Quantum Chromodynamics

HASCO Summer School, Göttingen,
17 July - 25 July 2023

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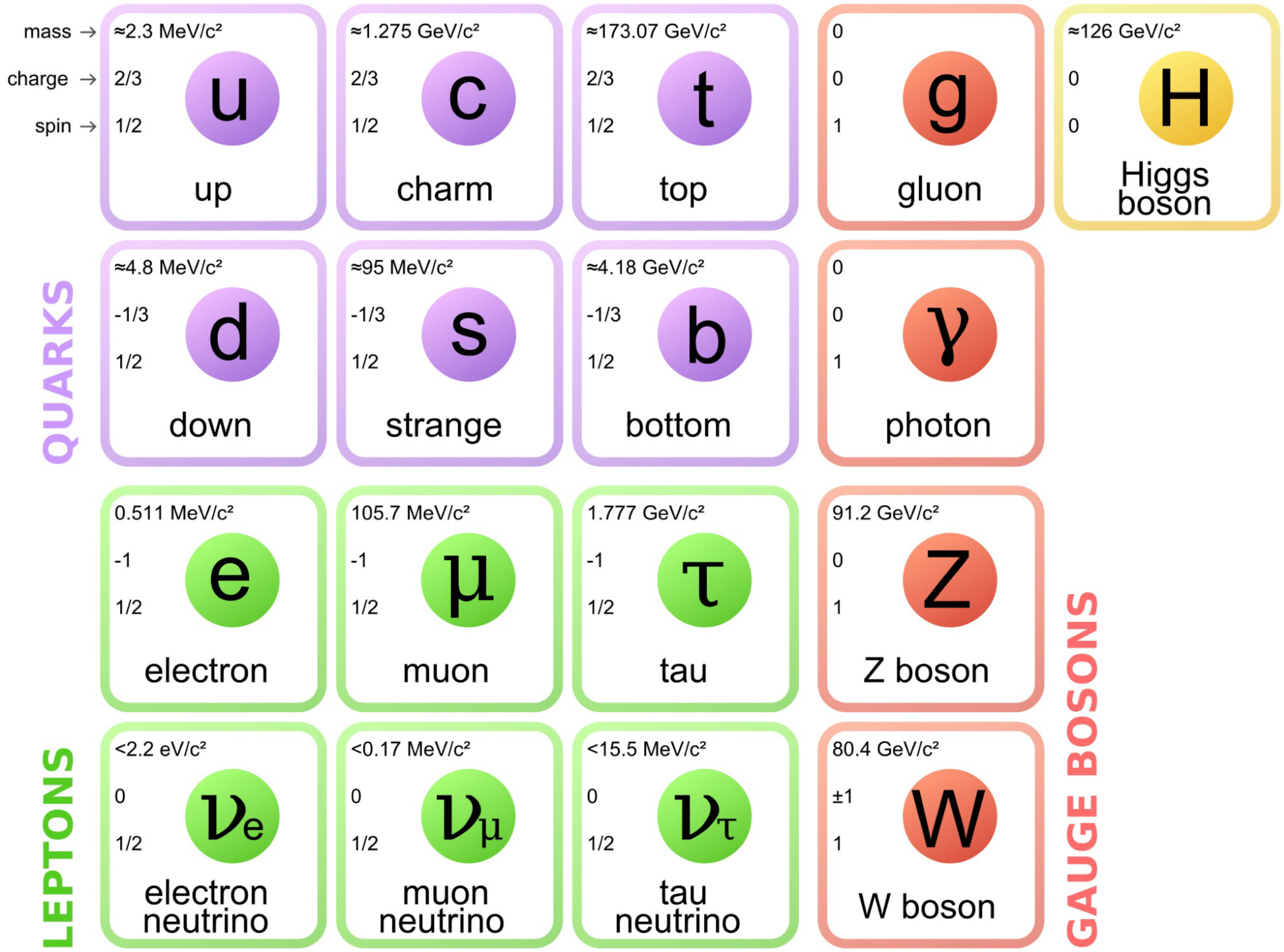
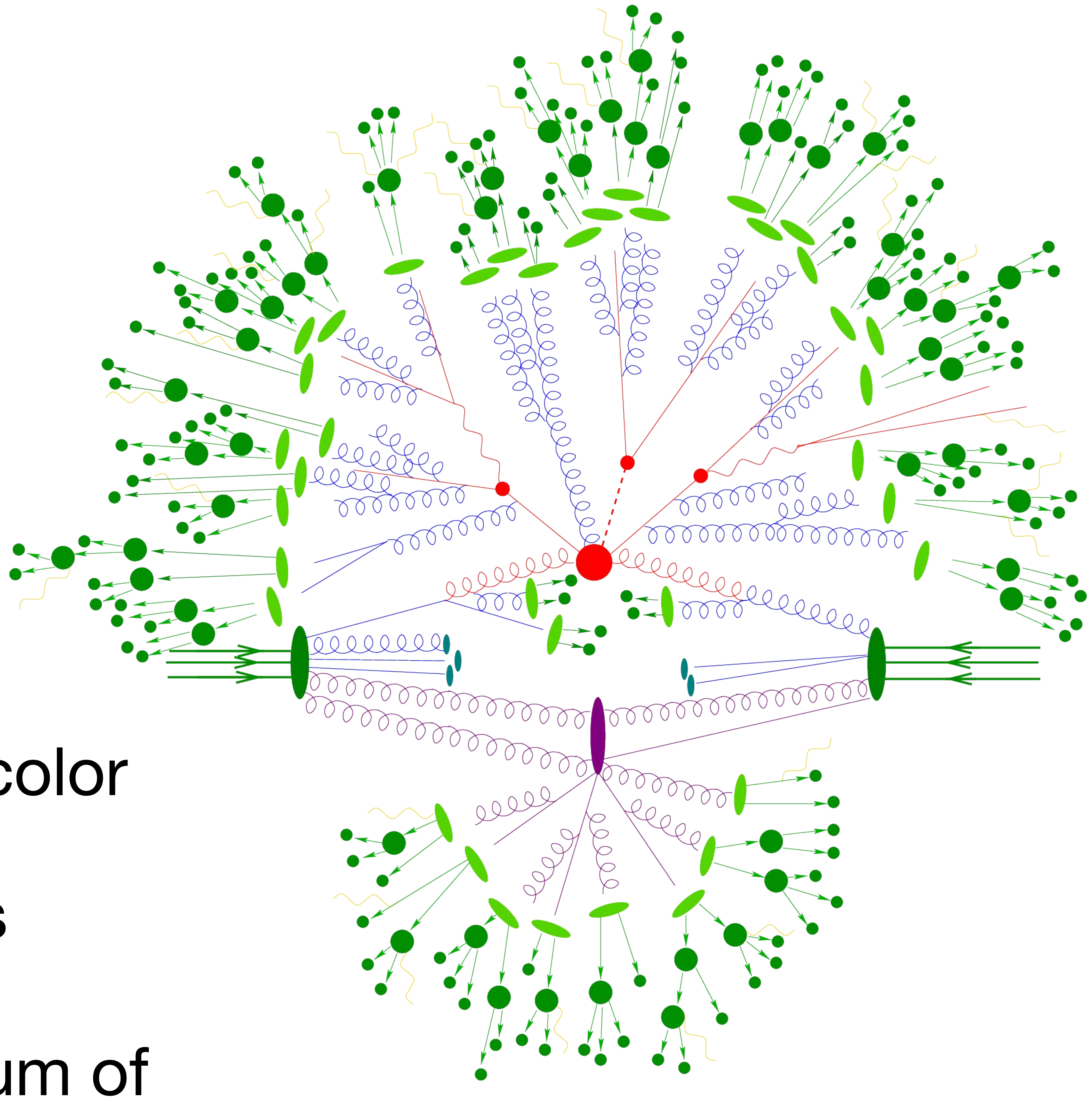
quantum chromodynamics - overview

- strong interaction part of the standard mode
  - jet production
  - internal structure of hadrons
- ingredients:
  - 3 families of quarks/anti-quarks, come in 3 colours
  - gluon, 8 colour states
  - coupling constant $\alpha_s \sim 0.1$, relatively large → "strong" coupling



QCD at colliders

- Events factorised into
  - Hard Process
  - QCD radiation
  - PDFs/Beams
  - Hadrons ✓
    - parton model: hadrons consist of color neutral combinations of 3 quarks (Baryons) or quark anti-quark pairs (Mesons)
    - lattice QCD confirms mass spectrum of hadrons as property of QCD



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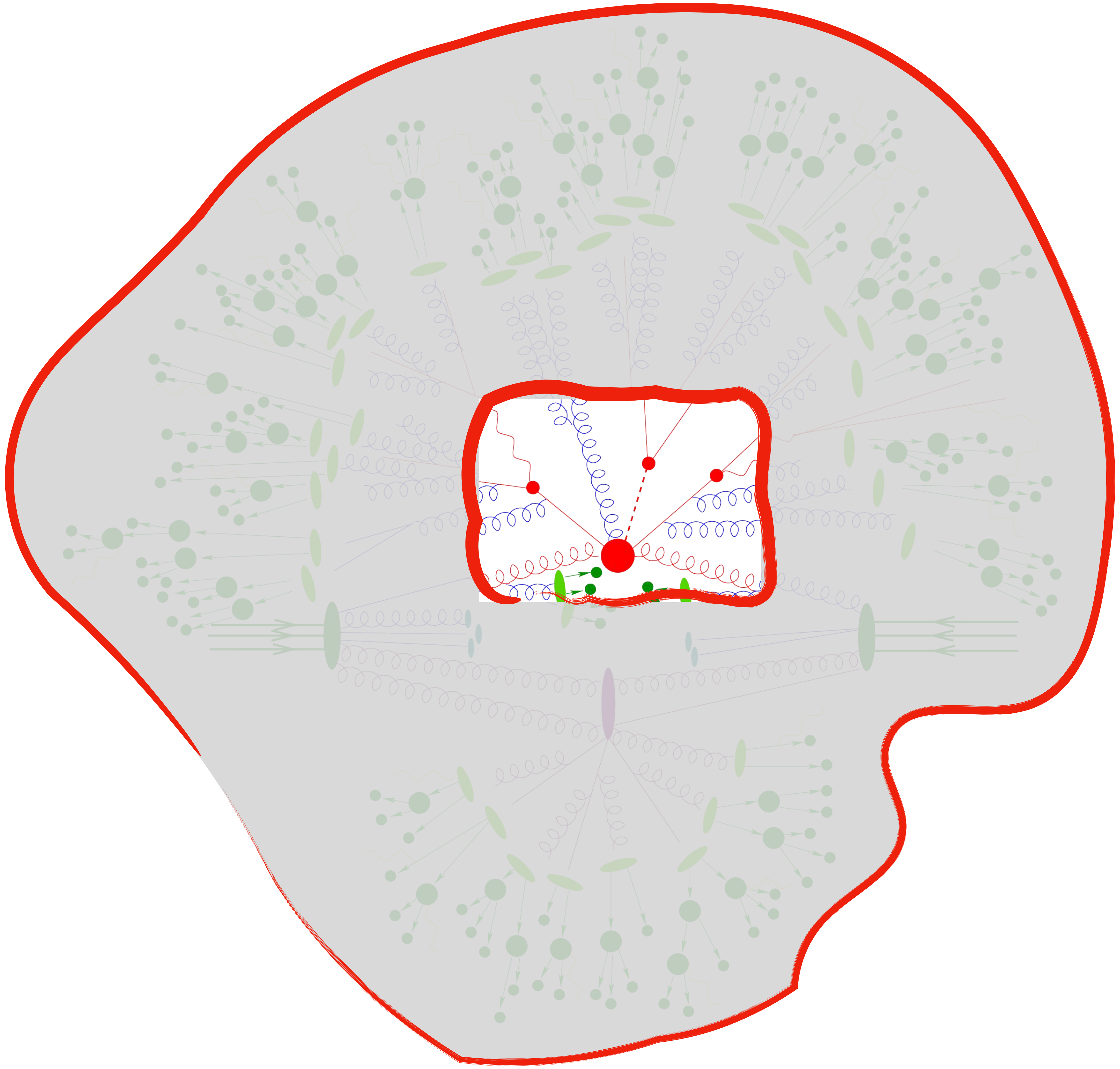


recap of pQCD so far

- running coupling $\alpha_s(\mu) \to \infty$ as $\mu \to \Lambda_{QCD}$ (confinement) and $\alpha_s(\mu) \to 0$ as $\mu \to \infty$ (asymptotic freedom) → LHC energies naively within range of perturbative QCD

- Feynman rules derived from Lagrangian for $SU(3)$ gauge theory

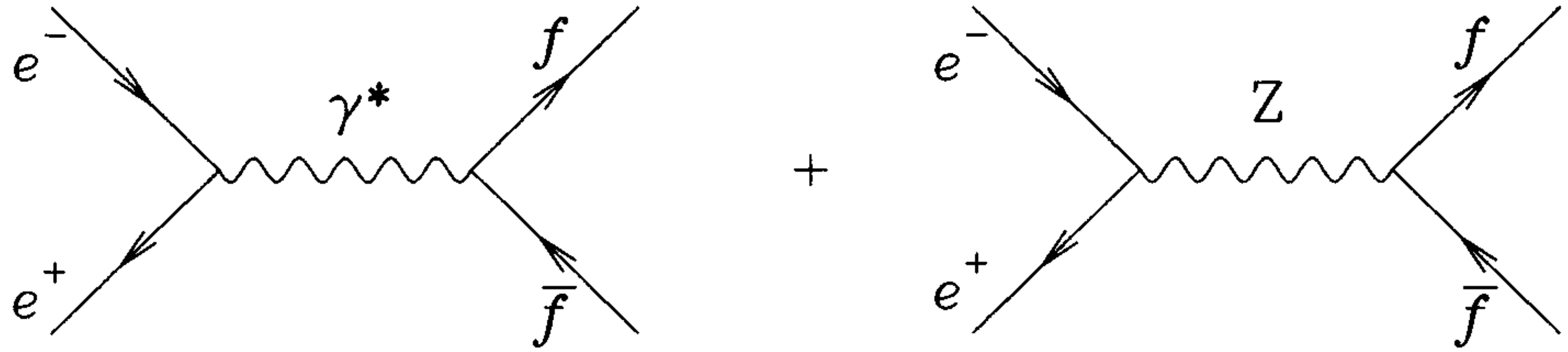
$$\mathscr{L}_{QCD} = \bar{\psi}_q^a \left(i\gamma^\mu (D_\mu)_{ab} - \delta_{ab} m_q \right) \psi_q^b - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

- non-abelian theory → interaction between gluons in addition to gluon-quark vertices

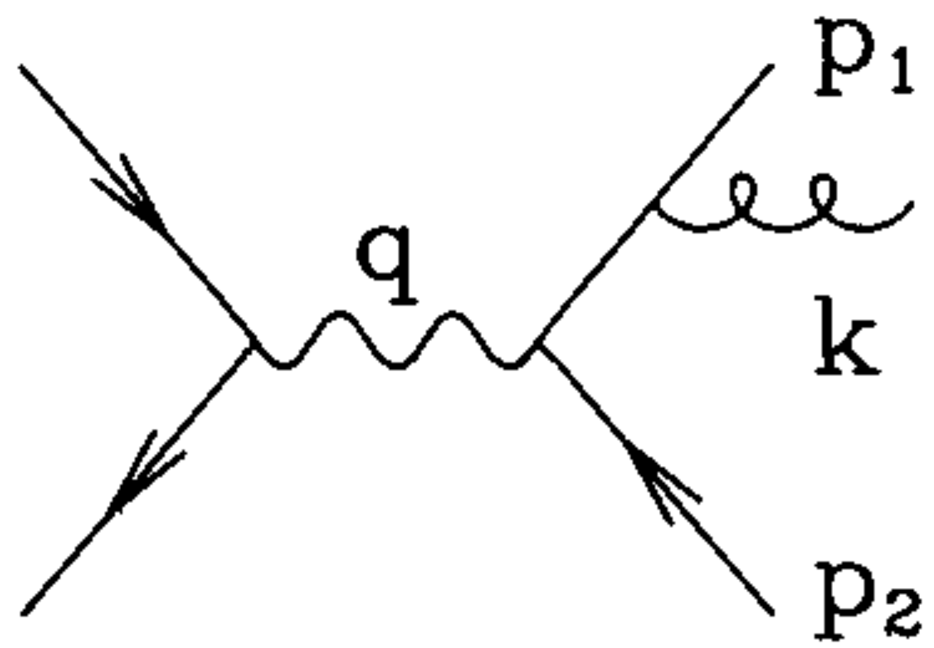
QCD calculations

- simplest process involving quarks: $e^+e^- \to \gamma^* \to q\bar{q}$

- not actually involving QCD, generic fermion production (but N_c times)

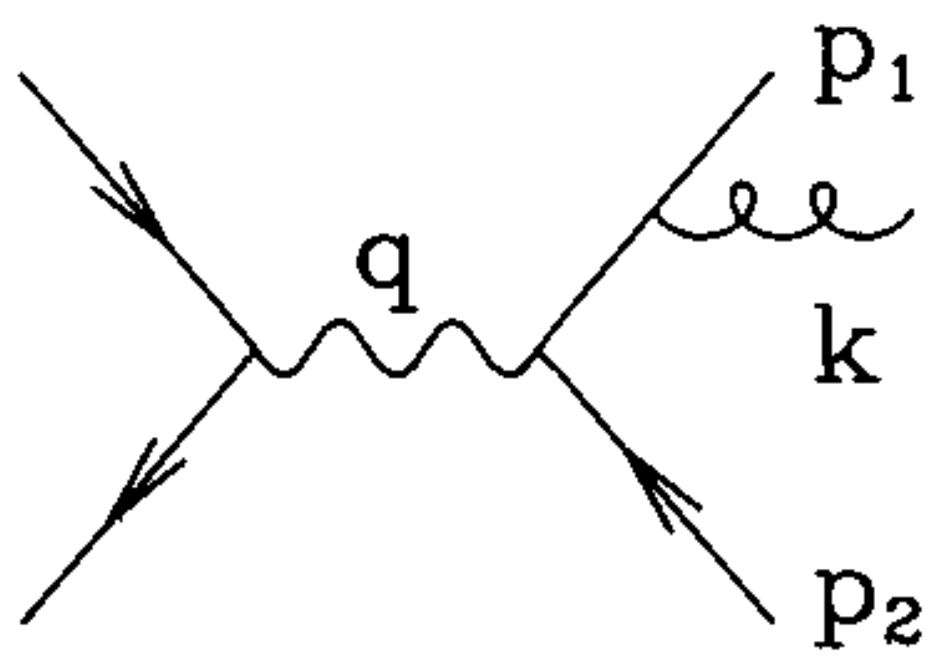


- next higher order (+ gluon attached to other quark + virtual corrections)



$$\sim \bar{u}(p_1)(-ig_s)t^A\gamma^\alpha \frac{i(\not{p}_1 + \not{k})}{(p_1+k)^2}(-ie)\gamma^\mu v(p_2)\epsilon_\alpha$$

QCD calculations — soft limit



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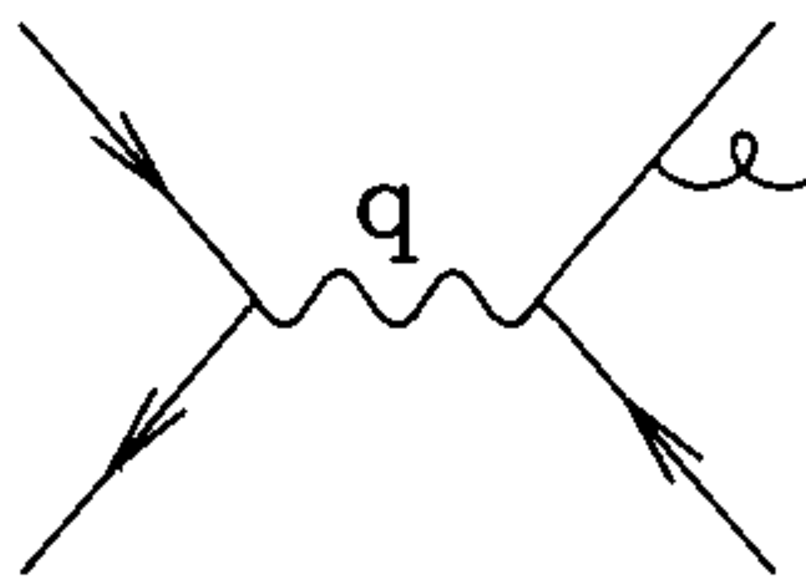

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$$\sim \bar{u}(p_1)(-ig_s)t^A\not{\epsilon}\frac{i\not{p}_1}{2p_1\cdot k}(-ie)\gamma^\mu v(p_2)$$

assume massless partons, $p_1^2 = 0,\ k^2 = 0$ and analyse the soft gluon $k \to 0$ limit

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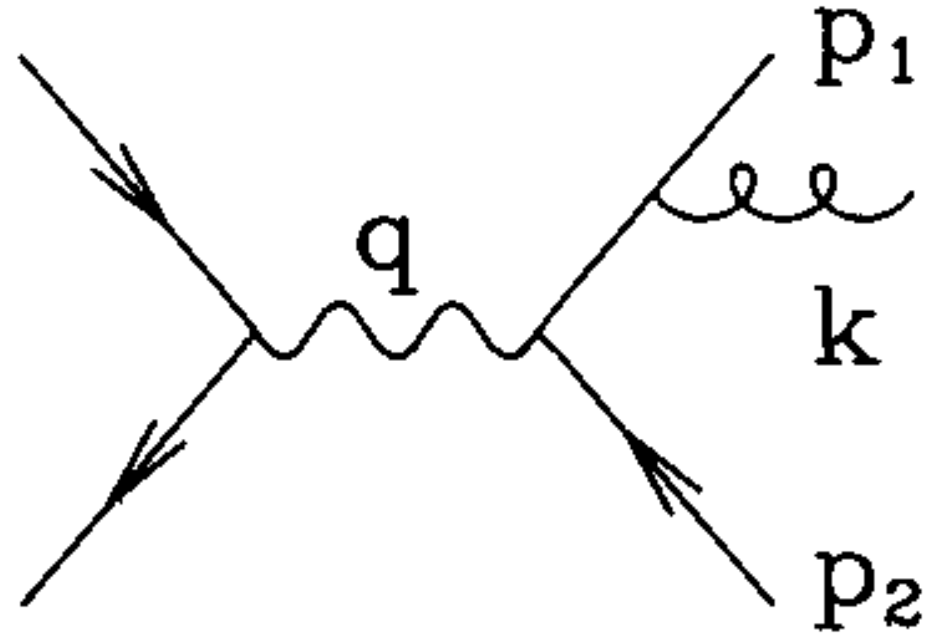

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$$\sim \bar{u}(p_1)(-ig_s)t^A\frac{ip_1\cdot\epsilon}{p_1\cdot k}(-ie)\gamma^\mu v(p_2)$$

use $\not{\epsilon}\not{p}_1 = 2\epsilon\cdot p_1 - \not{p}_1\not{\epsilon}$ and the Dirac equation $\bar{u}(p_1)\not{p}_1 = 0$

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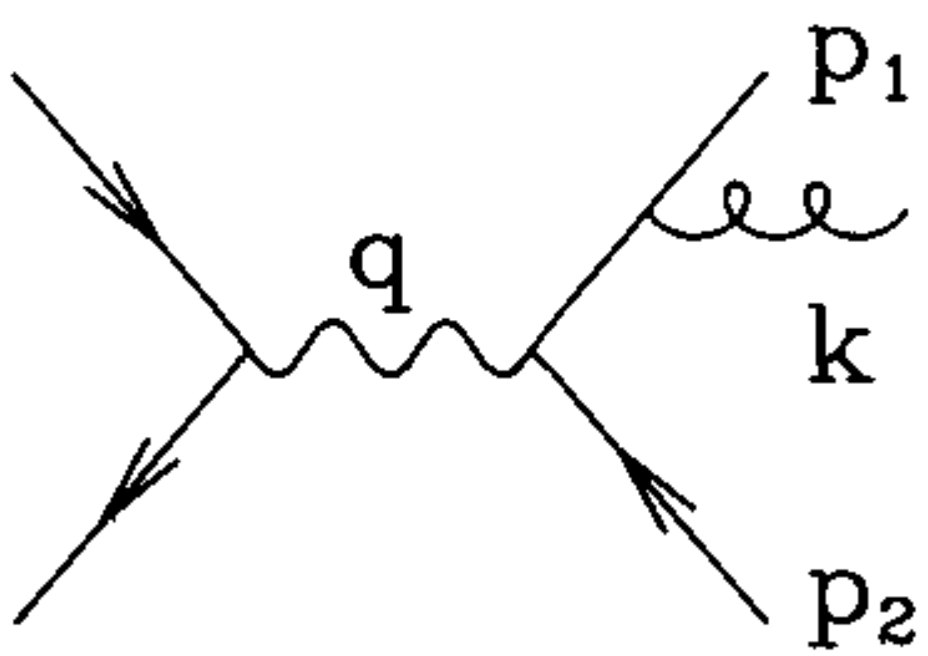

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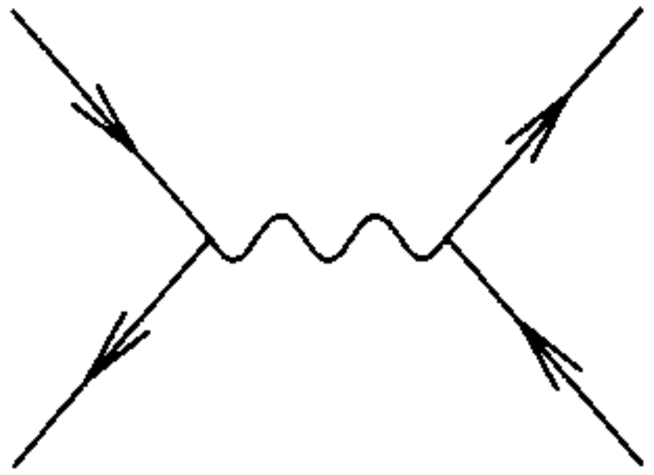

soft gluon emissions factorise!

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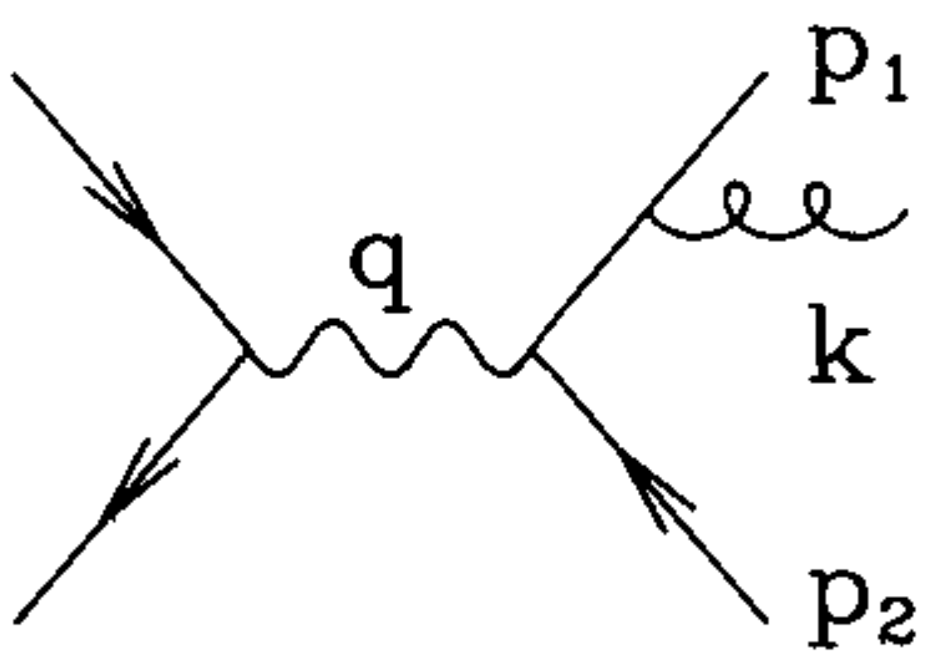

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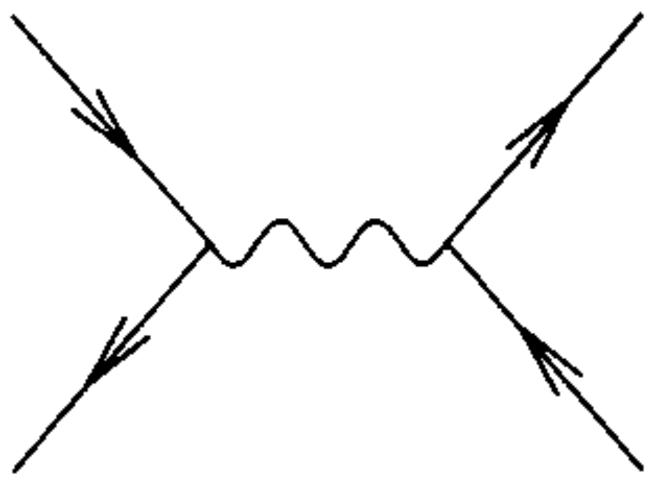
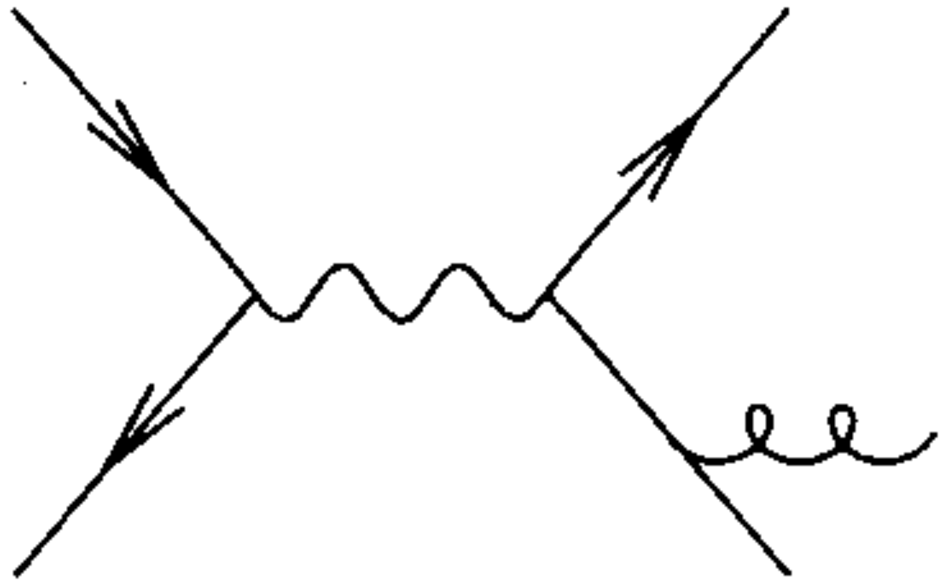
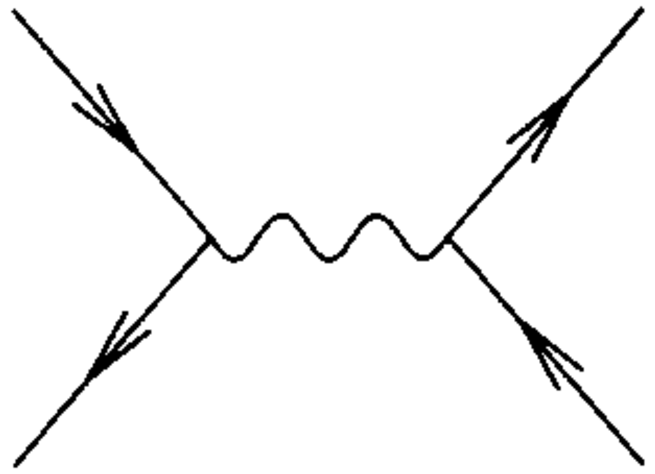




$$\sim g_s t^A \frac{p_2 \cdot \epsilon}{p_2 \cdot k} \times$$



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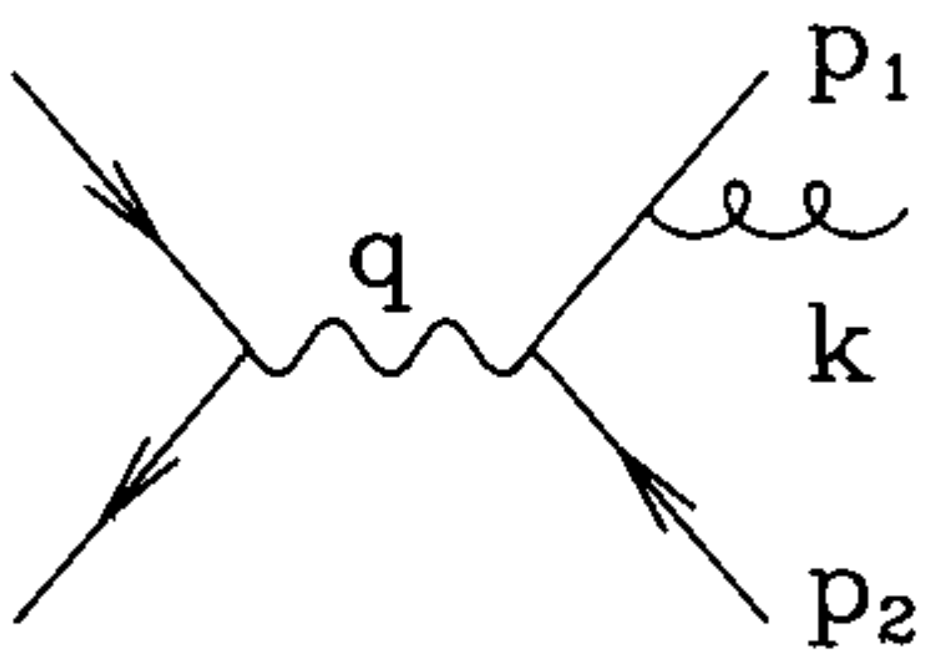
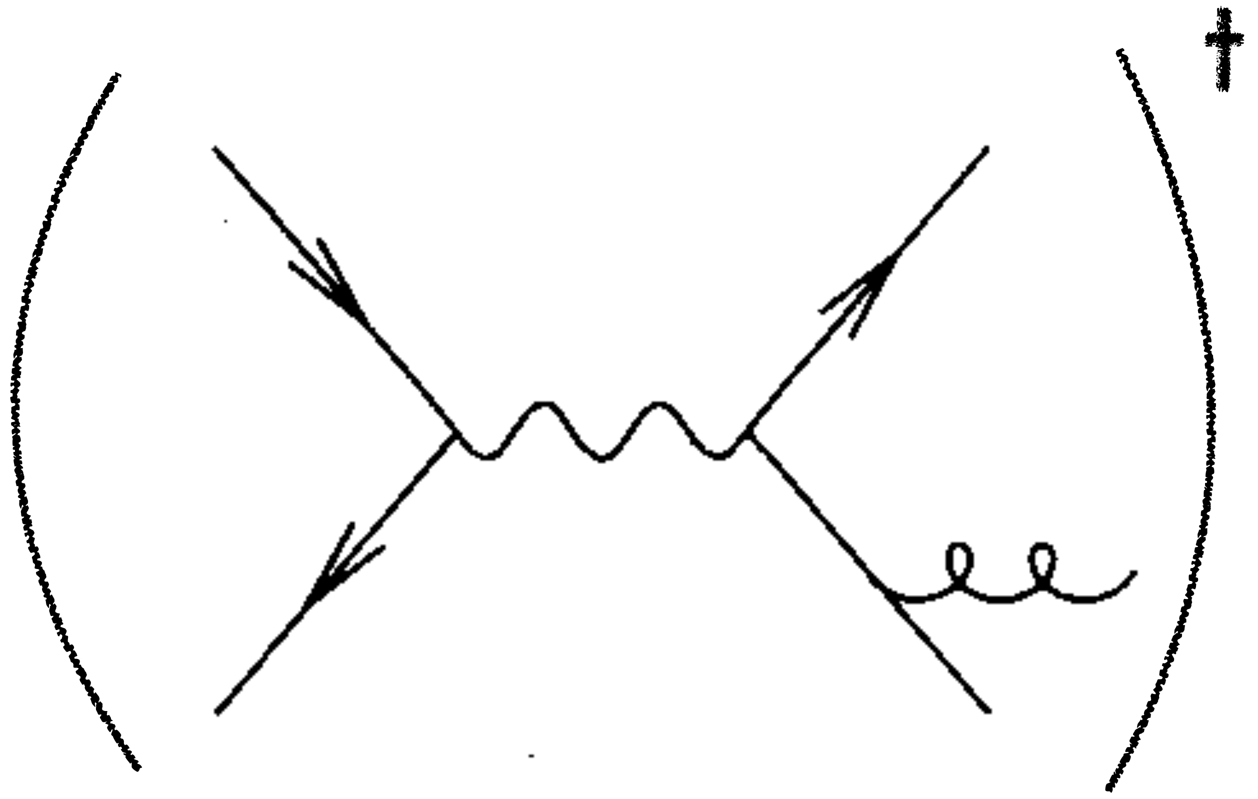
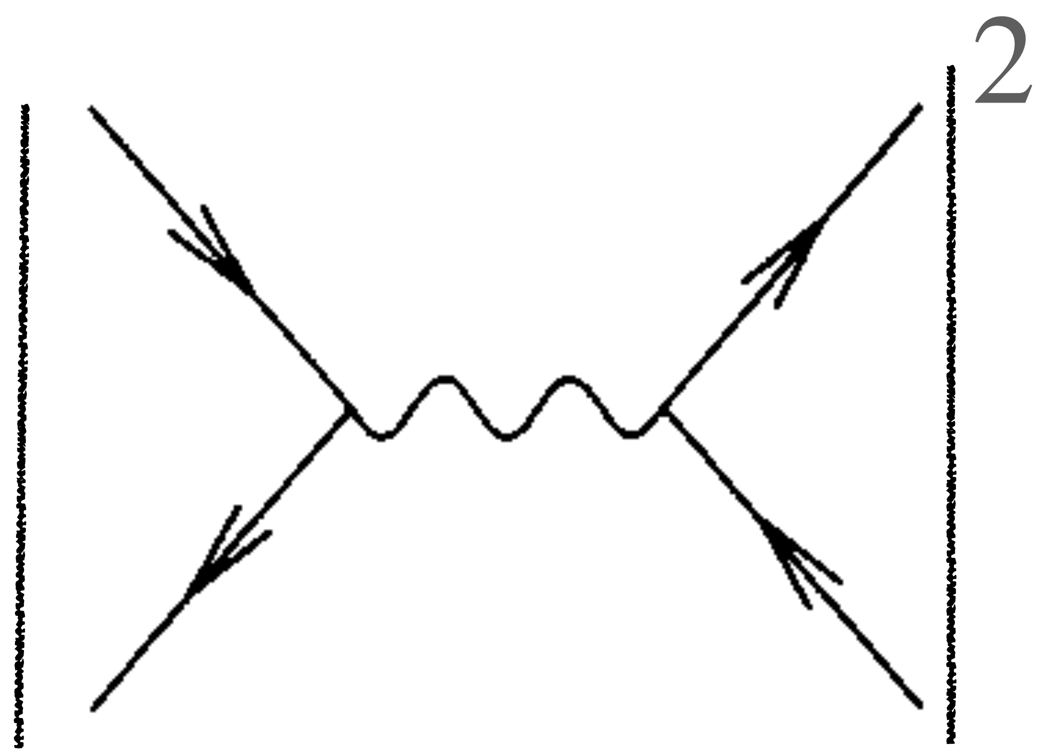




$$\sim 2 g_s^2 t^A t^B \frac{p_1 \cdot \epsilon}{p_1 \cdot k} \frac{p_2 \cdot \epsilon}{p_2 \cdot k}$$



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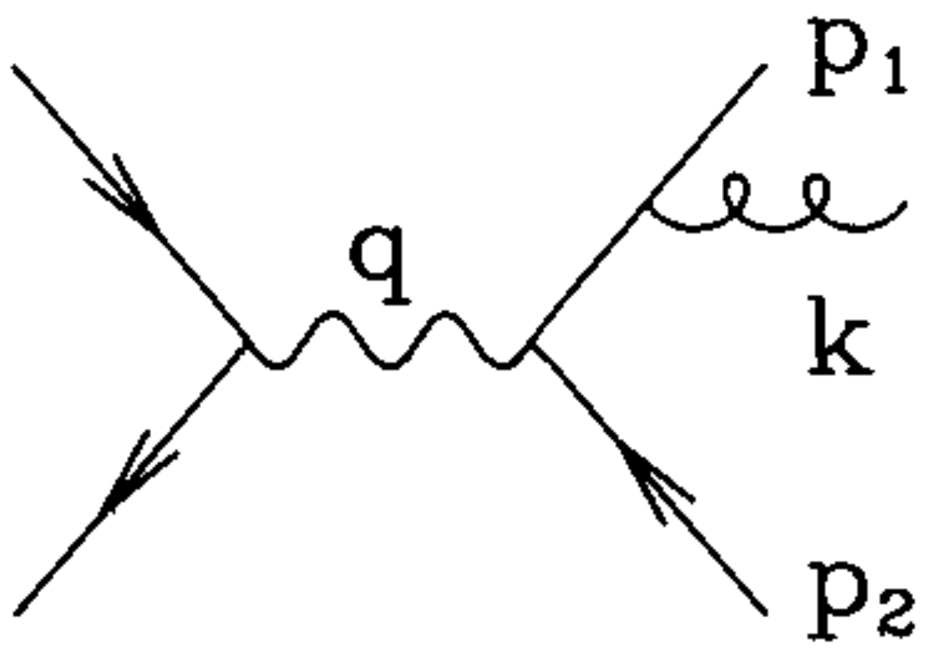
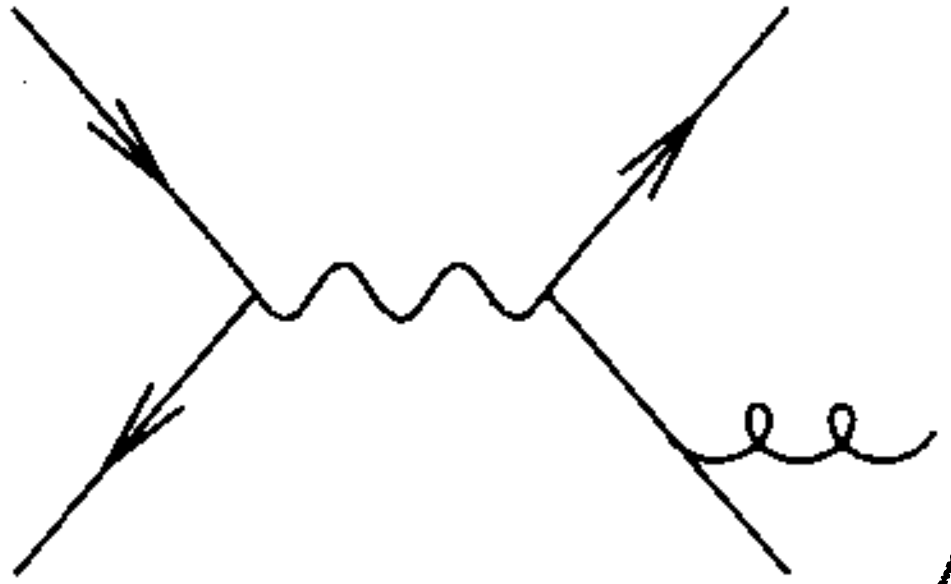
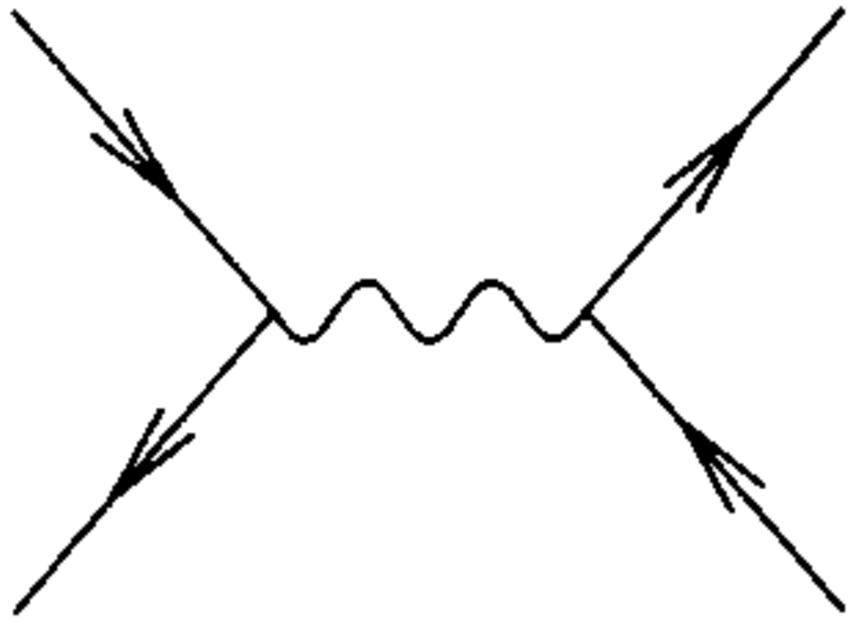
2 

$\Bigg($  $\Bigg)^{\dagger} \sim 2 g_s^2 t^A t^B \dfrac{p_1 \cdot \epsilon}{p_1 \cdot k} \dfrac{p_2 \cdot \epsilon}{p_2 \cdot k} \Bigg|$  $\Bigg|^2$

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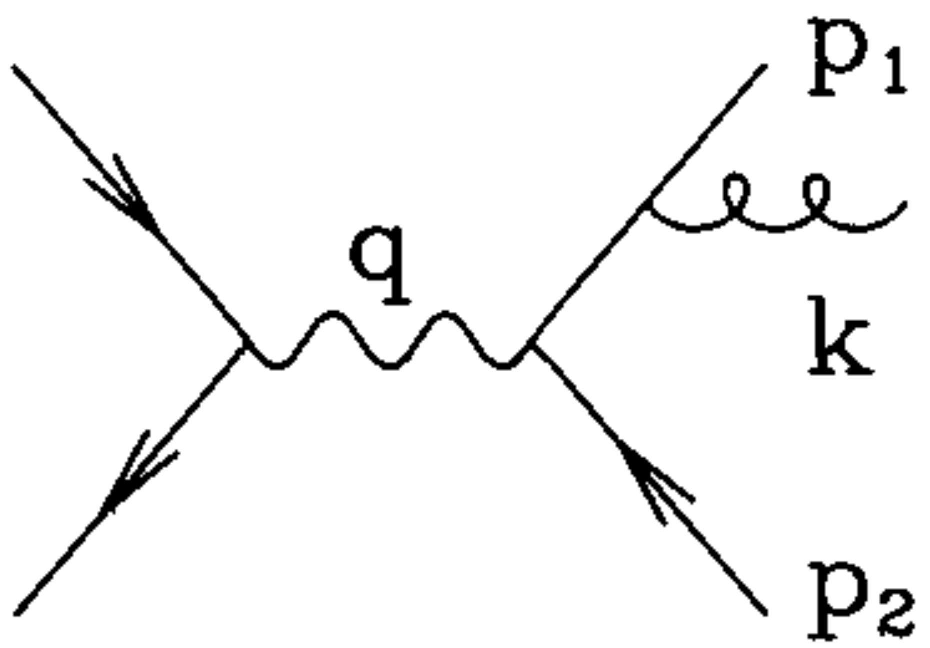
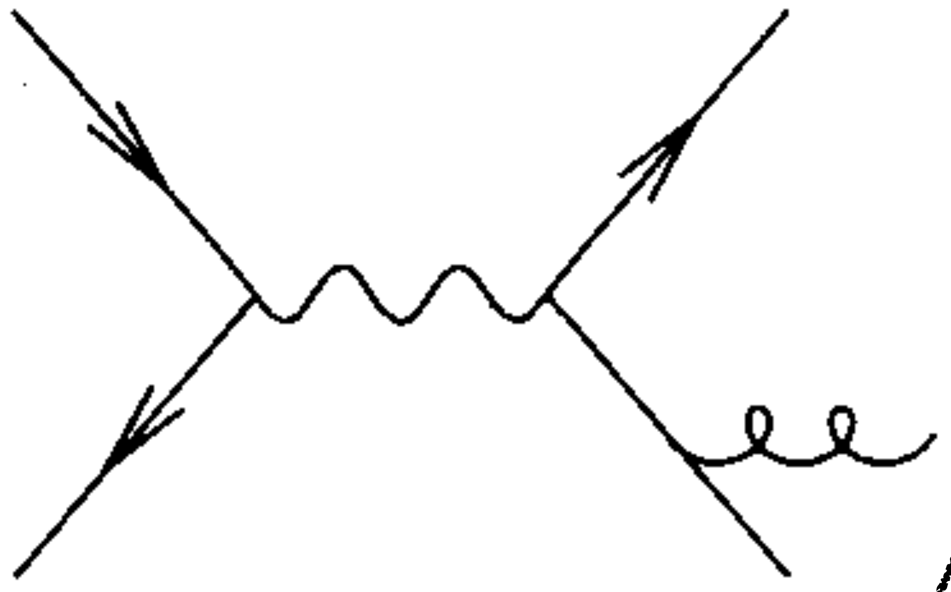
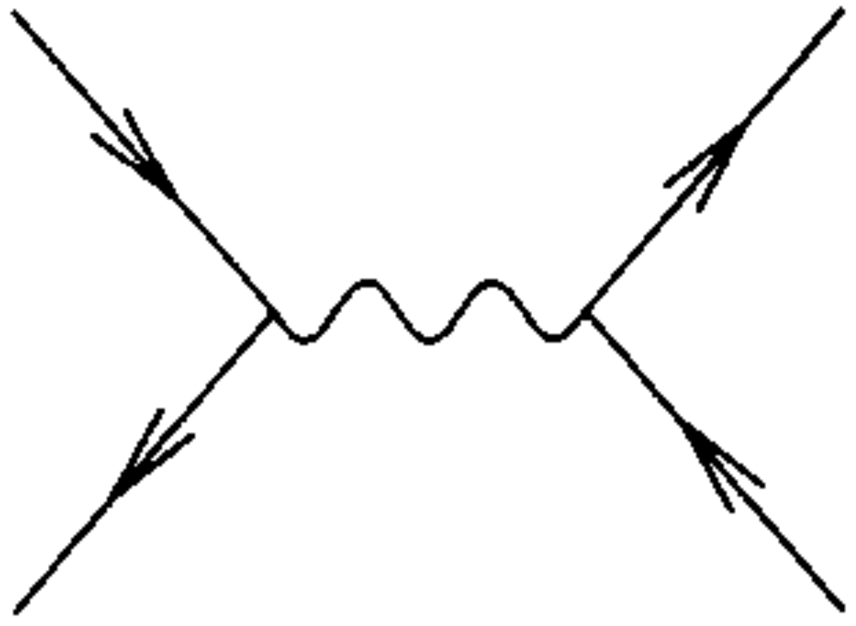
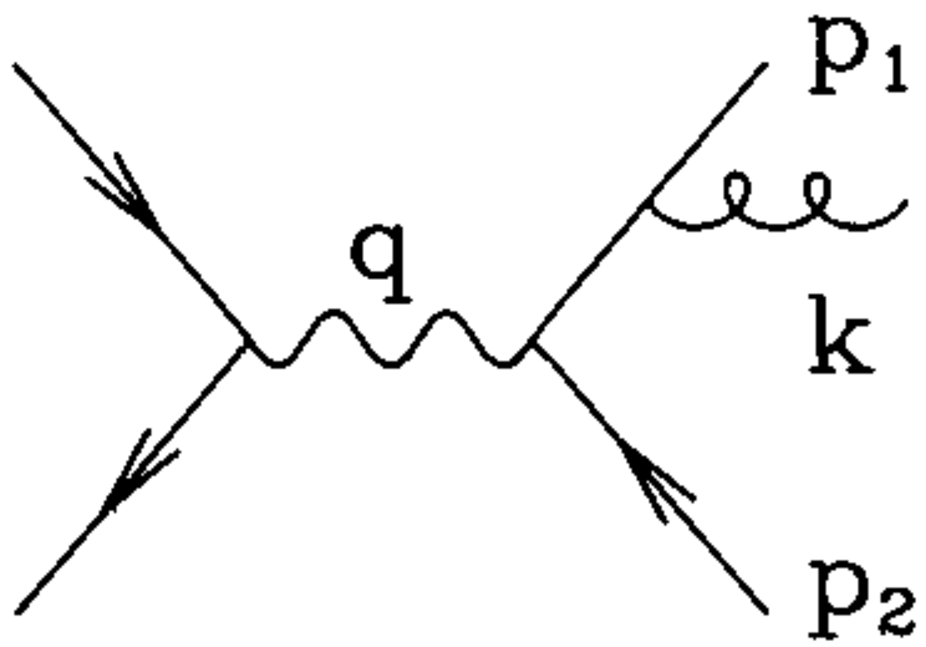
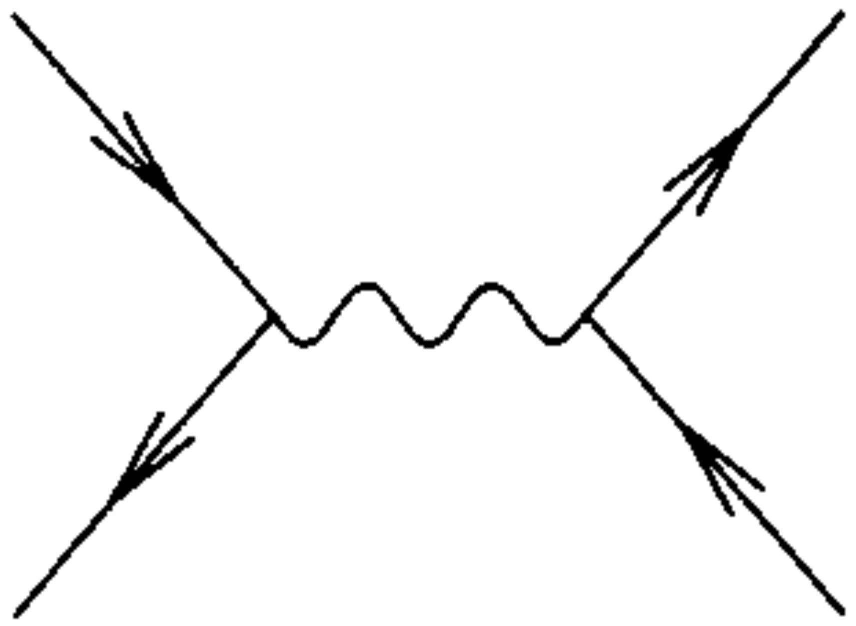
2 

$\Big($  $\Big)^{\dagger} \sim 2 g_s^2 t^A t^B \dfrac{p_1 \cdot \epsilon}{p_1 \cdot k} \dfrac{p_2 \cdot \epsilon}{p_2 \cdot k}$ $\Big|$  $\Big|^2$

perform sum over gluon polarisations $\epsilon_\mu \epsilon_\nu \to - g_{\mu\nu}$, and colours $t^A t^B \to C_F$

$\Big|$ 

$\Big|^2 \sim g_s^2 C_F \dfrac{2 p_1 \cdot p_2}{(p_1 \cdot k)(p_2 \cdot k)}$ $\Big|$  $\Big|^2$

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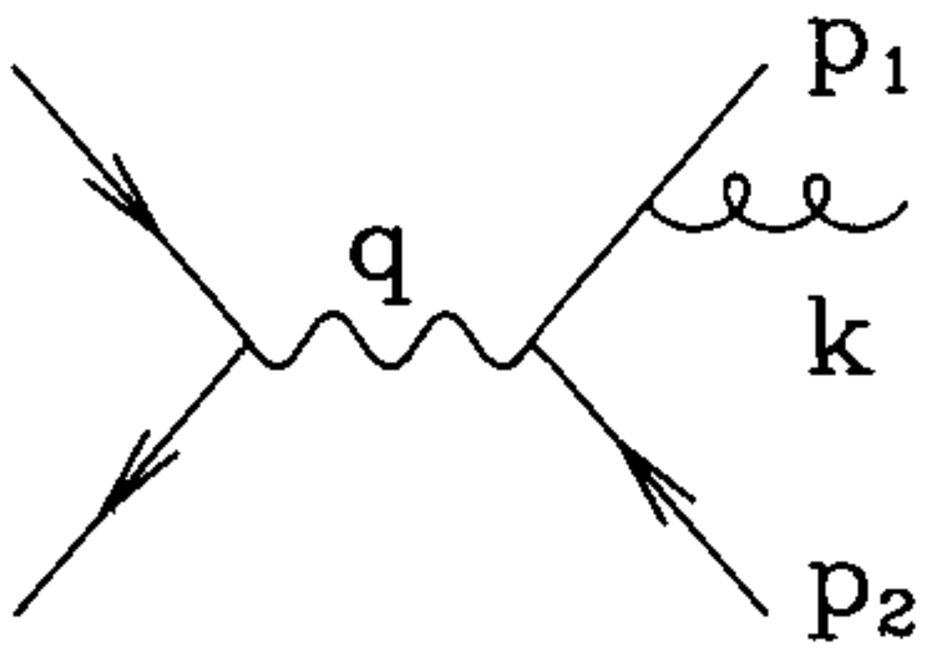
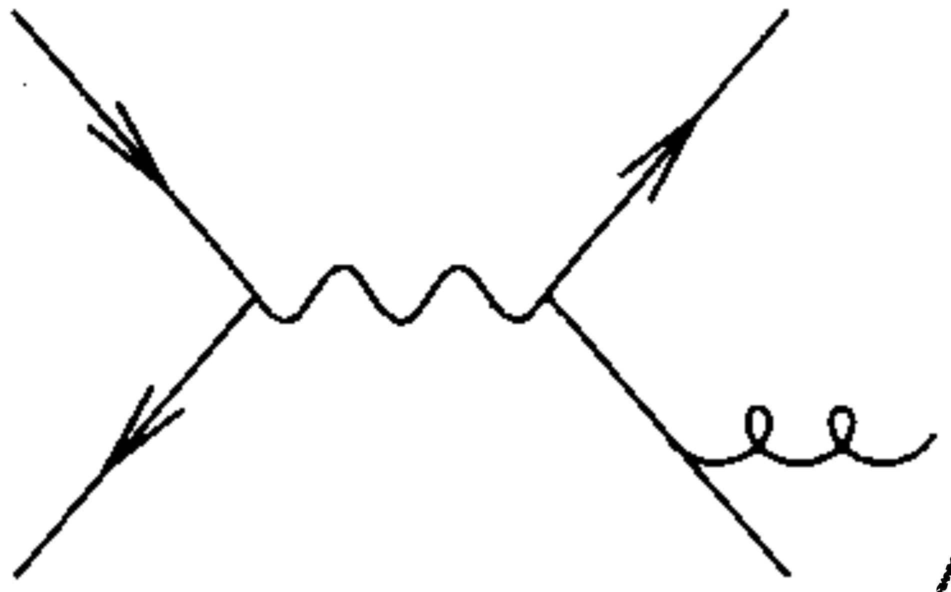
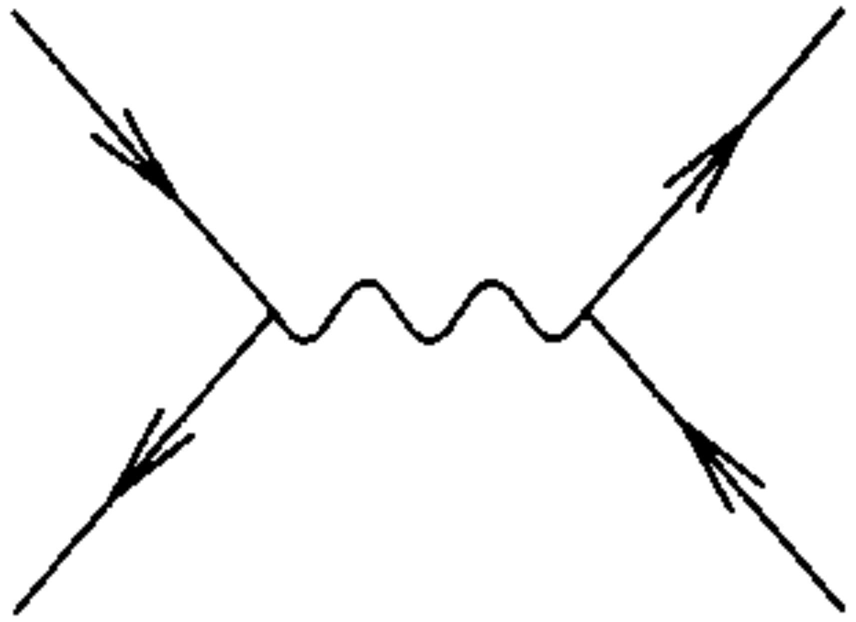
2 

$\Big($  $\Big)^\dagger \sim 2g_s^2 t^A t^B \dfrac{p_1 \cdot \epsilon}{p_1 \cdot k} \dfrac{p_2 \cdot \epsilon}{p_2 \cdot k} \Big|$  $\Big|^2$

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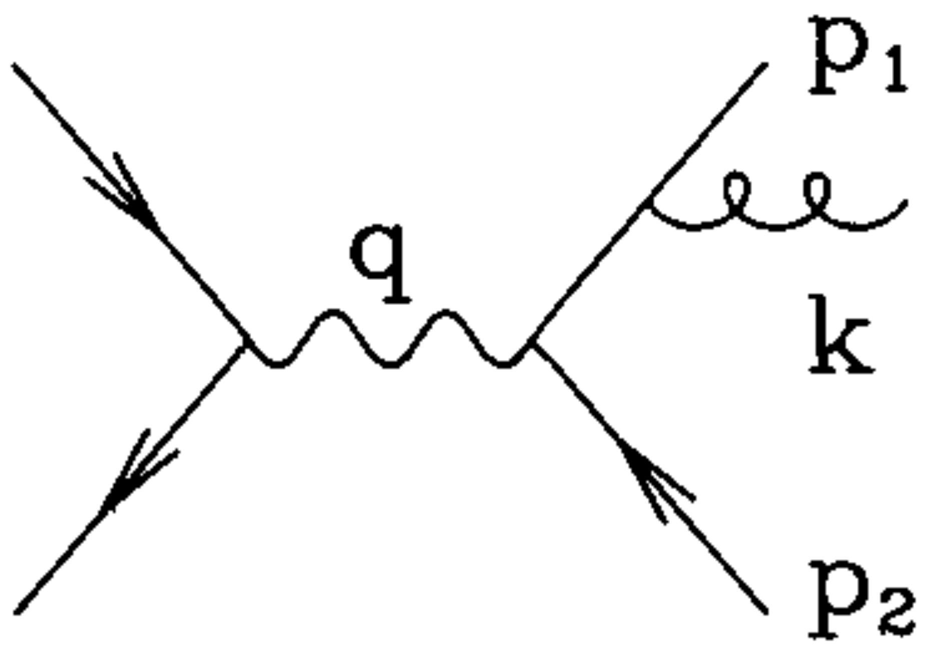
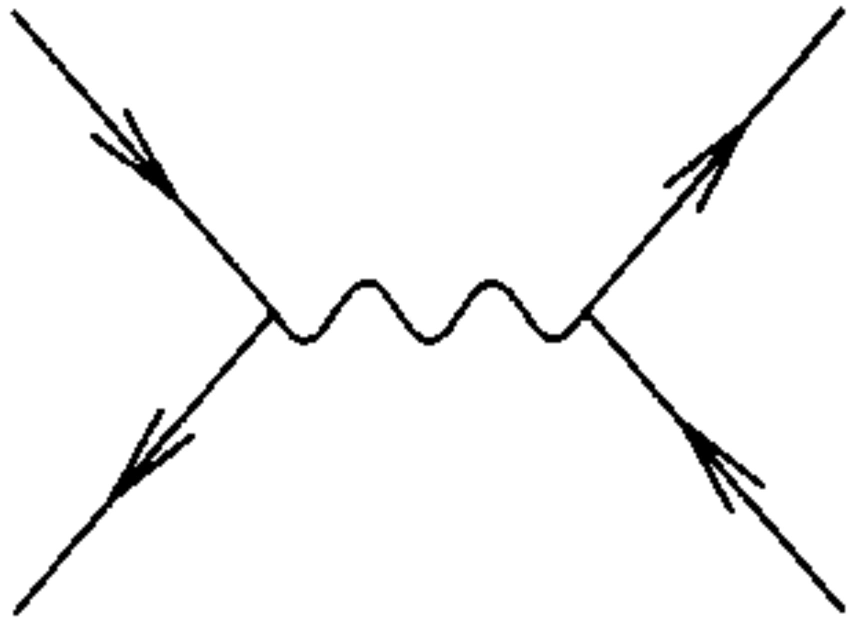
$\Big|$ 

$\Big|^2 \sim g_s^2 C_F \dfrac{2p_1 \cdot p_2}{(p_1 \cdot k)(p_2 \cdot k)} \Big|$  $\Big|^2$

Note: phase space factorises as well $d\phi_{q\bar{q}g} = d\phi_{q\bar{q}} d\phi_{+1}$

Factorisation with “eikonal” factor!

eikonal

$$\frac{2p_1 \cdot p_2}{(p_1 \cdot k)(p_2 \cdot k)}$$

observation: divergent if $k \parallel p_1$ or $k \parallel p_2$ or $k \to 0$

$\Rightarrow$ collinear and soft/infrared limits

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Explicitly in some reference frame, use $p_i \cdot k = E_i E_k (1 - \cos\theta_{ik})$

$$\frac{2p_1 \cdot p_2}{(p_1 \cdot k)(p_2 \cdot k)} \sim \frac{1}{E_k^2} \frac{1}{(1 - \cos\theta_{1k})(1 - \cos\theta_{2k})}$$

$\Rightarrow$ divergencies visible for $\theta_{ik} \to 0$ (collinear) and $E_k \to 0$ (soft)

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General structure, divergencies and factorisation in the soft and collinear limits is a universal property of QCD amplitudes!

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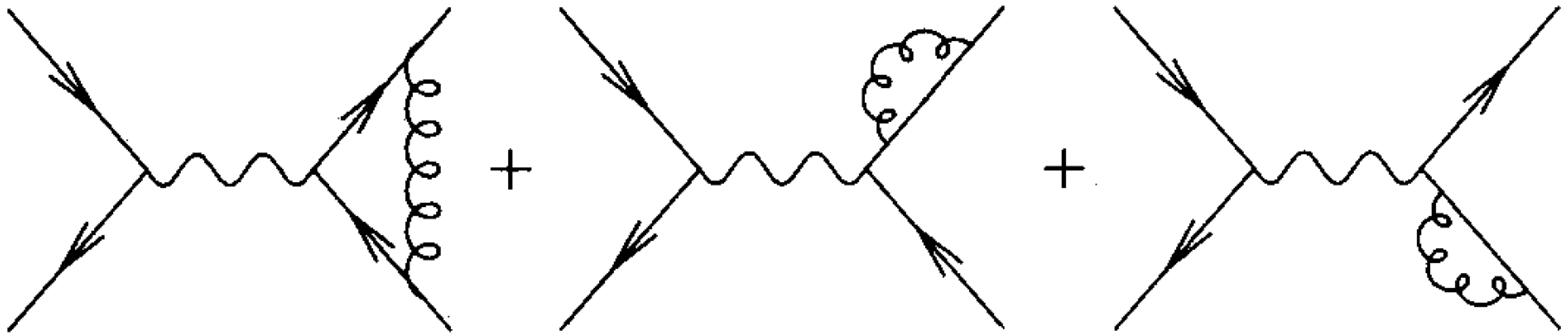

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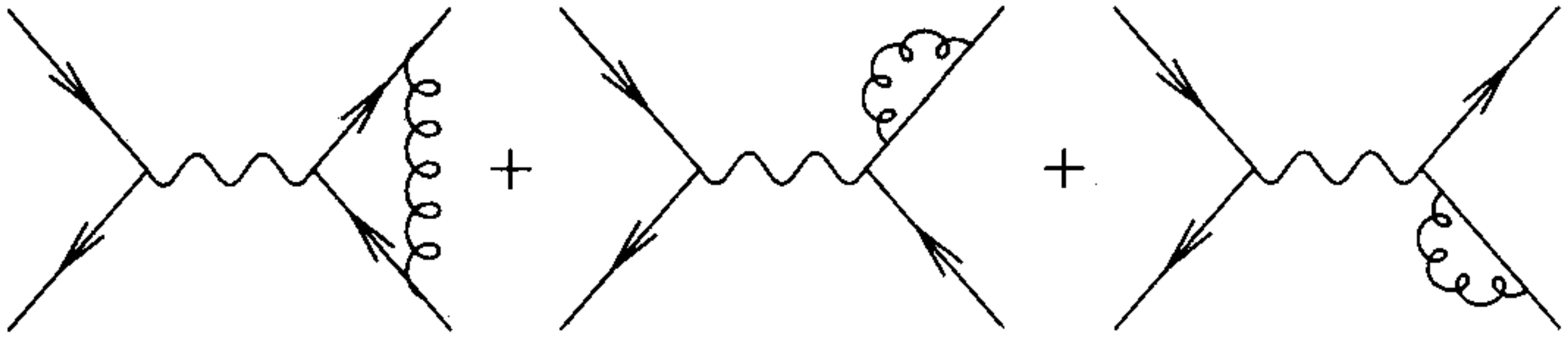

- on their own divergent as well ⇒ sum turns out to be finite!

- ⇒ we can calculate at least inclusive (enough) cross sections (e.g. $e^+e^- \to$ hadrons, but not $e^+e^- \to$ exactly 2 quarks)

What is “inclusive enough”?

- We have seen that not all observables are well defined in QCD, since we must not disturb the cancellation of real and virtual singularities
- We must exclude anything that is sensitive to arbitrarily soft and/or collinear emissions
  - typical example: multiplicities
- Observables that are **not** affected by a soft/collinear emission are called **infrared-collinear (IRC) safe**

IRC safe observables: Jets

- A typical example for the construction of IRC safe quantities are sequential recombination algorithms used to define jets

1. compute distance measure d_{ij} for each pair of final-state particles and the beam distance d_{iB} for each particle

2. determine minimum of all d_{ij}, d_{iB}

   A. if one of the d_{ij} is smallest, combine those particles i, j

   B. if one of the beam distances d_{iB} is smallest, i is a jet and removed from the procedure

3. go back to 1, repeat until all objects are clustered

IRC safe observables: Jets

- distance measures are a matter of choice
  - only formal requirement is IRC safety, i.e. a soft/collinear emission should not change the jets obtained from the algorithm

k_T - algorithm/Durham - algorithm:

$$d_{ij} = \min\left(k_{T,i}^2, k_{T,j}^2\right)\frac{\Delta R^2}{R^2}\,, \quad d_{iB} = \min\left(k_{T,i}^2, k_{T,j}^2\right)$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

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anti-k_T - algorithm:

$$d_{ij} = \min\left(k_{T,i}^{-2}, k_{T,j}^{-2}\right)\frac{\Delta R^2}{R^2}\,, \quad d_{iB} = \min\left(k_{T,i}^{-2}, k_{T,j}^{-2}\right)$$

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Cambridge/Aachen - algorithm:

$$d_{ij} = \frac{\Delta R^2}{R^2}\,, \quad d_{iB} = 1$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

IRC safe observables: Jets

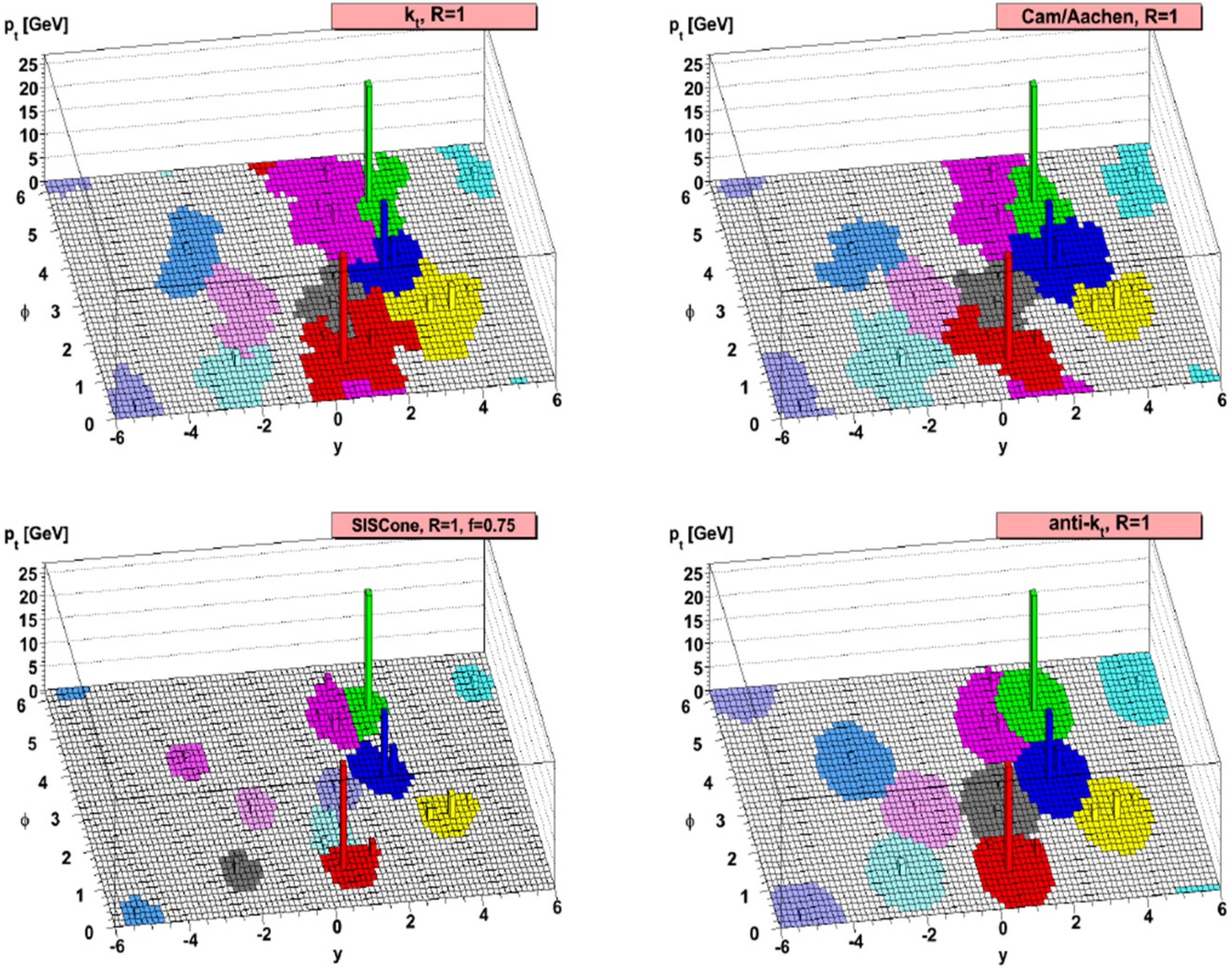
- Standard reference for implementations: FastJet program
  - Generalised k_t - algorithm

$$d_{ij} = \min\left(k_{T,i}^{2p}, k_{T,j}^{2p}\right)\frac{\Delta R^2}{R^2}\,, \quad d_{iB} = \min\left(k_{T,i}^2, k_{T,j}^2\right)$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

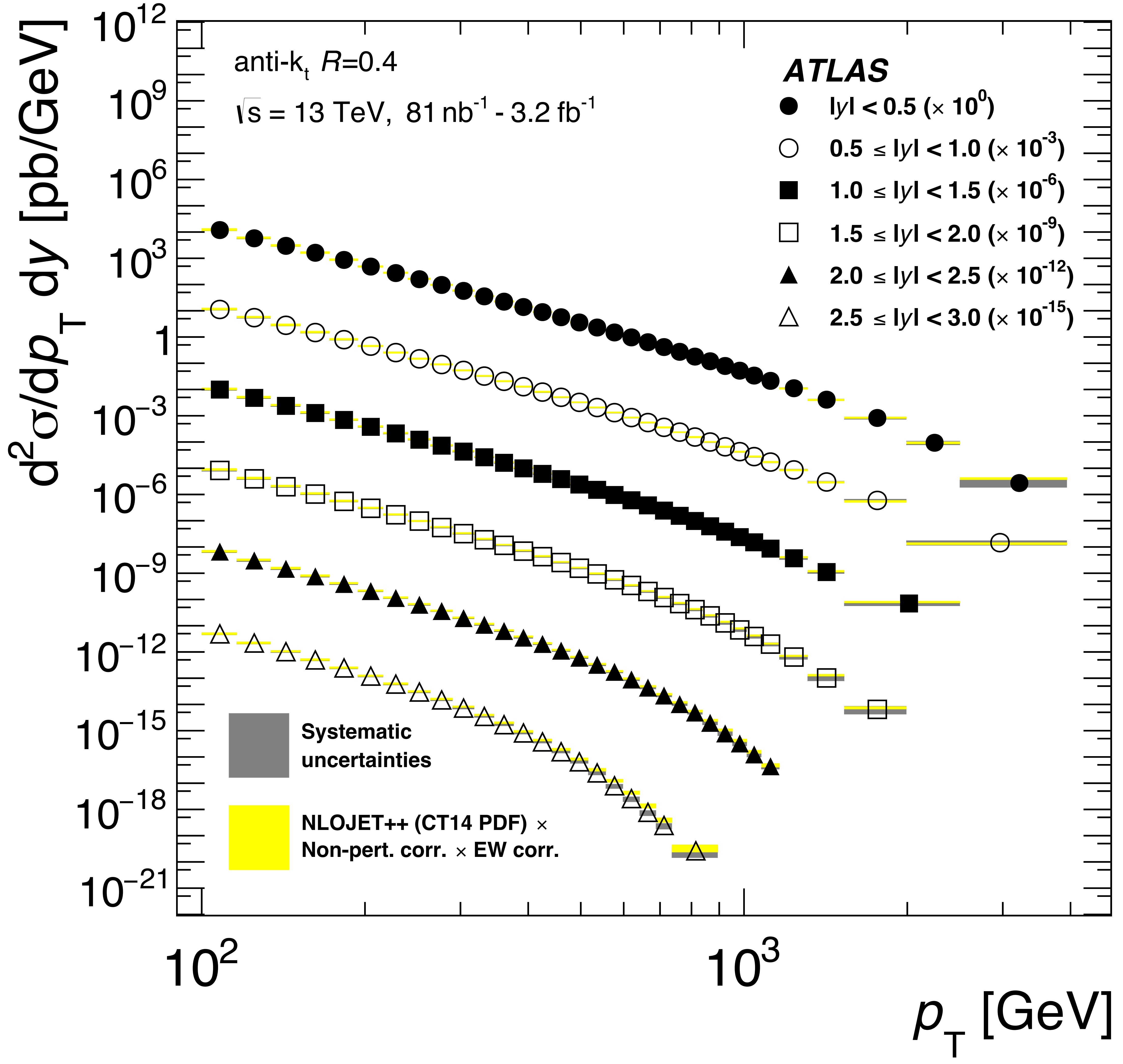
Durham	Cambridge/Aachen	anti-k_t
$p = 1$	$p = 0$	$p = -1$
closest match to structure of QCD matrix elements, theoretical interest	angular ordered splitting sequence, close match to QCD coherence	closest to defining jets as “cones” with radius R around hard particles, default choice in LHC experiments

jet algorithms



Jet cross sections at the LHC

- jets are infrared save, so we can compute their production cross section in perturbation theory
- powerful tests of perturbative QCD
- here: compared to measurement by ATLAS at $\sqrt{s} = 13$ TeV



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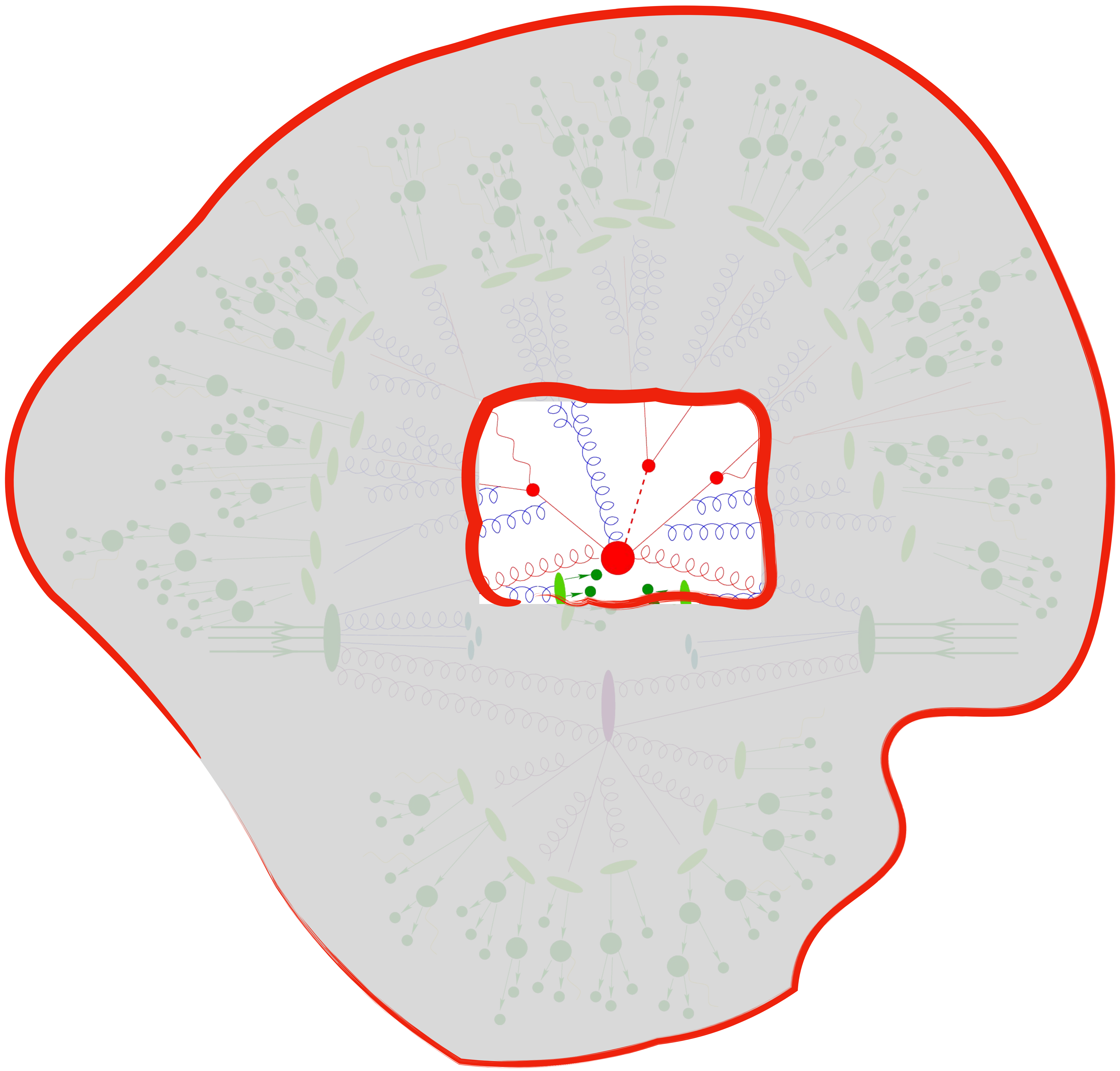

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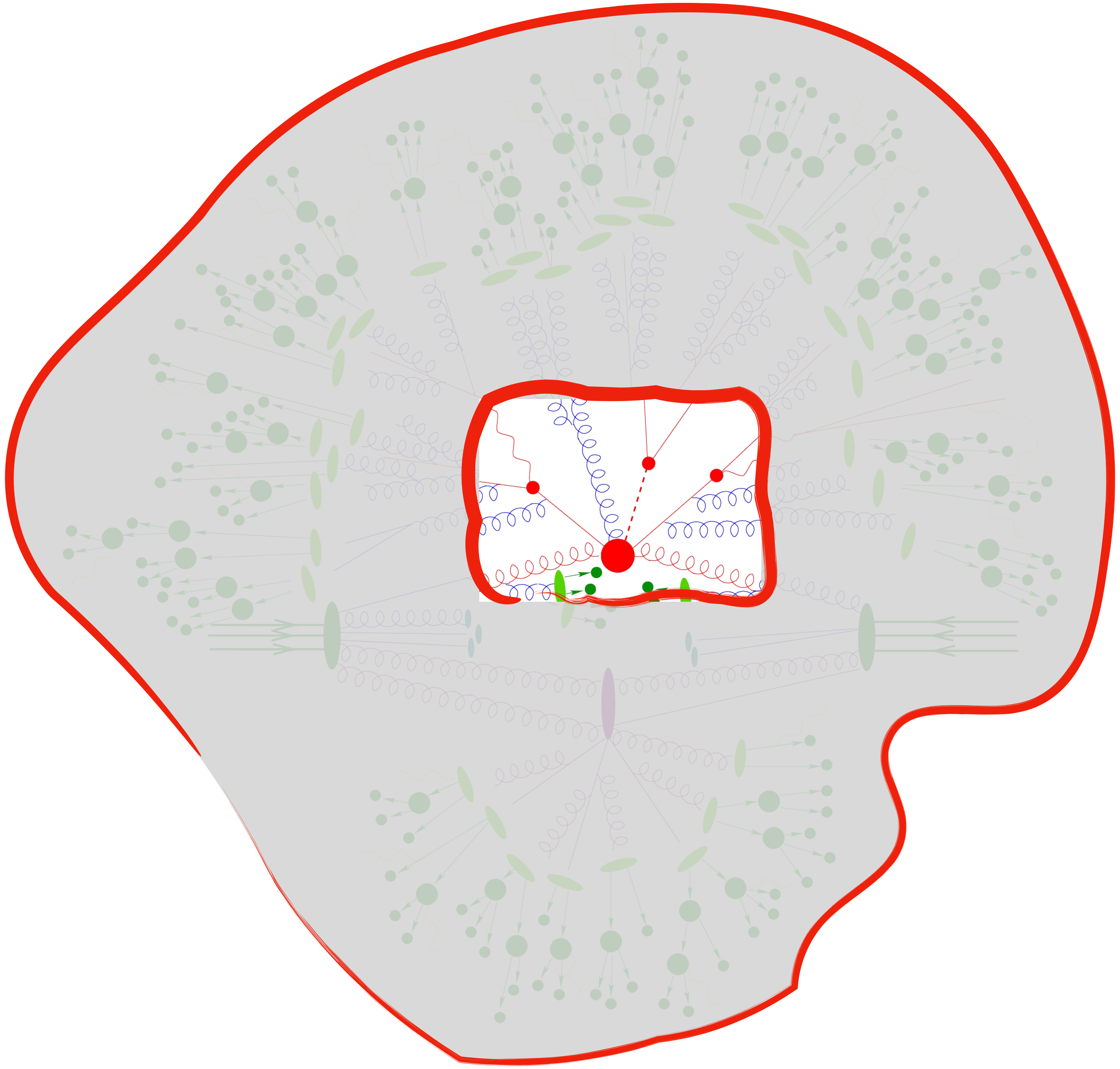

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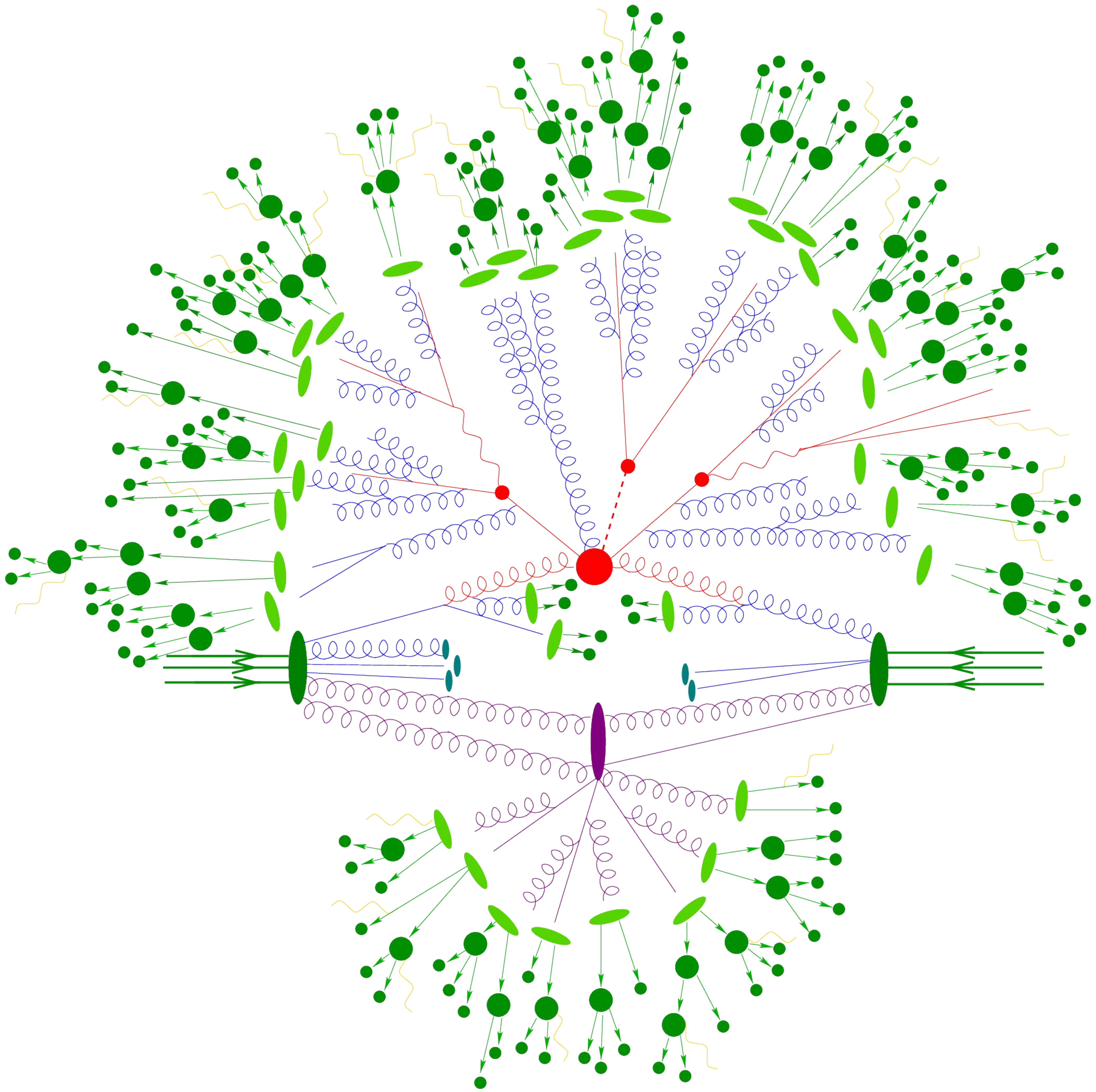

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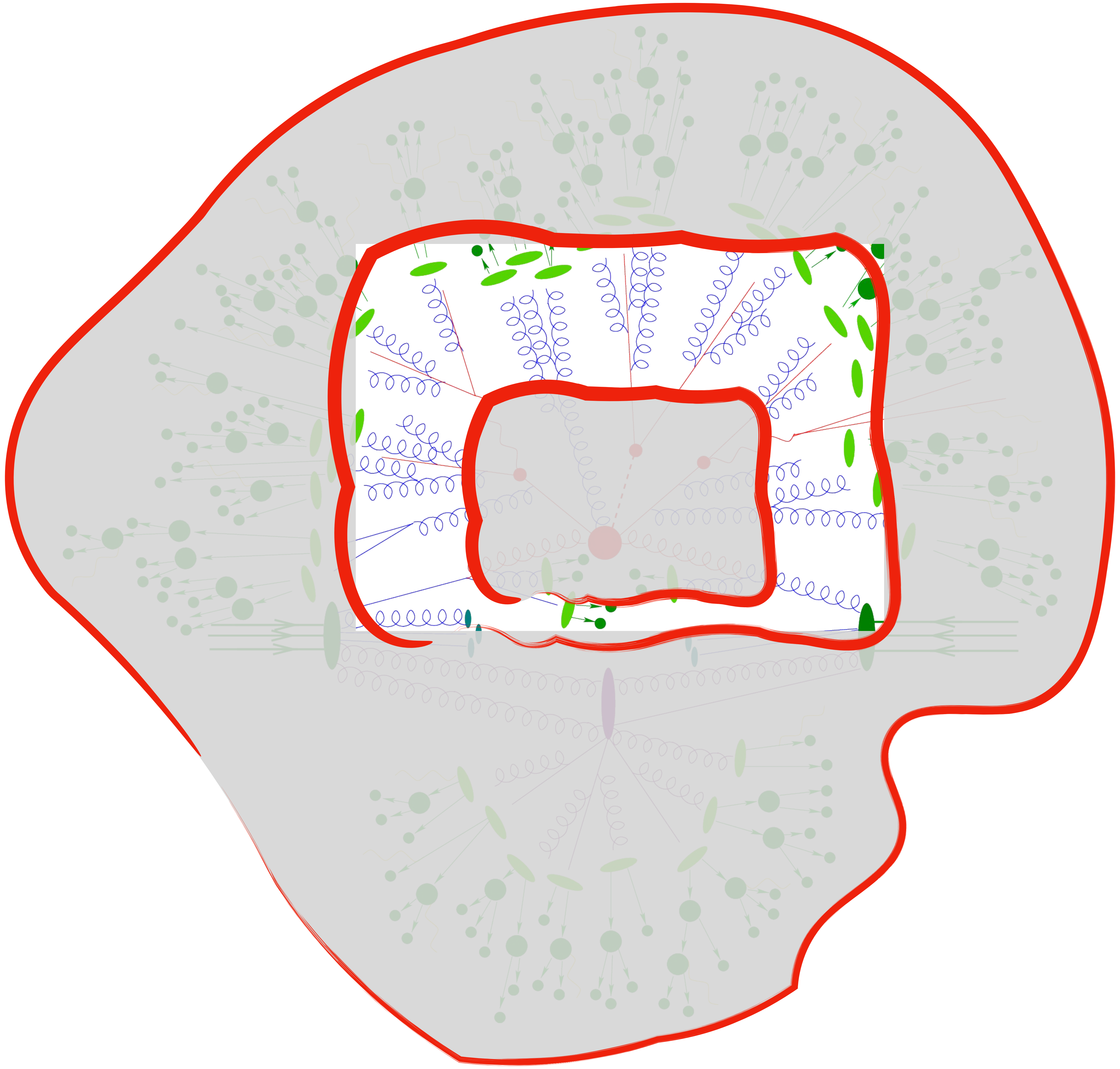
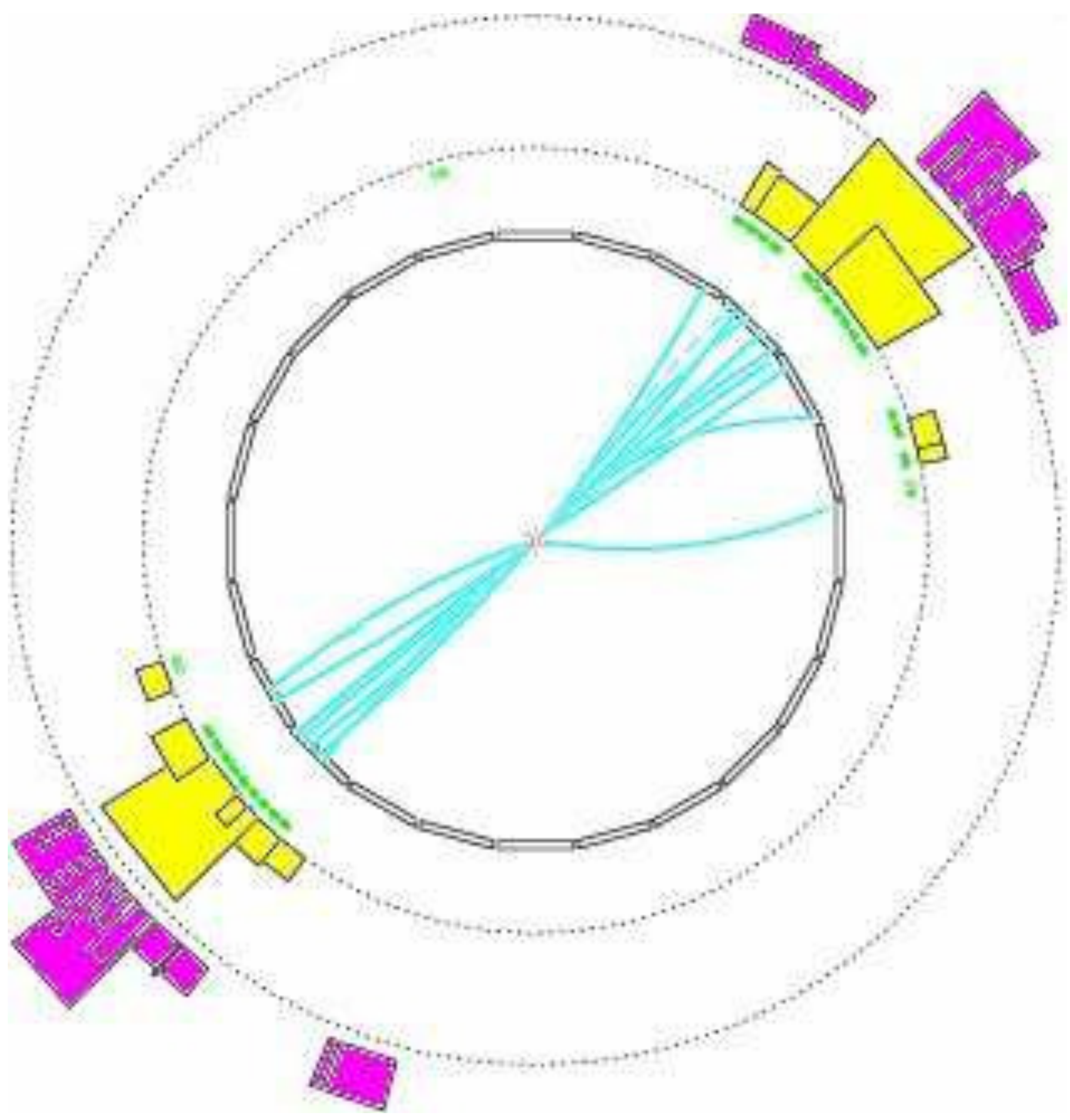
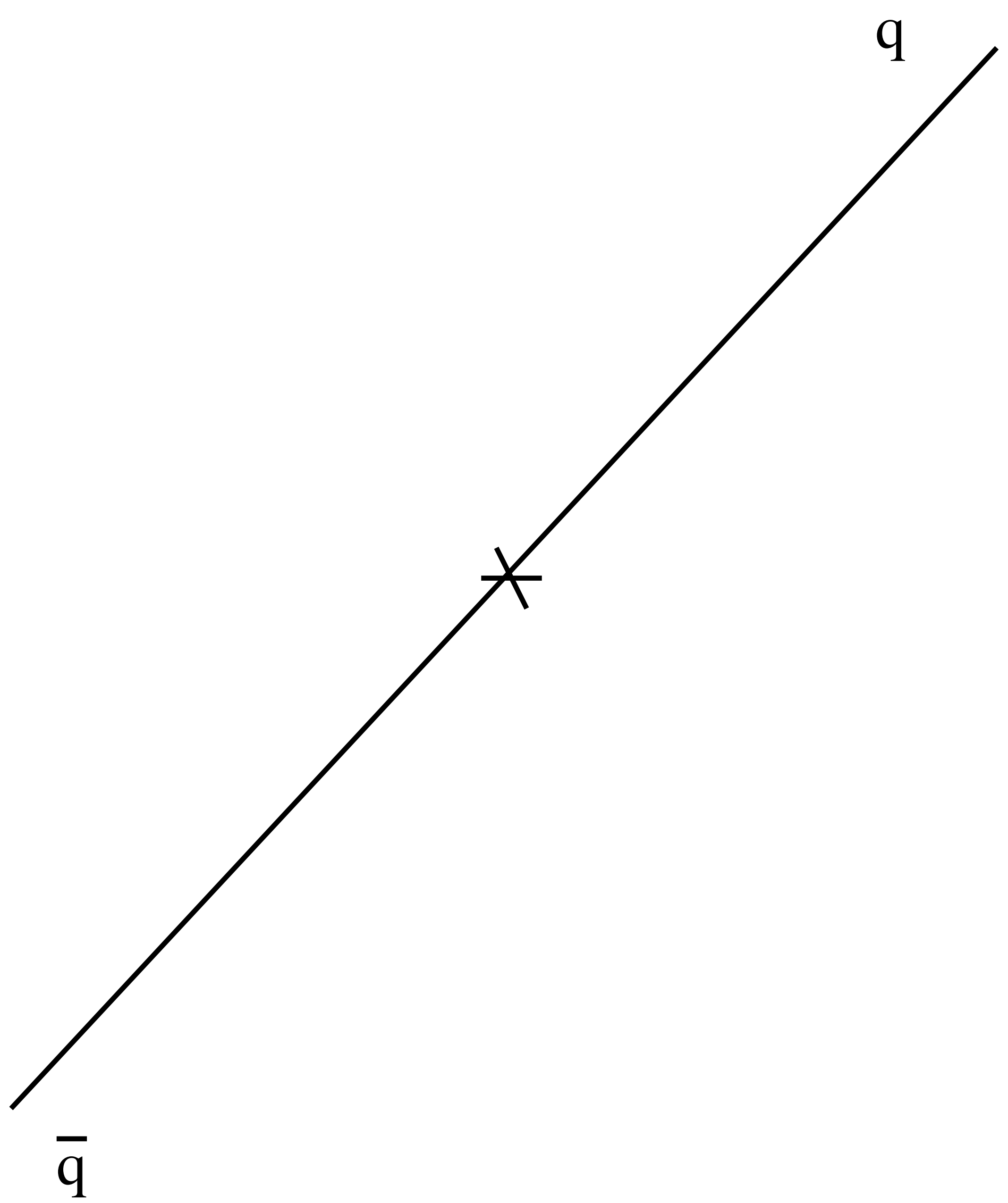


jet evolution

- so far jets look rather empty, consist of usually 1 parton at LO, at most 2 at NLO

- but we saw matrix elements for additional soft emissions diverging ⇒ no suppression of higher orders, should expect arbitrary number of soft/collinear gluons





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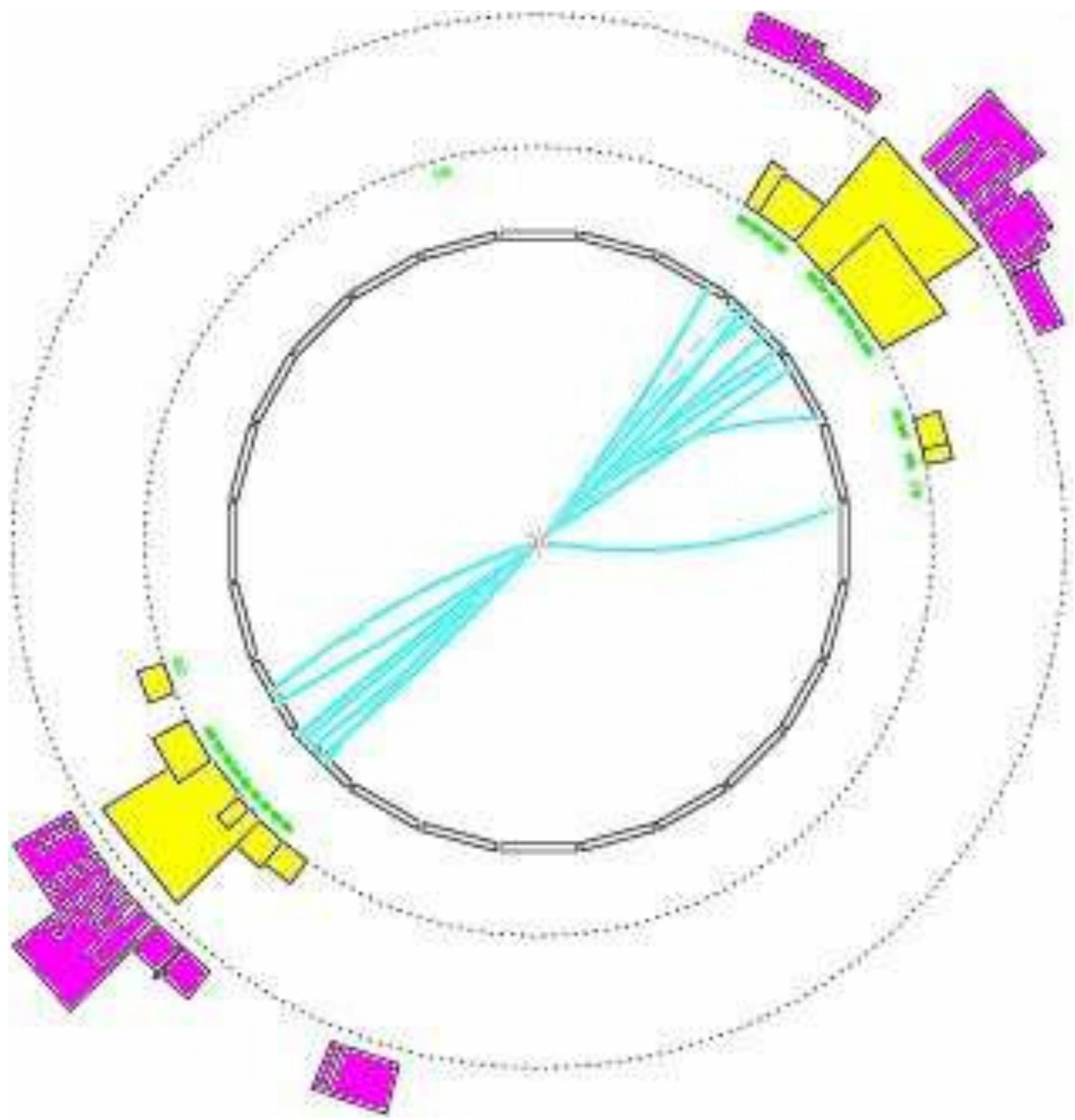

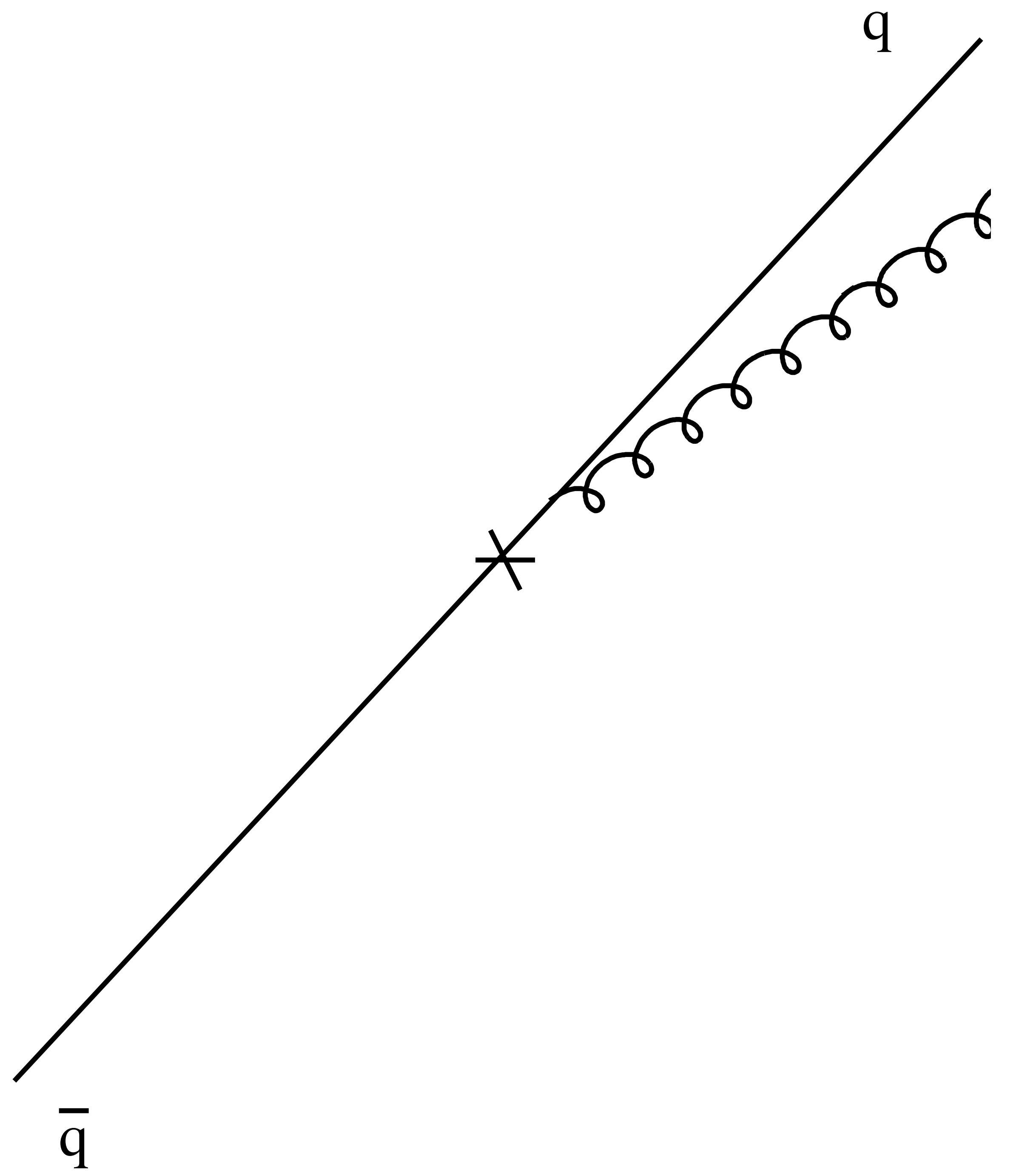

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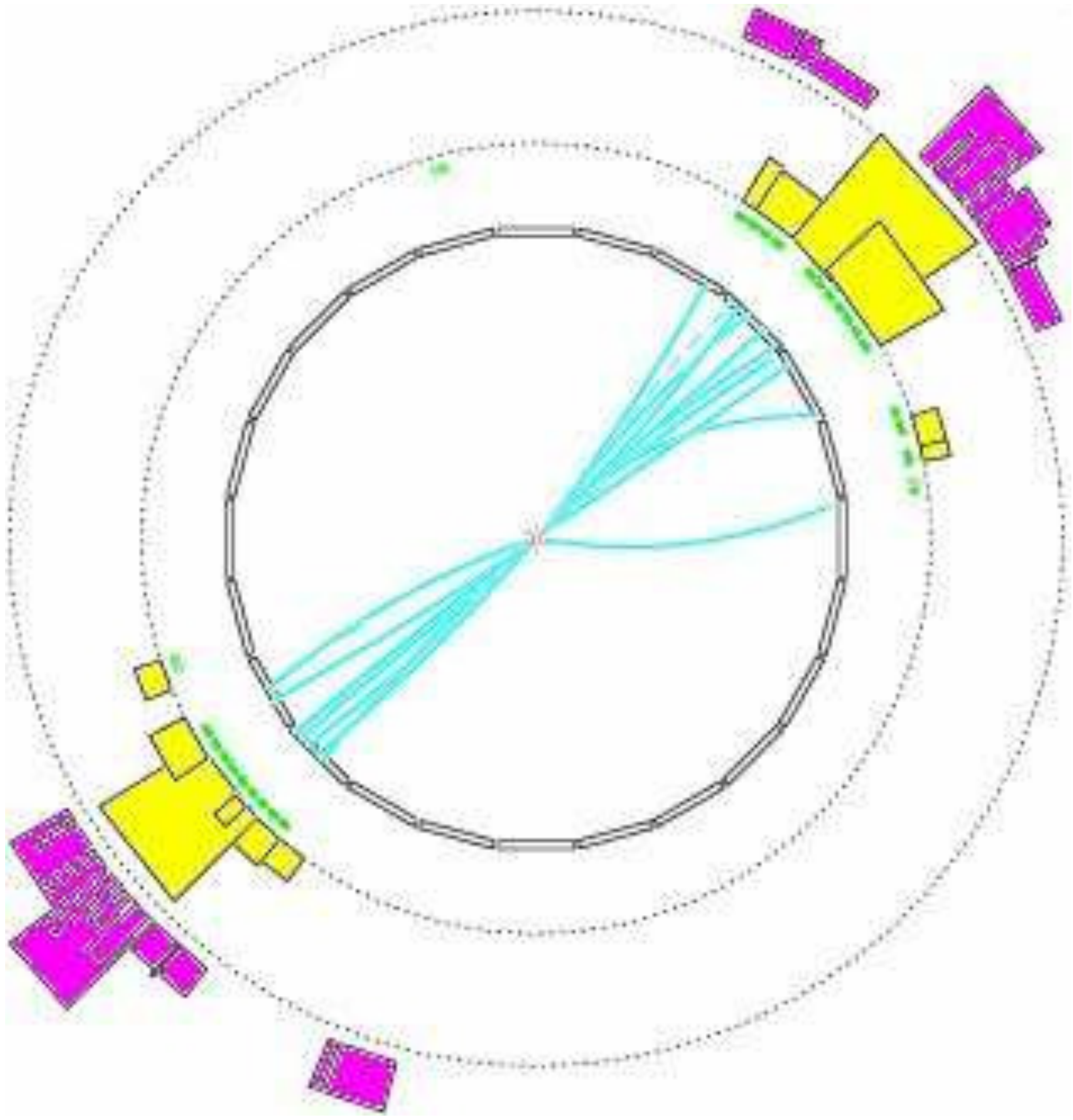

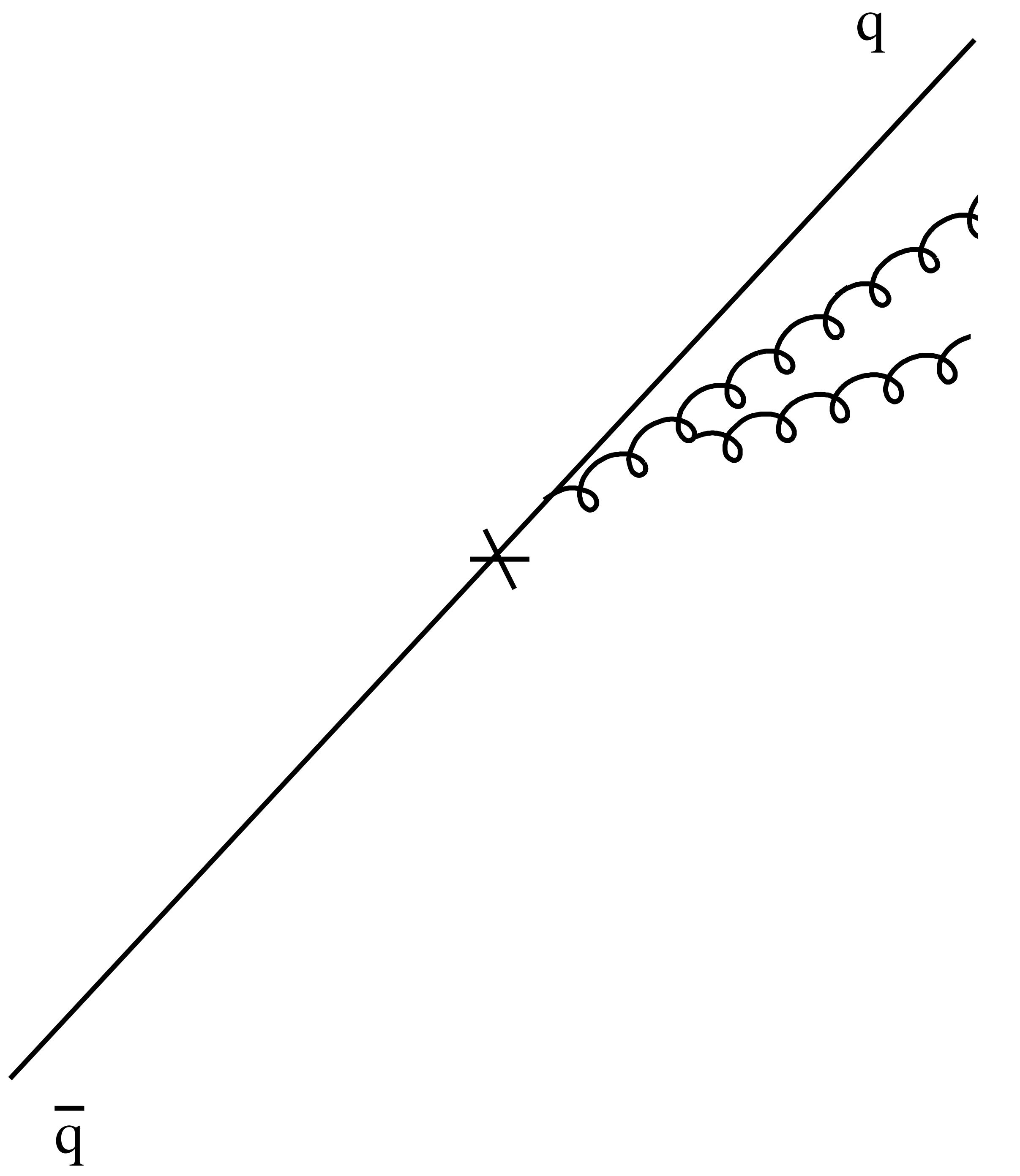

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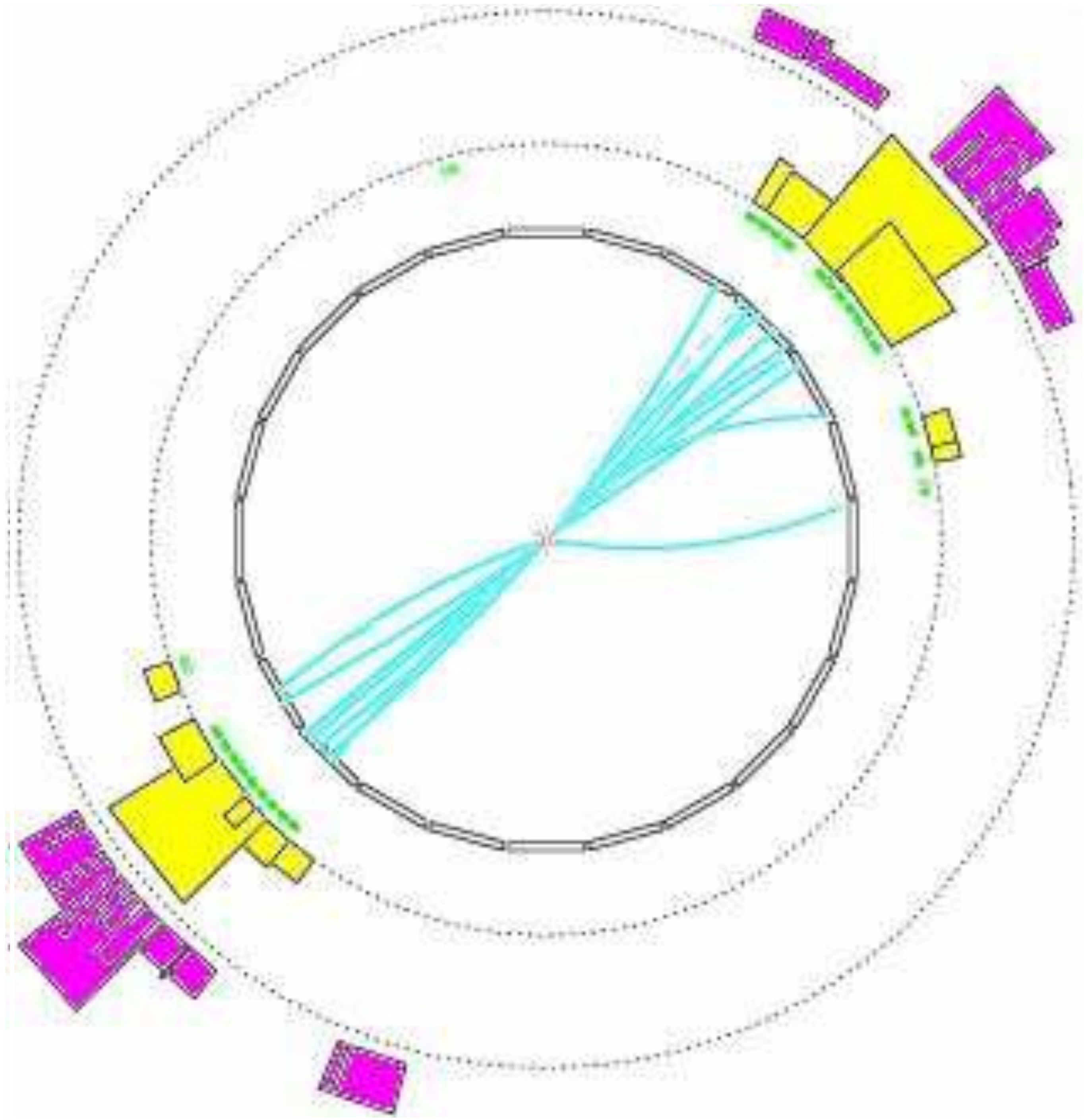

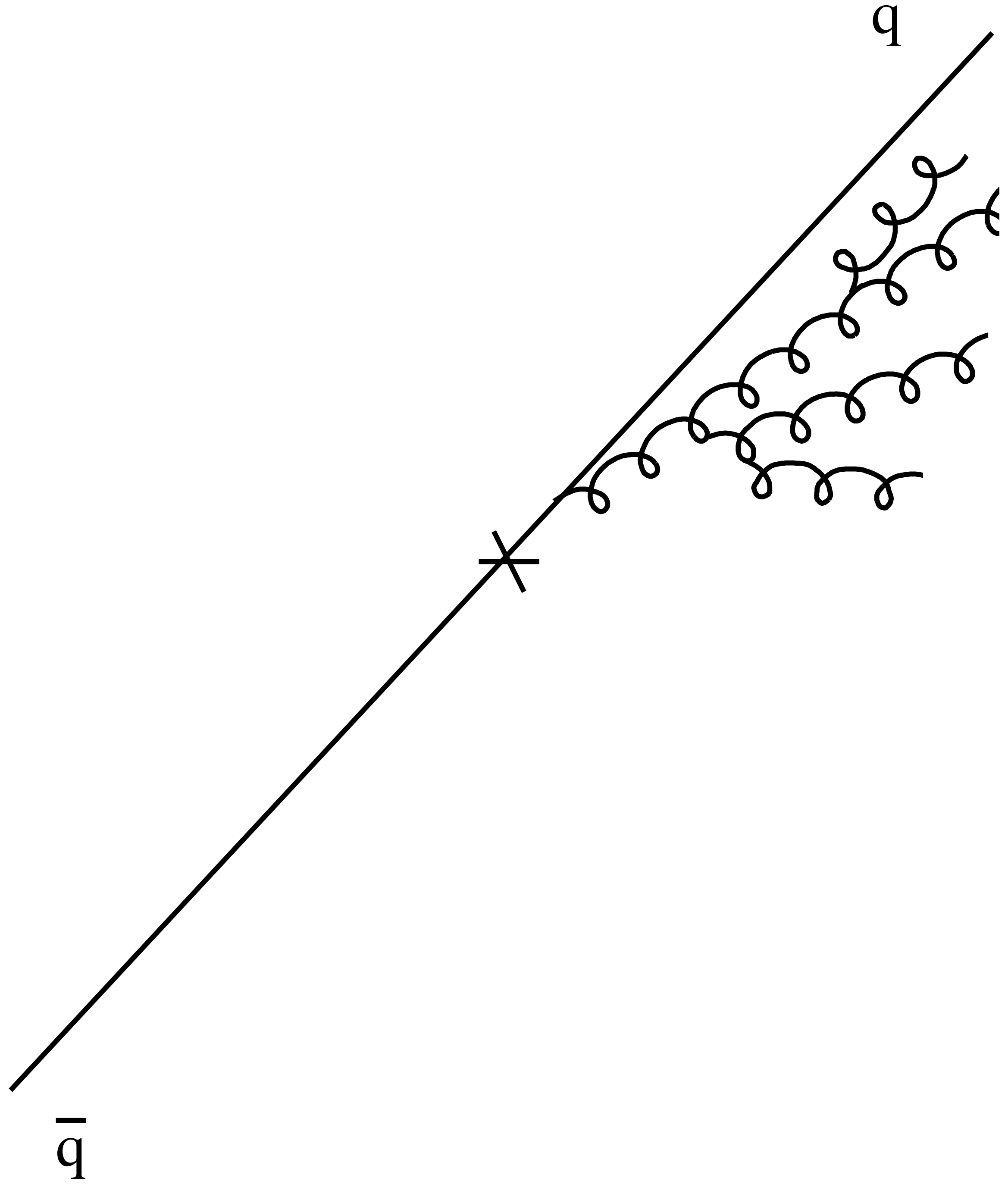

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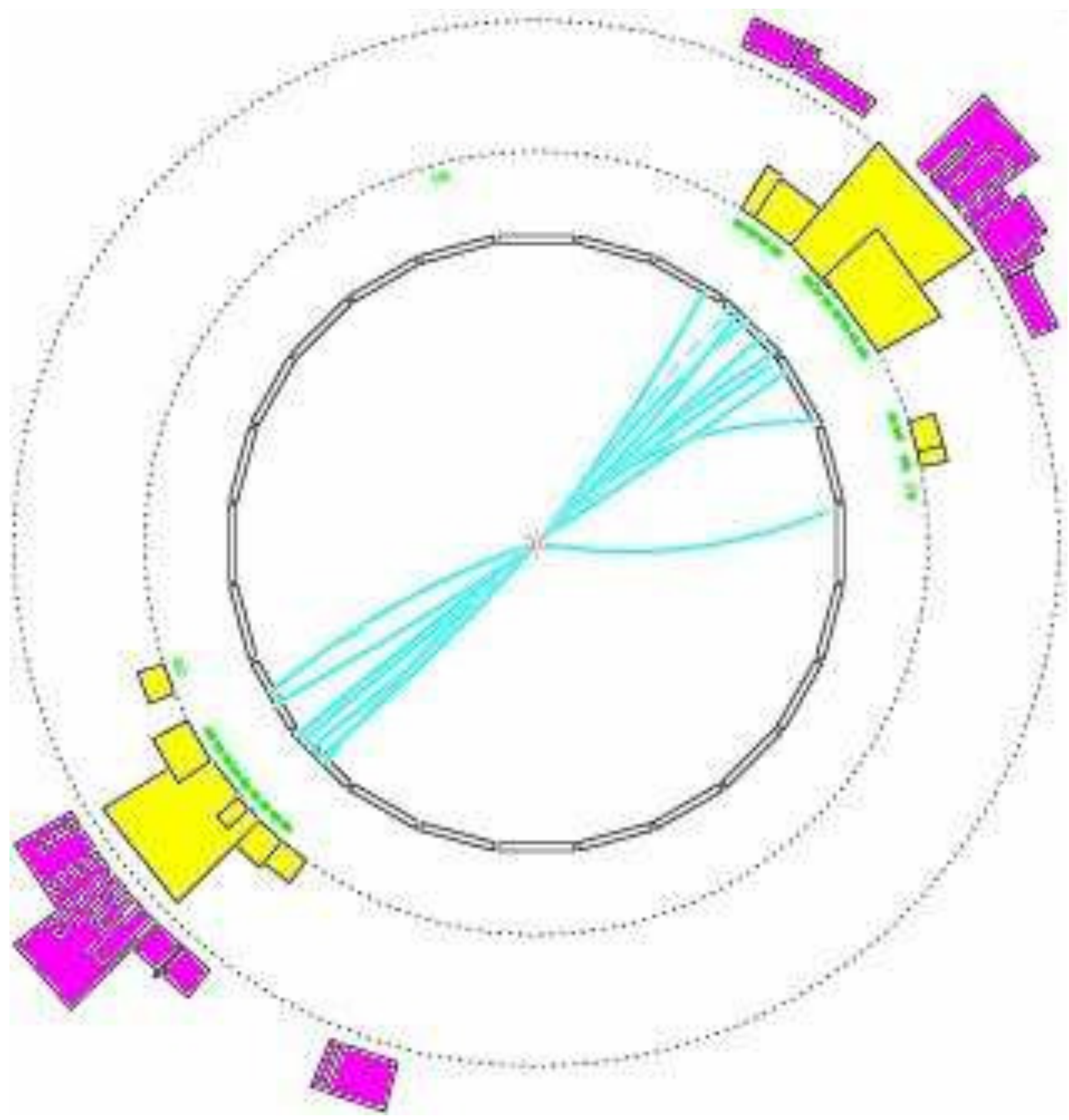

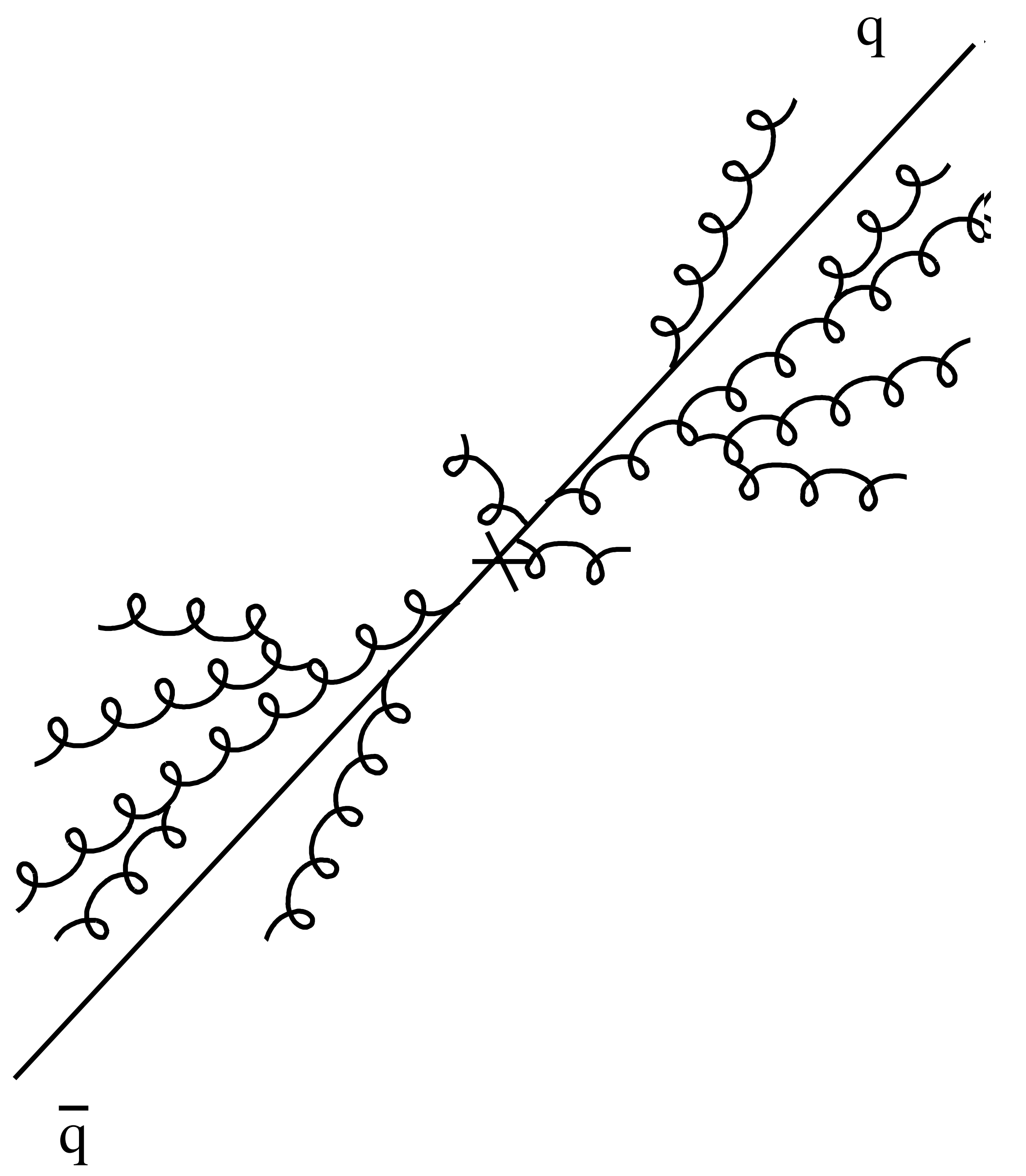

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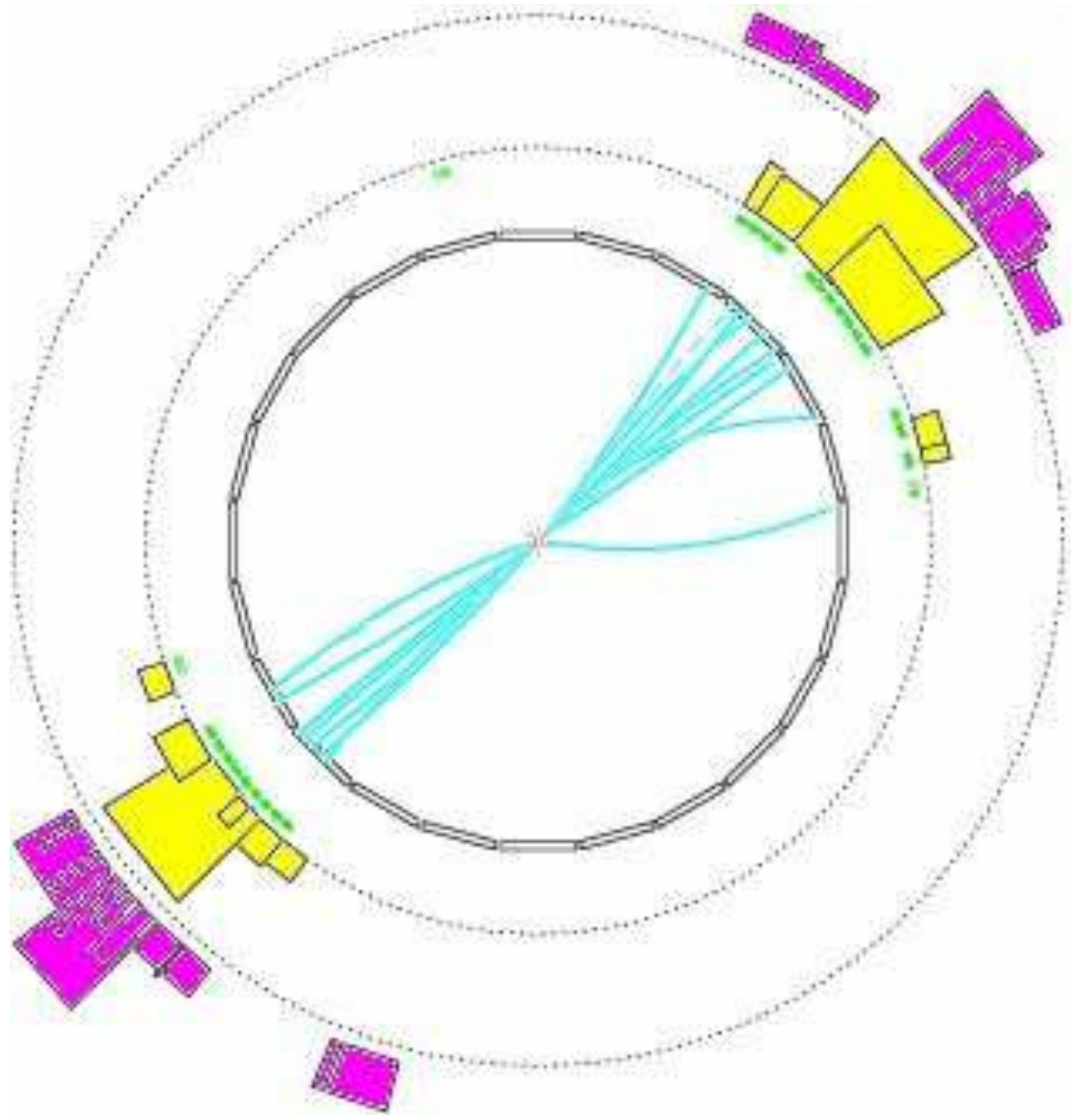
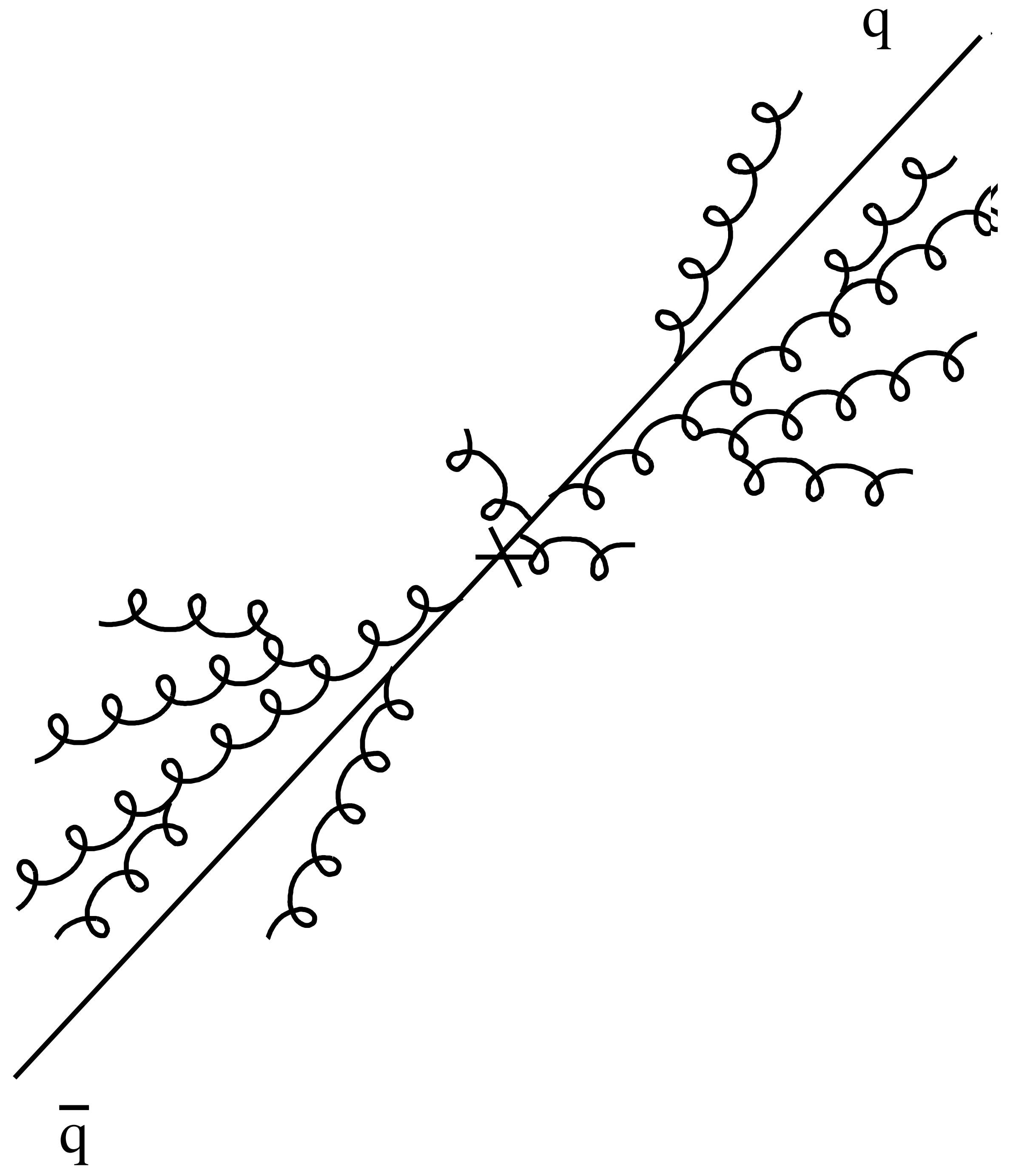
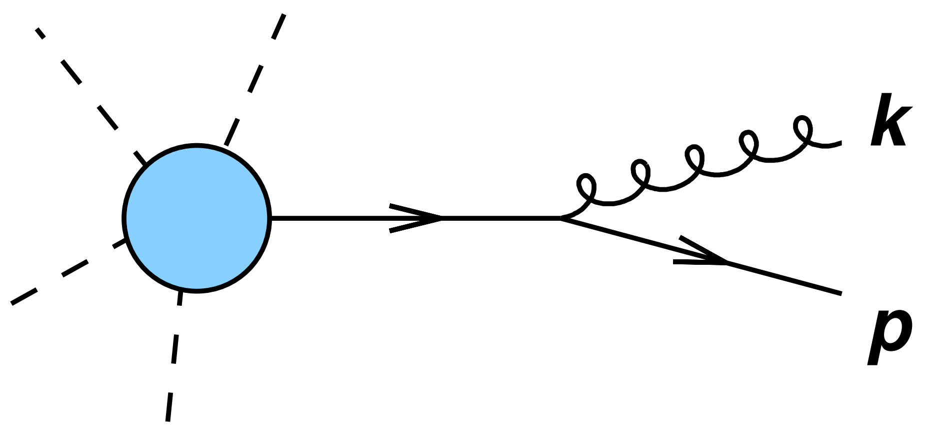




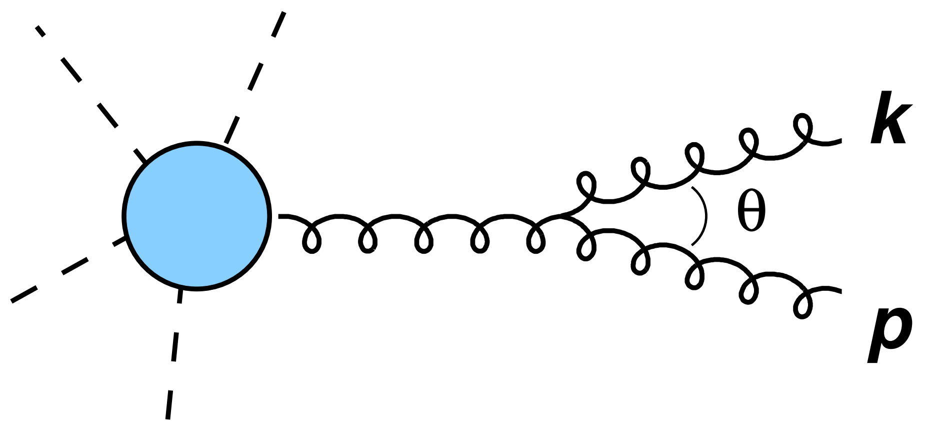
Nice pictures… Can we be quantitative about this?

average number of gluons

- we already saw how to calculate approximate higher orders via factorisation:



$$\simeq \frac{2\alpha_s C_F}{\pi}\frac{dE}{E}\frac{d\theta}{\theta}$$



$$\simeq \frac{2\alpha_s C_A}{\pi}\frac{dE}{E}\frac{d\theta}{\theta}$$

- picture: emission of additional gluons from emitter, same divergence structure, only different colour factor

- repeats at all orders → we can iteratively generate emissions from the hard process + from subsequent emissions

average number of gluons

- quark with energy Q, on average we expect

$$\langle N_g \rangle = \frac{2\alpha_s C_F}{\pi} \int^Q \frac{dE}{E} \int^{\pi/2} \frac{d\theta}{\theta} \Theta(E\theta > Q_0)$$

- note we cut $E\theta \sim k_t > Q_0$ to avoid soft and collinear divergencies

$$\langle N_g \rangle \sim \frac{\alpha_s C_F}{\pi} \ln^2 \frac{Q}{Q_0}$$

- reasonable values $Q = 200$ GeV, $Q_0 = 1$ GeV $\rightarrow \ln^2 \frac{Q}{Q_0} \approx 30$

$\rightarrow \langle N_g \rangle > 1 \Rightarrow$ adding single orders in perturbation theory not sufficient

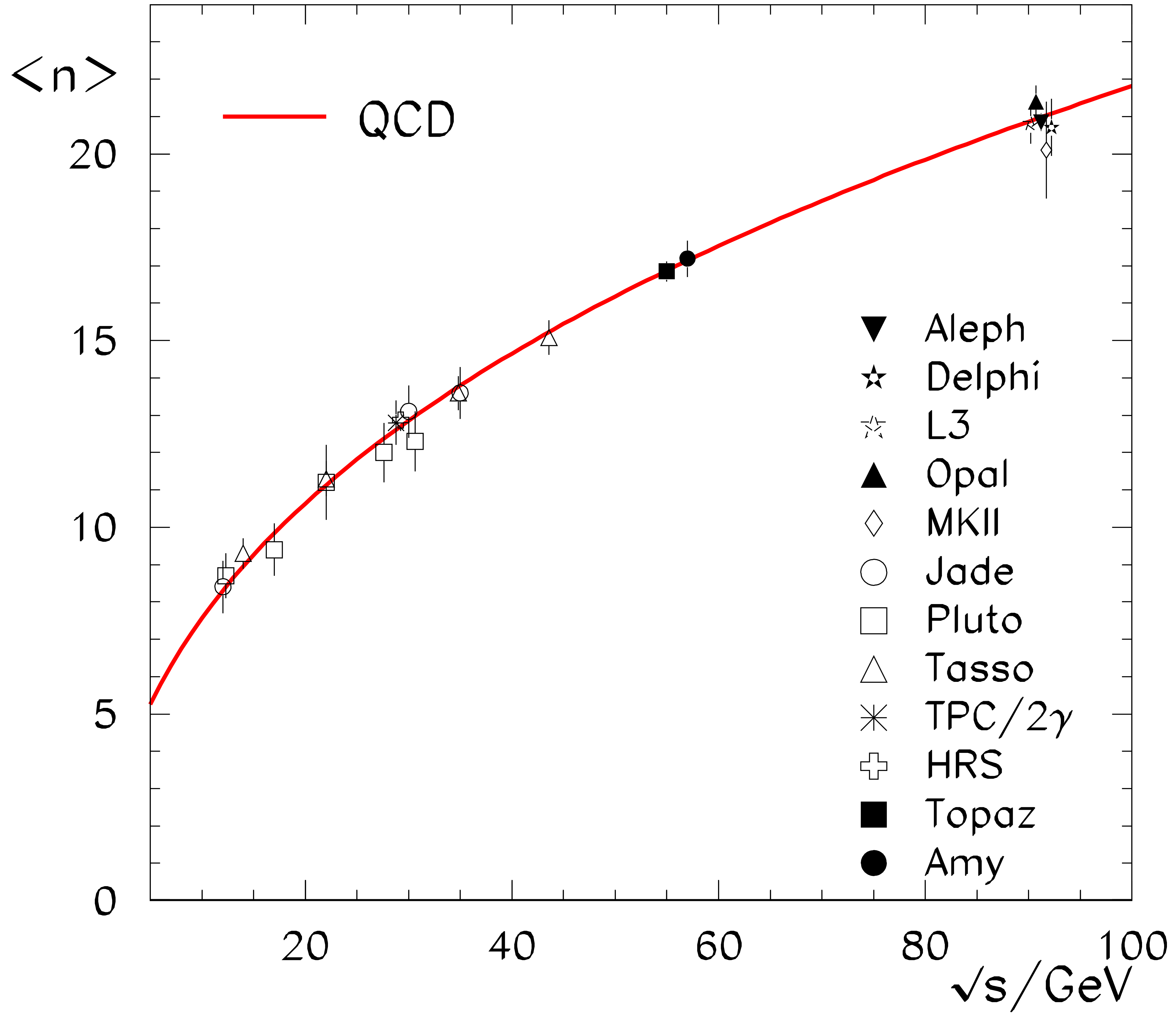
average number of gluons

- all orders result for gluon multiplicity:

$$\langle N_g \rangle \sim \frac{C_F}{C_A} \sum_{n=1}^{\infty} \frac{1}{(n!)^2} \left(\frac{C_A}{2\pi\beta_0\alpha_s(Q)} \right)^n$$

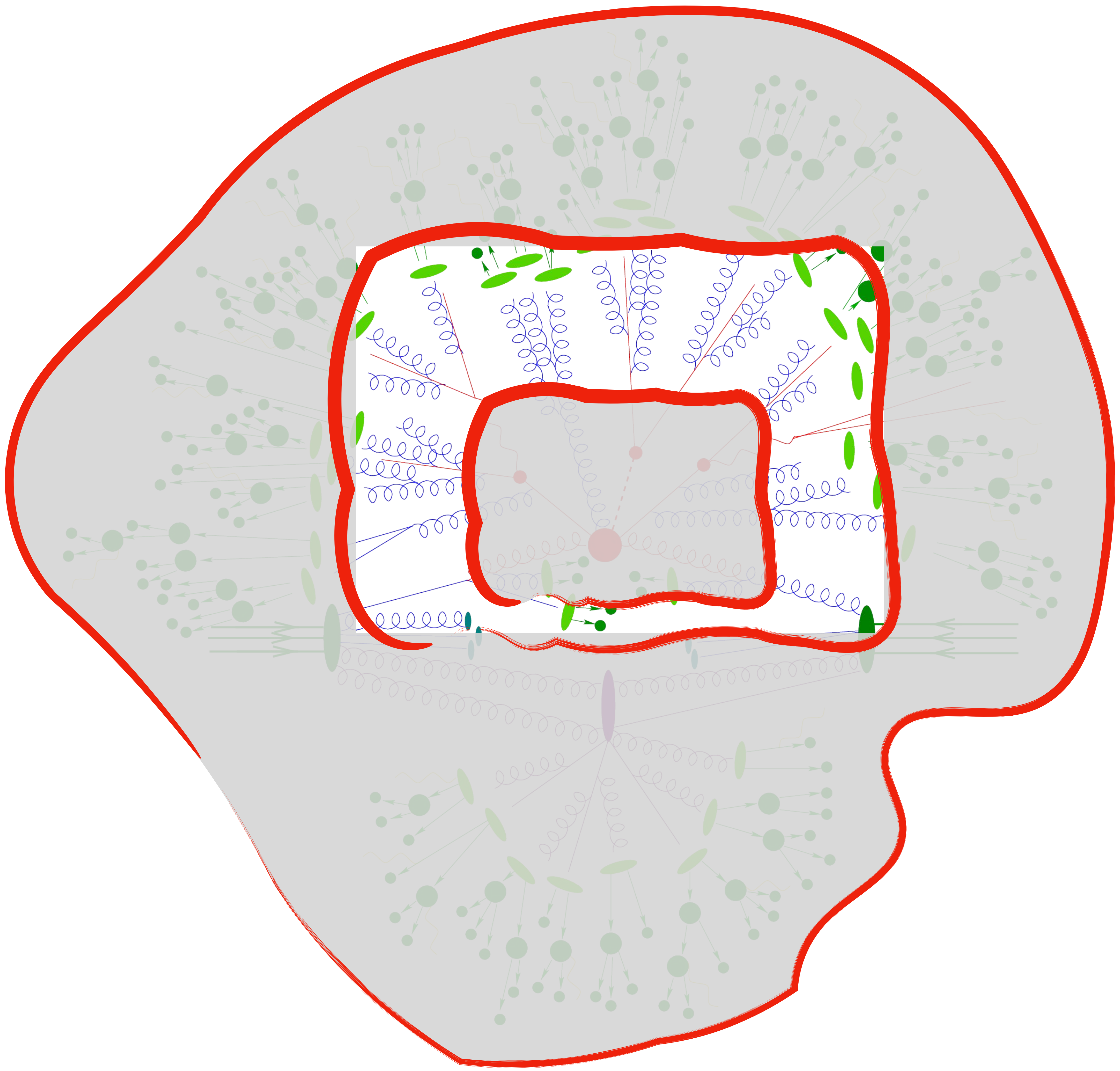
$$\langle N_g \rangle \sim \frac{C_F}{C_A} \exp\left(\sqrt{\frac{2C_A}{\pi\beta_0\alpha_s(Q)}} \right)$$

- comparison to data, assume $\langle N_g \rangle \sim \langle N_{had} \rangle$



QCD at colliders

- Events factorised into
  - Hard Process ✓
  - QCD radiation
  - PDFs/Beams
  - Hadrons ✓



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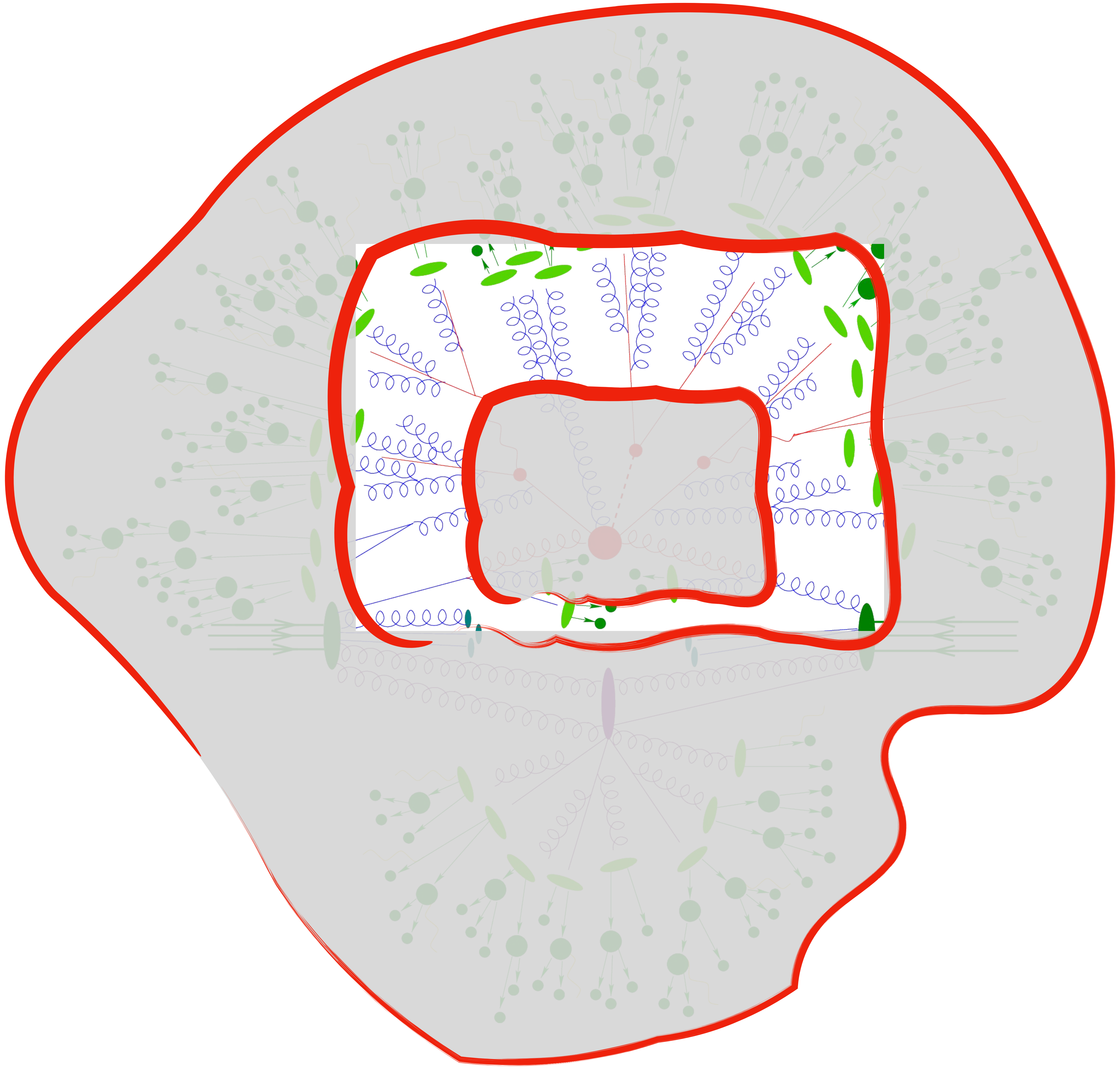

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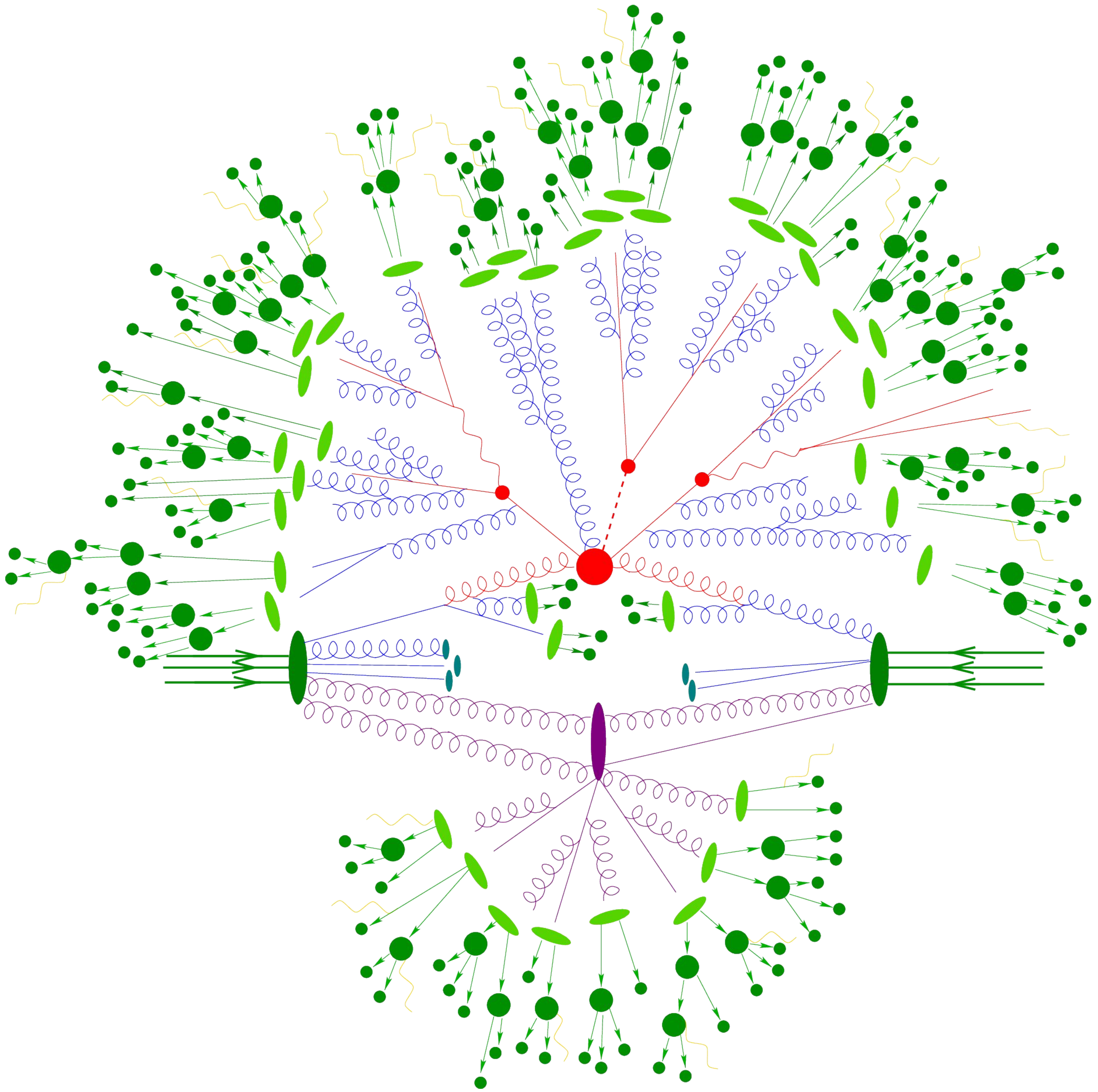

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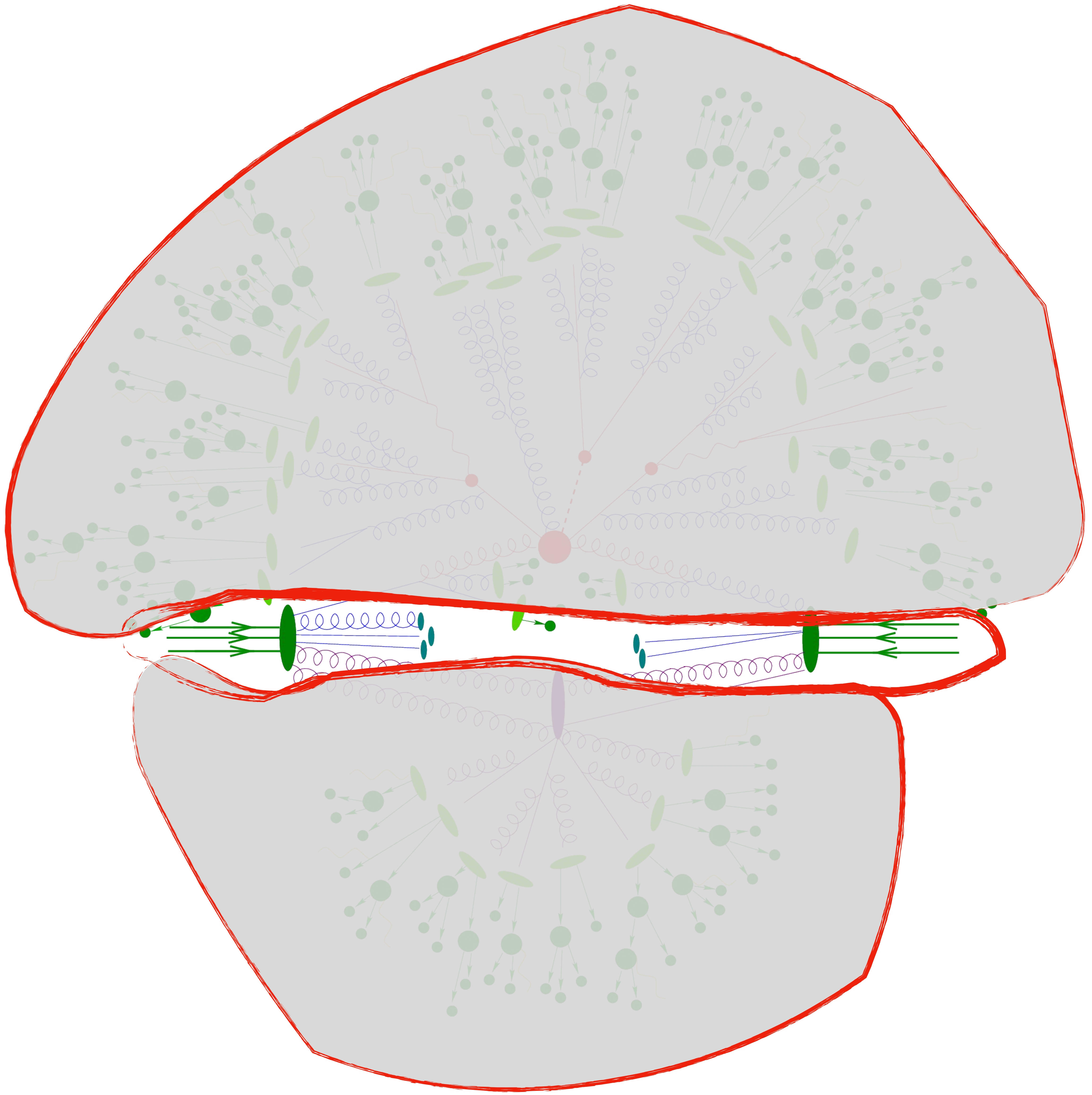
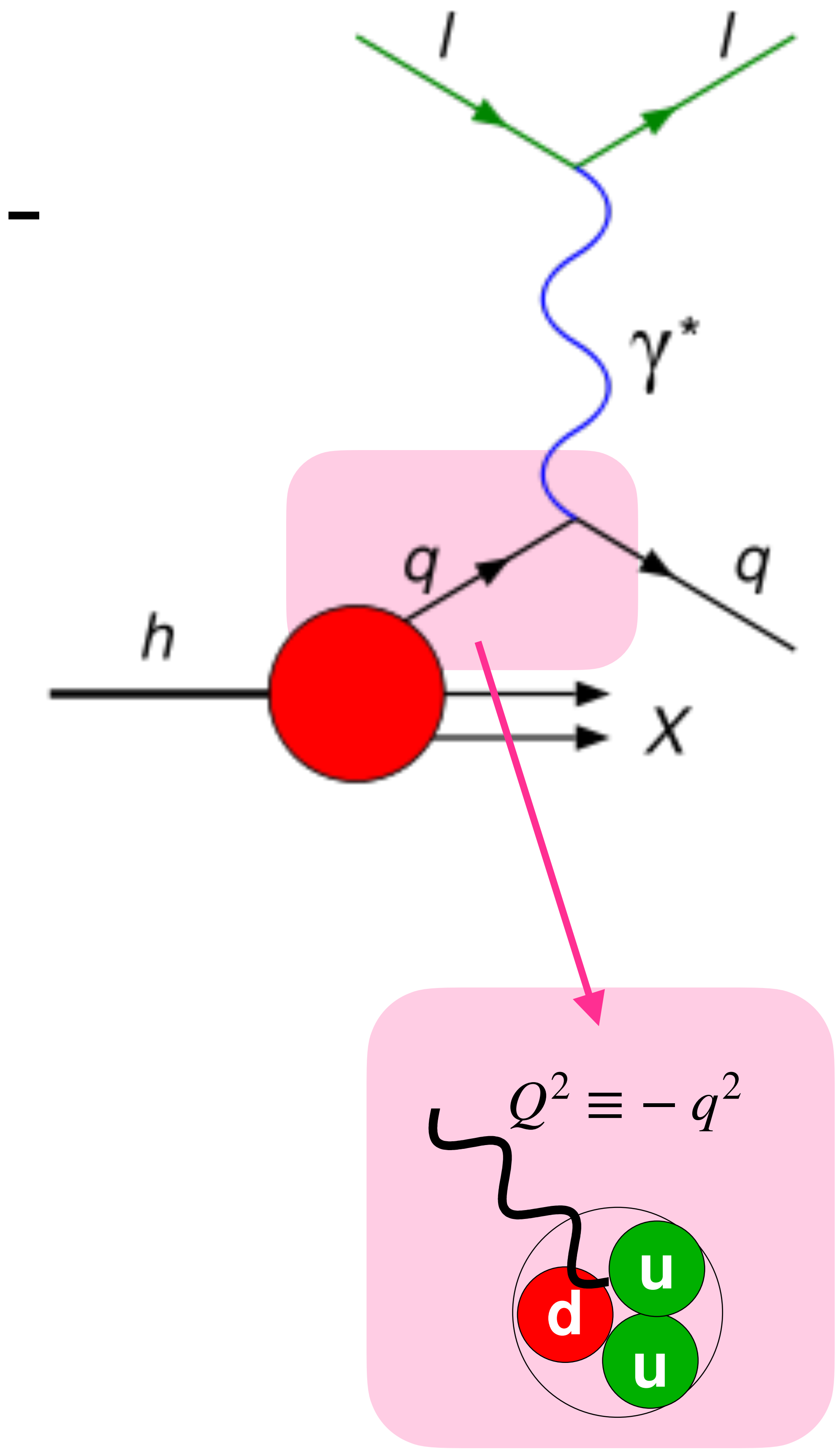
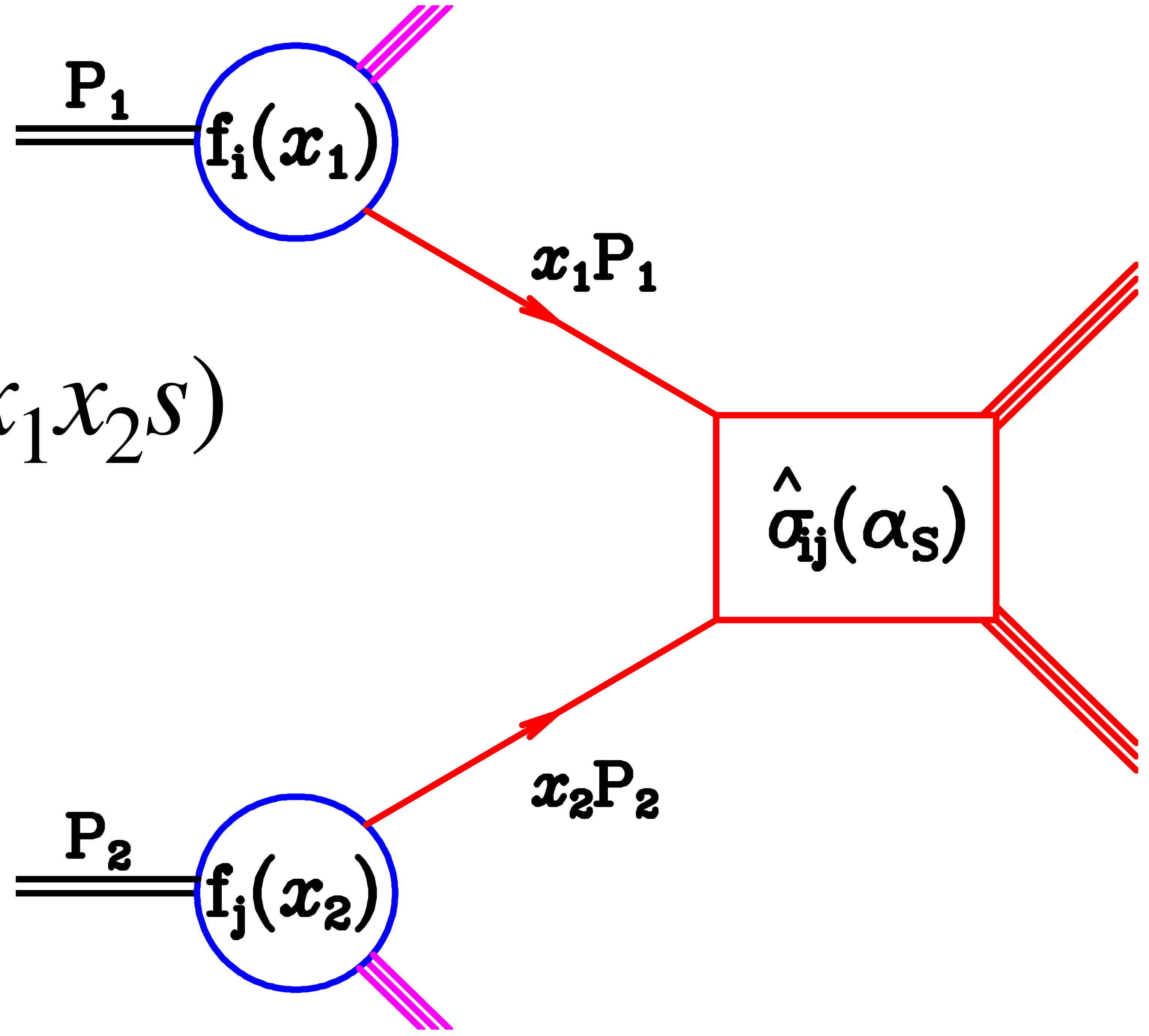


parton distribution functions

- initial states are not partons but hadrons made up of them
- in pQCD, we can only calculate matrix element with incoming partons - information about internal structure of hadrons
- parton model picture:
  - quarks bound inside proton
  - in collision, single parton is involved, carrying momentum fraction x of the proton momentum
  - which parton?
    - select according to probability distributions $f_p(x)$ for each parton species



parton distribution functions



- hadronic cross sections factorise

$$\sigma_{hh\to X}(s) = \sum_{p_1,p_2} \int dx_1 f_{p_1}(x_1) \int dx_2 f_{p_2}(x_2) \sigma_{p_1 p_2 \to X}(x_1 x_2 s)$$

- note:
  - partons assumed collinear with hadron/proton: $\vec{p}_i = x_i \vec{p}_h$
  - effective parton collision with reduced center of mass energy $\hat{s} = x_1 x_2 s$

parton distribution functions — sum rules

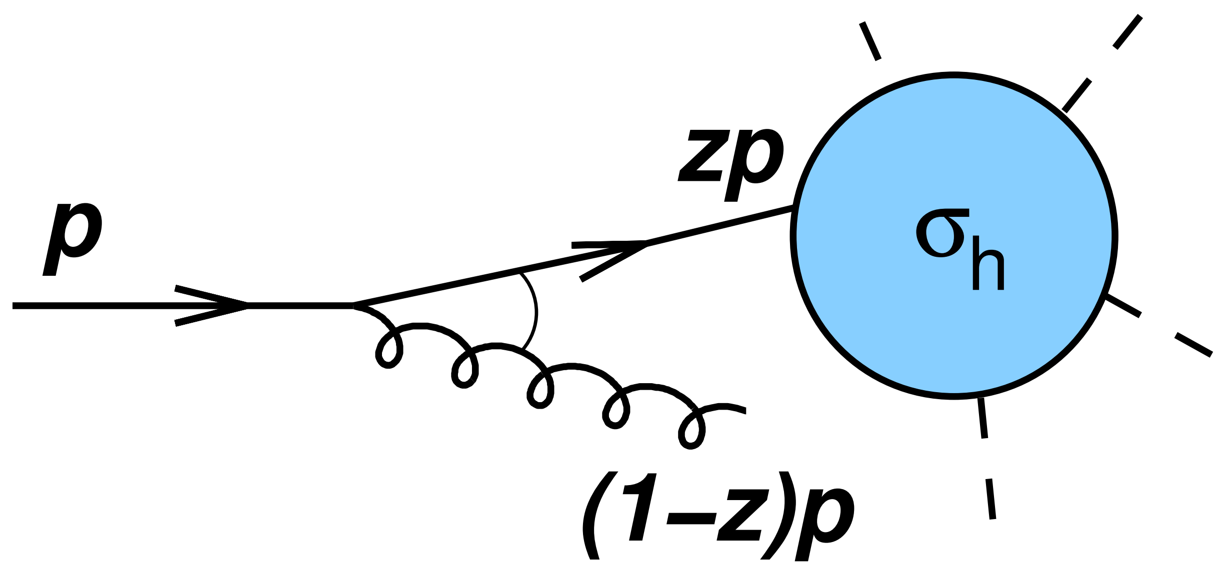
- can we say anything about the PDFs?
- we know overall make-up of hadrons ⇒ sum rules, e.g. for proton $|uud\rangle$:

$$\int_0^1 dx \left(f_u(x) - f_{\bar{u}}(x)\right) = 2 \qquad \text{and}$$

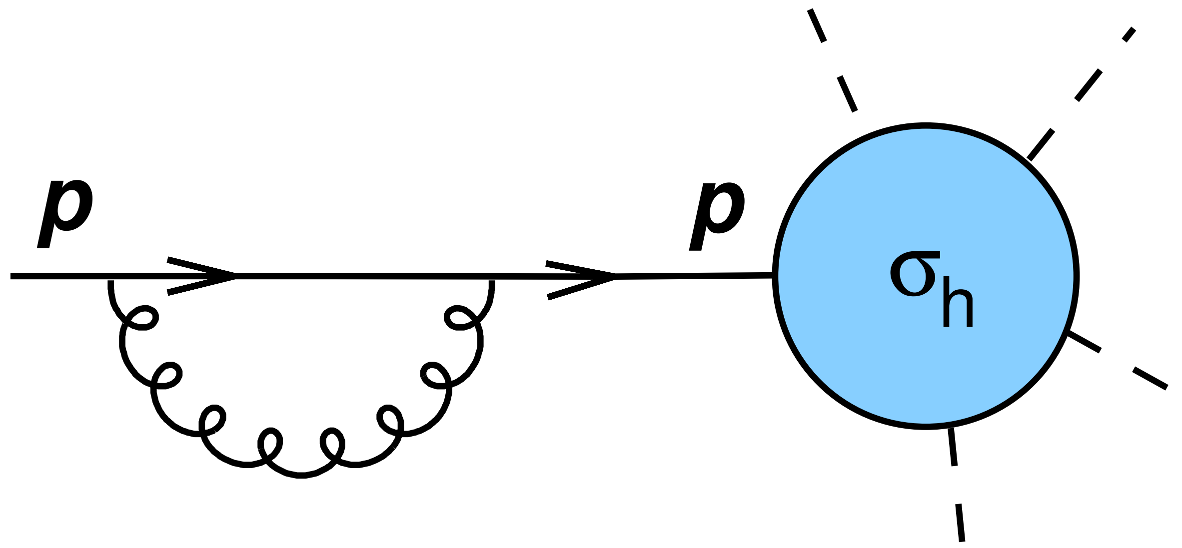
$$\int_0^1 dx \left(f_d(x) - f_{\bar{d}}(x)\right) = 1$$

pdf and factorisation scale

- lets have a closer look at real - virtual cancellation:



$$\sigma_{g+h}(p) \simeq \sigma_h(zp)\frac{\alpha_s C_F}{\pi}\frac{dz}{1-z}\frac{dk_t^2}{k_t^2}$$



$$\sigma_{V+h}(p) \simeq -\sigma_h(p)\frac{\alpha_s C_F}{\pi}\frac{dz}{1-z}\frac{dk_t^2}{k_t^2}$$

$$\sigma_{g+h} + \sigma_{V+h} \simeq \frac{\alpha_s C_F}{\pi}\underbrace{\int_0^{Q^2}\frac{dk_t^2}{k_t^2}}_{\text{infinite}}\underbrace{\int_0^1\frac{dz}{1-z}[\sigma_h(zp)-\sigma_h(p)]}_{\text{finite}}$$

sum finite for $z \to 1$ (soft), but not $k_t \to 0$ (collinear)

additional divergence regulated by factorisation scale μ_F and "absorbed" into pdf

pdf and factorisation scale

- full factorisation theorems include dependence on factorisation scale

$$\sigma_{hh\to X}(s) = \sum_{p_1,p_2} \int dx_1 f_{p_1}(x_1, \mu_F^2) \int dx_2 f_{p_2}(x_2, \mu_F^2) \sigma_{p_1 p_2 \to X}(\hat{s}, \mu_R^2, \mu_F^2)$$

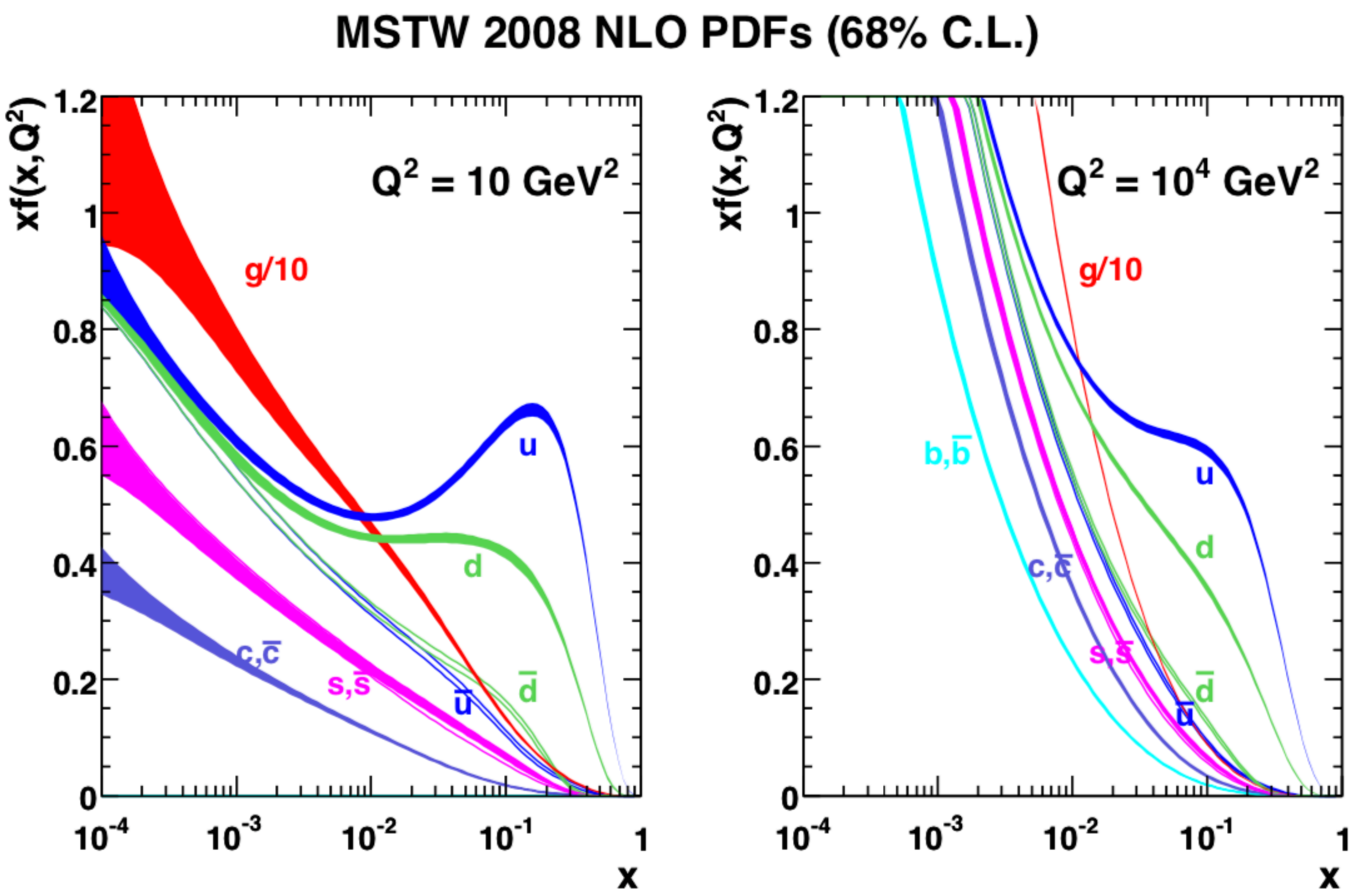
- emission with $k_t < \mu_F$ part of pdf

- emission with $k_t > \mu_F$ part of the hard process

- we can calculate the change of pdf with energy scale μ_F in perturbative QCD (collinear emissions, again use factorisation)

- typically $\mu_F \sim Q$ energy of the hard process

parton distribution functions — measured



- PDFs fitted to cross sections various processes, in ranges where fixed order QCD calculations are applicable
- note g is scaled by a factor $1/10 \rightarrow$ gluons by far dominating at the LHC

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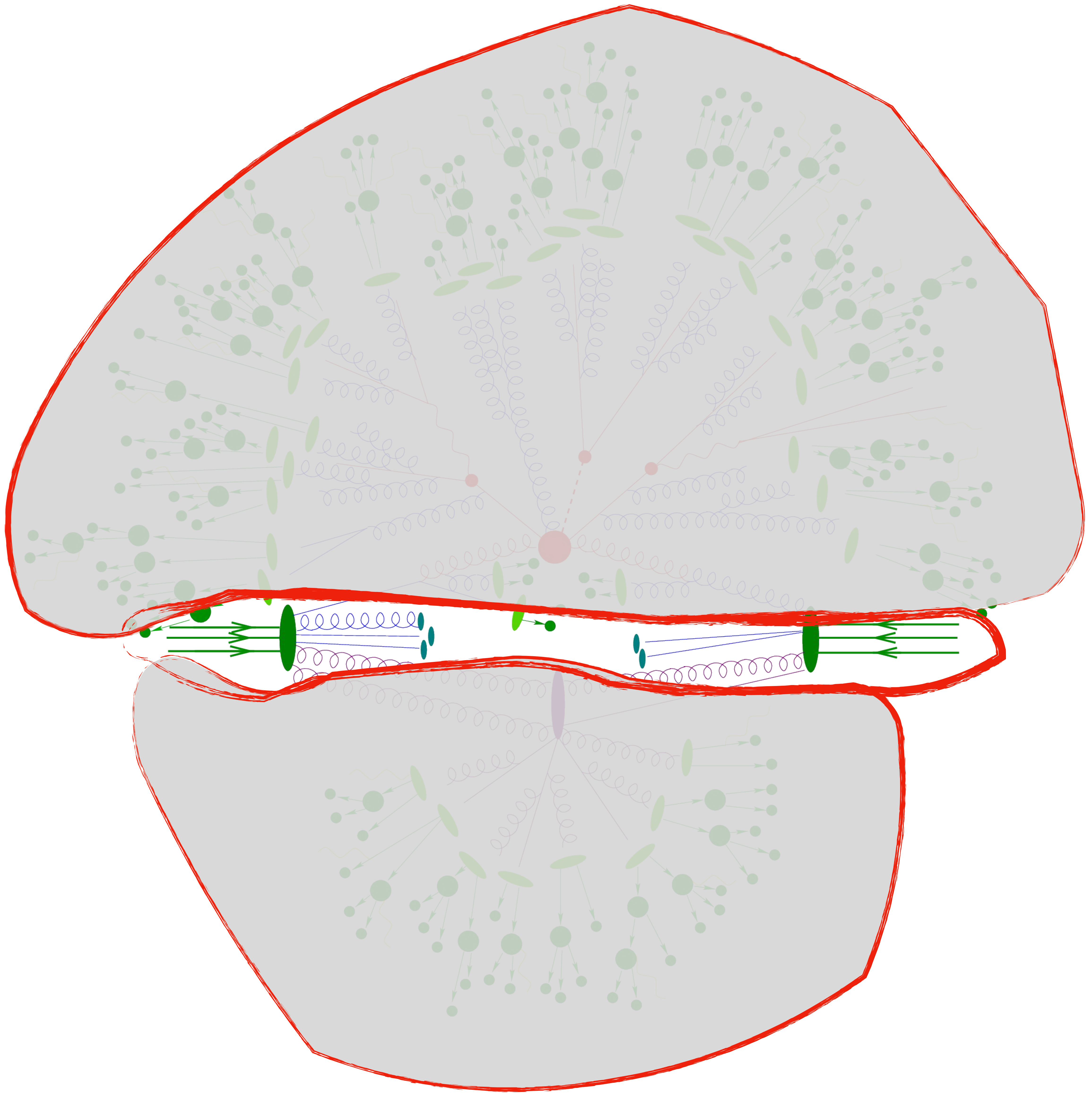

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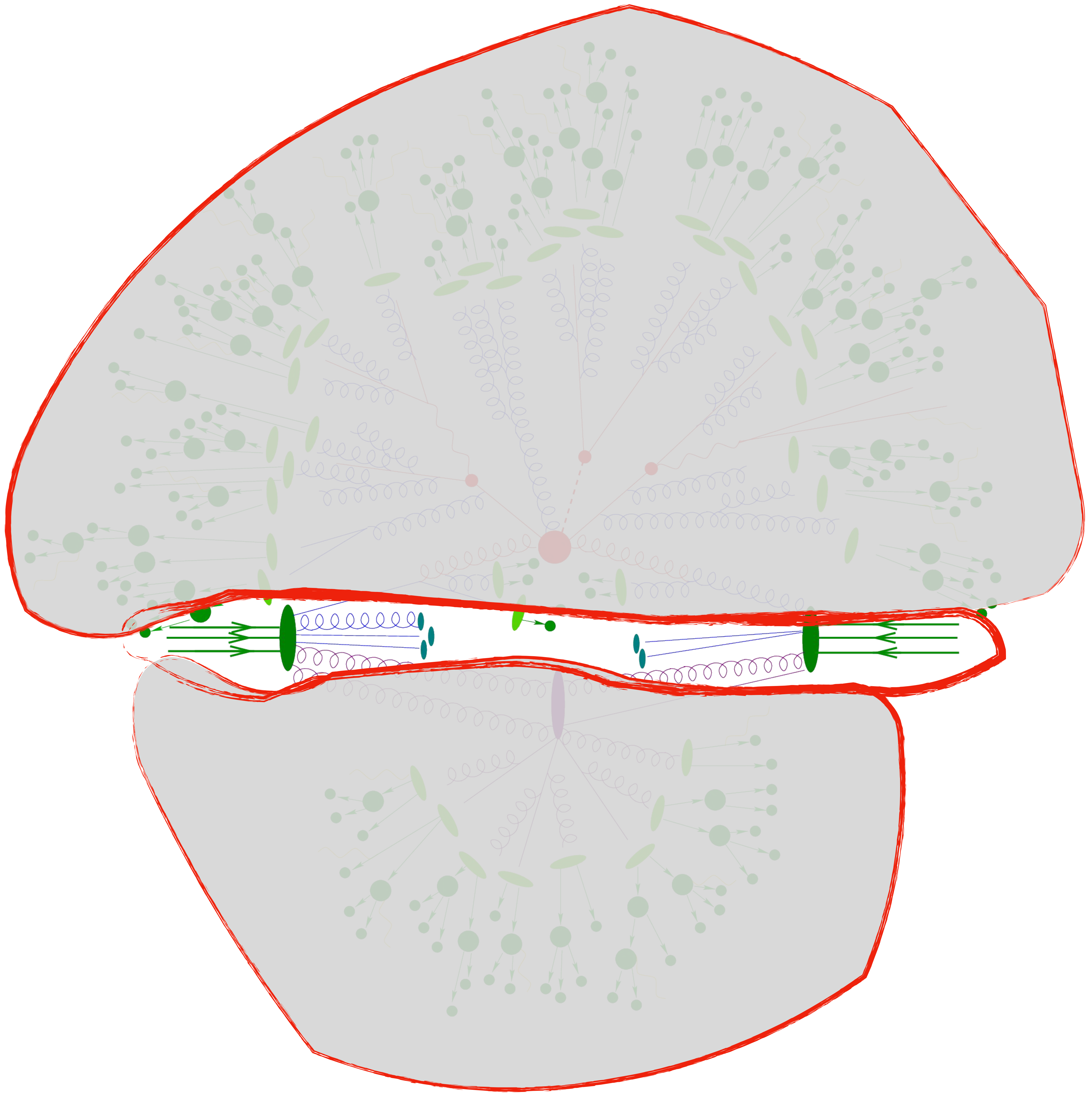

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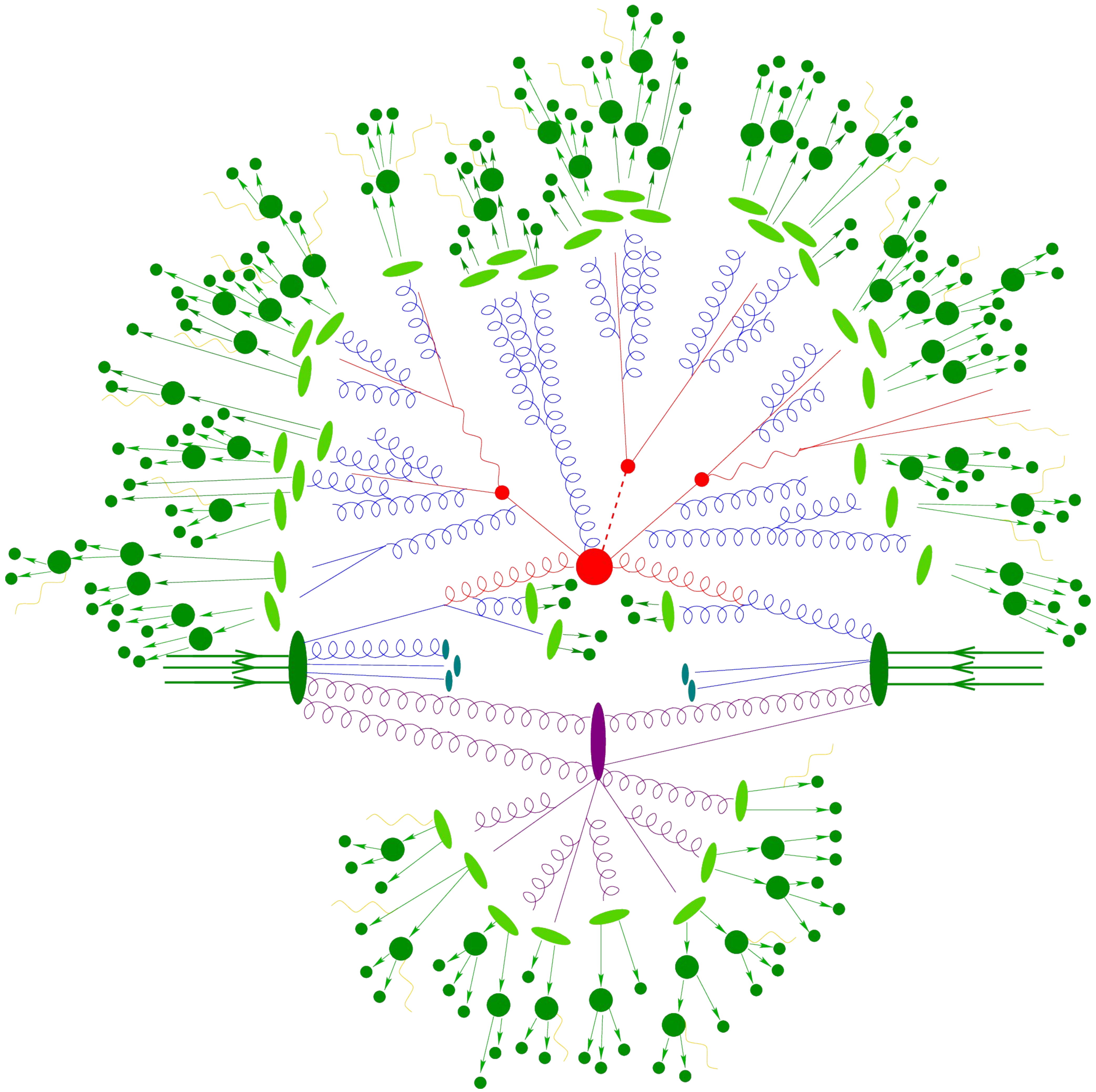

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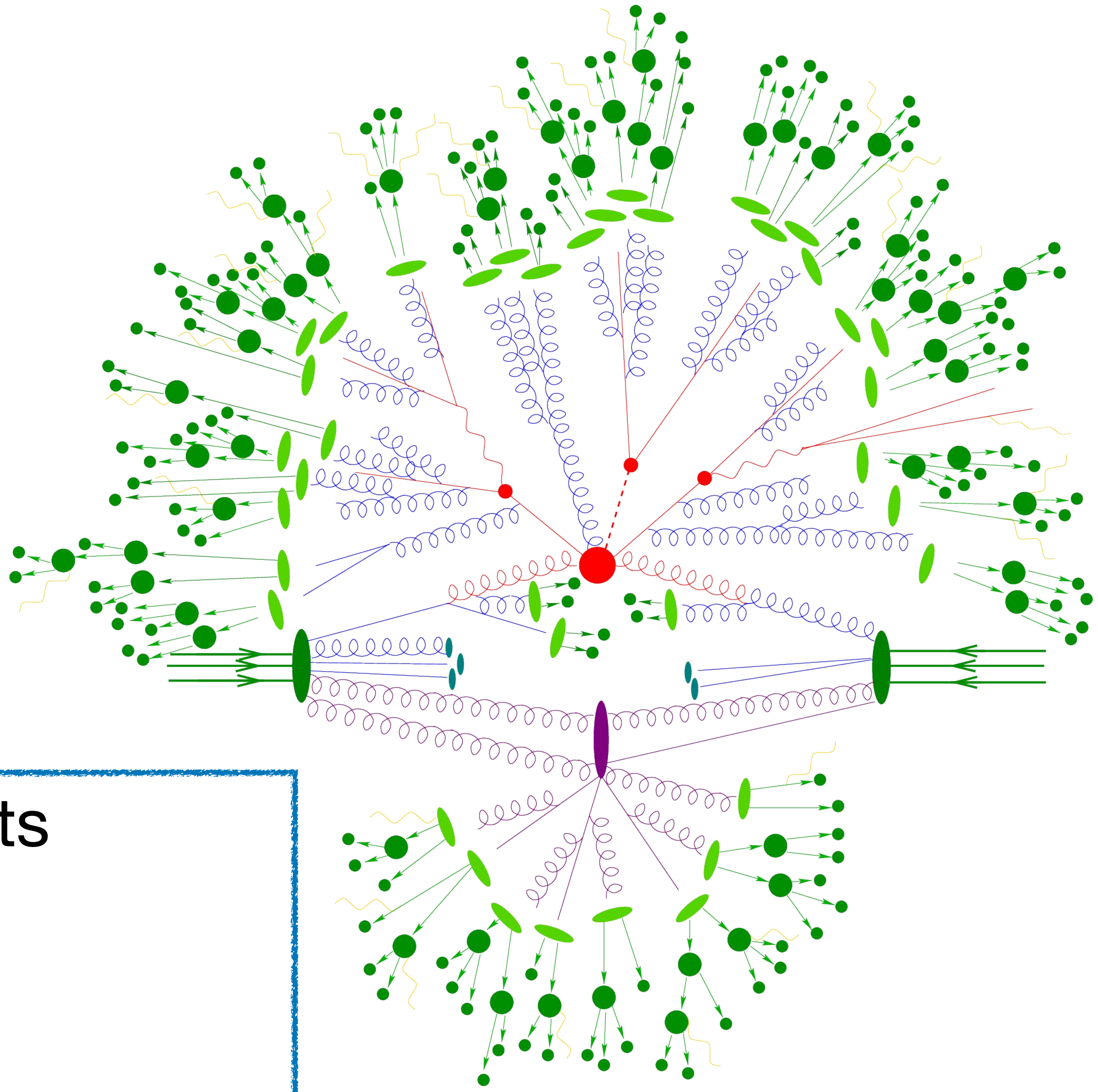


Left out so far: non-perturbative components

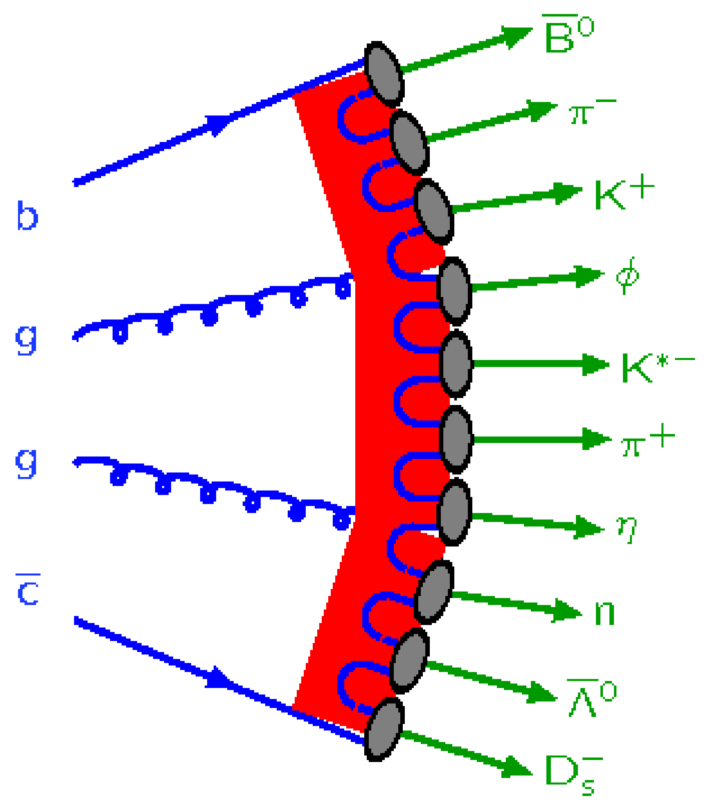
- parton - hadron transition
- underlying event

no first principle QCD calculation, modelling required

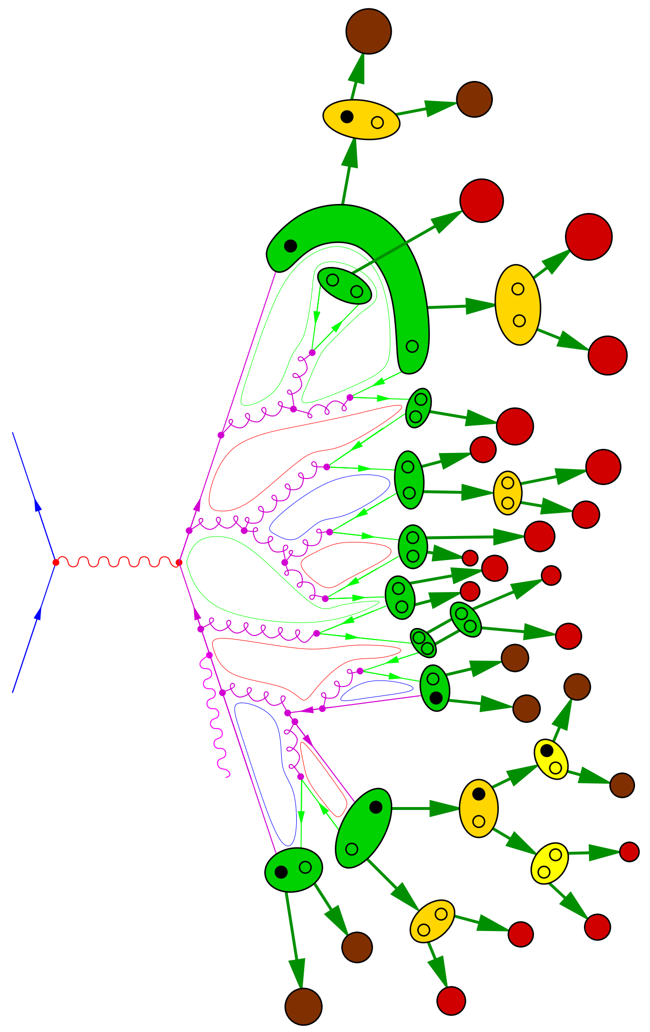
hadronisation models

- capture main non-perturbative aspects of QCD
- universality:
  - should not depend on process/ energy (typical: tune/measure at LEP, then apply at the LHC)
- work in large N_c limit ⇒ each quark uniquely connected to another one, form string/cluster

Lund-string fragmentation
implemented in PYTHIA



cluster-hadronisation model
implemented in HERWIG & SHERPA



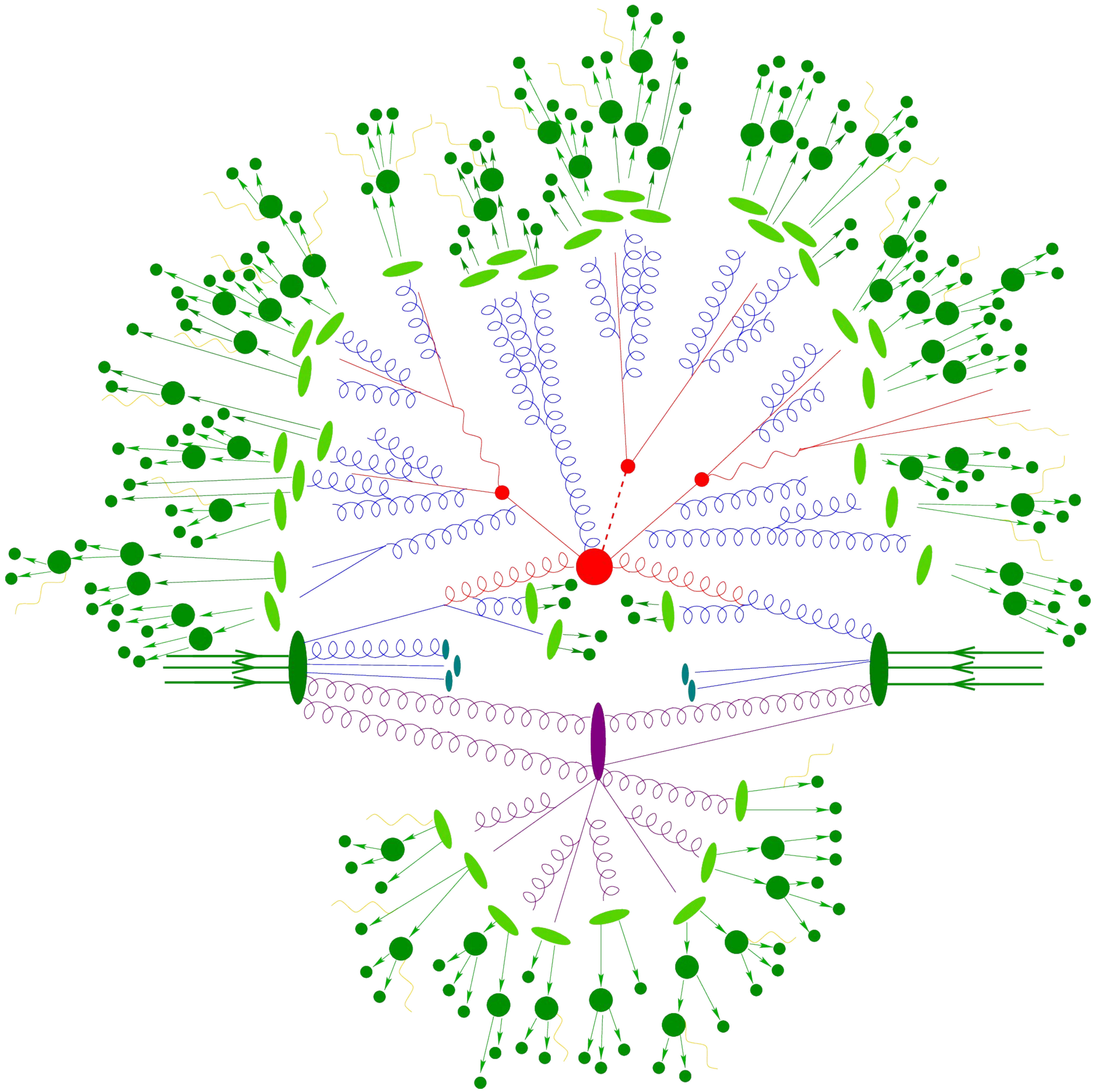
underlying event modelling

- primary parton collision → leaves energetic remnants, can in principle interact again
- simple model [Sjöstrand, Zijl Phys. Rev. D 36 (1987) 2019]:
  - hard process at scale $p_{t,hard}$
  - generate sequence of additional $2 \to 2$ scatterings ordered in p_t

$$\mathscr{P}(p_t) = \frac{1}{\sigma_{ND}} \frac{d\sigma_{QCD}^{2\to 2}}{dp_t^2} \exp\left[-\int_{p_t^2}^{p_{t,hard}^2} \frac{1}{\sigma_{ND}} \frac{d\sigma_{QCD}^{2\to 2}}{dp_t'^{\,2}} dp_t'^{\,2} \right]$$

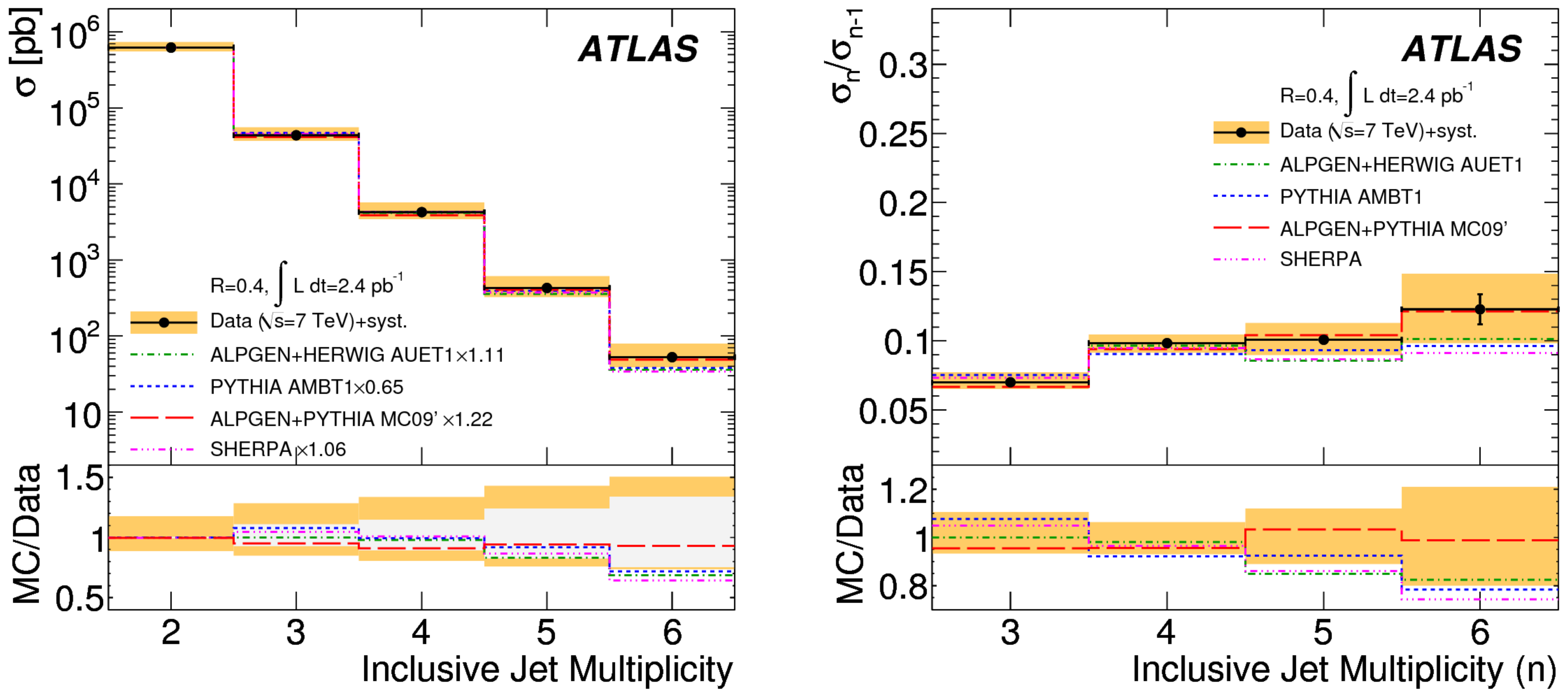
putting it all together - event generators

- Events factorised into
  - Hard Process
    - automated generation of up to NLO matrix elements
  - QCD radiation
    - Markov-Chain Monte Carlo in parton shower algorithms
    - matching to NLO calculations
  - PDFs/Beams/Underlying event
    - modelling of beam remnants / underlying event / multiple parton interactions
  - Hadrons
    - modelling of hadronisation
    - simulation of hadron decays



QCD in event generators

ATLAS pure jets analysis [G. Aad et al. Eur. Phys. J. C **71** (2011) 1763]



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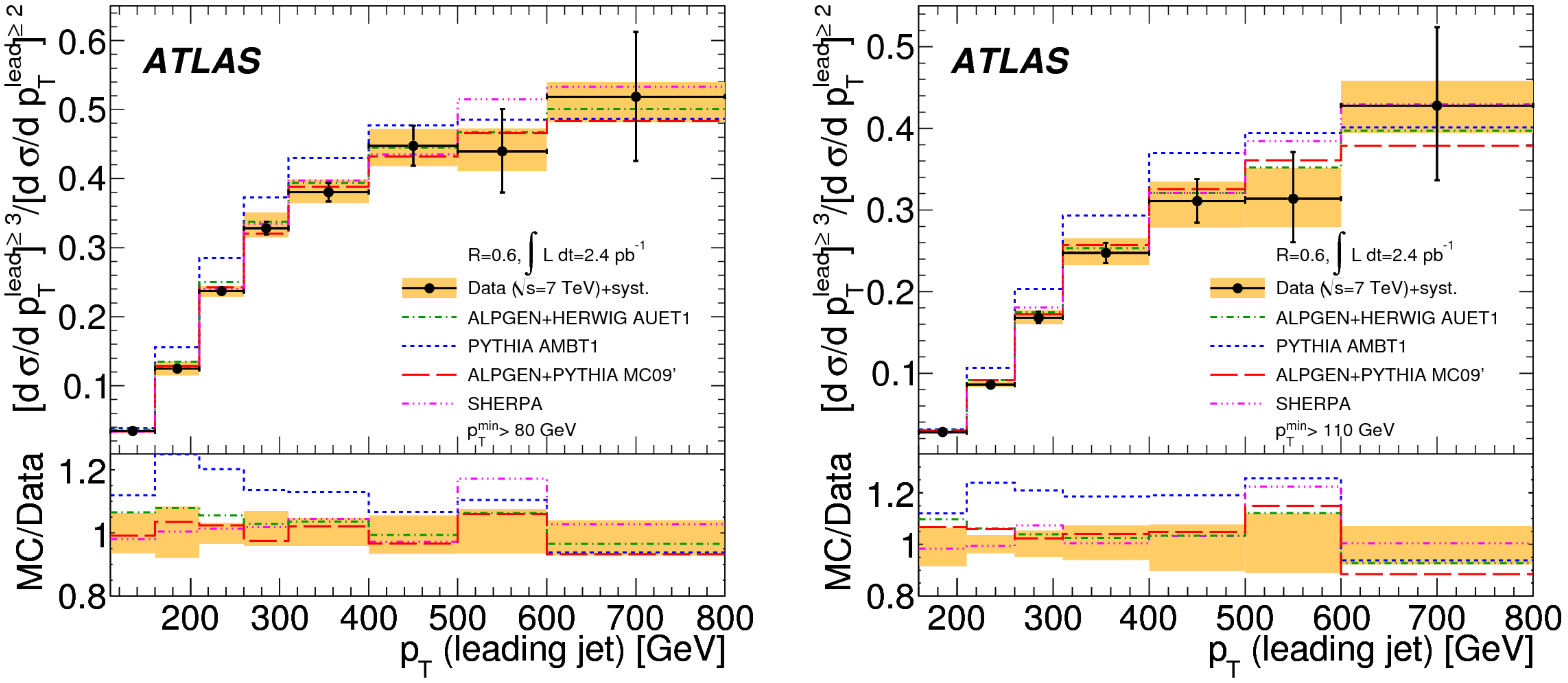

QCD in event generators

ATLAS $Z(\to e^+e^-/\mu^+\mu^-)$ + jets analysis [G. Aad et al. Phys. Rev. D **85** (2012) 032009]