

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

**Marius Wiesemann**



**Universität  
Zürich<sup>UZH</sup>**

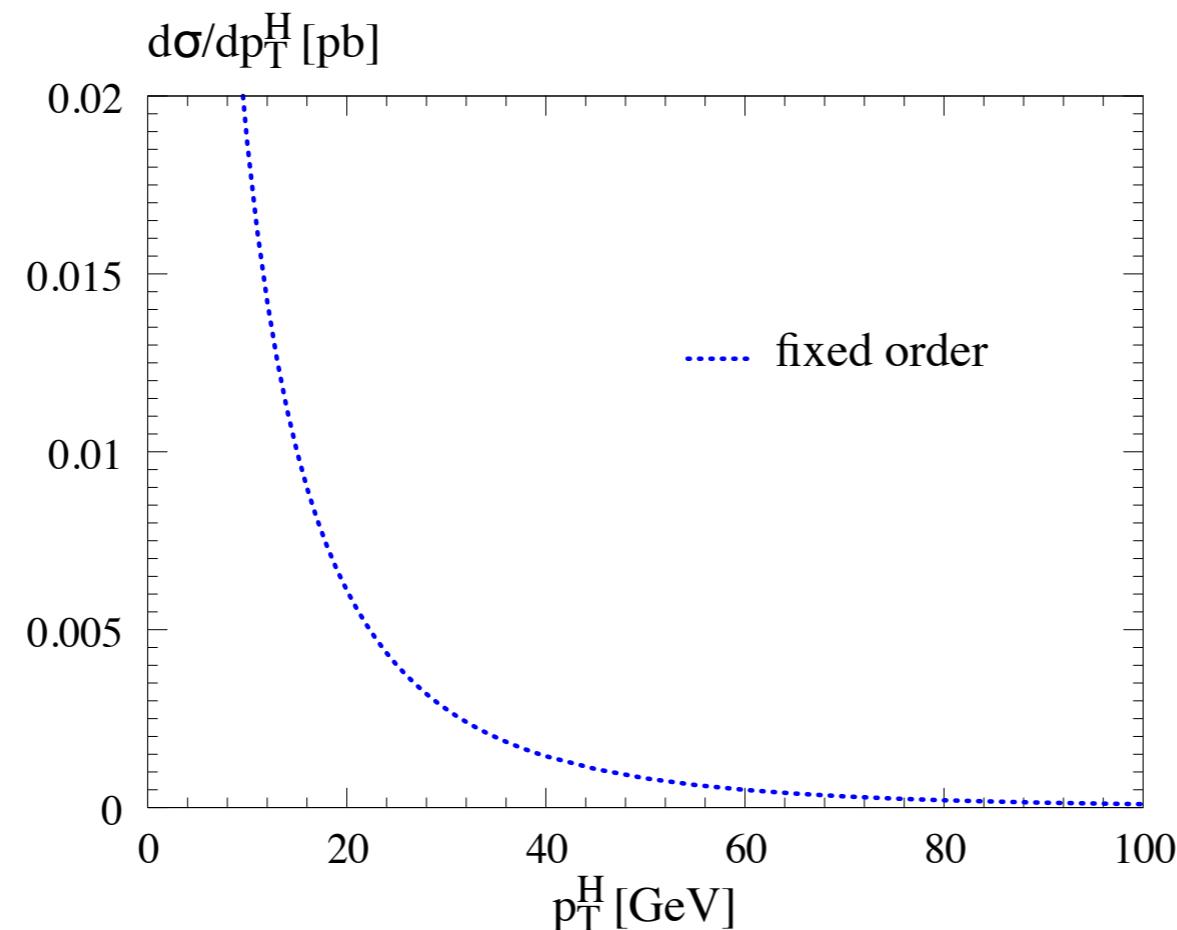
28th Rencontres de Blois, Blois (France)

29 May - 3 June, 2016

# $p_T$ resummation



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



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

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$$\alpha_s^2 : \ln(p_T^2/M^2), \ln^2(p_T^2/M^2), \ln^3(p_T^2/M^2), \ln^4(p_T^2/M^2)$$

...

- ▶ solution: all order resummation

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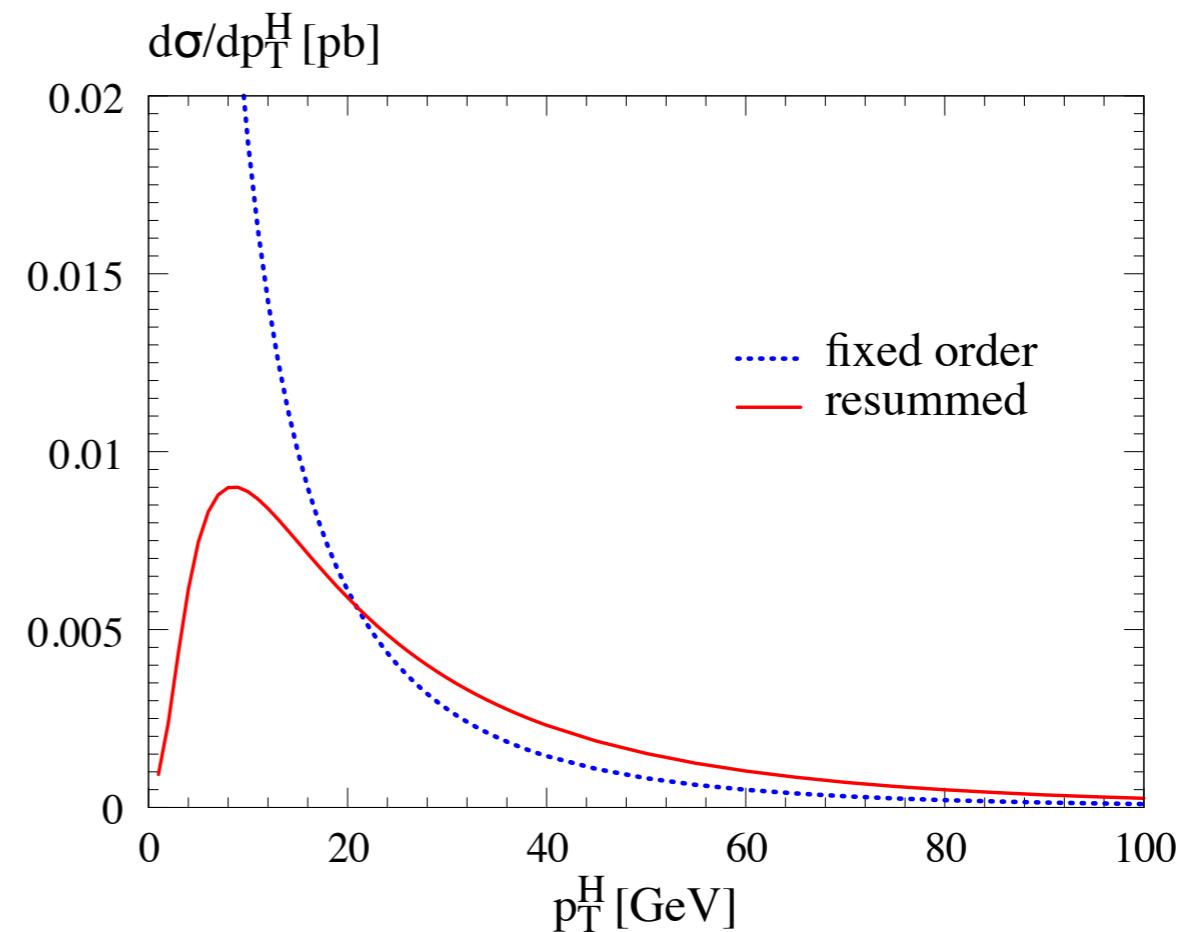
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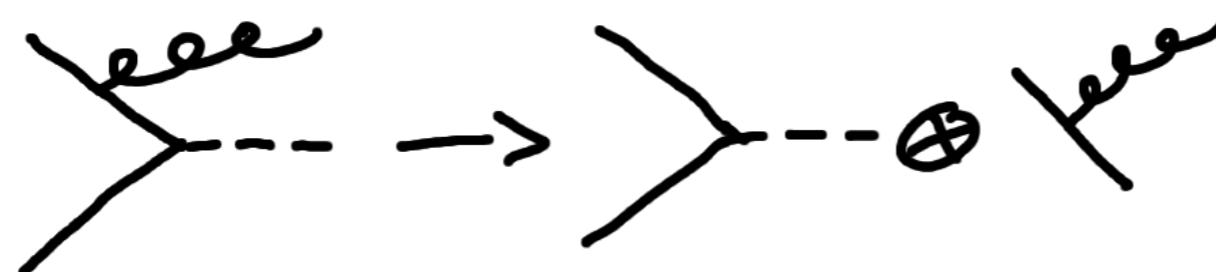
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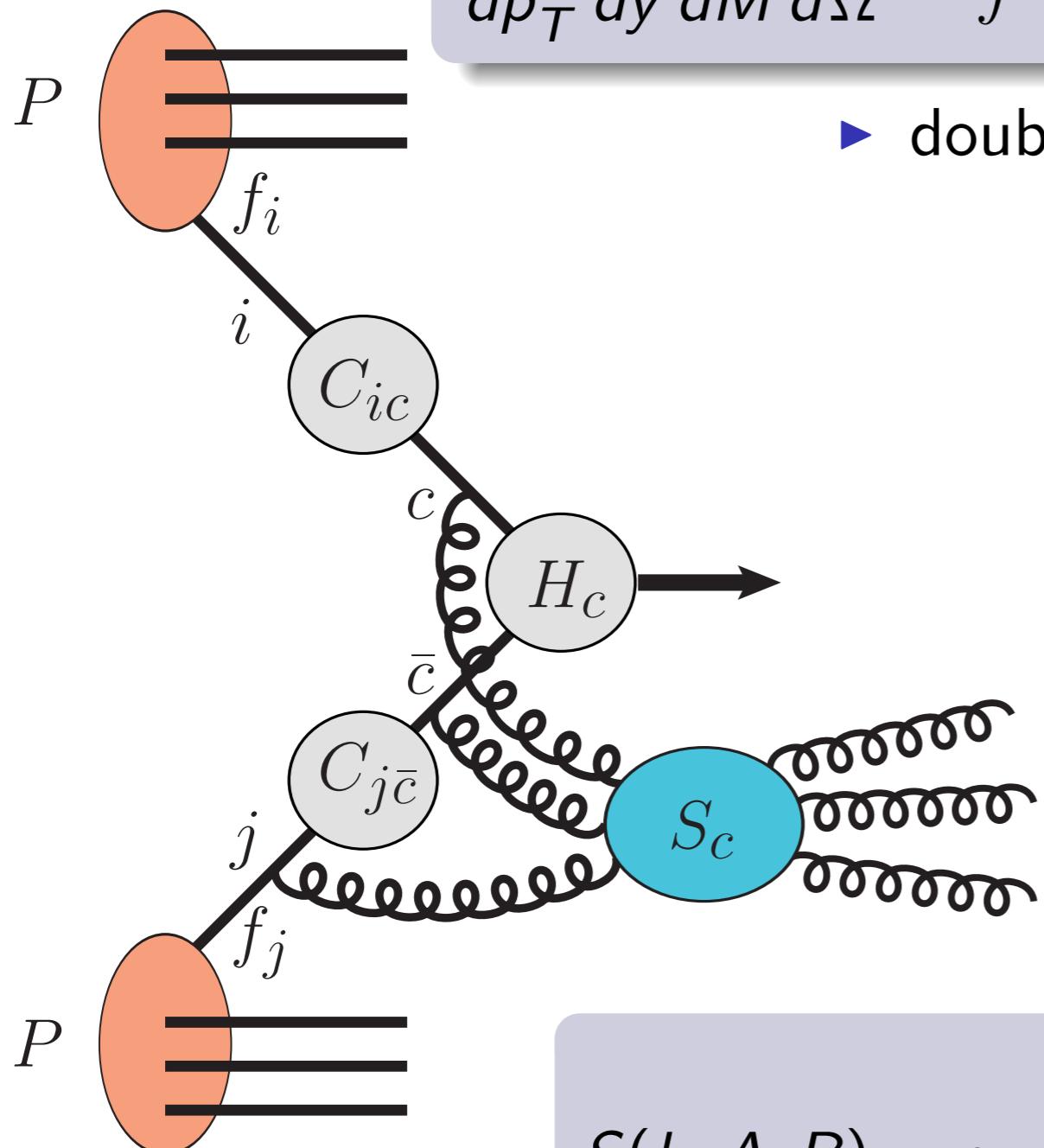
- ▶ solution: all order resummation
  - ▶ factorization of soft and collinear radiation in matrix elements



→ allows for resummation

- ▶ done in impact parameter ( $b$ ) space

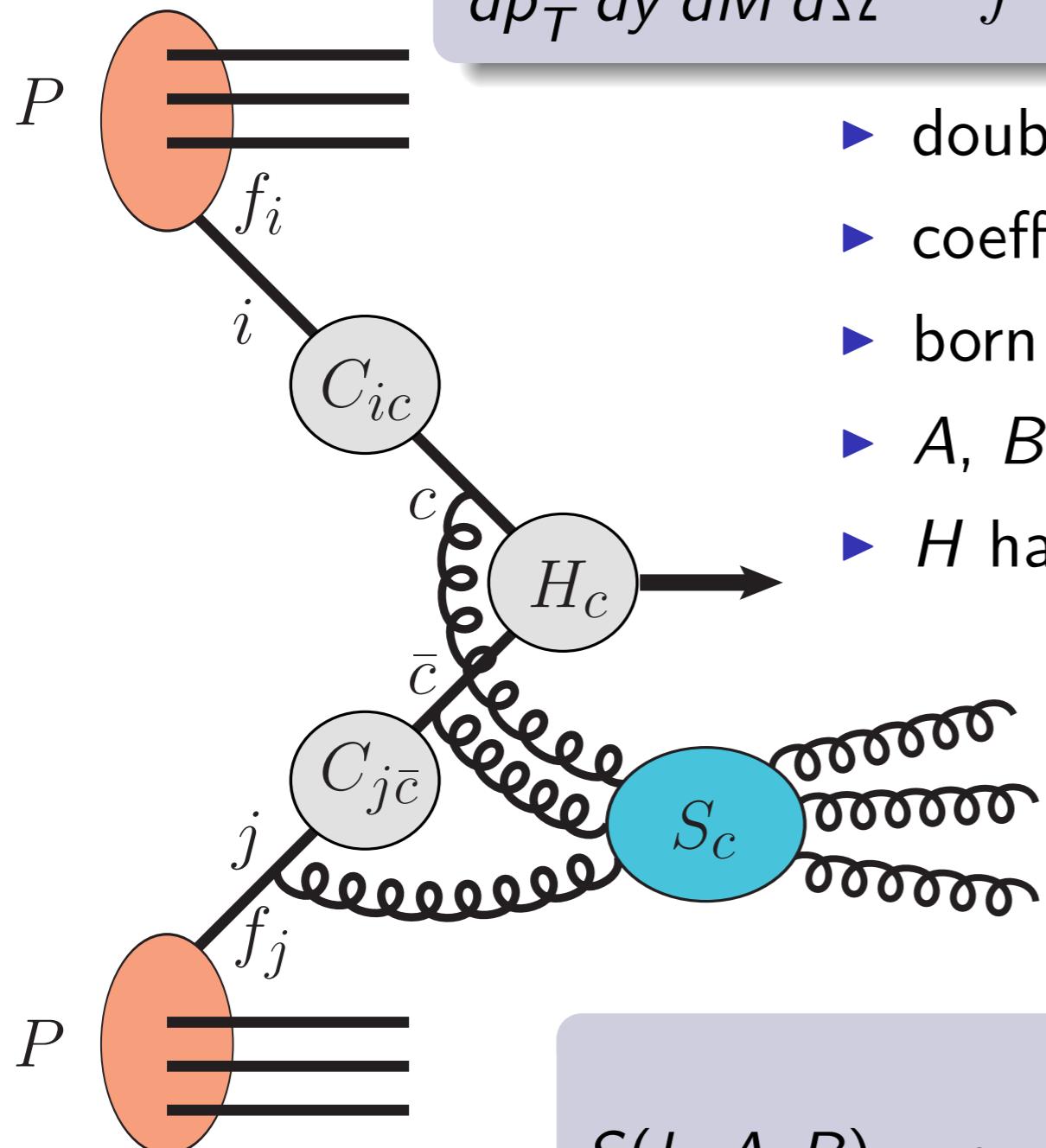
$$\frac{d\sigma_{N_1, N_2}^{(\text{res})}}{dp_T^2 dy dM d\Omega} \sim \int db \frac{b}{2} J_0(b p_T) S(b, A, B) \mathcal{H}_{N_1, N_2} f_{N_1} f_{N_2}$$



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

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

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



- ▶ 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 ( $M, \Omega$ )

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

# PT resummation



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

$$S_c(A, B) = \exp \left\{ \underbrace{L g^{(1)}(\alpha_s L) + g^{(2)}(\alpha_s L) + \alpha_s g^{(3)}(\alpha_s L) + \alpha_s^2 \dots}_{\text{LL}} \right\}$$

$$\qquad\qquad\qquad \underbrace{\qquad\qquad\qquad}_{\text{NLL}}$$

$$\qquad\qquad\qquad \underbrace{\qquad\qquad\qquad}_{\text{NNLL}}$$

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

# $p_T$ resummation

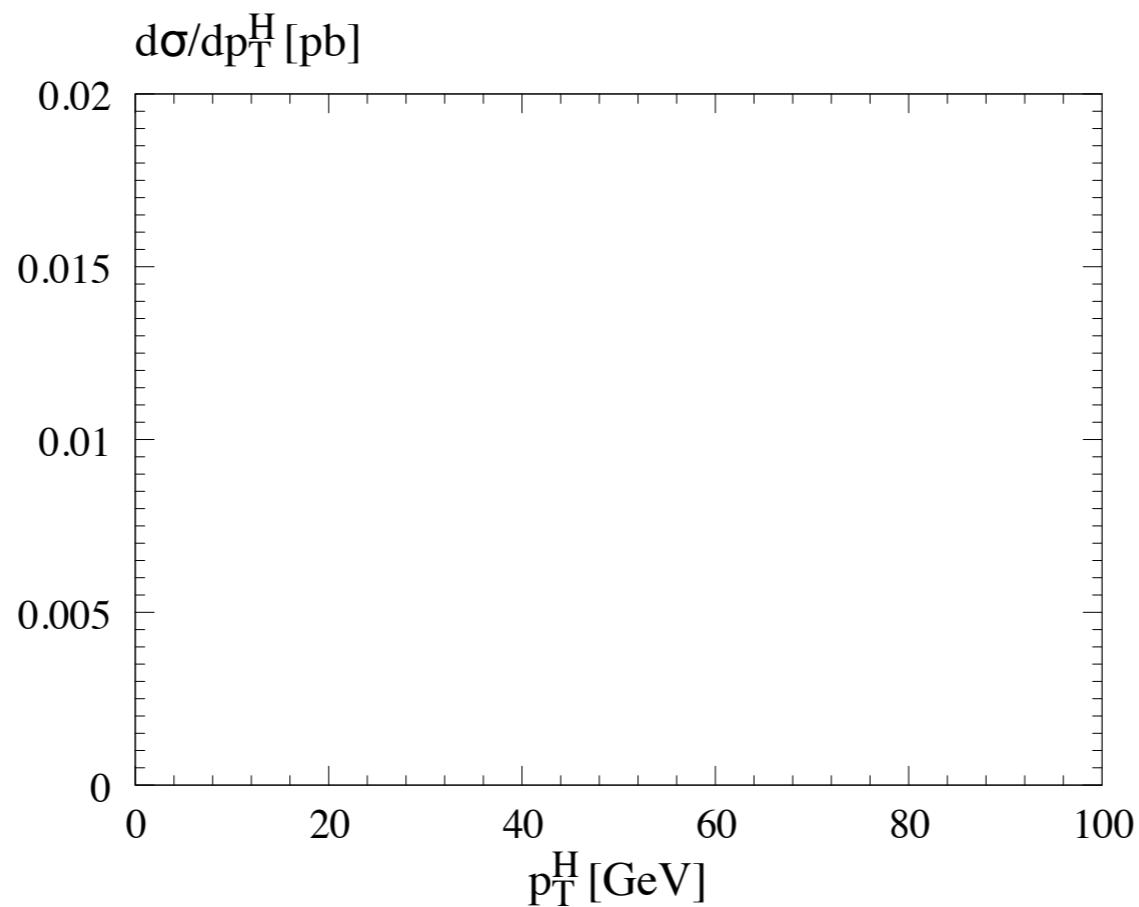


- ▶ developed already 30 years ago
  - [Parisi, Petronzio '79], [Dokshitzer, Diakonov, Troian '80], [Curci, Greco, Srivastava '79], [Bassetto, Ciafaloni, Marchesini '80], [Kodaira, Trentadue '82], [**Collins, Soper, Sterman '85**]
- ▶ we use newer formulation including various improvements:
  - [Catani, de Florian, Grazzini '01], [Bozzi, Catani, de Florian, Grazzini '06 '07]
    - ▶  $H$  embodies whole process dependence
    - ▶  $L = \ln(Q^2 b^2 / b_0^2) \rightarrow L' = \ln(Q^2 b^2 / b_0^2 + 1)$ 
      - reduction of impact at high  $p_T$  (low  $b$ )
      - unitarity constraint
    - ▶ rapidity dependence

# matching with fixed order



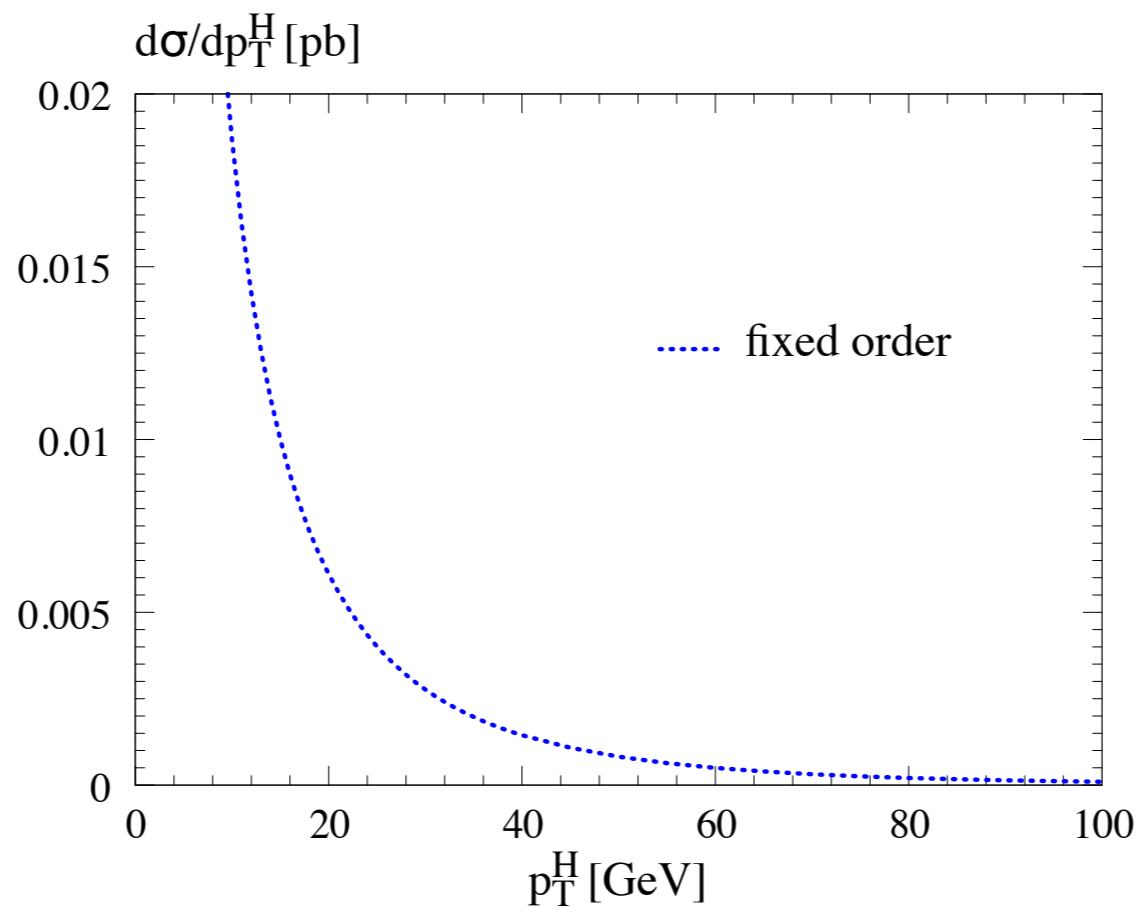
$$\left[ \frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}+\text{l.a.}} =$$



# matching with fixed order



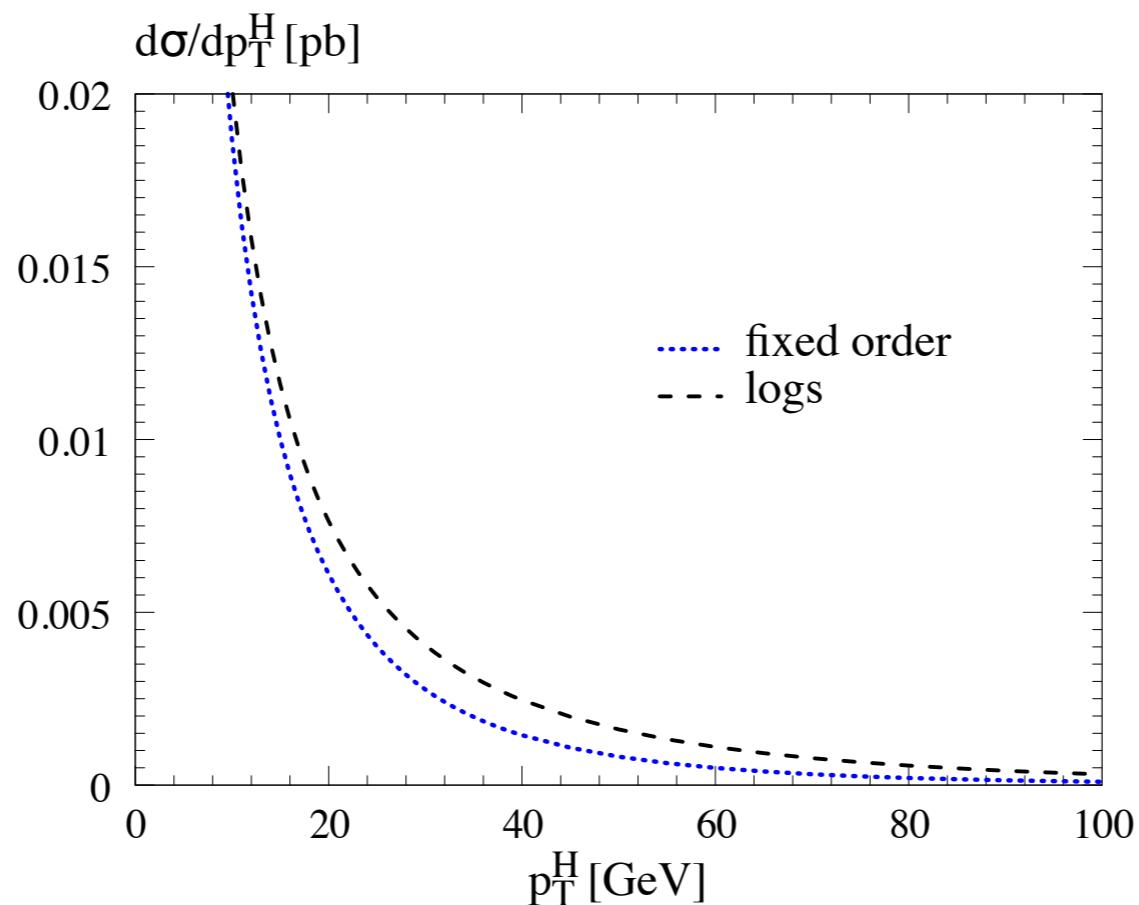
$$\left[ \frac{d\sigma}{dp_T^2} \right]_{\text{f.o.} + \text{l.a.}} = \left[ \frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}}$$



# matching with fixed order



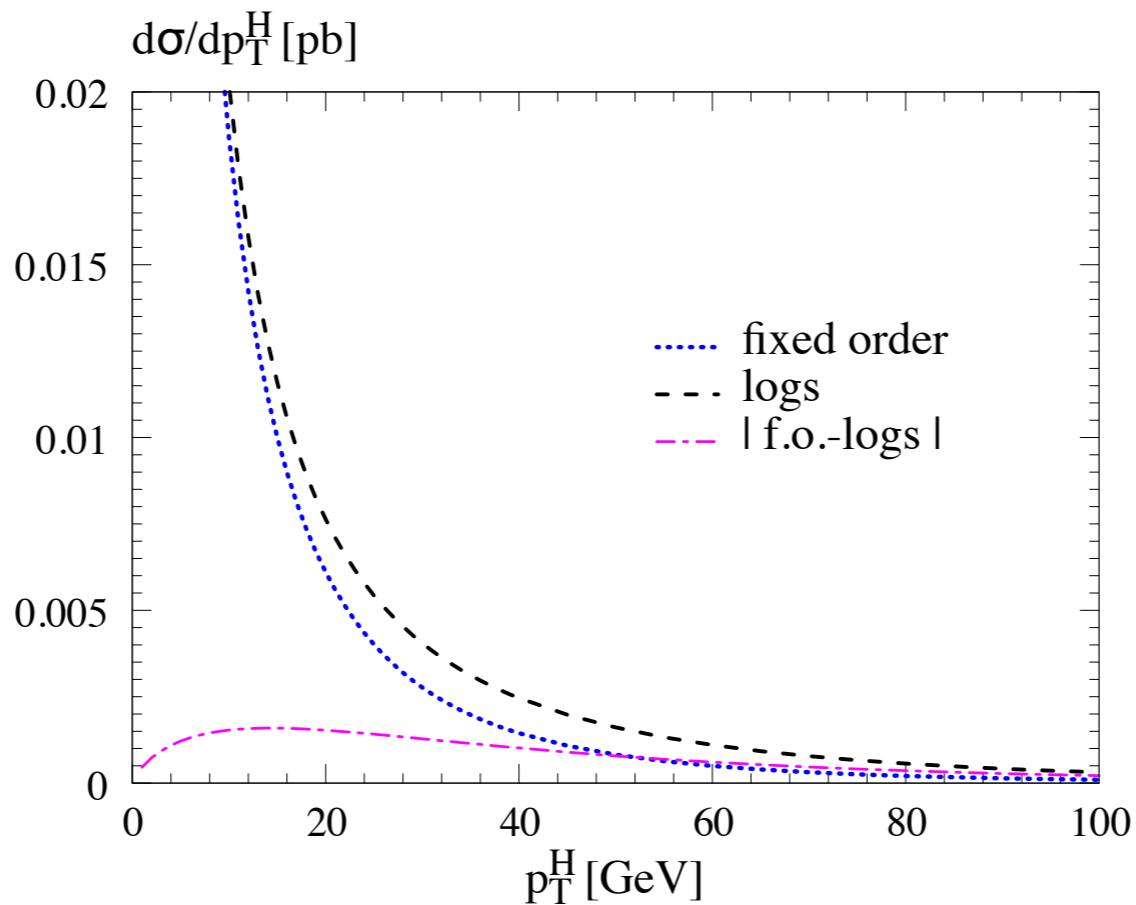
$$\left[ \frac{d\sigma}{dp_T^2} \right]_{\text{f.o.} + \text{l.a.}} = \left[ \frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}} - \left[ \frac{d\sigma^{(\text{res})}}{dp_T^2} \right]_{\text{f.o.}}$$



# matching with fixed order



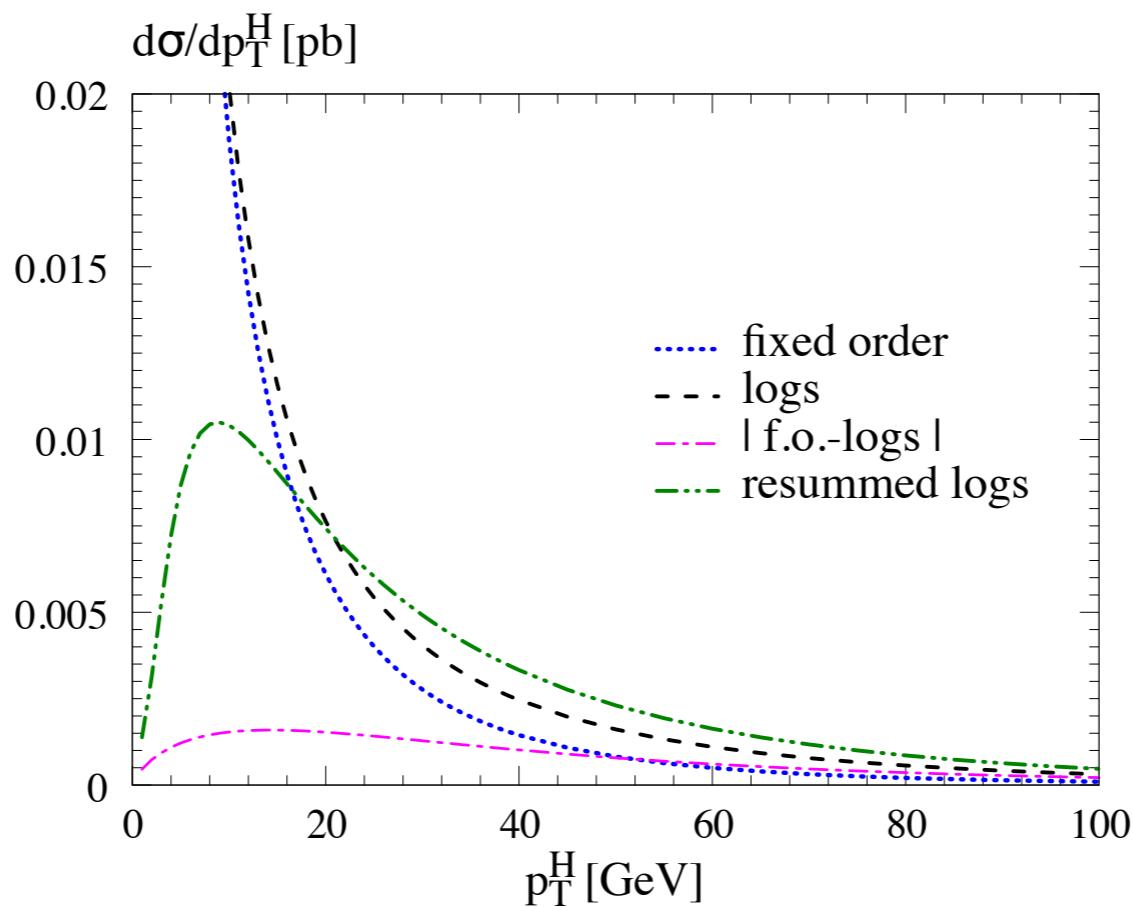
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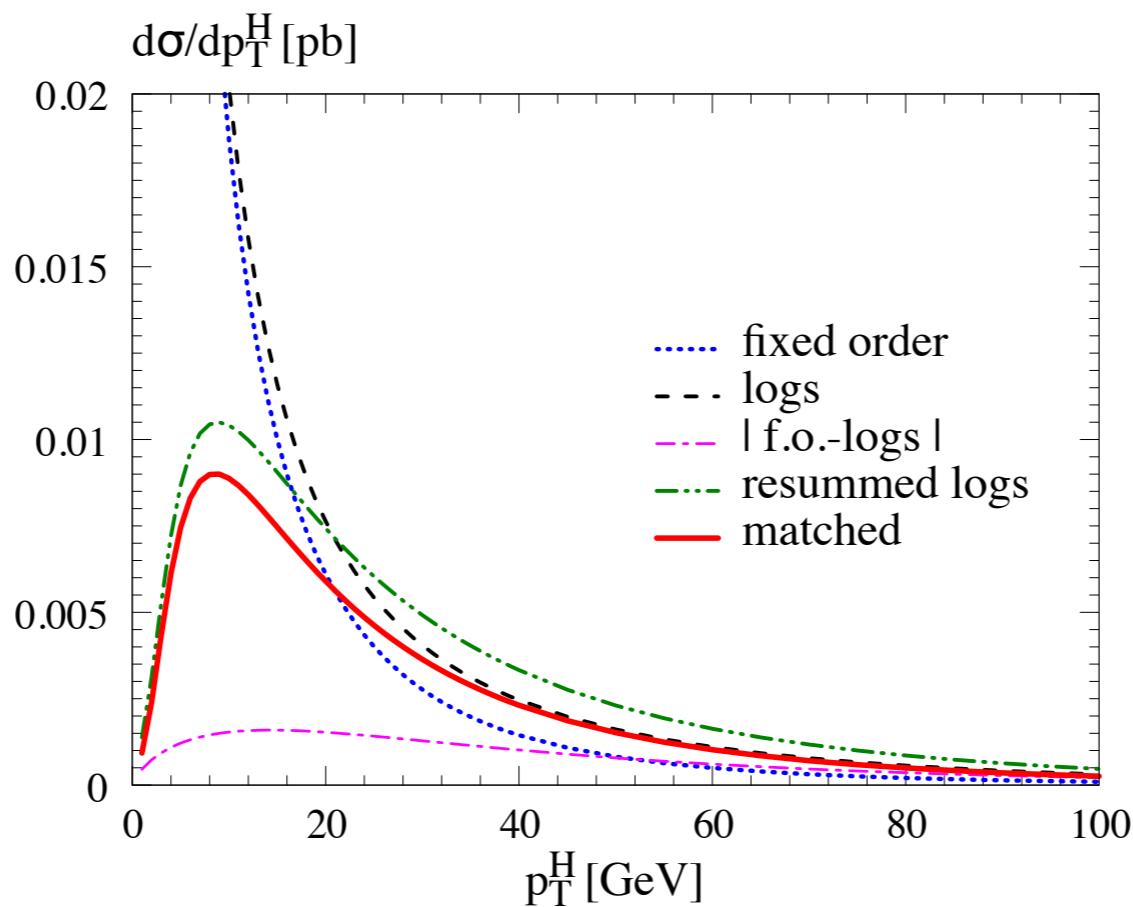
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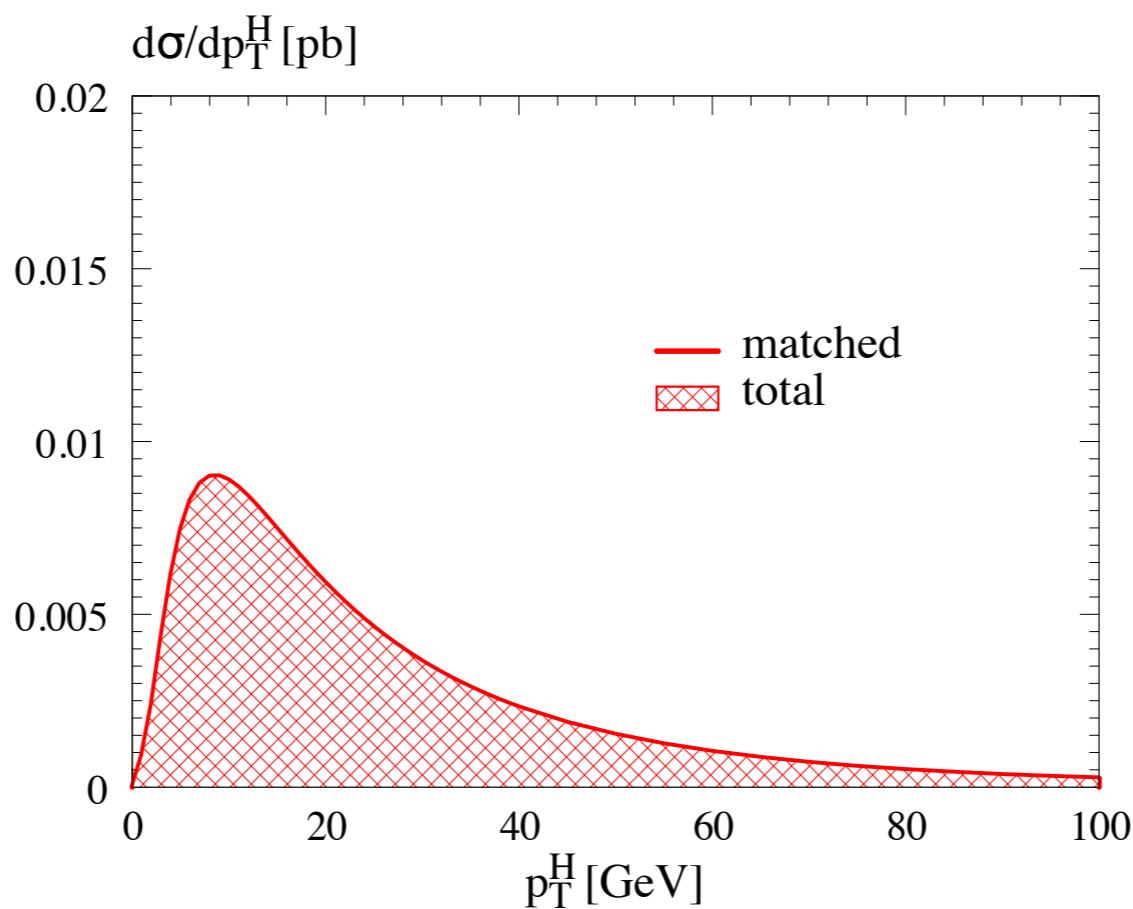
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# matching with fixed order



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



We implemented...



# The MATRIX framework

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

## Amplitudes

OPENLOOPs  
(COLLIER, CUTTOols, ...)

Dedicated 2-loop codes  
(VVAMP, GiNAC, TDHPL, ...)

MUNICH  
MULTI-chaNNel Integrator at Swiss (CH) precision

$q_T$  subtraction  $\Leftrightarrow$   $q_T$  resummation

NNLO

NNLL

## MATRIX

MUNICH Automates  $q_T$  Subtraction  
and Resummation to Integrate X-sections.

# The MATRIX



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```
[wiesemann:~/munich-http/MATRIX] ./matrix

-----+
| MATRIX: A fully-differential NNLO(NNLL) process library
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|-----+
| Version: 1.0.beta1           Dec 2015
|
| Munich -- the Multi-channel Integrator at swiss (CH) precision --
| Automates qT-subtraction and Resummation to Integrate X-sections
|
|   \   |   \   |   \   |   \   |   \   |   \   |   \   |
|   \   |   \   |   \   |   \   |   \   |   \   |   \   |
|   \   |   \   |   \   |   \   |   \   |   \   |   \   |
|   \   |   \   |   \   |   \   |   \   |   \   |   \   |
|   \   |   \   |   \   |   \   |   \   |   \   |   \   |
|   \   |   \   |   \   |   \   |   \   |   \   |   \   |
|-----+
| M. Grazzini          (grazzini@physik.uzh.ch)
| S. Kallweit          (kallweit@uni-mainz.de)
| D. Rathlev           (rathlev@physik.uzh.ch)
| M. Wiesemann         (marlusw@physik.uzh.ch)
|
|-----+
| MATRIX is based on a number of different computations and tools
| from various people and groups. Please acknowledge their efforts
| by citing the list of references which is created with every run.
|-----+



<<MATRIX-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                  available processes. Try pressing TAB for auto-completion. Type
                  "exit" or "quit" to stop.
|-----+>
<<MATRIX-READ>> No suitable process_id or command has been entered. Try again...
<<MATRIX-READ>> You have to choose a process_id from the following list:
-----+
process_id  ||  process                                ||  description
-----+
pph21      >> p p --> H                           >> on-shell Higgs production
ppz01      >> p p --> Z                           >> on-shell Z production
ppw01      >> p p --> W^+                         >> on-shell W+ production, NOT FULLY TESTED YET
ppwx01     >> p p --> W^-                         >> on-shell W- production, NOT FULLY TESTED YET
ppeex02    >> p p --> e^- e^+                         >> Z production with decay
ppnenex02  >> p p --> v_e^- v_e^+                         >> Z production with decay
ppxne02    >> p p --> e^+ v_e^-                         >> W+ production with decay, NOT FULLY TESTED YET
ppenex02   >> p p --> e^- v_e^+                         >> W- production with decay, NOT FULLY TESTED YET
pphh22     >> p p --> H H                           >> on-shell double Higgs production
ppaa02     >> p p --> gamma gamma                         >> on-shell gamma gamma production
ppzz02     >> p p --> Z Z                           >> on-shell ZZ production
ppeexa03   >> p p --> e^- e^+ gamma                         >> Z gamma & gamma gamma with decay
ppnenexa03 >> p p --> v_e^- v_e^+ gamma                         >> Z gamma & gamma gamma with decay
ppeeexex84 >> p p --> e^- e^- e^+ e^+                         >> ZZ & Z gamma & gamma gamma with decay
ppemexmx84 >> p p --> e^- mu^- e^+ mu^+                         >> ZZ & Z gamma & gamma gamma with decay
ppxnea03   >> p p --> e^+ v_e^- gamma                         >> W+ gamma with decay
ppenexa03   >> p p --> e^- v_e^+ gamma                         >> W- gamma with decay
ppemxnmx84 >> p p --> e^- mu^+ v_mu^- v_e^+                         >> W W production with decay
ppemexnmx84 >> p p --> e^- mu^- e^+ v_mu^+                         >> W-Z production with decay
ppeexmnm84 >> p p --> e^- e^+ mu^+ v_mu^-                         >> W-Z production with decay
|-----+>
<<MATRIX-MAKE>> pph21
<<MATRIX-MAKE>> Starting compilation...
```

# The Status



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

# NNLO+NNLL resummation

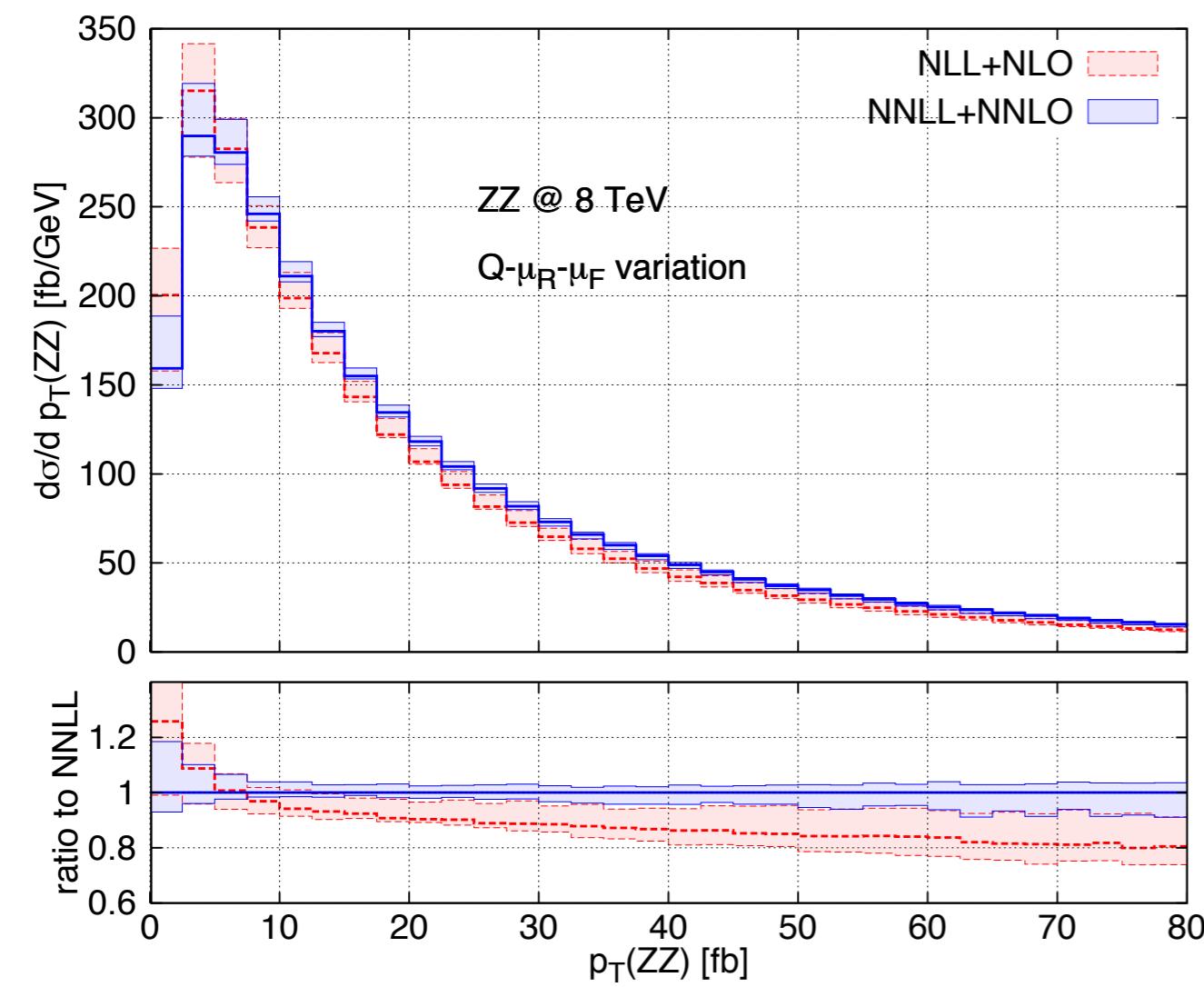
for ZZ and WW

[Grazzini, Kallweit, Rathlev, MW '15]

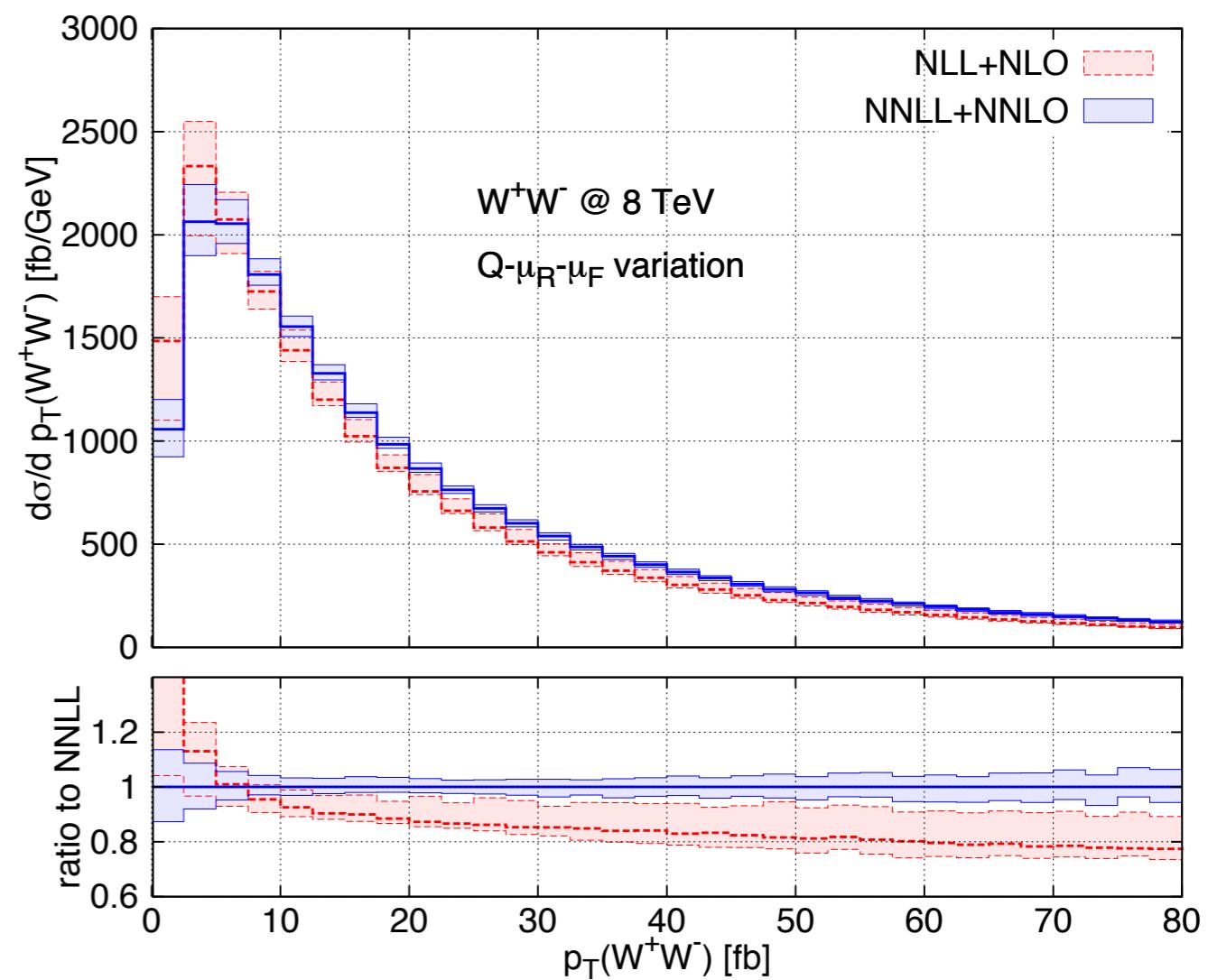


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$p_T$  spectrum of ZZ pair



$p_T$  spectrum of WW pair



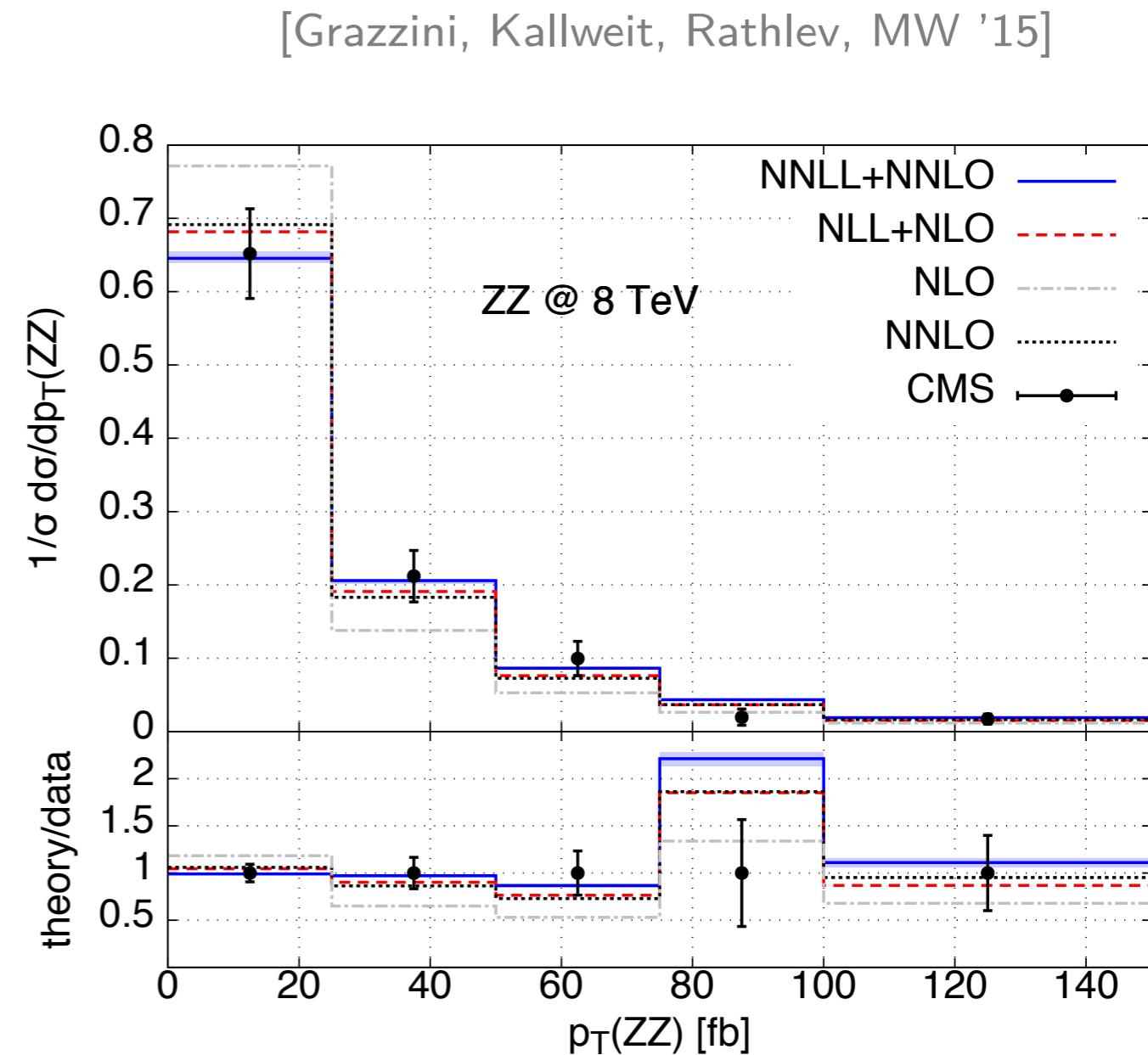
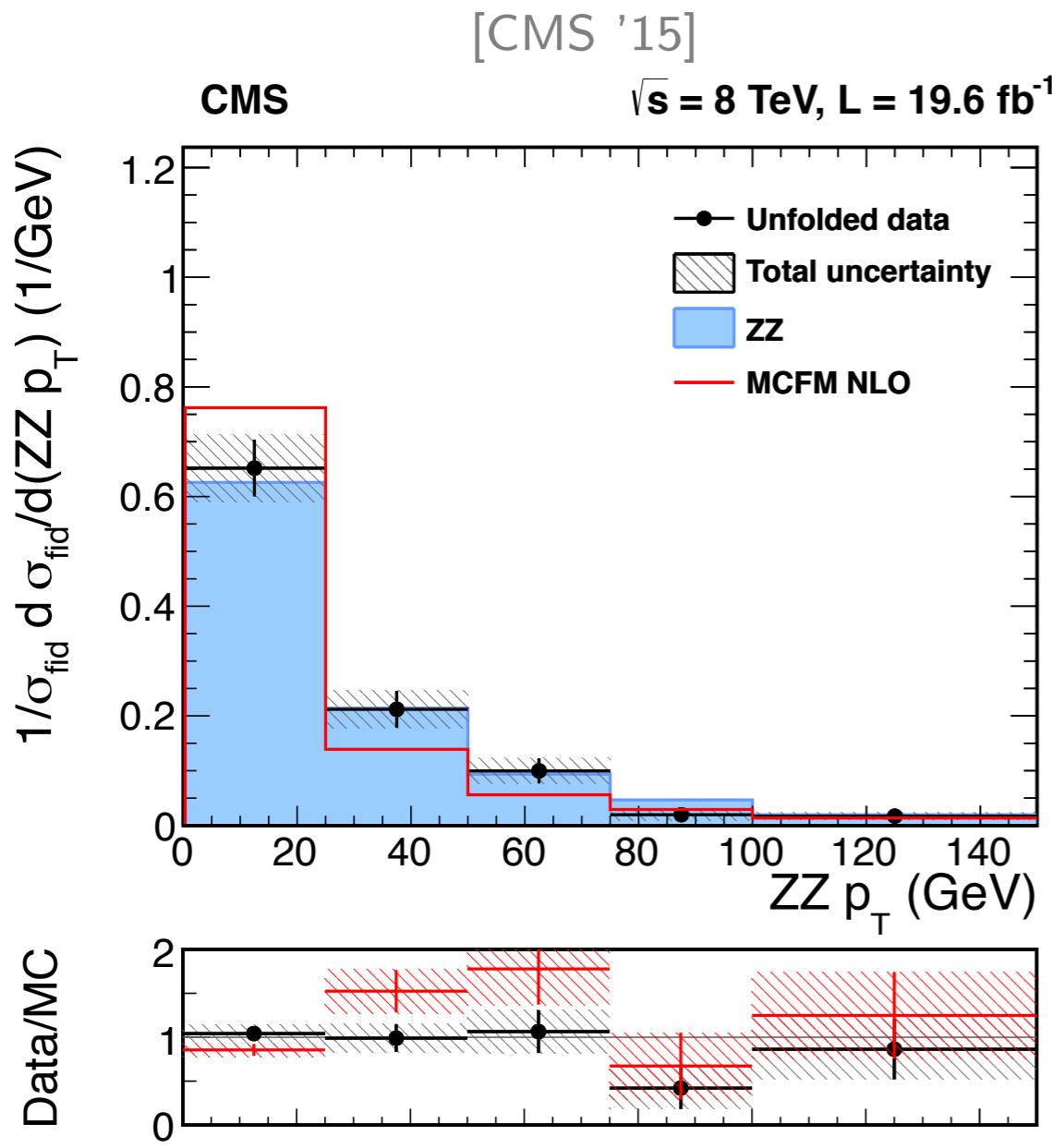
# NNLO+NNLL resummation for ZZ and WW



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[Grazzini, Kallweit, Rathlev, MW '15]

## p<sub>T</sub> spectrum of ZZ pair: comparison to data



# NNLO+NNLL resummation

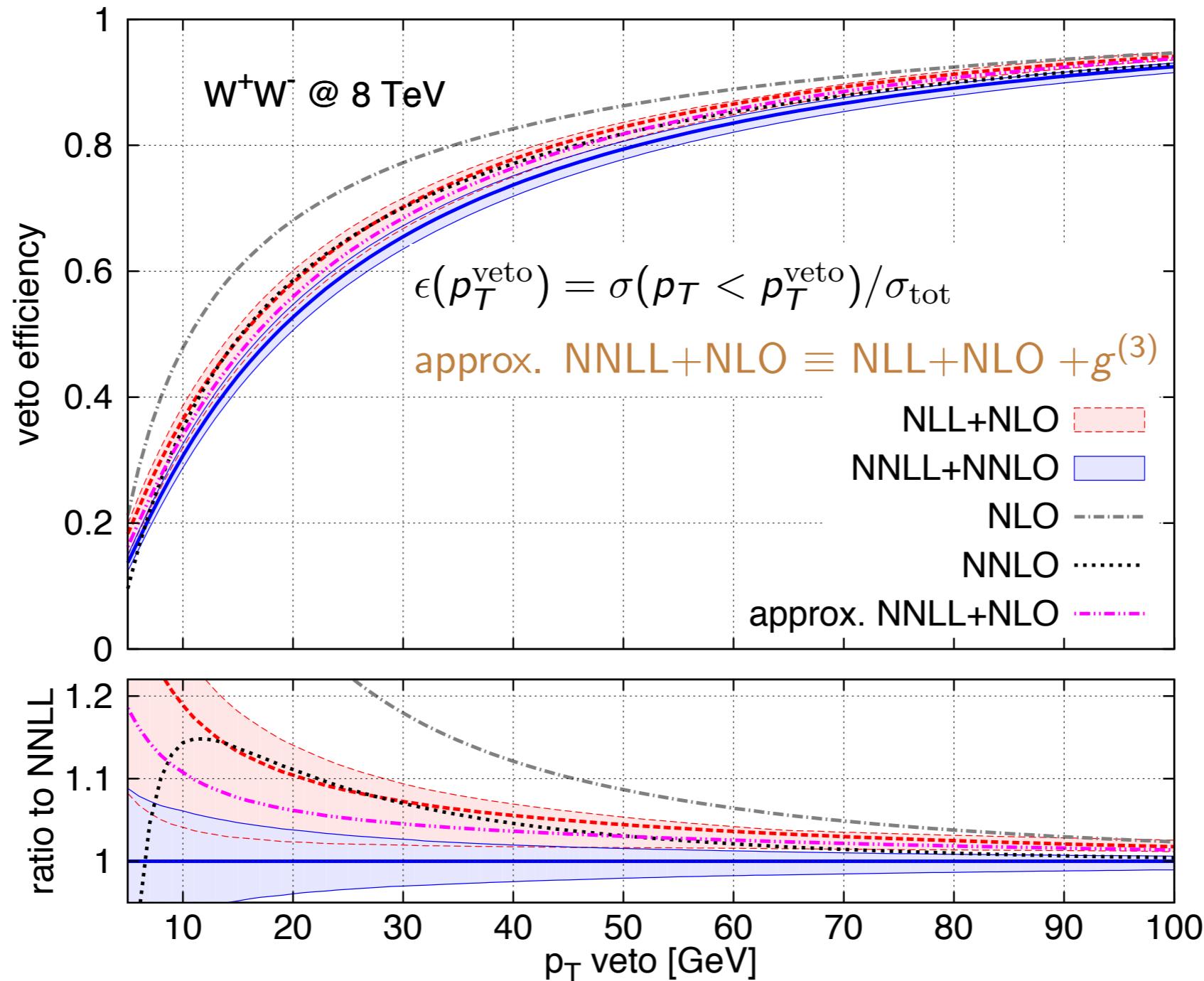
for ZZ and WW

[Grazzini, Kallweit, Rathlev, MW '15]



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## p<sub>T</sub> veto WW cross section

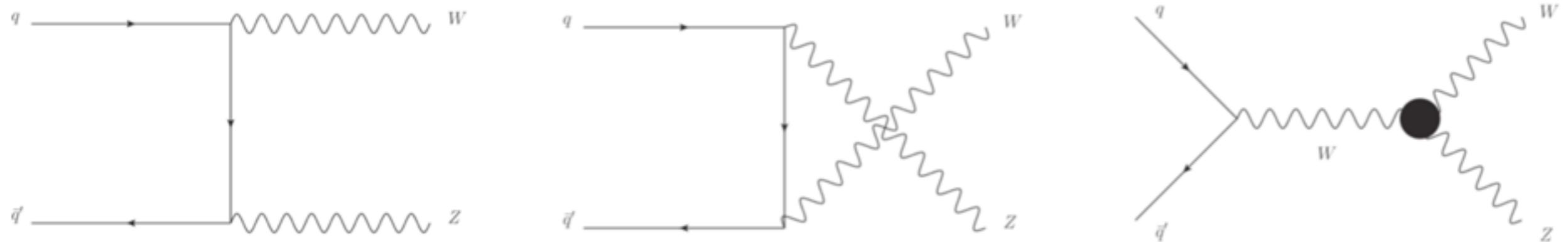


# WZ cross section at NNLO

[Grazzini, Kallweit, Rathlev, MW '16]



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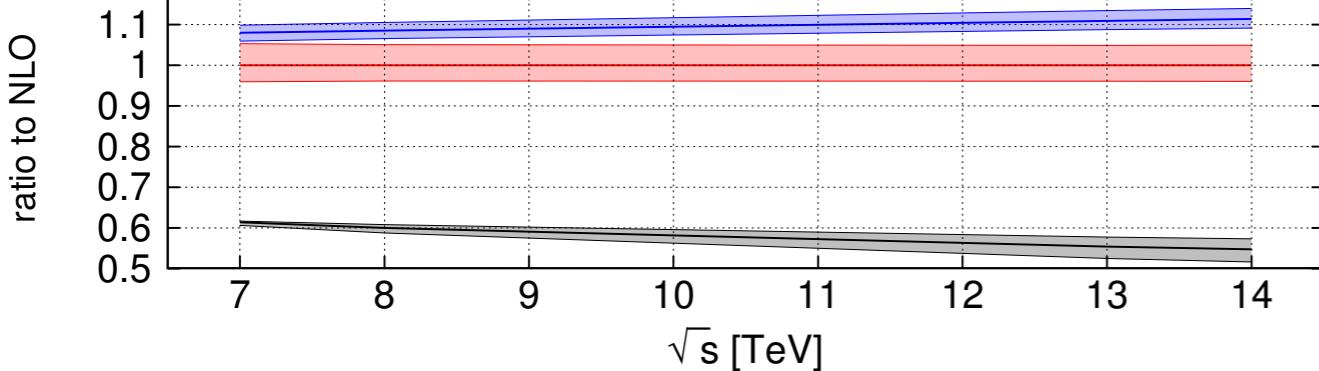
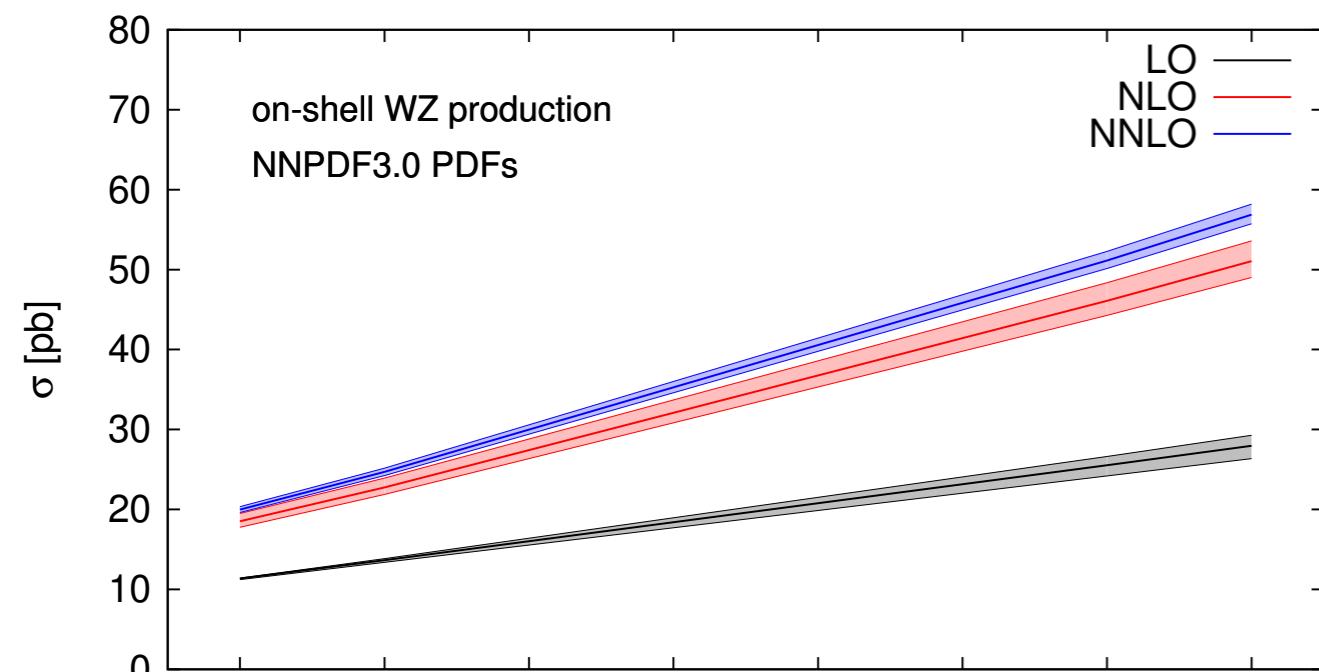
- first computation of NNLO corrections to WZ
- no loop-induced gg component at NNLO
- access to trilinear gauge coupling → relevance for BSM physics
- in principle: same two-loop amplitudes as for off-shell WW  
[Gehrmann, von Manteuffel, Tancredi '15]
- **HERE:** only inclusive cross section (minimal 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]

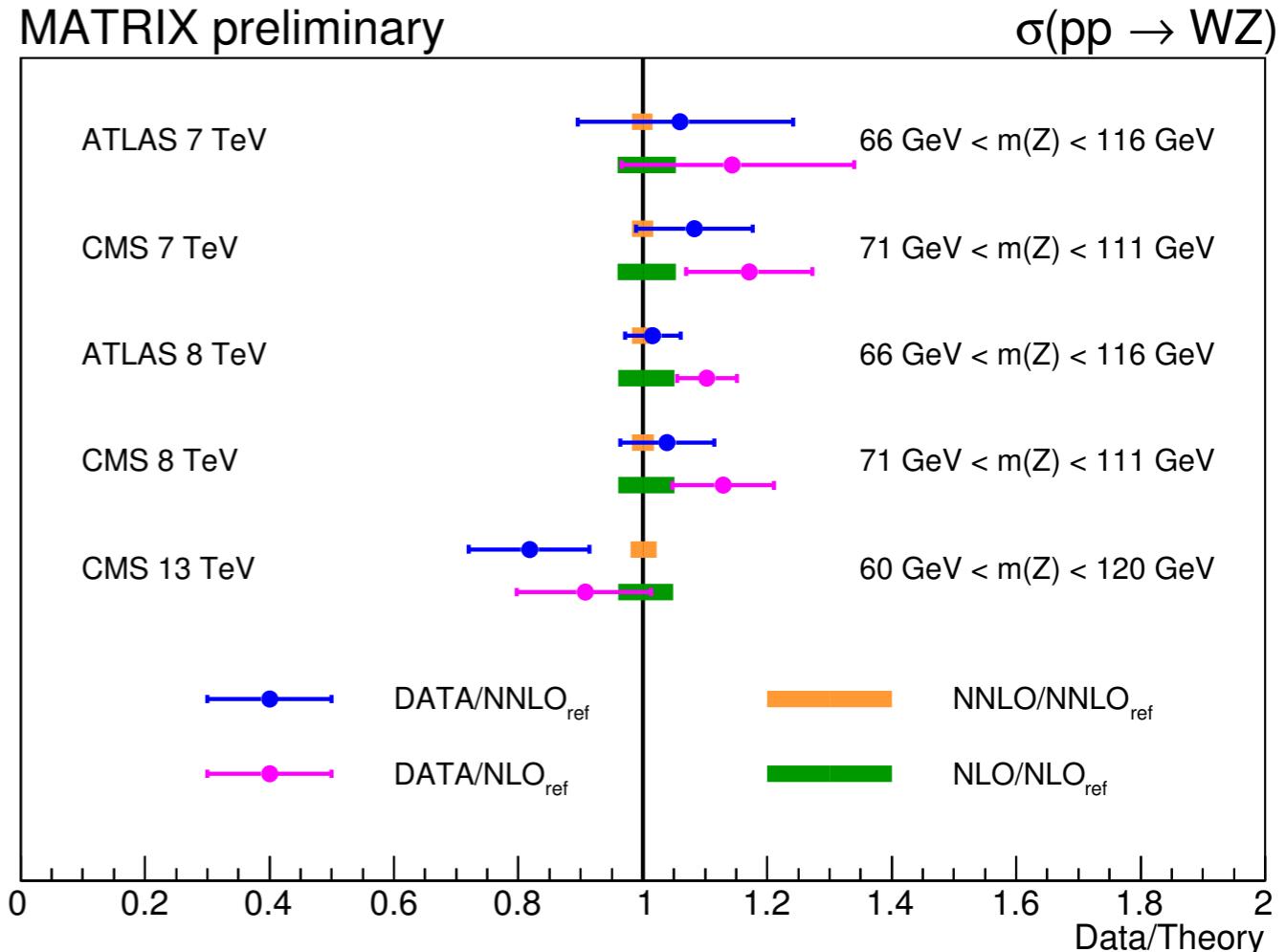


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- Huge radiative corrections due to approximate radiation zero  
**[Baur, Han, Ohnemus '94]**
- ~63-83% NLO corrections
- ~8-11% NNLO corrections

MATRIX preliminary



- 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

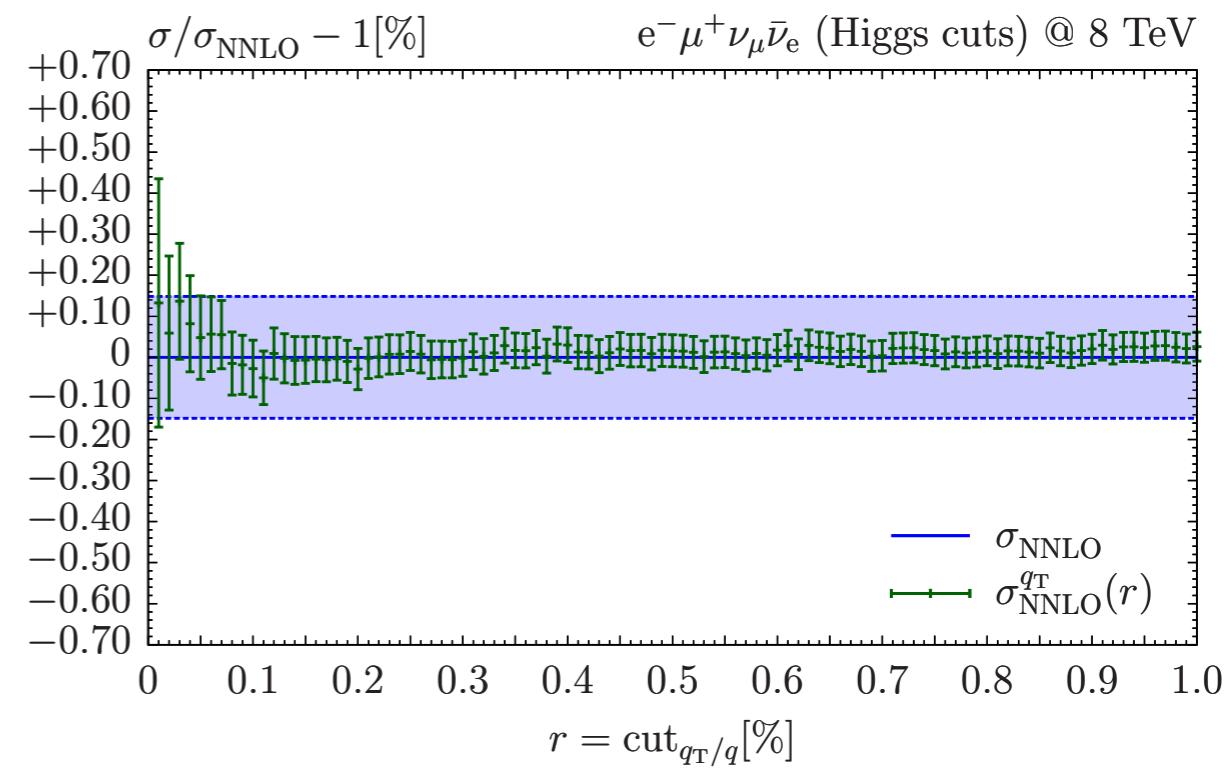
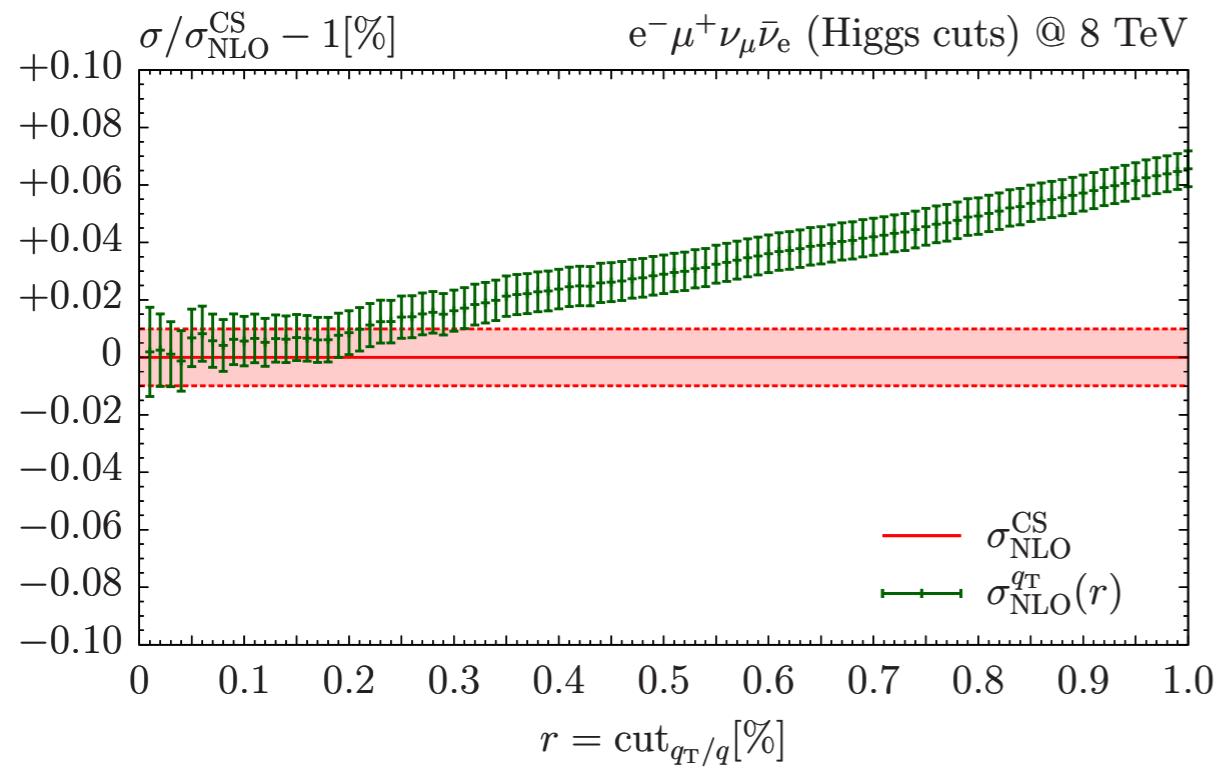
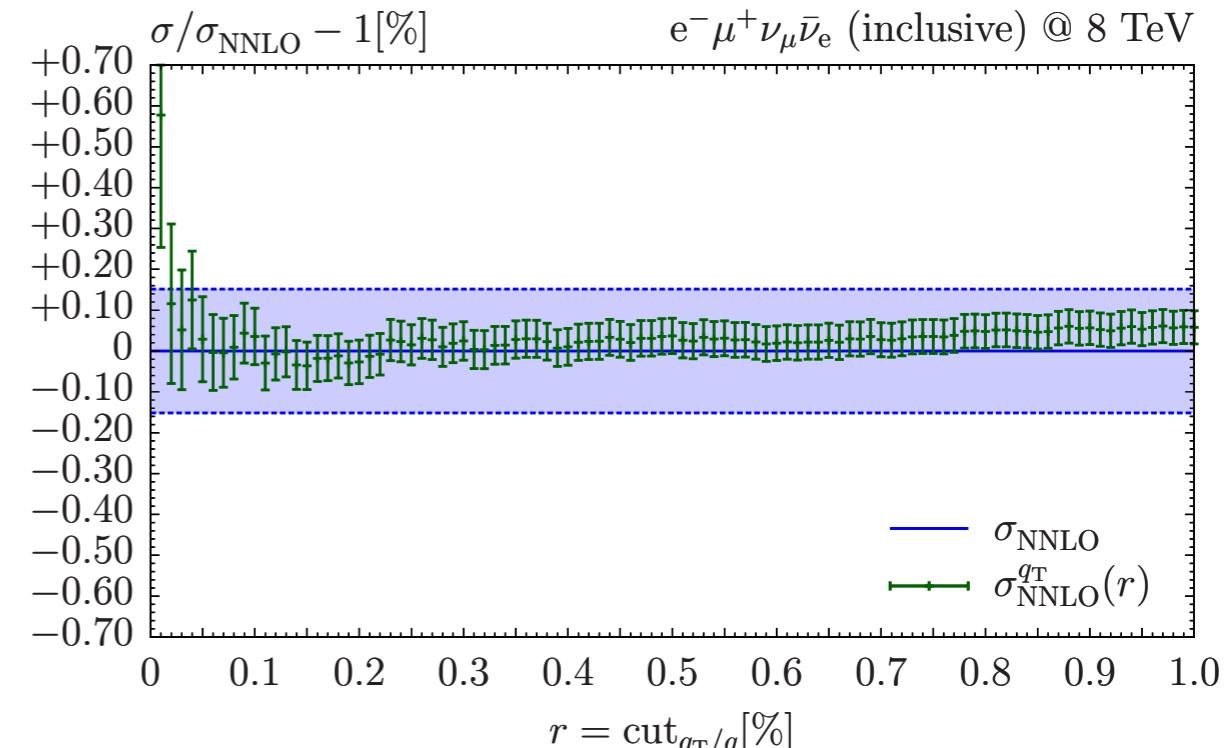
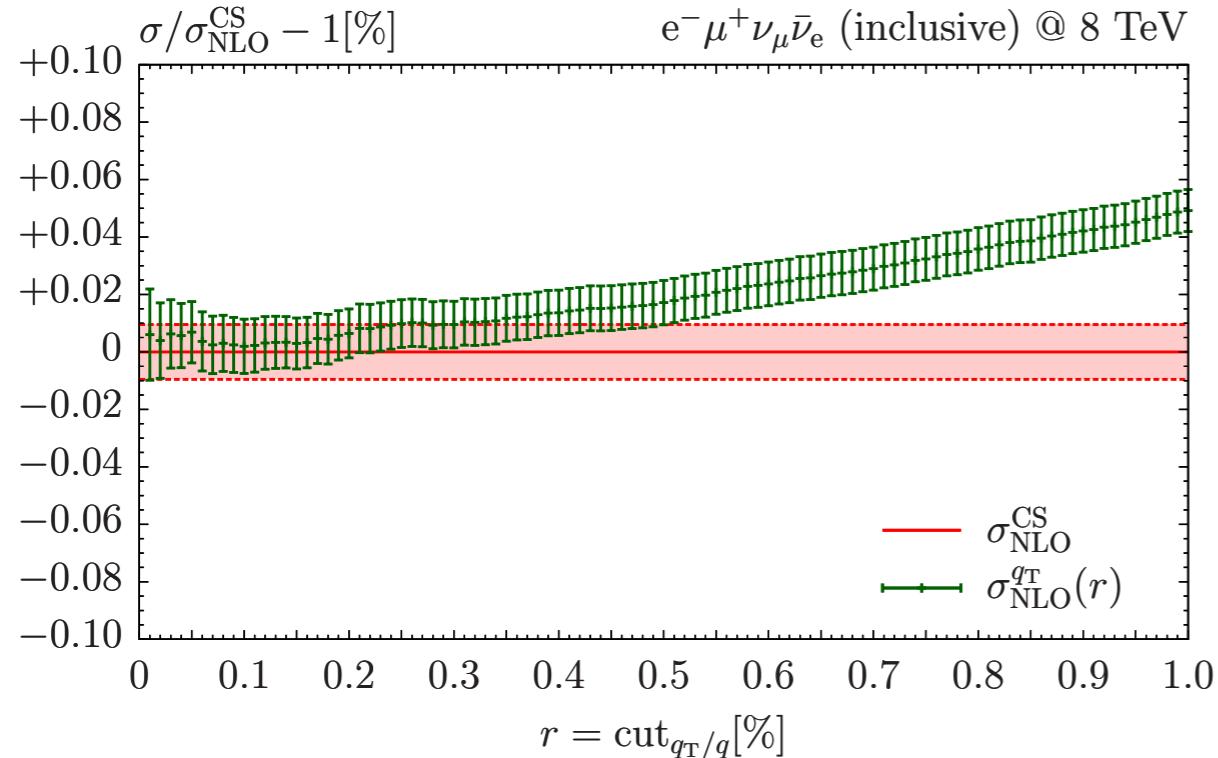
Stefan  
"Neo"  
Kallweit

Marius  
"Trinity"  
Wiesemann

# WW fully differential at NNLO

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

## stability of $r_{\text{cut}}$ dependence



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