

LHC Physics at High Luminosity and High Precision

Fermilab Users Meeting 2018

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Some tough questions

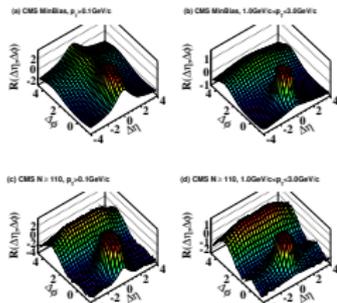
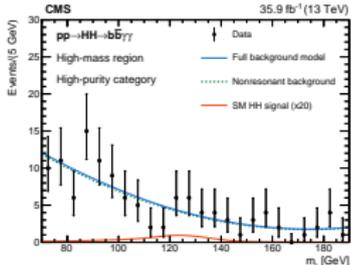
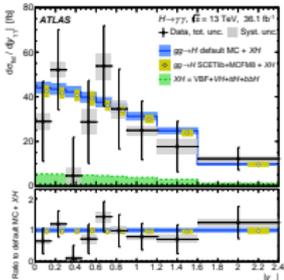
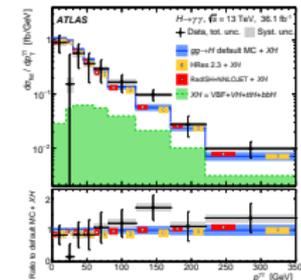
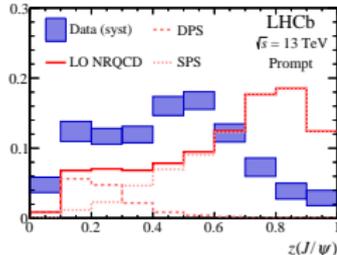
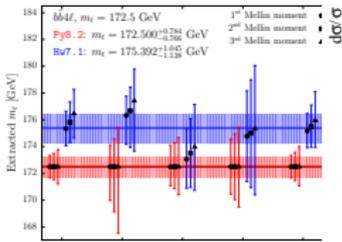
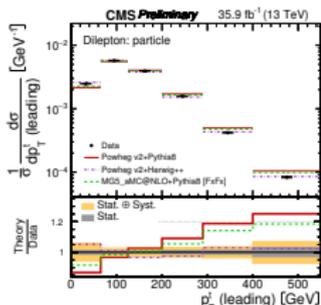
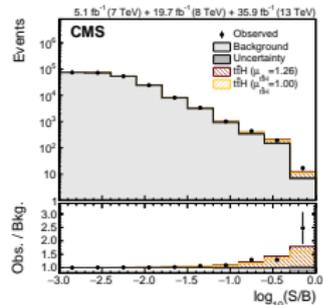
Can we hope that new physics will show up at 13/14 TeV if it was not seen already?

Will the next 20 years at LHC be dominated by indirect limit setting and calculating loops?

Should we look for new search strategies?

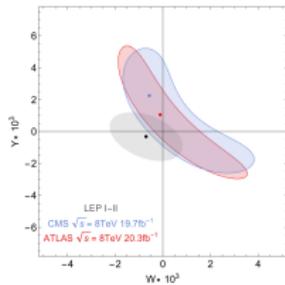
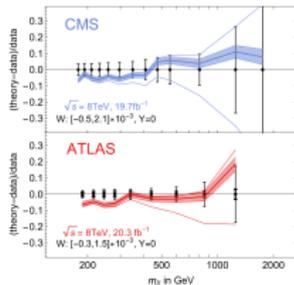
Motivational plots

from CMS-PAS-TOP-17-014, arXiv:1804.02610, 1701.05116, 1802.04146, 1806.00408, 1009.4122, 1609.08157

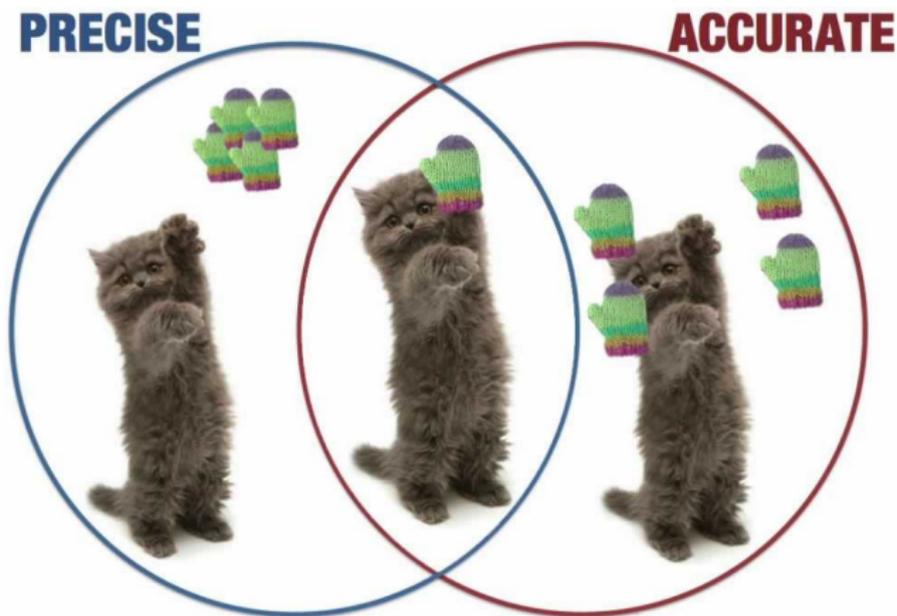


→ Still huge potential.

The energy frontier is becoming the **precision frontier!**



The case for precision calculations

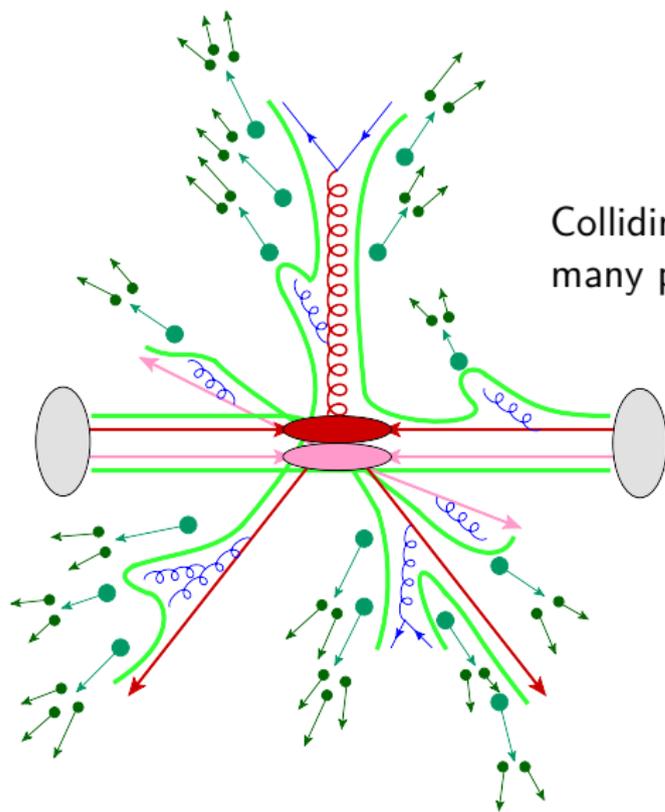


Secret hope: More precise for simple processes
→ More accurate for less simple processes.

Indirect bounds: Accurate predictions \leftrightarrow Better analyses

Accurate+precise theory tools \rightarrow better control of backgrounds & signals.

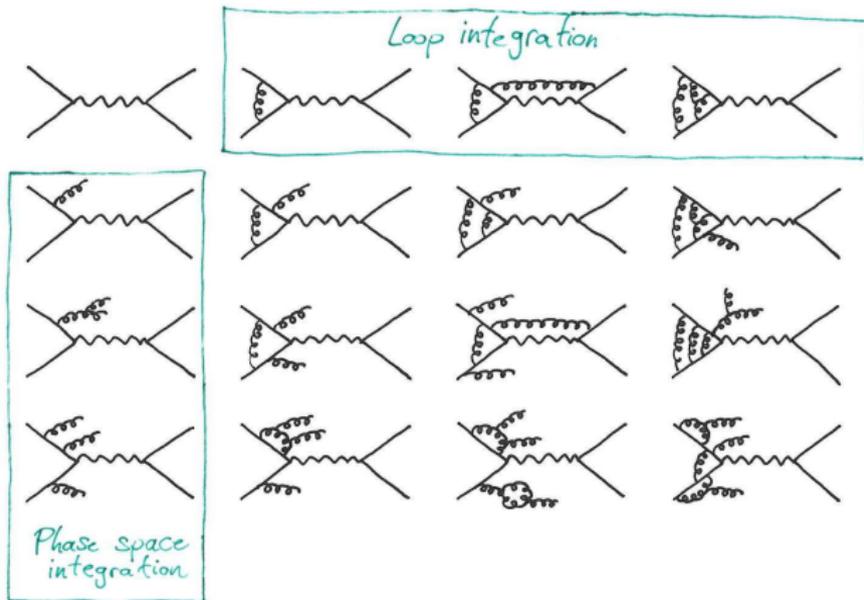
Colliding composite objects kick-starts many processes:



- hard scattering
- radiation cascade
- multiparton interactions
- hadronization and decay

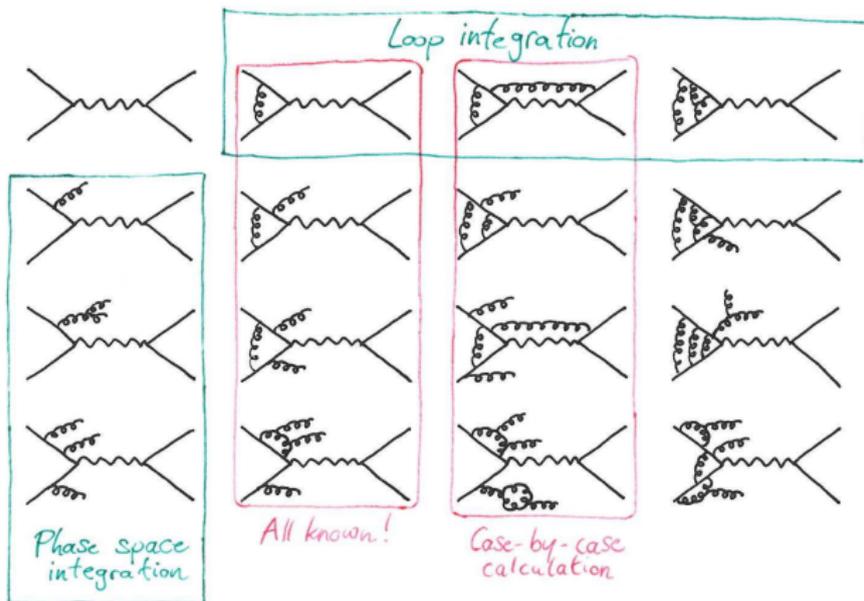
Need precision in all of these!

Calculating short-distance scattering cross sections



Perturbation theory...a quest for integrals.

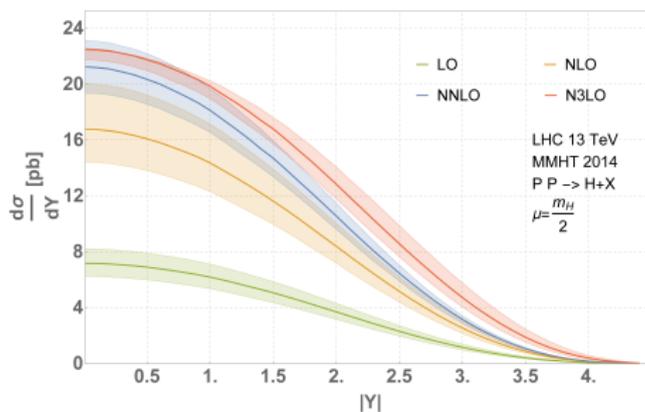
Calculating short-distance scattering cross sections



Perturbation theory...a quest for integrals. And we're still missing many beyond nex-to-leading order.

Short-distance records: Higgs production

Plot from arXiv:1710.03016, see also 1802.00833



Higher-order corrections to $gg \rightarrow H$ are very large – but brute-force “by-hand” calculations at

Next-to-next-to-next-to leading order (N³LO)

show the stabilization of perturbation theory.

Going differential @ NNLO

Plot from arXiv:1603.02663

Problem: Regularize IR divergences in loops/reals
...in four dimensions
...event-by-event

“Slicing”

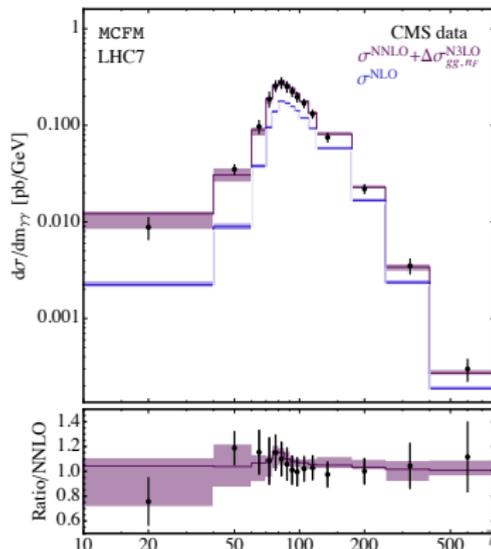
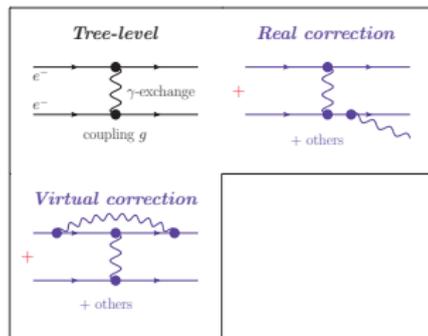
$$\sigma = [c + \ln(\text{cut})] f(0) + \int_{\text{cut}} dz \frac{f(z)}{z}$$

“Subtraction”

$$\sigma = [c + ct] f(0) + \int dz \frac{f(z) - f(0)}{z}$$

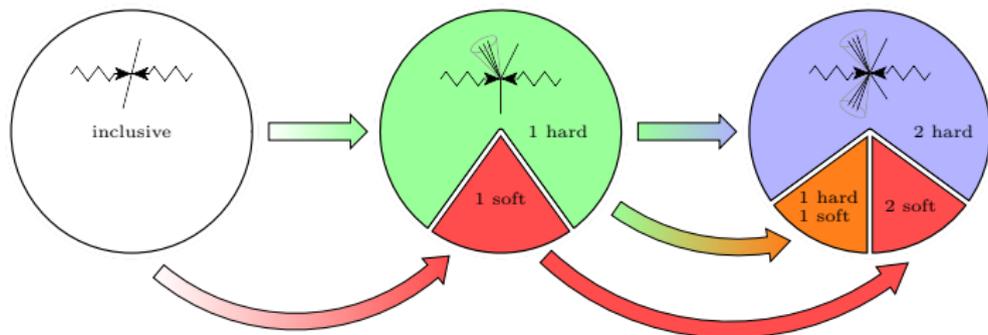
Subtraction methods dominate @ NLO.

Slicing popular @ NNLO.



Combining calculations

Plot from arXiv:1705.06700



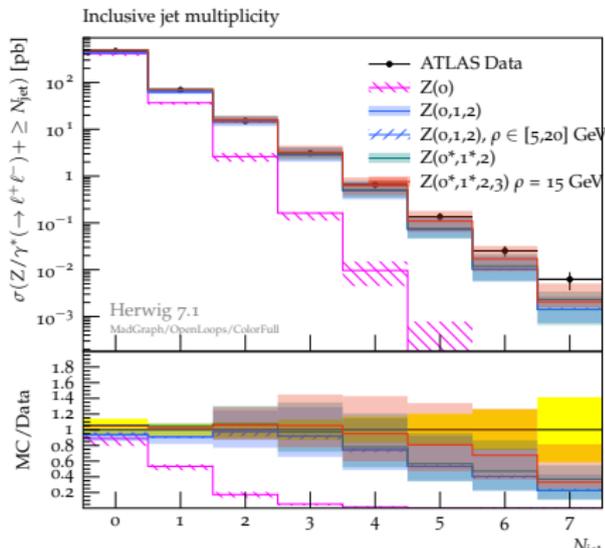
NLO SM (QCD) everywhere now considered minimum requirement.

Automatic NLO calculations for arbitrary processes are available.

Most flexible predictions obtained by combining many calculations.

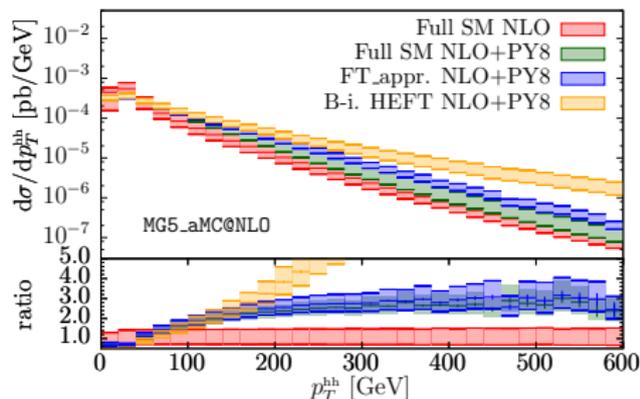
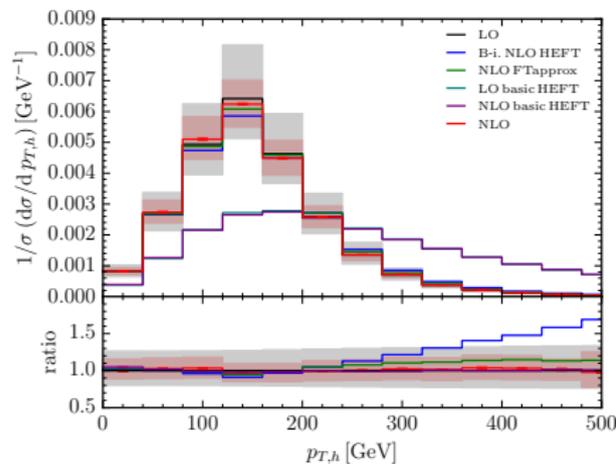
Problem here: Remove overlap!

⇒ **“Matching & merging”**



Double Higgs production

Plots from arXiv:1608.04798, 1703.09252



Understand the Higgs sector \Leftrightarrow understand the Higgs potential.

$\Rightarrow gg \rightarrow HH$ production very important at HL-LHC.

Second Higgs resolves the loop! Large m_t limit breaks down

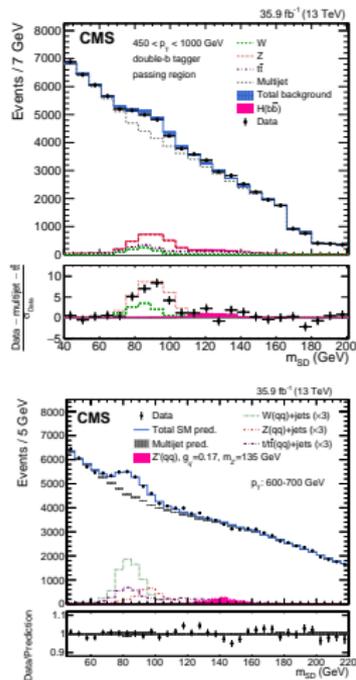
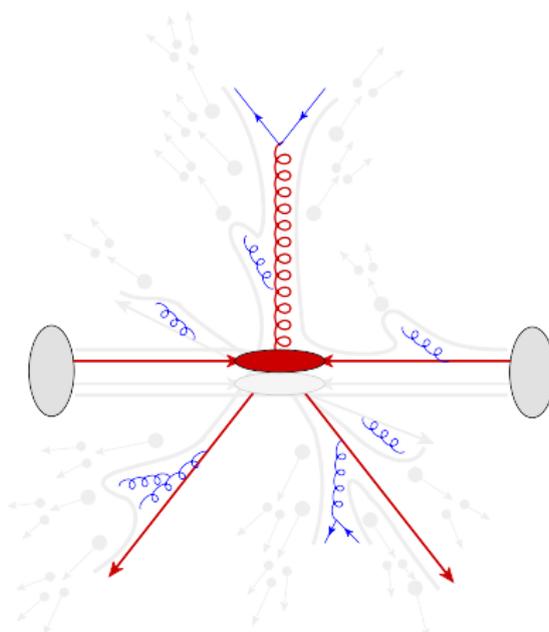
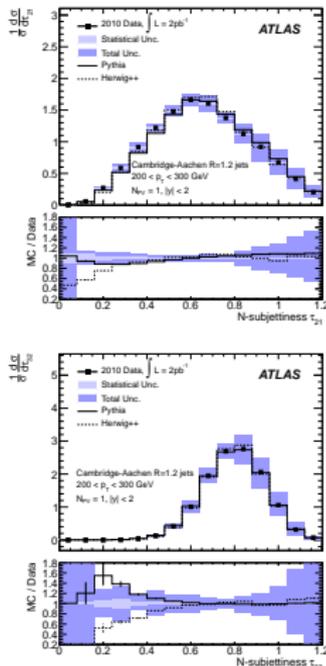
\Rightarrow Everything is one loop more difficult.

Very large phase space for further radiative corrections!

\Rightarrow Large impact of / uncertainty from radiative parton shower cascade.

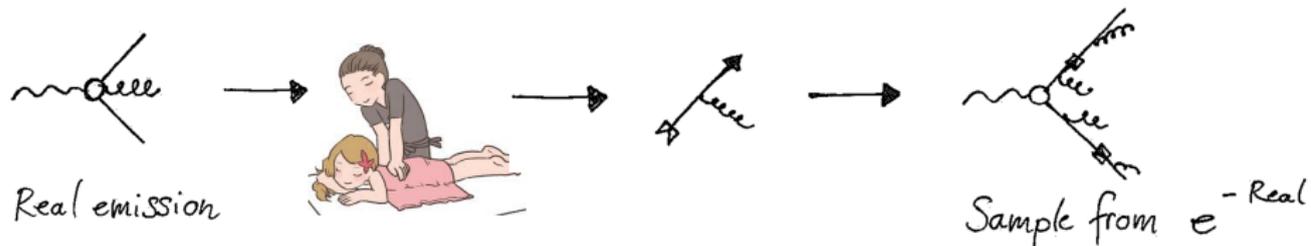
Parton showering

Plots from arXiv:1709.05543, 1710.00159, 1203.4606



Redistributes high- E particles & moments over many low-energy quanta.
 Crucial part of physics modeling, required for jet structure and evolution.
 → Improvements unlock data for precision measurements & bounds.

From fixed-order to all-order calculations



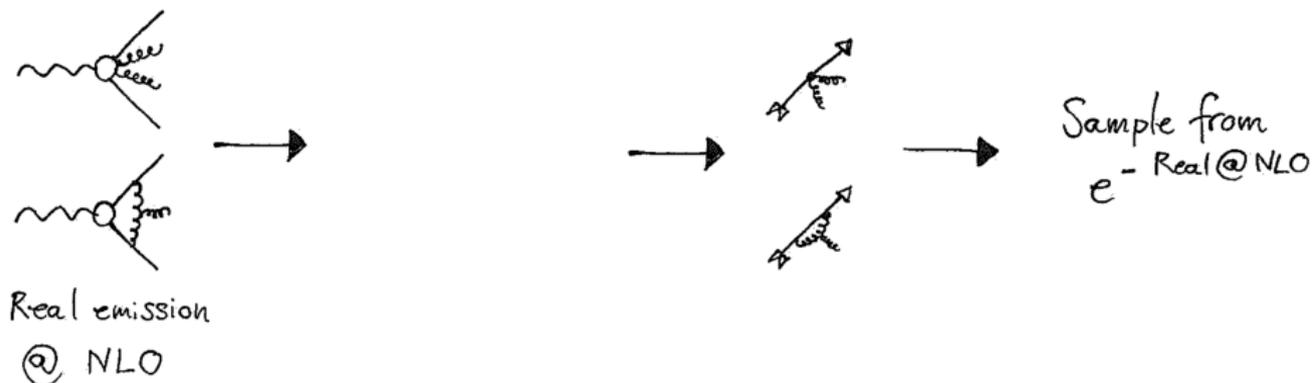
Parton shower how-to:

- ◇ Take real emission matrix element
- ◇ Massage to factorize universal emission kernels.
- ◇ Successively draw new branchings from **survival probability** e^{-Real}

⇒ Produces all-order results for (massless) theories in soft/collinear limits.

Parton showering beyond lowest order

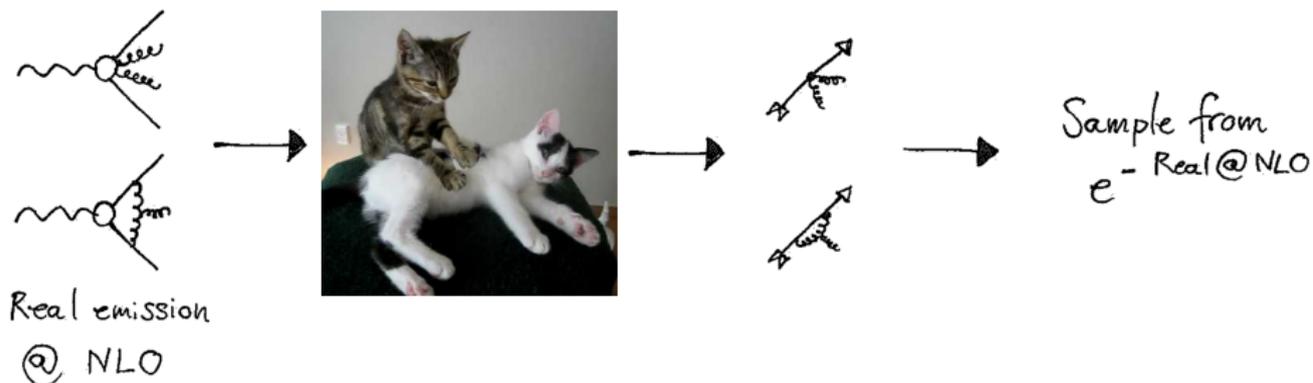
So a precise shower should be easy, right? Just bring out the big...



Complete “NLO jet evolution” tools still missing, but important to leverage full LHC potential!

Parton showering beyond lowest order

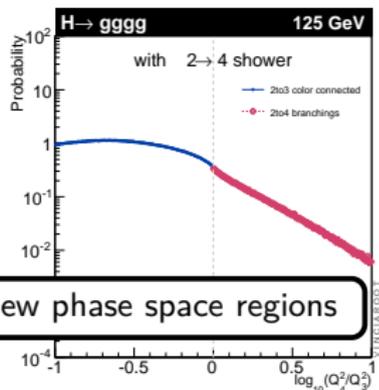
So a precise shower should be easy, right? Just bring out the big...kittens



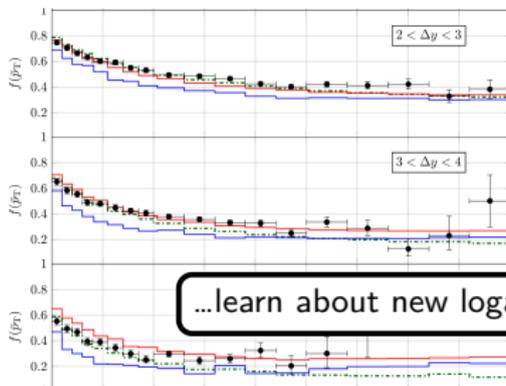
Complete “NLO jet evolution” tools still missing, but important to leverage full LHC potential!

Parton showering: Sample results beyond lowest order

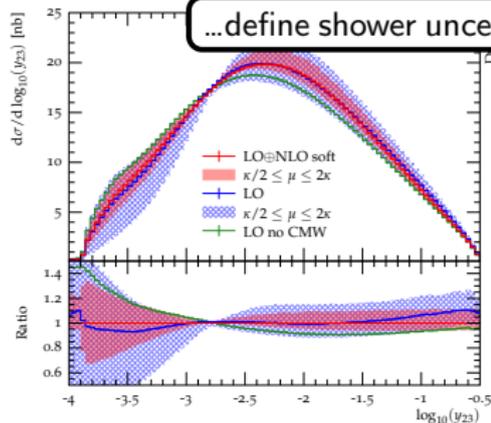
See arXiv:1611.00013, arXiv:1705.08093, arXiv:1711.02369, arXiv:1805.03757



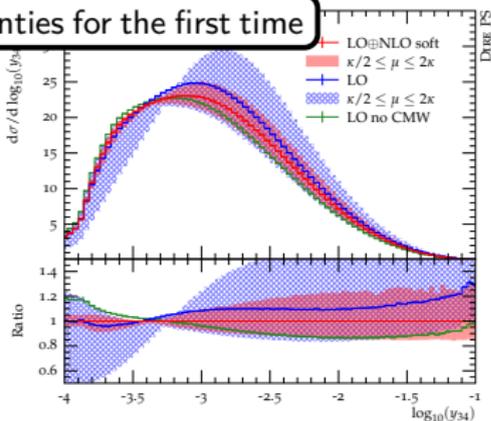
...reach new phase space regions



...learn about new logarithms



...define shower uncertainties for the first time

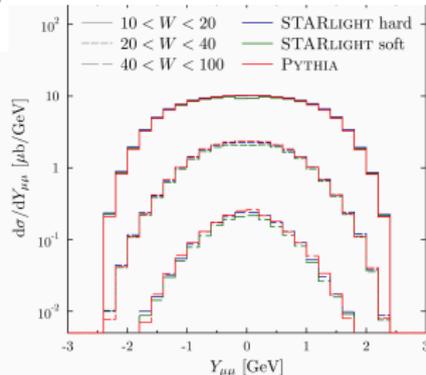
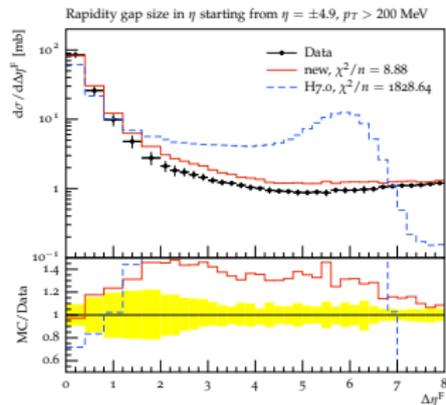
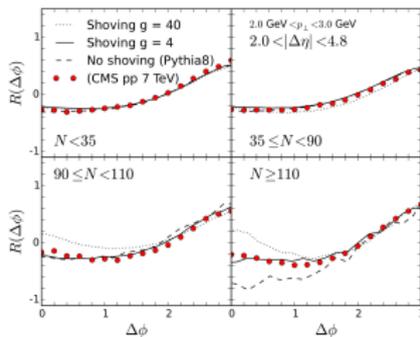
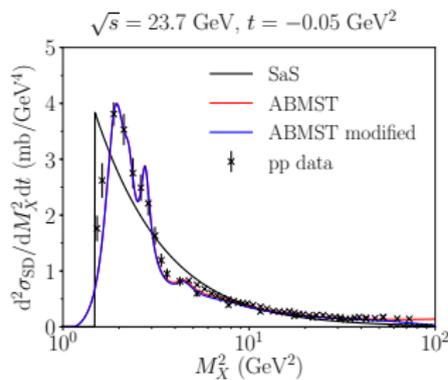


Beyond order counting

Plots from arXiv:1804.10373, 1710.09725, 1612.04701 & based on 1708.09759

LHC has *much more data* than analyzed for precision measurements – because some effects can't be calculated using a neat order-by-order counting.

⇒ Better calculations here can unlock whole new fields of study!



SUMMARY

The HL LHC will make the energy frontier into the precision frontier.

Measuring the Higgs & Yukawa sector will be crucial.

Precise fixed-order and all-order perturbative calculations will be necessary for both precision measurements and for indirect limits.

Much potential for unexpected results, we only need the calculations!

SUMMARY

The HL LHC will make the energy frontier into the precision frontier.

Measuring the Higgs & Yukawa sector will be crucial.

Precise fixed-order and all-order perturbative calculations will be necessary for both precision measurements and for indirect limits.

Much potential for unexpected results, we only need the calculations!

Thanks! Time to wake up!

