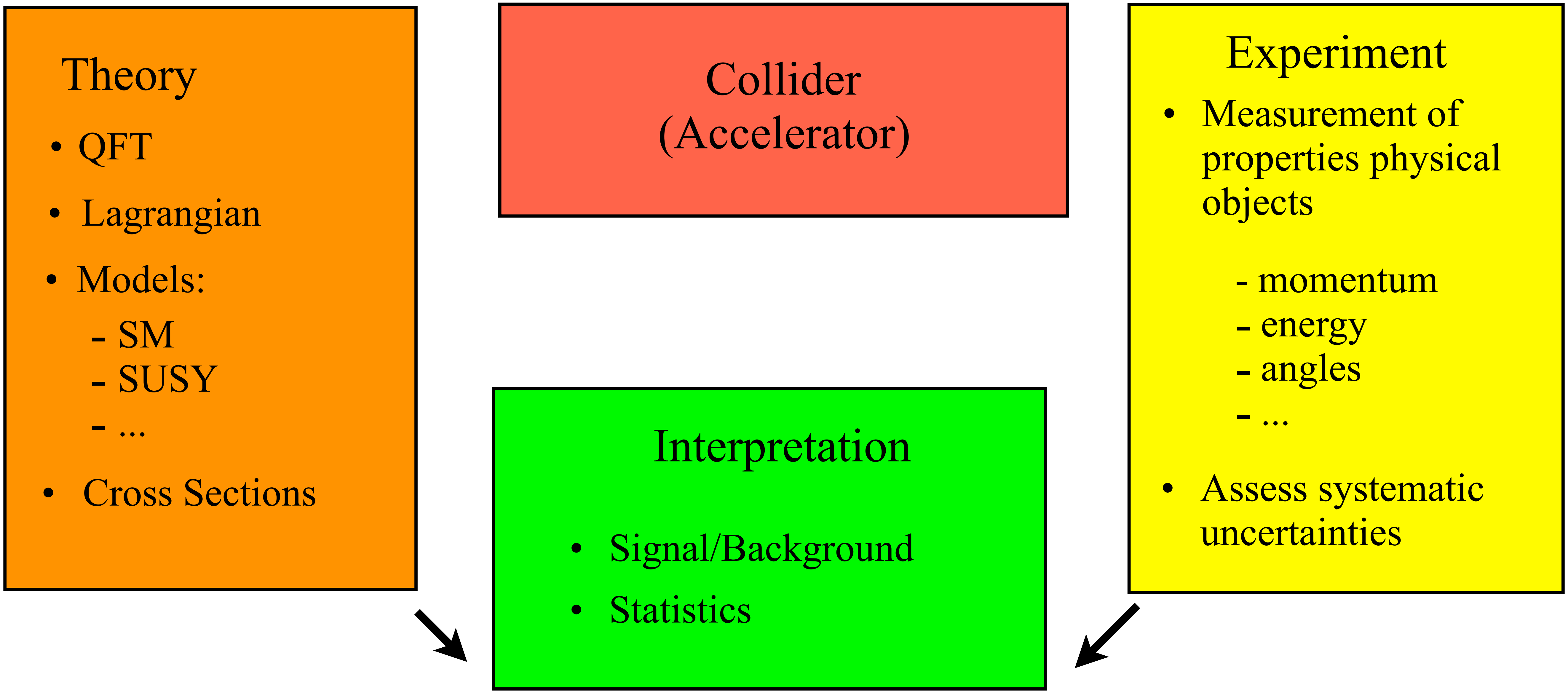
Collider Phenomenology: basics

Fabio Maltoni
Centre for Cosmology, Particle Physics and Phenomenology (CP3)
Université catholique de Louvain

Collider Physics

The purpose of collider physics is to test theoretical predictions experimentally in a controllable environment



Theory

- QFT
- Lagrangian
- Models:
  - SM
  - SUSY
  - ...
- Cross Sections

Collider (Accelerator)

Experiment

- Measurement of properties physical objects
  - momentum
  - energy
  - angles
  - ...
- Assess systematic uncertainties

Interpretation

- Signal/Background
- Statistics

Collider	Site	Initial State	Energy	Discovery / Target
SPEAR	SLAC	e^+e^-	4 GeV	charm quark, tau lepton
PETRA	DESY	e^+e^-	38 GeV	gluon
Sp$\bar{\text{p}}$S	CERN	$p\bar{p}$	600 GeV	W, Z bosons
LEP	CERN	e^+e^-	210 GeV	SM: elw and QCD
SLC	SLAC	e^+e^-	90 GeV	elw SM
HERA	DESY	ep	320 GeV	quark/gluon structure of proton
Tevatron	FNAL	$p\bar{p}$	2 TeV	top quark
BaBar / Belle	SLAC / KEK	e^+e^-	10 GeV	quark mix / CP violation
LHC	CERN	pp	7/8/14 TeV	Higgs boson, elw. sb, New Physics
ILC		e^+e^-	> 200 GeV	hi. res of elw sb / Higgs couplings
CLIC		e^+e^-	3 - 5 TeV	hi. res of elw sb / Higgs couplings
FCC		pp	100 TeV	disc. multi-TeV physics

The reach of collider facilities

$A + B \to M$ production in 2-particle collisions: $M^2 = (p_1 + p_2)^2$

<u>fixed target:</u>

$$p_1 \simeq (E, 0, 0, E)$$
$$p_2 = (m, 0, 0, 0)$$

$$M \simeq \sqrt{2mE}$$

root increase in M

- root E law: large energy loss in E_{kin}
- dense target: large collision rate / luminosity

<u>collider target:</u>

$$p_1 = (E, 0, 0, E)$$
$$p_2 = (E, 0, 0, -E)$$

$$M \simeq 2E$$

- linear E law: no energy loss
- less dense bunches: small collision rates

Collider characteristics

Energy: ranges from a few GeV to several TeV (LHC)

Luminosity: measures the rate of particles in colliding bunches

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$

$N_i =$ number of particles in bunches

$A =$ transverse bunch area

$f =$ bunch collision rate

$\mathcal{L}\sigma =$ observed rate for process with cross section σ

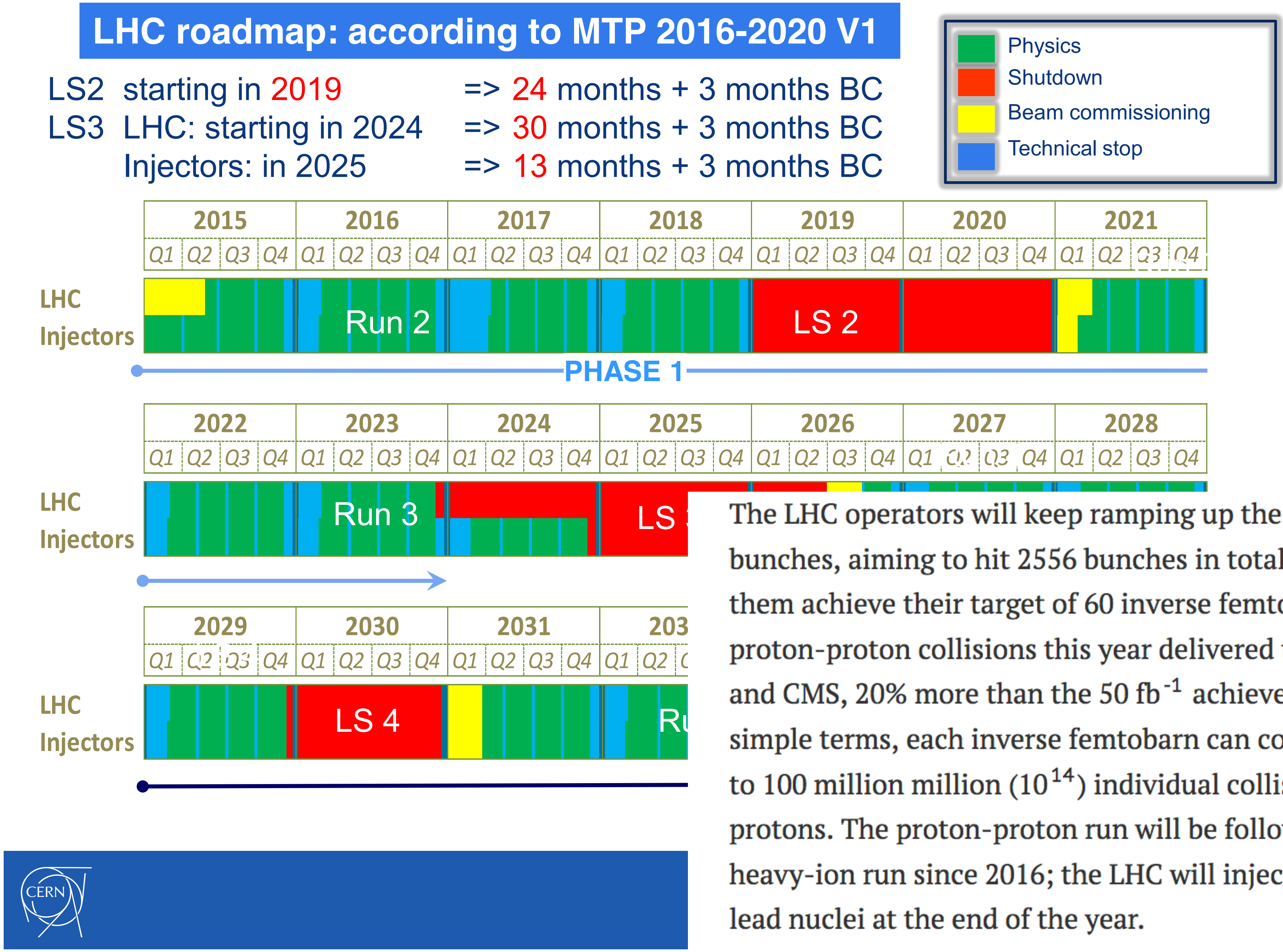
LHC (targeted): $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \rightarrow 300\ \mathrm{fb}^{-1}$ in 3 years

Circular vs linear collider:

charged particles in circular motion: permanently accelerated towards center -> emitting photons as synchrotron light $\Delta E \sim E^4/R$

- large loss of energy [hypothetical TeV collider at LEP: $\Delta E \simeq E$ per turn]
- no-more sharp initial state energy

LHC schedule



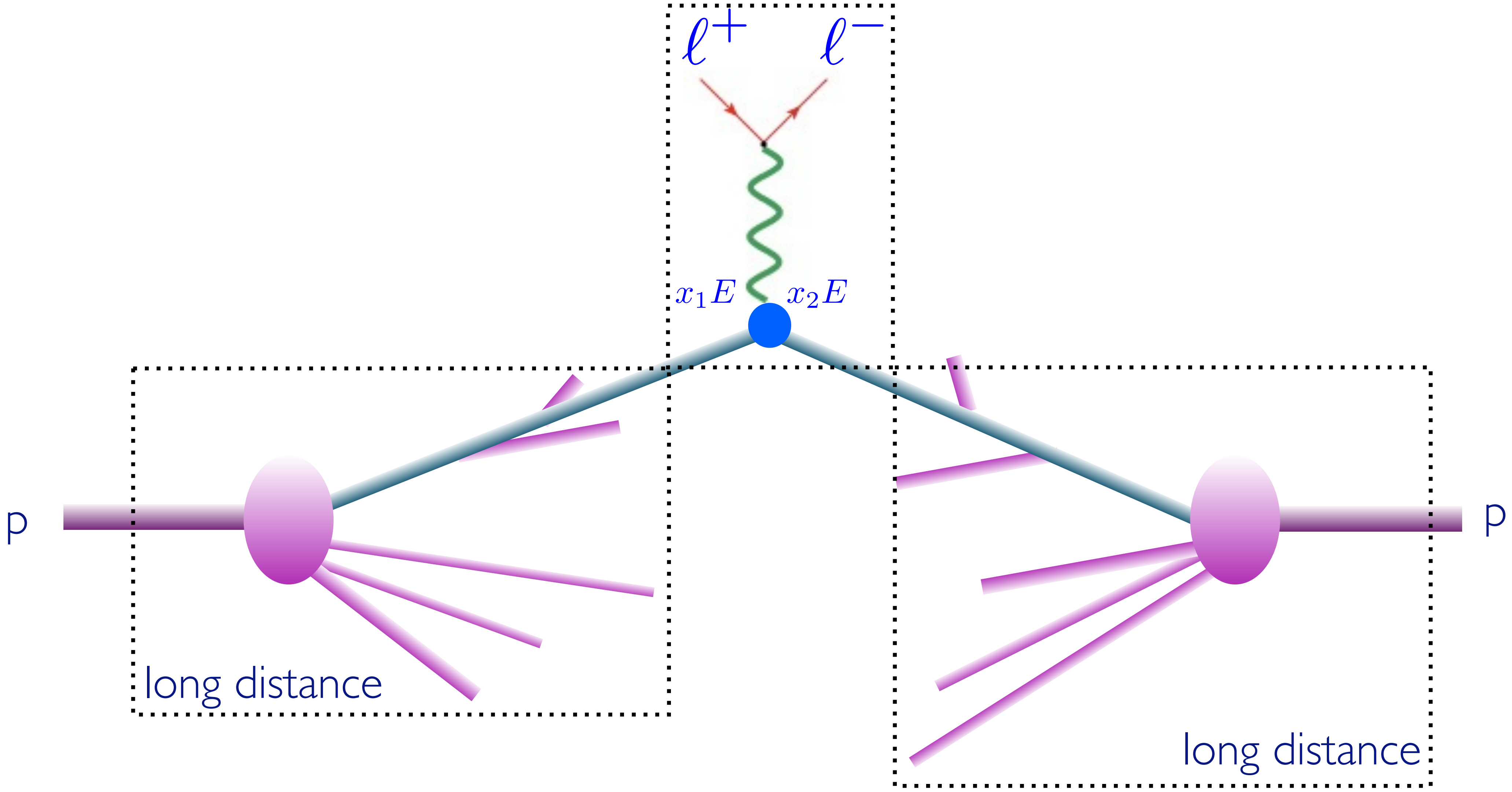
LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

- 🟩 Physics
- 🟥 Shutdown
- 🟨 Beam commissioning
- 🟦 Technical stop

The LHC operators will keep ramping up the number of bunches, aiming to hit 2556 bunches in total. This will help them achieve their target of 60 inverse femtobarns (fb^{-1}) of proton-proton collisions this year delivered to both ATLAS and CMS, 20% more than the 50 fb^{-1} achieved in 2017. In simple terms, each inverse femtobarn can correspond to up to 100 million million (10^{14}) individual collisions between protons. The proton-proton run will be followed by the first heavy-ion run since 2016; the LHC will inject and collide lead nuclei at the end of the year.

LHC master formula



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1,x_2,\alpha_S(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2})$$

LHC master formula

More exactly

$$\sigma_X = \sum_{a,b}\int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2)\, f_b(x_2,\mu_F^2)\times \hat{\sigma}_{ab\to X}\left(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

where the partonic cross section is calculated by

$$\hat{\sigma}_{a,b\to k} = \frac{1}{2s}\int\left[\Pi_{i=1}^{n}\frac{d^3\vec{q}_i}{(2\pi)^3 2E_i}\right]\left[(2\pi)^4\delta^4\left(\sum_i q_i^\mu - (p_1+p_2)^\mu\right)\right]|\mathcal{M}_{ab\to k}(\mu_F,\mu_R)|^2$$

[flux factor] × [phase space (LiPS)] × [squared matrix element]

Crucial pieces for the calculation of the hadronic cross section are the **parton distribution functions** $f_{i/p}$ and the **squared matrix element** $|\mathcal{M}|^2$

LHC master formula

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

Two ingredients necessary:

1. Parton Distribution Functions (from exp, but evolution from th).

2. Short distance coefficients as an expansion in α_S (from th).

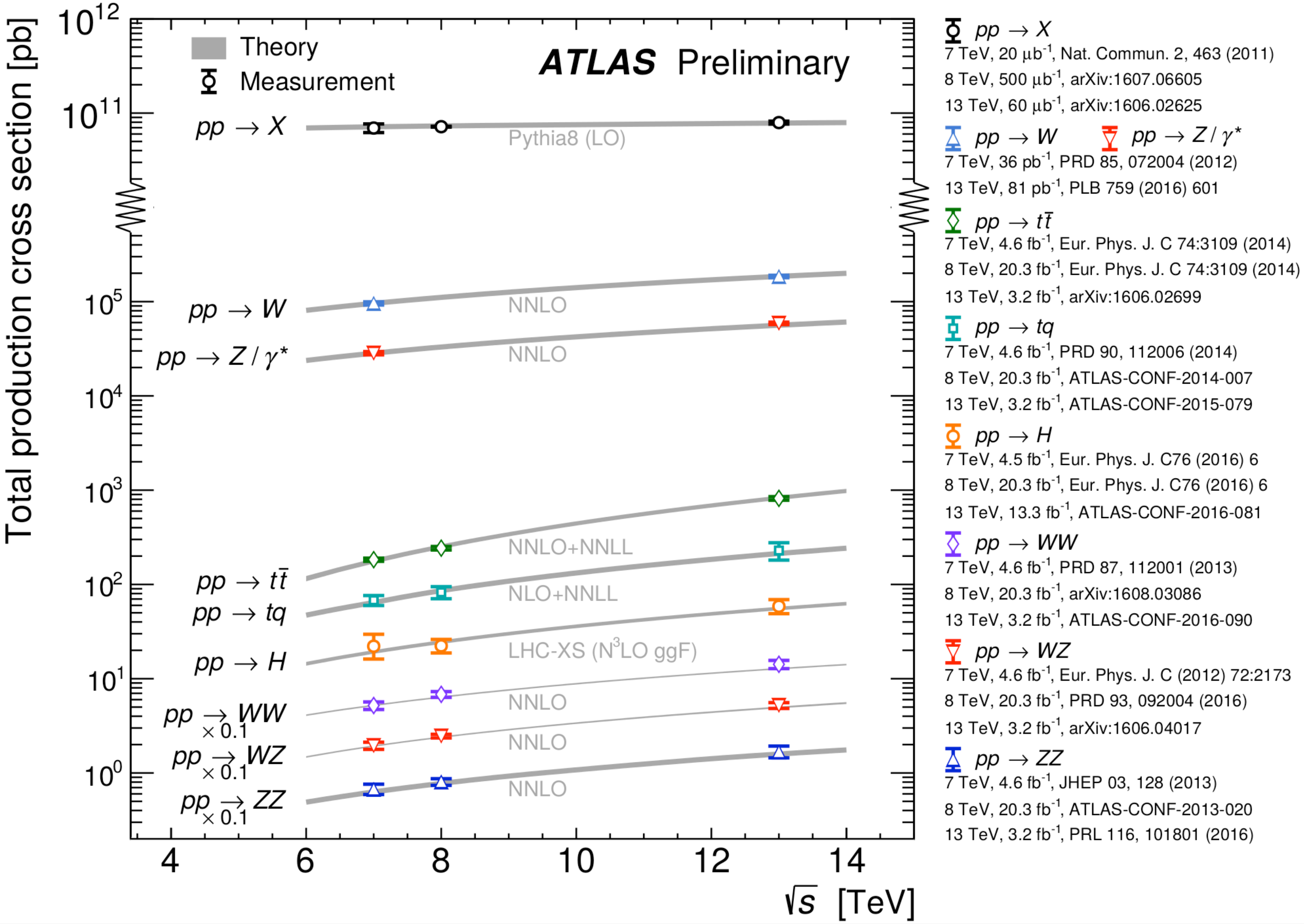
$$\hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

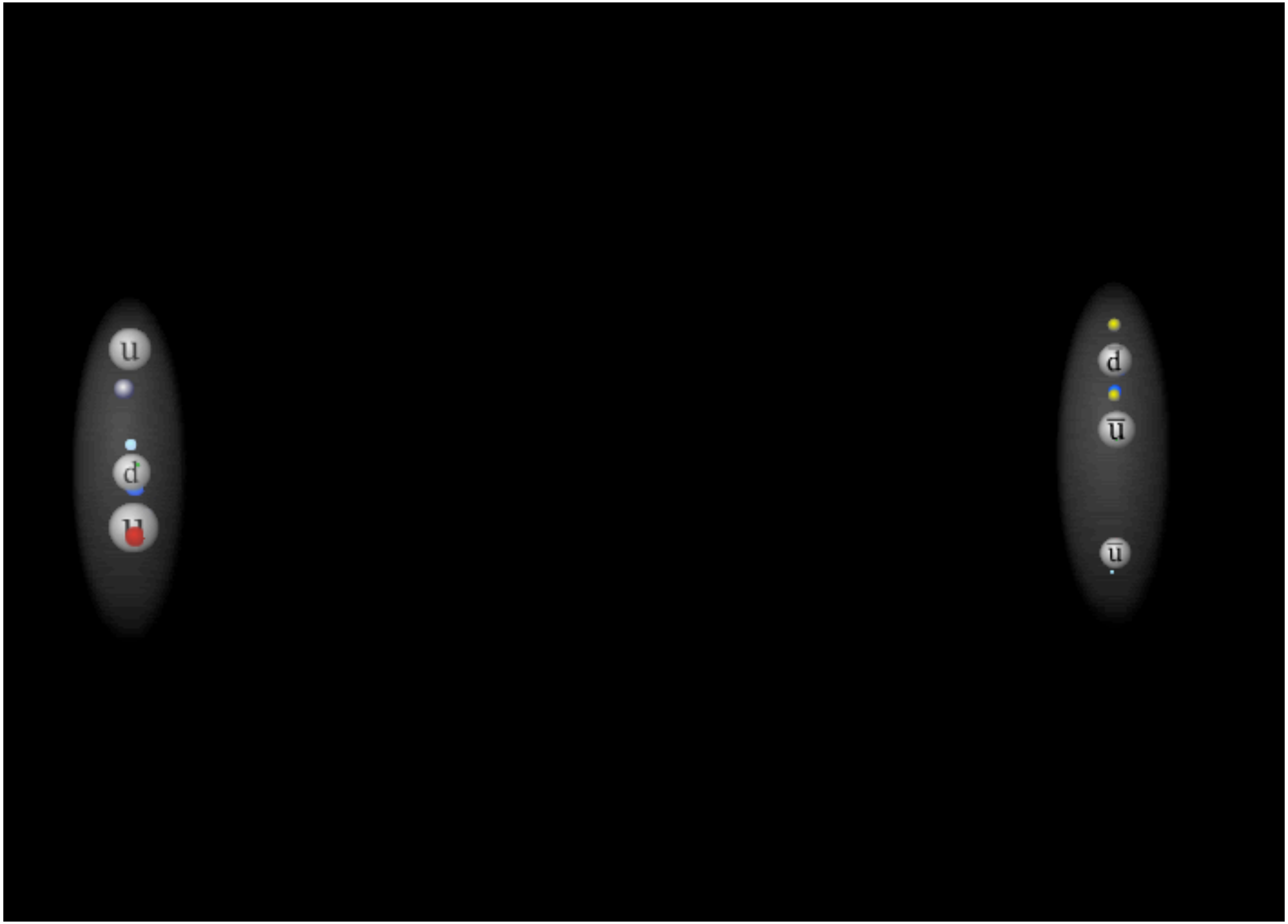
Leading order

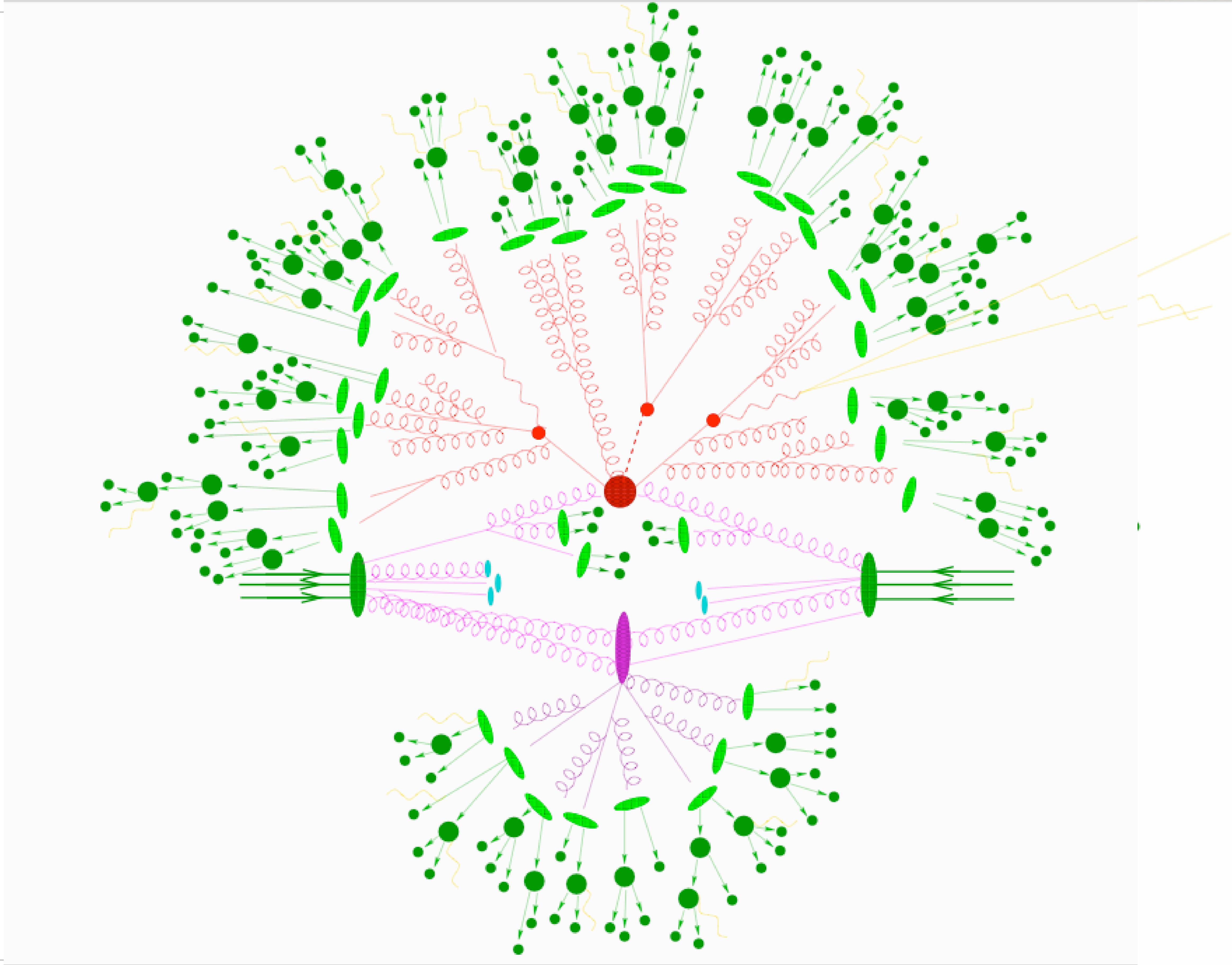
Next-to-leading order

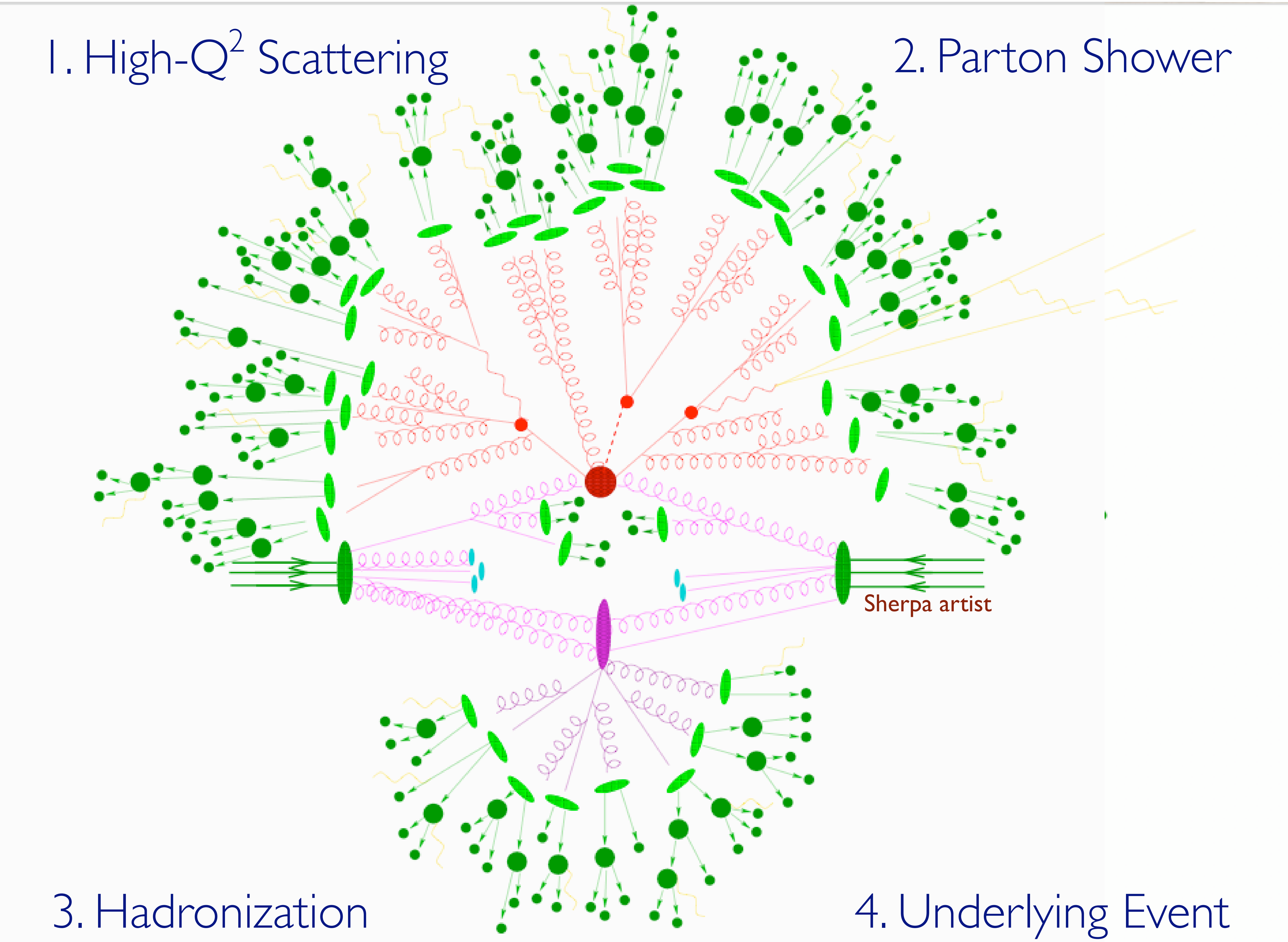
Next-to-next-to-leading order

LHC Physics = QCD + ϵ




u
d
u
d
ū
ū





1. High-Q^2 Scattering

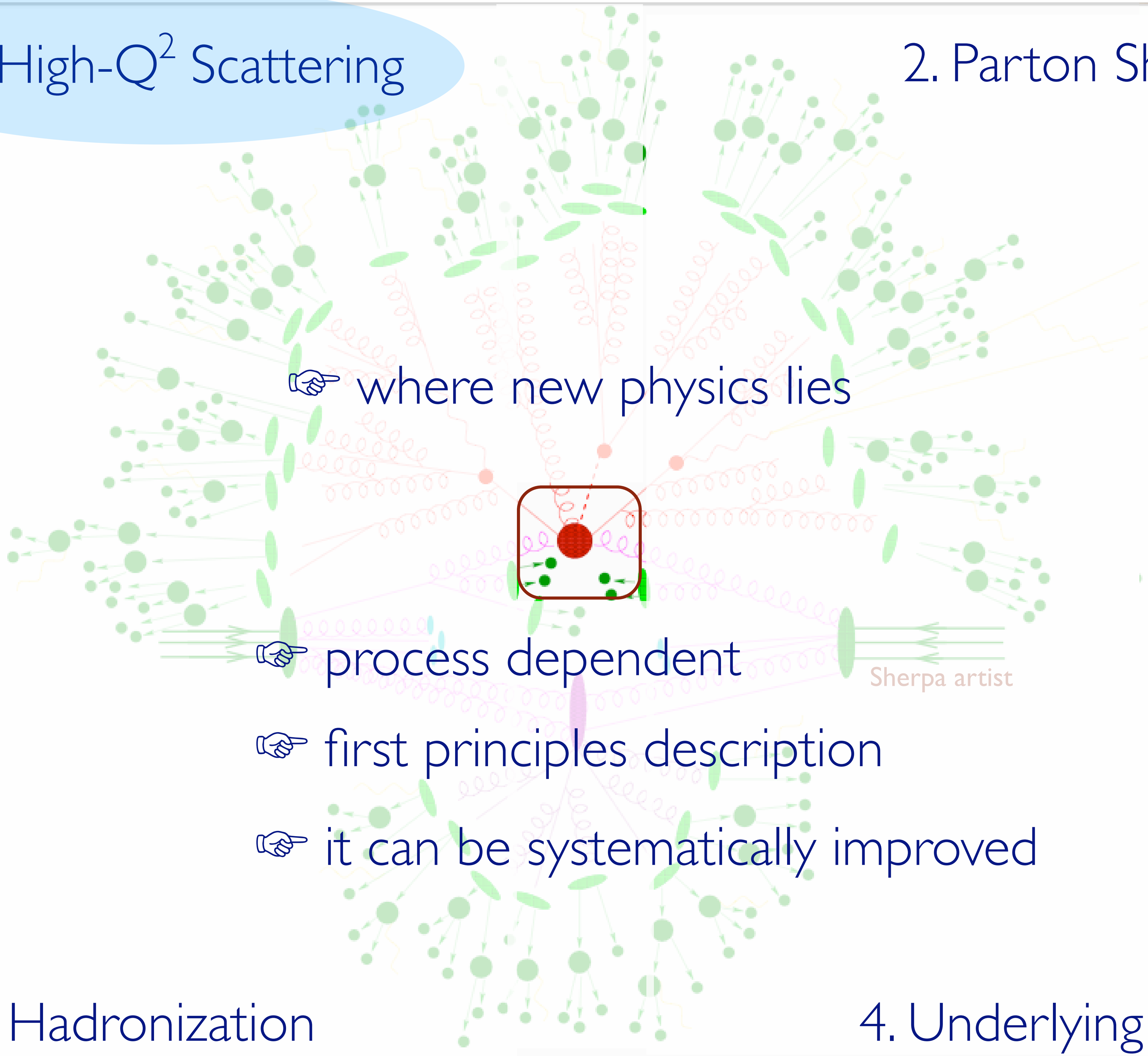
2. Parton Shower

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



☞ where new physics lies

☞ process dependent

☞ first principles description

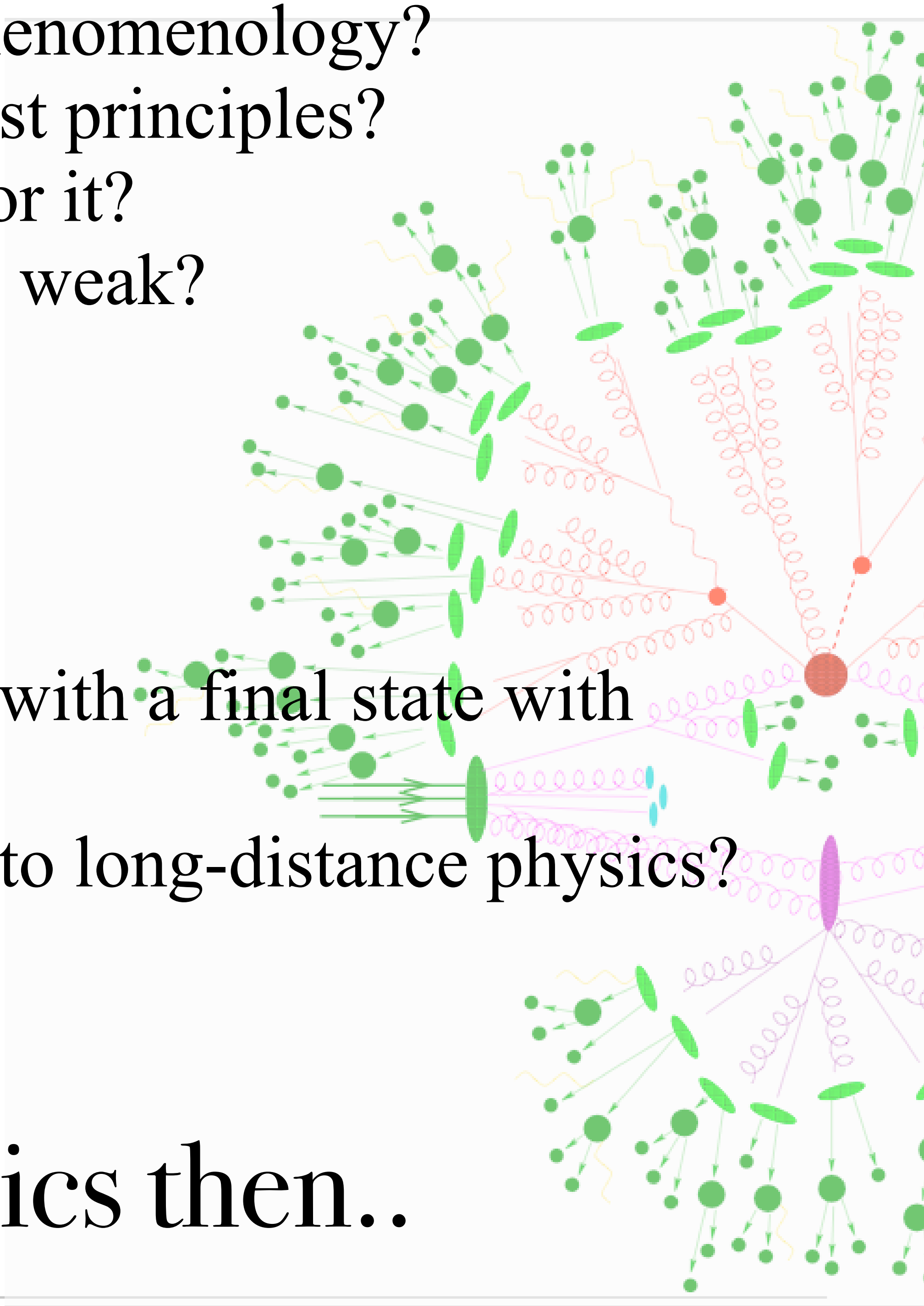
☞ it can be systematically improved

3. Hadronization

4. Underlying Event

Basic (QCD) questions

- What does the LHC master formula imply for phenomenology?
- Can the LHC master formula be derived from first principles?
- What are the key properties of QCD that allow for it?
- Why do we treat strong interactions as they were weak?
- Would an abelian gauge theory also work?
- What about non-perturbative physics?
- Are fixed-order calculations meaningful?
- What is resummation?
- How do I relate a calculation with a few partons with a final state with hundreds/thousands of hadrons?
- How do I define observables that are insensitive to long-distance physics?
- What are jets?
- What is an inclusive vs an exclusive quantity?



Let's go back to the basics then..