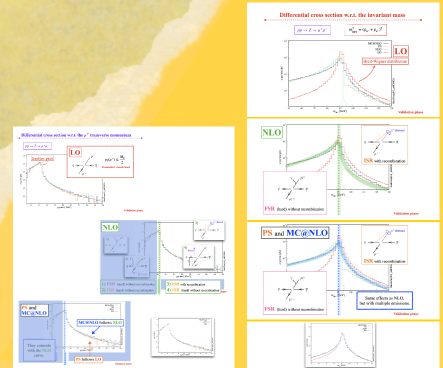
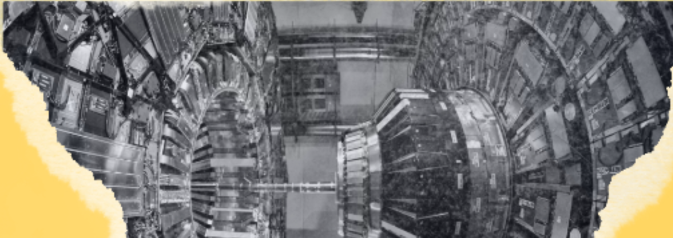
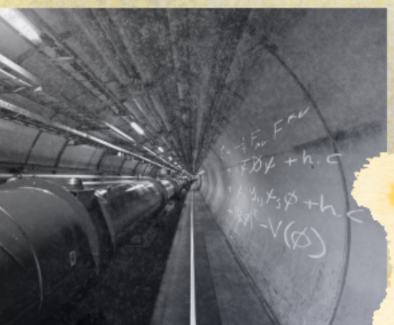
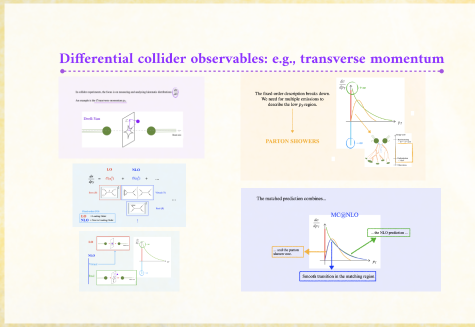
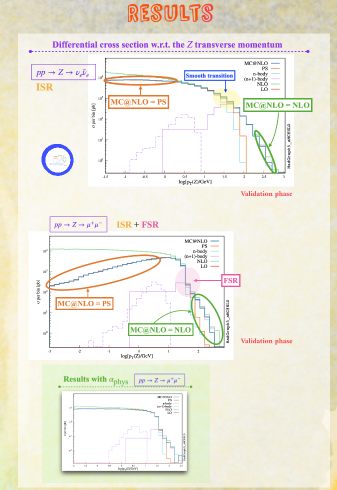
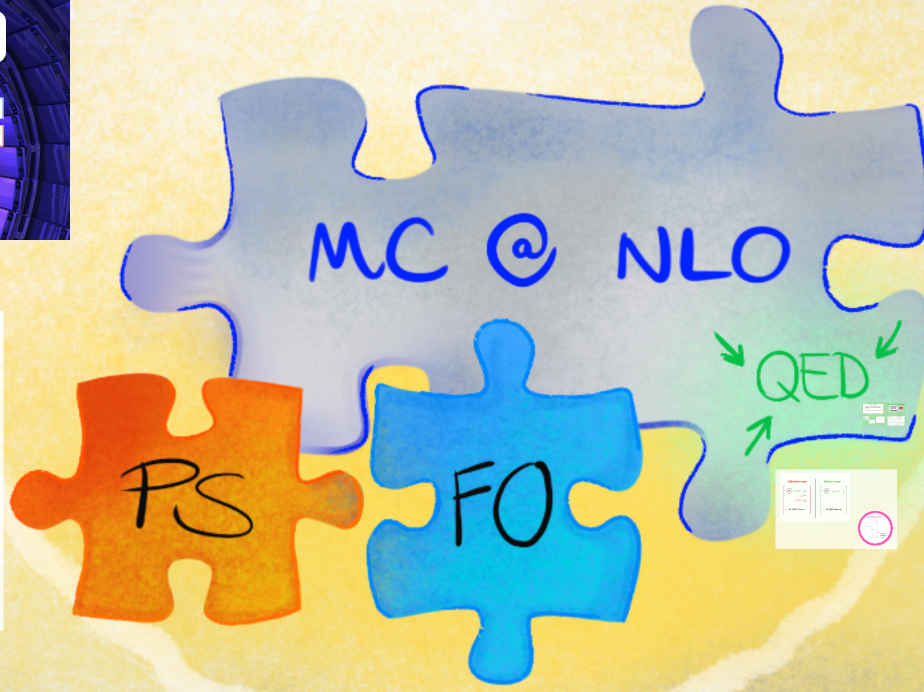
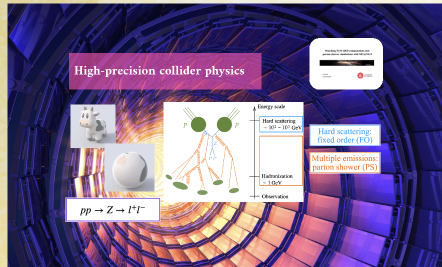
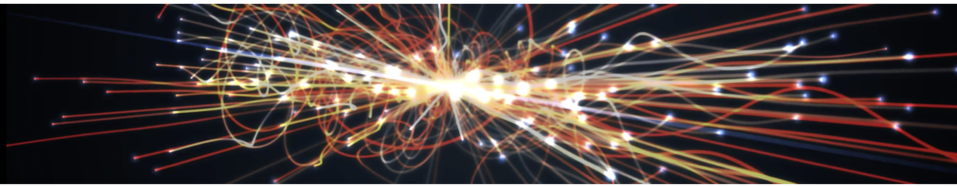


Matching NLO QED computations and parton-shower simulations with MC@NLO



Matching NLO QED computations and parton-shower simulations with MC@NLO



Credits: [https://
www.quantamagazine.org](https://www.quantamagazine.org)

25/11/2024

Camilla Forgione



UNIVERSITÀ
DI TORINO

High-precision collider physics

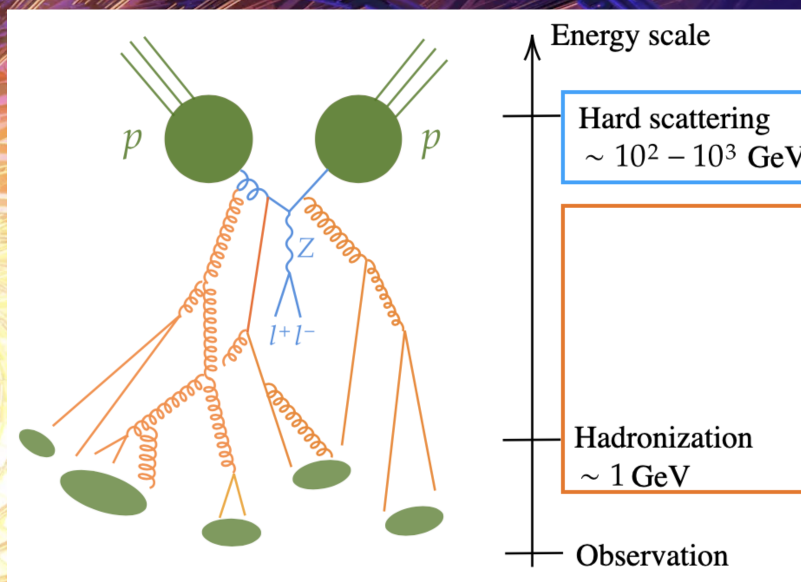
Matching NLO QED computations and parton-shower simulations with MC@NLO



25/11/2024
Cecilia Fregina



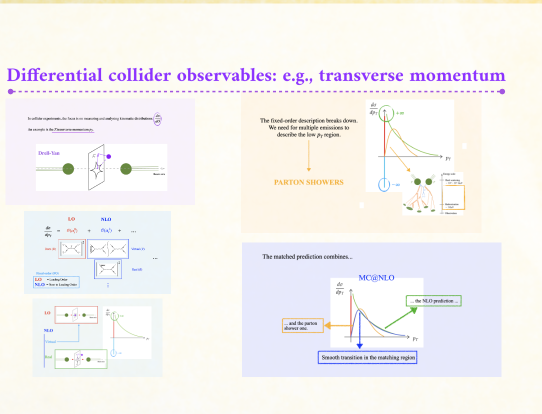
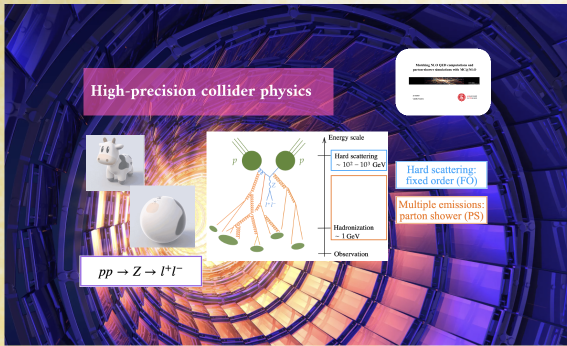
$$pp \rightarrow Z \rightarrow l^+l^-$$



Hard scattering:
fixed order (FO)

Multiple emissions:
parton shower (PS)

Matching NLO QED computations and parton-shower simulations with MC@NLO



pp - ISB

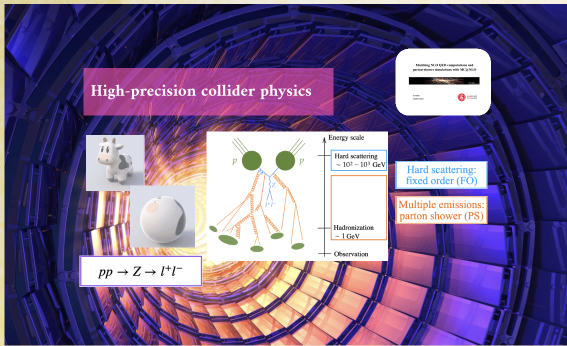
Conc

the order of the matching region

the order of the matching region

the order of the matching region

Matching NLO QED computations and parton-shower simulations with MC@NLO



Differential collider observables: e.g., transverse momentum

In order to compare the fixed order calculation to the experimental data, we need to describe the low p_T region.

The fixed order description breaks down. We need for multiple emissions to describe the low p_T region.

PARTON SHOWERS

The matched prediction combines...

MC@NLO

add the parton shower to the NLO production

Smooth transition in the matching region

pp - ISR

Conc

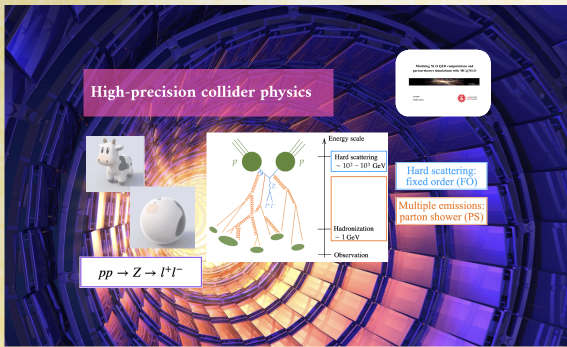
the fixed order calculation breaks down in the low p_T region. The parton shower (PS) is needed to describe the low p_T region.

MC@NLO

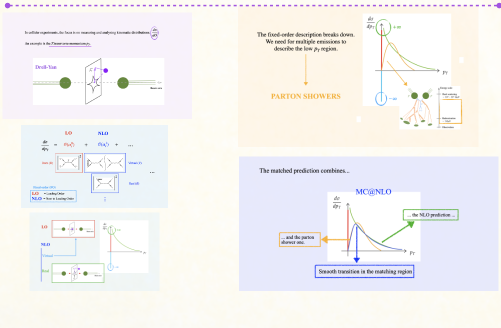
add the parton shower to the NLO production

Smooth transition in the matching region

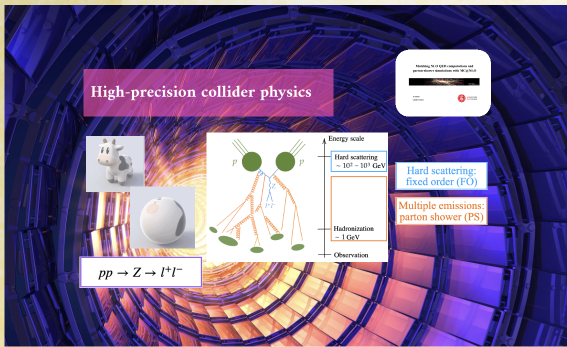
Matching **NLO** QED computations and **parton-shower** simulations with **MC@NLO**



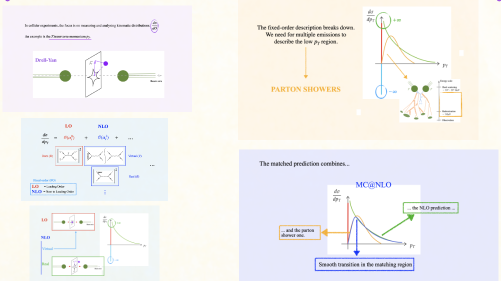
Differential collider observables: e.g., transverse momentum



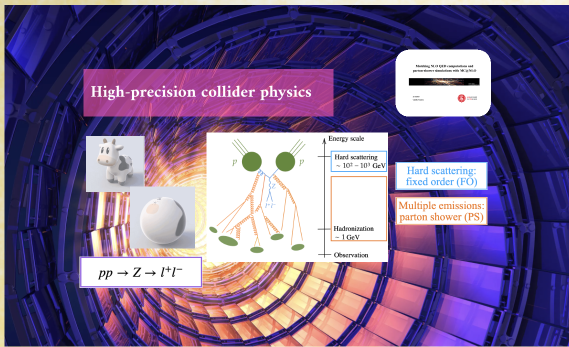
Matching **NLO QED** computations and **parton-shower** simulations with **MC@NLO**



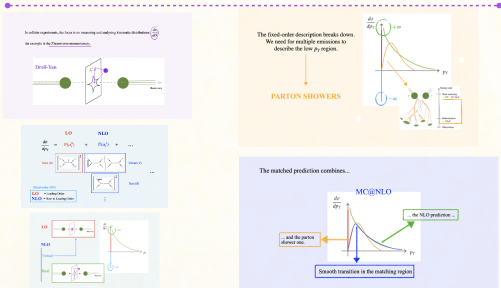
Differential collider observables: e.g., transverse momentum



Matching **NLO QCD** computations and **parton-shower** simulations with **MC@NLO**



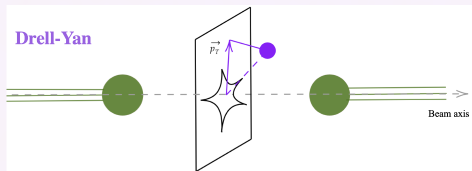
Differential collider observables: e.g., transverse momentum



Differential collider observables: e.g., transverse momentum

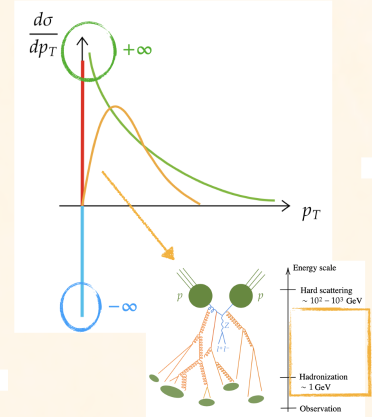
In collider experiments, the focus is on measuring and analysing kinematic distributions: $\left(\frac{d\sigma}{dO}\right)$

An example is the Z transverse momentum p_T .



The fixed-order description breaks down.
We need for multiple emissions to describe the low p_T region.

PARTON SHOWERS



$$\frac{d\sigma}{dp_T} = \mathcal{O}(\alpha_s^0) + \mathcal{O}(\alpha_s^1) + \dots$$

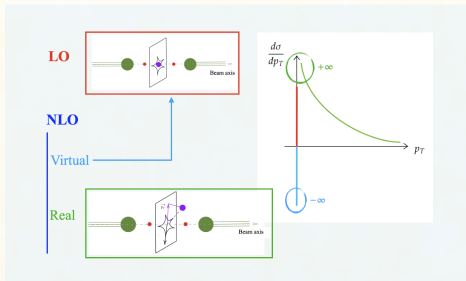
LO **NLO**

Born (B) Virtual (V) ...

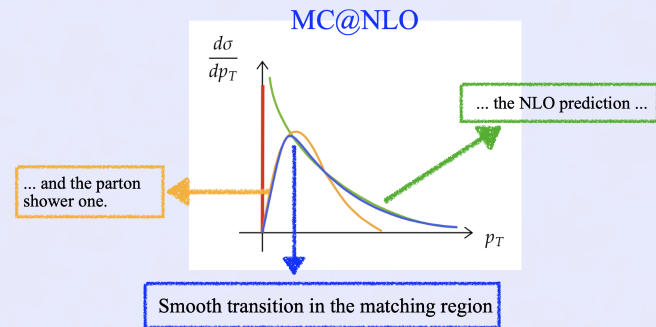
Real (R)

Fixed order (FO)

LO = Leading Order
NLO = Next to Leading Order

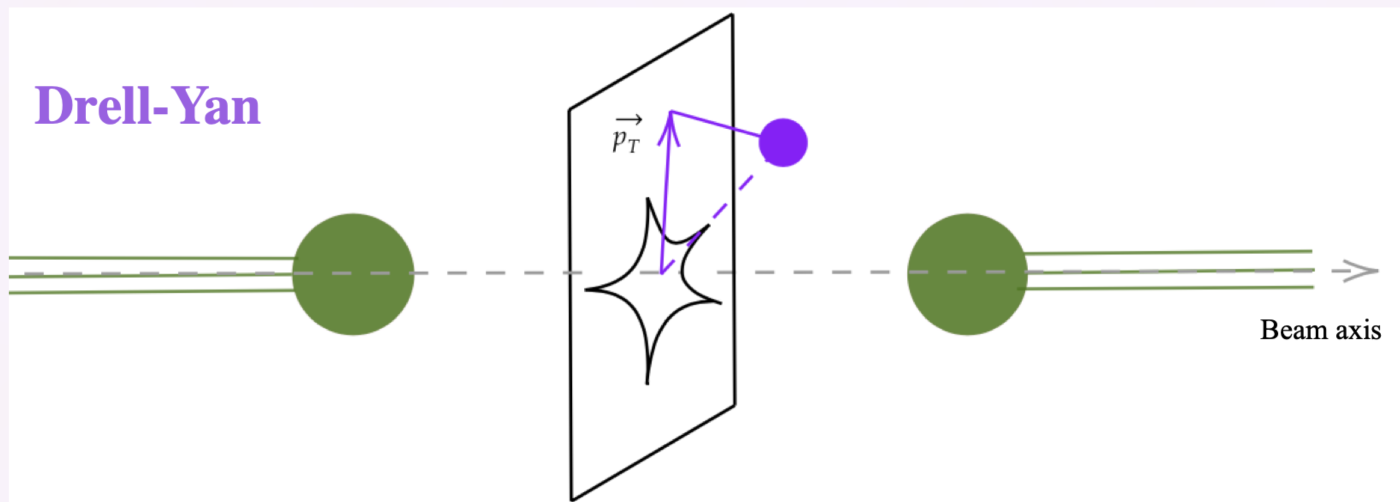


The matched prediction combines...



In collider experiments, the focus is on measuring and analysing kinematic distributions: $\frac{d\sigma}{dO}$

An example is the Z transverse momentum p_T .

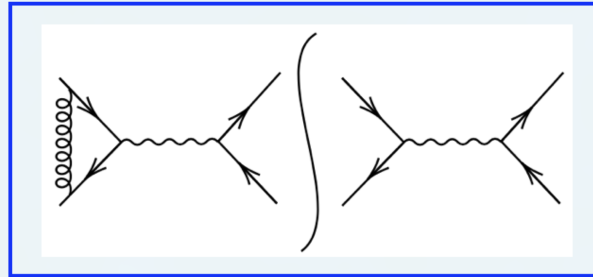
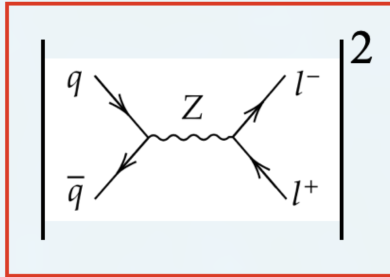


LO

NLO

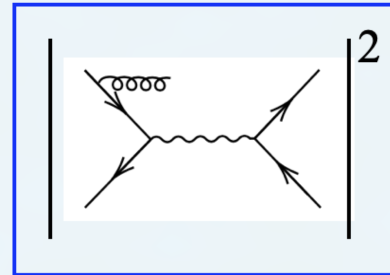
$$\frac{d\sigma}{dp_T} = \mathcal{O}(\alpha_s^0) + \mathcal{O}(\alpha_s^1) + \dots$$

Born (*B*)



Virtual (*V*)

...



Real (*R*)

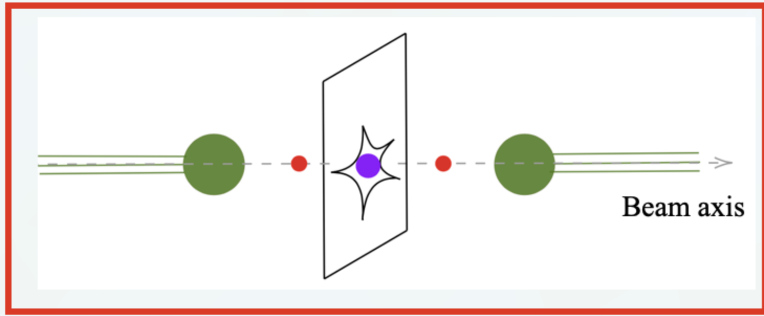
Fixed order (FO)

LO = Leading Order

NLO = Next to Leading Order

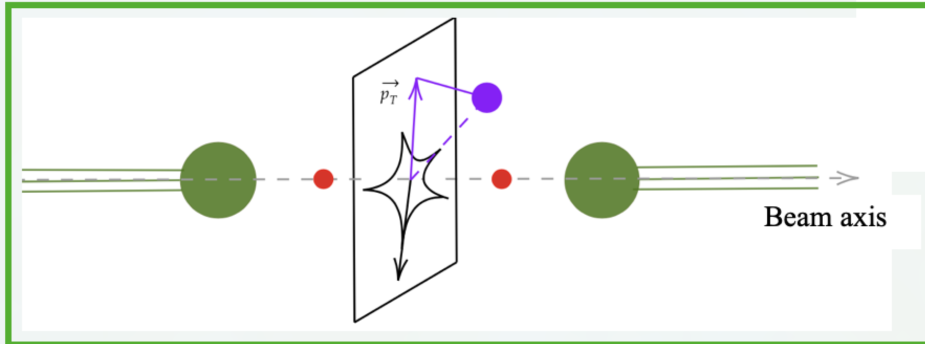
⋮

LO

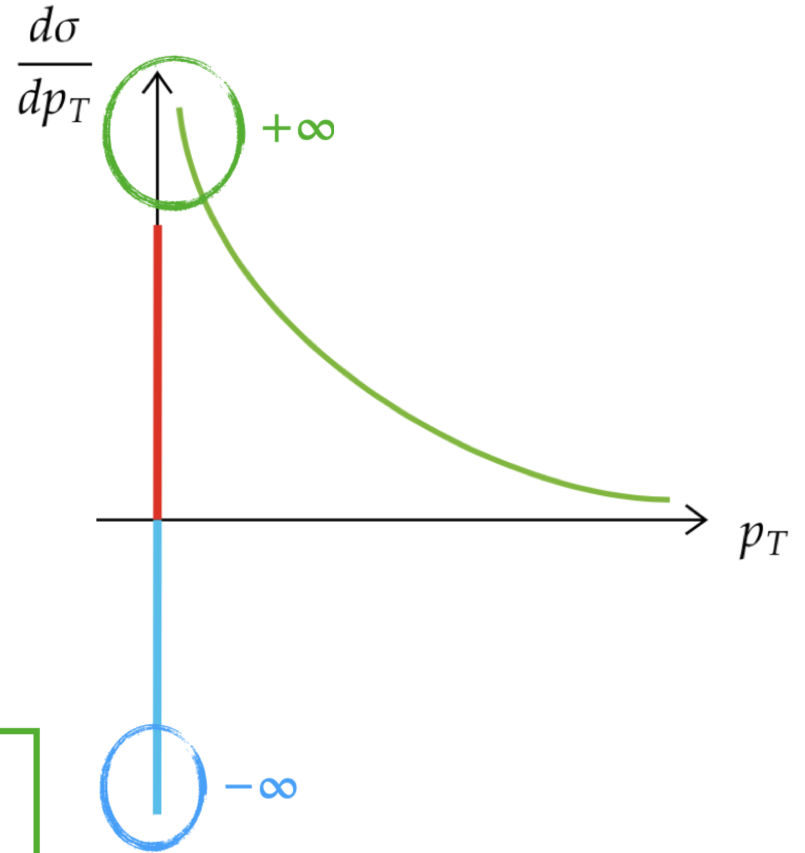


NLO

Virtual



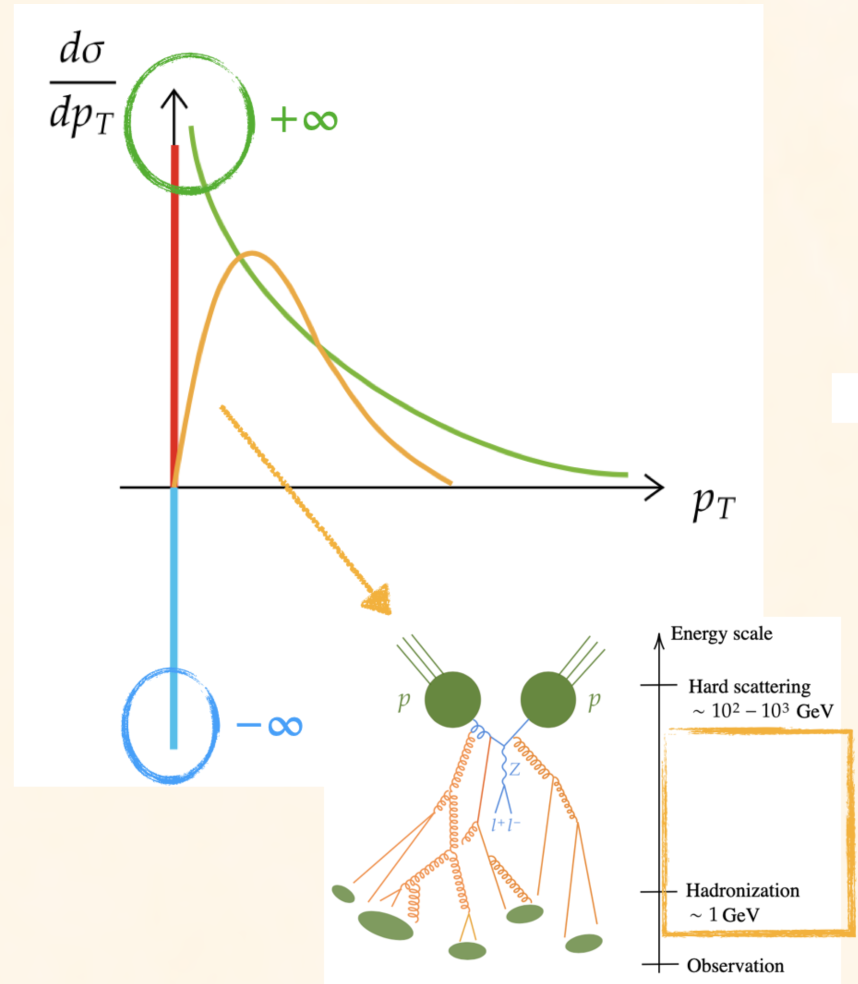
Real



The fixed-order description breaks down.
We need for multiple emissions to
describe the low p_T region.

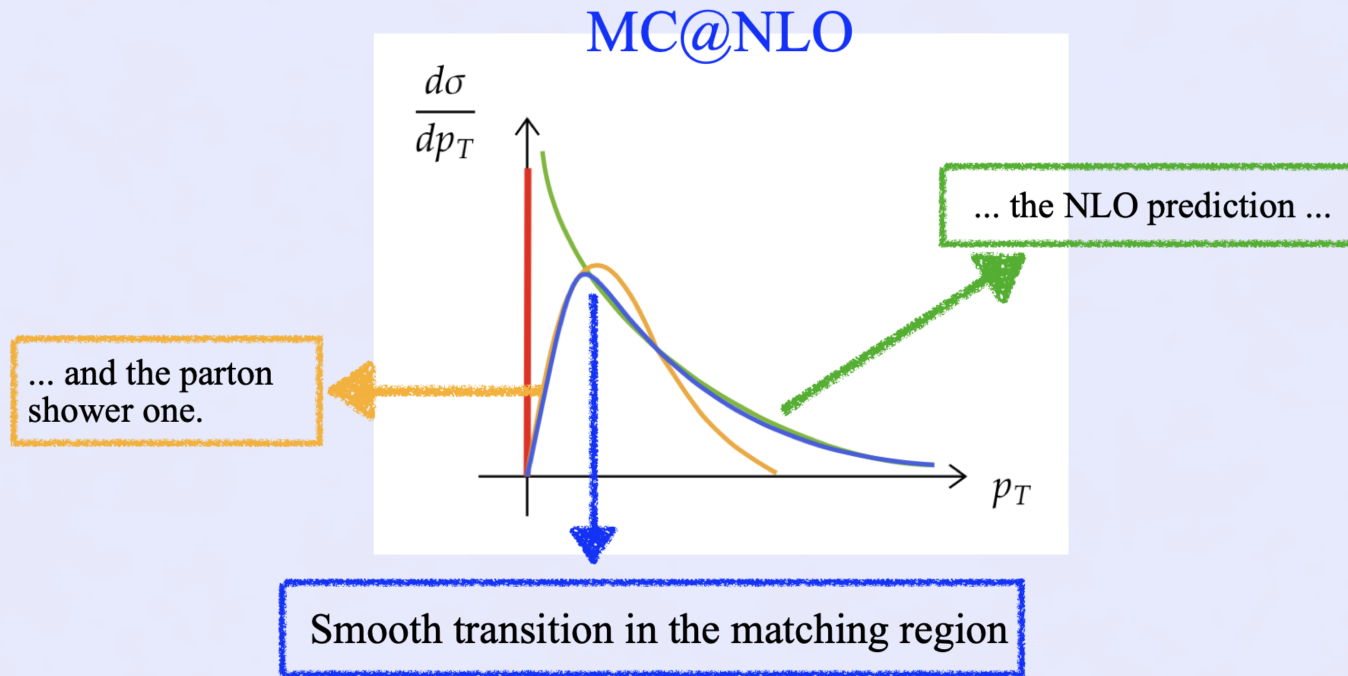


PARTON SHOWERS

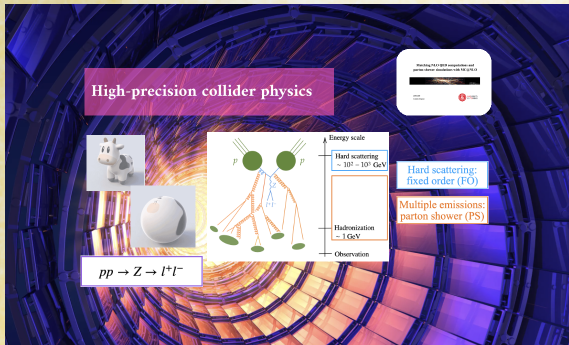


The matched prediction combines

The matched prediction combines...



Matching **NLO QCD** computations and **parton-shower** simulations with **MC@NLO**



Differential collider observables: e.g., transverse momentum

Collider observables are often a function of an underlying observable distribution.

Double Drell-Yan

The fixed-order description breaks down. We need the multiple emissions to describe the low p_T region.

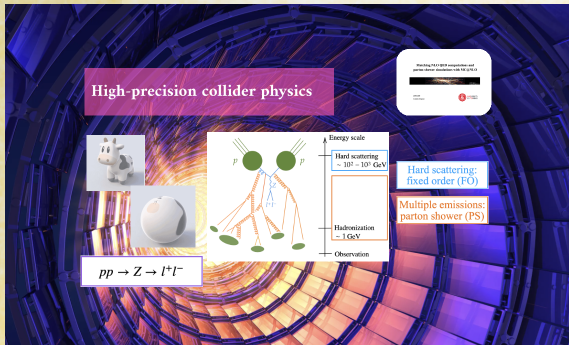
PARTON SHOWERS

The matched production combines...

MC@NLO

Search transition in the matching region

Matching **NLO QED** computations and **parton-shower** simulations with **MC@NLO**



Differential collider observables: e.g., transverse momentum

Double Drell-Yan: $pp \rightarrow l^+l^- + l^+l^-$

The fixed-order description breaks down. We need the multiple emissions to describe the low p_T region.

PARTON SHOWERS

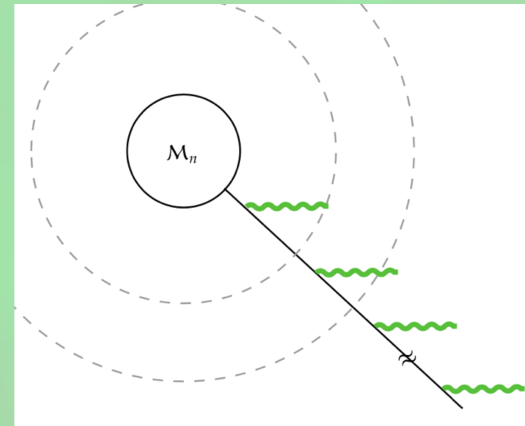
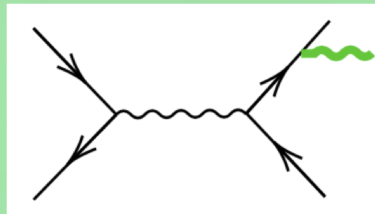
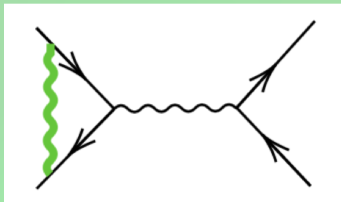
The matched production combines...

MC@NLO

Search transition in the matching region

Need for QED corrections

- As experimental precision continues to improve, accounting for QED effects in predictions becomes necessary.
- Future colliders will include at least one e^+e^- machine.



How

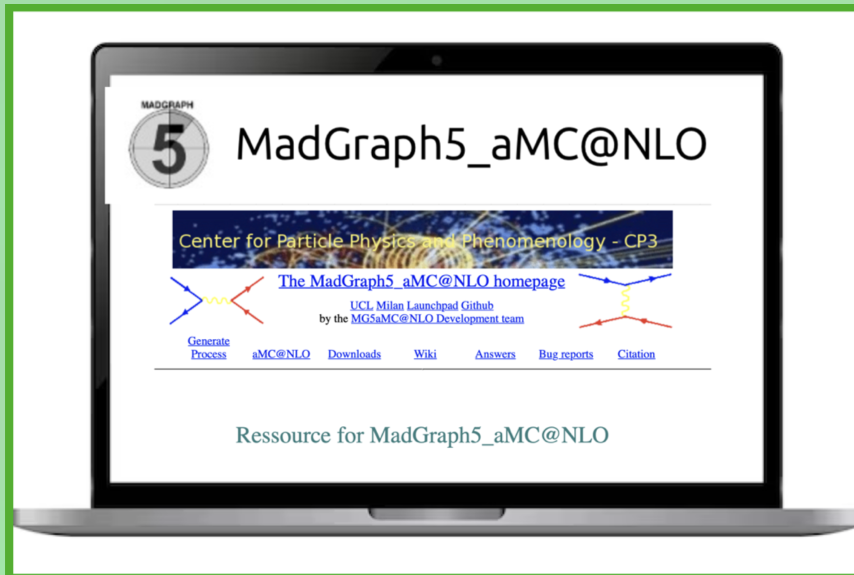
We simulated

$pp \rightarrow$

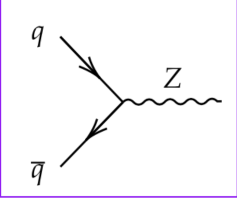
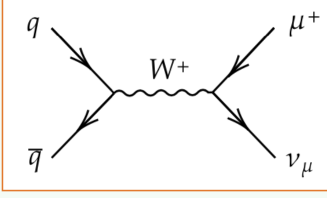
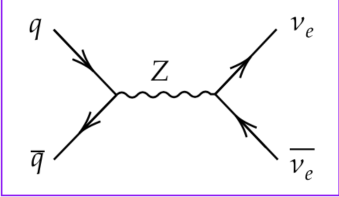
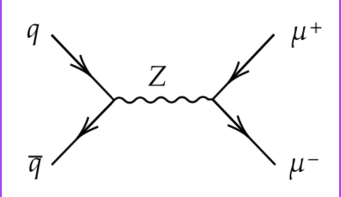
$pp \rightarrow$

ISI

How did we extend MC@NLO?



We simulated two processes: **charged Drell-Yan** and **neutral Drell-Yan** (in 3 versions)

ISR	ISR + FSR
<p>$pp \rightarrow Z$ (stable)</p> 	 <p>$pp \rightarrow W^+ \rightarrow \mu^+ \nu_\mu$</p>
<p>$pp \rightarrow Z \rightarrow \nu_e \bar{\nu}_e$</p> 	 <p>$pp \rightarrow Z \rightarrow \mu^+ \mu^-$</p>

ISR = initial state radiation

FSR = final state radiation

Validation setup

- α $\alpha_{\text{phys}}(M_Z) \sim \frac{1}{128}$
 $\downarrow \times 10$
 $\alpha_{\text{big}}(M_Z) \sim \frac{1}{12.8}$

- No QCD shower

Physical setup

- α $\alpha_{\text{phys}}(M_Z) \sim \frac{1}{128}$

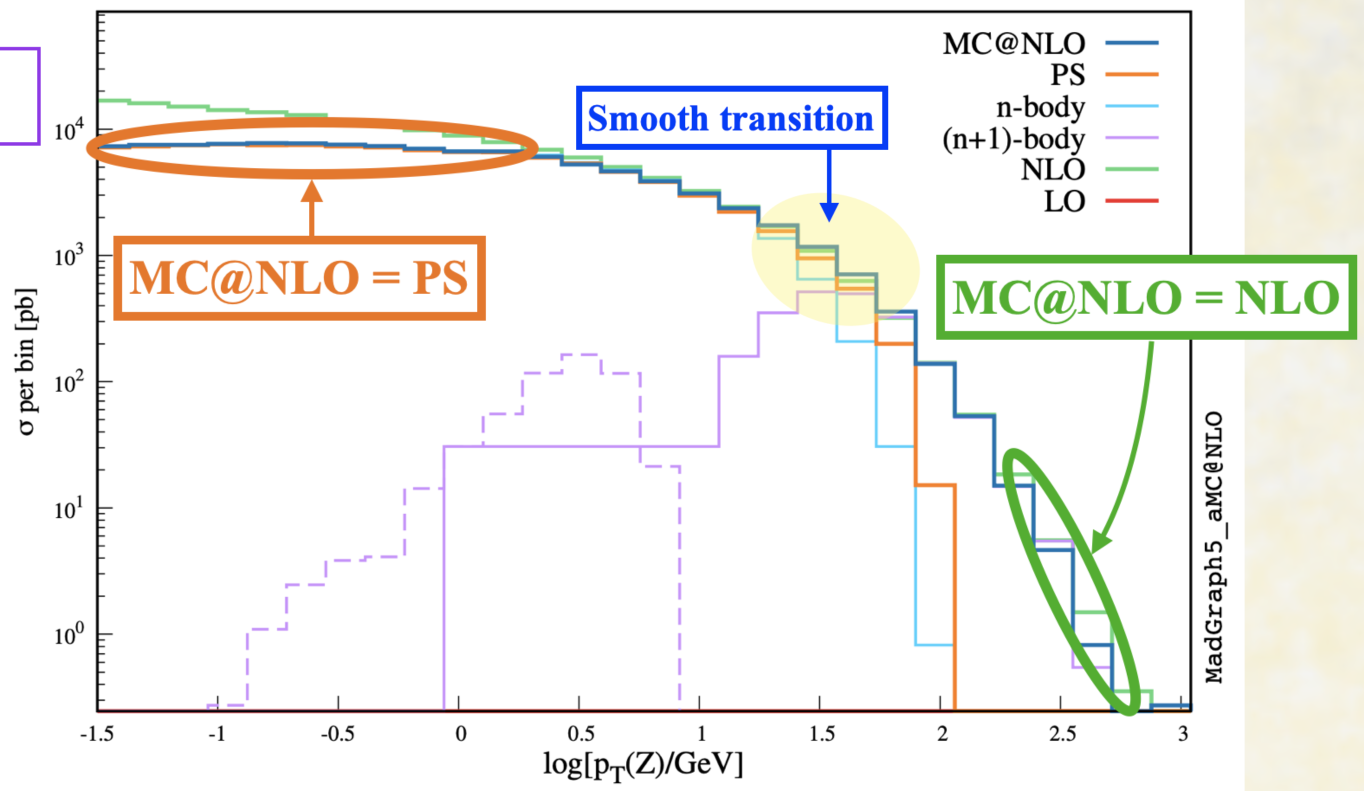
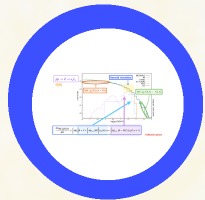
- No QCD shower

RESULTS

Differential cross section w.r.t. the Z transverse momentum

$$pp \rightarrow Z \rightarrow \nu_e \bar{\nu}_e$$

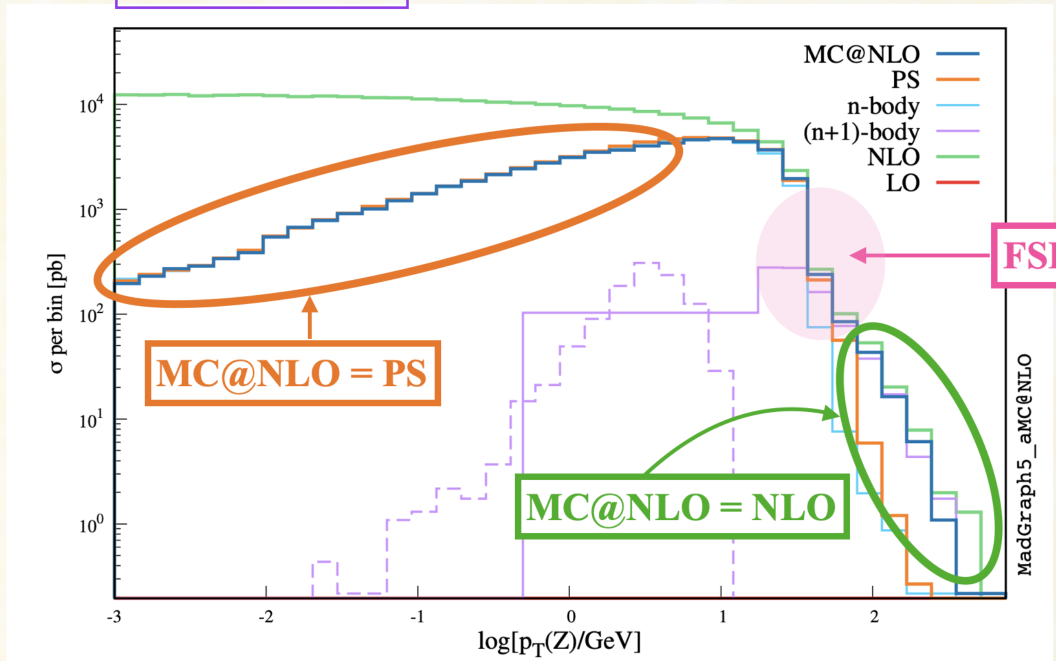
ISR



Validation phase

$$pp \rightarrow Z \rightarrow \mu^+ \mu^-$$

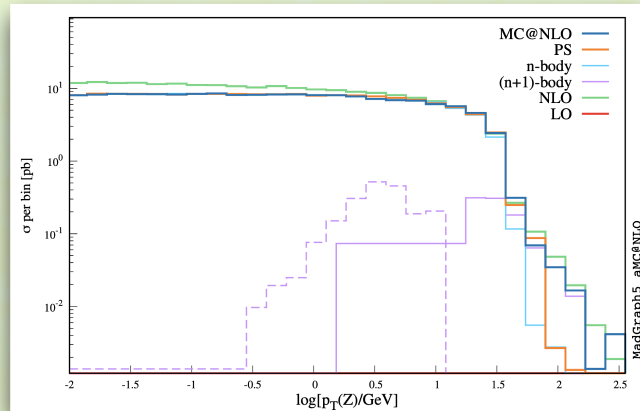
ISR + FSR



Validation phase

Results with α_{phys}

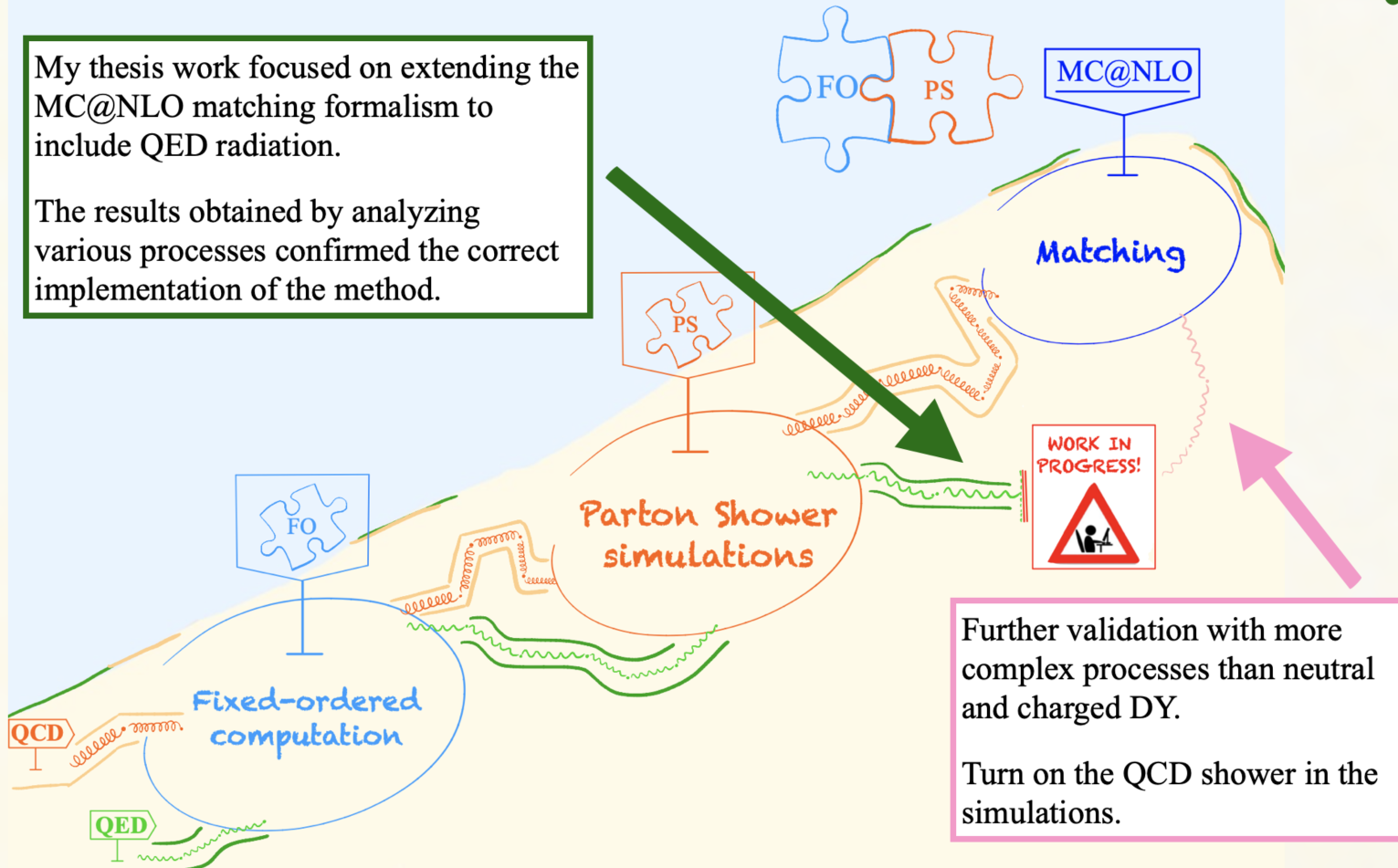
$$pp \rightarrow Z \rightarrow \mu^+ \mu^-$$



Conclusions and Future prospects

My thesis work focused on extending the MC@NLO matching formalism to include QED radiation.

The results obtained by analyzing various processes confirmed the correct implementation of the method.



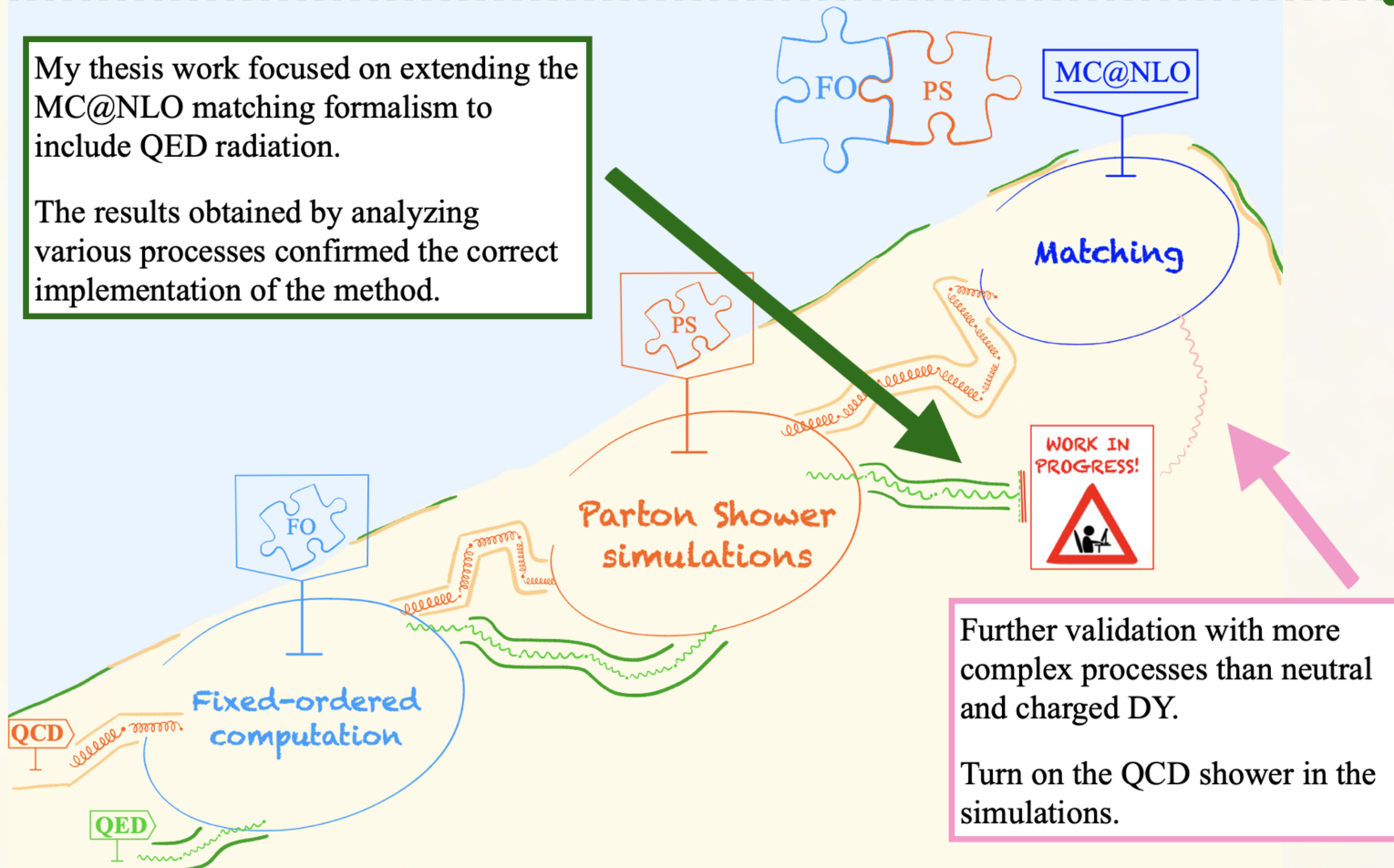
Further validation with more complex processes than neutral and charged DY.

Turn on the QCD shower in the simulations.

Conclusions and Future prospects

My thesis work focused on extending the MC@NLO matching formalism to include QED radiation.

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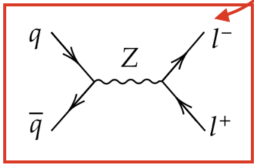
Turn on the QCD shower in the simulations.

Thank you for your attention!

Backup

Parton shower

$$\frac{d\sigma_{\text{LO}}}{dp_T} = \int d\phi_2 B \delta(p_T - p_T(2))$$



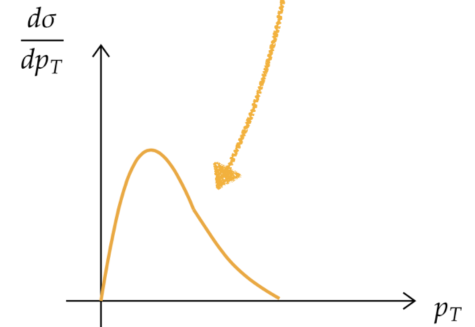
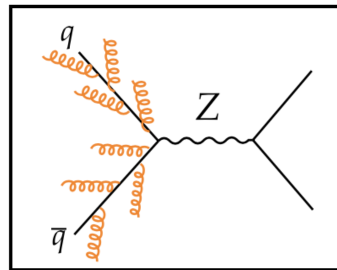
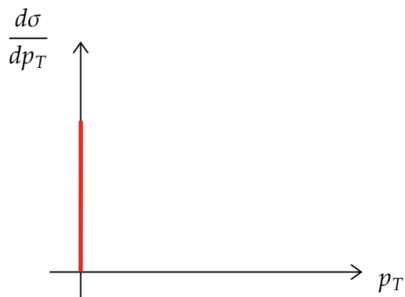
observable computed with Born kinematics

PS \rightarrow

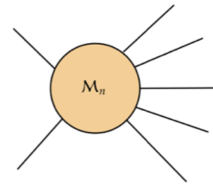
dresses up the Born amplitude with parton emissions

$$\frac{d\sigma_{\text{LO+PS}}}{dp_T} = \int d\phi_2 B I_{\text{PS}}(p_T, 2)$$

shower spectrum, starting from Born kinematics



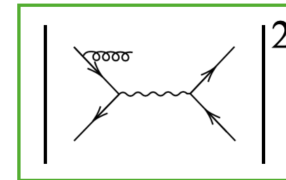
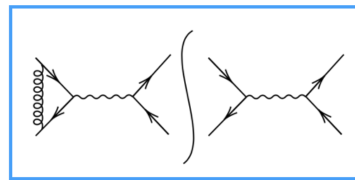
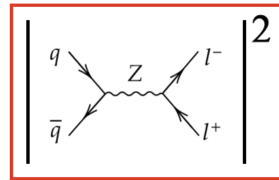
Master formula



$2 \rightarrow n$ scattering process

$$\frac{d\sigma_{\text{NLO}}}{dO} = \int d\phi_n (B + V) \delta(O - O(n)) + \int d\phi_{n+1} R \delta(O - O(n+1))$$

$n = 2$



PS

Master formula

$$\frac{d\sigma_{\text{MC@NLO}}}{dO} = \int d\phi_n \left[B + V + \left[d\phi_{(n+1)} \text{MC} \right] I_{\text{PS}}(O, n) \right] + \int d\phi_{n+1} \left[R - \text{MC} \right] I_{\text{PS}}(O, n+1)$$

Shower spectra starting from n -body kinematics

Shower spectra starting from $(n+1)$ -body kinematics

Monte Carlo counterterm

it ensures the finiteness of the terms in square brackets

$$\frac{d\sigma_{\text{NLO}}}{dO} = \int d\phi_n (B + V) \delta(O - O_n) + \int d\phi_{n+1} R \delta(O - O_{n+1})$$

PS
↓

$$\frac{d\sigma_{\text{MC@NLO}}}{dO} = \int d\phi_n (B + V) I_{\text{PS}}(O, n) + \int d\phi_{n+1} R I_{\text{PS}}(O, n + 1)$$

Two problems:

- **Double counting:** if we expand $\frac{d\sigma_{\text{MC@NLO}}}{dO}$ to $\mathcal{O}(\alpha_s)$, we do not reproduce $\frac{d\sigma_{\text{NLO}}}{dO}$.
- **Instability:** $(B + V)$ and R are separately divergent.

$$\frac{d\sigma_{\text{MC@NLO}}}{dO} = \int d\phi_n \left[B + V + \int d\phi_{(+1)\text{MC}} \right] I_{PS}(O, n) + \int d\phi_{n+1} [R - MC] I_{PS}(O, n + 1)$$

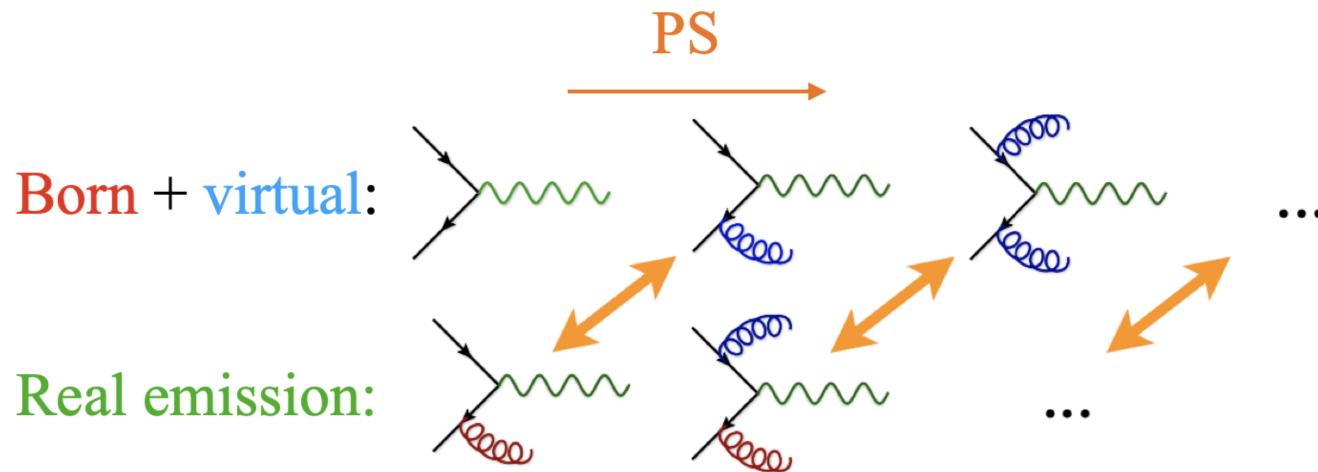
$$d\phi_{(+1)\text{MC}} \equiv B \sum_{abc} \frac{\alpha_s}{2\pi} \frac{dt}{t} dz \hat{P}_{a \rightarrow bc}(z)$$

Monte Carlo counterterm

- **No double counting:** if we expand $\frac{d\sigma_{\text{MC@NLO}}}{dO}$ to $\mathcal{O}(\alpha_s)$, we reproduce $\frac{d\sigma_{\text{NLO}}}{dO}$.
- **Stability:** terms in squared brackets are finite.

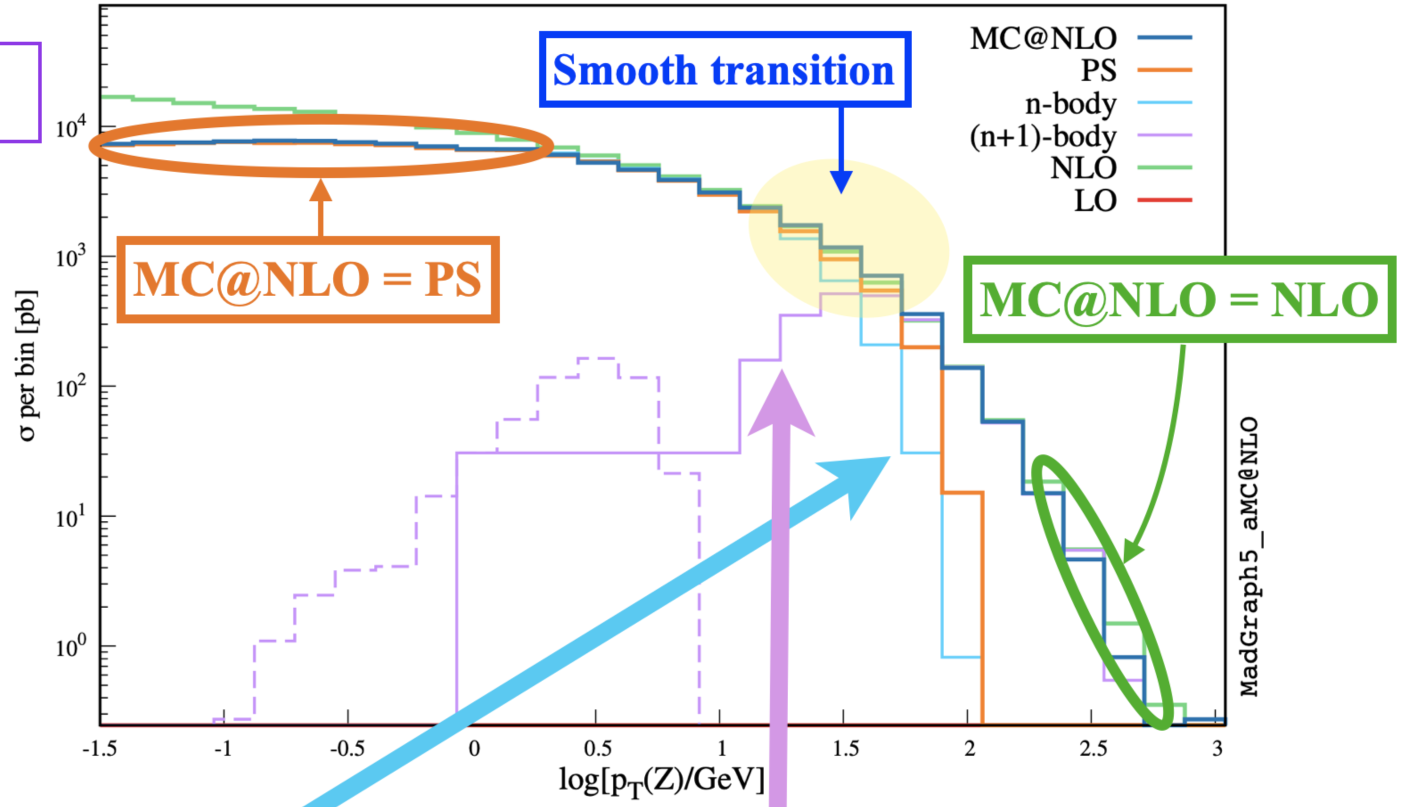
$$\frac{d\sigma_{\text{MC@NLO}}}{dO} = \int d\phi_n \left[B + V + \int d\phi_{(+1)} \text{MC} \right] I_{\text{PS}}(O, n) + \int d\phi_{n+1} [R - \text{MC}] I_{\text{PS}}(O, n + 1)$$

$$\int d\phi_{(+1)} \text{MC} \equiv B \sum_{abc} \frac{\alpha_s}{2\pi} \frac{dt}{t} dz \hat{P}_{a \rightarrow bc}(z)$$



$pp \rightarrow Z \rightarrow \nu_e \bar{\nu}_e$

ISR

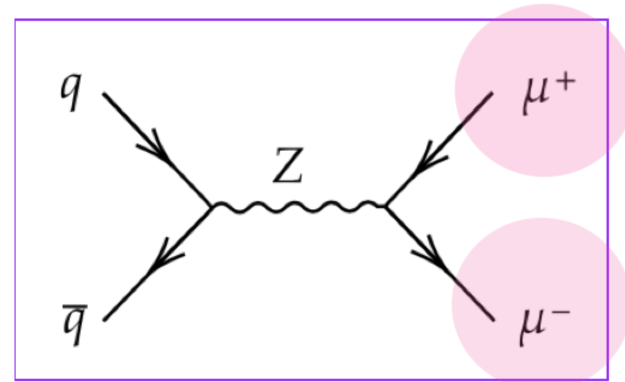
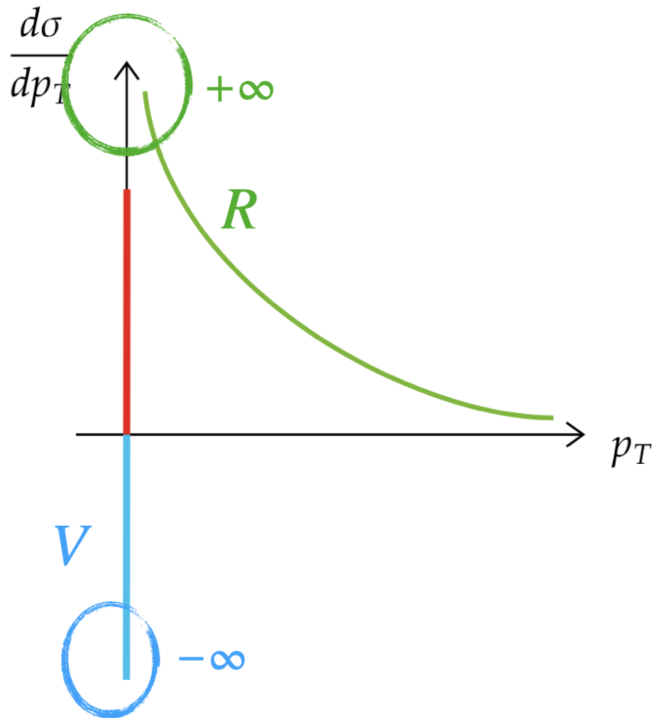


$$\frac{d\sigma_{\text{MC@NLO}}}{dO} = \int d\phi_n \left[B + V + \int d\phi_{(+1)} MC \right] I_{PS}(O, n) + \int d\phi_{n+1} [R - MC] I_{PS}(O, n + 1)$$

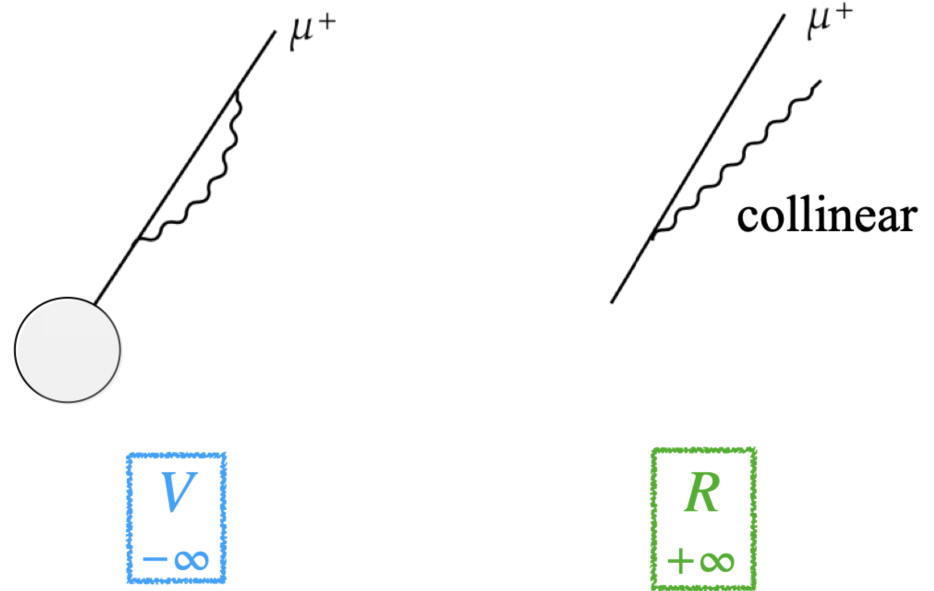
Validation phase

Recombination

$$pp \rightarrow Z \rightarrow l^+l^- \text{ [QCD]}$$

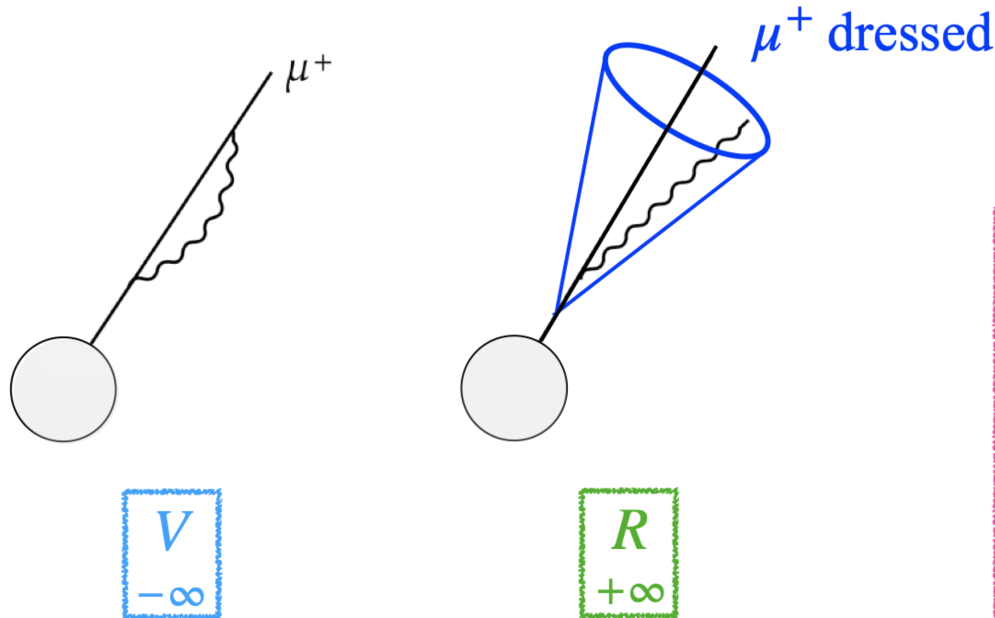


$$pp \rightarrow Z \rightarrow \mu^+\mu^- \text{ [QED]}$$



Infinites do not cancel out: the muon's energy is different in the two configurations.

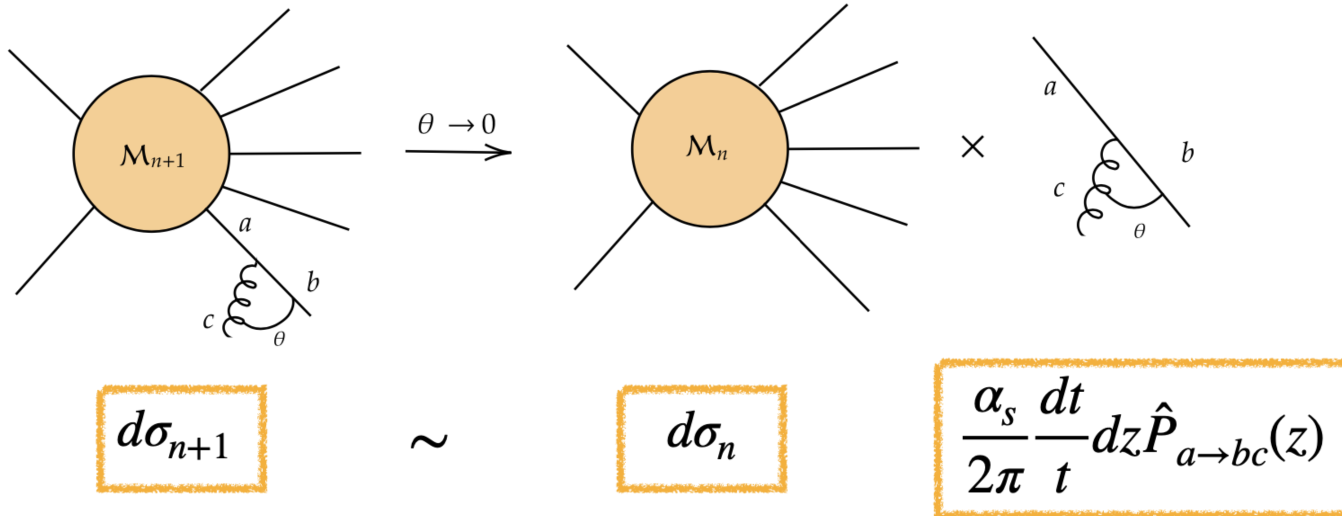
Infinities do not cancel out: the muon's energy is different in the two configurations.



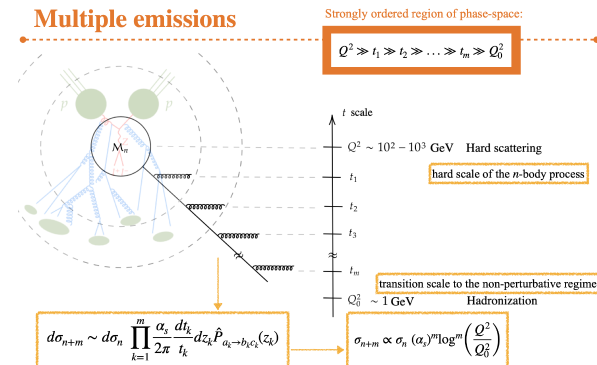
We considered **dressed** μ^+ and μ^- , meaning muons combined with their collinear photons, to study kinematic observables.

Now divergences cancel out properly.

Generalities of Parton Shower: collinear factorization



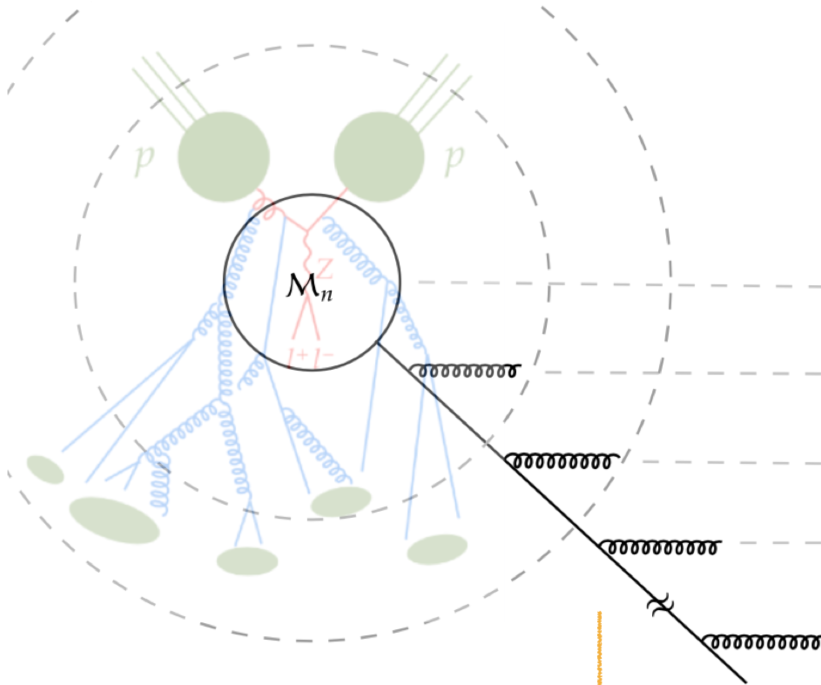
- $t =$ virtuality of a (could be its p_T);
- $z =$ energy fraction of b related to a ;
- $\hat{P}_{a \rightarrow bc} =$ Altarelli-Parisi splitting kernel



Multiple emissions

Strongly ordered region of phase-space:

$$Q^2 \gg t_1 \gg t_2 \gg \dots \gg t_m \gg Q_0^2$$



t scale

$Q^2 \sim 10^2 - 10^3$ GeV Hard scattering

hard scale of the n -body process

t_1

t_2

t_3

t_m

transition scale to the non-perturbative regime

$Q_0^2 \sim 1$ GeV Hadronization

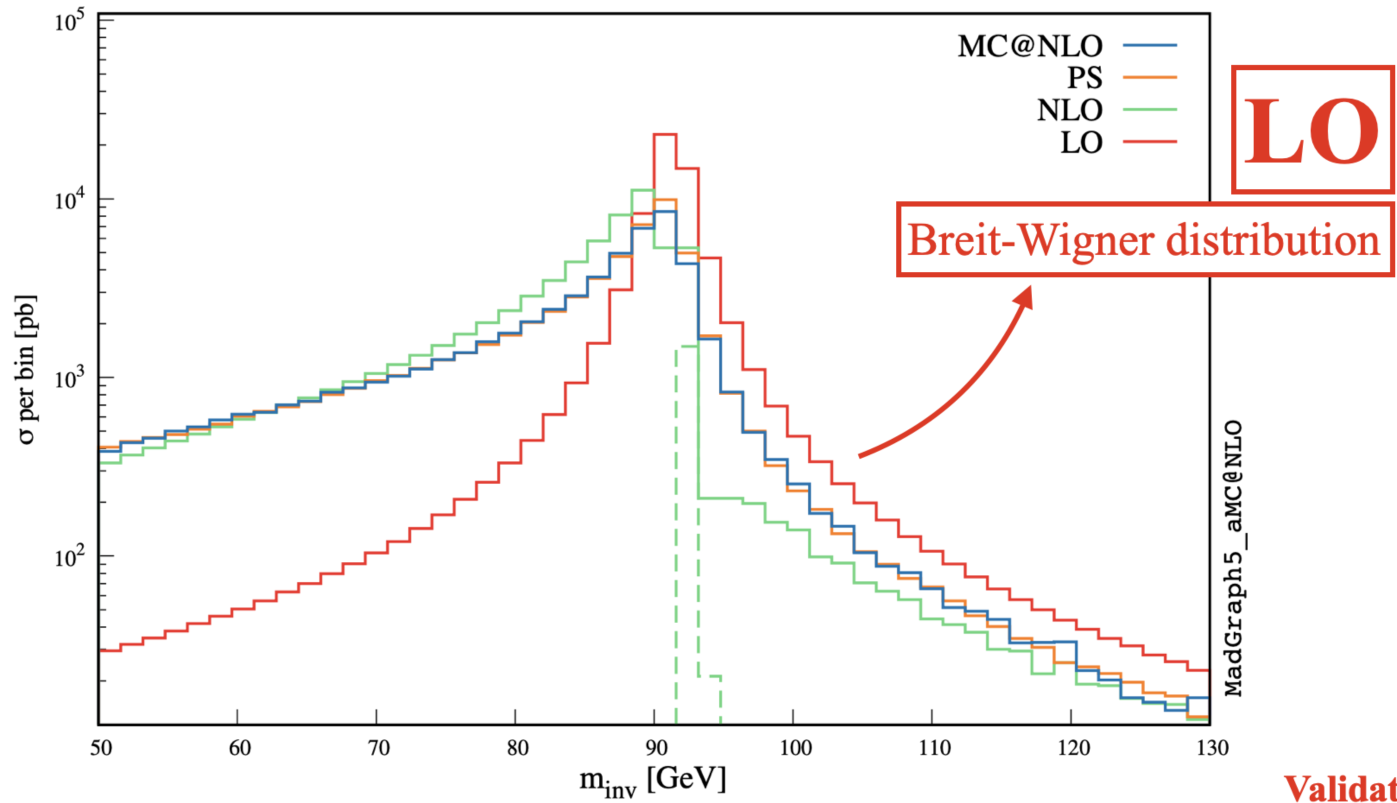
$$d\sigma_{n+m} \sim d\sigma_n \prod_{k=1}^m \frac{\alpha_s}{2\pi} \frac{dt_k}{t_k} dz_k \hat{P}_{a_k \rightarrow b_k c_k}(z_k)$$

$$\sigma_{n+m} \propto \sigma_n (\alpha_s)^m \log^m \left(\frac{Q^2}{Q_0^2} \right)$$

Differential cross section w.r.t. the invariant mass

$$pp \rightarrow Z \rightarrow \mu^+ \mu^-$$

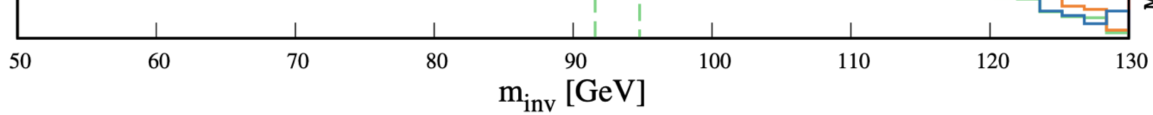
$$m_{\text{inv}}^2 = (p_{\mu^+} + p_{\mu^-})^2$$



NLO

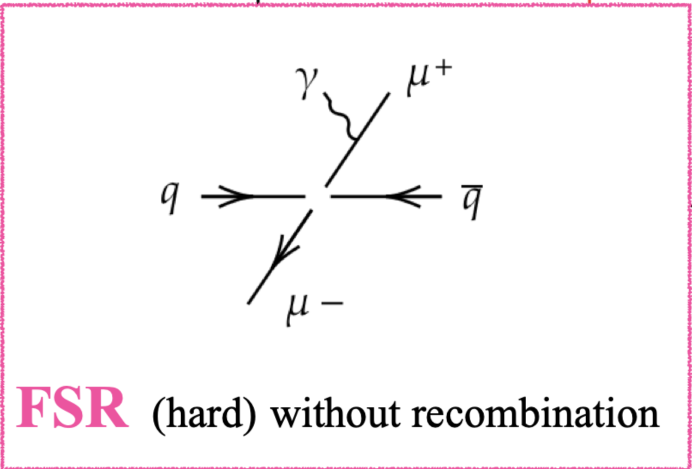
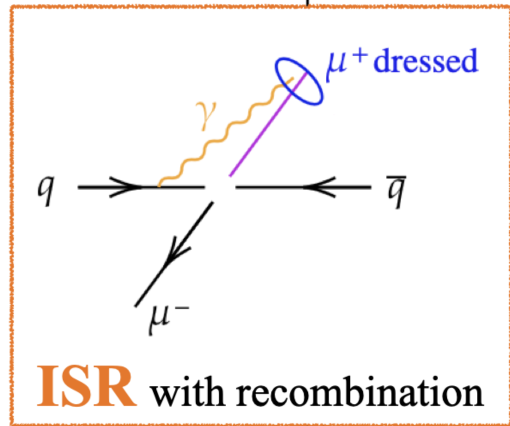
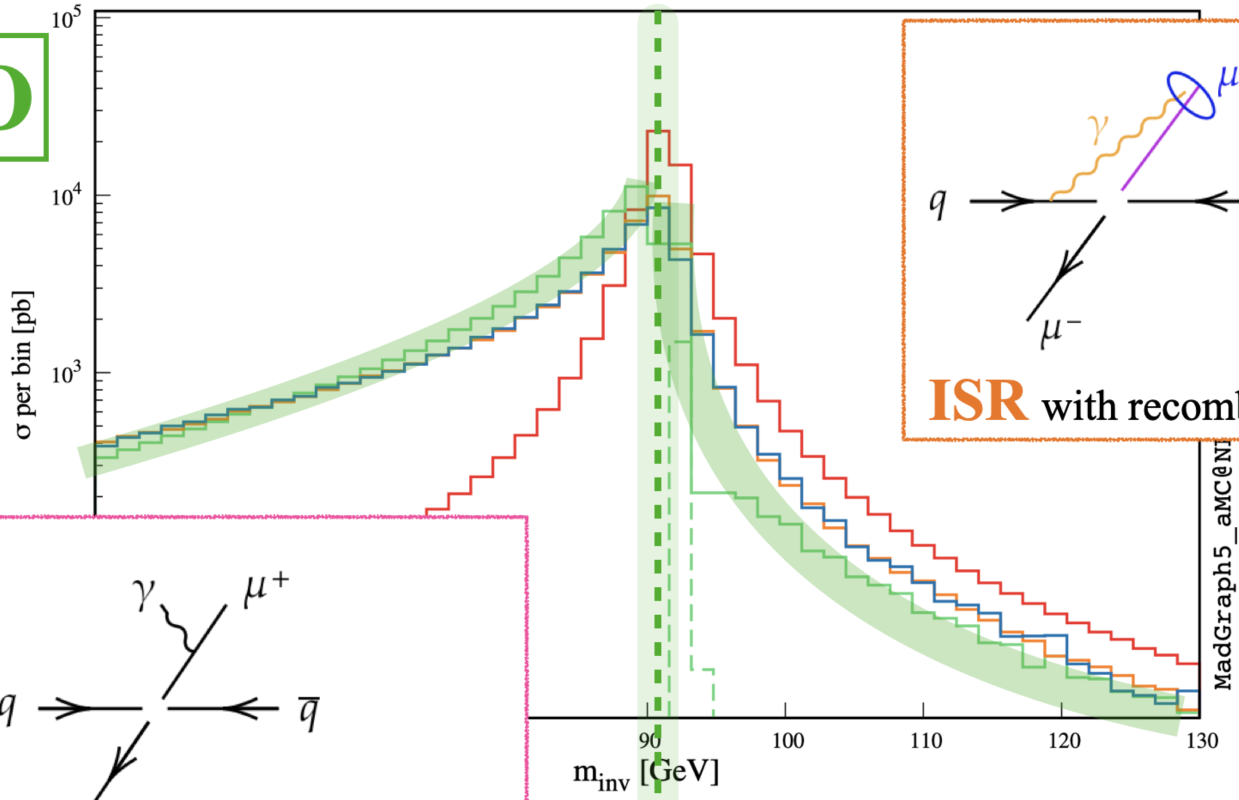
10^5

μ^+ dressed



Validation phase

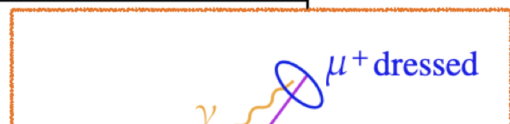
NLO



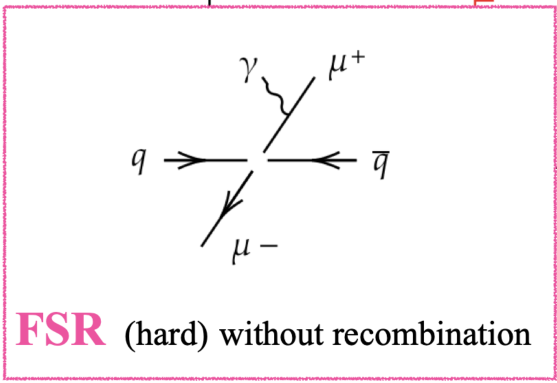
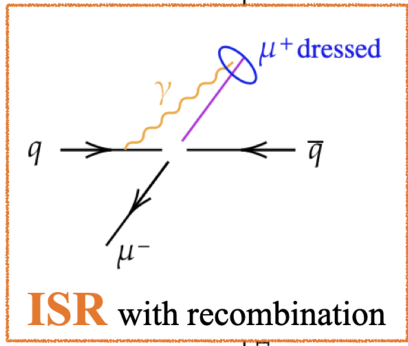
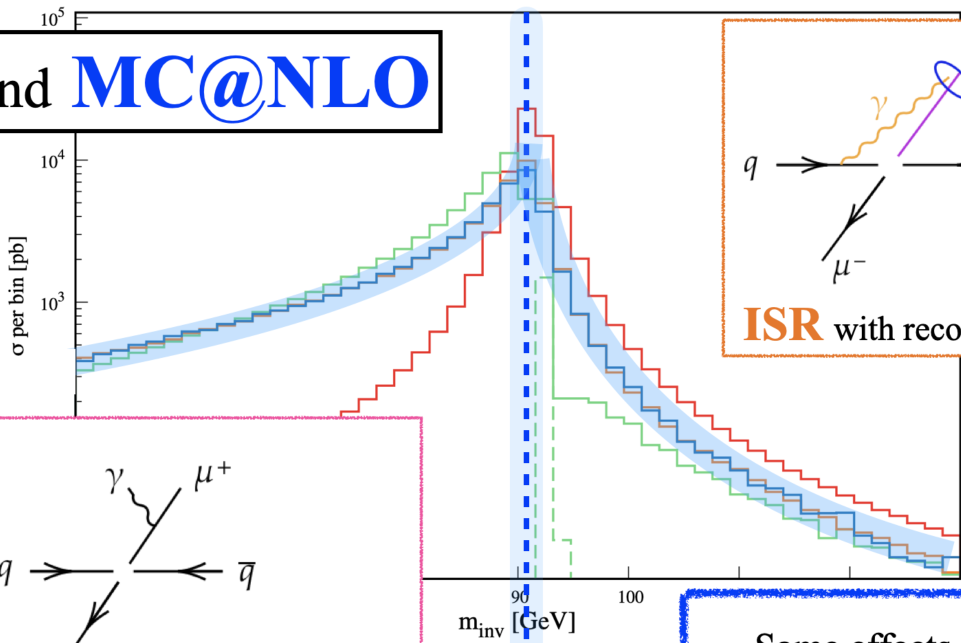
MadGraph5_aMC@NLO

Validation phase

PS and **MC@NLO**



PS and MC@NLO



Same effects as NLO,
but with multiple emissions.

Validation phase

