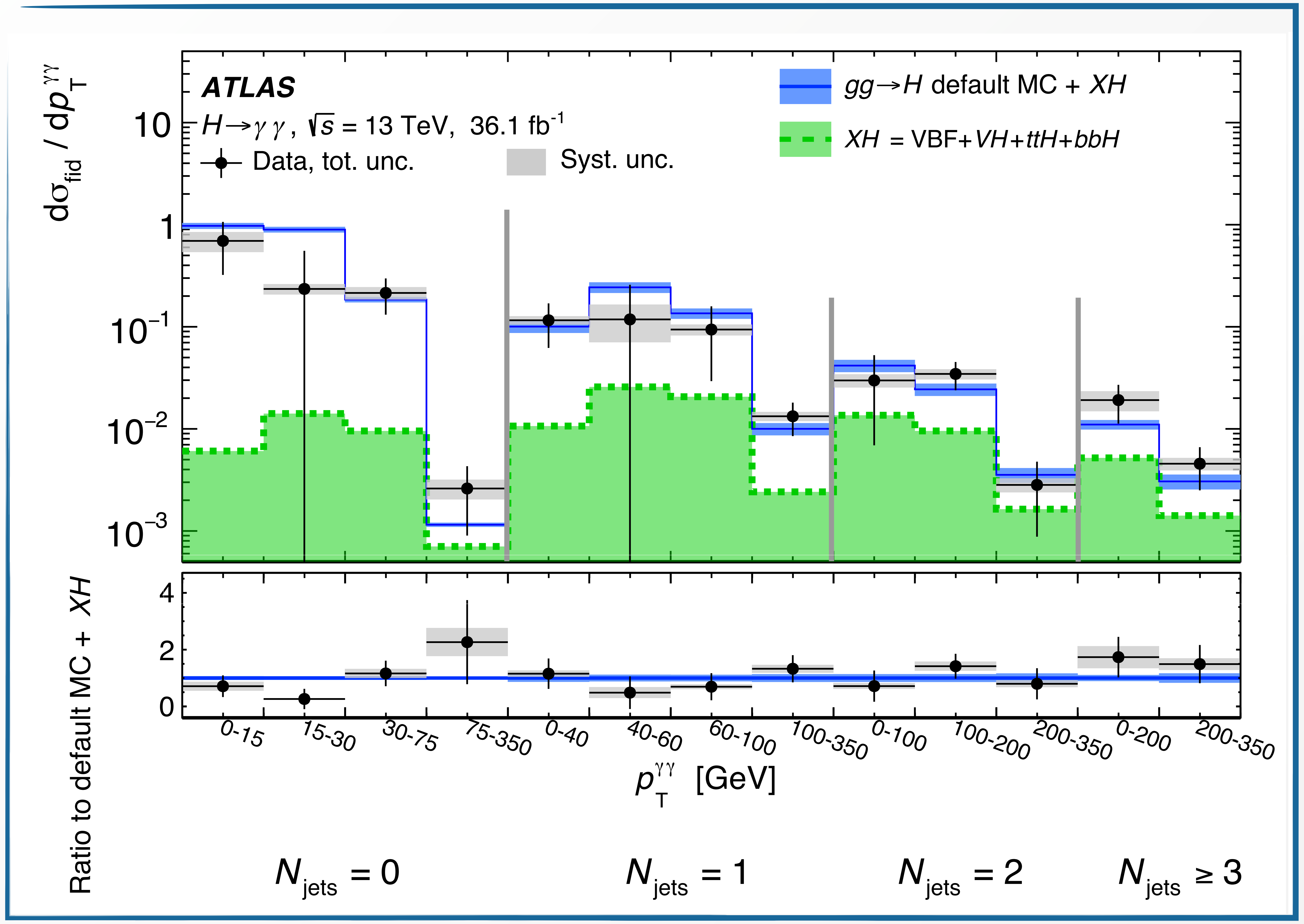
Colour-singlet transverse momentum with a jet veto: a double-differential resummation

Luca Rottoli

University of Milan-Bicocca & LBNL

Based on 1909.04704 with P. Monni and P. Torrielli

The Higgs transverse momentum



[ATLAS 1802.04146]

- Relatively easy to measure
- Sensitivity to New Physics (e.g. **light Yukawa** couplings, **trilinear** Higgs coupling) [Bishara *et al.* '16][Soreq *et al.* '16] [Bizon *et al.* '16]
- Experimental analyses categorize events into **jet bins** according to the jet multiplicity
- Precise access to Higgs boson kinematics
- Similar comments apply also to other analyses (e.g. VH with boosted Higgs, W^+W^- production…)

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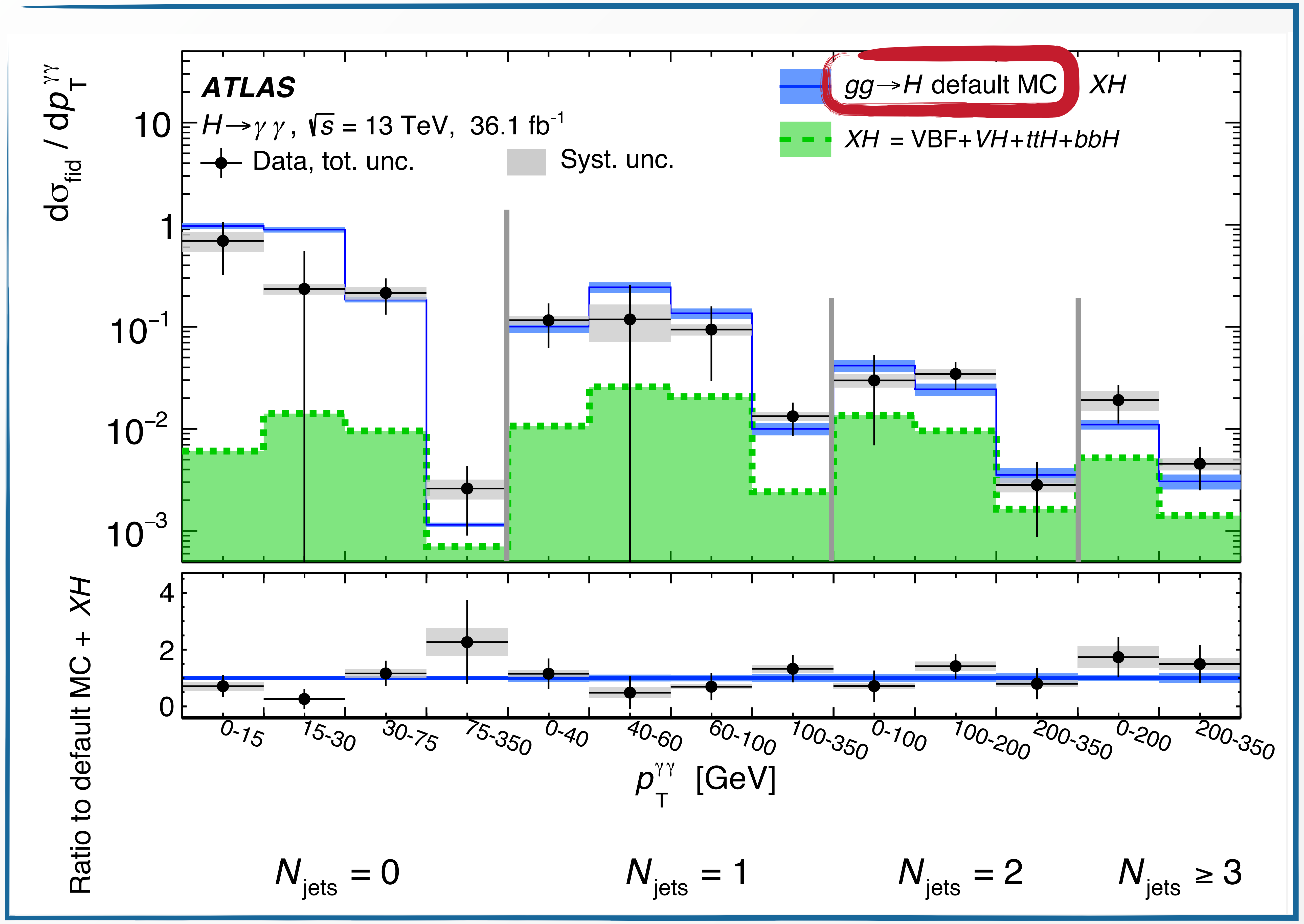

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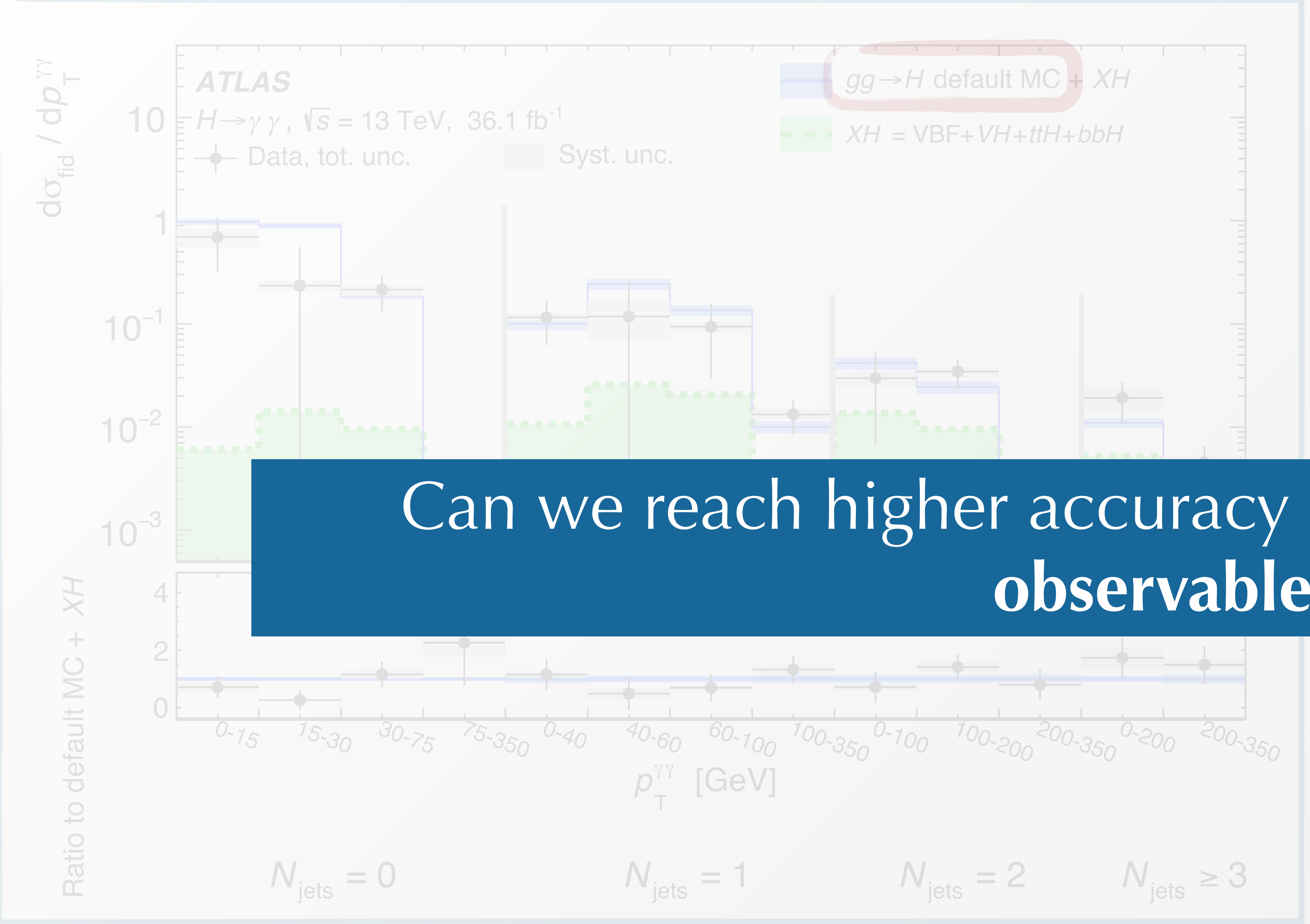

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Can we reach higher accuracy for **double-differential observables?**

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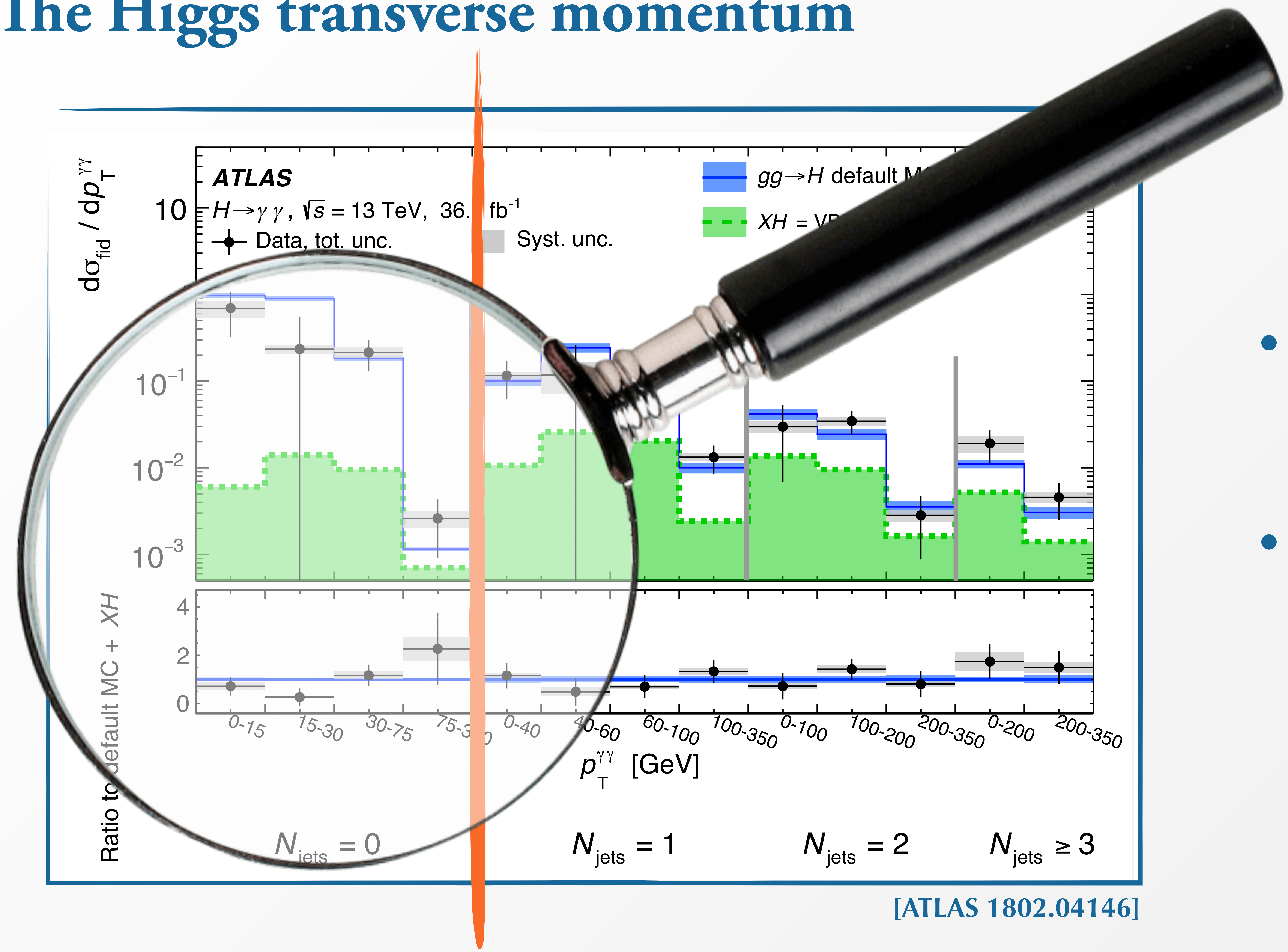

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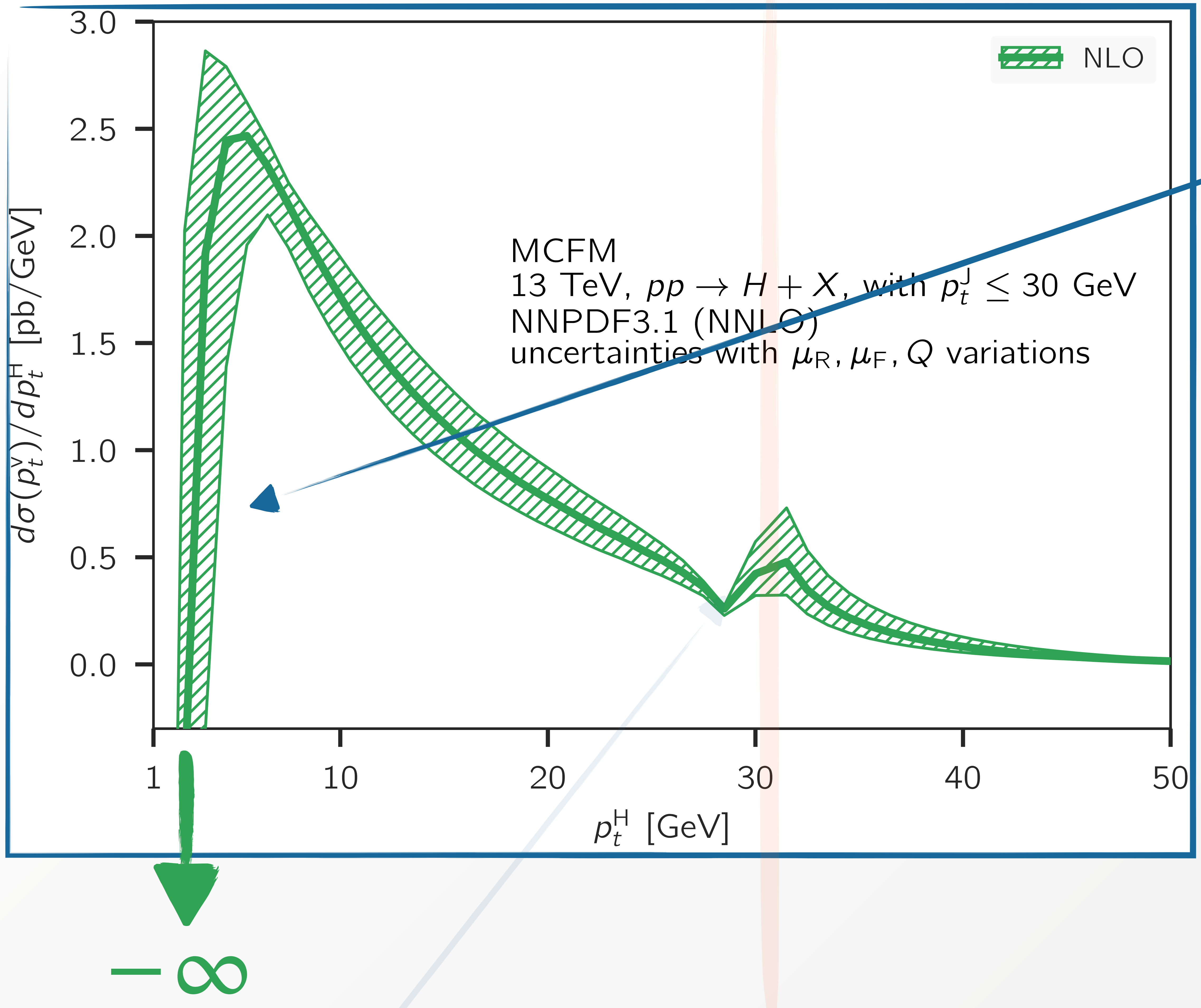
$p_\perp^J \leq 30\,\mathrm{GeV}$

- Focus on the **zero-jet bin** $p_\perp^J \leq p_\perp^{J,v}$
- Jet veto enforced to enhance the Higgs signal with respect to its backgrounds (e.g. $H \to W^+W^-$ vs $t\bar{t}$ event selection) or study of different production channels (e.g. STXS)

The appearance of large logarithms



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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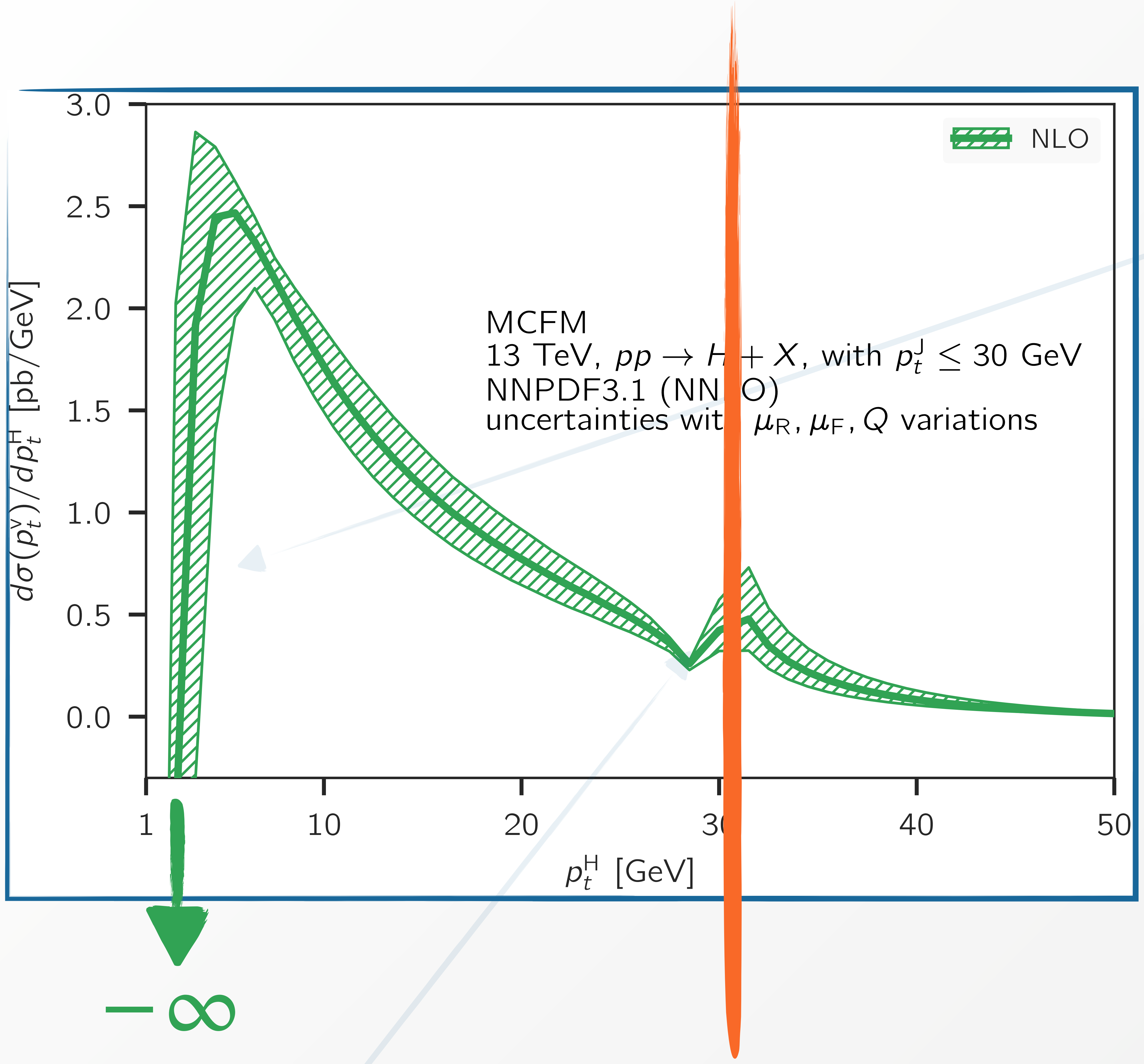

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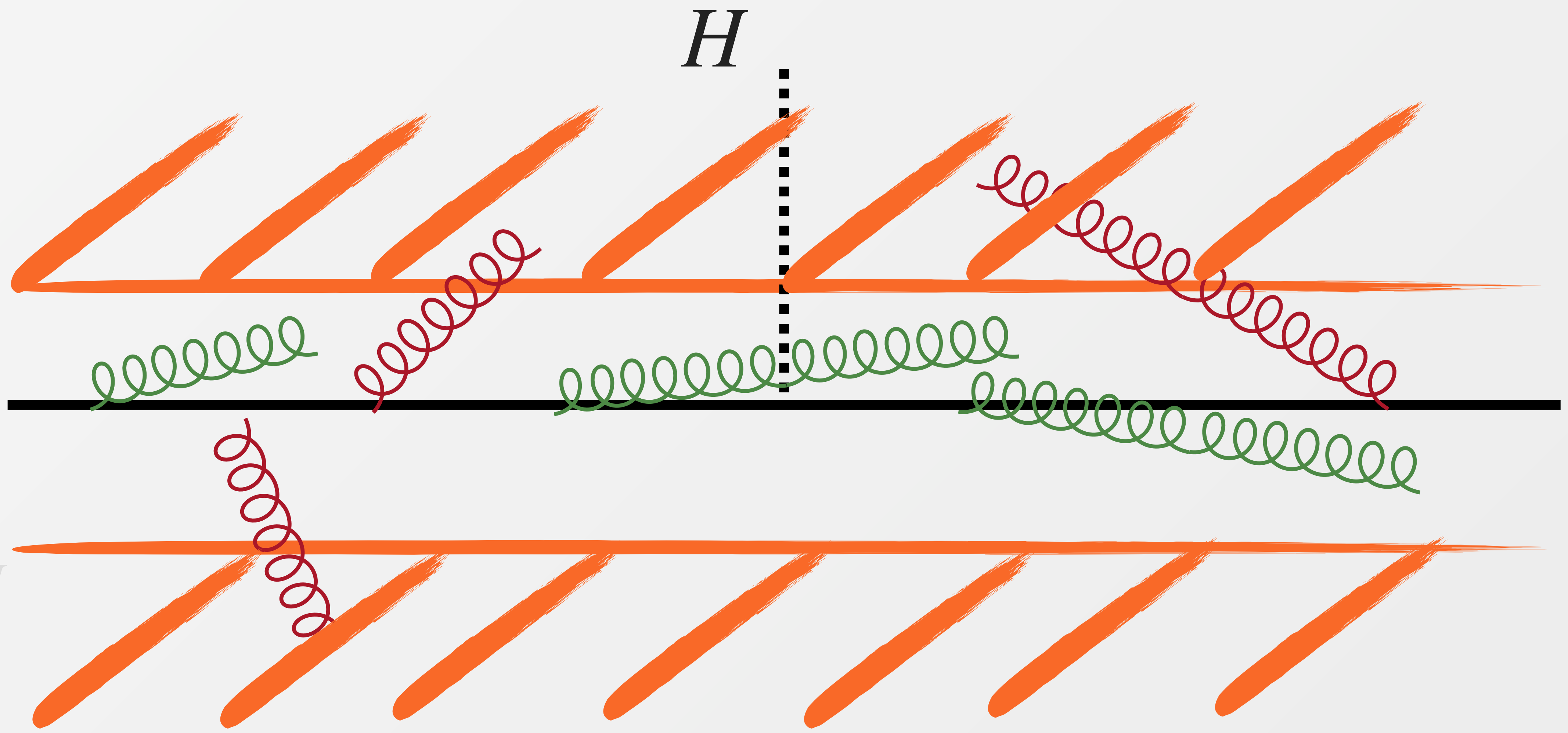

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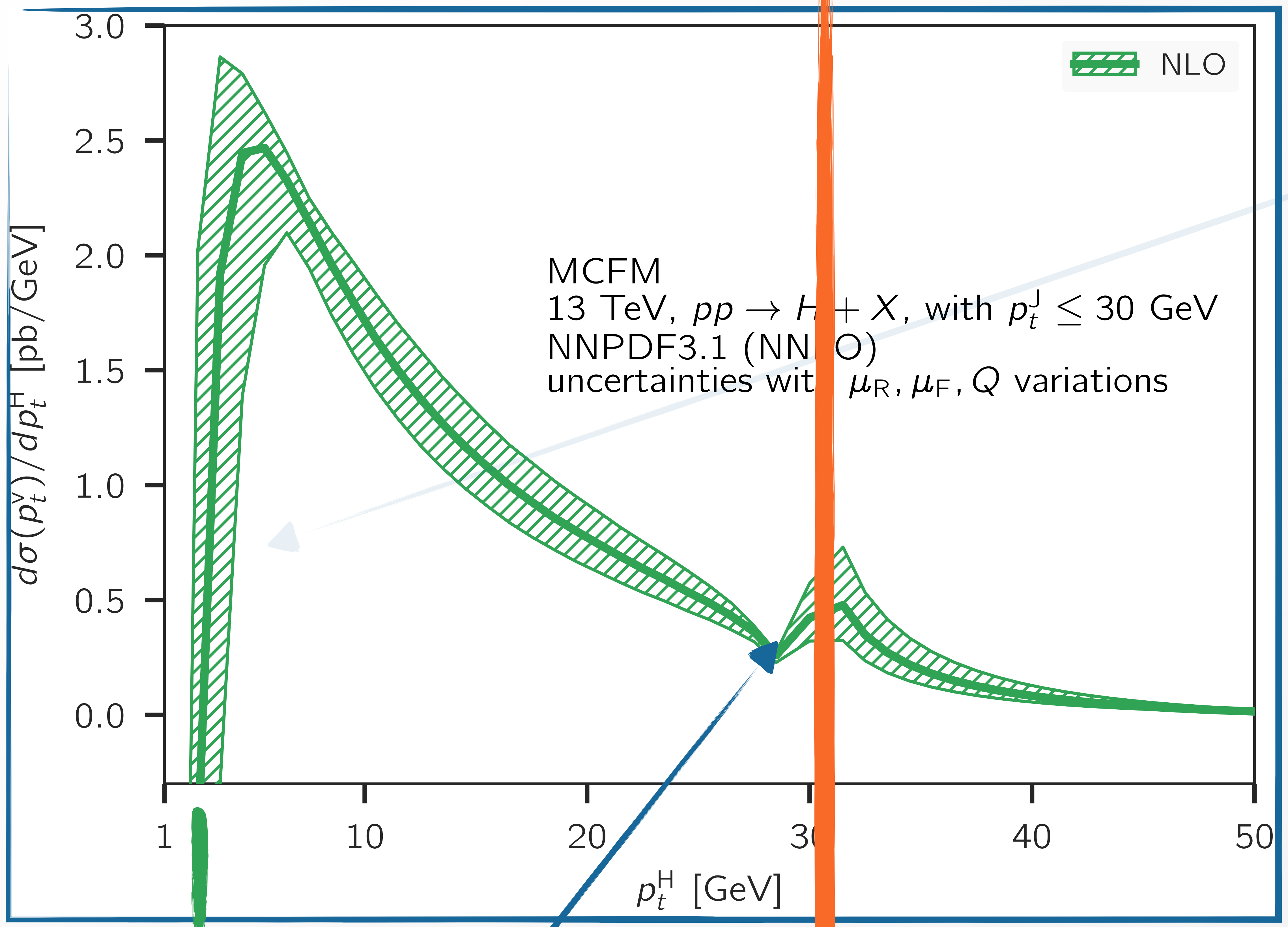

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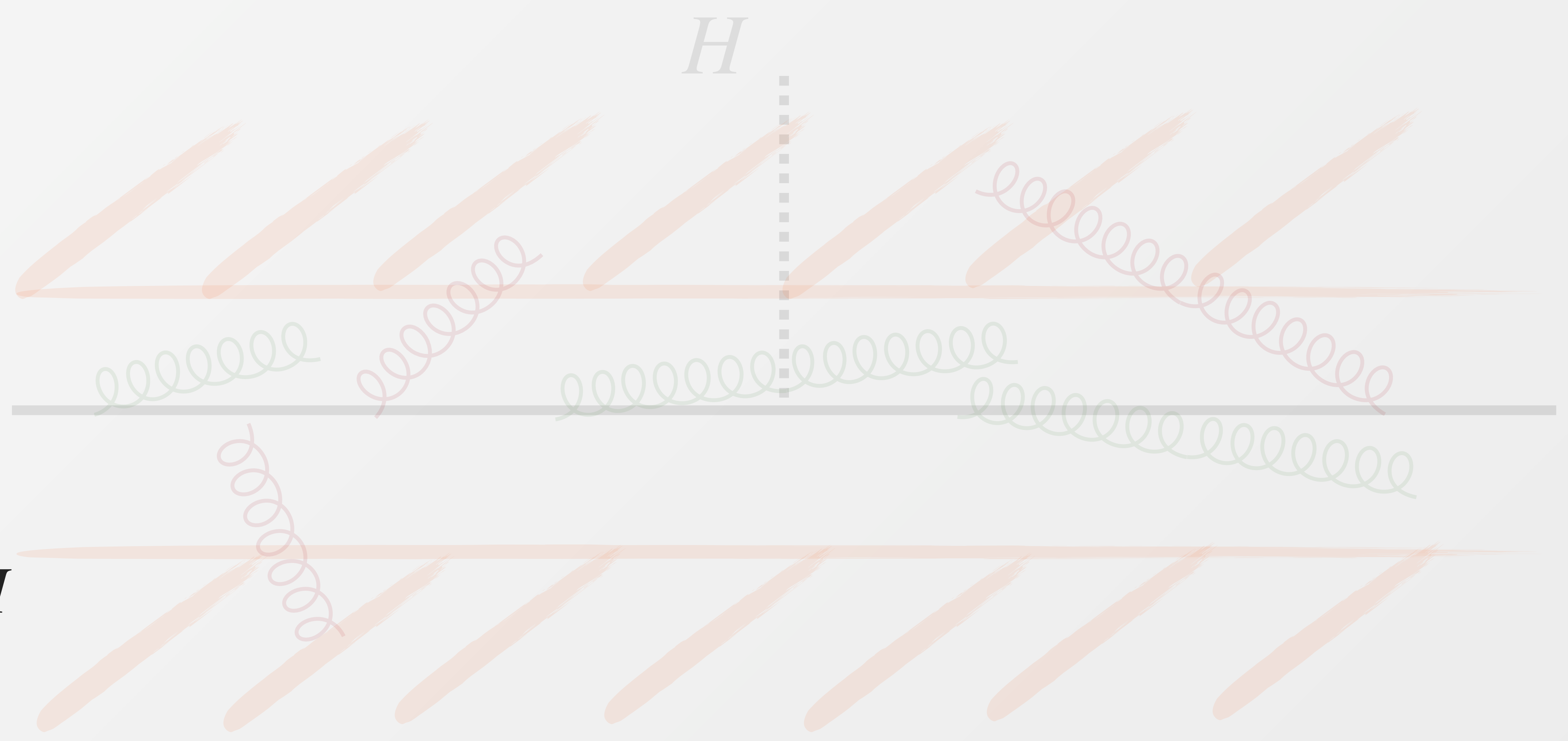

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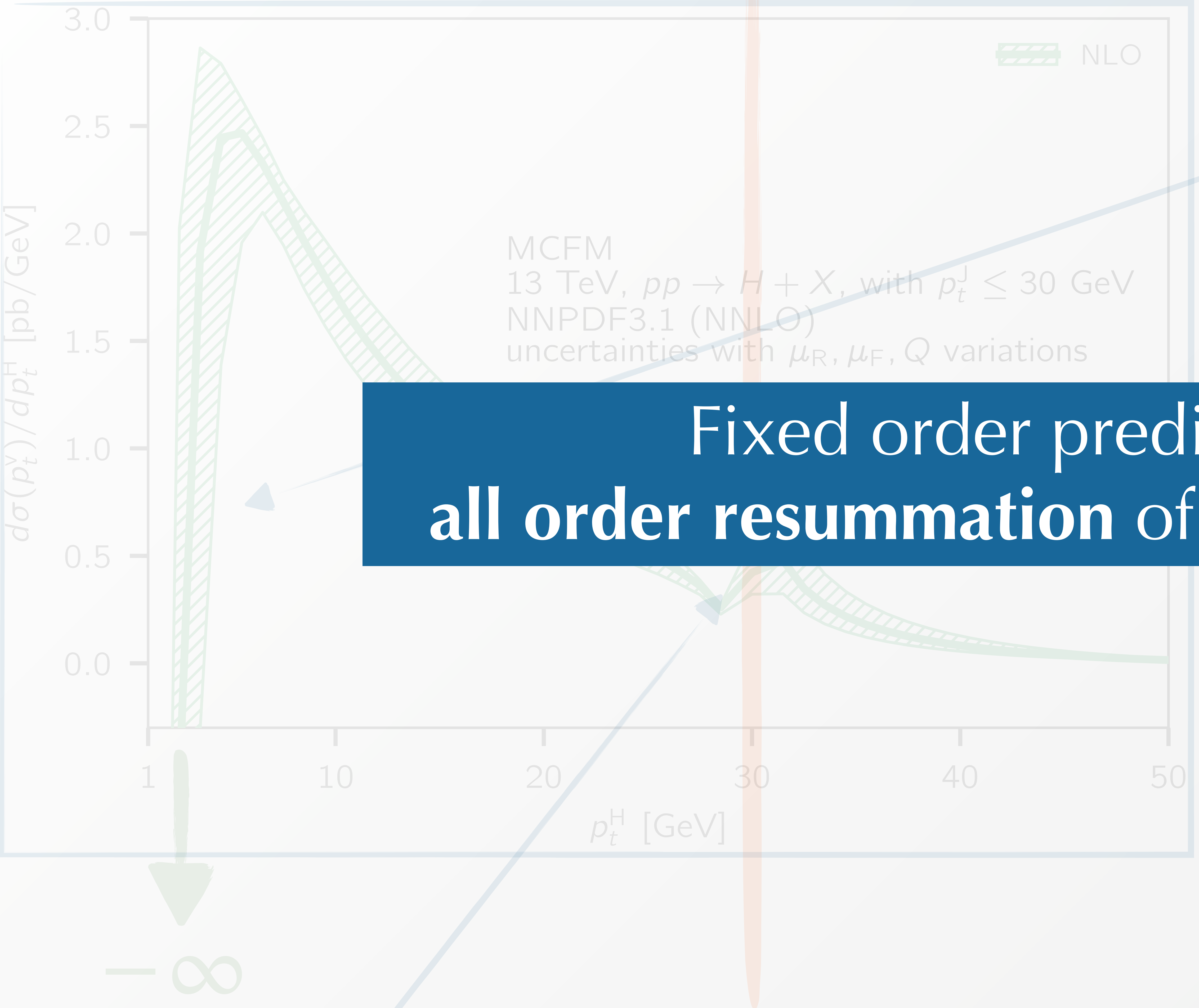

Large **transverse momentum** logarithms

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

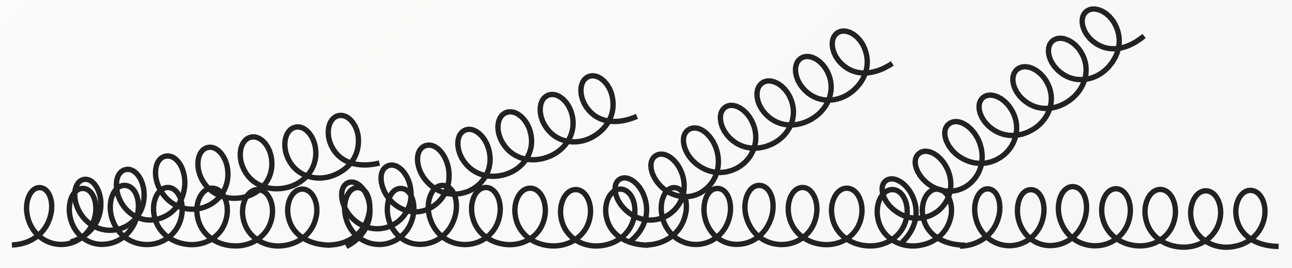
$$L = \ln(p_\perp^{\rm J,v}/m_H) \qquad p_\perp^{\rm J,v} < m_H$$

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

Resummation of the transverse momentum spectrum

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

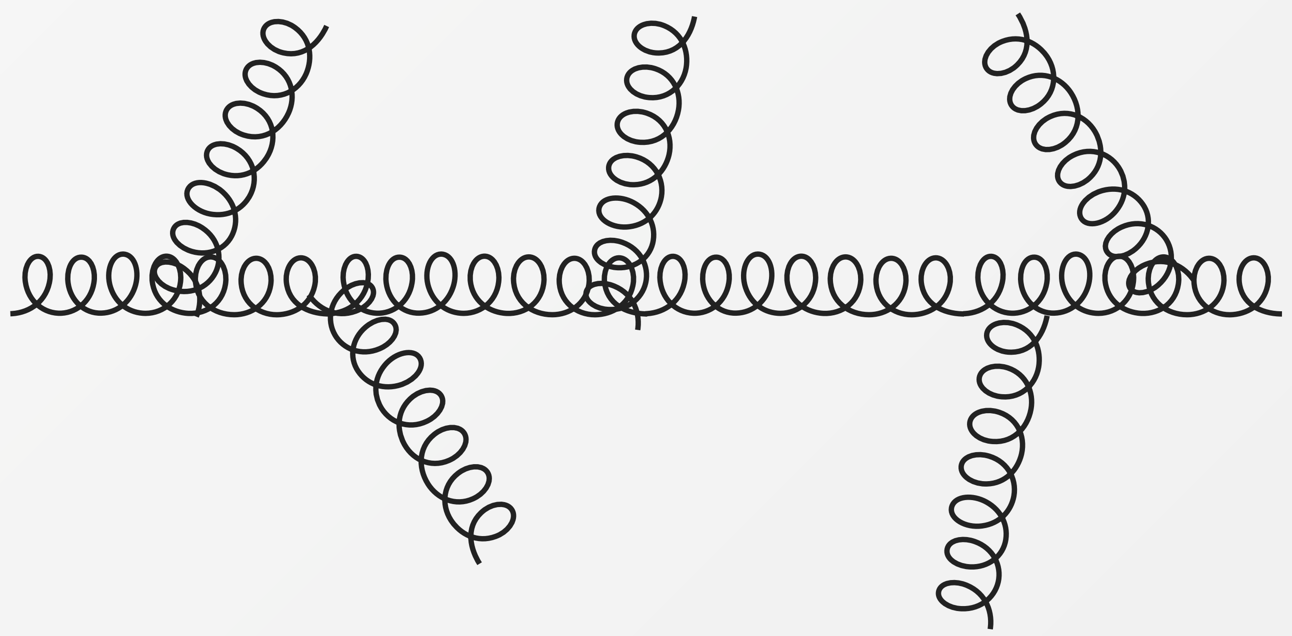
Two concurring mechanisms leading to a system with small $p_\perp$



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

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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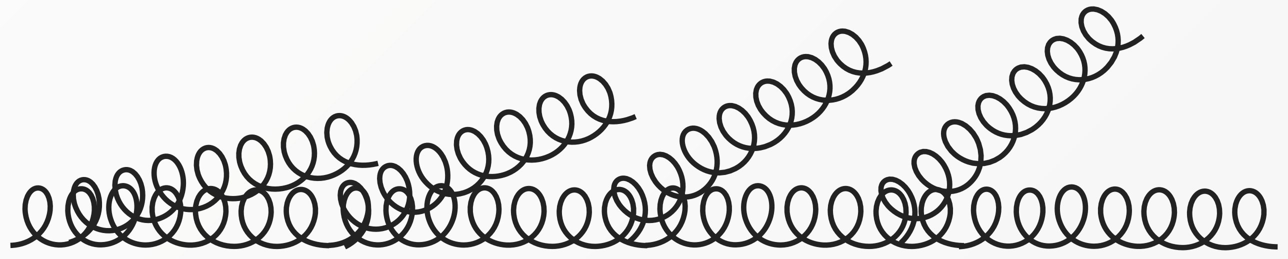

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Dominant at small $p_\perp$

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Power suppression

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

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

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

virtual corrections

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

Approach 2: momentum space

[Banfi, Salam, Zanderighi '01, '03, '04] [Bizon, Monni, Re, LR, Torrielli '16, '17, '18]
[Banfi, McAslan, Monni, Zanderighi, El-Menoufi '14, '18]
see also [Ebert, Tackmann, '18] within SCET

Approach exploits factorization properties of the QCD squared amplitudes

NLL formula with scale-independent PDFs

Simple observable

$$\sigma(p_\perp) = \sigma_0 \int \frac{dv_1}{v_1} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(v_1)} \qquad v_i = k_{t,i}/m_H, \quad \zeta_i = v_i/v_1$$

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

Transfer function

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

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

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CMW scheme

(inclusion of 2-loop cusp anomalous dimension)

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Direct space formulation: generality

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

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General

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

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

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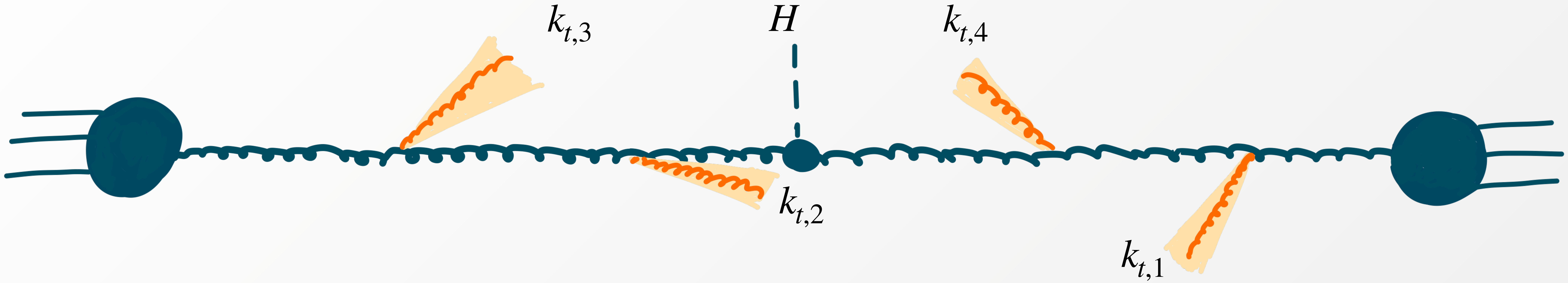
Double-differential resummation at NLL in b space

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



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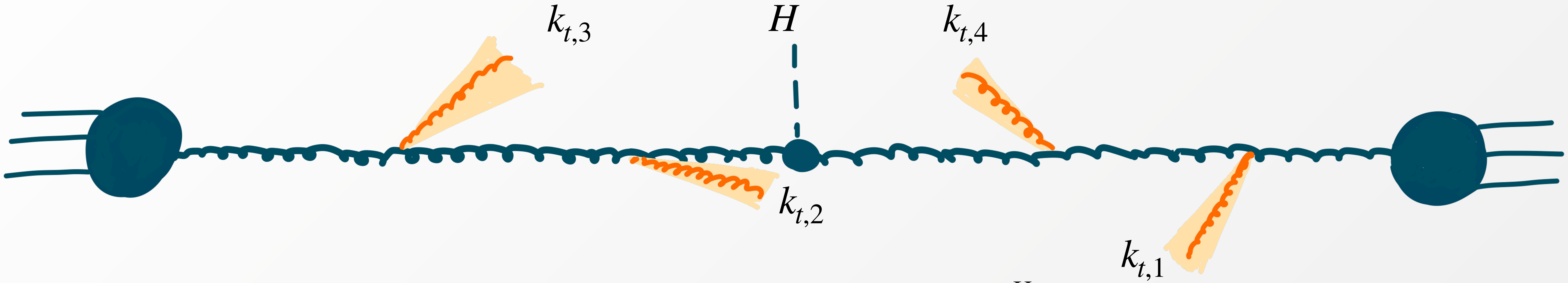

Additional constraint on **real radiation**

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

$p_\perp^H$ resummation formula

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

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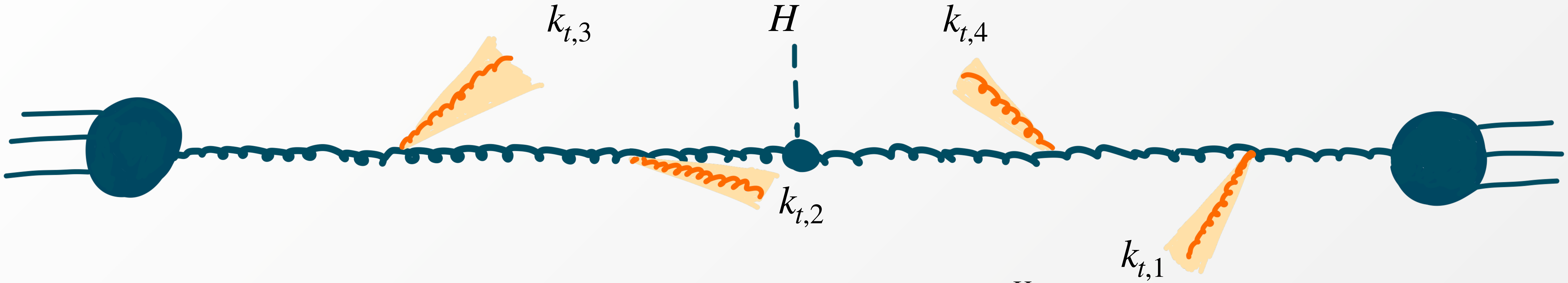
Double-differential resummation at NLL in b space

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**

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

$p_\perp^H$ resummation formula

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

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

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

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

$$S_{\rm NLL}(L) = -Lg_1(\alpha_s L) - g_2(\alpha_s L) + \int_0^{m_H} \frac{dk_t}{k_t} R'_{\rm NLL}(k_t) J_0(bk_t) \Theta(k_t - p_\perp^{\rm J,v}) \qquad R'_{\rm NLL}(k_t) = 4\left(\frac{\alpha_s^{\rm CMW}(k_t)}{\pi} C_A \ln\frac{m_H}{k_t} - \alpha_s(k_t)\beta_0\right)$$

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 at NNLL in b space

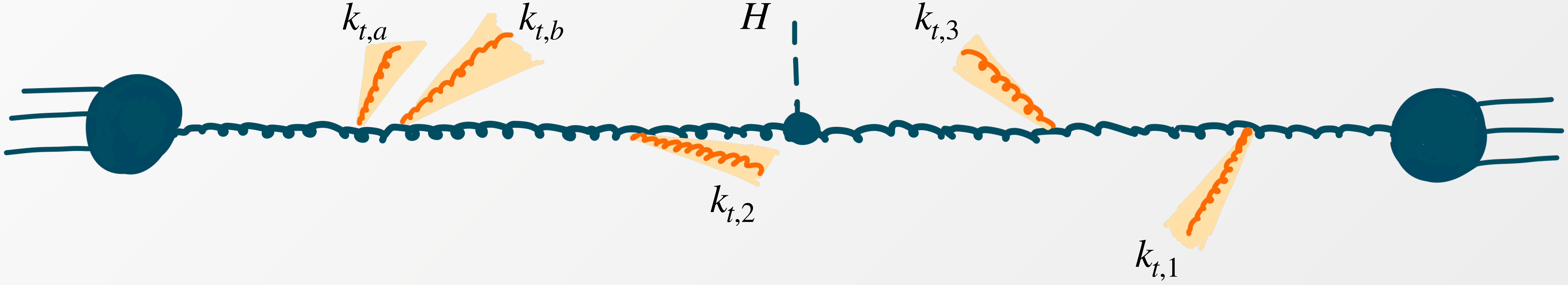
Additional corrections must be included at NNLL[Banfi et al. '12][Becher et al. '12 ,'13][Stewart et al. '13]

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

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

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

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



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]

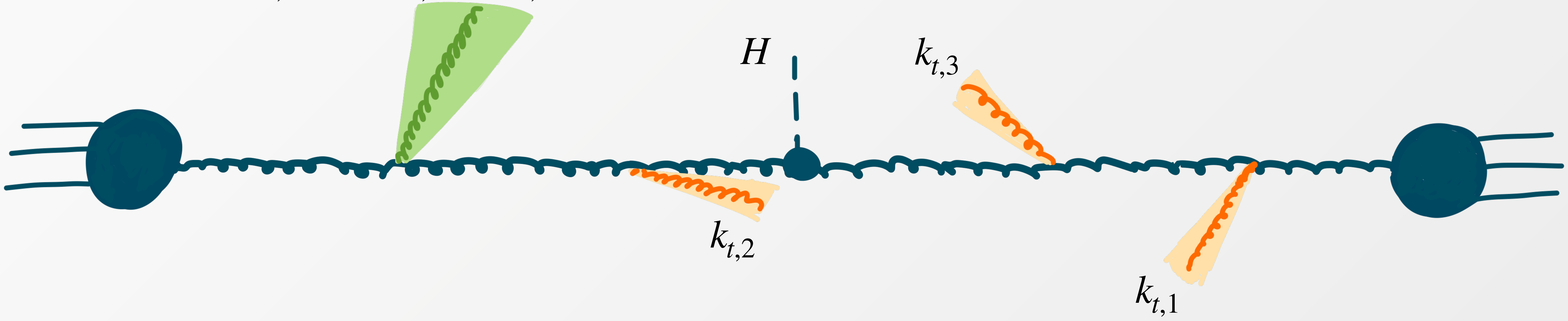
$$\frac{d\sigma(p_\perp^H, p_\perp^{\mathrm{J,v}})}{d^2\vec{p}_\perp^H} = \sigma_0 \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\mathrm{NNLL}}(L)} (1 + \mathcal{F}_{\mathrm{clust}} + \mathcal{F}_{\mathrm{correl}})$$

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

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

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

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



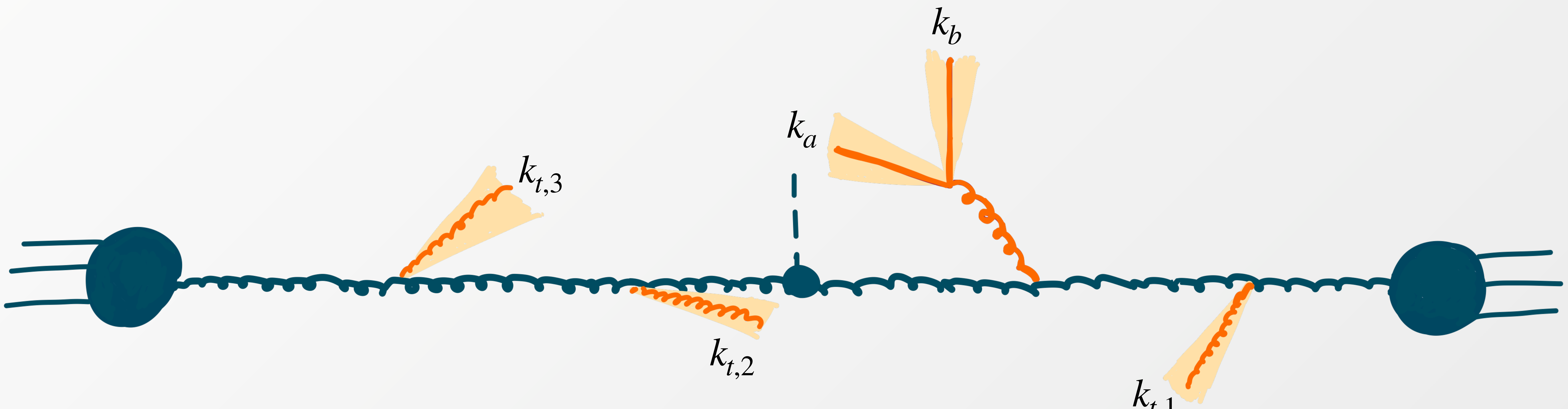
Double-differential resummation at NNLL in b space

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

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

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

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



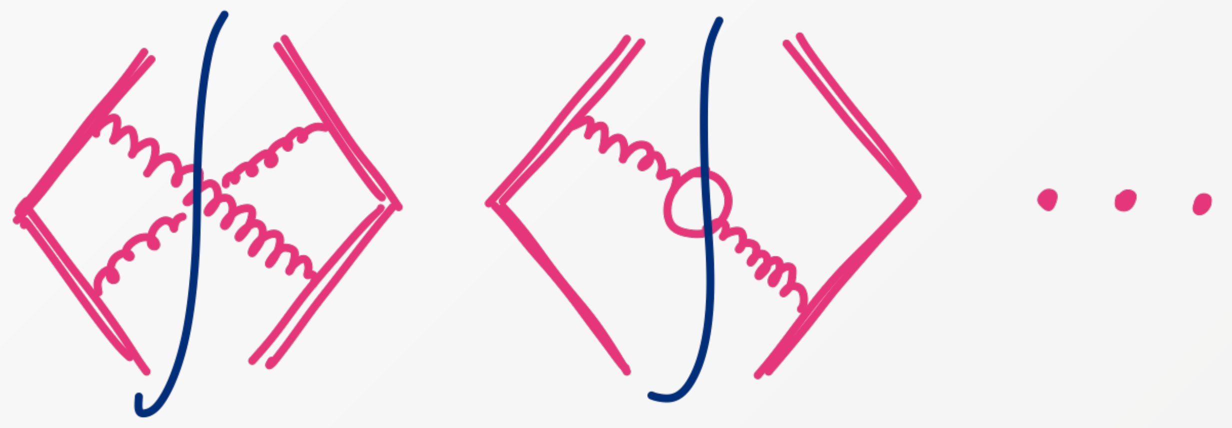
Double-differential resummation at NNLL in b space

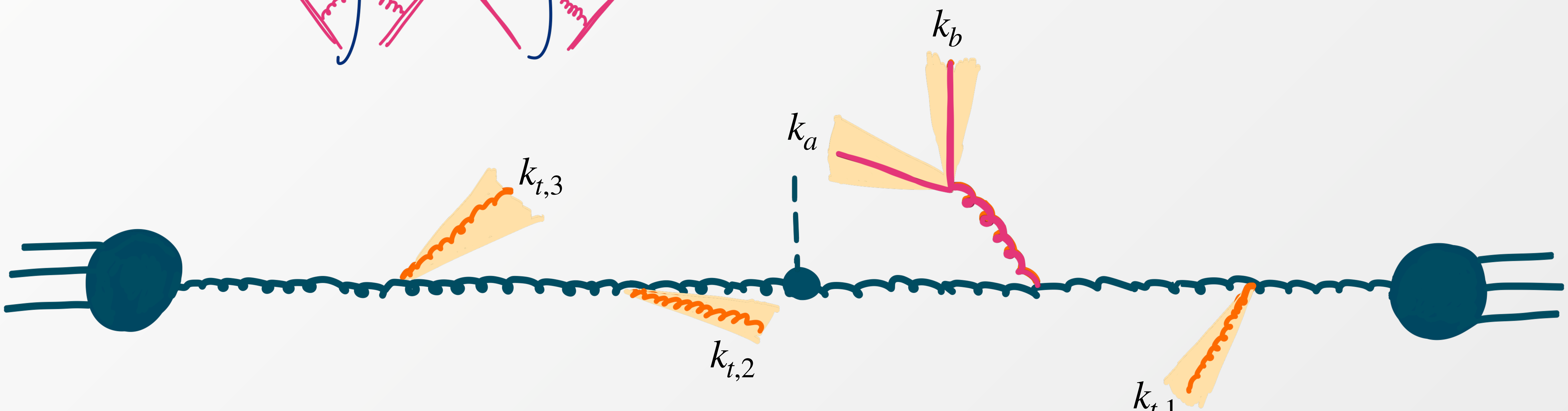
Additional corrections must be included at NNLL [Banfi et al. '12][Becher et al. '12 ,'13][Stewart et al. '13]

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

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

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





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**

$$\frac{d\sigma(p_\perp^H, p_\perp^{\mathrm{J,v}})}{dy_H d^2\vec{p}_\perp^H} = M^2_{\mathrm{gg}\to\mathrm{H}}\,\mathcal{H}(\alpha_s(m_H)) \int_{\mathcal{C}_1} \frac{d\nu_1}{2\pi i} \int_{\mathcal{C}_2} \frac{d\nu_2}{2\pi i} x_1^{-\nu_1} x_2^{-\nu_2} \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-S_{\mathrm{NNLL}}} \left(1 + \mathcal{F}_{\mathrm{clust}} + \mathcal{F}_{\mathrm{correl}}\right)$$
$$\times f_{\nu_1,a_1}(b_0/b) f_{\nu_2,a_2}(b_0/b) \left[\mathcal{P}\, e^{-\int_{p_\perp^{\mathrm{J,v}}}^{m_H} \frac{d\mu}{\mu} \mathbf{\Gamma}_{\nu_1}(\alpha_s(\mu)) J_0(b\mu)}\right]_{c_1 a_1} \left[\mathcal{P}\, e^{-\int_{p_\perp^{\mathrm{J,v}}}^{m_H} \frac{d\mu}{\mu} \mathbf{\Gamma}_{\nu_2}(\alpha_s(\mu)) J_0(b\mu)}\right]_{c_2 a_2}$$
$$\times C_{\nu_1,g b_1}(\alpha_s(b_0/b))\, C_{\nu_2,g b_2}(\alpha_s(b_0/b)) \left[\mathcal{P}\, e^{-\int_{p_\perp^{\mathrm{J,v}}}^{m_H} \frac{d\mu}{\mu} \mathbf{\Gamma}^{(C)}_{\nu_1}(\alpha_s(\mu)) J_0(b\mu)}\right]_{c_1 b_1} \left[\mathcal{P}\, e^{-\int_{p_\perp^{\mathrm{J,v}}}^{m_H} \frac{d\mu}{\mu} \mathbf{\Gamma}^{(C)}_{\nu_2}(\alpha_s(\mu)) J_0(b\mu)}\right]_{c_2 b_2}$$

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 in direct space

Just need to **combine measurement functions**!

At NLL

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

Double-differential resummation in direct space

Just need to **combine measurement functions**!

At NLL

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

Double-differential resummation in direct space

Just need to **combine measurement functions**!

At NLL

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

Double-differential resummation in direct space

Just need to **combine measurement functions**!

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

Same philosophy at NNLL

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

where e.g.

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

Double-differential resummation in direct space

Just need to **combine measurement functions**!

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

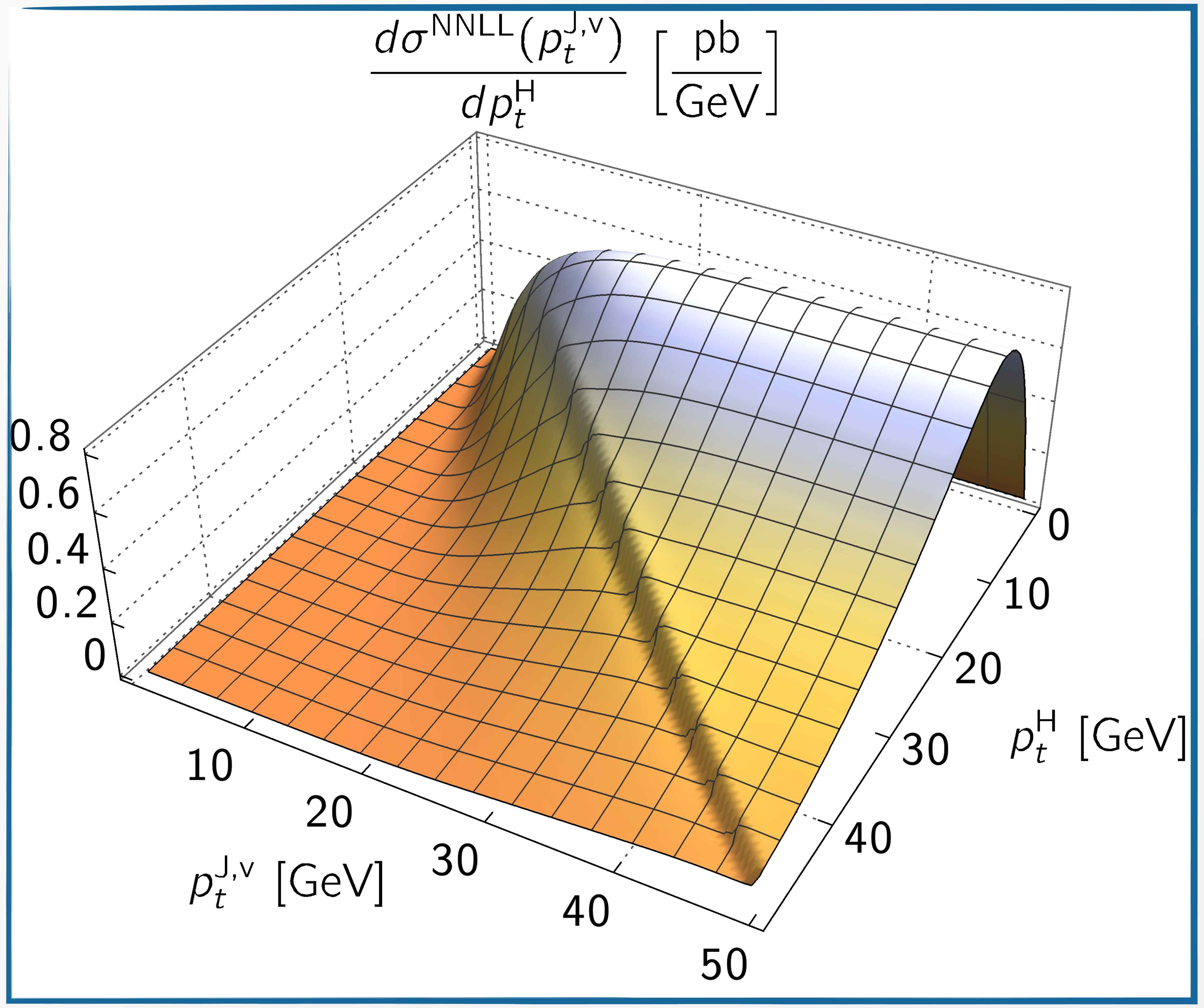
$$\sigma^{\mathrm{NNLL}}(p_\perp^{\mathrm{J,v}}) = \sigma^{\mathrm{NNLL}}_{\mathrm{incl}}(p_\perp^{\mathrm{J,v}}) + \sigma^{\mathrm{NNLL}}_{\mathrm{clust}}(p_\perp^{\mathrm{J,v}}) + \sigma^{\mathrm{NNLL}}_{\mathrm{corr}}(p_\perp^{\mathrm{J,v}})$$

where e.g

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

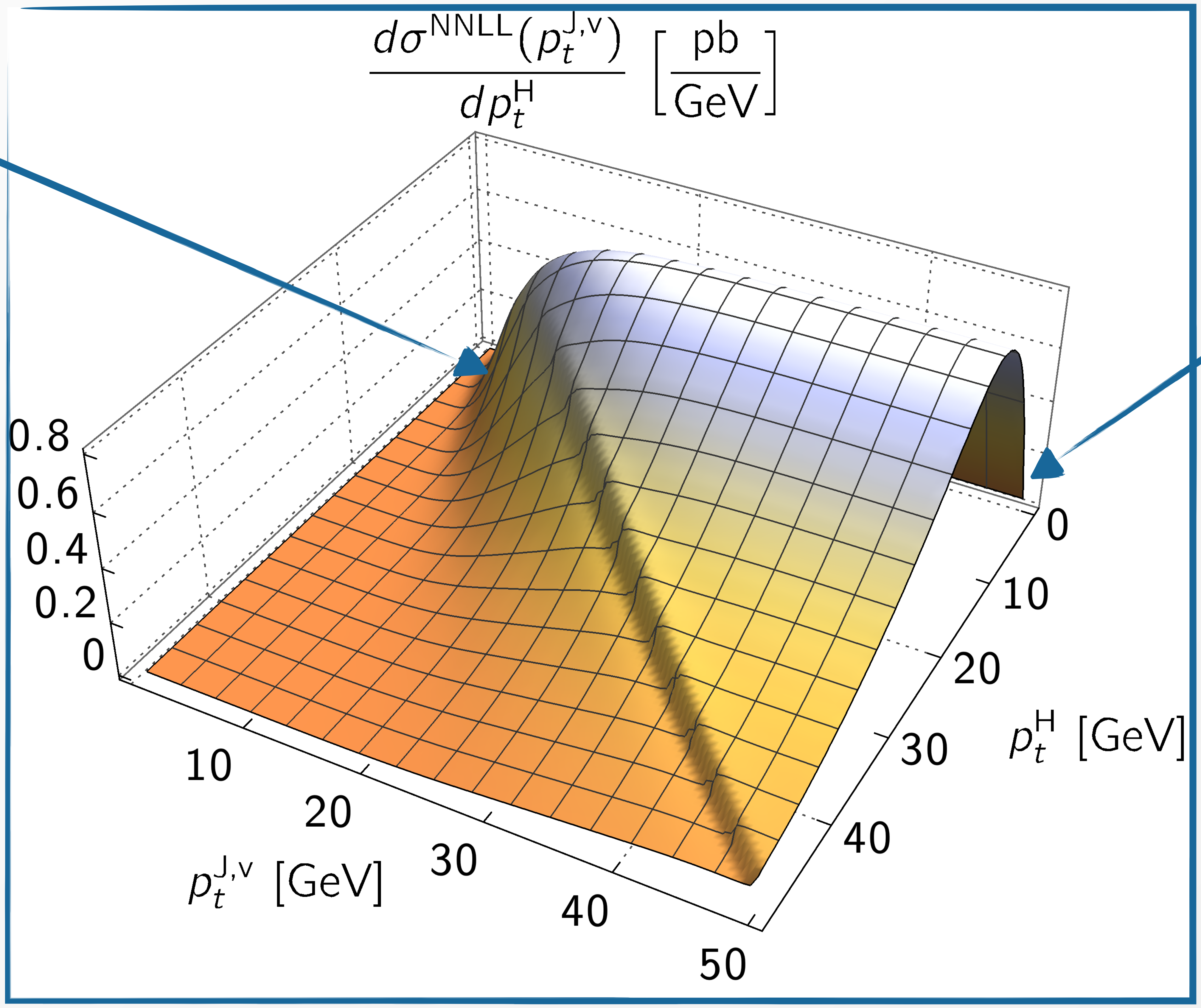
And analogously for other contributions

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



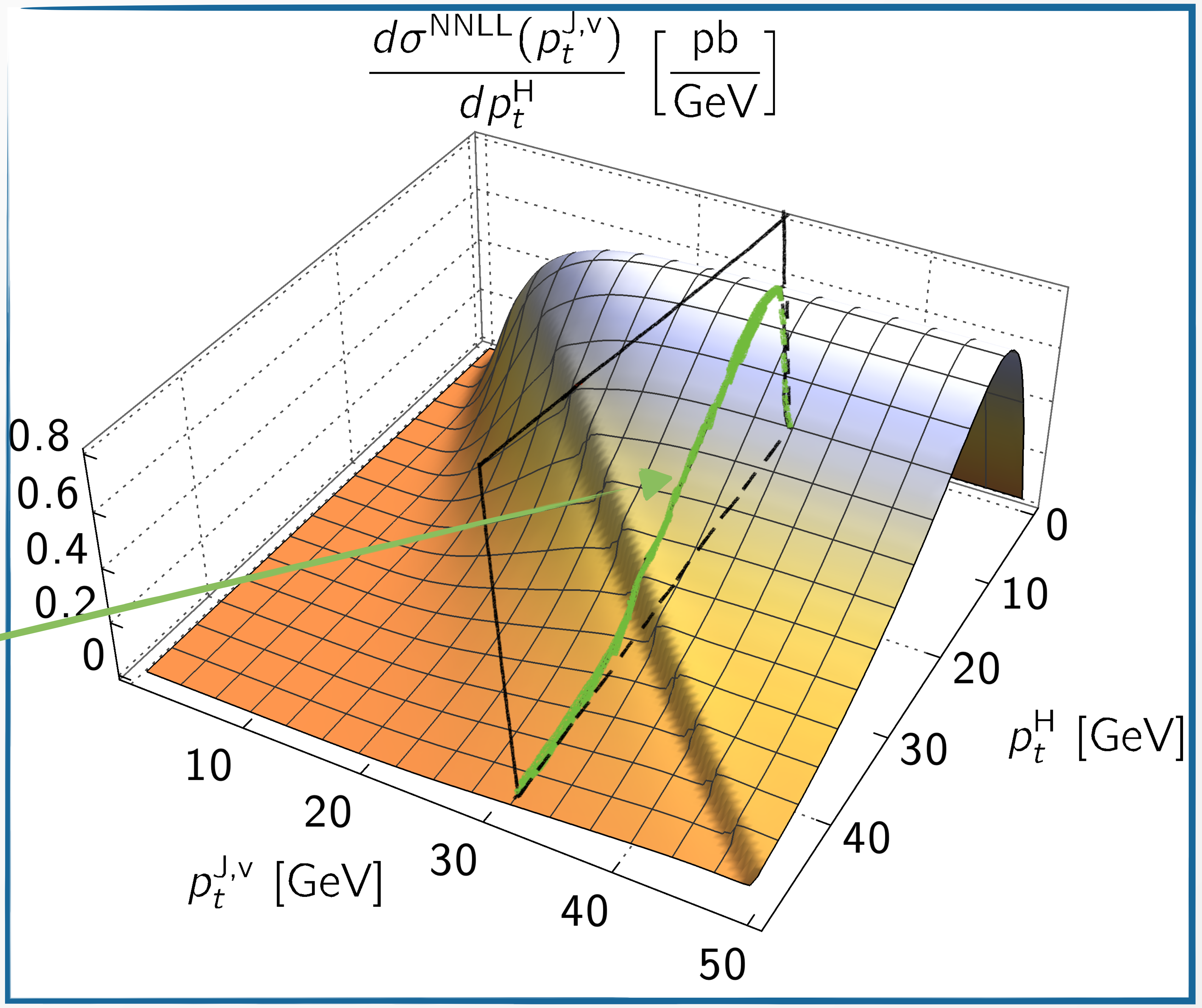
NNLL cross section differential in $p_\perp^H$, cumulative in $p_\perp^J \leq p_\perp^{J,v}$

Sudakov suppression at small $p_\perp^J$

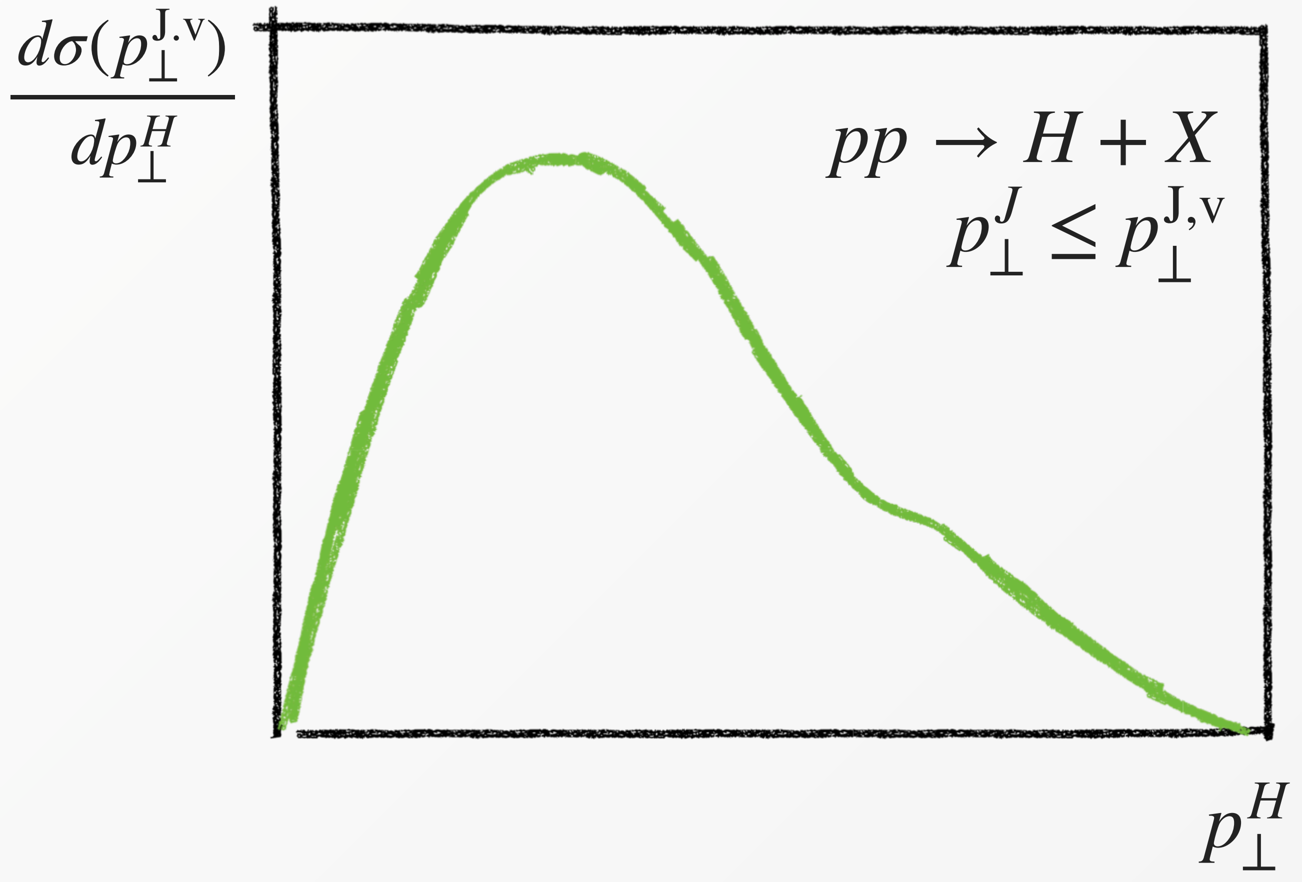


Peaked structure (Sudakov) + power-like suppression at very small $p_\perp^H$

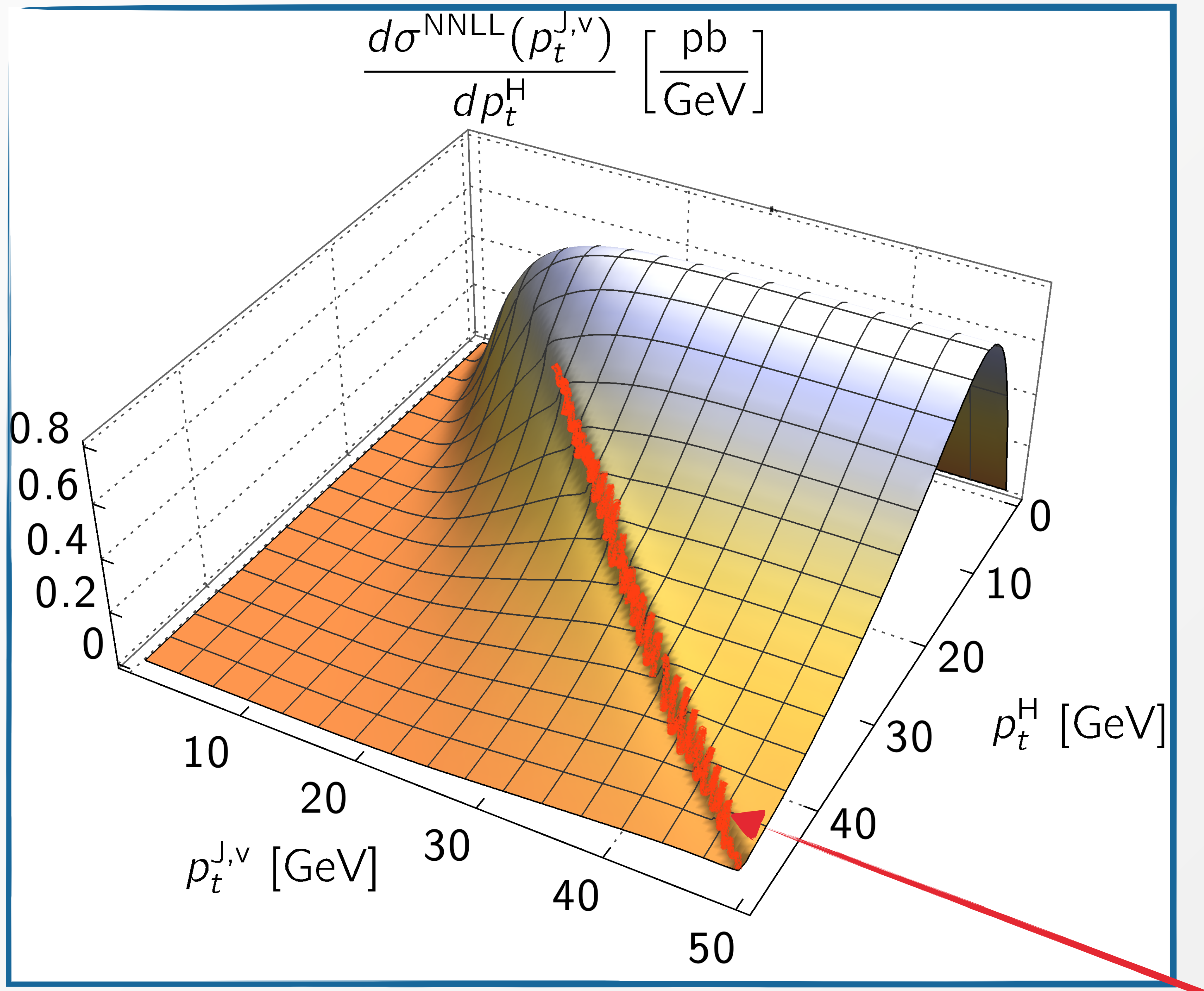
NNLL cross section differential in $p_\perp^H$, cumulative in $p_\perp^{\mathrm{J}} \leq p_\perp^{\mathrm{J,v}}$



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 $p_\perp^{\mathrm{J}} \le p_\perp^{\mathrm{J,v}}$

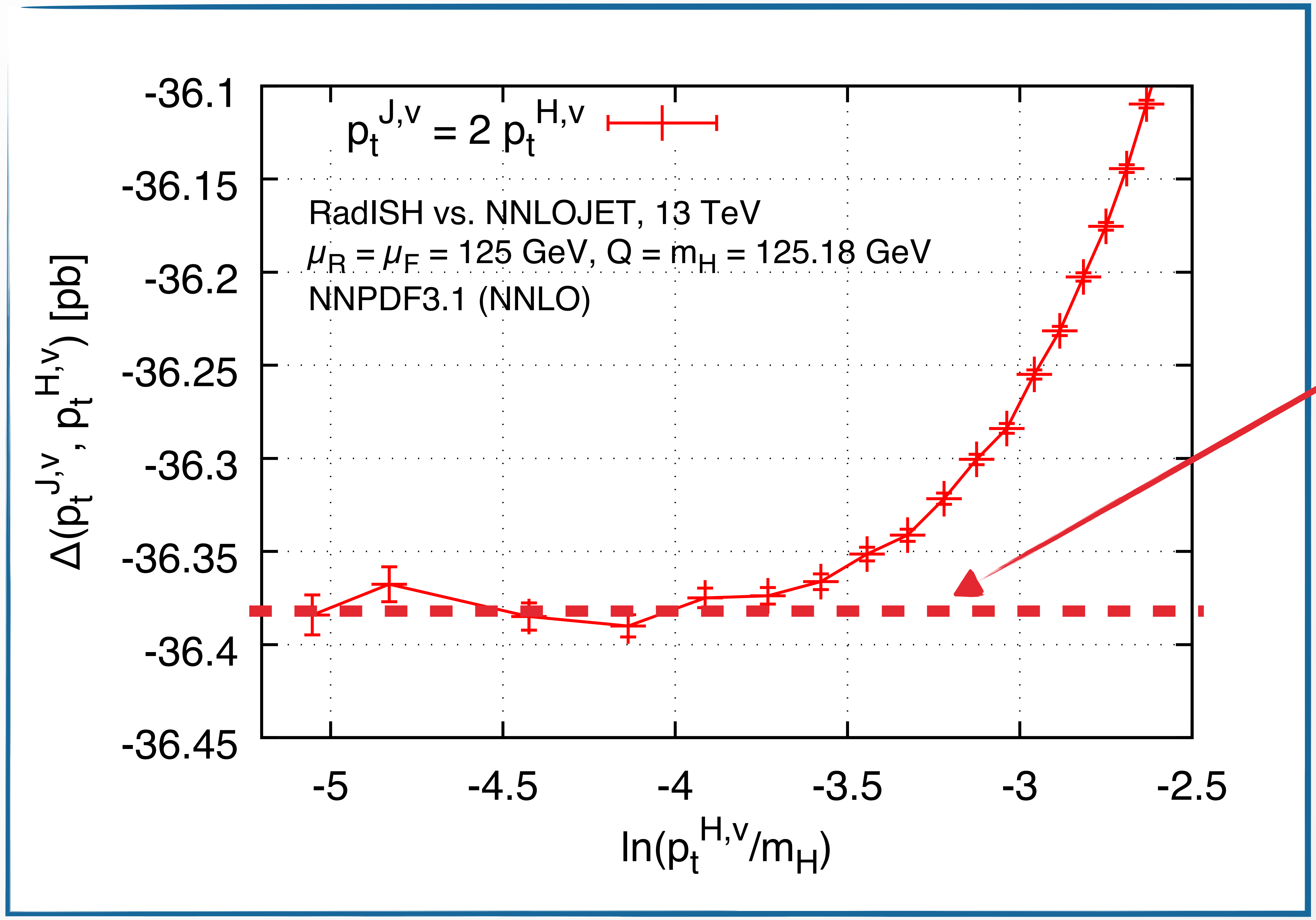


[Catani, Webber '97]

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

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

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



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

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

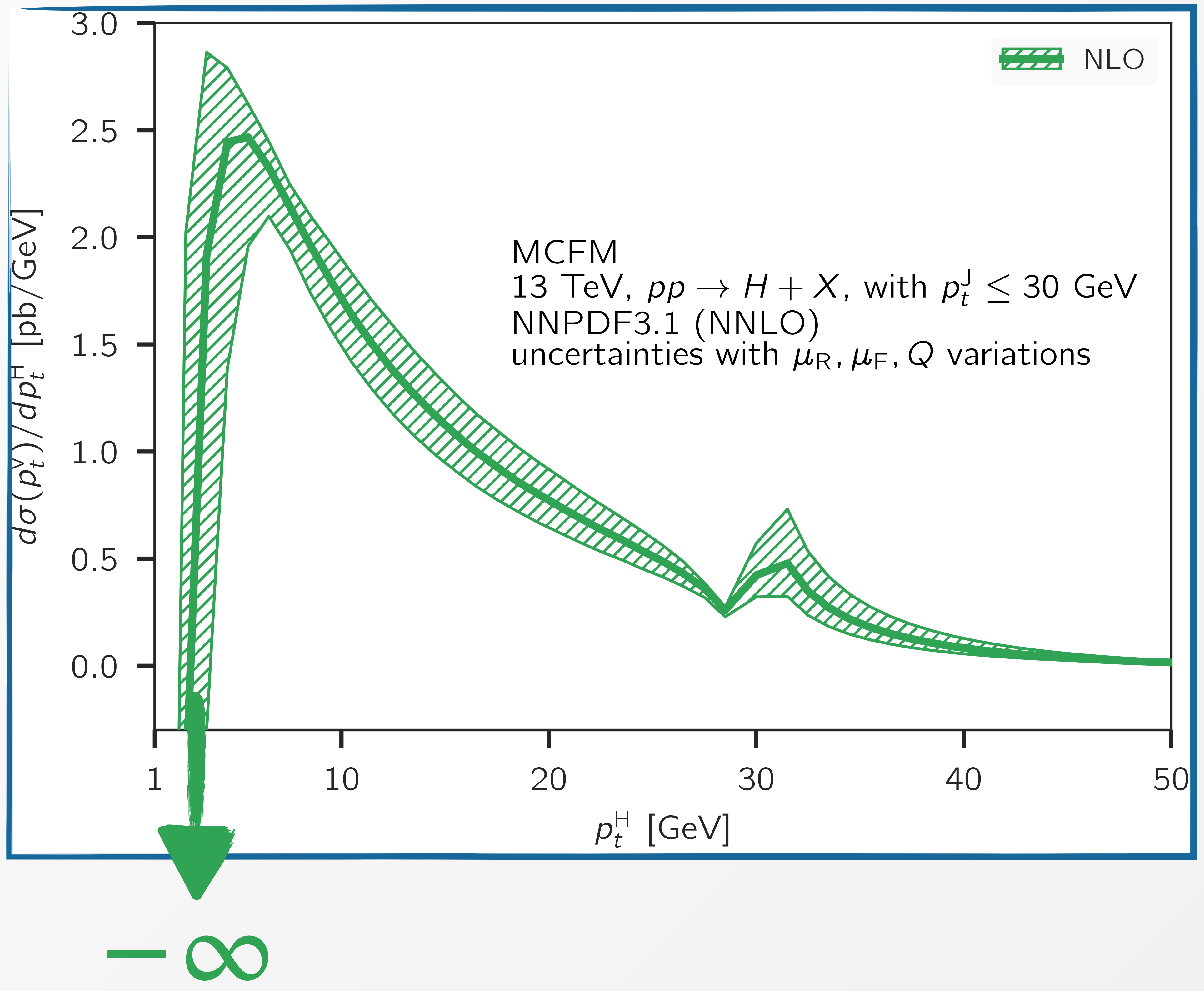
Very strong check: **NNLL resummation** of the larger logarithms when $p_\perp^H \sim p_\perp^{J,v} \ll m_H$

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

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

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

LHC results: Higgs transverse momentum with a jet veto

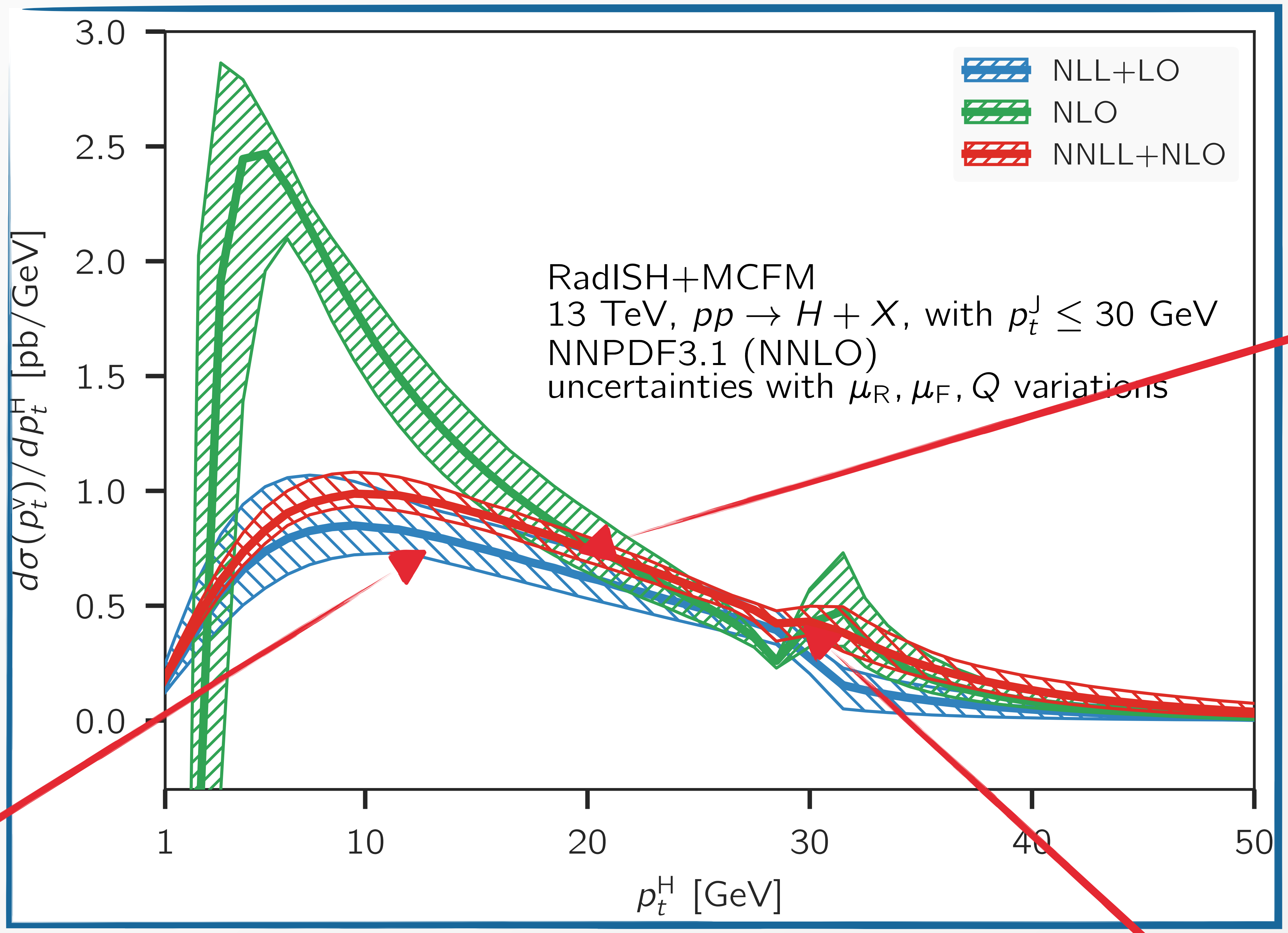


LHC results: Higgs transverse momentum with a jet veto

Multiplicative matching to fixed order (NLO H+j from **MCFM**, NNLO H from **ggHiggs**). Result integrates to the **NNLL′+NNLO** jet-vetoed cross section [Campbell, Ellis, Giele,'15] [Bonvini et al '13]

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

NNLO constant included through multiplicative matching (**NNLL′** accuracy)



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

good perturbative convergence to the left of the shoulder above, multi-particle configurations play a substantial role

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

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

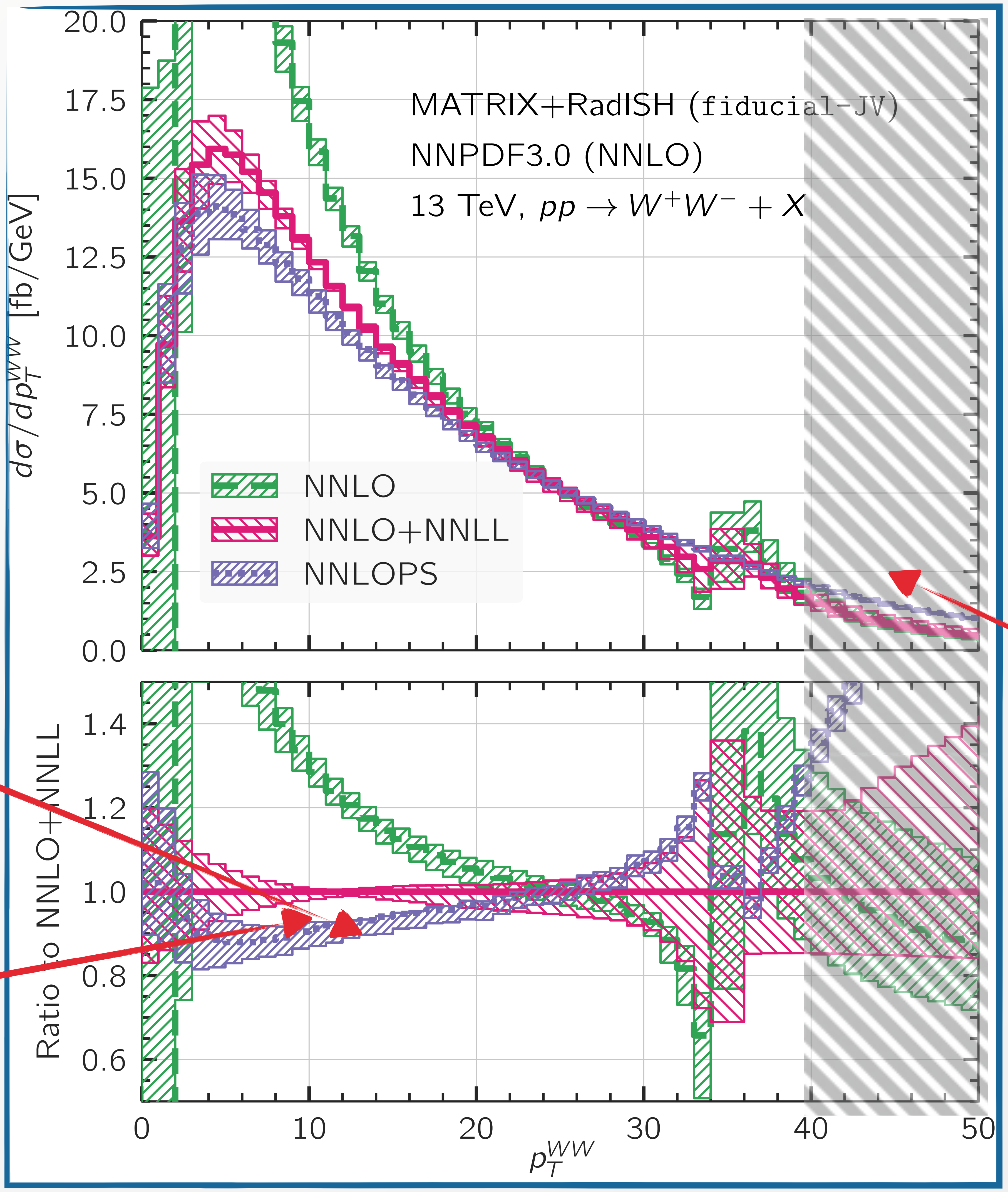
$$p_T^{\mathrm{miss}} > 20\,\mathrm{GeV}$$

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

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

LHC applications: W^+W^- production

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



RadISH+MATRIX interface for generic 2⟶1 and 2⟶2 colour singlet processes at NNLL and N³LL accuracy

[Kallweit, Wiesemann, Re, LR '2004.07720]

[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

Summary and outlook

- Precision of the data demands an increasing theoretical accuracy to fully exploit LHC potential. Higgs sector must be stress-tested, important information encoded in **(multi)-differential distributions**

- We derived a NNLL double-differential resummation for $p_\perp^{\mathrm{J,v}}$ and $p_\perp^H$. Ongoing studies being performed by experimental collaborations.

- Direct space formulation (RadISH) provides guidance to obtain **compact formulation in *b*-space** at NNLL accuracy and offers access to underlying dynamics

- Formalism has been applied to **more complex final states**; 2⟶1 and 2⟶2 colour singlet processes available via MATRIX+RadISH interface (https://matrix.hepforge.org/matrix+radish.html)

- Interesting to study higher-order structure and factorization properties of this observable (e.g. factorization theorem in SCET)

Backup

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

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

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

- allows one to include constant terms from NNLO (if N^{3}LO 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

Equivalence with b-space formulation

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

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, φ^*)

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

Joint resummation in direct space

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

$$\sigma^{\rm NNLL}_{\rm clust}(p_t^{\rm J,v},p_t^{\rm H,v}) = \int_0^{\infty}\frac{dk_{t,1}}{k_{t,1}}\frac{d\phi_1}{2\pi}\int d\mathcal{Z}\,e^{-R_{\rm NLL}(L_{t,1})}\mathcal{L}_{\rm NLL}\left(\mu_{\rm F}e^{-L_{t,1}}\right)8\,C_A^2\frac{\alpha_s^2}{\pi^2}\frac{L_{t,1}}{(1-2\beta_0\alpha_s L_{t,1})^2}\,\Theta\left(p_t^{\rm J,v}-\max_{i>1}\{k_{t,i}\}\right)$$
$$\times\left\{\int_0^{k_{t,1}}\frac{dk_{t,s_1}}{k_{t,s_1}}\frac{d\phi_{s_1}}{2\pi}\int_{-\infty}^{\infty}d\Delta\eta_{1s_1}\,J_{1s_1}(R)\left[\Theta\Big(p_t^{\rm J,v}-|\vec{k}_{t,1}+\vec{k}_{t,s_1}|\Big)-\Theta\Big(p_t^{\rm J,v}-k_{t,1}\Big)\right]\Theta\Big(p_t^{\rm H,v}-|\vec{k}_{t,1}+\cdots+\vec{k}_{t,n+1}+\vec{k}_{t,s_1}|\Big)\right.$$
$$+\frac{1}{2!}\hat{R}'(k_{t,1})\int_0^{k_{t,1}}\frac{dk_{t,s_1}}{k_{t,s_1}}\frac{dk_{t,s_2}}{k_{t,s_2}}\frac{d\phi_{s_1}}{2\pi}\frac{d\phi_{s_2}}{2\pi}\int_{-\infty}^{\infty}d\Delta\eta_{s_1s_2}\,J_{s_1s_2}(R)\left[\Theta\Big(p_t^{\rm J,v}-|\vec{k}_{t,s_1}+\vec{k}_{t,s_2}|\Big)-\Theta\Big(p_t^{\rm J,v}-\max\{k_{t,s_1},k_{t,s_2}\}\Big)\right]$$
$$\left.\times\,\Theta\Big(p_t^{\rm H,v}-|\vec{k}_{t,1}+\cdots+\vec{k}_{t,n+1}+\vec{k}_{t,s_1}+\vec{k}_{t,s_2}|\Big)\,\Theta\left(p_t^{\rm J,v}-k_{t,1}\right)\right\}, \qquad (42)$$

$$\sigma^{\rm NNLL}_{\rm correl}(p_t^{\rm J,v},p_t^{\rm H,v}) = \int_0^{\infty}\frac{dk_{t,1}}{k_{t,1}}\frac{d\phi_1}{2\pi}\int d\mathcal{Z}\,e^{-R_{\rm NLL}(L_{t,1})}\mathcal{L}_{\rm NLL}\left(\mu_{\rm F}e^{-L_{t,1}}\right)8\,C_A^2\frac{\alpha_s^2}{\pi^2}\frac{L_{t,1}}{(1-2\beta_0\alpha_s L_{t,1})^2}\,\Theta\left(p_t^{\rm J,v}-\max_{i>1}\{k_{t,i}\}\right)$$
$$\times\left\{\int_0^{k_{t,1}}\frac{dk_{t,s_1}}{k_{t,s_1}}\frac{d\phi_{s_1}}{2\pi}\int_{-\infty}^{\infty}d\Delta\eta_{1s_1}\,\mathcal{C}\left(\Delta\eta_{1s_1},\Delta\phi_{1s_1},\frac{k_{t,1}}{k_{t,s_1}}\right)\left(1-J_{1s_1}(R)\right)\right.$$
$$\times\left[\Theta\Big(p_t^{\rm J,v}-k_{t,1}\Big)-\Theta\Big(p_t^{\rm J,v}-|\vec{k}_{t,1}+\vec{k}_{t,s_1}|\Big)\right]\Theta\Big(p_t^{\rm H,v}-|\vec{k}_{t,1}+\cdots+\vec{k}_{t,n+1}+\vec{k}_{t,s_1}|\Big)$$
$$+\frac{1}{2!}\hat{R}'(k_{t,1})\int_0^{k_{t,1}}\frac{dk_{t,s_1}}{k_{t,s_1}}\frac{dk_{t,s_2}}{k_{t,s_2}}\frac{d\phi_{s_1}}{2\pi}\frac{d\phi_{s_2}}{2\pi}\int_{-\infty}^{\infty}d\Delta\eta_{s_1s_2}\,\mathcal{C}\left(\Delta\eta_{s_1s_2},\Delta\phi_{s_1s_2},\frac{k_{t,s_2}}{k_{t,s_1}}\right)\left(1-J_{s_1s_2}(R)\right)\Theta\left(p_t^{\rm J,v}-k_{t,1}\right)$$
$$\left.\times\left[\Theta\Big(p_t^{\rm J,v}-\max\{k_{t,s_1},k_{t,s_2}\}\Big)-\Theta\Big(p_t^{\rm J,v}-|\vec{k}_{t,s_1}+\vec{k}_{t,s_2}|\Big)\right]\Theta\Big(p_t^{\rm H,v}-|\vec{k}_{t,1}+\cdots+\vec{k}_{t,n+1}+\vec{k}_{t,s_1}+\vec{k}_{t,s_2}|\Big)\right\}. \qquad (43)$$

All-order resummation: branching formalism approach

[Banfi, Salam, Zanderighi '01, '03, '04][Banfi, McAslan, Monni, Zanderighi, El-Menoufi '14, '18] [Bizon, Monni, Re, LR, Torrielli '16, '17, '18]

Approach 2: factorization properties of the QCD squared amplitudes

Simple observable easy to calculate

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

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

i.e. conditional probability

Method entirely formulated in direct space

Ongoing attempts to formulate it within SCET language [Bauer, Monni '18, '19 + ongoing work]

All-order resummation: branching formalism approach

[Banfi, Salam, Zanderighi '01, '03, '04][Banfi, McAslan, Monni, Zanderighi, El-Menoufi '14, '18] [Bizon, Monni, Re, LR, Torrielli '16, '17, '18]

Approach 2: factorization properties of the QCD squared amplitudes

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 **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 numerically

k_t-ordering

All-order resummation: branching formalism approach

[Banfi, Salam, Zanderighi ’01, ‘03, ’04][Banfi, McAslan, Monni, Zanderighi, El-Menoufi ’14, ’18] [Bizon, Monni, Re, LR, Torrielli ’16, ’17, ’18]

Approach 2: factorization properties of the QCD squared amplitudes

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

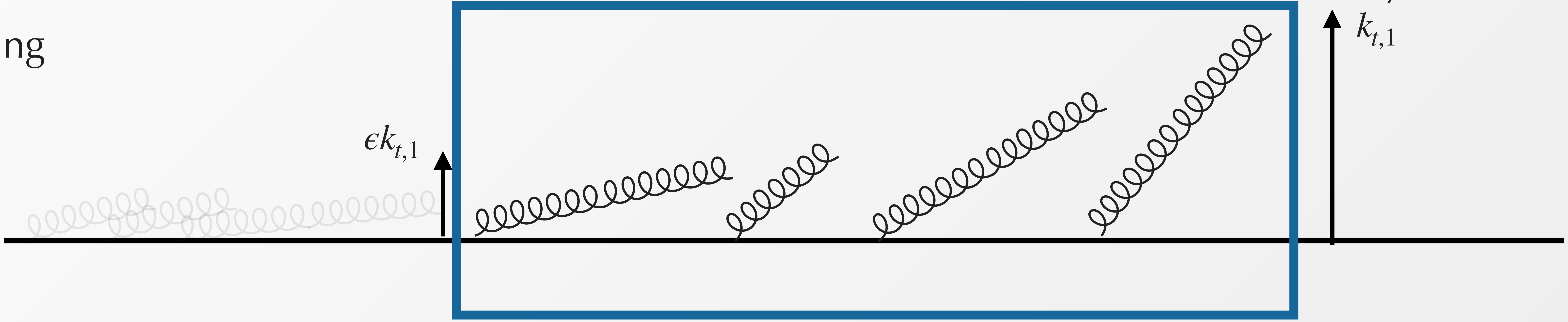
$$\tilde{\sigma} \sim \int [dk_1]\, e^{-R(q_0)} \longrightarrow$$

Unresolved emission can be treated as **unconstrained exponentiation**

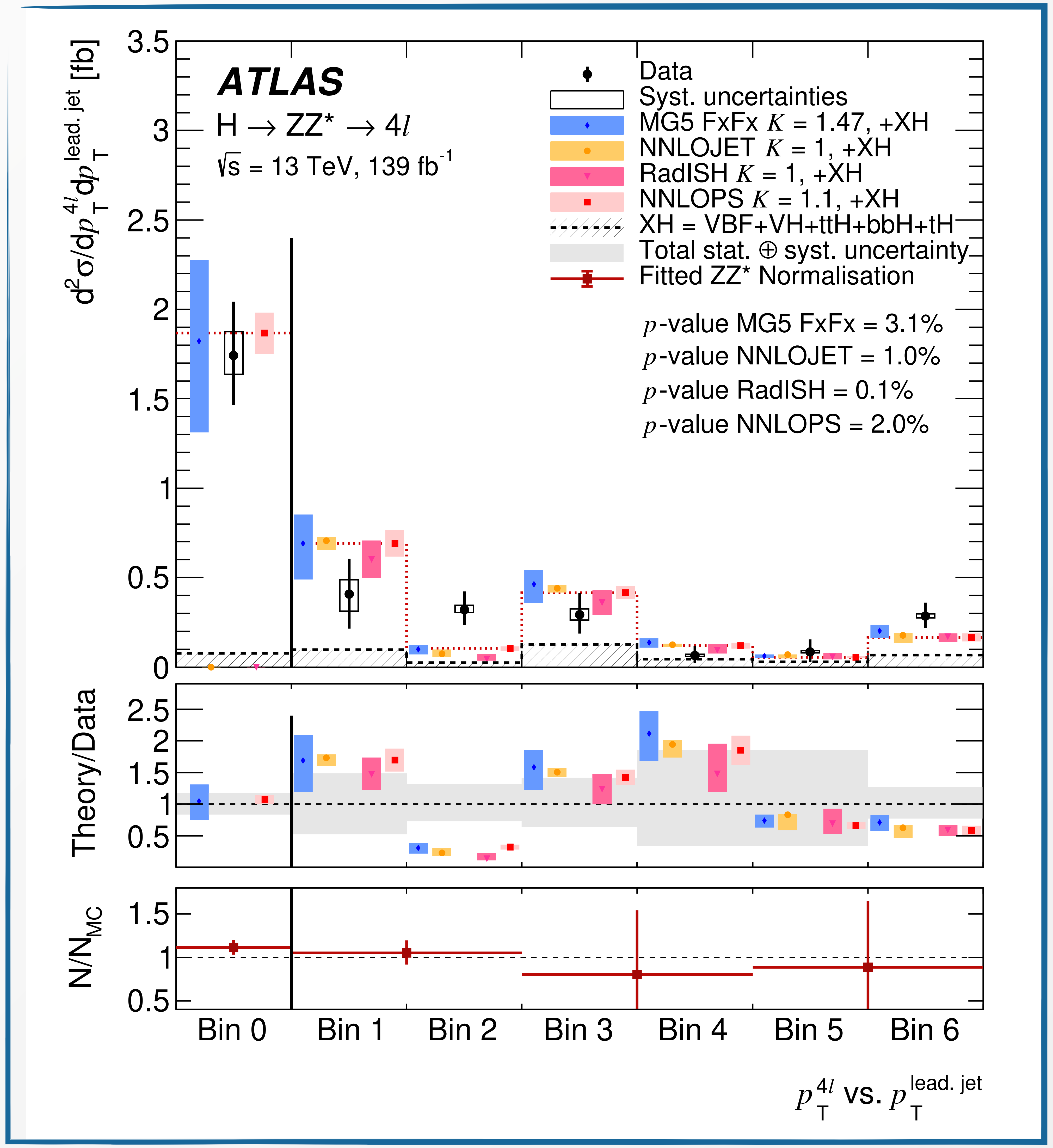
$$\times\, |\mathcal{M}(k_1)|^2 \left(\sum_{m=0}^{\infty} \frac{1}{m!} \int \prod_{i=2}^{m+1} [dk_i]\, |\mathcal{M}(k_i)|^2\, \Theta(V(k_i) - q_0)\, \Theta\left(v - V(k_1, \ldots, k_{m+1})\right) \right)$$

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

k_t-ordering



LHC results: Higgs transverse momentum with a jet veto



[ATLAS 2004.03969]

Asymptotic limits of the joint resummation formula

$p_\perp^{J,v} \sim m_H \gg p_\perp^H$

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

$$\mathscr{F}_{\rm clust} \underset{p_\perp^{J,v} \sim m_H \gg p_\perp^H}{\sim} 0 \qquad \mathscr{F}_{\rm correl} \underset{p_\perp^{J,v} \sim m_H \gg p_\perp^H}{\sim} 0$$

$$\rightarrow \quad \frac{d\sigma(p_\perp^{\rm J,v})}{dy_H d^2\vec{p}_\perp^H} = M^2_{\rm gg\to H} \mathscr{H}(\alpha_s(m_H)) \int_{\mathscr{C}_1} \frac{d\nu_1}{2\pi i} \int_{\mathscr{C}_2} \frac{d\nu_2}{2\pi i} x_1^{-\nu_1} x_2^{-\nu_2} \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} e^{-R_{\rm NNLL}}$$

$$\times f_{\nu_1,a_1}(b_0/b) f_{\nu_2,a_2}(b_0/b) C_{\nu_1,ga_1}(\alpha_s(b_0/b))\, C_{\nu_2,ga_2}(\alpha_s(b_0/b))$$

$p_\perp^H \sim m_H \gg p_\perp^{J,v}$

$$\lim_{b\to 0} J_0(bx) = 1 \qquad S_{\rm NNLL} \underset{p_\perp^H \sim m_H \gg p_\perp^{J,v}}{\sim} R_{\rm NNLL}(\ln(m_H/p_\perp^{J,v})) \qquad \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_\perp^H} = \delta^2(\vec{p}_\perp^H)$$

$$\rightarrow \quad \frac{d\sigma(p_\perp^{\rm J,v})}{dy_H} = M^2_{\rm gg\to H} \mathscr{H}(\alpha_s(m_H))\, e^{-R_{\rm NNLL}(\ln(m_H/p_\perp^{\rm J,v}))} \left(1 + \mathscr{F}_{\rm clust} + \mathscr{F}_{\rm correl}\right)$$

$$\times \left[f(p_\perp^{J,v}) \otimes C(\alpha_s(p_\perp^{J,v}))\right]_g (x_1) \left[f(p_\perp^{J,v}) \otimes C(\alpha_s(p_\perp^{J,v}))\right]_g (x_2)$$