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

Marius Wiesemann

University of Zürich

Radcor-Loopfest 2015, UCLA (USA)

June 15-19, 2015

in collaboration with:

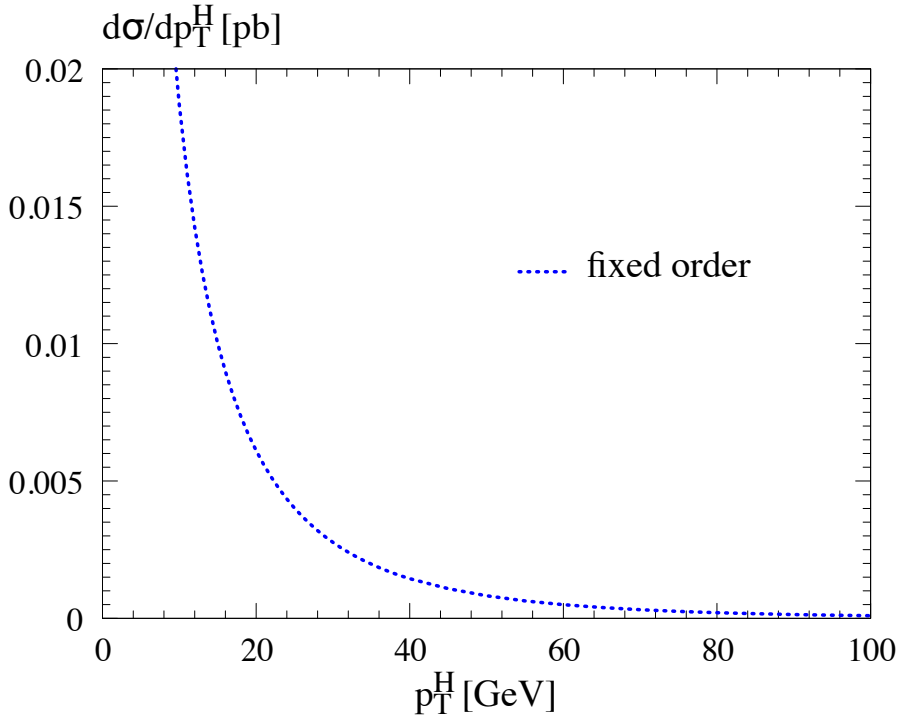
Massimiliano Grazzini, Stefan Kallweit and Dirk Rathlev

Outline

1. (Differential) Transverse momentum resummation
2. Our framework
3. Diboson production at the LHC
4. Resummed p_T spectra for ZZ and WW

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

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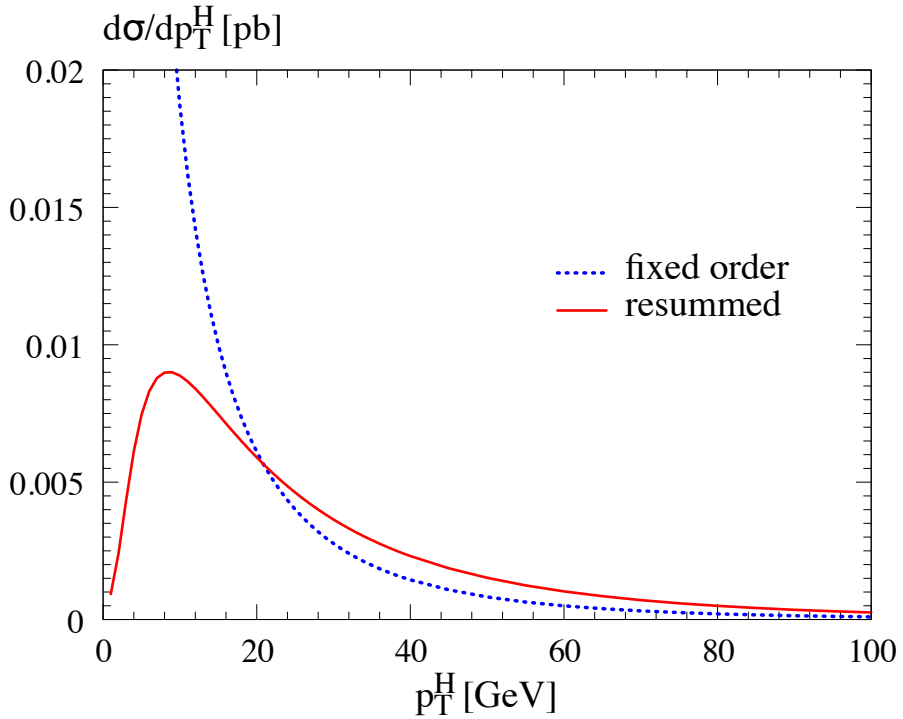

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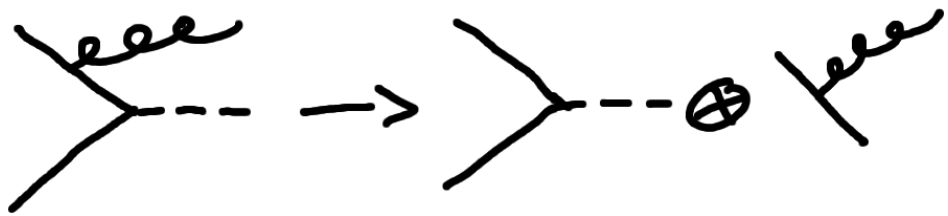
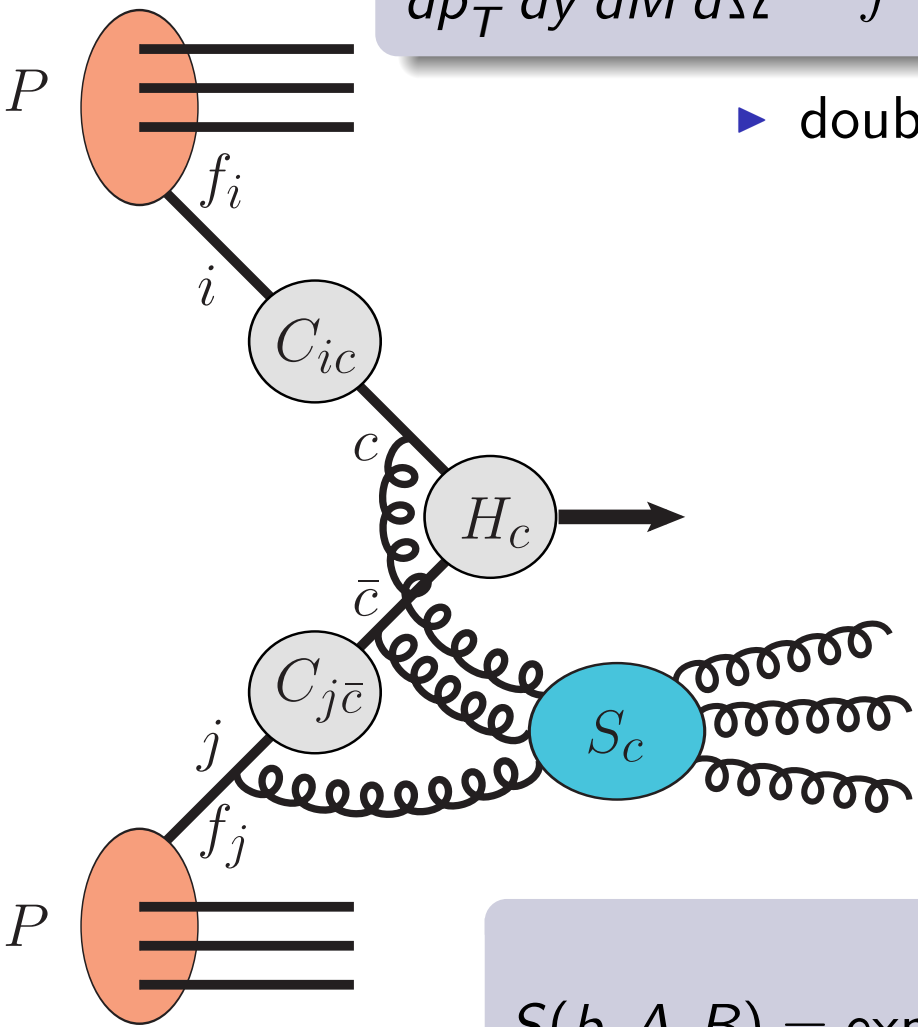
- solution: all order resummation
  - factorization of soft and collinear radiation in matrix elements



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

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



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

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

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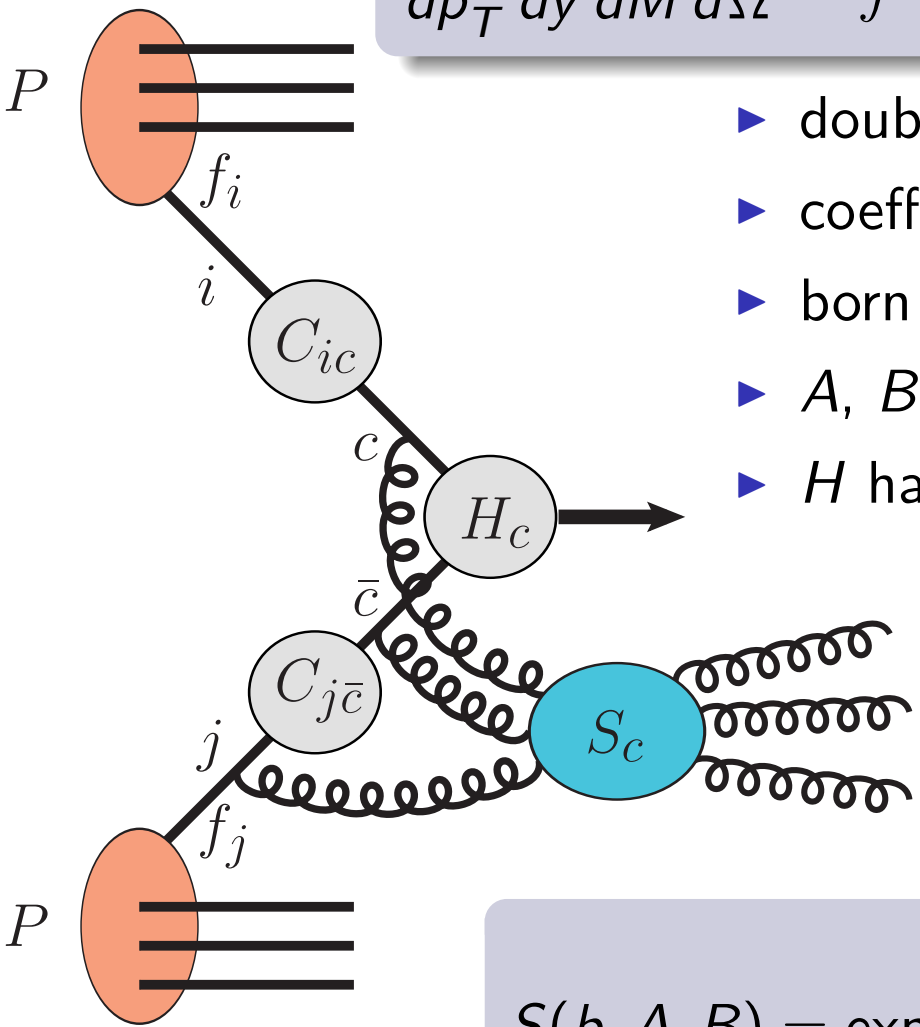

- double Mellin moments: $\mathcal{H}_{N_1,N_2} = H\, C_{N_1}\, C_{N_2}$
- coefficients A, B, C, H perturbative
- born initial state gg or $q\bar{q}$
- A, B, C process independent
- H hard coefficient: - process dependent
  - LO kinematics (M, Ω)

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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: $\alpha_s L \sim \mathcal{O}(1)$

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

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

Transverse momentum 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]

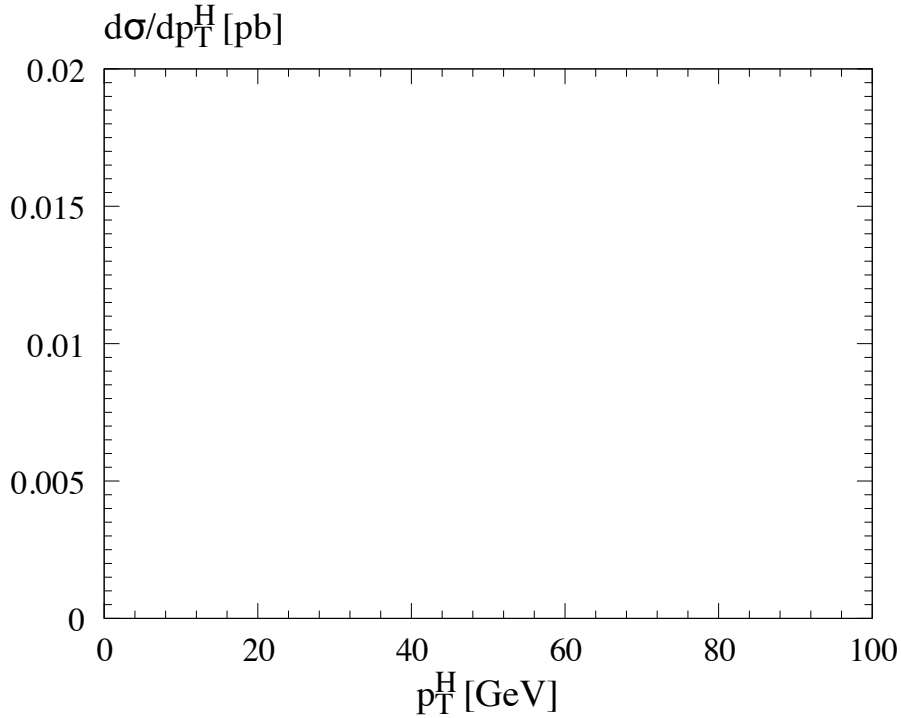
  - H embodies whole process dependence
  - $L = \ln(Q^2\, b^2/b_0^2) \to L' = \ln(Q^2\, b^2/b_0^2 + 1)$

    $\to$ reduction of impact at high p_T (low b)
    $\to$ unitarity constraint
  - rapidity dependence

Matching

- matched (resummed) cross section:

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



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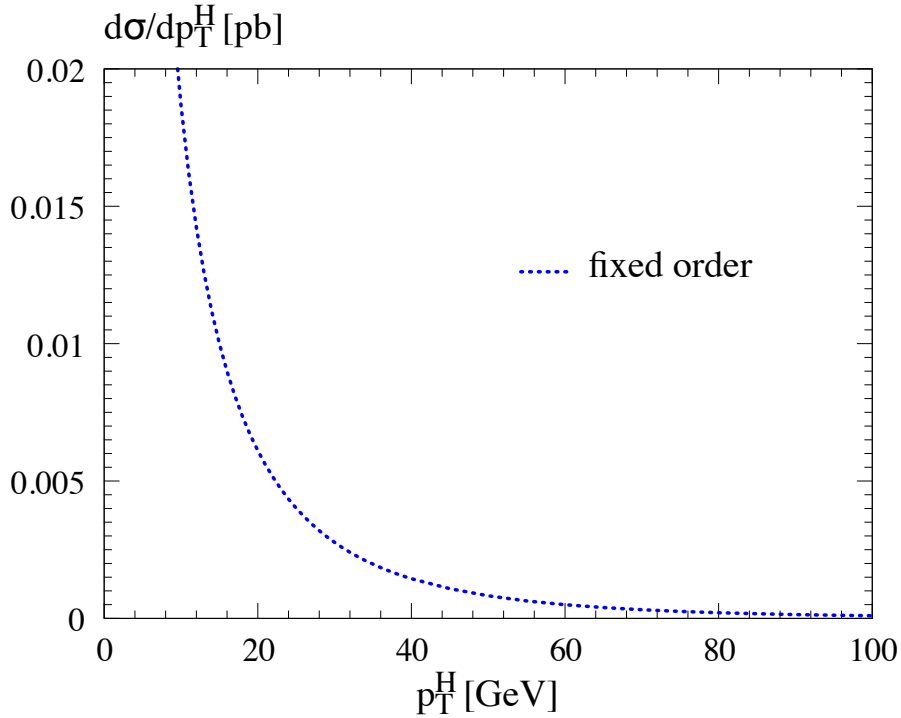

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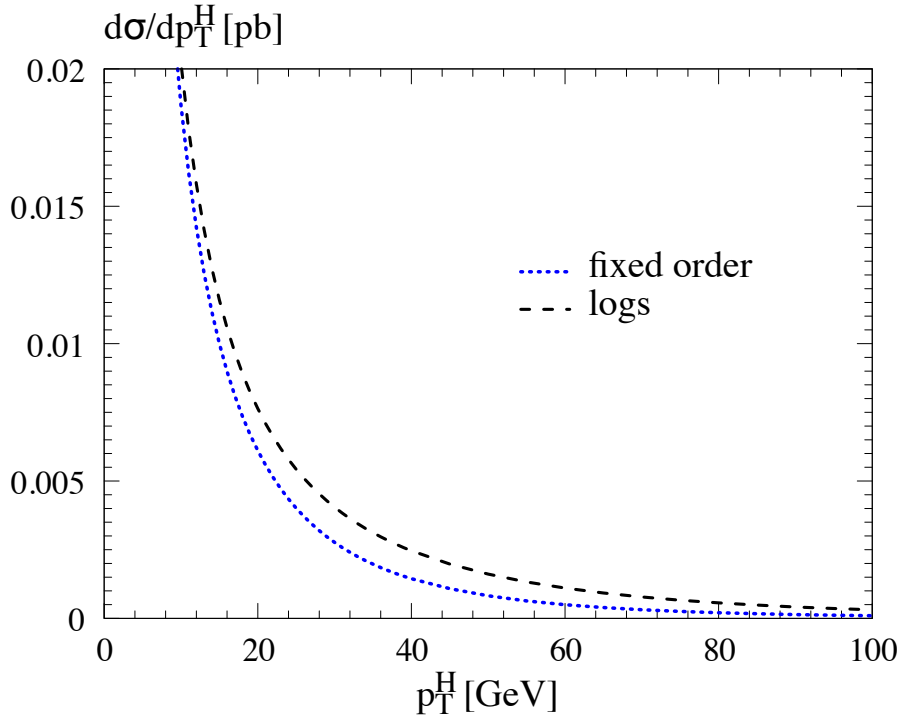

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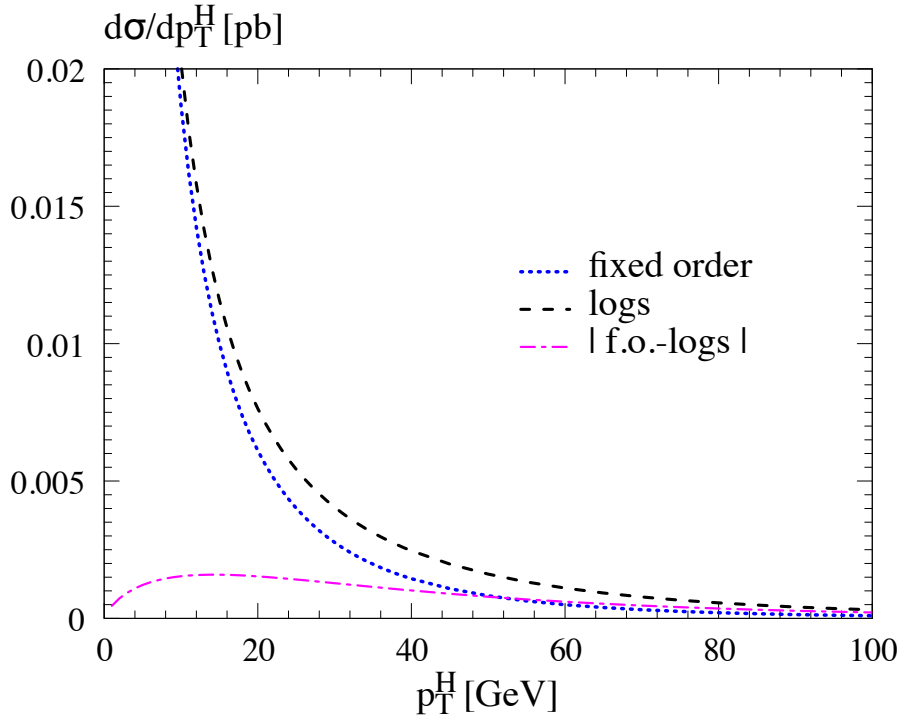

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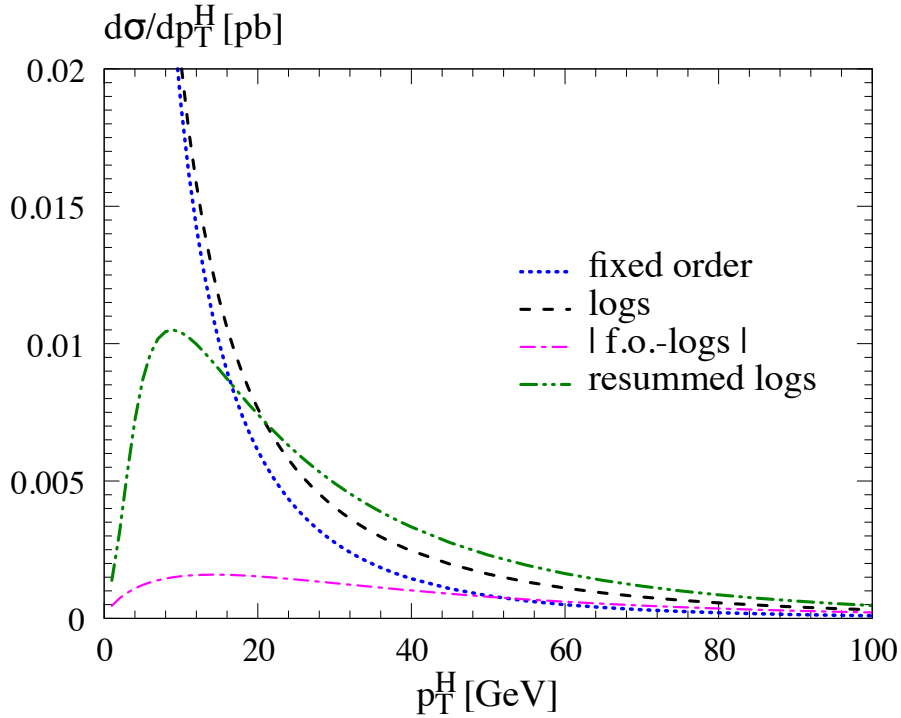

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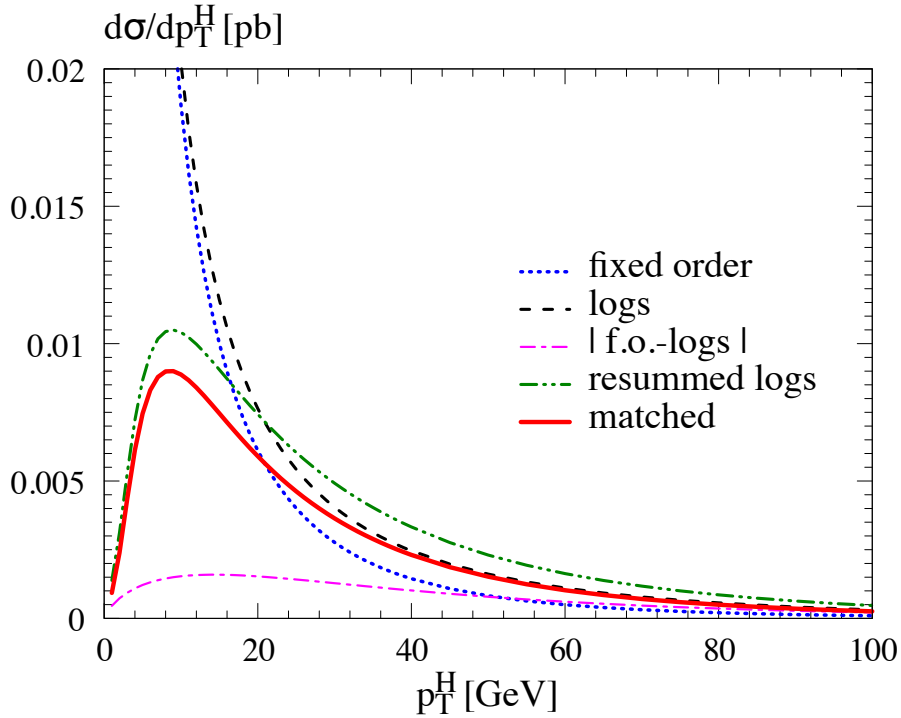
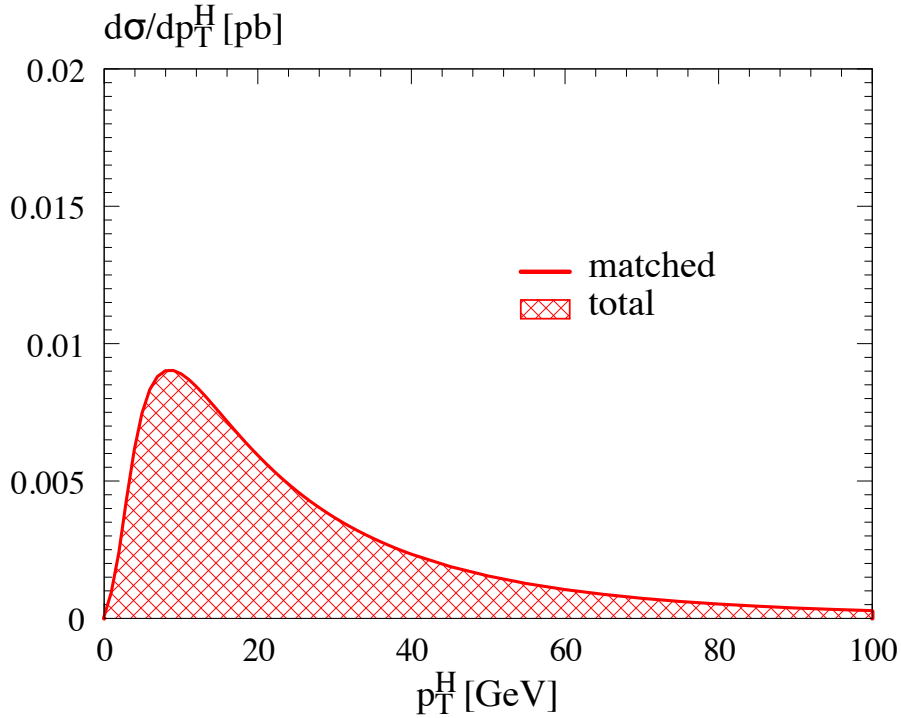


Matching

- unitarity (due to $L \to L'$):

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



Applications

- Higgs production through gluon fusion (heavy-top limit)
  [Bozzi, Catani, de Florian, Grazzini '06]
- Slepton pair production [Bozzi, Fuks, Klasen '06]
- Vector boson pair production: WW and ZZ (NLO+NLL)
  [Grazzini '06], [Grazzini, Frederix '08], [Meade, Ramani, Zeng '14]
- Drell-Yan [Bozzi, Catani, Ferrera, de Florian, Grazzini '10]
- Higgs production through gluon fusion with mass effects
  [Mantler, MW '12], [Grazzini, Sargsyan '13]
- MSSM/2HDM Higgs production [Harlander, Mantler, MW '14]
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- HERE: General automated framework for SM computations
  first application: ZZ and WW production at NNLO+NNLL
  [Grazzini, Kallweit, Rathlev, MW]

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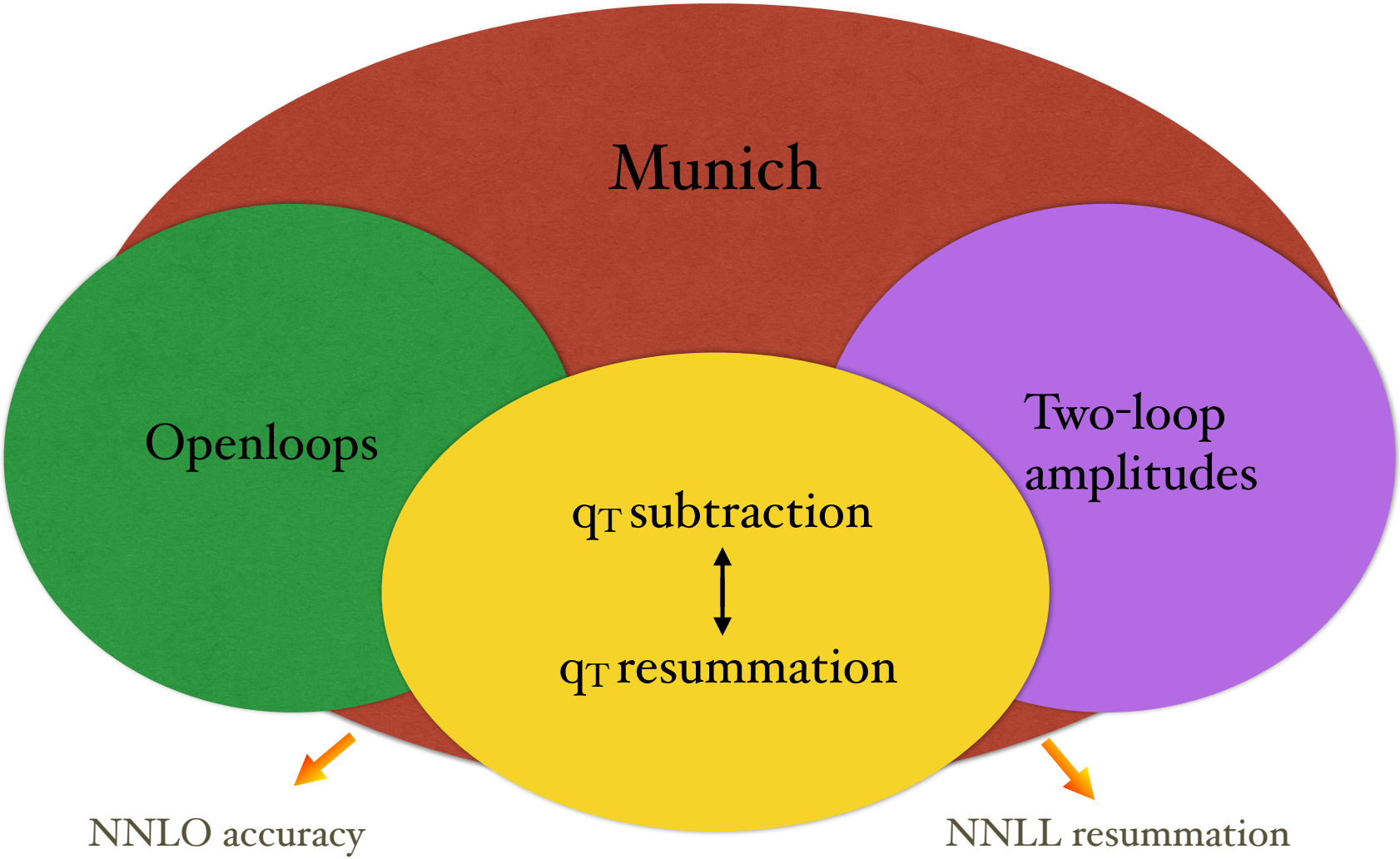

Our framework

Fully differential NNLO(+NNLL) for colorless Born-level processes

NNLO part applies:

- Automated NLO computation
  (`MUNICH` – MUlti-chaNnel Integrator at swiss (CH) precision [Kallweit])
- Automated q_T-subtraction [Catani, Grazzini '07]
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- Automated tree and one-loop amplitudes (`OpenLoops`)
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- Required: Two-loop matrix elements

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NNLL part applies:

- Automated q_T-resummation *(qq and gg-initiated)*
  [Grazzini, Rathlev, MW], [Catani, Cieri, de Florian, Ferrera, Grazzini '14]
- Based on `HRes` implementation *(only gg-initiated)*
  [de Florian, Ferrera, Grazzini, Tommasini '12]

Our framework

NNLO computations in this framework:

- $Z\gamma$ production $\rightarrow$ talk by Stefan Kallweit

  [Grazzini, Kallweit, Rathlev, Torre '13]

- ZZ production $\rightarrow$ talk by Dirk Rathlev

  [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]

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  (including well-known ones: W, Z, $\gamma\gamma$, $gg \rightarrow H$, $b\bar{b} \rightarrow H$)

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— ALL possible with NNLO+NNLL p_T-resummation now —

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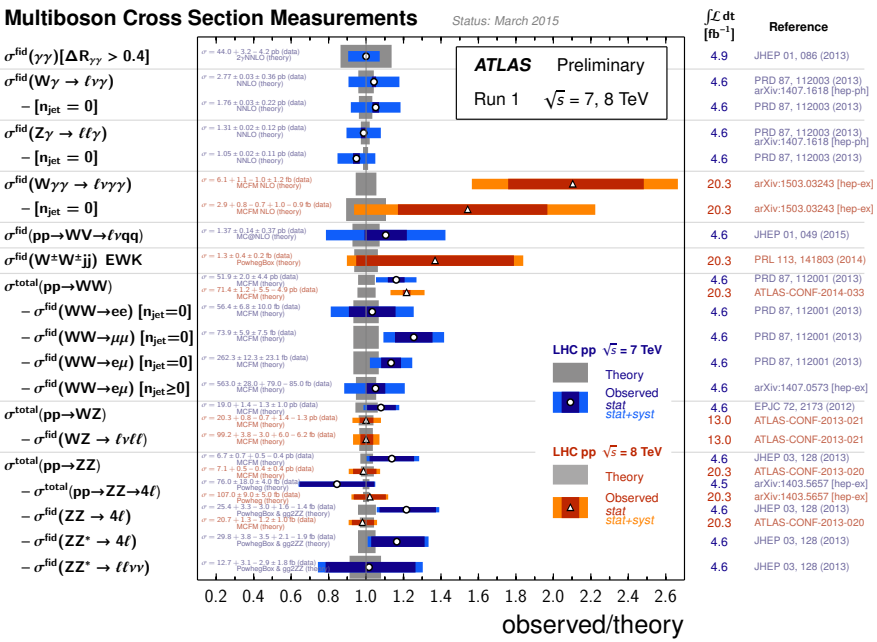
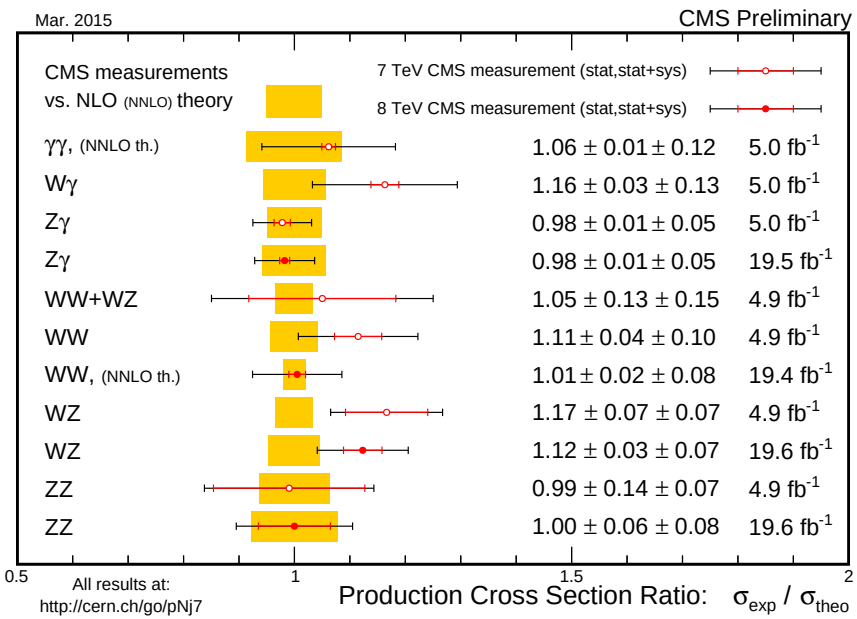
Diboson production at the LHC: rates

- Important LHC physics program
- Discrepancies in rates/distributions $\rightarrow$ direct signs of new physics
- Small deviations $\rightarrow$ direct access to anomalous couplings (EFT)
- Important background to Higgs physics
- Data from both experiments at 7 and 8 TeV:



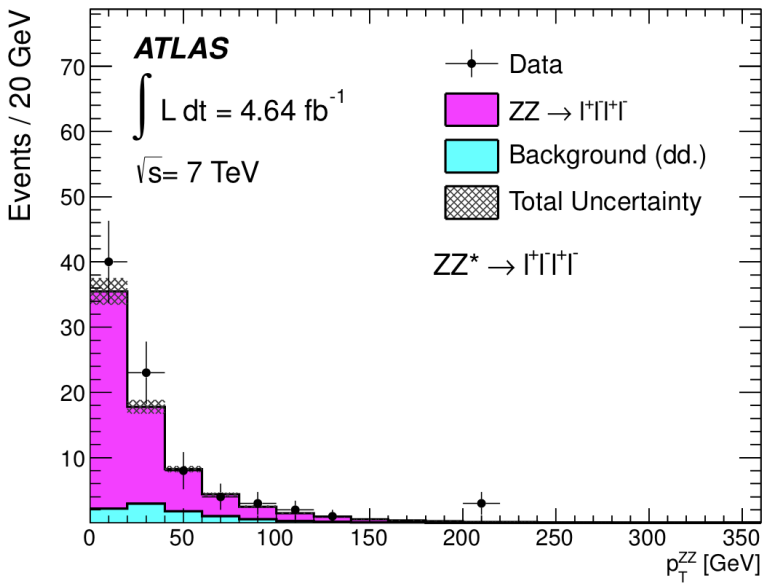
[ATLAS '15]



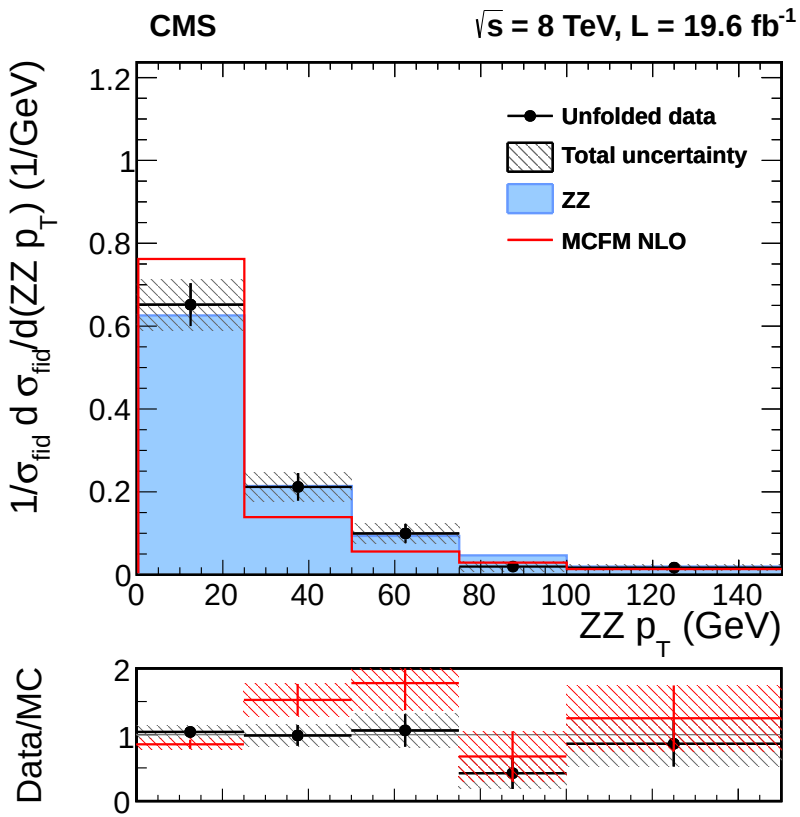
[CMS '15]

Diboson production at the LHC: distributions

- Higgs analyses rely on p_T- and jet-veto background rejection $\rightarrow$ resummation effects important
- Already distributions from 7 TeV (ATLAS) and 8 TeV (CMS)
- Will be continued with improved accuracy at 13 TeV
- Interesting here p_T of ZZ system: [CMS 8 TeV '14]



[ATLAS 7 TeV '12]



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Ingredients of the computation (ZZ and WW)

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- fixed-order p_T distribution from NNLO computations

  [Cascioli, Gehrmann, Grazzini et al. '14], [Gehrmann, Grazzini, Kallweit et al. '14], [Grazzini, Kallweit, Rathlev to be done]

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- resummation coefficients from Drell-Yan

  $A^{(1)}$, $A^{(2)}$, $B^{(1)}$ [Kodaira, Trentadue '82]

  $C^{(1)}$, $B^{(2)}$ [Davies, Stirling '84]

  $A^{(3)}$ [Becher, Neubert '11]

  $C^{(2)}$ $(\mathcal{H}^{(2)})$ [Catani, Cieri, de Florian, Grazzini '12]

- $+$ hard coefficients: $H^{(1)}$ and $H^{(2)}$

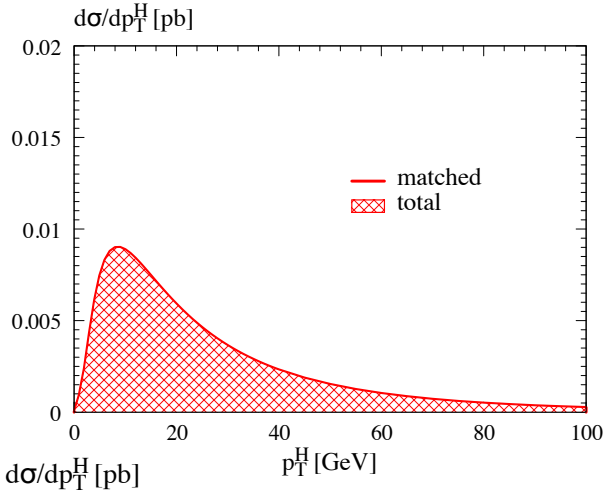
  (one-loop from `OpenLoops` [Cascioli, Maierhöfer, Pozzorini '12];

  two-loop from [Gehrmann, von Manteuffel, Tancredi '15]

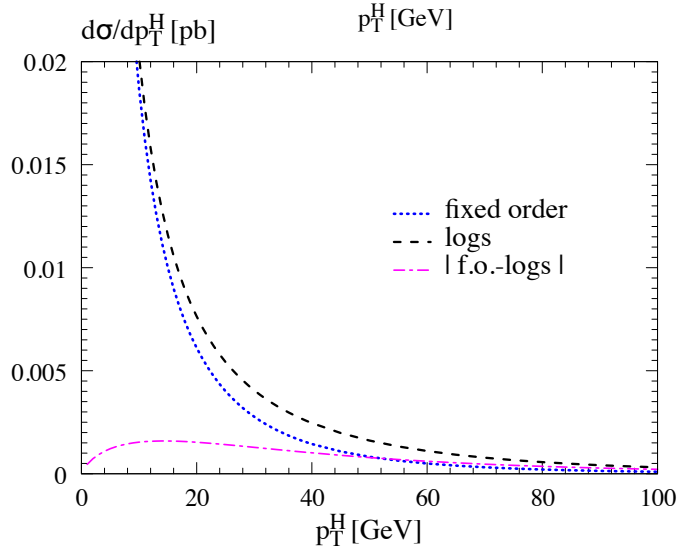
  $\rightarrow$ talk by Lorenzo Tancredi)

Checks

- NNLO p_T fixed-order checked vs. ZZ/WW+jet in `Sherpa`
- ZZ checked against NLO+NLL results [Frederix, Grazzini '08]
- p_T resummation checked with `DYRES` [Catani, de Florian, Ferrera, Grazzini]
- integral of matched cross section = total
  - for various μ_F, μ_R values
  - integral Q_{res}-independent



- fixed order ($p_T \to 0$) = logs ($p_T \to 0$)
  - for various μ_F, μ_R values
  - independent of Q_{res}



Results

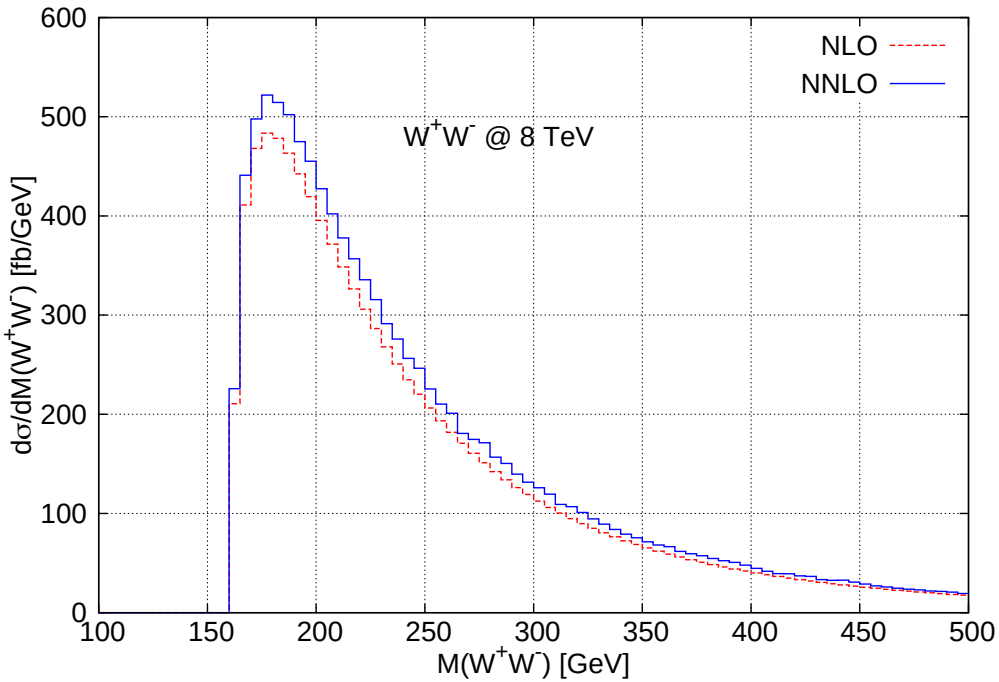
Disclaimer: focus on WW results, ZZ very similar

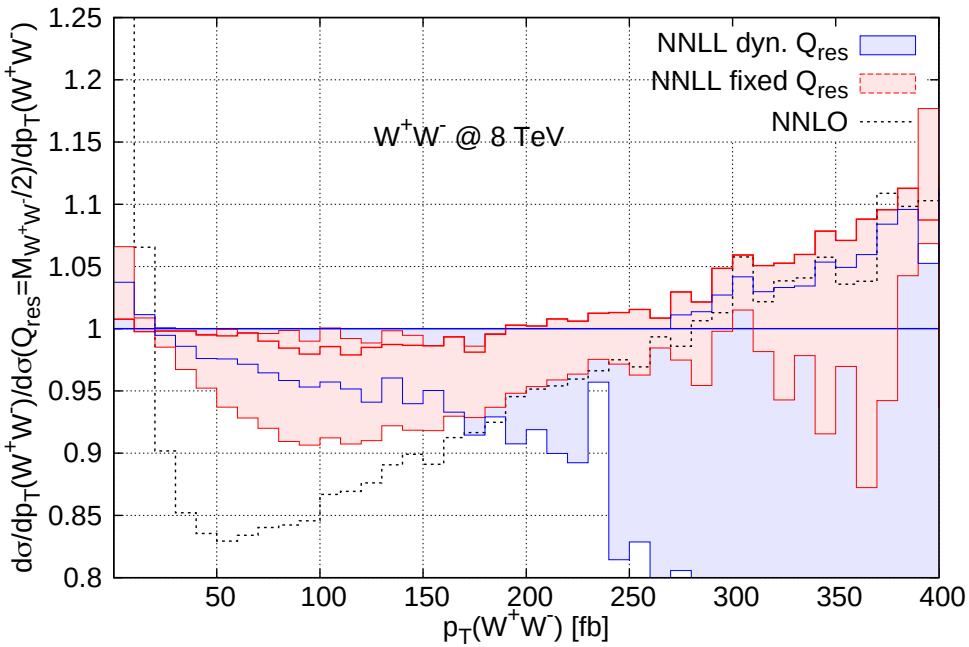
Choosing the resummation scale ($\mu_F = \mu_R = 2\, m_W$):

[Grazzini, Kallweit, Rathlev, MW]

Preliminary

dynamical scale / fixed scale:
$Q = \frac{M_{WW}}{2}$ / $Q = m_W$





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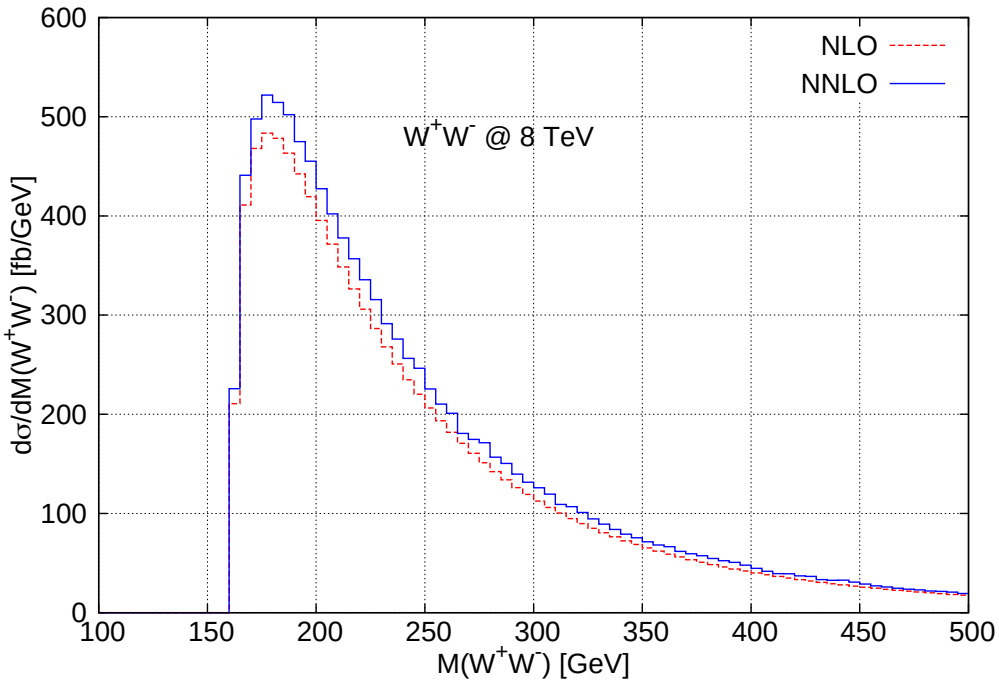
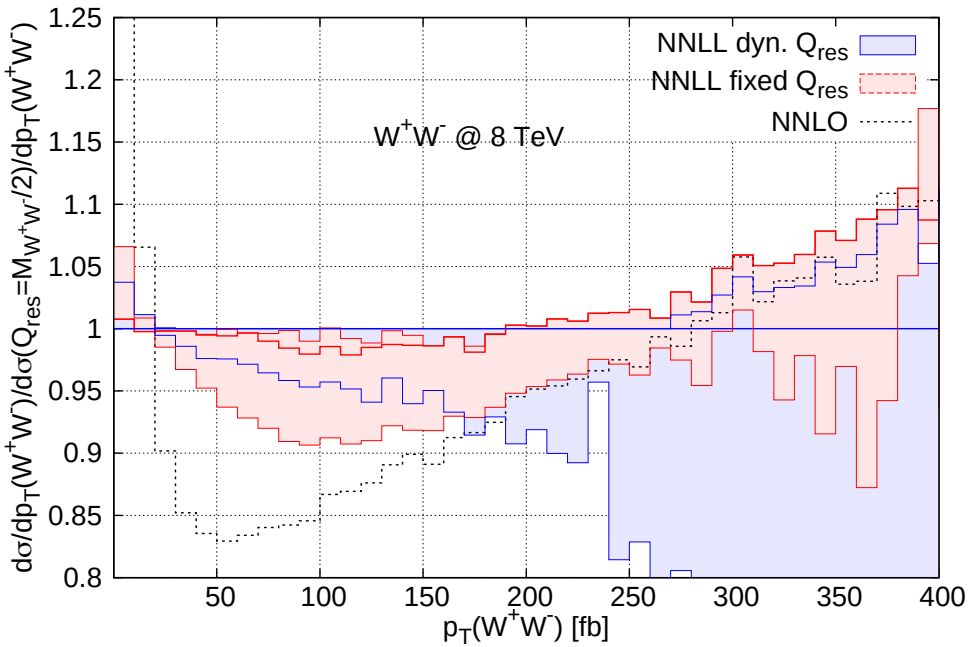
dynamical scale / fixed scale:
$Q = \frac{M_{WW}}{2}$ / $Q = m_W$





→ We apply a fixed resummation scale of $Q = m_W$

Results

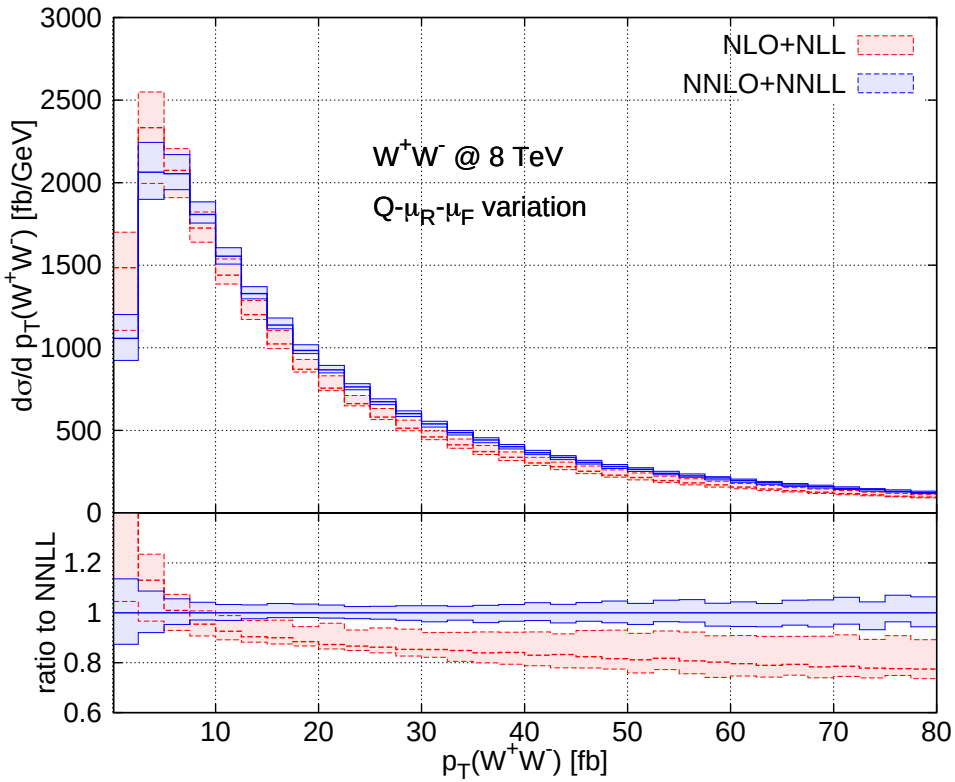
Scale uncertainties $Q+\mu_R+\mu_F$ (left: WW; right: ZZ) :

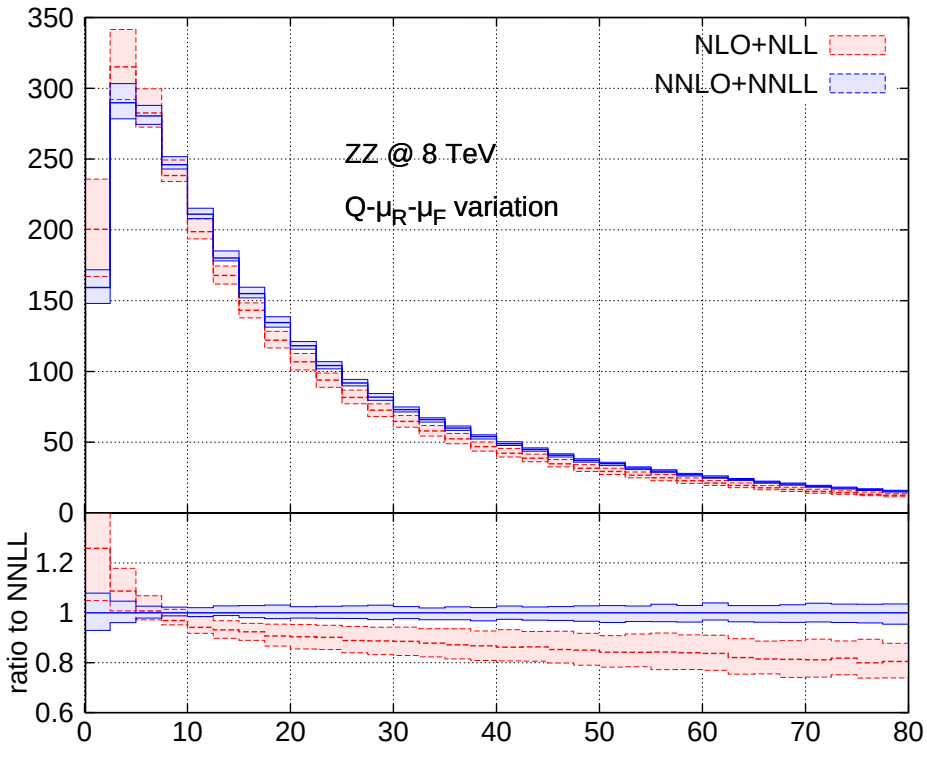
[Grazzini, Kallweit, Rathlev, MW]

$0.5 \leq \mu_F/\mu_R \leq 2$

$0.5 \leq Q/\mu_R \leq 2$

Preliminary



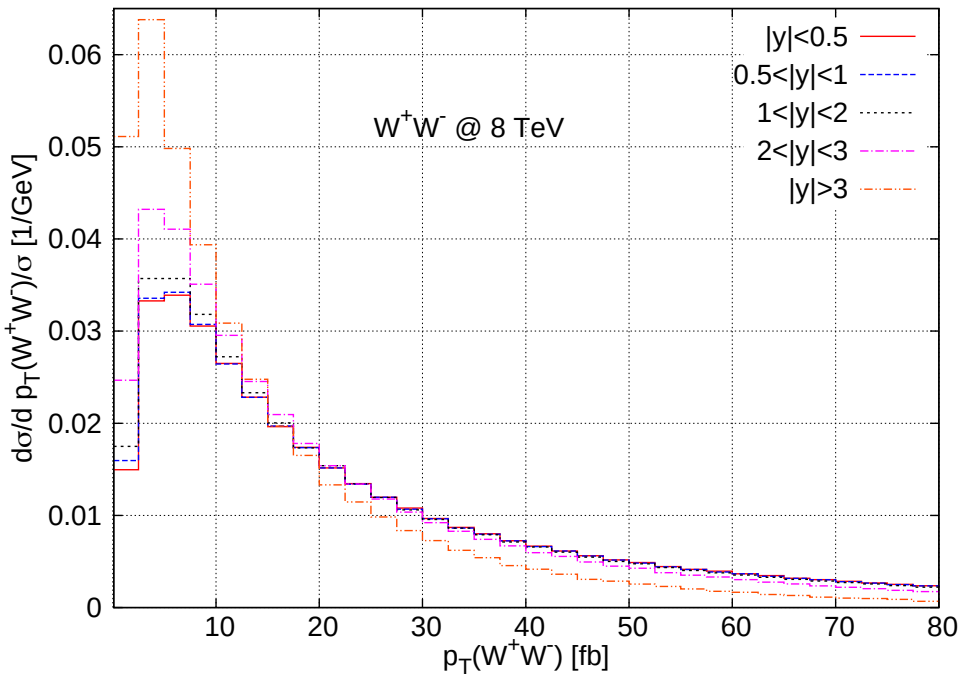


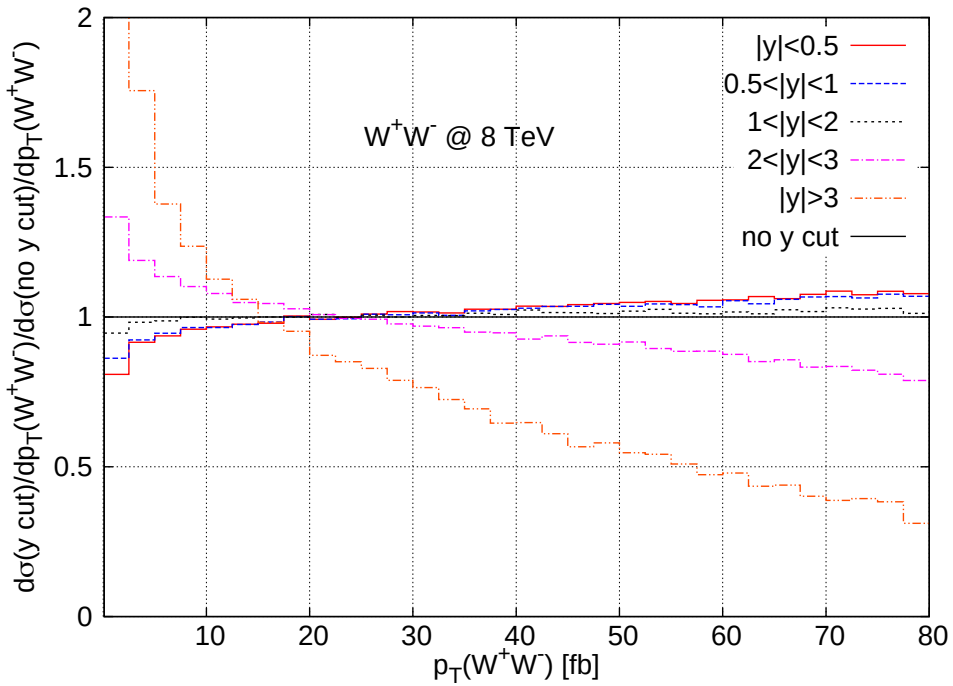
Results

Rapidity dependence of NNLO+NNLL spectrum:

[Grazzini, Kallweit, Rathlev, MW]

Preliminary





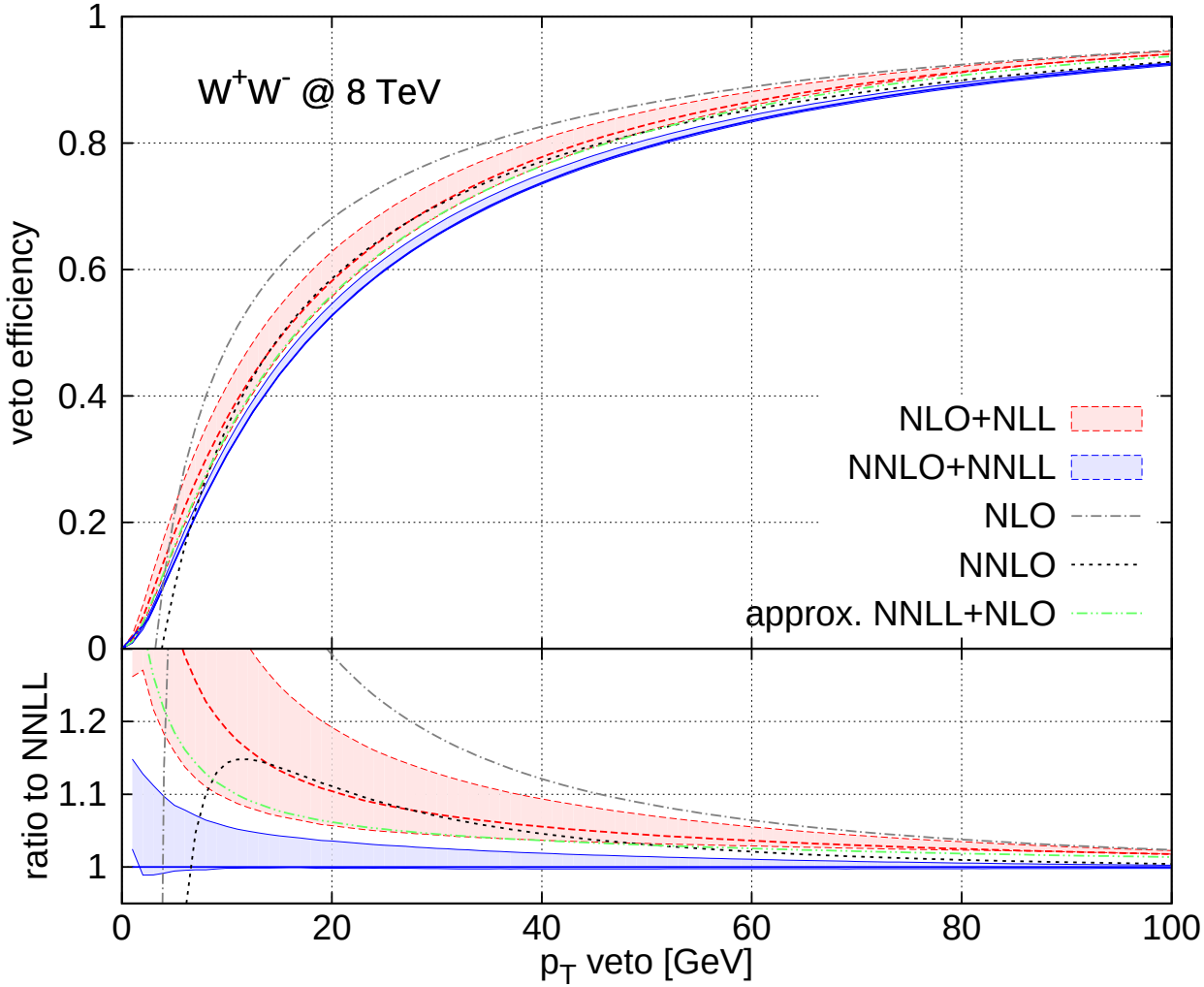
Results

approx. NNLL+NLO $\equiv$ NLL+NLO $+g^{(3)}$

p_T-veto cross section:

[Grazzini, Kallweit, Rathlev, MW]

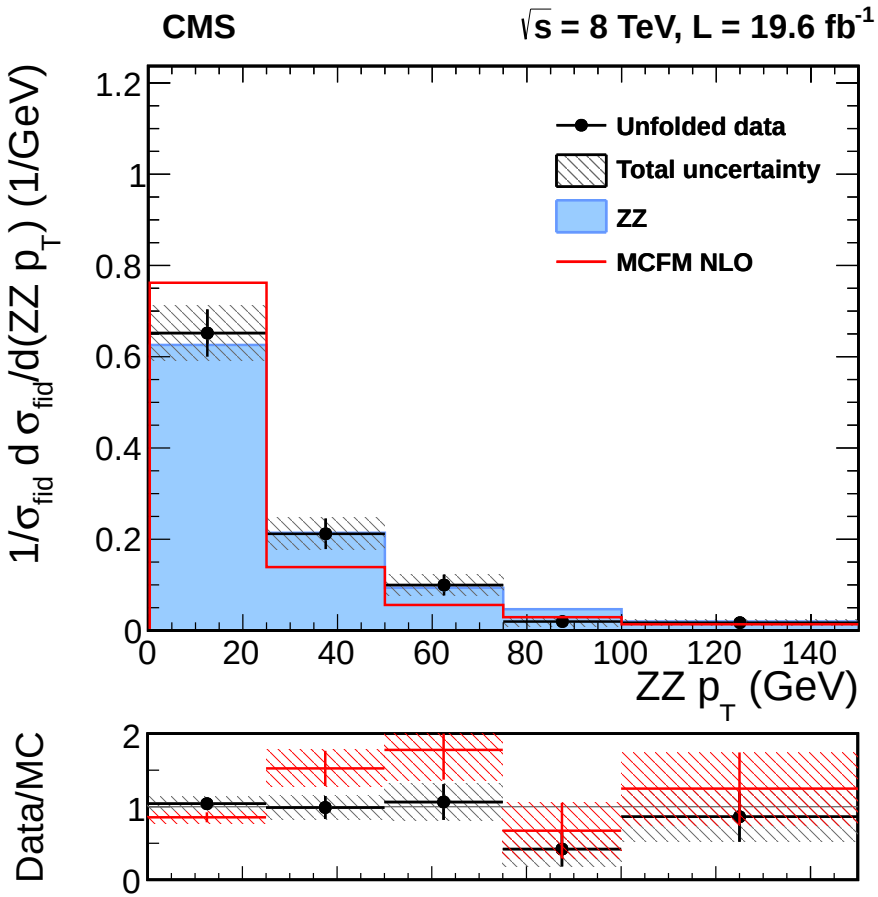
Preliminary



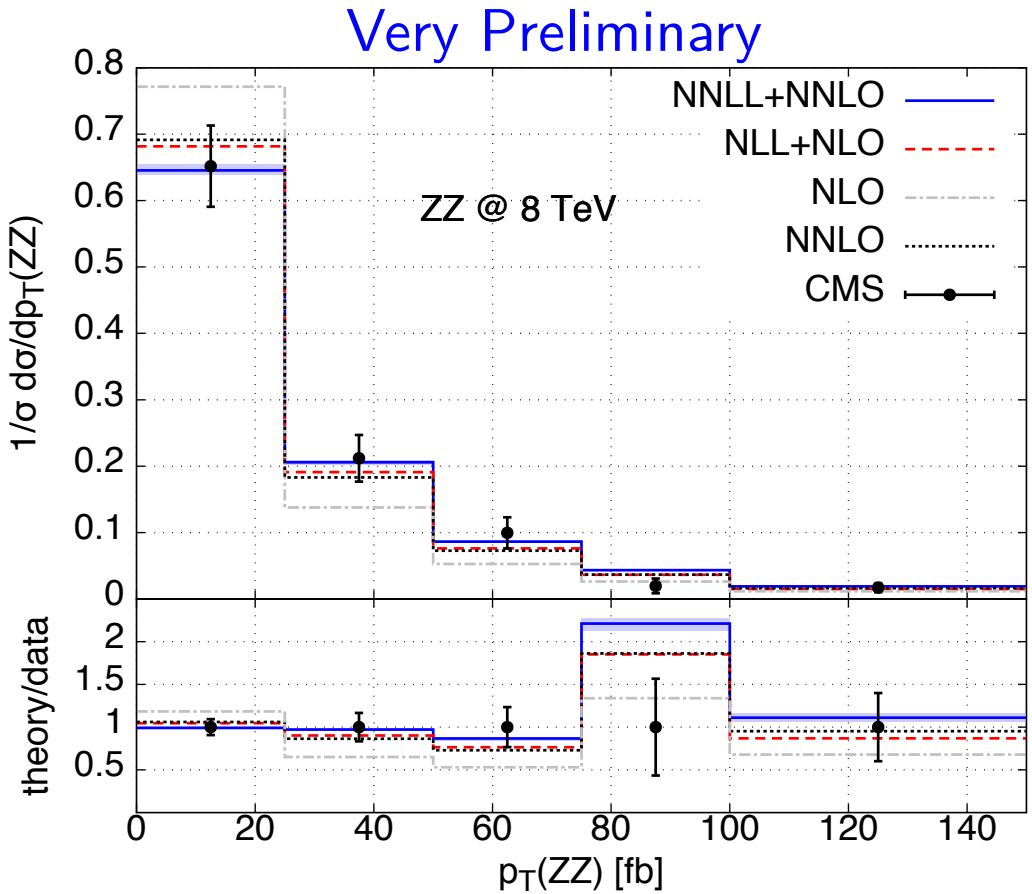
Results

Comparison with data:

[CMS '15]



[Grazzini, Kallweit, Rathlev, MW]



Conclusions and Outlook

Conclusions:

- Automated tool (except two loop virtuals) for resummed p_T spectra (NNLO+NNLL) of colorless final states
- First application: ZZ and WW production
- Fixed scale ($Q = m_V$) suitable for these processes
- Nice reduction of theoretical uncertainties at NNLO+NNLL
- Softer p_T spectra for larger rapidities
- p_T veto: logarithmic and perturbative higher orders important

Outlook:

- Full Z/W decays (off-shell effects; spin correlations)
  $\rightarrow$ p_T spectra in fiducial region
- Fully automated (except virtuals) user-friendly public program for both: NNLO and NNLO+NNLL codes
- Physics studies of more processes
- Colorful subtraction/resummation (method in development)

BackUp

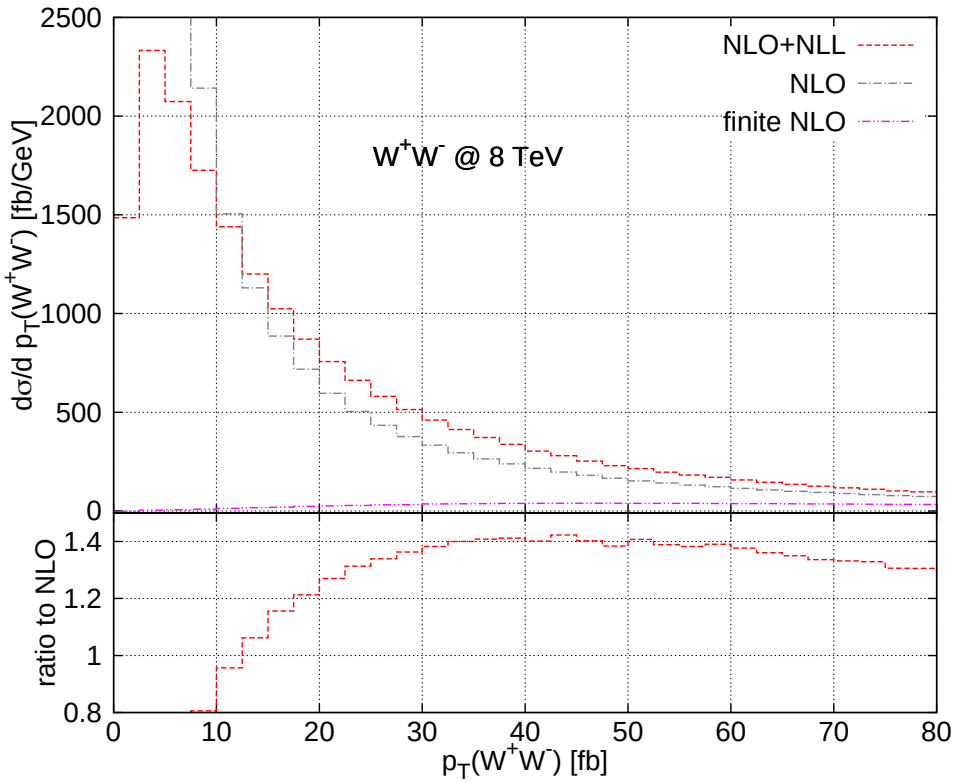
Results

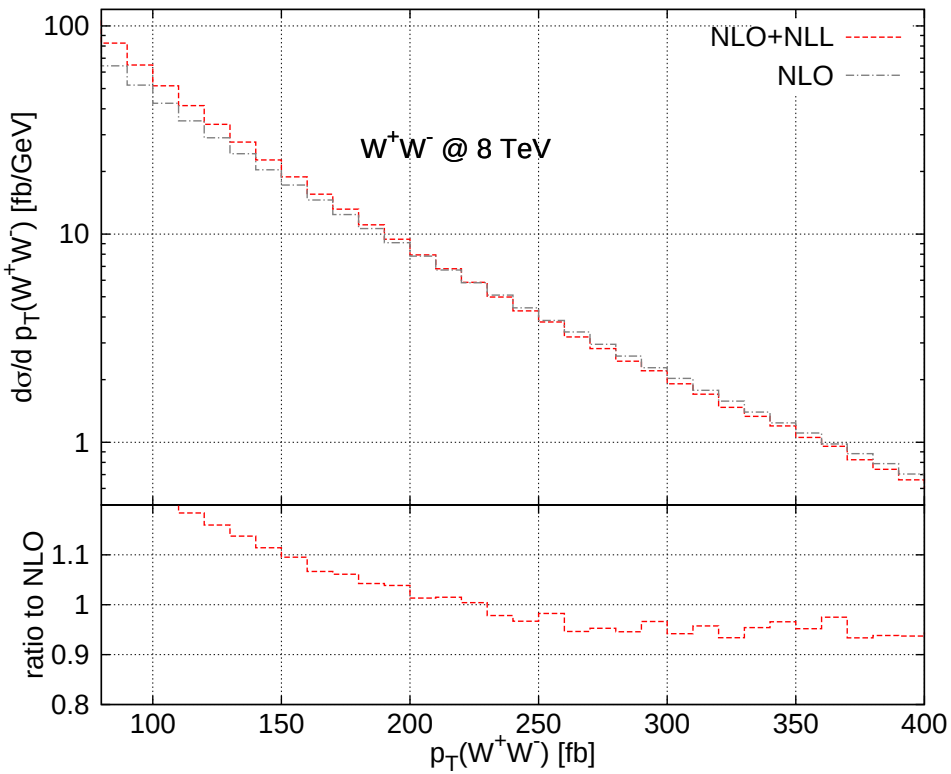
p_T distribution at NLO+NLL:

[Grazzini, Kallweit, Rathlev, MW]

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{NLO+NLL}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{NLO}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{NLO}} + \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{NLL}}$$

Preliminary





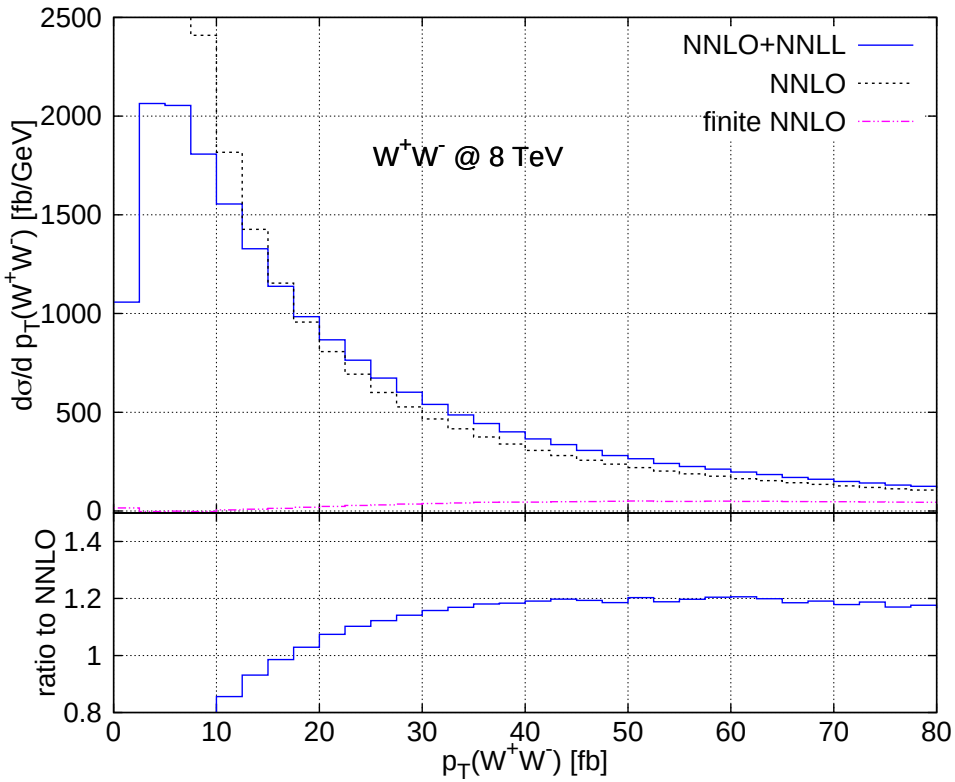
Results

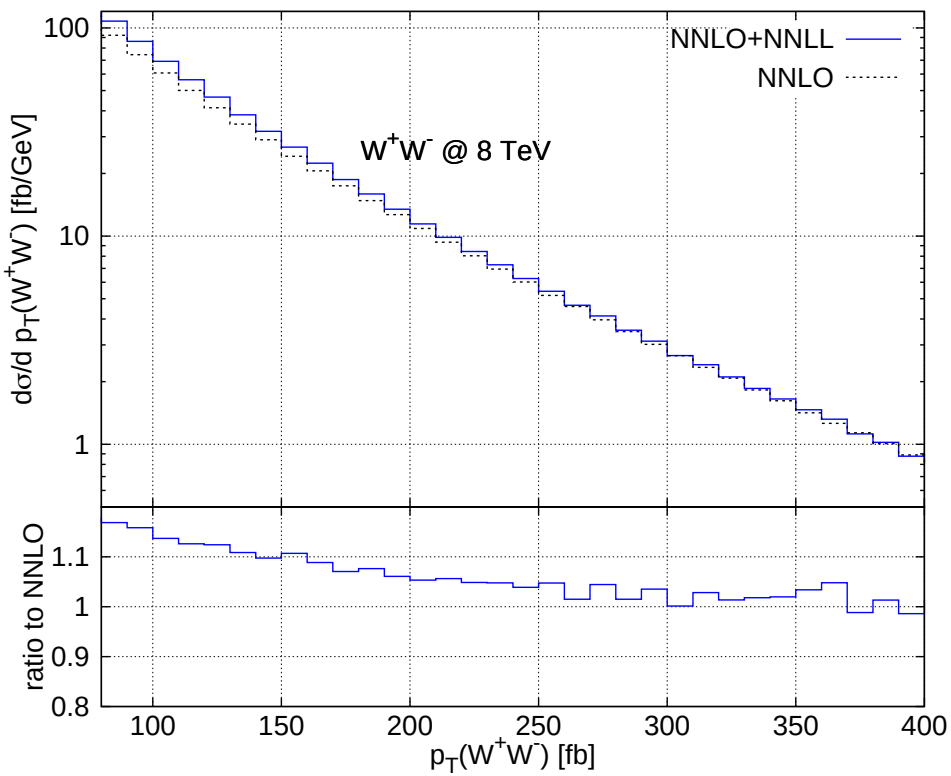
p_T distribution at NNLO+NNLL:

[Grazzini, Kallweit, Rathlev, MW]

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{NNLO+NNLL}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{NNLO}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{NNLO}} + \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{NNLL}}$$

Preliminary





Results

Scale uncertainties (left: Q; right: $\mu_R+\mu_F$) :

[Grazzini, Kallweit, Rathlev, MW]

Preliminary

$0.5 \leq \mu_F/\mu_R \leq 2$