Collider Phenomenology

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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$\bar{p}$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
FCC-ee/CEPC/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		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 $E_{\rm kin}$
- 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

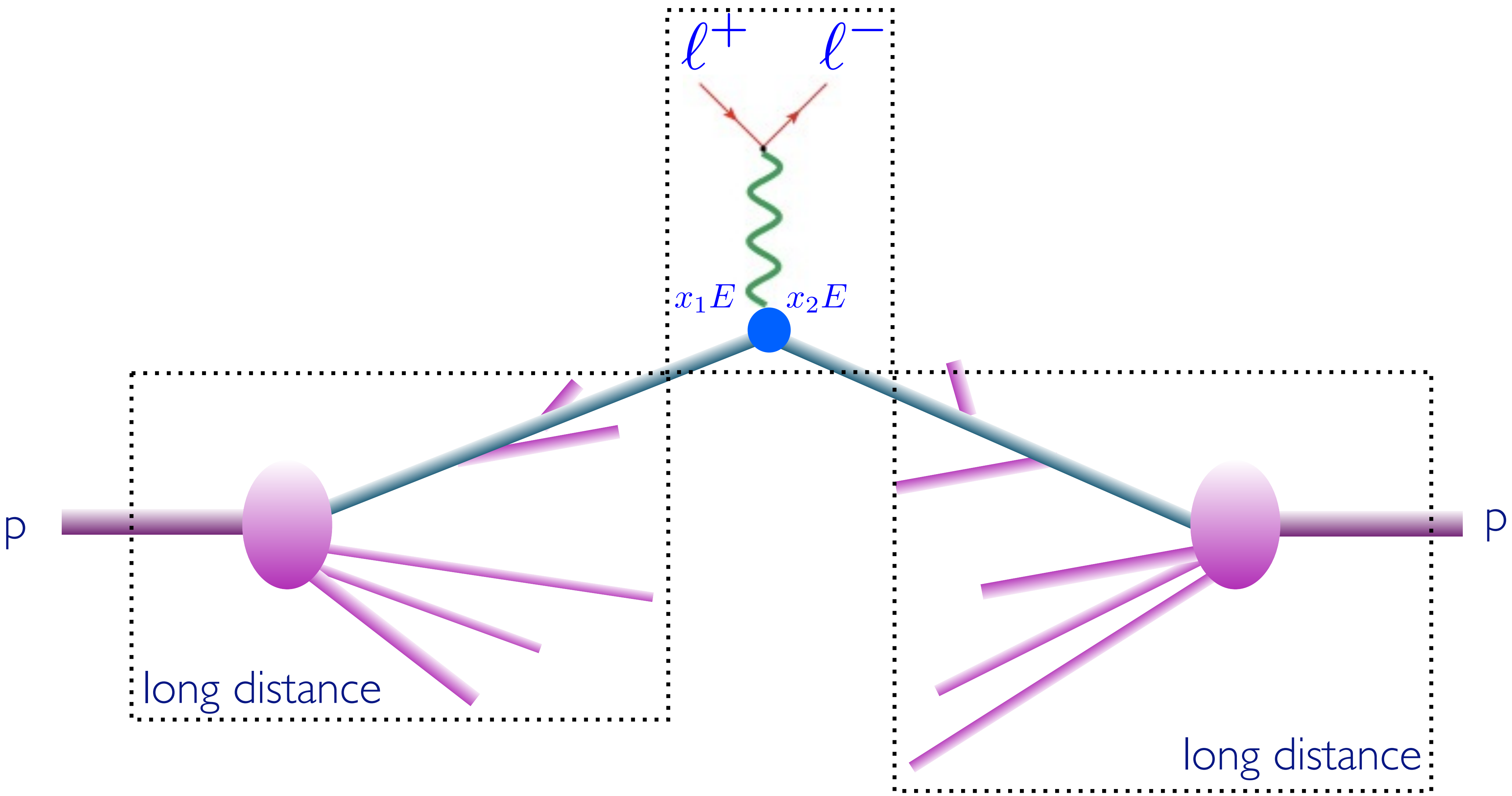
LHC (targeted): $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ → $300\ \mathrm{fb}^{-1}$ in 3 years

Circular vs linear collider:

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

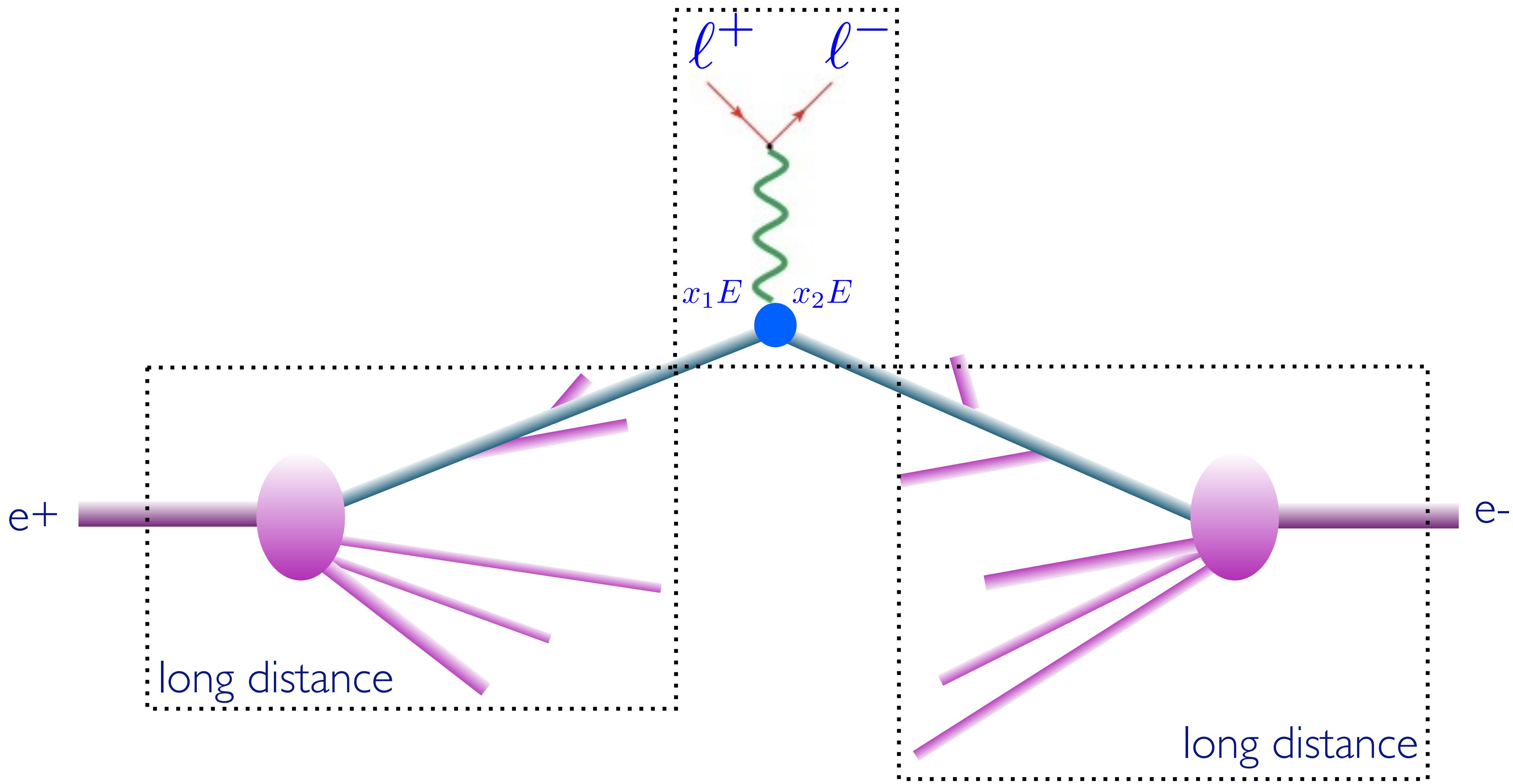
- large loss of energy [hypothetical TeV collider at LEP: $\Delta E \simeq E$ per turn]
- no-more sharp initial state energy

LHC master formula



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

CEPC master formula

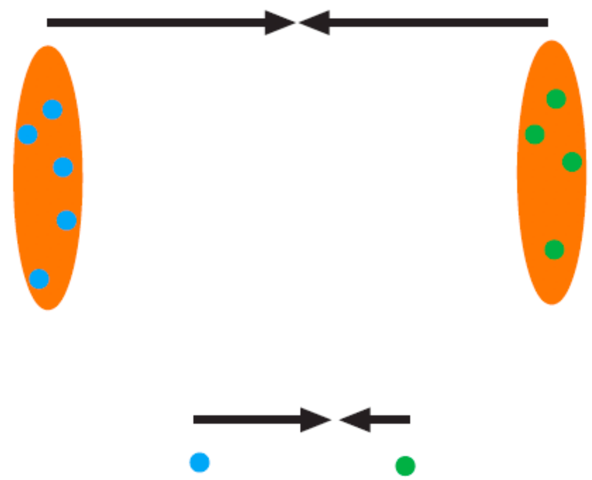


$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

Kinematics

We describe the collision in terms of parton energies

E1= x1 Ebeam
E2= x2 Ebeam

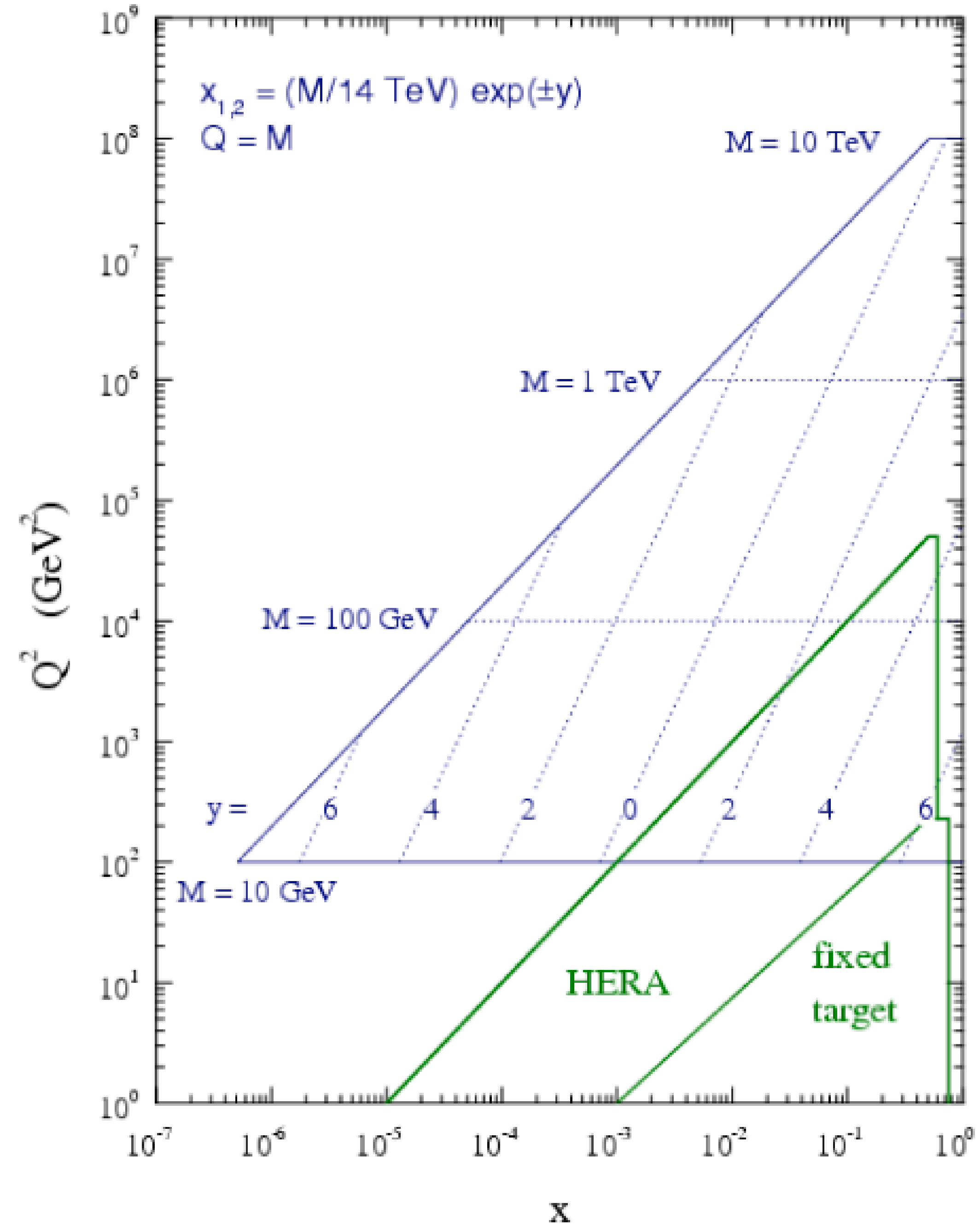


Obviously the partonic c.m.s. frame will be in general boosted. Let us say that the two partons annihilate into a particle of mass M.

$$M^2 = x_1 x_2 S = x_1 x_2 4 E_{\mathrm{beam}}^2$$

$$y = \frac{1}{2} \log \frac{x_1}{x_2}$$

$$x_1 = \frac{M}{\sqrt{S}} e^{y} \quad x_2 = \frac{M}{\sqrt{S}} e^{-y}$$



LHC master formula

More exactly

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

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** $|\mathcal{M}|^2$

A simple example: $t\bar{t}$

Let's see how to calculate the cross section for a simple process such as pp → ttbar. There are two initial states possible, gg and qqbar. For gg (which will dominate at the LHC) we obtain:

$$\frac{d\sigma}{d\hat{s}} = \int_0^1 \int_0^1 dx_1 dx_2\, g(x_1,\mu_F) g(x_2,\mu_F)\, \hat{\sigma}(\hat{s}) \delta(\hat{s} - x_1 x_2 s)$$

We introduce the variable tau, that is proportional to x1 and x2:

$$\tau \equiv \frac{\hat{s}}{s} = x_1 x_2$$

and obtain

$$\frac{d\sigma}{d\tau} = \int_0^1 \int_0^1 dx_1 dx_2\, g(x_1,\mu_F) g(x_2,\mu_F)\, \frac{\hat{\sigma}(\hat{s})}{\tau} \delta\left(1 - \frac{x_1 x_2}{\tau}\right)$$

A simple example: $t\bar{t}$

$$\frac{d\sigma}{d\tau} = \frac{\hat{\sigma}(\hat{s})}{\tau} \boxed{\int_\tau^1 \frac{dx_1}{x_1} g(x_1) g(\frac{\tau}{x_1})}$$

We define the dimensionless partonic luminosity:

$$\frac{dL_{gg}}{d\tau} \equiv \int_\tau^1 \frac{dx_1}{x_1} g(x_1) g(\frac{\tau}{x_1})$$

and calculate the total cross section as:

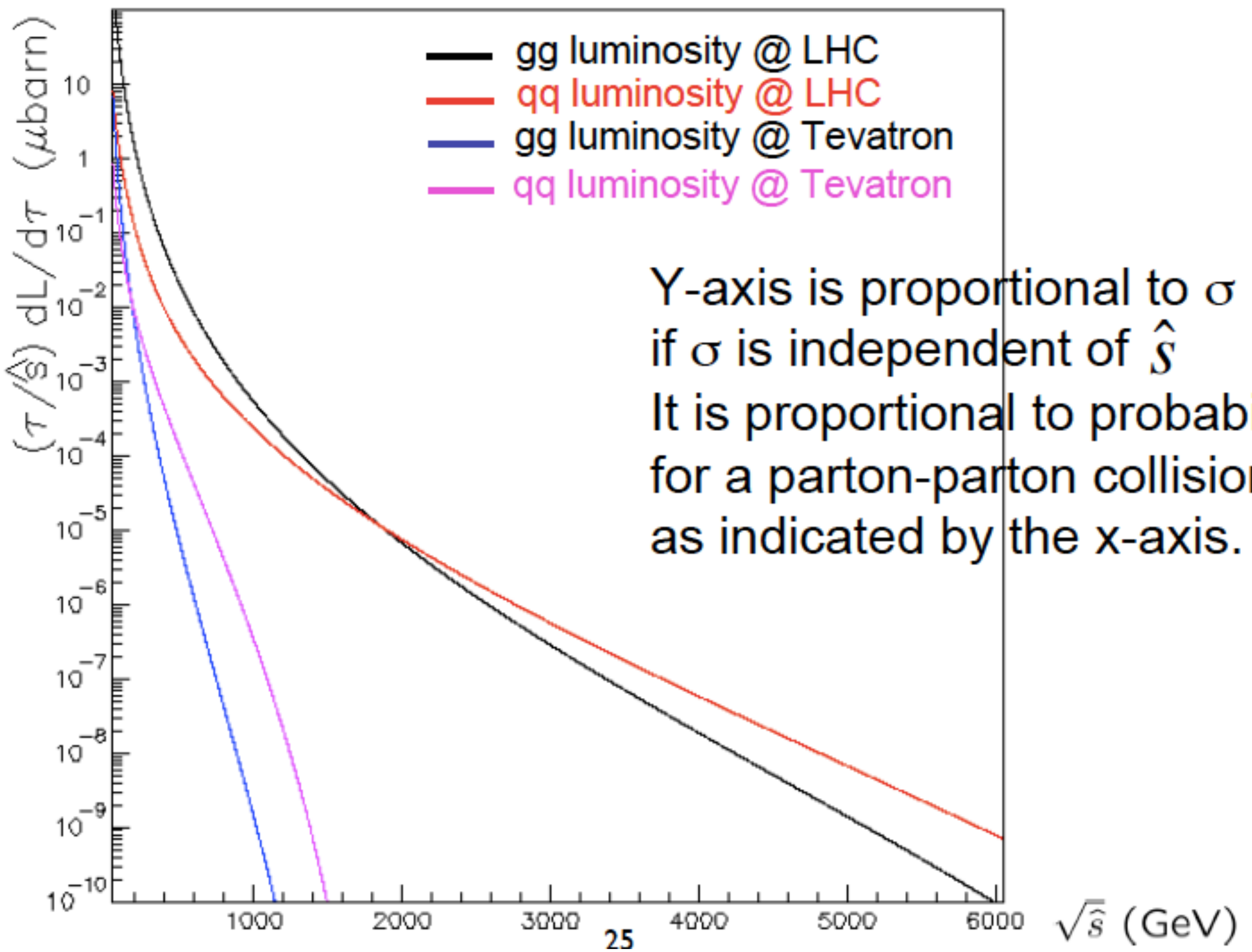
$$\sigma(pp \to t\bar{t} + X) = \int_{\tau_{\min}}^1 d\tau \cdot \hat{\sigma}_{gg\to t\bar{t}}(s\tau) \cdot \frac{dL}{d\tau}$$

$$= \int_{\tau_{\min}}^1 \frac{d\tau}{\tau} \cdot [\hat{s}\hat{\sigma}_{gg\to t\bar{t}}(\hat{s})] \cdot \frac{\tau dL}{\hat{s} d\tau}$$

CLOSE TO A CONSTANT

"CROSS SECTION"

A simple example: $t\bar{t}$



Y-axis is proportional to σ if σ is independent of $\hat{s}$
It is proportional to probability for a parton-parton collision with $\hat{s}$ as indicated by the x-axis.

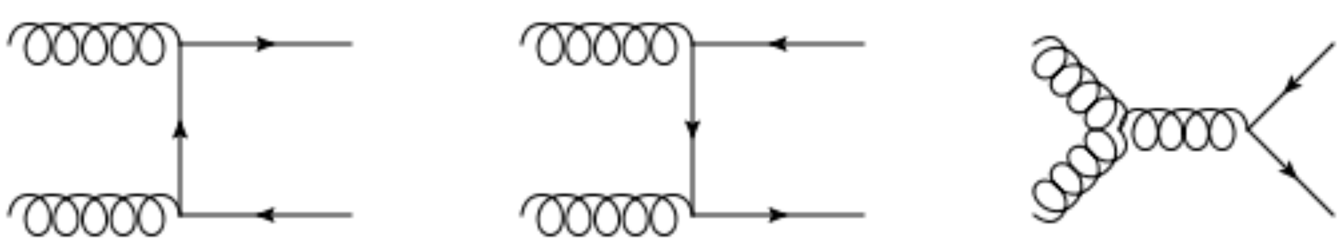
A simple example: $t\bar{t}$

$$\frac{dL_{gg}}{d\tau} \equiv \int_\tau^1 \frac{dx_1}{x_1} g(x_1) g(\frac{\tau}{x_1})$$

If we take for simplicity $$g(x) = \frac{1}{x^{1+\delta}} \Rightarrow \frac{dL_{gg}}{d\tau} = \frac{1}{\tau^{1+\delta}} \log \tau$$

i.e. the total "cross section" will scale as a power of 1/mt$^{1+delta}$ Log Mt

The short distance coefficient can be easily calculated at LO via the feynman diagrams:



A simple example: $t\bar{t}$

$$\frac{1}{256}|M|^2 = \frac{3g_s^4}{4}\frac{(m^2-t)(m^2-u)}{s^2} - \frac{g_s^4}{24}\frac{m^2(s-4m^2)}{(m^2-t)(m^2-u)} + \frac{g_s^4}{6}\frac{tu-m^2(3t+u)-m^4}{(m^2-t)^2}$$
$$+\frac{g_s^4}{6}\frac{tu-m^2(t+3u)-m^4}{(m^2-u)^2} - \frac{3g_s^4}{8}\frac{tu-2m^2t+m^4}{s(m^2-t)} - \frac{3g_s^4}{8}\frac{tu-2m^2u+m^4}{s(m^2-u)}$$

3 diagrams squared + the interferences. This amplitude is integrated over the phase space at fixed shat:

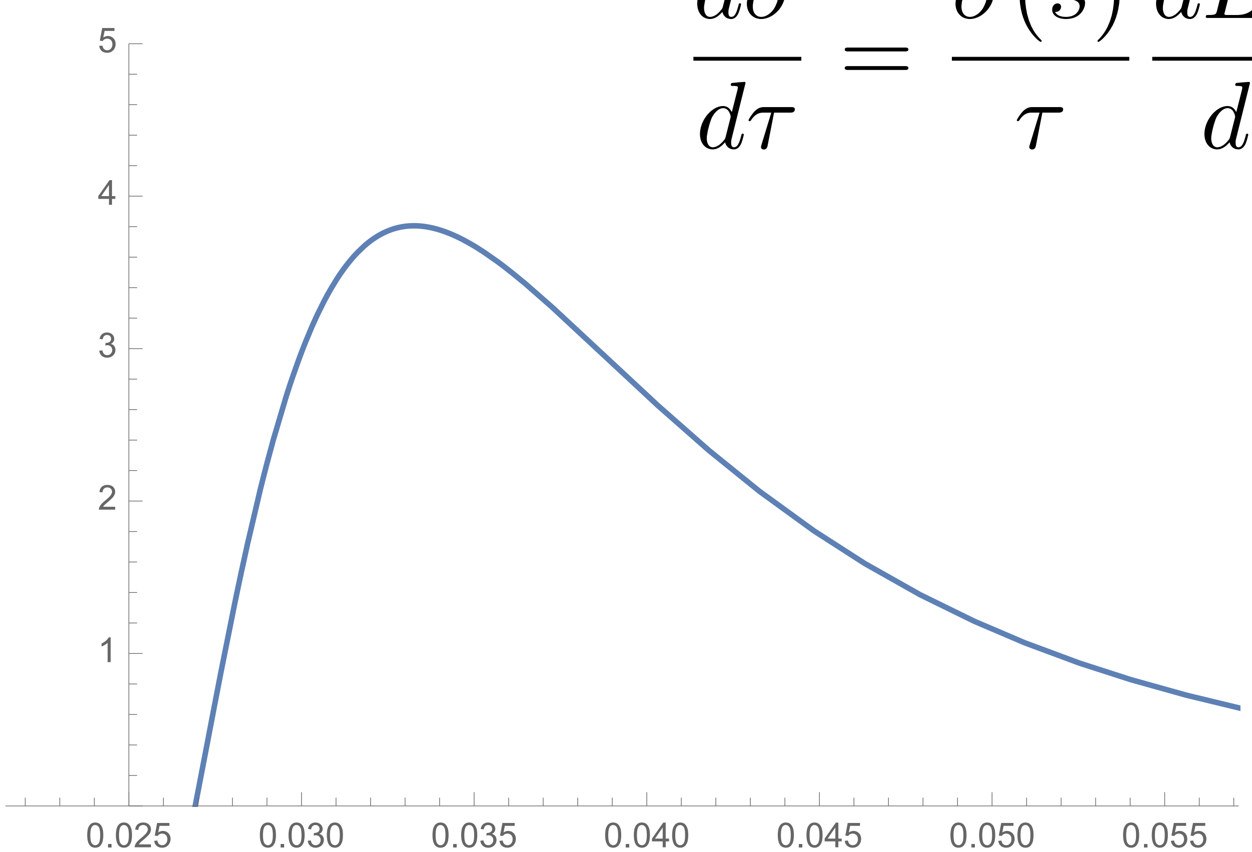
$$\hat{\sigma}_{gg\to t\bar{t}} = \frac{1}{2\hat{s}}\,\beta\,2\pi\int_{-1}^{+1} d\cos\theta^*\;|M|^2/256$$

eventually giving:

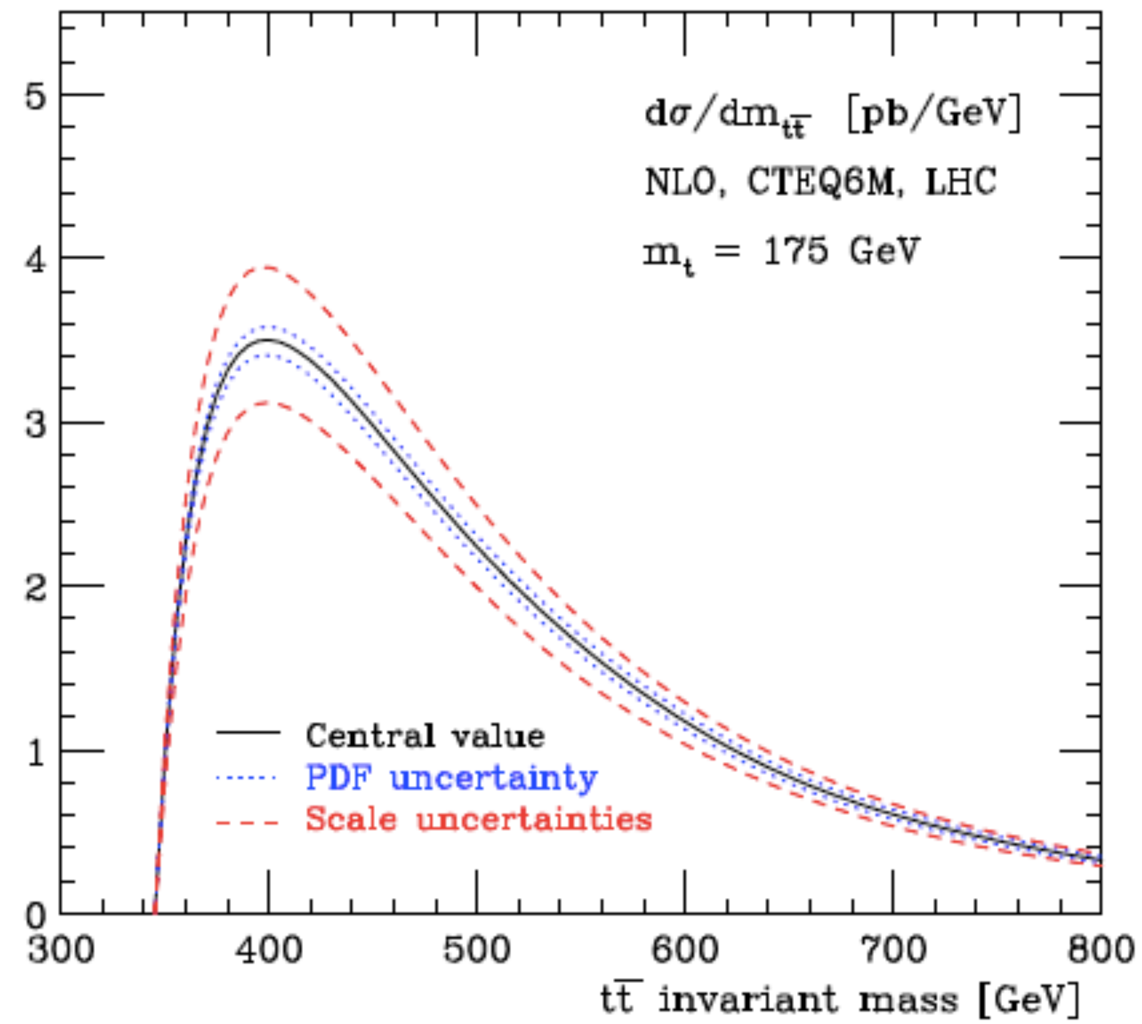
$$\beta = \sqrt{1-4m_t^2/\hat{s}}$$
$$\hat{\sigma}_{gg\to t\bar{t}} = \frac{\pi\alpha_s^2\beta}{48\hat{s}}\left(31\beta + \left(\frac{33}{\beta} - 18\beta + \beta^3\right)\ln\left[\frac{1+\beta}{1-\beta}\right] - 59\right)$$

A simple example: $t\bar{t}$

$$\frac{d\sigma}{d\tau} = \frac{\hat{\sigma}(\hat{s})}{\tau}\frac{dL_{gg}}{d\tau}$$



LO estimation with toy pdf (δ=0.3)



NLO result with proper MC

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

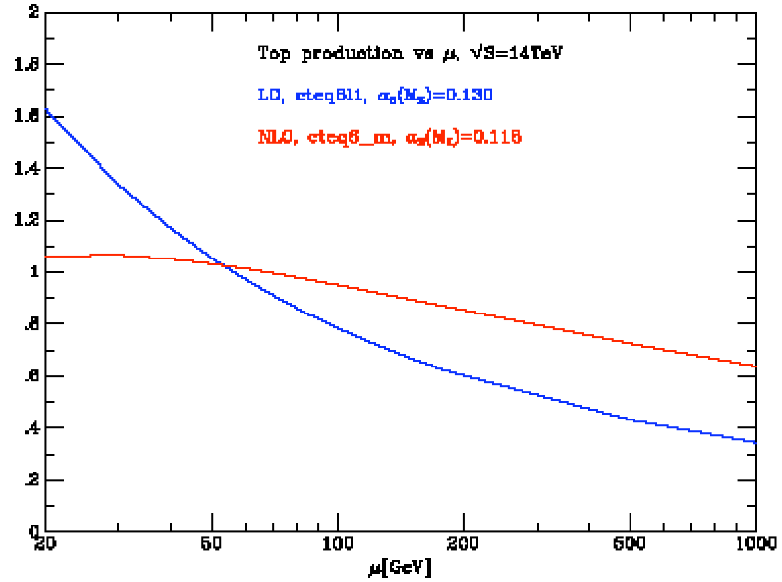
Next-to-next-to-leading order

Perturbative expansion

- Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions
  - the scale of αs is not defined
  - jets partons: jet structure starts to appear only beyond LO
  - Born topology might not be leading at the LHC

- To obtain reliable predictions at least NLO is needed

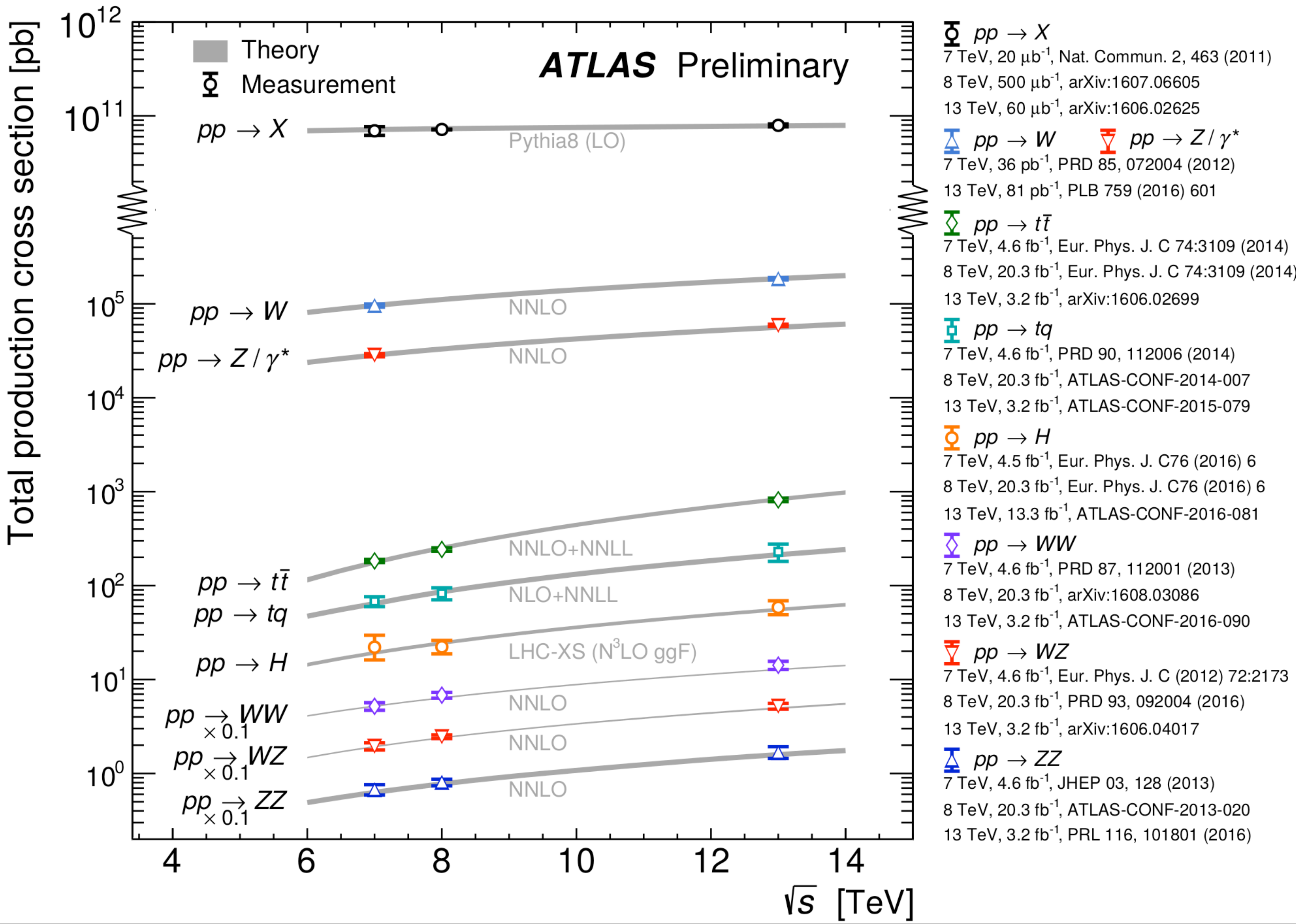
- NNLO allows to quantify uncertainties



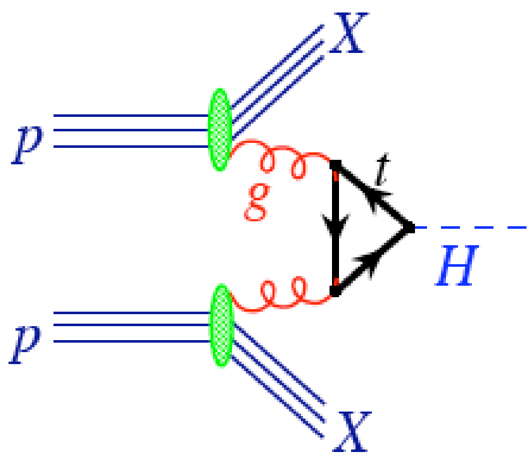
Furthermore:

- Resummation of the large logarithmic terms at phase space boundaries
- NLO ElectroWeak corrections ($\alpha_s^2 = \alpha_W$)
- Fully exclusive predictions available in terms of event simulation that can be used in experimental analysis

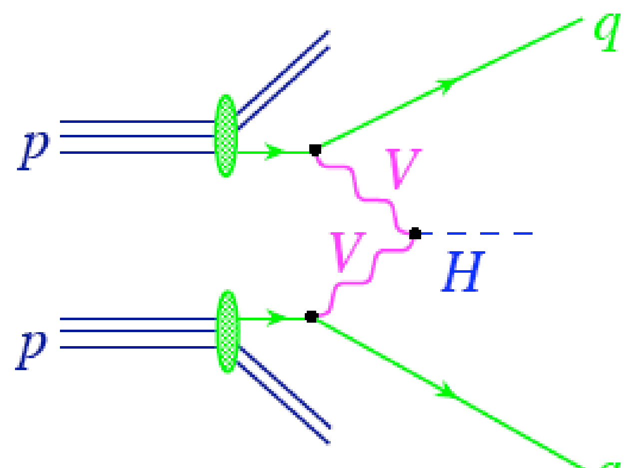
LHC Physics = QCD + ϵ



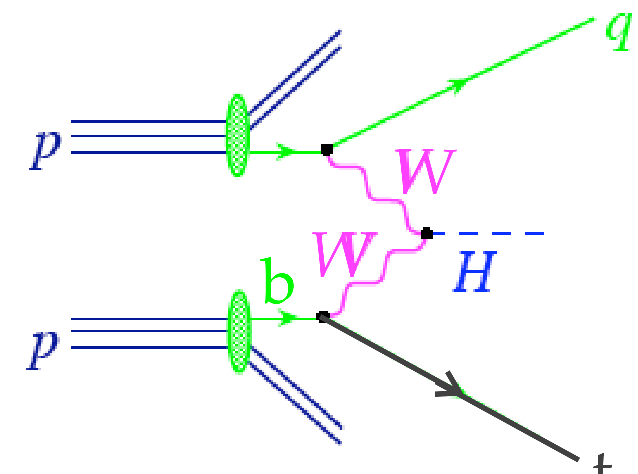
Higgs production channels



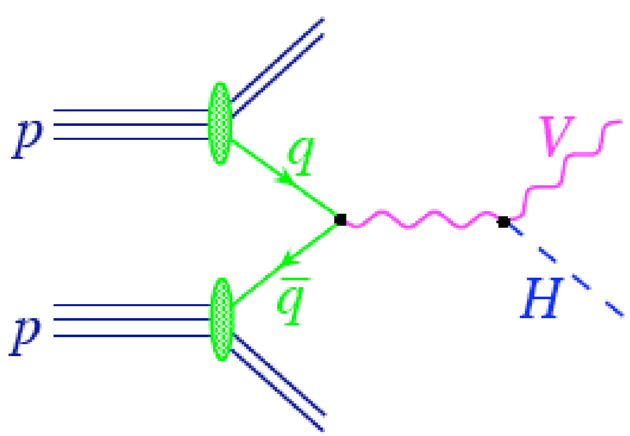
Gluon fusion



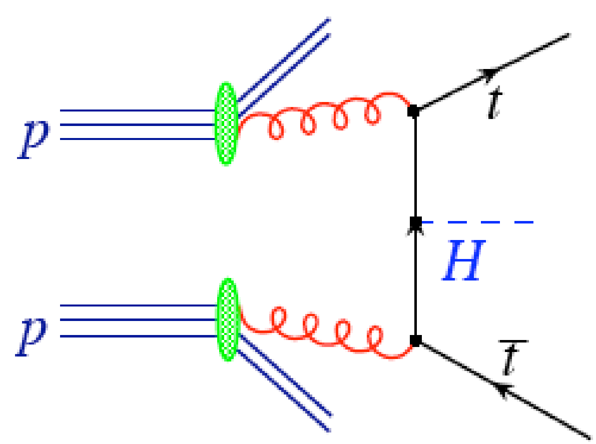
Weak-Boson Fusion



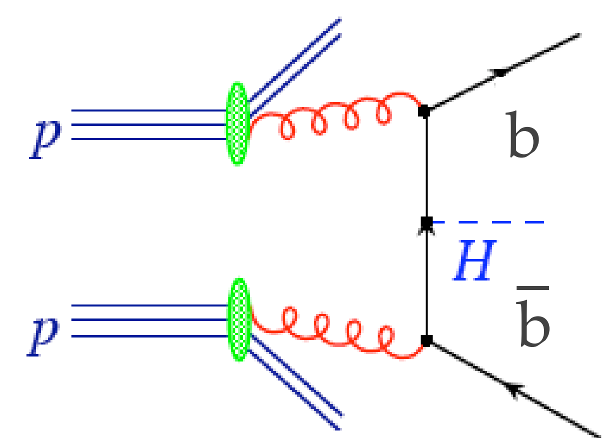
tHj



Higgs Strahlung

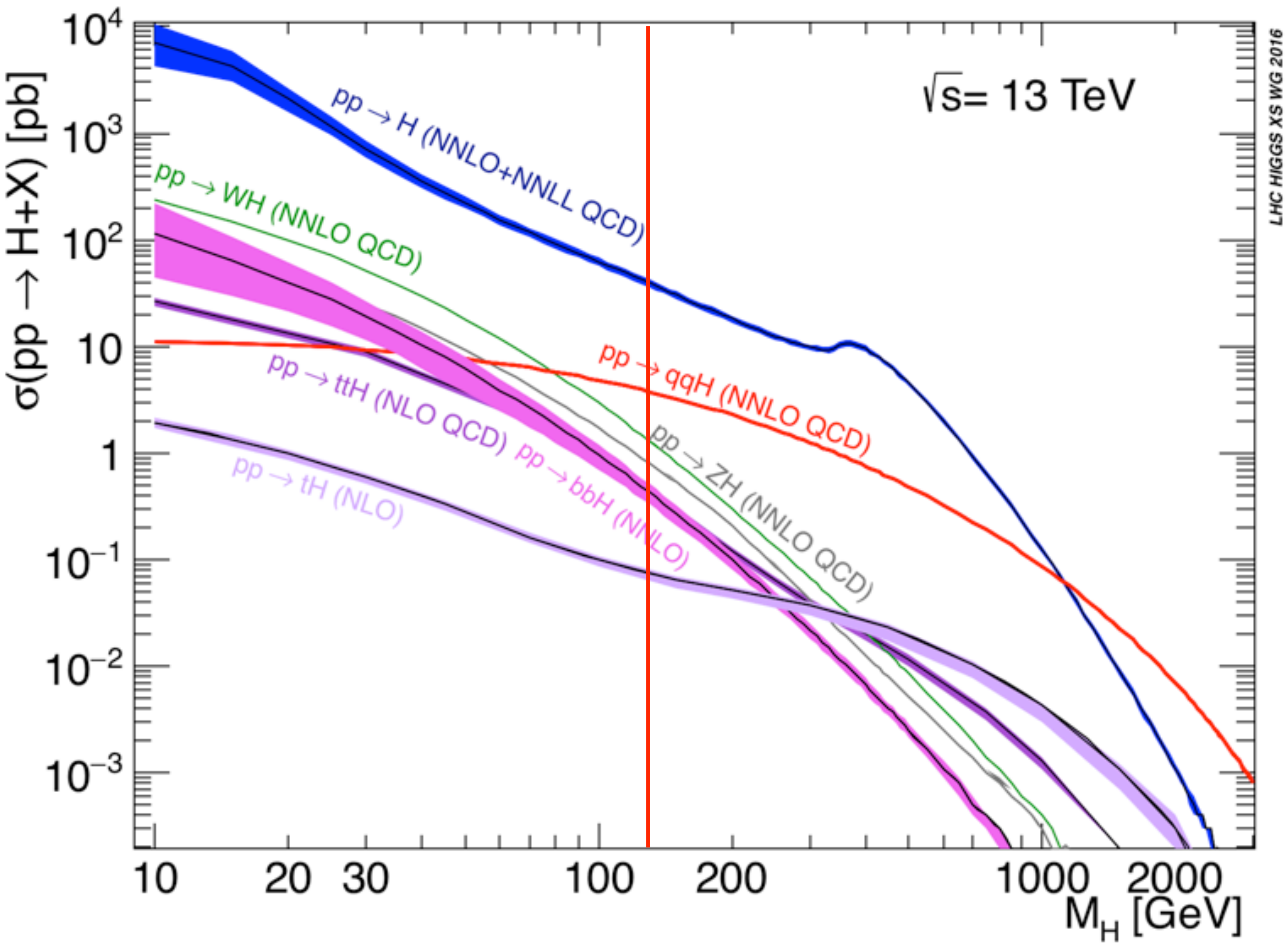


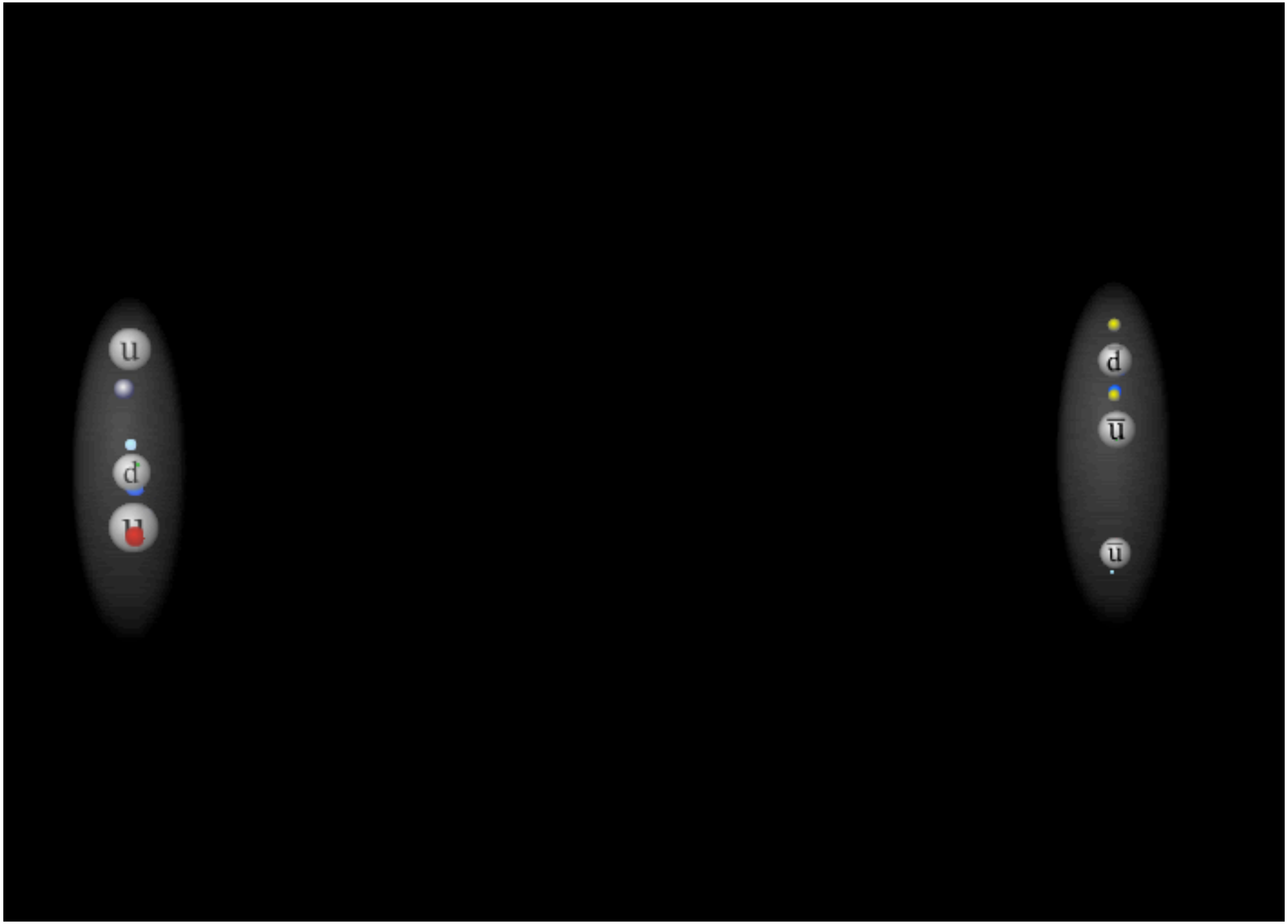
$t\bar{t}H$



bbH

Higgs production at the LHC

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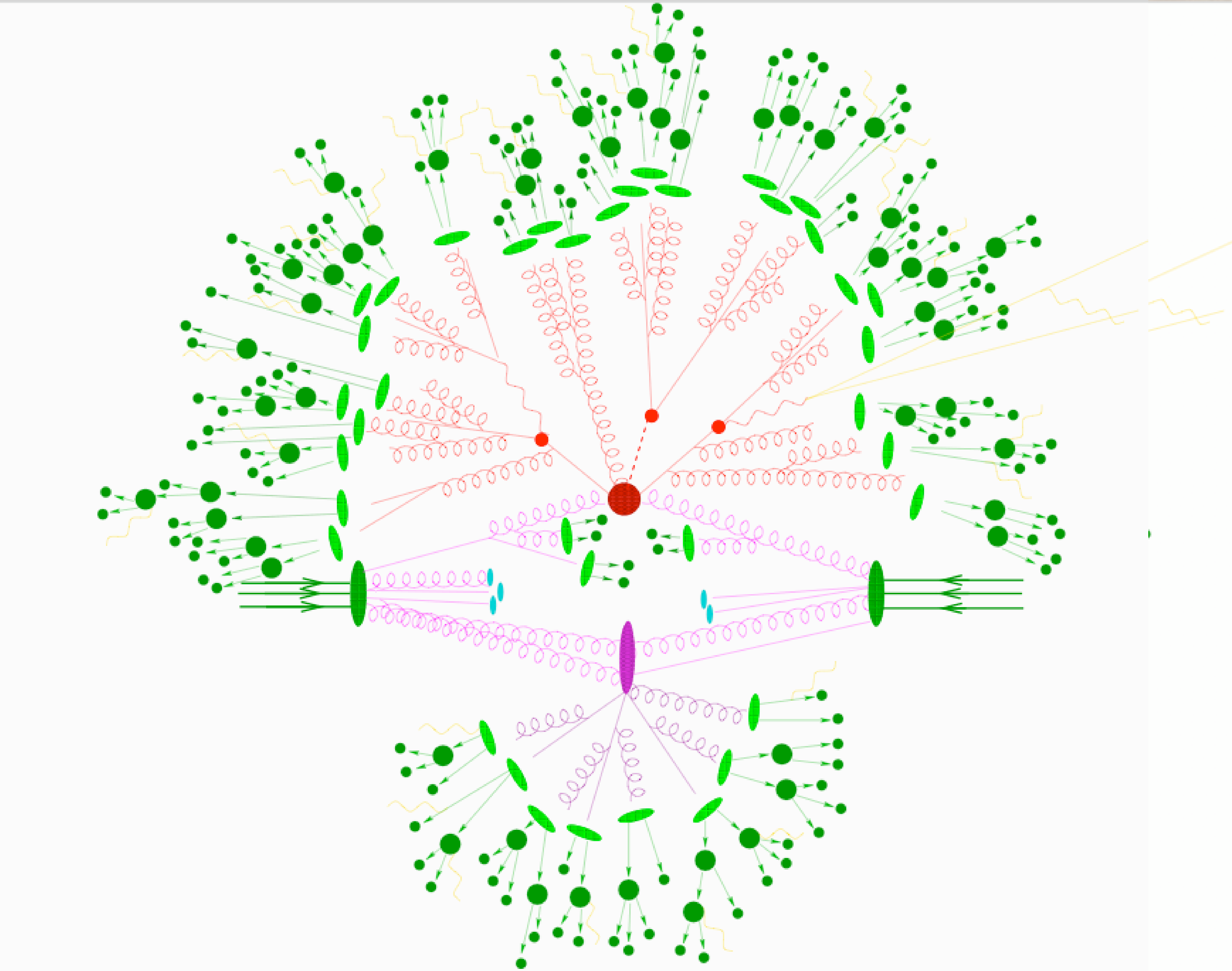
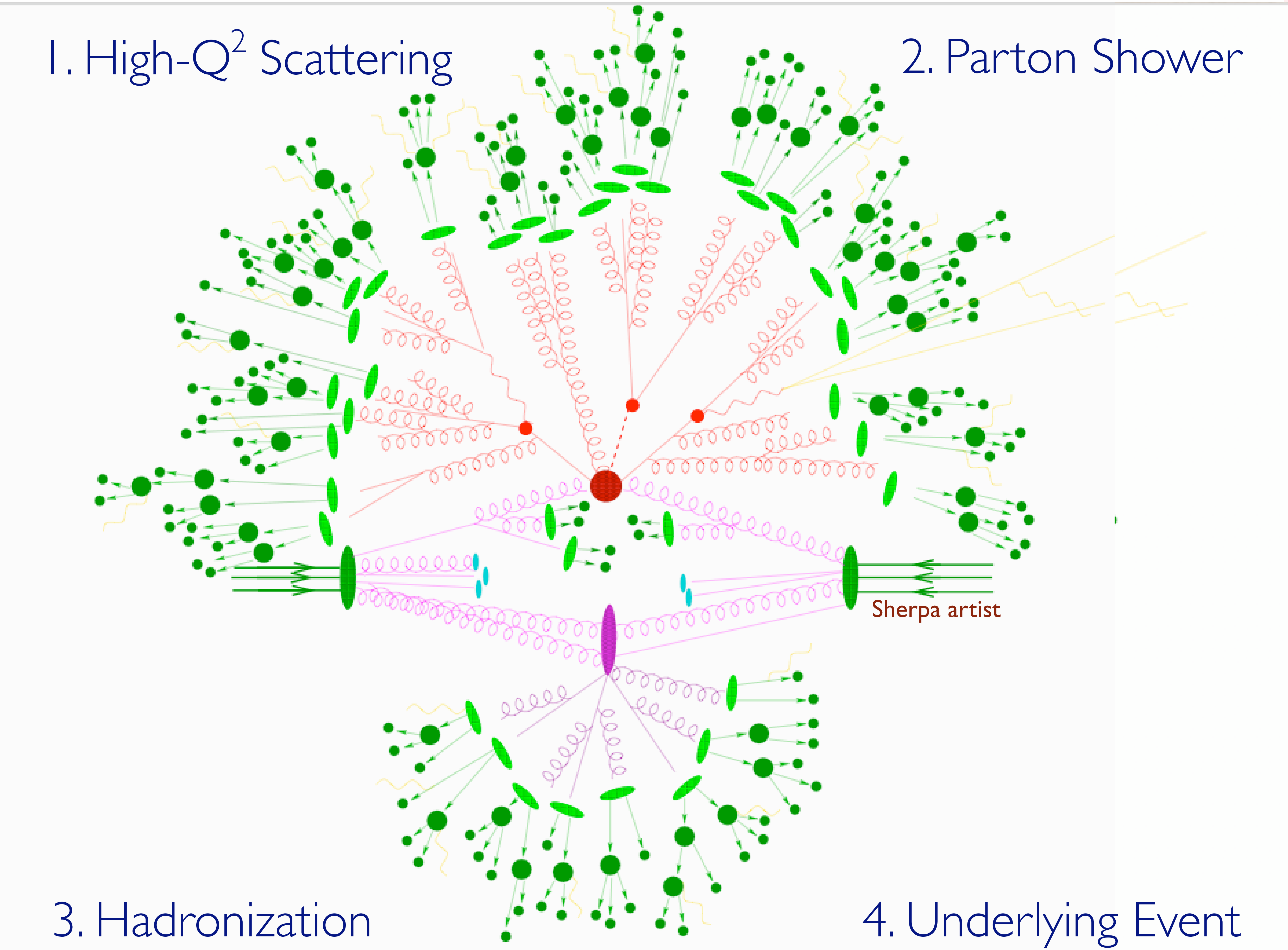
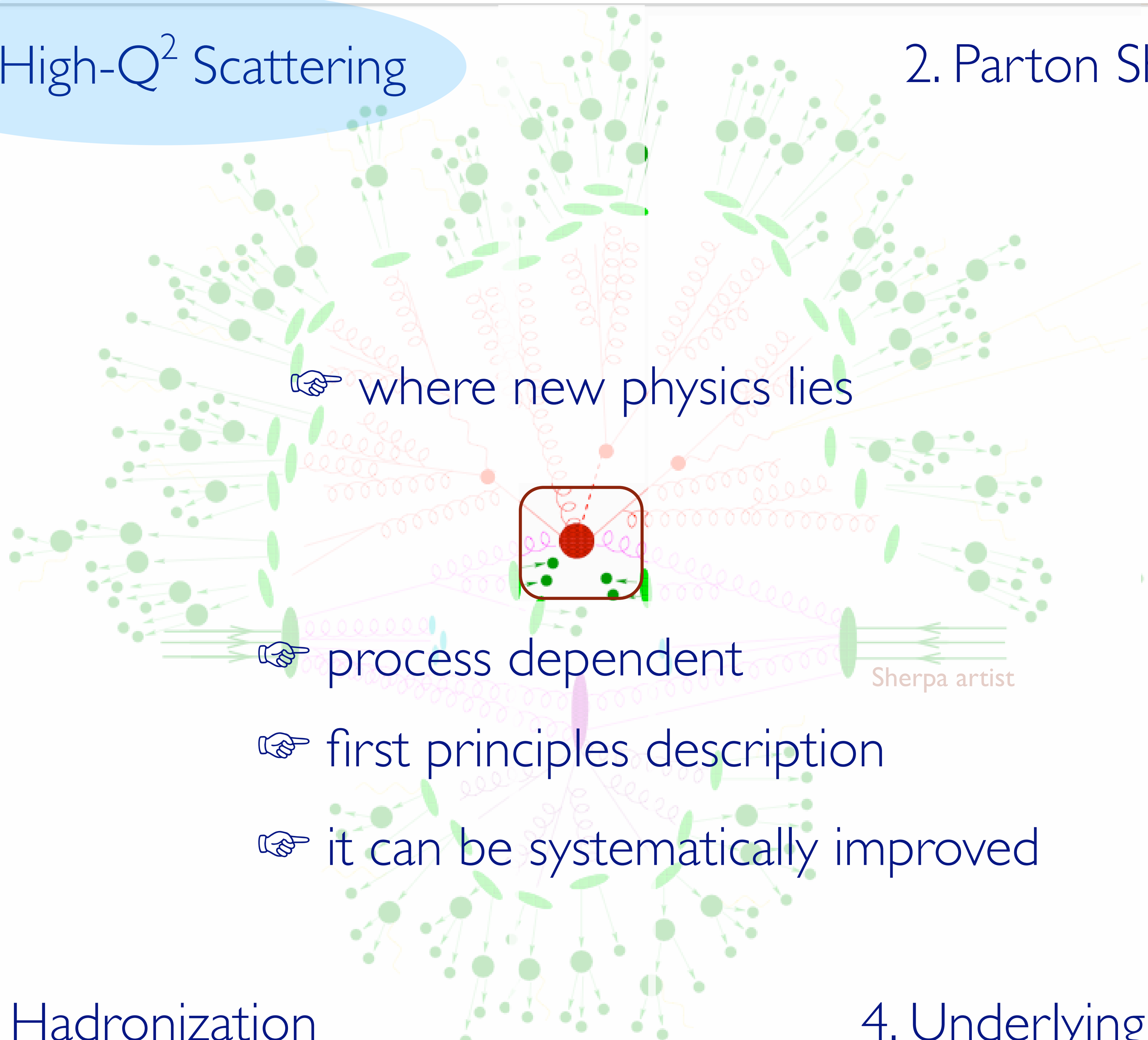



1. High-Q^2 Scattering
2. Parton Shower
Sherpa artist
3. Hadronization
4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



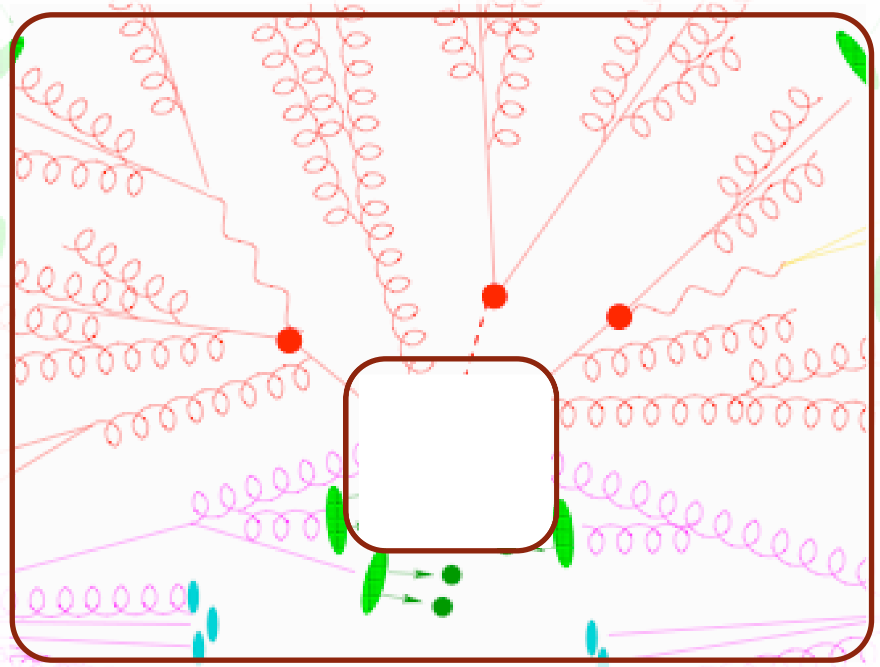
- ☞ where new physics lies
- ☞ process dependent
- ☞ first principles description
- ☞ it can be systematically improved

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



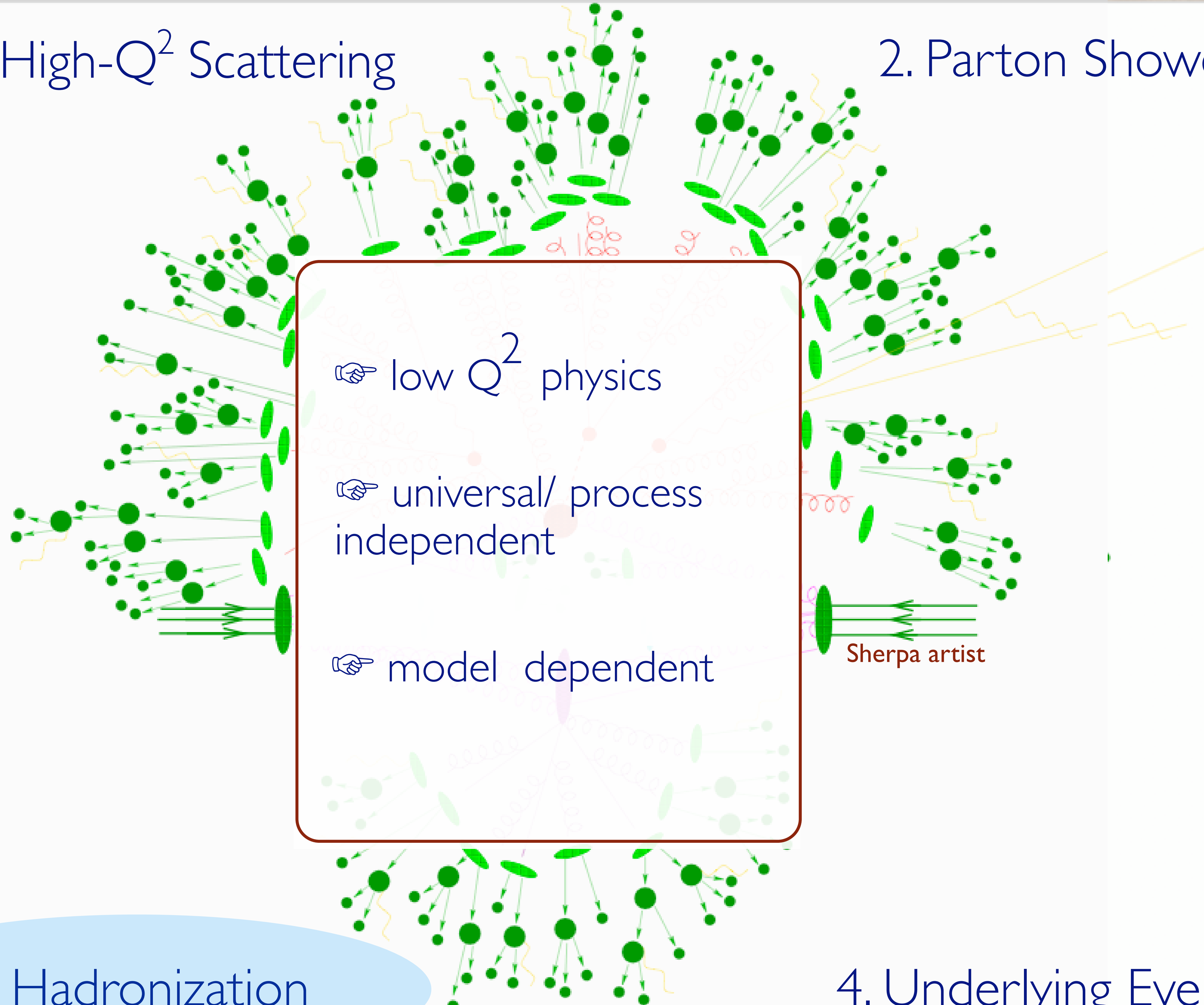
- ☞ QCD -"known physics"
- ☞ universal/ process independent
- ☞ first principles description

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



☞ low Q^2 physics

☞ universal/ process independent

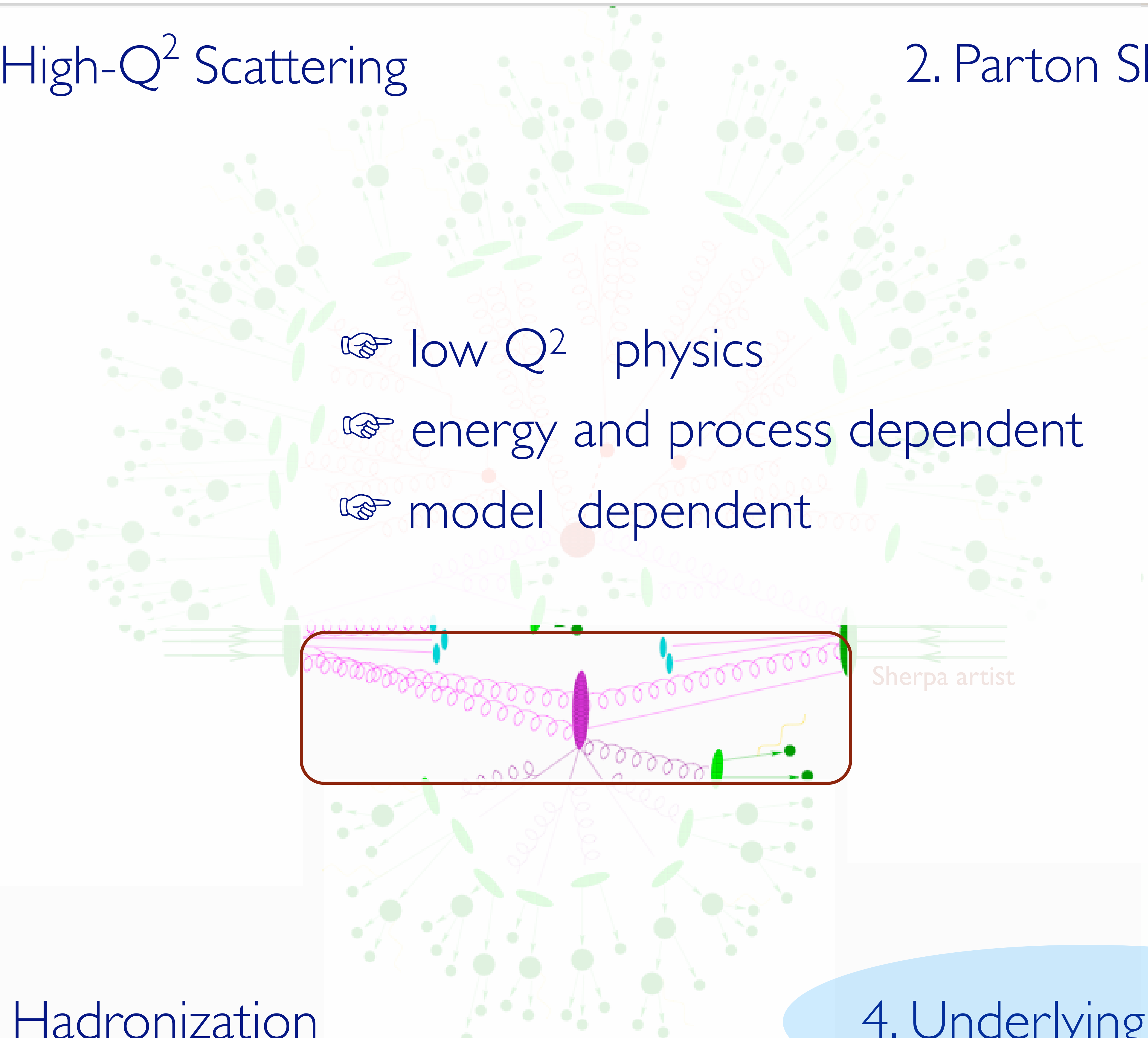
☞ model dependent

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

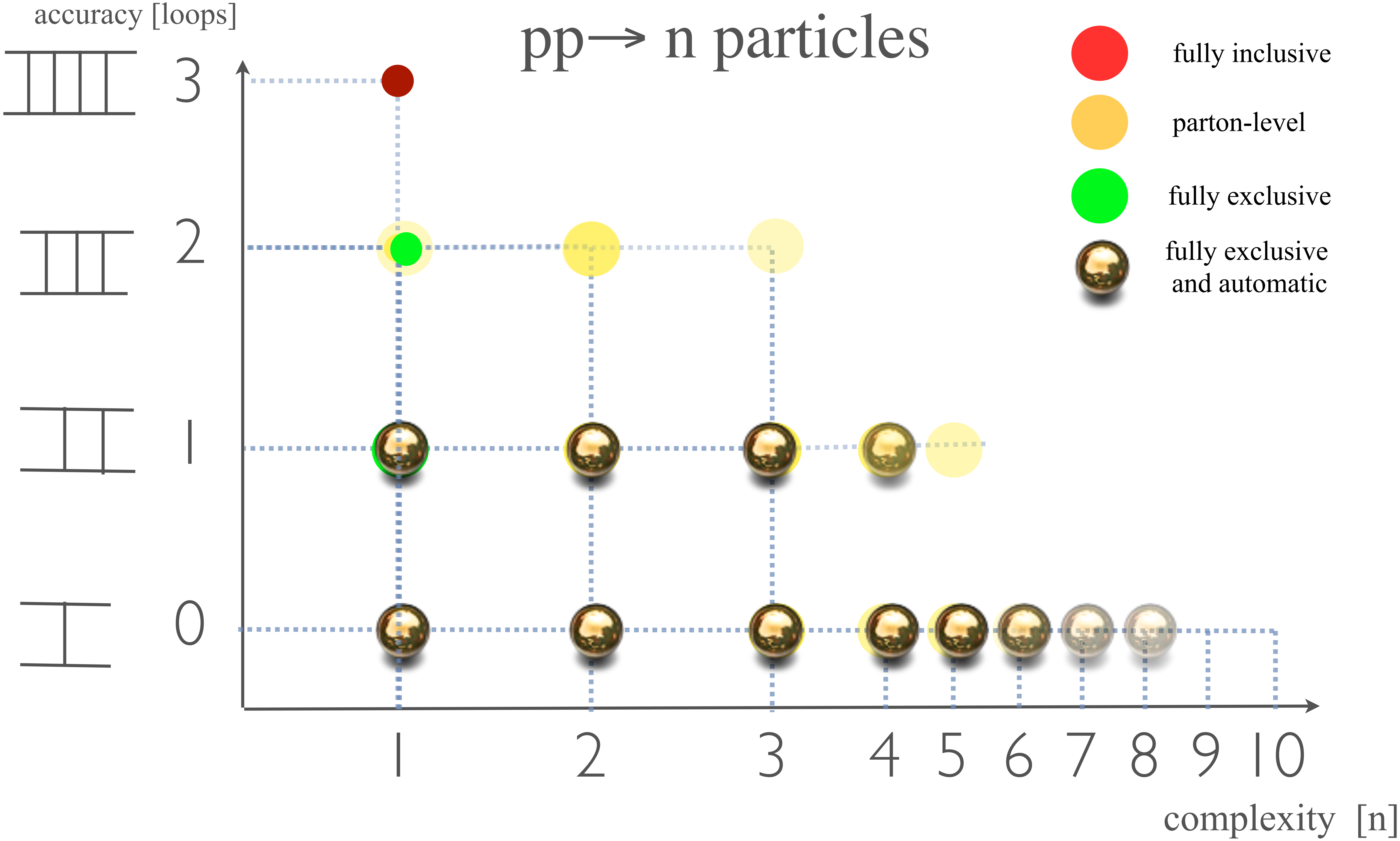


- low Q^2 physics
- energy and process dependent
- model dependent

3. Hadronization

4. Underlying Event

SM Status


accuracy [loops]
pp→ n particles
3
2
1
0
1
2
3
4
5
6
7
8
9
10
complexity [n]
fully inclusive
parton-level
fully exclusive
fully exclusive
and automatic

Summary so far

- High energy collisions allow to probe interactions at very short distances, but entail SM physics that has to be described with:
    - ✦ Identify observables that can be calculated and measured reliably.
    - ✦ Accurate/Precise predictions => difficult calculations, multi-loop, QCD, EW.
    - ✦ A fully exclusive approach (associate an history to each short distance event).

Discoveries in the precision era

Question:

Precise/accurate predictions are very difficult/expensive.
Are we sure they are really needed? For what exactly?

Short answer:

The discovery potential of any collider working in the precision phase (fixed energy, accumulating luminosity) is directly related to our ability to make precise predictions.

New Physics

- A new force has been discovered, the first elementary of Yukawa type ever seen.
- Its mediator looks a lot like the SM scalar: H-universality of the couplings
- No sign of……New Physics (from the LHC)!

- We have no bullet-proof theoretical argument to argue for the existence of New Physics between 8 and 13 TeV and even less so to prefer a NP model with respect to another.

New Physics

The obvious imperative:

LOOK FOR NP AT THE LHC BY COVERING THE WIDEST RANGE OF TH- AND/OR EXP-MOTIVATED SEARCHES.

Searches should aim at being sensitive to the highest-possible scales of energy

Searching for new physics

Model-dependent	⟷	Model-independent
SUSY, 2HDM, ED,...		simplified models, EFT, ...
Search for new states	⟷	Search for new interactions
specific models, simplified models		anomalous couplings, EFT...
Exotic signatures	⟷	Standard signatures
precision measurements		rare processes

Searching for new physics

Search for new states ⟷ Search for new interactions

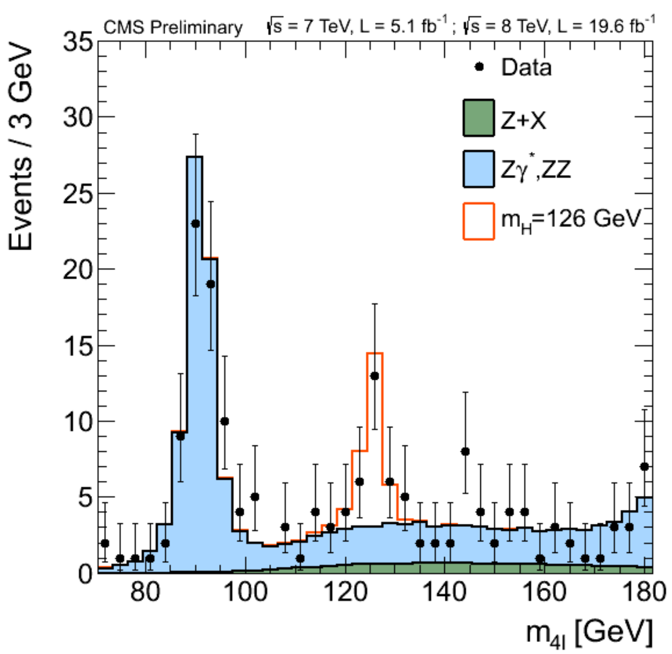
SUSY, EXOTICS, BSM HIGGS

SM

Searching for new resonances

peak

pp→H→4l

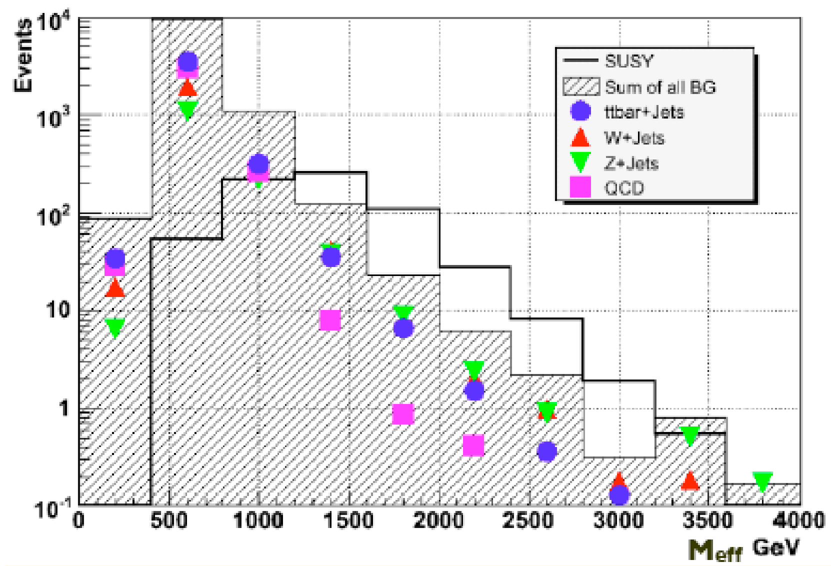


"easy"

Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)

shape

$pp\to\tilde{g}\tilde{g},\tilde{g}\tilde{q},\tilde{q}\tilde{q}\to jets+\not{E}_T$

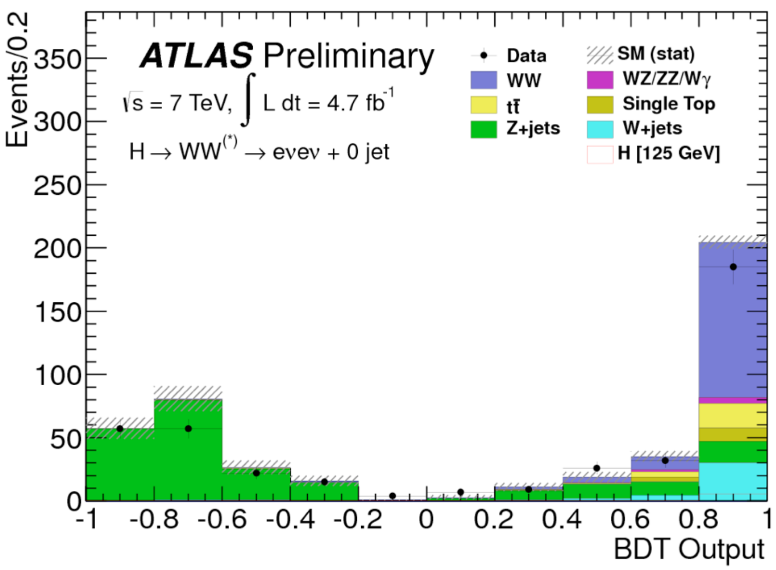


hard

Background shapes needed. Flexible MC for both signal and background tuned and validated with data.

discriminant

$pp\to H\to W^+W^-$

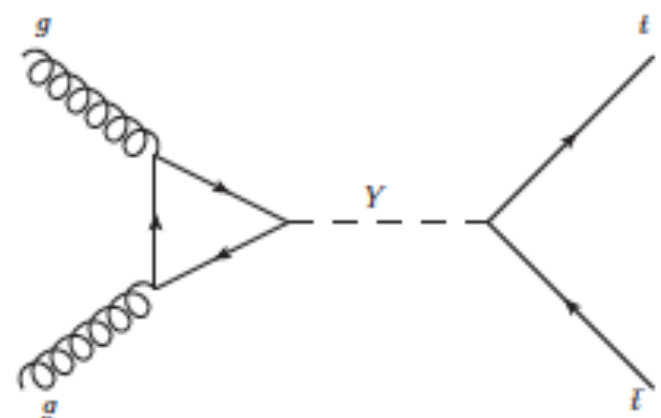


very hard

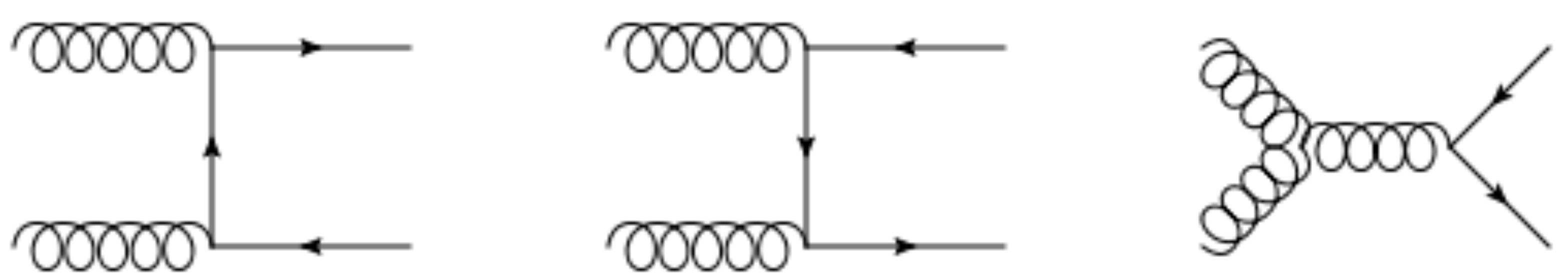
Background normalization and shapes known very well. Interplay with the best theoretical predictions (via MC) and data.

A simple example: $t\bar{t}$

Imagine a new scalar exists which couples mostly to top quark, similar to the SM Higgs, but it is heavier than $2m_t$. It would be produced as the SM Higgs via gluon fusion and then mostly decay to top quarks:

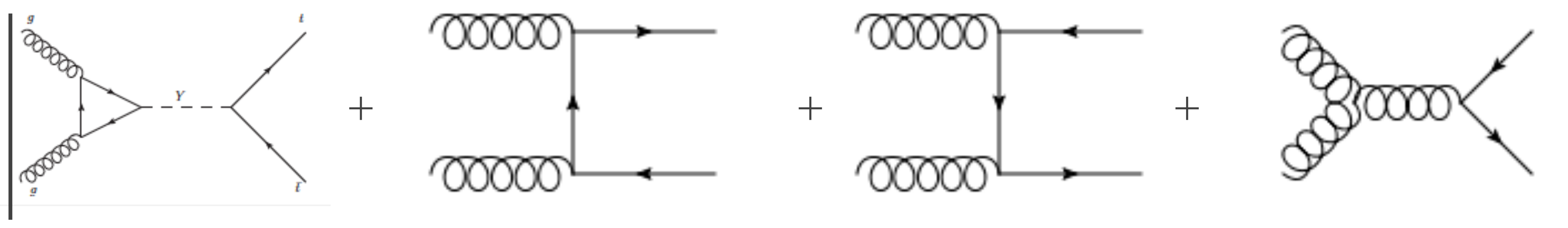


giving rise to a peak in the invariant mass distribution of m(tt). However, this process interferes with the QCD background:



A simple example: $t\bar{t}$

| Amp | ^2=



Taking our previous calculation of the SM amplitude and adding the scalar production:

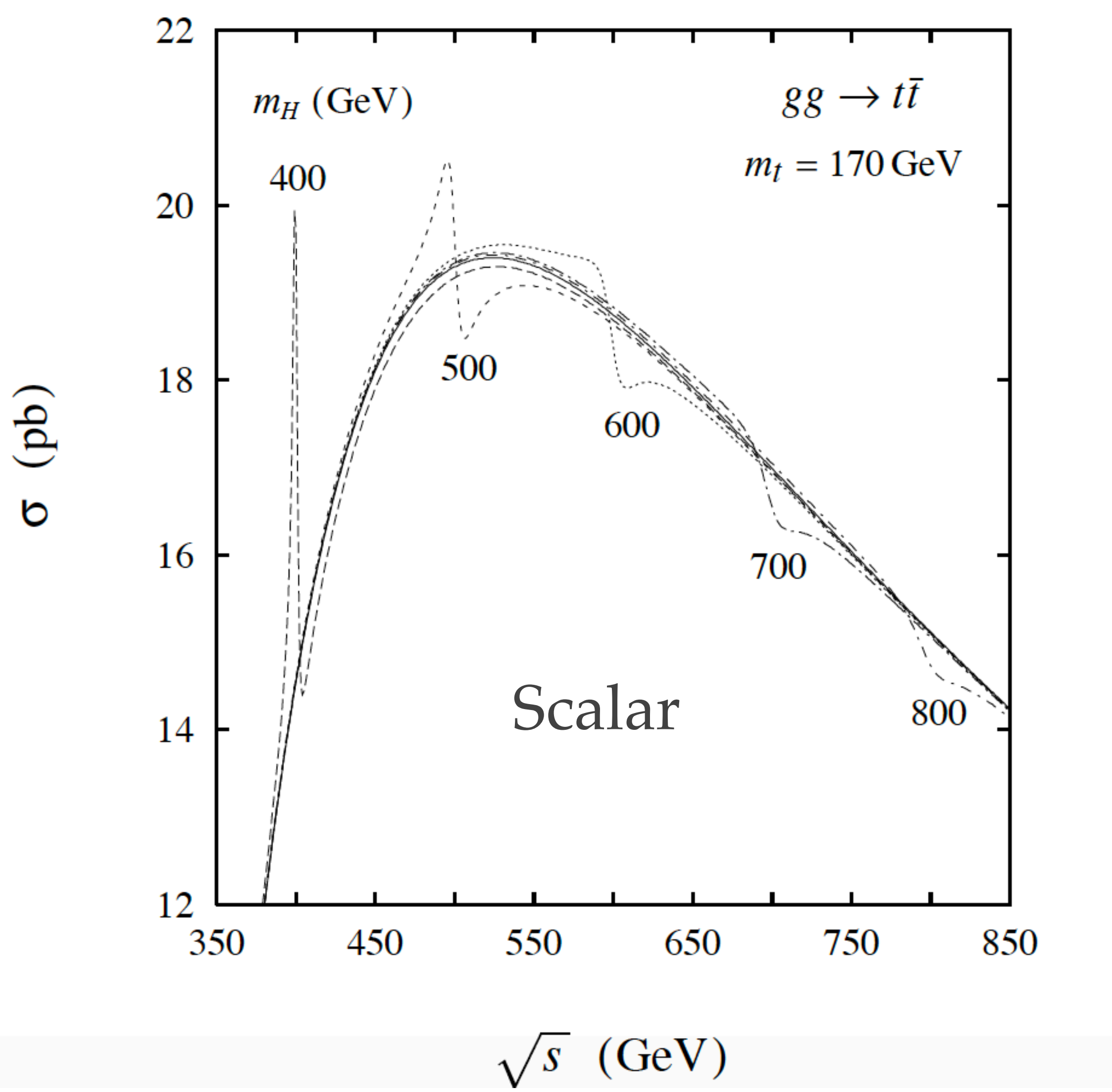
$$\hat{\sigma}(s) = \frac{\alpha_s^2 G_F^2 m^2 s^2}{768\,\pi^3}\beta^3 \left| \frac{N(s/m^2)}{s - m_H^2 + i m_H \Gamma_H(s)} \right|^2 \quad \longleftarrow \text{BW resonance}$$

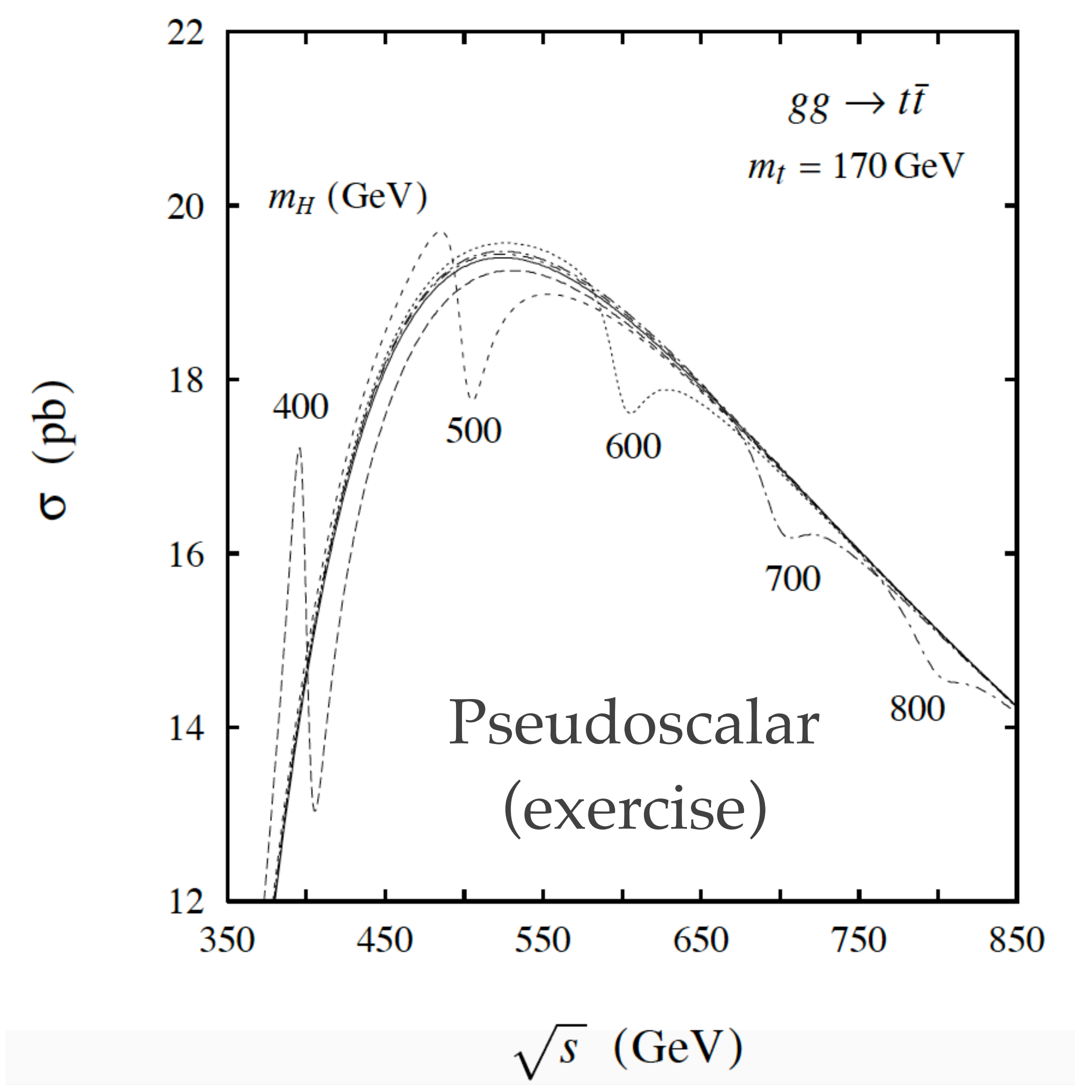
$$-\frac{\alpha_S^2 G_F m^2}{48\pi\sqrt{2}}\beta^2 \ln\frac{1+\beta}{1-\beta}\ \mathrm{Re}\left[\frac{N(s/m^2)}{s - m_H^2 + i m_H \Gamma_H(s)}\right] \quad \longleftarrow \text{Interference}$$

$$+\hat{\sigma}_{\mathrm{SM}}(s) \quad \longleftarrow \text{SM}$$

$$N(s/m^2) = \frac{3}{2}\frac{m^2}{s}\left[4 - \left(1 - \frac{4m^2}{s}\right) I(s/m^2)\right] \qquad I(s/m^2) = \left[\ln\frac{1+\beta}{1-\beta} - i\pi\right]^2 \qquad (s > 4m^2)$$

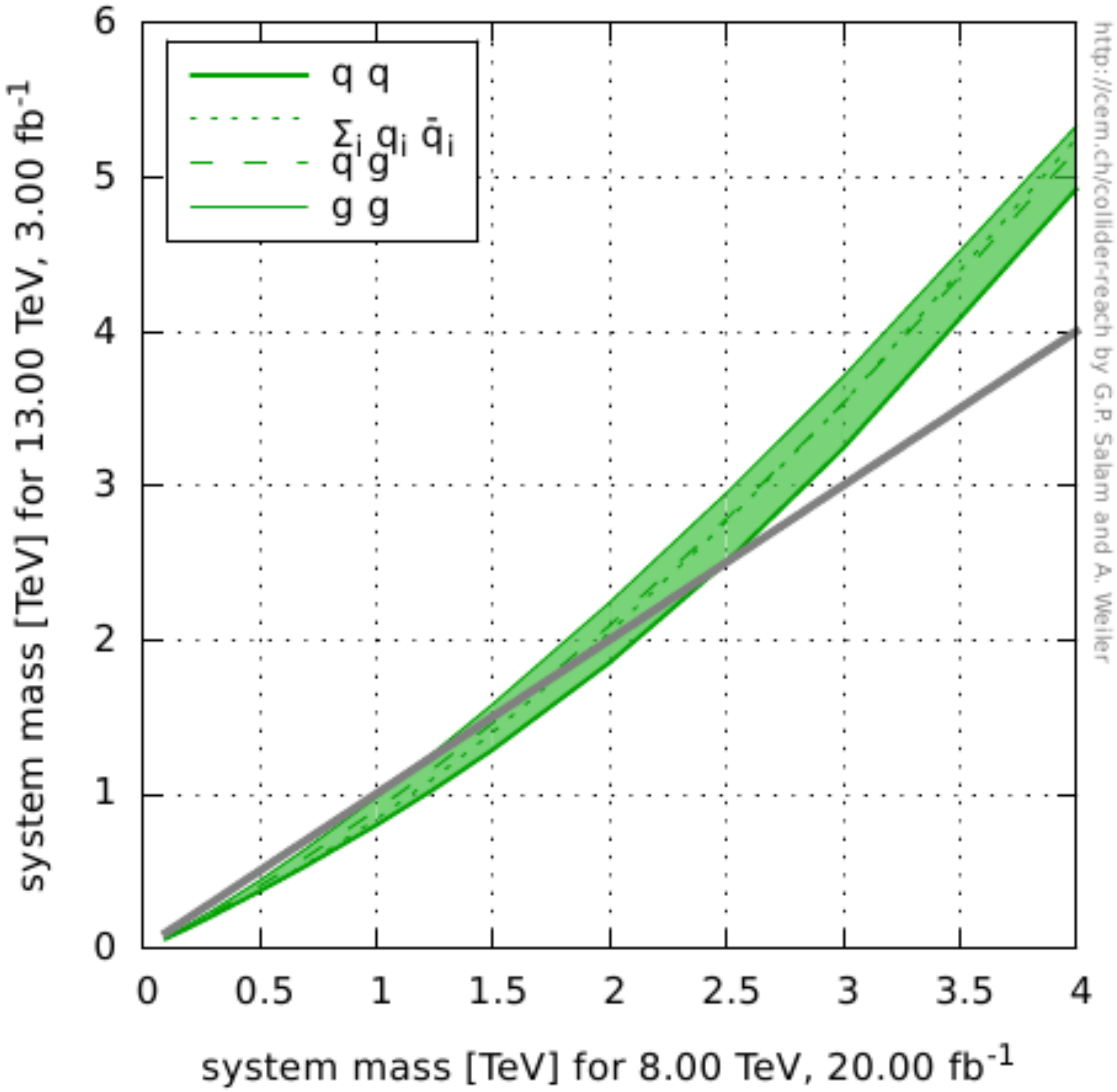
A simple example: $t\bar{t}$

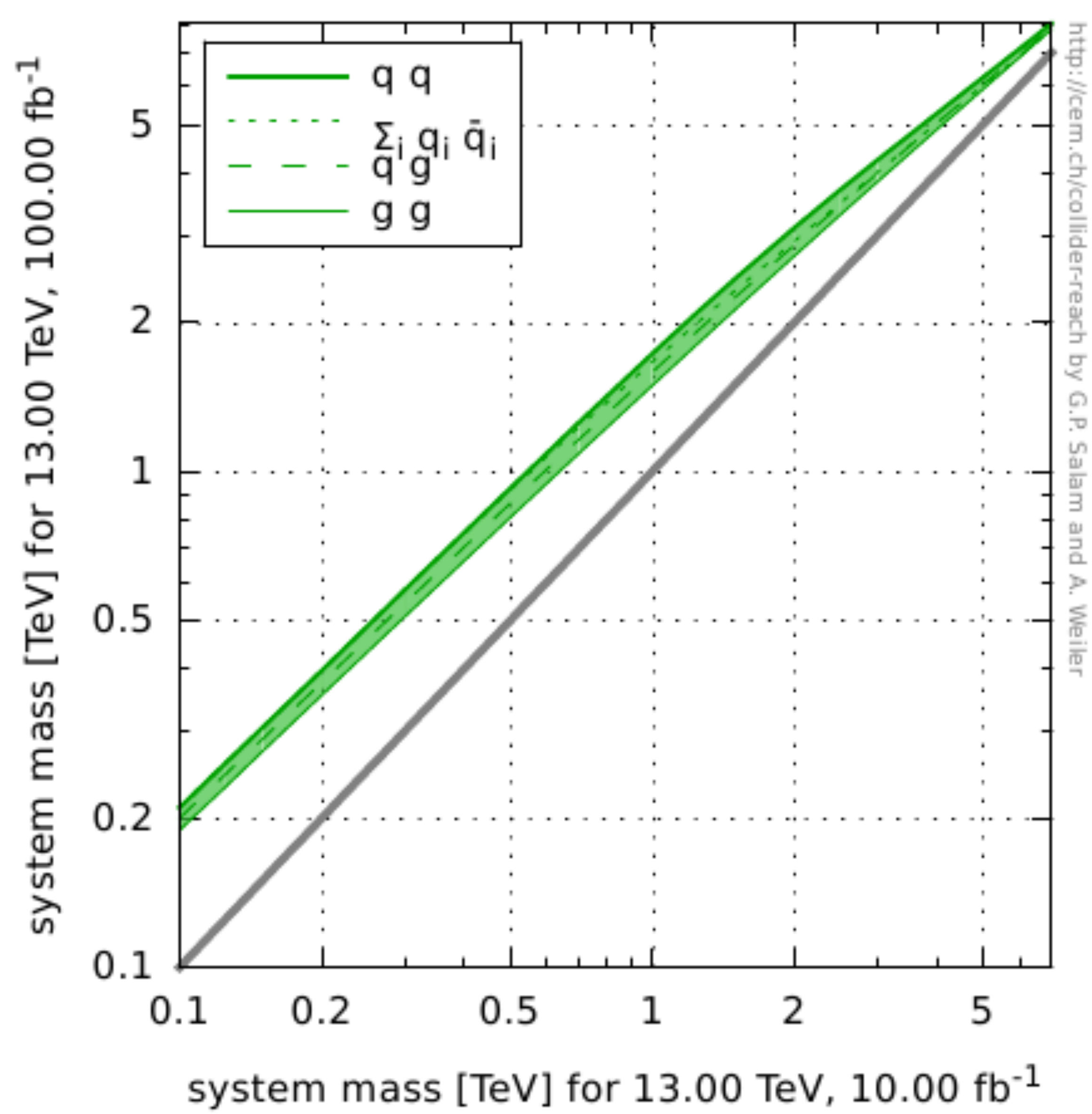




Peaks but also peak-dip and dip only structures. "Easy" to discover independently of the precise knowledge of the SM. However, needs accurate theory to characterise it.

Collider reach





Increasing the energy of a collider gives a big boost to the reach of resonance searches, while the gain due to the increase of luminosity is marginal (beware of assumptions here).

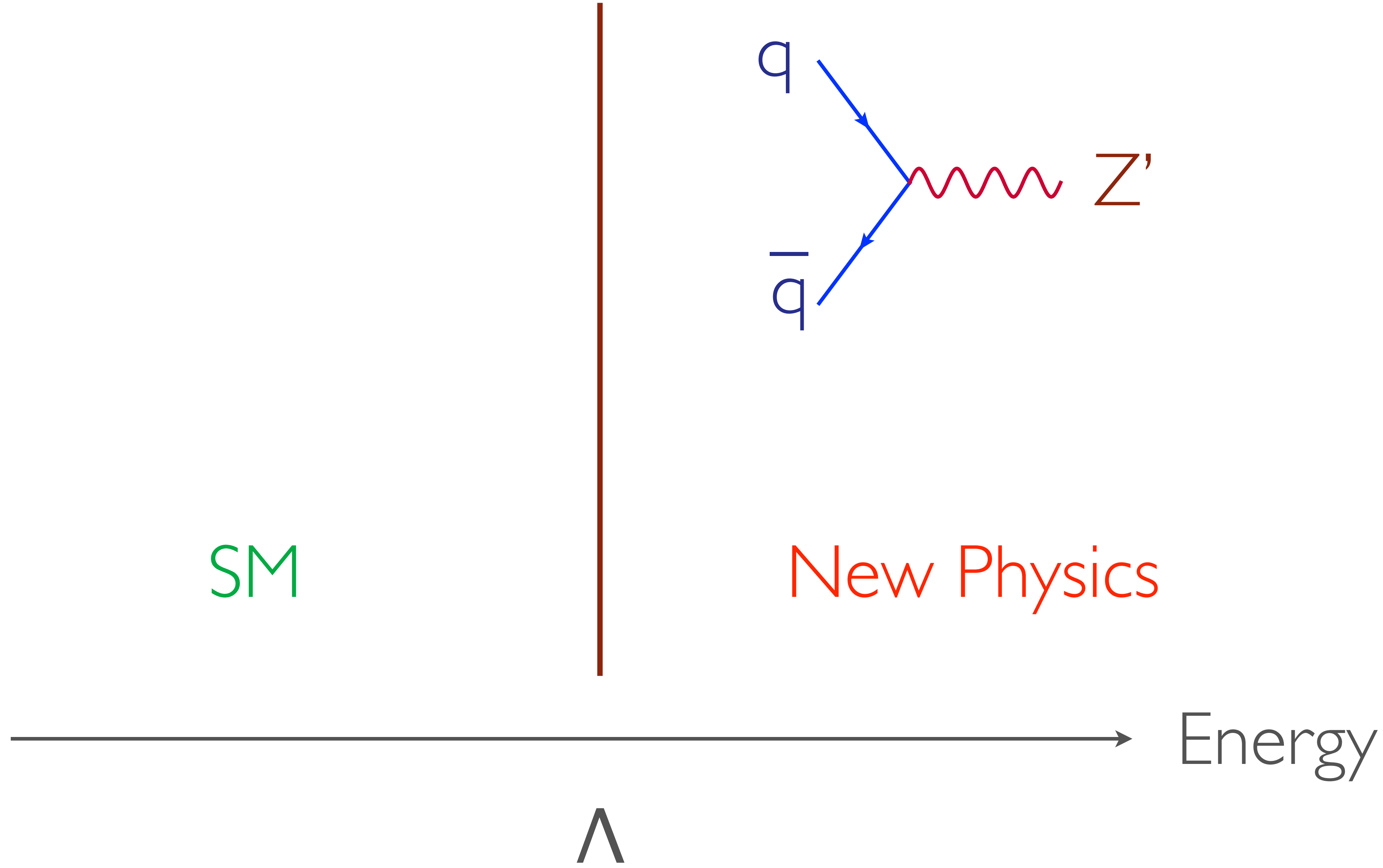
Searching for new physics

Search for new states ⟷ Search for new interactions

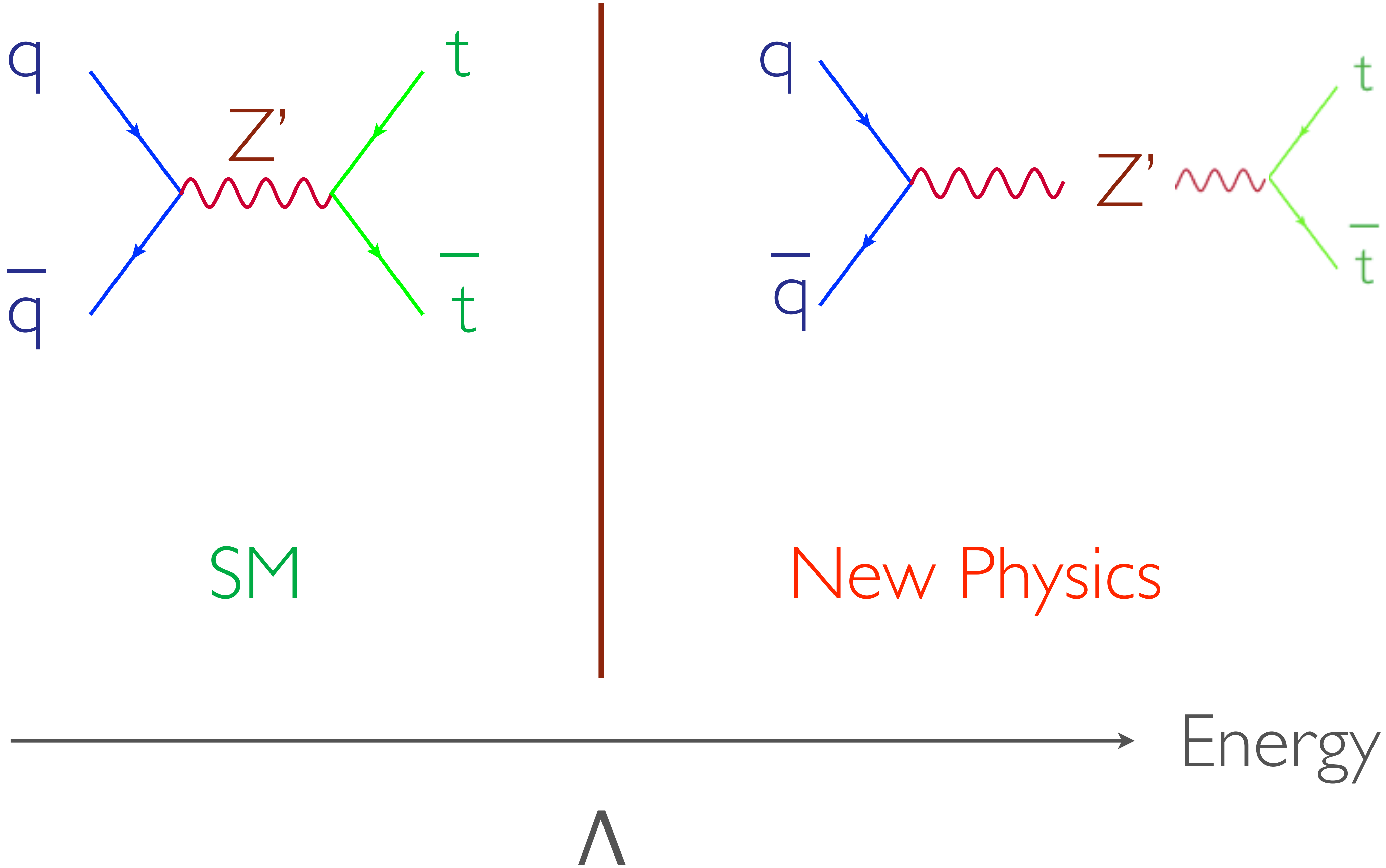
SUSY, EXOTICS, BSM HIGGS

SM

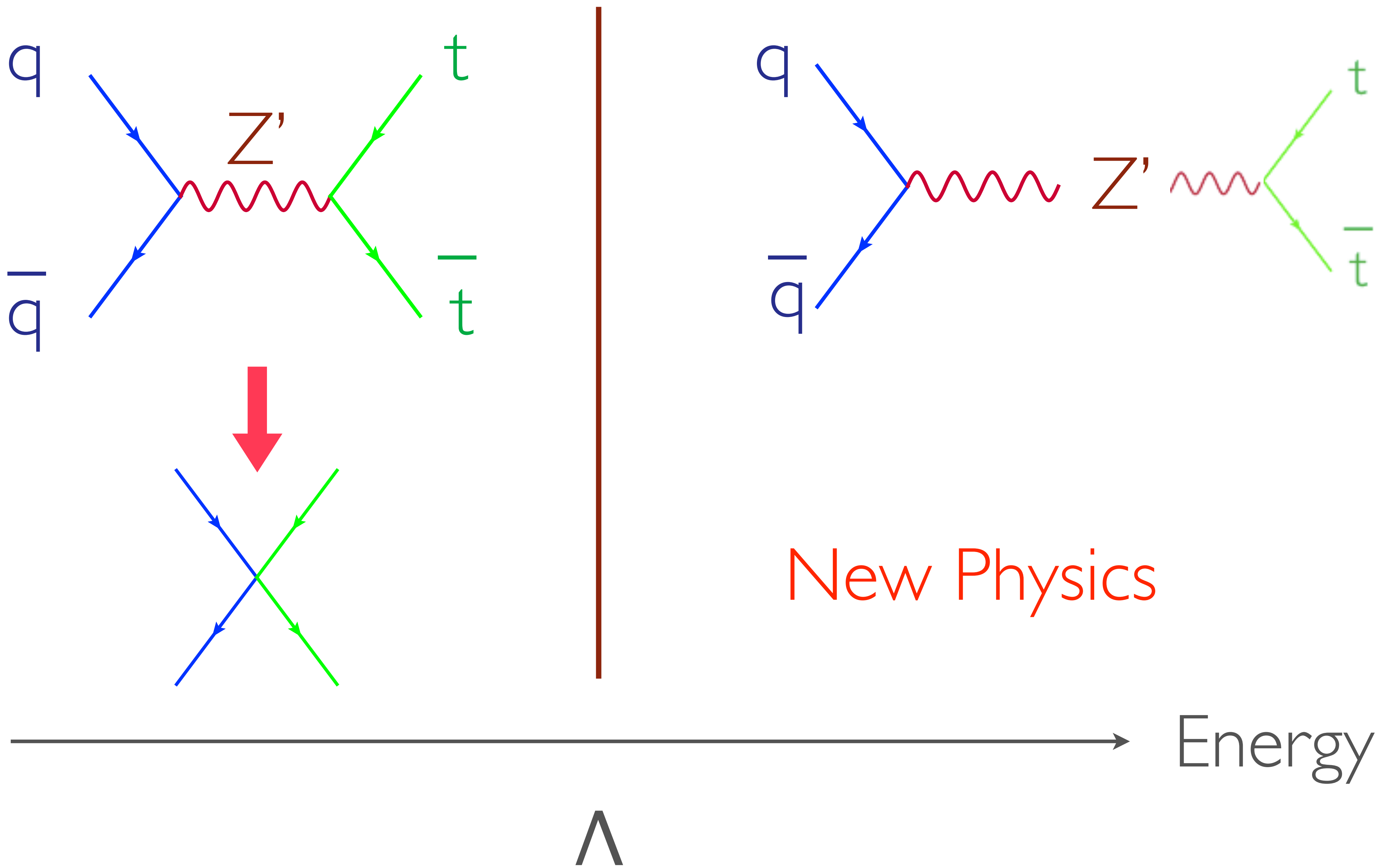
Search for New Interactions



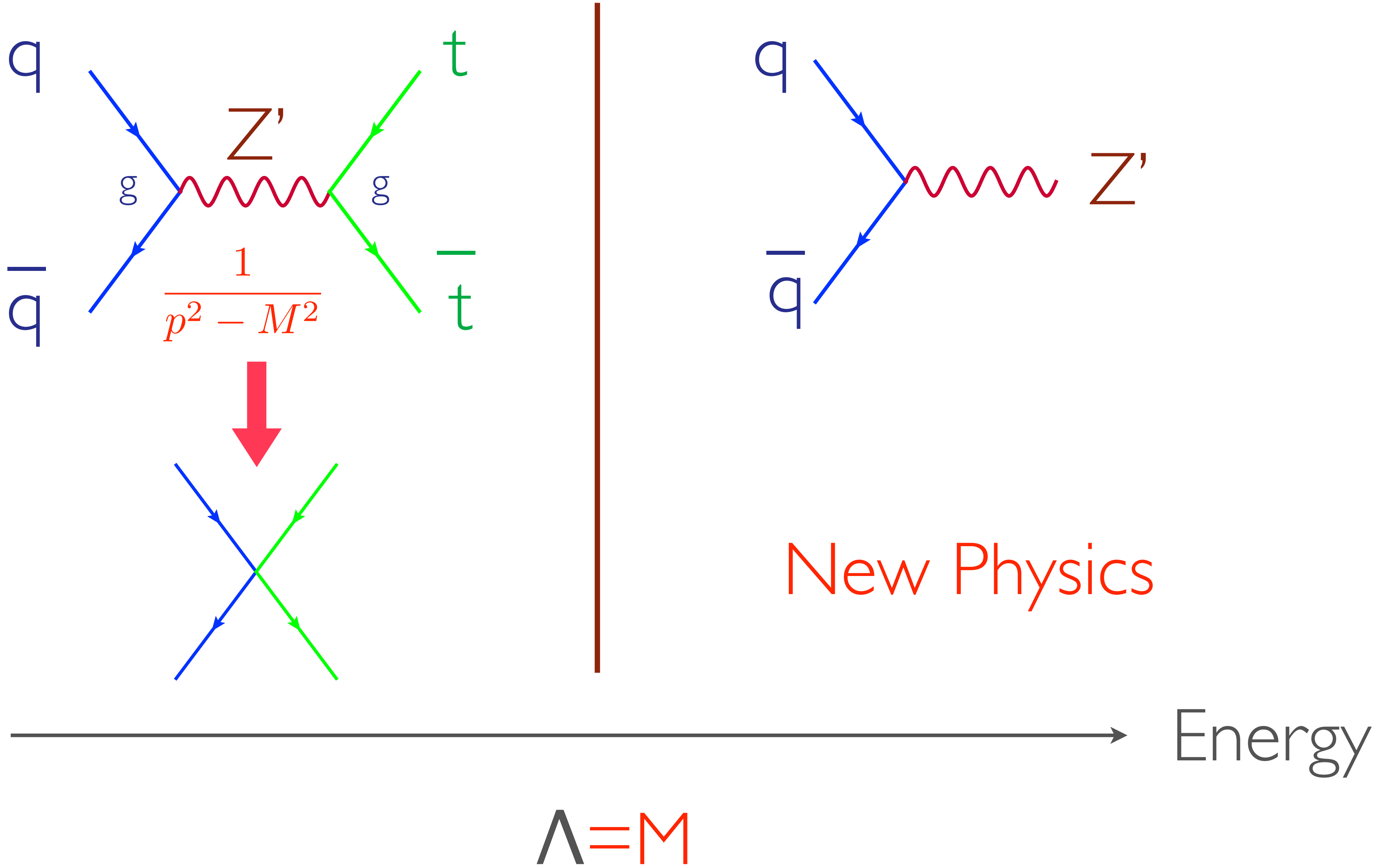
Search for New Interactions



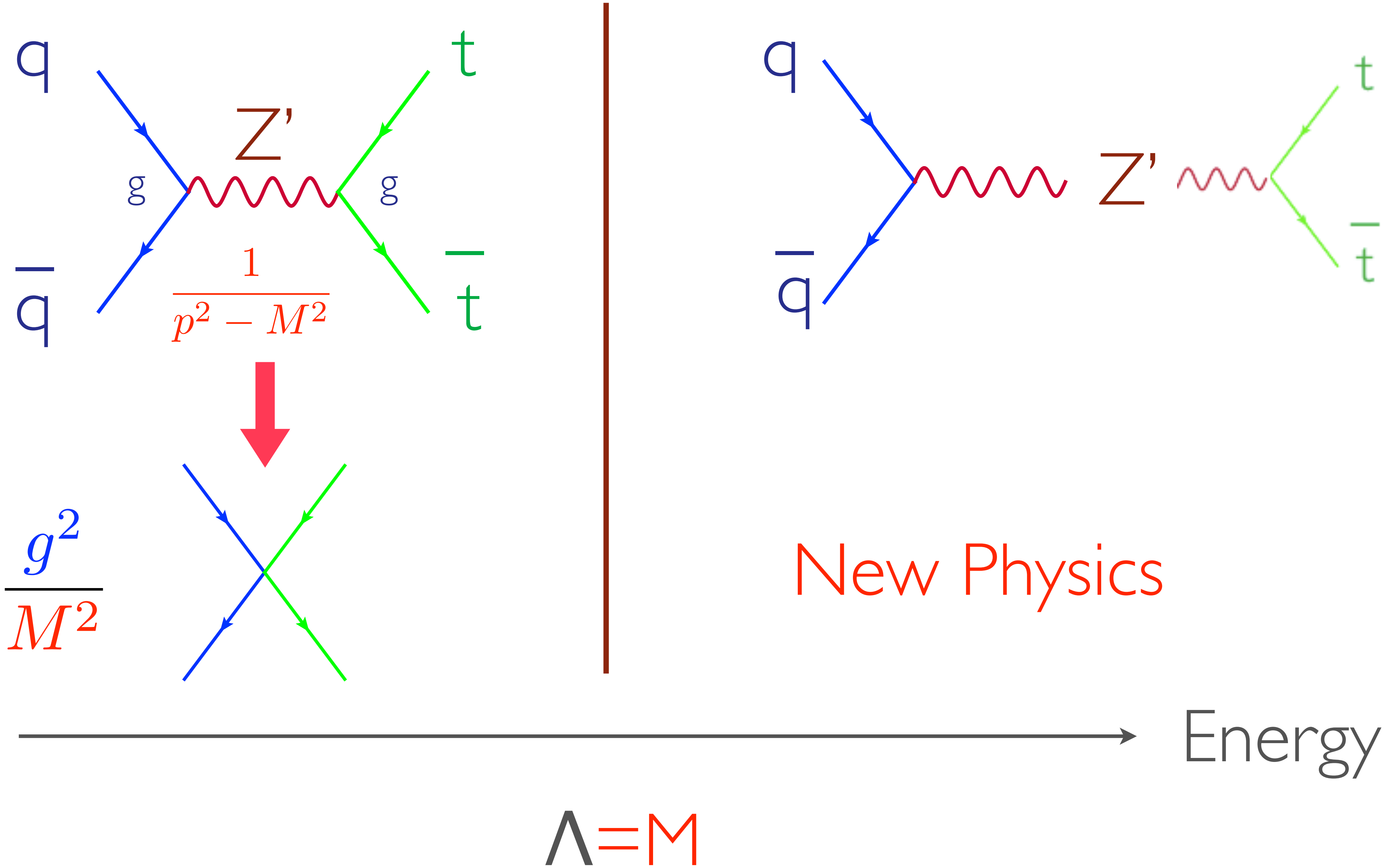
Search for New Interactions



Search for New Interactions

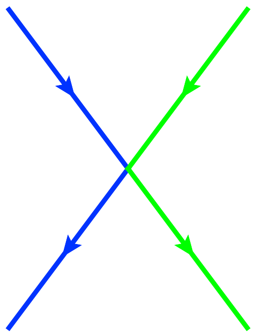


Search for New Interactions



Search for New Interactions

$$\frac{g^2}{M^2}$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{g^2}{M^2}\bar{\psi}\psi\bar{\psi}\psi$$

$$M^2 = g^2 v^2 \Rightarrow \Lambda = v$$

Λ is an upper bound on the scale of new physics

Search for New Interactions

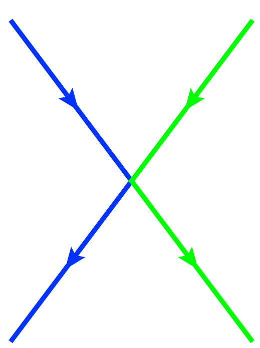
$$\hbar = c = 1$$

$$\dim A^{\mu} = 1$$

$$\dim \phi = 1$$

$$\dim \psi = 3/2$$

$$\frac{g^2}{M^2}$$



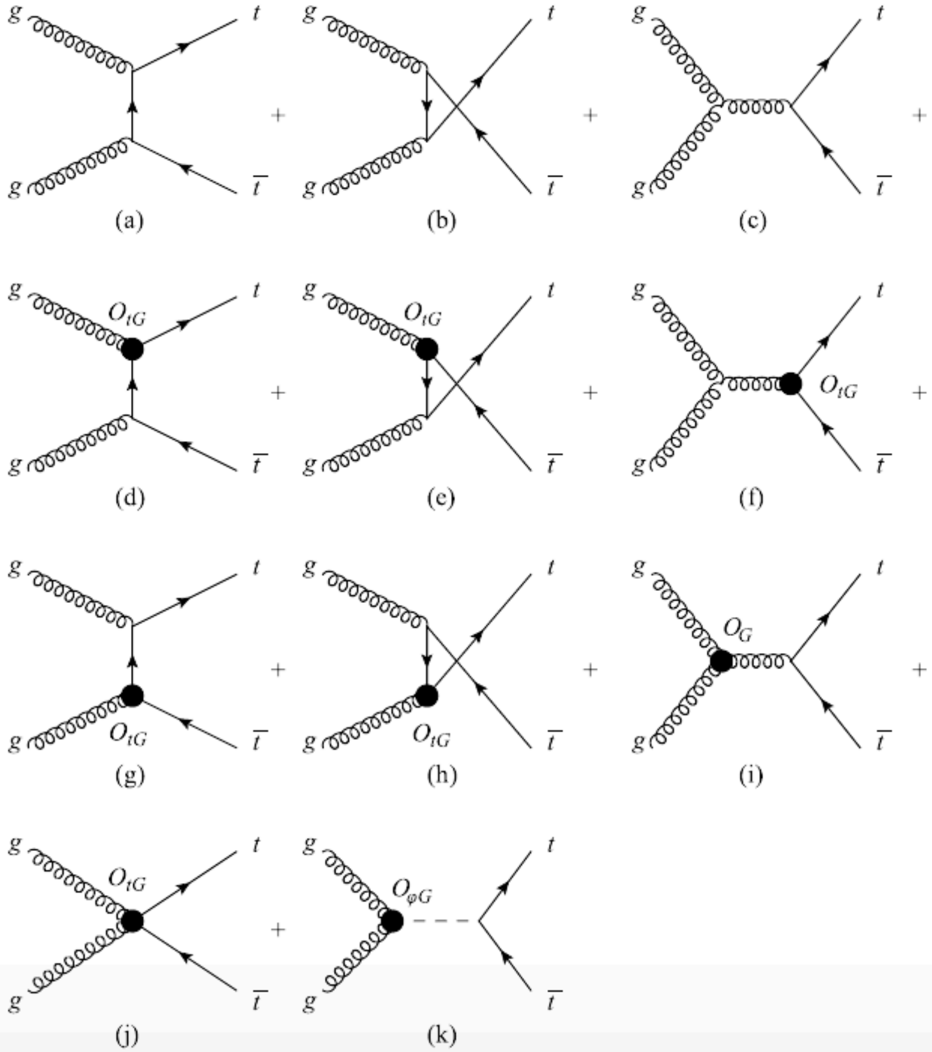
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{\mathrm{dim}=6}$$

59 operators *[Buchmuller, Wyler, 1986]*

A simple example: tt̄

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$$
$$O_G = f_{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$$
$$O_{\phi G} = \frac{1}{2}(\phi^+\phi)G^A_{\mu\nu}G^{A\mu\nu}$$

Three operators of dim=6 that enter tt



$$\beta = \sqrt{1-4m_t^2/\hat{s}}$$
$$\hat{\sigma}_{gg\to t\bar{t}} = \frac{\pi\alpha_s^2\beta}{48\hat{s}}\left(31\beta + \left(\frac{33}{\beta} - 18\beta + \beta^3\right)\ln\left[\frac{1+\beta}{1-\beta}\right] - 59\right)$$

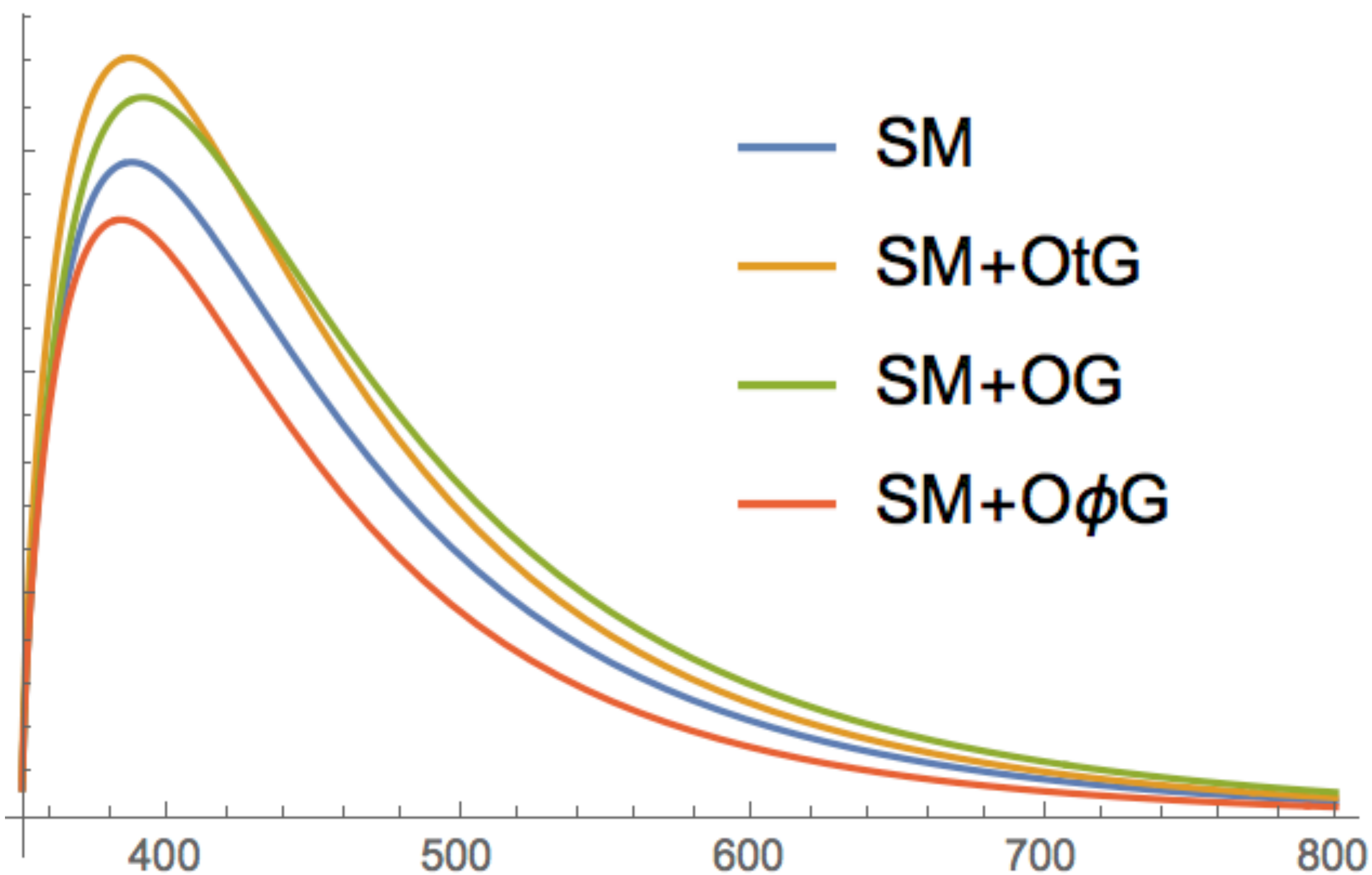
$$+ \mathrm{Re}C_{tG}\frac{g_s^3 v\sqrt{1-\beta^2}}{48\sqrt{2}\pi\Lambda^2\sqrt{s}}\left(8\ln\frac{1+\beta}{1-\beta} - 9\beta\right)$$

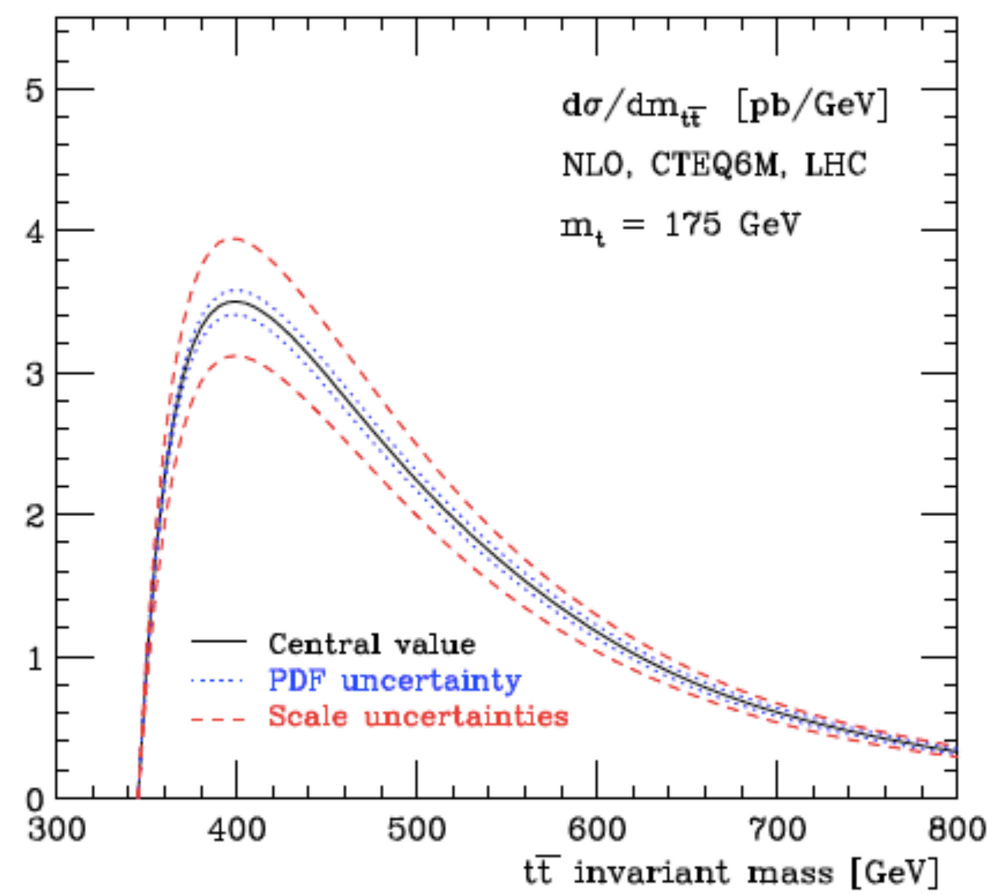
$$+ C_G\frac{9g_s^3(1-\beta^2)}{256\pi\Lambda^2}\left(\ln\frac{1+\beta}{1-\beta} - 2\beta\right)$$

$$- C_{\phi G}\frac{g_s^2 s\beta^2(1-\beta^2)}{256\pi\Lambda^2(s-m_h^2)}\ln\frac{1+\beta}{1-\beta}$$

A simple example: $t\bar{t}$

These new interactions lead to deformations of the SM distributions.



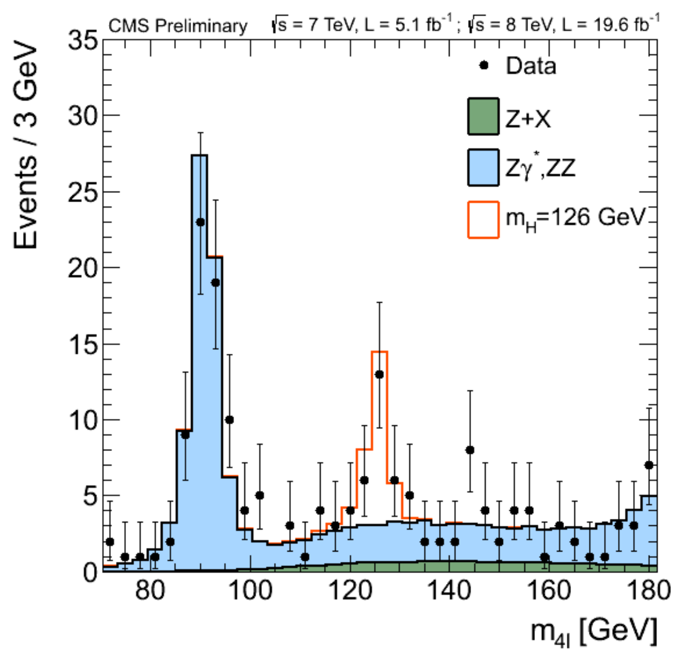


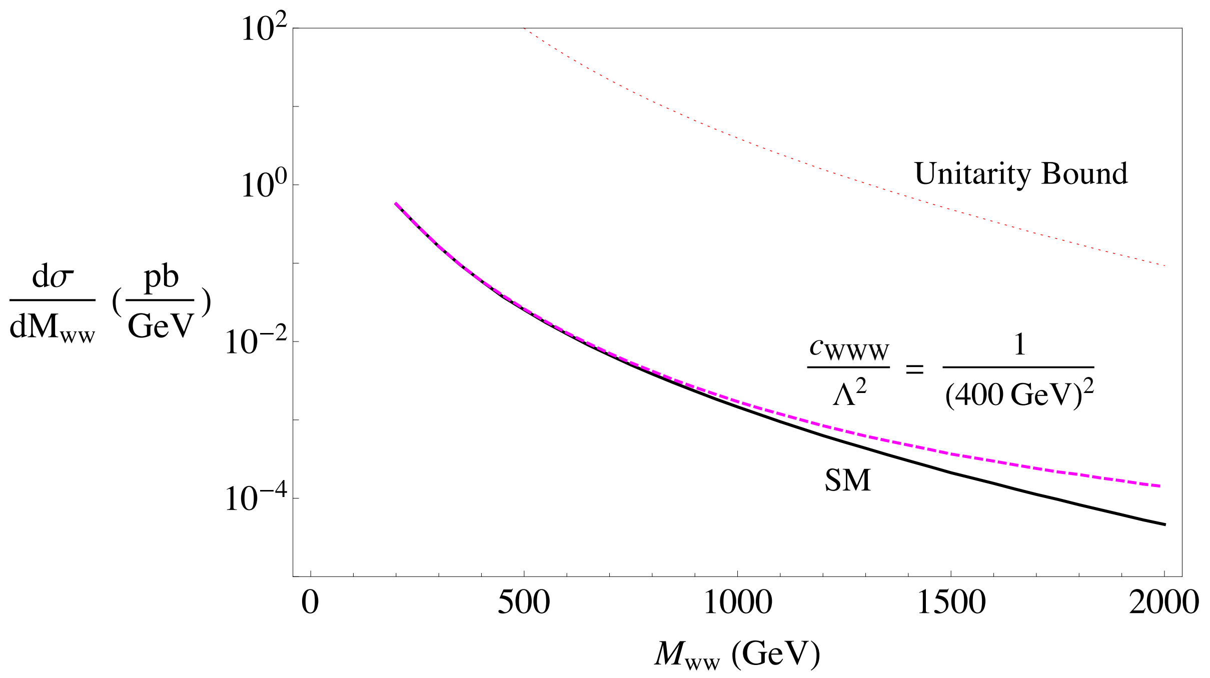
Need to know the SM distributions extremely well as well as the EFT ones!

Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states	⟷	Search for new interactions





"Peak" or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.

New generation of MC tools

Theory

Lagrangian
Gauge invariance
QCD
Partons
NLO
Resummation
...

Detector simulation
Pions, Kaons, ...
Reconstruction
B-tagging efficiency
Boosted decision tree
Neural network
...

Experiment

New generation of MC tools

Idea

Lagrangian

FeynRules

ME Generator

Signal & Bkg

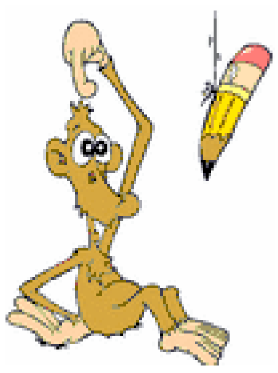
Events

PS+Had

Detect. Sim.

Data

Aims of the week



THINK

PARTICIPATE

WORK

- The morning lectures for reviewing or introducing new concepts
- The afternoons, the most important part of the school, will be devoted to the tutorials

Aims of the week

- Master the basic concepts of collider physics
- Learn about the latest techniques that allow to make accurate and predictions for events at the LHC in the SM and Beyond.
- Install the full chain of tools on your laptop.
- Apply and use the tools to make your own New Physics search, simulating signal and background.
- At the end of the week you'll be ready to roll

MaDream team

Hua-Sheng Shao

Olivier Mattelaer

Benjamin Fuks

Ken Mimasu

NLO

MG5aMC

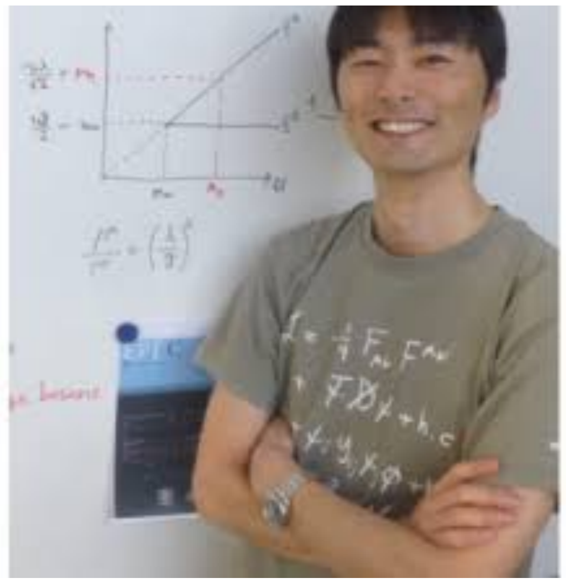
FeynRules
MadAnalysis

EFT

MaDream team

Leif Gellersen

PS and merging



Kentarou Mawatari

Dark Matter

Ambresh Shivaji

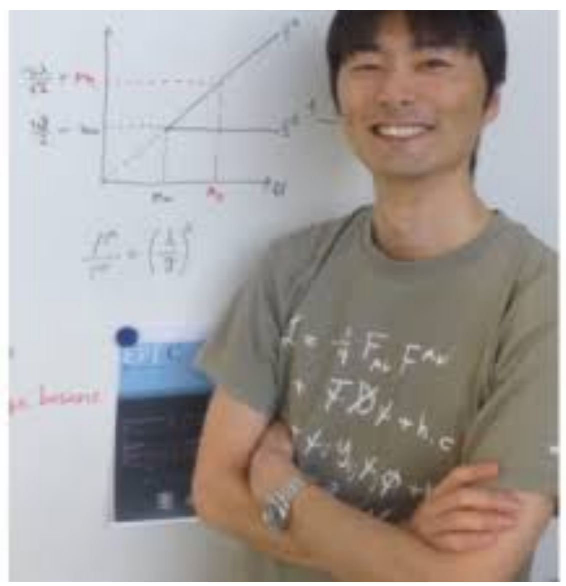
Higgs and Top

Richard Ruiz

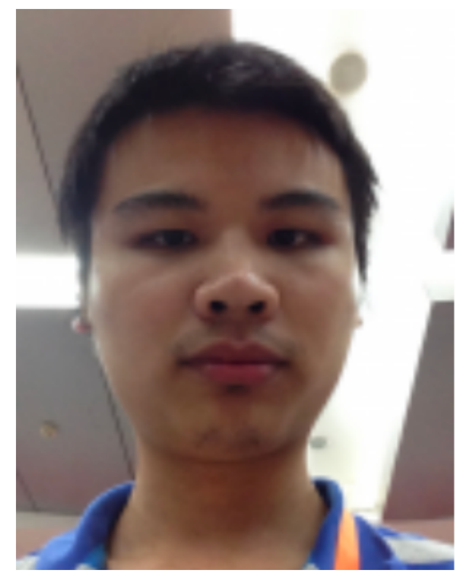
BSM and neutrinos

Tutorials and discussions

Olivier Mattelaer



Kentarou Mawatari



Xiaoran Zhao

Luca Mantani

We are here for you!