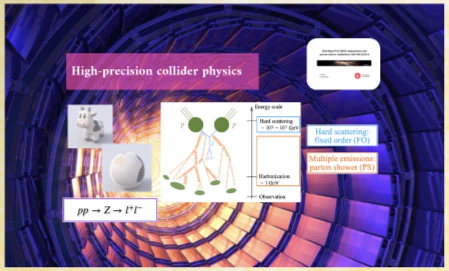
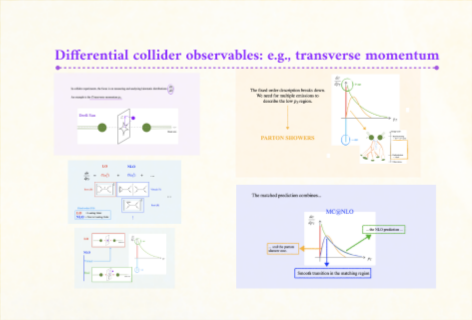
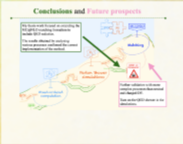
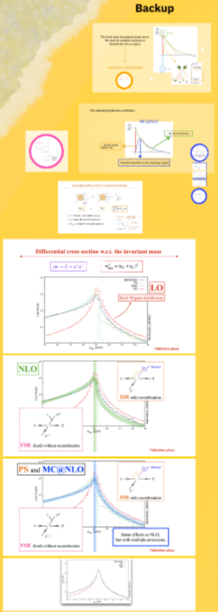
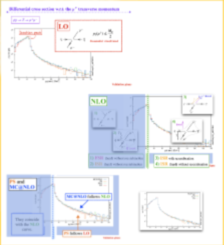
Matching NLO QED computations and parton-shower simulations with MC@NLO

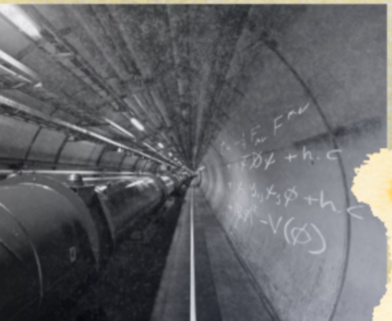


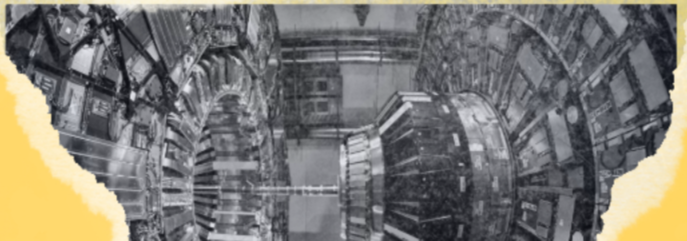




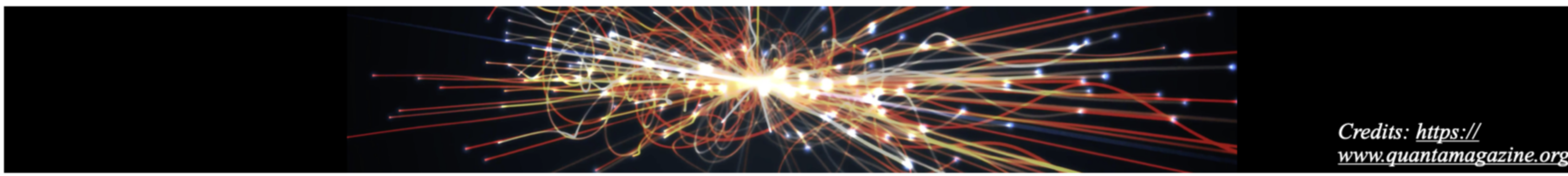








Matching NLO QED computations and parton-shower simulations with MC@NLO

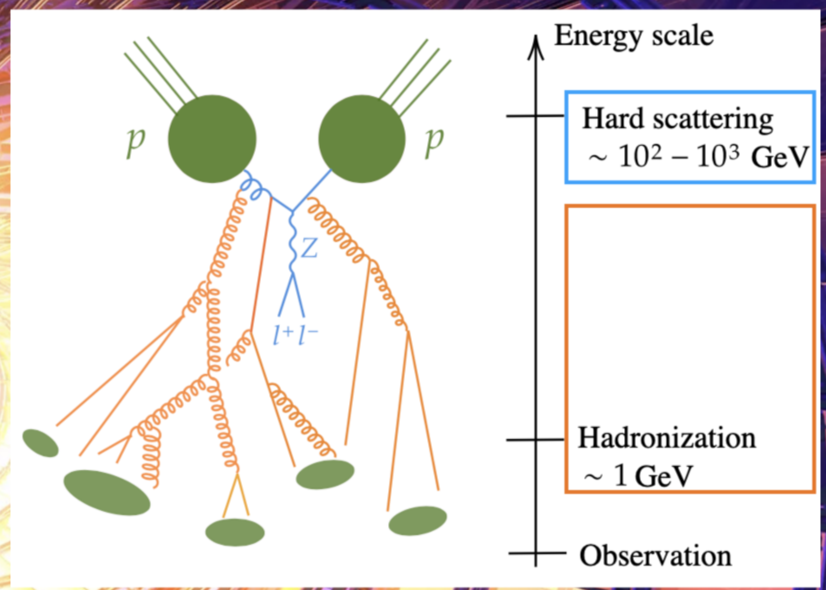


25/11/2024

Camilla Forgione

UNIVERSITÀ DI TORINO

High-precision collider physics

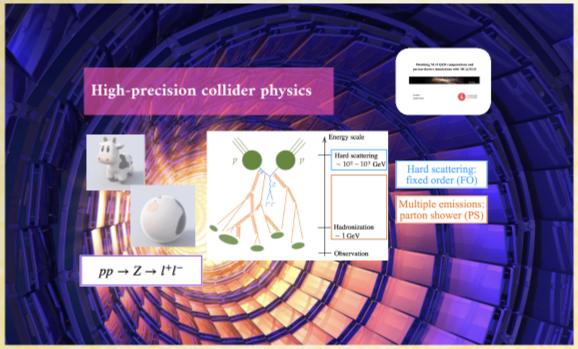


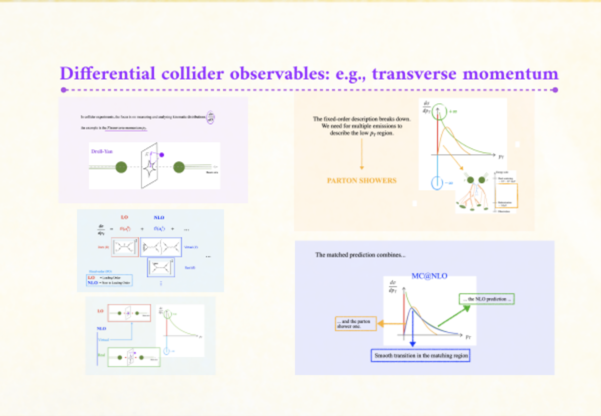
Hard scattering: fixed order (FO)

Multiple emissions: parton shower (PS)

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

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





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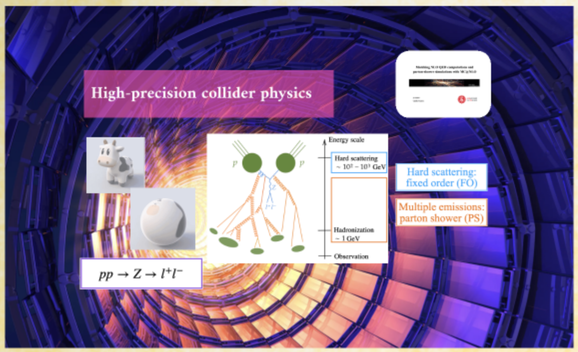

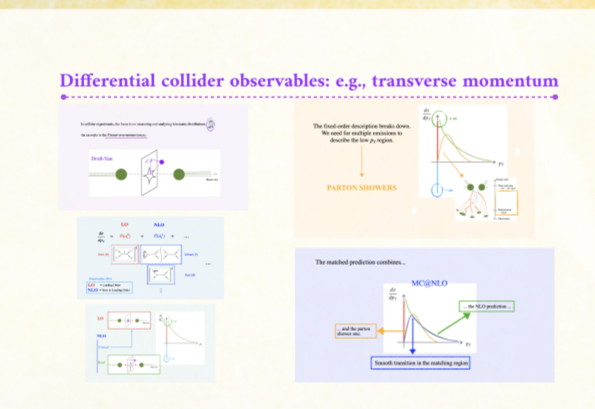

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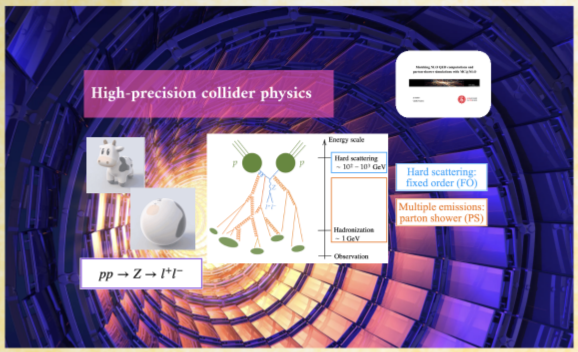

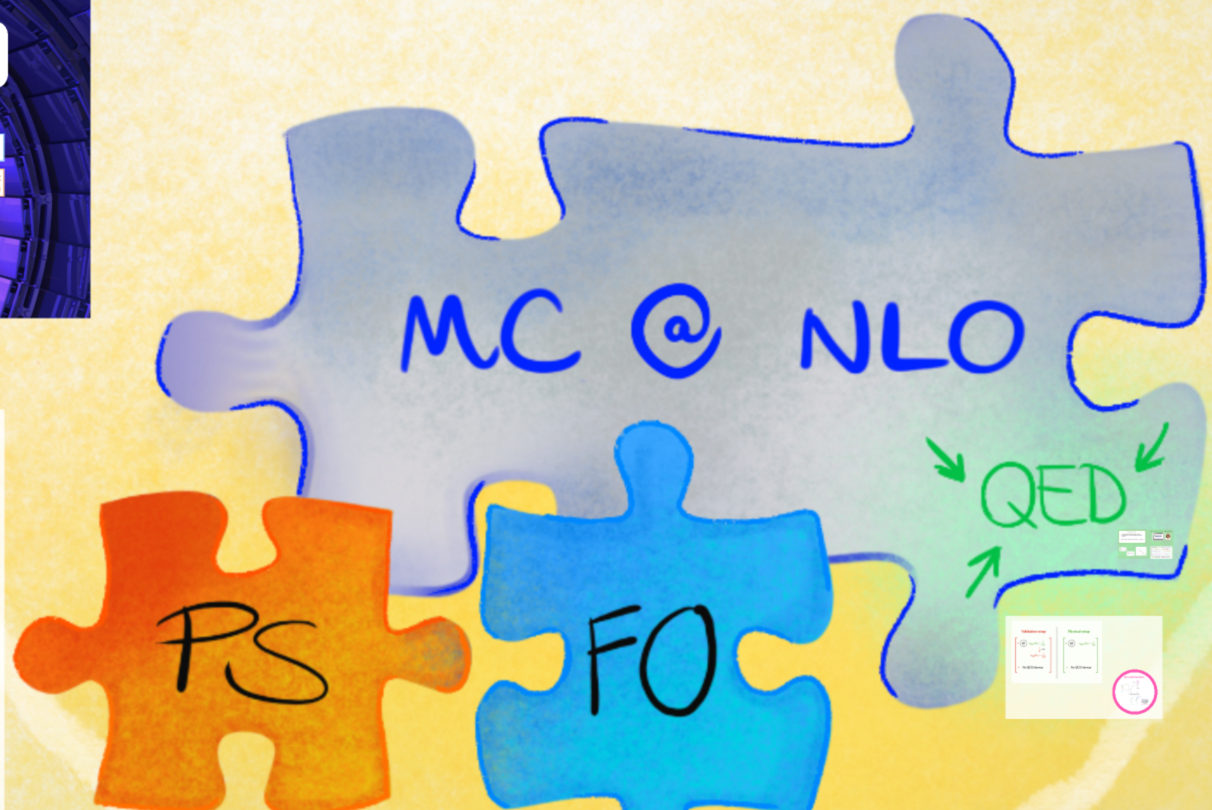

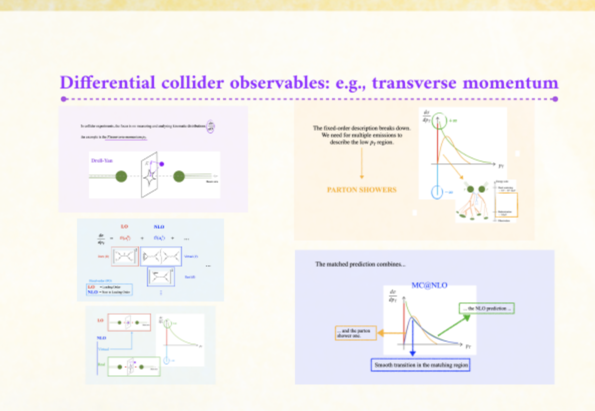

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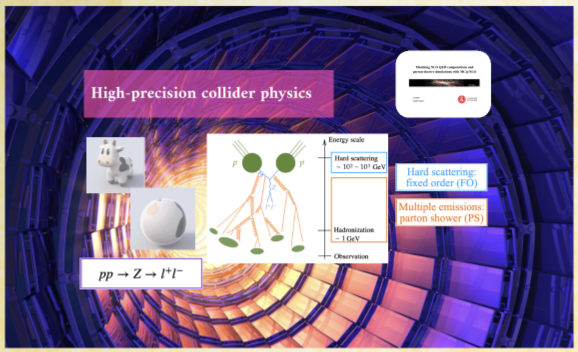
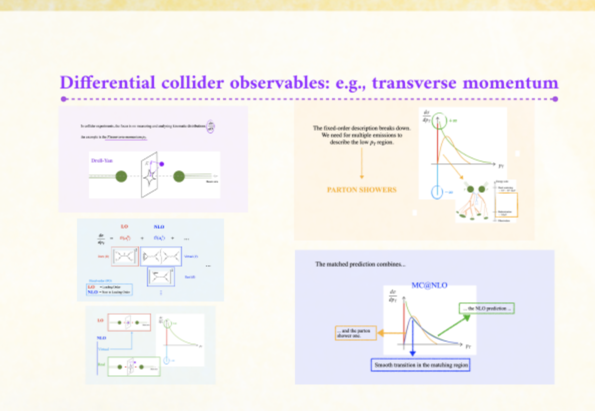
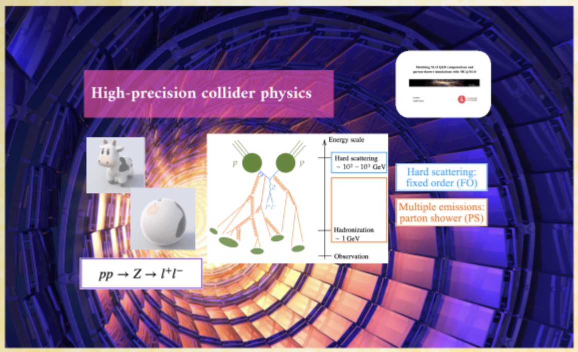
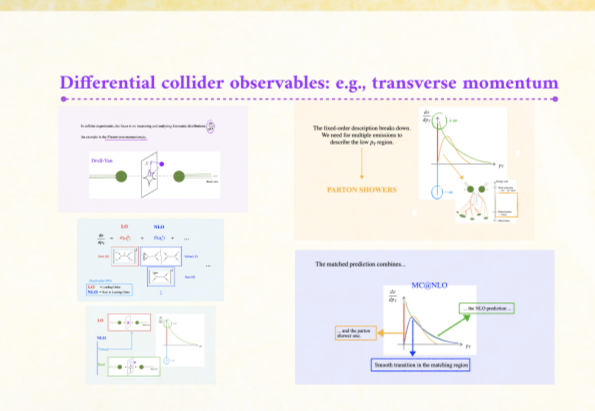




Matching NLO QCD computations and parton-shower simulations with MC@NLO

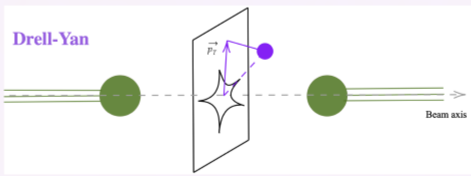




Differential collider observables: e.g., transverse momentum

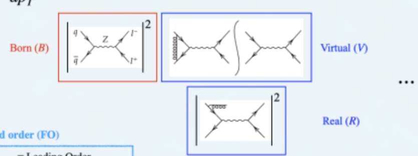
In collider experiments, the focus is on measuring and analysing kinematic distributions: $\frac{d\sigma}{dO}$

An example is the Z transverse momentum p_T.



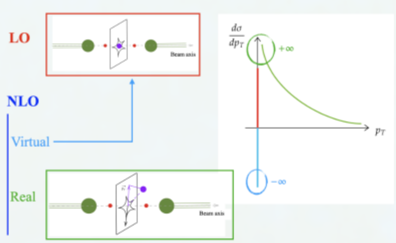
LO **NLO**

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



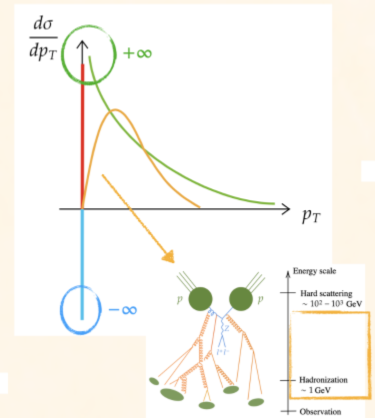
Fixed order (FO)

LO = Leading Order
NLO = Next to Leading Order

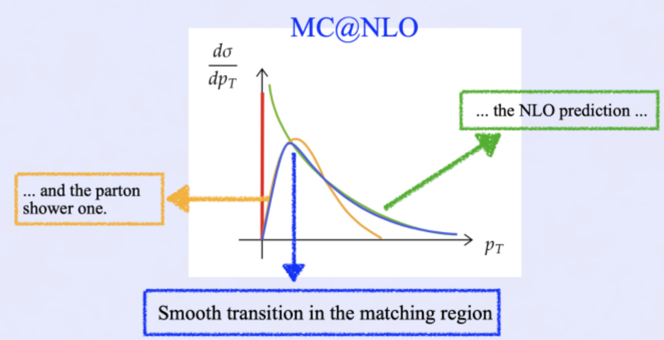


The fixed-order description breaks down.
We need for multiple emissions to
describe the low p_T region.

PARTON SHOWERS



The matched prediction combines...



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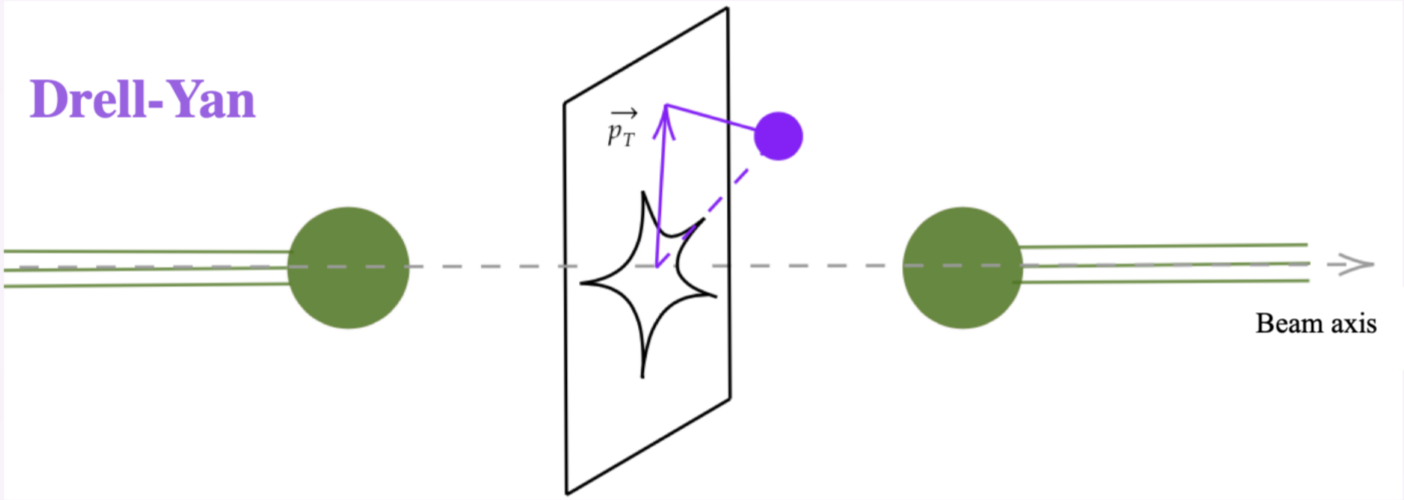
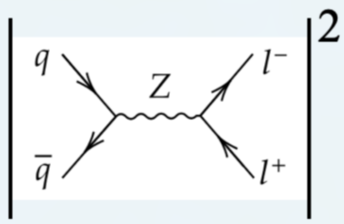


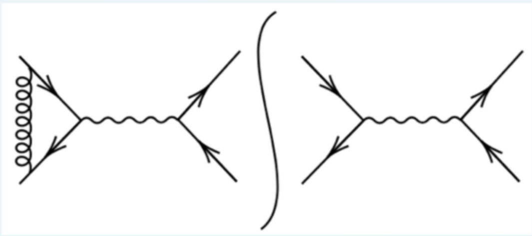
LO NLO

LO **NLO**

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

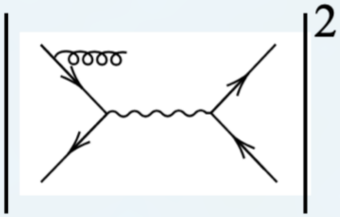
Born (B)





Virtual (V)

$\cdots$

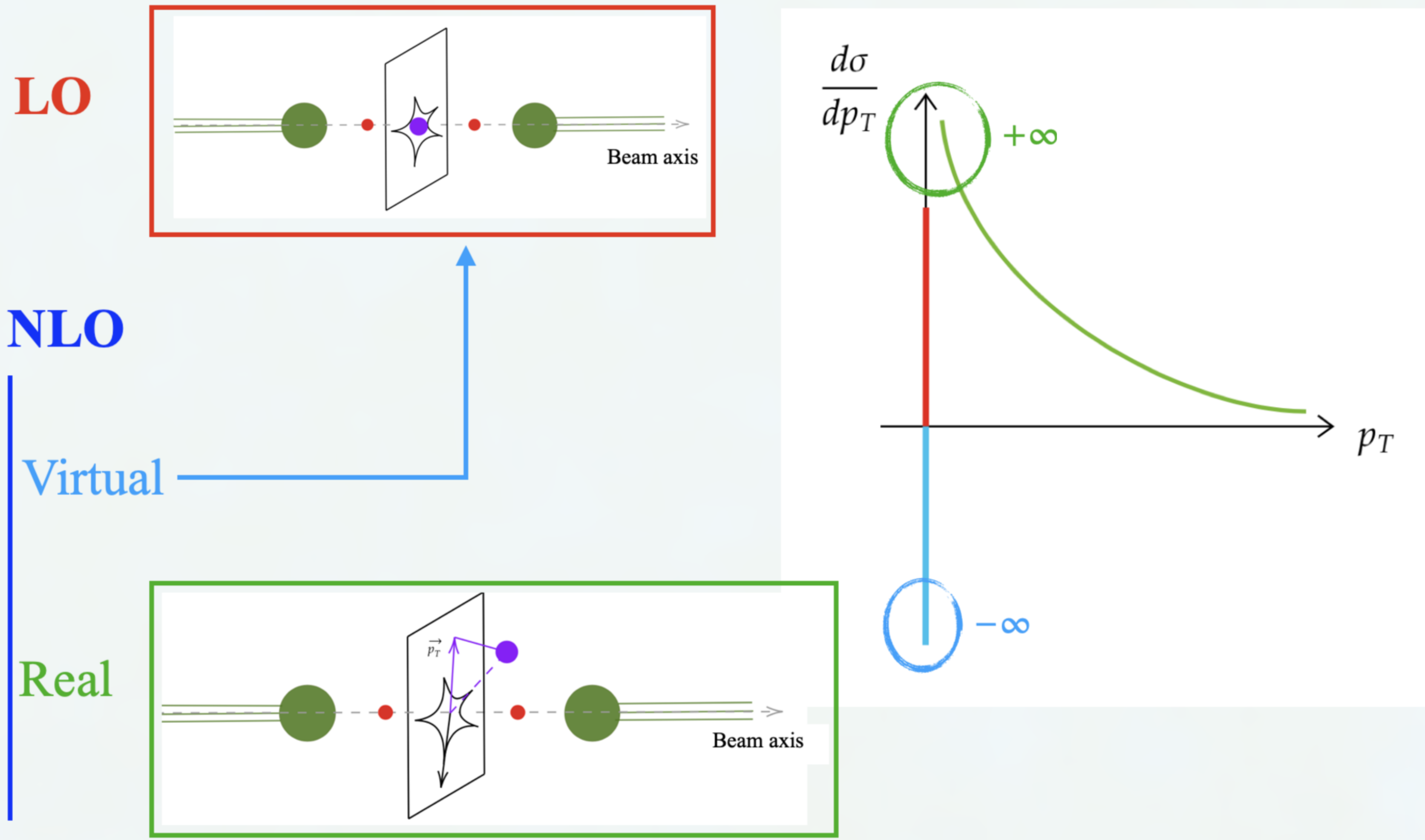


Real (R)

$\vdots$

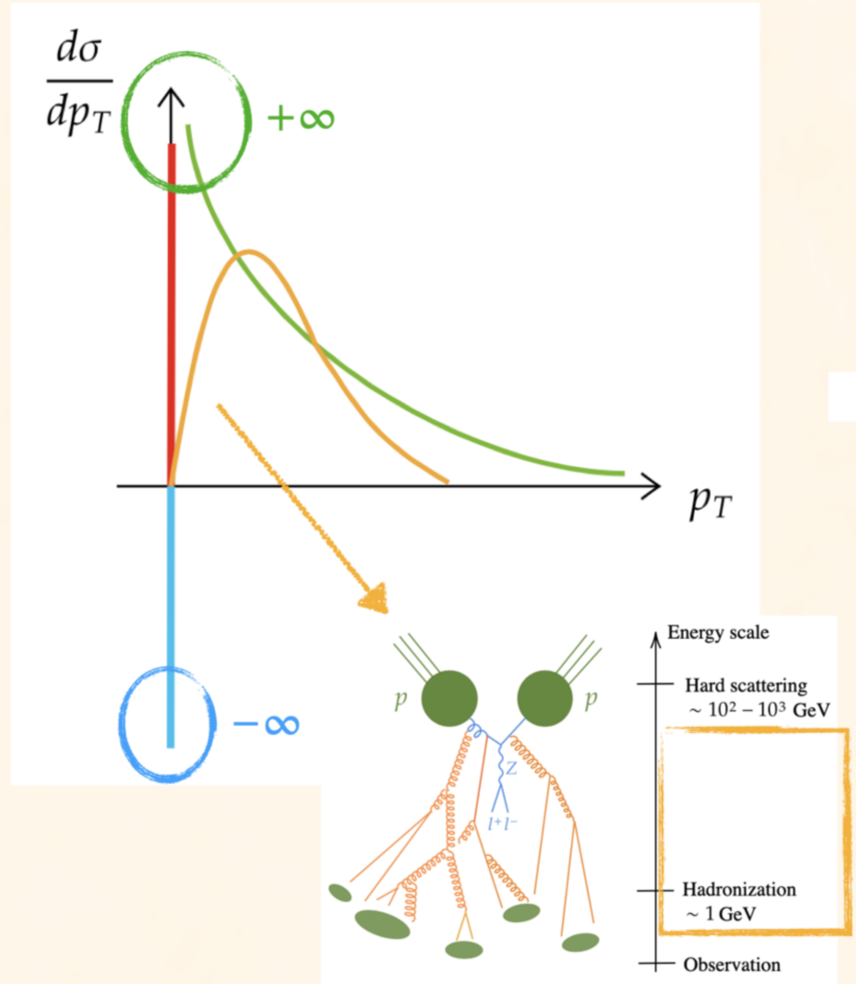
Fixed order (FO)

LO = Leading Order
NLO = Next to Leading Order


LO
Beam axis
NLO
Virtual
Real
Beam axis
$\vec{p}_T$
$\frac{d\sigma}{dp_T}$
$+\infty$
$-\infty$
p_T

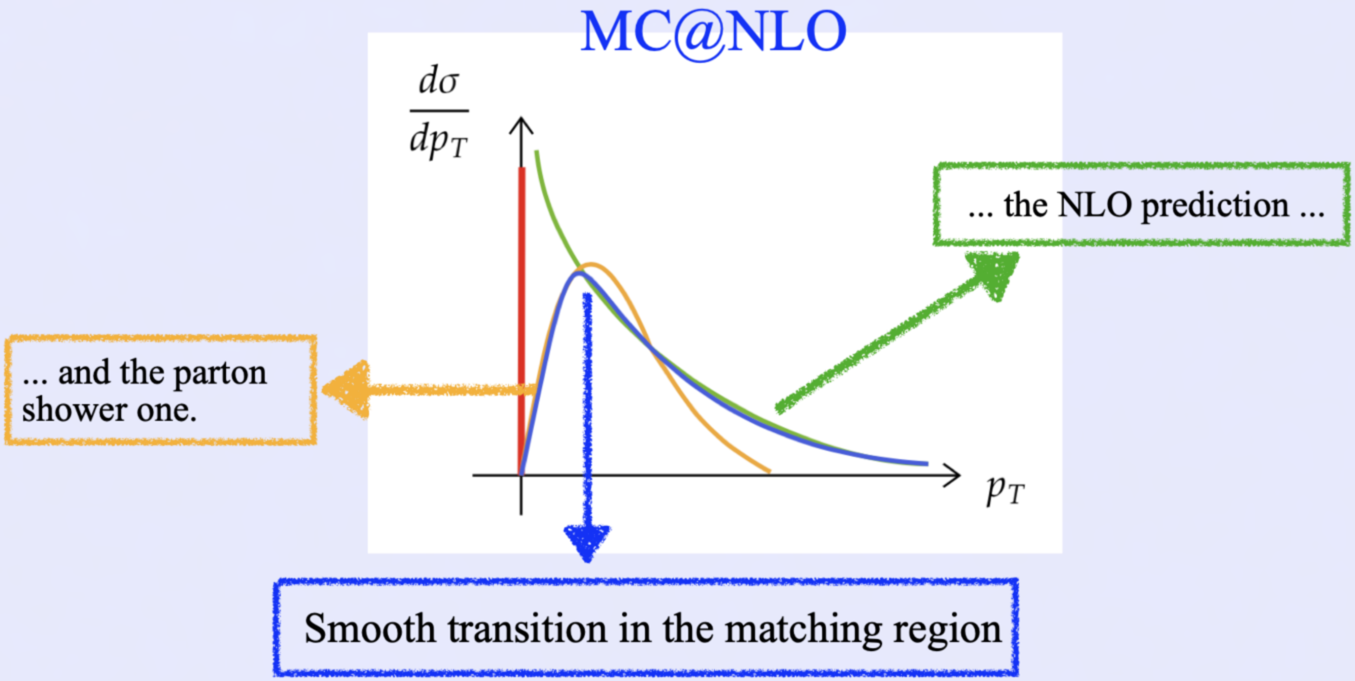
The fixed-order description breaks down. We need for multiple emissions to describe the low p_T region.

PARTON SHOWERS

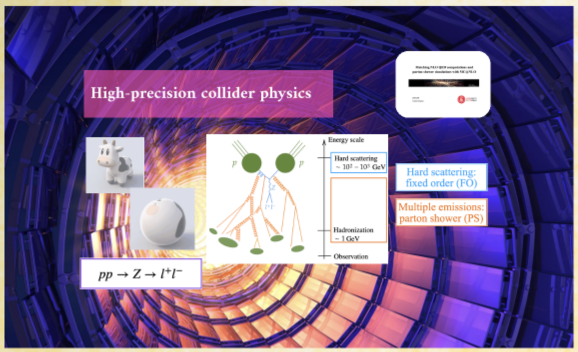


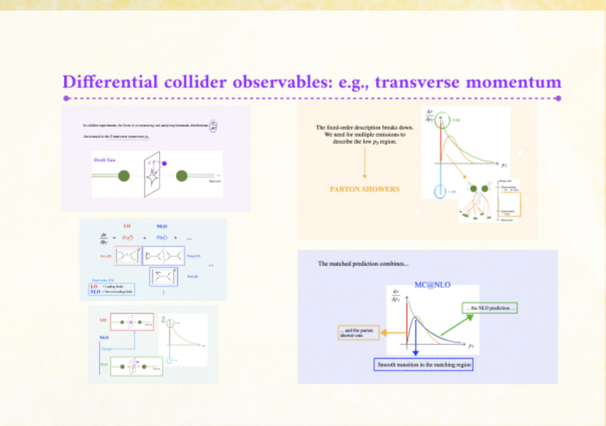
The matched prediction combines

The matched prediction combines...

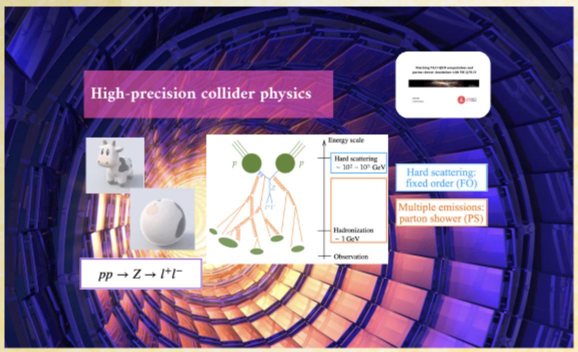


Matching NLO QCD computations and parton-shower simulations with MC@NLO

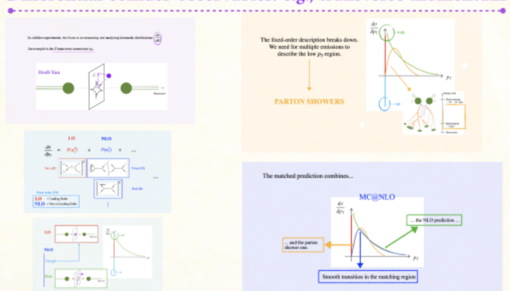




Matching NLO QED computations and parton-shower simulations with MC@NLO



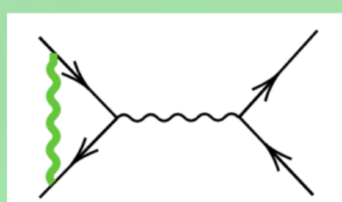
Differential collider observables: e.g., transverse momentum

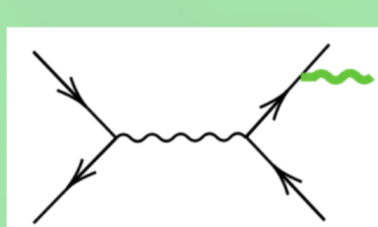


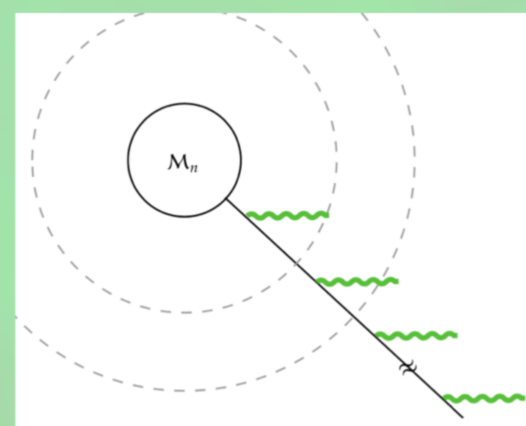
Need for **QED** corrections

- As experimental precision continues to improve, accounting for QED effects in predictions becomes necessary.

- Future colliders will include at least one e^+e^- machine.







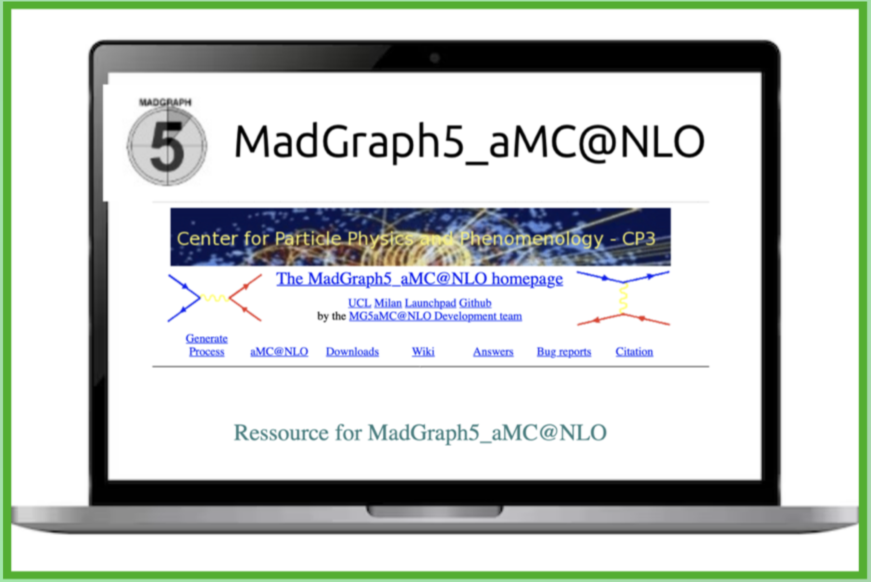
How

We simulated

$pp \to$
$pp \to$

IS

How did we extend MC@NLO?

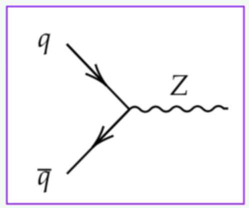


PYTHIA 8.3

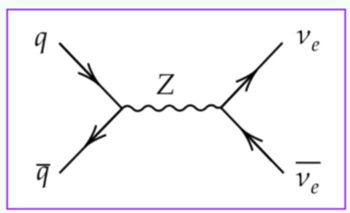
We simulated two processes: charged Drell-Yan and neutral Drell-Yan (in 3 versions)

ISR

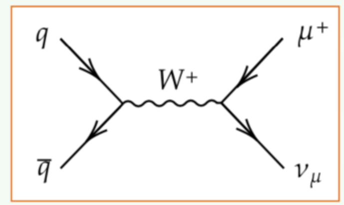
$pp \to Z$ (stable)



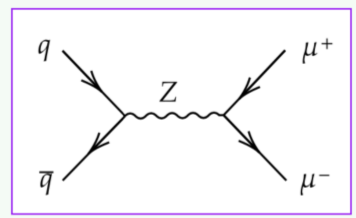
$pp \to Z \to \nu_e \bar{\nu}_e$



ISR + FSR



$pp \to W^+ \to \mu^+ \nu_\mu$



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

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

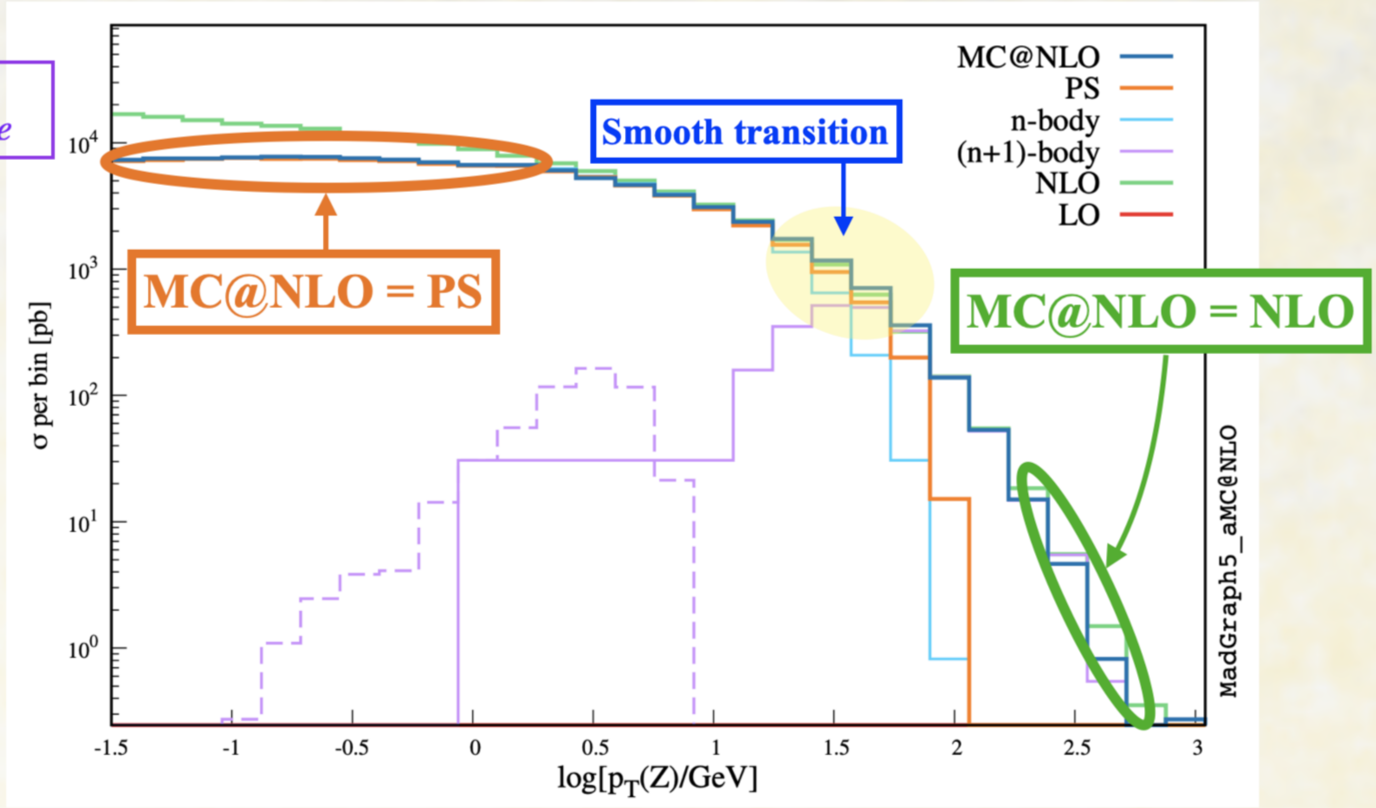
- No QCD shower

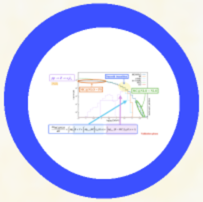
RESULTS

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

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

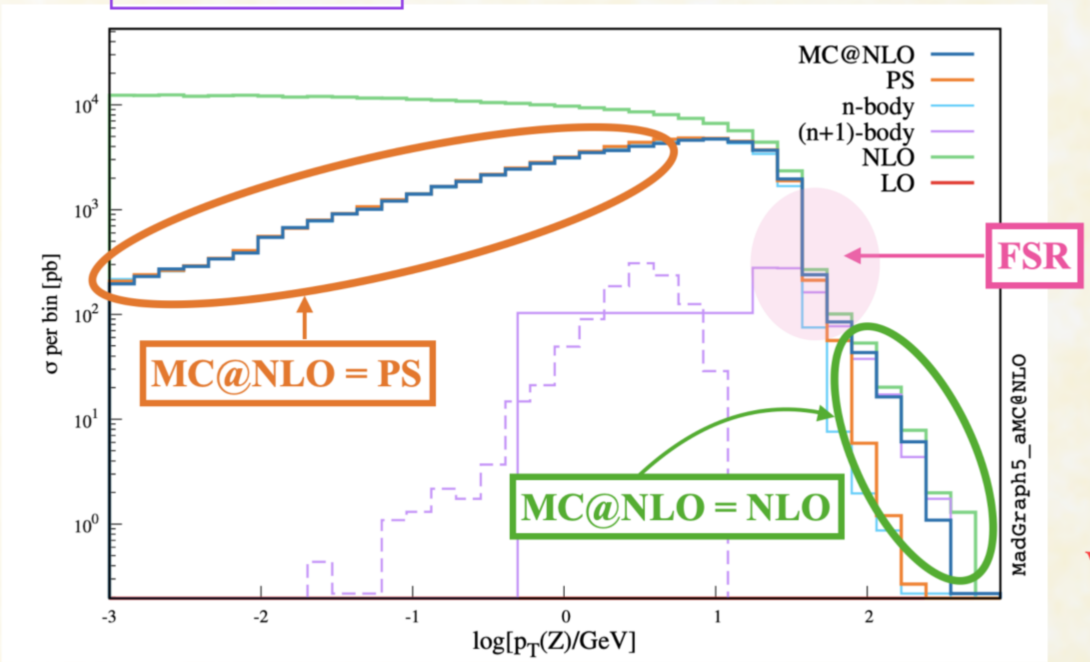
ISR





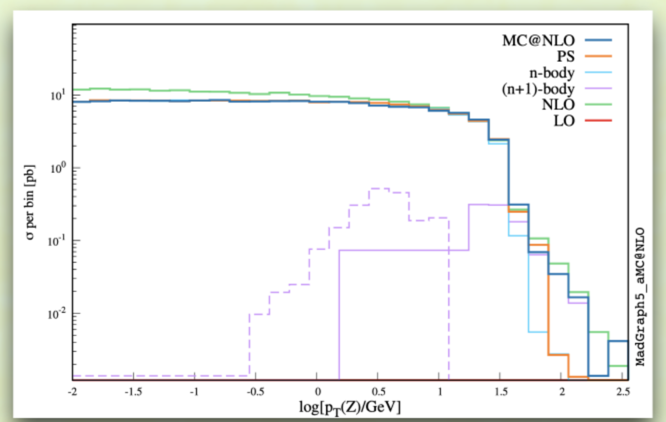
Validation phase

$pp \to Z \to \mu^+\mu^-$ **ISR + FSR**

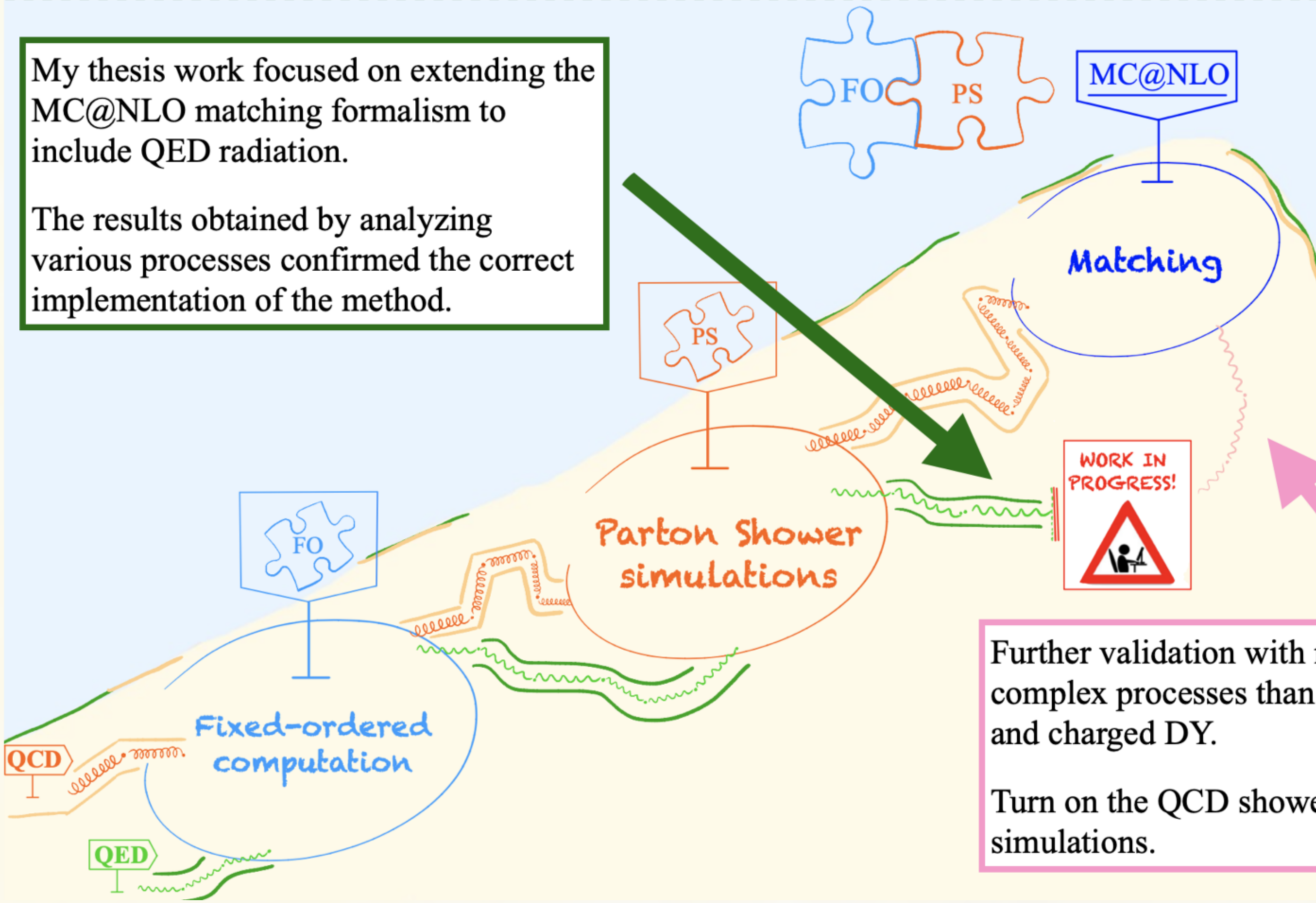


Validation phase

Results with α_{phys} $pp \to Z \to \mu^+\mu^-$



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

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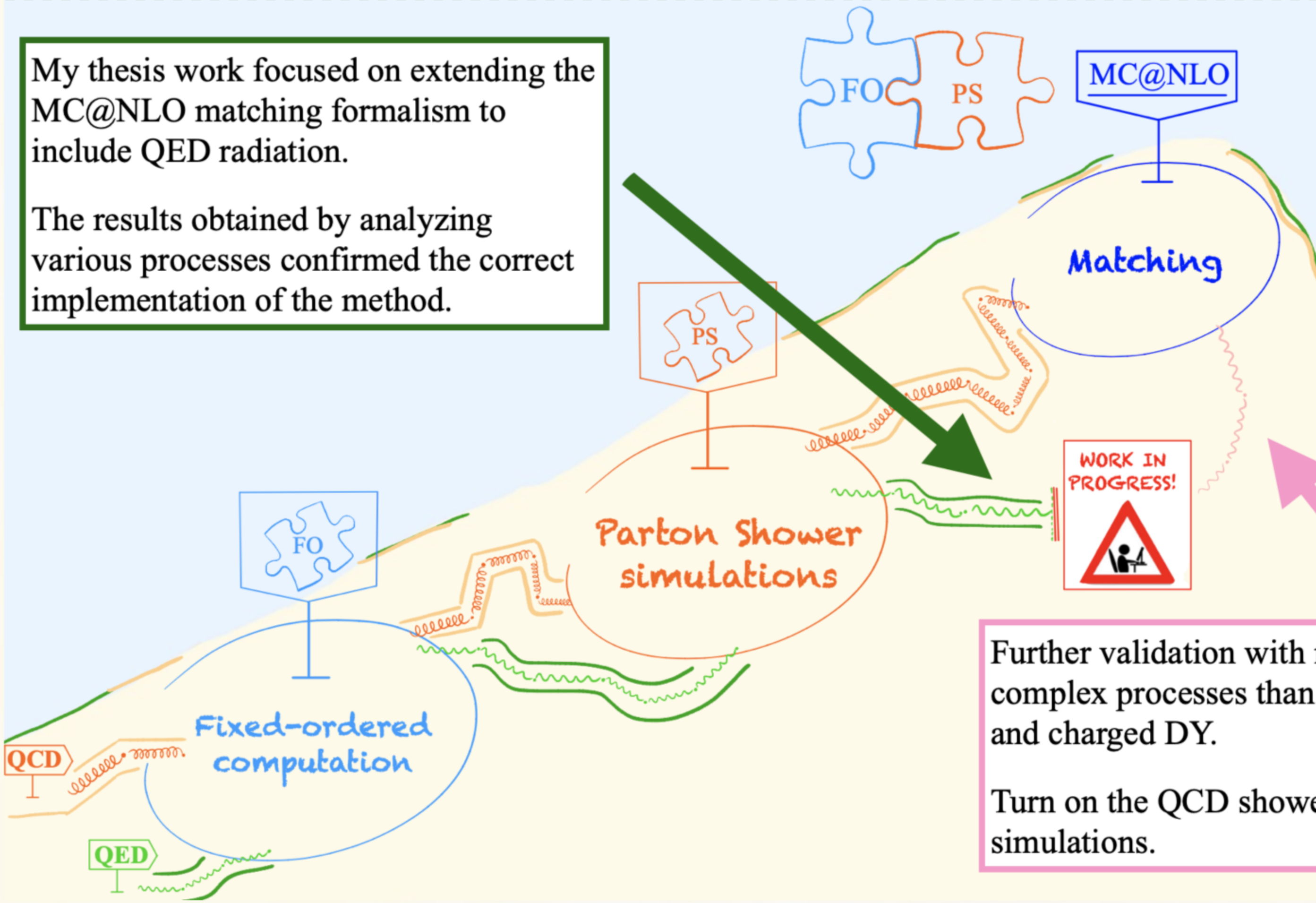


Further validation with more complex processes than neutral and charged DY.

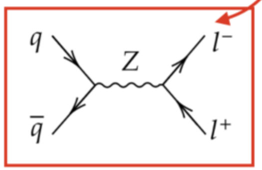
Turn on the QCD shower in the simulations.

Thank you for your attention!

Backup

Parton shower

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



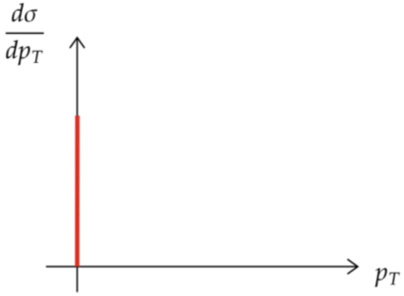
observable computed with Born kinematics

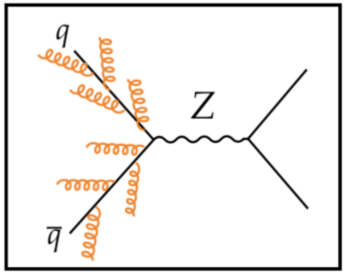
PS

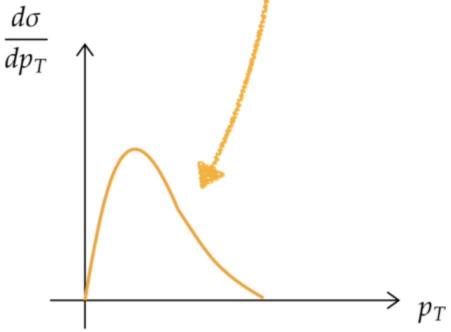
dresses up the Born amplitude with parton emissions

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

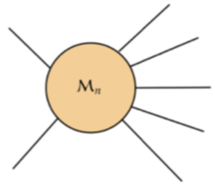
shower spectrum, starting from Born kinematics







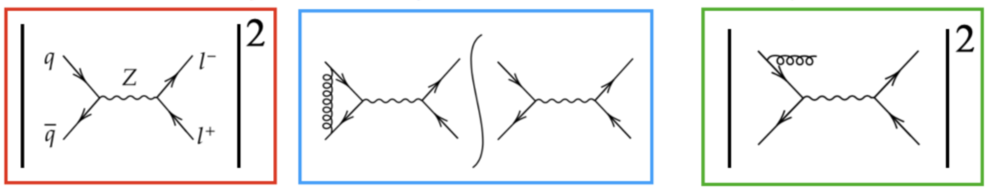
Master formula



$2 \to n$ scattering process

$$\frac{d\sigma^{\mathrm{NLO}}}{dO} = \int d\phi_n (B + V)\, \delta(O - O(n)) + \int d\phi_{n+1}\, R\, \delta(O - O(n+1))$$

$n = 2$



PS

Master formula

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

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

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

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.

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

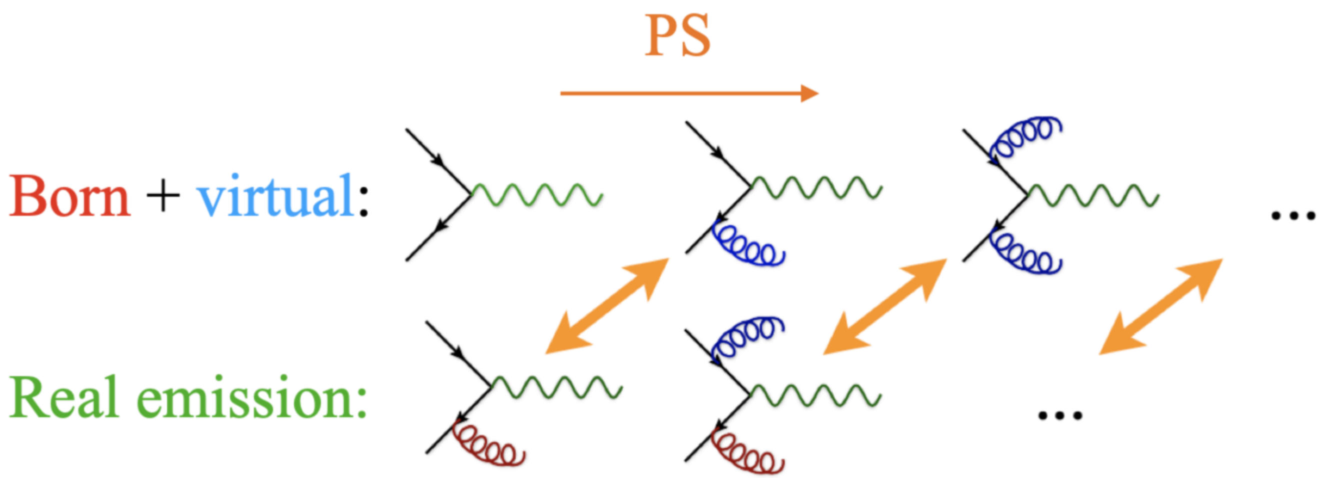
$$d\phi_{(+1)} MC \equiv B \sum_{abc} \frac{\alpha_s}{2\pi} \frac{dt}{t} dz \hat{P}_{a\to bc}(z)$$

Monte Carlo counterterm

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

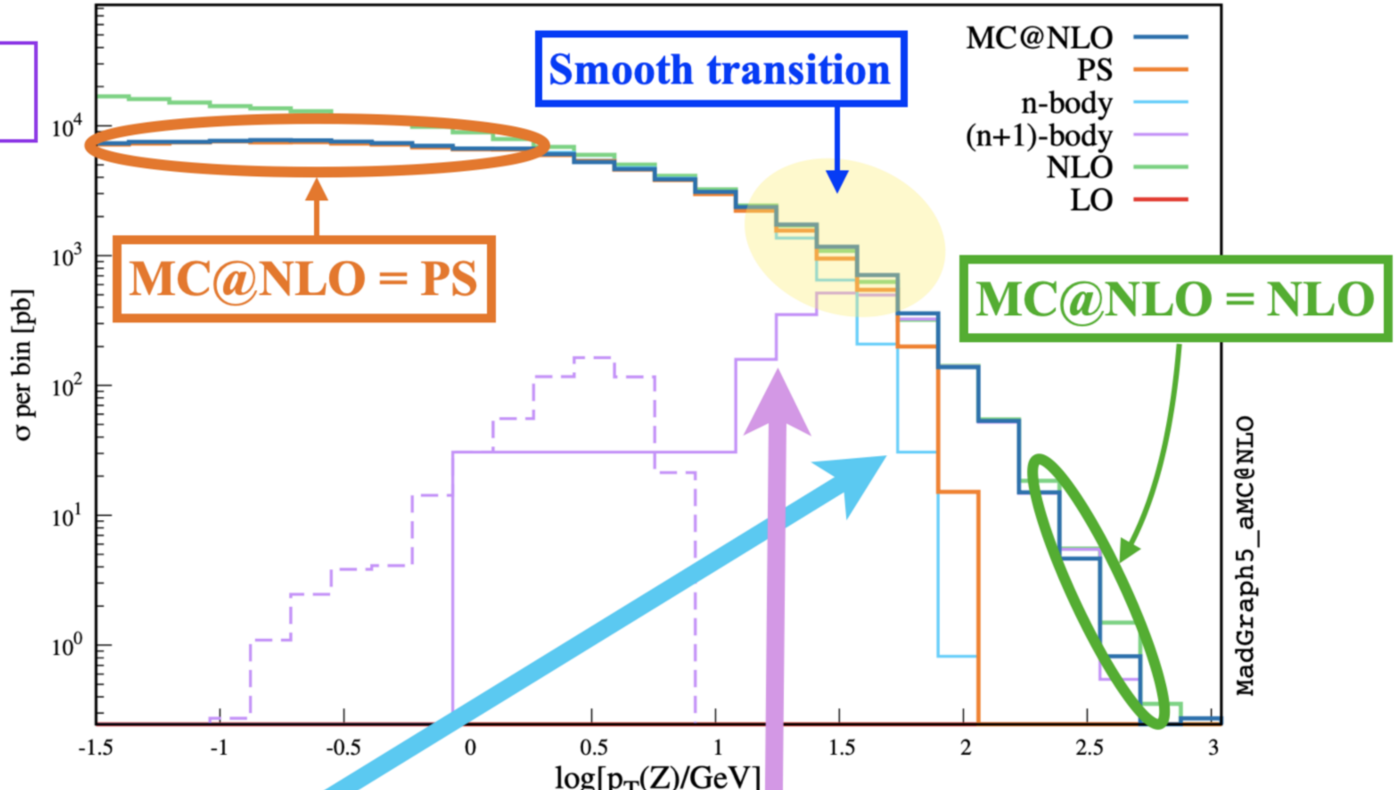
$$\frac{d\sigma_{\mathrm{MC@NLO}}}{dO} = \int d\phi_n \left[B + V + \int d\phi_{(+1)} MC \right] I_{PS}(O,n) + \int d\phi_{n+1} \left[R - MC \right] I_{PS}(O,n+1)$$

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



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

ISR

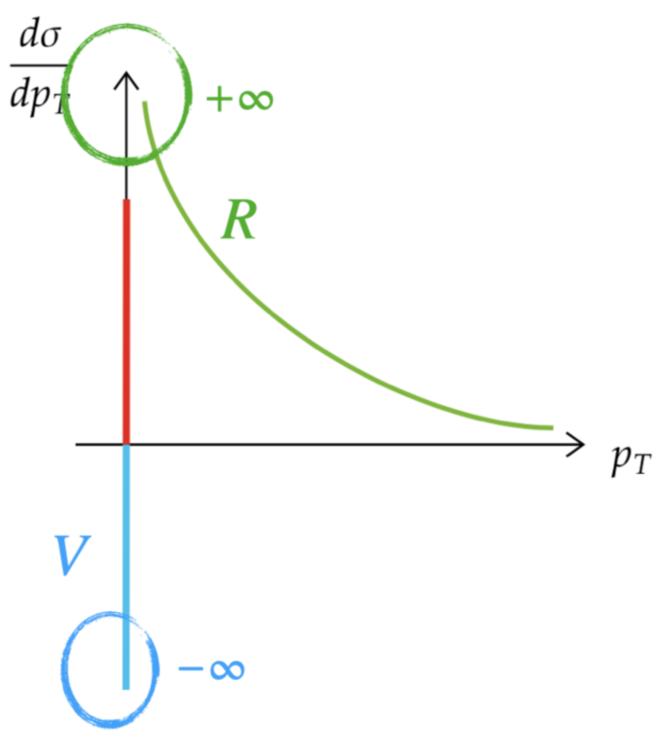


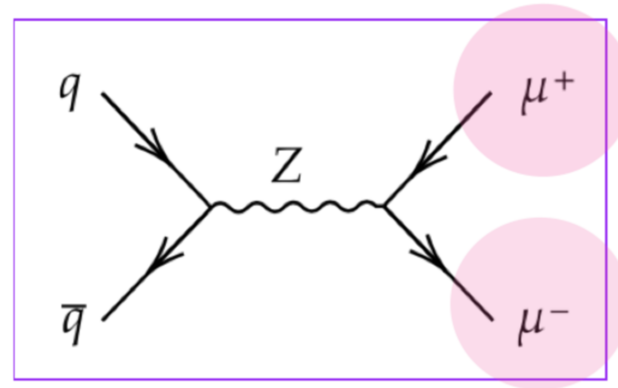
$$\frac{d\sigma_{\mathrm{MC@NLO}}}{dO} = \int d\phi_n \left[B + V + \int d\phi_{(+1)} MC\right] I_{PS}(O, n) + \int d\phi_{n+1} \left[R - MC\right] I_{PS}(O, n+1)$$

Validation phase

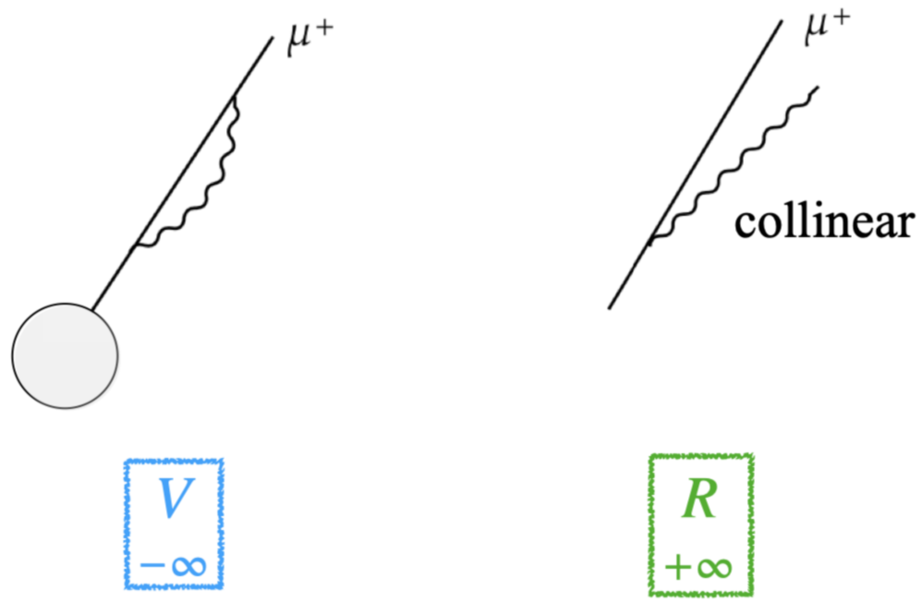
Recombination

$pp \to Z \to l^+l^-$ [QCD]





$pp \to Z \to \mu^+\mu^-$ [QED]



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

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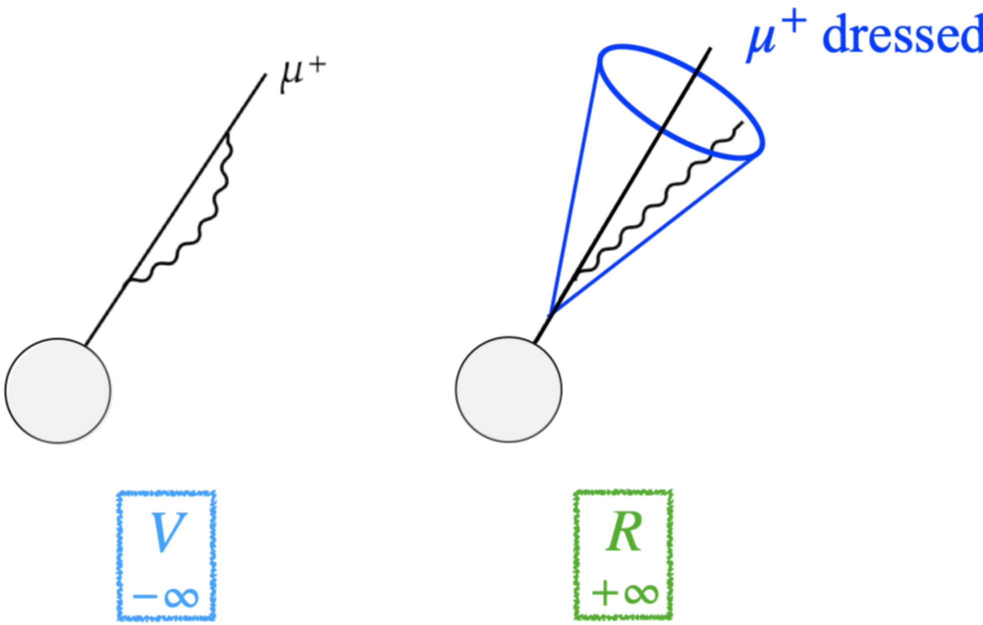
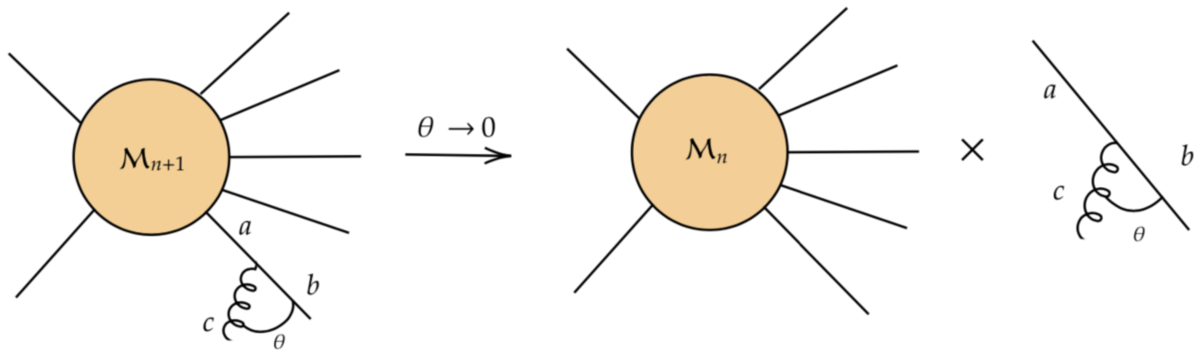


Now divergences cancel out properly.

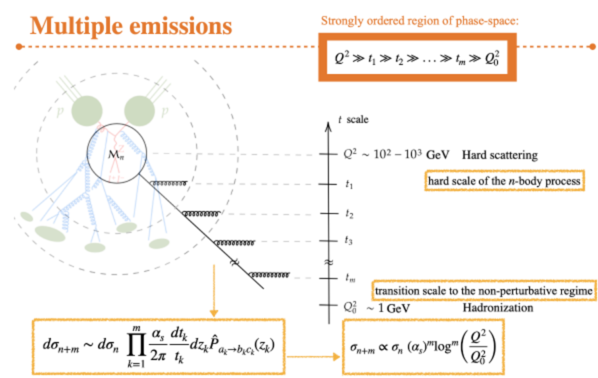
We considered dressed μ^+ and μ^-, meaning <u>muons combined with their collinear photons,</u> to study kinematic observables.

Generalities of Parton Shower: collinear factorization



$$d\sigma_{n+1} \quad \sim \quad d\sigma_n \quad \frac{\alpha_s}{2\pi}\frac{dt}{t}dz\hat{P}_{a\to bc}(z)$$

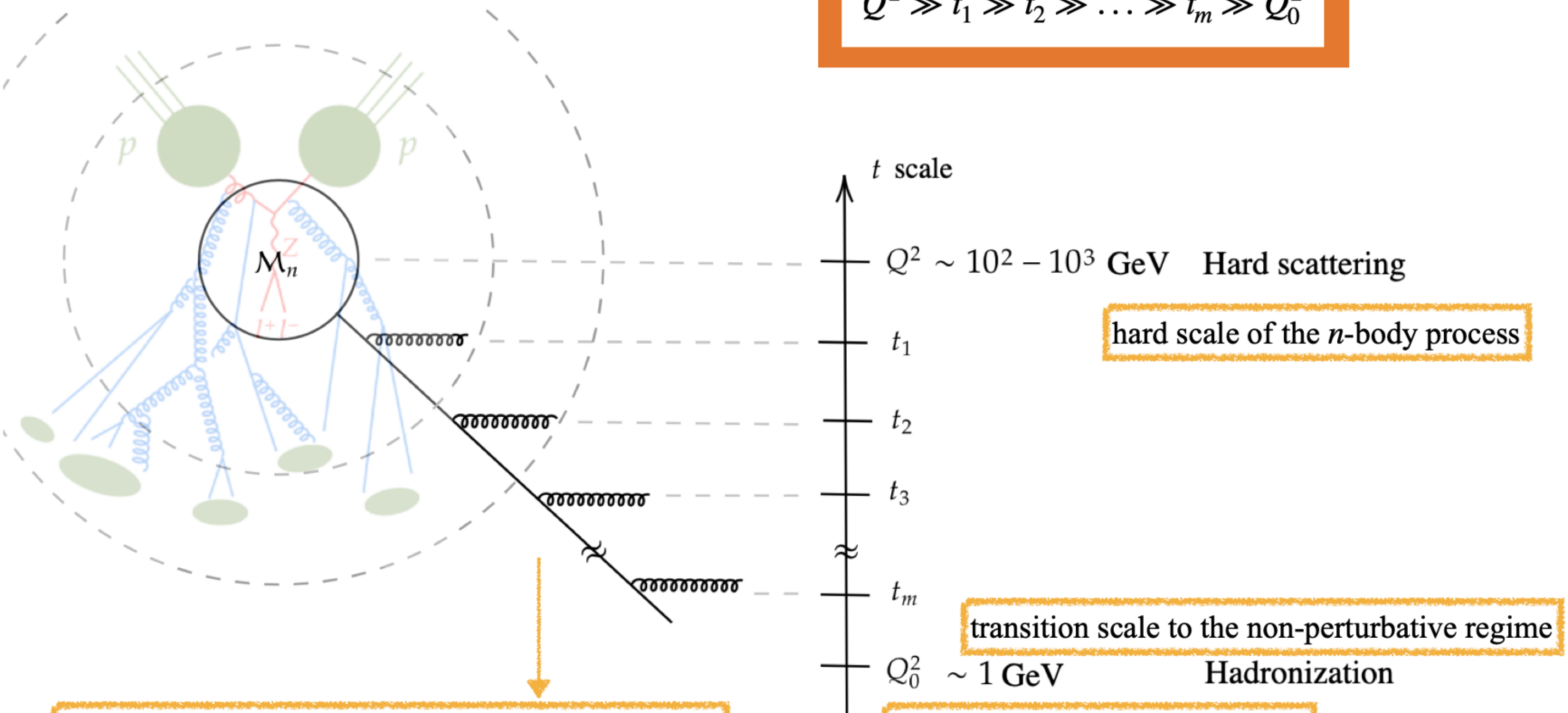
- t = virtuality of a (could be its p_T);
- z = energy fraction of b related to a;
- $\hat{P}_{a\to bc}$ = Altarelli-Parisi splitting kernel



Multiple emissions

Strongly ordered region of phase-space:

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



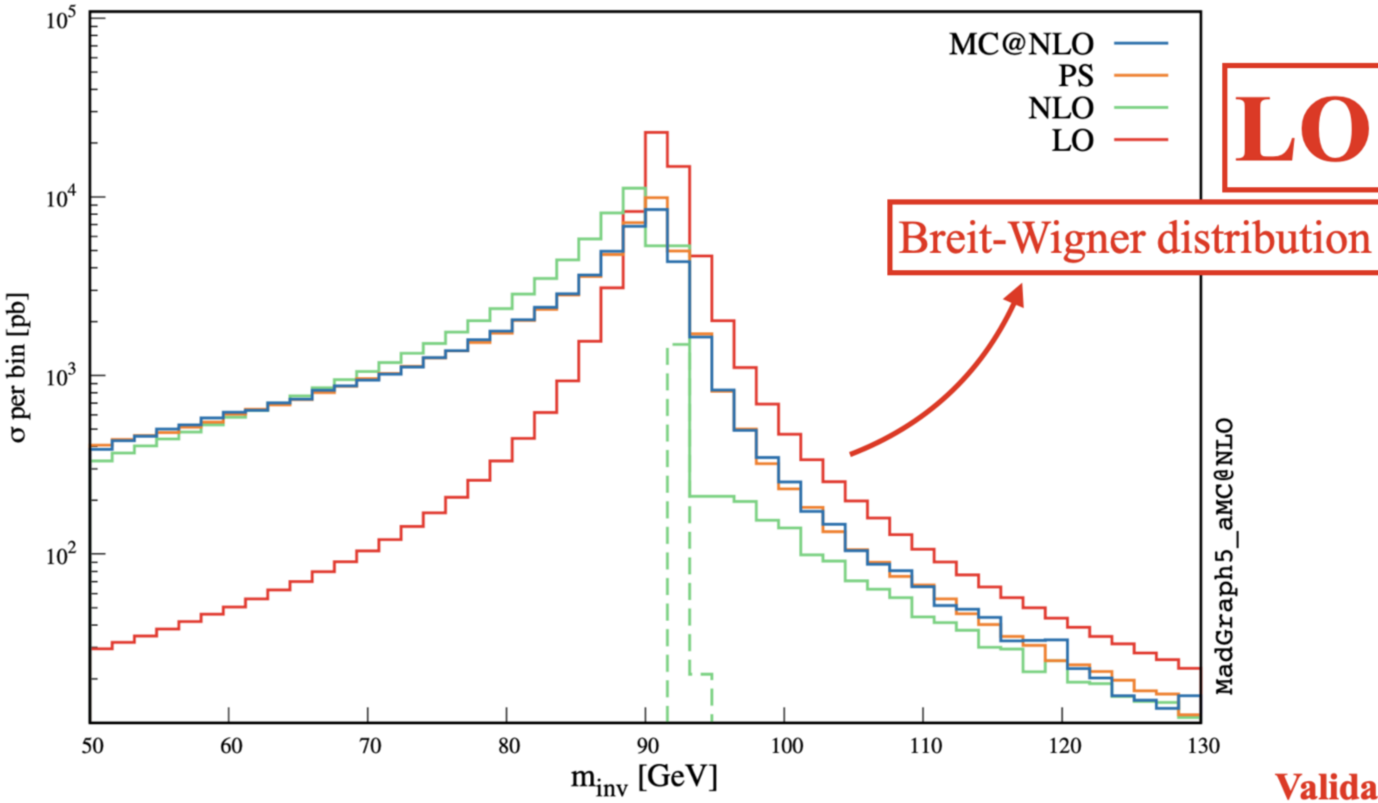
$$d\sigma_{n+m} \sim d\sigma_n \prod_{k=1}^{m} \frac{\alpha_s}{2\pi} \frac{dt_k}{t_k} dz_k \hat{P}_{a_k \to b_k c_k}(z_k)$$

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

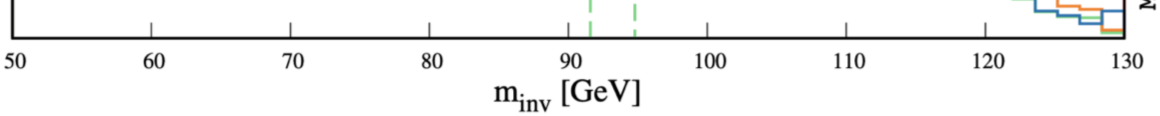
Differential cross section w.r.t. the invariant mass

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

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

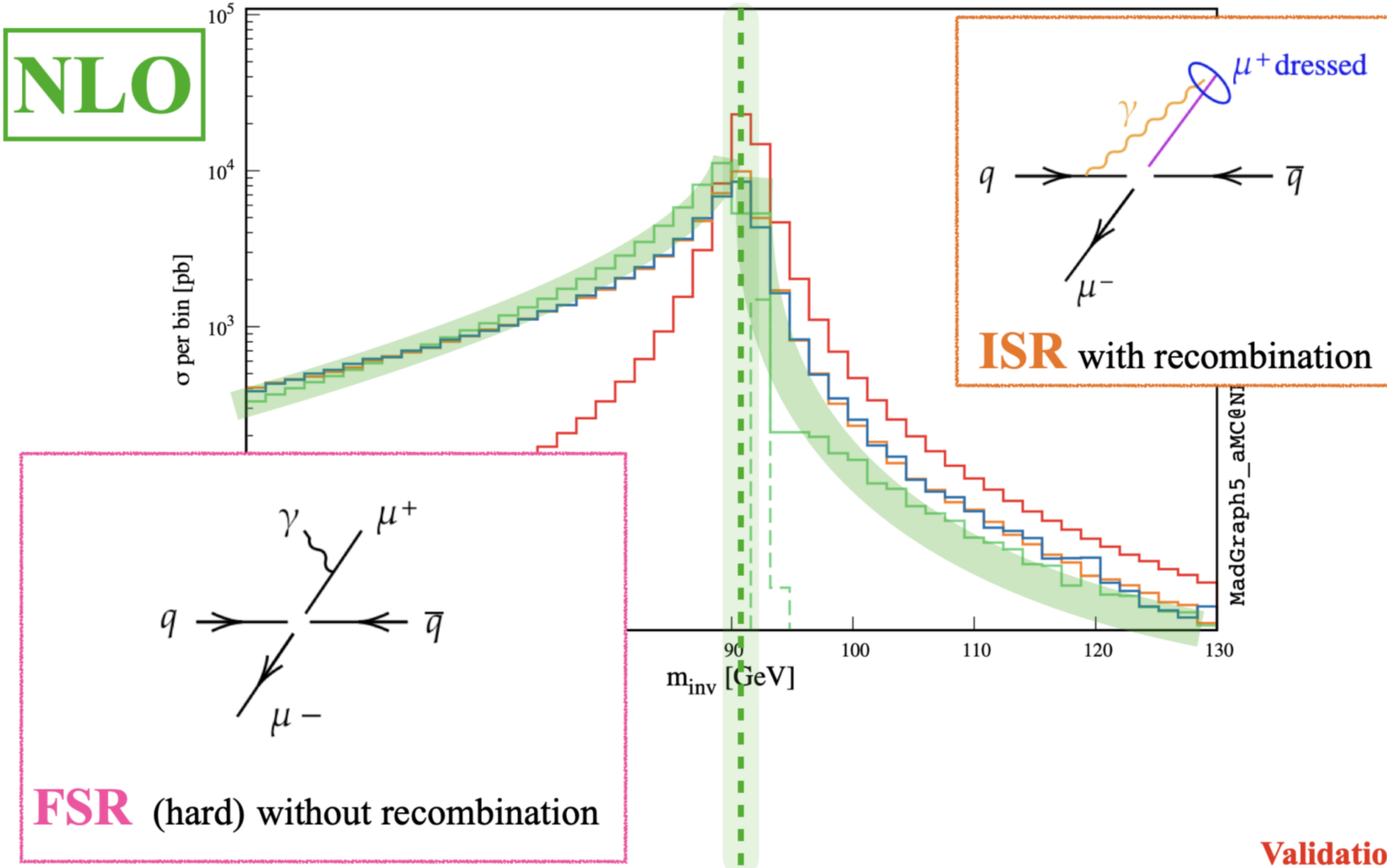


Validation phase



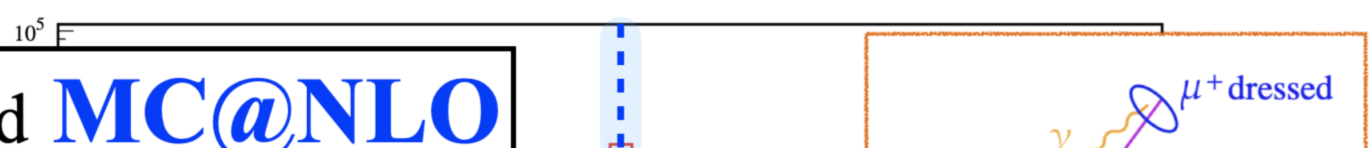
Validation phase

NLO

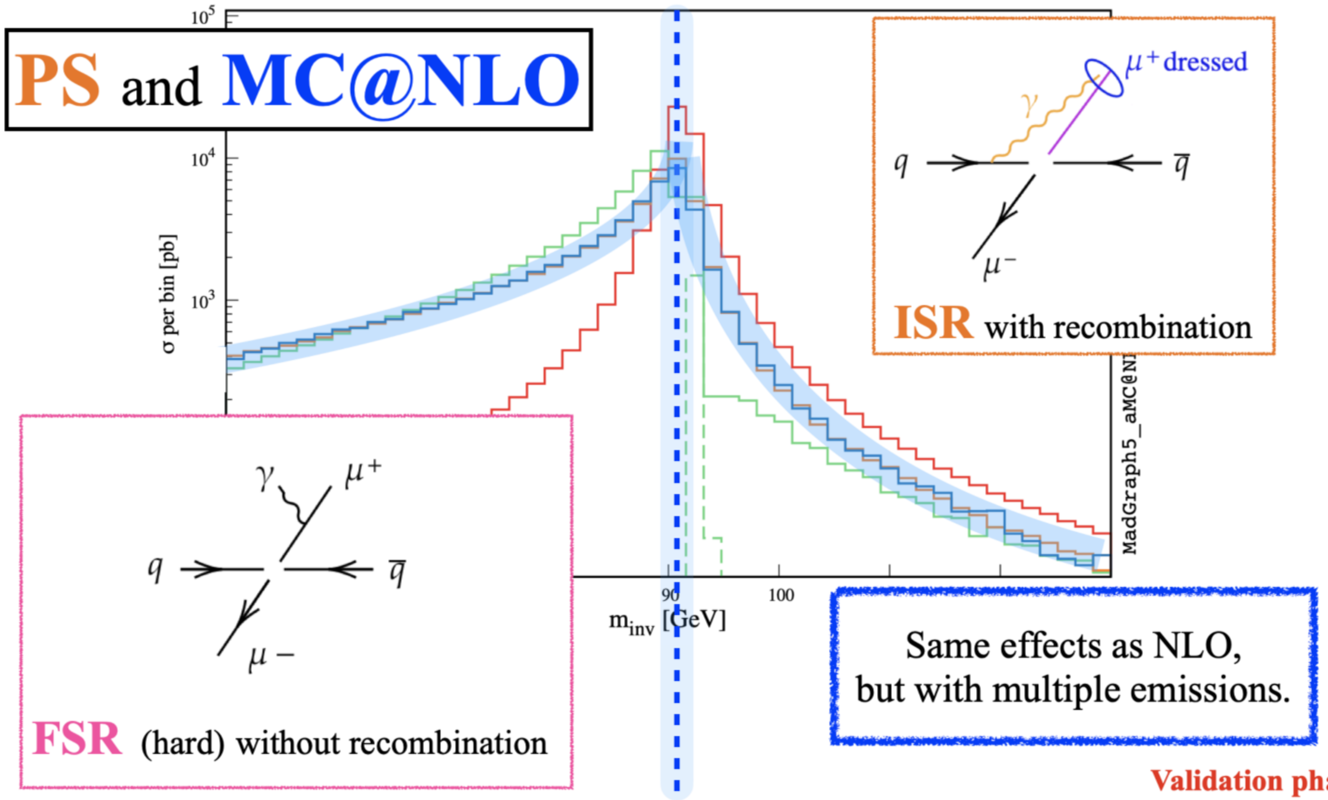


Validation phase

PS and MC@NLO



Validation phase



Validation phase