Higgs Pair Production: NLO Matching Uncertainties

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Higgs Couplings Workshop, Heidelberg

Introduction

Motivation: the Higgs Potential

$$V = \lambda_2 v^2 \; H^2 + \lambda_3 v \; H^3 + \lambda_4 v^2 \; H^4$$

$$\lambda_2^{\text{SM}} = \lambda_3^{\text{SM}} = \lambda_4^{\text{SM}} = \frac{m_H^2}{2v^2}$$

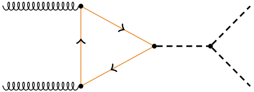
λ_3 can be measured in Higgs pair production

- Experimentally challenging

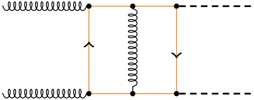
$$\sigma(pp \to HH) \sim \sigma(pp \to H) \times 10^{-3}$$

- Prospects for HL-LHC: around 10 % - 50 % precision on λ_3
- Theoretically also extremely challenging

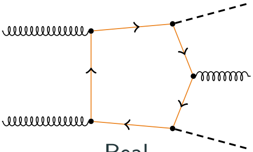
Higgs Pair Production at NLO



Born



Virtual



Real

Born and real corrections

Automated 1-loop tools: OpenLoops, GoSam, MadLoop, Recola, ...

Infrared subtraction

Born UV finite, use standard techniques: Catani-Seymour, FKS, ...

Virtual corrections

Two-loop integrals, massive propagators, external masses

Very hard ⇒ not available until recently

Low-Energy Approximation

Higgs Effective Field Theory

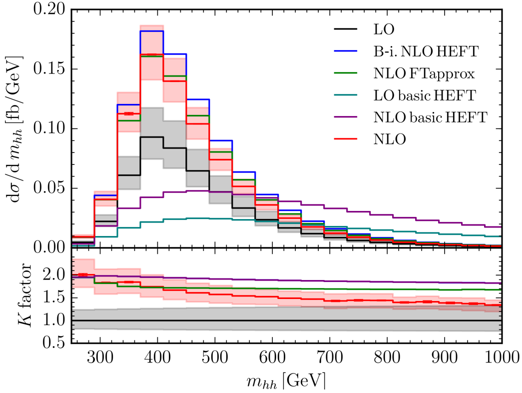
- Take into account only top quark contributions
- Work in low-energy limit: $\hat{s} \ll m_t^2$

$\Rightarrow$ Gives rise to point-like Higgs-gluon interactions

$\Rightarrow$ Reduces complexity immensely

$\Rightarrow$ Validity highly questionable, however: $m_{HH} > m_t$

New Level of Precision



Borowka et al. JHEP 10 (2016)

- Two-loop virtuals numerically evaluated
- Details: Gudrun Heinrich's talk

- HEFT-based approximations inaccurate
- NLO corrections large, well outside LO uncertainties

Motivation

New level of precision

- NLO corrections
- Full finite top mass effects

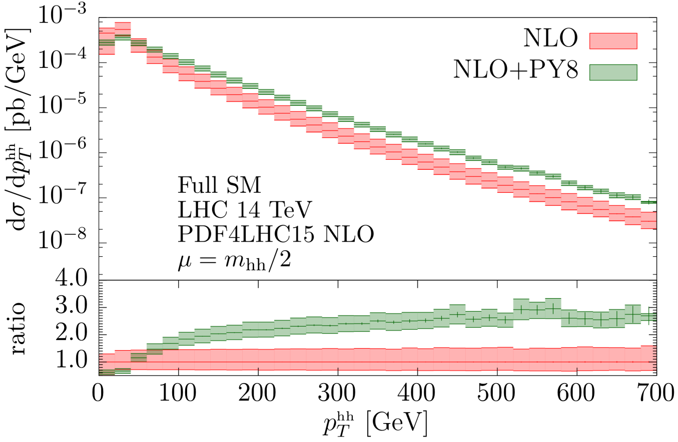
$\Rightarrow$ Meaningful fixed-order uncertainties

Fixed-order NLO not sufficient

- Small $p_\perp^{HH}$ region: spoiled by logs $\alpha_s^n \log^m \left[p_\perp^{HH}/m_{HH}\right]$
- Requires matching to parton shower / resummation

$\Rightarrow$ Need careful re-assessment of PS / matching uncertainties

Motivation



Heinrich et al.: JHEP 08 (2017)

Loop-Induced Processes at NLO in Sherpa

Born and real corrections

Interfaced from OpenLoops

Interface extended for color- and spin-correlated amplitudes

Infrared Substraction

Use Catani-Seymour method

Re-implemented for loop-induced external amplitudes

Process handling and interface to parton showers

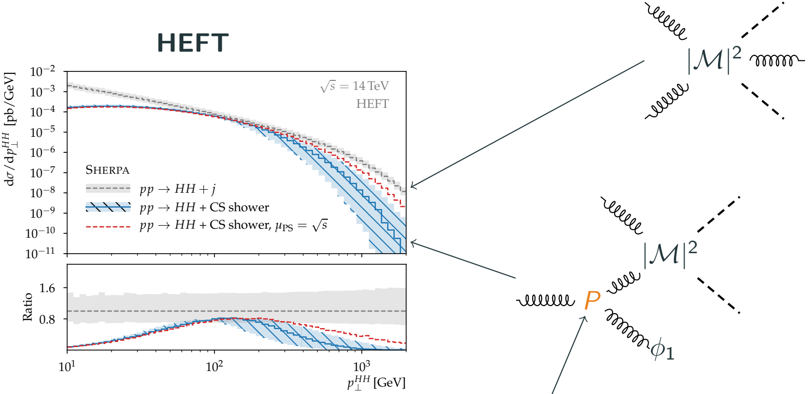
Re-implemented for loop-induced external amplitudes

Two parton showers available: CS shower / Dire shower

[Schumann, Krauss, JHEP 03 (2008)] [Höche, Prestel, Eur.Phys.J. C75 (2015)]

Parton Shower Effects at LO

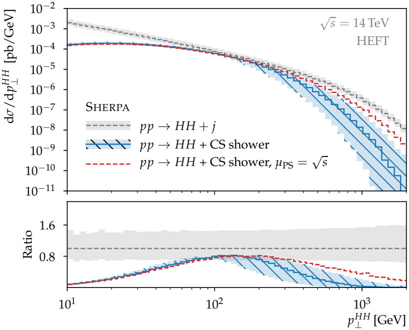
LO+PS Results

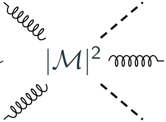


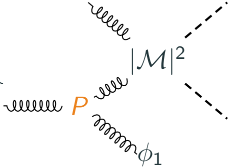
P: process independent parton shower kernels

LO+PS Results

HEFT







Uncertainty bands on LO+PS:

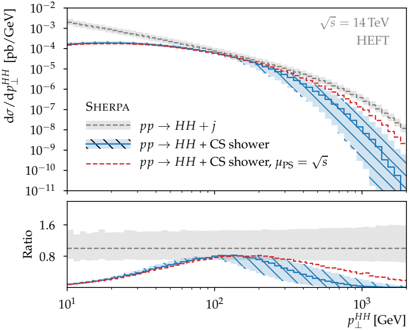
$\mu_{PS} \in \left\{ \frac{m_{HH}}{4}, \frac{m_{HH}}{2}, \frac{m_{HH}}{1} \right\}$

μ_{PS} implements phase space restriction: $t(\phi_1) < \mu_{PS}^2$

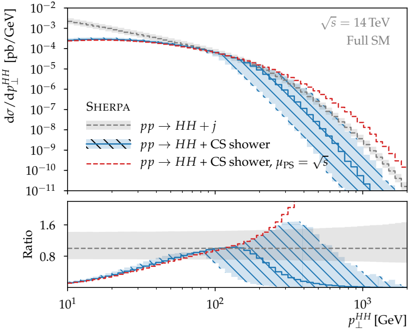
$\mu_{PS} = \sqrt{s} \to$ power shower, full phase space open

LO+PS Results

HEFT



Full SM



Qualitative differences between HEFT and full SM

- HEFT: PS approximation underestimates fixed-order
- Full SM: PS approximation overestimates fixed-order
- Sharply falling spectrum above m_t in full SM
- Parton shower kernels don't "know" hard process

Parton Shower Effects at NLO

NLO Parton Shower Matching: S-MC@NLO

$\sigma_{\text{NLO}} =$

$$\int \left[B(\phi_B) + V(\phi_B) + \int B(\phi_B) P(\phi_1) \Theta(\mu_{\text{PS}}^2 - t)\, \mathrm{d}\phi_1 \right] \mathrm{d}\phi_B$$

$$+ \int \left[R(\phi_R) - B(\phi_B) P(\phi_1) \Theta(\mu_{\text{PS}}^2 - t) \right] \mathrm{d}\phi_R$$

Modified subtraction

Use parton shower splitting kernels P for subtraction

Restrict subtraction terms to parton shower phase space

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Modified subtraction

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NLO Parton Shower Matching: S-MC@NLO

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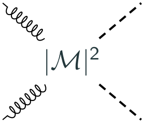
$$\int \bar{B}(\phi_B)\, \mathrm{d}\phi_B$$

S-events



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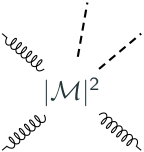
H-events



Interplay between parton shower and fixed order

NLO Parton Shower Matching: S-MC@NLO

Sudakov factor:
no-emission probability between μ^2_{PS} and t_0

$$\sigma_{\mathrm{MC@NLO}} =$$

$$\int \bar{B}(\phi_B) \left[\Delta(\mu^2_{\mathrm{PS}}, t_0) + \int \Delta(\mu^2_{\mathrm{PS}}, t) P(\phi_1) \Theta(\mu^2_{\mathrm{PS}} - t)\, \mathrm{d}\phi_1 \right] \mathrm{d}\phi_B$$

$$+ \int \left[R(\phi_R) - B(\phi_B) P(\phi_1) \Theta(\mu^2_{\mathrm{PS}} - t) \right] \mathrm{d}\phi_R$$

P: splitting kernel

Interplay between parton shower and fixed order

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Interplay between parton shower and fixed order

Consider observable insensitive to born kinematics ($p_\perp^{HH}$)

NLO Parton Shower Matching: S-MC@NLO

$$\sigma_{\text{MC@NLO}} =$$

$$\int \bar{B}(\phi_B)\Delta(\mu^2_{\text{PS}}, t)P(\phi_1)\Theta(\mu^2_{\text{PS}} - t)\,\mathrm{d}\phi_1\,\mathrm{d}\phi_B + \qquad \text{S-events}$$

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Consider observable insensitive to born kinematics ($p_\perp^{HH}$)

Focus on soft region: $t \ll \mu^2_{\text{PS}} \Rightarrow$ recover LO+PS with local K-factor

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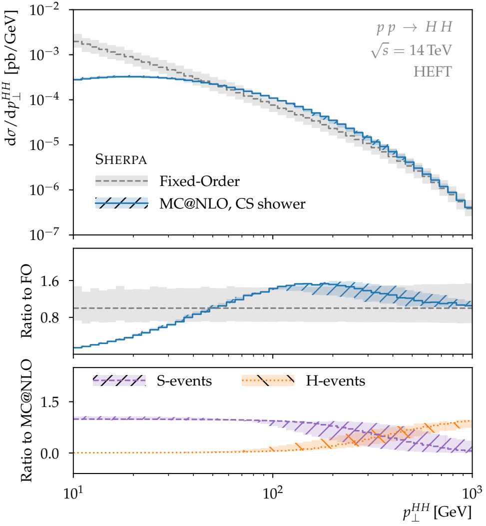
Interplay between parton shower and fixed order

Consider observable insensitive to born kinematics ($p_\perp^{HH}$)

Focus on soft region: $t \ll \mu_{\text{PS}}^2 \Rightarrow$ recover LO+PS with local K-factor

Focus on hard region: $t \approx \mu_{\text{PS}}^2 \Rightarrow$ recover fixed order, assuming $\bar{B} \approx B$

NLO Results



HEFT approximation

- μ_{PS} cancellation between S- and H-events
- PS uncertainties reduced
- Recover fixed-order in tail

$$\bar{B}(\phi_B)\Delta(\mu_{\text{PS}}^2, t)P(\phi_1)\Theta(\mu_{\text{PS}}^2 - t)\,\mathrm{d}\phi_B\,\mathrm{d}\phi_1$$

S-events

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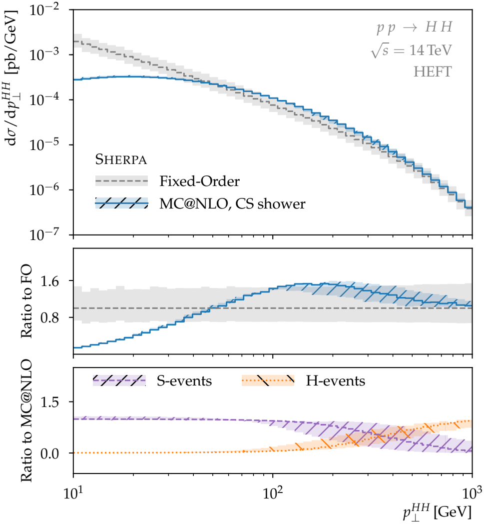
H-events

NLO Results



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$$(\bar{B} - B) \times P \ll R$$

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S-events

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H-events

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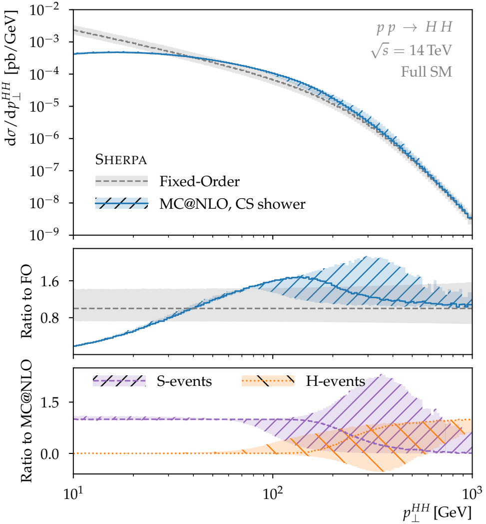

Full SM

- much larger uncertainties
- PS effects extend into tail
- large $\mu_{\mathrm{PS}} \Rightarrow$ don't recover fixed order

$$(\bar{B} - B) \times P \sim R$$

$$\bar{B}(\phi_B)\Delta(\mu_{\mathrm{PS}}^2, t)P(\phi_1)\Theta(\mu_{\mathrm{PS}}^2 - t)\,\mathrm{d}\phi_B\,\mathrm{d}\phi_1$$

S-events

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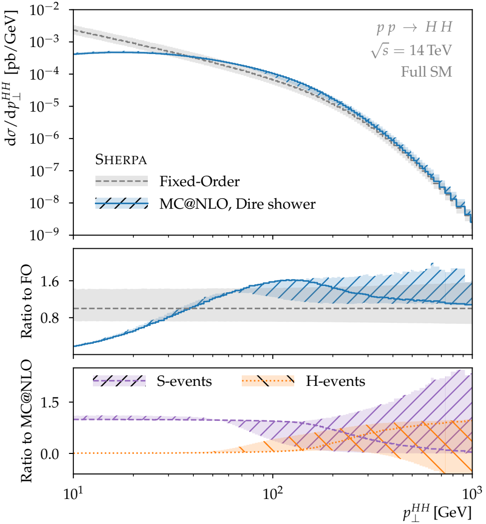
H-events

NLO Results



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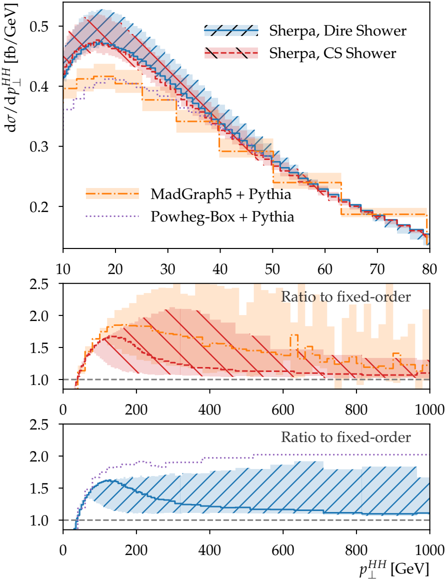
$$\Big[R(\phi_R) - B(\phi_B)P(\phi_1)\Theta(\mu_{\mathrm{PS}}^2 - t)\Big]\,\mathrm{d}\phi_R$$

H-events

Comparison to Literature: NLO+PS



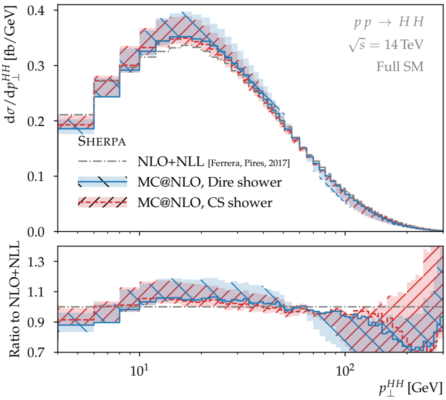
Heinrich et al.: JHEP 08 (2017)

- Larger differences in peak region due to differences in algorithms beyond choice of μ_{PS}: 15 %

- MC@NLO results within uncertainties in tail
  MadGraph uncertainties larger

- POWHEG: flat excess in tail
  known feature of matching method somewhat suppressed through "damping factor" $h_{damp} = 250$ GeV

Comparison to Literature: Analytic Resummation



Ferrera, Pires: JHEP 02 (2017)

- Next-to-leading log (NLL) parametrically equivalent to parton shower
- Uncertainties on NLO+NLL:
  3 % near $p_\perp^{HH} \approx 20$GeV
  10 % near $p_\perp^{HH} \approx 100$GeV
- Good agreement within uncertainties

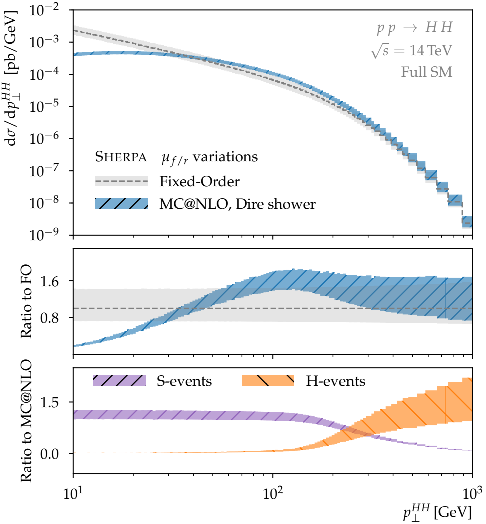
Conclusions

- Recent advances at fixed-order $\Rightarrow$ reduced uncertainties
- Studied uncertainties introduced though parton shower matching
- Found good agreement with analytic resummation
- Matching to fixed-order at large $p_\perp^{HH}$ requires judicious choice of μ_{PS}
- μ_{PS} variations may exceed FO uncertainties

$\Rightarrow$ Is μ_{PS} source of uncertainty or tuning parameter?

Backup

Effects on Fixed-Order Uncertainties



Full SM

- At small $p_\perp^{HH}$: NLO uncertainties
  seed cross section ($\bar{B}$) more inclusive

- At large $p_\perp^{HH}$: LO uncertainties
  seed cross section (R) 1-jet exclusive

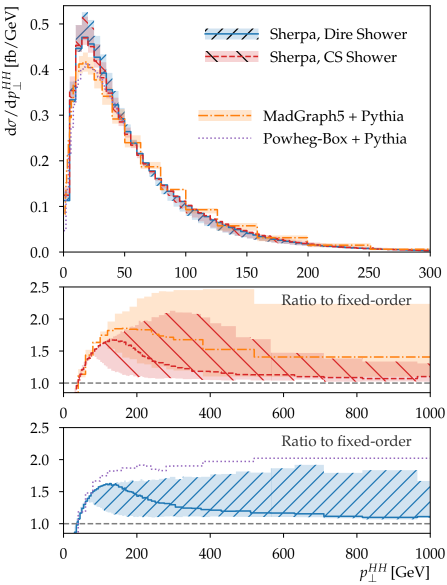
$$\bar{B}(\phi_B)\Delta(\mu_{\text{PS}}^2, t)P(\phi_1)\Theta(\mu_{\text{PS}}^2 - t)\, d\phi_B\, d\phi_1$$

S-events

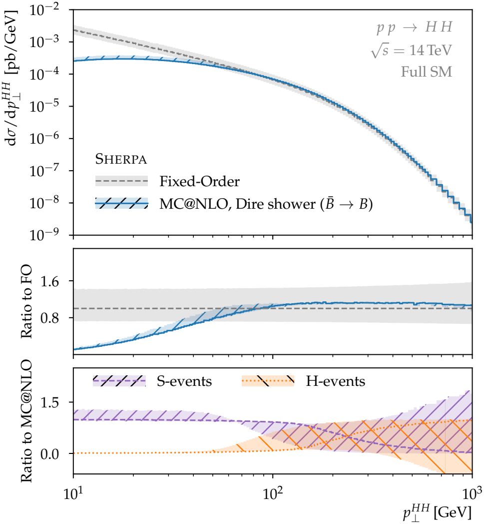
$$\left[R(\phi_R) - B(\phi_B)P(\phi_1)\Theta(\mu_{\text{PS}}^2 - t)\right] d\phi_R$$

H-events

NLO+PS: Alternative Comparison Plot



Replacing $\bar{B}$ by B



$$\bar{B}(\phi_B)\Delta(\mu_{\mathrm{PS}}^2, t)P(\phi_1)\Theta(\mu_{\mathrm{PS}}^2 - t)\,\mathrm{d}\phi_B\,\mathrm{d}\phi_1$$

S-events

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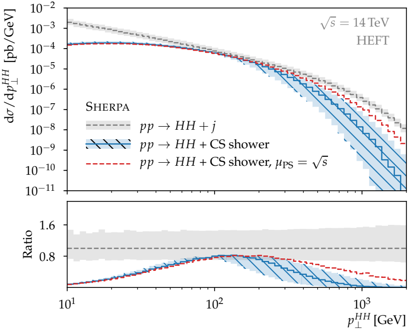
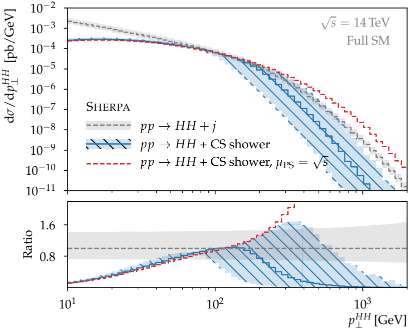
H-events

LO+PS Results: CS Shower

HEFT



Full SM



Uncertainty bands on LO+PS:

$\mu_{PS}^{CS} \in \left\{ \frac{m_{HH}}{4}, \frac{m_{HH}}{2}, \frac{m_{HH}}{1} \right\}$

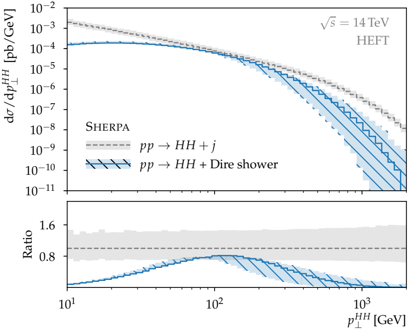
$\mu_{PS}^{Dire} \in \left\{ \frac{m_{HH}}{8}, \frac{m_{HH}}{4}, \frac{m_{HH}}{2} \right\}$

$\mu_{PS}^{CS} = \sqrt{s} \to$ power shower

$\mu_{PS}^{Dire} = \frac{m_{HH}}{2} \to$ power shower

LO+PS Results: Dire Shower

HEFT



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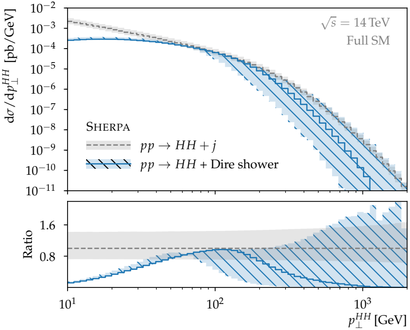

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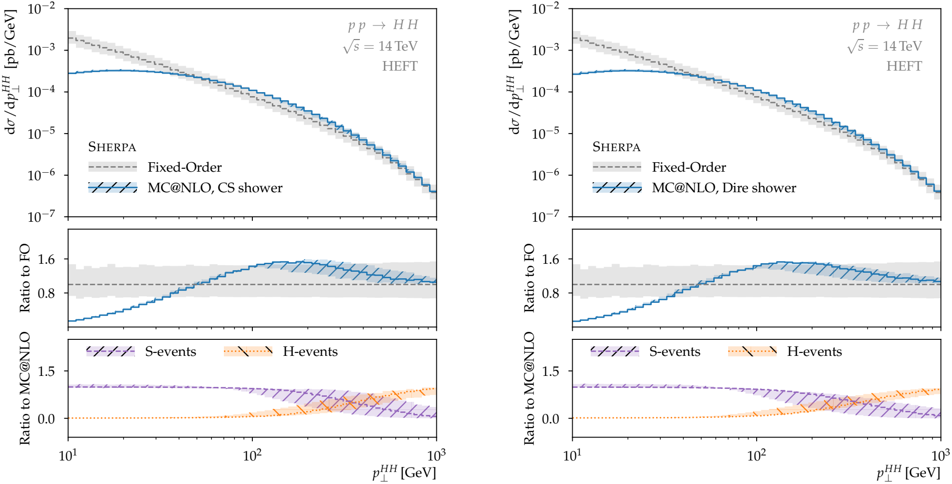
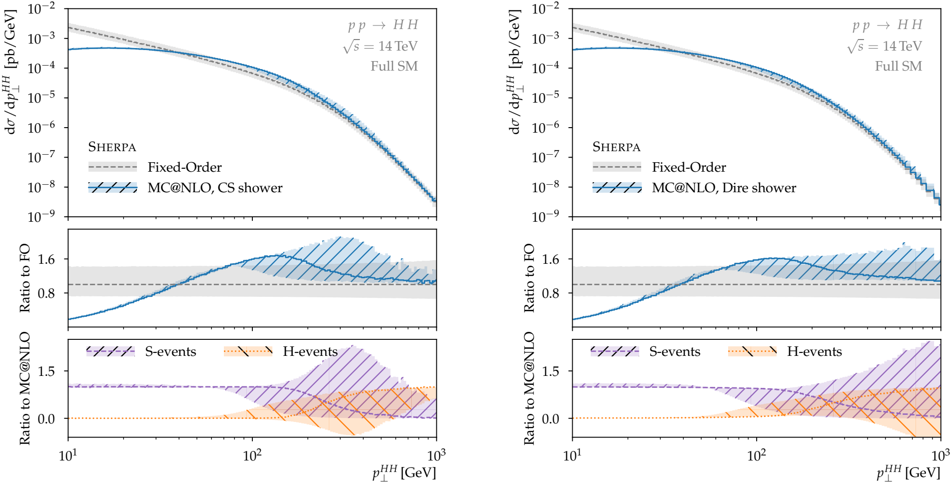
$\mu_{\text{PS}}^{\text{Dire}} \in \left\{ \frac{m_{HH}}{8}, \frac{m_{HH}}{4}, \frac{m_{HH}}{2} \right\}$ $\qquad \mu_{\text{PS}}^{\text{Dire}} = \frac{m_{HH}}{2} \to$ power shower

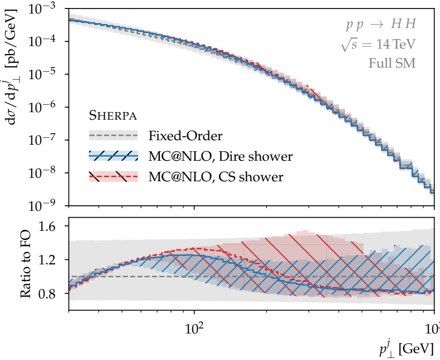
CS shower vs Dire: HEFT

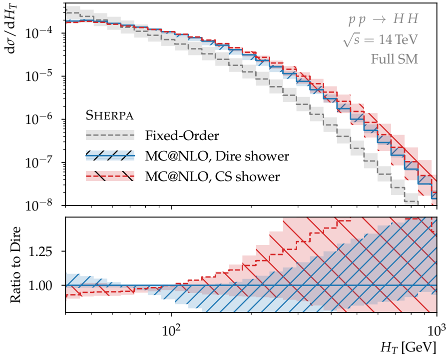


CS shower vs Dire: Full SM



Other Observables





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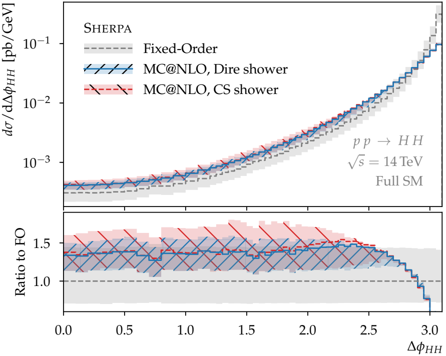
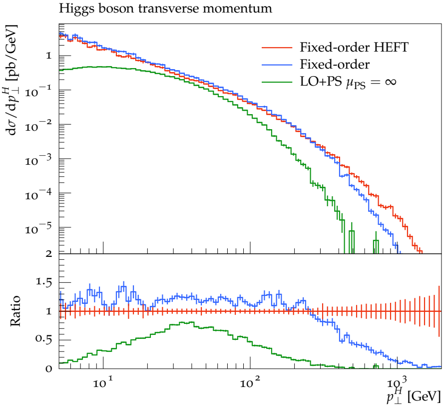
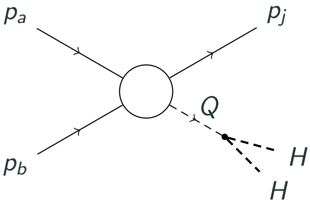


Single Higgs



Parton shower kinematics



$$\hat{t} = (p_a - p_j)^2$$
$$\hat{u} = (p_b - p_j)^2$$
$$\hat{s} = (p_a + p_b)^2$$

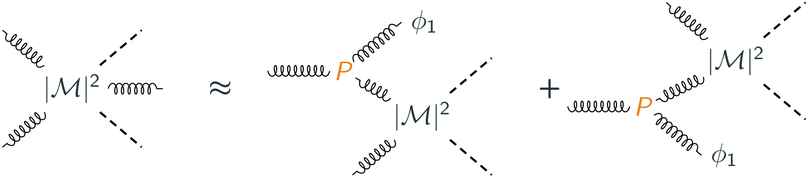
$$v = \frac{p_a p_j}{p_a p_b} = \frac{-\hat{t}}{\hat{s}} \geq 0 \qquad w = \frac{p_b p_j}{p_a p_b} = \frac{-\hat{u}}{\hat{s}} \geq 0$$

$$\hat{s} + \hat{t} + \hat{u} = Q^2 \quad \Rightarrow \quad v + w = (1 - \frac{Q^2}{\hat{s}}) < 1 \quad \Rightarrow \quad vw < \frac{1}{4}$$

$$\frac{t^{\text{Dire}}}{Q^2} = \frac{(p_a p_j)(p_b p_j)}{(p_a p_b)^2} = vw \qquad t^{\text{Dire}} < \frac{Q^2}{4}$$

$$\frac{t^{\text{CSS}}}{Q^2} = \frac{vw}{1 - (v + w)}.$$

Parton Shower Simulations



Soft and Collinear Limit

Hardness parameter / evolution variable $t(\phi_1) \to 0$

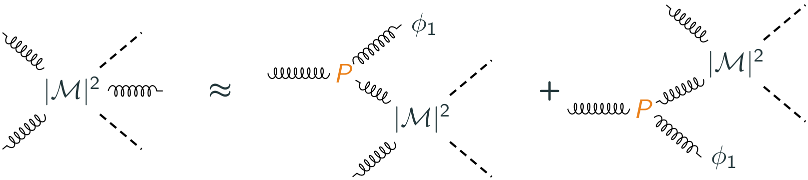
Matrix elements factorize

Derive process independent splitting kernels ***P***

Generate soft/collinear emissions probabilistically according to P

Parton shower scale implements phase space restriction: $t(\phi_1) < \mu^2_{\mathsf{PS}}$

Parton Shower Simulations



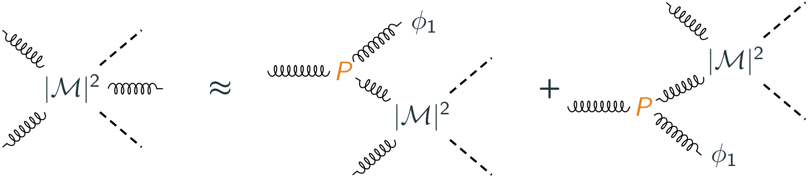
Sudakov form factor

$$\Delta(t_1, t_0) = \exp\left[-\int_{t_0}^{t_1} P(\phi_1)\,\mathrm{d}\phi_1\right]$$

No-emission probability between scales t_0 and t_1

Parton shower scale implements phase space restriction: $t(\phi_1) < \mu_{\mathsf{PS}}^2$

Parton Shower Simulations



Leading order plus parton shower cross section

$$\sigma_{\text{LO+PS}} = \int B(\phi_B)\left[\Delta(\mu_{\text{PS}}^2, t_0) + \int_{t_0}^{\mu_{\text{PS}}^2} \Delta(\mu_{\text{PS}}^2, t(\phi_1))P(\phi_1)\,\mathrm{d}\phi_1\right]\mathrm{d}\phi_B$$

no emission — hardest emission at $t(\phi_1)$

Parton shower scale implements phase space restriction: $t(\phi_1) < \mu_{\text{PS}}^2$

POWHEG

$\sigma_{\text{NLO}} =$

$$\int \left[B(\phi_B) + V(\phi_B) + \int R(\phi_B, \phi_1)\, \mathrm{d}\phi_1 \right] \mathrm{d}\phi_B$$

$$+ \int \left[R(\phi_R) - R(\phi_R) \right] \mathrm{d}\phi_R$$

$P = \frac{R}{B}$

POWHEG

$$\sigma_{\text{NLO}} =$$

$$\int \left[B(\phi_B) + V(\phi_B) + \int \frac{h_{\text{damp}}^2}{p_\perp^2 + h_{\text{damp}}^2} R(\phi_B, \phi_1)\, \mathrm{d}\phi_1 \right] \mathrm{d}\phi_B$$

$$+ \int \left[R(\phi_R) - \frac{h_{\text{damp}}^2}{p_\perp^2 + h_{\text{damp}}^2} R(\phi_R) \right] \mathrm{d}\phi_R$$

$$P = \frac{\frac{h_{\text{damp}}^2}{p_\perp^2 + h_{\text{damp}}^2} R}{B}$$