Precision calculation in high energy particle collisions

Timea Vitos
Supervisor: Rikkert Frederix

Lund University
Theoretical High Energy Physics

PhD Talks 2020,
February 5

Outline

1. Particles and interactions in the SM
2. Overview of particle collisions
3. Higher-order corrections

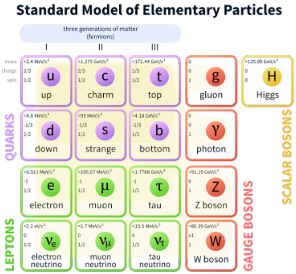
1. Particles and interactions in the SM

2. Overview of particle collisions

3. Higher-order corrections

Particles in the Standard Model

- Two types of particles: **Fermions and bosons**
- Fermions: spin-$\frac{1}{2}$ particles
  - Quarks: strong interaction (QCD), electromagnetic and weak interaction (EW)
  - Leptons: electromagnetic and weak interaction



- Bosons: integer spin particles
  - Gauge bosons: γ, $W^{\pm}$, Z (electroweak), g (strong)
  - Higgs boson: gives mass to particles

Energy scales

Mass of lightest quark (up):	$m_u \approx 2$ MeV
Mass of lightest hadron (pion):	$m_\pi \approx 140$ MeV
Breakdown of perturbative QCD:	≈ 1 GeV
Mass of heaviest quark (top):	$m_t \approx 173$ GeV
Energy of the LHC collisions:	7-13 TeV

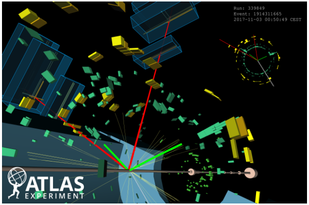


Figure: ATLAS detector image.

Energy scales

Mass of lightest quark (up):	$m_u \approx 2$ MeV
Mass of lightest hadron (pion):	$m_\pi \approx 140$ MeV
Breakdown of perturbative QCD:	≈ 1 GeV
Mass of heaviest quark (top):	$m_t \approx 173$ GeV
Energy of the LHC collisions:	7-13 TeV

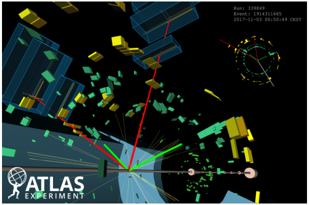
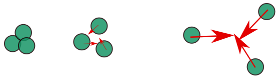


Figure: ATLAS detector image.

QCD coupling constant

Asymptotic freedom

- QCD parametrized by quark masses and coupling constant α_S
- Upon renormalization, the coupling constant α_S becomes energy dependent
- At low energies (large distances), QCD is strong
- At large energies (short distances), QCD is weaker
- $\rightarrow$ Asymptotic freedom



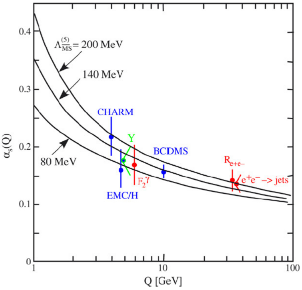


Figure: Figure from S. Bethke [1].

[1] S. Bethke. *Prog. Part. Nucl. Phys.*, 58, (2007).

1. Particles and interactions in the SM

2. Overview of particle collisions

3. Higher-order corrections

Particle collisions at the LHC

A sea of events for *pp* collisions

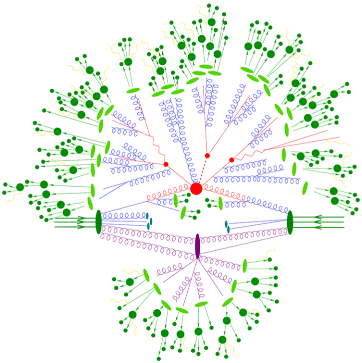


Figure: Schematic event generation with Sherpa.

The full process:

- Hard process (high energy)
- Parton shower (radiated quarks and gluons)
- Hadronization (low energy)

- High energy processes calculated with perturbation theory

[1] E. Bothmann *et al.* *SciPost Phys.*, 7, (2019).

Particle collisions at the LHC

A sea of events for *pp* collisions

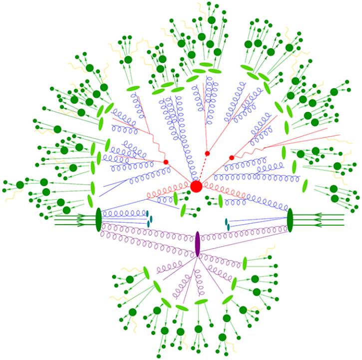


Figure: Schematic event generation with Sherpa.

The full process:

- Hard process (high energy)
- Parton shower (radiated quarks and gluons)
- Hadronization (low energy)

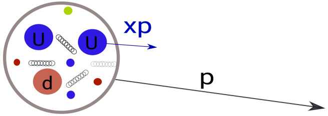
- High energy processes calculated with perturbation theory

- Probability for reaction to occur ∝ cross section σ

[1] E. Bothmann *et al.* *SciPost Phys.*, 7, (2019).

Cross section of the collision

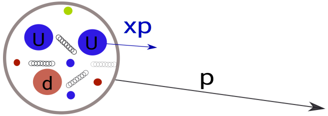
The factorization formula



- Parton model of hadrons

Cross section of the collision

The factorization formula

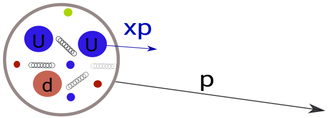


- Parton model of hadrons
- LHC collisions: $pp \to n$, where n is some final state
- Master formula for factorization of total cross section

$$\sigma(pp \to n) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a/p}(x_1, \mu_F) f_{b/p}(x_2, \mu_F) \hat{\sigma}(ab \to n)$$

- $f_{a/p}(x_i, \mu_F)$: parton distribution function
- $\hat{\sigma}(ab \to n)$: parton-level cross section

Cross section of the collision
The factorization formula



- Parton model of hadrons
- LHC collisions: $pp \to n$, where n is some final state
- Master formula for factorization of total cross section

$$\sigma(pp \to n) = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 f_{a/p}(x_1, \mu_F) f_{b/p}(x_2, \mu_F) \hat{\sigma}(ab \to n)$$

- $f_{a/p}(x_i, \mu_F)$: parton distribution function
- $\hat{\sigma}(ab \to n)$: parton-level cross section

Cross section of the collision

Parton-level cross section

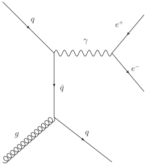
- The cross section is given by

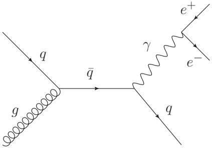
$$\hat{\sigma}(ab \to n) = \int d\Phi_n \frac{1}{2sx_a x_b} |\mathcal{M}|^2(\Phi_n, \mu_R, \mu_F)$$

- Φ_n : n-body phase space
- $\mathcal{M}$: invariant amplitude, obtained with perturbation theory

- Monte Carlo matrix-element generators: MADGRAPH5_aMC@NLO, POWHEG, ALPGEN

- Example: $pp \to e^+ e^- + jet$ at tree-level:





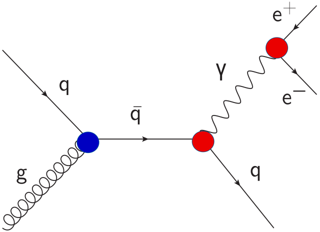
1. Particles and interactions in the SM

2. Overview of particle collisions

3. Higher-order corrections

Perturbative QCD and QED+weak

Obtaining precise results



- Expansion in QCD coupling constant α_S and electromagnetic coupling constant α (and weak couplings)
- Cross section in powers of the coupling constants:

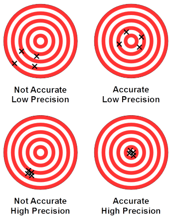
$$\sigma = \underbrace{\sigma^{(0,0)}}_{\text{LO}} + \underbrace{\alpha_S \sigma^{(0,1)}}_{\text{NLO QCD}} + \underbrace{\alpha \sigma^{(1,0)}}_{\text{NLO EW}} + \underbrace{\alpha_S^2 \sigma^{(0,2)}}_{\text{NNLO QCD}} + \underbrace{\alpha \alpha_S \sigma^{(1,1)}}_{\text{mixed higher orders}} + O(\alpha_S^2 \alpha)$$

- In most energy regions considered, $\alpha_S^2 \approx \alpha$, thus NNLO QCD competes with NLO EW

Subtractions at NLO

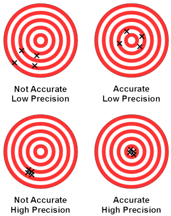
Avoiding singularities

- LO gives *accuracy* of the result
- Higher order corrections give *precision*
- Why need precision?
  - → Model verification
  - → Allow for new physics discoveries
  - → Pin down parton distribution functions

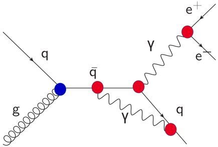


Subtractions at NLO
Avoiding singularities

- LO gives *accuracy* of the result
- Higher order corrections give *precision*
- Why need precision?
  - → Model verification
  - → Allow for new physics discoveries
  - → Pin down parton distribution functions



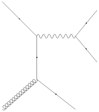
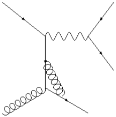
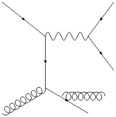
- Higher order diagrams obtained by adding further internal particles



Subtractions at NLO

Avoiding singularities

- Two types of corrections to tree-level diagrams: *virtual diagrams* and *real-emission diagrams*

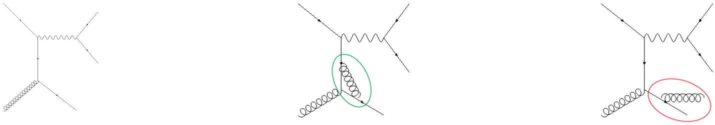




- Two types of divergences: soft divergence and collinear divergence
- In the sum of all diagrams, the divergences cancel
- Subtract terms from both virtual and real-emission diagrams to make them finite separately
- Match the hard process final state to parton showers

Subtractions at NLO

Avoiding singularities

- Two types of corrections to tree-level diagrams: *virtual diagrams* and *real-emission diagrams*



- Two types of divergences: soft divergence and collinear divergence
- In the sum of all diagrams, the divergences cancel
- Subtract terms from both virtual and real-emission diagrams to make them finite separately
- Match the hard process final state to parton showers

Present and future works

Angular coefficients

- Process $pp \to Z + jet \to l^+ l^- + jet$
- Expand cross section into spherical harmonics and corresponding angular coefficients A_i
- QCD predicts at LO that $A_0 = A_2$ (Lam-Tung relation)
- At NLO QCD and NNLO QCD, violation of this relation has been shown [2]

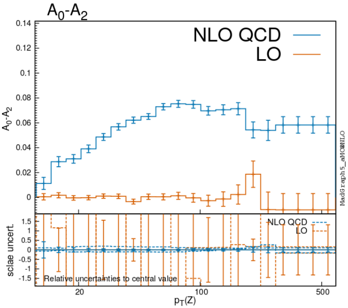


Figure: Violation of $A_0 = A_2$ at NLO QCD.

- Reproduced calculations at NLO QCD
- Outlook: calculate also the NLO EW corrections

[2] R. Gauld, A. Gehrmann–De Ridder, T. Gehrmann, *et al.* *J. High Energ. Phys.* 3 (2017).

Present and future works

Inclusive NNLO predictions

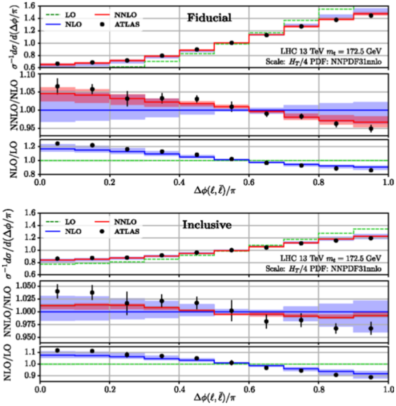


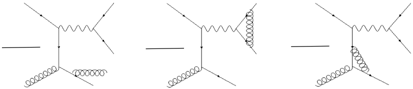
Figure: Figure from A. Behring *et al.*

- Process $pp \to t\bar{t}(+jet)$
- Theory predictions of NLO QCD and NNLO QCD for the top quark pair spin correlation [3]
- ATLAS data unfolded from *fiducial* to *inclusive* region
- NNLO QCD has better fit in fiducial than in inclusive region
- Outlook: examine the unfolding procedure

[3] A. Behring, M. Czakon, A. Mitov, *et al.* *Phys. Rev. Lett.* 123, 082001 (2019).

Summary

- Simulate particle collisions based on SM and compare to data
- For high energy processes, use perturbation theory in the coupling constants to obtain higher precision
- Match the hard process to parton showers and then to hadronization to obtain full reaction cross section
- At higher orders in the perturbative expansion, one needs to be careful with virtual and real-emission contributions



Thank you for listening!