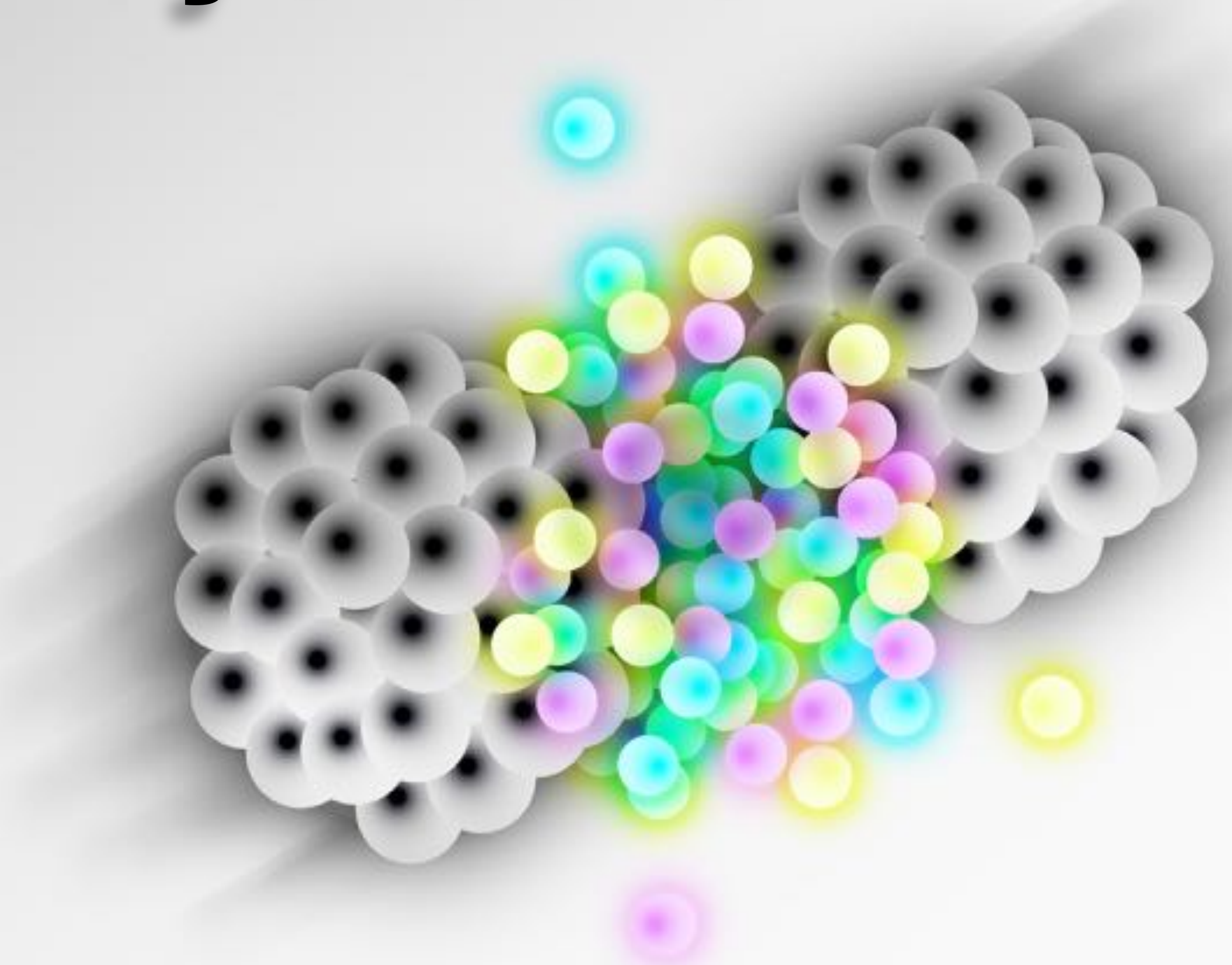
# Detector and physics simulation




**Liliana Apolinário**
**and**
**Patrícia Gonçalves**

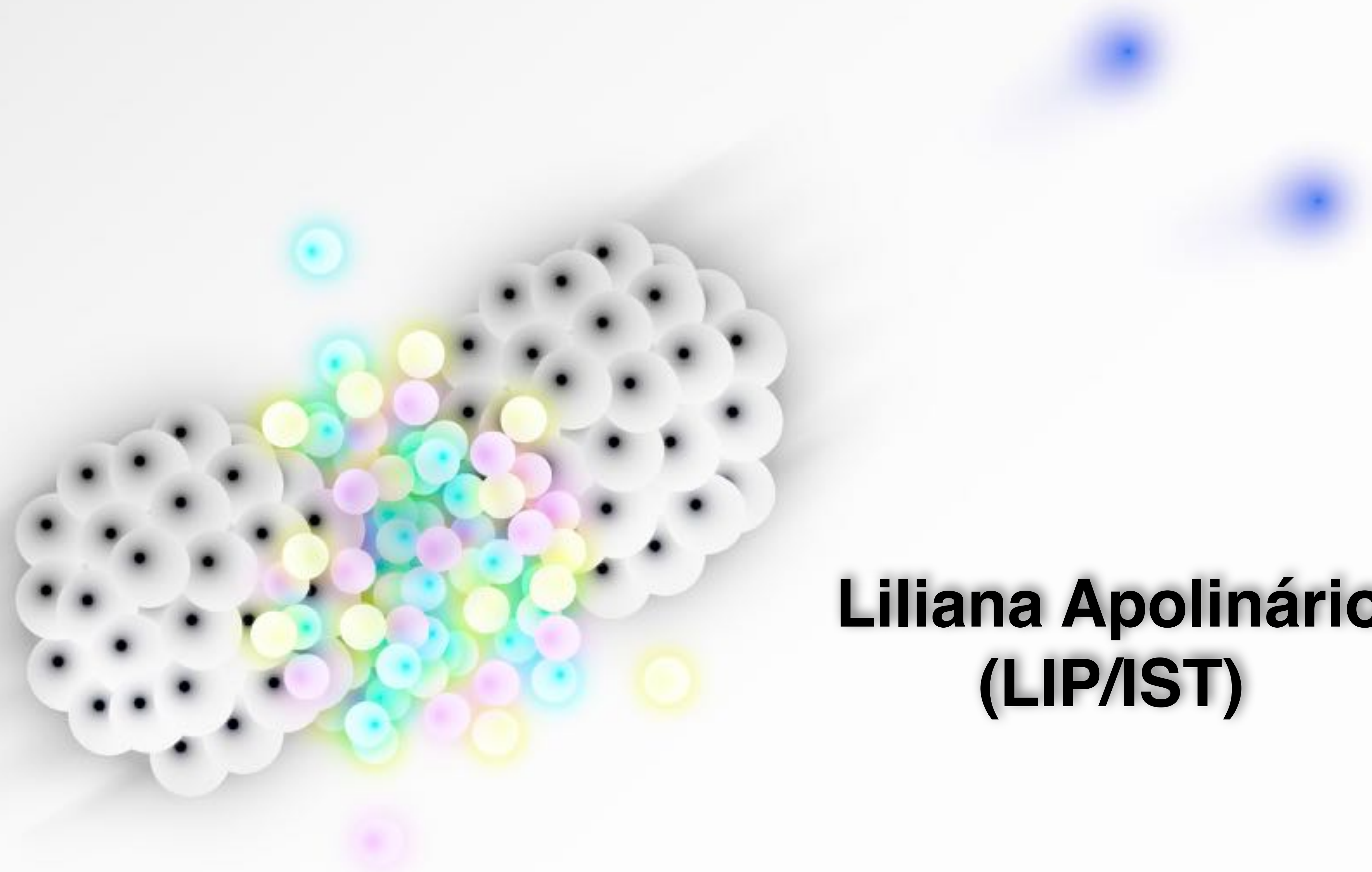
**(LIP/IST)**



**LIP Summer Internships**

**July 2018, FCUL, Lisbon**

# Physics Simulation



**Liliana Apolinário**
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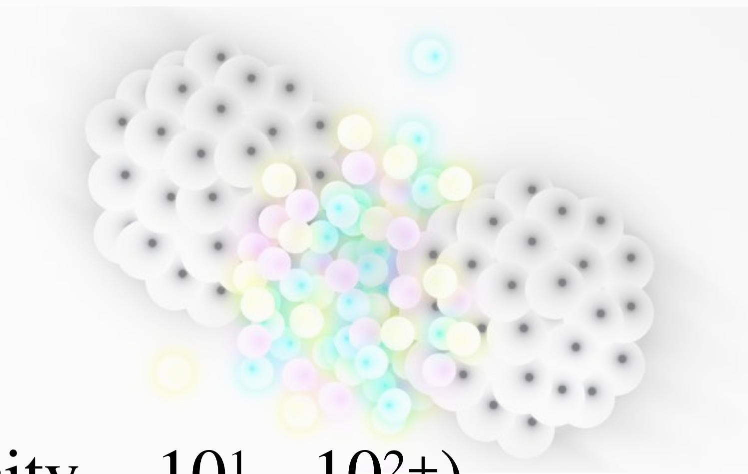
# Introduction I



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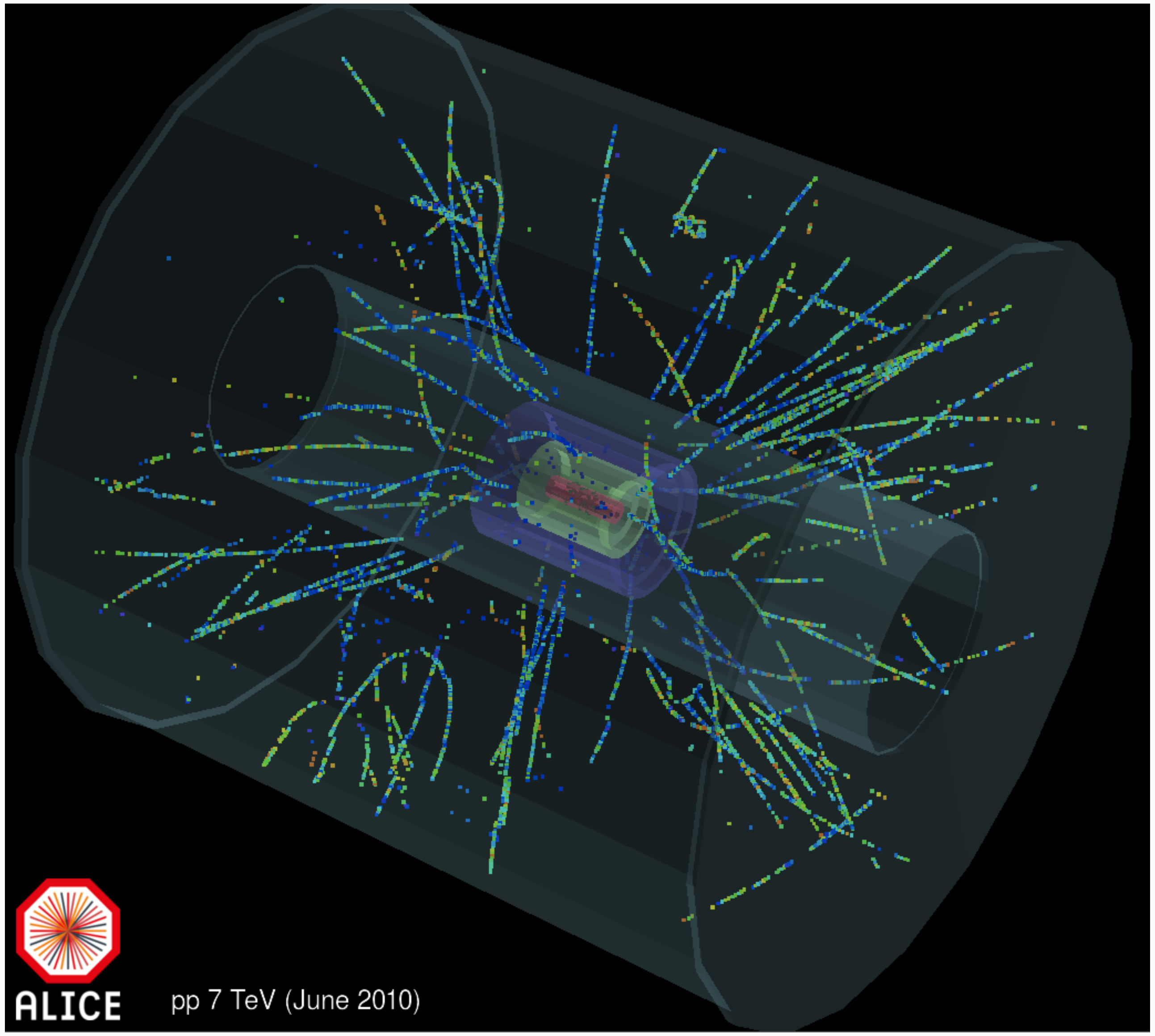

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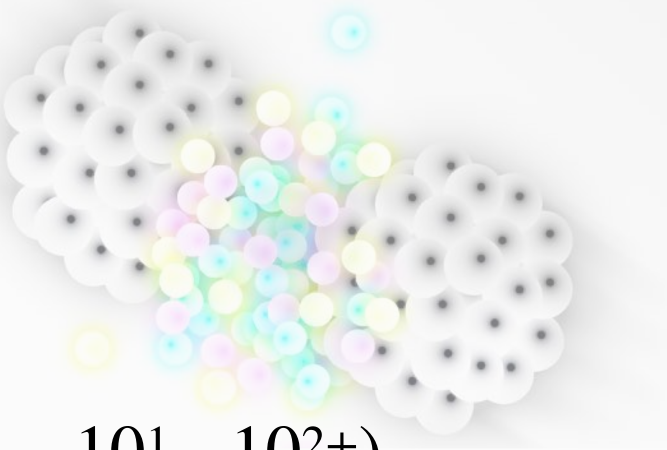

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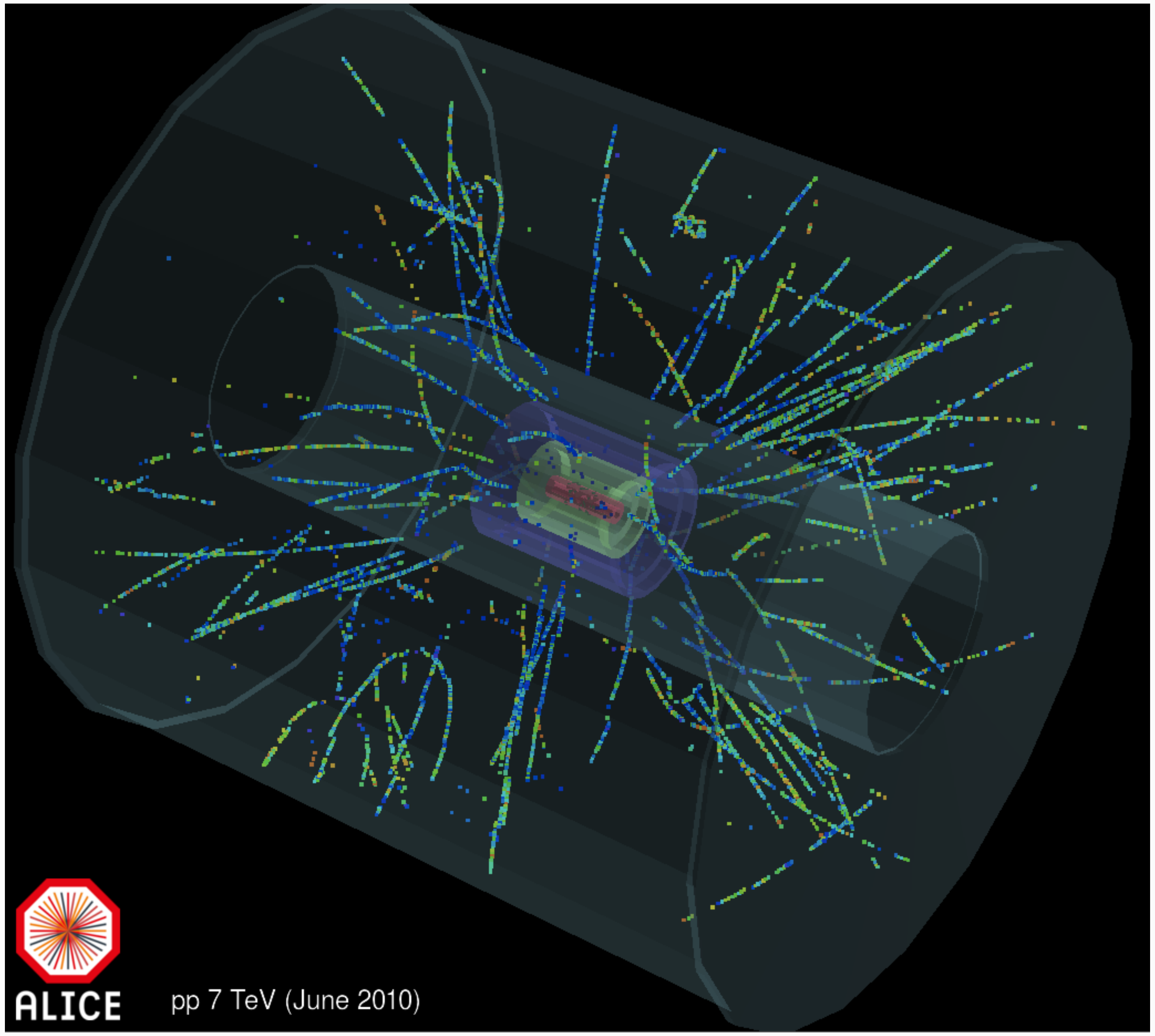
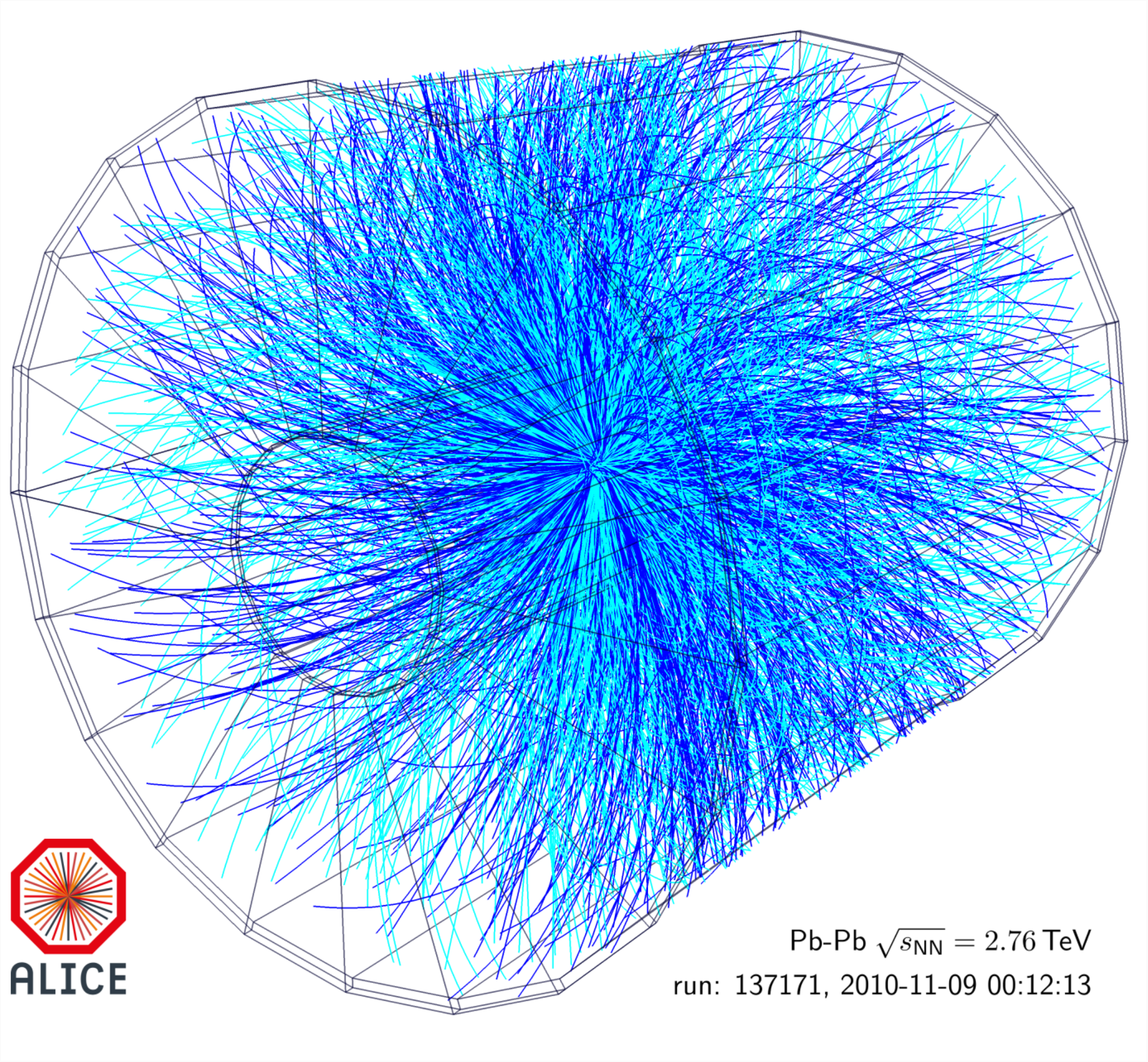
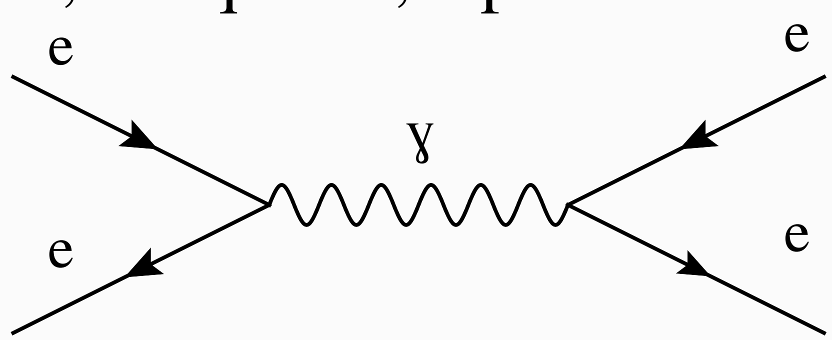


# Introduction I

- High-energy physics ⇒ Multiparticle production (multiplicity ~ $10^1$ - $10^{2+}$)
- To first approximation, all processes have a simple structure at the level of interactions between the fundamental objects of nature, i.e. quarks, leptons and gauge bosons.



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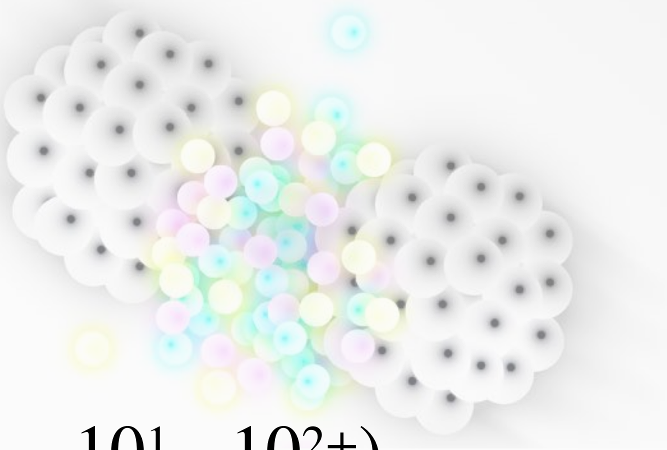

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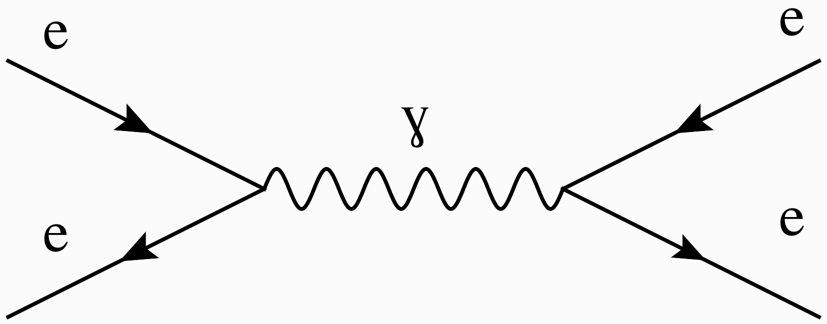


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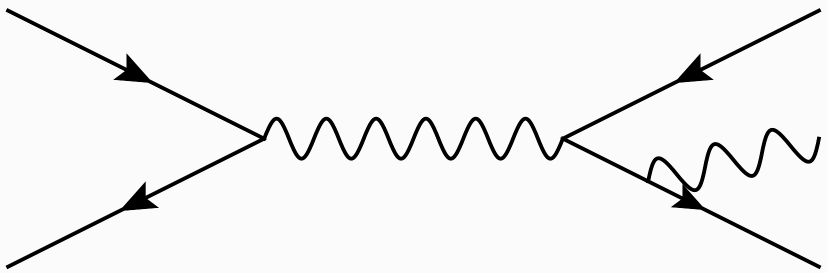

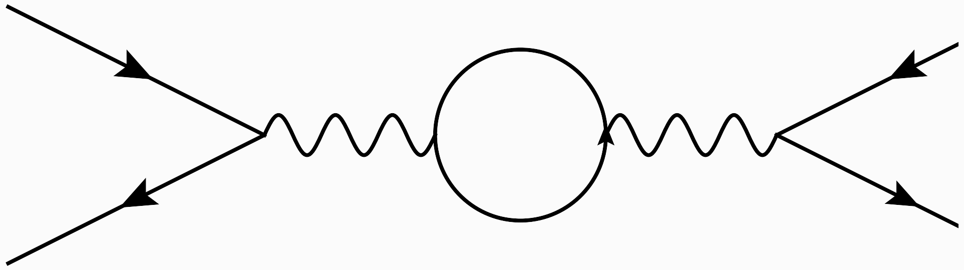

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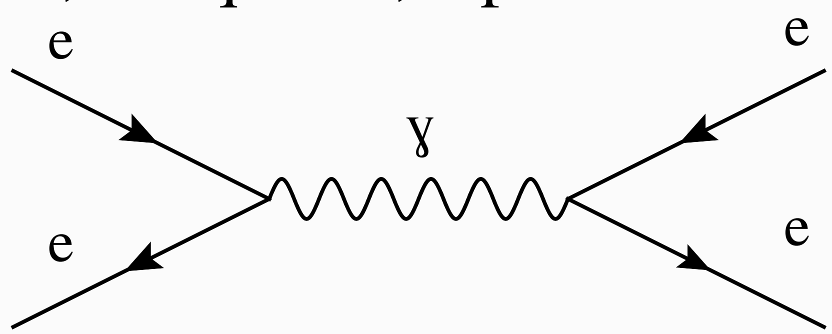


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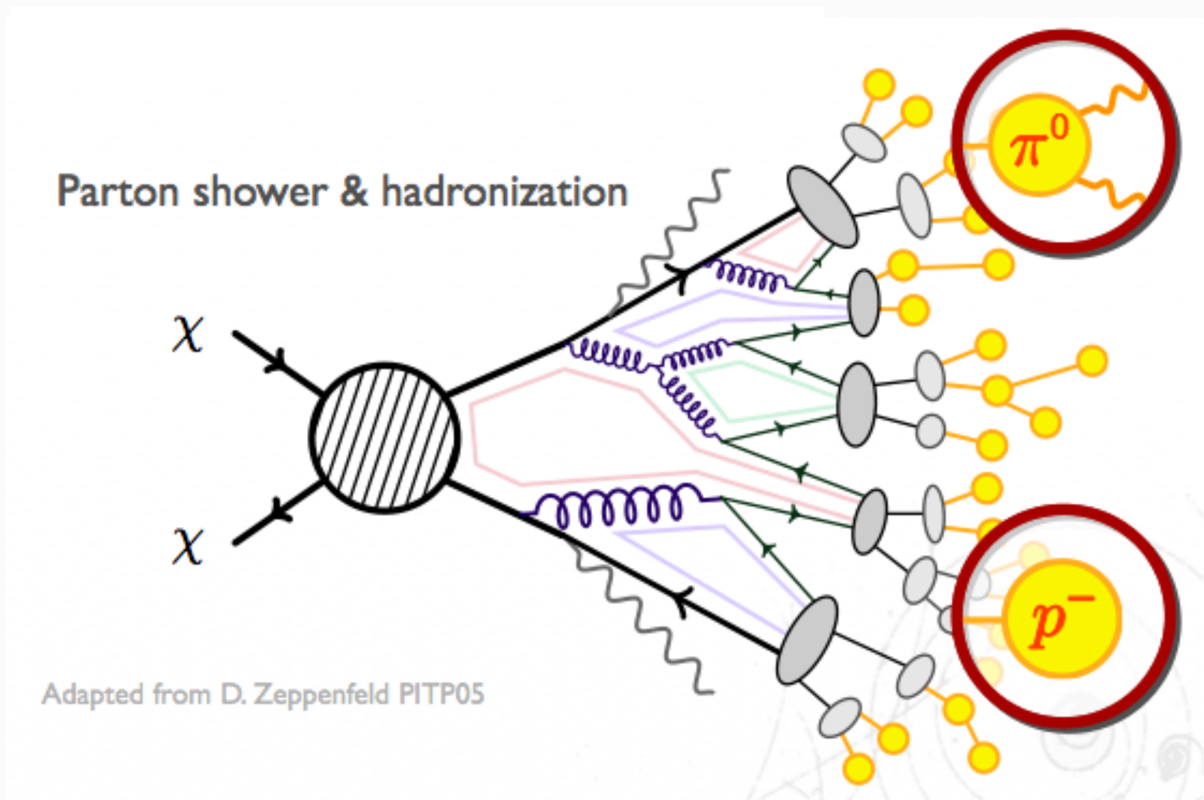

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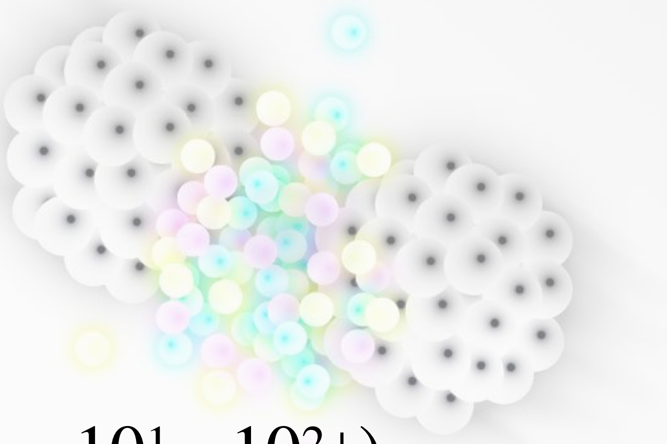

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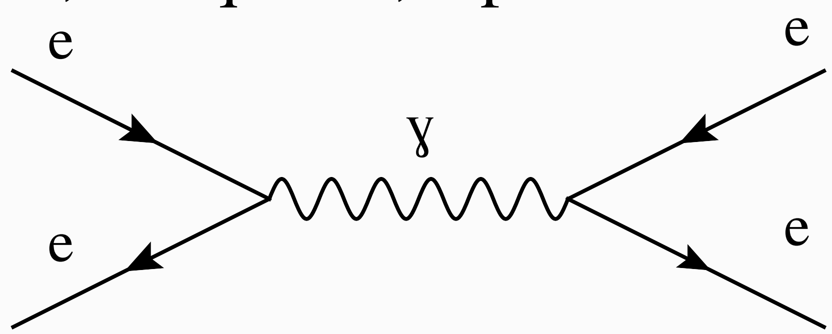


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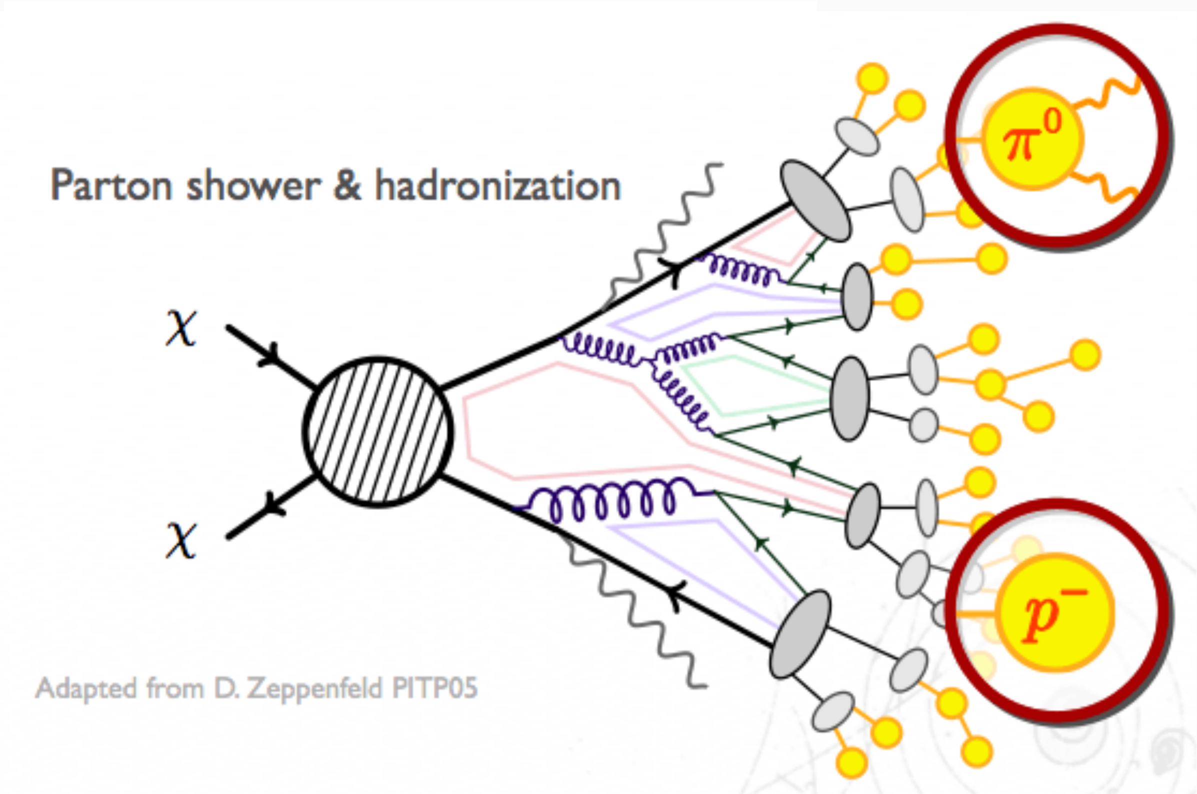
    Not easy to evaluate through analytical calculations…



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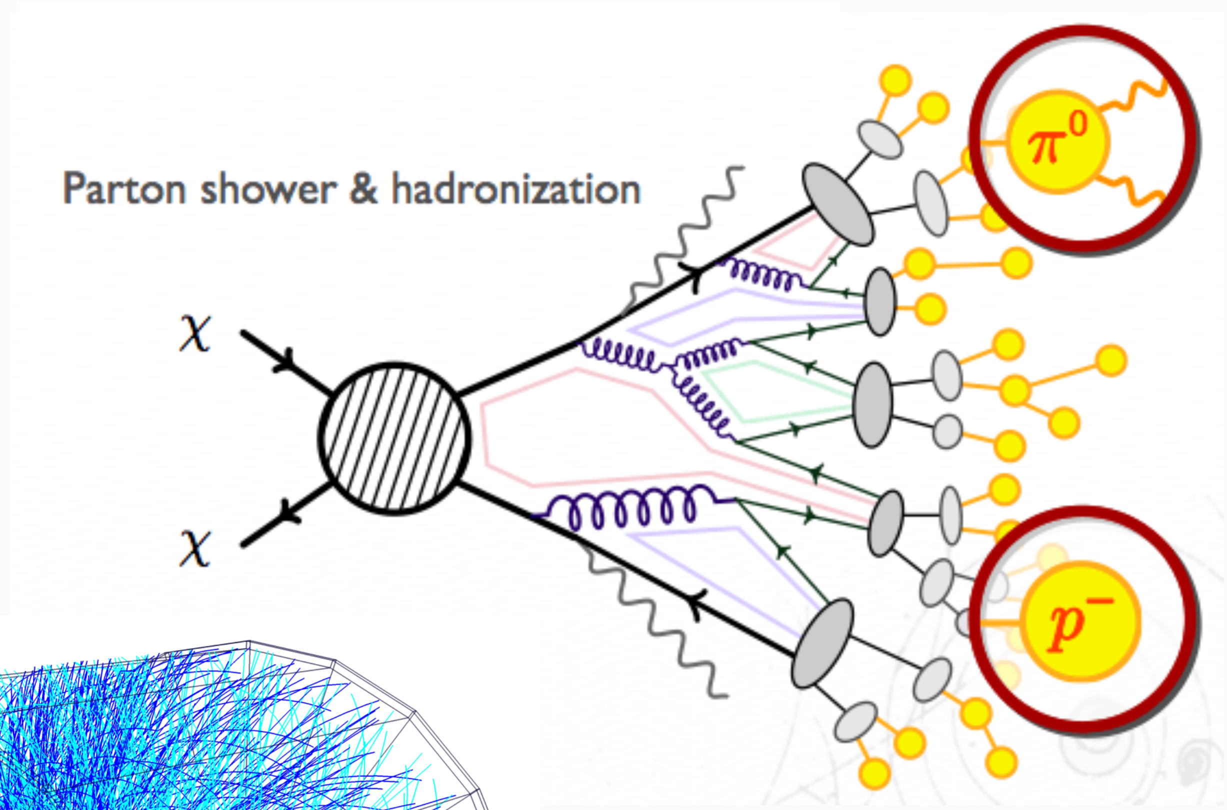


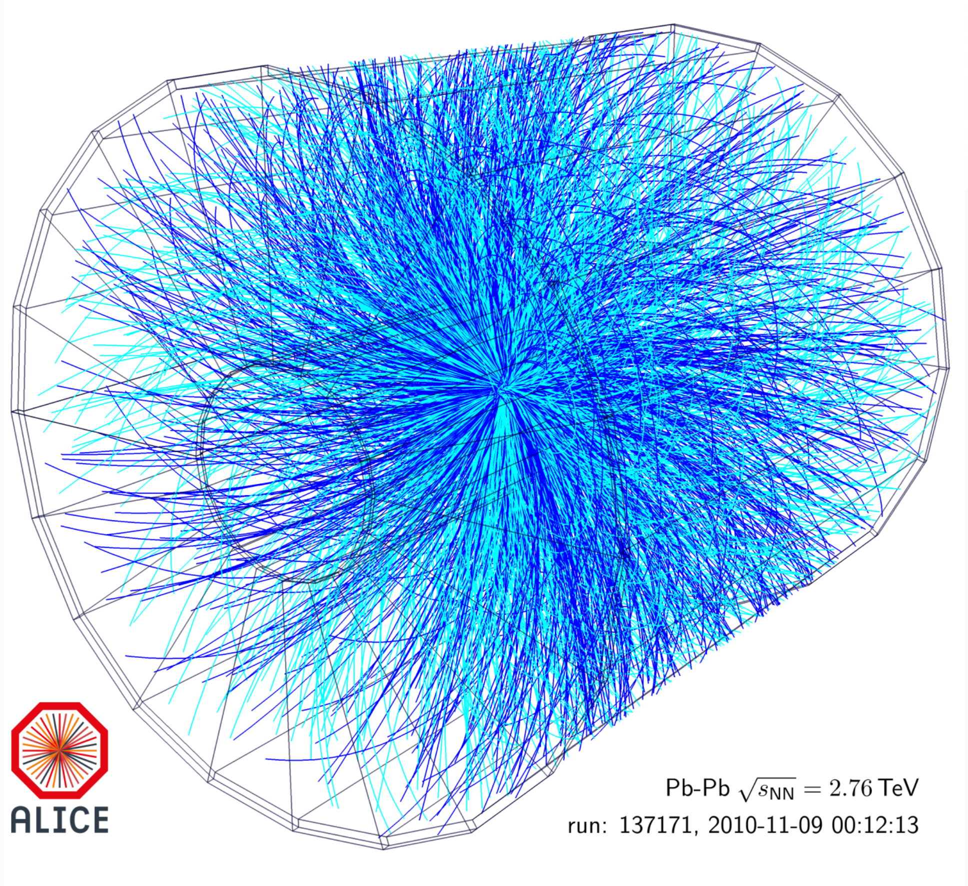


Picture becomes more complex, but original physics remains

(skeleton process has been dressed up and is no longer directly visible)

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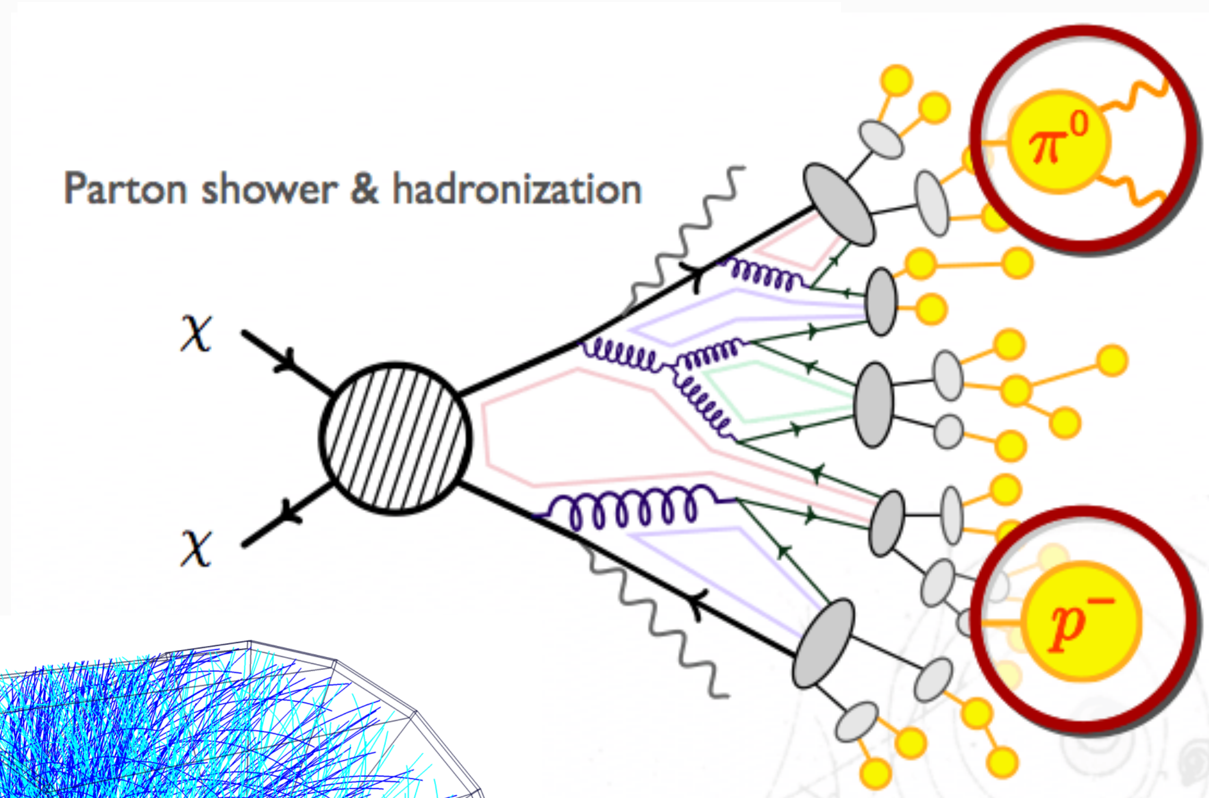


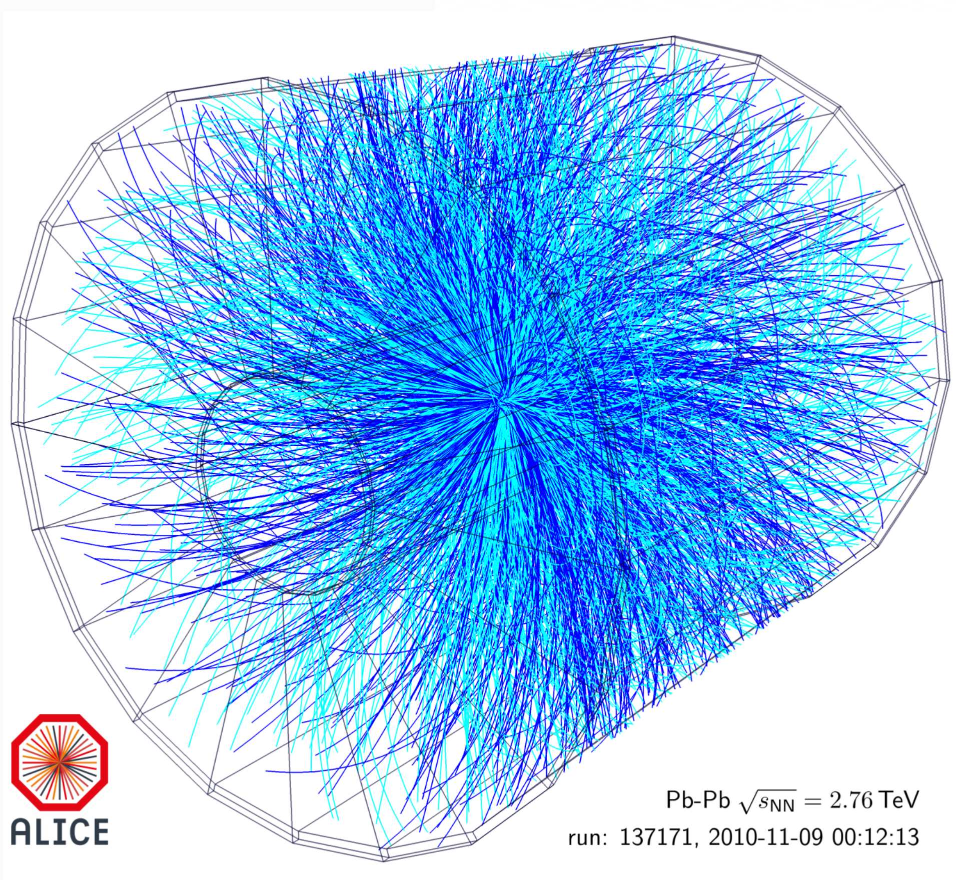


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Event Generators to the rescue!

# Introduction II

MC Event Generator

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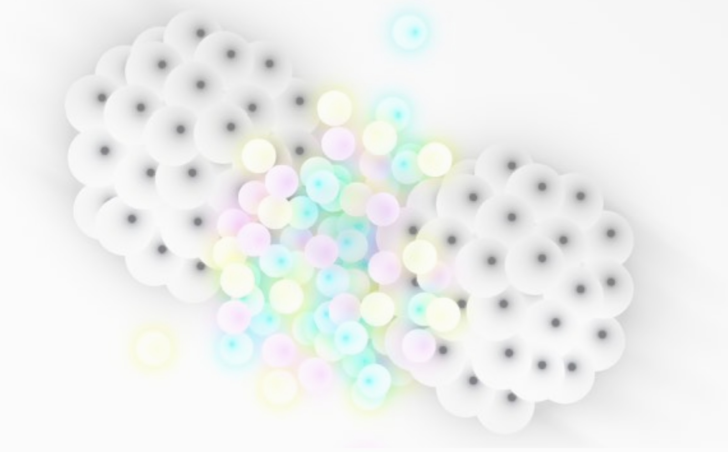
Problem 1

# Introduction II



MC Event Generator

| | |
|---|---|
| Problem 1 | |
| Problem 2 | |

# Introduction II

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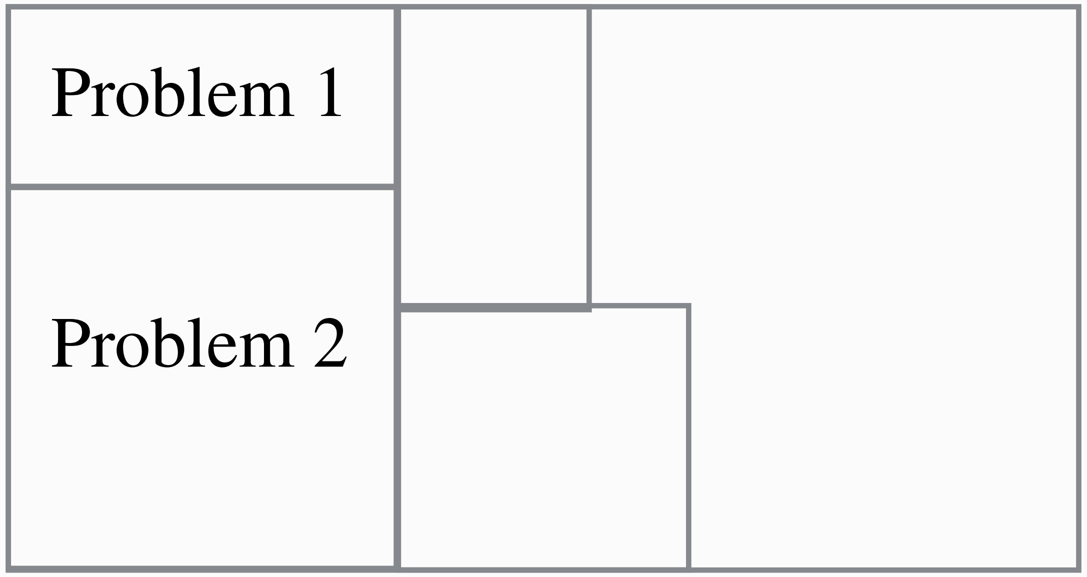

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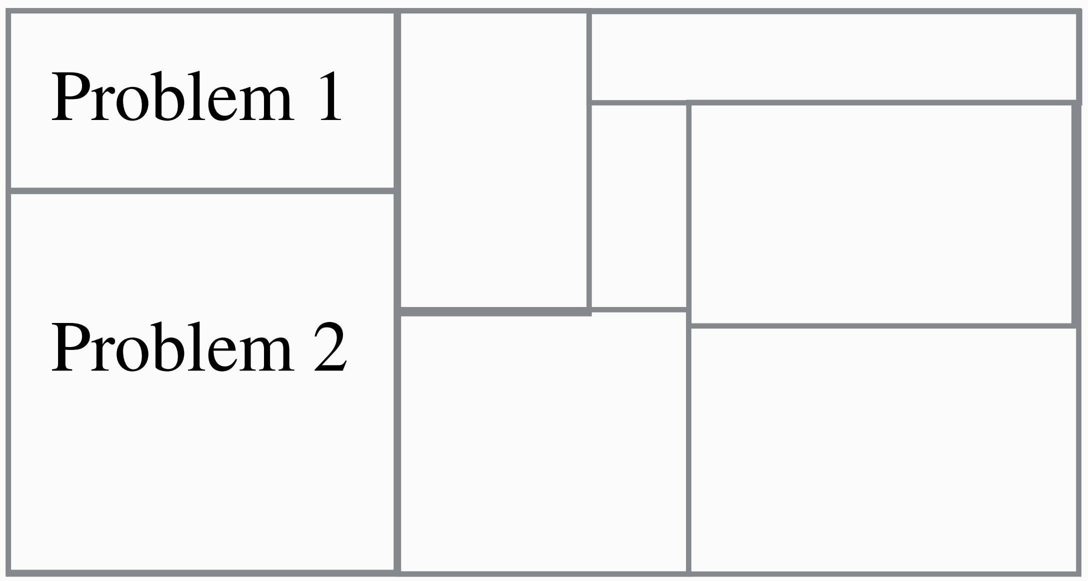

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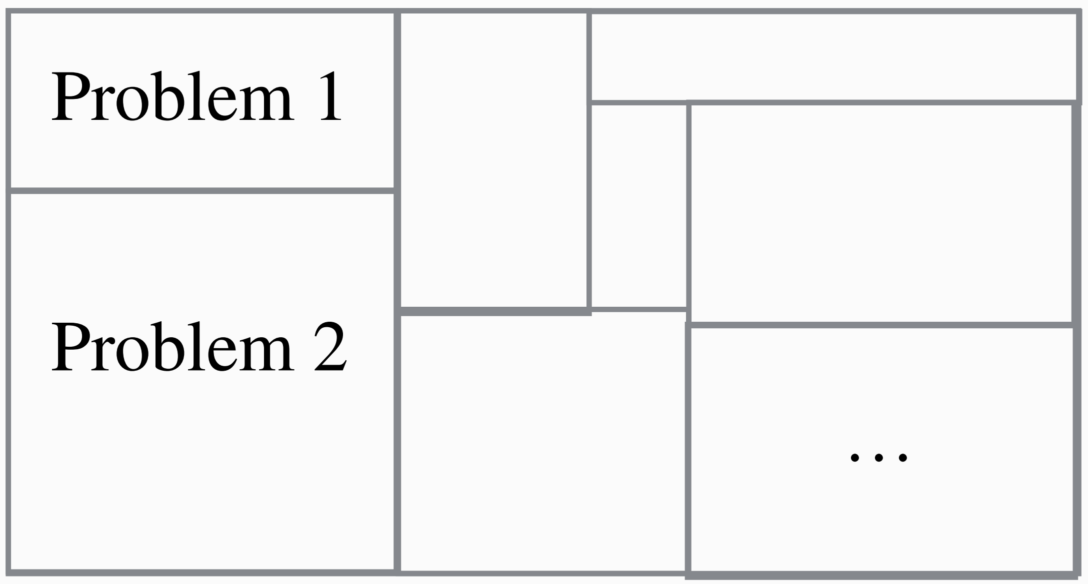


Factorization into simpler (and reasonably accurate) components

# Introduction II

MC Event Generator

Problem 1

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Factorization into simpler (and reasonably accurate) components

Output

Same average behaviour and fluctuations as real data

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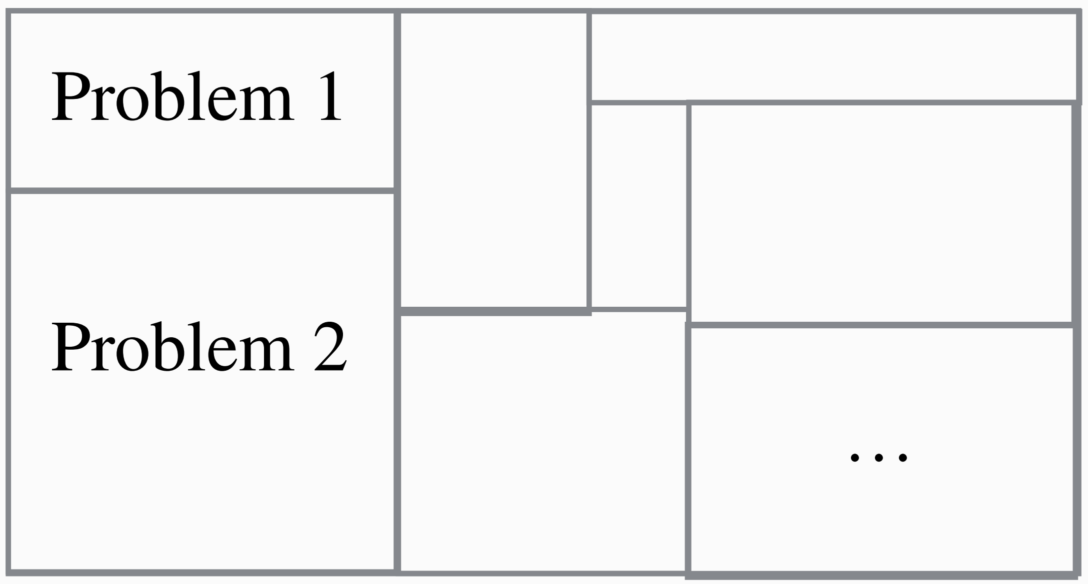


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Detector performance (propagation, magnetic field, shower calorimeter, ….)

Detector Simulation GEANT

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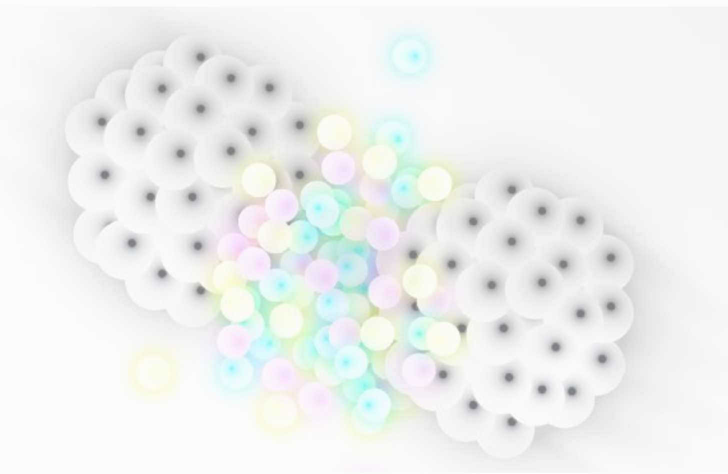
Detector Simulation GEANT

Final Output

Same format as the real data recorded by the detector

# High Energy Collision



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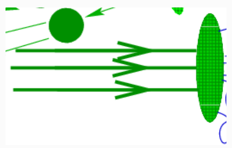

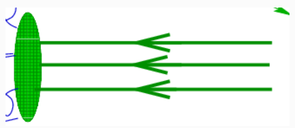

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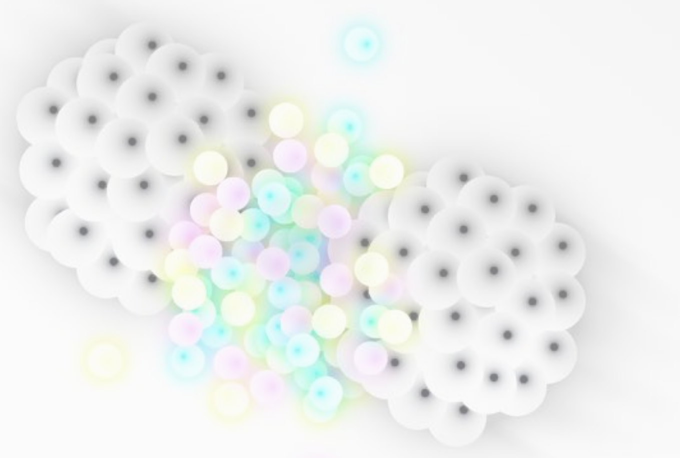

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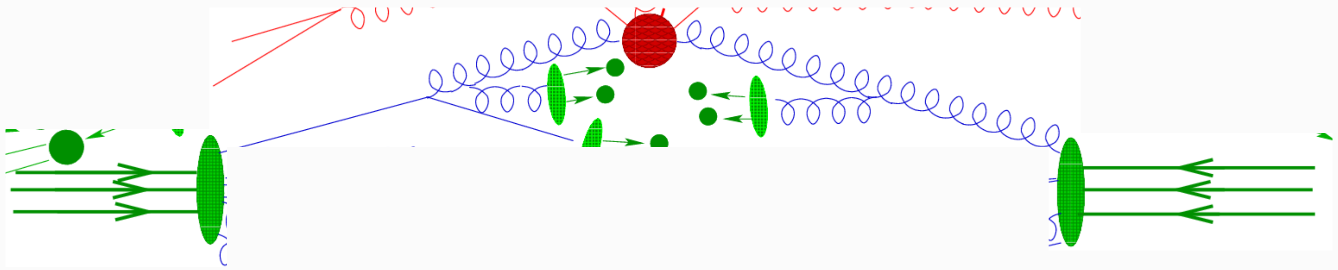

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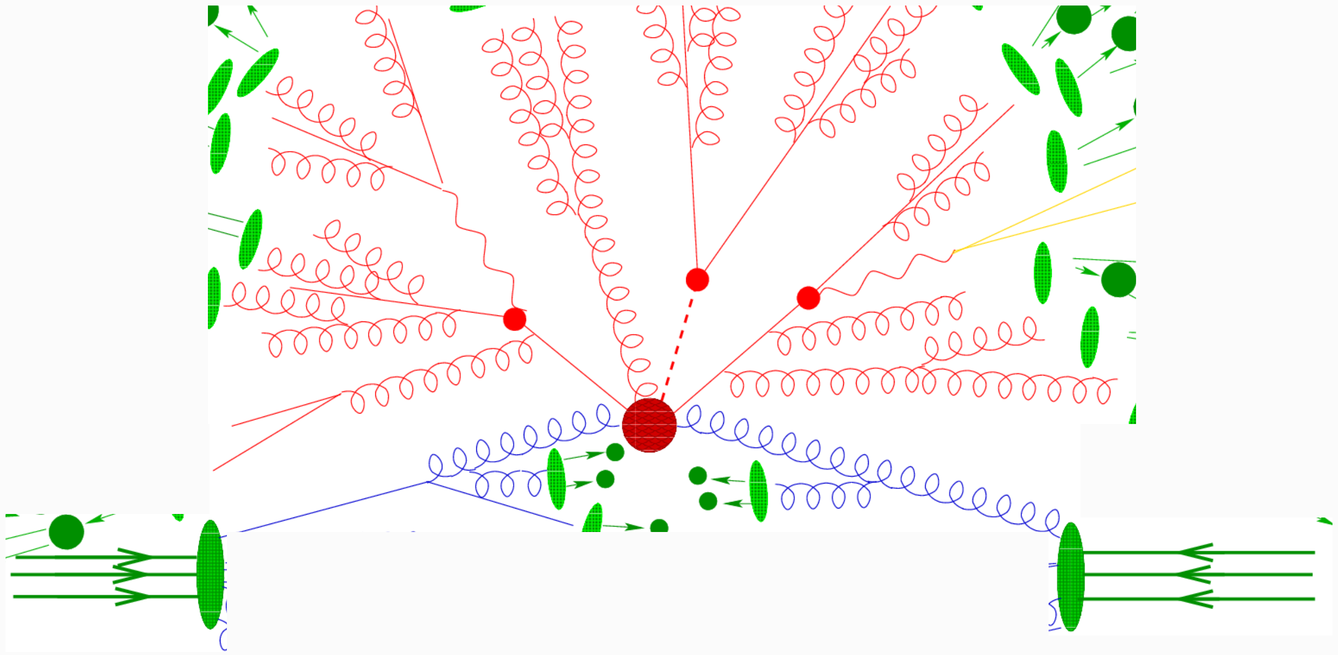

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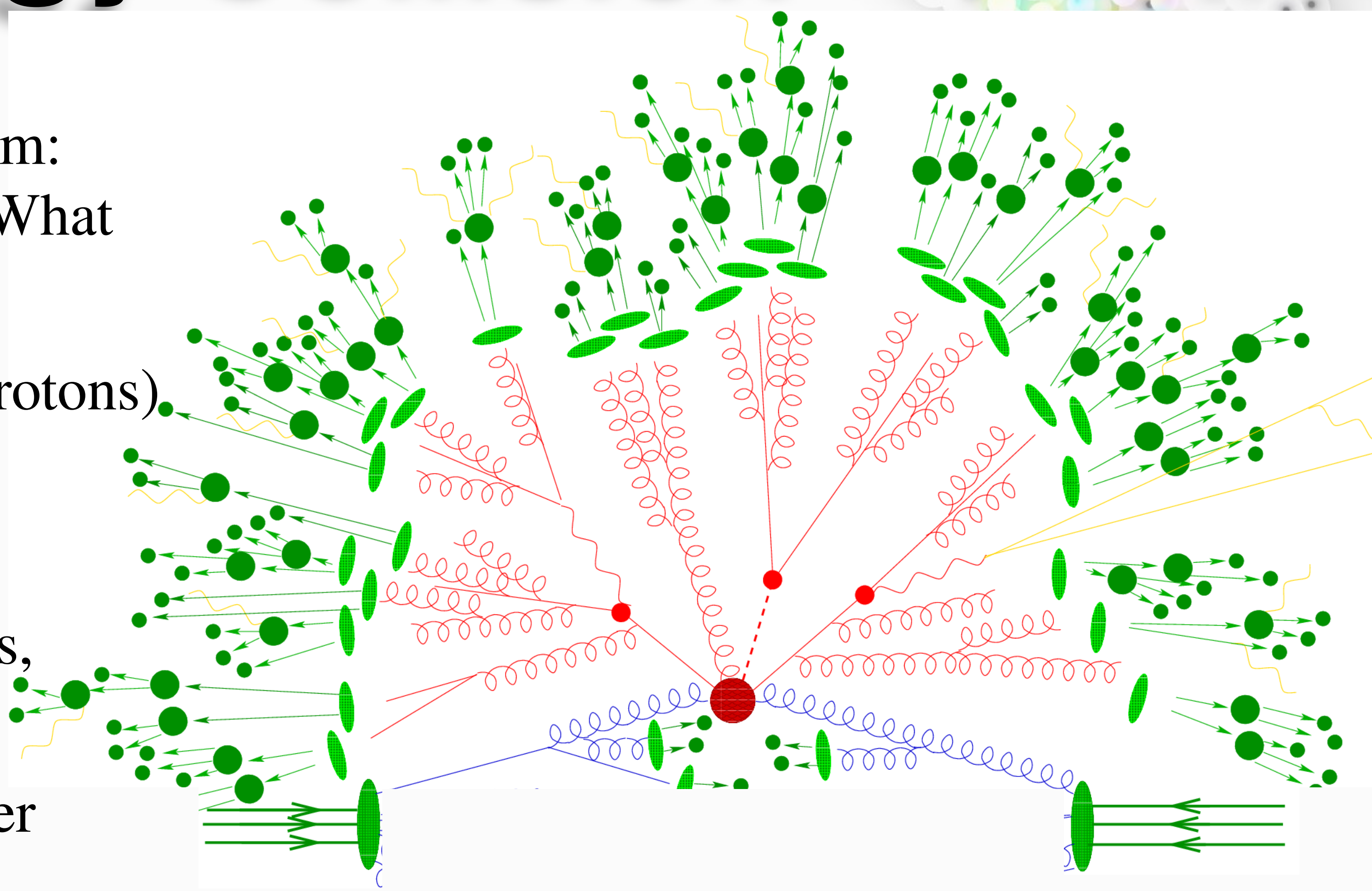

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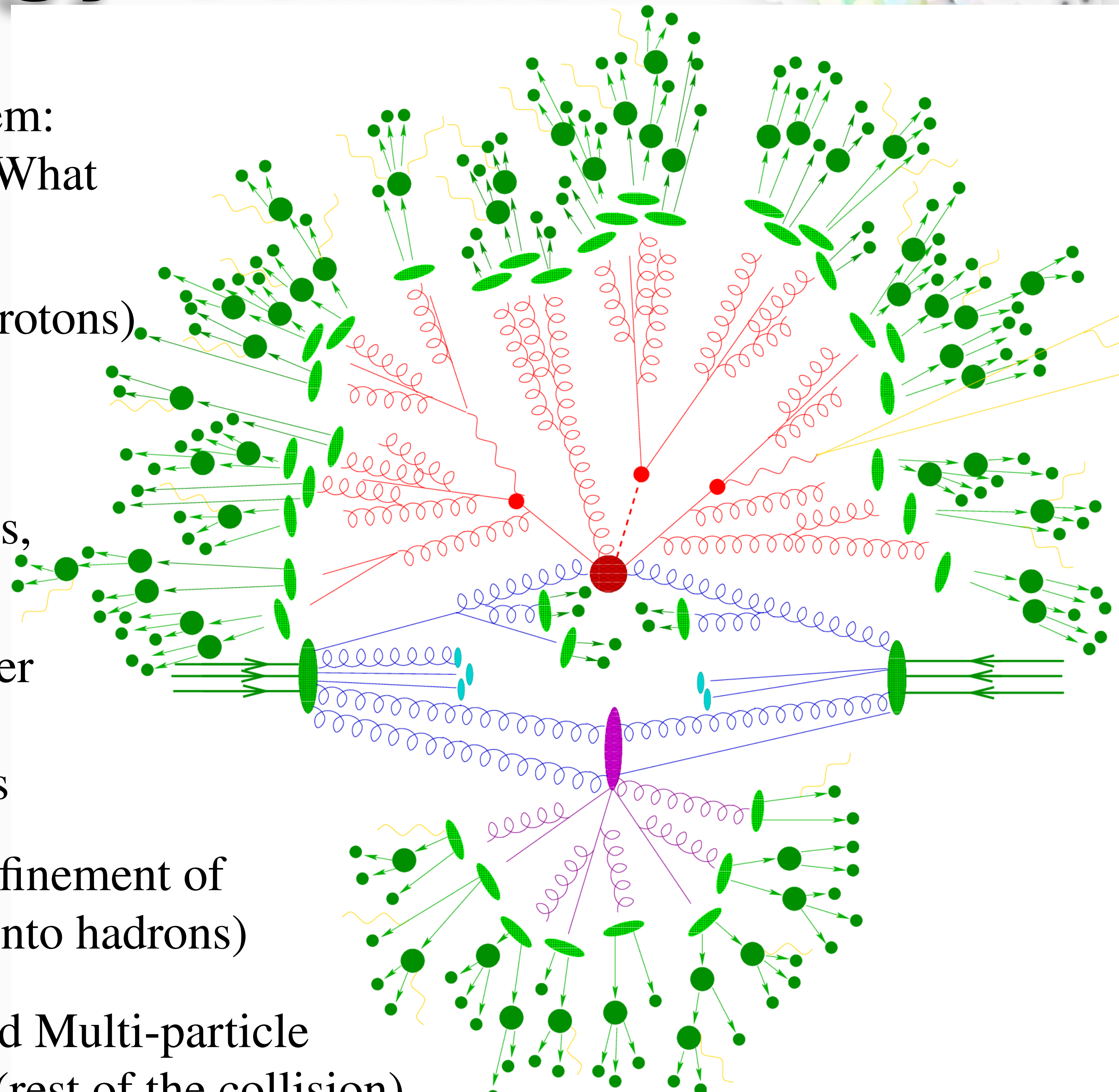
    - Beam Remnants and Multi-particle Interactions (MPI) (rest of the collision)



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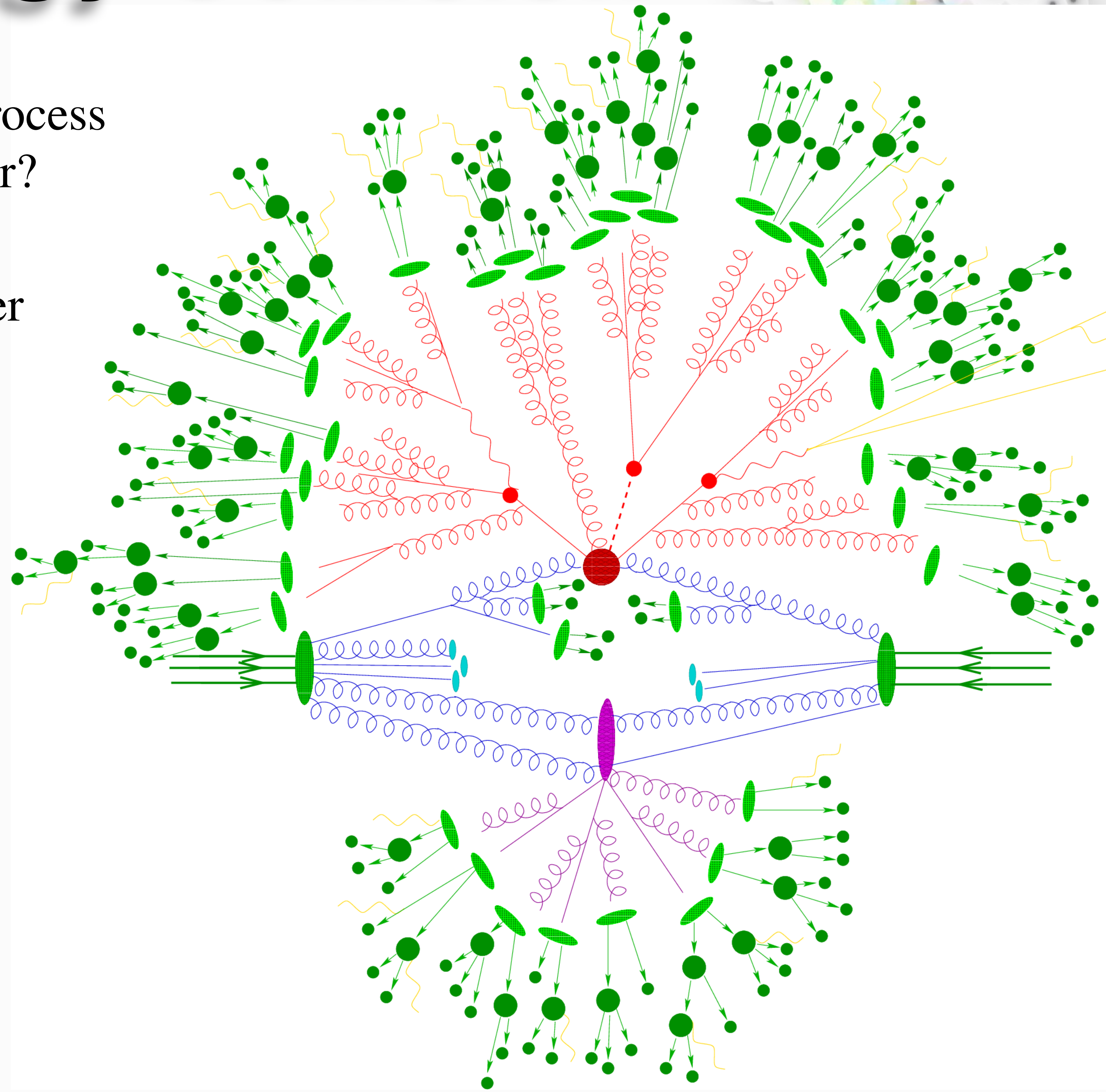
- How to describe such a process through an event generator?
  - Factorising into simpler problems:



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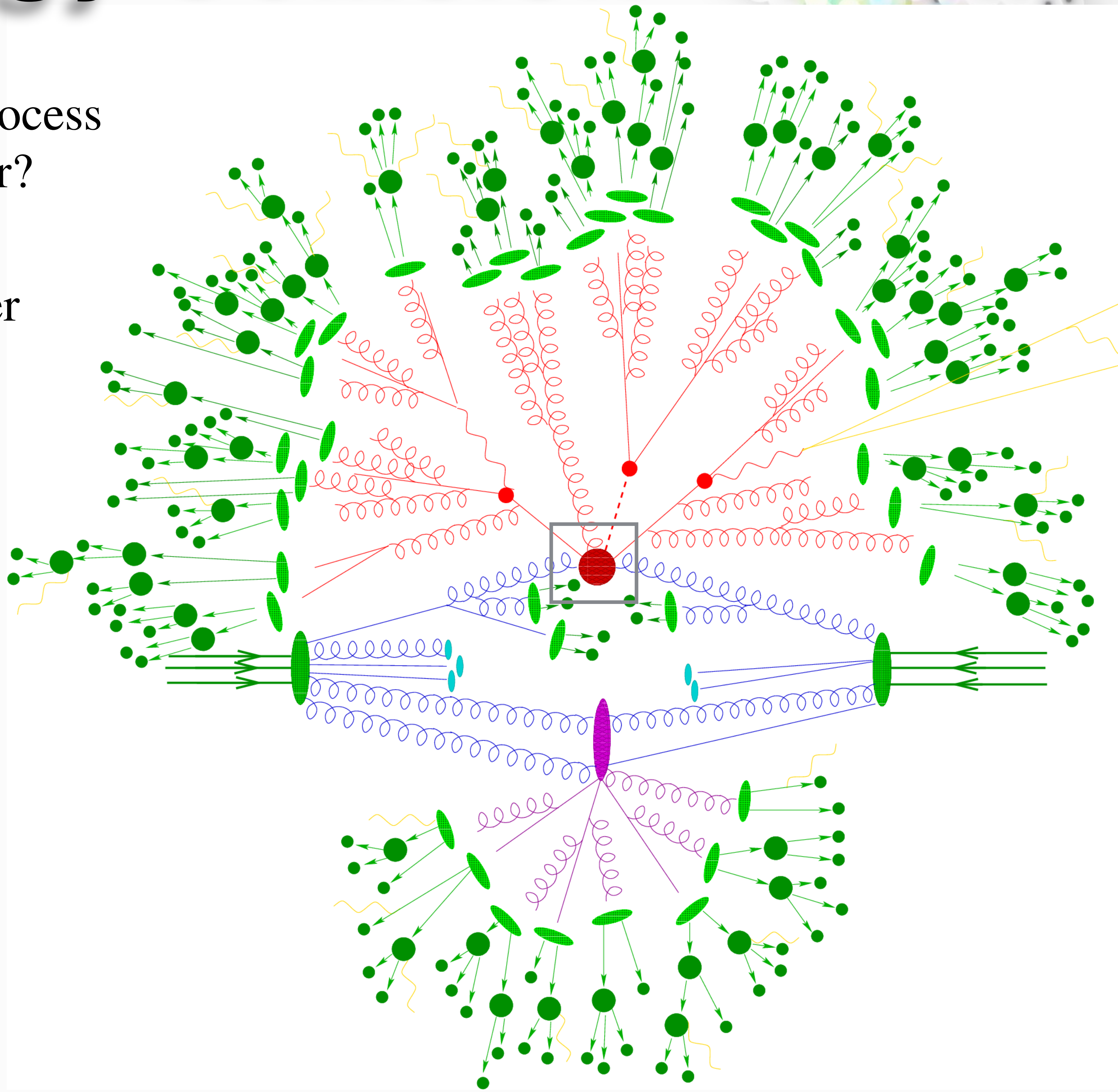

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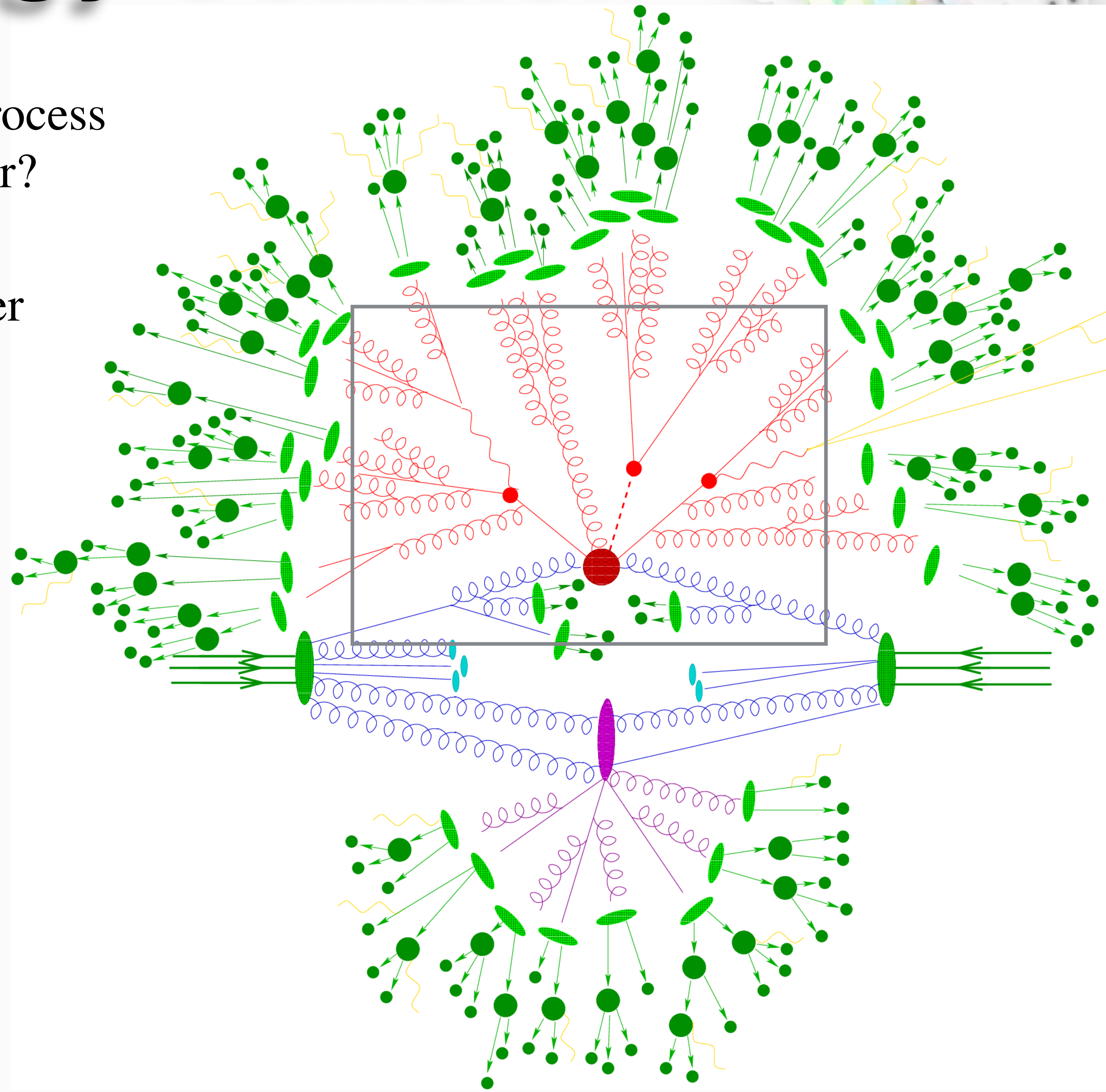

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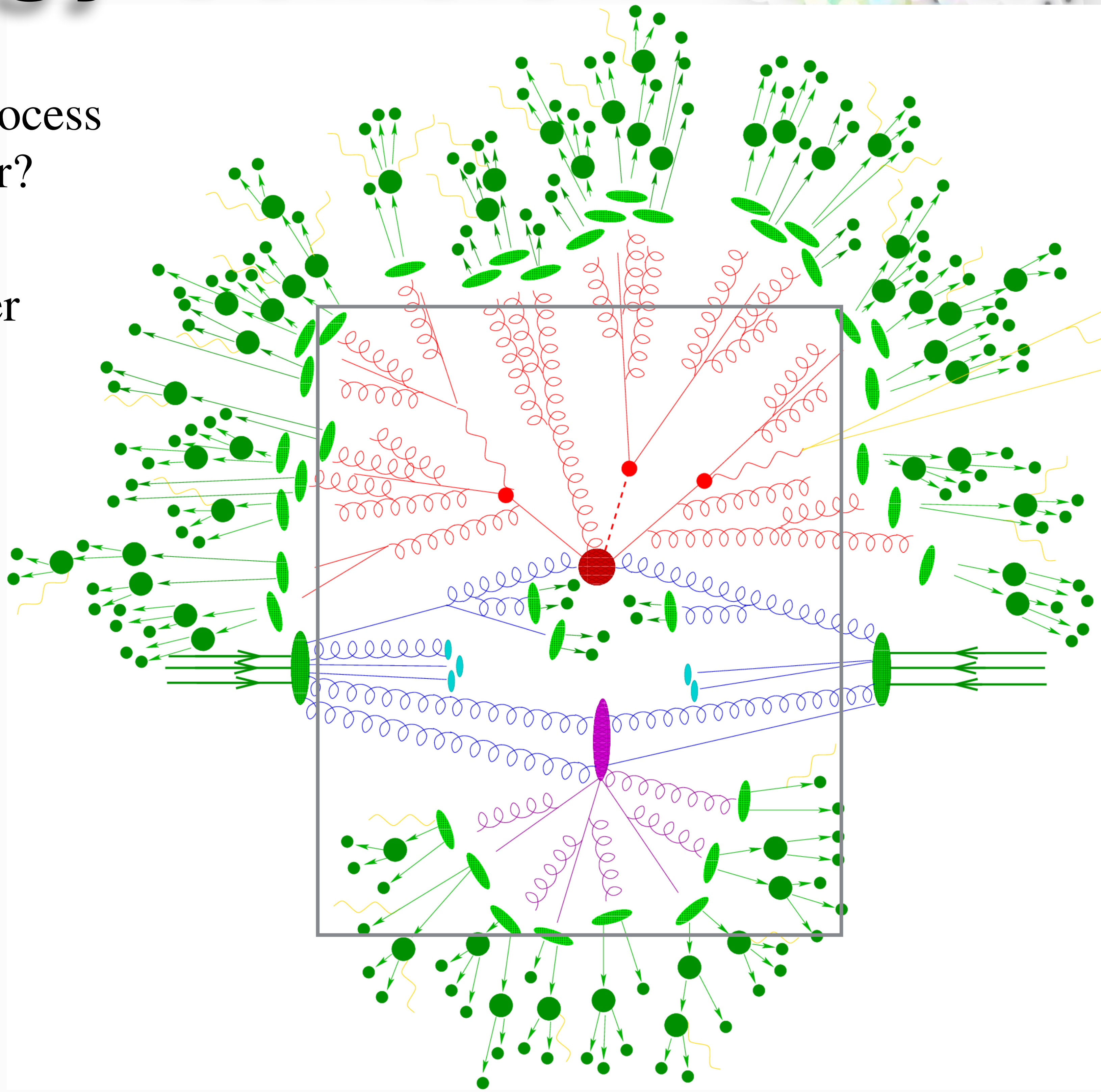

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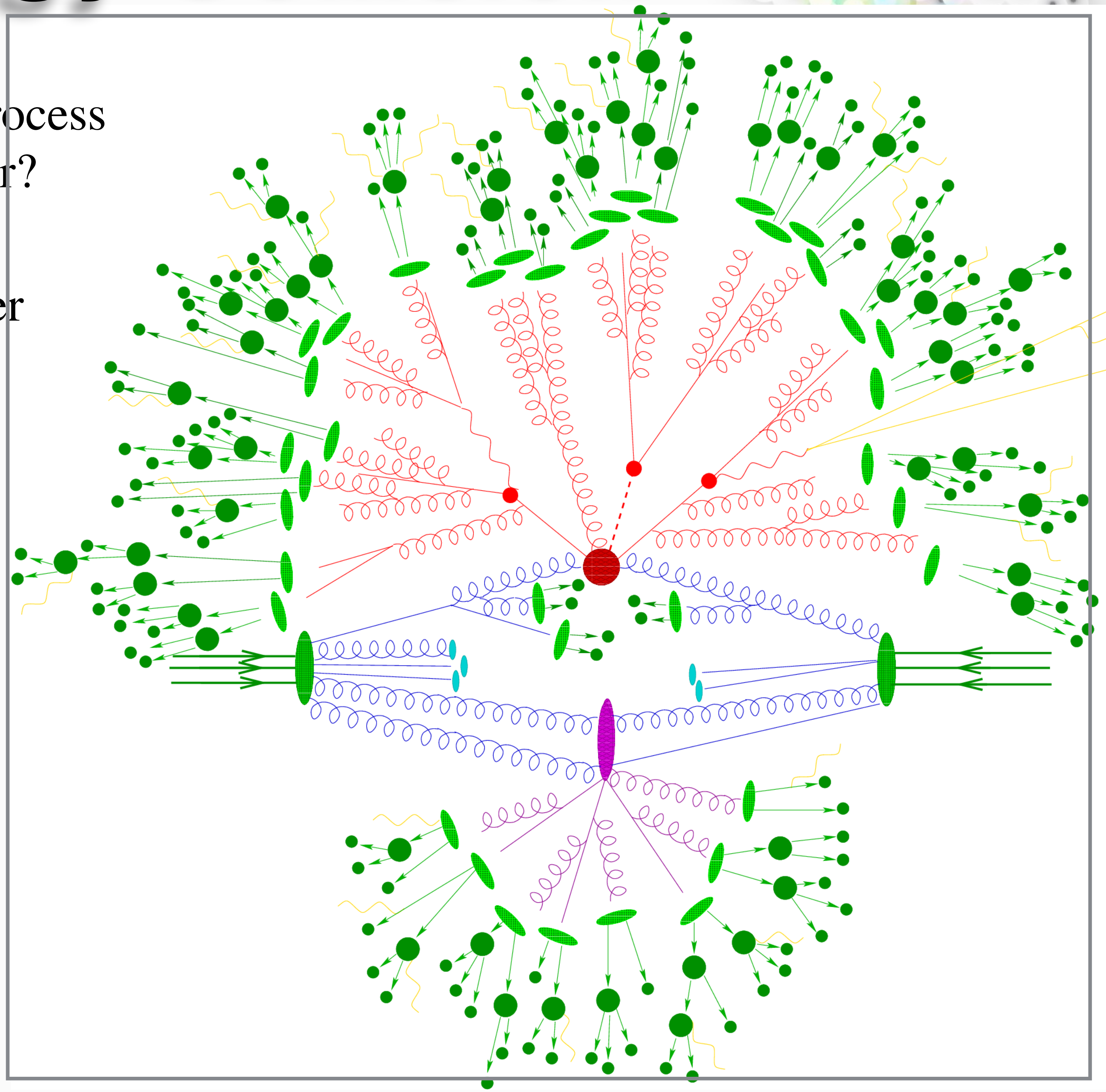

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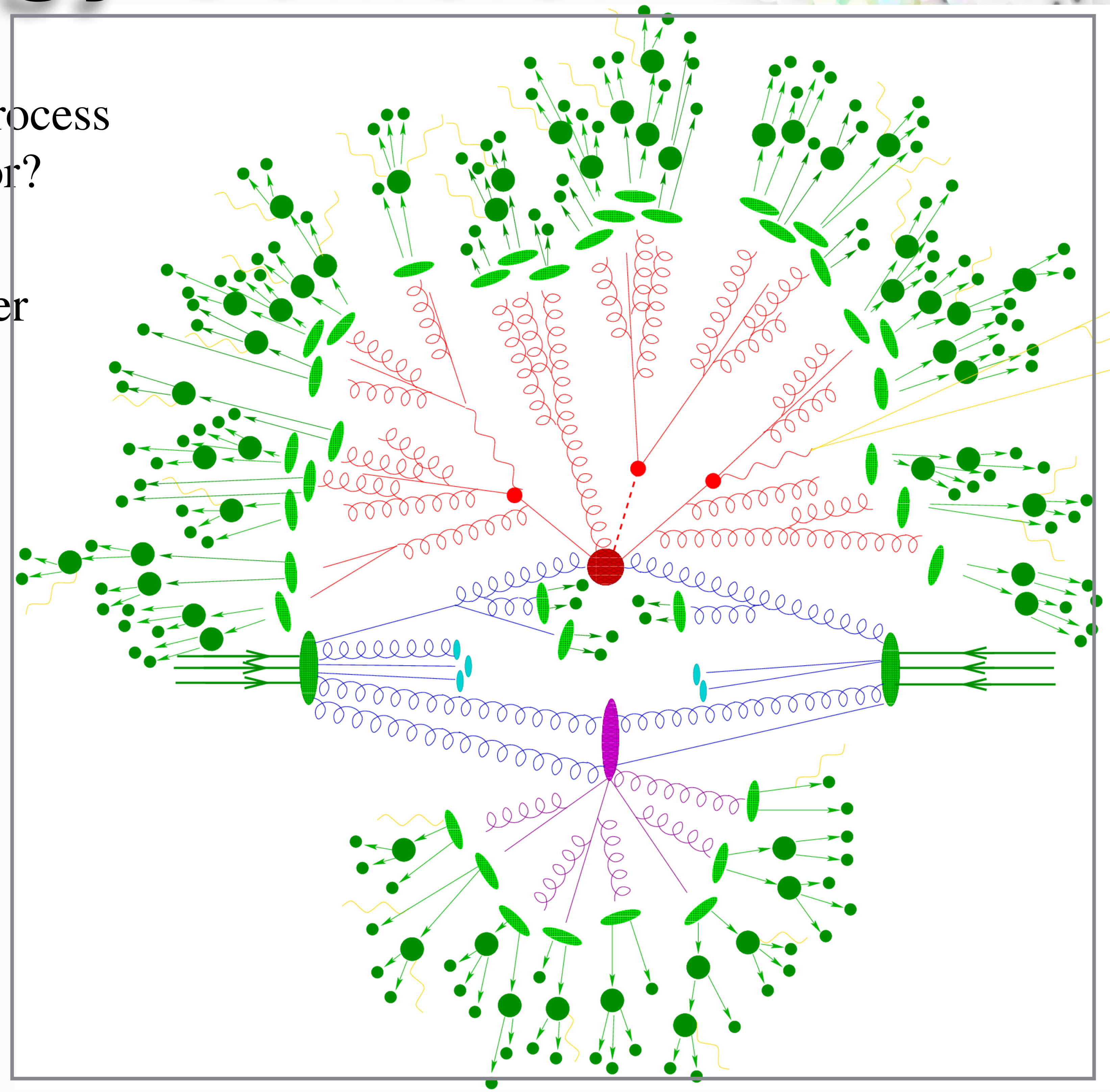
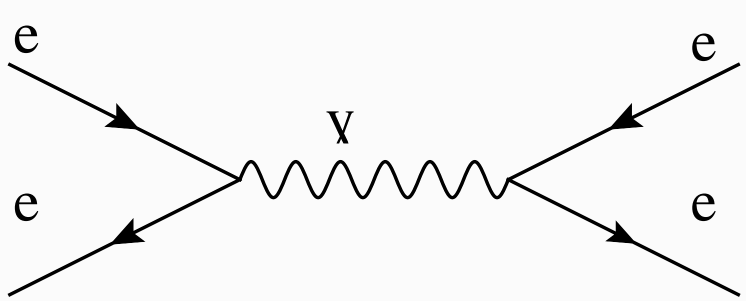


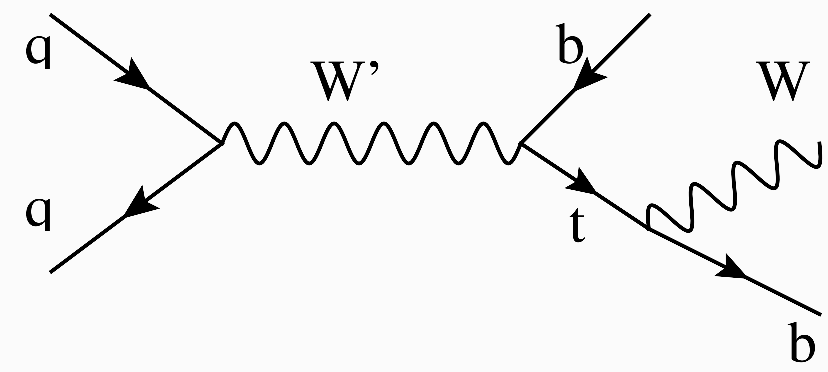
Separation in energy scale

- Factorising into simpler problems:
- Hard scattering
- Initial-state shower and final-state shower
- MPI and Beam Remnants
- Hadronization

# Hard Process

- Simple high energy process, like 2→1, 2→2, 2→3, … that can be calculated analytically from first principles:



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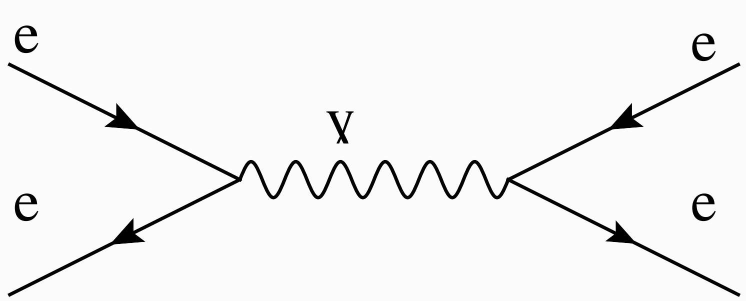


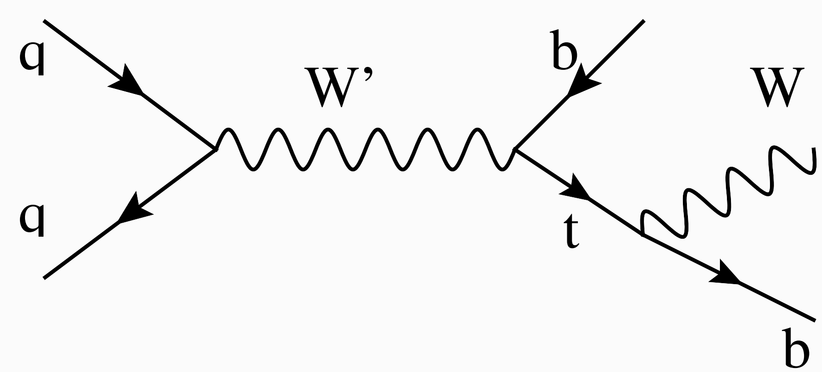


- What gives the main characteristics of the event
  - SM: Hard QCD, Soft QCD, Heavy-Flavour, DIS, W/Z, Higgs Production…
  - BSM: Technicolor, Compositeness, SUSY, …

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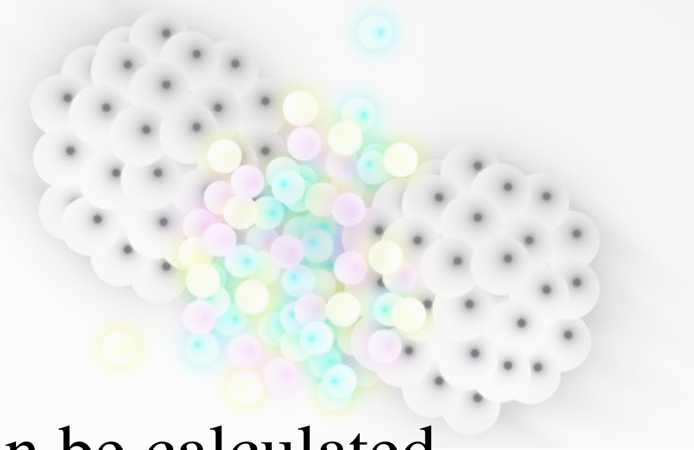

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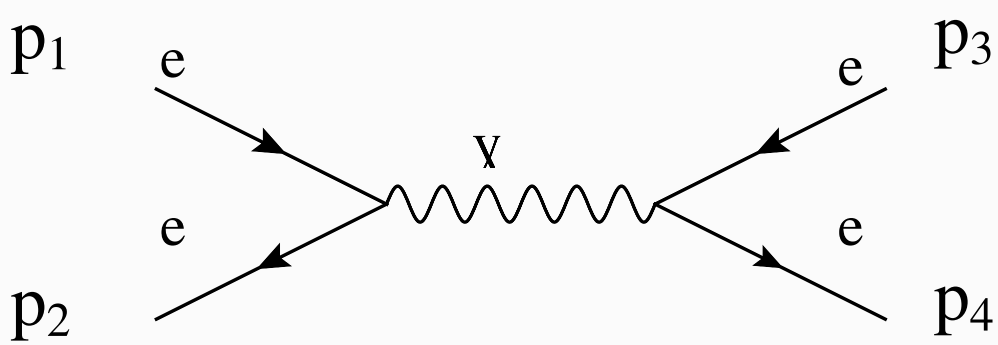
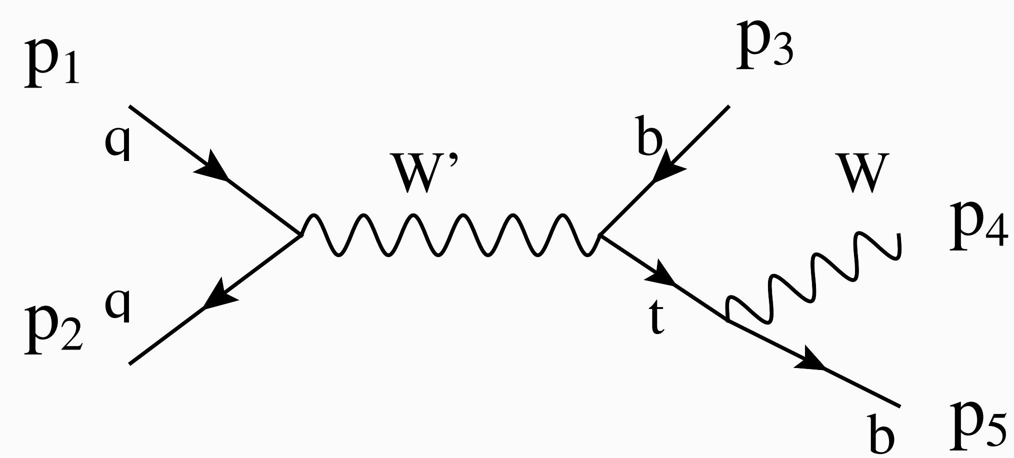


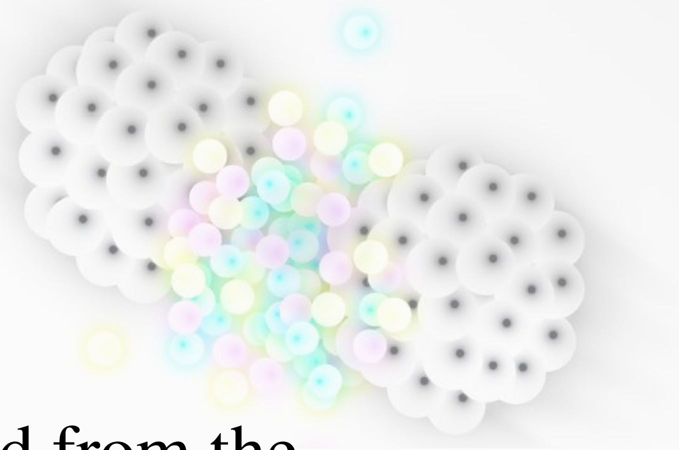




- What gives the main characteristics of the event
  - SM: Hard QCD, Soft QCD, Heavy-Flavour, DIS, W/Z, Higgs Production…
  - BSM: Technicolor, Compositeness, SUSY, …
- Given the topology and kinematics, one can evaluate the cross-section, σ.

# Parton Distributions

- Initial topology and kinematics is not fixed, but rather sampled from the parton distribution of the two incoming protons…

# Parton Distributions



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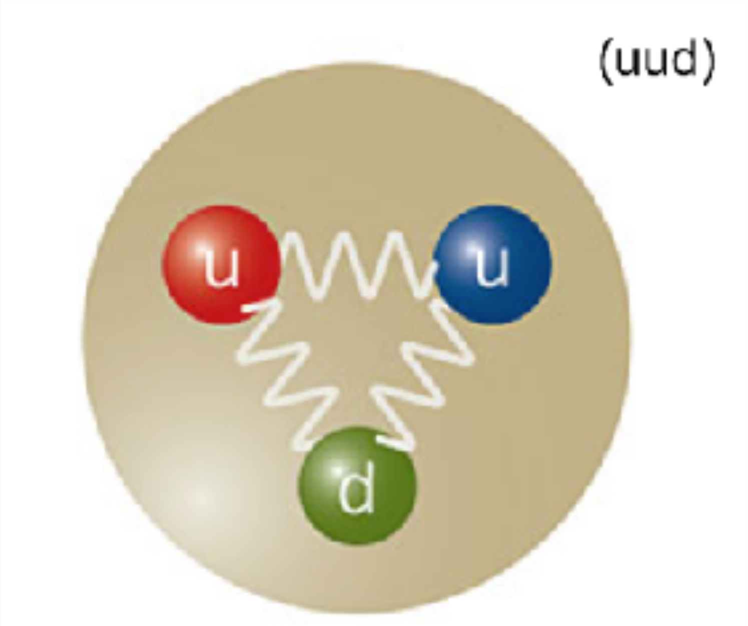
proton "i"

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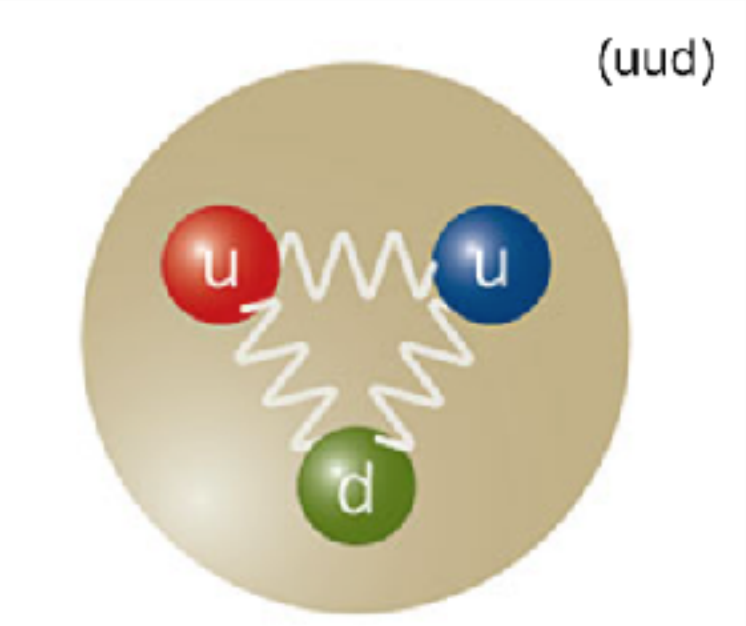

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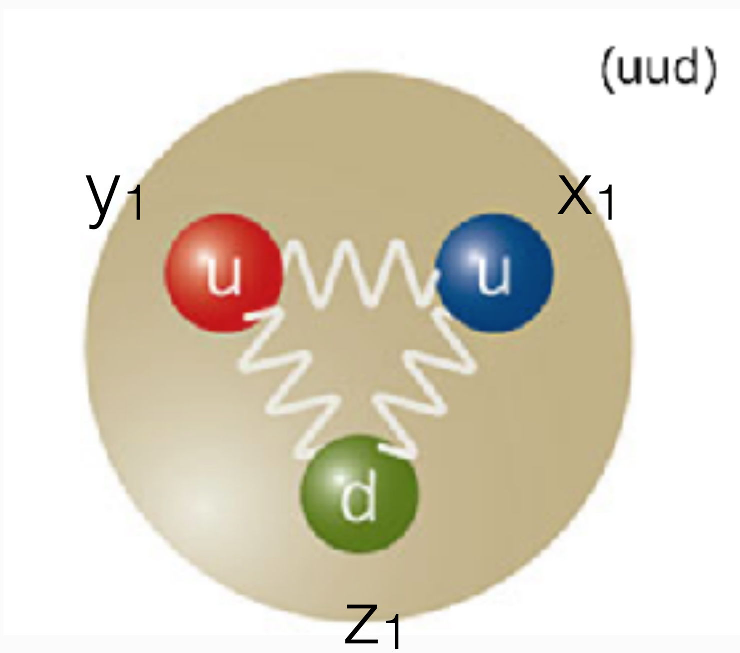
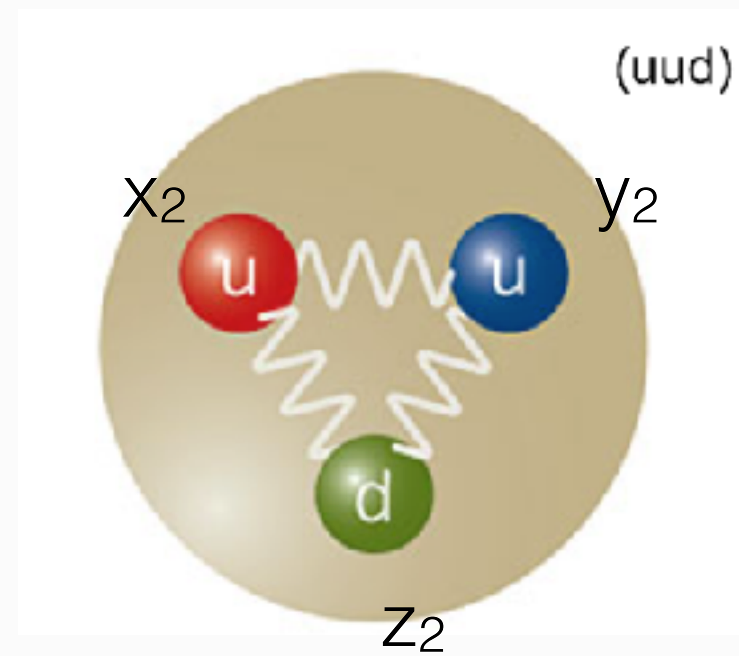



$x_1+y_1+z_1 = 1$

proton "j"




$x_2+y_2+z_2 = 1$

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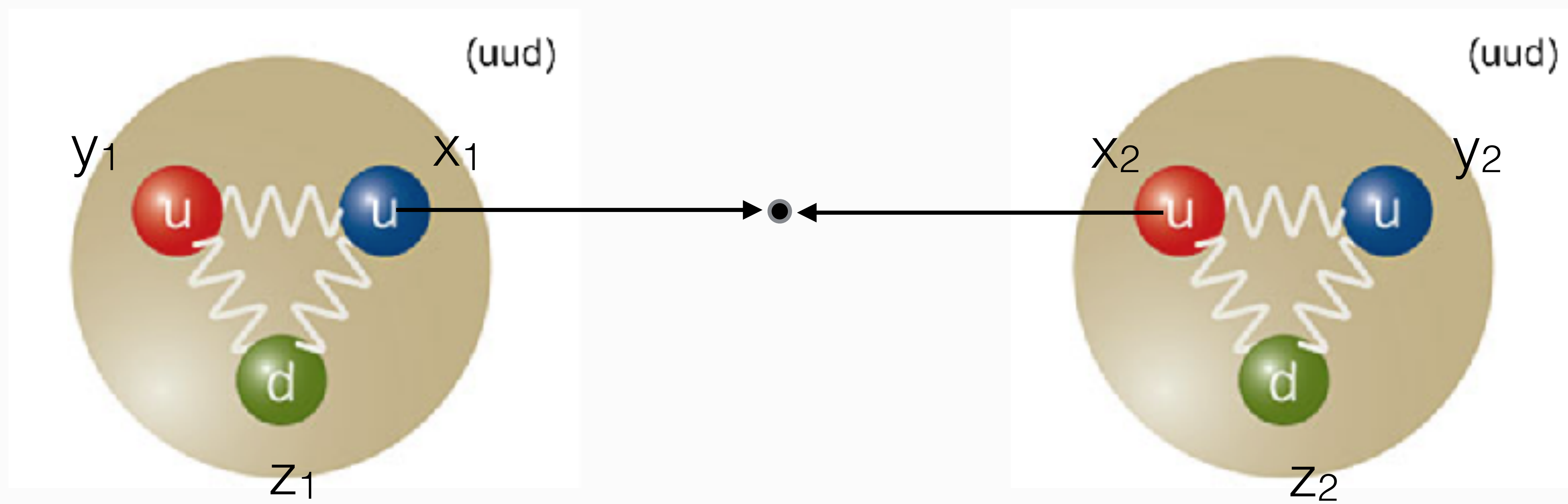
proton "i" proton "j"

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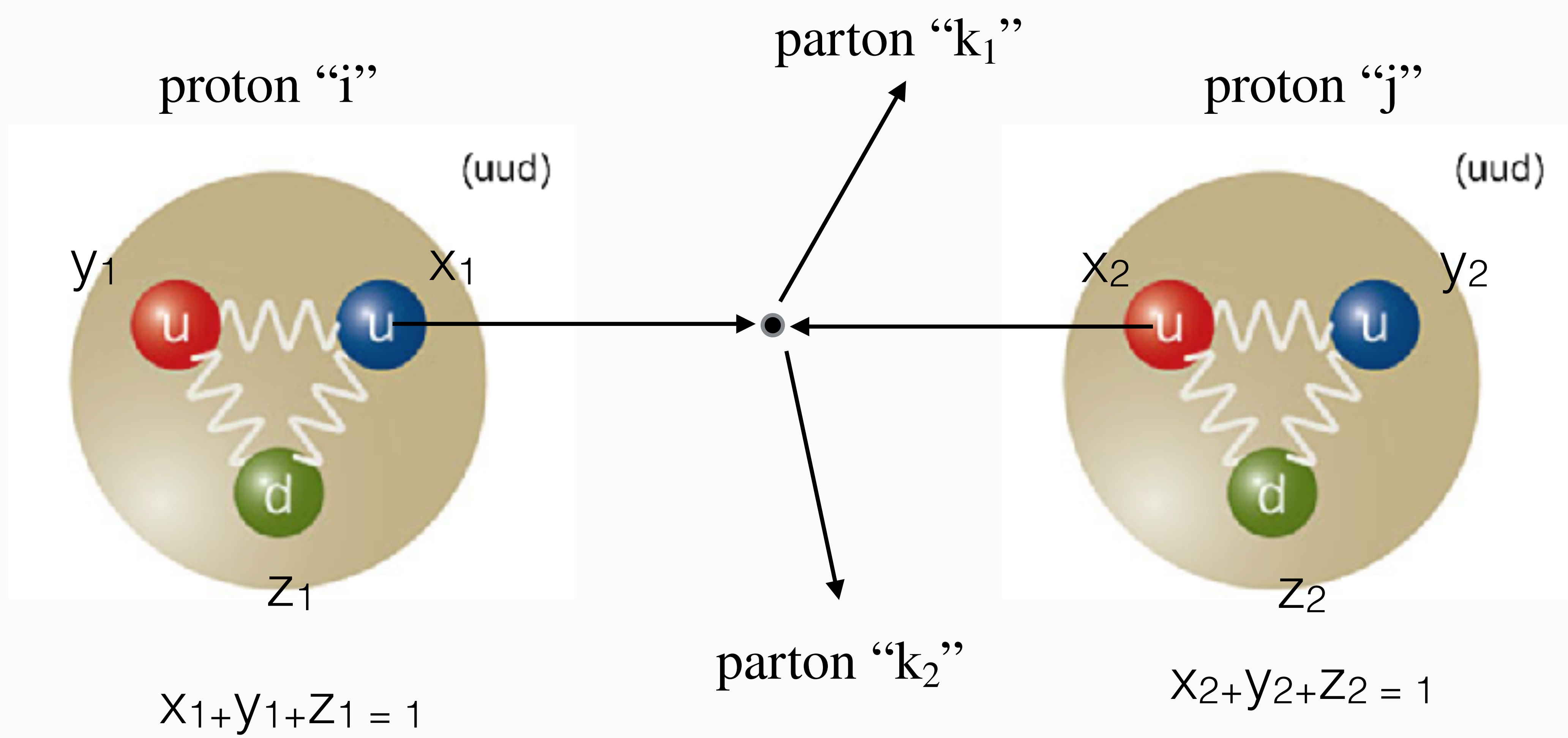


Elementary cross-section: $\sigma_{ij \to k_1 k_2}(x_1, x_2)$

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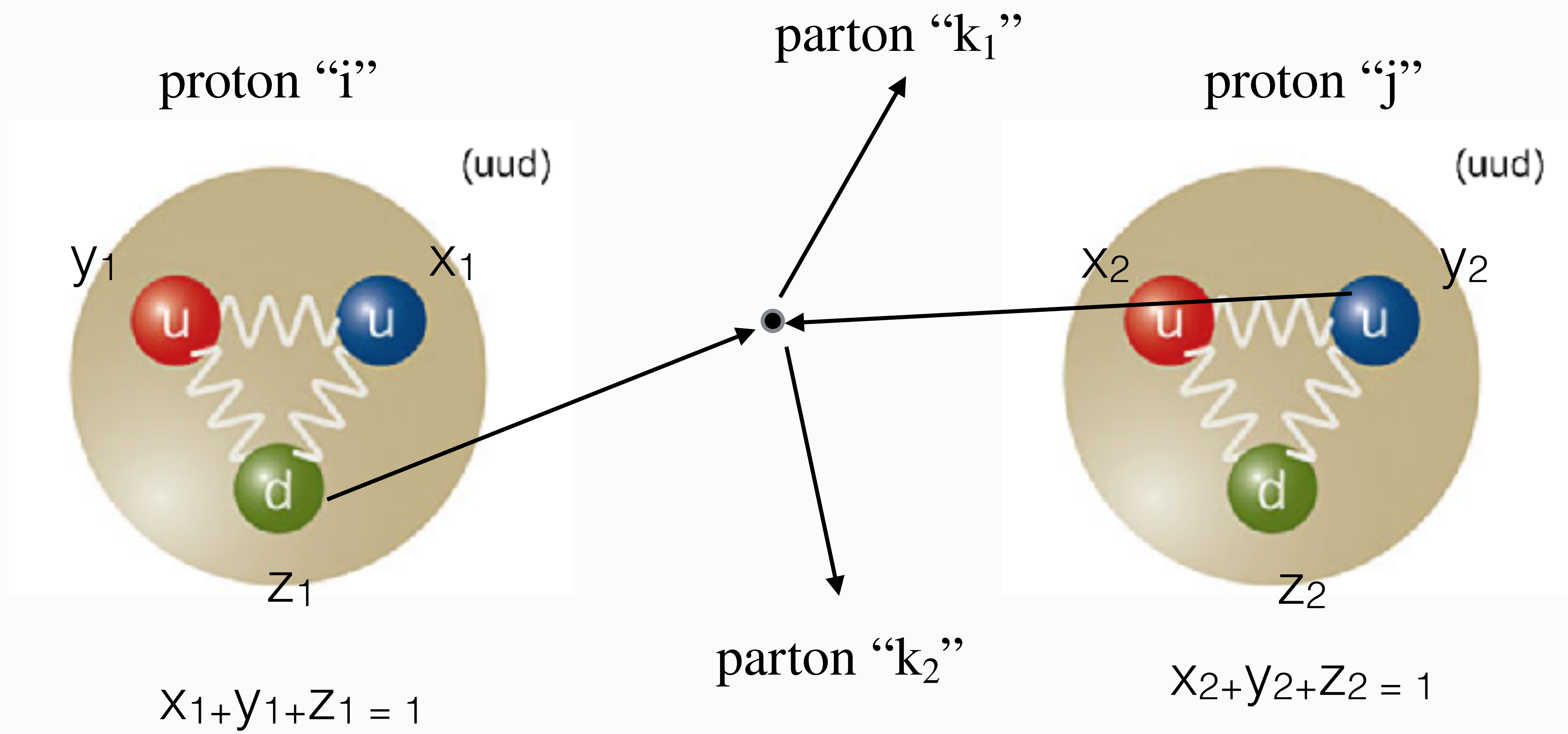


Elementary cross-section: $\sigma_{ij \to k_1 k_2}(x_1, x_2)$ $\sigma_{ij \to k_1 k_2}(z_1, y_2)$

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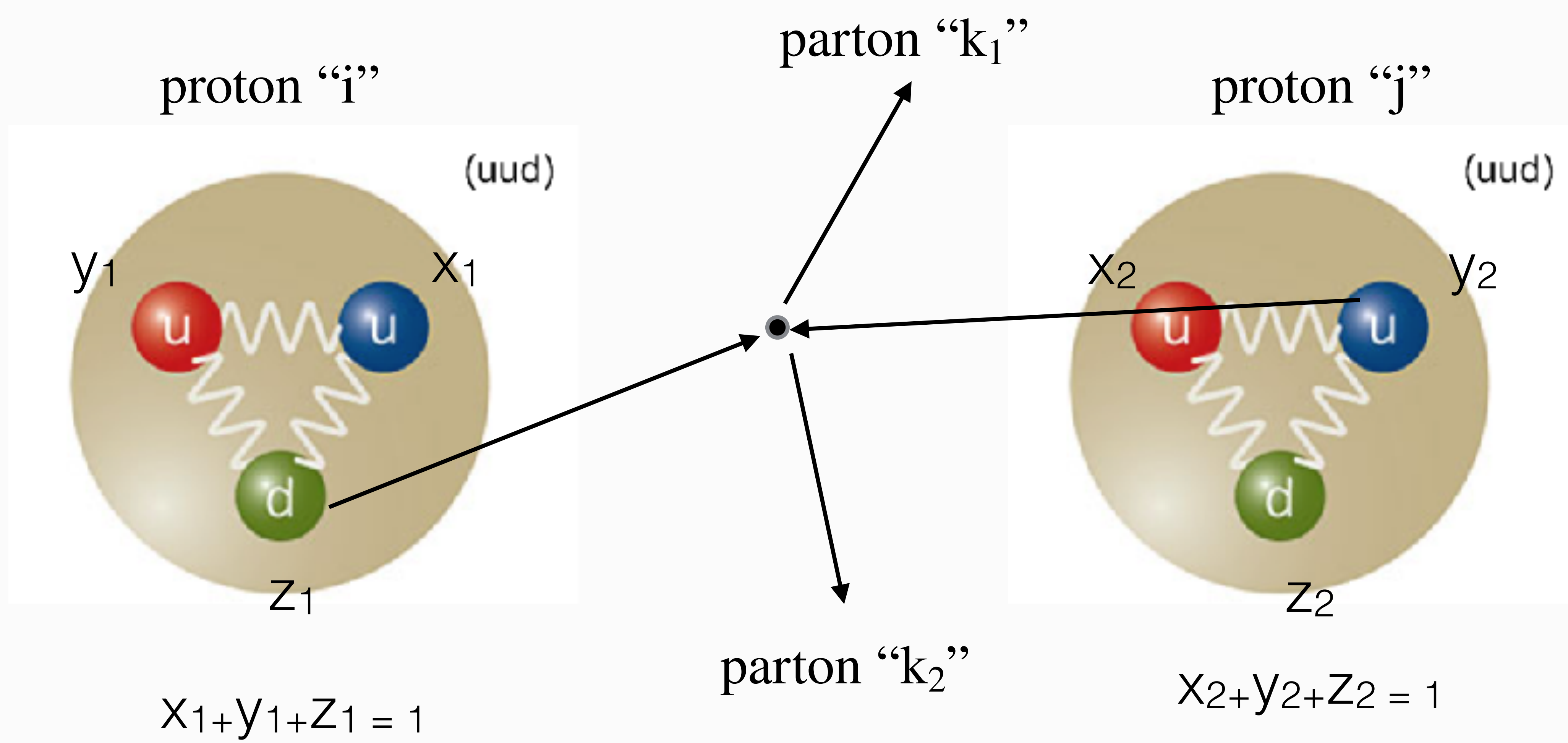


Elementary cross-section: $\sigma_{ij\to k_1 k_2}(x_1, x_2) \; + \; \sigma_{ij\to k_1 k_2}(z_1, y_2)$

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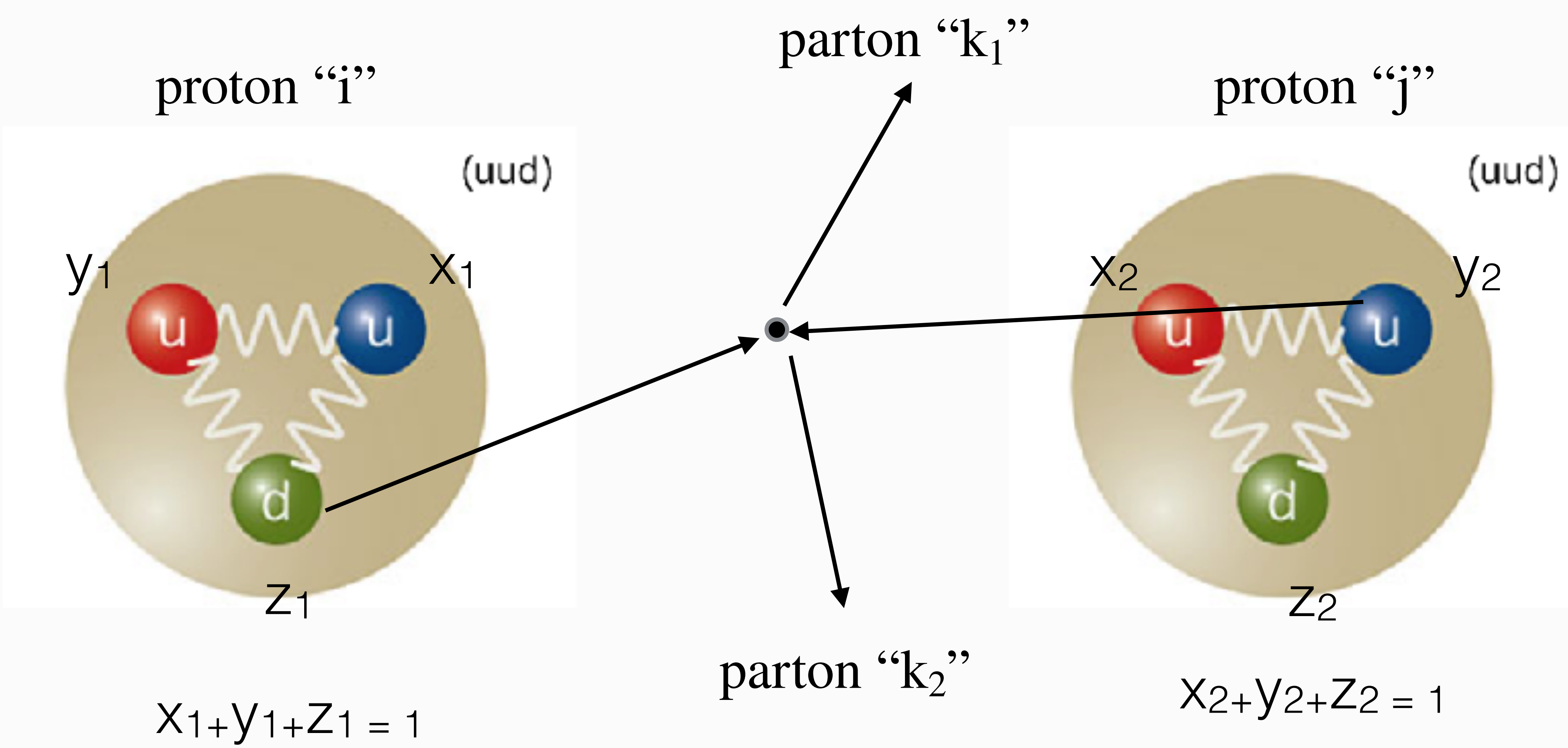


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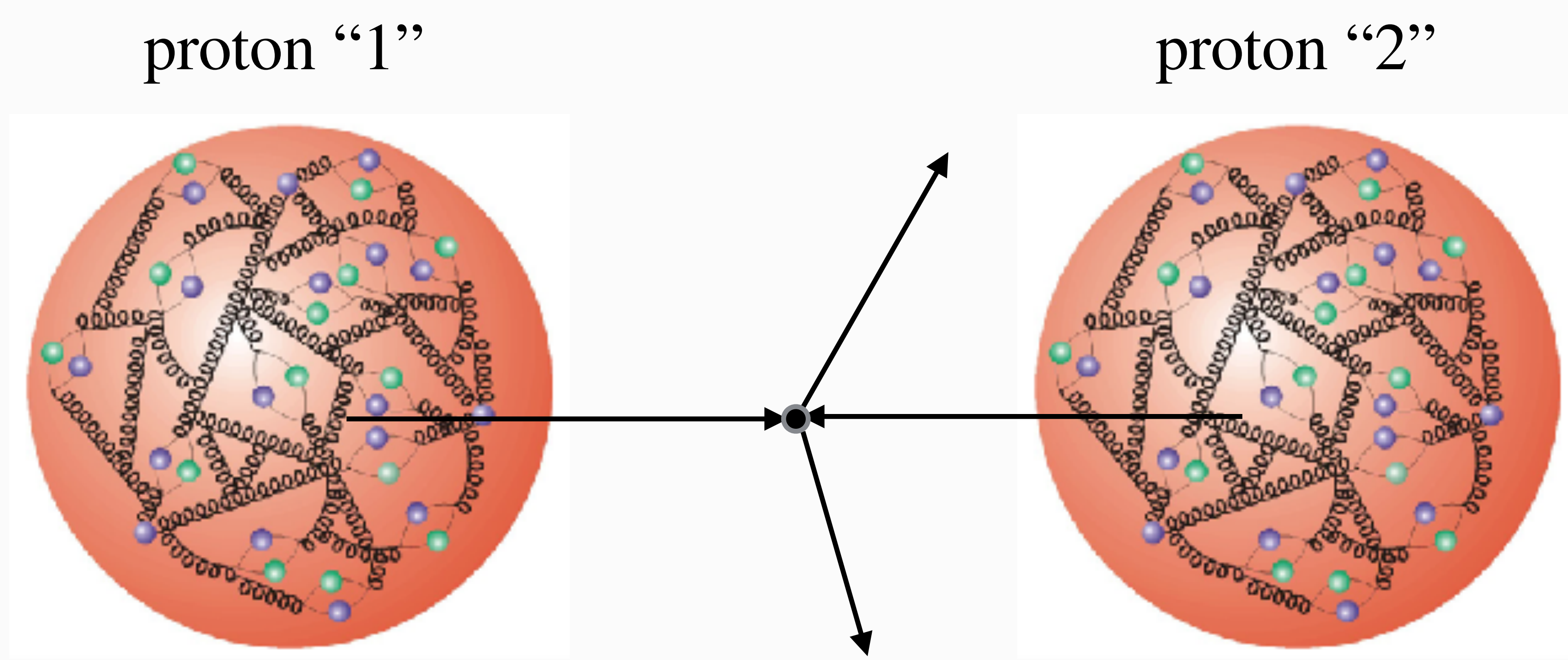

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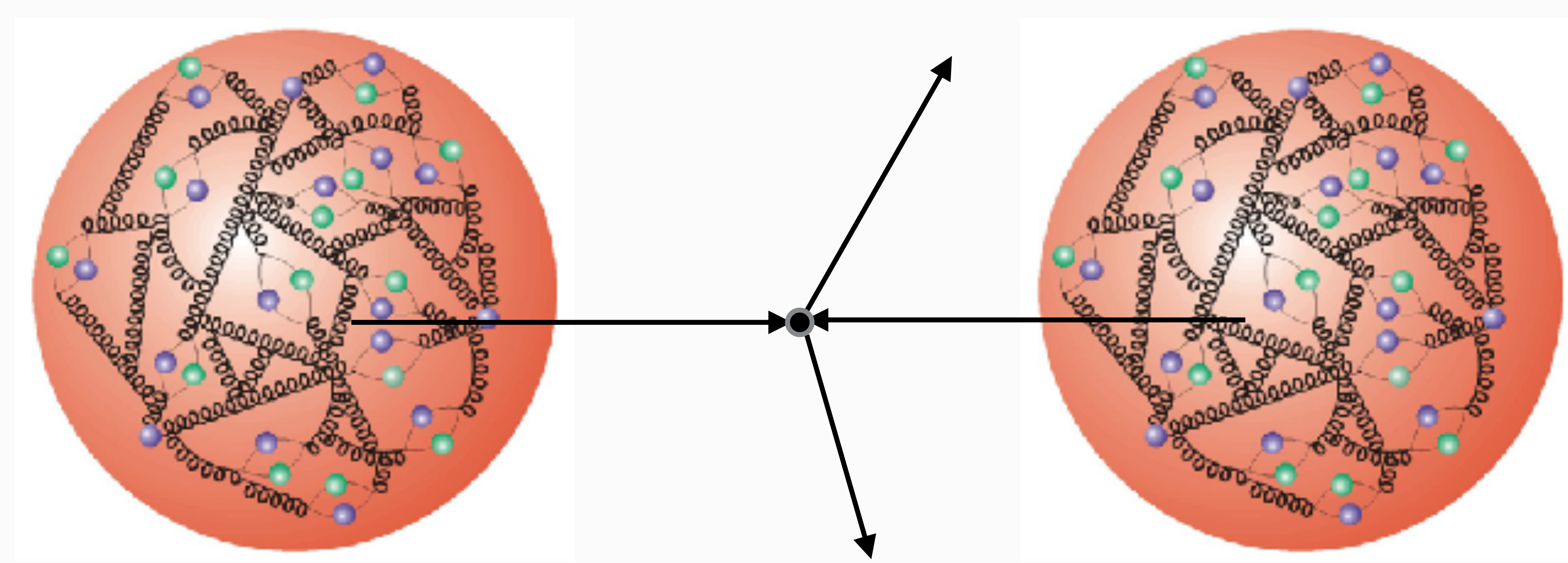
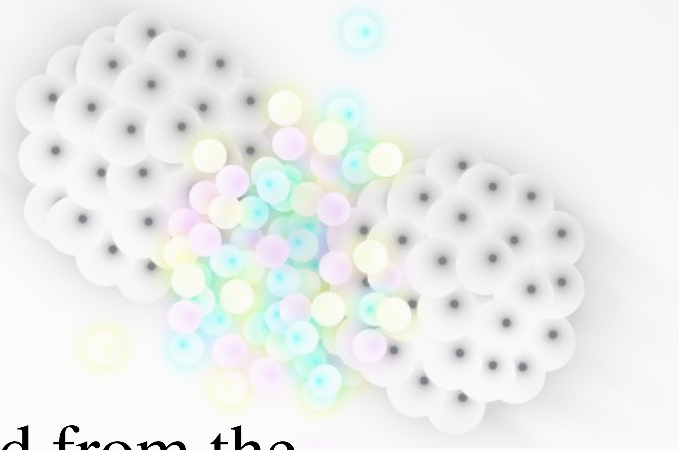
Elementary cross-section
(hard process)

proton “1” proton “2”





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Parton Distribution Functions (PDFs)

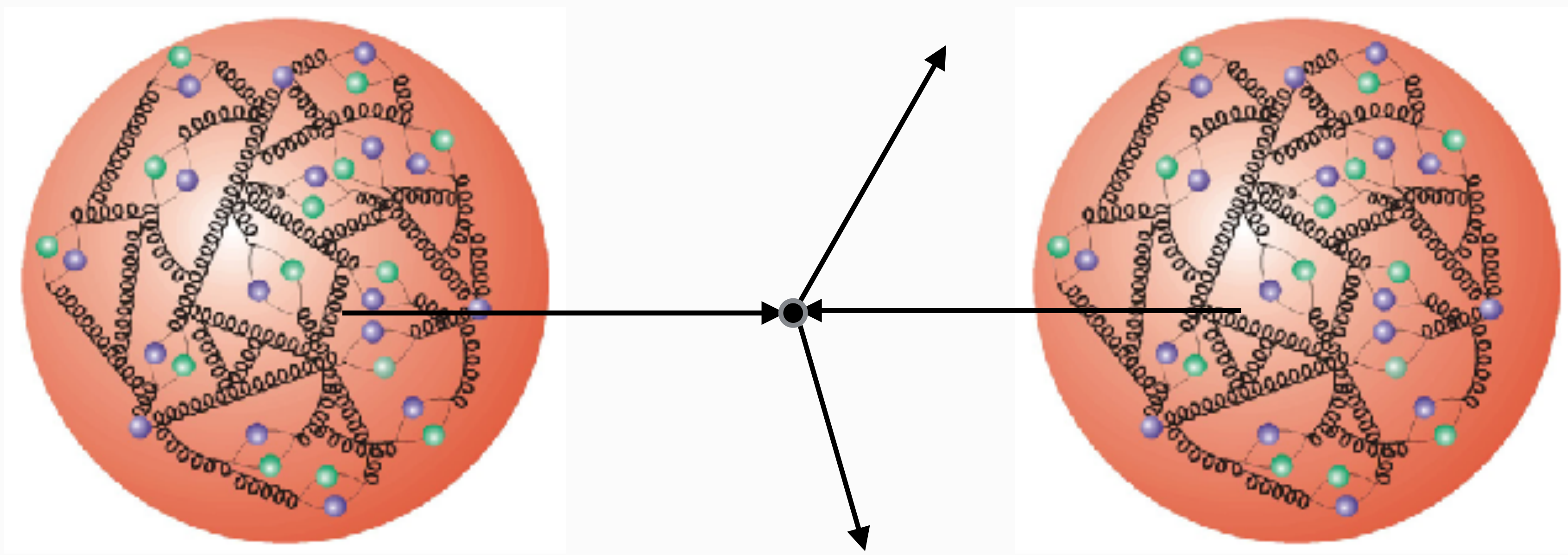
Elementary cross-section (hard process)

Probability to find a parton ‘i’ inside beam particle '1' carrying a fraction $x_1$ of the total momentum

(dependent on the hard process scale, $Q^2$)

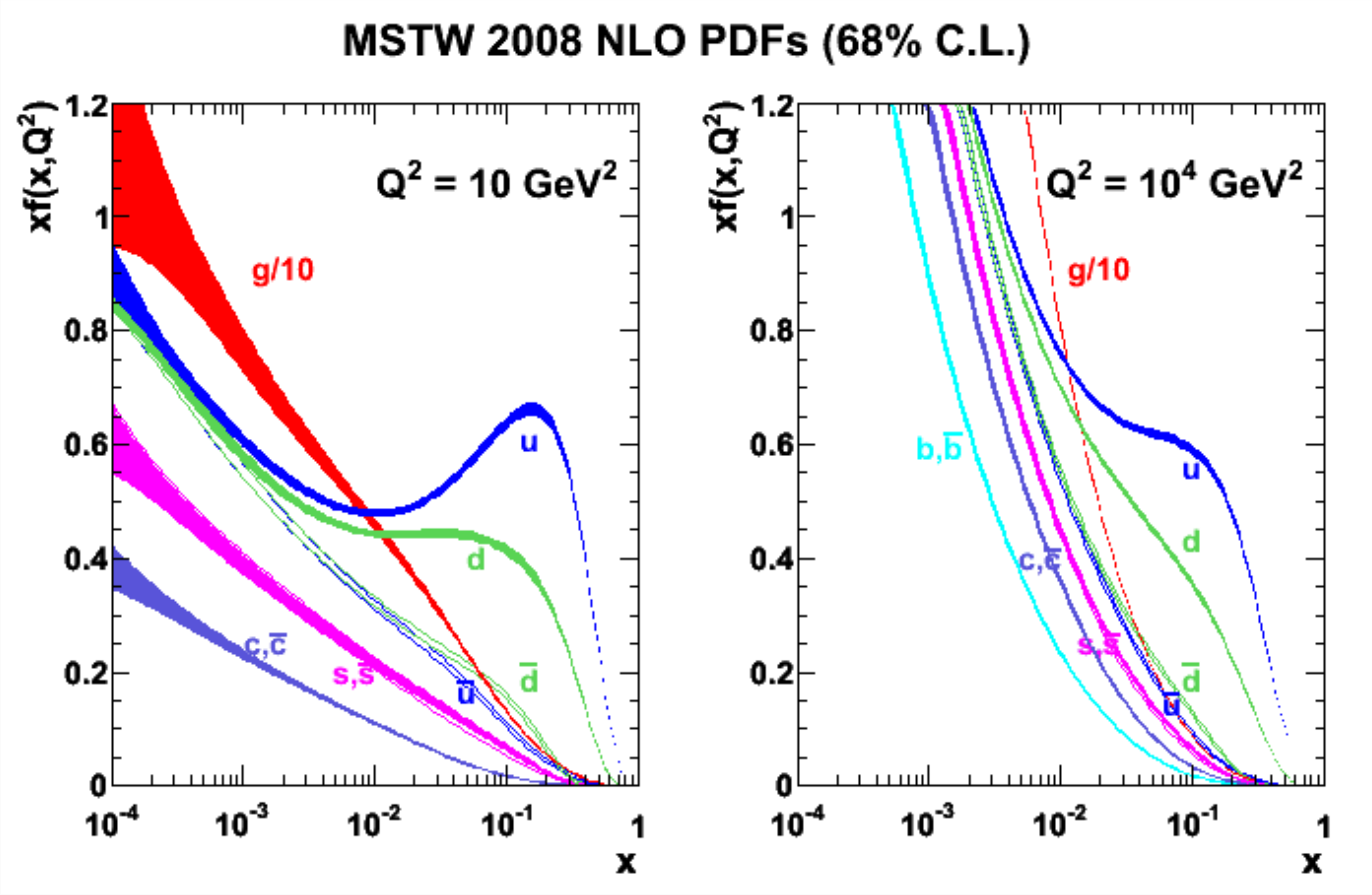
proton “1”

proton “2”



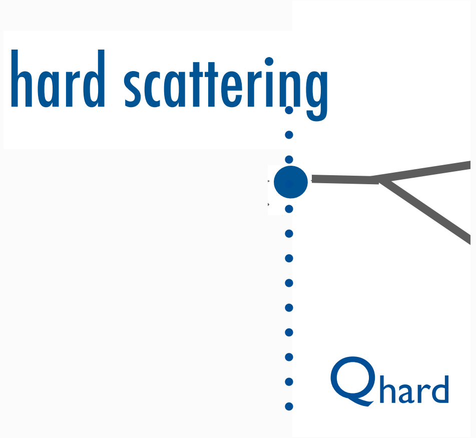
# Parton Distributions

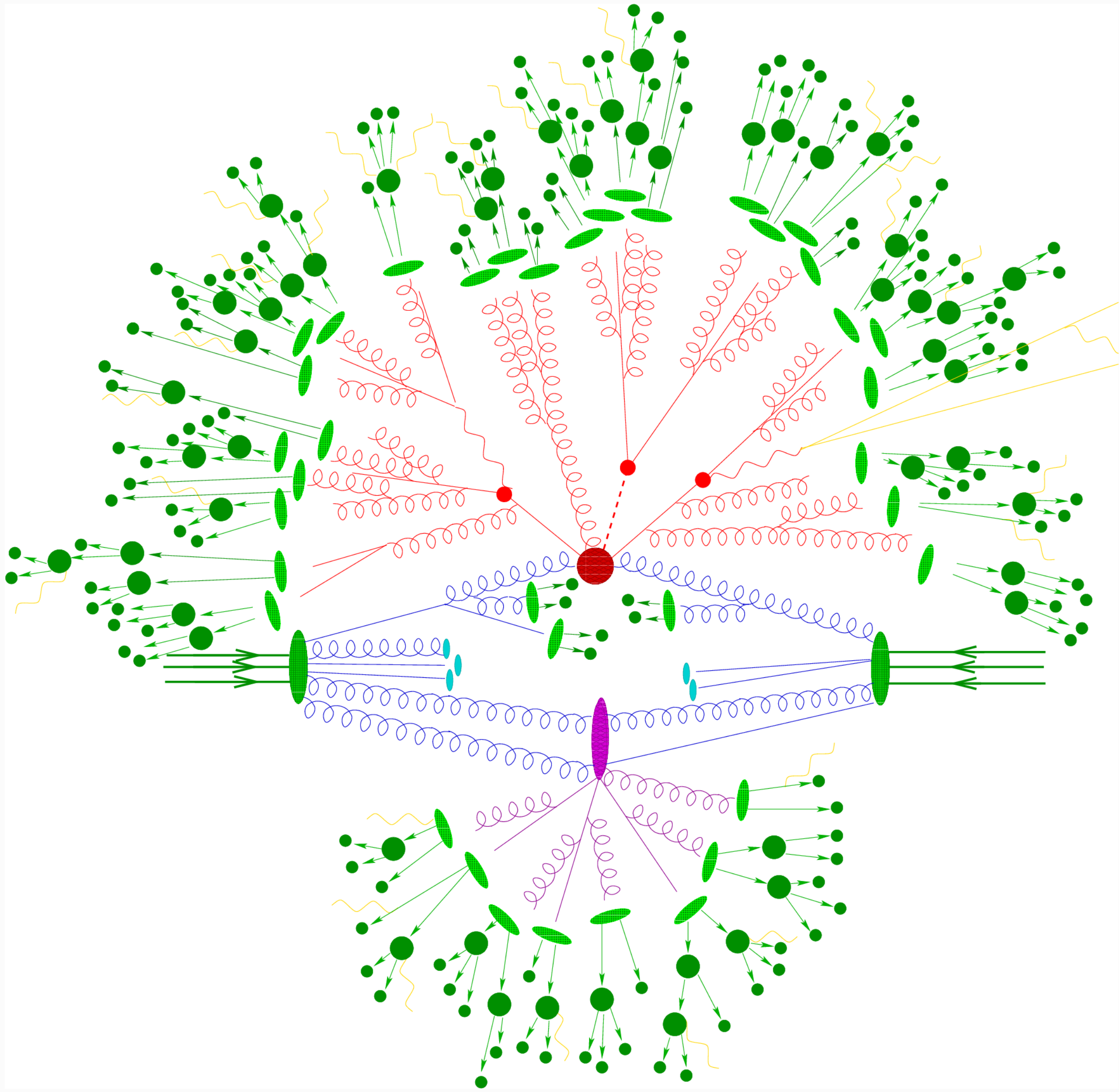
- Derivation from first principles does not yet exist. But its evolution, in $Q^2$, can be described analytically.
  - Rely on parameterisations:
    - conjunction of experimental data and evolution equations
  - Once established, (proton, Pb, Au, …) they are universal.



# Initial- and Final-State Showers

- Corrections to generate multi-particle production, 2→3, 2→4, etc…



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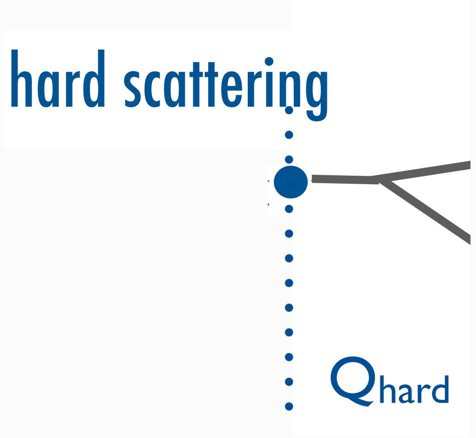


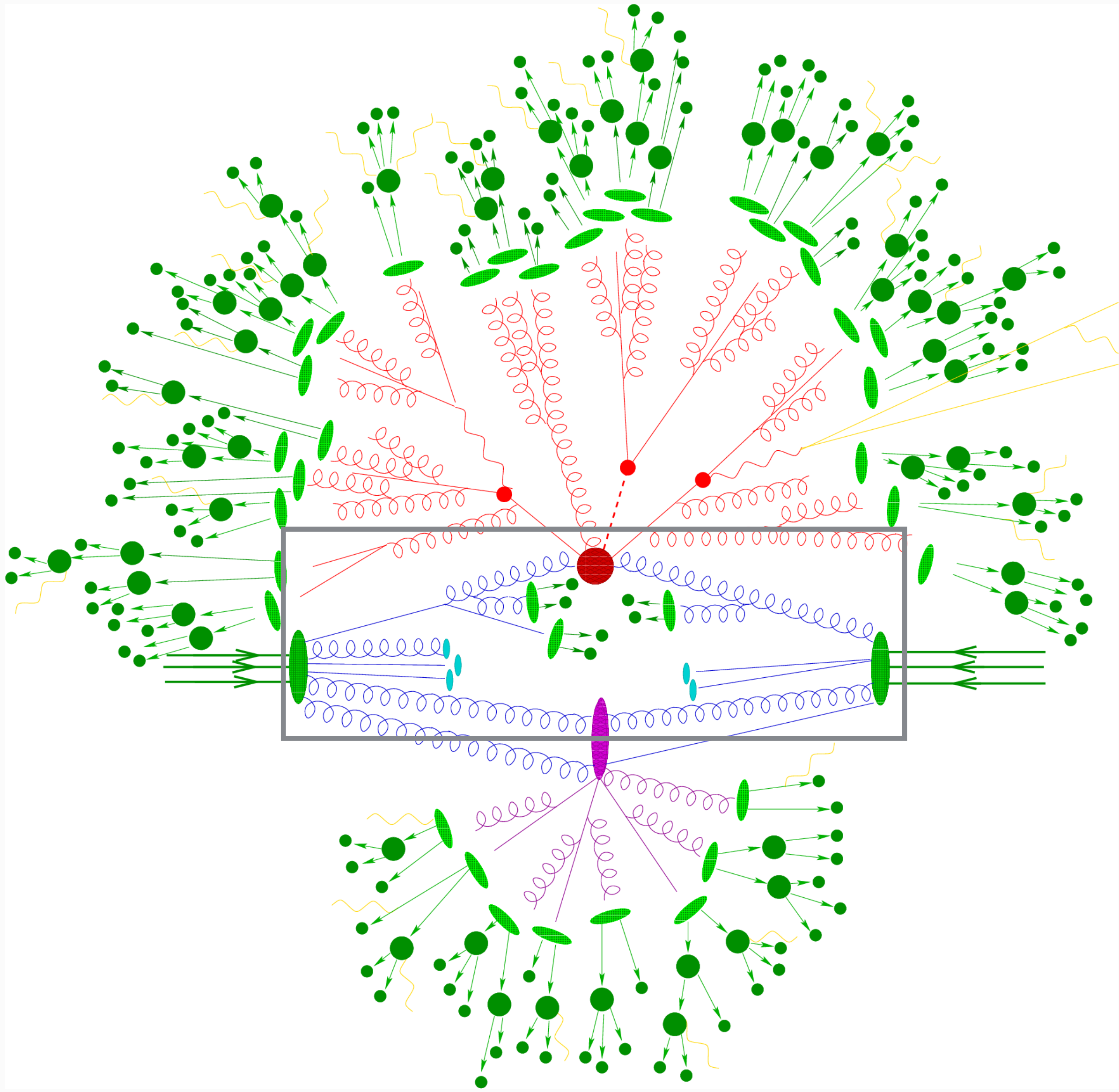

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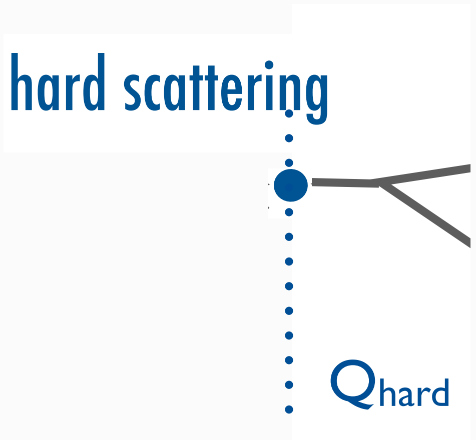


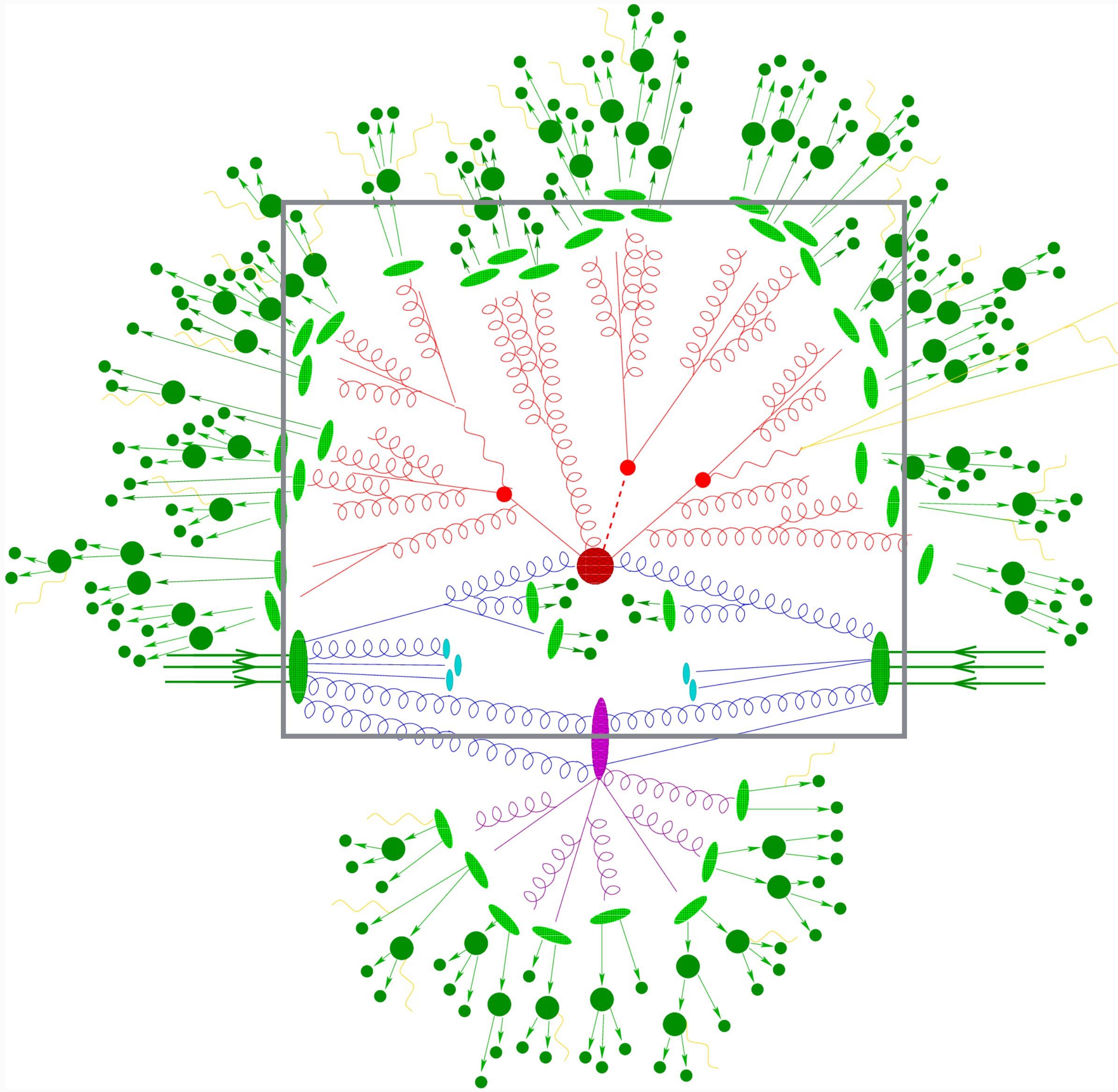

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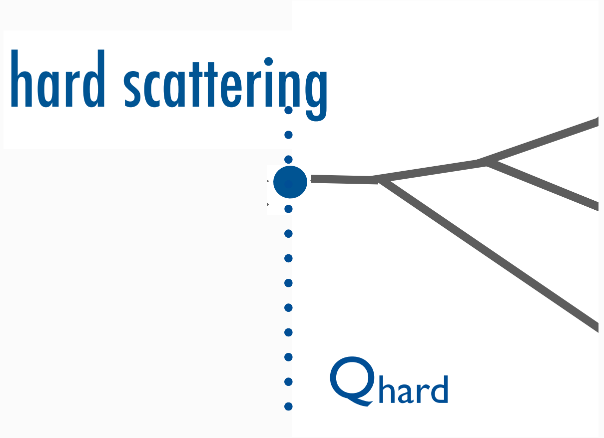


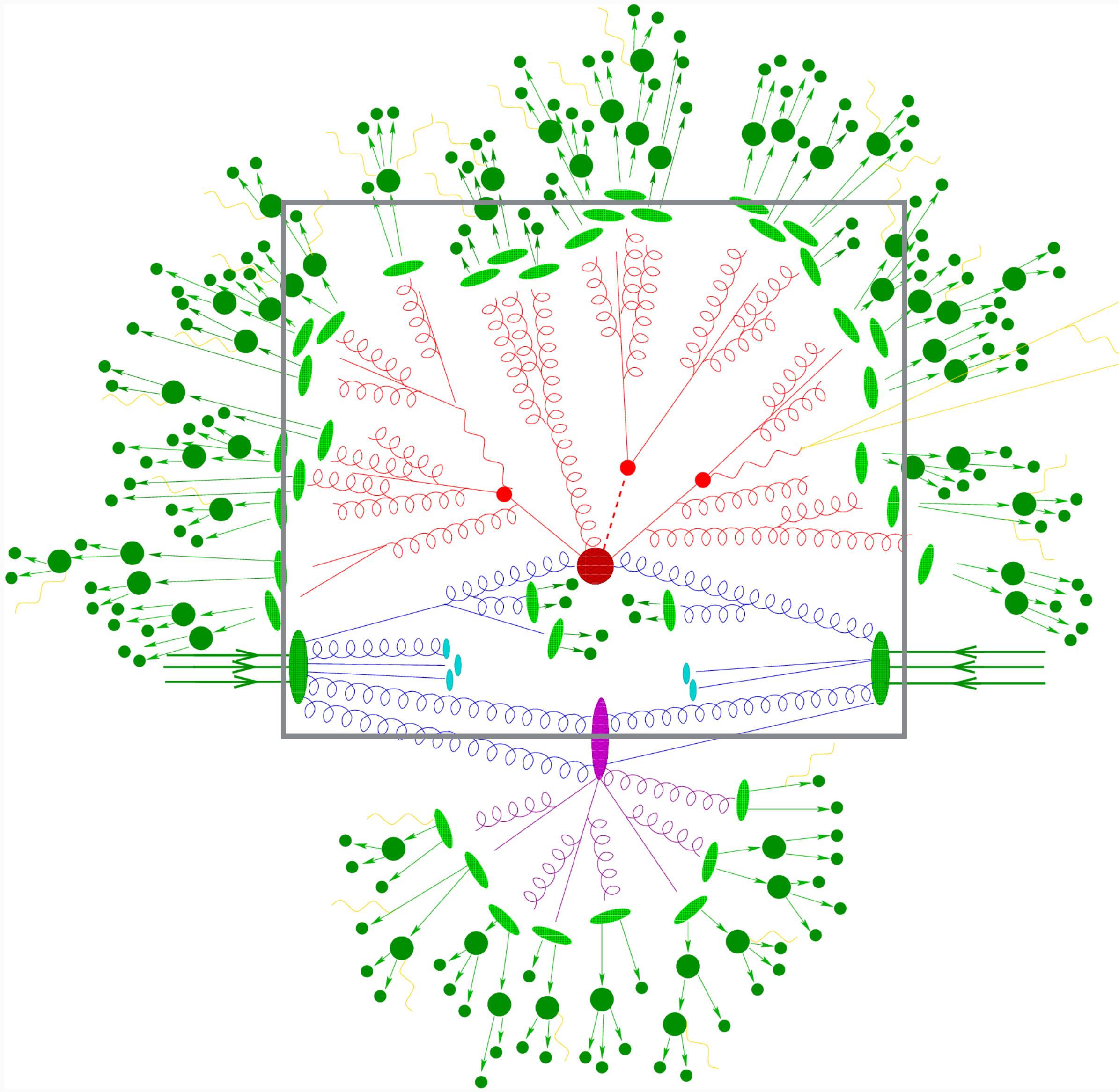

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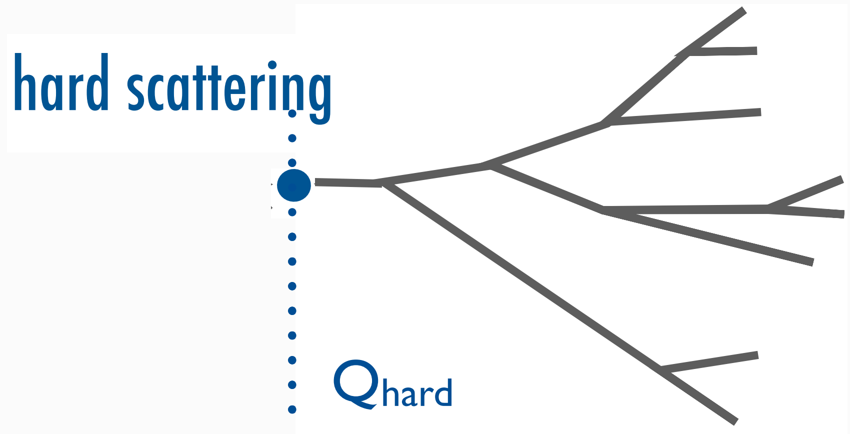


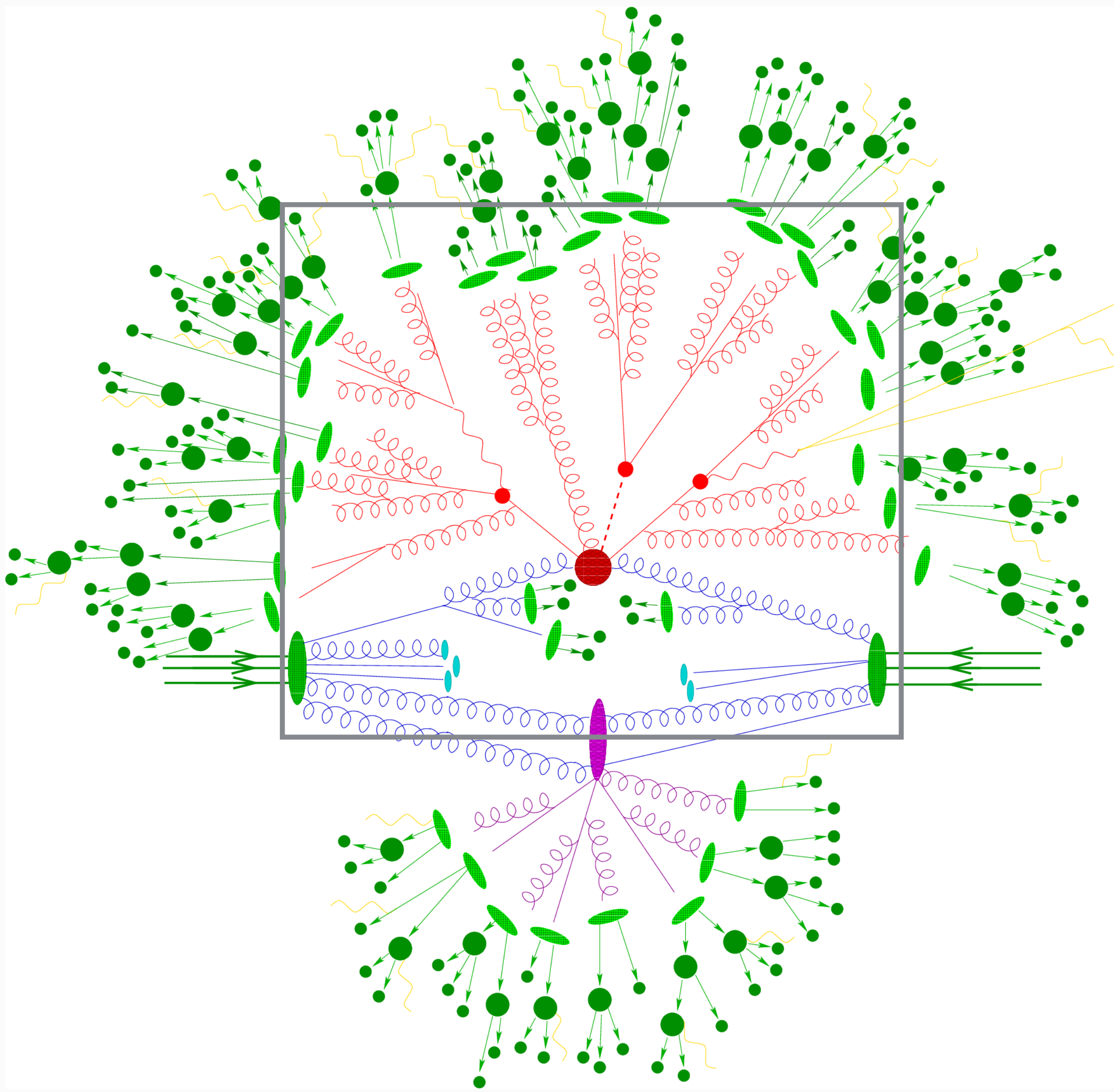

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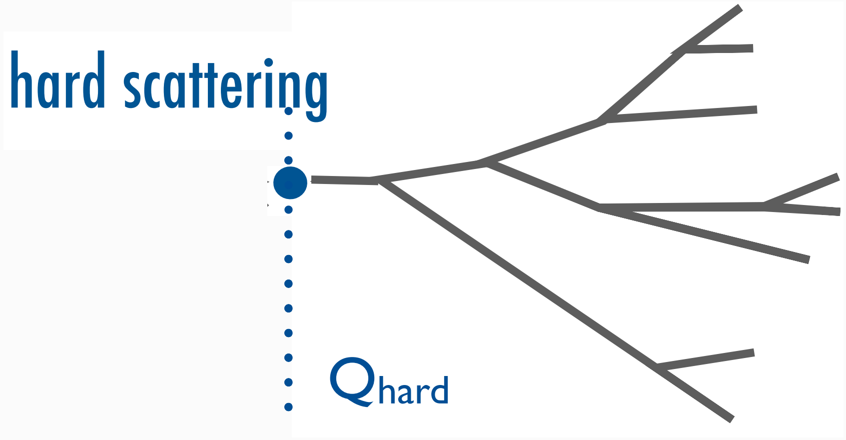


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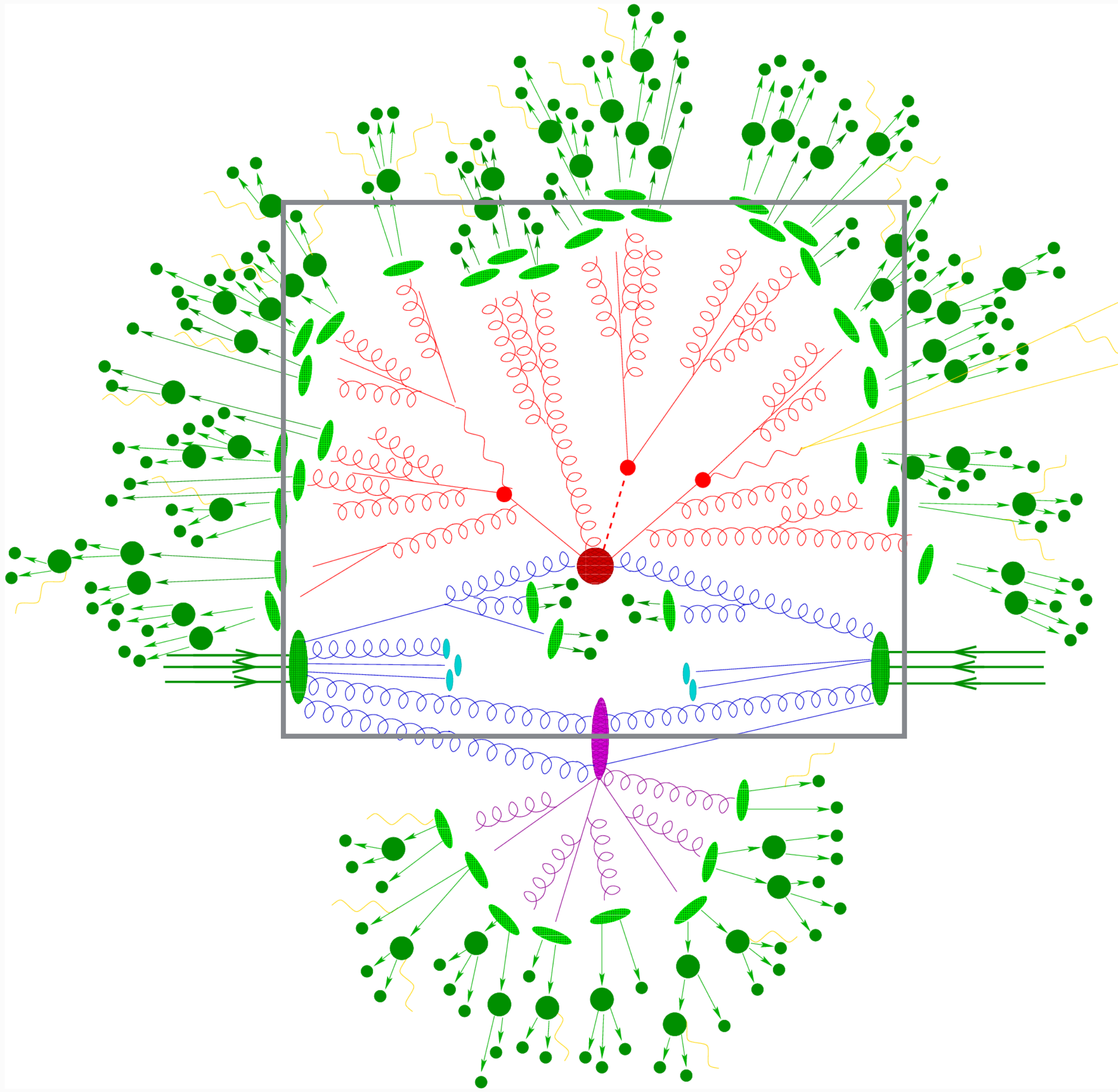

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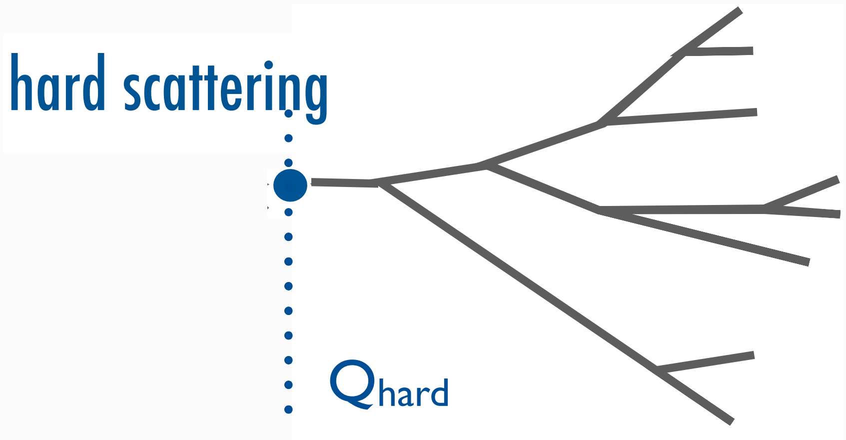
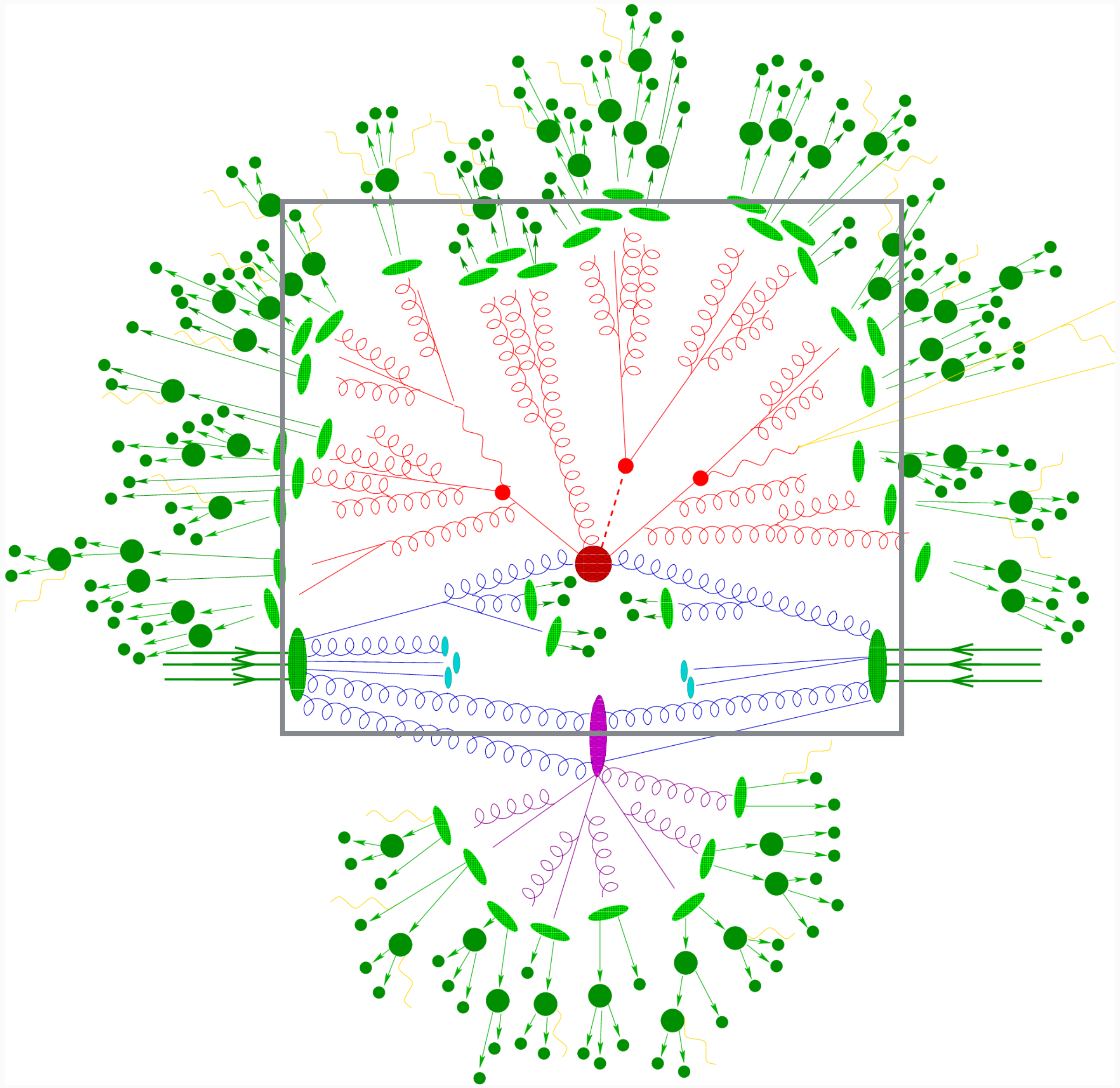



$$\frac{d^2\sigma^h}{dyd^2p_T} = \int dx_a dx_b f_a(x_a,\mu_f) f_b(x_b,\mu_f) \frac{d\sigma_{ab\to c}(x_a p_a, x_b p_b, \mu, \mu_f, \mu'_f, p_T/z)}{d\hat{t}} D_c^h(z,\mu'_f)$$



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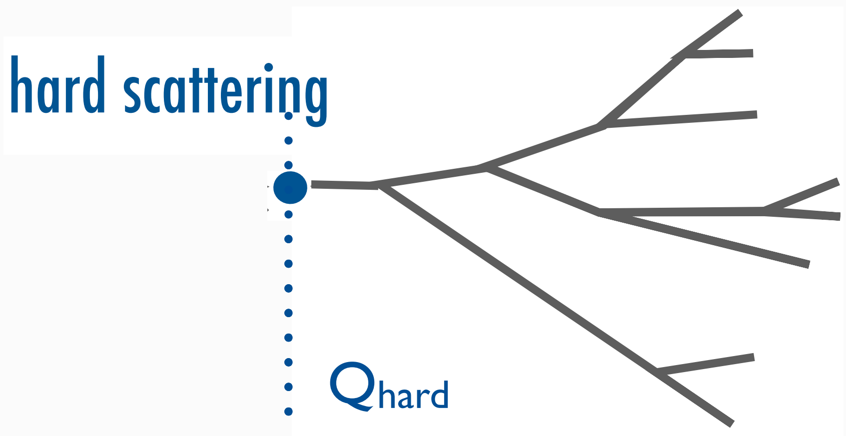


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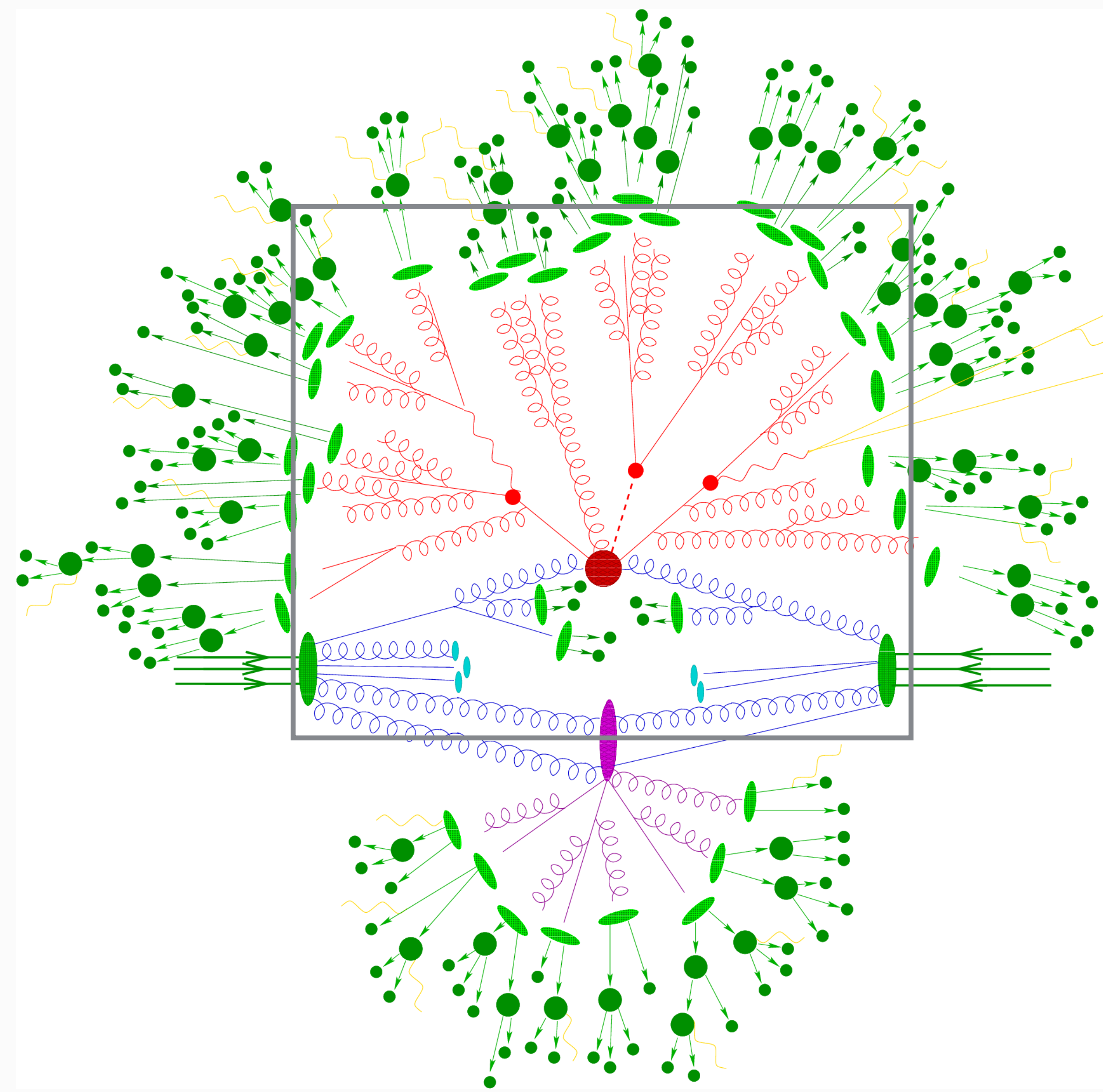
Fragmentation function (FF) of parton ‘c’ into product ‘h’



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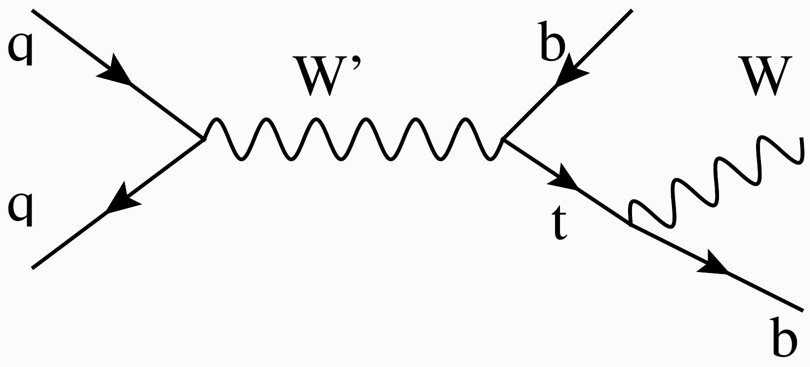

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$$Q^2 \frac{\partial D_a^h(x,Q^2)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \sum_b \hat{P}_{b\leftarrow a}(z) D_b^h\left(\frac{x}{z}, Q^2\right)$$
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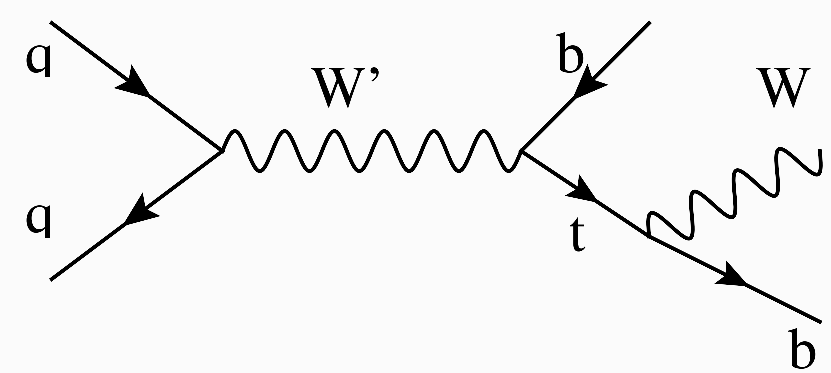

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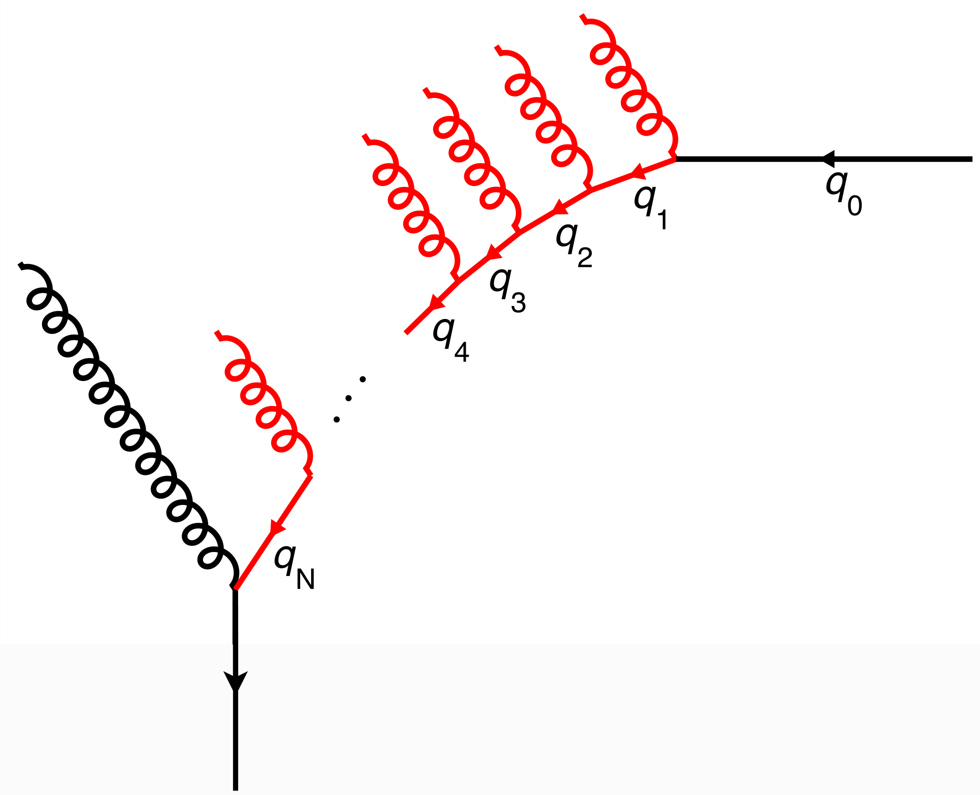

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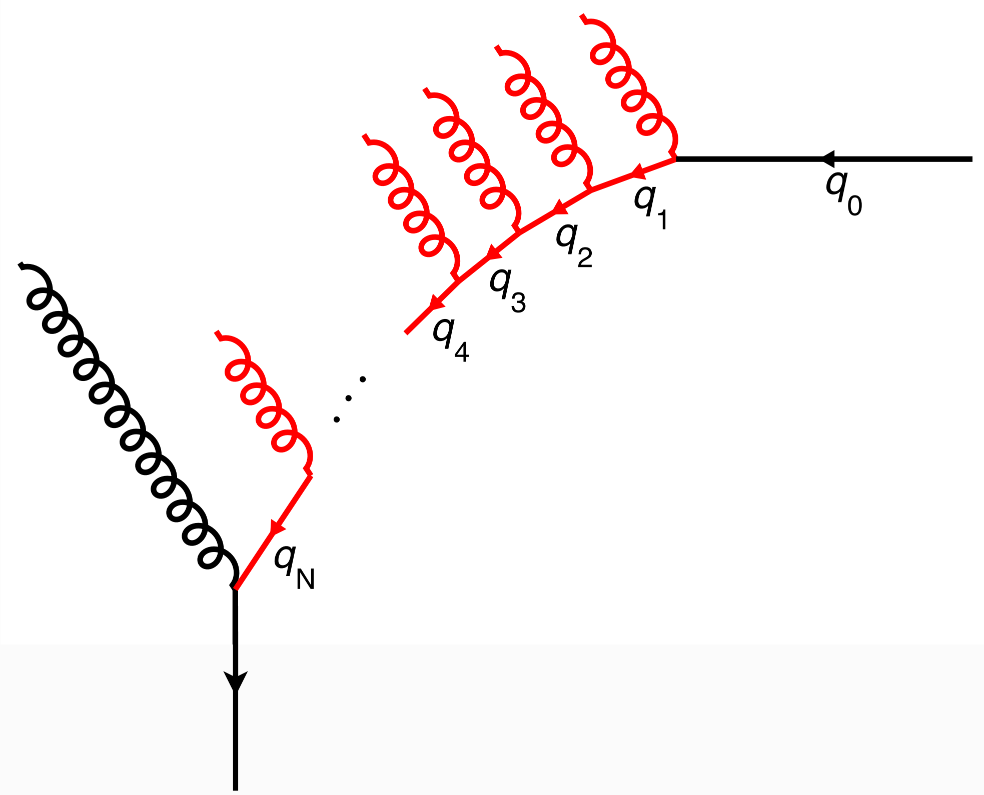
Splitting Function (SF)

Probability of parton ‘b’ splits into parton ‘a' with a fraction of energy z



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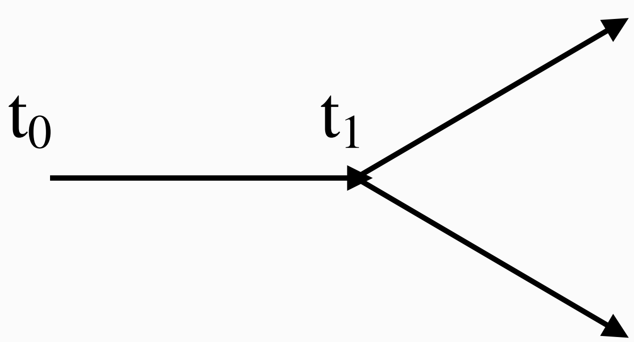

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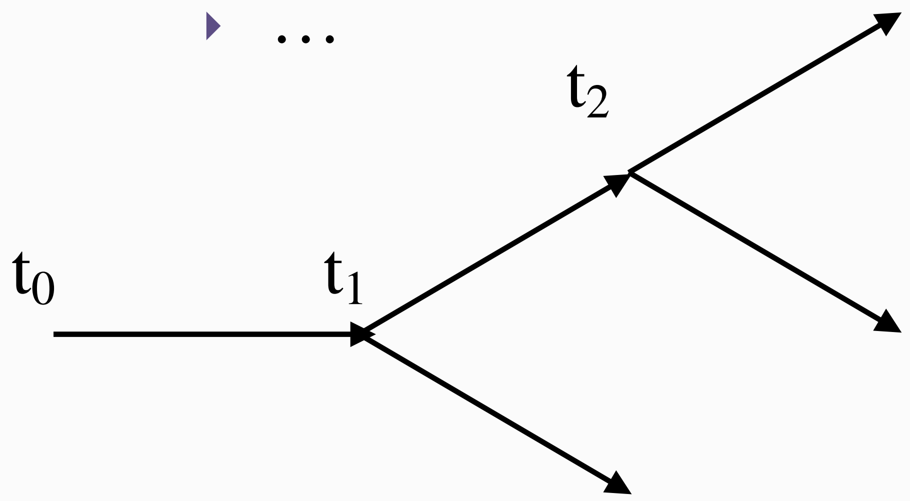

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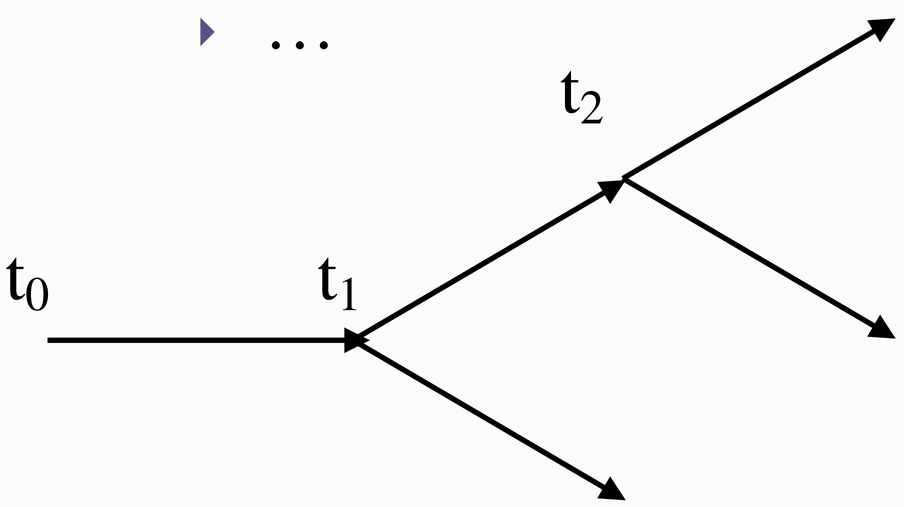


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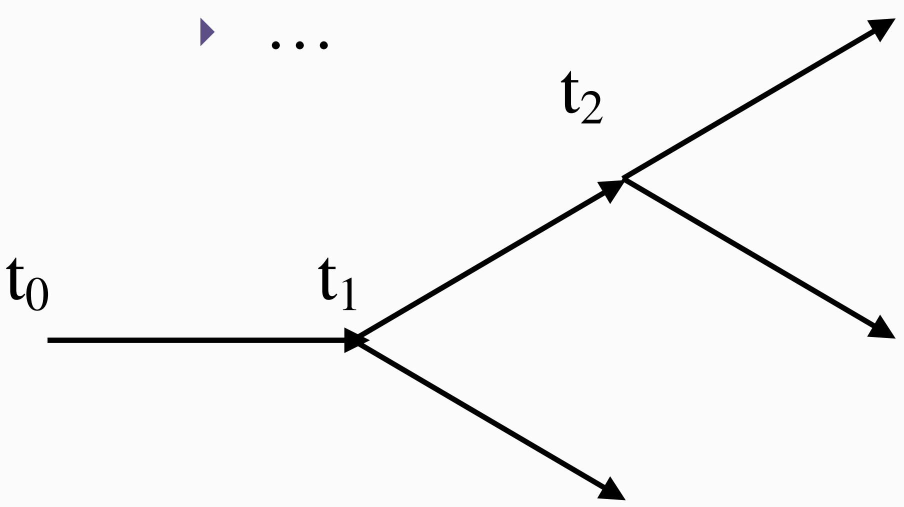


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| Just like a radioactive decay! | $N(t) = \exp\left\{-\int_{t_0}^{t_1} dt f(t') dt'\right\}$ <br> $\Rightarrow N(t) = N_0 e^{-\lambda t}$ |

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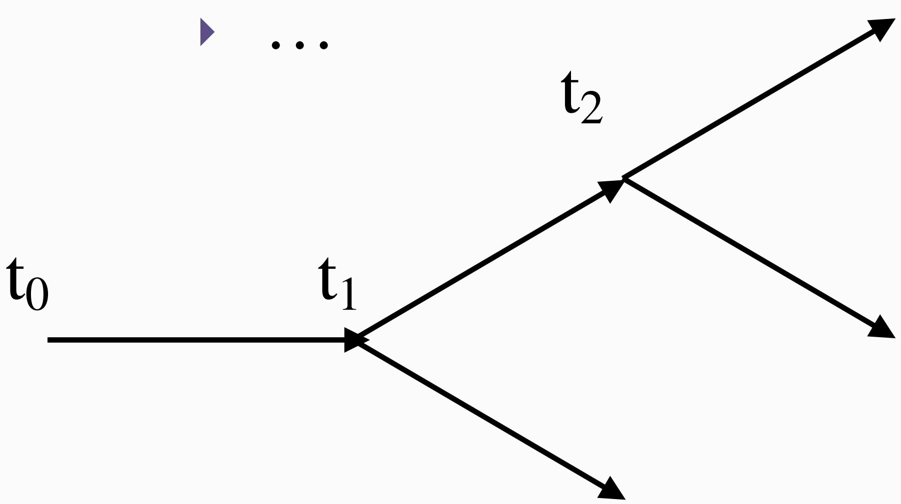


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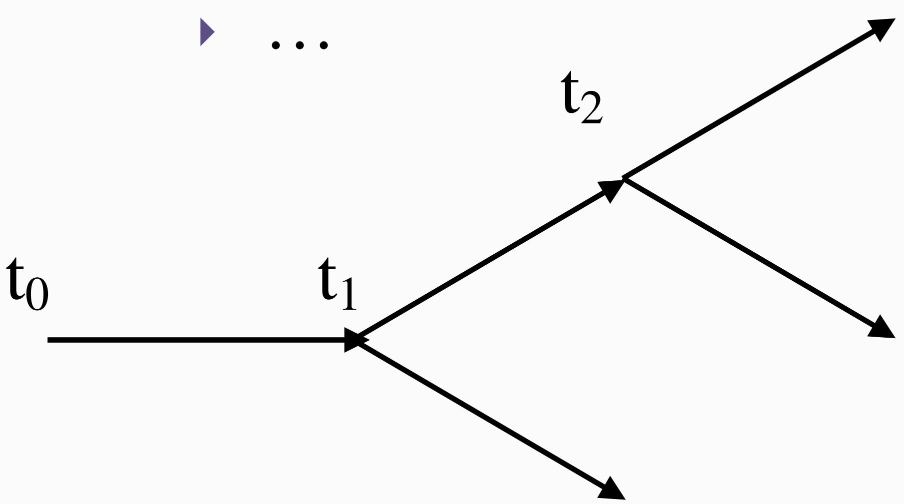


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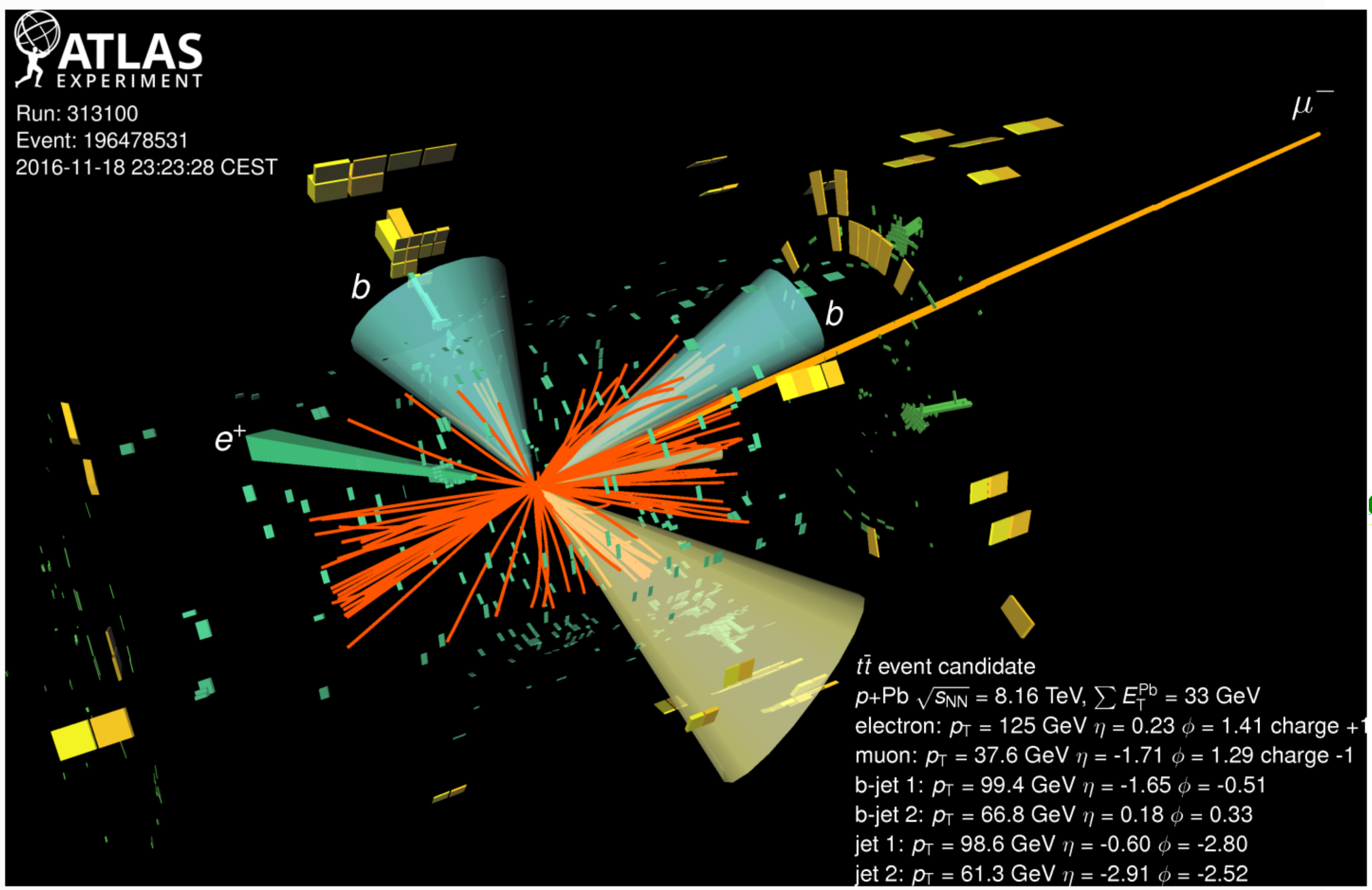
Given a random number, R, what is $t_1$?

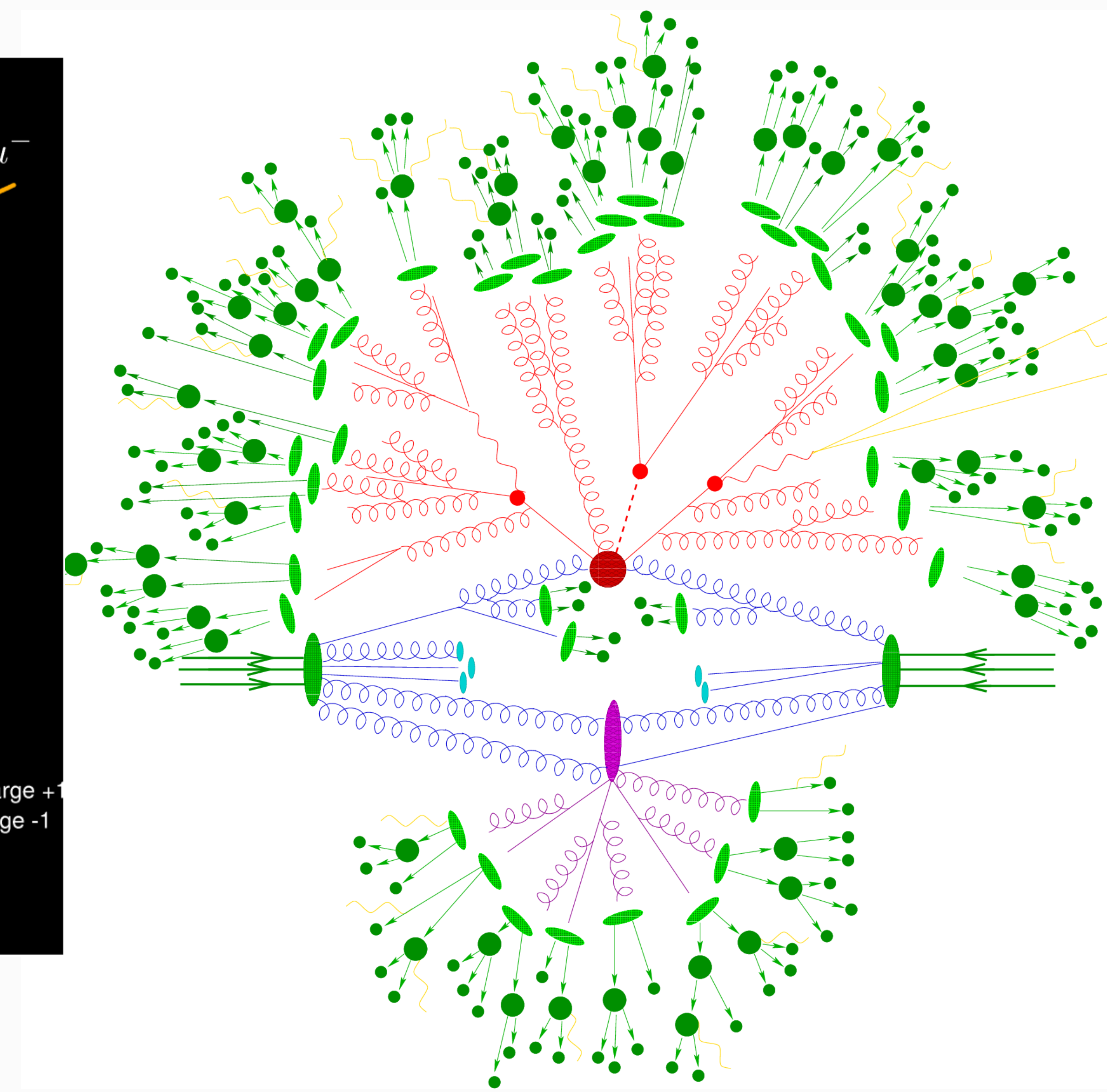
At $t_1$, it decays.

Probability of not decay between $t_0$ and $t_1$

# Initial- and Final-State Showers

- Results into spray of partons/particles that will form jets;
  - Resulting pattern will contribute to the event structure (2, 3,… jet event)



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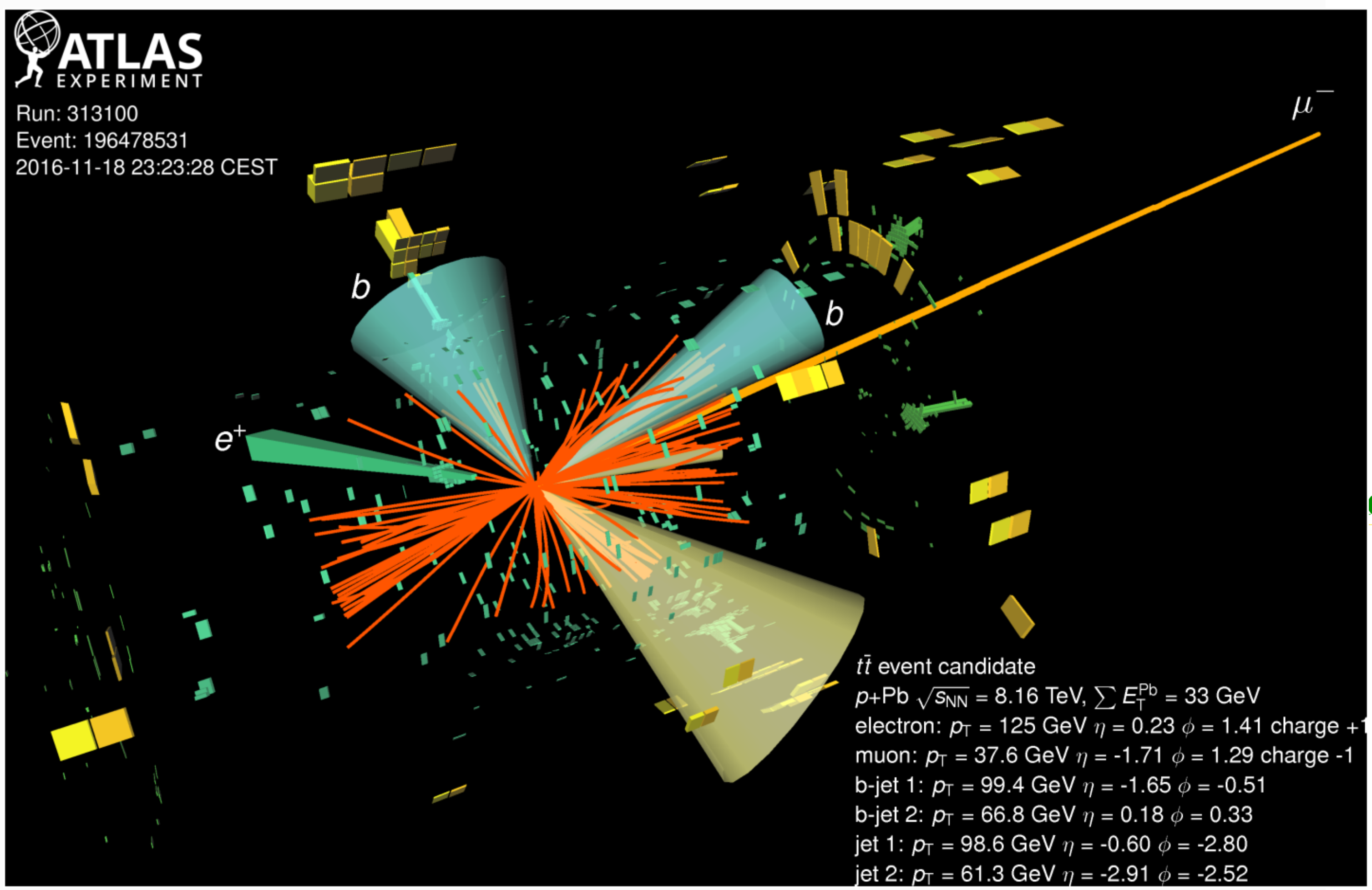
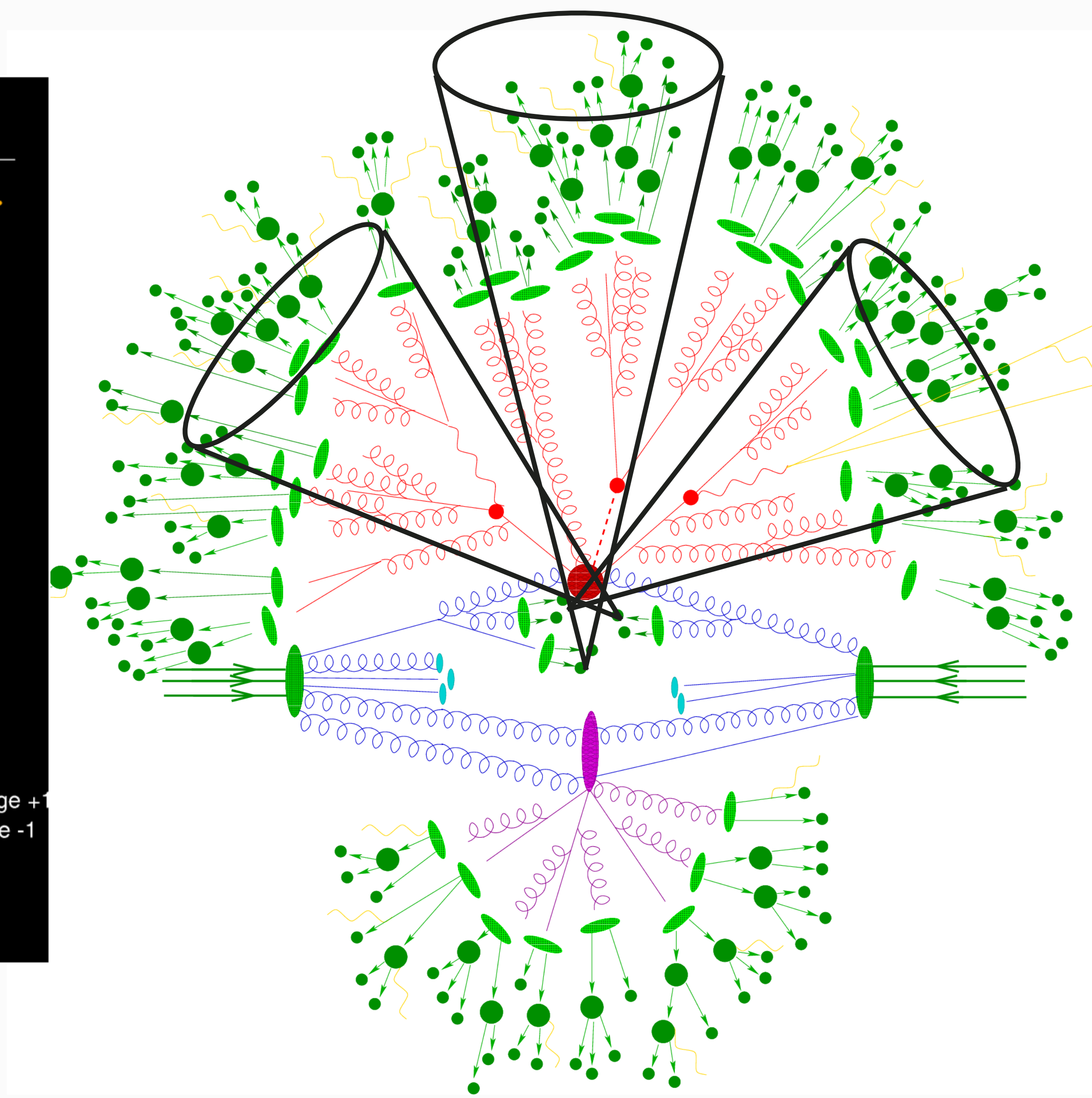
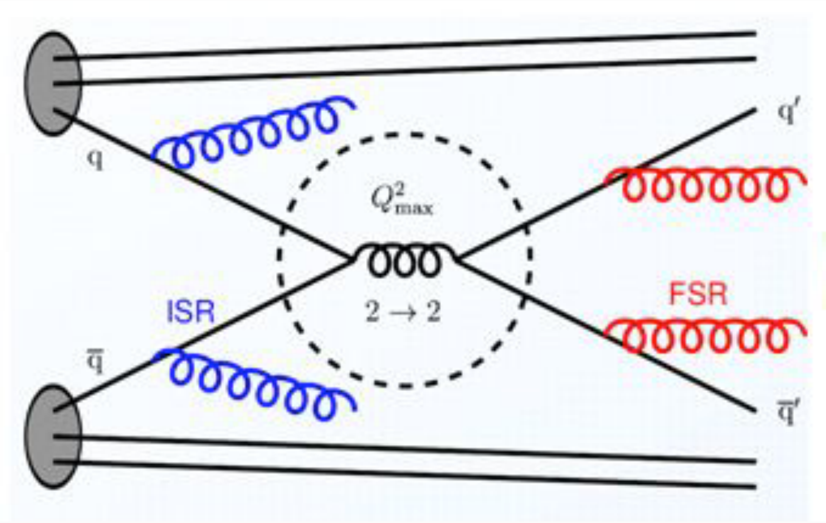


# MPI and Beam Remnants

- The initiator shower of the hard scattering takes only a fraction of the total beam energy. What is left behind is called the (coloured) beam remnant



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Initiator
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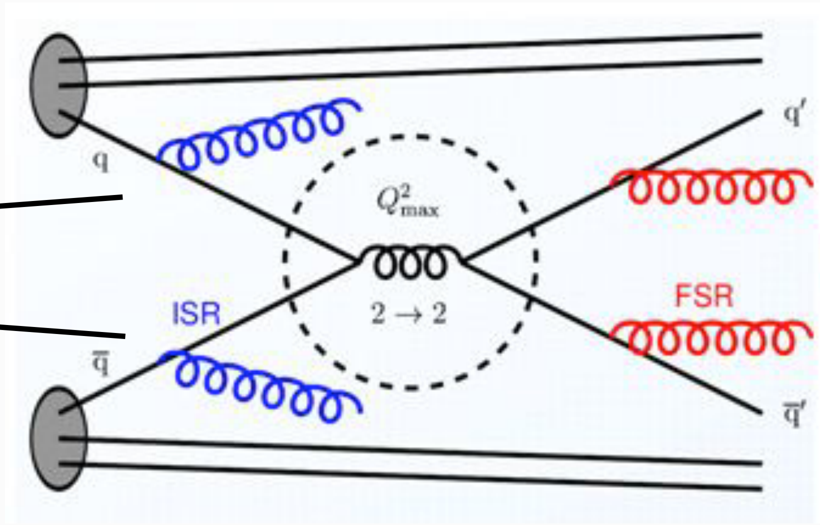

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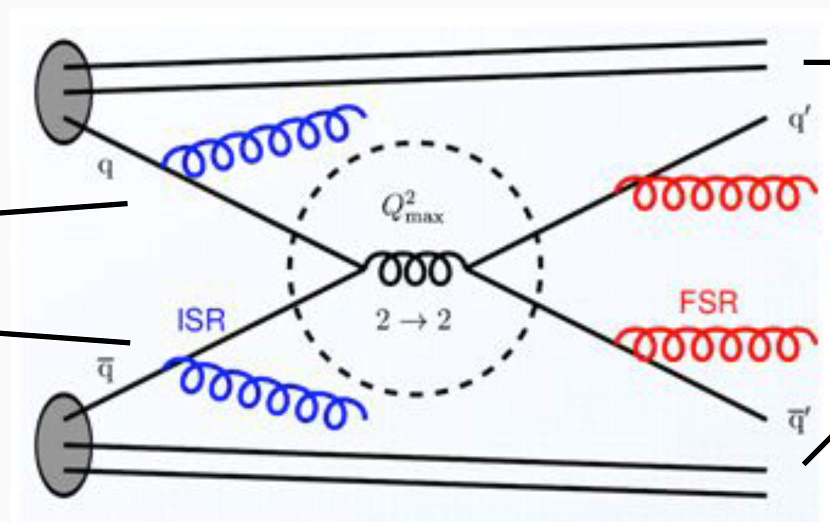


Beam Remnants

Underlying event (bkg)

(Color connected to the hard process)

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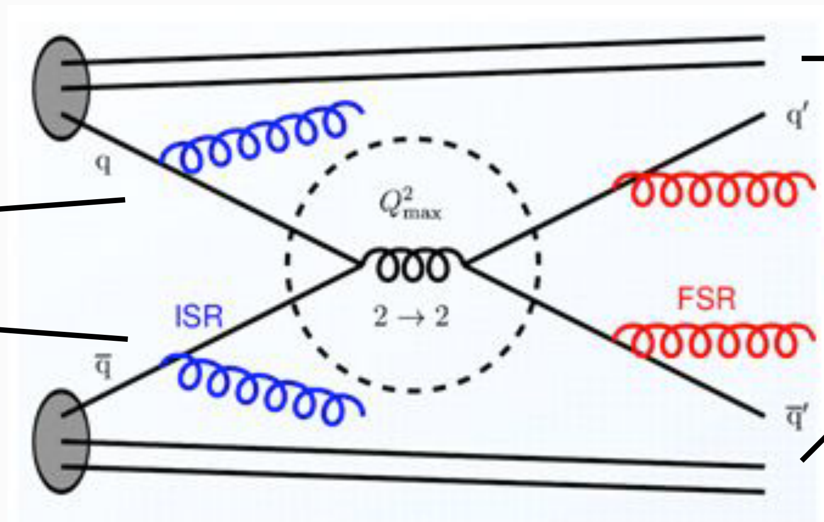
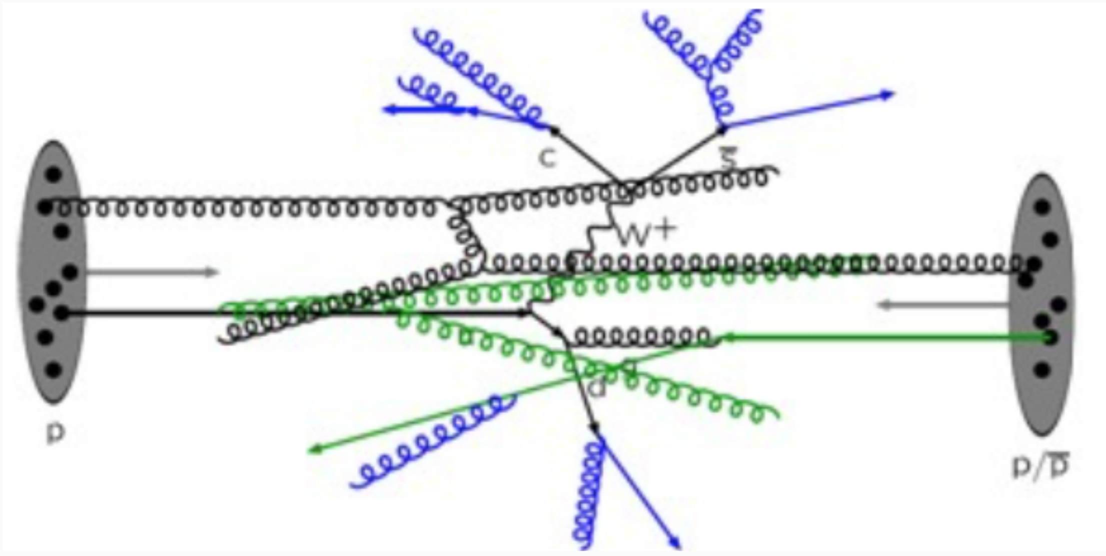



Beam Remnants

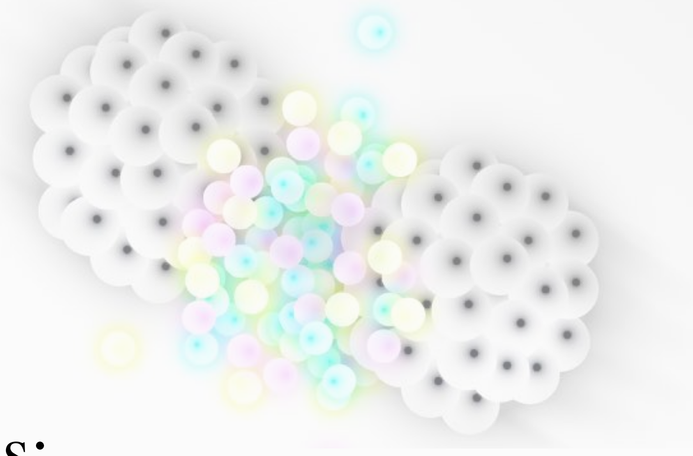
Underlying event (bkg)

(Color connected to the hard process)

- Dominant 2→2 QCD cross-sections are divergent for $p_T \to 0$ but drop rapidly for large $p_T$.
  - Probability of multiple parton interactions is not negligible for ep, pp or AA collisions

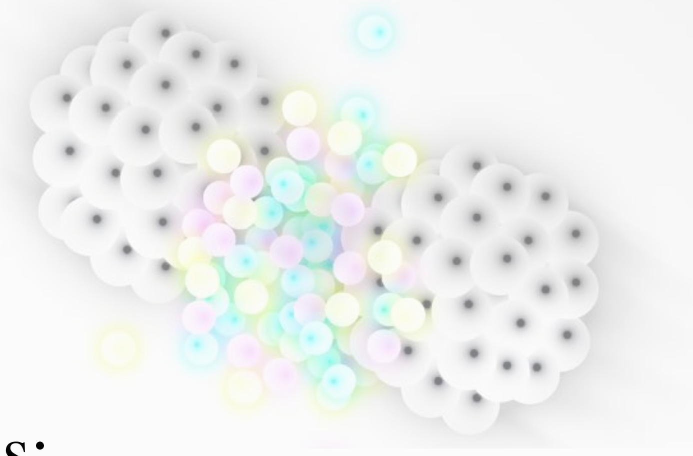


# Hadronization

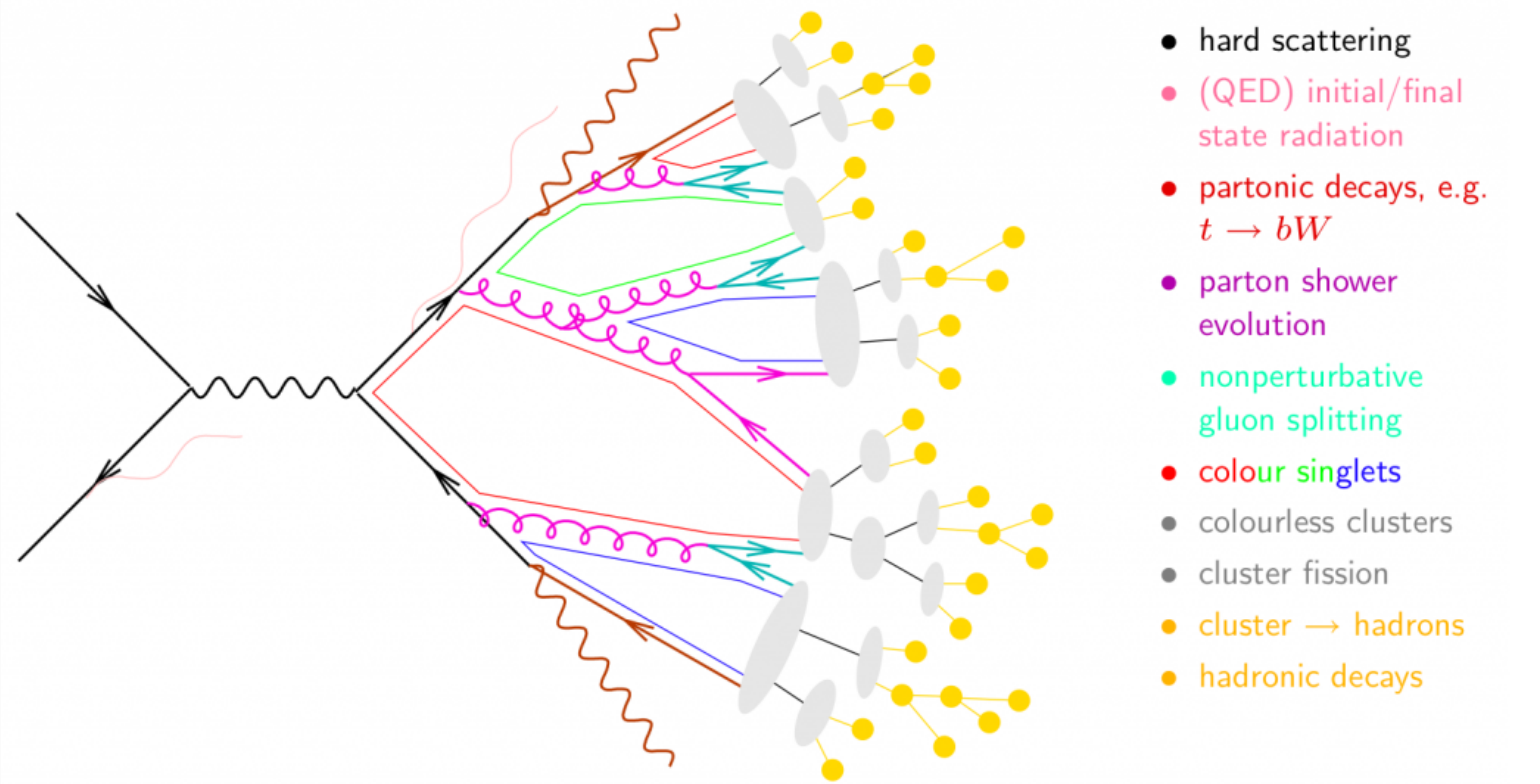


- Mechanism that confines back quarks and gluons into hadrons;
- QCD perturbation theory, formulated in terms of quarks and gluons, is valid at short distances only
- At long distances, in the confinement regime, coloured pardons are transformed into hadrons, a process called hadronization (or fragmentation)
  - Fragmentation process not understood from first principles (rely on phenomenological models)
    - All of them rely on the color flow between the constituents

# Hadronization

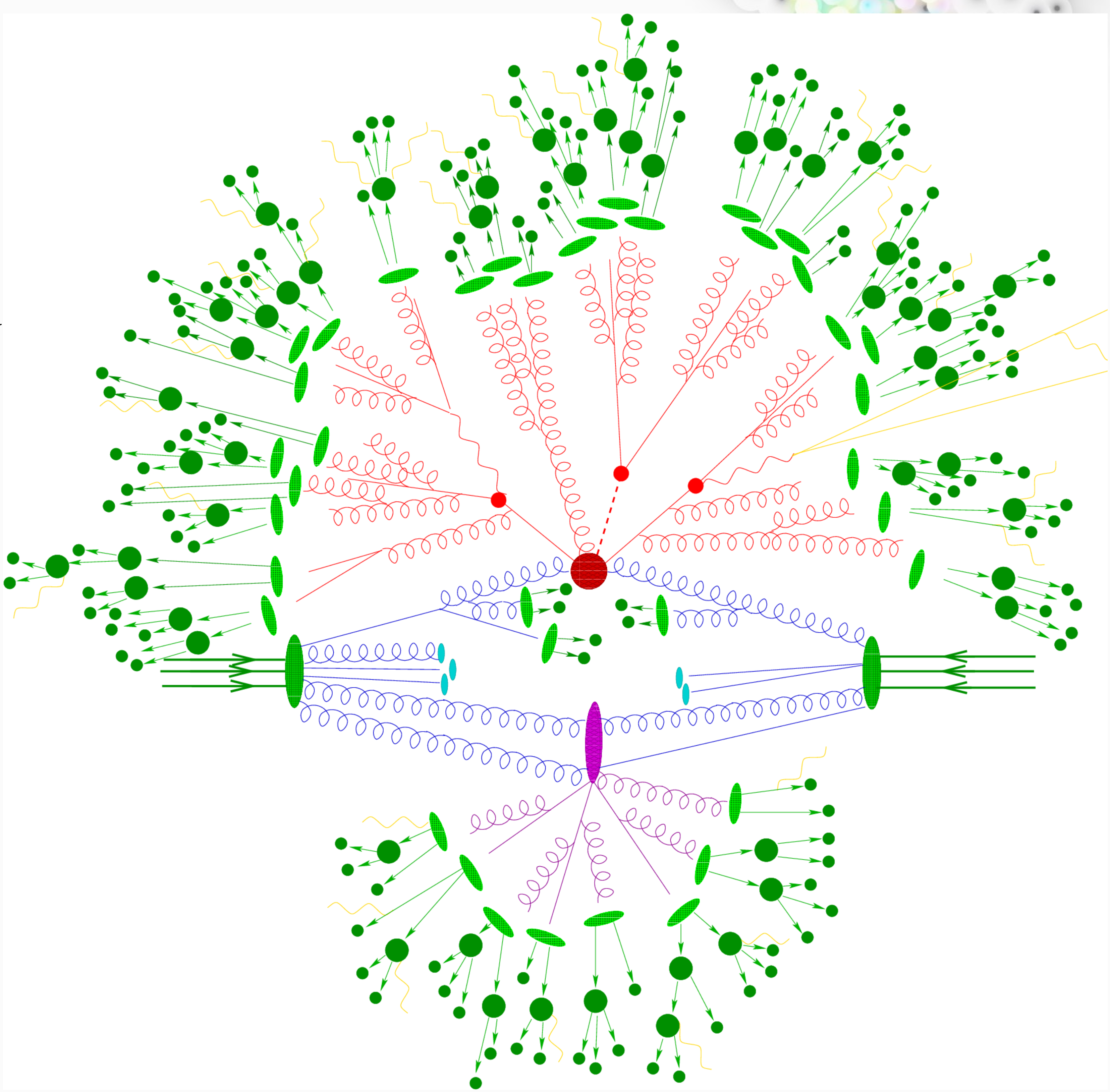


- Mechanism that confines back quarks and gluons into hadrons;



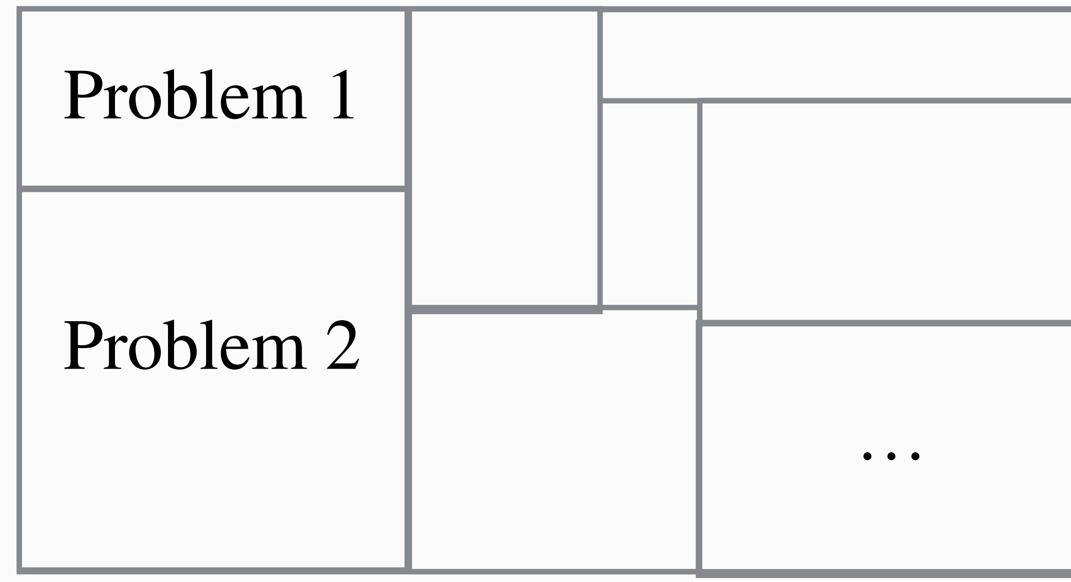
# Summary

- Result of an Event Generator:
  - ‘Real’ event as if could be observed by a perfect detector.
  - Output can be used now to interface to the detector simulation



# More MC Event Generators

- Typical hadronic event generator (PYTHIA) contains the subprocesses mentioned so far:



# More MC Event Generators

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| Hard Scattering | |
|---|---|
| IS Shower<br>PDFs | FS Shower<br>FFs |
| Beam Remnants/MPI | Hadro |

# More MC Event Generators

- Typical hadronic event generator (PYTHIA) contains the subprocesses mentioned so far:

<table>
<tr><td colspan="2">Hard Scattering</td></tr>
<tr><td>IS Shower<br>PDFs</td><td>FS Shower<br>FFs</td></tr>
<tr><td>Beam Remnants/MPI</td><td>Hadro</td></tr>
</table>

- Other type of event generators include:
  - Cosmic Rays (for Extensive Air Showers)
  - Heavy-ions (+ Nuclear initial-state, High multiplicity, soft processes, in-medium energy loss, Collective behavior of the medium)
  - Multi-purpose parton event generators (BSM physics)
  - …

# Detector Simulation

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