# Resummation of transverse observables with RadISH

**Luca Rottoli**

University of Zurich[UZH]

*Based on Bizon, Monni, Re, LR, Torrielli '17 - present*

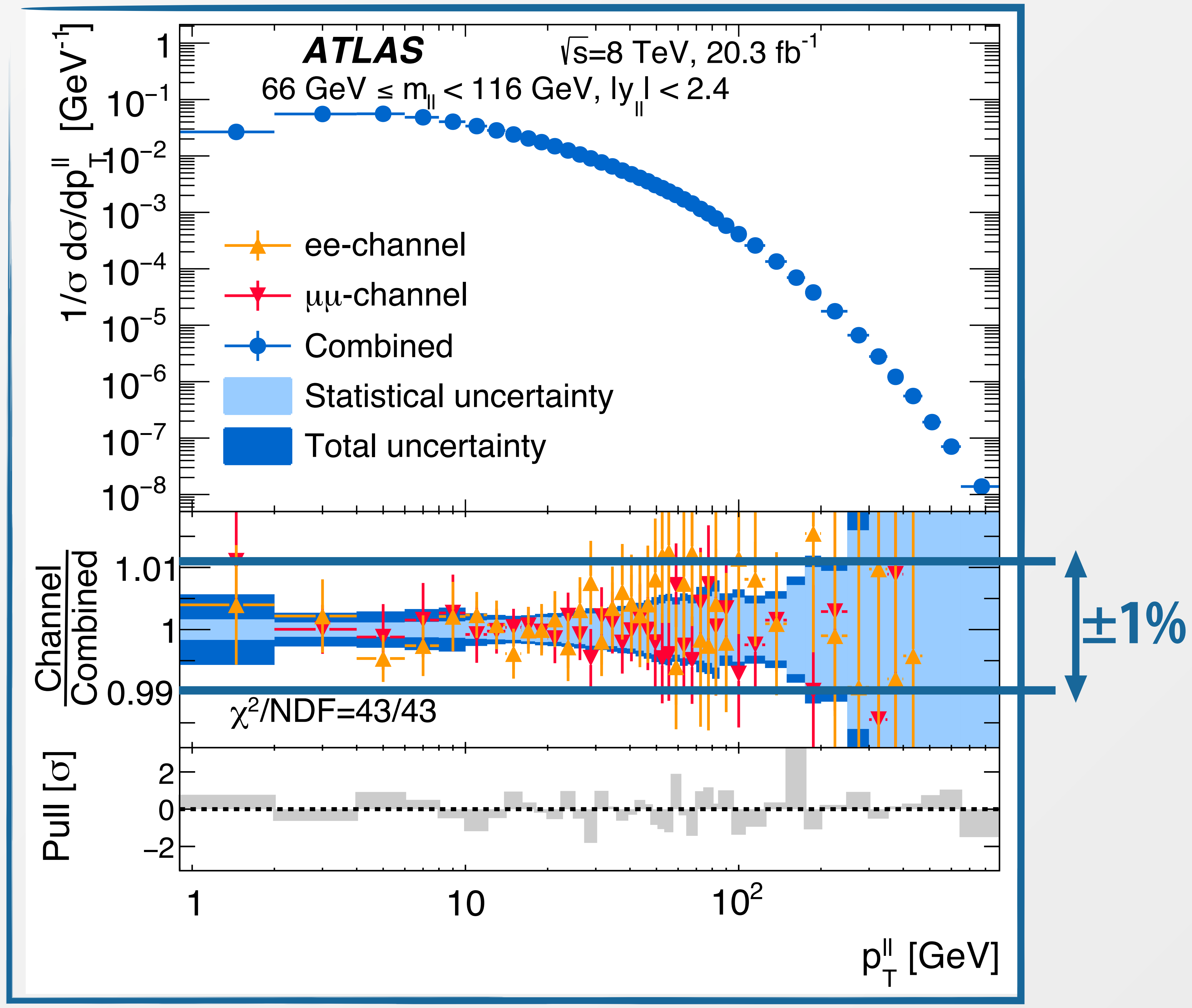
# The quest for precision

Transverse observables (i.e. observables which do not depend on the rapidity of the radiation) are a **clean experimental and theoretical environment** for precision physics

**Inclusive observables** (e.g. transverse momentum $p_t$) probe directly the kinematics of the colour singlet

$$V(k_1, \dots k_n) = V(k_1 + \dots + k_n)$$

- negligible or no sensitivity to multi-parton interactions
- reduced sensitivity to non-perturbative effects
- measured **extremely precisely at experiments**, challenging current theoretical predictions

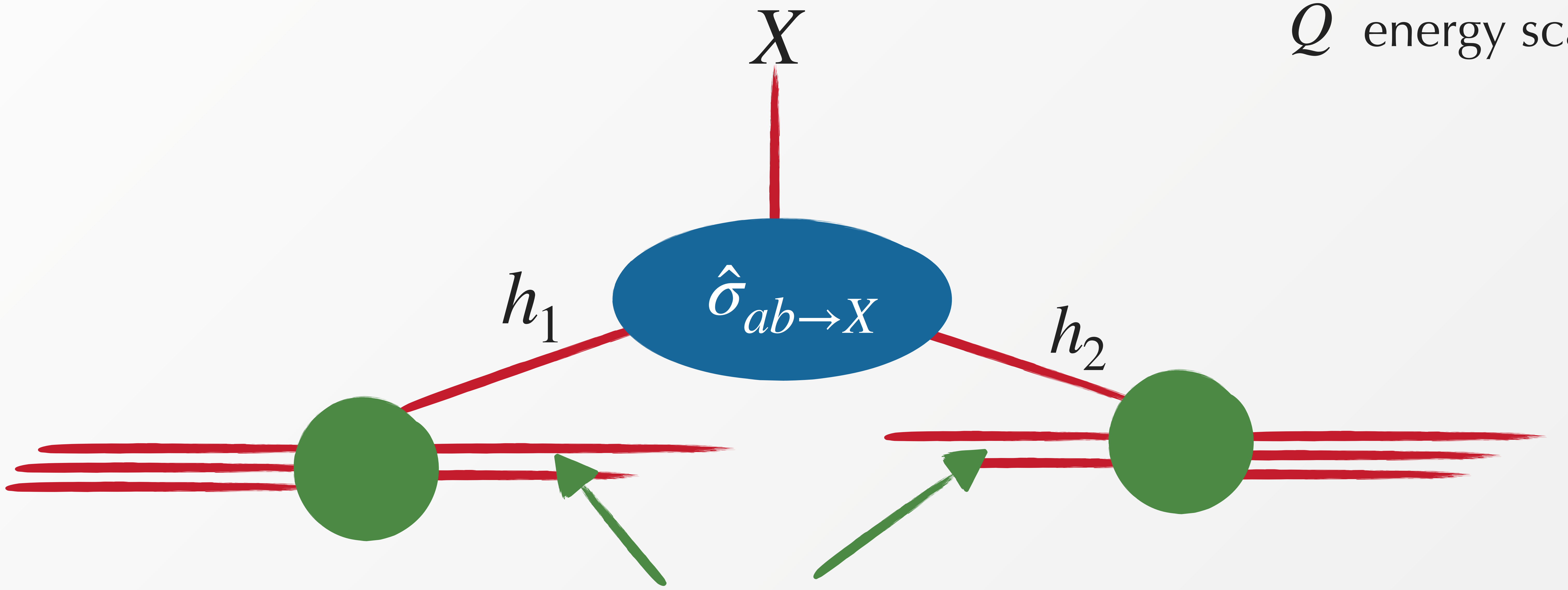



Important implications for extraction of SM parameters (strong coupling and PDF determination, ***W* mass measurements**…)

# Precision physics at the LHC: theory

Key concept: **collinear factorization**

$\sqrt{s}$ centre-of-mass energy
$Q$ energy scale of the process




$$\sigma(s,Q^2) = \sum_{a,b} \int dx_1 dx_2\, f_{a/h_1}(x_1,Q^2) f_{b/h_2}(x_2,Q^2)\, \hat{\sigma}_{ab\to X}(Q^2, x_1x_2s) + \mathcal{O}(\Lambda^p_{\mathrm{QCD}}/Q^p)$$

**Parton Distribution Functions (PDFs)**

Long-distance, non-perturbative, universal objects

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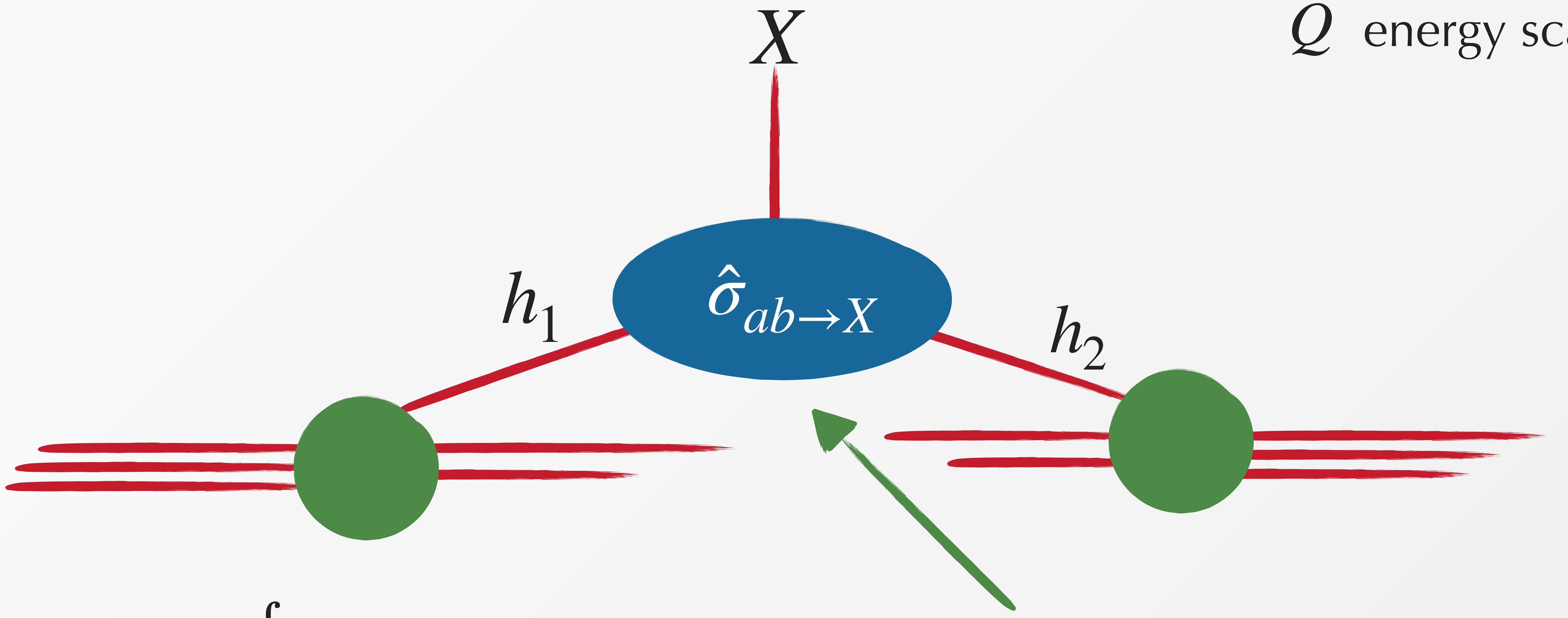


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**Hard-scattering matrix element**

Short-distance, perturbative, process-dependent

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Input parameters:

**strong coupling** $\alpha_s$

**PDFs** $f$

few percent uncertainty; improvable

**Non-perturbative effects**

percent effect; not yet under control

# Precision physics at the LHC: theory

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$$\tilde{\sigma} = 1 + \alpha_s \tilde{\sigma}_1 + \alpha_s^2 \tilde{\sigma}_2 + \alpha_s^3 \tilde{\sigma}_3 + \dots$$

**LO** **NLO** **NNLO** **N$^3$LO**

$\alpha_s \sim 0.1$

δ~10-20% **NLO**

δ~1-5% **NNLO** (or even N$^3$LO)

**NLO** now standard and largely automated

**NNLO** available for an increasing number of processes

**N$^3$LO** available for few hadron-collider processes (Higgs production in gluon fusion and VBF, DY production…)

# QCD beyond fixed order

Perturbative QCD at fixed order

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**LO NLO NNLO N$^3$LO**

**Assumption:** perturbative coefficients $\tilde{\sigma}_n$ are well behaved

Many observables studied at the LHC depend on more than one scale; **single** or **double** logs of the ratio of those scales at all orders in perturbation theory

$$(\alpha_s \ln R)^n \qquad (\alpha_s \ln^2 R)^n$$

If the logarithms are large the convergence of the series is spoiled

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Fixed order predictions no longer reliable:
**all order resummation** of the perturbative series mandatory

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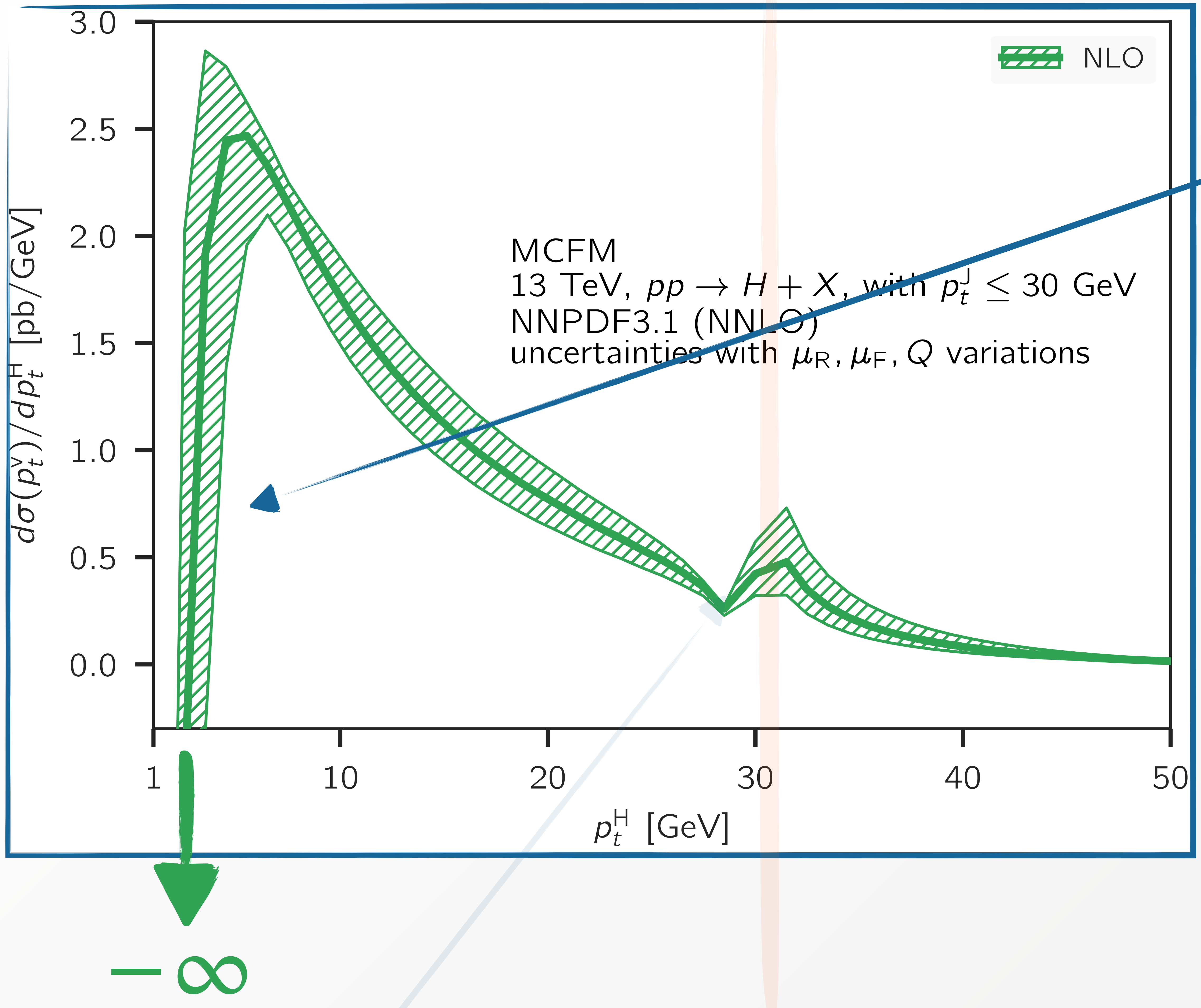
# Example: Higgs transverse momentum with a jet veto




Large **transverse momentum** logarithms

$$L = \ln(p_\perp^H / m_H) \qquad p_\perp^H \ll m_H$$

Large(ish) **jet veto** logarithms

$$L = \ln(p_\perp^{J,v} / m_H) \qquad p_\perp^{J,v} \ll m_H$$




Jet veto = 30 GeV

Integrable double logarithms at the shoulder for $p_\perp^{J,v} \sim p_\perp^H$

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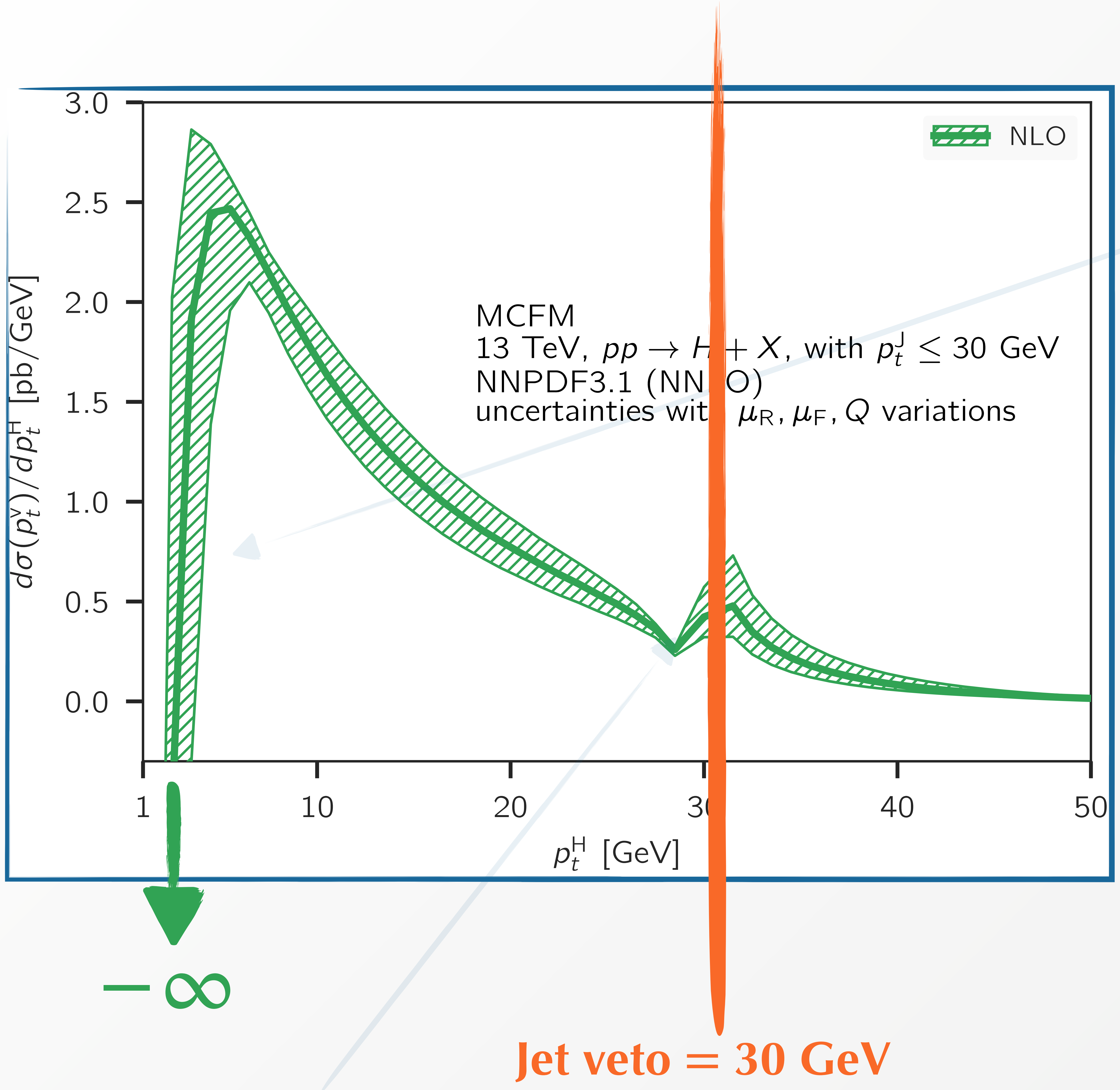


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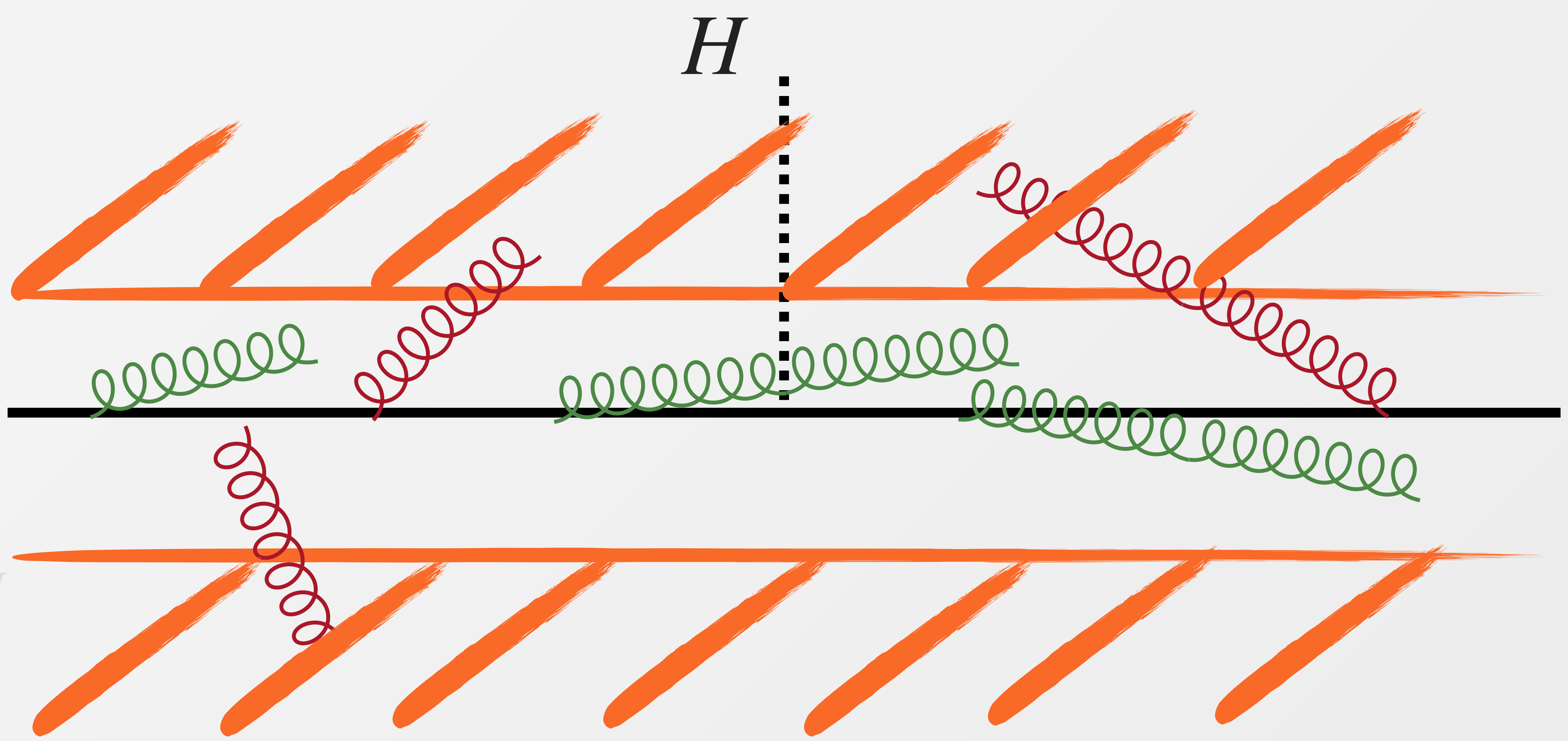


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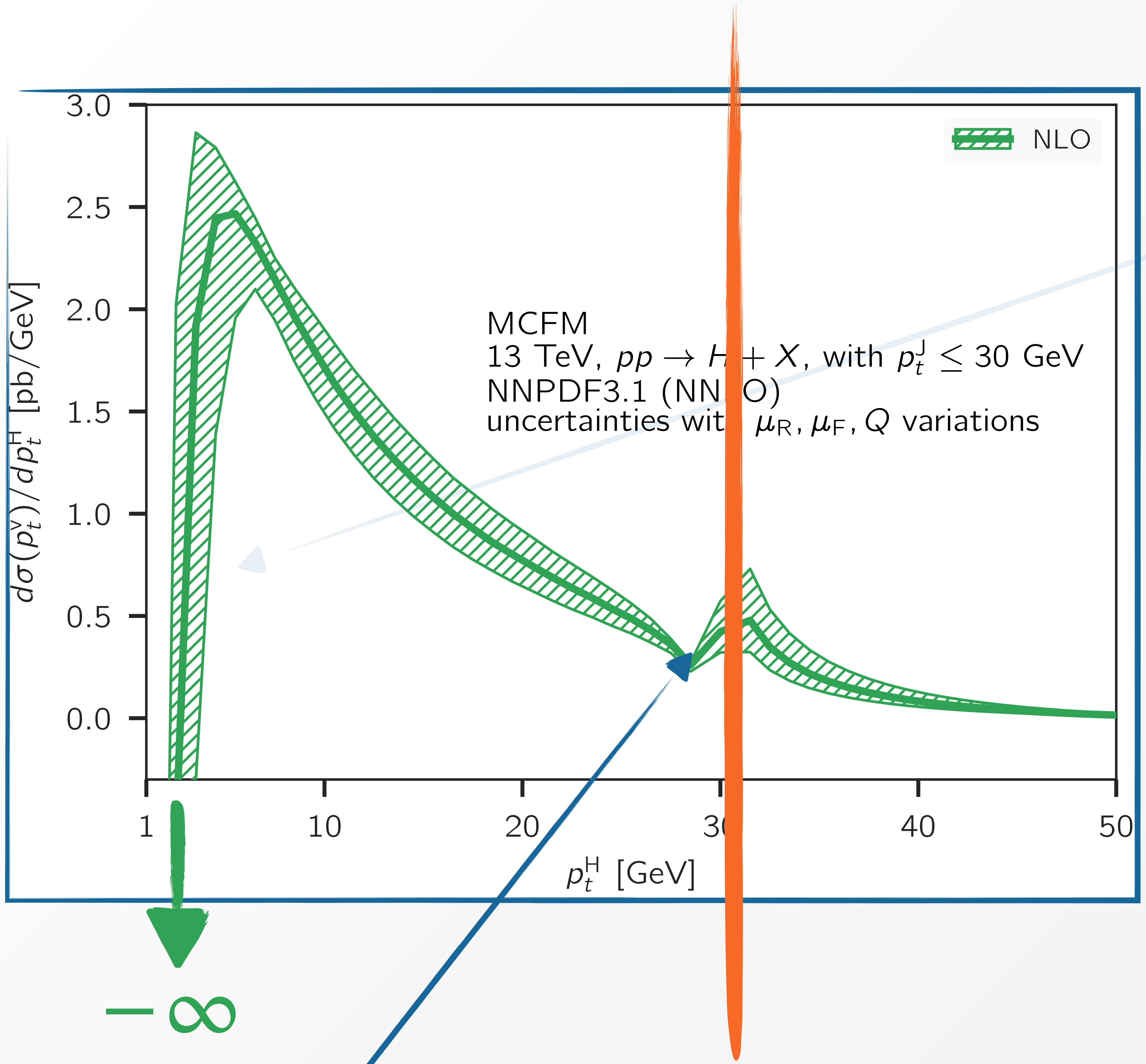


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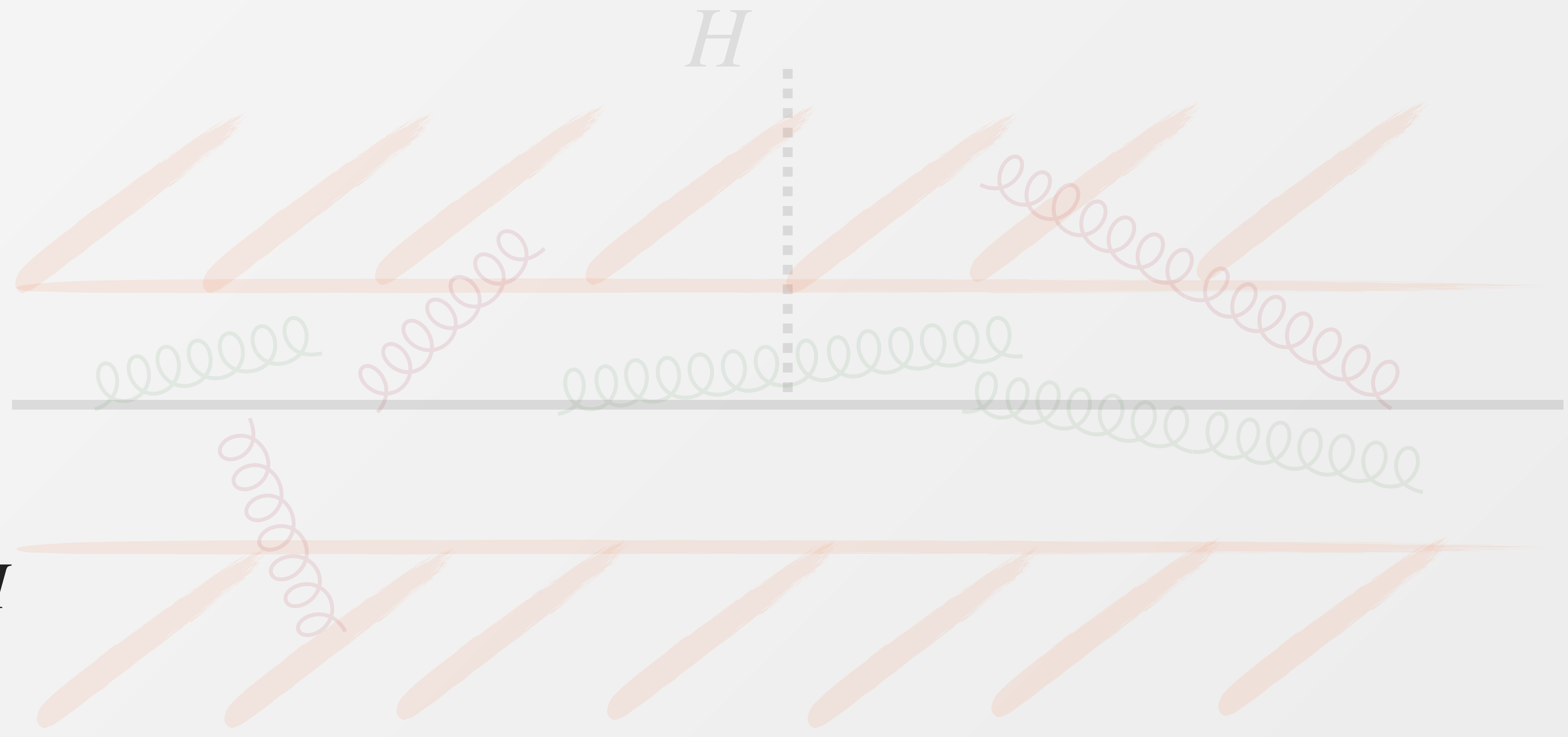


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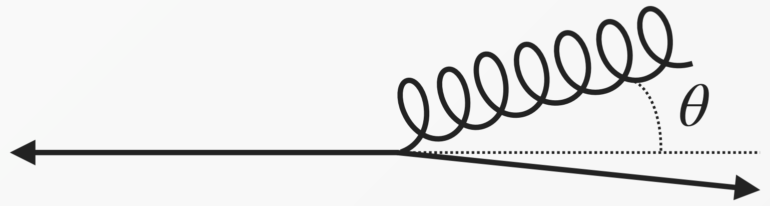
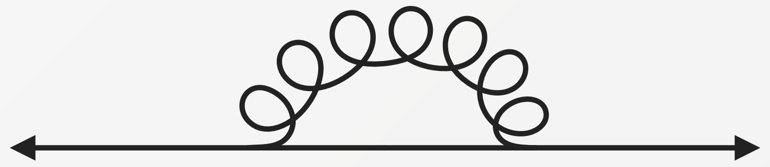
# It's not a bug, it's a feature

Real emission diagrams singular for **soft/collinear emission**. Singularities are cancelled by virtual counterparts for IRC safe observables

Consider processes where real radiation is **constrained** in a corner of the phase space, (exclusive boundary of the phase space, **restrictive cuts**)

$$\tilde{\sigma}_1(p_\perp) \sim \underbrace{\int \frac{d\theta}{\theta}\frac{dE}{E}\Theta\left(p_\perp - E\theta\right)} - \underbrace{\int \frac{d\theta}{\theta}\frac{dE}{E}}$$



$$\sim \quad -\int \frac{dE}{E}\frac{d\theta}{\theta}\Theta(E\theta - p_\perp)$$

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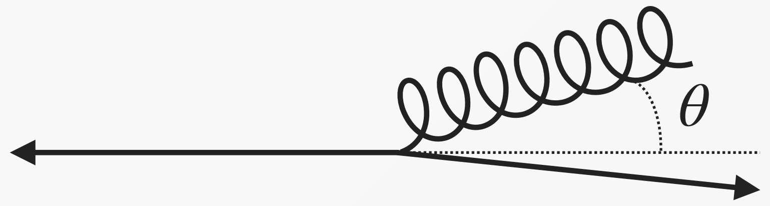
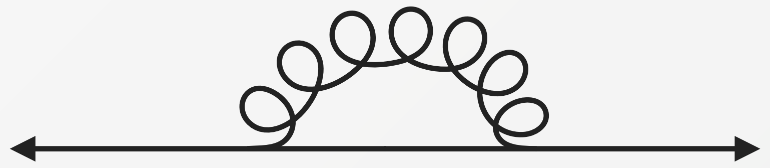


$p_\perp \to 0$: observable can become negative even in the perturbative regime

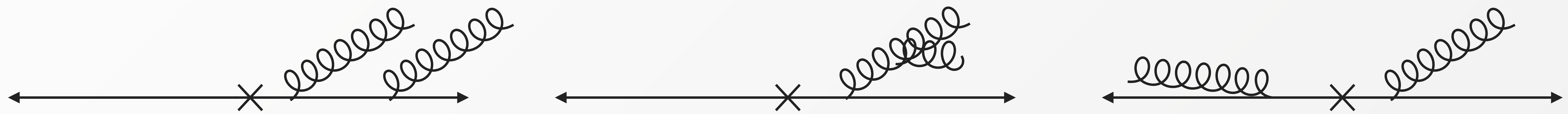
$$\sim -\int \frac{dE}{E}\frac{d\theta}{\theta}\Theta(E\theta - p_\perp) \sim -\frac{1}{2}\ln^2 p_\perp/m_H$$

**Sudakov logarithms**

**Double** logarithms **leftovers** of the real-virtual cancellation of IRC divergences

# Making pQCD great again: all-order resummation

Soft-collinear emission of two gluons



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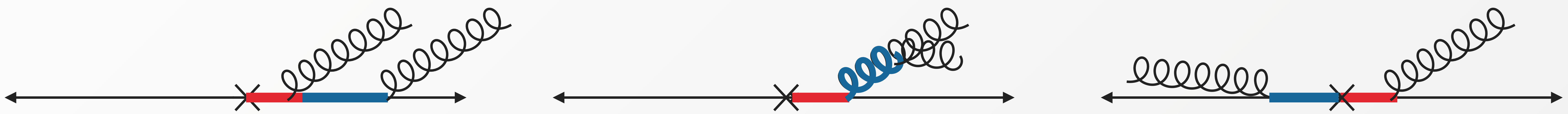

Two propagators nearly on shell, 4 divergences. Diagrams can potentially give $\alpha_s^2 \ln^4 p_\perp/m_H$

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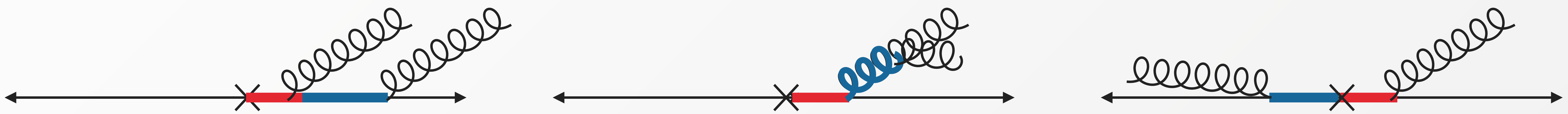

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**All order** structure

$$\tilde{\sigma}(v) = \sum_{n=0}^{\infty} \alpha_s^n \sum_{m=1}^{2n} c_{nm} L^m + \ldots \qquad L = \ln(p_\perp/m_H)$$

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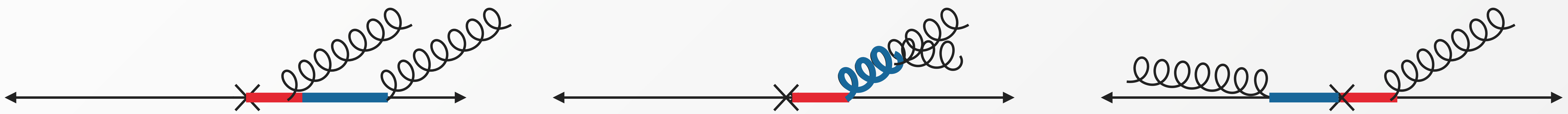

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Origin of the logs is simple. Resum them to all orders by **reorganizing** the series

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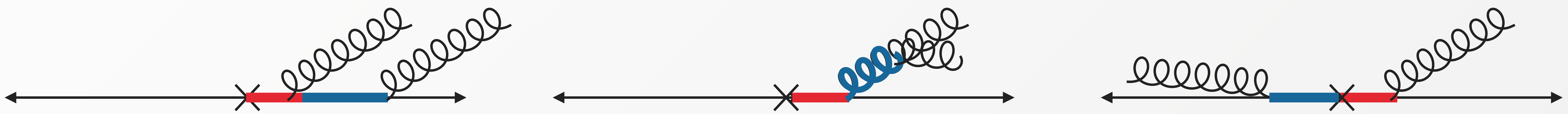

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**Poor man's leading logarithmic (LL) resummation** of the perturbative series

Accurate for $L \sim 1/\sqrt{\alpha_s}$

# Making pQCD great again: all-order resummation

$$\tilde{\sigma}(v) = f_1(\alpha_s L^2) + \frac{1}{L} f_2(\alpha_s L^2) + \ldots$$


**È la somma che fa il totale*

# All-order resummation: exponentiation

Independent emissions $k_1, \dots k_n$ (plus corresponding virtual contributions) in the soft and collinear limit with strong angular ordering

$$d\Phi_n \, |\mathscr{M}(k_1, \dots k_n)|^2 \to \frac{1}{n!} \alpha_s^n \prod_{i=1}^{n} \frac{dE_i}{E_i} \frac{d\theta_i}{\theta_i}$$

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Calculate observable with arbitrary number of emissions: **exponentiation**

$$\tilde{\sigma} \simeq \sum_{n=0}^{\infty} \frac{1}{n!}\alpha_s^n \prod_{i=1}^{n} \int \frac{dE_i}{E_i}\frac{d\theta_i}{\theta_i}[\Theta(p_\perp - E_i\theta_i) - 1] \simeq e^{-\alpha_s L^2}$$

**Sudakov suppression** [Sudakov '54]
Price for constraining real radiation

Exponentiated form allows for a **more powerful reorganization**

$$\tilde{\sigma} = \exp\left[\sum_n \left(\underbrace{\mathcal{O}(\alpha_s^n L^{n+1})}_{\textbf{LL}} + \underbrace{\mathcal{O}(\alpha_s^n L^n)}_{\textbf{NLL}} + \underbrace{\mathcal{O}(\alpha_s^n L^{n-1})}_{\textbf{NNLL}} + \ldots\right)\right]$$

Region of applicability now valid up to $L \sim 1/\alpha_s$, successive terms suppressed by $\mathcal{O}(\alpha_s)$

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Calculat

Price for constraining real radiation

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**Exponentiation in direct space generally not possible.**
**Phase-space constraints typically do not factorize in direct space**

$$\tilde{\sigma}(v) \sim \int \prod_i^n [dk_i] |\mathcal{M}(k_1, \ldots, k_n)|^2 \Theta_{\mathrm{PS}}(v - V(k_1, \ldots k_n))$$

***How to achieve resummation?***

Region of applicability now valid up to $L \sim 1/\alpha_s$, successive terms suppressed by $\mathcal{O}(\alpha_s)$

# All-order resummation: (re)-factorization

**Solution 1:** move to **conjugate space** where phase space factorization is manifest

Exponentiation in conjugate space; **inverse transform** to move back to direct space

**Extremely successful** approach

"direct QCD"

- Catani, Trentadue, Mangano, Marchesini, Webber, Nason, Dokshitzer…
- Collins, Soper, Sterman, Laenen, Magnea…

SCET

- Manohar, Bauer, Stewart, Becher, Neubert….

+ many others!

Emphasis on properties of QCD matrix elements and QCD radiation

Factorization properties in the singular region and associated RGEs (factorization → evolution → resummation)

SCET vs. dQCD **not an issue** **[Sterman *et al.* '13, '14][Bonvini, Forte, Ghezzi, Ridolfi, LR '12, '13, '14][Becher, Neubert *et al.* '08, '11, 14]**

Limitation: it is **process-dependent**, and must be performed manually and analytically **for each observable**
for some complex observable difficult/impossible to derive **factorization theorem**

# All-order resummation: CAESAR/ARES approach

**Solution 2:** Translate the resummability into properties of the observable in the presence of multiple radiation: **recursive infrared and collinear (rIRC) safety**

[Banfi, Salam, Zanderighi '01, '03, '04]
[Banfi, McAslan, Monni, Zanderighi, El-Menoufi '14, '18]

**Simple observable** easy to calculate

$$\tilde{\sigma} \sim \int \frac{dv_1}{v_1} \Sigma_s(v_1) \mathscr{F}(v, v_1)$$

**Transfer function** relates the resummation of the full observable to the one of the simple observable.

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i.e. conditional probability

Separation obtained by introducing a **resolution scale** $q_0 = \epsilon k_{t,1}$

$$\tilde{\sigma} \sim \int [dk_1] e^{-R(q_0)}$$

**Unresolved emission** can be treated as **totally unconstrained** $\longrightarrow$ **exponentiation**

$$\times |\mathcal{M}(k_1)|^2 \left( \sum_{m=0}^{\infty} \frac{1}{m!} \int \prod_{i=2}^{m+1} [dk_i] |\mathcal{M}(k_i)|^2 \Theta(V(k_i) - q_0) \Theta\left(v - V(k_1, \ldots, k_{m+1})\right) \right)$$

**Resolved emission** treated exclusively with **Monte Carlo methods.** Integral is finite, can be integrated in d=4 with a computer

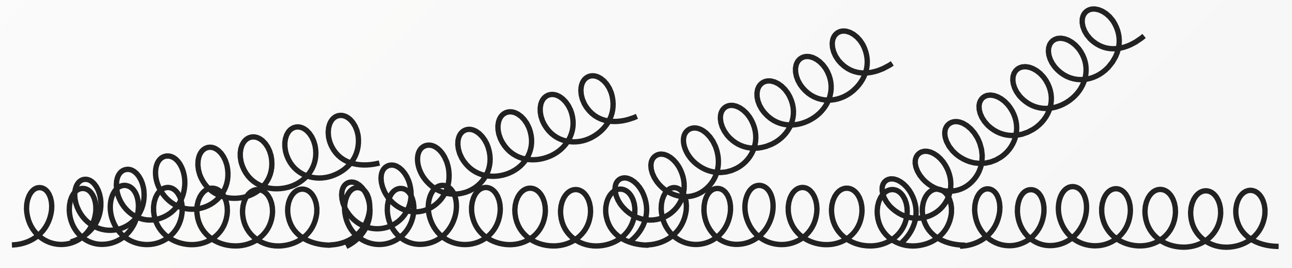
Approach recently formulated within SCET language [Bauer, Monni '18, '19 + ongoing work]

Method entirely formulated in **direct space**

# Resummation of the transverse momentum spectrum

Resummation of transverse momentum is particularly delicate because $p_\perp$ is a **vectorial quantity**

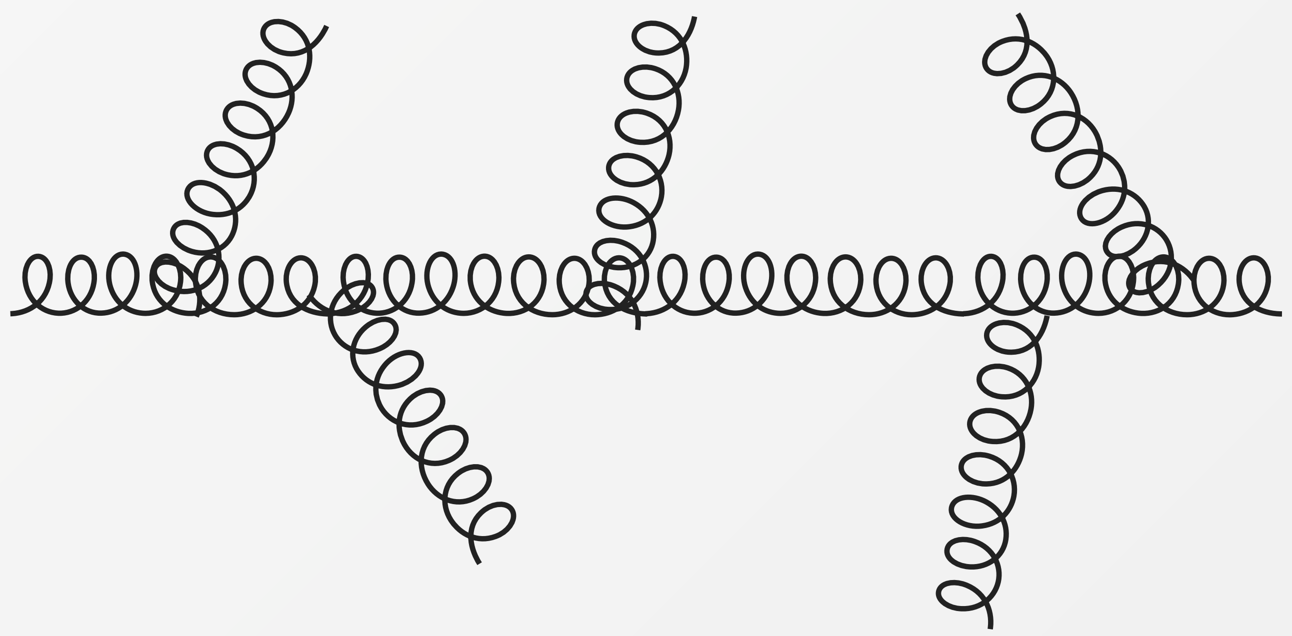
**Two concurring mechanisms** leading to a system with small $p_\perp$



$$p_\perp^2 \sim k_{t,i}^2 \ll m_H^2$$

cross section naturally suppressed as there is no phase space left for gluon emission (Sudakov limit)

**Exponential suppression**



$$\sum_{i=1}^{n} \vec{k}_{t,i} \simeq 0$$

**Large kinematic cancellations**

$p_\perp$ ~0 far from the Sudakov limit

**Power suppression**

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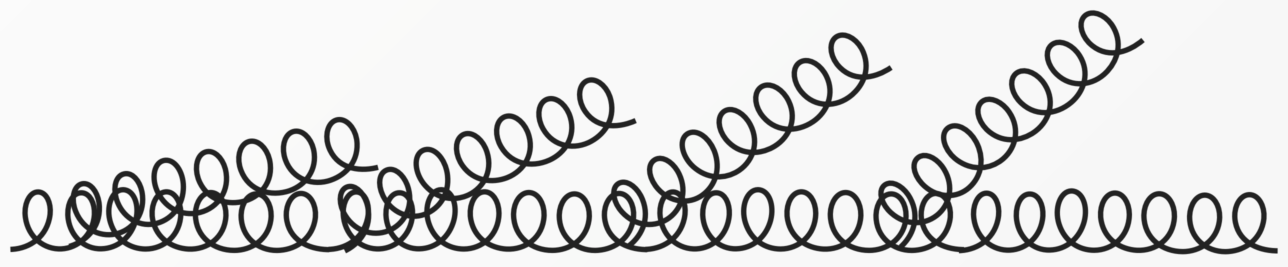

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# Resumption of the transverse momentum spectrum

**Approach 1: impact parameter space**

$$\delta^{(2)}\left(\vec{p}_t - \sum_{i=1}^{n} \vec{k}_{t,i}\right) = \int d^2b \frac{1}{4\pi^2} e^{i\vec{b}\cdot\vec{p}_t} \prod_{i=1}^{n} e^{-i\vec{b}\cdot\vec{k}_{t,i}}$$

two-dimensional momentum conservation

[Parisi, Petronzio '79; Collins, Soper, Sterman '85]

Exponentiation in conjugate space

NLL formula with scale-independent PDFs

$$\sigma = \sigma_0 \int d^2\vec{p}_\perp^H \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \int [dk_i] \, |M(k_i)|^2 \left(e^{i\vec{b}\cdot\vec{k}_{t,i}} - 1\right)$$

$$= \sigma_0 \int d^2\vec{p}_\perp^H \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-R_{\rm NLL}(L)}$$

virtual corrections

$$R_{\rm NLL}(L) = -Lg_1(\alpha_s L) - g_2(\alpha_s L) \qquad L = \ln(m_H b/b_0)$$

**Approach 2: momentum space (RadISH)**

[Bizon, Monni, Re, LR, Torrielli '16, '17, '18]

Approach exploits factorization properties of the QCD squared amplitudes

NLL formula with scale-independent PDFs

Simple observable

$$\sigma(p_\perp) = \sigma_0 \int \frac{dv_1}{v_1} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(v_1)}$$

$$v_i = k_{t,i}/m_H, \quad \zeta_i = v_i/v_1$$

$$\times \, \epsilon^{R'(v_1)} R'(v_1) \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_\epsilon^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'(v_1) \, \Theta\left(p_\perp - |\vec{k}_{t,i} + \cdots \vec{k}_{t,n+1}|\right)$$

Transfer function

Formula can be evaluated with Monte Carlo method; dependence on $\epsilon$ vanishes (as $\mathcal{O}(\epsilon)$) and result is **finite** in four dimensions

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[Parisi, Petronzio '79; Collins, Soper, Sterman '85]

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$$= \sigma_0 \int d^2\vec{p}_\perp^H \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-R_{\rm NLL}(L)}$$

**virtual corrections**

$$R_{\rm NLL}(L) = -Lg_1(\alpha_s L) - g_2(\alpha_s L) \qquad L = \ln(m_H b/b_0)$$

## Approach 2: momentum space (RadISH)

[Bizon, Monni, Re, LR, Torrielli '16, '17, '18]

Approach exploits factorization properties of the QCD squared amplitudes

NLL formula with scale-independent PDFs

**Simple observable**

$$\sigma(p_\perp) = \sigma_0 \int \frac{dv_1}{v_1} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(v_1)}$$

$$v_i = k_{t,i}/m_H, \quad \zeta_i = v_i/v_1$$

$$\times\, \epsilon^{R'(v_1)} R'(v_1) \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_\epsilon^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'(v_1)\, \Theta\left(p_\perp - |\vec{k}_{t,i} + \cdots \vec{k}_{t,n+1}|\right)$$

**Transfer function**

Formula can be evaluated with Monte Carlo method; dependence on $\epsilon$ vanishes (as $\mathcal{O}(\epsilon)$) and result is **finite** in four dimensions

# Resummation of the transverse momentum spectrum

**Approach 1: impact parameter space**

$$\delta^{(2)}\left(\vec{p}_t - \sum_{i=1}^{n} \vec{k}_{t,i}\right) = \int d^2b \frac{1}{4\pi^2} e^{i\vec{b}\cdot\vec{p}_t} \prod_{i=1}^{n} e^{-i\vec{b}\cdot\vec{k}_{t,i}}$$

two-dimensional momentum conservation

[Parisi, Petronzio '79; Collins, Soper, Sterman '85]

Exponentiation in conjugate space

NLL formula with scale-independent PDFs

$$\sigma = \sigma_0 \int d^2\vec{p}_\perp^H \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \int [dk_i] |M(k_i)|^2 \left(e^{i\vec{b}\cdot\vec{k}_{t,i}} - 1\right)$$

$$= \sigma_0 \int d^2\vec{p}_\perp^H \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-R_{\rm NLL}(L)}$$

virtual corrections

$R_{\rm NLL}(L) = -Lg_1(\alpha_s L) - g_2(\alpha_s L)$ $\quad L = \ln(m_H b/b_0)$

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**Transfer function**

Formula can be evaluated with Monte Carlo method; dependence on $\epsilon$ vanishes (as $\mathcal{O}(\epsilon)$) and result is **finite** in four dimensions

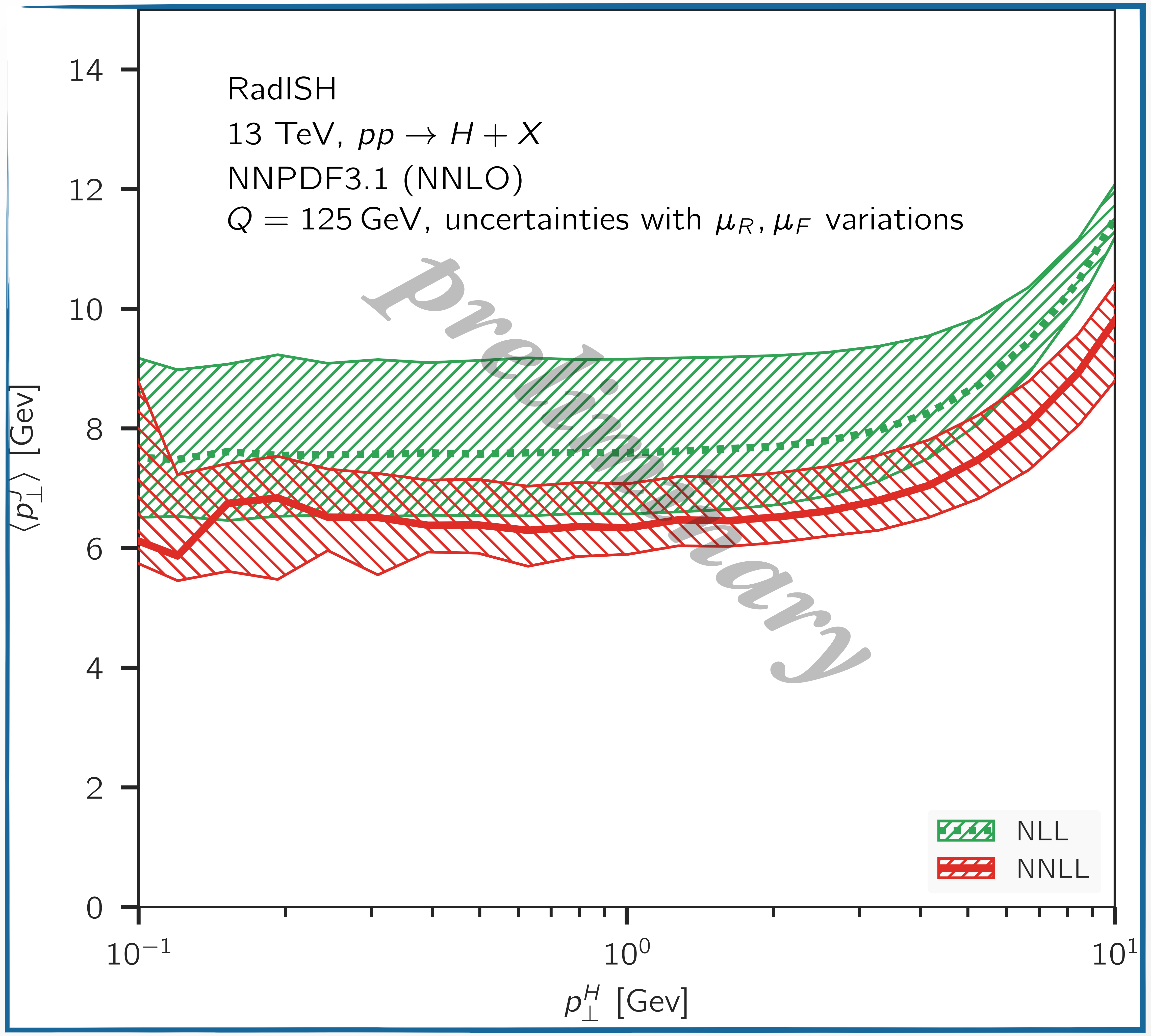
# Direct space formulation

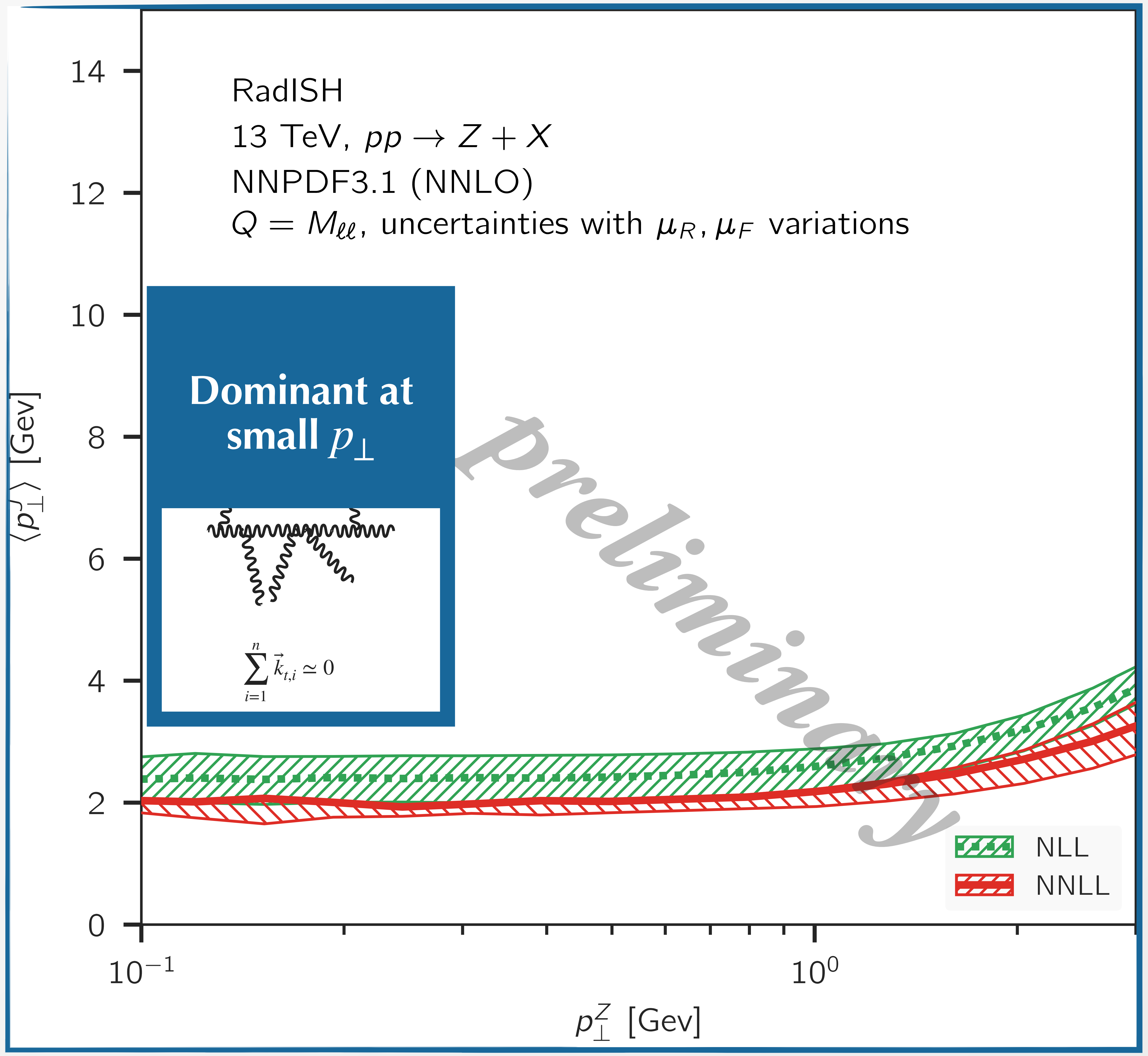
1. **More differential description** of the QCD radiation than that usually possible in a conjugate-space formulation

2. Similar in spirit to a **semi-inclusive parton shower**, but with higher-order logarithms, and **full control on the formal accuracy**

3. Thanks to its versatility, the approach can be exploited to formulate the resummation for entire classes of observables in an **unique framework**

# Direct space: access to differential information and underlying dynamics




Possible access to subleading jets and higher moments

# Direct space formulation

**Price to pay**: less compact formulation

**N³LL result**

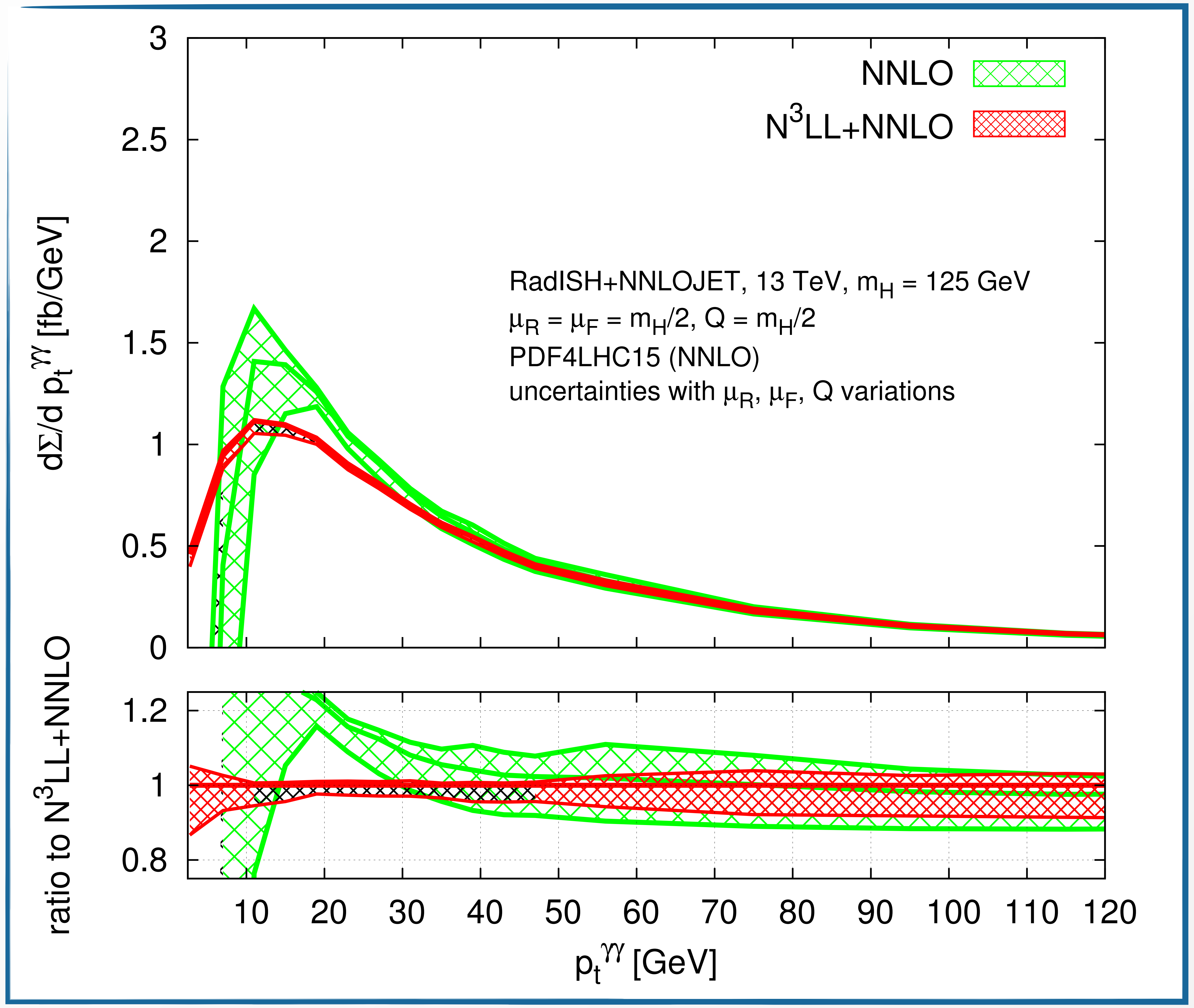
$$\frac{d\Sigma(v)}{d\Phi_B} = \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \partial_L \left(-e^{-R(k_{t1})} \mathcal{L}_{\mathrm{N^3LL}}(k_{t1})\right) \int d\mathcal{Z}[\{R', k_i\}] \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1})\right)$$

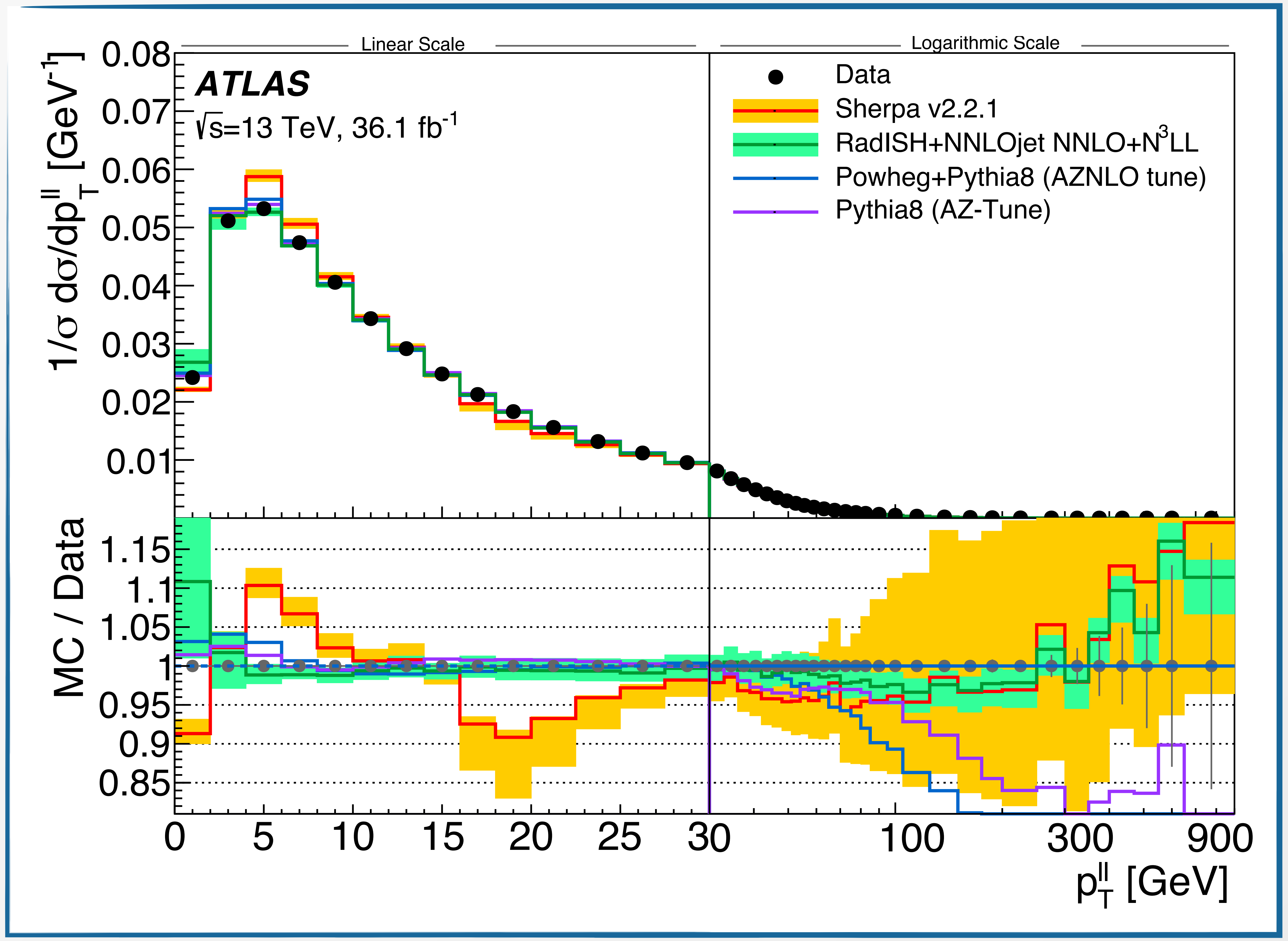
$$+ \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} e^{-R(k_{t1})} \int d\mathcal{Z}[\{R', k_i\}] \int_0^1 \frac{d\zeta_s}{\zeta_s} \frac{d\phi_s}{2\pi} \left\{ \left( R'(k_{t1}) \mathcal{L}_{\mathrm{NNLL}}(k_{t1}) - \partial_L \mathcal{L}_{\mathrm{NNLL}}(k_{t1}) \right) \right.$$
$$\times \left( R''(k_{t1}) \ln \frac{1}{\zeta_s} + \frac{1}{2} R'''(k_{t1}) \ln^2 \frac{1}{\zeta_s} \right) - R'(k_{t1}) \left( \partial_L \mathcal{L}_{\mathrm{NNLL}}(k_{t1}) - 2 \frac{\beta_0}{\pi} \alpha_s^2(k_{t1}) \hat{P}^{(0)} \otimes \mathcal{L}_{\mathrm{NLL}}(k_{t1}) \ln \frac{1}{\zeta_s} \right)$$
$$\left. + \frac{\alpha_s^2(k_{t1})}{\pi^2} \hat{P}^{(0)} \otimes \hat{P}^{(0)} \otimes \mathcal{L}_{\mathrm{NLL}}(k_{t1}) \right\} \left\{ \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1}, k_s)\right) - \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1})\right) \right\}$$

$$+ \frac{1}{2} \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} e^{-R(k_{t1})} \int d\mathcal{Z}[\{R', k_i\}] \int_0^1 \frac{d\zeta_{s1}}{\zeta_{s1}} \frac{d\phi_{s1}}{2\pi} \int_0^1 \frac{d\zeta_{s2}}{\zeta_{s2}} \frac{d\phi_{s2}}{2\pi} R'(k_{t1})$$
$$\times \left\{ \mathcal{L}_{\mathrm{NLL}}(k_{t1}) \left(R''(k_{t1})\right)^2 \ln \frac{1}{\zeta_{s1}} \ln \frac{1}{\zeta_{s2}} - \partial_L \mathcal{L}_{\mathrm{NLL}}(k_{t1}) R''(k_{t1}) \left( \ln \frac{1}{\zeta_{s1}} + \ln \frac{1}{\zeta_{s2}} \right) \right.$$
$$\left. + \frac{\alpha_s^2(k_{t1})}{\pi^2} \hat{P}^{(0)} \otimes \hat{P}^{(0)} \otimes \mathcal{L}_{\mathrm{NLL}}(k_{t1}) \right\}$$
$$\times \left\{ \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1}, k_{s1}, k_{s2})\right) - \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1}, k_{s1})\right) - \right.$$
$$\left. \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1}, k_{s2})\right) + \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1})\right) \right\} + \mathcal{O}\left(\alpha_s^n \ln^{2n-6} \frac{1}{v}\right), \qquad (3.18)$$

# Resummation of the transverse momentum spectrum at N3LL+NNLO

$N^3LL$ result matched to NNLO H+j, Z+j, $W^{\pm}$+j **[Bizon, LR *et al.* '17, '18, '19]**




**[ATLAS 1912.02844]**

H+j at same accuracy also in SCET **[Chen *et al.* '18]**

H+j, Z+j at N3LL′+NNLO recently computed **[Ebert *et al.* '21][Cieri *et al.* '21]**

# Results for $Z/W^+$ ratio

$Z$ and $W$ production share a similar pattern of QCD radiative corrections

Crucial to understand correlation between $Z$ and $W$ spectra to exploit data-driven predictions

$$\frac{1}{\sigma^W}\frac{d\sigma^W}{p_\perp^W} \sim \frac{1}{\sigma^Z_{\rm data}}\frac{d\sigma^Z_{\rm data}}{p_\perp^Z}\,\frac{\frac{1}{\sigma^W_{\rm theory}}\frac{d\sigma^W_{\rm theory}}{p_\perp^W}}{\frac{1}{\sigma^Z_{\rm theory}}\frac{d\sigma^Z_{\rm theory}}{p_\perp^Z}}$$

Several choices are possible:

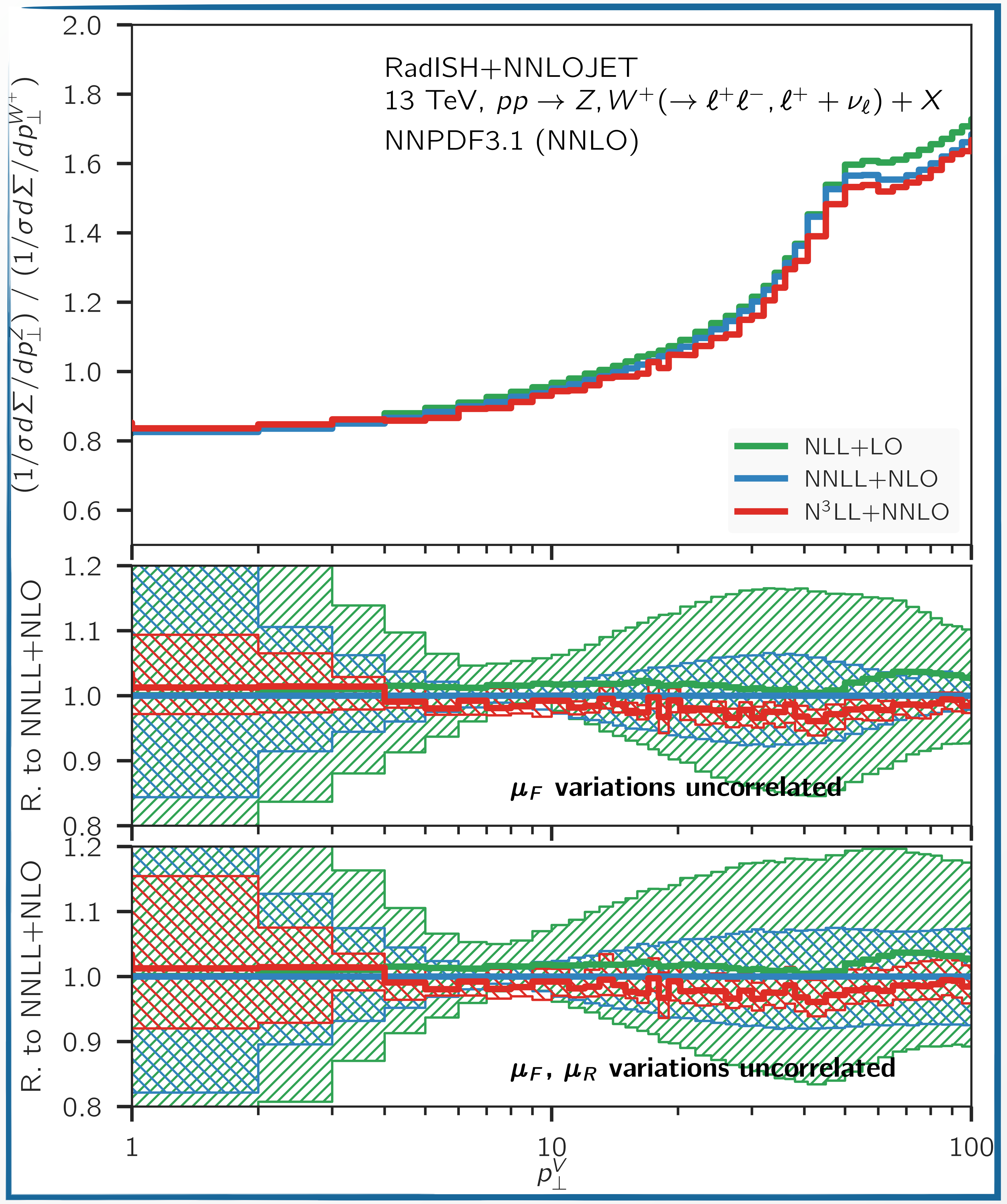
- **Correlate resummation and renormalisation** scale variations, keep **factorisation scale uncorrelated**, while keeping

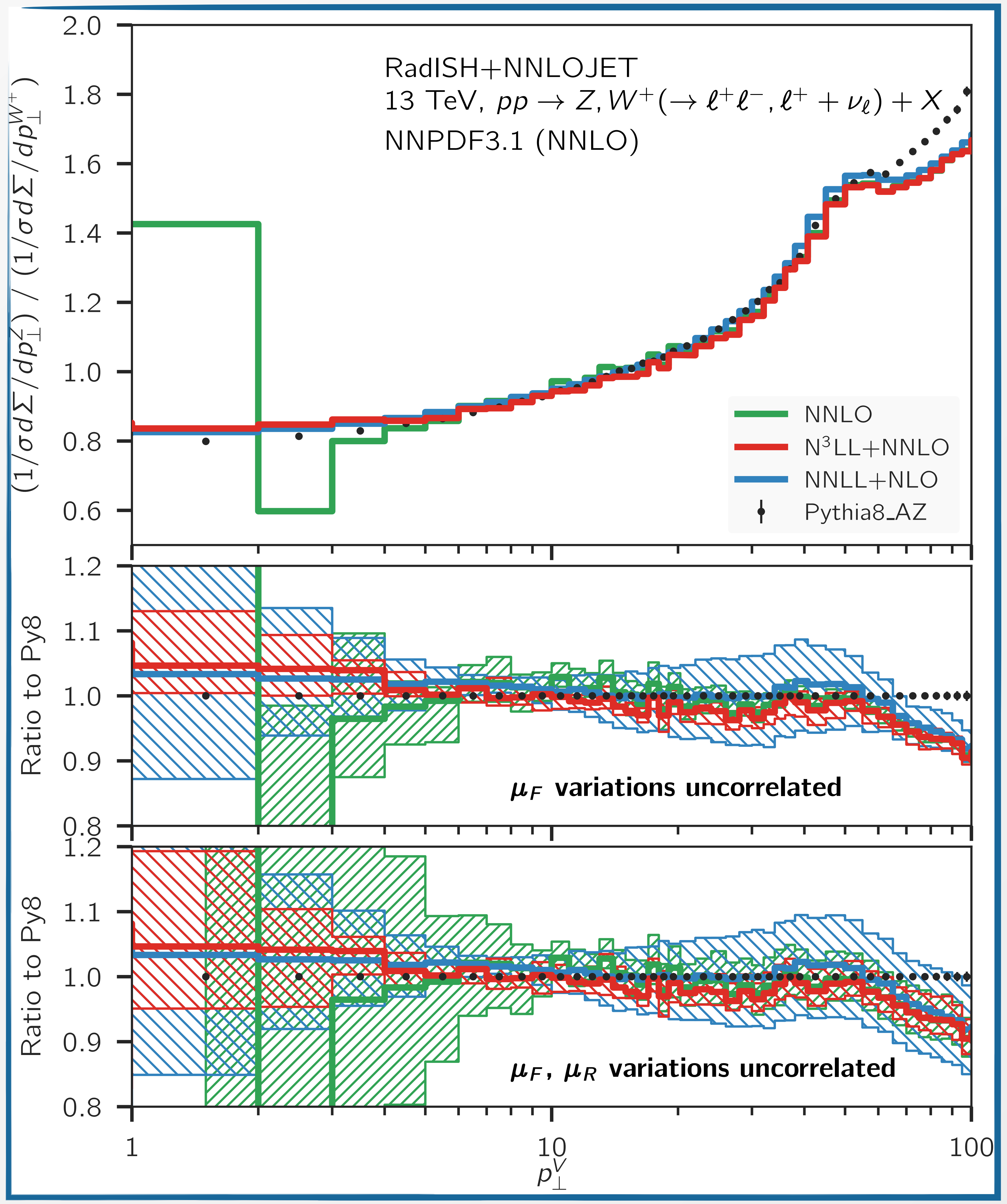
$$\frac{1}{2} \leq \frac{\mu_{\rm F}^{\rm num}}{\mu_{\rm F}^{\rm den}} \leq 2$$

- More **conservative** estimate: vary both **renormalisation and factorisation scales in an uncorrelated** way with

$$\frac{1}{2} \leq \frac{\mu^{\rm num}}{\mu^{\rm den}} \leq 2$$

# Results for $Z/W^+$ ratio



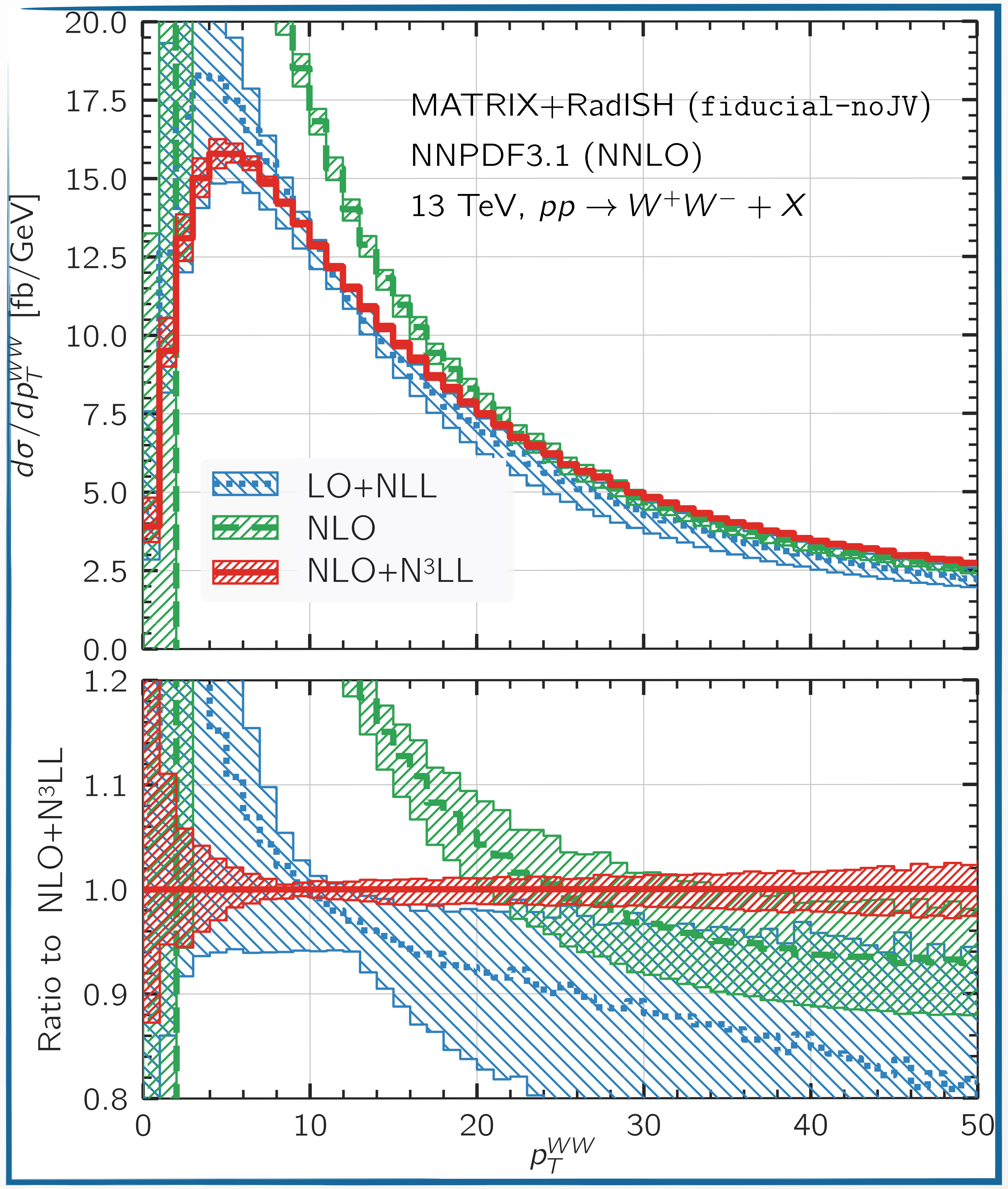

[Bizon, LR *et al.* '19]

# LHC results

RadISH+MATRIX fully automated framework for generic 2⟶1 and 2⟶2 colour singlet processes

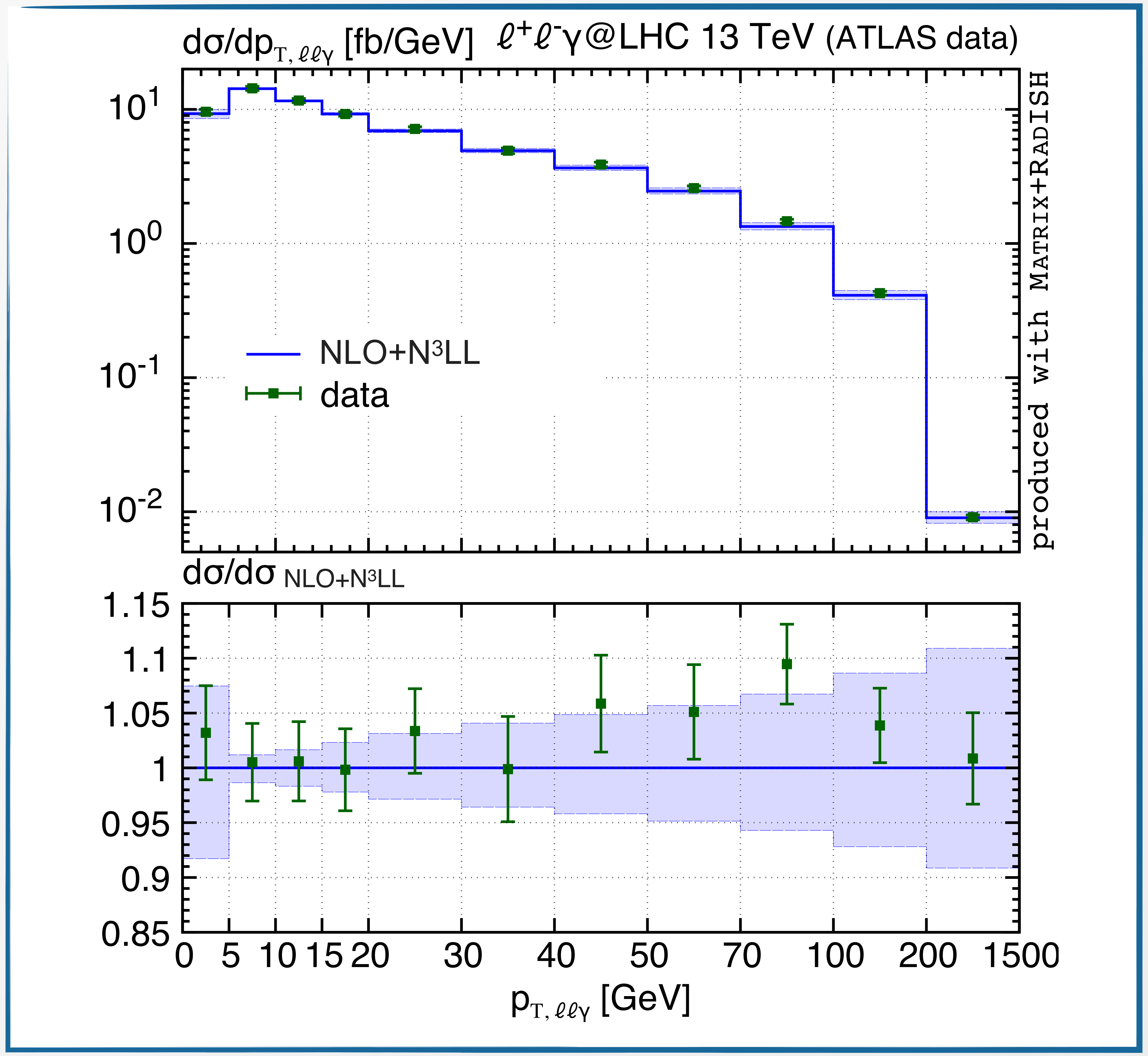
[Grazzini, Kallweit, Rathlev, Wiesemann '15, '17]

[Kallweit, Re, LR, Wiesemann 2004.07720]




[Kallweit, Re, LR, Wiesemann, 2004.07720]

W+W- production




$Z\gamma$ production

[Wiesemann, Rottoli, Torrielli 2006.09338]

# Direct space formulation: general considerations

NLL result for $p_\perp^H$

$$\sigma(p_\perp^H) = \sigma_0 \int d^2\vec{p}_\perp^H \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-R_{\rm NLL}(L)}$$

NLL result for $p_\perp^J$

$$\sigma(p_\perp^{\rm J}) = \sigma_0 e^{Lg_1(\alpha_s\beta_0 L)+g_2(\alpha_s\beta_0 L)}$$

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General formula for a generic transverse observable at NLL [Bizon, Monni, Re, LR, Torrielli '17]

$$\sigma(v) = \sigma_0 \int \frac{dk_{t,1}}{k_{t,1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(k_{t,1})} R'\left(k_{t,1}\right) d\mathcal{Z}\, \Theta\left(v - V(k_1, \ldots, k_{n+1})\right)$$

$$d\mathcal{Z} = \epsilon^{R'(k_{t,1})} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_\epsilon^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'\left(k_{t,1}\right)$$

$$R_{\rm NLL}(L) = -Lg_1(\alpha_s L) - g_2(\alpha_s L)$$

$$L = \ln(k_{t,1}/M)$$

$$R'_{\rm NLL}(k_t) = 4\left(\frac{\alpha_s^{\rm CMW}(k_t)}{\pi} C_A \ln\frac{m_H}{k_t} - \alpha_s(k_t)\beta_0\right)$$

**CMW scheme**

(inclusion of 2-loop cusp anomalous dimension)

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General

understanding of the structure in momentum space provides guidance to **double-differential resummation**

$$\sigma(v) = \sigma_0 \int \frac{dk_{t,1}}{k_{t,1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(k_{t,1})} R'\left(k_{t,1}\right) d\mathcal{Z}\, \Theta\left(p_T^H - |\vec{k}_{t,1} + \cdots \vec{k}_{t,n+1}|\right)$$

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# Double-differential resummation in direct space

Just need to **combine measurement functions**!

At NLL

$$\sigma(p_\perp^H) = \sigma_0 \int \frac{dk_{t,1}}{k_{t,1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(k_{t,1})} R'\left(k_{t,1}\right) d\mathcal{Z}\,\Theta\left(p_\perp^H - |\vec{k}_{t,1} + \cdots \vec{k}_{t,n+1}|\right)$$

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Same philosophy at NNLL, where additional corrections arise [Banfi et al. '12][Becher et al. '12 ,'13][Stewart et al. '13]

$$\sigma^{\mathrm{NNLL}}(p_\perp^{\mathrm{J,v}}) = \sigma^{\mathrm{NNLL}}_{\mathrm{incl}}(p_\perp^{\mathrm{J,v}}) + \sigma^{\mathrm{NNLL}}_{\mathrm{clust}}(p_\perp^{\mathrm{J,v}}) + \sigma^{\mathrm{NNLL}}_{\mathrm{corr}}(p_\perp^{\mathrm{J,v}})$$

**clustering correction**: jet algorithm can cluster two emissions into the same jet

**correlated correction**: amends the inclusive treatment of the **correlated squared amplitude** for two emission accounting for configurations where the two correlated emissions are not clustered in the same jet

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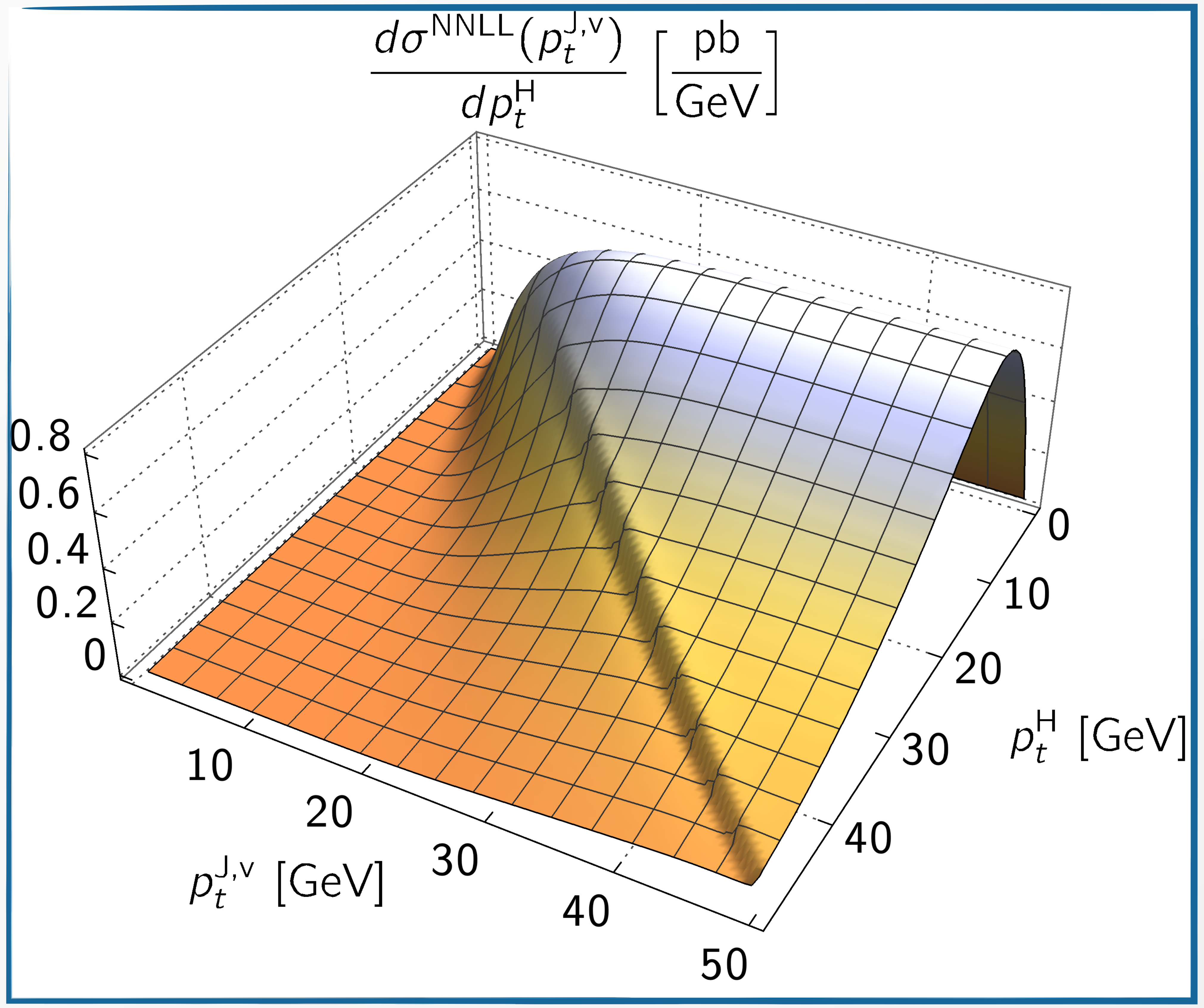
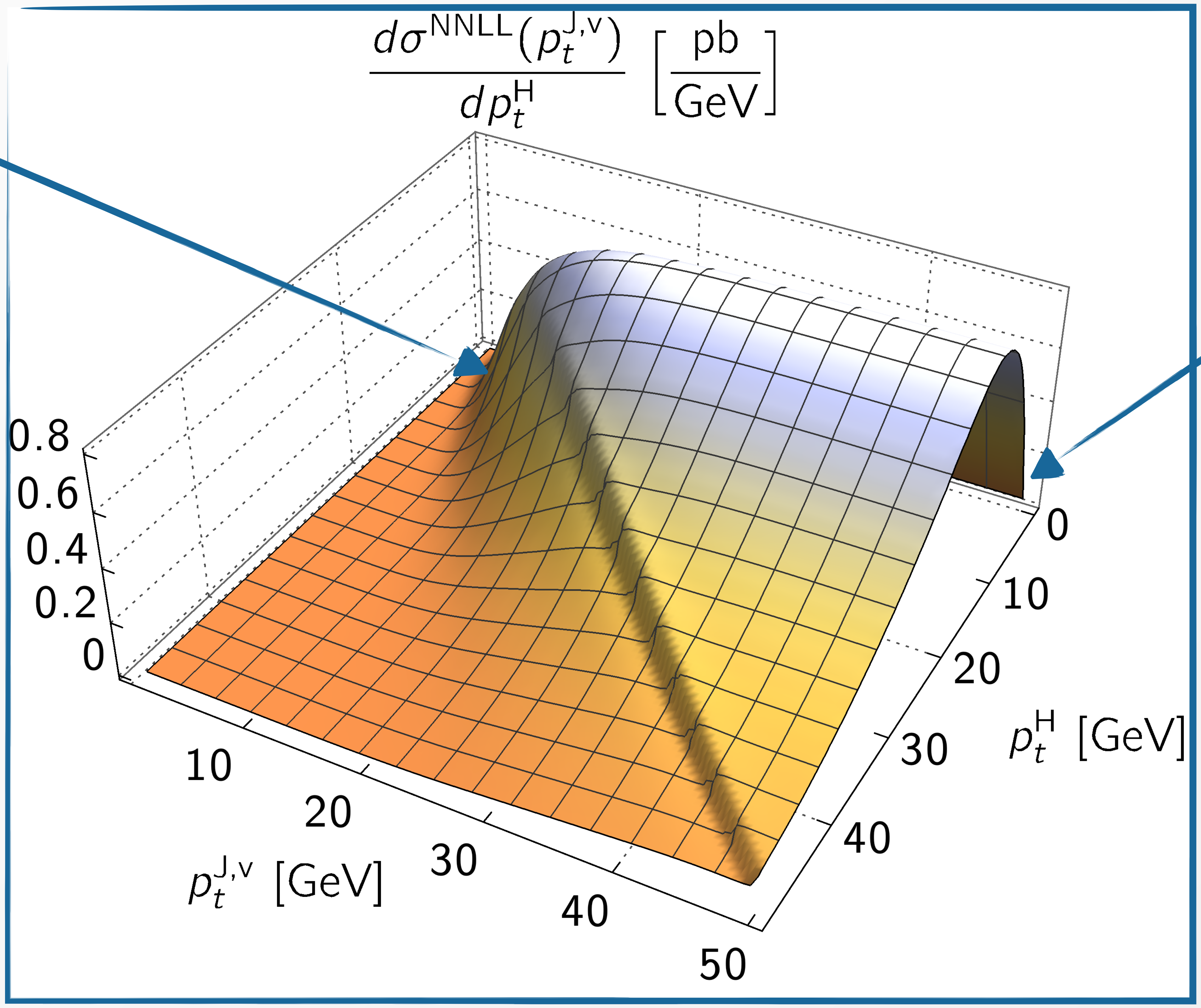
# NNLL cross section differential in $p_\perp^H$, cumulative in $p_\perp^J \leq p_\perp^{J,v}$



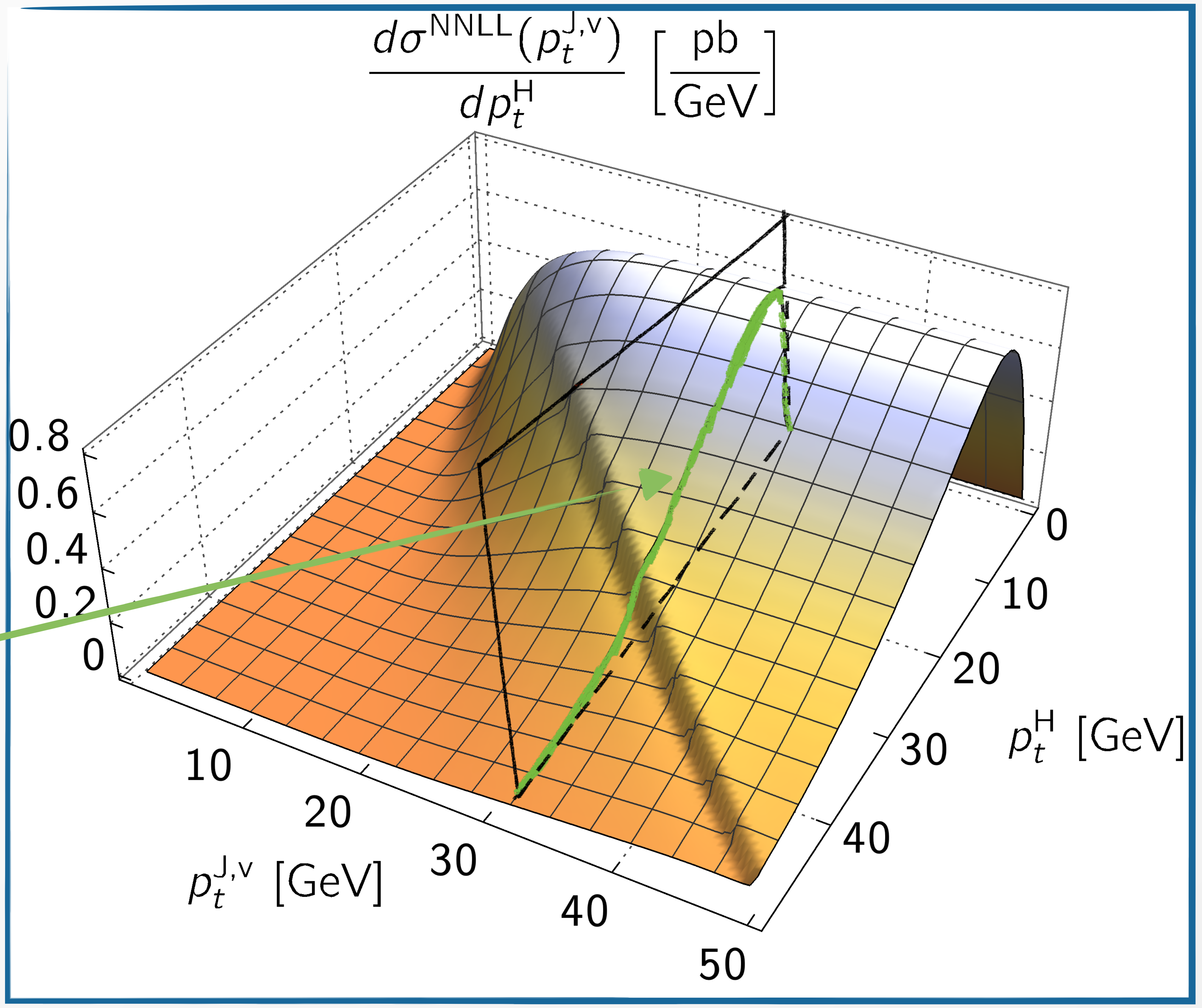
# NNLL cross section differential in $p_\perp^H$, cumulative in $p_\perp^J \leq p_\perp^{J,v}$

Sudakov suppression at small $p_\perp^J$

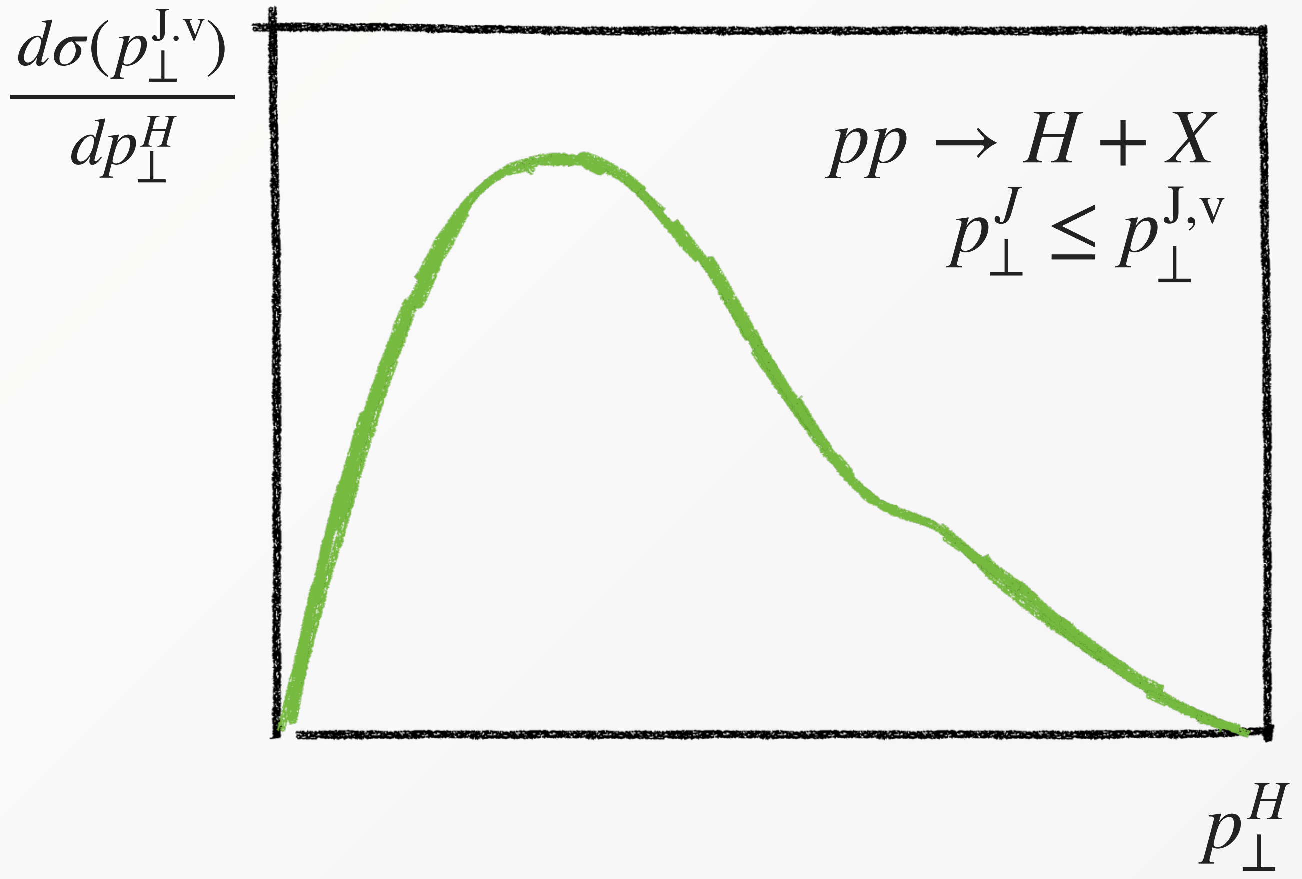



Peaked structure (Sudakov) + power-like suppression at very small $p_\perp^H$

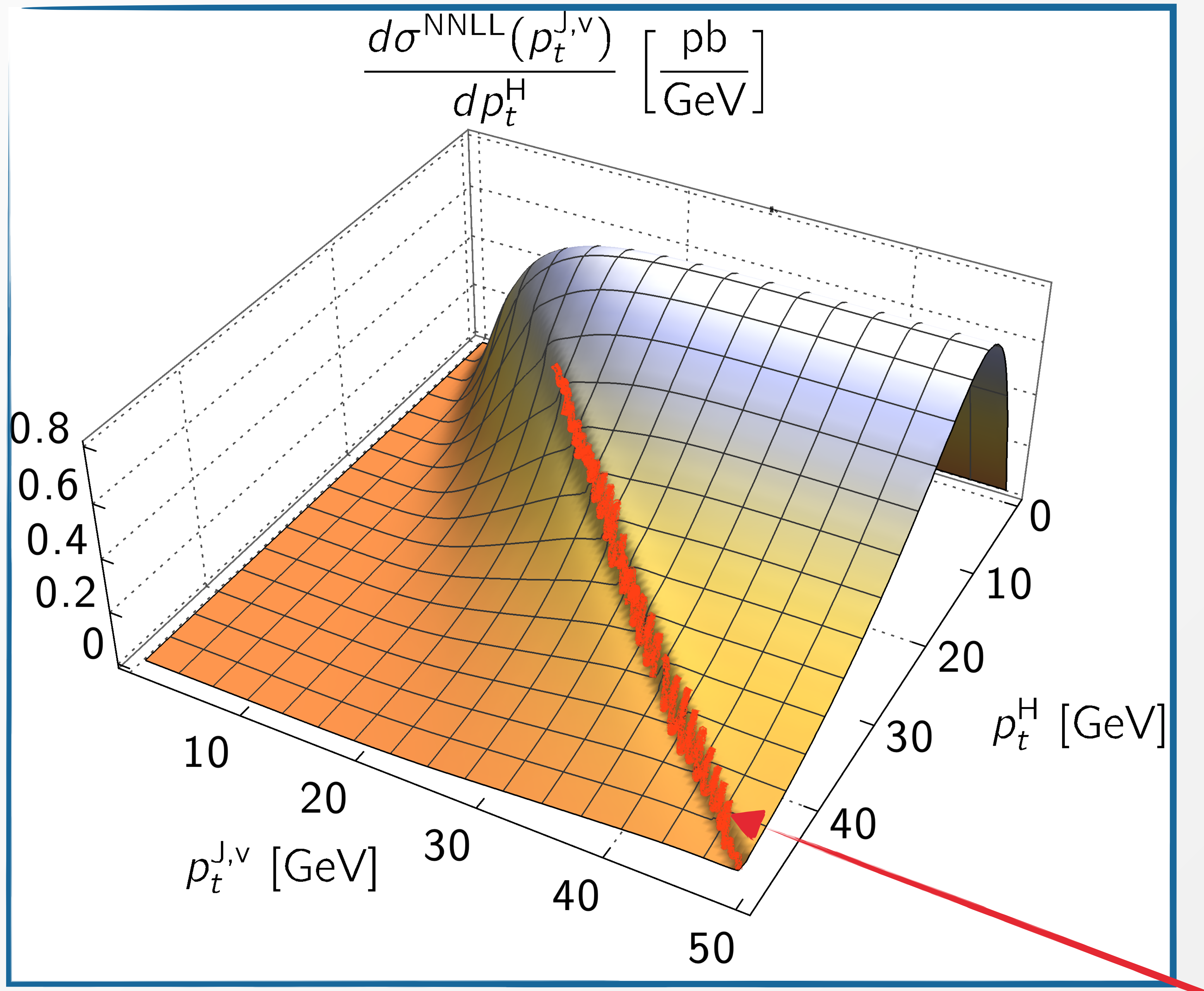
# NNLL cross section differential in $p_\perp^H$, cumulative in $p_\perp^{\mathrm{J}} \leq p_\perp^{\mathrm{J,v}}$




At a given value of $p_\perp^{\mathrm{J,v}}$ it corresponds to the $p_\perp^H$ cross section in the 0-jet bin



# NNLL cross section differential in $p_\perp^H$, cumulative in $p_\perp^J \leq p_\perp^{J,v}$

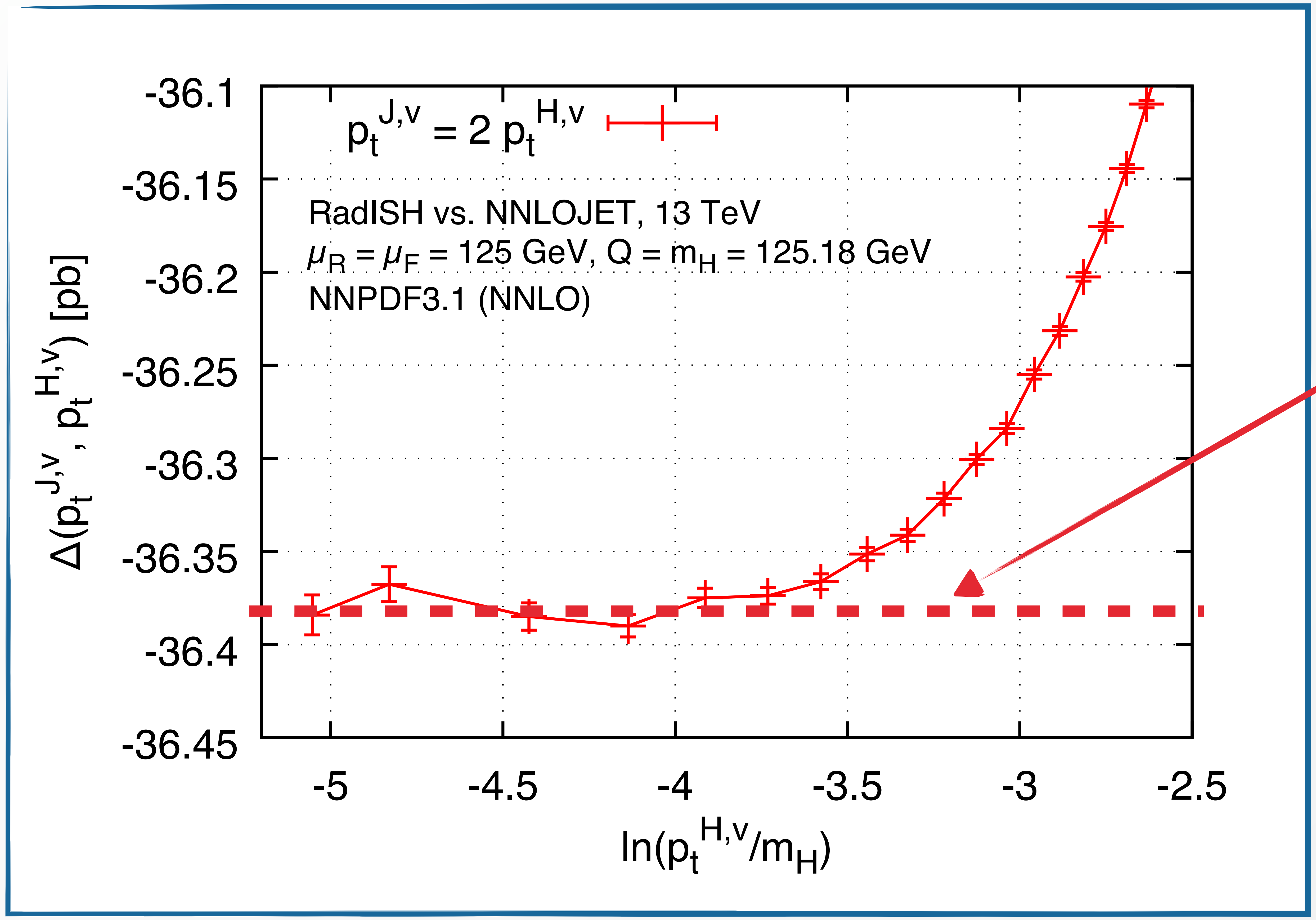



[Catani, Webber '97]

**Sudakov shoulder**: integrable singularity beyond LO at $p_\perp^H \simeq p_\perp^{J,v}$

Logarithms associated to the Shoulder are resummed in the limit $p_\perp^H \sim p_\perp^{J,v} \ll m_H$

# Accuracy check at $\mathcal{O}(\alpha_s^2)$




$$\Delta(p_\perp^{\mathrm{J,v}}, p_\perp^{H,\mathrm{v}}) = \sigma^{\mathrm{NNLO}}(p_\perp^{\mathrm{J,v}}, p_\perp^{H,\mathrm{v}}) - \sigma^{\mathrm{NNLL}}_{\mathrm{exp.}}(p_\perp^{\mathrm{J,v}}, p_\perp^{H,\mathrm{v}})$$

$$\sigma^{\mathrm{NNLO}}(p_\perp^H < p_\perp^{H,\mathrm{v}}, p_\perp^{\mathrm{J}} < p_\perp^{\mathrm{J,v}}) = \sigma^{\mathrm{NNLO}} - \int \Theta(p_\perp^H > p_\perp^{H,\mathrm{v}}) \vee \Theta(p_\perp^{\mathrm{J}} > p_\perp^{\mathrm{J,v}}) d\sigma_{H+\mathrm{J}}^{\mathrm{NLO}}$$

Comparison of the expansion of the resummed result with the fixed order at $\mathcal{O}(\alpha_s^2)$ in the limit $p_\perp^H \sim p_\perp^{\mathrm{J,v}} \ll m_H$

Difference at the double-cumulative level goes to a **constant** (all logarithmic terms correctly predicted)

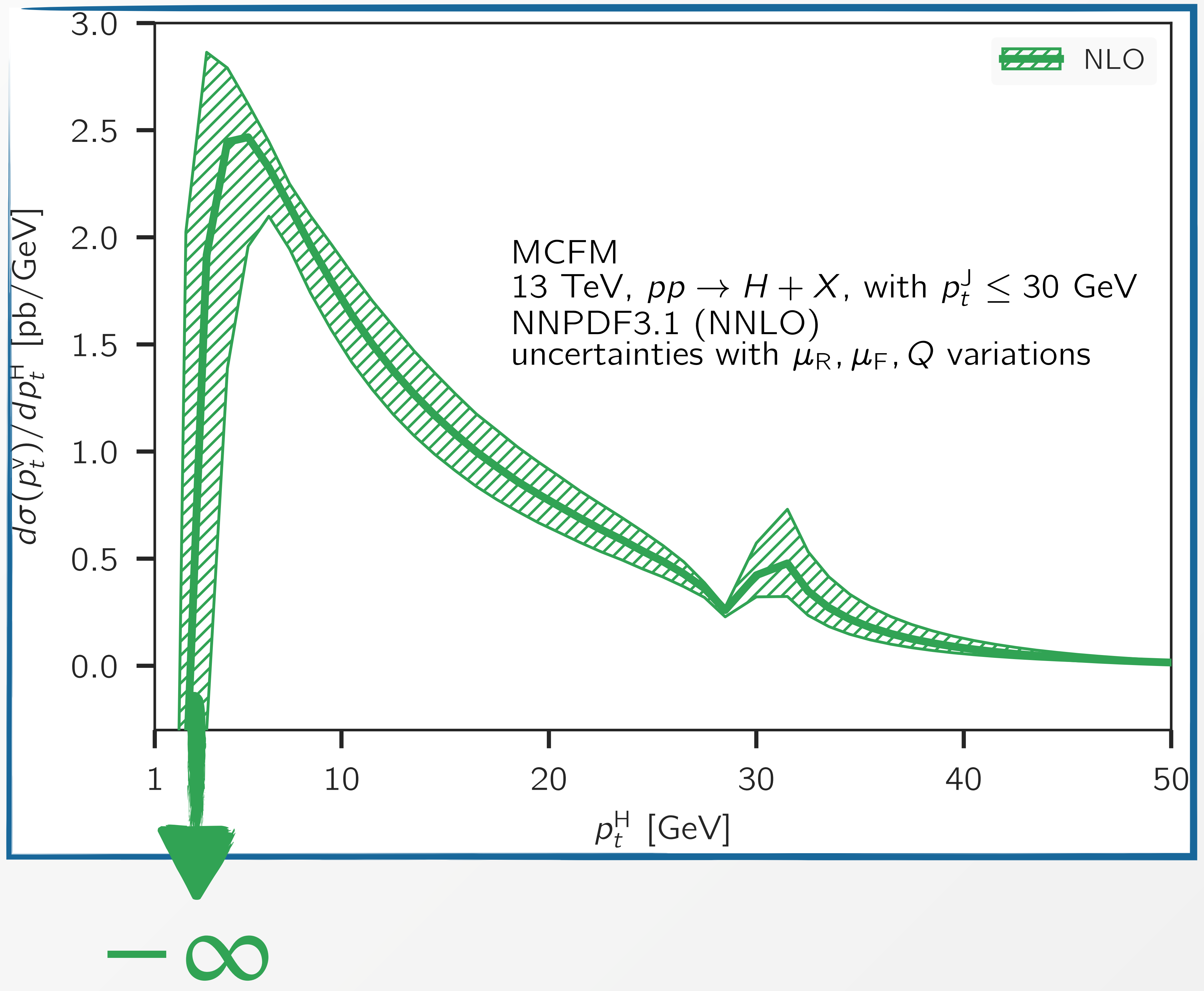
Very strong check: **NNLL resummation** of the logarithms associated to the shoulder

Analogous checks performed in the limits $p_\perp^H \ll p_\perp^{\mathrm{J,v}} < m_H$ and $p_\perp^{\mathrm{J,v}} \ll p_\perp^H < m_H$

# LHC results: Higgs transverse momentum with a jet veto

Multiplicative matching to fixed order (NLO H+j from MCFM, NNLO H from ggHiggs)

[Campbell, Ellis, Giele,'15] [Bonvini et al '13]



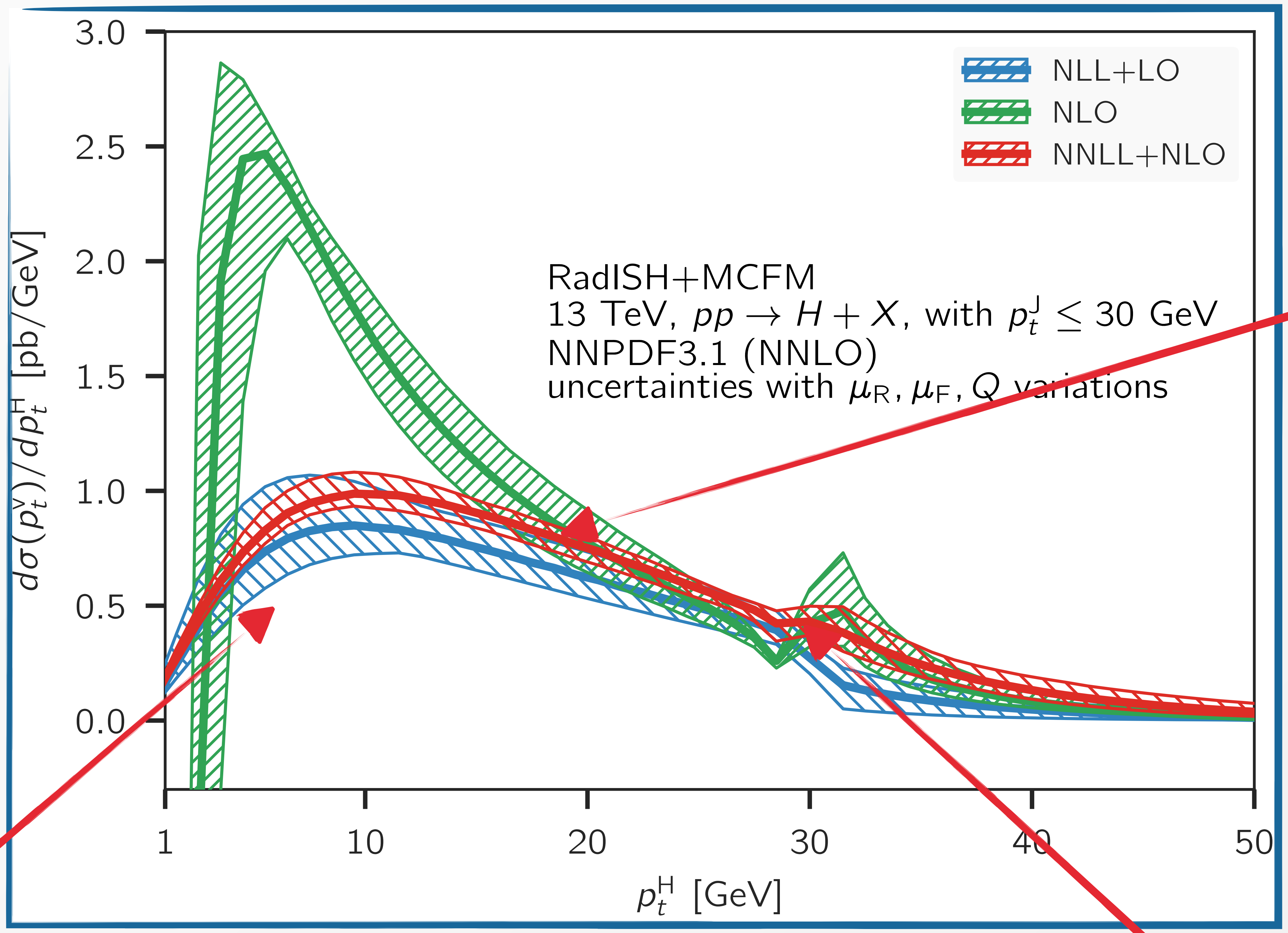
# LHC results: Higgs transverse momentum with a jet veto

Multiplicative matching to fixed order (NLO H+j from **MCFM**, NNLO H from **ggHiggs**)

[Campbell, Ellis, Giele,'15] [Bonvini et al '13]

large K-factor becomes relevant at larger $p_\perp^H$

residual uncertainties at **NNLL+NLO** at the 10% level




good perturbative convergence below 10 GeV

much reduced sensitivity to the Sudakov shoulder with respect to NLO spectrum

# LHC applications to more complex processes: $W^+W^-$ production

Jet vetoed analyses commonly enforced in LHC searches

For instance, $W^+W^-$ channel, which is relevant for BSM searches into leptons, missing energy and/or jets and Higgs measurements, suffers from a signal contamination due to large top-quark background

**Fiducial region** defined by a rather stringent jet veto

$$p_{T,\ell} > 27\,\text{GeV}, \quad |\eta_\ell| < 2.5, \quad m_{\ell^-\ell^+} > 55\,\text{GeV}, \quad p_{T,\ell^-\ell^+} > 30\,\text{GeV}$$

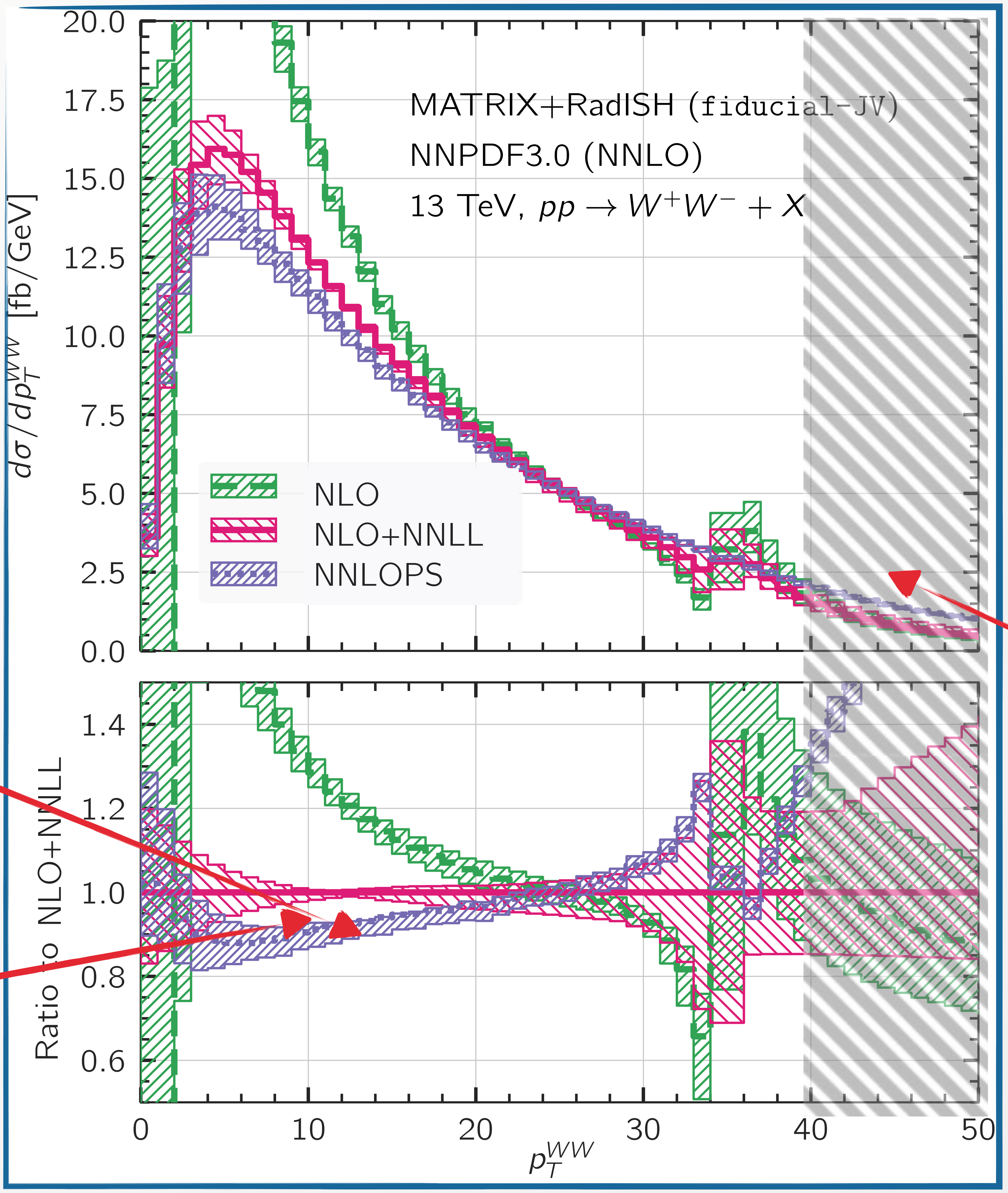
$$p_T^{\text{miss}} > 20\,\text{GeV}$$

$$\text{anti-}k_T \text{ jets with } R = 0.4;$$

$$N_{\text{jet}} = 0 \text{ for } p_T^J > 35\,\text{GeV}$$

# LHC applications: $W^+W^-$ production

NNLL+NLO spectrum obtained by interfacing RadISH with MATRIX [Grazzini, Kallweit, Rathlev, Wiesemann ’15, ’17]




[Wiesemann, Re, Zanderighi ’18]

Comparison with NNLOPS result (much lower log accuracy) shows differences at the $\mathcal{O}(10\%)$ level

Accidental cancellation of perturbative uncertainties; more conservative prescriptions can be considered

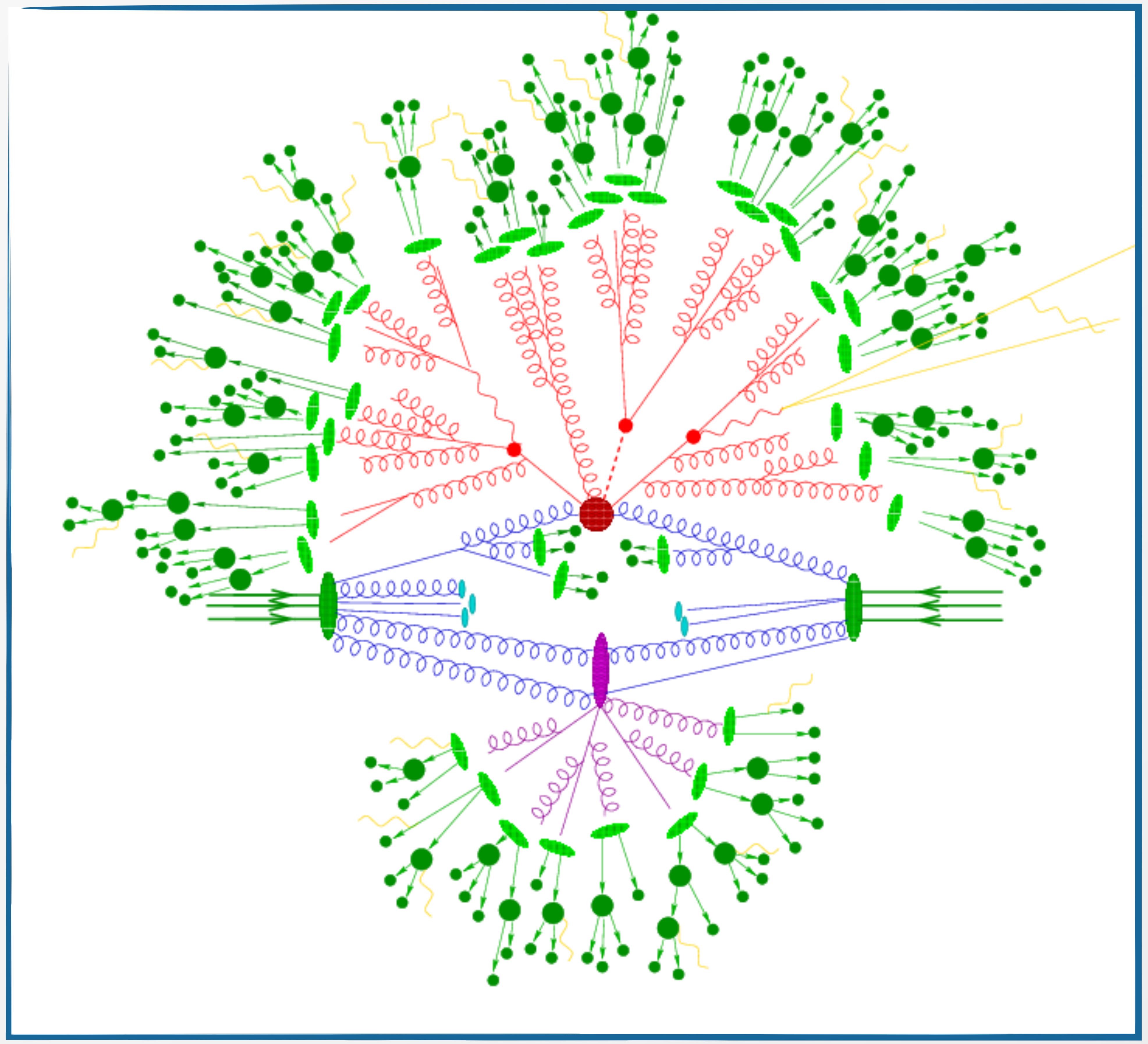
Multi-parton configurations become relevant above the shoulder

[Kallweit, Wiesemann, Re, LR ‘2004.07720]

# NNLO+PS using colour-singlet resummation at N3LL

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

Parton shower (PS) Monte-Carlo (MC) event generators have been the main bridge between experiments and theory in the past decades.



However, their accuracy is usually not sufficient to allow for a precise description of the experimental data

**Need to combine PS with high accuracy fixed order calculations**

Due to the increasing precision of the experimental data, several methods to combine NNLO computations with parton shower for selected processes are being developed [Hamilton, Nason, Re, Zanderighi '13] [Hoeche, Li, Prestel '14] [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '15] [Monni, Nason, Re, Wiesemann, Zanderighi '19]

# The GENEVA method in a nutshell

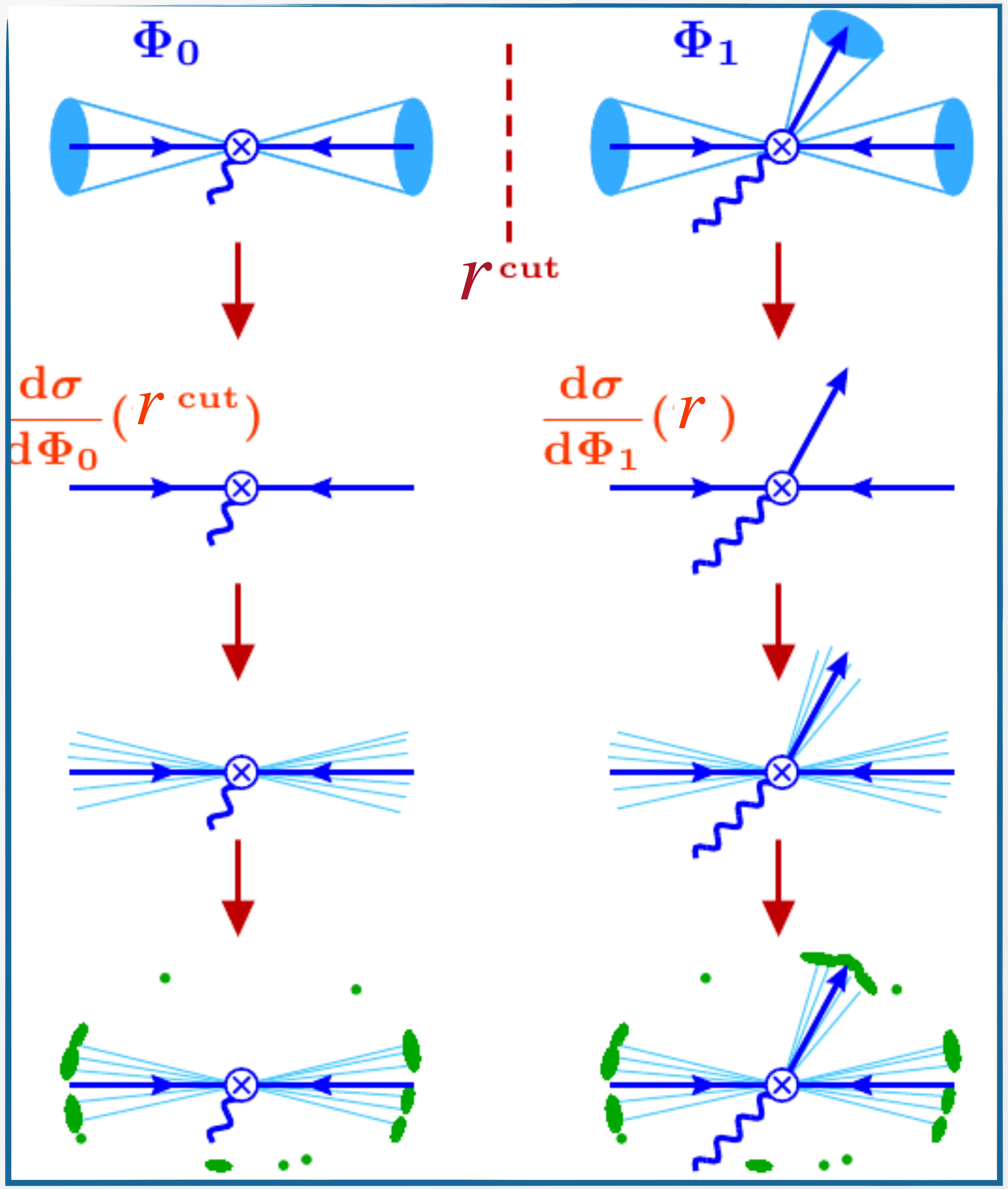
[Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '15]

- Design IR-finite definition of events, based on resolution parameter $r^{\text{cut}}$. Emissions below $r^{\text{cut}}$ 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 (N)NLO accurate and $r$ is resummed at NNLL′

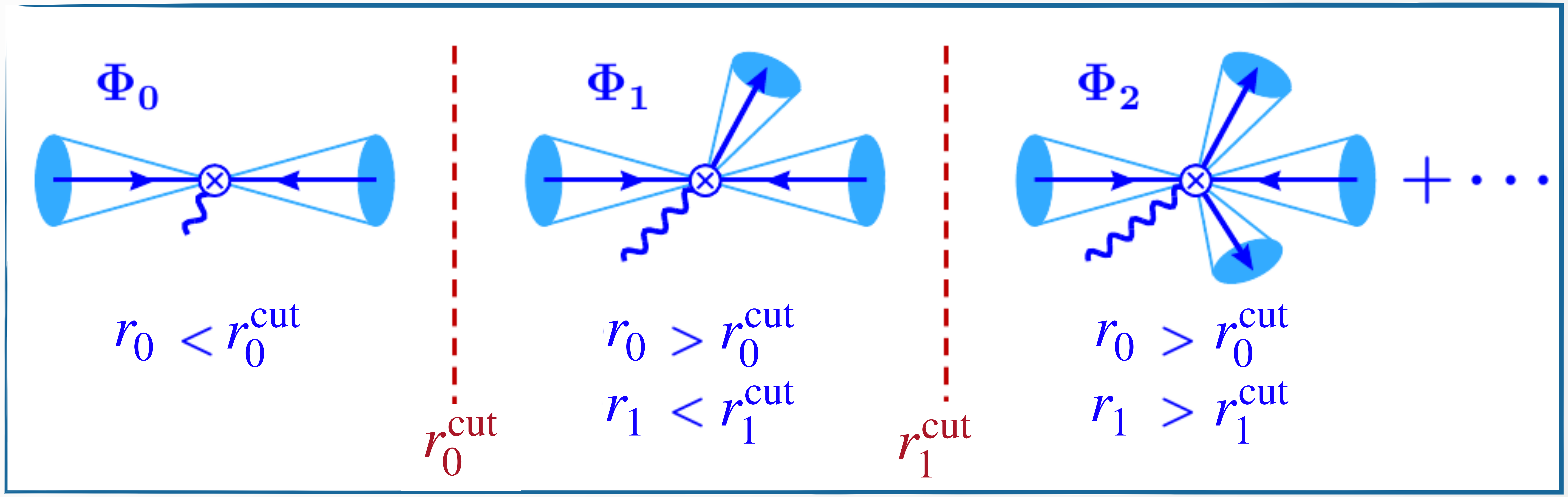
- Shower events

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



# The 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

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

# Resummation of the resolution parameter

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

E.g. inclusive 1-jet cross section:

$$\frac{d\sigma_1^{\text{MC}}}{d\Phi_1}(r_0 > r_0^{\text{cut}}) = \frac{d\sigma^{\text{res}}}{d\Phi_0 dr_0}\mathscr{P}(\Phi_1) + \frac{d\sigma^{\text{NLO}_1}}{d\Phi_1} - \left[\frac{d\sigma^{\text{res}}}{d\Phi_0 dr_0}\mathscr{P}(\Phi_1)\right]_{\text{NLO}} \Theta(r_0 > r_0^{\text{cut}})$$

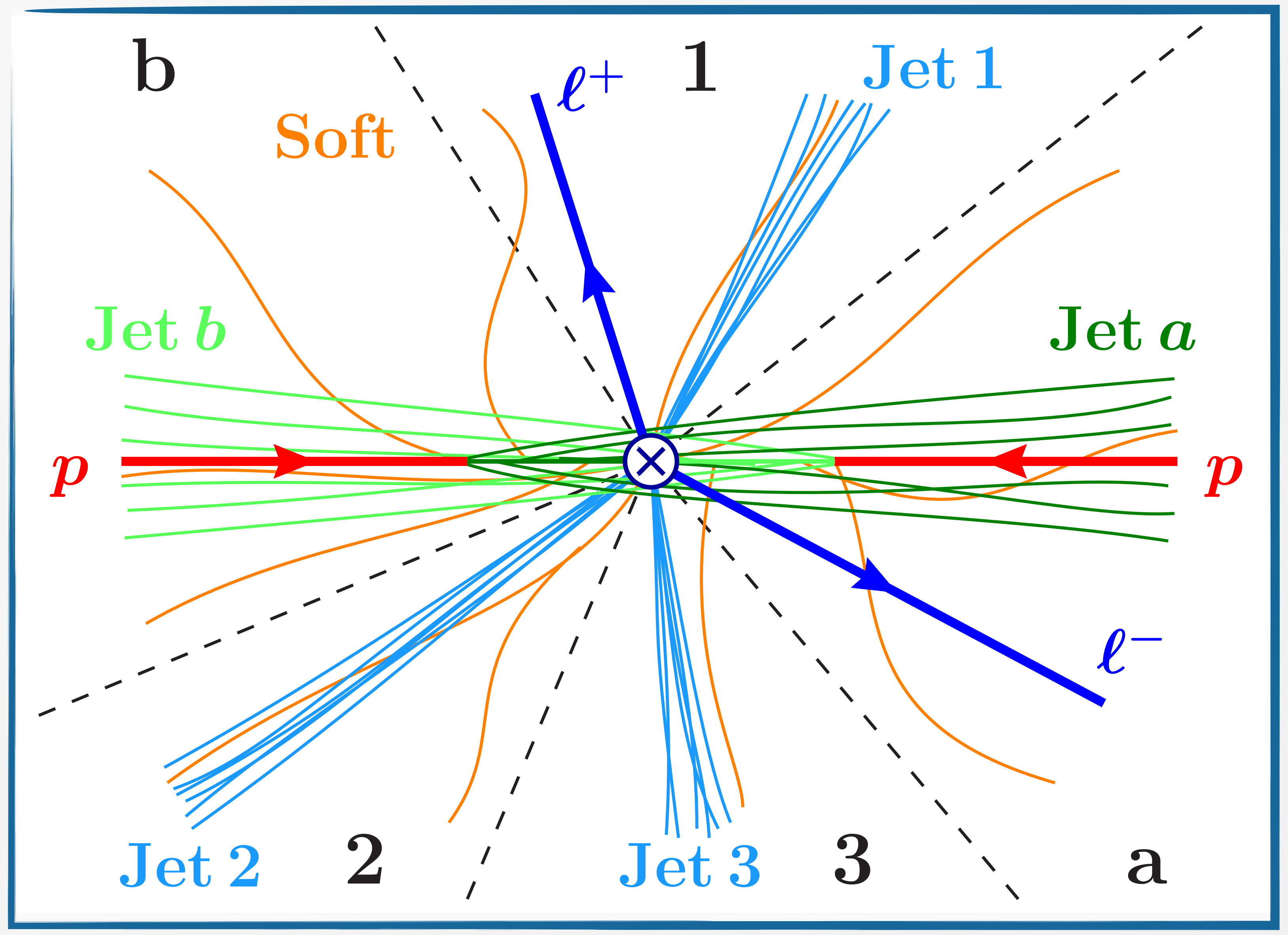
Since the resummed formula is only differential in $\Phi_0$, $r_0$, one has to make it differential in 2 more variables, e.g. energy ratio $z = E_m/E_s$ or azimuthal angle $\phi$. Use a normalised splitting probability to make the resummation differential in $\Phi_1$

$$\int \frac{d\Phi_1}{d\Phi_0 dr_0}\mathscr{P}(\Phi_1) = 1$$

# Choice of the resolution parameter

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 $q_j$

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




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

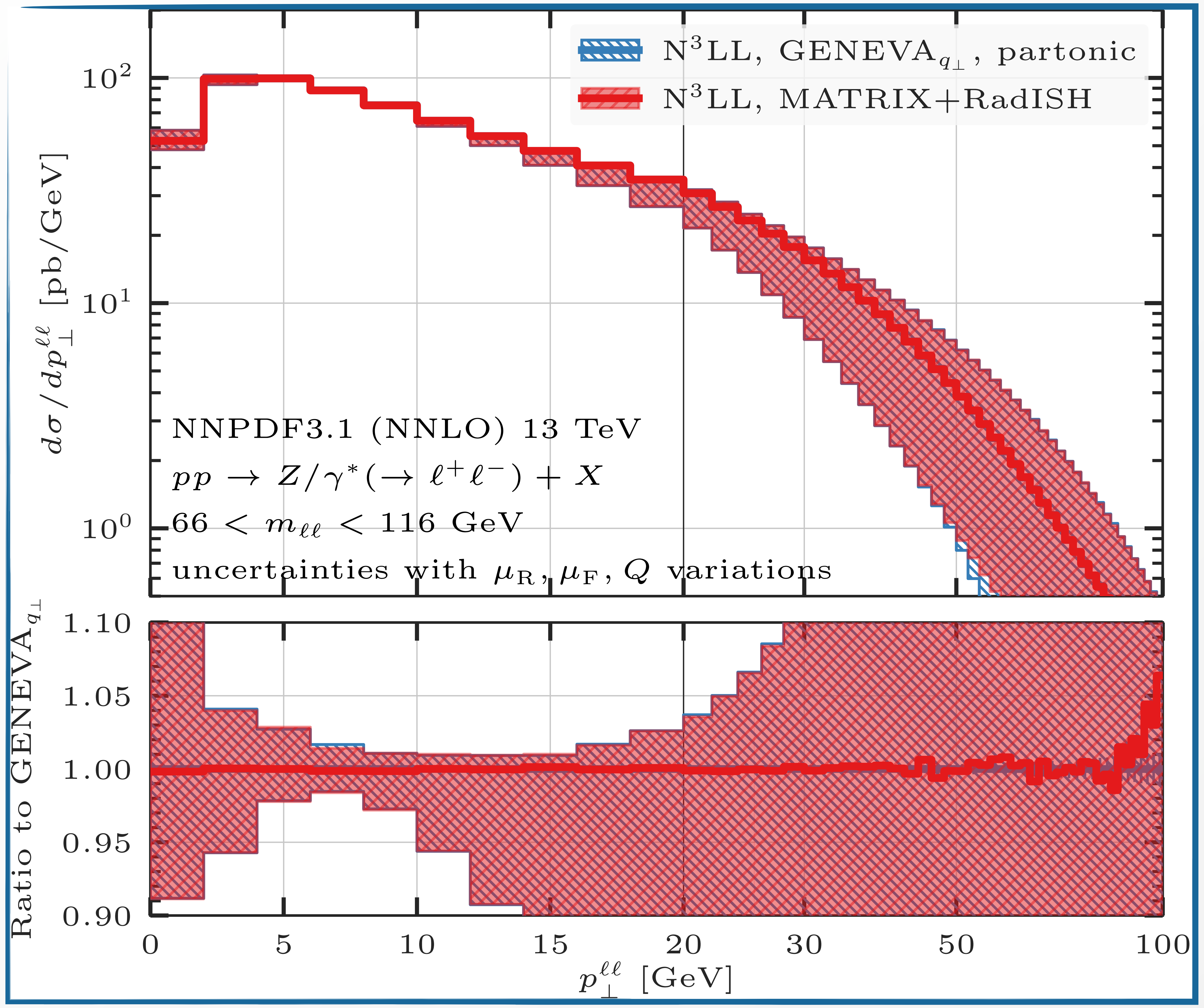
Extension of the Geneva method using the **transverse momentum of a colour-singlet system**, as implemented in RadISH, as a 0-jet separation variable [Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, LR ’21]

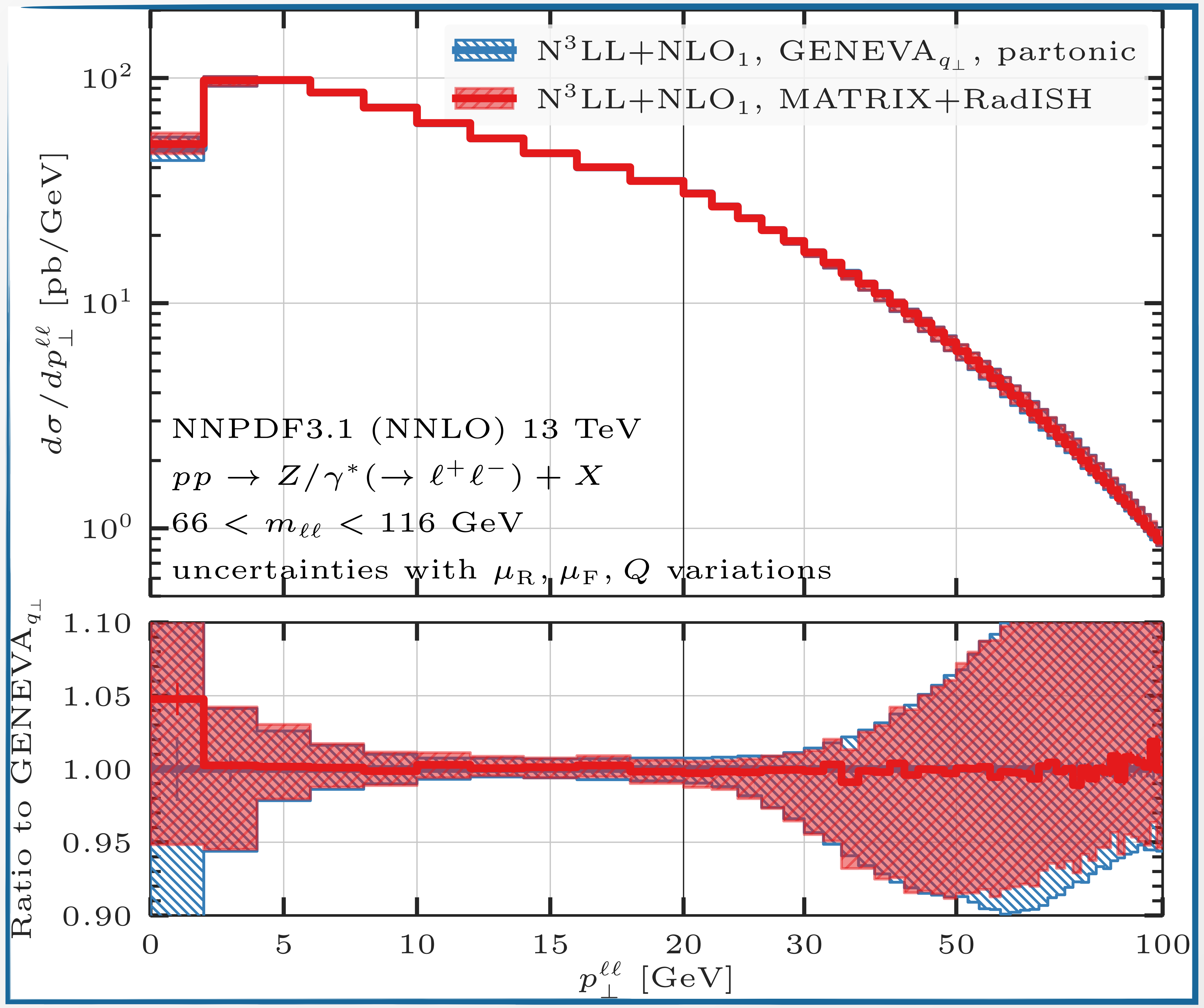
Advantages: **availability of higher-order resummation**, up to N$^3$LL, and **extreme precision** at which it is measured by the LHC experiments for different processes

Transverse-momentum resummation ingredients are also used in MiNNLOPS approach [Monni, Nason, Re, Wiesemann, Zanderighi ’19]

# Validation

Parton-level comparison for the $q_\perp$ spectrum

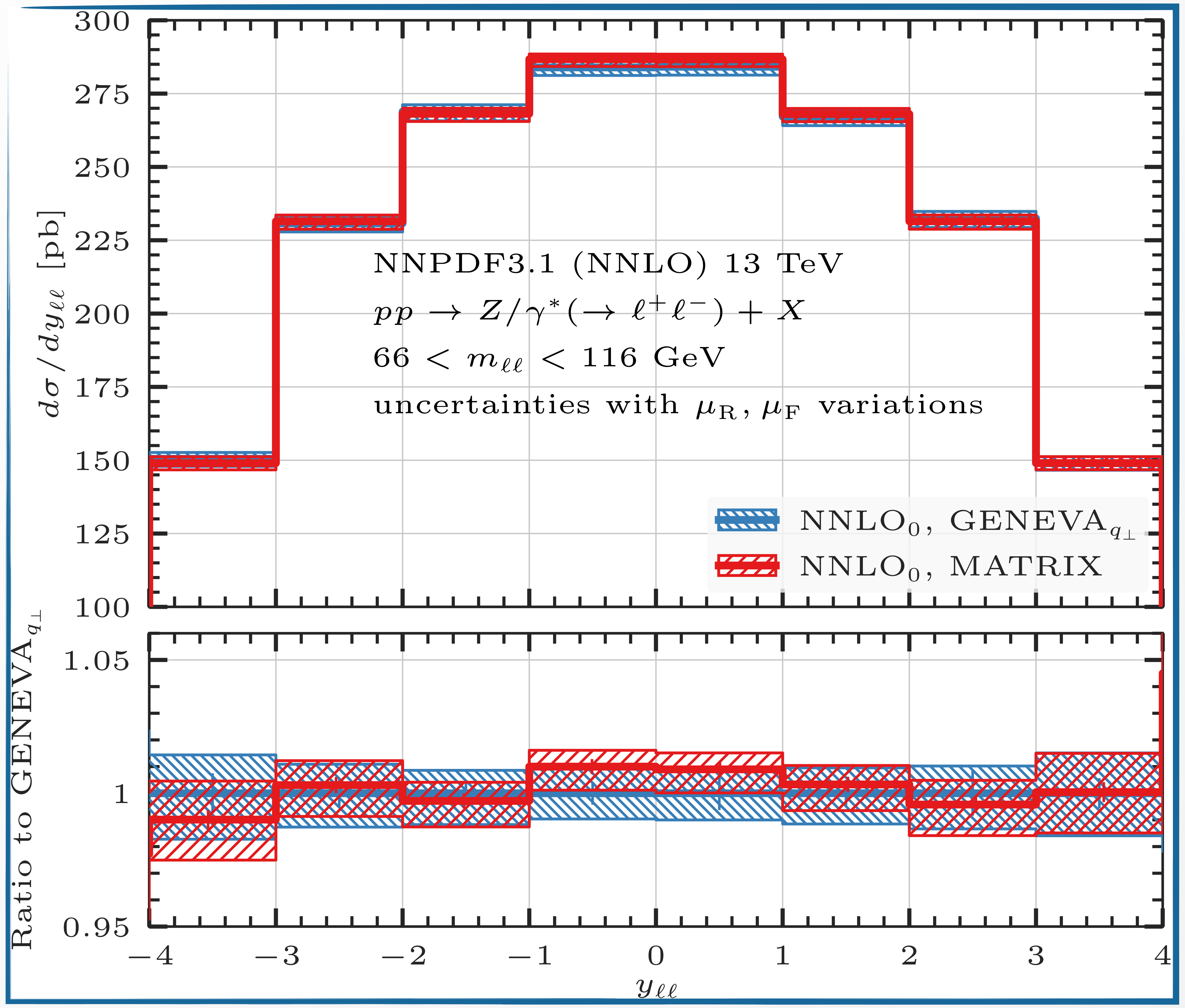


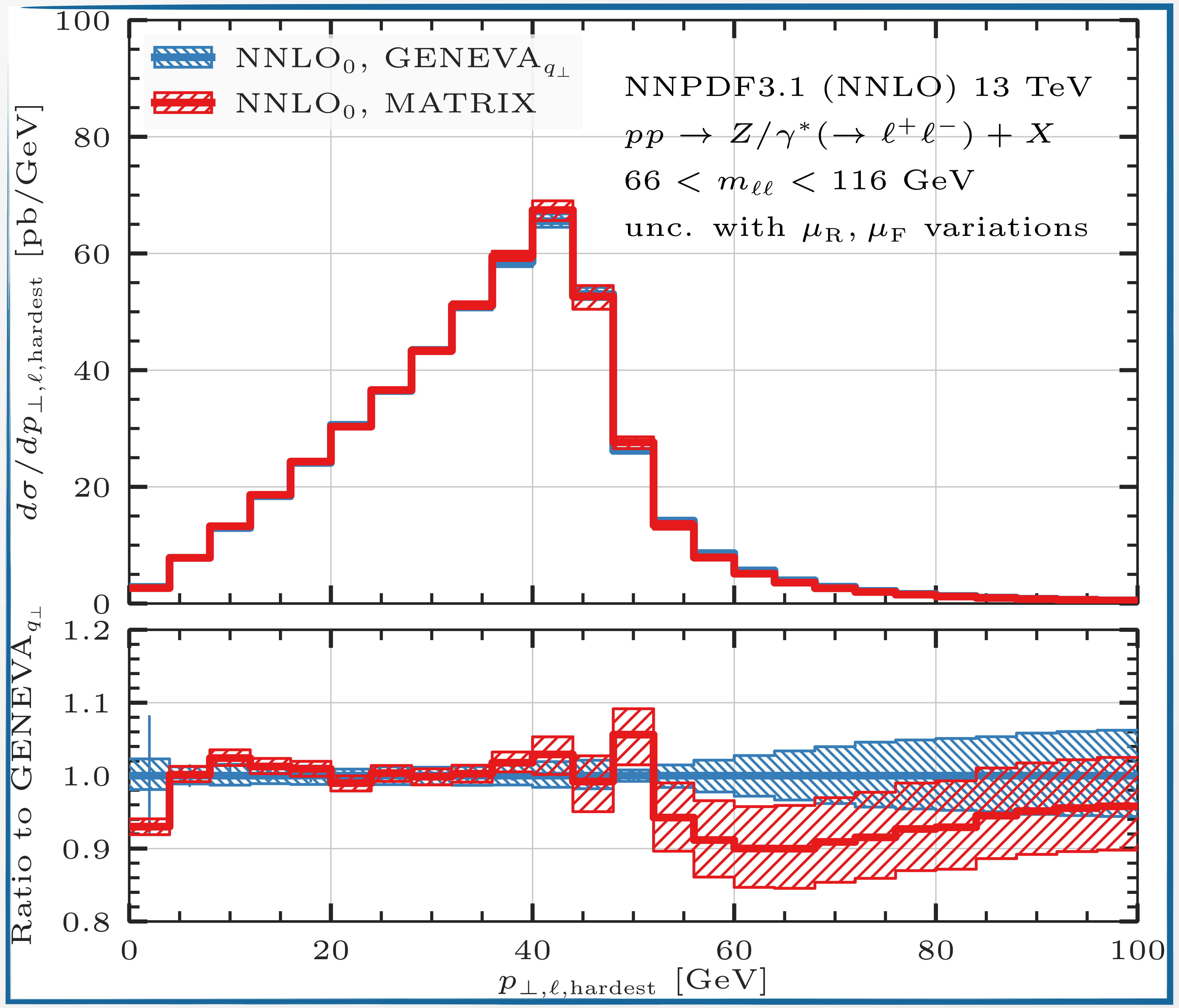




[Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, LR '21]

# Validation

Parton-level comparison for fixed-order distributions



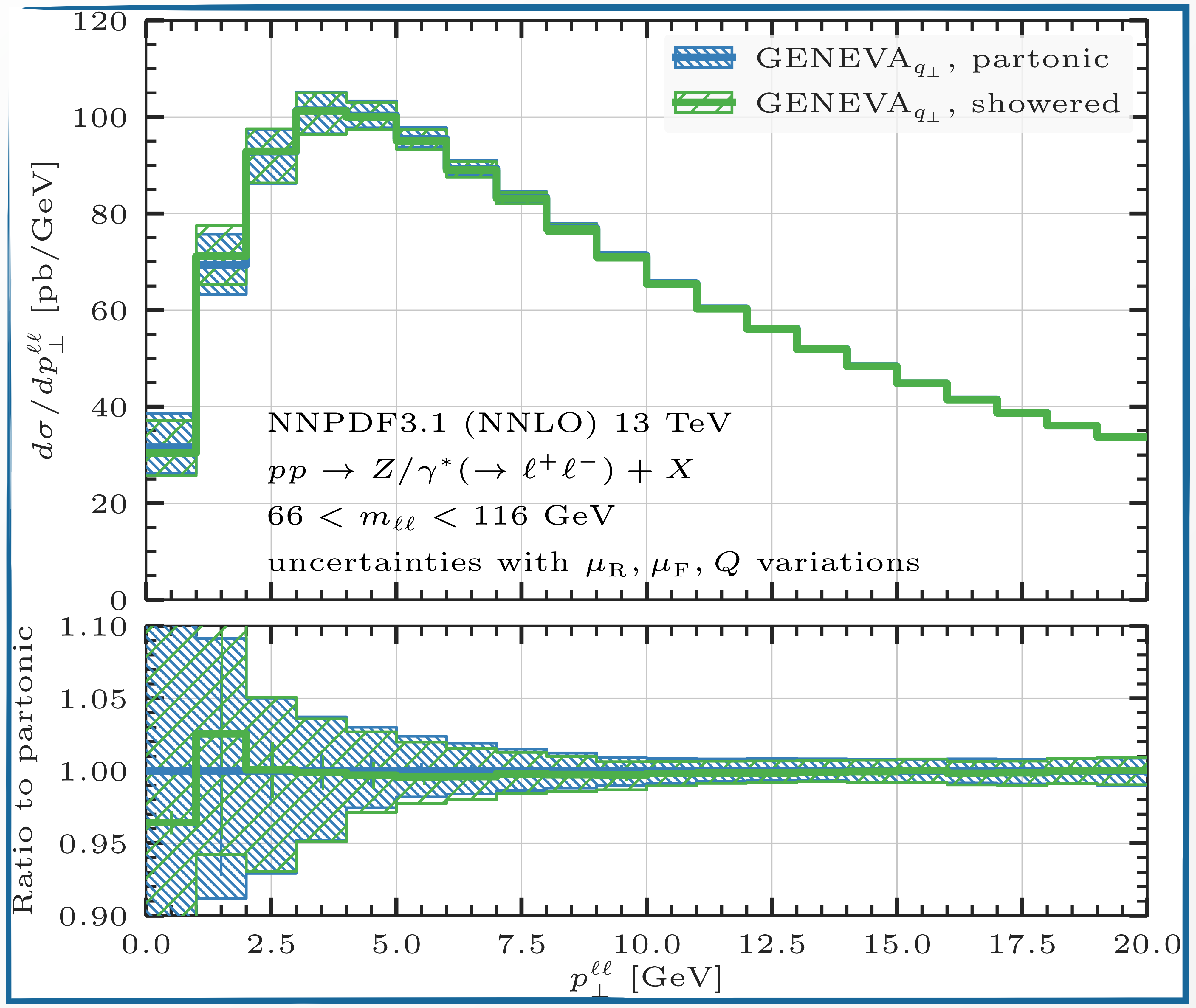



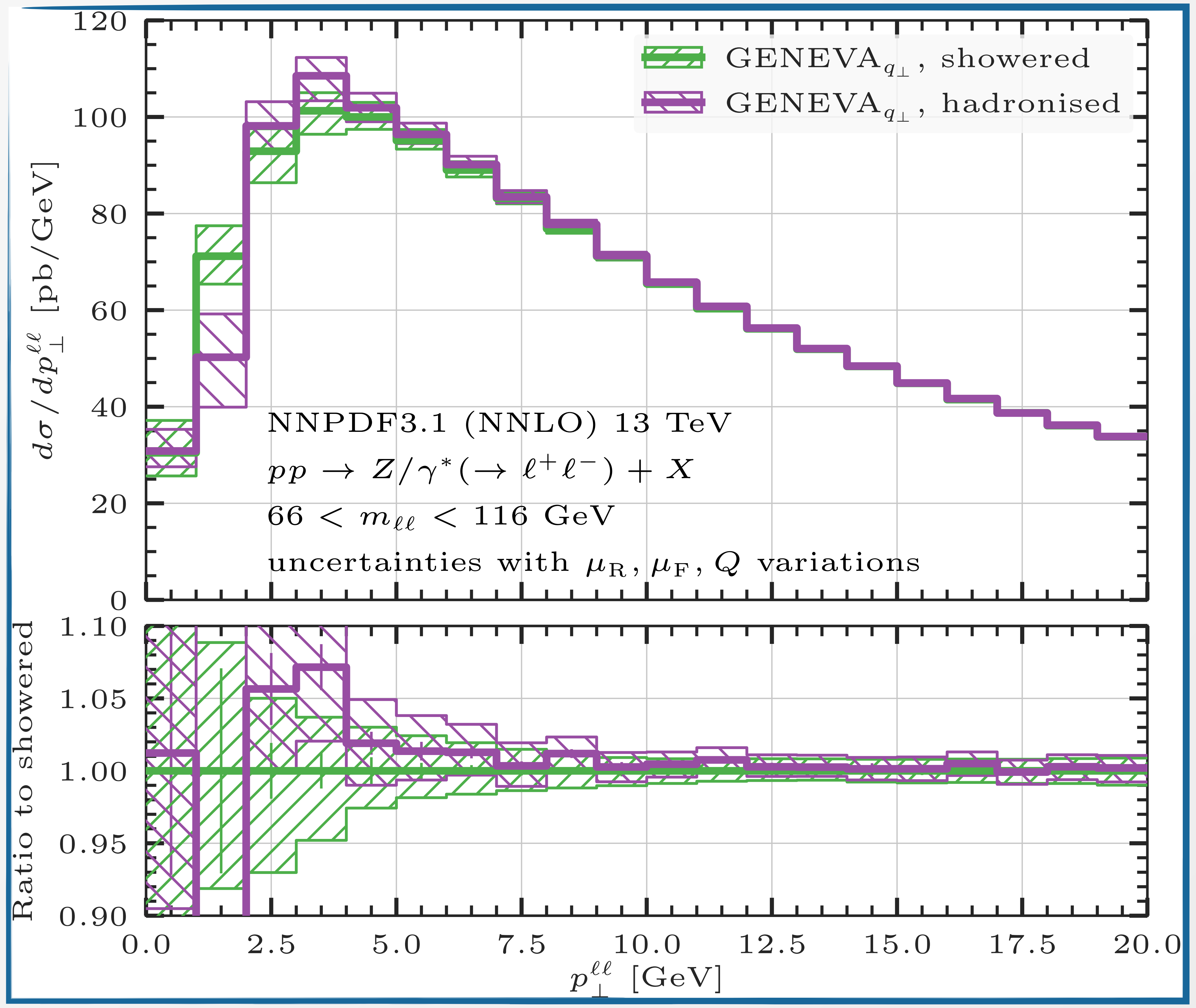

[Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, LR '21]

# Results after matching with parton shower

No additional constraint on the shower to preserve resummation accuracy

Formally, after the shower the predictions lose N$^3$LL accuracy that they retained at parton level

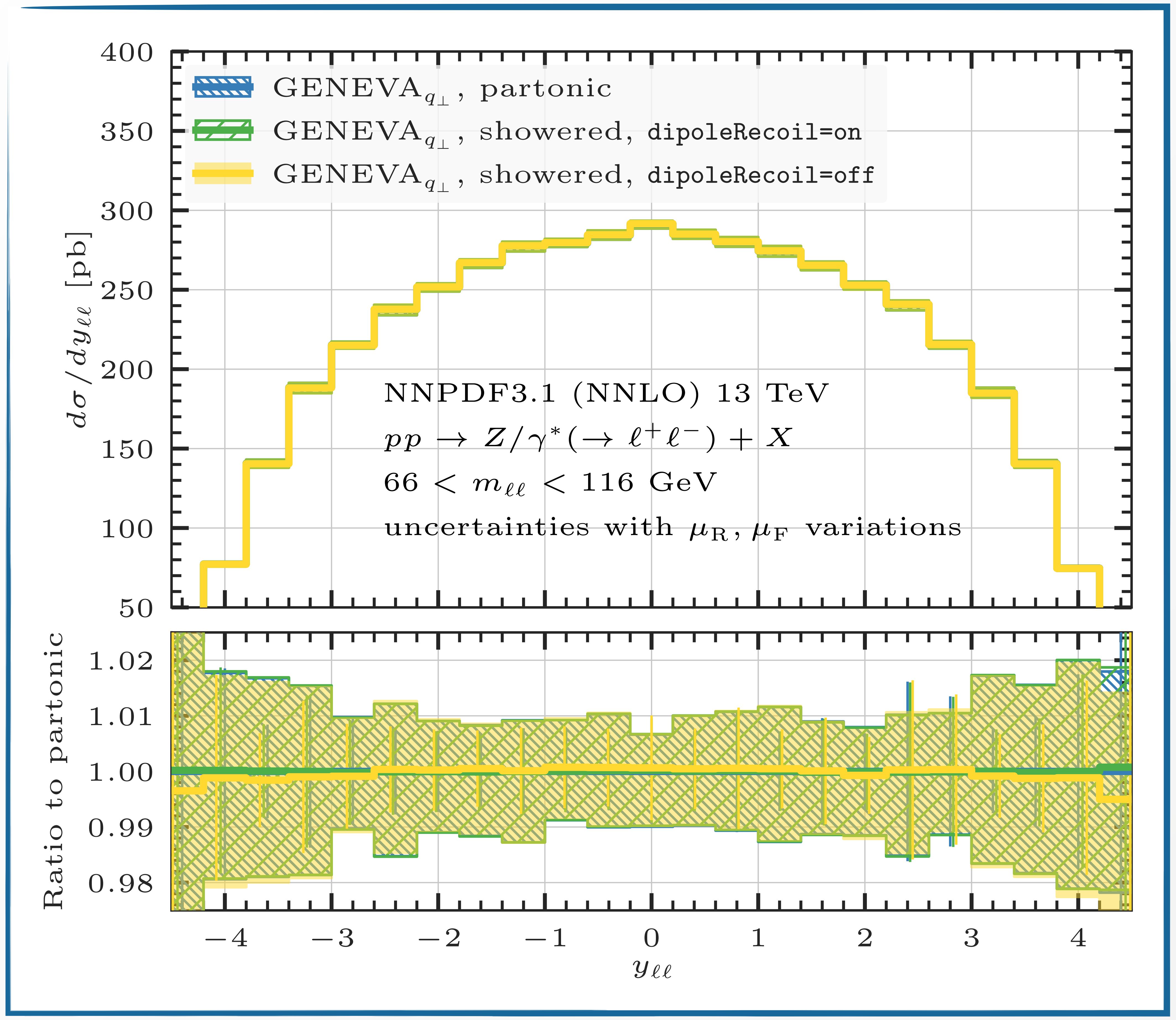


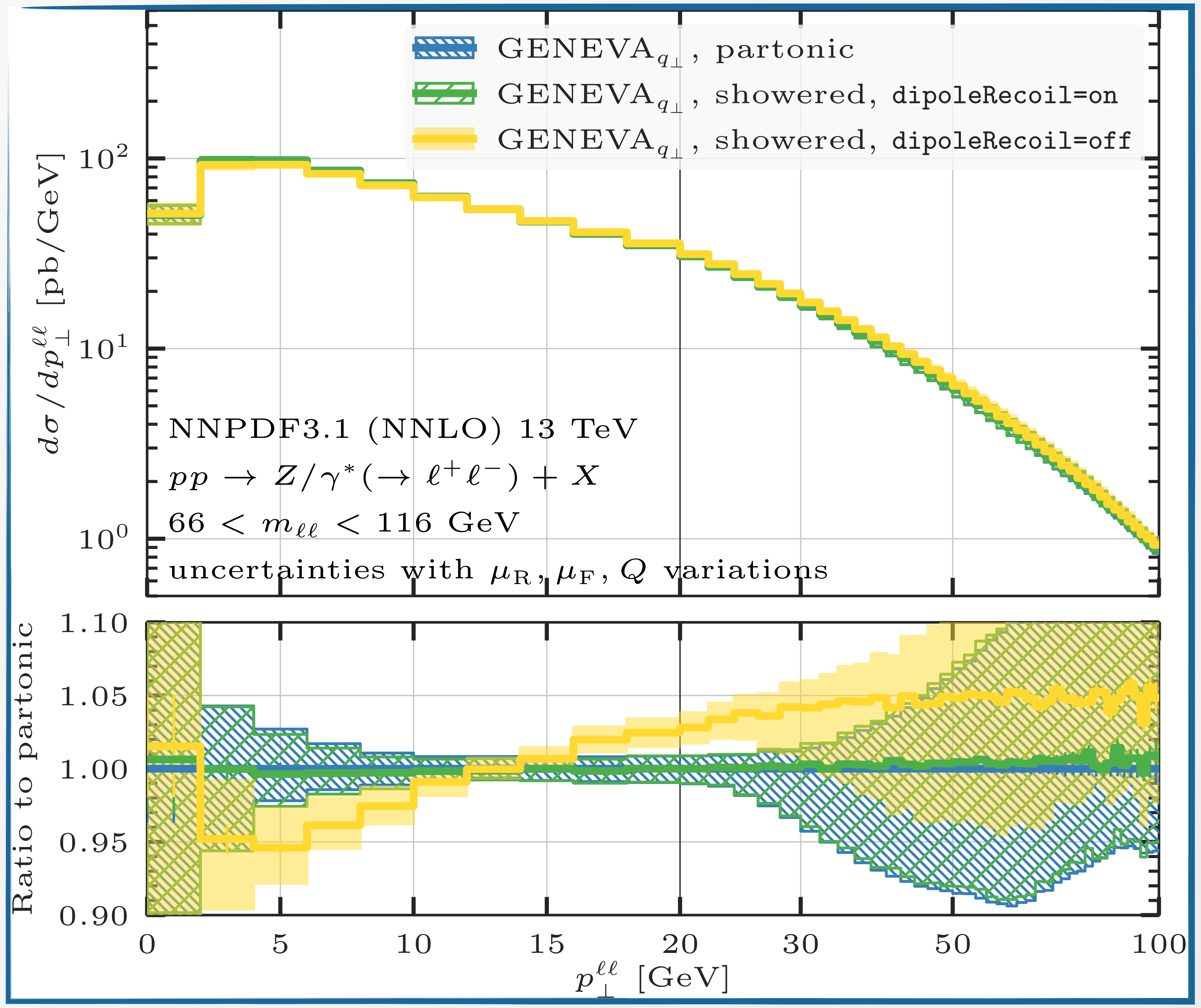




[Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, LR '21]

However, very good agreement between showered (before MPI and hadronisation) and parton-level results

# Results after matching with parton shower

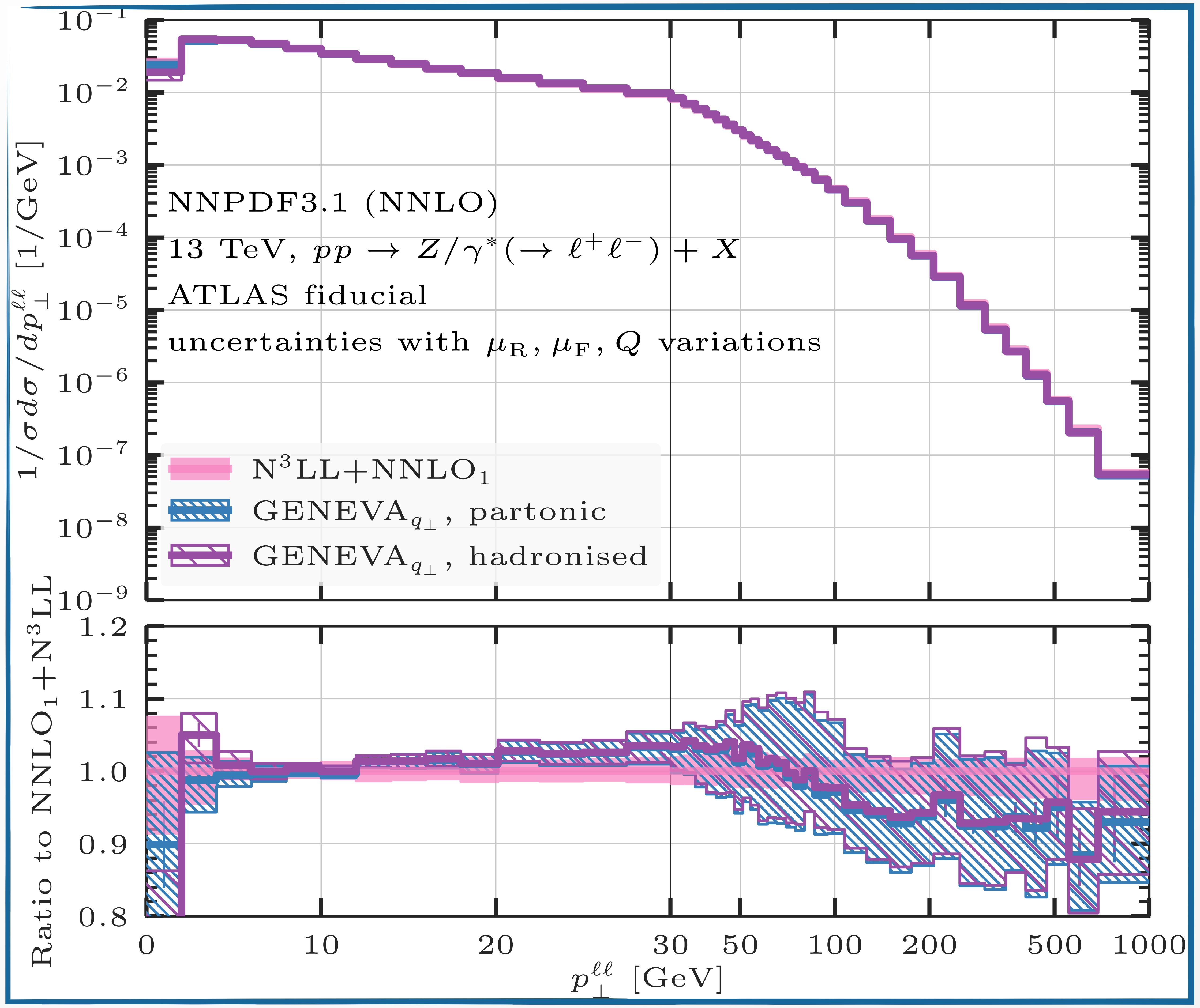


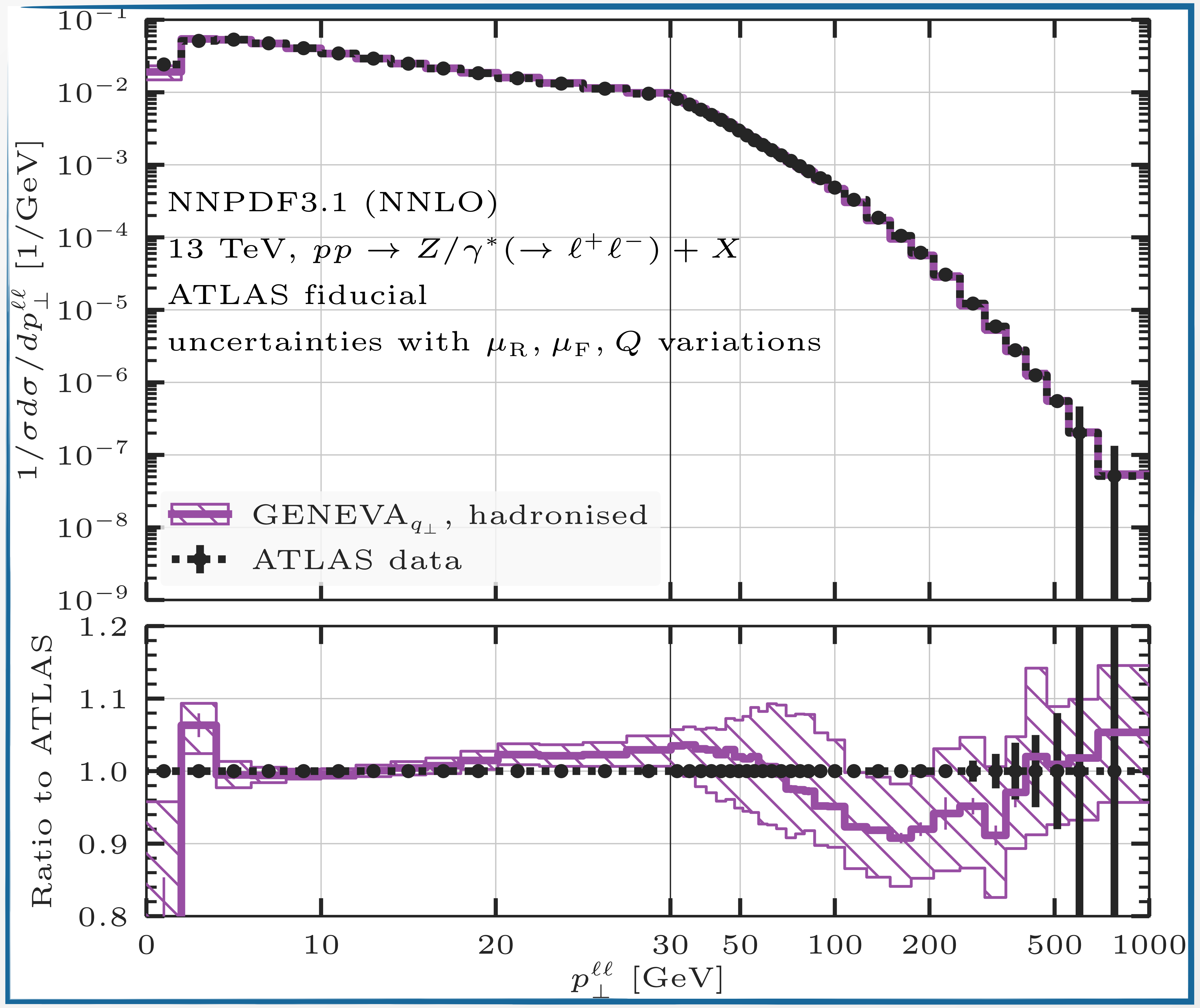




[Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, LR '21]

Non-negligible dependence on recoil scheme of the shower, which can affect the transverse momentum spectrum at the few percent level

# Comparison with state-of-the-art parton-level results and with experimental data




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

# Summary

- Precision of the data demands an increasing theoretical accuracy at the **multi-differential level** to fully exploit LHC potential
- New formalism formulated in **direct space** for all-order resummation up to **N$^3$LL accuracy** for inclusive, transverse observables.
- Direct space formulation (RadISH) provides guidance to obtain **elegant and compact formulation in *b*-space** for **joint resummation** for a **double-differential** kinematic observable involving a **jet algorithm** at NNLL accuracy and offers access to underlying dynamics
- Formalism can be readily extended to **more complex final states**; $2 \to 1$ and $2 \to 2$ colour singlet processes available via MATRIX+RadISH framework
- Transverse-momentum resummation as implemented in RadISH used within the GENEVA framework to construct an NNLO+PS event generator

# Backup

# All-order structure of the matrix element

$v = p_t/M$

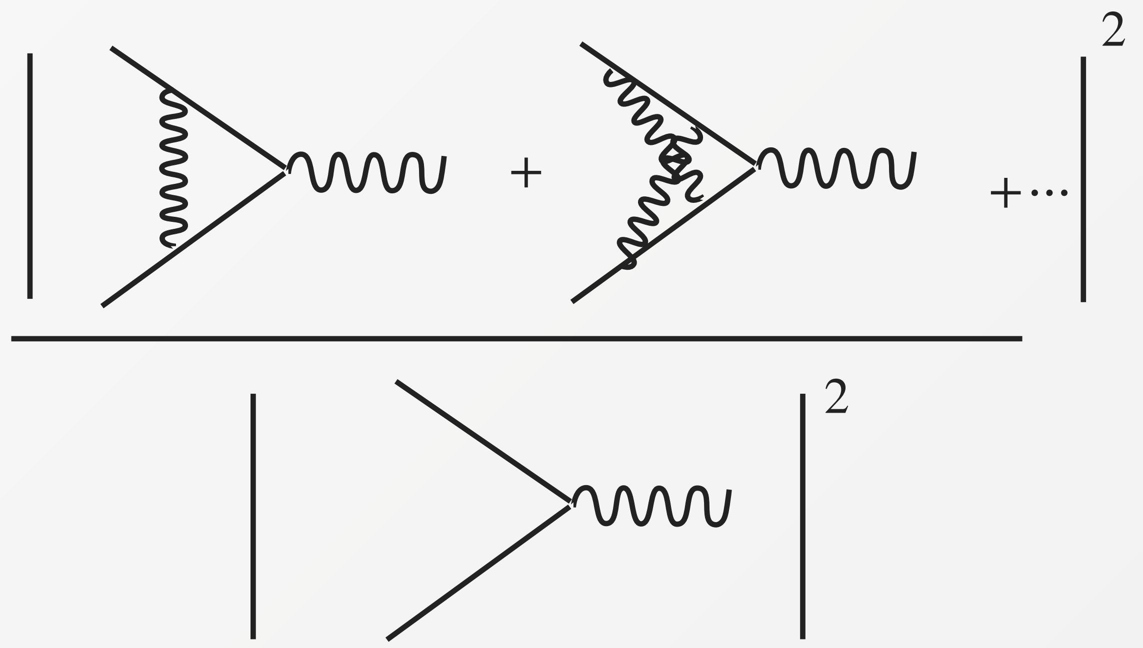
**single-particle phase space**

**matrix element for *n* real emissions**

$$\Sigma(v) = \int d\Phi_B \mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=1}^{n} [dk_i] |\mathcal{M}(\Phi_B, k_1, \ldots k_n)|^2 \Theta(v - V(\{\Phi_B\}, k_1, \ldots k_n))$$

**all-order form factor (virtuals)**

e.g. [Dixon, Magnea, Sterman '08]



# Transverse observable resummation with RadISH

1. Establish a **logarithmic counting** for the squared matrix element $|\mathcal{M}(\Phi_B, k_1, \dots k_n)|^2$

Decompose the squared amplitude in terms of ***n*-particle correlated blocks,** denoted by $|\tilde{\mathcal{M}}(k_1, \dots, k_n)|^2$ $(|\tilde{\mathcal{M}}(k_1)|^2 = |\mathcal{M}(k_1)|^2)$

LL NLL NNLL

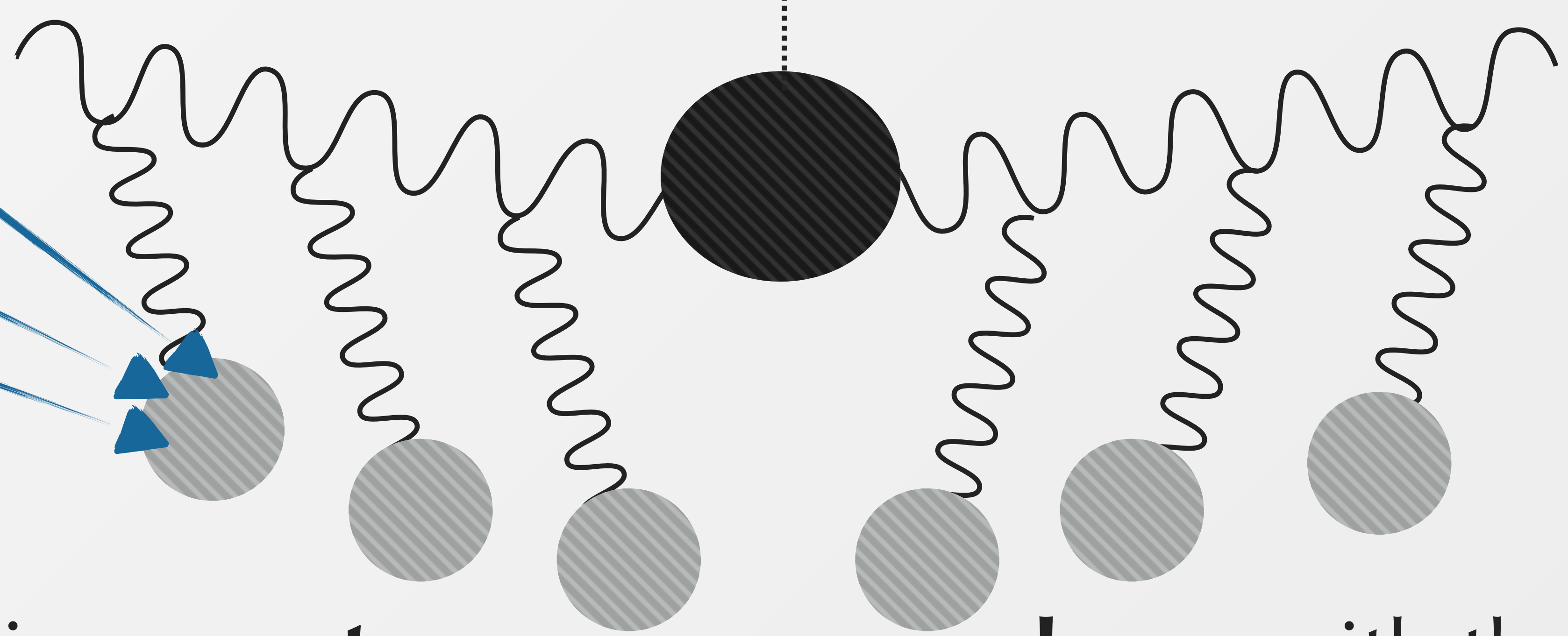
$$\sum_{n=0}^{\infty} |\mathcal{M}(\Phi_B, k_1, \dots, k_n)|^2 = |\mathcal{M}_B(\Phi_B|^2 \times \sum_{n=0}^{\infty} \frac{1}{n!} \left\{ \prod_{i=1}^{n} \left( |\mathcal{M}(k_i)|^2 + \int [dk_a][dk_b] |\tilde{\mathcal{M}}(k_a, k_b)|^2 \delta^{(2)}(\vec{k}_{ta} + \vec{k}_{tb} - \vec{k}_{ti}) \delta(Y_{ab} - Y_i) + \int [dk_a][dk_b][dk_c] |\tilde{\mathcal{M}}(k_a, k_b, k_c)|^2 \delta^{(2)}(\vec{k}_{ta} + \vec{k}_{tb} + \vec{k}_{tc} - \vec{k}_{ti}) \delta(Y_{abc} - Y_i) + \dots \right) \right\}$$

$$\equiv |\mathcal{M}_B(\Phi_B)|^2 \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} |\mathcal{M}(k_i)|^2_{\text{inc}}$$

*expression valid for inclusive observables

$$|\tilde{M}(k_1)|^2 = \frac{|M(k_1)|^2}{|M_B|^2} = |M(k_1)|^2$$

$$|\tilde{M}(k_1, k_2)|^2 = \frac{|M(k_1, k_2)|^2}{|M_B|^2} - \frac{1}{2!} |M(k_1)|^2 M|(k_2)|^2$$



Upon integration over the phase space, the expansion can be put in a **one to one correspondence** with the logarithmic structure

**Systematic recipe to include terms up to the desired logarithmic accuracy**

# Resummation in direct space: the $p_t$ case

2. Exploit rIRC safety to single out the IRC singularities of the real matrix element and achieve the **cancellation of the exponentiated divergences** of virtual origin

Introduce a slicing parameter $\epsilon \ll 1$ such that all inclusive blocks with $k_{t,i} < \epsilon k_{t,1}$, with $k_{t,1}$ hardest emission, can be neglected in the computation of the observable

$$\Sigma(v) = \int d\Phi_B |\mathcal{M}_B(\Phi_B)|^2 \mathcal{V}(\Phi_B)$$

unresolved emissions

$$\times \int [dk_1] |\mathcal{M}(k_1)|^2_{\text{inc}} \left( \sum_{l=0}^{\infty} \frac{1}{l!} \int \prod_{j=2}^{l+1} [dk_j] |\mathcal{M}(k_j)|^2_{\text{inc}} \Theta(\epsilon V(k_1) - V(k_j)) \right)$$

$$\times \left( \sum_{m=0}^{\infty} \frac{1}{m!} \int \prod_{i=2}^{m+1} [dk_i] |\mathcal{M}(k_i)|^2_{\text{inc}} \Theta(V(k_i) - \epsilon V(k_1)) \Theta\left(v - V(\Phi_B, k_1, \ldots, k_{m+1})\right) \right)$$

resolved emissions

**Unresolved emission** doesn't contribute to the evaluation of the observable: it can be exponentiated directly and employed to cancel the virtual divergences, giving rise to a Sudakov radiator

$$\mathcal{V}(\Phi_B) \exp\left\{ \int [dk] |\mathcal{M}(k)|^2_{\text{inc}} \Theta(\epsilon V(k_1) - V(k)) \right\} \simeq e^{-R(\epsilon V(k_1))}$$

# Resummation in direct space: the $p_t$ case

Result at NLL accuracy can be written as

$$\Sigma(v) = \sigma^{(0)} \int \frac{dv_1}{v_1} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(\epsilon v_1)} R'\left(v_1\right) \qquad v_i = V(k_i), \quad \zeta_i = v_i / v_1$$

$$\times \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_{\epsilon}^{1} \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'\left(\zeta_i v_1\right) \, \Theta\left(v - V(\Phi_B, k_1, \ldots, k_{n+1})\right)$$

Formula can be evaluated with Monte Carlo method; dependence on $\epsilon$ vanishes exactly and result is finite in four dimensions

It contains **subleading effect** which in the original CAESAR approach are disposed of by expanding $R$ and $R'$ around $v$

$$R(\epsilon v_1) = R(v) + \frac{dR(v)}{d\ln(1/v)} \ln\frac{v}{\epsilon v_1} + \mathcal{O}\left(\ln^2 \frac{v}{\epsilon v_1}\right)$$

$$R'\left(v_i\right) = R'(v) + \mathcal{O}\left(\ln\frac{v}{v_i}\right)$$

**Not possible!** valid only if the ratio $v_i/v$ remains of order one in the whole emission phase space, but for observables which feature kinematic cancellations there are configurations with $v_i \gg v$. **Subleading effects necessary**

# Resummation in direct space: the $p_t$ case

Result at NLL accuracy can be written as

$$\Sigma(v) = \sigma^{(0)} \int \frac{dv_1}{v_1} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(\epsilon v_1)} R'\left(v_1\right) \qquad v_i = V(k_i), \quad \zeta_i = v_i/v_1$$

$$\times \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_\epsilon^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'\left(\zeta_i v_1\right)\, \Theta\left(v - V(\Phi_B, k_1, \ldots, k_{n+1})\right)$$

Formula can be evaluated with Monte Carlo method; dependence on $\epsilon$ vanishes exactly and result is finite in four dimensions

Convenient to perform an expansion around $k_{t1}$ (more efficient and simpler implementation)

$$R(\epsilon k_{t1}) = R(k_{t1}) + \frac{dR(k_{t1})}{d\ln(1/k_{t1})} \ln\frac{1}{\epsilon} + \mathcal{O}\left(\ln^2\frac{1}{\epsilon}\right)$$

$$R'\left(k_{ti}\right) = R'(k_{t1}) + \mathcal{O}\left(\ln\frac{k_{t1}}{k_{ti}}\right)$$

**Subleading effects retained**: no divergence at small $v$, power-like behaviour respected

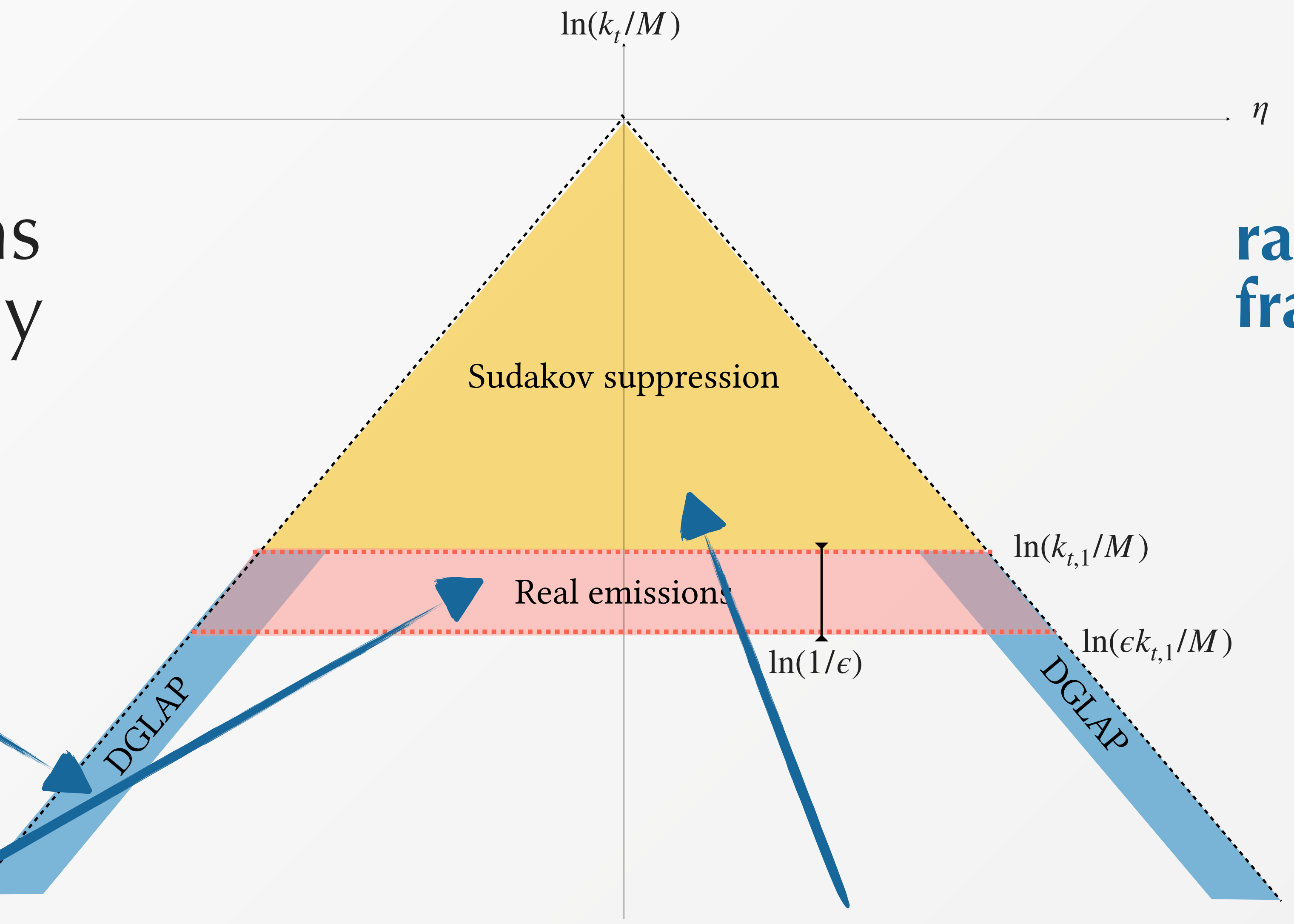
**Logarithmic accuracy** defined in terms of $\ln(M/k_{t1})$

Result formally equivalent to the $b$-space formulation

# Parton luminosities

Consider configurations in which emissions are ordered in $k_{t,i}$, $k_{t,1}$ hardest emission

Phase space for each secondary emission can be depicted in the Lund diagram




**DGLAP evolution** governs the radiation in the strictly collinear limit

**rapidity in the centre-of-mass frame of the incoming partons**

**resolved emissions** live in this strip

remaining **unresolved real emissions** are combined with the virtual corrections to give rise to Sudakov suppression

- DGLAP evolution can be performed **inclusively** up to $\epsilon k_{t,1}$ thanks to rIRC safety
- In the **overlapping region** hard-collinear emissions modify the observable's value: the evolution should be performed exclusively (unintegrated in $k_t$)
- At NLL the real radiation can be approximated with its soft limit: DGLAP can be performed inclusively up to $k_{t,1}$ (i.e. one can evaluate $\mu_F = k_{t,1}$)

# Beyond NLL

Extension to NNLL and beyond requires the systematic inclusion of the correlated blocks necessary to achieve the desired logarithmic accuracy

Moreover, one needs to **relax a series of assumptions** which give rise to subleading corrections neglected at NLL (for instance, exact rapidity bounds). These corrections can be included systematically by including additional terms in the expansion

$$R(\epsilon v_1) = R(v_1) + \frac{dR(v_1)}{d\ln(1/v_1)}\ln\frac{1}{\epsilon} + \mathcal{O}\left(\ln^2\frac{1}{\epsilon}\right)$$

Finally, one needs to specify a complete treatment for **hard-collinear radiation.** Starting at NNLL one or more real emissions can be hard and collinear to the emitting leg, and the available phase space for subsequent real emissions changes

Two classes of contributions:

- one soft by construction and which is analogous to the R′ contribution

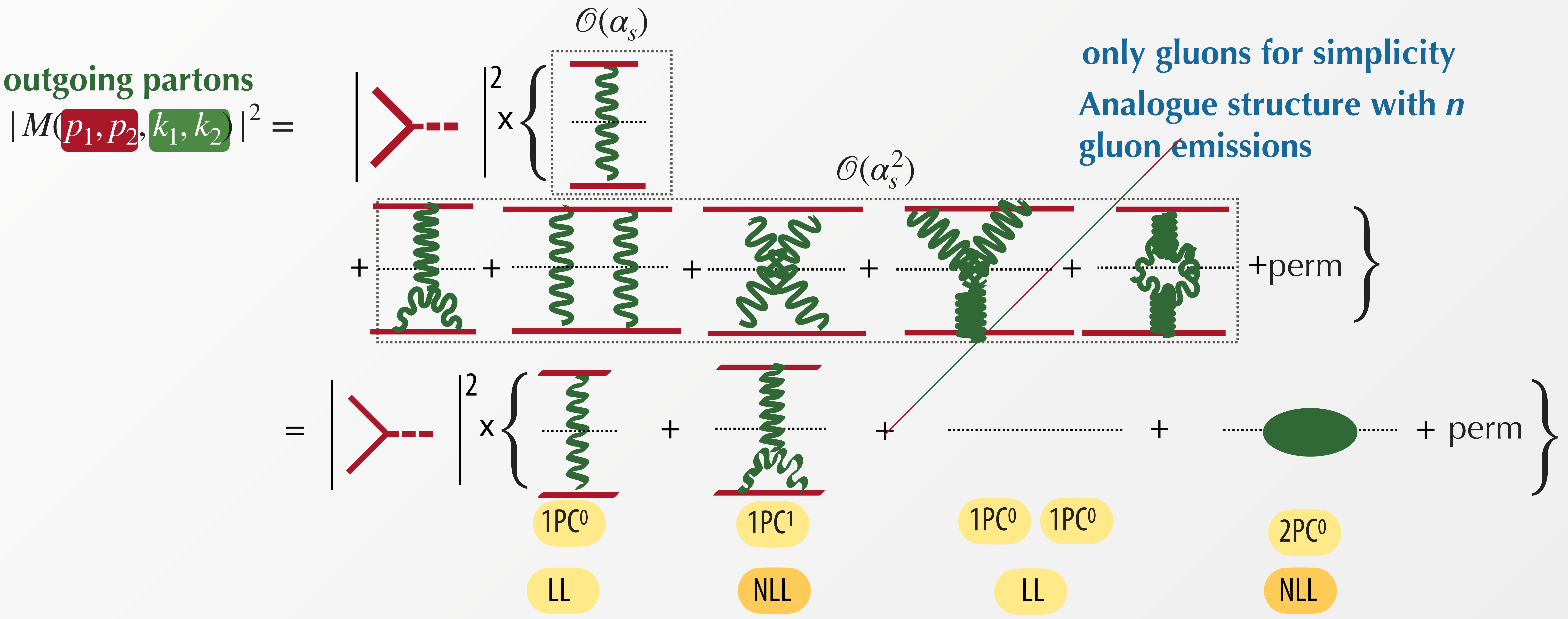
$$R'\left(v_i\right) = R'(v_1) + \mathcal{O}\left(\ln\frac{v_1}{v_i}\right)$$

- another hard and collinear (exclusive DGLAP step): last step of DGLAP evolution must be performed unintegrated in $k_t$

# Logarithmic counting

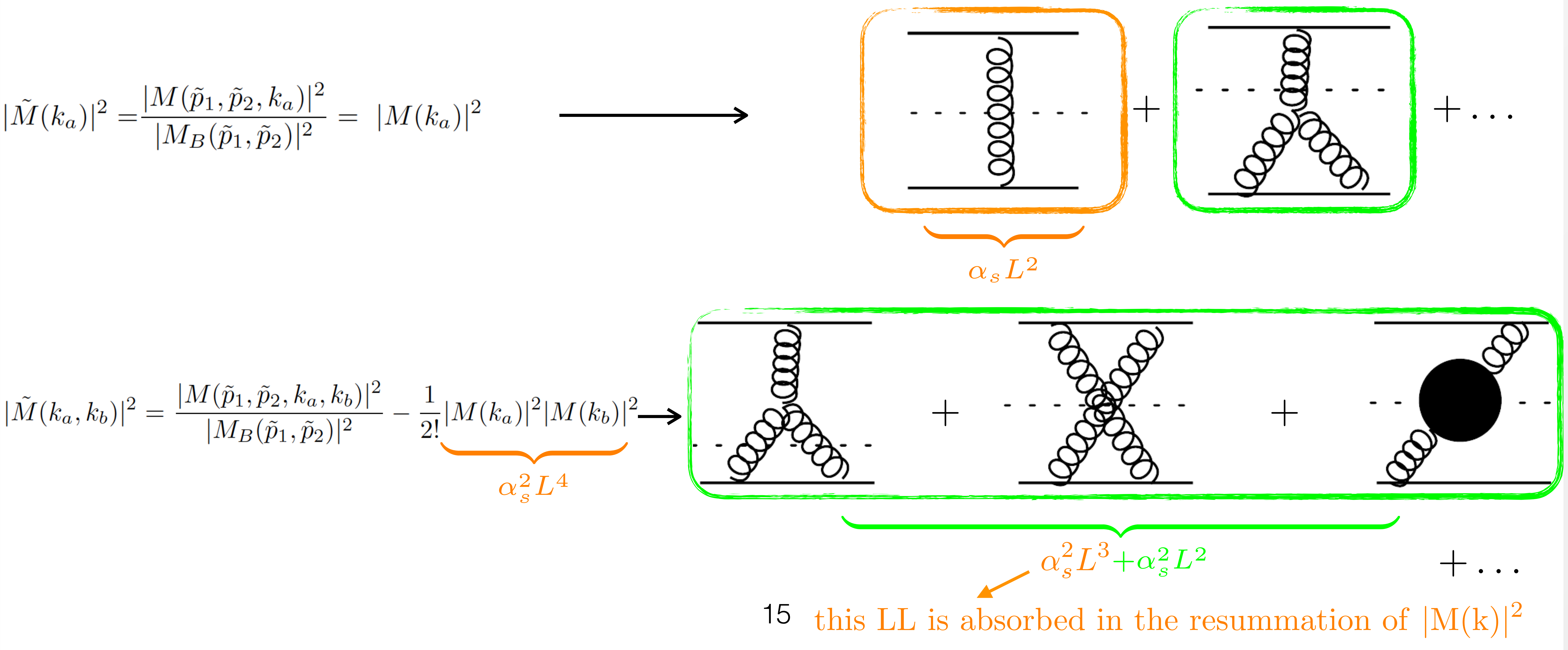
Necessary to establish a **well defined logarithmic counting**: possibile to do that by decomposing the squared amplitude in terms of n-particle correlated blocks (**nPC**)

e.g. $pp \to H$ + emission of up to 2 (soft) gluons $O(\alpha_s^2)$




Logarithmic counting defined in terms of **nPC blocks** (owing to rIRC safety of the observable)

# Logarithmic counting: correlated blocks




Thanks to P. Monni

# Resummation at NLL accuracy

Final result at NLL

$$\frac{d\Sigma(v)}{d\Phi_B} = \int \frac{dk_{t,1}}{k_{t,1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(k_{t,1})} \epsilon^{R'(k_{t,1})} \mathscr{L}_{\rm NLL}(k_{t,1}) R'\left(k_{t,1}\right)$$

$$\times \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_\epsilon^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'\left(\zeta_i k_{t,1}\right) \Theta\left(v - V(\Phi_B, k_1, \ldots, k_{n+1})\right)$$

This formula can be evaluated by means of fast Monte Carlo methods **`RadISH (Radiation off Initial State Hadrons)`**

Parton luminosity at NLL reads

$$\mathscr{L}_{\rm NLL}(k_{t,1}) = \sum_c \frac{d|M_B|^2_{c\bar{c}}}{d\Phi_B} f_c\left(x_1, k_{t,1}^2\right) f_{\bar{c}}\left(x_2, k_{t,1}^2\right)$$

At higher logarithmic accuracy, it includes **coefficient functions** and **hard-virtual** corrections

# Result at N$^3$LL accuracy

$$\frac{d\Sigma(v)}{d\Phi_B} = \int \frac{dk_{t1}}{k_{t1}}\frac{d\phi_1}{2\pi}\partial_L\left(-e^{-R(k_{t1})}\mathcal{L}_{\mathrm{N^3LL}}(k_{t1})\right)\int d\mathcal{Z}[\{R',k_i\}]\Theta\left(v - V(\{\tilde{p}\},k_1,\ldots,k_{n+1})\right)$$

$$+\int \frac{dk_{t1}}{k_{t1}}\frac{d\phi_1}{2\pi}e^{-R(k_{t1})}\int d\mathcal{Z}[\{R',k_i\}]\int_0^1\frac{d\zeta_s}{\zeta_s}\frac{d\phi_s}{2\pi}\left\{\left(R'(k_{t1})\mathcal{L}_{\mathrm{NNLL}}(k_{t1}) - \partial_L\mathcal{L}_{\mathrm{NNLL}}(k_{t1})\right)\right.$$
$$\times\left(R''(k_{t1})\ln\frac{1}{\zeta_s}+\frac{1}{2}R'''(k_{t1})\ln^2\frac{1}{\zeta_s}\right) - R'(k_{t1})\left(\partial_L\mathcal{L}_{\mathrm{NNLL}}(k_{t1}) - 2\frac{\beta_0}{\pi}\alpha_s^2(k_{t1})\hat{P}^{(0)}\otimes\mathcal{L}_{\mathrm{NLL}}(k_{t1})\ln\frac{1}{\zeta_s}\right)$$
$$\left.+\frac{\alpha_s^2(k_{t1})}{\pi^2}\hat{P}^{(0)}\otimes\hat{P}^{(0)}\otimes\mathcal{L}_{\mathrm{NLL}}(k_{t1})\right\}\left\{\Theta\left(v - V(\{\tilde{p}\},k_1,\ldots,k_{n+1},k_s)\right) - \Theta\left(v - V(\{\tilde{p}\},k_1,\ldots,k_{n+1})\right)\right\}$$

$$+\frac{1}{2}\int \frac{dk_{t1}}{k_{t1}}\frac{d\phi_1}{2\pi}e^{-R(k_{t1})}\int d\mathcal{Z}[\{R',k_i\}]\int_0^1\frac{d\zeta_{s1}}{\zeta_{s1}}\frac{d\phi_{s1}}{2\pi}\int_0^1\frac{d\zeta_{s2}}{\zeta_{s2}}\frac{d\phi_{s2}}{2\pi}R'(k_{t1})$$
$$\times\left\{\mathcal{L}_{\mathrm{NLL}}(k_{t1})\left(R''(k_{t1})\right)^2\ln\frac{1}{\zeta_{s1}}\ln\frac{1}{\zeta_{s2}} - \partial_L\mathcal{L}_{\mathrm{NLL}}(k_{t1})R''(k_{t1})\left(\ln\frac{1}{\zeta_{s1}}+\ln\frac{1}{\zeta_{s2}}\right)\right.$$
$$\left.+\frac{\alpha_s^2(k_{t1})}{\pi^2}\hat{P}^{(0)}\otimes\hat{P}^{(0)}\otimes\mathcal{L}_{\mathrm{NLL}}(k_{t1})\right\}$$
$$\times\left\{\Theta\left(v - V(\{\tilde{p}\},k_1,\ldots,k_{n+1},k_{s1},k_{s2})\right) - \Theta\left(v - V(\{\tilde{p}\},k_1,\ldots,k_{n+1},k_{s1})\right) -\right.$$
$$\left.\Theta\left(v - V(\{\tilde{p}\},k_1,\ldots,k_{n+1},k_{s2})\right) + \Theta\left(v - V(\{\tilde{p}\},k_1,\ldots,k_{n+1})\right)\right\} + \mathcal{O}\left(\alpha_s^n\ln^{2n-6}\frac{1}{v}\right), \qquad (3.18)$$

[Bizon, Monni, Re, LR, Torrielli '17]

All ingredients to perform resummation at **N$^3$LL accuracy** are now available

[Catani *et al.* '11, '12][Gehrmann *et al.* '14][Li, Zhu '16, Vladimirov '16][Moch *et al.* '18, Lee *et al.* '19]

Fixed-order predictions now available at **NNLO**

[A. Gehrmann-De Ridder *et al.* '15, 16, '17][Boughezal *et al.* '15, 16]

# Matching with fixed order

Multiplicative matching performed at the **double-cumulant level**

fixed-order double-cumulative result at NNLO

double-cumulative result at NNLL

$$\sigma_{\mathrm{NNLO}}(p_\perp^H < p_\perp^{H,\mathrm{v}}, p_\perp^{\mathrm{J}} < p_\perp^{\mathrm{J,v}}) = \sigma_{\mathrm{NNLO}} - \int \Theta(p_\perp^H > p_\perp^{H,\mathrm{v}}) \vee \Theta(p_\perp^{\mathrm{J}} > p_\perp^{\mathrm{J,v}}) d\sigma_{H+J,\mathrm{NLO}}$$

$$\sigma_{\mathrm{match}}(p_\perp^H < p_\perp^{H,\mathrm{v}}, p_\perp^{\mathrm{J}} < p_\perp^{\mathrm{J,v}}) = \frac{\sigma_{\mathrm{NNLL}}(p_\perp^H < p_\perp^{H,\mathrm{v}}, p_\perp^{\mathrm{J}} < p_\perp^{\mathrm{J,v}})}{\sigma_{\mathrm{NNLL}}(\{p_\perp^{\mathrm{J,v}}, p_\perp^{H,\mathrm{v}}\} \to \infty)} \left[ \sigma_{\mathrm{NNLL}}(\{p_\perp^{\mathrm{J,v}}, p_\perp^{H,\mathrm{v}}\} \to \infty) \frac{\sigma_{\mathrm{NNLO}}(p_\perp^H < p_\perp^{H,\mathrm{v}}, p_\perp^{\mathrm{J}} < p_\perp^{\mathrm{J,v}})}{\sigma_{\mathrm{NNLL,exp}}(p_\perp^H < p_\perp^{H,\mathrm{v}}, p_\perp^{\mathrm{J}} < p_\perp^{\mathrm{J,v}})} \right]_{\mathcal{O}(\alpha_s^2)}$$

asymptotic limit of the NNLL result

expansion of the double-cumulative result at NNLL

- NNLL+NNLO result for $p_\perp^{\mathrm{J,v}}$ recovered for $p_\perp^{\mathrm{H,v}} \to \infty$
- **NNLO constant** included through multiplicative matching (NNLL′ accuracy)

# Matching to fixed order: multiplicative matching

Cumulative cross section should reduce to the fixed order at large $v$

$$\Sigma^{\text{mult}}_{\text{matched}}(v) \sim \Sigma_{\text{res}}(v)\left[\frac{\Sigma_{\text{f.o.}}(v)}{\Sigma_{\text{res}}(v)}\right]_{\text{expanded}}$$

$$\Sigma_{\text{f.o}}(v) = \sigma_{f.o.} - \int_v^\infty \frac{d\sigma}{dv}dv$$

- allows to include constant terms from NNLO (if N³LO total xs available)
- physical suppression at small $v$ cures potential instabilities

To ensure that resummation does not affect the hard region of the spectrum when the matching is performed we introduce **modified logarithms**

This corresponds to restrict the rapidity phase space at large $k_t$

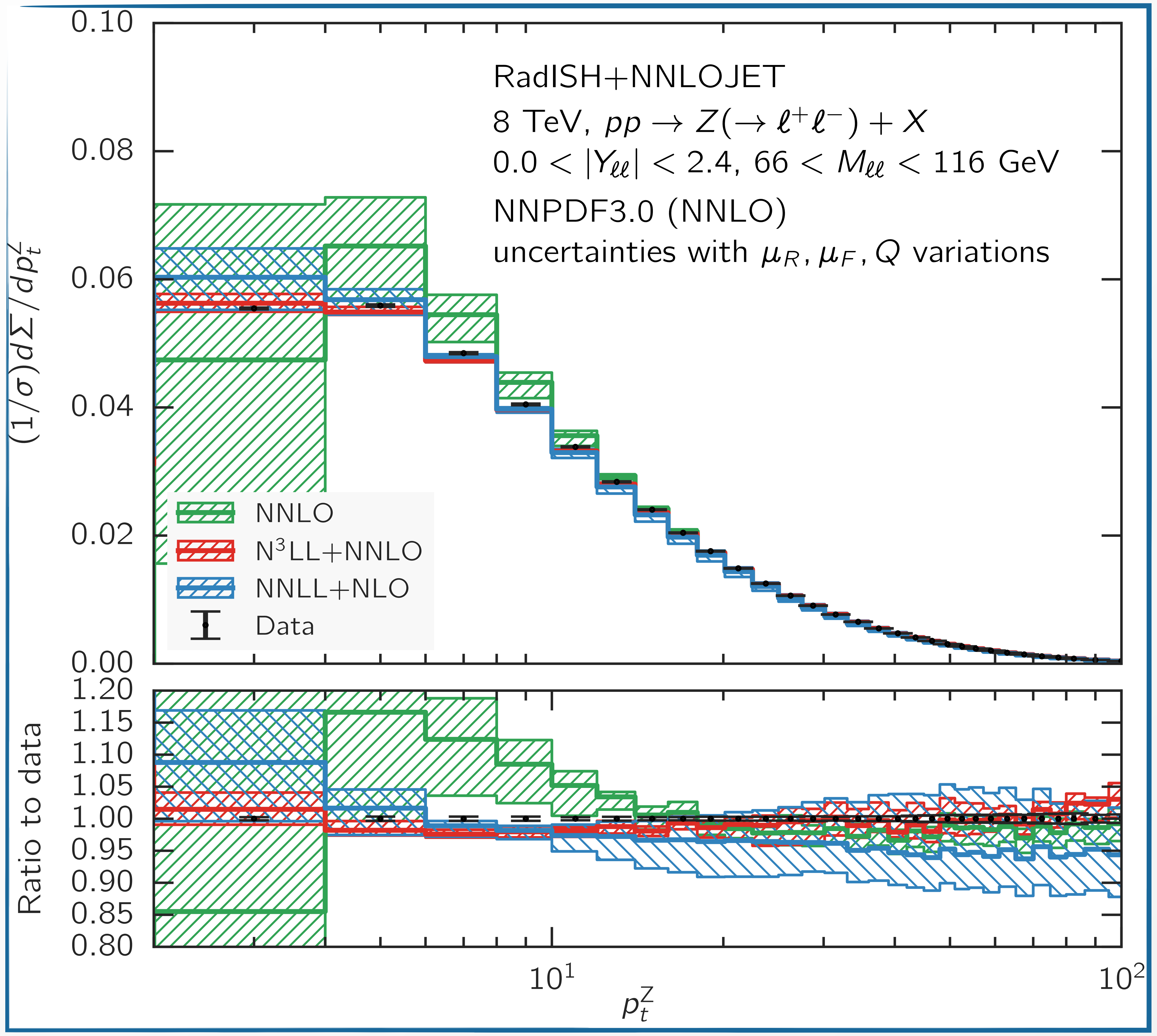
$$\int_{-\ln Q/k_{t,i}}^{\ln Q/k_{t,i}} d\eta \to \int_{-\ln Q/k_{t,1}}^{\ln Q/k_{t,1}} d\eta \to \int_{-\epsilon}^{\epsilon} d\eta \to 0$$

$$\ln(Q/k_{t1}) \to \frac{1}{p}\ln\left(1+\left(\frac{Q}{k_{t1}}\right)^p\right)$$

$Q$ : **perturbative resummation scale** used to probe the size of subleading logarithmic corrections

$p$ : arbitrary matching parameter

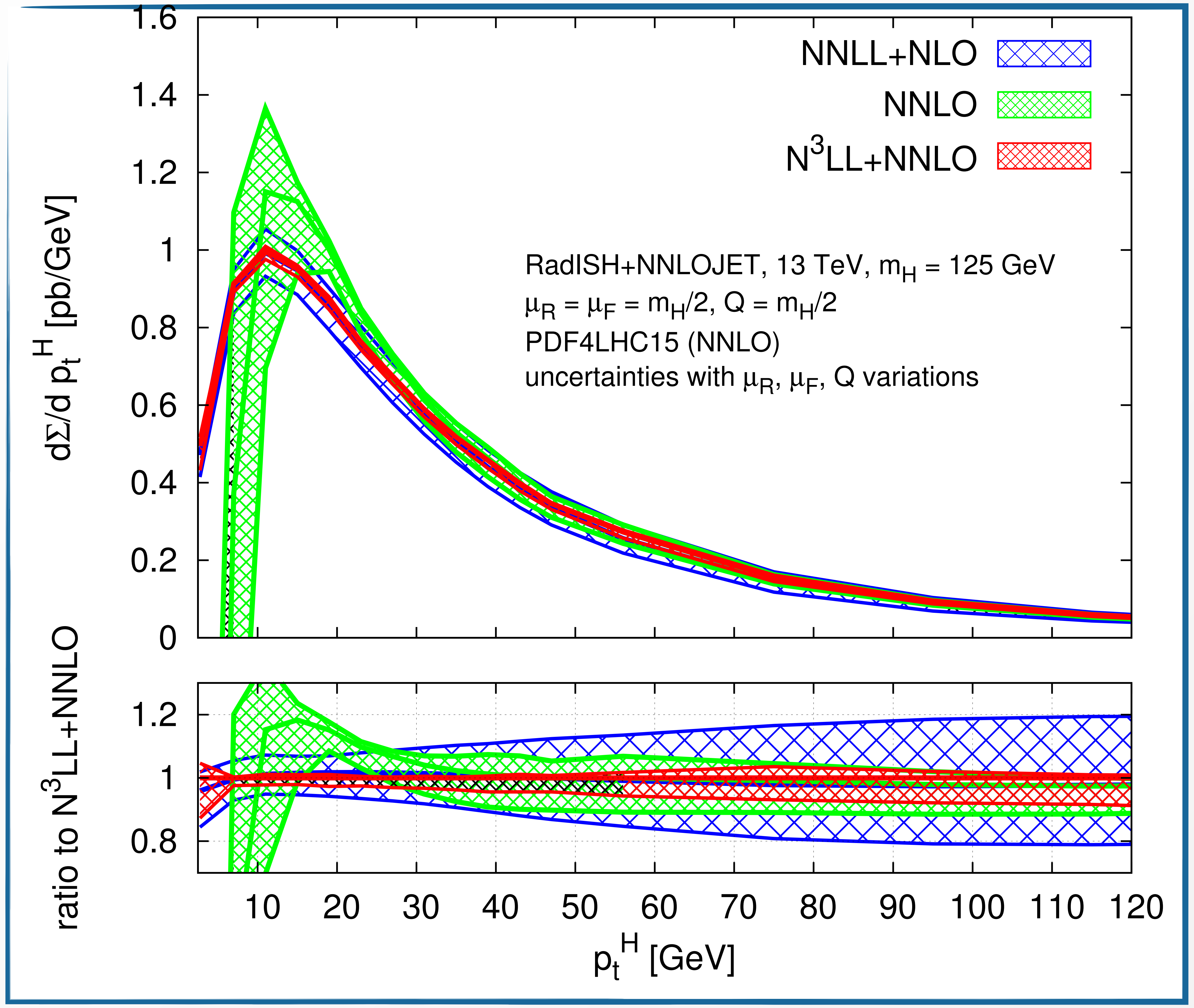
# Predictions for the $Z$ spectrum at 8 TeV

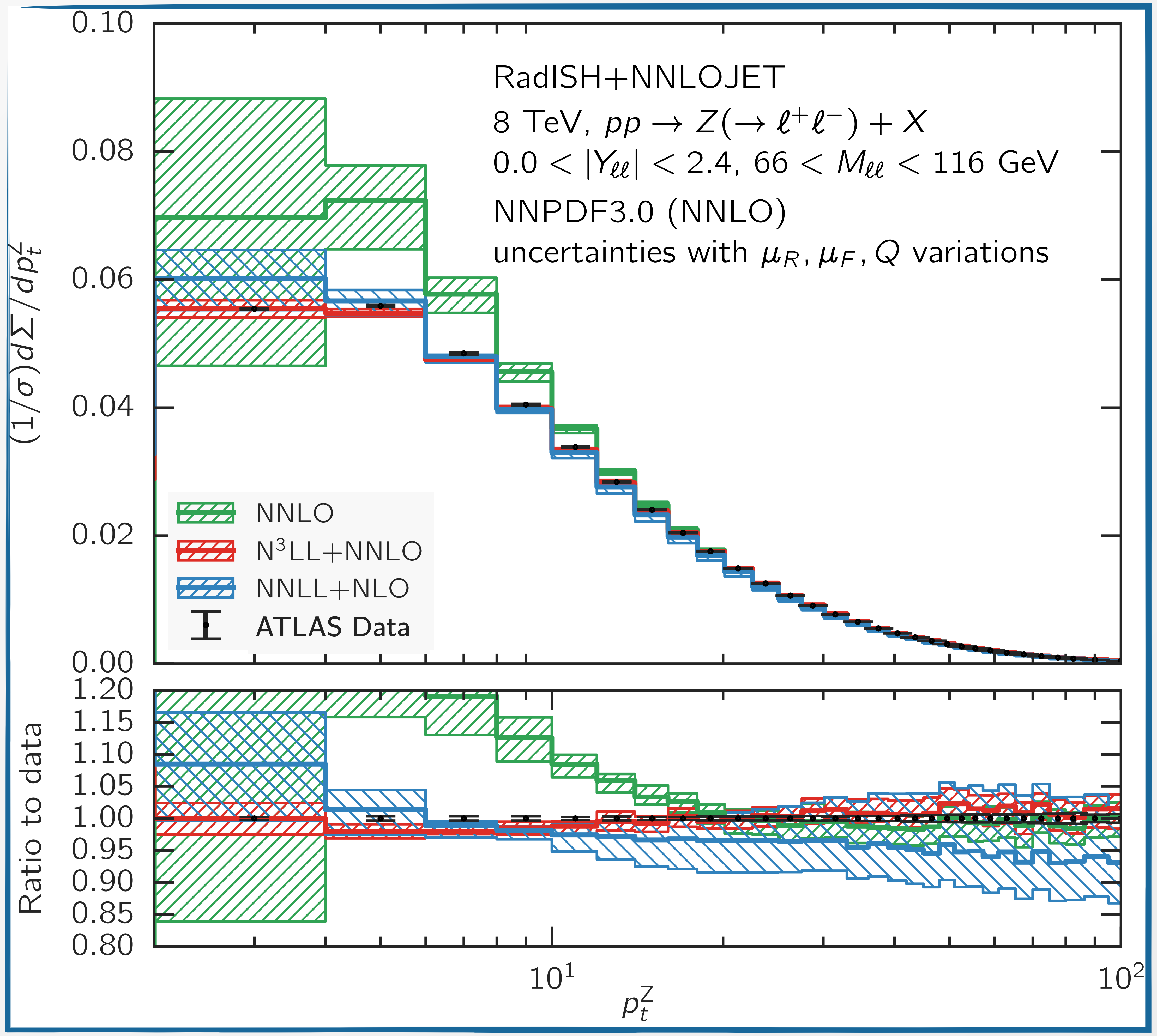



- Good description of the data in all fiducial regions
- Perturbative uncertainty at the few percent level, still does not match the precision of the ATLAS data

# Resummation of the transverse momentum spectrum at N³LL+NNLO

N³LL result matched to NNLO H+j, Z+j, W±+j **[Bizon, LR *et al.* '18, '19]**



# Theoretical predictions for $Z$ and $W$ observables at 13 TeV

Bizon, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, LR, Walker, 190x.xxxx

Results obtained using the following fiducial cuts (agreed with ATLAS)

$$p_t^{\ell^\pm} > 25\,\mathrm{GeV}, \quad |\eta^{\ell^\pm}| < 2.5, \quad 66\,\mathrm{GeV} < M_{\ell\ell} < 116\,\mathrm{GeV}$$

$$p_t^{\ell} > 25\,\mathrm{GeV}, \quad |\eta^{\ell}| < 2.5, \quad \not{E}_T^{\nu_\ell} > 25\,\mathrm{GeV}, \quad m_T > 50\,\mathrm{GeV}$$

using NNPDF3.1 with $\alpha_s(M_Z)$=0.118 and setting the central scales to

$$\mu_R = \mu_F = M_T = \sqrt{M_{\ell\ell'}^2 + p_T^2}, \quad Q = \frac{M_{\ell\ell'}}{2}$$

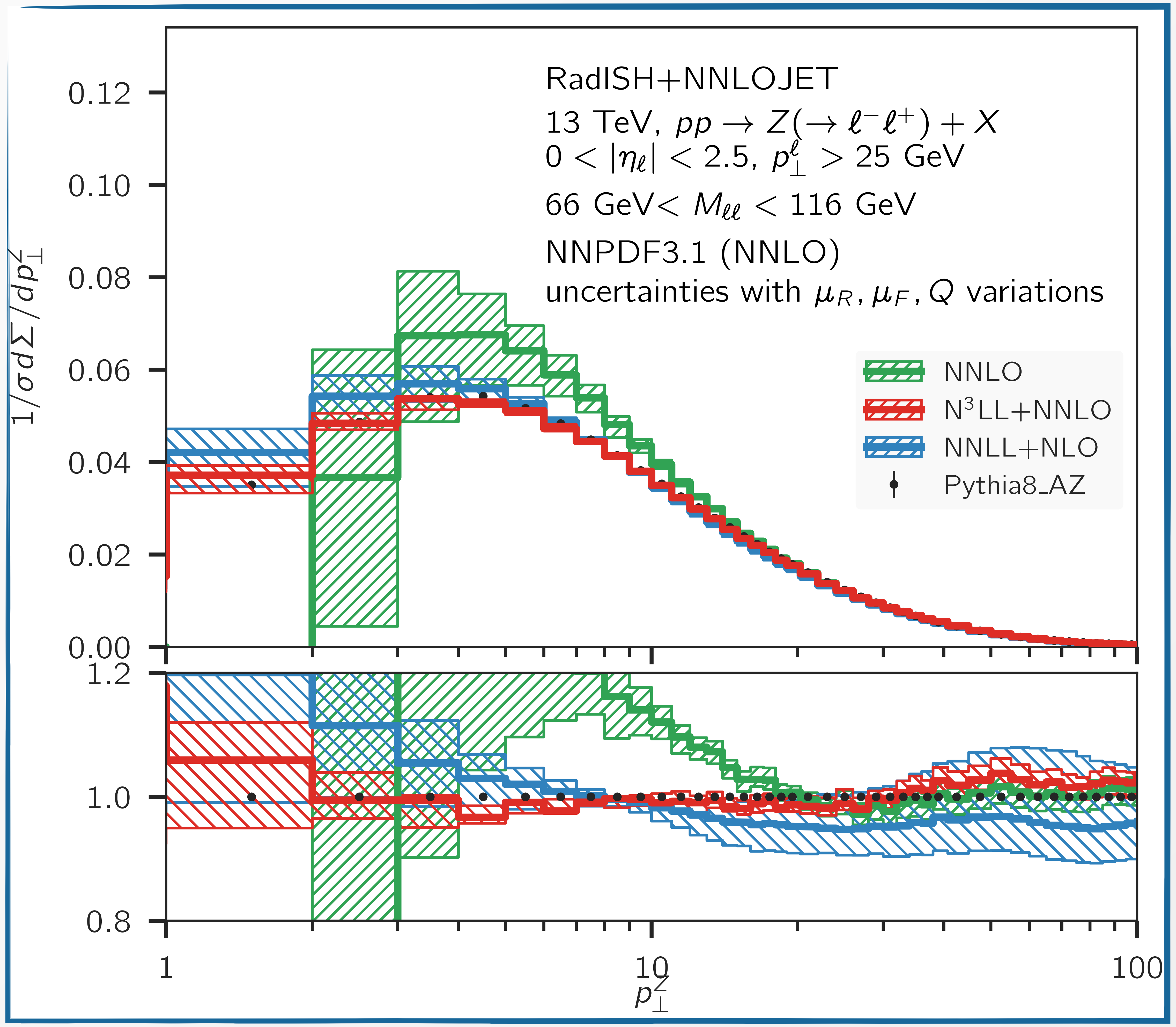
5 flavour (massless) scheme: no HQ effects, LHAPDF PDF thresholds

Scale uncertainties estimated by varying **renormalization** and **factorization** scale by a factor of two around their central value (**7 point variation**) and varying the **resummation** scale by a factor of 2 around its central value for factorization and renormalization scales set to their central value: **9 point envelope**

Matching parameter $p$ set to 4 as a default

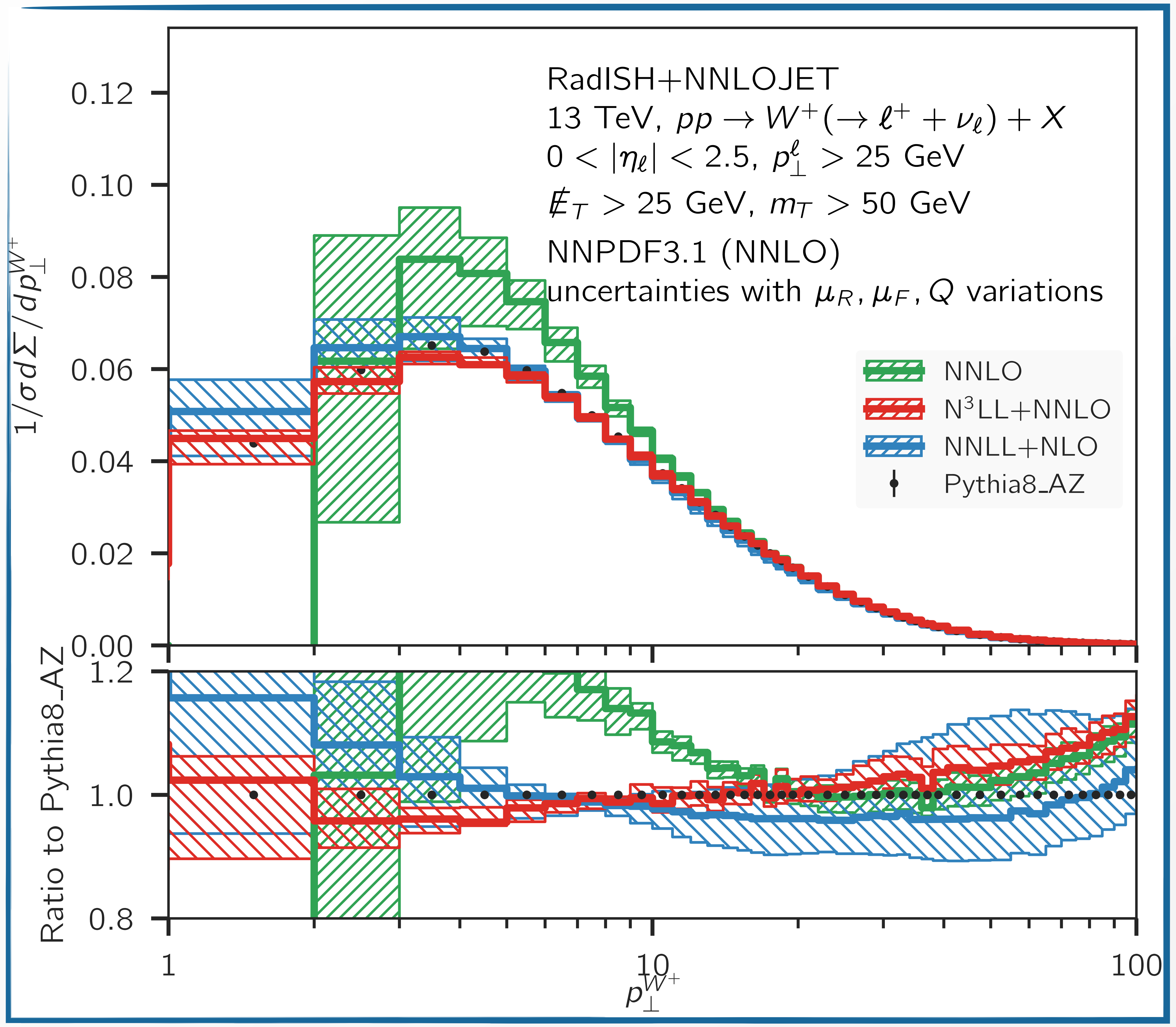
**No non perturbative parameters included** in the following

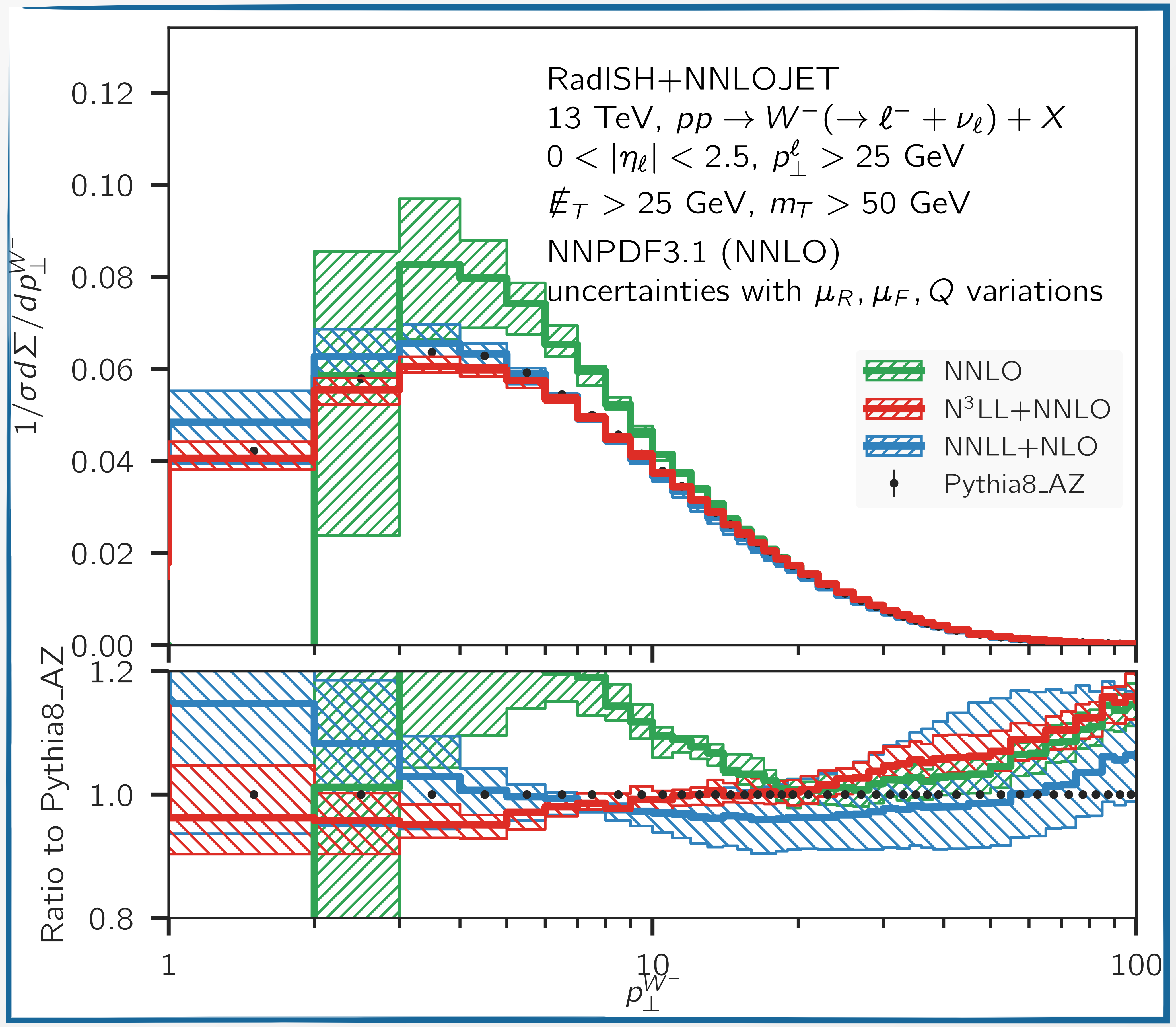
# Predictions for the $Z$ spectrum



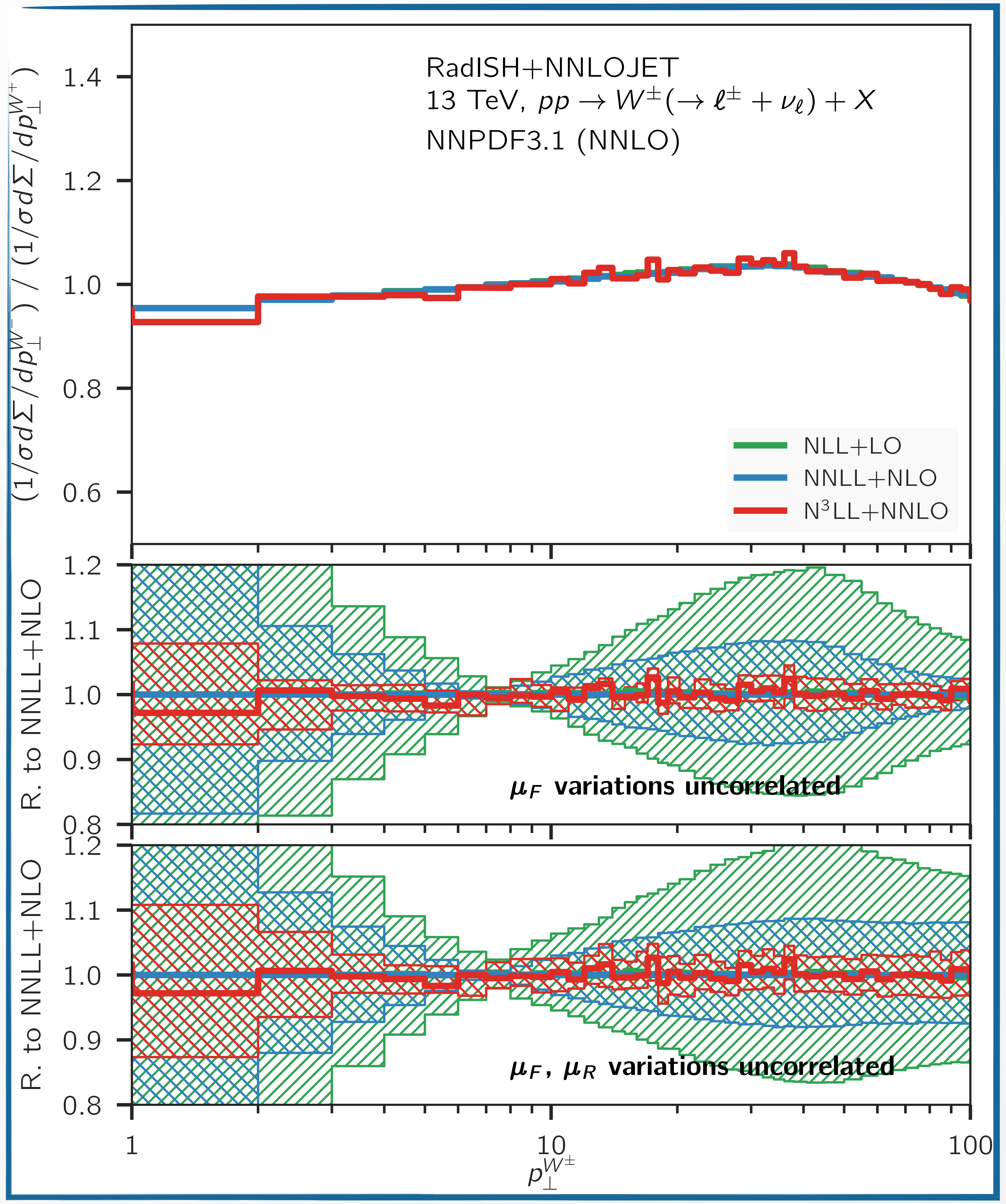

*Thanks to Jan Kretzschmar for providing the PYTHIA8 AZ tune results*

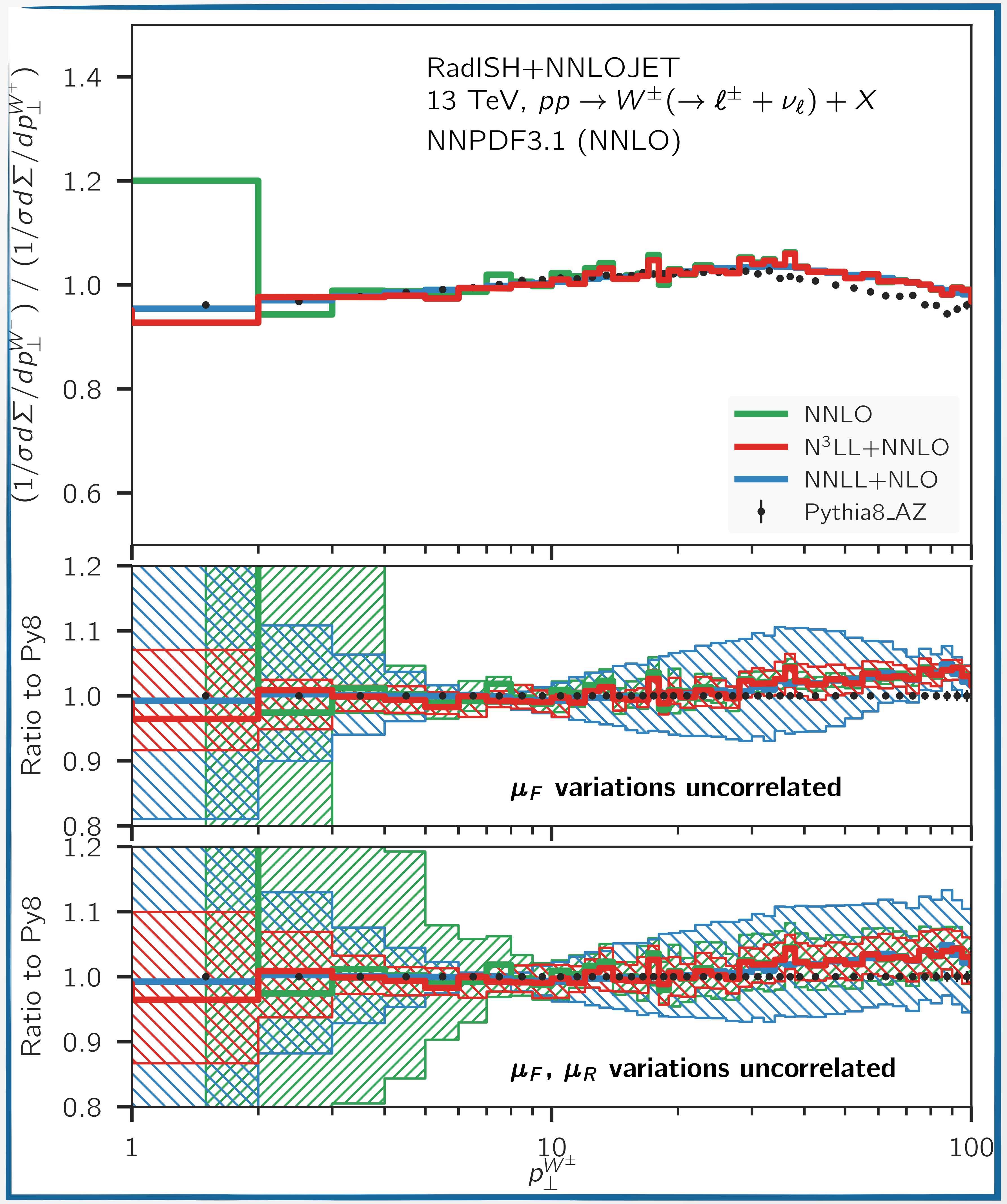
# Predictions for the $W^+$ and $W^-$ spectra



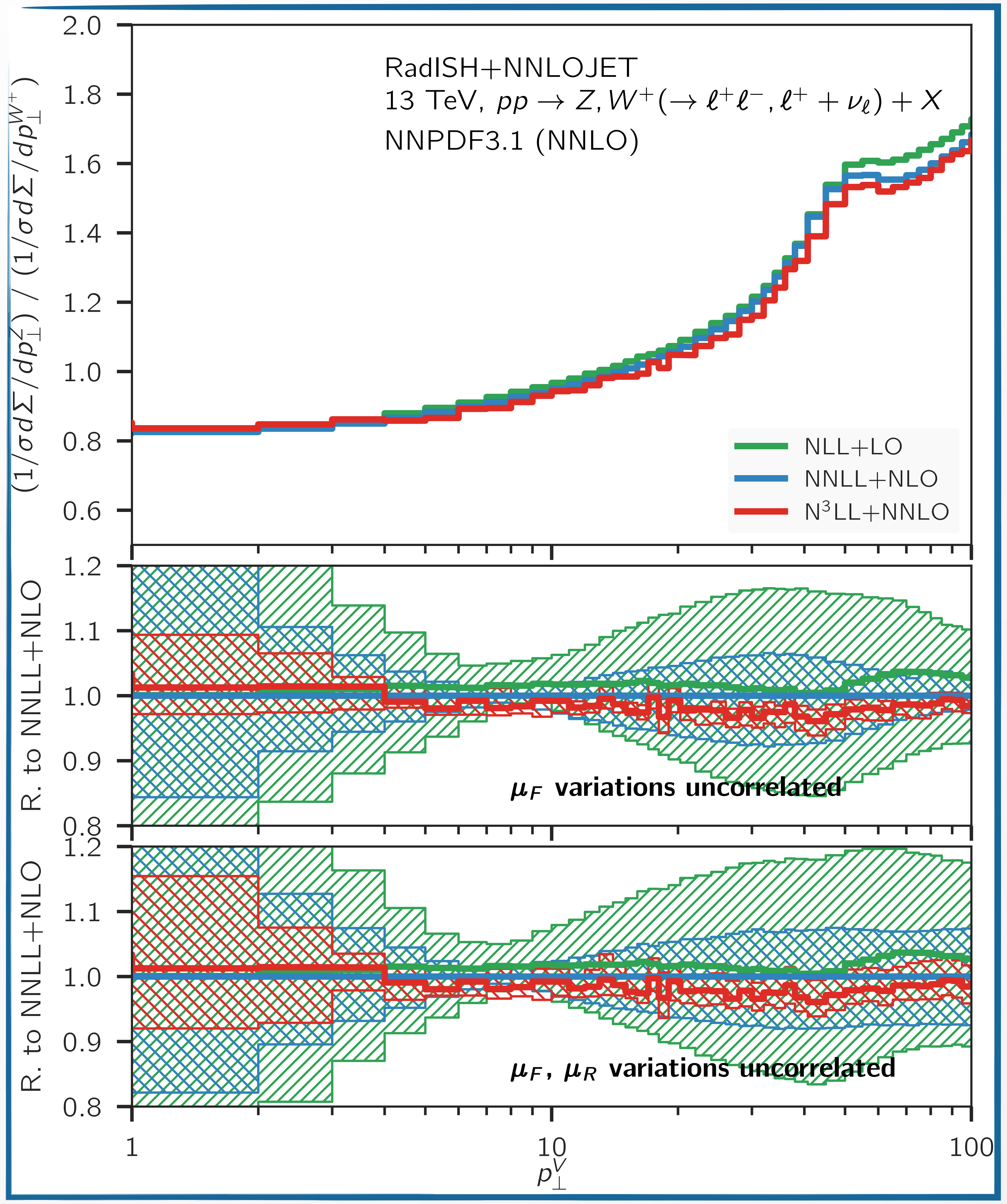



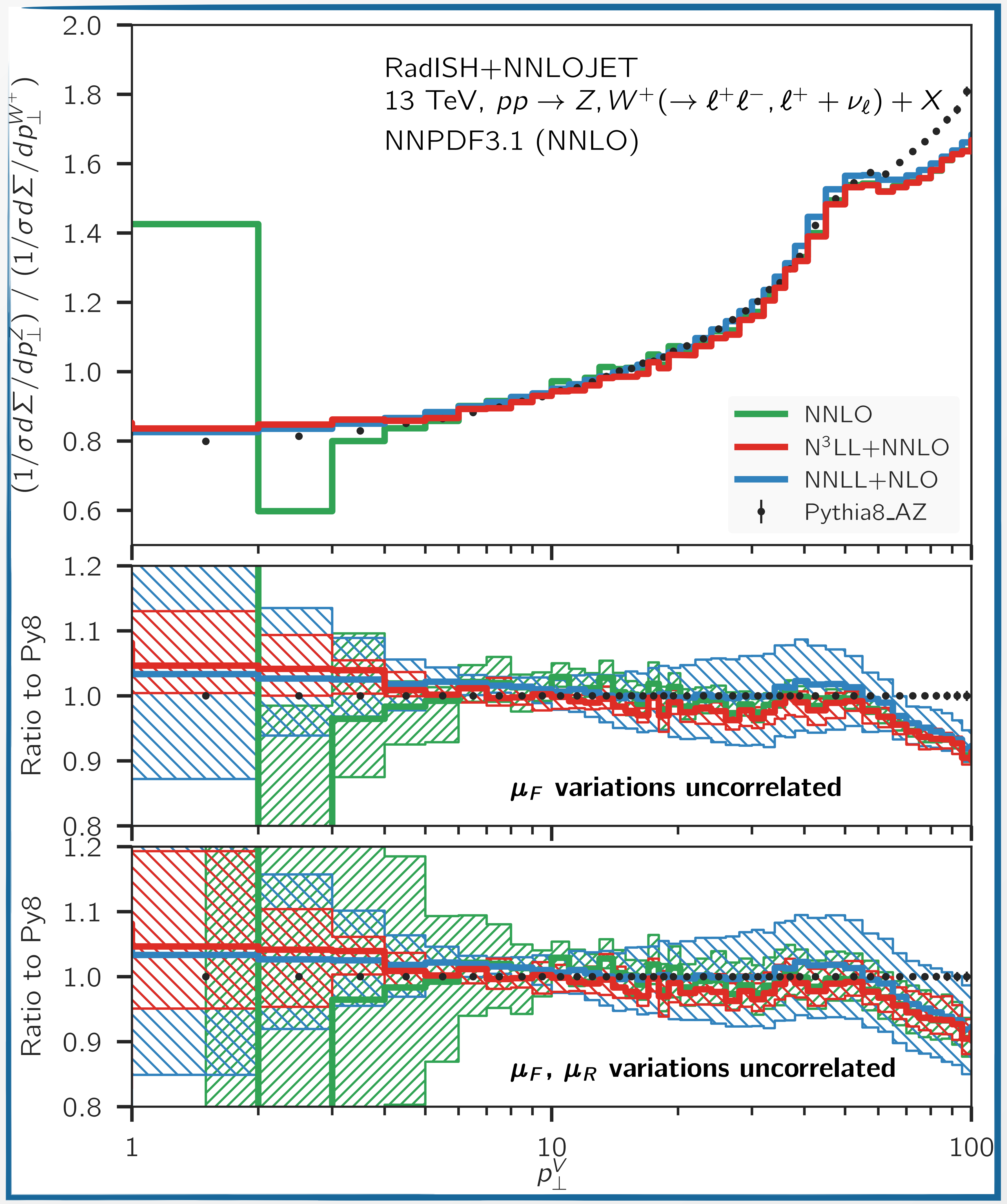
# Results for $W^-/W^+$ ratio



# Results for $Z/W^+$ ratio



# Equivalence with $b$-space formulation

$$\frac{d\Sigma(v)}{d\Phi_B} = \int_{\mathcal{C}_1} \frac{dN_1}{2\pi i} \int_{\mathcal{C}_2} \frac{dN_2}{2\pi i} x_1^{-N_1} x_2^{-N_2} \sum_{c_1,c_2} \frac{d|M_B|^2_{c_1c_2}}{d\Phi_B} \mathbf{f}^T_{N_1}(\mu_0) \hat{\mathbf{\Sigma}}^{c_1,c_2}_{N_1,N_2}(v) \mathbf{f}_{N_2}(\mu_0)$$

unresolved emission + virtual corrections

$$\hat{\mathbf{\Sigma}}^{c_1,c_2}_{N_1,N_2}(v) = \left[\mathbf{C}^{c_1;T}_{N_1}(\alpha_s(\mu_0)) H(\mu_R) \mathbf{C}^{c_2}_{N_2}(\alpha_s(\mu_0))\right] \int_0^M \frac{dk_{t1}}{k_{t1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi}$$
$$\times e^{-\mathbf{R}(\epsilon k_{t1})} \exp\left\{-\sum_{\ell=1}^{2}\left(\int_{\epsilon k_{t1}}^{\mu_0} \frac{dk_t}{k_t} \frac{\alpha_s(k_t)}{\pi} \mathbf{\Gamma}_{N_\ell}(\alpha_s(k_t)) + \int_{\epsilon k_{t1}}^{\mu_0} \frac{dk_t}{k_t} \mathbf{\Gamma}^{(C)}_{N_\ell}(\alpha_s(k_t))\right)\right\}$$

Result valid for all inclusive observables (e.g. $p_t$, $\varphi^*$)

resolved emission

$$\sum_{\ell_1=1}^{2}\left(\mathbf{R}'_{\ell_1}(k_{t1}) + \frac{\alpha_s(k_{t1})}{\pi} \mathbf{\Gamma}_{N_{\ell_1}}(\alpha_s(k_{t1})) + \mathbf{\Gamma}^{(C)}_{N_{\ell_1}}(\alpha_s(k_{t1}))\right)$$
$$\times \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_\epsilon^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} \sum_{\ell_i=1}^{2}\left(\mathbf{R}'_{\ell_i}(k_{ti}) + \frac{\alpha_s(k_{ti})}{\pi} \mathbf{\Gamma}_{N_{\ell_i}}(\alpha_s(k_{ti})) + \mathbf{\Gamma}^{(C)}_{N_{\ell_i}}(\alpha_s(k_{ti}))\right)$$
$$\times \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1})\right)$$

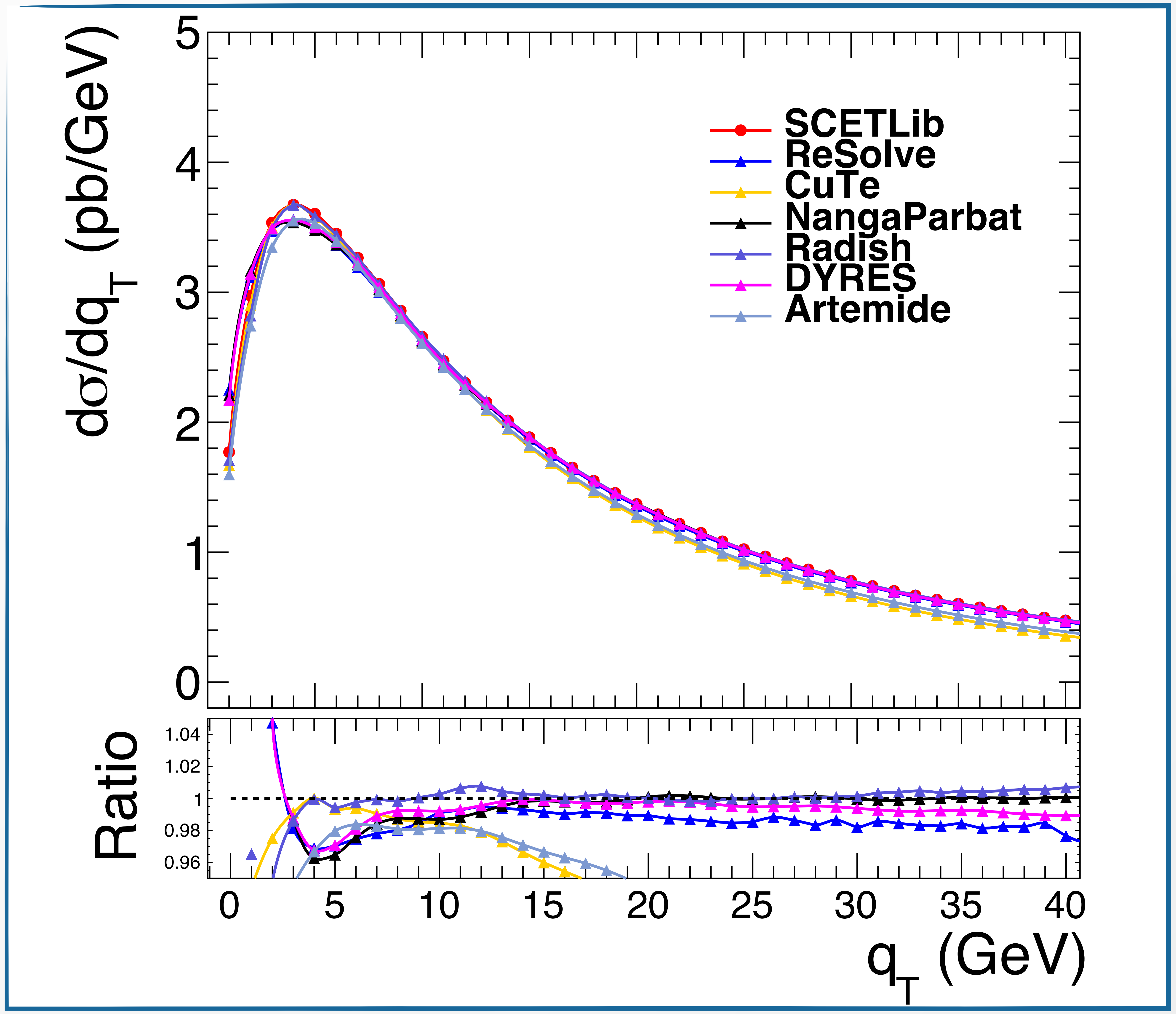
Formulation **equivalent to $b$-space** result (up to a **scheme change** in the anomalous dimensions)

$$\frac{d^2\Sigma(v)}{d\Phi_B dp_t} = \sum_{c_1,c_2} \frac{d|M_B|^2_{c_1c_2}}{d\Phi_B} \int b\, db\, p_t J_0(p_t b)\, \mathbf{f}^T(b_0/b) \mathbf{C}^{c_1;T}_{N_1}(\alpha_s(b_0/b)) H(M) \mathbf{C}^{c_2}_{N_2}(\alpha_s(b_0/b)) \mathbf{f}(b_0/b)$$
$$\times \exp\left\{-\sum_{\ell=1}^{2} \int_0^M \frac{dk_t}{k_t} \mathbf{R}'_\ell(k_t)(1 - J_0(bk_t))\right\}$$

$$(1 - J_0(bk_t)) \simeq \Theta(k_t - \frac{b_0}{b}) + \frac{\zeta_3}{12} \frac{\partial^3}{\partial \ln(Mb/b_0)^3} \Theta(k_t - \frac{b_0}{b})$$

$N^3LL$ effect: absorbed in the definition of $H_2$, $B_3$, $A_4$ coefficients wrt to CSS

# Equivalence with *b*-space formulation

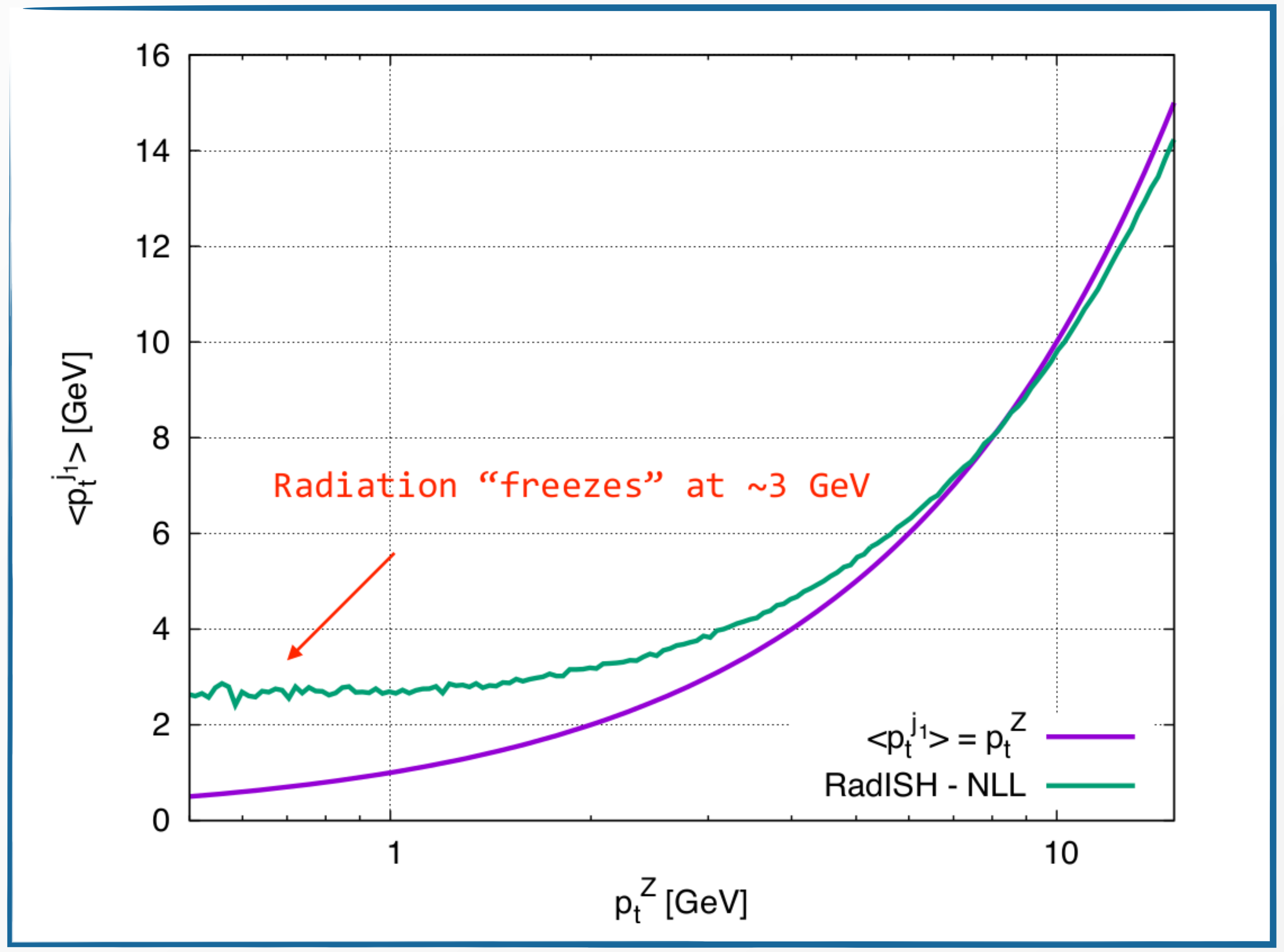


# The Landau pole and the small $p_T$ limit

Running coupling $\alpha_s(k_{t1}{}^2)$ and Sudakov radiator hit Landau pole at

$$\alpha_s(\mu_R^2)\beta_0 \ln Q/k_{t1} = \frac{1}{2} \qquad k_{t1} \sim 0.01\,\mathrm{GeV}, \quad \mu_R = Q = m_Z$$

Only real cutoff in the calculation: emission probability is set to zero below this scale and parton densities are frozen.




At small $p_t$ the large azimuthal cancellations dominate over the Sudakov suppression: the cutoff is never an issue in practice

$$\frac{d^2\Sigma(v)}{dp_t d\Phi_B} \simeq 2\sigma^{(0)}(\Phi_B) p_t \left(\frac{\Lambda^2_{\mathrm{QCD}}}{M^2}\right)^{\frac{16}{25}\ln\frac{41}{16}}$$

**Thanks to P. Monni**

# Behaviour at small $p_t$

Explicit evaluation shows that the Parisi-Petronzio perturbative scaling at small $p_t$ is reproduced. At NLL, Drell-Yan pair production, $n_f$=4

$$\frac{d^2\Sigma(v)}{dp_t d\Phi_B} = 4\,\sigma^{(0)}(\Phi_B)\,p_t \int_{\Lambda_{\rm QCD}}^{M} \frac{dk_{t1}}{k_{t1}^3} e^{-R(k_{t1})} \simeq 2\sigma^{(0)}(\Phi_B) p_t \left(\frac{\Lambda_{\rm QCD}^2}{M^2}\right)^{\frac{16}{25}\ln\frac{41}{16}}$$

As now higher logarithmic terms (up to N$^3$LL) are under control, the coefficient of this scaling can be systematically improved in *perturbation* theory (non-perturbative effects – of the same order – not considered)

N$^3$LL calculation allows one to have control over the terms of relative order $O(\alpha_s^2)$. Scaling $L \sim 1/\alpha_s$ valid in the deep infrared regime.

# Numerical implementation

$$\frac{d\Sigma(p_t)}{d\Phi_B} = \int_0^M \frac{dk_{t1}}{k_{t1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} \partial_L \left(-e^{-R'(k_{t1})} \mathcal{L}_{\rm NLL}(k_{t1})\right) \times$$
$$\times \underbrace{\epsilon^{R'(k_{t1})} \sum_{n=0}^{\infty} \frac{1}{n!} \left(\prod_{i=2}^{n+1} \int_{\epsilon k_{t1}}^{k_{t1}} \frac{dk_{ti}}{k_{ti}} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'(k_{t1})\right) \Theta(p_t - |\vec{k}_{t1} + \ldots + \vec{k}_{t(n+1)}|)}_{\equiv \int d\mathcal{Z}[\{R', k_i\}] \Theta(p_t - |\vec{k}_{t1} + \ldots + \vec{k}_{t(n+1)}|)} .$$

- $L = \ln(M/k_{t1})$; luminosity $\mathcal{L}_{\rm NLL}(k_{t1}) = \sum_{c_1,c_2} \frac{d|M_B|^2_{c_1c_2}}{d\Phi_B} f_{c_1}(x_1, k_{t1}) f_{c_2}(x_2, k_{t1})$.
- $\int d\mathcal{Z}[\{R', k_i\}]\Theta$ finite as $\epsilon \to 0$:

$$\epsilon^{R'(k_{t1})} = 1 - R'(k_{t1}) \ln(1/\epsilon) + \ldots = 1 - \int_{\epsilon k_{t1}}^{k_{t1}} R'(k_{t1}) + \ldots,$$

$$\int d\mathcal{Z}[\{R', k_i\}]\Theta = \left[1 - \int_{\epsilon k_{t1}}^{k_{t1}} R'(k_{t1}) + \ldots\right] \left[\Theta(p_t - |\vec{k}_{t1}|) + \int_{\epsilon k_{t1}}^{k_{t1}} R'(k_{t1}) \Theta(p_t - |\vec{k}_{t1} + \vec{k}_{t2}|) + \ldots\right]$$
$$= \Theta(p_t - |\vec{k}_{t1}|) + \underbrace{\int_0^{k_{t1}}}_{\epsilon \to 0} R'(k_{t1}) \underbrace{\left[\Theta(p_t - |\vec{k}_{t1} + \vec{k}_{t2}|) - \Theta(p_t - |\vec{k}_{t1}|)\right]}_{\text{finite: real-virtual cancellation}} + \ldots$$

- Evaluated with Monte Carlo techniques: $\int d\mathcal{Z}[\{R', k_i\}]$ is generated as a parton shower over secondary emissions.

Thanks to P. Torrielli

# Numerical implementation

- Secondary radiation:

$$d\mathcal{Z}[\{R', k_i\}] = \sum_{n=0}^{\infty} \frac{1}{n!} \left( \prod_{i=2}^{n+1} \int_0^{2\pi} \frac{d\phi_i}{2\pi} \int_{\epsilon k_{t1}}^{k_{t1}} \frac{dk_{ti}}{k_{ti}} R'(k_{t1}) \right) \epsilon^{R'(k_{t1})}$$

$$= \sum_{n=0}^{\infty} \left( \prod_{i=2}^{n+1} \int_0^{2\pi} \frac{d\phi_i}{2\pi} \int_{\epsilon k_{t1}}^{k_{t(i-1)}} \frac{dk_{ti}}{k_{ti}} R'(k_{t1}) \right) \epsilon^{R'(k_{t1})},$$

$$\epsilon^{R'(k_{t1})} = e^{-R'(k_{t1}) \ln 1/\epsilon} = \prod_{i=2}^{n+2} e^{-R'(k_{t1}) \ln k_{t(i-1)}/k_{ti}},$$

  with $k_{t(n+2)} = \epsilon k_{t1}$.

- Each secondary emissions has differential probability

$$dw_i = \frac{d\phi_i}{2\pi} \frac{dk_{ti}}{k_{ti}} R'(k_{t1}) e^{-R'(k_{t1}) \ln k_{t(i-1)}/k_{ti}} = \frac{d\phi_i}{2\pi} d\left( e^{-R'(k_{t1}) \ln k_{t(i-1)}/k_{ti}} \right).$$

- $k_{t(i-1)} \geq k_{ti}$. Scale $k_{ti}$ extracted by solving $e^{-R'(k_{t1}) \ln k_{t(i-1)}/k_{ti}} = r$, with $r$ random number extracted uniformly in $[0, 1]$. Shower ordered in $k_{ti}$.

- Extract $\phi_i$ randomly in $[0, 2\pi]$.

Thanks to P. Torrielli

# Joint resummation in direct space

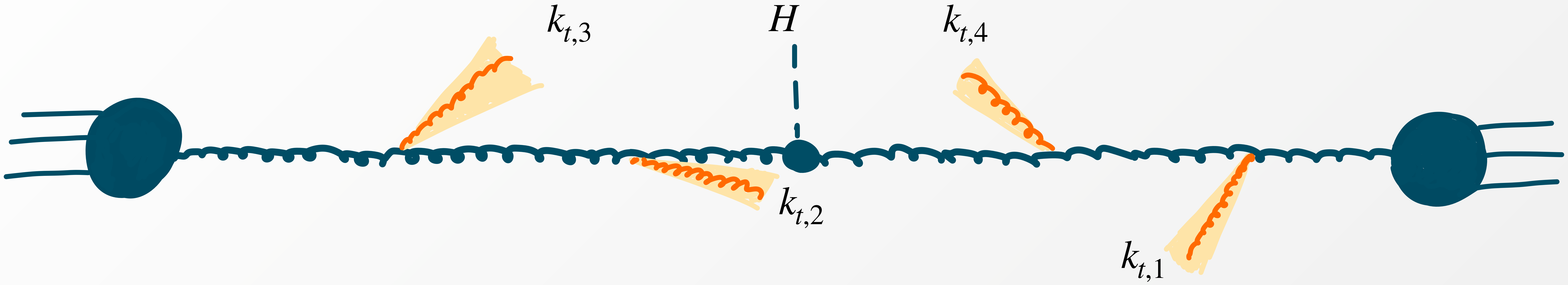
$$\sigma_{\rm incl}^{\rm NNLL}(p_t^{\rm J,v}, p_t^{\rm H,v}) = \int_0^{p_t^{\rm J,v}} \frac{dk_{t,1}}{k_{t,1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z} \Bigg\{ \frac{d}{d\,L_{t,1}} \left[ -e^{-R_{\rm NNLL}(L_{t,1})} \mathcal{L}_{\rm NNLL}\left(\mu_{\rm F} e^{-L_{t,1}}\right) \right] \Theta\Big(p_t^{\rm H,v} - |\vec{k}_{t,1} + \cdots + \vec{k}_{t,n+1}|\Big)$$
$$+ e^{-R_{\rm NLL}(L_{t,1})} \hat{R}'(k_{t,1}) \int_0^{k_{t,1}} \frac{dk_{t,s_1}}{k_{t,s_1}} \frac{d\phi_{s_1}}{2\pi} \left[ \left( \delta\hat{R}'(k_{t,1}) + \hat{R}''(k_{t,1}) \ln \frac{k_{t,1}}{k_{t,s_1}} \right) \mathcal{L}_{\rm NLL}\left(\mu_{\rm F} e^{-L_{t,1}}\right) - \frac{d}{d\,L_{t,1}} \mathcal{L}_{\rm NLL}\left(\mu_{\rm F} e^{-L_{t,1}}\right) \right]$$
$$\times \left[ \Theta\Big(p_t^{\rm H,v} - |\vec{k}_{t,1} + \cdots + \vec{k}_{t,n+1} + \vec{k}_{t,s_1}|\Big) - \Theta\Big(p_t^{\rm H,v} - |\vec{k}_{t,1} + \cdots + \vec{k}_{t,n+1}|\Big) \right] \Bigg\}, \tag{38}$$

$$\sigma_{\rm clust}^{\rm NNLL}(p_t^{\rm J,v}, p_t^{\rm H,v}) = \int_0^{\infty} \frac{dk_{t,1}}{k_{t,1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z}\, e^{-R_{\rm NLL}(L_{t,1})} \mathcal{L}_{\rm NLL}\left(\mu_{\rm F} e^{-L_{t,1}}\right) 8\, C_A^2 \frac{\alpha_s^2}{\pi^2} \frac{L_{t,1}}{(1-2\beta_0\alpha_s\, L_{t,1})^2} \Theta\left(p_t^{\rm J,v} - \max_{i>1}\{k_{t,i}\}\right)$$
$$\times \Bigg\{ \int_0^{k_{t,1}} \frac{dk_{t,s_1}}{k_{t,s_1}} \frac{d\phi_{s_1}}{2\pi} \int_{-\infty}^{\infty} d\Delta\eta_{1s_1}\, J_{1s_1}(R) \left[ \Theta\Big(p_t^{\rm J,v} - |\vec{k}_{t,1} + \vec{k}_{t,s_1}|\Big) - \Theta\Big(p_t^{\rm J,v} - k_{t,1}\Big) \right] \Theta\Big(p_t^{\rm H,v} - |\vec{k}_{t,1} + \cdots + \vec{k}_{t,n+1} + \vec{k}_{t,s_1}|\Big)$$
$$+ \frac{1}{2!} \hat{R}'(k_{t,1}) \int_0^{k_{t,1}} \frac{dk_{t,s_1}}{k_{t,s_1}} \frac{dk_{t,s_2}}{k_{t,s_2}} \frac{d\phi_{s_1}}{2\pi} \frac{d\phi_{s_2}}{2\pi} \int_{-\infty}^{\infty} d\Delta\eta_{s_1 s_2}\, J_{s_1 s_2}(R) \left[ \Theta\Big(p_t^{\rm J,v} - |\vec{k}_{t,s_1} + \vec{k}_{t,s_2}|\Big) - \Theta\Big(p_t^{\rm J,v} - \max\{k_{t,s_1}, k_{t,s_2}\}\Big) \right]$$
$$\times \Theta\Big(p_t^{\rm H,v} - |\vec{k}_{t,1} + \cdots + \vec{k}_{t,n+1} + \vec{k}_{t,s_1} + \vec{k}_{t,s_2}|\Big) \Theta\left(p_t^{\rm J,v} - k_{t,1}\right) \Bigg\}, \tag{42}$$

$$\sigma_{\rm correl}^{\rm NNLL}(p_t^{\rm J,v}, p_t^{\rm H,v}) = \int_0^{\infty} \frac{dk_{t,1}}{k_{t,1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z}\, e^{-R_{\rm NLL}(L_{t,1})} \mathcal{L}_{\rm NLL}\left(\mu_{\rm F} e^{-L_{t,1}}\right) 8\, C_A^2 \frac{\alpha_s^2}{\pi^2} \frac{L_{t,1}}{(1-2\beta_0\alpha_s\, L_{t,1})^2} \Theta\left(p_t^{\rm J,v} - \max_{i>1}\{k_{t,i}\}\right)$$
$$\times \Bigg\{ \int_0^{k_{t,1}} \frac{dk_{t,s_1}}{k_{t,s_1}} \frac{d\phi_{s_1}}{2\pi} \int_{-\infty}^{\infty} d\Delta\eta_{1s_1}\, \mathcal{C}\left(\Delta\eta_{1s_1}, \Delta\phi_{1s_1}, \frac{k_{t,1}}{k_{t,s_1}}\right) (1 - J_{1s_1}(R))$$
$$\times \left[ \Theta\Big(p_t^{\rm J,v} - k_{t,1}\Big) - \Theta\Big(p_t^{\rm J,v} - |\vec{k}_{t,1} + \vec{k}_{t,s_1}|\Big) \right] \Theta\Big(p_t^{\rm H,v} - |\vec{k}_{t,1} + \cdots + \vec{k}_{t,n+1} + \vec{k}_{t,s_1}|\Big)$$
$$+ \frac{1}{2!} \hat{R}'(k_{t,1}) \int_0^{k_{t,1}} \frac{dk_{t,s_1}}{k_{t,s_1}} \frac{dk_{t,s_2}}{k_{t,s_2}} \frac{d\phi_{s_1}}{2\pi} \frac{d\phi_{s_2}}{2\pi} \int_{-\infty}^{\infty} d\Delta\eta_{s_1 s_2}\, \mathcal{C}\left(\Delta\eta_{s_1 s_2}, \Delta\phi_{s_1 s_2}, \frac{k_{t,s_2}}{k_{t,s_1}}\right) (1 - J_{s_1 s_2}(R))\, \Theta\left(p_t^{\rm J,v} - k_{t,1}\right)$$
$$\times \left[ \Theta\Big(p_t^{\rm J,v} - \max\{k_{t,s_1}, k_{t,s_2}\}\Big) - \Theta\Big(p_t^{\rm J,v} - |\vec{k}_{t,s_1} + \vec{k}_{t,s_2}|\Big) \right] \Theta\Big(p_t^{\rm H,v} - |\vec{k}_{t,1} + \cdots + \vec{k}_{t,n+1} + \vec{k}_{t,s_1} + \vec{k}_{t,s_2}|\Big) \Bigg\}. \tag{43}$$

# Double-differential resummation at NLL in $b$ space

At NLL, emissions are **strongly ordered** in angle. $k_t$-type algorithms will associate **each emission** to a **different** jet



# Double-differential resummation at NLL in *b* space

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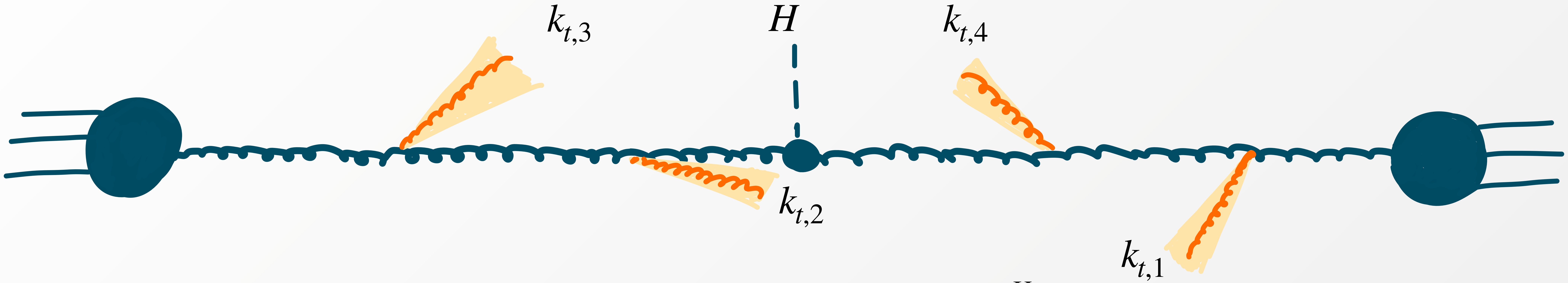



Additional constraint on **real radiation**

$$\Theta(p_\perp^{\mathrm{J,v}} - \max\{k_{t,1}, \ldots, k_{t,n}\}) = \prod_{i=1}^{n} \Theta(p_\perp^{\mathrm{J,v}} - k_{t,i})$$

$p_\perp^H$ resummation formula

$$\frac{d\sigma}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-R_{\mathrm{NLL}}(L)}$$

$$L = \ln(m_H b / b_0)$$

**Joint $p_\perp^H$, $p_\perp^{\mathrm{J,v}}$ resummation formula**

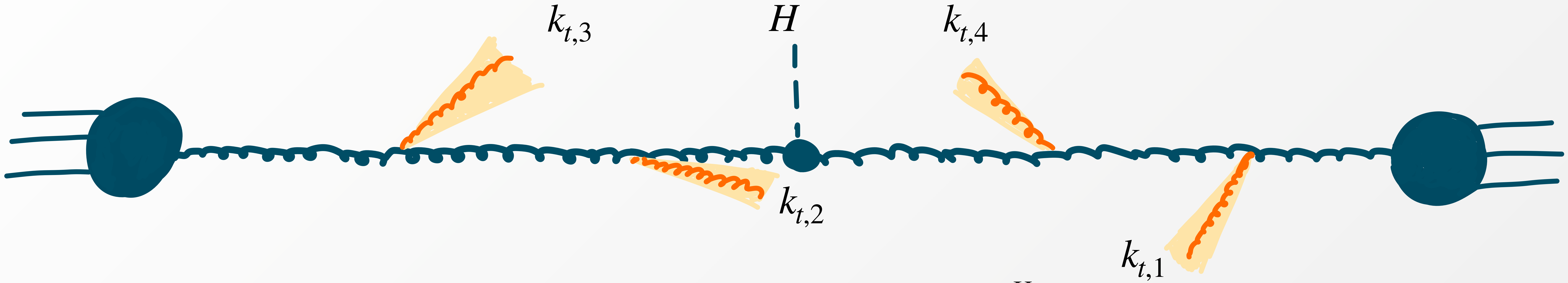
$$\frac{d\sigma(p_\perp^H, p_\perp^{\mathrm{J,v}})}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\mathrm{NLL}}(L)}$$

$$S_{\mathrm{NLL}}(L) = -Lg_1(\alpha_s L) - g_2(\alpha_s L) + \int_0^{m_H} \frac{dk_t}{k_t} R'_{\mathrm{NLL}}(k_t) J_0(bk_t)\Theta(k_t - p_\perp^{\mathrm{J,v}})$$

$$R'_{\mathrm{NLL}}(k_t) = 4\left(\frac{\alpha_s^{\mathrm{CMW}}(k_t)}{\pi} C_A \ln\frac{m_H}{k_t} - \alpha_s(k_t)\beta_0\right)$$

# Double-differential resummation at NLL in $b$ space

At NLL, emissions are **strongly ordered** in angle. $k_t$-type algorithms will associate **each emission** to a **different** jet




Additional constraint on **real radiation**

$$\Theta(p_\perp^{\mathrm{J,v}} - \max\{k_{t,1}, \ldots, k_{t,n}\}) = \prod_{i=1}^{n} \Theta(p_\perp^{\mathrm{J,v}} - k_{t,i})$$

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$$\frac{d\sigma}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-R_{\mathrm{NLL}}(L)}$$

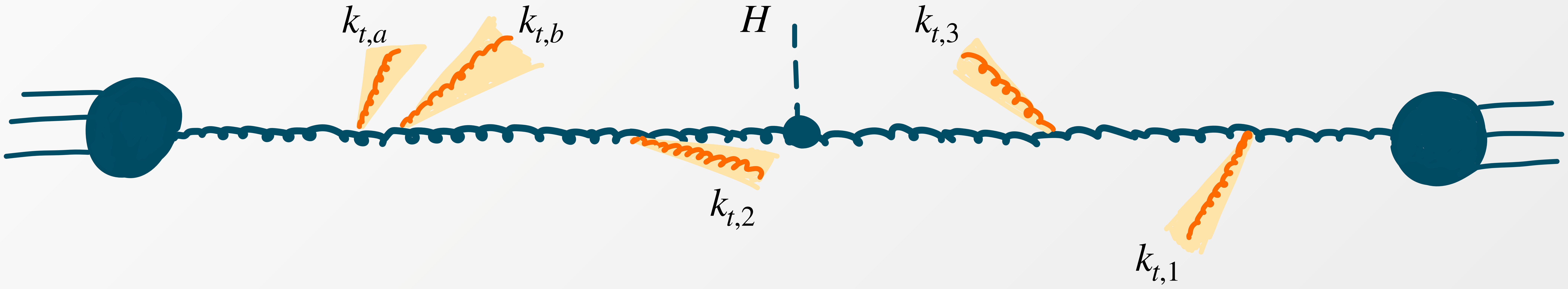
$$L = \ln(m_H b/b_0)$$

# Double-differential resummation at NNLL in $b$ space

Additional corrections must be included at NNLL [Banfi et al. '12][Becher et al. '12 ,'13][Stewart et al. '13]

$$\frac{d\sigma(p_\perp^H, p_\perp^{\mathrm{J,v}})}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\mathrm{NNLL}}(L)} \left(1 + \mathcal{F}_{\mathrm{clust}} + \mathcal{F}_{\mathrm{correl}}\right)$$

**clustering correction**: jet algorithm can cluster two emissions into the same jet



# Double-differential resummation at NNLL in $b$ space

Additional corrections must be included at NNLL [Banfi et al. '12][Becher et al. '12 ,'13][Stewart et al. '13]

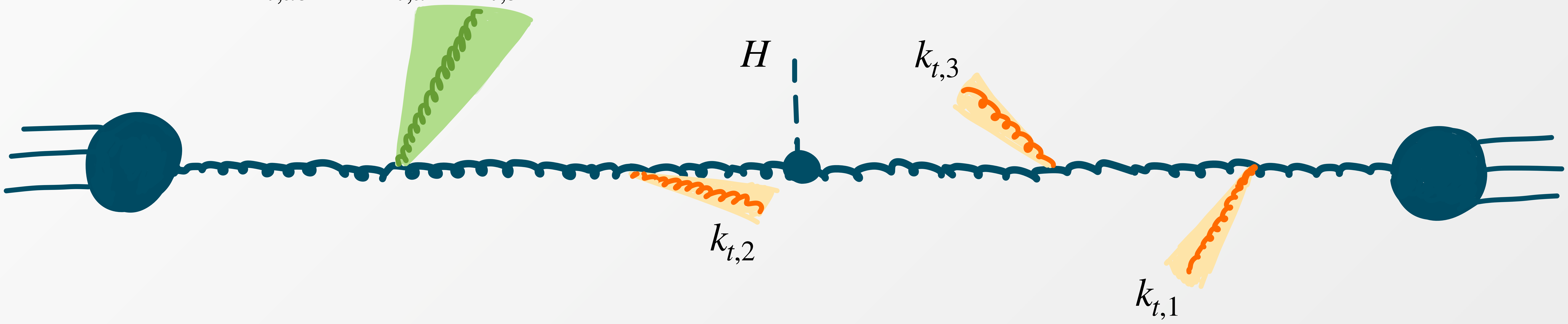
$$\frac{d\sigma(p_\perp^H, p_\perp^{\rm J,v})}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\rm NNLL}(L)} (1 + \mathscr{F}_{\rm clust} + \mathscr{F}_{\rm correl})$$

**clustering correction**: jet algorithm can cluster two emissions into the same jet

$$\mathscr{F}_{\rm clust} = \frac{1}{2!}\int [dk_a][dk_b] M^2(k_a) M^2(k_b) J_{ab}(R)\, e^{i\vec{b}\cdot\vec{k}_{t,ab}} \left[\Theta(p_\perp^{\rm J,v} - k_{t,ab}) - \Theta(p_\perp^{\rm J,v} - \max\{k_{t,a}, k_{t,b}\})\right]$$

$$J_{ab}(R) = \Theta\left(R^2 - \Delta\eta_{ab}^2 - \Delta\phi_{ab}^2\right)$$

$k_{t,ab} = |\vec{k}_{t,a} + \vec{k}_{t,b}|$

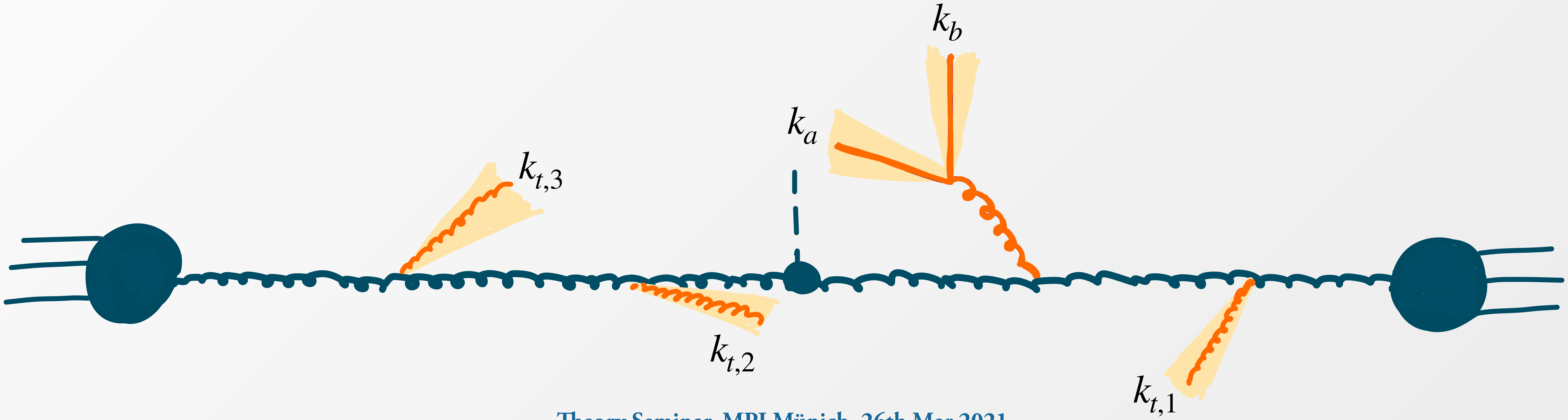


# Double-differential resummation at NNLL in $b$ space

Additional corrections must be included at NNLL [Banfi et al. '12][Becher et al. '12 ,'13][Stewart et al. '13]

$$\frac{d\sigma(p_\perp^H, p_\perp^{\mathrm{J,v}})}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\mathrm{NNLL}}(L)} (1 + \mathcal{F}_{\mathrm{clust}} + \mathcal{F}_{\mathrm{correl}})$$

**correlated correction**: amends the inclusive treatment of the **correlated squared amplitude** for two emission accounting for configurations where the two correlated emissions are not clustered in the same jet



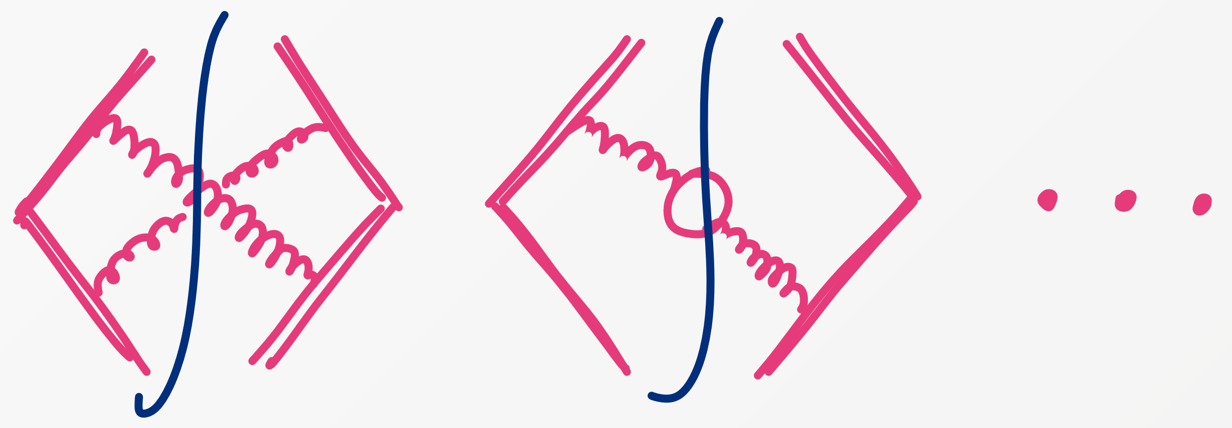
# Double-differential resummation at NNLL in $b$ space

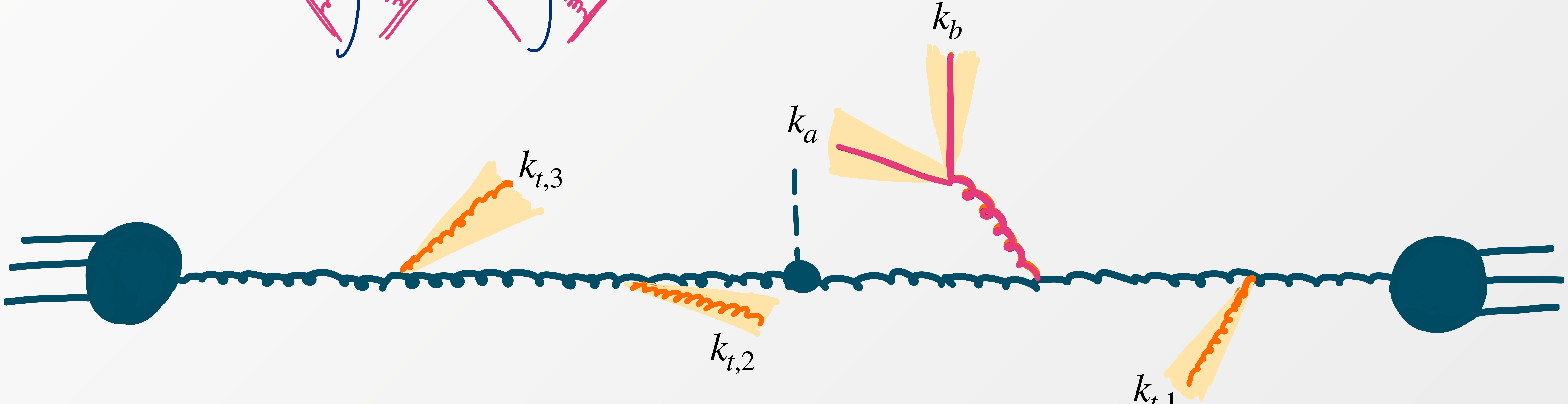
Additional corrections must be included at NNLL [Banfi et al. '12][Becher et al. '12 ,'13][Stewart et al. '13]

$$\frac{d\sigma(p_\perp^H, p_\perp^{\mathrm{J,v}})}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\mathrm{NNLL}}(L)} (1 + \mathscr{F}_{\mathrm{clust}} + \mathscr{F}_{\mathrm{correl}})$$

**correlated correction**: amends the inclusive treatment of the **correlated squared amplitude** for two emission accounting for configurations where the two correlated emissions are not clustered in the same jet

$$\mathscr{F}_{\mathrm{correl}} = \frac{1}{2!} \int [dk_a][dk_b] \tilde{M}^2(k_a, k_b)(1 - J_{ab}(R)) e^{i\vec{b}\cdot\vec{k}_{t,ab}} \times \left[\Theta(p_\perp^{\mathrm{J,v}} - \max\{k_{t,a}, k_{t,b}\}) - \Theta(p_\perp^{\mathrm{J,v}} - k_{t,ab})\right]$$





# Double-differential resummation at NNLL in $b$ space

NNLL prediction finally requires the consistent treatment of non-soft collinear emissions off the initial state particles

Soft and non-soft emission cannot be clustered by a $k_t$-type jet algorithm. Non-soft collinear radiation can be handled by taking a Mellin transform of the resummed cross section, giving rise to **scale evolution of PDFs** and of the $\mathcal{O}(\alpha_s)$ **collinear coefficient functions**

Final result at NNLL, including **hard-virtual corrections** at and $\mathcal{O}(\alpha_s)$ **collinear coefficient functions**

$$\frac{d\sigma(p_\perp^H, p_\perp^{\mathrm{J,v}})}{dy_H d^2\vec{p}_\perp^H} = \frac{2\pi}{s} M^2_{\mathrm{gg}\to\mathrm{H}} \mathcal{H}(\alpha_s(m_H)) \int_{\mathcal{C}_1}\frac{d\nu_1}{2\pi i}\int_{\mathcal{C}_2}\frac{d\nu_2}{2\pi i} x_1^{-\nu_1} x_2^{-\nu_2}\int\frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\mathrm{NNLL}}}\left(1+\mathcal{F}_{\mathrm{clust}}+\mathcal{F}_{\mathrm{correl}}\right)$$

$$\times \left[\mathcal{P}e^{\int_0^{m_H}\frac{d\mu}{\mu}\boldsymbol{\Gamma}_{\nu_1}(\alpha_s(\mu))(\Theta(p_t^{\mathrm{J,v}}-\mu)J_0(b\mu)-1)}\right]_{c_1a_1}\left[\mathcal{P}e^{\int_0^{m_H}\frac{d\mu}{\mu}\boldsymbol{\Gamma}_{\nu_2}(\alpha_s(\mu))(\Theta(p_t^{\mathrm{J,v}}-\mu)J_0(b\mu)-1)}\right]_{c_2a_2} f_{\nu_1,a_1}(m_H) f_{\nu_2 a_2}(m_H)$$

$$\times \left[e^{\int_0^{m_H}\frac{d\mu}{\mu}[\Gamma^{(C)}_{\nu_1}(\alpha_s(\mu))]_{gc_1}(\Theta(p_t^{\mathrm{J,v}}-\mu)J_0(b\mu)-1)}\right]\left[e^{\int_0^{m_H}\frac{d\mu}{\mu}[\Gamma^{(C)}_{\nu_2}(\alpha_s(\mu))]_{gc_2}(\Theta(p_t^{\mathrm{J,v}}-\mu)J_0(b\mu)-1)}\right] C_{\nu_1,gc_1}(\alpha_s(m_h))\, C_{\nu_2,gc_2}(\alpha_s(m_H))$$

**Mellin moments**

**Flavour indices**

Asymptotic limits reproduce $p_\perp^{\mathrm{J,v}}$ ($p_\perp^{\mathrm{H}}$) canonical resummation when $p_\perp^H \gg p_\perp^{\mathrm{J,v}}$ ($p_\perp^{\mathrm{J,v}} \gg p_\perp^H$)

# Double-differential resummation at NNLL in $b$ space

Crucial observation: in $b$ space the phase space constraints entirely factorize ⟶ $e^{i\vec{b}\cdot\vec{k}_{t,i}}$

The jet veto constraint can be included by implementing the jet veto resummation at the $b$-space integrand level **directly in impact-parameter space**

**Inclusive** contribution: phase space constraint of the form

$$\Theta(p_\perp^{\mathrm{J,v}} - \max\{k_{t,1}, \ldots, k_{t,n}\}) = \prod_{i=1}^{n} \Theta(p_\perp^{\mathrm{J,v}} - k_{t,i})$$

Promote radiator at NNLL

$$\frac{d\sigma(p_\perp^H, p_\perp^{\mathrm{J,v}})}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\mathrm{NLL}}(L)} \longrightarrow \frac{d\sigma(p_\perp^H, p_\perp^{\mathrm{J,v}})}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\mathrm{NNLL}}(L)}$$

$$S_{\mathrm{NNLL}} = -Lg_1(\alpha_s L) - g_2(\alpha_s L) - \alpha_s g_3(\alpha_s L) + \int_0^{m_H} \frac{dk_t}{k_t} R'_{\mathrm{NNLL}}(k_t) J_0(bk_t) \Theta(k_t - p_\perp^{\mathrm{J,v}})$$

# Double-differential resummation in direct space

Just need to **combine measurement functions**!

At NLL

$$\sigma(p_\perp^{\mathrm{J,v}}, p_\perp^H) = \sigma_0 \int \frac{dk_{t,1}}{k_{t,1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(k_{t,1})} R'\left(k_{t,1}\right) d\mathcal{Z}\, \Theta\left(p_\perp^{\mathrm{J,v}} - \max\left\{k_{t,1}, \ldots k_{t,n+1}\right\}\right) \Theta\left(p_\perp^H - |\vec{k}_{t,1} + \cdots \vec{k}_{t,n+1}|\right)$$

Same philosophy at NNLL

$$\sigma^{\mathrm{NNLL}}(p_\perp^{\mathrm{J,v}}) = \sigma^{\mathrm{NNLL}}_{\mathrm{incl}}(p_\perp^{\mathrm{J,v}}) + \sigma^{\mathrm{NNLL}}_{\mathrm{clust}}(p_\perp^{\mathrm{J,v}}) + \sigma^{\mathrm{NNLL}}_{\mathrm{corr}}(p_\perp^{\mathrm{J,v}})$$

where e.g.

$$\sigma^{\mathrm{NNLL}}_{\mathrm{clust}}(p_\perp^{\mathrm{J,v}}) \simeq \int_0^\infty \frac{dk_{t,1}}{k_{t,1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z}\, e^{-R(k_{t,1})}\, 8\, C_A^2 \frac{\alpha_s^2(k_{t,1})}{\pi^2} \Theta\left(p_\perp^{\mathrm{J,v}} - \max_{i>1}\{k_{t,i}\}\right)$$
$$\times \int_0^{k_{t,1}} \frac{dk_{t,s_1}}{k_{t,s_1}} \frac{d\phi_{s_1}}{2\pi} \int_{-\infty}^{\infty} d\Delta\eta_{1s_1} J_{1s_1}(R) \left[\Theta\left(p_\perp^{\mathrm{J,v}} - |\vec{k}_{t,1} + \vec{k}_{t,s_1}|\right) - \Theta\left(p_\perp^{\mathrm{J,v}} - k_{t,1}\right)\right]$$

# Double-differential resummation in direct space

Just need to **combine measurement functions**!

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$$\sigma(p_\perp^{\mathrm{J,v}}, p_\perp^{H}) = \sigma_0 \int \frac{dk_{t,1}}{k_{t,1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(k_{t,1})} R'\left(k_{t,1}\right) d\mathcal{Z}\, \Theta\left(p_\perp^{J,v} - \max\left\{k_{t,1}, \ldots k_{t,n+1}\right\}\right) \Theta\left(p_\perp^{H} - |\vec{k}_{t,1} + \cdots \vec{k}_{t,n+1}|\right)$$

Same philosophy at NNLL

$$\sigma^{\mathrm{NNLL}}(p_\perp^{\mathrm{J,v}}) = \sigma_{\mathrm{incl}}^{\mathrm{NNLL}}(p_\perp^{\mathrm{J,v}}) + \sigma_{\mathrm{clust}}^{\mathrm{NNLL}}(p_\perp^{\mathrm{J,v}}) + \sigma_{\mathrm{corr}}^{\mathrm{NNLL}}(p_\perp^{\mathrm{J,v}})$$

where e.g

$$\sigma_{\mathrm{clust}}^{\mathrm{NNLL}}(p_\perp^{\mathrm{J,v}}, p_\perp^{H}) \simeq \int_0^\infty \frac{dk_{t,1}}{k_{t,1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z}\, e^{-R(k_{t,1})}\, 8\, C_A^2 \frac{\alpha_s^2(k_{t,1})}{\pi^2} \Theta\left(p_\perp^{\mathrm{J,v}} - \max_{i>1}\{k_{t,i}\}\right)$$
$$\times \int_0^{k_{t,1}} \frac{dk_{t,s_1}}{k_{t,s_1}} \frac{d\phi_{s_1}}{2\pi} \int_{-\infty}^{\infty} d\Delta\eta_{1s_1} J_{1s_1}(R) \left[\Theta\left(p_\perp^{\mathrm{J,v}} - |\vec{k}_{t,1} + \vec{k}_{t,s_1}|\right) - \Theta\left(p_\perp^{\mathrm{J,v}} - k_{t,1}\right)\right]$$
$$\times\, \Theta\left(p_\perp^{H} - |\vec{k}_{t,1} + \ldots + \vec{k}_{t,n+1} + \vec{k}_{t,s_1}|\right)$$

And analogously for other contributions

# Resummation of the resolution parameter

Since the resummed formula is only differential in $\Phi_0$, $r_0$, one has to make it differential in 2 more variables, e.g. energy ratio $z = E_m/E_s$ or azimuthal angle $\phi$. Use a normalised splitting probability to make the resummation differential in $\Phi_1$

$$\mathcal{P}(\Phi_1) = \frac{p_{sp}(z,\phi)}{\sum_{sp}\int_{z_{min}(\mathcal{T}_0)}^{z_{max}(\mathcal{T}_0)} \mathrm{d}z\mathrm{d}\phi\, p_{sp}(z,\phi)} \frac{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0 \mathrm{d}z \mathrm{d}\phi}{\mathrm{d}\Phi_1}, \qquad \int \frac{\mathrm{d}\Phi_1}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0} \mathcal{P}(\Phi_1) = 1$$

- $p_{sp}$ are based on AP splittings for FSR, weighted by PDF ratio for ISR.

8

# Comparison of resolution parameters