Comparison of theoretical modeling of additional radiation in off-shell Higgs production

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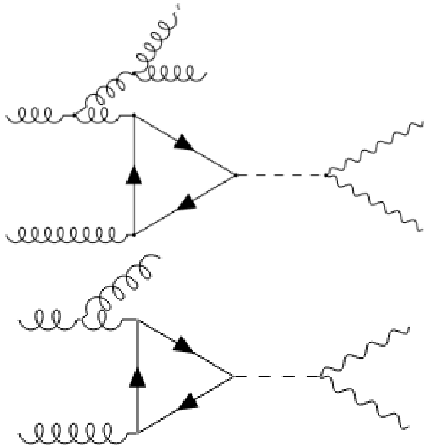
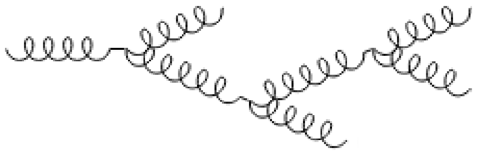
Motivation

- QCD radiation plays an important role in a p-p collisions and in particular in $gg \to H$



- Two different ways to include radiation:
  - ➢ by matrix element ⟶ computation of higher order real corrections
  - ➢ using a parton shower ⟶ markov process

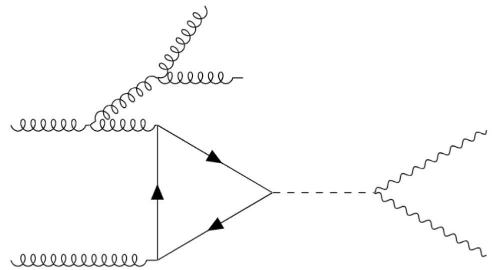


- Currently best fixed order computation: exact NLO ⟶ supplies one jet (matrix element level)

[B. Agarwal, Jones, Kerner, von Manteuffel (2024)]

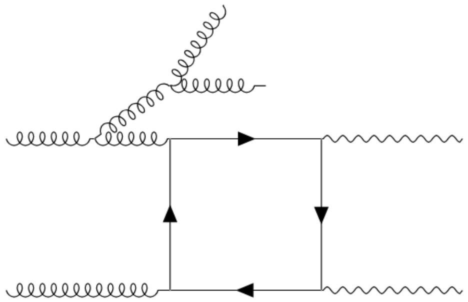
- How to add more radiation?
  - ➢ NNLO calculation ⟶ Unfeasible for background, interference and full contributions
  - ➢ LO+2-jet merging ⟶ NNLO real corrections
  - ➢ Parton shower ⟶ NLO+PS

Going beyond fixed NLO



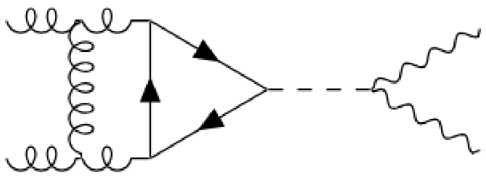
LO+2-jet merging:

- feasible for signal
- very challenging for the background



NLO+PS:

- available for both signal and background [Alioli, Ferrario, Lindert, Röntsch (2021)]
- lack of double real corrections
- include virtual corrections



Ultimate goal: compare 2-jet merging and NLO+PS

Strategy

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Strategy:

i. Setup and tune parameters with LO comparison

ii. Comparison of NLO+PS with LO+1-jet merging ← Currently at this stage

iii. Comparison of NLO+PS with LO+2-jet merging

Monte Carlo generators used:

- NLO+PS → POWHEG+PYTHIA [Alioli, Ferrario, Lindert, Röntsch (2021)], [Nason (2004)], [Frixione et al (2007)], [Alioli et al (2010)], [Sjostrand, Mrenna, Skands (2007)]
- 1-jet merging
  - → MadGraph+PYTHIA (MLM) [Alwall, Frederix, Frixione (2014)], [Hirschi and Mattelaer (2015)], [Alwall, Visscher, Maltoni (2008)], [Sjostrand, Mrenna, Skands (2007)]
  - → Sherpa (CKKW) [Bothmann, Chahal, Höche (2009)], [Höche, Krauss, Schumann, Siegert (2019)]

Setup

- Focus only on: $gg \to ZZ \to e^+e^-\mu^+\mu^-$
- Masses and widths:

$$m_H = 125.1\,\text{GeV} \qquad \Gamma_H = 0.004\,03\,\text{GeV}$$

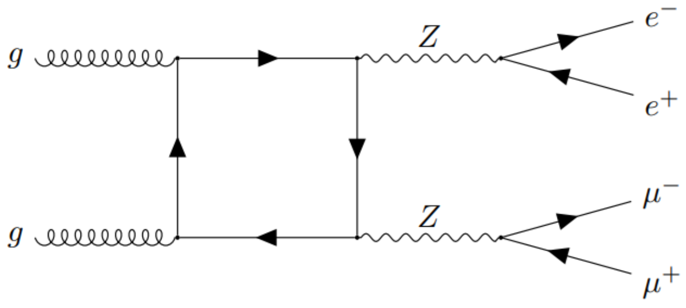
$$m_Z = 91.1876\,\text{GeV} \qquad \Gamma_Z = 2.4952\,\text{GeV}$$

$$m_W = 80.3980\,\text{GeV} \qquad \Gamma_W = 2.1054\,\text{GeV}$$

$$m_t = 173.2\,\text{GeV} \qquad \Gamma_t = 0\,\text{GeV}$$

with massless bottom quark $m_b = 0\ GeV$.

- EW parameters: m_Z, m_W and $\alpha = (132.3384)^{-1}$
- PDF set: `NNPDF30_nlo_as_01180`
- Center of mass energy: $\sqrt{s} = 13\ TeV$
- Ren/Fac scales: $\mu = \mu_R = \mu_F = \frac{m_{4\ell}}{2}$



Cuts and parameters:

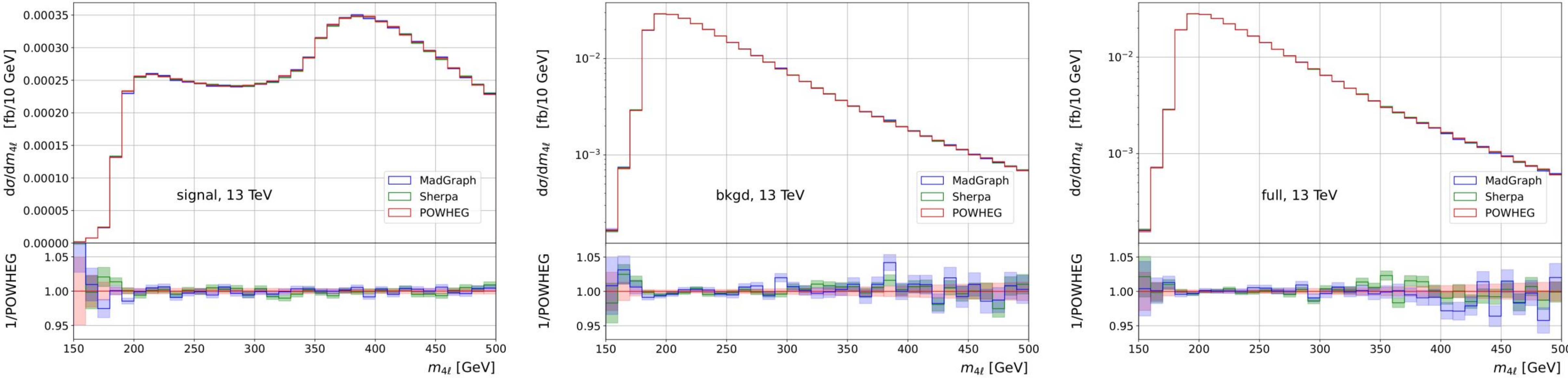
- $150\,\text{GeV} < m_{4\ell} < 500\,\text{GeV}$
- $60\,\text{GeV} < m_{\ell\ell} < 120\,\text{GeV}$
- Powheg top mass scheme: reweighting
- Hadronization off
- MPI off

i) LO validation

PRELIMINARY

- Tuning of parameters across the three generators by computing fixed LO
- No variations (all uncertainties here are statistical)
- All cross sections lie one σ of each other
- Also m_{4l} distributions lie one σ into each other

σ_{LO} [fb]	POWHEG	MADGRAPH	SHERPA
signal	0.08745(5)	0.08742(1)	0.08741(5)
bkgd	2.725(1)	2.724(1)	2.726(1)
full	2.617(1)	2.617(1)	2.616(1)



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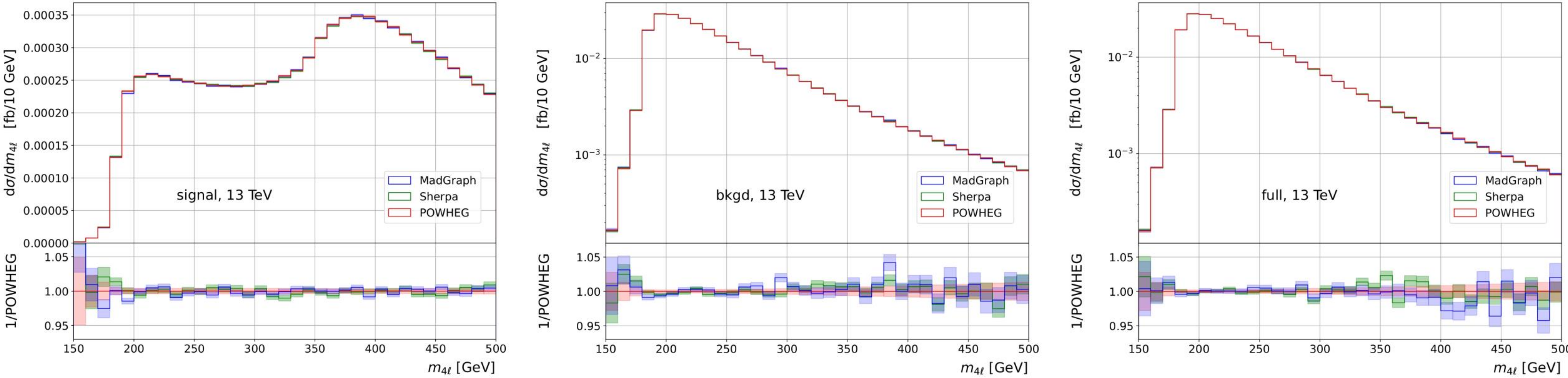


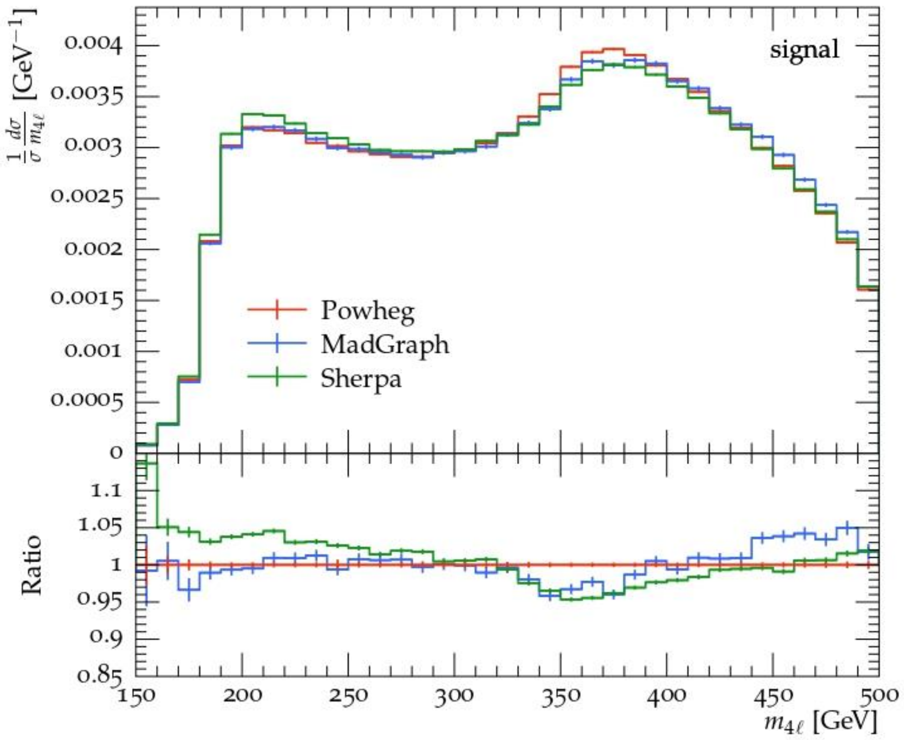
Full control of parameters for LO results → any difference beyond LO is due to different ways of adding QCD radiation

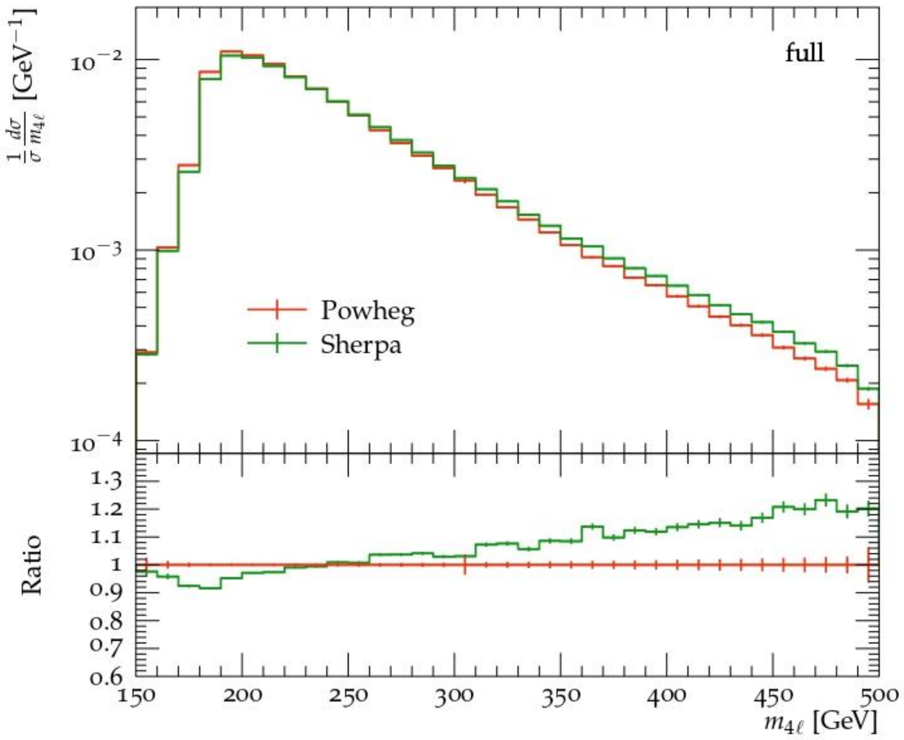
ii) NLO+PS vs 1-jet merging

PRELIMINARY

1. Normalized invariant mass of the four leptons
   - Inclusive observable
   - Expect only minor corrections from additional radiation
   - Observe a 5% difference in signal and a 15% for bkgd and full

MadGraph for background and full does not converge with the same cuts used for the other generators

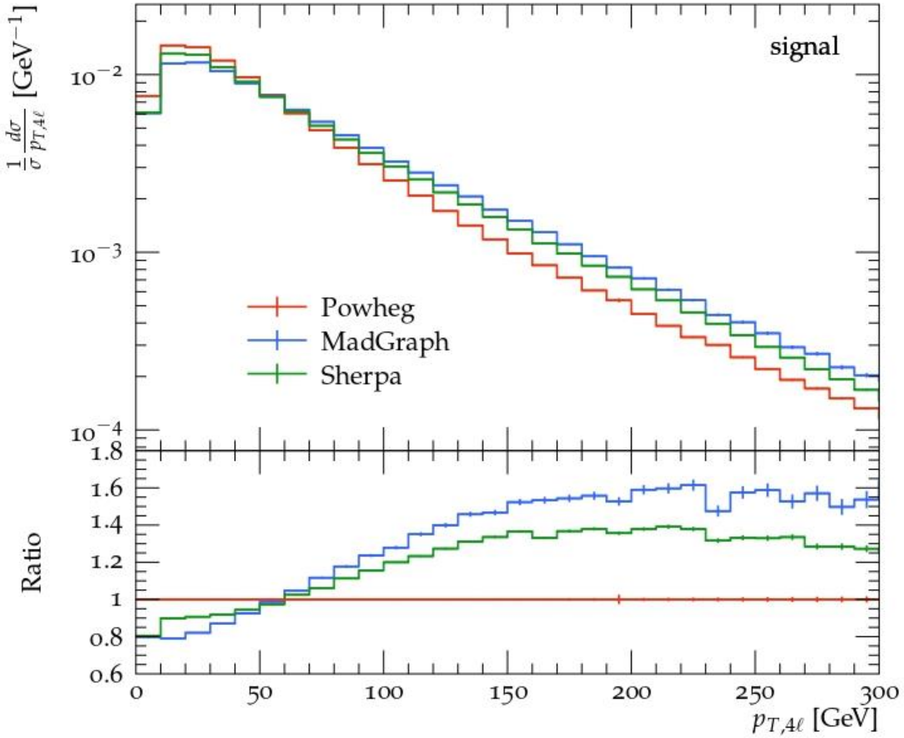


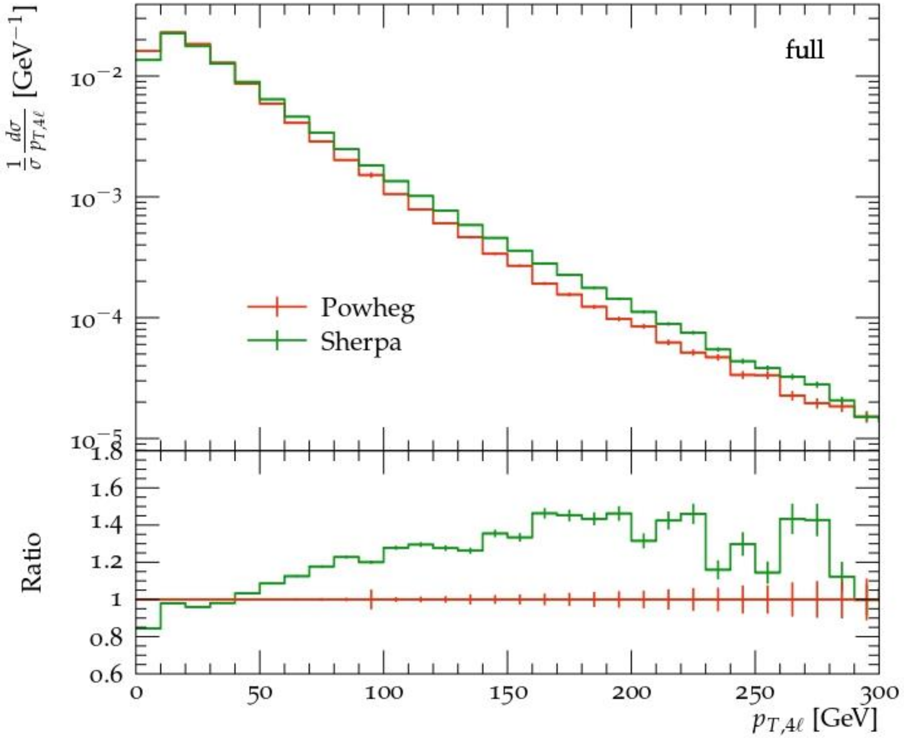


ii) NLO+PS vs 1-jet merging

PRELIMINARY

2. Normalized transverse momentum of the four leptons
   - Exclusive observable
   - Most sensitive quantity for additional radiation effects
   - Depend on parton shower and matrix element details → observe harder spectrum from merging





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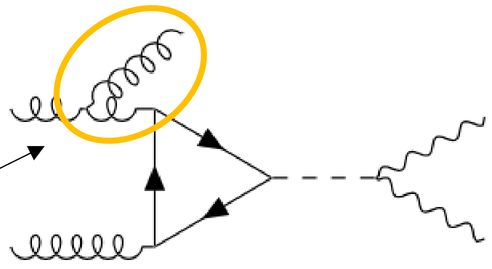
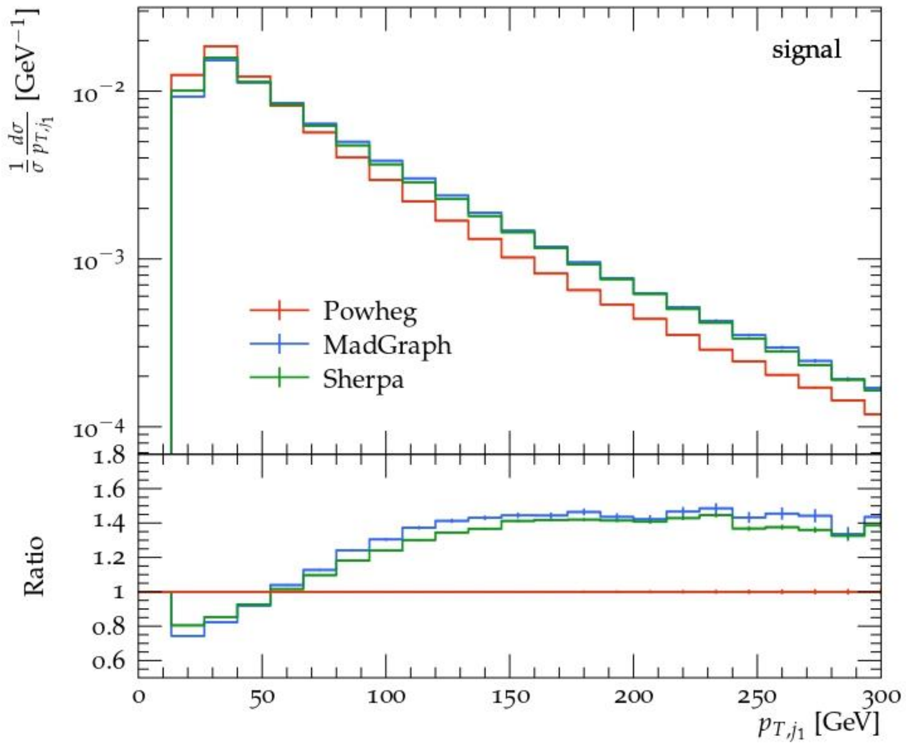
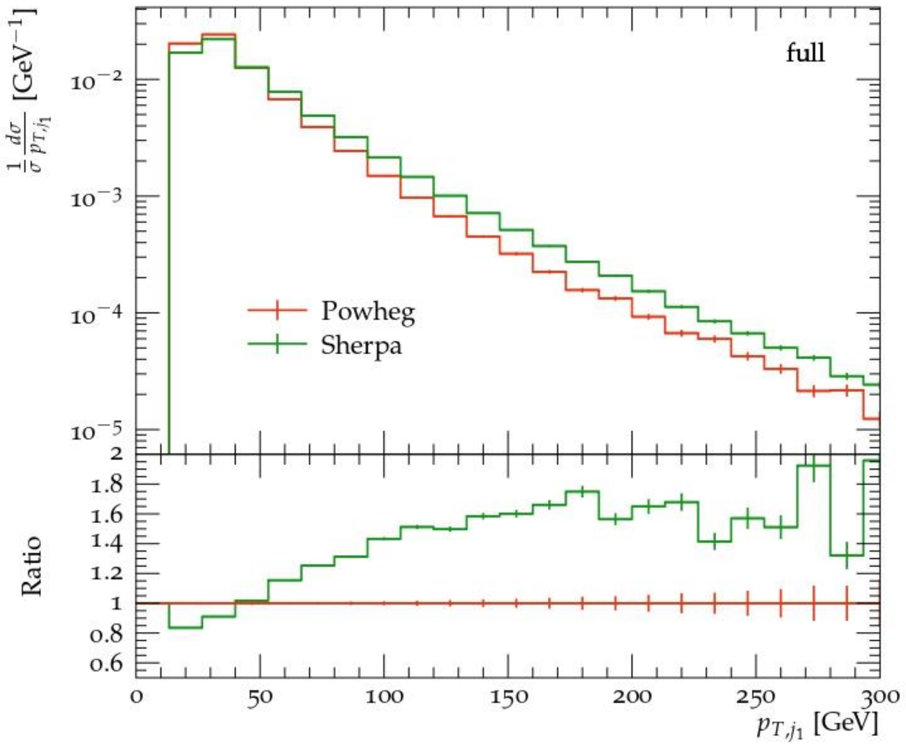


PRELIMINARY

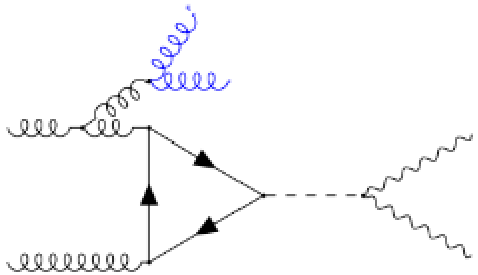
3. Normalized transverse momentum of the hardest jet
   - Sensitive to matrix element NLO real corrections
   - Same behaviour of $p_{T,4l}$ → merging produce an harder spectrum
   - Good agreement of MadGraph and Sherpa → differences of $p_{T,4l}$ are only in parton shower





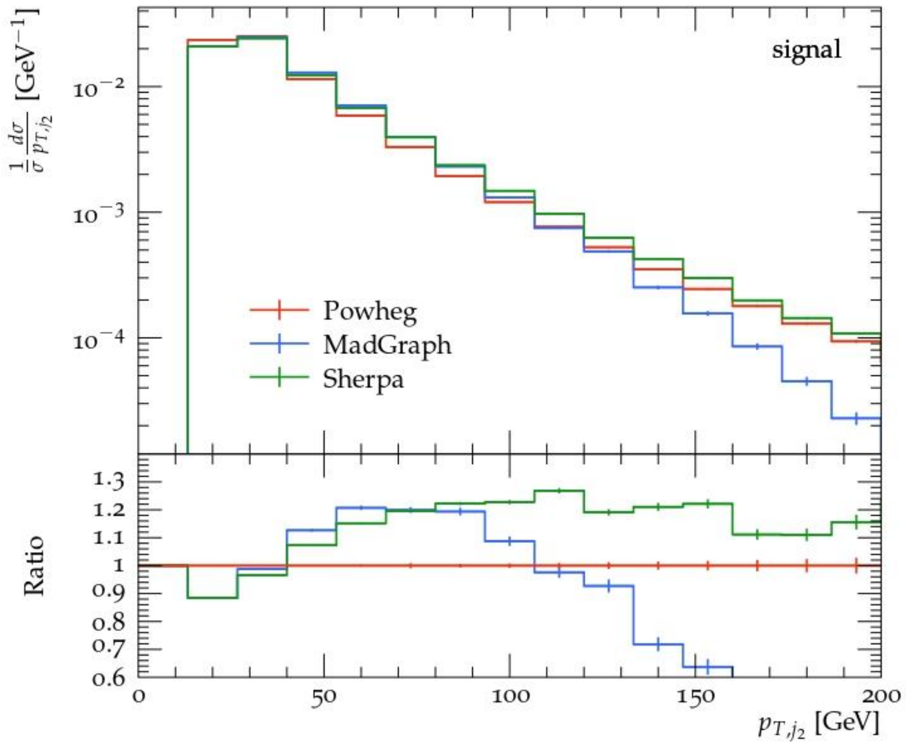
ii) NLO+PS vs 1-jet merging

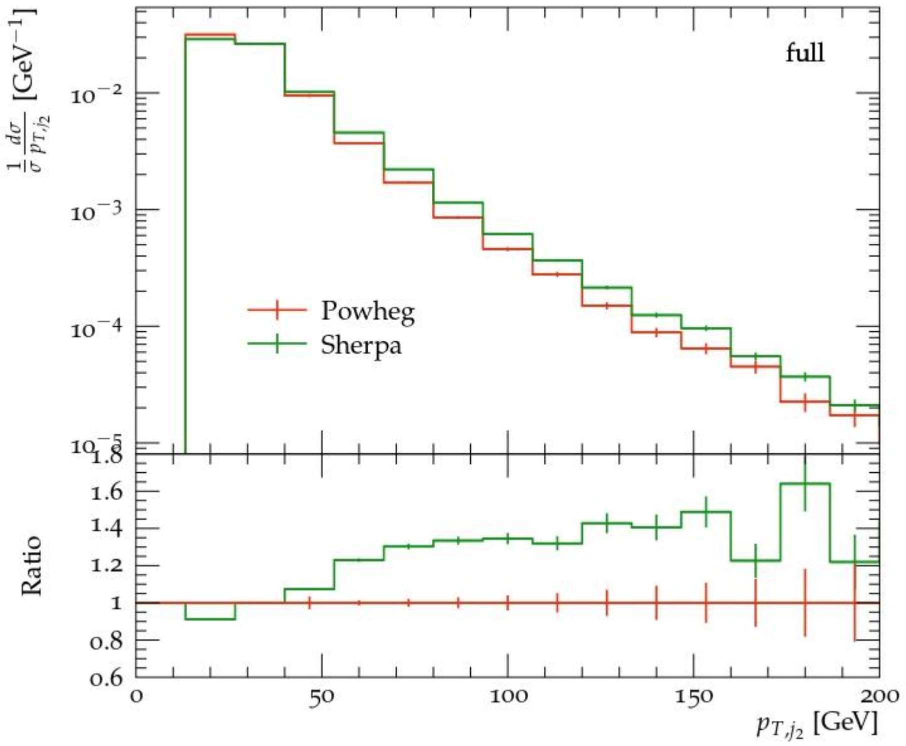
PRELIMINARY



4. Normalized transverse momentum of the subleading jet
   - Sensitive to parton shower
   - Good agreement of MadGraph and Sherpa for $p_{T,j_2} < 80\ GeV$
   - Disagreement of MadGraph and Sherpa for $p_{T,j_2} > 80\ GeV$

→ different parton shower
→ different merging procedure



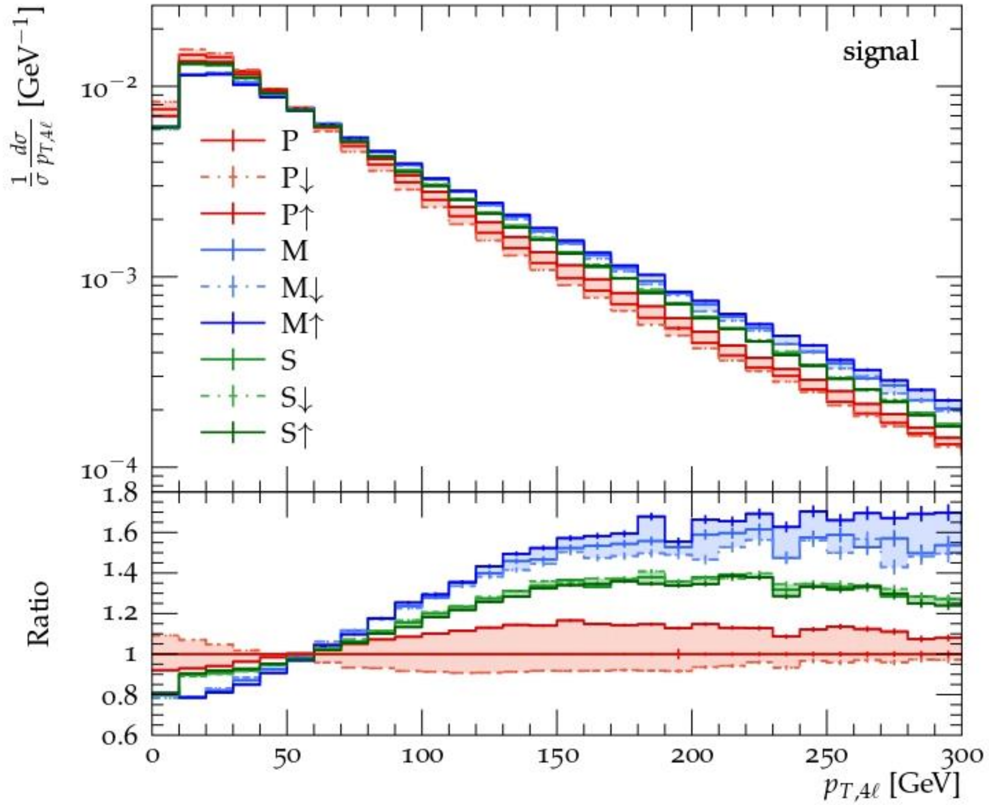


Variations on matching/merging parameters

PRELIMINARY

Important to understand theoretical uncertainties for each method:

- Powheg: h_{damp}
  - P nominal: $h_{\text{damp}} = 100$ GeV
  - P ↑: $h_{\text{damp}} = 150$ GeV → Harder spectrum
  - P ↓: $h_{\text{damp}} = 75$ GeV → Softer spectrum
- MadGraph (MLM): $xqcut$ and $Qcut$
  - M nominal: $xqcut = 10 \;\; Qcut = 20$
  - M ↑: $xqcut = 20 \;\; Qcut = 30$
  - M ↓: $xqcut = 5 \;\; Qcut = 15$
- Sherpa (CKKW): $Qcut$
  - S nominal: $Qcut = 20$
  - S ↑: $Qcut = 30$
  - S ↓: $Qcut = 15$



⟹ biggest uncertainty from h_{damp} in Powheg (20%)

More on transverse momentum - $p_{T,4l}$

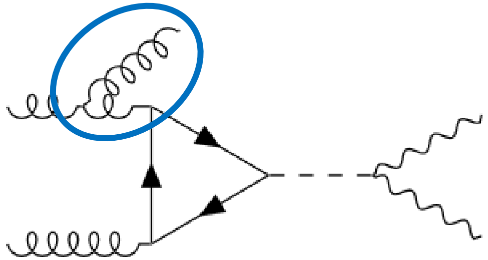
PRELIMINARY

Why is merging producing a harder spectrum?

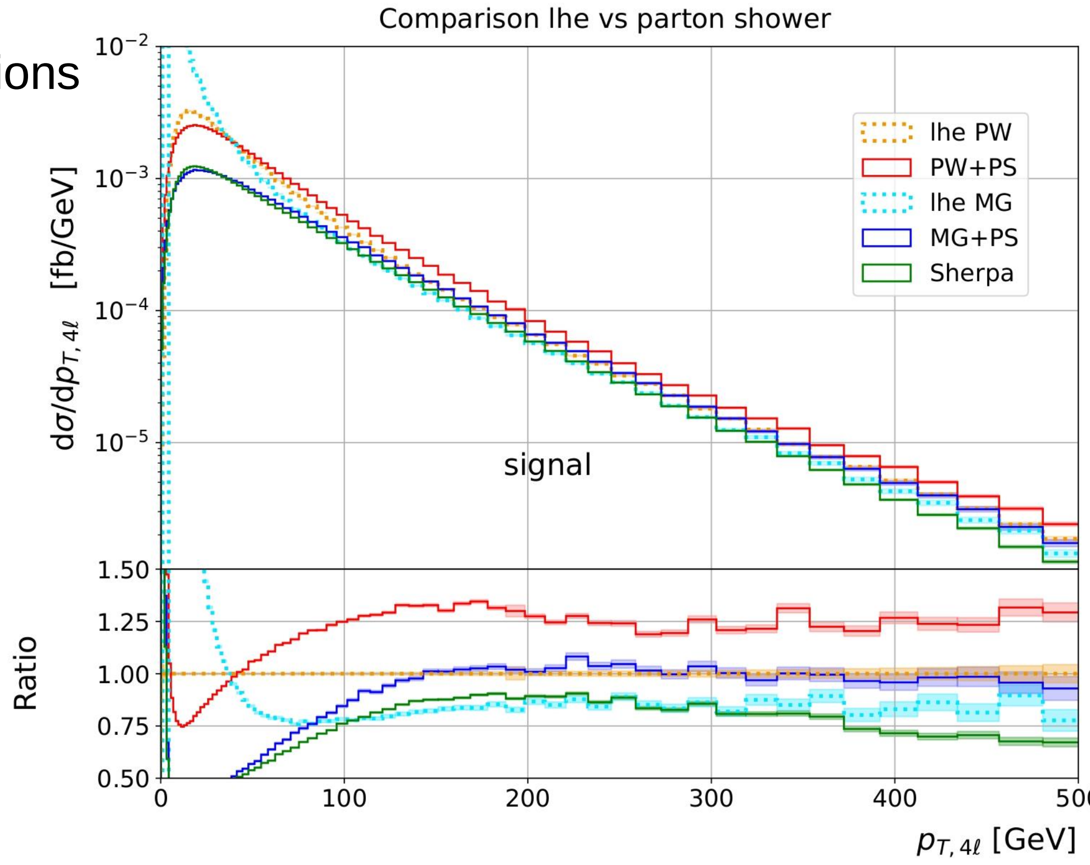
Compare <u>unnormalized</u> distributions ⟶ total area = cross section

- $\sigma_{Powheg-NLO} \approx 2\sigma_{merging-LO}$ ⟵ missing virtual corrections
- At high p_T both NLO+PS and 1-jet merging are dominated by the 1-jet matrix element corrections

  ⇒ expect same tail



⇒ less events at the Sudakov peak for merging



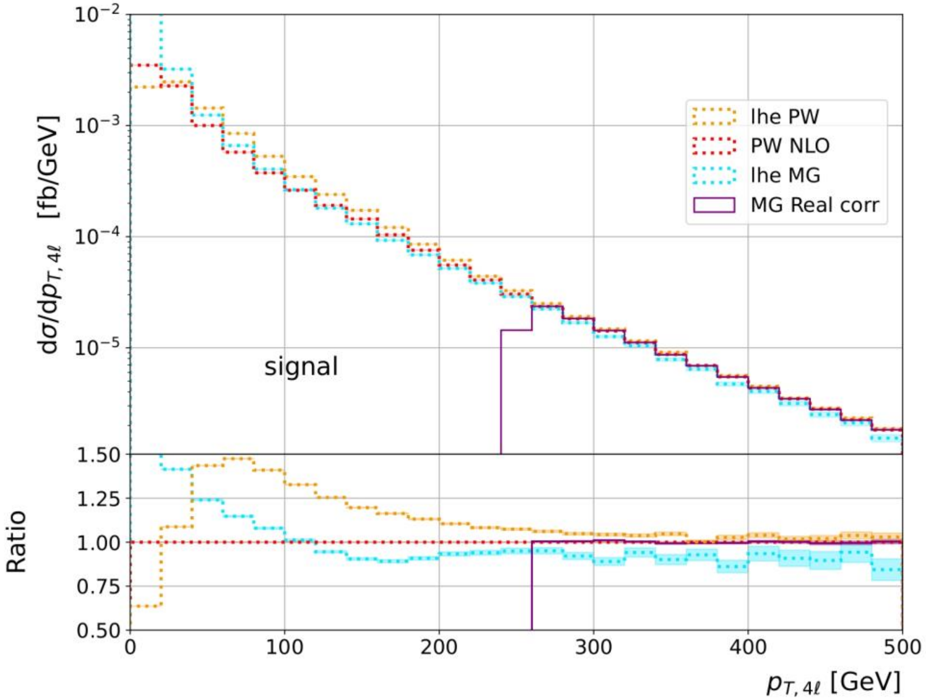
More on transverse momentum - $p_{T,4l}$

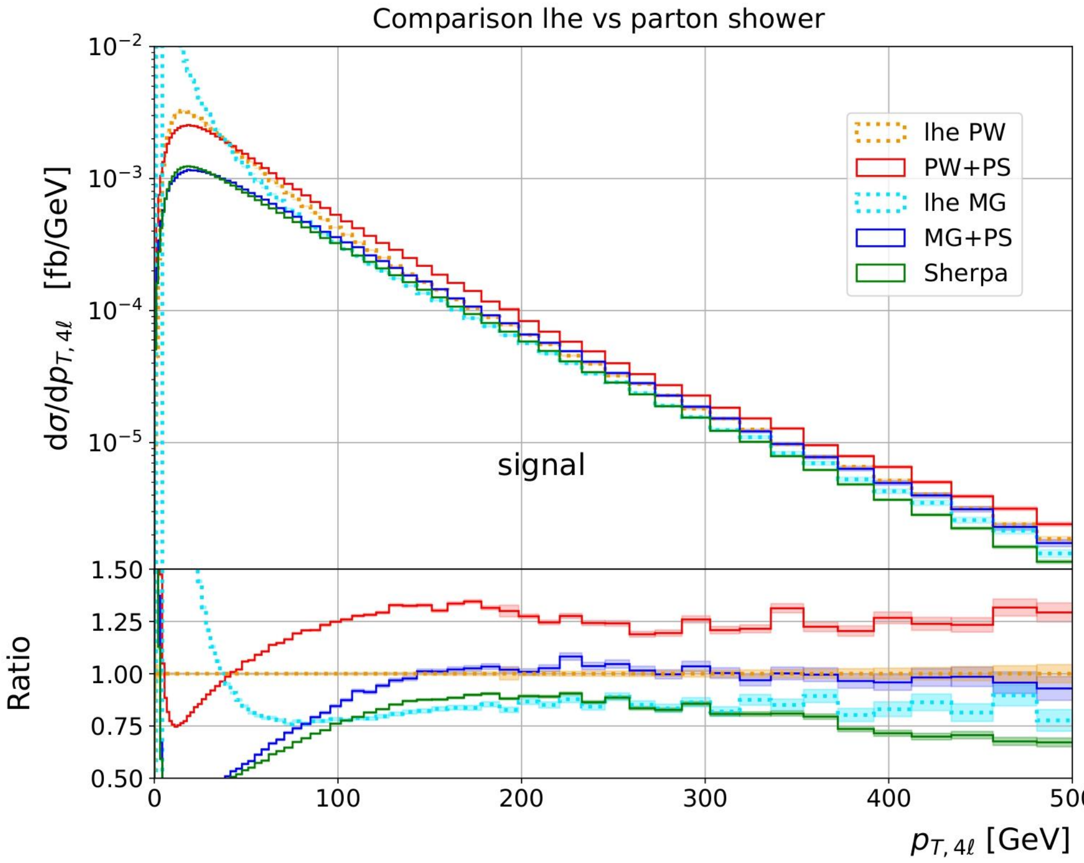
PRELIMINARY

Do the distributions agree at high p_T?

Still working on it.

- Real corrections comparison between MadGraph and Powheg ⇒ very good agreement





More on transverse momentum - $p_{T,4l}$

PRELIMINARY

Do the distributions agree at high p_T?

Still working on it.

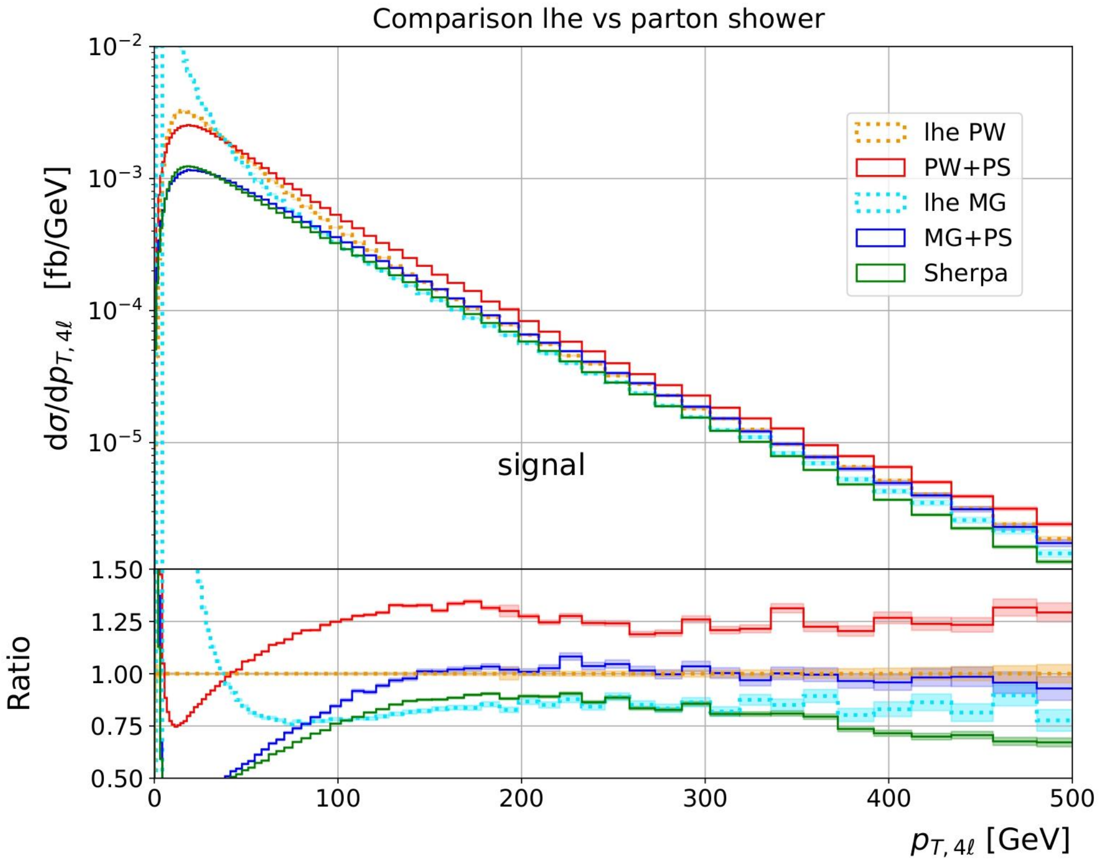
- Real corrections comparison between MadGraph and Powheg ⇒ very good agreement

- It is unfortunately a known fact that the shower modifies quite substantially the spectrum of the color singlet in gg-initiated processes at large p_T.

  [Alioli, Caola, Luisoni, Röntsch (2016)]

  [Alioli, Ravasio, Lindert, Röntsch (2021)]

- Both Powheg and MadGraph receive a ~20% push from the parton shower at high energies respect to the LHE level.



Conclusions

Goal:

- compare NLO+PS and LO+2-jet merging for $gg \to ZZ \to e^+e^-\mu^+\mu^-$

Status:

- LO validation of Powheg, MadGraph and Sherpa
- Preliminary comparison of NLO+PS and LO+1-jet merging

Future work:

- Run MadGraph for background and full contributions (with different cuts)
- Comparison of NLO+PS and LO+2-jet merging

Thank you for your attention

Backup slides

Top mass approximations

- In Powheg NLO virtual corrections for the background are not exact
- Two approximations available in Powheg:
  1. $1/m_t$ expansion: works for $m_{4l} < 2m_t \approx 340\ GeV$
  2. reweighting: assume that contribution of massive top quark at two loops is the same as at one loop

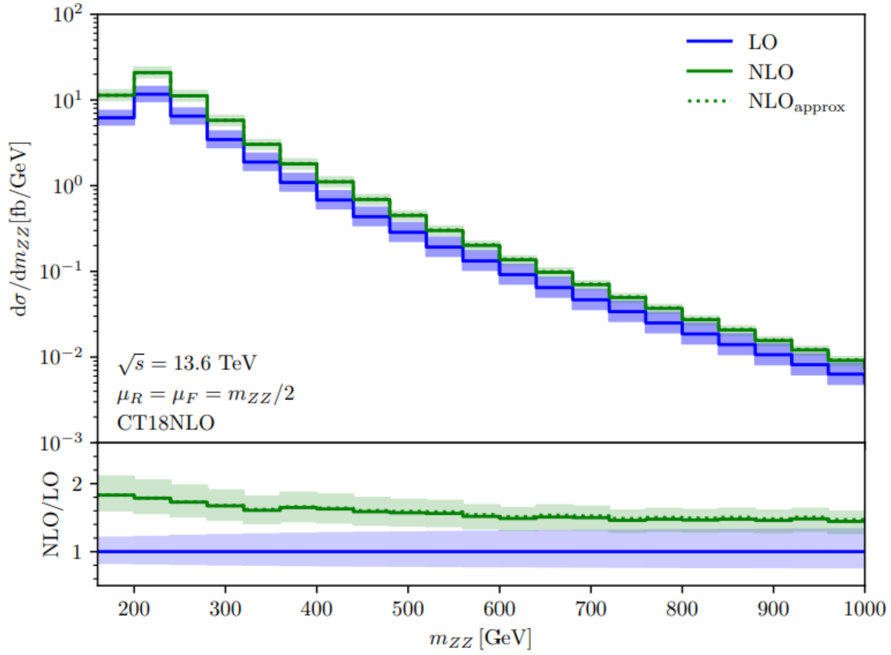
$$A_{\text{bkgd}}^{\text{2loop,rwgt}} = A_{\text{bkgd}}^{\text{2loop,exact}}(u,d,s,c,b) \times \frac{A_{\text{bkgd}}^{\text{1loop,exact}}(u,d,s,c,t,b)}{A_{\text{bkgd}}^{\text{1loop,exact}}(u,d,s,c,b)}$$

Approx used for previous plots

  3. mixed scheme: $1/m_t$ expansion $m_{4l} < 2m_t$ and reweighting for $m_{4l} > 2m_t$

- no strict theoretical justification for using the reweighting approximation, but it works

[B. Agarwal, Jones, Kerner, von Manteuffel (2024)]

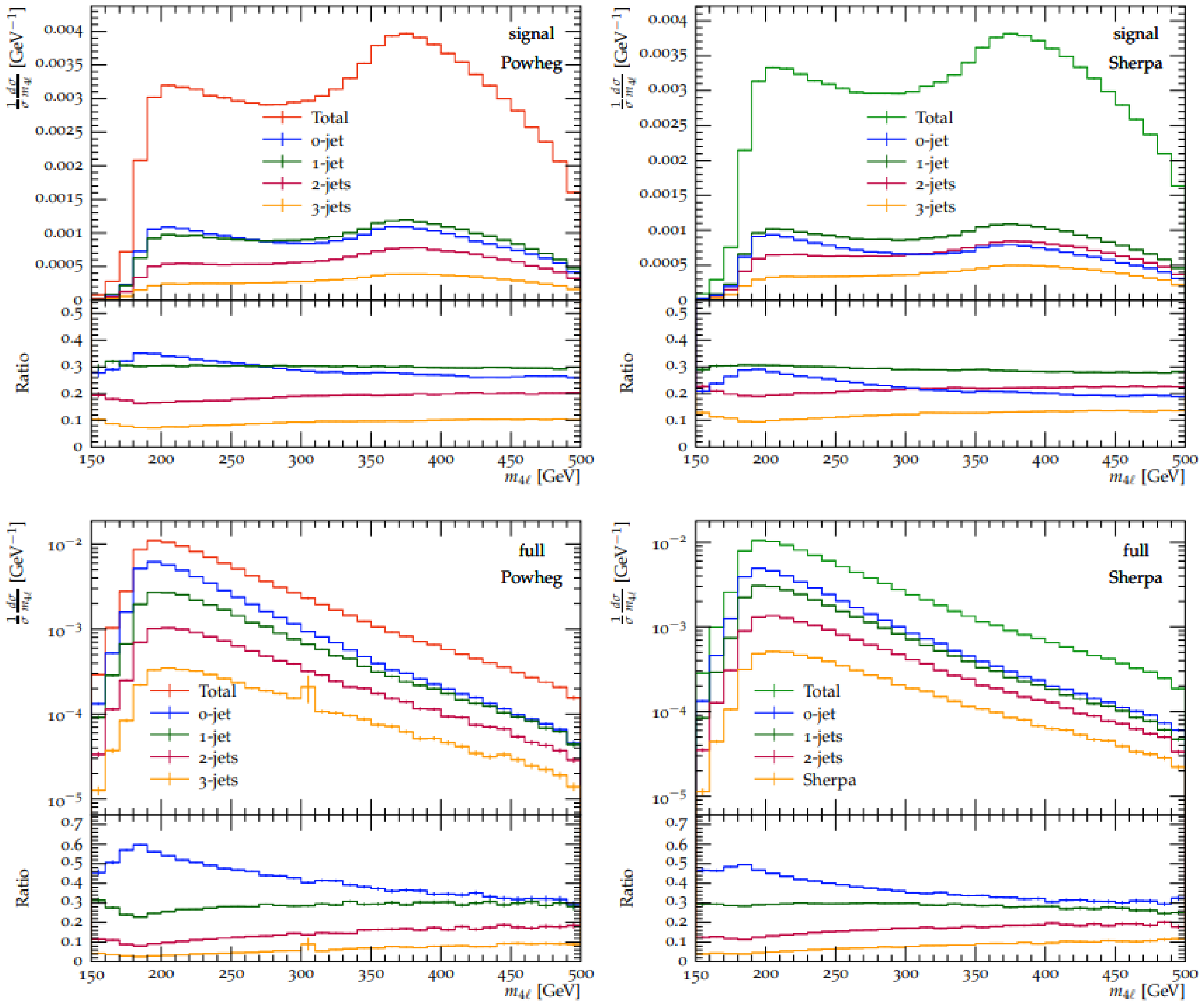


Jet multiplicity - m_{4l}

PRELIMINARY

- 0-, 1-, 2-, and 3-jet invariant mass distributions of the four leptons
- almost independent of the number of jets per event:
  - 0-jet events is the least flat,
  - 1-jet, 2-jet, … are more flat.
- Signal:
  - Powheg: 1-jet dominant after 300 GeV, 2-jet below the 0-jet for all values of m_{4l}.
  - Sherpa: 0-jet falls below the 2-jet at 340 GeV, 1-jet always dominant.

hardness of radiation from merging



Jet multiplicity - $p_{T,4l}$

PRELIMINARY

- 0-, 1-, 2-, and 3-jet transverse momentum distributions of the four leptons
- non-trivial dependence of the number of jets per event:
  - 0-jet contributes to events with low p_T, does not account for the tail
  - 1-jet, 2-jet, … describe the tail
- significant difference between 0-jet rate and 1-jet rate

↑

parton from the matrix element imparts a strong boost to the four lepton system

- next jet originates from the parton shower, contributing a smaller boost to the four lepton system