An introduction to POWHEG

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Important references:

hep-ph/0409146, arXiv:0709.2092, arXiv:1002.2581

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Outline

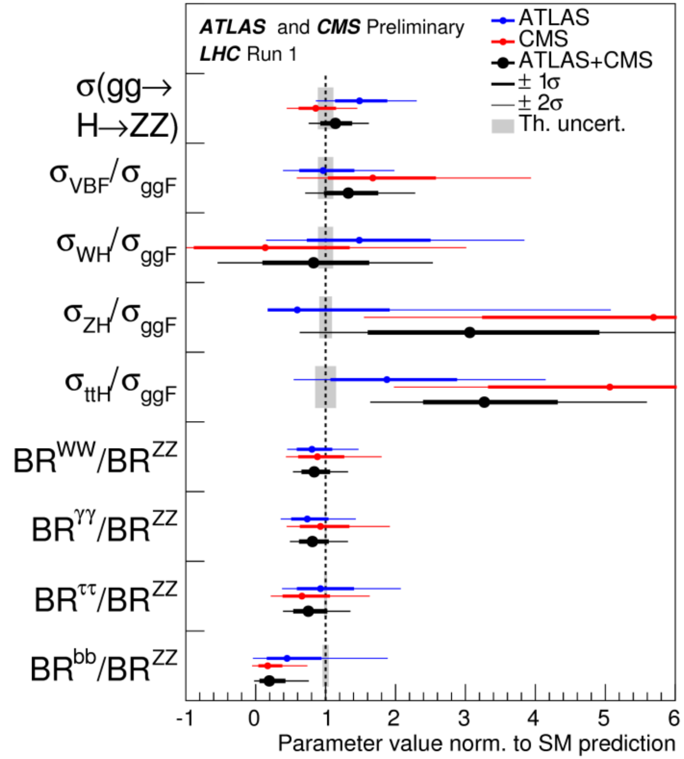
- Brief motivation: the quest of precision
- Monte Carlo (MC) event generators
- Parton shower vs fixed order calculations
- How to merge NLO+PS: the POWHEG master formula
- Phenomenological impact
- Conclusions and outlook

Motivation: the quest for precision

New Physics at the LHC?

- After Higgs boson discovery focus on its properties and on hints for BSM physics
  - So far no sign of new physics at the TeV scale from direct searches
- Possible hits for new physics could come from very precise measurements e.g. in the Higgs sector
  - Very accurate predictions are needed, both
    - in shape
    - in normalization

Precise description of scattering process at all stages!



Monte Carlo Event Generators

What they are and what they do

PDF‘s

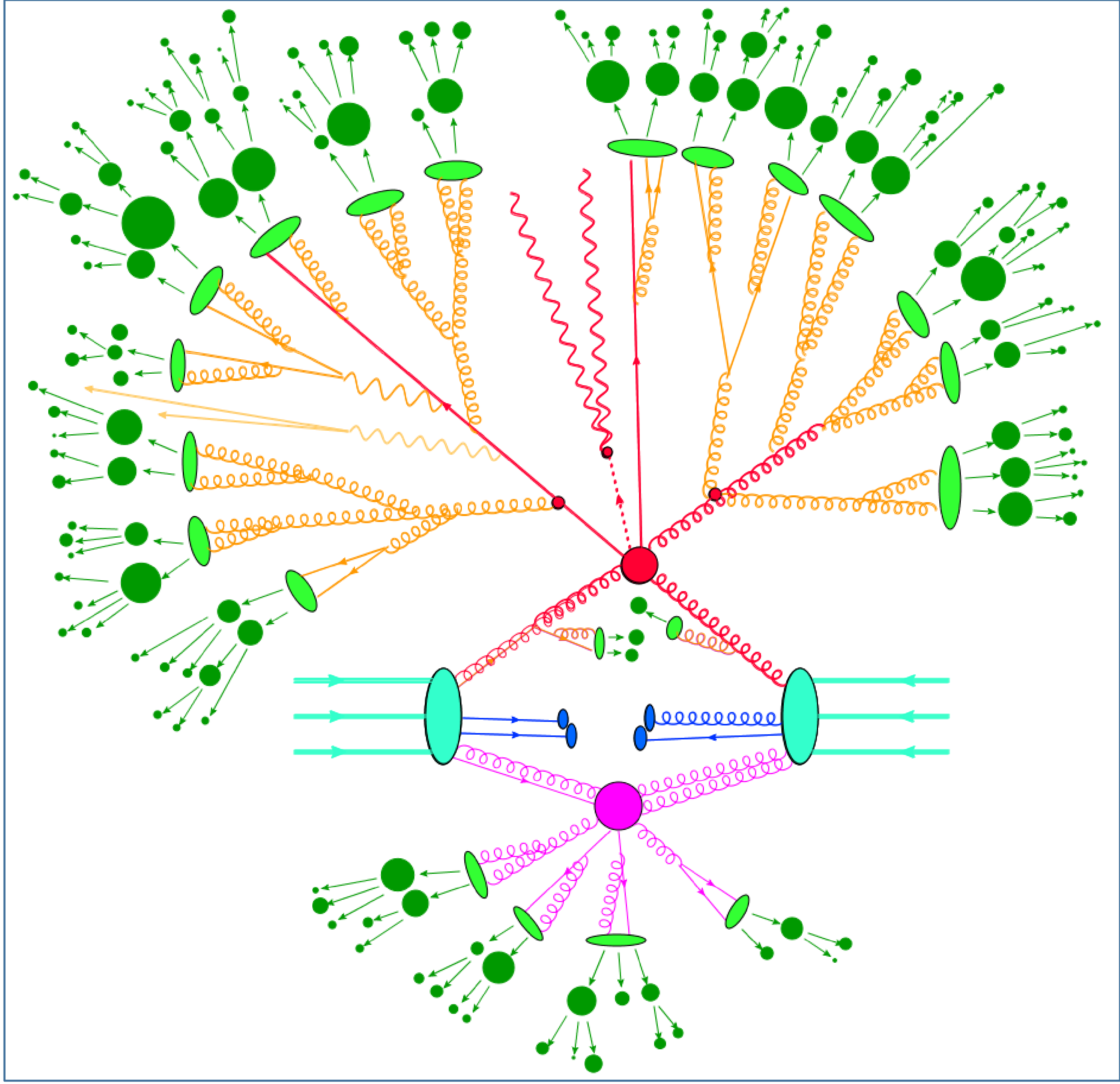
Hard scattering
$\Lambda_{QCD} \ll \mu \approx Q$

Parton shower
$\Lambda_{QCD} < \mu < Q$

Beam remnants

Hadronization and
Hadron decay
$\mu \approx \Lambda_{QCD}$

Multiple interactions



PDF's → Determined from data

Hard scattering $\Lambda_{QCD} \ll \mu \approx Q$ → Hard process computed using fixed order (FO) perturbation theory at LO, NLO, NNLO, N^3LO,…

Parton shower $\Lambda_{QCD} < \mu < Q$ → Hierarchy of scales appearing as large logarithms in the calculation. Computed using resummation or MC parton showers (PS)

Beam remnants

Hadronization and Hadron decay $\mu \approx \Lambda_{QCD}$

Multiple interactions

→ Cannot be computed directly: non-perturbative models tuned to e^+e^- data

$$\sigma_{h_1 h_2 \to X} = \sum_{a,b} \int_0^1 dx_1 dx_2 \underbrace{f_{h_1/a}(x_1, \mu_F^2)\, f_{h_2/b}(x_2, \mu_F^2)}_{\text{PDFs}} \times \underbrace{\hat{\sigma}_{a,b\to X}\left(x_1, x_2, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)}_{\text{partonic cross section}} \underbrace{\left[+\mathcal{O}\left(\frac{1}{Q^2}\right)\right]}_{\text{np corrections}}$$

PDF's → Determined from data → PDF set

Hard scattering $\Lambda_{QCD} \ll \mu \approx Q$ → Hard process computed using fixed order (FO) perturbation theory at LO, NLO, NNLO, N^{3}LO,… → Theorists' calculation

FO + PS matching: different orders ↔ different schemes

Parton shower $\Lambda_{QCD} < \mu < Q$ → Hierarchy of scales appearing as large logarithms in the calculation. Computed using resummation or MC parton showers (PS) → Theorists' calculation, Pythia, Herwig, …

Beam remnants

Hadronization and Hadron decay $\mu \approx \Lambda_{QCD}$

Multiple interactions

→ Cannot be computed directly: non-perturbative models tuned to e$^+$e$^-$ data → Pythia, …

$$\sigma_{h_1 h_2 \to X} = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{h_1/a}(x_1, \mu_F^2)\, f_{h_2/b}(x_2, \mu_F^2) \times \hat{\sigma}_{a,b\to X}\left(x_1, x_2, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right) \left[+\mathcal{O}\left(\frac{1}{Q^2}\right)\right]$$

PDFs — partonic cross section — np corrections

- Monte Carlo Event Generators try to give the best full description of a collision combining theoretical predictions for the different stages of an event and providing a fully exclusive final state in terms of hadrons and leptons which is as close as possible to what is measured in a real experiment

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS	V-X	V-Y	V-Z	V-C*T
30	NU_E	12	1	28	23	0	0	64.30	25.12	-1194.4	1196.4	0.00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
31	E+	-11	1	29	23	0	0	-22.36	6.19	-234.2	235.4	0.00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
230	PI0	111	1	155	24	0	0	0.31	0.38	0.9	1.0	0.13	4.209E-11	6.148E-11	-3.341E-11	5.192E-10
231	RHO+	213	197	155	24	317	318	-0.06	0.07	0.1	0.8	0.77	4.183E-11	6.130E-11	-3.365E-11	5.189E-10
232	P	2212	1	156	24	0	0	0.40	0.78	1.0	1.6	0.94	4.156E-11	6.029E-11	-4.205E-11	5.250E-10
233	NBAR	-2112	1	156	24	0	0	-0.13	-0.35	-0.9	1.3	0.94	4.168E-11	6.021E-11	-4.217E-11	5.249E-10
234	PI-	-211	1	157	9	0	0	0.14	0.34	286.9	286.9	0.14	4.660E-13	8.237E-12	1.748E-09	1.749E-09
235	PI+	211	1	157	9	0	0	-0.14	-0.34	624.5	624.5	0.14	4.056E-13	8.532E-12	2.462E-09	2.462E-09
236	P	2212	1	158	9	0	0	-1.23	-0.26	0.9	1.8	0.94	-4.815E-11	1.893E-11	7.520E-12	3.252E-10
237	DLTABR--	-2224	197	158	9	319	320	0.94	0.35	1.6	2.2	1.23	-4.817E-11	1.900E-11	7.482E-12	3.252E-10
238	PI0	111	1	159	9	0	0	0.74	-0.31	-27.9	27.9	0.13	-1.889E-10	9.893E-11	-2.123E-09	2.157E-09
239	RHO0	113	197	159	9	321	322	0.73	-0.88	-19.5	19.5	0.77	-1.888E-10	9.859E-11	-2.129E-09	2.163E-09
240	K+	321	1	160	9	0	0	0.58	0.02	-11.0	11.0	0.49	-1.890E-10	9.873E-11	-2.135E-09	2.169E-09
241	KL_1-	-10323	197	160	9	323	324	1.23	-1.50	-50.2	50.2	1.57	-1.890E-10	9.879E-11	-2.132E-09	2.166E-09
242	K-	-321	1	161	24	0	0	0.01	0.22	1.3	1.4	0.49	4.250E-11	6.333E-11	-2.746E-11	5.211E-10
243	PI0	111	1	161	24	0	0	0.31	0.38	0.2	0.6	0.13	4.301E-11	6.282E-11	-2.751E-11	5.210E-10

- Can be fed to a detector-simulation software to determine efficiencies

Parton showers and fixed order

Two complementary approach for parton level computations

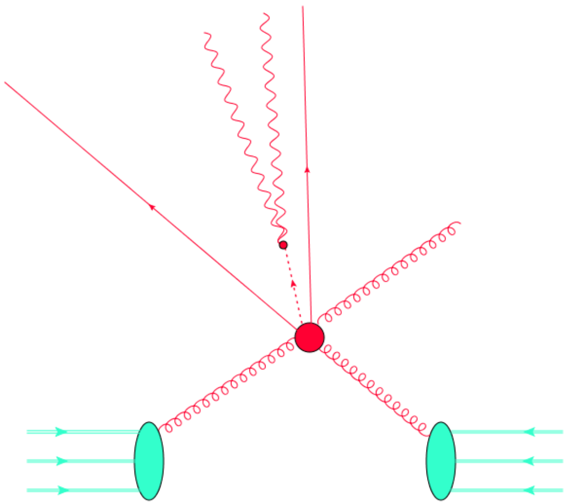
Basics on parton showers

- Describe evolution from hard process at scale Q to low energy (long distance) non-perturbative physics at scale Λ_{QCD}

- Proceeds via successive quark & gluon production

➢ Start from a low multiplicity process at high Q

➢ Color-charged partons like to radiate



Basics on parton showers

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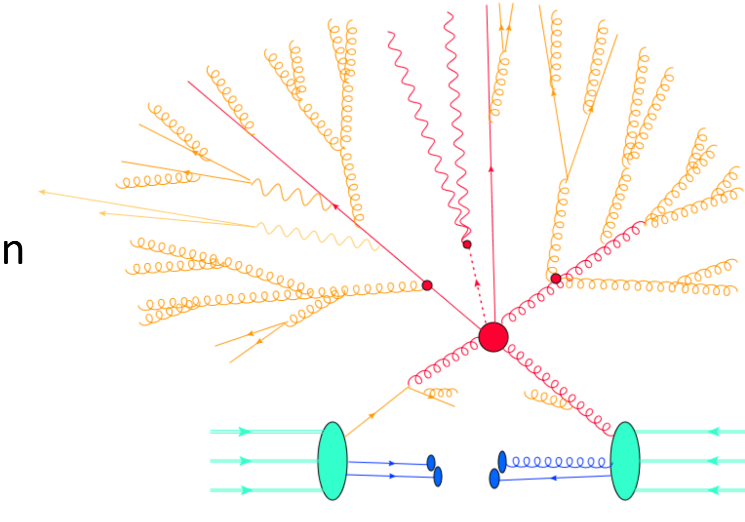
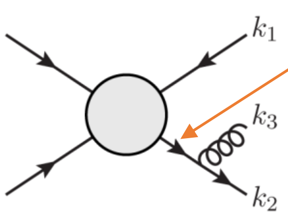
➢ Start from a low multiplicity process at high Q

➢ Color-charged partons like to radiate

➢ Leading contribution from soft/collinear emissions (propagators become small)

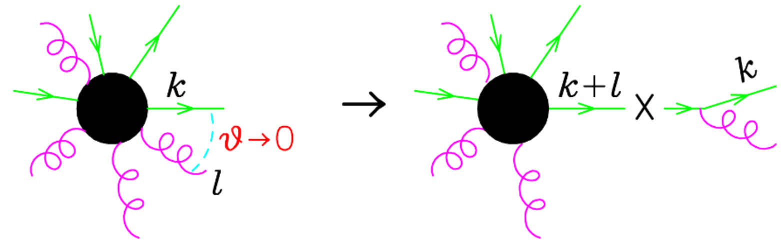




$$\frac{1}{(k_2 + k_3)^2} = \frac{1}{2E_2E_3\,(1 - \cos\theta_{23})} \longrightarrow \infty \quad \text{if} \quad E_3 \to 0 \quad \text{or} \quad \theta_{23} \to 0.$$

Basics on parton showers

- In this limit QCD amplitudes factorize:



  - Factorization of phase space: $d\mathbf{\Phi}_{n+1} = d\mathbf{\Phi}_n \, d\Phi_r$ $\qquad d\Phi_r \div dt\, dz\, d\varphi$

  - Factorization of matrix element:

$$|M_{n+1}|^2 d\mathbf{\Phi}_{n+1} \Longrightarrow |M_n|^2 \, d\mathbf{\Phi}_n \boxed{\frac{\alpha_s}{2\pi} \frac{dt}{t} P_{q,qg}(z)\, dz \, \frac{d\varphi}{2\pi}}$$

$$\begin{cases} \dfrac{dt}{t} \approx \dfrac{d\theta}{\theta} & \text{collinear singularity} \\ \dfrac{dz}{1-z} \approx \dfrac{dE_g}{E_g} & \text{soft singularity} \end{cases}$$

t : $(k+l)^2,\ p_T^2,\ E^2\theta^2 \ldots$

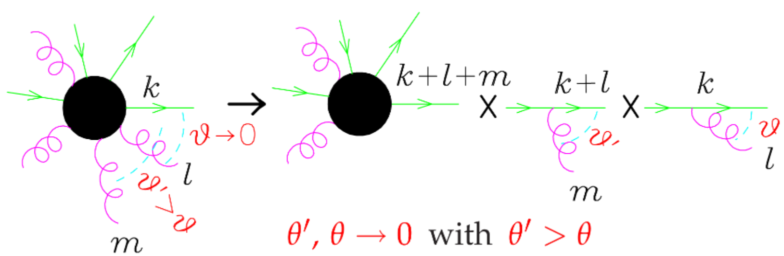
$z = k^0/(k^0+l^0)$: energy (or $p_\parallel$ or p^+) fraction of quark

$P_{q,qg}(z) = C_F \dfrac{1+z^2}{1-z}$: Altarelli-Parisi splitting function

(ignore $z \to 1$ IR divergence for now)

Gives rise to double logarithmic structure $\alpha_s L^2$

  - For successive emissions iterate this formula:

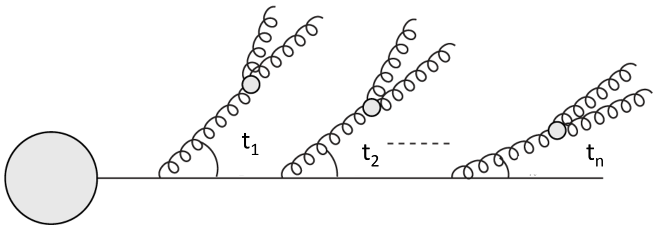


$\theta', \theta \to 0$ with $\theta' > \theta$

$$|M_{n+1}|^2 d\mathbf{\Phi}_{n+1} \Longrightarrow |M_{n-1}|^2 d\mathbf{\Phi}_{n-1} \times \frac{\alpha_s}{2\pi}\frac{dt'}{t'} P_{q,qg}(z')\, dz' \frac{d\varphi'}{2\pi} \times \frac{\alpha_s}{2\pi}\frac{dt}{t} P_{q,qg}(z)\, dz \frac{d\varphi}{2\pi}\, \theta(t'-t)$$

Basics on parton showers

- Dominant contribution comes from strongly ordered emissions



$t_1 > t_2 > \ldots > t_n$

- Virtual corrections are also taken into account in the same approximation (they have same structure but opposite sign) leading to a Sudakov form factor $\Delta(t_1, t_2)$:

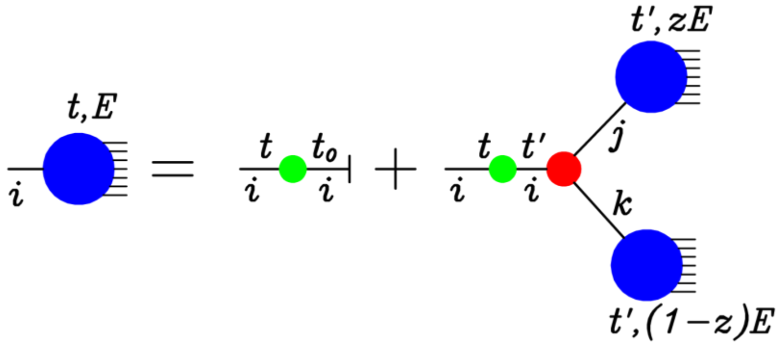
$$\Delta(t_1, t_2) \equiv \exp\left\{-\int_{t_2}^{t_1} \frac{dt}{t} \frac{\alpha_S(t)}{2\pi} \int dz\, P_{i,jk}(z)\right\}$$

  - Corresponds to the probability of having no resolved emission between t_1 and t_2

- Therefore, Shower Monte Carlo (SMC) cross section for first emission given by ($d\Phi_r = dt\, dz\, d\varphi$)

$$\langle O \rangle = \int d\mathbf{\Phi}_n\, B(\mathbf{\Phi}_n) \left\{ O(\mathbf{\Phi}_n)\Delta_{t_0} + \int_{t_0} \frac{dt}{t}\, dz\, d\varphi\, O(\mathbf{\Phi}_n, \Phi_r)\, \Delta_t \frac{\alpha_S}{2\pi} P(z) \right\}$$

Basics on parton showers: final recipe



$$\mathcal{S}_i(t,E) = \Delta_i(t,t_0)\,\mathbb{1} + \sum_{(jk)} \int_{t_0}^{t} \frac{\alpha_S(t')}{2\pi} \frac{dt'}{t'} \int dz \int \frac{d\varphi}{2\pi}\, \Delta_i(t,t')\, P_{i,jk}(z)\, \mathcal{S}_j(t',zE)\; \mathcal{S}_k(t',(1-z)E)$$

- Consider all Born graphs
- At each vertex: generate radiation variables and include factor $\frac{dt}{t}\, dz\, \frac{\alpha_s(t)}{2\pi} P_{i,jk}(z) \frac{d\varphi}{2\pi}$
- Include a factor $\Delta_i(t_1, t_2)$ to each internal parton i from hardness t1 to hardness t2
- Include a factor $\Delta_i(t, t_0)$ on final lines (t_0 is IR cutoff)

- This allows to resum the leading logarithmic contributions to all orders
  - Probabilistic formulation of shower evolution
  - Can change shapes of distributions but not the overall normalization: at the inclusive level the cross section remains unchanged (unitarity of PS)
  - Attaching this to a LO matrix element allows to reach LO+LL accuracy

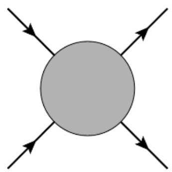
Fixed order calculations

- **Partonic cross section:** for hard processes computed as series exp. in the strong coupling $\alpha_s \sim 0.1$

$$\hat{\sigma}_{a,b\to X} = \alpha_s^n \left[\sigma_0 + \alpha_s\sigma_1 + \alpha_s^2\sigma_2 + \alpha_s^3\sigma_3 + \mathcal{O}(\alpha_s^4)\right]$$

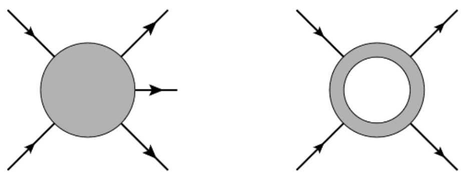
LO | NLO | NNLO | N^3LO

- LO:



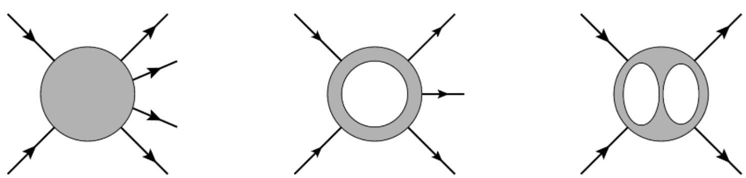
Predicts only the order of magnitude:
- scale in coupling is not defined
- 1 parton ⟷ 1 jet

- NLO:



First reliable predictions:
- scale choices can be made
- first description of jet substructure

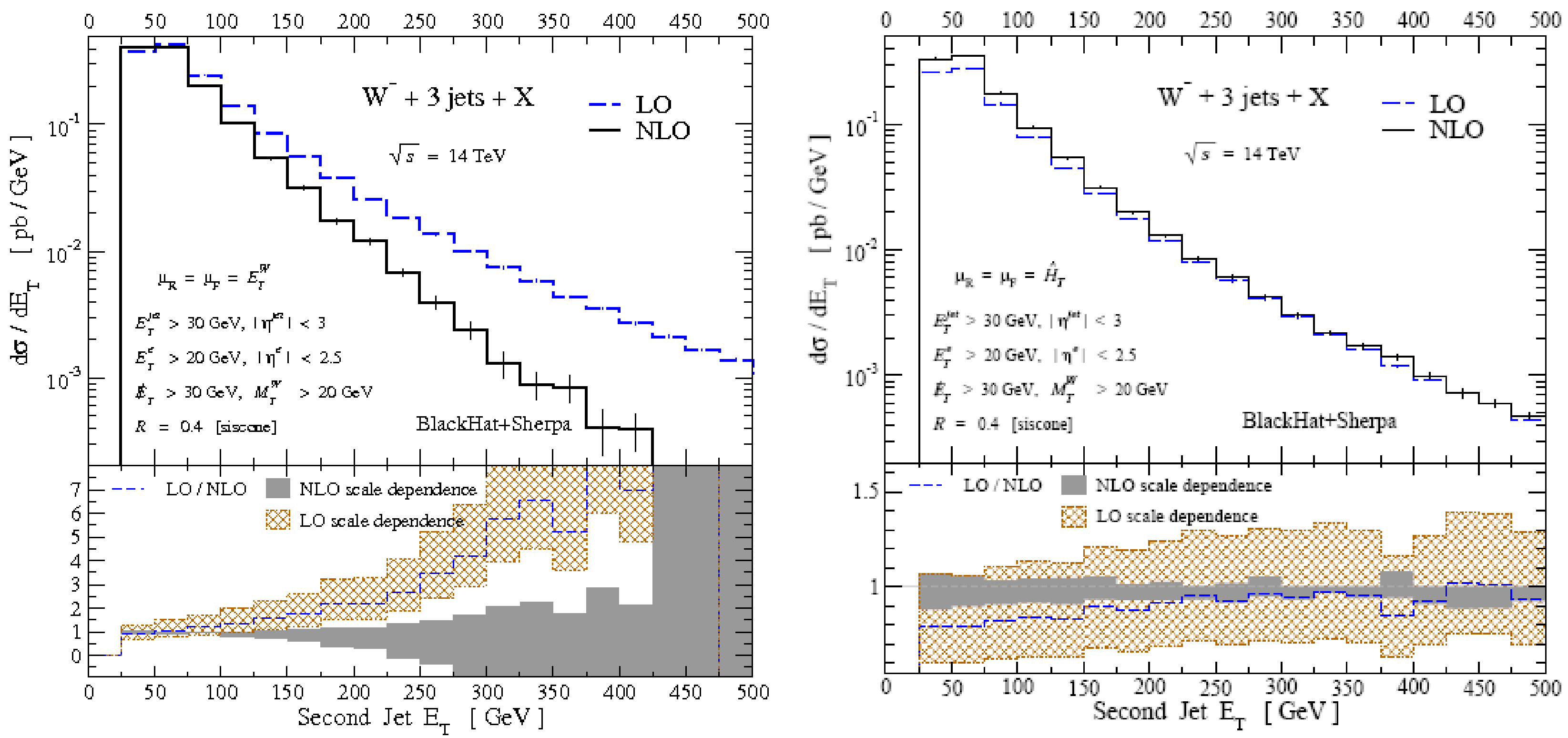
- NNLO:



Possible to quantify uncertainties:
- convergence can be checked
- richer jet substructure

Importance of NLO calculations

- To control the theoretical uncertainties in the computation of LHC processes NLO predictions are needed:

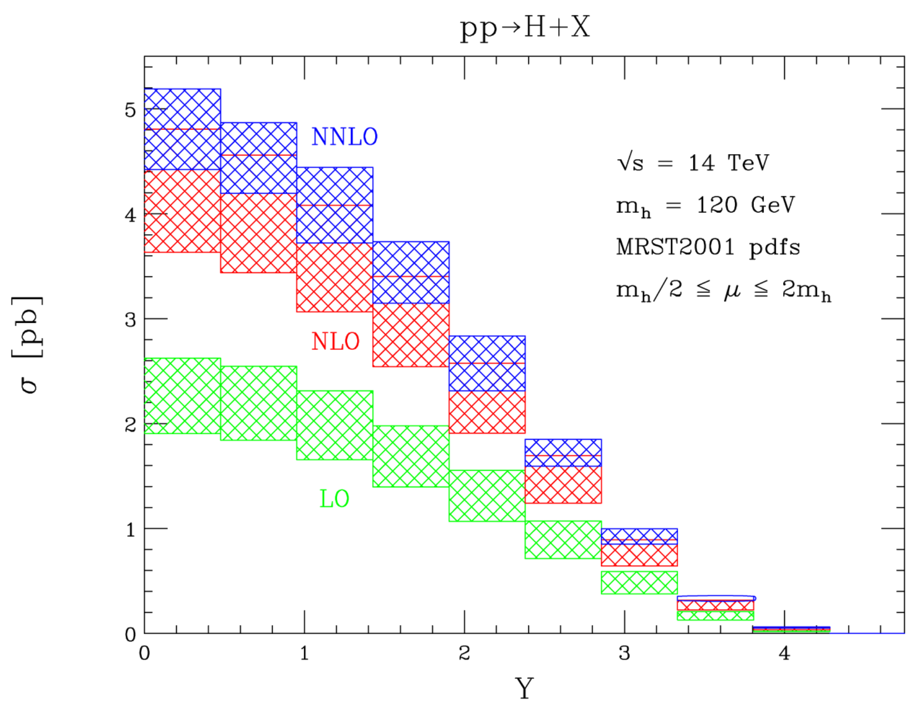


Consequences of a bad (wrong) scale choice!

Sometimes not even NLO is enough

- In some processes NLO corrections are still large: need to compute cross section at even higher accuracy to obtain a precise theoretical prediction

- Canonical example: Higgs boson production



[Anastasiou, Melnikov, Petriello, '05]

- Huge NLO [O(100%)] and NNLO [O(20%)] effects!

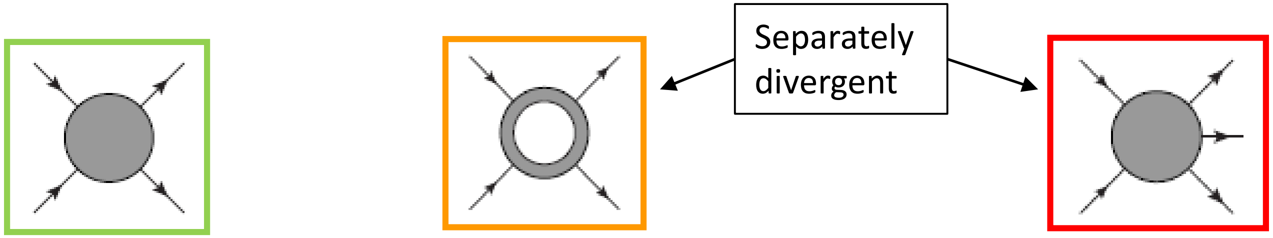
- Now known at N^3LO:

LO	$15.05 \pm 14.8\%$
NLO	$38.2 \pm 16.6\%$
NNLO	$45.1 \pm 8.8\%$
N3LO	$45.2 \pm 1.9\%$

[Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger, '15-'16]

Structure of a NLO calculation

- NLO calculation for an observable O consists of different ingredients:



$$\langle O \rangle = \int O \, d\sigma = \int d\mathbf{\Phi}_n \, O(\mathbf{\Phi}_n) \left[B(\mathbf{\Phi}_n) + V_b(\mathbf{\Phi}_n) \right] + \int d\mathbf{\Phi}_n \, d\Phi_r \, O(\mathbf{\Phi}_n, \Phi_r) \, R(\mathbf{\Phi}_n, \Phi_r)$$

- [Parametrized (n+1)-body phase space Φ_{n+1} in terms of Born and radiation $\mathbf{\Phi}_{n+1} = \{\mathbf{\Phi}_n, \Phi_r\}$]

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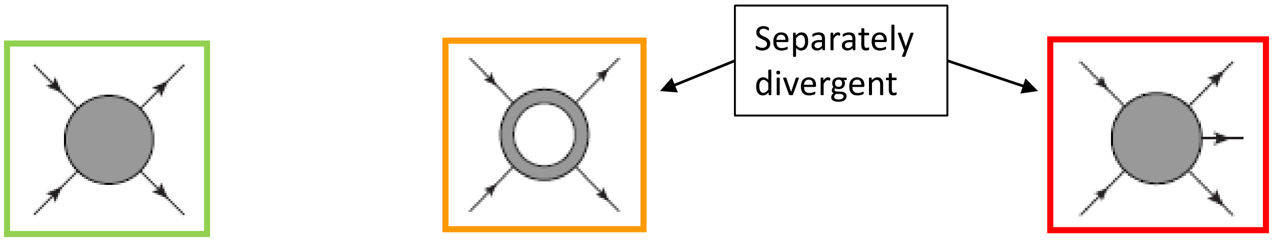


$$\langle O \rangle = \int O\, d\sigma = \int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\, [B(\mathbf{\Phi}_n) + V_b(\mathbf{\Phi}_n)] + \int d\mathbf{\Phi}_n\, d\Phi_r\, O(\mathbf{\Phi}_n, \Phi_r)\, R(\mathbf{\Phi}_n, \Phi_r)$$

- [Parametrized (n+1)-body phase space $\mathbf{\Phi}_{n+1}$ in terms of Born and radiation $\mathbf{\Phi}_{n+1} = \{\mathbf{\Phi}_n, \Phi_r\}$]

- Divergent parts can be regulated e.g. with a subtraction scheme:

$$\begin{aligned} \langle O \rangle &= \int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n) \left[B(\mathbf{\Phi}_n) + V_b(\mathbf{\Phi}_n) + \int d\Phi_r\, C(\mathbf{\Phi}_n, \Phi_r) \right] \\ &+ \int d\mathbf{\Phi}_n\, d\Phi_r\, \underbrace{[O(\mathbf{\Phi}_n, \Phi_r)\, R(\mathbf{\Phi}_n, \Phi_r) - O(\mathbf{\Phi}_n)\, C(\mathbf{\Phi}_n, \Phi_r)]}_{\text{finite}} \end{aligned}$$

- Defining:

$$V(\mathbf{\Phi}_n) = V_b(\mathbf{\Phi}_n) + \int d\Phi_r\, C(\mathbf{\Phi}_n, \Phi_r) \quad \Longleftarrow \text{ finite}$$

$$\langle O \rangle = \int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\, [B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n)] + \int d\mathbf{\Phi}_n\, d\Phi_r\, [O(\mathbf{\Phi}_n, \Phi_r)\, R(\mathbf{\Phi}_n, \Phi_r) - O(\mathbf{\Phi}_n)\, C(\mathbf{\Phi}_n, \Phi_r)]$$

PS vs NLO: pro and cons

NLO

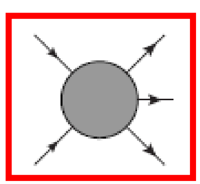
- ✓ Normalization accurate at NLO
- ✓ reduced scale uncertainties
- ✓ Accurate shapes at high p_T
- ✗ Limited multiplicity
- ✗ Fails on resummation regions

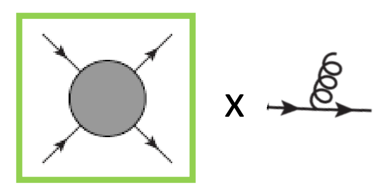
PS

- ✓ Sudakov suppression at small p_T
- ✓ Realistic & flexible (hadron level)
- ✗ Limited precision (LO uncertainty)
- ✗ Bad description at high pT

➡ Two approaches are very complementary: ideal to merge them trying to keep the good features of both!

PROBLEM: avoid double counting! First extra emission is accounted for in both..





Several ways exist: MC@NLO [Frixione, Webber 2001], POWHEG [Nason 2004]
and more recently also: KrKNLO, Vincia, Geneva

NLO+PS: the POWHEG method

NLO+PS combination: SMC accuracy vs NLO

- Let's consider again the SMC cross section for first emission:

$$\langle O \rangle = \int d\mathbf{\Phi}_n \, B(\mathbf{\Phi}_n) \left\{ O(\mathbf{\Phi}_n)\Delta_{t_0} + \int_{t_0} \frac{dt}{t} \, dz \, d\varphi \, O(\mathbf{\Phi}_n, \Phi_r) \, \Delta_t \, \frac{\alpha_s}{2\pi} P(z) \right\}$$

$$\text{with} \quad \Delta_t = \exp\left[- \int_t \frac{dt'}{t'} \, dz' \, d\varphi' \, \frac{\alpha_s}{2\pi} P(z') \right]$$

- Expand it in α_s to get NLO_{SMC}:

$$\langle O \rangle = \int d\mathbf{\Phi}_n \, B(\mathbf{\Phi}_n) \left\{ O(\mathbf{\Phi}_n) + \int_{t_0} \frac{dt}{t} \, dz \, d\varphi \left[O(\mathbf{\Phi}_n, \Phi_r) - O(\mathbf{\Phi}_n) \right] \frac{\alpha_s}{2\pi} P(z) \right\}$$

- This is the inexact NLO implemented in parton showers, as compared to the exact NLO:

$$\langle O \rangle = \int d\mathbf{\Phi}_n \, O(\mathbf{\Phi}_n) \left[B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) \right] + \int d\mathbf{\Phi}_n \, d\Phi_r \left[O(\mathbf{\Phi}_n, \Phi_r) \, R(\mathbf{\Phi}_n, \Phi_r) - O(\mathbf{\Phi}_n) \, C(\mathbf{\Phi}_n, \Phi_r) \right]$$

How do we reach exact NLO accuracy retaining shower resummation?

NLO+PS combination: towards NLO accuracy

$$\begin{aligned}\langle O\rangle &= \int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\,[B(\mathbf{\Phi}_n)+V(\mathbf{\Phi}_n)] \\ &+ \int d\mathbf{\Phi}_n\, d\Phi_r\,[O(\mathbf{\Phi}_n,\Phi_r)\,R(\mathbf{\Phi}_n,\Phi_r) - O(\mathbf{\Phi}_n)\,C(\mathbf{\Phi}_n,\Phi_r)] \\ &= \int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\left\{B(\mathbf{\Phi}_n)+V(\mathbf{\Phi}_n)+\int d\Phi_r\,[R(\mathbf{\Phi}_n,\Phi_r)-C(\mathbf{\Phi}_n,\Phi_r)]\right\} \\ &+ \int d\mathbf{\Phi}_n\, d\Phi_r\, R(\mathbf{\Phi}_n,\Phi_r)\,[O(\mathbf{\Phi}_n,\Phi_r)-O(\mathbf{\Phi}_n)]\end{aligned}$$

Define: $\overline{B}(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n)+V(\mathbf{\Phi}_n)+\int d\Phi_r\,[R(\mathbf{\Phi}_n,\Phi_r)-C(\mathbf{\Phi}_n,\Phi_r)]$

And rewrite this as:

$$\langle O\rangle = \int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\,\overline{B}(\mathbf{\Phi}_n) + \int d\mathbf{\Phi}_n\, d\Phi_r\, R(\mathbf{\Phi}_n,\Phi_r)\,[O(\mathbf{\Phi}_n,\Phi_r)-O(\mathbf{\Phi}_n)]$$

Very similar structure, but upper one accurate at NLO

Let's compare it again to the NLO_{SMC}:

$$\langle O\rangle = \int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\,B(\mathbf{\Phi}_n) + \int d\mathbf{\Phi}_n\, d\Phi_r\, B(\mathbf{\Phi}_n)\,\frac{\alpha_s}{2\pi}\,P(z)\,\frac{1}{t}\,[O(\mathbf{\Phi}_n,\Phi_r)-O(\mathbf{\Phi}_n)]$$

NLO+PS combination: POWHEG

In summary: $\mathrm{NLO}_{\mathrm{SMC}} \leftrightarrow \mathrm{NLO}:$ $B(\mathbf{\Phi}_n) \leftrightarrow \overline{B}(\mathbf{\Phi}_n)$ $B(\mathbf{\Phi}_n)\frac{\alpha_s}{2\pi}P(z)\frac{1}{t} \leftrightarrow R(\mathbf{\Phi}_n, \Phi_r)$

Back to all order: the emission probability in SMC was

$$\langle O \rangle = \int d\mathbf{\Phi}_n \, B(\mathbf{\Phi}_n) \left\{ O(\mathbf{\Phi}_n)\, \Delta_{t_0} + \int_{t_0} d\Phi_r \, O(\mathbf{\Phi}_n, \Phi_r)\, \Delta_t \, \frac{\alpha_s}{2\pi} P(z)\, \frac{1}{t} \right\}$$

with $$\Delta_t = \exp\left[-\int d\Phi_r' \, \frac{\alpha_s}{2\pi} P(z')\, \frac{1}{t'}\, \theta(t'-t) \right]$$

All order emission probability in POWHEG:

$$\langle O \rangle = \int d\mathbf{\Phi}_n \, \overline{B}(\mathbf{\Phi}_n) \left\{ O(\mathbf{\Phi}_n)\, \Delta_{t_0} + \int d\Phi_r \, O(\mathbf{\Phi}_n, \Phi_r)\, \Delta_t \, \frac{R(\mathbf{\Phi}_n, \Phi_r)}{B(\mathbf{\Phi}_n)} \right\}$$

$$\Delta_t = \exp\left[-\int d\Phi_r' \, \frac{R(\mathbf{\Phi}_n, \Phi_r')}{B(\mathbf{\Phi}_n)}\, \theta(t'-t) \right]$$

with $t = k_T(\mathbf{\Phi}_n, \Phi_r)$ and $\overline{B}(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \int d\Phi_r \left[R(\mathbf{\Phi}_n, \Phi_r) - C(\mathbf{\Phi}_n, \Phi_r) \right]$

POSITIVE if $\overline{B}$ is positive (i.e. NLO < LO).

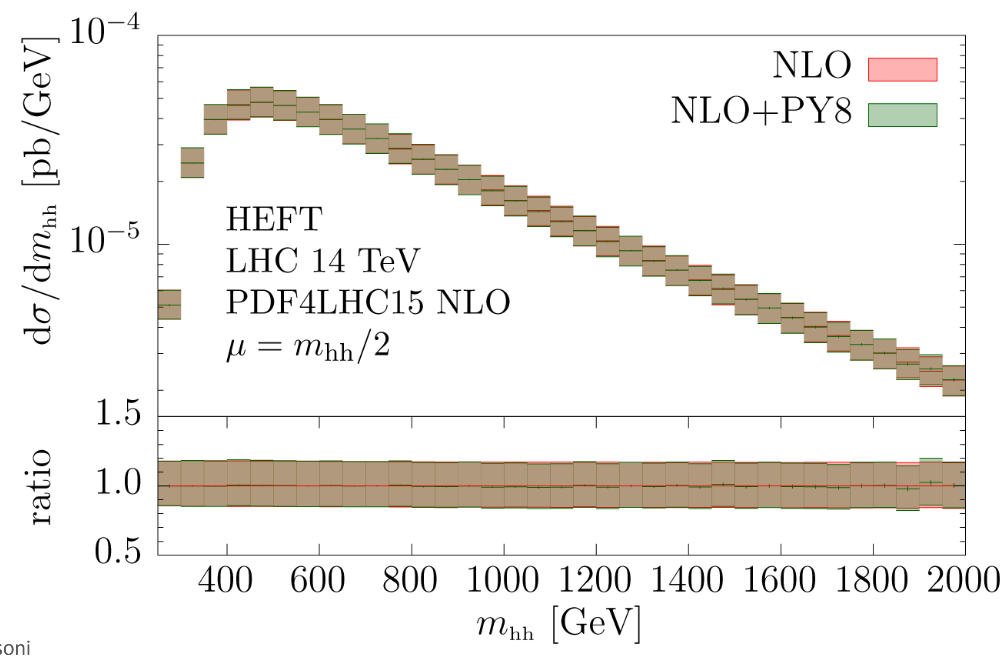
Phenomenological impact

- What is the impact of PS corrections to NLO?
- What should stay unchanged, what could/should instead change?

- Consider most recent POWHEG implementation: HH-production

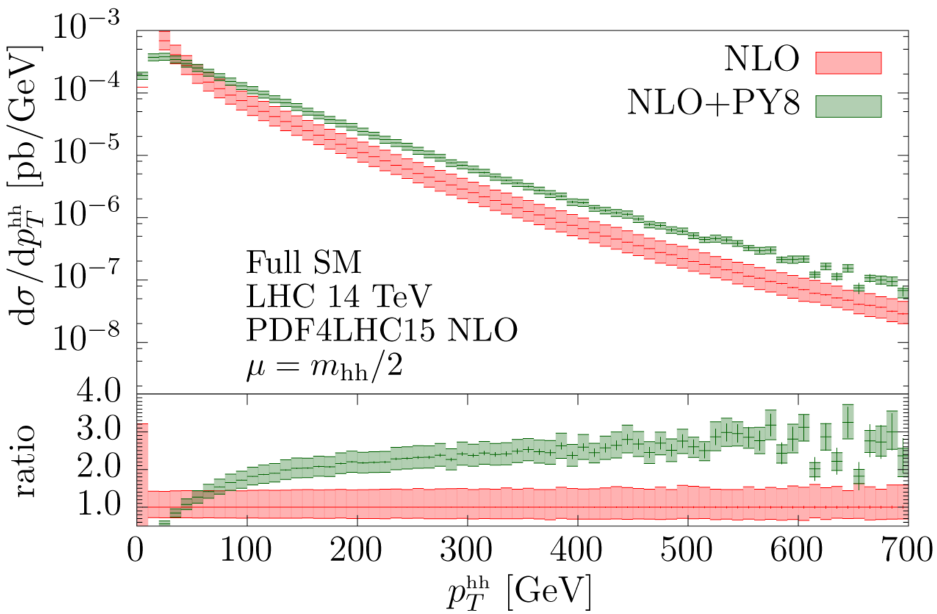
[Heinrich, Jones, Kerner, G.L., Vryonidou to appear Wednesday]

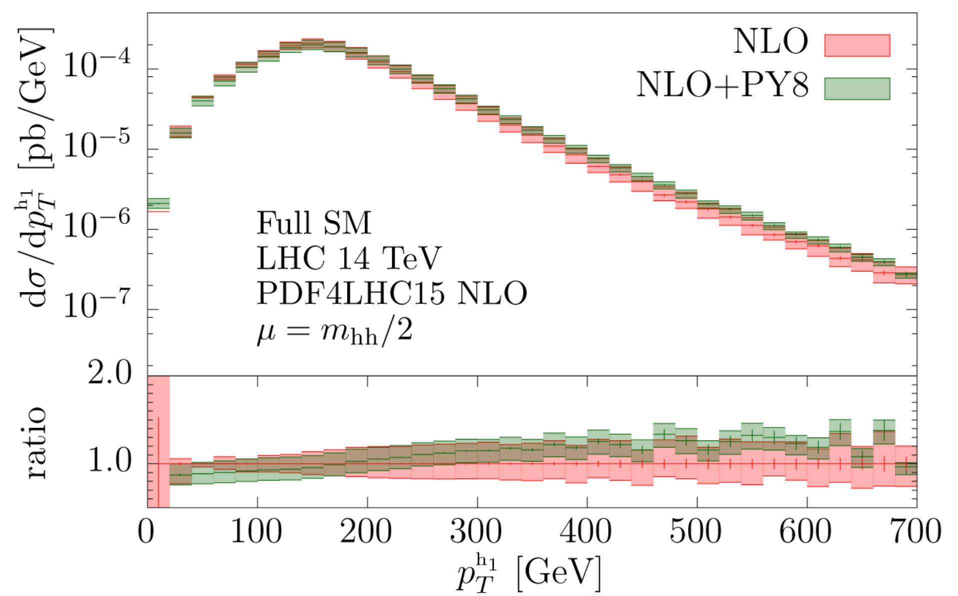
➢ Parton shower cannot affect observables inclusive in the radiation:



Phenomenological impact

- Parton shower should instead modify the shape of observable sensitive to QCD (QED) radiation





Conclusions and Outlook

- Fixed order computation and parton showers are two complementary approaches to compute a cross section
  - Describe two different regimes in a particle scattering
- Best solution is to combine (match) them together!
- POWHEG is one possible matching scheme
- NLO+PS has been extended to merge different multiplicity calculations at NLO and match them to PS:

  MiNLO   MEPS@NLO   FxFx   UNLOPS

- In meanwhile first schemes exist for NNLO+PS matching: this is the future!