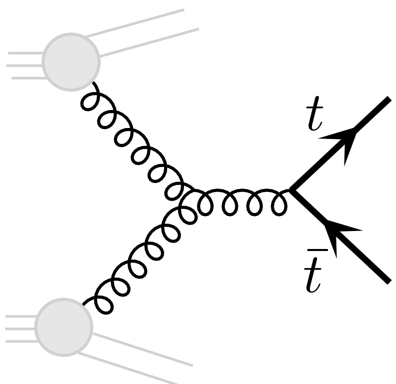
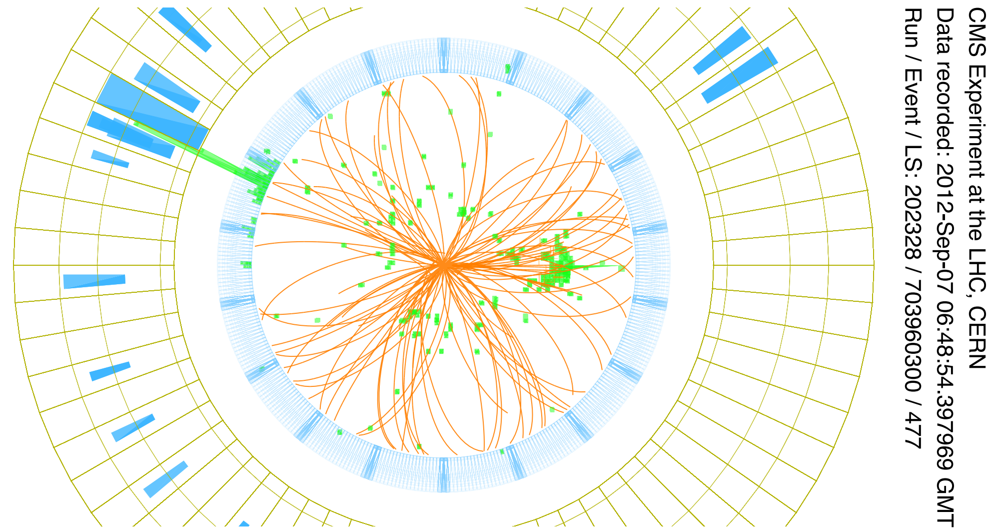
Bridging theory and experiment

Theory



Experiment



- How do we go from left to right?
  - **Monte Carlo Event Generators**
  - Detector simulation

Monte Carlo Event Generators

- Software that generates fully exclusive unweighted[a] collider events using factorisation, resummation, and modelling
- What does that consist of?
  - Hard scattering amplitudes (fixed order)
    - MadGraph5_aMCNLO, OpenLoops, Sherpa, WHIZARD, ...
  - Parton showers: ISR / FSR (QCD + QED)
    - Pythia, Herwig, Sherpa
  - Non-perturbative physics: hadronisation, decays, underlying event
    - Pythia, Herwig, Sherpa
  - Analysis and validation
    - Rivet (experimental measurements), MadAnalysis5 (phenomenology)

[a] Unweighted = each event has the same weights (up to a sign)

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Theoretical framework

- Factorisation: separation of scales
  - Long-distance physics absorbed into PDFs
  - Short-distance physics computed perturbatively

$$\sigma_{AB\to X}(Q) = \sum_{i,j} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \, f_{i/A}(x_1, \mu_F) \, f_{j/B}(x_2, \mu_F) \, \hat{\sigma}_{ij\to X}(x_1 x_2 s; Q, \mu_F, \mu_R) \; + \; \cdots$$

- Where

$$\sigma_{ij\to X} = \alpha_s^n \hat{\sigma}^{(0)}_{ij\to X} + \alpha_s^{n+1} \hat{\sigma}^{(1)}_{ij\to X} + \alpha_s^{n+2} \hat{\sigma}^{(2)}_{ij\to X} + \mathcal{O}(\alpha_s^{n+3})$$

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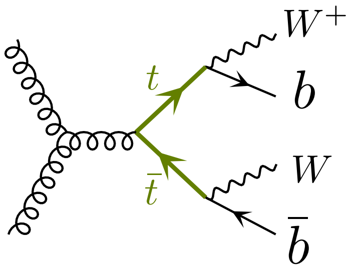
Example:



- Quiz:
  - Common name for this term?
  - What is the value of n?

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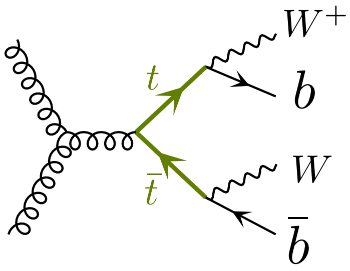

- Quiz:
  - Common name for this term? LO
  - What is the value of n? 2

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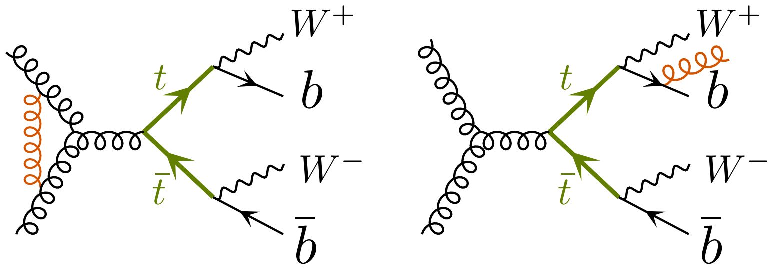
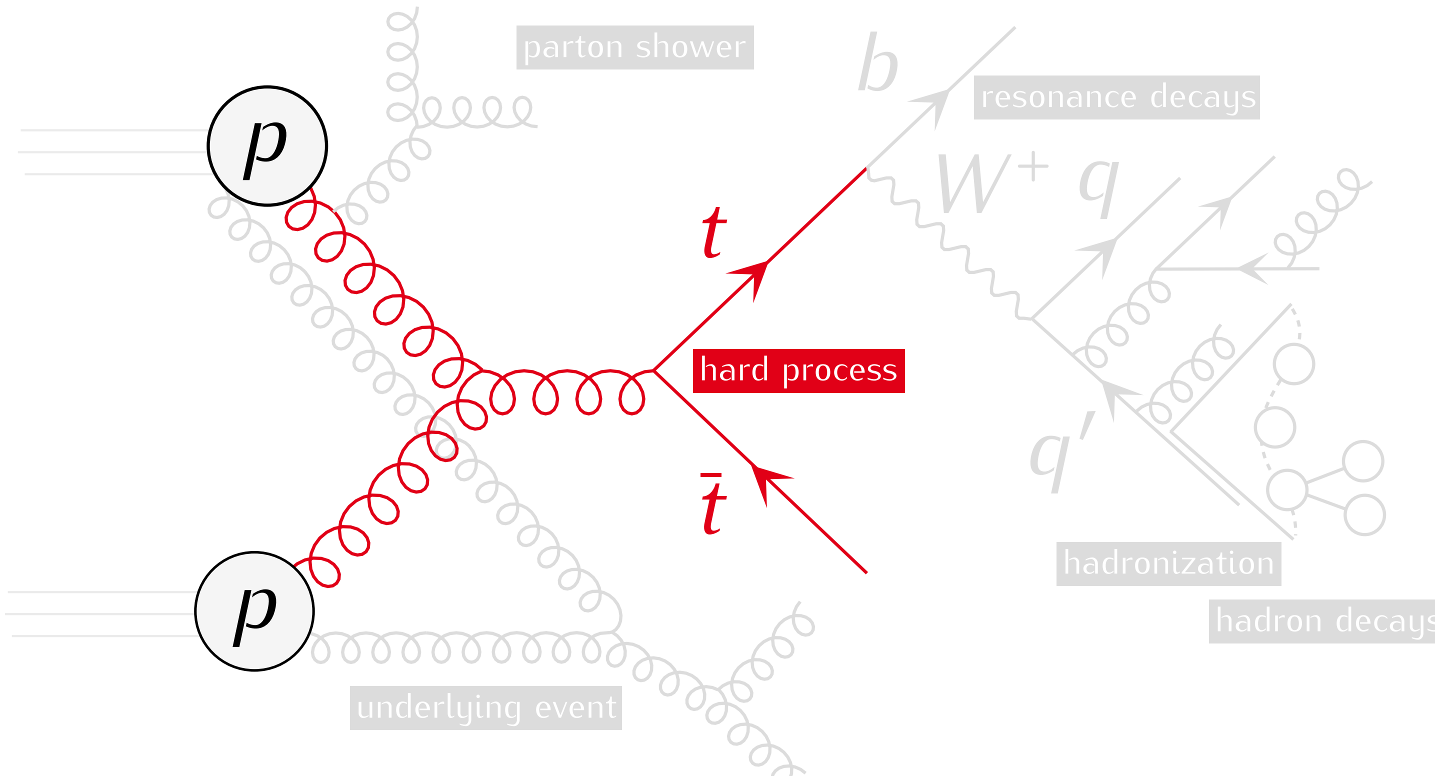


Next-to-Leading Order (NLO) in QCD

  - Note: unweighting beyond LO not well defined in fixed order calculations

Monte Carlo Event Generators



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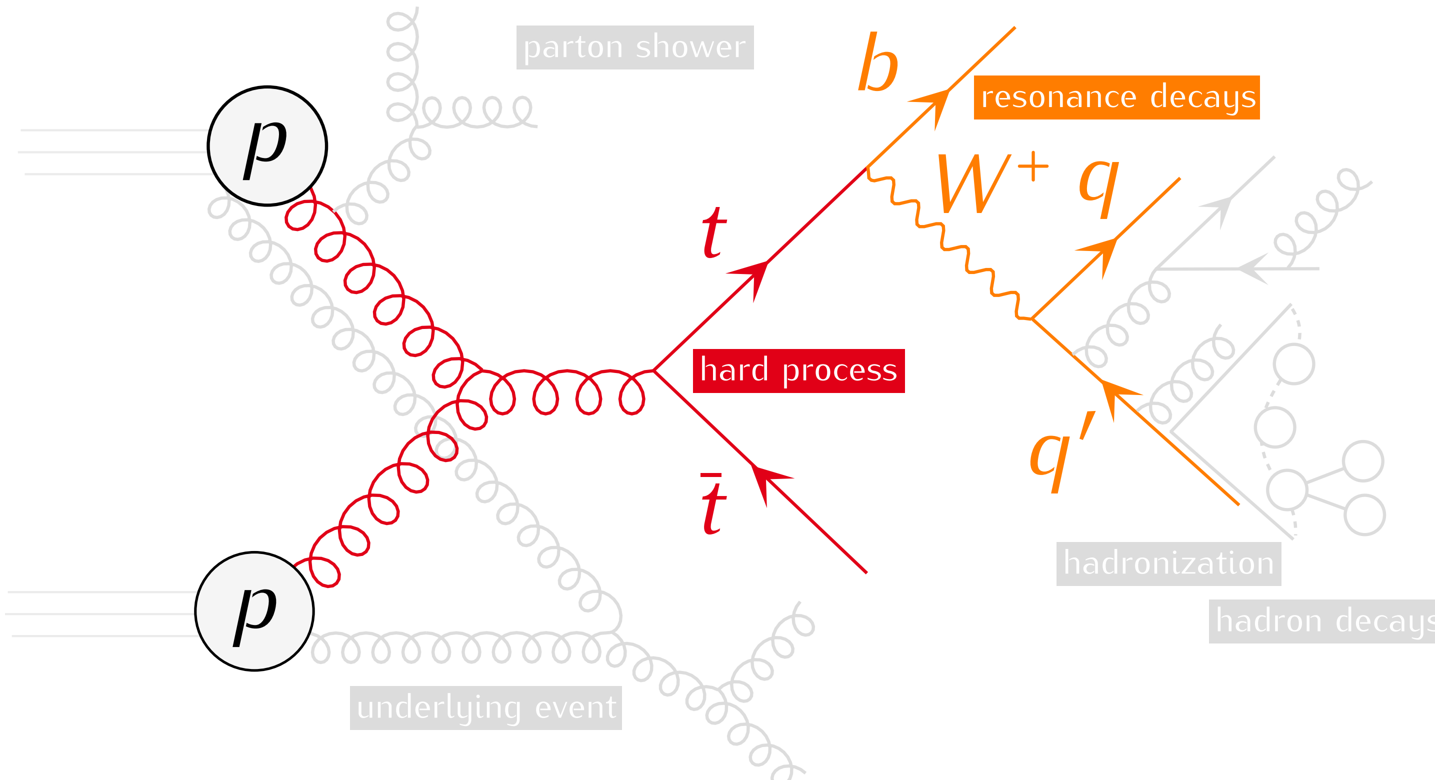

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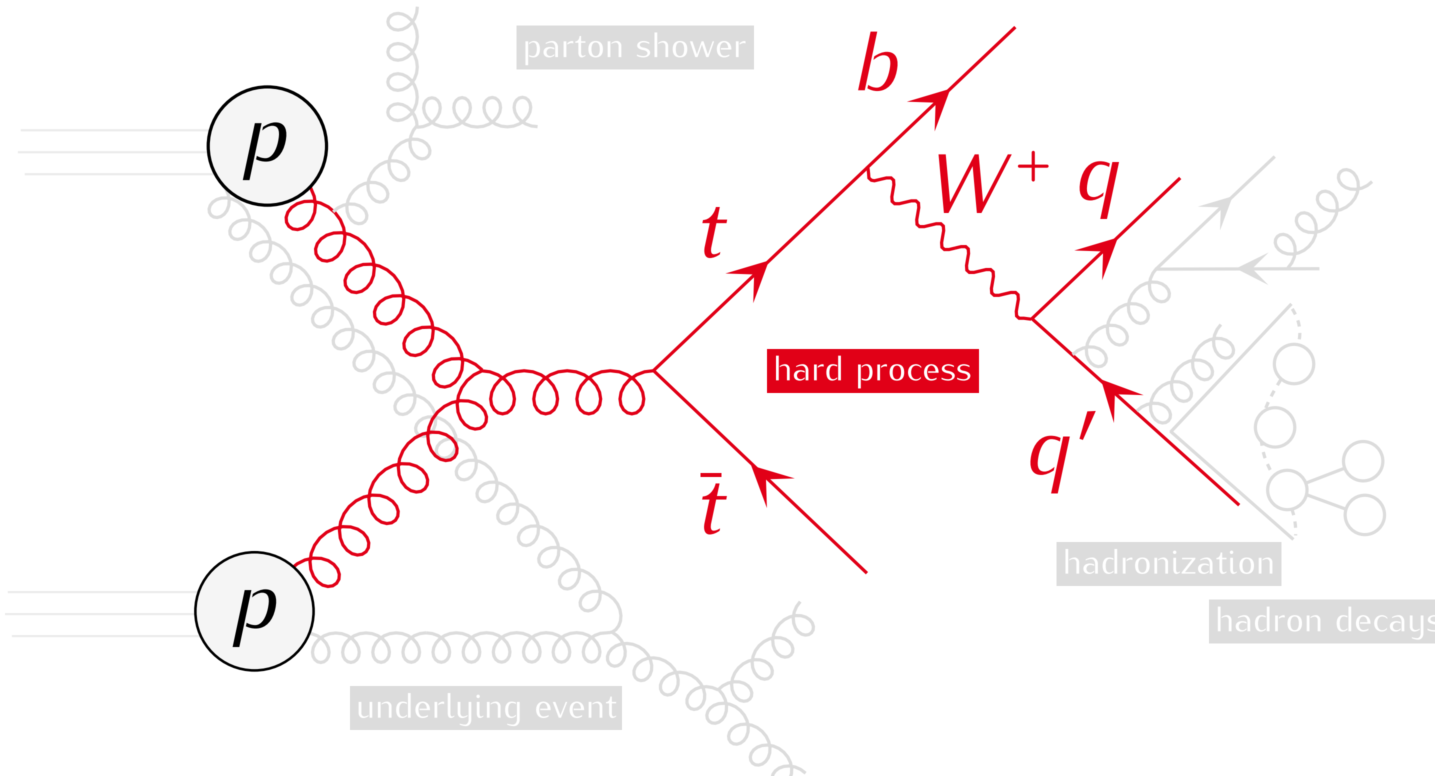

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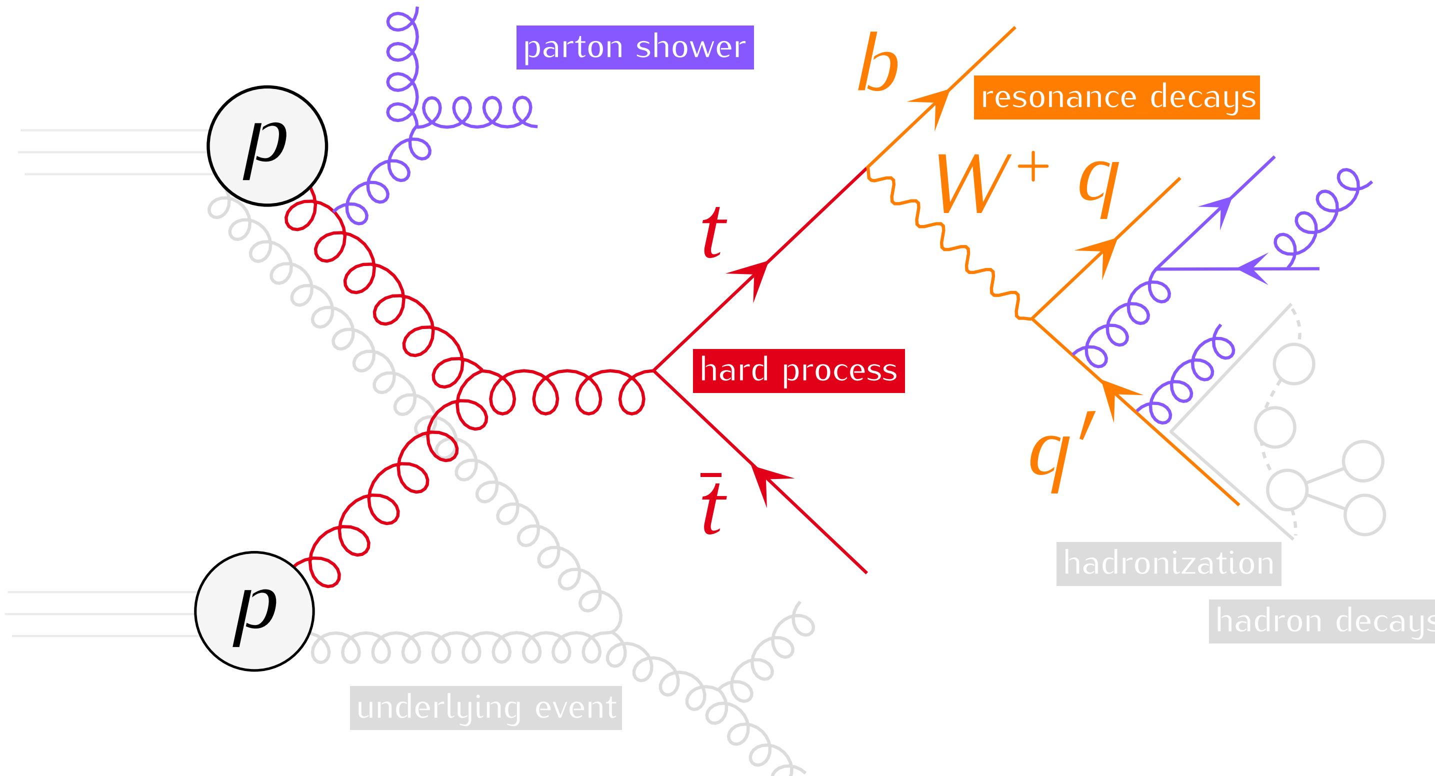

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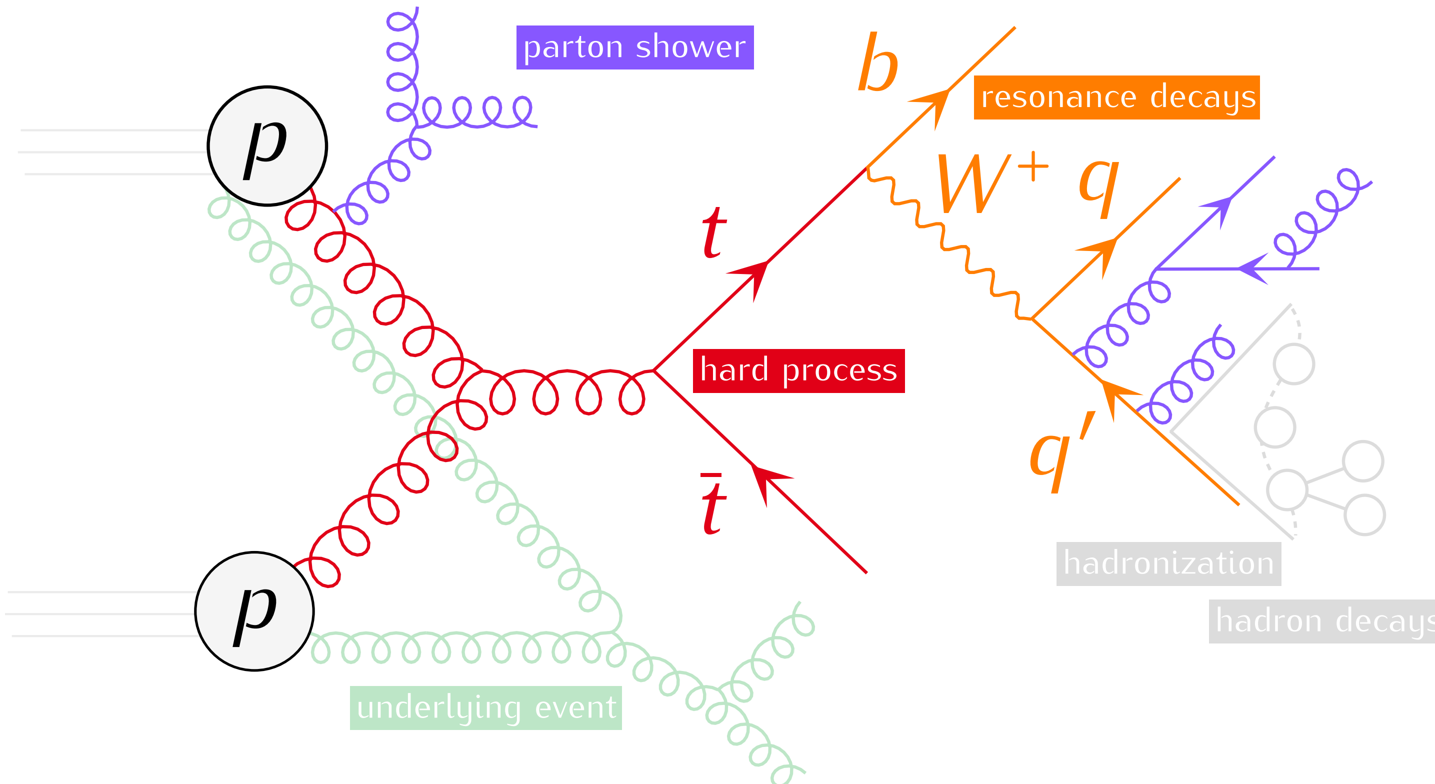

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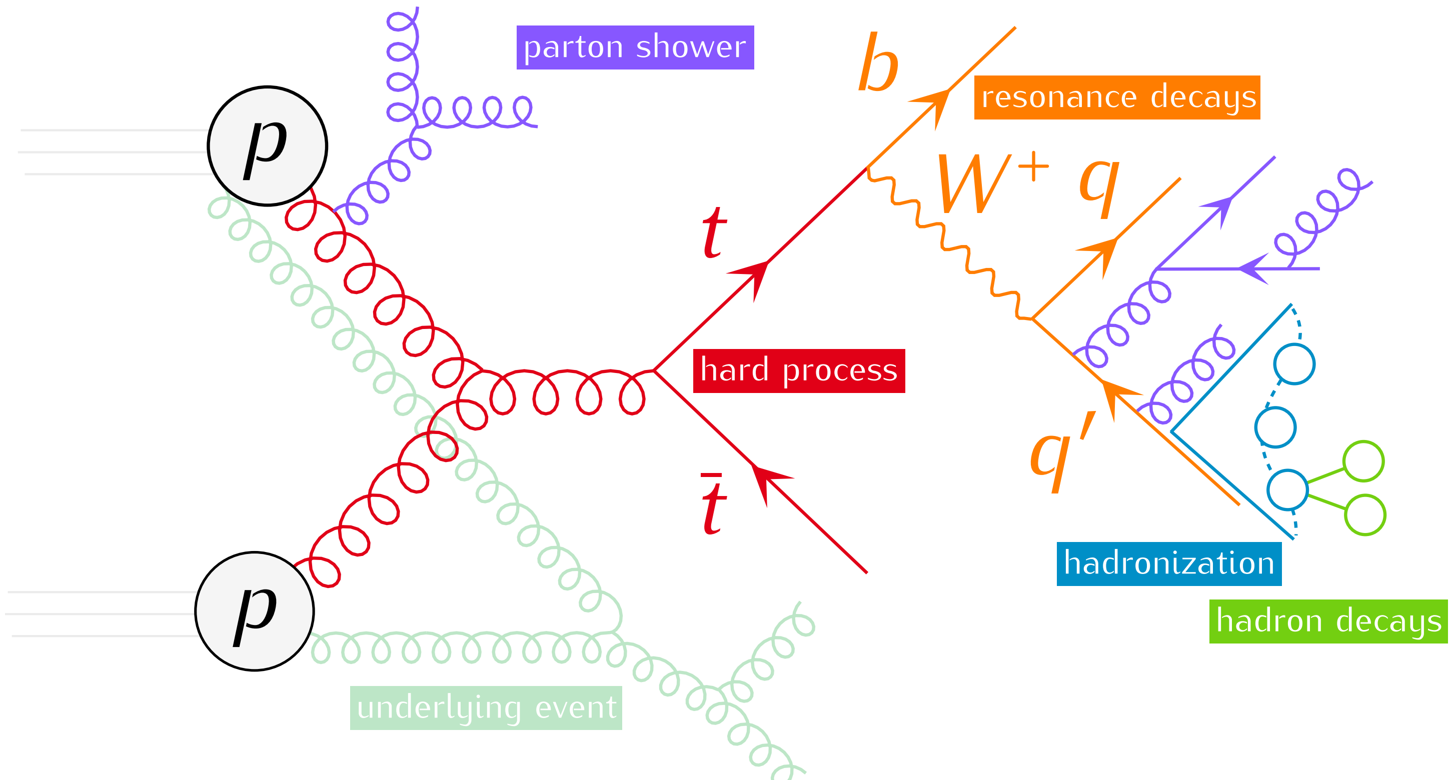
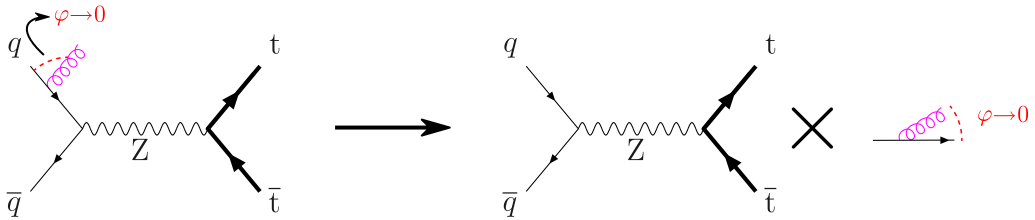


† inspired by M. Seidel

Parton Showers

- In the collinear limit:



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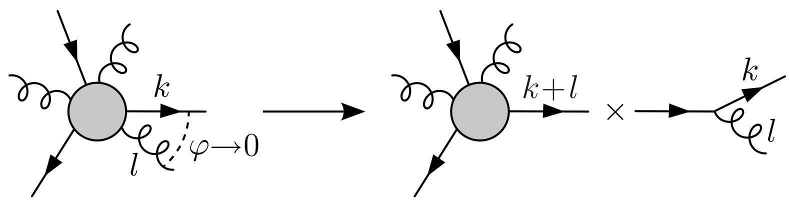


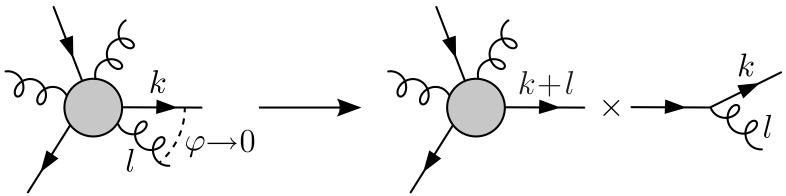
$$|\mathcal{M}_{n+1}|^2 \, \mathrm{d}\Phi_{n+1} \;\longrightarrow\; |\mathcal{M}_n|^2 \, \mathrm{d}\Phi_n \times \frac{\alpha_s}{2\pi} \frac{\mathrm{d}t}{t} P_{q,gg}(z) \, \mathrm{d}z \, \frac{\mathrm{d}\phi}{2\pi}$$

  - t hardness measure ($\to 0$), z momentum fraction, ϕ azimuthal angle
  - $P_{q,gg}(z)$ Altarelli–Parisi splitting for $q \to qg$

- Can be applied recursively: n splittings naively correspond to real corrections at N^{n}LO

Parton Showers

- In the collinear limit:



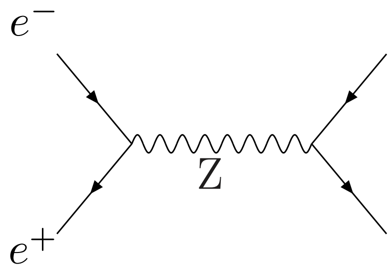
$$|\mathcal{M}_{n+1}|^2 \, \mathrm{d}\Phi_{n+1} \longrightarrow |\mathcal{M}_n|^2 \, \mathrm{d}\Phi_n \times \frac{\alpha_s}{2\pi} \frac{\mathrm{d}t}{t} P_{q,gg}(z) \, \mathrm{d}z \, \frac{\mathrm{d}\phi}{2\pi}$$

- Virtual corrections taken into account via Sudakov form factor

$$\mathrm{d}P(t, t+\mathrm{d}t) = \frac{\alpha_s}{2\pi} \frac{\mathrm{d}t}{t} \int \frac{\mathrm{d}\phi}{2\pi} \int P_{i,jl}(z) \, \mathrm{d}z$$

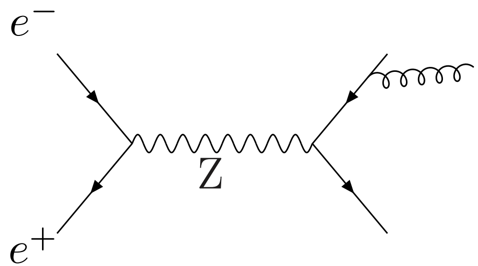
  - $\mathrm{d}P$ probability of $i \to jl$ splitting in $[t, t+\mathrm{d}t]$
  - $1 - \mathrm{d}P$ probability of no emission, equivalent of virtual correction

Parton Showers



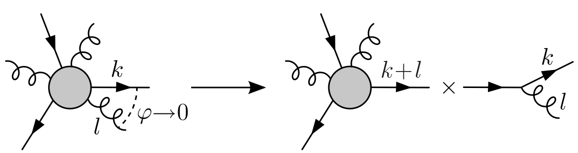
$$W = W_B$$

Parton Showers



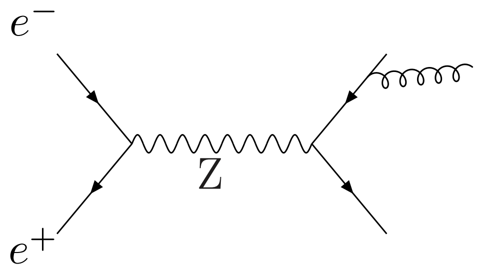
$$W = W_B \times V$$

- Real correction in collinear approximation:



$$|\mathcal{M}_{n+1}|^2 \, \mathrm{d}\Phi_{n+1} \longrightarrow |\mathcal{M}_n|^2 \, \mathrm{d}\Phi_n \times \underbrace{\frac{\alpha_s}{2\pi} \frac{\mathrm{d}t}{t} P_{q,gg}(z) \, \mathrm{d}z \, \frac{\mathrm{d}\phi}{2\pi}}_{V}$$

Parton Showers



$$W = W_B \times V \times \Delta$$

- Virtual corrections in collinear approximation:

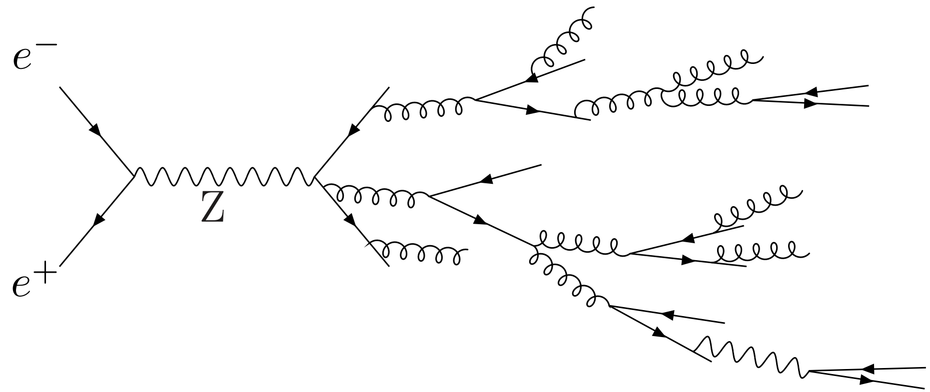
Δ

$$dP(t, t + dt) = \frac{\alpha_s}{2\pi} \frac{dt}{t} \int \frac{d\phi}{2\pi} \int P_{i,jl}(z)\, dz$$

- dP probability of $i \to jl$ splitting in $[t, t + dt]$
- $1 - dP$ probability of no emission, equivalent of virtual correction

Parton Showers

- Parton Showers can be automated:



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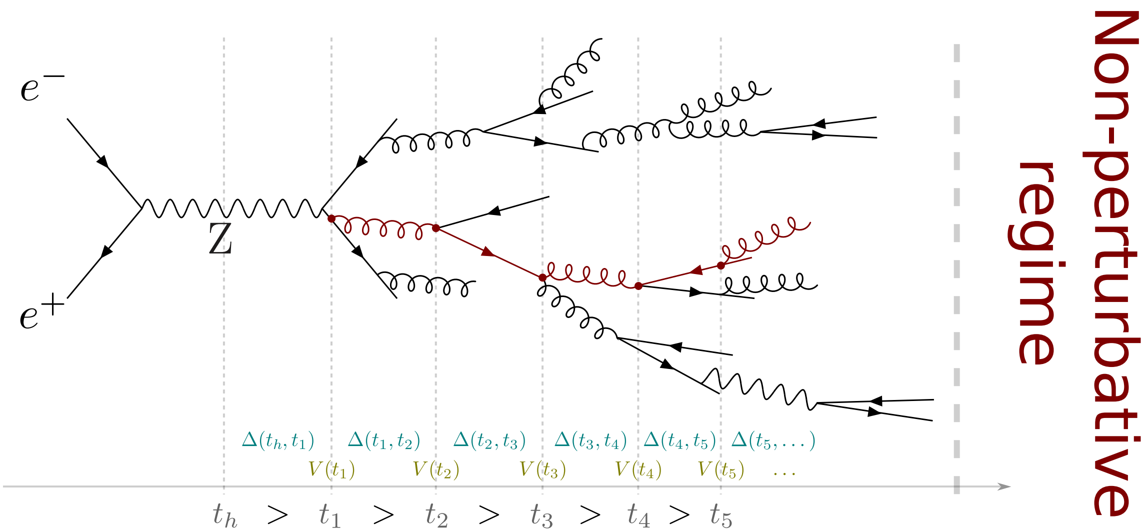

  - Variable t measures hardness
    - Vanishes in the collinear limit
  - Weight of the event is the Born weight times the splitting and Sudakov factors
  - The ordering ensures equivalence to leading-logarithmic resummation

Parton Showers

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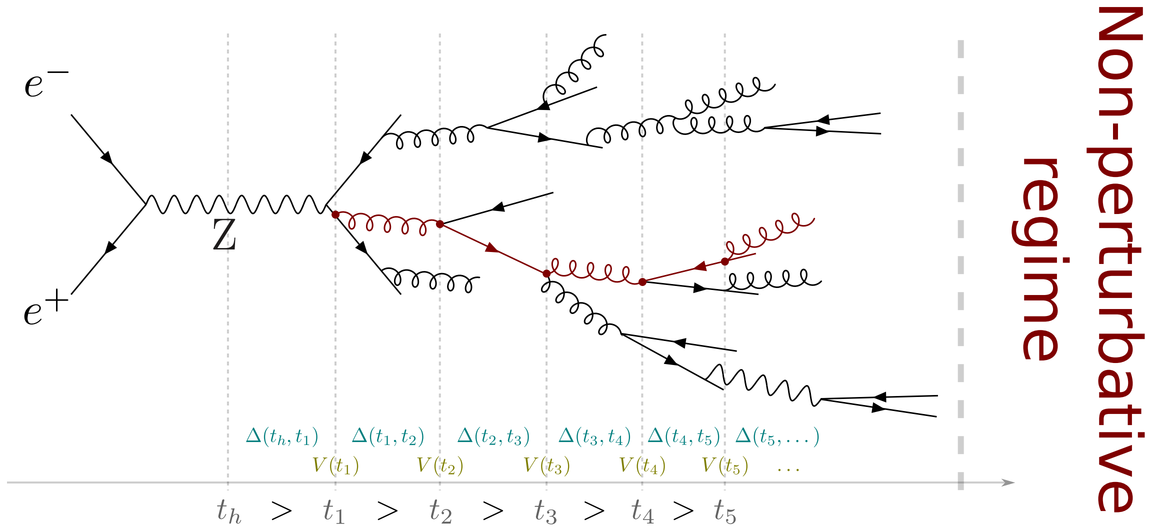

  - With the purpose of:
    - Resumming leading-logarithms
    - Generating final state multiplicities unfeasible at FO
    - Modelling of clustering, hadronization, multi-parton scattering

Hadronization

- Hadronisation
  - Parton showers evolve down to $\sim \Lambda_{QCD}$
  - Below this scale, perturbation theory is no longer applicable at which point hadronisation takes over
  - Hadronisation
    - Coloured partons cannot exist as asymptotic states
    - Transition from partons to colourless hadrons
    - Implemented via phenomenological models
  - Hadron decays
    - Many produced hadrons are unstable
    - Decays simulated to obtain stable final-state particles

Underlying Event & Colour Reconnection

- Underlying event
  - Multiple parton interactions (MPI)
    - More than one parton–parton interaction in a single collision
    - Occurs independently of the primary hard scattering
  - Beam remnants
    - Parts of the incoming hadrons not participating in the hard scattering or MPI
    - Carry leftover longitudinal momentum and colour quantum numbers
    - Hadronise together with other partons in the event
- Colour reconnection
  - Rearrangement of colour connections among final-state partons
  - Acts on showered partons and beam remnants
  - Links MPI and beam remnants to the hadronisation stage

Summary

- Monte Carlo event generators bridge theory and experiment
  - Implement the collinear factorisation idea
  - Starting from a fixed order scattering amplitude
  - They add parton showers that reorganise perturbation theory
    - Resum leading logarithms via probabilistic evolution
    - Generate fully exclusive final states
  - Beyond perturbation theory, modelling is unavoidable
    - Hadronisation turns coloured partons into hadrons
    - Underlying event includes MPI and beam remnants
    - Colour reconnection links global event structure to hadronisation
  - Outcome
    - Realistic particle-level events
    - Directly comparable to experimental measurements

Hands on Session Outline

- Event generation with `Pythia`
  - Baseline hard processes and parton showers
  - Inclusive event generation
- Analysis and data comparison with `Rivet`
  - Apply experimental analyses to MC events
  - Compare generator predictions to measurements
- Improved hard scattering with `MG5_aMC@NLO`
  - Replace internal matrix elements
  - LO multi-leg hard processes interfaced to showers
- NLO event generation with `POWHEG BOX`
  - Generate NLO-accurate hard events
  - Consistent showering with `Pythia`