Unparticle physics

Prakash Mathews

Saha Institute of Nuclear Physics

- Banks-Zaks & Georgi's $\mathcal{U}$-particle proposal
- Necessary $\mathcal{U}$-particle ingredients
- Di-lepton & di-photon production at hadron collider to NLO in QCD
- Summary

Phys. Lett. B657 (2007) 198 with V Ravindran

Phys. Rev. D77 (2008) 055013 & 0804.4054 with MC Kumar, V Ravindran & A Tripathi

Banks-Zaks Perturbative IR fixed point

Banks & Zaks Nucl. Phys. B196 (1982) 189

- QCD β function calculated up to 4-loops in the $\overline{\text{MS}}$ scheme

$$\frac{\partial a_s}{\partial \ln \mu^2} = \beta(a_s) = -\beta_0 a_s^2 - \beta_1 a_s^3 - \beta_2 a_s^4 - \beta_3 a_s^5 + \mathcal{O}(a_s^6)$$

$$a_s = \alpha_s/4\pi = g_s^2/16\pi^2, \; g_s = g_s(\mu^2)$$

- 4-loops β function for $N_c = 3$

$$\beta_0 = 11 - \tfrac{2}{3} N_f \qquad \beta_1 = 102 - \tfrac{38}{3} N_f \qquad \beta_2 = \tfrac{2857}{2} - \tfrac{5033}{18} N_f + \tfrac{325}{54} N_f^2$$

$$\beta_3 = \left(\tfrac{149753}{6} + 3564\zeta_3\right) - \left(\tfrac{1078361}{162} + \tfrac{6503}{27}\zeta_3\right) N_f + \left(\tfrac{50065}{162} + \tfrac{6472}{81}\zeta_3\right) N_f^2 + \tfrac{1093}{729} N_f^3$$

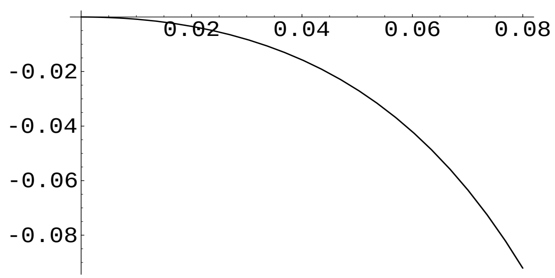
Ritbergen, Vermaseren, Larin Phys. Lett. B400 (1997) 379

- Varying N_f or N_c affects asymptotic freedom

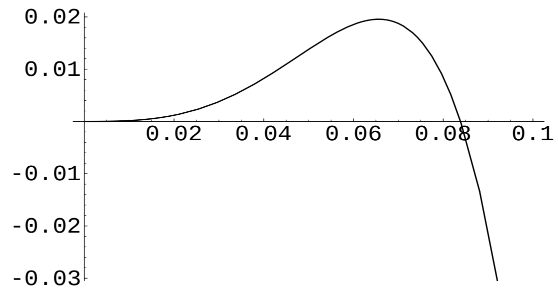
- N_f dependence
  - $\beta_3 > 0$ for $N_f > 0$
  - β_2 changes sign before β_1
    $\beta_1(N_f = 8.05) = 0$
    $N' = 8.05$
  - β_1 changes sign before β_0
    $\beta_0(N_f = 16.5) = 0$
    $N^* = 16.5$

β-function

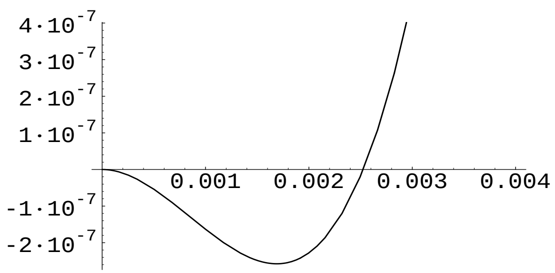
- Implies the presence of a non-trivial zero of the β function

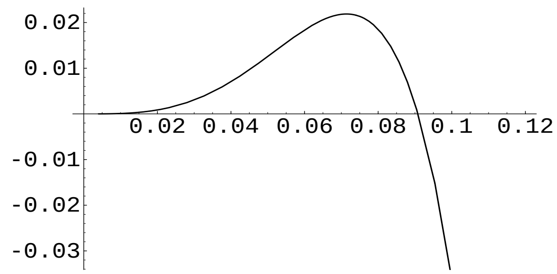


$N_f = 6 \ (N_f < N')$



$N_f = 17 \ (N_f > N^*)$





$N' < (N_f = 16.1) < N^*$

- As $N_f \longrightarrow N^*$, zeros of the $\beta(\alpha_s)$ occurs at lower values of a_s— the zero of the β function is in the perturbation region

$\beta(a_s; N_f)$-function

- The theory can in principle be studied as an expansion in powers of $(N_f - N^*)$
- If $N' < N_f < N^*$ the β function has a non trivial zero & if $N_f = N^*(1 - 11\,\varepsilon)$, then the zero is at

$$a_s^* = \frac{\varepsilon/3}{21 + 11C_F - (5 + C_F)\varepsilon}$$

- Close to N^*, is highly perturbative region (a_s is small), hence two loop is sufficient to extract the IR fixed point
- $(N_f - N^*)$ expansion suggests that for N_f in the range $N' < N_f < N^*$, close to N^* the theory has an:
  - Exact scale invariant sector
  - No particle interpretation
  - No mass gaps

Scenario Proposed by Georgi: Unparticles

A SCALE INVARIANT SECTOR WEAKLY COUPLED TO THE SM

H. Georgi, Phys. Rev. Lett. 98 (2007) 221601

- Scale invariant sector (Banks-Zaks) which is hidden from the SM at low energies
- In the UV theory the hidden sector could couple to the SM fields through some non-renormalisable interactions by the exchange of massive particles M

$$\mathcal{L}_{UV} = \frac{O_{BZ} O_{SM}}{M^{d_{BZ}+d_{SM}-4}}$$

- The hidden sector has a non-trivial IR fixed point, $\Lambda_{\mathcal{U}}$, below which the hidden sector exhibits scale invariance and the operators $O_{BZ} \longrightarrow O_{\mathcal{U}}$ unparticle operator with scaling dimension $d_{\mathcal{U}}$

$$\begin{aligned} \mathcal{L}_{\mathcal{U}} &= C_{\mathcal{U}} \frac{\Lambda_{\mathcal{U}}^{d_{BZ}-d_{\mathcal{U}}}}{M^{d_{BZ}+d_{SM}-4}} O_{\mathcal{U}} O_{SM} \\ &= \frac{\lambda}{\Lambda_U^{d_{\mathcal{U}}}} O_{\mathcal{U}} O_{SM} \qquad\qquad d_{SM} = 4 \\ \lambda &= C_{\mathcal{U}} \left(\frac{\Lambda_{\mathcal{U}}}{M} \right)^{d_{BZ}} \end{aligned}$$

LOW ENERGY EFFECTIVE THEORY WHICH IS SCALE INVARIANT BELOW THE CUT OFF SCALE $\Lambda_{\mathcal{U}}$

General $\mathcal{U}$-particle coupling to the SM

- Unparticle operators with different Lorentz structure $O_{\mathcal{U}}$, $O_{\mathcal{U}}^{\mu}$, $O_{\mathcal{U}}^{\mu\nu}$ has been considered

$$\frac{\lambda_s}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}\overline{\psi}\psi O_{\mathcal{U}} \quad \frac{\lambda_s}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}}G_{\mu\nu}G^{\mu\nu}O_{\mathcal{U}} \qquad \frac{\lambda_v}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}\overline{\psi}\gamma_{\mu}\psi O_{\mathcal{U}}^{\mu} \qquad \frac{\lambda_t}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}}T_{\mu\nu}O_{\mathcal{U}}^{\mu\nu}$$

Scalar Vector Tensor

- λ_{κ} dimensionless coupling corresponding $\mathcal{U}$-particle operator $O_{\mathcal{U}}^{\kappa}$
- $T_{\mu\nu}$ energy momentum tensor of the SM
- $d_{\mathcal{U}}$ scaling dimension of $O_{\mathcal{U}}^{\kappa}$

Phase space for real emission

- Scale invariance can be used to fix the 2-point function of the unparticle

$$\langle 0|O_{\mathcal{U}}(x)O^{\dagger}_{\mathcal{U}}(0)|0\rangle = \int \frac{d^4P}{(2\pi)^4} \exp(-iP.x)\rho_{\mathcal{U}}(P^2)$$

  Spectral density $\rho_{\mathcal{U}}$

$$\rho_{\mathcal{U}} = (2\pi)^4 \int d\tilde{k} |\langle 0|O_U(0)|k\rangle|^2 \delta^4(p-k)$$

  $|k\rangle$ is an unparticle state with 4-momentum k^{μ} produced from vacuum by O_U

$$\begin{aligned} \rho_{\mathcal{U}}(P^2) &= \int d^4x \exp(iP.x)\langle 0|O_{\mathcal{U}}(x)O^{\dagger}_{\mathcal{U}}|0\rangle \\ &= A_{d_U}\Theta(P^0)\Theta(P^2)(P^2)^{\alpha} \end{aligned}$$

- Scale invariance is used to fix the *exponent* α, while the *normalisation* A_{d_U} is fixed by comparing with the n-particle phase space

Scale Invariance

- Scale transformation: $x \longrightarrow \lambda x \qquad O_U(\lambda x) \longrightarrow \lambda^{-d_U} O_U(x)$

$$A_{d_U}\Theta(P^0)\Theta(P^2)(P^2)^\alpha = \lambda^{-2(d_U-2)} \int d^4x \exp(i\lambda P.x) < 0|O_U(x)O_U^\dagger(0)|0 >$$
$$= \lambda^{-2(d_U-2)} A_{d_U}\Theta(\lambda P^0)\Theta(\lambda^2 P^2)(\lambda^2 P^2)^\alpha$$

Scale invariance fixes $\alpha = (d_U - 2)$

- Phase space of n massless particles

$$(2\pi)^4\delta^4\left(P - \sum_{j=1}^{n} p_j\right)\prod_{j=1}^{n}\delta(p_j^2)\theta(p_j^0)\frac{d^4p_j}{(2\pi)^4} = A_n\Theta(P^0)\Theta(P^2)(P^2)^{n-2}$$

$$A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}}\frac{\Gamma(n+1/2)}{\Gamma(n-1)\Gamma(2n)}$$

- Comparing the spectral density & n-particle phase space, Georgi adopted the normalisation

$$A_{d_U} \equiv A_n$$

with $n \longrightarrow d_U$ now taking *non-integral* values. An alternate normalisation definition could be absorbed in the Wilson coefficient $C_{\mathcal{U}}$

1-particle phase space $d_U \to 1$

- $d_U = 1 + \varepsilon$

$$\lim_{\varepsilon \to 0_+} \begin{pmatrix} A_{d_U} = 2\pi\varepsilon \\ (P^2)^{n-2} = \frac{1}{(P^2)^{1-\varepsilon}} \end{pmatrix} \qquad \lim_{\varepsilon \to 0_+} \frac{\varepsilon}{a^{1-\varepsilon}} = \delta(a)$$

$$\rho(P^2) \longrightarrow 2\pi\theta(P^0)\delta(P^2)$$

reproduces the 1-particle phase space

- Phase of A + B $\longrightarrow \mathcal{U}$ + 1 + 2 + 3 + $\cdots\ n-1$

$$d\Phi(P) = (2\pi)^4\delta^4\left(P - \sum_j^n p_j\right)\prod_j^n d\tilde{\phi}(p_j)\frac{d^4p_j}{(2\pi)^4}$$

Particle	$d\tilde{\phi} = 2\pi\theta(p^0)\delta(p^2)$
Unparticle	$d\tilde{\phi}_U = A_{d_U}\theta(P^0)\theta(P^2)(P^2)^{d_U-2}$

- $\mathcal{U}$-particles does not have a definite invariant mass, instead a continuous mass spectrum

UNPARTICLE STUFF WITH SCALE DIMENSION d_U LOOKS LIKE A NON-INTEGRAL NUMBER d_U OF INVISIBLE MASSLESS PARTICLES

$\mathcal{U}$-particle propagator

H. Georgi, Phys. Lett. B650 (2007) 275

- Exchange of a virtual $\mathcal{U}$-particle corresponding to operator O_U^κ between the SM particles would need the propagator. Using Källen-Lehmann spectral representation

$$\int d^4x \, \exp(iP.x) \langle 0|T(O_U(x) O_U(0)|0\rangle = \frac{i}{2\pi} \int_0^\infty dM^2 \, \rho_U(M^2) \frac{1}{P^2 - M^2 + i\varepsilon}$$

$\rho_{\mathcal{U}}(P^2) = A_{d_U} \Theta(P^0) \Theta(P^2) (P^2)^{d_U - 2}$ the integral convergent for $1 < d_U < 2$

- The unparticle propagator is

$$\Delta_F^\kappa(P^2) = \frac{i A_{d_\mathcal{U}}}{2 \sin(d_\mathcal{U} \pi)} \frac{B_\kappa}{(-P^2 - i\varepsilon)^{2 - d_\mathcal{U}}}$$

$O_\mathcal{U}$	1
$O_\mathcal{U}^\rho$	$\eta_{\mu\nu}(P) = -g_{\mu\nu} + \frac{P_\mu P_\nu}{P^2}$
$O_\mathcal{U}^{\rho\sigma}$	$B_{\mu\nu\alpha\beta}(P) = \frac{1}{2}\left(\eta_{\mu\alpha}\eta_{\nu\beta} + \eta_{\mu\beta}\eta_{\nu\alpha} - \frac{2}{3}\eta_{\mu\nu}\eta_{\alpha\beta}\right)$

- Scale invariance and the transverse properties of the vector and tensor operators fixes the $\mathcal{U}$-particle propagator

Complex phase

- Peculiar propagator of scale invariant $\mathcal{U}$-particle

$$(-P^2 - i\varepsilon)^{d_U - 2} = \begin{cases} |P^2|^{d_U - 2} & P^2 < 0 \quad \text{No Complex Phase} \\ |P^2|^{d_U - 2} \exp(-i d_U \pi) & P^2 > 0 \quad \text{Complex Phase} \end{cases}$$

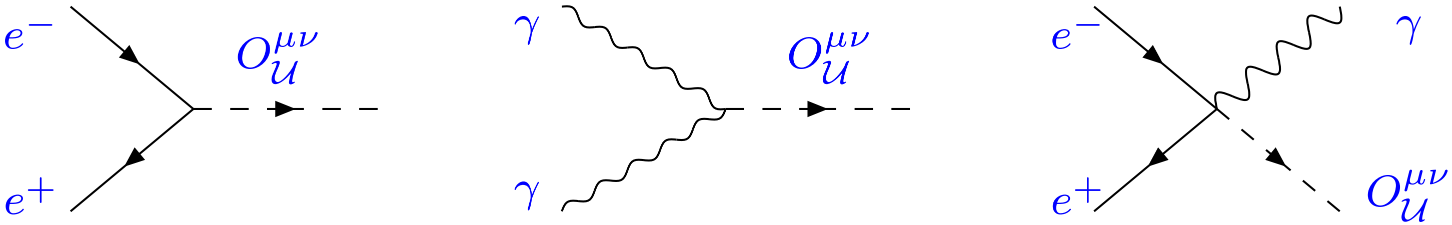
- The $\mathcal{U}$-particle propagator has an unusual phase in the time-like region, which can produce interesting interference patterns of s-channel $\mathcal{U}$-particle exchange and the SM processes
- $d_U \to 1^+$ the standard results are retrieved

$$\lim_{d_U \to 1^+} \Delta_F^{\kappa}(P^2) = \frac{B_\kappa}{P^2}$$

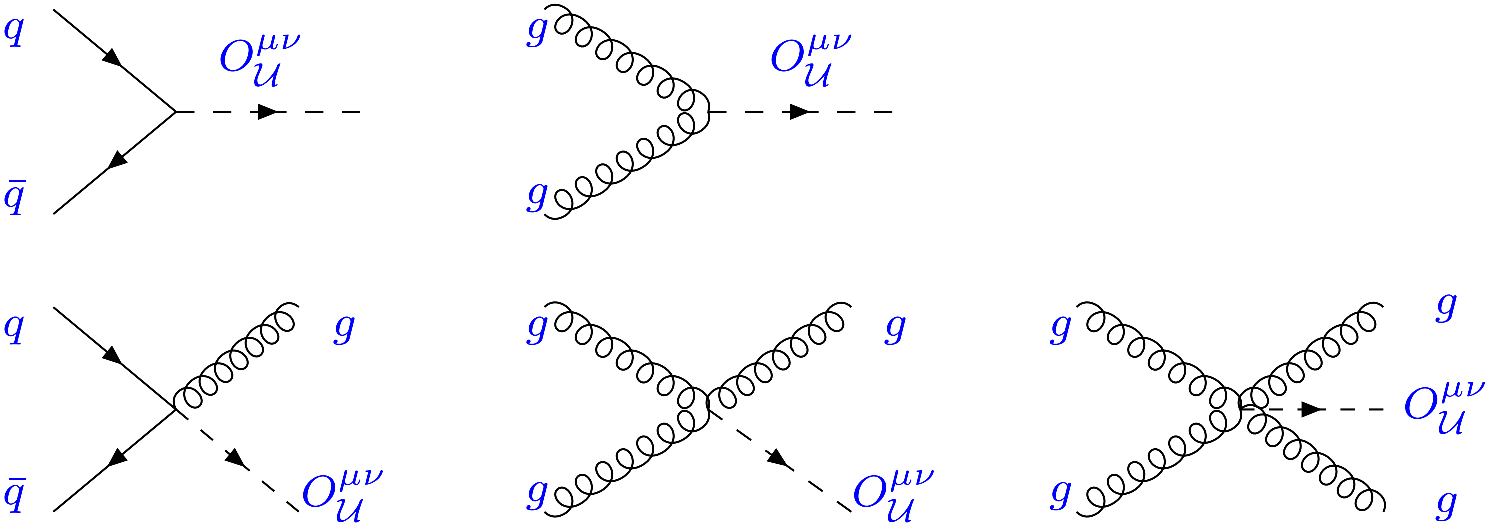
UNPARTIClE PHYSICS ASSOCIATED WITH HIDDEN SCALE INVARIANT SECTOR WITH NONTRIVIAL INFRARED FIXED POINT AT A HIGH ENERGY SCALE HAS INTERESTING PHENOMENOLOGICAL CONSEQUENCES AT PRESENT AND FUTURE COLLIDERS

Feynman Rules— Tensor $\mathcal{U}$ coupling

- QED



- QCD



Feynman Rules— Tensor $\mathcal{U}$ coupling

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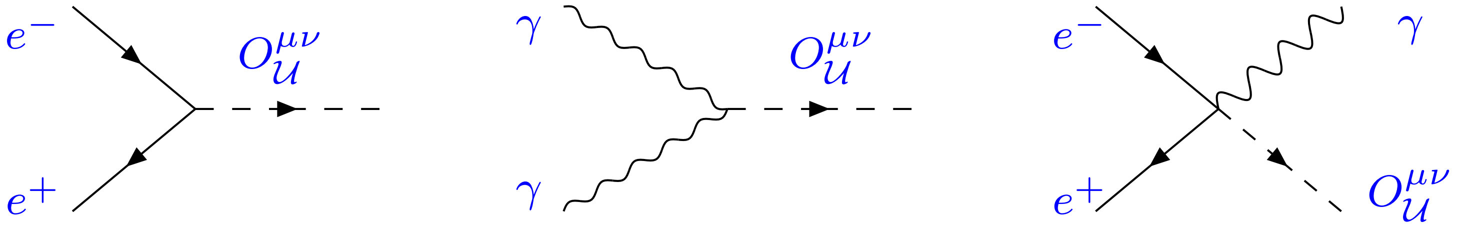

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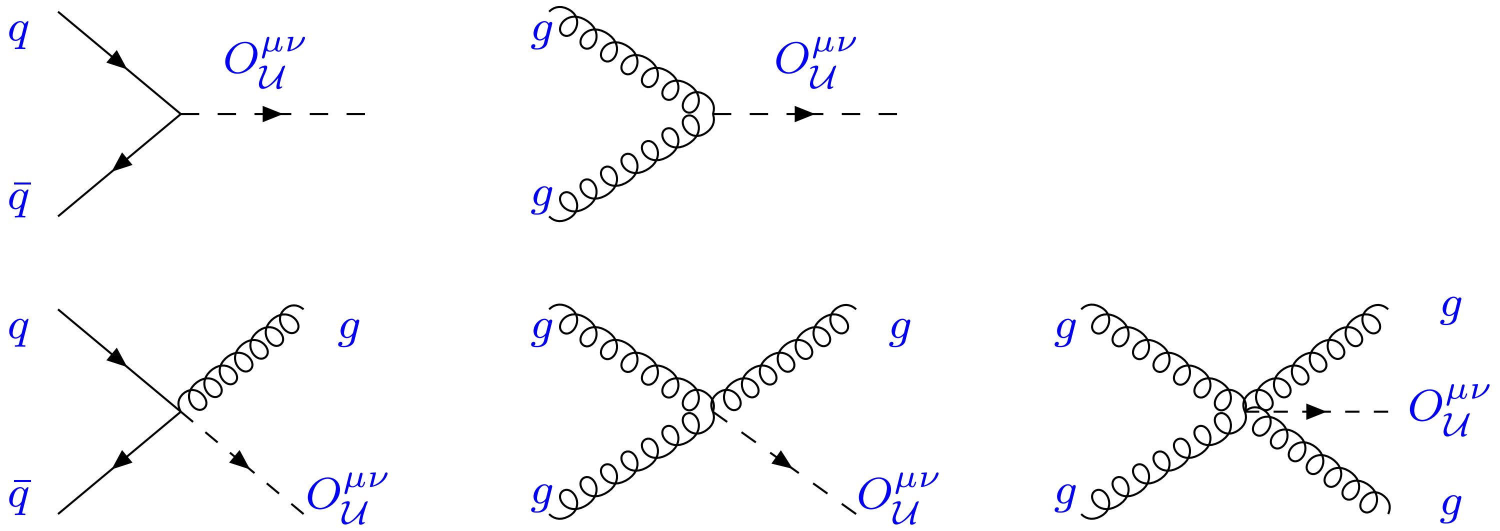
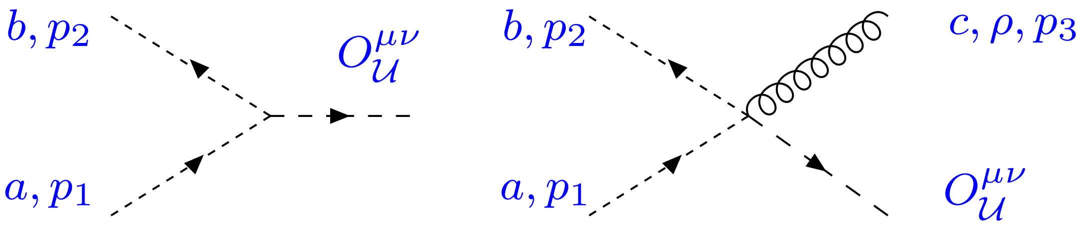


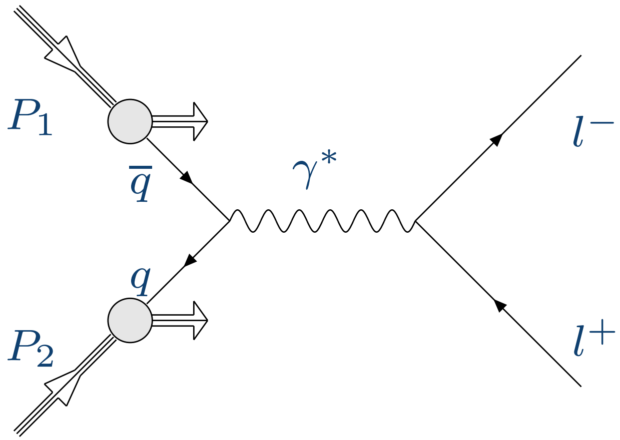


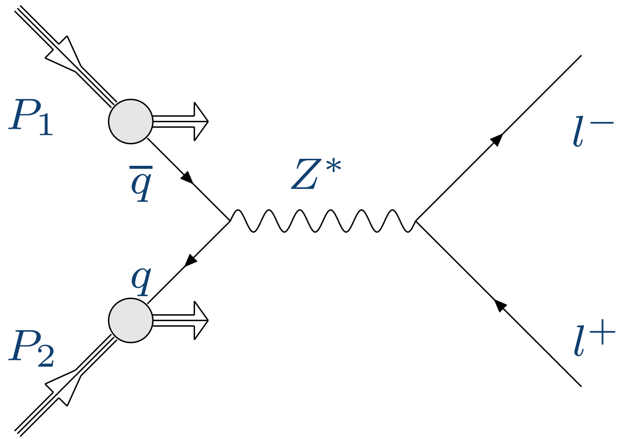
Ghost Couplings

Drell-Yan Process

$$P_1(p_1) + P_2(p_2) \longrightarrow [\gamma, Z, \mathcal{U}] + \text{hadronic states}(X)$$
$$\hookrightarrow l^+(k_1) + l^-(k_2) \qquad (k_1 + k_2)^2 = Q^2$$

To Leading Order in QCD





SM

Drell-Yan Process

$$P_1(p_1) + P_2(p_2) \longrightarrow [\gamma, Z, \mathcal{U}] + \text{hadronic states}(X)$$
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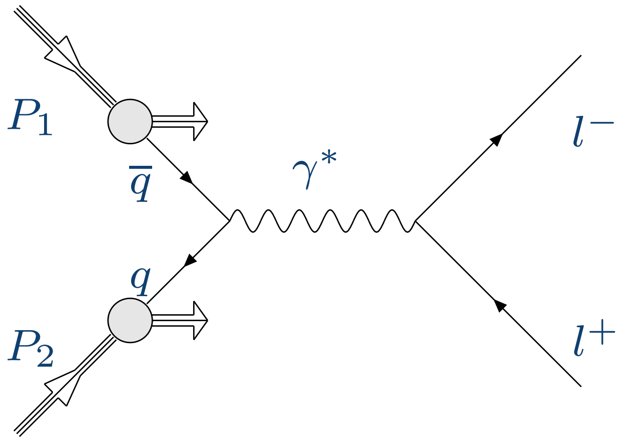
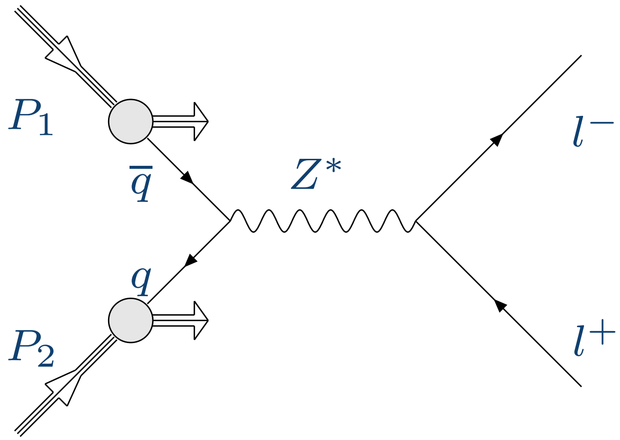
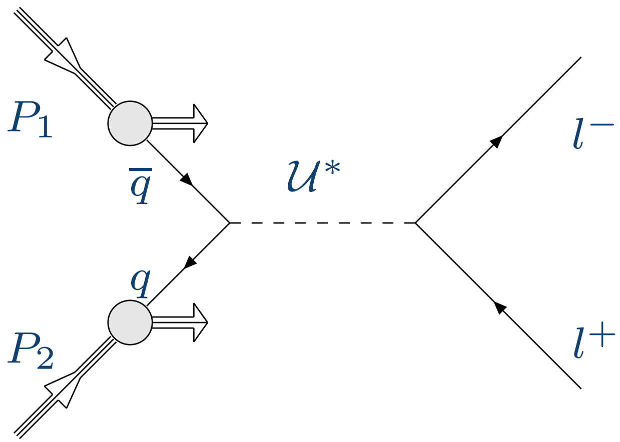




SM



Drell-Yan Process

$$P_1(p_1) + P_2(p_2) \longrightarrow [\gamma, Z, \mathcal{U}] + \text{hadronic states}(X)$$
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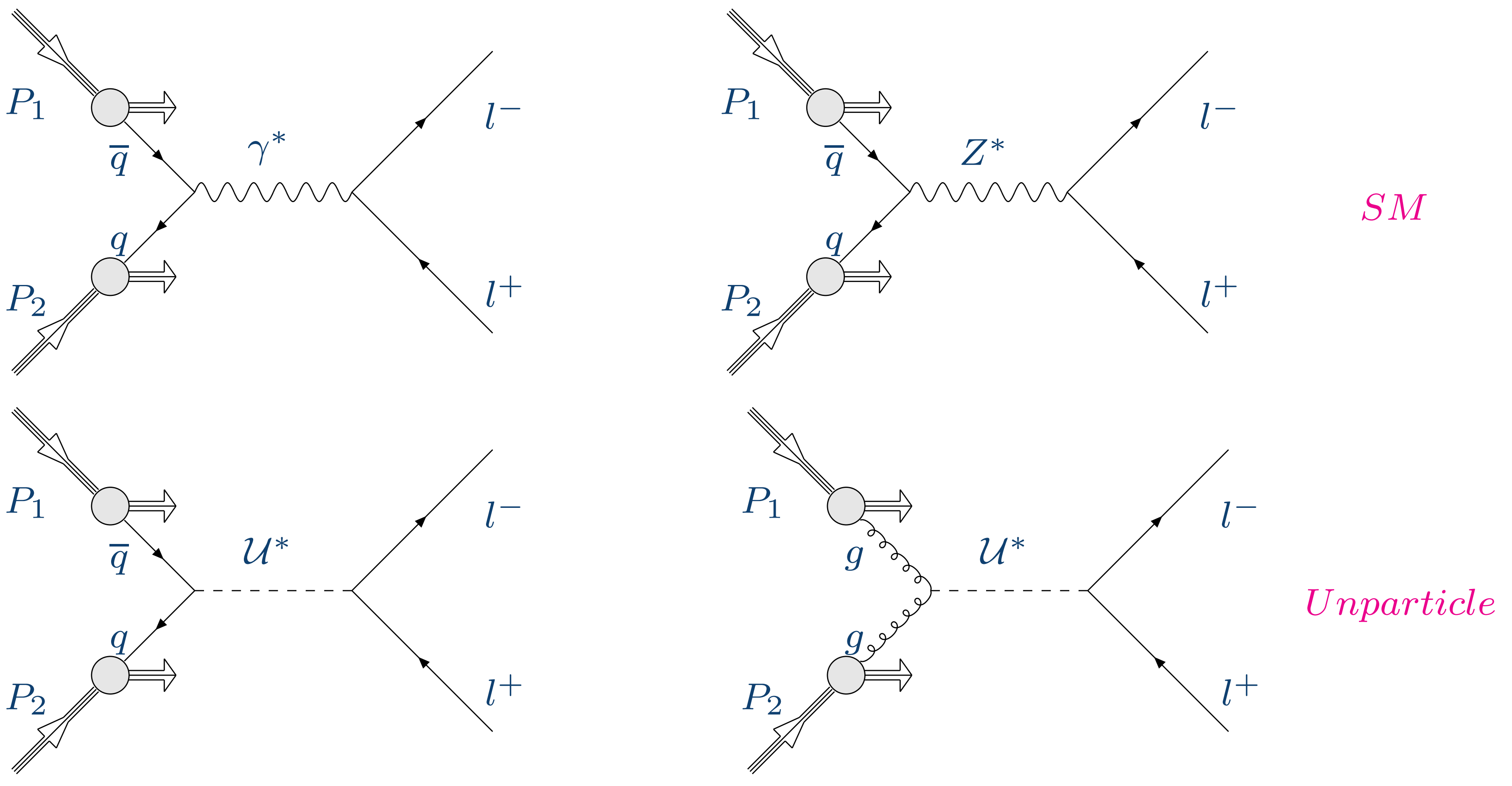
To Leading Order in QCD



Di-photon Process

$$P_1(p_1) + P_2(p_2) \longrightarrow \gamma(k_1) + \gamma(k_2) + X$$

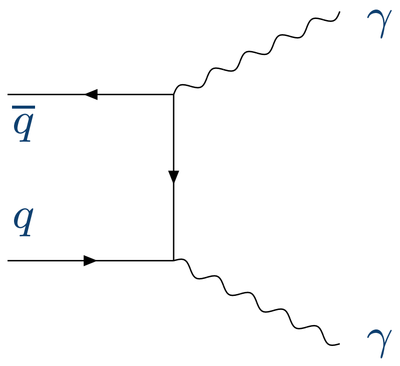
To Leading Order in QCD

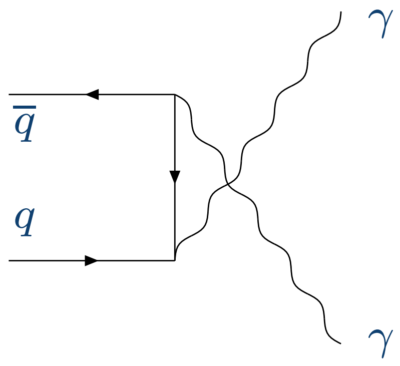
SM

Di-photon Process

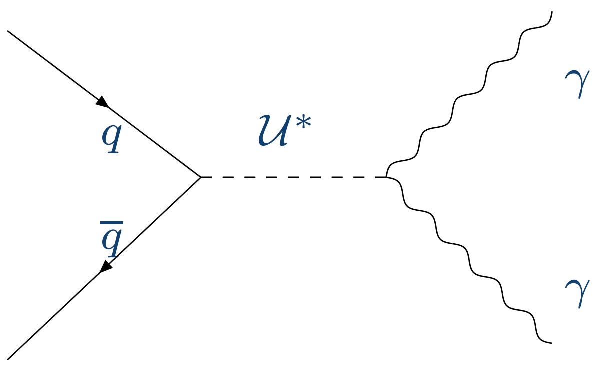
$$P_1(p_1) + P_2(p_2) \longrightarrow \gamma(k_1) + \gamma(k_2) + X$$

To Leading Order in QCD





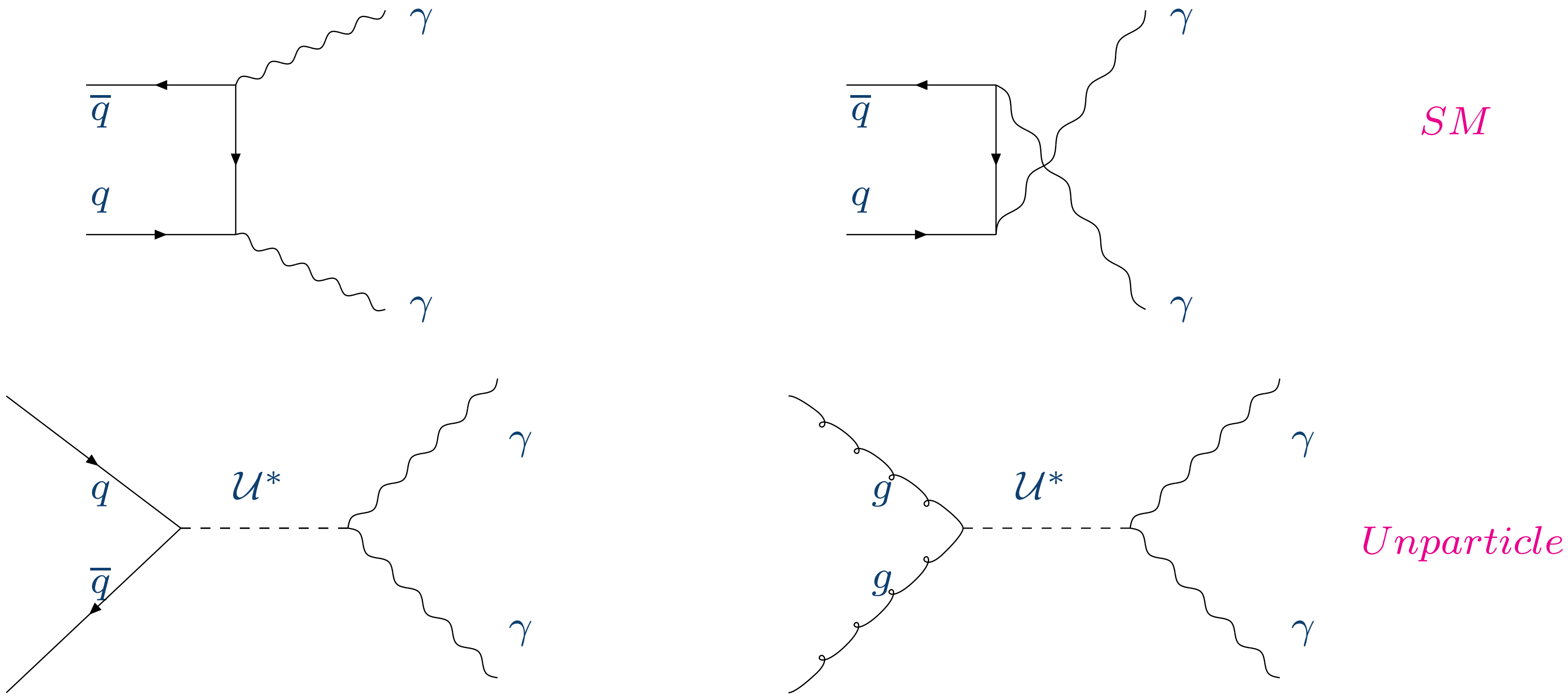
SM



Di-photon Process

$$P_1(p_1) + P_2(p_2) \longrightarrow \gamma(k_1) + \gamma(k_2) + X$$

To Leading Order in QCD



Parton Model

Hadronic cross section in terms of partonic cross sections convoluted with appropriate PDF:

$$2S\, d\sigma^{P_1 P_2}\left(\tau, Q^2\right) = \sum_{ab} \int_\tau^1 \frac{dx}{x} \Phi_{ab}\left(x, \mu_F\right) 2\hat{s}\, d\hat{\sigma}^{ab}\left(\frac{\tau}{x}, Q^2, \mu_F\right)$$

- Partonic cross section perturbatively calculable:

$$d\hat{\sigma}^{ab}\left(z, Q^2, \mu_F\right) = \sum_{i=0}^{\infty} \left(\frac{\alpha_s(\mu_R^2)}{4\pi}\right)^i d\hat{\sigma}^{ab,(i)}\left(z, Q^2, \mu_F, \mu_R\right)$$

- Non-perturbative partonic flux:

$$\Phi_{ab}(x, \mu_F) = \int_x^1 \frac{dz}{z} f_a\left(z, \mu_F\right) f_b\left(\frac{x}{z}, \mu_F\right)$$

- $f_a^{P_1}(x, \mu_F)$ are Parton distribution functions, x is the partonic momentum fraction
  - μ_R is the Renormalisation scale
  - μ_F is the Factorisation scale

Source of Theoretical Uncertainties

- Renormalisation scale:
  Due to UV divergence at beyond Leading Order

$$\alpha_s \rightarrow \alpha_s(\mu_R^2)$$

- Factorisation scale:
  Originate from light quarks and massless gluon. Parton distribution functions are renormalised at the factorisation scale μ_F

$$f_a(x) \rightarrow f_a(x, \mu_F^2) \qquad a = q, \bar{q}, g$$

- Parton Distribution Functions:
  Not calculable but extracted from experiments in some factorisation scheme by various groups by global fits to available data on DIS, DY and other hadronic process
- Observables are "free" of μ_R and μ_F
- "Fixed order" perturbative results depend on μ_R and μ_F
- Can in principle give large uncertainties

IT IS HENCE IMPORTANT FOR $\mathcal{U}$-PARTICLE SEARCHES TO HAVE BETTER CONTROL OVER THE THEORETICAL UNCERTAINTIES

Next-to-Leading Order process involving $\mathcal{U}$-particles

- Compute NLO QCD corrections to LO DY processes

$$d\hat{\sigma}_{ab}(\hat{s}, Q^2, \mu_F^2) = d\hat{\sigma}_{ab}^{(0)}(\hat{s}, Q^2, \mu_F^2)\left[1 + \frac{\alpha_s(\mu_R^2)}{4\pi}\Delta_{ab}^{(1)}(\hat{s}, Q^2, \mu_F^2, \mu_R^2)\right]$$

- Soft and collinear divergences regulated in dimensional regularisation $n = 4 + \varepsilon$
- Collinear mass factorisation is done in $\overline{MS}$ scheme
- Coefficient functions to NLO evaluated for invariant mass distribution of di-leptons

$$\frac{d\sigma(Q)}{dQ}$$

with V. Ravindran Phys. Lett. B657 (2007) 198

Contributing Subprocess

Leading Order:

Standard Model	$\mathcal{U}$-particle
$q+\bar{q}\rightarrow\gamma/Z$	$q+\bar{q}\rightarrow\mathcal{U}$ $g+g\rightarrow\mathcal{U}$

Next-to-Leading Order:

Standard Model	$\mathcal{U}$-particles
$q+\bar{q}\rightarrow\gamma/Z+g$, $q+\bar{q}\rightarrow\gamma/Z$ + one loop $q+g\rightarrow\gamma/Z+q$, $\bar{q}+g\rightarrow\gamma/Z+\bar{q}$	$q+\bar{q}\rightarrow\mathcal{U}+g$, $q+\bar{q}\rightarrow\mathcal{U}$ + one loop $q+g\rightarrow\mathcal{U}+q$, $\bar{q}+g\rightarrow\mathcal{U}+\bar{q}$ $g+g\rightarrow\mathcal{U}+g$, $g+g\rightarrow\mathcal{U}$ + one loop

Mass Factorisation

Drell-Yan coefficient function ($\overline{MS}$ scheme)

$$\bar{\Delta}^i_{ab}(z, Q^2, \frac{1}{\varepsilon}) \;=\; \sum_{c,d} \Gamma_{ca}\left(z, \mu_F^2, \frac{1}{\varepsilon}\right) \otimes \Gamma_{db}\left(z, \mu_F^2, \frac{1}{\varepsilon}\right) \otimes \Delta^i_{cd}(z, Q^2, \mu_F^2)$$

(Bare) **(Mass Factorised)**

$$\Delta^i_{ab} = \Delta^{(0),i}_{ab} + \frac{\alpha_s(\mu_R^2)}{4\pi}\,\Delta^{(1),i}_{ab}$$

$$\Gamma_{cd}(z, \mu_F) \;=\; \delta_{cd}\delta(1-z) + \frac{\alpha_s(\mu_R^2)}{4\pi}\,\frac{1}{\varepsilon}\left(\frac{\mu_F^2}{\mu_R^2}\right)^{\varepsilon/2} P^{(0)}_{cd}(z)$$

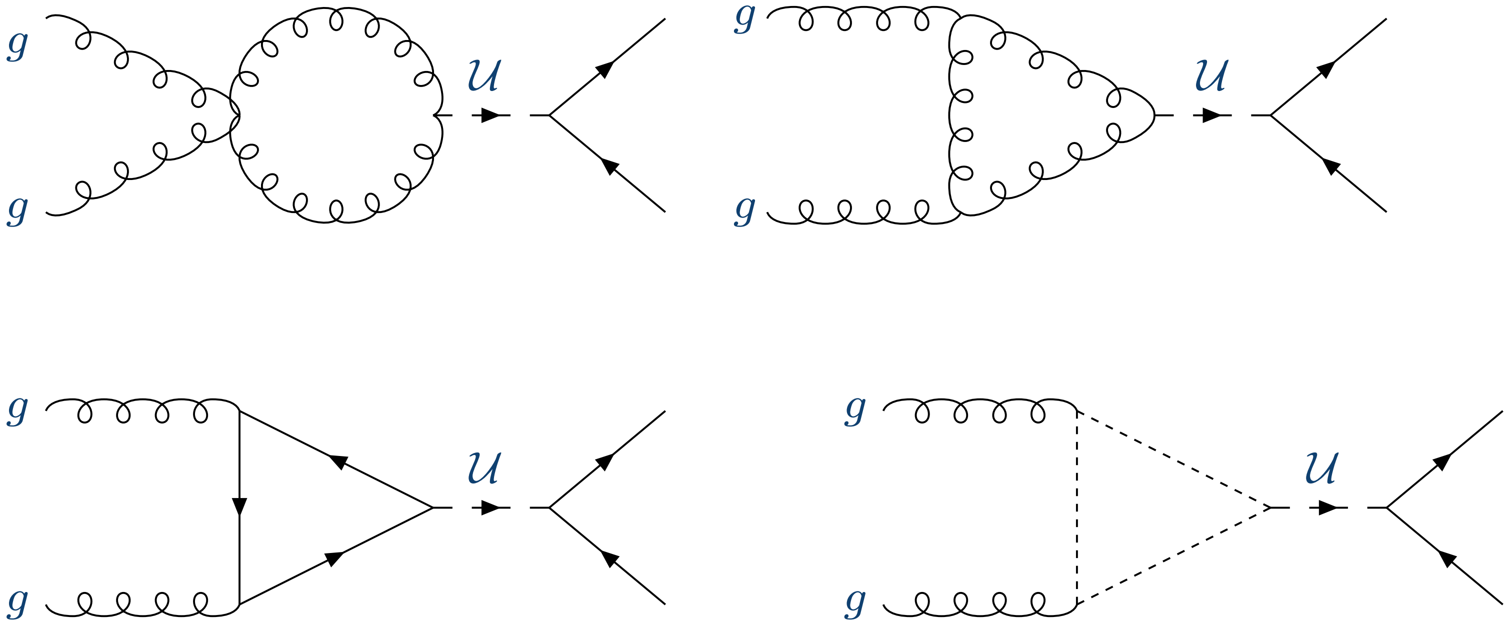
$P^{(0)}_{cd}(z)$ LO Altarelli-Parisi splitting functions

Δ^i_{ab} TO BE EVALUATED ORDER BY ORDER IN PERTURBATION THEORY

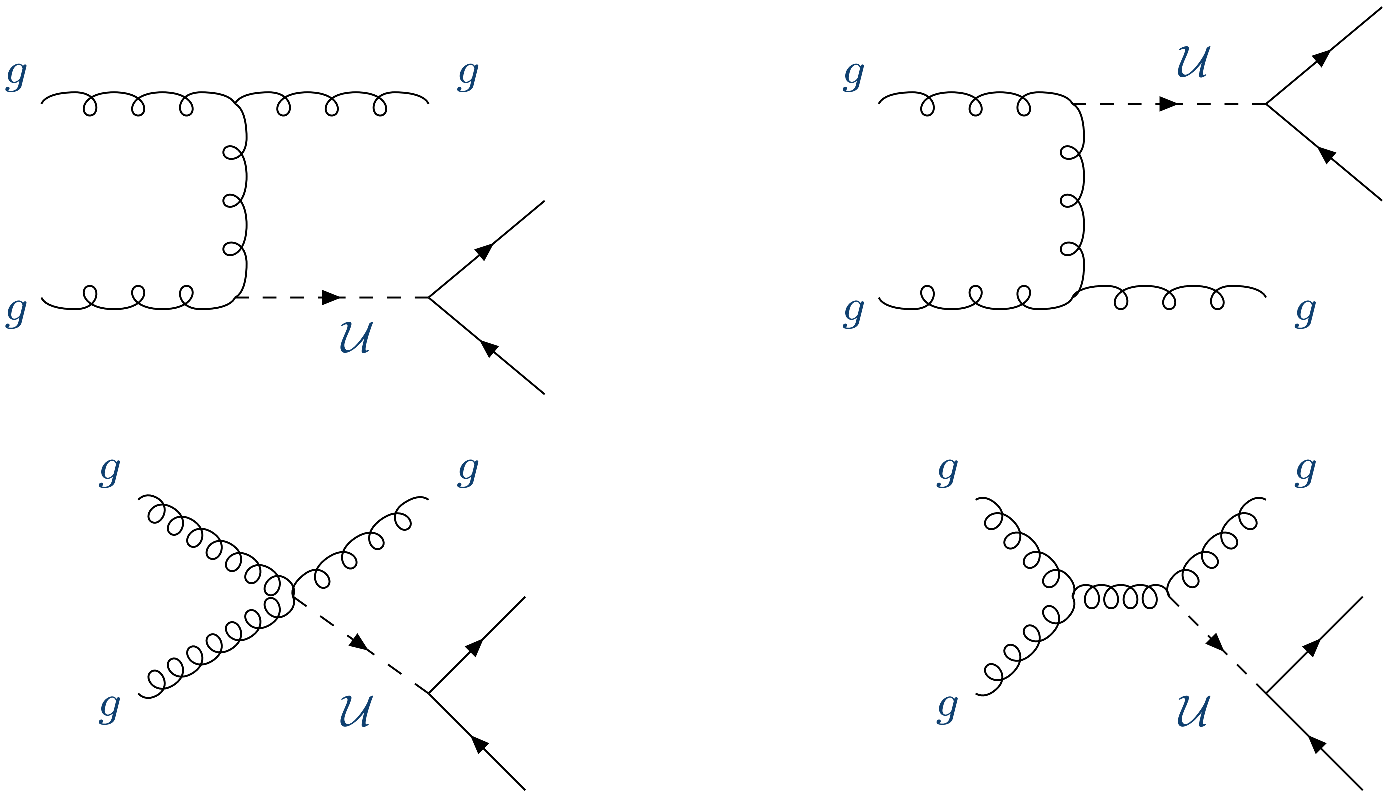
Virtual Corrections $g\,\bar{g} \rightarrow \mathcal{U}$

$$\bar{\boldsymbol{\Delta}}^{\mathcal{U}}_{gg} = \boldsymbol{\Delta}^{(0)\mathcal{U}}_{gg} + a_s \frac{2}{\varepsilon} \boldsymbol{\Gamma}^{(1)}_{gg} \otimes \boldsymbol{\Delta}^{(0)\mathcal{U}}_{gg} + a_s \boldsymbol{\Delta}^{(1)\mathcal{U}}_{gg}$$

$g + g \rightarrow \mathcal{U}$ (1 loop):



Real emission $g\, g \to g\, \mathcal{U}$



Invariant mass distribution of lepton pair

$$2S\,\frac{d\sigma^{P_1P_2}}{dQ^2}(\tau,Q^2) =$$

$$\sum_q \mathcal{F}_{SM,q}\Bigg[H_{q\bar{q}}(\tau,Q^2)\otimes\Big(\Delta^{(0)\gamma Z}_{q\bar{q}}(\tau,Q^2)+a_s\Delta^{(1)\gamma Z}_{q\bar{q}}(\tau,Q^2)\Big)$$

$$+\Big(H_{qg}(\tau,Q^2)+H_{gq}(\tau,Q^2)\Big)\otimes a_s\Delta^{(1)\gamma Z}_{qg}(\tau,Q^2)\Bigg]$$

Invariant mass distribution of lepton pair

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$$\sum_q \mathcal{F}_{SM,q}\Big[H_{q\bar q}(\tau,Q^2)\otimes\Big(\Delta_{q\bar q}^{(0)\gamma Z}(\tau,Q^2)+a_s\Delta_{q\bar q}^{(1)\gamma Z}(\tau,Q^2)\Big)$$

$$+\Big(H_{qg}(\tau,Q^2)+H_{gq}(\tau,Q^2)\Big)\otimes a_s\Delta_{qg}^{(1)\gamma Z}(\tau,Q^2)\Big]$$

$$+\sum_q \mathcal{F}_{\mathcal{U}}\Big[H_{q\bar q}(\tau,Q^2)\otimes\Big(\Delta_{q\bar q}^{(0)\mathcal{U}}(\tau,Q^2)+a_s\Delta_{q\bar q}^{(1)\mathcal{U}}(\tau,Q^2)\Big)$$

$$+\Big(H_{qg}(\tau,Q^2)+H_{gq}(\tau,Q^2)\Big)\otimes a_s\Delta_{qg}^{(1)\mathcal{U}}(\tau,Q^2)$$

$$+H_{gg}(\tau,Q^2)\otimes\Big(\Delta_{gg}^{(0)\mathcal{U}}(\tau,Q^2)+a_s\Delta_{gg}^{(1)\mathcal{U}}(\tau,Q^2)\Big)\Big]$$

Invariant mass distribution of lepton pair

$$2S\,\frac{d\sigma^{P_1P_2}}{dQ^2}(\tau,Q^2) =$$

$$\sum_q \mathcal{F}_{SM,q}\Big[H_{q\bar q}(\tau,Q^2)\otimes\Big(\Delta^{(0)\gamma Z}_{q\bar q}(\tau,Q^2)+a_s\Delta^{(1)\gamma Z}_{q\bar q}(\tau,Q^2)\Big)$$

$$+\Big(H_{qg}(\tau,Q^2)+H_{gq}(\tau,Q^2)\Big)\otimes a_s\Delta^{(1)\gamma Z}_{qg}(\tau,Q^2)\Big]$$

$$+\sum_q \mathcal{F}_{\mathcal{U}}\Big[H_{q\bar q}(\tau,Q^2)\otimes\Big(\Delta^{(0)\mathcal{U}}_{q\bar q}(\tau,Q^2)+a_s\Delta^{(1)\mathcal{U}}_{q\bar q}(\tau,Q^2)\Big)$$

$$+\Big(H_{qg}(\tau,Q^2)+H_{gq}(\tau,Q^2)\Big)\otimes a_s\Delta^{(1)\mathcal{U}}_{qg}(\tau,Q^2)$$

$$+H_{gg}(\tau,Q^2)\otimes\Big(\Delta^{(0)\mathcal{U}}_{gg}(\tau,Q^2)+a_s\Delta^{(1)\mathcal{U}}_{gg}(\tau,Q^2)\Big)\Big]$$

COEFFICIENT FUNCTIONS FREE OF MASS SINGULARITIES

Observables

$\mathcal{U}$-particle parameters $(\lambda, \Lambda, d_{\mathcal{U}})$

Distributions:

$$\frac{d\sigma(Q)}{dQ} \qquad \frac{d\sigma(Y)}{dY}$$

K-Factor:

$$K = \left[\frac{d\sigma_{LO}(Q)}{dQ}\right]^{-1}\left[\frac{d\sigma_{NLO}(Q)}{dQ}\right]$$

R-Factor:

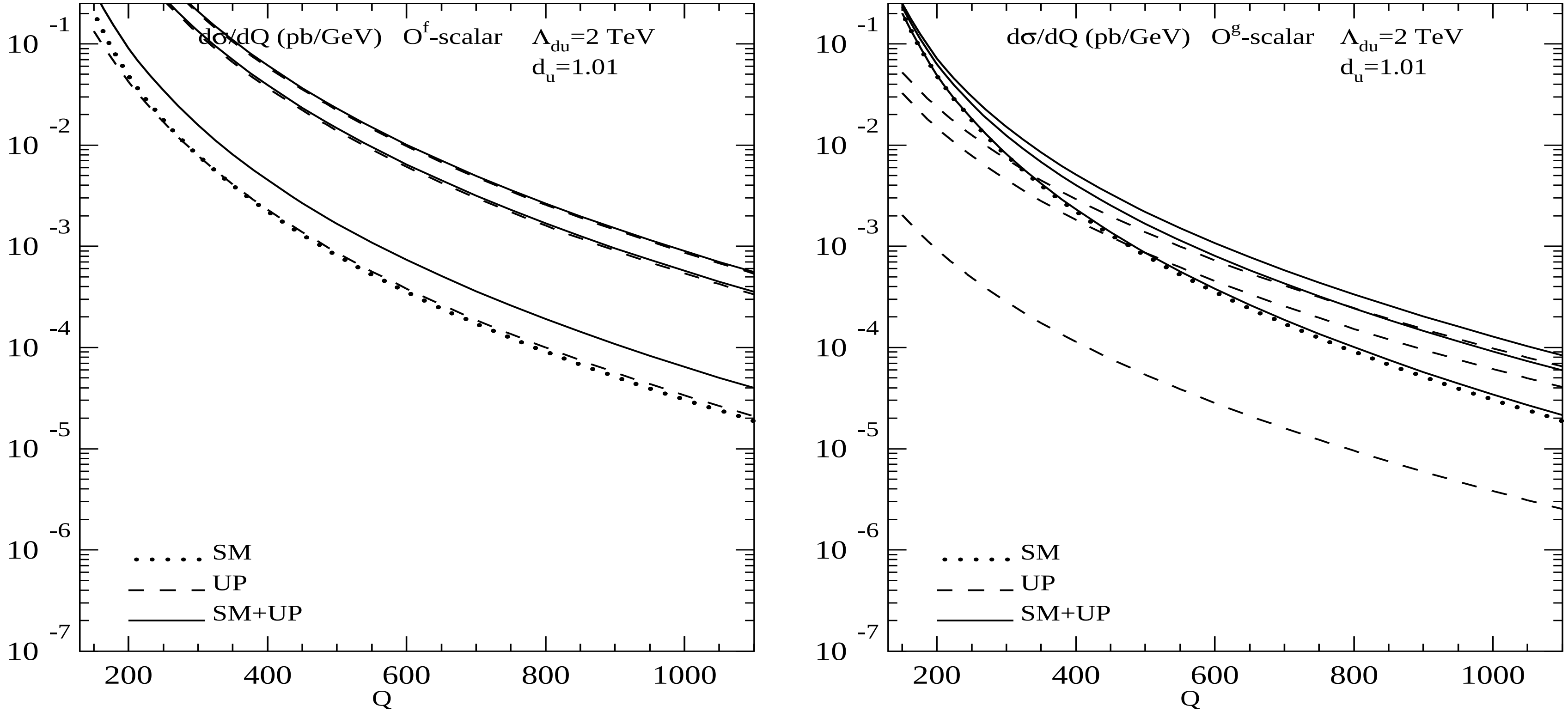
$$R_{LO} = \left[\frac{d\sigma_{LO}(Q,\mu=\mu_0)}{dQ}\right]^{-1}\left[\frac{d\sigma_{LO}(Q,\mu)}{dQ}\right]$$

$$R_{NLO} = \left[\frac{d\sigma_{NLO}(Q,\mu=\mu_0)}{dQ}\right]^{-1}\left[\frac{d\sigma_{NLO}(Q,\mu)}{dQ}\right]$$

- Factorisation scale dependence of the above observables in going from LO to NLO

Invariant mass distribution of lepton pair: Scalar $\mathcal{U}$-particle

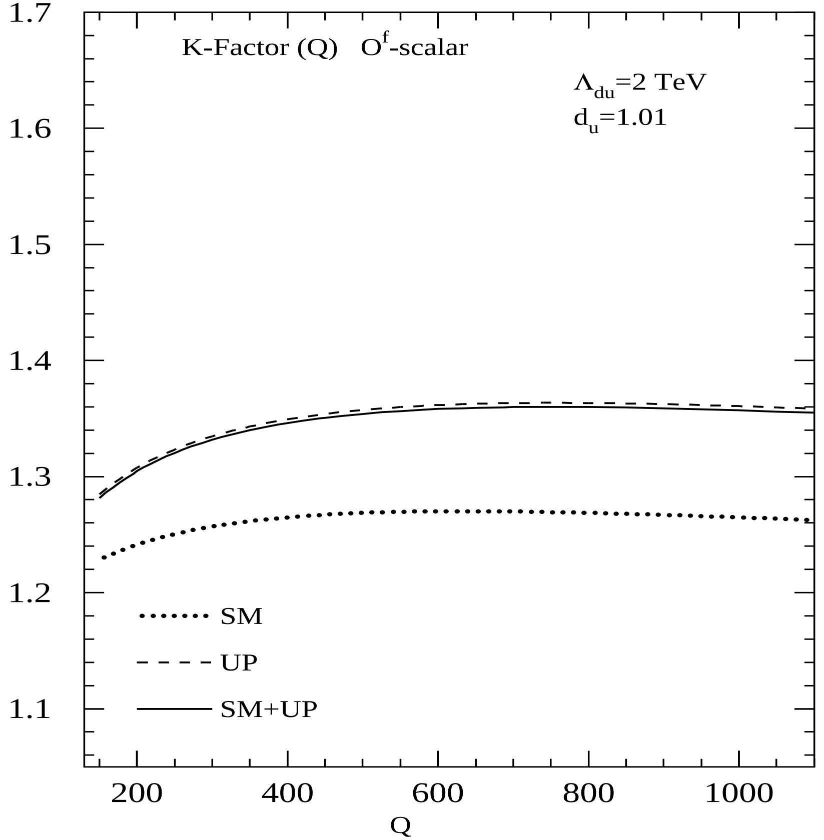
$$\frac{d\sigma^{DY}(Q)}{dQ}$$

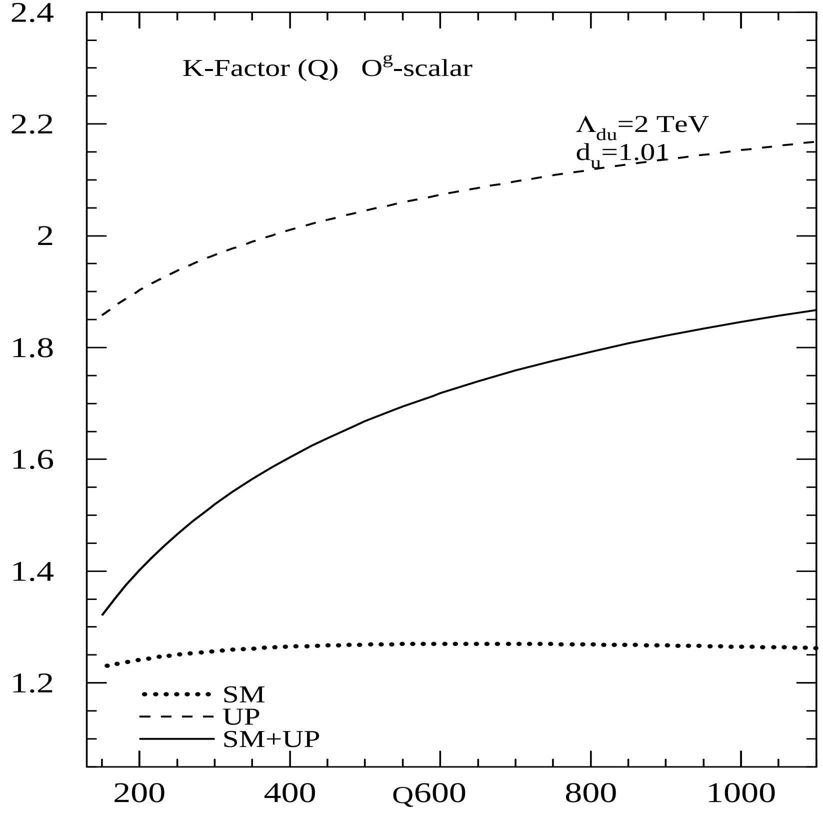


- $q\bar{q} \longrightarrow \ell^+\ell^-$ $qg \longrightarrow q\,\ell^+\ell^-$ $\bar{q}g \longrightarrow \bar{q}\,\ell^+\ell^-$
- $gg \longrightarrow \ell^+\ell^-$
- Bottom set corresponds to $\lambda_s = 0.4$, middle $\lambda_s = 0.8$ and upper $\lambda_s = 0.9$

Scalar K-factor

$$K_{DY} = \left[\frac{d\sigma_{LO}(Q)}{dQ}\right]^{-1}\left[\frac{d\sigma_{NLO}(Q)}{dQ}\right]$$



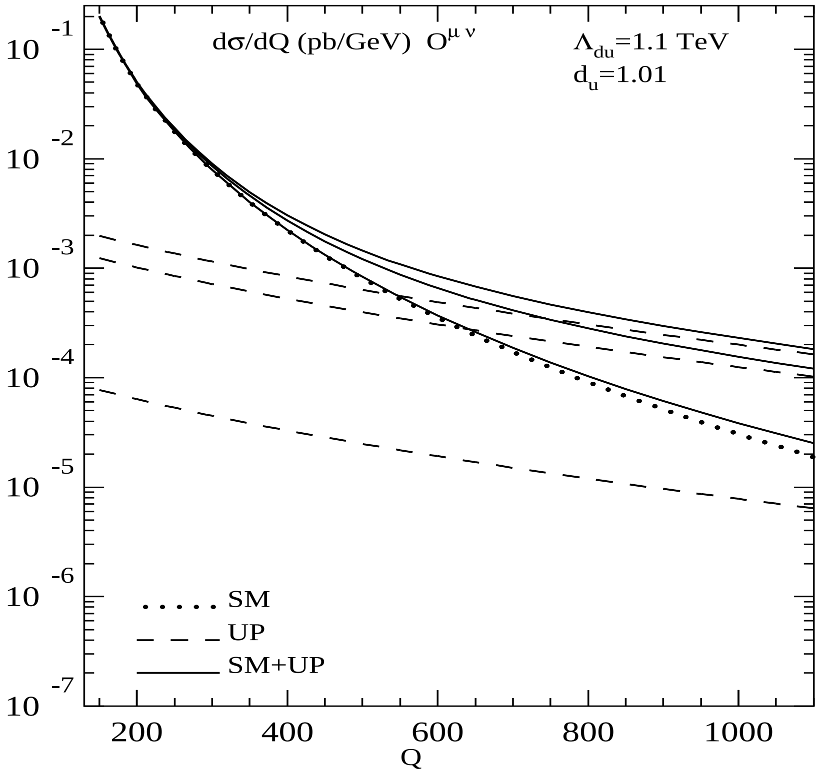


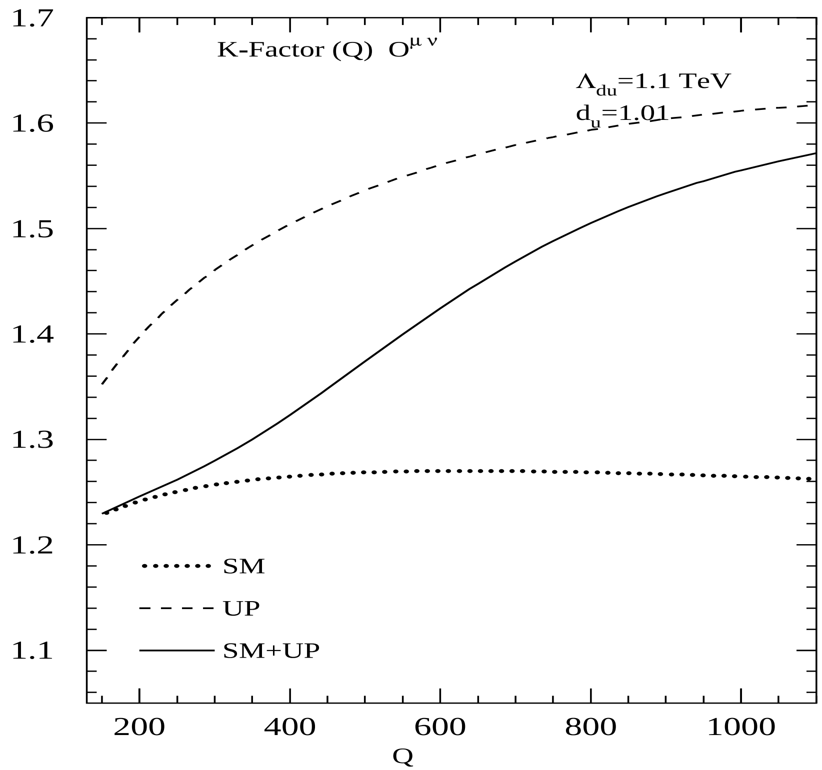
- Scalar coupling quarks
- Scalar coupling to gluons

Tensor $\mathcal{U}$

$\frac{d\sigma^{DY}(Q)}{dQ}$

K-Factor

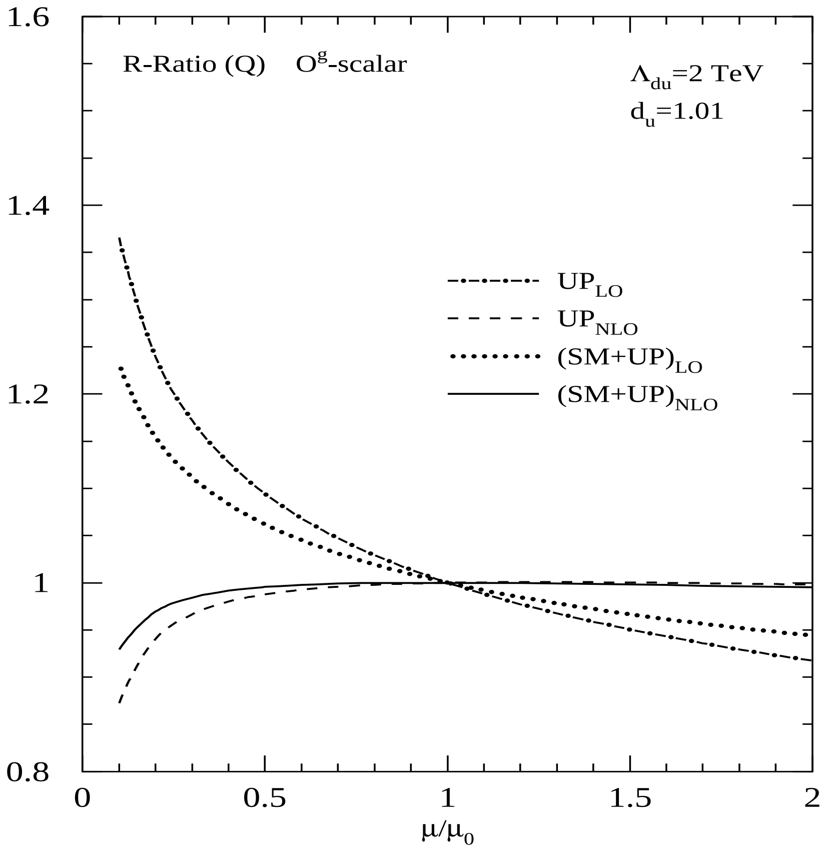


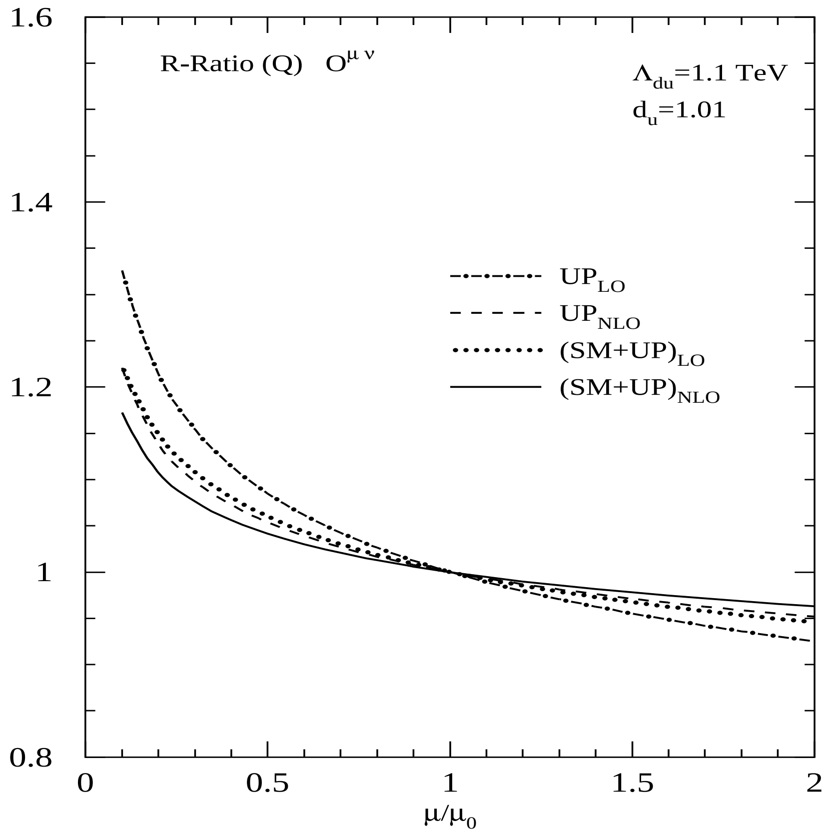


- Tensor $\mathcal{U}$-particles producing a di-lepton pair with invariant mass Q. $\lambda_t = 0.4,\ 0.8$ and 0.9

Factorisation scale dependence

$$R_{LO,NLO} = \left[\frac{d\sigma_{LO,NLO}(Q,\mu=\mu_0)}{dQ}\right]^{-1}\left[\frac{d\sigma_{LO,NLO}(Q,\mu)}{dQ}\right]$$





- Factorisation scale variation of LO and NLO invariant mass distribution of di-lepton from scalar unparticle coupling to gluons (left) and tensor unparticle operator (right) for $\lambda_{s,t} = 0.9$

Contributing Subprocess to digamma production

Leading Order:

Standard Model	$\mathcal{U}$-particle
$q + \bar{q} \rightarrow \gamma\gamma$	$q + \bar{q} \rightarrow \mathcal{U}$ $g + g \rightarrow \mathcal{U}$

Next-to-Leading Order:

Standard Model	$\mathcal{U}$-particles
$q + \bar{q} \rightarrow \gamma\gamma + g$, $q + \bar{q} \rightarrow \gamma\gamma$ + one loop $q + g \rightarrow \gamma\gamma + q$, $\bar{q} + g \rightarrow \gamma\gamma + \bar{q}$	$q + \bar{q} \rightarrow \mathcal{U} + g$, $q + \bar{q} \rightarrow \mathcal{U}$ + one loop $q + g \rightarrow \mathcal{U} + q$, $\bar{q} + g \rightarrow \mathcal{U} + \bar{q}$ $g + g \rightarrow \mathcal{U} + g$, $g + g \rightarrow \mathcal{U}$ + one loop

Phys. Rev. D77 (2008) 055013 & 0804.4054 with MC Kumar, V Ravindran & A Tripathi

Phase-space slicing method

• To study various kinematical distributions of the diphoton event with experimental cuts at NLO, a fully analytical calculation would be tedious

• Two cutoff phase space slicing method— phase space integrals are split into regions that are sensitive to soft & collinear singularities & that are free of them

$$d\sigma^{real}_{ab} = d\sigma^{real}_{ab,soft}(\delta_s) + d\sigma^{real}_{ab,col}(\delta_s, \delta_c) + d\sigma^{real}_{ab,fin}(\delta_s, \delta_c)$$

• Integrals involving soft and collinear regions in phase space are regulated using dimensional regularisation. Including the virtual gluon corrections to born process at NLO in QCD σ^V_{ab} and mass factorisation counter terms, the resulting cross section would be free of all IR singularities in QCD.

$$\Delta_{ab} = d\sigma^{S+V+F}_{ab}(\delta_s, \delta_c) + d\sigma^{real}_{ab,fin}(\delta_s, \delta_c)$$

• Even though the two terms on the RHS depends on the parameters δ_s and δ_c the LHS is independent of these parameters

Di-photon production

• In addition to the singularities from partons, the photons in the final states can also give collinear singularities when they become collinear to one of the final state partons.

• Photons can also be produced via fragmentation from quarks and gluons in addtion to the direct hard process.

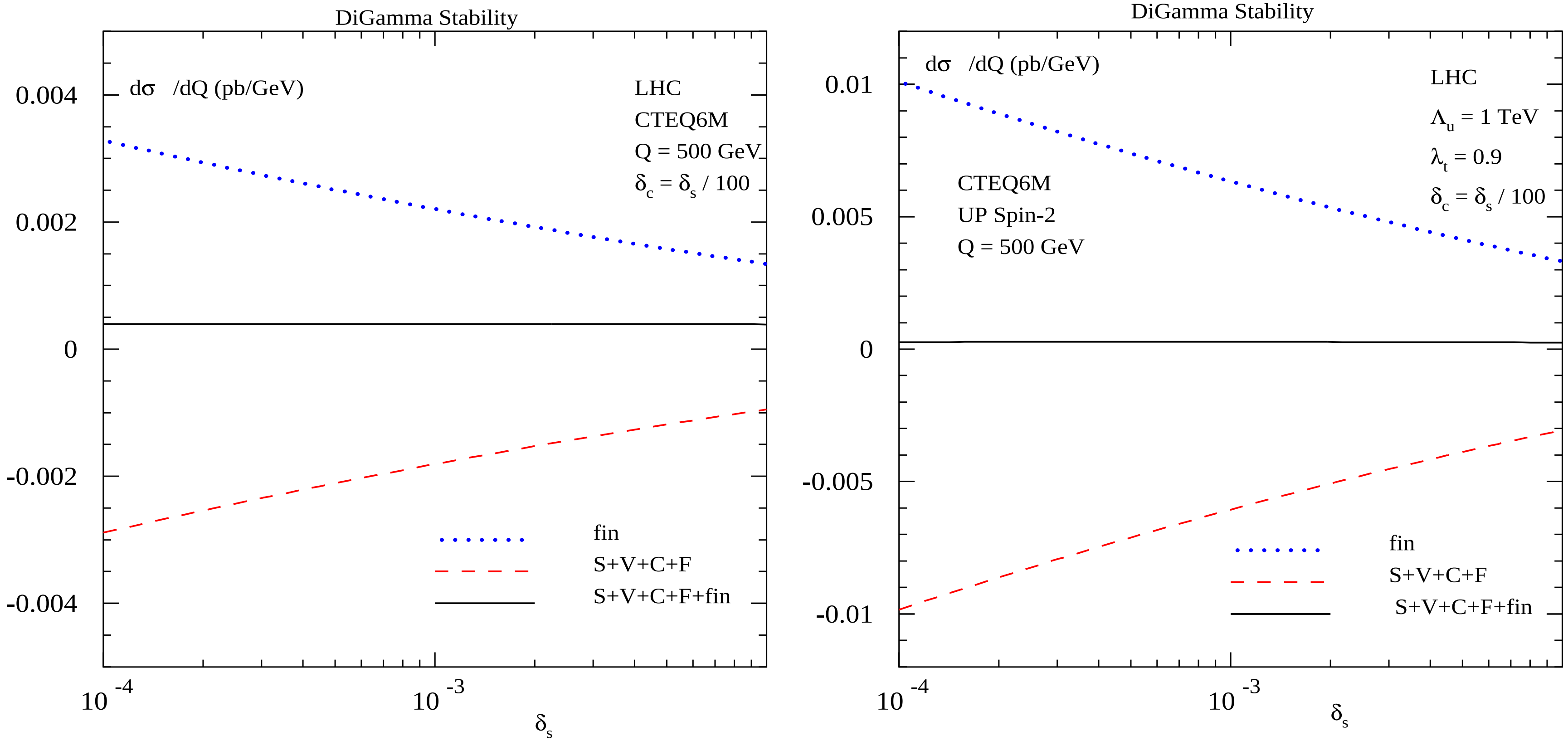
• These final state QED singularities could be absorbed into the fagmentation functions, which are additional non perturbative inputs poorly know to date.

Binoth *et.al* arXiv:hep-ph/9911340

• We adopt an alternate smooth cone isolation criterion proposed by Frixione which ensures that the fragmentation contribution and the final state QED singularities are suppressed with out affecting any of the singularities discussed earlier.

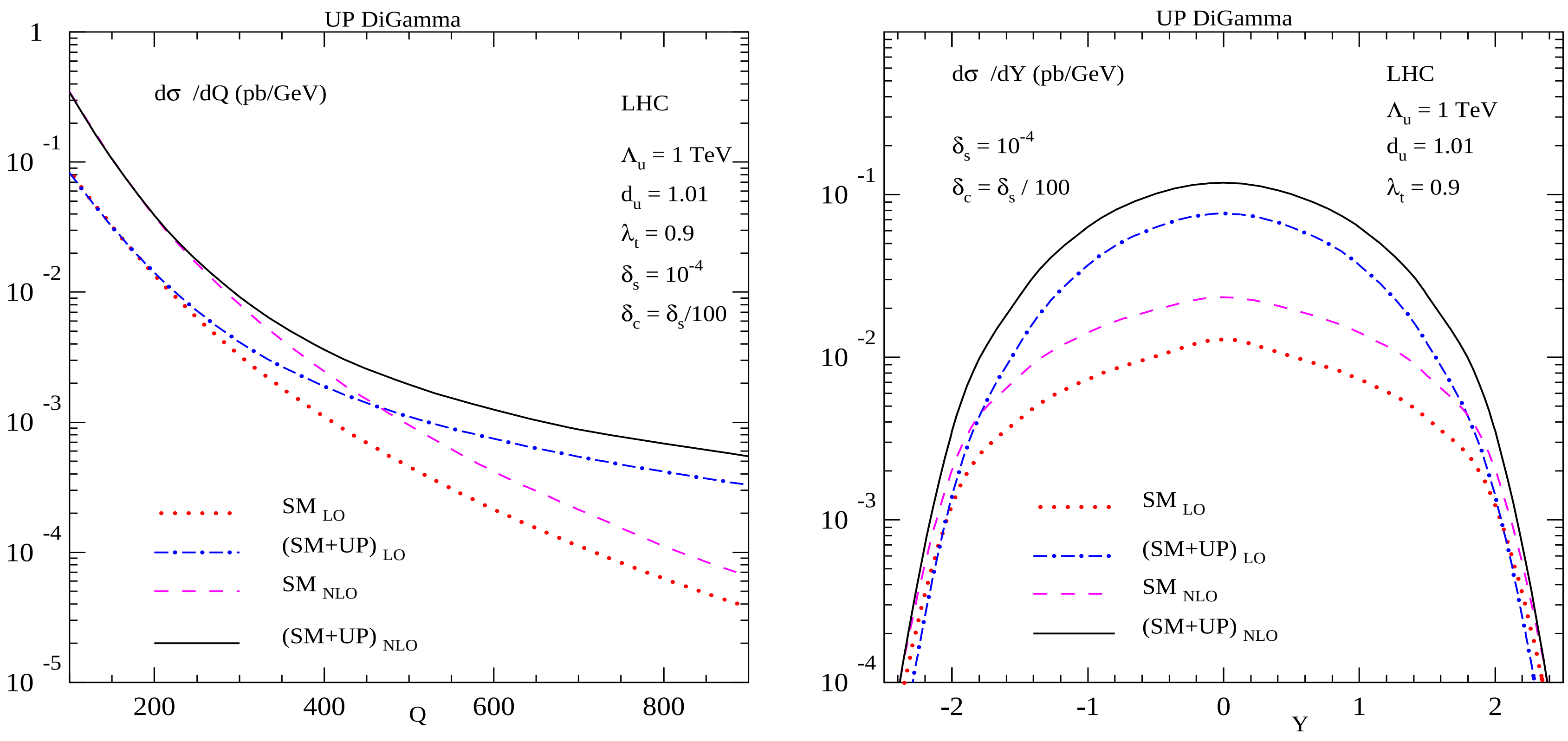
Frixione arXiv:hep-ph/9801442

Stability plots for $d\sigma/dQ$



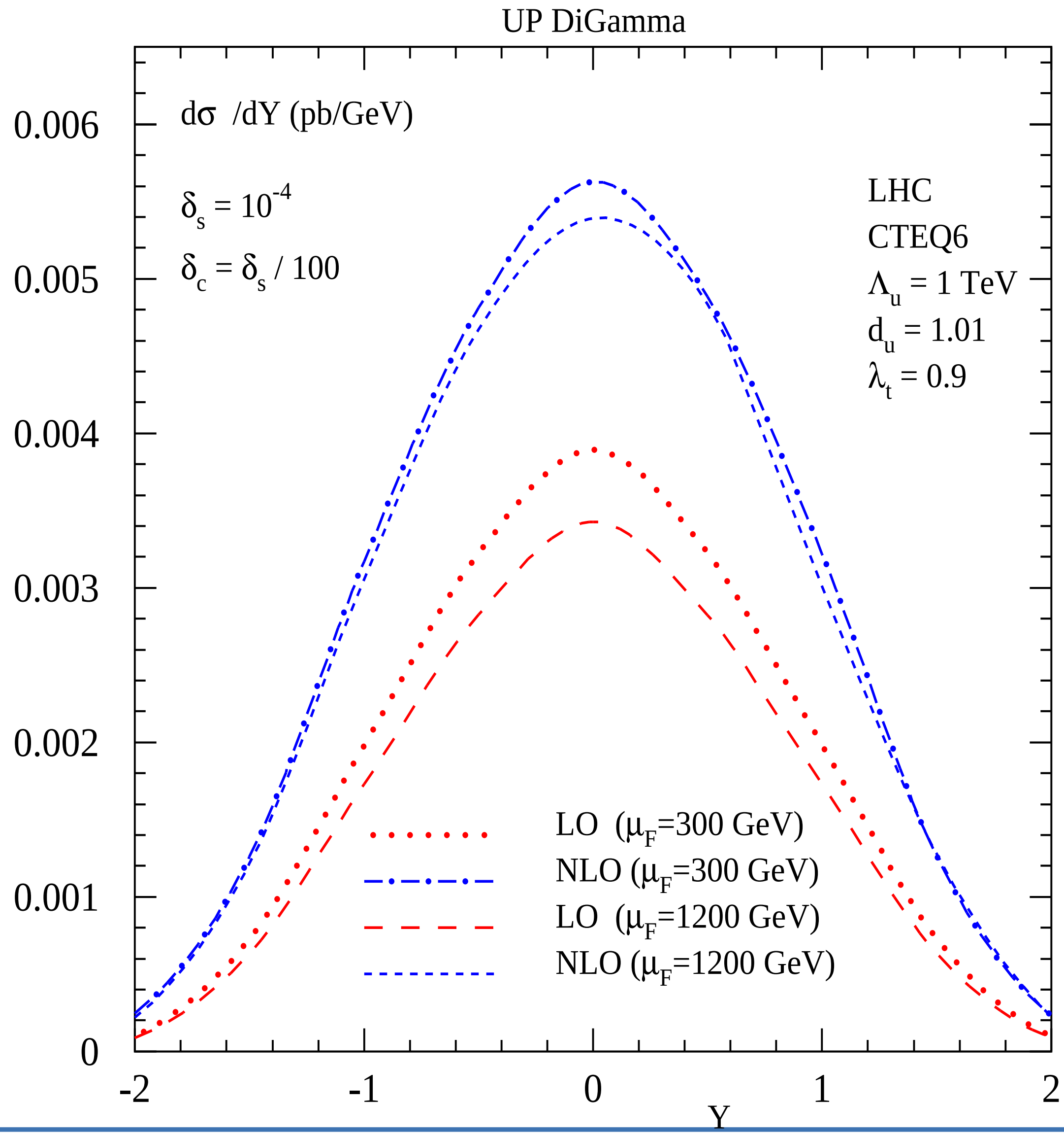
Stability of $d\sigma/dQ$ for SM (left panel) and unparticle (right panel) against the choice of $\delta_c = \delta_s/100$

Di-photon invariant mass & Rapidity distribution



Invariant mass (left panel) and rapidity (right panel) distributions of the di-photon system with $d_{\mathcal{U}} = 1.01$, $\Lambda_{\mathcal{U}} = 1$ TeV and $\lambda_t = 0.9$. For rapidity distribution Q is integrated in the range 600 GeV $< Q < 0.9\Lambda_{\mathcal{U}}$

Factorisation scale variation



Summary

- Next to Leading Order coefficient functions for dilepton & diphoton production process in scale invariant $\mathcal{U}$-particle theories at TeV-scale are now available
- Inclusion of QCD corrections to NLO stabilises the cross section with respect to scale variation
- Quantitative impact of the QCD corrections for searches of $\mathcal{U}$-particle at hadron colliders investigated
- Di-lepton and di-photon production can be used to unravel various aspects of the unparticle physics