NNLO Drell Yan with Parton Shower

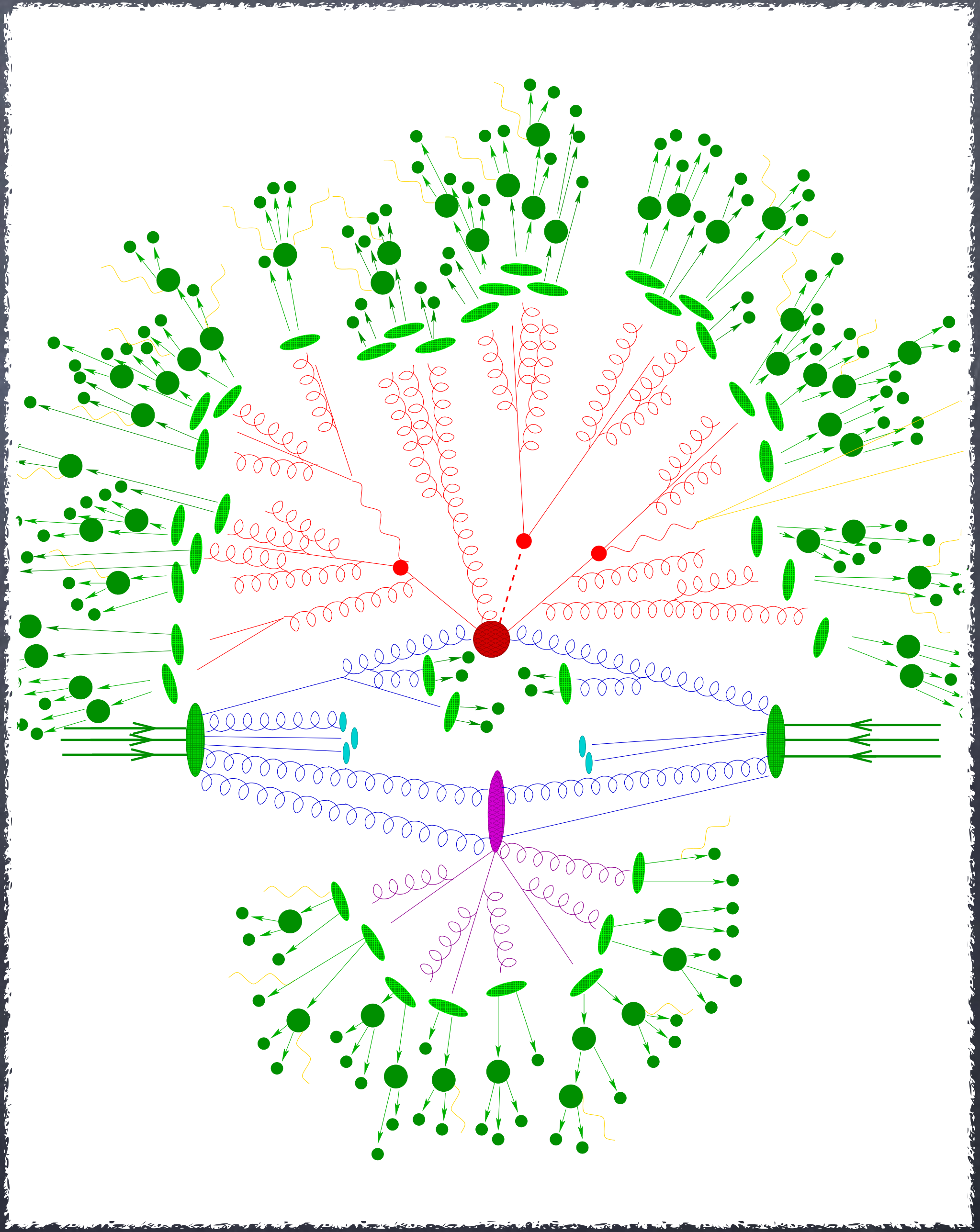
Ye Li
SLAC National Accelerator Laboratory

in collaboration
with **Stefan Hoeche**
and **Stefan Prestel**

June 30, 2014

Outline

- DY W/Z Production at NNLO
- Parton Shower Matching and Merging
- Application to DY Process



DY Process

- Drell Yan process is very important at hadron collider
  - Detector Calibration
  - Luminosity Monitor
  - PDF Determination
  - New Physics Search
  - QCD and EW Study

- NLO is only qualitative, need NNLO for high precision and reduced theoretical uncertainty

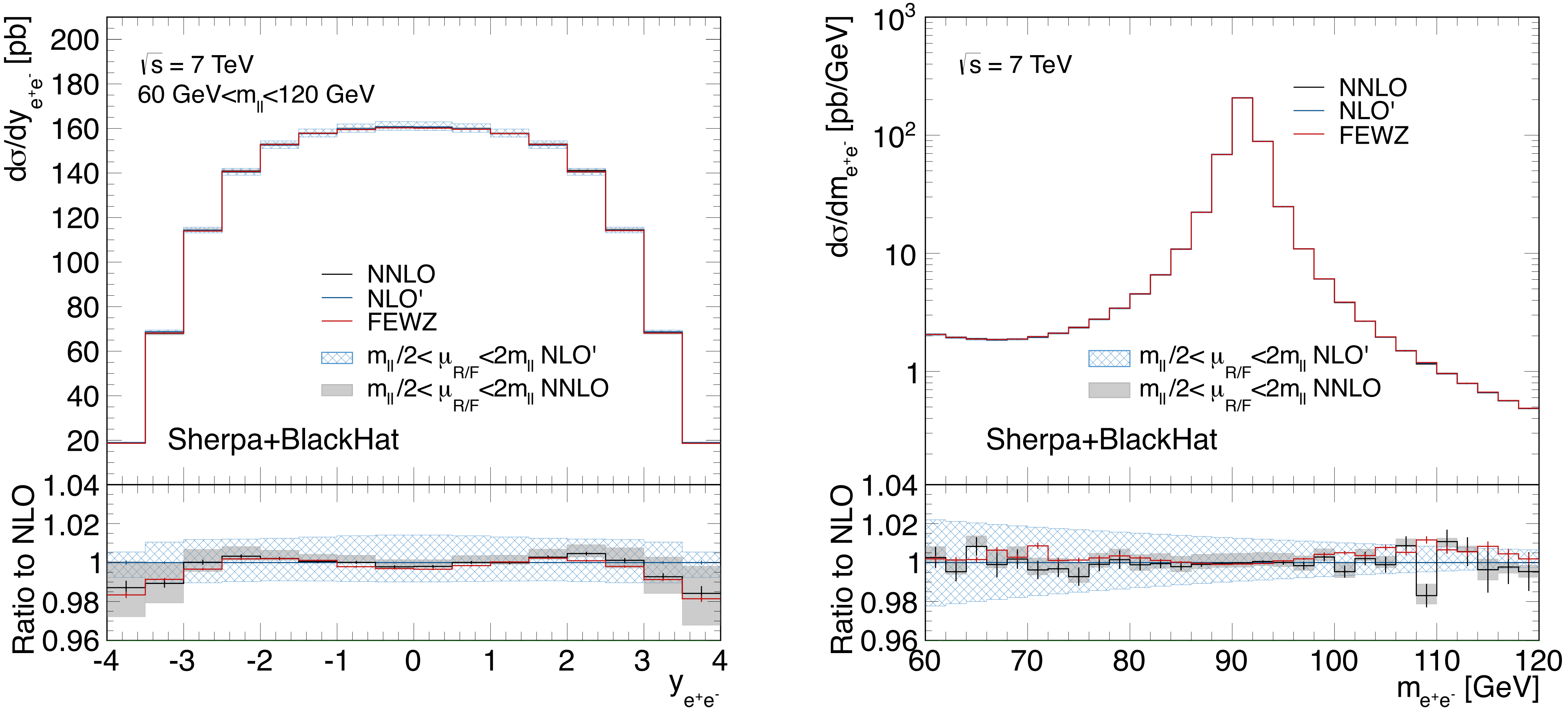
- Available fully differential code at NNLO
  - FEWZ, DYNNLO
  - Fixed order only, i.e. no automatic resummation from parton shower

Implementation of NNLO in Sherpa

- Use qT subtraction method by Catani and Grazzini
  - easy to do
    - Sherpa already has W/Z+1jet at NLO from Blackhat - very stable
    - low qT behavior obtained from existing SCET results - well established
  - generically compatible with PS matching
    - qt cutoff roughly corresponds to parton shower cutoff scale
- Implementation in Sherpa: event generation, interface with Rivet

Catani, Grazzini hep-ph/0703012
Catani et al. arXiv:0903.2120

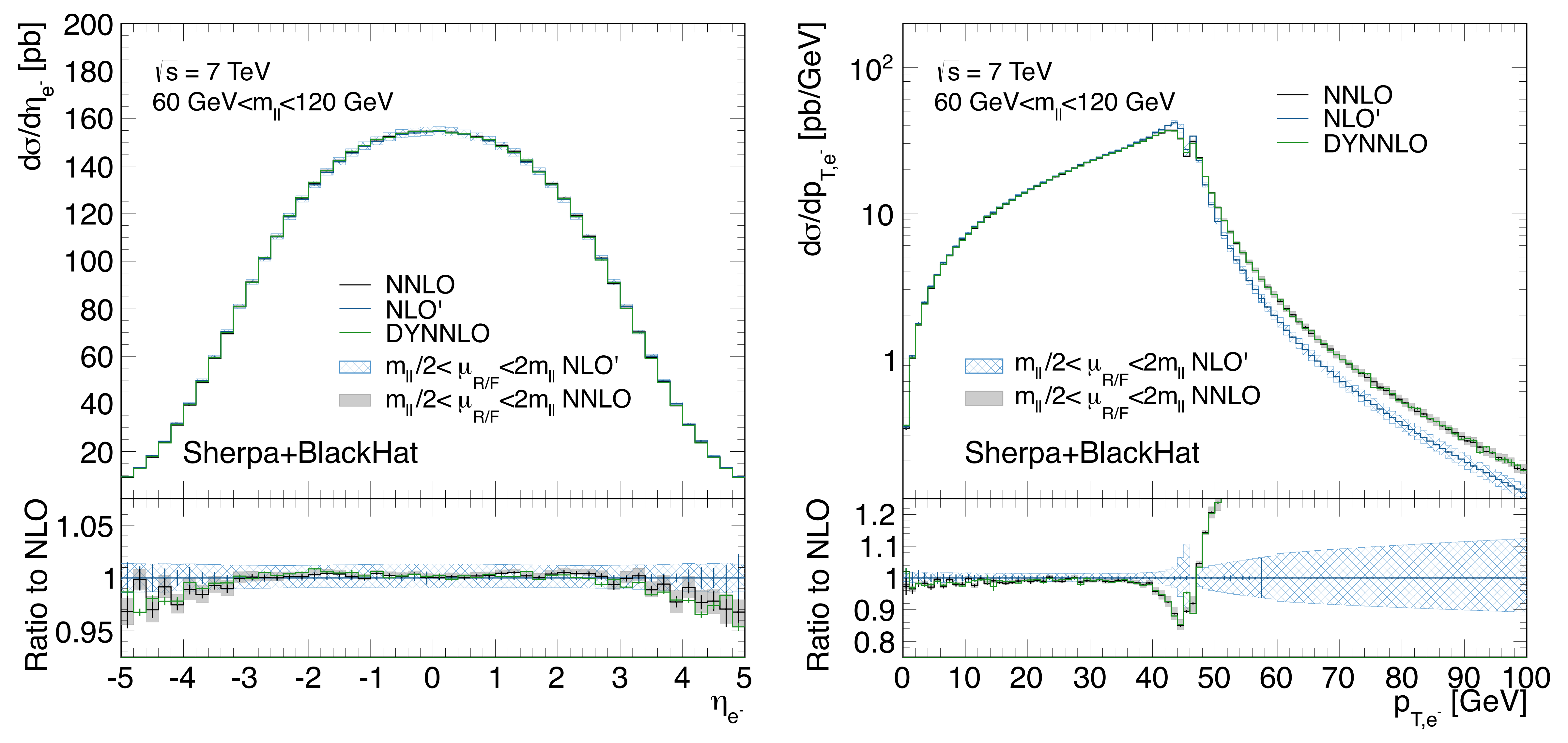
Validation with FEWZ and VRAP



E_{cms}	7 TeV	14 TeV	33 TeV	100 TeV
VRAP	$973.99(9)^{+4.70}_{-1.84}$ pb	$2079.0(3)\ ^{+14.7}_{-6.9}$ pb	$4909.7(8)\ ^{+45.1}_{-27.2}$ pb	$13346(3)\ ^{+129}_{-111}$ pb
SHERPA	$973.7(3)\ ^{+4.78}_{-2.21}$ pb	$2078.2(10)^{+15.0}_{-8.0}$ pb	$4905.9(28)^{+45.1}_{-27.9}$ pb	$13340(14)^{+152}_{-110}$ pb

Hoeche, Prestel, YL arXiv:1405.3607

Validation with DYNNLO



Hoeche, Prestel, YL arXiv:1405.3607

Merging

- Merging
  - combining ME of processes with different jet multiplicities
  - higher order virtual matrix elements are approximated by expansion of Sudakov factor
  - real radiation is resummed by parton shower in soft/collinear region
  - unitarity of the inclusive cross section of lower jet multiplicity is broken
- Example for LO merging: MLM, CKKW
- Extension to NLO merging: MEPS@NLO, UNLOPS, MiNLO

Matching

- Combining fixed order NLO calculation with parton shower
- Most widely used approaches: MC@NLO, POWHEG
  - modified subtraction methods, which remove the first order expansion of the PS from the NLO, and add the shower on top, therefore restoring the NLO real emission pattern
- Here we will use UNLOPS approach: essentially unitarized merging of processes with n and n+1 jet multiplicities
  - respect unitarity of inclusive result for n jet process: real matrix element is used for the first emission in the parton shower
  - inclusion of 1-loop virtual correction to the n jet process

Loennblad,Prestel arXiv:1211.7278
Hoeche, Prestel, YL arXiv:1405.3607

Unitary ME+PS Merging

- For any infrared observable "O" under parton shower:
  - "B" is the tree level matrix element
  - "F" is generating function of parton shower
  - "Π" is the Sudakov factor, corresponding to probability of no emission; "K" is the splitting kernel used in parton shower

$$
\begin{aligned}
\langle\mathcal{O}\rangle &= \int d\Phi_0 \mathrm{B}_0 \mathcal{F}_0(\mu_Q^2, \mathcal{O}) \\
&= \int d\Phi_0 \mathrm{B}_0 \Pi_0(t_c, \mu_Q^2)\mathcal{O}(\Phi_0) + \int_{t_c} d\Phi_1 \mathrm{B}_0 \mathrm{K}_0 \Pi_0(t, \mu_Q^2)\mathcal{F}_1(t, \mathcal{O}) \\
&= \int d\Phi_0 \mathrm{B}_0 \mathcal{O}(\Phi_0) - \int_{t_c} d\Phi_1 \mathrm{B}_0 \mathrm{K}_0 \Pi_0(t, \mu_Q^2)\mathcal{O}(\Phi_0) \\
&\qquad + \int_{t_c} d\Phi_1 \mathrm{B}_0 \mathrm{K}_0 \Pi_0(t, \mu_Q^2)\mathcal{F}_1(t, \mathcal{O})
\end{aligned}
$$

Unitary ME+PS Merging

- To implement NLO matching
  - use actual matrix element for the first emission $\mathrm{B}_0\mathrm{K}_0 \to w_1\mathrm{B}_1$
    - "w" adjusts the renormalization and factorization scale of the real radiation matrix element to match parton shower

$$w_1 = \frac{\alpha_S(t)}{\alpha_S(\mu_R^2)}\frac{f_a(x_a,t)}{f_a(x_a,\mu_F^2)}\frac{f_b(x_b,t)}{f_b(x_b,\mu_F^2)}$$

  - add virtual correction to the zero bin by using jet-vetoed NLO cross section

$$\mathrm{B}_0 \to \bar{\mathrm{B}}_0^{\mathrm{t_c}} = \bar{\mathrm{B}}_0 - \int_{\mathrm{t_c}} \mathrm{d}\Phi_1\mathrm{B}_1$$

Unitary ME+PS Merging

$$
\begin{aligned}
\langle O \rangle = & \Big\{ \int \mathrm{d}\Phi_0 \, \bar{\mathrm{B}}_0^{t_c} + \int_{t_c} \mathrm{d}\Phi_1 \Big[1 - \Pi_0(t_1, \mu_Q^2) \, w_1 \Big] \mathrm{B}_1 \Big\} \, O(\Phi_0) \\
& + \int_{t_c} \mathrm{d}\Phi_1 \, \Pi_0(t_1, \mu_Q^2) \, w_1 \, \mathrm{B}_1 \, \mathcal{F}_1(t_1, O)
\end{aligned}
$$

- Easy to implement using truncated shower
- Extension to NNLO
  - Use standard MC@NLO for the first two emission
    - subtlety arises in mapping two-emission events to zero bin since parton shower always yields ordered emission while actual matrix element does not, leaving sub-leading logarithms of the cutoff not fully resummed: minimum impact given a reasonable cut-off
  - Promote vetoed cross section to NNLO

Final Formula

$$\begin{aligned}\langle O\rangle = & \int \mathrm{d}\Phi_0\,\bar{\bar{\mathrm{B}}}_0^{t_c}\,O(\Phi_0)\\ & + \int_{t_c} \mathrm{d}\Phi_1 \left[1-\Pi_0(t_1,\mu_Q^2)\left(w_1 + w_1^{(1)} + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1\, O(\Phi_0)\\ & + \int_{t_c} \mathrm{d}\Phi_1\, \Pi_0(t_1,\mu_Q^2)\left(w_1 + w_1^{(1)} + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1\, \bar{\mathcal{F}}_1(t_1,O)\\ & + \int_{t_c} \mathrm{d}\Phi_1 \left[1-\Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}\, O(\Phi_0) + \int_{t_c} \mathrm{d}\Phi_1 \Pi_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}\, \bar{\mathcal{F}}_1(t_1,O)\\ & + \int_{t_c} \mathrm{d}\Phi_2 \left[1-\Pi_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}\, O(\Phi_0) + \int_{t_c} \mathrm{d}\Phi_2\, \Pi_0(t_1,\mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}\, \mathcal{F}_2(t_2,O)\\ & + \int_{t_c} \mathrm{d}\Phi_2\, \mathrm{H}_1^{\mathrm{E}}\, \mathcal{F}_2(t_2,O)\end{aligned}$$

- Tree level amplitude and subtraction from Amegic or Comix

  [Krauss,Kuhn,Soff] hep-ph/0109036, [Gleisberg,Krauss] arXiv:0709.2881, [Gleisberg,Hoeche] arXiv:0808.3674
- One loop virtual matrix element from Blackhat

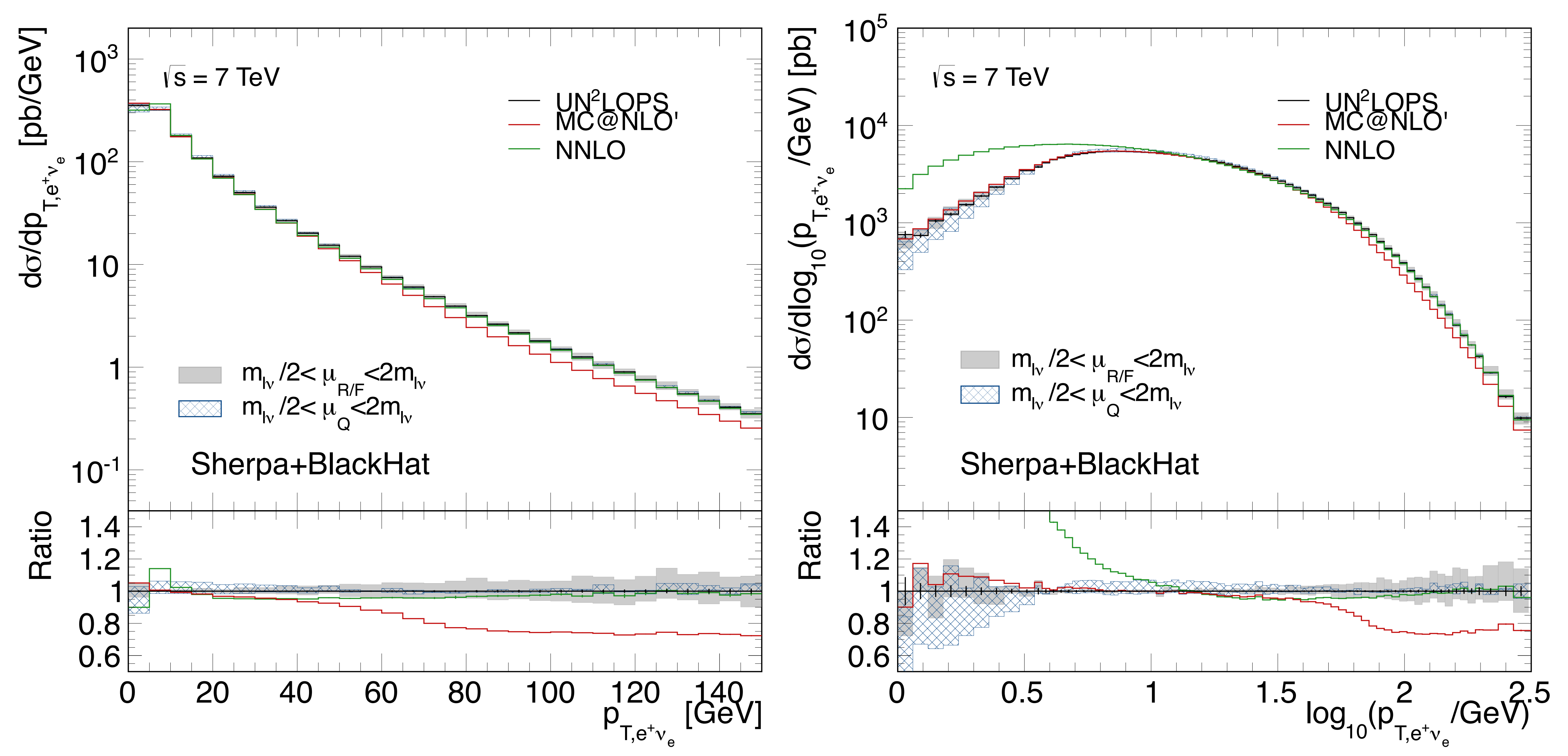
  [Berger et al.] arXiv:0803.4180, [Berger et al.] arXiv:0907.1984 arXiv:1004.1659 arXiv:1009.2338
- NNLO vetoed cross section using recent SCET results

  [Becher,Neubert] arXiv:1007.4005, [Gehrmann,Luebbert,Yang] arXiv:1209.0682 arXiv:1403.6451 arXiv:1401.1222
- Parton shower based on Catani-Seymour dipole

  [Schumann,Krauss] arXiv:0709.1027
- Combined in Sherpa event generation framework

  [Gleisberg et al.] hep-ph/0311263 arXiv:0811.4622

Hoeche, Prestel, YL arXiv:1405.3607

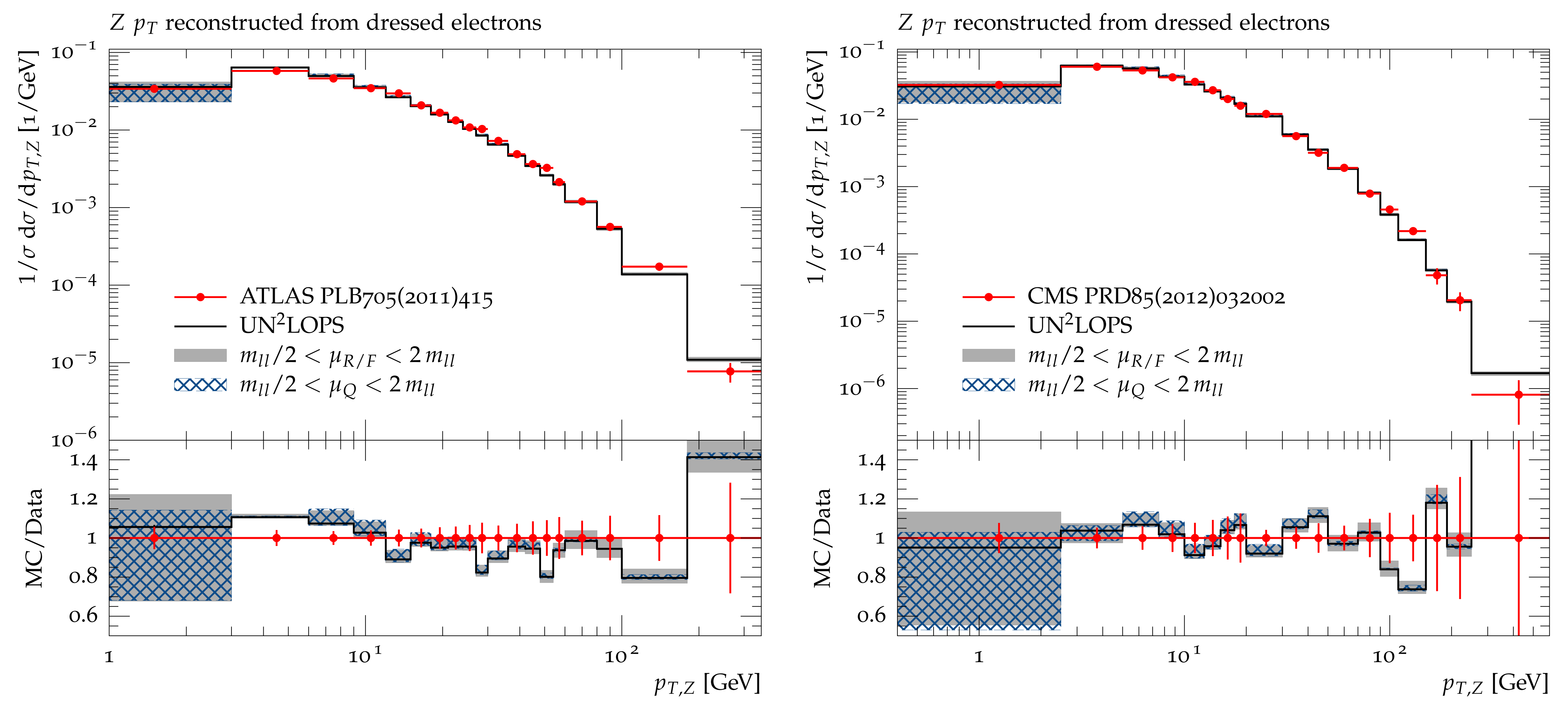


Comparison with S-MC@NLO

- Good agreement with S-MC@NLO at low W pT
- W+1jet K factor at high W pT

Comparison with experimental data

Hoeche, Prestel, YL arXiv:1405.3607

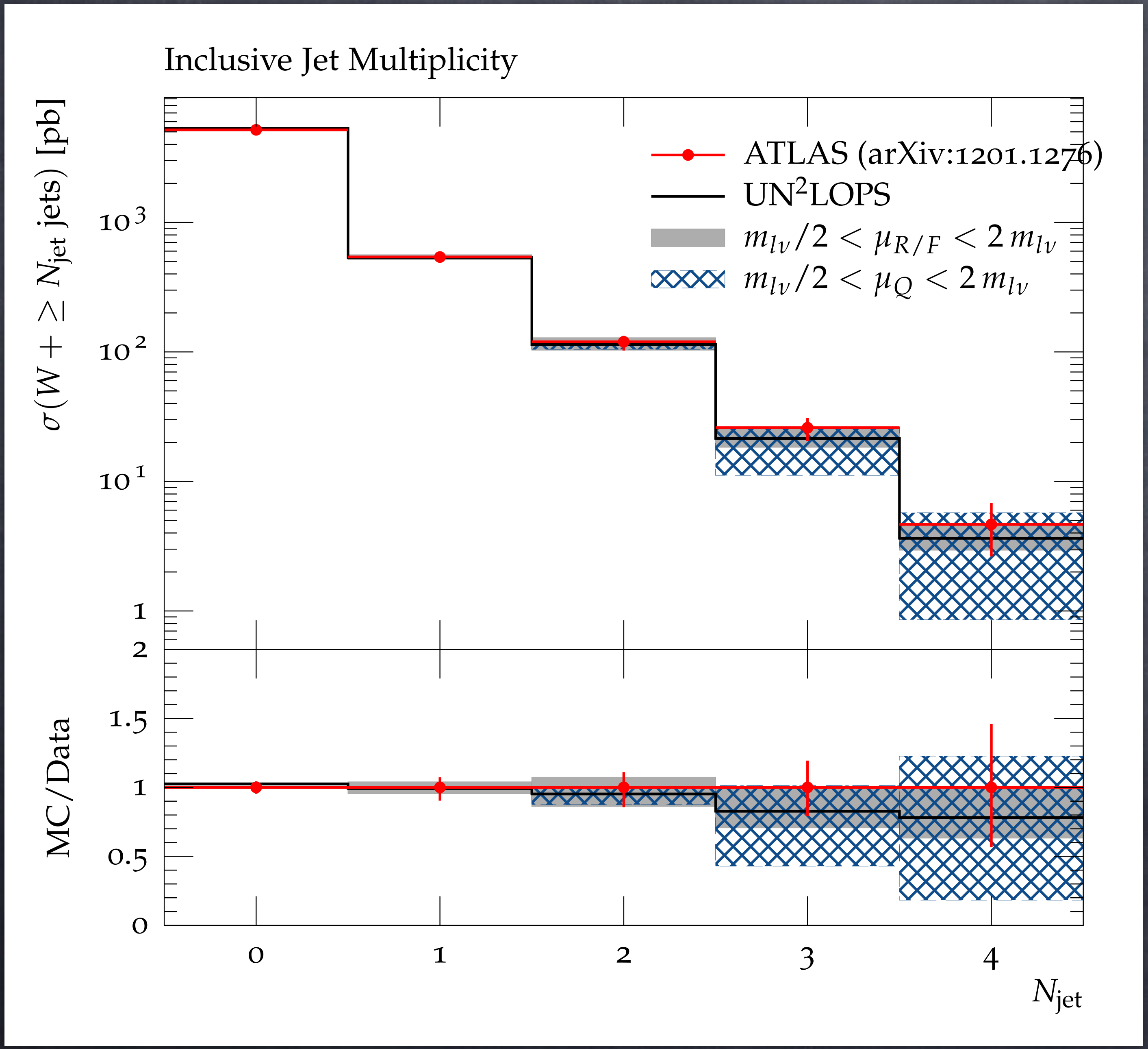


Z p_T reconstructed from dressed electrons

Z p_T reconstructed from dressed electrons

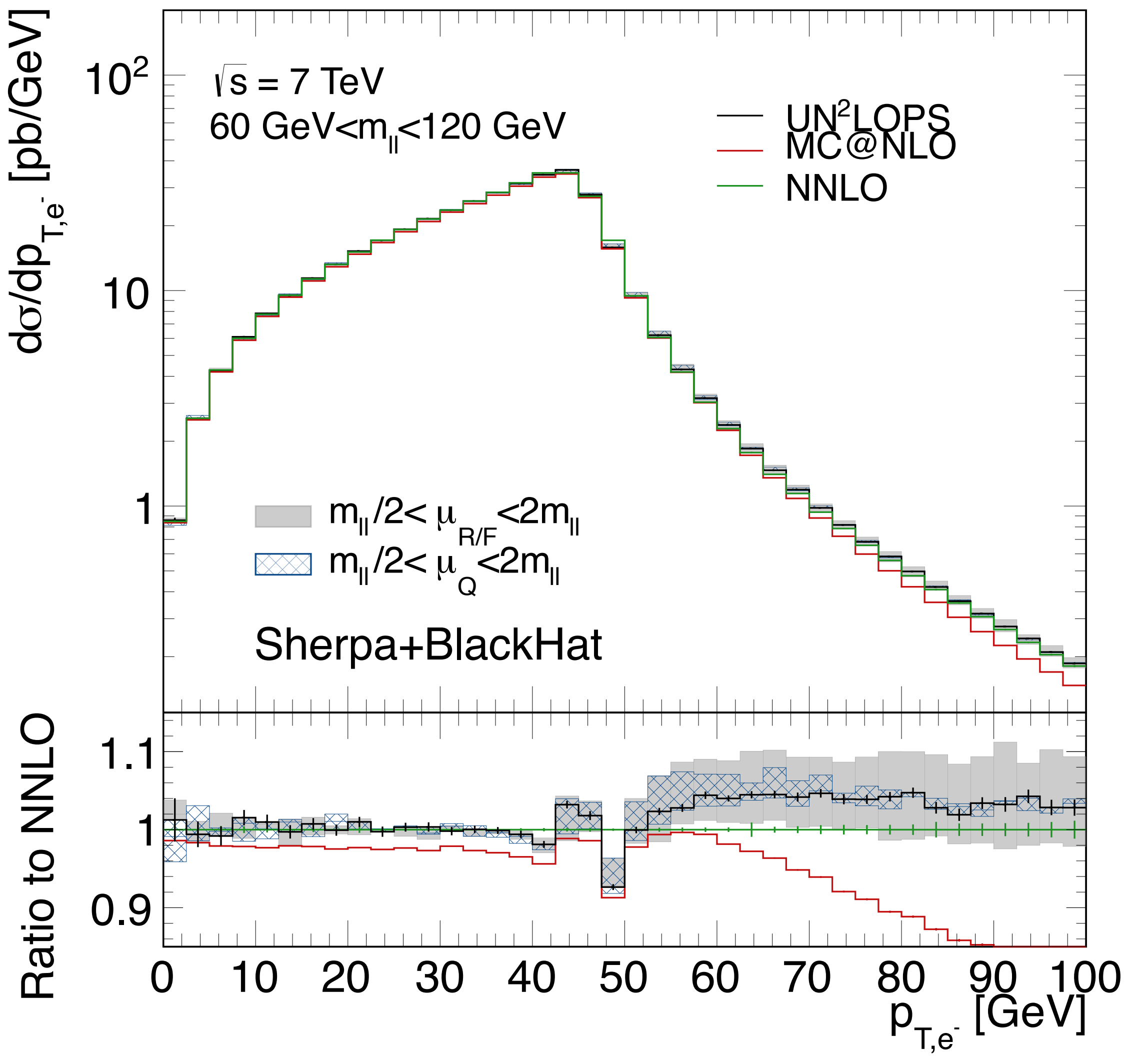
- Generic setting of sherpa used, no tuning of the shower performed

Comparison with experimental data

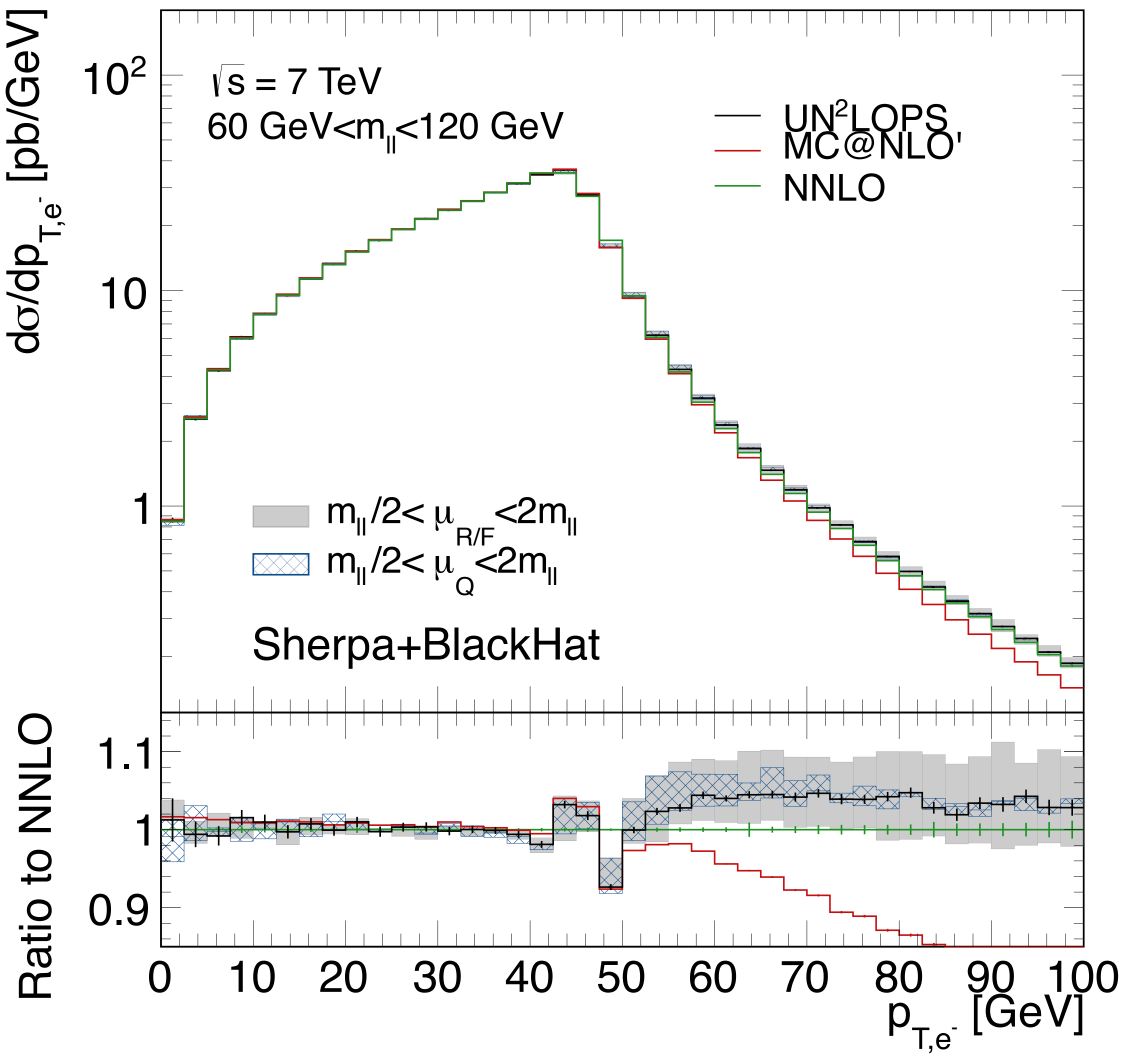


- Excellent agreement in the zero jet bin with reduced scale uncertainty
- Easily merge with NLO results of processes with higher jet multiplicities

Impact of PDFs

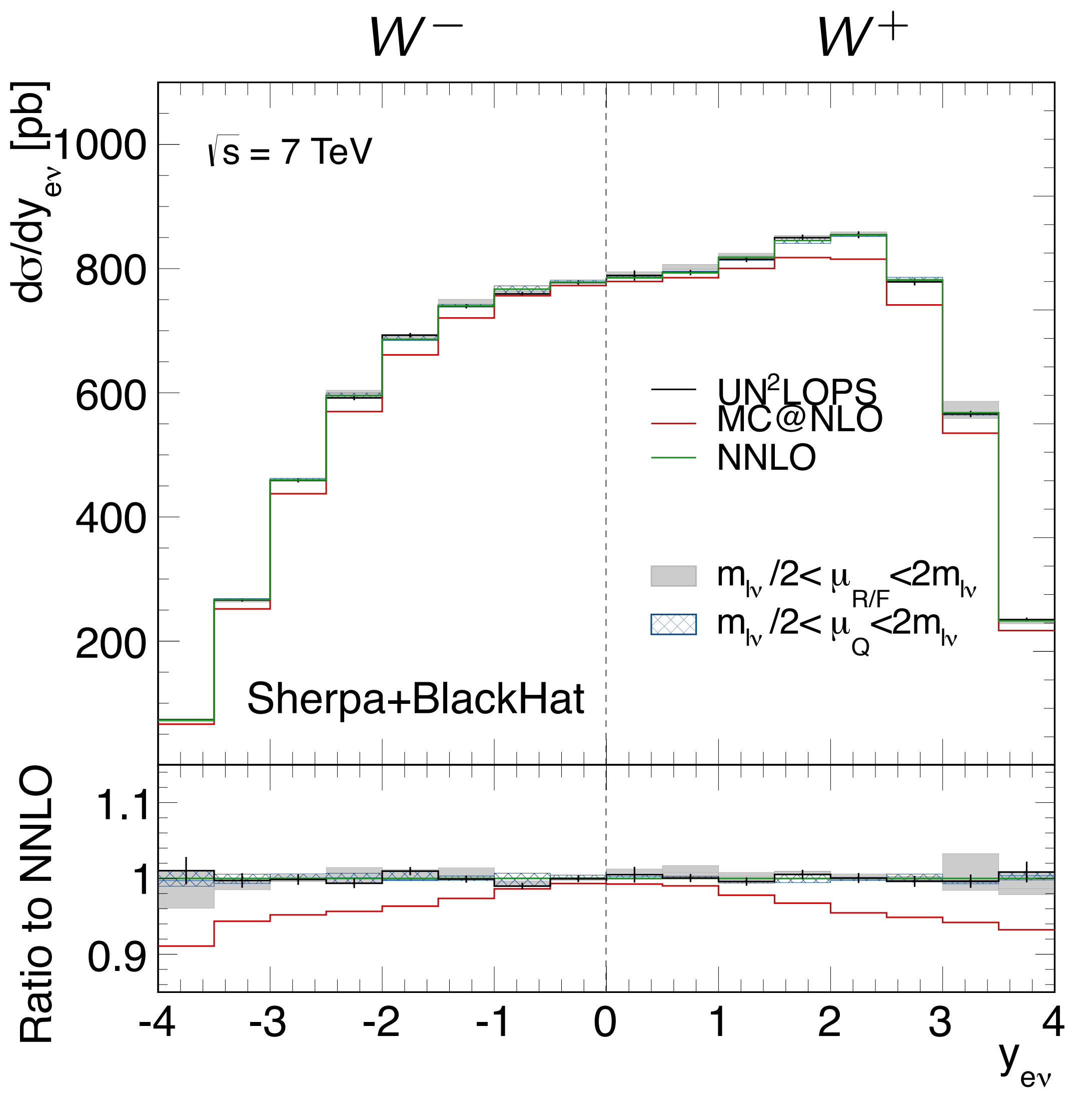


- S-MC@NLO with NLO PDFs

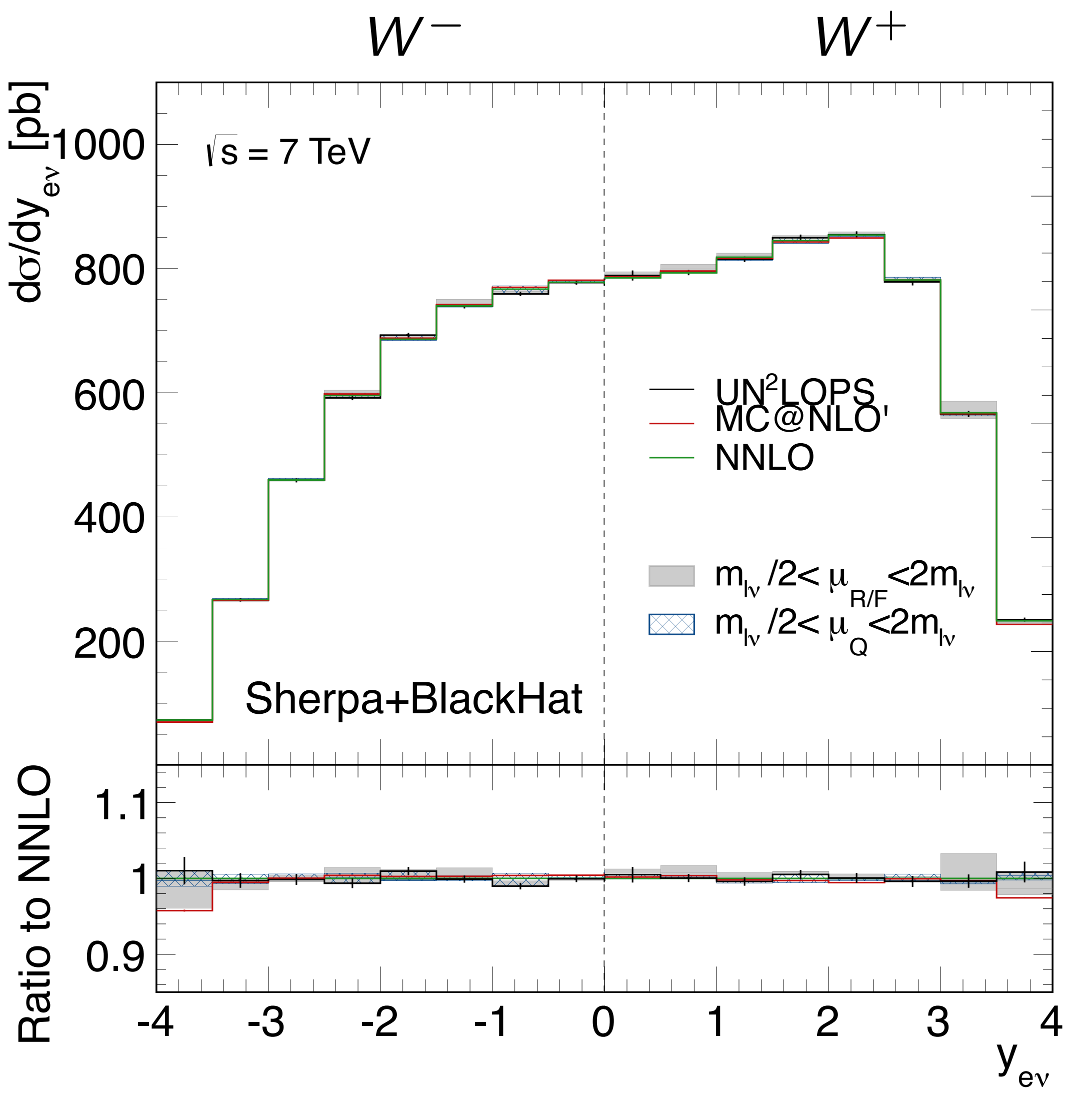


- S-MC@NLO with NNLO PDFs

Impact of PDFs

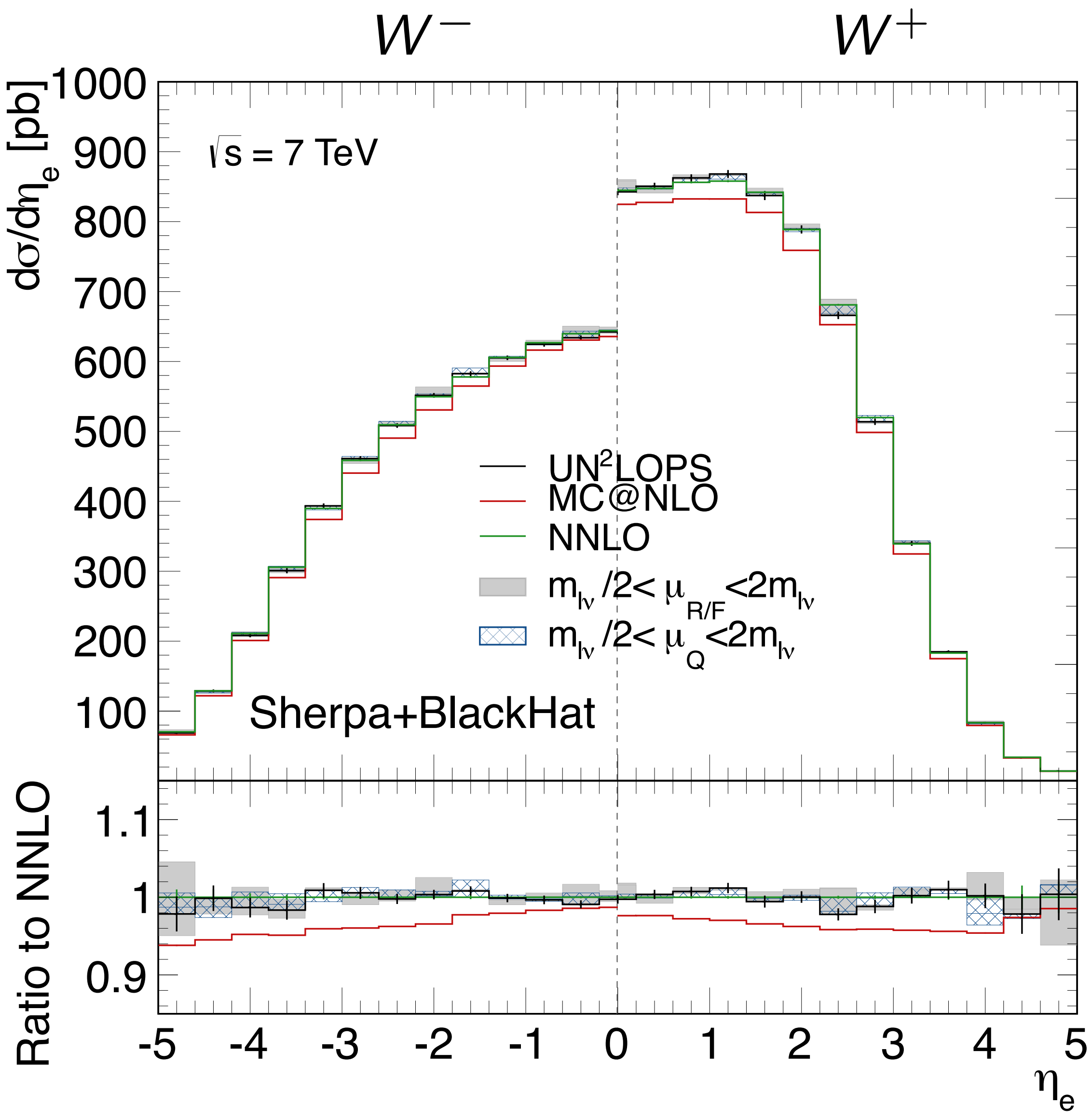


- S-MC@NLO with NLO PDFs

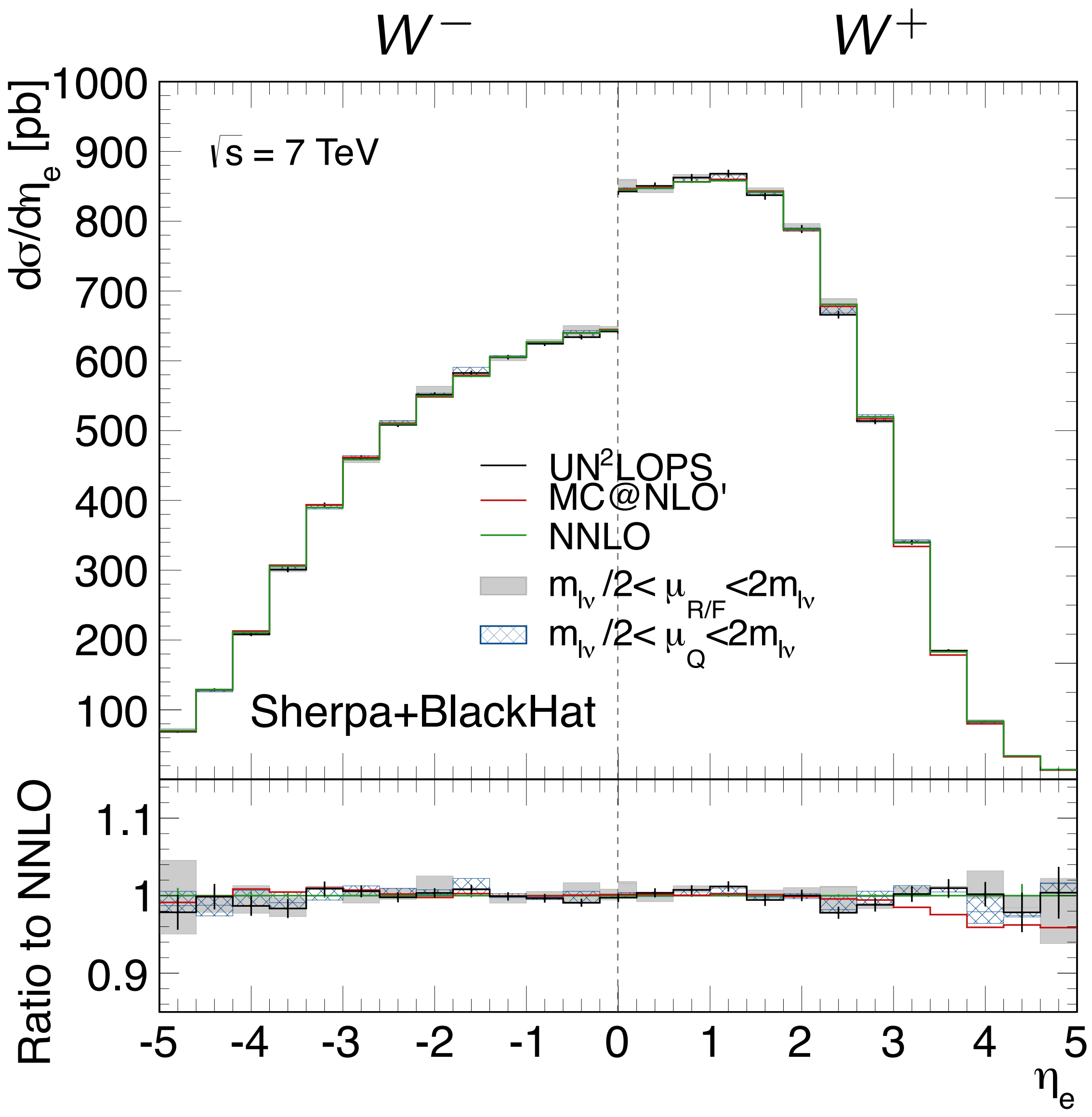


- S-MC@NLO with NNLO PDFs

Impact of PDFs



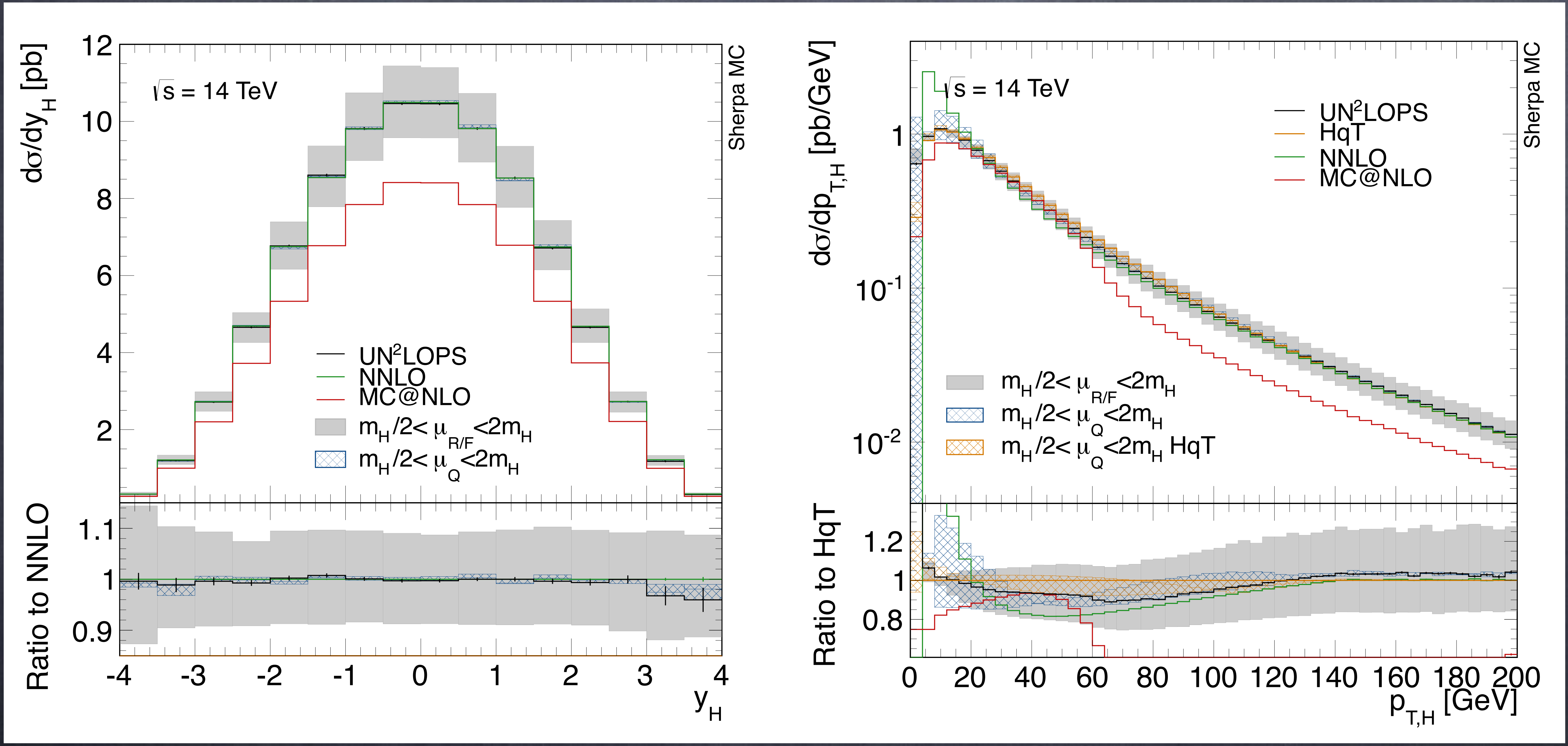
- S-MC@NLO with NLO PDFs



- S-MC@NLO with NNLO PDFs

Other Application: Higgs

Hoeche, Prestel, YL arXiv:1407.xxxx



- Based on an independent implementation of gluon fusion process at NNLO: verified with HNNLO

Outlook

- First practical implementation of NNLO+PS for DY processes
  - Matching scheme can be easily applied to a variety of processes
  - Any NNLO code can be used in the matching by providing a jet vetoed cross section in the interface
- Event generation at both NNLO and NNLO+PS and interface with analysis tools such as Rivet available, thanks to the Sherpa framework
  - Released as part of Sherpa soon
- Interesting phenomenology (NLO vs NNLO PDFs), may hint towards usefulness of NNLO PDFs for parton shower
- PS improvement desired for better overall accuracy