Resolution observables in NNLO+PS matching through MiNNLO and Geneva

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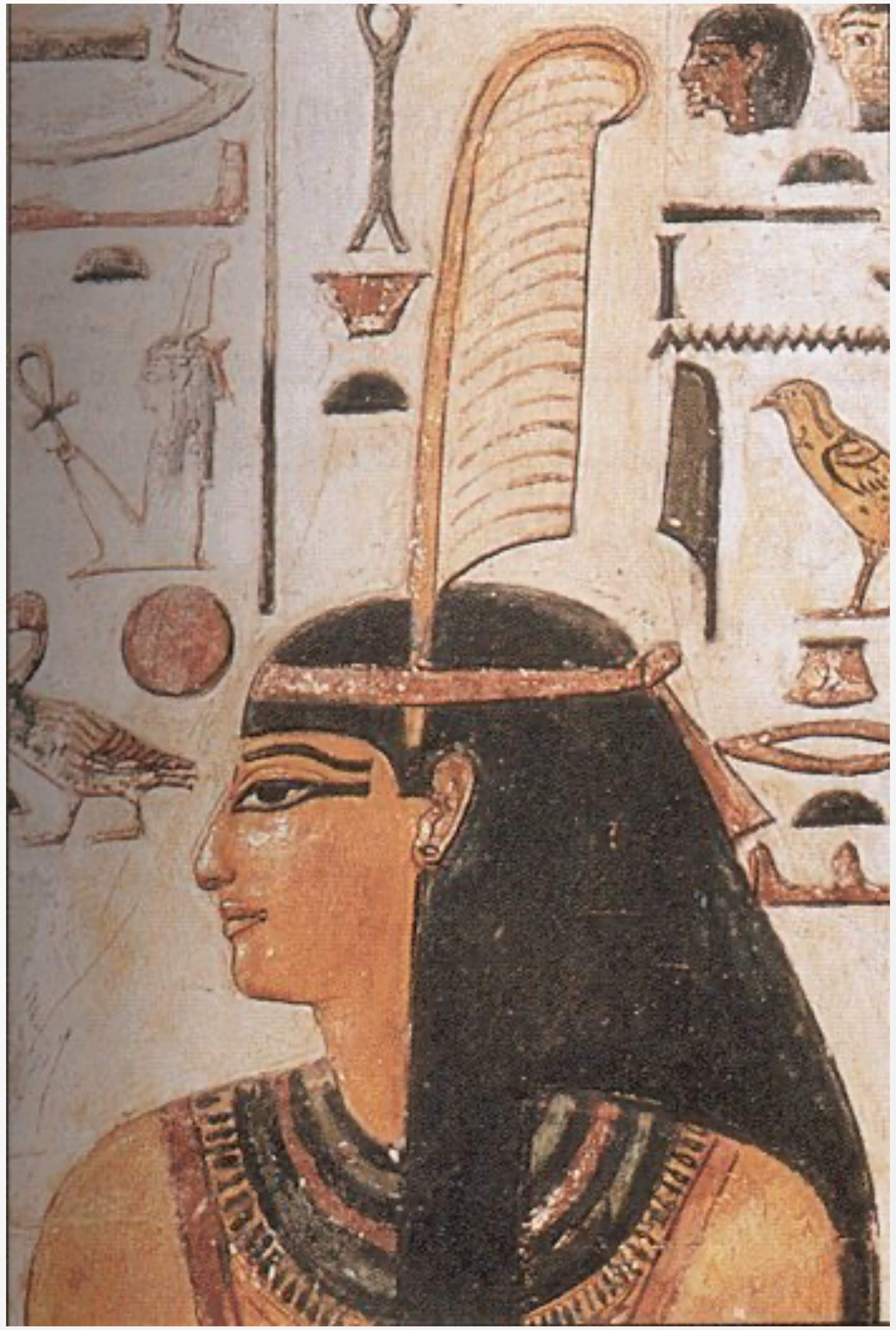
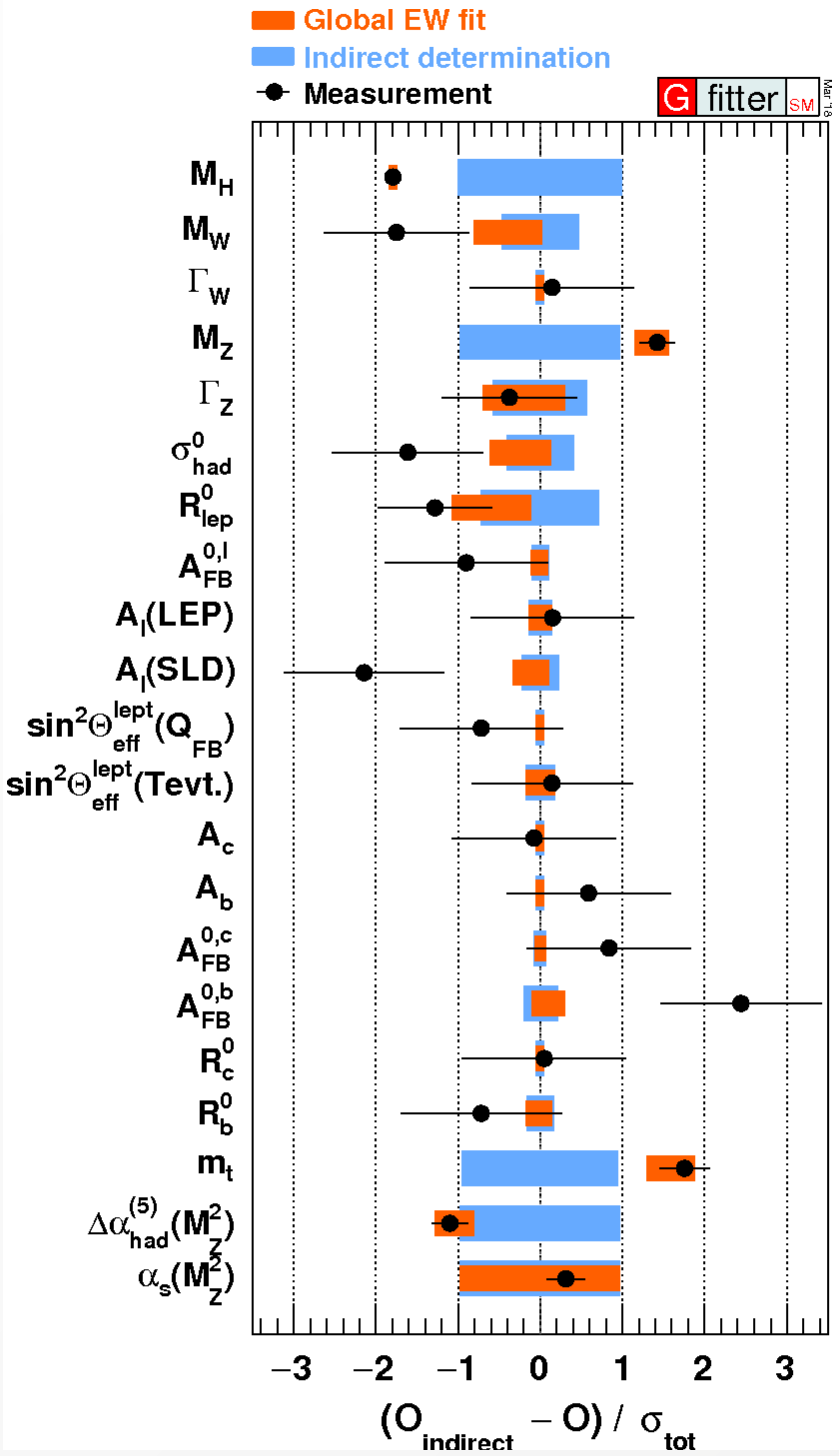
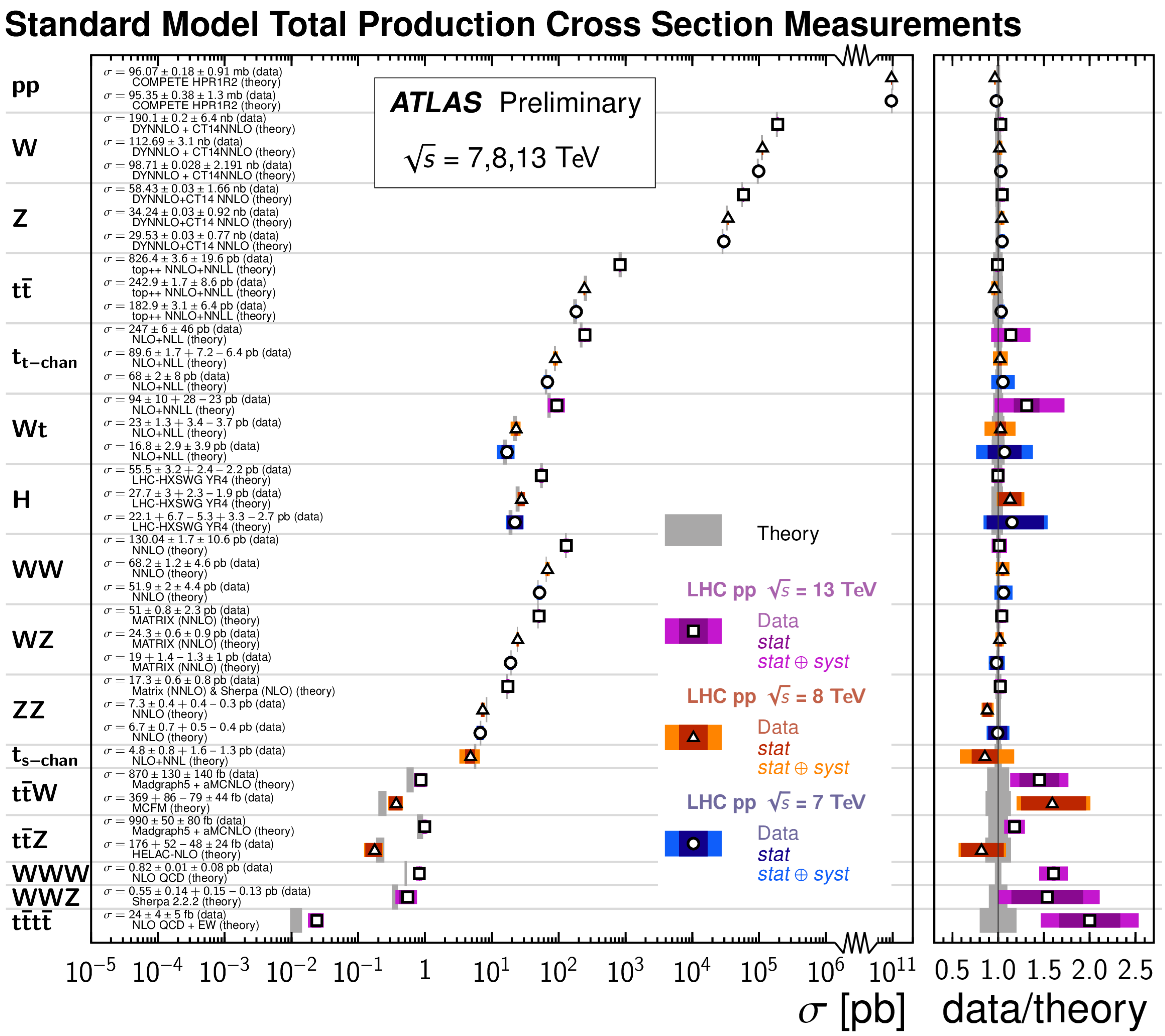
Swiss National Science Foundation





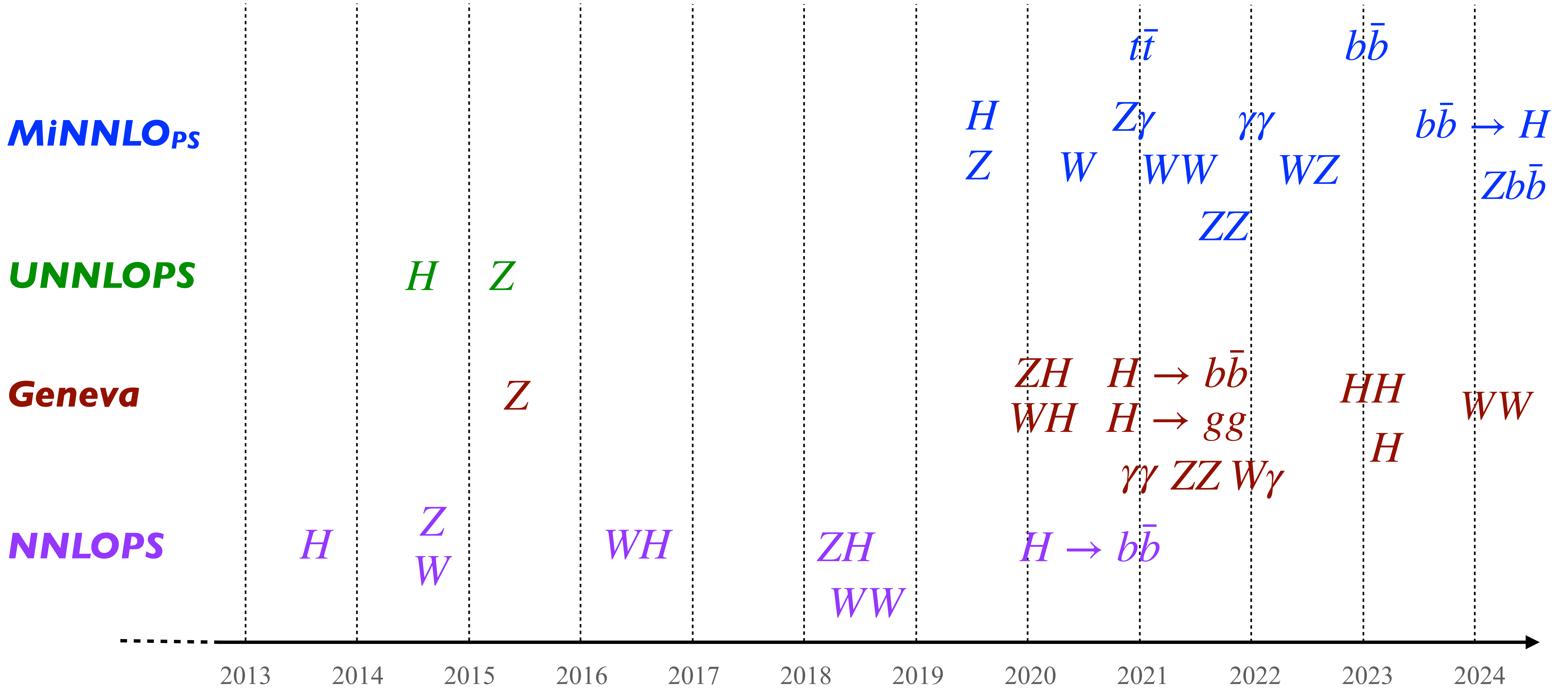
Global EW fit
Indirect determination
Measurement
G fitter SM
M_H
M_W
Γ_W
M_Z
Γ_Z
σ^0_{had}
R^0_{lep}
$A^{0,l}_{FB}$
A_l(LEP)
A_l(SLD)
$\sin^2\Theta^{lept}_{eff}(Q_{FB})$
$\sin^2\Theta^{lept}_{eff}$(Tevt.)
A_c
A_b
$A^{0,c}_{FB}$
$A^{0,b}_{FB}$
R^0_c
R^0_b
m_t
$\Delta\alpha^{(5)}_{had}(M_Z^2)$
$\alpha_s(M_Z^2)$
−3 −2 −1 0 1 2 3
$(O_{indirect} - O) / \sigma_{tot}$



Standard Model Total Production Cross Section Measurements
ATLAS Preliminary
$\sqrt{s}$ = 7,8,13 TeV
pp
W
Z
$t\bar{t}$
t_{t-chan}
Wt
H
WW
WZ
ZZ
t_{s-chan}
$t\bar{t}W$
$t\bar{t}Z$
WWW
WWZ
$t\bar{t}t\bar{t}$
Theory
LHC pp $\sqrt{s}$ = 13 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 8 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 7 TeV
Data
stat
stat ⊕ syst
σ [pb]
data/theory

NNLO+PS timeline

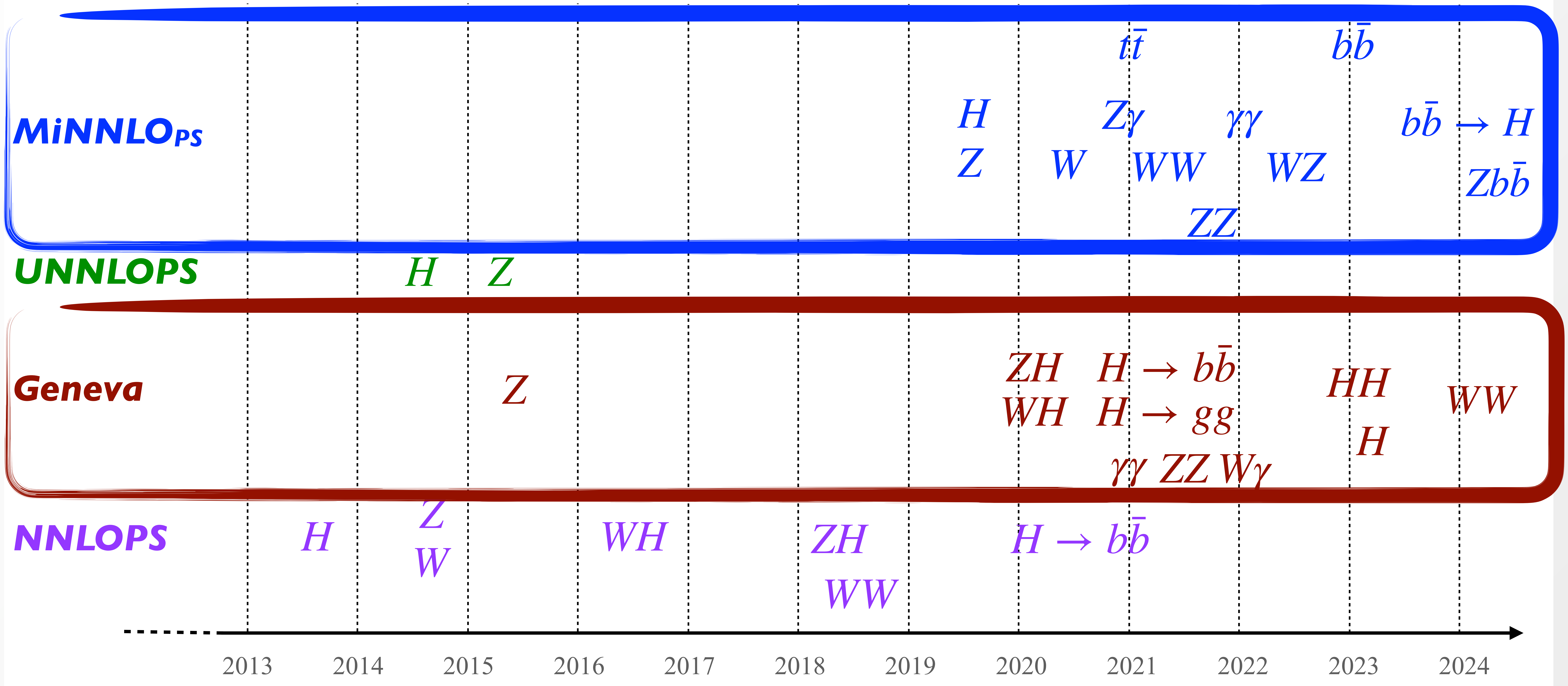
Wiesemann @ SM@LHC 2023



Progress in NNLO+PS with sector showers **[Campbell, Höche, Li, Preuss, Skands '21]**

NNLO+PS timeline

Wiesemann @ SM@LHC 2023



Progress in NNLO+PS with sector showers [Campbell, Höche, Li, Preuss, Skands '21]

NNLO+PS: general strategy

Recast perturbative NNLO calculation in a Monte Carlo language (radiation ordered in a given resolution variable)

- Introduce a **set of resolution variables** to measure hardness of first, second… emission
- Logarithmic dependence on resolution parameters **resummed explicitly** or via **Sudakov form factors**
- Fix remaining degrees of freedom by **matching** to NNLO computation (exploiting **resummation properties** of resolution variable)

NNLO+PS: GENEVA vs. MiNNLO$_{PS}$

GENEVA and MiNNLO$_{PS}$ methods achieve NNLO+PS accuracy following the same general strategy, **with some important differences:**

GENEVA

- Originally developed using **jettiness-like** observables ($\mathcal{T}_0$, $\mathcal{T}_1$)
- **High-accuracy resummation** of residual logarithmic dependence
- **Additive-like** matching to reach NNLO accuracy (jettiness/q_T subtraction)

MiNNLO$_{PS}$

- Originally developed using **transverse-momentum** observables
- **Sudakov factors** used to resum logarithmic dependence on resolution parameters
- **Multiplicative-like** matching to reach NNLO accuracy (also inspired by jettiness/q_T subtraction)

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GENEVA method in a nutshell

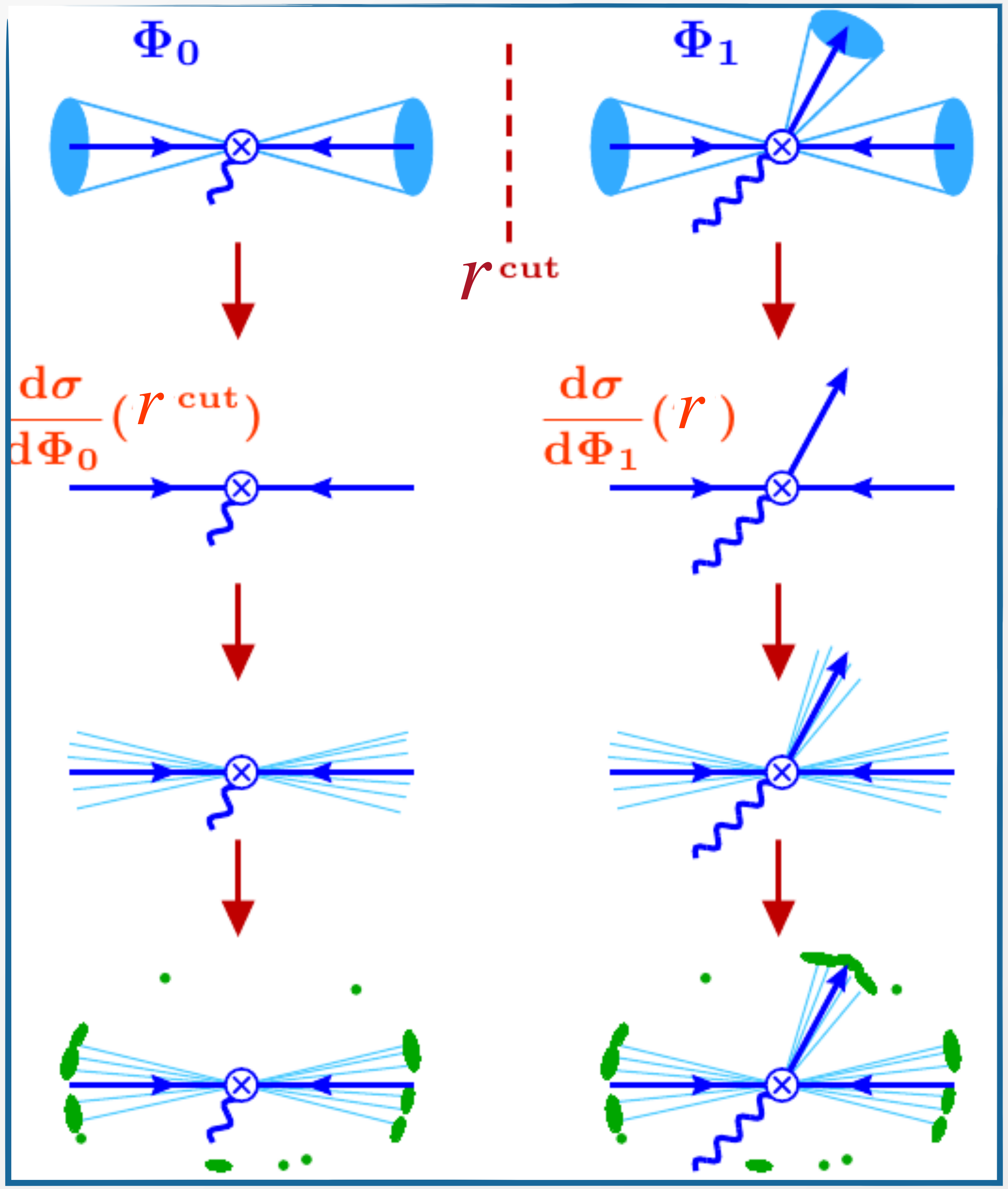
[Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '15]

- Design IR-finite definition of events, based on **resolution parameter** r^{cut}. Emissions below r^{cut} are ***unresolved*** and the kinematic configuration considered is the one of the event before the emission

- Associate differential cross-sections to events such that 0-jet events are NNLO accurate and r is resummed at NNLL′

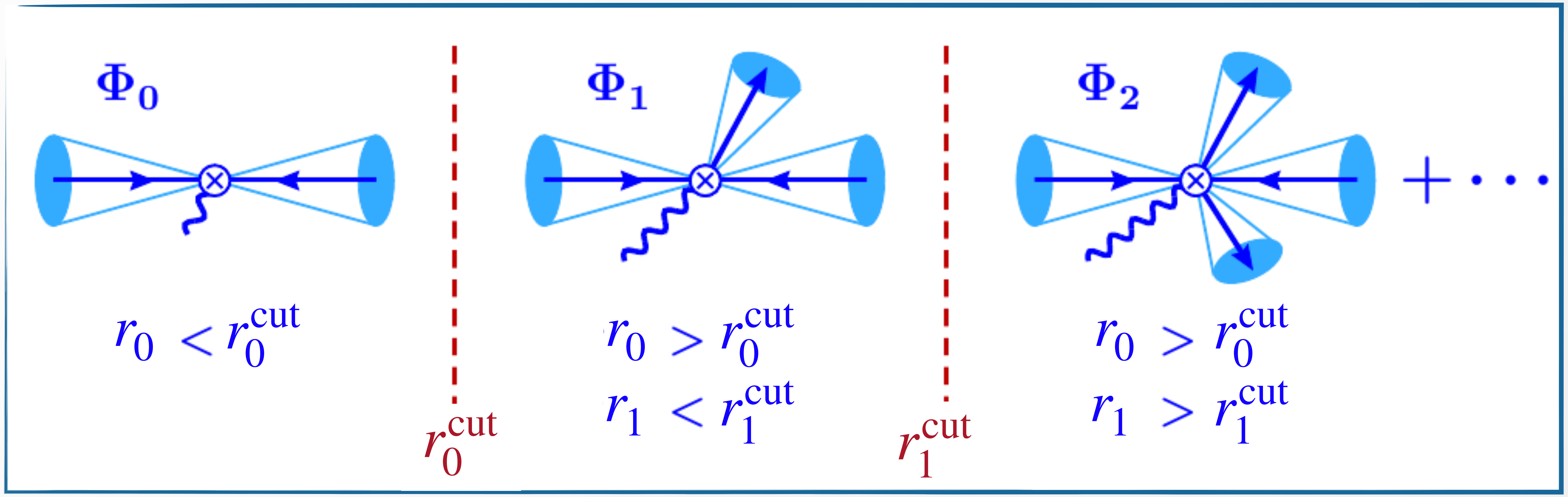
- Shower events

- Hadronise, add multi-parton interactions (MPI) and compare with data



GENEVA method in a nutshell

Procedure can be iterated, thus slicing the phase space into jet-bins



Exclusive 0-jet bin

$$\frac{d\sigma_0^{\rm MC}}{d\Phi_0}(r_0^{\rm cut})$$

Exclusive 1-jet bin

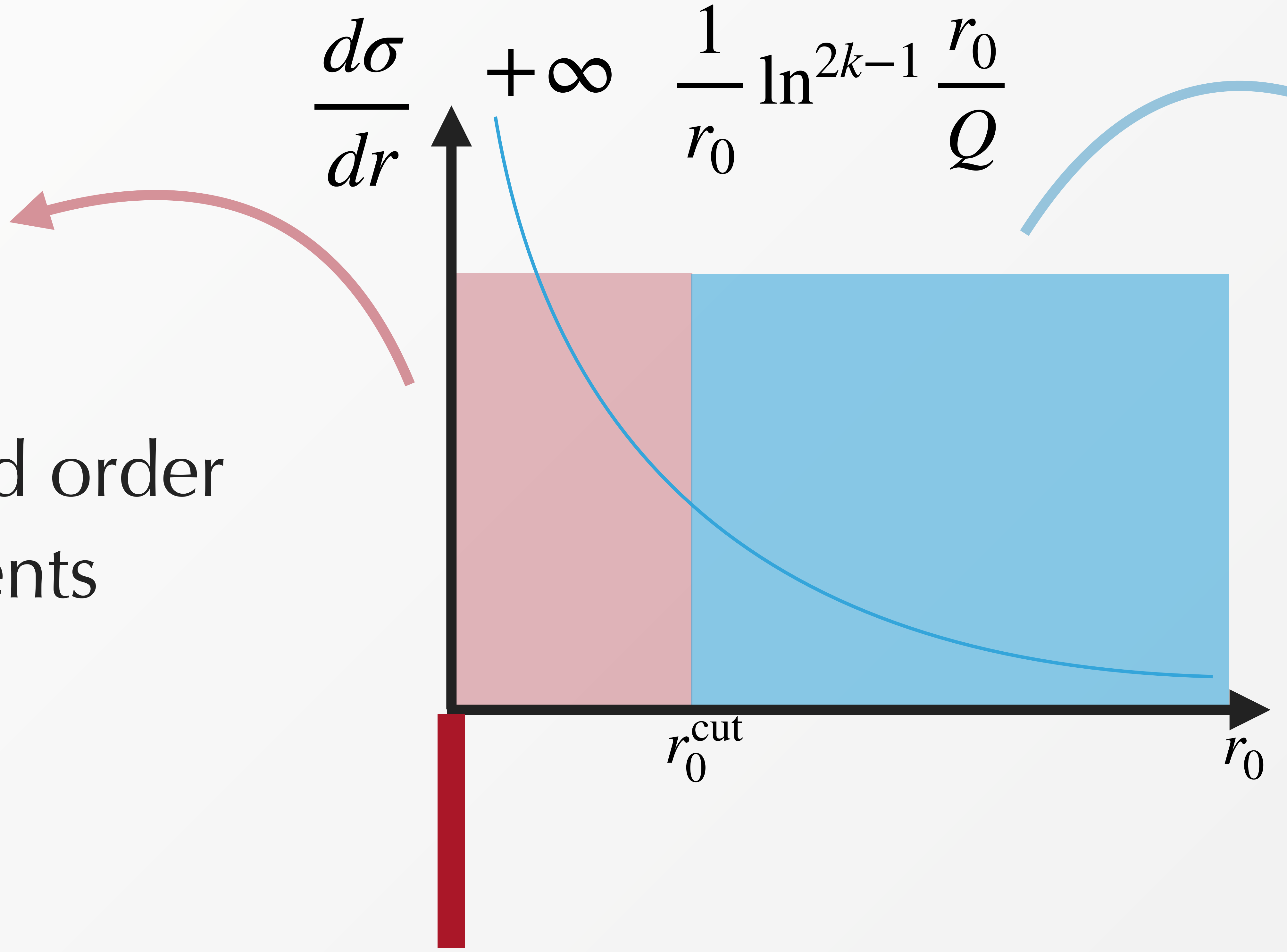
$$\frac{d\sigma_1^{\rm MC}}{d\Phi_1}(r_0 > r_0^{\rm cut}; r_1^{\rm cut})$$

Inclusive 2-jet bin

$$\frac{d\sigma_2^{\rm MC}}{d\Phi_2}(r_0 > r_0^{\rm cut}, r_1 > r_1^{\rm cut})$$

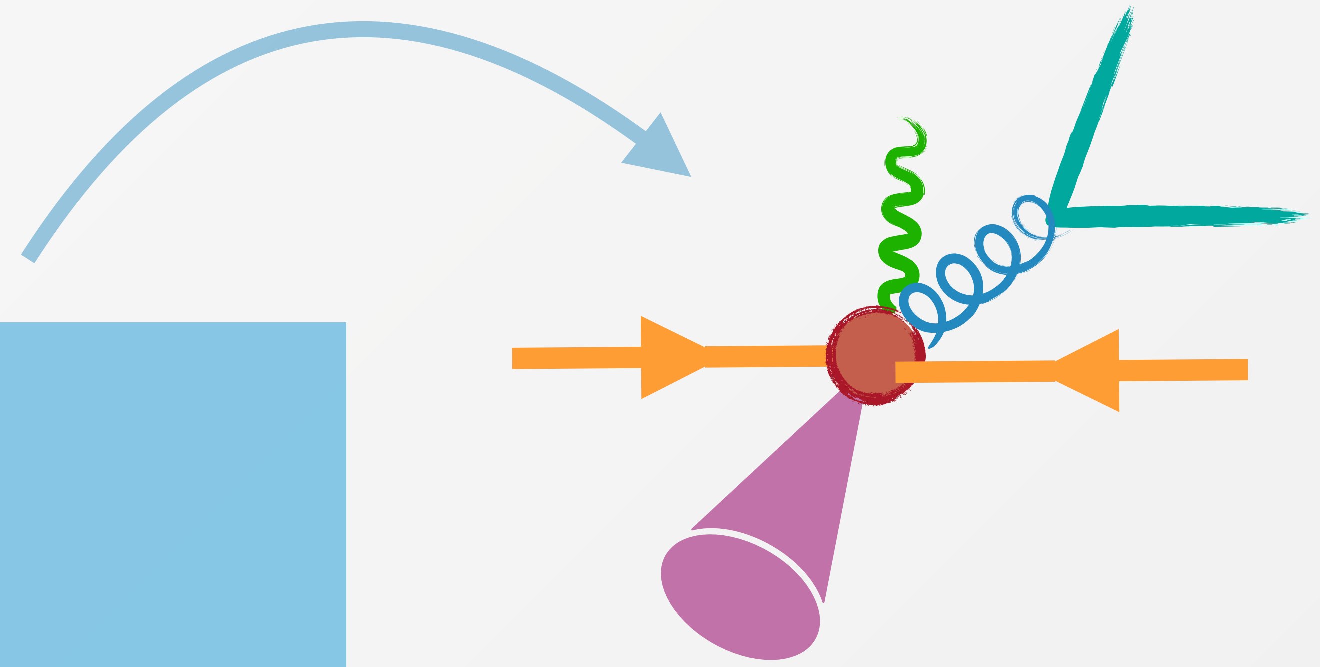
GENEVA method in a nutshell: resummation of the resolution parameter

As we take $r_0^{\text{cut}} \to 0$, large logarithms of r_0^{cut}, r_0 appear, which must be resummed lest they spoil the perturbative convergence



resummation of r_0

- Expand to fixed order
- $\mathcal{O}(\alpha_s^2)$ ingredients



$$d\sigma_F^{\text{MC}} = d\sigma_F^{\text{res}} + [d\sigma_{FJ}]_{\text{f.o.}} - [d\sigma_F^{\text{res}}]_{\text{f.o.}}$$

NNLO accuracy guaranteed up to power correction in r_0^{cut}

GENEVA method in a nutshell: resummation of the resolution parameter

$$d\sigma_F^{\rm MC} = d\sigma_F^{\rm res} + [d\sigma_{FJ}]_{\rm f.o.} - [d\sigma_F^{\rm res}]_{\rm f.o.}$$

Above formula can be compared to the q_T or **jettiness subtraction formalism**
[Catani, Grazzini '08][Gaunt, Stahlhofen, Tackmann, Walsh '15]

However, we are interested in a **fully differential Monte Carlo event generator**. Since the resummed component is only differential in Born phase space Φ_0 and r_0, one has to make it differential in 2 more variables, e.g. energy ratio $z = E_m/E_s$, azimuthal angle ϕ.

$$\frac{d\sigma_{FJ}^{\rm MC}}{d\Phi_{FJ}}(r_0 > r_0^{\rm cut}) = \frac{d\sigma^{\rm res}}{d\Phi_F dr_0}\mathscr{P}(\Phi_{FJ}) + \frac{d\sigma^{\rm NLO_{FJ}}}{d\Phi_{FJ}} - \left[\frac{d\sigma^{\rm res}}{d\Phi_F dr_0}\mathscr{P}(\Phi_{FJ})\right]_{\rm NLO}$$

Here $\mathscr{P}(\Phi_{FJ})$ is a normalised splitting probability to make the resummation differential in Φ_{FJ}

$$\int \frac{d\Phi_{FJ}}{d\Phi_{FJ} dr_0}\mathscr{P}(\Phi_{FJ}) = 1$$

GENEVA method in a nutshell: 1-/2-jet separation

An analogue separation is performed for the 1-jet cross section, which is partitioned into an exclusive 1-jet cross section and an inclusive 2-jet cross section

$$d\sigma_{FJ}^{\mathrm{MC}} = d\sigma_{FJ}^{\mathrm{res}} + [d\sigma_{FJJ}]_{\mathrm{f.o.}} - [d\sigma_{FJ}^{\mathrm{res}}]_{\mathrm{f.o.}}$$

Integrated quantities retain NLO accuracy via **local subtraction**; resummation accuracy at NLL is sufficient

Analogously to the 0-/1-jet separation, a **normalised splitting function** $\mathscr{P}(\Phi_{FJJ})$ is needed to make the extend the differential dependence of $d\sigma_{FJ}^{\mathrm{res}}$

$$U_1(\Phi_{FJ}, r_1^{\mathrm{cut}}) + \int \frac{d\Phi_{FJJ}}{d\Phi_{FJ}} U_1'(\Phi_{FJ}, r_1)\mathscr{P}(\Phi_{FJJ})\theta(r_1 > r_1^{\mathrm{cut}}) = 1$$

Sudakov form factor resumming r_1 dependence

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MiNNLO$_{PS}$

- Originally developed using **transverse-momentum** observables
- **Sudakov factors** used to resum logarithmic dependence on resolution parameters
- **Multiplicative-like** matching to reach NNLO accuracy (also inspired by jettiness/q_T subtraction)

MiNNLO$_{PS}$ in a nutshell [Monni, Nason, Re, Wiesemann, Zanderighi '19]

Starting point of MiNNLO$_{PS}$ construction is analogue to the formulae above

$$d\sigma^F = d\sigma_F^{\rm res} + [d\sigma_{FJ}]_{\rm f.o.} - [d\sigma_F^{\rm res}]_{\rm f.o.}$$

Up to the second perturbative order, the resummed component can be written as a total derivative

$$\frac{d\sigma_F^{\rm res}}{dp_T d\Phi_B} = \frac{d}{dp_T}\{e^{-S}\mathscr{L}\} = e^{-S}\underbrace{\{S'\mathscr{L} + \mathscr{L}'\}}_{\equiv D}$$

where the luminosity $\mathscr{L}$ and the Sudakov form factor S are written in terms of the ingredients of q_T resummation at N^{3}LL accuracy

$$\mathscr{L} \sim H(C\otimes f)(C\otimes f) \qquad\qquad S(p_T) = \int_{p_T}^{Q} \frac{dq}{q}\left(A(\alpha_s(q))\ln\frac{Q^2}{q^2} + B(\alpha_s(q))\right)$$

MiNNLO$_{\rm PS}$ in a nutshell

By factoring out the Sudakov exponential factor

$$d\sigma^F = d\sigma_F^{\rm res} + [d\sigma_{FJ}]_{\rm f.o.} - [d\sigma_F^{\rm res}]_{\rm f.o.} = e^{-S}\left\{ D + \frac{[d\sigma_{FJ}]_{\rm f.o.}}{[e^{-S}]_{\rm f.o}} - \frac{[d\sigma_F^{\rm res}]_{\rm f.o.}}{[e^{-S}]_{\rm f.o}} \right\}$$

Expanding up to $\mathcal{O}(\alpha_s^3(p_T))$ one gets

$$\frac{d\sigma_F^{\rm MiNNLO}}{dp_T d\Phi_B} = e^{-S(p_T)}\Bigg\{ \underbrace{\frac{\alpha_s(p_T)}{2\pi}\frac{d\sigma_{FJ}^{(1)}}{dp_T d\Phi_B}}_{\mathcal{O}(\alpha_s(p_T))}\underbrace{\left(1+\frac{\alpha_s}{2\pi}S^{(1)}(p_T)\right)+\left(\frac{\alpha_s(p_T)}{2\pi}\right)^2\frac{d\sigma_{FJ}^{(2)}}{dp_T d\Phi_B}}_{\mathcal{O}(\alpha_s(p_T^2))}$$

$$+\underbrace{\left[D(p_T) - \frac{\alpha_s}{2\pi}D^{(1)}(p_T) - \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2 D^{(2)}(p_T)\right]}_{\mathcal{O}(\alpha_s(p_T)^3)} + \text{regular terms } \mathcal{O}(\alpha_s^3)\Bigg\}$$

MiNNLO$_{PS}$ in a nutshell

First line equivalent to the **MiNLO′ formulation**

$$\frac{d\sigma_F^{\mathrm{MiNNLO}}}{dp_T d\Phi_B} = e^{-S(p_T)}\Bigg\{ \underbrace{\frac{\alpha_s(p_T)}{2\pi}\frac{d\sigma_{FJ}^{(1)}}{dp_T d\Phi_B}}_{\mathcal{O}(\alpha_s(p_T))}\left(1+\underbrace{\frac{\alpha_s}{2\pi}S^{(1)}(p_T)\right)+\left(\frac{\alpha_s(p_T)}{2\pi}\right)^2\frac{d\sigma_{FJ}^{(2)}}{dp_T d\Phi_B}}_{\mathcal{O}(\alpha_s(p_T^2))}$$

$$+\underbrace{\left[D(p_T)-\frac{\alpha_s}{2\pi}D^{(1)}(p_T)-\left(\frac{\alpha_s(p_T)}{2\pi}\right)^2 D^{(2)}(p_T)\right]}_{\mathcal{O}(\alpha_s(p_T)^3)}+\text{regular terms }\mathcal{O}(\alpha_s^3)\Bigg\}$$

MiNNLO$_{PS}$ in a nutshell

First line equivalent to the **MiNLO′ formulation**

Second lines contains the additional terms needed to reach **NNLO accuracy**, upon integration in q_T

$$\frac{d\sigma_F^{\mathrm{MiNNLO}}}{dp_T d\Phi_B} = e^{-S(p_T)}\Bigg\{ \underbrace{\frac{\alpha_s(p_T)}{2\pi}\frac{d\sigma_{FJ}^{(1)}}{dp_T d\Phi_B}\Big(1 + }_{\mathcal{O}(\alpha_s(p_T))}\underbrace{\frac{\alpha_s}{2\pi}S^{(1)}(p_T)\Big) + \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2 \frac{d\sigma_{FJ}^{(2)}}{dp_T d\Phi_B}}_{\mathcal{O}(\alpha_s(p_T^2))}$$

$$+ \underbrace{\left[D(p_T) - \frac{\alpha_s}{2\pi}D^{(1)}(p_T) - \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2 D^{(2)}(p_T)\right]}_{\mathcal{O}(\alpha_s(p_T)^3)} + \text{regular terms } \mathcal{O}(\alpha_s^3)\Bigg\}$$

MiNNLO$_{PS}$ in a nutshell

First line equivalent to the **MiNLO′ formulation**

Second lines contains the additional terms needed to reach **NNLO accuracy**, upon integration in q_T

Regular terms contribute **beyond NNLO accuracy**

$$\frac{d\sigma_F^{\text{MiNNLO}}}{dp_T d\Phi_B} = e^{-S(p_T)} \Big\{ \underbrace{\frac{\alpha_s(p_T)}{2\pi} \frac{d\sigma_{FJ}^{(1)}}{dp_T d\Phi_B}}_{\mathcal{O}(\alpha_s(p_T))} \Big(1 + \underbrace{\frac{\alpha_s}{2\pi} S^{(1)}(p_T) \Big) + \Big(\frac{\alpha_s(p_T)}{2\pi} \Big)^2 \frac{d\sigma_{FJ}^{(2)}}{dp_T d\Phi_B}}_{\mathcal{O}(\alpha_s(p_T^2))}$$

$$\underbrace{+ \Big[D(p_T) - \frac{\alpha_s}{2\pi} D^{(1)}(p_T) - \Big(\frac{\alpha_s(p_T)}{2\pi} \Big)^2 D^{(2)}(p_T) \Big]}_{\mathcal{O}(\alpha_s(p_T)^3)} + \text{regular terms } \mathcal{O}(\alpha_s^3) \Big\}$$

MiNNLO$_{\rm PS}$ in a nutshell

NNLO subtraction accomplished thanks to the presence of a **Sudakov form factor** which **exponentially suppressed** the $q_T \to 0$ limit

$$\frac{d\sigma_F^{\rm MiNNLO}}{dp_T d\Phi_B} = e^{-S(p_T)} \Bigg\{ \underbrace{\frac{\alpha_s(p_T)}{2\pi}\frac{d\sigma_{FJ}^{(1)}}{dp_T d\Phi_B}\left(1+\frac{\alpha_s}{2\pi}S^{(1)}(p_T)\right)}_{\mathcal{O}(\alpha_s(p_T))} + \underbrace{\left(\frac{\alpha_s(p_T)}{2\pi}\right)^2 \frac{d\sigma_{FJ}^{(2)}}{dp_T d\Phi_B}}_{\mathcal{O}(\alpha_s(p_T^2))}$$

$$+ \underbrace{\left[D(p_T) - \frac{\alpha_s}{2\pi}D^{(1)}(p_T) - \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2 D^{(2)}(p_T)\right]}_{\mathcal{O}(\alpha_s(p_T)^3)} + \text{regular terms } \mathcal{O}(\alpha_s^3) \Bigg\}$$

MiNNLO$_{\text{PS}}$ in a nutshell

NNLO+PS construction achieved by applying the above formulae to the POWHEG calculation for F+j production, making it NNLO accurate

$$\frac{d\sigma}{d\Phi_{FJ}} = \tilde{B}^{FJ} \times \left\{ \Delta_{\text{pwg}}(\Lambda_{\text{pwg}}) + \int d\Phi_{\text{rad}} \Delta(p_{T,\text{rad}}) \frac{R(\Phi_{FJ}, \Phi_{\text{rad}})}{B(\Phi_{FJ}} \right\}$$

$\downarrow$

$$\frac{d\sigma}{d\Phi_{FJ}} = \tilde{B}^{\text{MiNNLO}_{\text{PS}}}_{FJ} \times \left\{ \Delta_{\text{pwg}}(\Lambda_{\text{pwg}}) + \int d\Phi_{\text{rad}} \Delta(p_{T,\text{rad}}) \frac{R(\Phi_{FJ}, \Phi_{\text{rad}})}{B(\Phi_{FJ}} \right\}$$

MiNNLO$_{\text{PS}}$ in a nutshell

NNLO+PS construction achieved by applying the above formulae to the POWHEG calculation for F+j production, making it NNLO accurate

$$\tilde{B}^{FJ} \sim \left\{ d\sigma_{FJ}^{(1)} + d\sigma_{FJ}^{(2)} \right\}$$

$$\tilde{B}^{\mathrm{MiNNLOPS}}(\Phi_{FJ}) \simeq e^{-S(p_T)} \left\{ \frac{\alpha_s}{2\pi} \left[\frac{d\sigma}{d\Phi_{FJ}} \right]^{(1)} \left(1 + \frac{\alpha_s}{2\pi} [S(p_T)]^{(1)} \right) + \left(\frac{\alpha_s}{2\pi} \right)^2 \left[\frac{d\sigma}{d\Phi_{FJ}} \right]^{(2)} \right.$$
$$\left. + \left(D(p_T) - D^{(1)}(p_T) - D^{(2)}(p_T) \right) \times \mathscr{P}(\Phi_{\mathrm{FJ}}) \right\}$$

Here $\mathscr{P}(\Phi_{FJ})$ again is needed to spread the last term in the Φ_{FJ} phase space

Choice of the resolution parameter (1)

Original incarnation of GENEVA uses ***N*-jettiness** (beam thrust) as 0-jet resolution parameter, defined in terms of beams $q_{a,b}$ and jet-directions q_j

$$\mathcal{T}_N = \frac{2}{Q}\sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots q_N \cdot p_K\}$$

Similarly, MiNNLO$_{PS}$ has been originally formulated by creating a connection to the **transverse momentum resummation** formalism

Any resolution variable which can be **resummed at high enough accuracy** can be used

The **availability of different resolution variables** within the same formalism allows one to study the **robustness of the frameworks** and **assess the uncertainties** associated to the choice of the resolution parameter

Extension(s) of the GENEVA framework

The GENEVA method was formulated in **full generality**, making its extension formally viable

Technically challenging as it requires acting on all aspects of the framework (interplay with resummation, subtractions, mapping, shower interface…)

First method to be extended to use a different resolution variable

[Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, LR '21]

$$\mathcal{T}_0 \to q_T$$

Availability of N^{3}LL resummation for q_T and **extreme precision** at which this observable is measured by the LHC experiments motivated the extension of the GENEVA framework

Recently extended to use also the leading jet p_T as resolution variable

[Gavardi, Lim, Alioli, Tackmann '23]

$$\mathcal{T}_0 \to p_T^{j_1}$$

thanks to the recent availability of NNLL′ ingredients for $p_T^{j_1}$

[Abreu, Gaunt, Monni, LR, Szafron '22]

Extension of the MiNNLO$_{\text{PS}}$ framework

Extension of the MiNNLO$_{\text{PS}}$ formalism to other (SCET$_{\text{I}}$) resolution variables **less straightforward**, due to the connection with the transverse resummation formalism

Differences with respect to the transverse momentum case arise from the **different singular structure** (SCET$_{\text{I}}$ vs SCET$_{\text{II}}$) which leads to a richer structure up to order α_s^2

$$\frac{d\sigma^{\text{sing}}(\mathcal{T}_0)}{d\Phi_B} = e^{-\mathcal{S}(\mathcal{T}_0)}\Big[\mathcal{L}(\mathcal{T}_0)\Big(1 - \frac{\zeta_2}{2}[(\mathcal{S}')^2 - \mathcal{S}''] - \zeta_3\mathcal{S}'\mathcal{S}'' + \frac{3\zeta_4}{16}(\mathcal{S}'')^2 + \frac{\zeta_3}{3}\mathcal{S}'''\Big)$$
$$+\mathcal{L}'(\mathcal{T}_0)\big(\zeta_2\mathcal{S}' + \zeta_3\mathcal{S}''\big) - \frac{\zeta_2}{2}\mathcal{L}''(\mathcal{T}_0) + \mathcal{O}(\alpha_s^3)\Big]$$

[Ebert, LR, Wiesemann, Zanderighi, Zanoli '23]

To be compared with

$$\frac{d\sigma^{\text{sing}}(p_T)}{d\Phi_B} = e^{-\mathcal{S}(p_T)}\Big[\mathcal{L}(p_T)\Big(1 - \frac{\zeta_3}{4}\mathcal{S}'\mathcal{S}'' + \frac{\zeta_3}{12}\mathcal{S}'''\Big) - \frac{\zeta_3}{4}\frac{\alpha_s(p_T)}{\pi}\mathcal{S}''\hat{P}\otimes\mathcal{L}(p_T) + \mathcal{O}(\alpha_s^3)\Big]$$

[Monni, Nason, Re, Wiesemann, Zanderighi '19]

Extension of the MiNNLOPS framework

It turns out that the MiNNLOPS construction is **sufficiently flexible** to allow for its extension to a rather different variable such as jettiness, provided that the POWHEG calculation is modified in a suitable manner

$$q_T \to \mathcal{T}_0$$

With the POWHEG $\tilde{B}$ function now reading

$$\tilde{B}^{\mathrm{MiNNLOPS}}(\Phi_{FJ}) \simeq e^{-S(\mathcal{T}_0)}\left\{ \frac{\alpha_s}{2\pi}\left[\frac{d\sigma}{d\Phi_{FJ}}\right]^{(1)}\left(1+\frac{\alpha_s}{2\pi}[S(\mathcal{T}_0)]^{(1)}\right)+\left(\frac{\alpha_s}{2\pi}\right)^2\left[\frac{d\sigma}{d\Phi_{FJ}}\right]^{(2)} + \left(D(\mathcal{T}_0)-D^{(1)}(\mathcal{T}_0)-D^{(2)}(\mathcal{T}_0)\right)\times\mathcal{P}(\Phi_{\mathrm{FJ}})\right\}$$

[Ebert, LR, Wiesemann, Zanderighi, Zanoli '23]

Choice of the resolution parameter (2)

The choice of resolution variables is **in principle immaterial** to reach NNLO accuracy

However, its choice has important consequences

- Size of **missing power corrections** **(in the GENEVA method)**
- Ease of **interface with the shower**
- Overall description of **physical events** after matching and showering
- Extension to **more complicated processes**

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Resolution parameter and missing power corrections

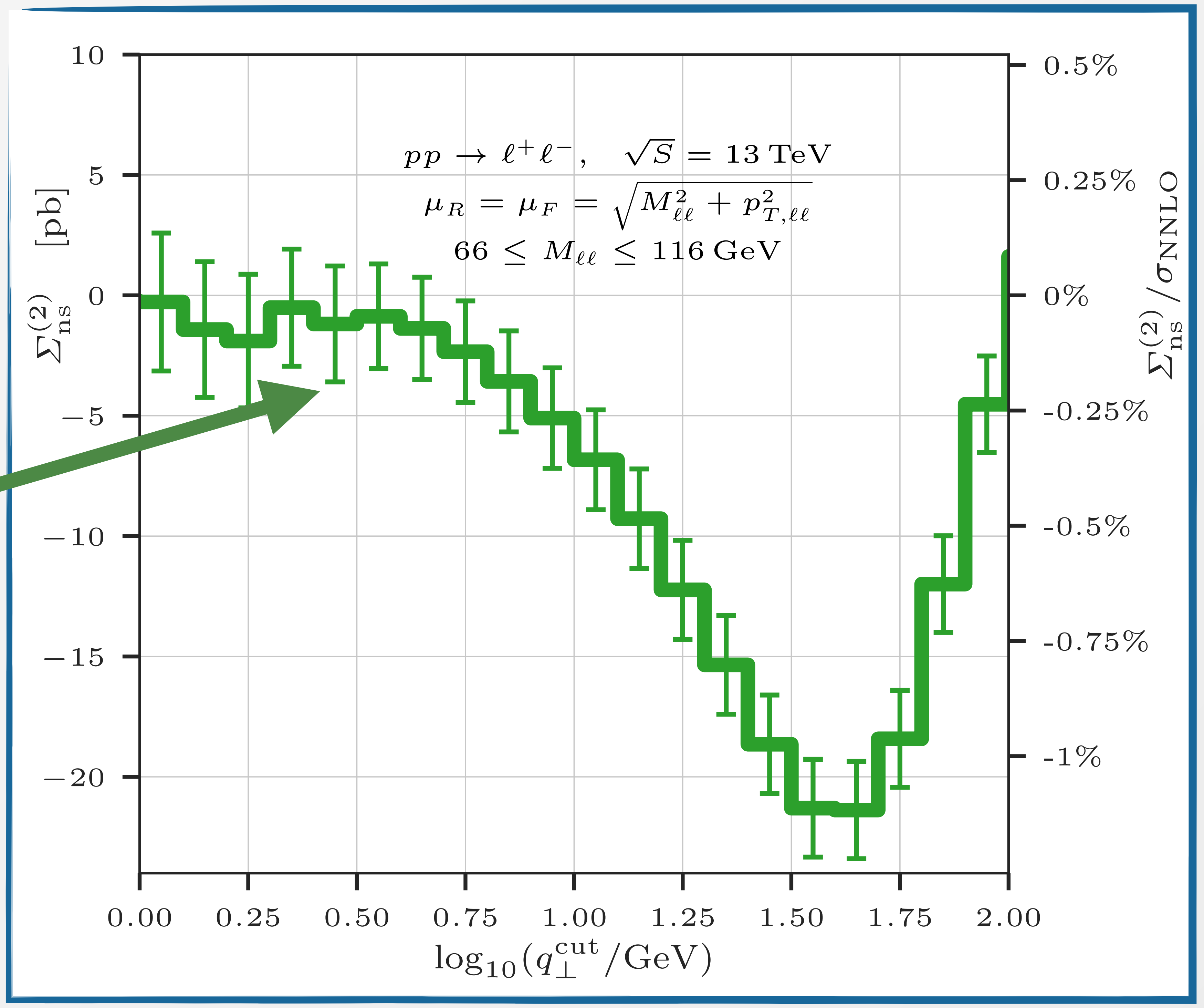
The GENEVA method relies on a **non-local subtraction scheme** to reach NNLO accuracy

As such, it is prone to the same limitation of non-local subtraction schemes, i.e. sensitivity to **missing power corrections** below the technical cutoff r_0^{cut}

GENEVA$_{\mathcal{T}_0}$ typically relies on an overall reweighing of the events to reproduce the NNLO cross section due to larger missing power corrections using $\mathcal{T}_0$

This drawback is removed relying on transverse momentum observables (q_T, p_T^j)

Reduced size of power corrections using transverse-momentum based observables removes the need of such reweighing improving comparisons with fixed-order computations



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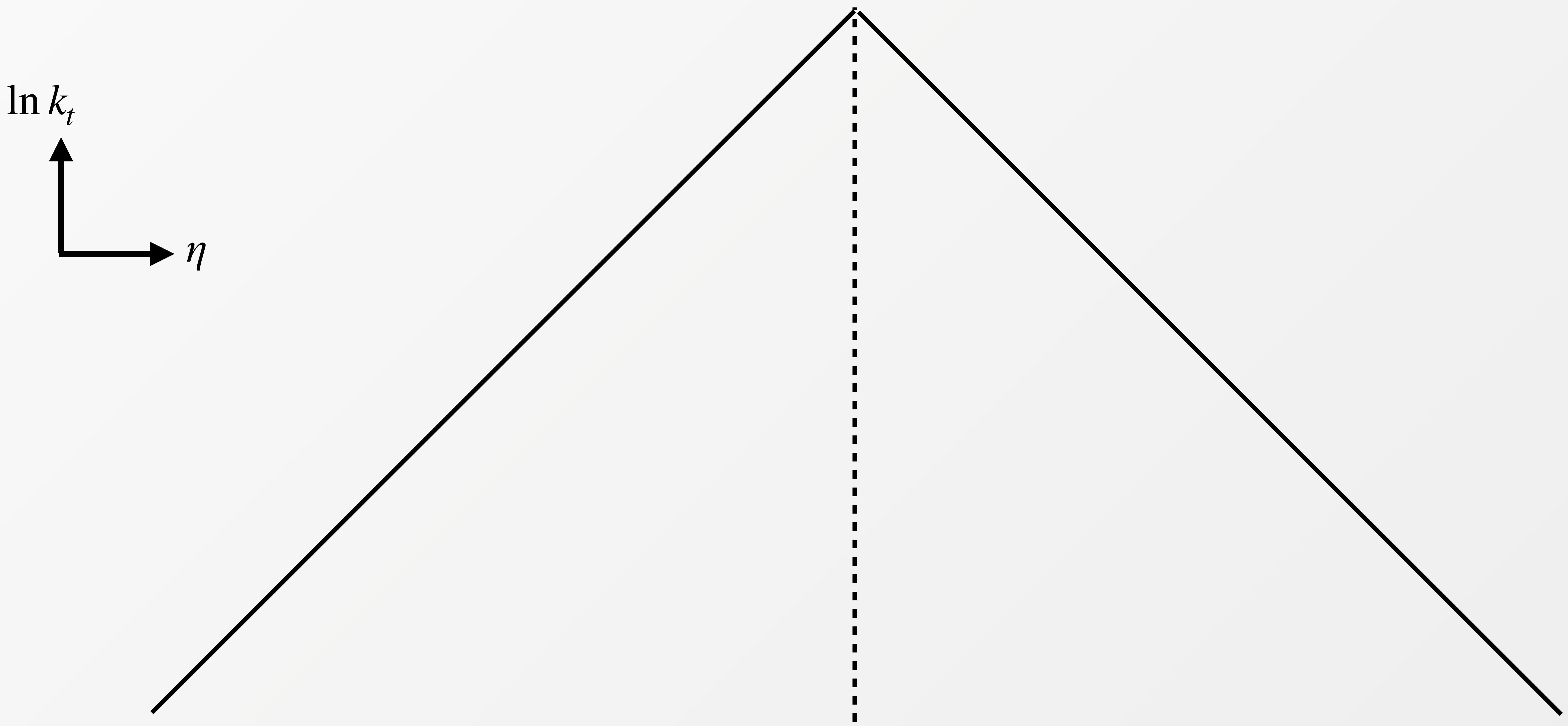
Interplay with the parton shower

The interplay with the parton shower is likely the **most delicate aspect** of NNLO+PS methods

For simplicity, let's consider the interplay between the generator and the parton shower at NLO+PS using a Lund plane representation of the of the phase space for soft and/or collinear emissions

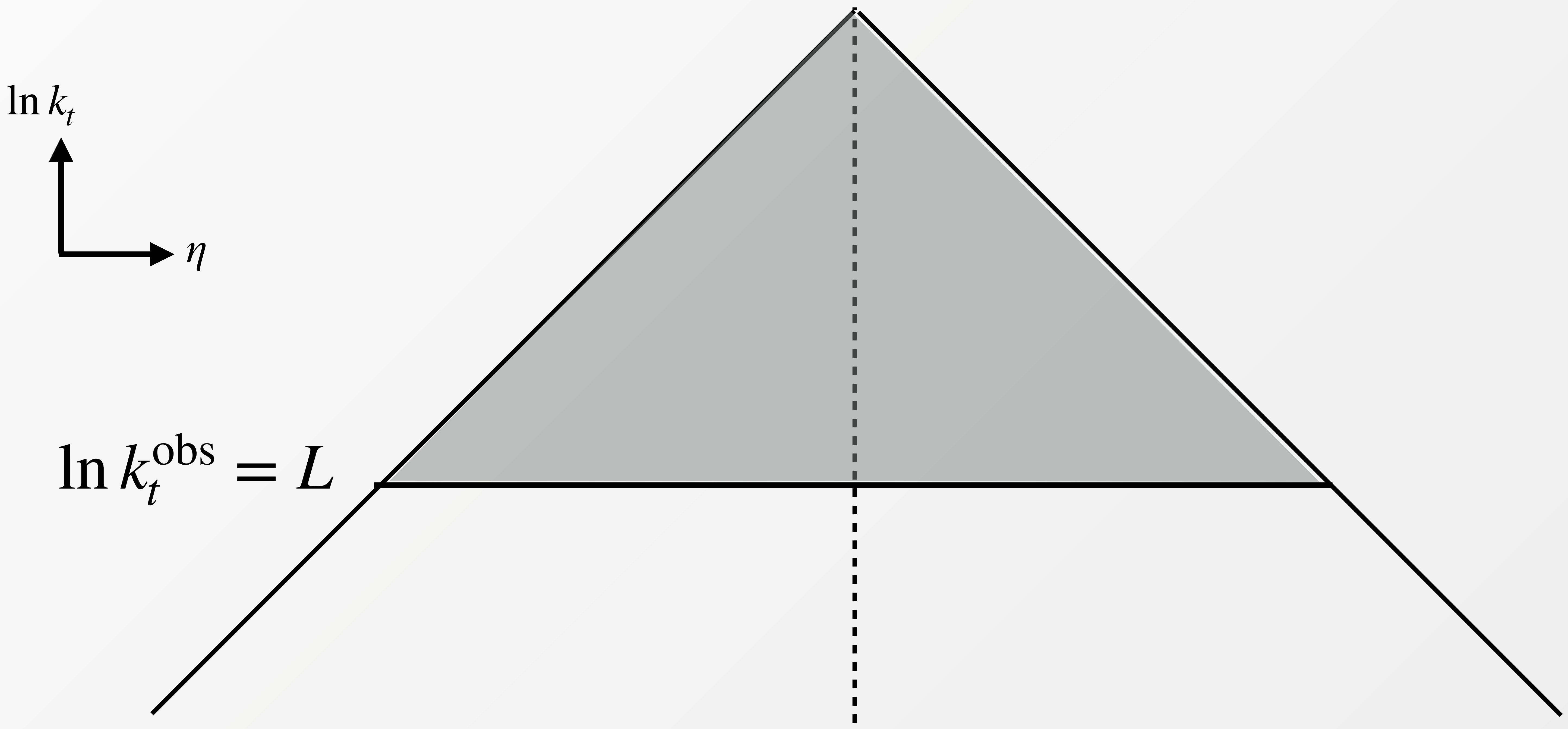


Interplay with the parton shower

Let's assume to be interested in calculating the probability $\Sigma(O < e^L)$ that an observable O is below a given threshold (here $L < 0$).

Let us consider an observable which for a single soft collinear emission scales as

$$O \sim \frac{k_t}{Q}$$

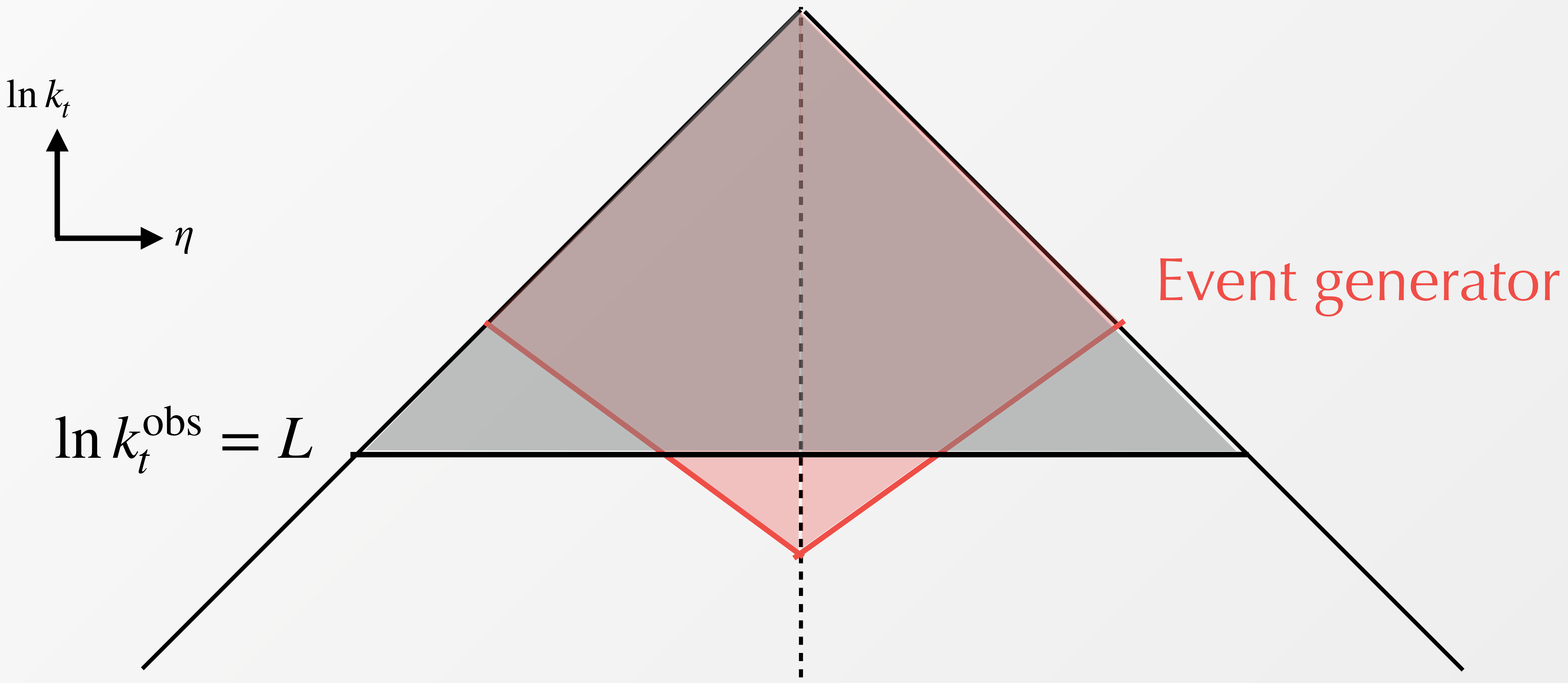


Interplay with the parton shower

The event generator generates the hardest emission with an associated Sudakov suppression factor

Let's assume that the event generator is characterised by an resolution variable scaling as

$$O_{EG} \sim \frac{k_t}{Q} e^{-\beta_{EG}|\eta|}$$

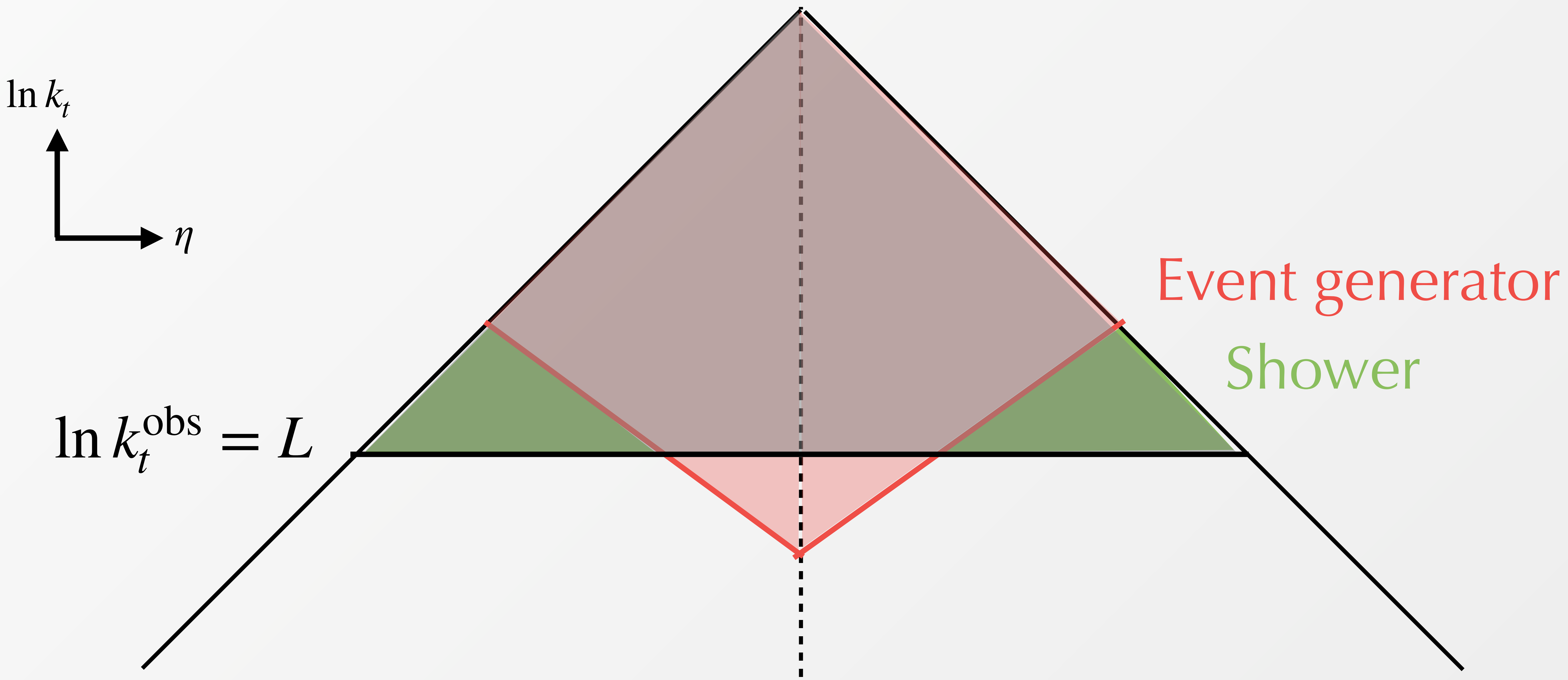


Interplay with the parton shower

The remaining phase space which contributes to the probability $\Sigma(O < e^L)$ is filled by the parton shower

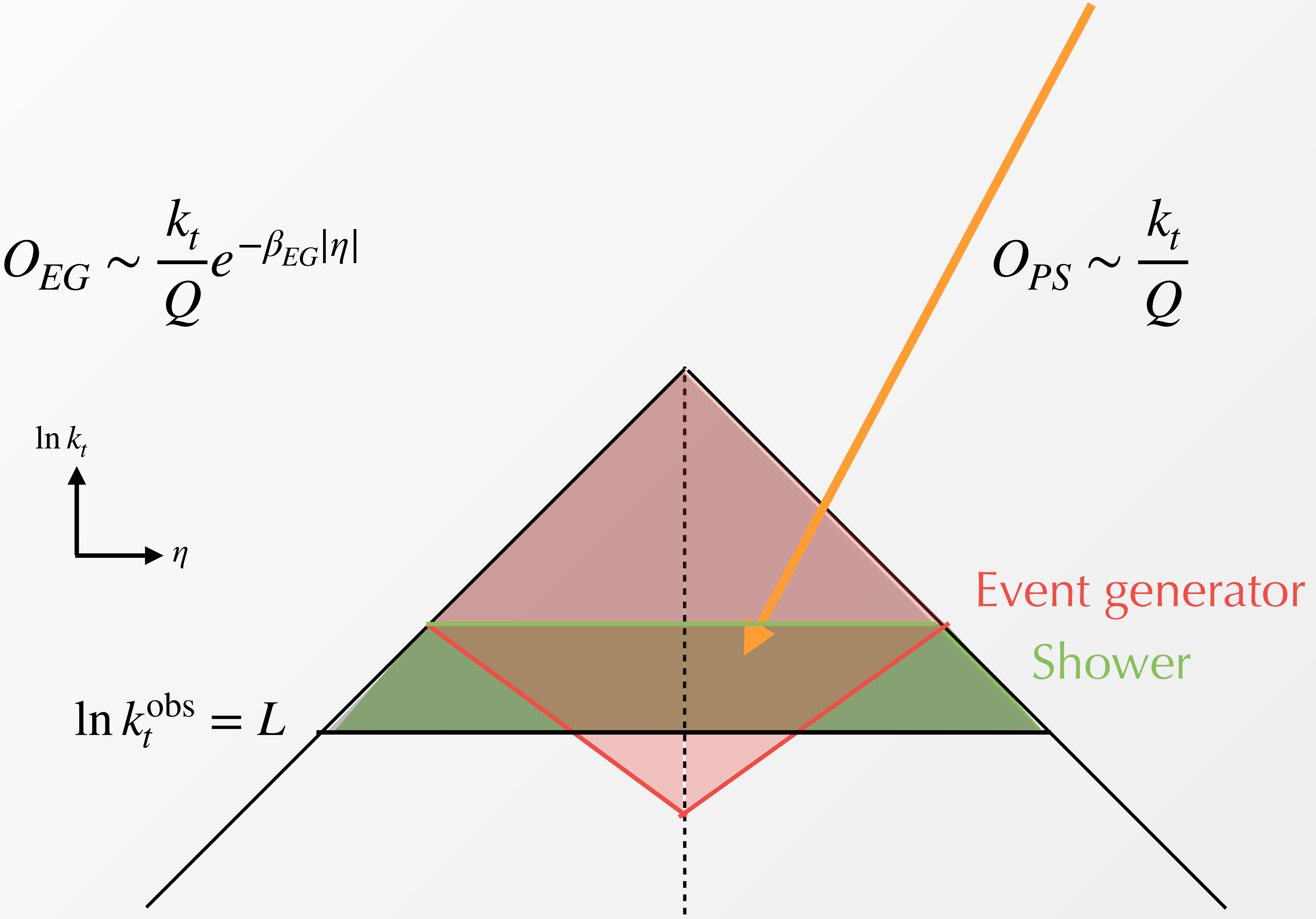
Here we again assume

$$O_{PS} \sim \frac{k_t}{Q} e^{-\beta_{PS}|\eta|}$$



Interplay with the parton shower

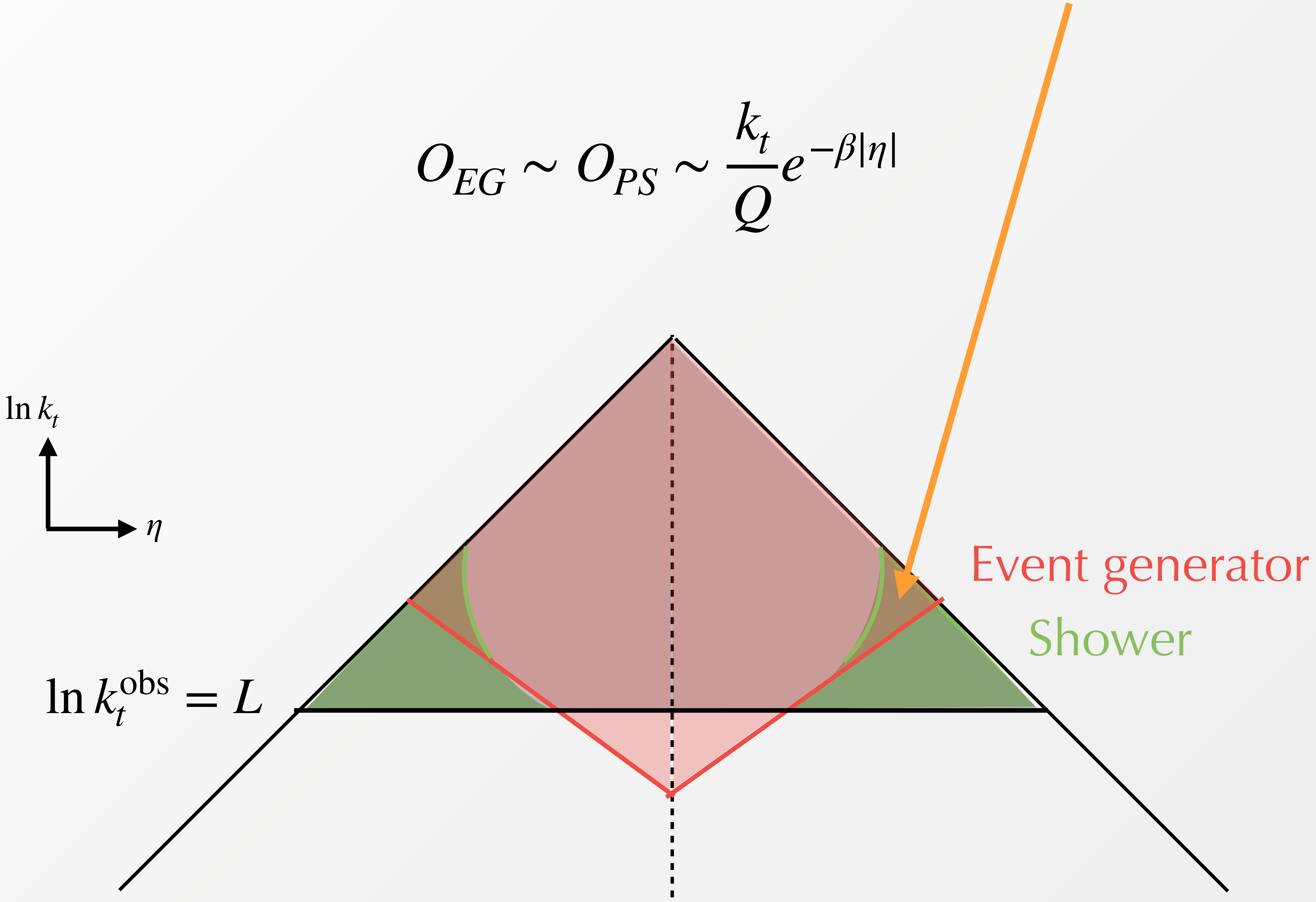
A mismatch between $\beta_{\rm PS}$ and $\beta_{\rm EG}$ breaks LL accuracy due to **double counting**



Interplay with the parton shower

To achieve NLL (and beyond) accuracy after matching, in addition to have $\beta_{PS} = \beta_{EG}$, one must ensure the absence of contour mismatch in e.g. the hard-collinear region

$$O_{EG} \sim O_{PS} \sim \frac{k_t}{Q} e^{-\beta|\eta|}$$



Interplay with the parton shower

At NNLO+PS the picture is more complex since the event generator takes care both of the **first** and **second hardest** emission, with the remaining emissions provided by the PS

- MiNNLO$_{q_T}$ (and GENEVA$_{p_T^{j,1}}$) allow for a **straightforward matching (at LL accuracy)** when (k_t-ordered) shower are employed, thanks to similarities between their resolution variables
- GENEVA$_{\mathcal{T}_0}$ (and GENEVA$_{q_T}$) resort to **truncated-vetoed shower** in the effort to preserve LL accuracy of the parton shower when matching with (k_t-ordered) showers
- MiNNLO$_{\mathcal{T}_0}$ **formally breaks LL accuracy** when matched to PYTHIA, as a change in the POWHEG mapping will be required to treat consistently the second emission

Interplay with the parton shower

Formalisms based on transverse-momentum like observables ($\beta = 0$) are favoured when matching with k_t-ordered showers as they facilitate the matching

Use of showers with a resolution variables with $\beta \neq 0$ (e.g. DEDUCTOR) or angular ordered showers (e.g. HERWIG) would require additional care, **especially beyond LL**

Too many handles in LL accurate parton showers **make formal accuracy not so relevant practically** (predictions for 1-jet obs. can change significantly **simply by acting on the tune**)

These aspects **will become central** when (N)NLL-accurate (and beyond) parton showers for hadron collisions will become publicly available

Phenomenology

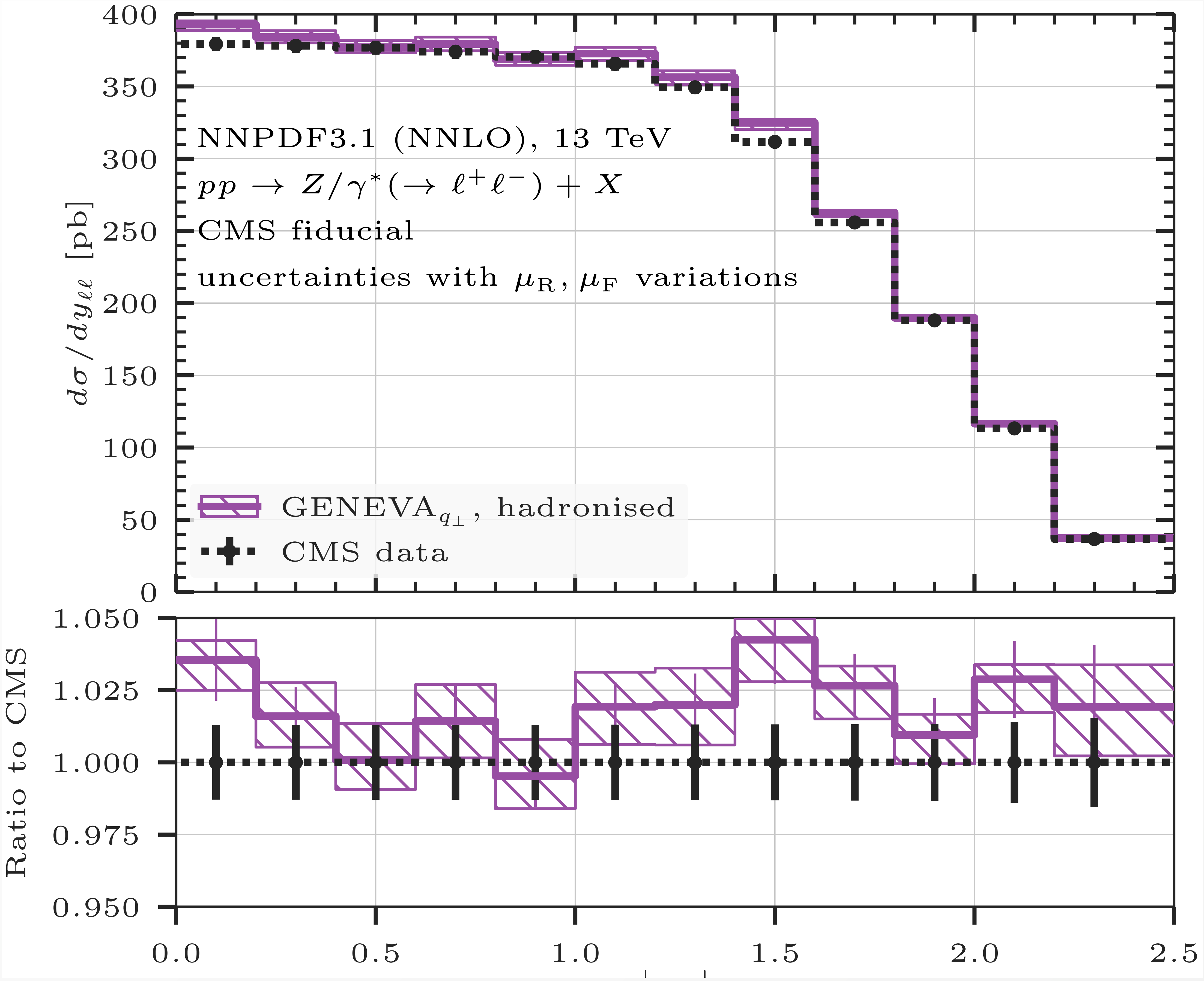
The choice of resolution variables is **in principle immaterial** to reach NNLO accuracy

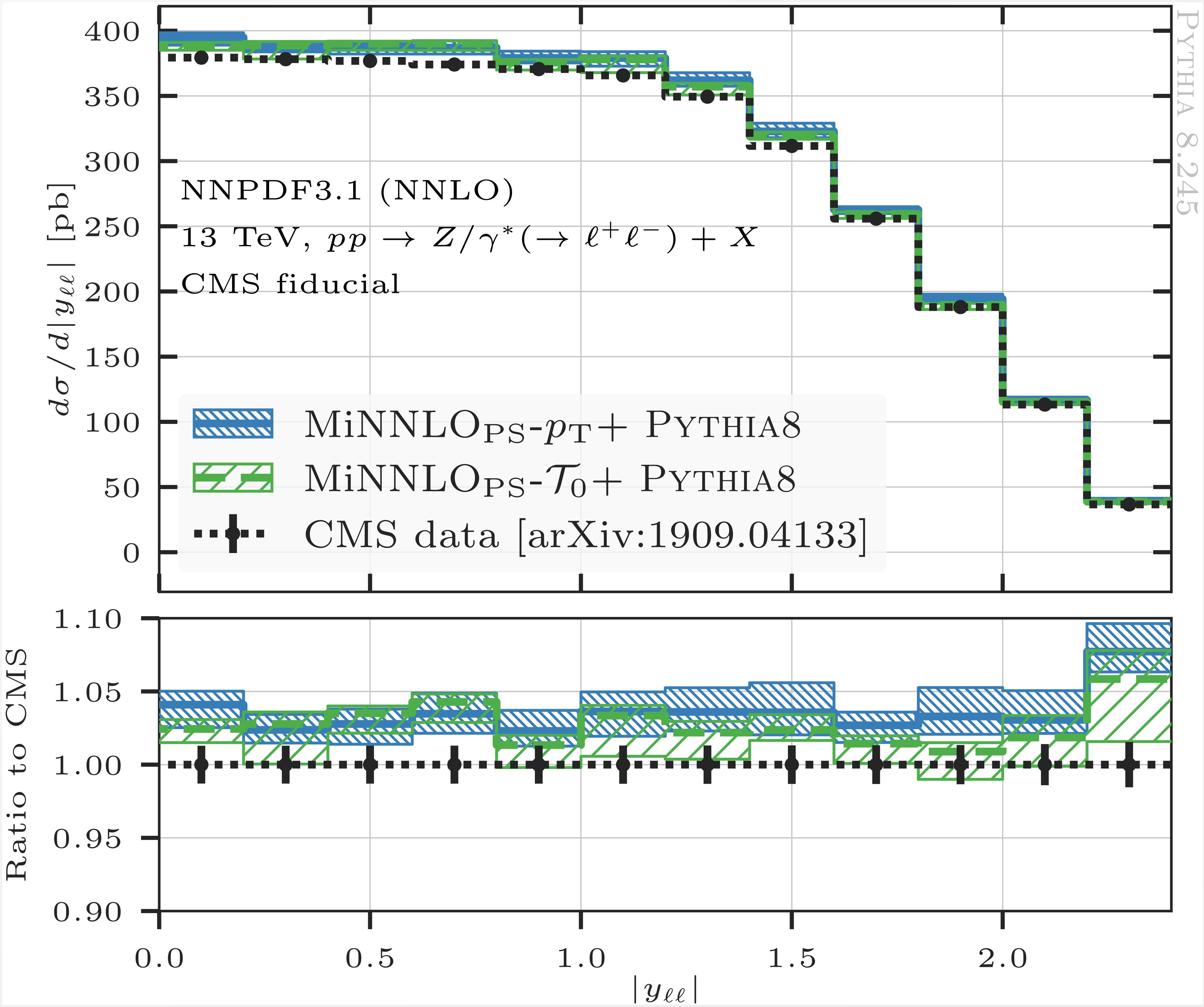
However, its choice has important consequences

- Size of **missing power corrections** **(in the GENEVA method)**
- Ease of **interface with the shower**
- Overall description of **physical events** after matching and showering
- Extension to **more complicated processes**

Phenomenology: NNLO inclusive distributions

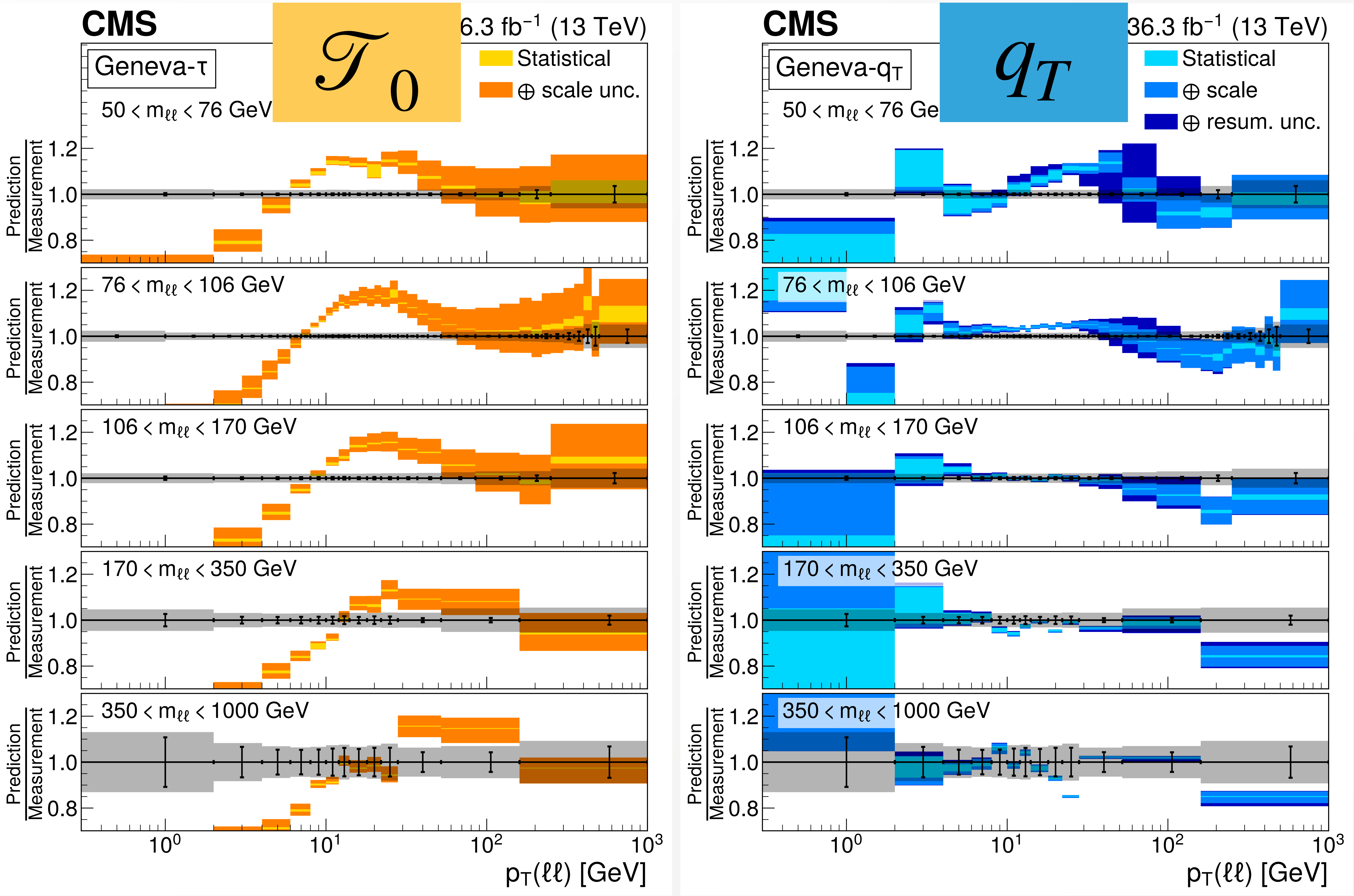
Results for NNLO inclusive observable should be (almost) independent on the resolution variable used





Phenomenology: transverse observables

The situation is instead different for more differential observables, for which the details of the implementation and the **interplay with the parton shower** play an important role

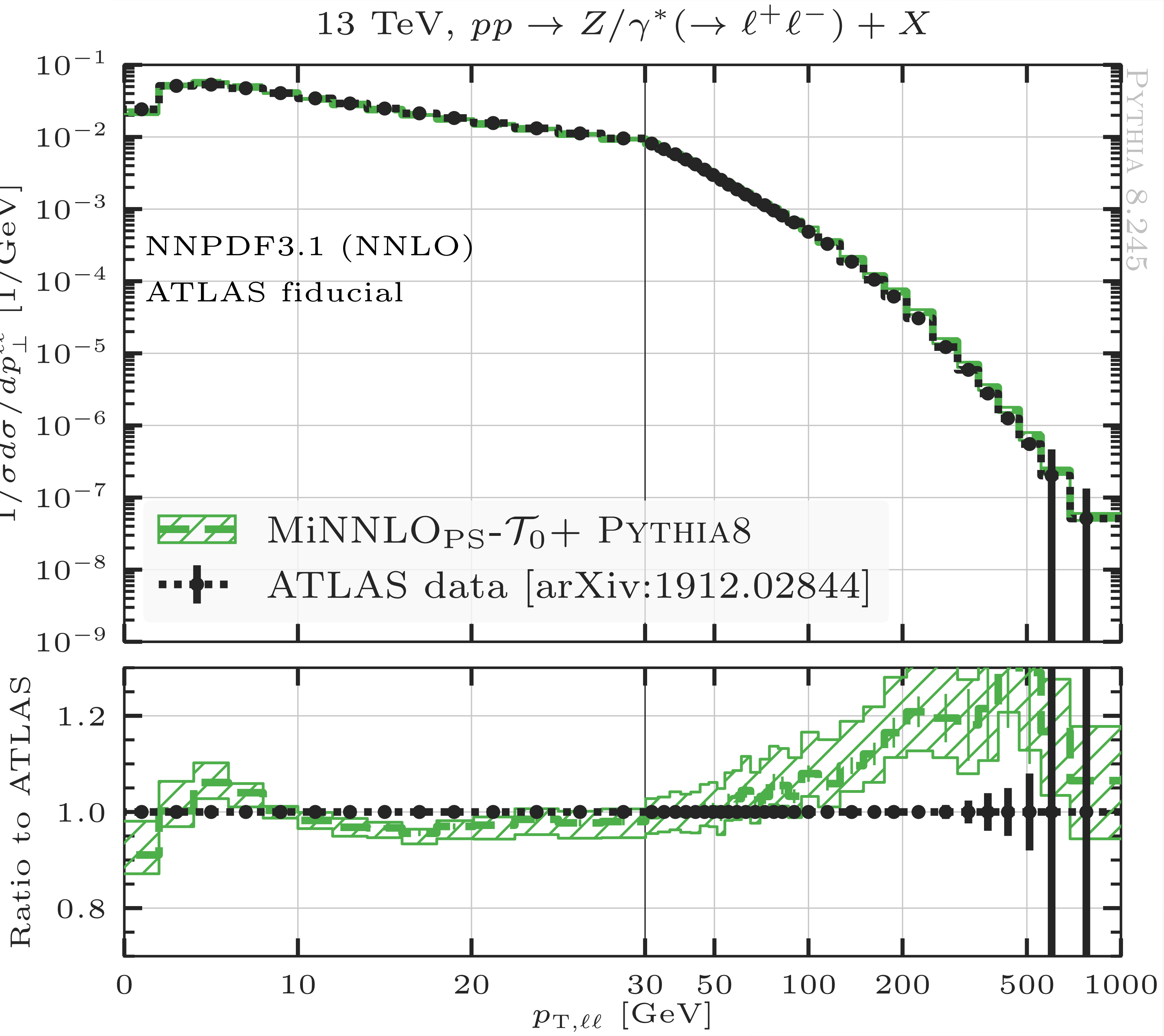


It would be interesting to see how GENEVA-p_T^j performs (e.g. dependence on the jet radius), even more so since it features a different 1-2 jet separation variable

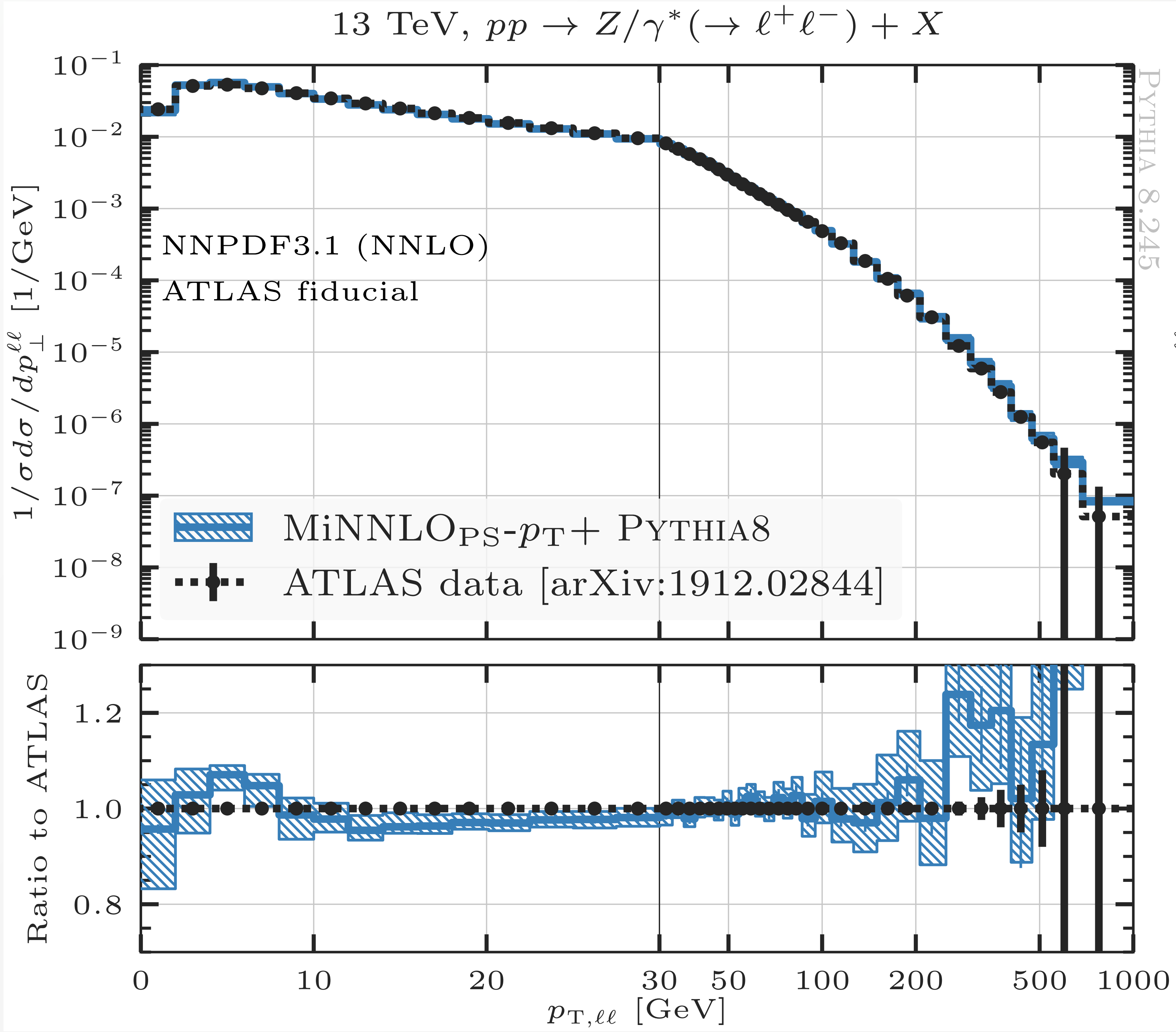
[CMS, 2205.04897]

Phenomenology: transverse observables

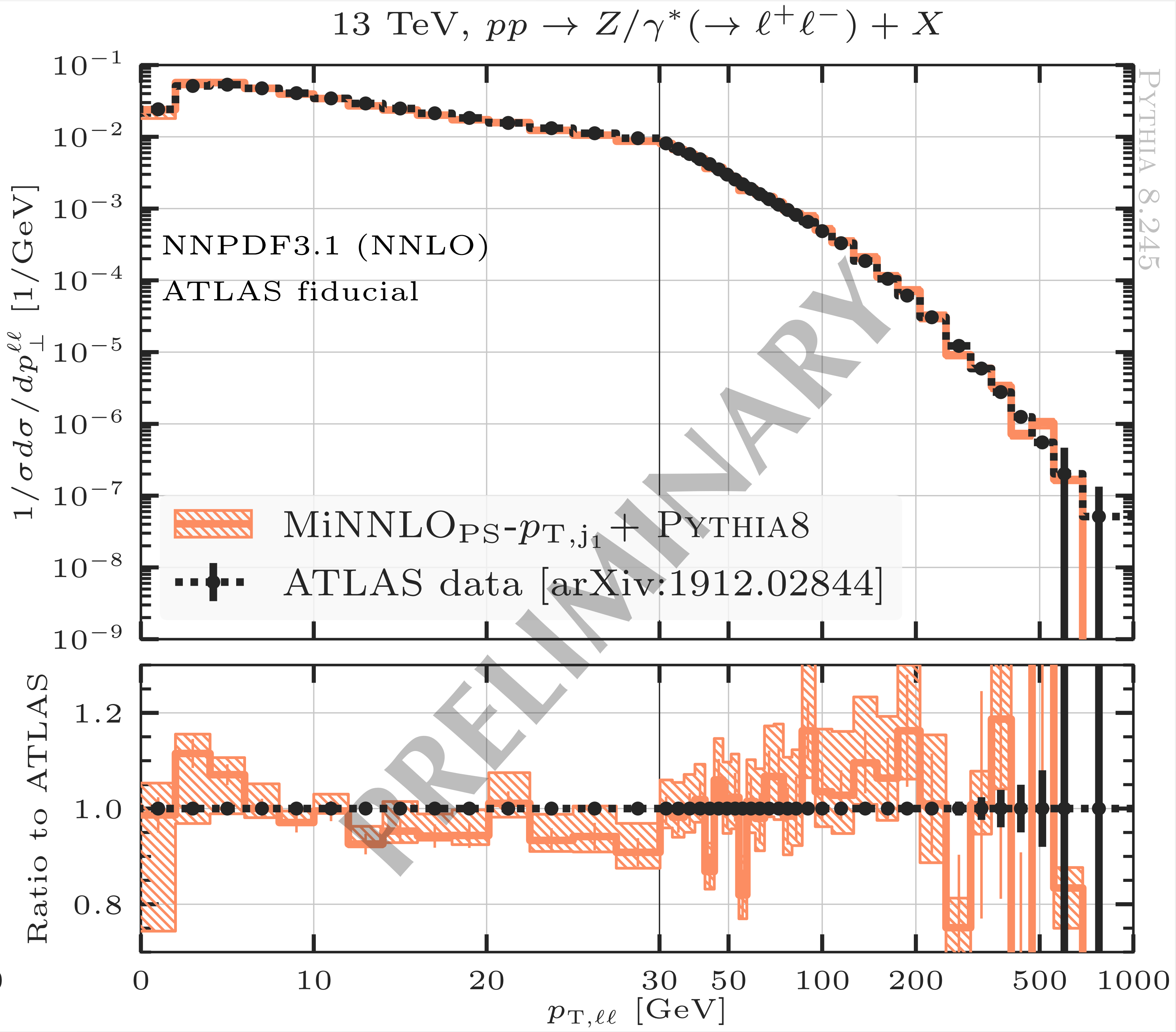
The situation is instead different for more differential observables, for which the details of the implementation and the **interplay with the parton shower** play an important role



$\mathcal{T}_0$



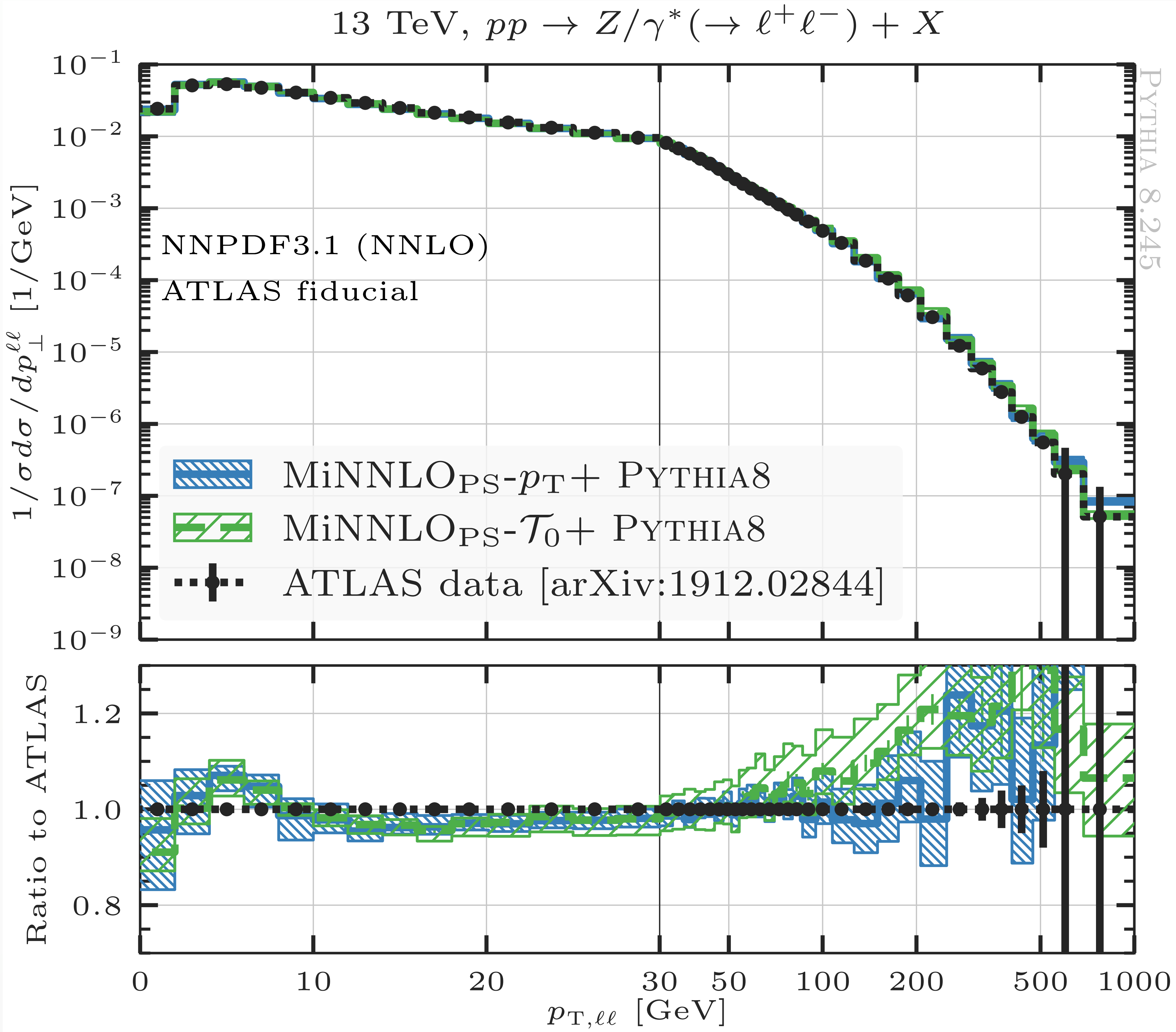
q_T

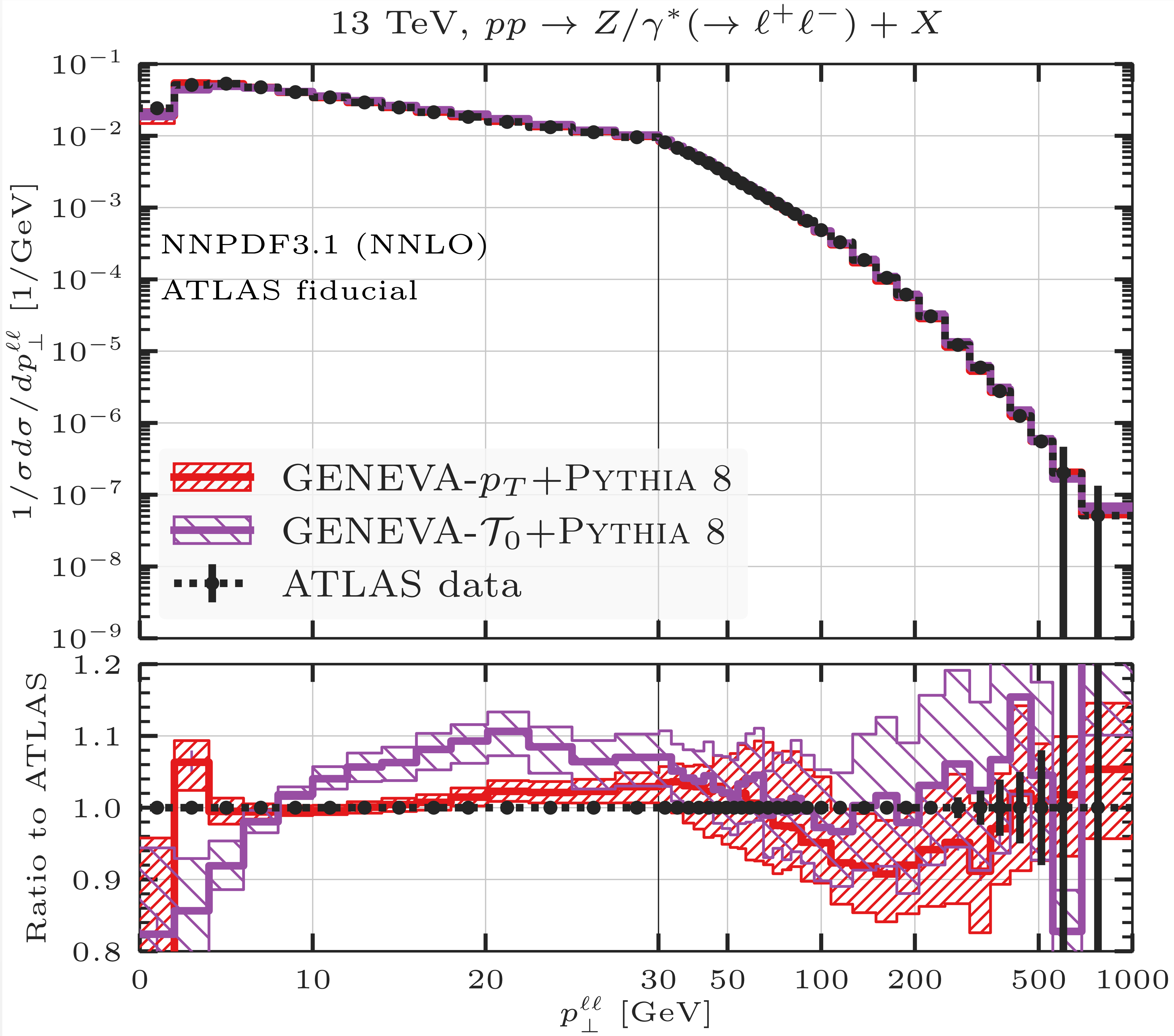


p_T^j

Phenomenology: transverse observables

The situation is instead different for more differential observables, for which the details of the implementation and the **interplay with the parton shower** play an important role

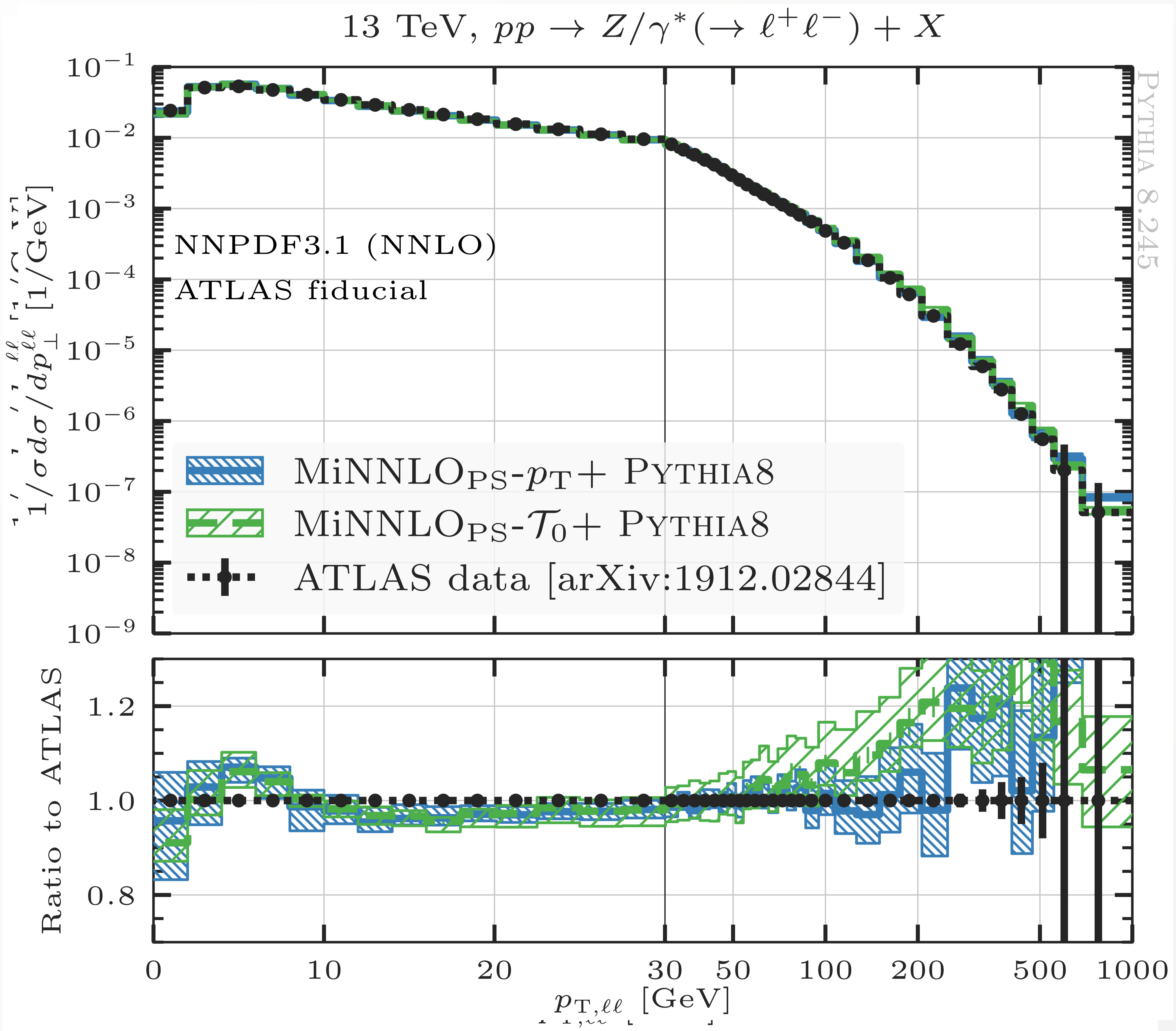


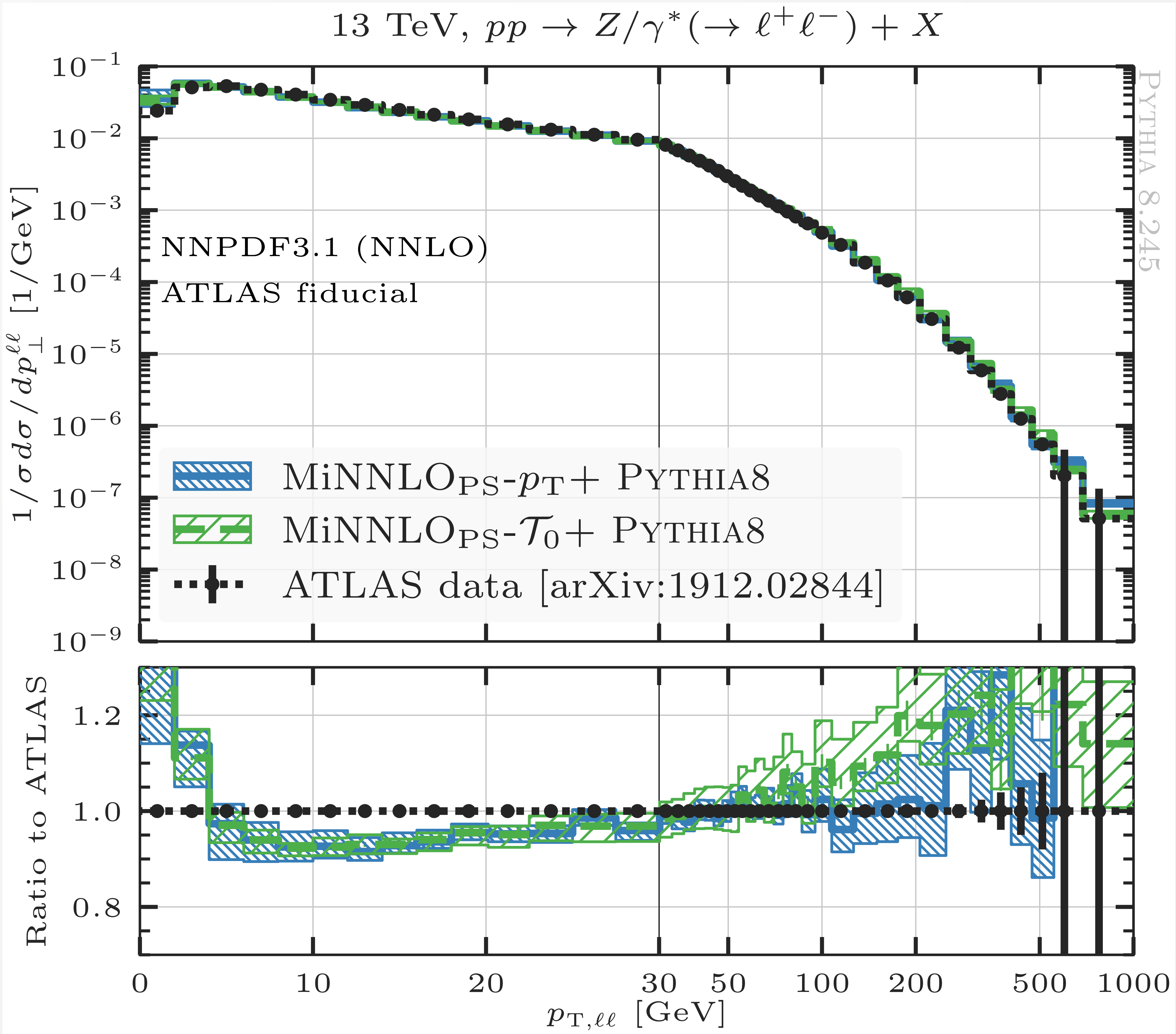


Caveat: different tunes used for GENEVA and MiNNLO

Phenomenology: transverse observables

The situation is instead different for more differential observables, for which the details of the implementation and the **interplay with the parton shower** play an important role



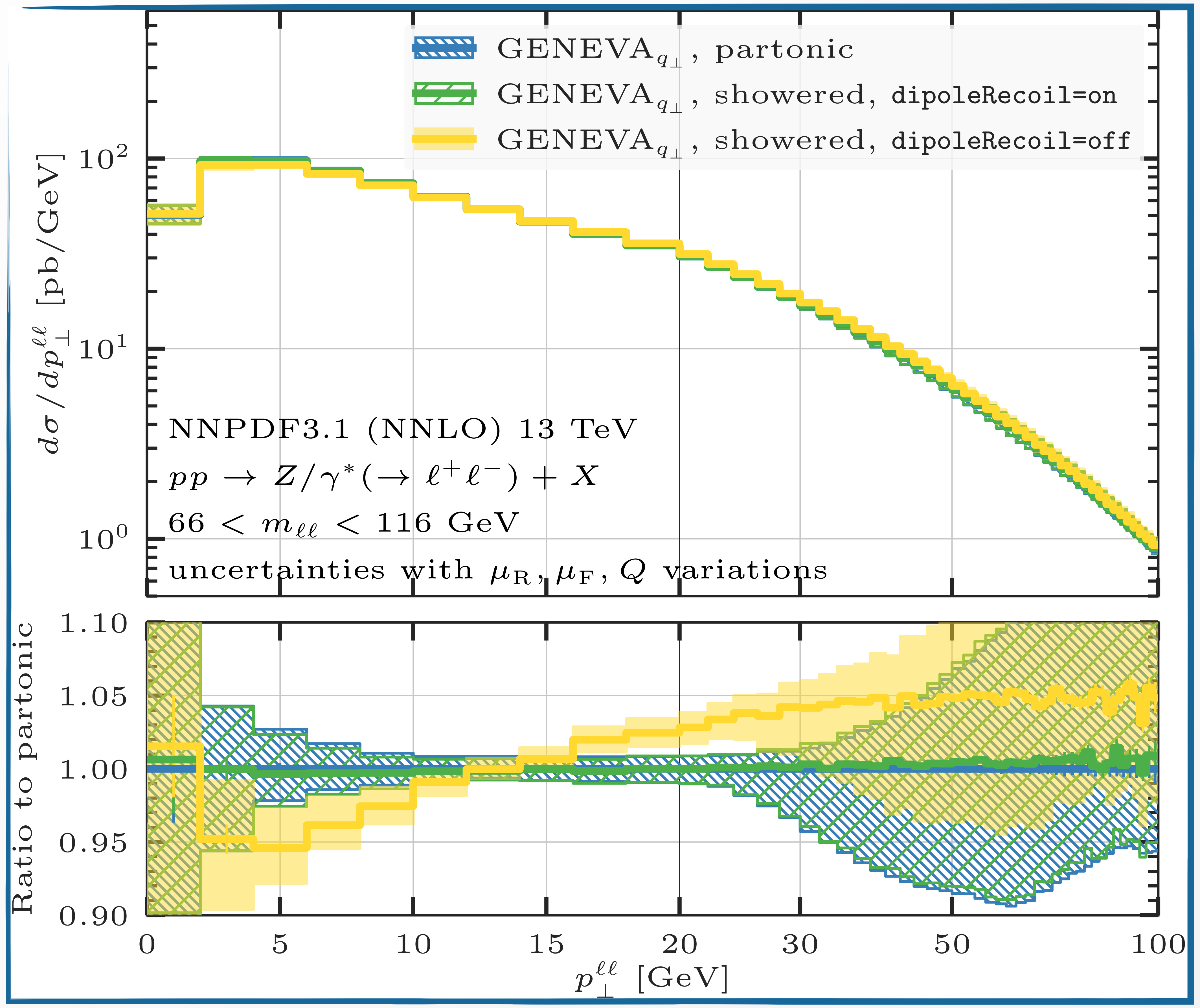


NNLO$_{PS}$-optimised CMS tune

MonashStar tune

Phenomenology: transverse observables

Analogue dependence on tune settings was observed in GENEVA



Non-negligible dependence on the recoil scheme of the shower, which can affect the transverse momentum spectrum at the few percent level (**besides affecting shower accuracy**)

Tunes obtained by comparing LO predictions to data are bound to **absorb higher order corrections into the tune parameters**

Phenomenology: transverse observables

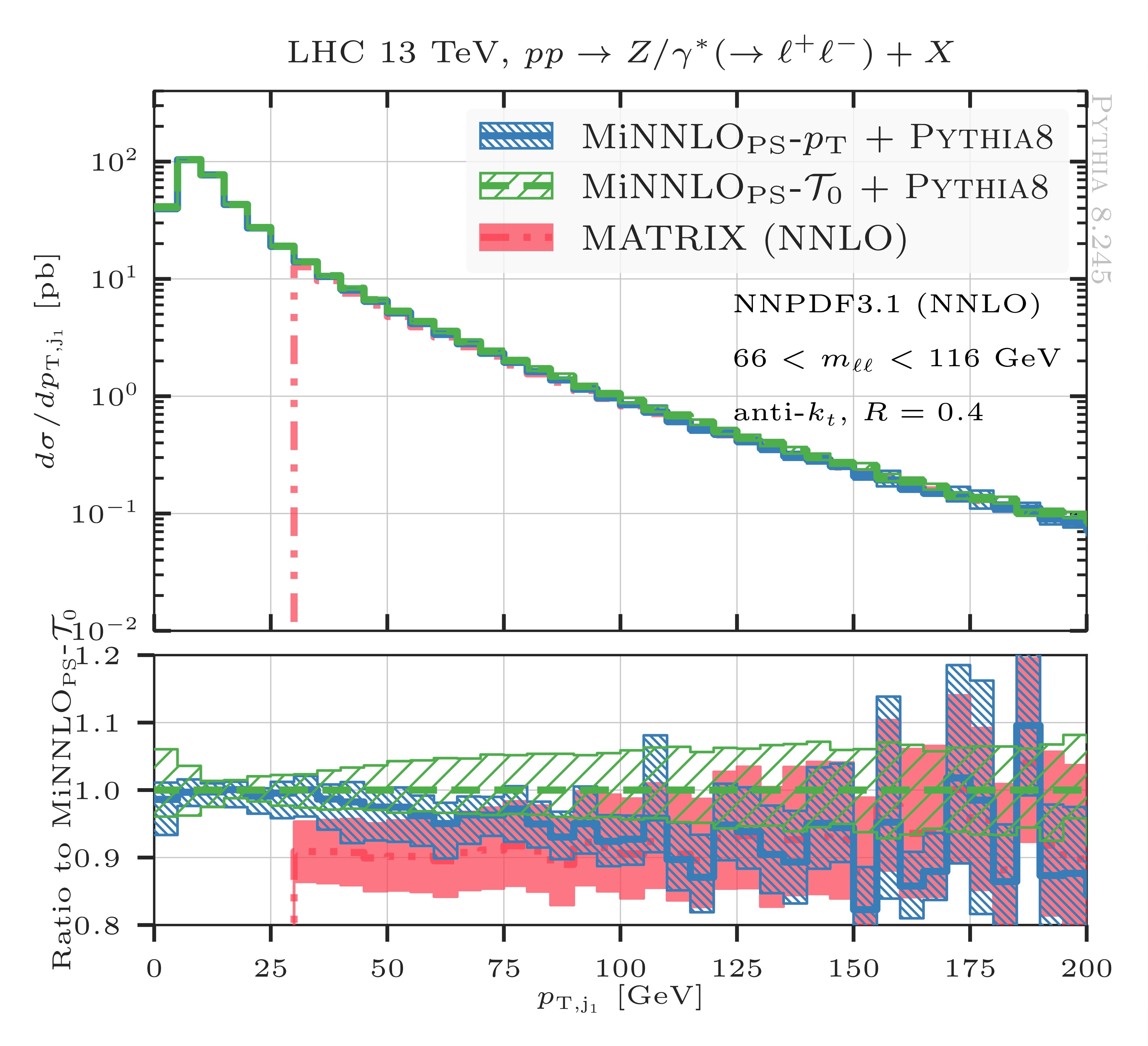
Although formally equivalent (and NLO accurate), the description of observables in the 1-jet phase space is also affected by the details of the implementation

With what accuracy the different formalisms resume **Sudakov shoulder** logs?

Phenomenology: transverse observables

Although formally equivalent (and NLO accurate), the description of observables in the 1-jet phase space is also affected by the details of the implementation

These differences are partially driven by how the (**formally higher order**) corrections re-distributed in the V+j phase space



$$\cdots + \left(D(p_T) - D^{(1)}(p_T) - D^{(2)}(p_T)\right) \times \mathscr{P}(\Phi_{FJ})$$

$$\cdots + \left(D(\mathcal{T}_0) - D^{(1)}(\mathcal{T}_0) - D^{(2)}(\mathcal{T}_0)\right) \times \mathscr{P}(\Phi_{FJ})$$

Choice of the resolution parameter (2)

The choice of resolution variables is **in principle immaterial** to reach NNLO accuracy

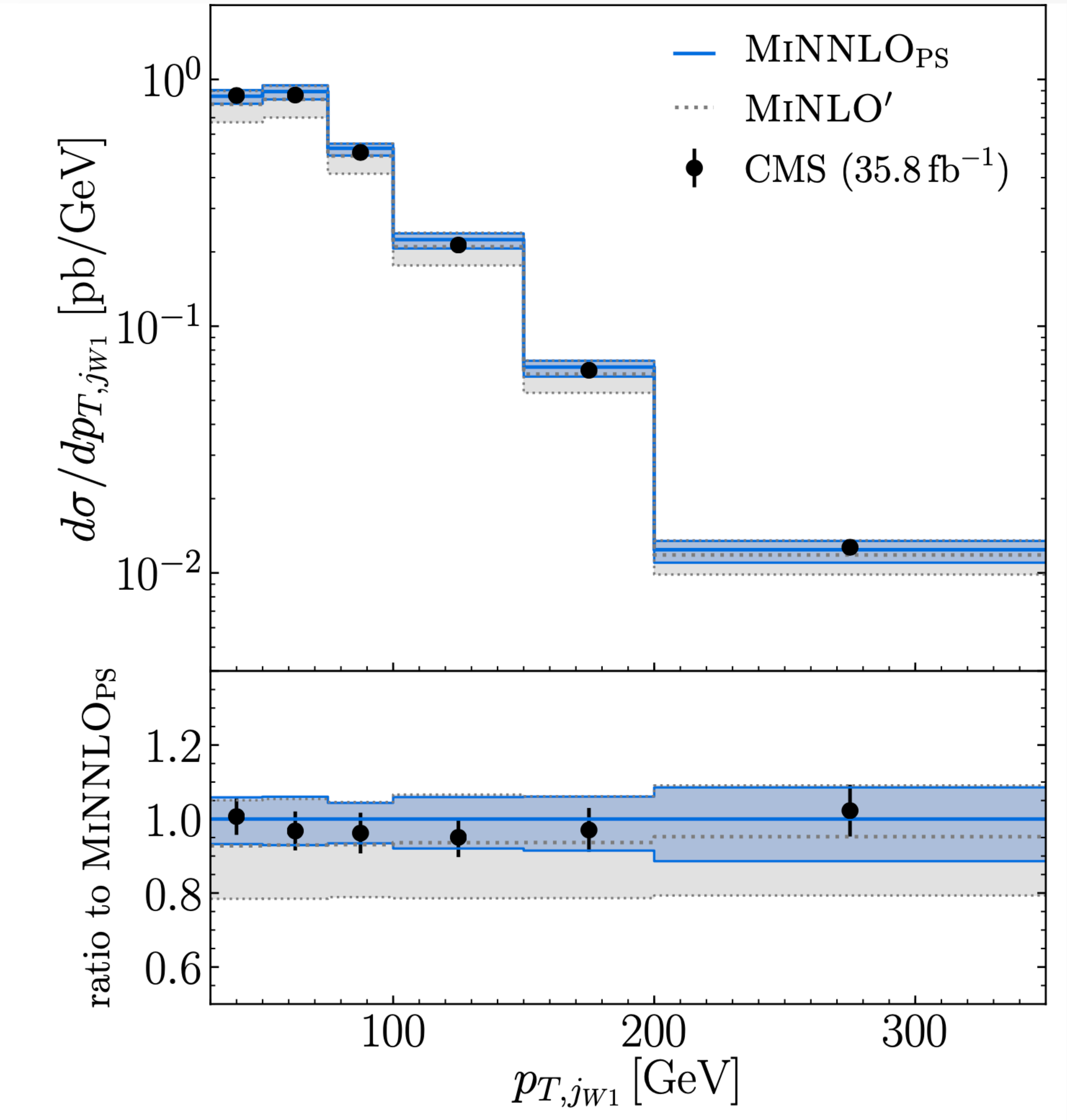
However, its choice has important consequences

- Size of **missing power corrections (in the GENEVA method)**
- Ease of **interface with the shower**
- Overall description of **physical events** after matching and showering
- Extension to **more complicated processes**

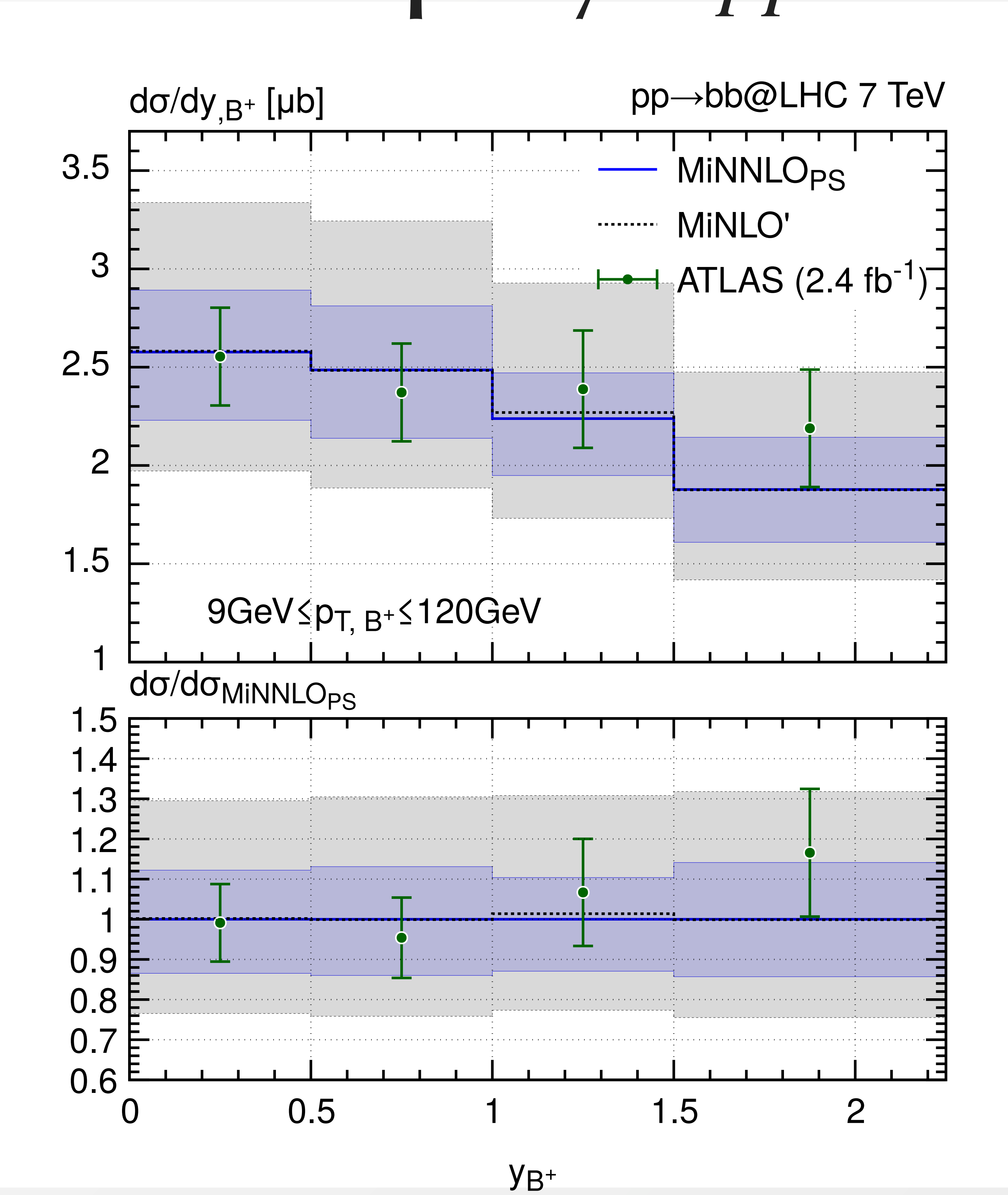
Towards complexity

MiNNLO$_{PS}$ has been extended to processes such at $Q\bar{Q}$ thanks to the availability of q_T resummation for heavy quark pair production (+ F)

p_T of hadronic W decay's jet in $t\bar{t}$



B^+ meson rapidity in $pp \to b\bar{b}$

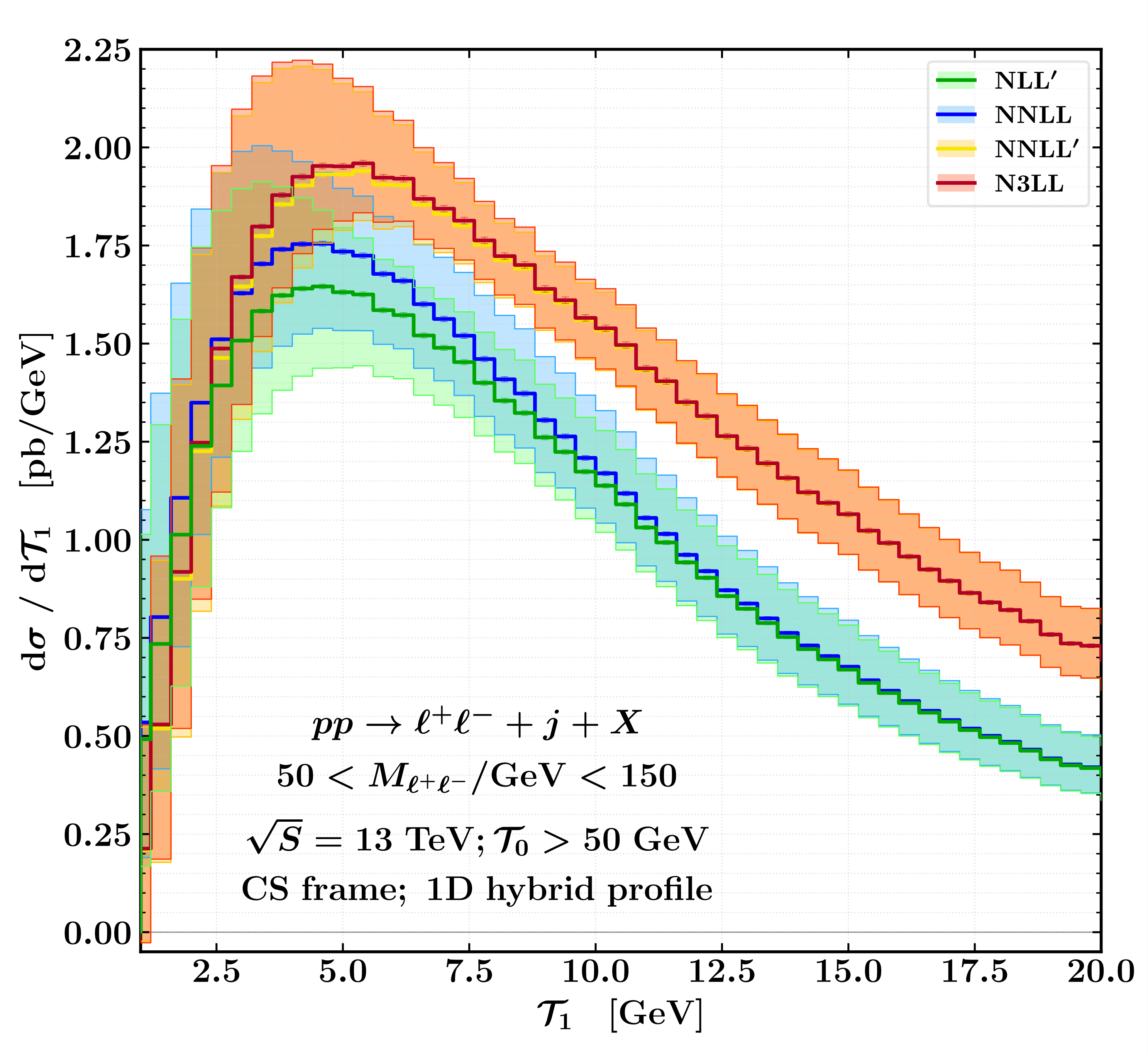


[Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '21][Mazzitelli, Ratti, Wiesemann, Zanderighi '23]

Towards complexity

On the other hand, jettiness is currently the only variable whose ingredients are known to reach **NNLO accuracy for *F+j* processes**

NNLO+PS for *F+j* using 1-jettiness appear to be viable both within GENEVA and within MiNNLOPS frameworks (albeit it will come with some limitations as discussed)



[Alioli et al, ’23]

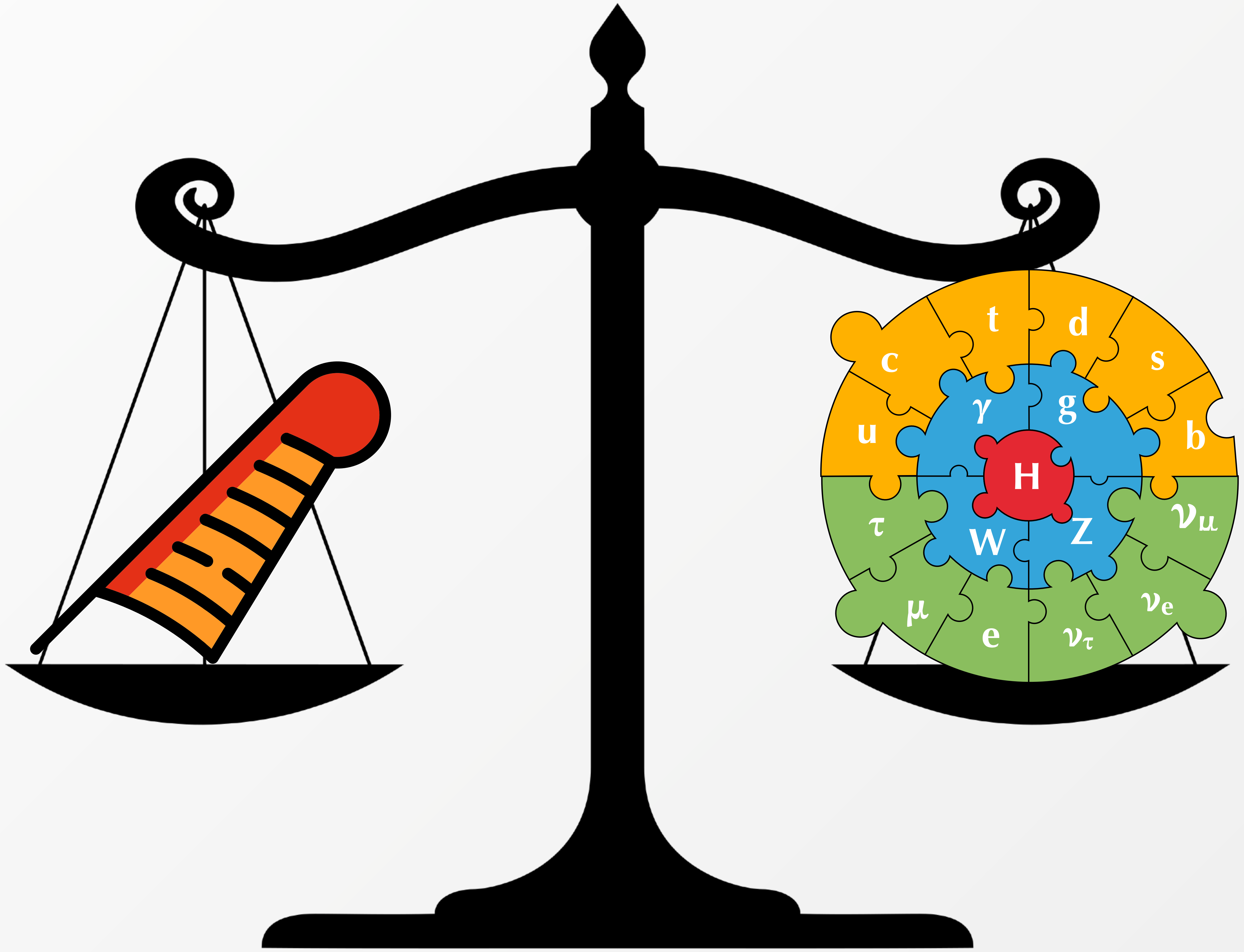
$$\frac{d\sigma^{\rm sing}(\mathcal{T}^{\rm cut})}{d\Phi_{\rm FJ}} = \sum_\kappa \tilde{\mathcal{L}}_\kappa(\mathcal{T}^{\rm cut}) e^{-\mathcal{S}_\kappa(\mathcal{T}^{\rm cut})}\,.$$

[Ebert, LR, Wiesemann, Zanderighi, Zanoli ’23]

Availability of NNLL′ ingredients for a transverse-like observable for jet processes would allow for an (appealing?) **alternative to *N*-jettiness**

Conclusion and open questions

- A new generation of tools with **higher formal accuracy** are being developed, led by the advancement in the understanding of perturbative QCD
- Comparisons between different formalisms and alternative resolution variables lead to **challenging open questions** regarding the reliability of **current uncertainties** at NNLO+PS level, even for 'simple' candle processes such as Drell-Yan (how about the Higgs?)
- Will these differences persists when matching with parton showers with higher logarithmic accuracy?
- Essential to delve deeper into the methods and understand better our tools if we aim to establish NNLO+PS matching as a **novel standard of precision** for LHC processes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