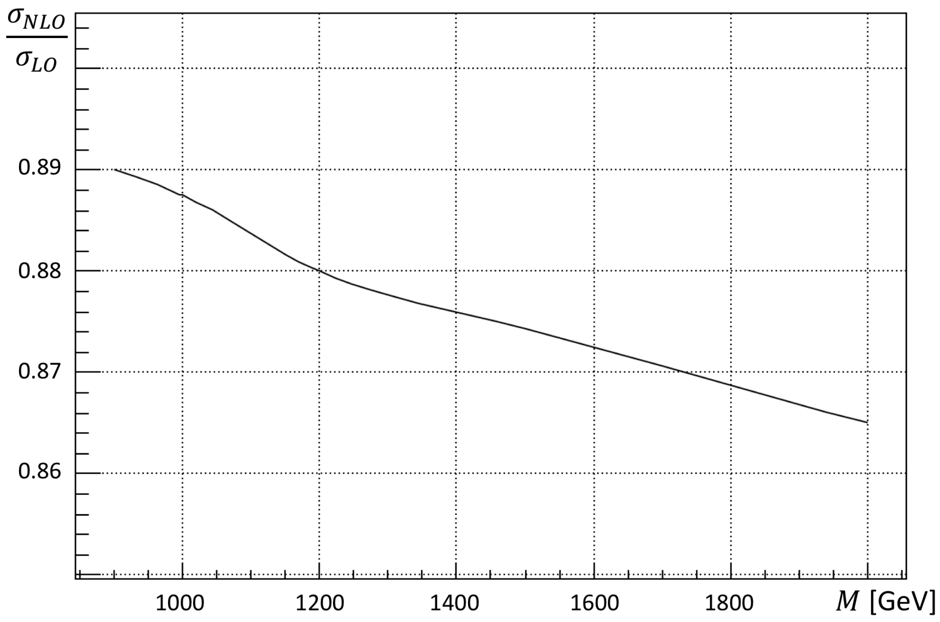


Fig.12 Mass dependence of the NLO cross section

Fig.13 Mass dependence of the κ-Factor



Mass Splitting

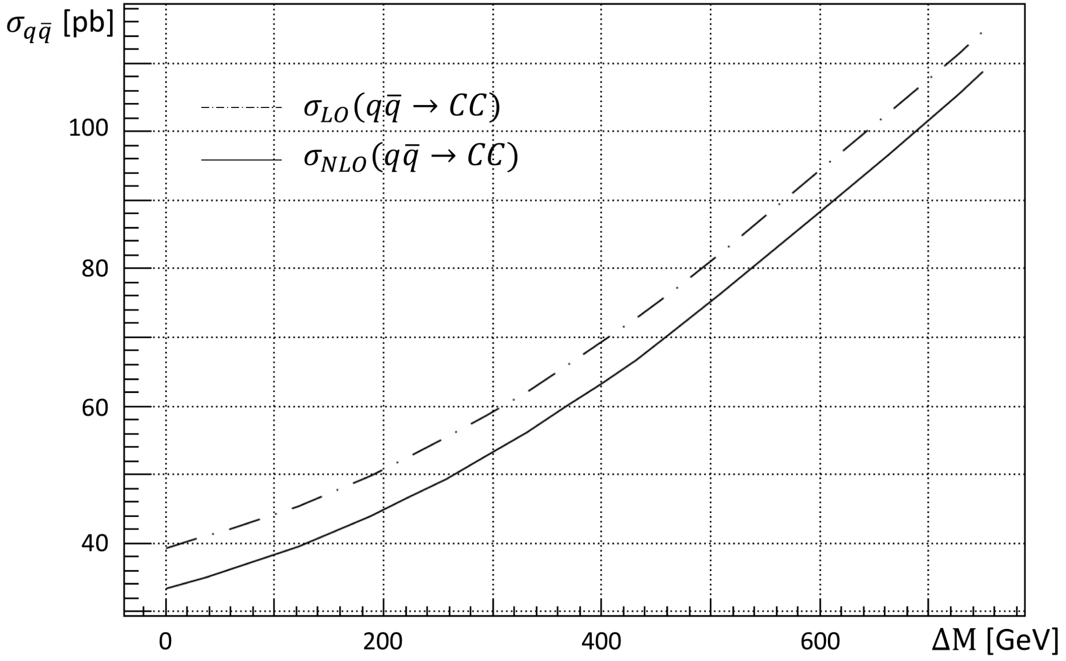
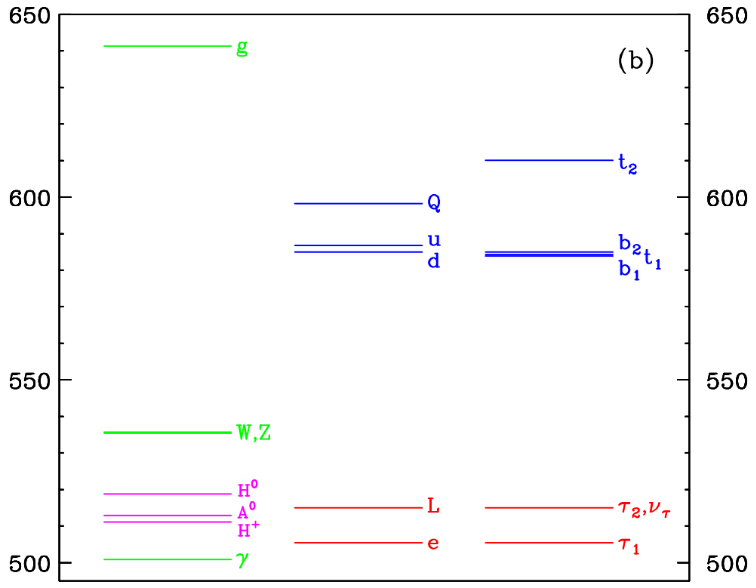


Fig.14 Quark Channel dependence on the splitting ΔM

Fig.15 Corrected mass spectrum



The degenerate modes also receive radiative corrections in UED
↔ All masses are independent in Coloron Models anways

$$\Delta M = \delta M_C - \delta M_Q = \frac{\alpha_s}{4\pi} M^2 \left[-\frac{3}{2}\frac{\xi(3)}{\pi} + \frac{17}{2} \ln\left(\frac{\Lambda^2}{\mu^2}\right) \right]^{1)}$$

[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

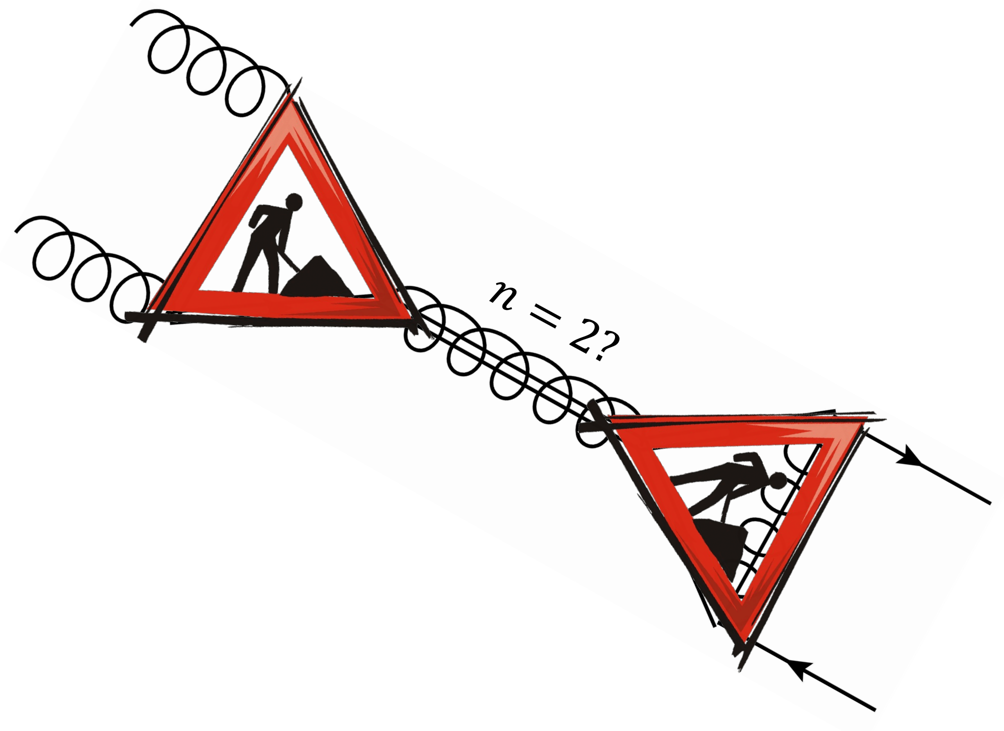
- Very modular procedure for different models and different processes

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!