Transverse-momentum resummation of colorless final states at the NNLL+NNLO

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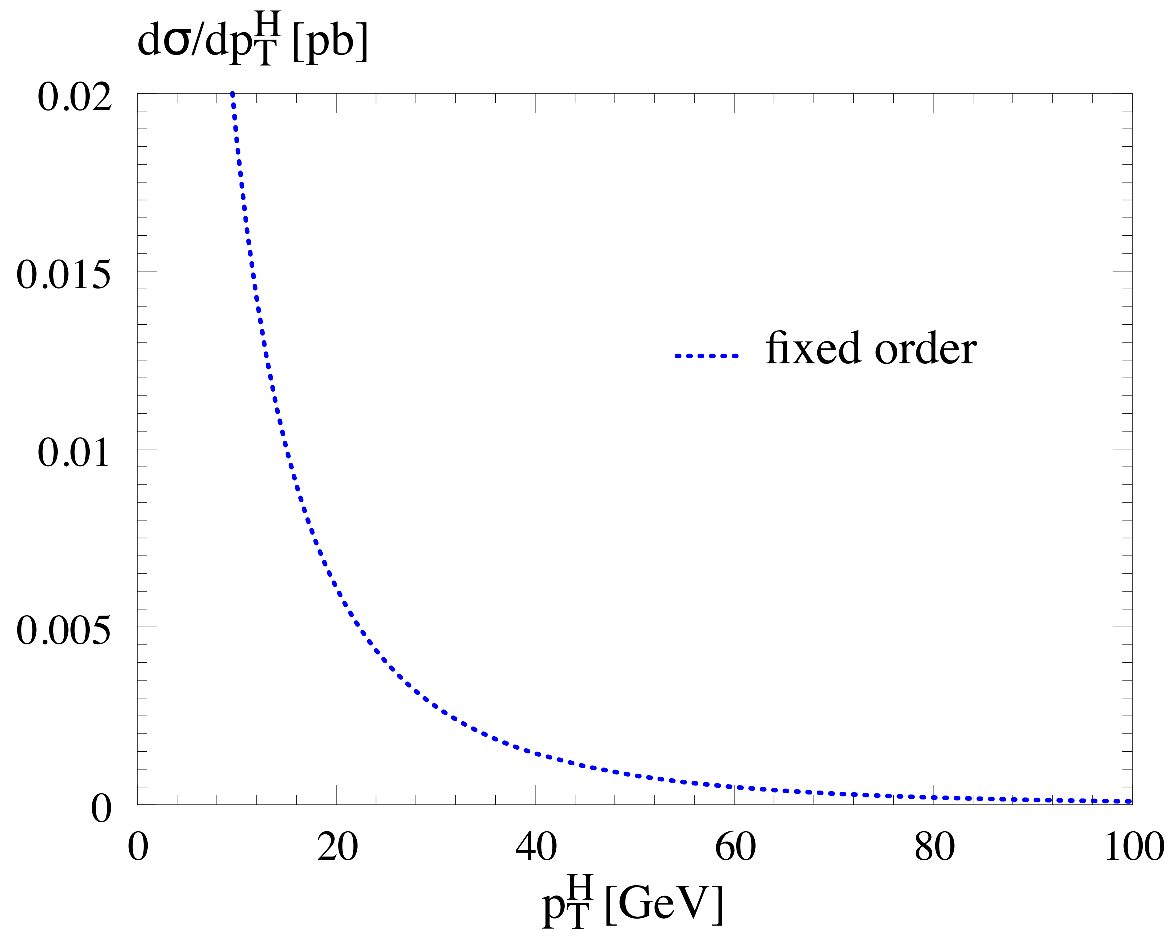
p_T resummation

- production of colorless particles (system $\mathcal{F}$, invariant mass M)
- problem: p_T distribution of $\mathcal{F}$ diverges at $p_T \to 0$



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- reason: large logs $\ln p_T^2/M^2$ for $p_T \ll M$

$$\begin{aligned}
\alpha_s : &\quad \ln(p_T^2/M^2),\ \ln^2(p_T^2/M^2) \\
\alpha_s^2 : &\quad \ln(p_T^2/M^2),\ \ln^2(p_T^2/M^2),\ \ln^3(p_T^2/M^2),\ \ln^4(p_T^2/M^2) \\
\dots &
\end{aligned}$$

- solution: all order resummation

p_T resummation

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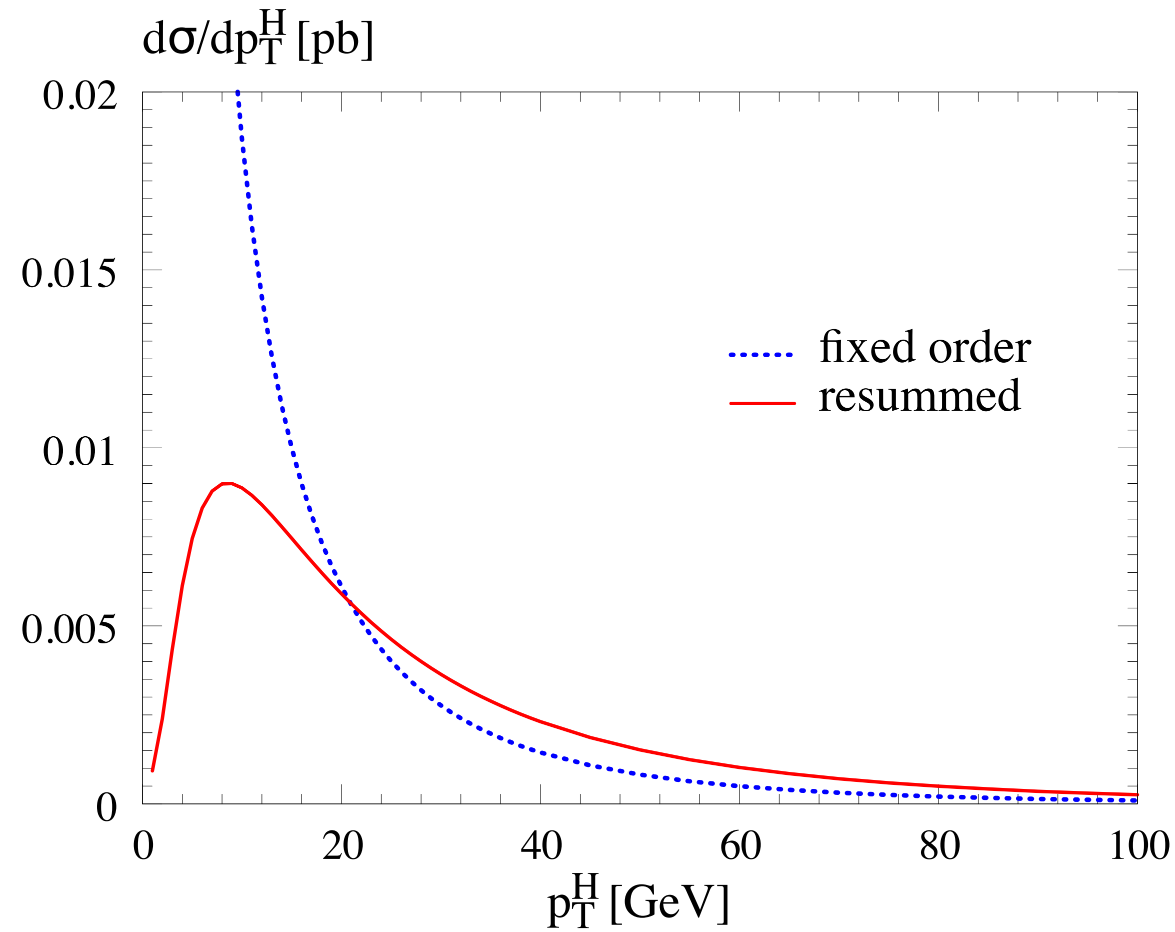

p_T resummation

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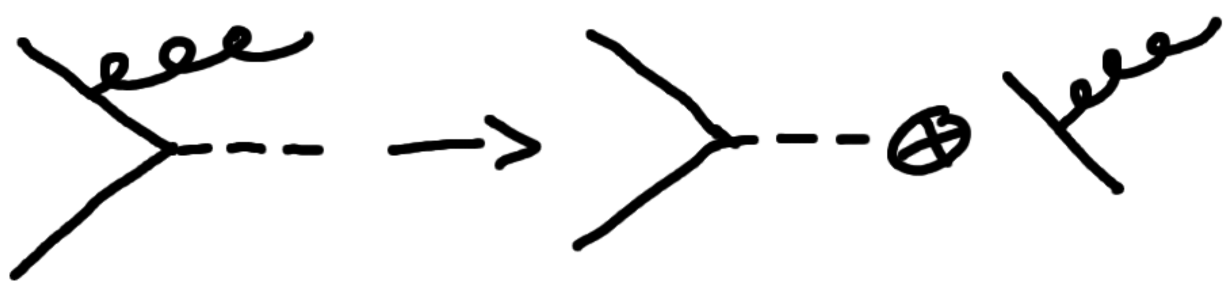
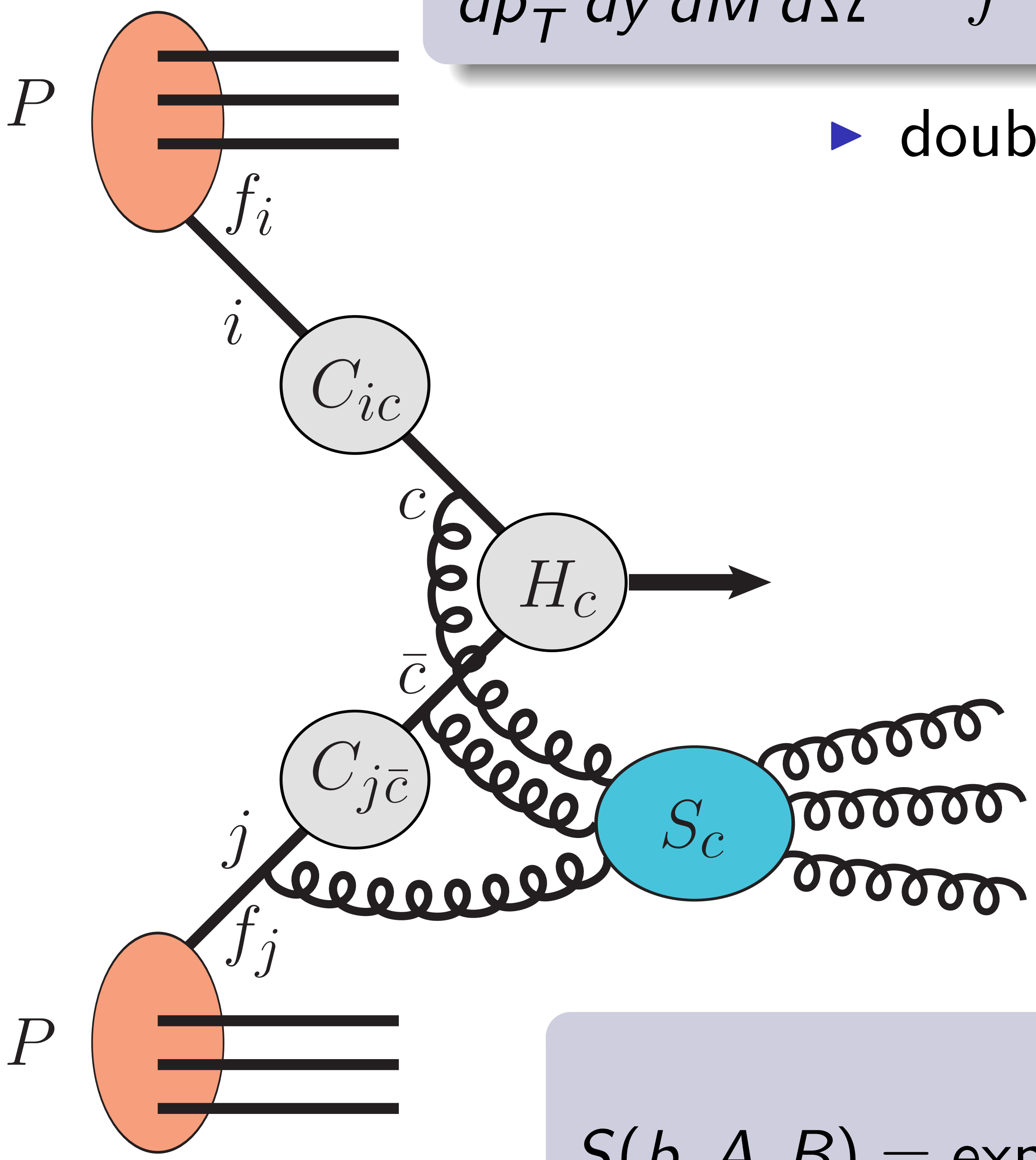
- solution: all order resummation
  - factorization of soft and collinear radiation in matrix elements



$\to$ allows for resummation
  - done in impact parameter (b) space

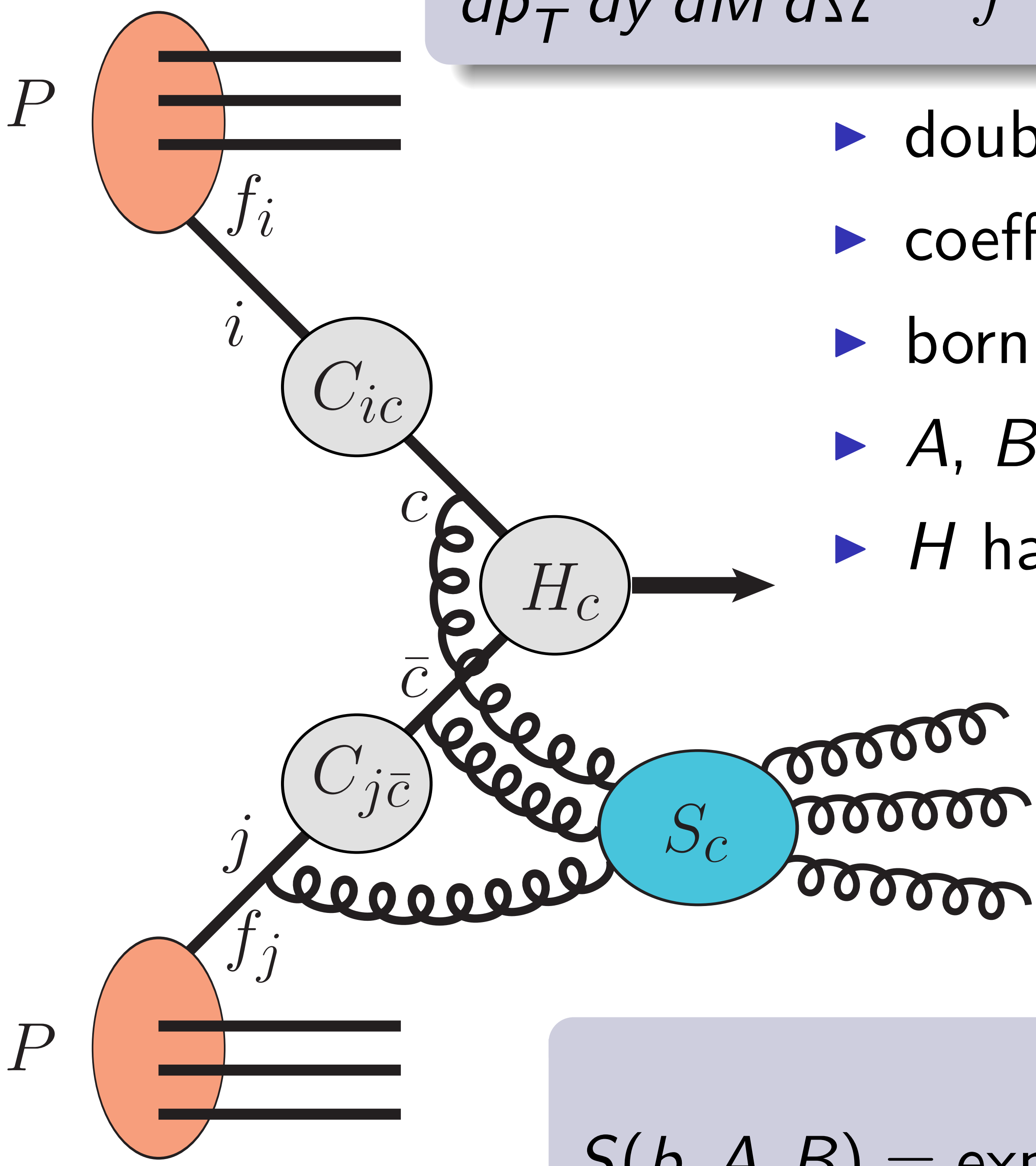
$$\frac{d\sigma^{(\text{res})}_{N_1,N_2}}{dp_T^2\, dy\, dM\, d\Omega} \sim \int db\, \frac{b}{2}\, J_0(b\, p_T)\, S(b, A, B)\, \mathcal{H}_{N_1,N_2}\, f_{N_1}\, f_{N_2}$$

- double Mellin moments: $\mathcal{H}_{N_1,N_2} = H\, C_{N_1}\, C_{N_2}$



$$S(b, A, B) = \exp\left\{ -\int_{b_0^2/b^2}^{m_H^2} \frac{dq^2}{q^2} \left[A \ln\left(\frac{m_H^2}{q^2} \right) + B \right] \right\}$$

$$\frac{d\sigma^{(\mathrm{res})}_{N_1,N_2}}{dp_T^2\, dy\, dM\, d\Omega} \sim \int db\, \frac{b}{2}\, J_0(b\, p_T)\, S(b, A, B)\, \mathcal{H}_{N_1,N_2}\, f_{N_1}\, f_{N_2}$$



- double Mellin moments: $\mathcal{H}_{N_1,N_2} = H\, C_{N_1}\, C_{N_2}$
- coefficients A, B, C, H perturbative
- born initial state gg or $q\bar{q}$
- A, B, C process independent
- H hard coefficient: - process dependent
  - LO kinematics (M, Ω)

$$S(b, A, B) = \exp\left\{ -\int_{b_0^2/b^2}^{m_H^2} \frac{dq^2}{q^2} \left[A \ln\left(\frac{m_H^2}{q^2}\right) + B \right] \right\}$$

p_T resummation

- $L = \ln(Q^2\, b^2/b_0^2) \quad \leftrightarrow \quad \ln(Q^2/p_T^2)$, Q: resummation scale
- Sudakov: $\quad \alpha_s L \sim \mathcal{O}(1)$

$$S_c(A,B) = \exp\Big\{ \underbrace{\underbrace{\underbrace{L\,g^{(1)}(\alpha_s L)}_{LL} + g^{(2)}(\alpha_s L)}_{NLL} + \alpha_s g^{(3)}(\alpha_s L)}_{NNLL} + \alpha_s^2 \cdots \Big\}$$

- LL: $g^{(1)} \to A^{(1)}$
  NLL: $H^{(1)},\ C^{(1)},\ g^{(2)} \to A^{(2)},\ B^{(1)}$
  NNLL: $H^{(2)},\ C^{(2)},\ g^{(3)} \to A^{(3)},\ B^{(2)}$

p_T resummation

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- developed already 30 years ago

  [Parisi, Petronzio '79], [Dokshitzer, Diakonov, Troian '80], [Curci, Greco, Srivastava '79], [Bassetto, Ciafaloni, Marchesini '80], [Kodaira, Trentadue '82], [Collins, Soper, Sterman '85]

- we use newer formulation including various improvements:

  [Catani, de Florian, Grazzini '01], [Bozzi, Catani, de Florian, Grazzini '06 '07]

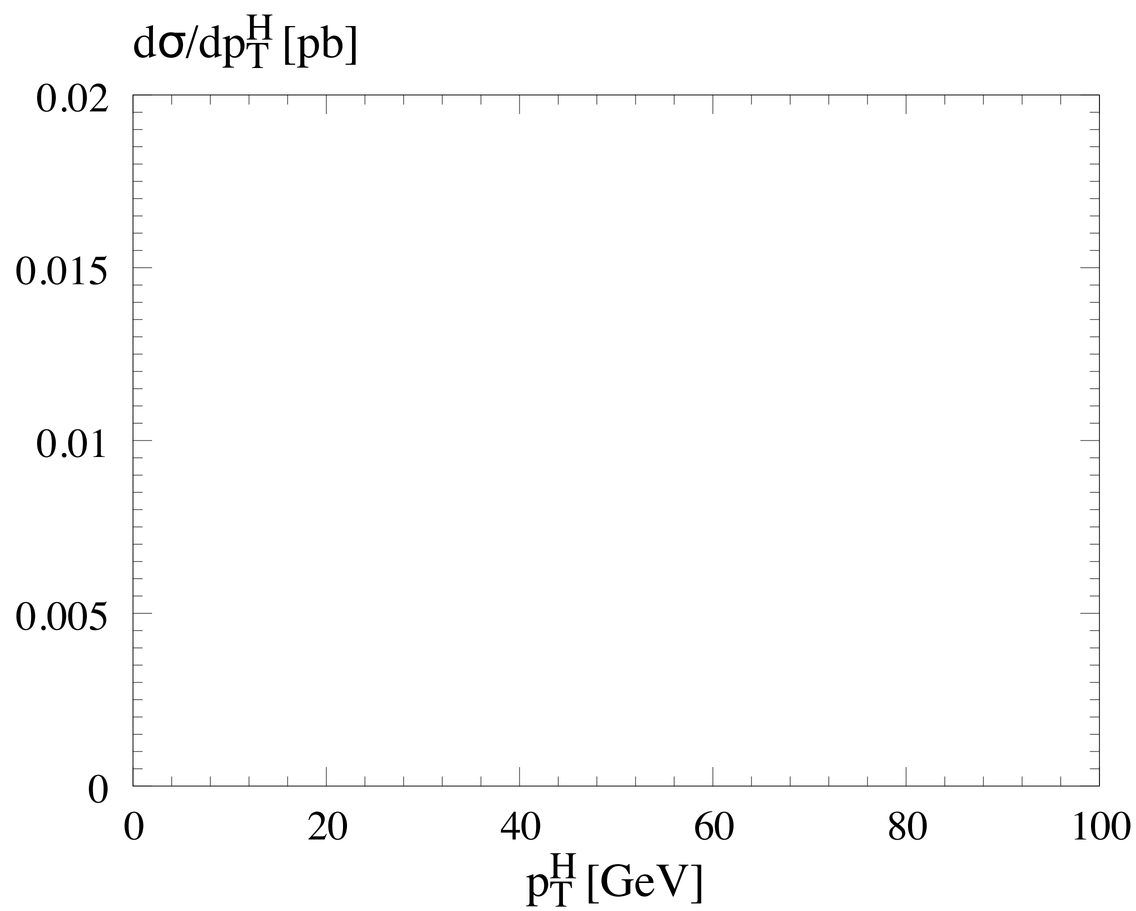
  - H embodies whole process dependence
  - $L = \ln(Q^2\, b^2/b_0^2) \to L' = \ln(Q^2\, b^2/b_0^2 + 1)$

    $\to$ reduction of impact at high p_T (low b)

    $\to$ unitarity constraint
  - rapidity dependence

matching with fixed order

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} =$$



matching with fixed order

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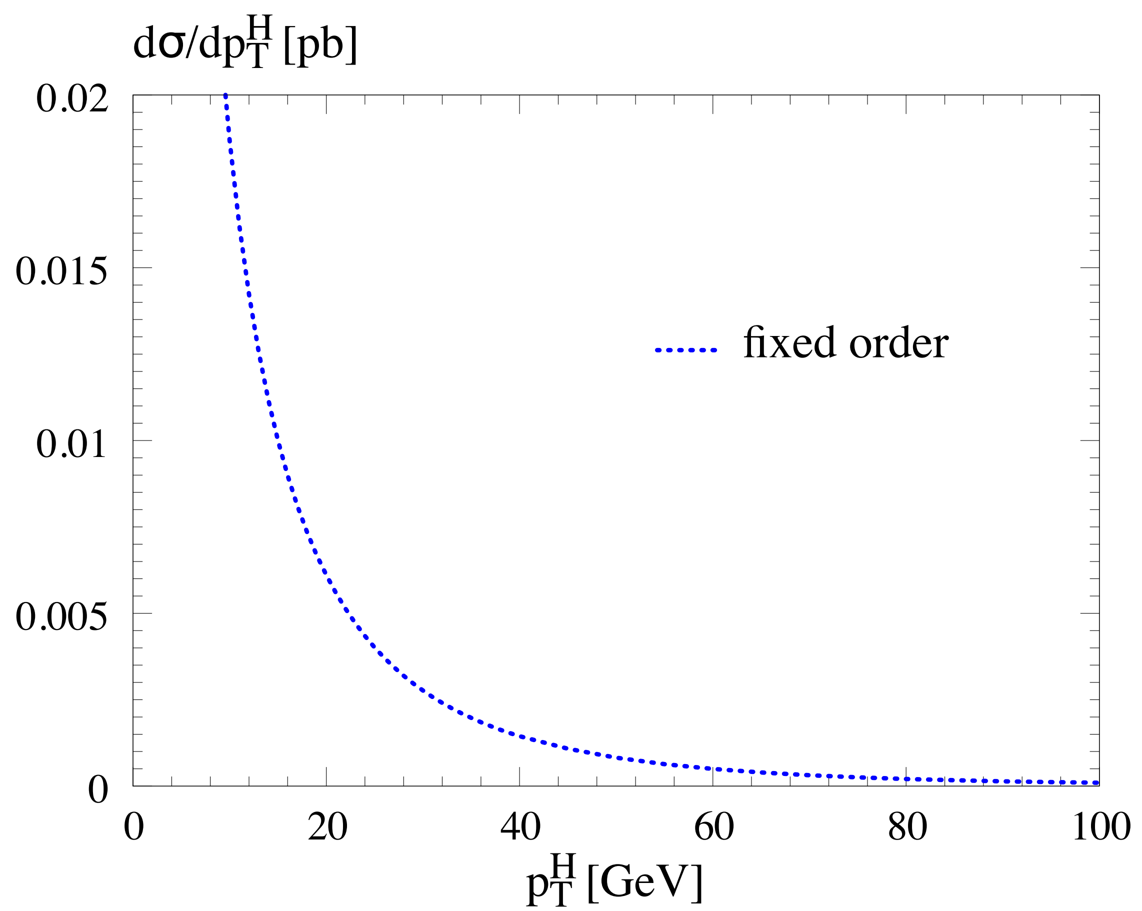
$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}}$$



matching with fixed order

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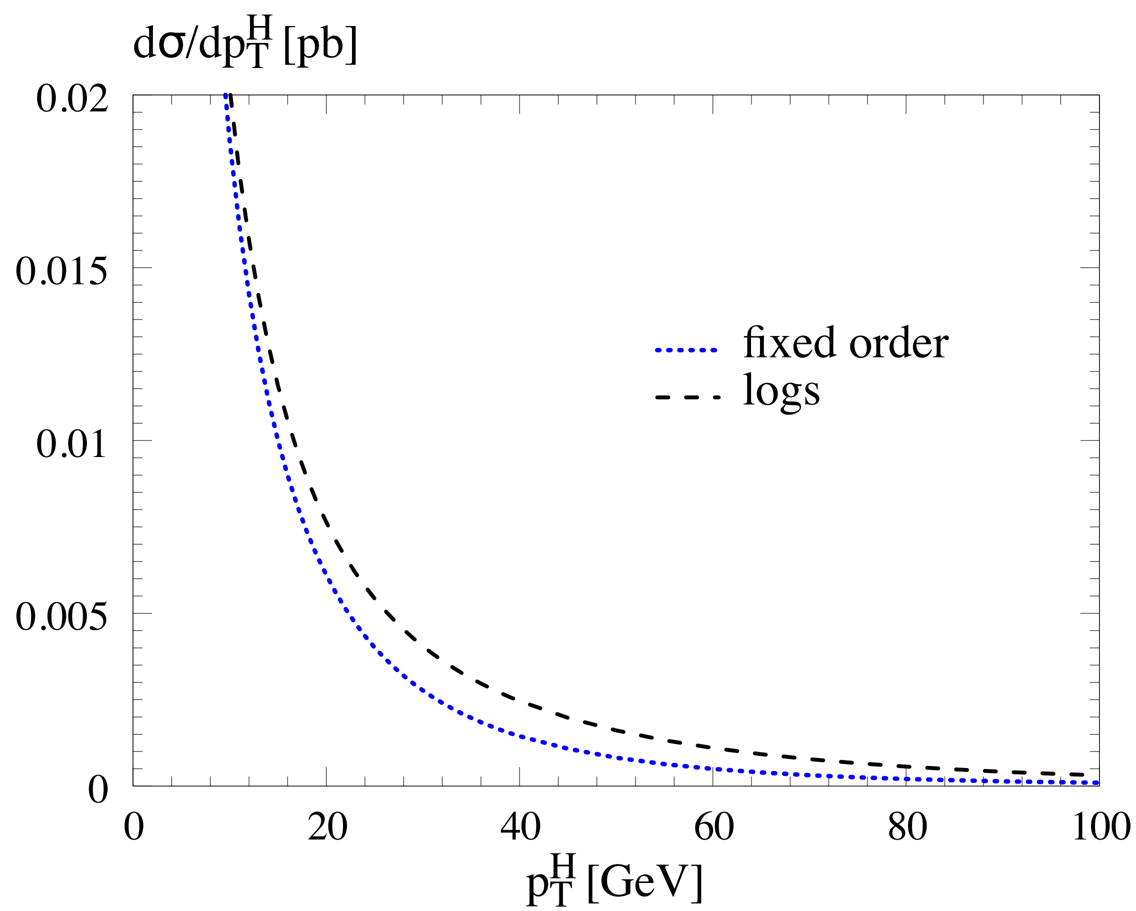
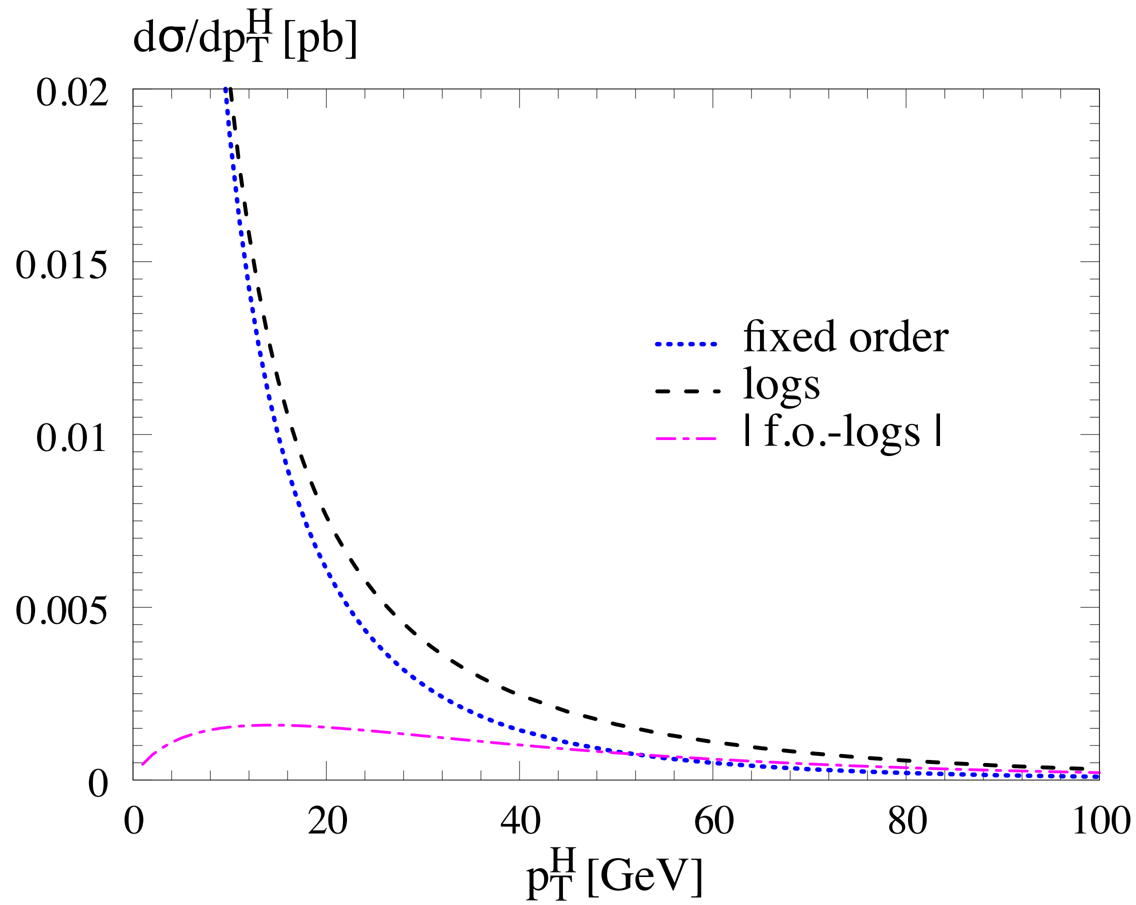
$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}}$$



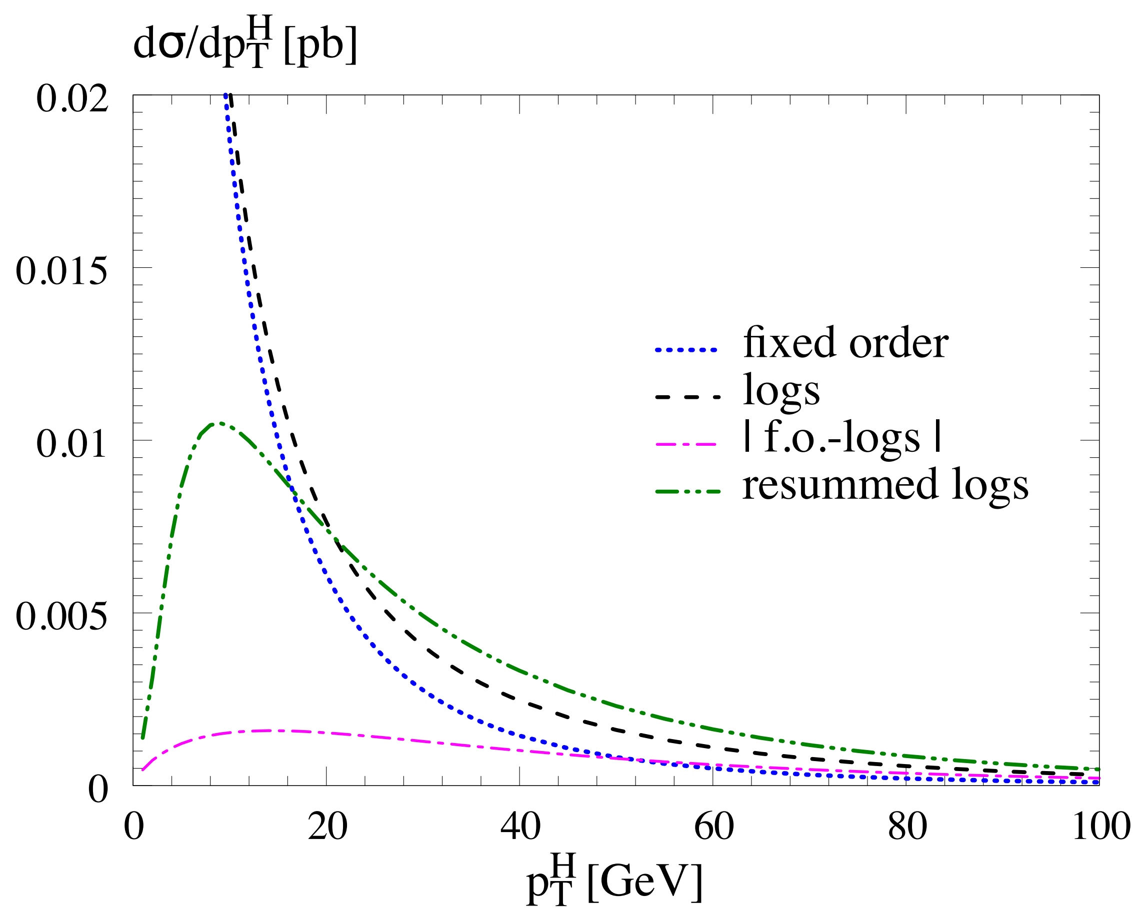
matching with fixed order

$$\left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{f.o.}}$$



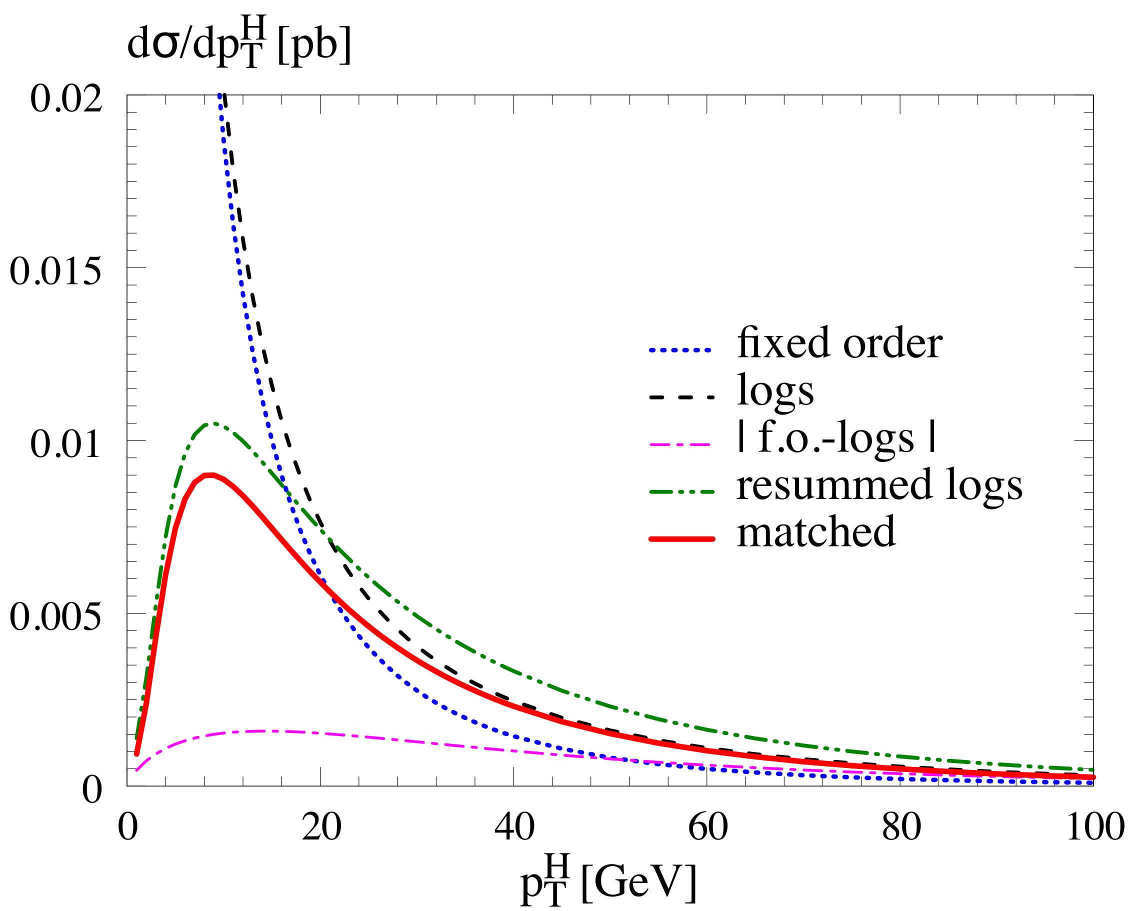
matching with fixed order

$$\left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{f.o.}} + \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{l.a.}}$$



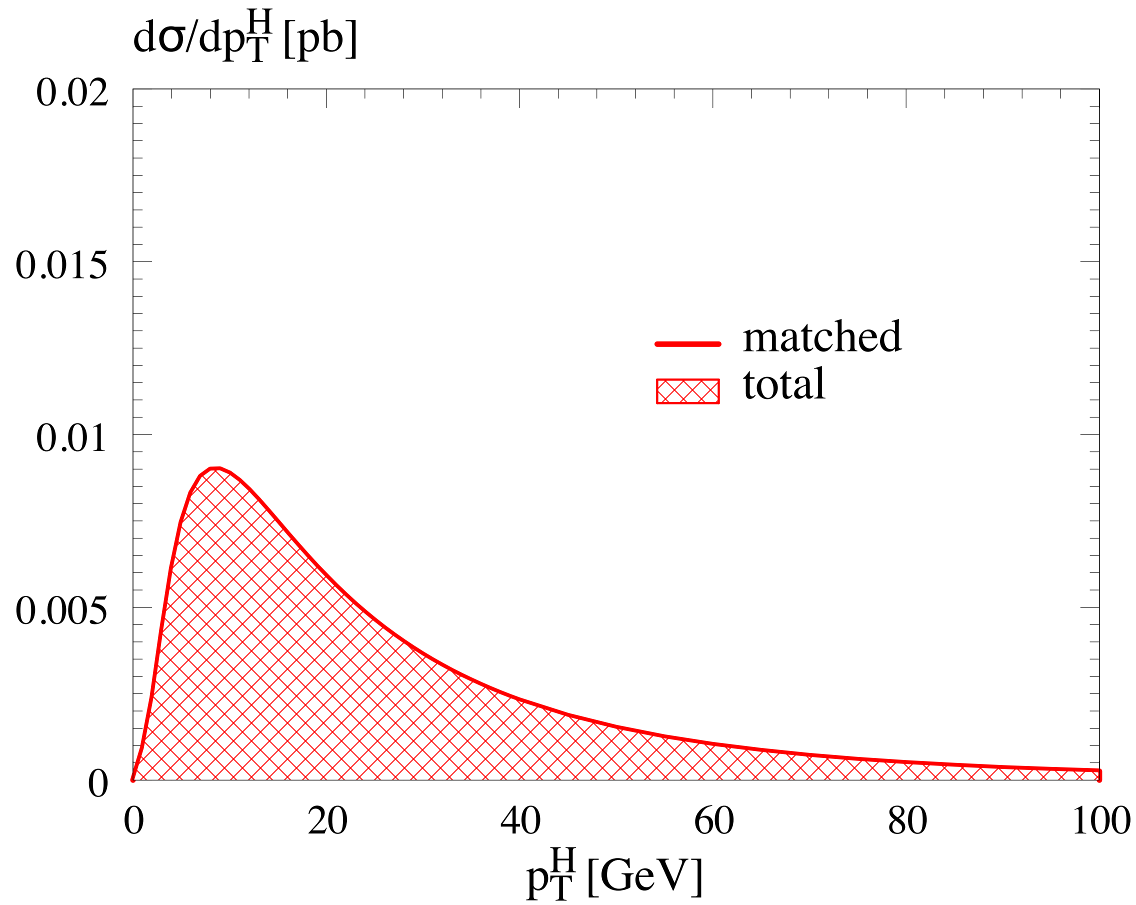
matching with fixed order

$$\left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{f.o.}} + \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{l.a.}}$$



matching with fixed order

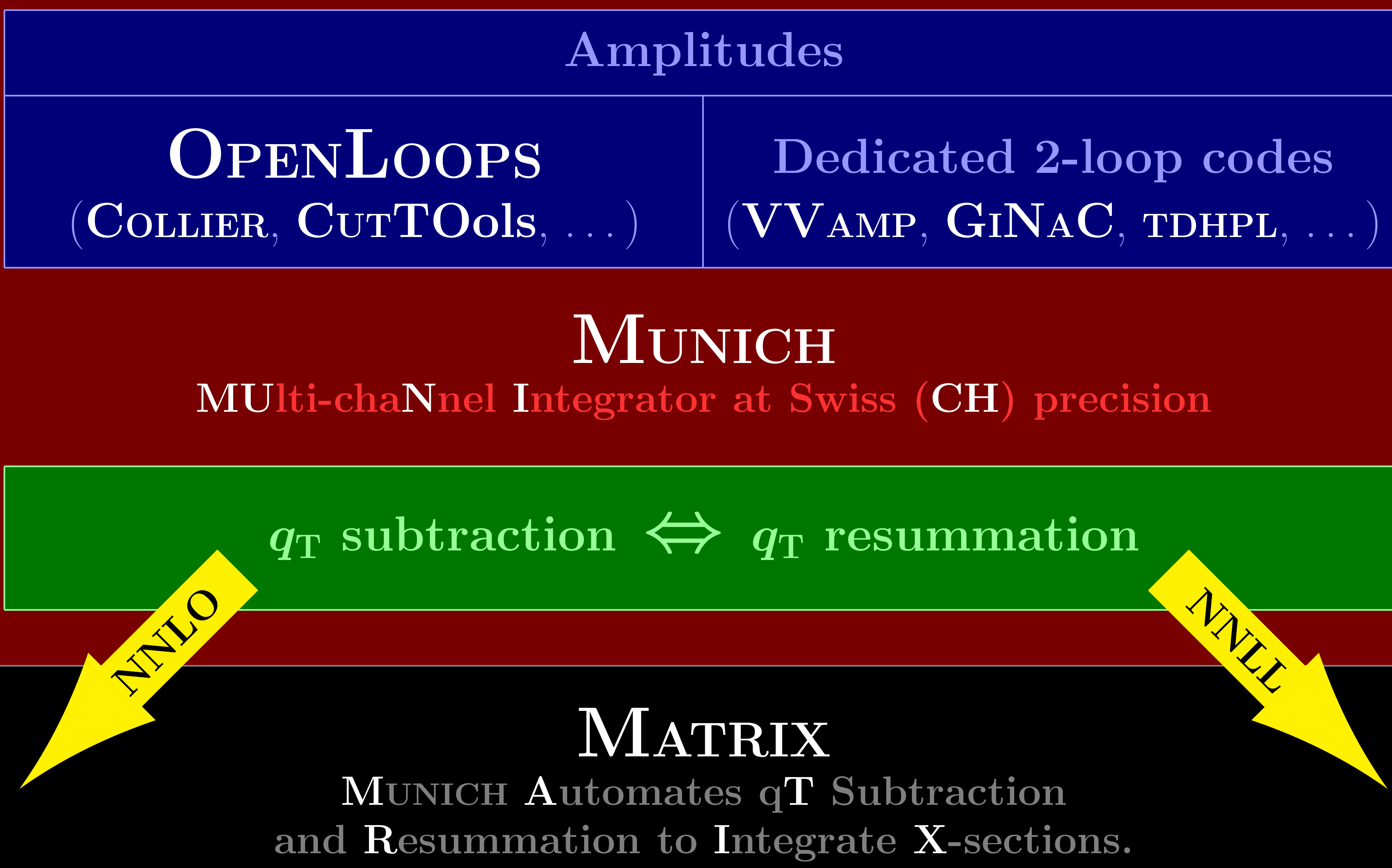
$$\int \mathrm{d}p_T^2 \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} \equiv \left[\sigma^{(\text{tot})}\right]_{\text{f.o.}} .$$



We implemented...

The MATRIX framework

[Grazzini, Kallweit, Rathlev, MW] (+Hanga, Sargsyan)



The MATRIX

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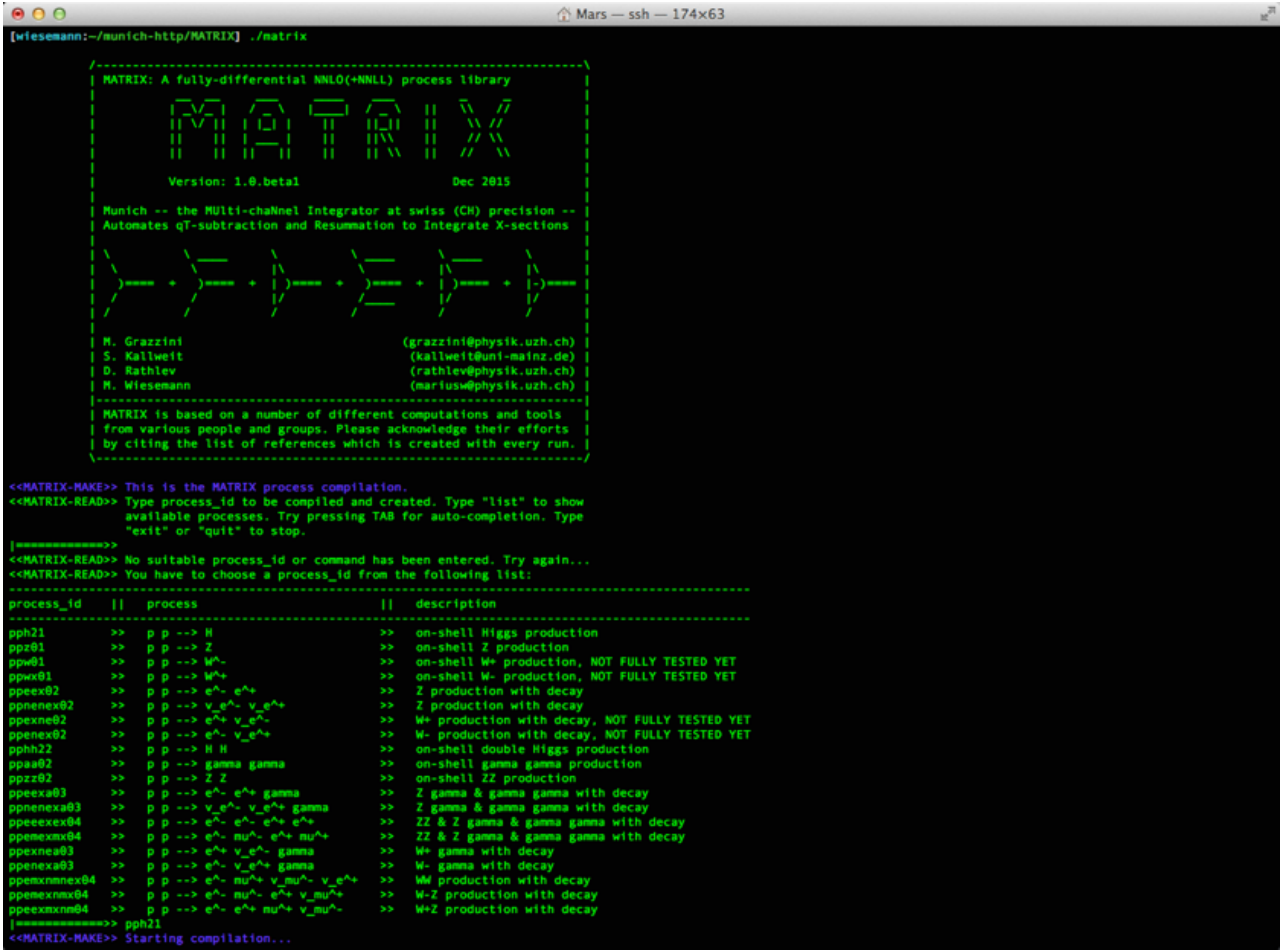

The Status

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process	status	comment
$pp \to Z/\gamma^* (\to \ell^+\ell^-)$	✓	validated analytically (+ DYNNLO)
$pp \to W \to \ell\nu$	(✓)	to be validated
$pp \to H$	(✓)	under validation
$pp \to \gamma\gamma$	✓	validated with 2γNNLO
$pp \to Z\gamma \to \ell^+\ell^- \gamma$	✓	[Grazzini, Kallweit, Rathlev, Torre '13]
$pp \to W\gamma \to \ell\nu\gamma$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp \to ZZ$	✓	[Cascioli et al. '14]
$pp \to ZZ \to 4\ell$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp \to WW$	✓	[Gehrmann et al. '14]
$pp \to WW \to \ell\nu\, \ell'\nu'$	✓	[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]
$pp \to WZ$	✓	NEW HERE: inclusive cross section

NNLO+NNLL resummation for ZZ and WW [Grazzini, Kallweit, Rathlev, MW '15]

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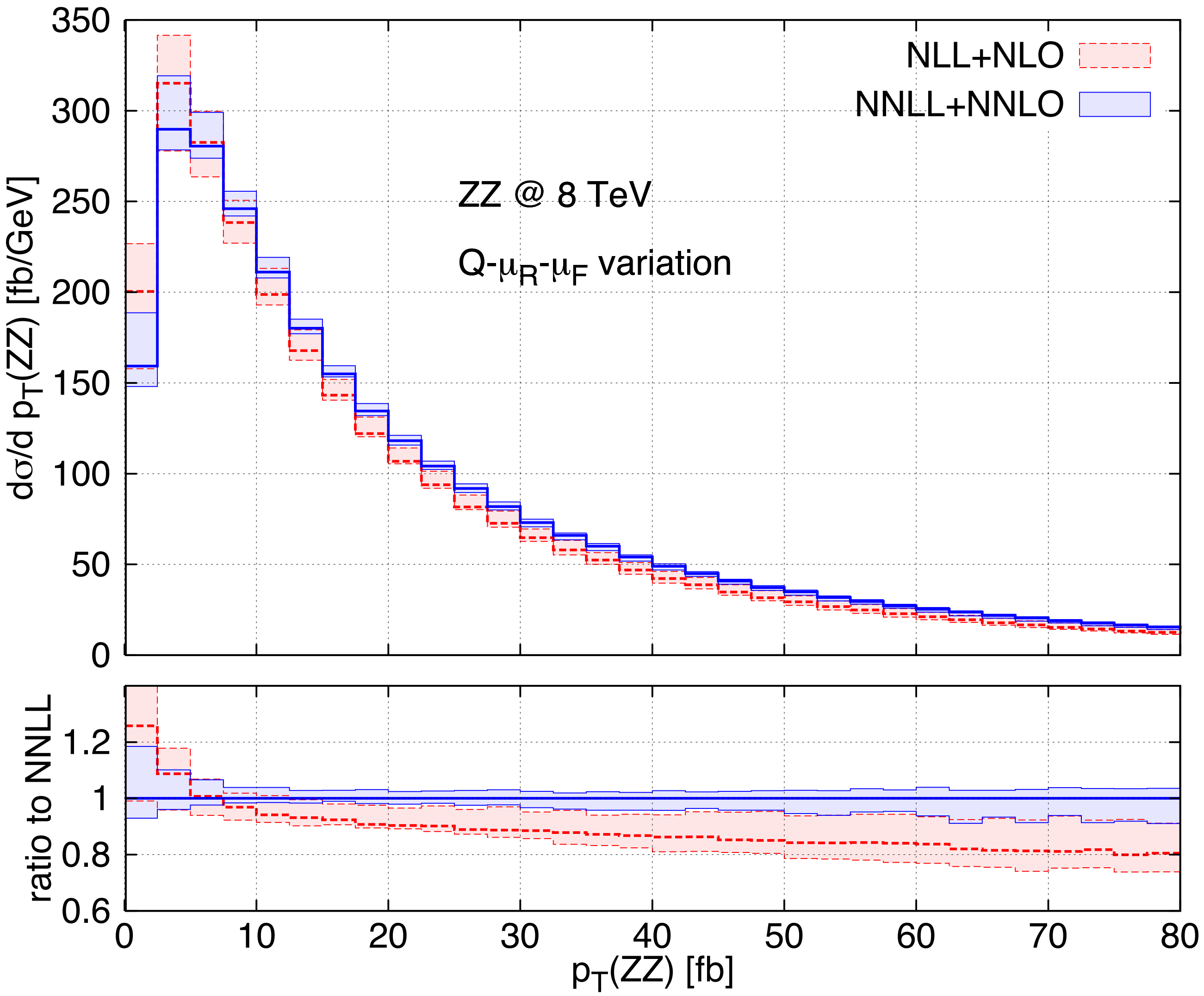
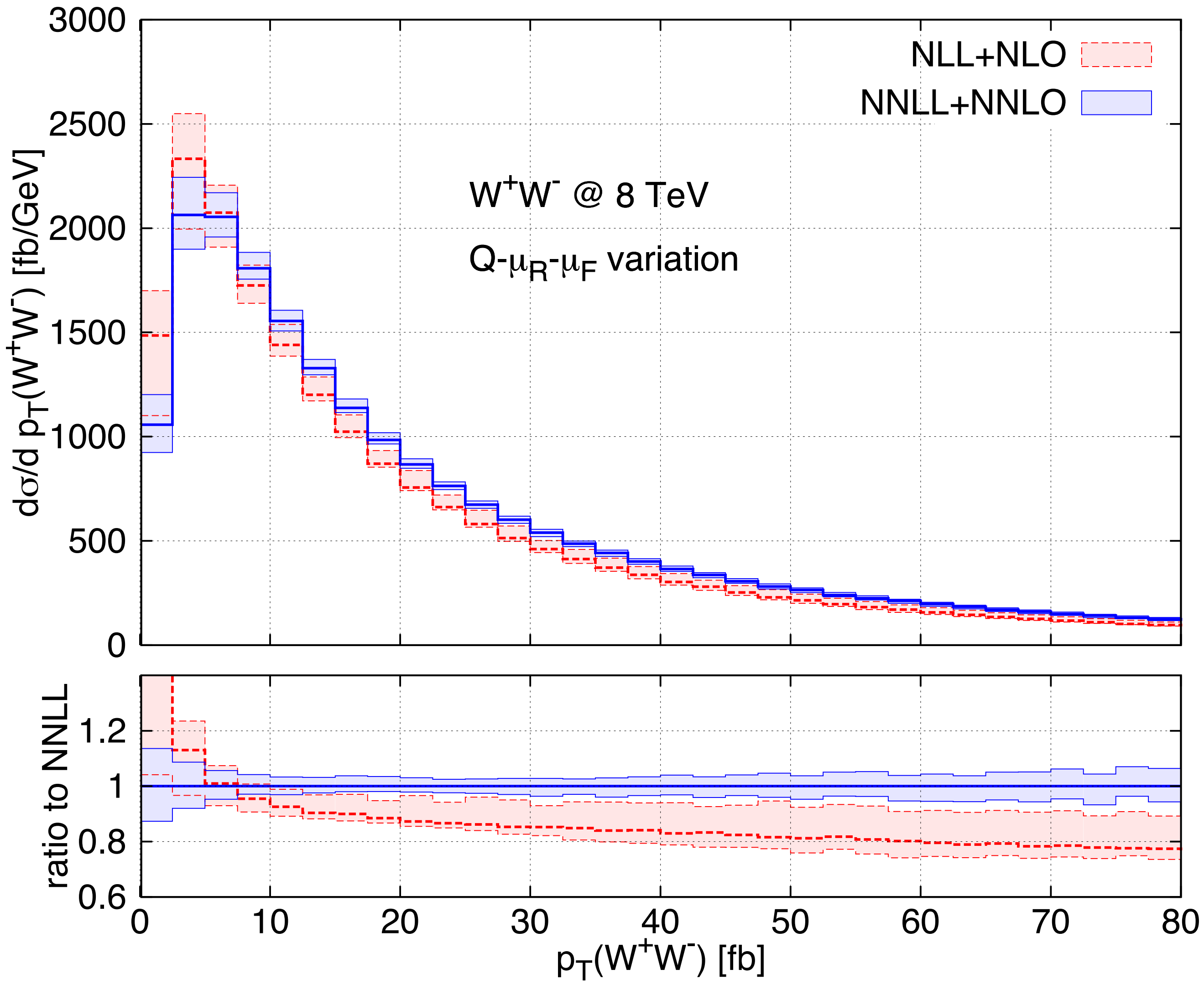
p_T spectrum of ZZ pair



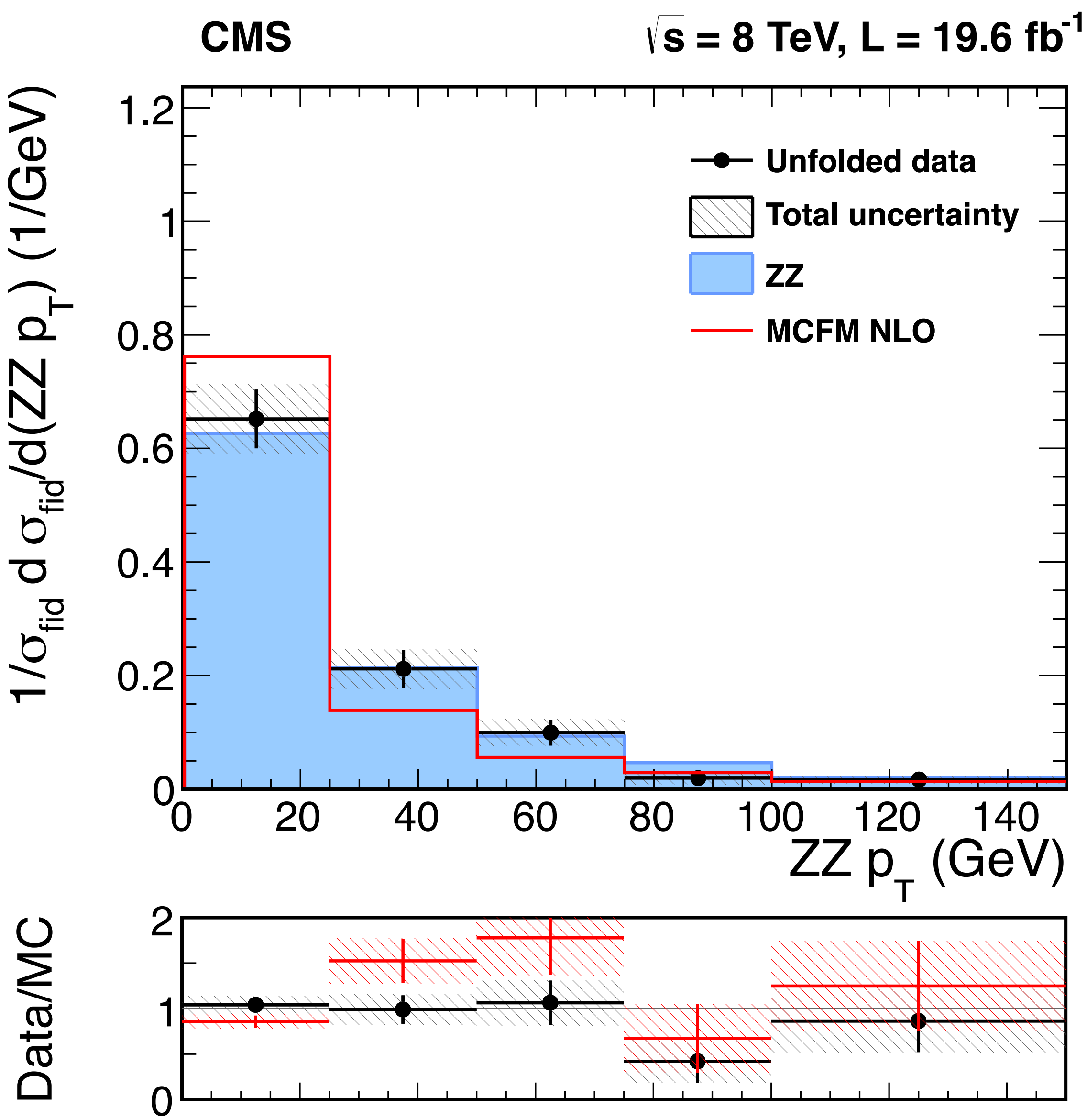
p_T spectrum of WW pair



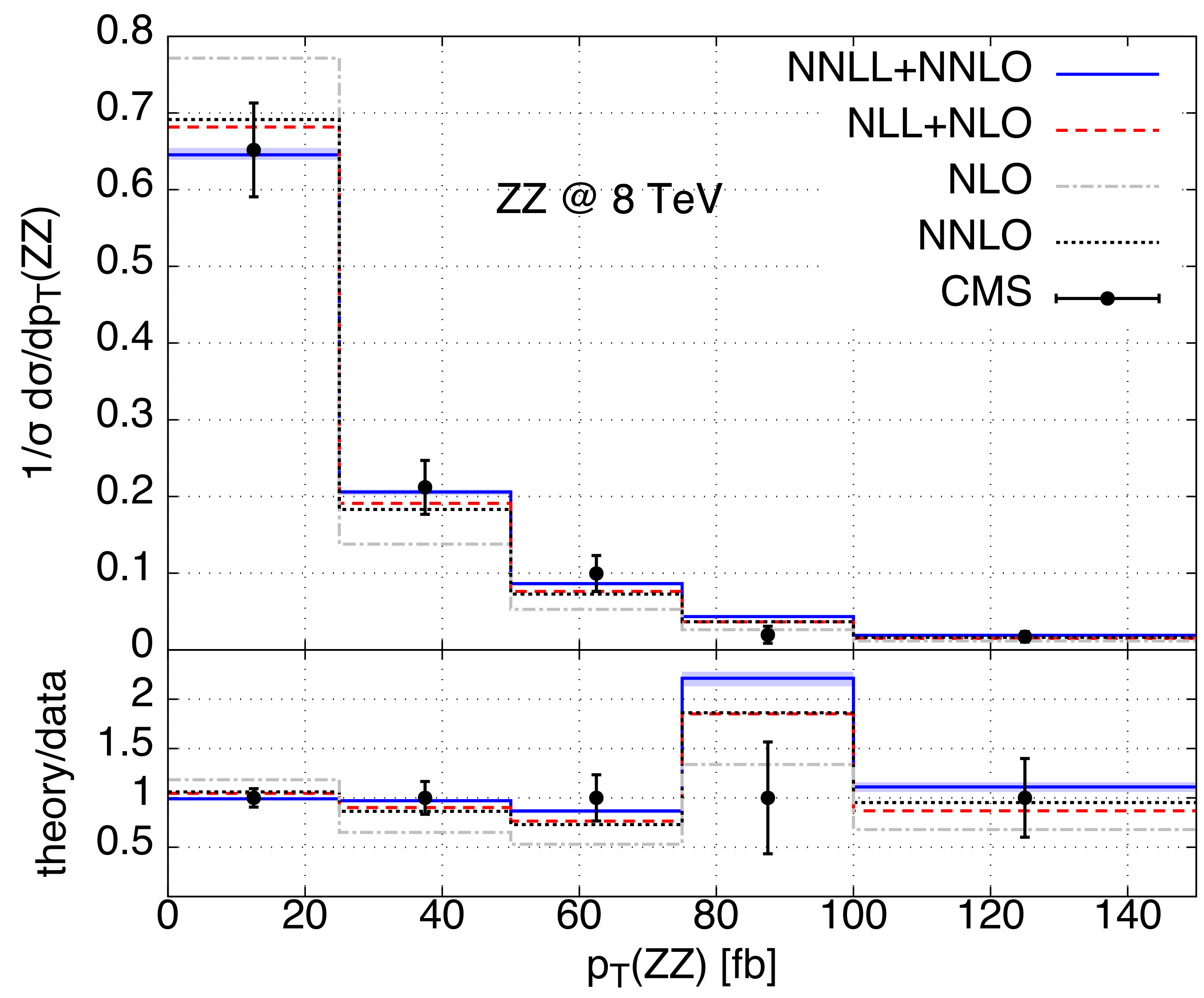
NNLO+NNLL resummation for ZZ and WW [Grazzini, Kallweit, Rathlev, MW '15]

p_T spectrum of ZZ pair: comparison to data

[CMS '15]



[Grazzini, Kallweit, Rathlev, MW '15]



NNLO+NNLL resummation for ZZ and WW [Grazzini, Kallweit, Rathlev, MW '15]

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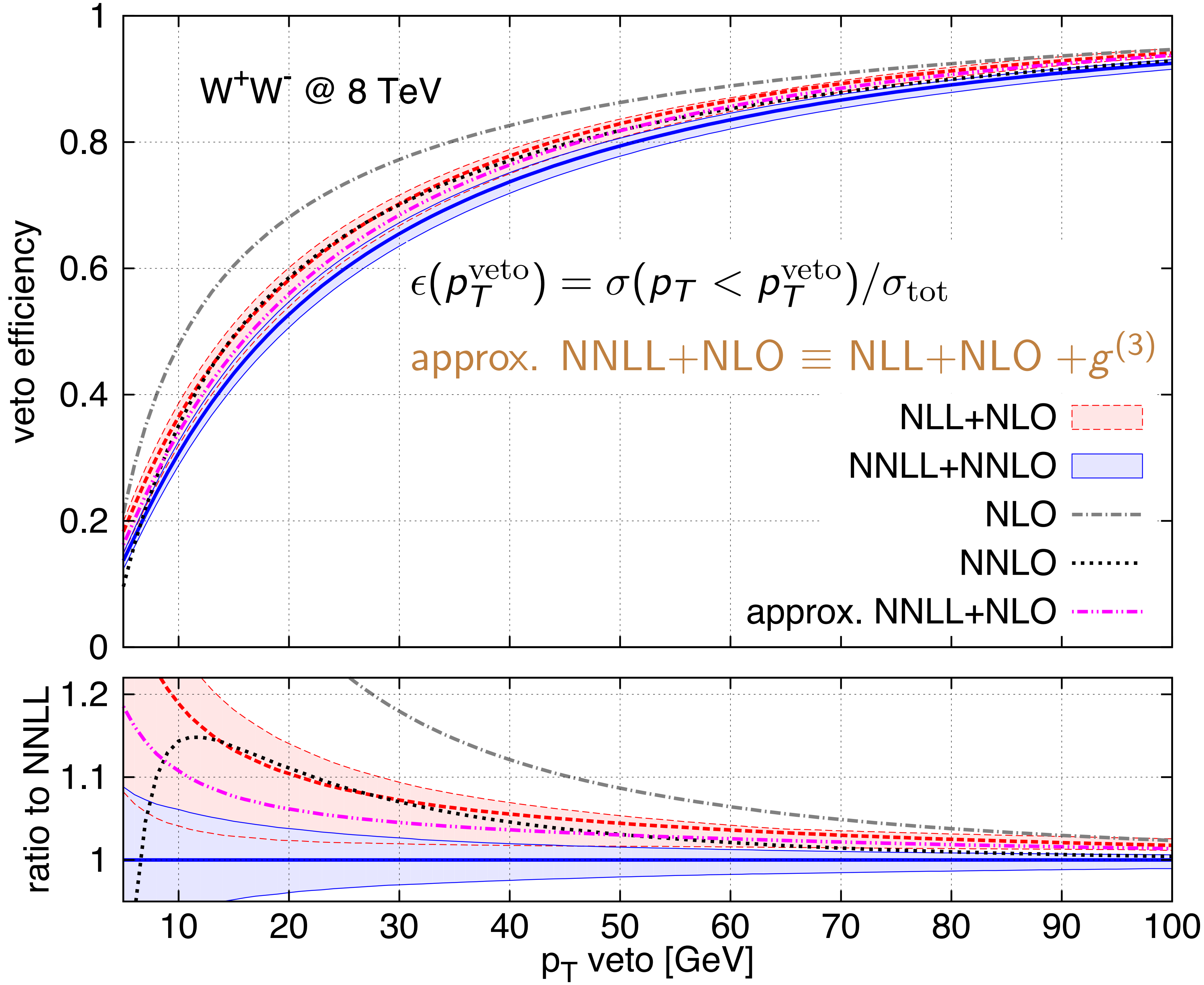
p_T veto WW cross section



WZ cross section at NNLO

[Grazzini, Kallweit, Rathlev, MW '16]

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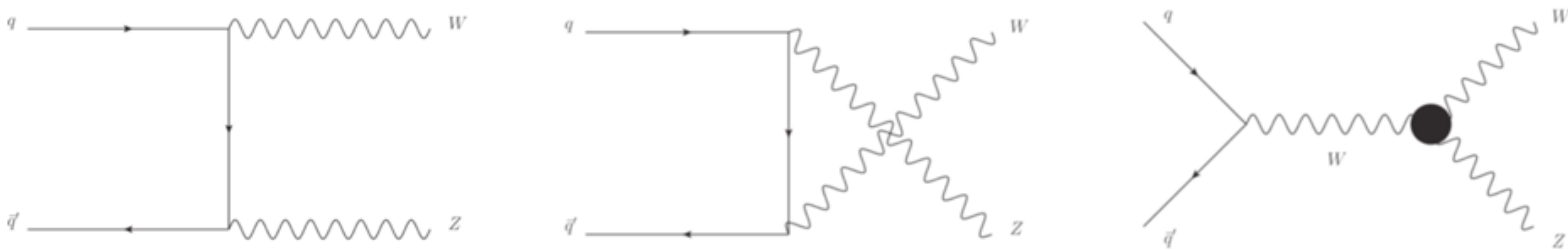
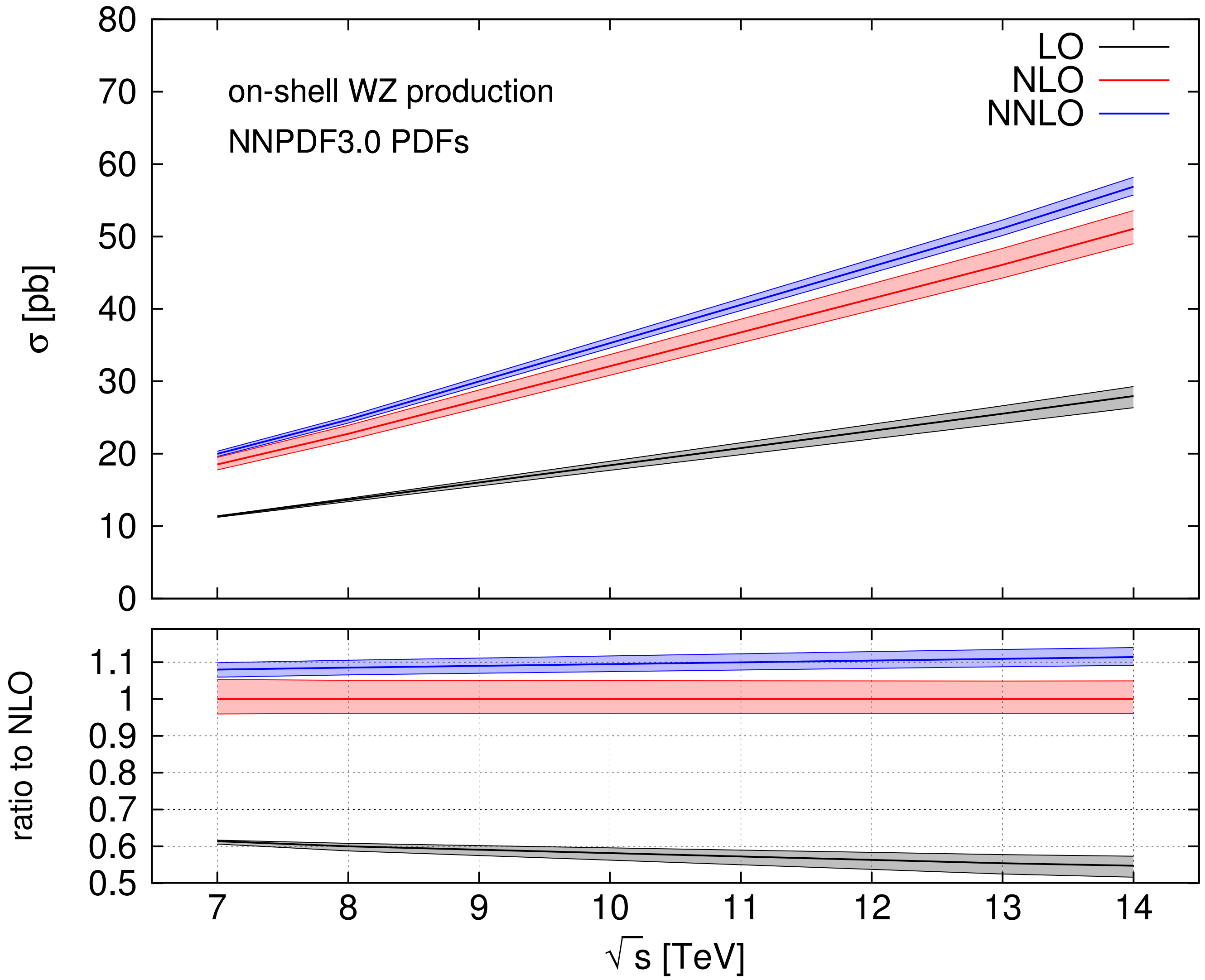


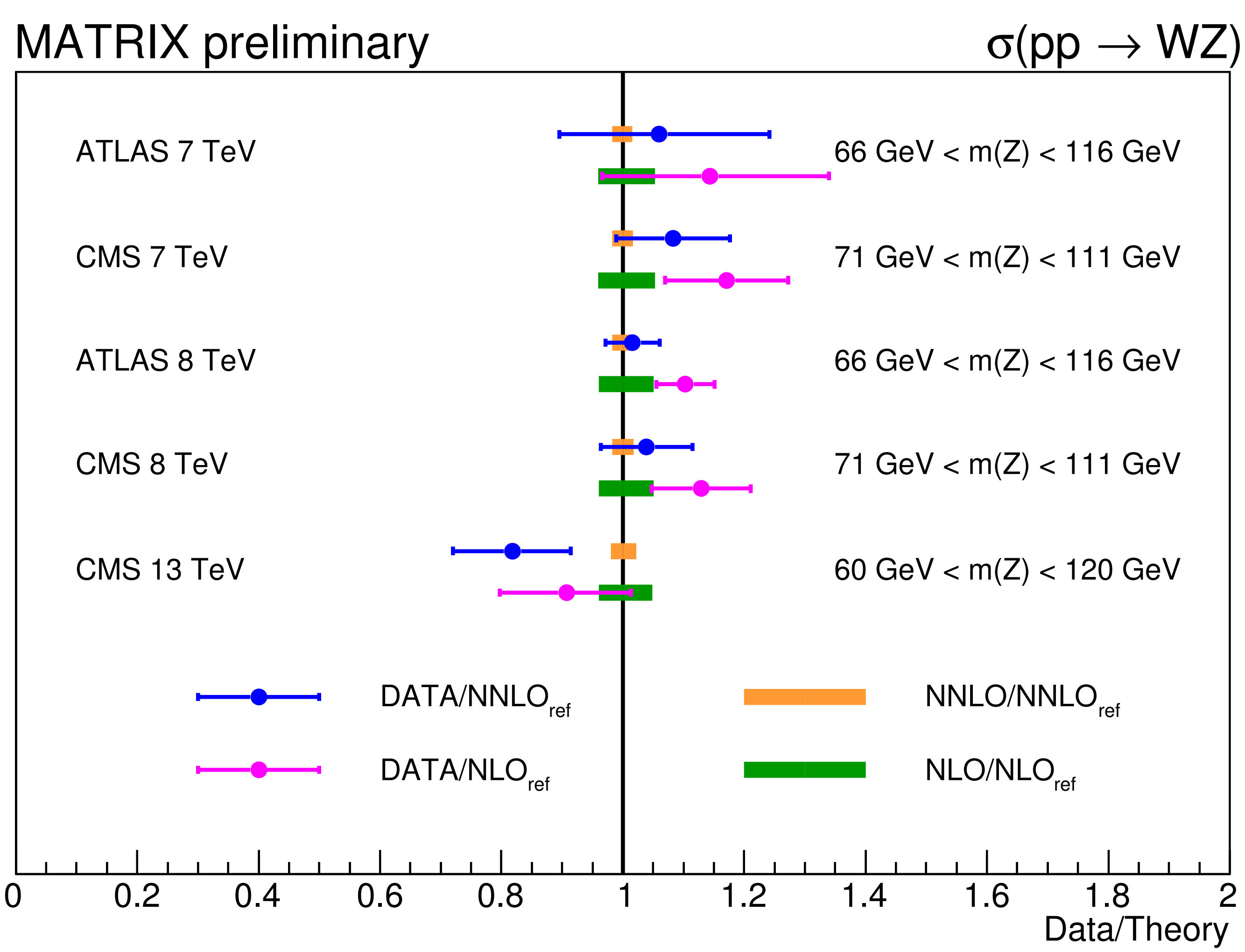
- first computation of NNLO corrections to WZ
- no loop-induced gg component at NNLO
- access to trilinear gauge coupling → relevance for BSM physics
- in principle: same two-loop amplitudes as for off-shell WW [Gehrmann, von Manteuffel, Tancredi '15]
- HERE: only inclusive cross section (minimal cuts on reconstructed Z mass)
- BUT: computation in principle ready for off-shell WZ with decays (amplitudes with different-mass vector bosons already in on-shell case)

WZ cross section at NNLO

[Grazzini, Kallweit, Rathlev, MW '16]



- Huge radiative corrections due to approximate radiation zero [Baur, Han, Ohnemus '94]
- ~63-83% NLO corrections
- ~8-11% NNLO corrections



- NNLO corrections nicely improve agreement with data at 7 and 8 TeV
- slightly worse for 13 TeV CMS, but still large uncertainties

Summary

- Automated: NNLO cross sections and NNLL p_T spectra (except 2-loop) for color-neutral particle production
- Implemented in MATRIX framework
- First application at NNLL+NNLO: ZZ and WW p_T spectra
- p_T veto: perturbative and logarithmic corrections sizable
- WZ at NNLO: diboson processes completed at NNLO

Outlook

- SOON: closed beta of MATRIX for large list of $2\rightarrow 1$, $2\rightarrow 2$ NNLO processes
- EXTENSION: NNLL p_T resummation for all available NNLO processes
- more physics applications:
  - NNLO cross section for WZ production
  - NNLO+NNLL for ZZ and WW with decays (with fiducial cuts)
  - NLO QCD corrections to loop-induced gg channel of diboson processes


FREE YOUR MIND.
THE MATRIX

Thank You !

Back Up

The MATRIX team

Dirk "Cypher" Rathlev	Massimiliano "Morpheus" Grazzini	Stefan "Neo" Kallweit	Marius "Trinity" Wiesemann

WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

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stability of r_{cut} dependence